Precision flavor physics:

Recent measurements of the CKM angle γ at LHCb

Moritz Karbach
moritz.karbach@cern.ch

Particle Physics Seminar LAL
17.02.2015

LHC, CERN, Geneva

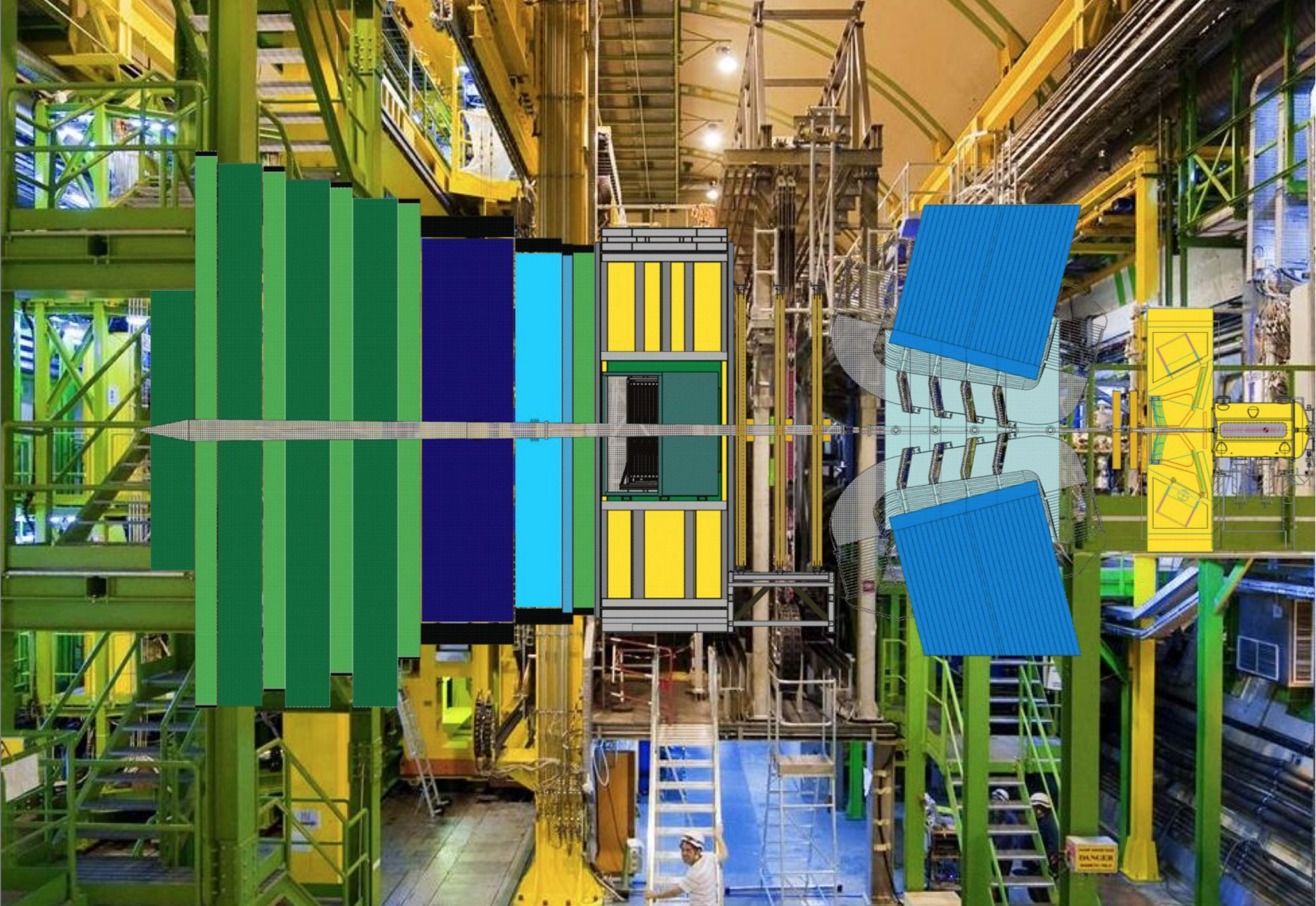
pp collisions at 7-8 TeV

Long Shutdown 1: 2013-2015

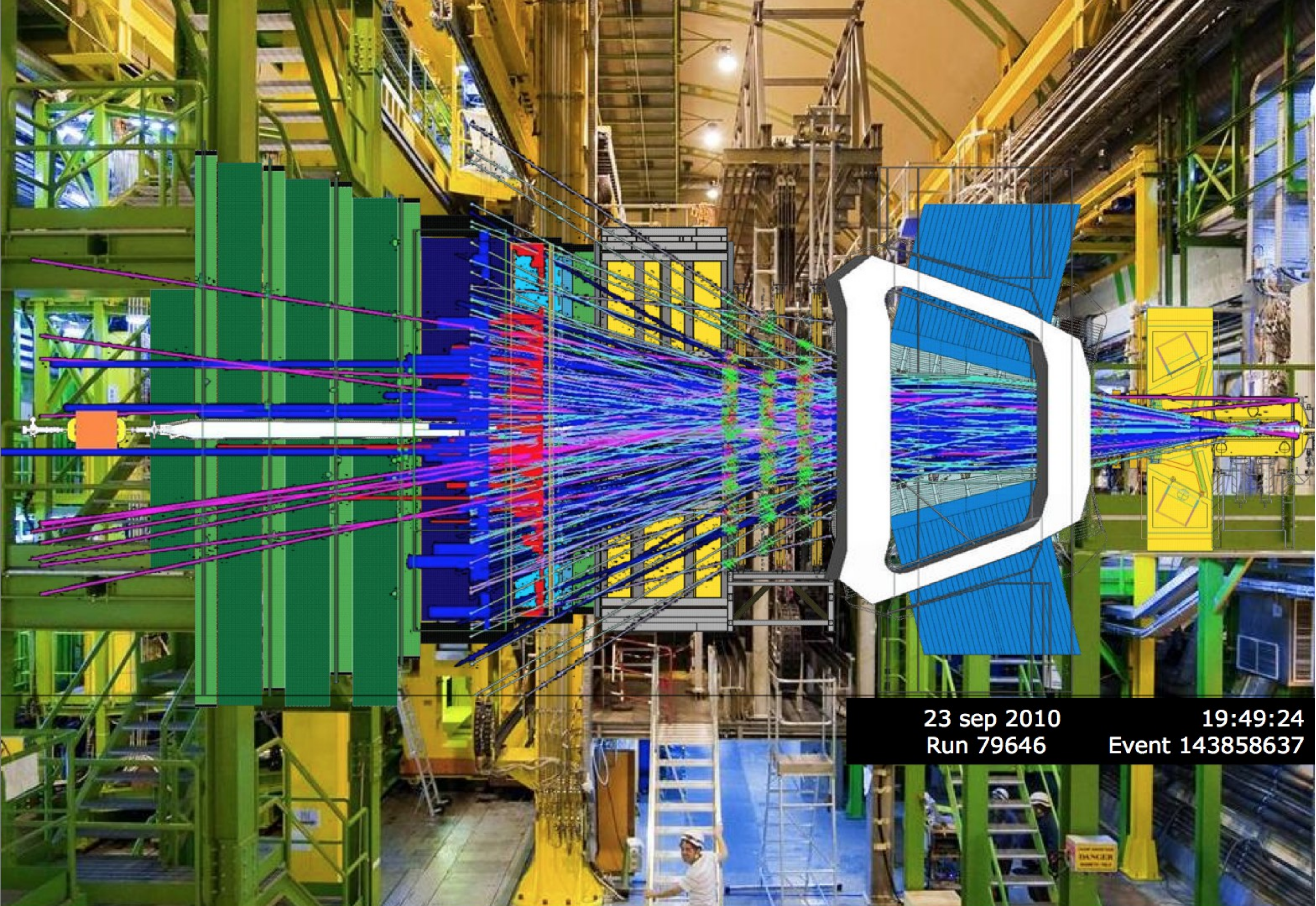
then: 13-14 TeV

The LHCb Detector

The LHCb Detector

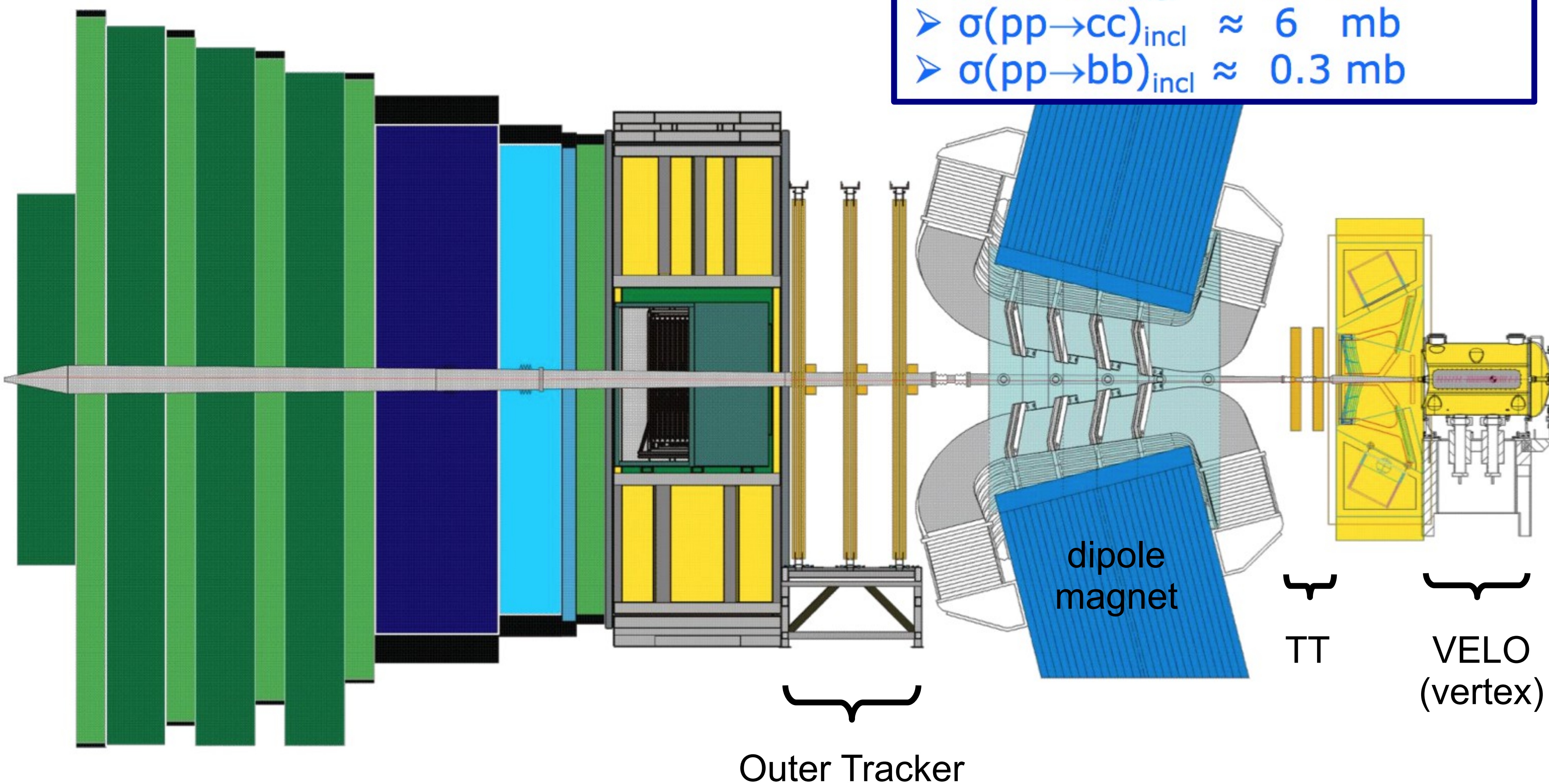


The LHCb Detector



Forward arm spectrometer

- $2<\eta<5$
- $\sigma(pp\to X)_{inel} \approx 60$ mb
- $\sigma(pp\to cc)_{incl} \approx 6$ mb
- $\sigma(pp\to bb)_{incl} \approx 0.3$ mb



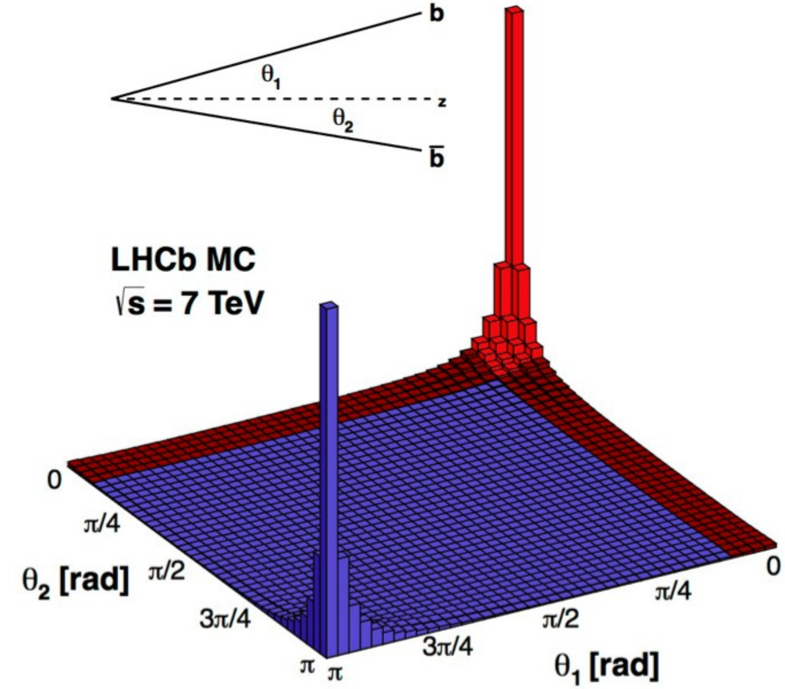
Outer Tracker

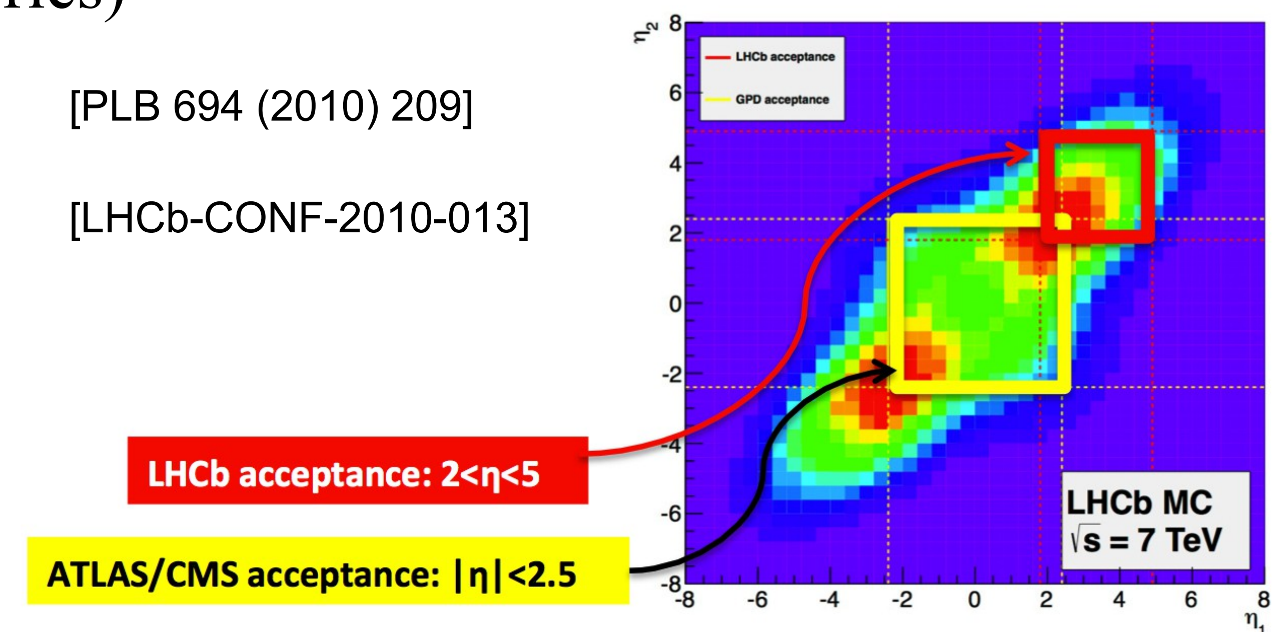
LHCb

- one arm forward spectrometer
- b pair production angles strongly correlated
- covers **1.9 < η < 4.9**
- 100'000 bb pairs produced per second (10^4 x B factories)

$\sigma(b\bar{b}) = 284 \pm 53 \mu\text{b}$ [PLB 694 (2010) 209]

$\sigma(c\bar{c}) \approx 20 \times \sigma(b\bar{b})$ [LHCb-CONF-2010-013]





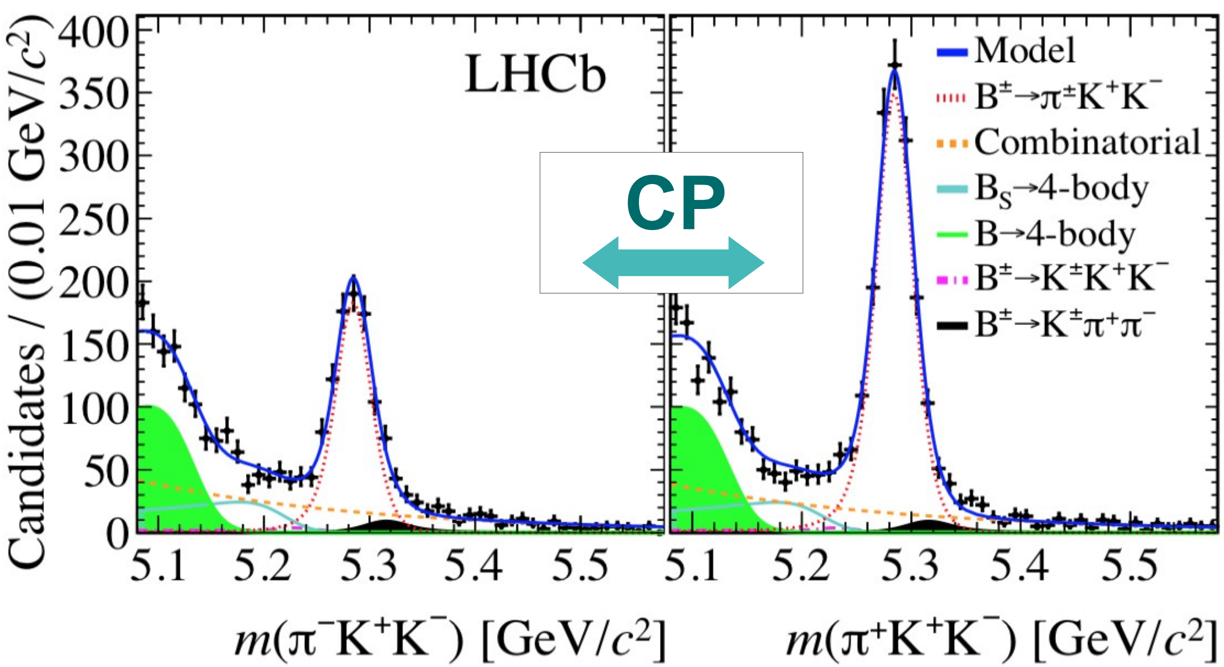
CP violation

- Matter/Antimatter, baryon genesis
- CP violation is one crucial ingredient (Sacharov)
- The CKM matrix is the one place in the SM with CP violation.

CP violation

- Matter/Antimatter, baryon genesis
- CP violation is one crucial ingredient (Sacharov)
- The CKM matrix is the one place in the SM with CP violation.

$B^- \to K^+ K^- \pi^-$ $B^+ \to K^+ K^- \pi^+$



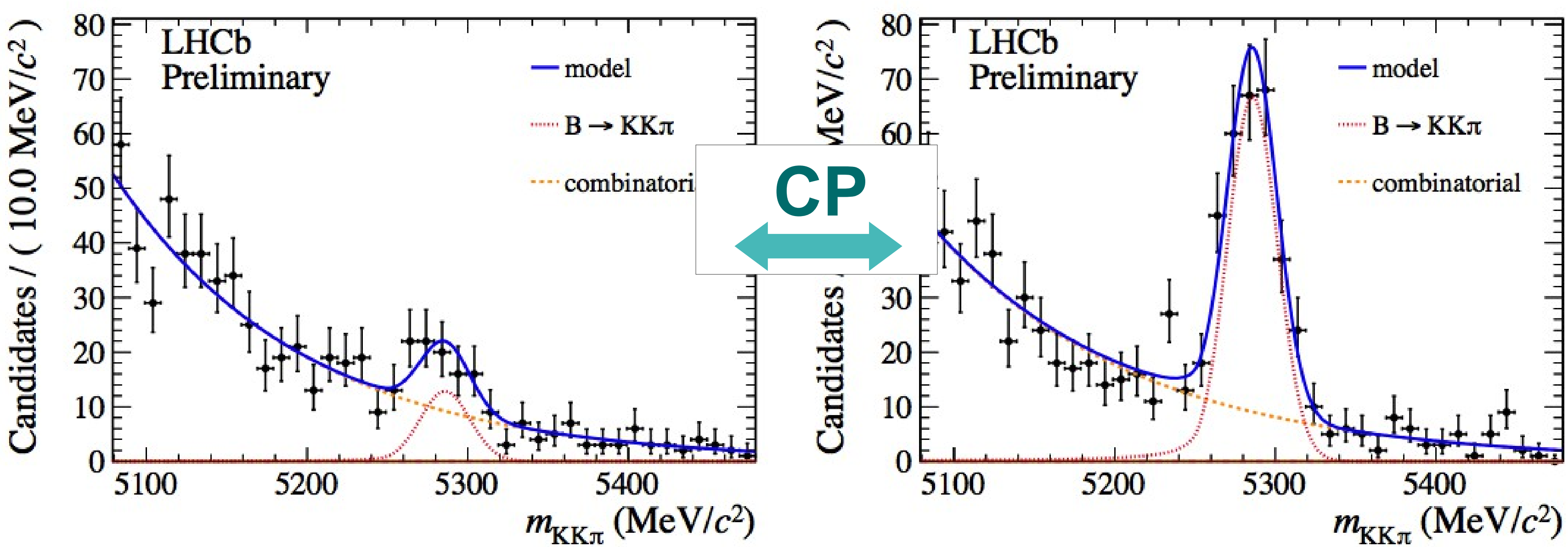
$3\,\text{fb}^{-1}$

PRDD90 (2014) 112004
arXiv:1408.5373

CP violation

- Matter/Antimatter, baryon genesis
- CP violation is one crucial ingredient (Sacharov)
- The CKM matrix is the one place in the SM with CP violation.

$B^- \to K^+ K^- \pi^-$ $B^+ \to K^+ K^- \pi^+$



$1\,\mathrm{fb}^{-1}$

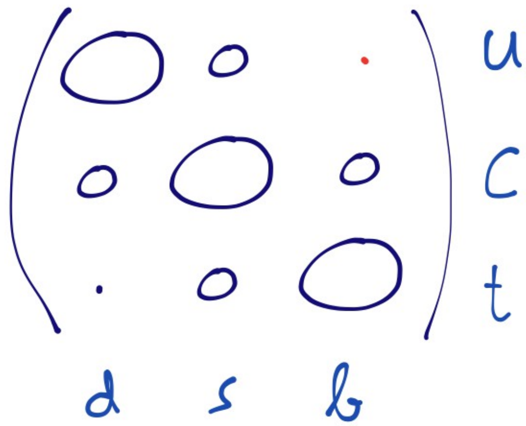
CP asymmetry in B → KKπ in **selected kinematic** range [LHCb-CONF-2012-028]

CP Violation in the SM: CKM matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

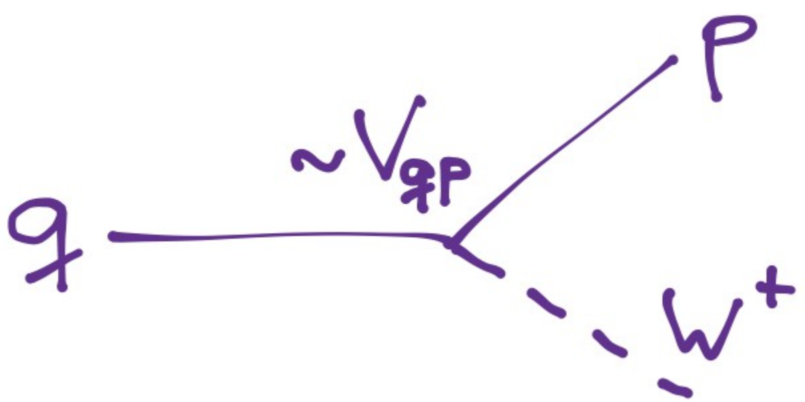
flavor eigenstates

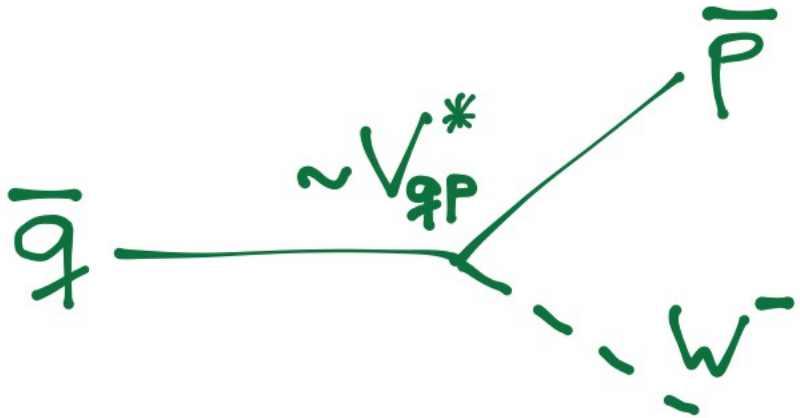
mass eigenstates



Cabibbo
Kobayashi
Maskawa

matrix elements determine transition probabilities:





CP Violation in the SM: CKM matrix

Unitarity condition

$$V^\dagger V = 1$$

implies

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

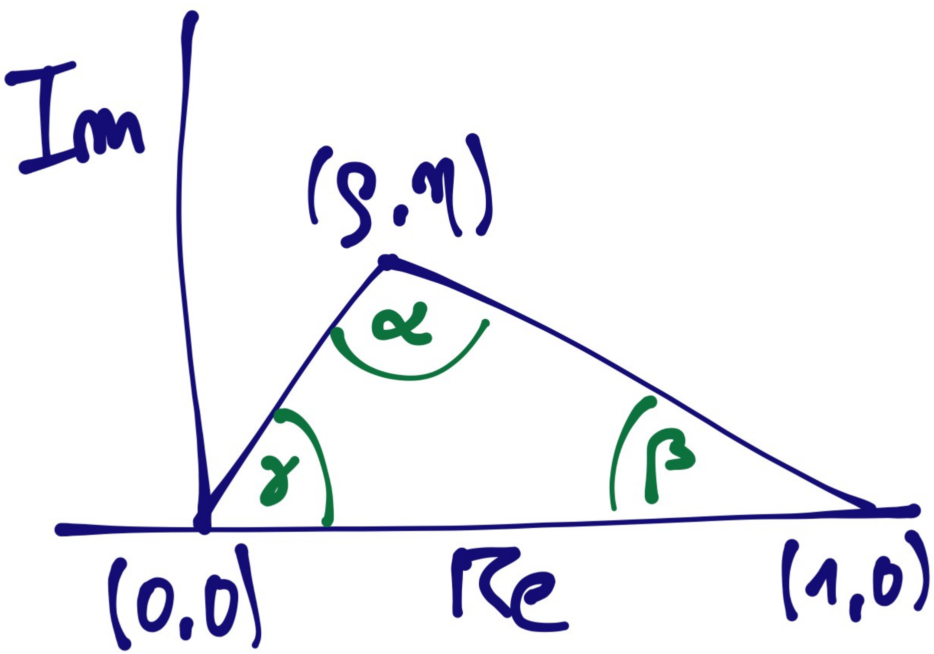
normalize it:

$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + 1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0$$

CP Violation in the SM: CKM matrix

$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + 1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0$$

Triangle in the complex plane.

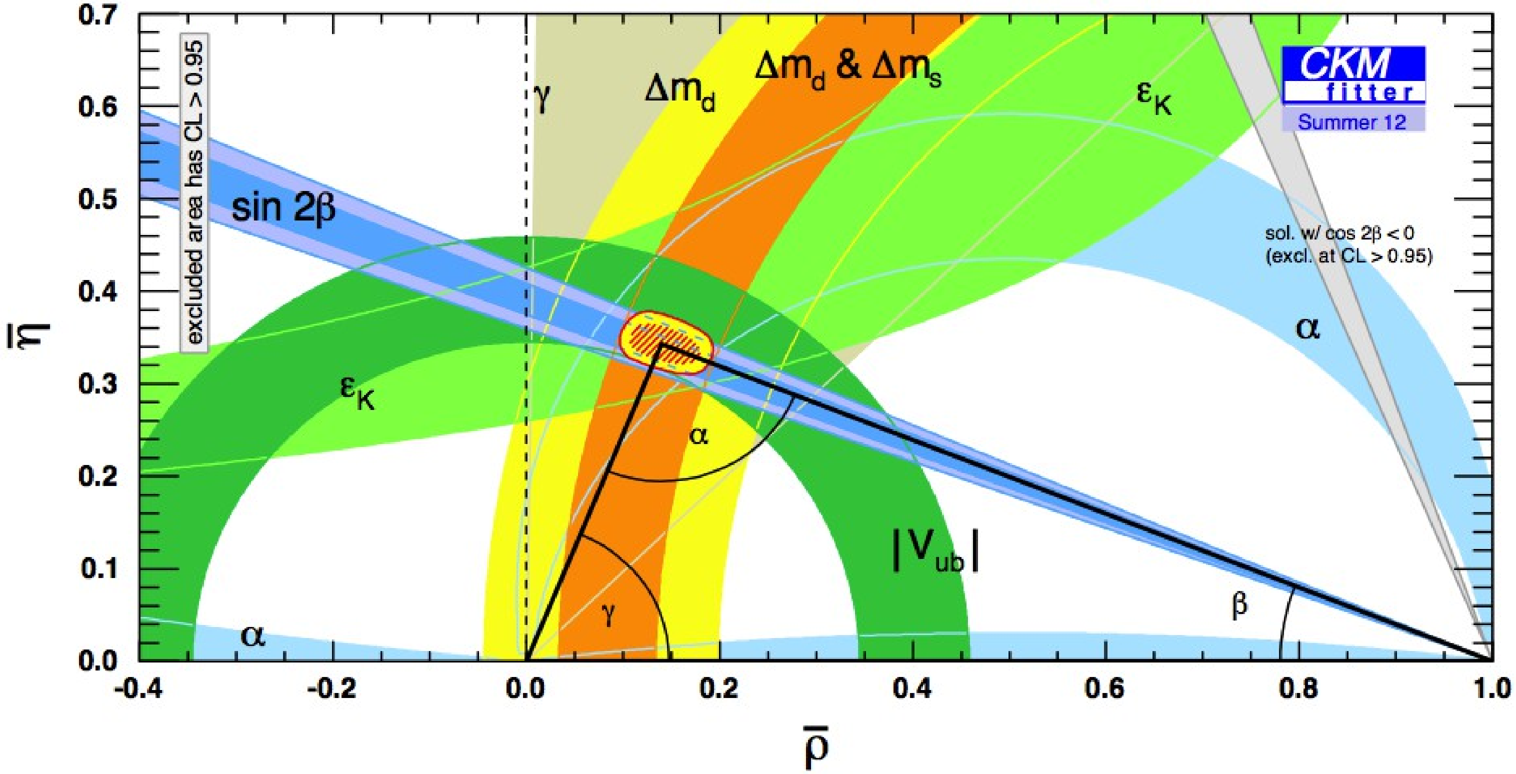


$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

Area corresponds to the **total CP violation** in the Standard Model.

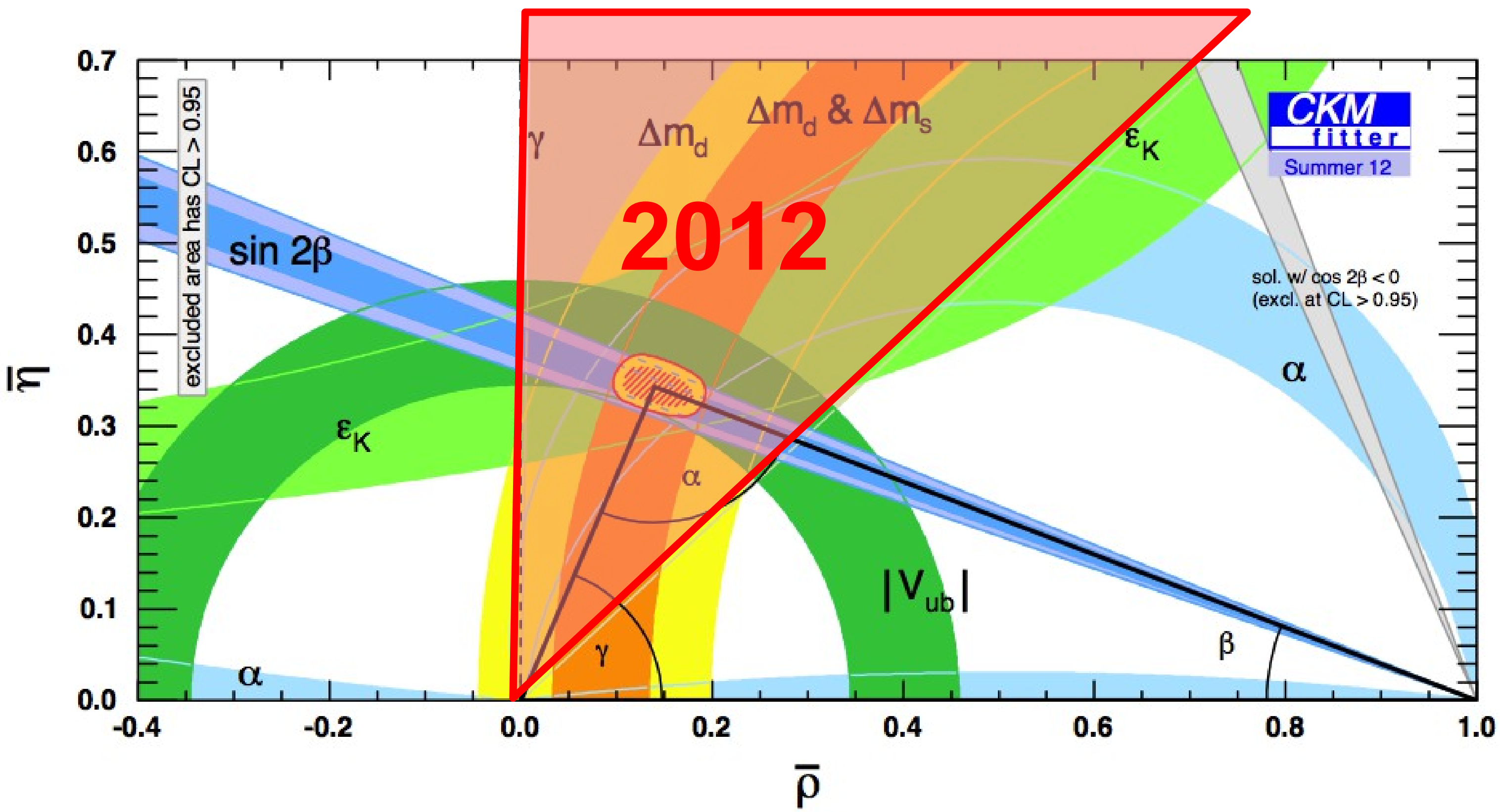
CKM angle γ

This is the *least well known* angle of the unitarity triangle.



CKM angle γ

This is the *least well known* angle of the unitarity triangle.



CKM angle γ

This is the *least well known* angle of the unitarity triangle.

"combined γ measurements"

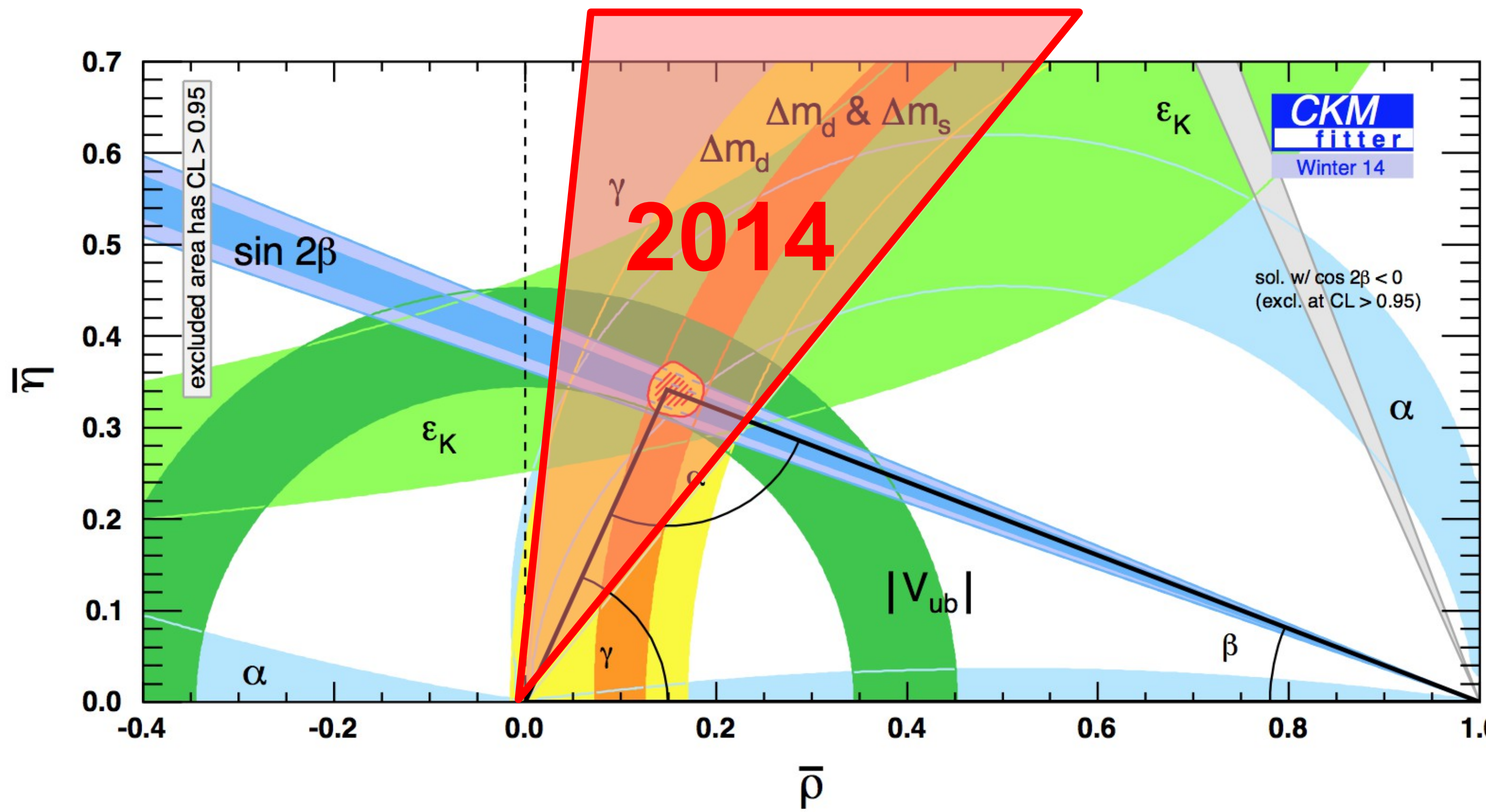
$$\gamma = (73.2^{+6.3}_{-7.0})^\circ$$

CKM*fitter* CKM2014

"γ meas. not in triangle fit"

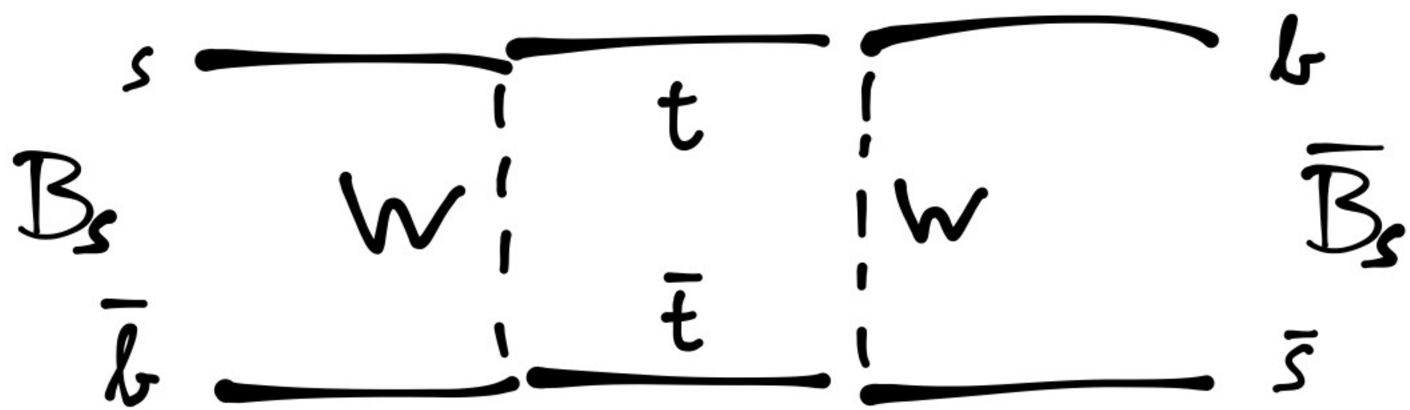
$$\gamma = (66.4^{+1.3}_{-3.3})^\circ$$

CKM*fitter* Moriond 2014



New Physics in (anti)particle oscillation?

Some neutral particles can transition into their own anti-particle (mixing):

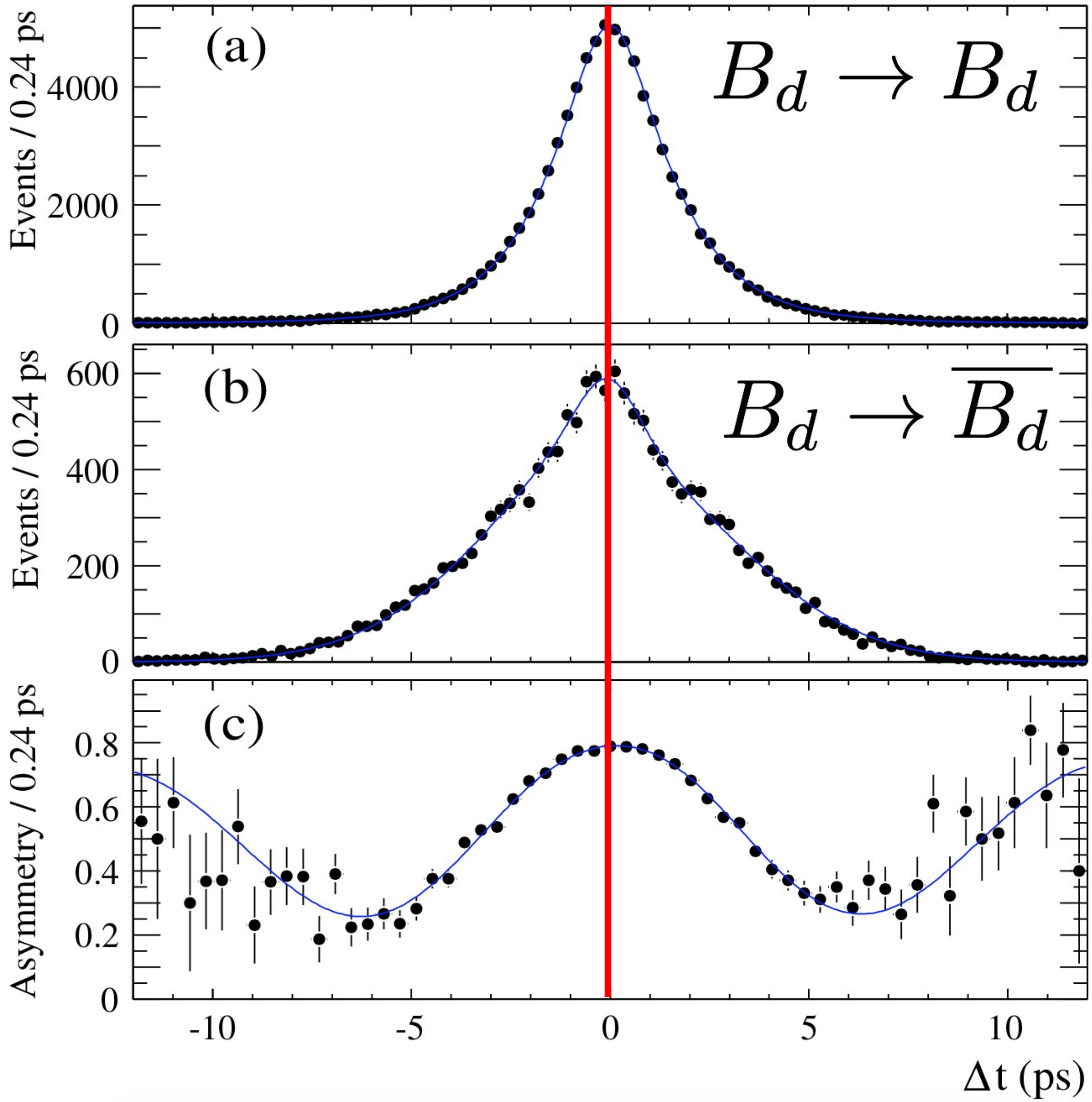


There are only 4 particles that can oscillate:

- D^0 mesons: *very, very* slowly
- K^0 mesons: very slowly
- B_d mesons: slowly
- B_s mesons: fast!

New Physics in (anti)particle oscillation?

BaBar 2002; Physics of the B factories, arXiv:1406.6311, 2014



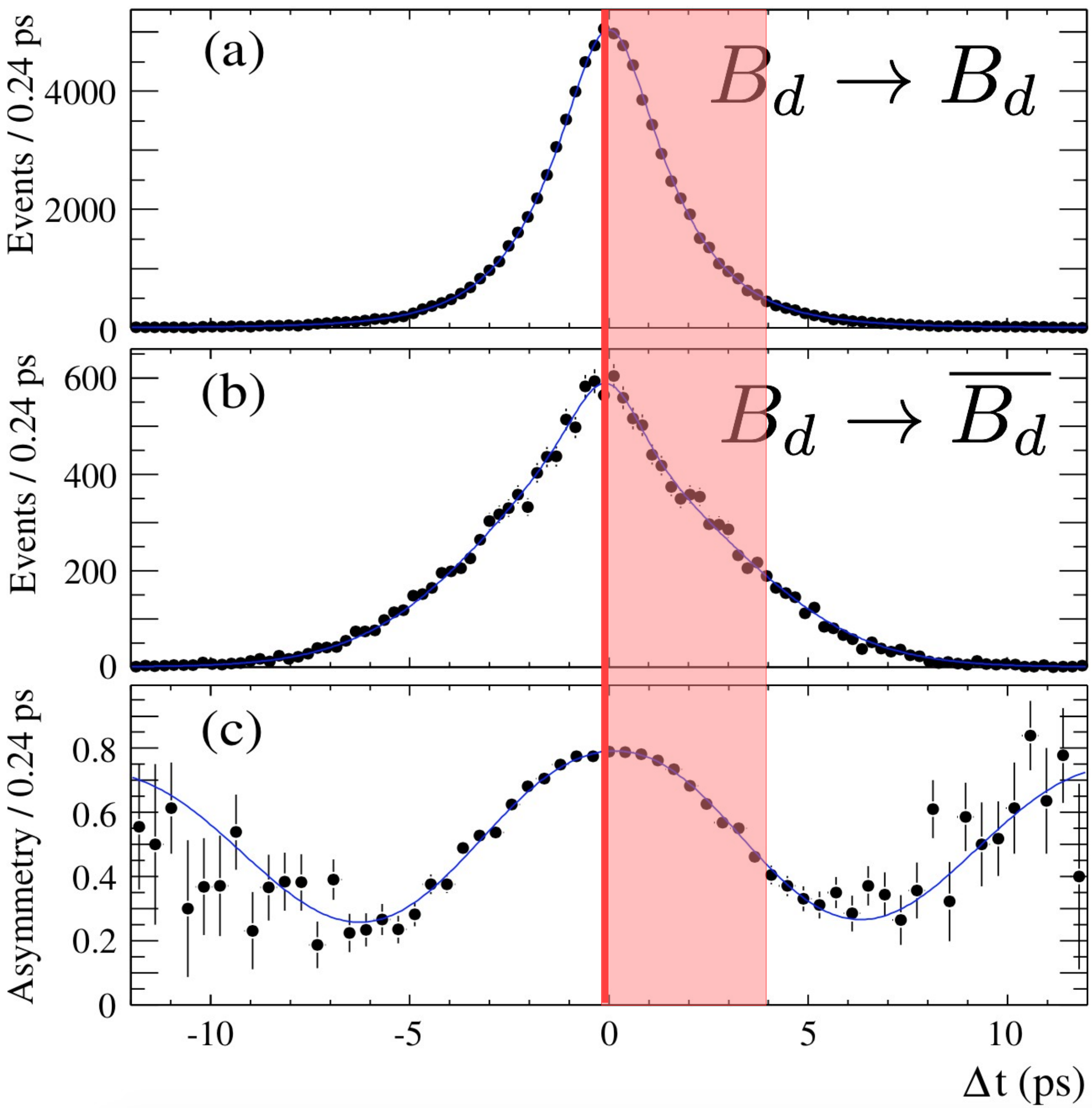
"unmixed"

"mixed"

asymmetry

New Physics in (anti)particle oscillation?

BaBar 2002; Physics of the B factories, arXiv:1406.6311, 2014

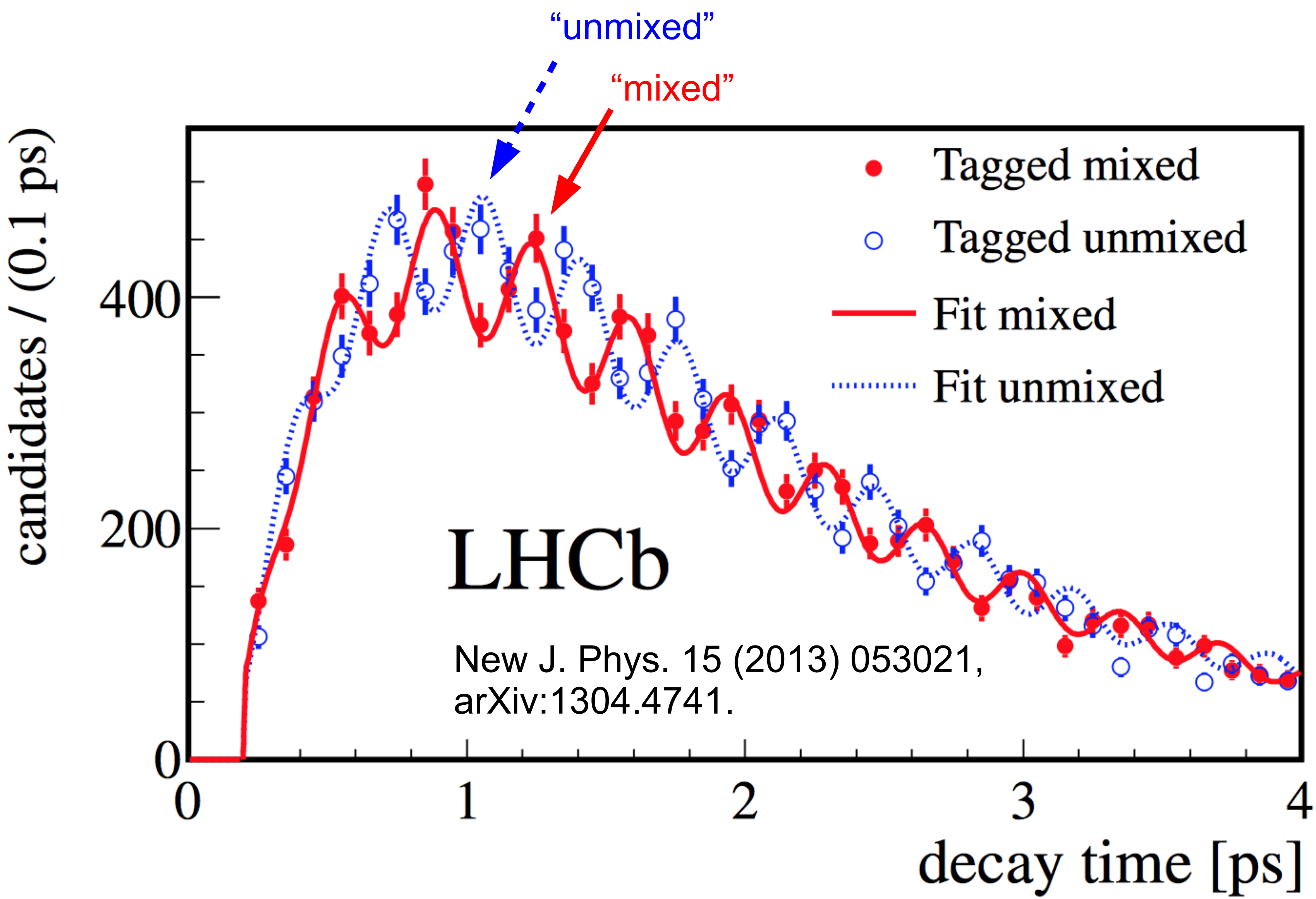


"unmixed"

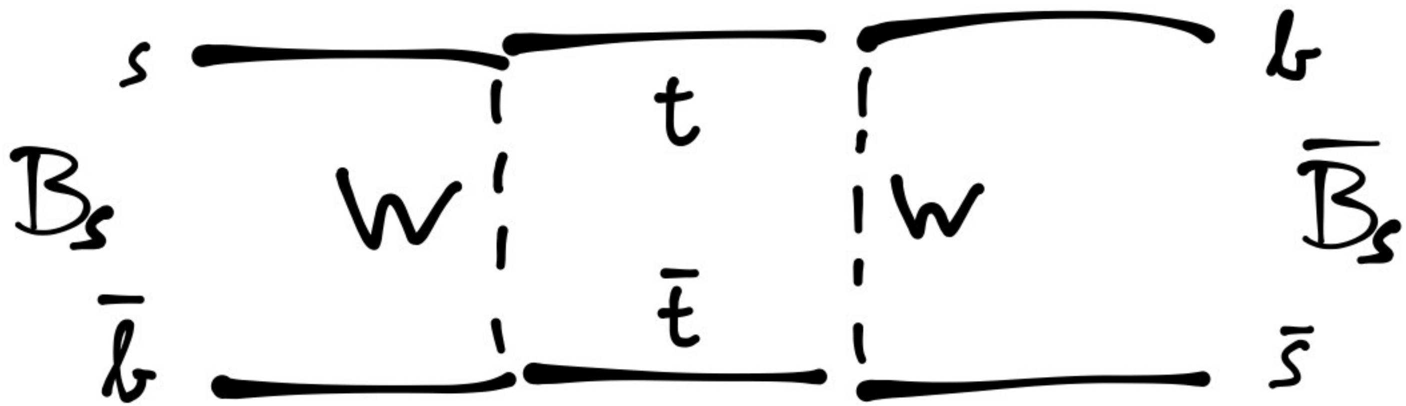
"mixed"

asymmetry

New Physics in (anti)particle oscillation?

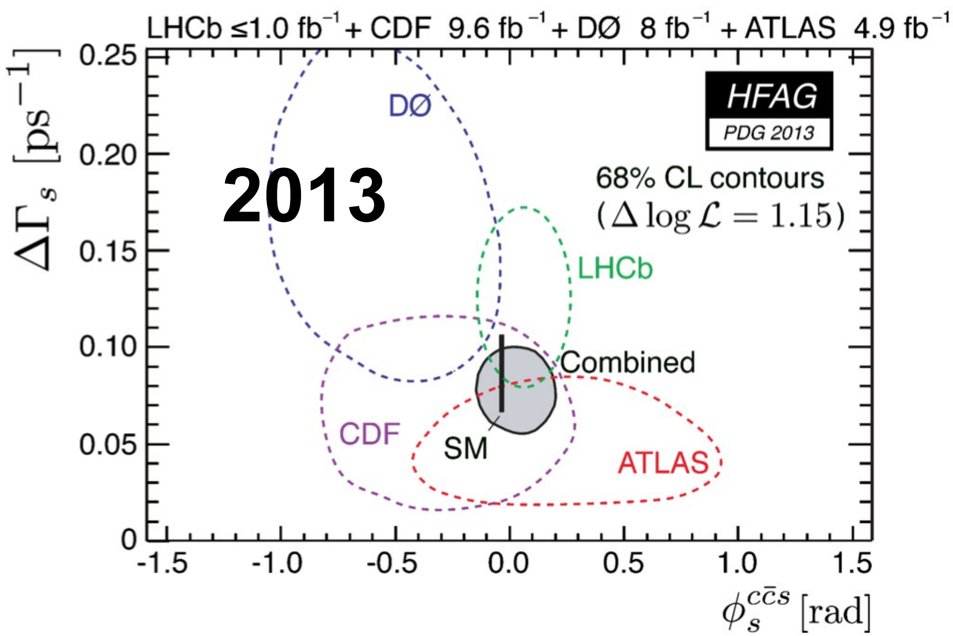


New Physics in (anti)particle oscillation?



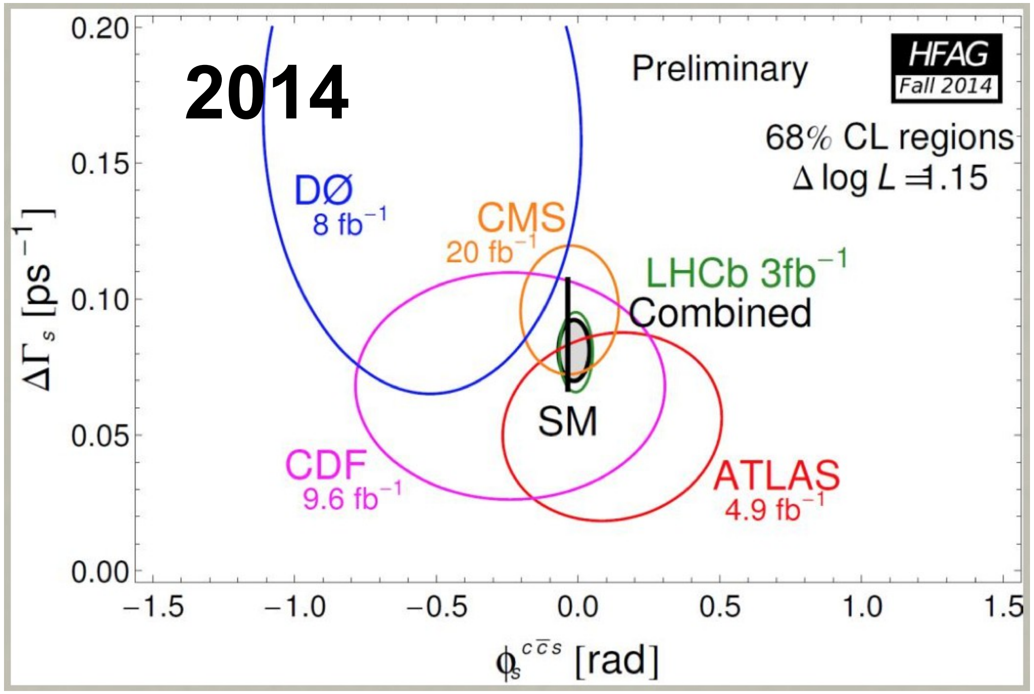
- mixing introduces a weak mixing phase $2\beta_s$
- the mixing phase could (have been...) easily affected by new physics!

New Physics in (anti)particle oscillation?

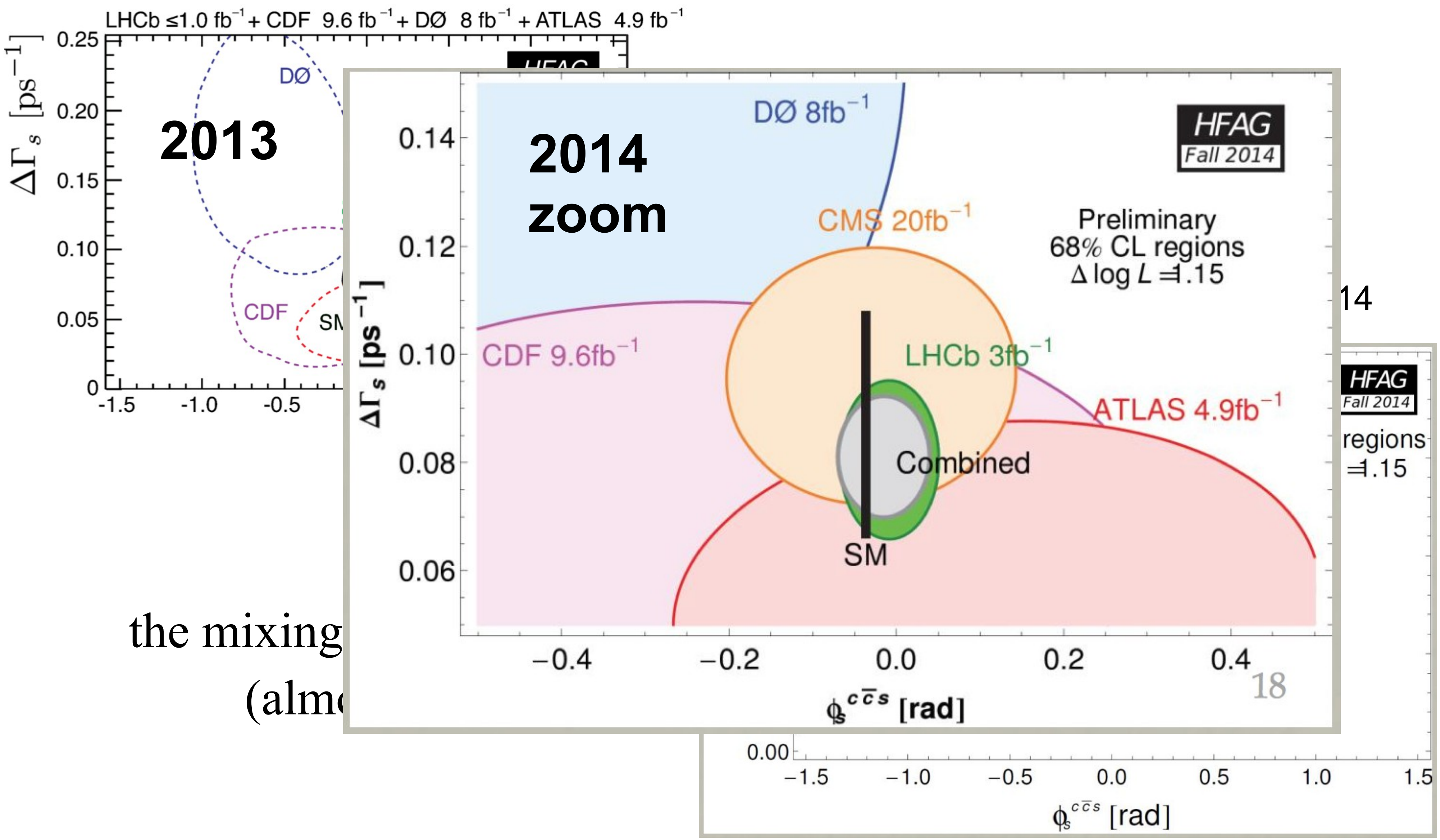


the mixing phase $2\beta_s$
(almost!)

LHCb Implications Workshop Oct 2014



New Physics in (anti)particle oscillation?



the mixing

(alm

Phys. Rev. D89 (2014) 033016, arXiv:1309.2293.

New Physics in (anti)particle oscillation?

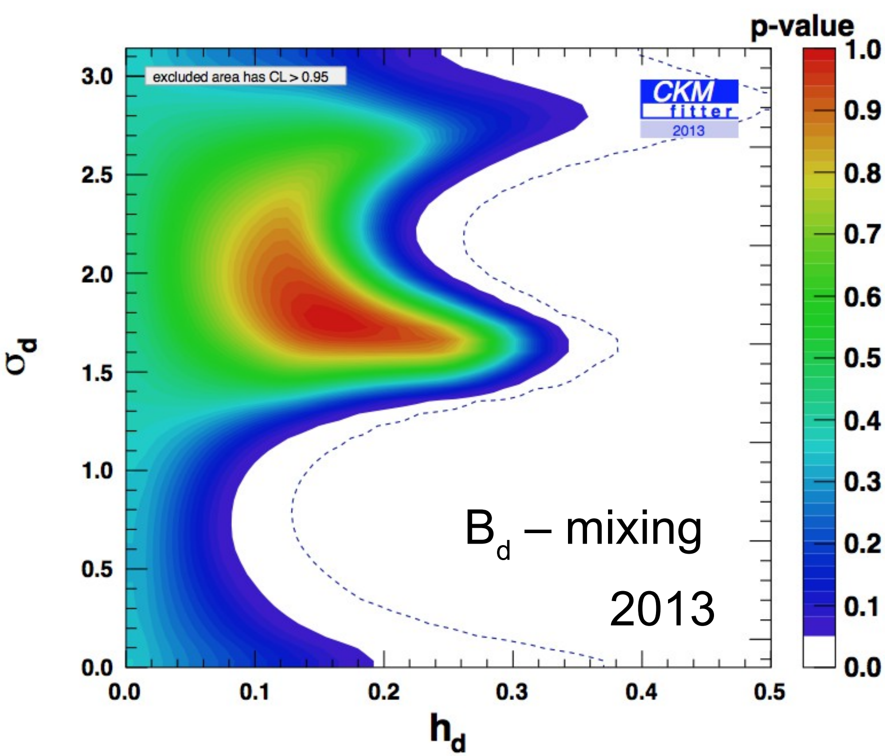
- Example: model independent analysis of the room for new physics in meson mixing (Ligeti et al. 2013):

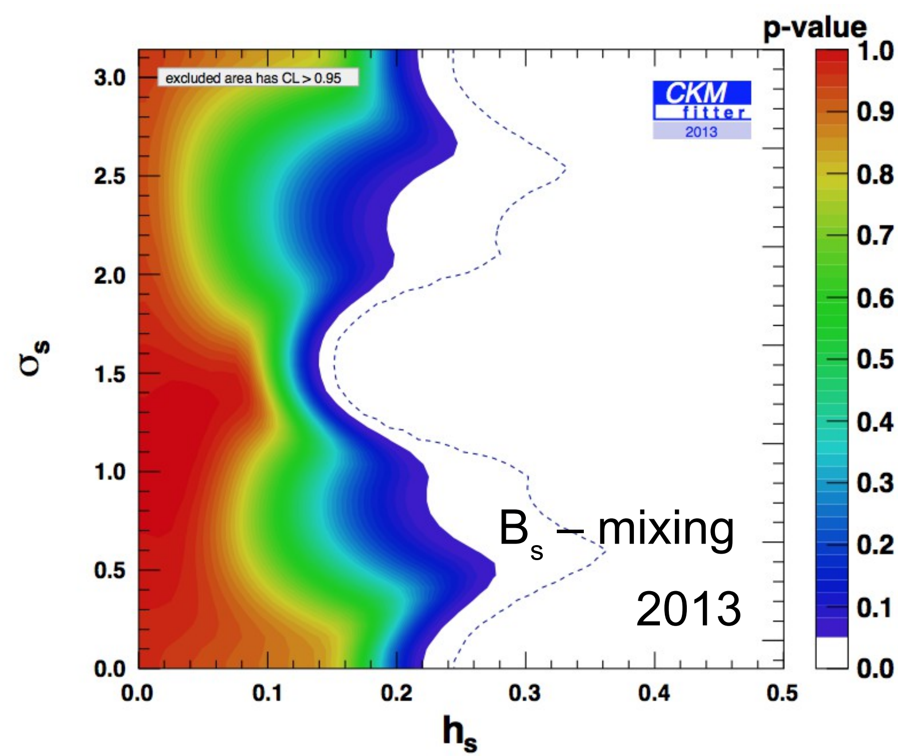
$$M_{12}^{d,s} = (M_{12}^{d,s})_{\rm SM} \times \left(1 + h_{d,s}\, e^{2i\sigma_{d,s}}\right)$$

mixing operator — NP magnitude — NP phase

plots assume this value:

$$\gamma = (68^{+8.0}_{-8.5})^\circ$$





Phys. Rev. D89 (2014) 033016, arXiv:1309.2293.

New Physics in (anti)particle oscillation?

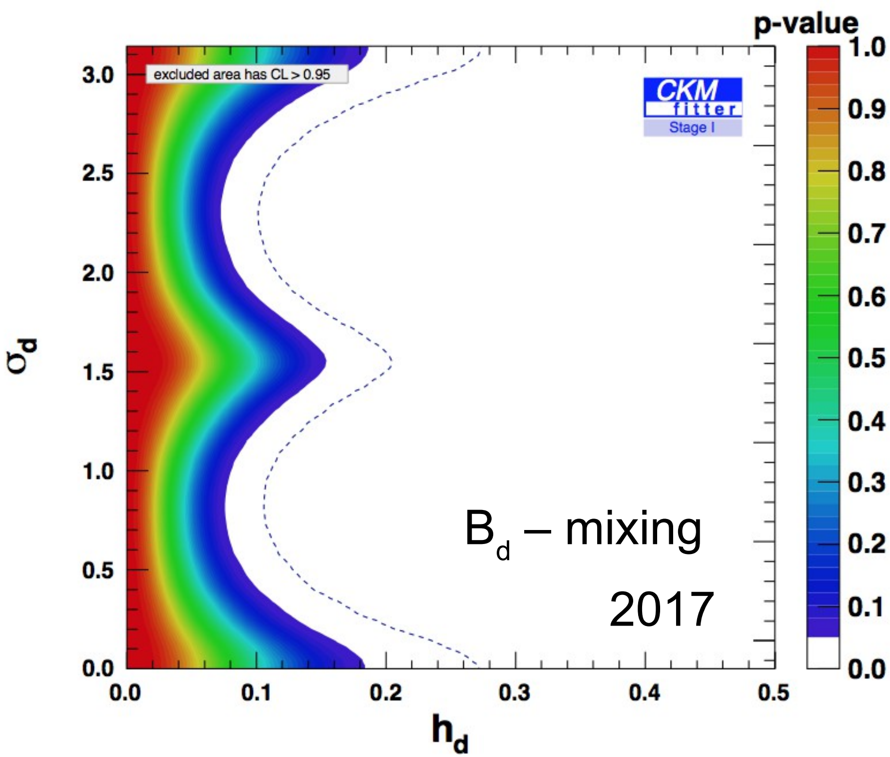
- Example: model independent analysis of the room for new physics in meson mixing (Ligeti et al. 2013):

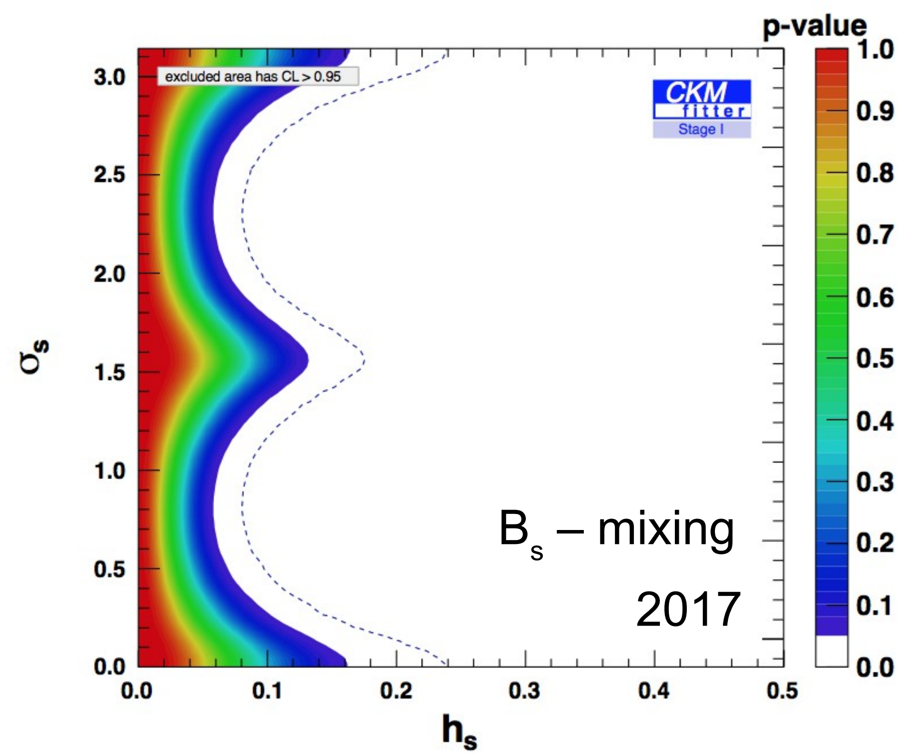
$$M_{12}^{d,s} = (M_{12}^{d,s})_{\rm SM} \times \left(1 + h_{d,s}\, e^{2i\sigma_{d,s}}\right)$$

mixing operator — NP magnitude — NP phase

plots assume this value:

$$\gamma = (68^{+4.0}_{-4.0})^\circ$$





Phys. Rev. D89 (2014) 033016, arXiv:1309.2293.

New Physics in (anti)particle oscillation?

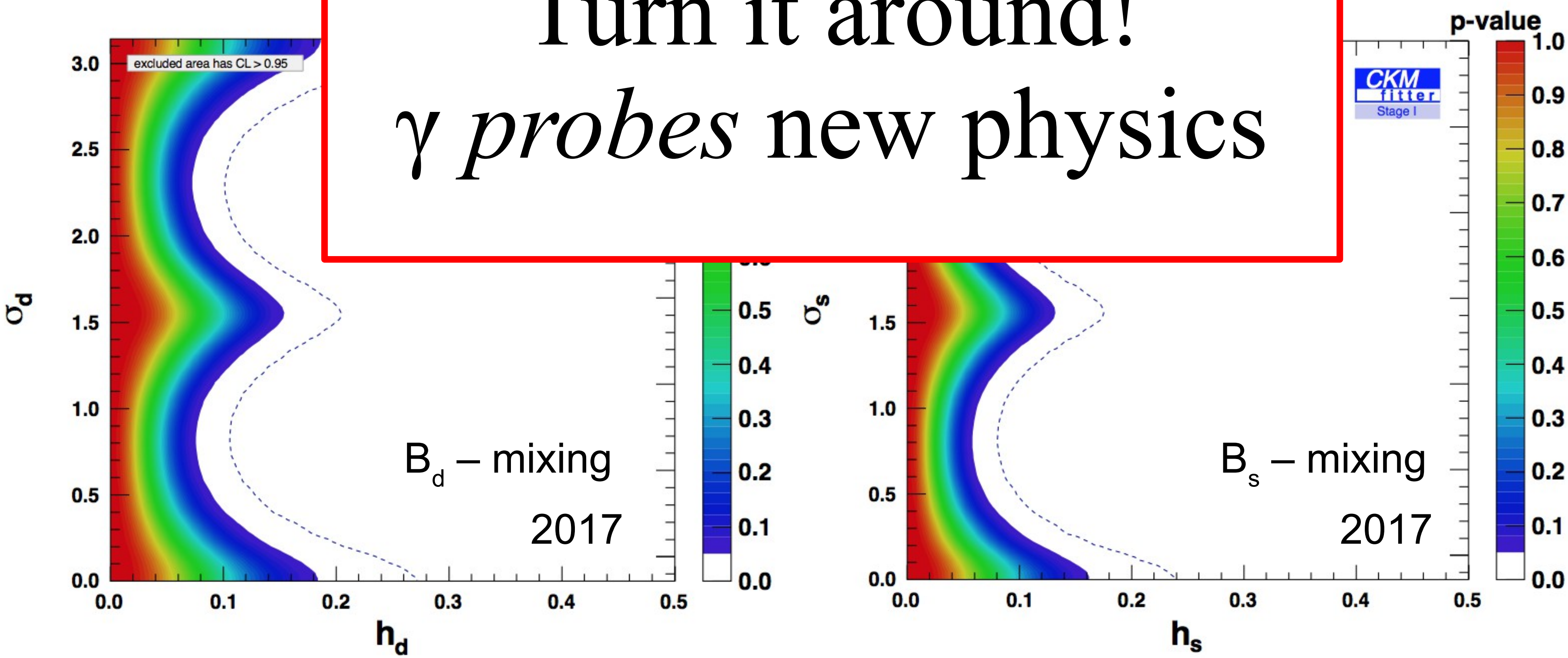
- Example: model independent analysis of the room for new physics in meson mixing (Ligeti et al. 2013):

$$M_{12}^{d,s} = (M_{12}^{d,s})_{\rm SM} \times \left(1 + h_{d,s}\, e^{2i\sigma_{d,s}}\right)$$

mixing operator

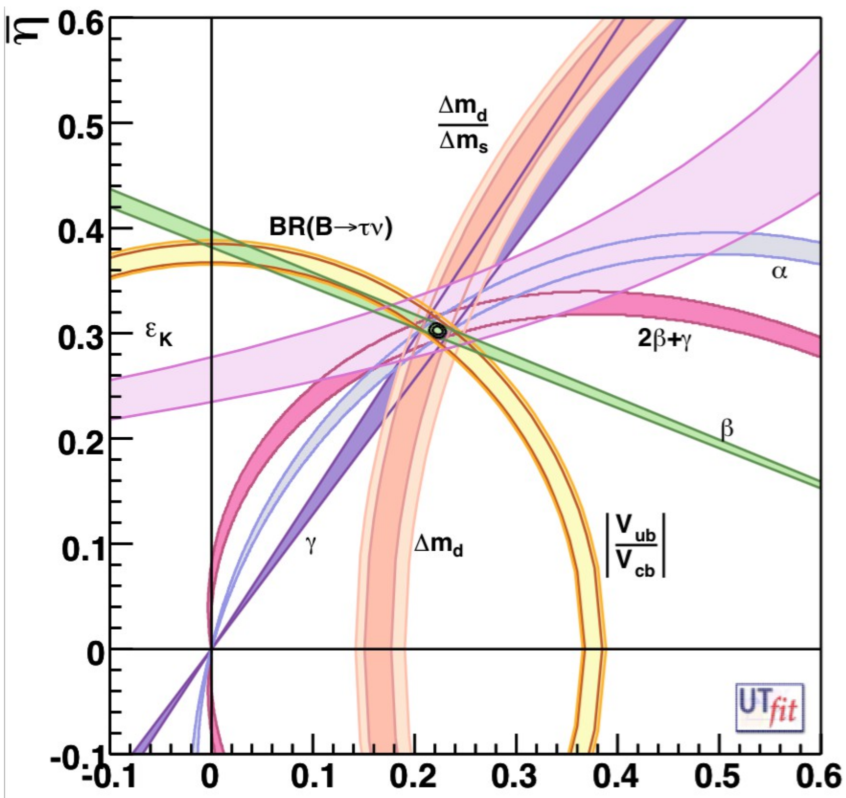
plots assume this value:

$: (68^{+4.0}_{-4.0})^\circ$



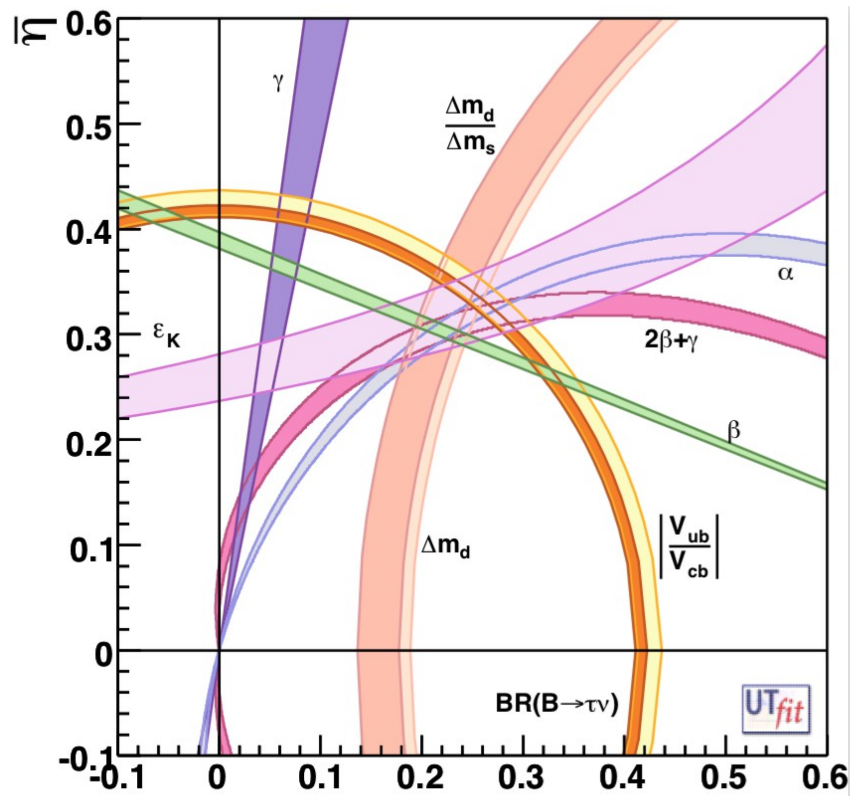
Turn it around!
γ *probes* new physics

the ultimate test



0710.3799

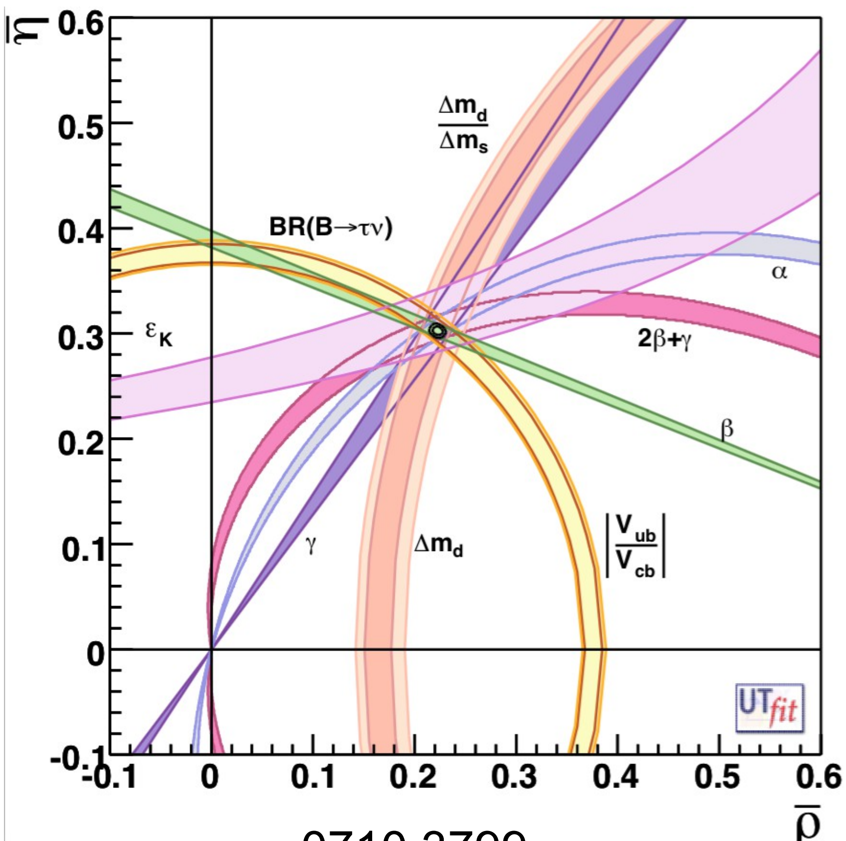
"the nightmare"



1110.3920

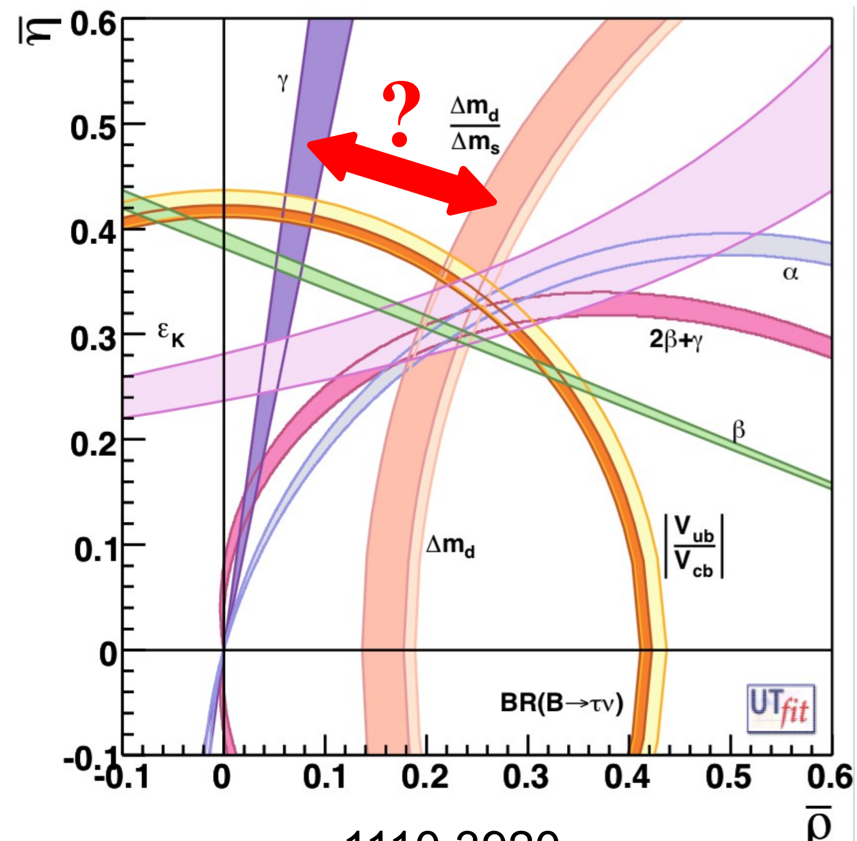
"the dream"

the ultimate test



0710.3799

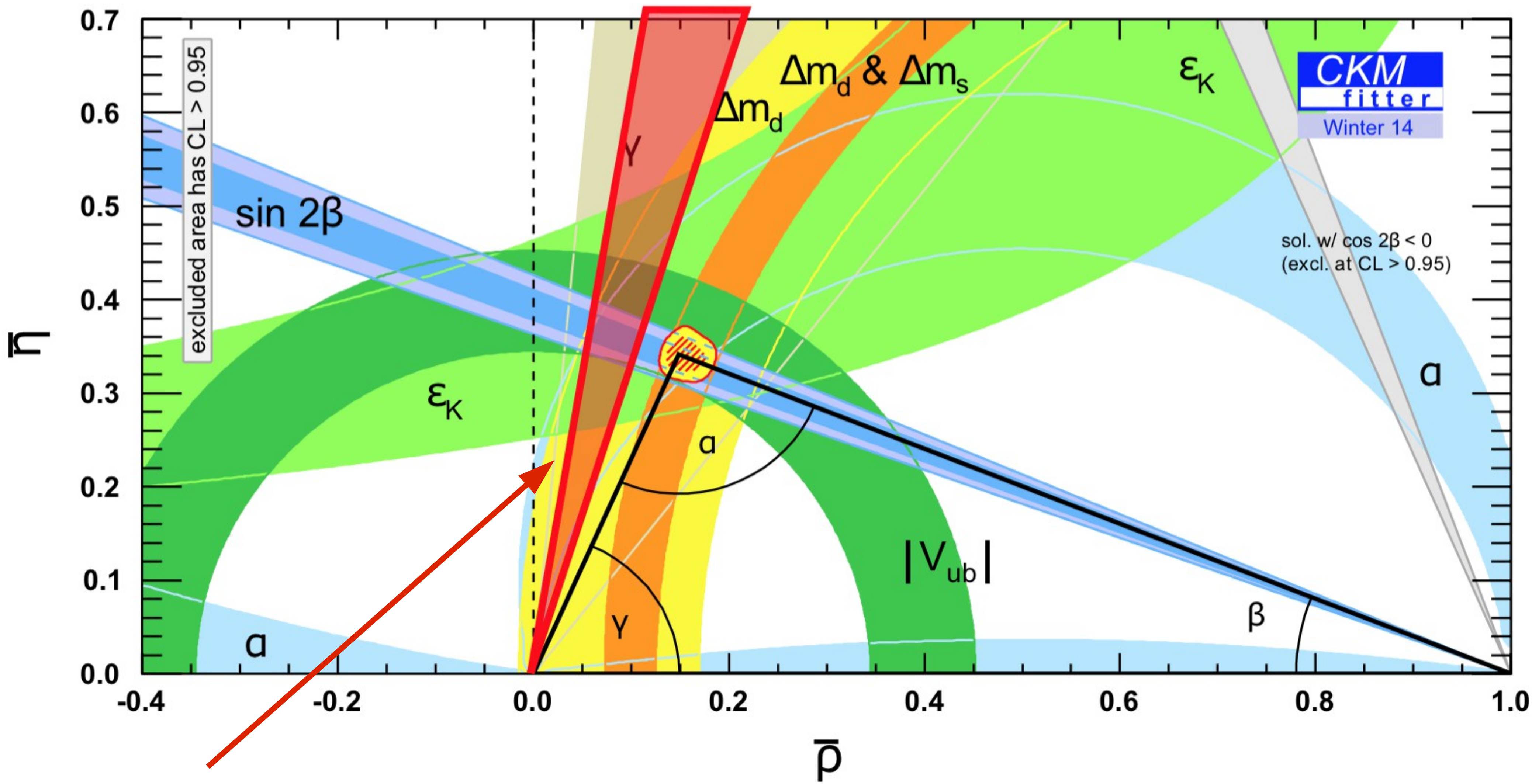
"the nightmare"



1110.3920

"the dream"

the ultimate test



LHCb precision in **2020**

theory

γ is known very well

- γ can be determined entirely from **tree decays**.
  - this is a unique property among all CP violation parameters
  - hadronic parameters can all be determined from the data
  - negligible theoretical uncertainty (Zupan and Brod 2013):

$$\delta\gamma/\gamma \approx \mathcal{O}(10^{-7})$$

JHEP 1401 (2014) 051, arXiv:1308.5663.

- γ can probe for new physics at extremely **high energy scales** (Zupan)
  - (N)MFV new physics scenarios: ~O(10^2 TeV)
  - gen. FV new physics scenarios: ~O(10^3 TeV)

γ is **not** known very well

experiment

it is quite challenging to measure!

- The decay rates are small.

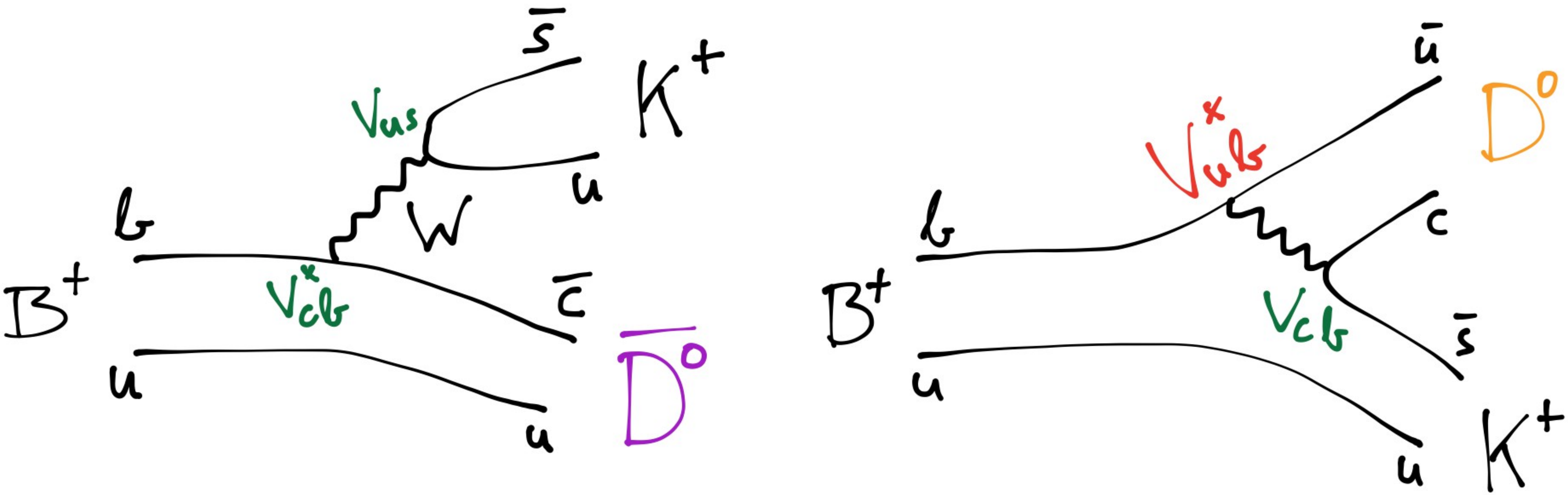
$$\mathrm{BR}(B^- \to DK^-, D \to \pi K) \approx 2 \times 10^{-7}$$

- Low interference effects of typically 10%.
- Fully hadronic decays – hard to trigger on.
- Many channels contain a K_S in the final state – low efficiency.
- Many channels contain a π^0 in the final state – very challenging at LHCb.
- Many decay channels involved.
- Many observables – statistically challenging.

First(*) method to measure γ

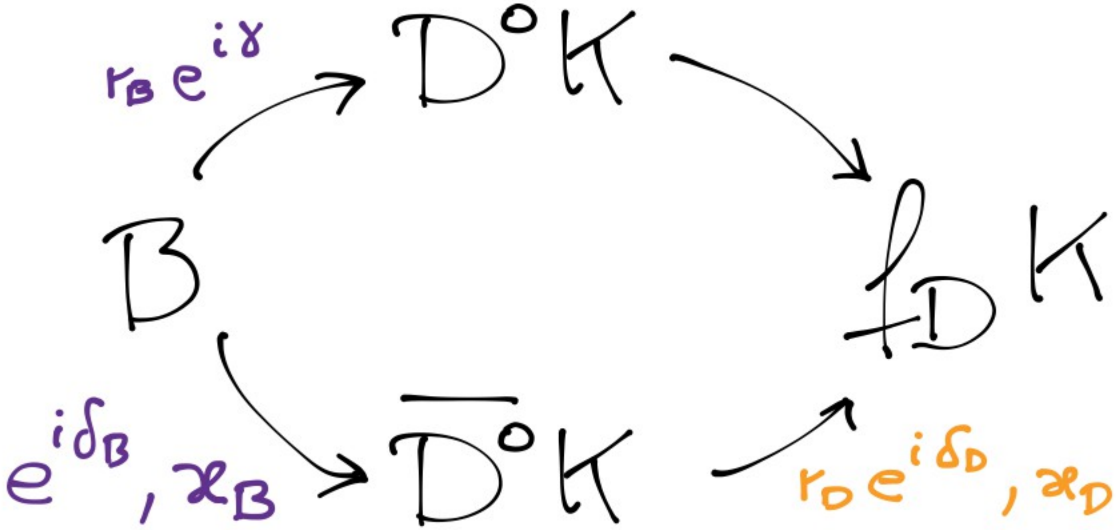
(*) of this talk

first method to measure γ



We need to reconstruct the $D/\overline{D}$ meson in a final state accessible to both to achieve interference.

first method to measure γ



Depending on the final state f_D the method is called:

"GLW"

Gronau, London, Wyler (1991)

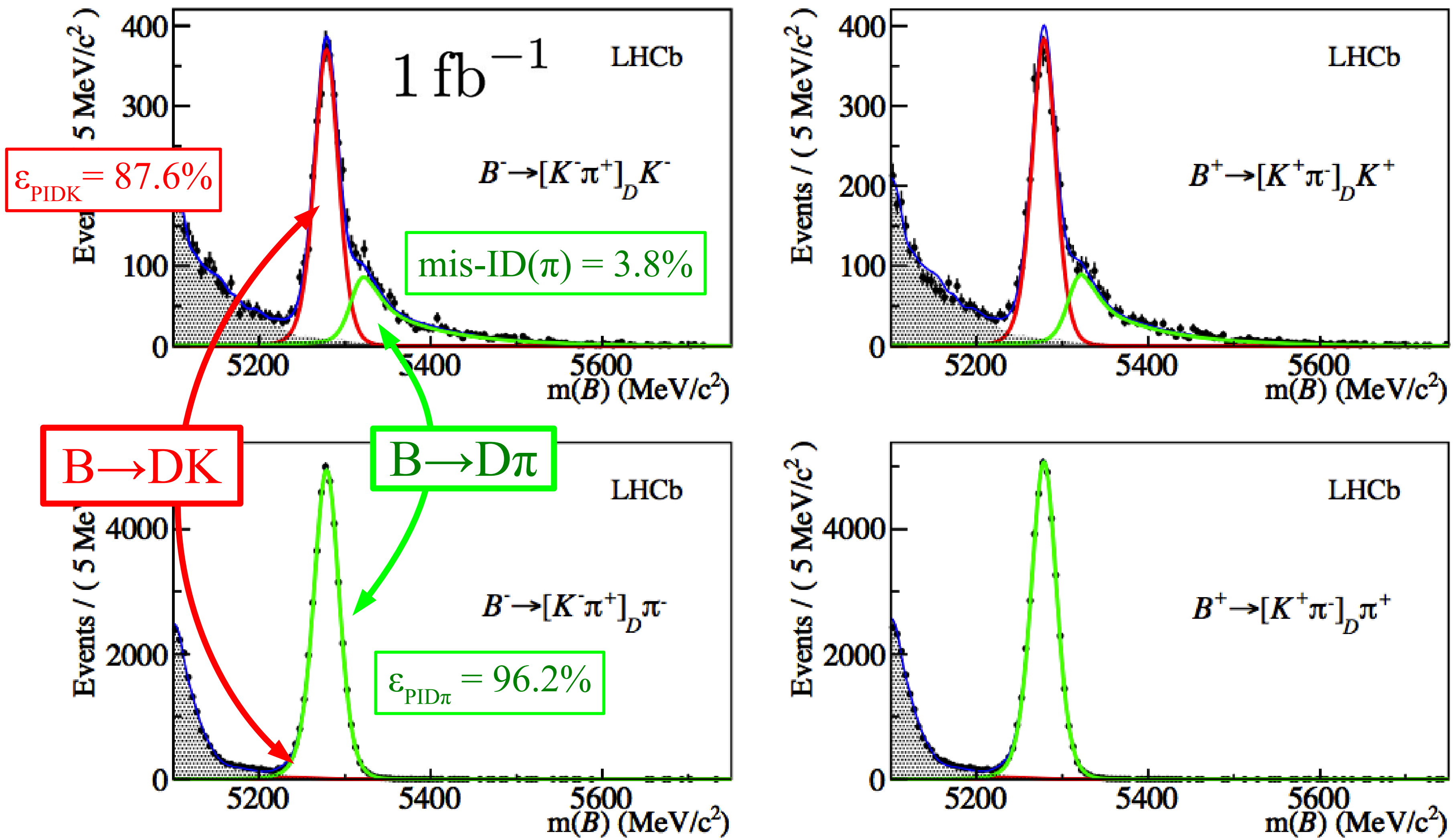
Phys. Lett. B253 (1991) 483
Phys. Lett. B265 (1991) 172

"ADS"

Atwood, Dunietz, Soni (1997, 2001)

Phys. Rev. D63 (2001) 036005
Phys. Rev. Lett. 78 (1997) 3257

$B \to D(K\pi)h$: ADS favored mode



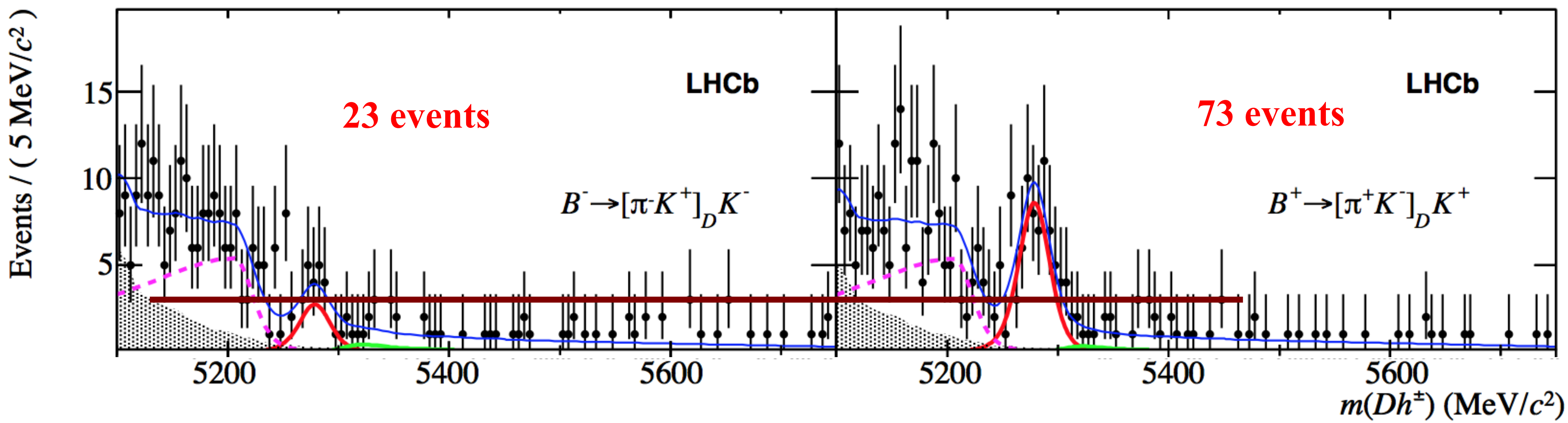
Phys. Lett. B712 (2012) 203, arXiv:1203.3662.

$B \to D(\pi K)K$: ADS suppressed mode

$$\mathcal{B}(B^{\pm} \to D_{ADS} K^{\pm}) \approx 2 \cdot 10^{-7} \qquad \text{(!!)}$$

$$A_{CP} = -0.520 \pm 0.150 \pm 0.021$$

$1\,\mathrm{fb}^{-1}$



Phys. Lett. B712 (2012) 203, arXiv:1203.3662.

first method to measure γ

- Define observables as **yield ratios** (many systematics cancel).

- Charge **asymmetries**:

$$A_h^f = \frac{\Gamma(B^- \to [f]_D h^-) - \Gamma(B^+ \to [f]_D h^+)}{\Gamma(B^- \to [f]_D h^-) + \Gamma(B^+ \to [f]_D h^+)}$$

- **Kaon/pion** ratio:

$$R^f_{K/\pi} = \frac{\Gamma(B^\pm \to [f]_D K^\pm)}{\Gamma(B^\pm \to [f]_D \pi^\pm)}$$

Form a system of equations. Need more observables than parameters!

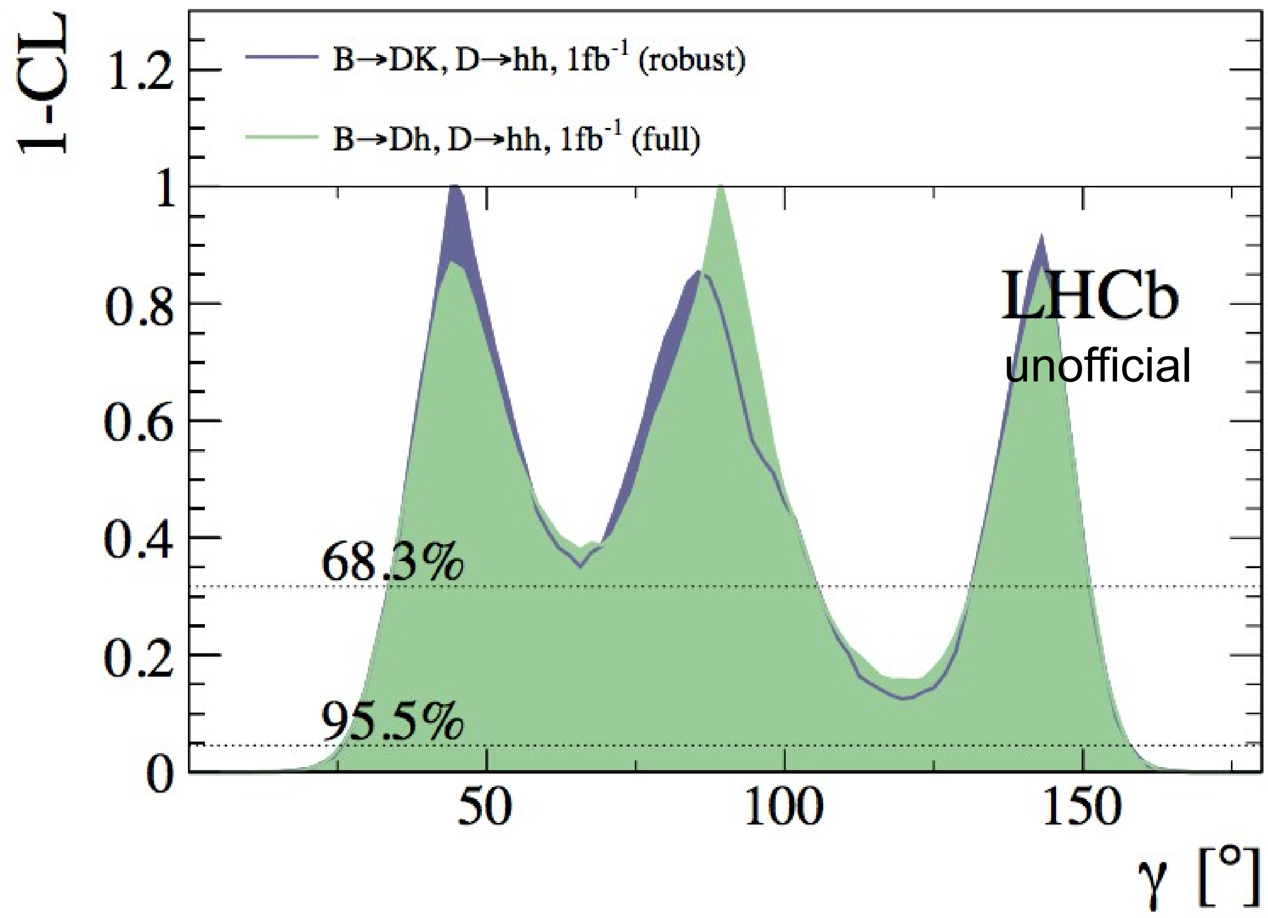
→ many different D decays

- **Suppressed/favored** decay ratio (2-body example):

$$R_h^\pm = \frac{\Gamma(B^\pm \to [\pi^\pm K^\mp]_D h^\pm)}{\Gamma(B^\pm \to [K^\pm \pi^\mp]_D h^\pm)}$$

$$= r_B^2 + r_D^2 + 2 r_B r_D \cos(\pm\gamma + \underbrace{\delta_B + \delta_D}_{\text{strong phase diff.}})$$

first method to measure γ



Second method to measure γ

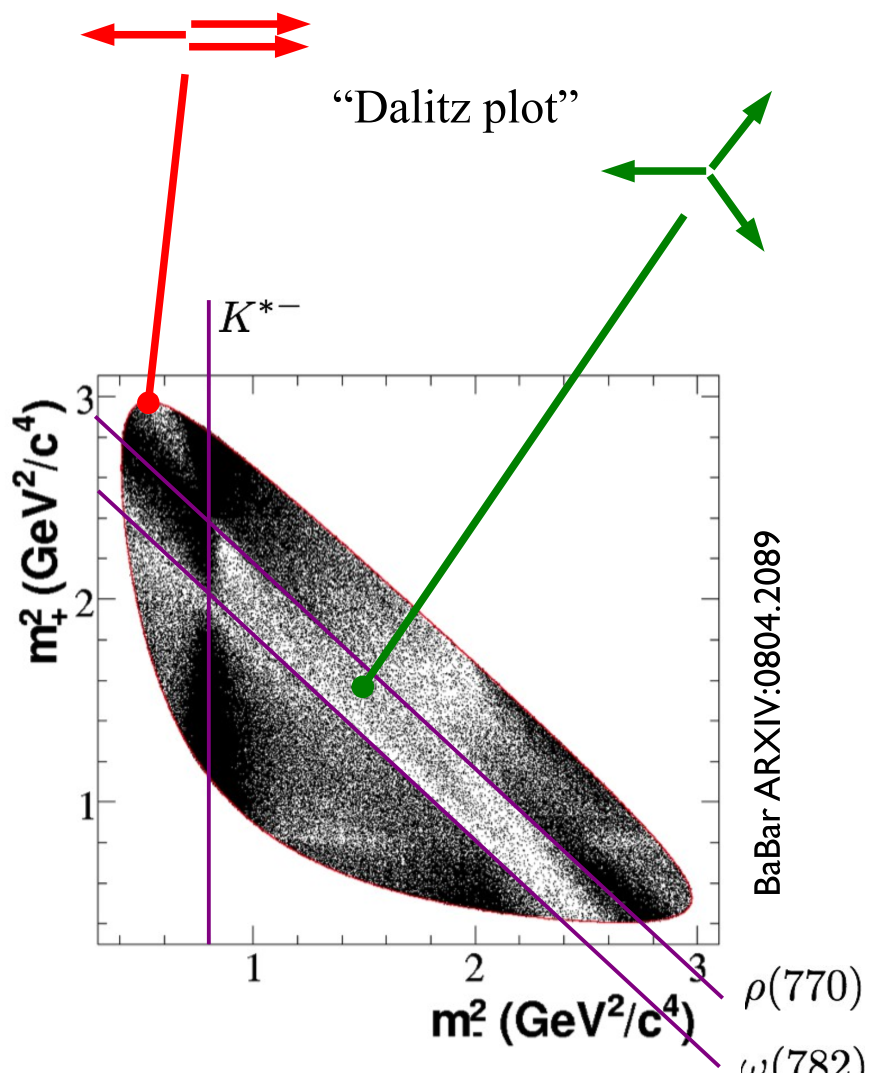
second method: "GGSZ"

- **Idea**: perform an GLW/ADS type analysis in every bin of the D decay phase space
- GGSZ uses $B \to DK$ followed by self-conjugate three-body final states

$$D^0 \to K^0_S \pi^- \pi^+$$
$$D^0 \to K^0_S K^- K^+$$

- Most precise at B-factories.
- Observables: the "cartesian coordinates"

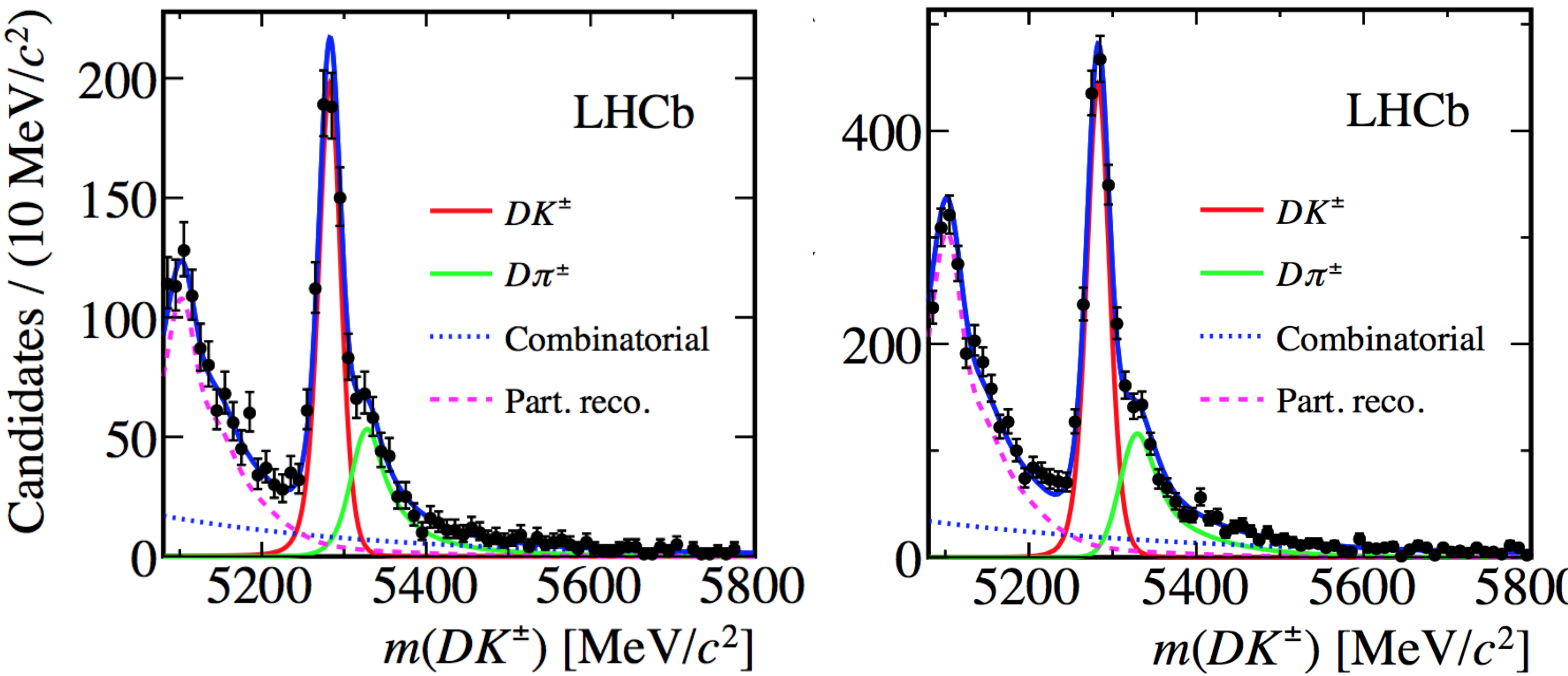
$$x_\pm = r_B \cos(\delta_B \pm \gamma)$$
$$y_\pm = r_B \sin(\delta_B \pm \gamma)$$



$$D^0 \to K^0_S \pi^- \pi^+$$

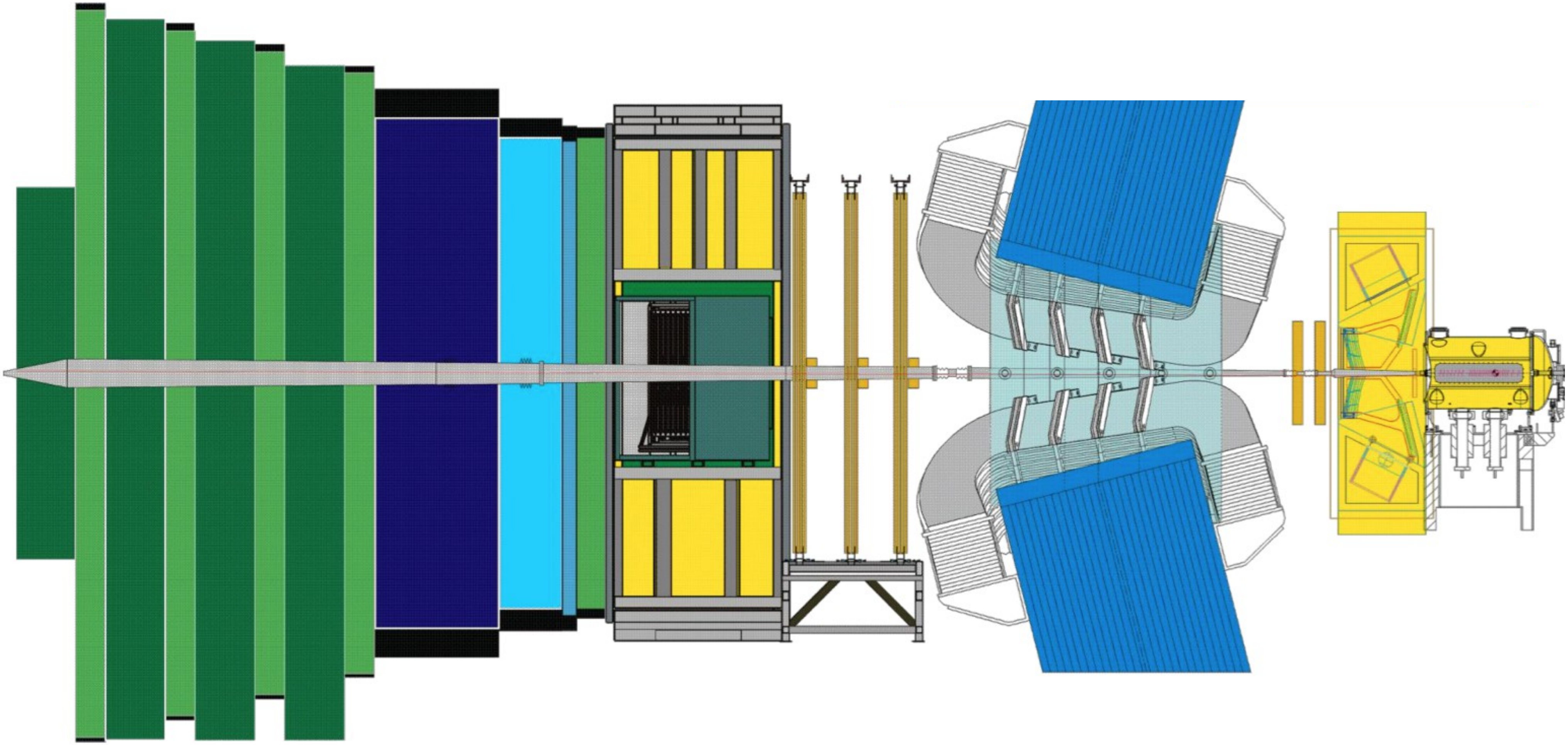
second method: "GGSZ"

"long K_S" (N~700) | "downstream K_S" (N~1600)

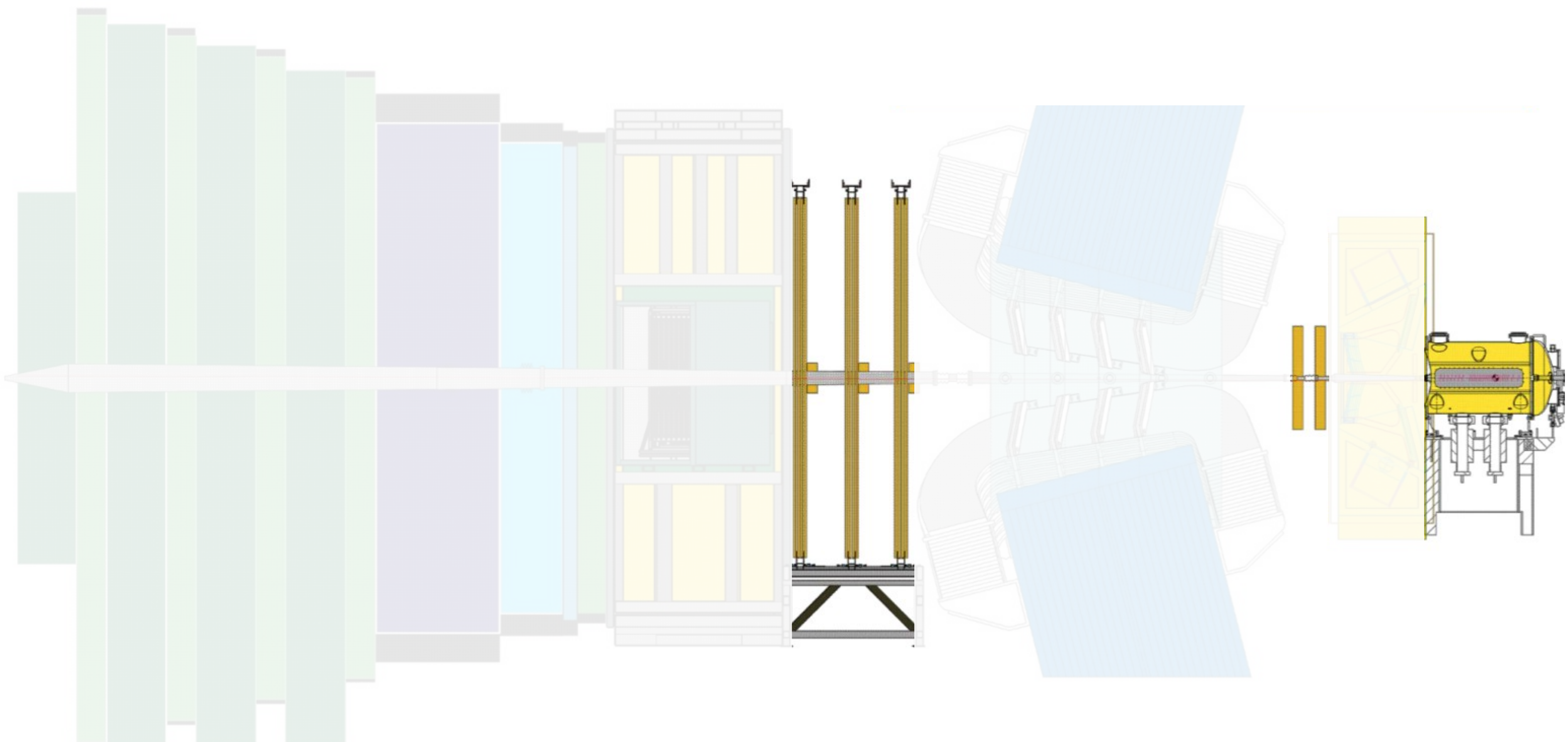


JHEP 1410 (2014) 97, arXiv:1408.2748.

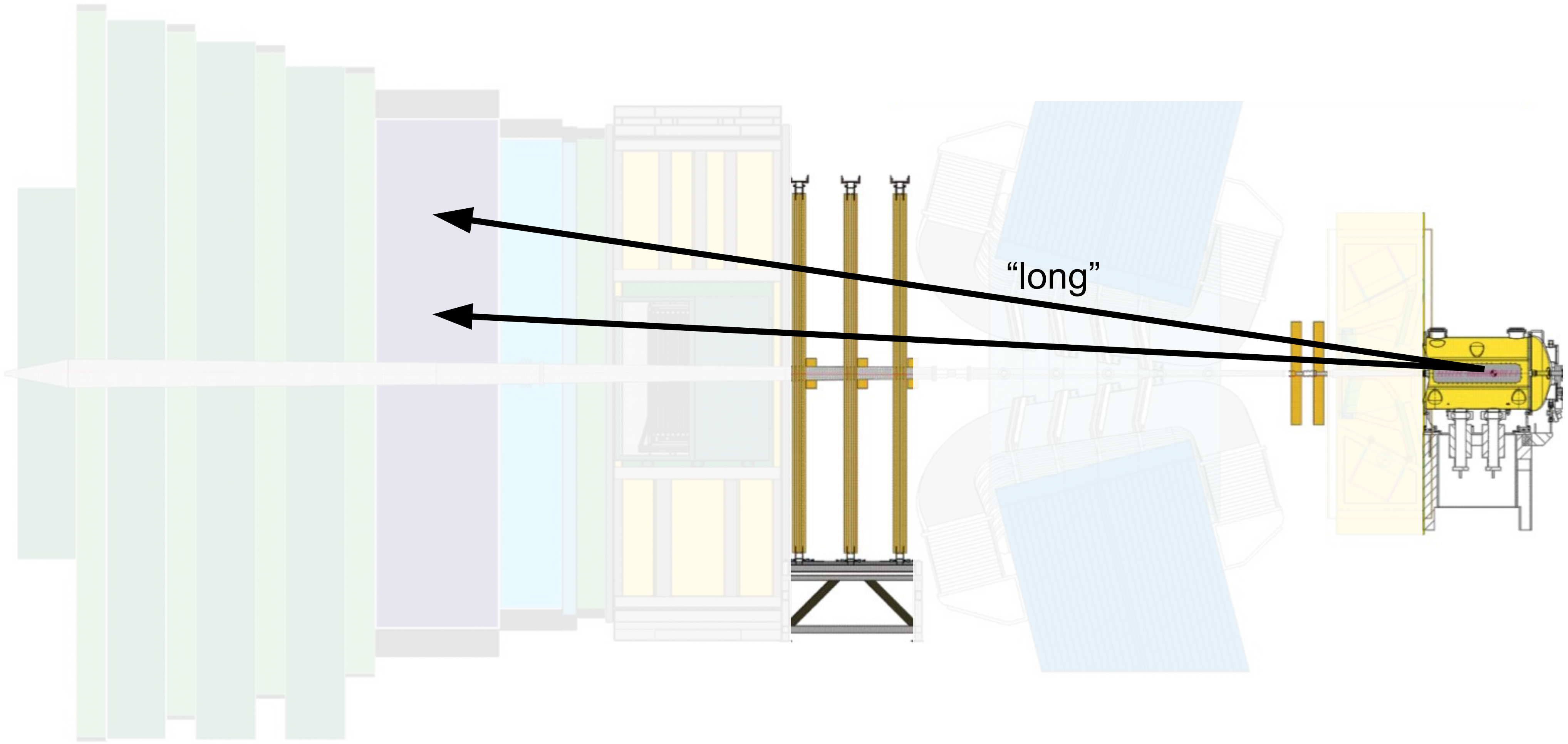
K_S reconstruction



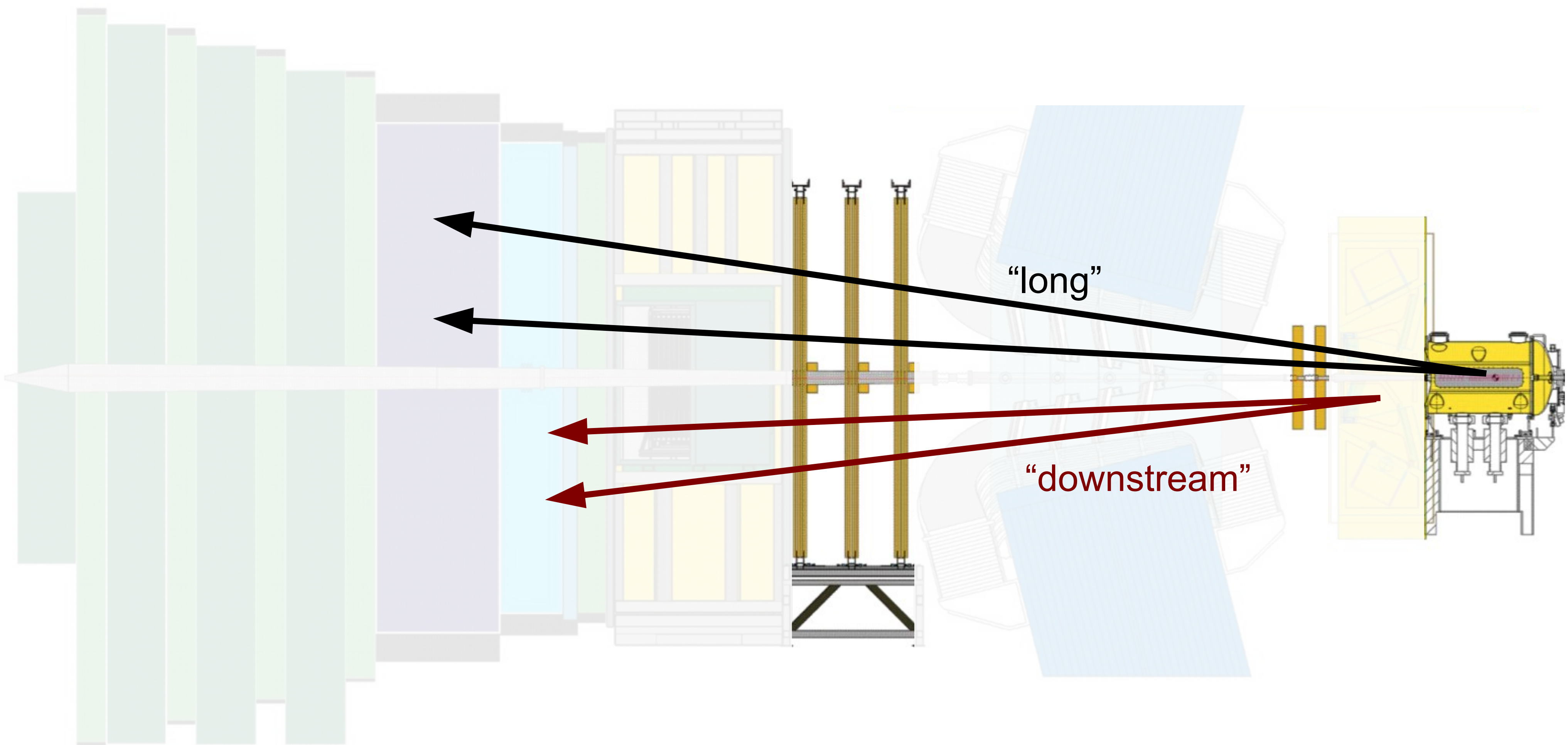
K_S reconstruction



K_S reconstruction

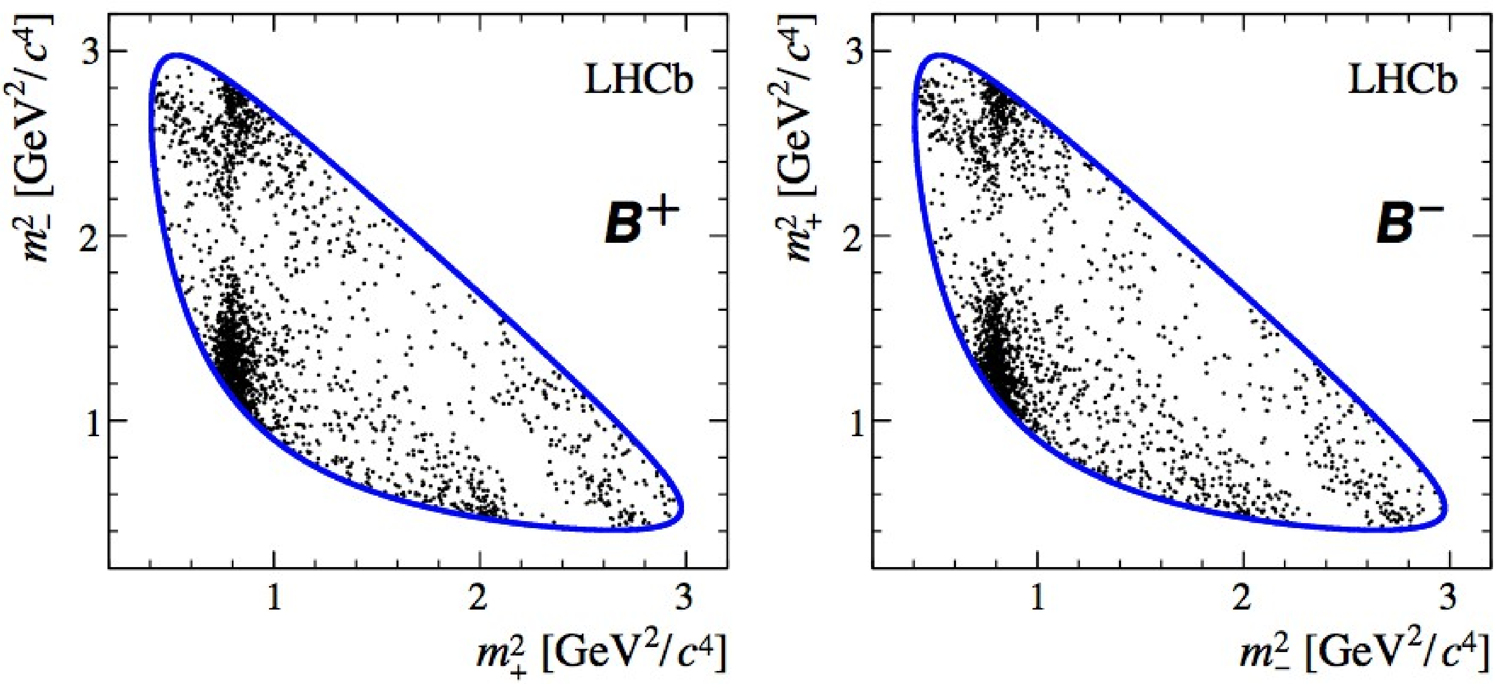


K_S reconstruction



second method: “GGSZ”

$K_S^0\pi^+\pi^-$ data ($\sim$ 2600 candidates):

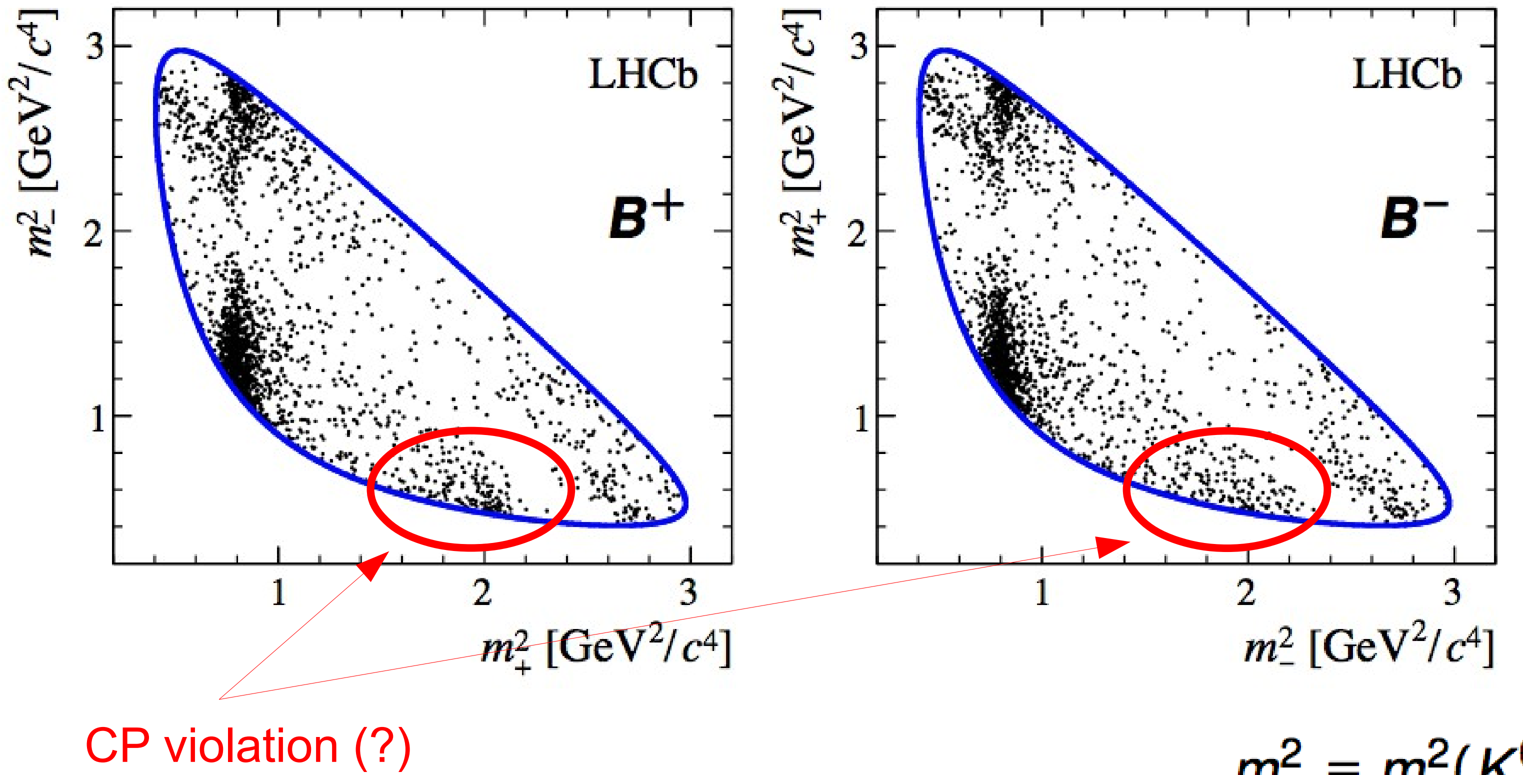


$$m_\pm^2 \equiv m^2(K_S^0\pi^\pm)$$

JHEP 1410 (2014) 97, arXiv:1408.2748.

second method: "GGSZ"

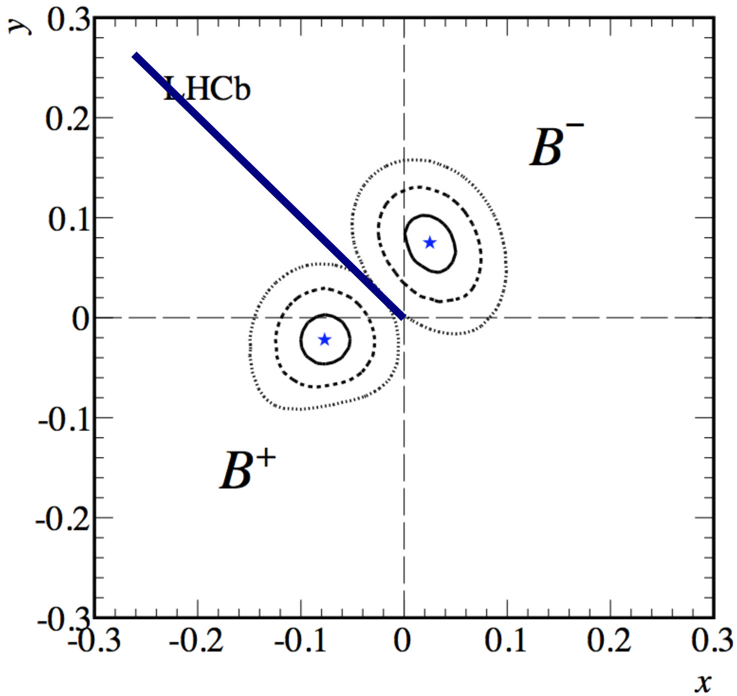
$K_S^0\pi^+\pi^-$ data (~ 2600 candidates):



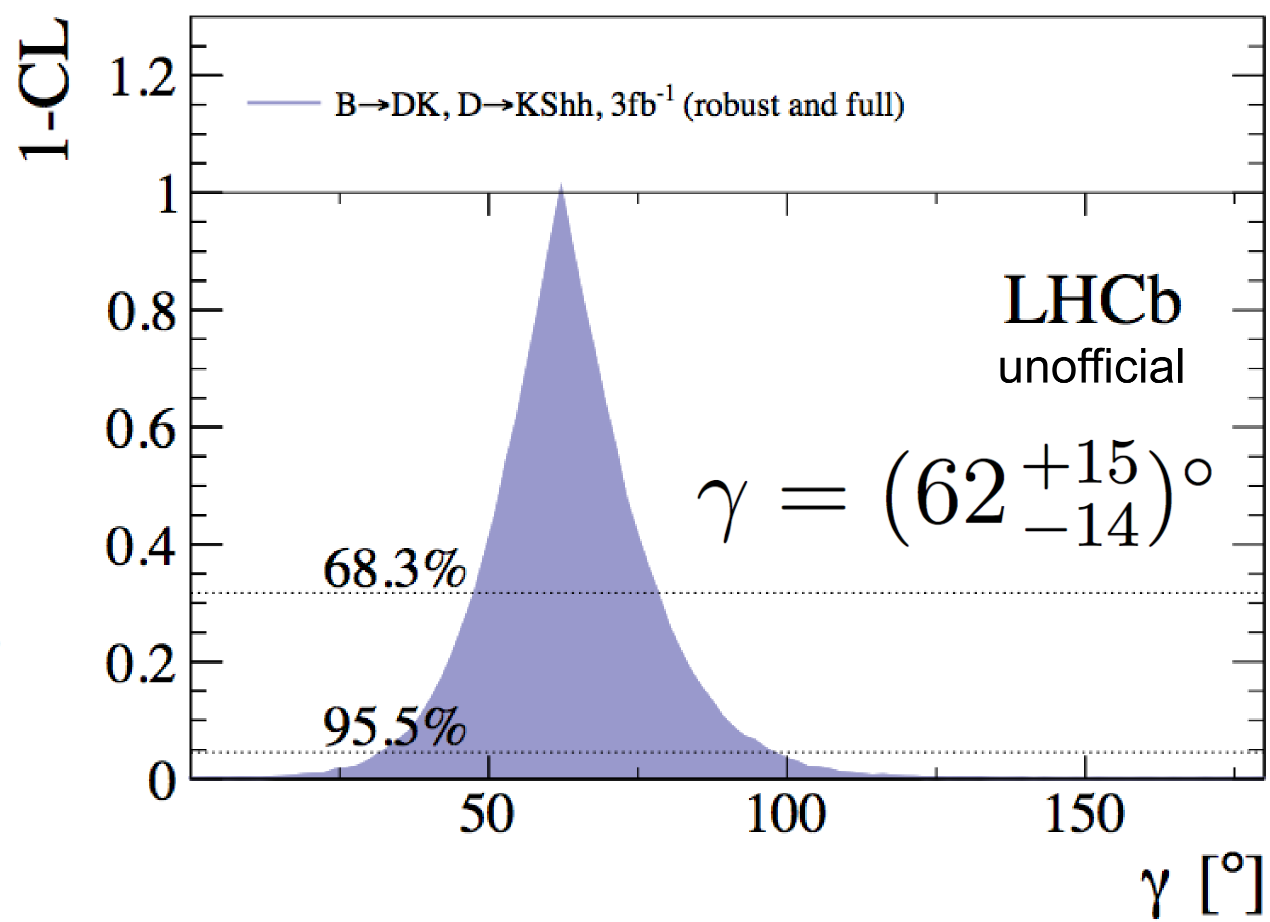
$m_\pm^2 \equiv m^2(K_S^0\pi^\pm)$

JHEP 1410 (2014) 97, arXiv:1408.2748.

second method: “GGSZ”



$$x_\pm = r_B \cos(\delta_B \pm \gamma)$$
$$y_\pm = r_B \sin(\delta_B \pm \gamma)$$



JHEP 1410 (2014) 97,
arXiv:1408.2748.

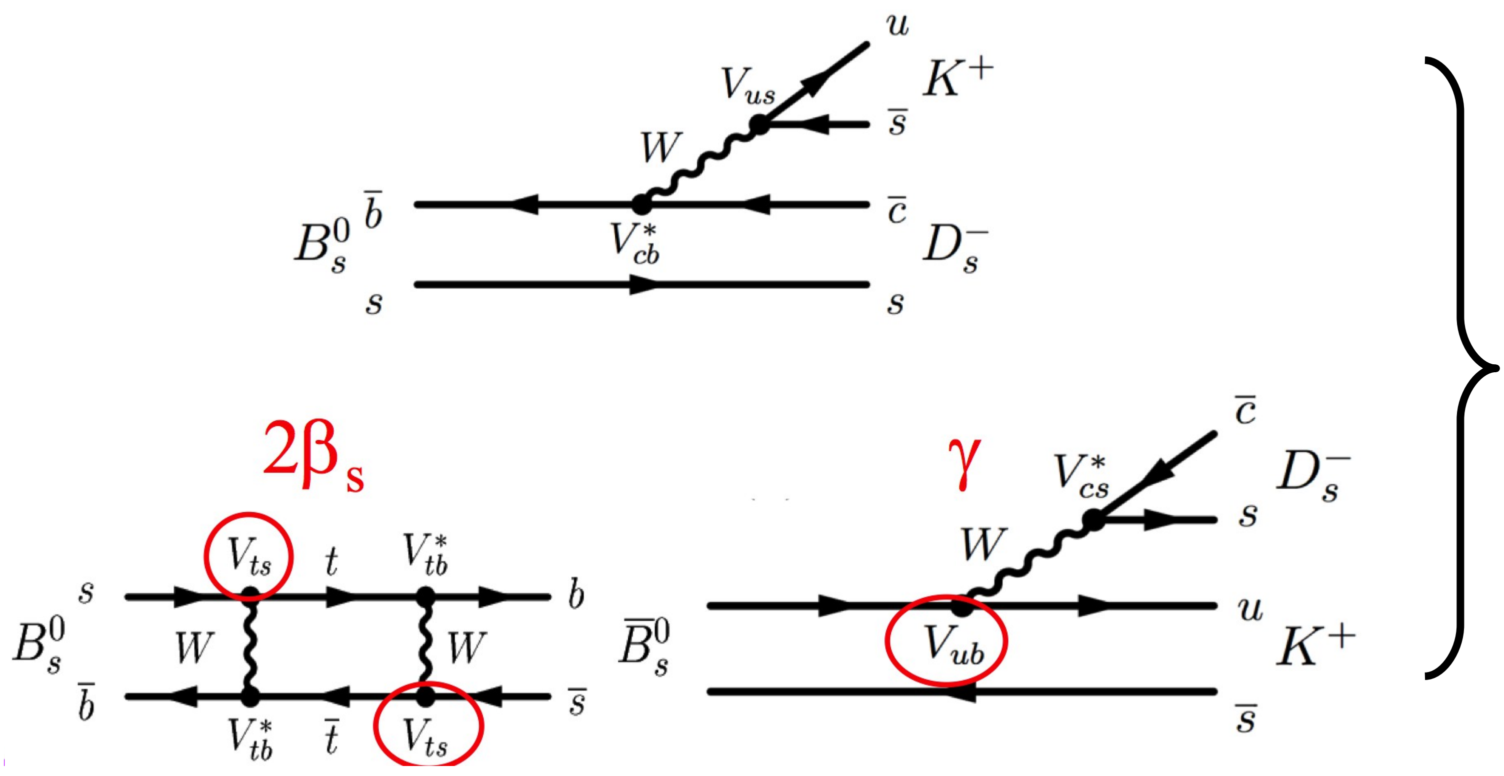
World's most precise *single* measurement!

Third method to measure γ

third method: time-dependent

Using charged-particle final states, interference is achieved through **mixing**.

$$B_s \to D_s^{\pm} K^{\mp}$$



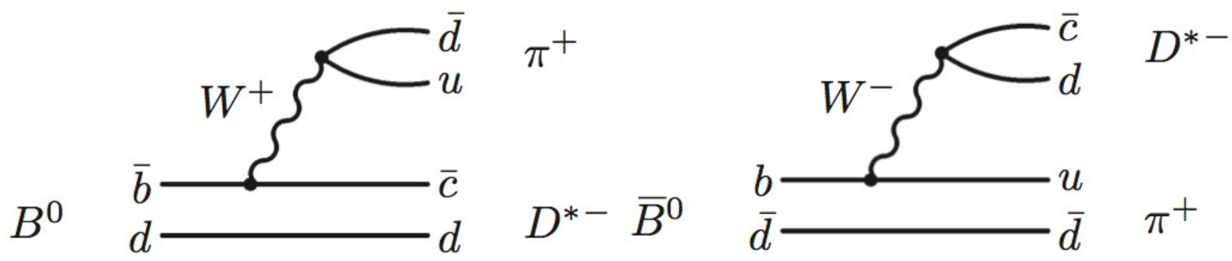
weak phase:

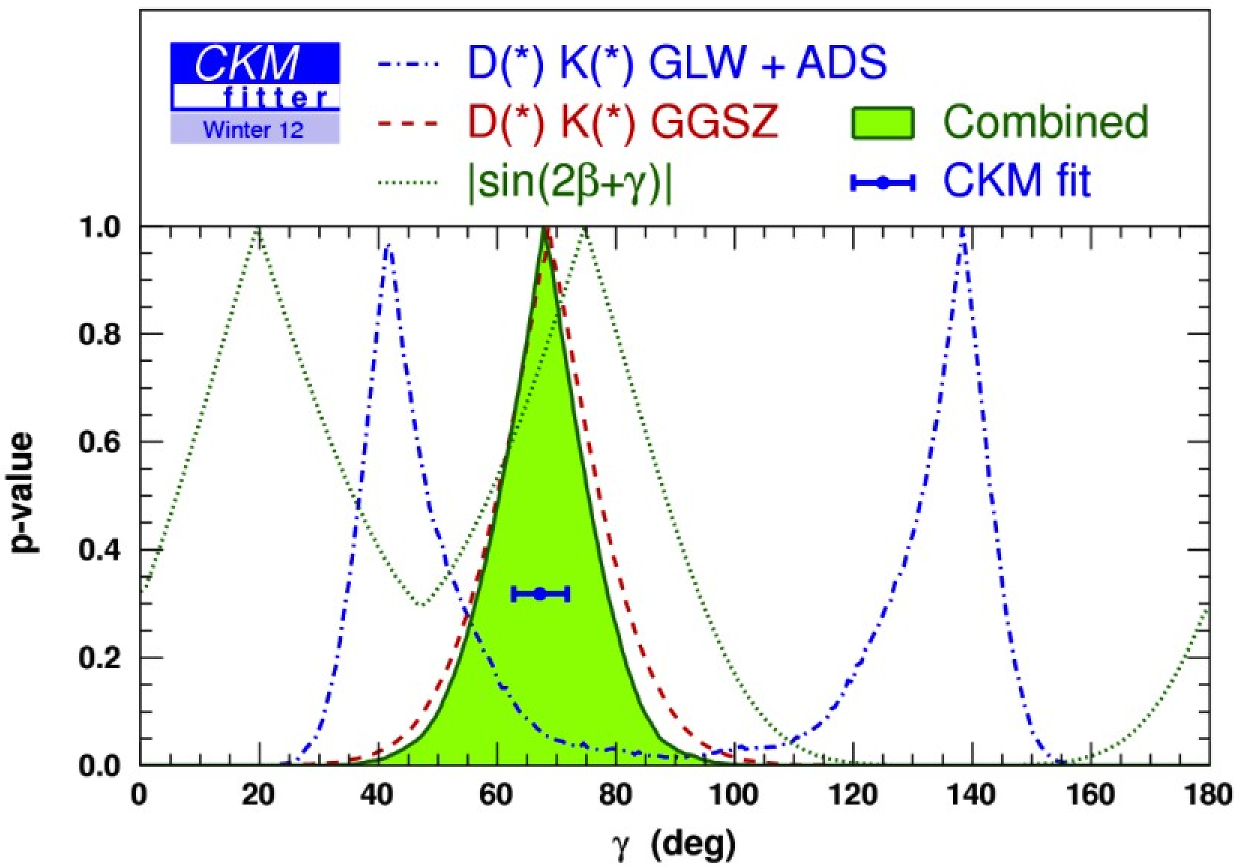
$$(\gamma - 2\beta_s)$$

Phys. Lett. B387 (1996) 361, arXiv:hep-ph/9605221.

third method: time-dependent

B-factories performed such measurements with $B^0 \to D^+ \pi^-$, constraining $\sin(2\beta+\gamma)$





BaBar 2005, hep-ex/0504035

Belle 2011, arXiv:1102.0888

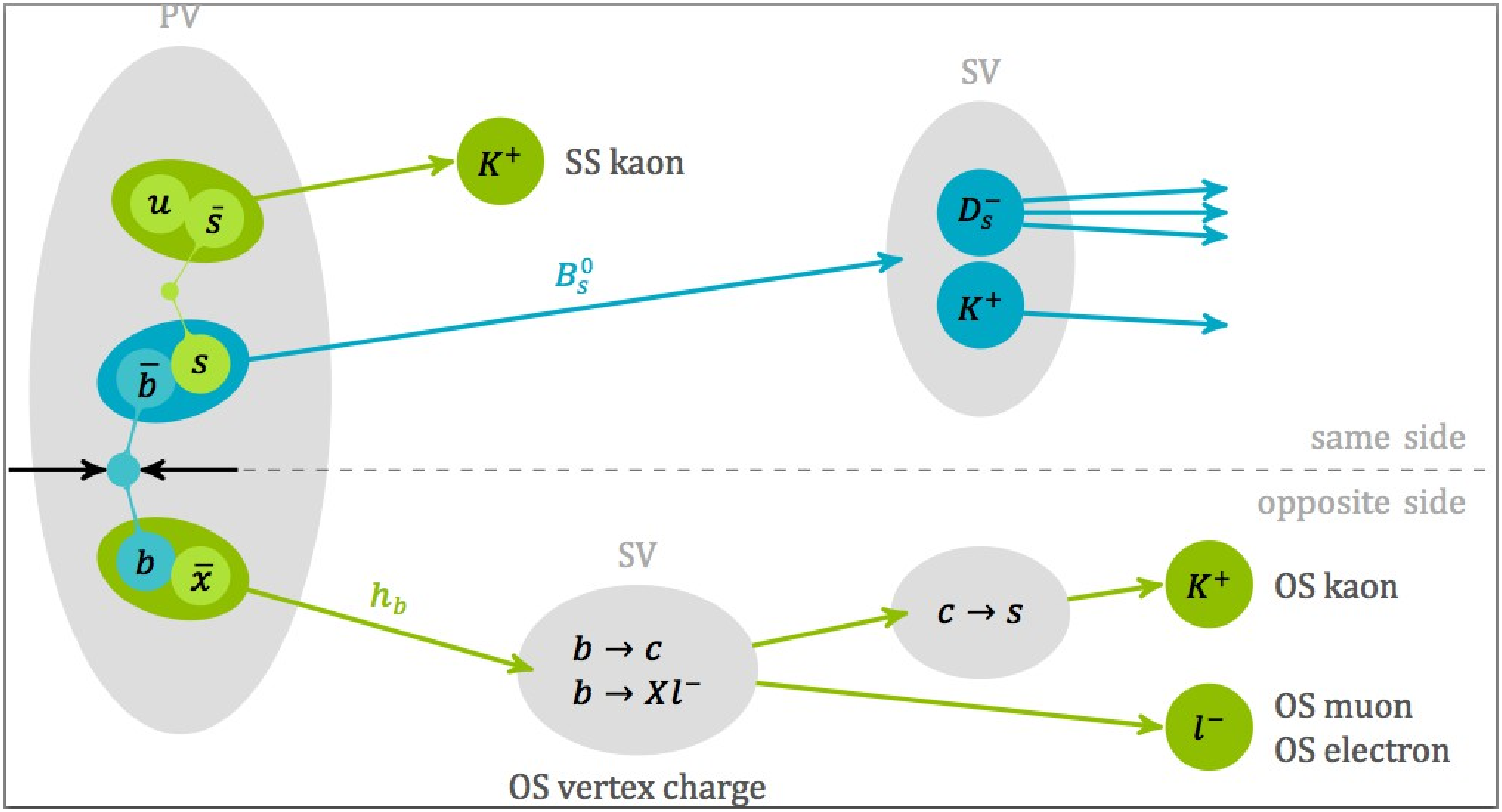
third method: time-dependent

- B_s is much better suited than B_d !
- expected **large interference** effects of ~ 40%
- finite decay width difference adds sensitivity:
  $\Delta\Gamma_s = 0.091 \pm 0.011\ ps^{-1}$ (HFAG fall 2012)

- It is still a pure, **clean tree decay**.

- ***Only* possible at LHCb:**
  - B_s statistics: large b-quark production cross section
  - fully hadronic: full real-time reconstruction on trigger level
  - time resolution: $\sigma(t) \sim 50fs$
  - flavor tagging: distinguish B_s from anti-B_s (tagging power ~5%)

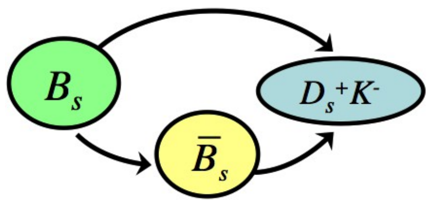
flavor tagging



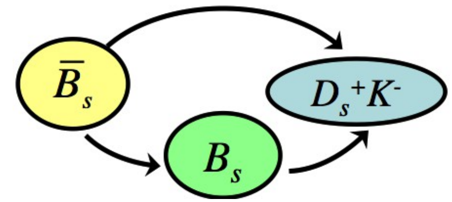
$$\varepsilon_{\text{eff}} = \varepsilon(1-2\omega)^2 \qquad \sigma \propto 1/\sqrt{\varepsilon_{\text{eff}}}$$

$$\varepsilon_{\text{eff}} = 5.07\% \text{ (for } B_s \to D_s K)$$

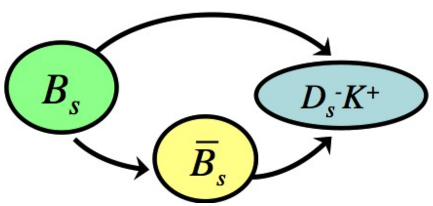
third method: time-dependent



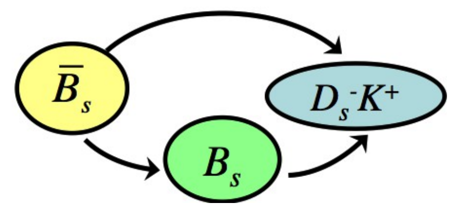
$$B_s^0 \to D_s^+ K^-$$



$$\overline{B_s^0} \to D_s^+ K^-$$



$$B_s^0 \to D_s^- K^+$$



$$\overline{B_s^0} \to D_s^- K^+$$

each has their own time dependence ...

third method: time-dependent

$$\frac{d\Gamma_{B_s^0\to f}(t)}{dt\, e^{-\Gamma_s t}} = \frac{1}{2}|A_f|^2(1+|\lambda_f|^2) \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + D_f \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_f \cos(\Delta m_s t) - S_f \sin(\Delta m_s t)\right] \tag{1}$$

$$\frac{d\Gamma_{\bar{B}_s^0\to f}(t)}{dt\, e^{-\Gamma_s t}} = \frac{1}{2}|A_f|^2\left|\frac{p}{q}\right|^2(1+|\lambda_f|^2) \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + D_f \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - C_f \cos(\Delta m_s t) + S_f \sin(\Delta m_s t)\right] \tag{2}$$

$$\frac{d\Gamma_{\bar{B}_s^0\to \bar{f}}(t)}{dt\, e^{-\Gamma_s t}} = \frac{1}{2}|\bar{A}_{\bar{f}}|^2(1+|\bar{\lambda}_{\bar{f}}|^2) \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + D_{\bar{f}} \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_{\bar{f}} \cos(\Delta m_s t) - S_{\bar{f}} \sin(\Delta m_s t)\right] \tag{3}$$

$$\frac{d\Gamma_{B_s^0\to \bar{f}}(t)}{dt\, e^{-\Gamma_s t}} = \frac{1}{2}|\bar{A}_{\bar{f}}|^2\left|\frac{q}{p}\right|^2(1+|\bar{\lambda}_{\bar{f}}|^2) \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + D_{\bar{f}} \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - C_{\bar{f}} \cos(\Delta m_s t) + S_{\bar{f}} \sin(\Delta m_s t)\right] \tag{4}$$

third method: time-dependent

$$\frac{d\Gamma_{B_s^0\to f}(t)}{dt\,e^{-\Gamma_s t}} = \frac{1}{2}|A_f|^2(1+|\lambda_f|^2) \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + D_f \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_f \cos(\Delta m_s t) - S_f \sin(\Delta m_s t)\right] \quad (1)$$

$$\frac{d\Gamma_{\bar{B}_s^0\to f}(t)}{dt\,e^{-\Gamma_s t}} = \frac{1}{2}|A_f|^2\left|\frac{p}{q}\right|^2(1+|\lambda_f|^2) \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + D_f \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - C_f \cos(\Delta m_s t) + S_f \sin(\Delta m_s t)\right] \quad (2)$$

$$\frac{d\Gamma_{\bar{B}_s^0\to \bar{f}}(t)}{dt\,e^{-\Gamma_s t}} = \frac{1}{2}|\bar{A}_{\bar{f}}|^2(1+|\bar{\lambda}_{\bar{f}}|^2) \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + D_{\bar{f}} \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_{\bar{f}} \cos(\Delta m_s t) - S_{\bar{f}} \sin(\Delta m_s t)\right] \quad (3)$$

$$\frac{d\Gamma_{B_s^0\to \bar{f}}(t)}{dt\,e^{-\Gamma_s t}} = \frac{1}{2}|\bar{A}_{\bar{f}}|^2\left|\frac{q}{p}\right|^2(1+|\bar{\lambda}_{\bar{f}}|^2) \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + D_{\bar{f}} \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - C_{\bar{f}} \cos(\Delta m_s t) + S_{\bar{f}} \sin(\Delta m_s t)\right] \quad (4)$$

third method: time-dependent

$$\frac{d\Gamma_{B_s^0\to f}(t)}{dt\, e^{-\Gamma_s t}} = \frac{1}{2}|A_f|^2(1+|\lambda_f|^2) \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + D_f \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_f \cos(\Delta m_s t) - S_f \sin(\Delta m_s t)\right] \quad (1)$$

$$\frac{d\Gamma_{\bar{B}_s^0\to f}(t)}{dt\, e^{-\Gamma_s t}} = \frac{1}{2}|A_f|^2\left|\frac{p}{q}\right|^2(1+|\lambda_f|^2) \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + D_f \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - C_f \cos(\Delta m_s t) + S_f \sin(\Delta m_s t)\right] \quad (2)$$

$$\frac{d\Gamma_{\bar{B}_s^0\to \bar{f}}(t)}{dt\, e^{-\Gamma_s t}} = \frac{1}{2}|\bar{A}_{\bar{f}}|^2(1+|\bar{\lambda}_{\bar{f}}|^2) \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + D_{\bar{f}} \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_{\bar{f}} \cos(\Delta m_s t) - S_{\bar{f}} \sin(\Delta m_s t)\right] \quad (3)$$

$$\frac{d\Gamma_{B_s^0\to \bar{f}}(t)}{dt\, e^{-\Gamma_s t}} = \frac{1}{2}|\bar{A}_{\bar{f}}|^2\left|\frac{q}{p}\right|^2(1+|\bar{\lambda}_{\bar{f}}|^2) \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + D_{\bar{f}} \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - C_{\bar{f}} \cos(\Delta m_s t) + S_{\bar{f}} \sin(\Delta m_s t)\right] \quad (4)$$

third method: time-dependent

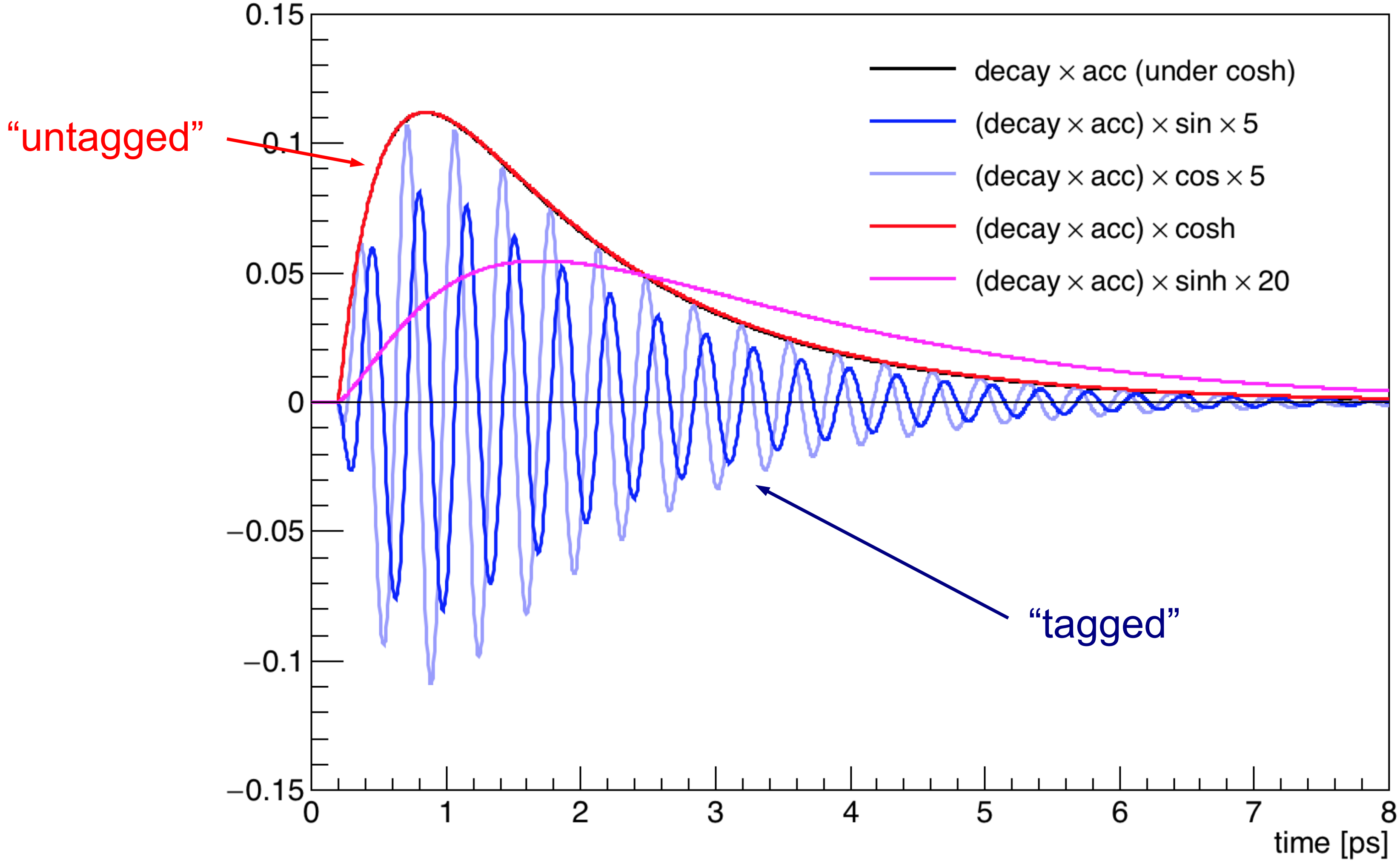
$$\frac{d\Gamma_{B_s^0\to f}(t)}{dt\, e^{-\Gamma_s t}} = \frac{1}{2}|A_f|^2(1+|\lambda_f|^2) \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + D_f \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_f \cos(\Delta m_s t) - S_f \sin(\Delta m_s t)\right] \quad (1)$$

$$\frac{d\Gamma_{\bar{B}_s^0\to f}(t)}{dt\, e^{-\Gamma_s t}} = \frac{1}{2}|A_f|^2\left|\frac{p}{q}\right|^2(1+|\lambda_f|^2) \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + D_f \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - C_f \cos(\Delta m_s t) + S_f \sin(\Delta m_s t)\right] \quad (2)$$

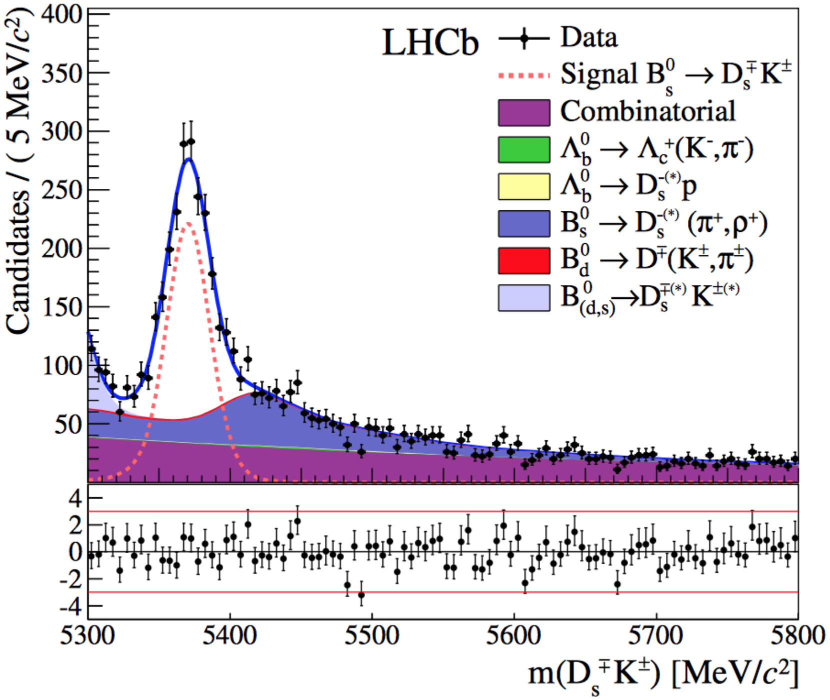
$$\frac{d\Gamma_{\bar{B}_s^0\to \bar{f}}(t)}{dt\, e^{-\Gamma_s t}} = \frac{1}{2}|\bar{A}_{\bar{f}}|^2(1+|\bar{\lambda}_{\bar{f}}|^2) \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + D_{\bar{f}} \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_{\bar{f}} \cos(\Delta m_s t) - S_{\bar{f}} \sin(\Delta m_s t)\right] \quad (3)$$

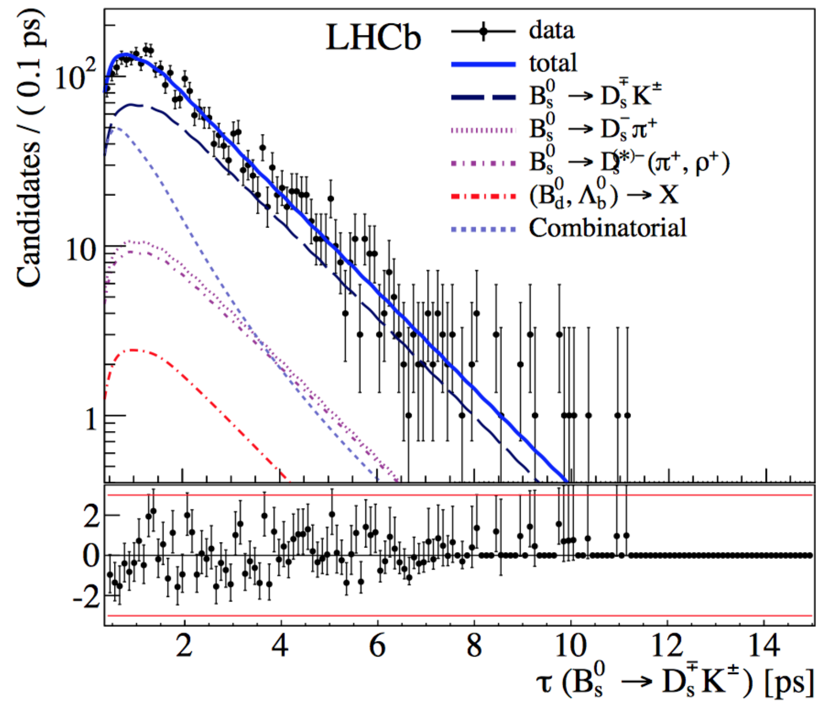
$$\frac{d\Gamma_{B_s^0\to \bar{f}}(t)}{dt\, e^{-\Gamma_s t}} = \frac{1}{2}|\bar{A}_{\bar{f}}|^2\left|\frac{q}{p}\right|^2(1+|\bar{\lambda}_{\bar{f}}|^2) \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + D_{\bar{f}} \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - C_{\bar{f}} \cos(\Delta m_s t) + S_{\bar{f}} \sin(\Delta m_s t)\right] \quad (4)$$

third method: time-dependent



third method: time-dependent

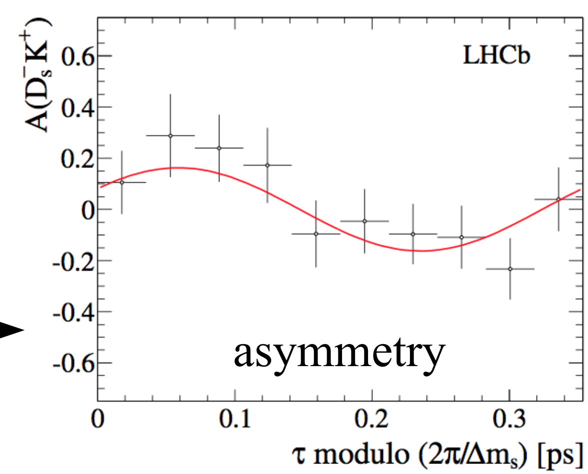




$N_{sig} \sim 1770\ (1\ fb^{-1})$

JHEP 1411 (2014) 060,
arXiv:1407.6127.

hint of an oscillation! →



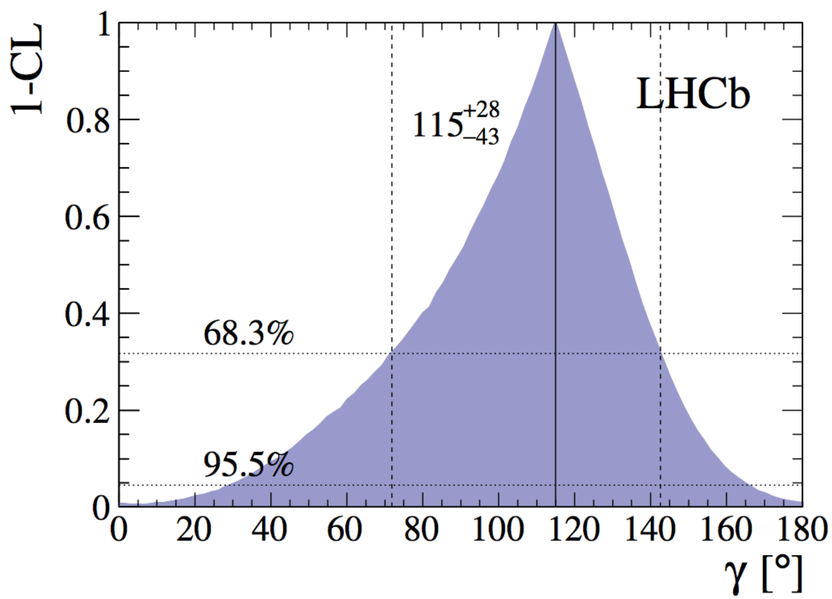
third method: time-dependent

Assuming the Bs mixing phase to be (LHCb, arXiv:1304.2600)

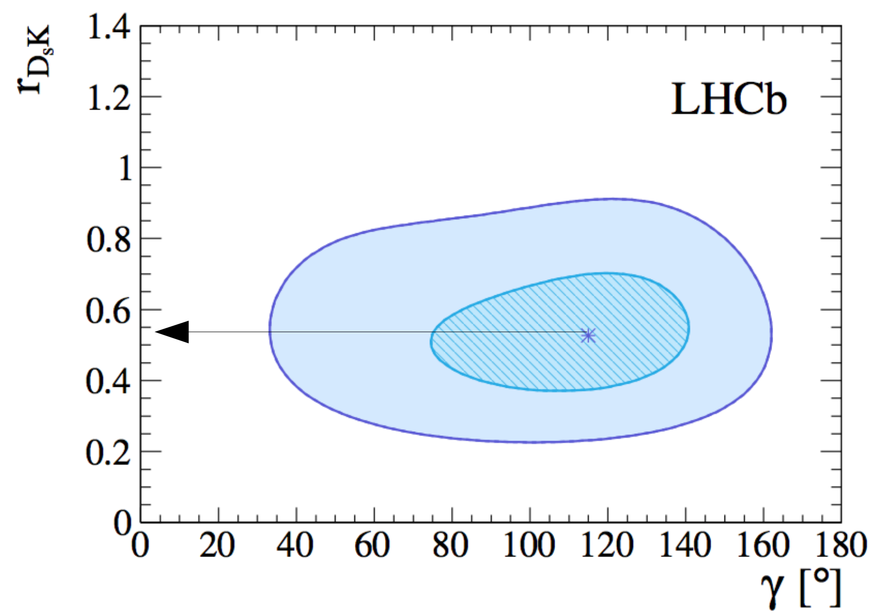
$$\phi_s = 0.01 \pm 0.07\,(\text{stat}) \pm 0.01\,(\text{syst})\,\text{rad}$$

we constrain γ (arXiv:1407.6127):

$$\gamma = (115^{+28}_{-43})^\circ$$



interference parameter is large!



Combining all LHCb tree-level γ measurements

γ combination

Two combinations:

robust	$\boldsymbol{B \to DK}$**-like**
full	$B \to DK$-like and $B \to D\pi$

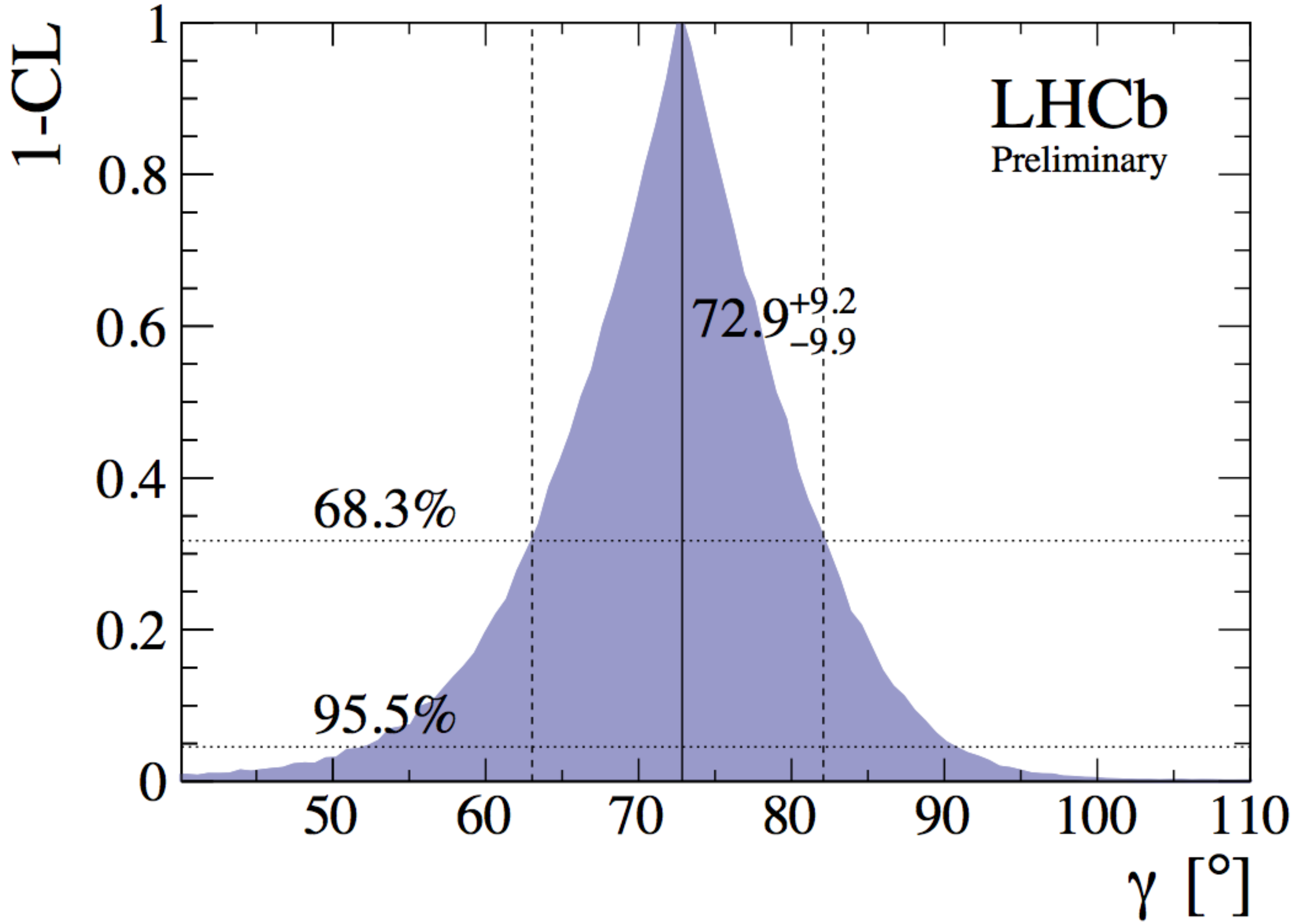
Inputs:

- $B^+ \to Dh^+$, $D \to hh$, GLW/ADS, 1 fb^{-1} 1203.3662
- $B^+ \to Dh^+$, $D \to K\pi\pi\pi$, ADS, 1 fb^{-1} 1303.4646
- updated: $B^+ \to DK^+$, $D \to K^0_S hh$, model-ind. GGSZ, 3 fb^{-1} 1408.2748
- **new:** $B^+ \to DK^+$, $D \to K^0_S K\pi$, GLS, 3 fb^{-1} 1402.2982
- **new:** $B^0 \to D^0 K^{*0}$, $D \to hh$, GLW/ADS, 3 fb^{-1} 1407.8136
- **new:** $B^0_s \to D_s^{\mp} K^{\pm}$, 1 fb^{-1} 1407.6127

γ combination

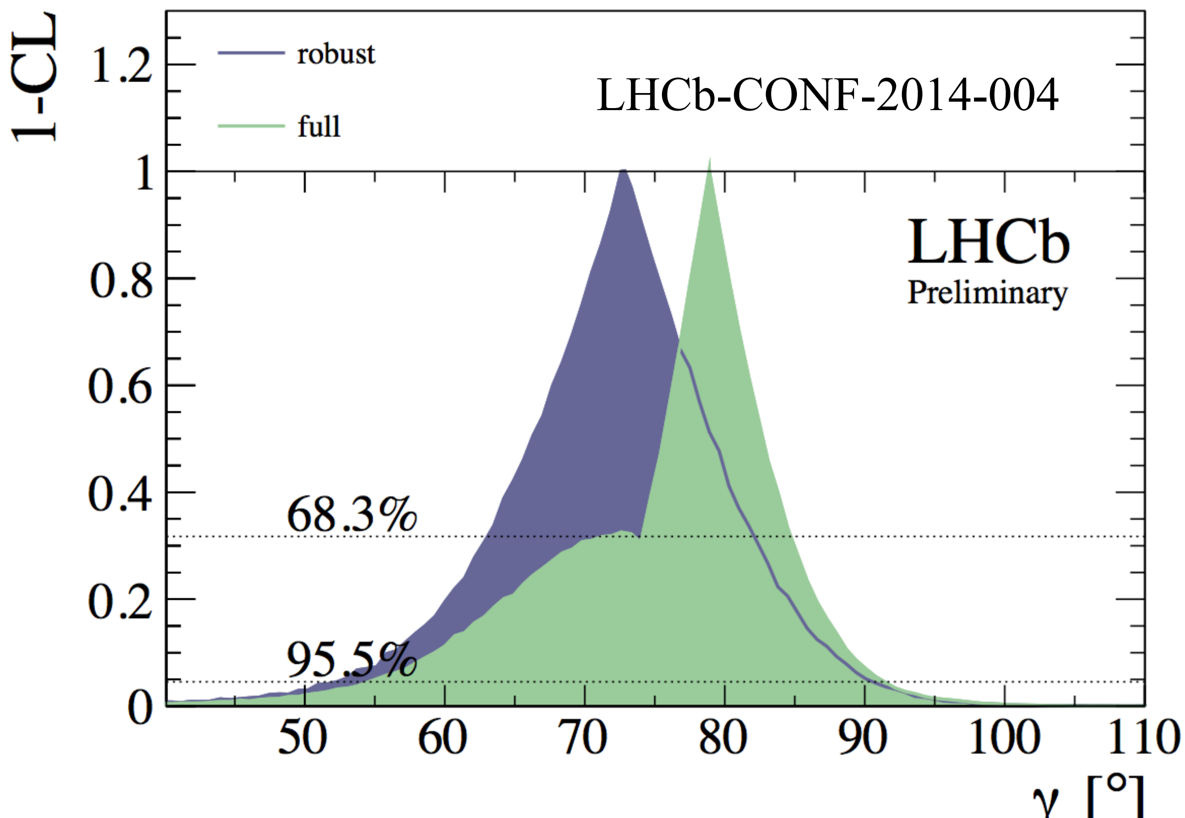
LHCb-CONF-2014-004

Frequentist (plugin-method)



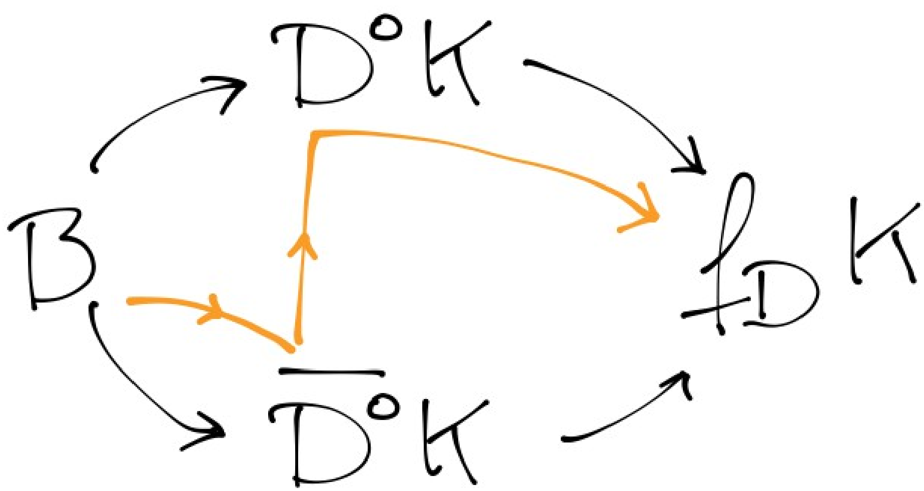
on the way to the degree precision

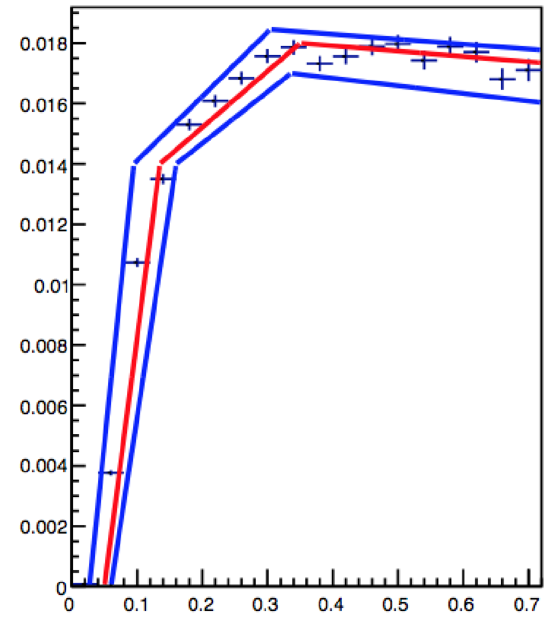
- We add another channel: $B \to D^0\pi$, "full combination"
- Less sensitivity to γ, but larger statistics
- A fluctuation causes much increased apparent sensitivity, and highly non Gaussian behavior – to be interpreted with care!



on the way to the degree precision

- The effect of D^0 mixing does affect the determination of γ.
- Already accounted for in the LHCb combination!
- Next up: also K^0 mix …





$$\Delta \approx \sqrt{x_D^2 + y_D^2}/r_B$$

Figure: LHCb D^0 decay time acceptance for $B^+ \to DK^+$, $D \to hh$.

γ combination

Table: Summary of results for γ from the B factories BaBar and Belle, and from LHCb, and combiners. Errors correspond to 68% confidence or credibility.

experiment	result	date
BaBar	$(69^{+17}_{-16})^\circ$	Jan 2013
Belle	$(68^{+15}_{-14})^\circ$	Jan 2013
LHCb 1–3 fb^{-1} prelim.	$(67 \pm 12)^\circ$	Apr 2013
LHCb 1 fb^{-1}	$(72.6^{+9.7}_{-17.2})^\circ$	Aug 2013
LHCb 1–3 fb^{-1} prelim.	$(72.9^{+9.2}_{-9.9})^\circ$	Sep 2014
UTfit	$(68.3 \pm 7.5)^\circ$	post Moriond 2014
CKMfitter	$(70.0^{+7.7}_{-9.0})^\circ$	Moriond / Jun 2014
CKMfitter	$(73.2^{+6.3}_{-7.0})^\circ$	Sep 2014

Outlook

Updates of the existing

Many inputs yet to be updated to 3 fb^{-1}:

- $B^+ \to Dh^+$, $D \to hh$, GLW/ADS, 1 fb^{-1} 1203.3662
- $B^+ \to Dh^+$, $D \to K\pi\pi\pi$, ADS, 1 fb^{-1} 1303.4646
- updated: $B^+ \to DK^+$, $D \to K^0_S hh$, model-ind. GGSZ, 3 fb^{-1} 1408.2748
- **new:** $B^+ \to DK^+$, $D \to K^0_S K\pi$, GLS, 3 fb^{-1} 1402.2982
- **new:** $B^0 \to D^0 K^{*0}$, $D \to hh$, GLW/ADS, 3 fb^{-1} 1407.8136
- **new:** $B^0_s \to D^\mp_s K^\pm$, 1 fb^{-1} 1407.6127

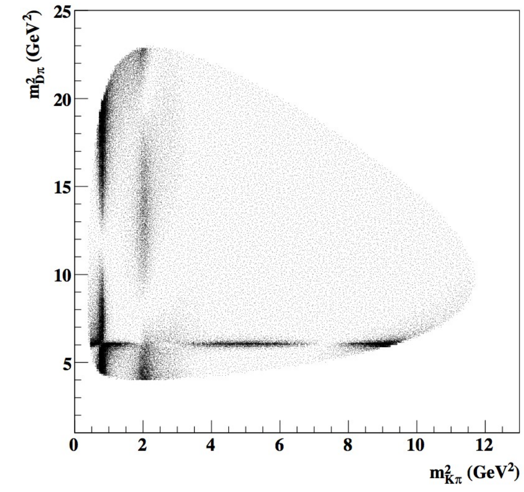
More channels to be added

There are many more possibilities:

$B^+ \to Dh^+, D \to K\pi\pi^0$	ADS
$B^+ \to Dh^+, D \to \pi\pi\pi^0$	GLW
$B^+ \to Dh^+, D \to KK\pi\pi$	GGSZ
$B^0 \to DK^{*0}, D \to Khh$	GGSZ
$B^+ \to DK\pi\pi, D \to hh, Khh$	GLW/ADS/GGSZ

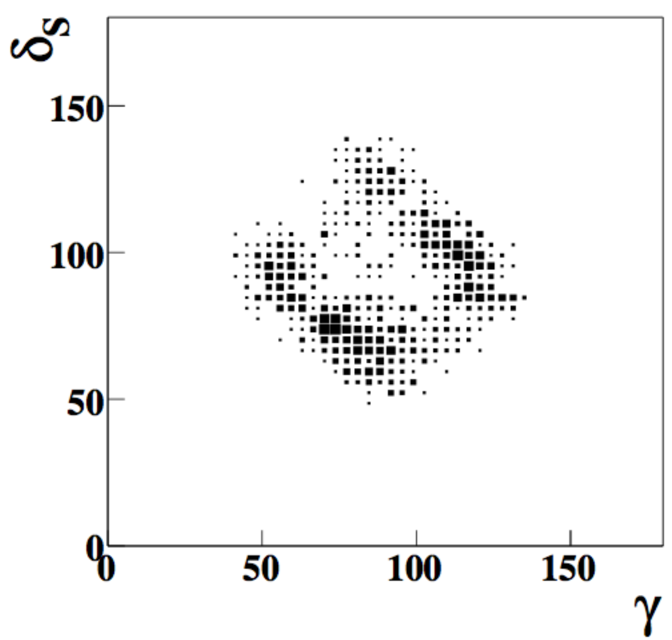
$\ldots$

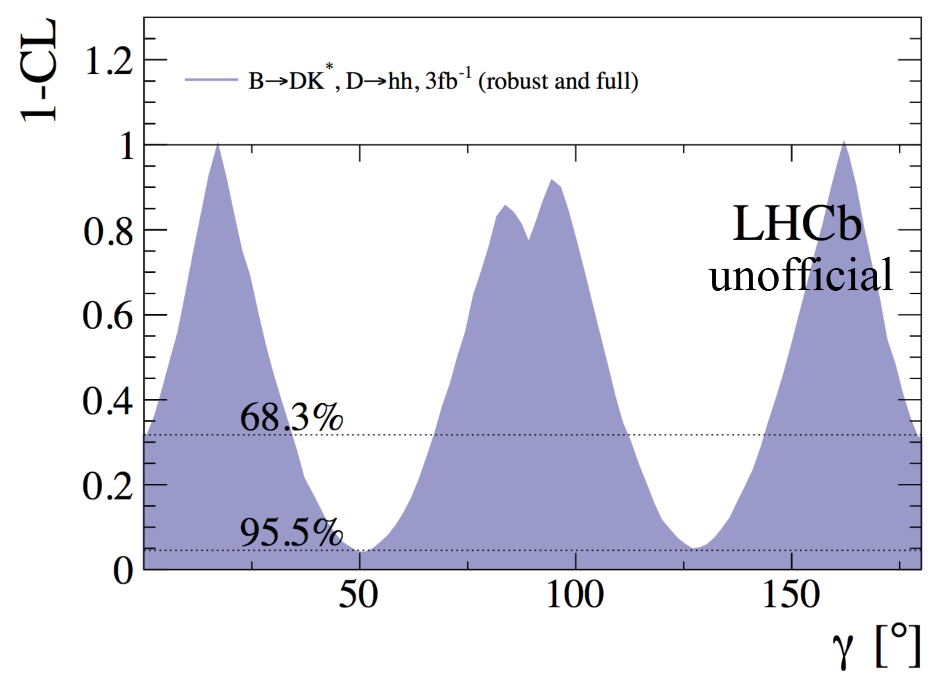
A new method



- Idea: analyze the B^0 Dalitz plot in $B^0 \to D^0 K\pi$
- Gershon, Williams [arXiv:0909.1495]
- This resolves ambiguities!
- A 10deg error on γ seems not unreasonable! (Dalitz model unknown).

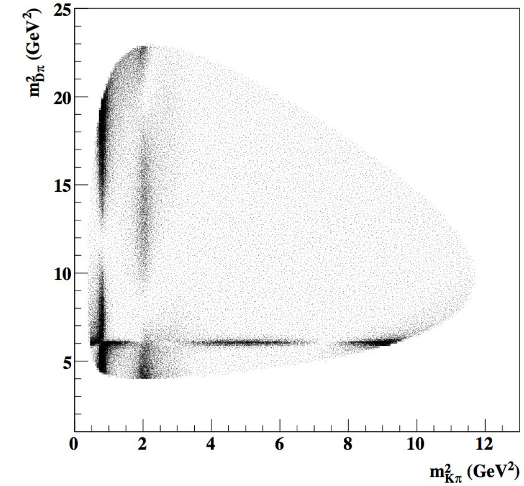
$B^0 \to D^0 K^{*0} \to D^0 K\pi$ already contributes now!



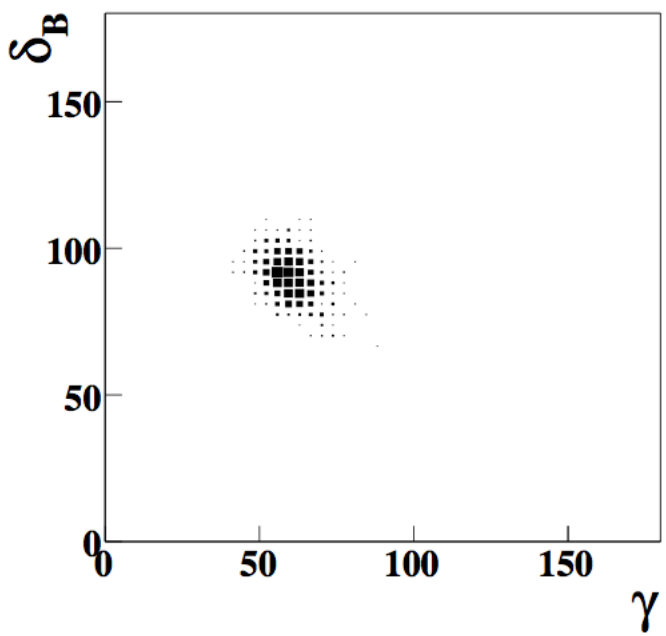


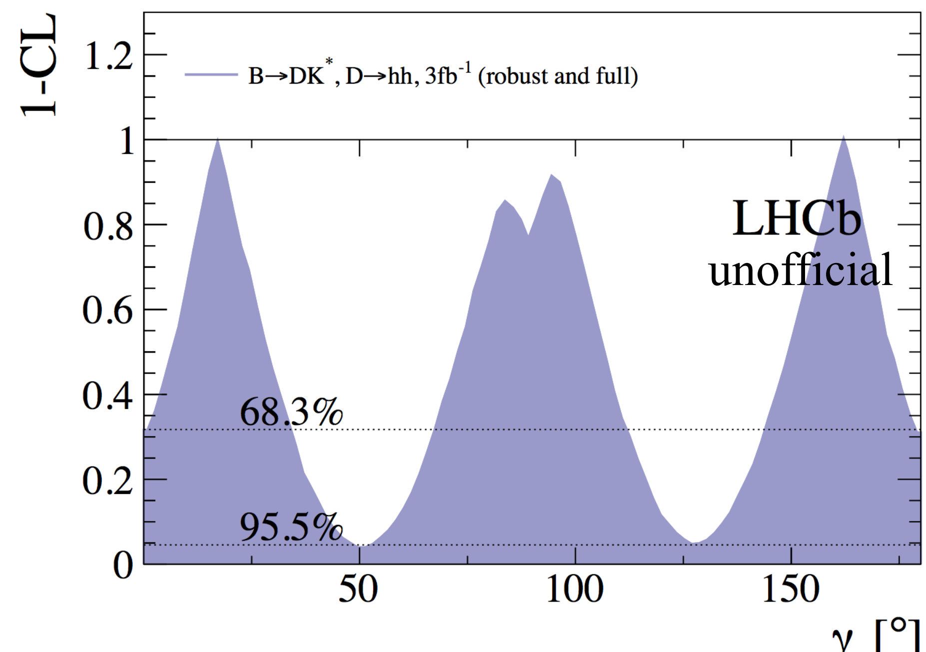
A new method

- Idea: analyze the B0 Dalitz plot in $B^0 \to D^0 K\pi$
- Gershon, Williams [arXiv:0909.1495]
- This resolves ambiguities!
- A 10deg error on γ seems not unreasonable! (Dalitz model unknown).



$B^0 \to D^0 K^{*0} \to D^0 K\pi$
already contributes now!





LHCb Run2 expectations

Table 28: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the expected sensitivity is given for the integrated luminosity accumulated by the end of LHC Run 1, by 2018 (assuming 5 fb^{-1} recorded during Run 2) and for the LHCb Upgrade (50 fb^{-1}). An estimate of the theoretical uncertainty is also given – this and the potential sources of systematic uncertainty are discussed in the text.

	Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
☺ ☺ (☺)	B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.050	0.025	**0.009**	~ 0.003
☺ ☺		$\phi_s(B_s^0 \to J/\psi\, f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
☺		$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
☺ ☺	Gluonic	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.023**	0.02
☺	penguin	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.029**	< 0.02
☺		$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.04**	0.02
	Right-handed	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$	0.20	0.13	**0.030**	< 0.01
	currents	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.8%**	0.2 %
	Electroweak	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	penguin	$q_0^2\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
		$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
		$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
	Higgs	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	penguin	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\%$
☺ (☺ ☺)	Unitarity	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**1.1°**	negligible
☺	triangle	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.4°**	negligible
☺ (☺ ☺)	angles	$\beta(B^0 \to J/\psi\, K_S^0)$	1.7°	0.8°	**0.31°**	negligible
	Charm	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.5**	–
	CP violation	ΔA_{CP} (10^{-3})	0.8	0.5	**0.12**	–

Smileys indicate "on trackness", added by Tim Gershon (LHCb Implications Workshop Oct 2014)

LHCb Run2 expectations

Table 28: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the expected sensitivity is given for the integrated luminosity accumulated by the end of LHC Run 1, by 2018 (assuming 5 fb^{-1} recorded during Run 2) and for the LHCb Upgrade (50 fb^{-1}). An estimate of the theoretical uncertainty is also given – this and the potential sources of systematic uncertainty are discussed in the text.

	Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
☺ ☺ (☺)	B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.050	0.025	**0.009**	~ 0.003
☺ ☺		$\phi_s(B_s^0 \to J/\psi\, f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
☺		$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
☺ ☺	Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.023**	0.02
☺		$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.029**	< 0.02
☺		$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.04**	0.02
	Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$	0.20	0.13	**0.030**	< 0.01
		$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.8%**	0.2 %
	Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
		$q_0^2\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
		$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
		$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
	Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
		$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\%$
☺ (☺ ☺)	Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°		
☺		$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°		
☺ (☺ ☺)		$\beta(B^0 \to J/\psi\, K_S^0)$	1.7°	0.8°		
	Charm CP violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.5**	–
		ΔA_{CP} (10^{-3})	0.8	0.5	**0.12**	–

$\sigma(\gamma) \approx 4^\circ$

Smileys indicate "on trackness", added by Tim Gershon (LHCb Implications Workshop Oct 2014)

current systematic effects

Tree-level measurements of γ will **not be limited** by systematics for a long time (not at **100 times** the current dataset).

going well beyond LHCb upgrade!

- **first** method ($B \to DK$ GLW/ADS)
  - instrumental charge asymmetries (known to the per-mille level, $B \to J/\psi K$ asymmetry needed as input, magnet polarity flip)
  - calibration of particle identification

example result:

$$A_{CP} = 0.0849 \pm 0.0201(\text{stat.}) \pm 0.0010(\text{syst.})$$

current systematic effects

Tree-level measurements of γ will **not be limited** by systematics for a long time (not at **100 times** the current dataset).

going well beyond LHCb upgrade!

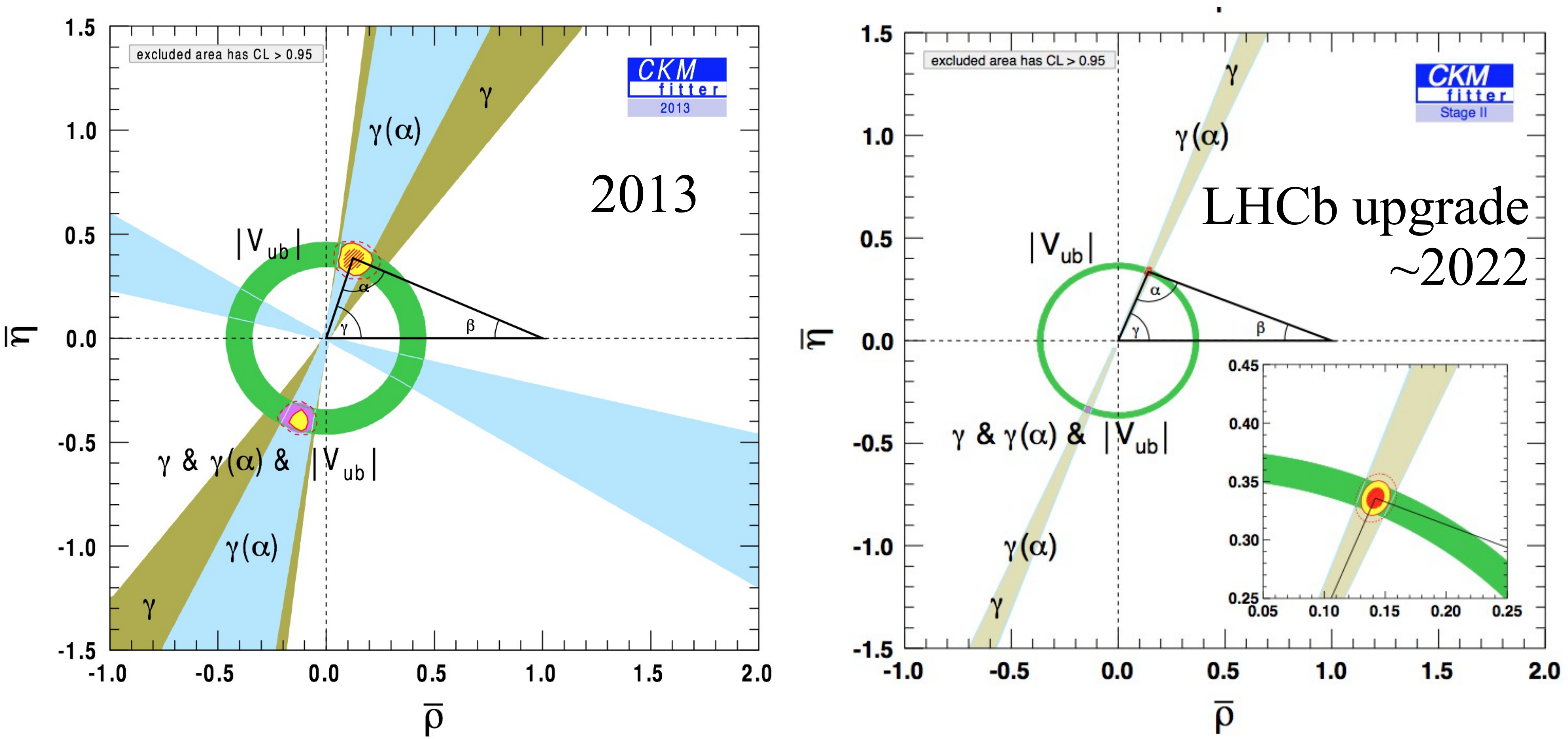
- **first** method ($B \to DK$ GLW/ADS)
  - instrumental charge asymmetries (known to the per-mille level, $B \to J/\psi K$ asymmetry needed as input, magnet polarity flip)
  - calibration of particle identification
- **second** method ($B \to DK$ GGSZ)
  - efficiency corrections over the Dalitz plot
- **third** method ($B_s \to D_s K$ time dependent)
  - decay time resolution
  - decay time acceptance
  - knowledge of Δms, $\Delta\Gamma s$, Γs

completely different sources!

Conclusion

Conclusion

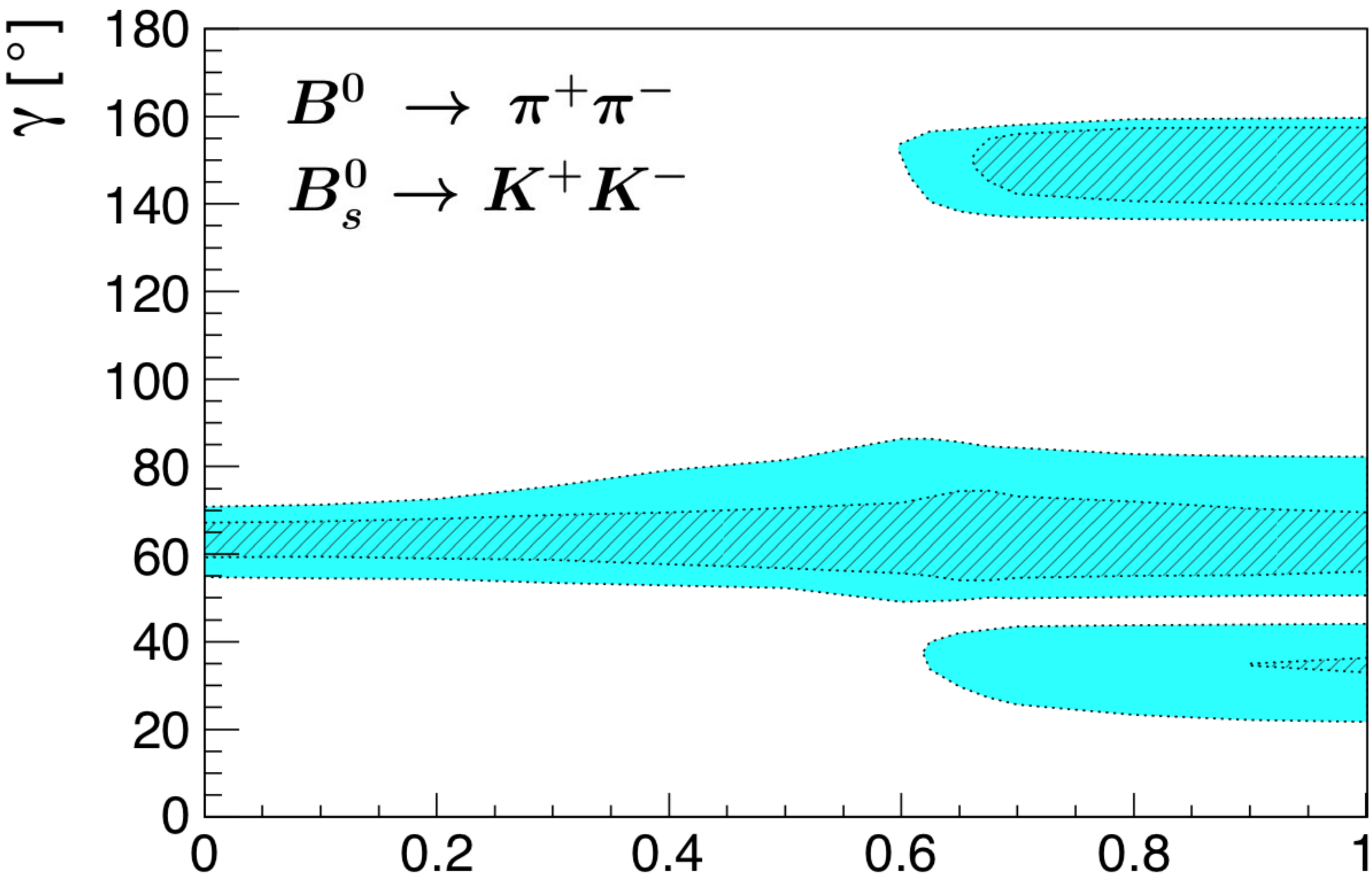
LHCb is getting closer to a tree-level precision measurement of the CKM triangle!
(Might need a little help with |Vub| though!)



Ligeti et al., 1309.2293

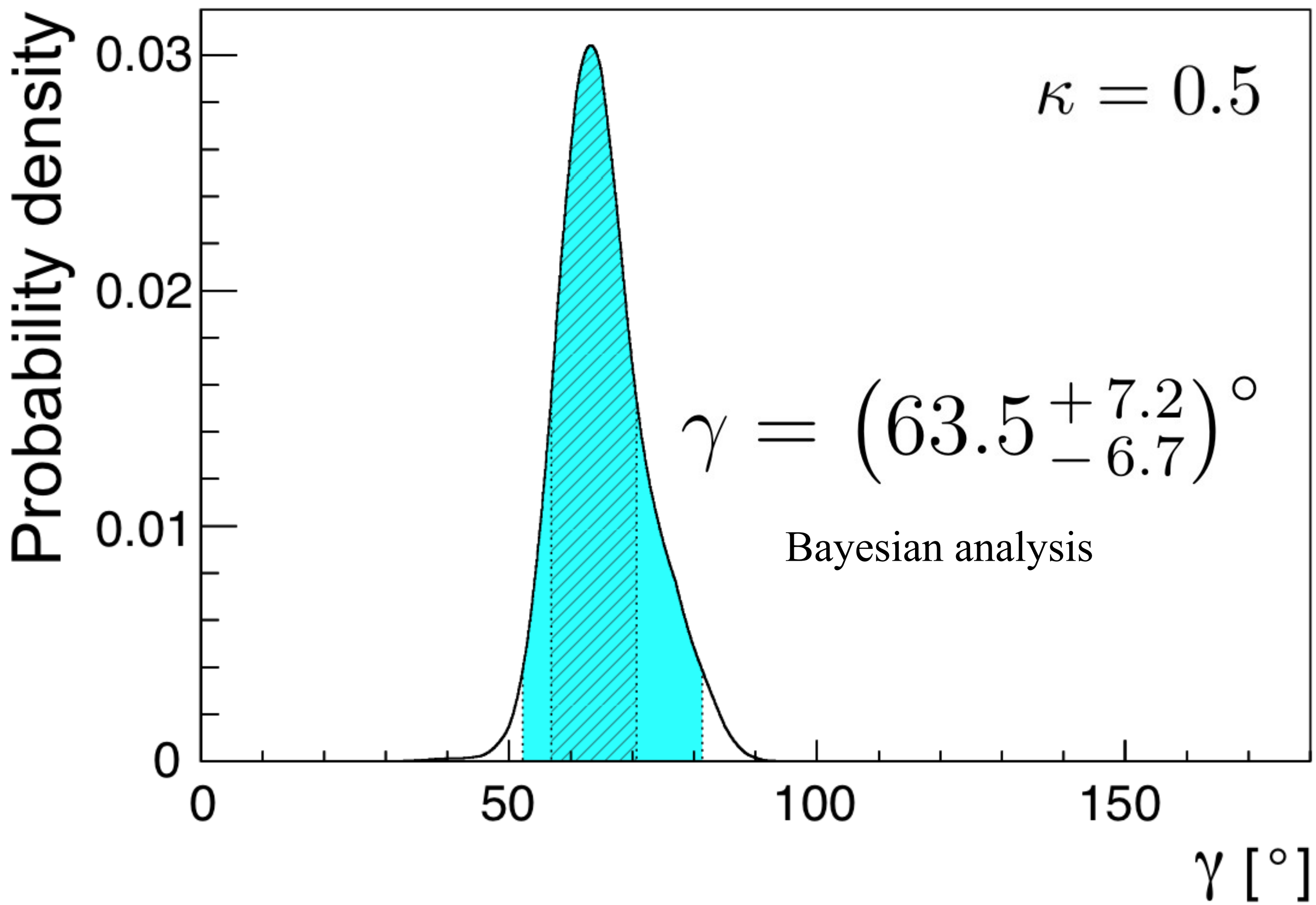
Backup

"γ from loops"



U spin (same mass of d and s-quark) breaking κ

"γ from loops"



Probability density
0.03
0.02
0.01
0
0
50
100
150
γ [°]
$\kappa = 0.5$
$\gamma = \left(63.5\,^{+7.2}_{-6.7}\right)^\circ$
Bayesian analysis

"γ from loops"

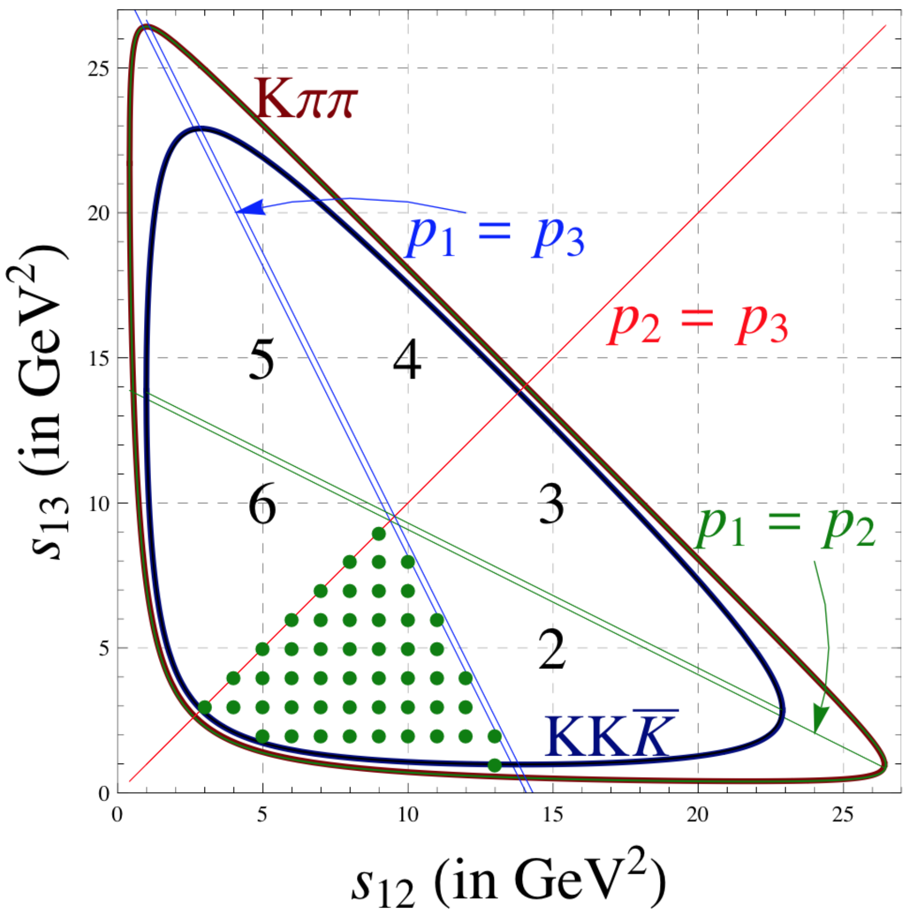


FIG. 1: Kinematic boundaries and symmetry axes of $B \to K\pi\pi$ and $B \to KK\bar{K}$ Dalitz plots. The symmetry axes divide each plot into six zones, five of which are marked 2-6. The fifty dots in the region of overlap of the first of six zones from all Dalitz plots are used for the γ measurement.

New method by London, Bhattacharya, Imbeault, Rey-Le Lorier:

$$B \to hhh$$

$$h = K, \pi$$

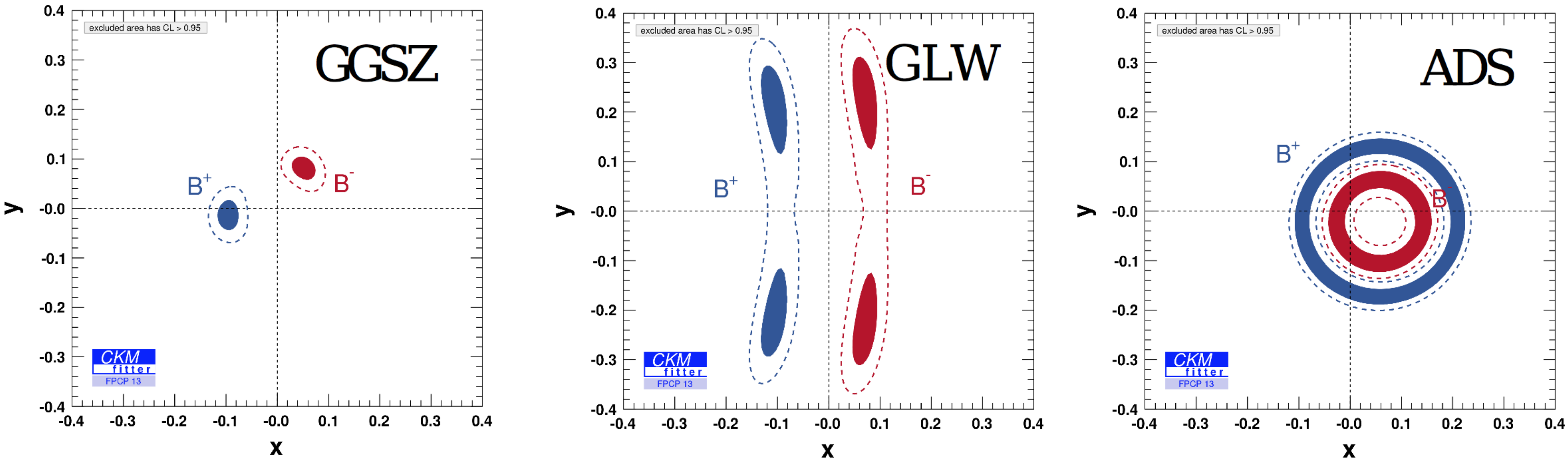
$$\gamma = (77 \pm 3)^\circ$$

(take with a grain of salt)

Well suited for LHCb!

GGSZ or the "Dalitz" method

illustration:



Karim Trabelsi, CKM2014

$$x_{\pm} = r_B \cos(\delta_B \pm \gamma) \qquad y_{\pm} = r_B \sin(\delta_B \pm \gamma)$$

Combination

Table 2: Observables used in the robust combination.

LHCb Analysis	Observables
$B^+ \to DK^+$, $D \to hh$, GLW/ADS	$A_{CP}^{DK,KK}$, $A_{CP}^{DK,\pi\pi}$, $R_{K/\pi}^{KK}$, $R_{K/\pi}^{\pi\pi}$, $R_{K/\pi}^{K\pi}$, $A_{\rm fav}^{DK,K\pi}$, $R_{+}^{DK,K\pi}$, $R_{-}^{DK,K\pi}$
$B^+ \to DK^+$, $D \to K\pi\pi\pi$, ADS	$R_{+}^{DK,K3\pi}$, $R_{-}^{DK,K3\pi}$, $A_{\rm fav}^{DK,K3\pi}$
$B^+ \to DK^+$, $D \to K^0_{\rm S}hh$, model-independent GGSZ	x_-, x_+, y_-, y_+
$B^+ \to DK^+$, $D \to K^0_{\rm S}K\pi$, GLS	$R_{DK,\,\rm fav/sup}^{K_SK\pi}$, $A_{\rm fav}^{DK,\,K_SK\pi}$, $A_{\rm sup}^{DK,\,K_SK\pi}$
$B^0 \to DK^{*0}$ GLW/ADS	$A_{CP}^{DK^{*0},\,KK}$, $A_{\rm fav}^{DK^{*0},\,K\pi}$, $R_{CP}^{DK^{*0},\,KK}$, $A_{CP}^{DK^{*0},\,\pi\pi}$, $R_{CP}^{DK^{*0},\,\pi\pi}$, $R_{+}^{DK^{*0},\,K\pi}$, $R_{-}^{DK^{*0},\,K\pi}$
$B^0_s \to D_s^{\mp}K^{\pm}$	C_f, $A_f^{\Delta\Gamma}$, $A_{\bar f}^{\Delta\Gamma}$, S_f, $S_{\bar f}$

Auxiliary Input	Observables
CLEO-c	$\kappa_D^{K3\pi}$, $\delta_D^{K3\pi}$
Belle, CLEO	$R_{WS}(D \to K\pi\pi\pi)$
CLEO	$R_D^{K_SK\pi}$, $\kappa_D^{K_SK\pi}$, $\delta_D^{K_SK\pi}$
LHCb toy	$\kappa_B^{DK^{*0}}$
LHCb	ϕ_s
HFAG	x_D, y_D, $\delta_D^{K\pi}$, $R_D^{K\pi}$, $A_{CP}^{\rm dir}(KK)$, $A_{CP}^{\rm dir}(\pi\pi)$

Combination

Table 3: Confidence intervals and central values for the robust combination.

quantity	robust combination
γ ($^\circ$)	72.9
68% CL ($^\circ$)	$[63.0, 82.1]$
95% CL ($^\circ$)	$[52.0, 90.5]$
r_B^{DK}	0.0914
68% CL	$[0.0826, 0.0997]$
95% CL	$[0.0728, 0.1078]$
δ_B^{DK} ($^\circ$)	126.8
68% CL ($^\circ$)	$[115.3, 136.7]$
95% CL ($^\circ$)	$[101.6, 145.2]$

Combination

Table 4: Observables used in the full combination in addition to those of the robust combination given in Table 2.

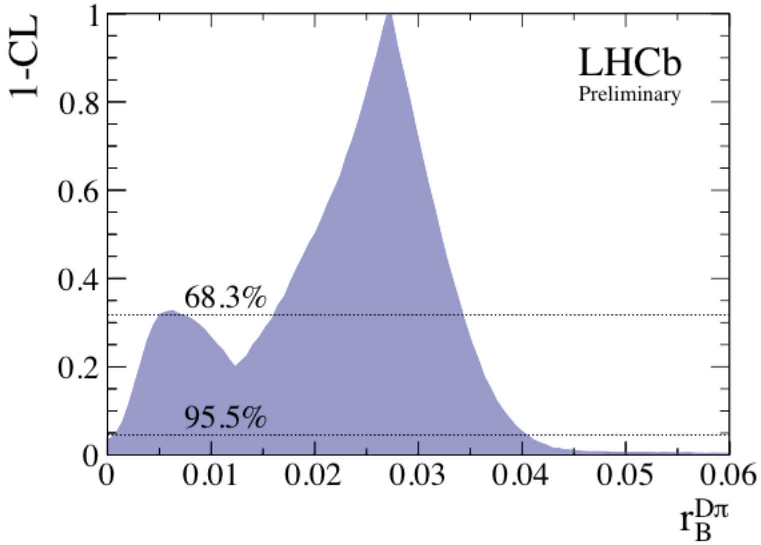
$B^+ \to DK^+$, $D \to hh$, GLW/ADS	$A_{CP}^{D\pi,KK}$, $A_{CP}^{D\pi,\pi\pi}$, $A_{\text{fav}}^{D\pi,K\pi}$, $R_+^{D\pi,K\pi}$, $R_-^{D\pi,K\pi}$
$B^+ \to DK^+$, $D \to K\pi\pi\pi$, ADS	$R_+^{D\pi,K3\pi}$, $R_-^{D\pi,K3\pi}$, $A_{\text{fav}}^{D\pi,K3\pi}$, $R_{K/\pi}^{K3\pi}$

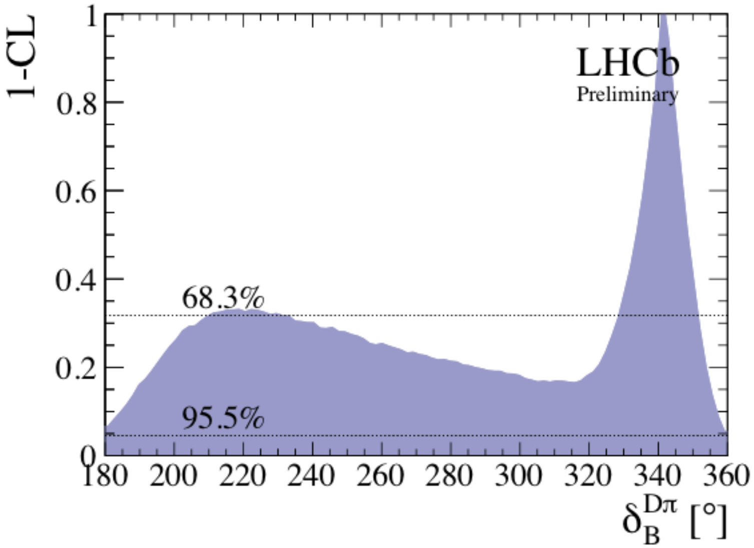
Combination

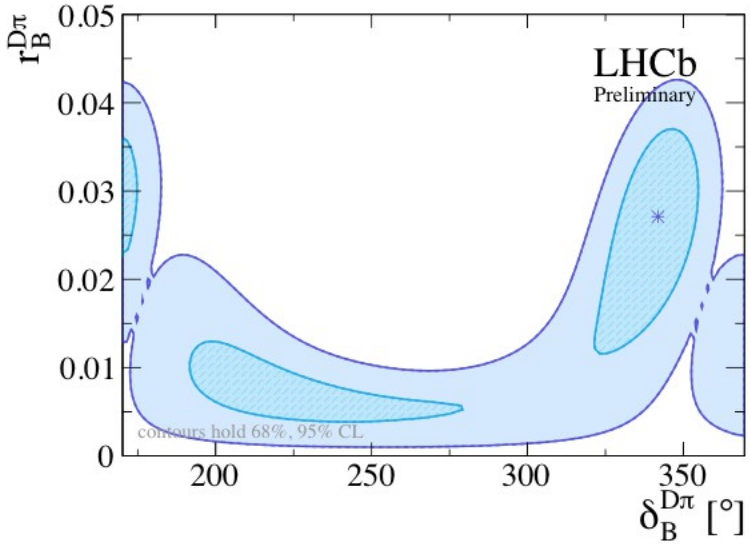
Table 5: Confidence intervals and central values for the full combination. The two columns correspond to the two minima found by the fit. The most probable value is given in the left column, corresponding to a large value of $r_B^{D\pi}$.

quantity	full	
γ (°)	78.9	72.8
68% CL (°)	[71.5, 84.7]	
95% CL (°)	[54.6, 91.4]	
r_B^{DK}	0.0928	
68% CL	[0.0845, 0.1008]	
95% CL	[0.0732, 0.1085]	
δ_B^{DK} (°)	128.9	
68% CL (°)	[118.9, 137.9]	
95% CL (°)	[102.0, 145.9]	
$r_B^{D\pi}$	0.027	0.006
68% CL	[0.016, 0.034]	[0.005, 0.007]
95% CL	[0.001, 0.040]	
$\delta_B^{D\pi}$ (°)	341.8	215.6
68% CL (°)	[328.7, 351.4]	[210.2, 231.5]
95% CL (°)	no constraint	

Combination



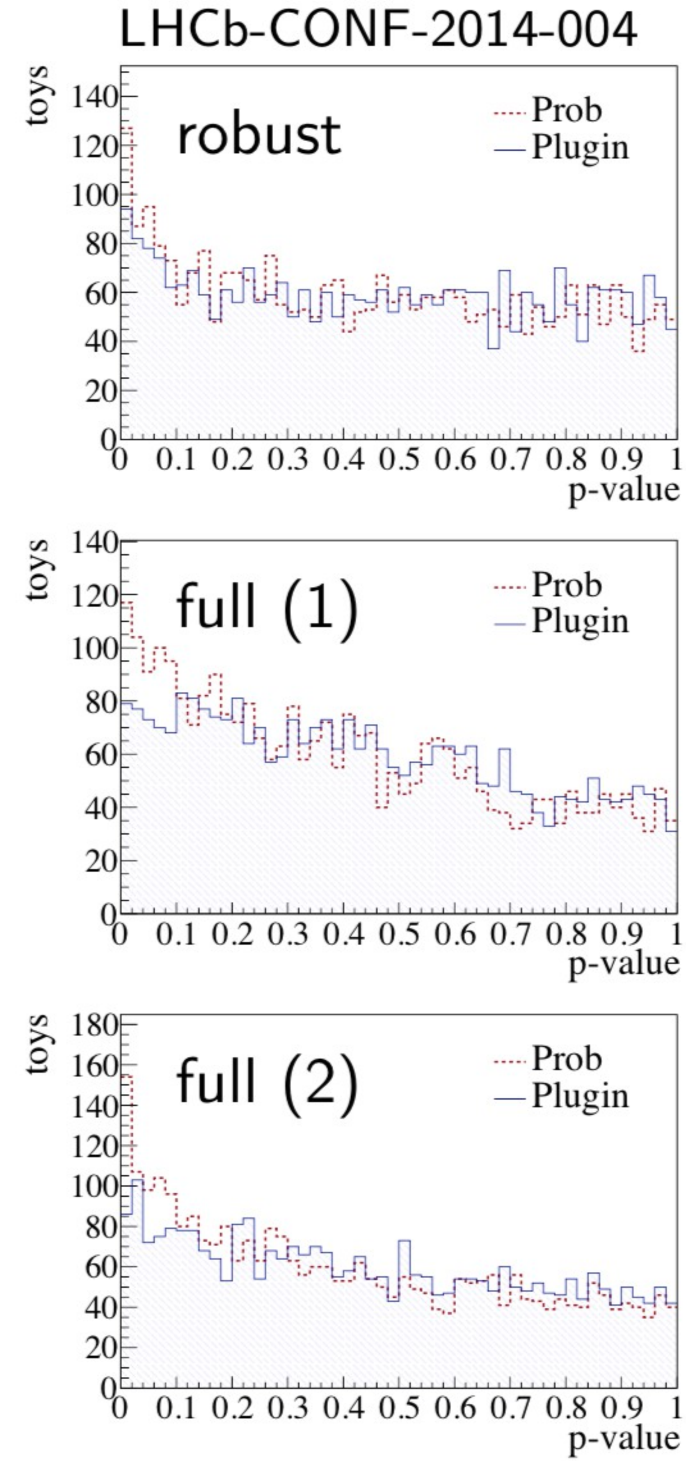




Coverage test

- We test the frequentist coverage at the minima of the combinations.
- We find that the profile likelihood construction undercovers quite a bit.
- The robust plugin method has good coverage.
- The coverage of the full combination is worse than of the robust. Expected due to the low value of $r_B^{D\pi}$.

$\eta = 0.683$	α (prof. LH.)	α (plugin)
robust	0.6158	0.6494
full (1), $r_B^{D\pi} = 0.027$	0.5593	0.6154
full (2), $r_B^{D\pi} = 0.006$	0.5454	0.6120



Auxiliary input from HFAG

comparing old and new

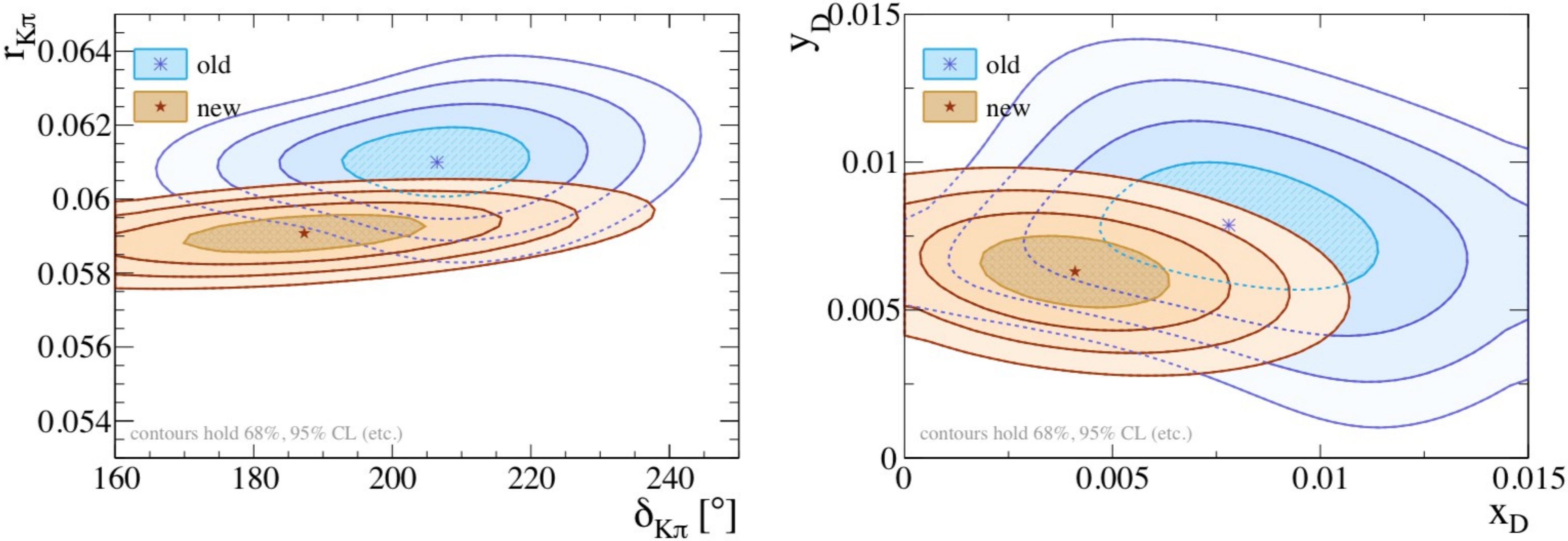


Figure: Profile likelihood contours: The "old" contour corresponds to what was used in the previous (2013) combination (the 2009 CLEO input [25] together with the 2013 LHCb charm mixing measurement [26]). The "new" contour is what is used in this combination (HFAG 2014). The contours are two-dimensional 1–4σ contours.

Auxiliary input from HFAG

The parameter $R_D^{K\pi}$ is the squared ratio of the doubly-Cabibbo-suppressed amplitude $D^0 \to \pi^- K^+$ to the favored one $D^0 \to K^- \pi^+$. It is not the ratio of branching ratios. It gets often measured in time-dependent wrong-sign D^0 mixing measurements:

$$R_{WS} = R_D^{K\pi} + \sqrt{R_D^{K\pi}} \left(x \cos(\delta_D^{K\pi}) \pm y \sin(\delta_D^{K\pi}) \right) \frac{t}{\tau} + \frac{x_D^2 + y_D^2}{4} \left(\frac{t}{\tau} \right)^2$$

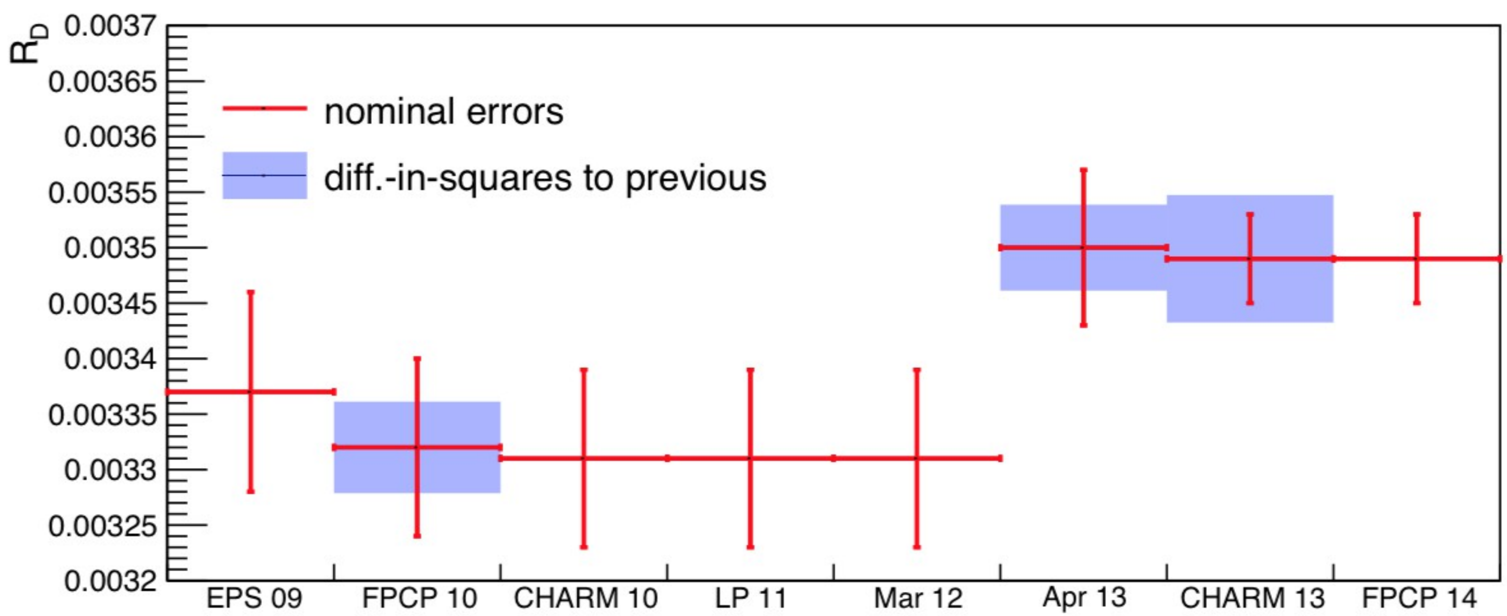


Figure: Evolution of HFAG results on $R_D^{K\pi}$.