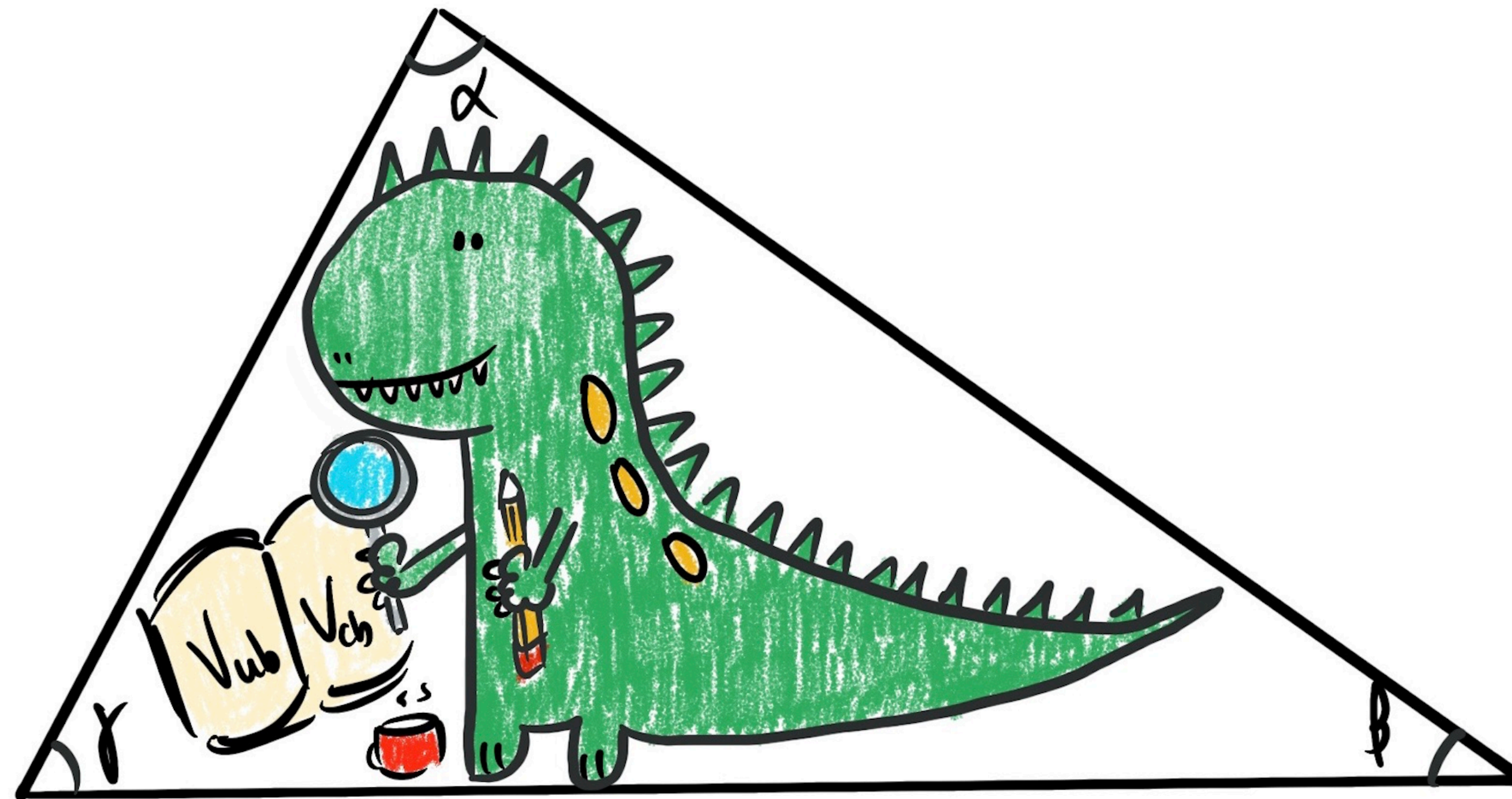


Flavour Physics

Yasmine Amhis
IDPASC school



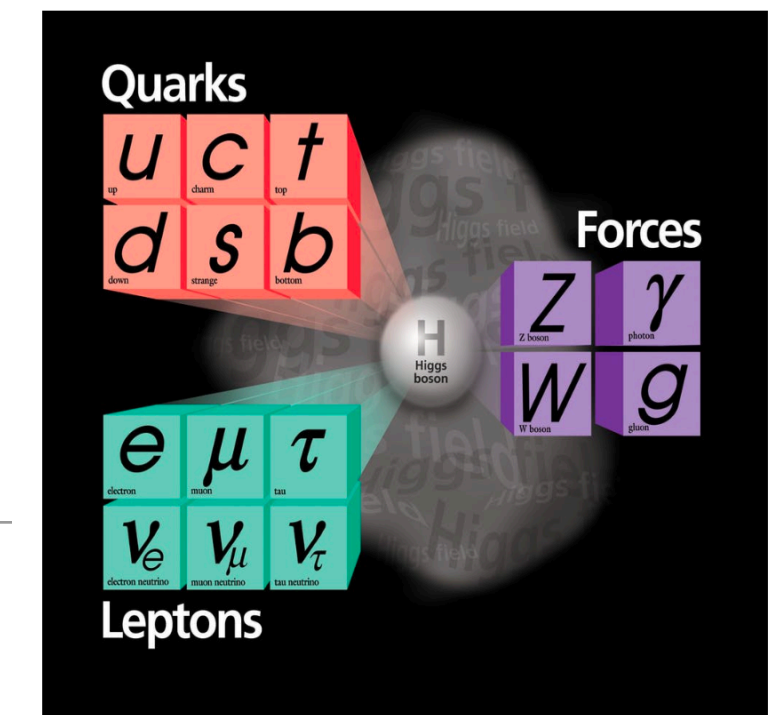
July 2025

Quick survey of the room

A lot of material taken from previous lectures of mine but also from Mark Williams, Tim Gershon, Gerhard Raven, Andreas Hocker, Gino Isidori, Yosef Nir and others I probably forgot.



Disclaimer



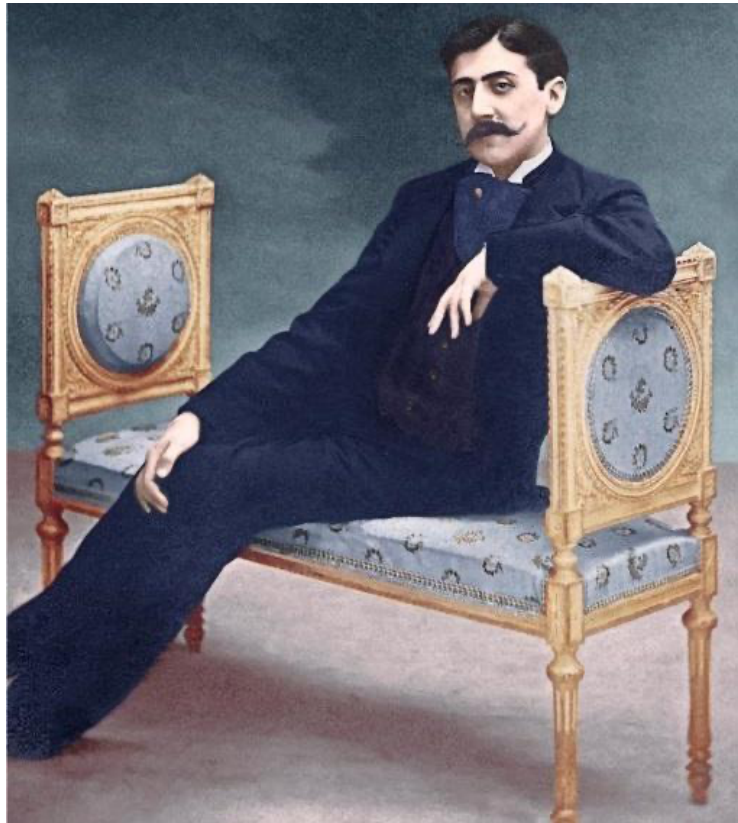
Flavour Physics is packed with Jargon (K , π , D^* , K^* , ADS, C_9 , OS etc.)

However the underlying physics is fascinating

Rich phenomenology and experimental techniques

Exciting implications !

Please bare with me



A hitchhiker guide to flavour physics

Questionnaire de Proust

What is the observable?

A branching ratio? A phase?

What is the process? A penguin? A tree?

What are we testing/measuring? NP? SM?

What is the statistics? Rare decay? Normalisation ?

What is the topology of the decay?

Are we ever going to see it?

What about the systematics?

Do we really care about it?

If you are lost go back to these questions

Structure of these lectures

- Examples of historical/recent measurements.
- What makes them experimentally challenging? Blood sweat & tears.
- How do we loop back to the underlying phenomenology ?



The Standard Model



A very powerful predictive theory which has resisted many decades of experimentalist trying to “break it”.
Yet, given that the SM can not explain...

* Need to add neutrino mass (Majorana or Dirac?)

Motivation for BSM

Plausible EFT Solutions

- Dark matter
- Baryon asymmetry
- Strong CP
- Fermion masses and mixings
- Grand unification

Challenge EFT Paradigm

- Hierarchy problem
- Cosmological constant
- Initial conditions for inflation / Eternal inflation
- UV completion of gravity





What is Flavour Physics?



WIKIPEDIA
The Free Encyclopedia

Flavour (particle physics)

In [particle physics](#), **flavour** or **flavor** refers to the *species* of an [elementary particle](#). The [Standard Model](#) counts six flavours of [quarks](#) and six flavours of [leptons](#). They are conventionally parameterized with *flavour quantum numbers* that are assigned to all [subatomic particles](#). They can also be described by some of the [family symmetries](#) proposed for the quark-lepton generations.

0.511 MeV/c²
-1
½ **e**
electron

105.7 MeV/c²
-1
½ **μ**
muon

1.777 GeV/c²
-1
½ **τ**
tau

<2.2 eV/c²
0
½ **ν_e**
electron neutrino

<0.17 MeV/c²
0
½ **ν_μ**
muon neutrino

<15.5 MeV/c²
0
½ **ν_τ**
tau neutrino

Coined by Gell-mann and Fritsch on visit to ice cream parlour (Pasadena, 1971)
“Just as ice cream has both color and flavor so do quarks.”



fermions (Matter)

Quarks

u u u

c c c

t t t

d d d

s s s

b b b

Leptons

e

μ

τ

ν_e

ν_μ

ν_τ

x

Matter

antimatter

Bosons (forces)

g g g g g g g g

γ

w^+

w^-

Z

H

What do we have within the Standard Model ?

3 gauge couplings

2 Higgs parameters

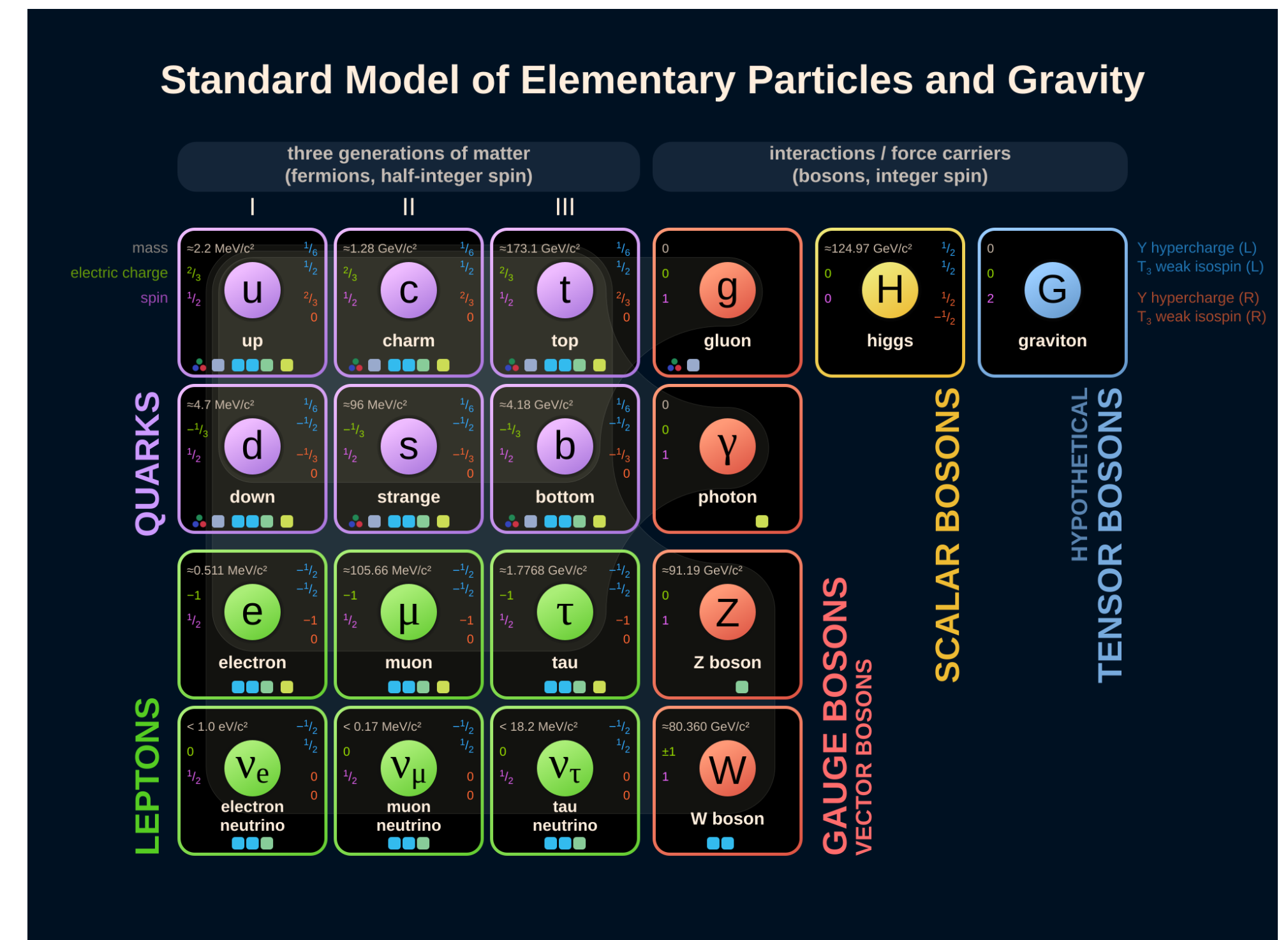
6 quark masses

3 quark mixing angles + 1 phase

3 (+3) lepton masses

(3 lepton mixing angles + 1 phase)

() = with Dirac neutrino masses



What do we have within the Standard Model ?

3 gauge couplings

2 Higgs parameters

6 quark masses

3 quark mixing angles + 1 phase

3 (+3) lepton masses

(3 lepton mixing angles + 1 phase)

() = with Dirac neutrino masses

Flavour Physics

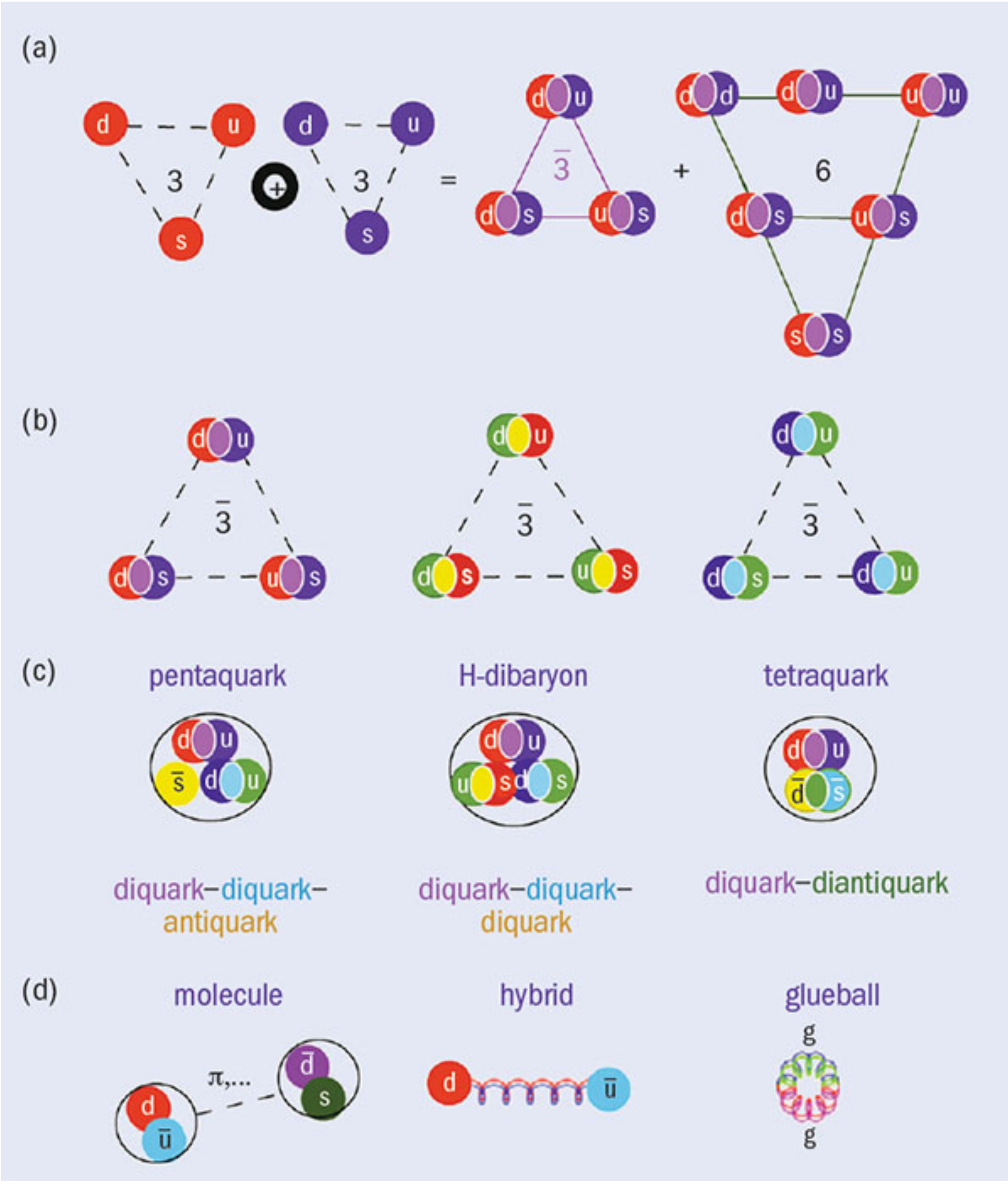
CKM

PMNS

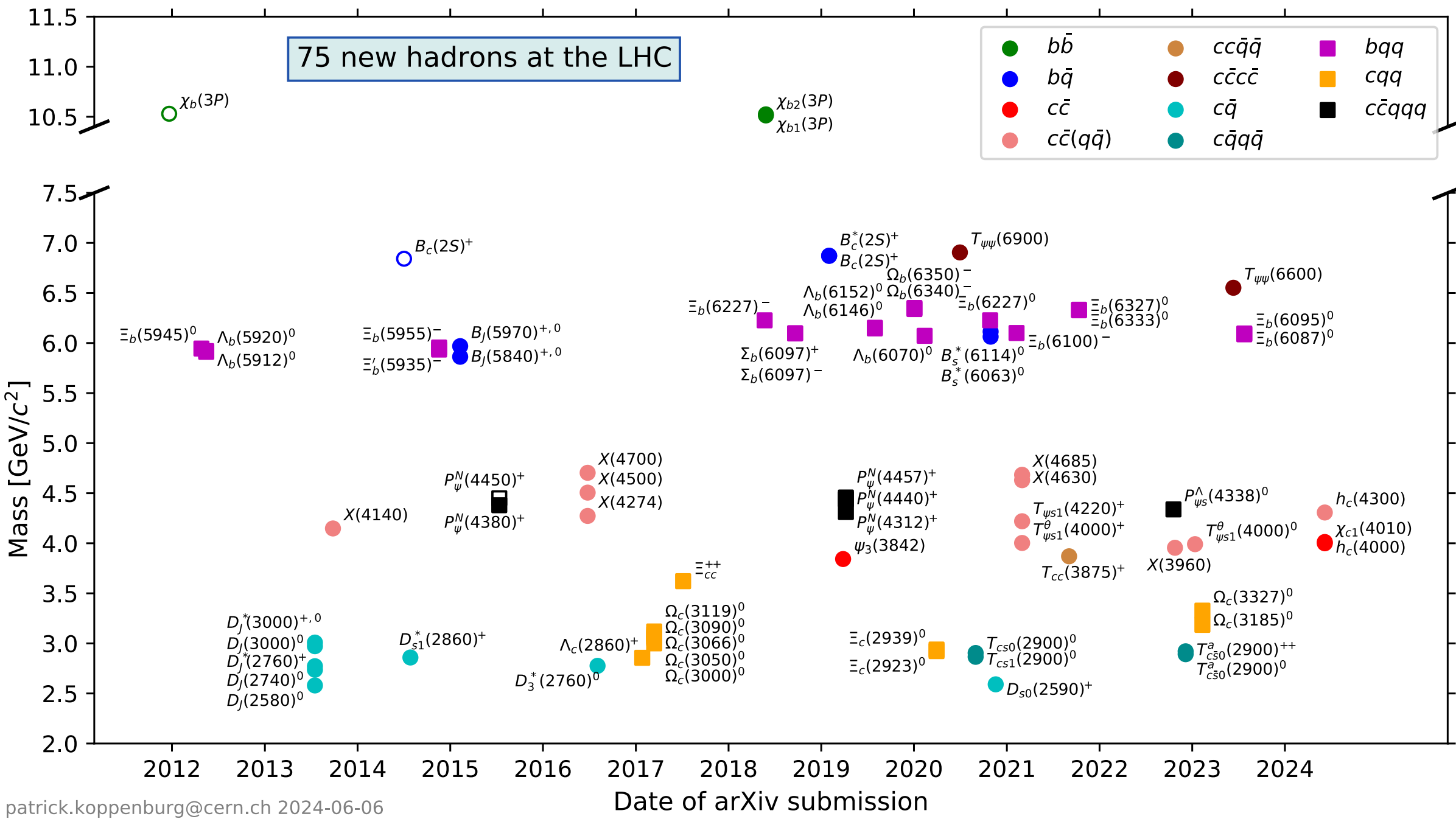


Hadrons !

One fundamental particle was discovered at the LHC so far...but also 75 new hadrons at the LHC



<https://cerncourier.com/a/exotic-hadrons-bend-the-rules/>



Hadron

Article Talk

From Wikipedia, the free encyclopedia

(Redirected from **Hadrons**)

In **particle physics**, a **hadron** (/ˈhædrɒn/ ⓘ ⓘ; from Ancient Greek ἁδρός (*hadrós*) 'stout, thick') is a **composite subatomic particle** made of two or more **quarks held together** by the **strong interaction**. They are analogous to **molecules**, which are held together by the **electric force**. Most of the **mass** of ordinary **matter** comes from two hadrons: the **proton** and the **neutron**, while most of the mass of the protons and neutrons is in turn due to the **binding energy** of their constituent quarks, due to the strong force.

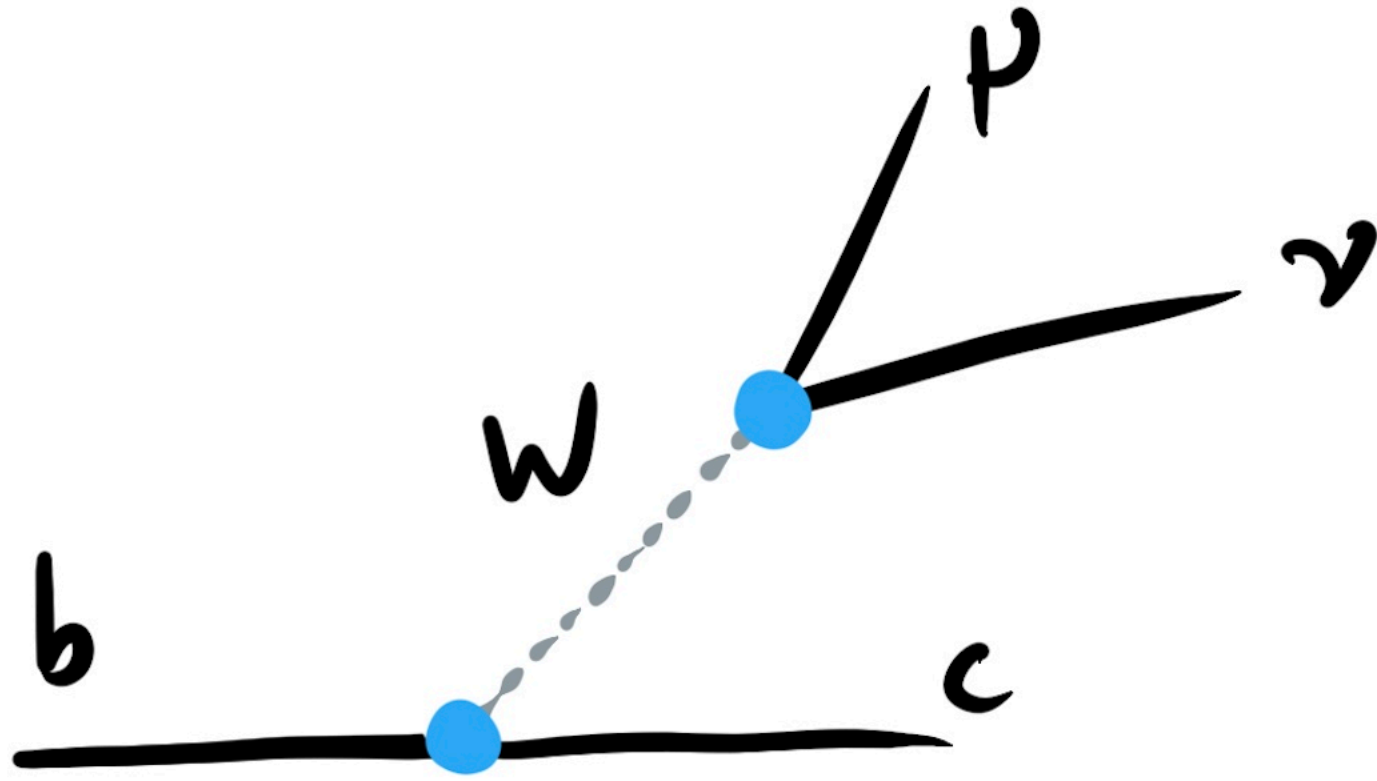
Hadrons are categorized into two broad families: **baryons**, made of an odd number of **quarks** (usually three quarks) and **mesons**, made of an even number of quarks (usually two quarks: one quark and one **antiquark**).^[1] Protons and neutrons (which make the majority of the mass of an **atom**) are examples of baryons; **pions** are an example of a meson. "Exotic" **hadrons**, containing more than three valence quarks, have been discovered in recent years. A **tetraquark** state (an **exotic meson**), named the **Z(4430)[−]**, was discovered in 2007 by the **Belle Collaboration**^[2] and confirmed as a resonance in 2014 by the **LHCb** collaboration.^[3] Two **pentaquark** states (**exotic baryons**), named **P_c⁺(4380)** and **P_c⁺(4450)**, were discovered in 2015 by the **LHCb** collaboration.^[4] There are several more exotic hadron candidates and other colour-singlet quark combinations that may also exist.

A hadron is a composite **subatomic particle**. Every hadron must fall into one of the two fundamental classes of particle, **bosons** and **fermions**

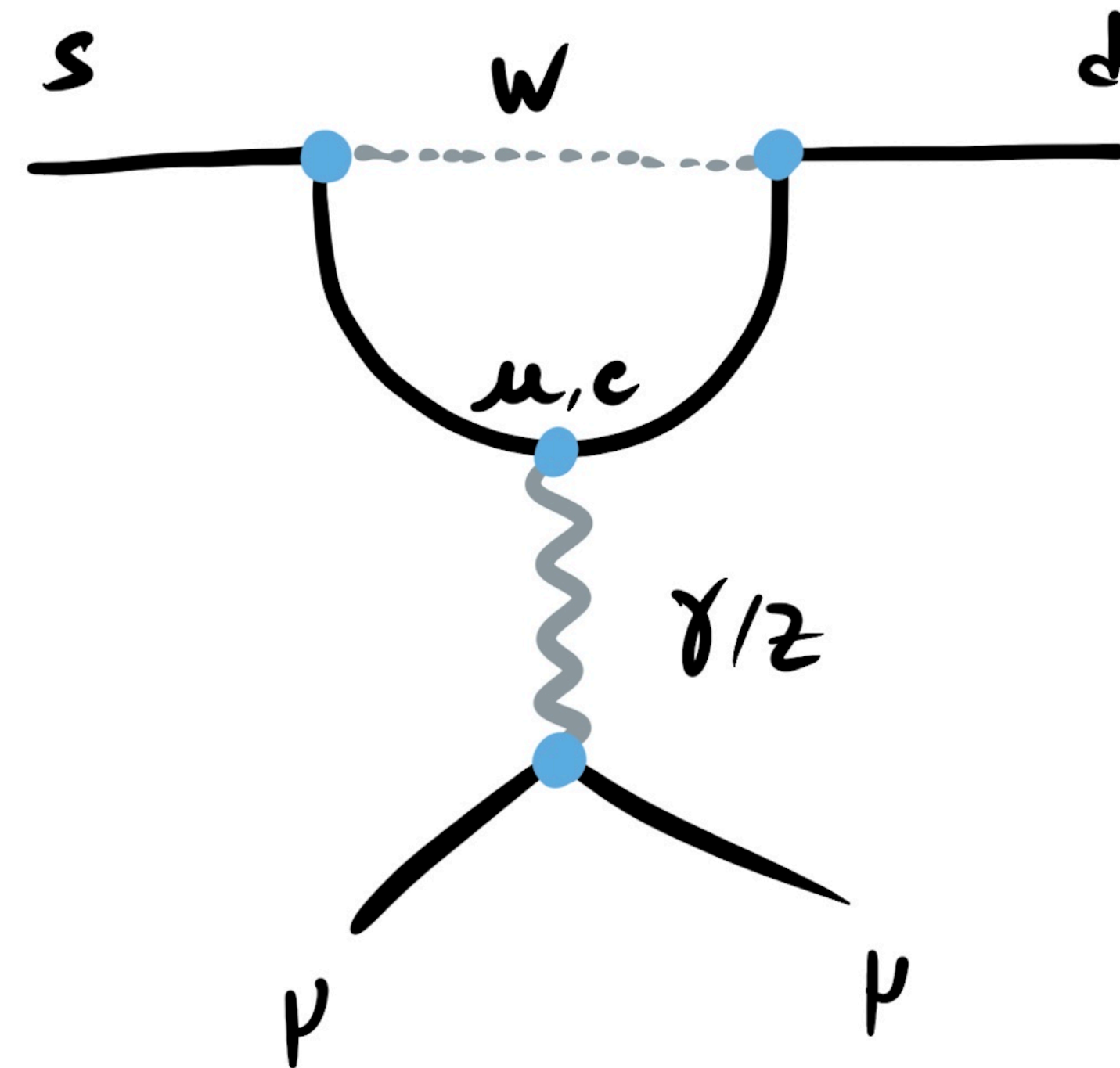
This is the land of spectroscopy !

Trees vs penguins

Flavour Changing Charged Currents

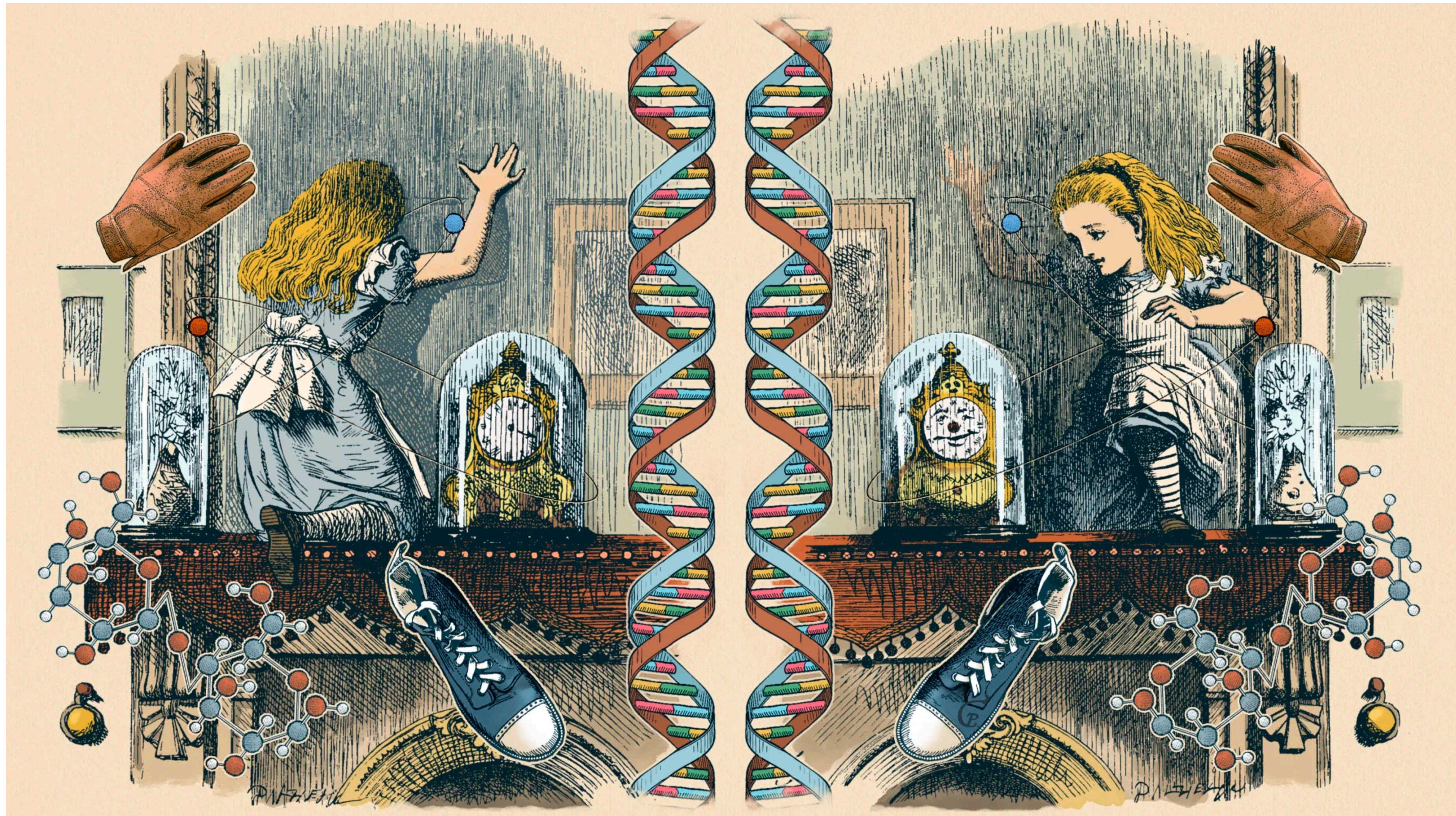


Flavour Changing Neutral Currents



Rule of thumb: you can't access all the parameters at once
you have to pick your battles

Discrete symmetries



Discrete Symmetries

Discrete symmetry transformations lead to multiplicative conservation laws

The following discrete transformations are fundamental in particle physics:

☀ **Parity P (“handedness”):**

reflection of space around an arbitrary center;
 P invariance $\rightarrow$ physics does not distinguish *right* and *left*

☀ **Particle-antiparticle transformation C :**

change of all additive quantum numbers (for example the electrical charge) in its opposite (“charge conjugation”)

☀ **Time reversal T :**

the time arrow is reversed in the equations;
 T invariance $\rightarrow$ if a movement is allowed by a the physics law, the movement in the opposite direction is also allowed

In particle physics:

$$P|e_L^-\rangle = |e_R^-\rangle$$

$$P|\pi^0\rangle = -|\pi^0\rangle$$

$$P|n\rangle = +|n\rangle$$

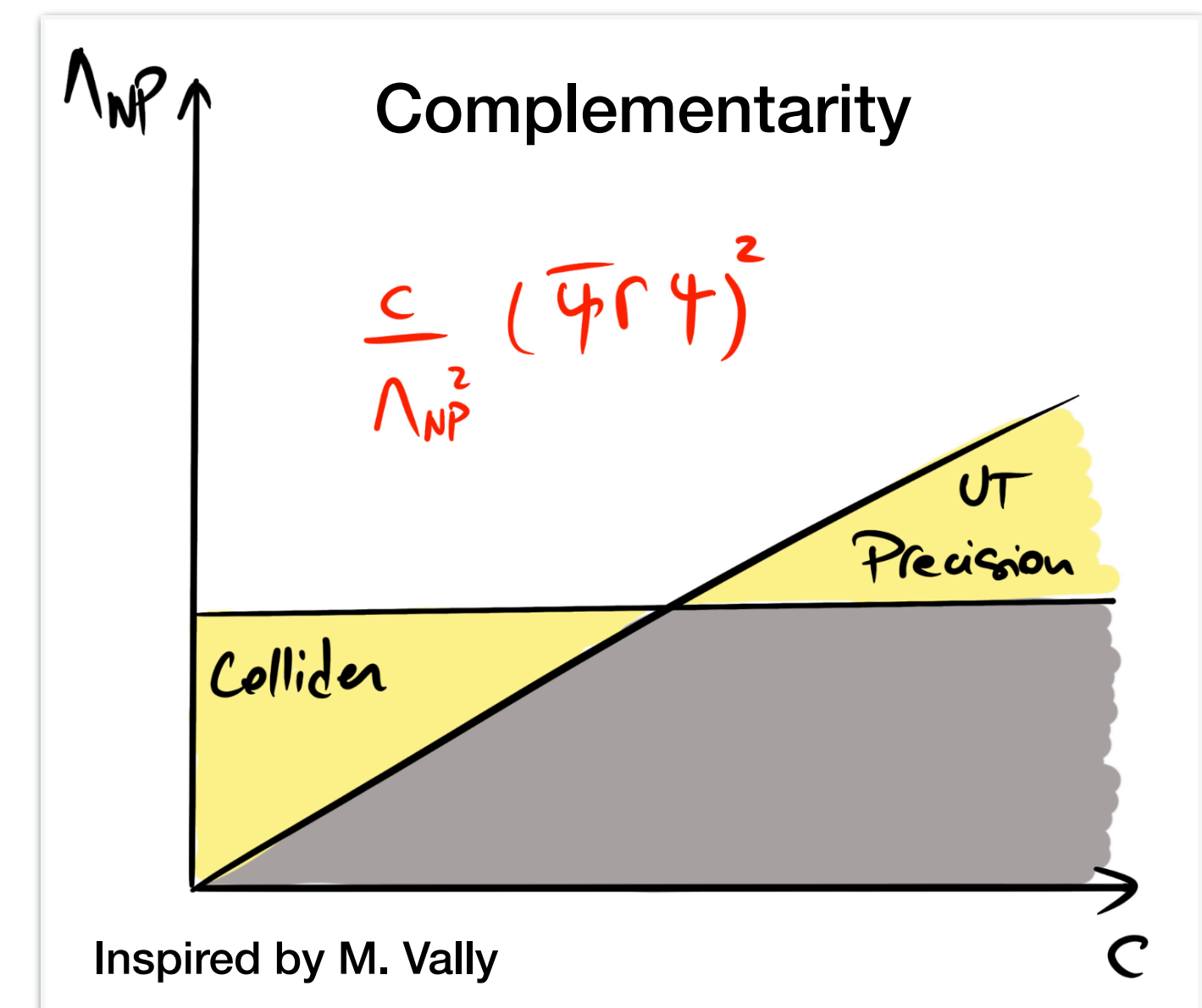
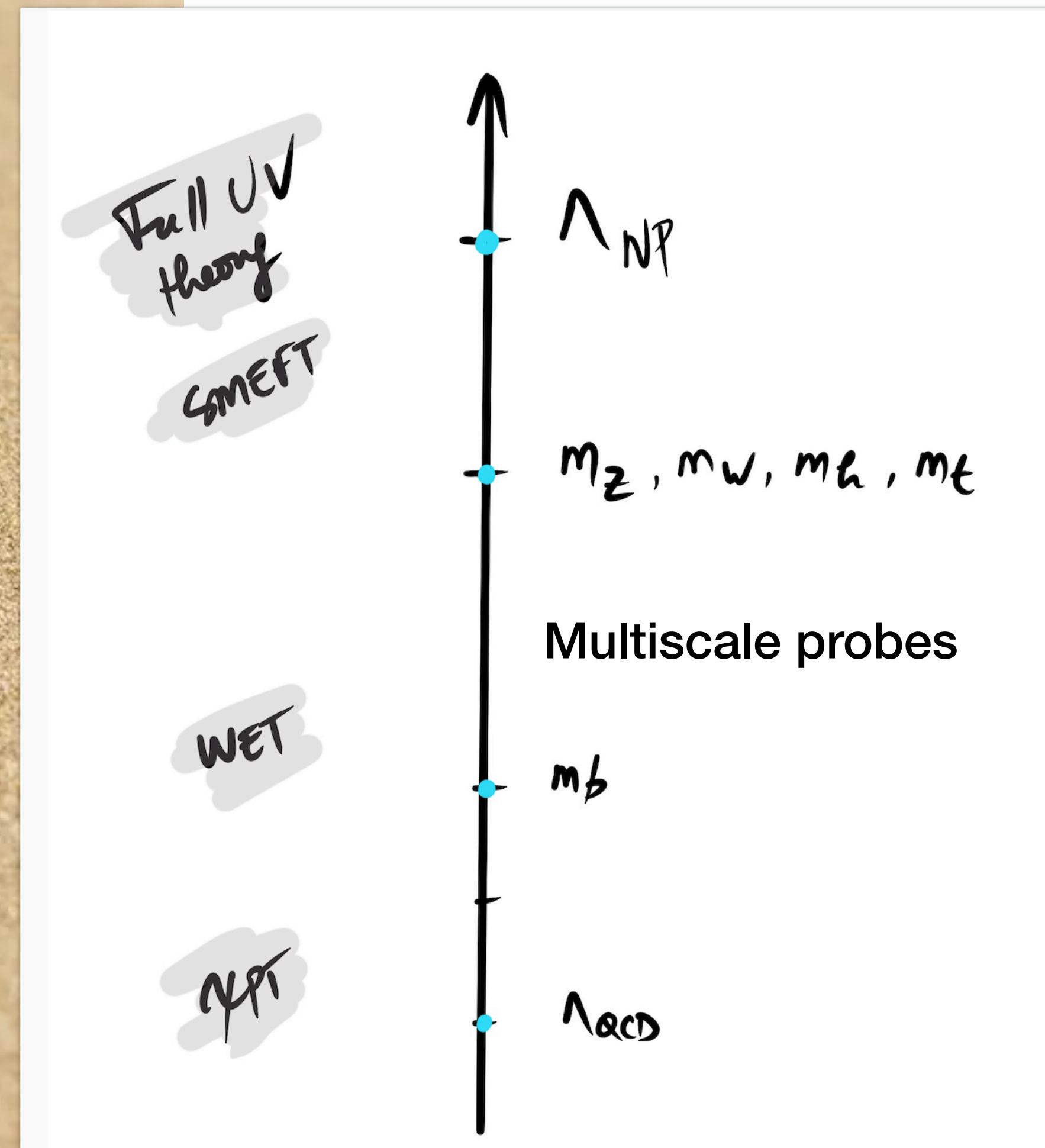
$$C|e_L^-\rangle = |e_L^+\rangle$$

$$C|u\rangle = |\bar{u}\rangle$$

$$C|d\rangle = |\bar{d}\rangle$$

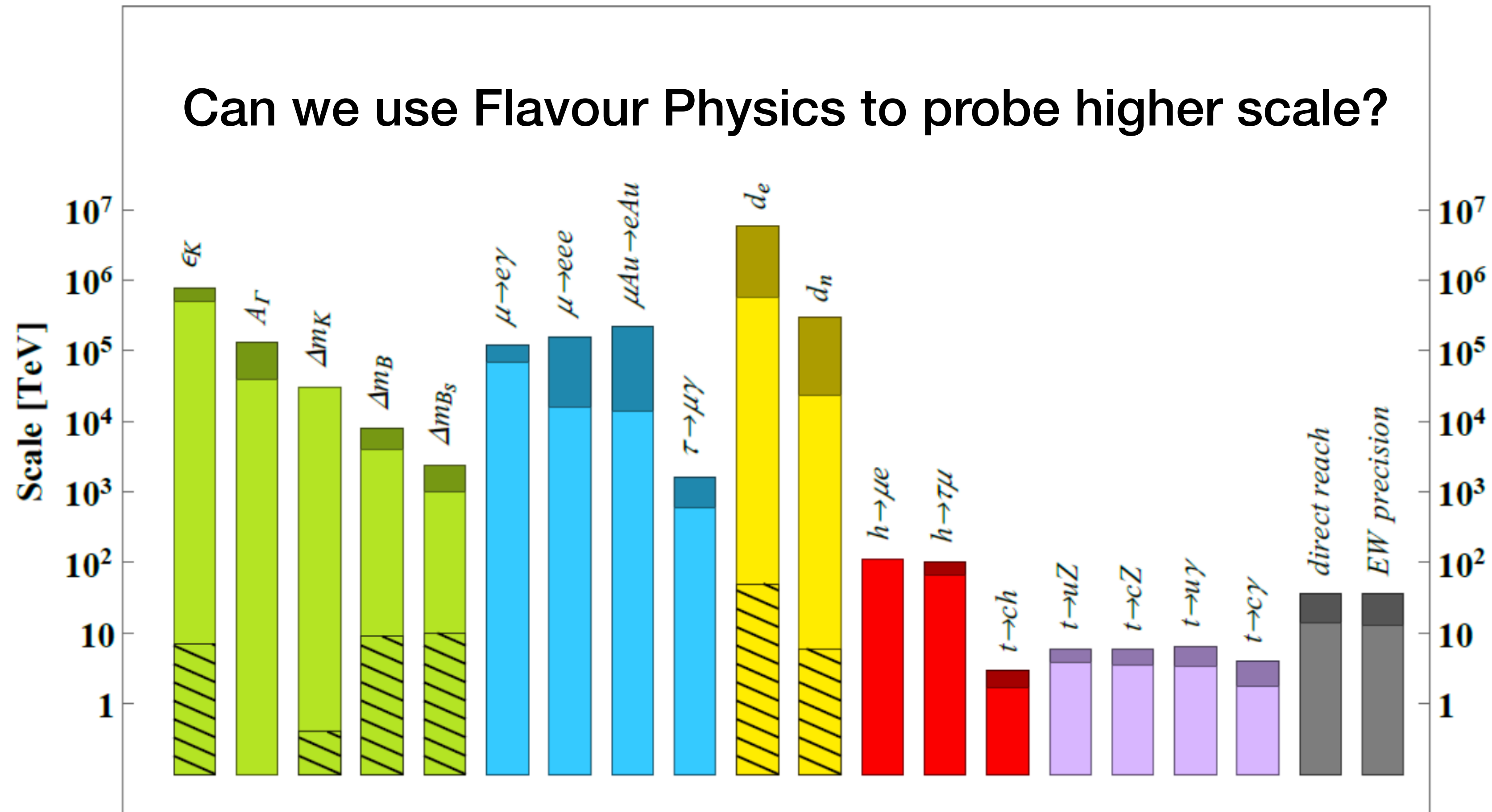
$$C|\pi^0\rangle = +|\pi^0\rangle$$

Flavour Physics as probe



Many observables & techniques are available

Oldie but goodie - an indirect road to discoveries and high scales



1910.11775

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{C_5}{\Lambda_M} \mathcal{O}^{(5)} + \sum_a \frac{C_6^a}{\Lambda^2} \mathcal{O}_a^{(6)} + \dots$$

Examples of Flavored Discoveries

- The smallness of $\Gamma(K_L \rightarrow \mu^+ \mu^-)/\Gamma(K^+ \rightarrow \mu^+ \nu)$
 $\Rightarrow$ Predicting the charm quark
- The size of Δm_K
 $\Rightarrow m_c$
- The size of Δm_B
 $\Rightarrow m_t$
- The measurement of ϵ_K
 $\Rightarrow$ Third generation
- The measurement of ν flavor transitions
 $\Rightarrow m_\nu \neq 0$

Y. Nir

The strength of flavour physics and indirect searches

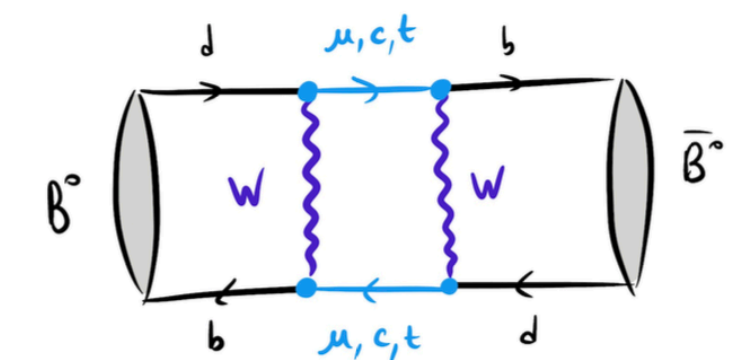
PLB 192 (1987)

OBSERVATION OF B^0 - $\bar{B}^0$ MIXING

ARGUS Collaboration

In summary, the combined evidence of the investigation of B^0 meson pairs, lepton pairs and B^0 meson-lepton events on the Υ (4S) leads to the conclusion that B^0 - $\bar{B}^0$ mixing has been observed and is substantial.

Parameters	Comments
$r > 0.09$ (90%CL)	this experiment
$x > 0.44$	this experiment
$B^{1/2} f_B \approx f_\pi < 160$ MeV	B meson ($\approx$ pion) decay constant
$m_b < 5$ GeV/c ²	b-quark mass
$\tau < 1.4 \times 10^{-12}$ s	B meson lifetime
$ V_{ub} < 0.018$	Kobayashi-Maskawa matrix element
$\eta_{\text{QCD}} < 0.86$	QCD correction factor ^{a)}
$m_t > 50$ GeV/c ²	t quark mass



$$\mathcal{M}(B^0 - \bar{B}^0) \propto \sum_{ij} (V_{ib} V_{id}^*) (V_{jb} V_{jd}^*) F(m_{\mu_i}^2, m_{\mu_j}^2)$$

Emphasis the complementarity of direct vs indirect searches

The GIM mechanism

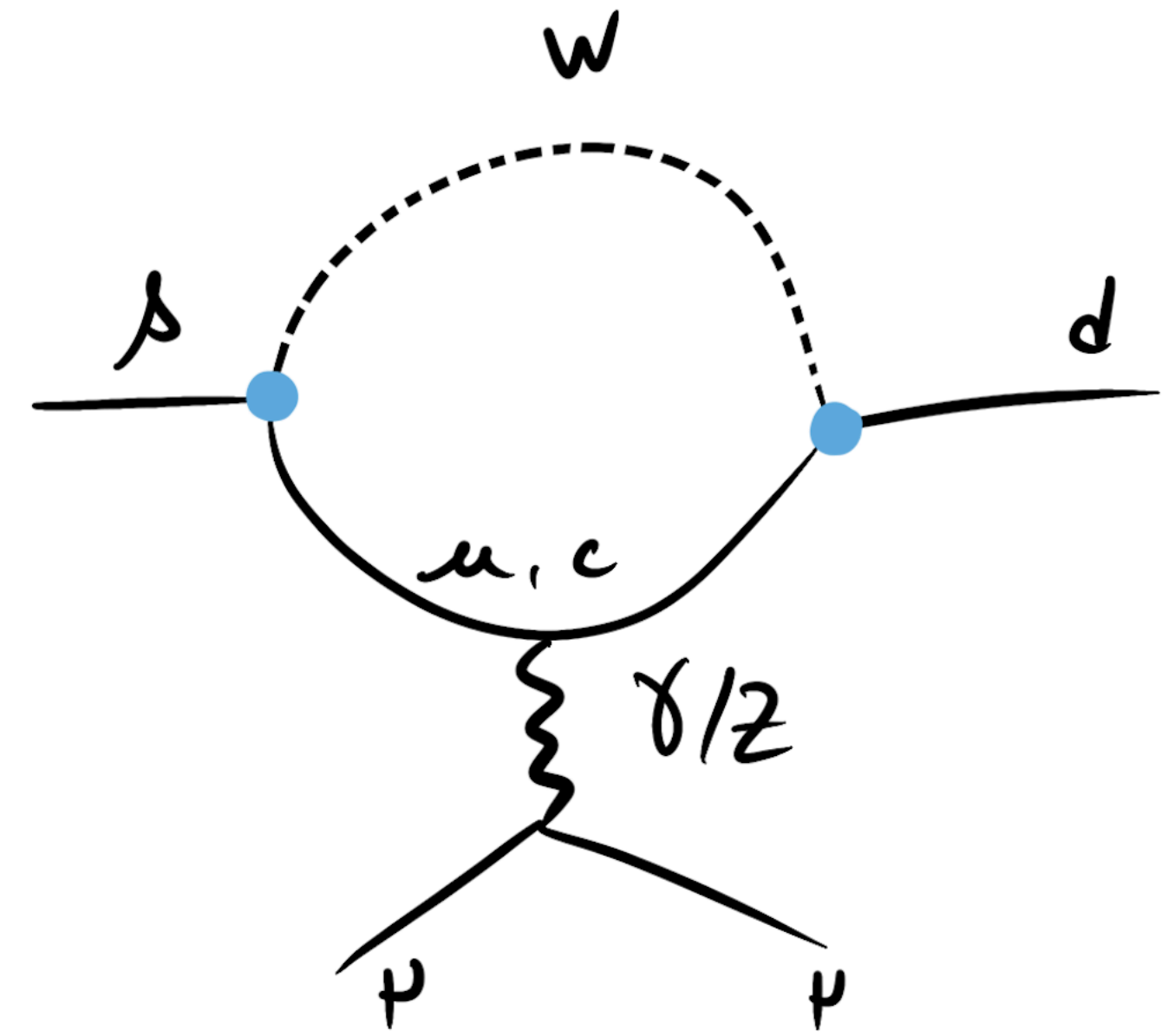
- $K^+ \rightarrow \mu^+ \nu_\mu$ & $\pi^0 \mu^+ \nu_\mu$ so why not $K^0 \rightarrow \mu^+ \mu^-$ & $\pi^0 \mu^+ \mu^-$?
- GIM (Glashow, Iliopoulos, Maiani) mechanism (1970)
 - No free level flavour changing neutral currents
 - Suppression of FN CN via loops
 - Requires that quarks come in pairs (predicting charm)

$$A = V_{us} V_{ud}^* \times f\left(\frac{m_u}{m_W}\right) + V_{cs} V_{cd}^* \times f\left(\frac{m_c}{m_W}\right)$$

2x2 Unitarity

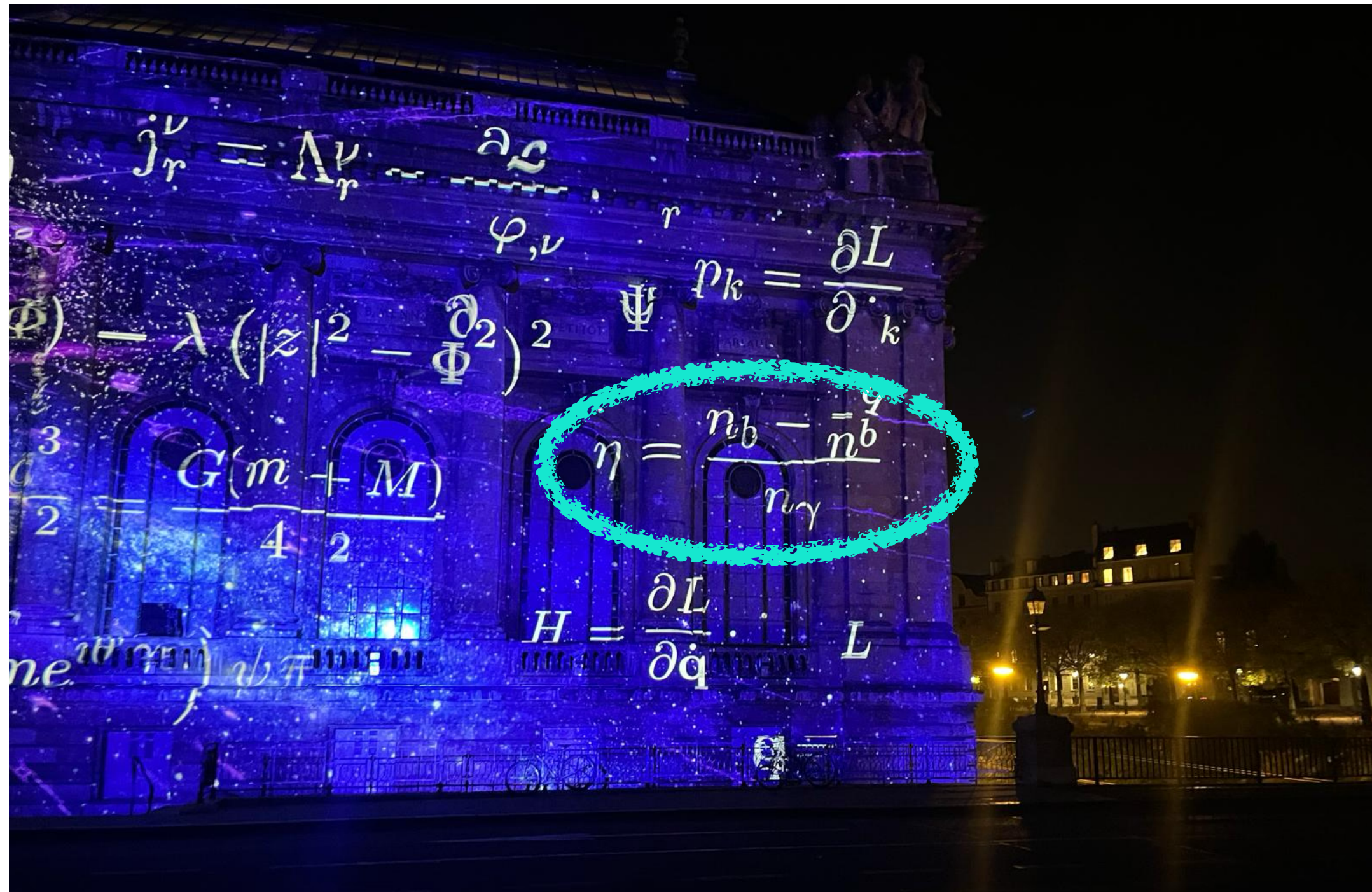
$$V_{us} V_{ud}^* + V_{cs} V_{cd}^* = 0$$

$$m_u, m_c < m_W, f\left(\frac{m_u}{m_W}\right) \sim f\left(\frac{m_c}{m_W}\right) : A \sim 0$$

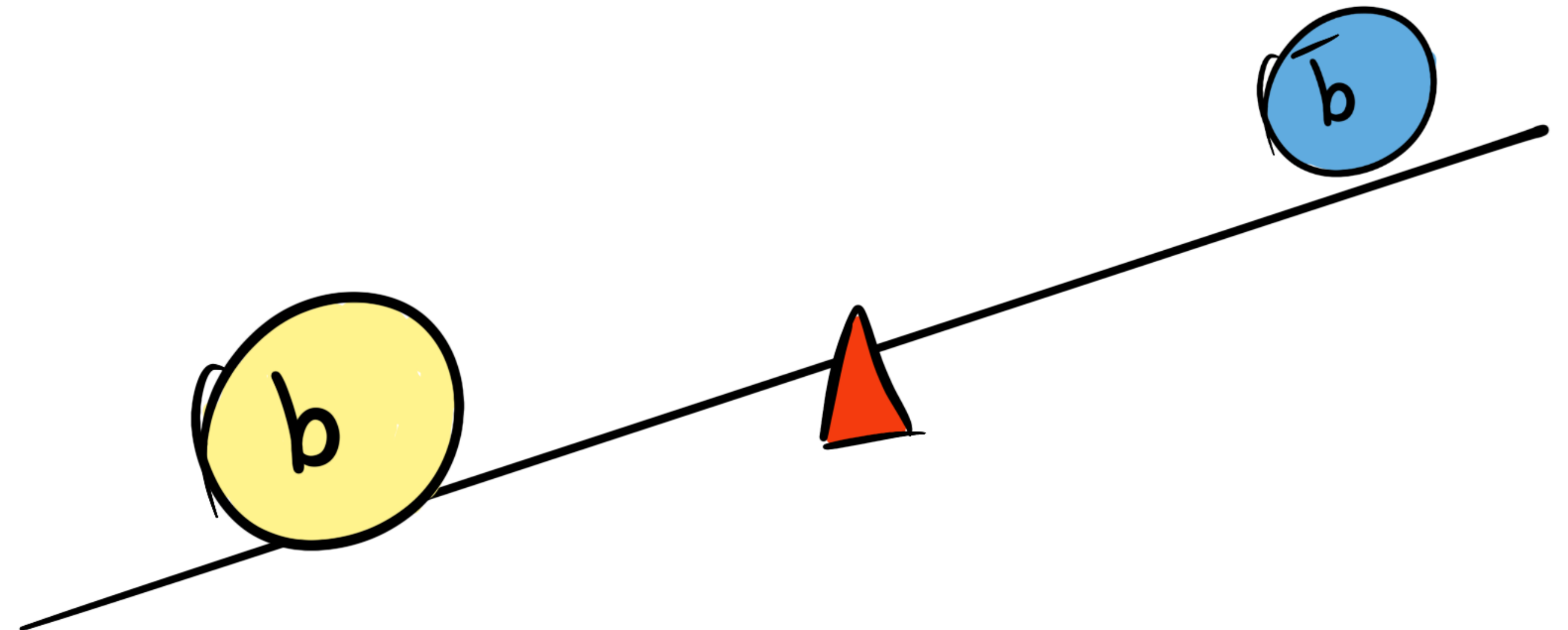


Kaon mixing $\rightarrow$ predict m_c

Towards Baryogenesis



Art & History Museum in Geneva



Sakharov conditions [\[edit\]](#)

In 1967, [Andrei Sakharov](#) proposed^[11] a set of three necessary conditions that a [baryon](#)-generating interaction must satisfy to produce matter and antimatter at different rates. These conditions were inspired by the recent discoveries of the [cosmic microwave background](#)^[12] and [CP-violation](#) in the neutral [kaon](#) system.^[13] The three necessary "Sakharov conditions" are:

- [Baryon number](#) B violation.
- [C-symmetry](#) and [CP-symmetry](#) violation.
- Interactions out of [thermal equilibrium](#).

Baryon number violation is a necessary condition to produce an excess of baryons over anti-baryons. But C-symmetry violation is also needed so that the interactions which produce more baryons than anti-baryons will not be counterbalanced by interactions which produce more anti-baryons than baryons. CP-symmetry violation is similarly required because otherwise equal numbers of [left-handed](#) baryons and [right-handed](#) anti-baryons would be produced, as well as equal numbers of left-handed anti-baryons and right-handed baryons.^[5] Finally, the last condition, known as the out-of-equilibrium decay scenario, states that the rate of a reaction which generates baryon-asymmetry must be less than the rate of expansion of the universe. This ensures the particles and their corresponding antiparticles do not achieve thermal equilibrium due to rapid expansion decreasing the occurrence of pair-annihilation. The interactions must be out of thermal equilibrium at the time of the baryon-number and C/CP symmetry violating decay occurs to generate the asymmetry.^{[5]:46}

CKM Matrix

- W -mediated interactions are the only ones that are not diagonal
- All flavor changing processes depend on the CKM parameters
- 4 CKM parameters $\Leftrightarrow \gg$ 4 measured FC processes
- Stringent tests of the CKM mechanism for FC processes

CKM Matrix

$$V = V_{uL} V_{dL}^\dagger$$

$$\mathcal{L}_{W,q} = -\frac{g}{\sqrt{2}} \bar{u}_{Lj} V_{jb} \gamma_\mu W^{+\mu} d_{Lb} + \text{h.c.}$$

Freedom to permute the various generations:

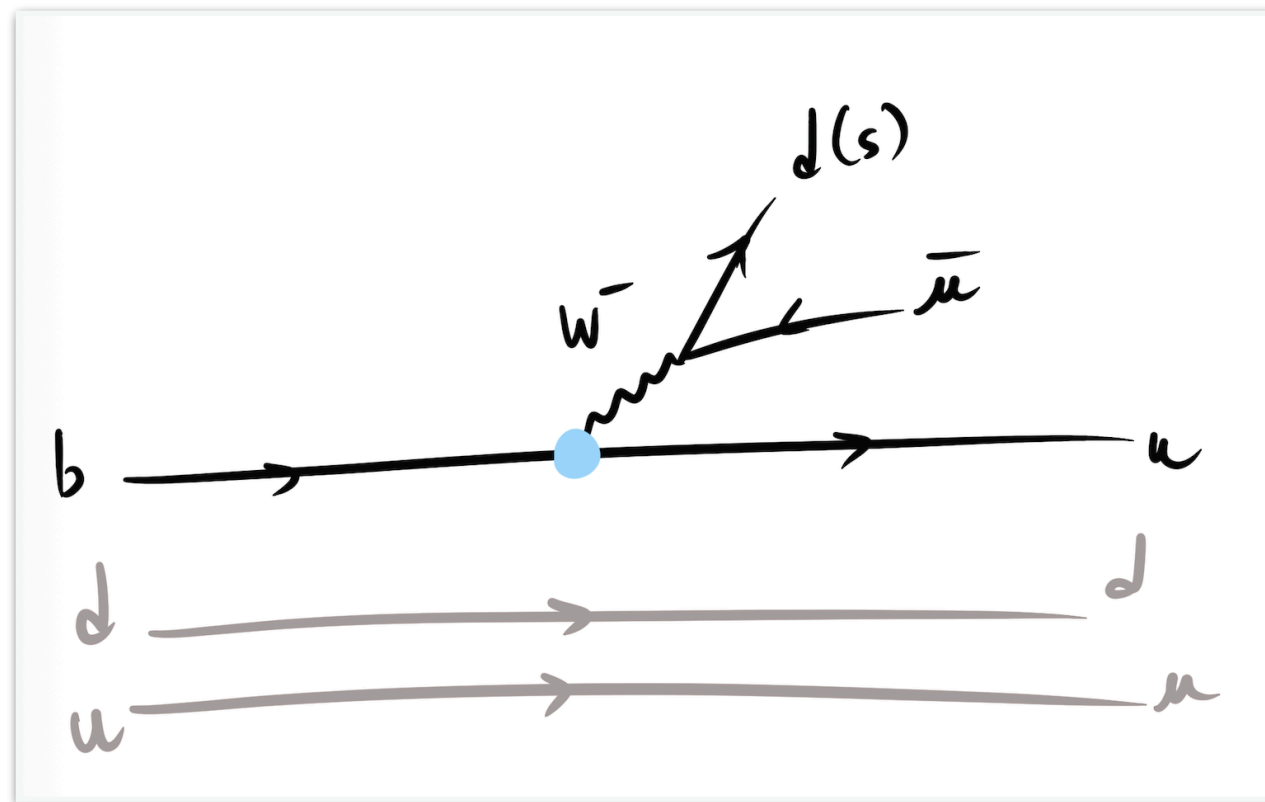
Order by masses: $(u_1, c_1, t_1) \rightarrow (u, c, t); (d_1, s_1, b_1) \rightarrow (d, s, b)$

$$\mathcal{L}_{W,q} = -\frac{g}{\sqrt{2}} (\bar{u}_L \bar{c}_L \bar{t}_L) \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \gamma_\mu W^{+\mu} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \text{h.c.}$$

Freedom to redefine the phases of the quark fields, m_q remain real, but the phase structure of V changes. We end up with $3_R + 1_I$ terms.

CKM - matrix

Let's consider this current



$$\lambda = 0.22 \quad A, |\rho + i\eta| = \mathcal{O}(1)$$

$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

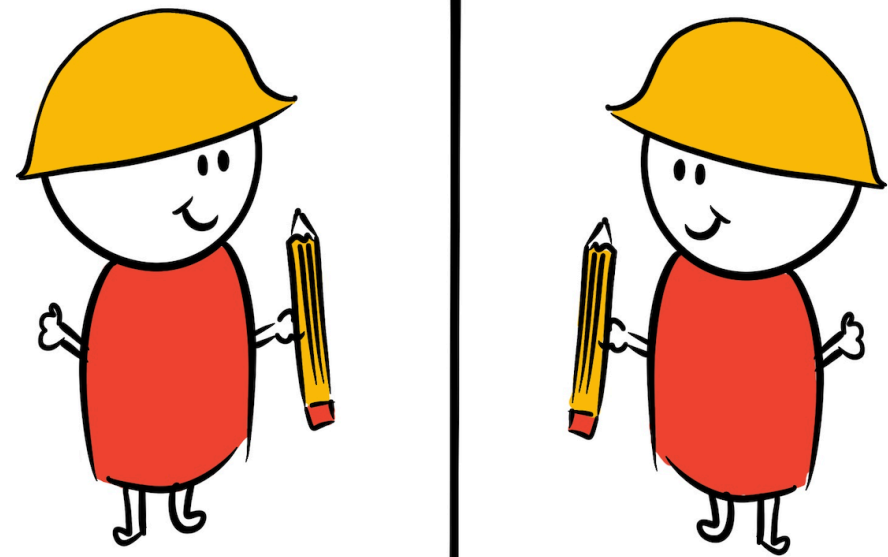
$$V_{CKM} \approx \begin{bmatrix} 1 - \lambda^2/2 & \lambda & \lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

Wolfenstein parametrisation

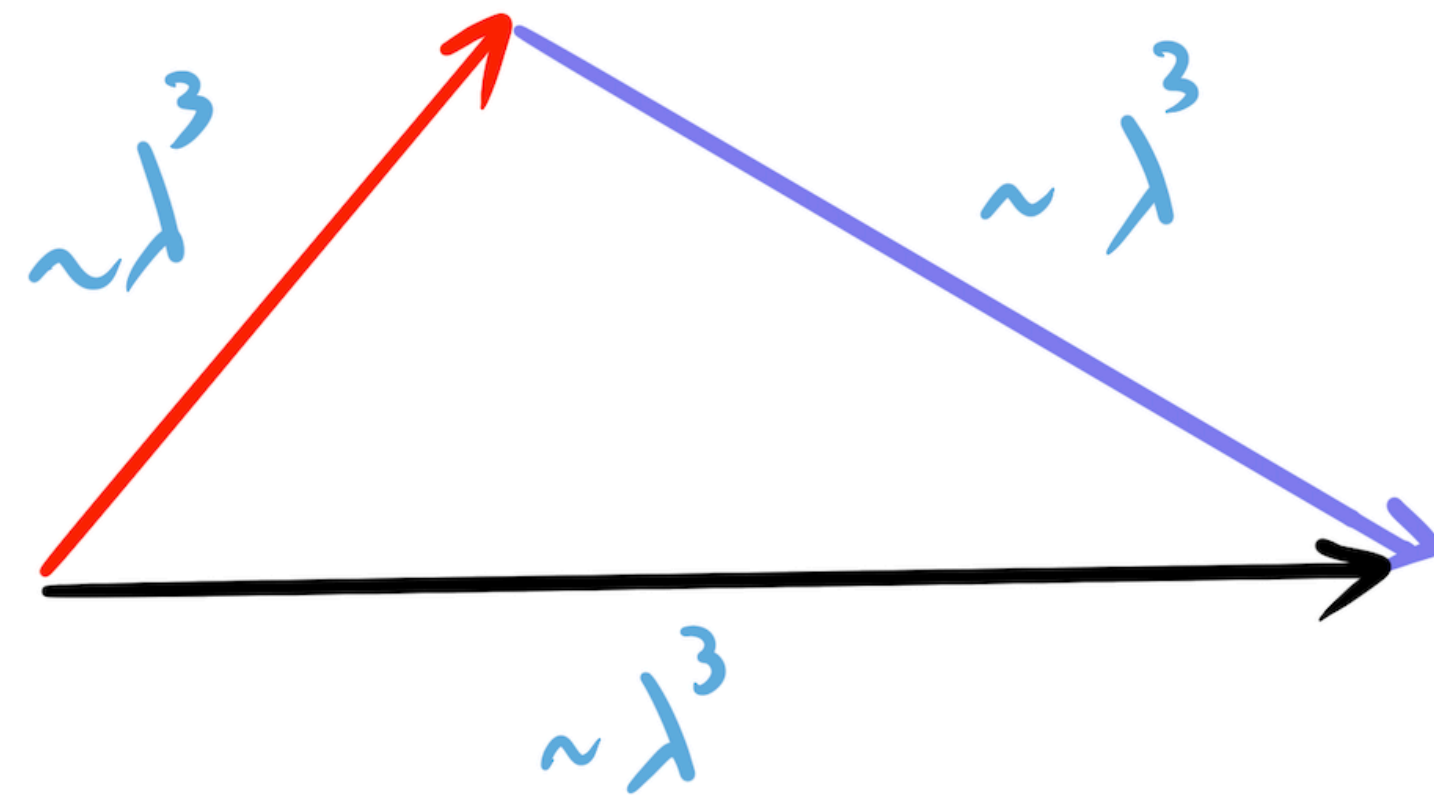
CKM - matrix

$$(V^\dagger V)_{ij} = \delta_{ij}$$

$$i = b, j = d$$



$$\underline{V_{ub}^* V_{ud}} + \underline{V_{cb}^* V_{cd}} + \underline{V_{tb}^* V_{td}} = 0$$



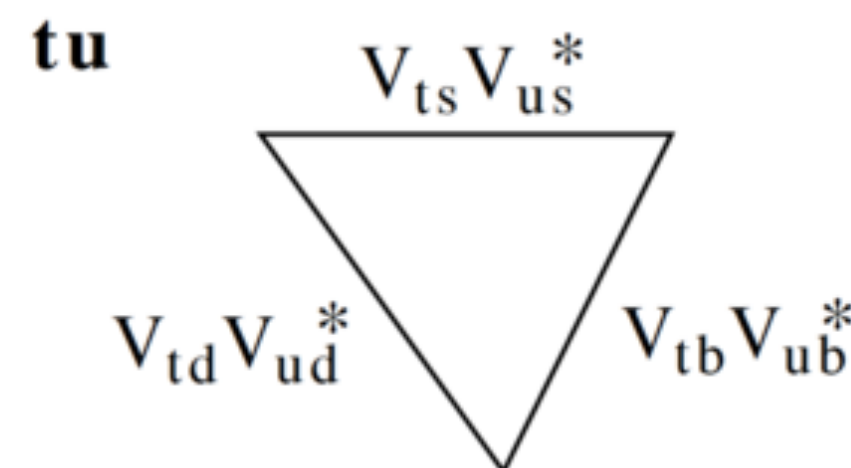
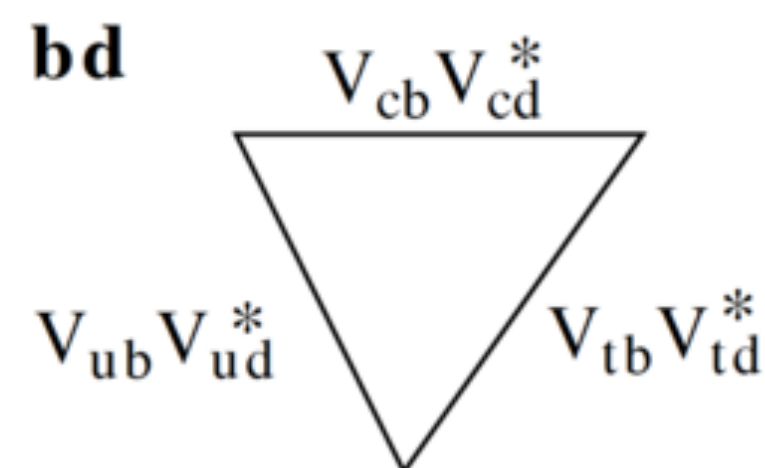
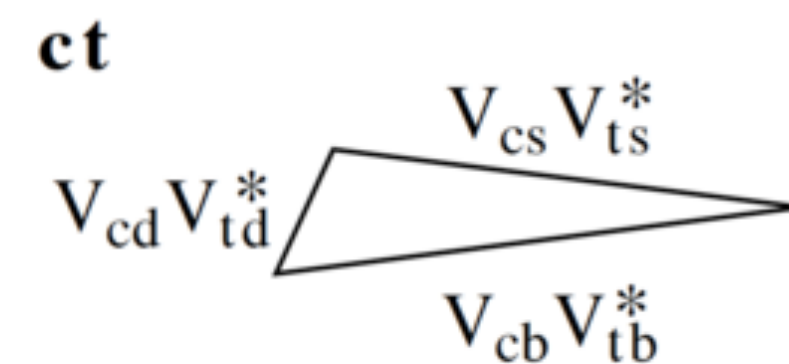
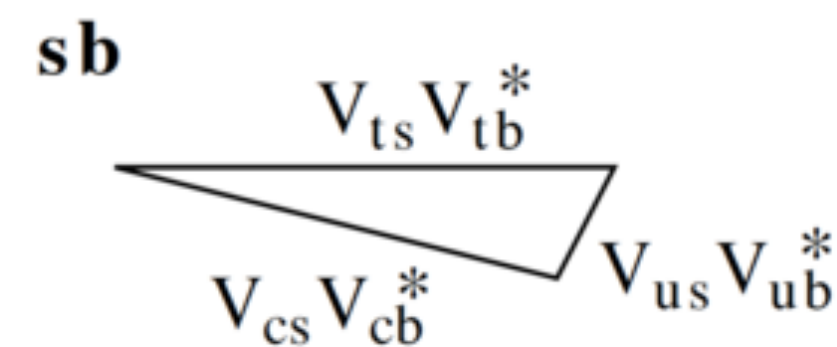
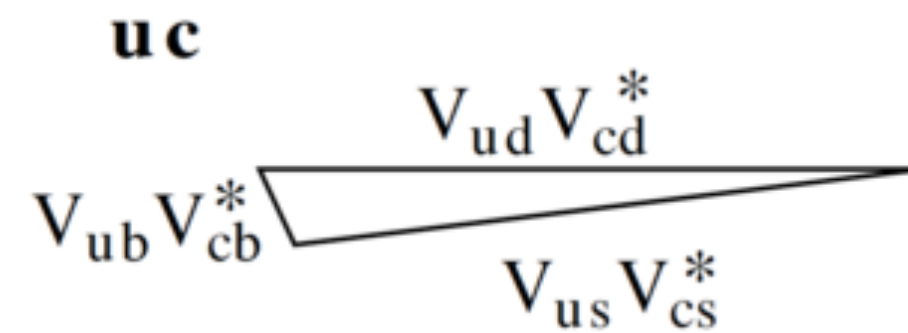
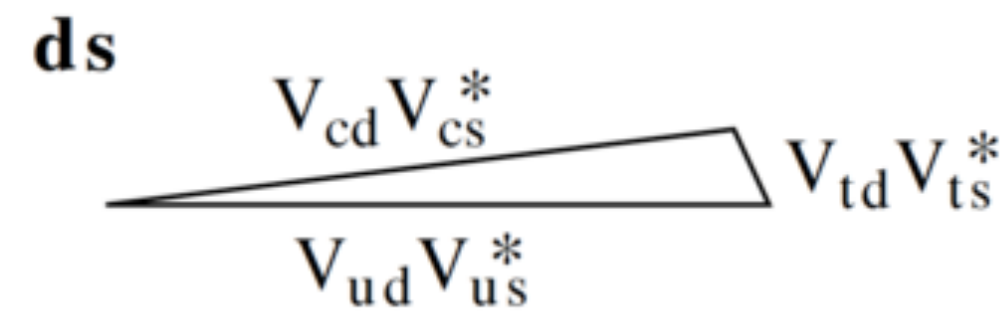
Building the unitarity triangles

The other triangles

The unitarity of the CKM matrix, $(VV^\dagger)_{ij} = (V^\dagger V)_{ij} = \delta_{ij}$, leads to twelve distinct complex relations among the matrix elements. The six relations with $i \neq j$ can be represented geometrically as triangles in the complex plane. Two of these,

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 , \quad (13.35a)$$

$$V_{td}V_{ud}^* + V_{ts}V_{us}^* + V_{tb}V_{ub}^* = 0 , \quad (13.35b)$$



$$\alpha \equiv \varphi_2 \equiv \arg \left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*} \right) \simeq \arg \left(-\frac{1 - \rho - i\eta}{\rho + i\eta} \right) ,$$

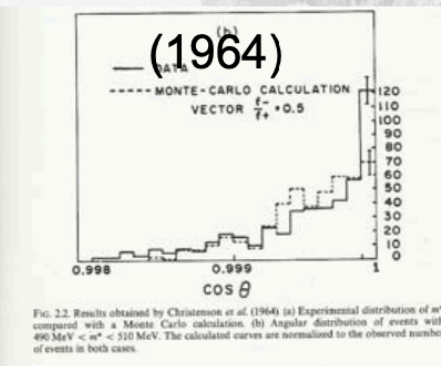
$$\beta \equiv \varphi_1 \equiv \arg \left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*} \right) \simeq \arg \left(\frac{1}{1 - \rho - i\eta} \right) ,$$

$$\gamma \equiv \varphi_3 \equiv \arg \left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right) \simeq \arg (\rho + i\eta) .$$

💡 http://www.scholarpedia.org/article/Experimental_determination_of_the_CKM_matrix

CP Violation through the History of Particle Physics

- Discovery of strange particles (Rochester, Butler) (1946, '47)
- Neutral kaons can mix (Gell-Mann, Pais) (1952)
- K_L discovery (Lederman *et al.*) (1956)
- P violation: possible explanation (Lee, Yang) (1956)
- P violation found in β decay (Wu *et al.*) (1957)
later: maximum P and C violation, but CP invariance
- Cabibbo-Theory (1963)
- ➡ CP violation (CPV) discovered (Cronin, Fitch *et al.*) (1964)

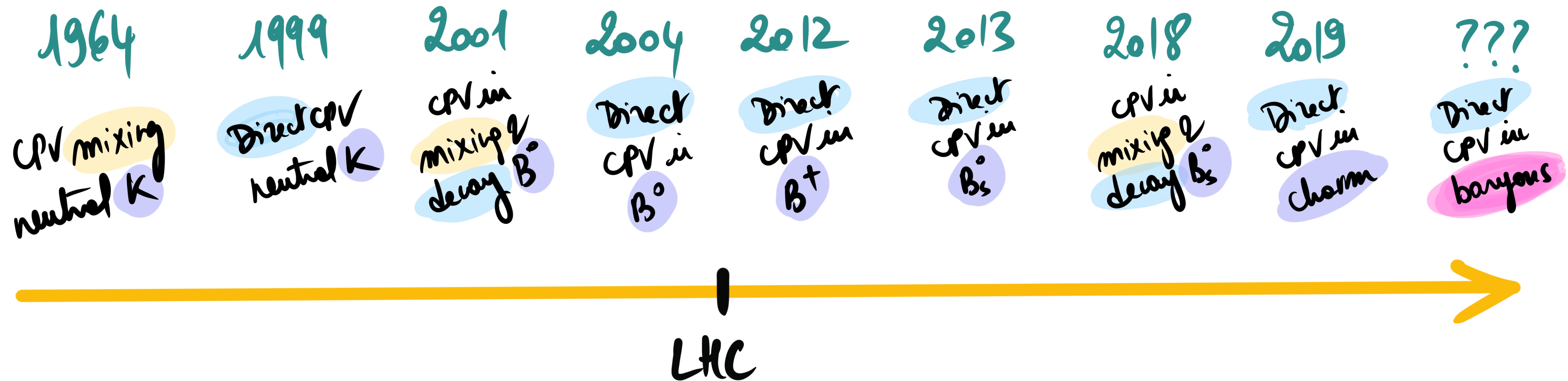


CP Violation is a Family History of Quarks

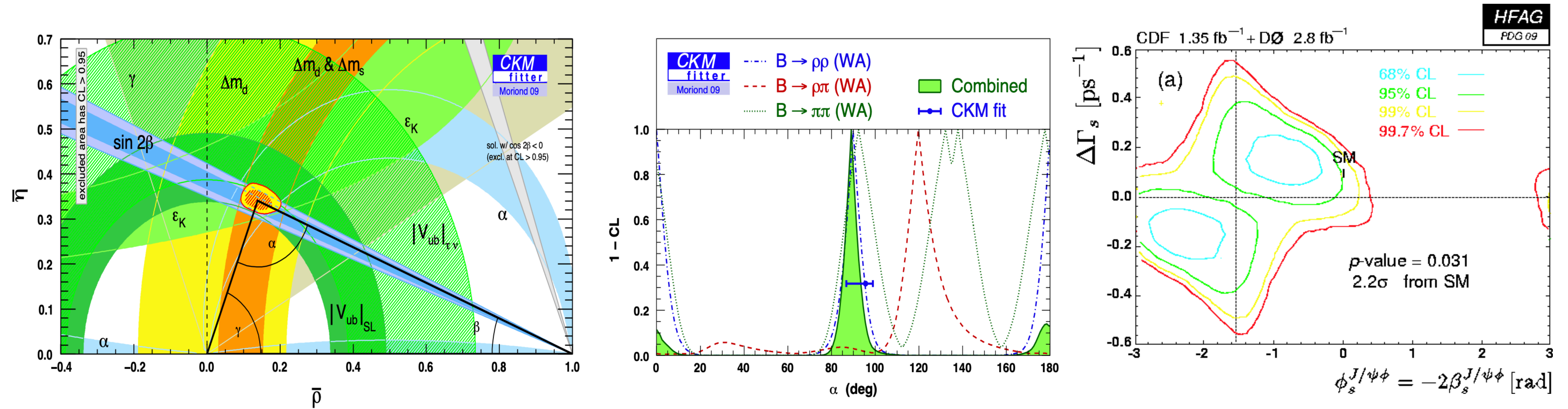
- GIM-Mechanism (Glashow, Illiopolous, Maiani) (1970)
- CPV phase requires 3 families (Kobayashi-Maskawa) (1973)
- J/ψ resonance: c quarks (Ting, Richter) (1974)
- Discovery of τ lepton: 3rd family (Perl *et al.*) (1975)
- Υ resonance: b quarks (Lederman *et al.*) (1977)
- Broad $\Upsilon(4S)$ (CLEO) (1980)
- B mesons live long ($|V_{cb}|$ small) (MAC, MARK II) (1983)
- B mesons oscillate (ARGUS) (1987)
- t -quark discovery (CDF) (1995)
- $\varepsilon'/\varepsilon \neq 0$ (NA31, NA48, KTeV) (1999)
- Start of B Factories: BABAR (PEP II), Belle (KEKB) (1999)
- ➡ CPV in B system : $\sin(2\beta) \neq 0$ (BABAR, Belle) (2001)
- ➡ Direct CPV in B system : $A_{CP}(K^+\pi^-) \neq 0$ (BABAR, Belle) (2004)

Twenty years later where are we?

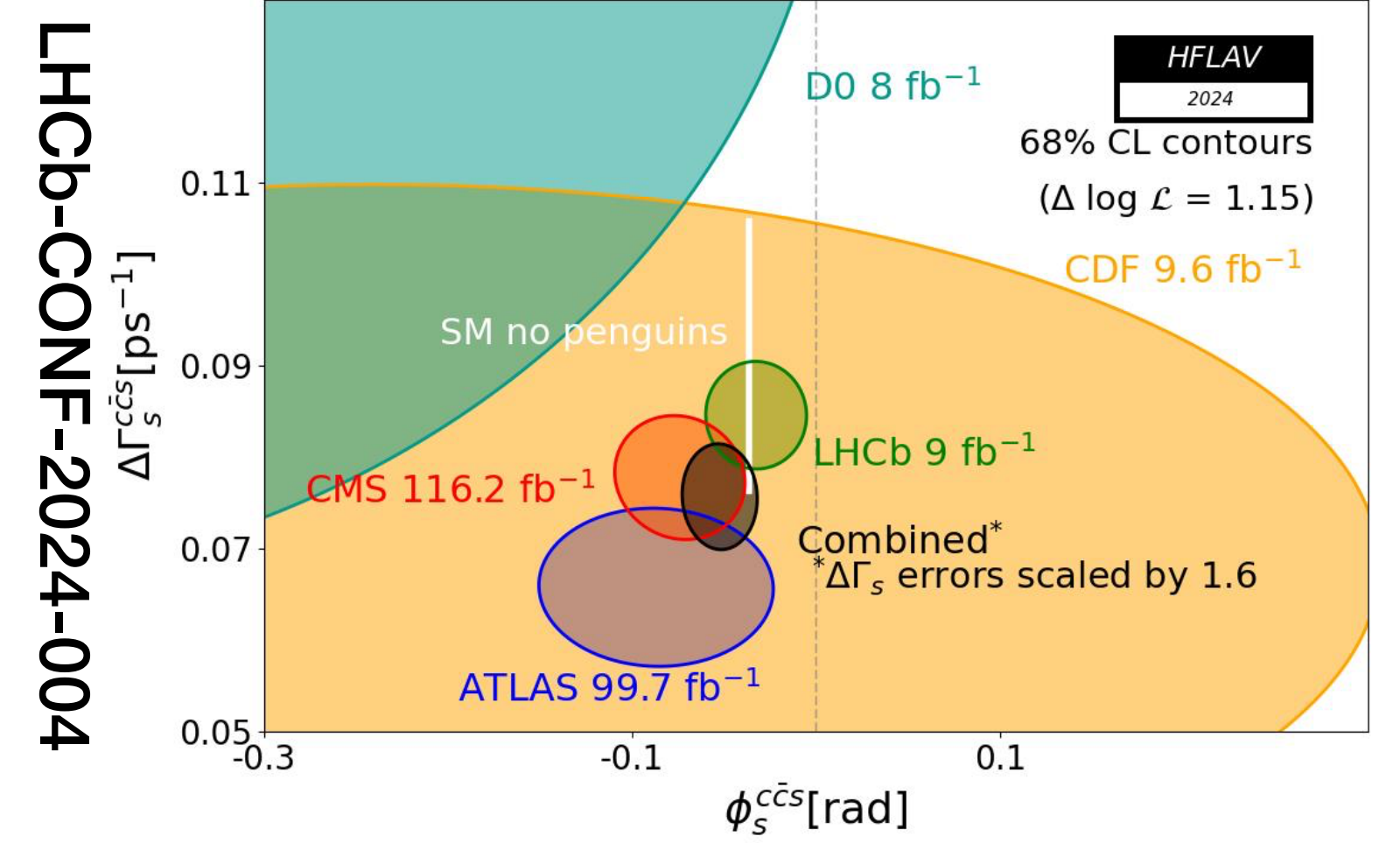
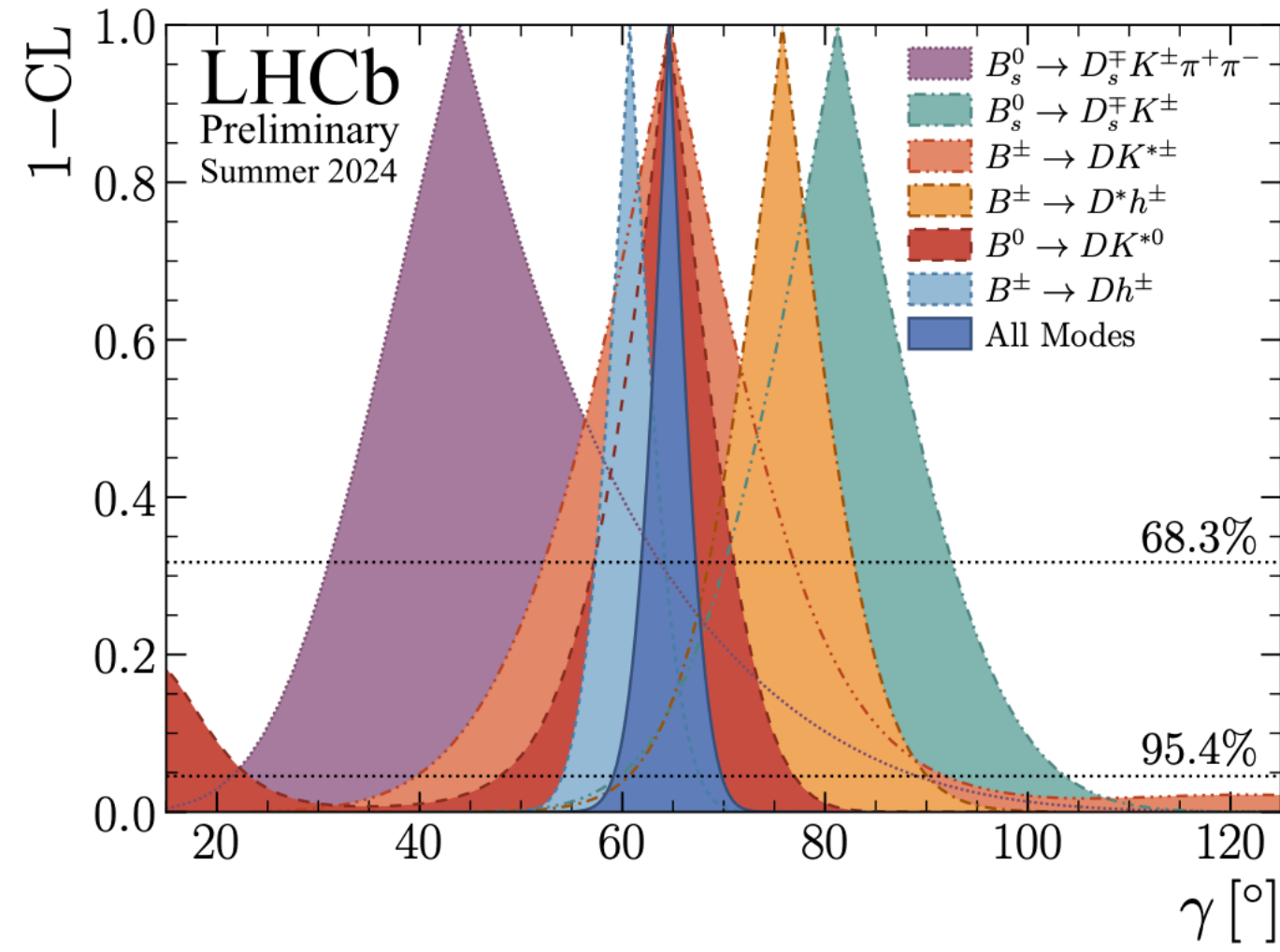
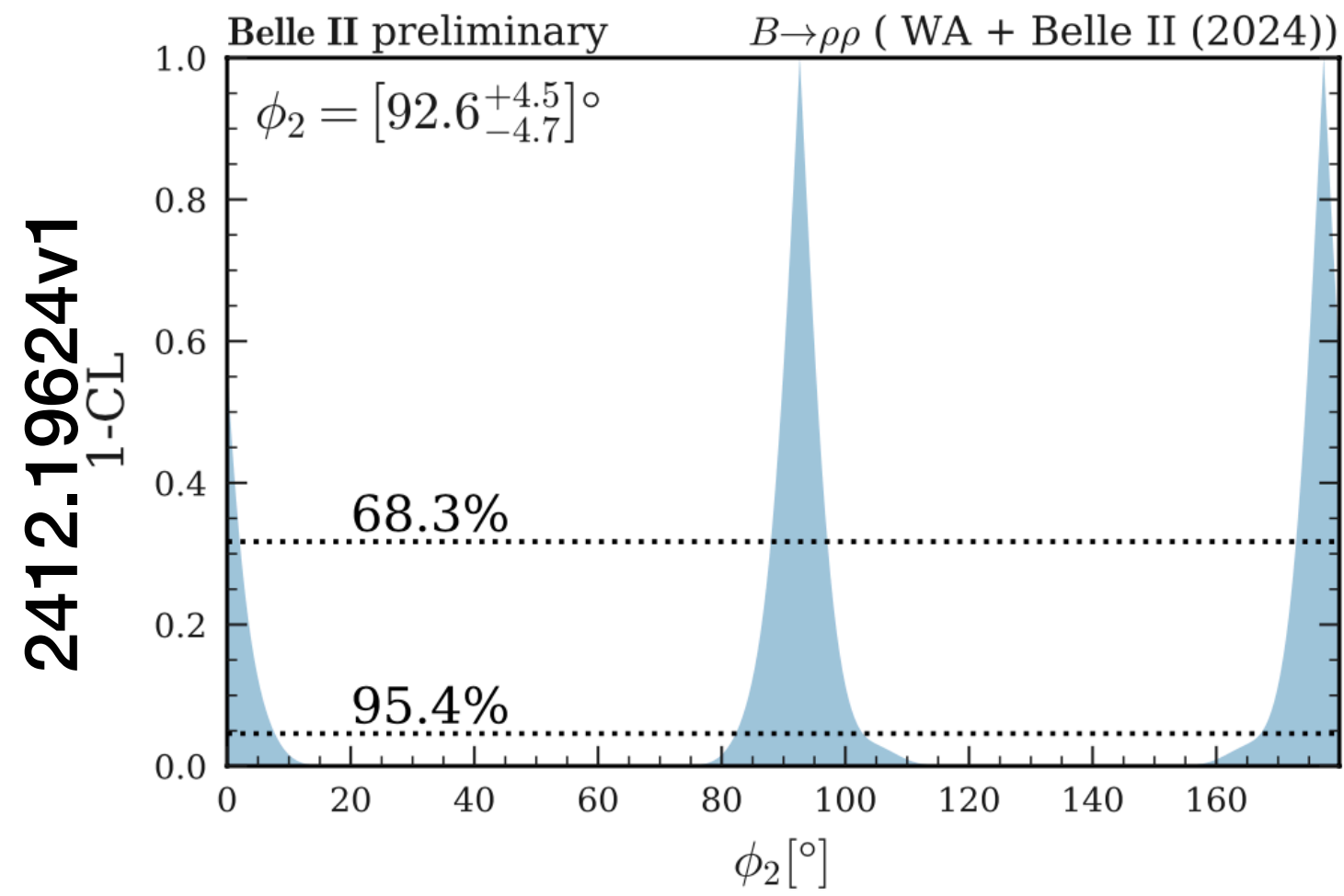
CPV violation timeline



All the phases...in 2009

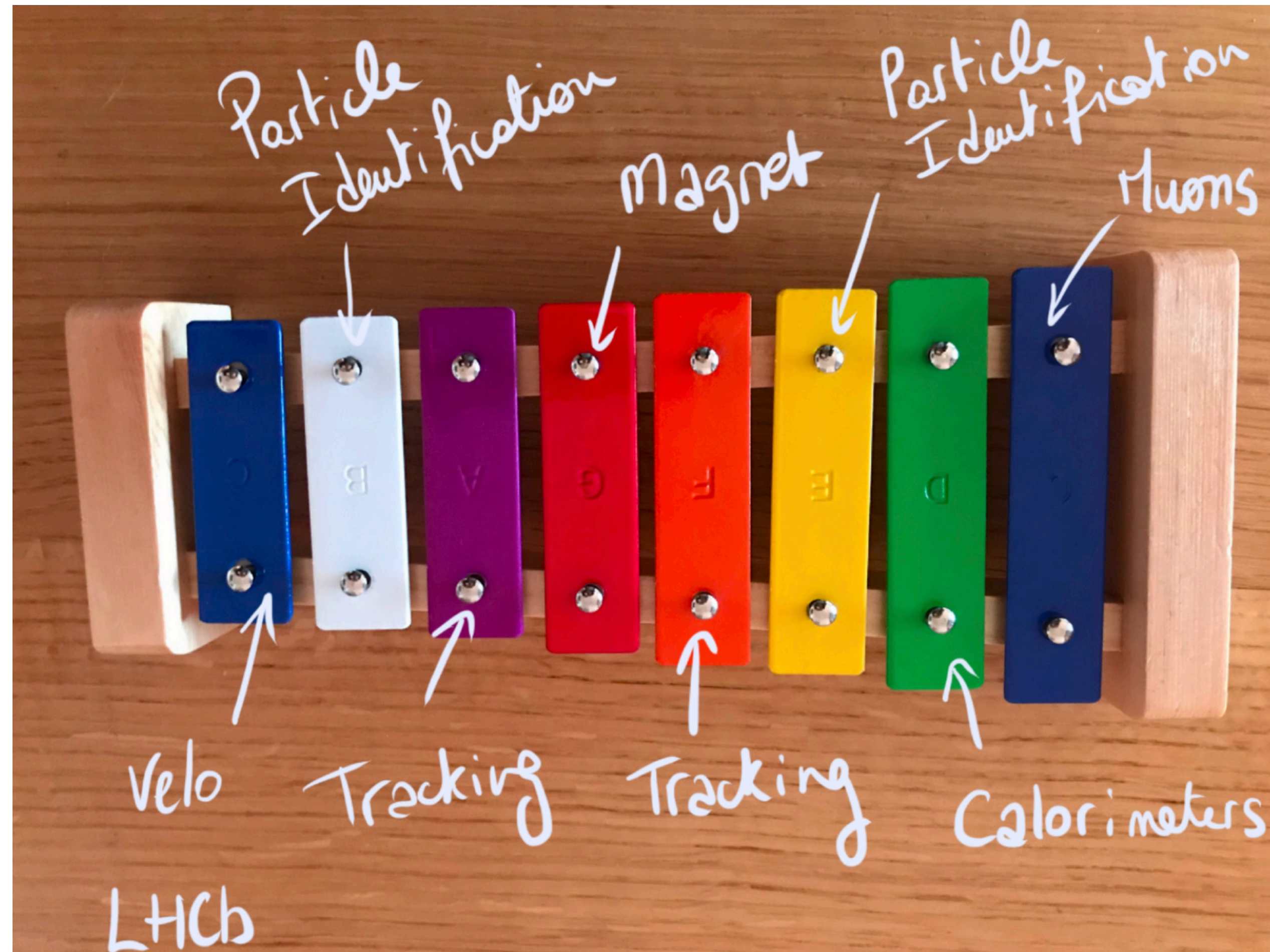


All the phases...Today



arXiv:2411.18639

You can't make an omelette without breaking a few eggs



Need a collider



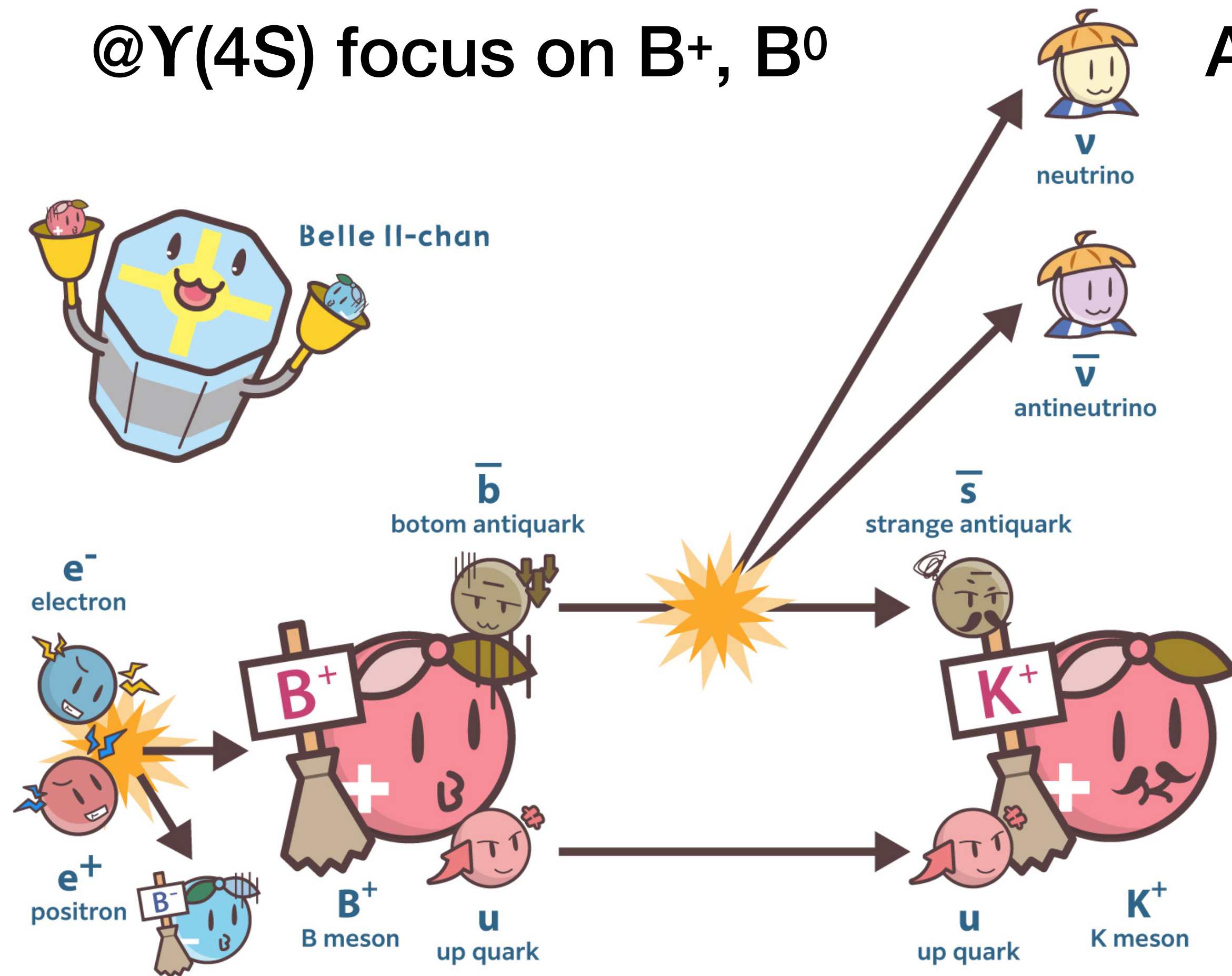
Need a detector

**Often we can't have
everything at the same time**

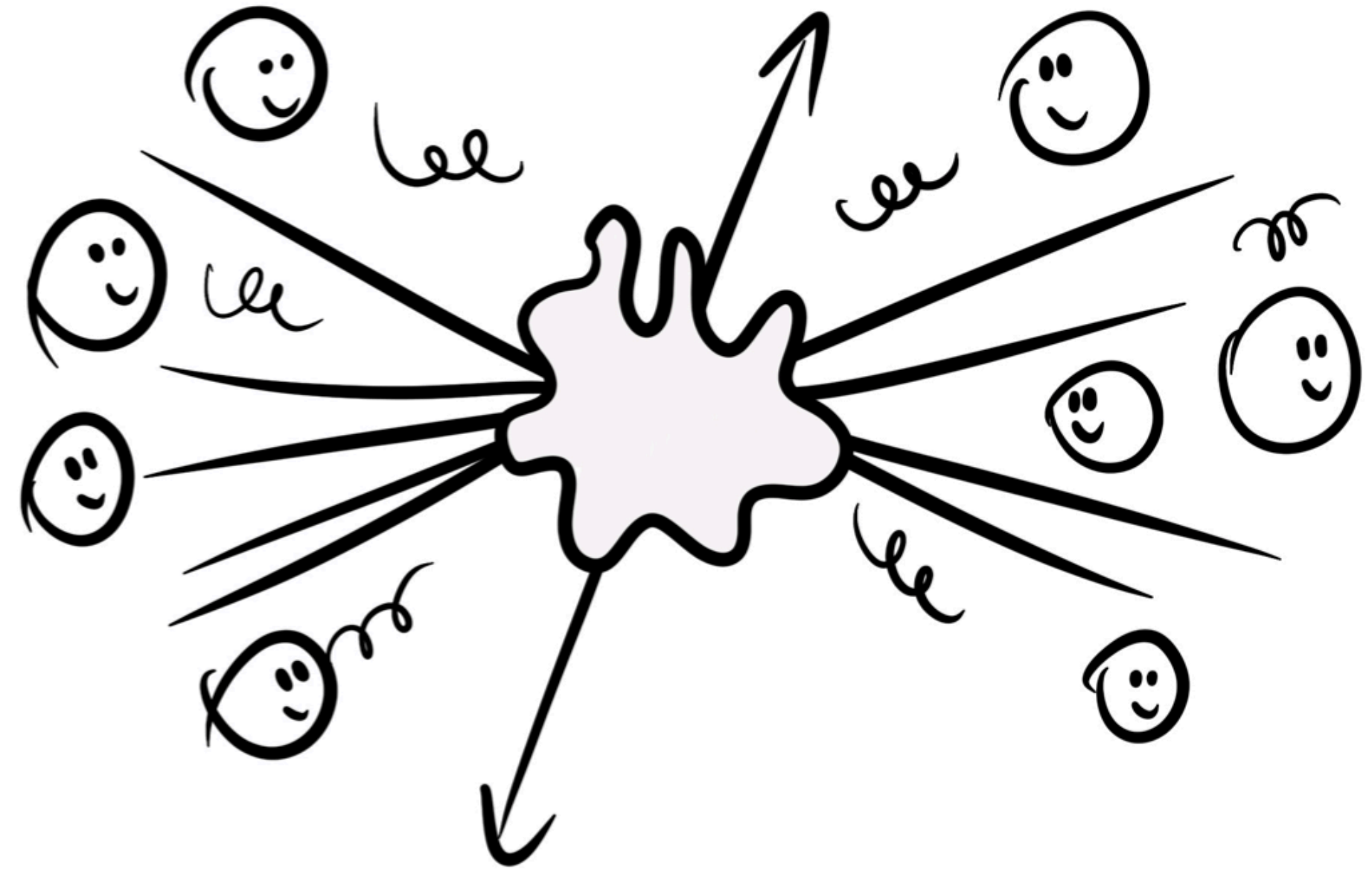
...decisions decisions...

Leptons or Hadrons

@Y(4S) focus on B^+ , B^0

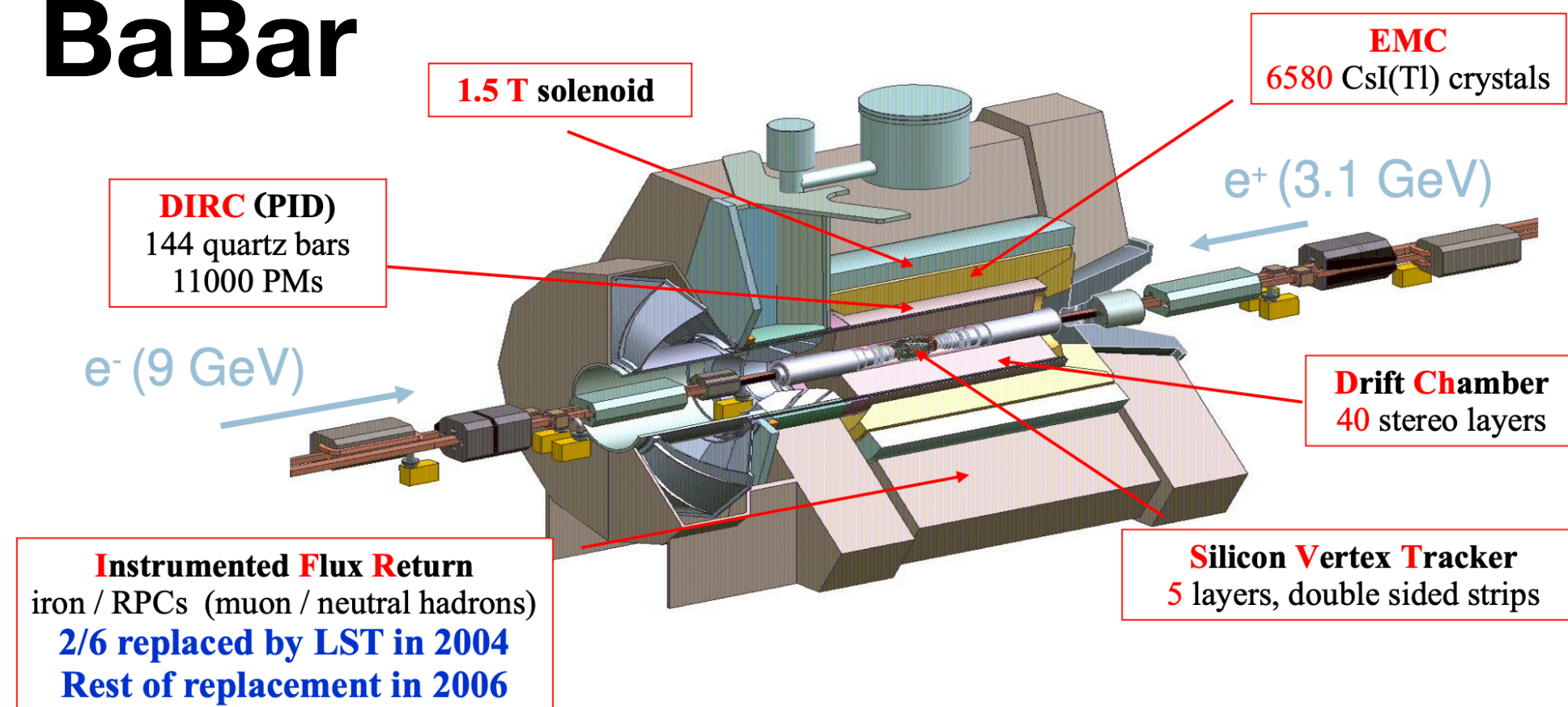


All specifies are created $B_{u,d,s,c}$ baryons etc

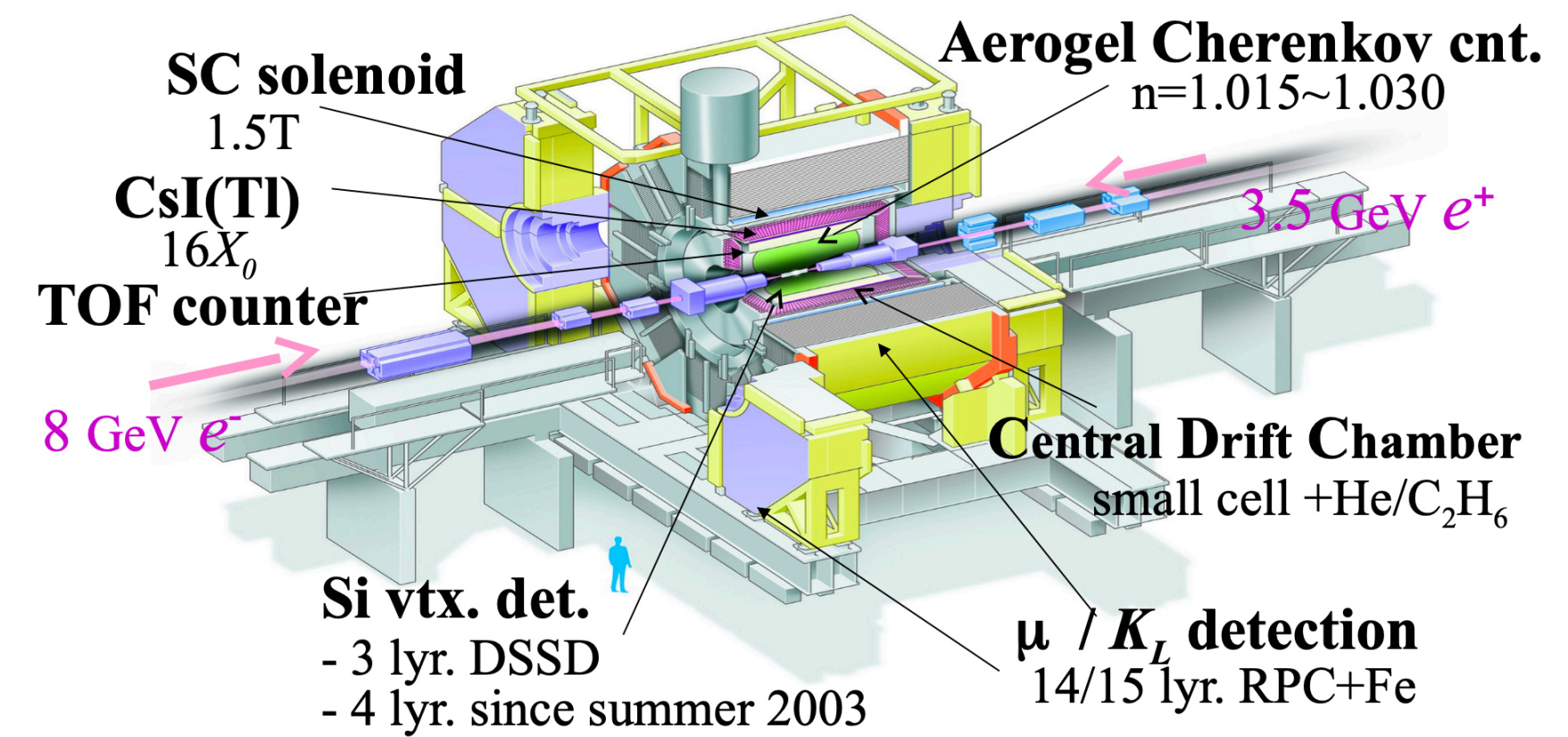


Naturally there are different challenges/advantages to each

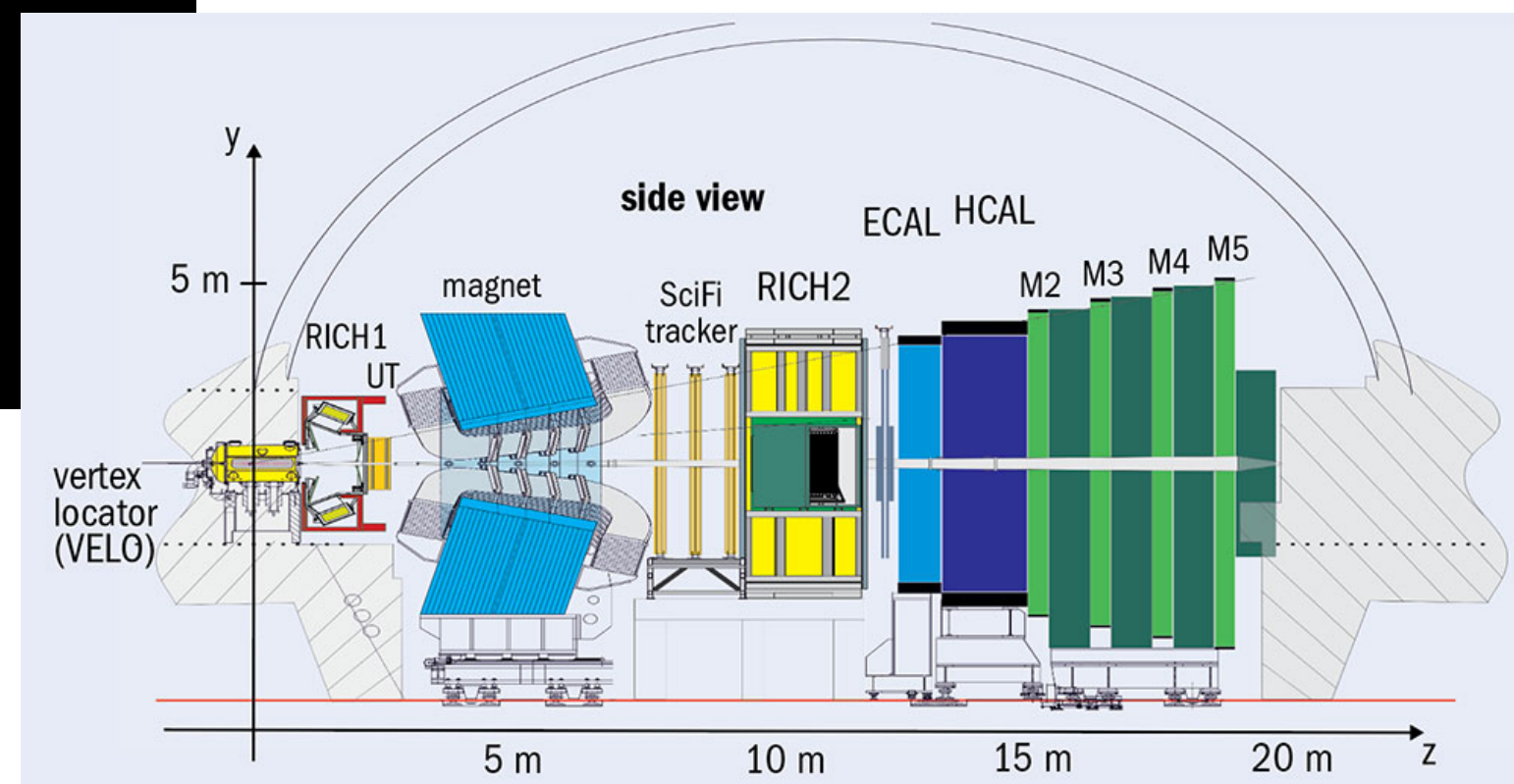
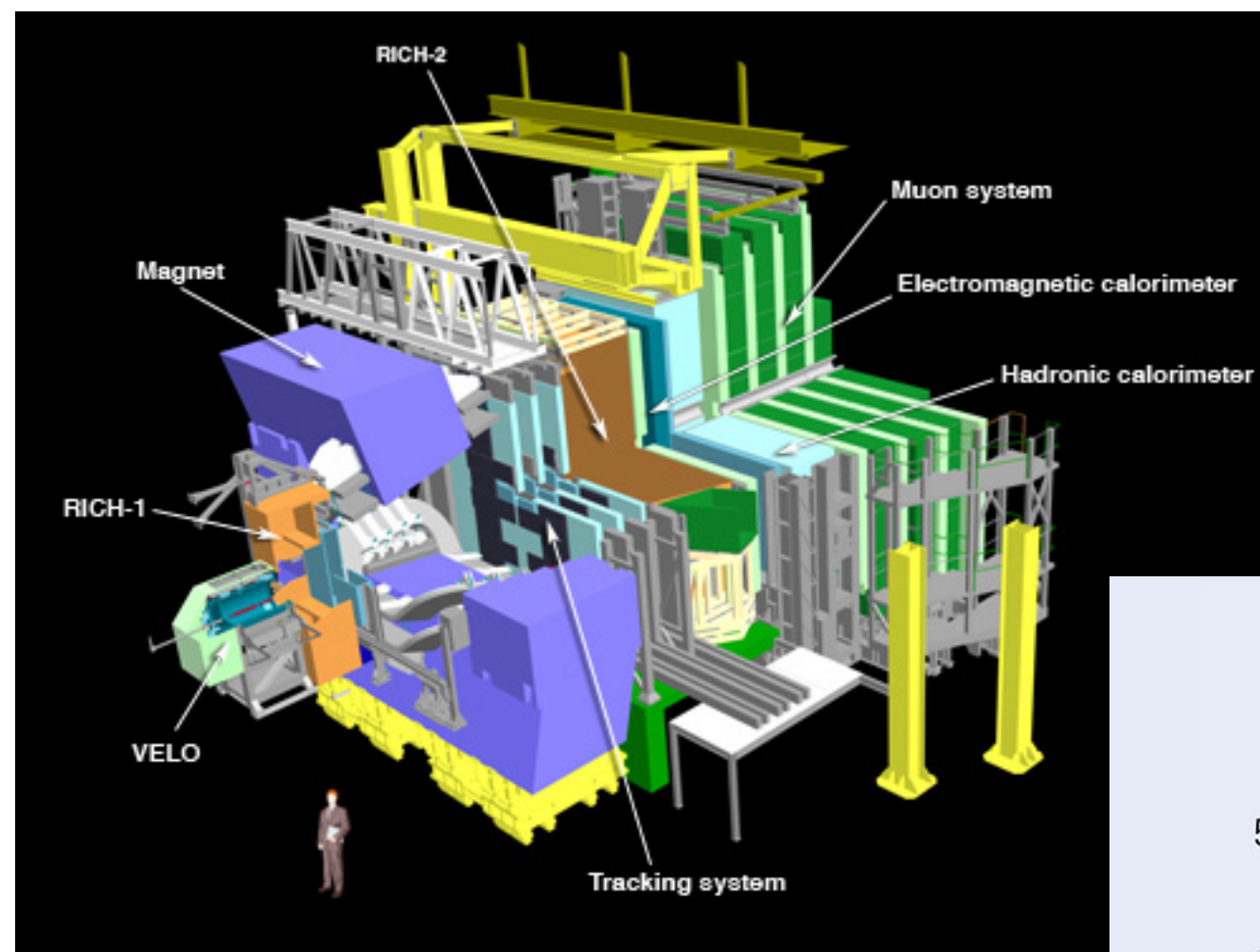
BaBar



Belle



LHCb & its Upgrades

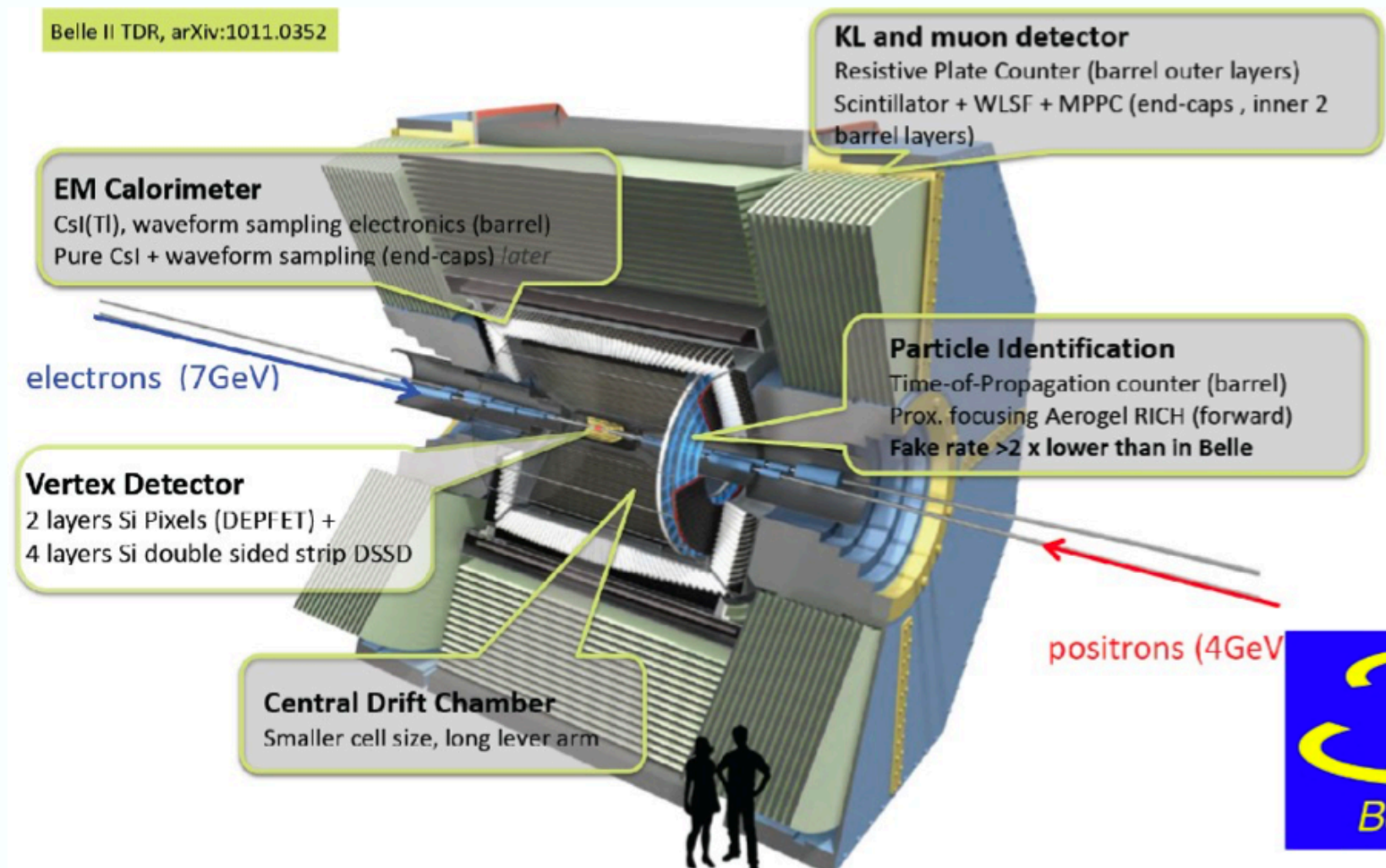


Belle II Detector

Deal with higher background (10-20×), radiation damage, higher occupancy, higher event rates (LI trigg. 0.5→30 kHz)

Improved performance and hermeticity

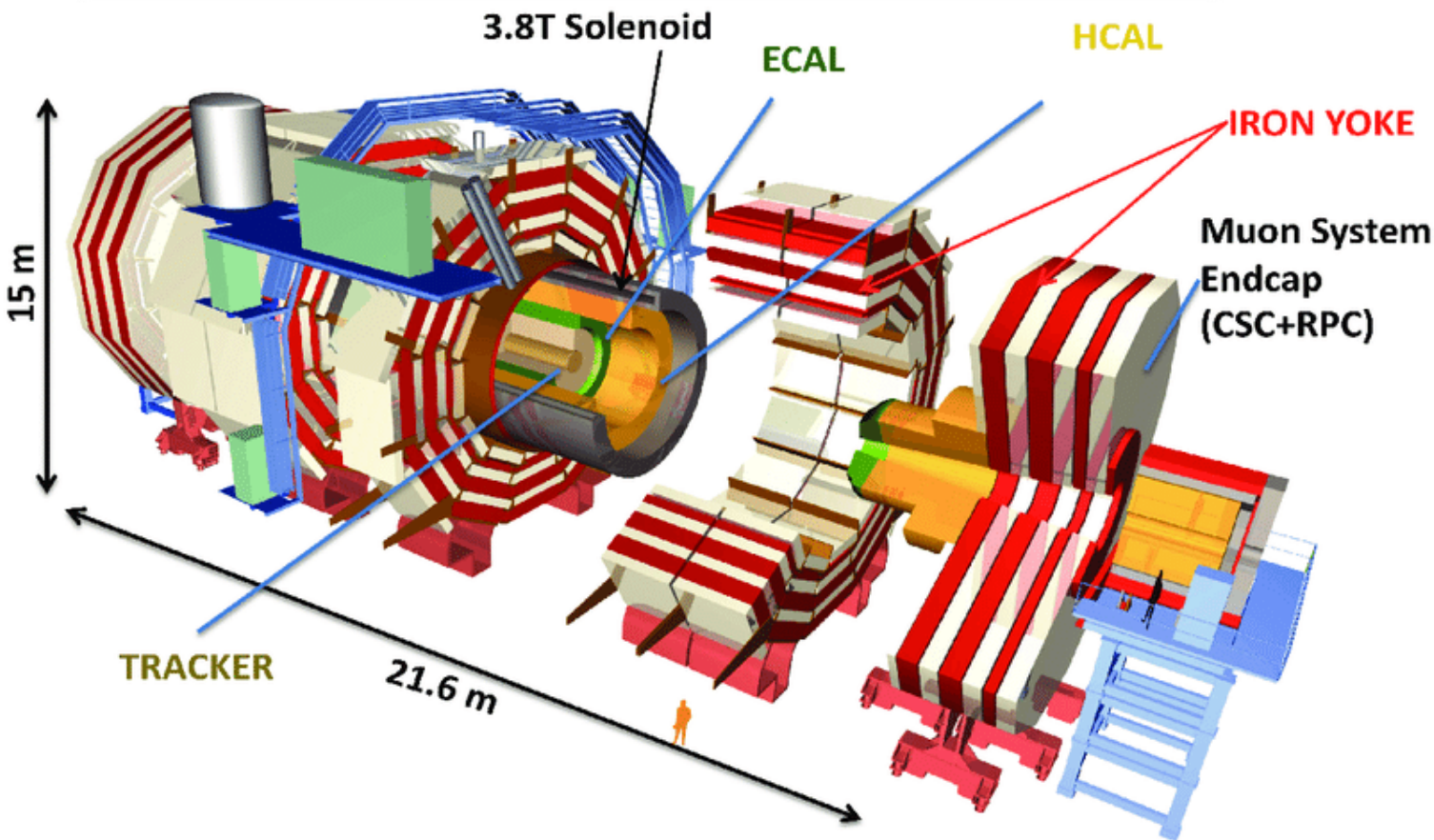
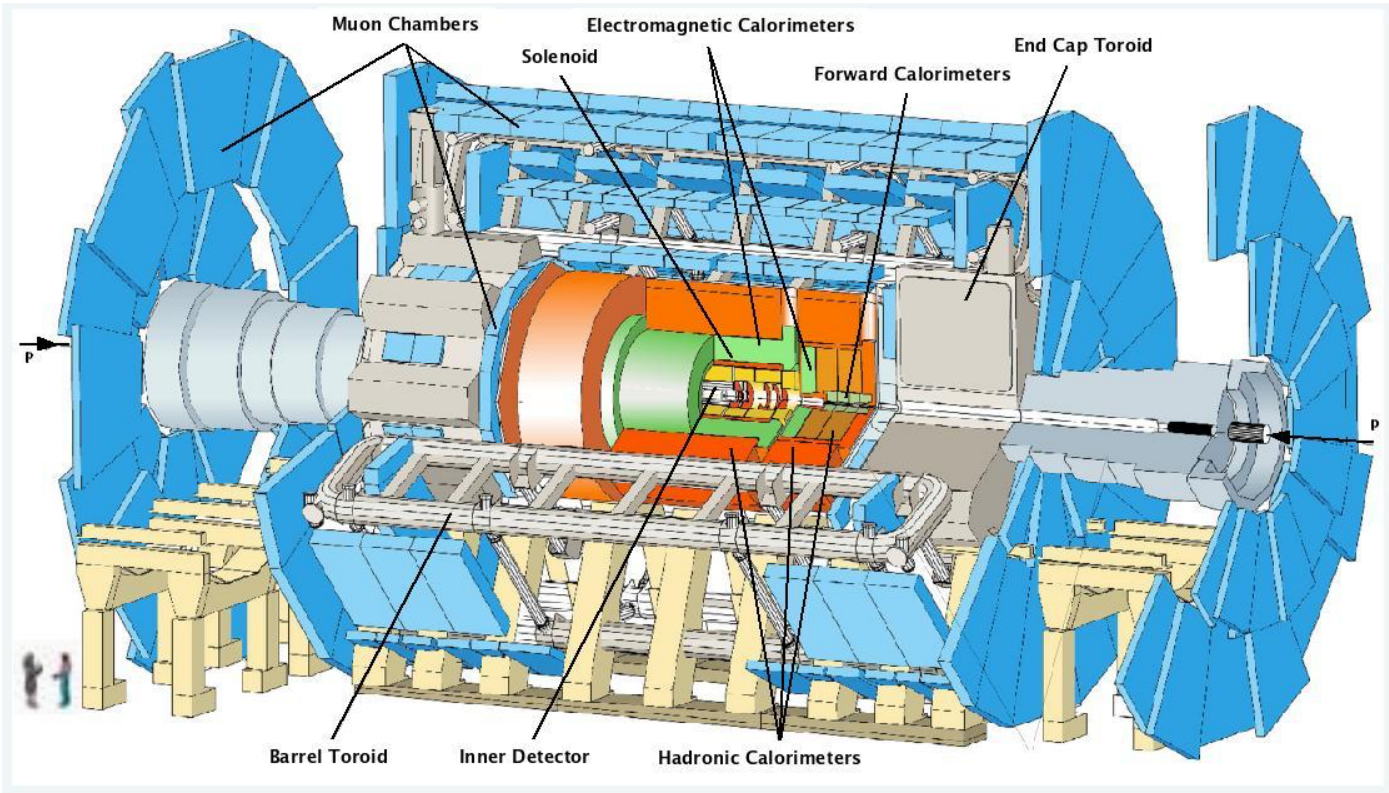
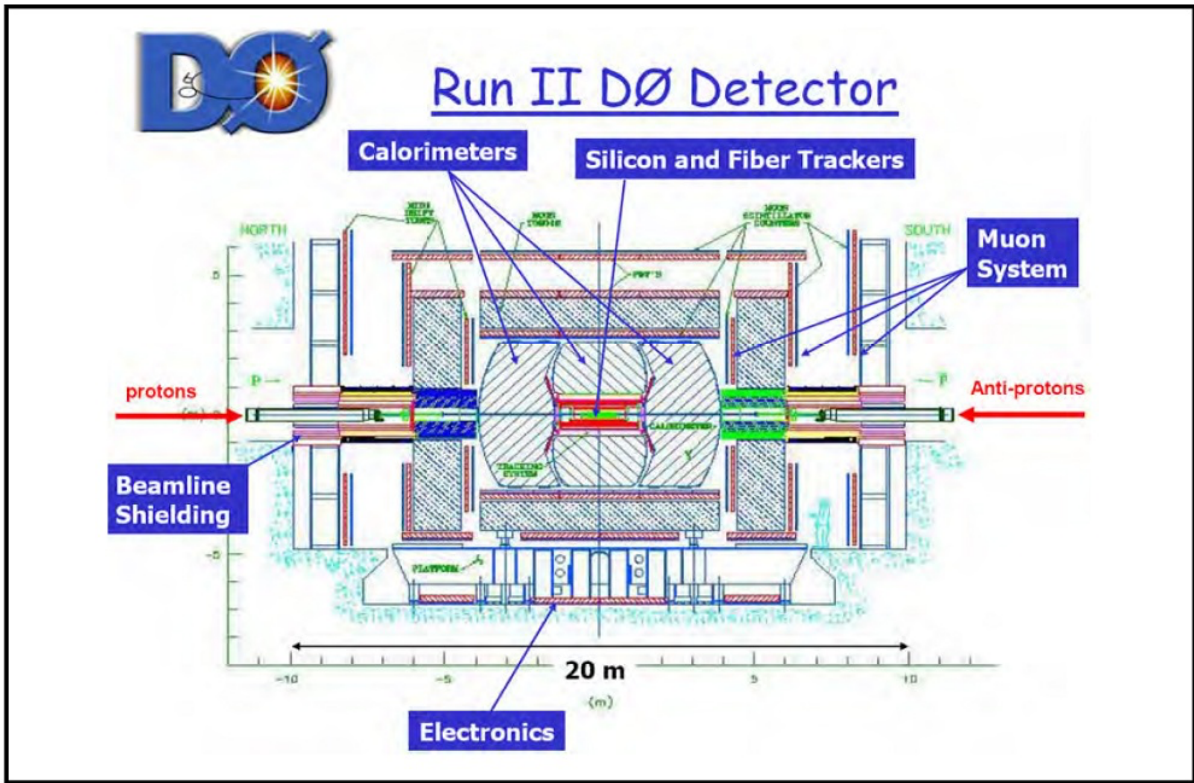
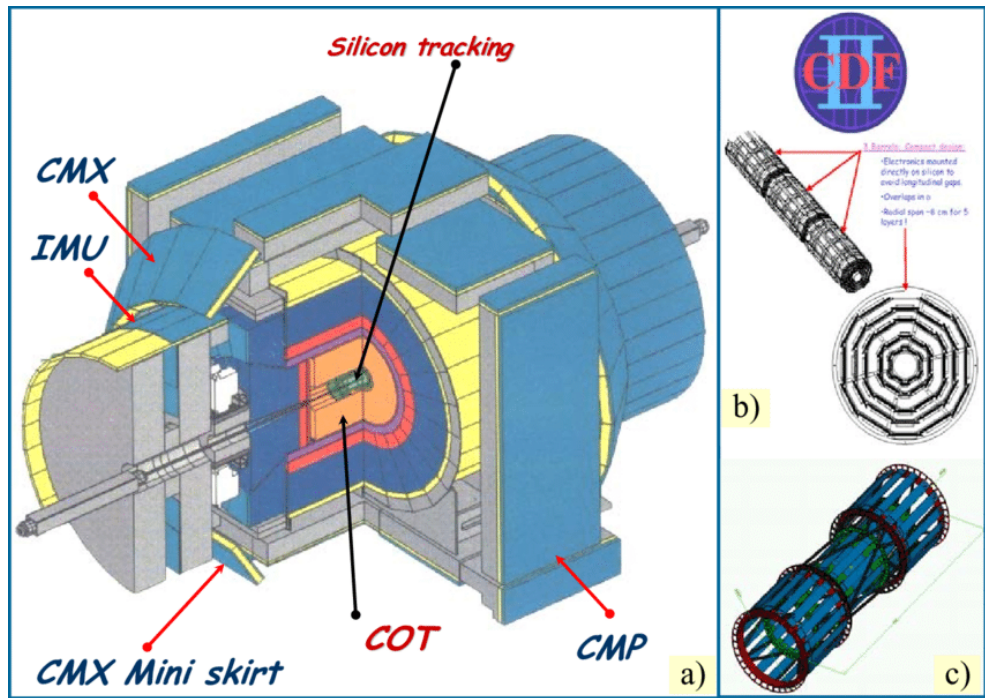
Belle II TDR, arXiv:1011.0352



Have a look at all the TDRs

But also ...

On the other side of the Ocean

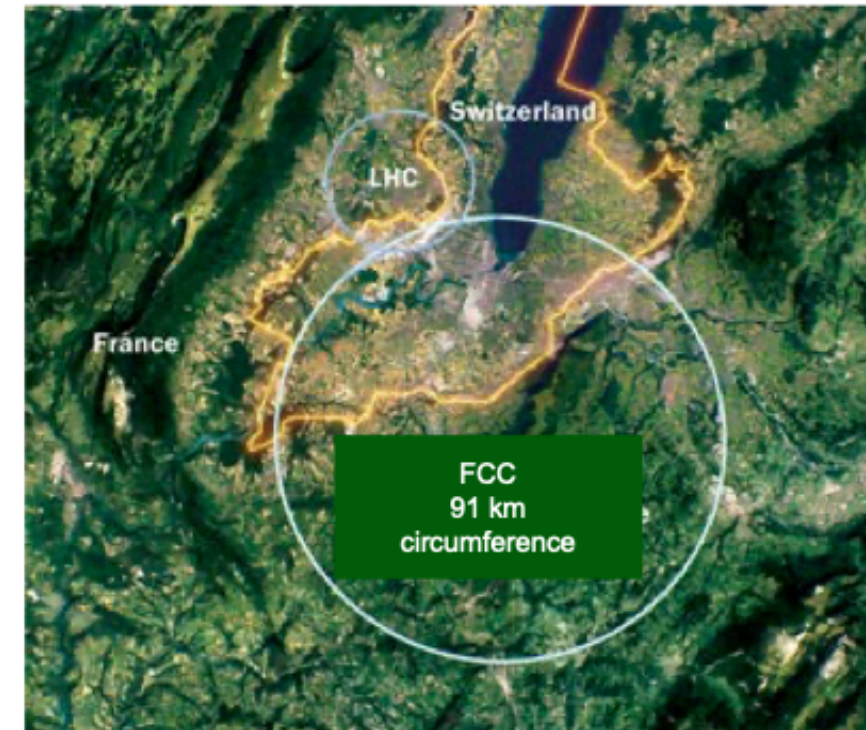


On the other side of the ring

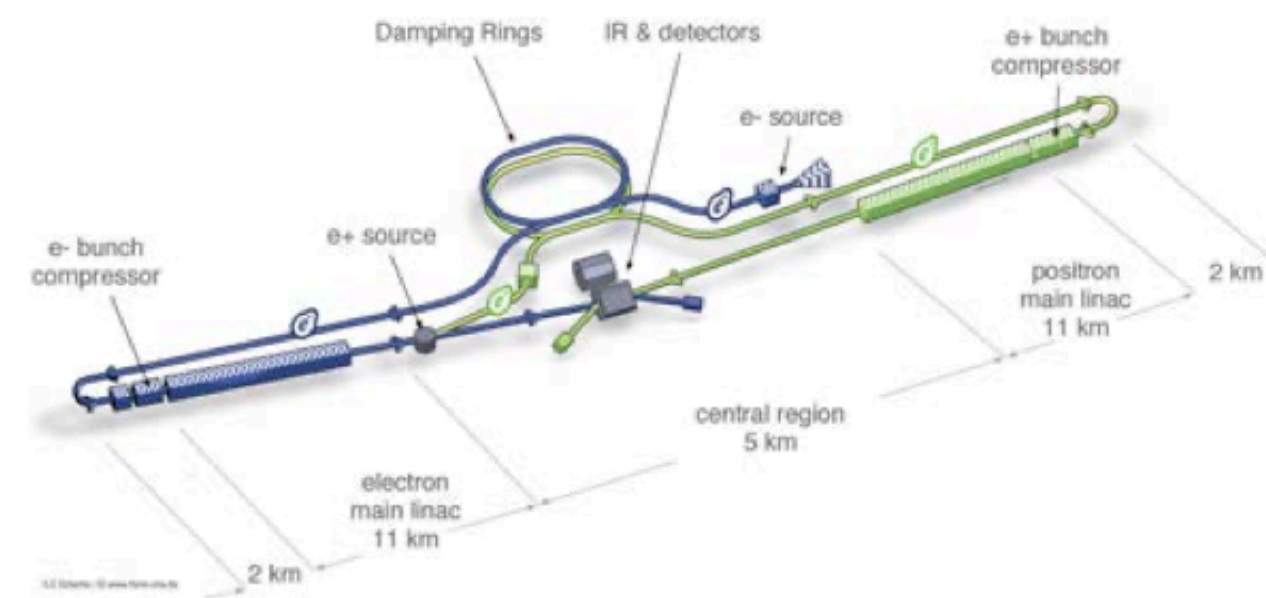
Proposed large-scale projects at CERN, ~ 2045

e^+e^- colliders
("Higgs factories")

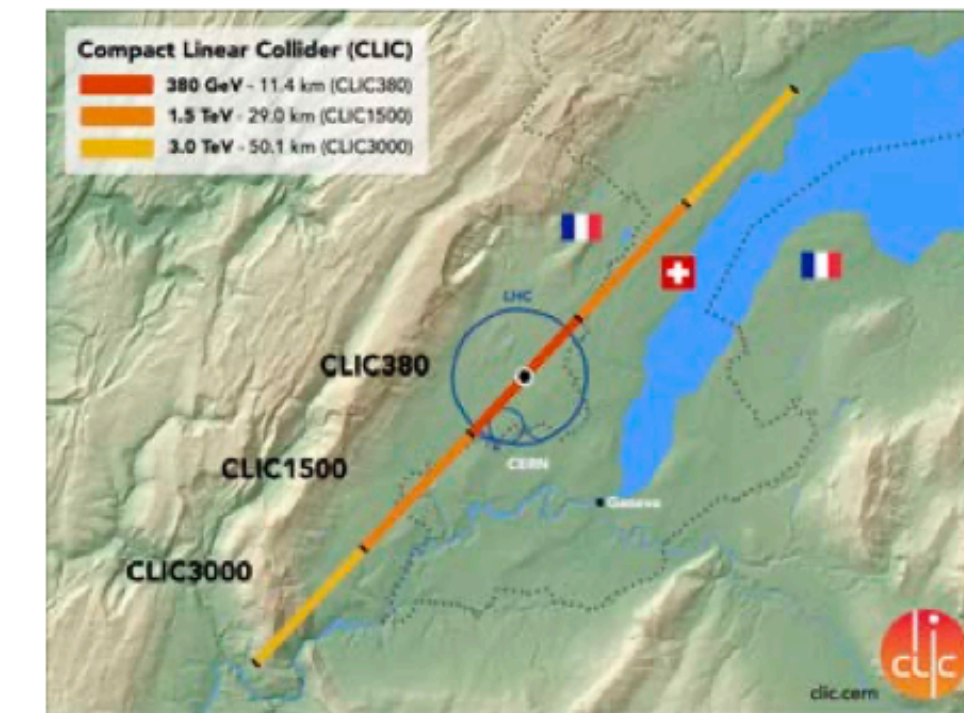
FCC- ee (e^+e^- , circular, 91 – 365 GeV)



LCF (e^+e^- , linear, 91 – 240, 550 GeV)



CLIC (e^+e^- , linear, 380 GeV, 1.5 TeV)



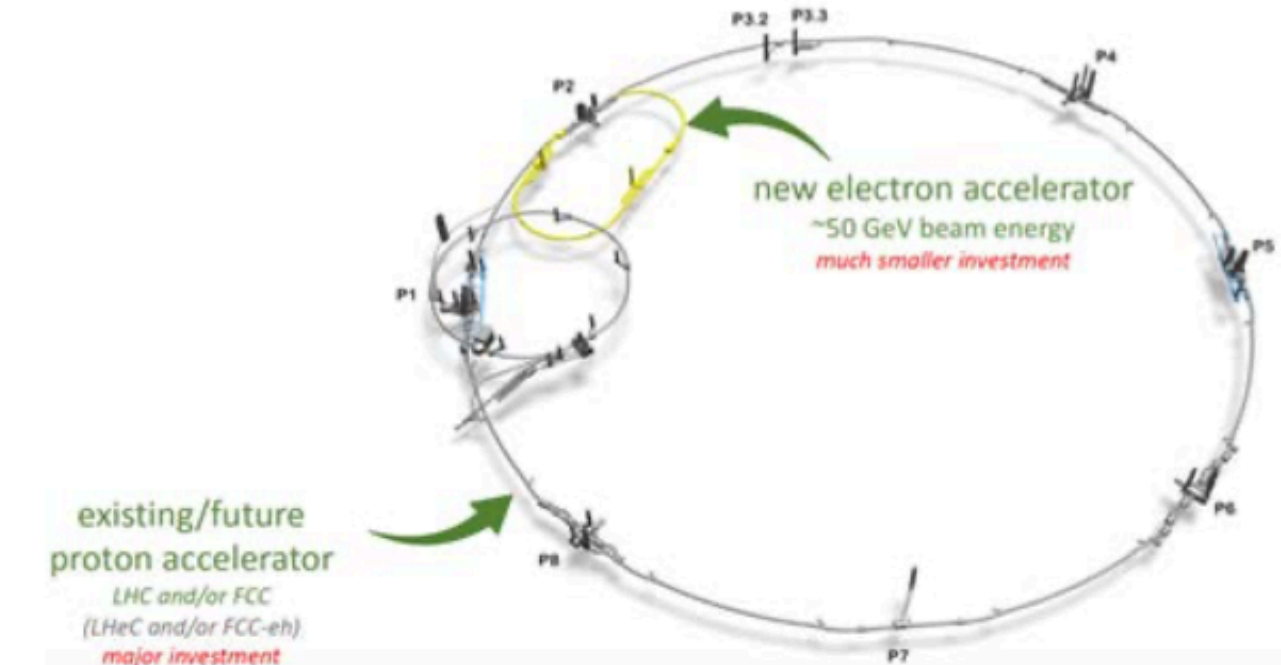
Intermediate projects

(Leave room (time, budget, resources) for further development of THE machine that can probe directly the energy frontier at the 10 TeV parton scale)

LEP3 (e^+e^- , circular, 91 – 230 GeV)

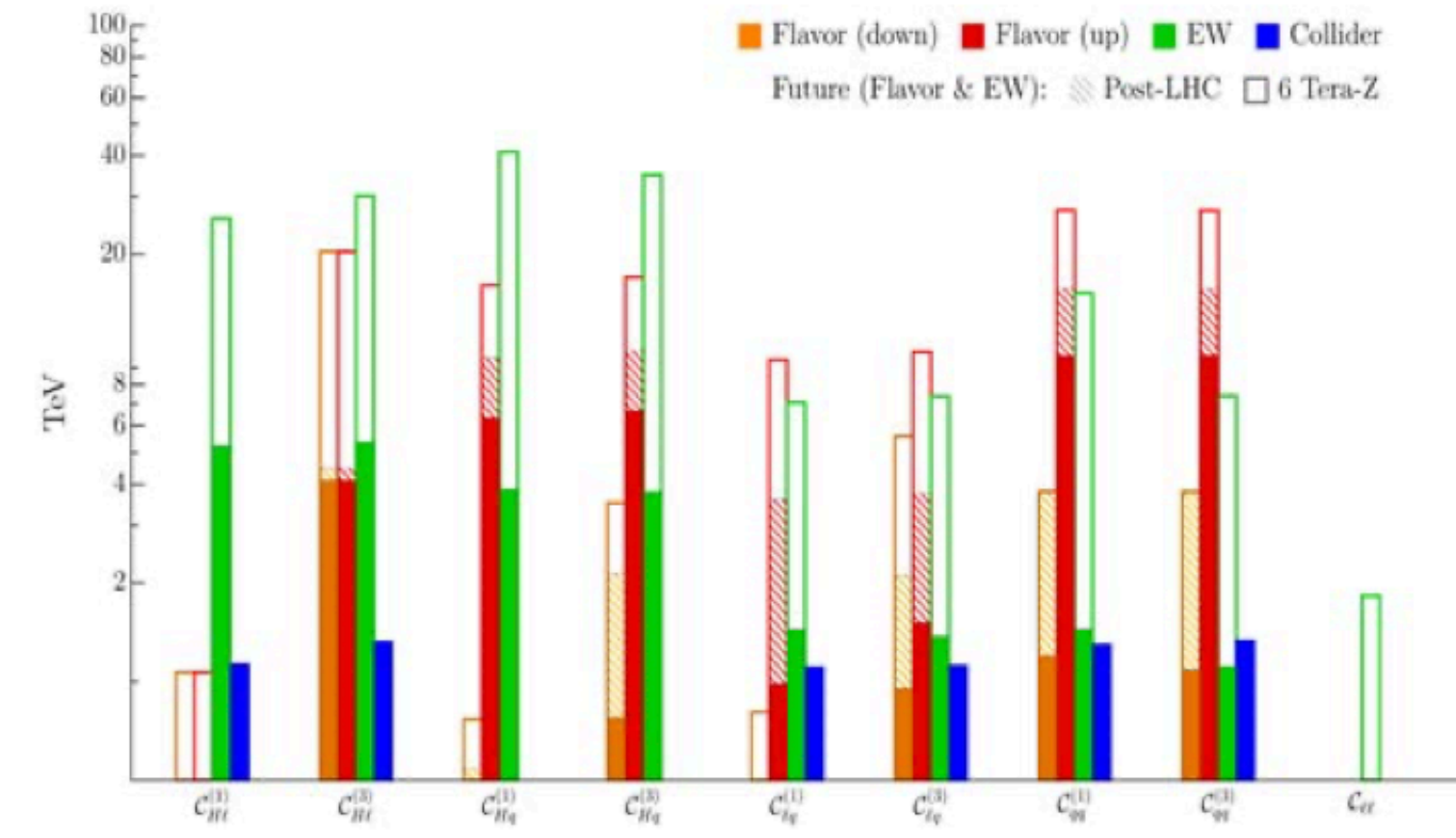
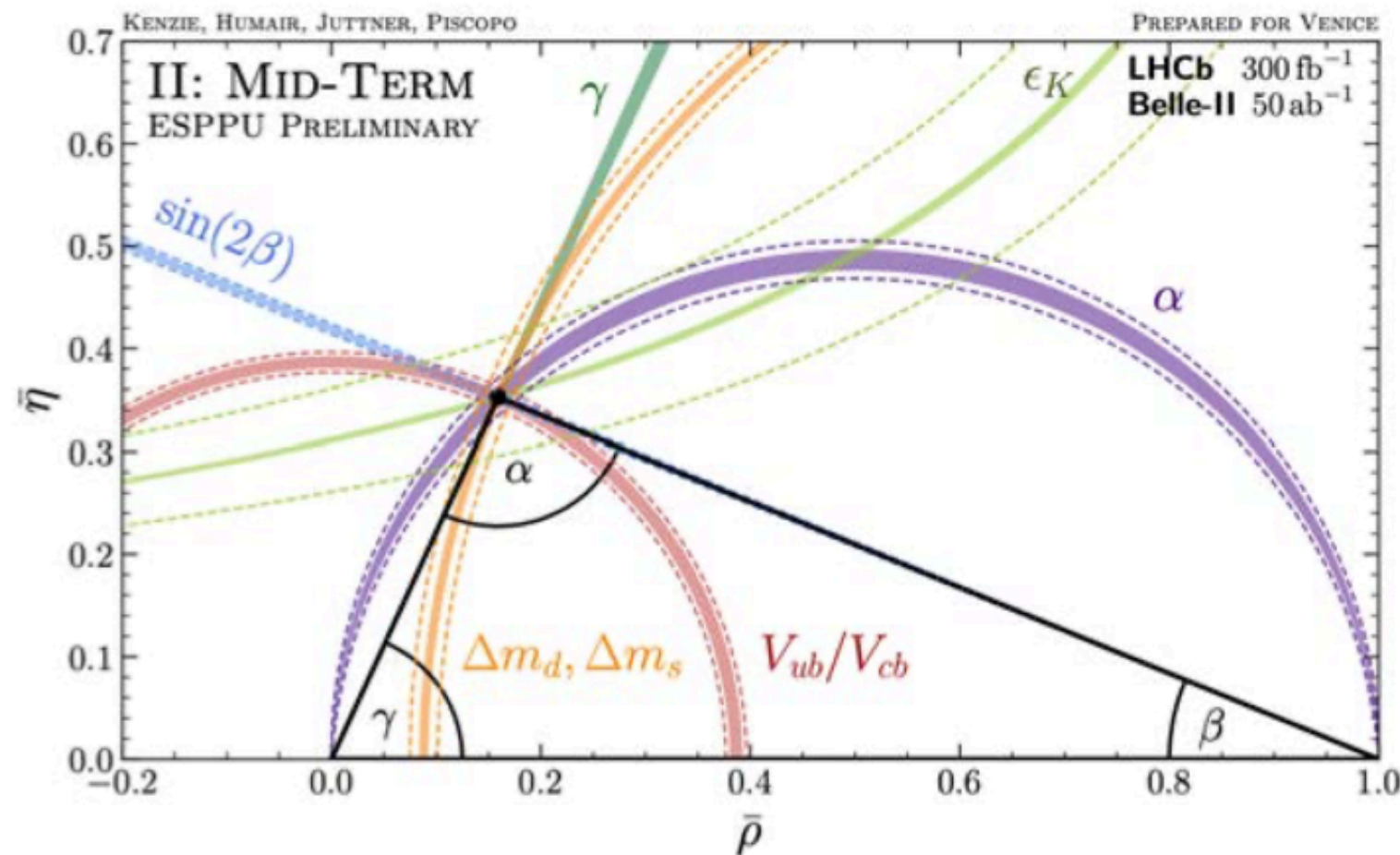
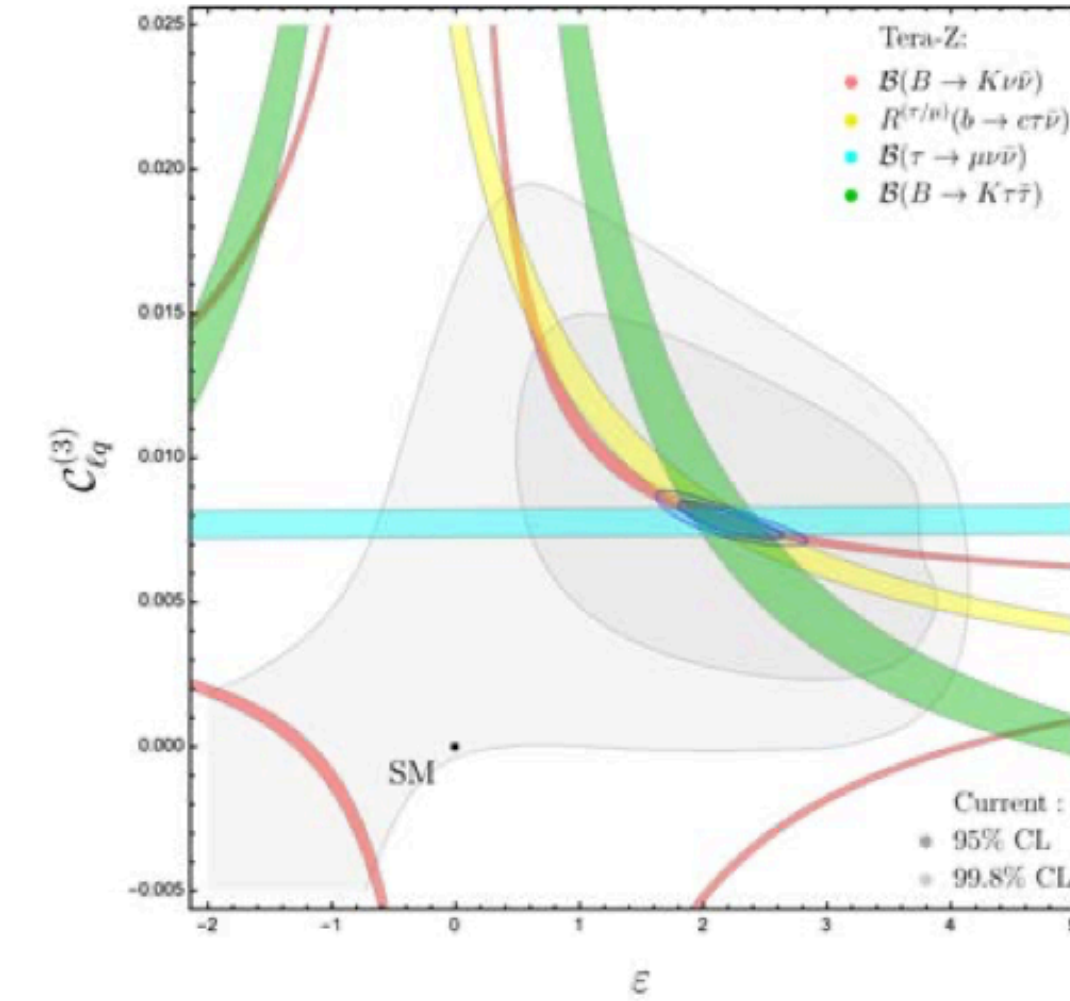


LHeC (ep, circular, electron ERL, 50 GeV e^- , > 1 TeV ep collisions)



Flavour Physics

- Precision **Higgs**, **electroweak**, and **flavour physics** are three facets of for indirect discoveries
→ their **synergy is essential to maximise the discovery potential**
- B/D/tau physics: major improvements from full exploitation of available facilities up to 2040s (LHCb-II, ATLAS/CMS, Belle-II)
Beyond that, **$6 \cdot 10^{12} Z^0$ would provide a further major step forward**
Giga-Z is not an option for flavour physics
- Support needed for theory (key role of Lattice QCD)



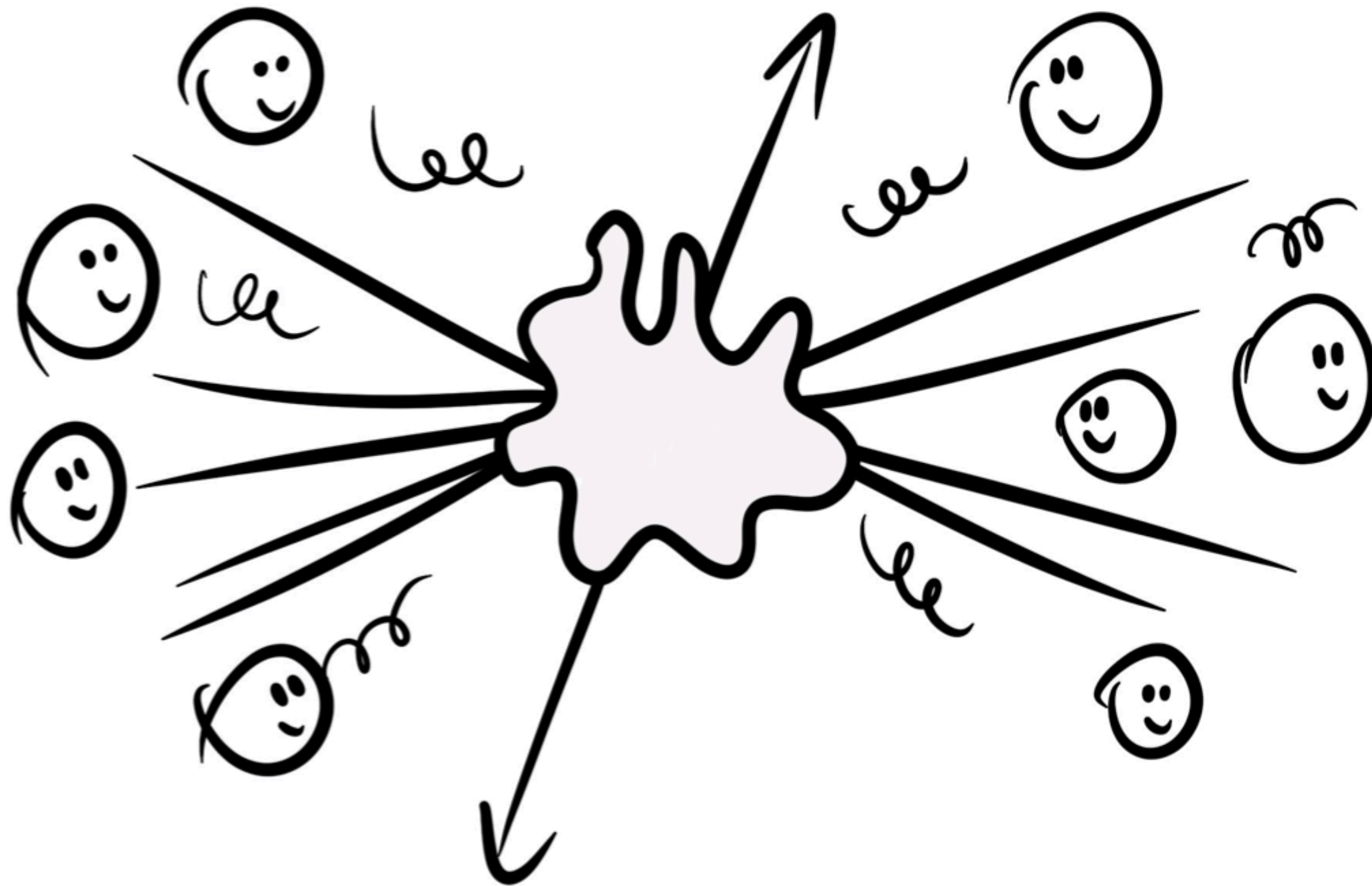
The story starts with collisions

物語は衝突から始まる

But many things are produced. Some “events” are more infesting than others. You will often hear the words:

“Signal”: something we care about

“Background”: something we don’t care about but need to understand very well.

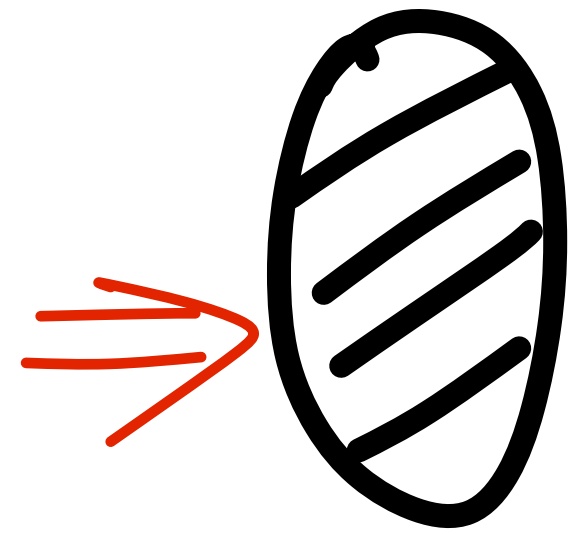


いろんなものがいっぱい生成されてしまいます。ある事象は他よりもずっといっぱいできるのです。

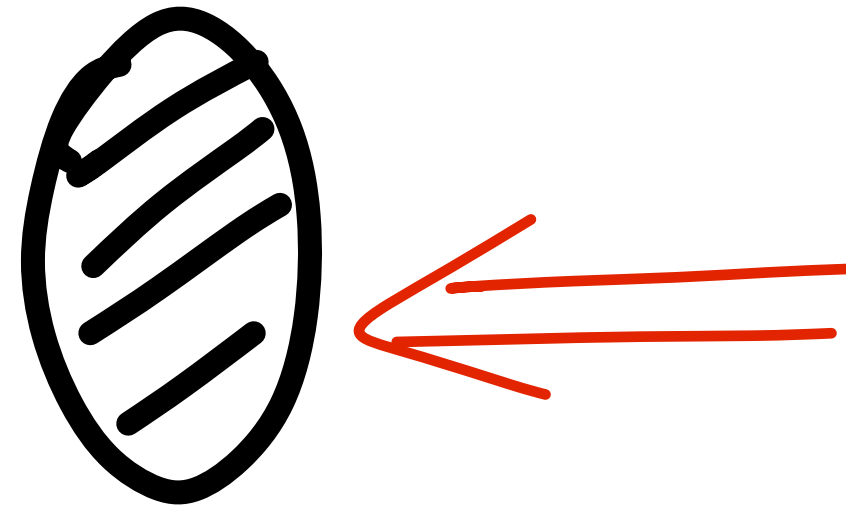
「信号」：ほしいもの

「背景」： いらないものだけど、ちゃんと理解しておかないといけない。

Production

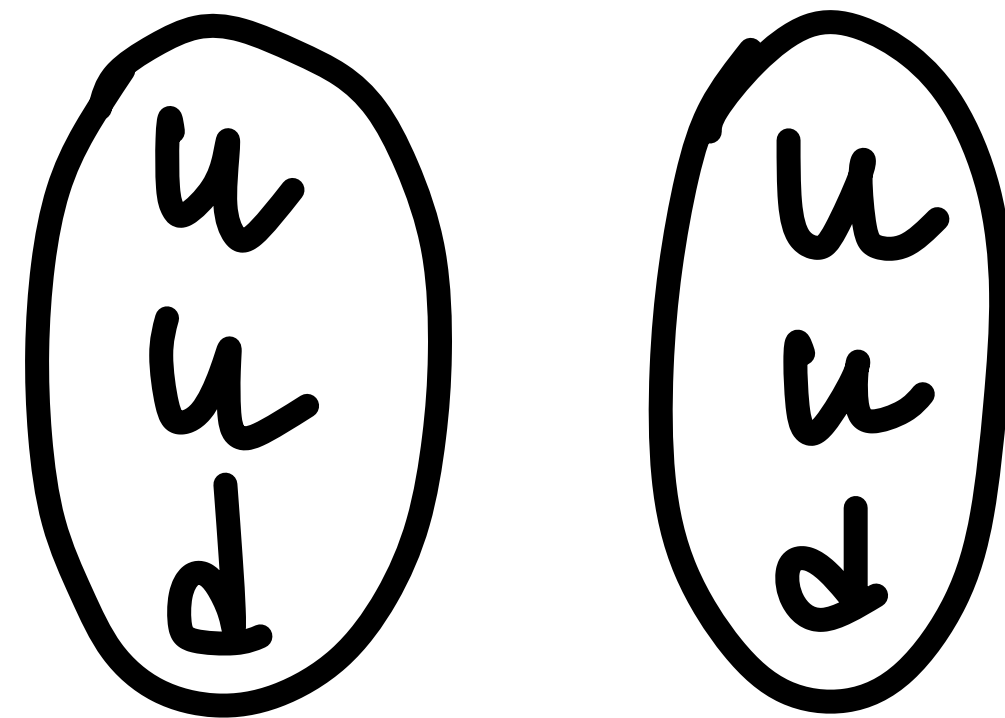


Proton



Proton

The protons produced at the LHC collide.
But actually the protons contain quarks
and gluons also.



3 quarks

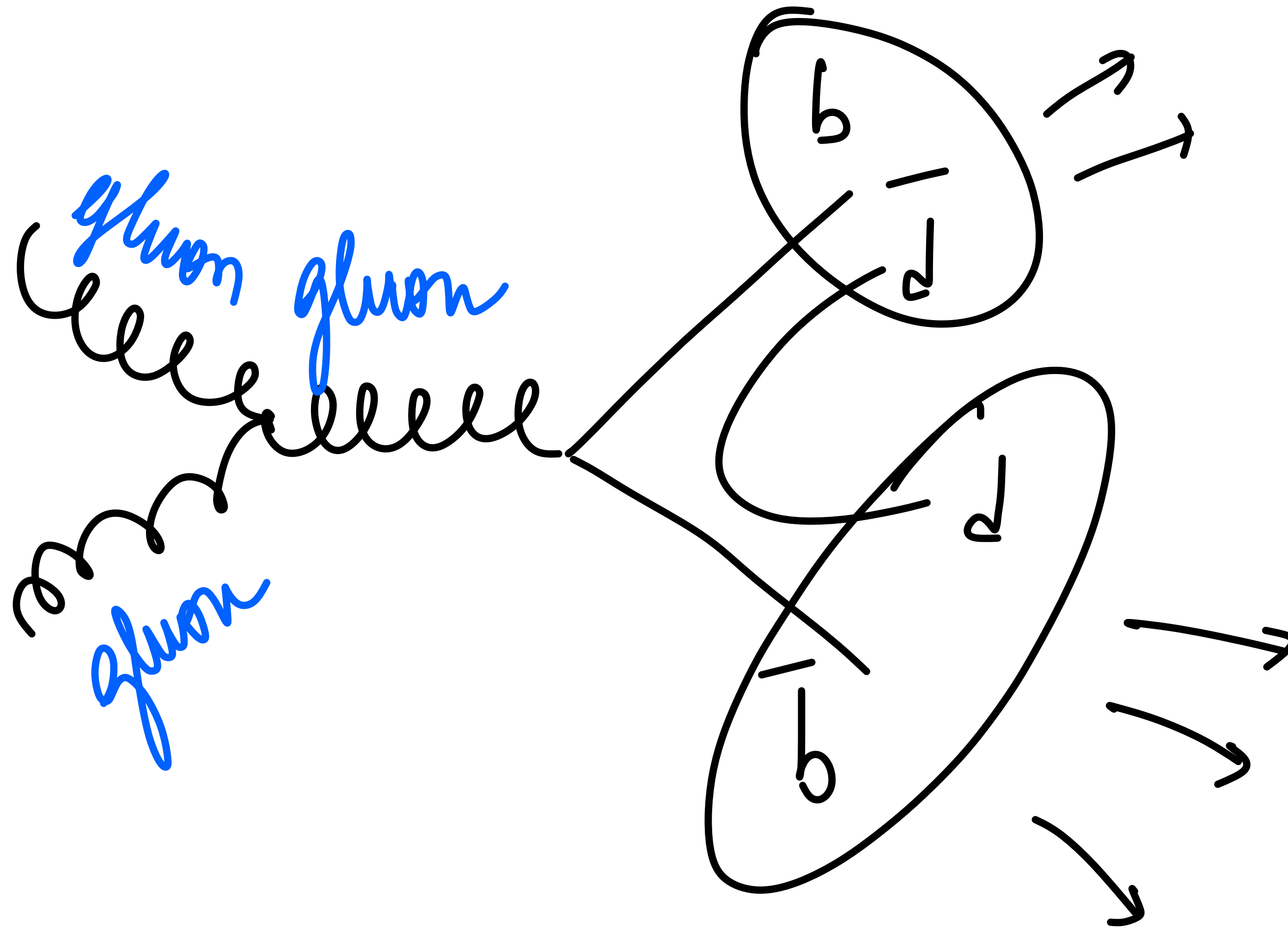


3 quarks + gluons

LHC では陽子が衝突します。

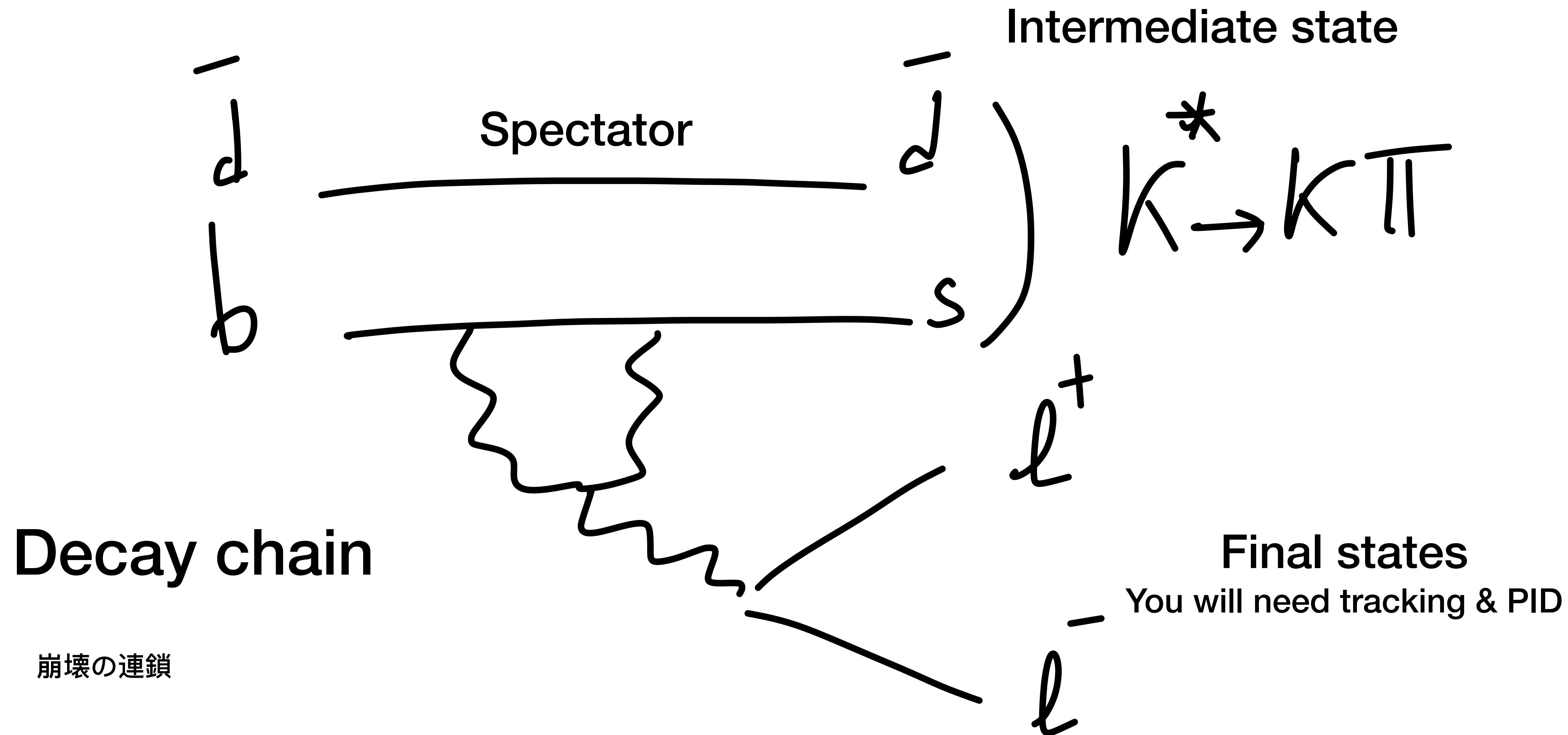
でも実際には、陽子にはクォークに加えてグルーオンが含まれています。

Gluon fusion



The dominating process is Gluon fusion
And this is followed by “hadronisation”

一番多いのは、グルーオンの合体で
す。そこから「ハドロン化」の過程を
へて いろんな粒子が出てきます。



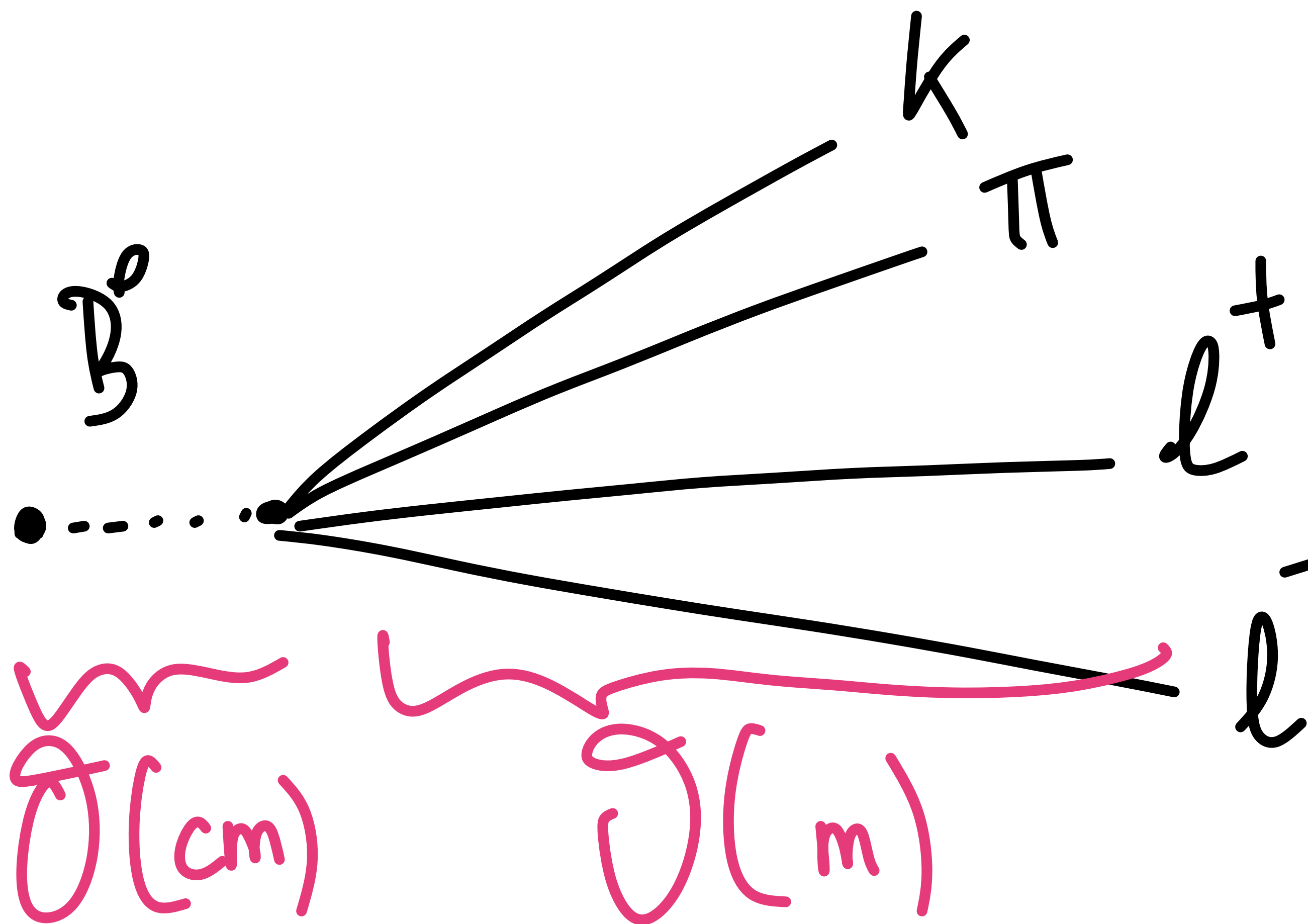
What's the nature of the “final states?”

最後にできた状態の性質は?



Boost !

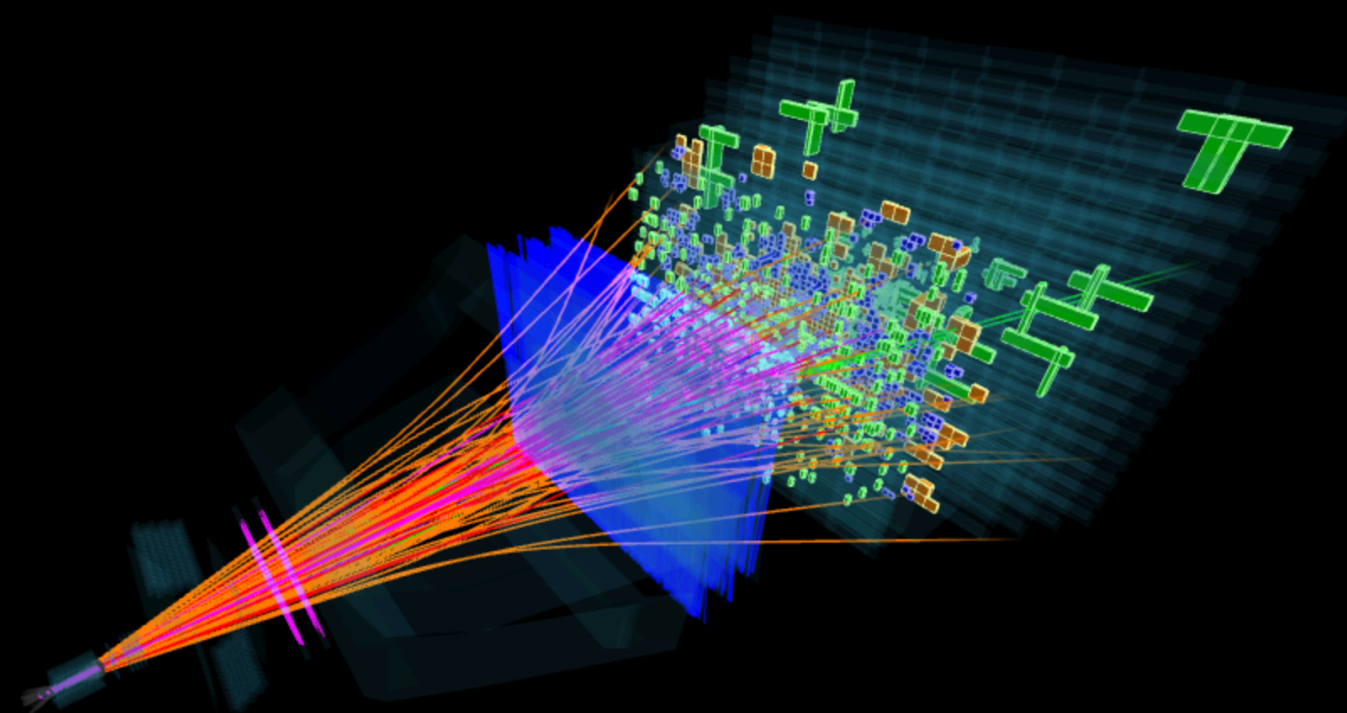
加速!



$$t_{lab} = \tau \cdot \gamma$$



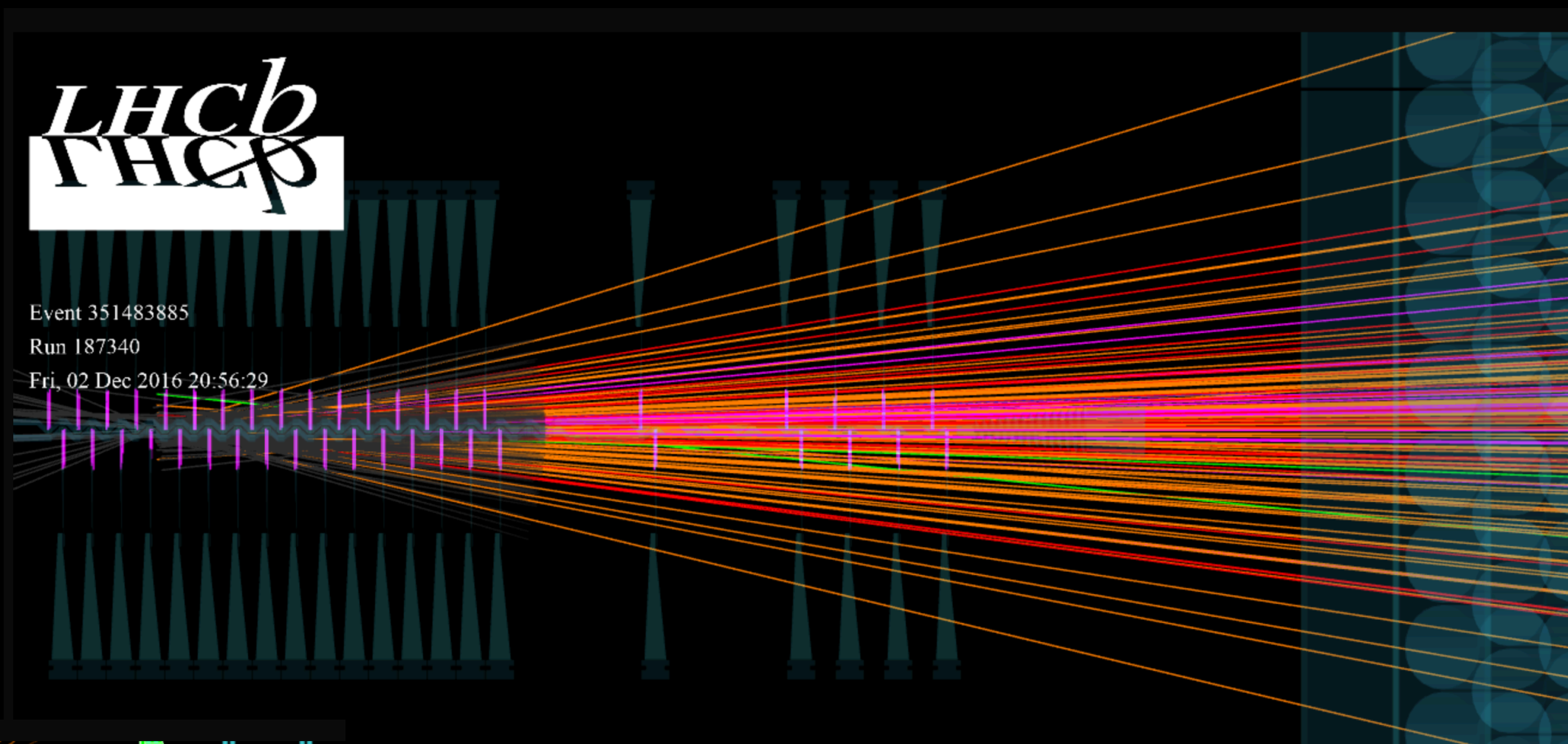
Event 351483885
Run 187340
Fri, 02 Dec 2016 20:56:29



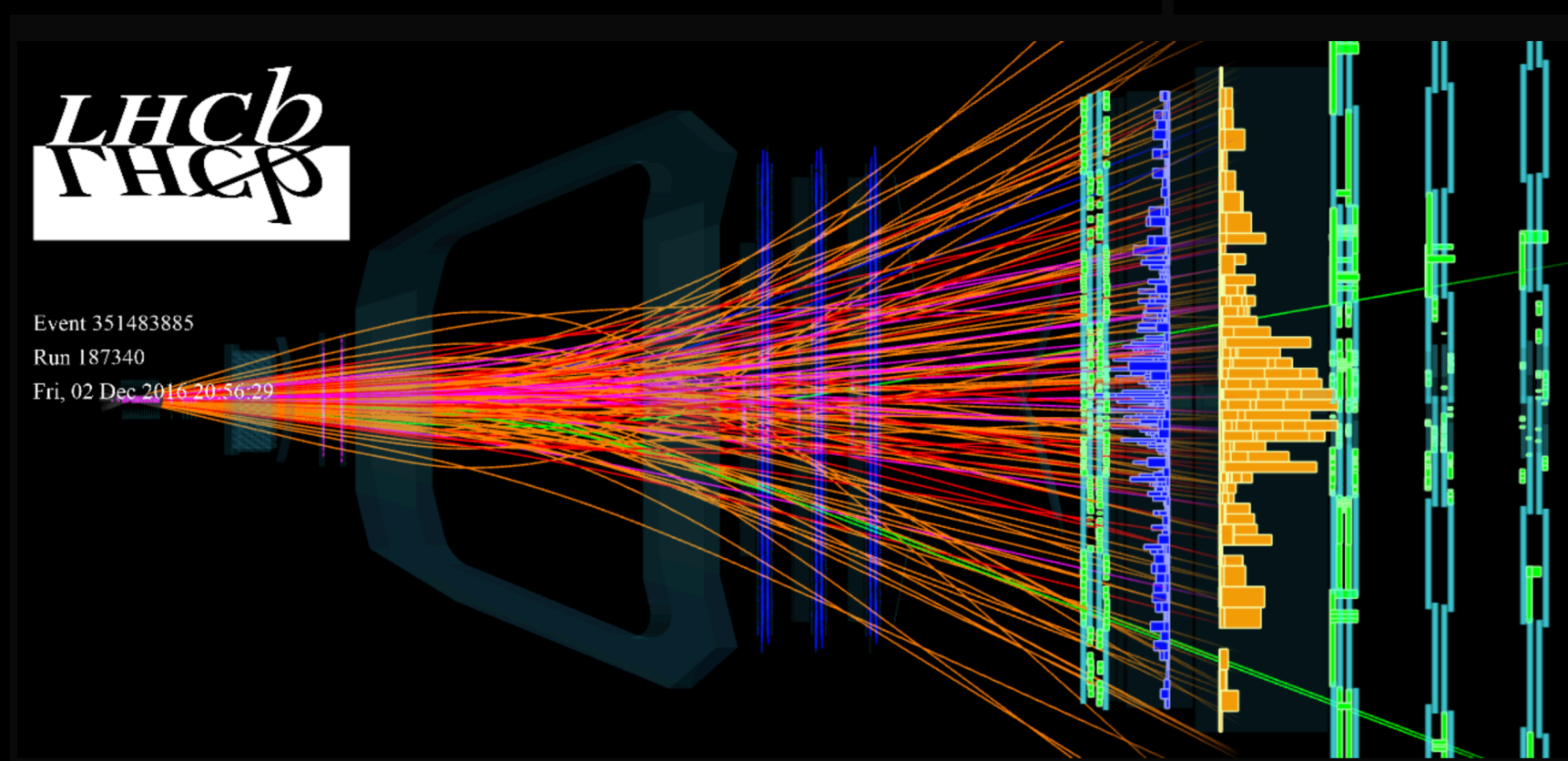
Reconstruction



Event 351483885
Run 187340
Fri, 02 Dec 2016 20:56:29



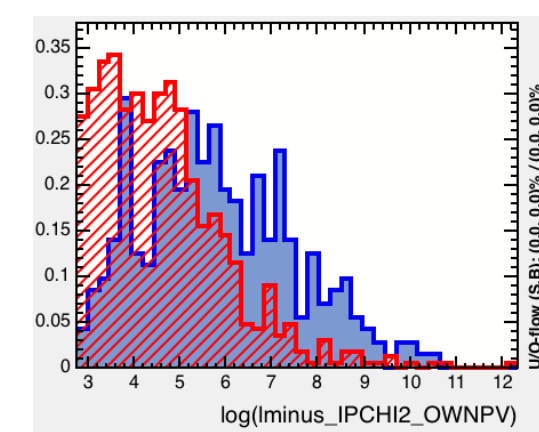
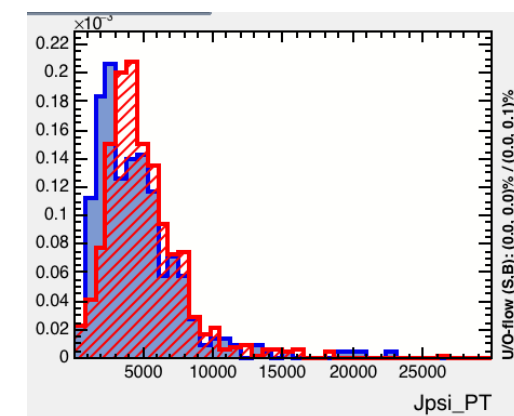
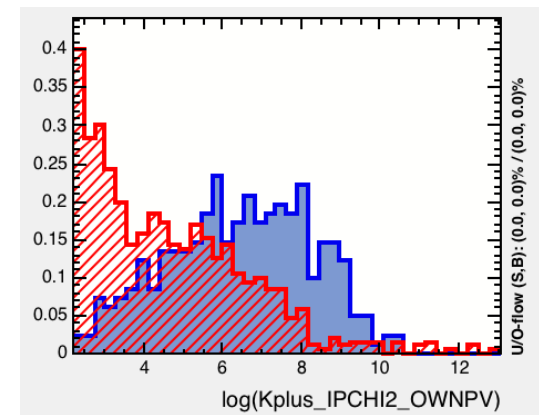
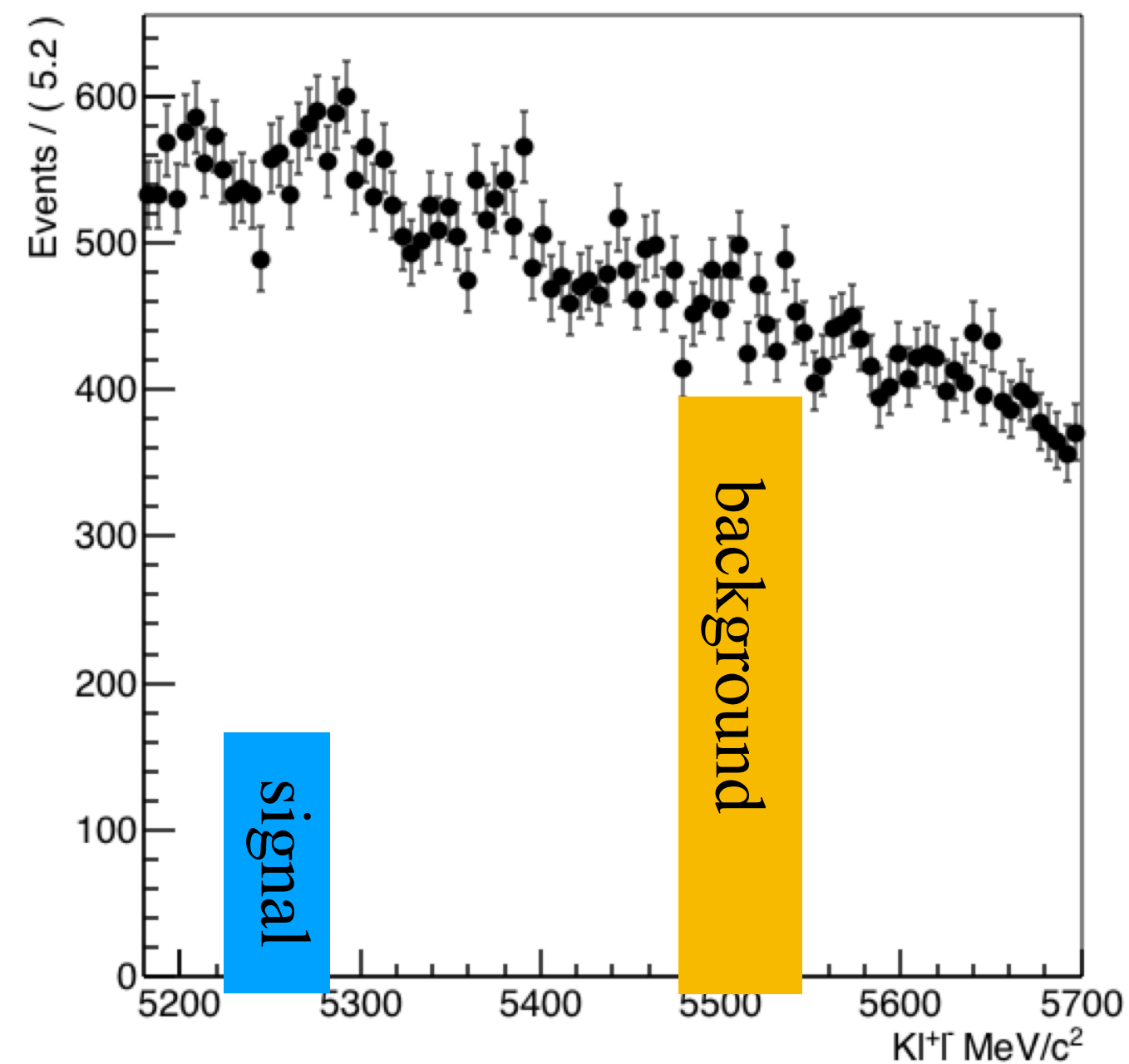
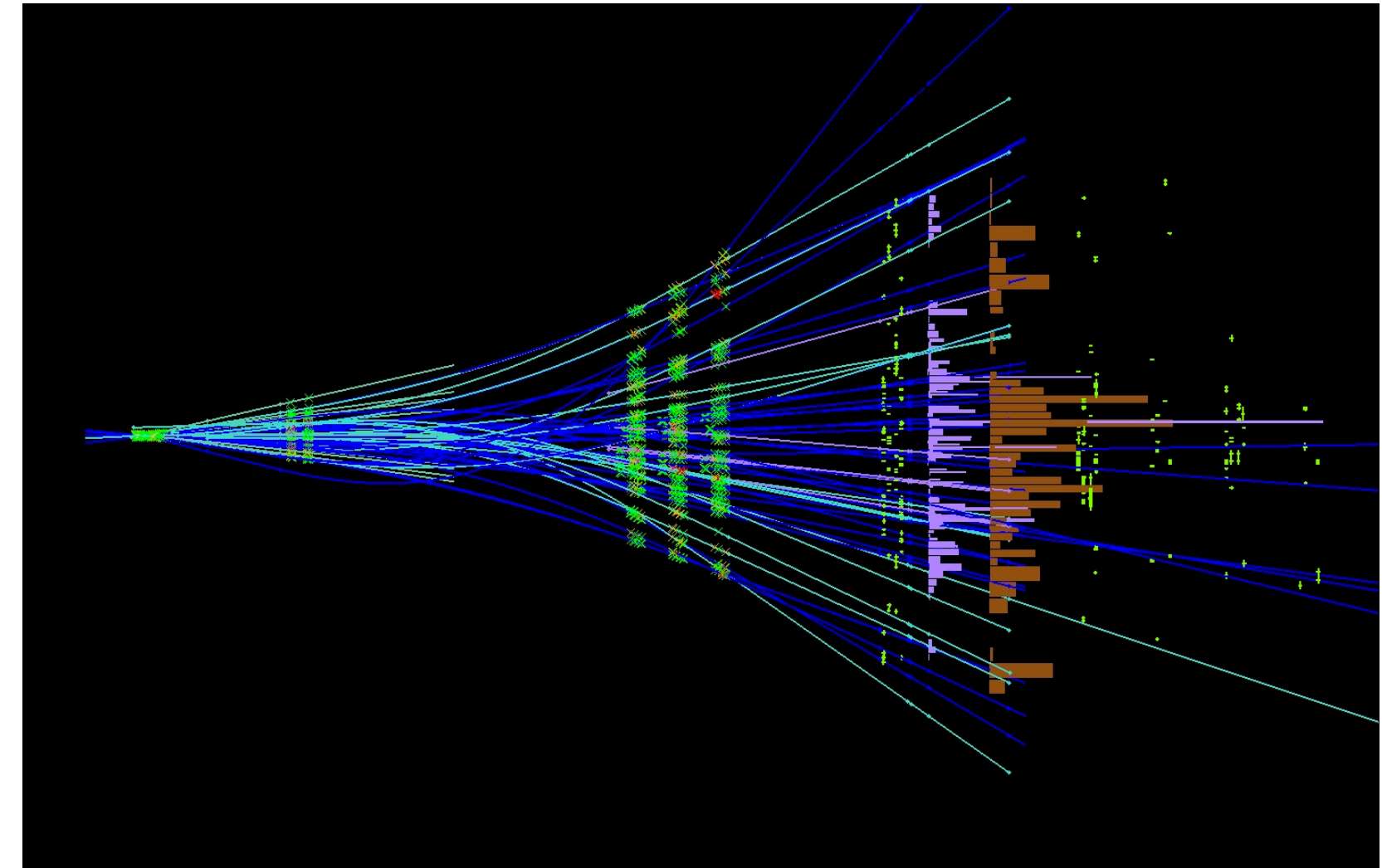
Event 351483885
Run 187340
Fri, 02 Dec 2016 20:56:29



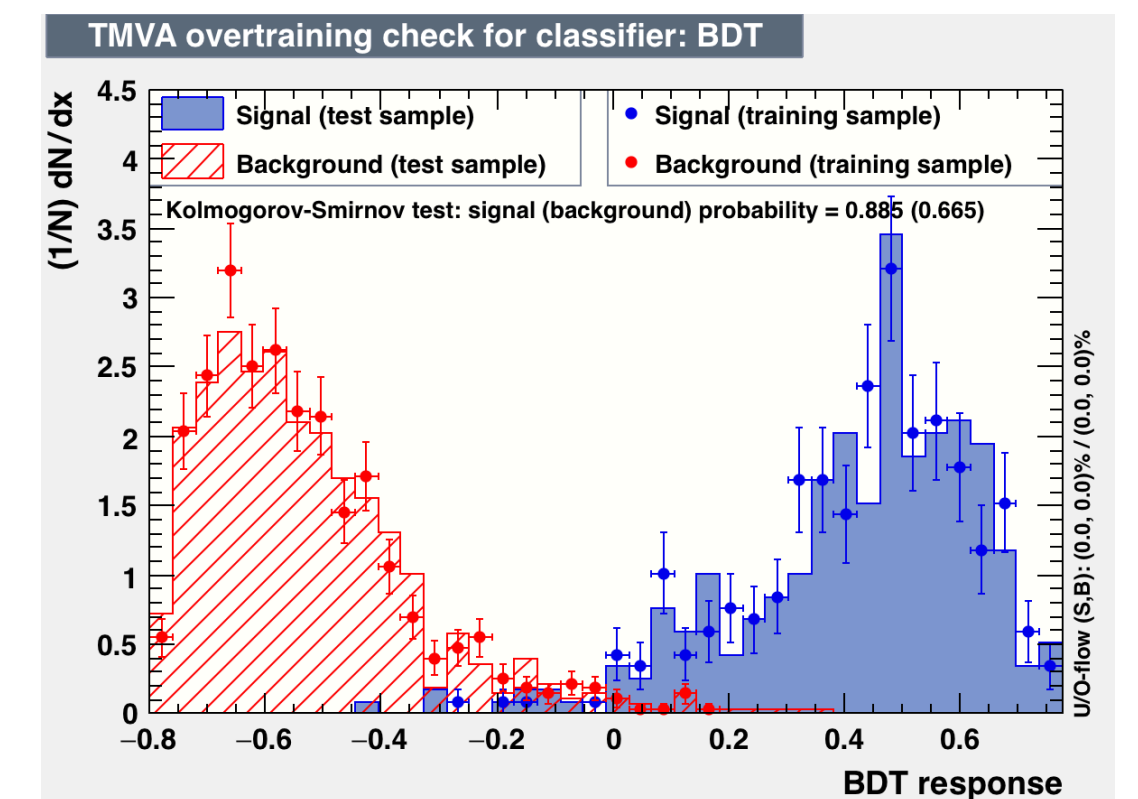
Quadrivector $(E, \vec{p})$

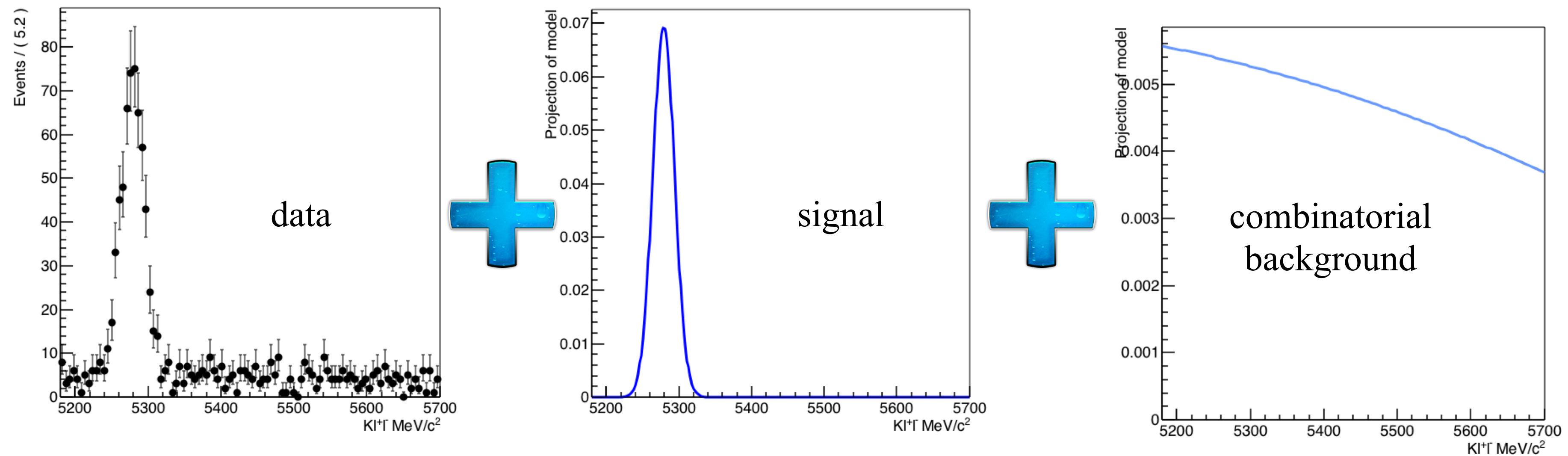
$$B \rightarrow K \pi \ell^+ \ell^-$$

$$\begin{pmatrix} m_B \\ \vec{0} \end{pmatrix} = \begin{pmatrix} E_K \\ \vec{p}_K \end{pmatrix} + \begin{pmatrix} E_\pi \\ \vec{p}_\pi \end{pmatrix} + \begin{pmatrix} E_{\ell^+} \\ \vec{p}_{\ell^+} \end{pmatrix} + \begin{pmatrix} E_{\ell^-} \\ \vec{p}_{\ell^-} \end{pmatrix}$$



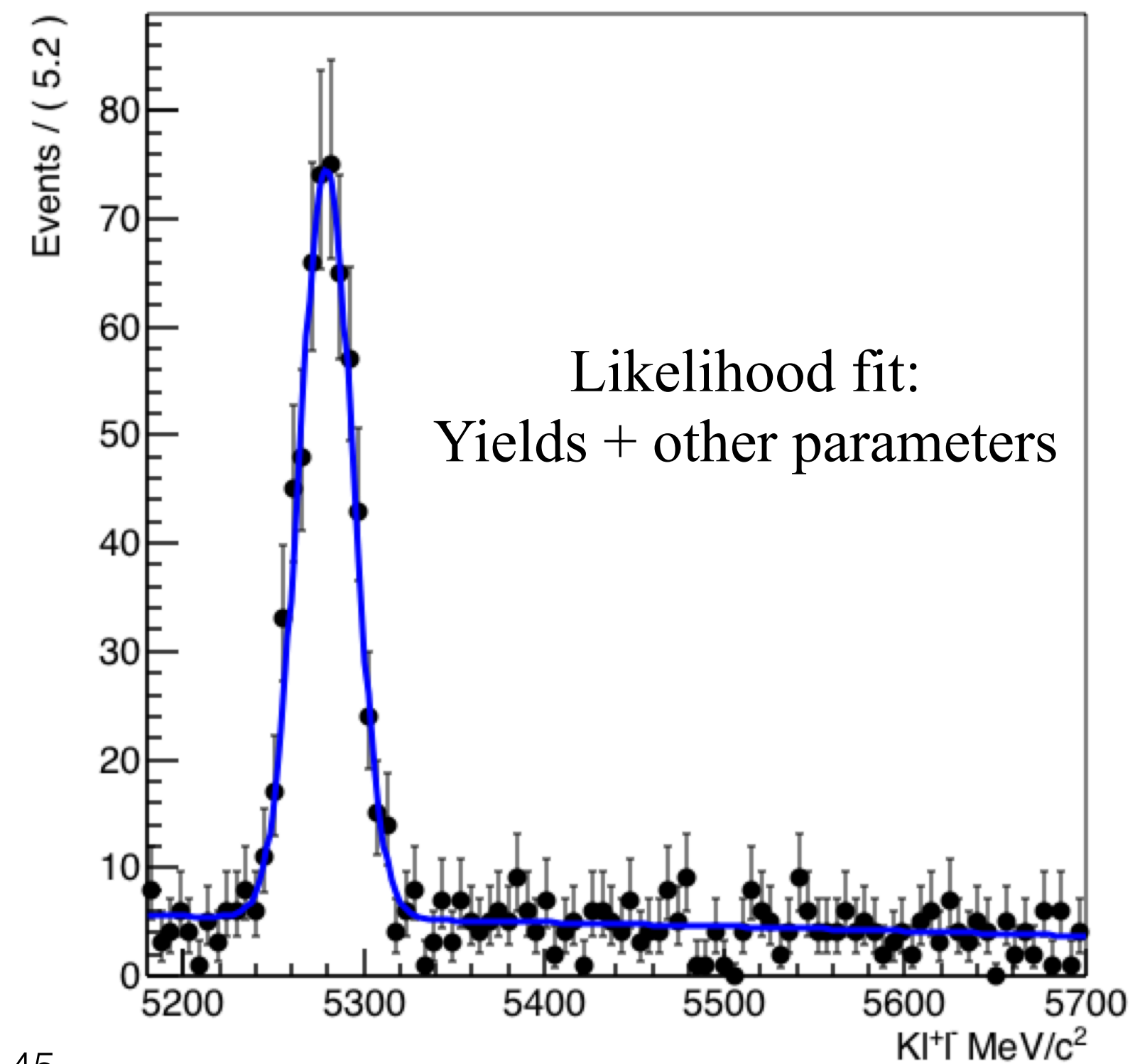
Dump in your favour AI





Depending on the difficulty of the fit,
some parameters can be
constrained from simulation etc.
A likelihood is minimised to find the best
set of parameters that describe the data.

データをフィットするのが難しいこともある
ので、いくつかのパラメータにはシミュレ
ーションで制限をつけたりします。とにかく、
もっともよくデータを再現するパラメータを
探すのです。

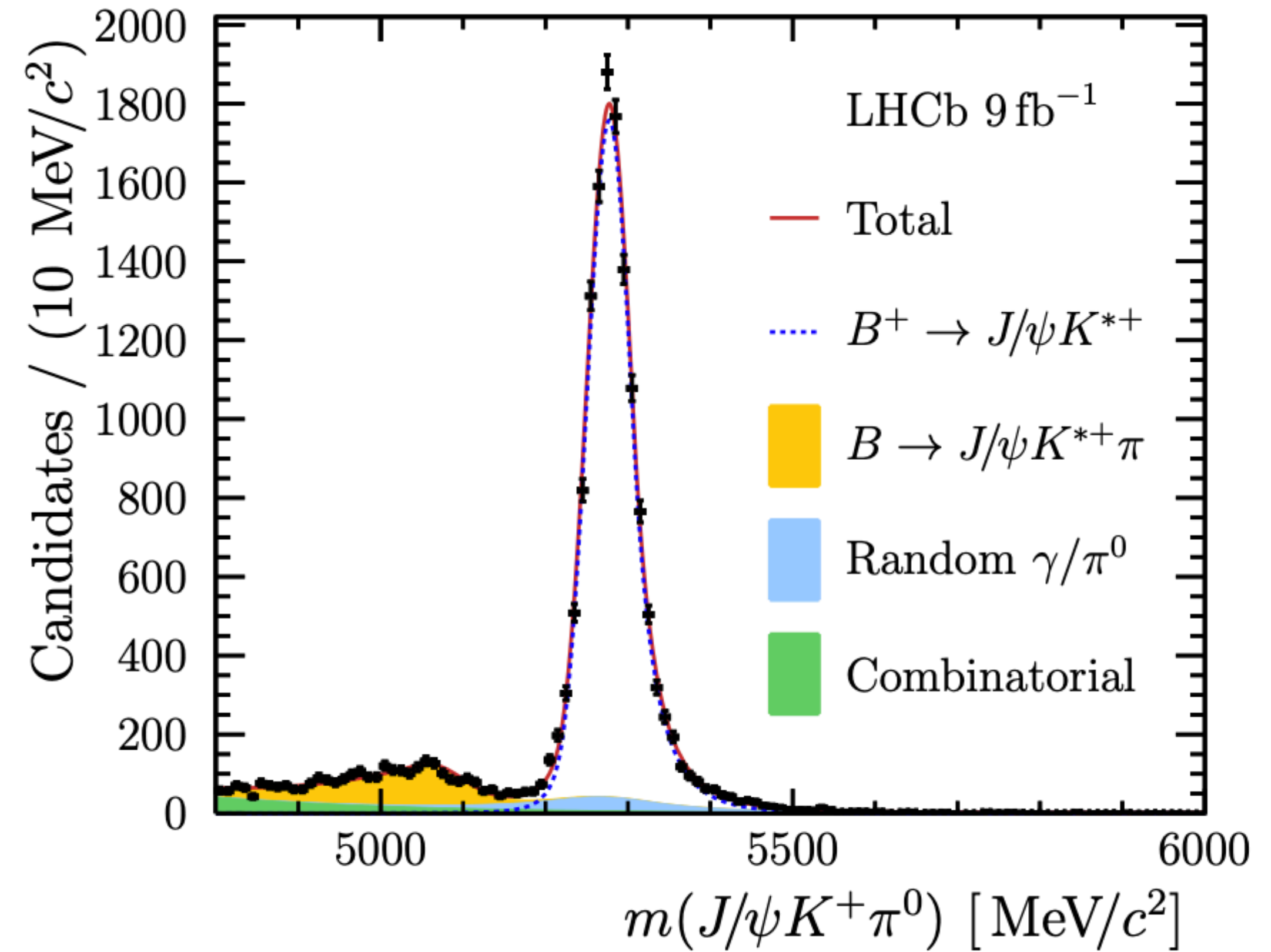
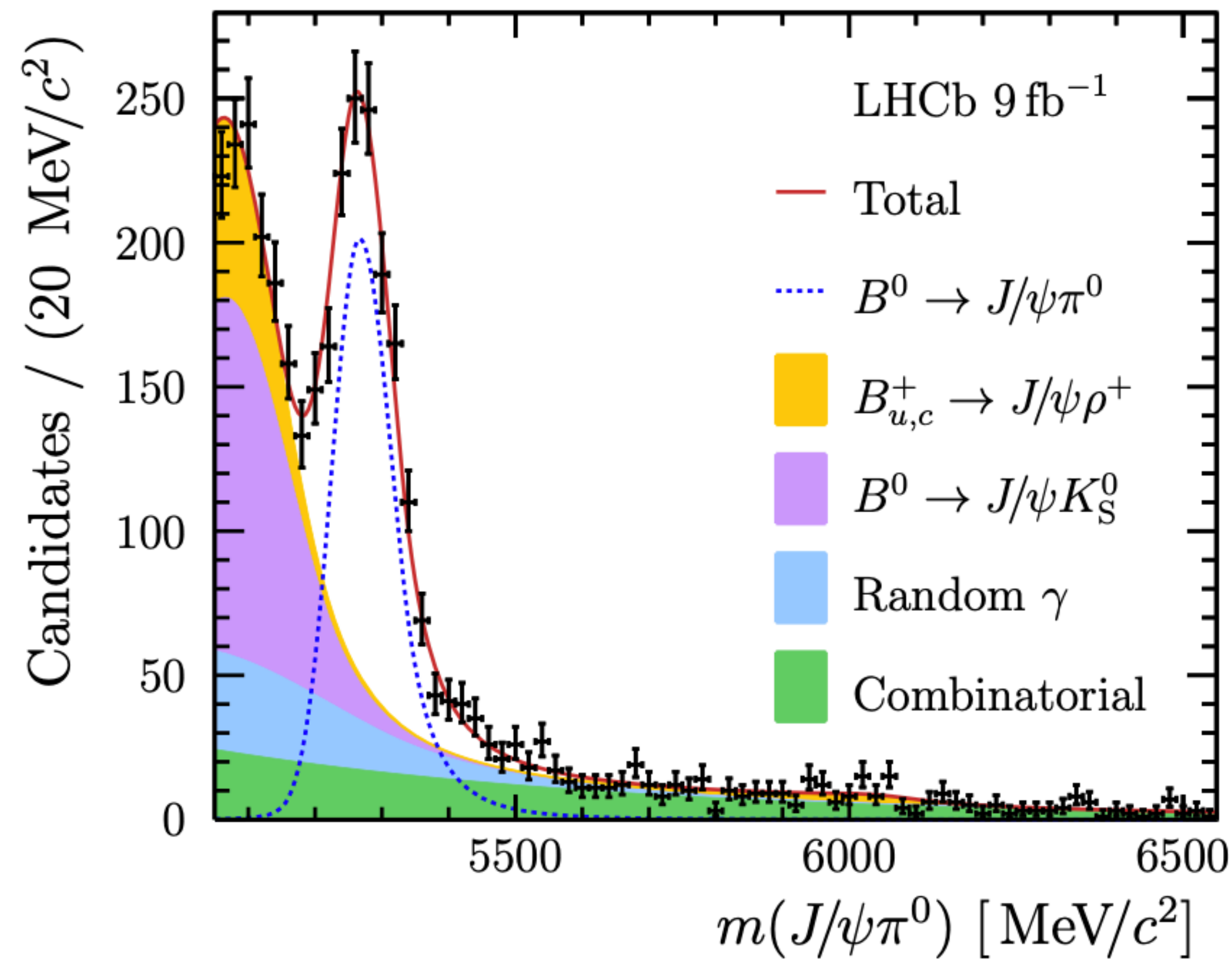


Bim publish

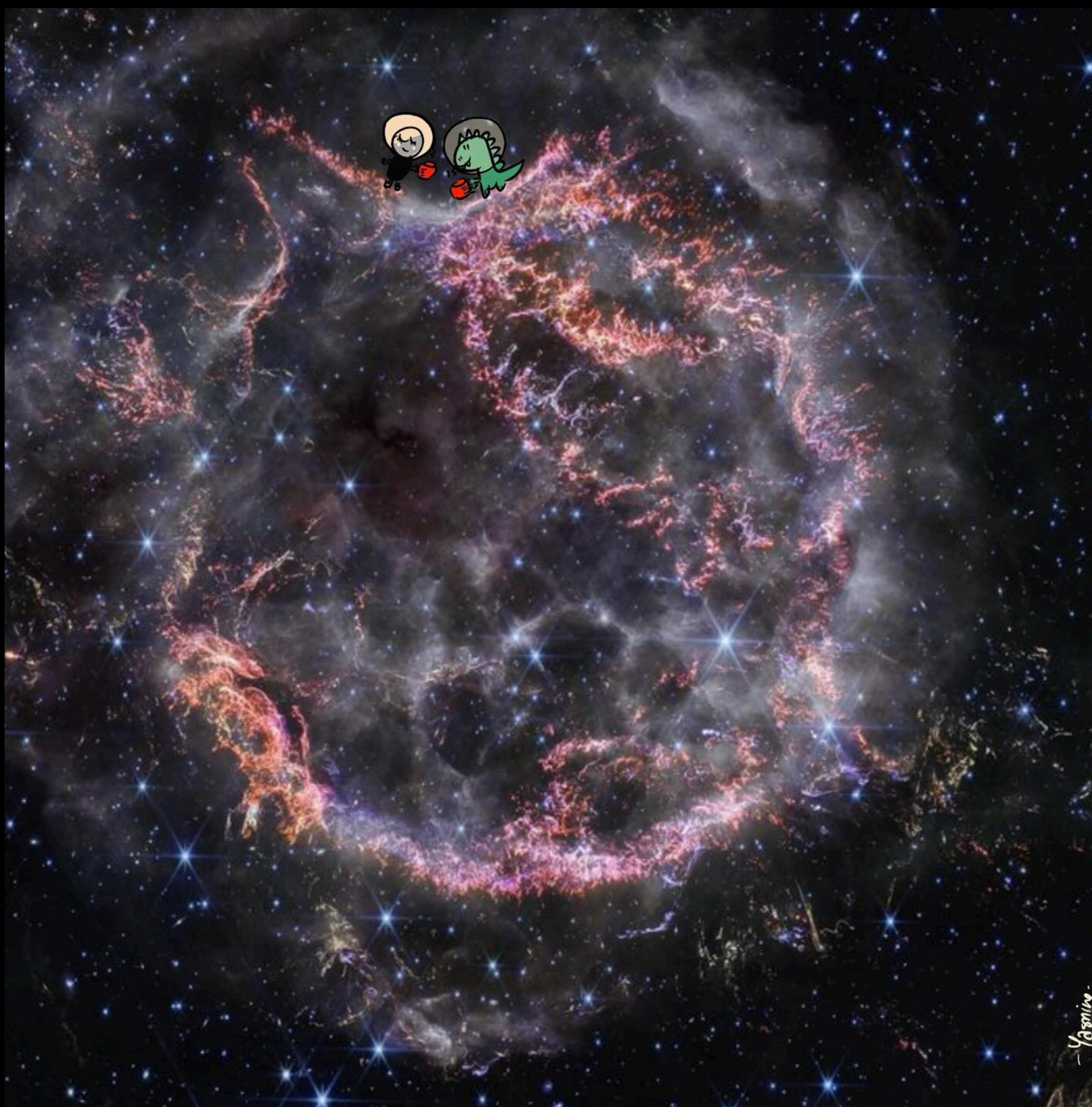


Hope referee B is cool

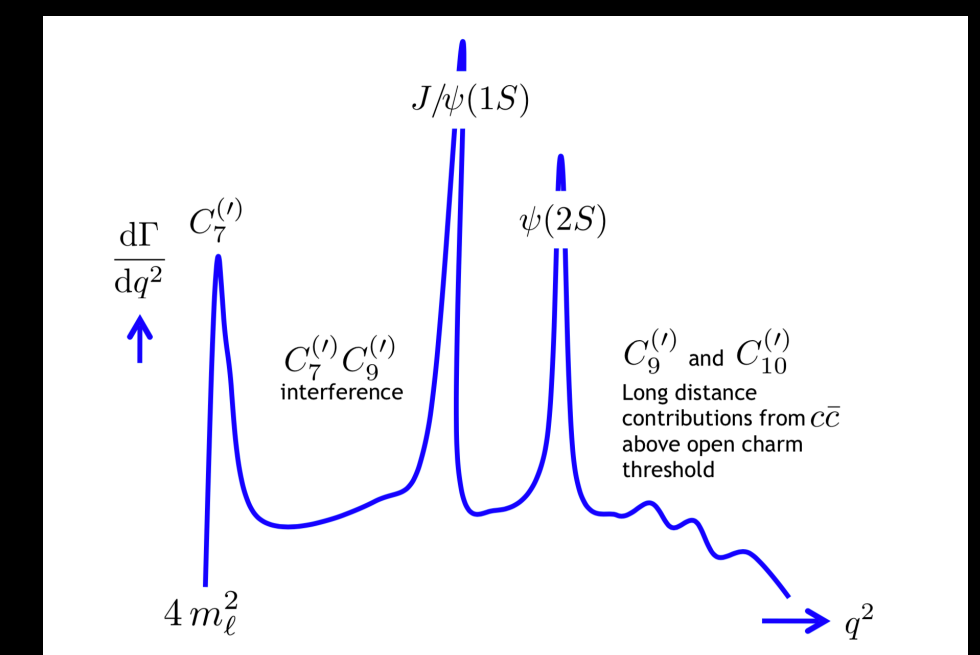
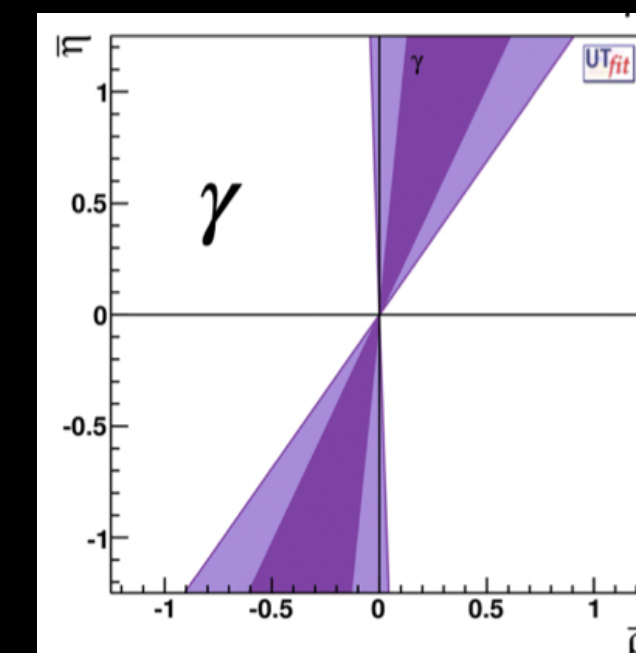
In real life, it will look like this ...



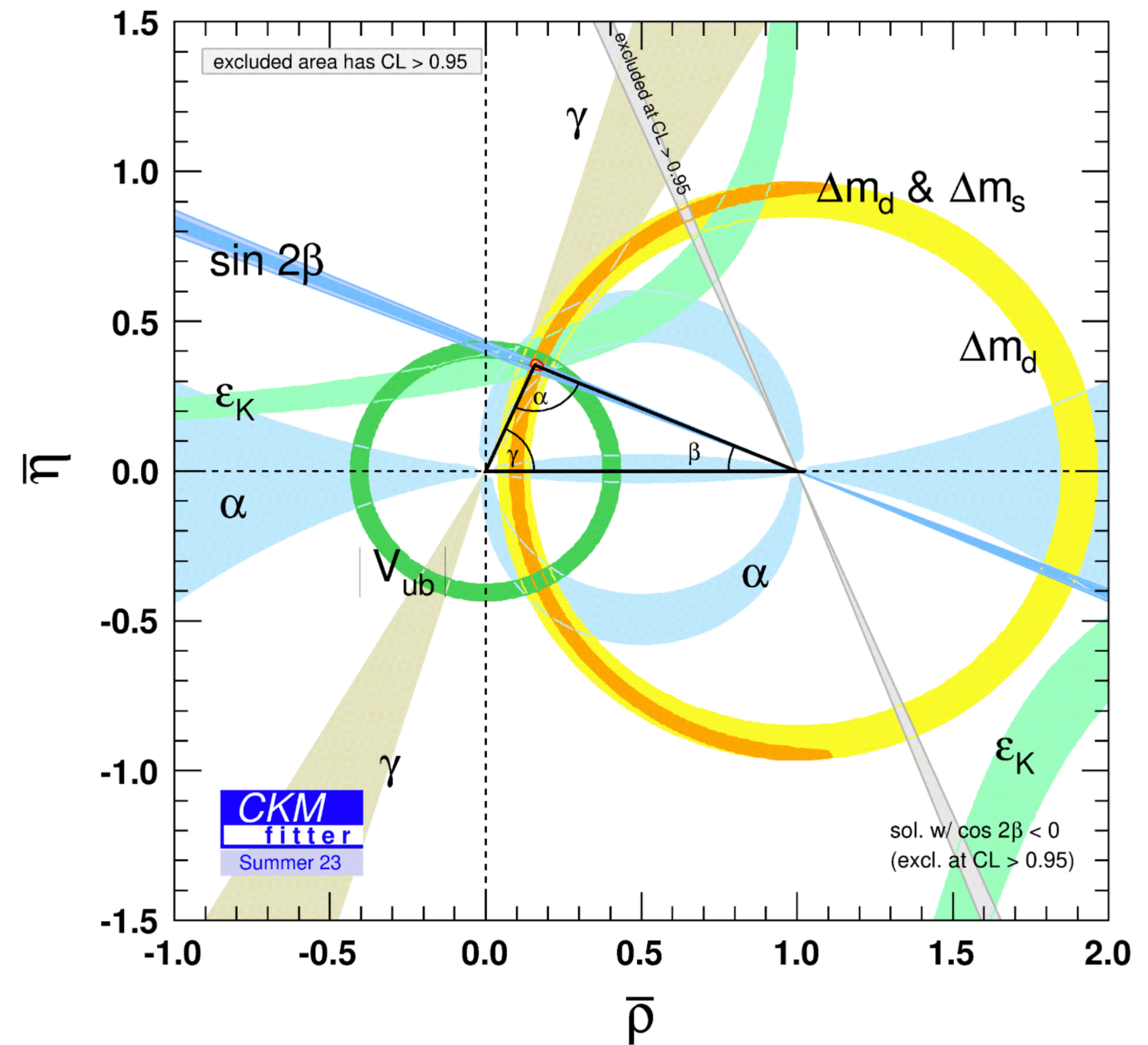
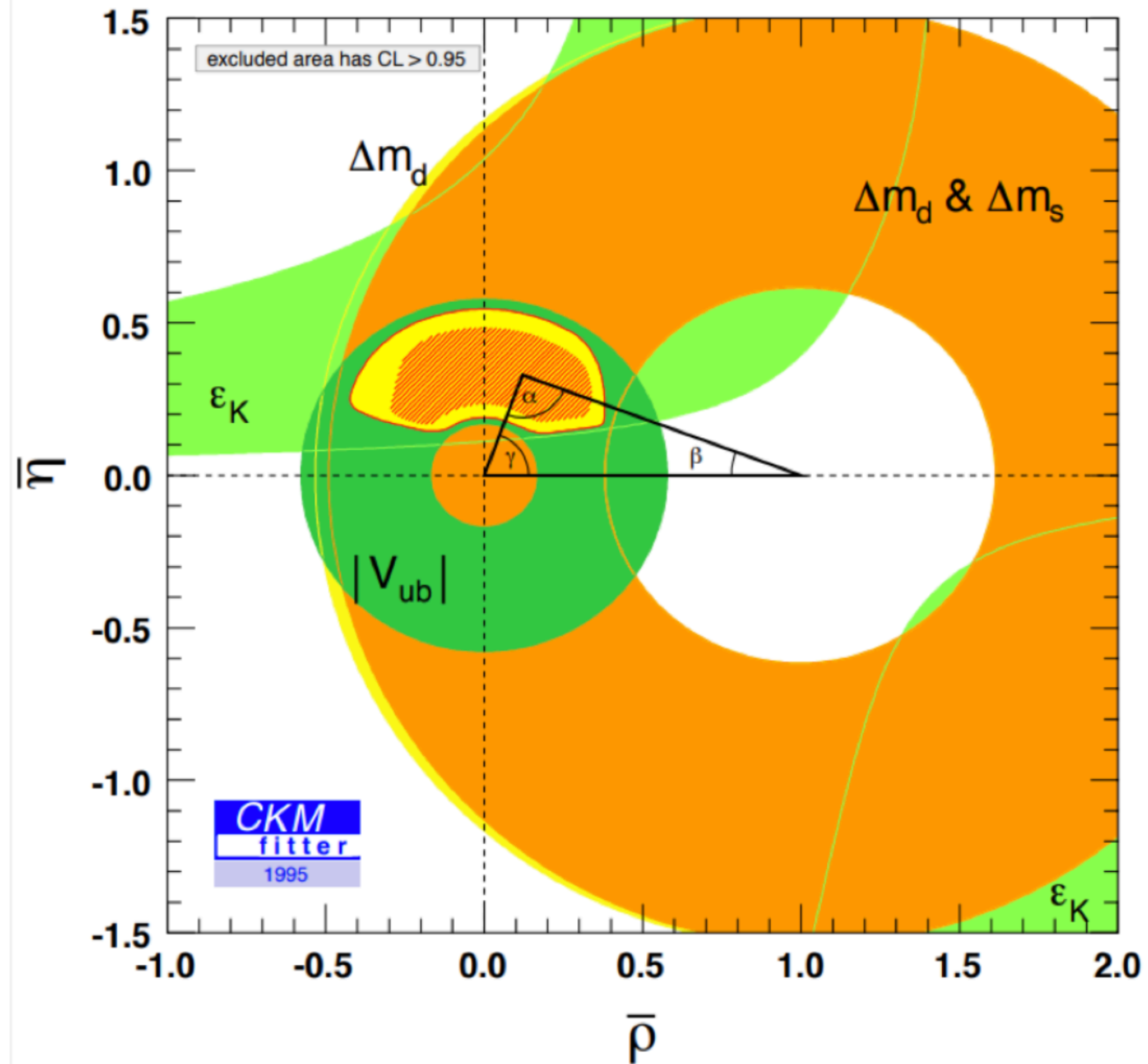
<https://arxiv.org/pdf/2402.05528>



Let me take a bit of water



Next steps



CP Violation in Decay

- $\left| \frac{A_f}{\bar{A}_f} \right| \neq 1$

A_f Amplitude $B \rightarrow f$
 $\bar{A}_f$ Amplitude $\bar{B} \rightarrow \bar{f}$

CP Violation in mixing

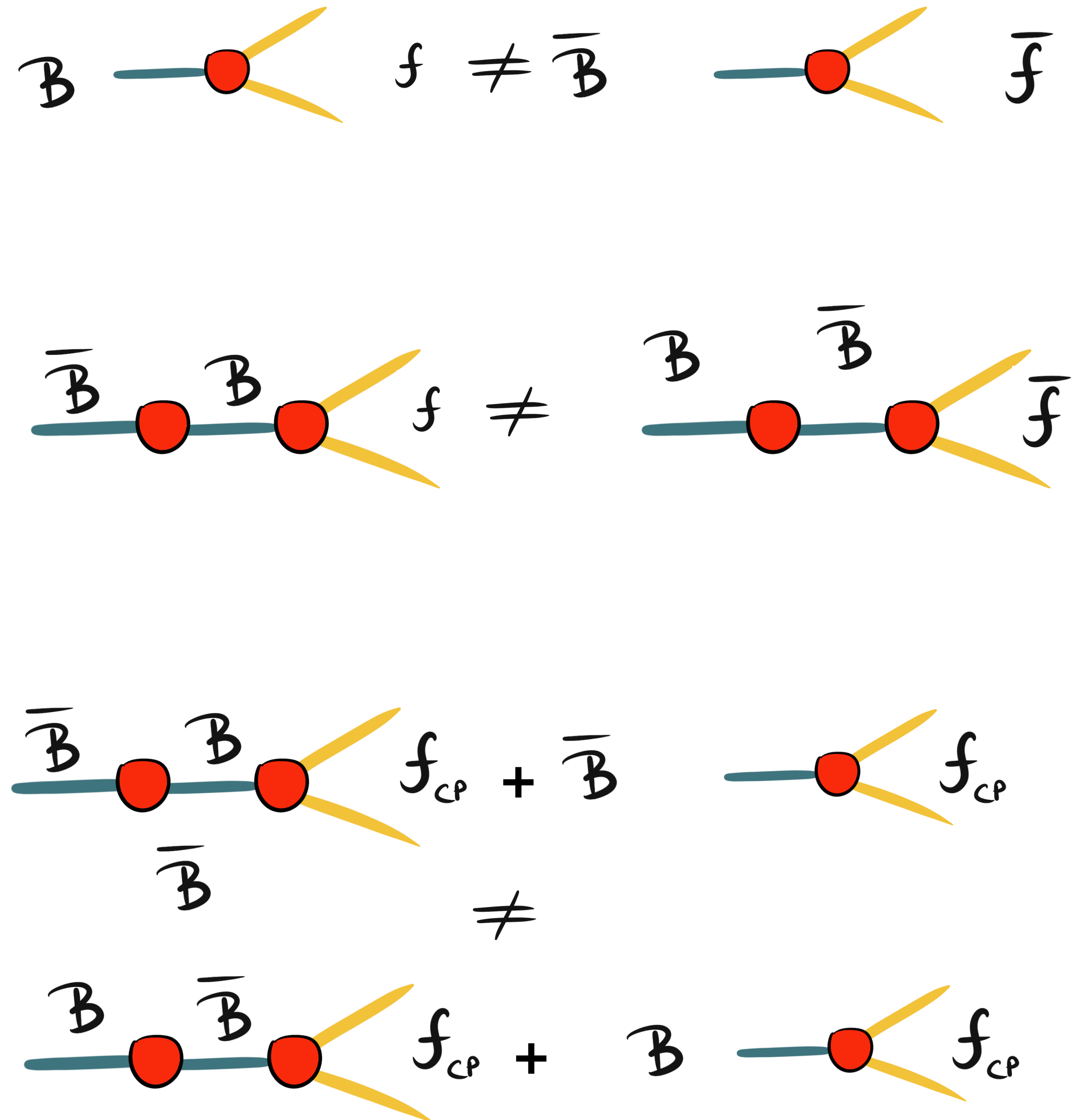
- $|\eta_P| \neq 1$

CP Violation in the interference between mixing and decay

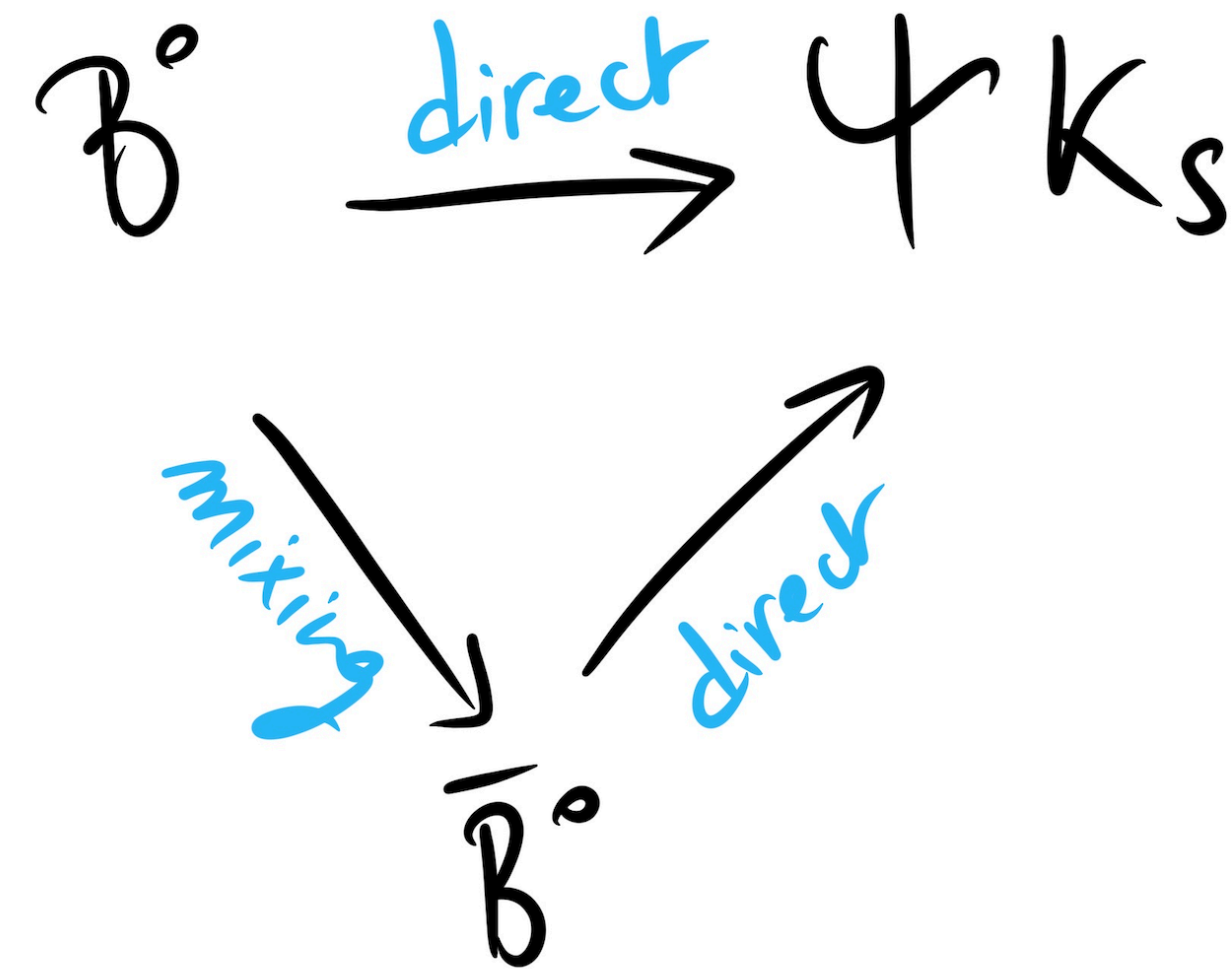
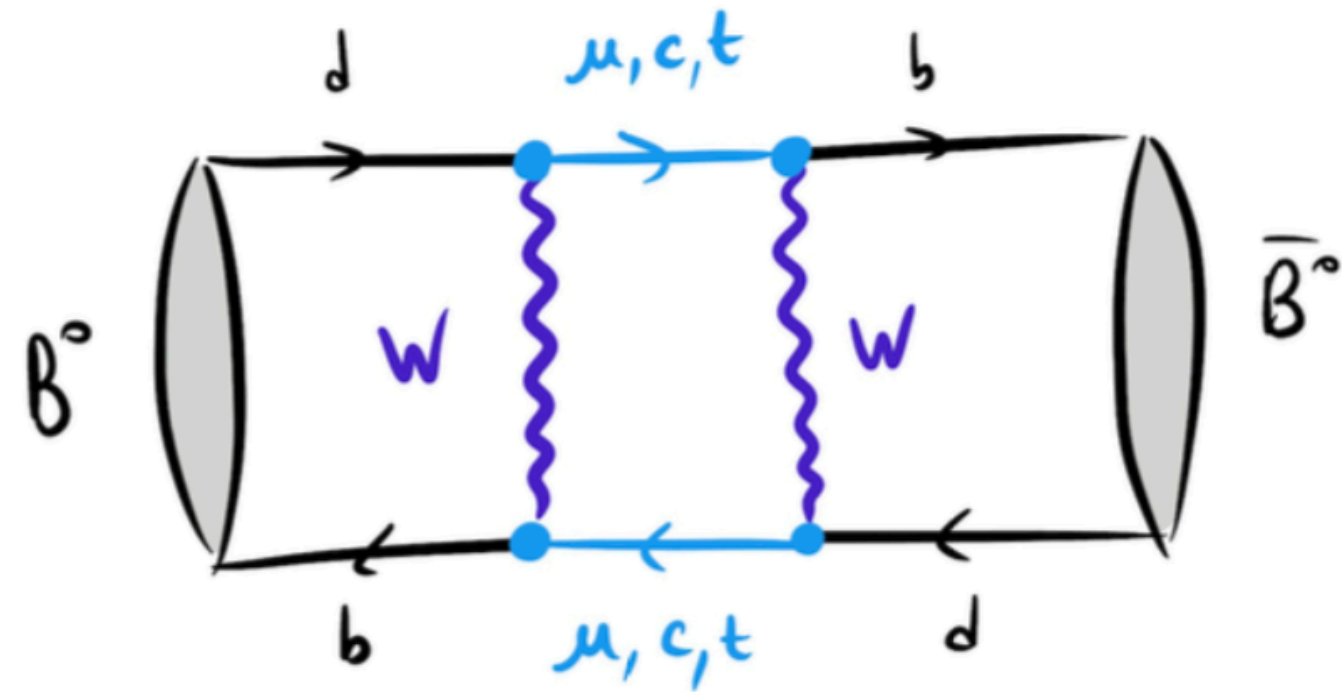
- $\text{Im}(\lambda_f) = \text{Im}\left(\frac{q}{p} \frac{\bar{A}_f}{A_f}\right) \neq 0$

λ_f = parameter that quantifies CP violation

$$\text{CP} |f_{CP}\rangle = \eta_f^{\text{CP}} |f_{CP}\rangle \quad \text{with} \quad \eta_{CP} = \pm 1$$



Let's start with sin2beta with the “golden” mode $B^0 \rightarrow \psi(\ell^+\ell^-)K_S^0(\pi^+\pi^-)$



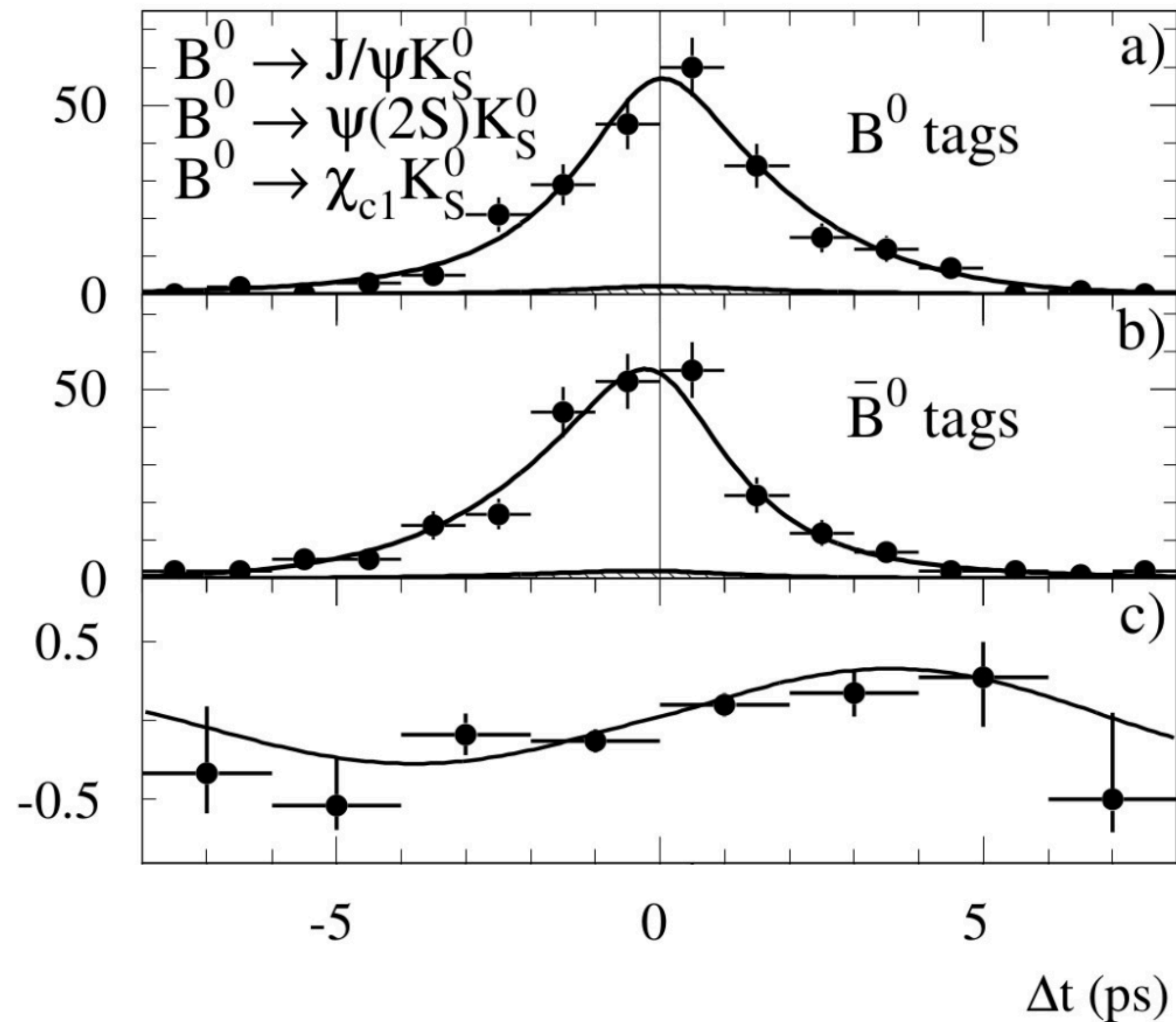
Time dependent analysis $\rightarrow$ requires flavour tagging

$$A^{\psi}(t) = \frac{\Gamma(\bar{B}^0 \rightarrow \psi K_S) - \Gamma(B^0 \rightarrow \psi K_S)}{\Gamma(\bar{B}^0 \rightarrow \psi K_S) + \Gamma(B^0 \rightarrow \psi K_S)} \approx \underbrace{D_{\Delta t} D_{FT}}_{\text{Experimental dilution}} S \sin(\Delta m_d t)$$

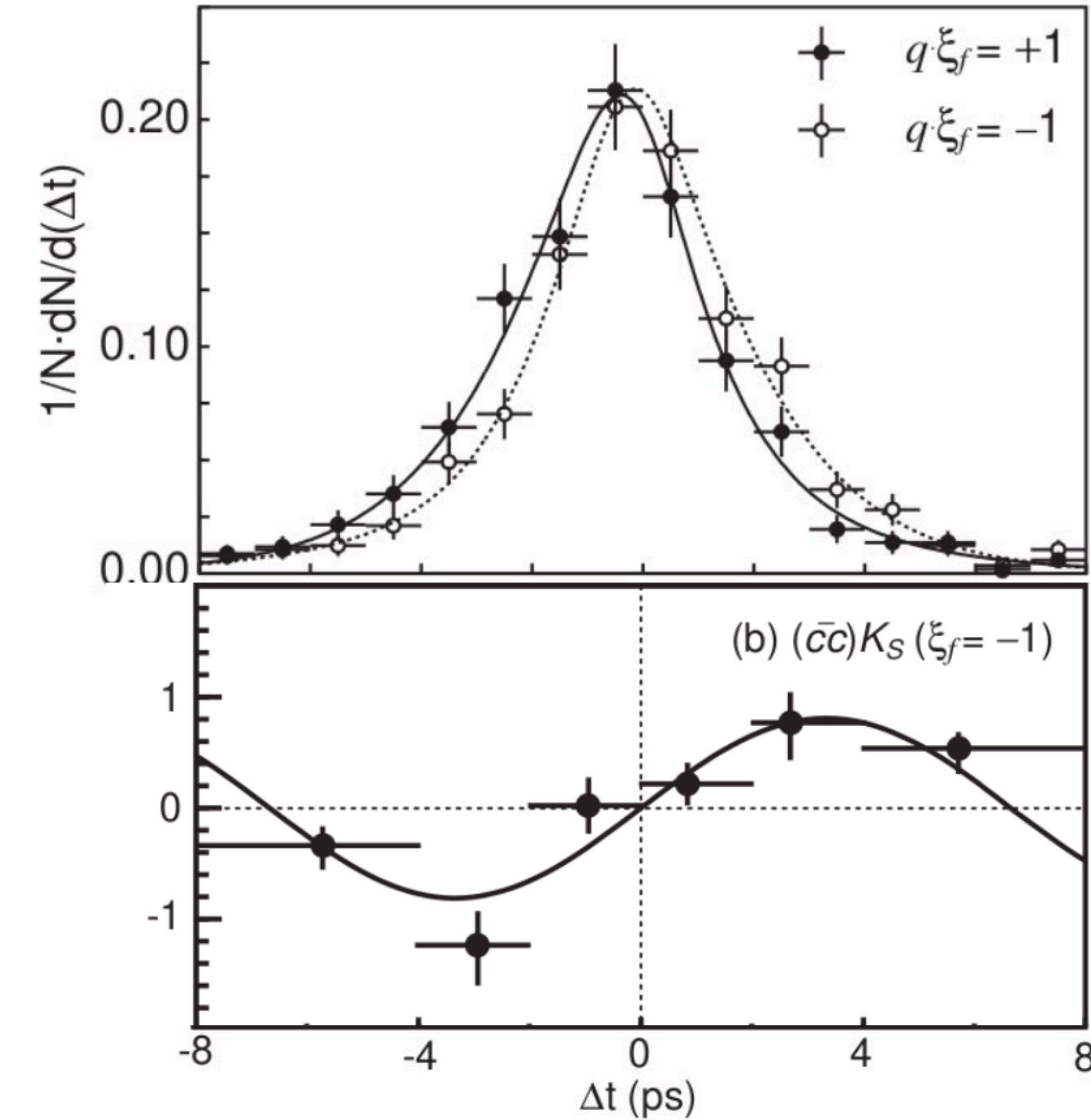
sin 2 β aka the raison d'être of B-factories - 2001

BaBar, PRL 87 (2001) 091801

Belle, PRL 97 (2001) 091802



$$\sin 2\beta = 0.59 \pm 0.14 \text{ (stat)} \pm 0.05 \text{ (syst)}.$$

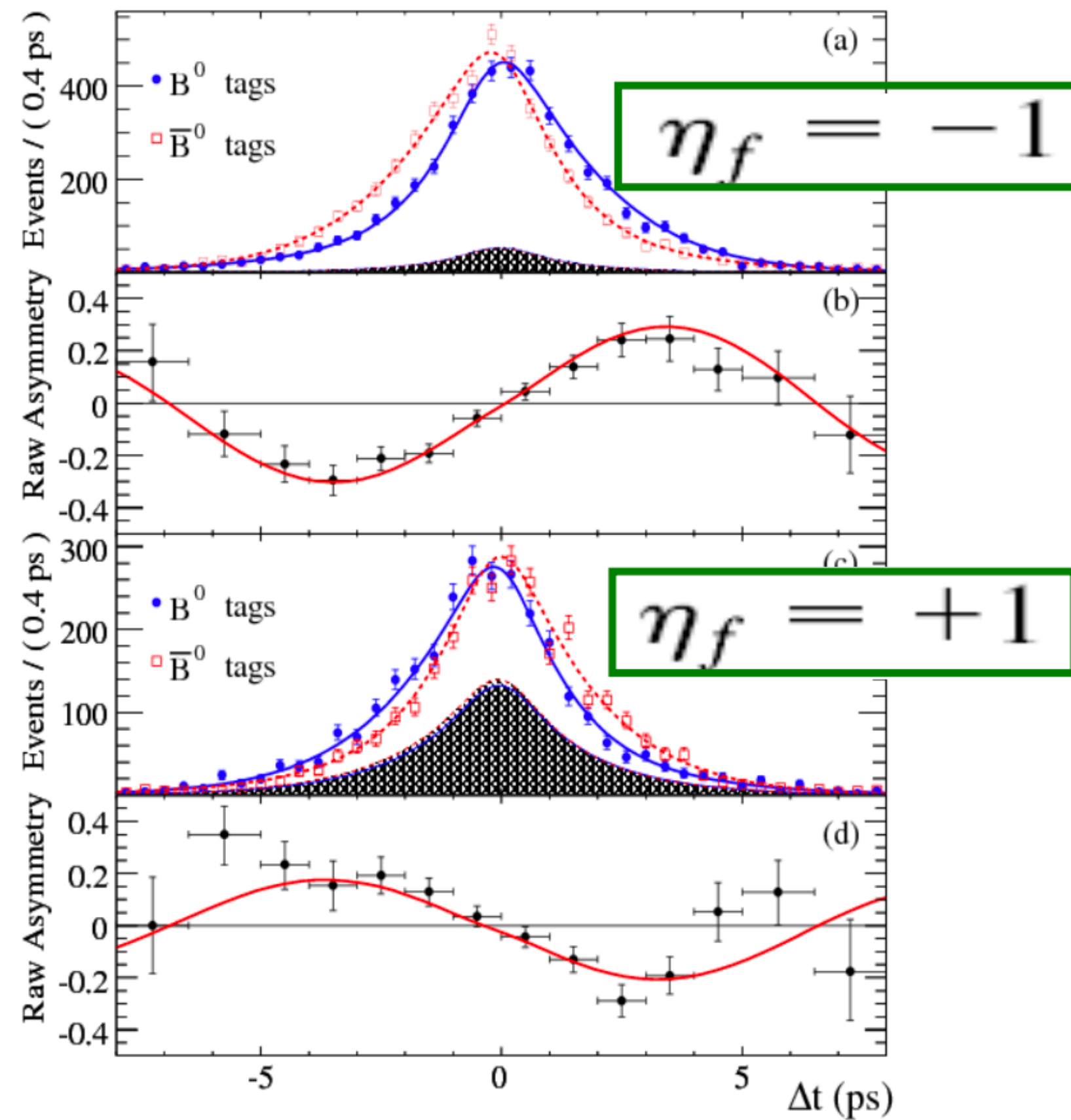


$$\sin 2\phi_1 = 0.99 \pm 0.14 \text{ (stat)} \pm 0.06 \text{ (syst)}.$$

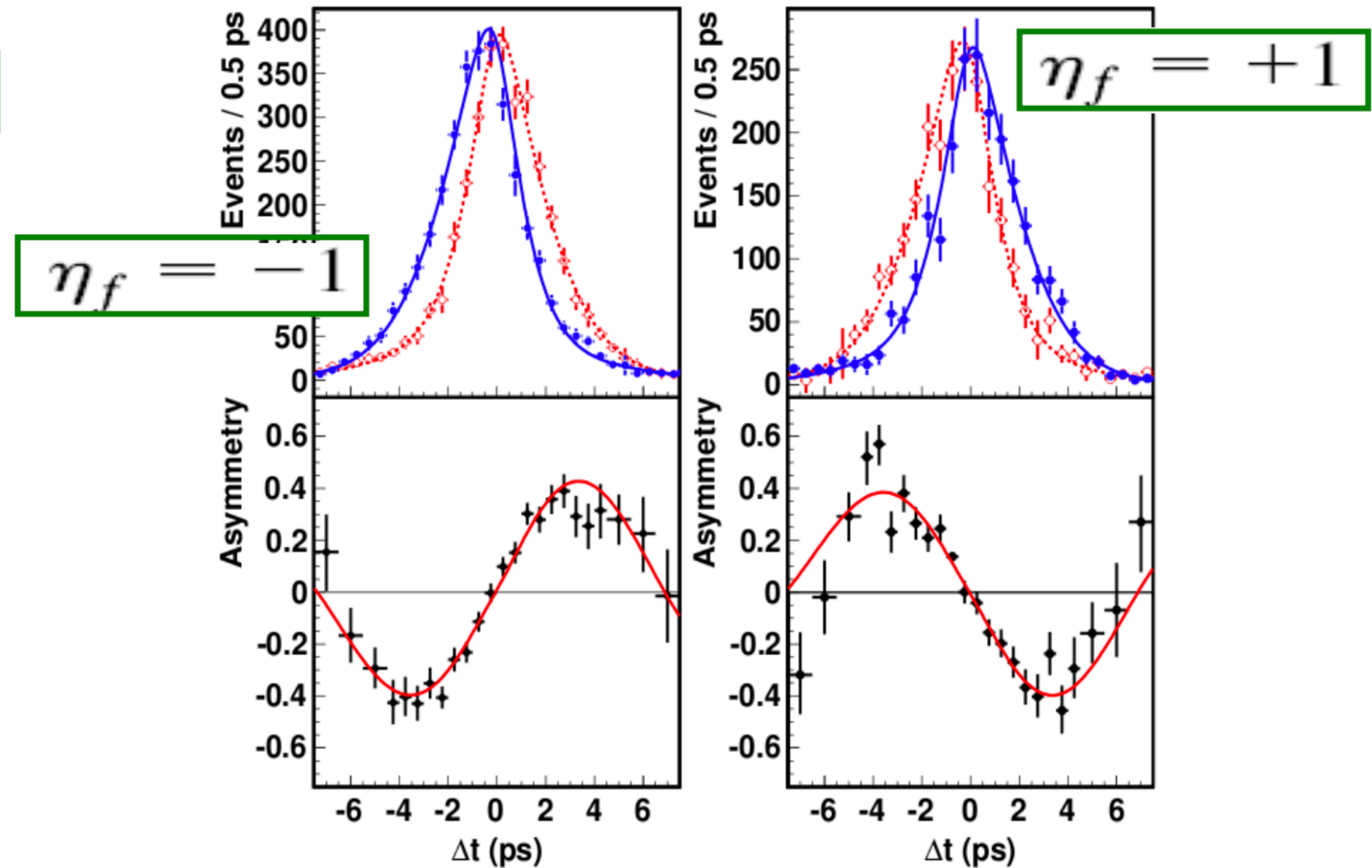
Different conventions on each side of the pacific

Legacy from B-Factories

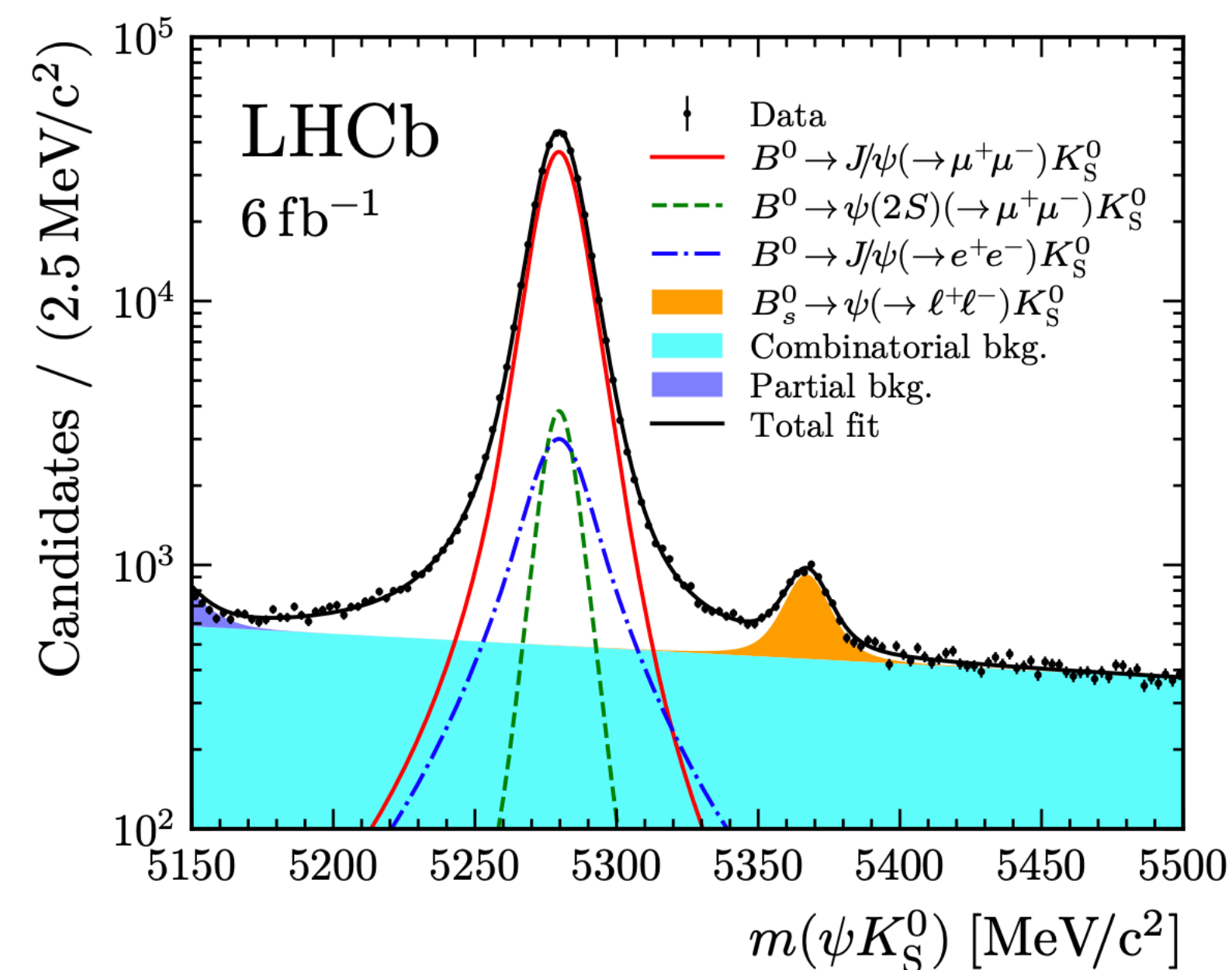
BaBar, PRD 79 (2009) 072009



Belle, PRL 108 (2012) 171802

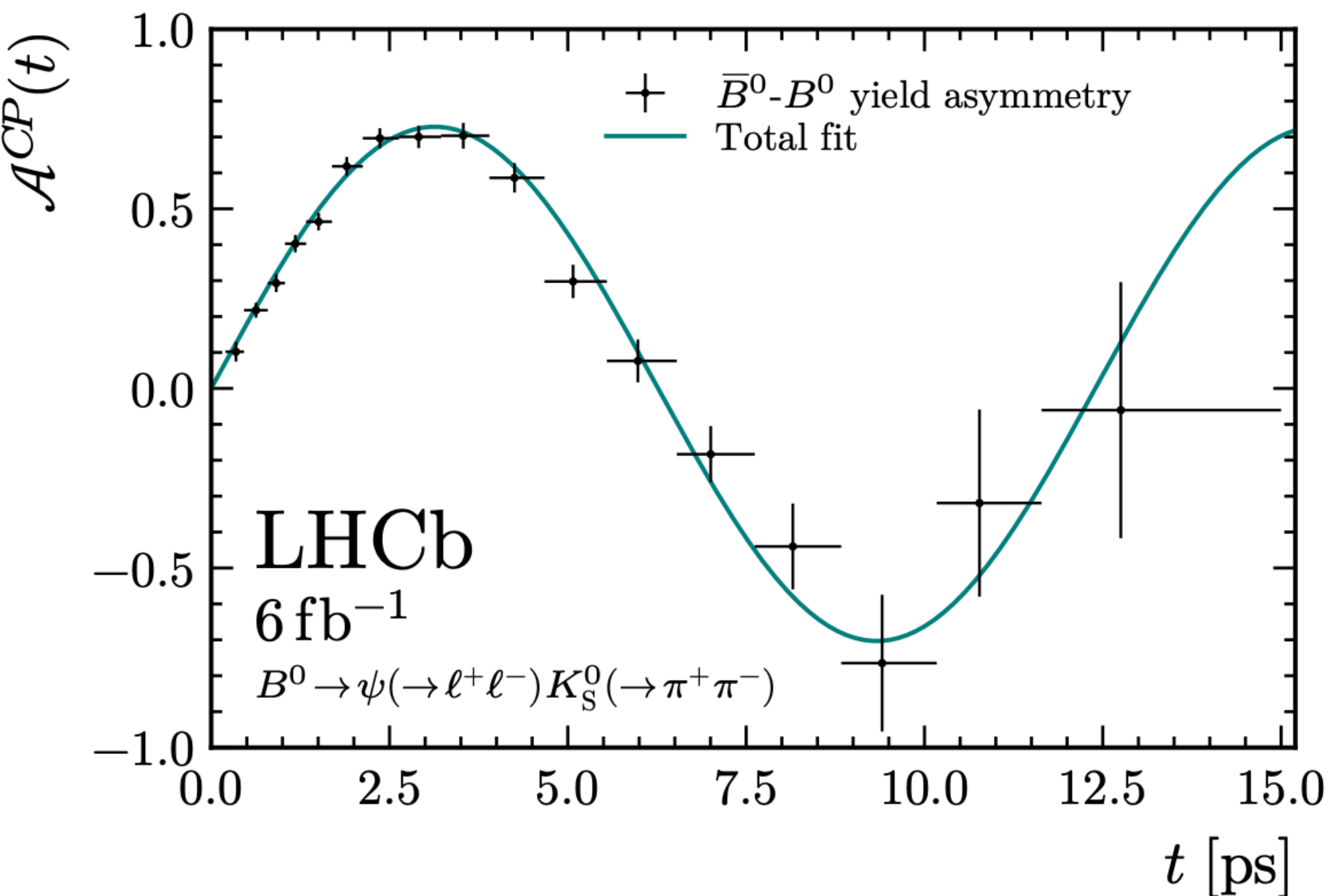


Text book like result !

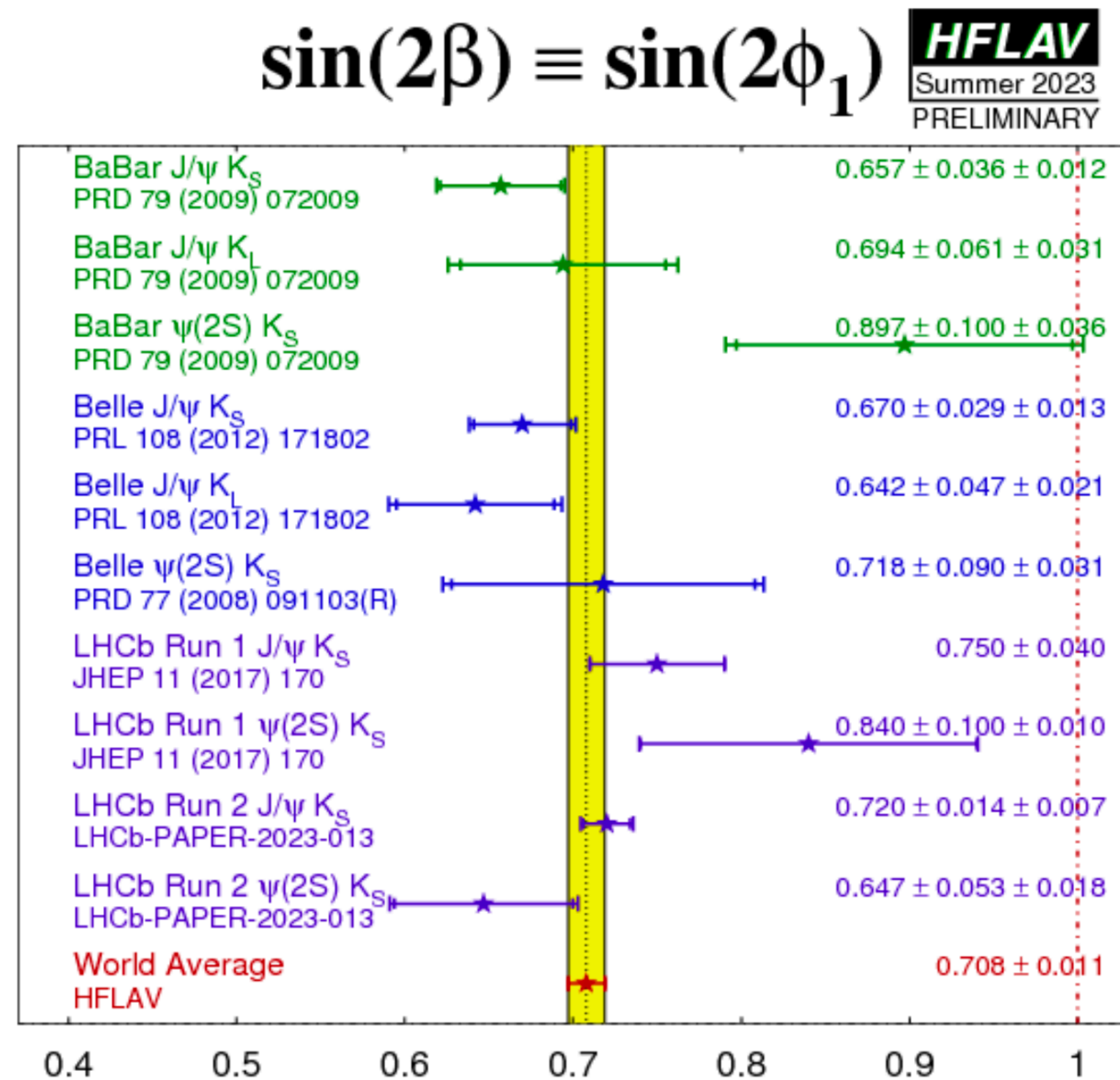


Trigger wise dilepton decays
are a day at the beach

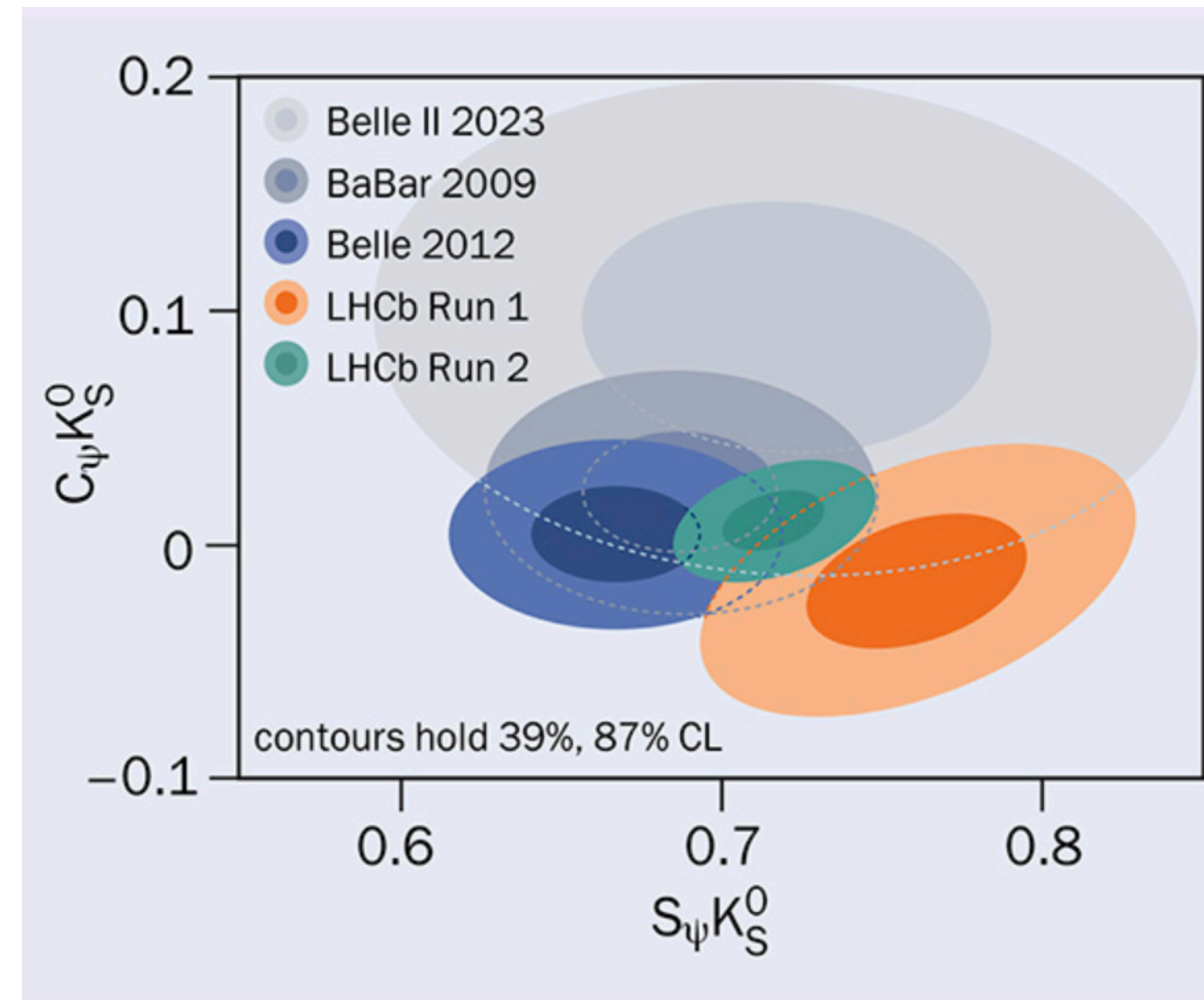
Combination of a few decay channels



Summary plot

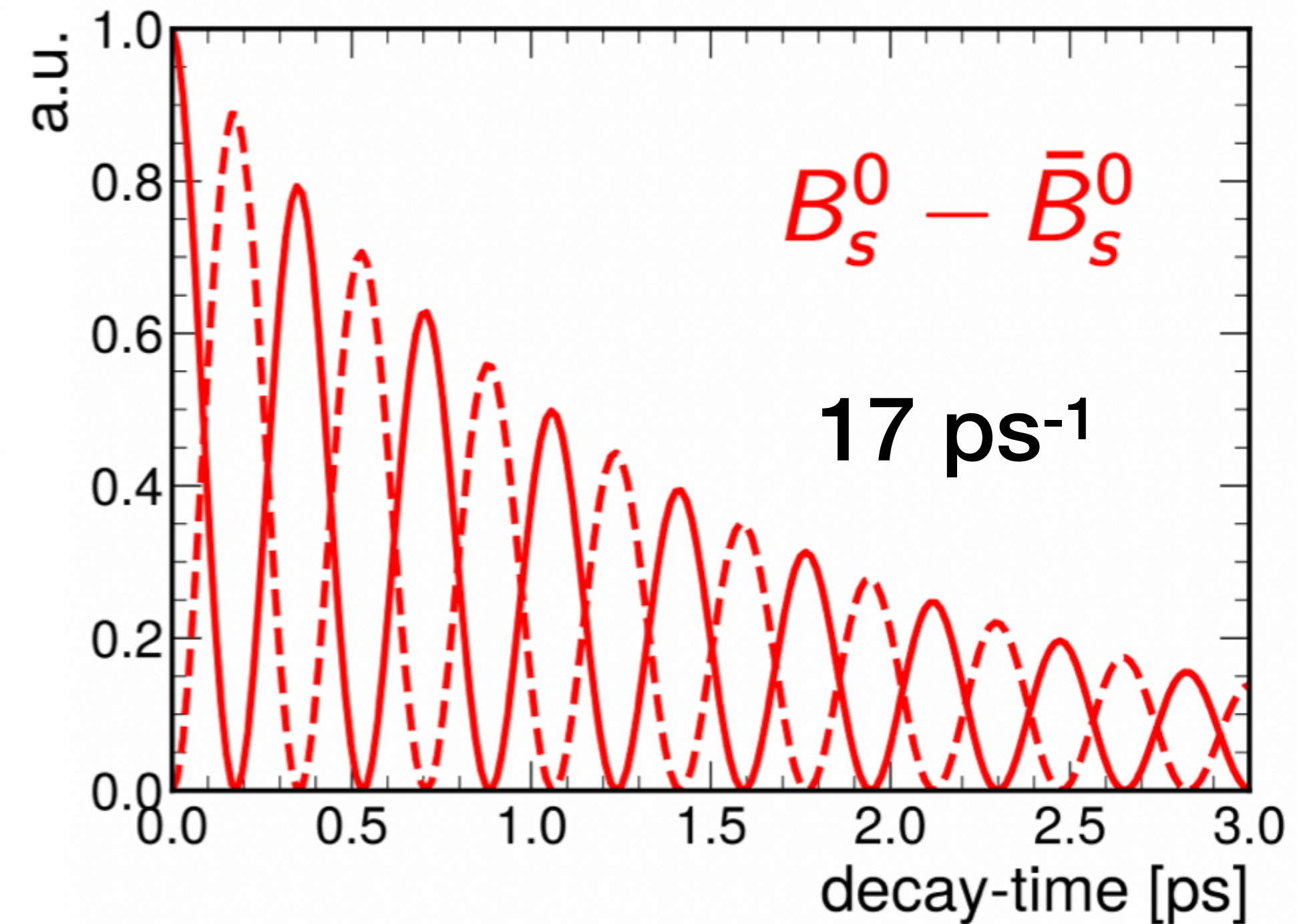
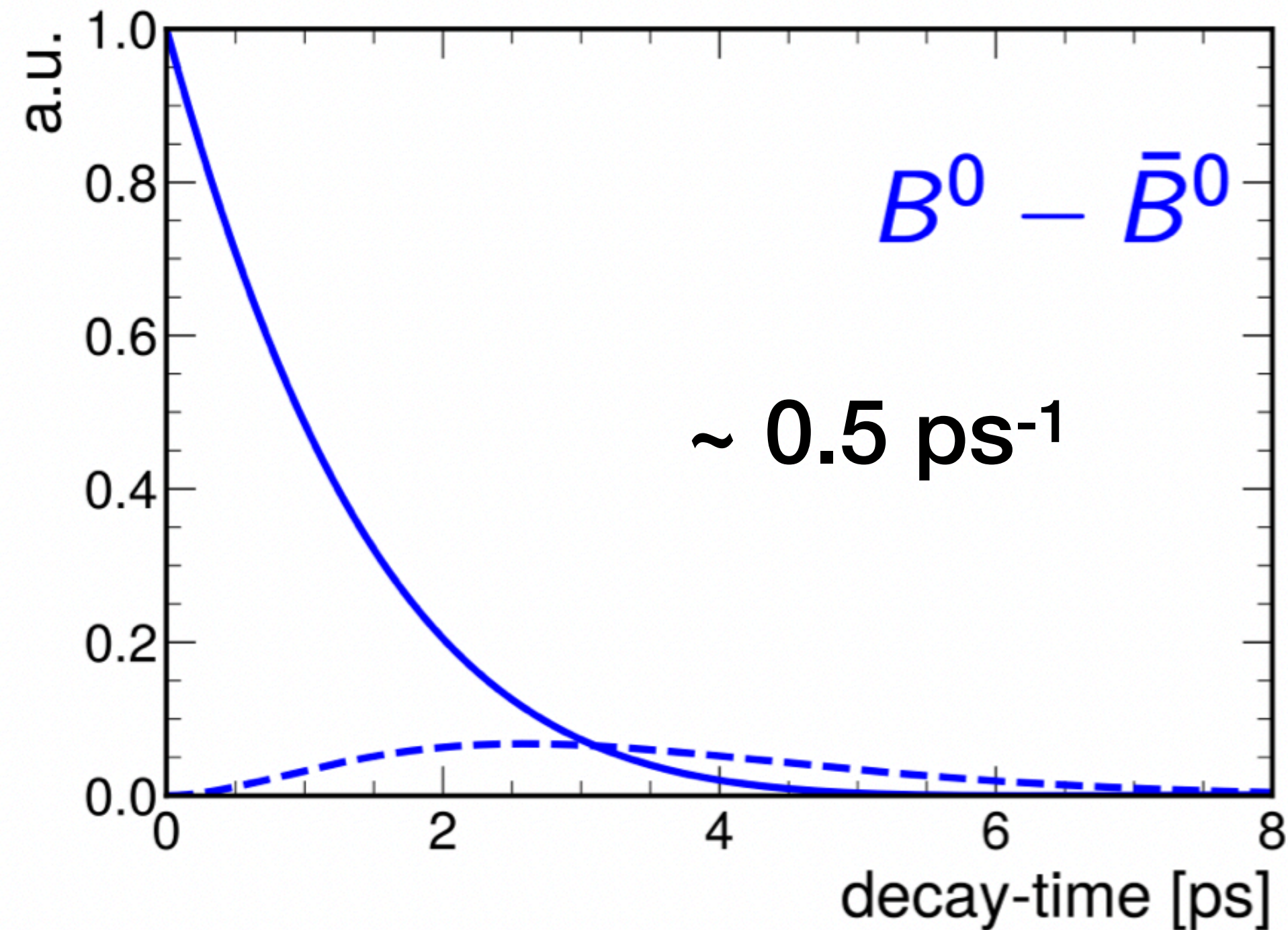


Is there room for NP in this corner ?



A nice read <https://cerncourier.com/a/lhcb-sets-record-precision-on-cp-violation/>

It's interesting to see what a “just” a difference in the spectator quark can do



An other fascinating topic is simple lifetime measurements.
If you are interested in this Google my dear colleague Alex Lenz

A few lines about the mixing formalism

$$i \frac{d}{dt} \begin{pmatrix} |B_q^0(t)\rangle \\ |\bar{B}_q^0(t)\rangle \end{pmatrix} = \mathcal{H} \begin{pmatrix} |B_q^0(t)\rangle \\ |\bar{B}_q^0(t)\rangle \end{pmatrix}$$

$$\text{Where } \mathcal{H} = \left(M - \frac{i}{2} \Gamma \right) = \begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{22} \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22} \end{pmatrix}$$

Mass Matrix
Dispersive

Decay Matrix
Absorptive

$$M = M^\dagger \quad \text{and} \quad \Gamma = \Gamma^\dagger, \quad \text{CPT} \Rightarrow M_{11} = M_{22} = M_q \quad \text{and} \quad \Gamma_{11} = \Gamma_{22} = \Gamma_q$$

in case of mixing = M_{12} and Γ_{12} are non-zero

A few lines about the mixing formalism

The mass eigenstates =

$$|B_H\rangle \propto p |B_q'\rangle + q |\bar{B}_q'\rangle$$

$$|B_L\rangle \propto p |\bar{B}_q'\rangle - q |B_q'\rangle$$

The time evolution =

$$|B_{H/L}(t)\rangle = e^{-i m_{H/L} t} e^{-i \Gamma_{H/L} t/2} |B_{H/L}\rangle$$

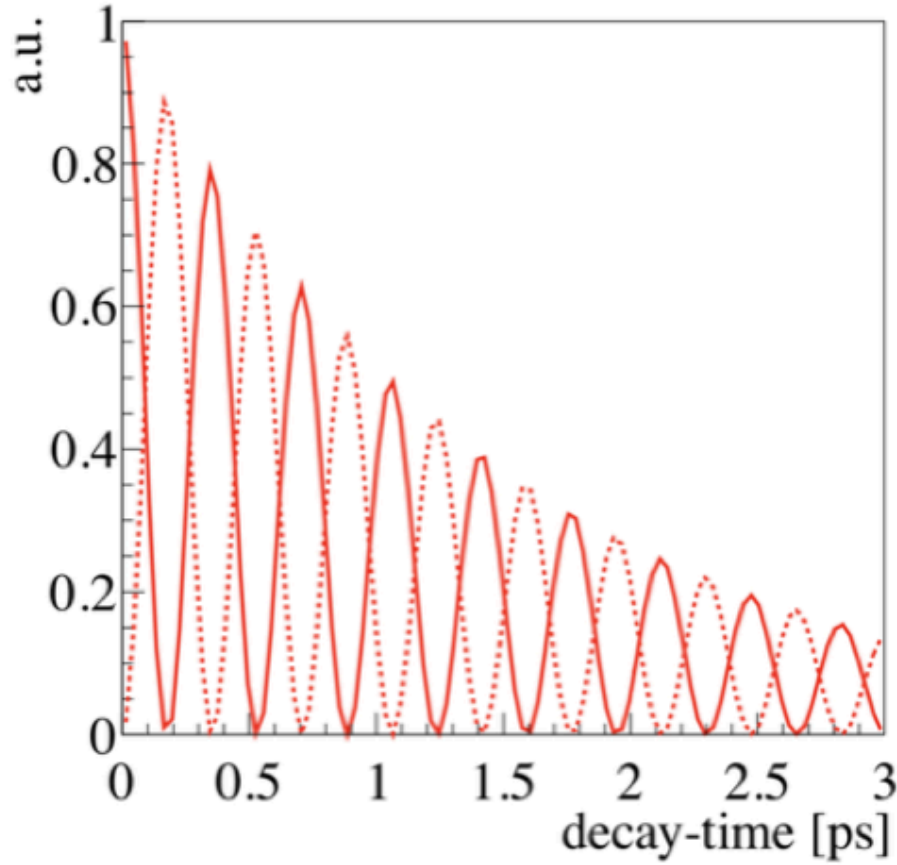
$$m_q = \frac{m_H + m_L}{2}, \quad \Gamma_q = \frac{\Gamma_L + \Gamma_H}{2} = \frac{1}{2}$$

$$\Delta m_q = m_H - m_L, \quad \Delta \Gamma_q = \Gamma_L - \Gamma_H$$

CERN-THESIS-2014-361 a very pedagogical reference.

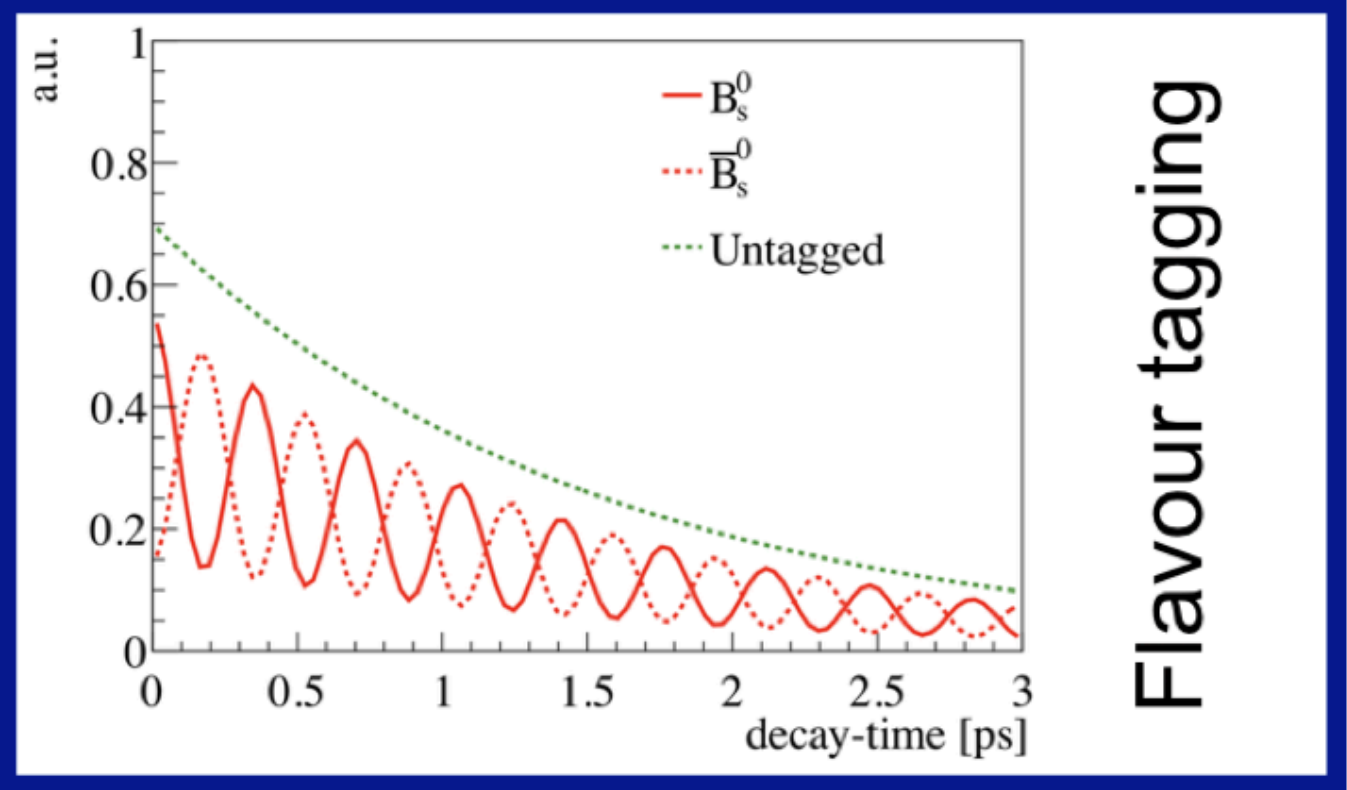
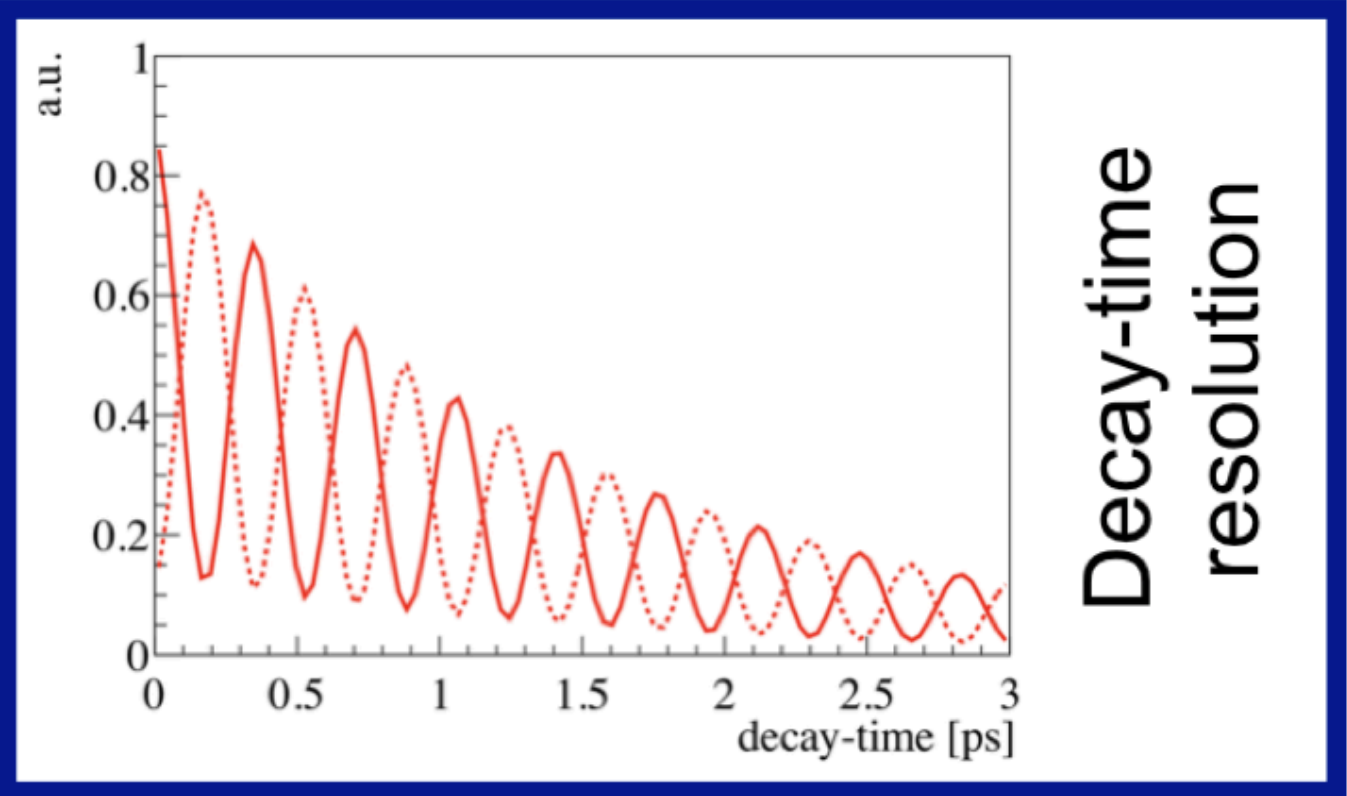
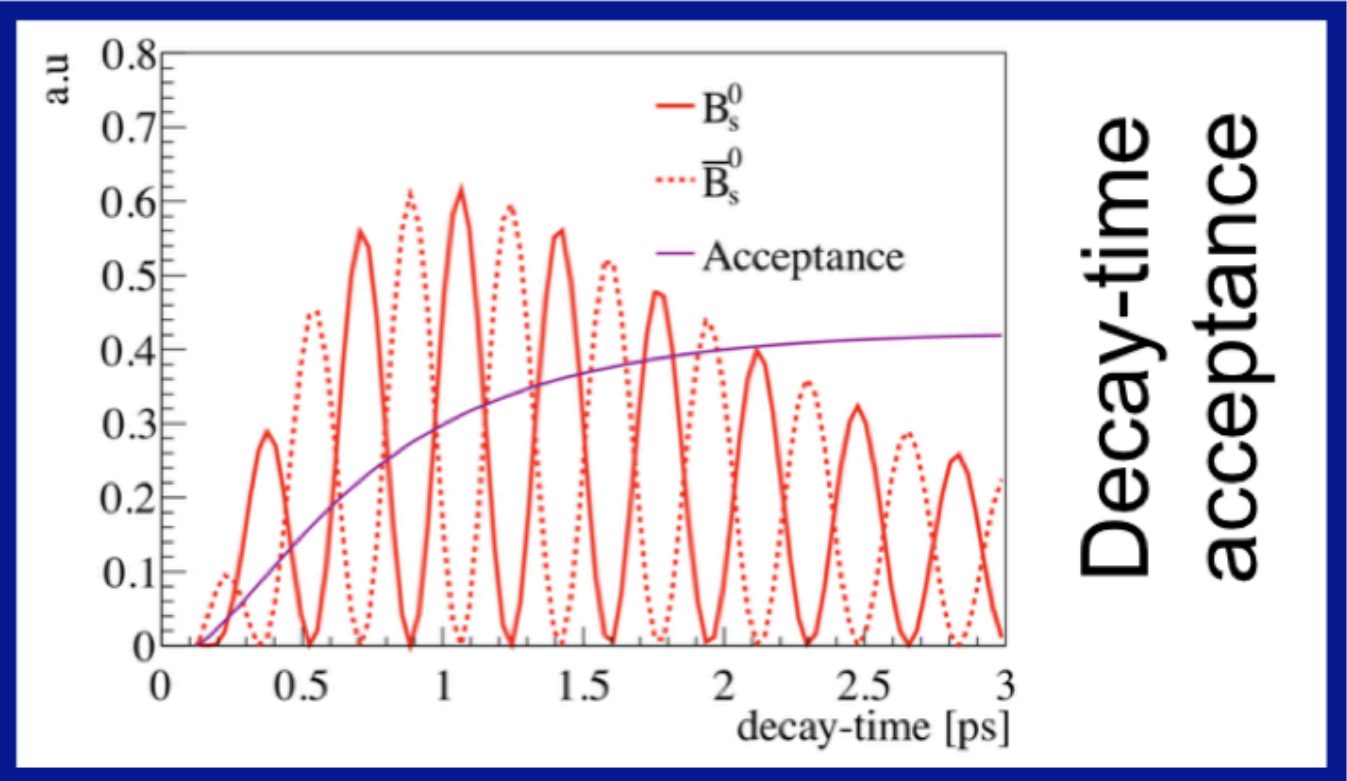
We have to make
the actual omelette

Perfect

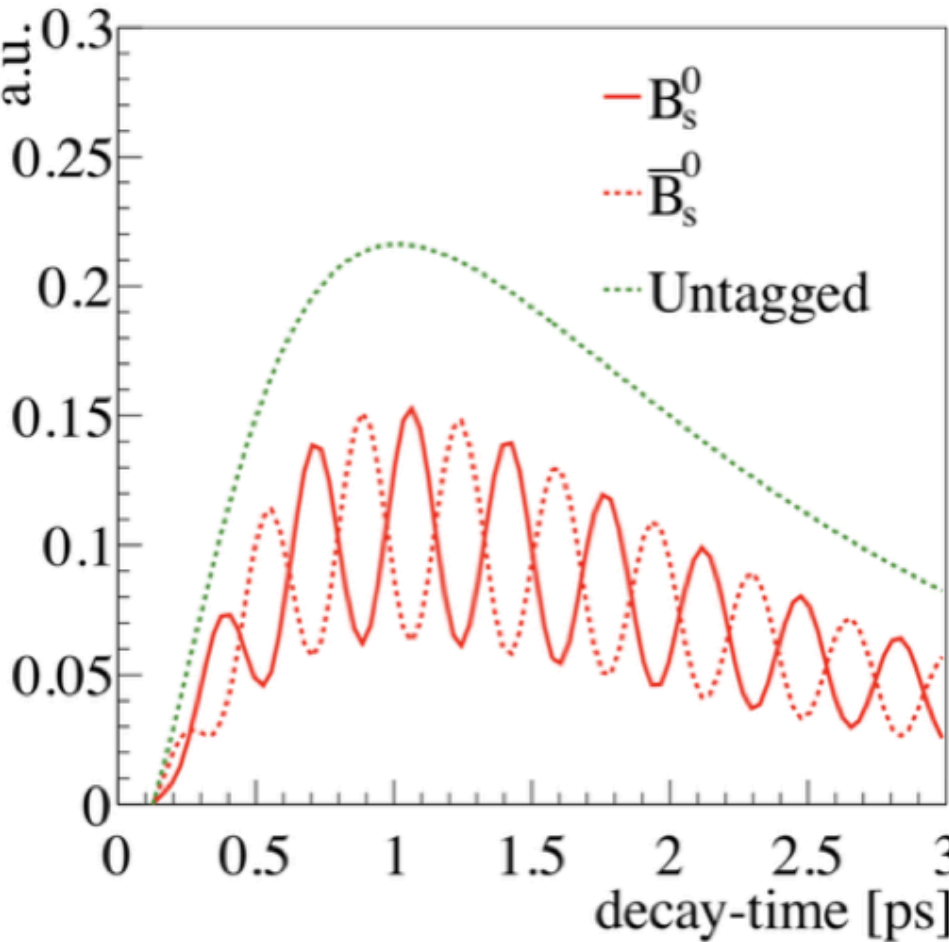


$$P(t) \sim e^{-\Gamma_s t} \left(\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) \pm \cos(\Delta m_s t) \right)$$

Detector effects



Data





A small parenthesis

If you'll indulge me a little parenthesis

From my PhD 2006-2009

The channels in question

$B^0 \rightarrow D^- \rho^+(770)$  Gamma Extraction: U-spin modes

$B_s^0 \rightarrow D_s^- \rho^+$  B_s Oscillations measurement.

[Submitted on 22 Sep 2006]

Observation of Bs–Bsbar Oscillations 22 days after the start of my thesis

CDF Collaboration

We report the observation of Bs–Bsbar oscillations from a time–dependent measurement of the Bs–Bsbar oscillation frequency Δm_s . Using a data sample of 1 fb^{-1} of p–pbar collisions at $\sqrt{s}=1.96 \text{ TeV}$ collected with the CDF II detector at the Fermilab Tevatron, we find signals of 5600 fully reconstructed hadronic Bs decays, 3100 partially reconstructed hadronic Bs decays, and 61500 partially reconstructed semileptonic Bs decays. We measure the probability as a function of proper decay time that the Bs decays with the same, or opposite, flavor as the flavor at production, and we find a signal for Bs–Bsbar oscillations. The probability that random fluctuations could produce a comparable signal is 8×10^{-8} , which exceeds 5 sigma significance. We measure

$\Delta m_s = 17.77 \pm 0.10 \text{ (stat)} \pm 0.07 \text{ (syst)} \text{ ps}^{-1}$

and extract

$|V_{td}/V_{ts}| = 0.2060 \pm 0.0007 \text{ (exp)} + 0.0081 - 0.0060 \text{ (theor)}.$

[Submitted on 22 Sep 2006]

Observation of B_s – B_s bar Oscillations 22 days after the start of my thesis

CDF Collaboration

We report the observation of B_s – B_s bar oscillations from a time-dependent measurement of the B_s – B_s bar oscillation frequency Δm_s . Using a data sample of 1 fb^{-1} of p – $\bar{p}$ collisions at $\sqrt{s}=1.96 \text{ TeV}$ collected with the CDF II detector at the Fermilab Tevatron, we find signals of 5600 fully reconstructed hadronic B_s decays, 3100 partially reconstructed hadronic B_s decays, and 61500 partially reconstructed semileptonic B_s decays. We measure the probability as a function of proper decay time that the B_s decays with the same, or opposite, flavor as the flavor at production, and we find a signal for B_s – B_s bar oscillations. The probability that random fluctuations could produce a comparable signal is 8×10^{-8} , which exceeds 5 sigma significance. We measure

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CERN releases analysis of LHC incident One year after the start of my thesis

16 OCTOBER, 2008

Geneva, 16 October 2008. Investigations at CERN following a large helium leak into sector 3-4 of the Large Hadron Collider (LHC) tunnel have confirmed that cause of the incident was a faulty electrical connection between two of the accelerator's magnets. This resulted in mechanical damage and release of helium from the magnet cold mass into the tunnel.

[Submitted on 22 Sep 2006]

Observation of B_s - B_s^* Oscillations 22 days after the start of my thesis

CDF Collaboration

We report the observation of B_s - B_s^* oscillations from a time-dependent measurement of the B_s - B_s^* oscillation frequency Δm_s . Using a data sample of 1 fb^{-1} of p - $\bar{p}$ collisions at $\sqrt{s}=1.96 \text{ TeV}$ collected with the CDF II detector at the Fermilab Tevatron, we find signals of 5600 fully reconstructed hadronic B_s decays, 3100 partially reconstructed hadronic B_s decays, and 61500 partially reconstructed semileptonic B_s decays. We measure the probability as a function of proper decay time that the B_s decays with the same, or opposite, flavor as the flavor at production, and we find a signal for B_s - B_s^* oscillations. The probability that random fluctuations could produce a comparable signal is 8×10^{-8} , which exceeds 5 sigma significance. We measure

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The end of the universe if not something very close



In 2008

B factories and Tevatron students



LHC students



These were dark days for us



End - of the small parenthesis

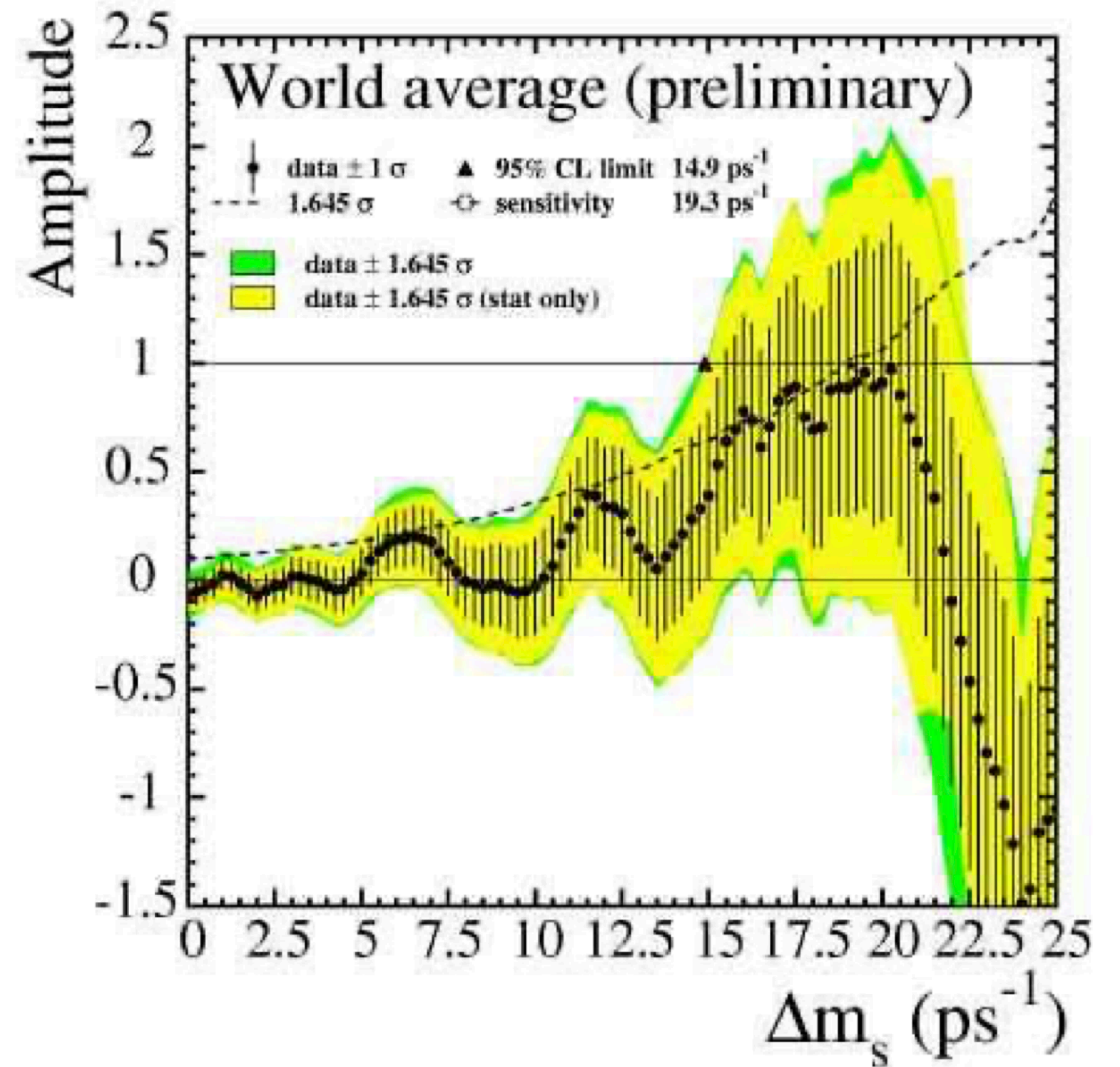
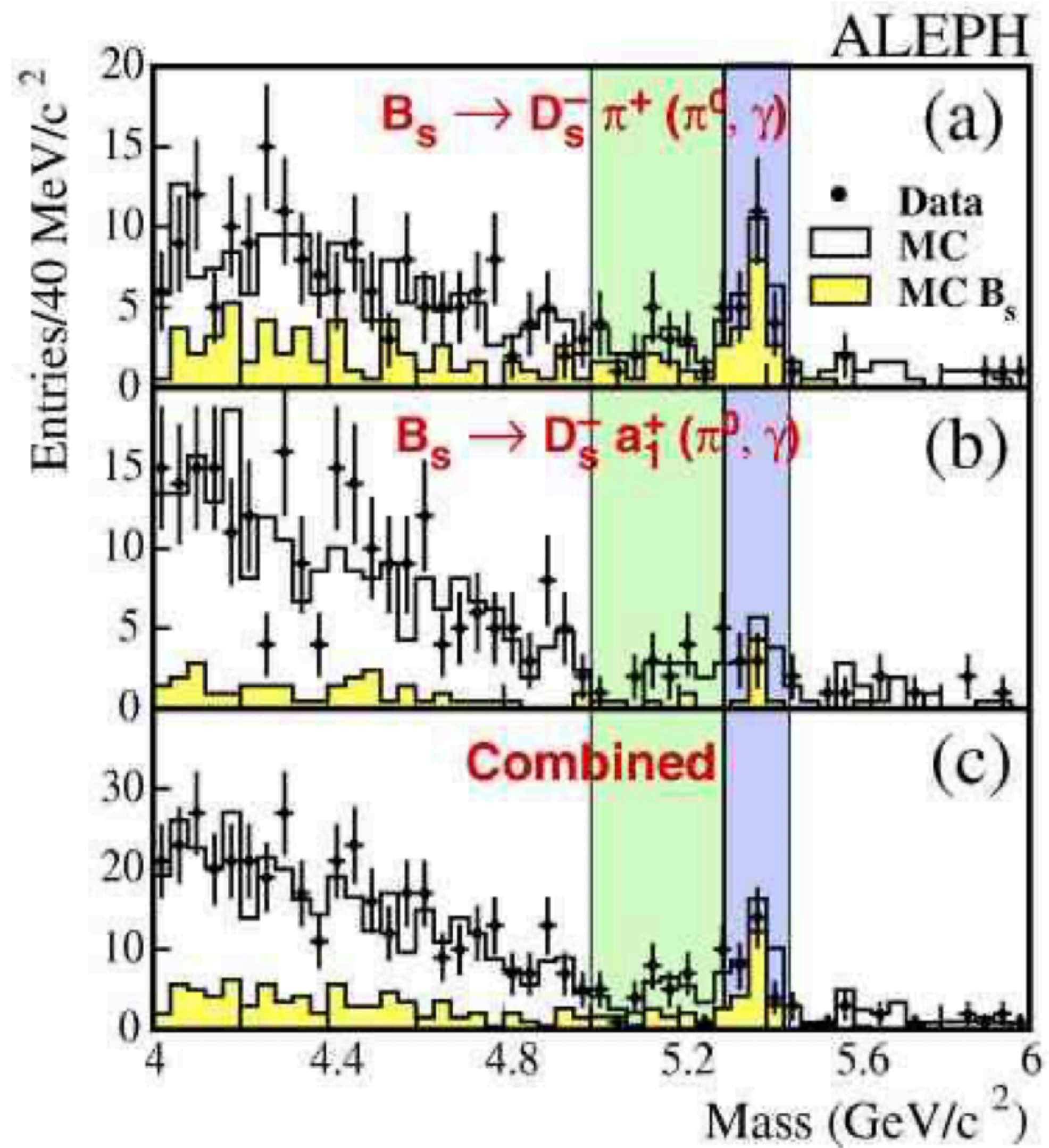
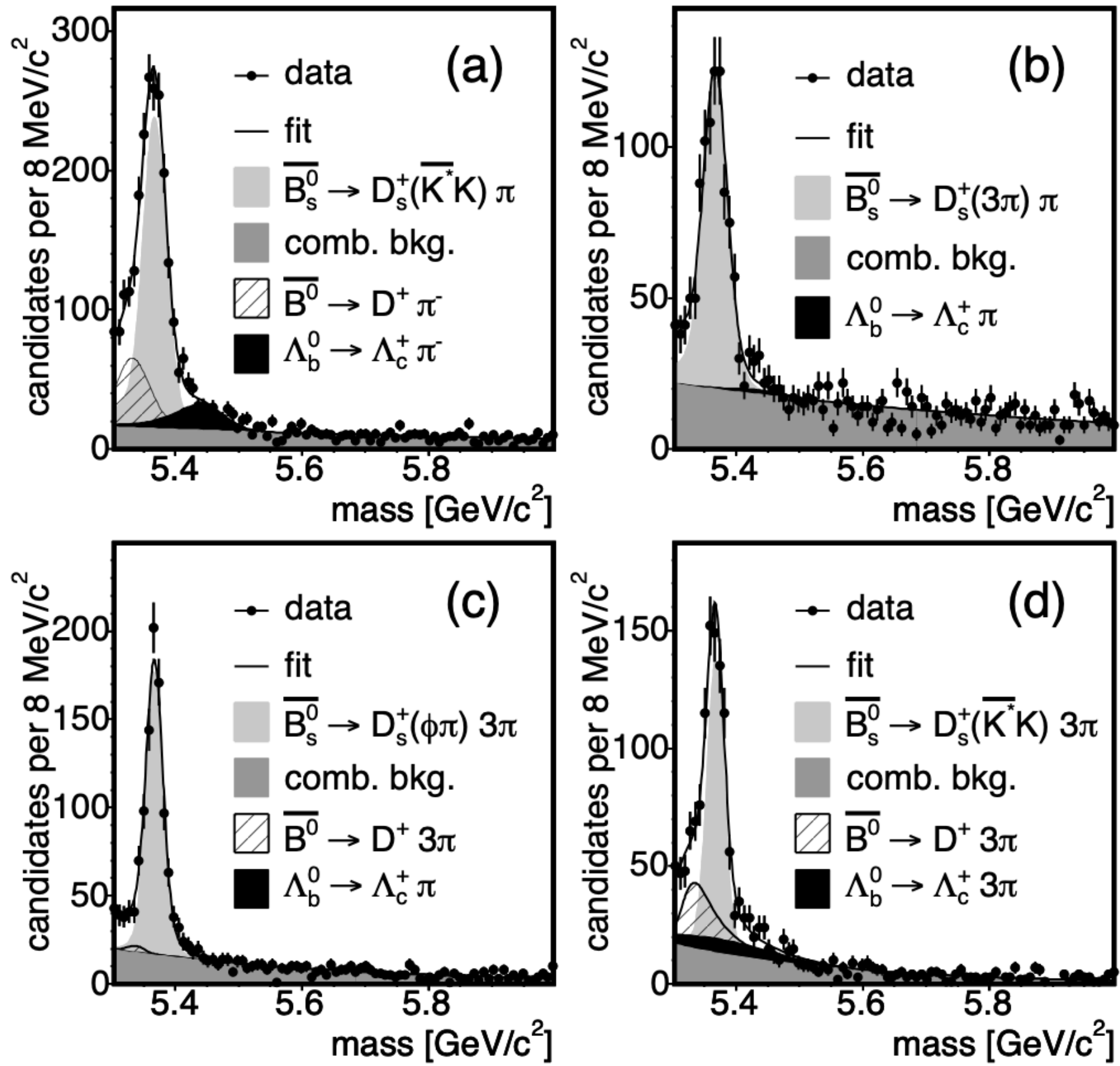


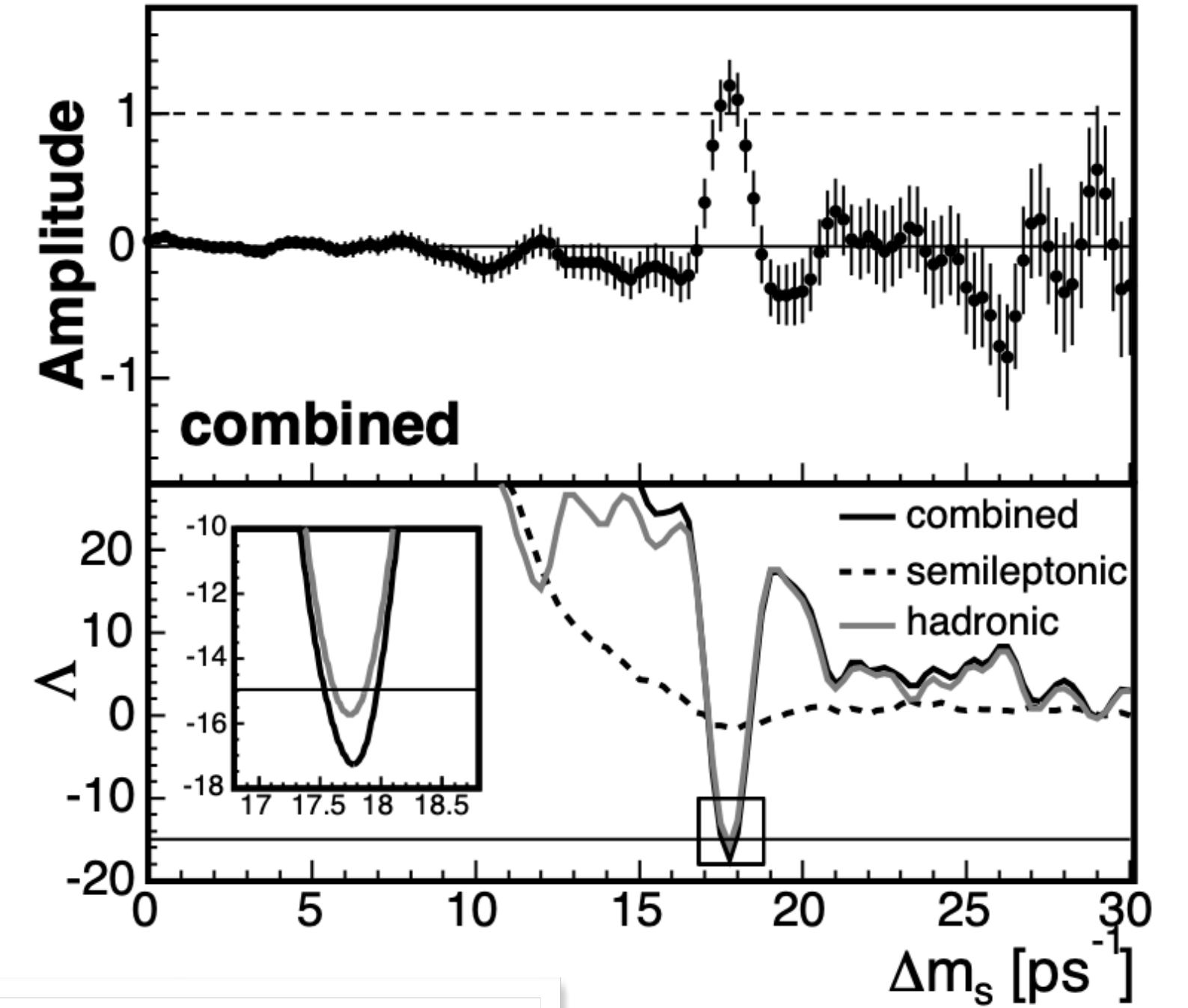
Figure 7: The combined B_s^0 oscillation results from ALEPH, CDF, DELPHI, OPAL, and SLD shown as amplitude versus hypothesized Δm_s [11]. The dots with error bars show the fitted amplitude values and uncertainties. An observed (expected) 95% C.L. lower limit on Δm_s of 14.9 ps⁻¹ (19.3 ps⁻¹) is obtained.

<https://arxiv.org/pdf/hep-ex/0209007>

My personal end of the universe at the time



- (a) $\bar{B}_s^0 \rightarrow D_s^+(\bar{K}^* K) \pi$
- (b) $\bar{B}_s^0 \rightarrow D_s^+(3\pi) \pi$
- (c) $\bar{B}_s^0 \rightarrow D_s^+(\phi\pi) 3\pi$
- (d) $\bar{B}_s^0 \rightarrow D_s^+(\bar{K}^* K) 3\pi$
- (e) $\bar{B}_s^0 \rightarrow D_s^+(3\pi) 3\pi$



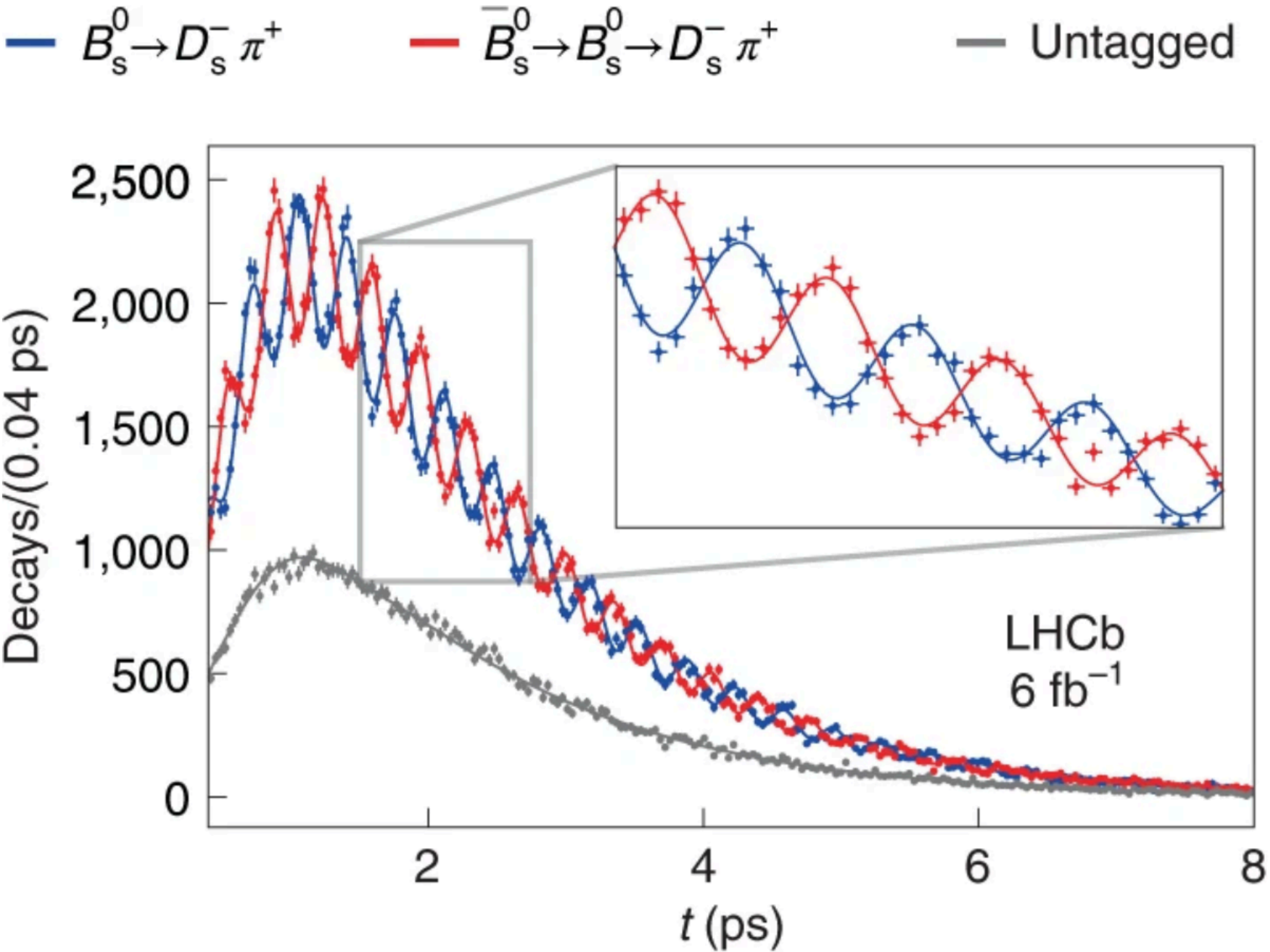
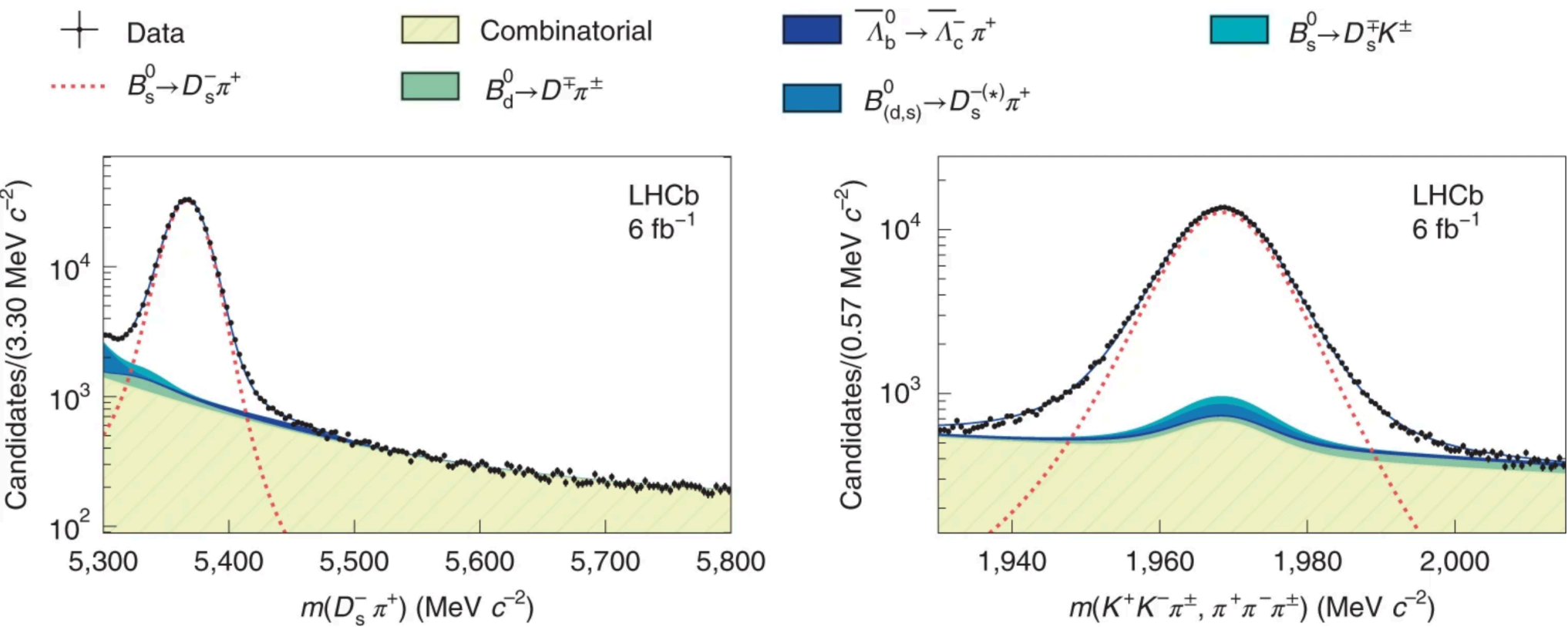
Observation of B_s^0 - $\bar{B}_s^0$ Oscillations

A. Abulencia,²³ J. Adelman,¹³ T. Affolder,¹⁰ T. Akimoto,⁵⁵ M.G. Albrow,¹⁶ D. Ambrose,¹⁶ S. Amerio,⁴³ D. Amidei,³⁴ A. Anastassov,⁵² K. Anikeev,¹⁶ A. Annovi,¹⁸ J. Antos,¹ M. Aoki,⁵⁵ G. Apollinari,¹⁶ J.-F. Arguin,³³ T. Arisawa,⁵⁷ A. Artikov,¹⁴ W. Ashmanskas,¹⁶ A. Attal,⁸ F. Azfar,⁴² P. Azzi-Bacchetta,⁴³ P. Azzurri,⁴⁶ N. Bacchetta,⁴³ W. Badgett,¹⁶ A. Barbaro-Galtieri,²⁸ V.E. Barnes,⁴⁸ B.A. Barnett,²⁴ S. Baroiant,⁷ V. Bartsch,³⁰ G. Bauer,⁵⁹ F. Bedeschi,⁴⁶ S. Behari,²⁴ S. Belforte,⁵⁴ G. Bellitini,⁴⁶ J. Bellinger,⁵⁰ A. Belloni,⁵² D. Benjamin,¹⁵ A. Berezvas,¹⁶ J. Berlinger,²⁸ T. Berry,²⁹ A. Bhatti,⁵⁰ M. Binkley,⁴⁶ D. Biselli,⁴⁸ R.E. Blair,⁸ C. Blocker,⁶ B. Blumenfeld,²⁴ A. Bocci,¹⁵ A. Bodek,⁴⁹ V. Boesvert,⁴⁹ G. Bolla,⁴⁸ A. Bolshov,³² D. Bortoletto,⁴⁸ J. Boudreau,⁴⁷ A. Boveia,¹⁰ B. Bran,¹⁰ L. Brigliadori,² C. Bromberg,³⁵ E. Brubaker,¹³ J. Budagov,¹⁴ H.S. Budd,⁴⁹ S. Budd,²³ S. Budroni,⁴⁶ K. Burkett,¹⁶ G. Busetto,⁴³ P. Bussey,²⁰ K. L. Byrum,² S. Cabrera,¹⁵ M. Campanelli,¹⁹ M. Campbell,³⁴ F. Canelli,¹⁶ A. Canepa,⁵⁸ S. Carrillo,¹⁷ D. Carlsmith,⁵⁰ R. Carosi,⁴⁶ S. Carron,³³ B. Casal,¹¹ M. Casarsa,⁵⁴ A. Castro,⁵ P. Catastini,⁴⁶ D. Cauz,⁵⁴ M. Cavalli-Sforza,³ A. Cerri,²⁸ L. Cerrito,³⁰ S.H. Chang,²⁷ Y.C. Chen,¹ M. Chertok,⁷ G. Chiarelli,⁴⁶ G. Chlachidze,¹⁴ F. Chlebana,¹⁶ I. Cho,²⁷ K. Cho,²⁷ D. Chokheli,¹⁴ J.P. Chou,²¹ G. Choudalakis,³² S.H. Chuang,⁵⁹ K. Chung,¹² W.H. Chung,⁵⁹ Y.S. Chung,⁴⁹ M. Cijlak,⁴⁶ C.I. Ciobanu,²³ M.A. Ciocci,⁴⁶ A. Clark,¹⁹ D. Clark,⁶ M. Coca,¹⁵ G. Compostella,⁴³ M.E. Convery,⁵⁰ J. Conway,⁷ B. Cooper,³⁵ K. Copie,³⁴ M. Cordelli,¹⁸ G. Cortiana,⁴³ F. Crescioli,⁴⁶ C. Cuenca Almenar,⁷ J. Cuevas,¹¹ R. Culbertson,¹⁶ J.C. Cully,³⁴ D. Cyr,³⁹ S. DaRanco,²¹ S. D'Auria,²⁰ T. Davies,²⁰ M. D'Onofrio,⁷ D. Dagenhart,⁶ P. de Barbaro,⁴⁹ S. De Cecco,⁵¹ A. Delchev,²⁹ G. De Lentdecker,⁴⁹ M. Dell'Orso,⁴⁶ F. Delli Paoli,⁴³ L. Demortier,⁵⁰ J. Deng,¹⁵ M. Desai,⁵ D. De Pedis,⁵¹ P.F. Derwent,¹⁶ G.P. Di Giovanni,¹⁴ C. Dionisi,⁵¹ B. Di Ruzza,⁵⁴ J.R. Dittmann,⁴ P. DiToro,⁵² C. Dörz,²⁵ S. Donati,⁴⁶ M. Donega,¹⁹ P. Dong,² J. Douini,⁴³ D. Dorigo,⁴³ S. Dube,⁵² J. Efron,³⁹ R. Erbacher,⁷ D. Errede,²³ S. Errede,²³ R. Eusebi,¹⁶ H.C. Fang,²⁸ S. Farrington,²⁹ I. Fedorko,⁴⁶ W.T. Fedorko,¹³ R.G. Feild,⁶⁰ M. Feindt,²⁵ J.P. Fernandez,³¹ R. Field,¹⁷ G. Flanagan,⁴⁸ A. Foland,²¹ S. Forrester,⁷ G.W. Foster,¹⁶ M. Franklin,²¹ J.C. Freeman,²⁸ H. J. Frisch,¹³ I. Furic,¹³ M. Gallinaro,⁵⁰ J. Galyardt,¹² J.E. Garcia,⁴⁶ F. Garbersen,¹⁰ A.F. Garfinkel,⁴⁸ C. Gay,⁶⁰ H. Gerberich,²³ D. Gerdes,³⁴ S. Giagu,⁵¹ P. Giannetti,⁴⁶ A. Gibson,²⁸ K. Gibson,⁴⁷ J.L. Gimmell,⁴⁹ C. Ginsburg,¹⁶ N. Gioularis,¹⁴ M. Giordani,⁵⁴ P. Giromini,¹⁸ M. Giunta,⁴⁶ G. Giurgiu,¹² V. Glagolev,¹⁴ D. Glezinski,¹⁶ M. Gold,³⁷ N. Goldschmidt,¹⁷ J. Goldstein,⁴² G. Gomez,¹¹ G. Gomez-Ceballos,¹¹ M. Goncharov,⁵³ O. González,³¹ I. Gorelov,³⁷ A.T. Goshaw,¹⁵ K. Goulianos,⁵⁰ A. Gressle,⁴³ M. Griffiths,²⁹ S. Grinstein,²¹ C. Grosso-Pilcher,¹³ R.C. Group,¹⁷ U. Grundler,²³ J. Guimaraes da Costa,²¹ Z. Gunay-Unalan,⁵⁰ C. Haber,²³ K. Hahn,⁵² S.R. Hahn,¹⁶ E. Halkiadakis,⁵² A. Hamilton,³³ B.-Y. Han,⁴⁹ J.Y. Han,⁴⁹ R. Handerl,⁵² F. Happacher,¹⁸ K. Hara,⁵⁵ M. Hase,⁵⁶ S. Harper,⁴² R.F. Harr,¹⁸ R.M. Harris,¹⁶ M. Hartz,⁴⁷ K. Hatakeyama,³⁰ J. Hauser,⁸ A. Heijboer,²⁵ B. Heinemann,²⁹ J. Heinrich,²⁵ C. Henderson,³² M. Herndon,⁵⁹ J. Heuser,²⁵ D. Hidas,¹⁵ C.S. Hill,¹⁶ D. Hirschbuhl,²⁵ A. Hocker,¹⁶ A. Holloway,²¹ S. Hou,¹ M. Houlden,²⁹ S.-C. Hsu,⁹ B.T. Huffman,⁴² R.E. Hughes,³⁹ U. Husemann,⁴⁹ J. Huston,³⁵ J. Incandella,¹⁰ G. Introzzi,⁴⁶ M. Iori,⁵¹ Y. Ishizawa,⁵⁵ A. Ivanov,⁷ B. Iyutin,³² E. James,¹⁶ D. Jang,⁵² B. Jayatilaka,³⁴ D. Jeans,⁵¹ H. Jensen,¹⁶ E.J. Jeon,²⁷ S. Jindariani,¹⁷ M. Jones,⁴⁸ K.K. Joo,²⁷ S.Y. Jun,¹² J.E. Jung,²⁷ T.R. Junk,²³ T. Kamon,⁵³ P.E. Karchin,⁵⁸ Y. Kato,⁴¹ Y. Kemp,²⁵ R. Kephart,¹⁶ U. Kerzel,²⁵ V. Khotilovich,⁵³ B. Kilminster,²⁹ D.H. Kim,²⁷ H.S. Kim,²⁷ J.E. Kim,²⁷ M.J. Kim,¹² S.B. Kim,²⁷ S.H. Kim,⁵⁵ Y.K. Kim,¹³ N. Kimura,⁵⁵ L. Kirsch,⁵ S. Klimentov,¹⁷ M. Klute,³² B. Knuteson,³² B.R. Ko,¹⁵ K. Kondo,⁵⁷ D.J. Kong,²⁷ J. Konigsberg,¹⁷ A. Korytov,¹⁷ A.V. Kotwal,¹⁵ A. Kovalev,⁴⁵ A.C. Kraan,⁴⁵ J. Kraus,²³ I. Kravchenko,³² M. Kreps,²⁵ J. Kroll,⁴³ N. Krummacker,⁴ M. Kruse,¹⁵ V. Krutelyov,¹⁰ T. Kubo,⁵⁵ S. E. Kuhlmann,² T. Kuhr,²⁵ Y. Kusaka,²¹ S. Kwang,⁵¹ A.T. Laasanen,⁴⁸ S. Lai,⁵⁵ S. Lami,⁴⁸ S. Lammell,¹⁴ M. Lancaster,²⁹ R.L. Lander,⁷ K. Lannon,³⁹ A. Lath,⁵² G. Latino,⁴⁹ I. Lazzizzera,⁴³ T. LeCompte,² J. Lee,⁴⁹ J. Lee,²⁷ Y.J. Lee,²⁷ S.W. Lee,⁵³ R. Lefevre,³ N. Leonard,³² S. Leone,⁴⁸ S. Levy,¹³ J.D. Lewis,¹⁶ C. Lin,¹⁶ C.S. Lin,¹⁶ M. Lindgren,¹⁶ E. Lipeles,⁹ T.M. Liss,²³ A. Lister,⁷ D.O. Litvinsev,¹⁶ T. Liu,¹⁶ N.S. Lockyer,⁴⁵ A. Loginov,³⁶ M. Loret,⁴³ P. Loverre,⁵¹ R.-S. Lu,¹ D. Lucchesi,⁴³ P. Lujan,²⁸ P. Lukens,¹⁶ G. Lungu,¹⁷ L. Lyons,⁴² J. Lys,²⁸ R. Lysak,¹ E. Lytken,⁴⁸ P. Mack,²⁵ D. MacQueen,³³ R. Madrak,¹⁶ K. Maeshima,¹⁶ K. Makhoul,³² T. Maki,²² P. Maksimovic,²⁴ S. Malde,⁴² G. Manca,²⁹ F. Margaroli,⁵ R. Marginean,¹⁶ C. Marino,²⁹ C.P. Marino,²³ A. Martin,⁶⁰ M. Martin,²⁴ V. Martin,²⁰ M. Martinez,³ T. Maruyama,⁵⁵ P. Mastrandrea,⁵¹ T. Masubuchi,⁵⁵ H. Matsunaga,⁵⁵ M.E. Mattson,²⁸ R. Mazini,³³ P. Mazzanti,⁵ K.S. McFarland,⁴⁹ P. McIntyre,⁵³ R. McNulty,²⁹ A. Mehta,²⁹ P. Mehtala,²² S. Menzemer,¹¹ A. Menzione,⁴⁶ P. Merle,⁴⁸ C. Mesropian,⁵⁰ A. Messina,⁵¹ T. Miao,¹⁶ N. Miladinovic,⁶ J. Miles,³² R. Miller,³⁵ C. Mills,¹⁰ M. Milnik,²⁵ A. Mitra,⁴ G. Mitselmakher,¹⁷ A. Miyamoto,²⁶ S. Moed,¹⁹ N. Moggi,⁵ B. Mohr,⁸

Finally...

A counting experiment

$$A(t) = \frac{N(B_s^0 \rightarrow D_s^- \pi^+, t) - N(\bar{B}_s^0 \rightarrow D_s^- \pi^+, t)}{N(B_s^0 \rightarrow D_s^- \pi^+, t) + N(\bar{B}_s^0 \rightarrow D_s^- \pi^+, t)},$$

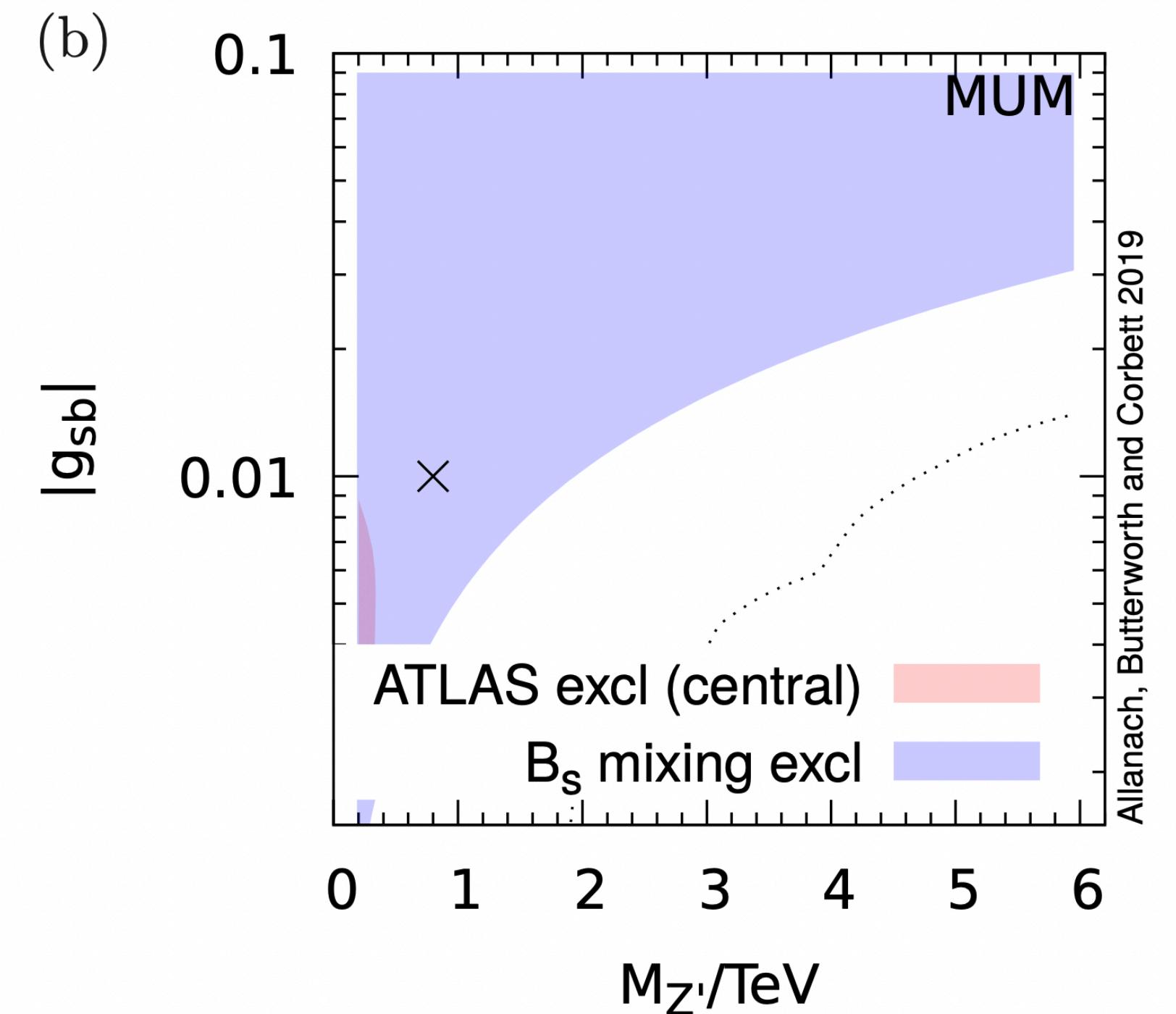
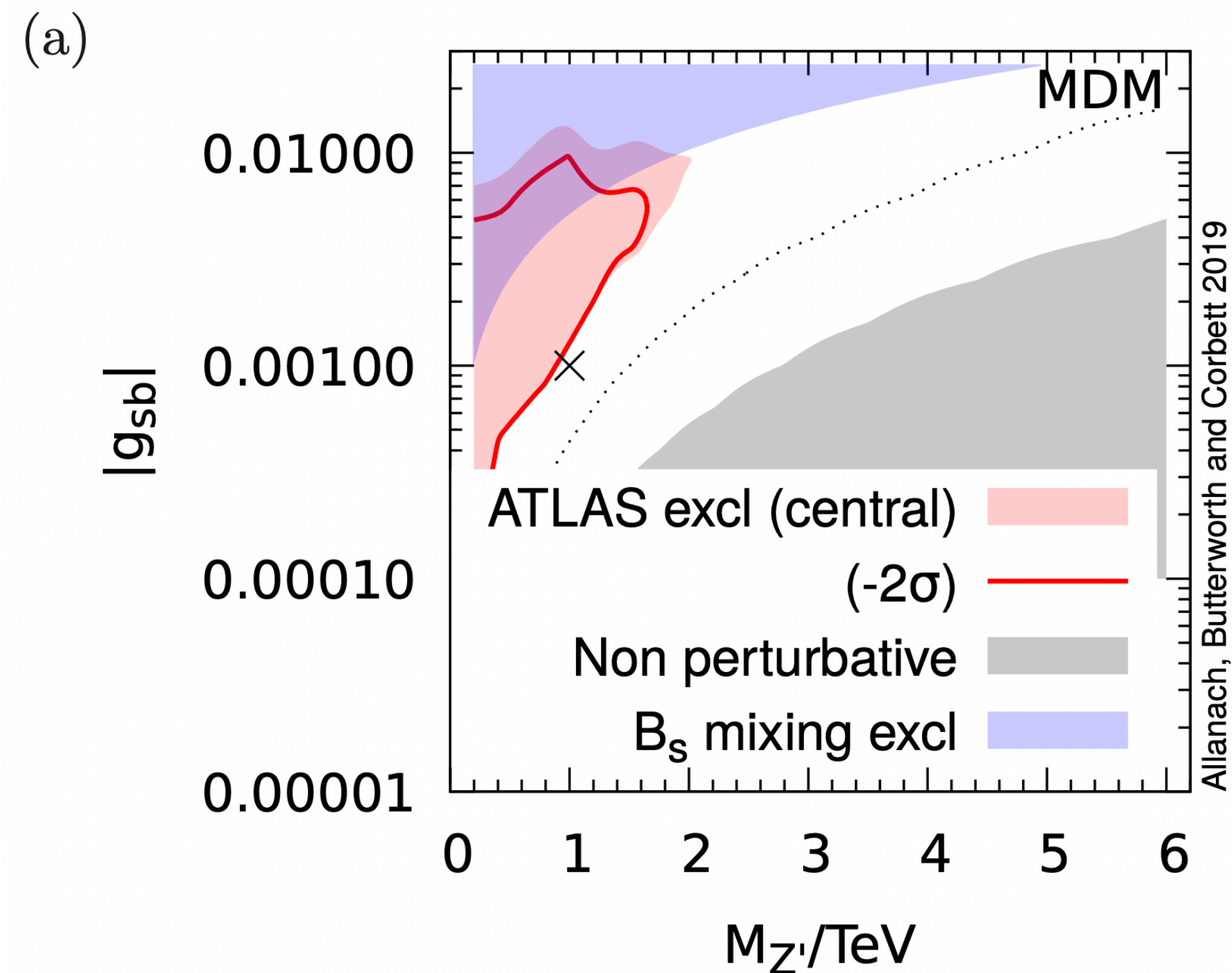
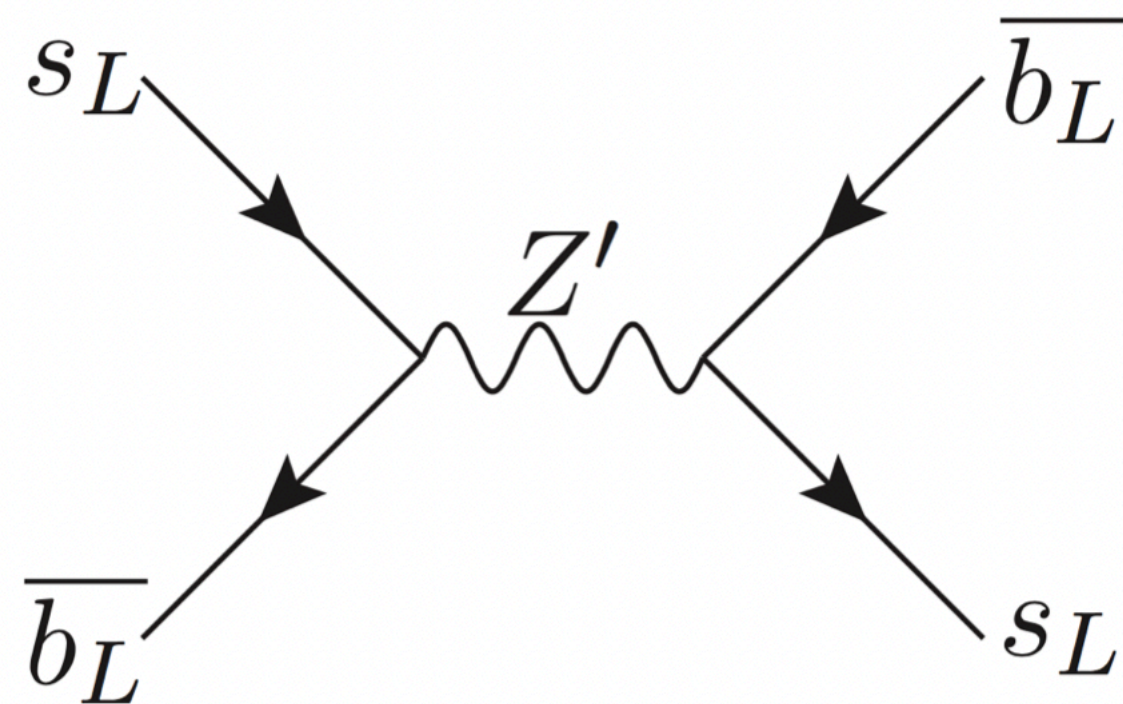


Decay mode	Data sample	$\Delta m_s \text{ ps}^{-1}$
$B_s^0 \rightarrow D_s^- \pi^+$	2011	$17.768 \pm 0.023 \pm 0.006$
$B_s^0 \rightarrow D_s^- \pi^- \pi^+ \pi^+$	2011-2018	$17.757 \pm 0.007 \pm 0.008$
$B_s^0 \rightarrow D_s^- \pi^+$	2015-2018	$17.7683 \pm 0.0051 \pm 0.0032$
Average		17.7666 ± 0.0057

Importance of PID, proper time resolution, flavour tagging

Loop back to the models

SM $\Delta m_q = \frac{G_f^2}{6\pi^2} m_{B_q} M_W^2 f\left(\frac{m_t^2}{M_W^2}\right) \eta_{QCD} B_{B_q} f_{B_q}^2 |V_{tb}^* V_{tq}|^2 \quad q = d, s$



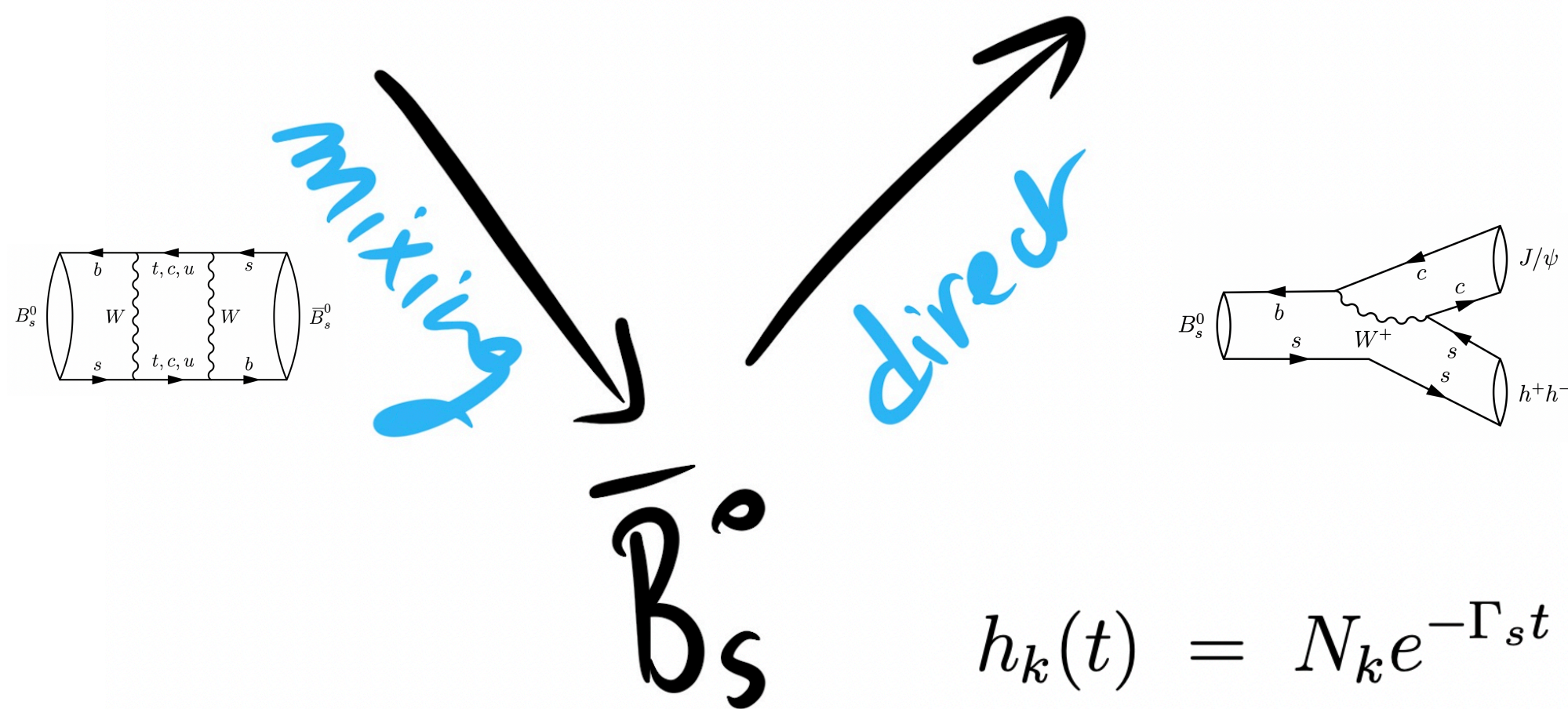
arXiv:1904.10954 one example out of the billion out there.

Let's us add complexity - $B_s \rightarrow J/\psi (\rightarrow \mu^+ \mu^-) \Phi (K^+ K^-)$

Mixture of CP odd and CP even eigenstates



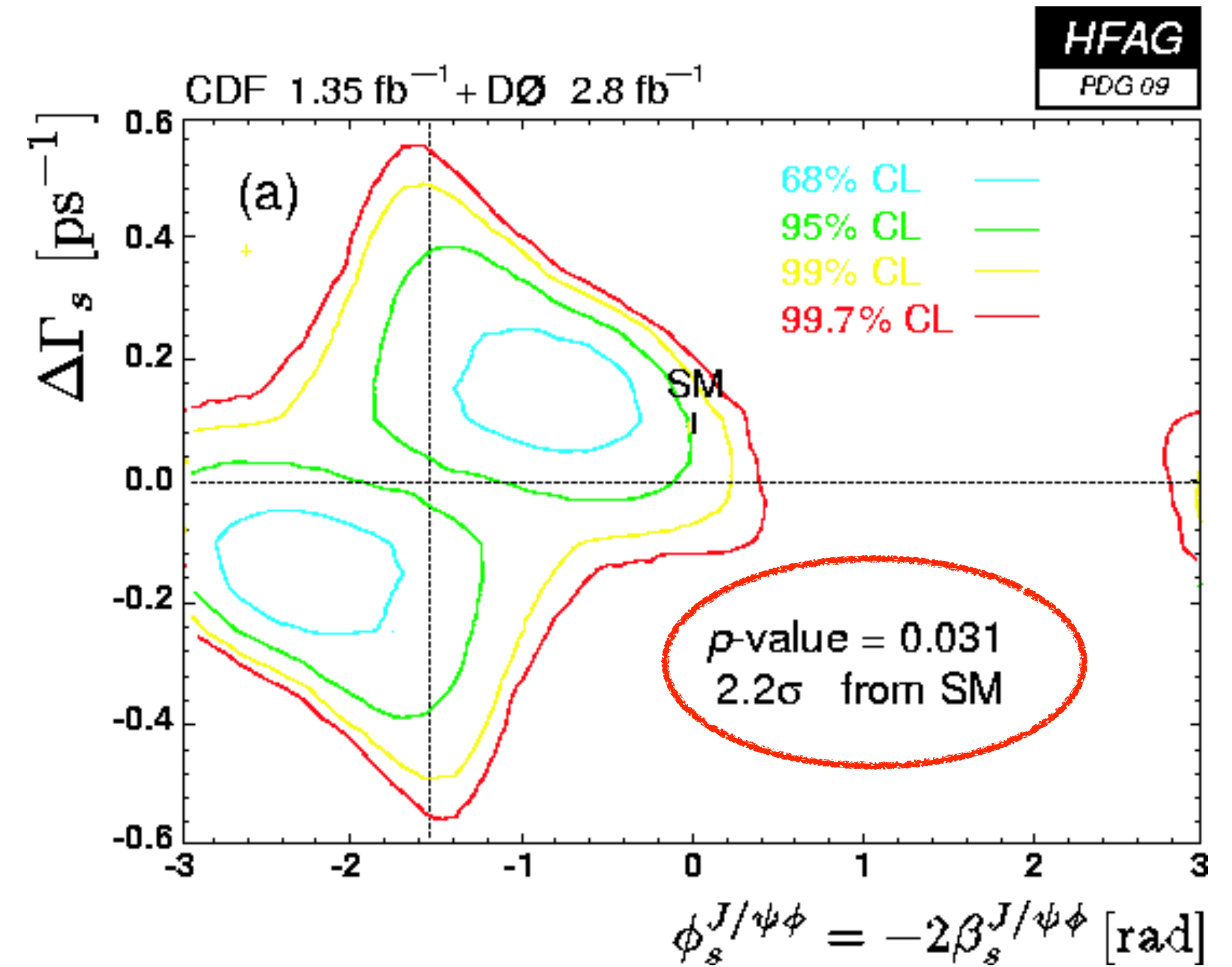
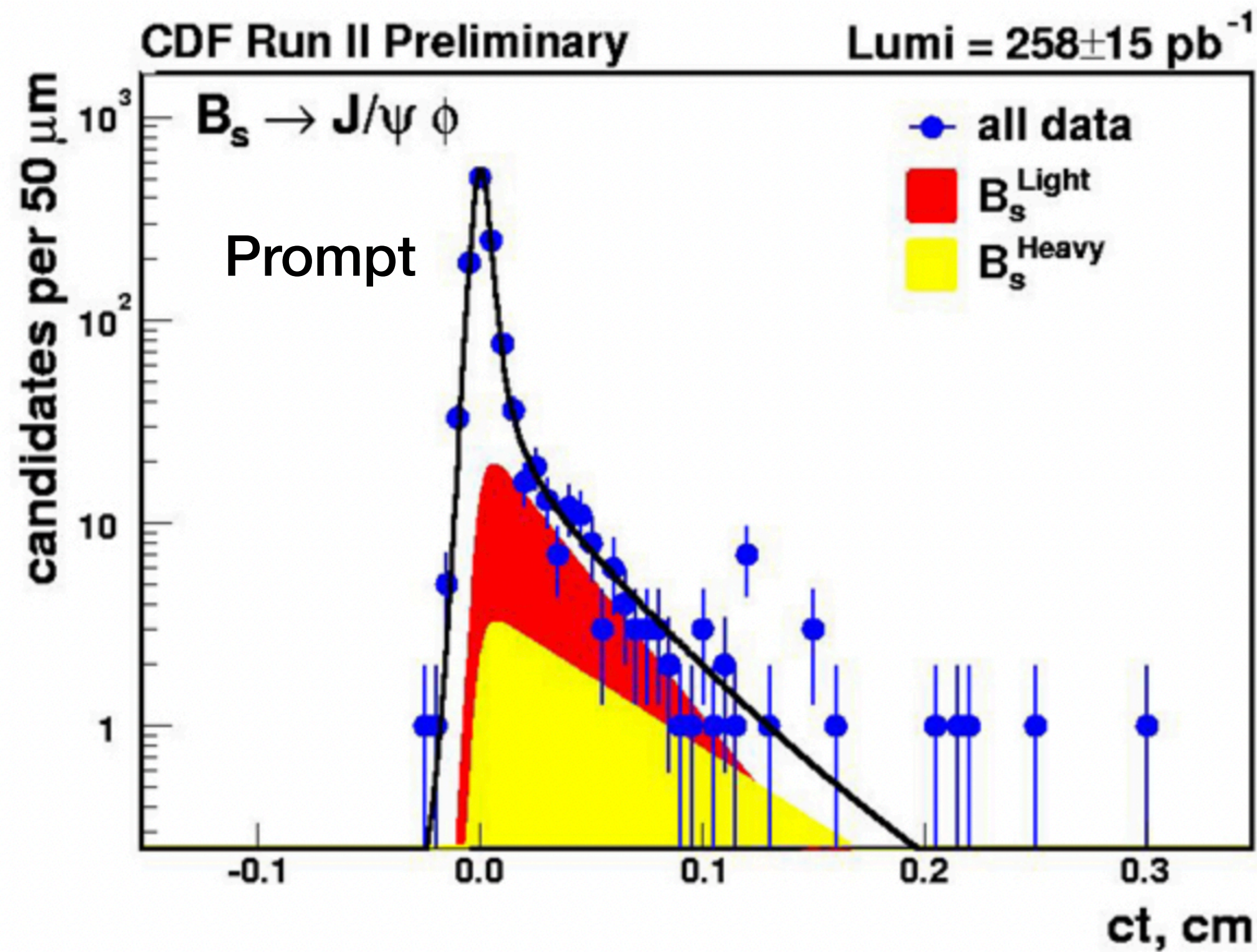
None negligible difference between the heavy and the light state of your the B_s mesons $\Delta\Gamma_s$



$$\frac{d^4\Gamma(B_s^0 \rightarrow J/\psi K^+ K^-)}{dt \, d\Omega} \propto \sum_{k=1}^{10} h_k(t) \, f_k(\Omega) .$$

$$h_k(t) = N_k e^{-\Gamma_s t} \left[a_k \cosh \left(\frac{1}{2} \Delta\Gamma_s t \right) + b_k \sinh \left(\frac{1}{2} \Delta\Gamma_s t \right) + c_k \cos(\Delta m_s t) + d_k \sin(\Delta m_s t) \right],$$

Fermilab paved the path of B_s physics



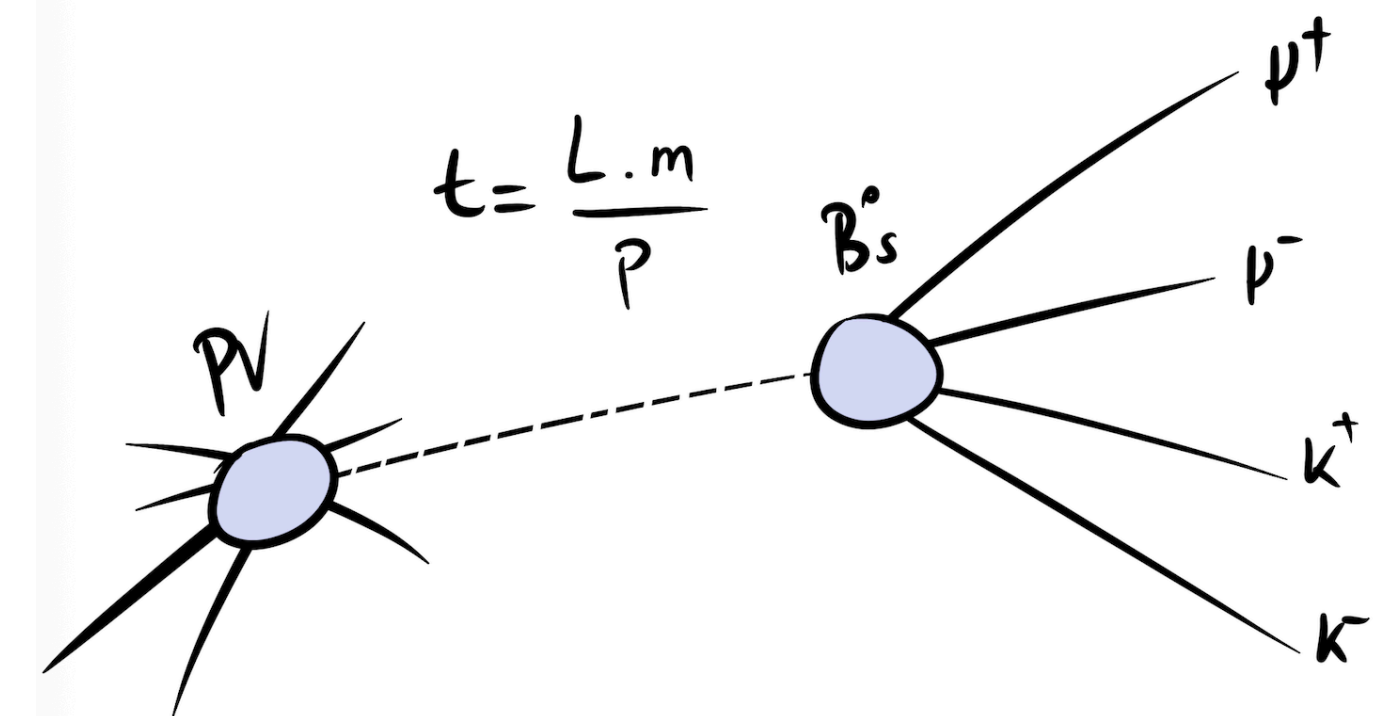
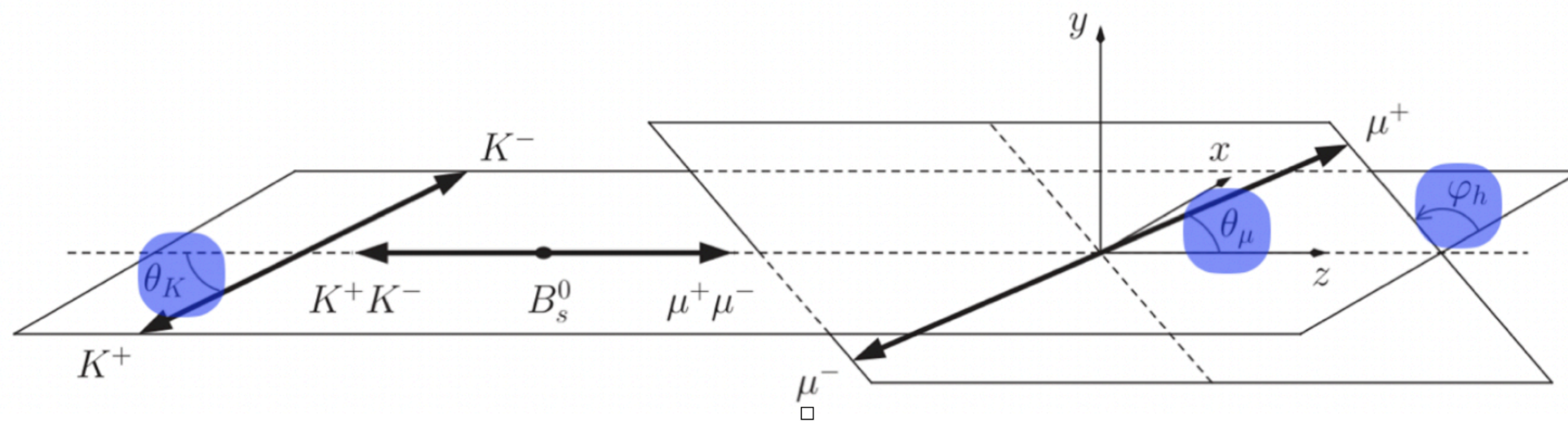
Time dependent angular analysis

We will come back to the to angular analyses in the second lecture

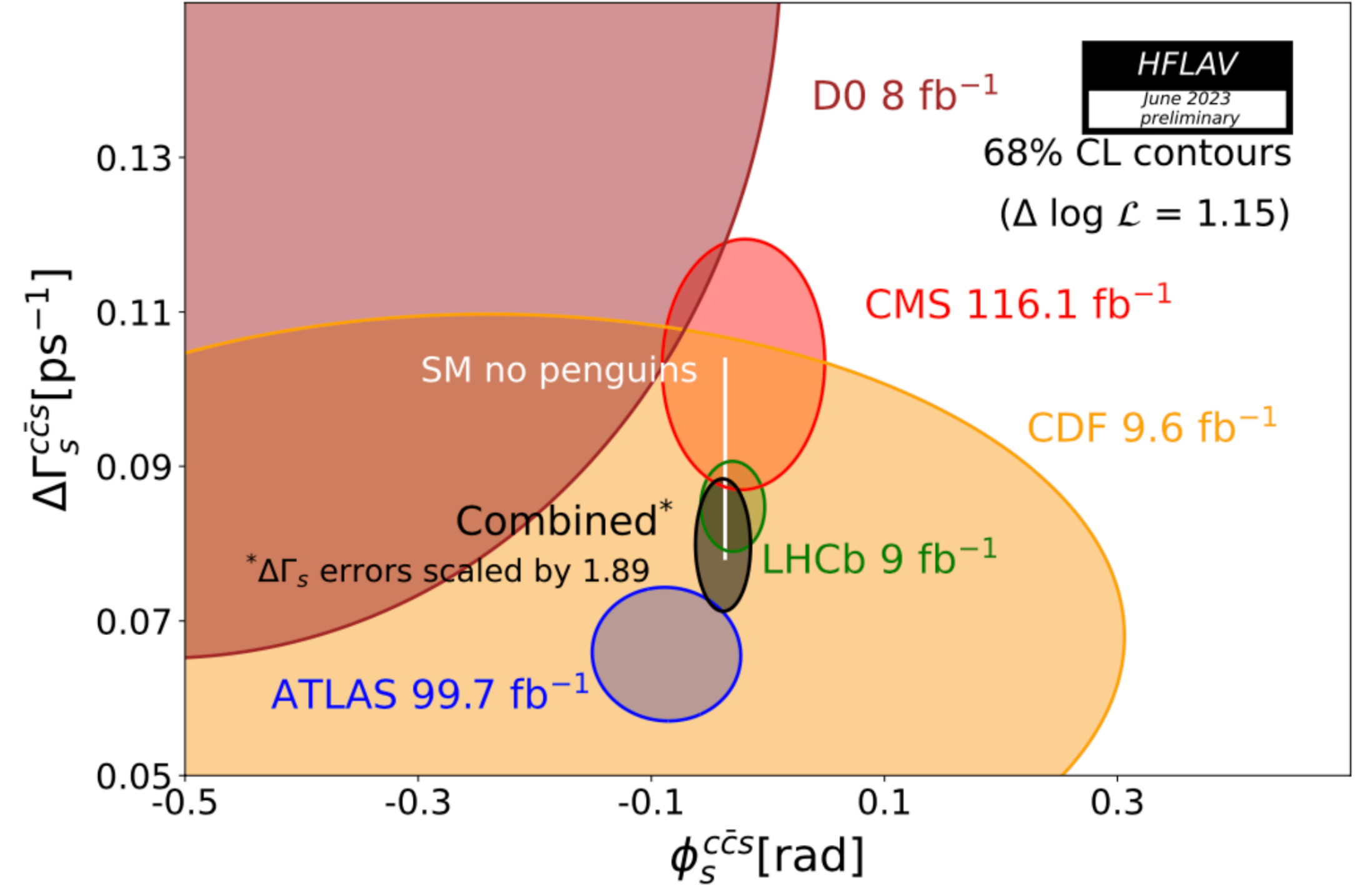
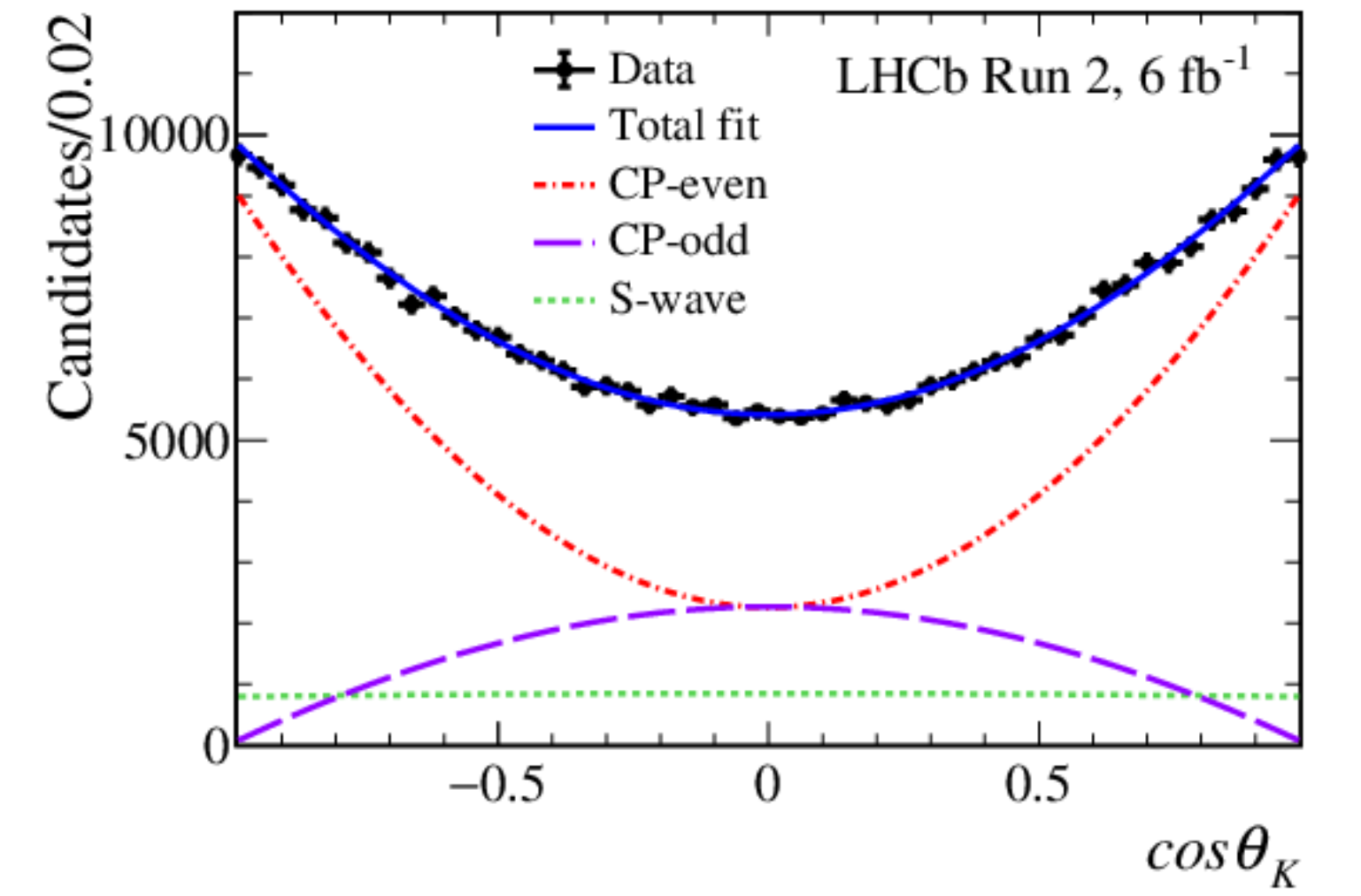
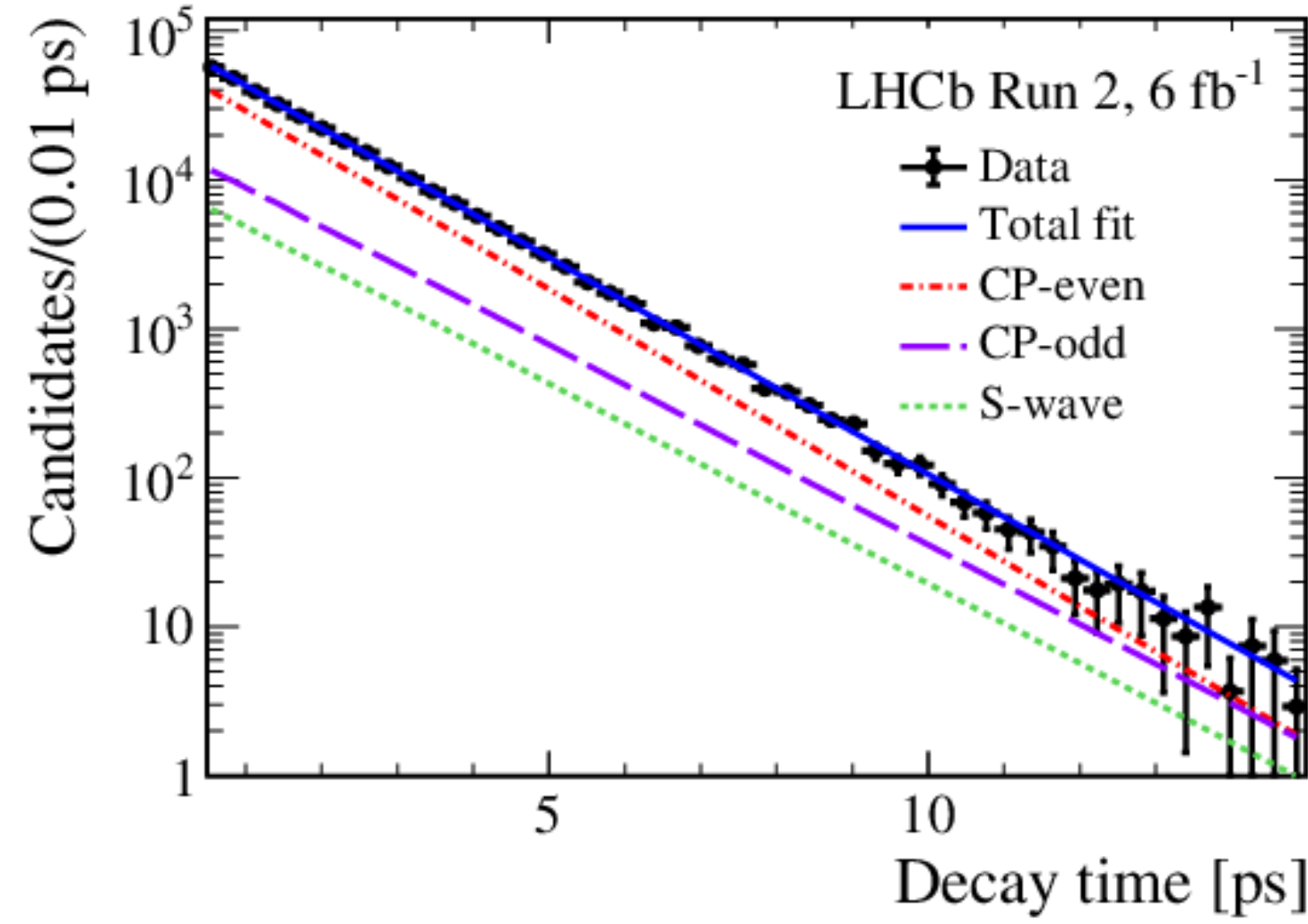
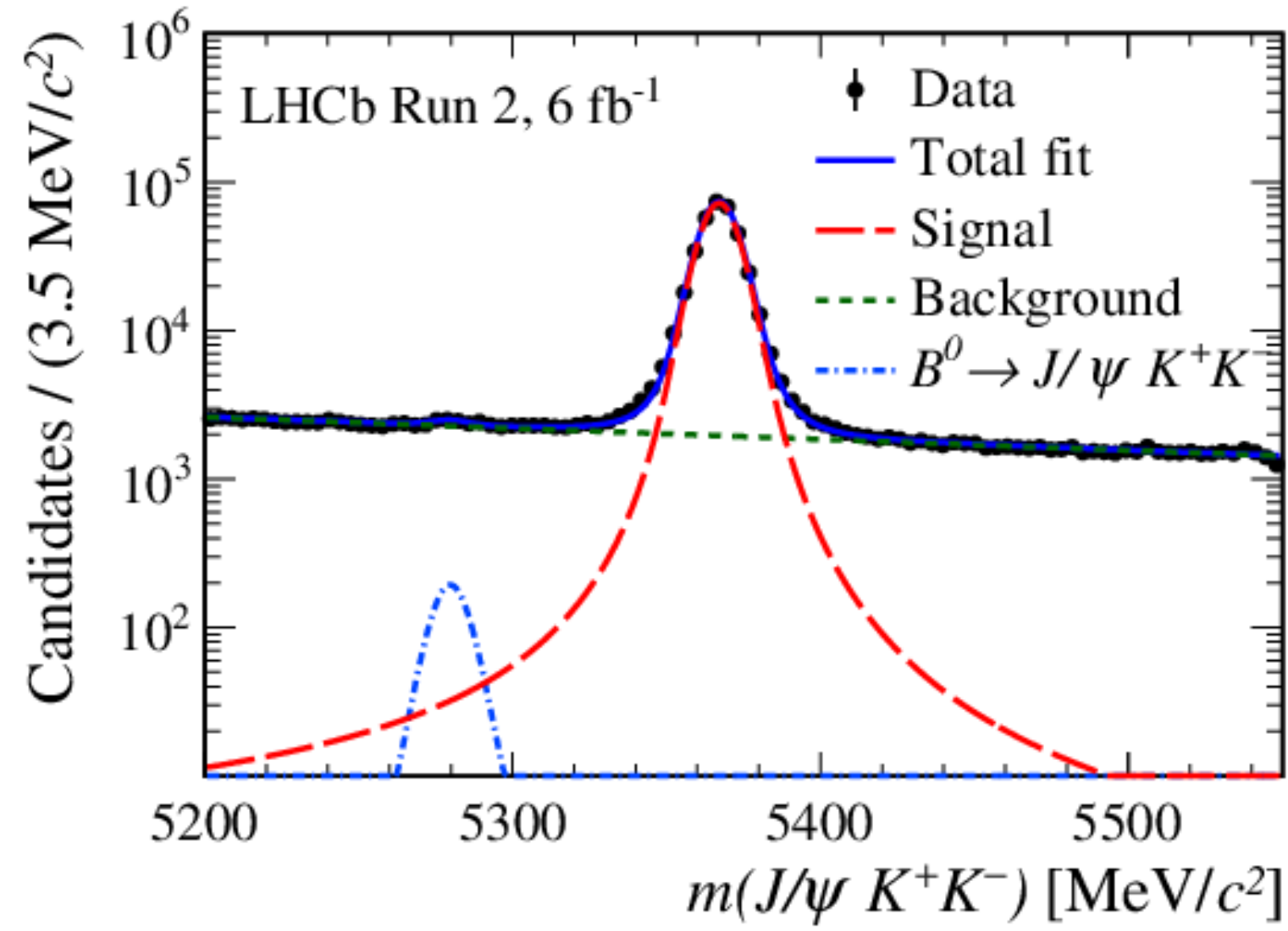
It's “just” yet another counting experiment

$$A_{CP}(t) = \frac{\Gamma(\bar{B}_s^0 \rightarrow \psi \phi) - \Gamma(B_s^0 \rightarrow \psi \phi)}{\Gamma(\bar{B}_s^0 \rightarrow \psi \phi) + \Gamma(B_s^0 \rightarrow \psi \phi)} = \eta_f \sin \phi_s \sin(\Delta m_s t)$$

$\eta_f = (-1)^L$ CP eigenvalues of the final state



Mixture of CP odd and CP even requires an angular analysis



Very similar experimental techniques
between the LHC three collaborations

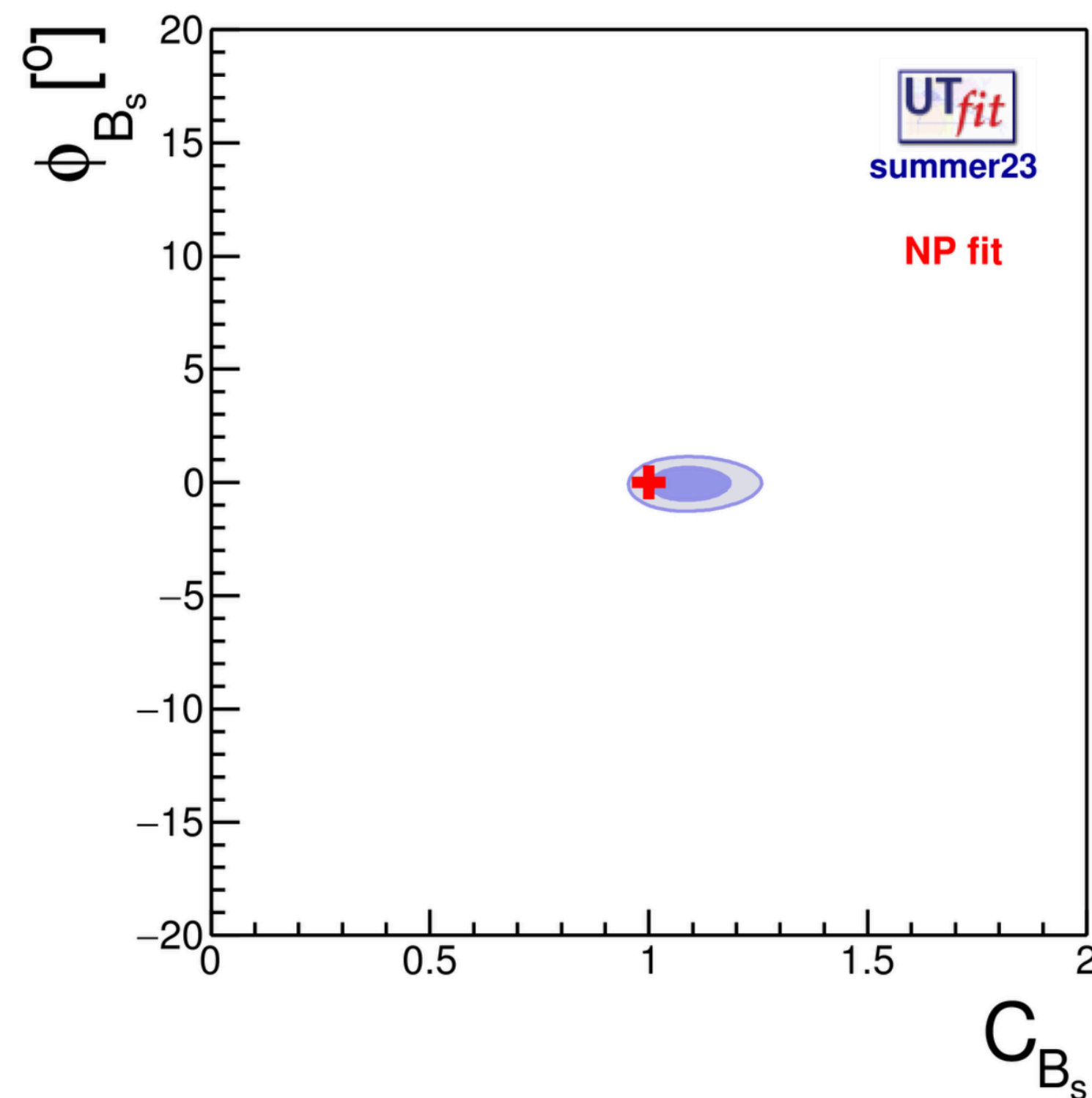
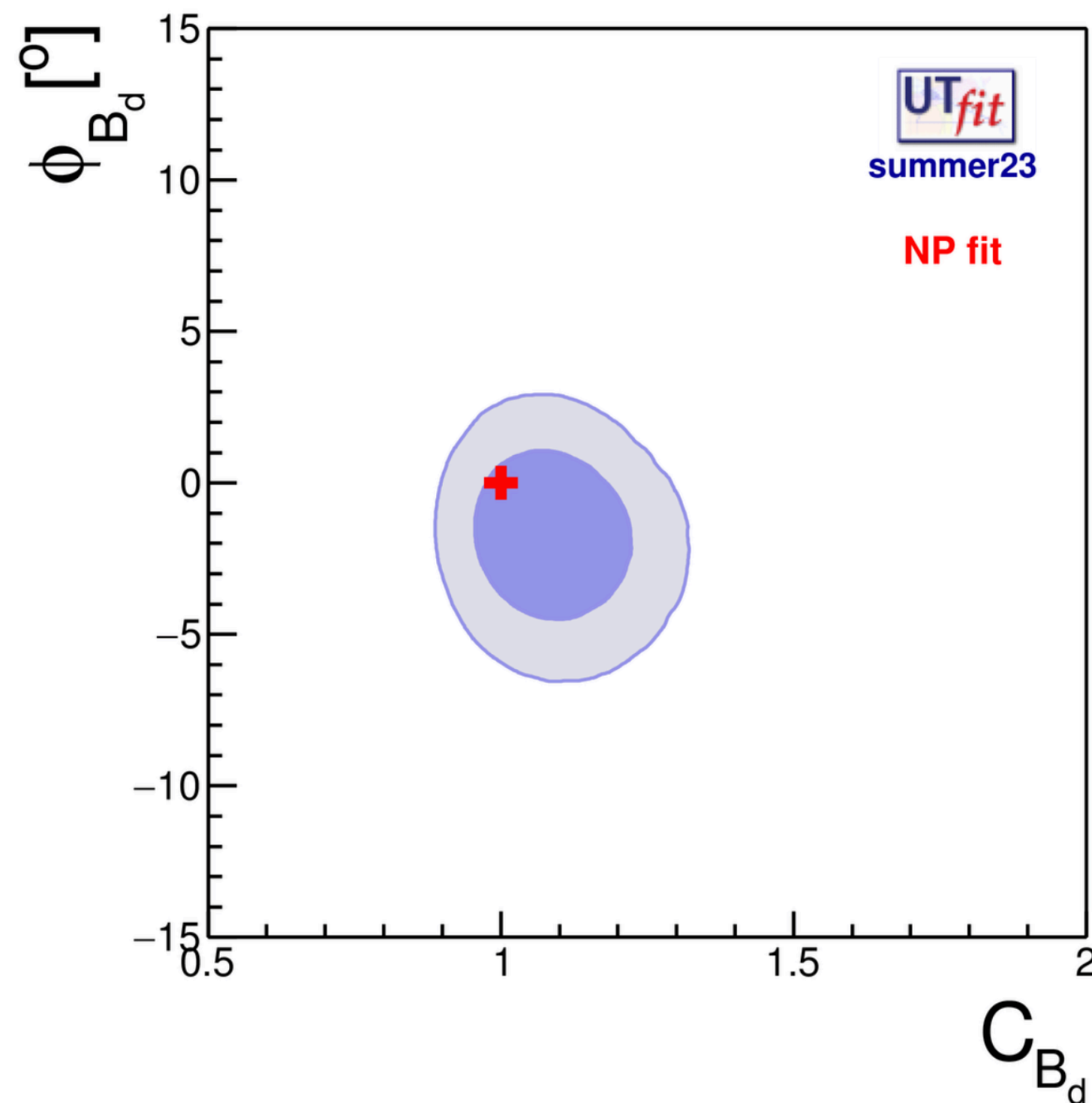
arXiv:2308.01468

An example of a UT fit

Adopt a given parametrisation

$$A_1 = C_{B_q} e^{2i\phi_{B_q}^{sm}} A_1^{sm} e^{2i\phi_1^{sm}}$$

+ SM



An example of NP interpretations

$$C_{B_q} e^{2i\phi_{B_q}} = \frac{\langle B_q | H_{\text{eff}}^{\text{full}} | \bar{B}_q \rangle}{\langle B_q | H_{\text{eff}}^{\text{SM}} | \bar{B}_q \rangle} = 1 + \frac{A_q^{\text{NP}}}{A_q^{\text{SM}}} e^{2i\phi_q^{\text{NP}}}$$

Let us first consider MFV models and update our results presented in Ref. [11, 12]. In practice, the most convenient strategy in this case is to fit the shift in the Inami-Lim top-quark function entering B_d , B_s and K^0 mixing. We fit for this shift using the experimental measurements of Δm_d , Δm_s and ϵ_K , after determining the parameters of the CKM matrix with the universal unitarity triangle analysis [17].⁷ We obtain the following lower bounds at 95% probability:

$$\Lambda > 5.5 \text{ TeV} \quad (\text{small } \tan \beta), \quad (13)$$

$$\Lambda > 5.1 \text{ TeV} \quad (\text{large } \tan \beta). \quad (14)$$

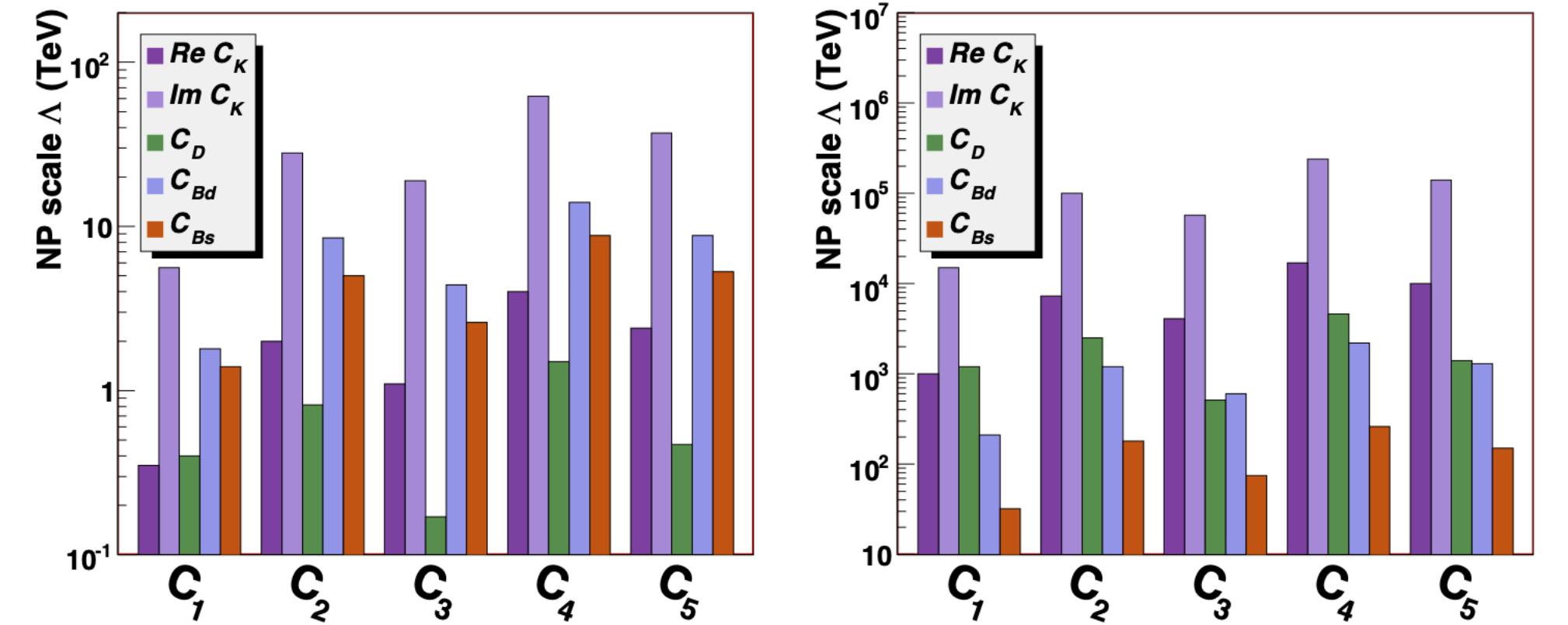
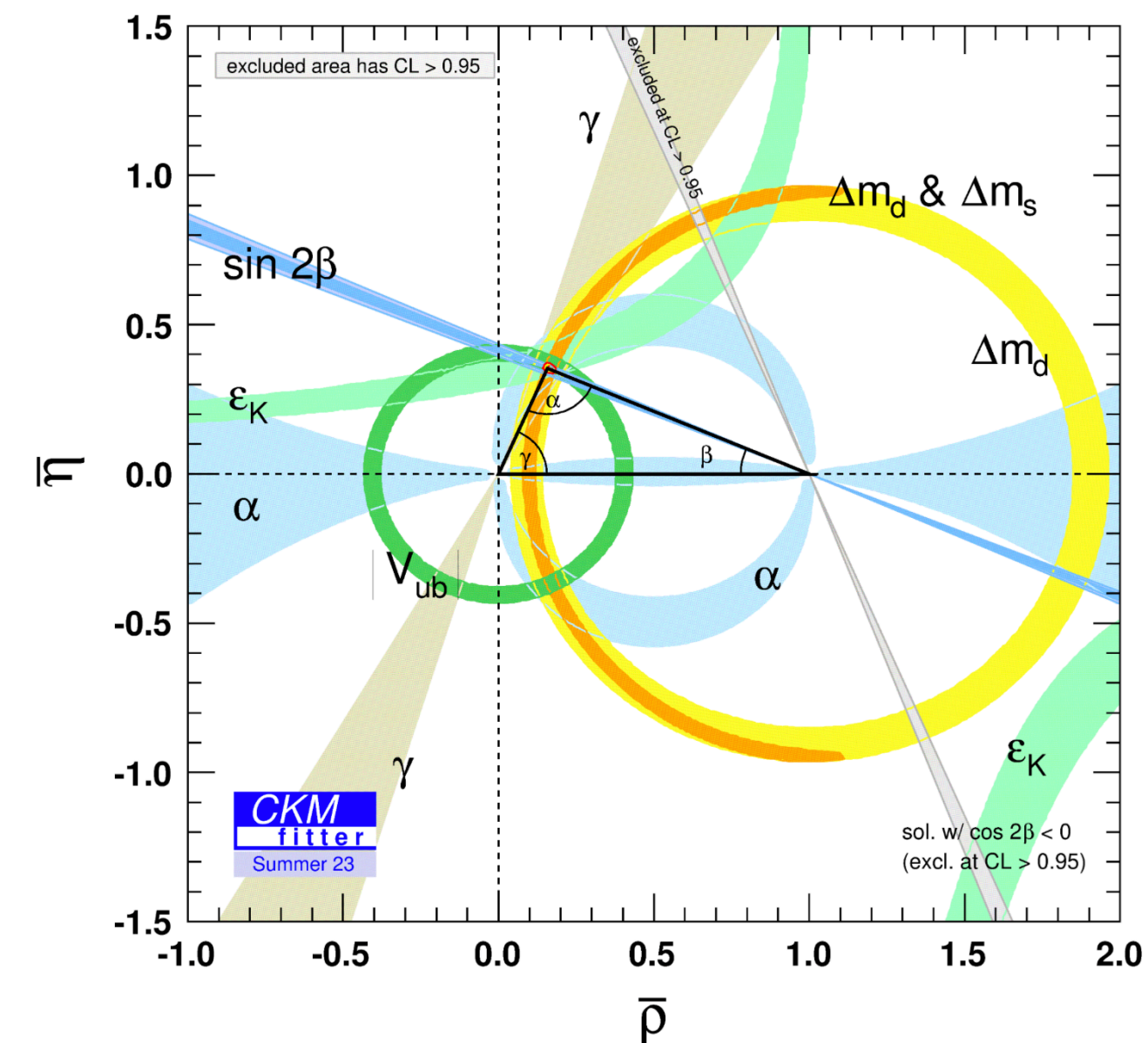


FIG. 7: Summary of the 95% probability lower bound on the NP scale Λ for strongly-interacting NP in NMFV (left) and general NP (right) scenarios.

How to measure γ ?

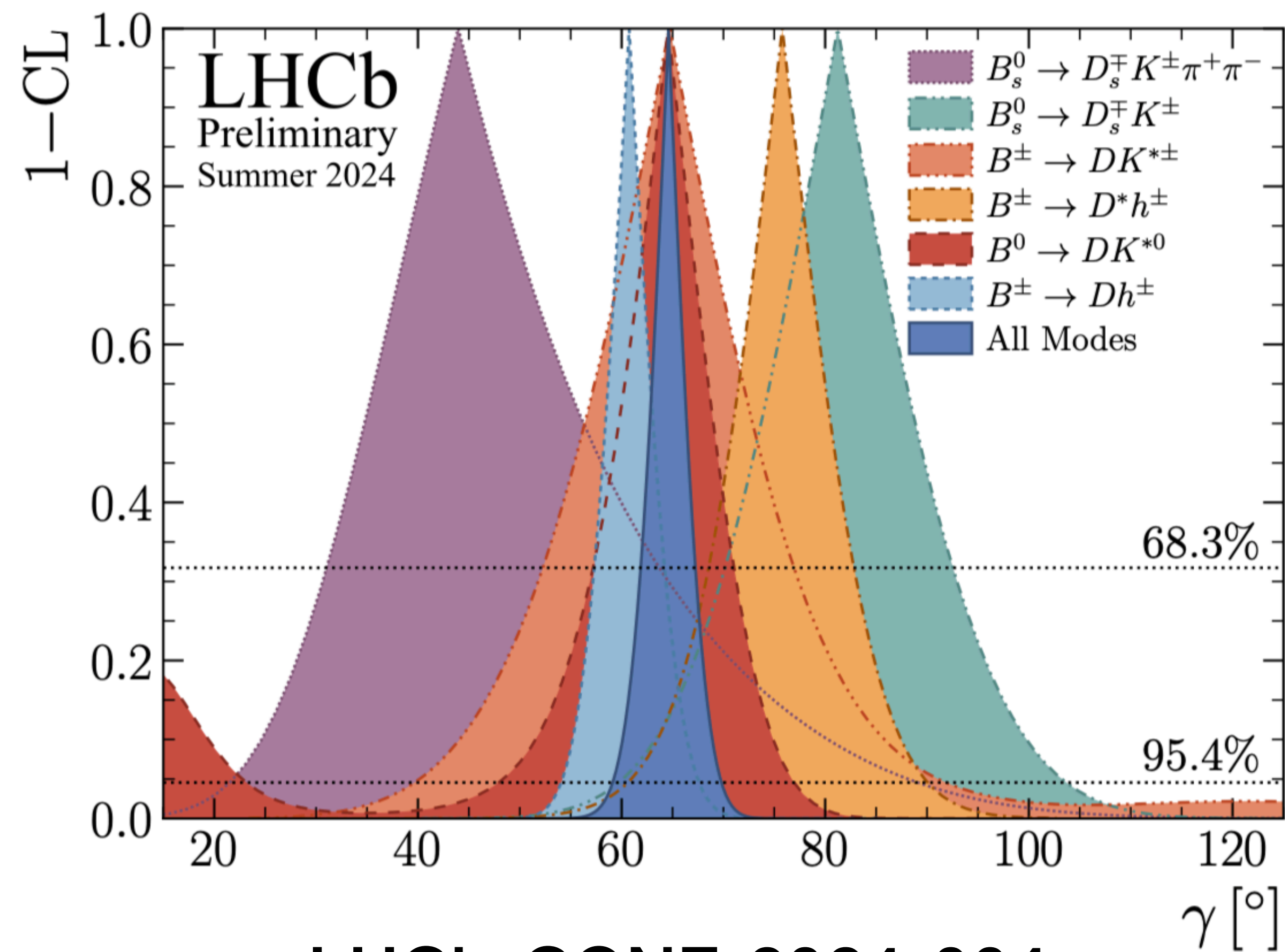
$$\gamma \equiv \varphi_3 \equiv \arg \left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right) \simeq \arg(\rho + i\eta) .$$

It's all about interferences !



< Beautiful Mont-Blanc analogy >

There is a myriad of techniques to measure this angle



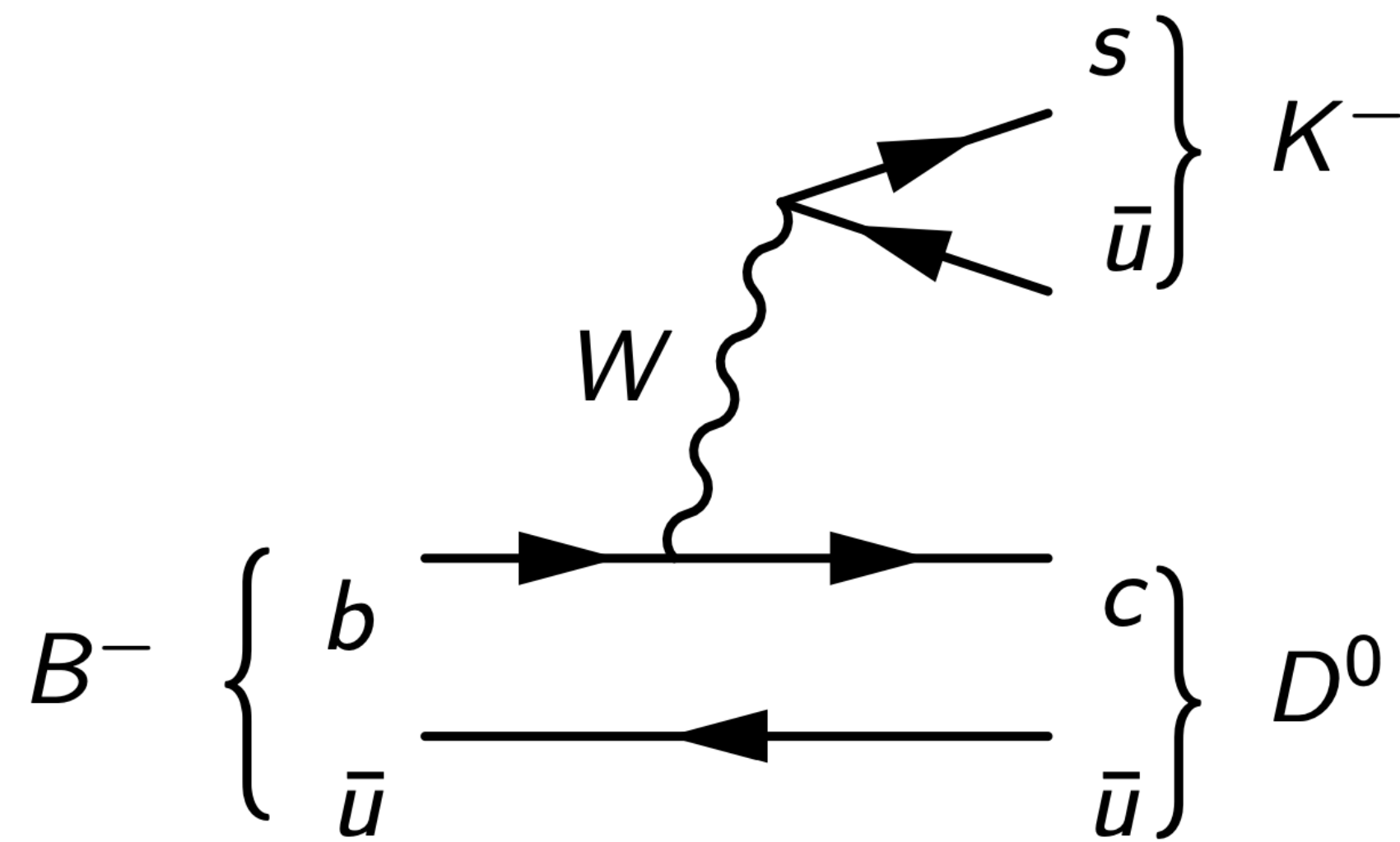
LHCb-CONF-2024-004

<i>B</i> decay	<i>D</i> decay	Ref.	Dataset	Status since Ref. [14]
$B^\pm \rightarrow Dh^\pm$	$D \rightarrow h^\pm h'^\mp$	[35]	Run 1&2	<i>As before</i>
$B^\pm \rightarrow Dh^\pm$	$D \rightarrow h^+ h^- \pi^+ \pi^-$	[19]	Run 1&2	New
$B^\pm \rightarrow Dh^\pm$	$D \rightarrow K^\pm \pi^\mp \pi^+ \pi^-$	[36]	Run 1&2	<i>As before</i>
$B^\pm \rightarrow Dh^\pm$	$D \rightarrow h^\pm h'^\mp \pi^0$	[37]	Run 1&2	<i>As before</i>
$B^\pm \rightarrow Dh^\pm$	$D \rightarrow K_S^0 h^+ h^-$	[38]	Run 1&2	<i>As before</i>
$B^\pm \rightarrow Dh^\pm$	$D \rightarrow K_S^0 K^\pm \pi^\mp$	[39]	Run 1&2	<i>As before</i>
$B^\pm \rightarrow D^* h^\pm$	$D \rightarrow h^\pm h'^\mp$ (PR)	[35]	Run 1&2	<i>As before</i>
$B^\pm \rightarrow D^* h^\pm$	$D \rightarrow K_S^0 h^+ h^-$ (PR)	[20]	Run 1&2	New
$B^\pm \rightarrow D^* h^\pm$	$D \rightarrow K_S^0 h^+ h^-$ (FR)	[21]	Run 1&2	New
$B^\pm \rightarrow DK^{*\pm}$	$D \rightarrow h^\pm h'^\mp$	[22] [†]	Run 1&2	Updated
$B^\pm \rightarrow DK^{*\pm}$	$D \rightarrow h^\pm \pi^\mp \pi^+ \pi^-$	[22] [†]	Run 1&2	Updated
$B^\pm \rightarrow DK^{*\pm}$	$D \rightarrow K_S^0 h^+ h^-$	[22] [†]	Run 1&2	New
$B^\pm \rightarrow Dh^\pm \pi^+ \pi^-$	$D \rightarrow h^\pm h'^\mp$	[40]	Run 1	<i>As before</i>
$B^0 \rightarrow DK^{*0}$	$D \rightarrow h^\pm h'^\mp$	[23]	Run 1&2	Updated
$B^0 \rightarrow DK^{*0}$	$D \rightarrow h^\pm \pi^\mp \pi^+ \pi^-$	[23]	Run 1&2	Updated
$B^0 \rightarrow DK^{*0}$	$D \rightarrow K_S^0 h^+ h^-$	[24]	Run 1&2	Updated
$B^0 \rightarrow D^\mp \pi^\pm$	$D^+ \rightarrow K^- \pi^+ \pi^+$	[41]	Run 1	<i>As before</i>
$B_s^0 \rightarrow D_s^\mp K^\pm$	$D_s^+ \rightarrow h^+ h^- \pi^+$	[25, 42] [†]	Run 1&2	Updated
$B_s^0 \rightarrow D_s^\mp K^\pm \pi^+ \pi^-$	$D_s^+ \rightarrow h^+ h^- \pi^+$	[43]	Run 1&2	<i>As before</i>

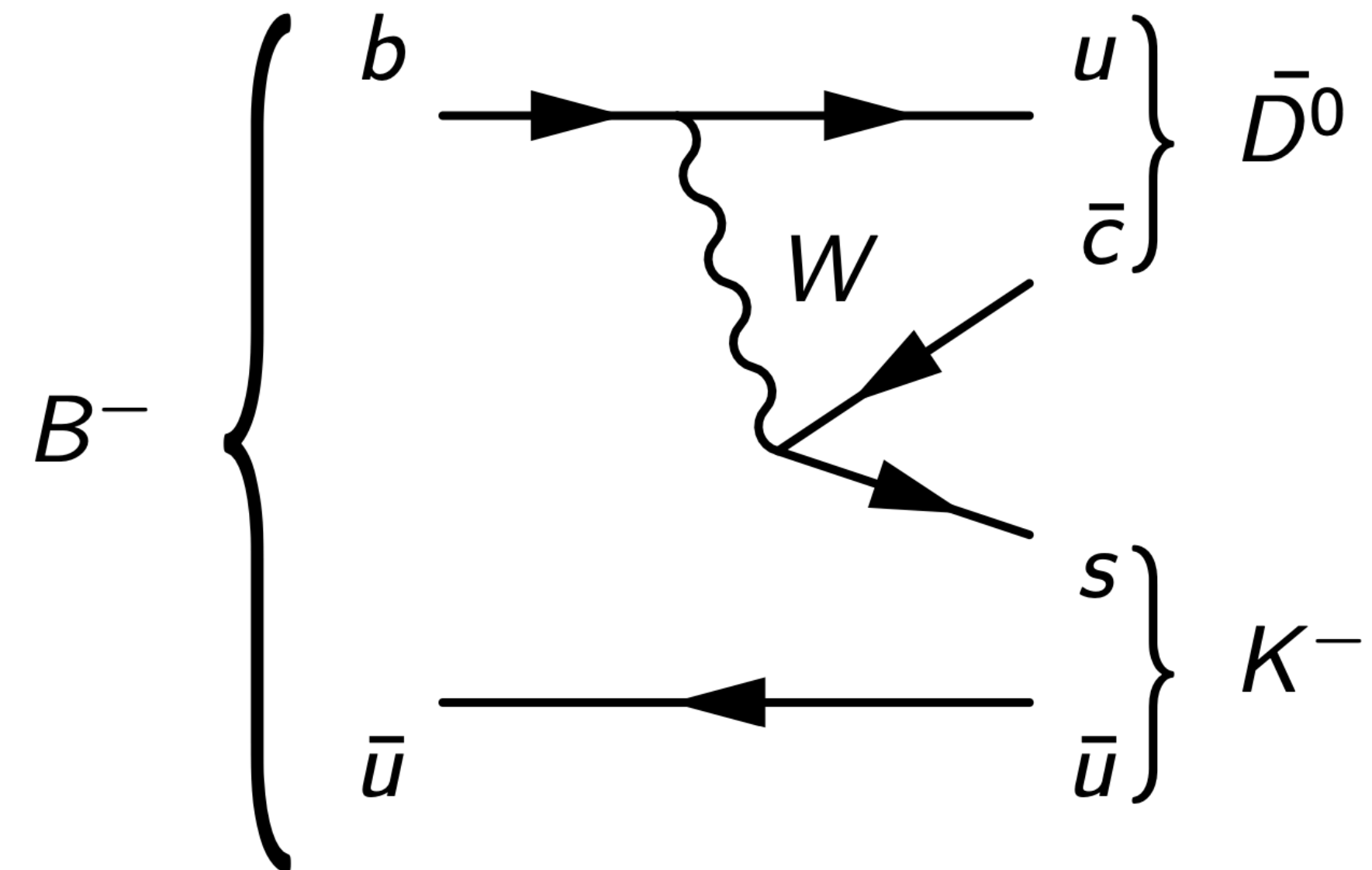
ADS, GLW, BPGGSZ, etc.

Which interference are we talking about ?

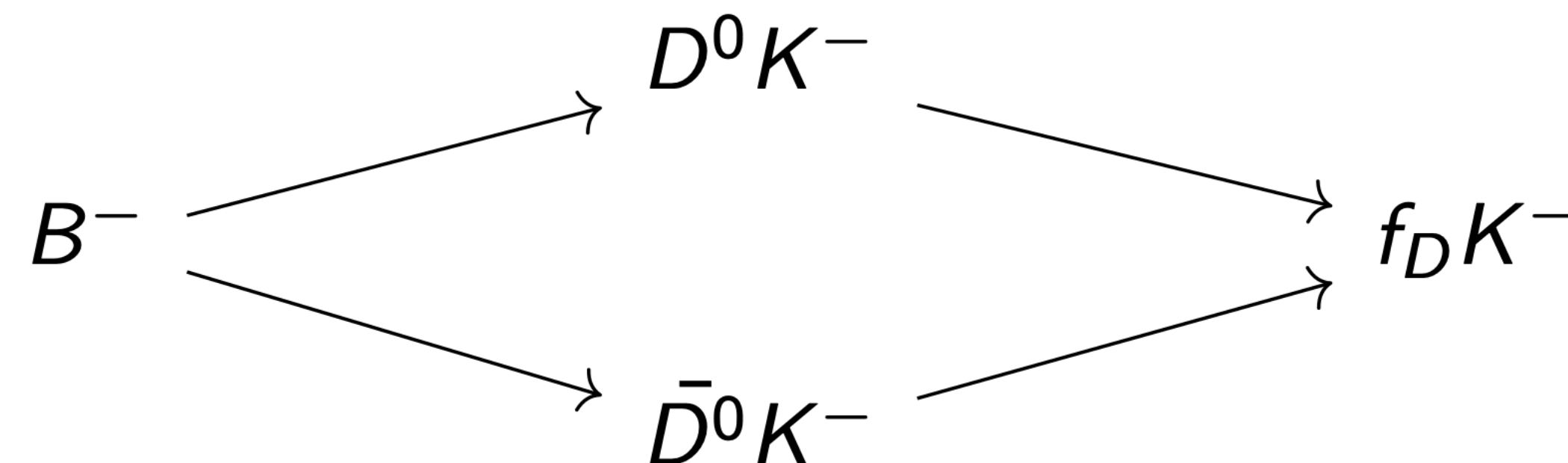
$$V_{\text{CKM}} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| e^{-i\beta} & -|V_{ts}| e^{i\beta_s} & |V_{tb}| \end{pmatrix} = \begin{pmatrix} \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet \end{pmatrix}$$



Favoured $B^- \rightarrow D^0 K^-$



CKM+colour suppressed $B^- \rightarrow \bar{D}^0 K^-$



We can write down the amplitudes

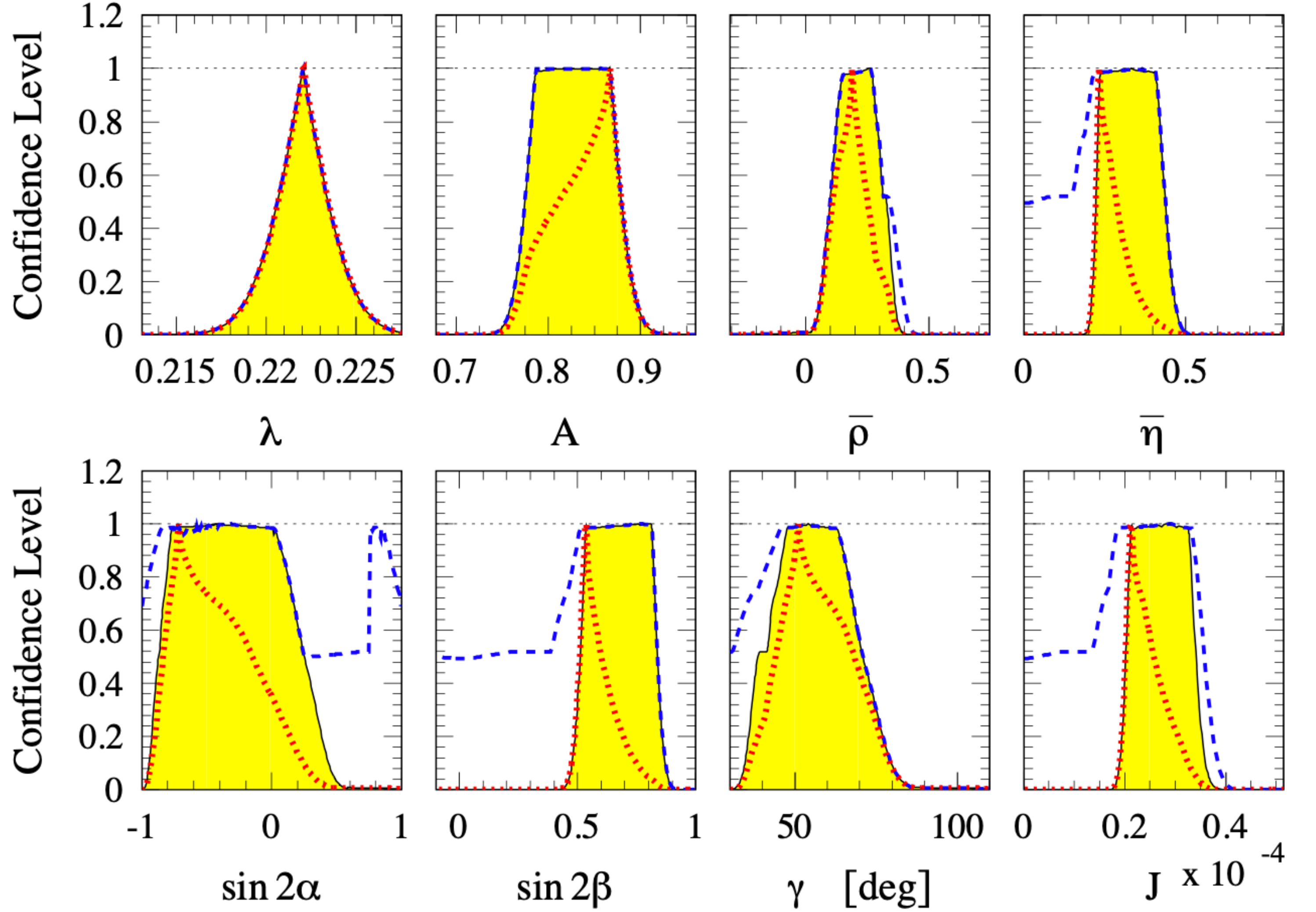
$$\mathcal{A}(B^-) = \mathcal{A}_B (\mathcal{A}_{D^0} + r_B e^{i(\delta_B - \gamma)} \mathcal{A}_{\bar{D}^0})$$

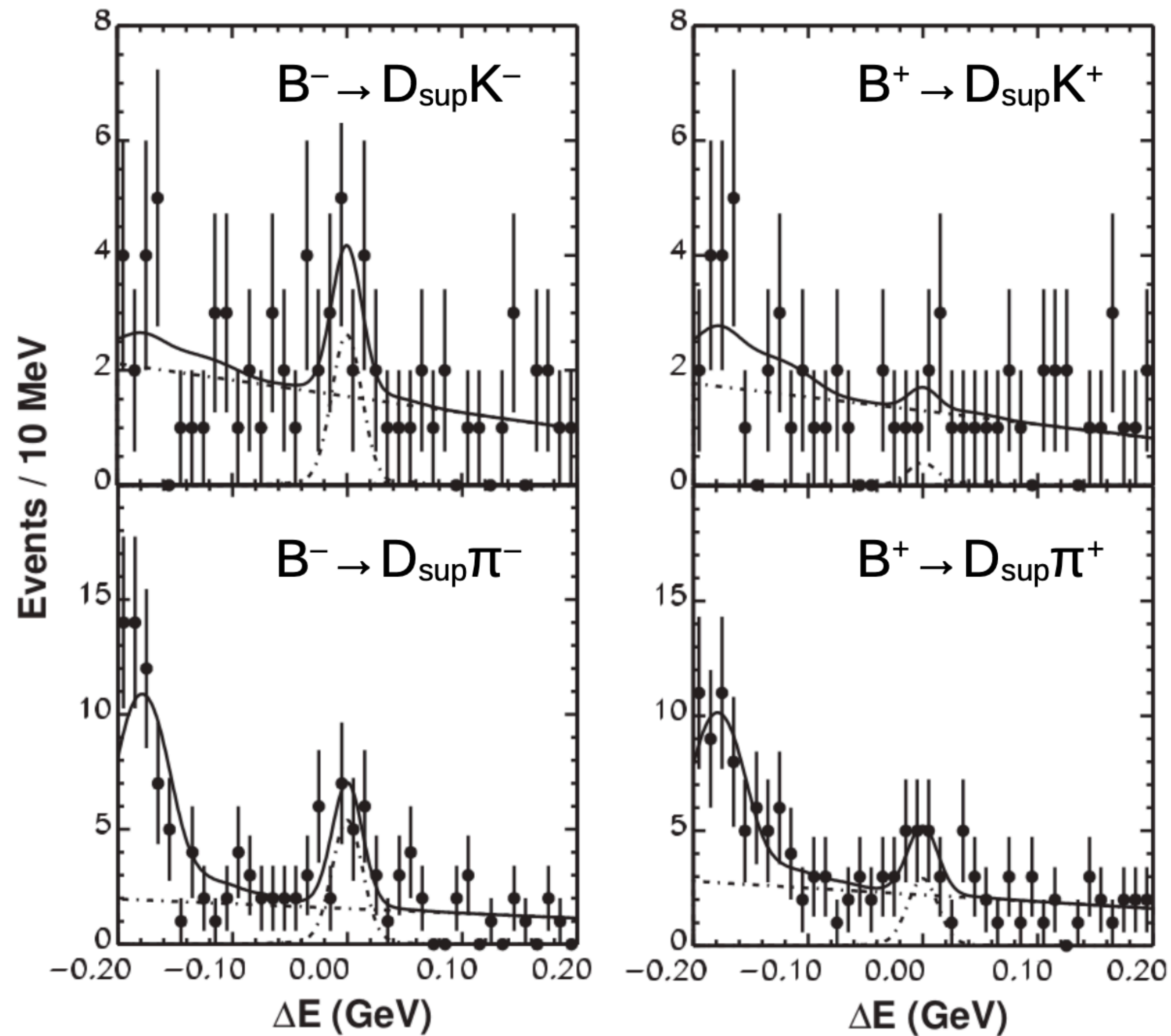
$$\mathcal{A}(B^+) = \mathcal{A}_B (\mathcal{A}_{\bar{D}^0} + r_B e^{i(\delta_B + \gamma)} \mathcal{A}_{D^0})$$

- r_B : The magnitude of the interferences
- δ_B : Strong phase difference, accounts for all unknown QCD phases
- γ : The weak phase, swaps under CP

Parameter	$\geq 32\%$ CL	half width	$\geq 5\%$ CL	half width	δ_{32}	δ_5
λ	0.2221 ± 0.0021		0.2221 ± 0.0041		0	0
A	0.782 - 0.888	0.053	0.758 - 0.906	0.074	10	3
$\bar{\rho}$	0.09 - 0.29	0.10	0.04 - 0.37	0.16	29	6
$\bar{\eta}$	0.22 - 0.32	0.05	0.21 - 0.42	0.11	58	21
J (10^{-5})	2.0 - 2.9	0.5	1.9 - 3.5	0.8	38	11
$\sin 2\alpha$	-0.88 - 0.04	0.46	-0.95 - 0.33	0.64	27	12
$\sin 2\beta$	0.50 - 0.67	0.09	0.47 - 0.81	0.17	50	19
α	$89^\circ - 121^\circ$	16°	$80^\circ - 126^\circ$	23°	27	12
β	$15.0^\circ - 21.0^\circ$	3.0°	$14.0^\circ - 27.0^\circ$	6.5°	59	25
$\gamma = \delta$	$42^\circ - 74^\circ$	16°	$34^\circ - 82^\circ$	24°	16	0
$\sin \theta_{12}$	0.2221 ± 0.0021		0.2221 ± 0.0041		0	0
$\sin \theta_{13}$ (10^{-3})	2.70 - 4.03	0.67	2.49 - 4.38	0.95	17	8
$\sin \theta_{23}$ (10^{-3})	38.4 - 43.2	2.4	38.0 - 43.6	2.8	0	0
$ V_{ud} $	0.97504 ± 0.00049		0.97504 ± 0.00094		0	0
$ V_{us} $	0.2221 ± 0.0021		0.2221 ± 0.0042		0	0
$ V_{ub} $ (10^{-3})	2.70 - 3.71	0.51	2.45 - 4.38	0.96	37	7
$ V_{cd} $	0.2220 ± 0.0021		0.2220 ± 0.0042		0	0
$ V_{cs} $	0.97414 ± 0.00049		0.97414 ± 0.00098		13	4
$ V_{cb} $ (10^{-3})	38.7 - 43.2	2.3	38.1 - 43.6	2.8	4	0
$ V_{td} $ (10^{-3})	7.2 - 9.2	1.0	6.6 - 9.6	1.5	23	6
$ V_{ts} $ (10^{-3})	38.0 - 42.7	2.4	37.4 - 43.1	2.9	8	3
$ V_{tb} $	0.99907 - 0.99926	9×10^{-5}	0.99905 - 0.99928	11×10^{-5}	10	8
Δm_s (ps^{-1})	15.5 - 33.7	9.1	15.0 - 41.3	13.1	0	3
$\text{BR}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu})$ (10^{-11})	1.2 - 2.6	0.7	1.1 - 3.8	1.4	50	13
$\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ (10^{-11})	6.6 - 9.5	1.5	5.4 - 10.4	2.5	35	14
$\text{BR}(B^+ \rightarrow \tau^+ \nu_\tau)$ (10^{-5})	4.6 - 12.4	3.9	3.6 - 21.0	8.7	49	13
$\text{BR}(B^+ \rightarrow \mu^+ \nu_\mu)$ (10^{-7})	1.8 - 4.9	1.6	1.4 - 8.3	3.5	48	10
$f_{B_d} \sqrt{B_d}$ (MeV)	194 - 246	26	185 - 272	44	33	12
B_K	> 0.72		> 0.55		31	10
m_t (GeV)	124 - 406	141	102 - 550	224	6	5

Table 3: Fit results including the world average on $\sin 2\beta_{\text{WA}}$. As in Table 2, ranges are given for the quantities that are limited by systematic theoretical errors. The two right columns give the relative improvements (in percent) of the $\geq 32\%$ CL and $\geq 5\%$ CL half widths with respect to the fit results without $\sin 2\beta$ given in Tab. 2. The last three lines give the ranges obtained for chosen theoretical parameters when removing their respective bounds in the fit.





ADS technique

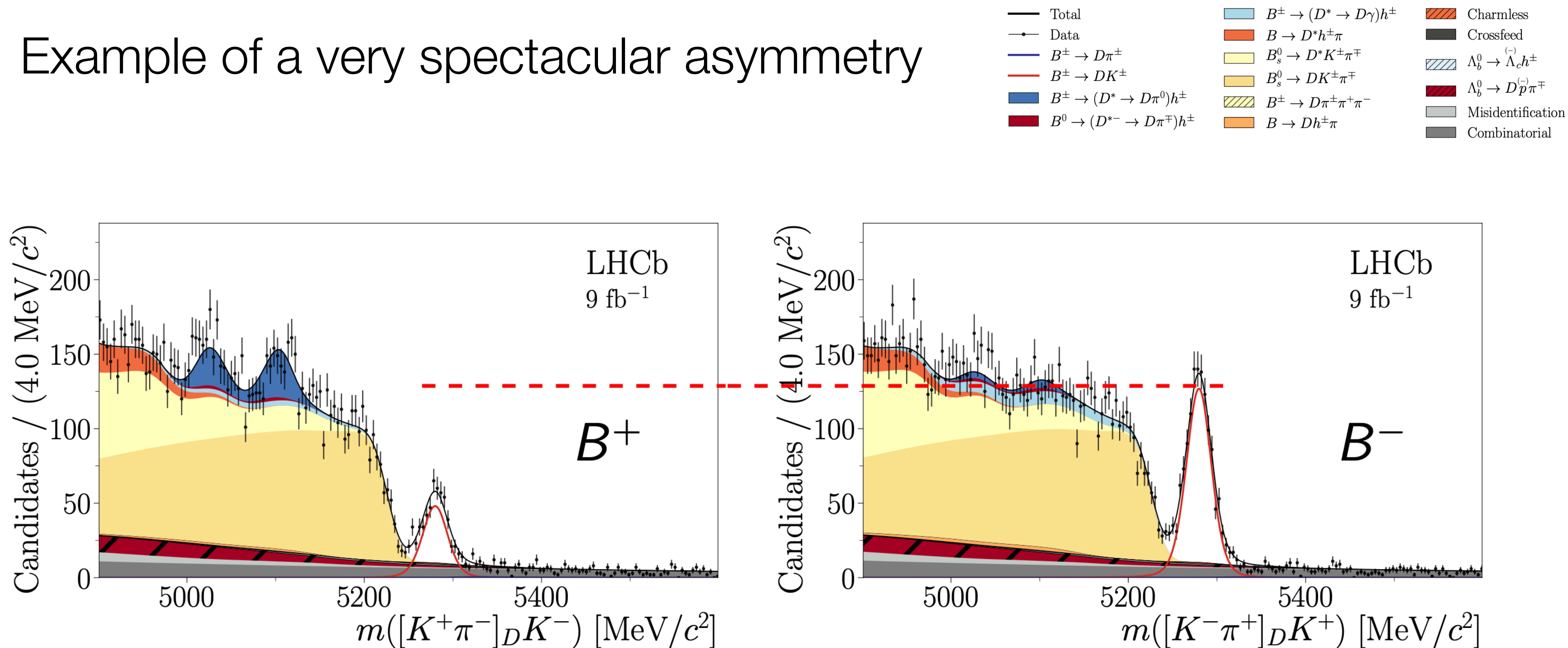
$$\mathcal{A}_{DK} = 0.88^{+0.77}_{-0.62}(\text{stat}) \pm 0.06(\text{syst}),$$

$$\mathcal{A}_{D\pi} = 0.30^{+0.29}_{-0.25}(\text{stat}) \pm 0.06(\text{syst}),$$

Here, both $B \rightarrow Dh$ peak at 0 when correctly identified

Belle, PRL 94 (2005) 091601

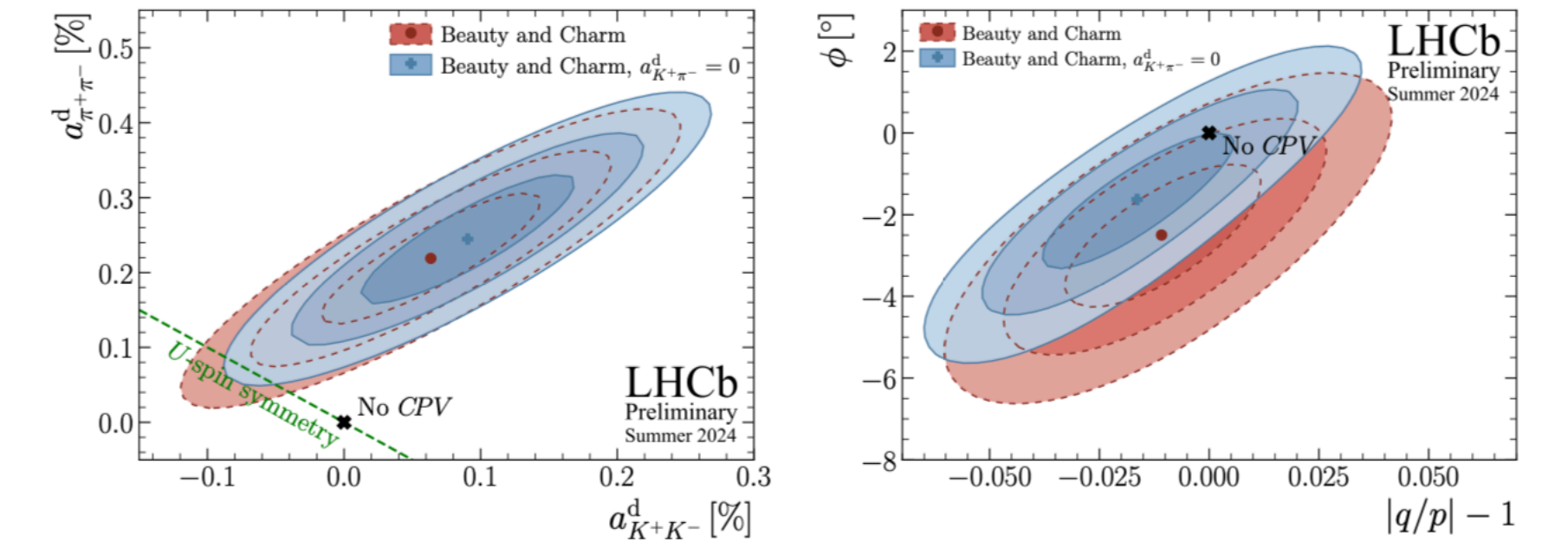
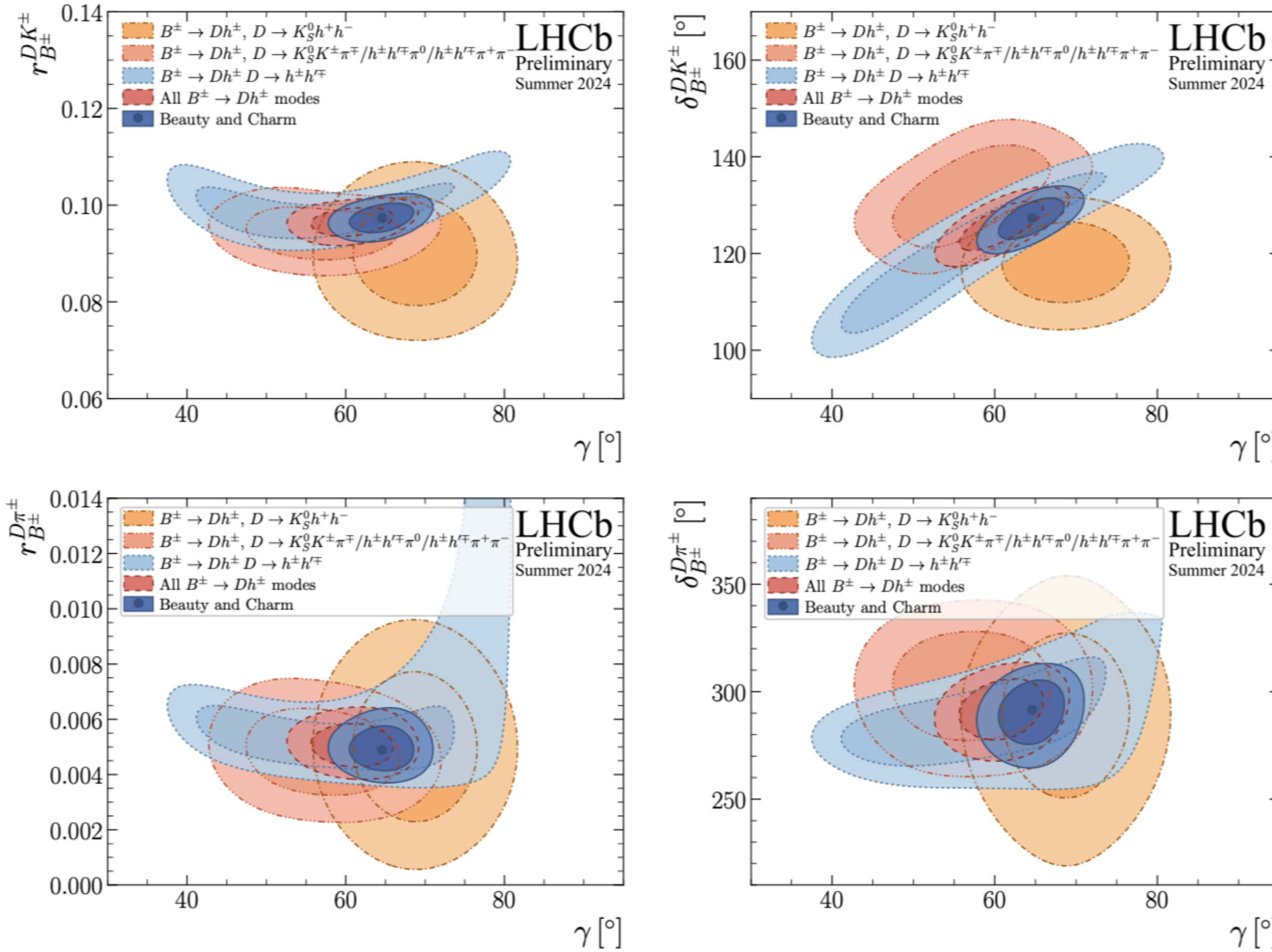
Example of a very spectacular asymmetry



LHCb, JHEP 04 (2021) 081

Just drawing a line does not do justice to this work

Putting everything together



Importance of charm inputs

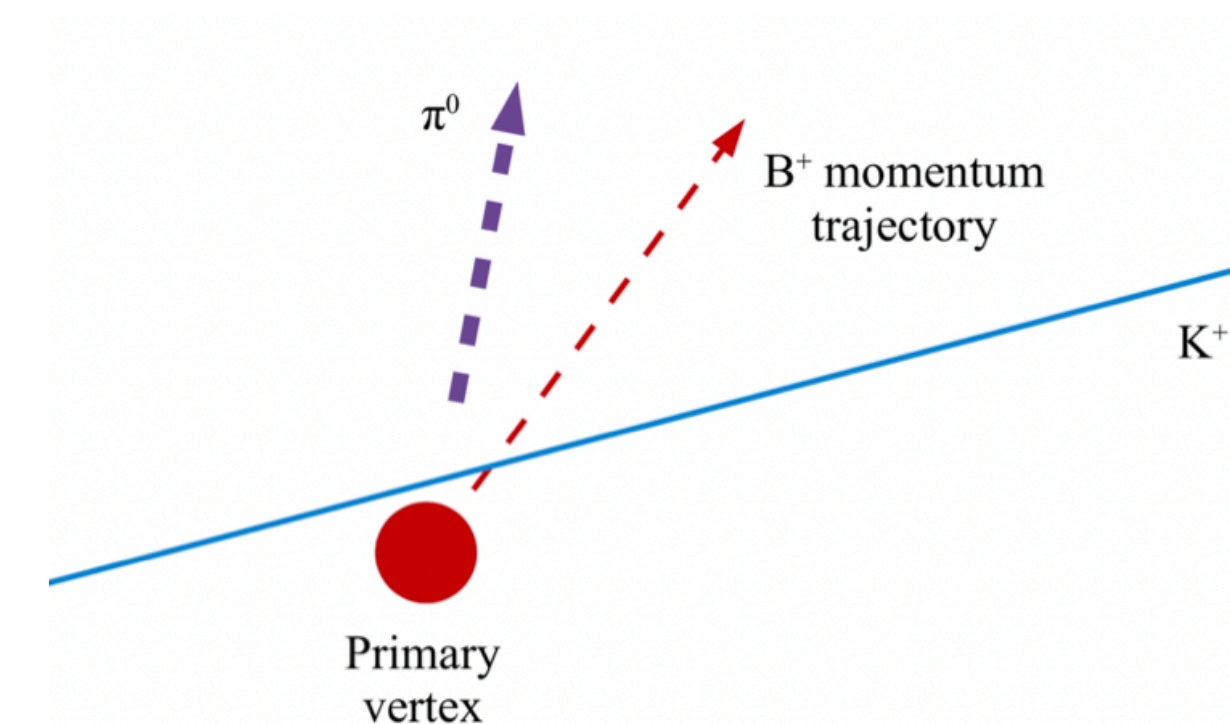
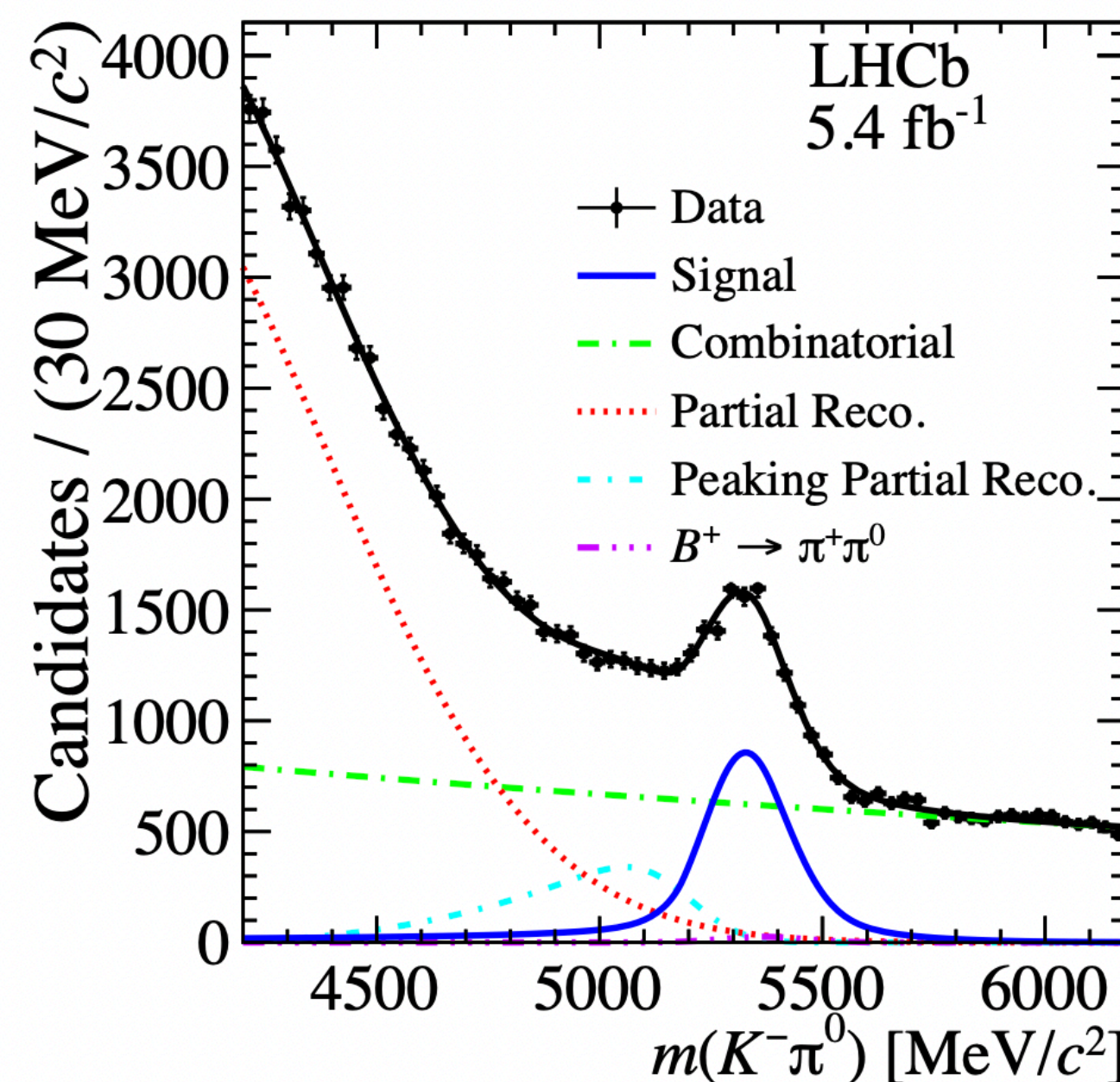
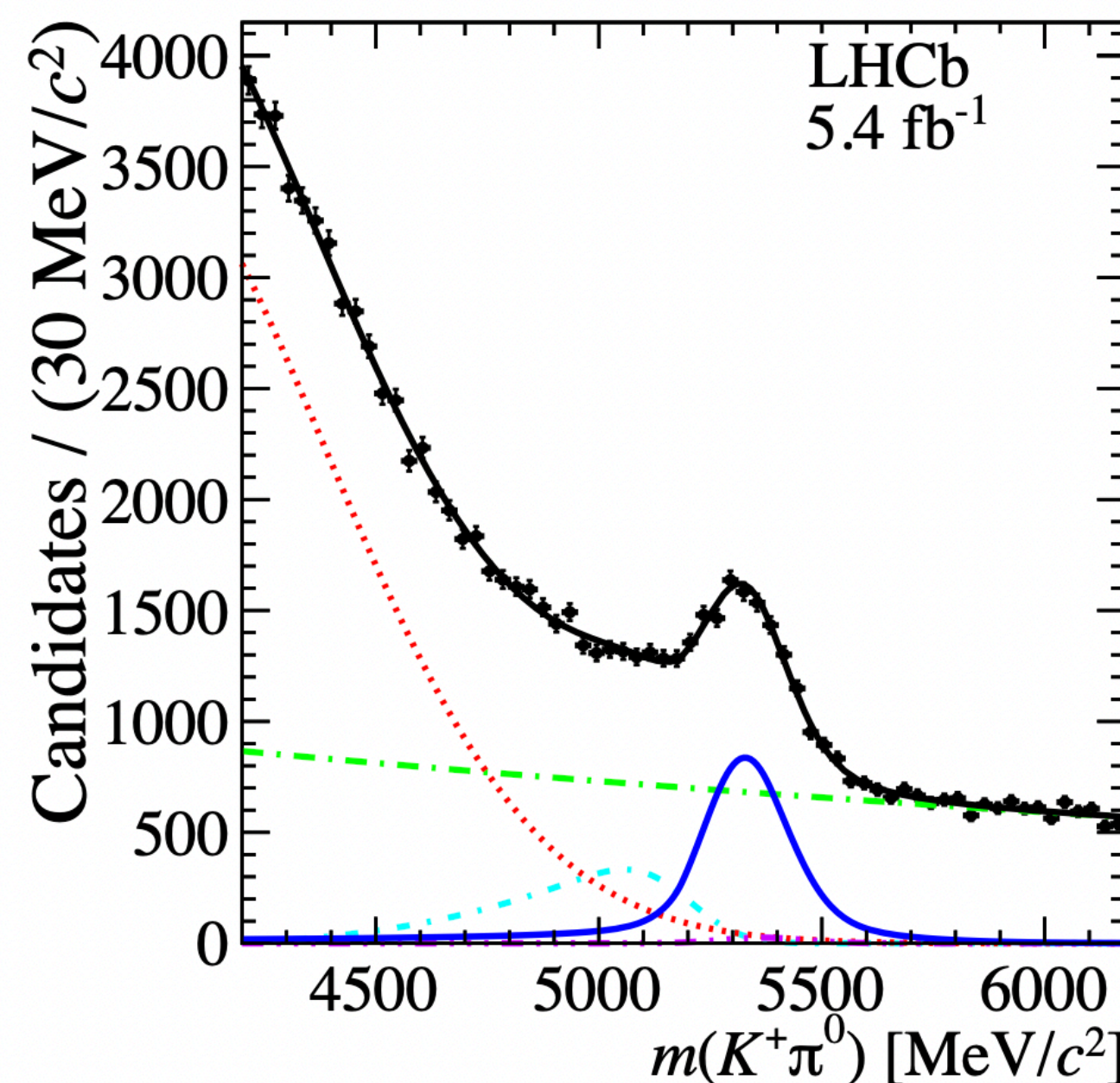
	γ	$r_{B^\pm}^{DK^\pm}$	$\delta_{B^\pm}^{DK^\pm}$	$r_{B^\pm}^{D\pi^\pm}$	$\delta_{B^\pm}^{D\pi^\pm}$	$r_D^{K\pi}$	$\delta_D^{K\pi}$	x	y	$ q/p $	ϕ	$a_{K^+K^-}^d$	$a_{\pi^+\pi^-}^d$	$a_{K^+\pi^-}^d$
γ	1.00	0.36	0.62	-0.02	0.19	-	-	-	-	-	-	-	-	-
$r_{B^\pm}^{DK^\pm}$		1.00	0.21	-	0.07	-0.04	-0.10	0.02	-0.08	-	-	-	-	-
$\delta_{B^\pm}^{DK^\pm}$			1.00	-0.04	0.18	-0.11	-0.39	0.06	-0.32	-	-0.01	-	-	0.02
$r_{B^\pm}^{D\pi^\pm}$				1.00	0.57	0.04	0.02	-	0.01	-	-	-	-	-
$\delta_{B^\pm}^{D\pi^\pm}$					1.00	0.01	-0.13	0.02	-0.11	-	-	-	-	-
$r_D^{K\pi}$						1.00	0.29	0.18	-0.07	-0.04	0.01	-	-	-0.02
$\delta_D^{K\pi}$							1.00	-0.05	0.84	-	0.04	-0.02	-0.02	-0.05
x								1.00	0.22	-0.09	0.09	0.01	-	-
y									1.00	-0.04	0.04	-0.01	-0.01	-0.06
$ q/p $										1.00	0.72	0.11	0.10	-0.16
ϕ											1.00	-0.04	-0.04	0.33
$a_{K^+K^-}^d$												1.00	0.87	0.22
$a_{\pi^+\pi^-}^d$													1.00	0.20
$a_{K^+\pi^-}^d$														1.00

LHCb-CONF-2024-004

Consistent analyses

An other example of a direct CP violation measurement

$$A_{CP} = \frac{\Gamma(B^- \rightarrow K^- \pi^0) - \Gamma(B^+ \rightarrow K^+ \pi^0)}{\Gamma(B^- \rightarrow K^- \pi^0) + \Gamma(B^+ \rightarrow K^+ \pi^0)}$$



$$A_{CP}(B^+ \rightarrow K^+ \pi^0) = 0.025 \pm 0.015 \pm 0.006 \pm 0.003,$$

Consistent with the world average

[ARXIV:2012.12789](https://arxiv.org/abs/2012.12789)

Part of the $K\pi$ puzzle expressed via this sum rule

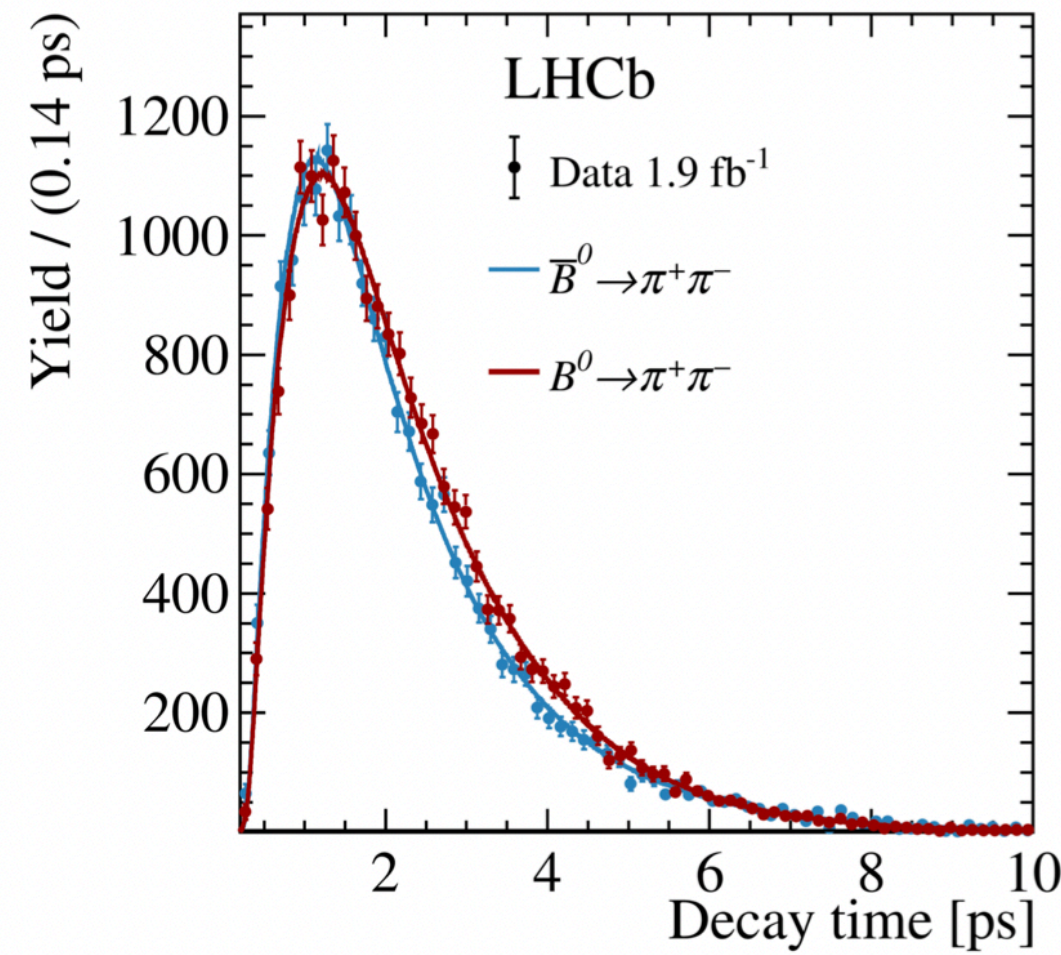
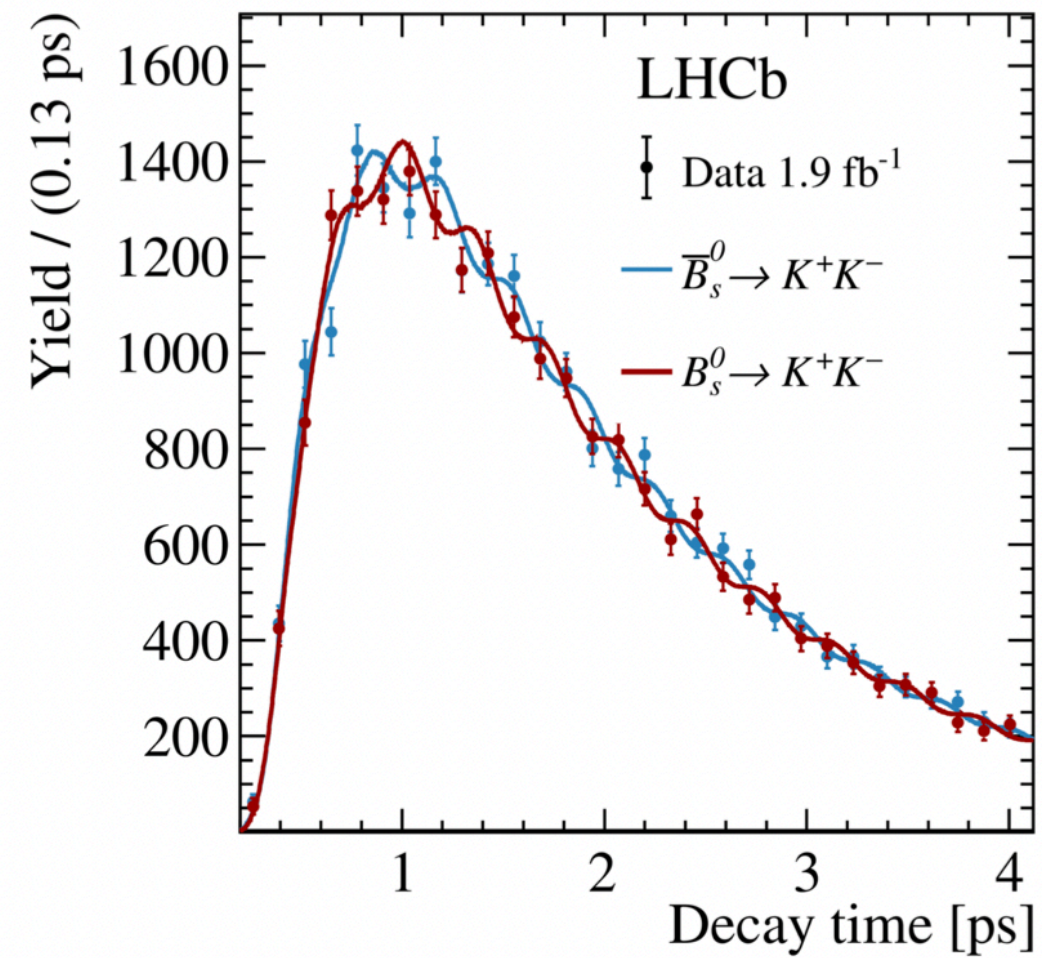
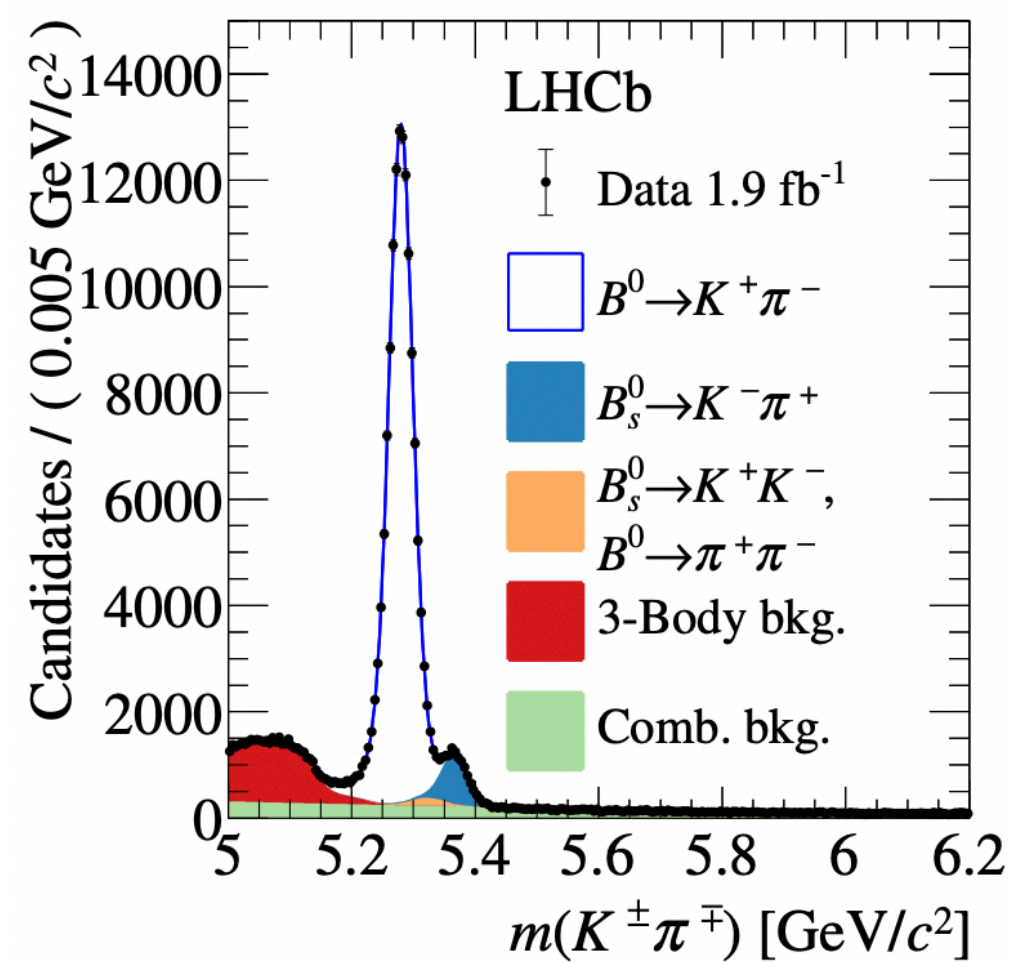
$$A_{CP}(K^+ \pi^-) + A_{CP}(K^0 \pi^+) \frac{\mathcal{B}(K^0 \pi^+)}{\mathcal{B}(K^+ \pi^-)} \frac{\tau_0}{\tau_+} = A_{CP}(K^+ \pi^0) \frac{2\mathcal{B}(K^+ \pi^0)}{\mathcal{B}(K^+ \pi^-)} \frac{\tau_0}{\tau_+} + A_{CP}(K^0 \pi^0) \frac{2\mathcal{B}(K^0 \pi^0)}{\mathcal{B}(K^+ \pi^-)}$$

B → hh

$$A_{CP}(t) = \frac{\Gamma_{\bar{B}_{(s)}^0 \rightarrow f}(t) - \Gamma_{B_{(s)}^0 \rightarrow f}(t)}{\Gamma_{\bar{B}_{(s)}^0 \rightarrow f}(t) + \Gamma_{B_{(s)}^0 \rightarrow f}(t)} = \frac{-C_f \cos(\Delta m_{d(s)} t) + S_f \sin(\Delta m_{d(s)} t)}{\cosh\left(\frac{\Delta \Gamma_{d(s)}}{2} t\right) + A_f^{\Delta \Gamma} \sinh\left(\frac{\Delta \Gamma_{d(s)}}{2} t\right)},$$

An important quantity to control is detector asymmetries $A_{\text{det}}^{K\pi} = A_{\text{RAW}}^{K\pi\pi} - A_{\text{RAW}}^{\bar{K}^0\pi} - A_{\text{det}}^{K^0}$.

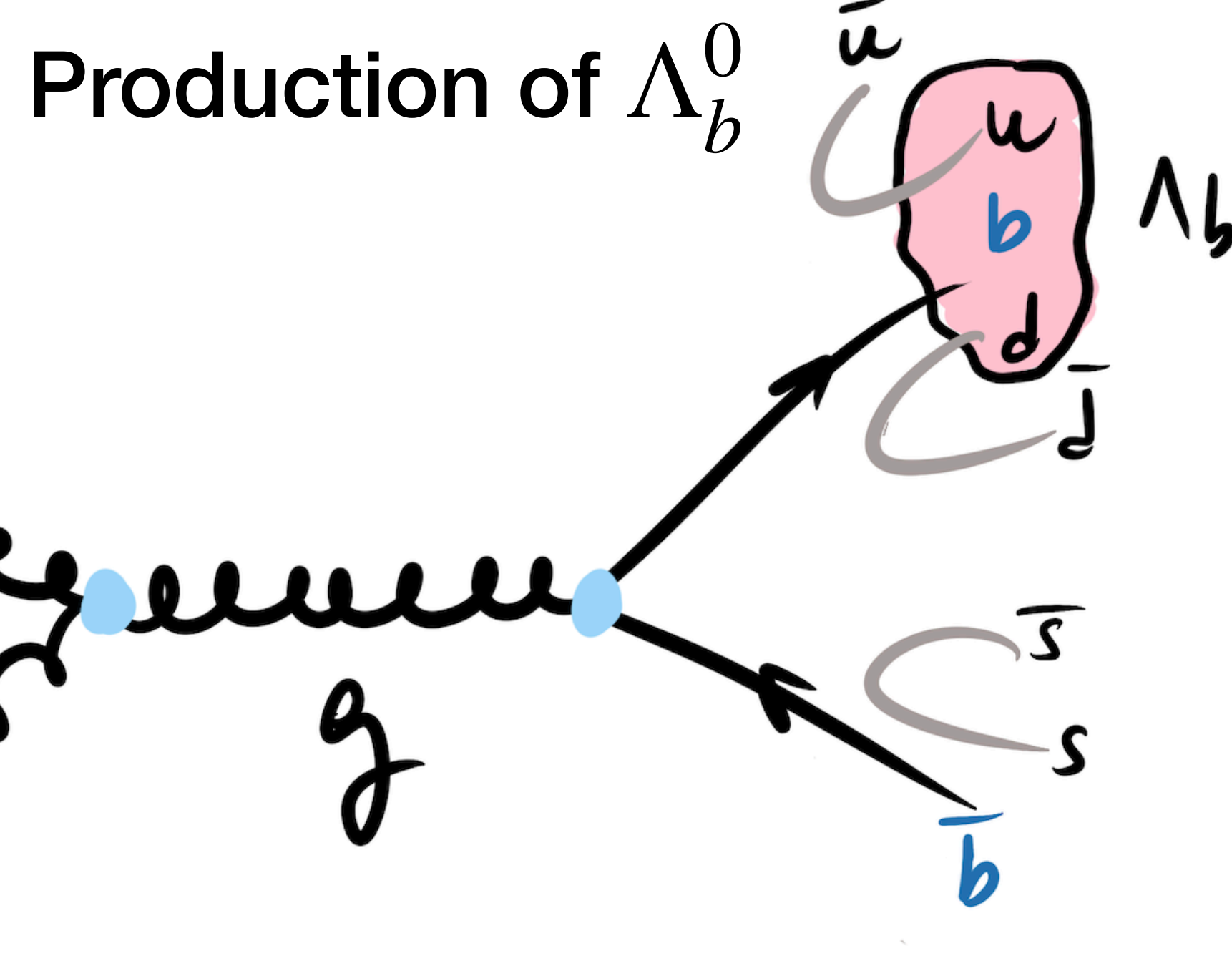
Analyses that explore U spin symmetry



$$\begin{aligned} C_{\pi\pi} &= -0.320 \pm 0.038, \\ S_{\pi\pi} &= -0.672 \pm 0.034, \\ A_{CP}^{B^0} &= -0.0831 \pm 0.0034, \\ A_{CP}^{B_s^0} &= 0.225 \pm 0.012, \\ C_{KK} &= 0.172 \pm 0.031, \\ S_{KK} &= 0.139 \pm 0.032, \\ \mathcal{A}_{KK}^{\Delta\Gamma} &= -0.897 \pm 0.087 \end{aligned}$$

This constitutes the first observation of time-dependent CP violation in decays of the B_s meson.

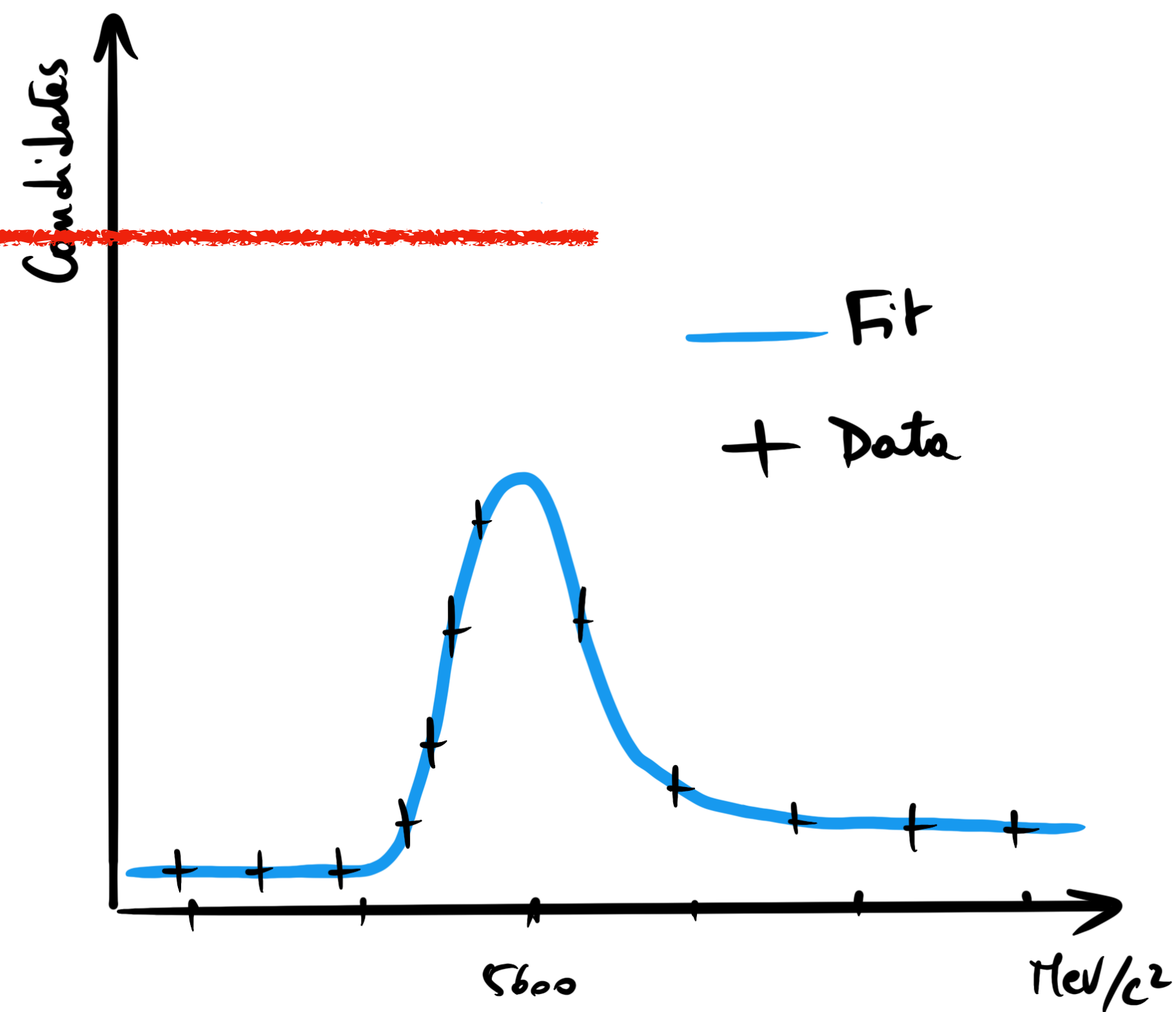
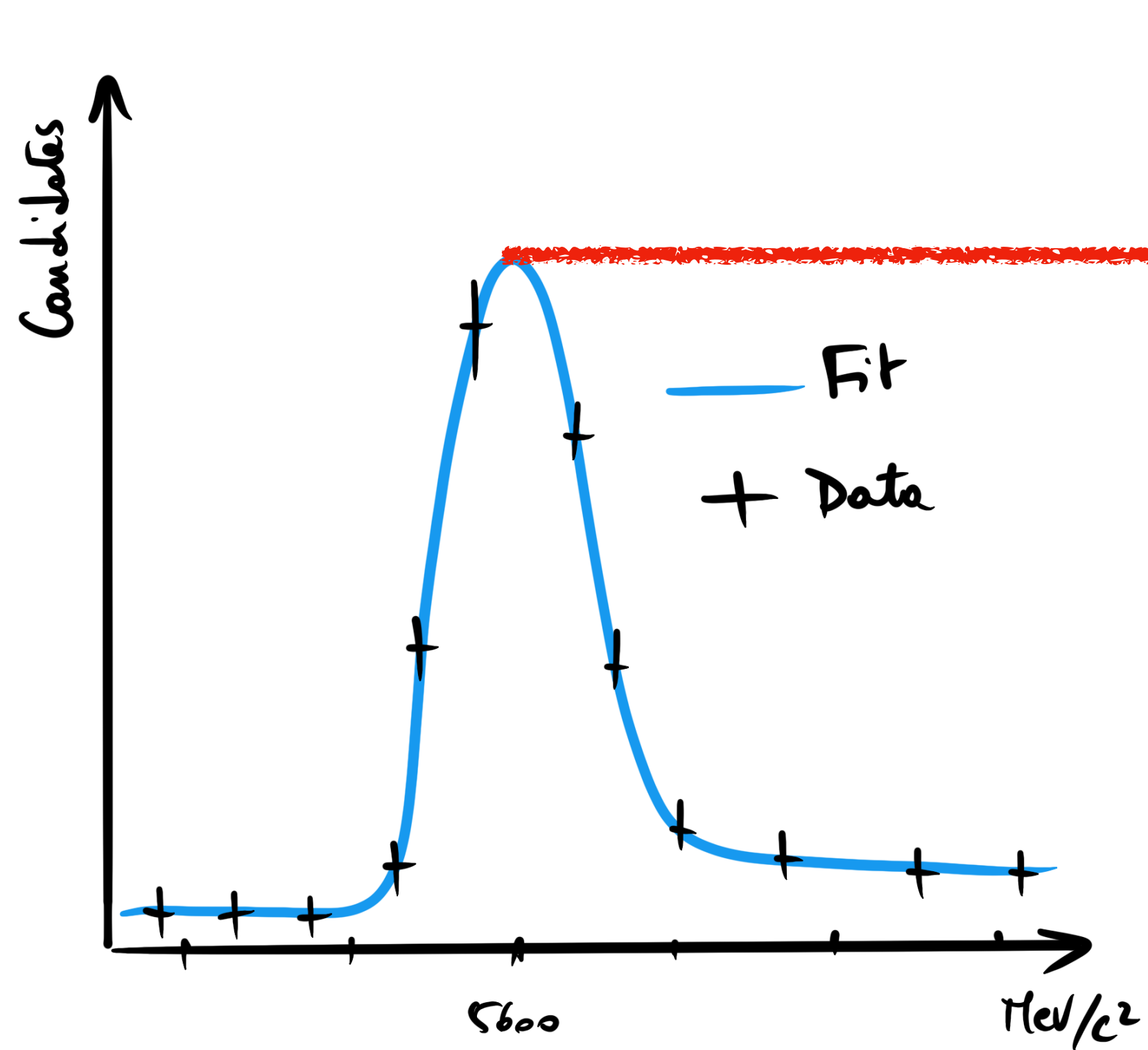
Observation of charge-parity symmetry breaking in baryon decays



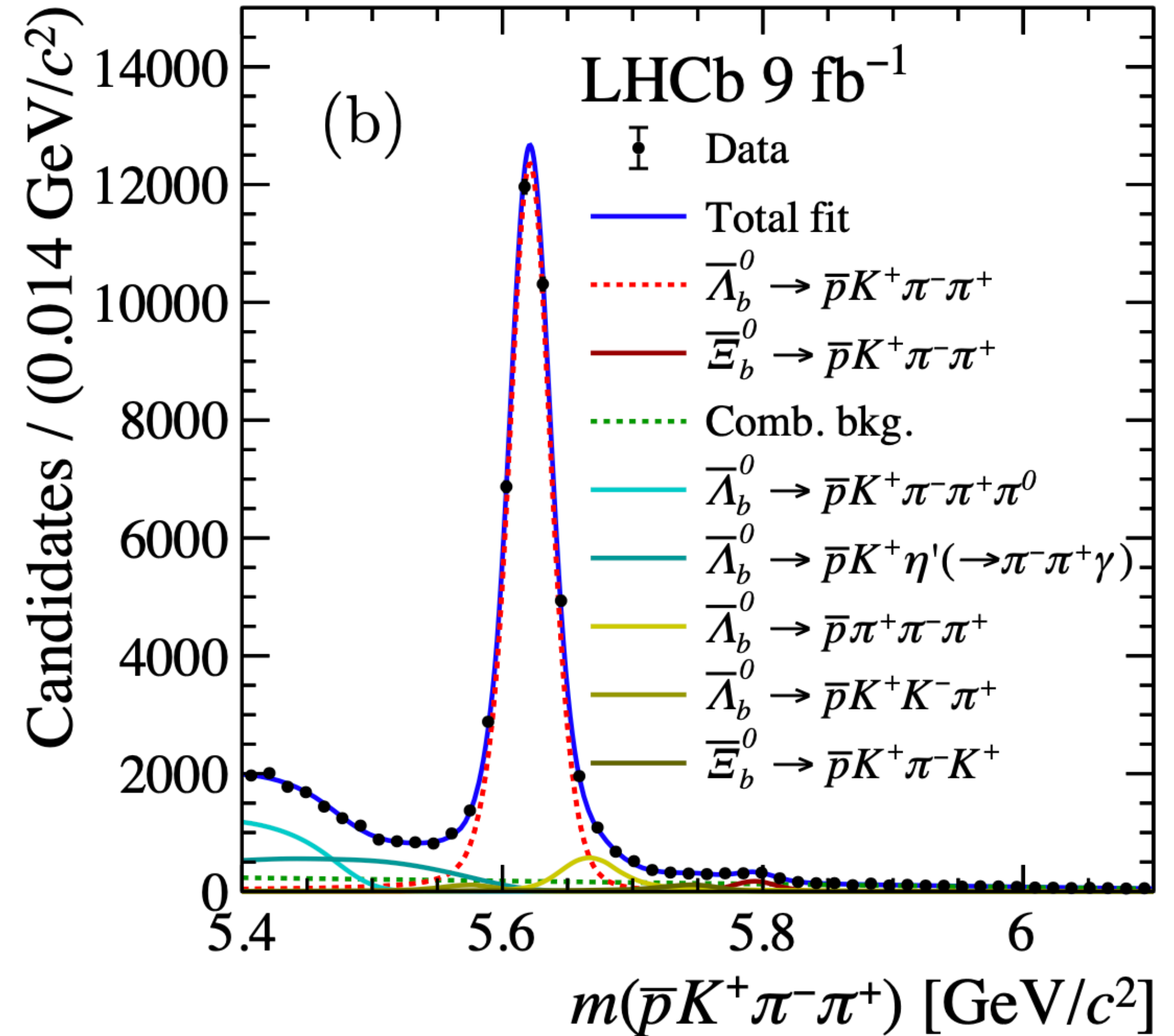
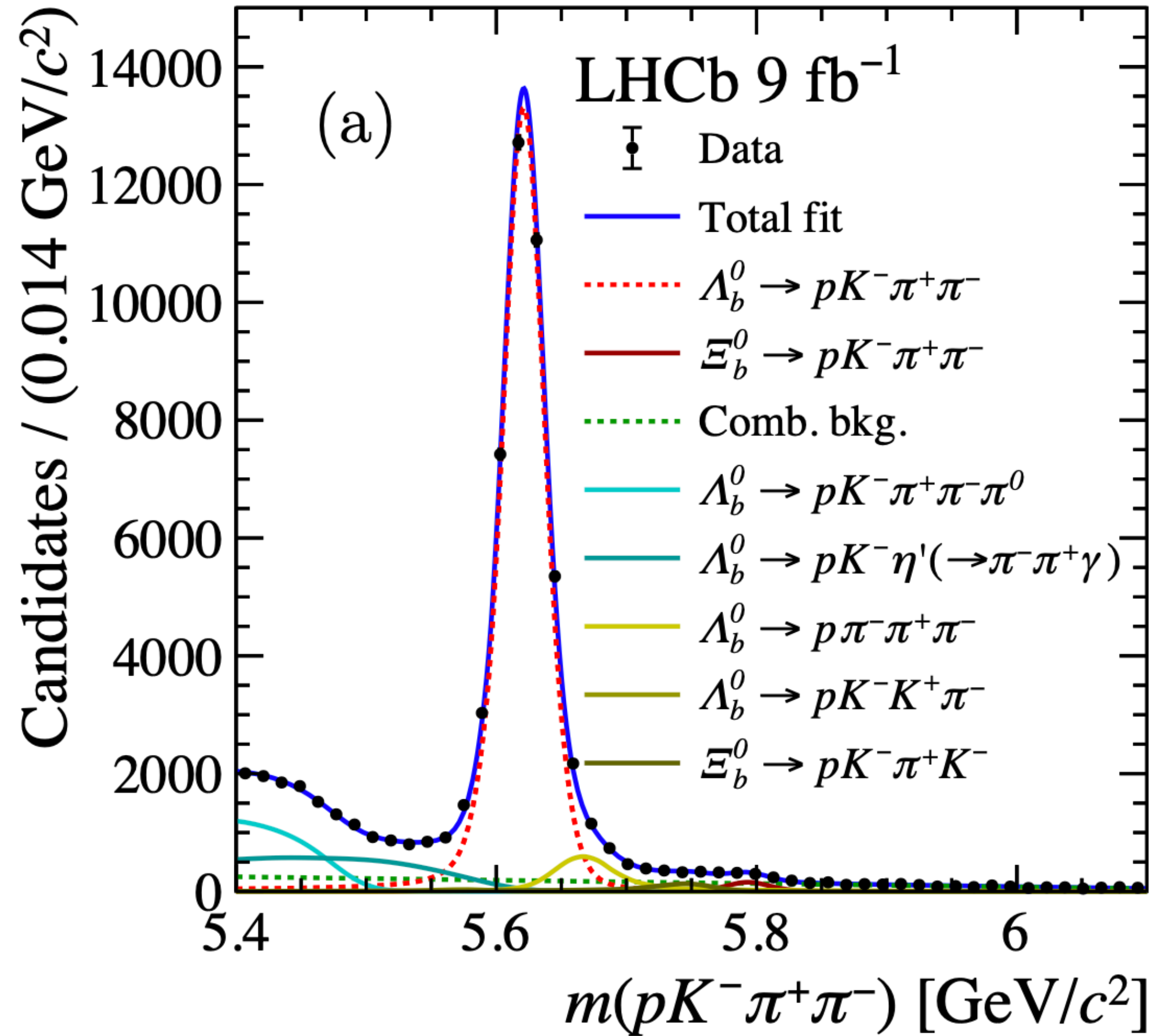
Expression of the asymmetry

$$A_{CP}^f = \frac{\Gamma(\Lambda_b^0 \rightarrow f) - \Gamma(\bar{\Lambda}_b^0 \rightarrow \bar{f})}{\Gamma(\Lambda_b^0 \rightarrow f) + \Gamma(\bar{\Lambda}_b^0 \rightarrow \bar{f})}$$

$$A_{\text{Raw}}^f = \frac{N(\Lambda_b^0 \rightarrow f) - N(\bar{\Lambda}_b^0 \rightarrow \bar{f})}{N(\Lambda_b^0 \rightarrow \bar{f}) + N(\bar{\Lambda}_b^0 \rightarrow f)}$$



Signal mode



Very pure selection & careful modelling of the backgrounds

From Raw to CP observable

$$A_{CP}^f = A_{Raw}^f - A_P^{f, \Lambda_b^0} - A_D^f$$

Production asymmetry

$$A_P^{f, \Lambda_b^0} = \frac{\sigma(\Lambda_b^0) - \sigma(\bar{\Lambda}_b^0)}{\sigma(\Lambda_b^0) + \sigma(\bar{\Lambda}_b^0)}$$

Detection asymmetry

$$A_D^f = \frac{\epsilon(f) - \epsilon(\bar{f})}{\epsilon(f) + \epsilon(\bar{f})}$$

$$A_{CP}^c = A_{Raw}^c - A_P^{c, \Lambda_b^0} - A_D^c \rightarrow$$

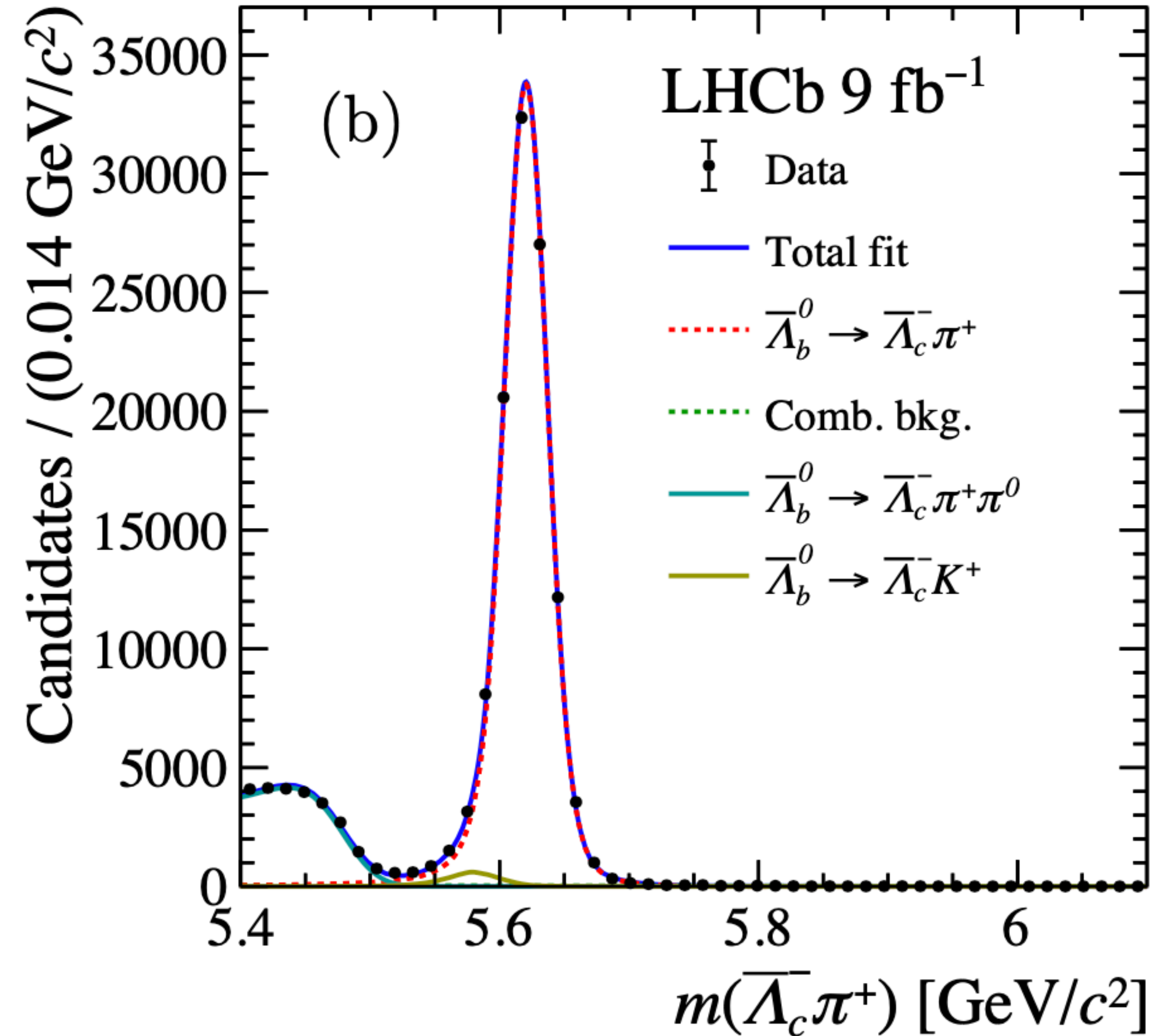
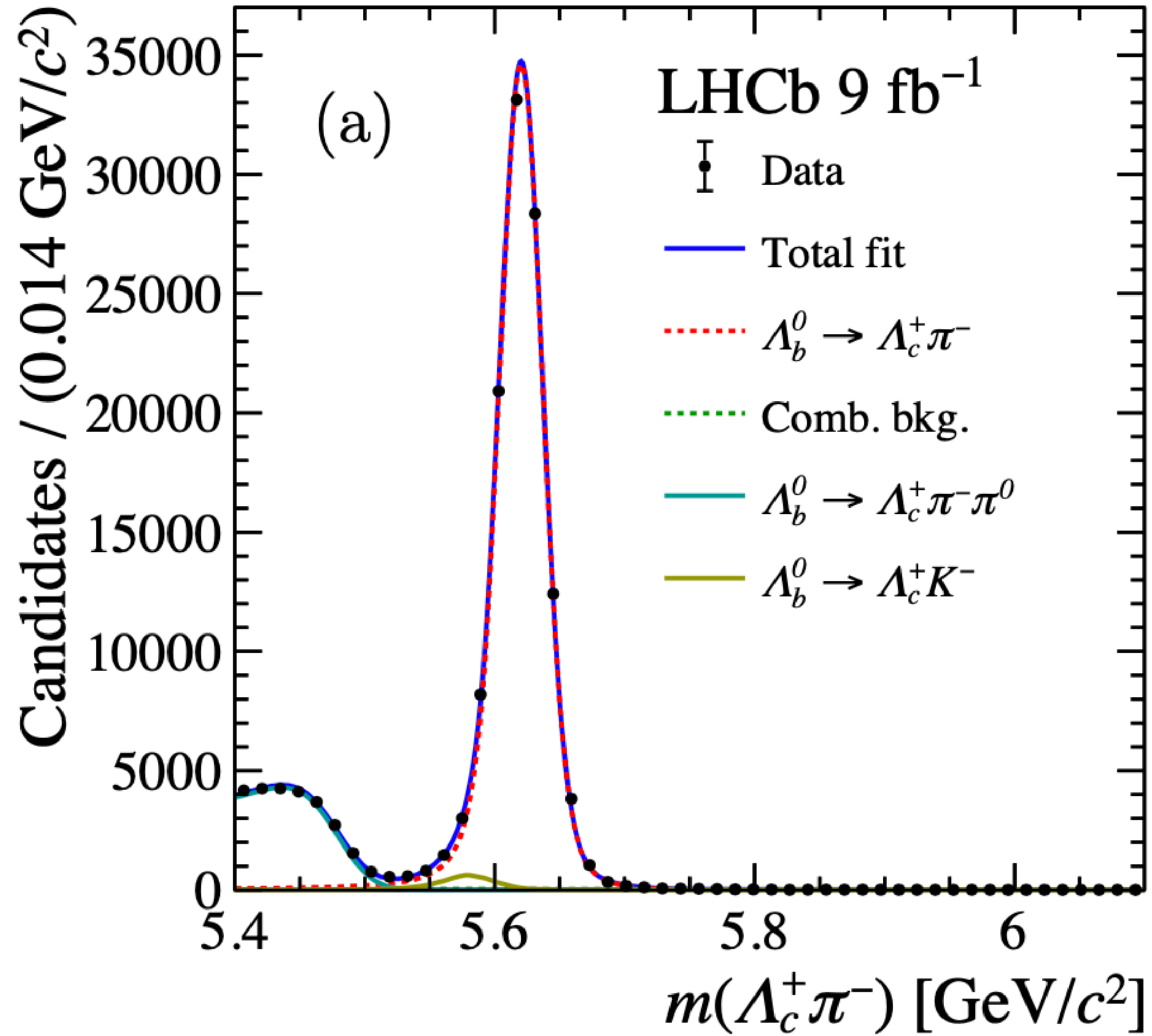
Measured for the control mode for which

$$A_{CP} \sim 0$$

$$A_{CP}^f = A_{Raw}^f - A_P^{f, \Lambda_b^0} - A_D^f \rightarrow$$

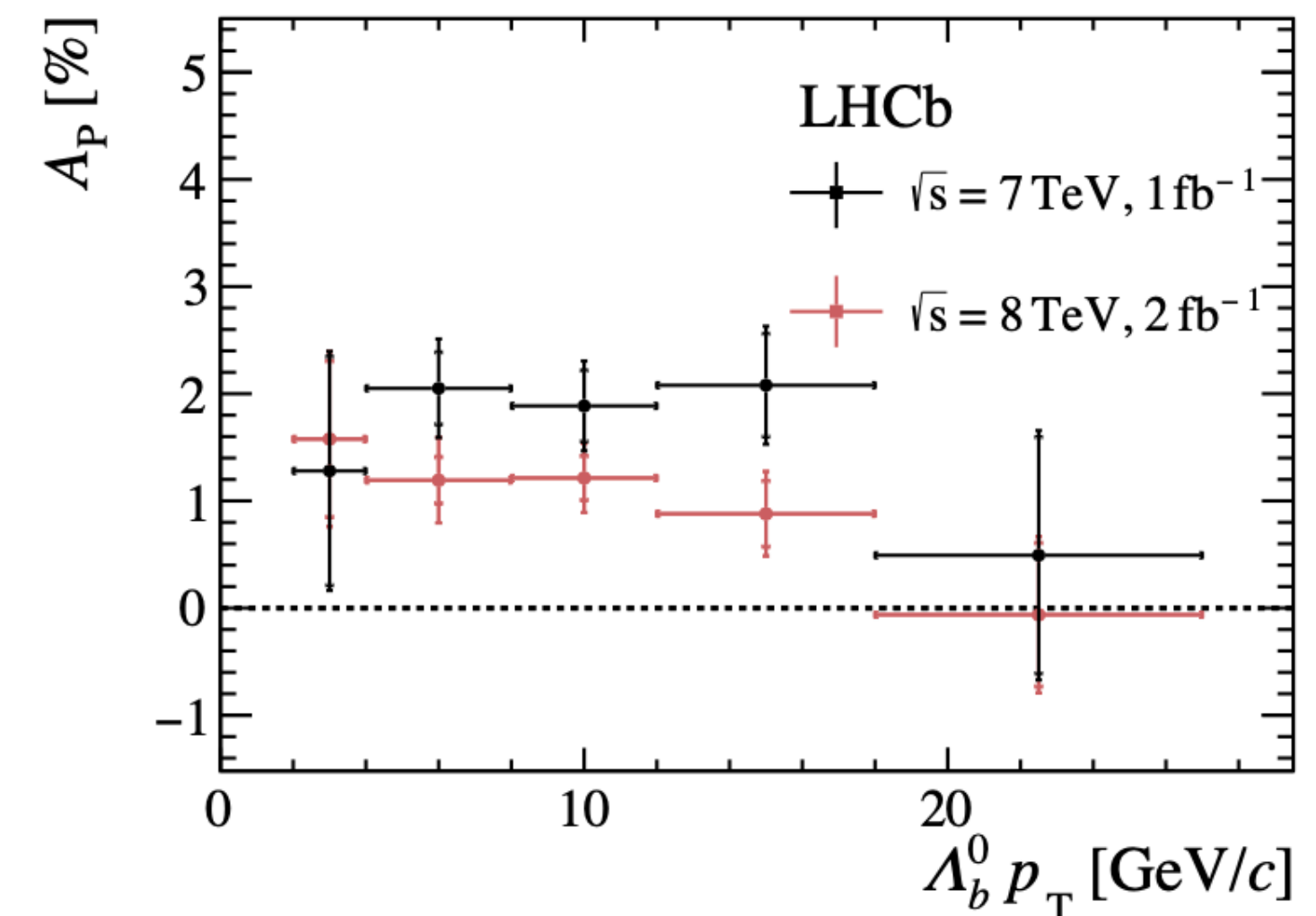
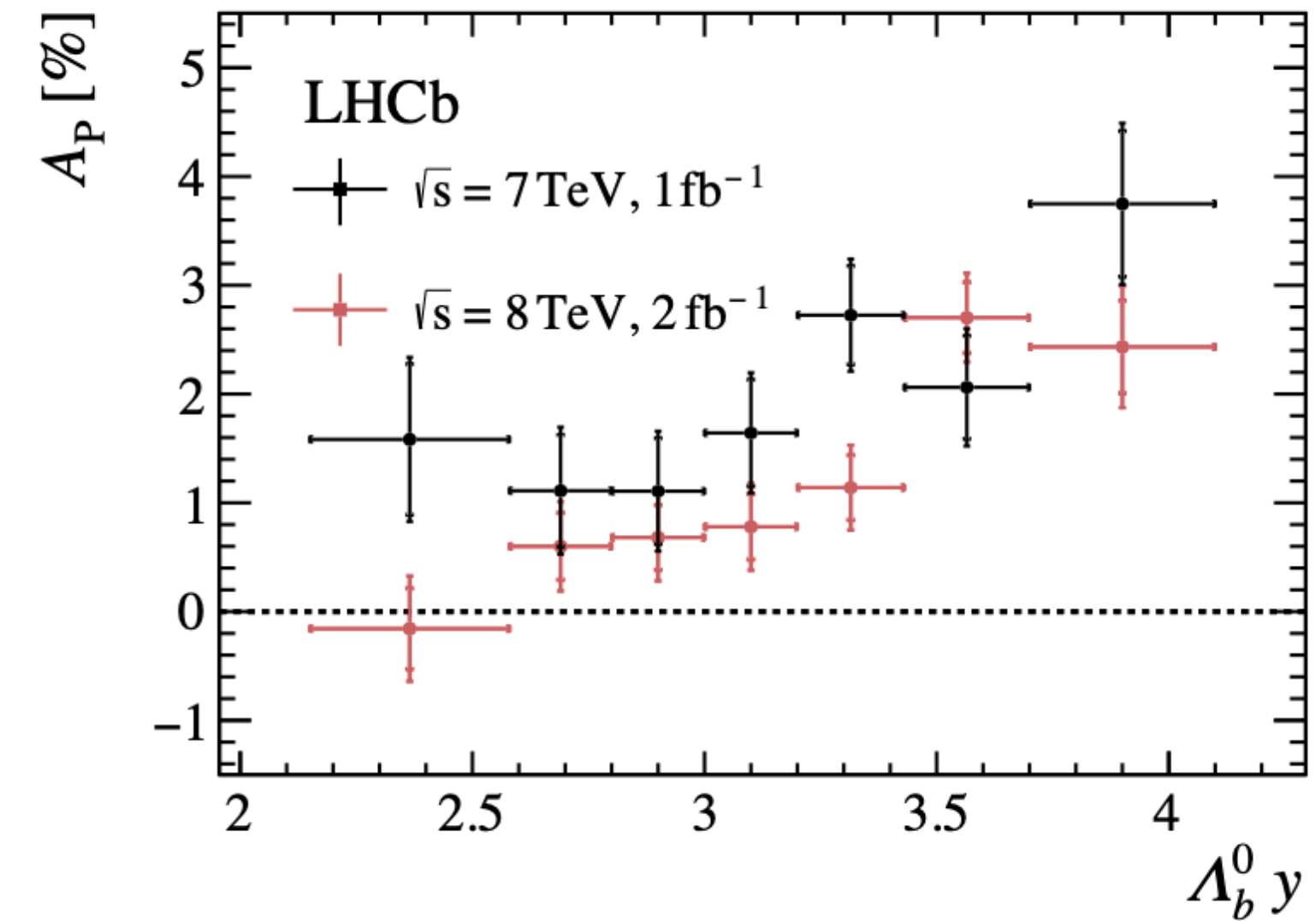
Measured for the signal

Control mode



Production asymmetries

- Production asymmetry dominated by gluon fusion.
- Hadronization asymmetry of Λ_b^0 and $\bar{\Lambda}_b^0$ in pp collisions.
- A_p 1-2% measured by LHCb as a function of kinematics.
- ΔA_p vanishes



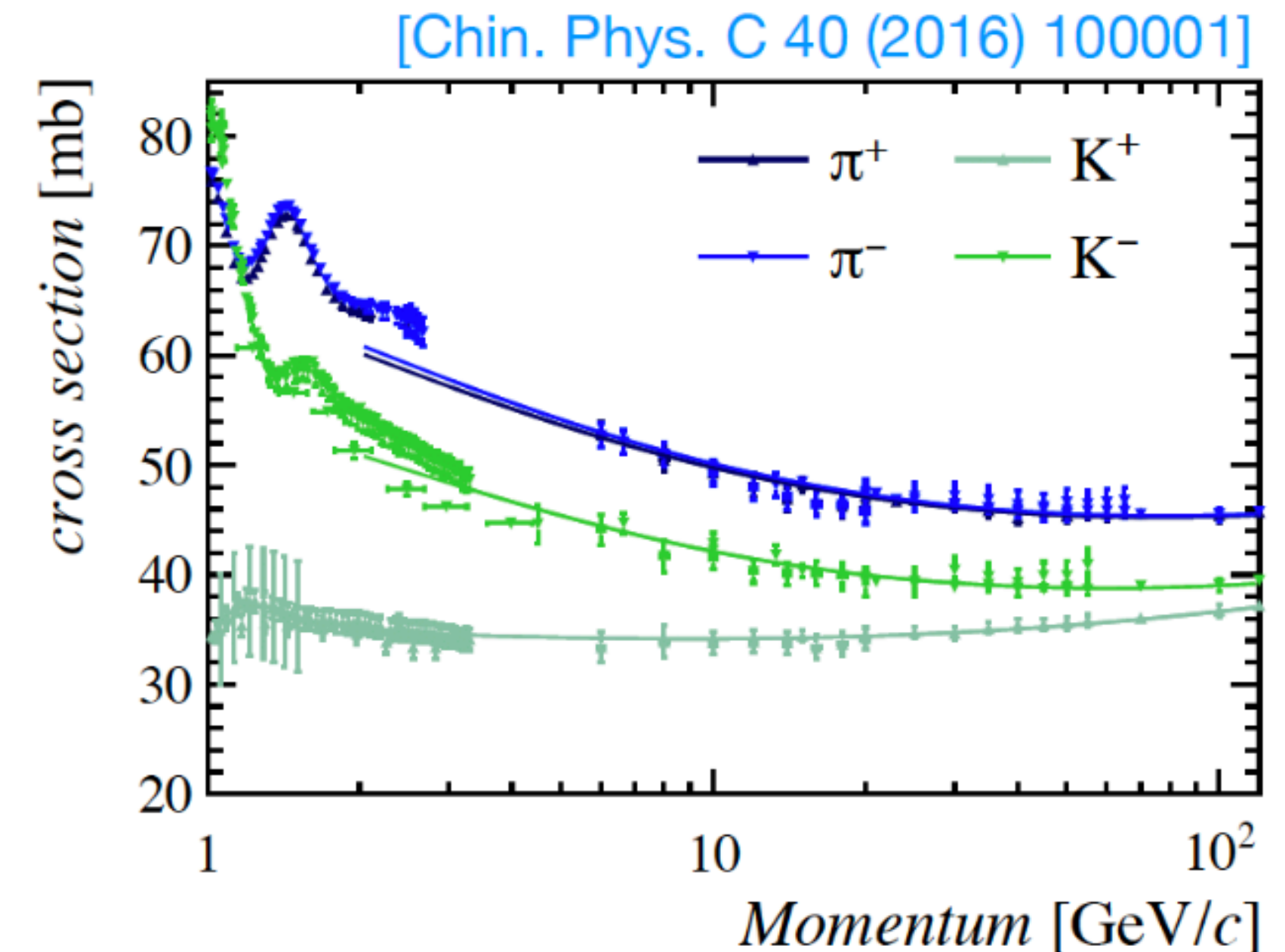
Detector asymmetries

Matter, antimatter interact with detector (made by matter) differently

- f : different combinations of p , K , π etc.
- Including effects from reconstruction of particles, PID, trigger effects

Obtained using data-driven method with calibration channels

$$A_D(\pi^\pm) \approx 0.1\%, A_D(K^\pm) \approx 1\%, A_D(p/\bar{p}) \approx 1 - 2\%$$



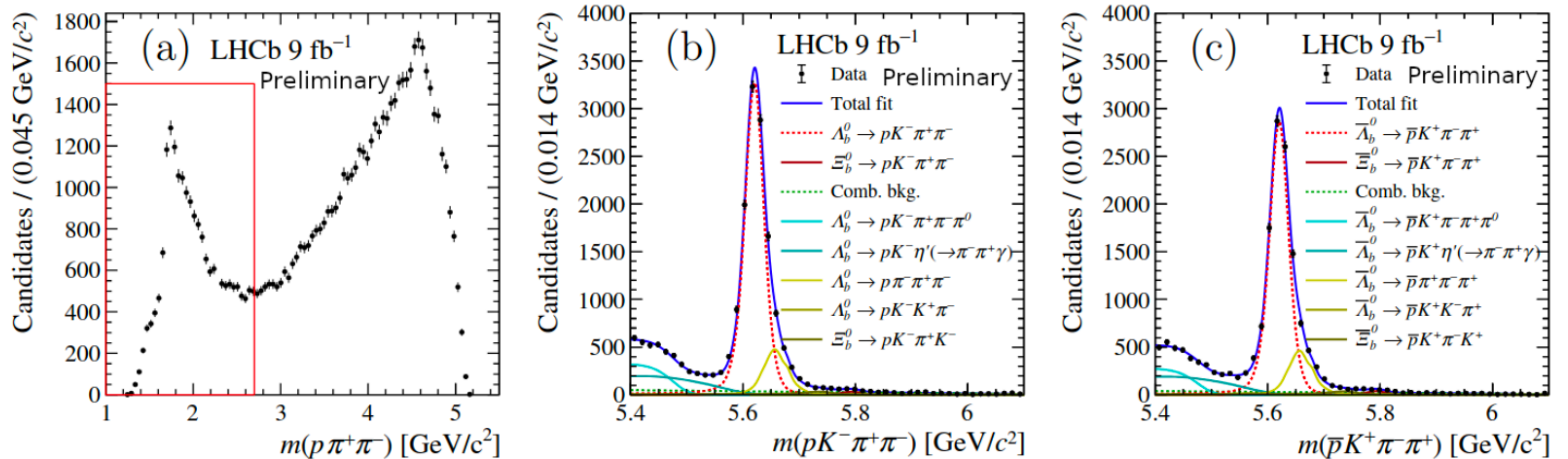
- ΔA_D vanishes

Putting everything together

$$\mathcal{A}_{CP} = (2.45 \pm 0.46 \pm 0.10)\% .$$

This CP asymmetry differs from zero by 5.2 standard deviations, marking the observation of CP violation !

Taking it one step further



Studies in different mass region to study local effects

Taking it one step further

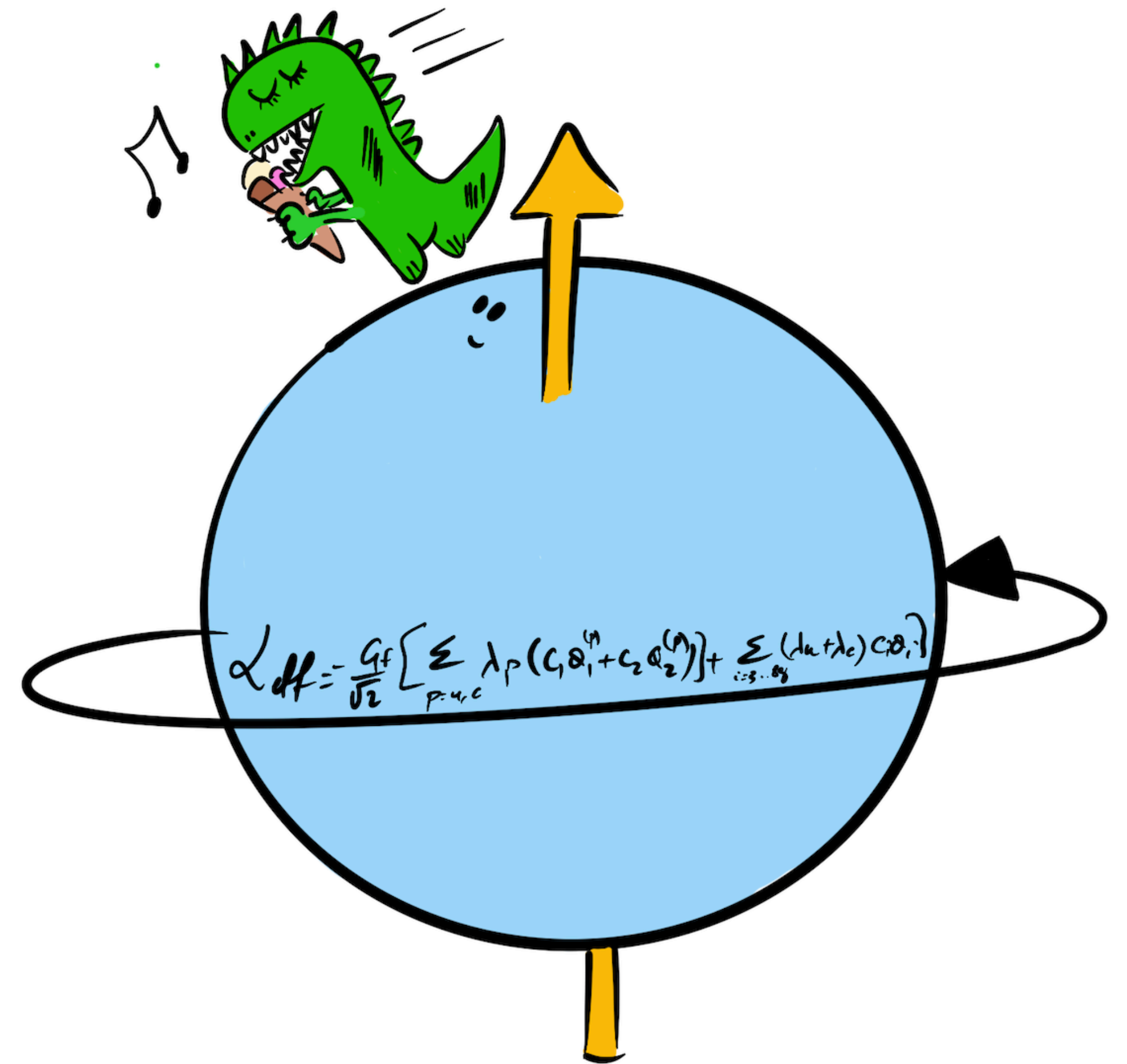
Observe up to 6 standard deviations locally

Decay topology	Mass region (GeV/c ²)	$\mathcal{A}_{CP}$
$\Lambda_b^0 \rightarrow R(pK^-)R(\pi^+\pi^-)$	$m_{pK^-} < 2.2$ $m_{\pi^+\pi^-} < 1.1$	$(5.3 \pm 1.3 \pm 0.2)\%$
$\Lambda_b^0 \rightarrow R(p\pi^-)R(K^-\pi^+)$	$m_{p\pi^-} < 1.7$ $0.8 < m_{\pi^+K^-} < 1.0$ or $1.1 < m_{\pi^+K^-} < 1.6$	$(2.7 \pm 0.8 \pm 0.1)\%$
$\Lambda_b^0 \rightarrow R(p\pi^+\pi^-)K^-$	$m_{p\pi^+\pi^-} < 2.7$	$(5.4 \pm 0.9 \pm 0.1)\%$
$\Lambda_b^0 \rightarrow R(K^-\pi^+\pi^-)p$	$m_{K^-\pi^+\pi^-} < 2.0$	$(2.0 \pm 1.2 \pm 0.3)\%$

This discovery strongly suggests that
specific intermediate resonances play a key role in
generating CP violation

Some conclusions

- There has been an incredible progress in the last decades.
- The CKM mechanism seems to be working really well.
- Yet there is still plenty to understand to reconcile our observations and expectations.



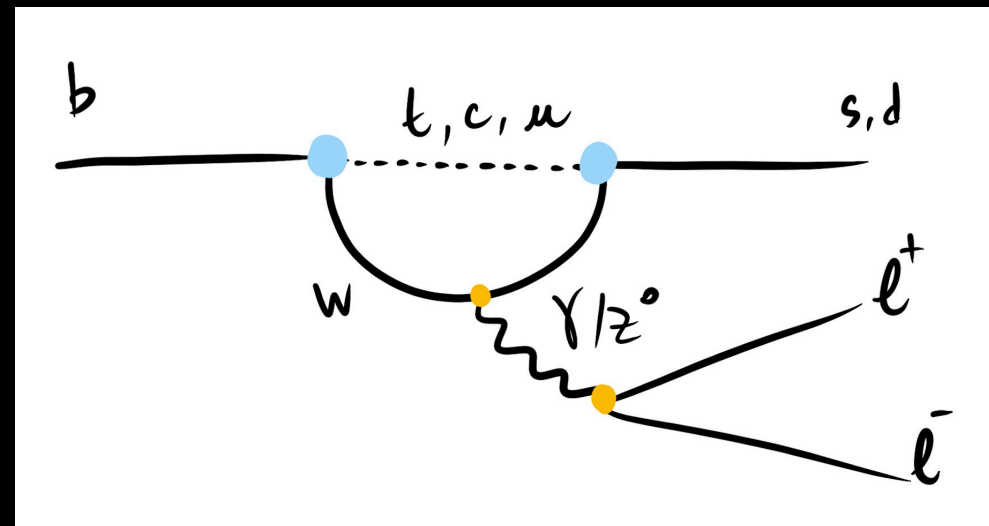
Let's take a little break and we continue with
EFTs and all the good stuff.



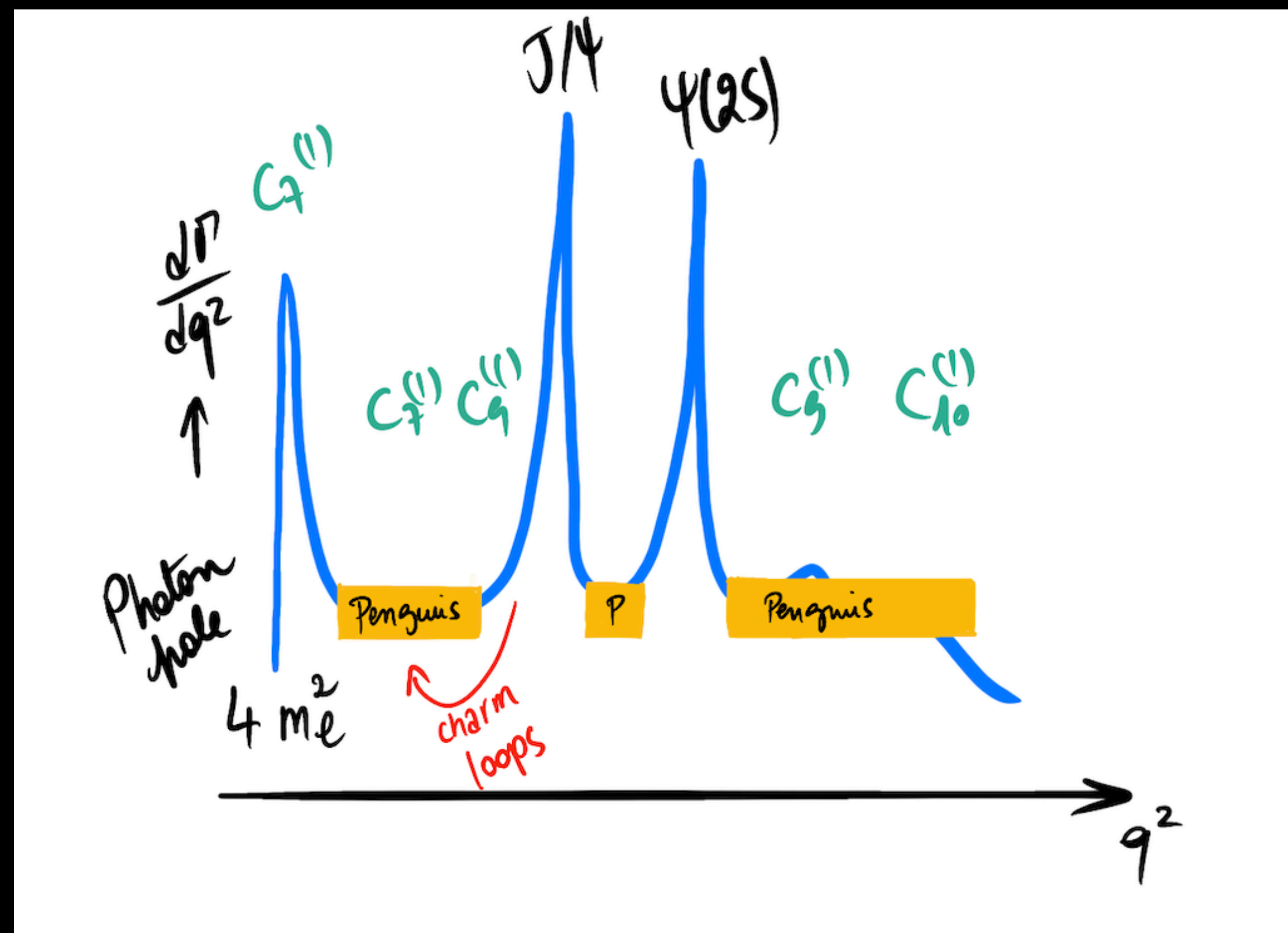
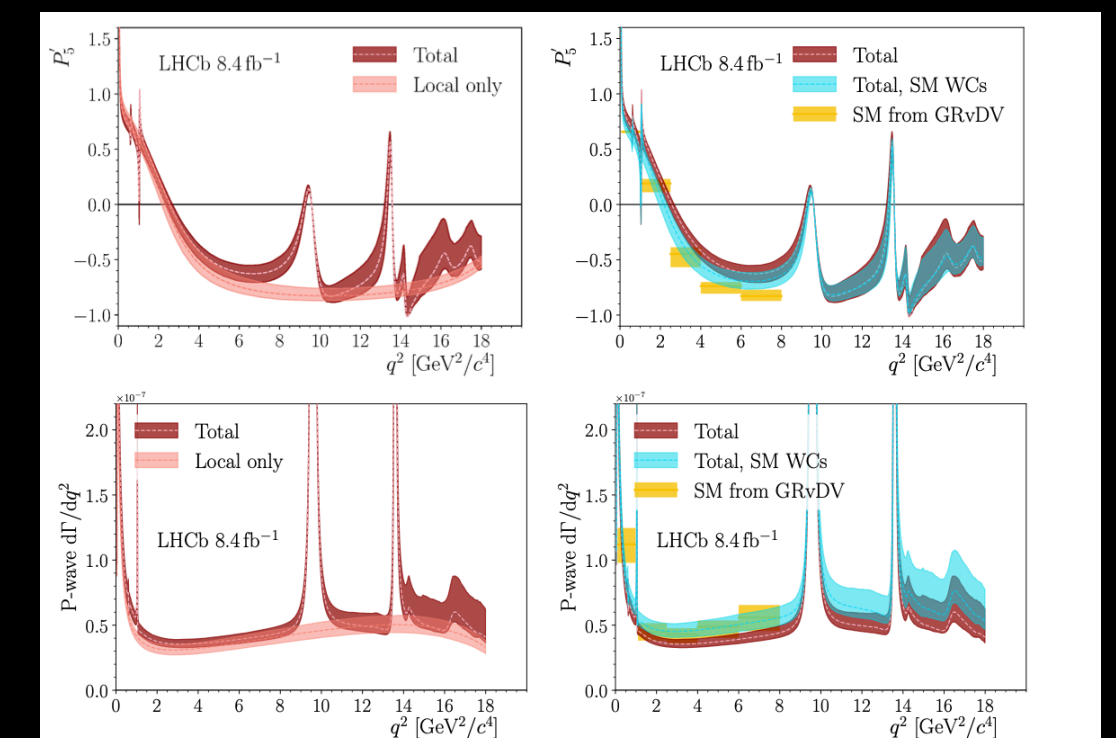
Searching for New Physics with penguins

$b \rightarrow s\ell^+\ell^-$ transitions are a great laboratory to search for New Physics in an indirect way

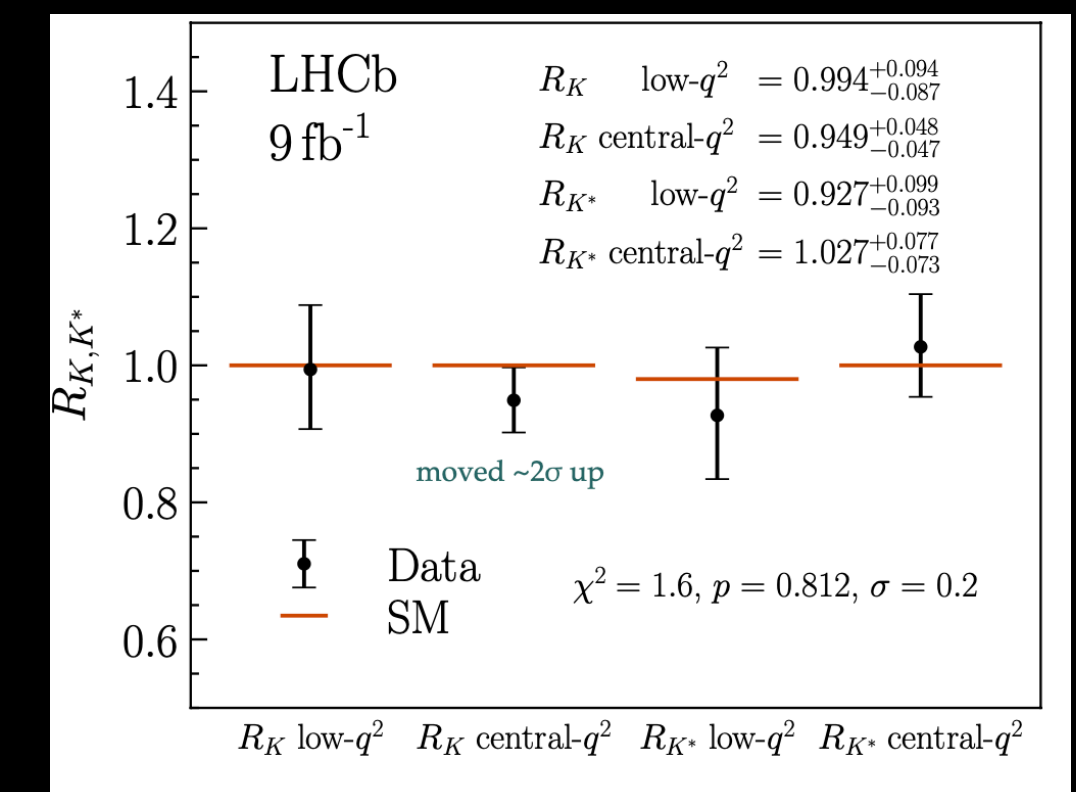
$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \lambda^{\text{CKM}} \sum_i C_i \mathcal{O}_i + \text{h.c.}$$



Study local and non-local effects



Lepton Universality tests

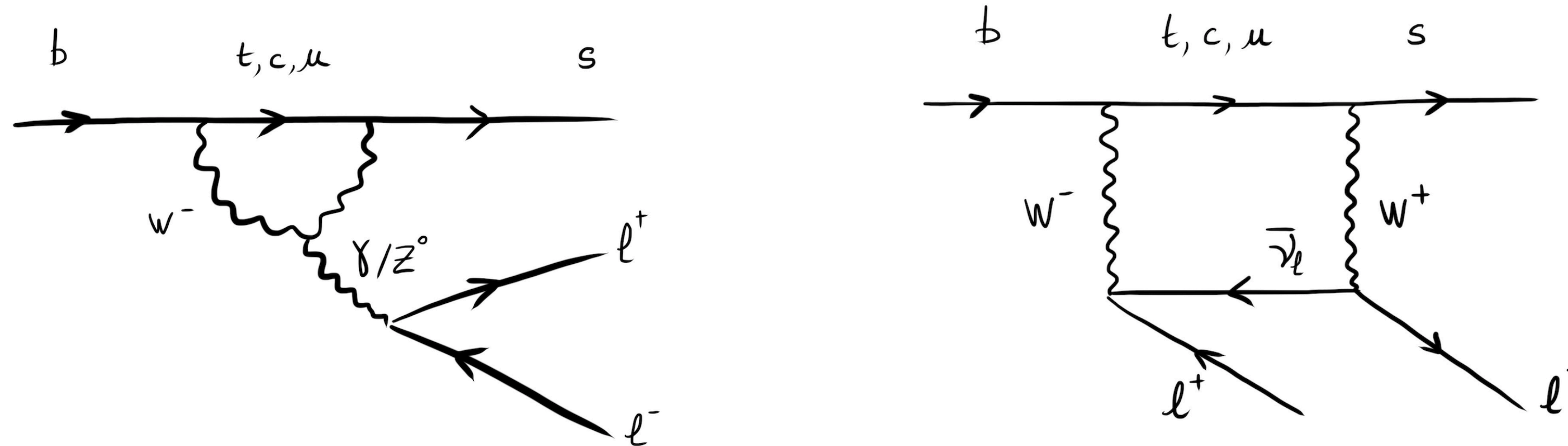


Angular Analyses Lepton Universality tests

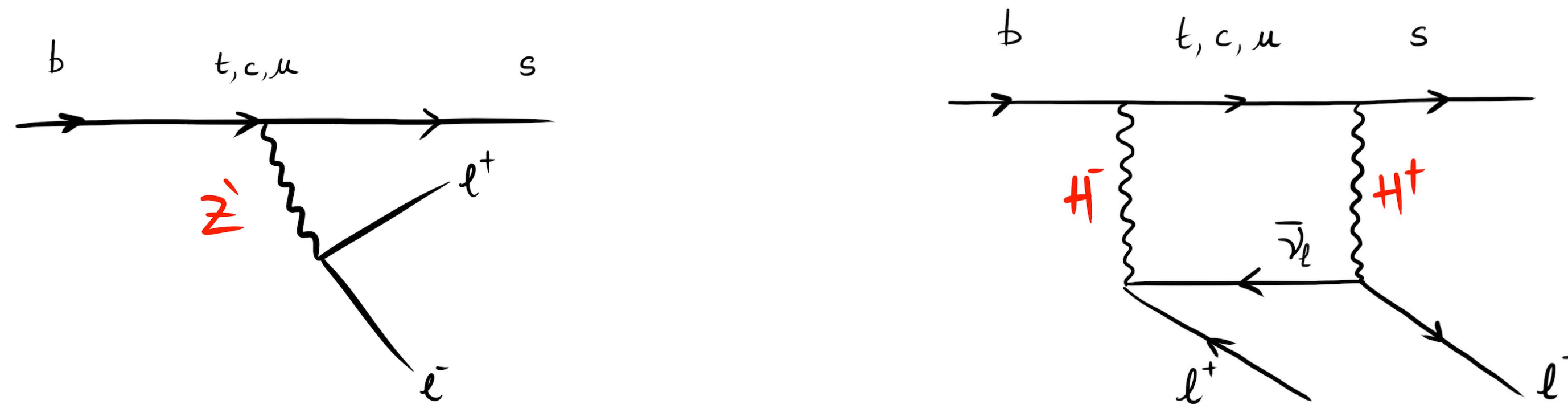


Are we the same?

Standard Model

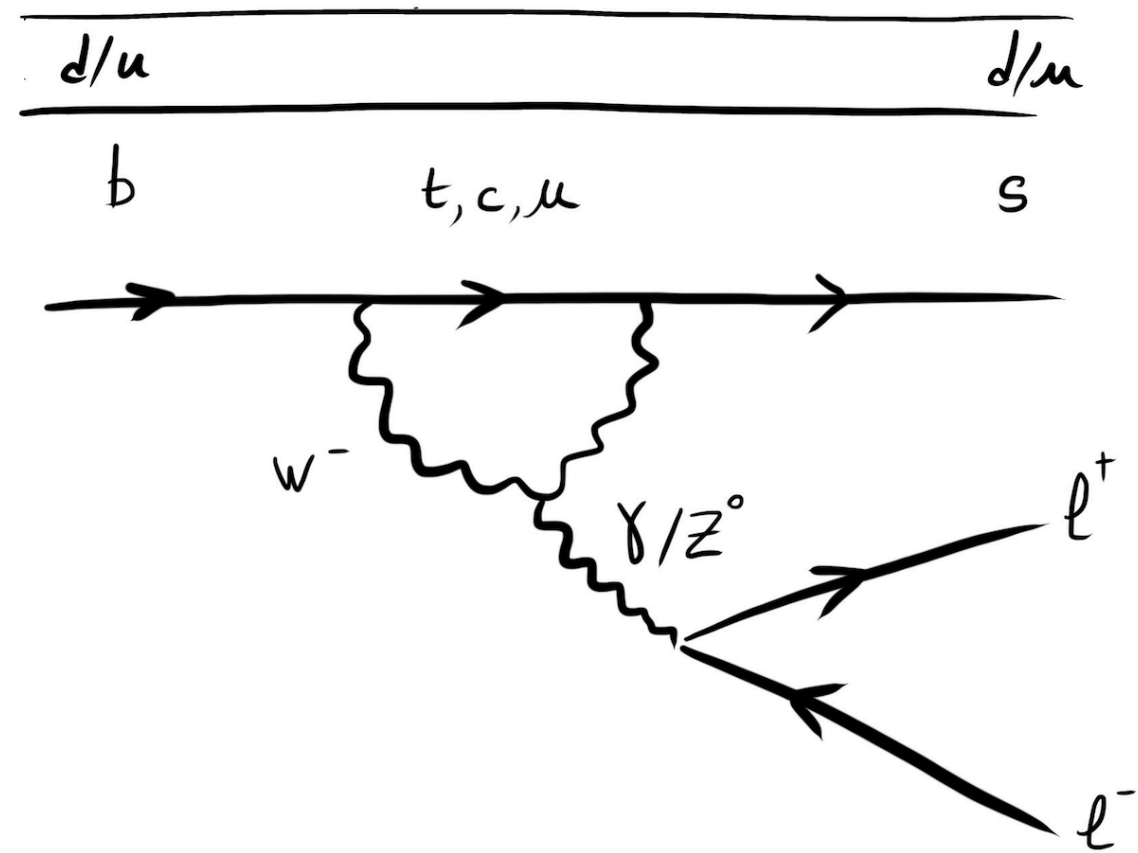


New Physics

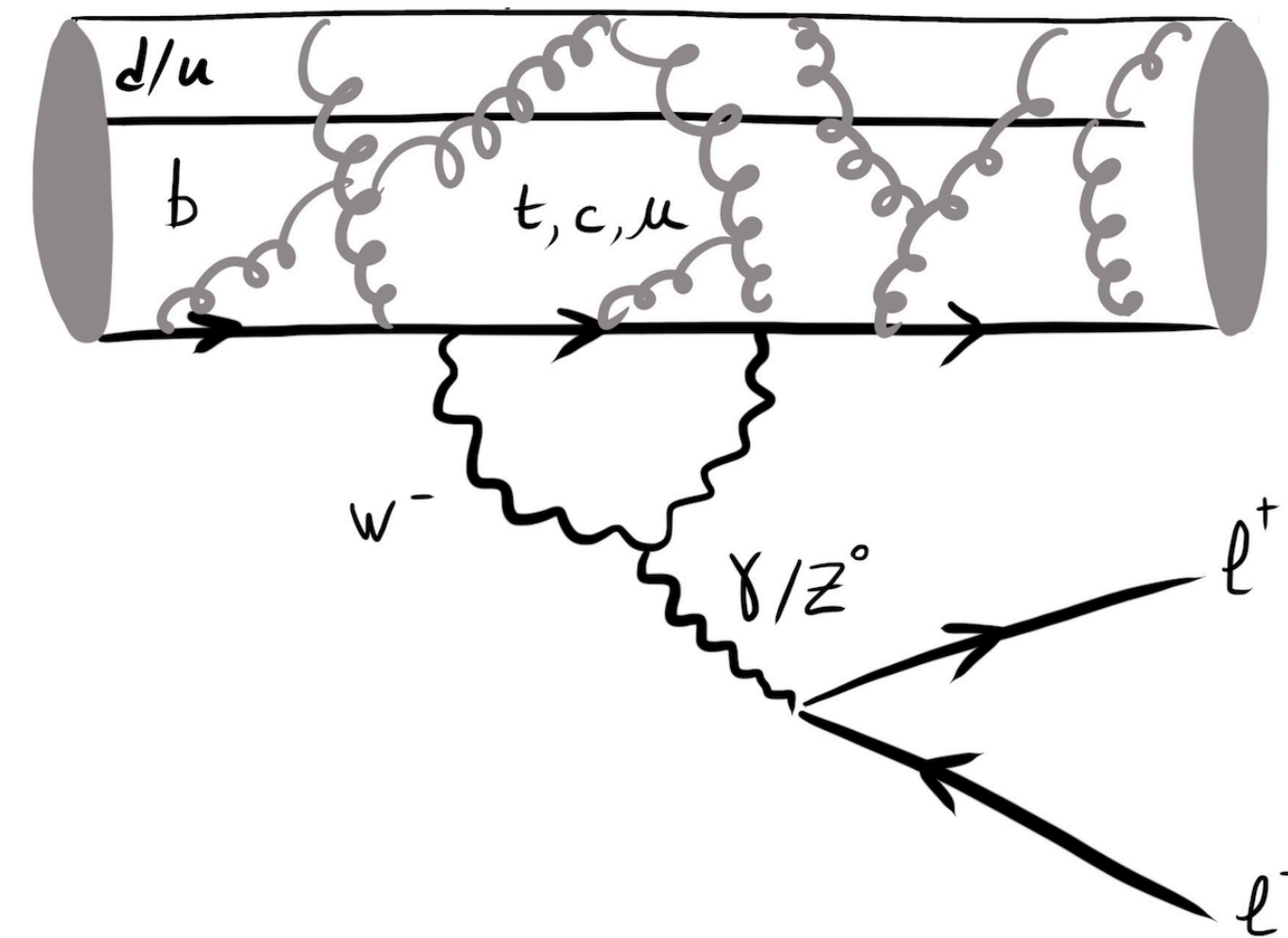
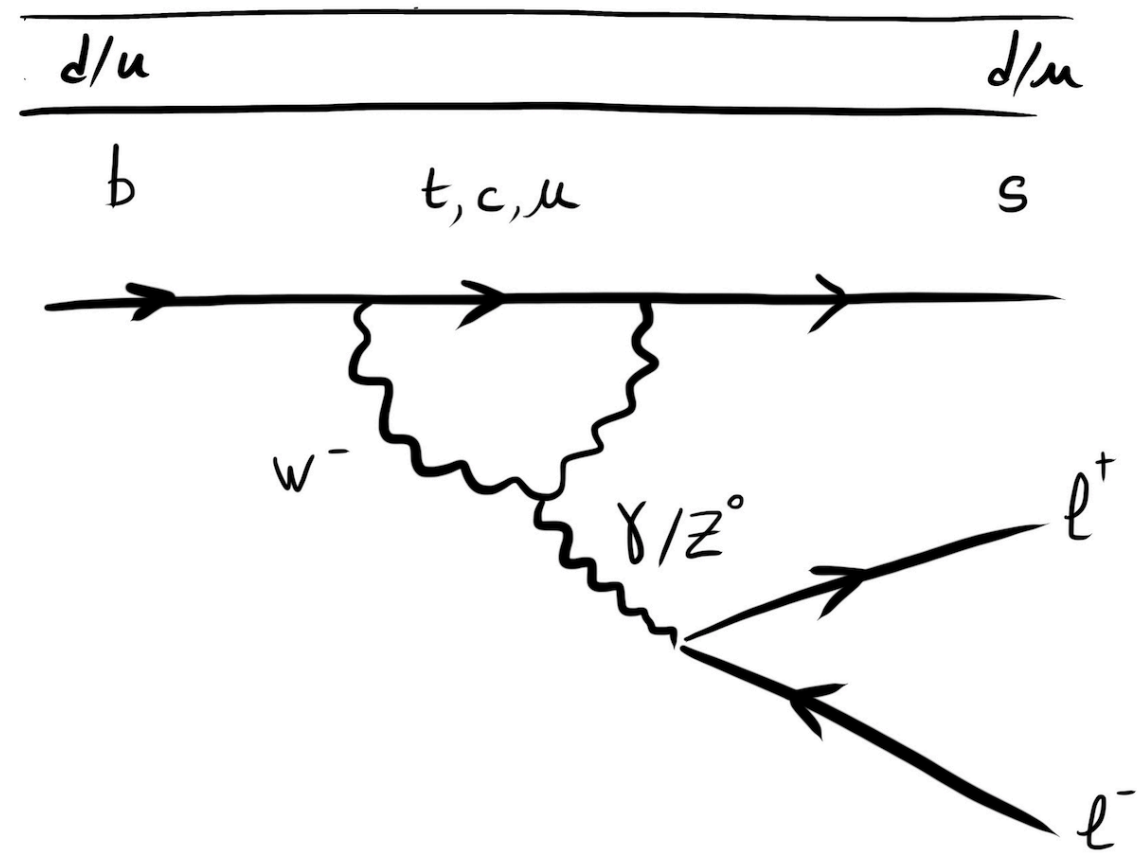


Note to self next time add LQs

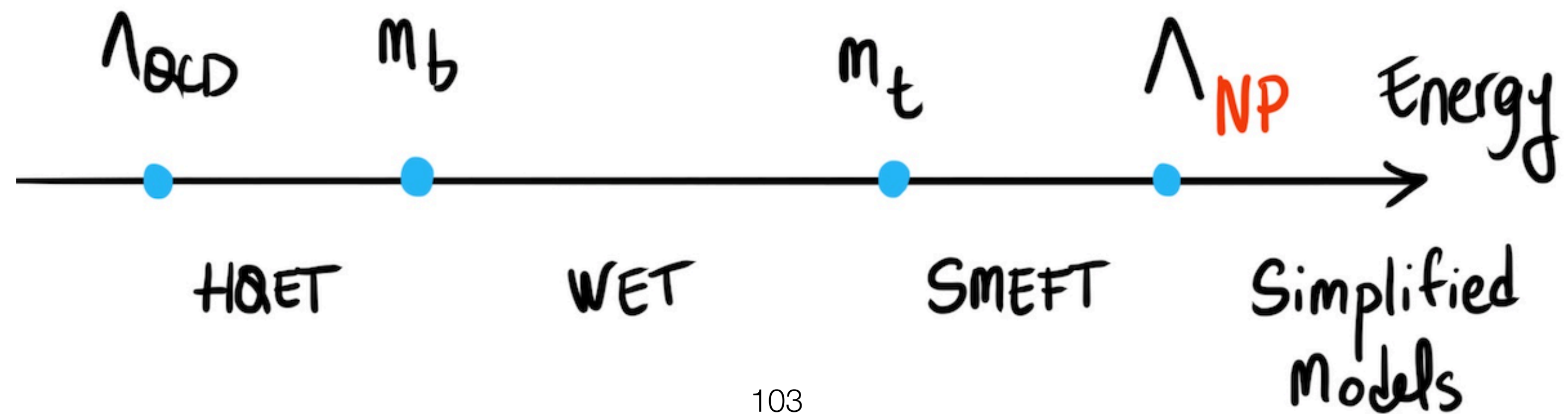
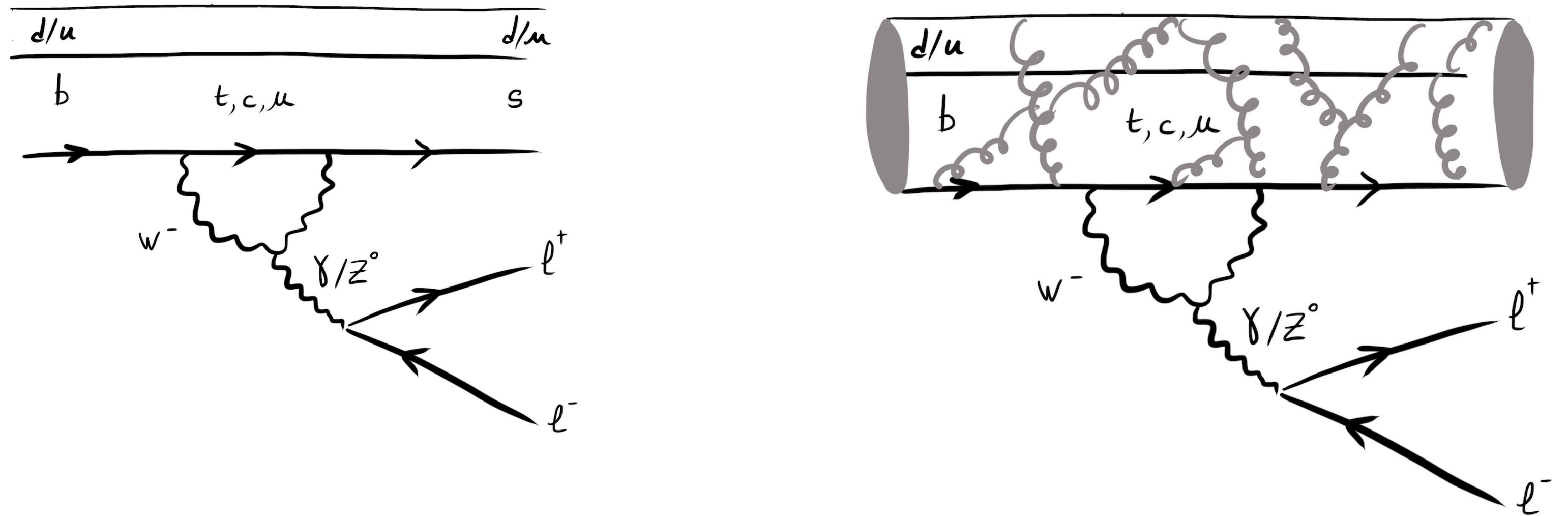
Effective Field Theory



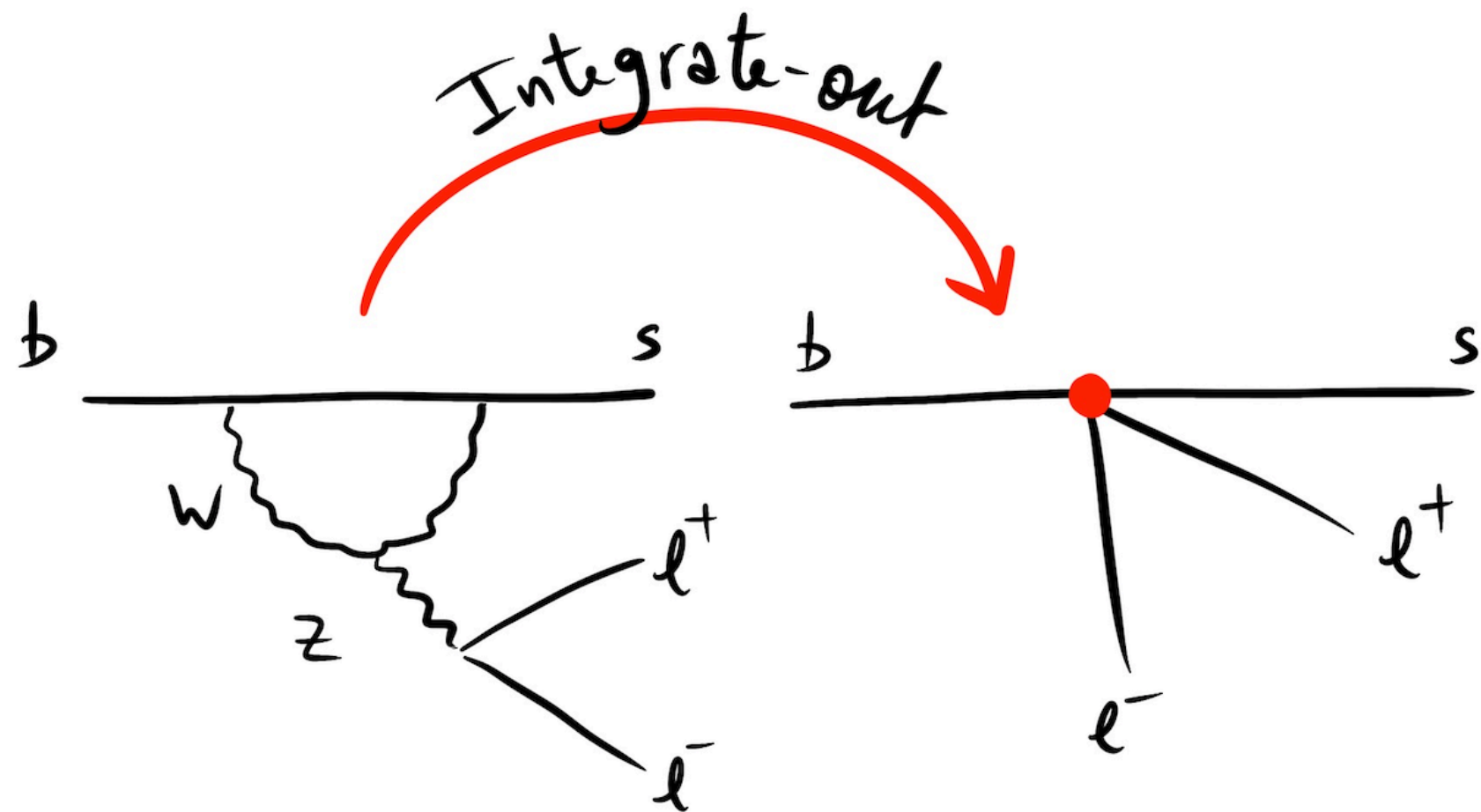
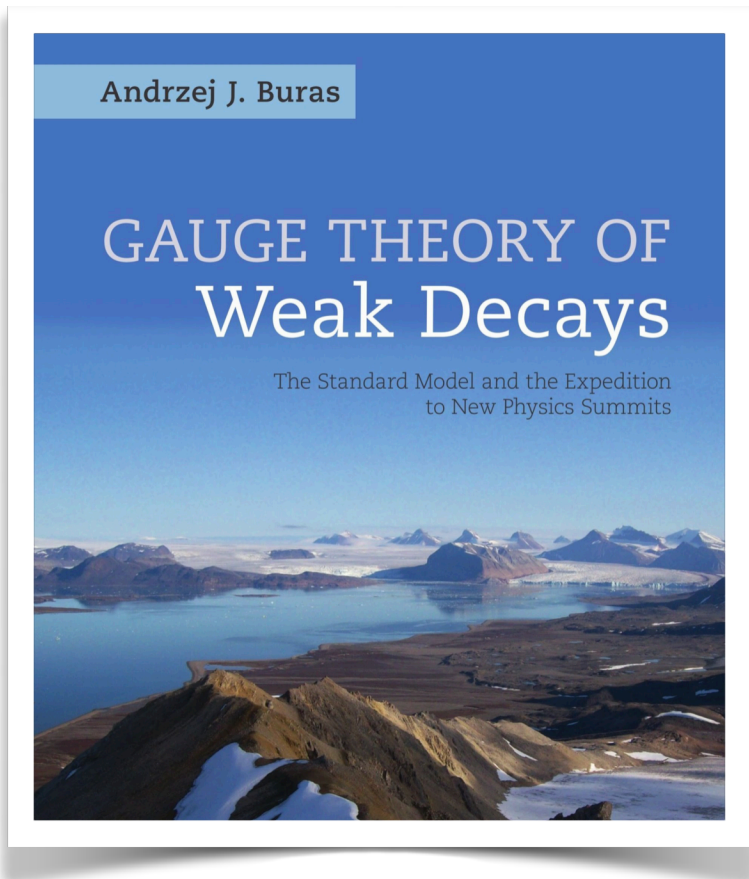
Effective Field Theory



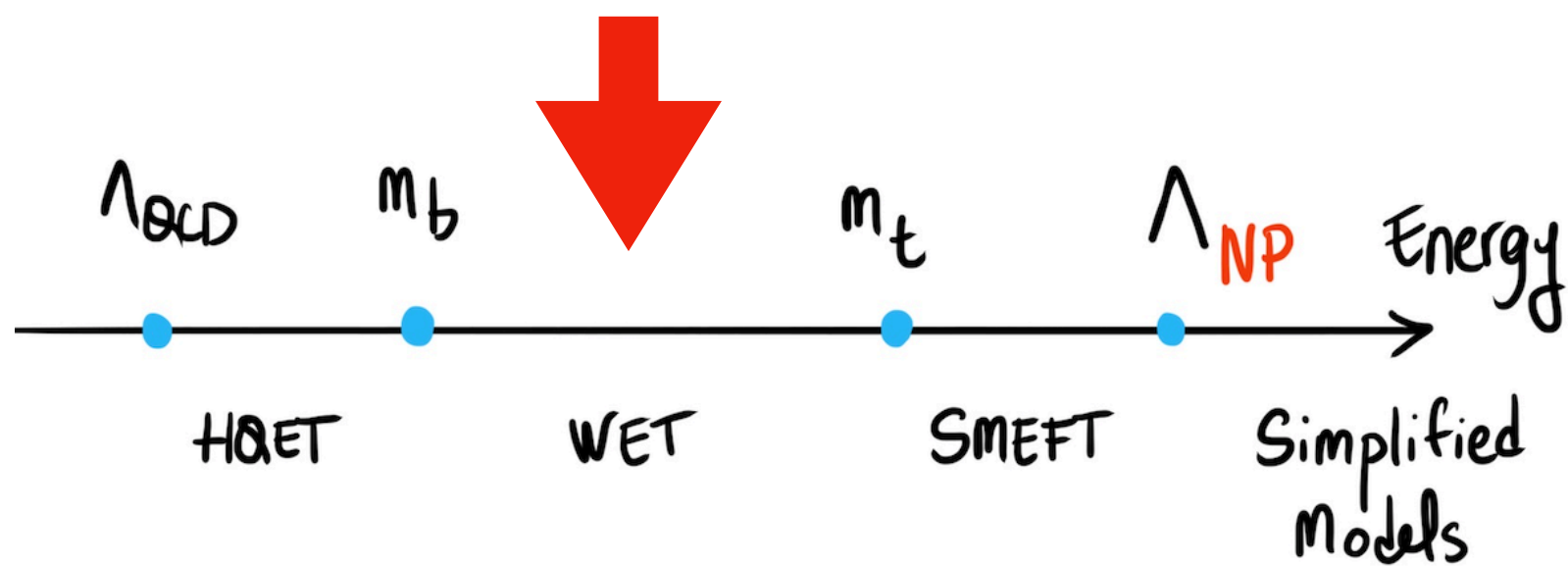
Effective Field Theory



Effective Field Theory



$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \lambda^{\text{CKM}} \sum_i C_i \mathcal{O}_i + h.c.,$$



Effective Field Theory

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \lambda^{\text{CKM}} \sum_i C_i \mathcal{O}_i + h.c.,$$

SD: Wilson coefficients + perturbative

LD: Local operators + non perturbative
(LCSR, Lattice, etc.)

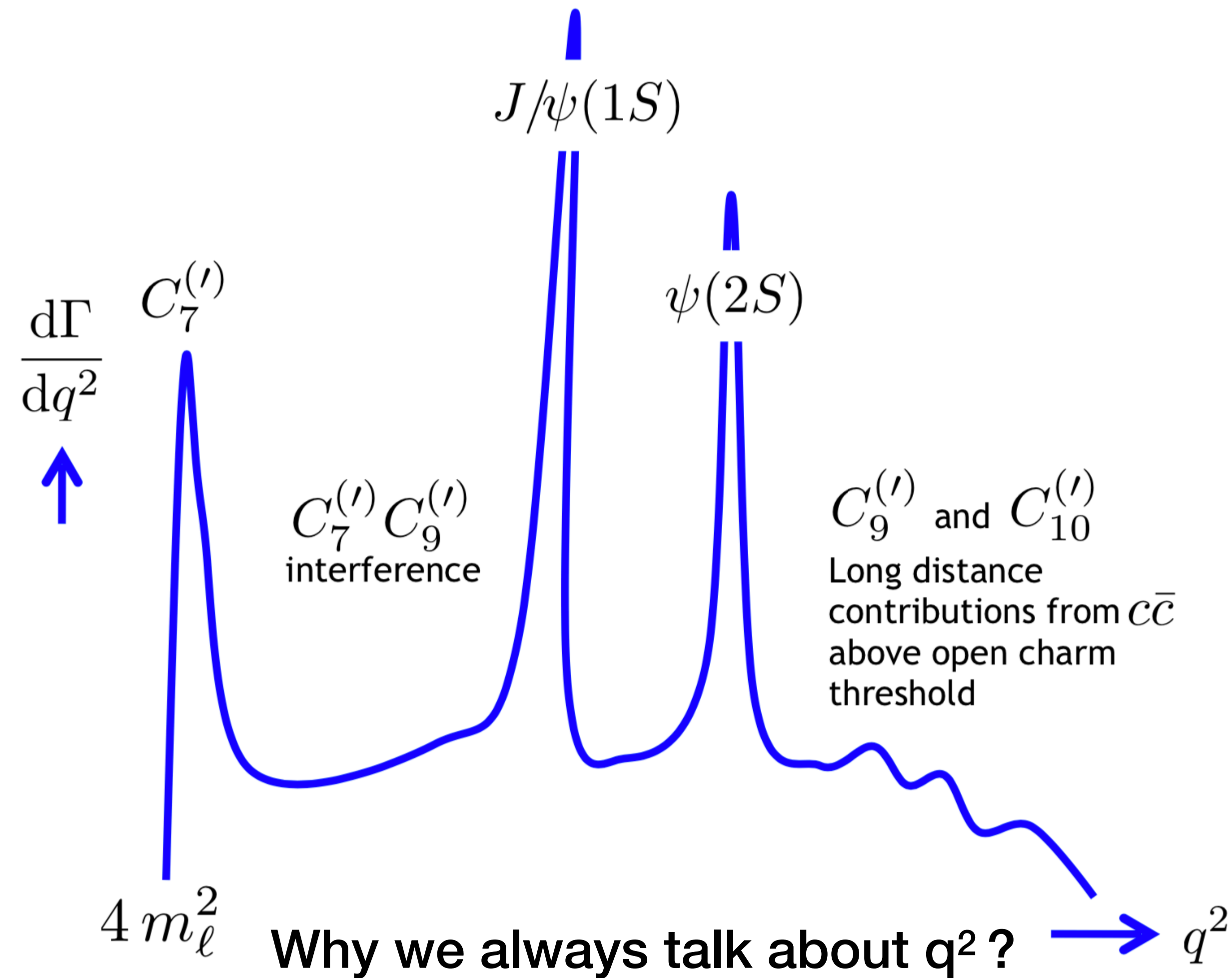
Effective Field Theory

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \lambda^{\text{CKM}} \sum_i C_i \mathcal{O}_i + h.c.,$$

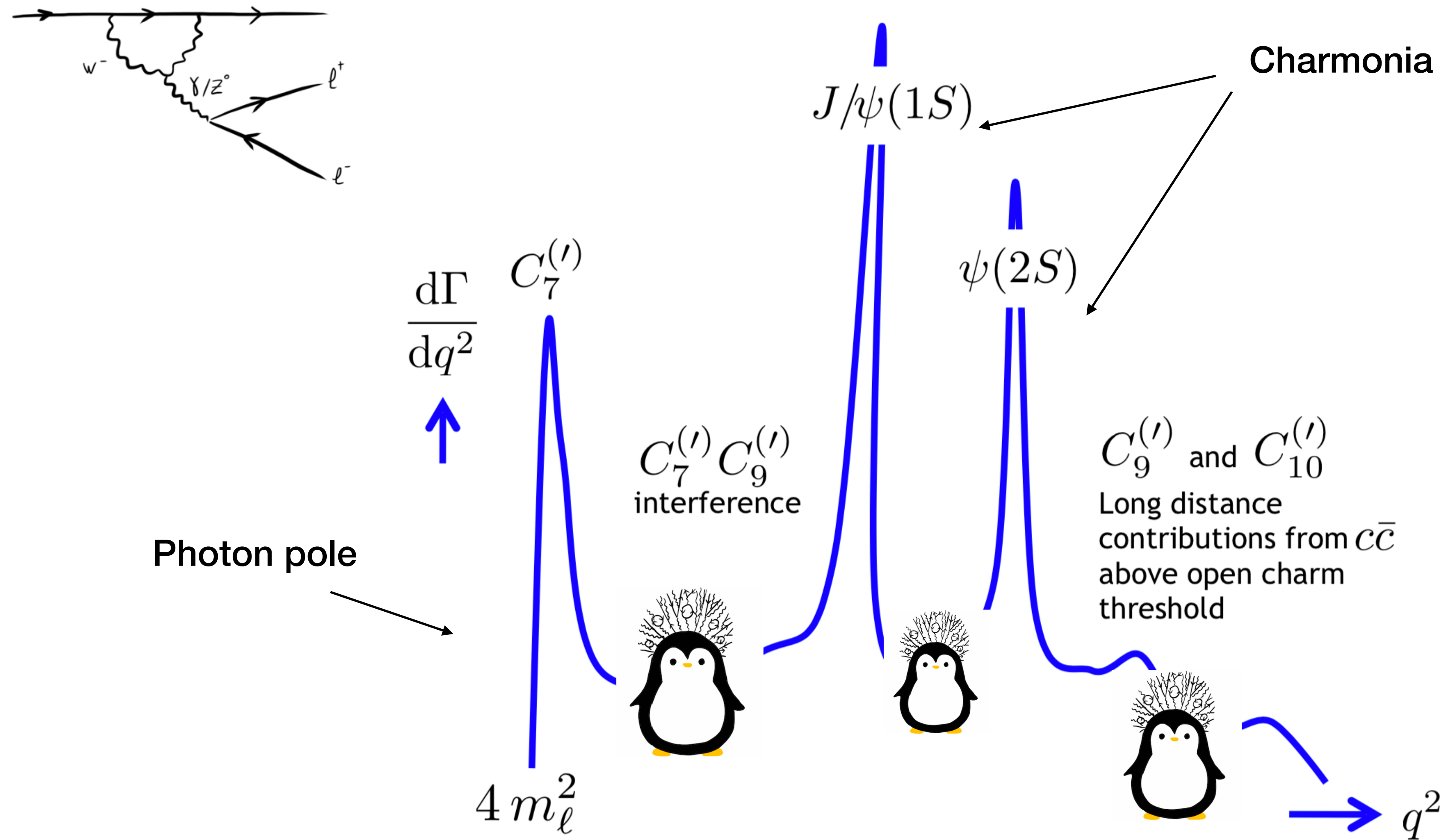
SD: Wilson coefficients + perturbative

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(LCSR, Lattice, etc.)

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \lambda^{\text{CKM}} \sum_i C_i \mathcal{O}_i + h.c.,$$



$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \lambda^{\text{CKM}} \sum_i C_i \mathcal{O}_i + h.c.,$$



To summarize, the resulting Standard Model operator basis for FCNC processes (without leptons, for simplicity) contains the “current-current operators” (with $p = u, c$)

$$\begin{aligned} Q_1^{(p)} &= (\bar{s}_i p_i)_{V-A} (\bar{p}_j b_j)_{V-A}, \\ Q_2^{(p)} &= (\bar{s}_i p_j)_{V-A} (\bar{p}_j b_i)_{V-A}, \end{aligned} \quad (32)$$

the “QCD penguin operators”

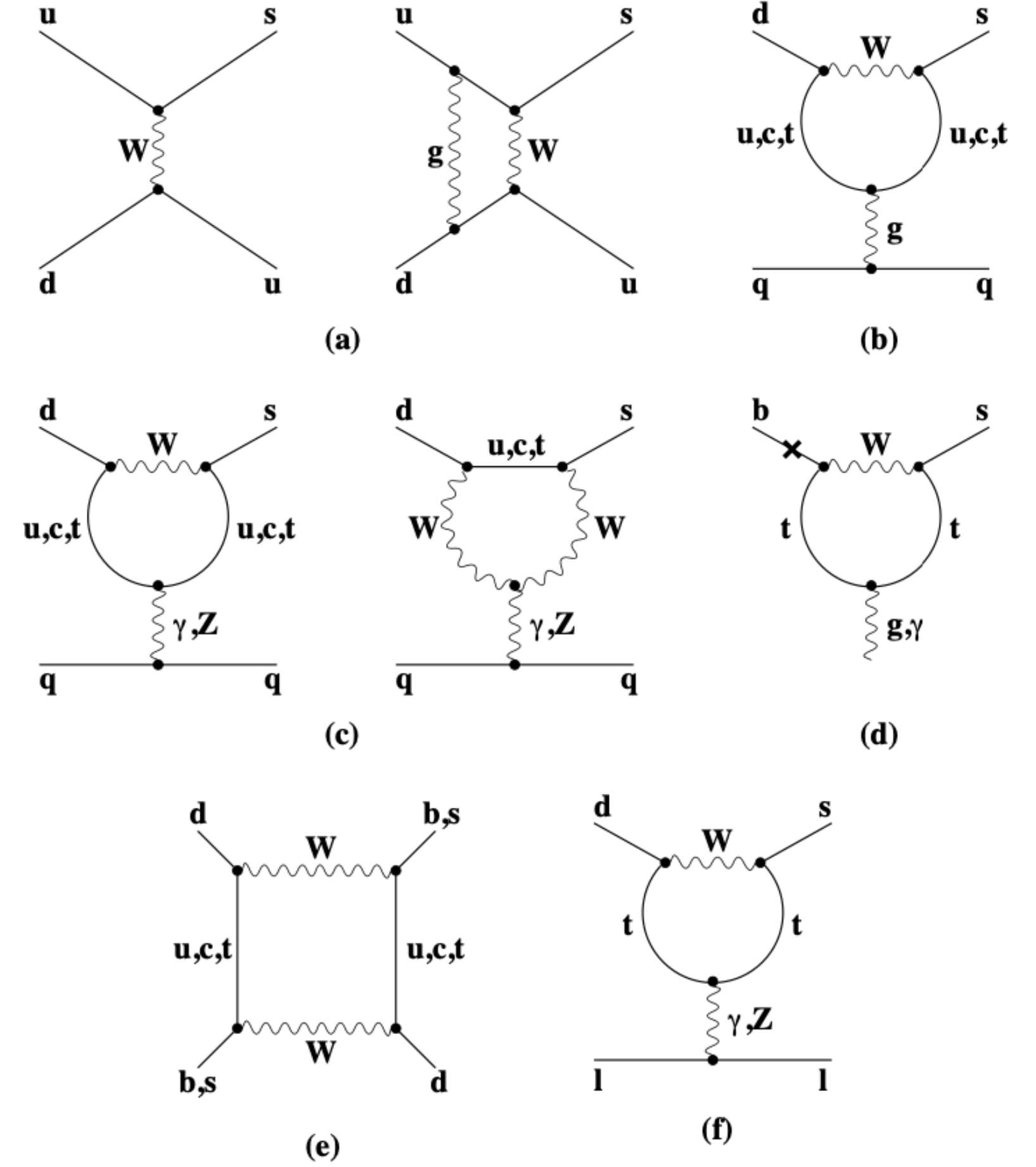
$$\begin{aligned} Q_3 &= (\bar{s}_i b_i)_{V-A} \sum_{q=u,d,s,c,b} (\bar{q}_j q_j)_{V-A}, \\ Q_4 &= (\bar{s}_i b_j)_{V-A} \sum_{q=u,d,s,c,b} (\bar{q}_j q_i)_{V-A}, \\ Q_5 &= (\bar{s}_i b_i)_{V-A} \sum_{q=u,d,s,c,b} (\bar{q}_j q_j)_{V+A}, \\ Q_6 &= (\bar{s}_i b_j)_{V-A} \sum_{q=u,d,s,c,b} (\bar{q}_j q_i)_{V+A}, \end{aligned} \quad (33)$$

the “electroweak penguin operators” (with e_q the electric charges of the quarks in units of $|e|$)

$$\begin{aligned} Q_7 &= (\bar{s}_i b_i)_{V-A} \sum_{q=u,d,s,c,b} \frac{3}{2} e_q (\bar{q}_j q_j)_{V+A}, \\ Q_8 &= (\bar{s}_i b_j)_{V-A} \sum_{q=u,d,s,c,b} \frac{3}{2} e_q (\bar{q}_j q_i)_{V+A}, \\ Q_9 &= (\bar{s}_i b_i)_{V-A} \sum_{q=u,d,s,c,b} \frac{3}{2} e_q (\bar{q}_j q_j)_{V-A}, \\ Q_{10} &= (\bar{s}_i b_j)_{V-A} \sum_{q=u,d,s,c,b} \frac{3}{2} e_q (\bar{q}_j q_i)_{V-A}, \end{aligned} \quad (34)$$

and the electromagnetic and chromo-magnetic dipole operators

$$\begin{aligned} Q_{7\gamma} &= -\frac{em_b}{8\pi^2} \bar{s}_L \sigma_{\mu\nu} F^{\mu\nu} b_R, \\ Q_{8g} &= -\frac{g_s m_b}{8\pi^2} \bar{s}_L \sigma_{\mu\nu} G_a^{\mu\nu} t_a b_R. \end{aligned} \quad (35)$$



The unitarity of the CKM matrix implies $\lambda_u + \lambda_c + \lambda_t = 0$, where $\lambda_p \equiv V_{pb}V_{ps}^*$. We will use this relation to eliminate CKM factors involving couplings of the top quark. Note also that in the limit $m_u = m_c = 0$ (which is justified at dimension-6 order) the penguin graphs always involve $\lambda_t = -(\lambda_u + \lambda_c)$. The final result for the effective weak Lagrangian reads

$$\mathcal{L}_{\text{eff}} = -\frac{G_F}{\sqrt{2}} \left[\sum_{p=u,c} \lambda_p \left(C_1 Q_1^{(p)} + C_2 Q_2^{(p)} \right) + \sum_{i=3,\dots,10,7\gamma,8g} (\lambda_u + \lambda_c) C_i Q_i \right]. \quad (36)$$

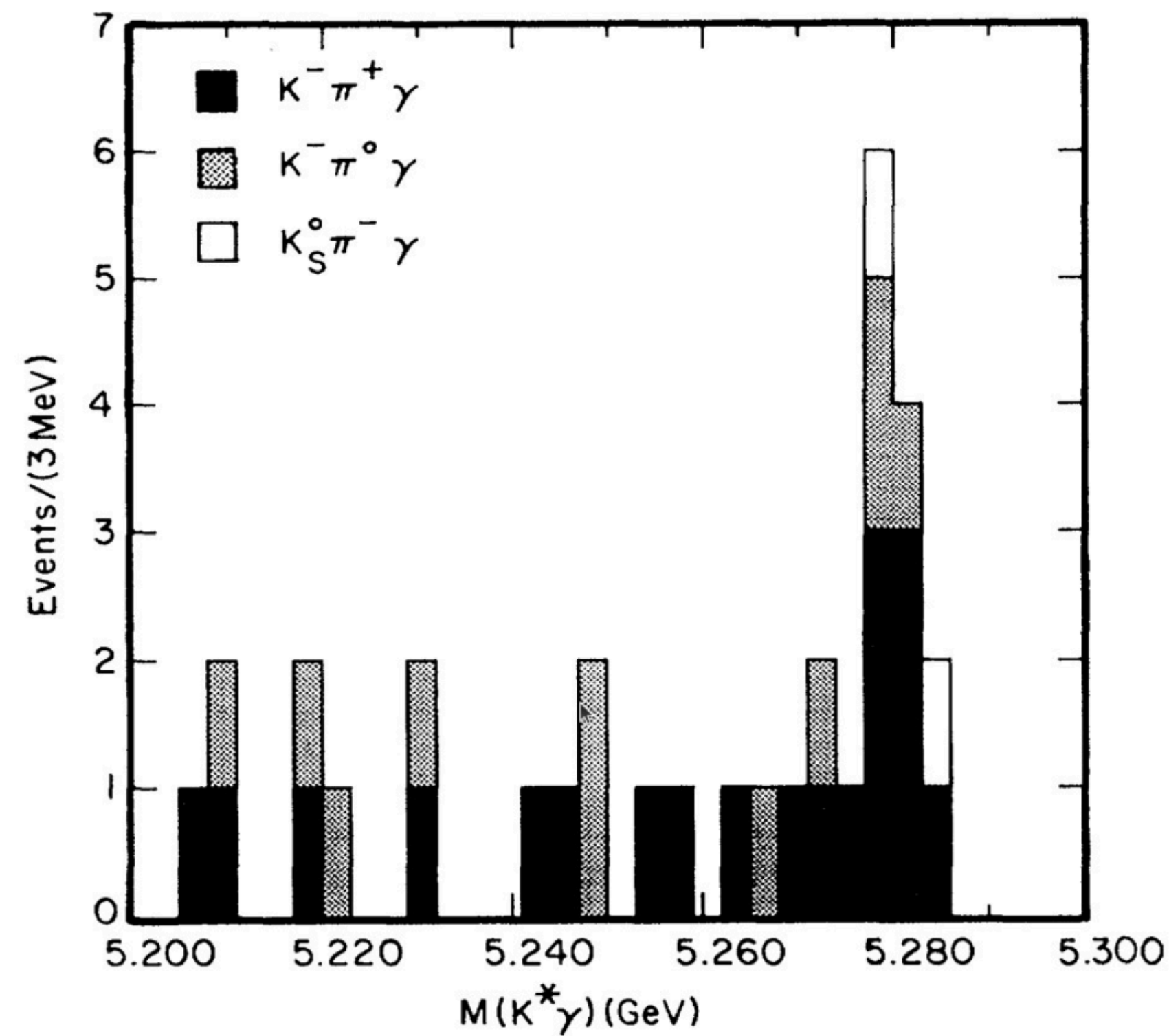
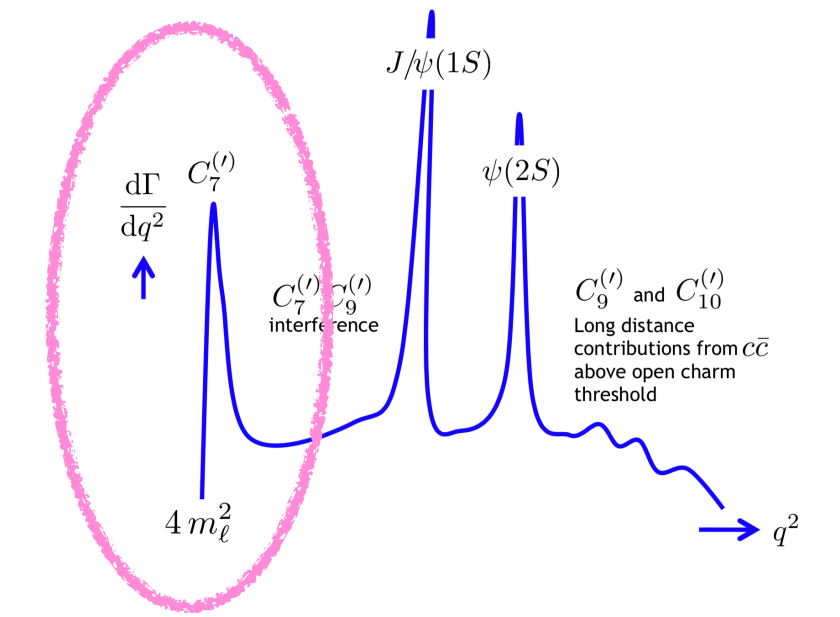
16

Note that

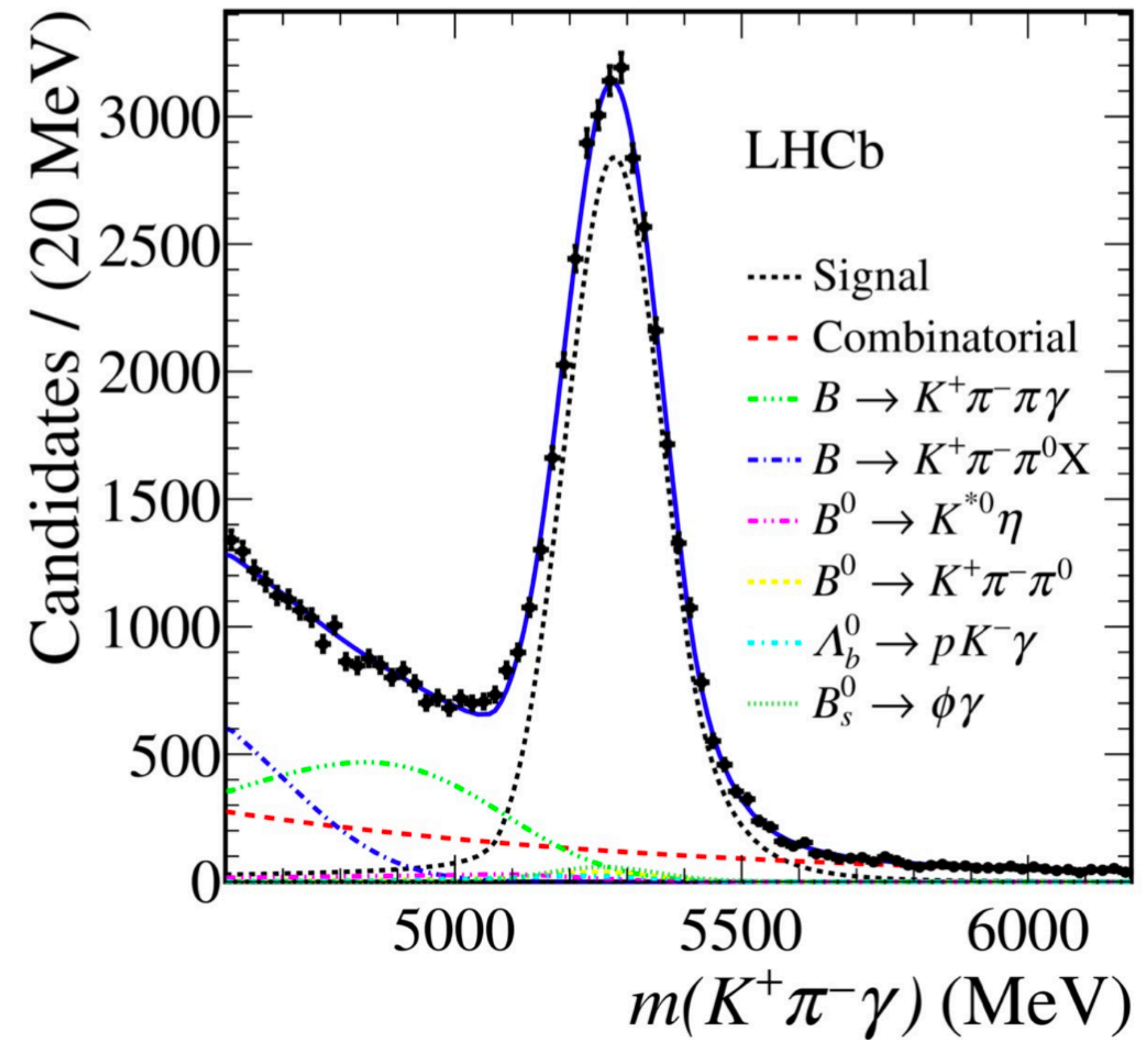
$$\frac{\lambda_u}{\lambda_c} = \frac{V_{ub}V_{us}^*}{V_{cb}V_{cs}^*} \sim e^{-i\gamma} \quad (37)$$

has a non-zero, relative CP-violating phase. This allows for the phenomenon of CP violation from amplitude interference in FCNC processes – a phenomenon that is currently being studied extensively at the B -factories (see, e.g., [1]).

Photon pole - family of radiative decays



CLEO, PRL 71 (1993) 674



LHCb, PRL 123 (2019) 031801

Example of an indirect search

SEARCHES FOR NEW PHYSICS | NEWS

In pursuit of right-handed photons

10 November 2020

A report from the LHCb experiment

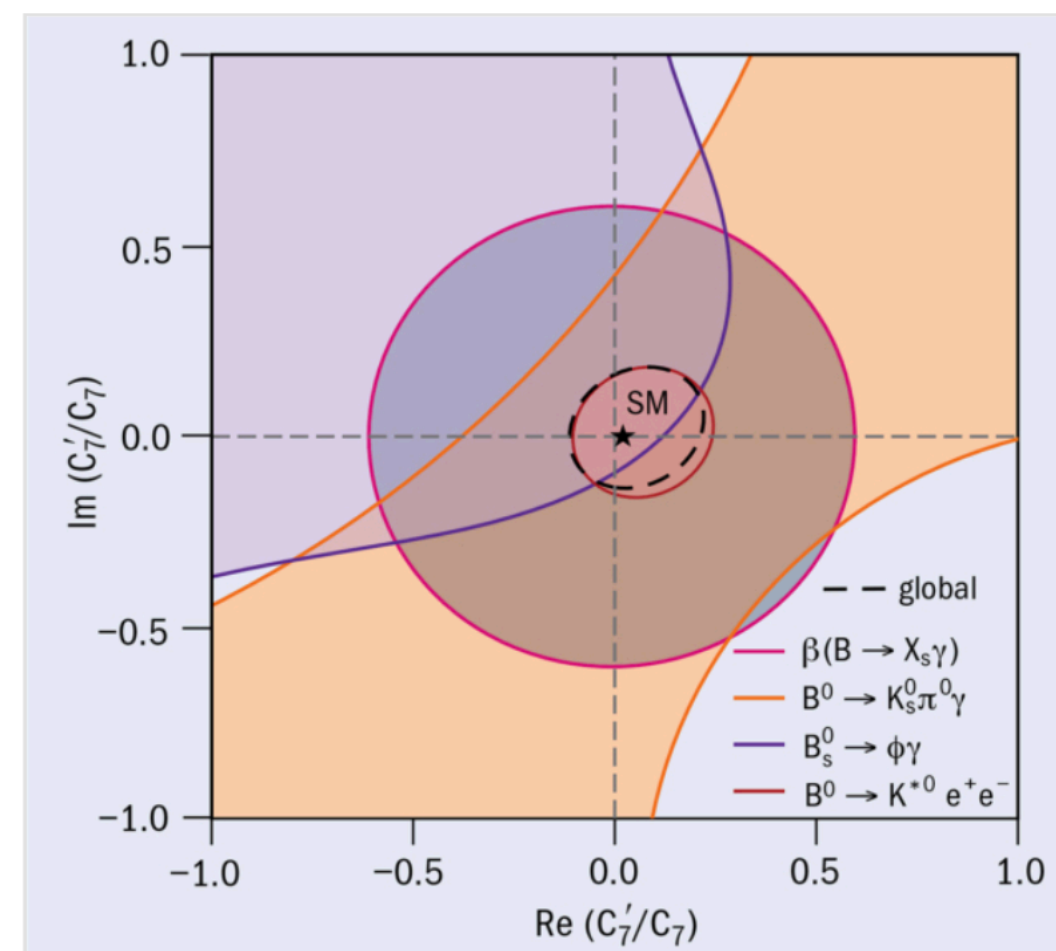


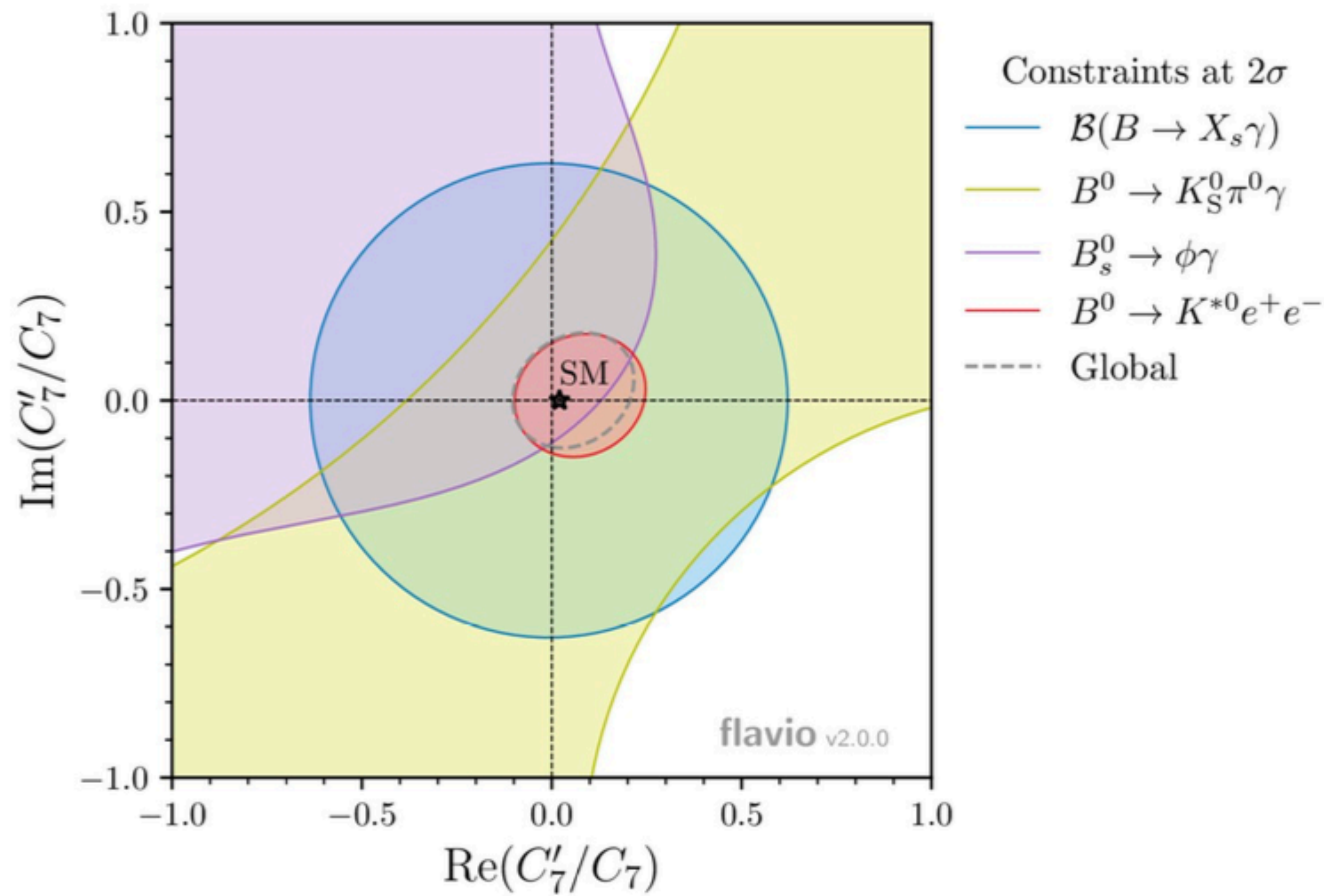
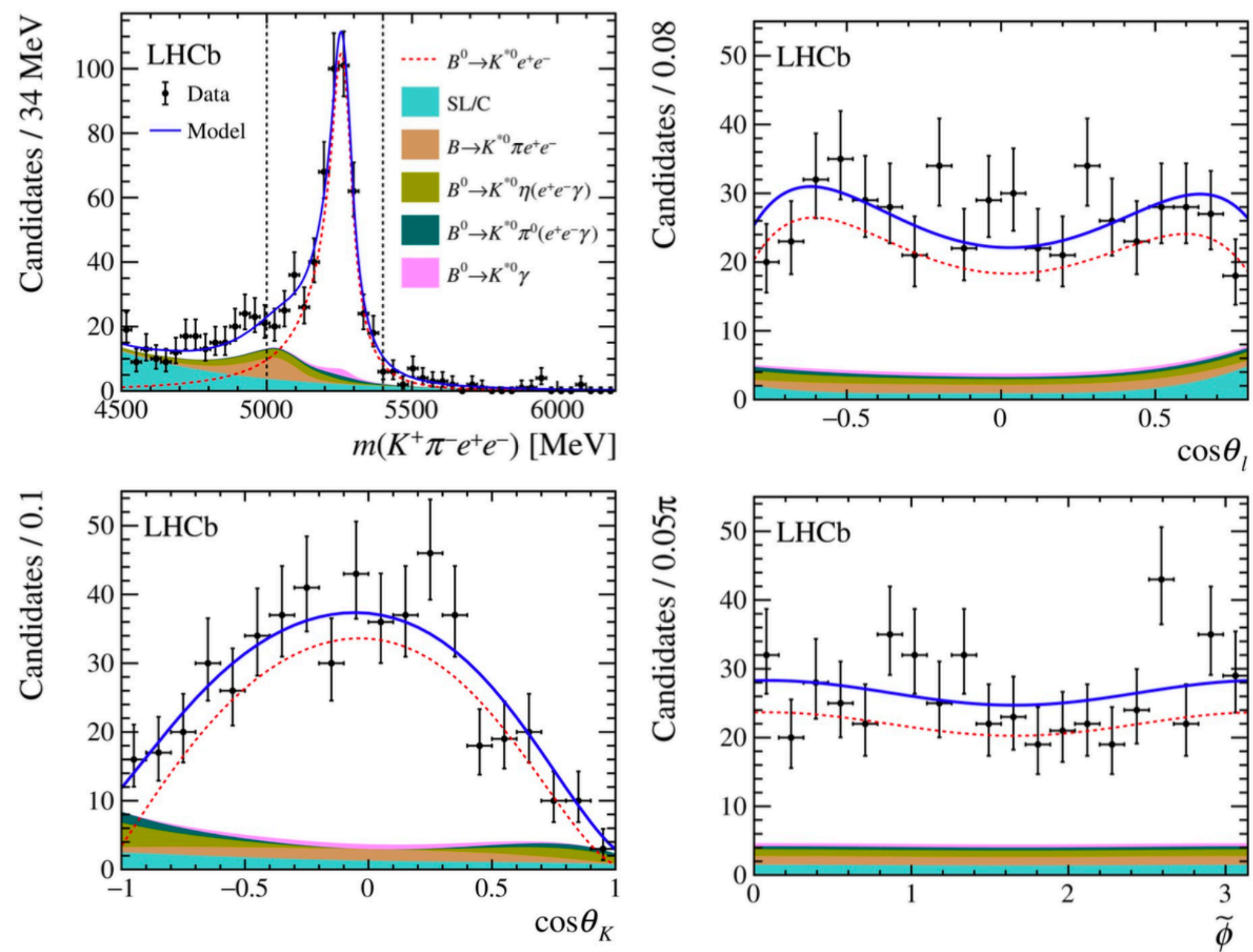
Fig. 1. 2σ constraints on the ratio of right- and left-handed Wilson coefficients, C'_7/C_7 , using the flavio software package. C_7 quantifies the coupling strength to photons, and is fixed to its SM value. Any deviation in C'_7/C_7 , from (0,0) would signify new physics. The new LHCb measurement is shown in red. Credit: CERN

left-handed.

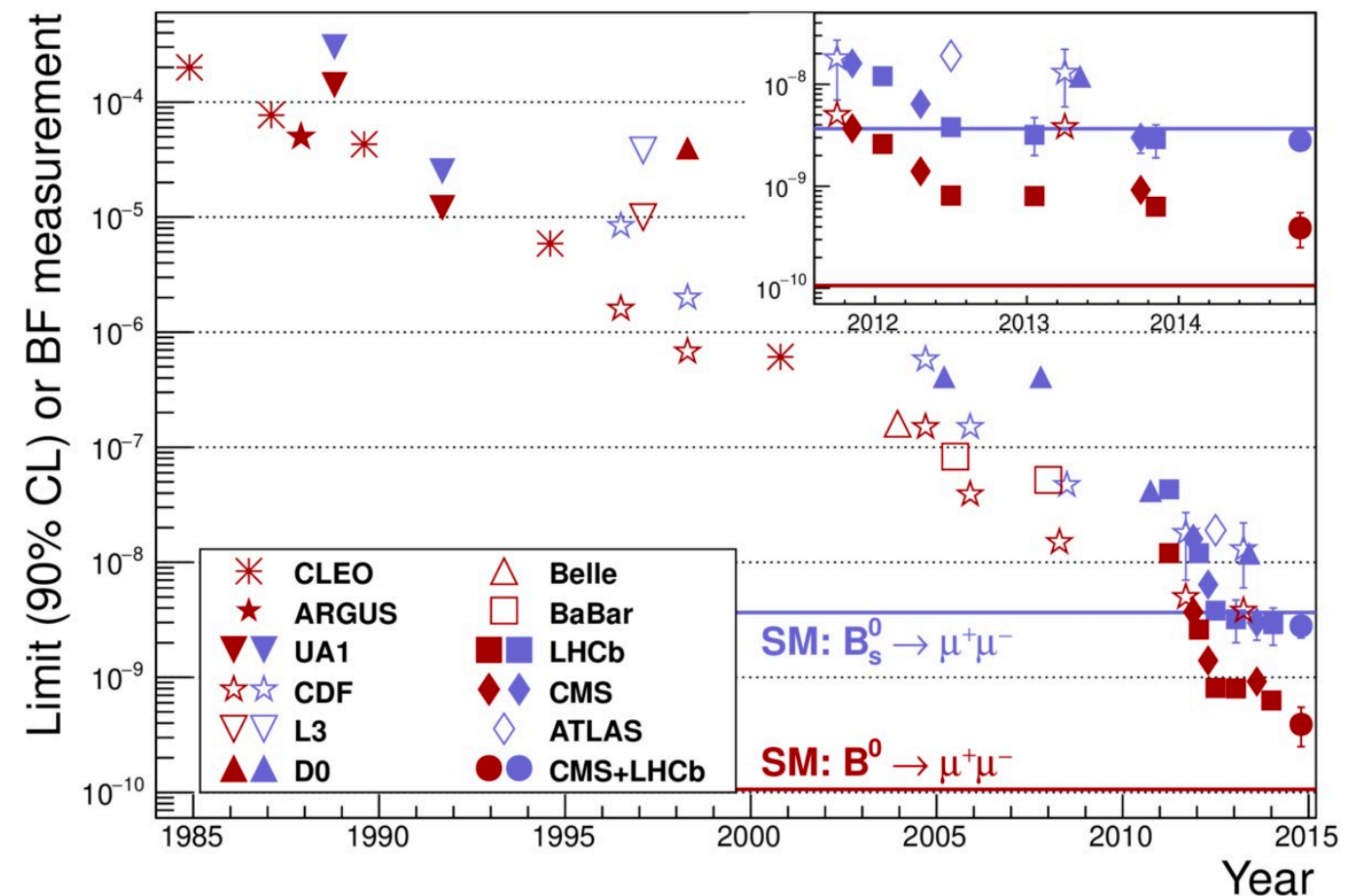
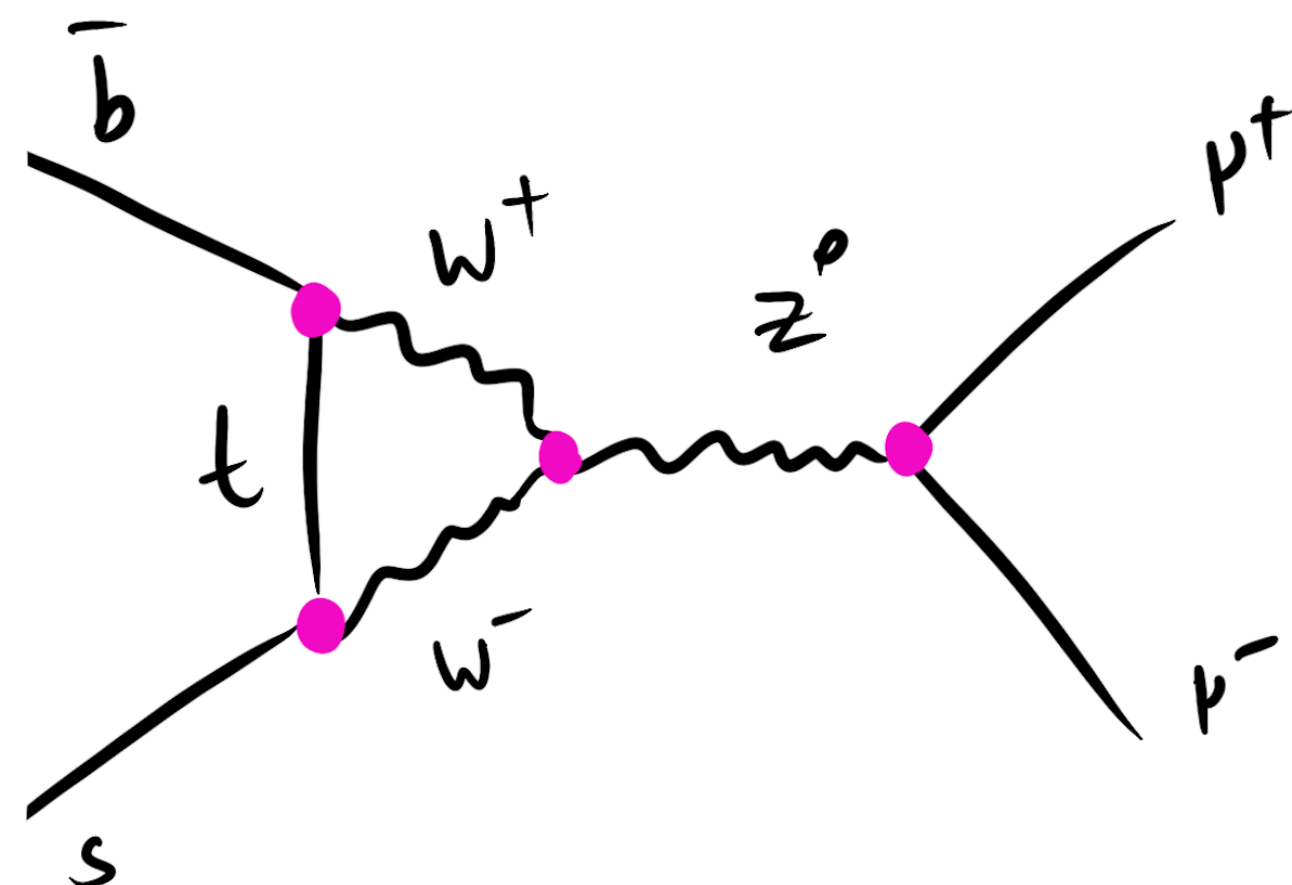
On 17 January 1957, a few months after Chien-Shiung Wu's discovery of parity violation, Wolfgang Pauli wrote to Victor Weisskopf: "*Ich glaube aber nicht, daß der Herrgott ein schwacher Linkshänder ist*" (I cannot believe that God is a weak left-hander). But maximal parity violation is now well established within the Standard Model (SM). The weak interaction only couples to left-handed particles, as dramatically seen in the continuing absence of experimental evidence for right-handed neutrinos. In the same way, the polarisation of photons originating from transitions that involve the weak interaction is expected to be completely

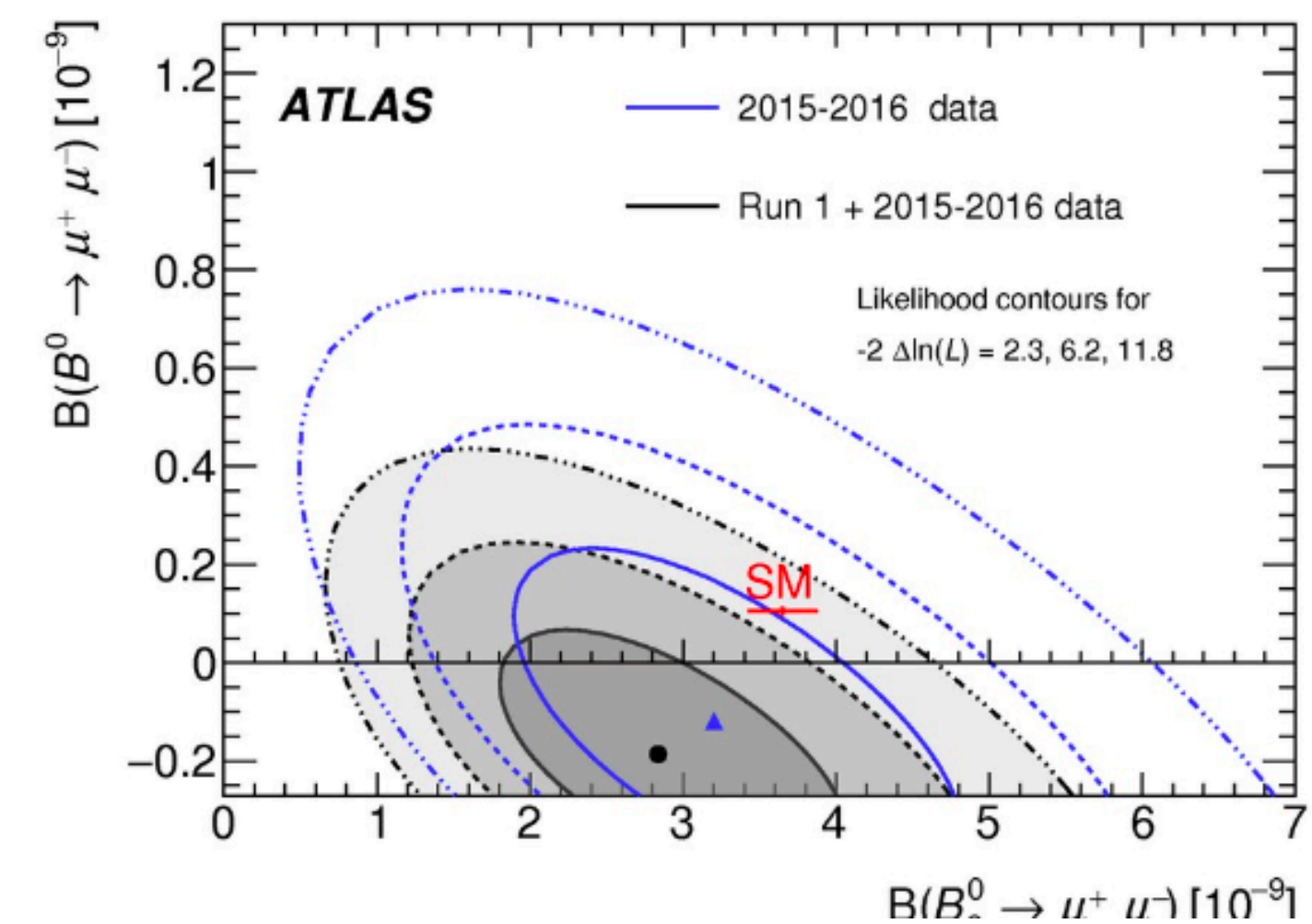
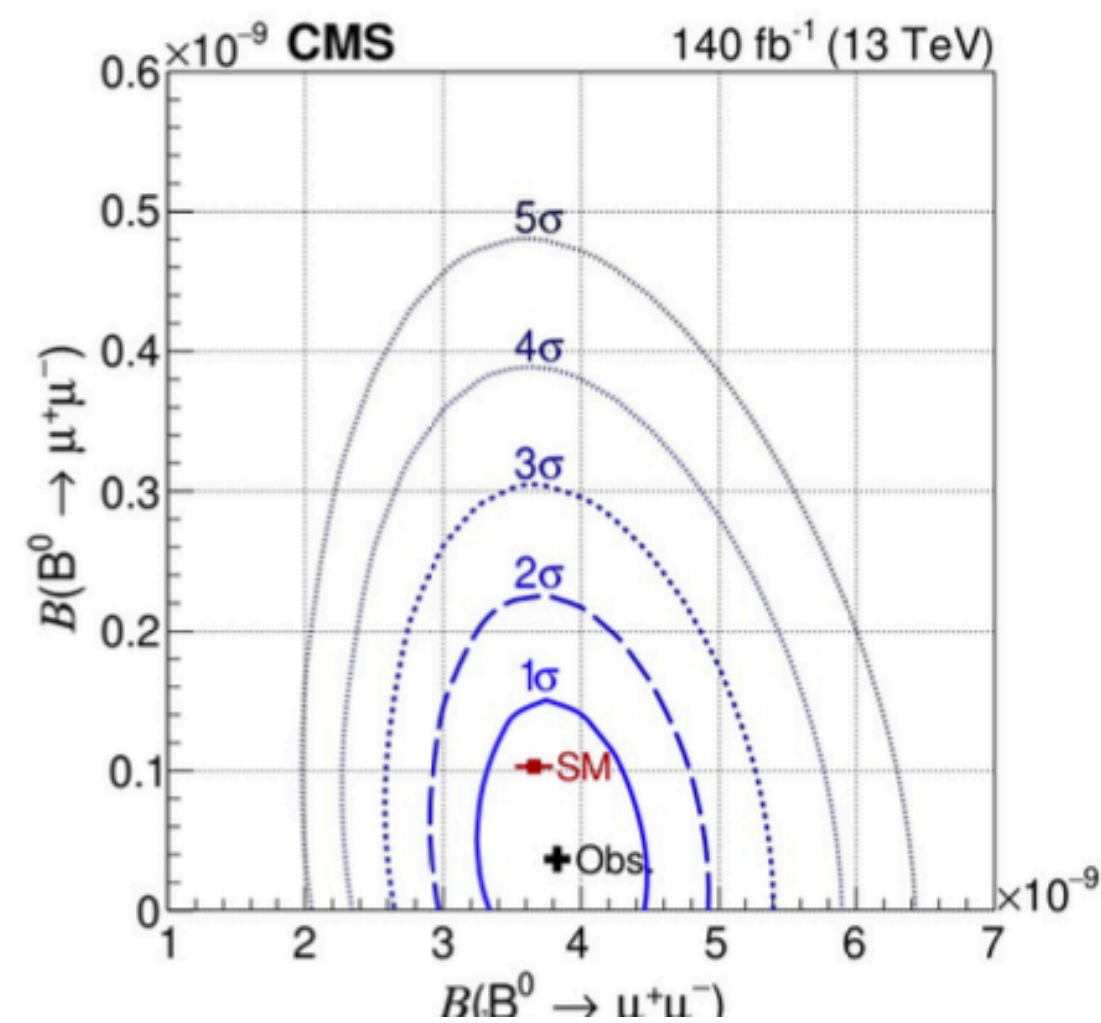
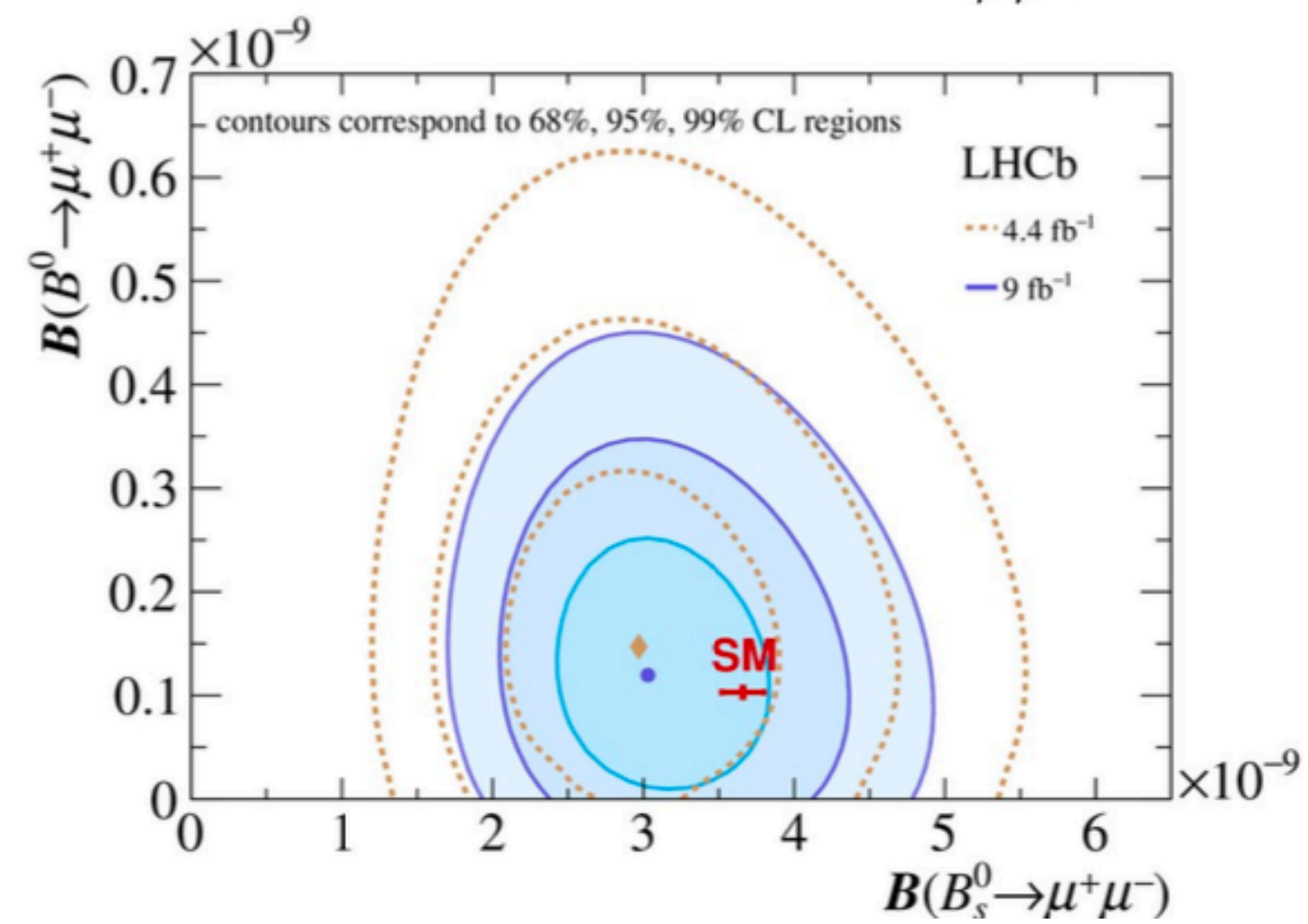
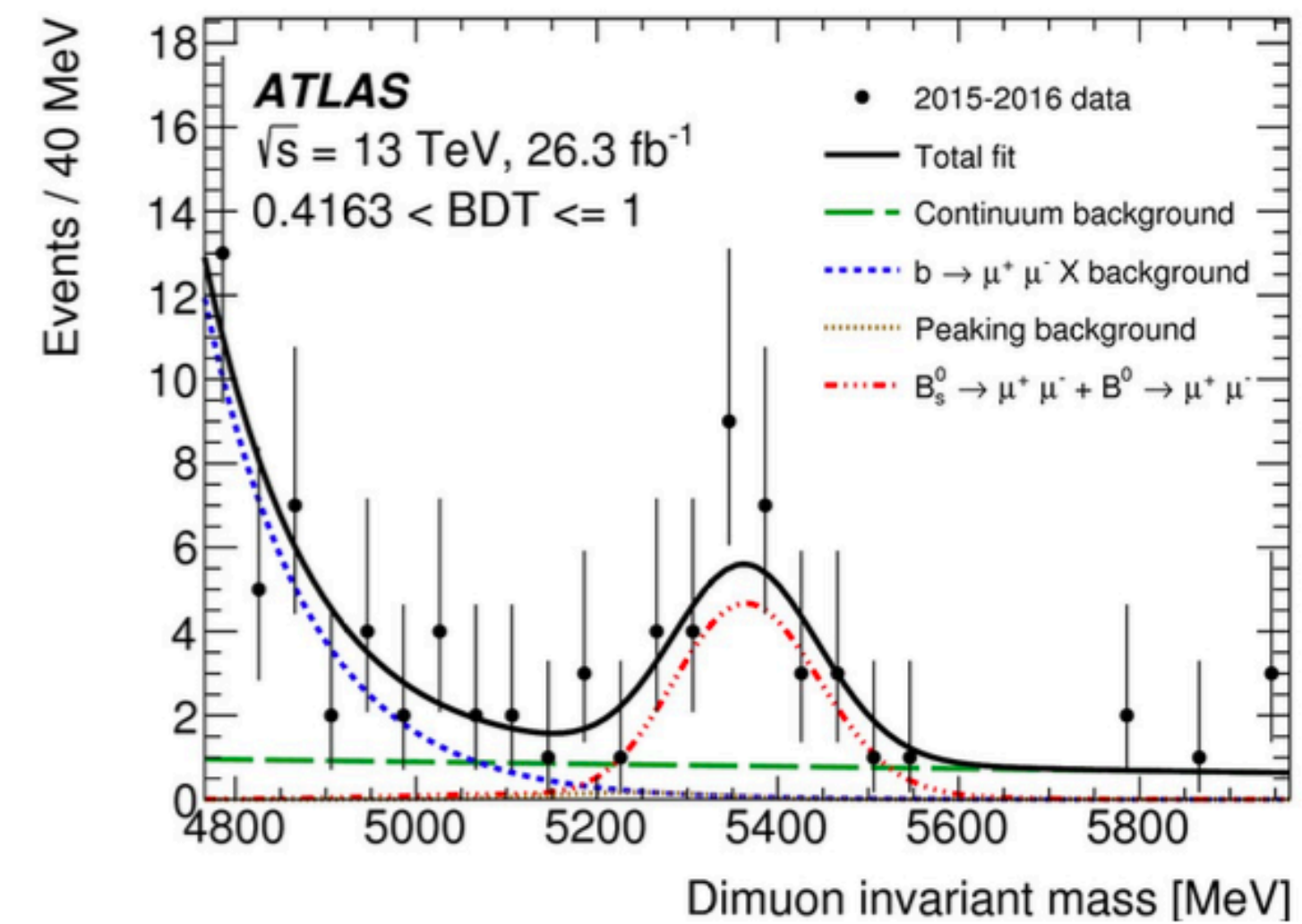
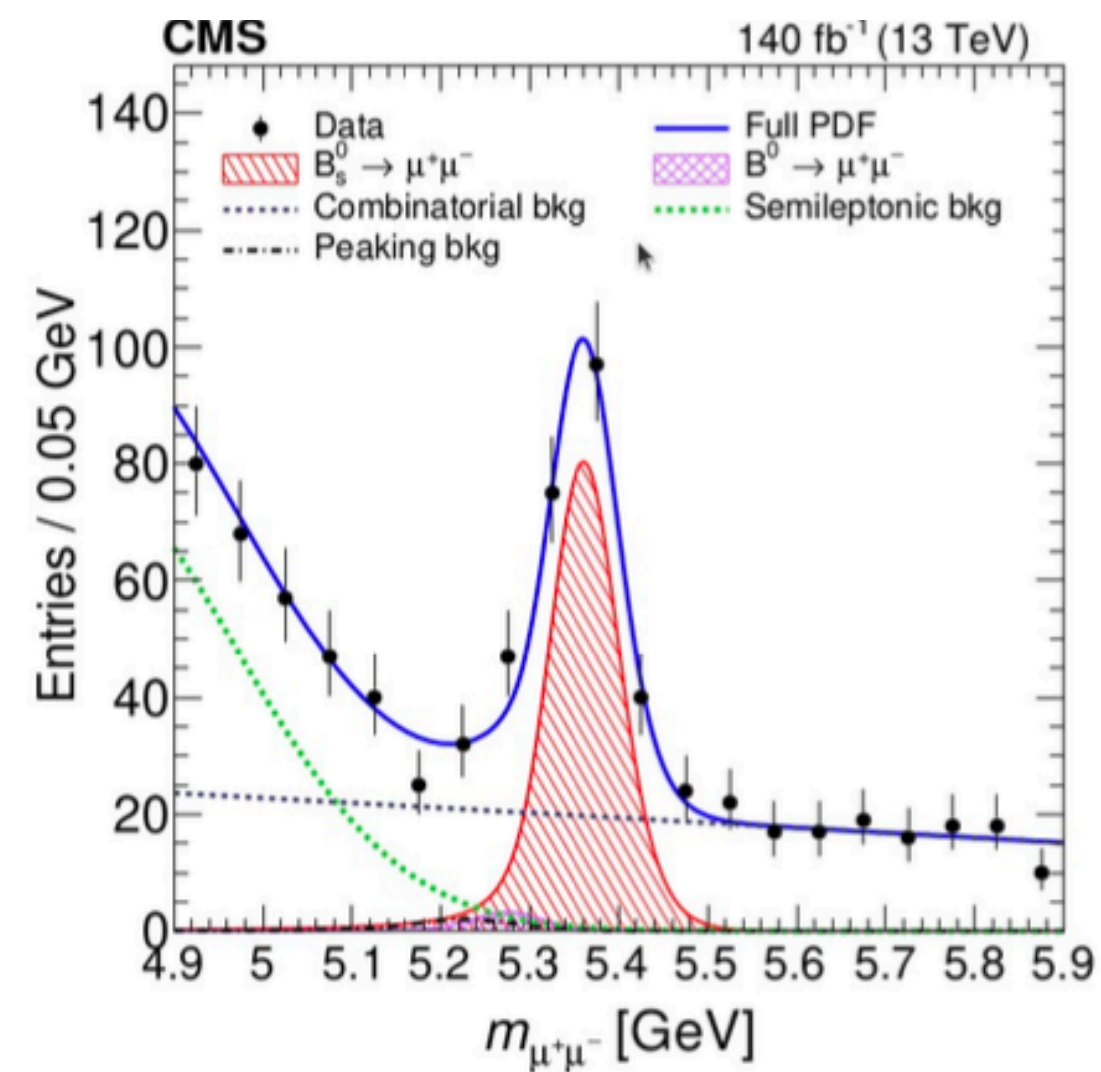
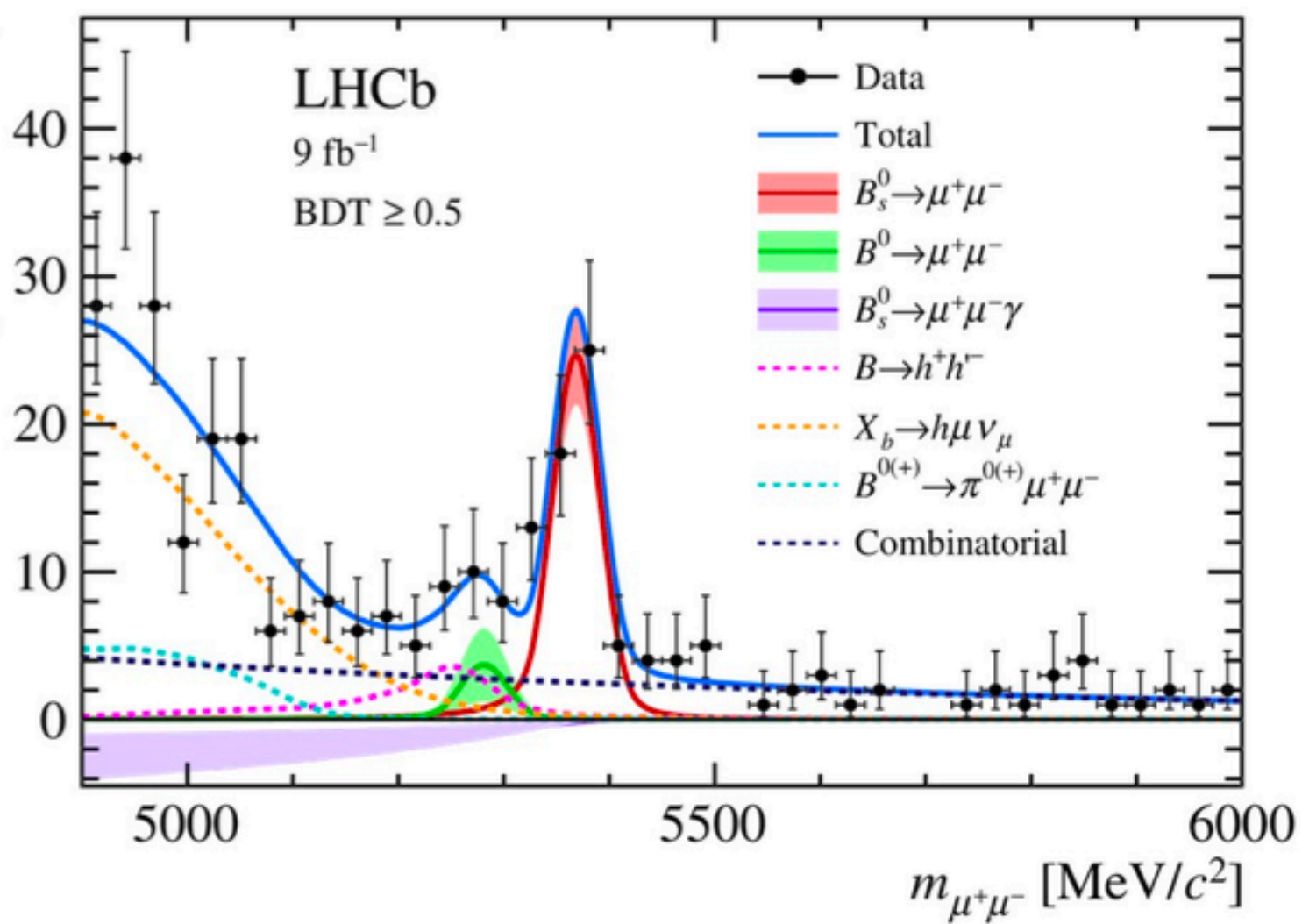
A glimpse of what goes on here

$B^0 \rightarrow K^{*0} e^+ e^-$
Very low q^2



What else? What happens if we look for ultra-rare decays?

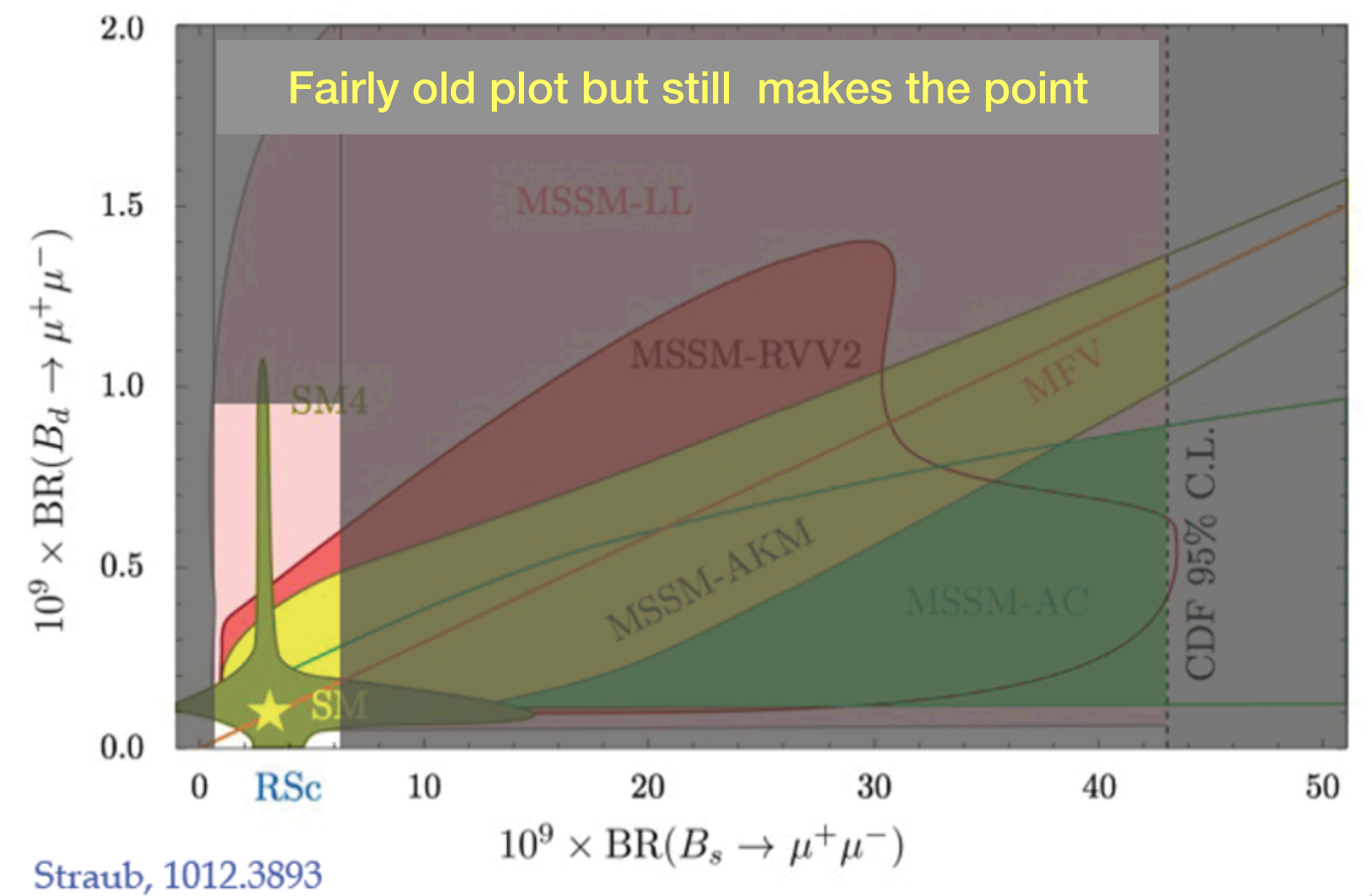
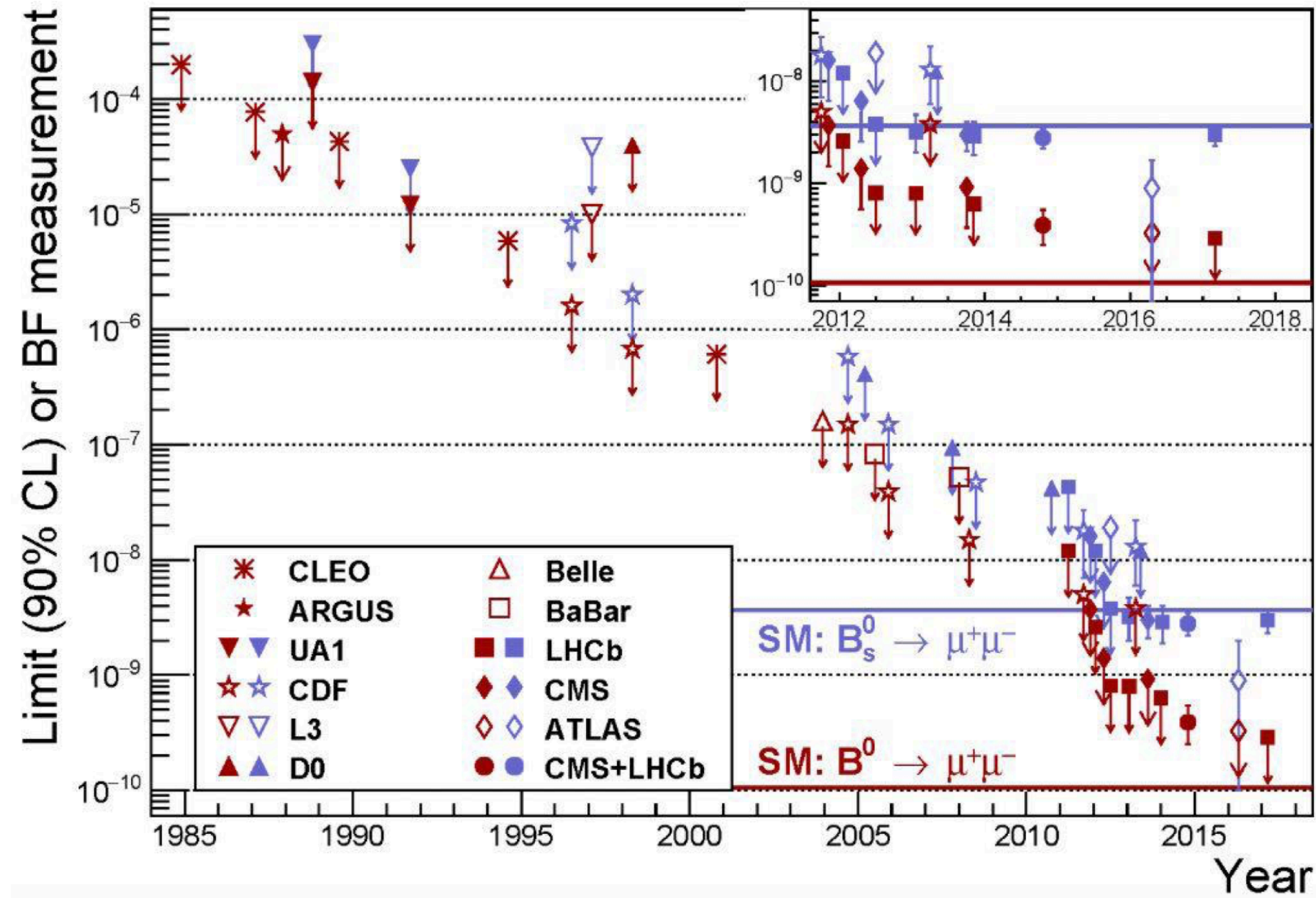
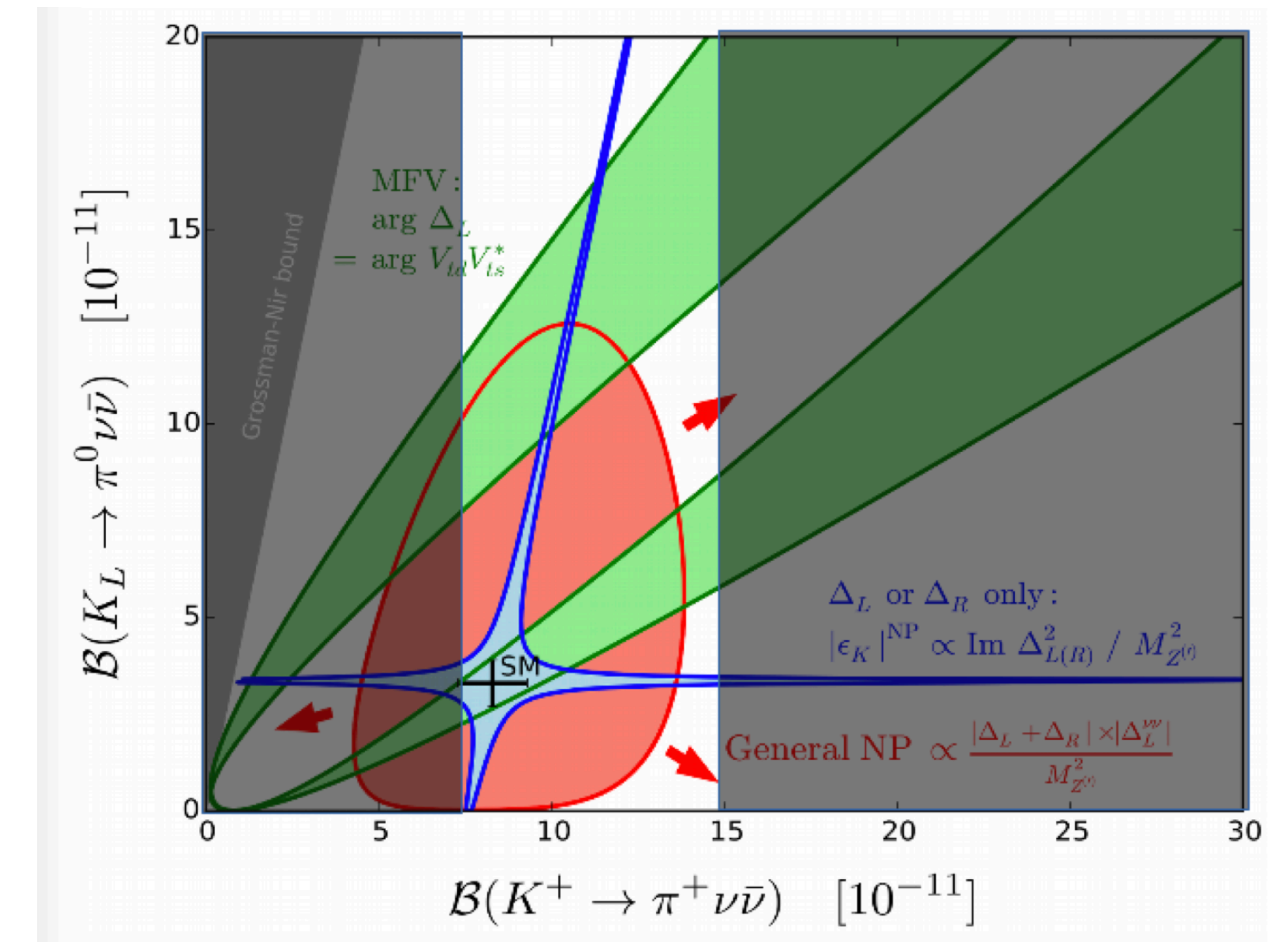
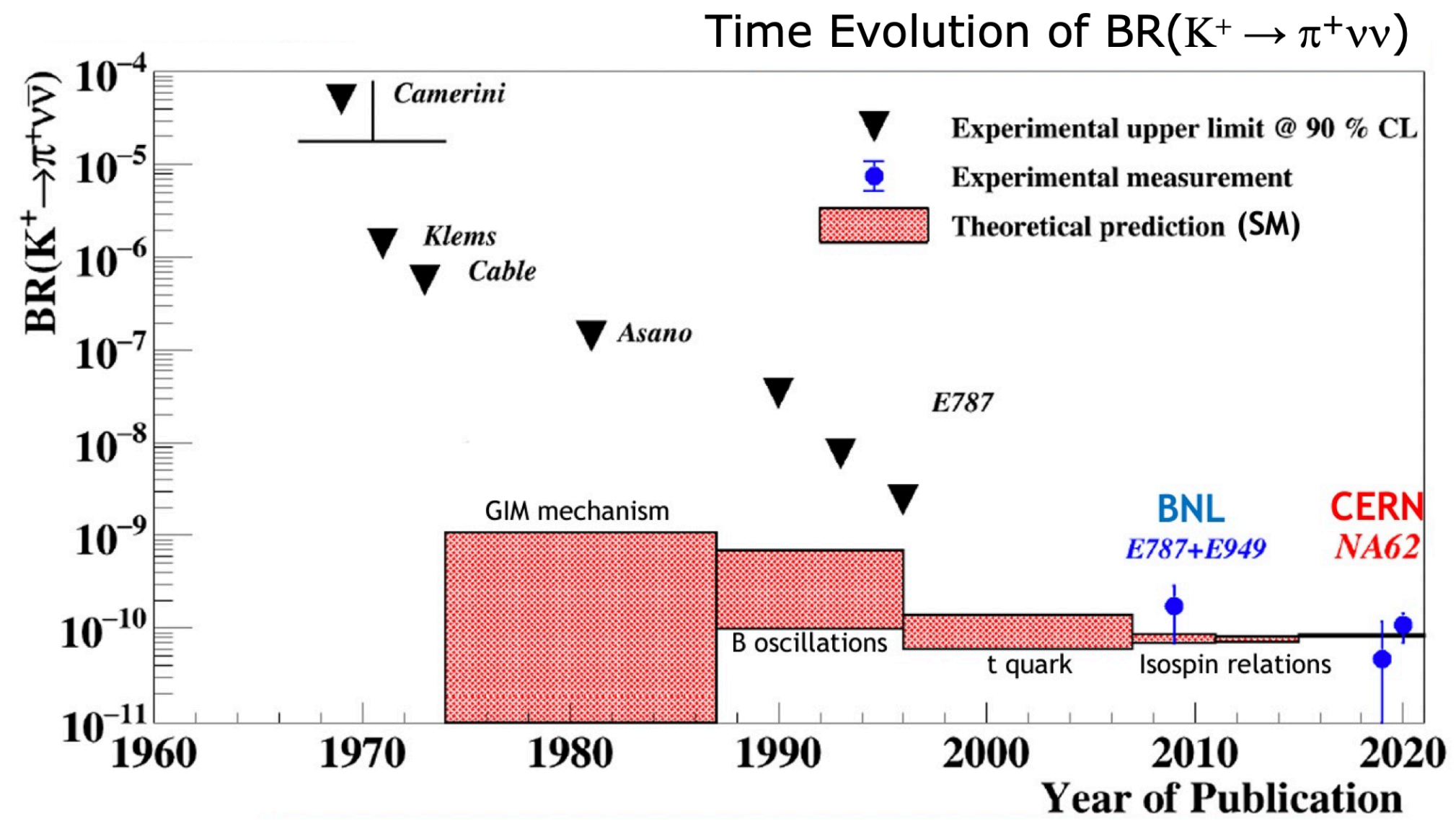




LHCb, PRL 128 (2022) 041801

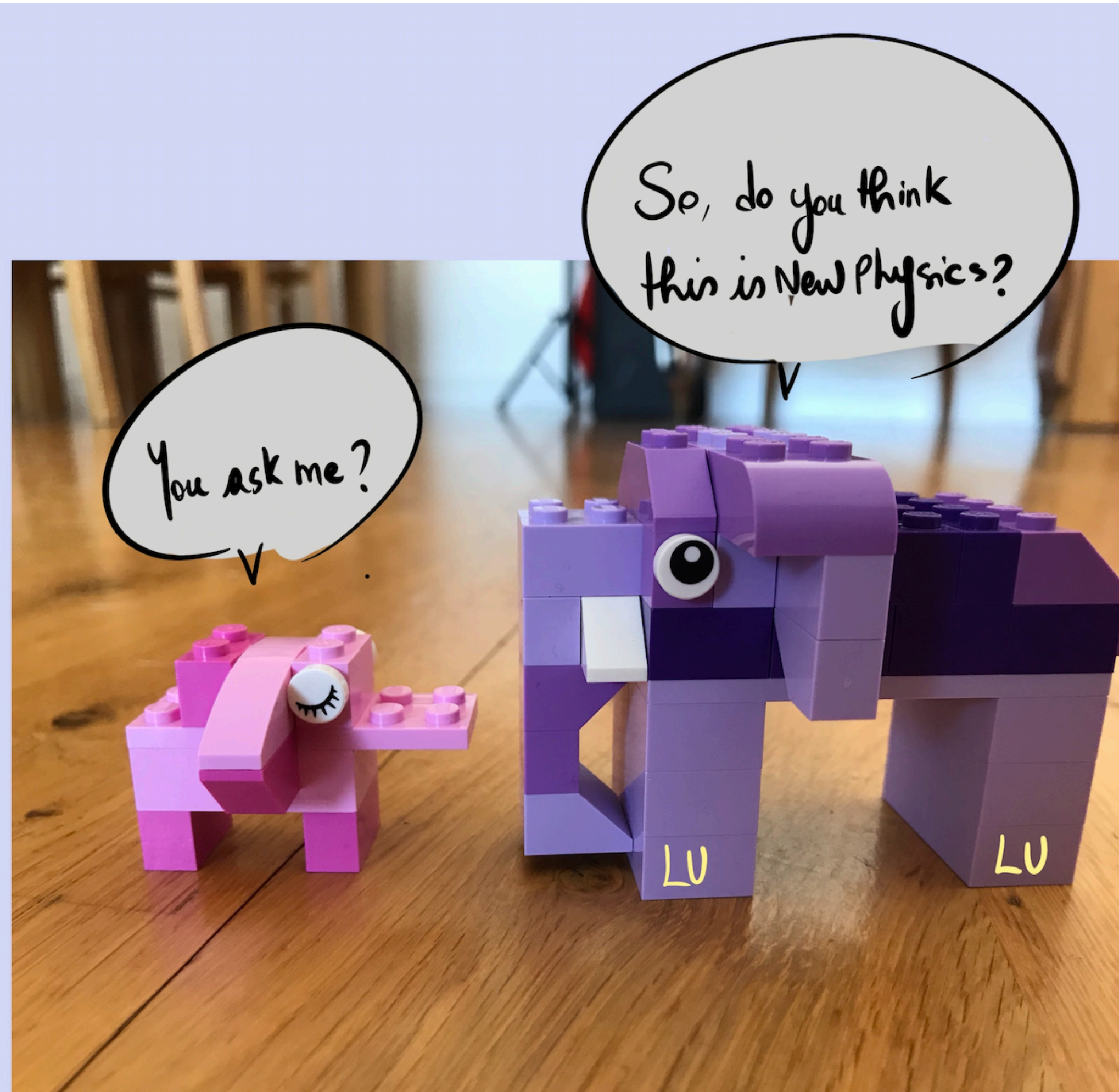
CMS, PL B842 (2023) 137955

ATLAS, JHEP 04 (2019) 098



Always be grateful to D.Straub for inventing Flavio

The idea behind a lepton universality test



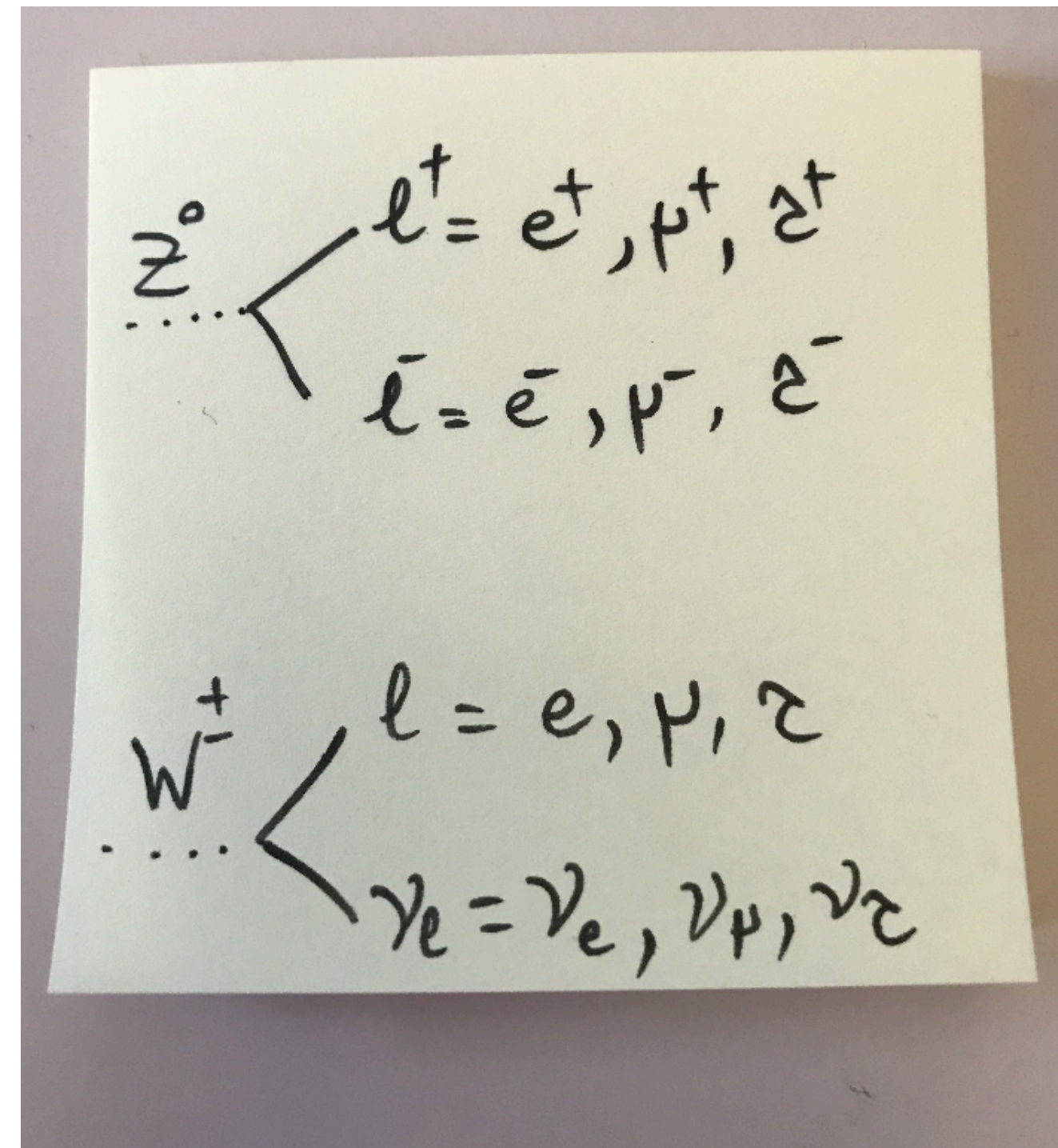
It's very simple
we expect the coupling to the leptons
to be the same

これはシンプル。

レプトンとの結合はどれも同じだと期待できます。
それをテストしてみようというわけです。

Lepton Universality tests

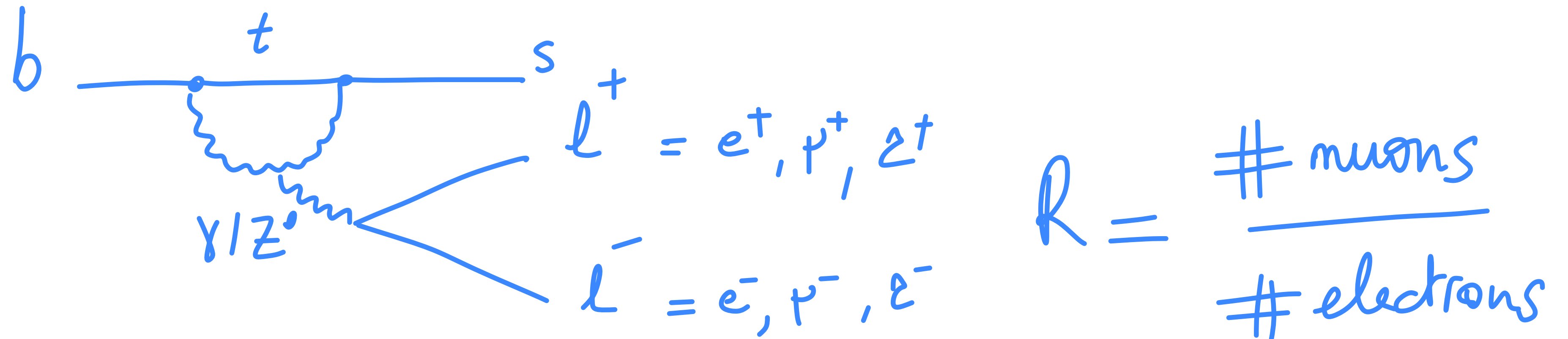
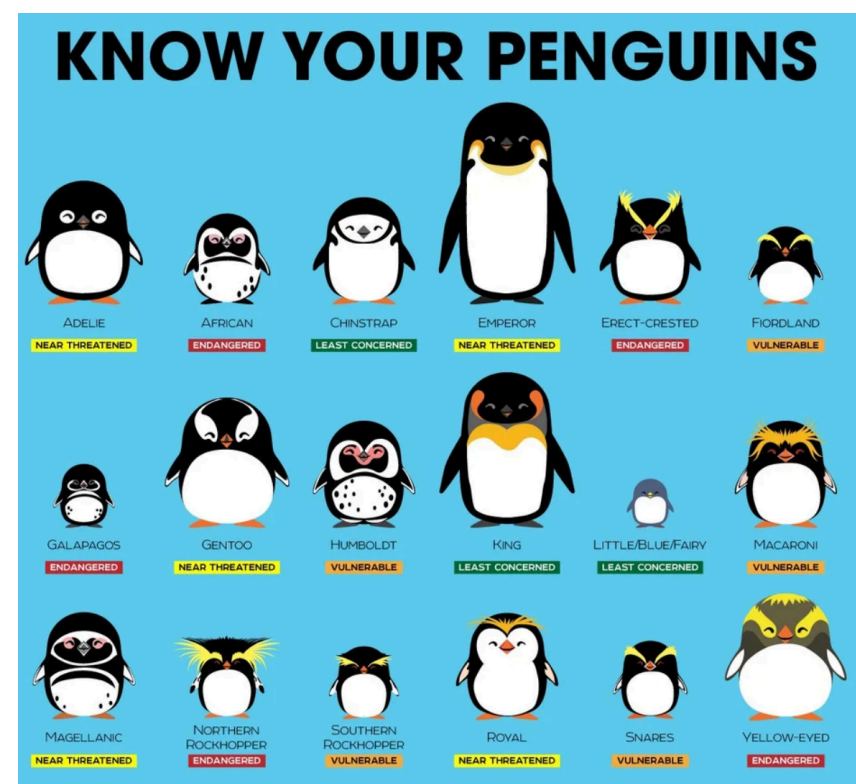
レプトン普遍性のテスト



From the PDG or equivalent :

$$\frac{\Gamma_{Z \rightarrow \mu^+ \mu^-}}{\Gamma_{Z \rightarrow e^+ e^-}} = 1.0009 \pm 0.0028,$$

$$\frac{\Gamma_{Z \rightarrow \tau^+ \tau^-}}{\Gamma_{Z \rightarrow e^+ e^-}} = 1.0019 \pm 0.0032.$$



“The” observable

$$R_H \equiv \frac{\int \frac{d\Gamma(B \rightarrow H \mu^+ \mu^-)}{dq^2} dq^2}{\int \frac{d\Gamma(B \rightarrow H e^+ e^-)}{dq^2} dq^2},$$

A powerful probe to look for NP in an indirect way.

Today, we discuss three papers: 1705.05802, 1903.09252, 2103.11769

The “Simplicity” of Lepton Universality test

Loop induced

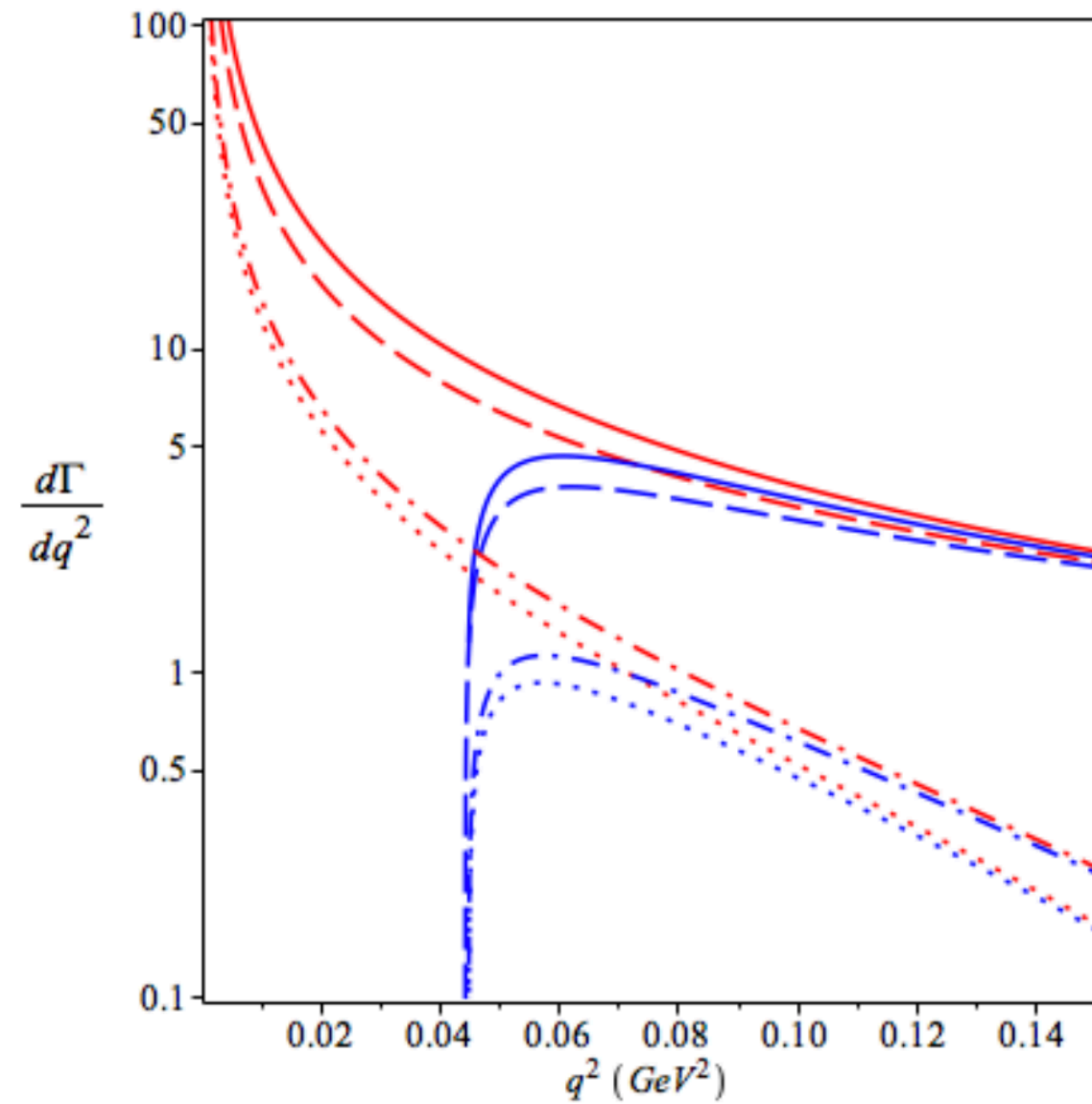
$$R_H \equiv \frac{\int \frac{d\Gamma(B \rightarrow H \mu^+ \mu^-)}{dq^2} dq^2}{\int \frac{d\Gamma(B \rightarrow H e^+ e^-)}{dq^2} dq^2},$$

Similar observables in charged currents

$$R_{D^*}^{(\tau/\mu)}[q_{\min}^2] = \frac{\int_{q_{\min}^2}^{q_{\max}^2} dq^2 \frac{d\mathcal{B}}{dq^2}(B \rightarrow D^* \tau \bar{\nu})}{\int_{q_{\min}^2}^{q_{\max}^2} dq^2 \frac{d\mathcal{B}}{dq^2}(B \rightarrow D^* \mu \bar{\nu})}$$

Tree level

What can we expect in the SM



1605.07633

$$R_{K^*}[1.1, 6.0]^{\text{SM}} = 1.00 \pm 0.01_{\text{QED}}$$

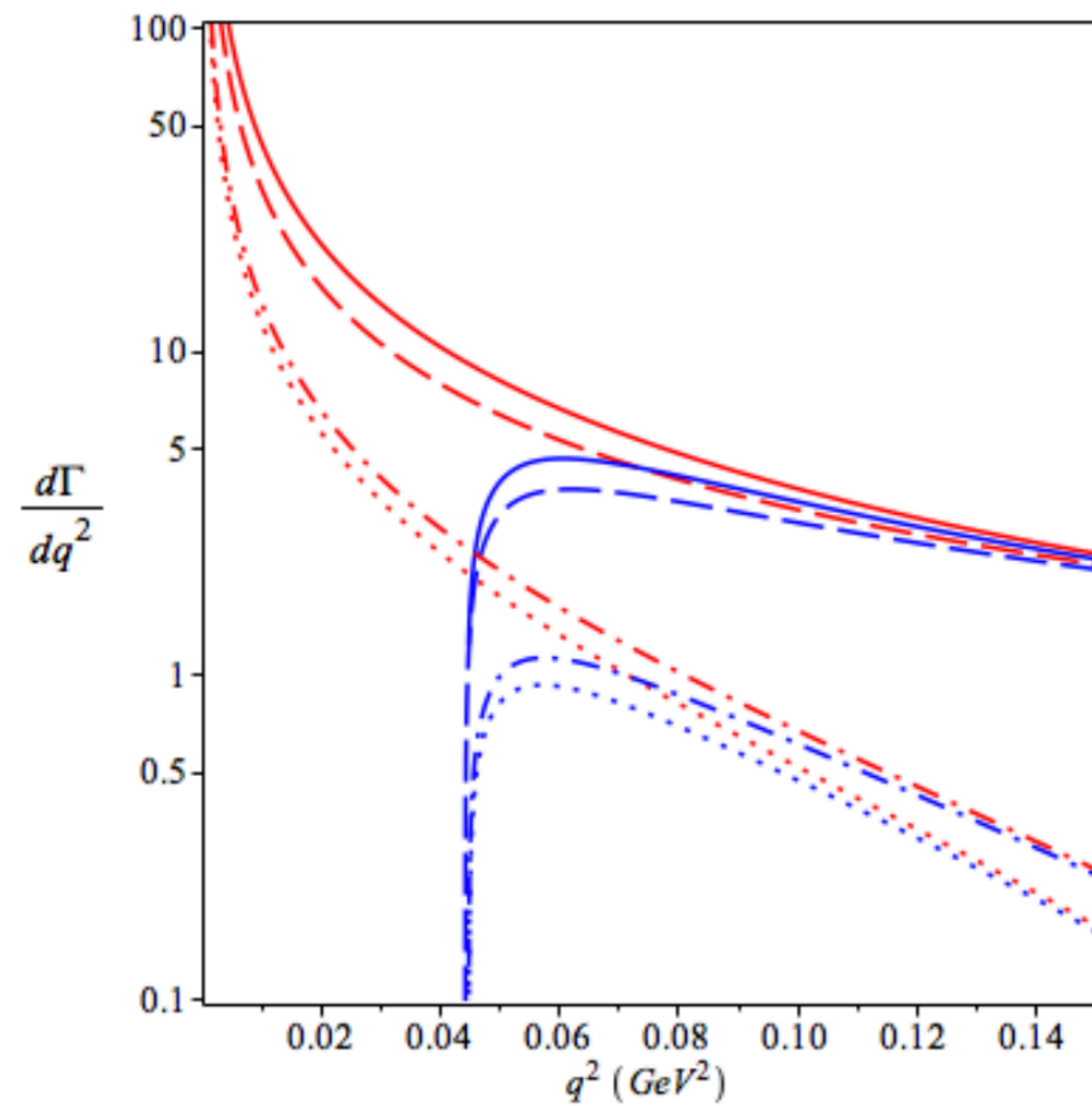
$$R_{K^+}[1.0, 6.0]^{\text{SM}} = 1.00 \pm 0.01_{\text{QED}}$$

Assuming V-A currents

$$R_\phi(B_s) \approx R_{\pi K}(B) \approx R(\Lambda_b)_\Lambda \approx R(\Lambda_b)_{pK} \approx \dots \approx R_K$$

1909.02519

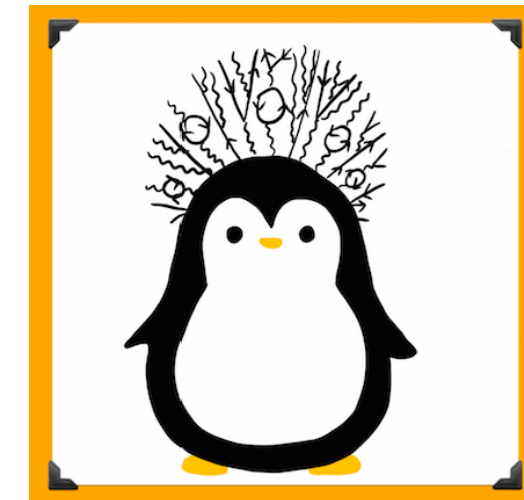
What can we expect in the SM



$$R_{K^*}[1.1, 6.0]^{\text{SM}} = 1.00 \pm 0.01_{\text{QED}}$$

$$R_{K^+}[1.0, 6.0]^{\text{SM}} = 1.00 \pm 0.01_{\text{QED}}$$

$$R_\phi(B_s) \approx R_{\pi K}(B) \approx R(\Lambda_b)_\Lambda \approx R(\Lambda_b)_{pK} \approx \dots \approx R_K$$



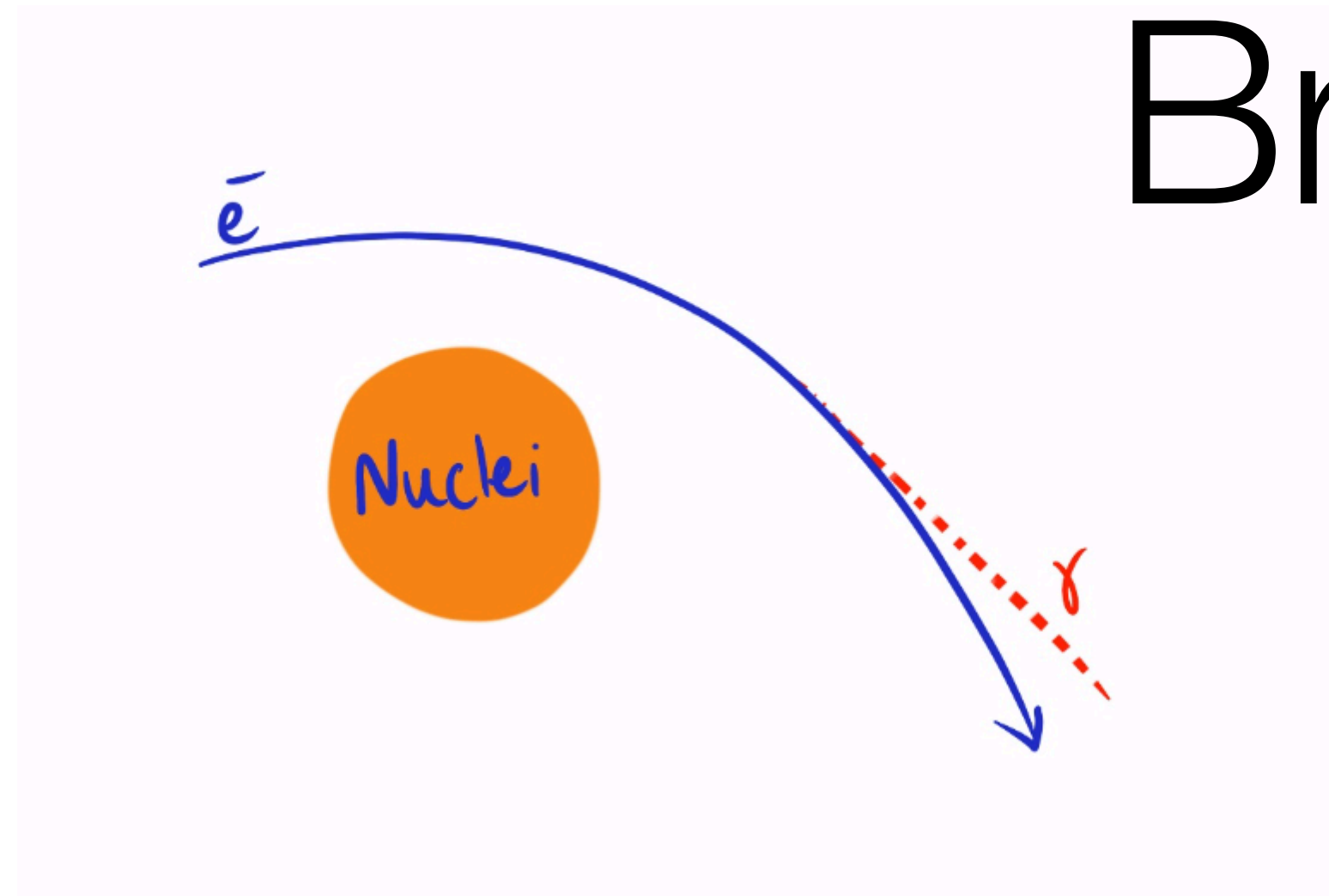
1605.07633

1909.02519

Why are electrons complicated?



Bremsstrahlung



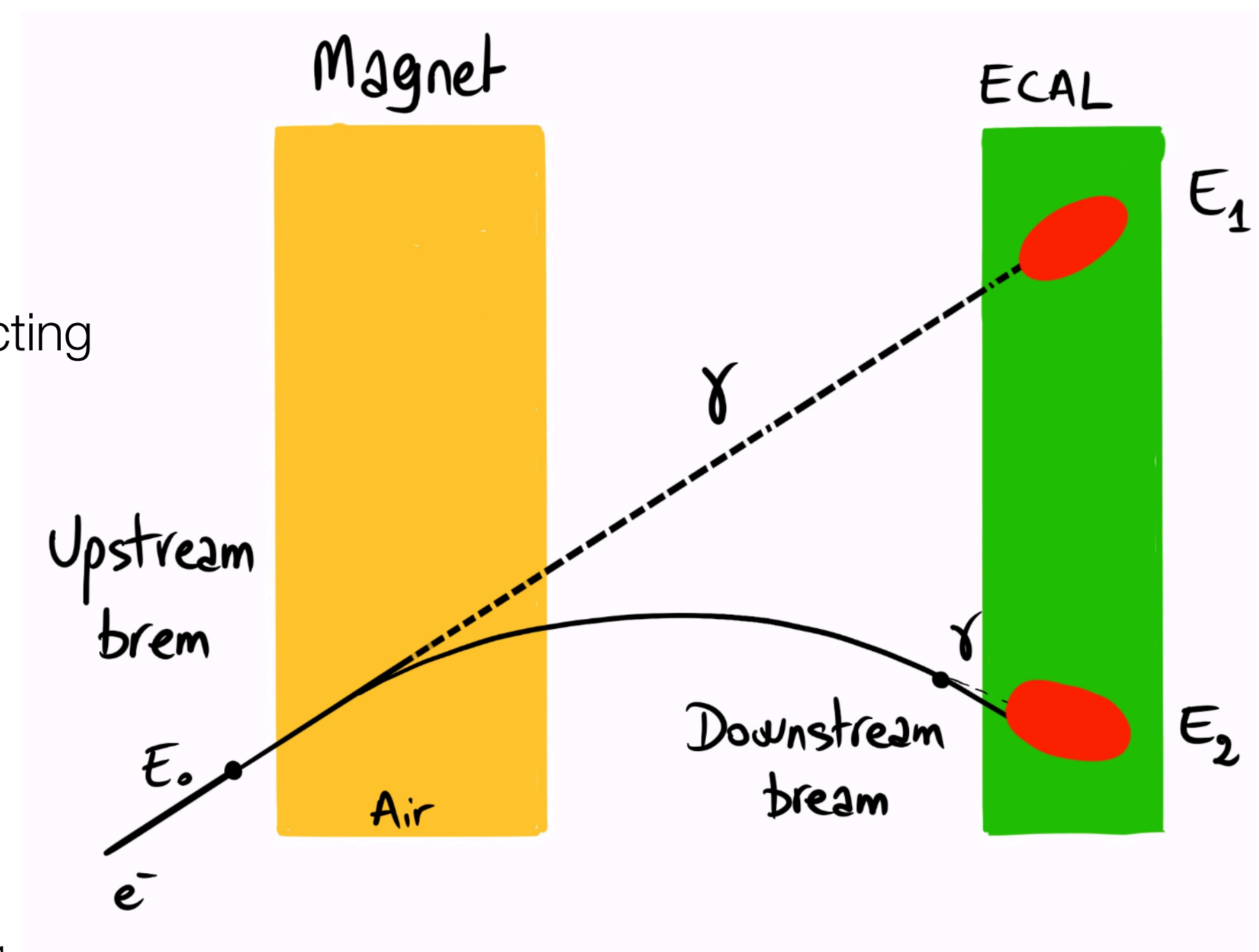
$$\sigma \propto 1/m_l^2$$

$$\text{Energy loss} \propto E_e$$

$$\text{Energy loss} \propto \text{material}$$

Match electron tracks to photon clusters in the ECAL
Correct electron momenta by “attaching” photons.

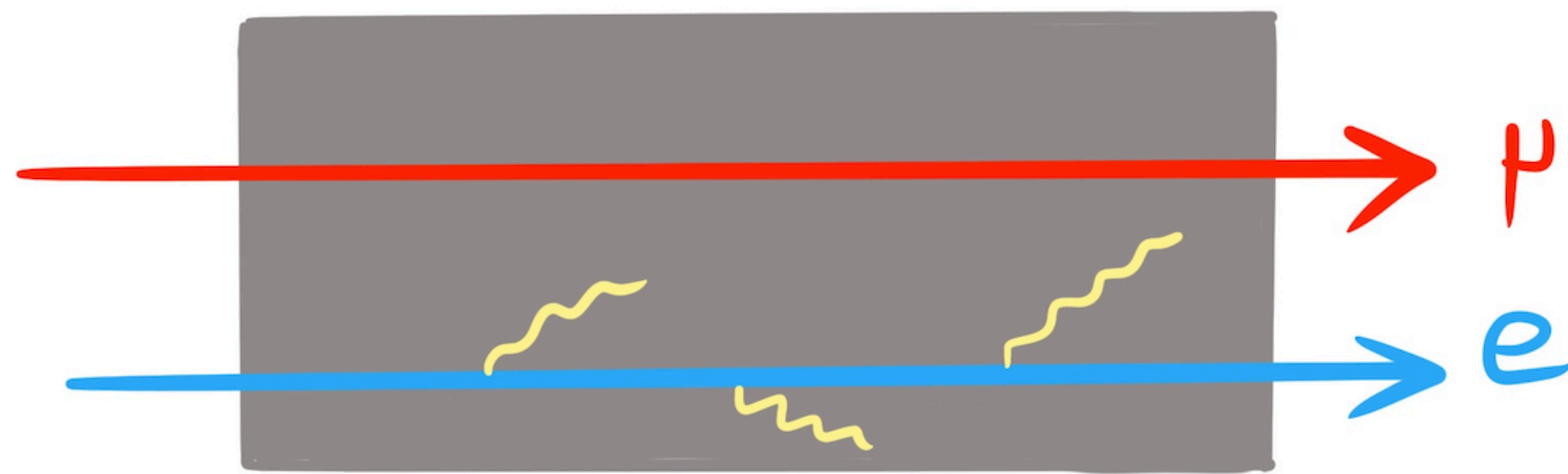
Three categories of events: 0, 1, > 1 photons
Different invariant mass shapes due to under- or over-correcting
ECAL resolution is worse than tracker.
Bin migration included in systematics.



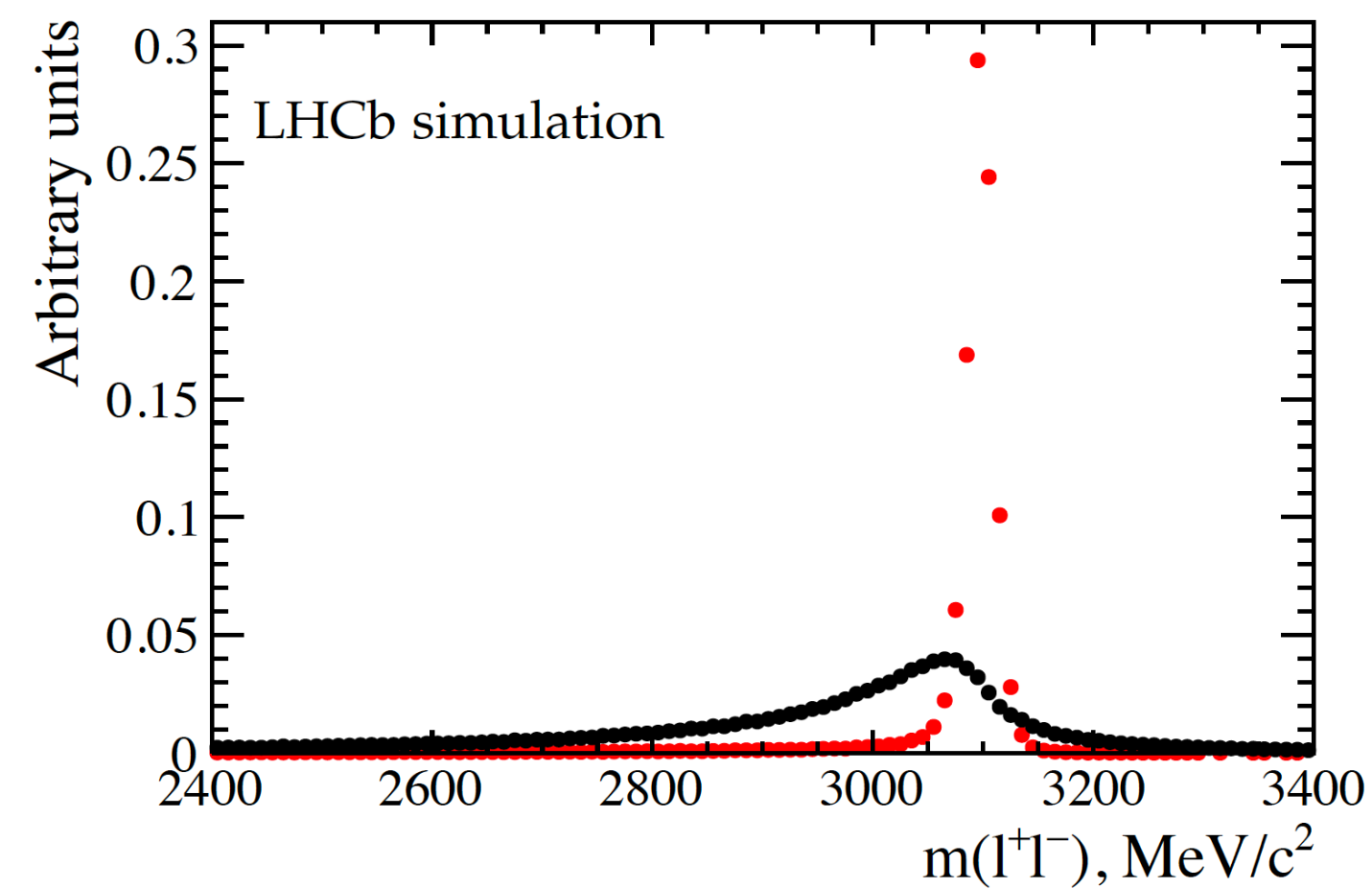
Electrons vs muons

Even after Bremsstrahlung recovery, electrons still have degraded momentum, mass, q^2 resolution.

Particle ID and track reconstruction efficiencies also larger for muons than for electrons.

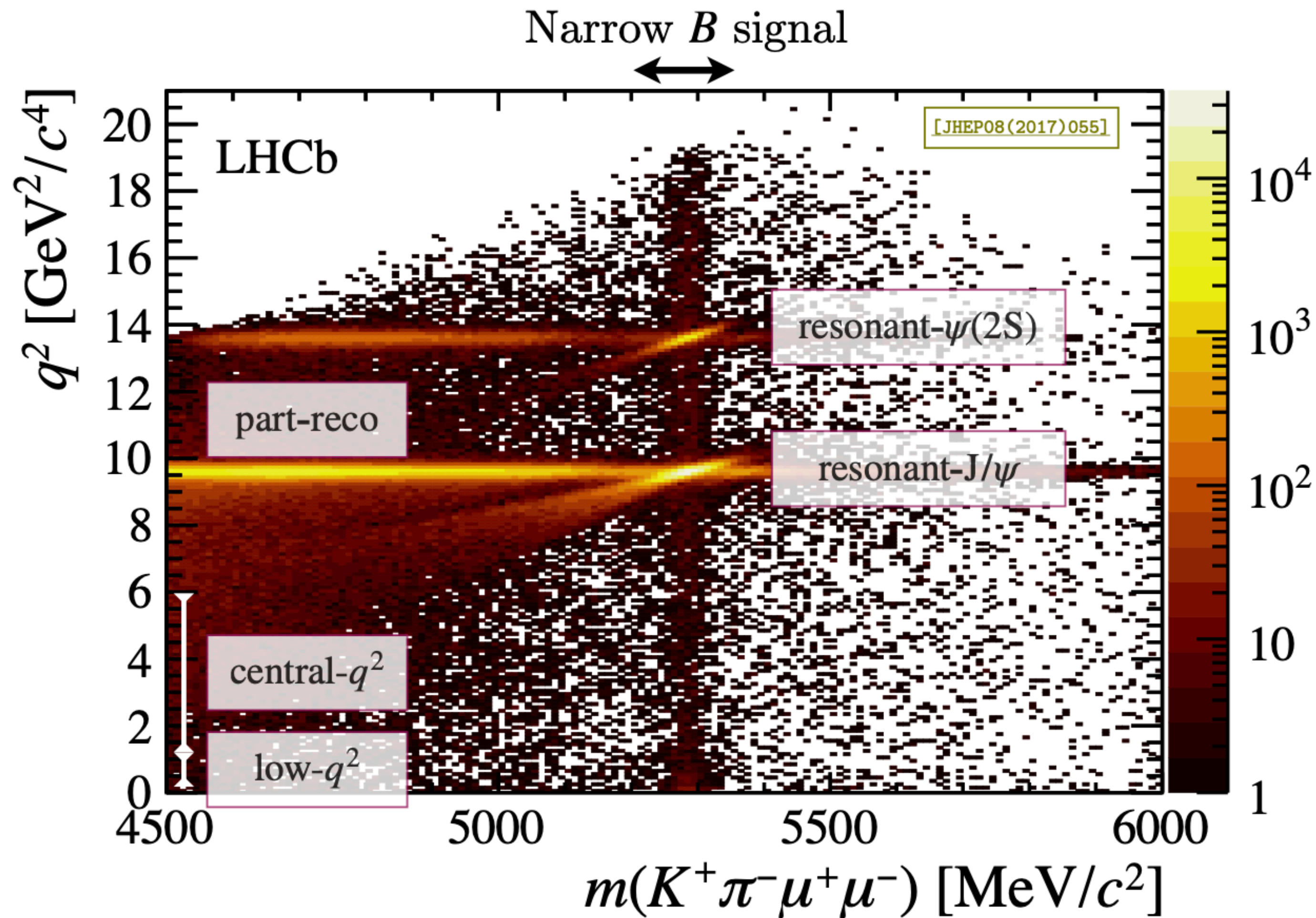


Get the differences between
electron and muon efficiencies
fully under control



From Vitalii Lisovskyi my former PhD student

What does the data look like?



What is actually measured is

$$R_{K,K^*}(q_a^2, q_b^2) = \frac{\int_{q_a^2}^{q_b^2} \frac{d\Gamma(B^{(+,0)} \rightarrow K^{(+,*0)} \mu^+ \mu^-)}{dq^2} dq^2}{\int_{q_a^2}^{q_b^2} \frac{d\Gamma(B^{(+,0)} \rightarrow K^{(+,*0)} e^+ e^-)}{dq^2} dq^2} \times \frac{\Gamma(J/\psi \rightarrow e^+ e^-)}{\Gamma(J/\psi \rightarrow \mu^+ \mu^-)}$$

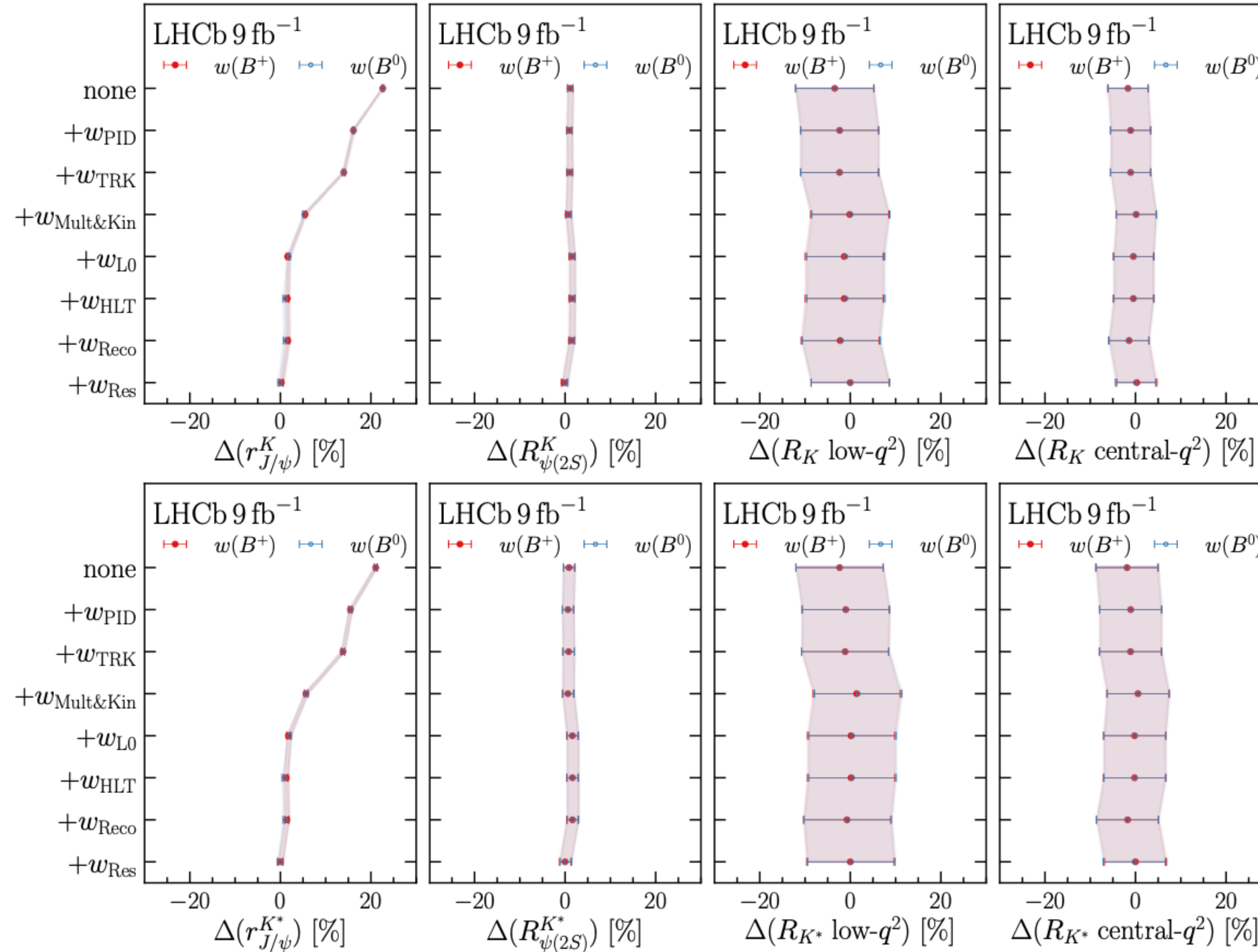
Measured to be 1 Phys. Lett. B731, 227 (2014)

$$R_{(K,K^*)} = \frac{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \rightarrow K^{(+,*0)} \mu^+ \mu^-)}{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \rightarrow K^{(+,*0)} e^+ e^-)} \times \frac{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \rightarrow K^{(+,*0)} J/\psi(e^+ e^-))}{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \rightarrow K^{(+,*0)} J/\psi(\mu^+ \mu^-))}$$

$r_{J/\psi}^{-1} = 1$

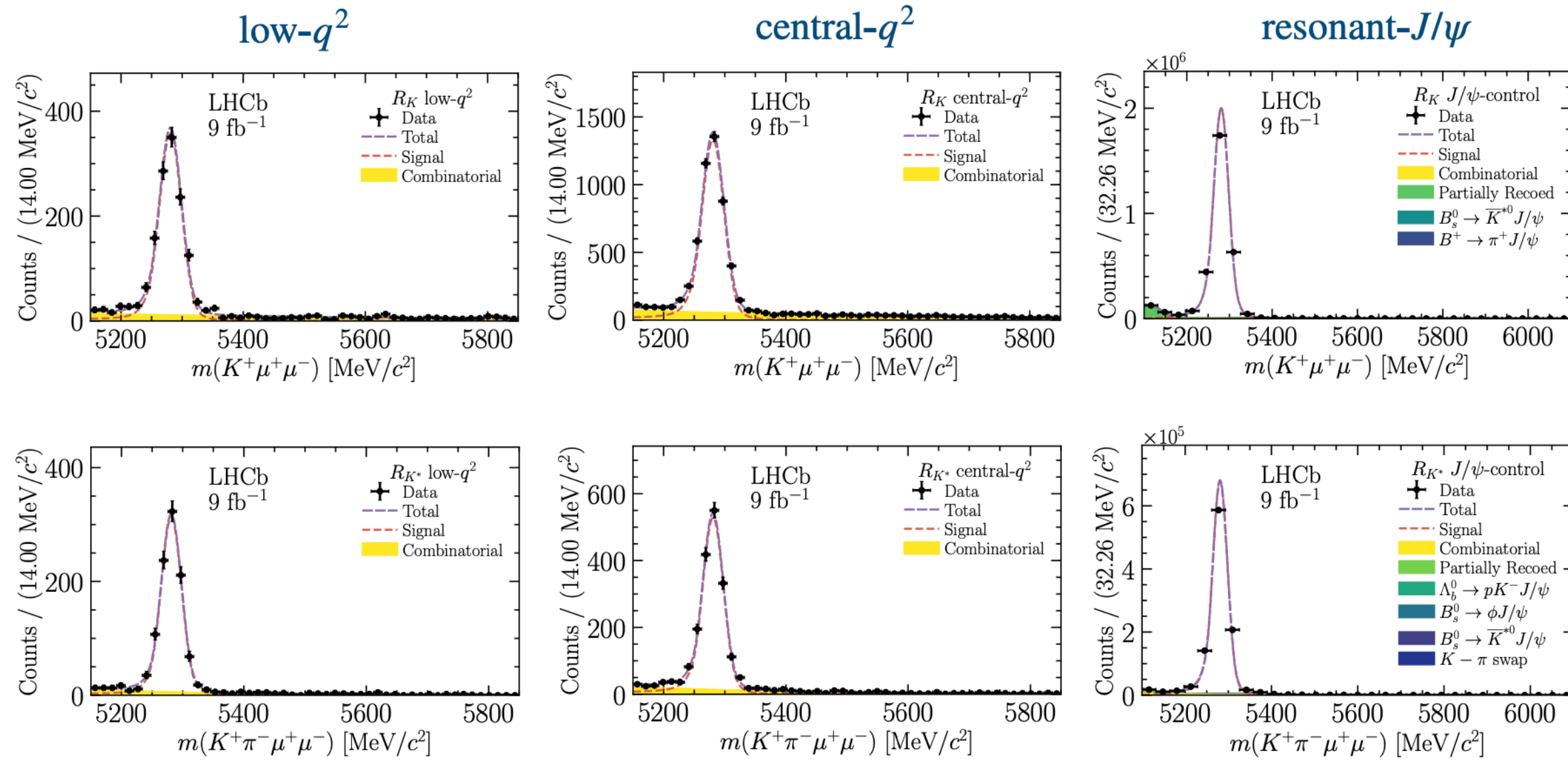
Try to calibrate as much as possible from data

Getting the single/double ratios correct is very painful but it pays off



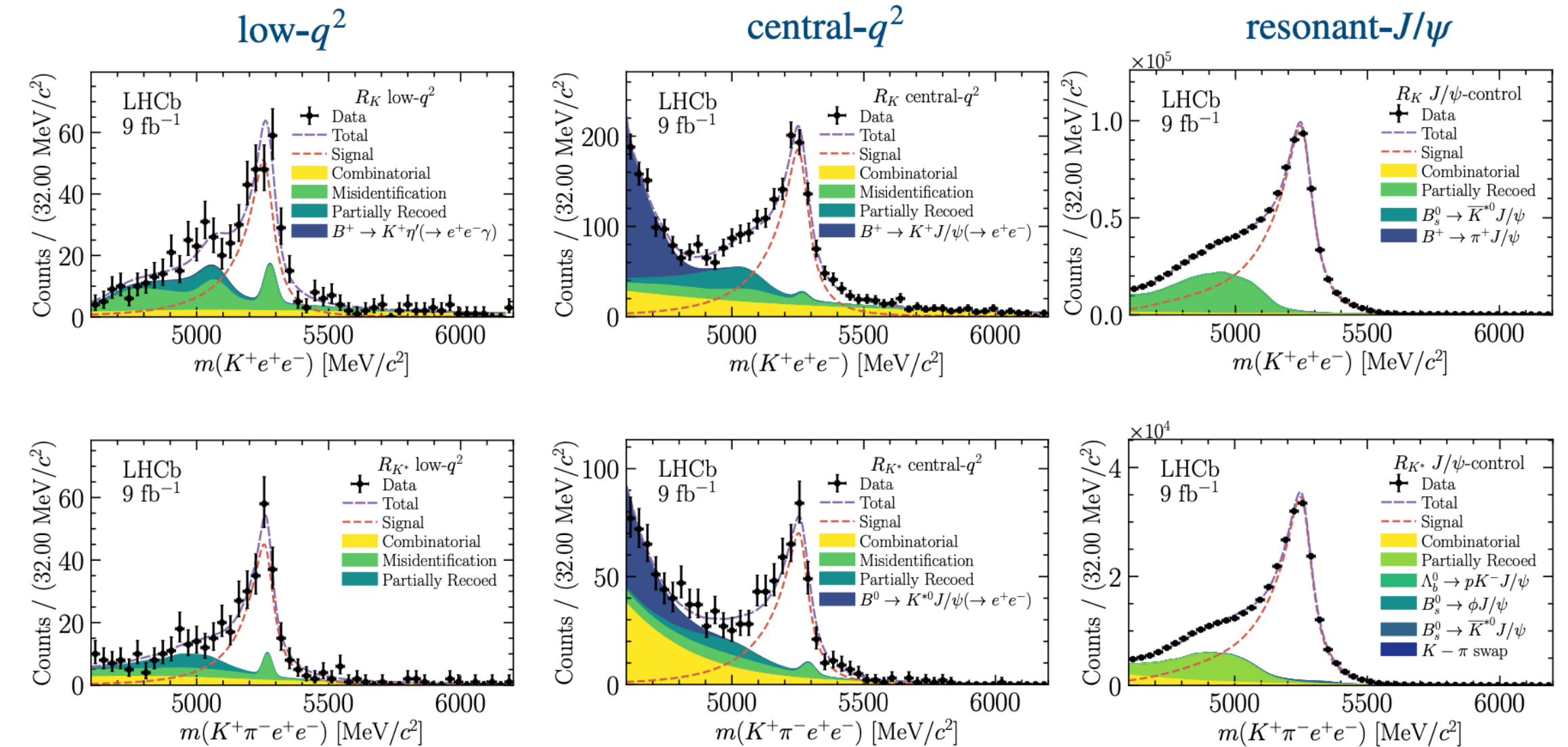
Checked also in various bins of kinematic etc.

Now we look at the data



Once again the muons are a day at the beach

The electrons less so



The cold shower

Taking a cold shower is good for your health, here's why

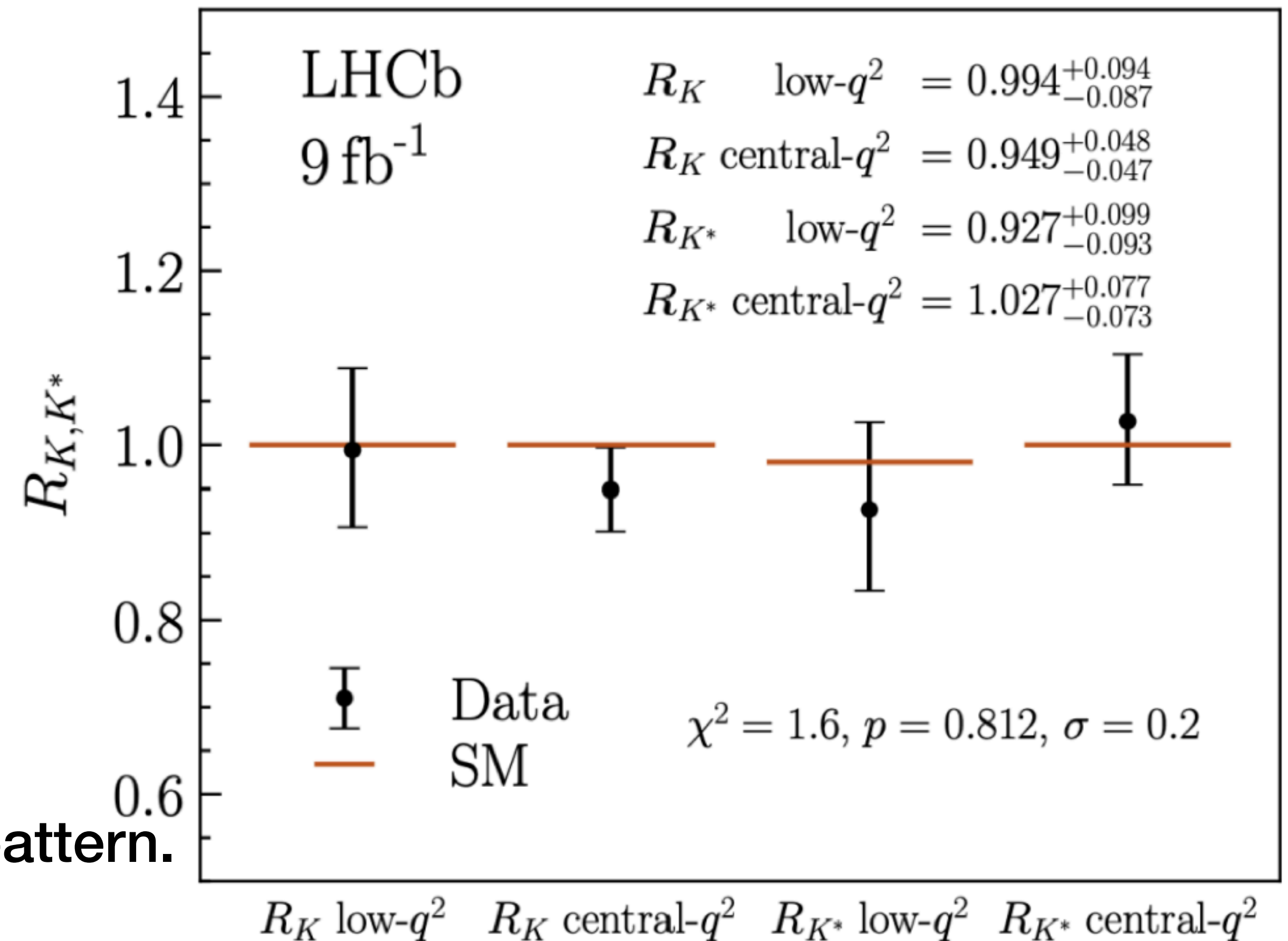
It's widely known that a hit of cold water can do wonders for your body. [Swedish bathhouses](#) are among an age-old Nordic healing tradition, the world's [happiest people](#) go ice swimming, and [Brits swear](#) by a jolt of cold water for a mood-boost. But when all is said and freezing, what good does a cold shower actually do? We break down four reasons why

Why a cold shower?

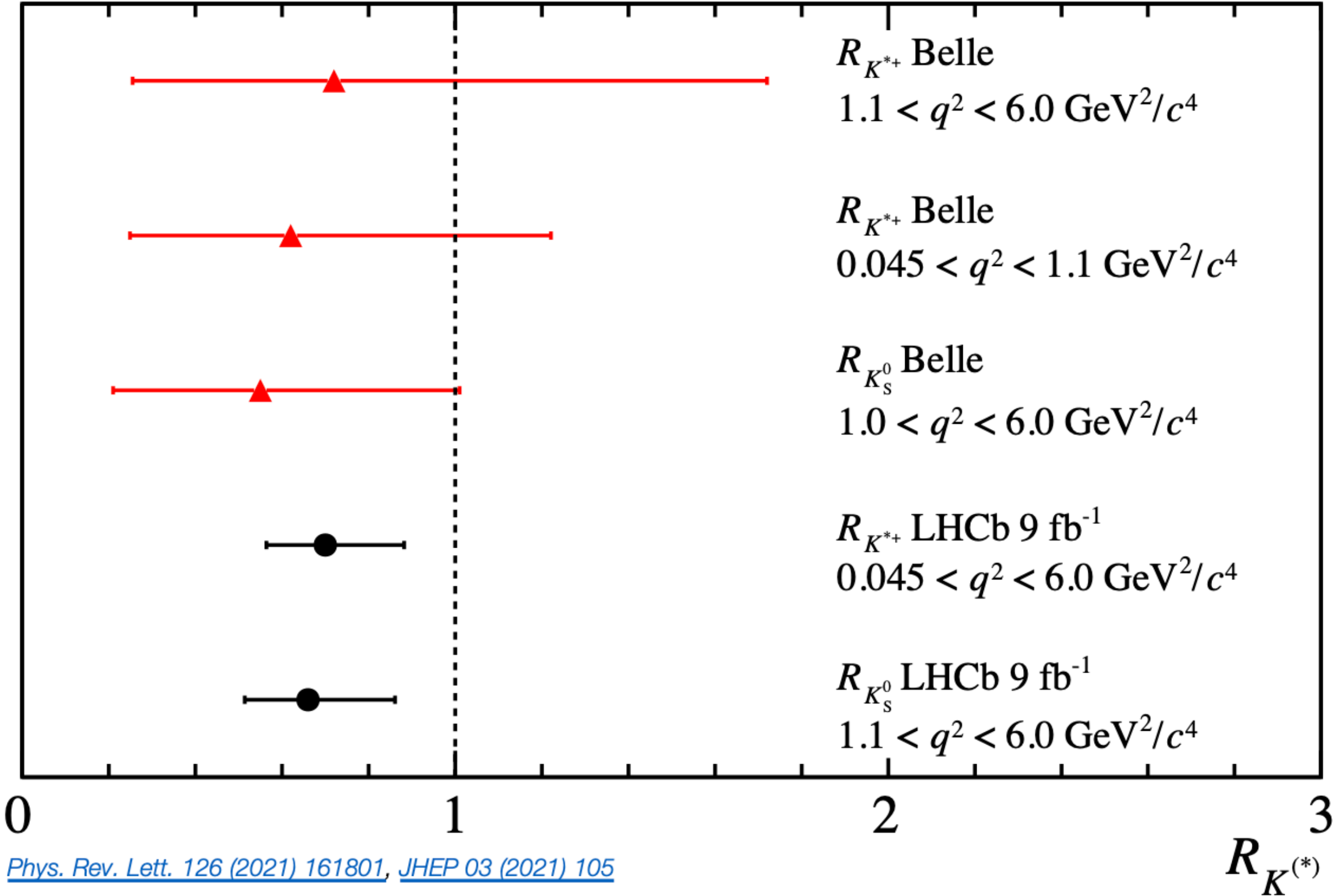
The result before that indicated a consistent pattern.

But !

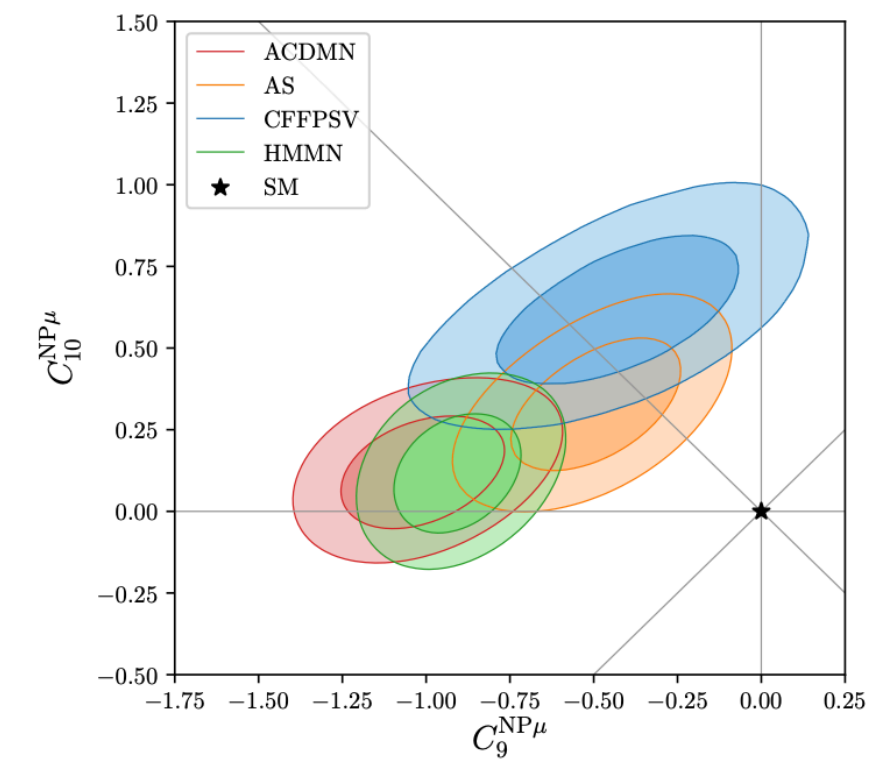
These results are still statistically limited...



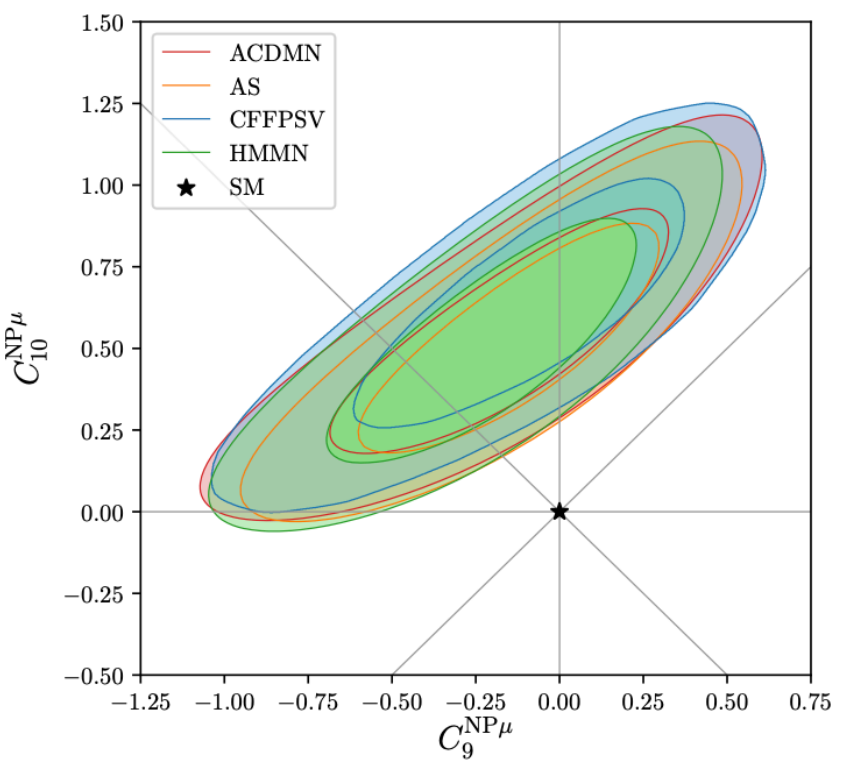
Just for reference - the pre-cold shower picture



2-dimensional fits



global fit



fit to LFU observables + $B_s \rightarrow \mu\mu$

B. Capdevila, M. Fedele, S. Neshatpour, P. Stangl

Flavour Anomaly Workshop, 20 Oct. 2021

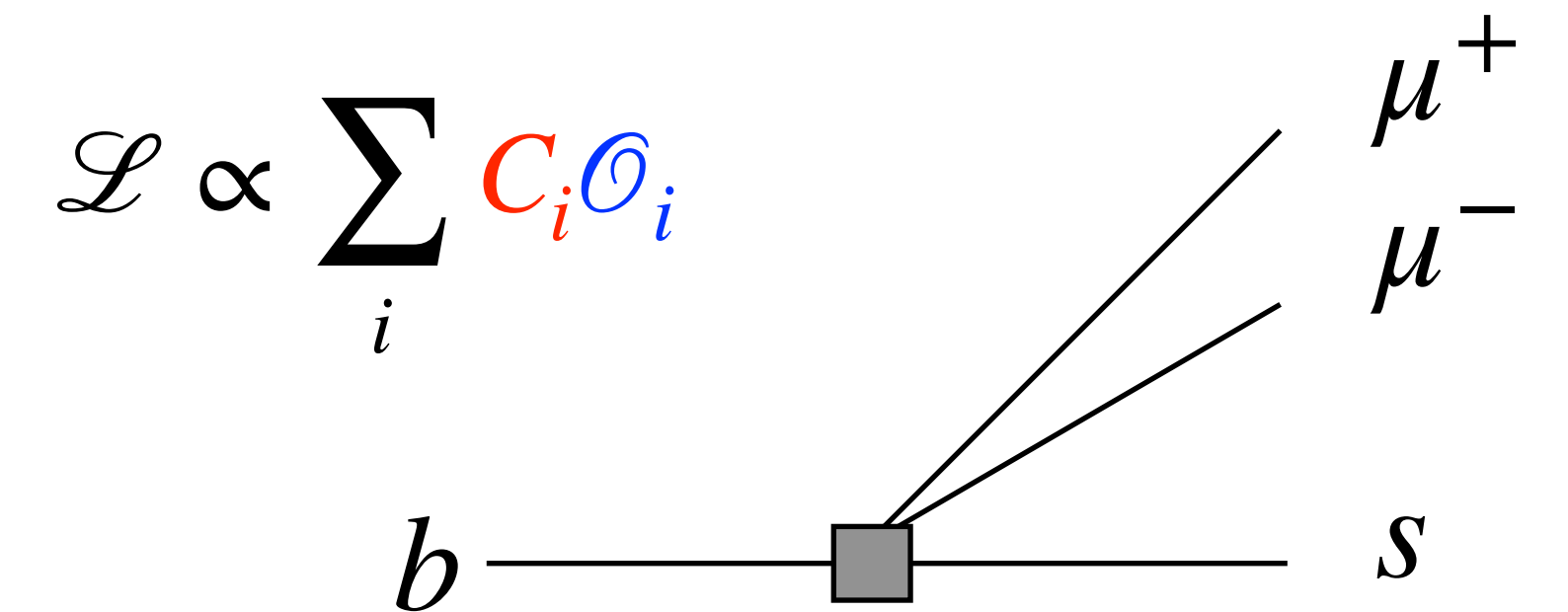
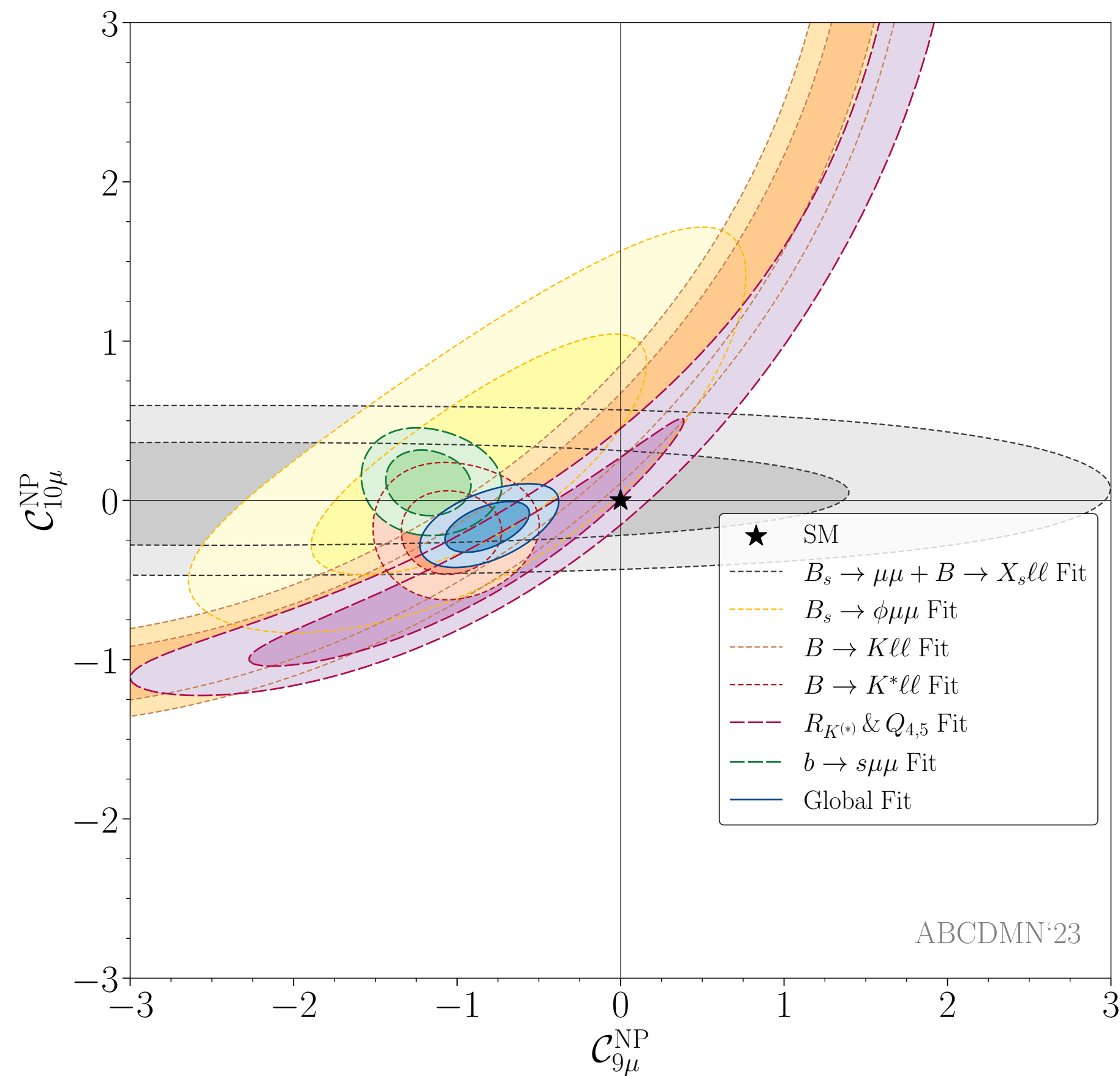
16/18



Local and
nonlocal effects
in $b \rightarrow s\ell^+\ell^-$

$B^0 \rightarrow K^{*0} \mu^+ \mu^-$: A very brief history

Tensions in $b \rightarrow s \mu^+ \mu^-$ decays have persisted for ~10 years



Electromagnetic	$\mathcal{O}_7^{()}$	$(\bar{s} \sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$
Vector	$\mathcal{O}_9^{()}$	$(\bar{s} \gamma_\mu P_{L(R)} b) (\bar{\ell} \gamma^\mu \ell)$
Axial vector	$\mathcal{O}_{10}^{()}$	$(\bar{s} \gamma_\mu P_{L(R)} b) (\bar{\ell} \gamma^\mu \gamma_5 \ell)$

Current measurements point to an anomalous vector contribution

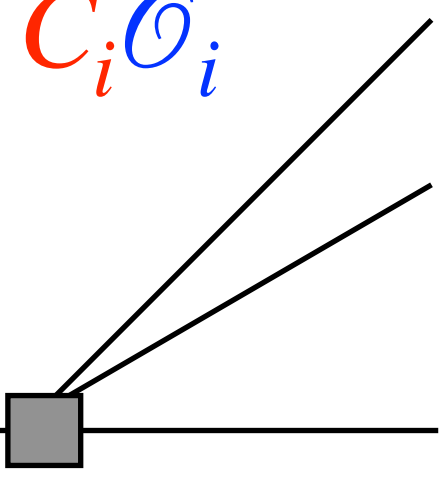
Is this New Physics or a Standard Model QCD effect?

$B^0 \rightarrow K^{*0} \mu^+ \mu^-$: A very brief history

$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ has caused lots of interest in the community

$b \rightarrow s \mu^+ \mu^-$ Weak Effective Theory

$$\mathcal{L} \propto \sum_i C_i \mathcal{O}_i$$

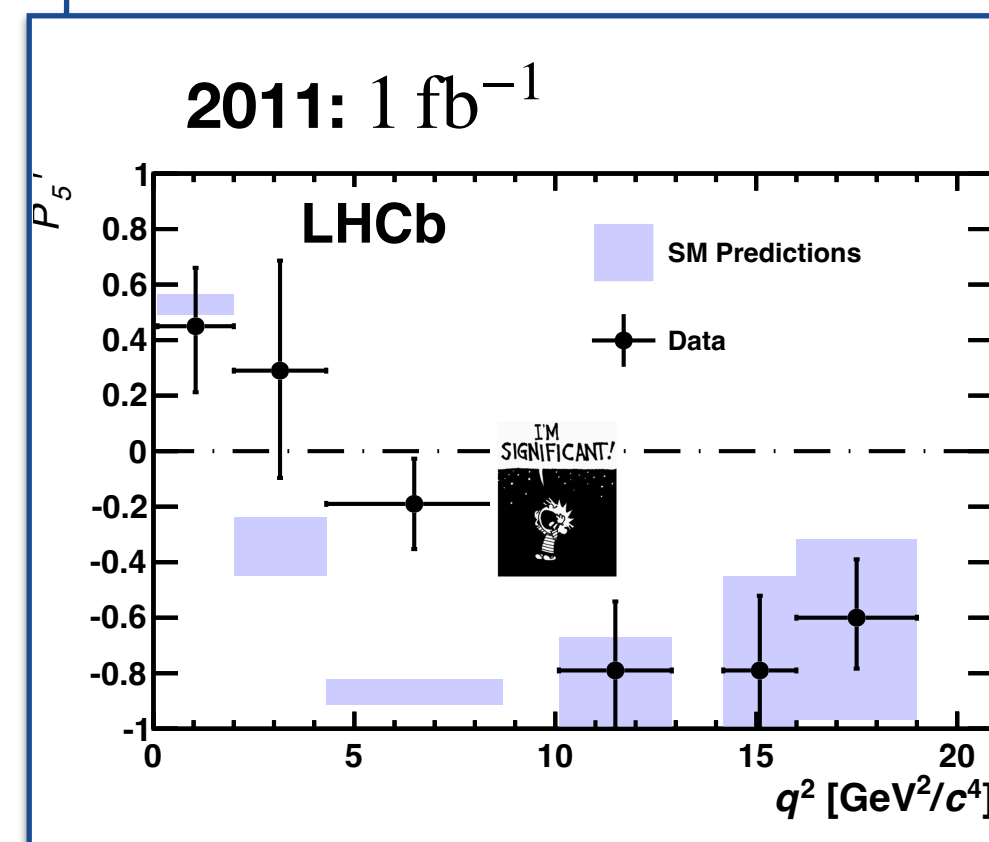
b  s

Electromagnetic C_7

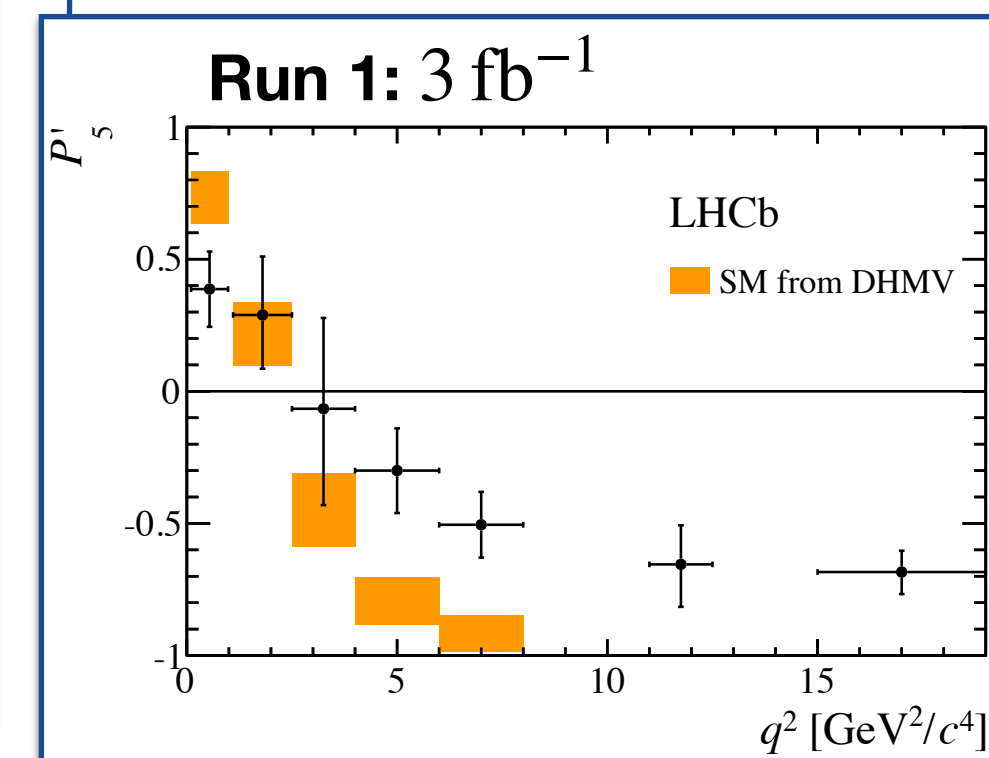
Vector C_9

Axial vector C_{10}

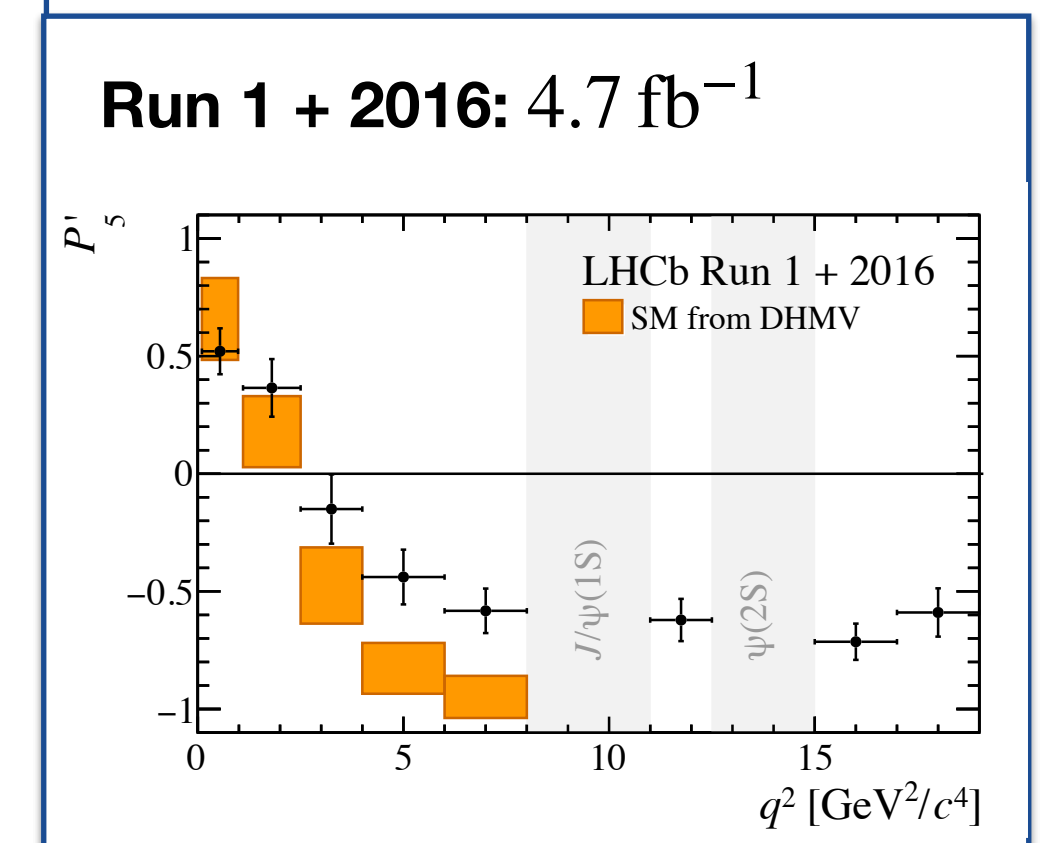
Tensions have persisted for ~10 years



[LHCb-PAPER-2013-037]

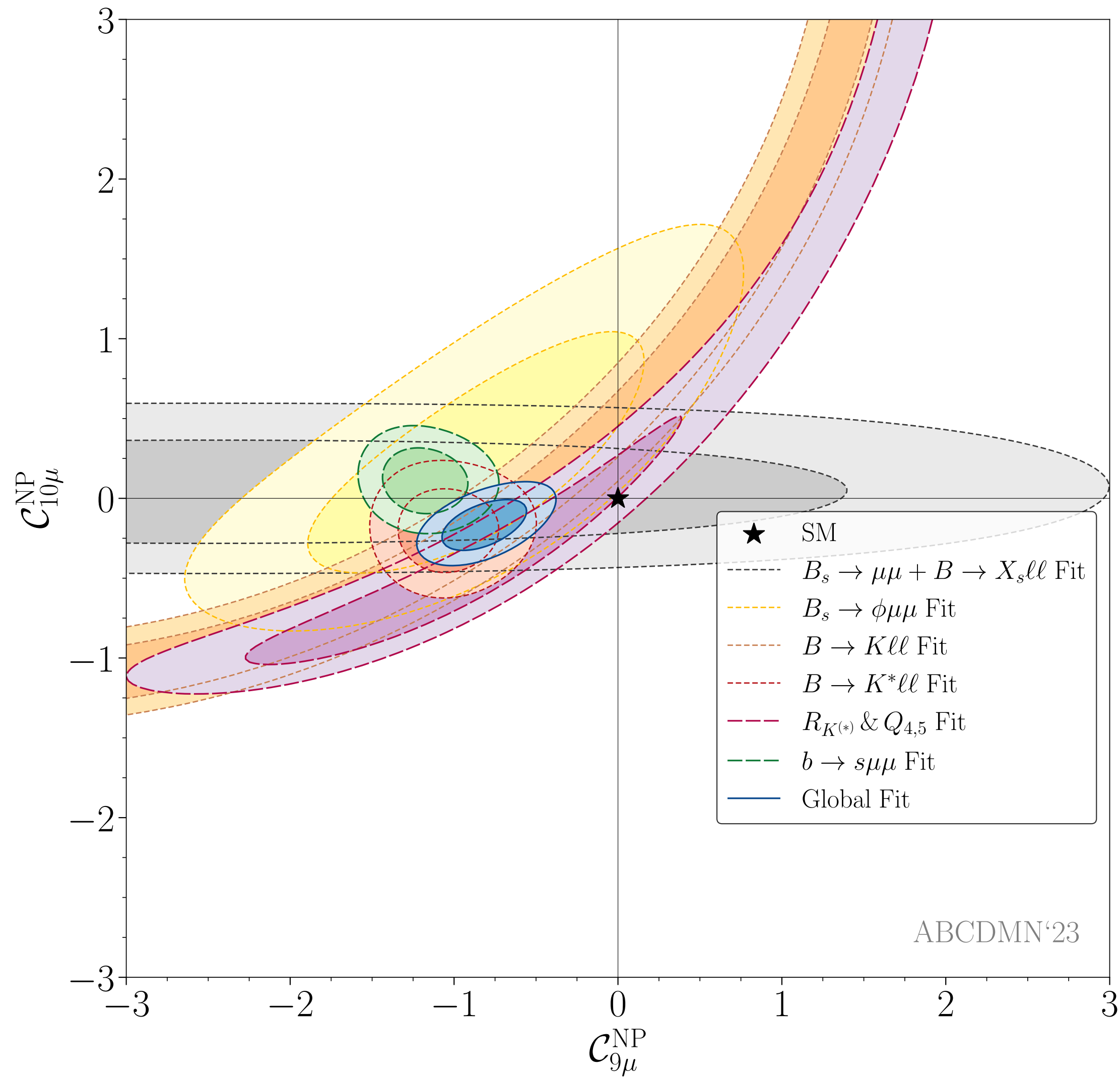


[LHCb-PAPER-2015-051]



[LHCb-PAPER-2020-002]

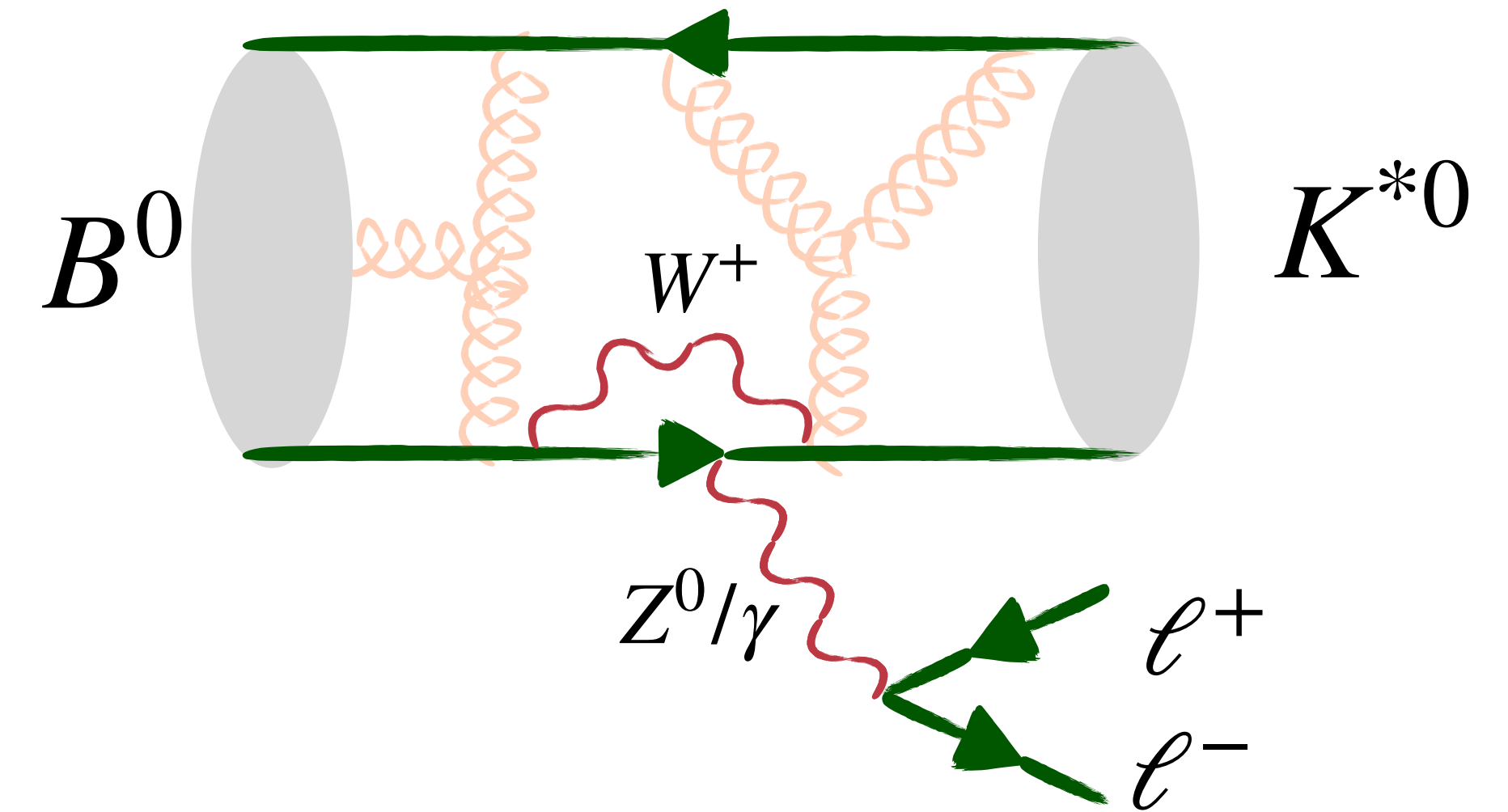
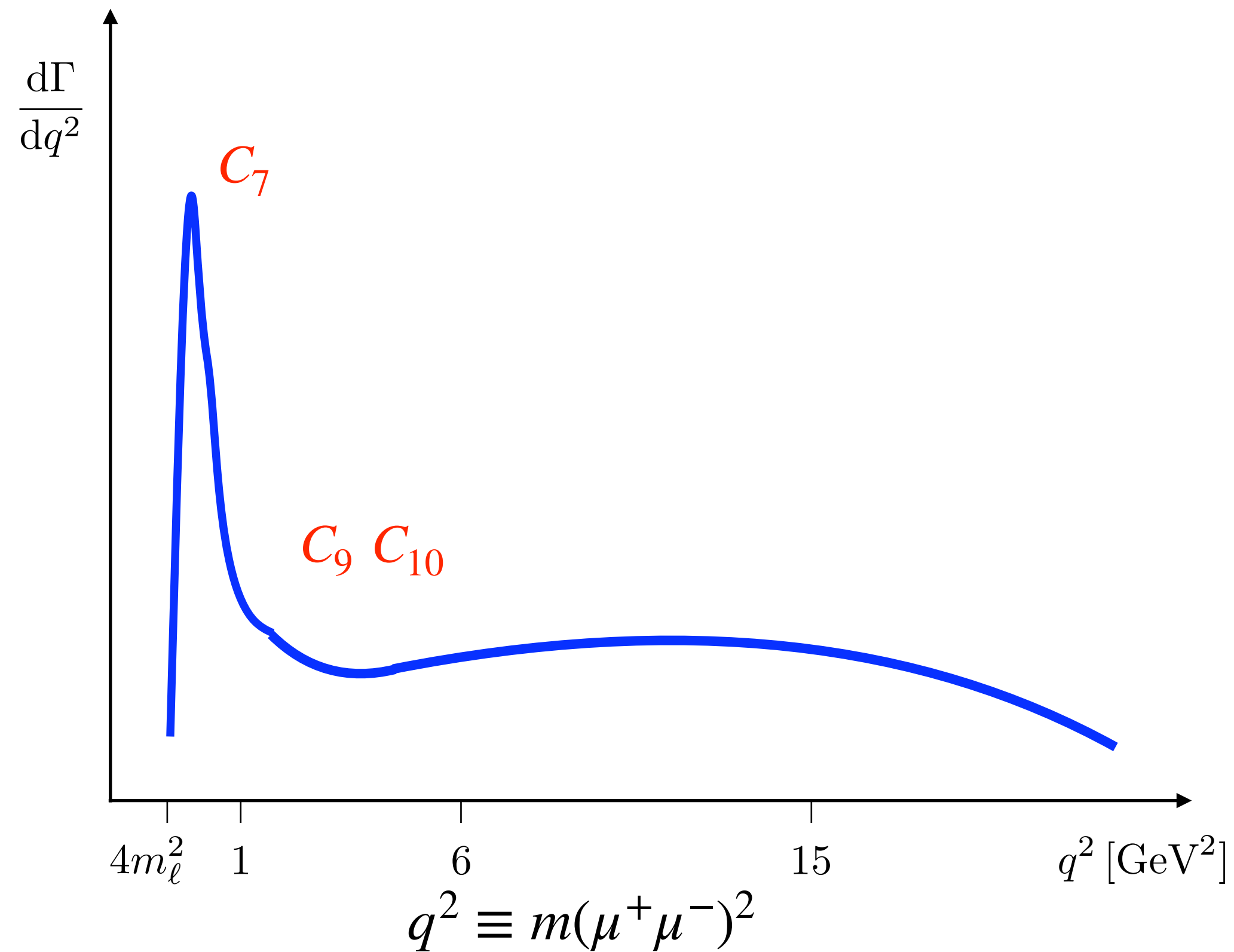
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$: A very brief history



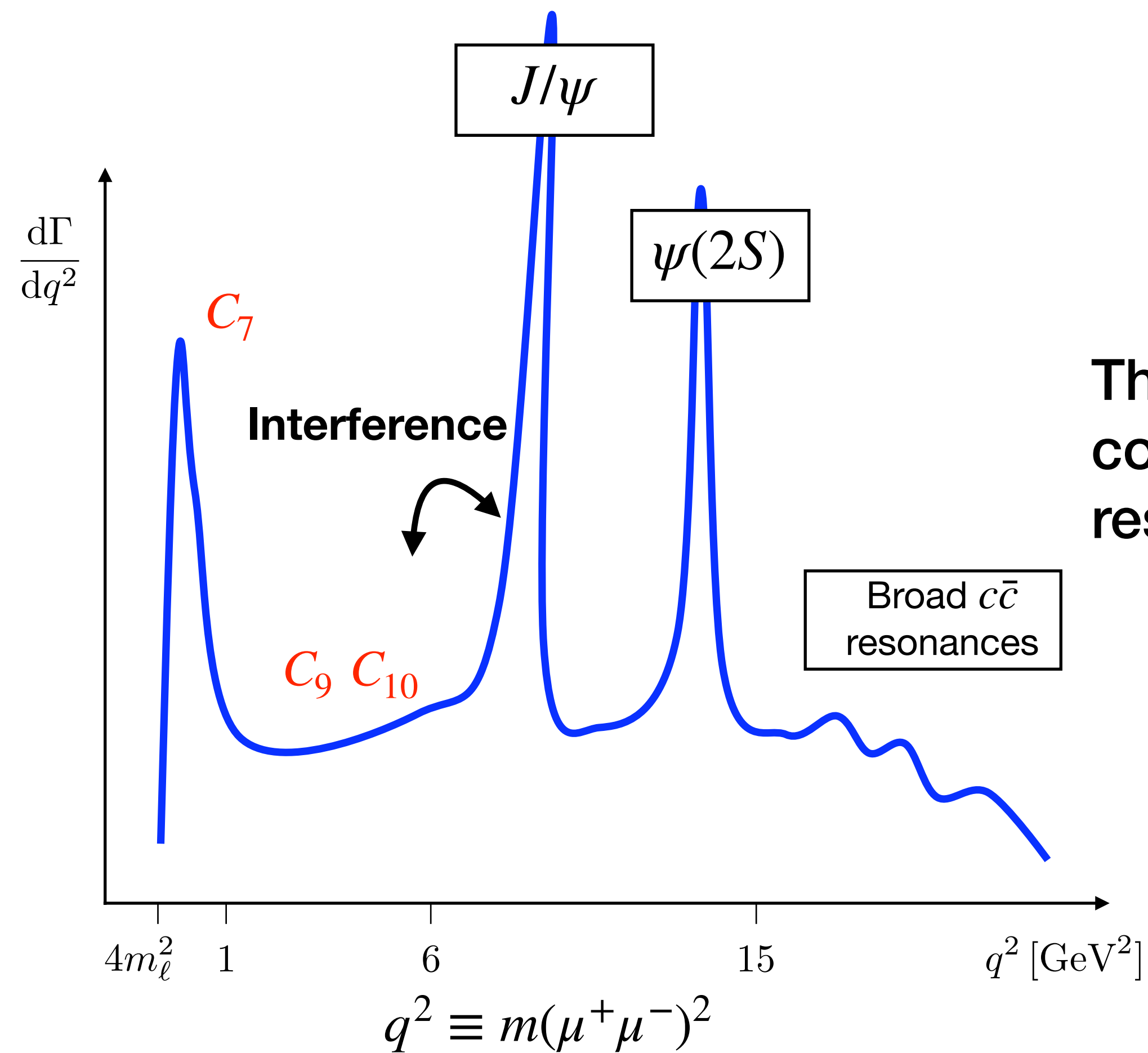
Current measurements point to an anomalous vector contribution - one example of a global fit out of the many.

What does the topology look like ?

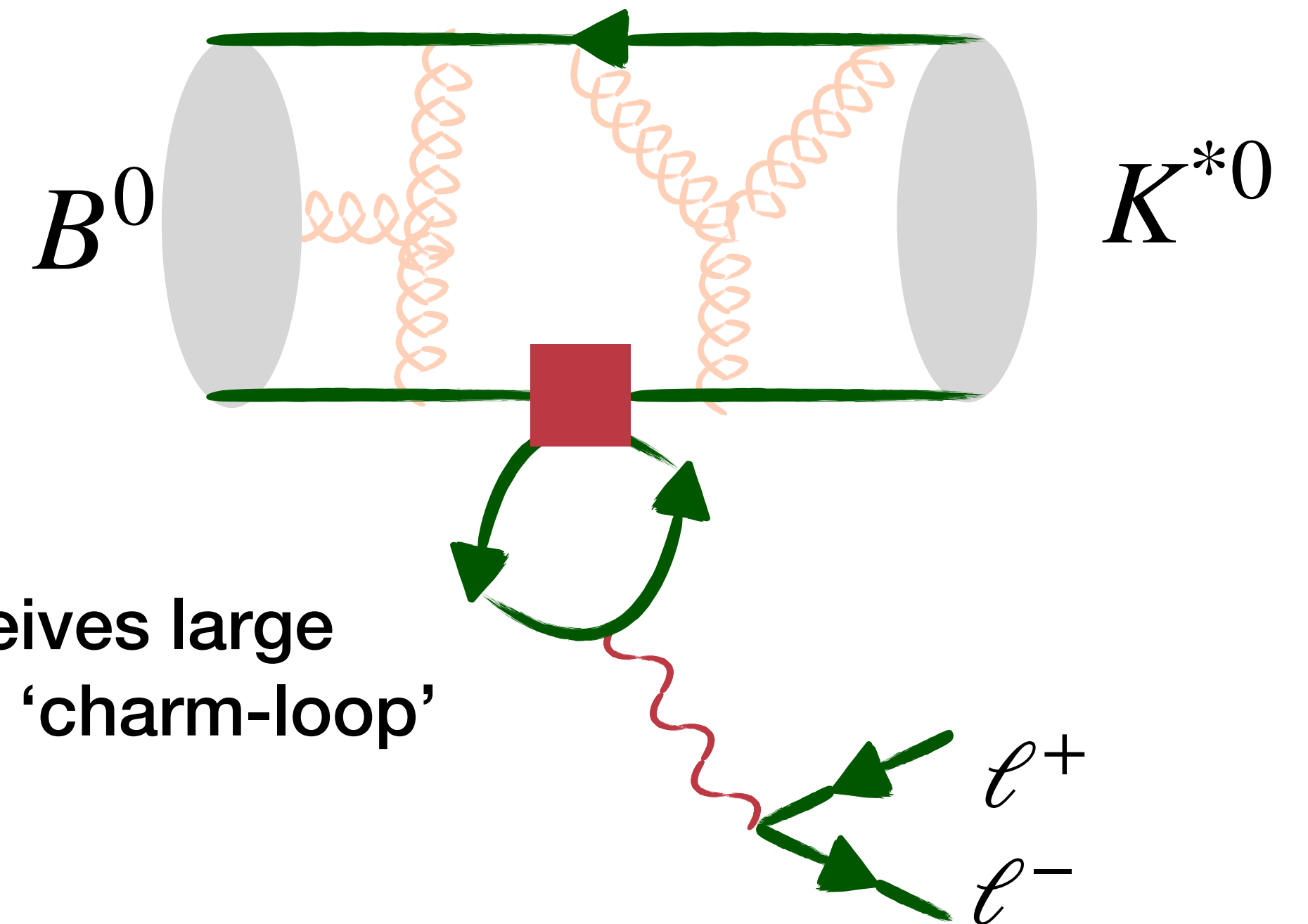
The $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decay doesn't live in isolation...



The $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decay doesn't live in isolation...



The final state receives large contributions from 'charm-loop' resonances



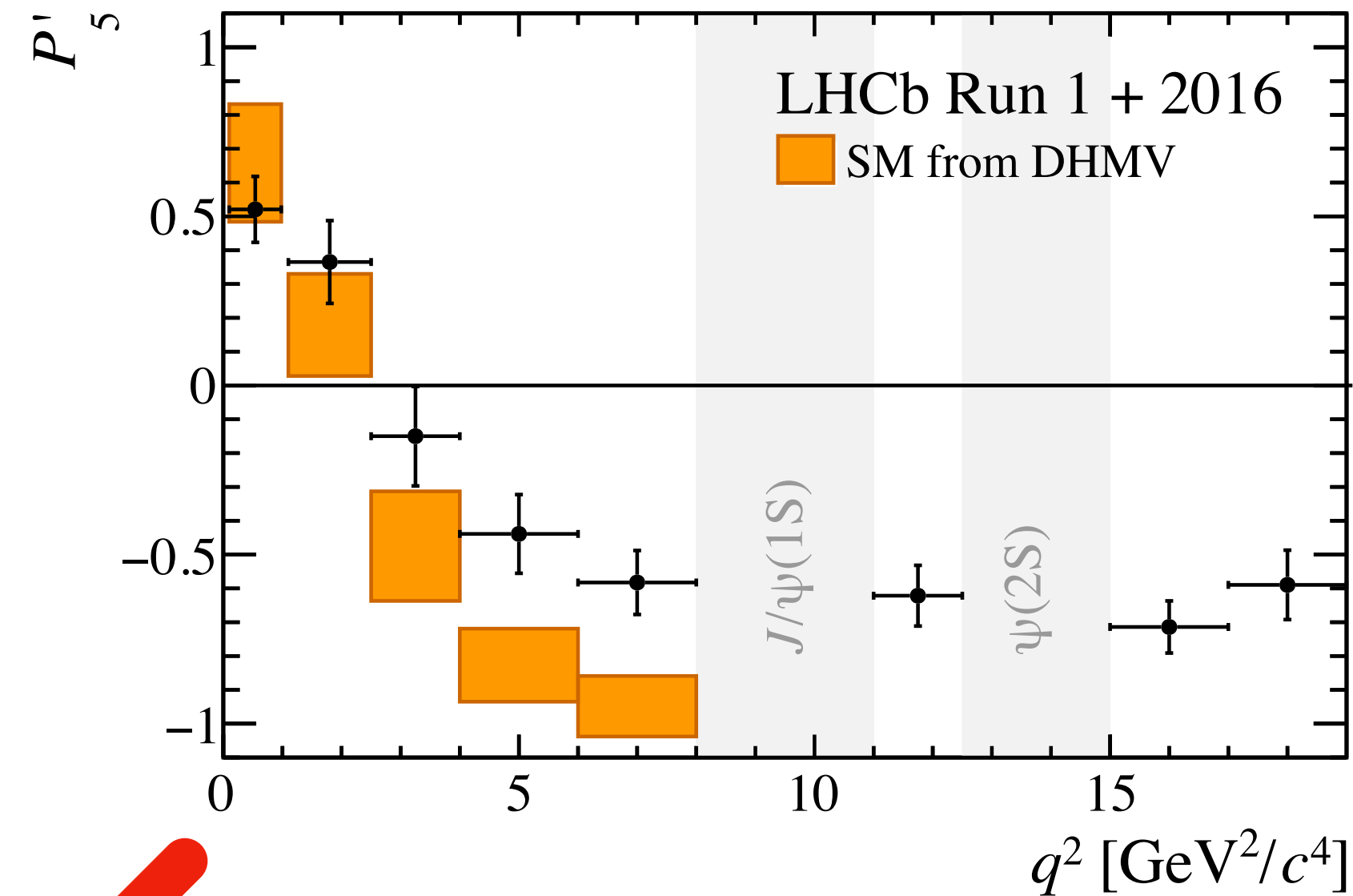
Many of the contributions are vector-like
 → This mimics the C_9 contribution

Can we model them?

Terminology

Binned measurements

[LHCb-PAPER-2020-002]

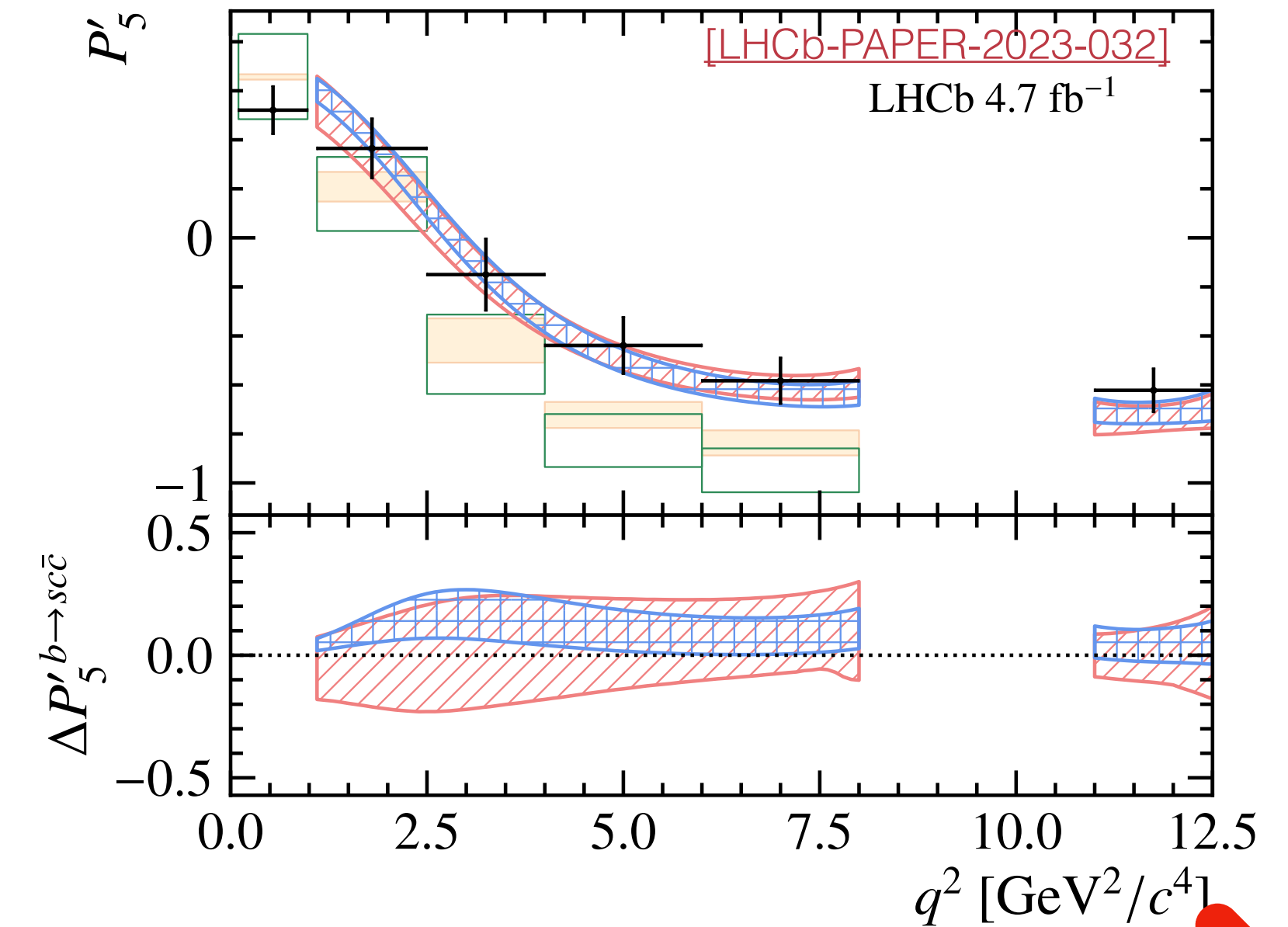


Model independent

Measure observables in bins of q^2

Unbinned measurements

[LHCb-PAPER-2023-032]



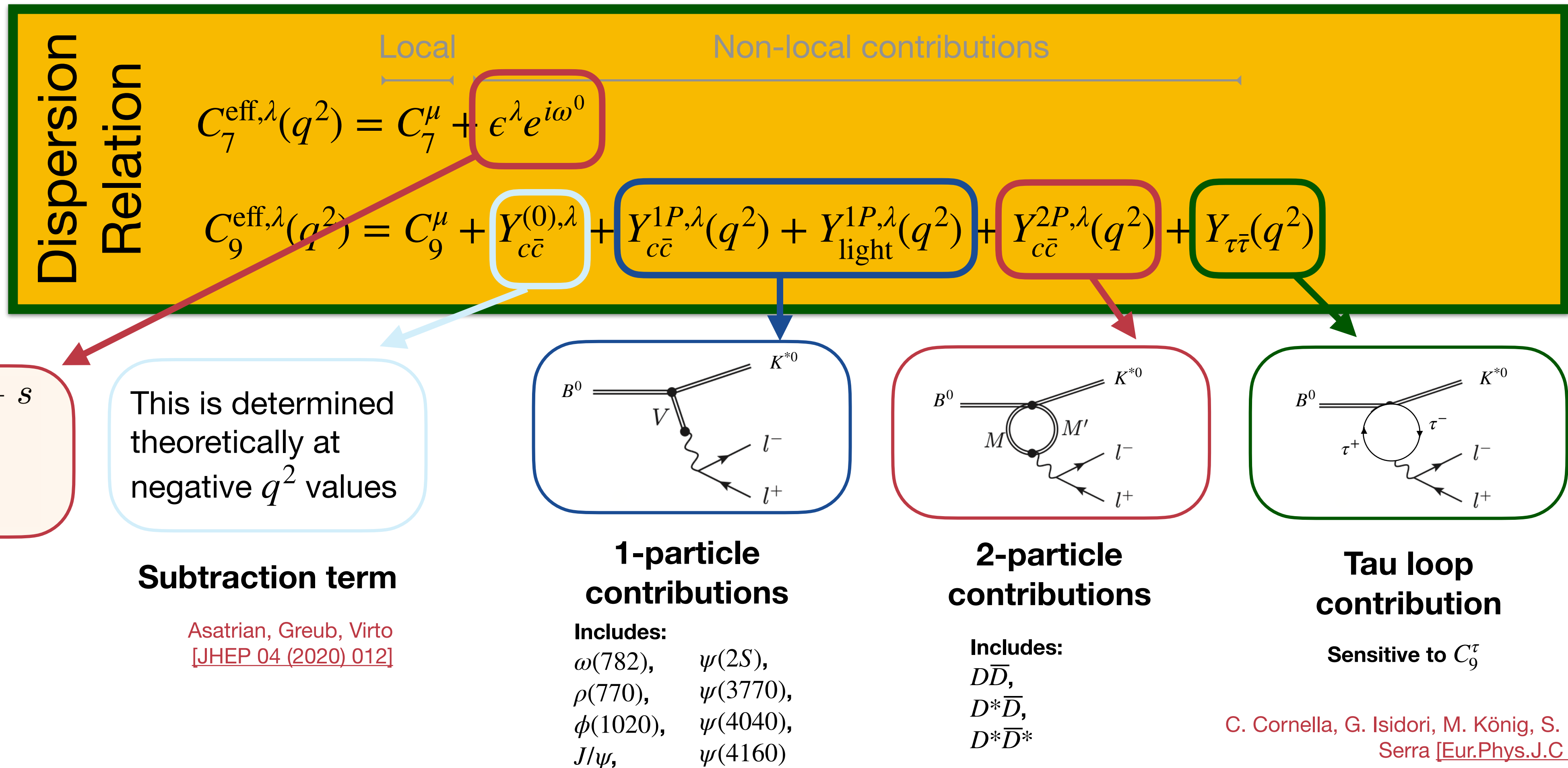
Model dependent

Use model of local and nonlocal contributions to extract Wilson coefficients directly

Run 1 + 2016: 4.7 fb⁻¹

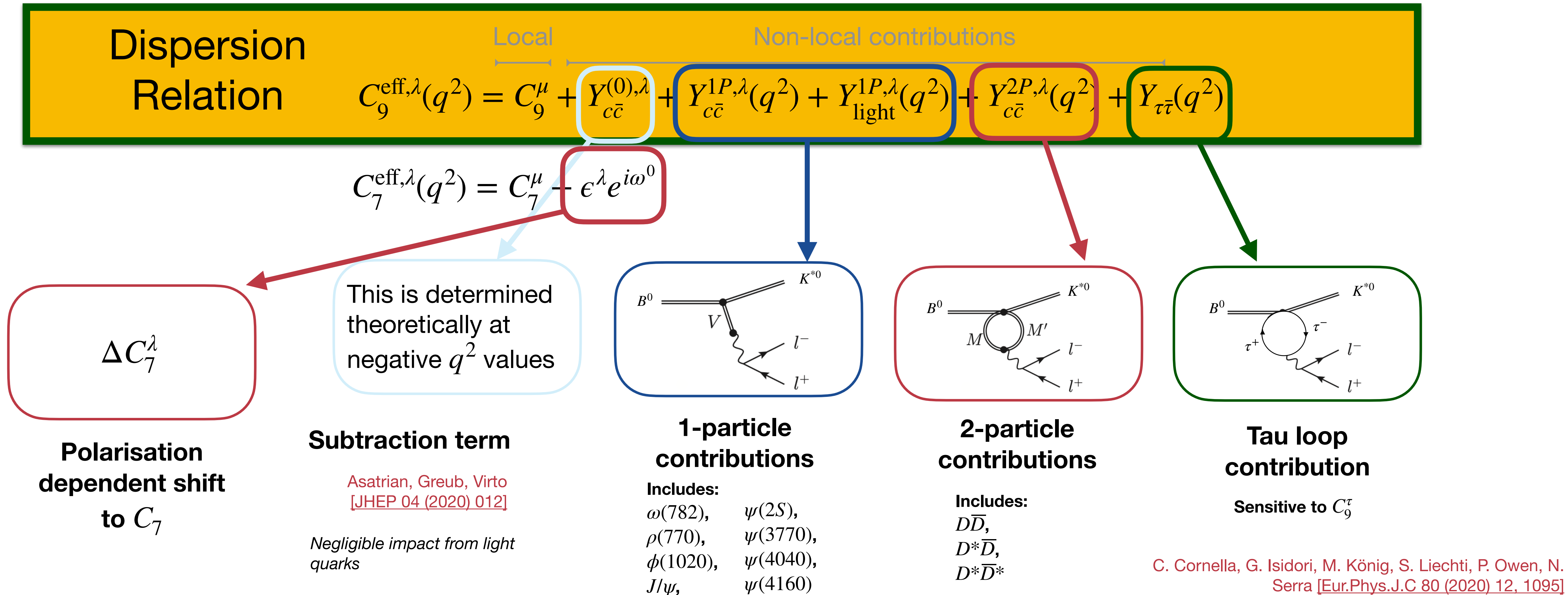
Dispersion relation

- ✓ **Unbinned** amplitude analysis to the whole $q^2 \equiv m^2(\mu^+\mu^-)$ region
- ✓ **First measurement** using the full Run1 [2011-2012] and Run2 [2016-2018] data



Dispersion relation

- ✓ **Unbinned** amplitude analysis to the whole $q^2 \equiv m^2(\mu^+\mu^-)$ region
- ✓ **First measurement** using the full Run1 [2011-2012] and Run2 [2016-2018] data



Strategy

Angular analysis preformed in the three decay angles and q^2

From Simulation

- Acceptance model

From Data

- Resolution
- S-wave parameters
- Background model

From Theory

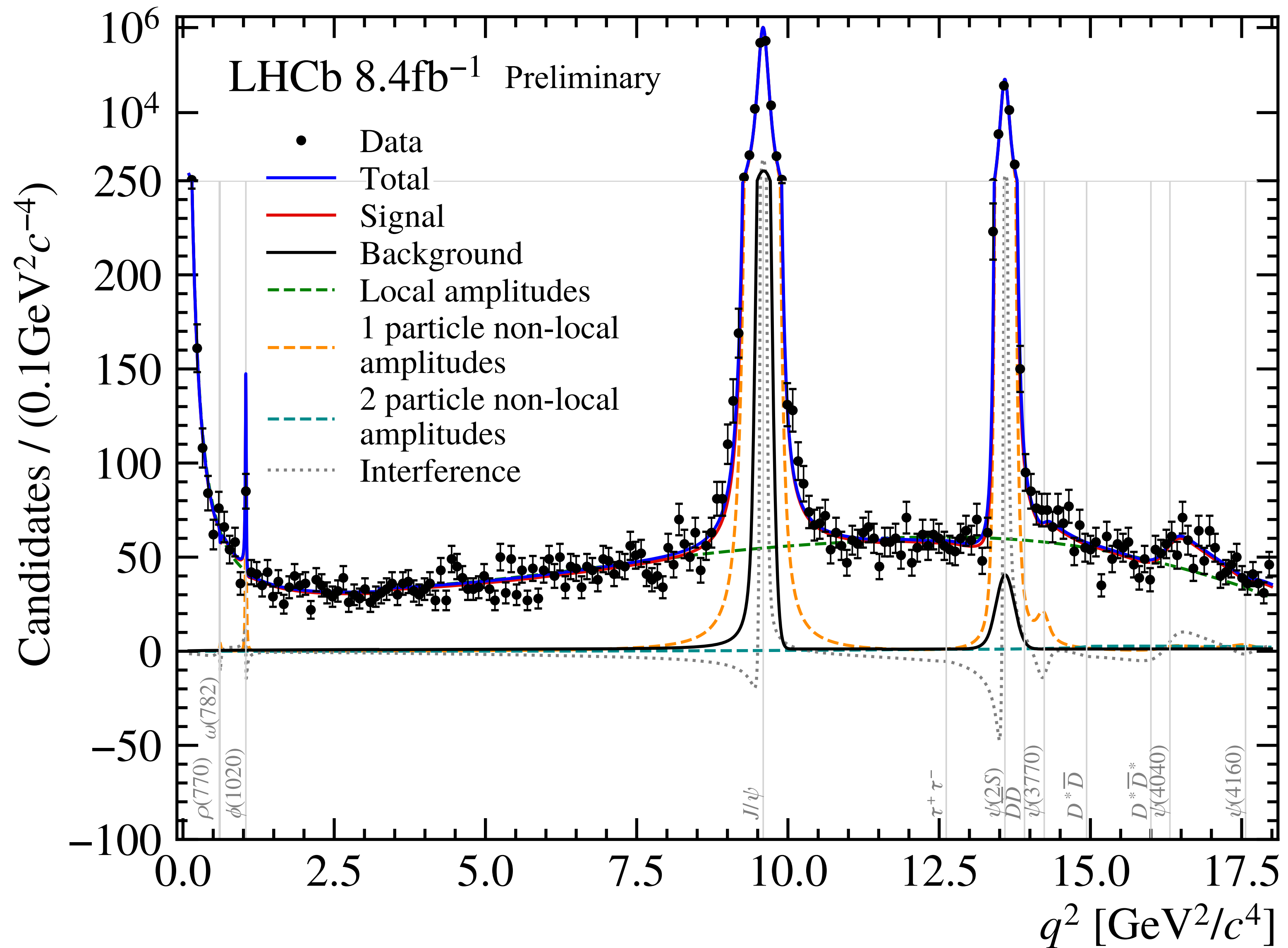
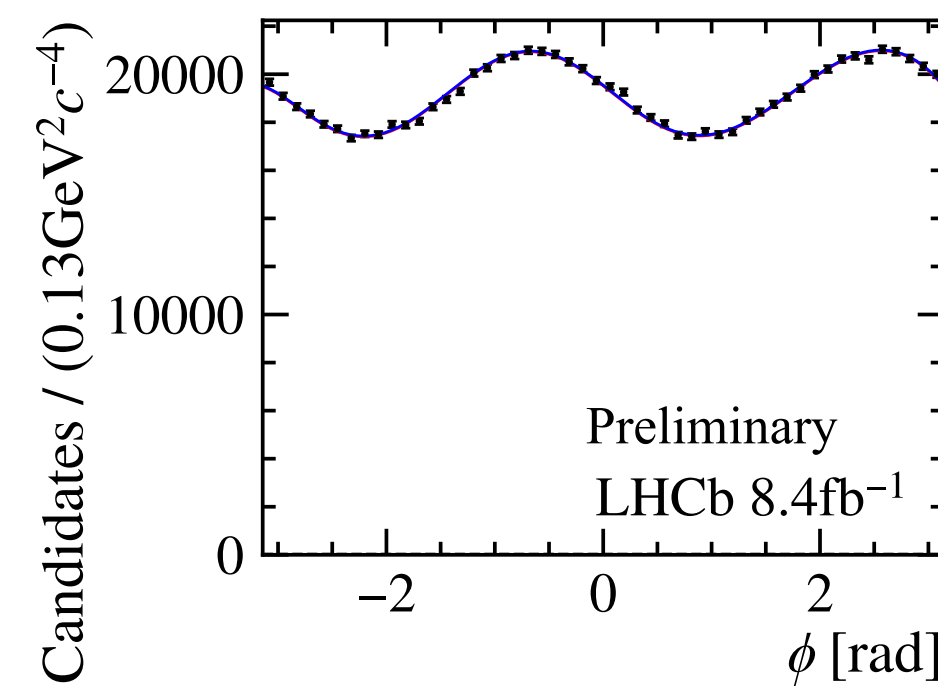
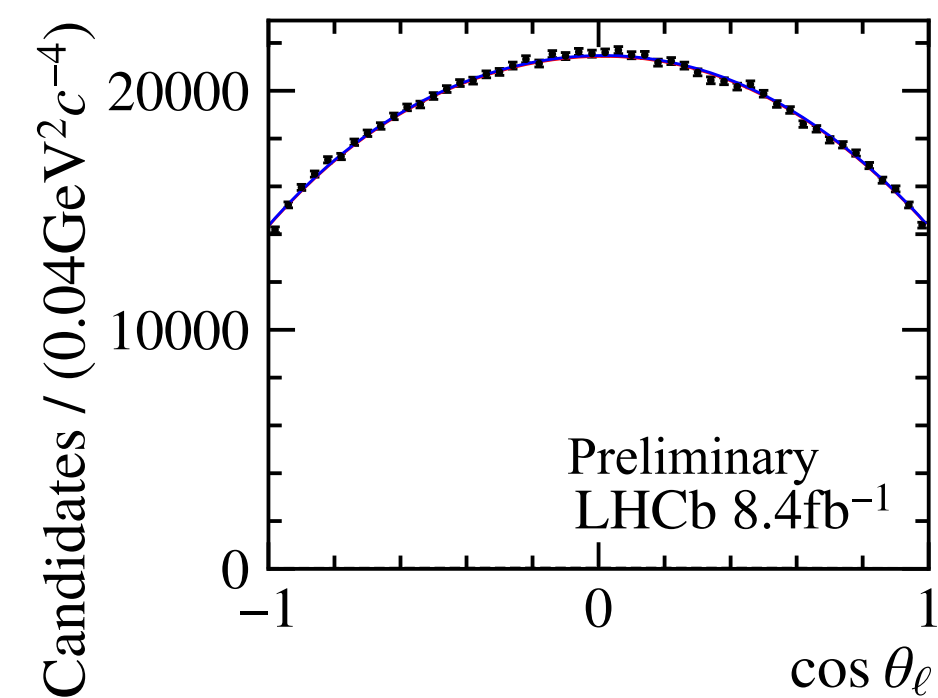
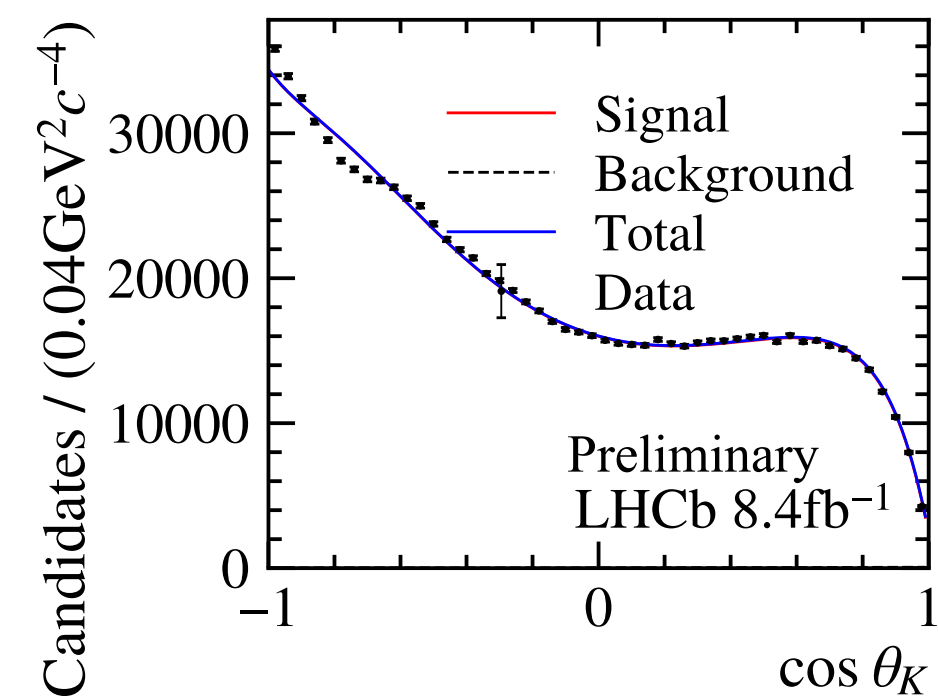
- Local $B \rightarrow K^*$ Form factors

Gaussian constrained GRvDV [[JHEP 09, 133 \(2022\)](#)]

Fit determines 150 parameters:

- $\Re(C_9), \Re(C_{10}), \Re(C'_9), \Re(C'_{10}), \Re(C_9^T)$
- Mag. and Phase of 1-particle resonances
- Real+Imag $D^{(*)}\overline{D}^{(*)}$ per helicity
- ΔC_7 per helicity
- Form factors

Projections



Results

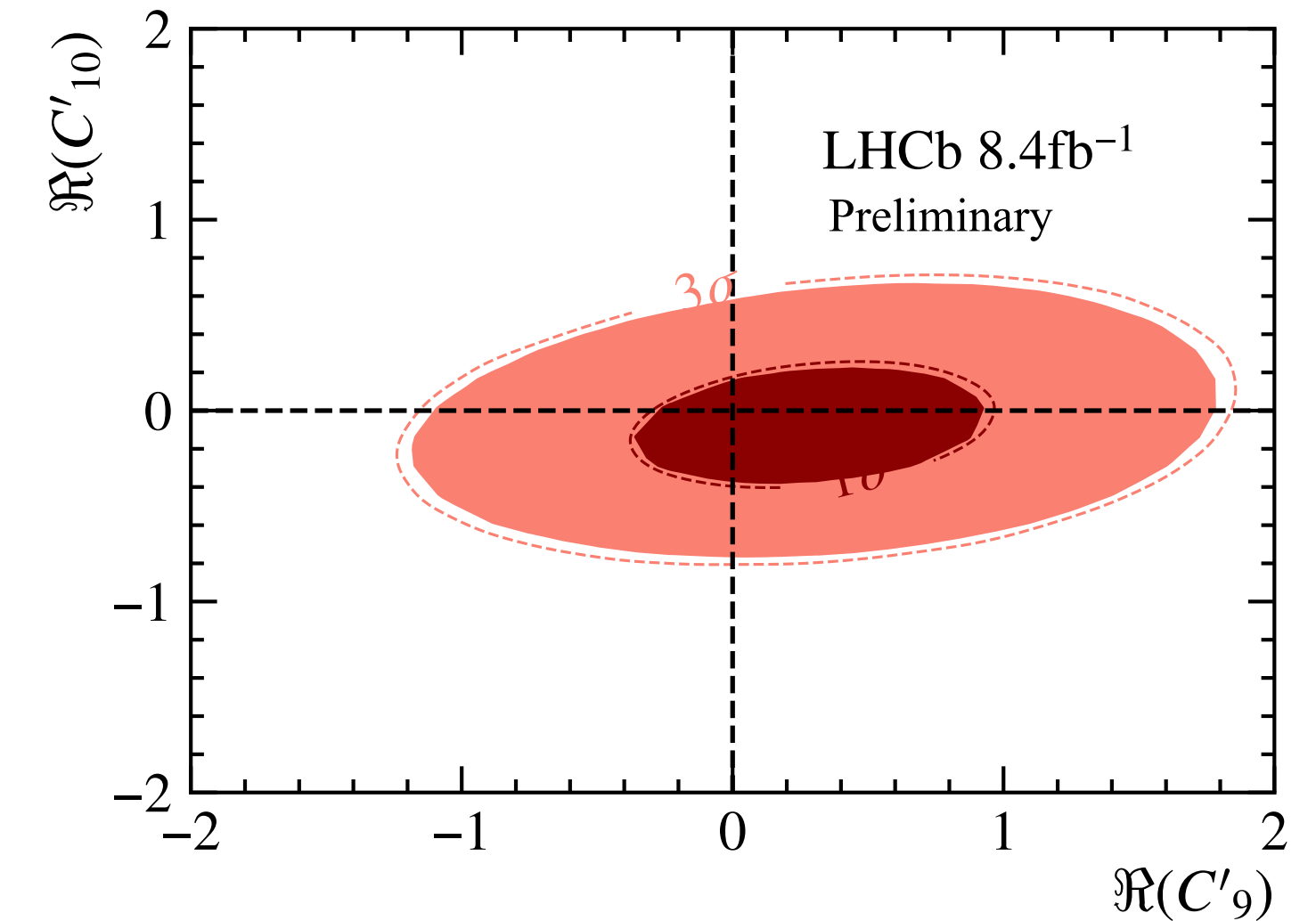
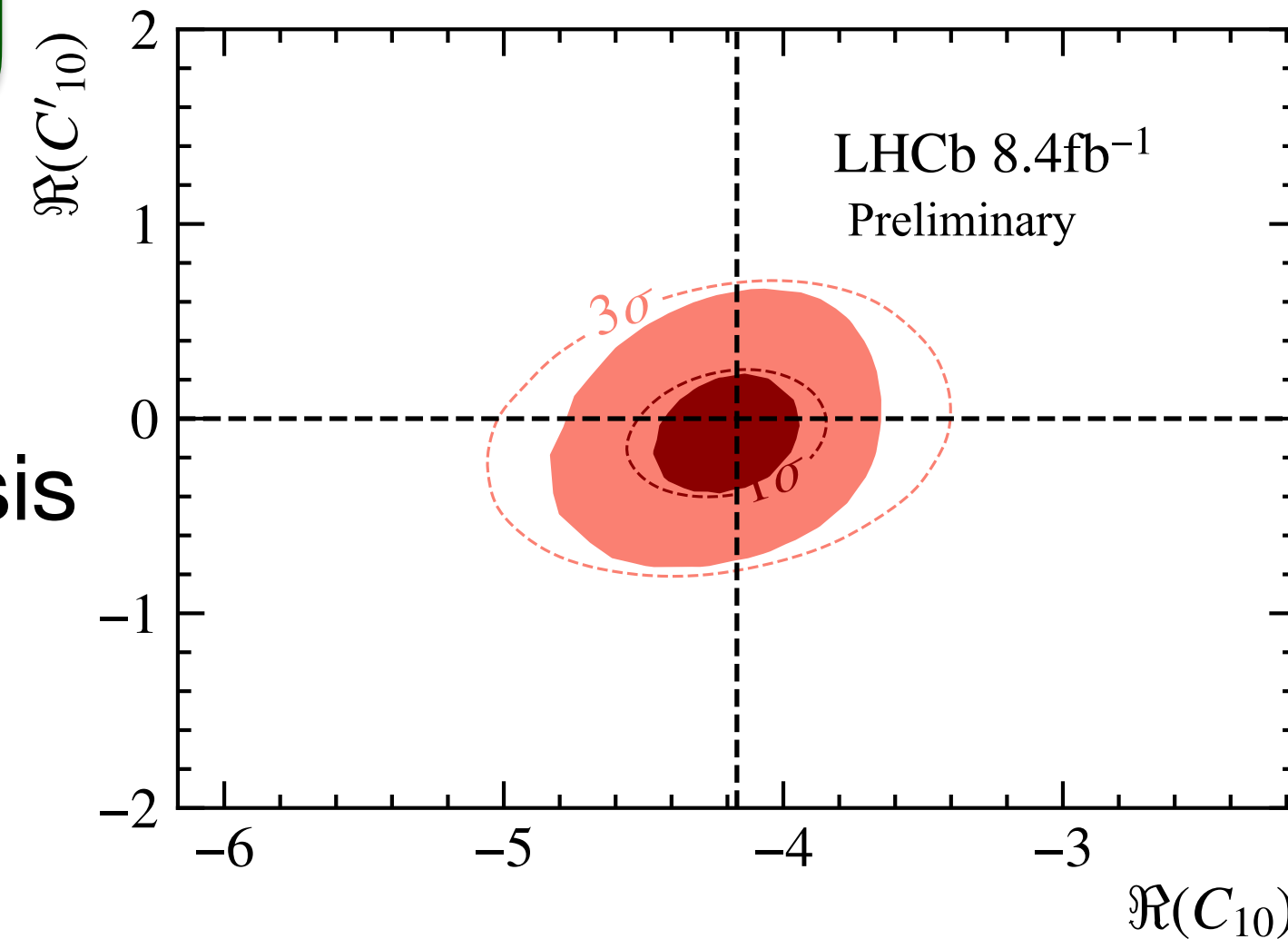
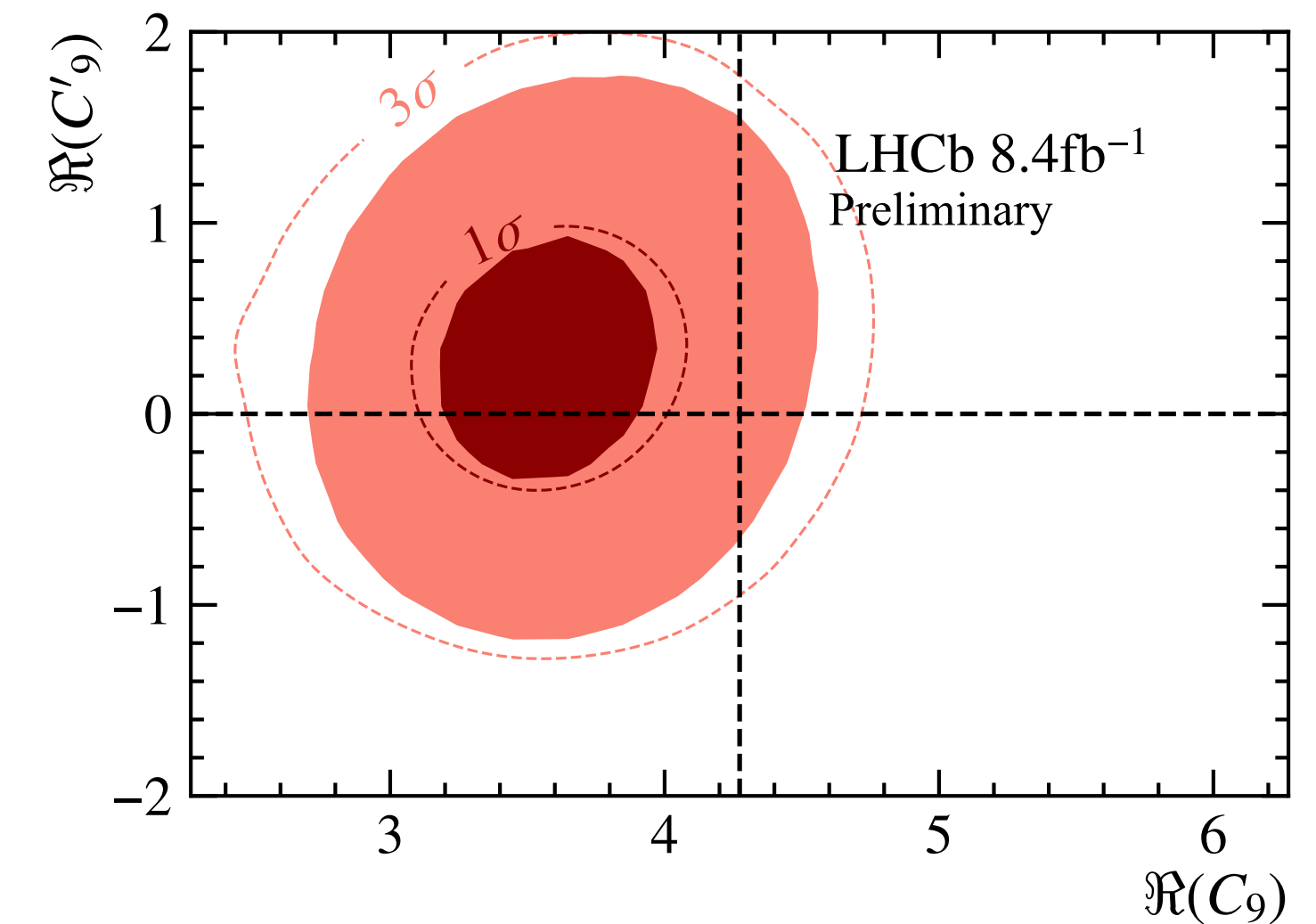
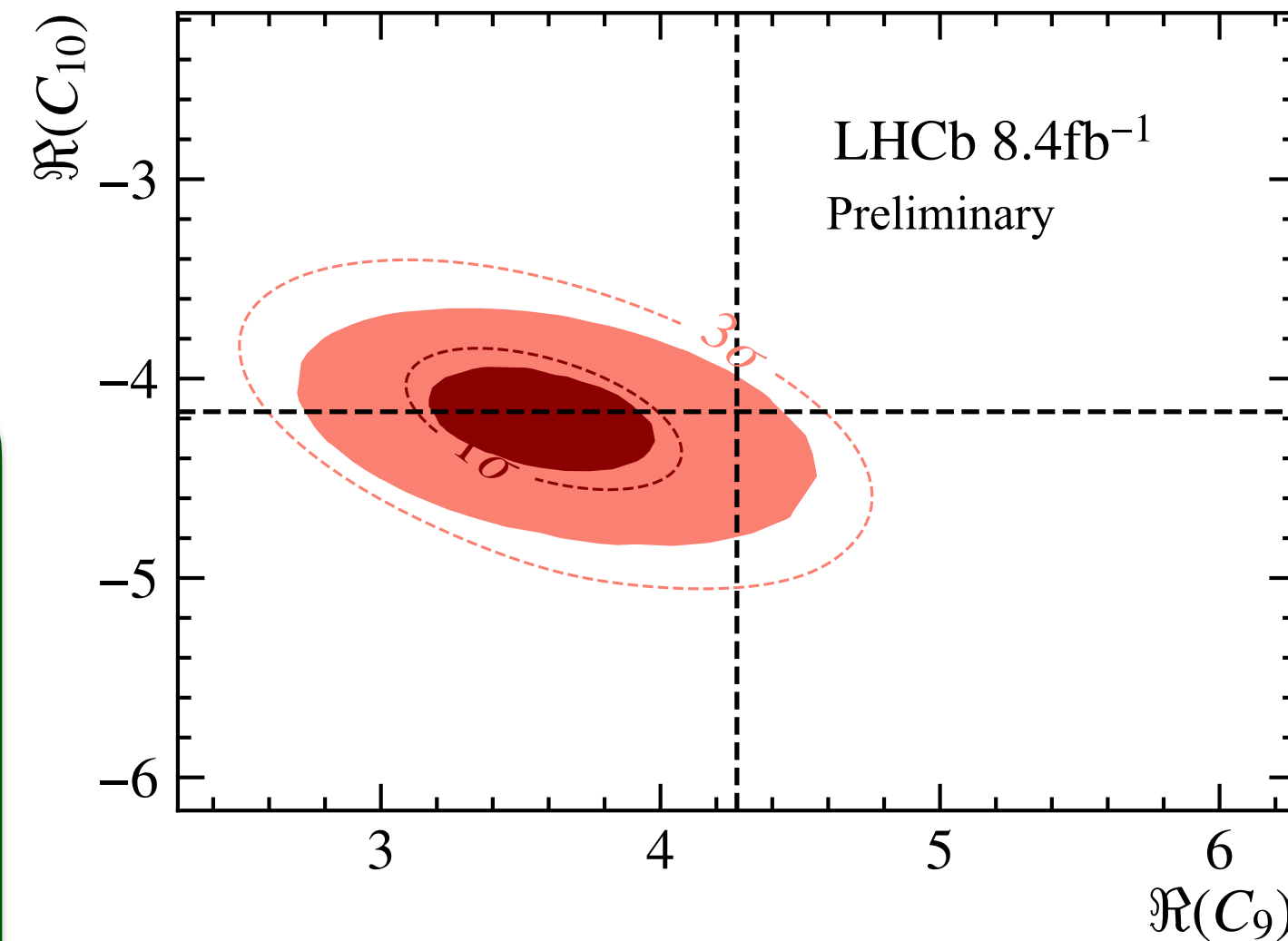
Biggest deviation is C_9 with
 $\Delta C_9^{NP} = -0.71$ at 2.1σ from SM

C_9	$3.56 \pm 0.28 \pm 0.18$	2.1σ
C_{10}	$-4.02 \pm 0.18 \pm 0.16$	0.6σ
C'_9	$0.28 \pm 0.41 \pm 0.12$	0.7σ
C'_{10}	$-0.09 \pm 0.21 \pm 0.06$	0.4σ
C_9^τ	$-116 \pm 264 \pm 98$	0.4σ

Global significance $\sim 1.5\sigma$ from SM

In agreement with previous unbinned analysis

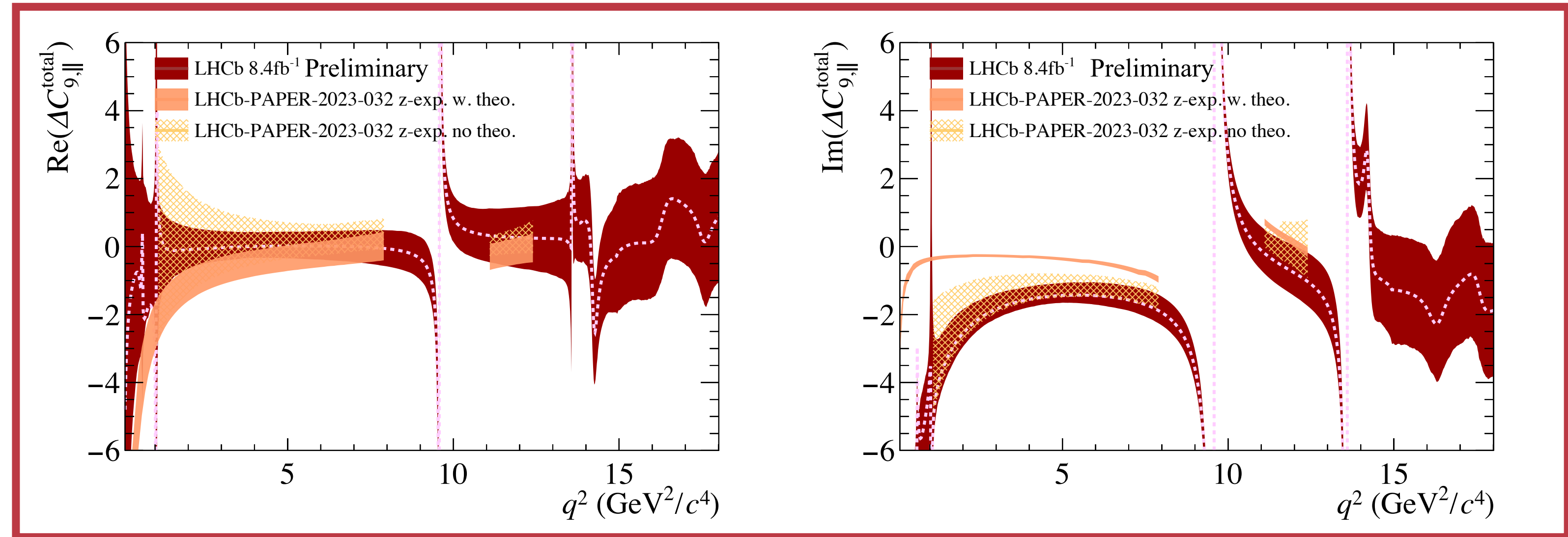
$\mathcal{B}(B^0 \rightarrow J/\psi K^{*0})$ dominates systematic uncertainty



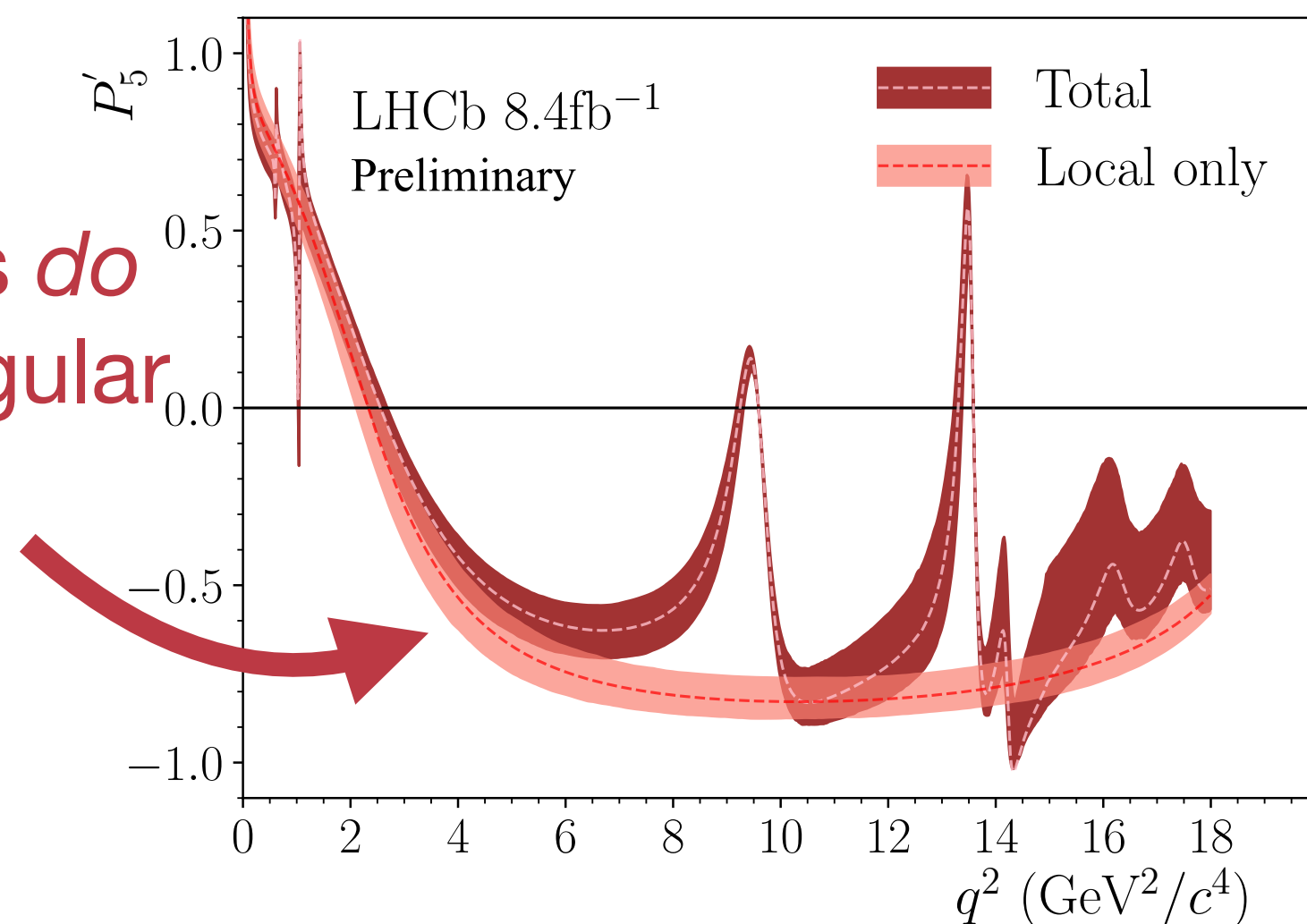
Non local effects

Impact of the nonlocal amplitudes
on the Wilson coefficients shown per
helicity e.g. $\parallel$

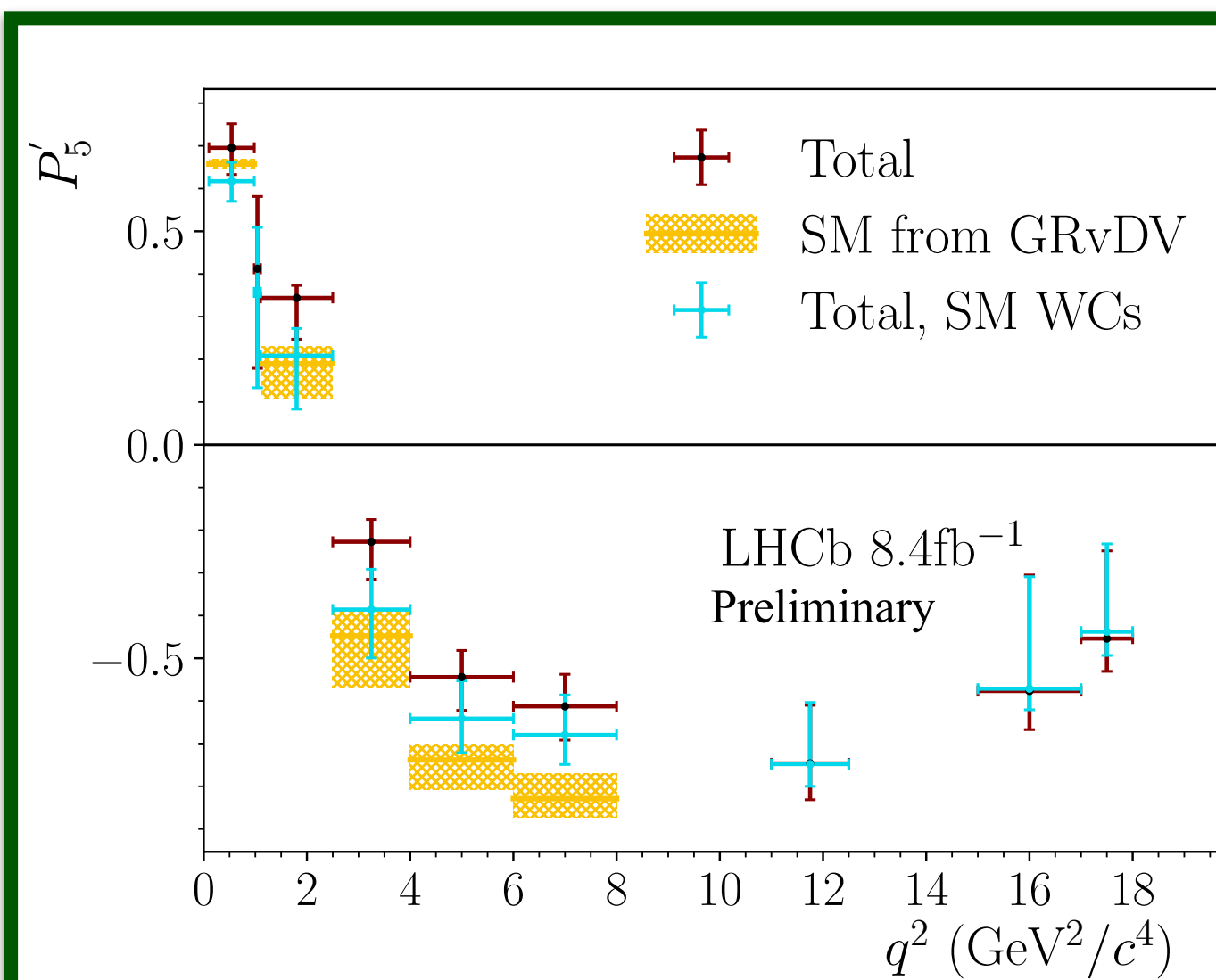
Good agreement with previous
analysis



Nonlocal
contributions *do*
influence angular
observables



Integrate in bins



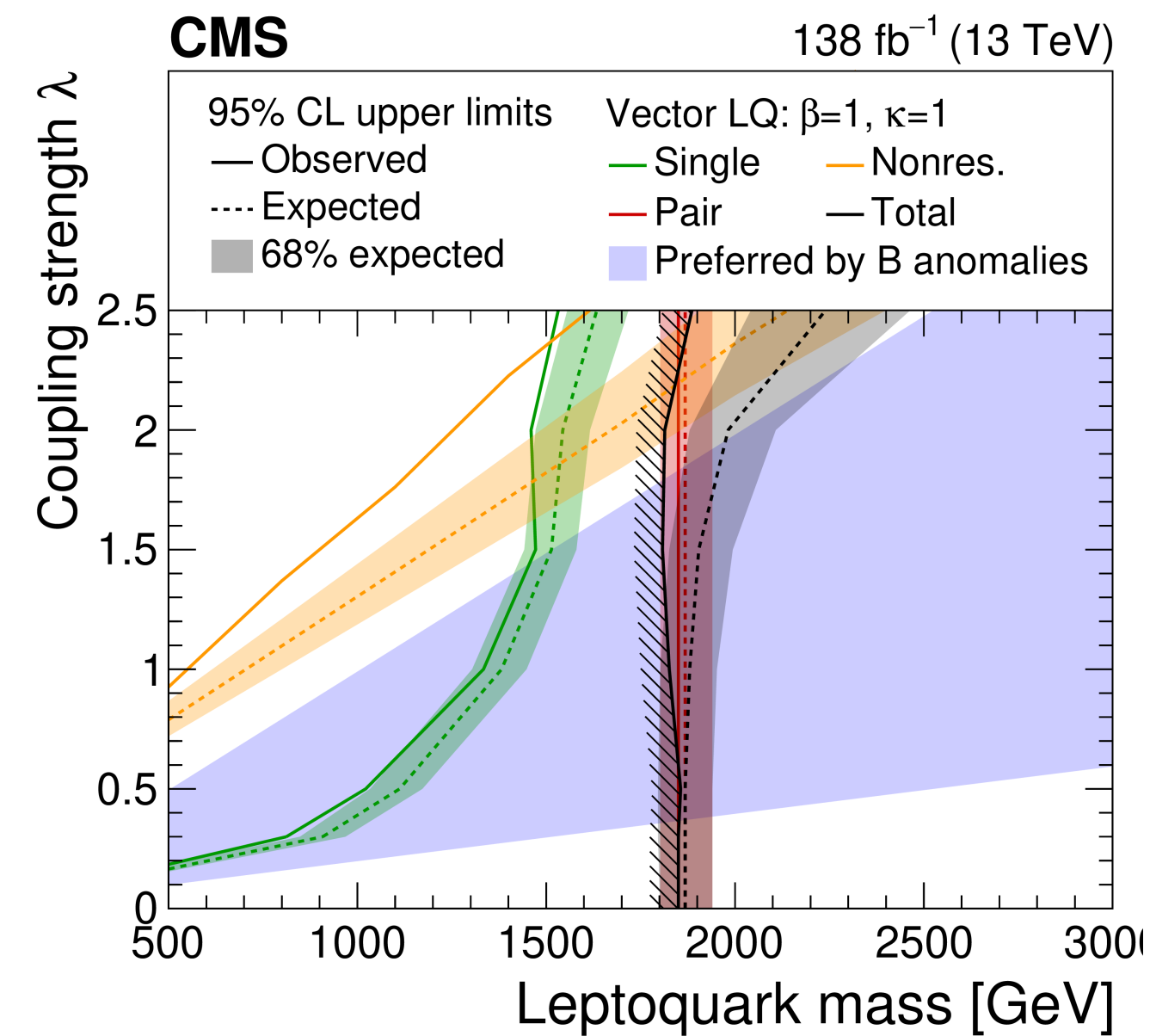
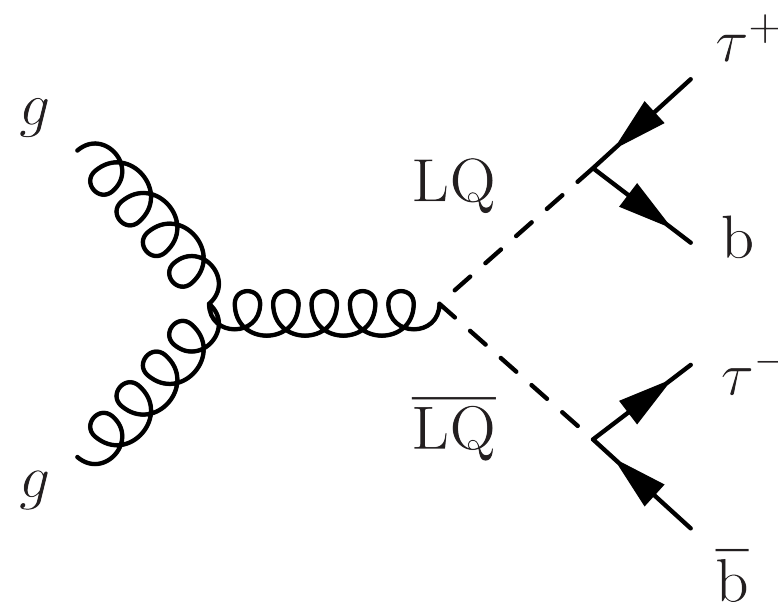
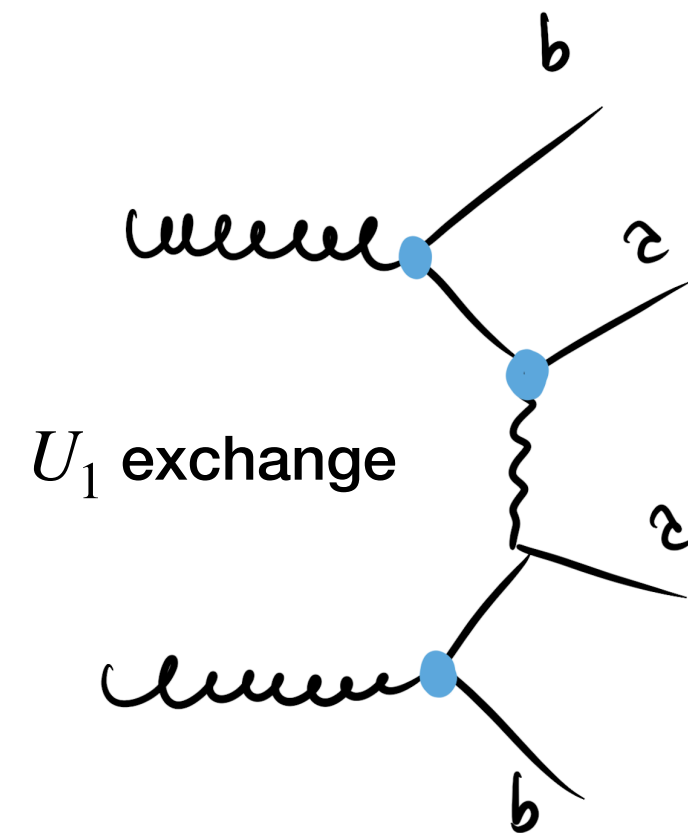
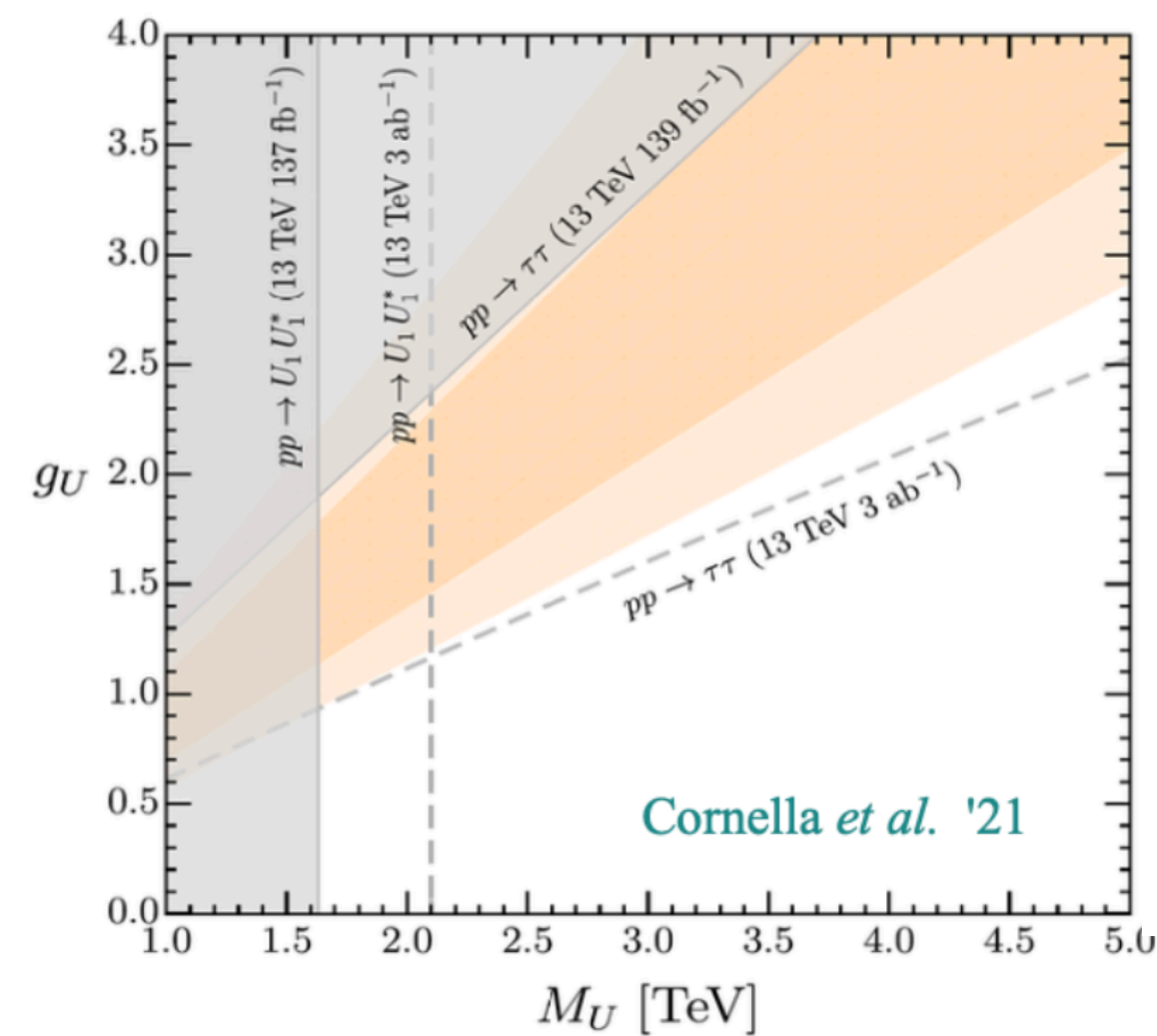
Red vs. Cyan
Impact of allowing NP

Cyan vs. Yellow
*Impact of nonlocal
modelling*

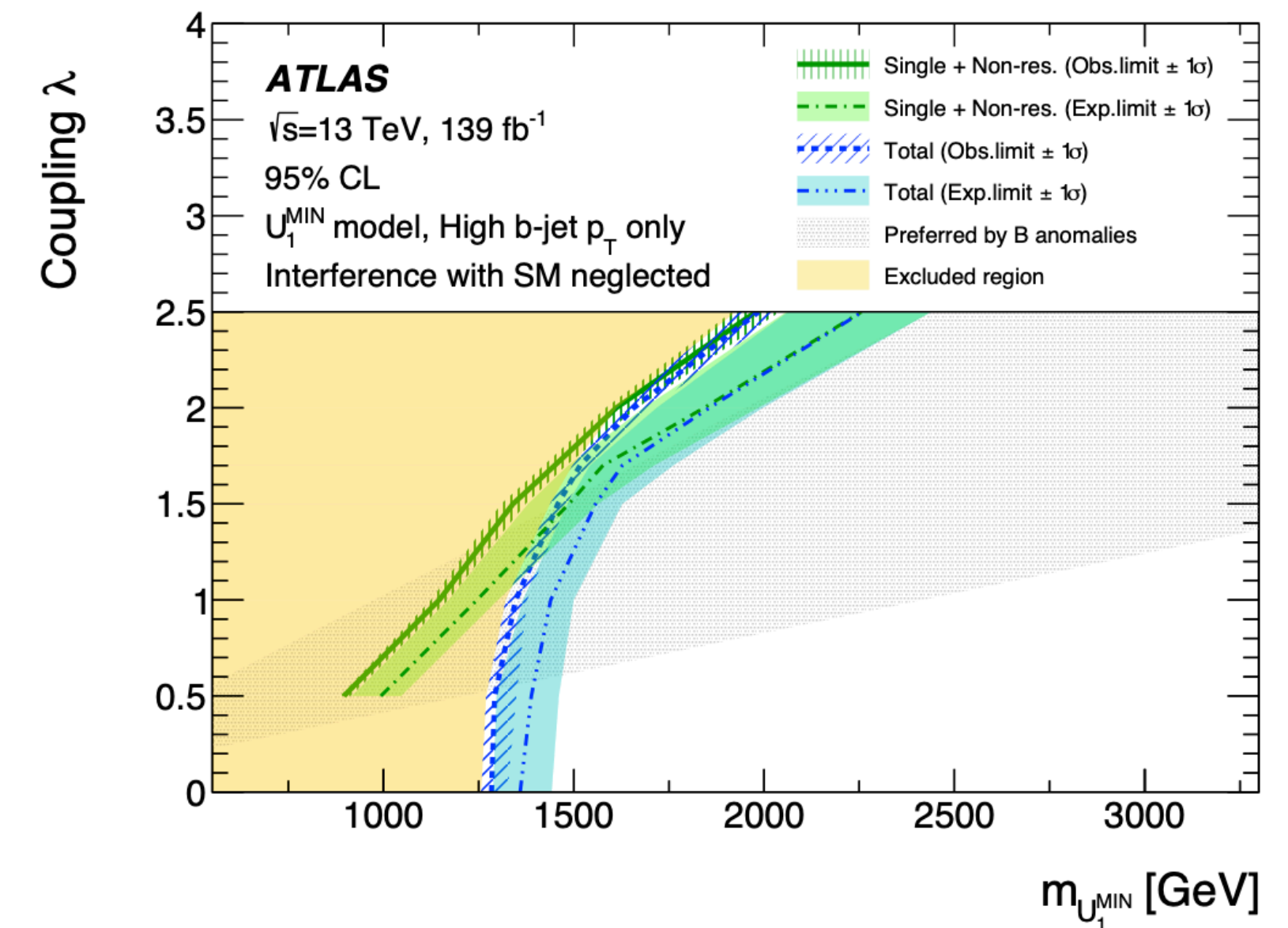
Note: bins are correlated!

Model building & direct searches

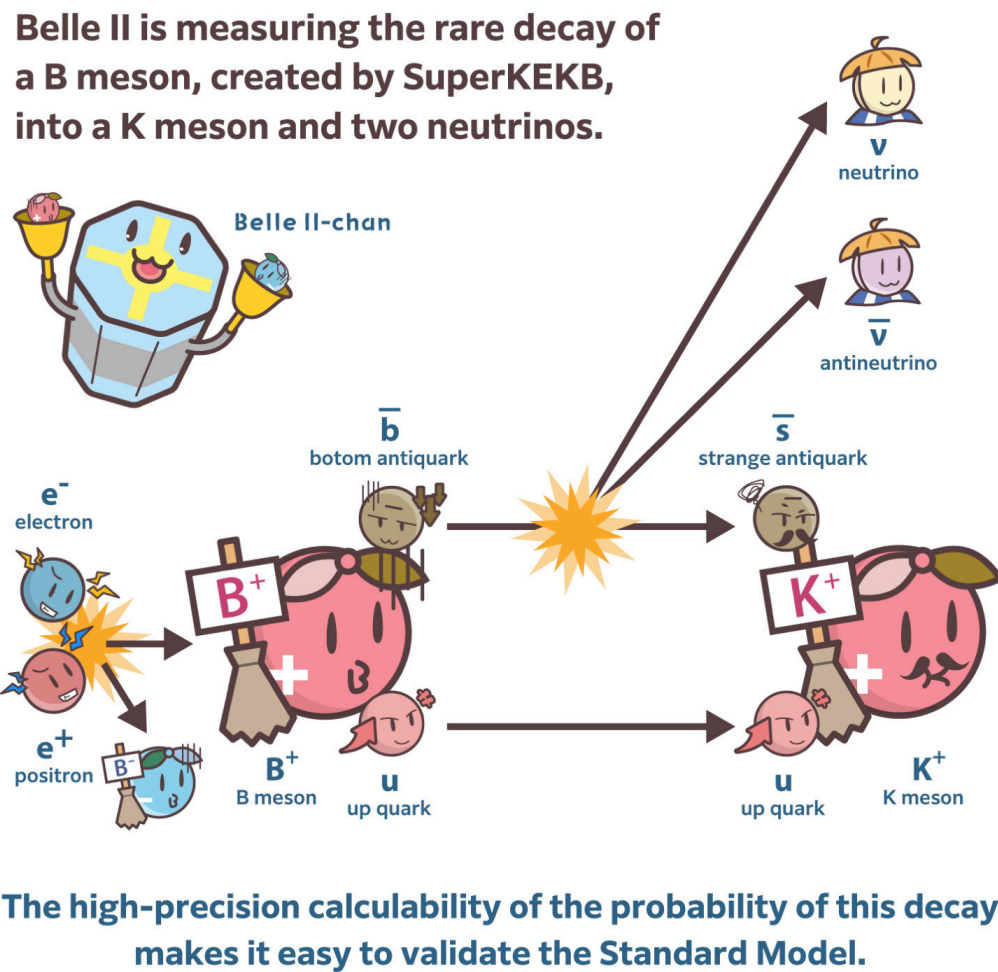
U_1 Leptoquark candidate quite popular



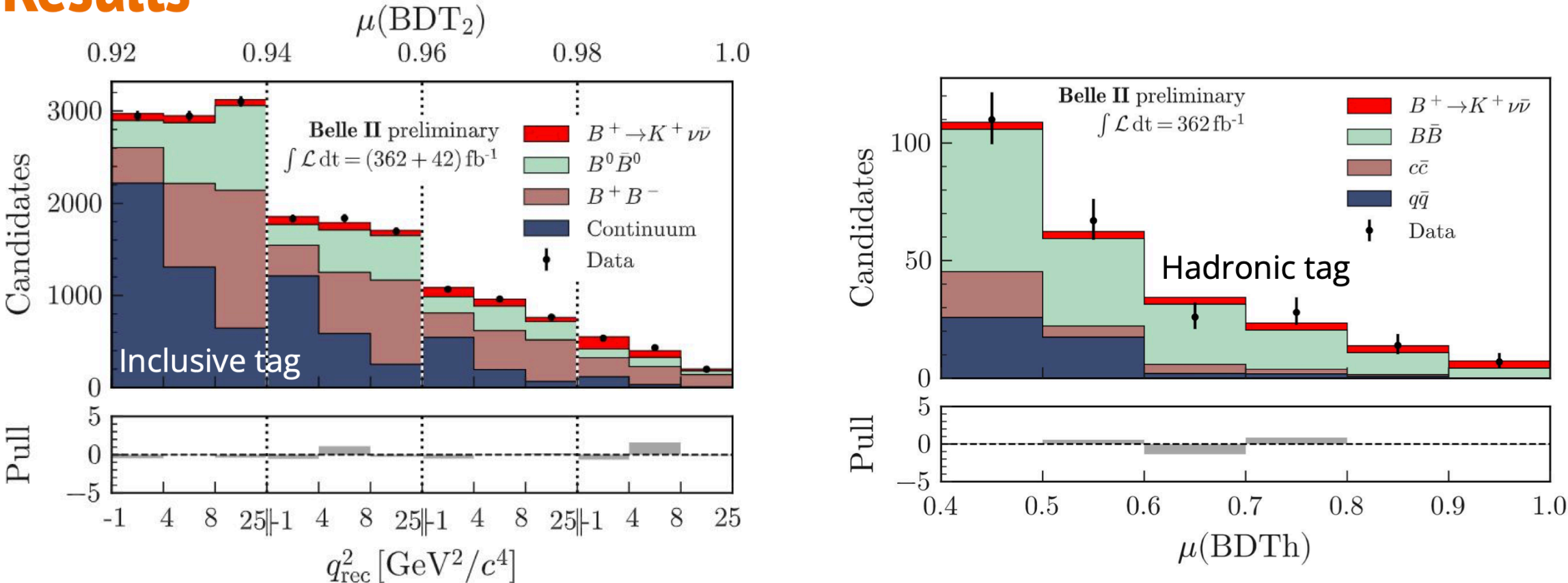
CMS-EXO-19-016



Observation of $B \rightarrow K \nu \bar{\nu}$ on the side of the world



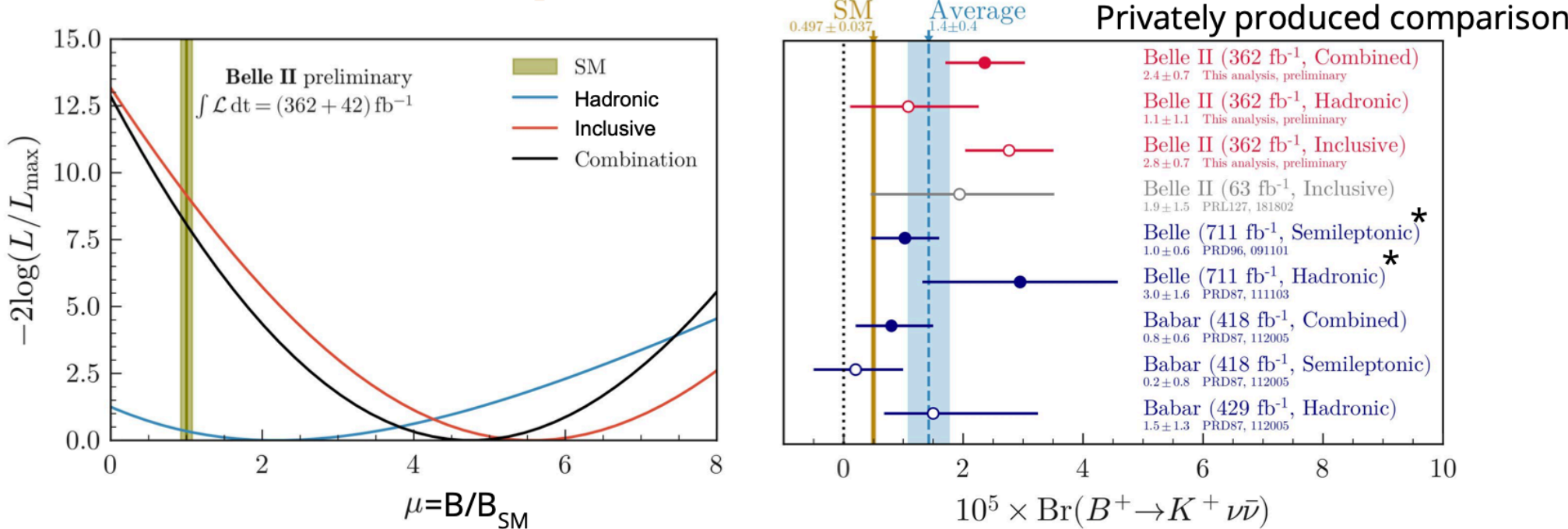
Results



- Maximum likelihood fit to data using signal and background templates
- Branching fractions: $B_{\text{incl.}} = (2.8 \pm 0.5(\text{stat}) \pm 0.5(\text{stat})) \times 10^{-5}$, $B_{\text{had.}} = (1.1^{+0.9}_{-0.8}(\text{stat})^{+0.8}_{-0.5}(\text{syst})) \times 10^{-5}$
- For inclusive analysis, **evidence for $B \rightarrow K \nu \bar{\nu}$** at 3.6σ , branching fraction within 3.0σ of standard model (both considering total uncertainty)
- For hadronic tag, the result is consistent with null hypothesis and SM at 1.1σ and 0.6σ

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Combination and comparison with other measurements



- Inclusive and hadronic measurements are combined, taking into account common correlated uncertainties. The resulting branching fraction is $B_{\text{comb}}(B^+ \rightarrow K^+ \nu \bar{\nu}) = (2.4 \pm 0.7) \times 10^{-5} = [2.4 \pm 0.5(\text{stat})^{+0.5}_{-0.4}(\text{syst})] \times 10^{-5}$ significance of **observation** is 3.6σ the result is within 2.8σ vs standard model
- Some tensions between inclusive and semileptonic results for Belle and BaBar, however overall compatibility of the results is good with $\chi^2/\text{dof} = 4.3/4$

*Belle reports upper limits only; branching fractions are estimated using published number of events and efficiency

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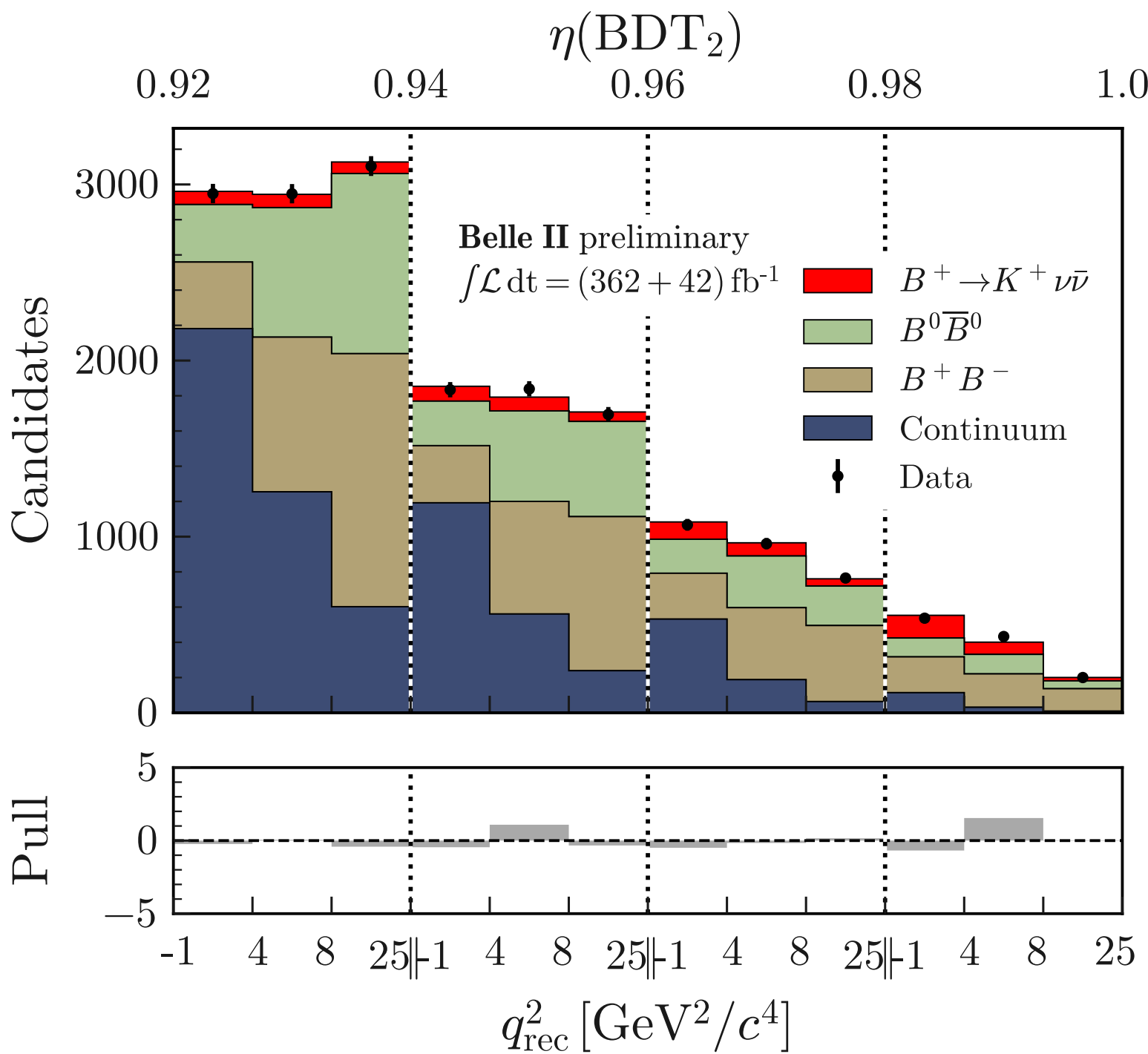
Very interesting result !
Looking forward to seeing impact on phenomenology work

More information

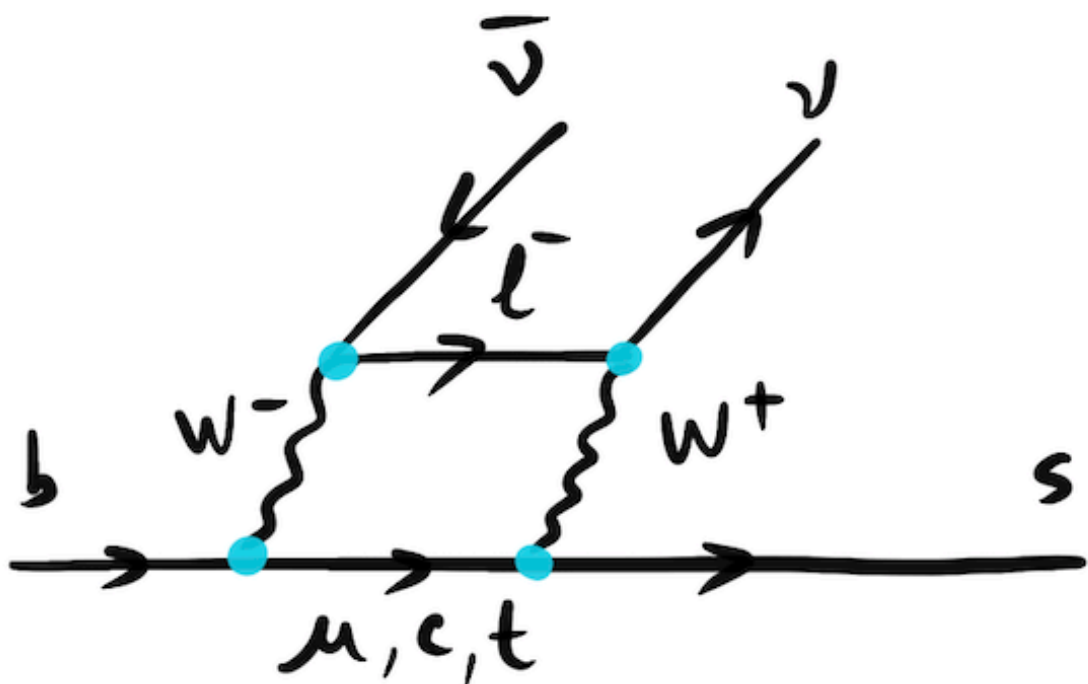
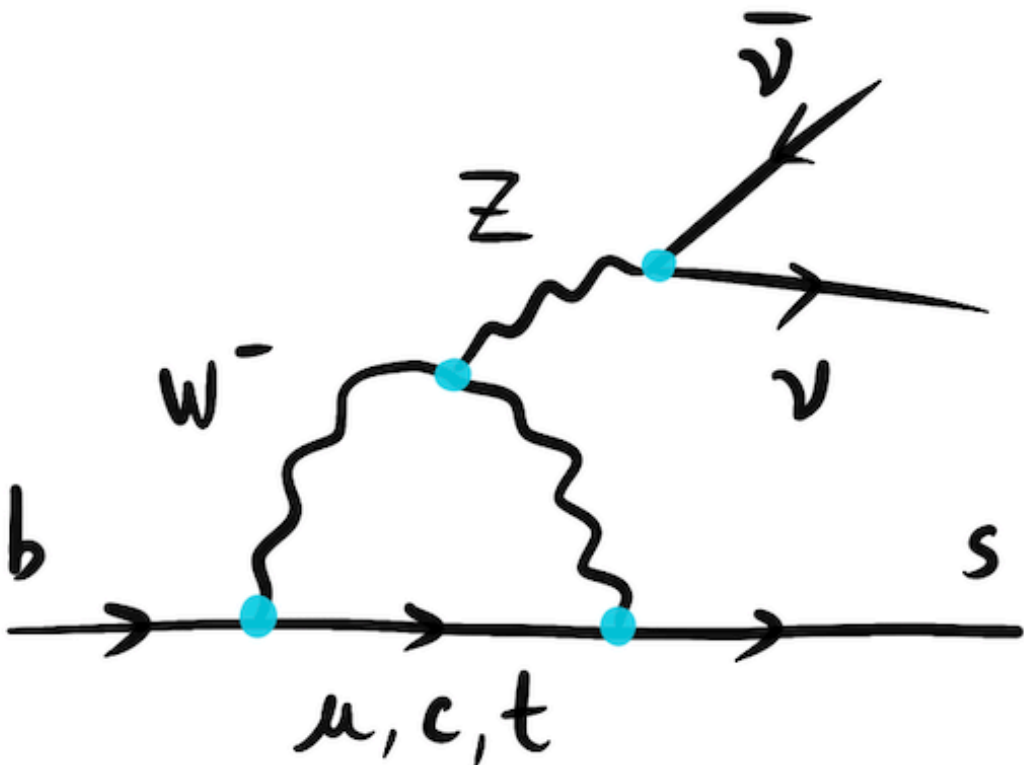
$b \rightarrow s\nu\bar{\nu}$ motivation

- Most probably impossible at LHCb
- Belle II cannot do all B flavours
- Yet to be observed, besides evidence for $B^+ \rightarrow K^+\nu\bar{\nu}$
 - 2.7σ tension with SM [[arxiv:2311.14647](#)]
- Theoretically cleaner than the corresponding $b \rightarrow sl^+l^-$
- Can be used to extract the CKM factor and hadronic form factors, and constrain Wilson coefficients
- Novel probes of CPV from new physics [[arxiv:2208.10880](#)]

Decay	B-factories	FCC-ee
$B^+ \rightarrow K^+\nu\bar{\nu}$	✓	✓
$B^+ \rightarrow K^{*+}\nu\bar{\nu}$	✓	✓
$B^0 \rightarrow K_S^0\nu\bar{\nu}$	✓	✓
$B^0 \rightarrow K^{*0}\nu\bar{\nu}$	✓	✓
$B_s^0 \rightarrow \phi\nu\bar{\nu}$	✗	✓
$\Lambda_b^0 \rightarrow \Lambda^{(*)0}\nu\bar{\nu}$	✗	✓

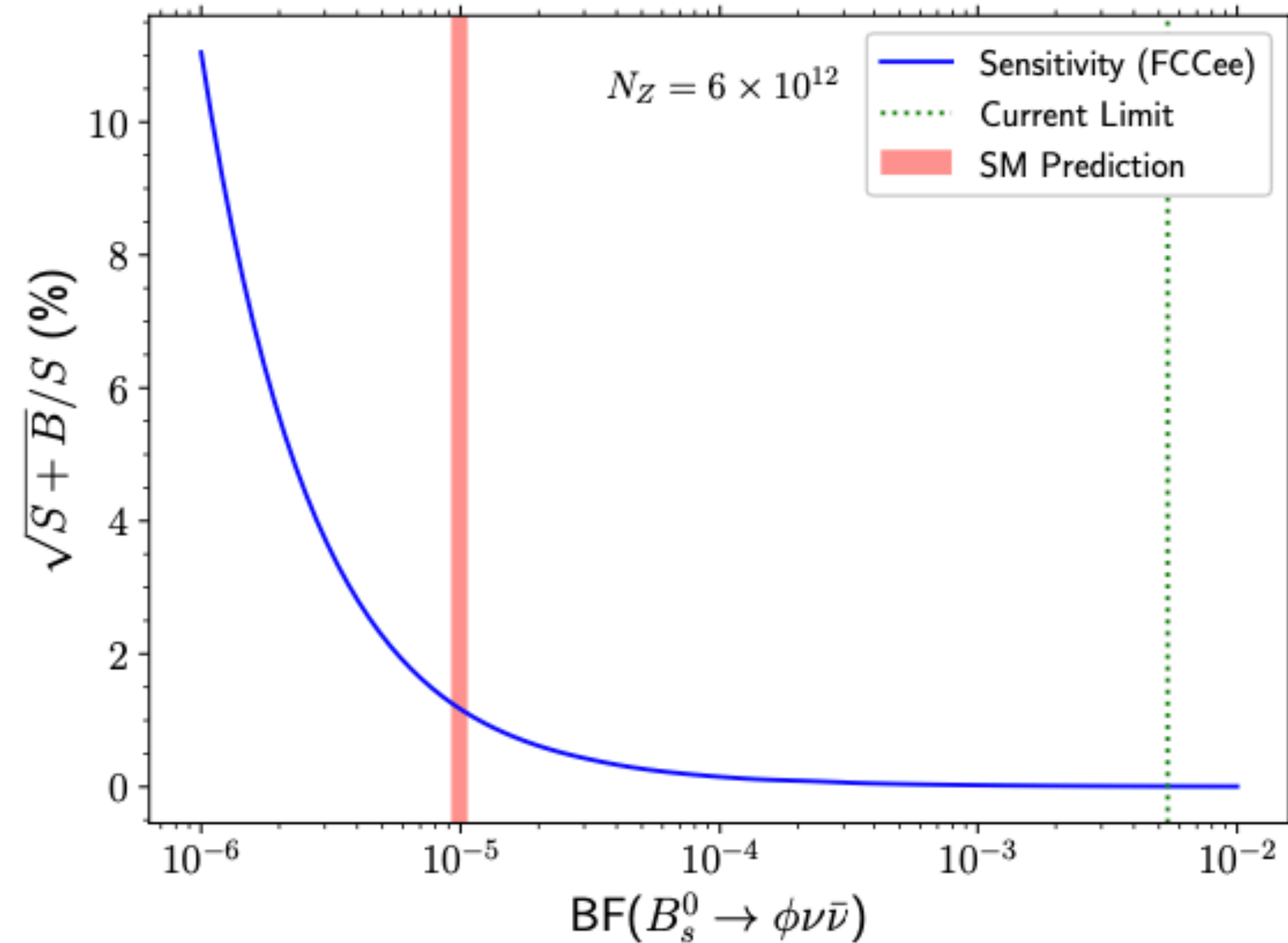
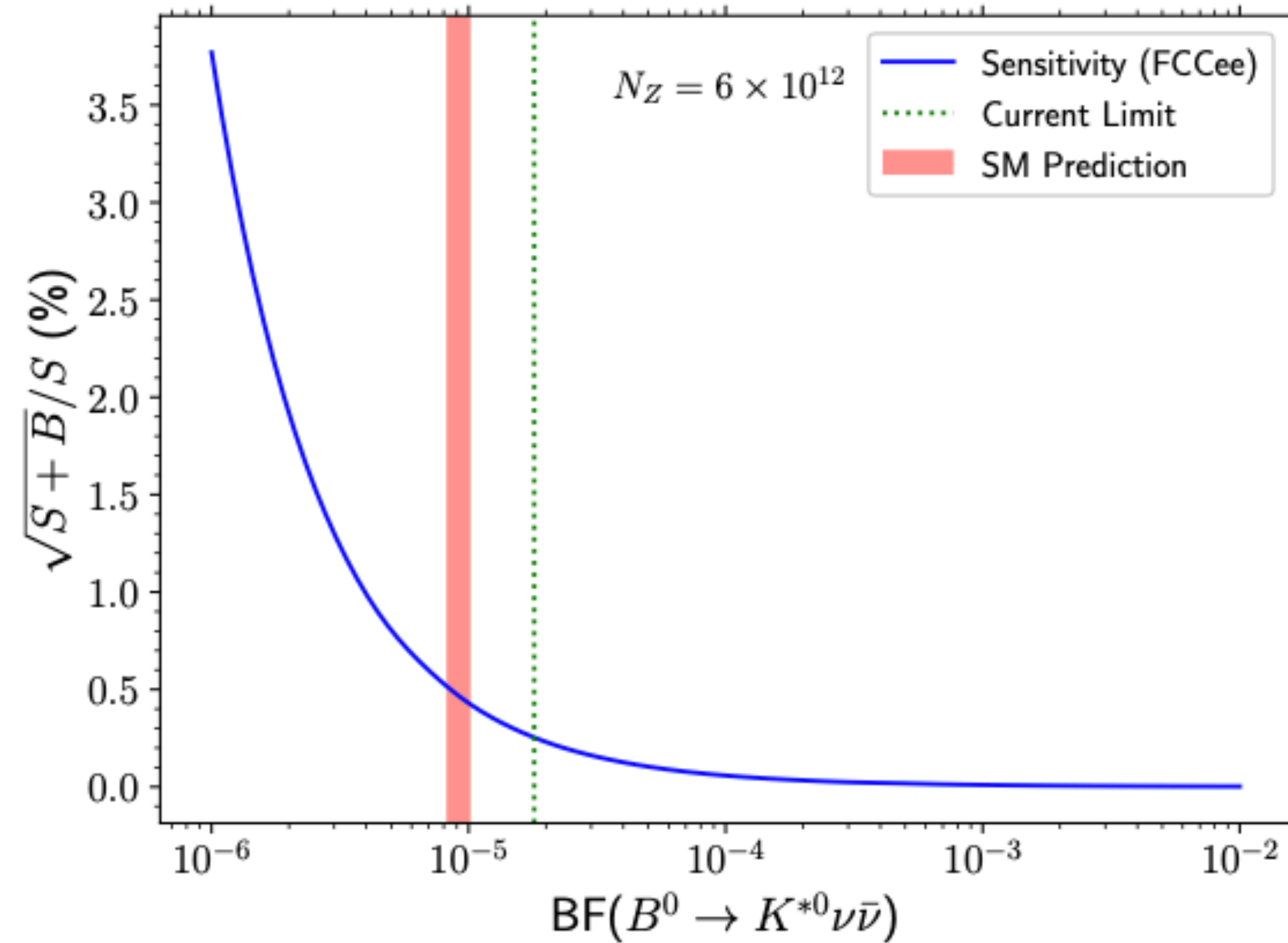


Plot of the maximum likelihood fit for $B^+ \rightarrow K^+\nu\bar{\nu}$ from inclusive tagging



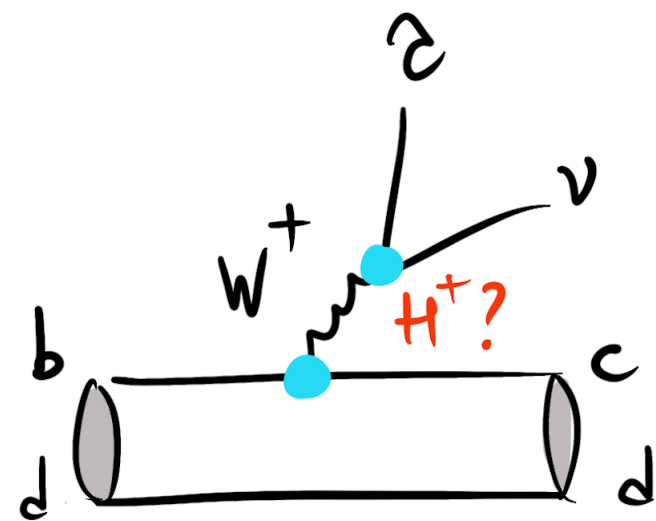
$b \rightarrow s\nu\bar{\nu}$ projections

Studies on sensitivity at FCC-ee [JHEP 01 (2024) 144] and at CEPC [PRD 105 (2022) 114036]

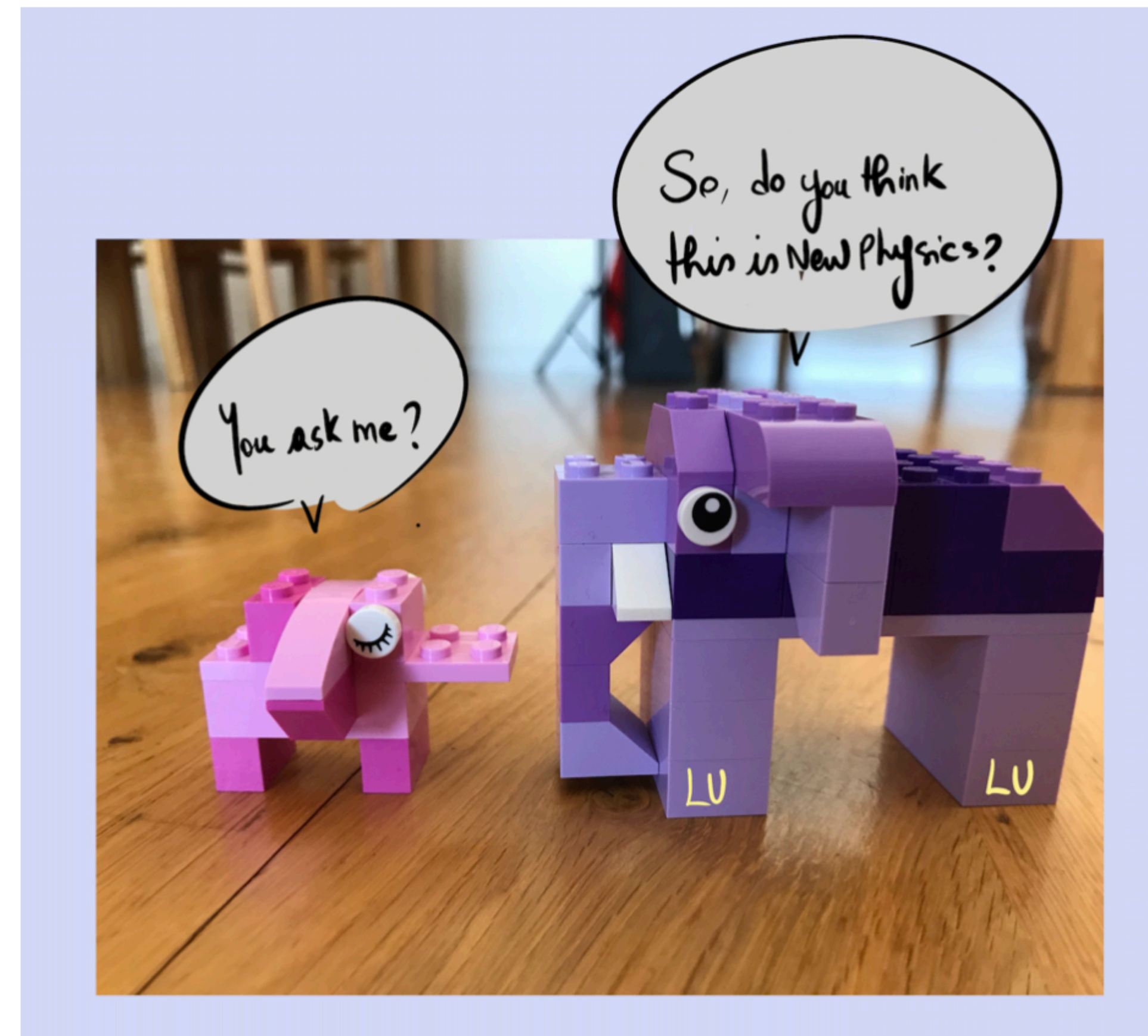
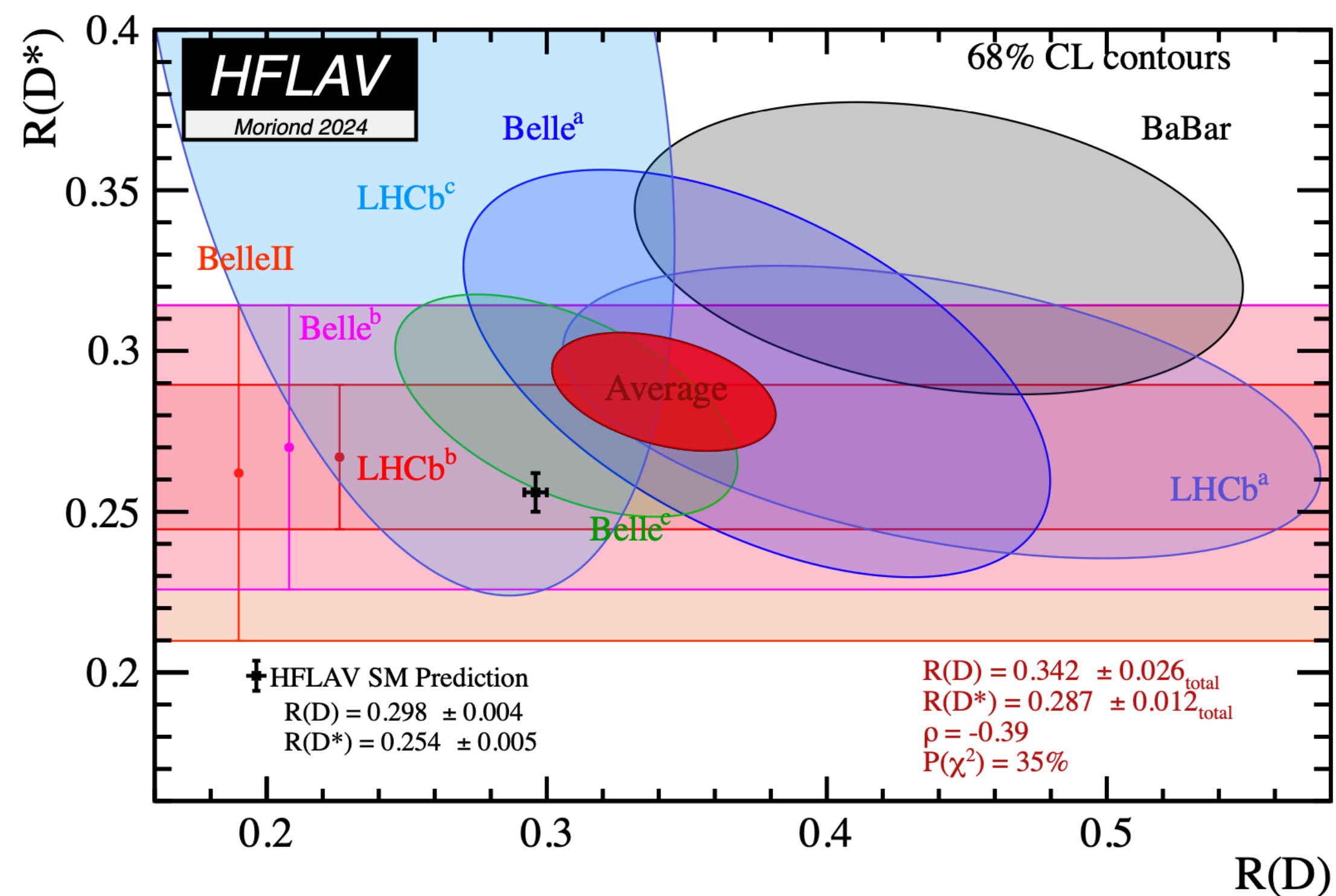


This kind of precision means that differential measurements will be possible



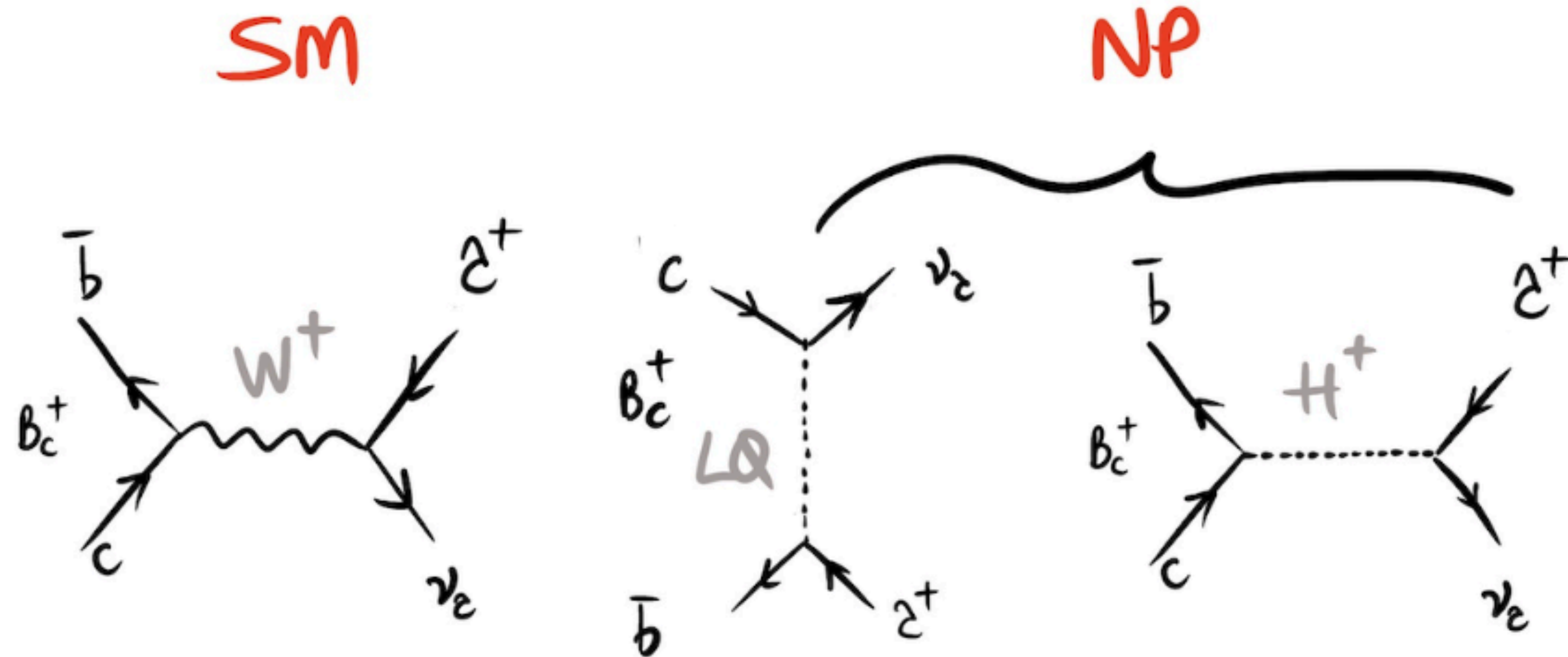


Charged currents



<https://hflav.web.cern.ch/content/semileptonic-b-decays>

Why do we care about this decay?



- Can be used to measure the CKM element $|V_{cb}|$ and highly sensitive to scalar contributions from NP.
- No possible at LHCb due to missing energy-lack of constraints and reconstructed information.
- No B_c production at Belle II.
- A Tera-Z machine is an ideal machine to study this decay.

With an EFT at $\mu = m_b$

$$\mathcal{H}_{\text{eff}} = \frac{4 G_F}{\sqrt{2}} V_{cb} \left[(1 + C_{V_L}) (\bar{c}_L \gamma^\mu b_L) (\bar{\nu}_L \gamma_\mu \nu_L) \right. \\ + C_{V_R} (\bar{c}_R \gamma^\mu b_R) (\bar{\nu}_L \gamma_\mu \nu_L) \\ + C_{S_L} (\bar{c}_L b_R) (\bar{\nu}_R \nu_L) \\ \left. + C_{S_R} (\bar{c}_R b_L) (\bar{\nu}_R \nu_L) \right] + \text{h.c.}$$

C_i are the Wilson coefficients,
null in the SM using this convention.

If one uses :

$$C_{V(A)} = C_{V_R} \pm C_{V_L} \text{ and } C_{S(P)} = C_{S_R} \pm C_{S_L}.$$

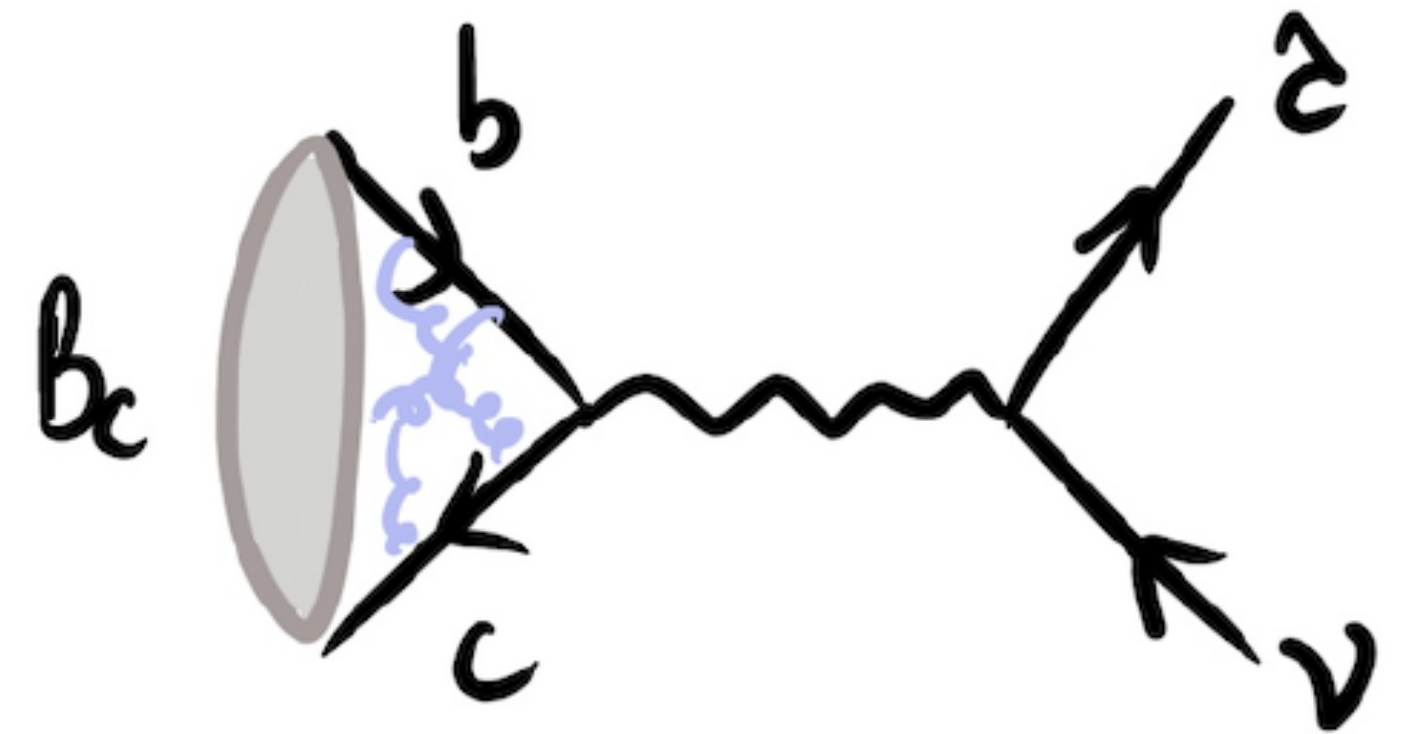
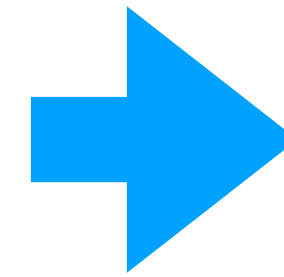
$$\mathcal{B}(B_c \rightarrow \tau \nu) = \overset{\text{SM}}{\mathcal{B}(B_c \rightarrow \tau \nu)} \left| 1 - C_A - C_P \frac{m_{B_c}^2}{m_\tau^2 (m_b + m_c)} \right|^2$$

C_P lifts the SM helicity suppression
sizeable enhancement !

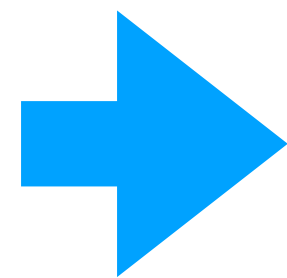


SM prediction

Tree-level Feynman diagram in the SM



$$\mathcal{B}(B_c \rightarrow \tau \nu)^{\text{SM}} = \tau_{B_c} G_F^2 \frac{|V_{cb}|^2 f_{B_c}^2 m_{B_c}}{8\pi} \cdot m_\tau^2 \left(1 - \frac{m_\tau^2}{m_{B_c}^2}\right)^2$$



$$\mathcal{B}(B_c^+ \rightarrow \tau^+ \nu_\tau)^{\text{SM}} = 1.95(9) \times 10^{-2}$$

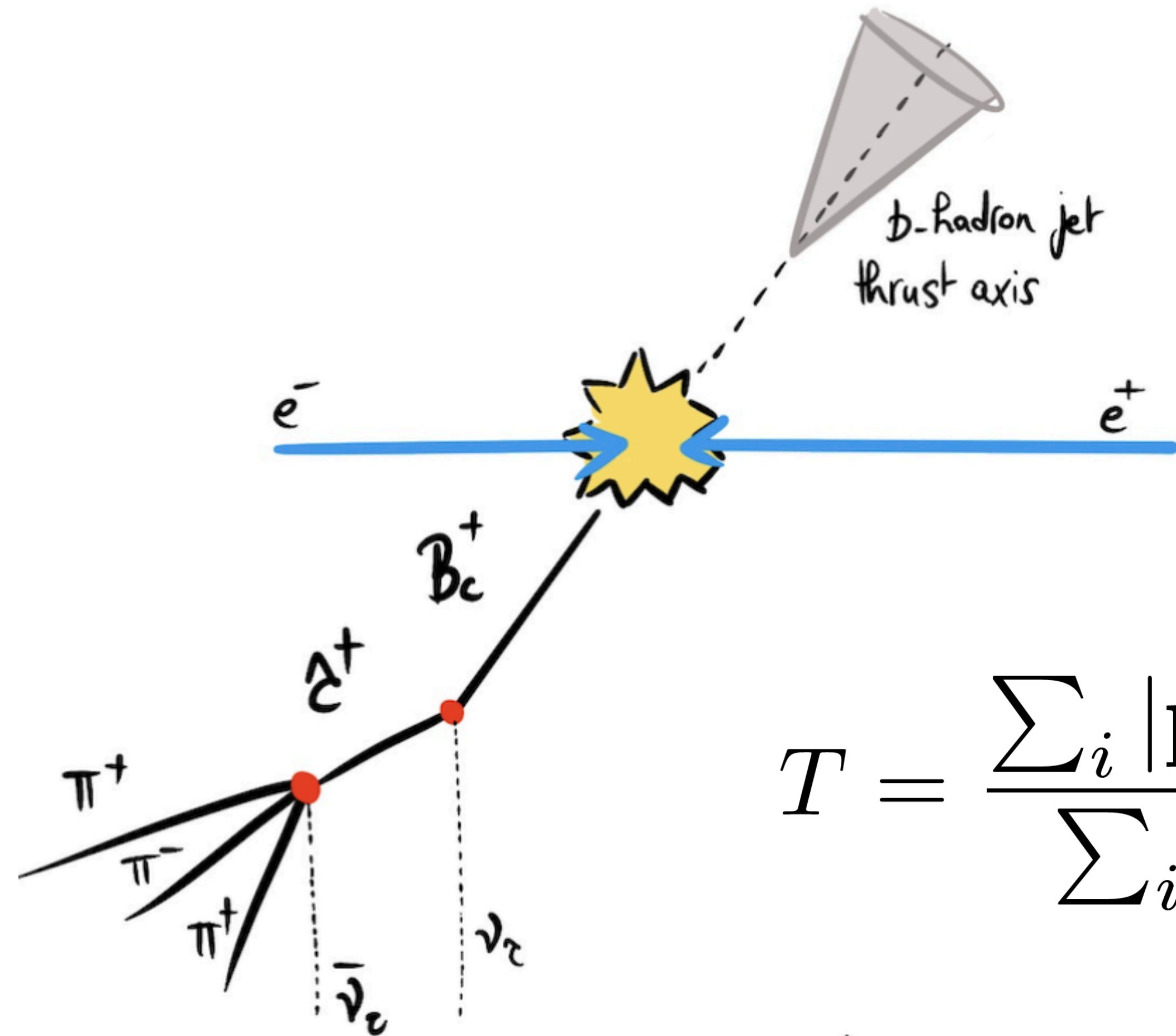
Decay constant from HPQCD and V_{cb} exclusive HFLAV.

Looking forward to improvements of the decay constant computation with LQCD techniques.

Decay topology

B_c lifetime very short ~ 0.5 ps,
i.e too many degrees of freedom
to fully reconstruct the decay.

Explore the thrust axis properties
and the hadronic τ decays.



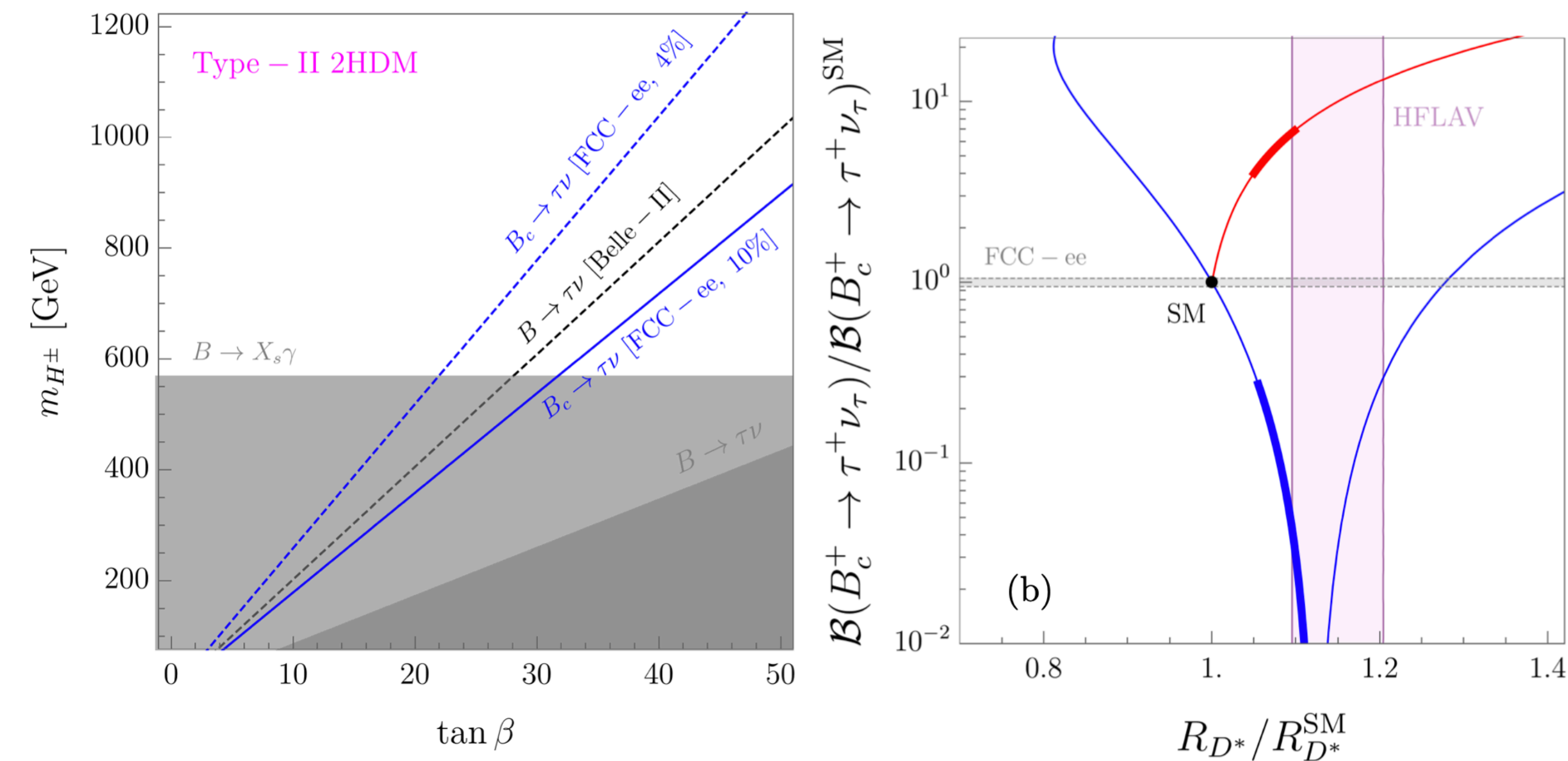
$$T = \frac{\sum_i |\mathbf{p}_i \cdot \hat{\mathbf{n}}|}{\sum_i |\mathbf{p}_i|}$$

Note : arXiv:2007.08234 explored leptonic τ decays.



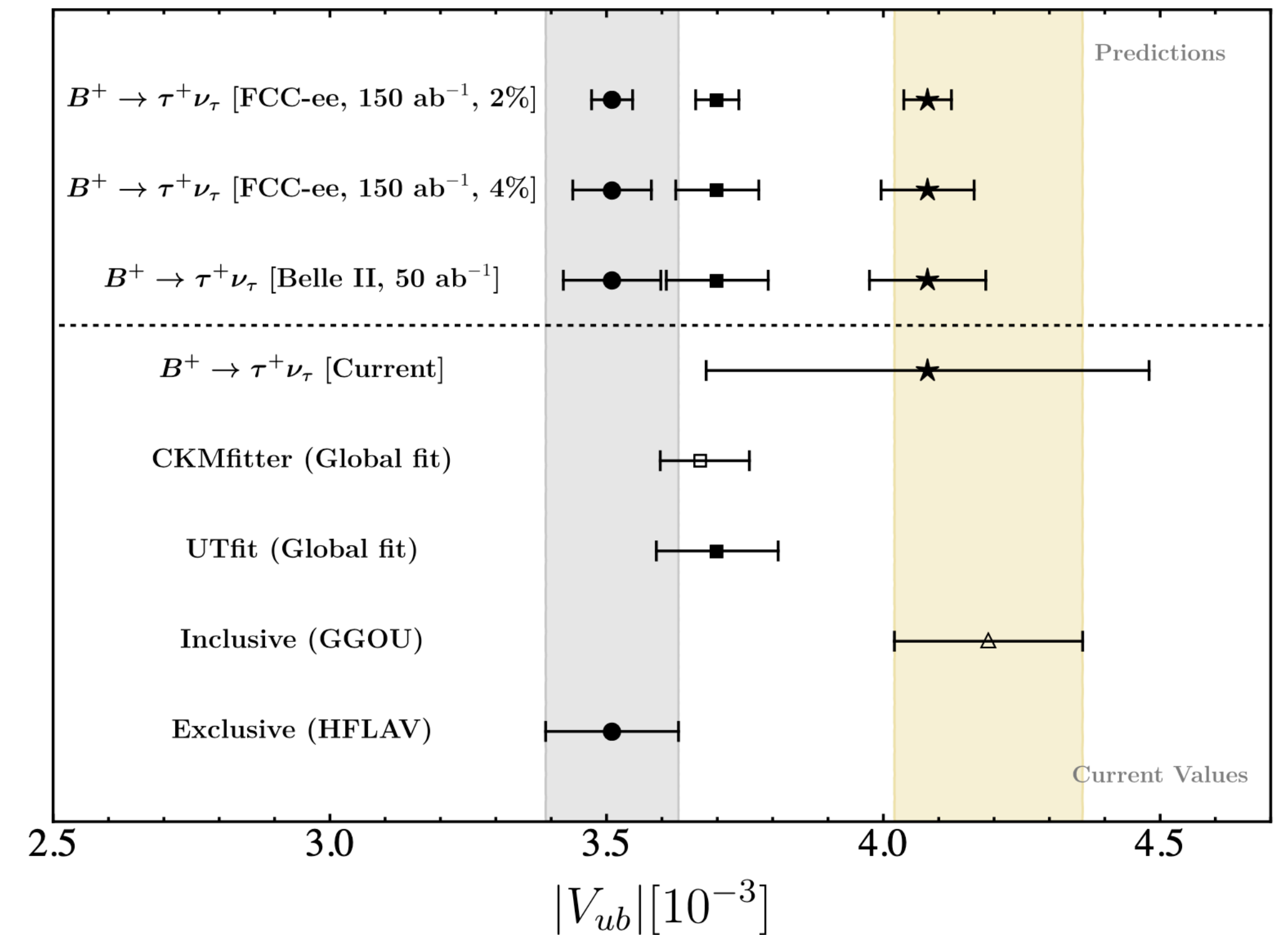
Results

Impact evaluated on NP models and Lepton Universality observables



But also... $B^+ \rightarrow \tau^+ \nu_\tau$

arXiv:2305.02998

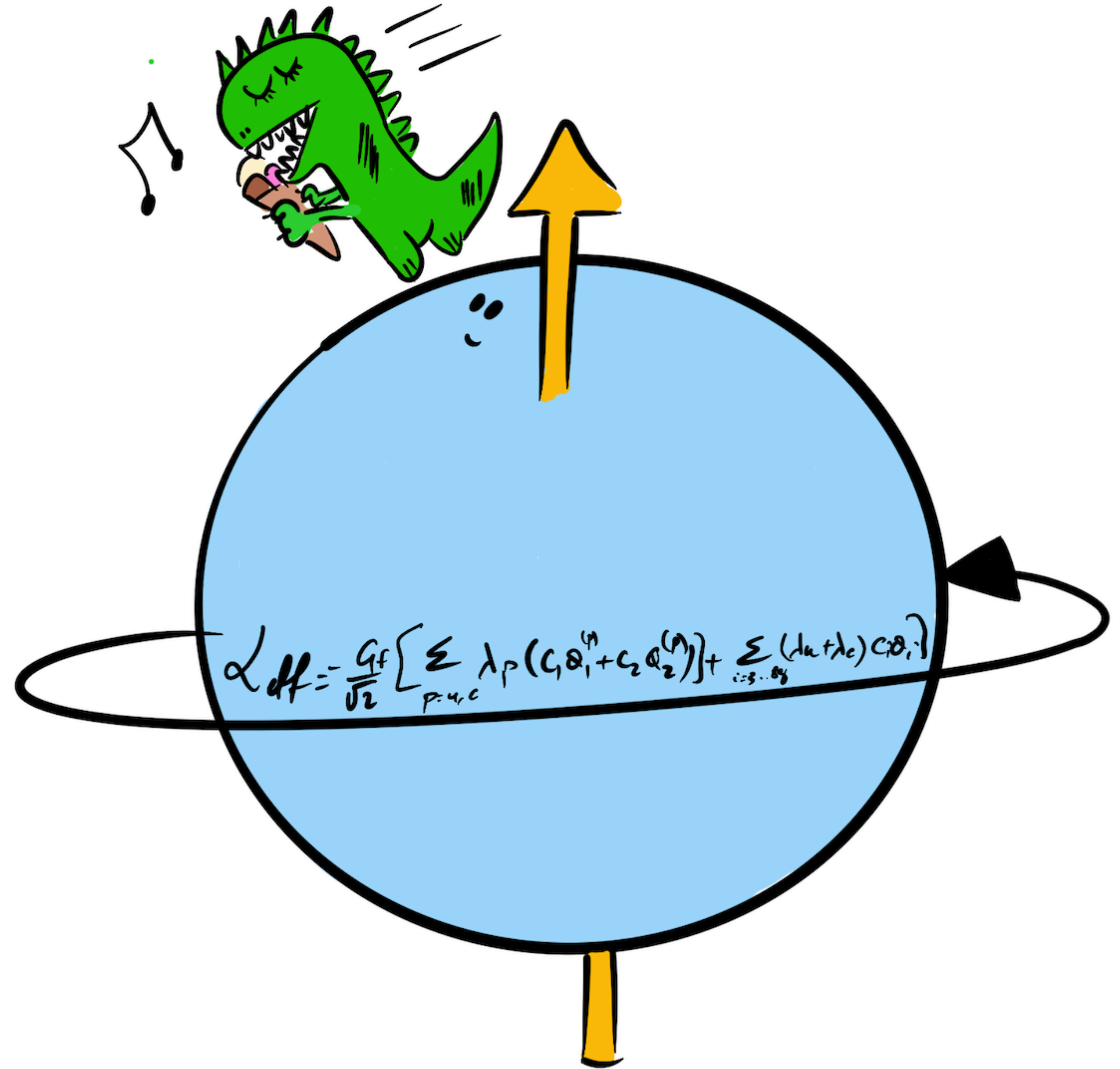


Comparison between current determinations of $|V_{ub}|$ and predicted determinations from Belle II and FCC-ee, where the FCC-ee values correspond to 2% and 4% uncertainty on $\mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau)$. Different central values are taken from the current Exclusive, Global and $B^+ \rightarrow \tau^+ \nu_\tau$ values.



To almost conclude

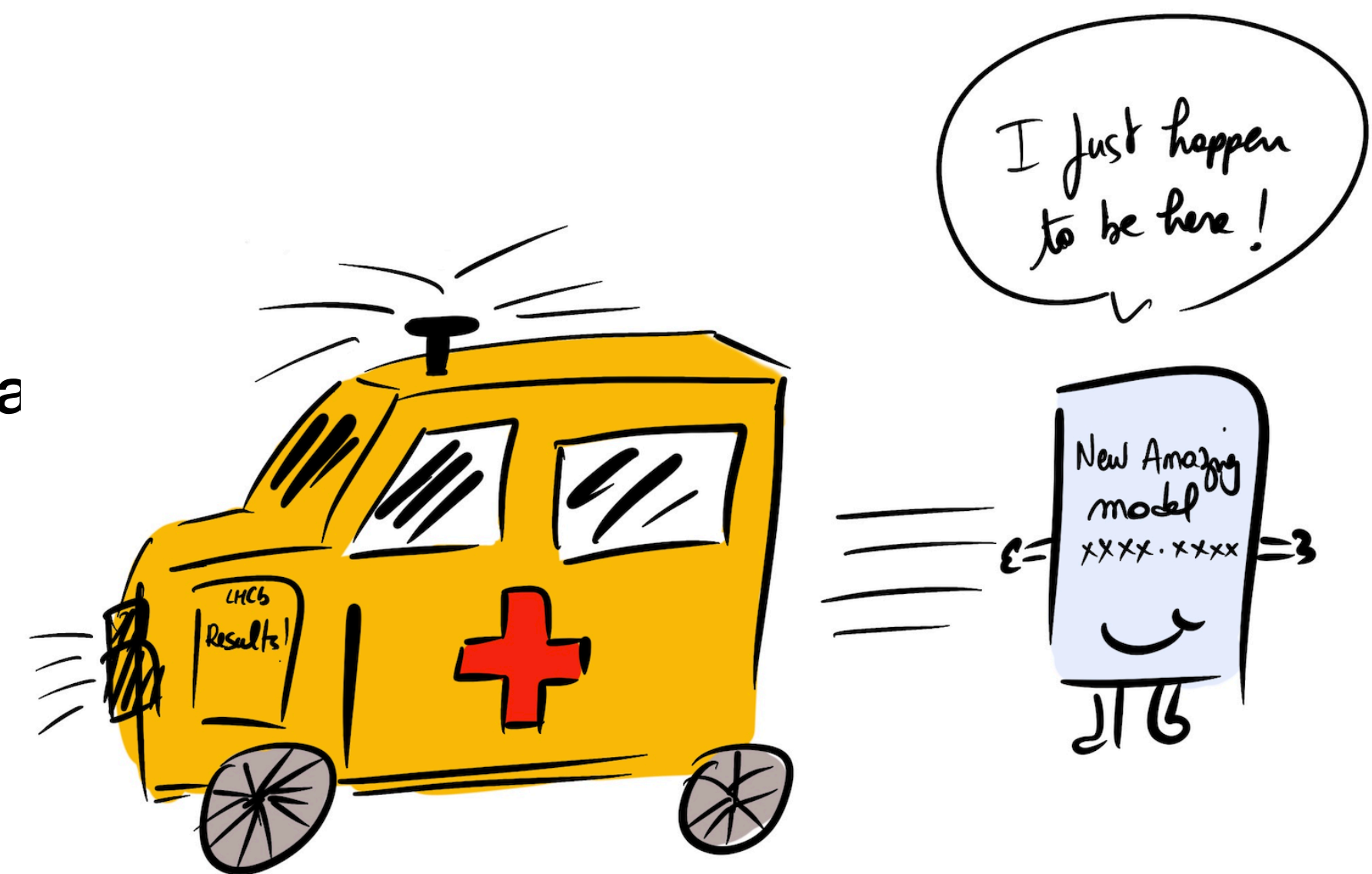
- We need New Physics !
- Flavour Physics is a super cool laboratory to search for it.
- So far the Standard Model seems to be putting up a good fight.
- We can only rely on the imagination of physicists to make the next breakthroughs.
- There are a number of experiments lined up to pursue this adventure !



Good practices for PhD students

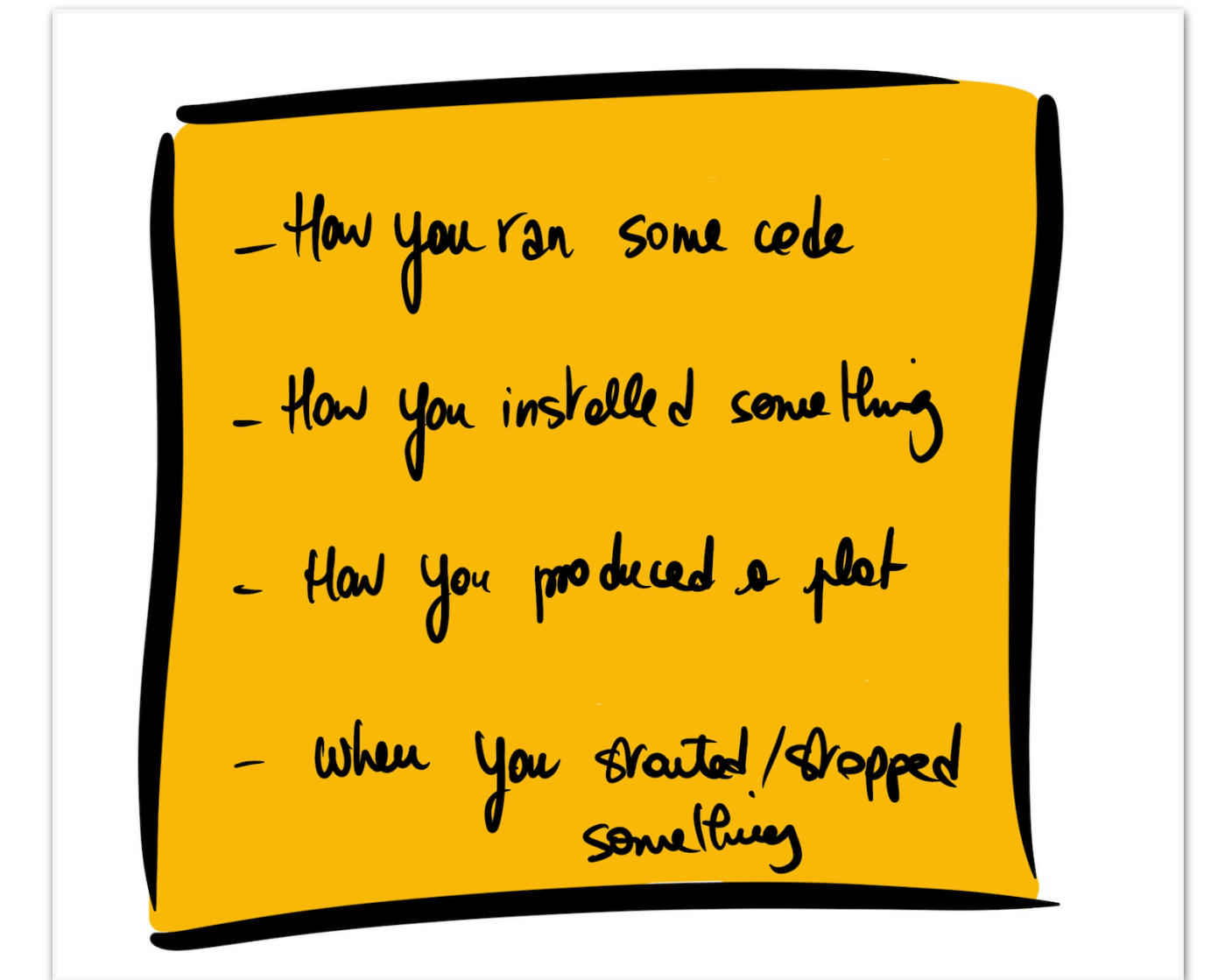
If one day you become a PhD student

- Keep an eye on arXiv.
- Check the theory and experimental summeries talks at conferences a workshops
- Check the review articles.
- Check other submitted PhDs manuscripts.
- Don't be shy and ask questions.



And please please please

- Log your work, it does not matter if you use notebooks, software, whatever.
- Keep track of everything you do, we forget details, we forget obvious things. We always think that we will remember.
- The amount of information to store only increases, so help your future you and write down things.



Jun 6, 2022 • 4 min read

Track, review, keep or toss.



Nov 4, 2023 • 3 min read

3 tips for new PhD graduates

<https://www.yasmineamhis.com/post/track-review-keep-or-toss>

<https://www.yasmineamhis.com/post/3-tips-for-new-phd-graduates>

A colouring book for children is available at the CERN Science Gateway



More information yasmineamhis.com