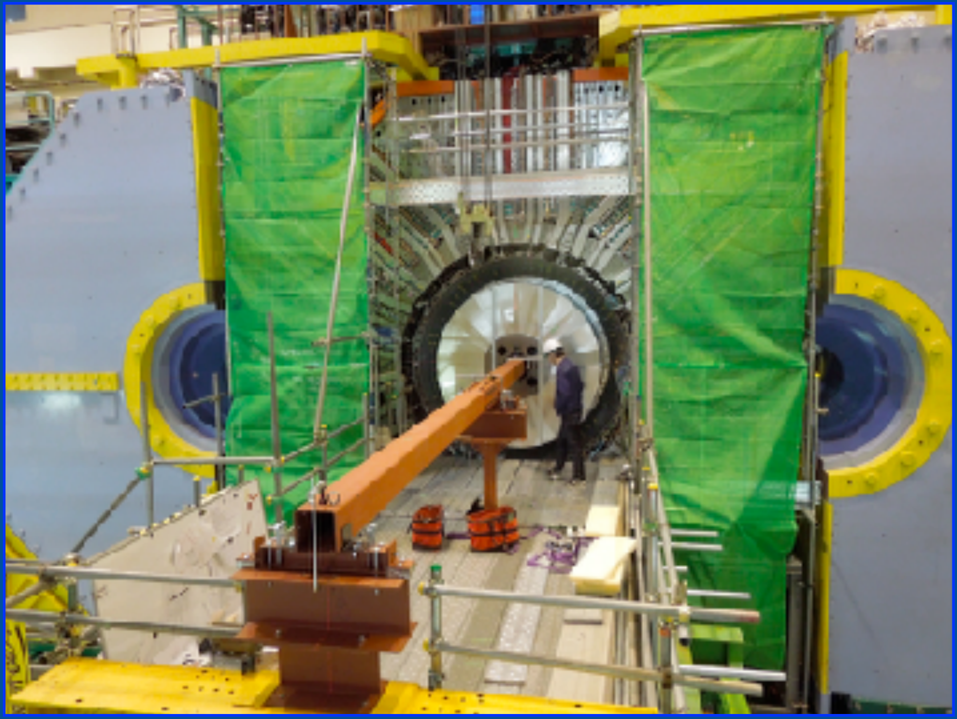


Belle II: Searching for New Phenomena at the Intensity Frontier

https://www.facebook.com/belle2collab
https://twitter.com/belle2collab

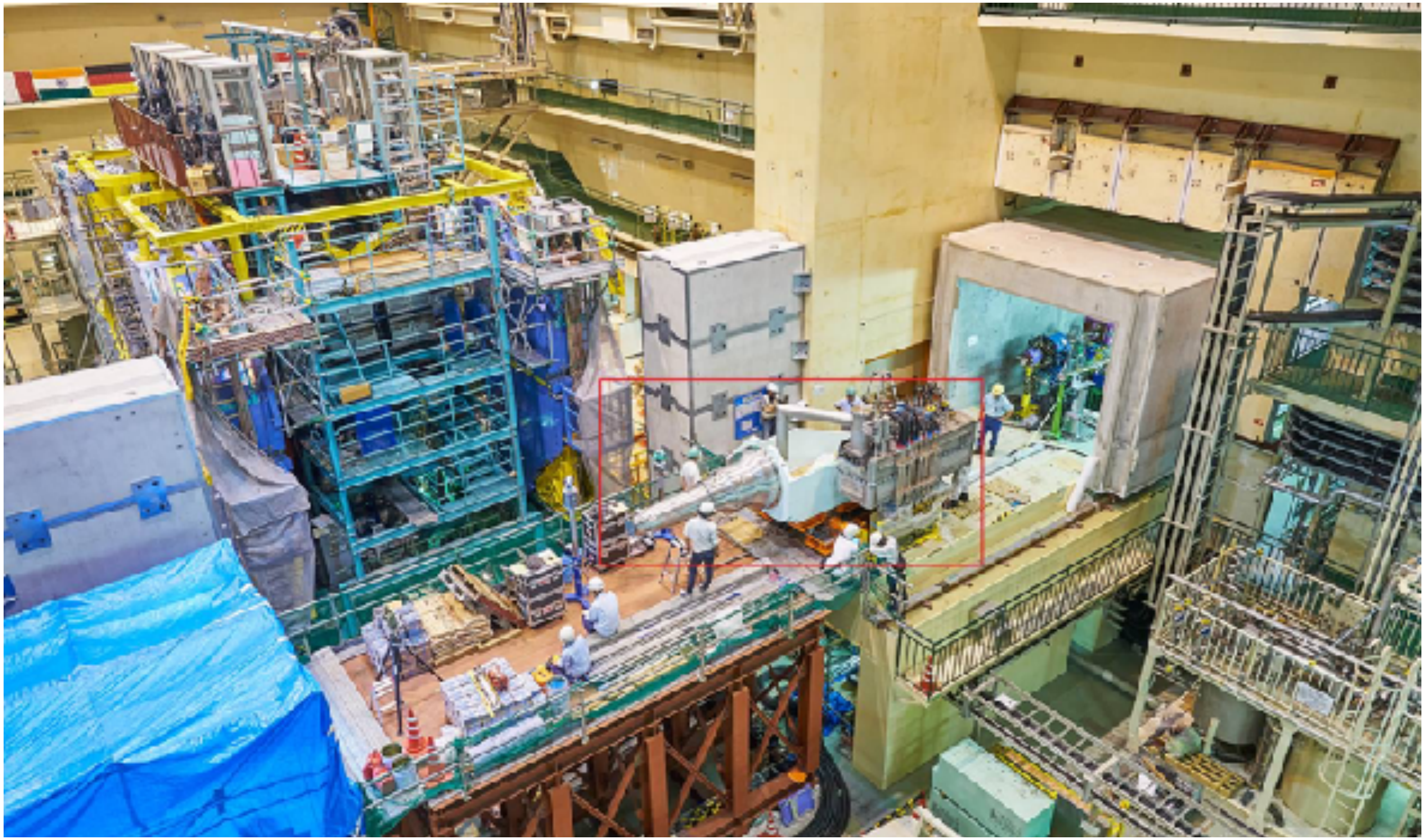
Phillip Urquijo
ARC Future Fellow
The Uni. of Melbourne

LAL Seminar
December 2016

Belle II Mission

To search for new phenomena that may solve the missing antimatter puzzle

Builds on 2008 Nobel Prize success, M Kobayashi and T Maskawa , **→ Belle experiment credited ~500 publications.**



Belle II >600 collaborators, 100 institutes

The case for new physics manifesting in Belle II

Issues (addressable at a Flavour factory)

→ NP beyond the direct reach of the LHC

- Baryon asymmetry in cosmology
  → New sources of CPV in quarks and charged leptons
- Finite neutrino masses
  → Tau LFV.
- Quark and Lepton flavour & mass hierarchy
  → higher symmetry, massive new particles, extended gauge sector
- 19 free parameters
  → Extensions of SM relate some, (GUTs)
- + Puzzling nature of exotic "new" QCD states.

In this talk I will highlight areas where Melbourne in particular has been contributing.

Australian Contributions to Belle II

Adelaide
Melbourne
Sydney

~30 Australian collaborators

Hardware

SVD Construction
L1 Trigger
Test-beams
Monitoring
DAQ/HLT

Computing

Grid services
Analysis computing
Reconstruction
Calibration

Physics

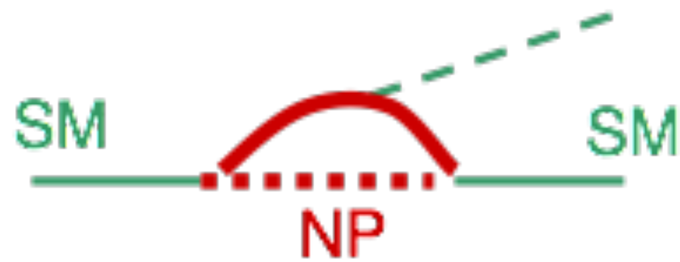
Coordination
Rare B decays
Semileptonic
B CP violation
Dark sector
τ flavour

Searches for New Phenomena

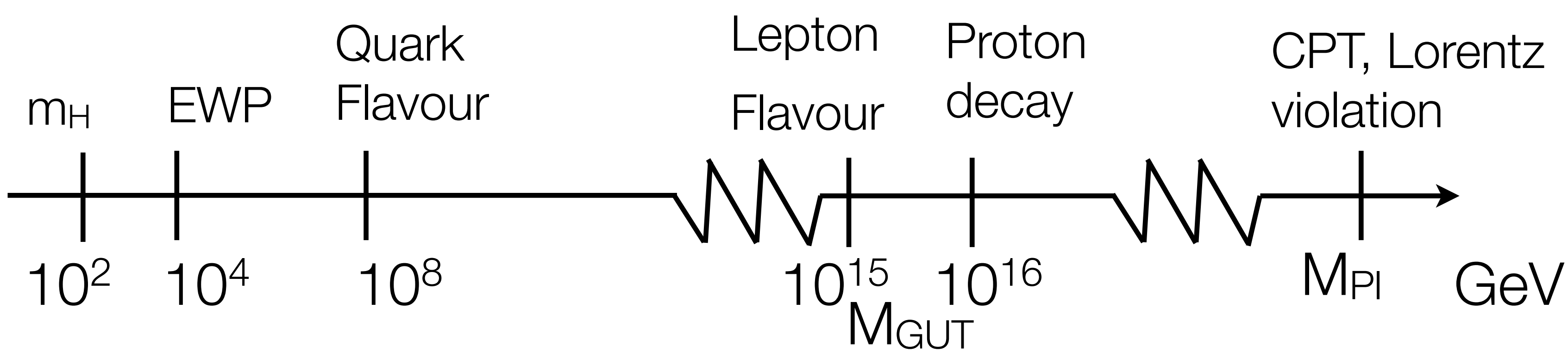
- **Energy Frontier**: Production of **new particles** from *collisions* at high-***Energy*** (**LHC**)
  - *Limited by Beam energy*

- **Flavour Frontier**: **virtual production** to probe *scales* beyond energy frontier.
  - Often **first clues** about NP
  - e.g. **weak force**,

c, b, t quarks, Higgs boson.



Maximum Energy/Mass Scale reach:



Searches for New Phenomena

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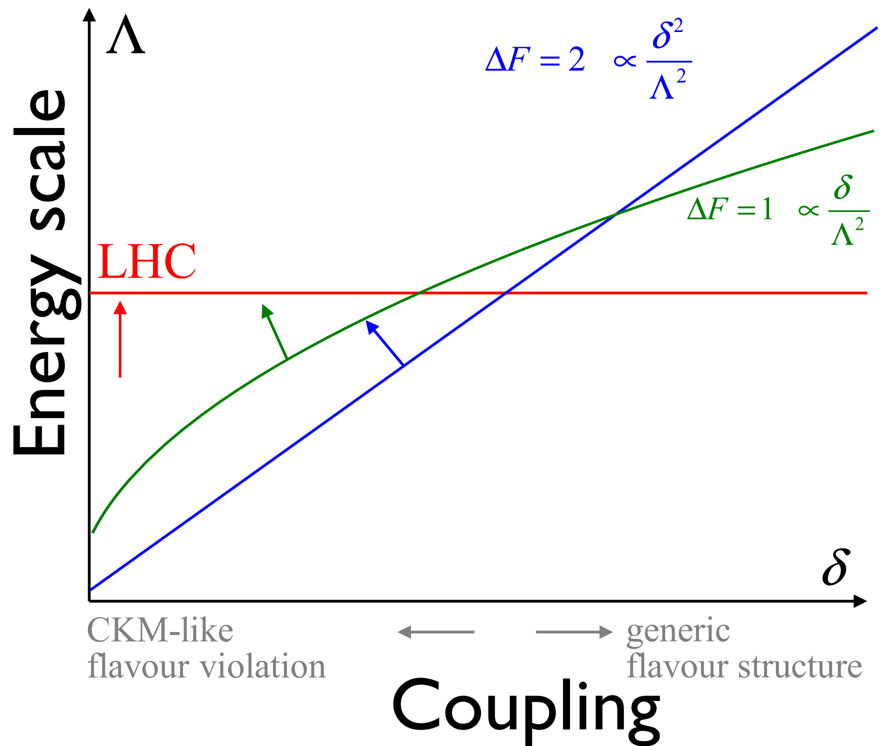
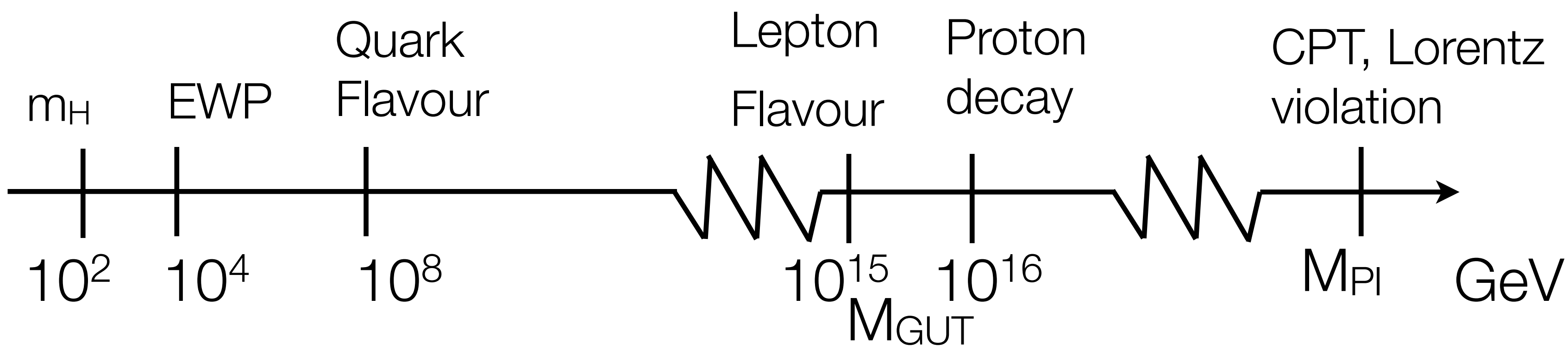


Maximum Energy/Mass Scale reach:



Cabibbo-Kobayashi-Maskawa matrix

$$\mathcal{L}_W \sim g V_{ij} \bar{u}_{Li} d_{Lj} W^-$$

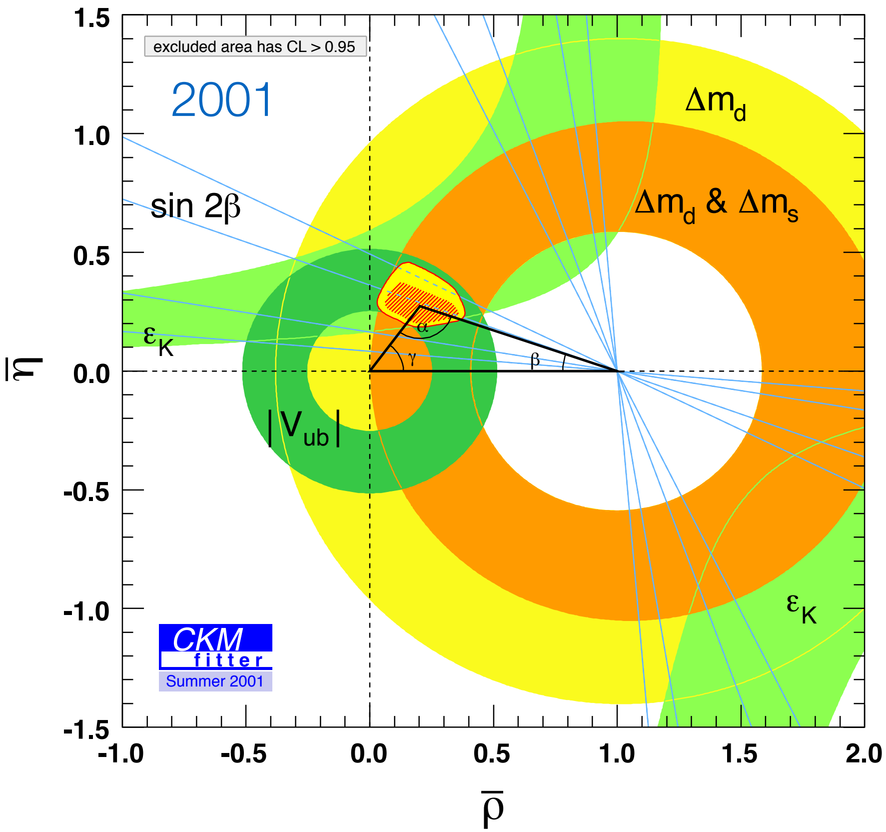
$$\mathbf{V}_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

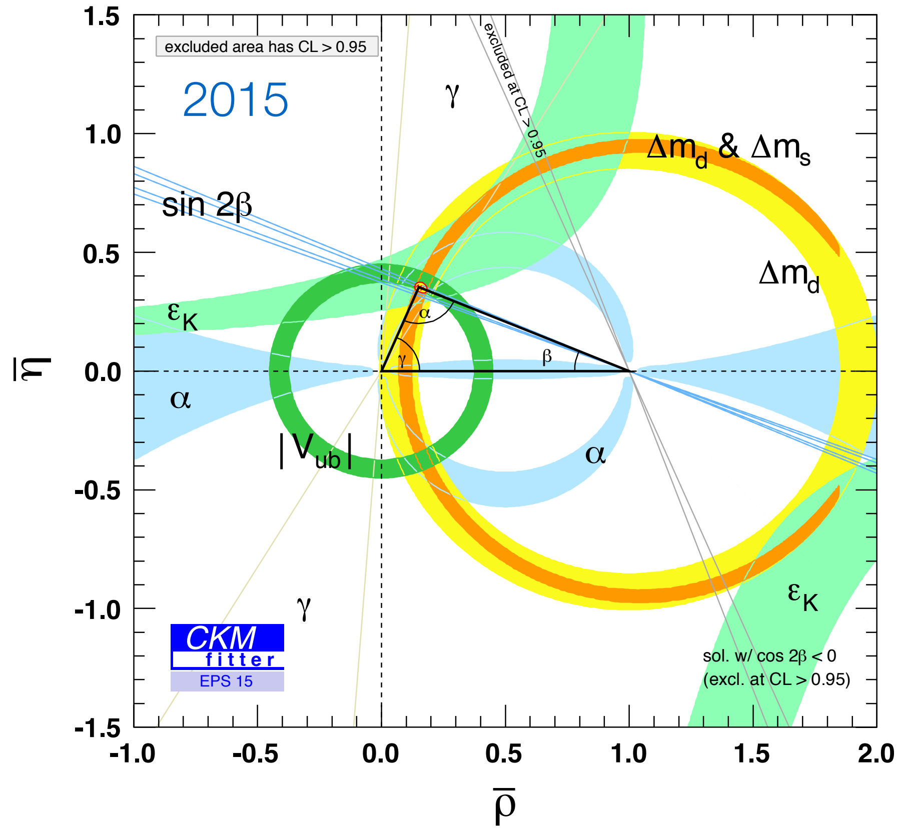
Maskawa & I (2015)

- 2 Gens: CP **conserving**
- 3 Gens: CP **violating,only source of CPV in SM**
- **4 Gens or More Gauge Bosons → many more CPV phases.**

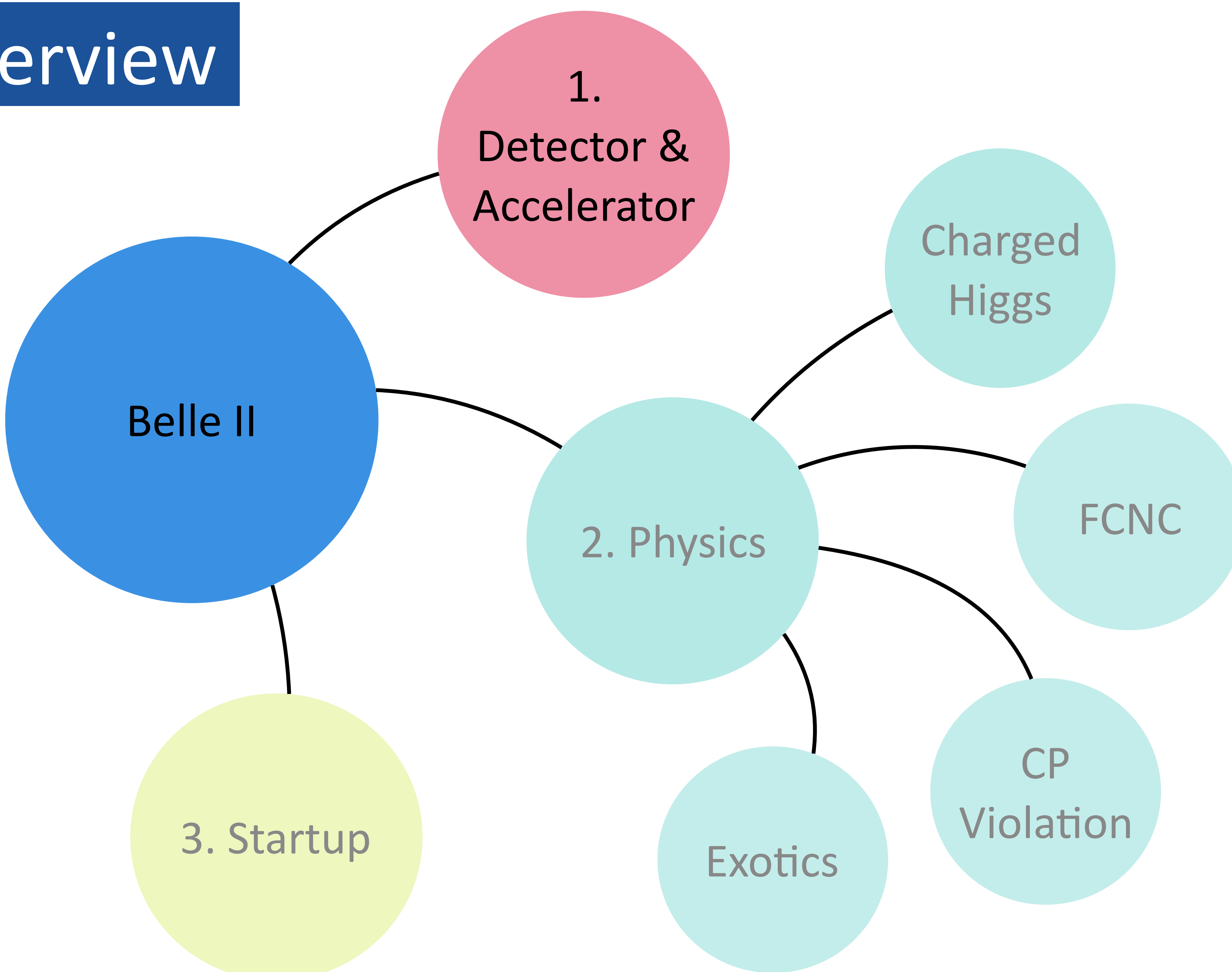
CKM Picture over the years

- Existence of CPV phase established in 2001 by BaBar & Belle
  - Picture still holds 15 years later, constrained with remarkable precision
  - But: still leaves room for new physics contributions

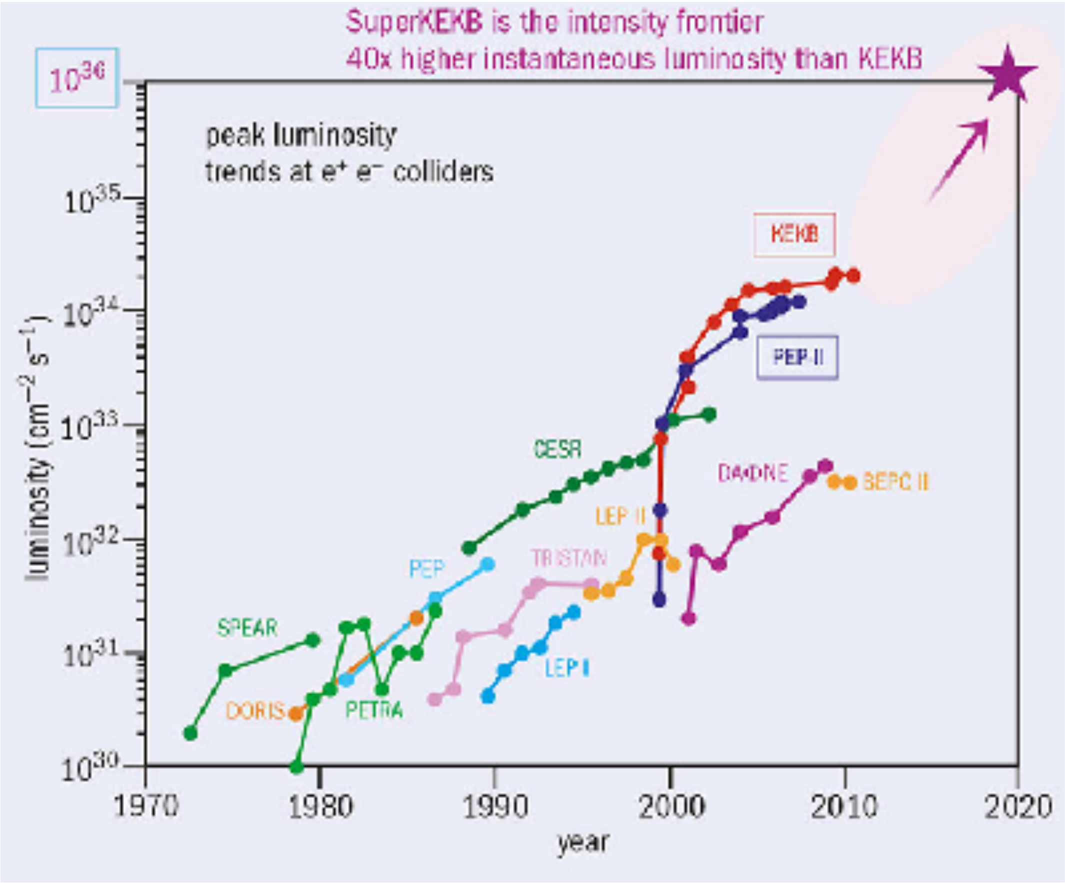


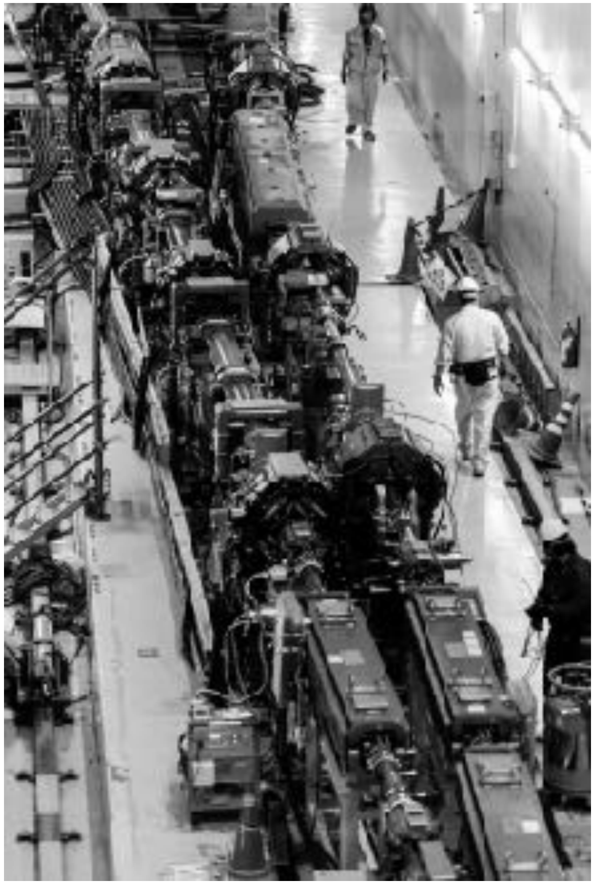


Overview


1.
Detector &
Accelerator
Belle II
Charged
Higgs
2. Physics
FCNC
3. Startup
Exotics
CP
Violation

Belle II at the e⁺e⁻ intensity frontier





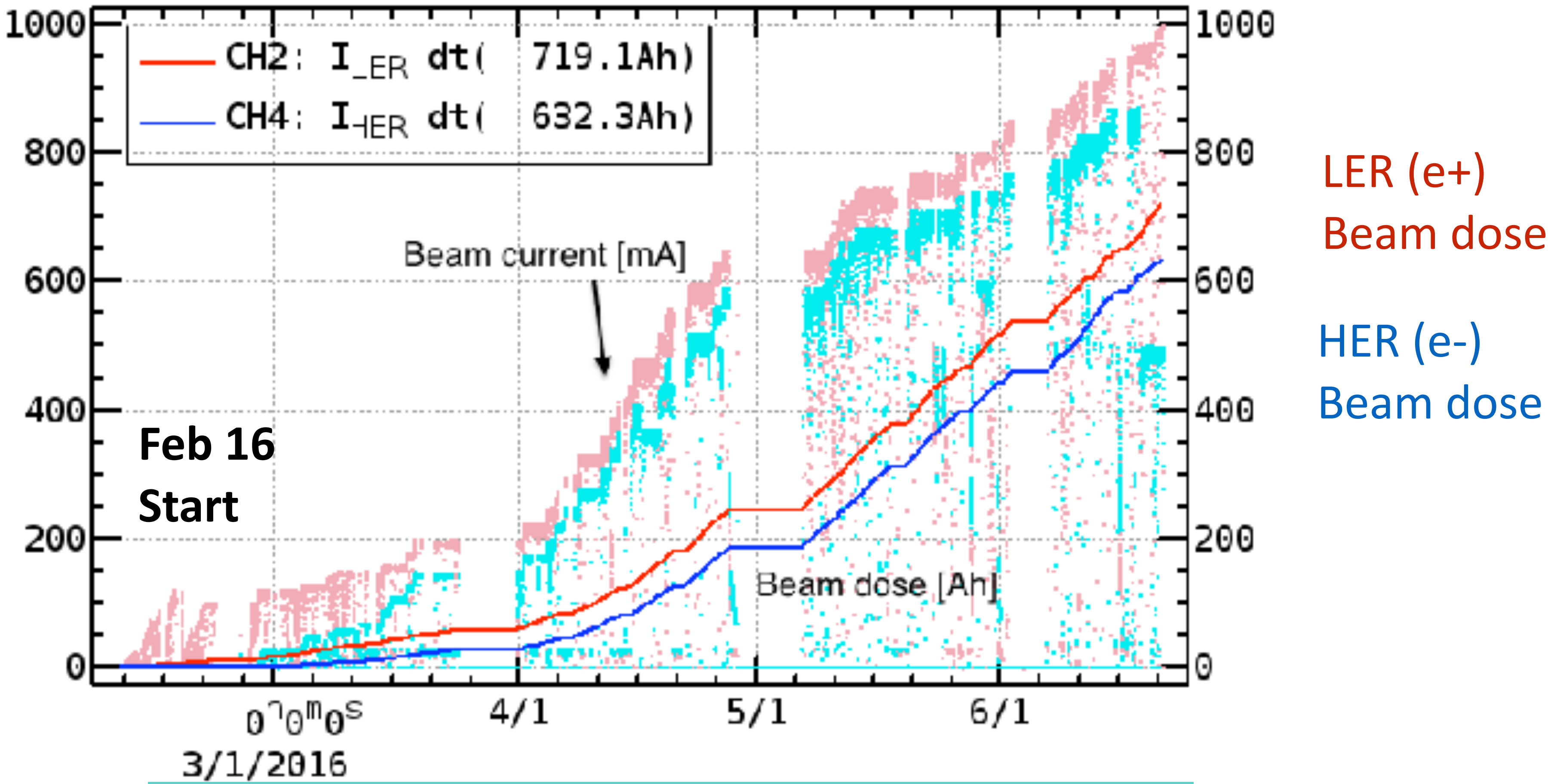
$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm\,\zeta_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

Lorentz factor; beam current; beam-beam parameter; beam size aspect ratio; vertical β function; geometric factors

- Compared to KEKB
  - 20x smaller vertical beam size
  - 2x current

First operation of SuperKEKB (4 GeV e+'s & 7 GeV e-'s)

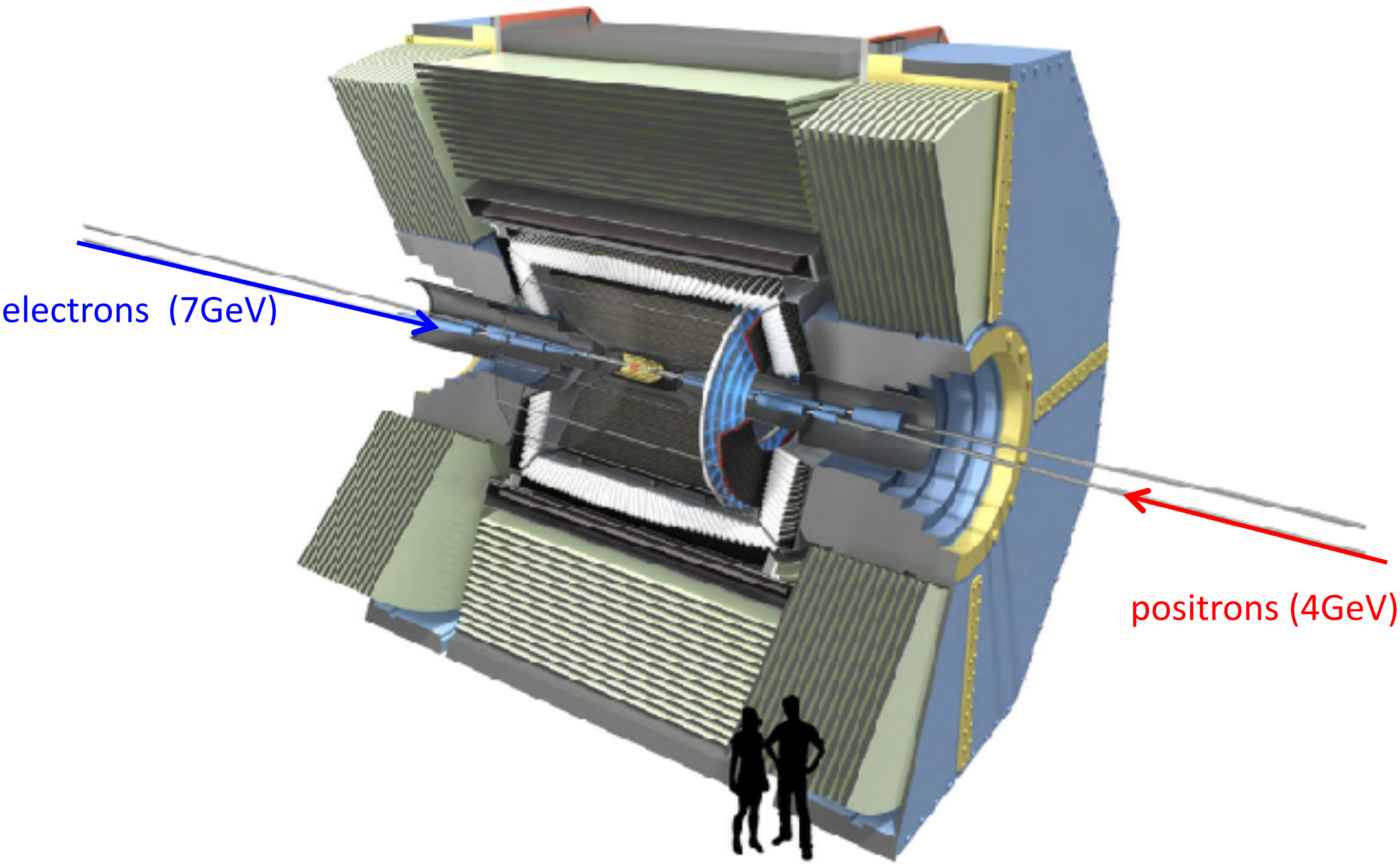
- LER: Beam current 1 Amp, Beam dose 780 Ah, pressure 10^{-6} Pa
- HER: Beam current 0.87 Amp, Beam dose 660 Ah pressure 10^{-7} Pa



5 Months operation

Belle II Detector [600+ collaborators, 101 institutes, 23 nations]

Belle II TDR, arXiv:1011.0352



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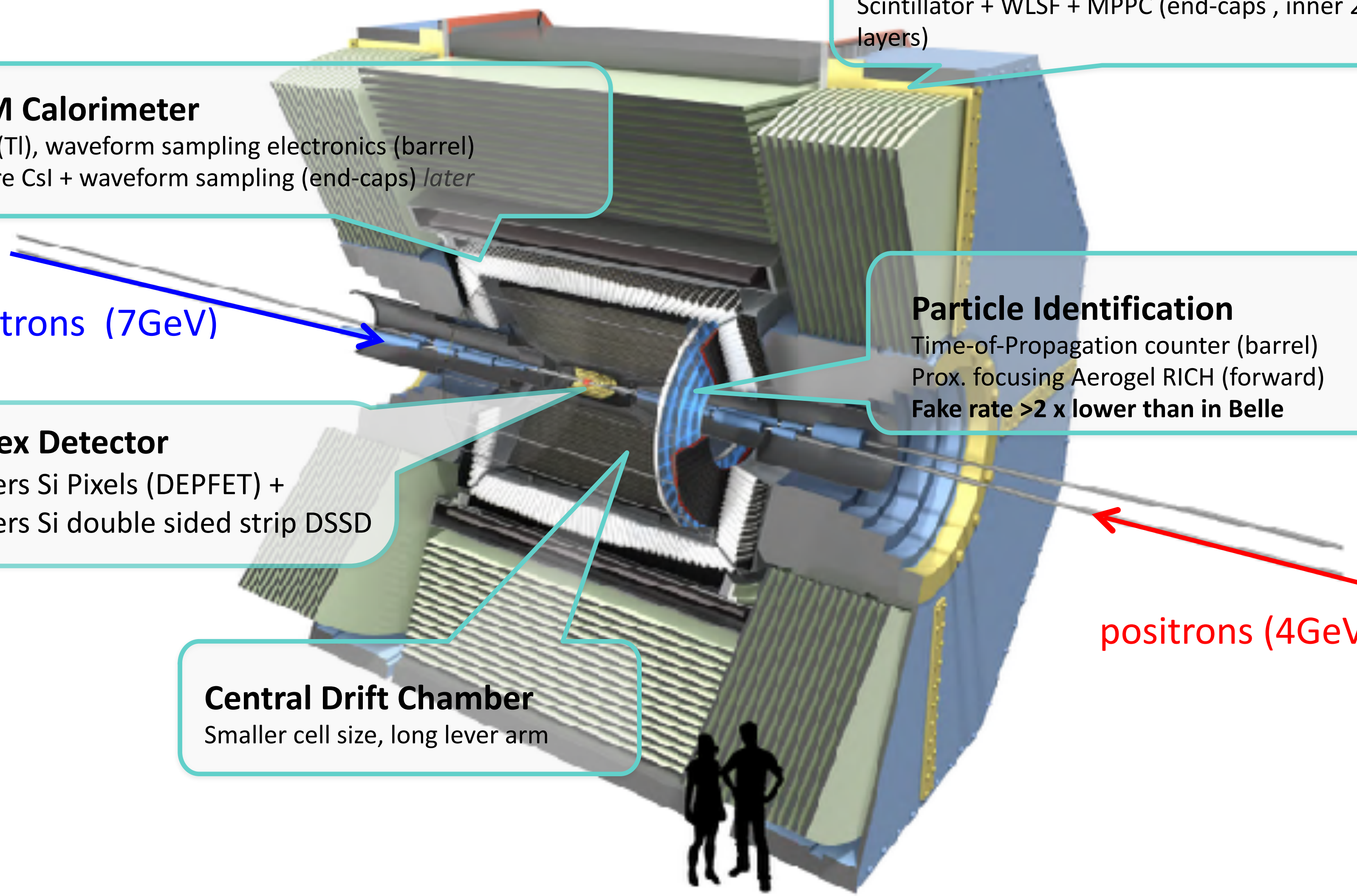


KL and muon detector
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps , inner 2 barrel layers)

EM Calorimeter
CsI(Tl), waveform sampling electronics (barrel)
Pure CsI + waveform sampling (end-caps) *later*

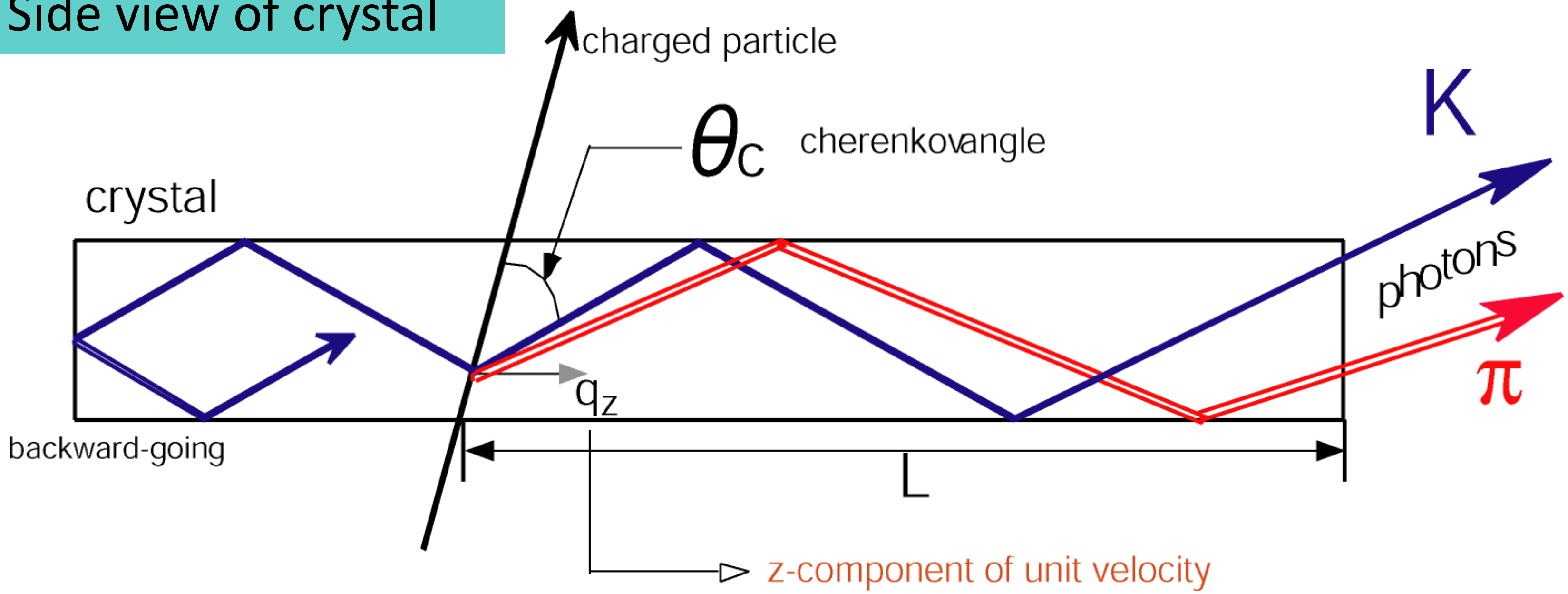
Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (forward)
Fake rate >2 x lower than in Belle

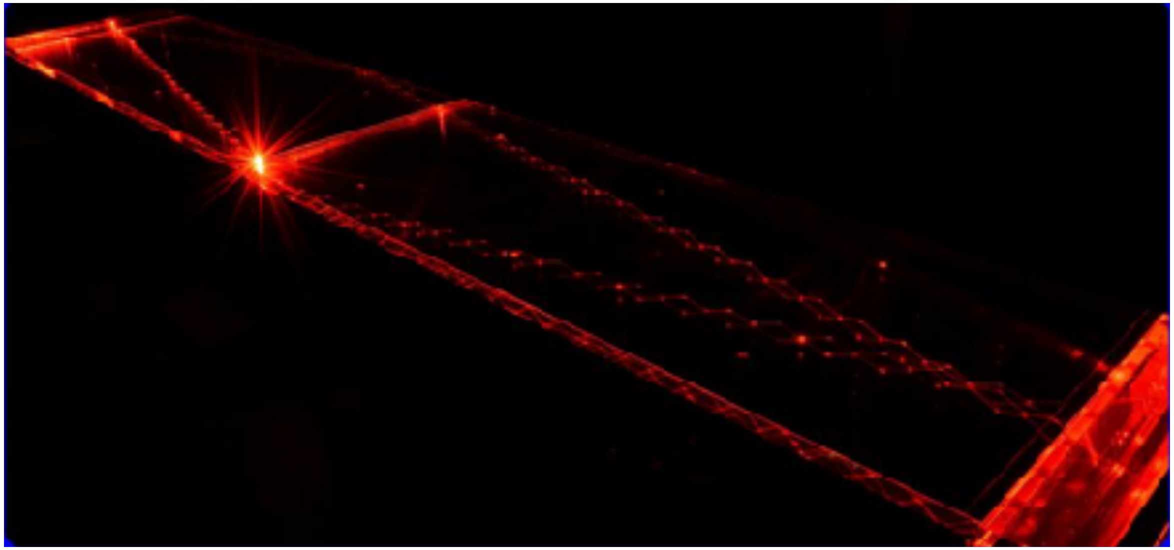
Vertex Detector
2 layers Si Pixels (DEPFET) +
4 layers Si double sided strip DSSD

Central Drift Chamber
Smaller cell size, long lever arm

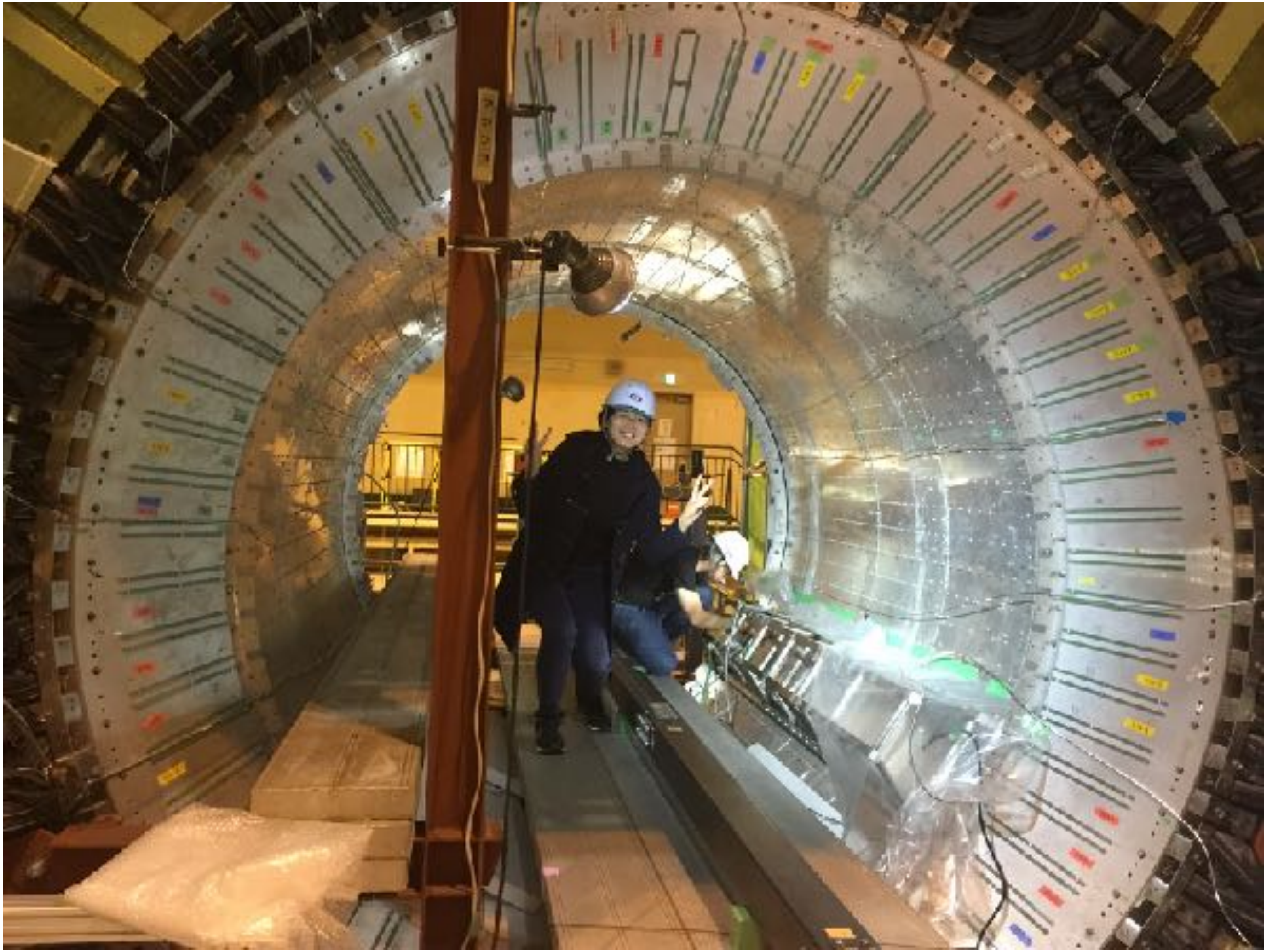
Time-of-Propagation(TOP) Detector

Side view of crystal



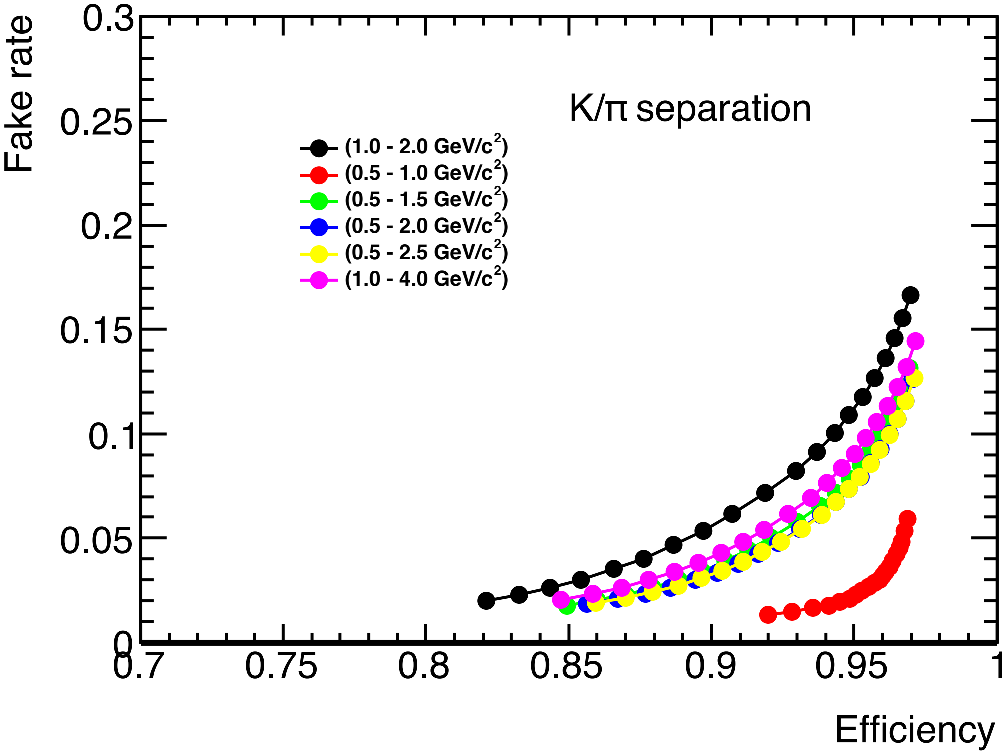


Feb: 1st TOP bar May: fully installed!

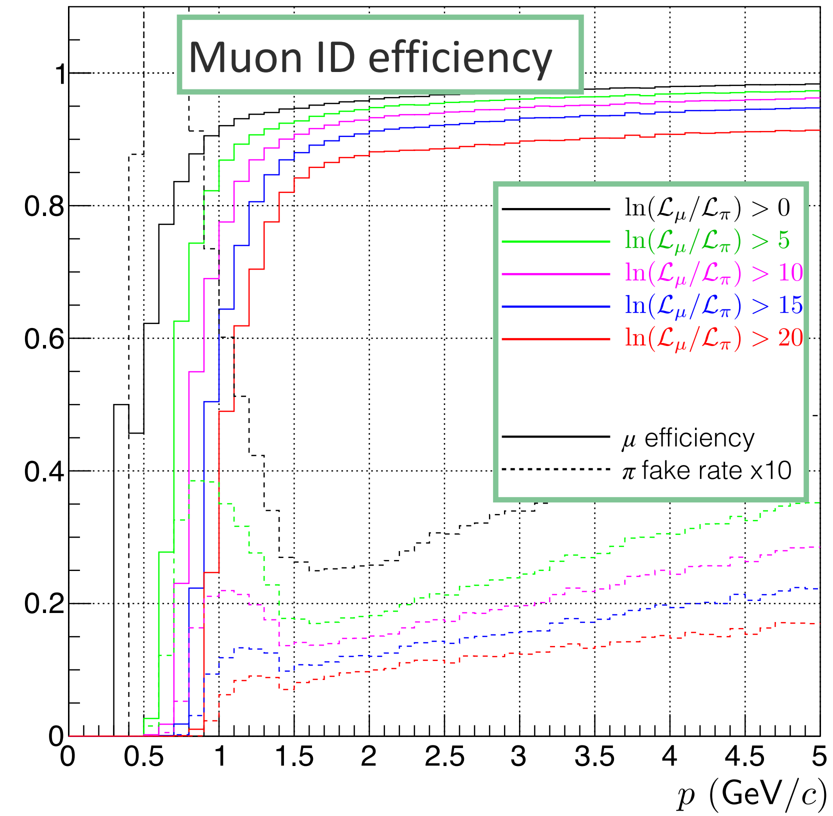


Particle Identification

(TOP, ARICH, dE/dx[CDC])

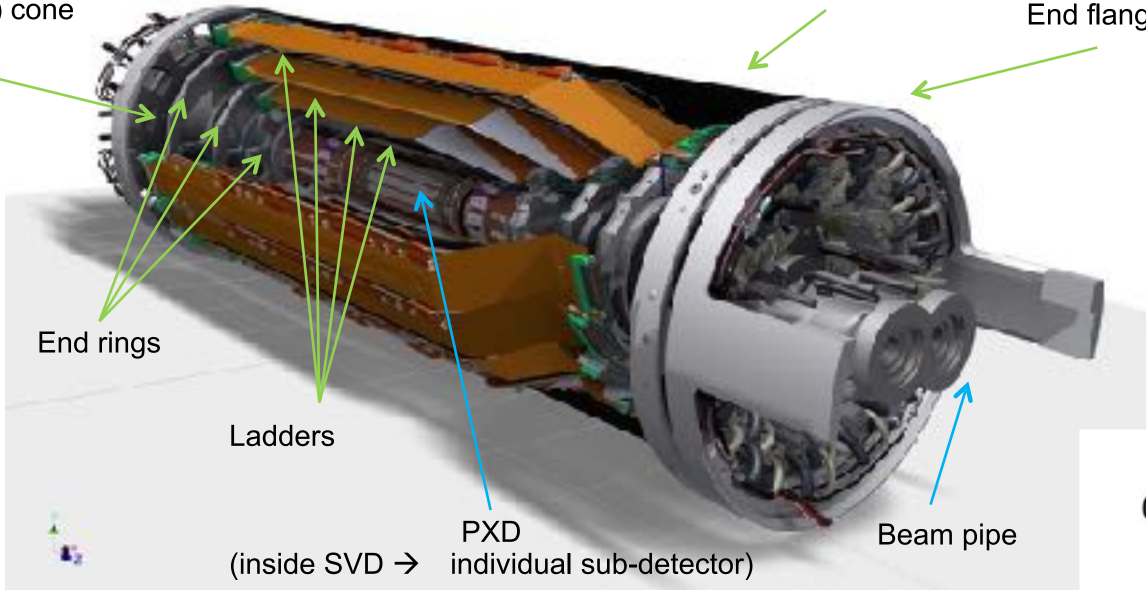


(TOP, ARICH, dE/dx[CDC], KLM)

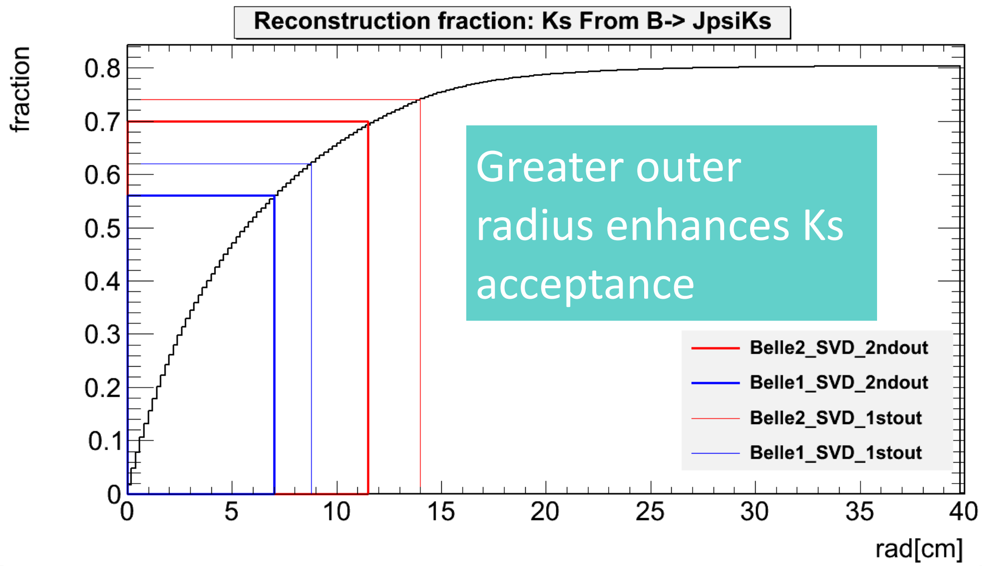


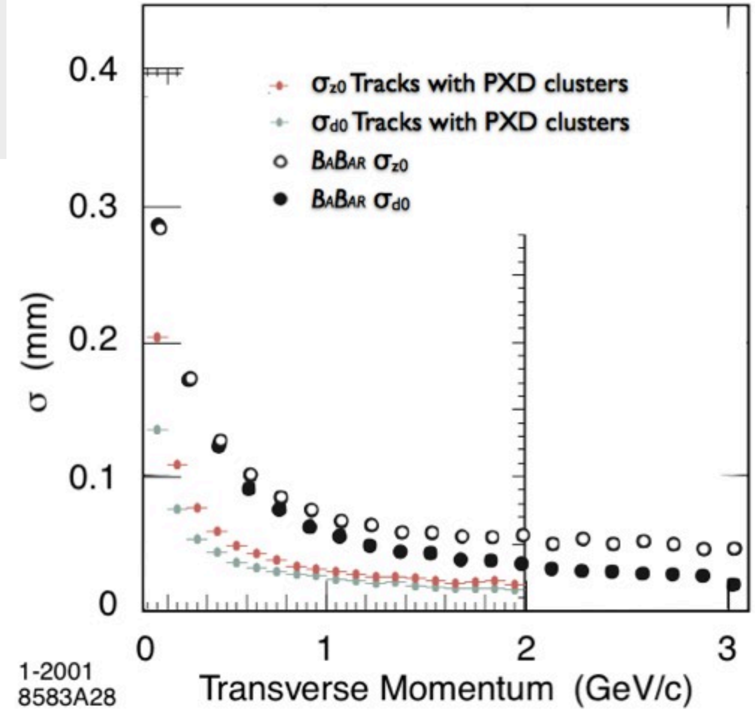
Fake rates > 2x lower than Belle (even better in some *p* regions)

Silicon Vertex Detector

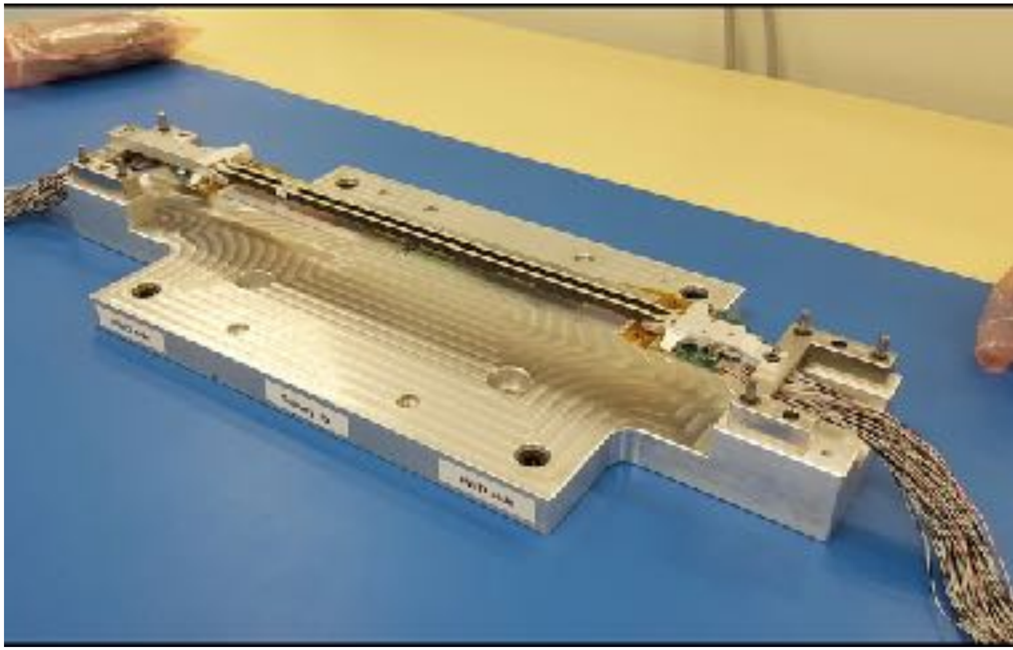


IP resolution much better than Belle & Babar

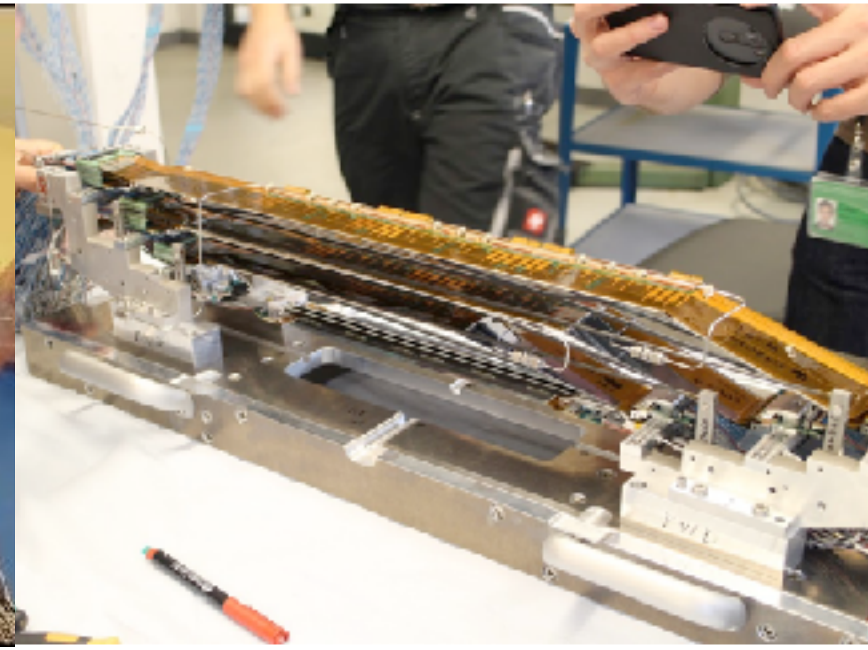




SVD Layer 3 Construction, All ladders now built



Construction @ Melbourne



April 2016: DESY testbeam
2 *full-sized* Belle II pixel modules

So when do we start Belle II ?

BEAST PHASE I:
Feb-June 2016
(Belle II roll-in in March 2017).

PHASE II Operation: Starts in ~Jan 2018
[Begin with damping ring commissioning; First collisions; *limited physics without vertex detectors*]

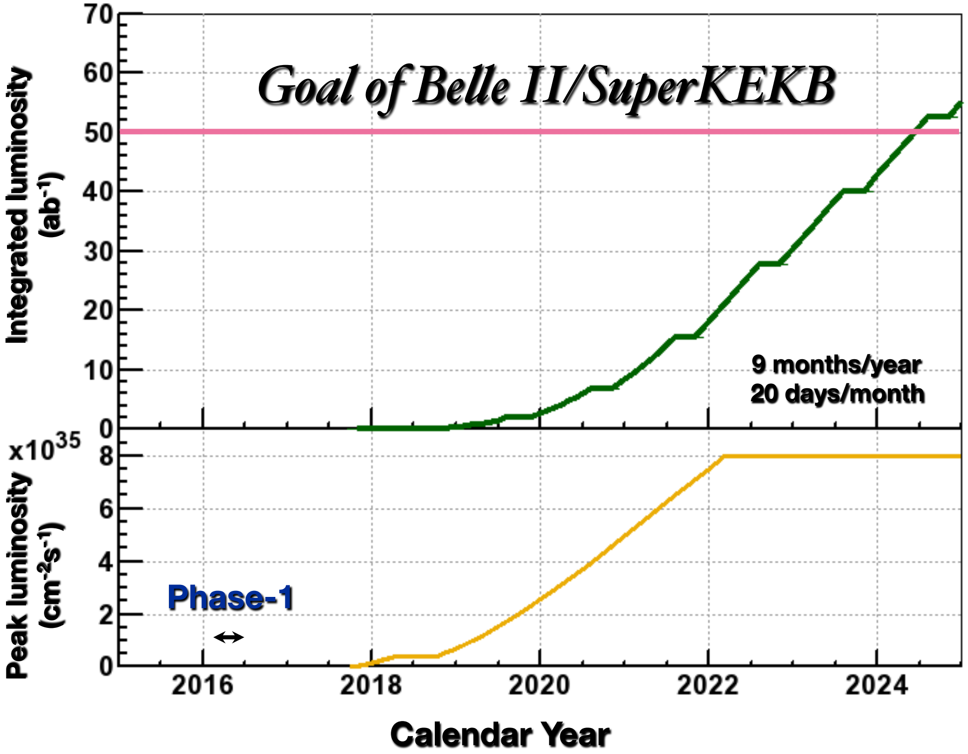
Phase III: Belle II Physics Running:
late 2018 [vertex detectors in]

QCSL at the IP, Aug 2016

QCSR will be at KEK, Dec 2016

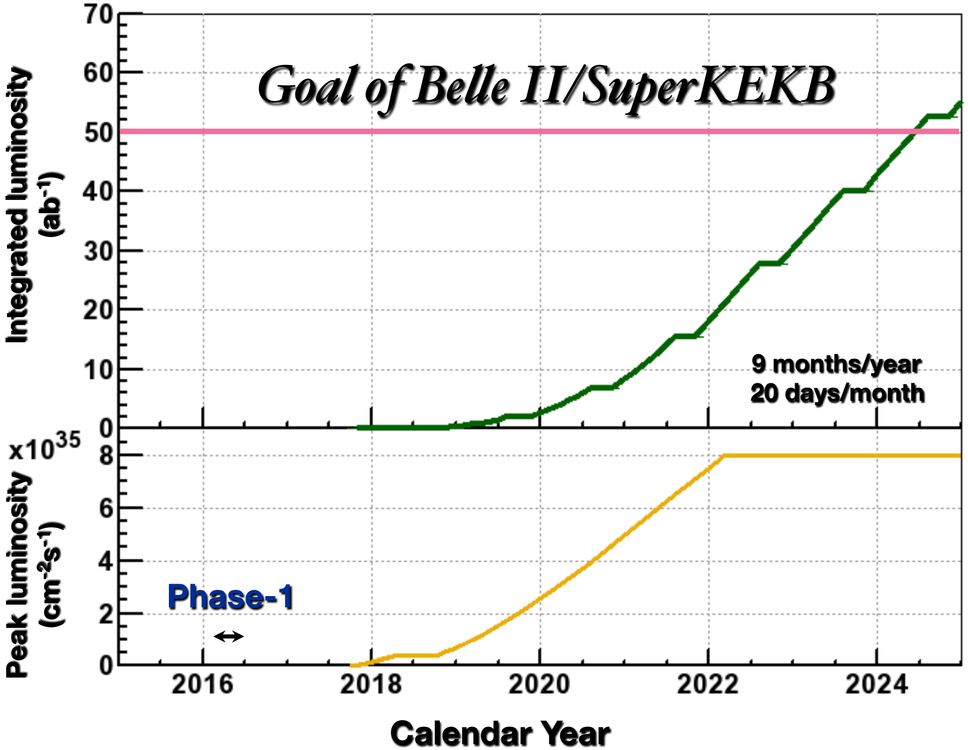
Latest SuperKEKB Luminosity Profile

PU, j.nuclphysbps 263–264 (2015) 15–23



LHC era		HL-LHC era		
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2020-22)	Run 4 (2025-28)	Run 5+ (2030+)
3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	100 fb^{-1}

Latest SuperKEKB Luminosity Profile



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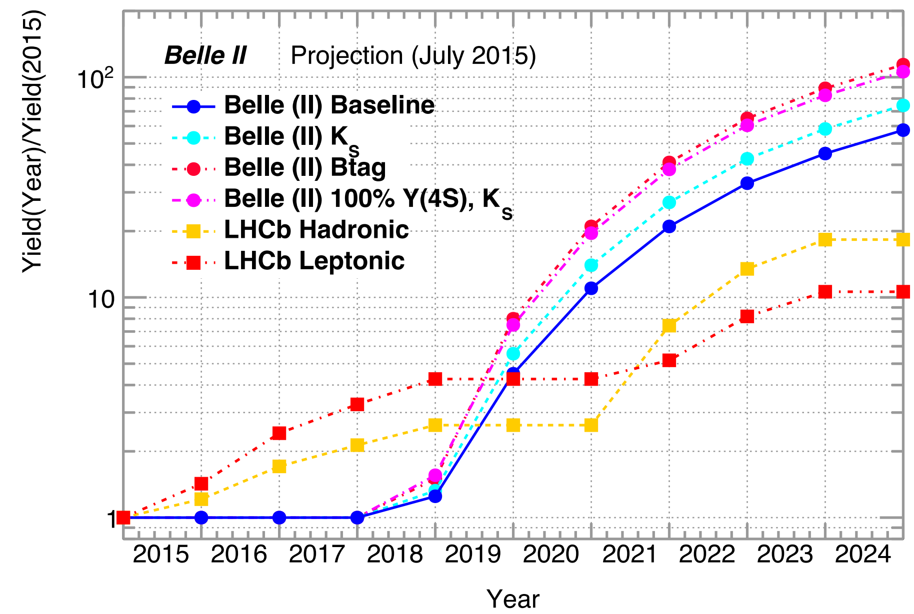

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Doing physics in an e+e- collider

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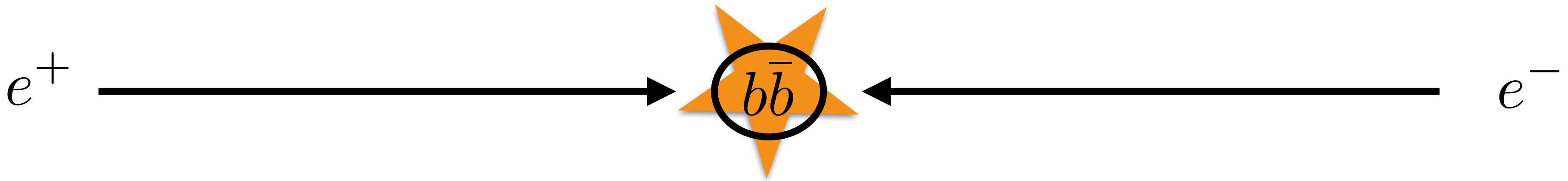
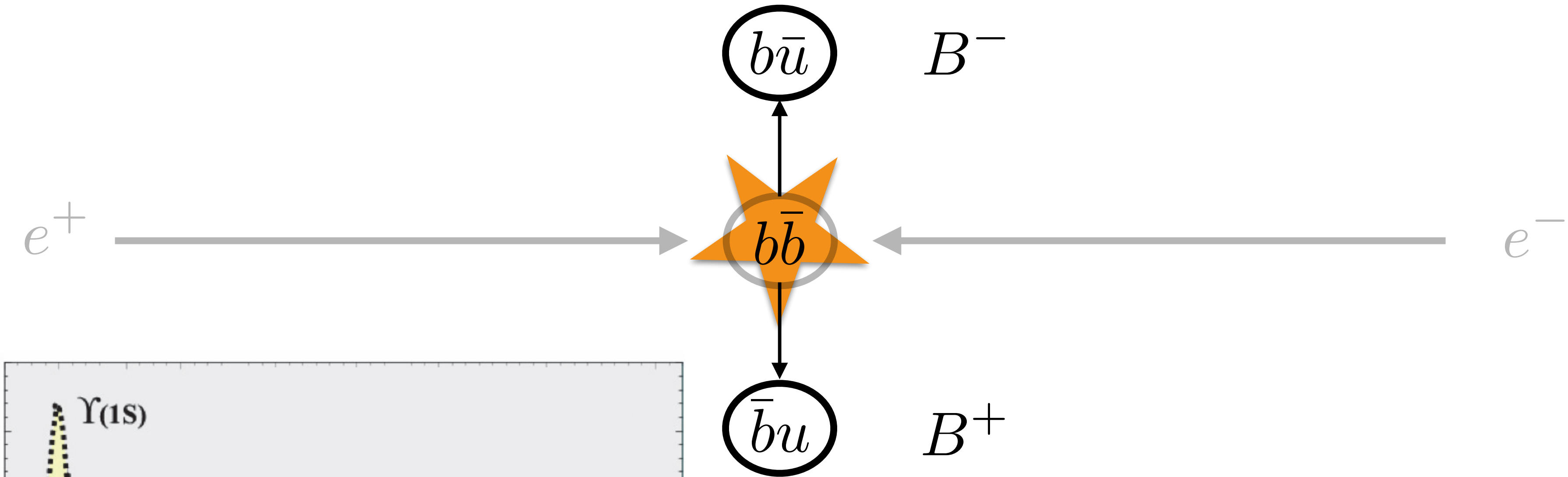
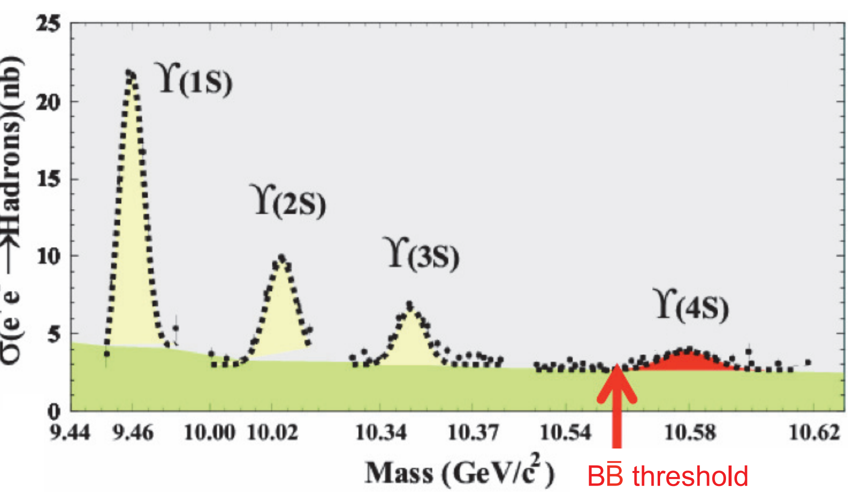


Doing physics in an e+e- collider

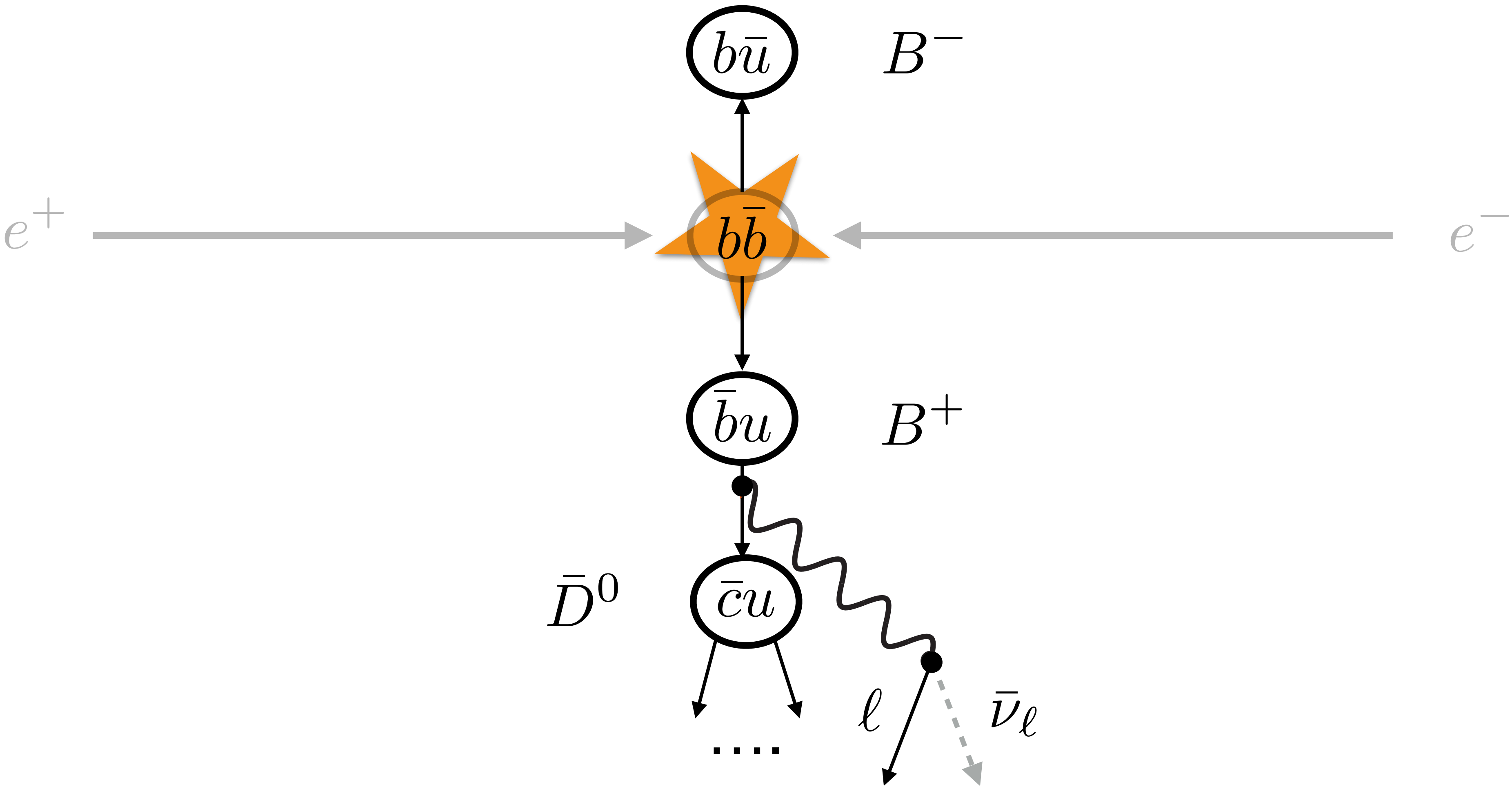




$$\Upsilon(1S) = \langle b\bar{b} \rangle$$

$$\Upsilon(4S) = \langle b\bar{b} \rangle$$

Doing physics in an e+e- collider



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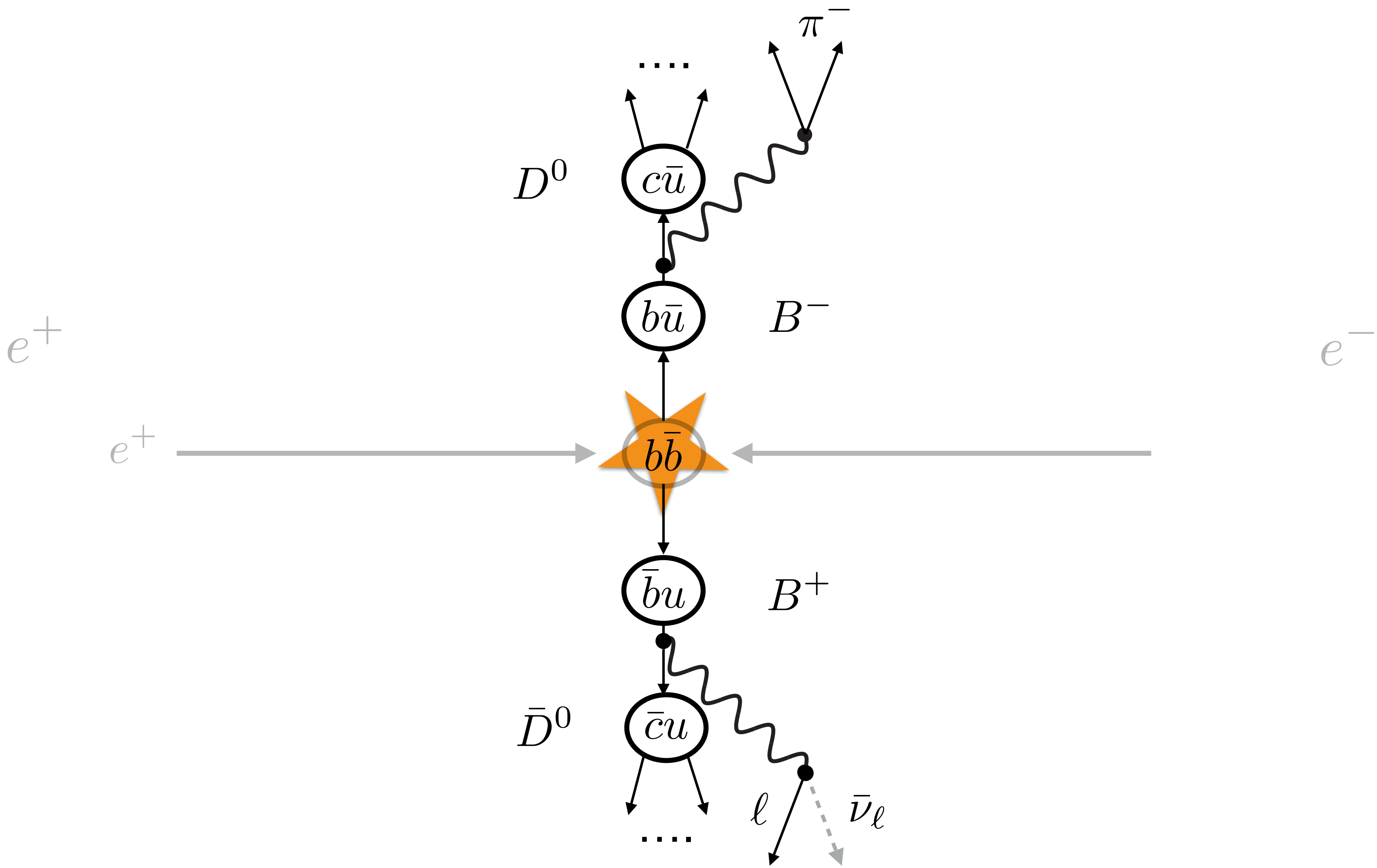
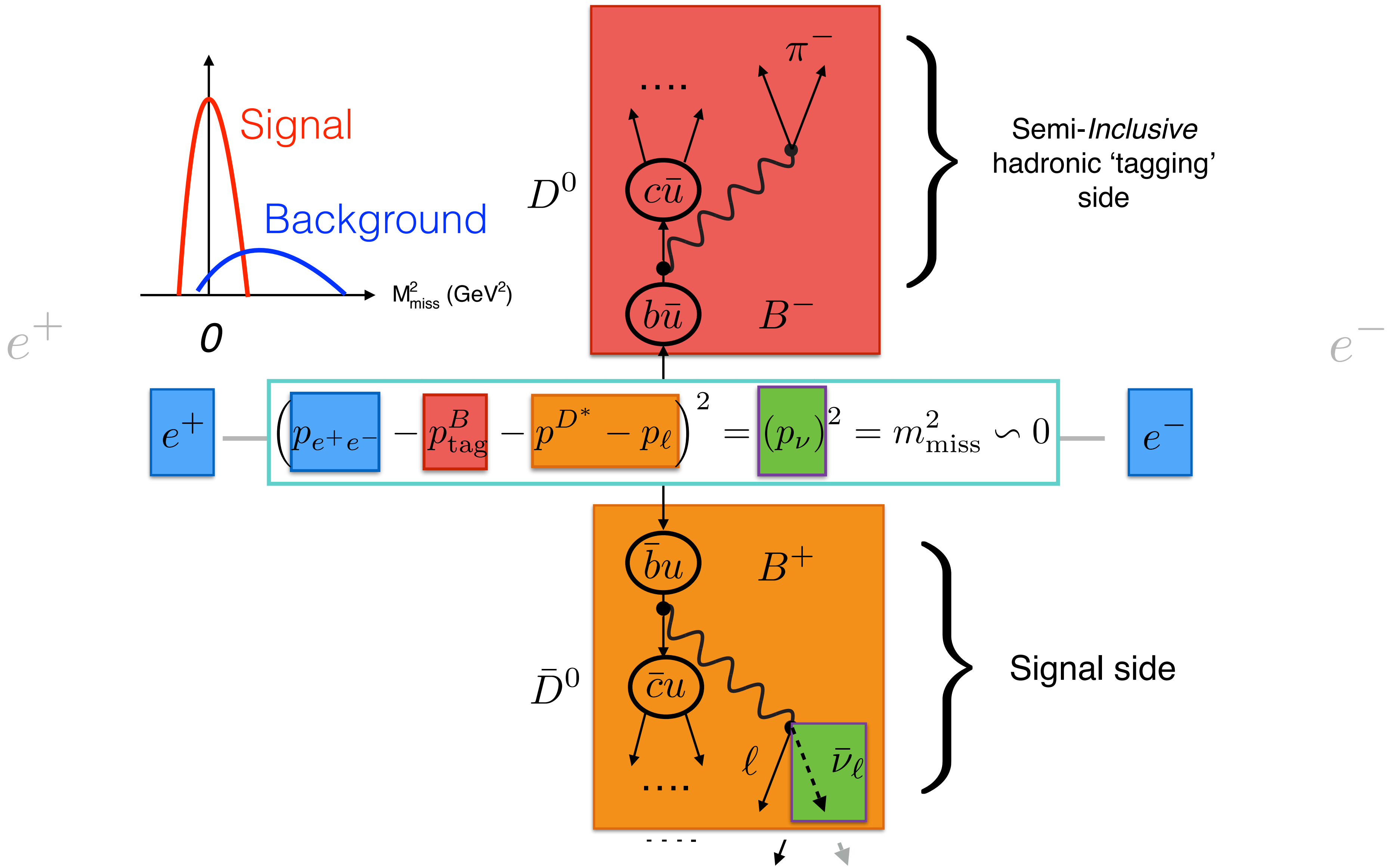


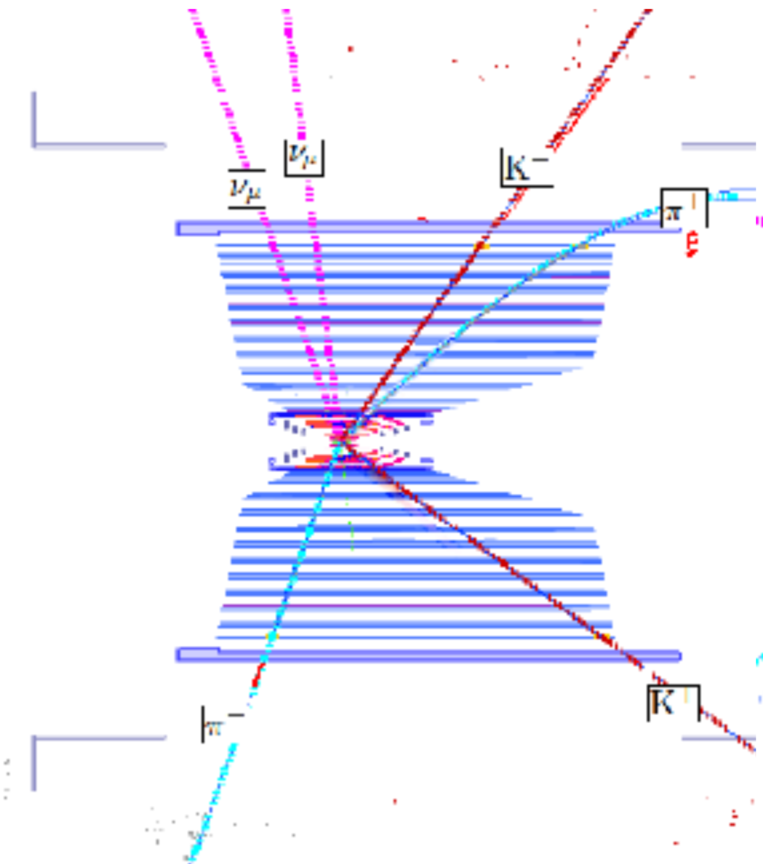
Doing physics in an e+e- collider



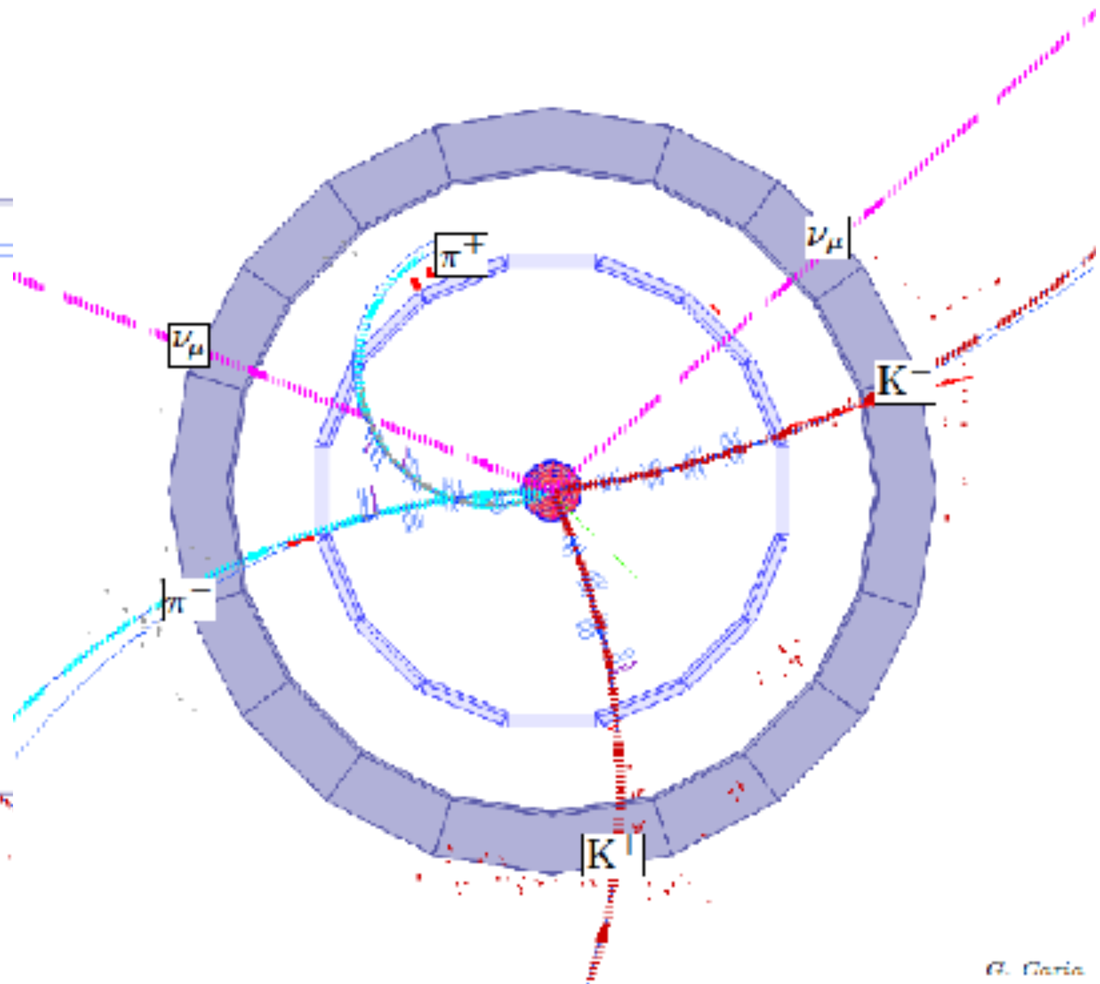
"Missing Energy Decay" in a Belle II GEANT4 simulation

Signal B→ K ν ν   tag mode: B→ Dπ; D→ Kπ

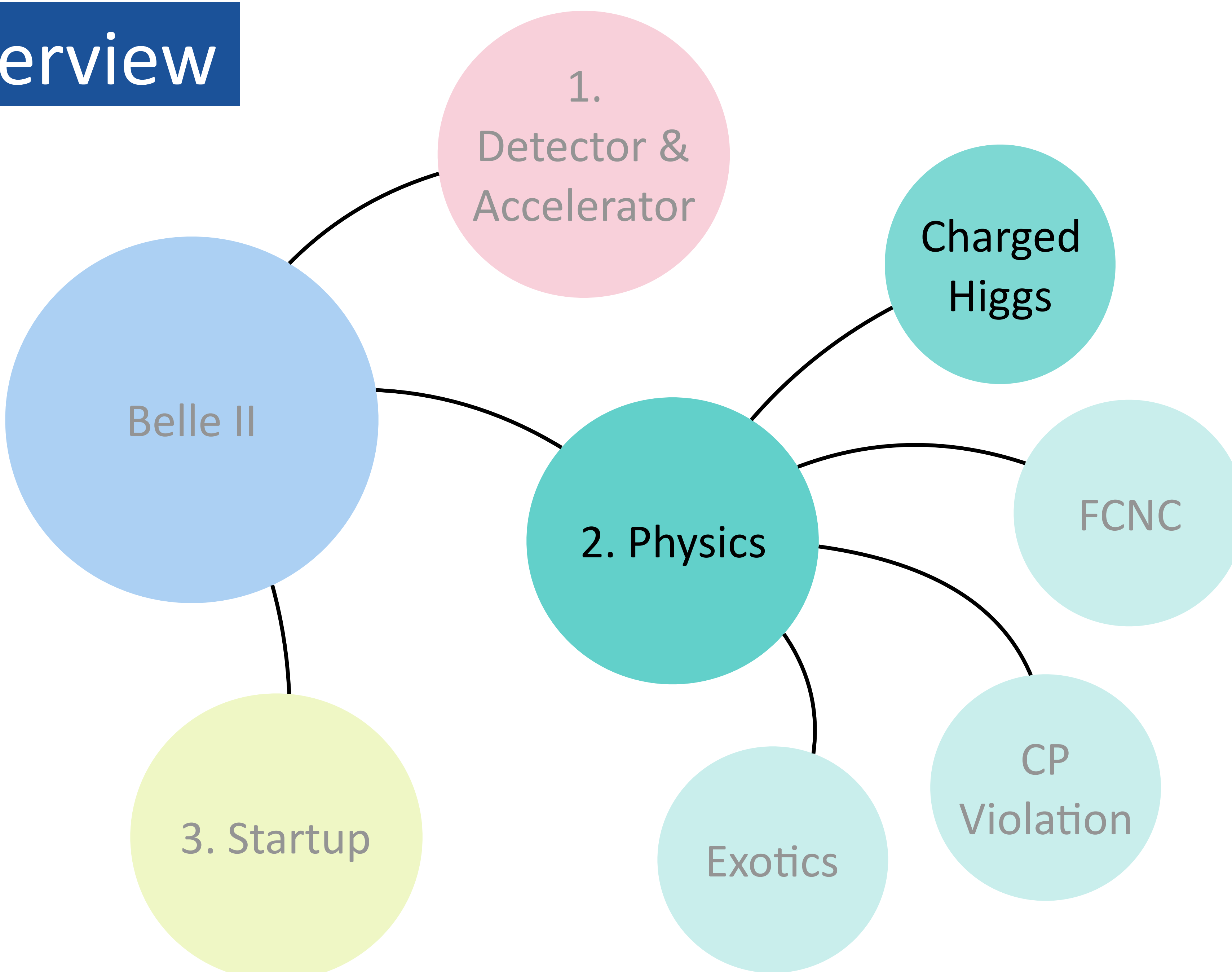
View in r-z



Zoomed view of the vertex region in r--phi



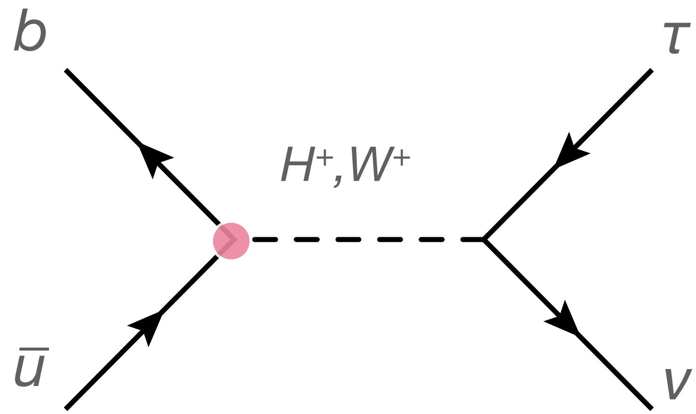
Overview


1.
Detector &
Accelerator
Charged
Higgs
Belle II
2. Physics
FCNC
3. Startup
CP
Violation
Exotics

Belle II Flagship: H^+ Search in $B^+ \to \tau\nu, \mu\nu$

Belle, $B \to \tau\nu$ (Had) PRL110 131801 (2013)
Belle, $B \to \tau\nu$ (SL) PRD 92, 5, 051102 (2015)

Helicity suppressed - very small in SM.
NP could interfere *e.g.* **charged Higgs.**



$$\mathrm{BR}(B_u \to \tau\nu_\tau) = \frac{G_F^2 f_B^2 |V_{ub}|^2}{8\pi} \tau_B m_B m_\tau^2 \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 \left[1 - \left(\frac{m_B^2}{m_{H^+}^2}\right) \lambda_{bb}\lambda_{\tau\tau}\right]^2$$

$\mathbf{BF_{SM}}$

$\mathbf{R_H}$

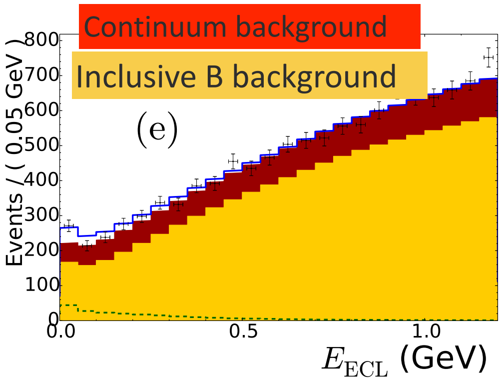
The B meson decay constant

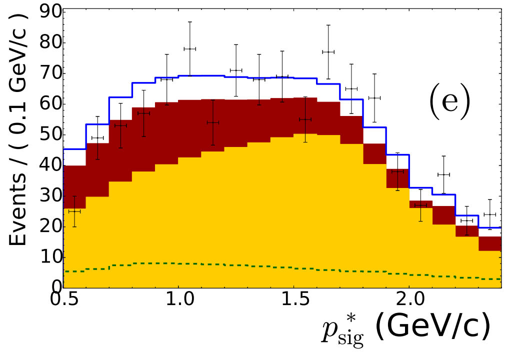
$|V_{ub}|$: from indep. measurements.

Type	λDD	λLL
I	cot β	cot β
II	- tan β	- tan β
III	- tan β	cot β
IV	cot β	- tan β

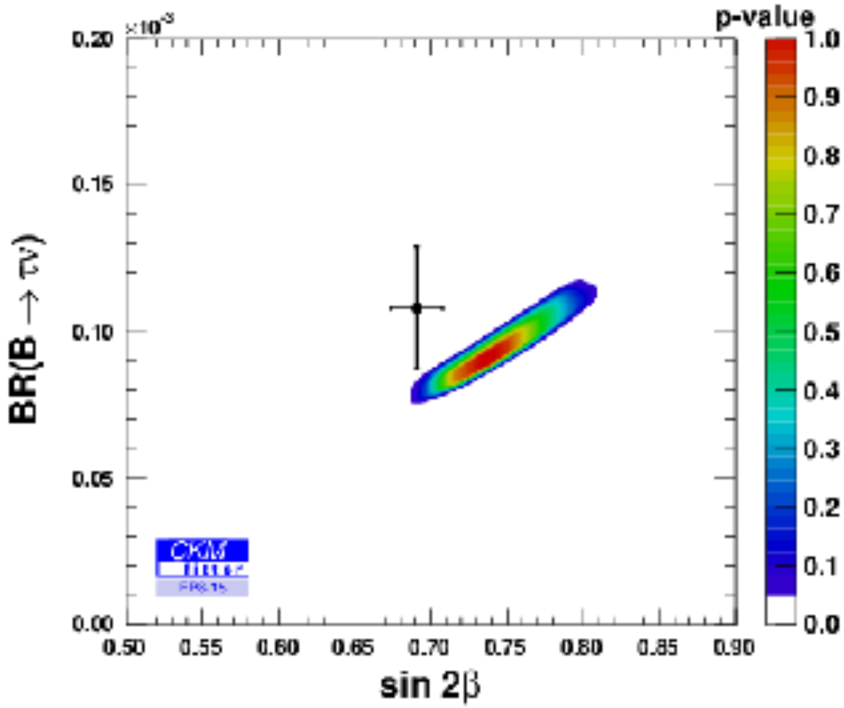
B→τ/e/μν(γ) Projections

Belle, B→ τ ν (Had) PRL110 131801 (2013)
Belle, B→ τ ν (SL) PRD 92, 5, 051102 (2015)





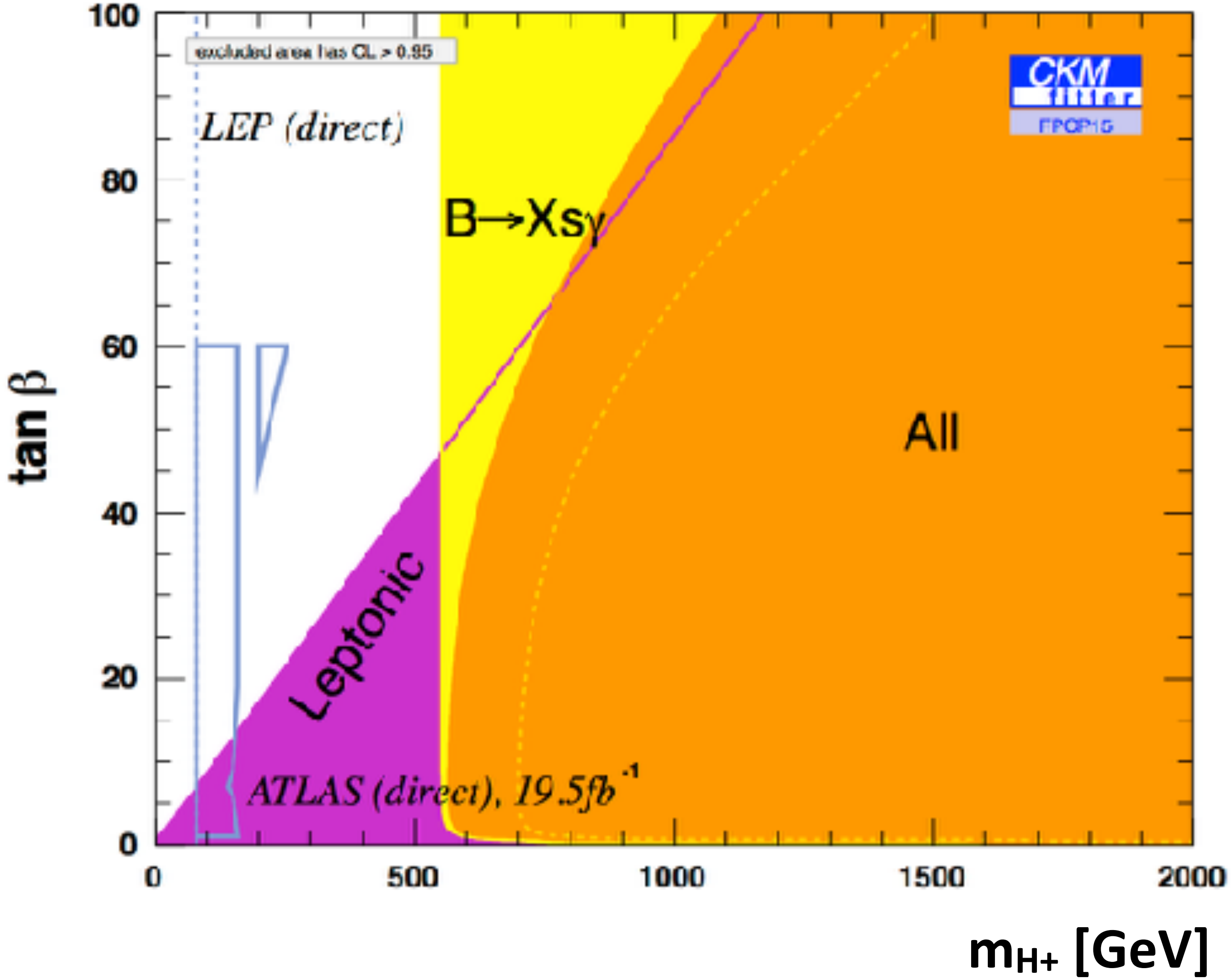
With the full B factory statistics only "evidence". No single observation from either Belle or BaBar.
Belle II → 5 σ discovery



	Belle Ave.	Belle II	
		5 ab^{-1}	50 ab^{-1}
B→τν	96(1±22%)	10%	3%
B→μν	<1.7	20%	7%

NP Fits with CKMFitter

L. Pesantez, PU, CKMFitter, 2015

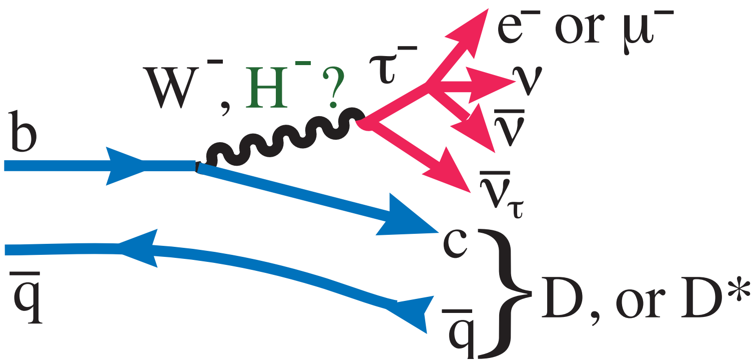


The current combined $B\to\tau\upsilon$ limit places a stronger constraint than direct searches from LHC exps. for the next few years.

Currently inclusive $b\to s\gamma$ rules out m_{H+} below ~540 GeV/c^2 range at 95% CL (independent of tanβ assuming no other NP)

Anomaly in B → D(*) τ ν

Belle, Phys.Rev.D 92, 072014 (2015)
Belle, Phys.Rev.D 94, 072007 (2016)
Belle, arXiv:1612.00529 (to PRL)



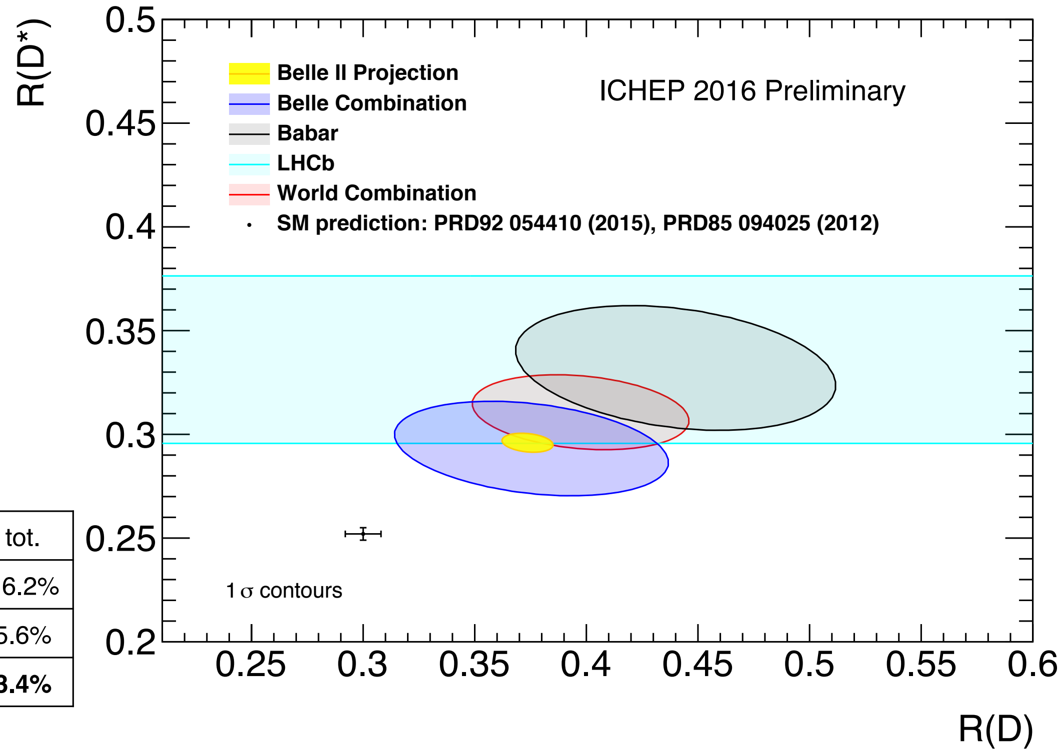
- Combination is near 4 σ from SM.
- Appears to rule out Type II 2HDM (inconsistently favoured R_D and R_{D^*})

$R(D^*)$

Error	stat.	tot.
B-Factories	7.1%	9.0%
Belle II 5/ab	2.1%	3.2%
Belle II 50/ab	0.7%	**2.1%**

$R(D)$

Error	stat.	tot.
B-Factories	13%	16.2%
Belle II 5/ab	3.8%	5.6%
Belle II 50/ab	1.2%	**3.4%**

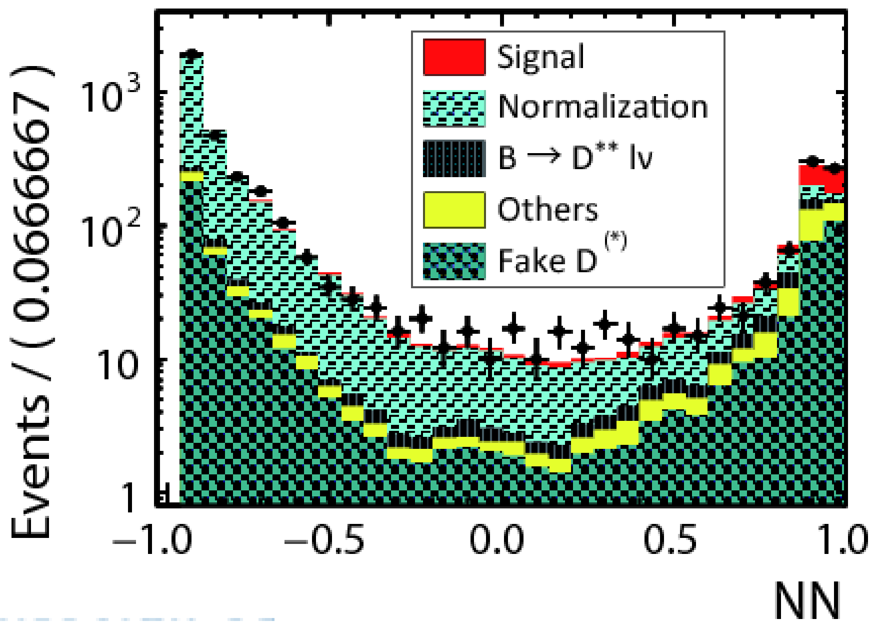


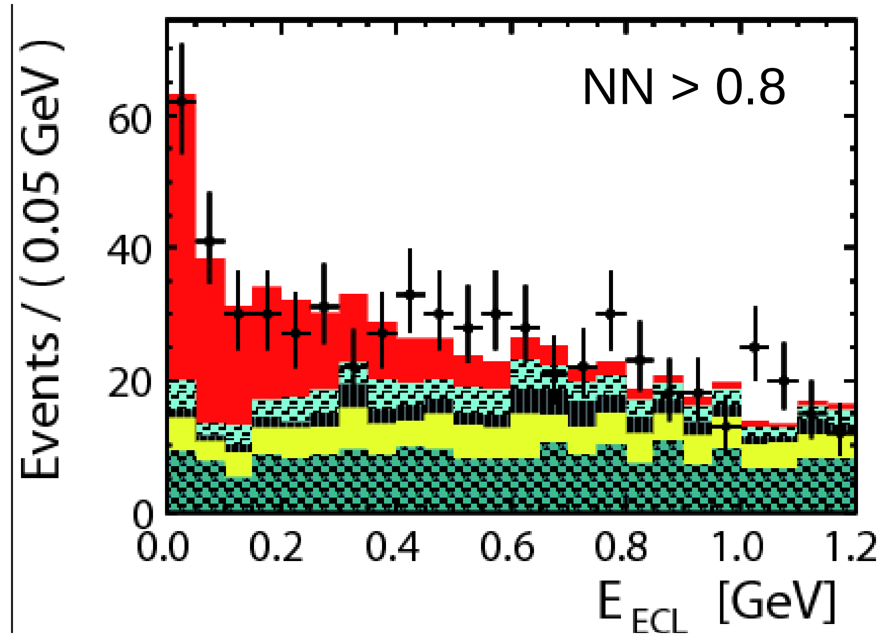
B→ $D^{(*)} \tau \nu$

Belle, Phys.Rev.D 92, 072014 (2015)
Belle, Phys.Rev.D 94, 072007 (2016)
Belle, arXiv:1612.00529 (to PRL)

- Reconstruct one B in Y(4S)→BB event
  Either hadronic or semileptonic decay mode
  First application of semileptonic tagging for B →D(*)τν
- Look for signal in the recoil, B→D*τν, D* → Dπ, D→many, τ→lνν,

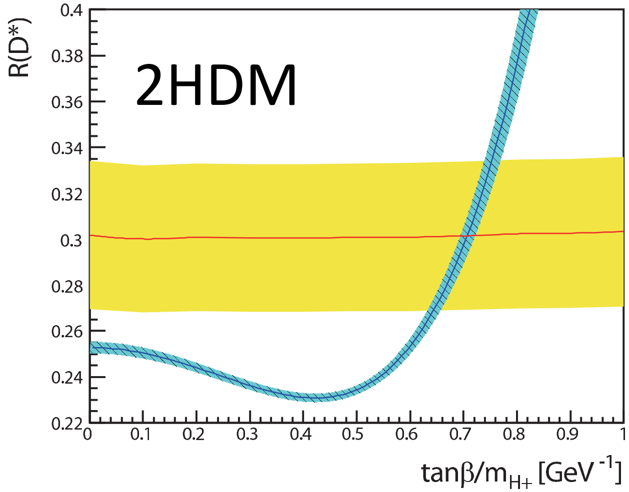
R(D*) = 0.302 ± 0.030 ± 0.011

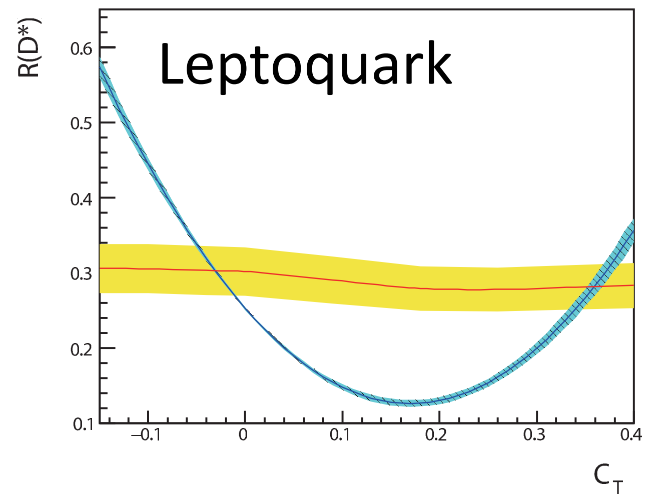


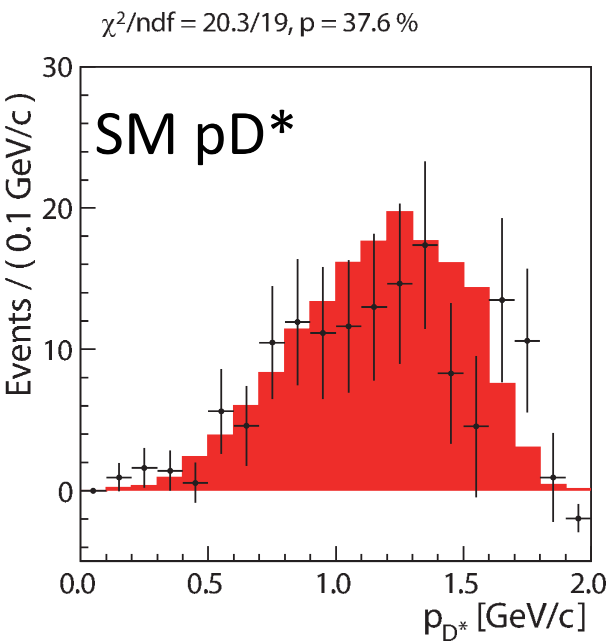


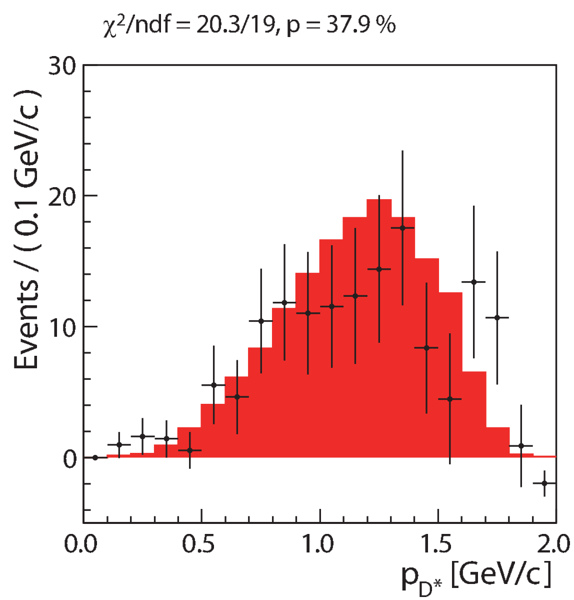
Limits on Type II 2HDM From Belle

Belle, Phys.Rev.D 94, 072007 (2016)

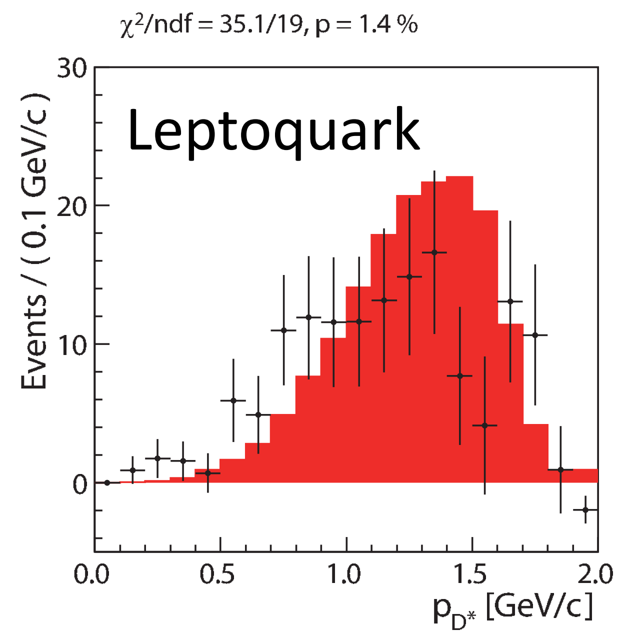






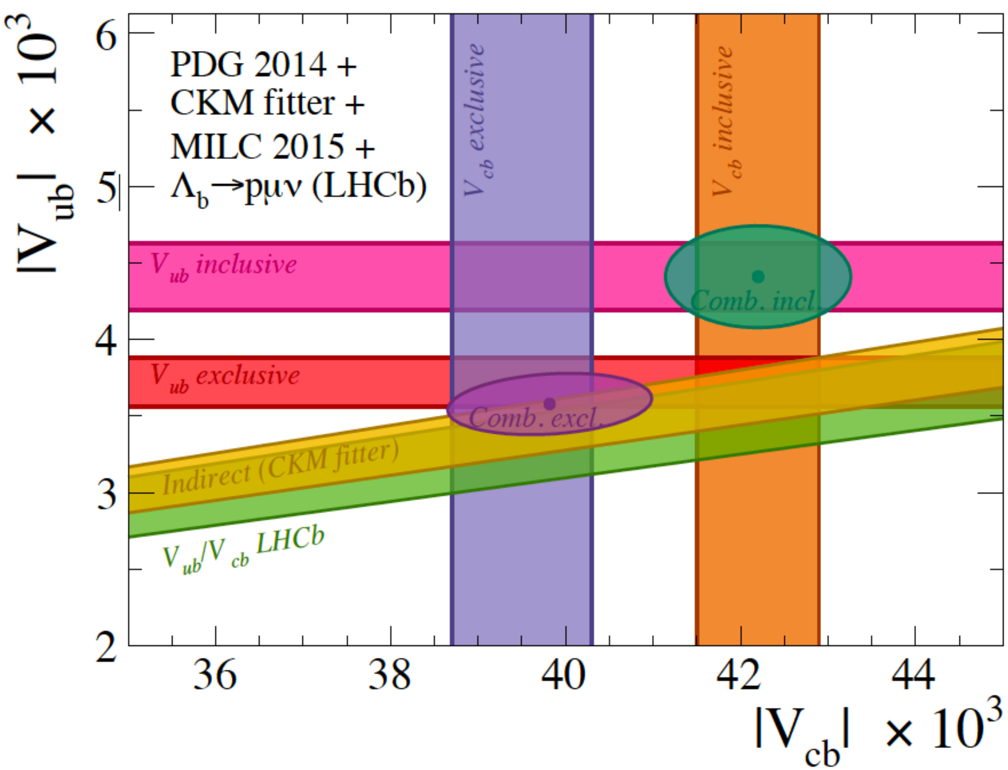


(b)Type-II 2HDM with $\tan\beta/m_{H+} = 0.7$ GeV^{-1}.



The $|V_{ub}|$ puzzle: $B \rightarrow X_u \ell \nu$

- Inclusive versus exclusive determinations (form factor - exclusive vs heavy quark symmetry - inclusive) **3 σ anomaly**
- Only Belle II can resolve this puzzle ~ 2% precision expected.



- Discrepancy could be ***right handed currents*** with coupling V_{ub}^R
  - $B \rightarrow \pi \ell \nu$ rate goes as $|V_{ub}^L + V_{ub}^R|^2$
  - $B \rightarrow \tau \nu$ rate goes as $|V_{ub}^L - V_{ub}^R|^2$
  - $B \rightarrow X_u \ell \nu$ rate goes as $|V_{ub}^L| + |V_{ub}^R|^2$

untagged $B \rightarrow \pi \ell \bar{\nu}_\ell$

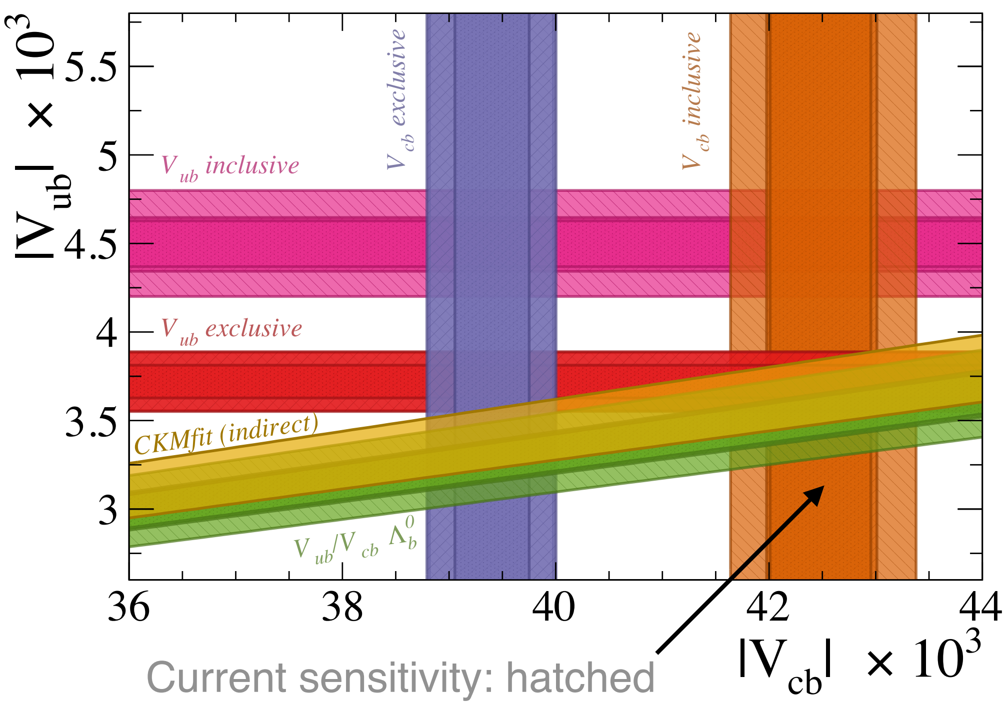
Error on $|V_{ub}|$	stat.	tot.
B-Factories	2.7%	9.4%
Belle II 5/ab	1.0%	4.2%
Belle II 50/ab	0.3%	**2.2%**

$B \rightarrow X_u \ell \bar{\nu}_\ell$

Error on $|V_{ub}|$	stat.	tot.
B-Factories	4.5%	6.5%
Belle II 5/ab	1.1%	3.4%
Belle II 50/ab	0.4%	**3%**

The $|V_{ub}|$ puzzle: $B \to X_u \, l \, \nu$

- Inclusive versus exclusive determinations (form factor - exclusive vs heavy quark symmetry - inclusive) **3 σ anomaly**
- Only Belle II can resolve this puzzle ~ 2% precision expected.



Current sensitivity: hatched
5/ab or 10/fb: cross-hatched
50/ab or 22/fb: dotted

- Discrepancy could be ***right handed currents*** with coupling V_{ub}^R
  - $B \to \pi \, l \, \nu$ rate goes as $|V_{ub}^L + V_{ub}^R|^2$
  - $B \to \tau \, \nu$ rate goes as $|V_{ub}^L - V_{ub}^R|^2$
  - $B \to X_u \, l \, \nu$ rate goes as $|V_{ub}^L| + |V_{ub}^R|^2$

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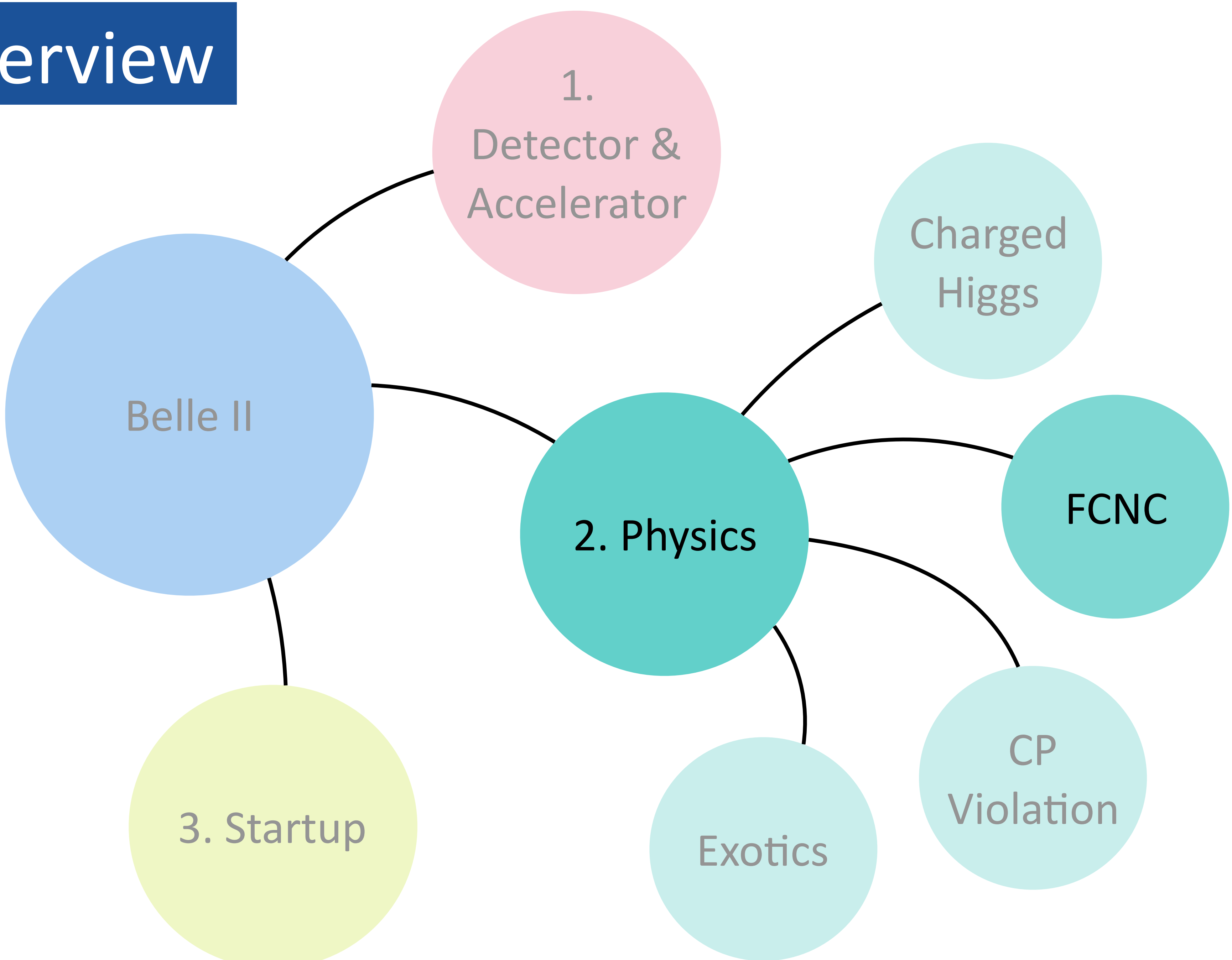
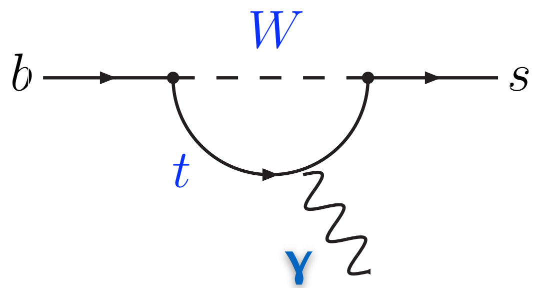
Overview


1. Detector & Accelerator
Charged Higgs
Belle II
2. Physics
FCNC
3. Startup
CP Violation
Exotics

Flavour changing neutral currents

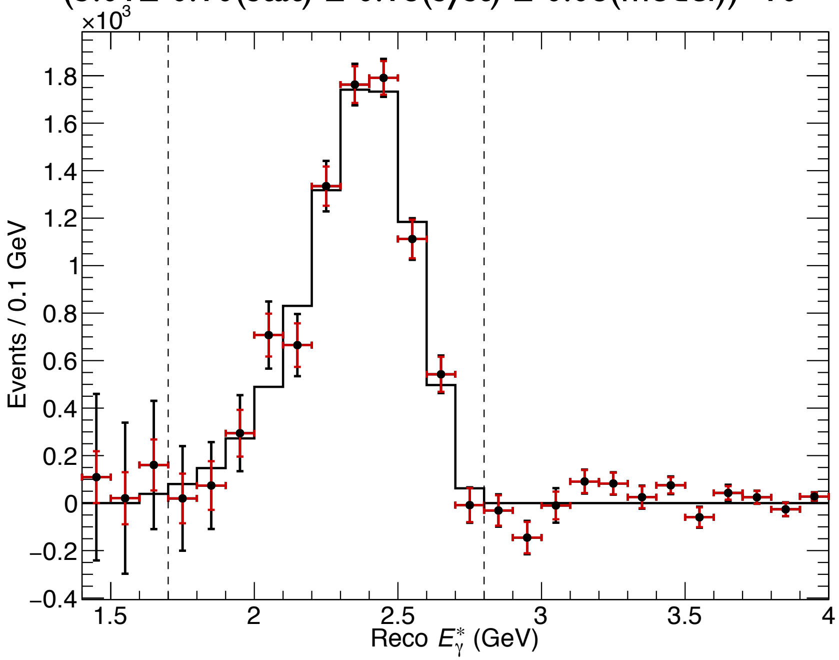
Belle arXiv:1608.02344

- FCNC or penguin decays are very sensitive to new particles and interactions.



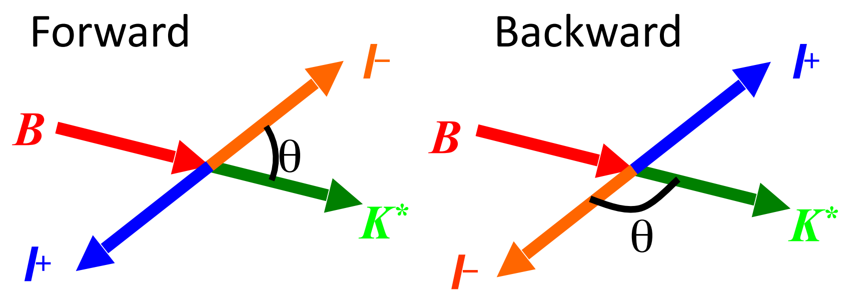
- Massive, beyond SM, particles may contribute to B decay processes in loop diagrams. b→s & b→d can be probed
  - B_s mixing
  - b → s g (e.g. TDCPV in B^0 → Φ Ks, etc.)
  - b → s γ (e.g. decay rate, TDCPV)
  - b → s $l^+ l^-$ (e.g. F-B asymmetry test of chirality)
  - b → s ν $\underline{\nu}$

Br(B→Xsγ)=
(3.01± 0.10(stat) ± 0.18(syst) ± 0.08(model))×10^{-4}



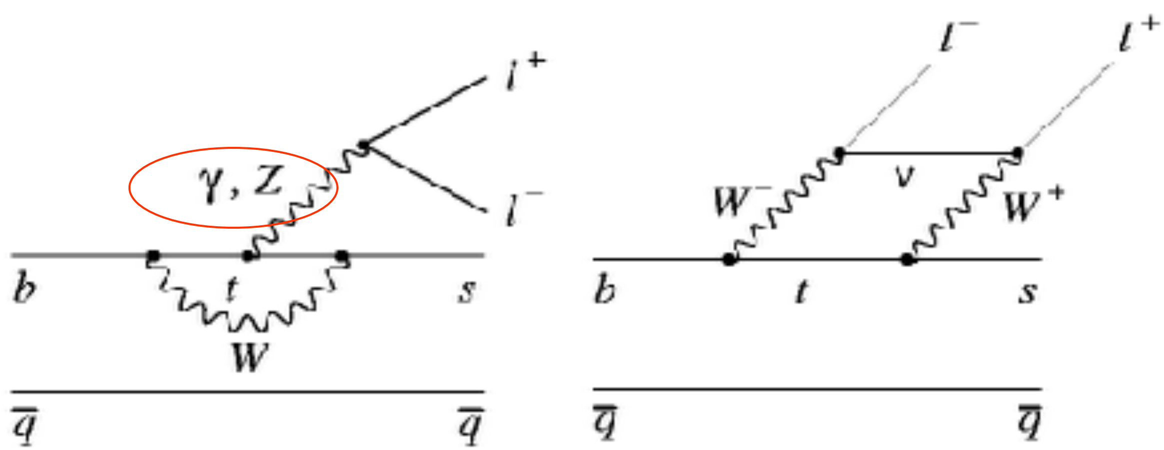
$A_{FB}(B \to K^* l^+ l^-)(q^2)$

The SM forward-backward asymmetry in $b \to s\, l^+ l^-$ arises from the **interference** between γ and Z^0 contributions.



$$A_{FB}(B \to K^*\ell^+\ell^-) = -C_{10}\xi(q^2)\left[Re(C_9)F_1 + \frac{1}{q^2}C_7F_2\right]$$

Ali, Mannel, Morozumi, PLB273, 505 (1991)

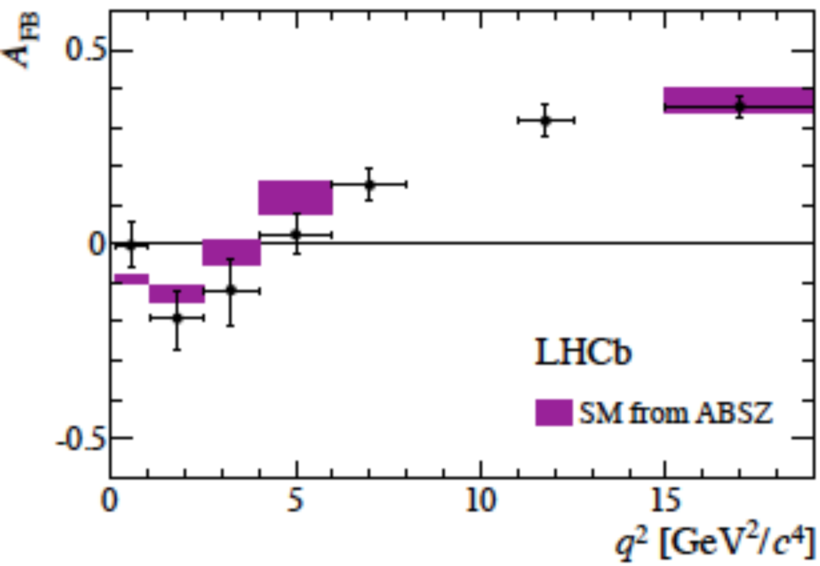


Multiple heavy particles of the SM (W, Z, top) enter in this decay.

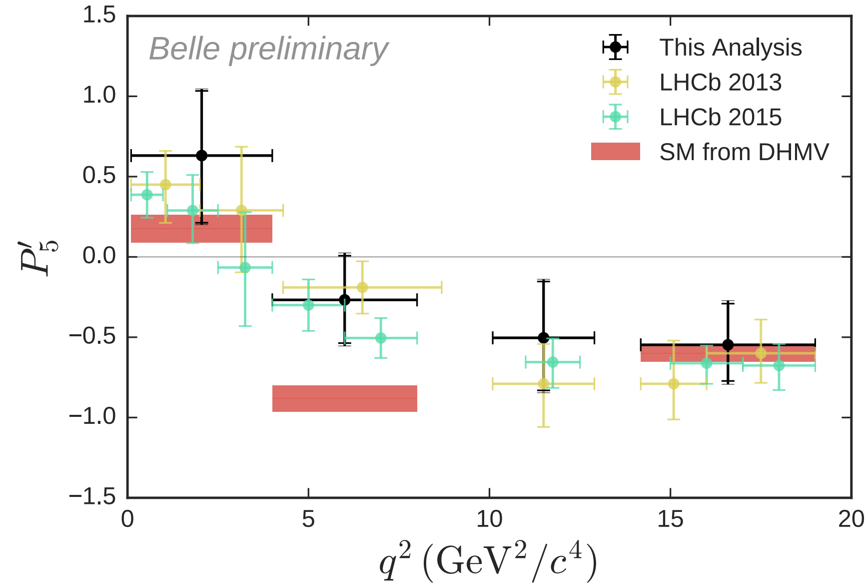
LHCb & Belle results on B→ K* μ⁺μ⁻ (q²)

Belle arXiv:1604.04042

$$A_{FB}(B \to K^{*}\ell^{+}\ell^{-}) = -C_{10}\xi(q^2)\left[Re(C_9)F_1 + \frac{1}{q^2}C_7F_2\right]$$



$$P_5' = \sqrt{2}\frac{\mathrm{Re}\left(A_0^{\mathrm{L}}A_\perp^{\mathrm{L}*} - A_0^{\mathrm{R}}A_\perp^{\mathrm{R}*}\right)}{\sqrt{\left(|A_0^{\mathrm{L}}|^2 + |A_0^{\mathrm{R}}|^2\right)\left(|A_\parallel^{\mathrm{L}}|^2 + |A_\parallel^{\mathrm{R}}|^2 + |A_\perp^{\mathrm{L}}|^2 + |A_\perp^{\mathrm{R}}|^2\right)}}$$

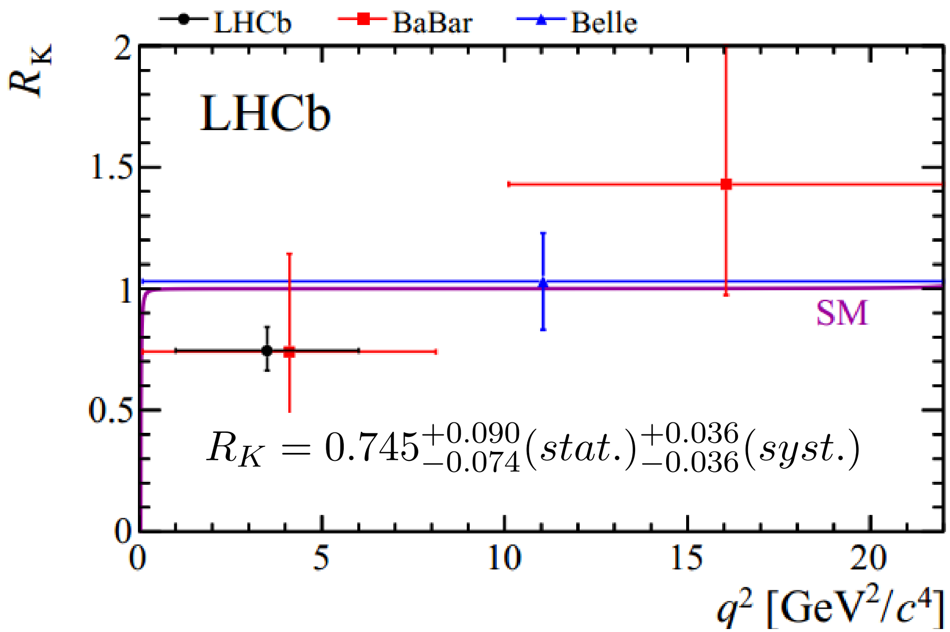


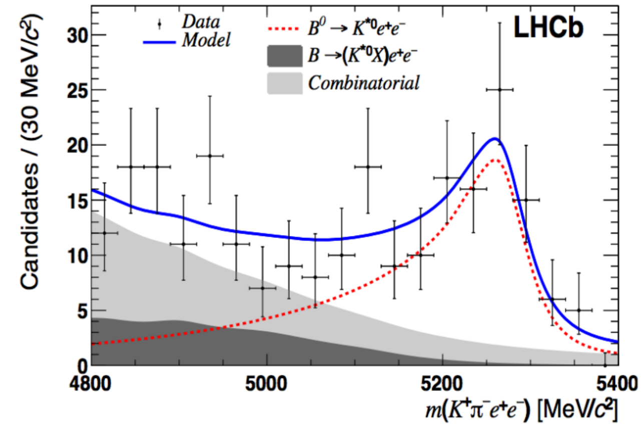
"The P_5' measurements are only compatible with the SM prediction at a level of 3.7σ…..A mild tension can also be seen in the A_{FB} distribution, where the measurements are systematically <=1σ below the SM prediction in the region $1.1<q^2< 6.0$ GeV²"

$B \to X_s \ell\ell$ C_7/C_9 ratio

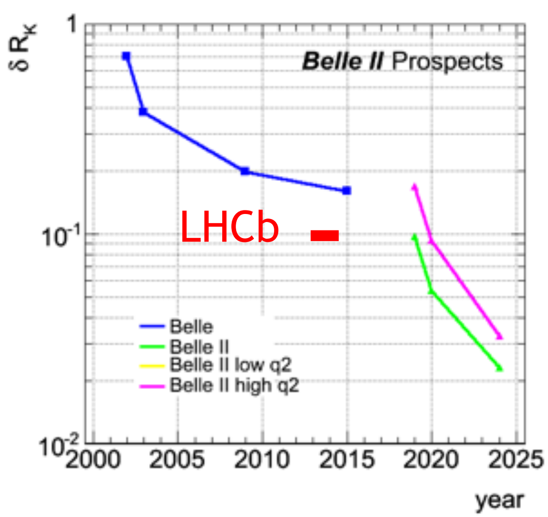
Error	tot.
B-Factories	19%
Belle II 5/ab	9%
Belle II 50/ab	**6%**

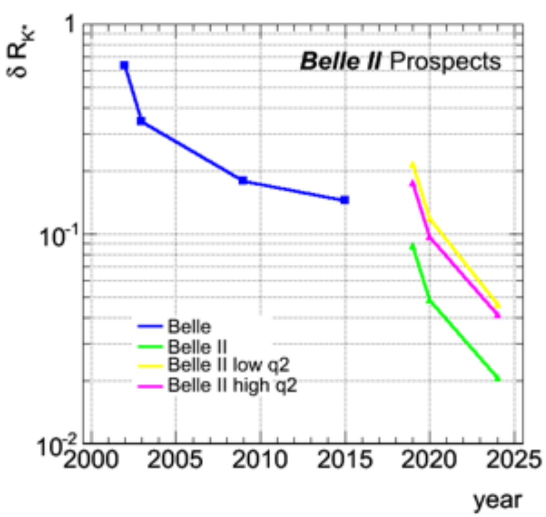
Lepton Flavour Universality Violation

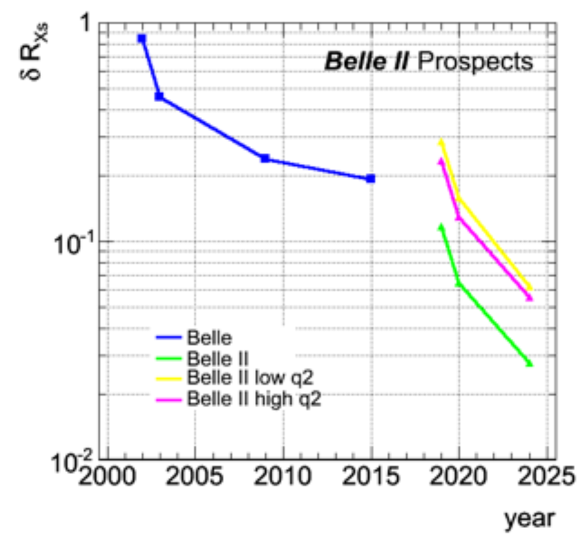




- Belle II much more powerful on **e** modes.







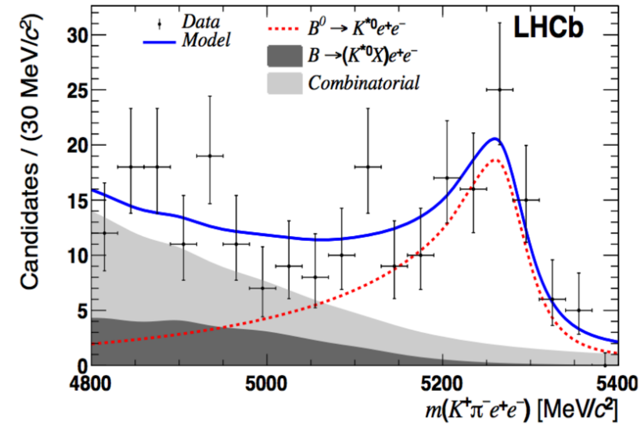
Melbourne MSc Thesis, A. Duong


New Scientist

HOME NEWS TECHNOLOGY SPACE PHYSICS HEALTH EARTH HUMANS LIFE TOPICS EVENTS JOBS

FEATURE 27 April 2016

That's odd: Unruly penguins hint where all the antimatter went



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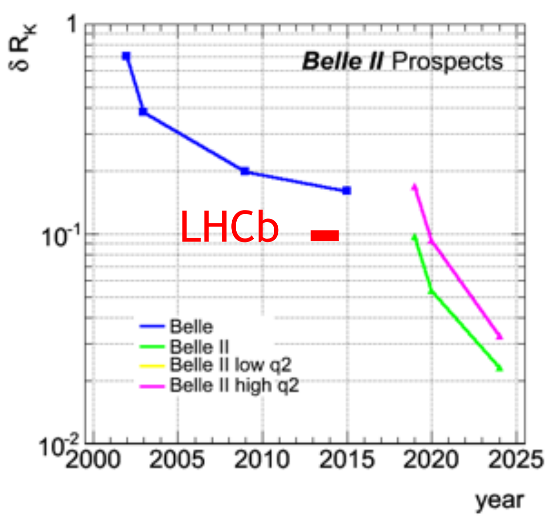
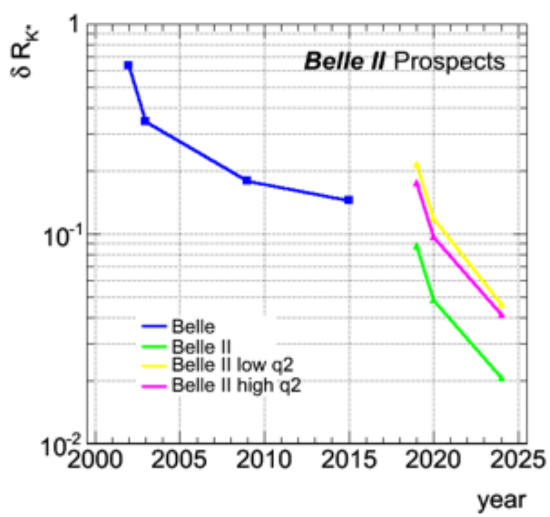
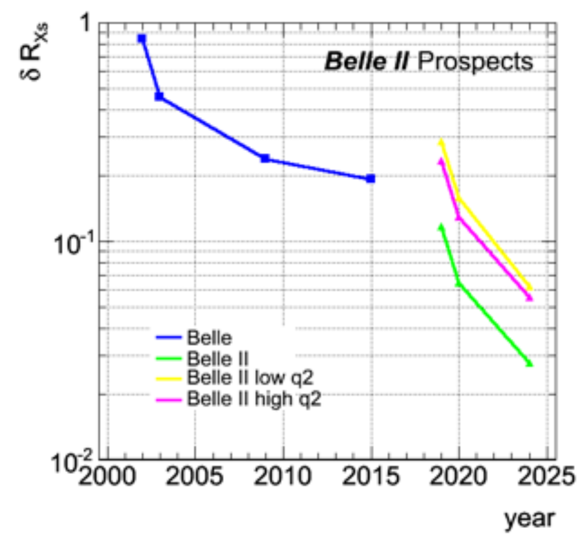
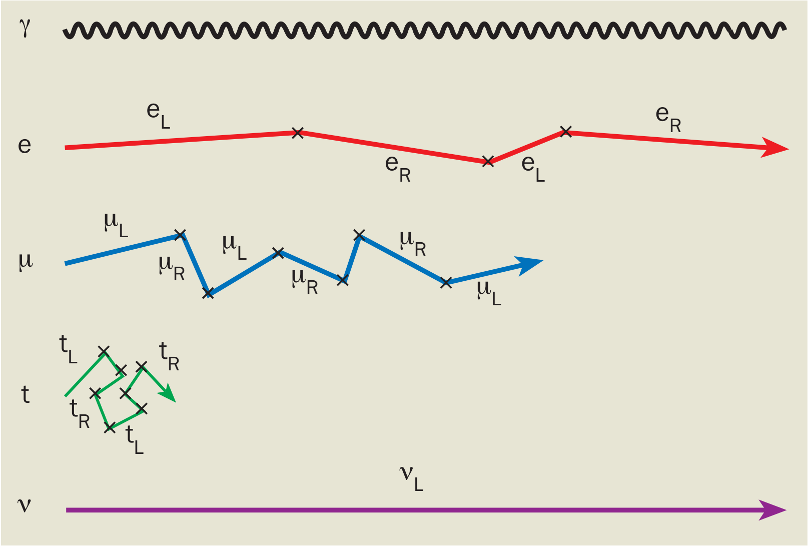






Beyond SM in the Lepton Sector

- No right-handed neutrinos in the SM, implies they are massless.
- Neutrino oscillations show they have small but finite masses.
  - Where are the R-handed Neutrinos?
- Mechanism beyond SM is needed.



Seesaw mechanisms are candidates

Seesaw (tree level)

$m^{\nu}_{ij} = y_i y_j v^2/M$ $M = 10^{14}$ GeV (for y_i=O(1))

Quantum Effects (Radiative Seesaw) N-th order of perturbation

$m^{\nu}_{ij} = [1/(16\pi^2)]^N C_{ij} v^2/M$ M=1 TeV

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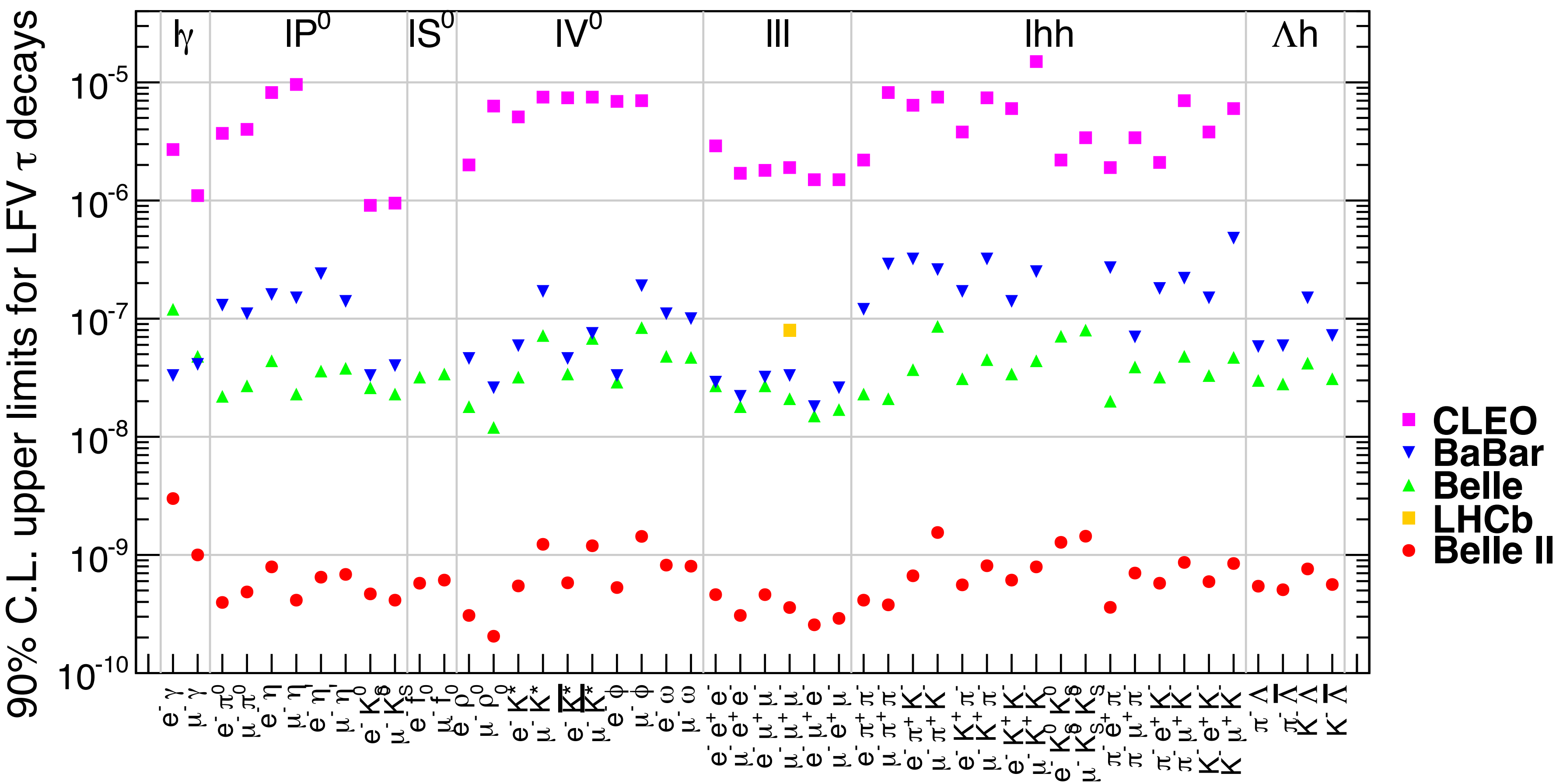
Nature of NP in τ LFV



Nature of NP in τ LFV

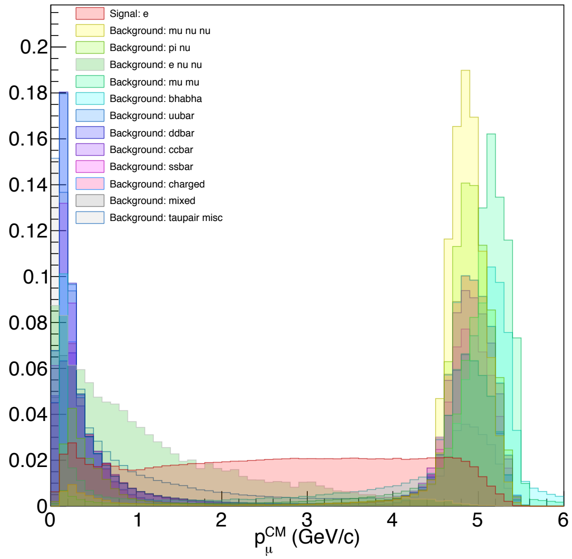
If we find a signature, we can determine its nature.

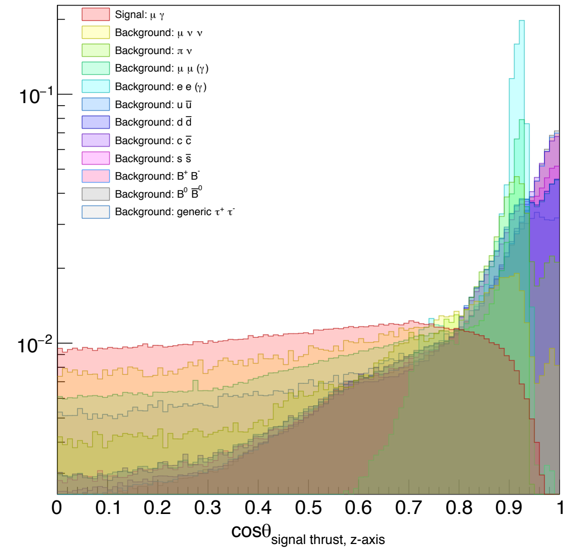
$$\mathcal{L} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

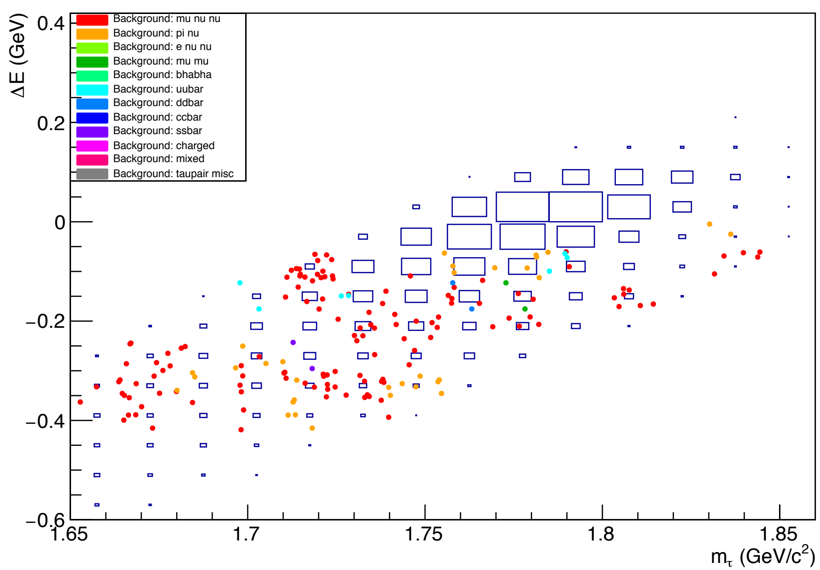
	$\tau \to 3\mu$	$\tau \to \mu\gamma$	$\tau \to \mu\pi^+\pi^-$	$\tau \to \mu K\bar{K}$	$\tau \to \mu\pi$	$\tau \to \mu\eta^{(\prime)}$
$\mathrm{O}_{\mathrm{S,V}}^{4\ell}$	✓	–	–	–	–	–
O_{D}	✓	✓	✓	✓	–	–
$\mathrm{O}_{\mathrm{V}}^{\mathrm{q}}$	–	–	✓ (I=1)	✓(I=0,1)	–	–
$\mathrm{O}_{\mathrm{S}}^{\mathrm{q}}$	–	–	✓ (I=0)	✓(I=0,1)	–	–
O_{GG}	–	–	✓	✓	–	–
$\mathrm{O}_{\mathrm{A}}^{\mathrm{q}}$	–	–	–	–	✓ (I=1)	✓ (I=0)
$\mathrm{O}_{\mathrm{P}}^{\mathrm{q}}$	–	–	–	–	✓ (I=1)	✓ (I=0)
$\mathrm{O}_{\mathrm{G\tilde{G}}}$	–	–	–	–	–	✓

τ → l γ with Beam background

Melbourne MSc Thesis, B. Moore

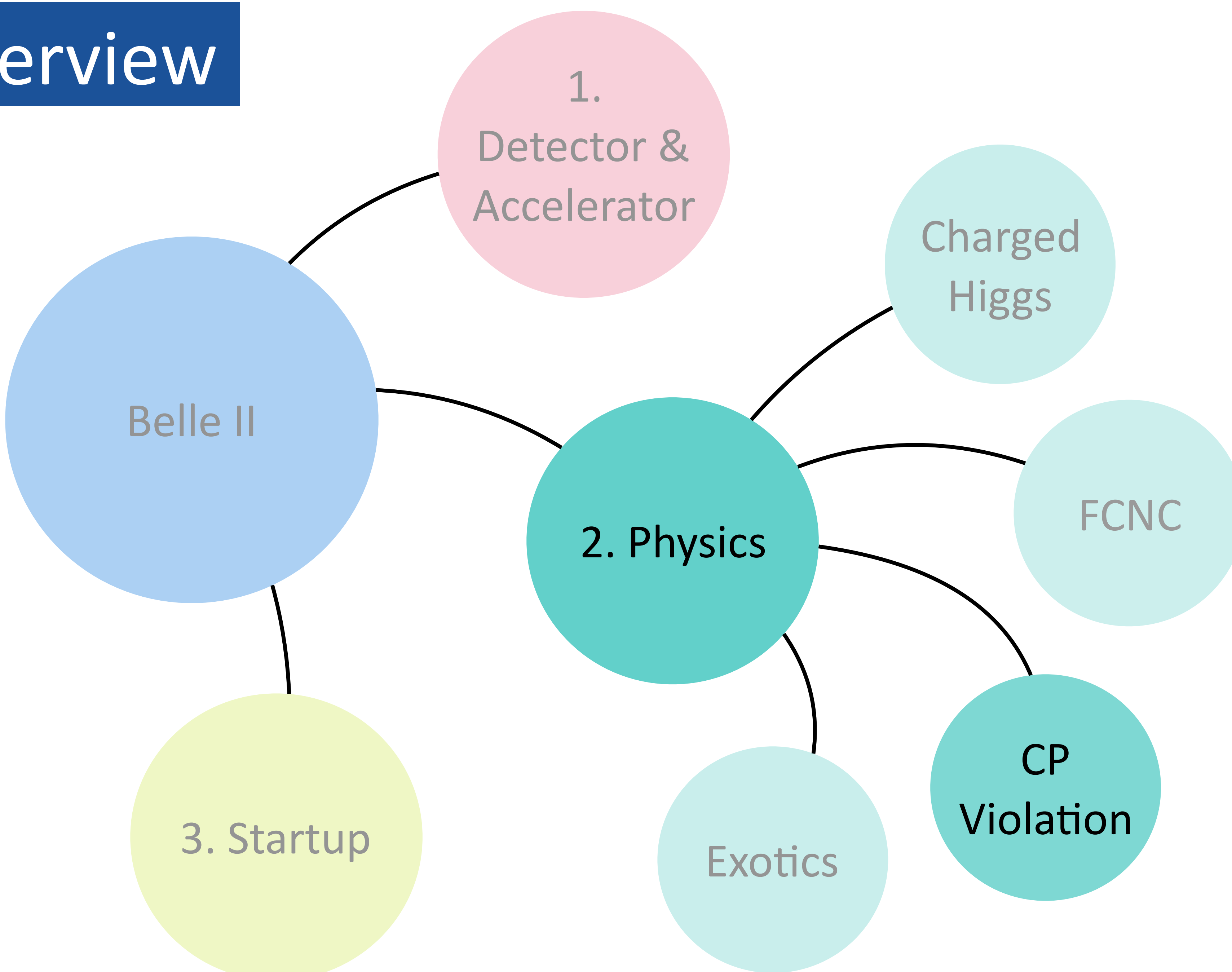






- Despite beam background, zero background for τ → l γ is achievable.

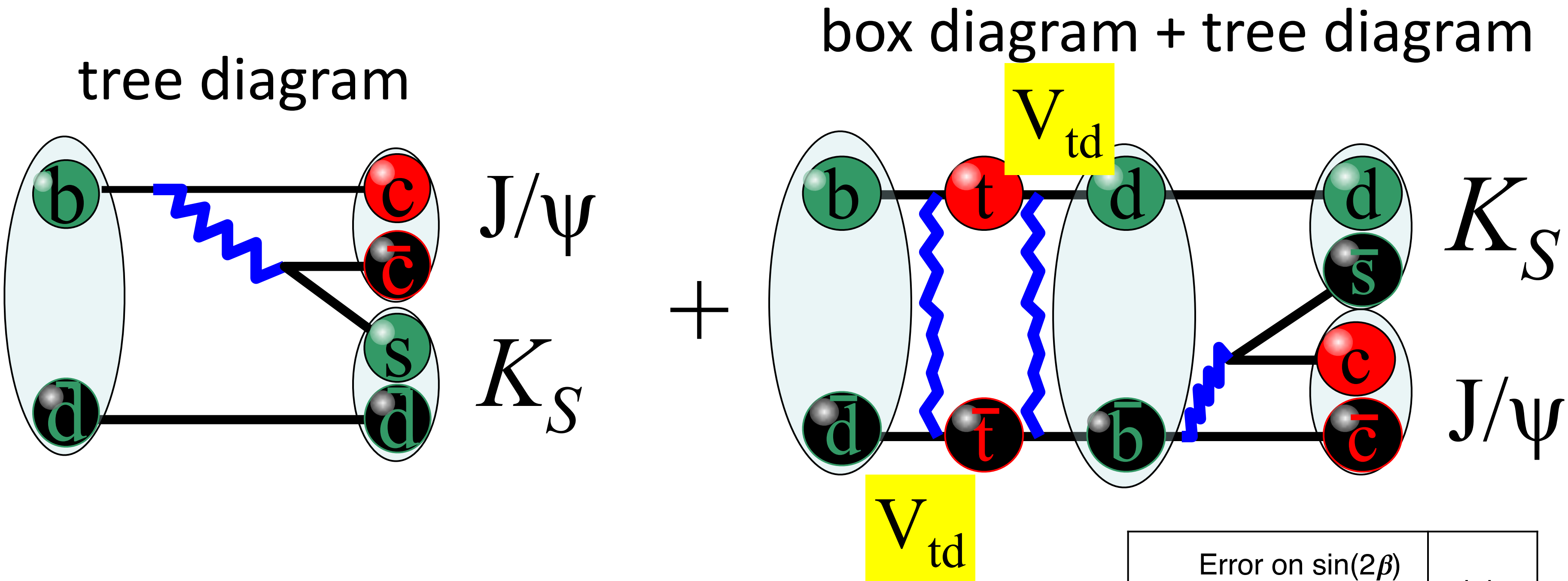
Overview


1.
Detector &
Accelerator
Charged
Higgs
Belle II
2. Physics
FCNC
CP
Violation
3. Startup
Exotics

Time-dependent CP violation

"A Double-Slit experiment" with particles and antiparticles

QM interference between two diagrams

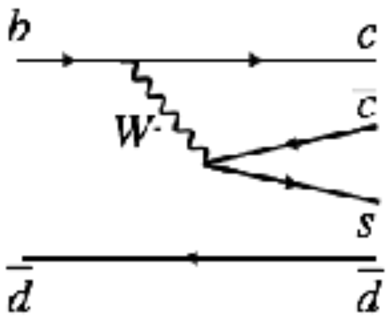


Measures the phase of V_{td} or equivalently the phase of B_d –anti B_d mixing.

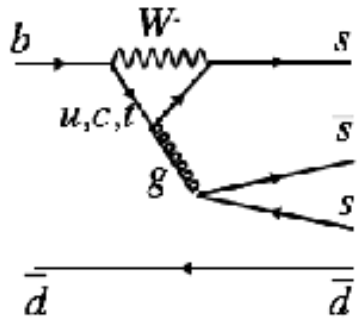
Error on sin(2β) from B → J/ψ K_s	tot.
LHCb 22/fb	**0.014**
Belle II 50/ab	**0.007**

Belle II Analysis

- Tree

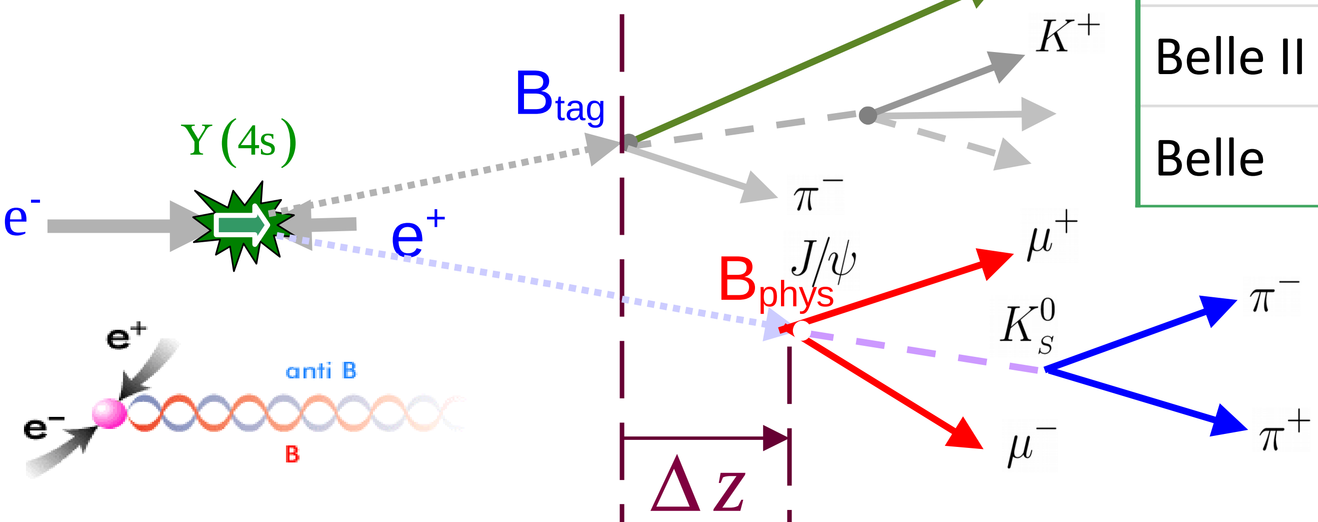


- Gluonic Penguin (NP sensitive)



- K-shorts in most signatures: VXD Larger acceptance (+30%) for π from K_S

B→J/ψ Ks	B_{CP} μm	B_{tag} μm	Δt ps
Belle II	22	52	0.71
Belle	63	89	0.92

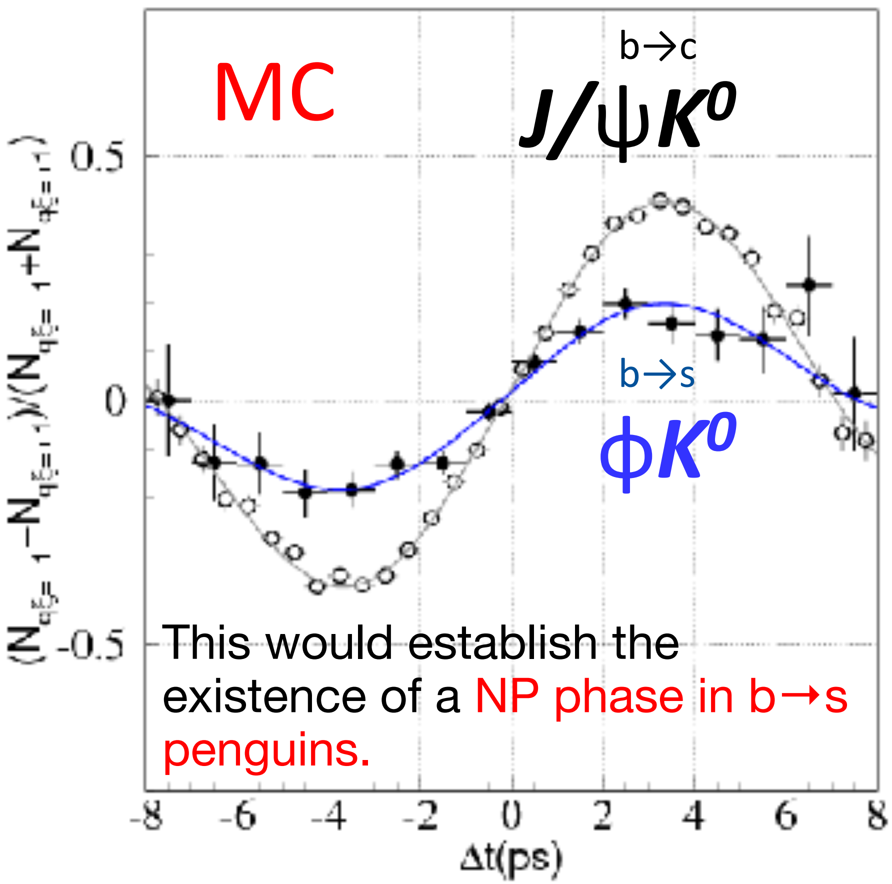


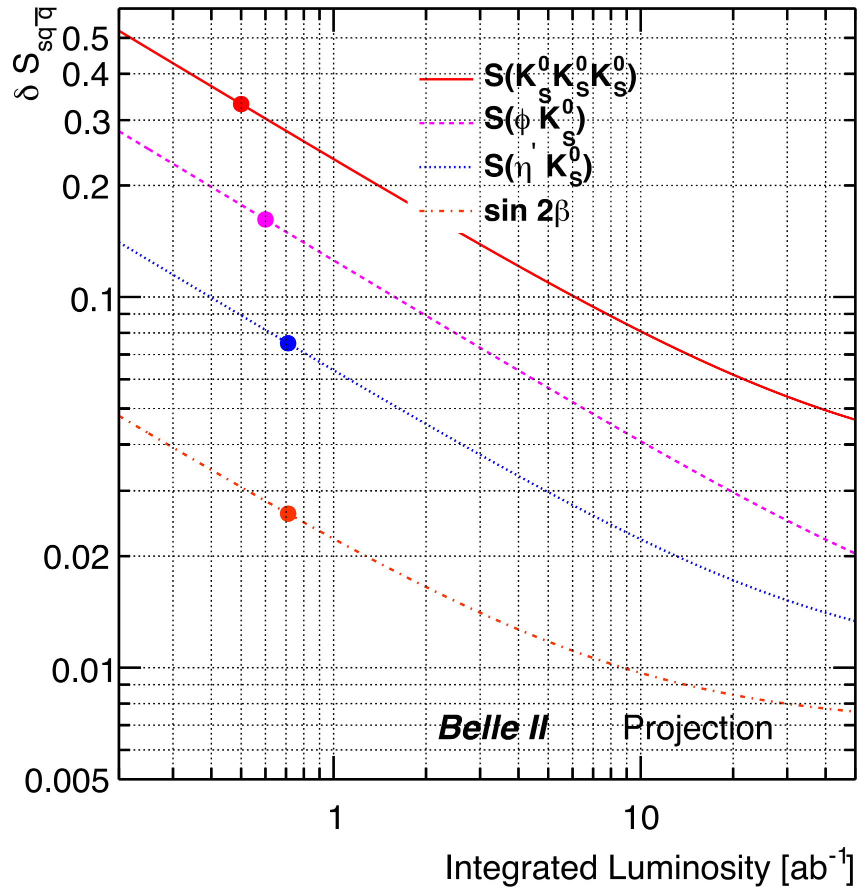
Coherent B meson pair production

Belle ~ 200 μm
Belle II ~ 130 μm

Gluonic penguins, S_{CP}

$B \to \phi K^0$ at 50/ab with ~2010 WA values

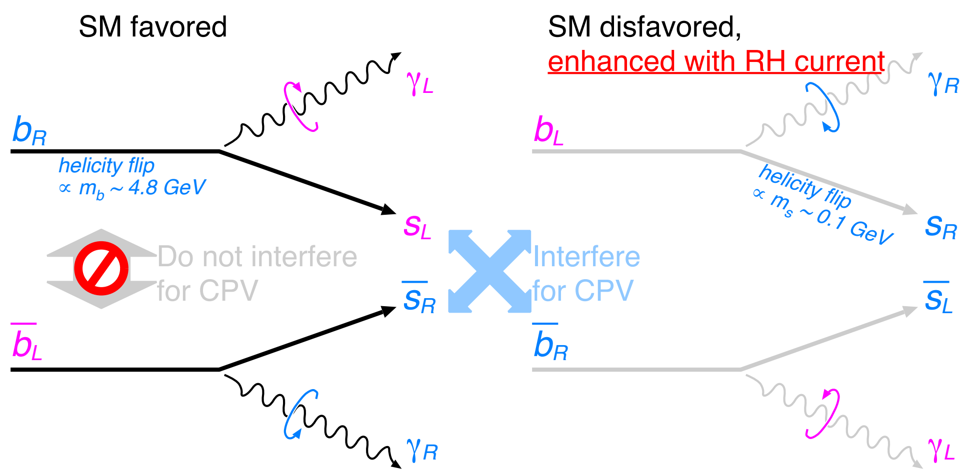


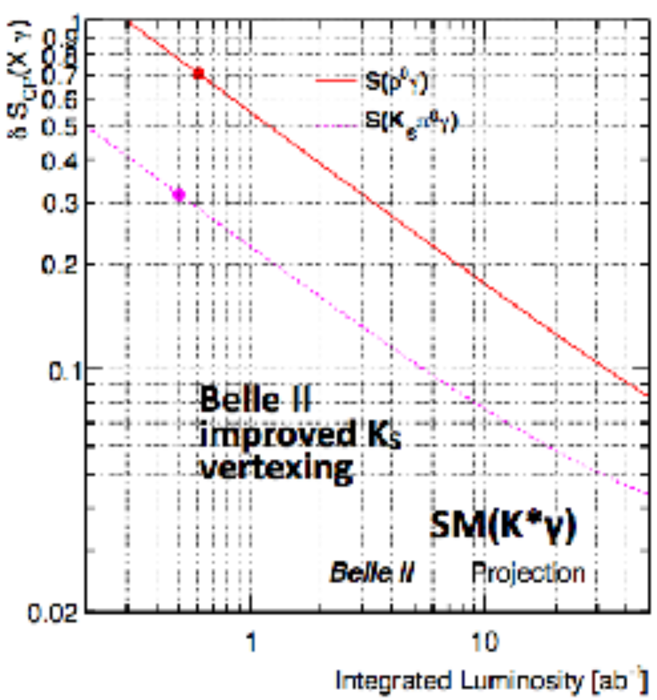


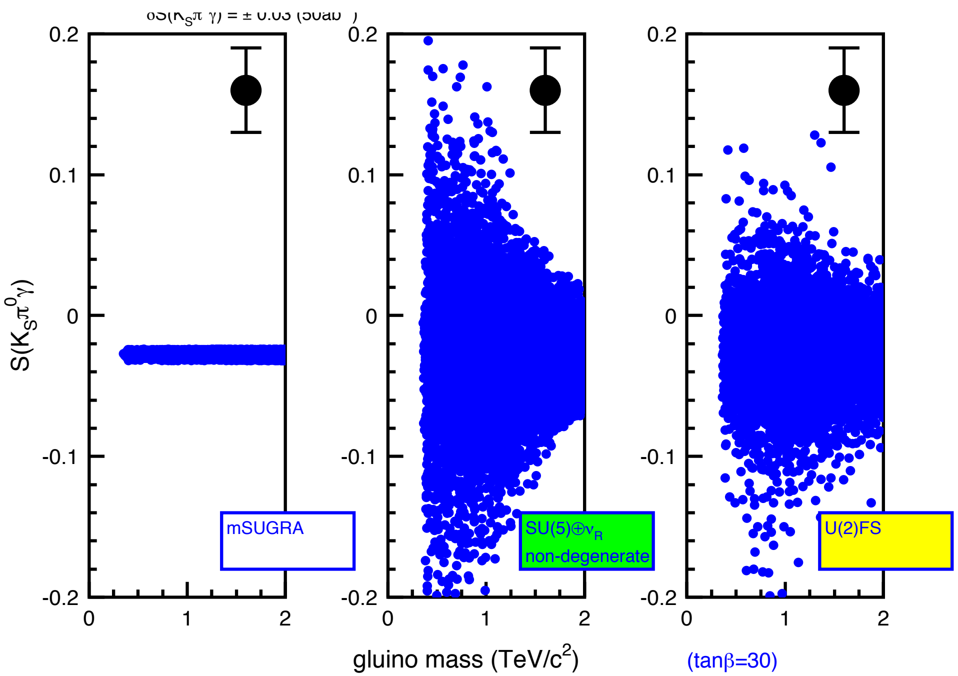
Belle II will lead on all TCPV in B decays

Radiative Penguins, S_{CP}

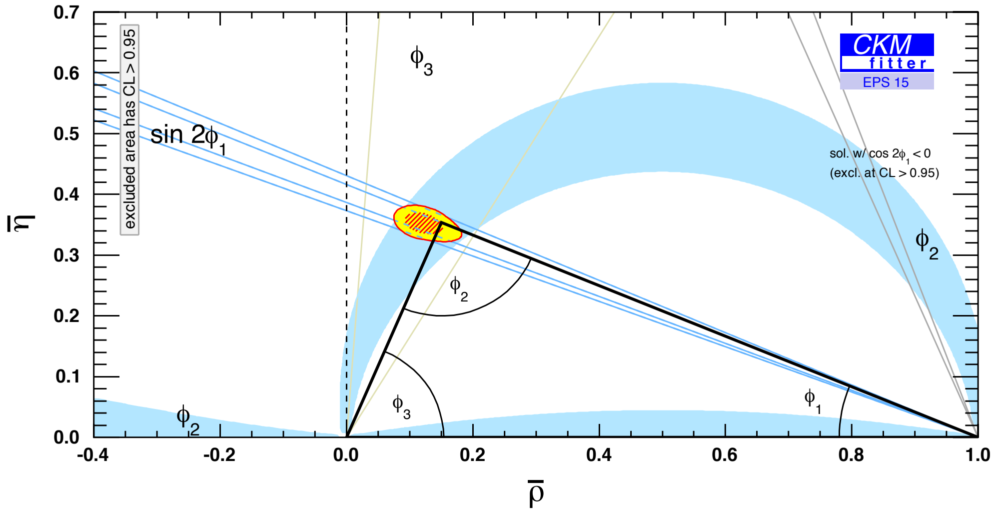
- SM EW purely L-handed.
- Right-handed current is a signature of NP $S = -2(m_s/m_b)\sin(2\phi_1) = (-2.3\pm1.6)\%$
- WA Experiment ~ 22% precision





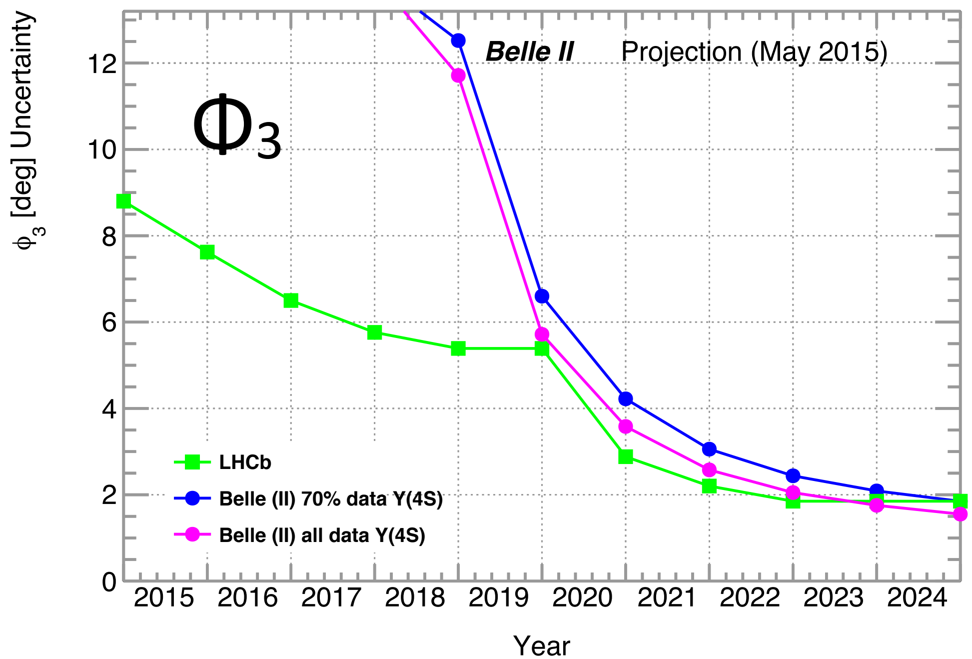


Tree Direct CPV, Φ_3



Φ_3 Babar = $(70 \pm 18)^o$
Φ_3 Belle = $(73\ ^{+13}_{-15})^o$
Φ_3 LHCb = $(75 \pm 9)^o$

Error on γ	tot.
LHCb 22/fb	**2°**
Belle II 50/ab	**1.5°**



Belle II will lead on Φ_1 and Φ_2 angles & on UT sides

NP in B_d mixing: Fit results

Phys. Rev. D 89, 033016 (2014)

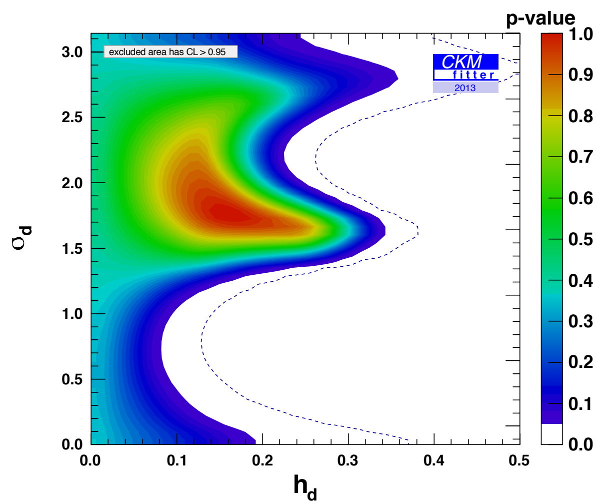
- Mixing

$$i\frac{d}{dt}\begin{pmatrix}|B_q(t)\rangle\\|\bar{B}_q(t)\rangle\end{pmatrix}=\left(M^q-\frac{i}{2}\Gamma^q\right)\begin{pmatrix}|B_q(t)\rangle\\|\bar{B}_q(t)\rangle\end{pmatrix}$$

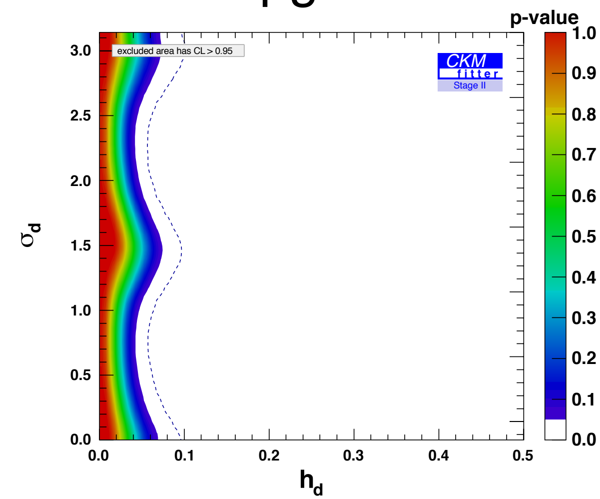
- Parameterise NP.

$$M_{12}=M_{12}^{SM}\times\left(1+he^{2i\sigma}\right)$$

2013



LHCb Upg.+ Belle II



- 95% CL, NP≲(many × SM) ⟹ NP≲(0.05 × SM)

$$h\simeq 1.5\frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2}\frac{(4\pi)^2}{G_F\Lambda^2}\simeq\frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2}\left(\frac{4.5\ \text{TeV}}{\Lambda}\right)^2$$

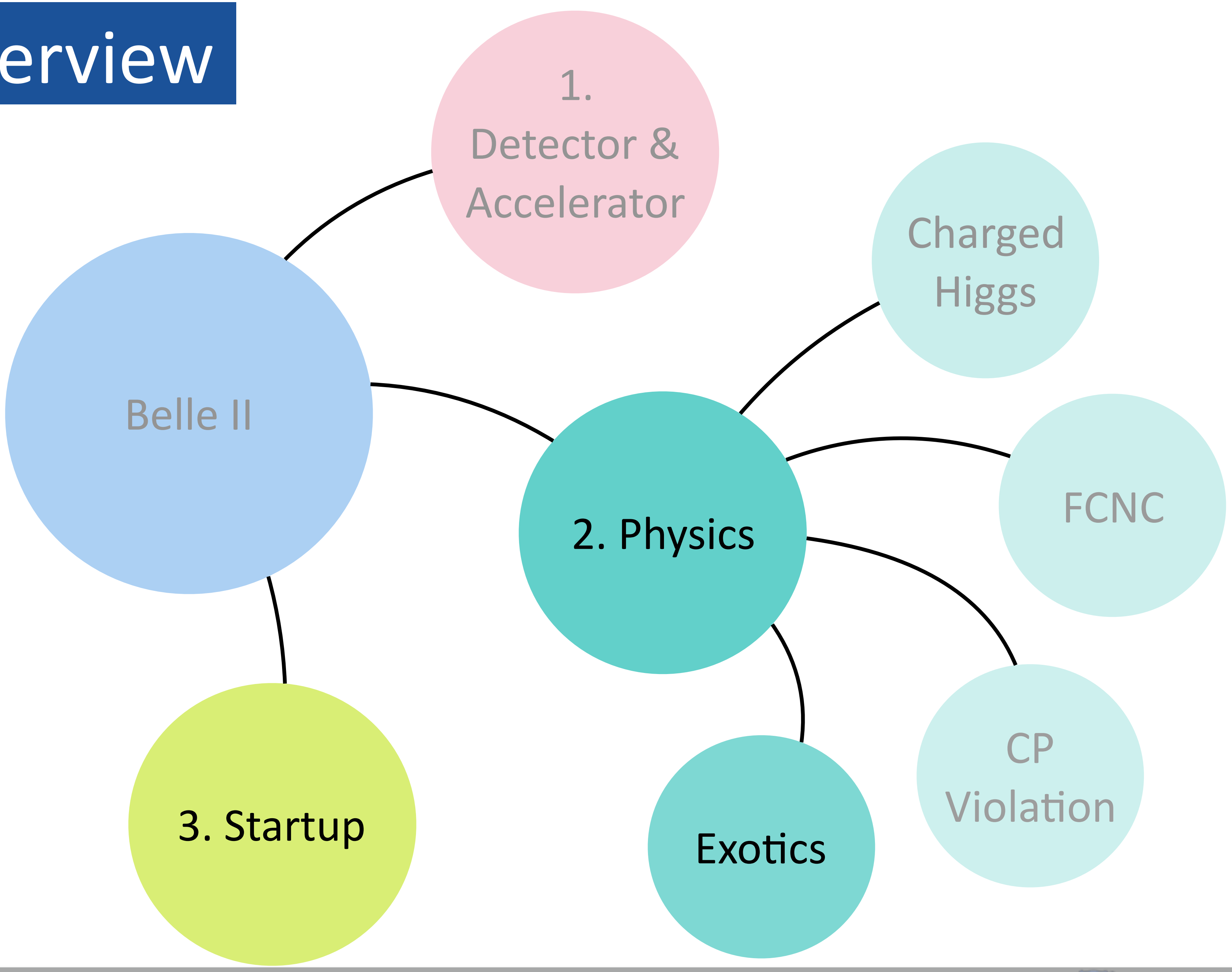
$$\sigma=\arg(C_{ij}\lambda_{ij}^{t*})$$

By Stage II,

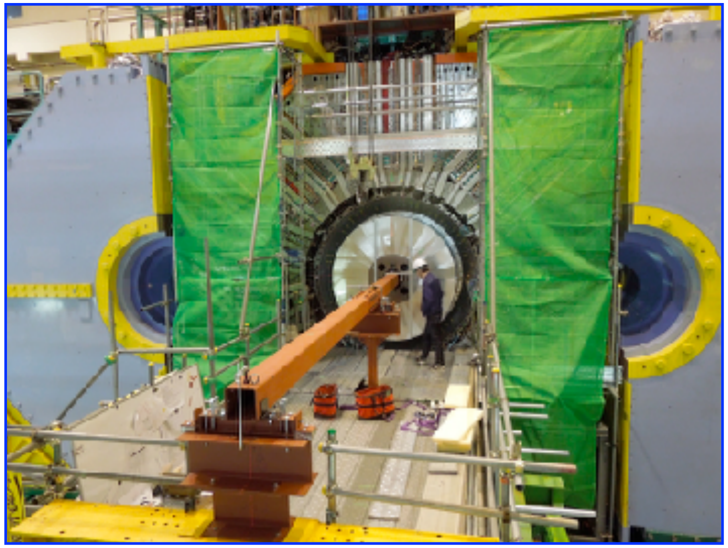
- Λ ~ 20 TeV (**tree**)
- Λ ~ 2 TeV (**loop**)

- Stage II: similar sensitivity to gluino masses explored at LHC 14TeV

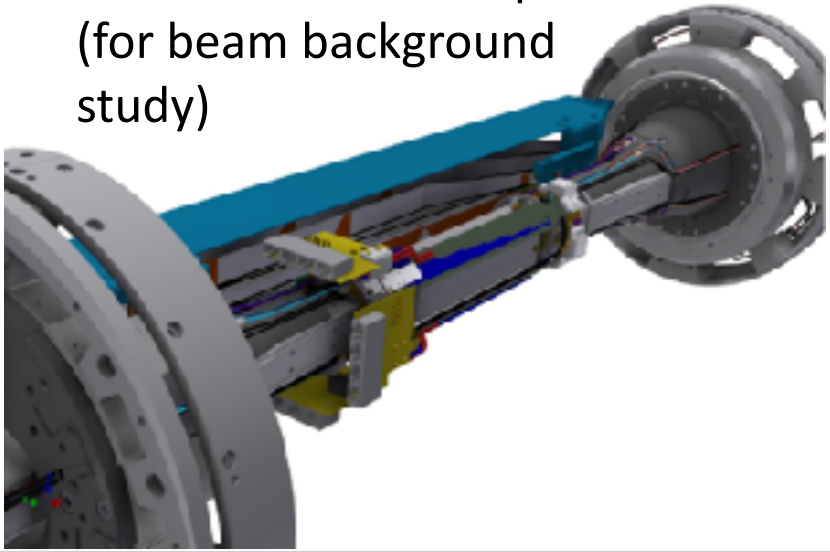
Overview

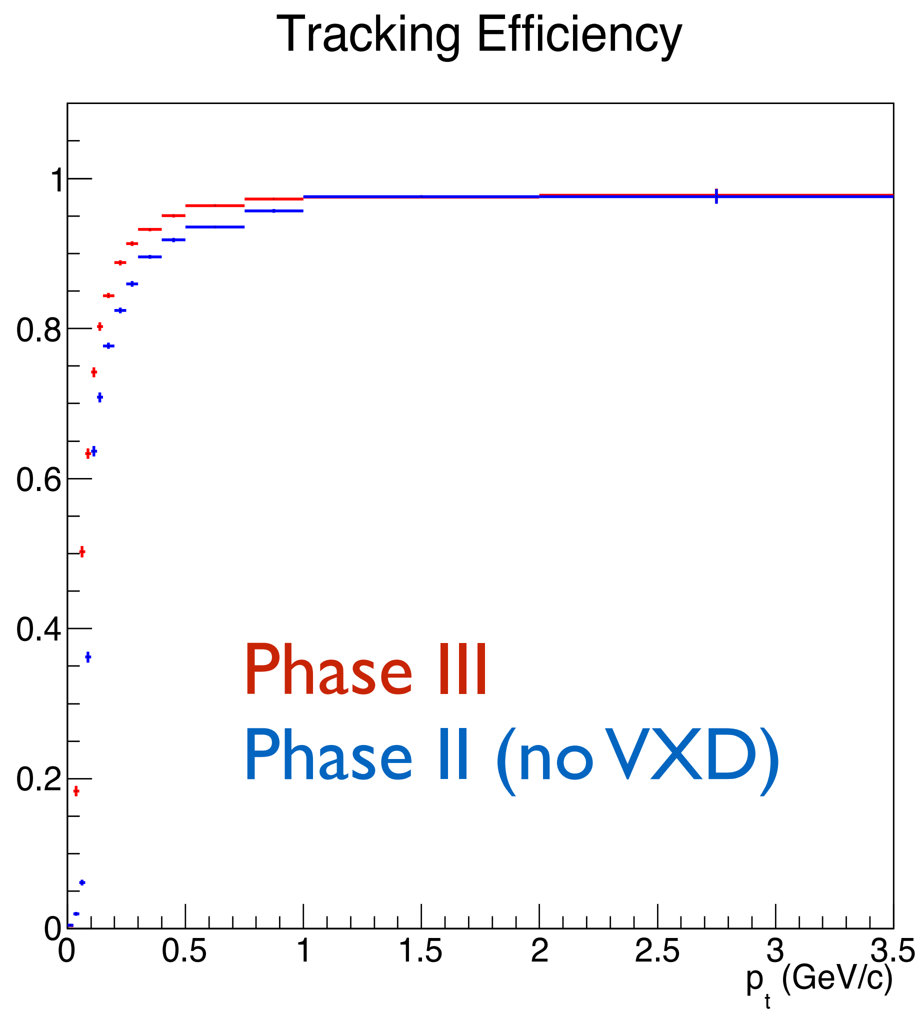

1.
Detector &
Accelerator
Charged
Higgs
Belle II
2. Physics
FCNC
CP
Violation
Exotics
3. Startup

Phase II: First collision Run, Jan-Jun 2018



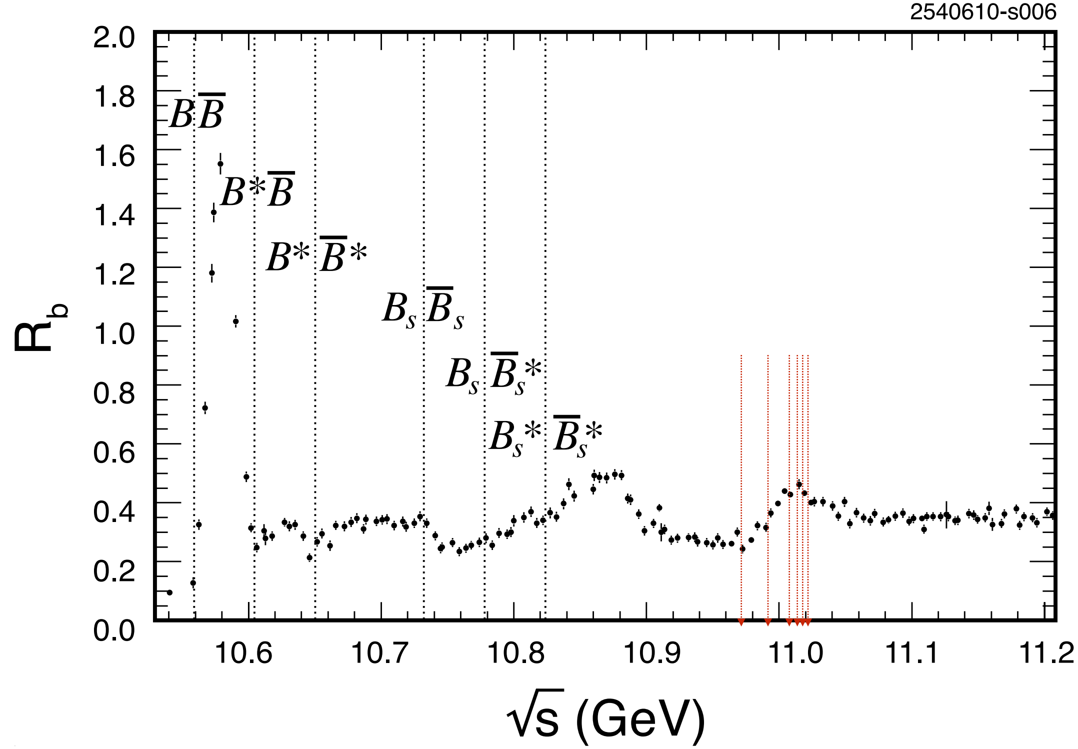
No VXD, only the BEAST silicon detector setup (for beam background study)





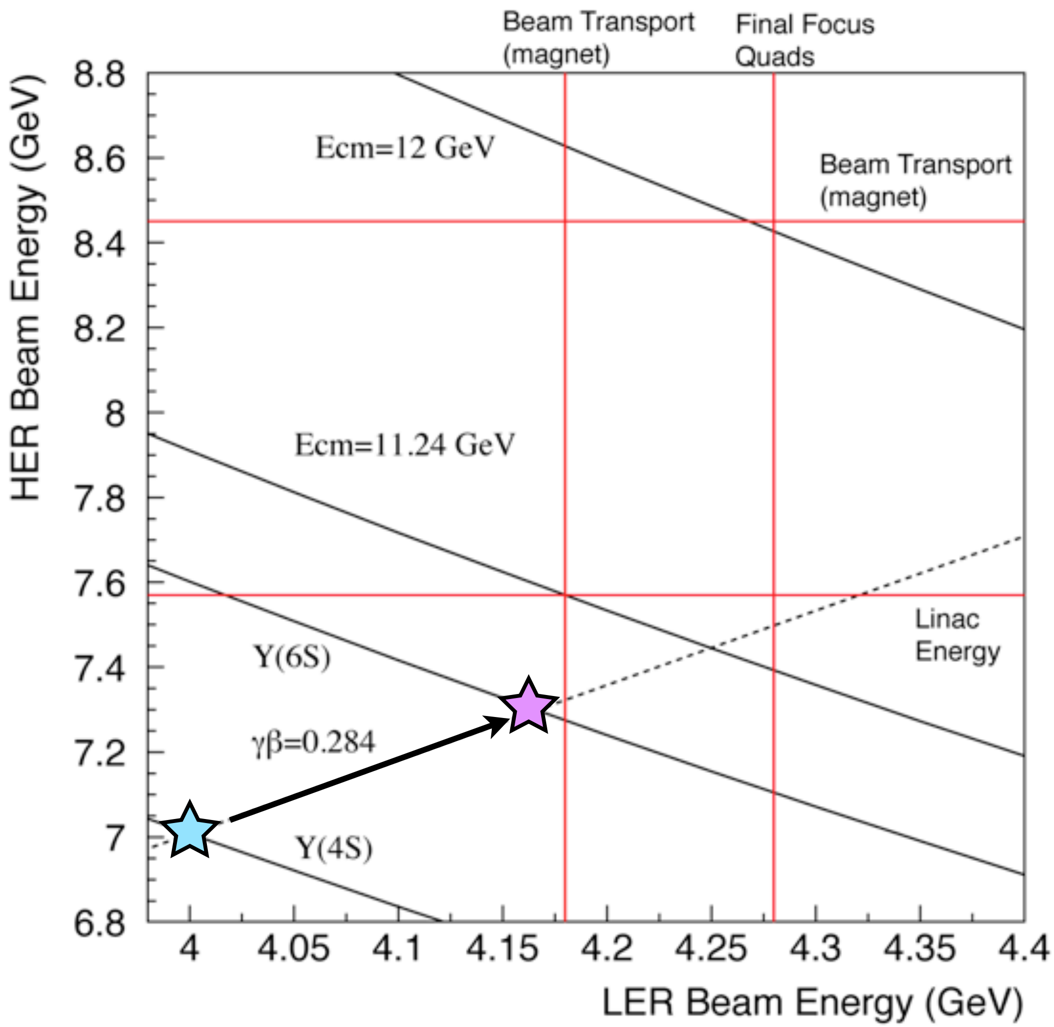
Phase II Unique data sets

- **Only ~20-40 fb^{-1} in Phase II**
  - New trigger menu to greatly enhance low multiplicity physics
  - Unique E_{CM} , e.g. Y(6S) for bottomonium - strong interaction studies



Experiment	Scans/Off. Res.	$\Upsilon(5S)$ 10876 MeV		$\Upsilon(4S)$ 10580 MeV		$\Upsilon(3S)$ 10355 MeV		$\Upsilon(2S)$ 10023 MeV		$\Upsilon(1S)$ 9460 MeV	
	fb^{-1}	fb^{-1}	10^6	fb^{-1}	10^6	fb^{-1}	10^6	fb^{-1}	10^6	fb^{-1}	10^6
CLEO	17.1	0.4	0.1	16	17.1	1.2	5	1.2	10	1.2	21
BaBar	54	R_b scan		433	471	30	122	14	99	–	
Belle	100	121	36	711	772	3	12	25	158	6	102

Accelerator E_{CM} reach



- Start with Υ(4S) operation at Phase II
- 20 days to collect 10fb-1 @ Υ(6S)
- 5 months total Phase II operation

E_{CM} max with constant $\gamma\beta=0.284$ is ~ 11.1 GeV

Exotic 4-quark States

Belle arXiv:1508.06562

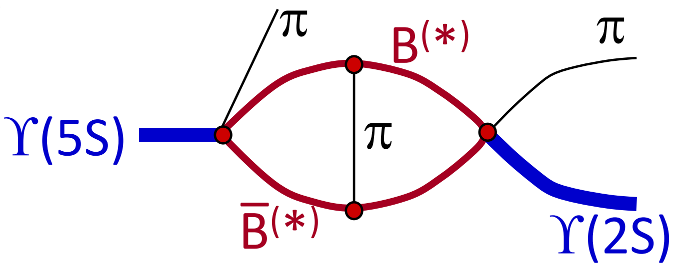
Z_b, W_{bx} — postulated states

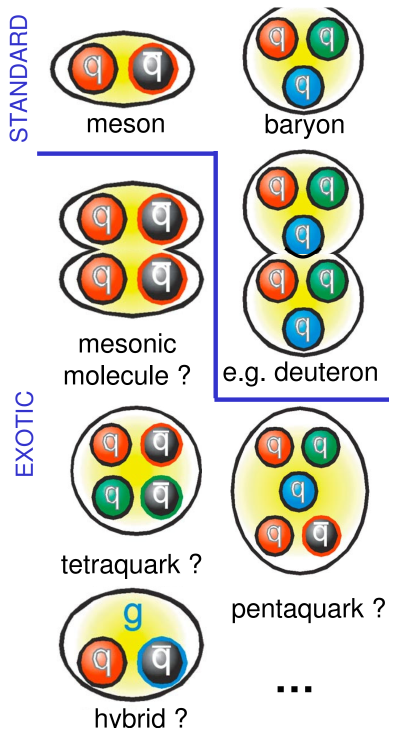
Bottomonium - atomic-like bound bb states

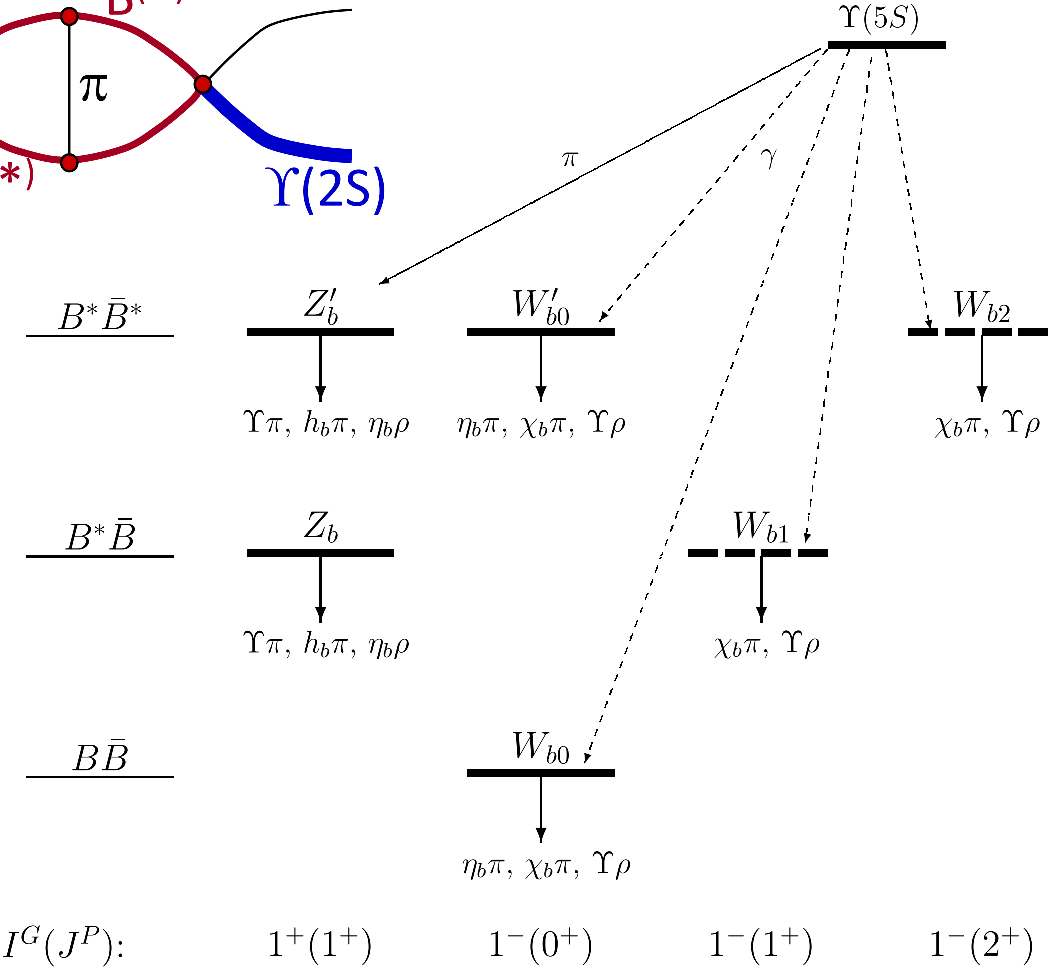
Bottomonium-like - additional quark pair

Deuteron-like molecule

π, ρ , ω, σ exchange



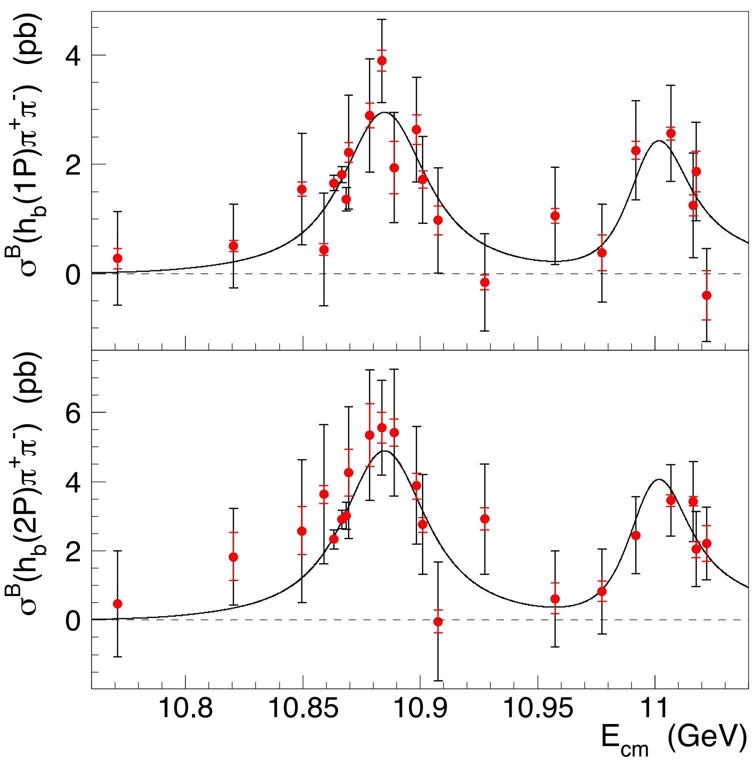


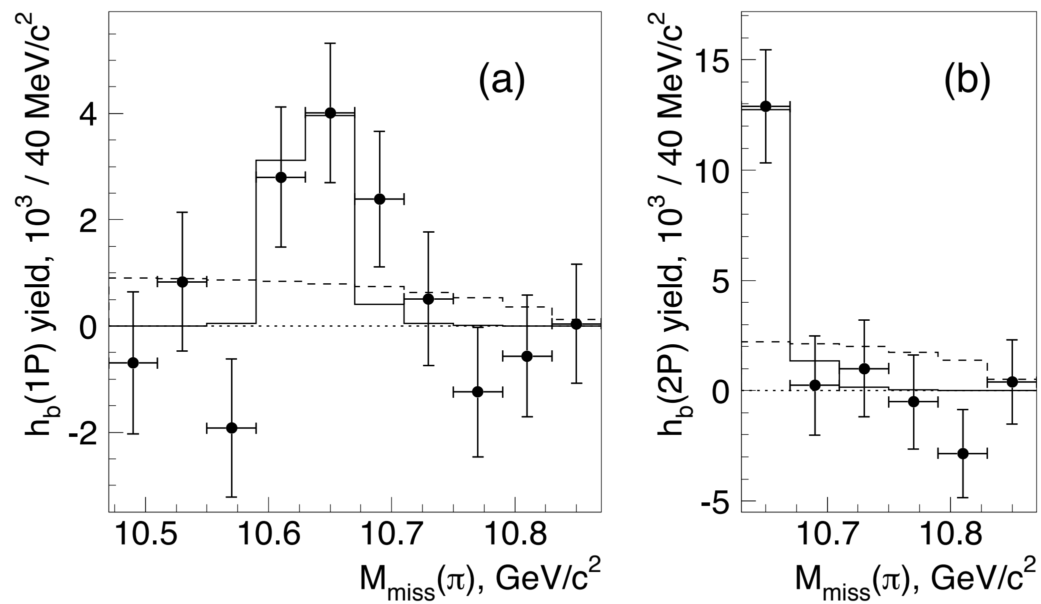


Z_b Υ(6S) Scan analysis

Belle arXiv:1508.06562

- Anomalous Υ(5S)→ ππΥ(pS) transitions led to discovery of $Z_b^{\pm}$(106XX)
  - Preliminary evidence for Υ(6S)→ ππh(nP), via $\pi Z_b^{\pm}$(106XX)
  - Resonance structure of Υ(6S) channel not fully studied
- Can be probed in phase II!





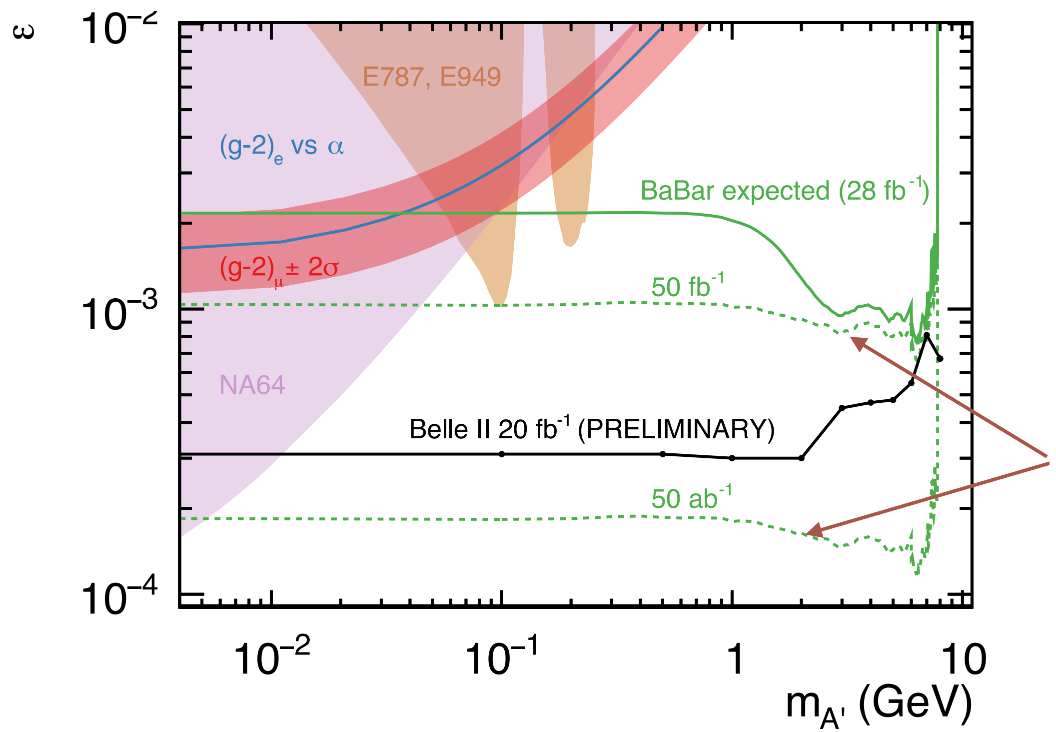
Dark Sector

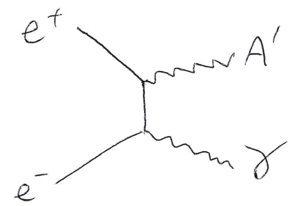
- Belle II can probe 'dark forces' with dedicated Triggers
  - 'dark forces': involving dark-matter particles that serve as portals from dark to SM sectors.

dark photon mass coupling strength

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{m^2_{A'}}{2}A'_{\mu}A'^{\mu} - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}$$

  - Also probes dark higgs through Υ(nS) resonances.





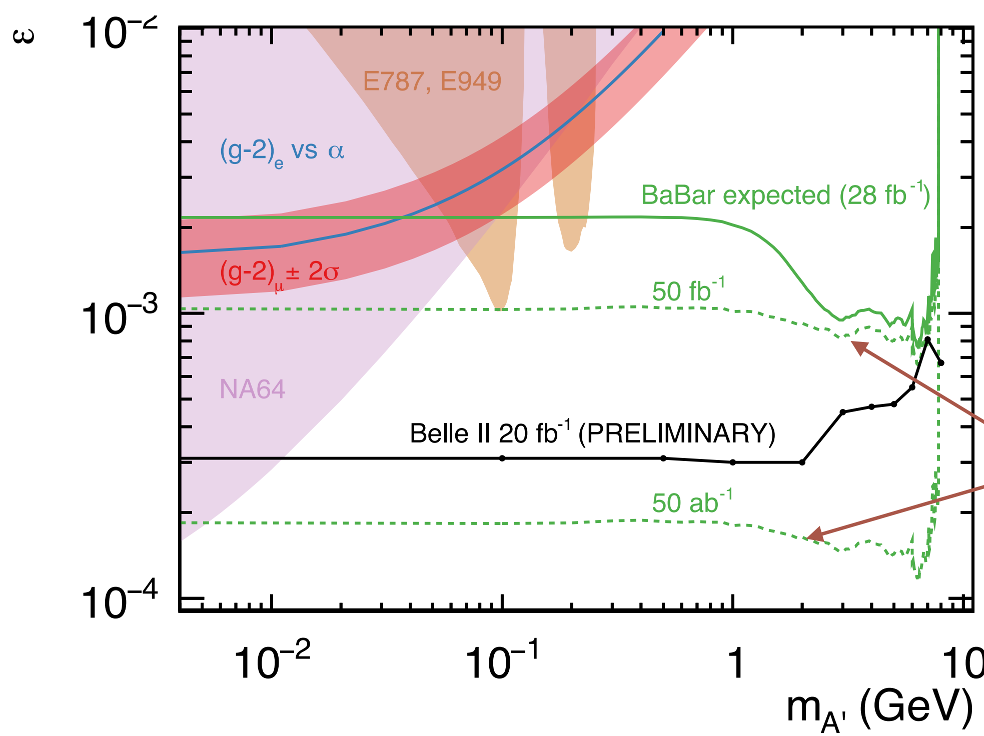
$$\sigma \propto \varepsilon^2\alpha^2\left(1 - m^2_{A'}/E^2_{CM}\right)/E^2_{CM}$$

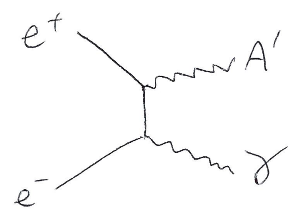
- Belle II can probe ‘dark forces’ with dedicated Triggers
  - ‘dark forces’: involving dark-matter particles that serve as portals from dark to SM sectors.

dark photon mass coupling strength

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{m^2_{A'}}{2}A'_{\mu}A'^{\mu} - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}$$

  - Also probes dark higgs through Υ(nS) resonances.





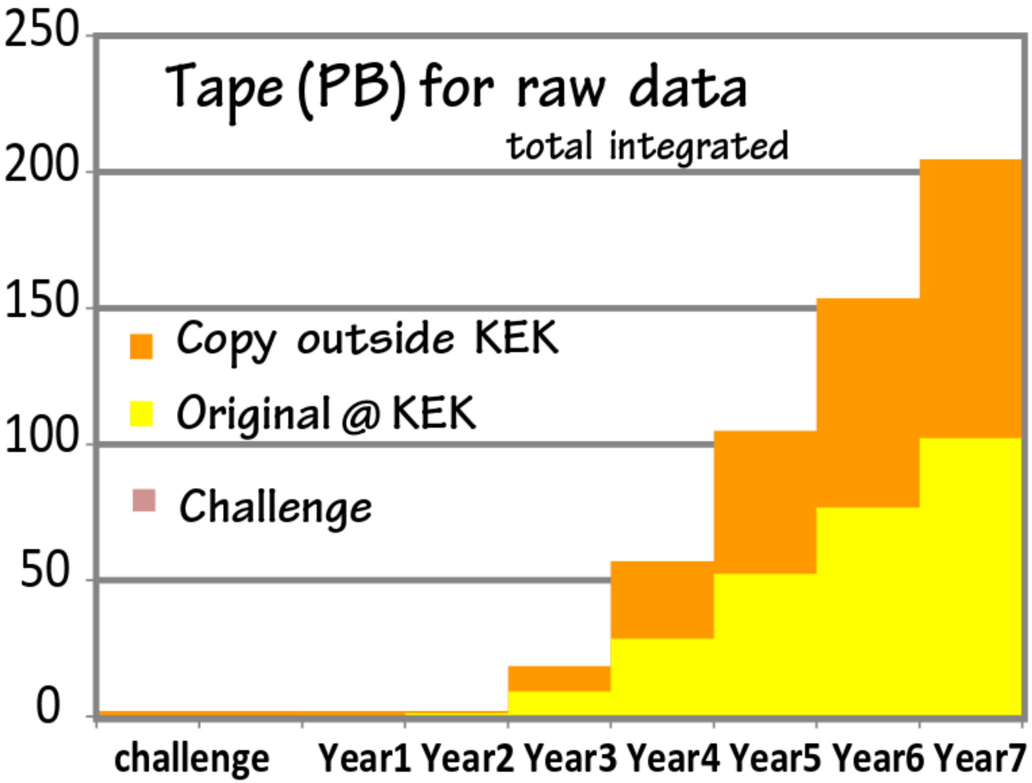
$$\sigma \propto \varepsilon^2\alpha^2\left(1 - m^2_{A'}/E^2_{CM}\right)/E^2_{CM}$$

- Belle II simulation based extrapolation
- Direct extrapolation from Babar

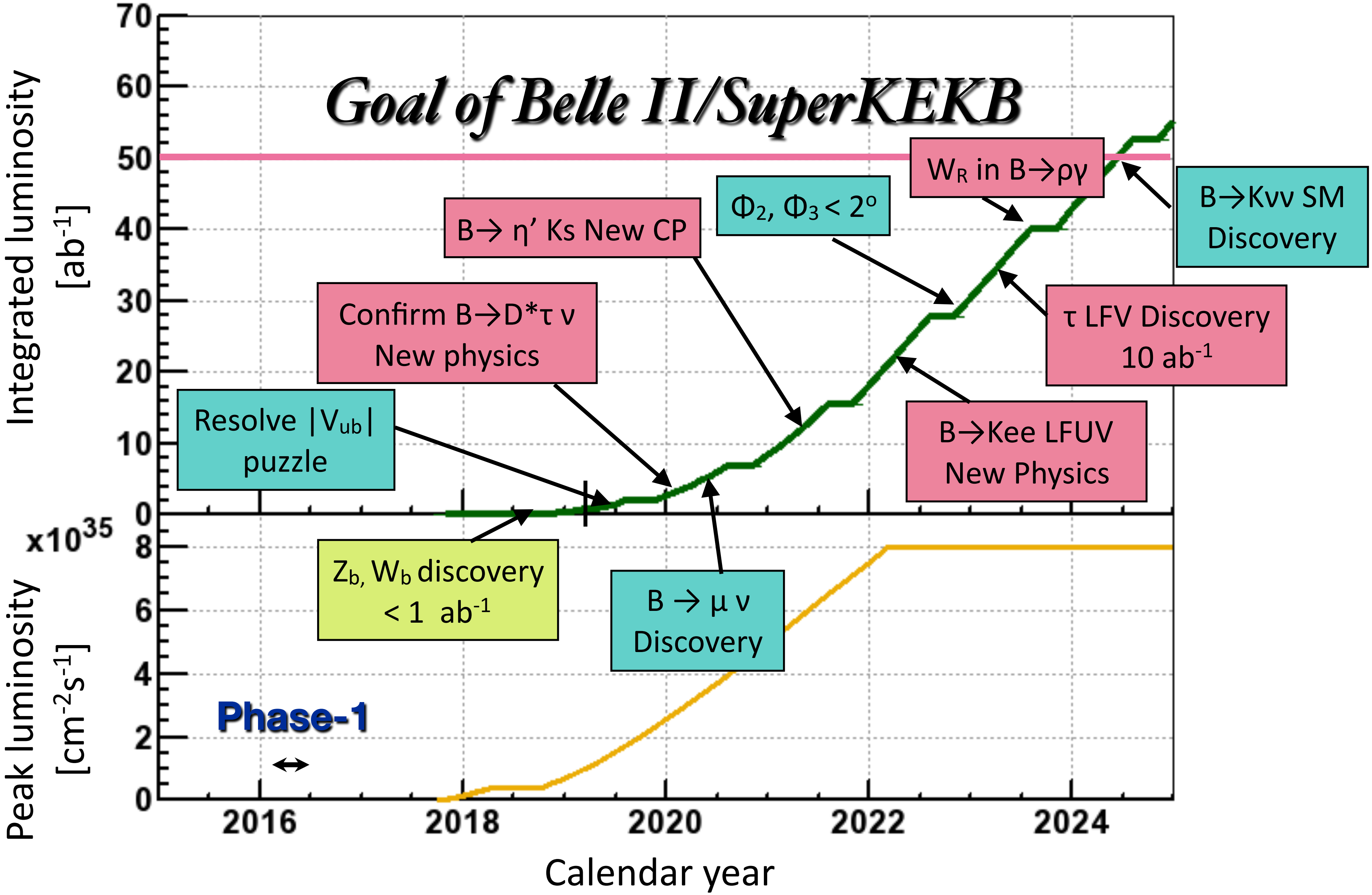
Trigger & dataset

- HLT output estimated to be ~11 nb = 11 kHz at nominal luminosity .
- Largest dataset in particle physics outside of LHC.

Trigger Hut, KEK, C-H Li (UniMelb)
Designed the physics triggers for Belle II



Roadmap



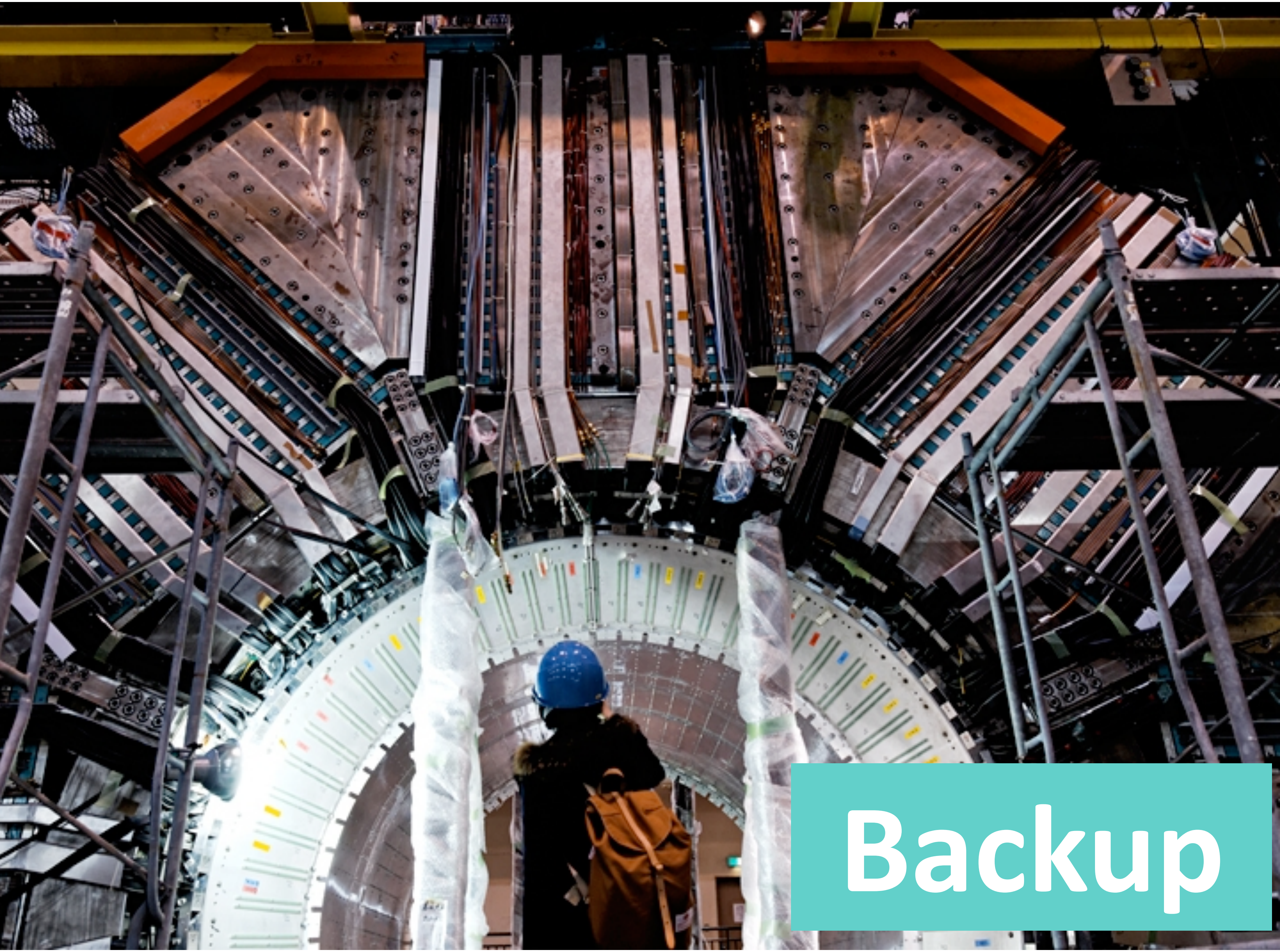
Goal of Belle II/SuperKEKB
Integrated luminosity [ab^{-1}]
70
60
50
40
30
20
10
0
Peak luminosity [cm^{-2}s^{-1}]
x10^{35}
8
6
4
2
0
2016
2018
2020
2022
2024
Calendar year
Phase-1
Resolve |V_{ub}| puzzle
Confirm B→D*τ ν New physics
B→ η' Ks New CP
Φ$_2$, Φ$_3$ < 2^o
W$_R$ in B→ργ
B→Kνν SM Discovery
τ LFV Discovery 10 ab^{-1}
B→Kee LFUV New Physics
Z$_b$, W$_b$ discovery < 1 ab^{-1}
B → μ ν Discovery

Summary

- SuperKEKB has been brought to life - first turns occurred in February. Current reached 1 Amp!
- Phase II starts January 2018, Phase III Late 2018
- 50 × integrated luminosity @ Belle II will probe significantly into > 1 TeV mass scale

- **Rich physics program at SuperKEKB/BelleII**
  - New sources of CPV, New gauge bosons, Lepton Flavour Violation, Dark Sectors.
  - **Numerous anomalies to probe with the first 5 ab^{-1} (many more than shown).**

- **The Belle II physics book to be published in 2017 (ed. PU & E. Kou)**


Backup

Golden modes: B physics

SuperKEKB TDR (2014)

	Observables	Belle (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
UT angles	$\sin 2\beta$	$0.667 \pm 0.023 \pm 0.012$ [64]	0.012	0.008
	α [°]	85 ± 4 (Belle+BaBar) [24]	2	1
	γ [°]	68 ± 14 [13]	6	1.5
Gluonic penguins	$S(B \to \phi K^0)$	$0.90^{+0.09}_{-0.19}$ [19]	0.053	0.018
	$S(B \to \eta' K^0)$	$0.68 \pm 0.07 \pm 0.03$ [65]	0.028	0.011
	$S(B \to K^0_S K^0_S K^0_S)$	$0.30 \pm 0.32 \pm 0.08$ [17]	0.100	0.033
	$\mathcal{A}(B \to K^0 \pi^0)$	$-0.05 \pm 0.14 \pm 0.05$ [66]	0.07	0.04
UT sides	$\lvert V_{cb}\rvert$ incl.	$41.6 \cdot 10^{-3}(1 \pm 1.8\%)$ [8]	1.2%	
	$\lvert V_{cb}\rvert$ excl.	$37.5 \cdot 10^{-3}(1 \pm 3.0\%_{\text{ex.}} \pm 2.7\%_{\text{th.}})$ [10]	1.8%	1.4%
	$\lvert V_{ub}\rvert$ incl.	$4.47 \cdot 10^{-3}(1 \pm 6.0\%_{\text{ex.}} \pm 2.5\%_{\text{th.}})$ [5]	3.4%	3.0%
	$\lvert V_{ub}\rvert$ excl. (had. tag.)	$3.52 \cdot 10^{-3}(1 \pm 8.2\%)$ [7]	4.7%	2.4%
Missing E decays	$\mathcal{B}(B \to \tau\nu)$ [10^{-6}]	$96(1 \pm 27\%)$ [26]	10%	5%
	$\mathcal{B}(B \to \mu\nu)$ [10^{-6}]	< 1.7 [67]	20%	7%
	$R(B \to D\tau\nu)$	$0.440(1 \pm 16.5\%)$ [29]†	5.6%	3.4%
	$R(B \to D^*\tau\nu)^\dagger$	$0.332(1 \pm 9.0\%)$ [29]†	3.2%	2.1%
	$\mathcal{B}(B \to K^{*+}\nu\overline{\nu})$ [10^{-6}]	< 40 [30]	< 15	30%
	$\mathcal{B}(B \to K^{+}\nu\overline{\nu})$ [10^{-6}]	< 55 [30]	< 21	30%
Rad. & EW penguins	$\mathcal{B}(B \to X_s\gamma)$	$3.45 \cdot 10^{-4}(1 \pm 4.3\% \pm 11.6\%)$	7%	6%
	$A_{CP}(B \to X_{s,d}\gamma)$ [10^{-2}]	$2.2 \pm 4.0 \pm 0.8$ [68]	1	0.5
	$S(B \to K^0_S \pi^0 \gamma)$	$-0.10 \pm 0.31 \pm 0.07$ [20]	0.11	0.035
	$S(B \to \rho\gamma)$	$-0.83 \pm 0.65 \pm 0.18$ [21]	0.23	0.07
	C_7/C_9 ($B \to X_s\ell\ell$)	$\sim$20% [36]	10%	5%
	$\mathcal{B}(B_s \to \gamma\gamma)$ [10^{-6}]	< 8.7 [42]	0.3	–
	$\mathcal{B}(B_s \to \tau\tau)$ [10^{-3}]	–	< 2 [44]‡	–

Golden modes: D and Tau physics

SuperKEKB TDR (2014)

	Observables	Belle (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
Charm Rare	$\mathcal{B}(D_s \to \mu\nu)$	$5.31 \cdot 10^{-3}(1 \pm 5.3\% \pm 3.8\%)$ [46]	2.9%	0.9%
	$\mathcal{B}(D_s \to \tau\nu)$	$5.70 \cdot 10^{-3}(1 \pm 3.7\% \pm 5.4\%)$ [46]	3.5%	2.3%
	$\mathcal{B}(D^0 \to \gamma\gamma)$ [10^{-6}]	< 1.5 [49]	30%	25%
Charm CP	$A_{CP}(D^0 \to K^+K^-)$ [10^{-2}]	$-0.32 \pm 0.21 \pm 0.09$ [69]	0.11	0.06
	$A_{CP}(D^0 \to \pi^0\pi^0)$ [10^{-2}]	$-0.03 \pm 0.64 \pm 0.10$ [70]	0.29	0.09
	$A_{CP}(D^0 \to K^0_S\pi^0)$ [10^{-2}]	$-0.21 \pm 0.16 \pm 0.09$ [70]	0.08	0.03
Charm Mixing	$x(D^0 \to K^0_S\pi^+\pi^-)$ [10^{-2}]	$0.56 \pm 0.19 \pm {}^{0.07}_{0.13}$ [52]	0.14	0.11
	$y(D^0 \to K^0_S\pi^+\pi^-)$ [10^{-2}]	$0.30 \pm 0.15 \pm {}^{0.05}_{0.08}$ [52]	0.08	0.05
	$\lvert q/p\rvert(D^0 \to K^0_S\pi^+\pi^-)$	$0.90 \pm {}^{0.16}_{0.15} \pm {}^{0.08}_{0.06}$ [52]	0.10	0.07
	$\phi(D^0 \to K^0_S\pi^+\pi^-)$ [°]	$-6 \pm 11 \pm {}^{4}_{5}$ [52]	6	4
Tau	$\tau \to \mu\gamma$ [10^{-9}]	< 45 [71]	< 14.7	< 4.7
	$\tau \to e\gamma$ [10^{-9}]	< 120 [71]	< 39	< 12
	$\tau \to \mu\mu\mu$ [10^{-9}]	< 21.0 [72]	< 3.0	< 0.3

The periodic table of particle physics

$\begin{pmatrix} m_\nu, \\ m_u, \\ \vdots \end{pmatrix}$

Families

in units of **GeV = 10^9eV**

Families				
1	ν_e (≈0)	ν_μ (≈0)	ν_τ (≈0)	$< 10^{-9}$
2	e^- ($5\cdot10^{-4}$)	μ^- (0.105)	τ^- (1.78)	
3	u ($3\cdot10^{-3}$)	c (1.3)	t (170)	
4	d ($6\cdot10^{-3}$)	s (0.100)	b (4.5)	

Very hierarchical structure

Particles in a given family distinguished only by the mass!

Seesaw mechanisms can generate mass

Seesaw mechanisms are candidates

<u>Seesaw (tree level)</u>

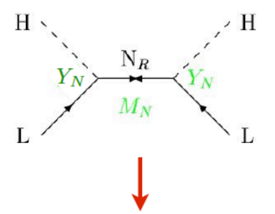
$m^{\nu}_{ij} = y_i y_j v^2/M$ M = 10^{14} GeV (for y_i=O(1))

<u>Quantum Effects (Radiative Seesaw)</u> N-th order of perturbation

$m^{\nu}_{ij} = [1/(16\pi^2)]^N C_{ij} v^2/M$ M=1 TeV

Type I:
Fermion singlet

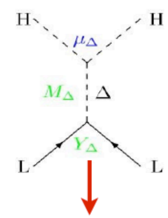
N_{R_i}



$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

Type II:
Scalar triplet

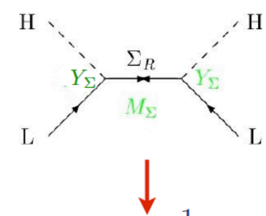
$\Delta \equiv (\Delta^{++}, \Delta^{+}, \Delta^{0})$



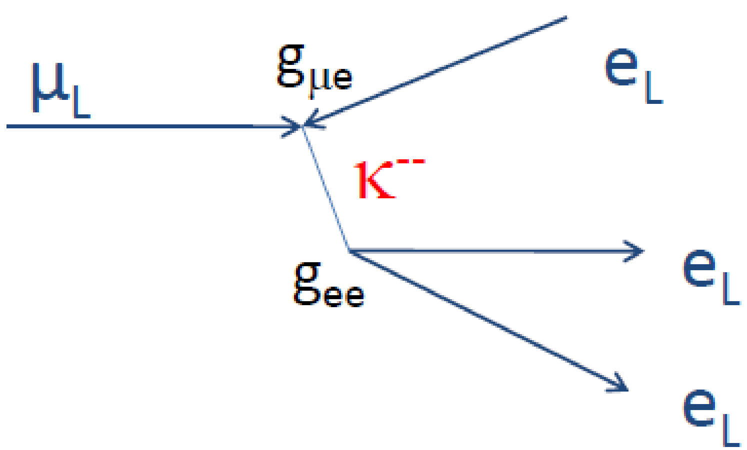
$$m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

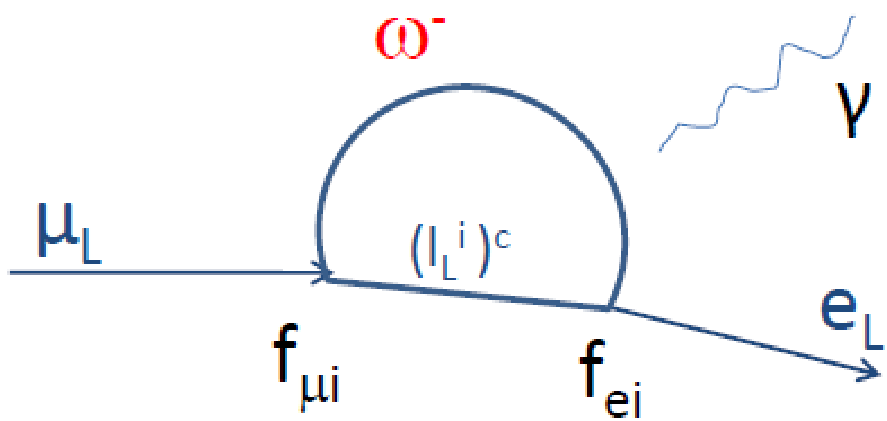
Type III:
Fermion triplet

$\Sigma_i \equiv (\Sigma_i^+, \Sigma_i^0, \Sigma_i^-)$



$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$



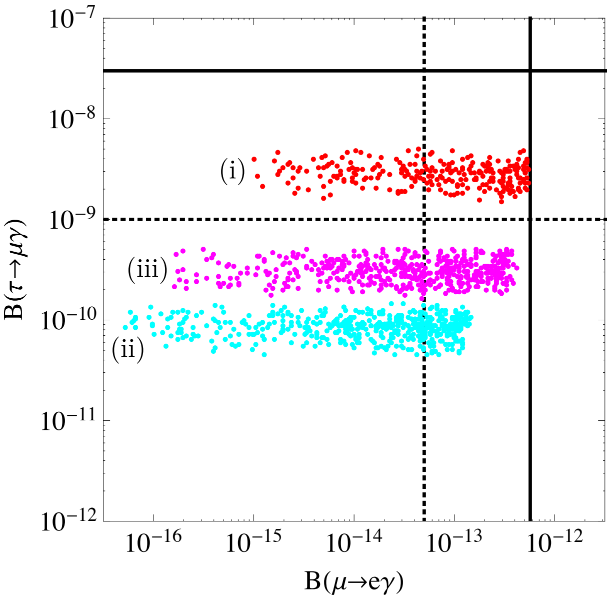


Nature of NP in τ LFV

Non-degenerate, SUSY, Type 1 Seesaw

LHC synergy with H → τ μ anomaly: Leptoquarks

T. Goto et al. Phys. Rev. D 91, 033007 (2015)



SUSY parameter:

$M_{1/2} = 1.5\,\mathrm{TeV},\ \mu > 0,$

(i) $A_0 = -2,\ M_0 = 2\,\mathrm{TeV},\ \tan\beta = 30$

(ii) $A_0 = 0,\ M_0 = 6\,\mathrm{TeV},\ \tan\beta = 30$

(iii) $A_0 = 0,\ M_0 = 6\,\mathrm{TeV},\ \tan\beta = 50$

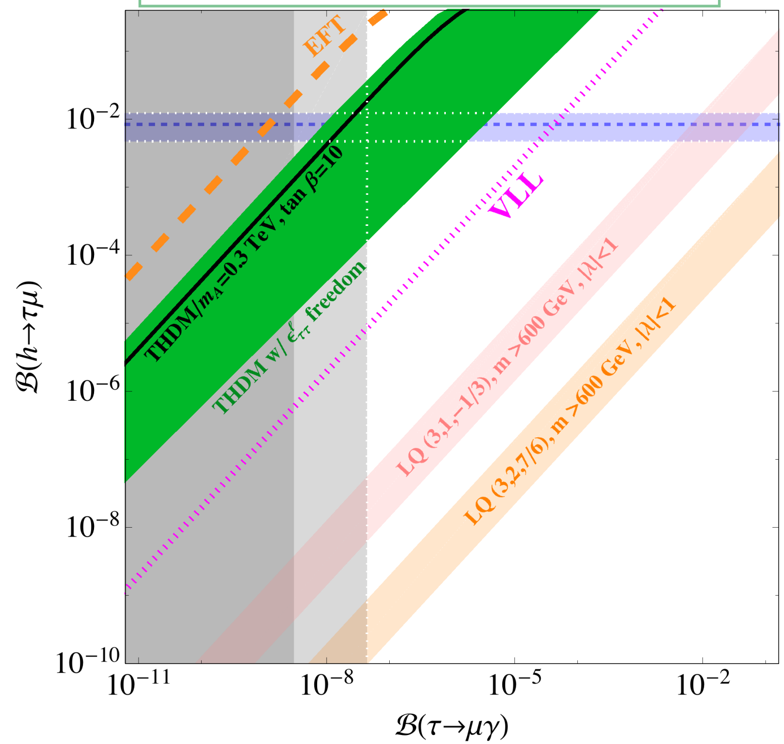
Neutrino Yukawa:

$0 \le \theta \le \pi/2,$

$1.5 < y_{2,3} < 2.0,$

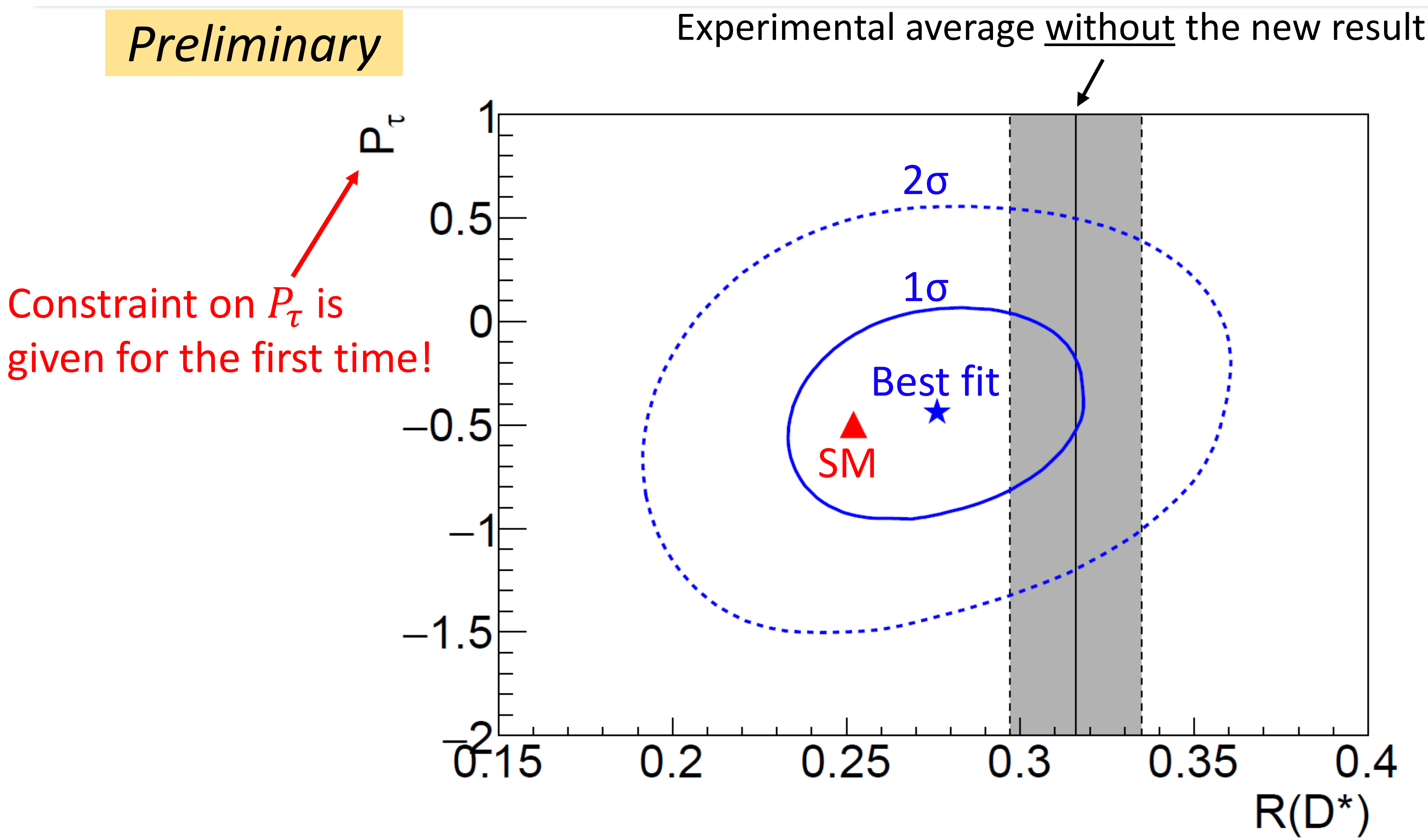
$0.01 < y_1 < 0.1$

I. Dorsner et al., JHEP 1506 (2015) 108



B → D* τ ν, τ → h ν

Preliminary



- By combining $R(D^*)$ and P_τ, our result is consistent with the SM within 0.6σ

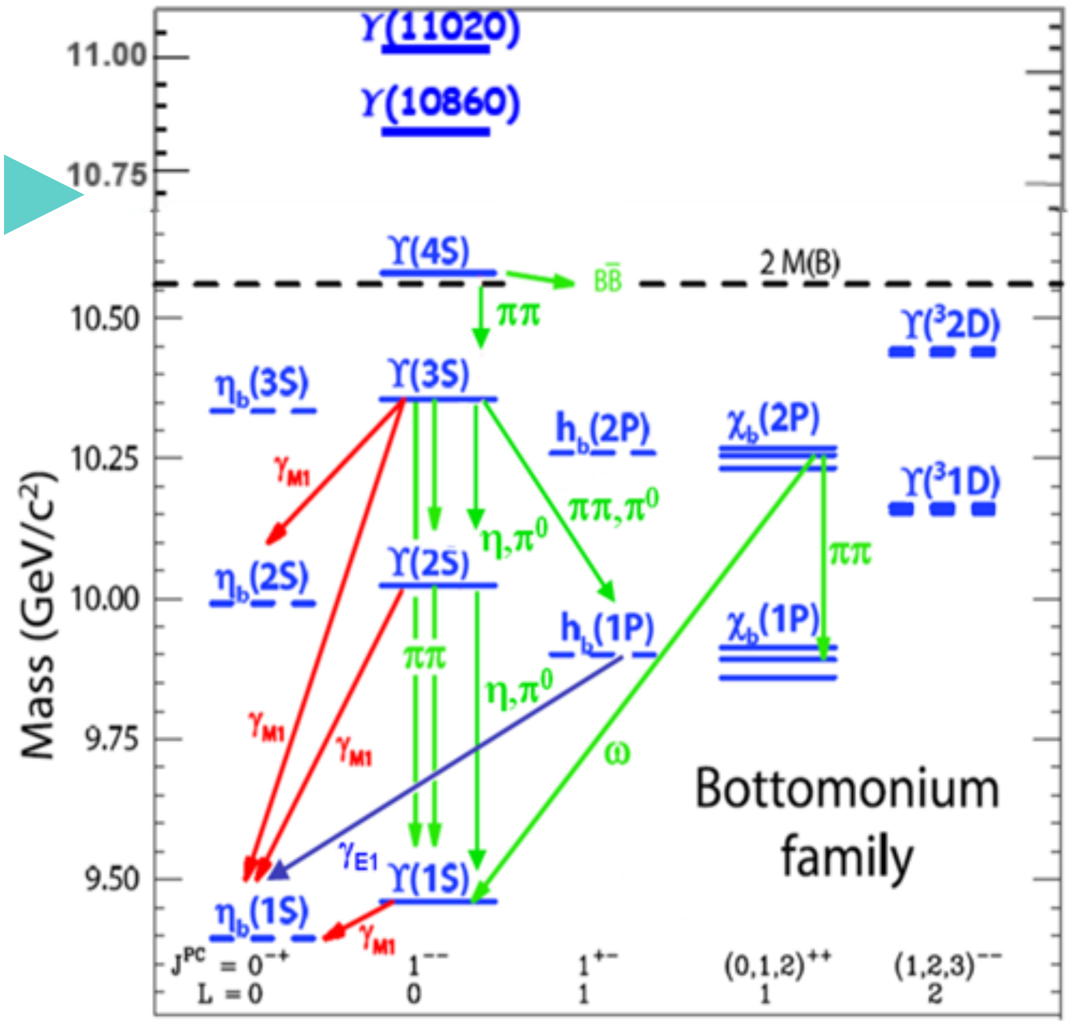
Bottomonia

Bottomonium

- atomic-like bound bb states

Bottomonium-like

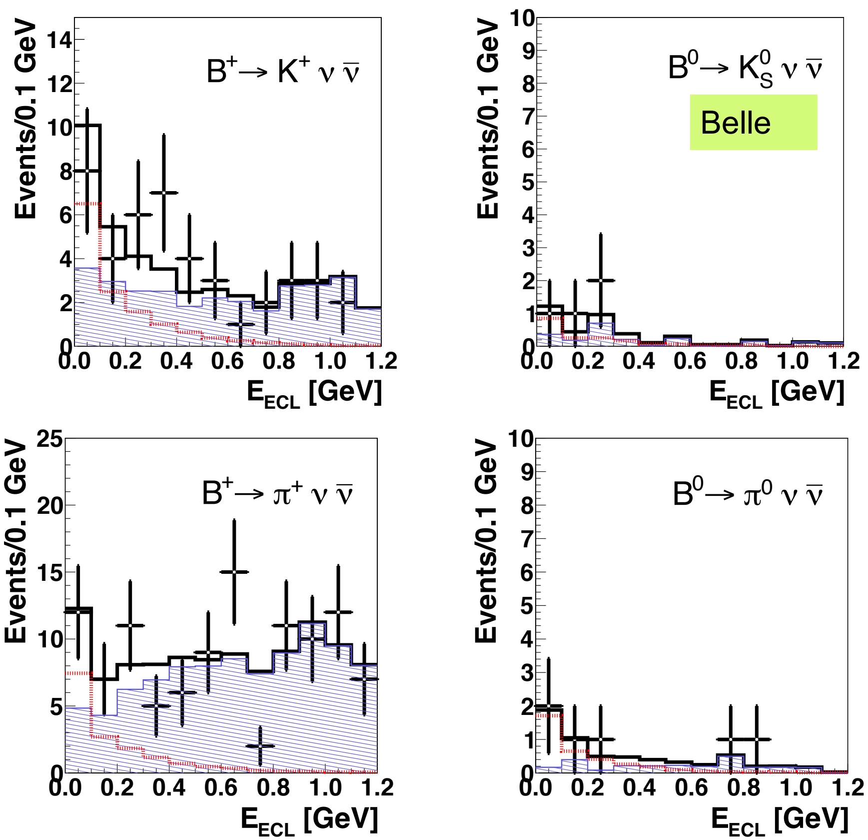
- additional quark pair



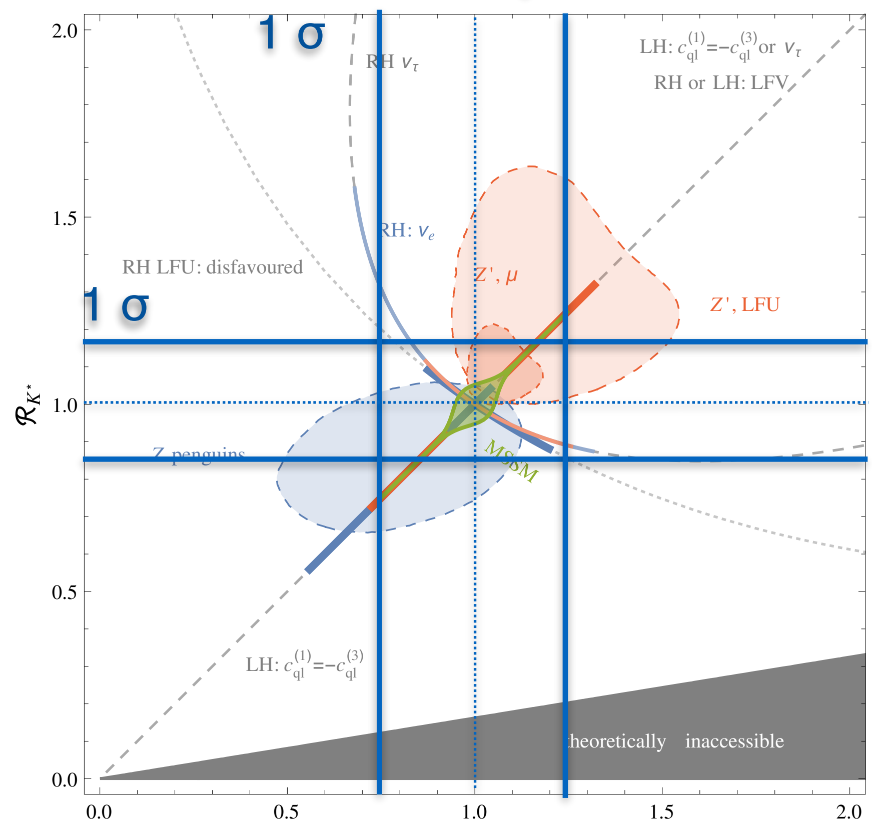
Where else can we look? Isolate Z' penguins

Babar, $B \to K^{(*)} \nu \nu$, PRD 87, 112005 (2013)
Belle, $B \to K^{(*)}/\pi/\rho\ \nu \nu$, PRD 87, 111103(R) (2013)

- R_K anomaly could imply NP here.
- We expect 5σ on $B \to K^{(*)} \nu \nu$!



Belle II expected



sensitive to L-R symmetry

BG-NNS, arXiv: 1409.4557

$$\mathcal{B}(B \to K^{*+} \nu\bar{\nu})_{SM} = (9.2 \pm 1.0) \times 10^{-6}$$
$$\mathcal{B}(B \to K^{+} \nu\bar{\nu})_{SM} = (4.0 \pm 0.5) \times 10^{-6}$$

4 ways for NP to manifest in Flavour

- Common model-building step is to extend the gauge structure of the SM.

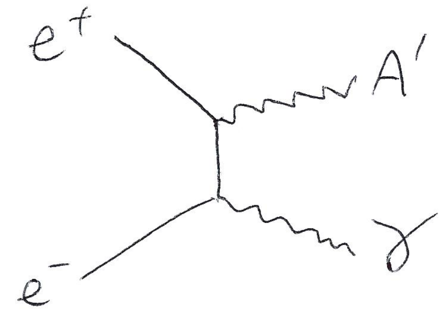
1. An additional U(1)x gauge symmetry (e.g. a Z′): Flavour changing neutral current.

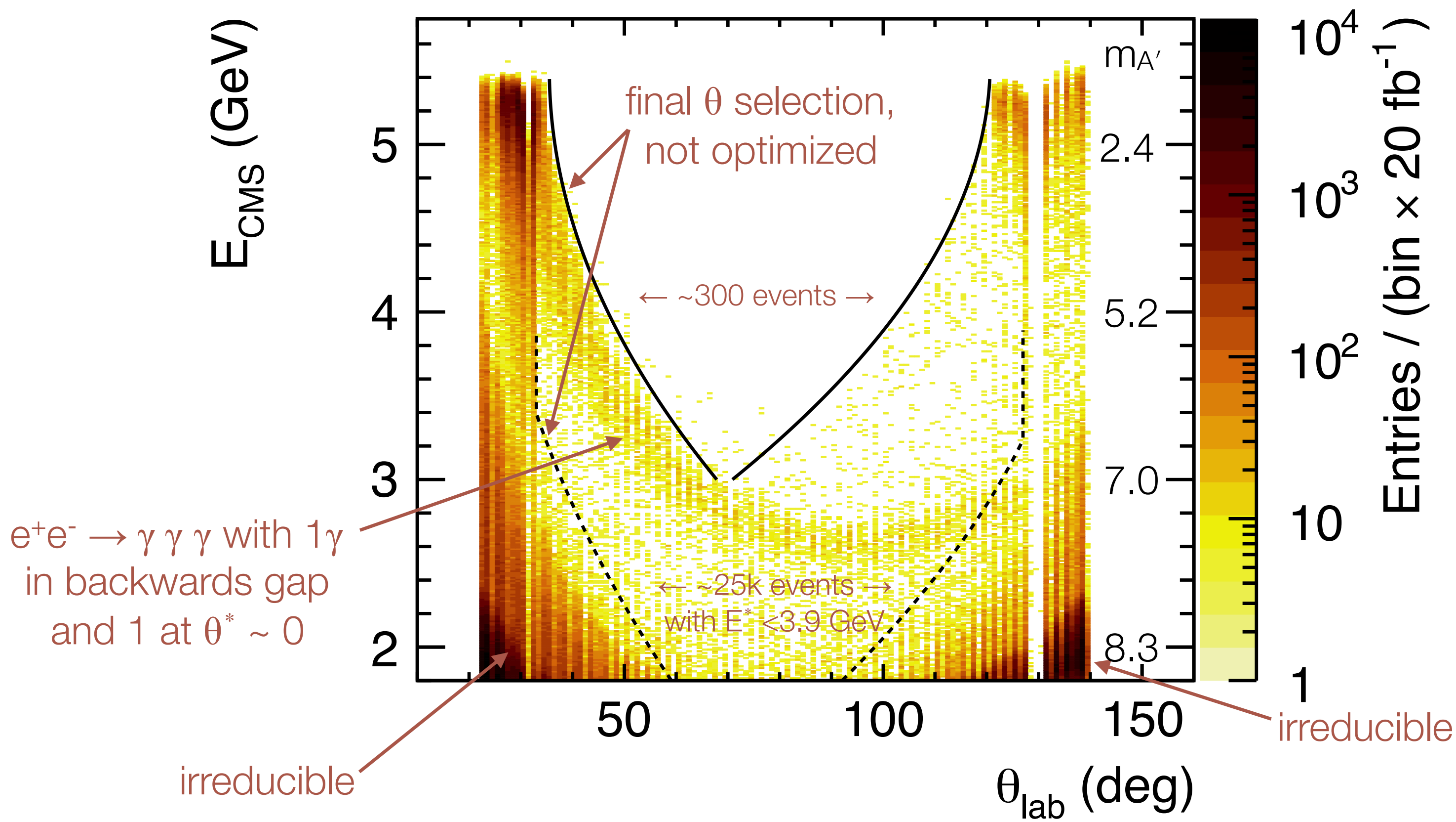
2. An additional Higgs doublet: charged Higgs.

3. Restoration of Left-Right Symmetry: i.e. Additional Right handed SU(2): $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
   - → New heavy gauge bosons W′, Z′ and new heavy charged and neutral Higgs particles.
   - → Quark flavour mixing matrices $V_L = V_{CKM}$ and V_R describing left- and right-handed charged current interactions — 5 more CP phases.

4. Add a heavy seesaw neutrino partner: majorana mass term, LFV.

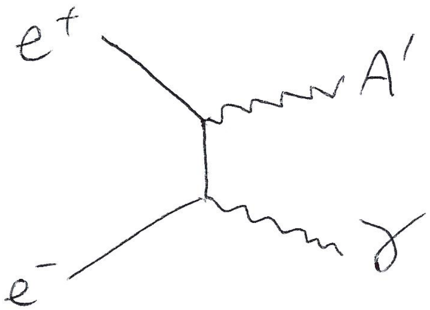
- Single photon triggered (*New*)
- BaBar: 28fb^{-1} single-photon trigger (Υ(2S,3S)) unpublished.





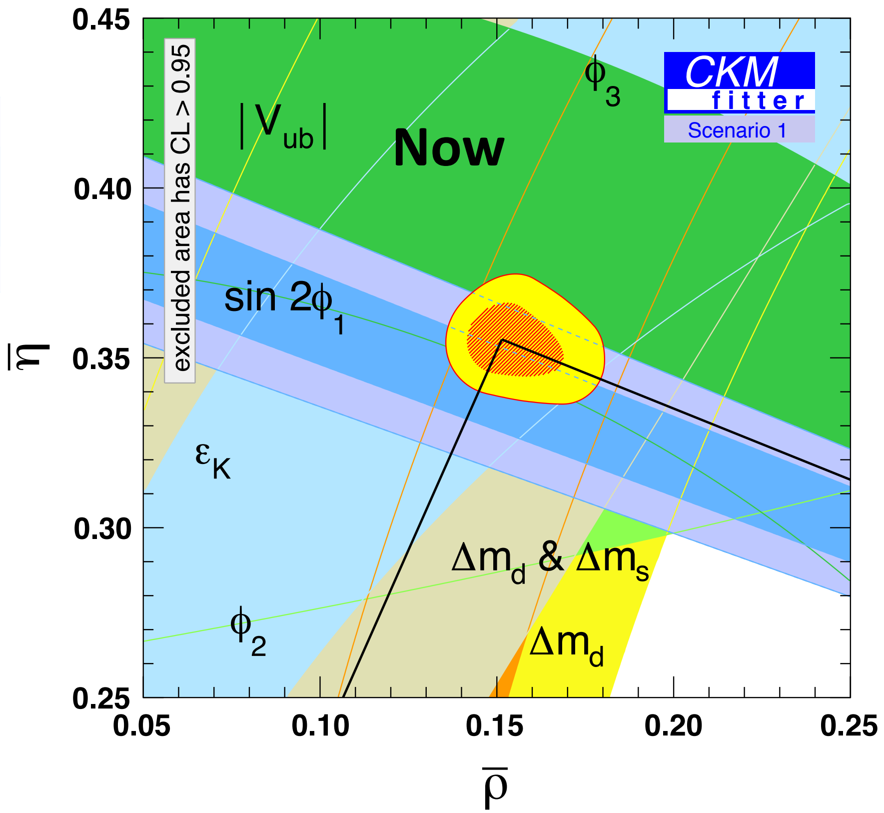
Dark photon to invisible, e+e- → γ A', A' → invisible.

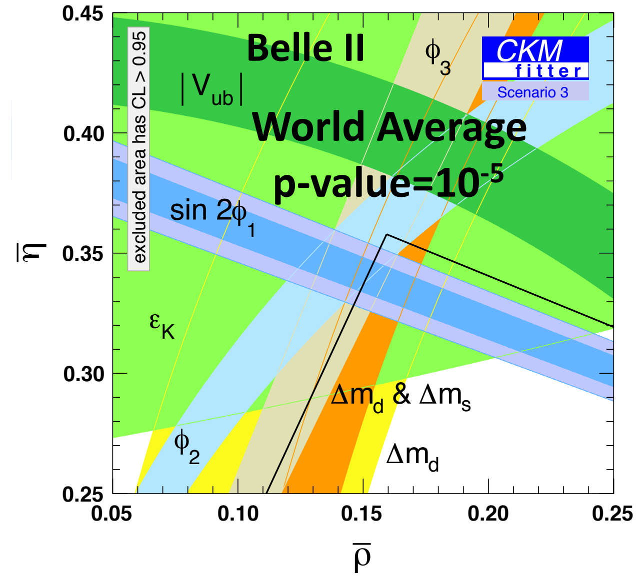
- Single photon triggered (*New*)
- BaBar: 28fb^{-1} single-photon trigger (Y(2S,3S)) unpublished.

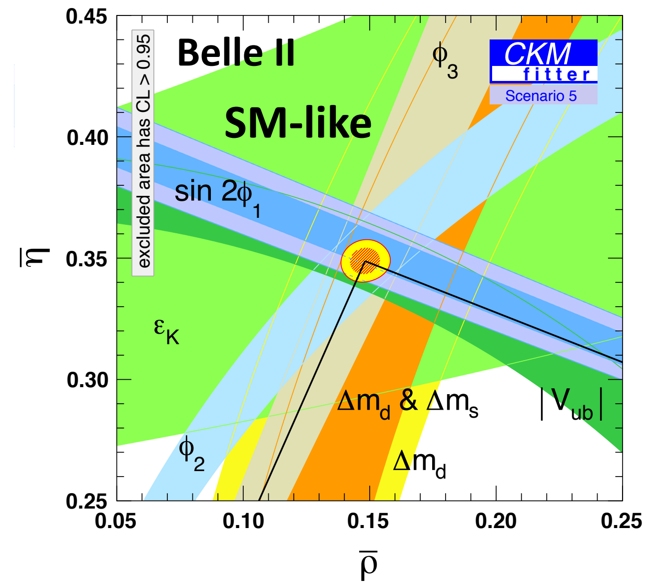


Belle II & LHCb projections

PU, CKMfitter preliminary







Phase	J [10^{-5}]	Δ
2016	3.140 [+0.069 -0.084]	2%
Belle II + LHCb upgrade - SM-like	3.125 ± 0.033	1%