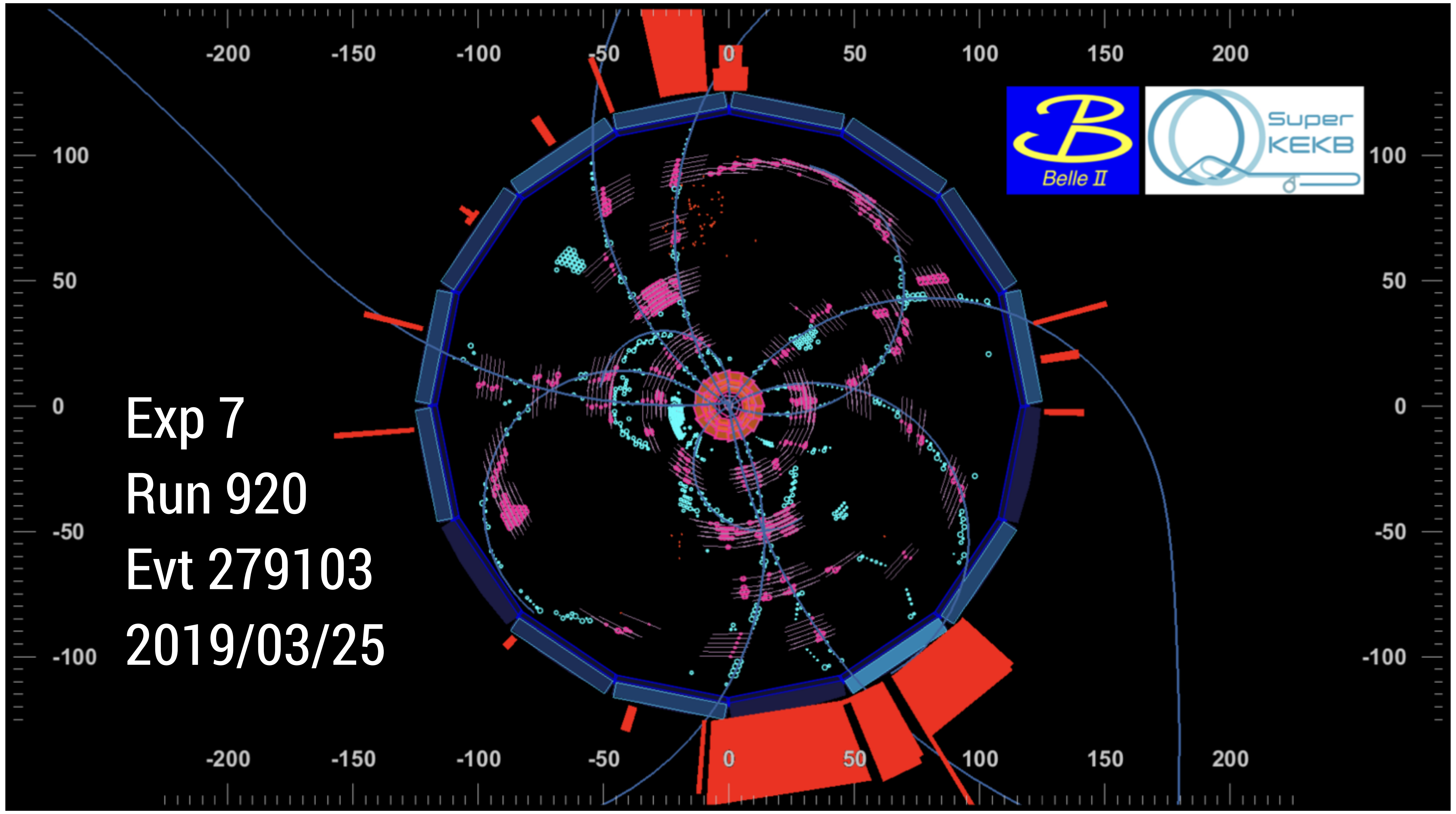
Flavour measurements in the next five years (Focusing on Belle II)



Phillip Urquijo
The University of Melbourne

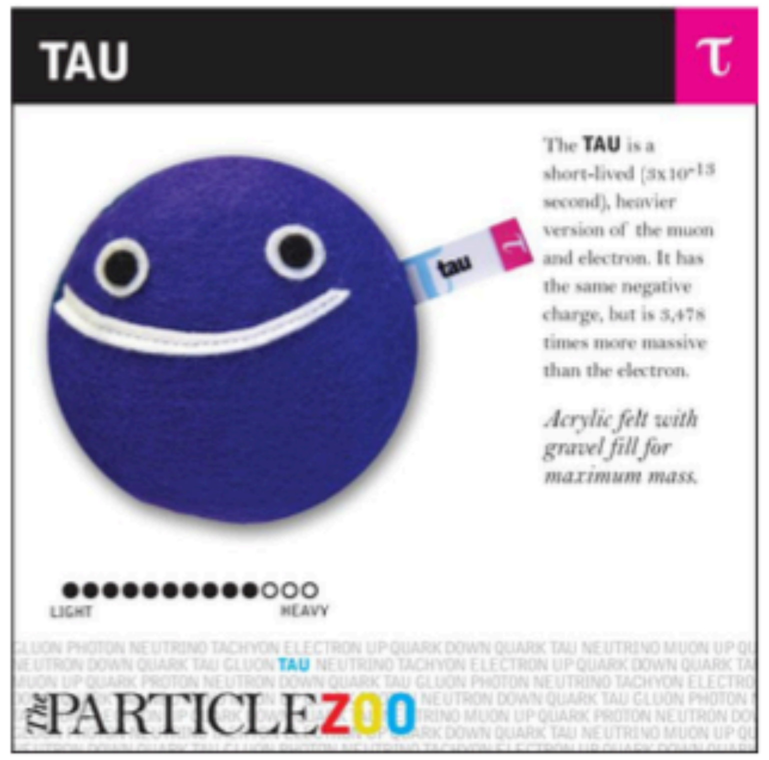
WHEPP
IIT Guwahati, December 2019

Belle II

THE UNIVERSITY OF MELBOURNE

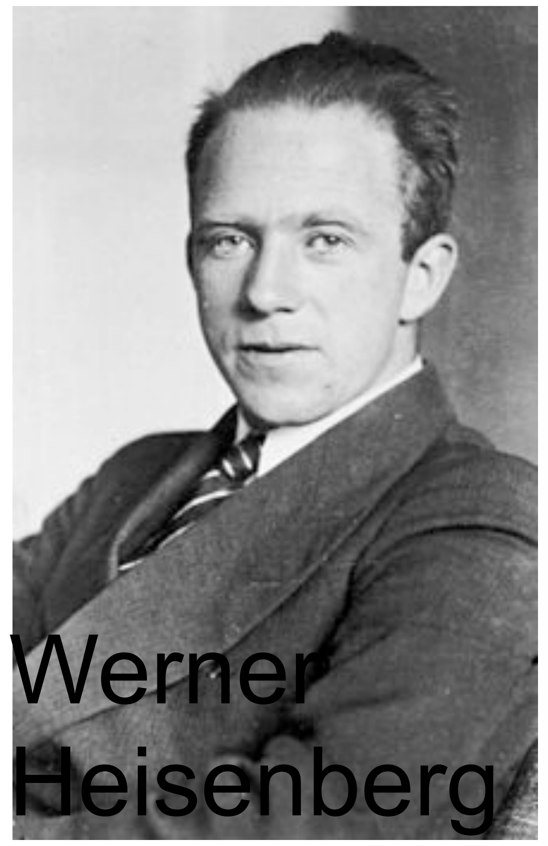
Driving questions for flavour physics research

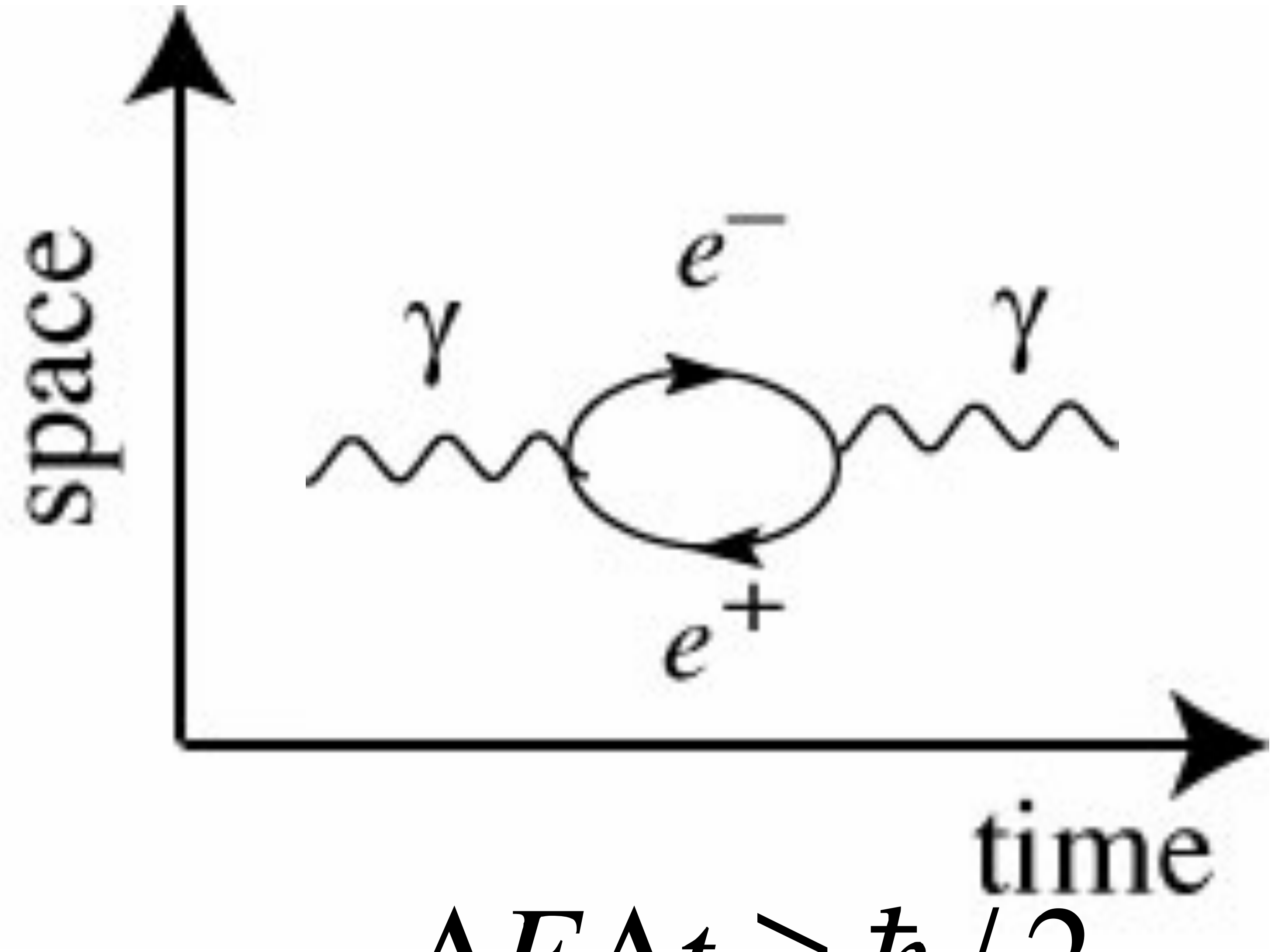
- **Matter antimatter asymmetry**
  → <u>New sources of CP Violation</u>
- Quark and Lepton flavour & mass hierarchy
  →extended gauge sector coupling to third generation ($H^{\pm}$, W', Z')
  →restored L-R symmetry
- **Finite neutrino masses**
  → <u>LFV and LFUV.</u>
- 19 free parameters
  → GUTs, **<u>leptoquarks</u>**
- Hidden and dark sectors at the GeV scale, may have flavour properties.



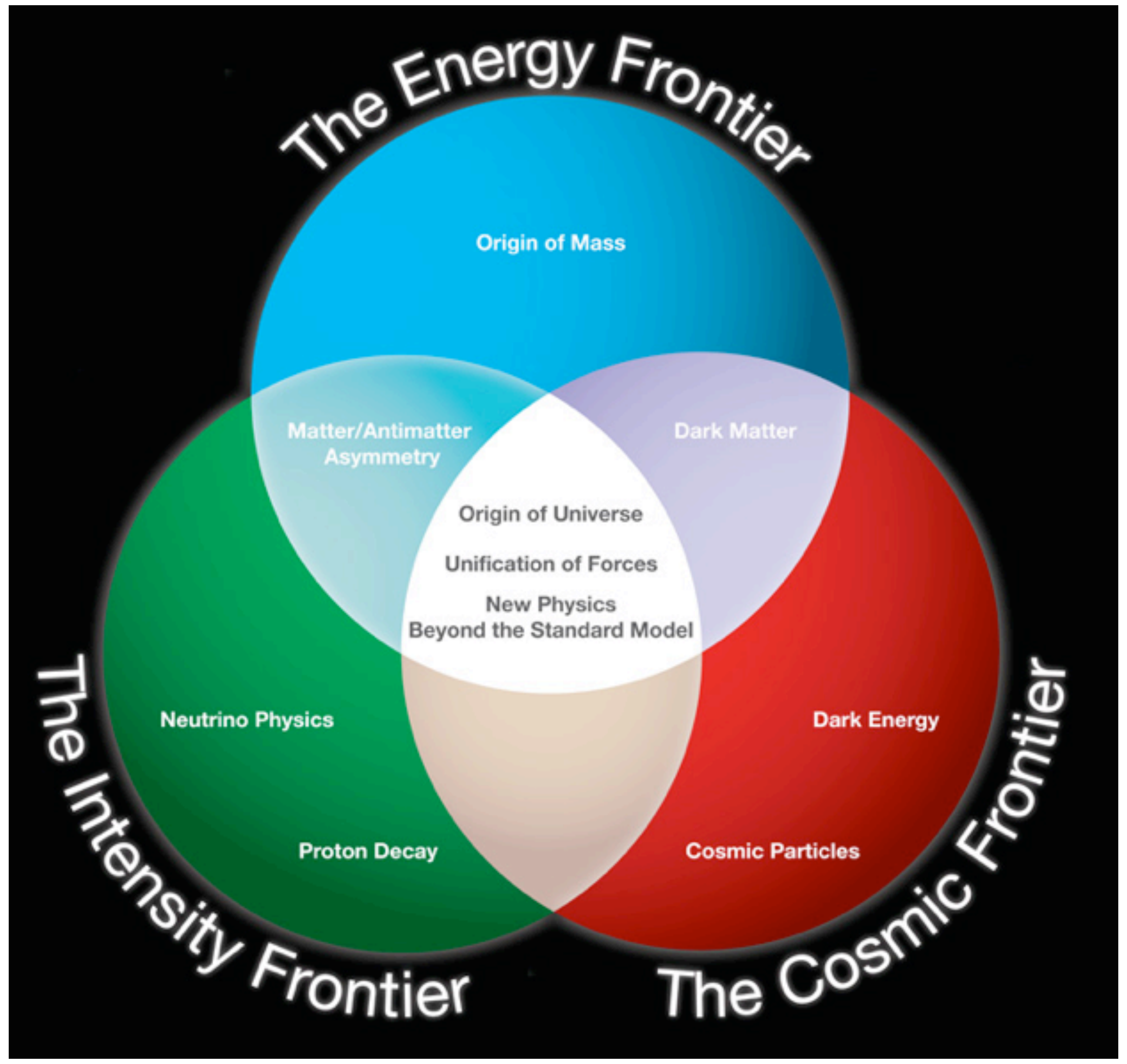
- **Leptonic and Semileptonic decays**
  - CKM matrix element magnitudes
  - Violations of lepton flavour universality
- **Direct and indirect CP violation**
  - SM Weak CP phase
  - New sources of CP violation

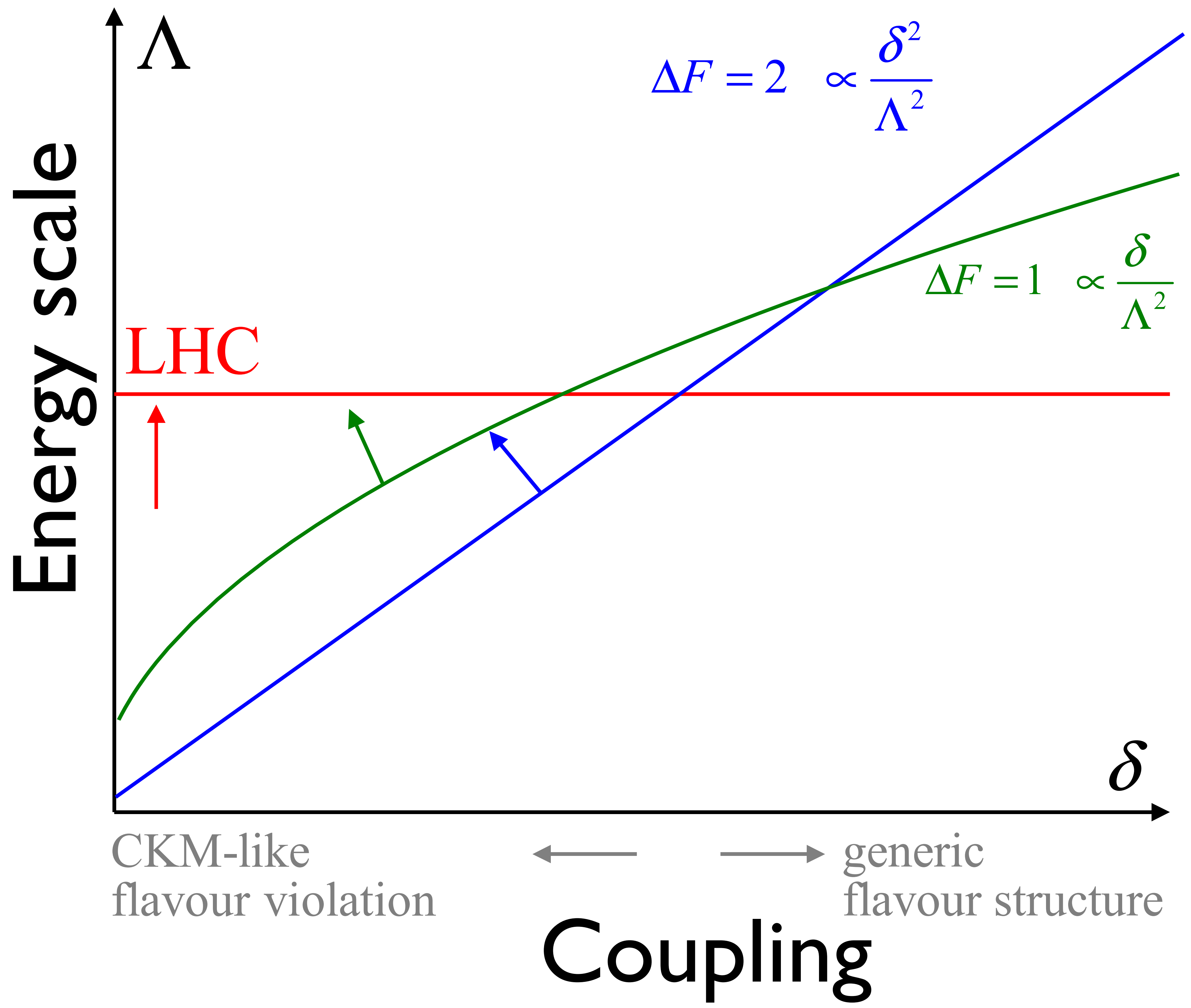
How to search for new phenomena in flavour transitions





$$\Delta E \Delta t \geq \hbar / 2$$





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

MENU nature International journal of science

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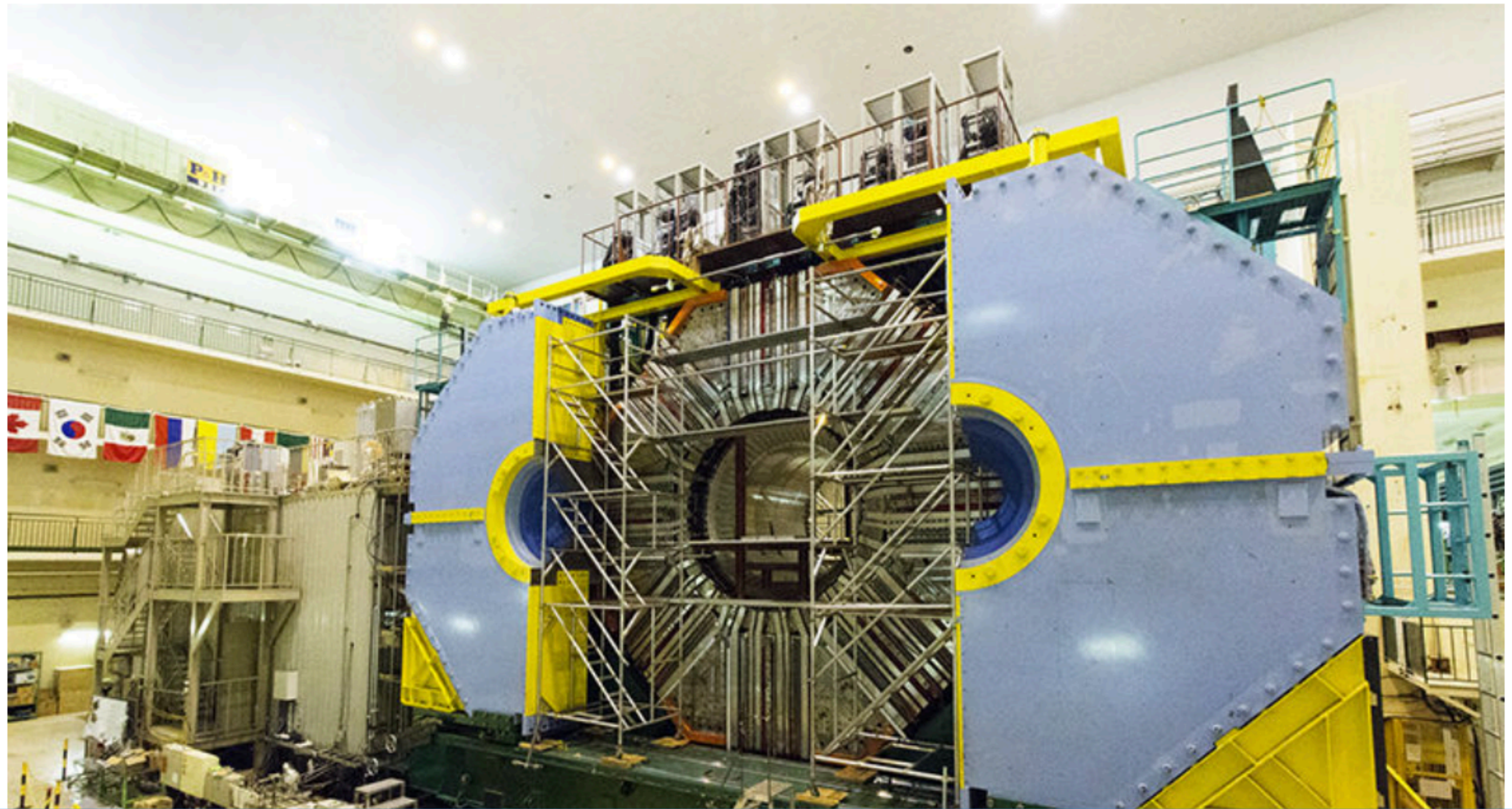
NEWS · 12 JANUARY 2018

Revamped collider hunts for cracks in the fundamental theory of physics

Experiment smashes electrons into positrons to search for unseen particles and problems with overarching physics framework.

Elizabeth Gibney



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PHYSICS

Lawbreaking Particles May Point to a Previously Unknown Force in the Universe

Scientists aren't yet certain that electrons and their relatives are violating the Standar
Model of particle physics, but the evidence is mounting

By Jesse Dunietz on July 17, 2017

New Scientist

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FEATURE 27 April 2016

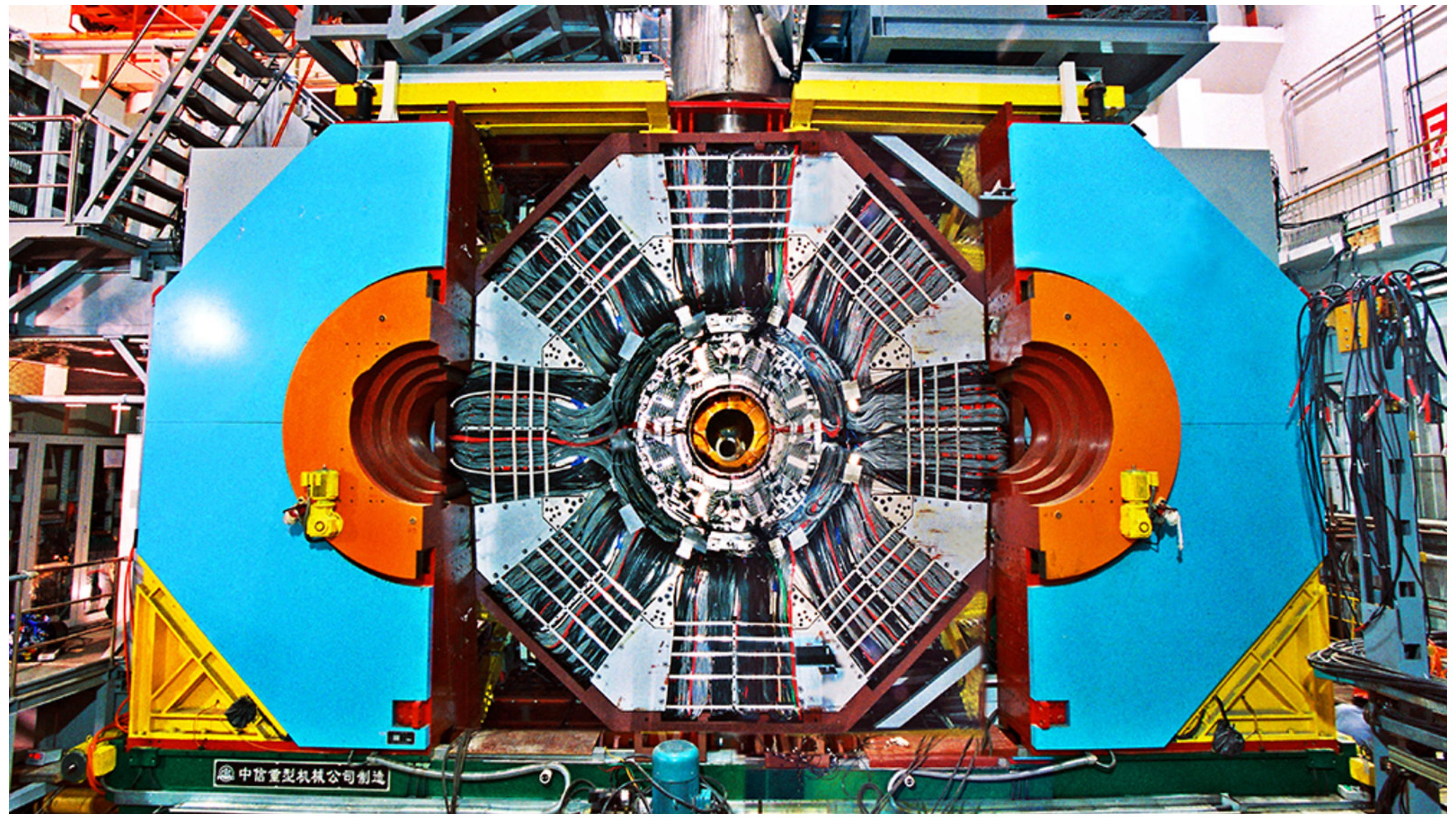
That's odd: Unruly penguins hint where all the antimatter went

Rare "penguin" particle decays should all happen at the same rate. They don't – perhaps providing a clue to why we live in a universe made of matter

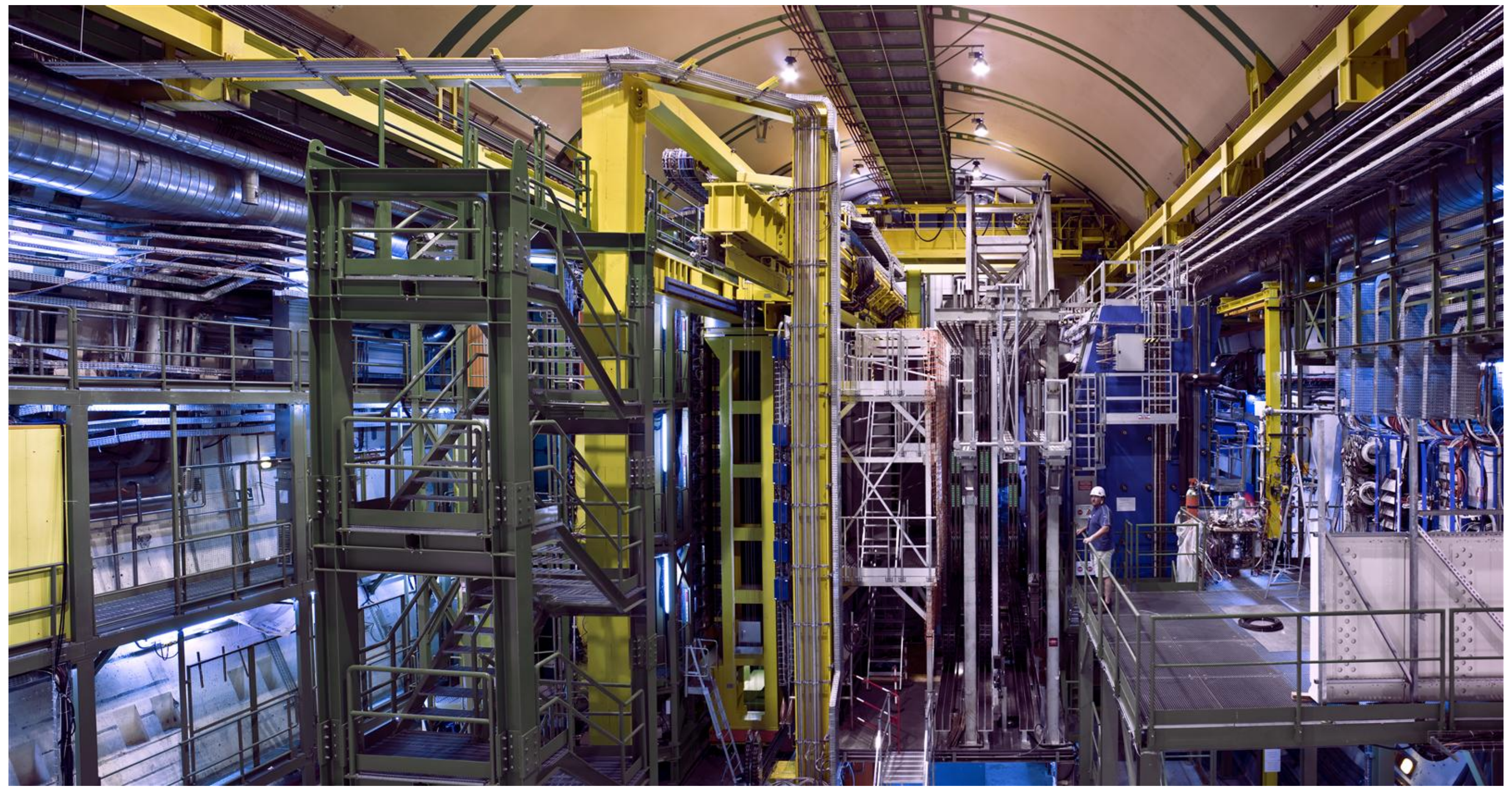
Heavy flavour experiments

- 5 active experiments, all with strengths/weaknesses: BESIII, LHCb, **Belle II**, ATLAS, CMS.

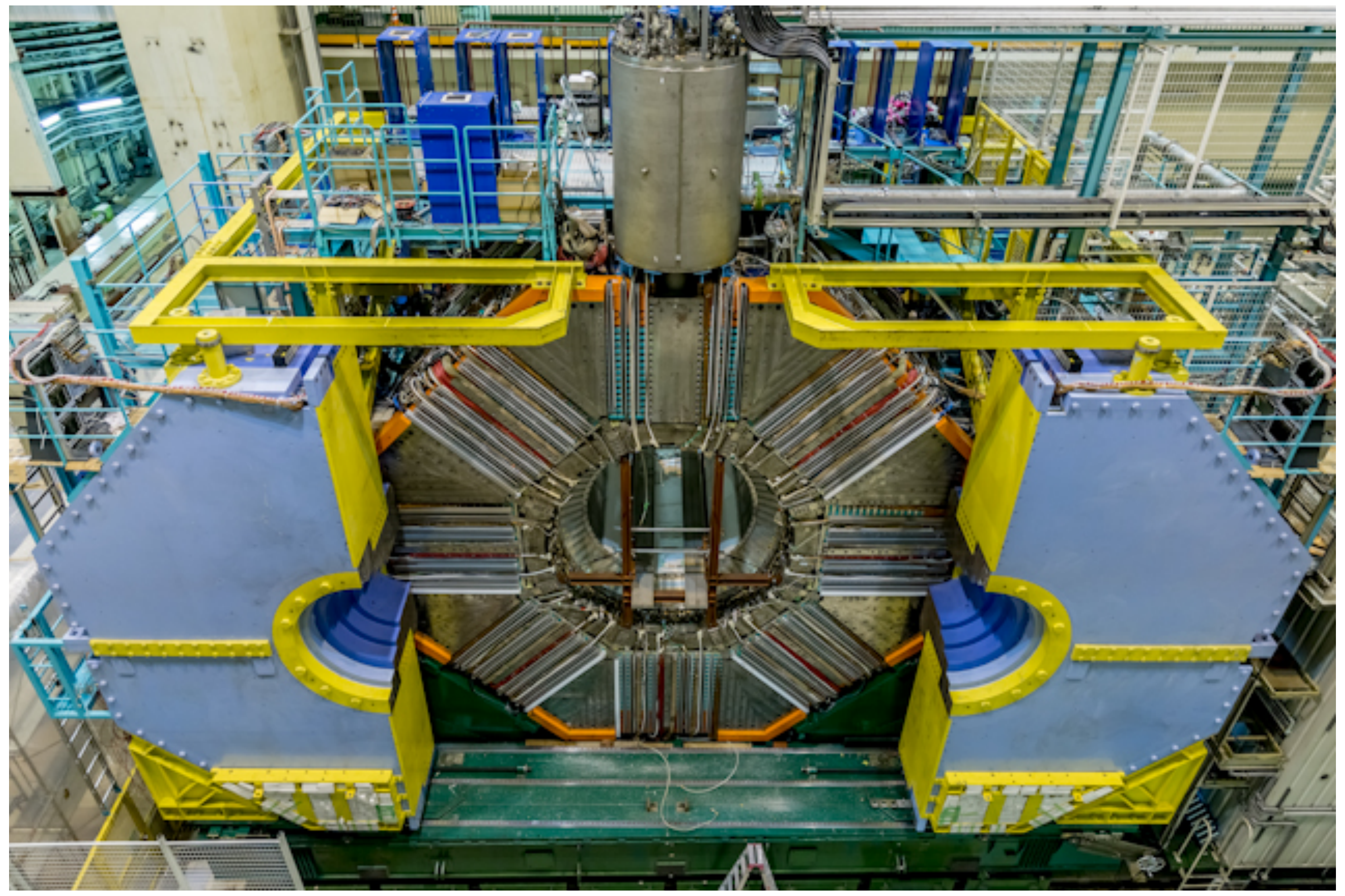
BESIII e^+e^- charm factory



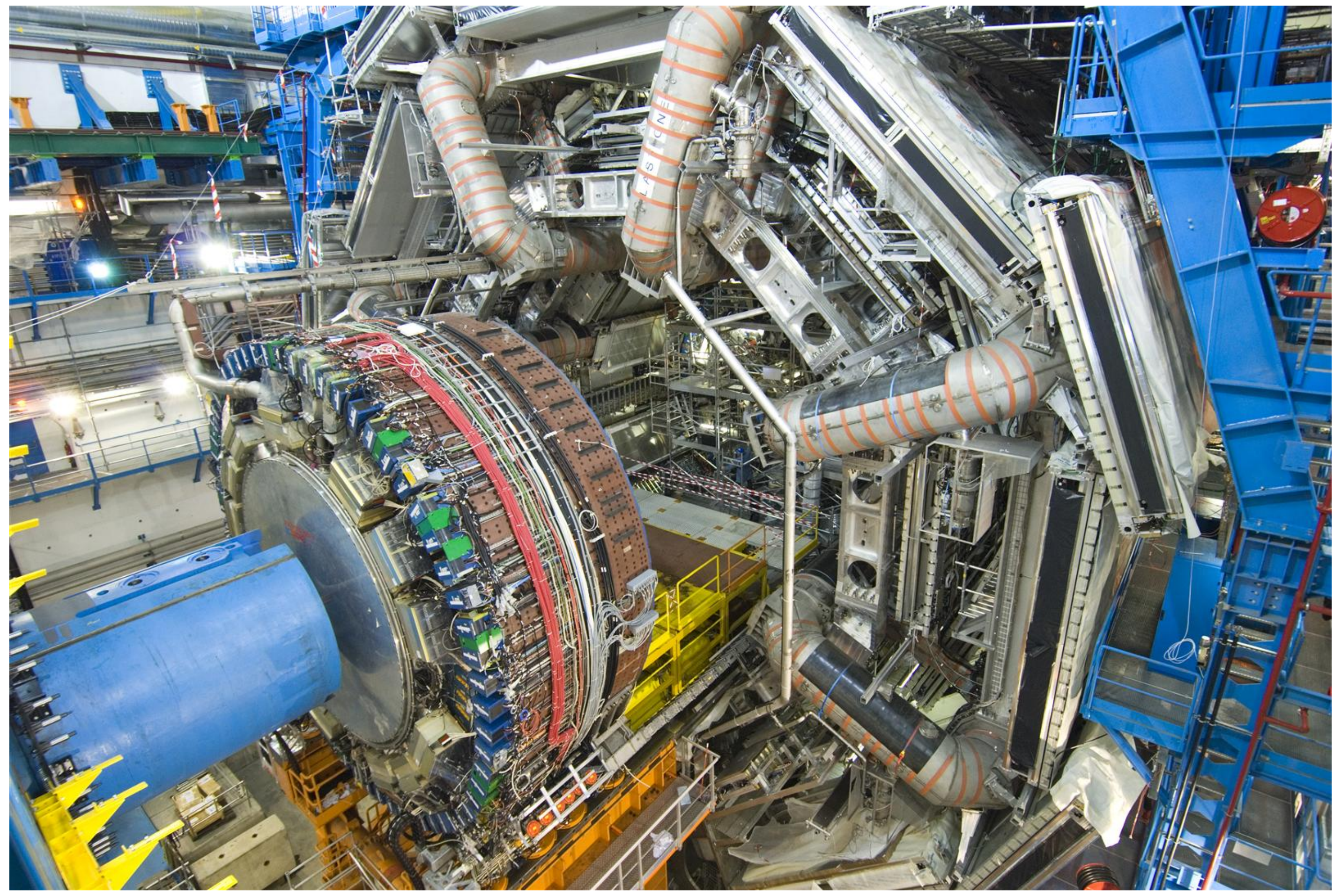
LHCb Beauty/Charm LHC detector



Belle II B/Charm/tau factory at e^+e^-

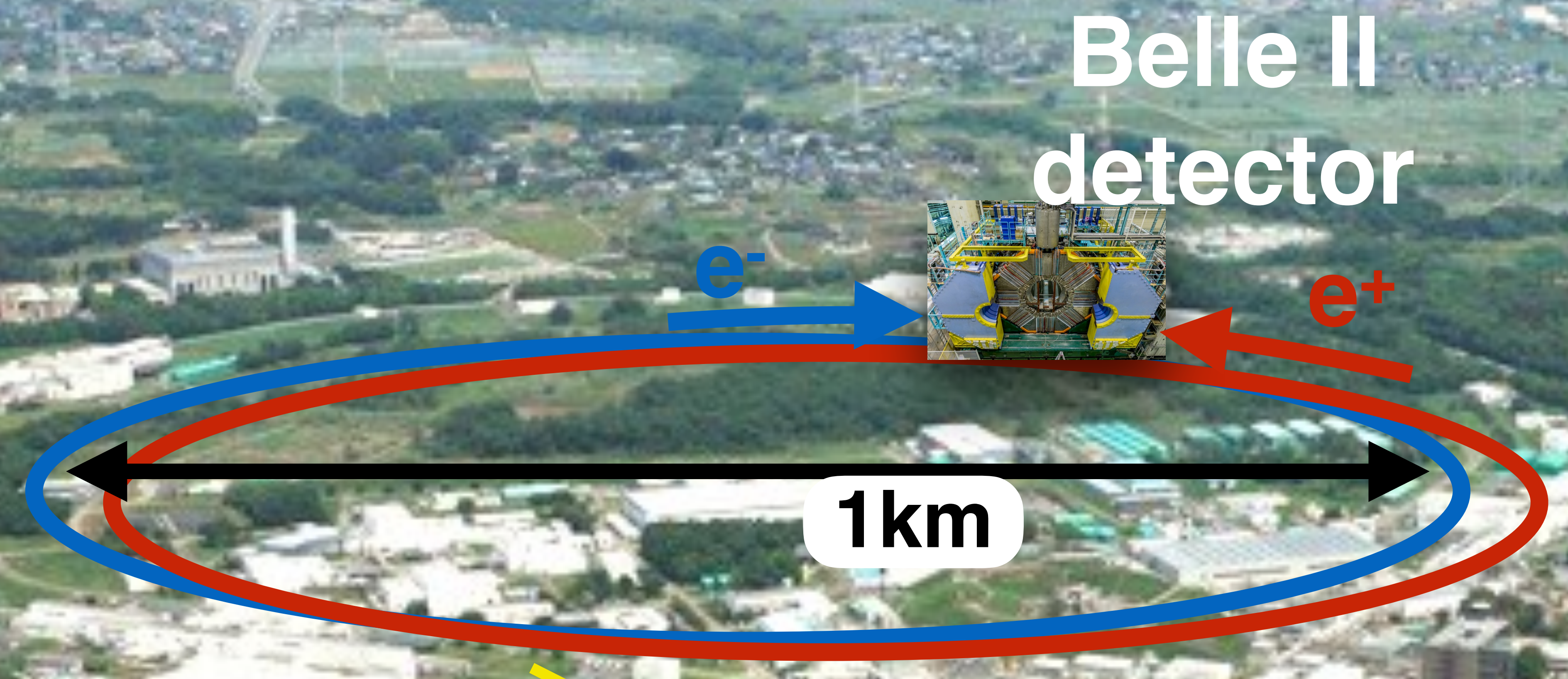


ATLAS, CMS General purpose LHC detectors



Belle II @ Super-KEKB

Intensity frontier flavour-factory experiment, Successor to Belle @KEKB (1999-2010)

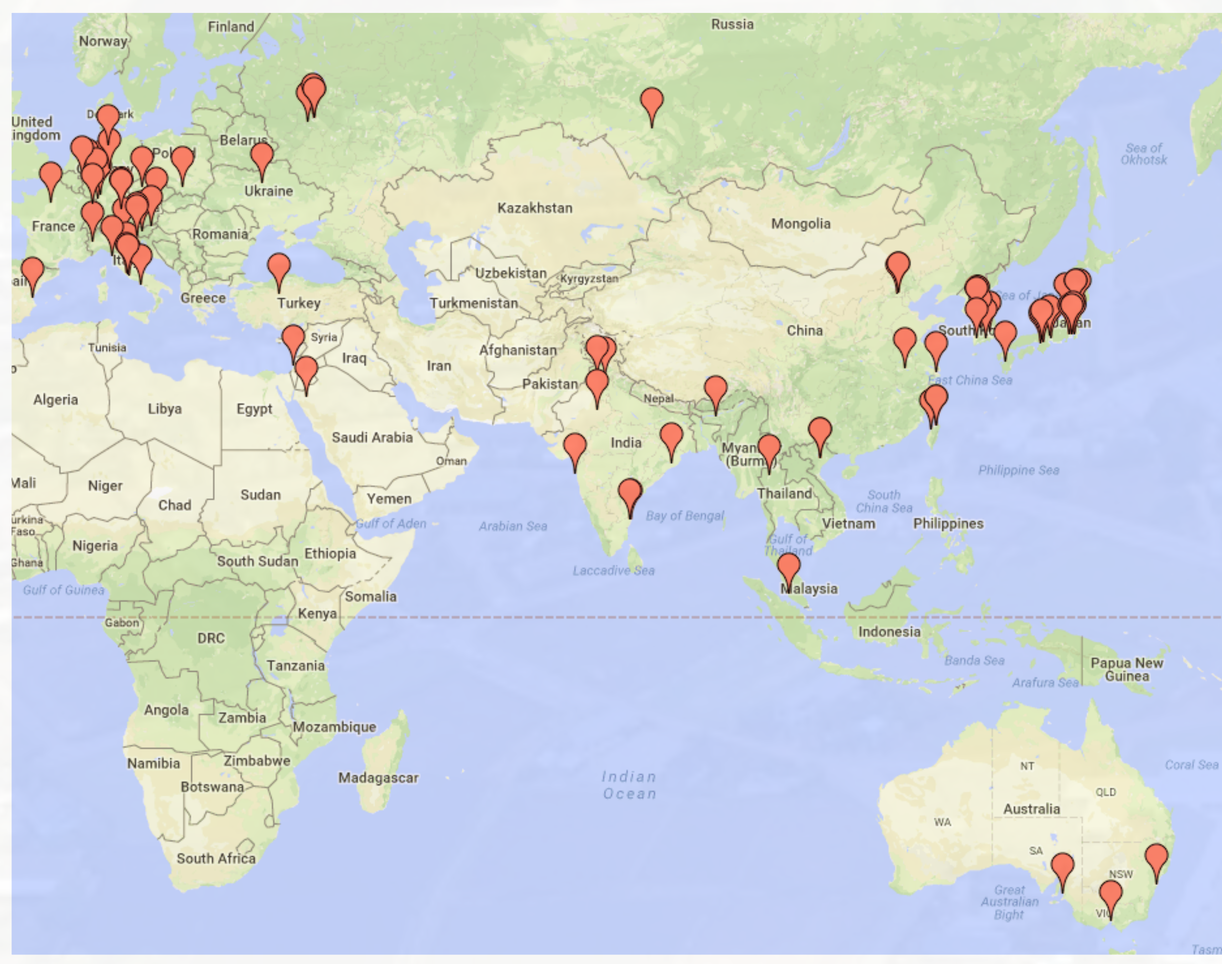


7 GeV e^-, 4 GeV e^+

E_{CM} Υ(4S) = 10.58 GeV + scans

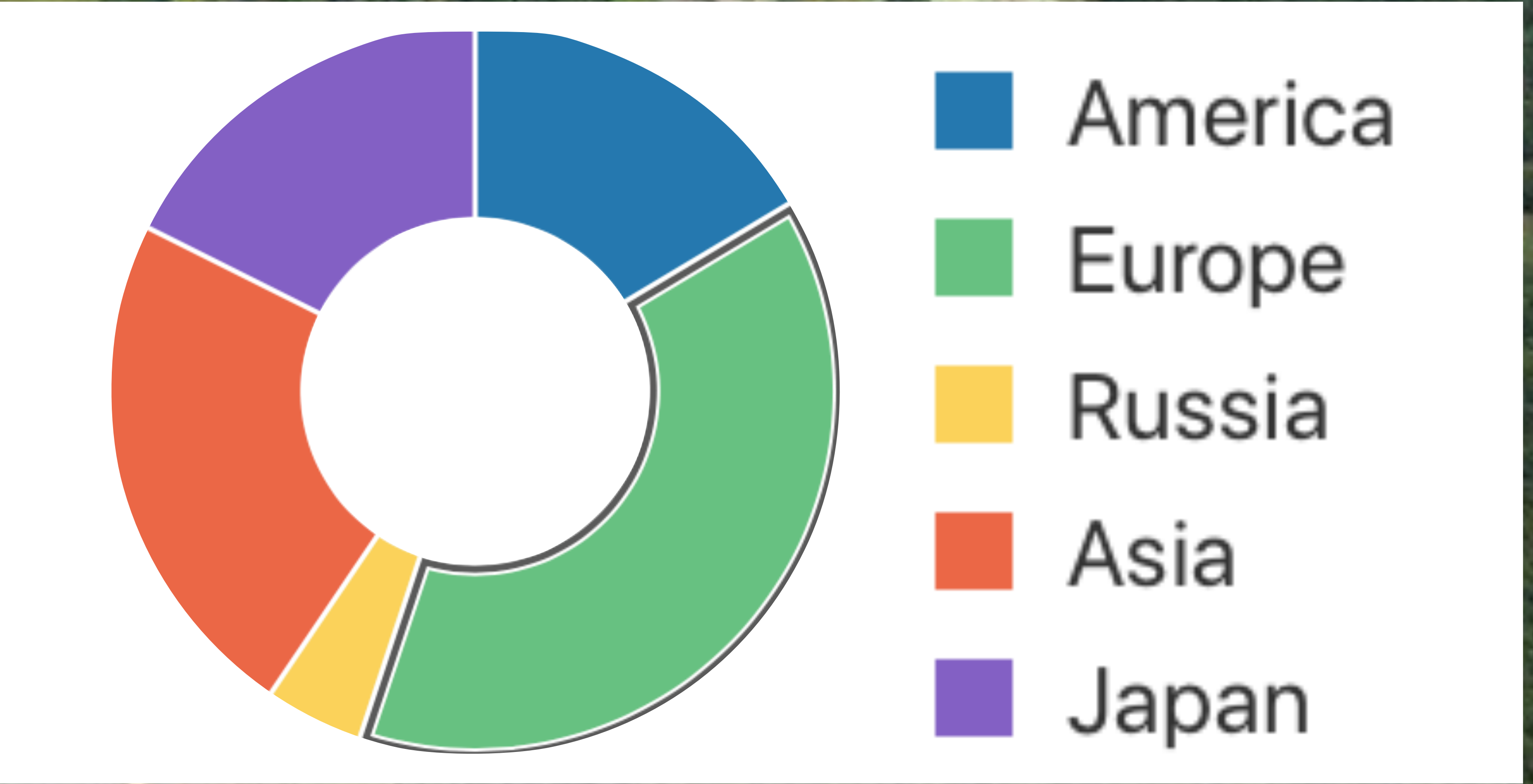
Υ(4S) → B anti-B

B + Charm + τ factory



~950 researchers
(306 grad students)
from 25 countries.

Indian team comprises ~50 members



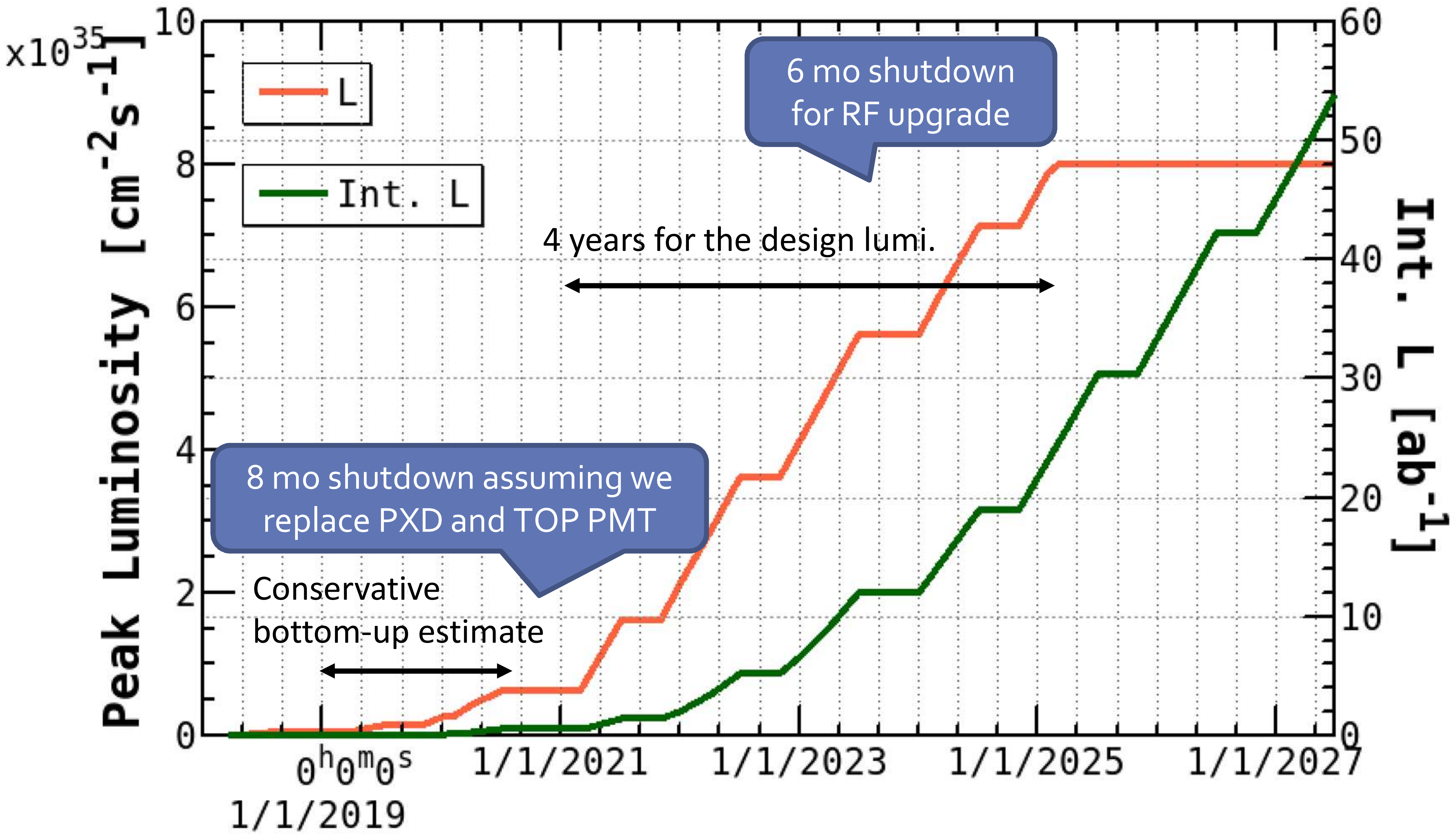
SuperKEKB - 2019 – "Phase 3"

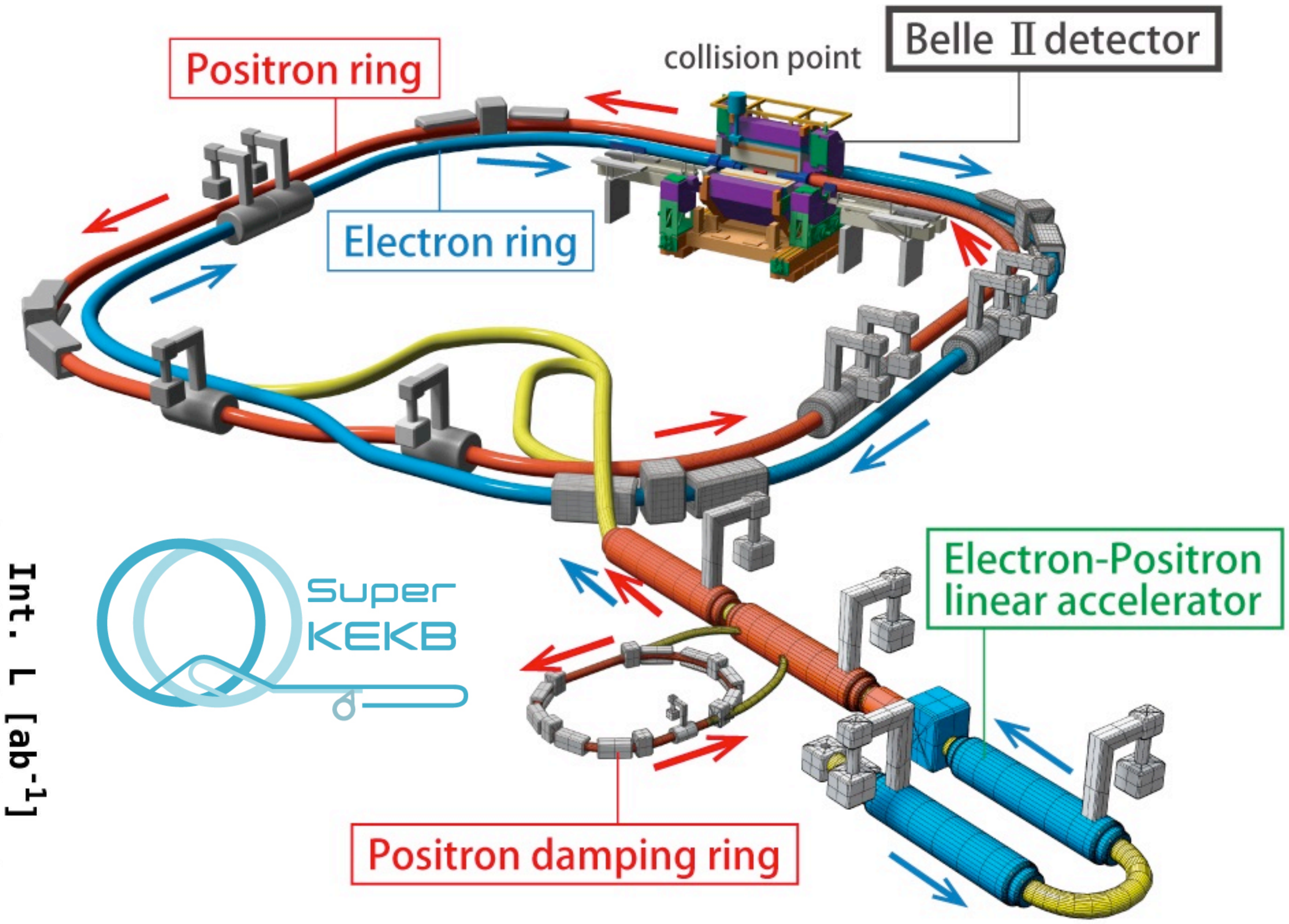
First new collider since the LHC

1) New e^+ damping ring.
2) New 3 km e^+ ring vacuum chamber.
3) New superconducting final focus.

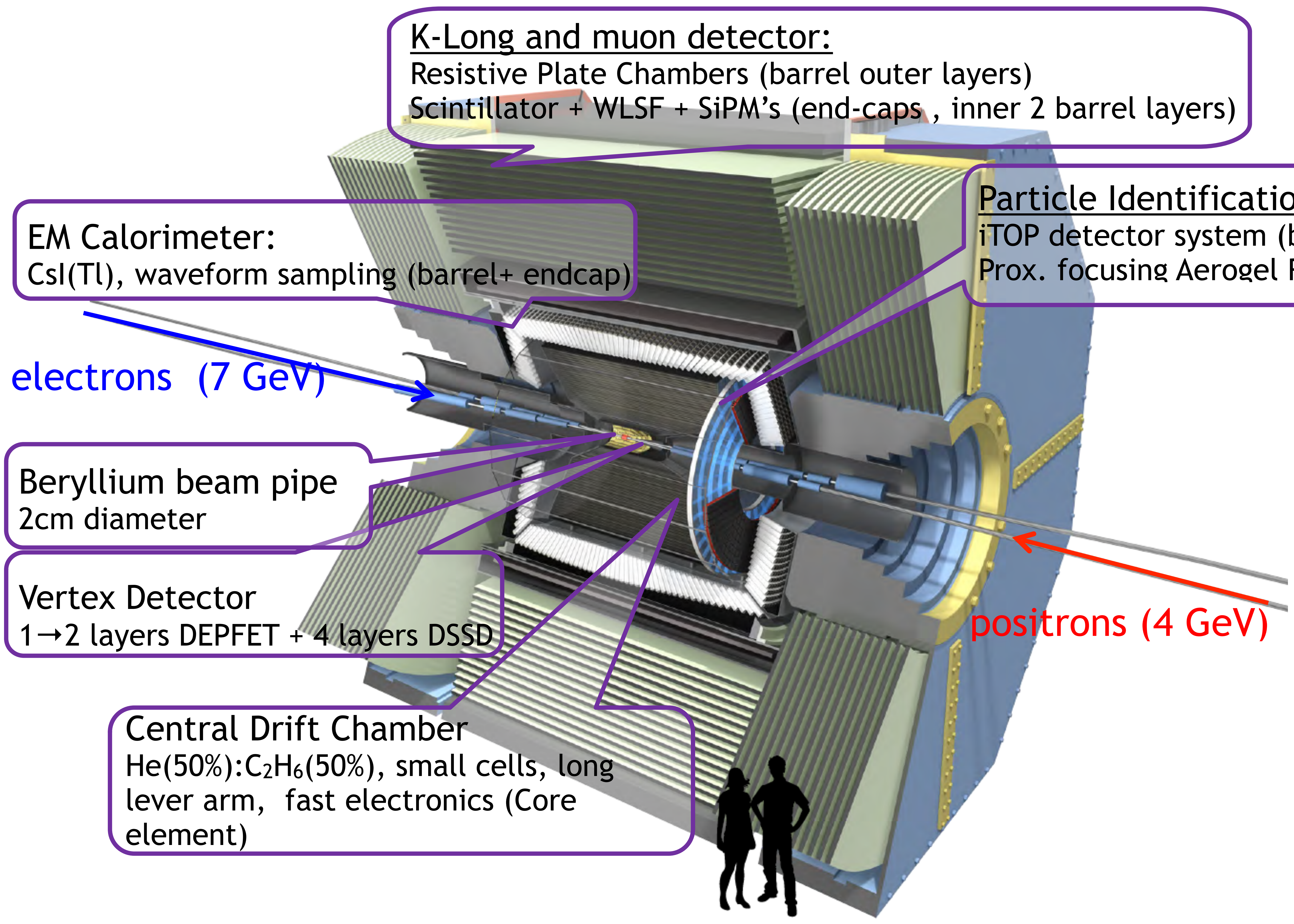
Commissioned in 2018. Full detector physics run commenced March 2019.

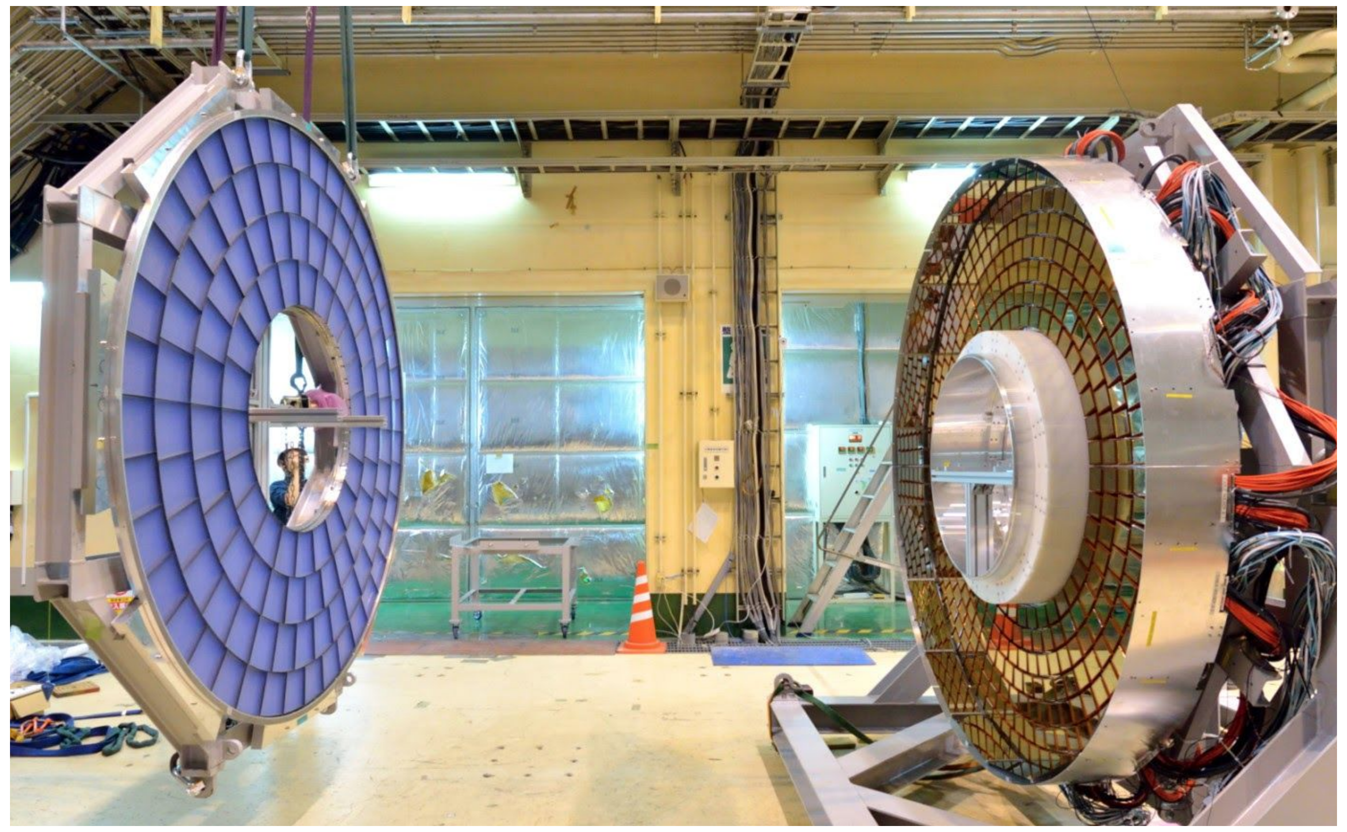
1x10^{34}/cm/s exceeded Dec 2019

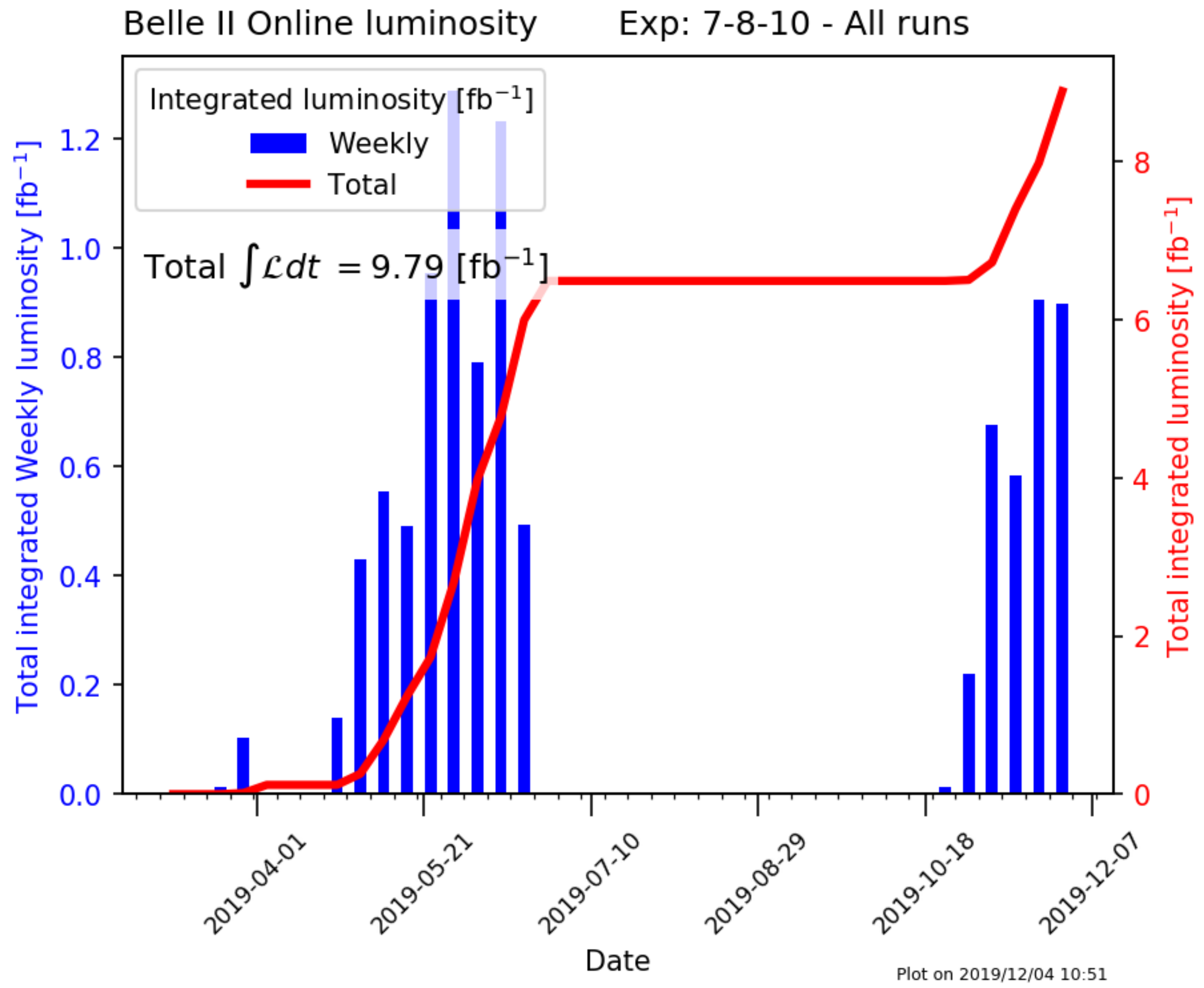




Belle II Detector, 2019 commissioning of new VXD





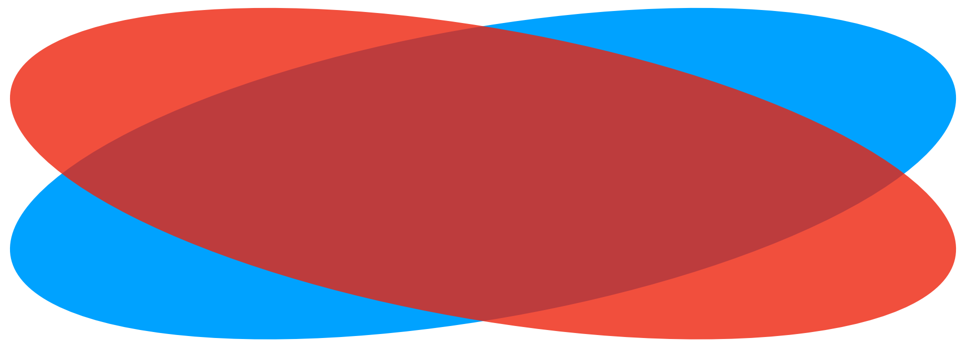


Nano-beams and VXD operation

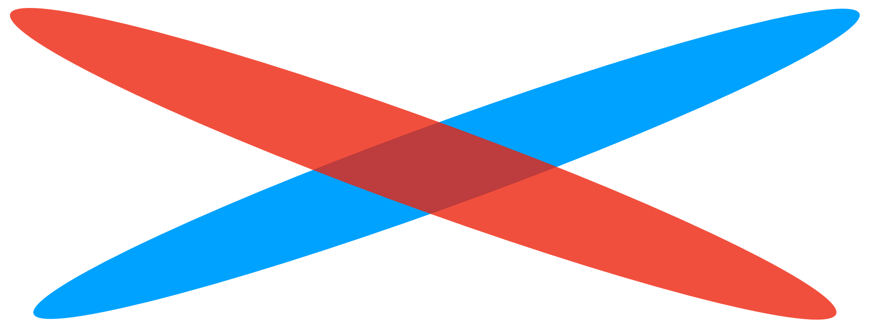
Effective bunch length *reduced x 1/10*
Measured in 2-track events in Belle II data with one wedge of the silicon detector.

Tiny beam size is a useful constraint for Time-dependent CPV analyses.

KEKB

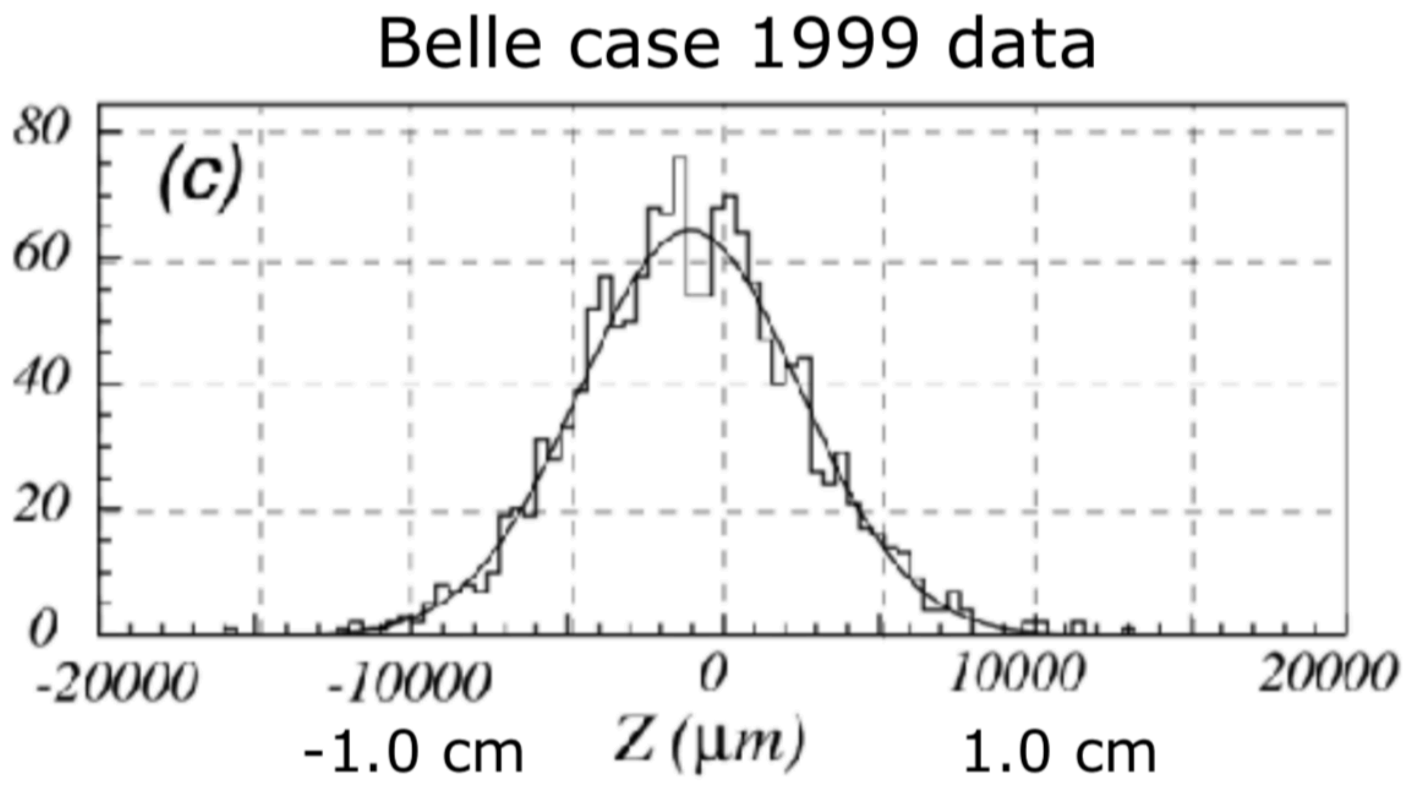


SuperKEKB



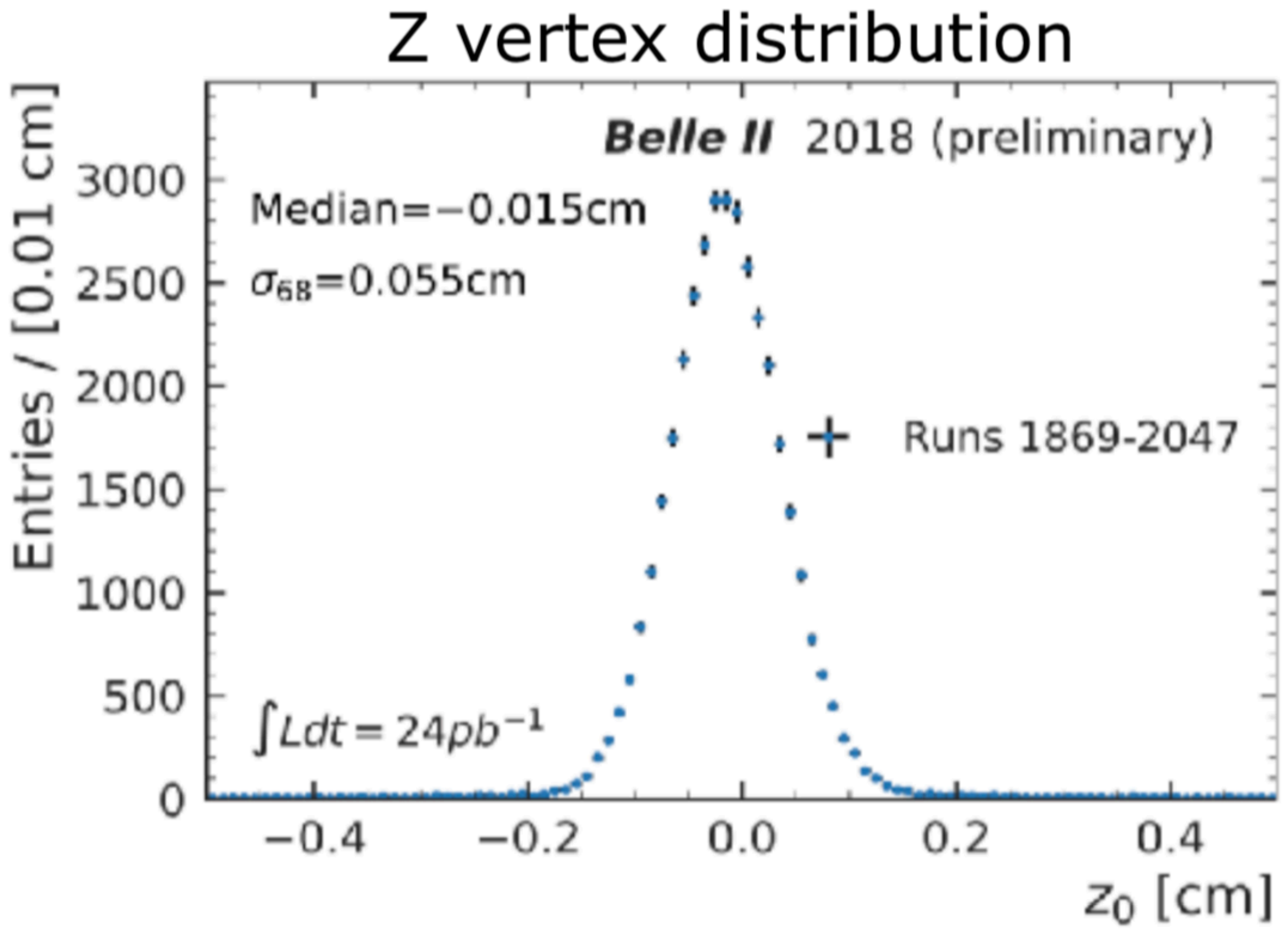
The vertex distribution is constrained in the nano-beam scheme.

Ordinary collision (KEKB)

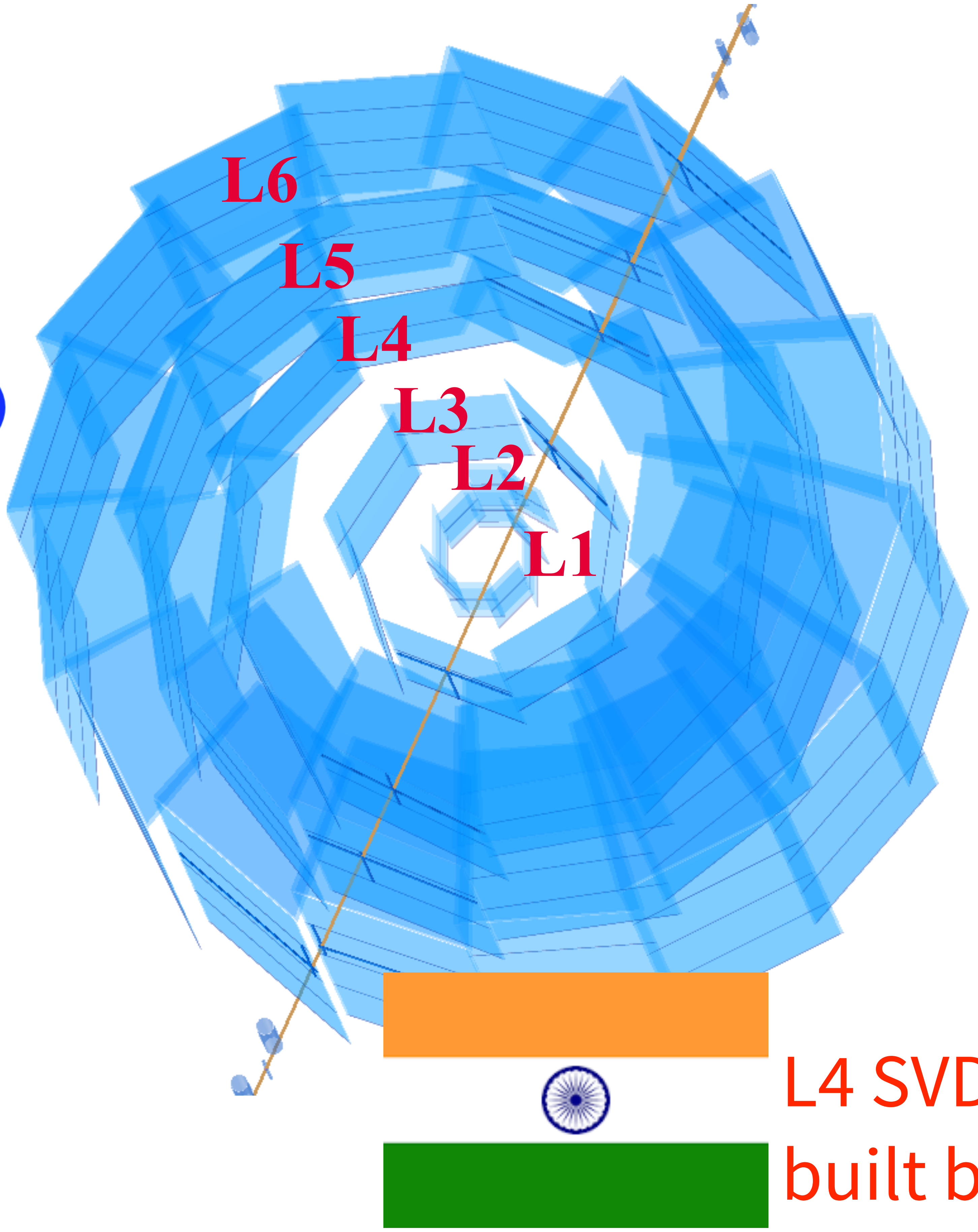


σ = 4.5 mm

Nano-Beam (SuperKEKB Phase2)



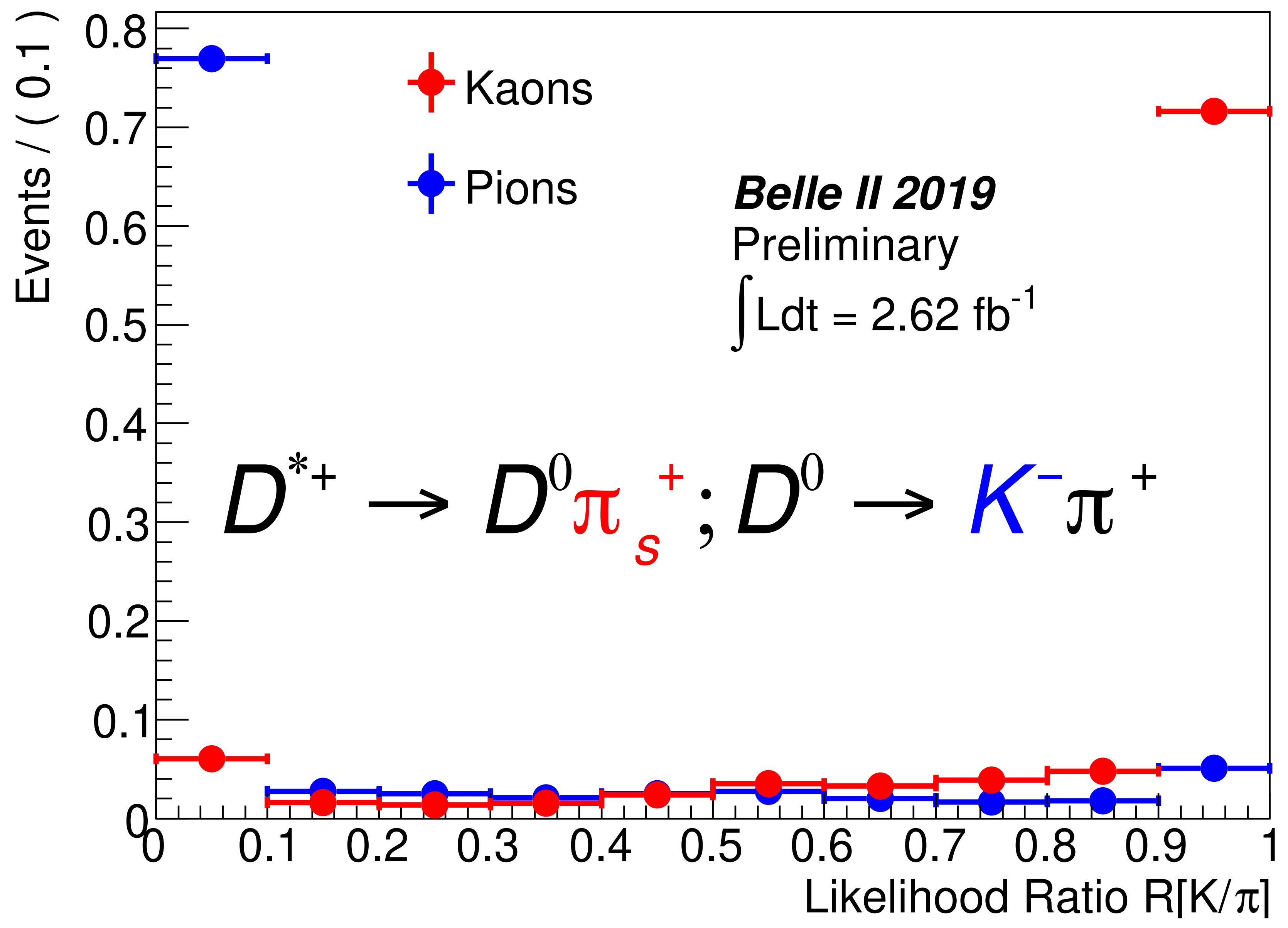
σ = 550 µm



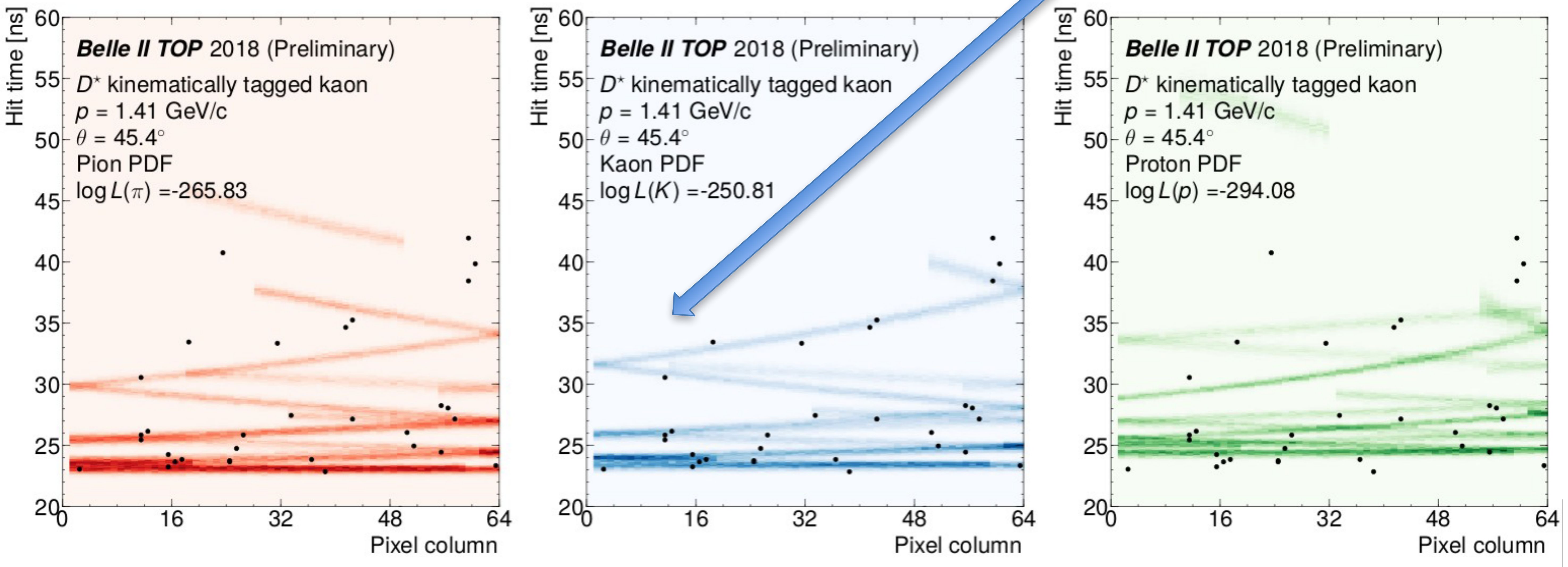
L4 SVD designed & built by Indian groups

Hadron ID- Key for flavour measurement

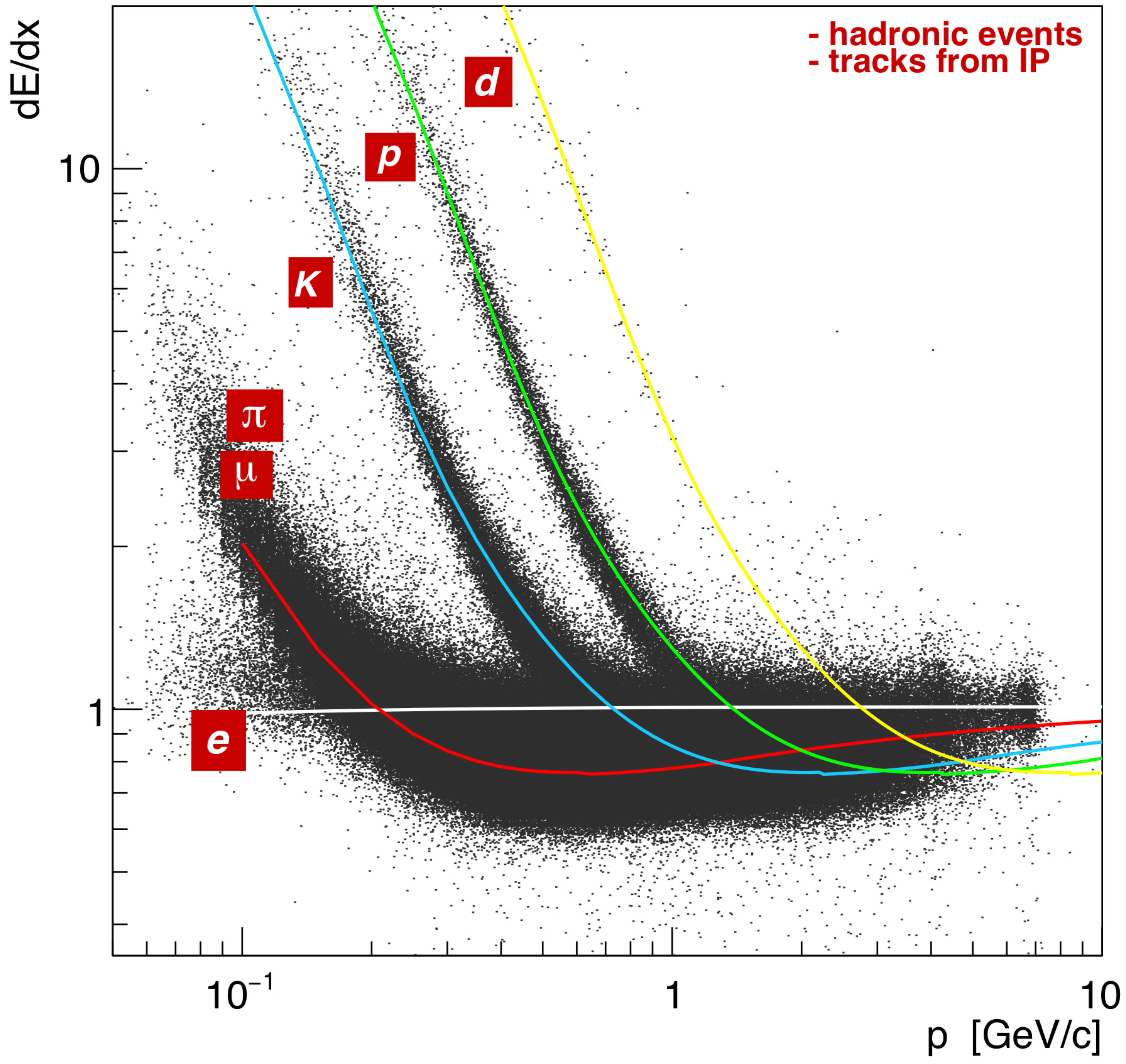
Some *results* involving charged tracks and TOP particle id in Phase 3



Kaon in the TOP; Cherenkov x vs t pattern

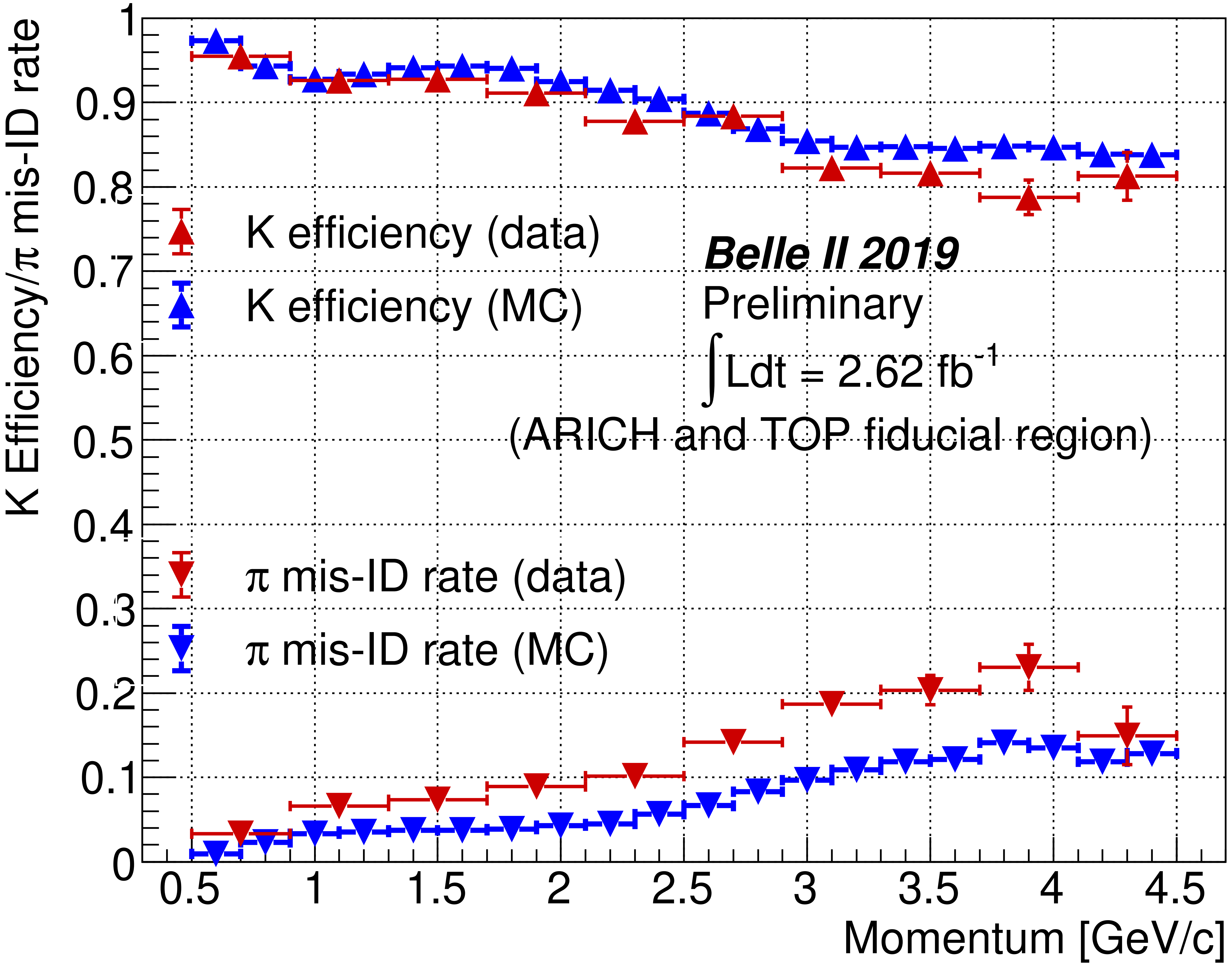


CDC-dE/dx distribution and predictions

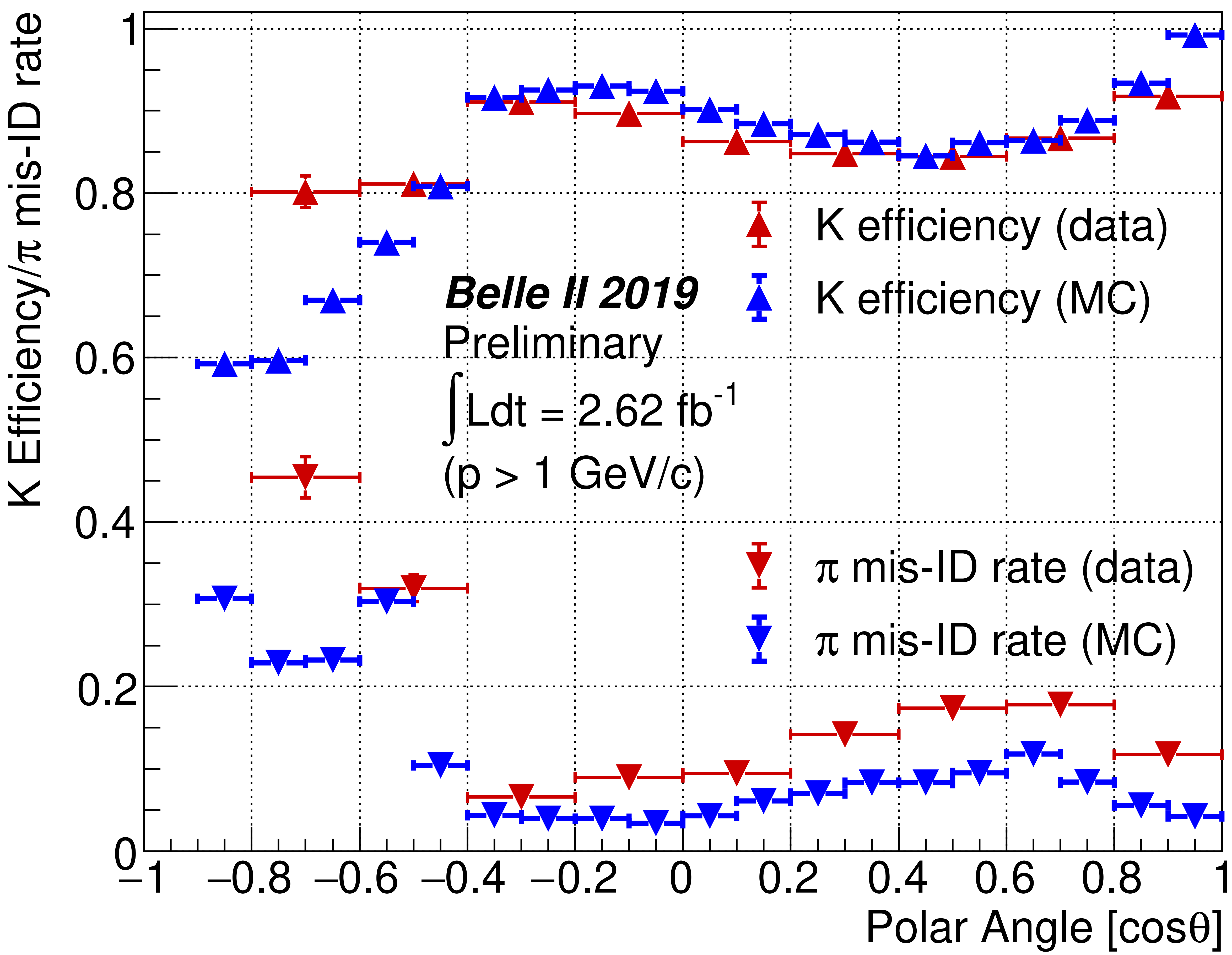


Particle ID with CDC (dE/dx), TOP (barrel), ARICH (forward endcap)

High momentum PID performance



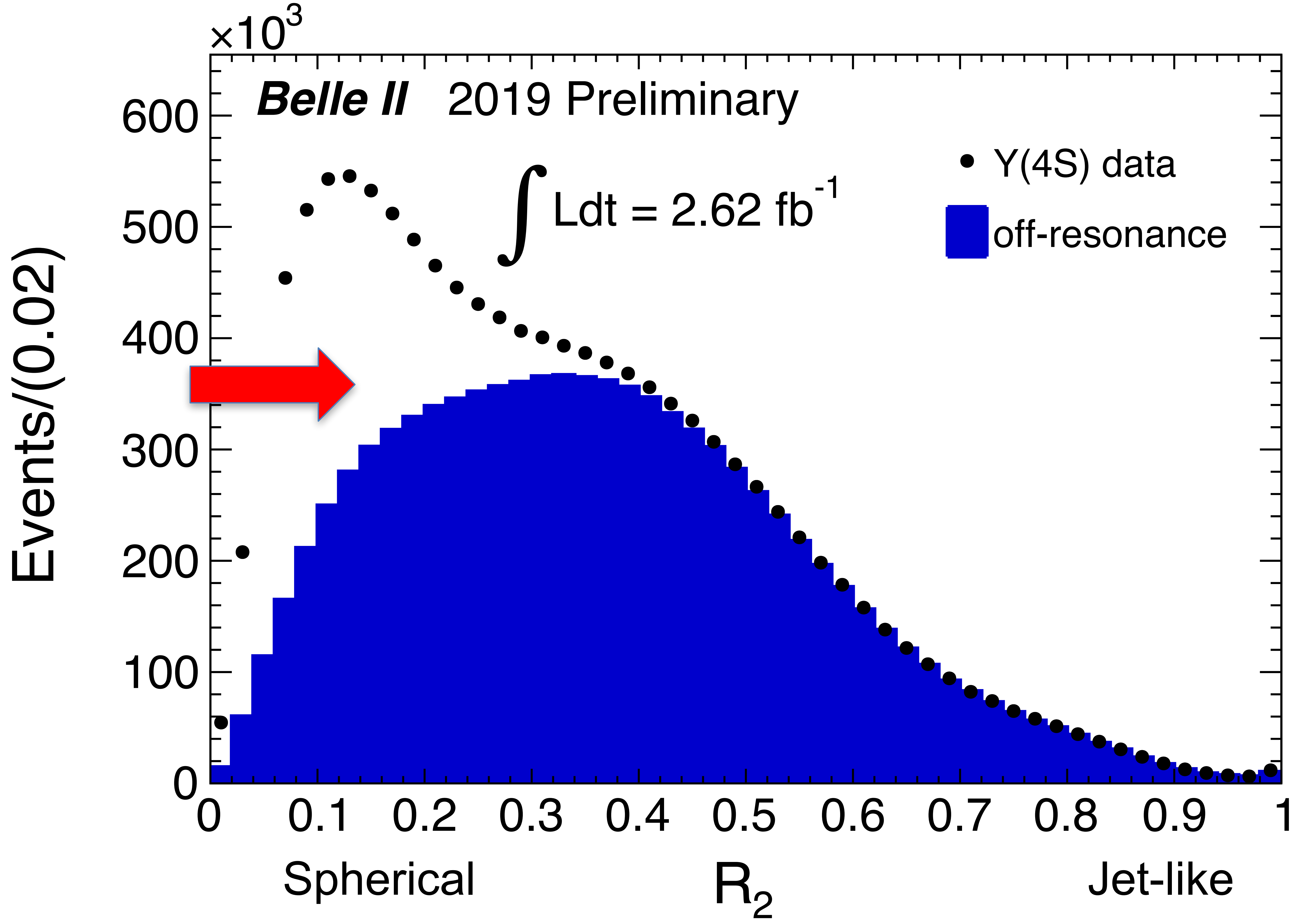
$D^{*+} \rightarrow D^0 \pi_s^+ ; D^0 \rightarrow K^- \pi^+$

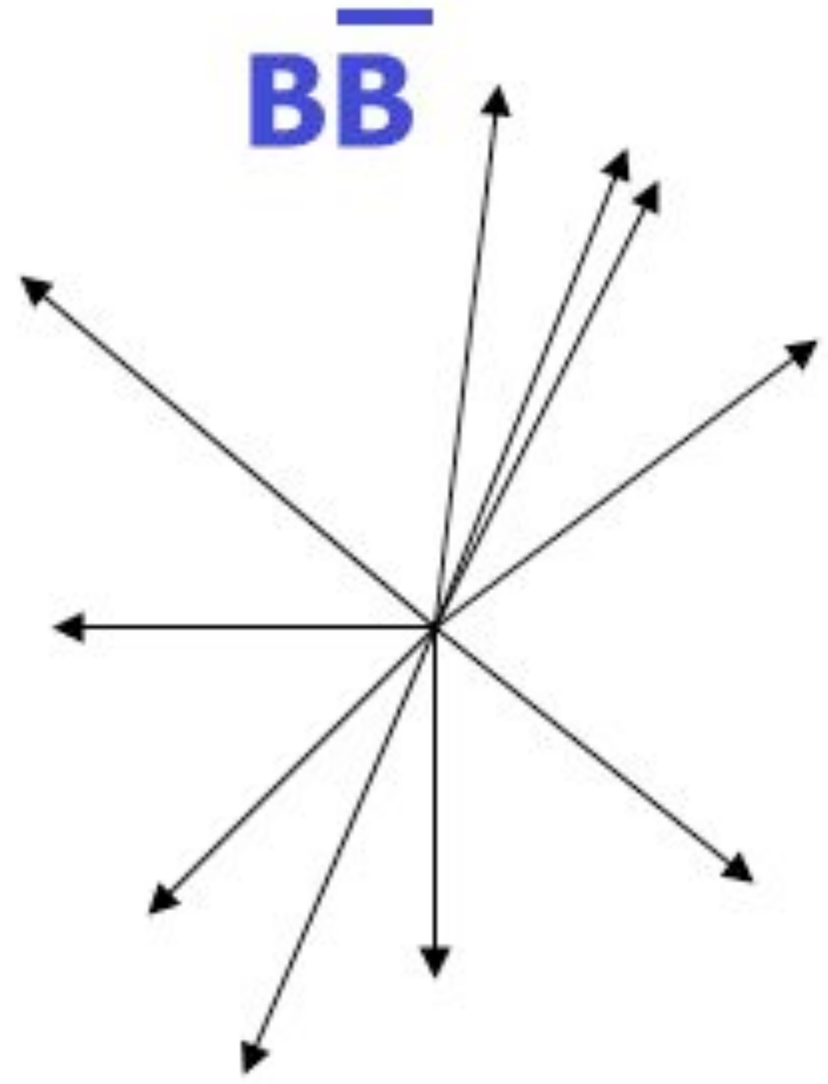


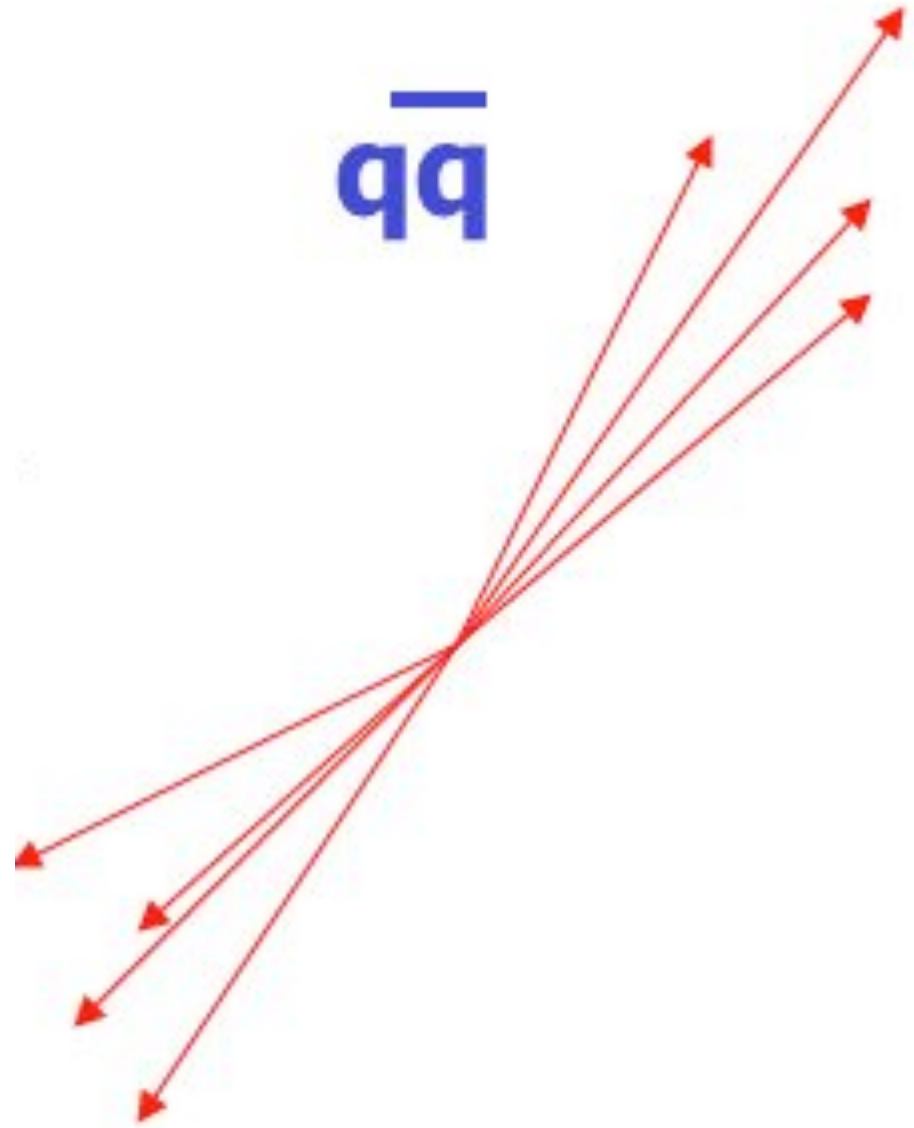
MC simulation (MC12, July 2019) does not include embedded random triggers to correctly represent background.

Lepton ID discussed later in the talk.

Event Topology tells us we are seeing B's







We are on the Υ(4S) resonance and recording B-anti B pairs with ~99% efficiency.

N(B anti-B) ~ 1.1 x 10^6 per fb^{-1} on Υ(4S).

Standard Candles, ee→γγ, ee(γ), ττ (γ)

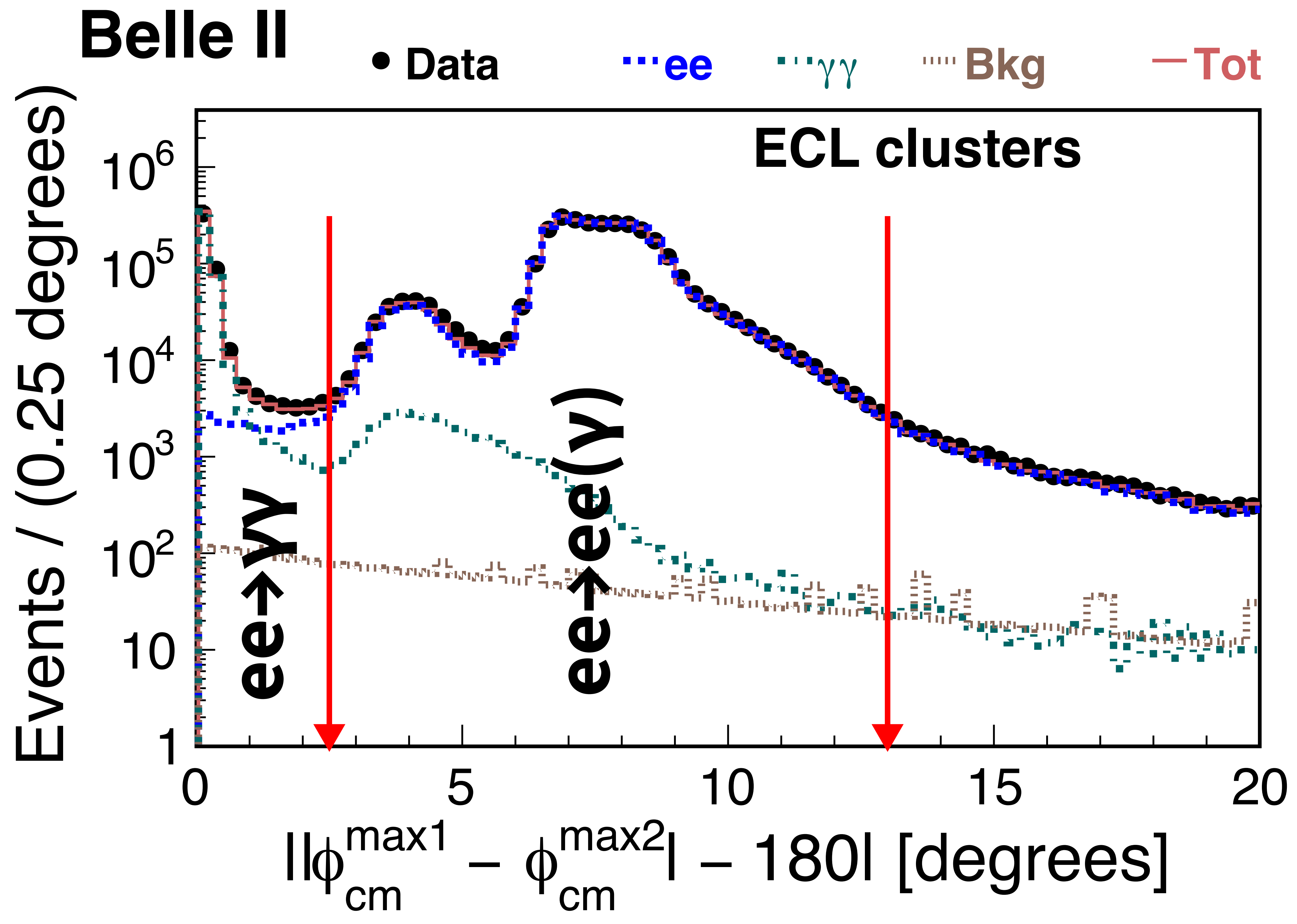
Phase 2 run, April-July 2018

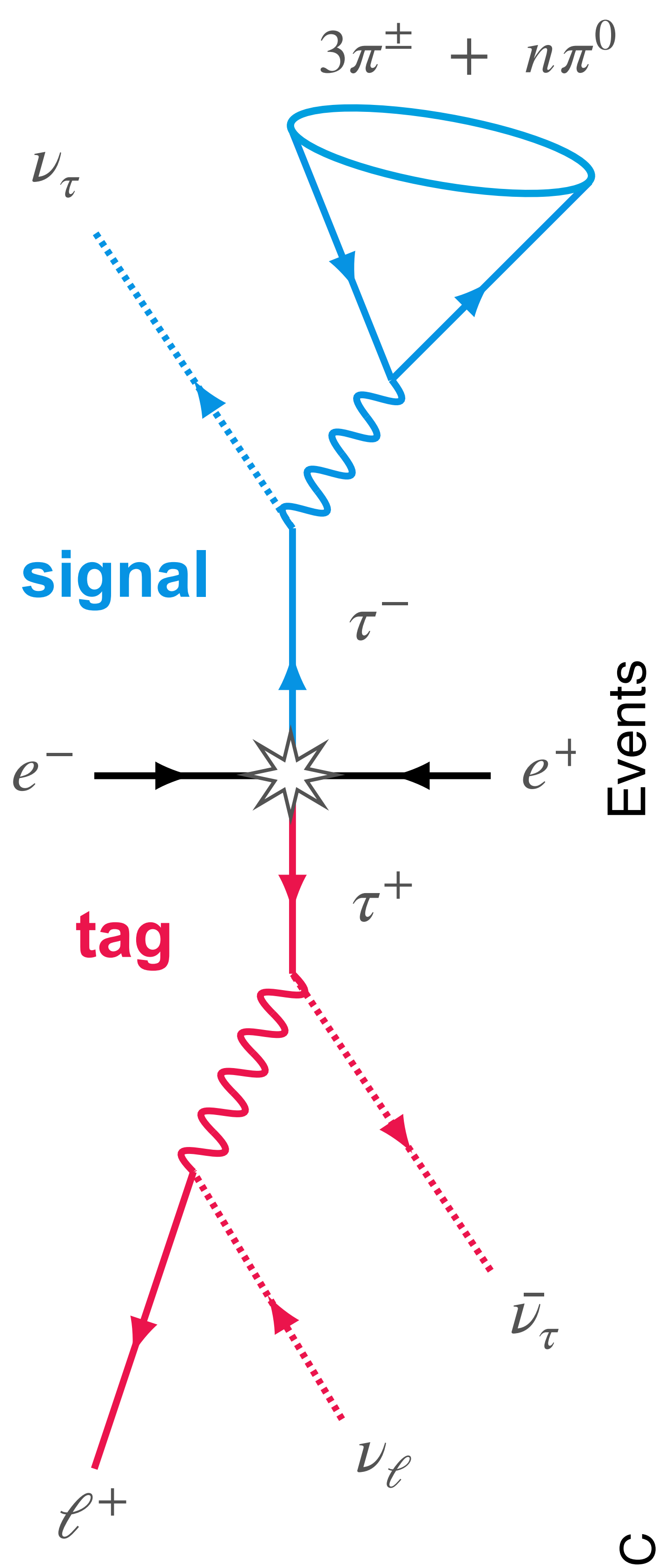
Integrated luminosity

Measured with ee→ ee(γ), γγ

(496.3±0.3±3.0) pb⁻¹

<1% precision reached already!

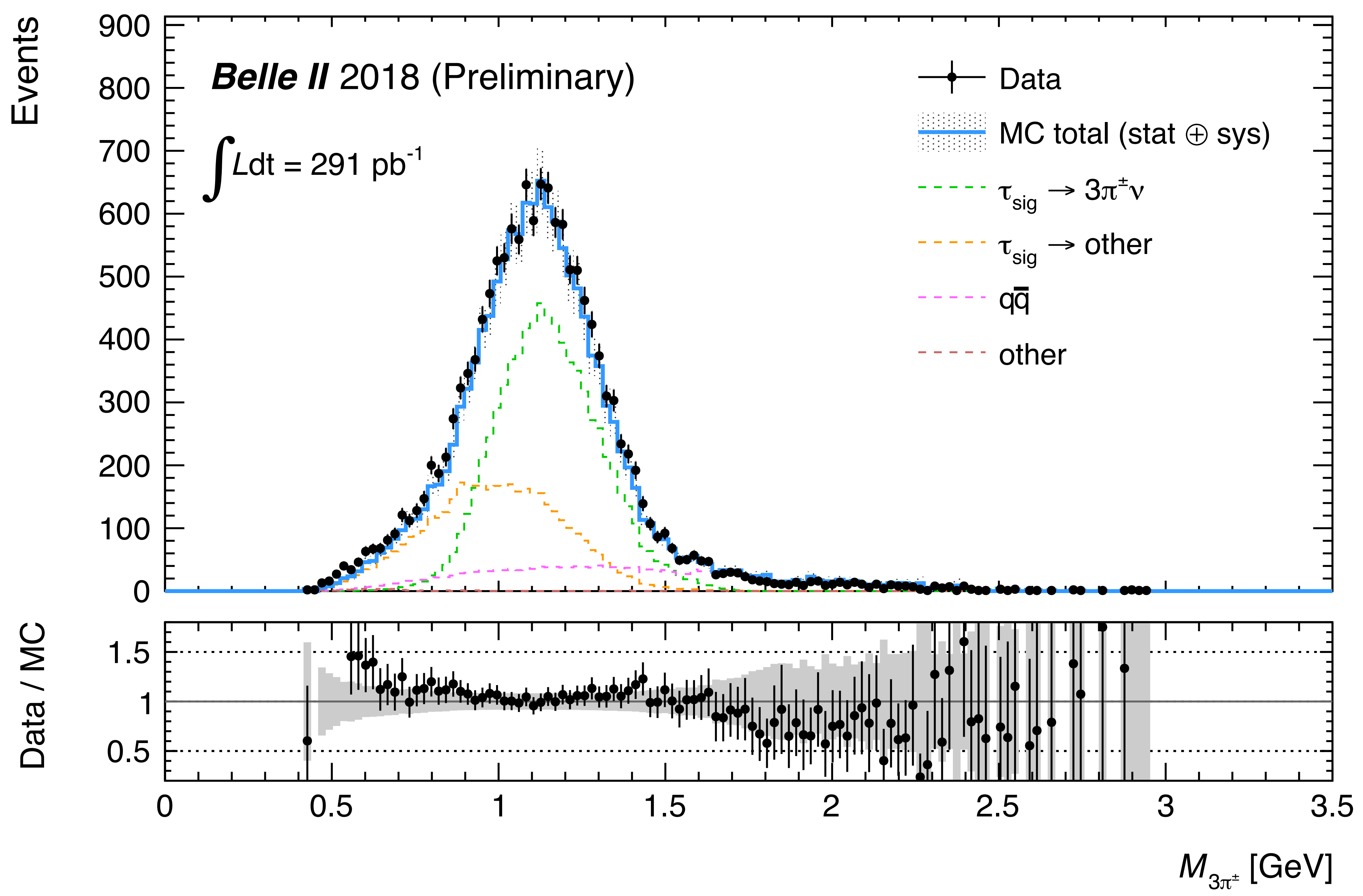




ee→ττ(γ)

Used for early trigger & track efficiency measurements

exclusive decay: $\tau_{signal} \to 3\pi^{\pm}\nu_{\tau}$

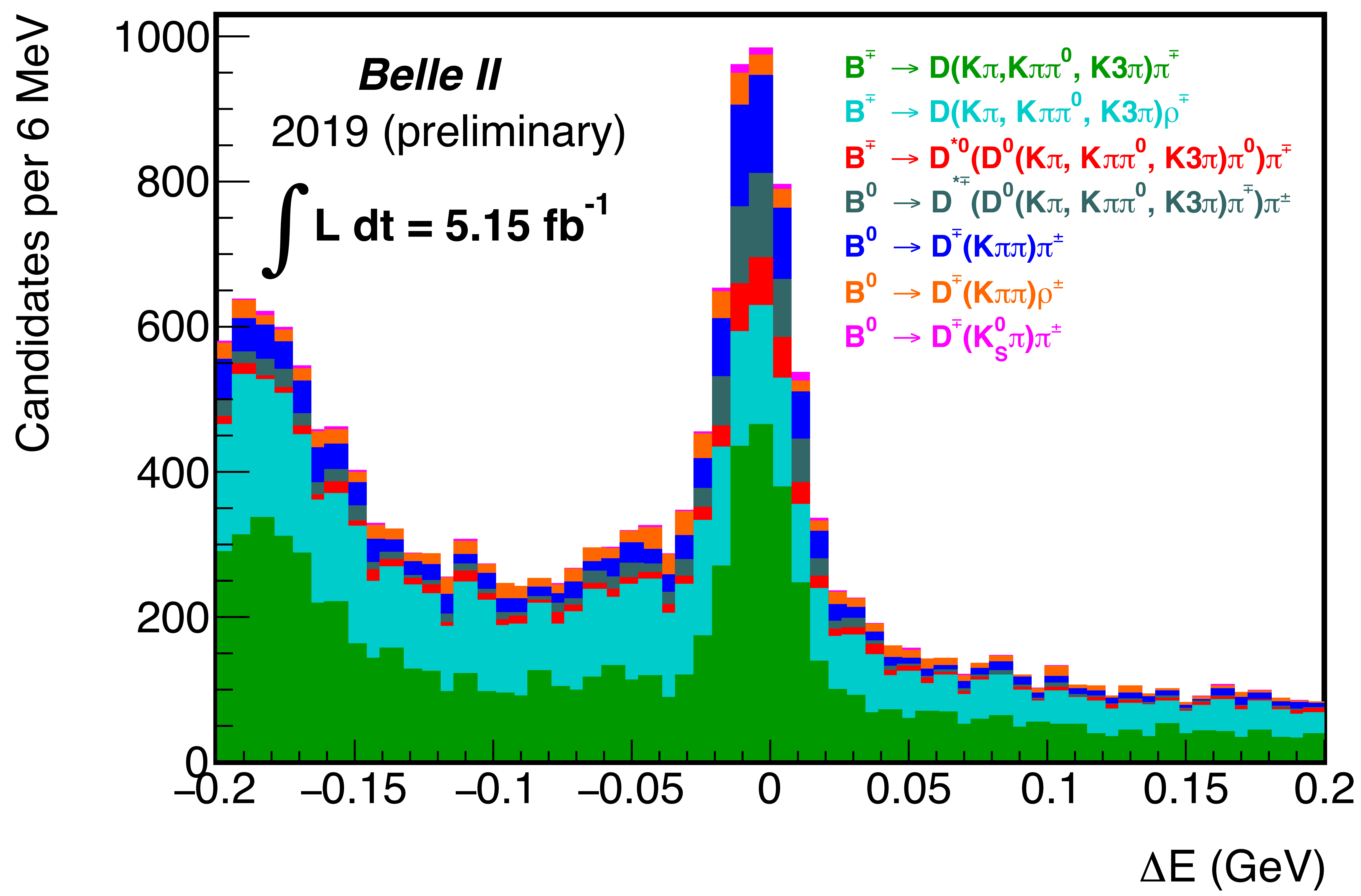


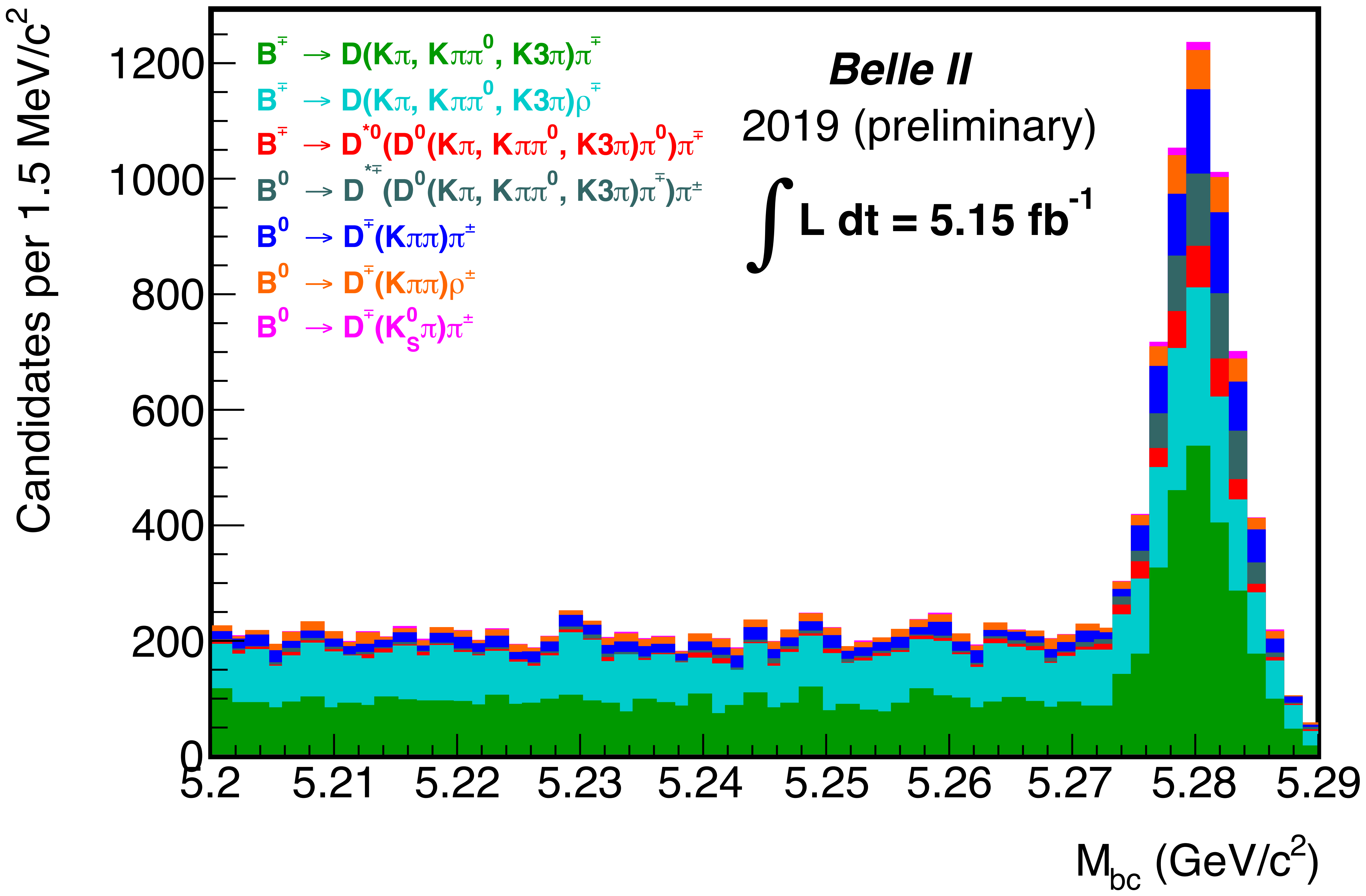
arXiv:1910.05365, accepted to Chinese physics C - first paper on Belle II data

We have rediscovered the B meson (2019 dataset)

$$\Delta E = E_{cm}/2 - E_{recon}$$

$$M_{bc} = \sqrt{(E_{cm}/2)^2 - p^2_{recon}}$$





5500 Fully reconstructed hadronic B decays

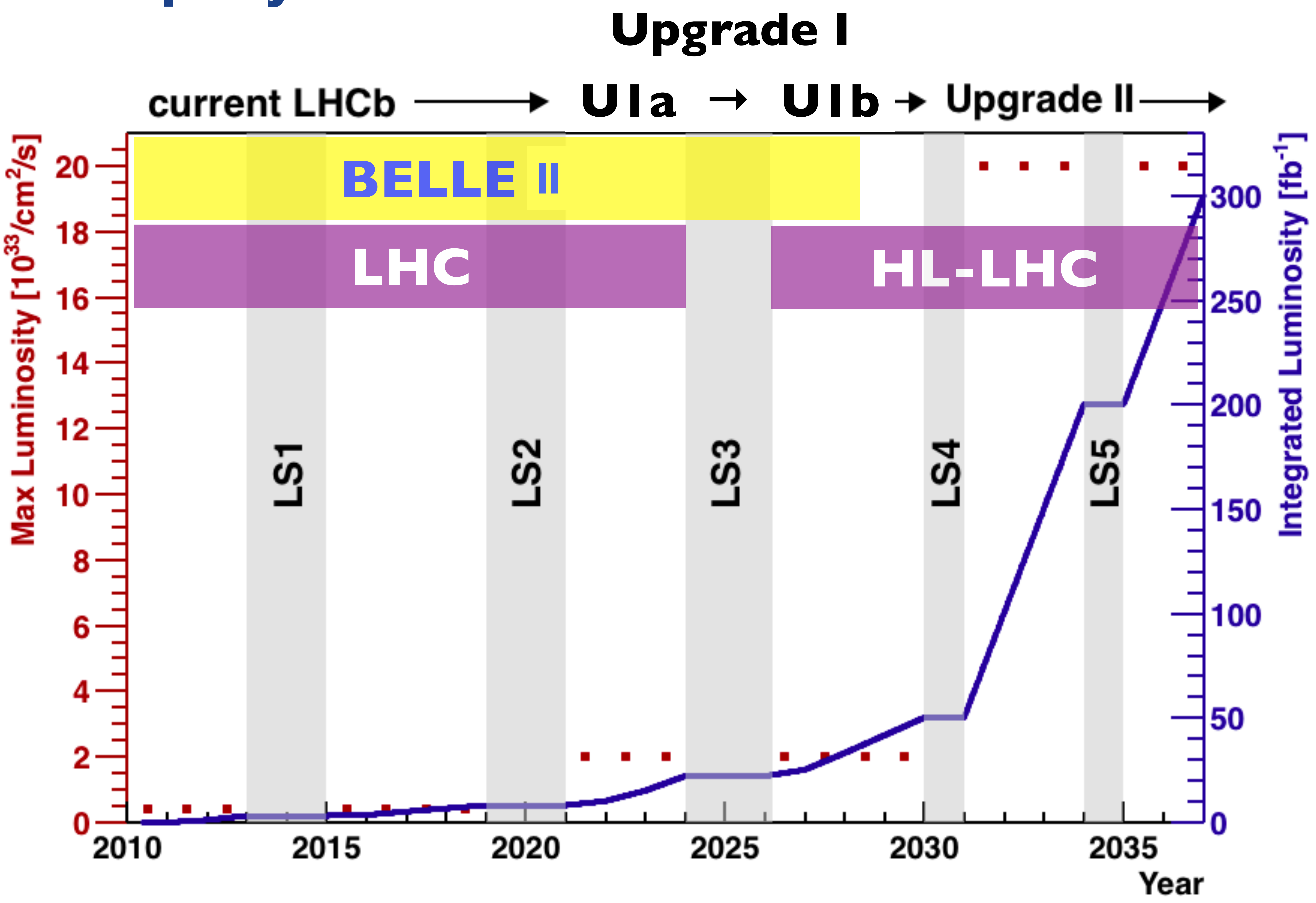
Demonstration of Belle II's B Physics Capabilities: Modes with neutrals, and K_S mesons are efficiently reconstructed along with all-charged final states containing kaons and pions.

Flavour data sets from colliders

Experiment	$\int L$ dt: Now	$\int L$ dt: 5 years	σ(bb)	σ(cc)	σ(ss)	Operation
Babar	530 fb^{-1}	-	1.1 nb	1.6 nb	0.4 nb	1999-2008
Belle	1040 fb^{-1}	-	1.1 nb	1.6 nb	0.4 nb	1999-2010
Belle II	**>0.5 fb^{-1} (50 ab^{-1})**	**15-20 ab^{-1}**	**1.1 nb**	**1.6 nb**	**0.4 nb**	**2018-**
BESIII	~16 fb^{-1}	~30 fb^{-1}	-	6 nb (3770 MeV)	-	2008-
KLOE-2	5.5 fb^{-1}	-	-	-	~3 μb (1020 MeV)	2014-2018
ATLAS	140 fb^{-1}	~300 fb^{-1}	250-500 μb	-	-	2009-
CMS	140 fb^{-1}	~300 fb^{-1}	250-500 μb	-	-	2009-
LHCb	8 fb^{-1}	23 fb^{-1}	250-500 μb	1200- 2400 μb	(~10^{13} K_S / fb^{-1})	2009-

- **Order of magnitude increase in e+e- Υ(4S) dataset - focus of this presentation.**
- Advances in lattice QCD will also be crucial for improved precision tests of the SM.

LHCb projected datasets



LHCb run 3 will have an upgraded trigger improving hadronic mode sensitivity.

CKM, the Unitarity Triangle and CP Violation

- The SM describes the mixing of quarks of different generations through the weak force.

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

3 Generations, 1 Phase: single source of CPV in the SM.

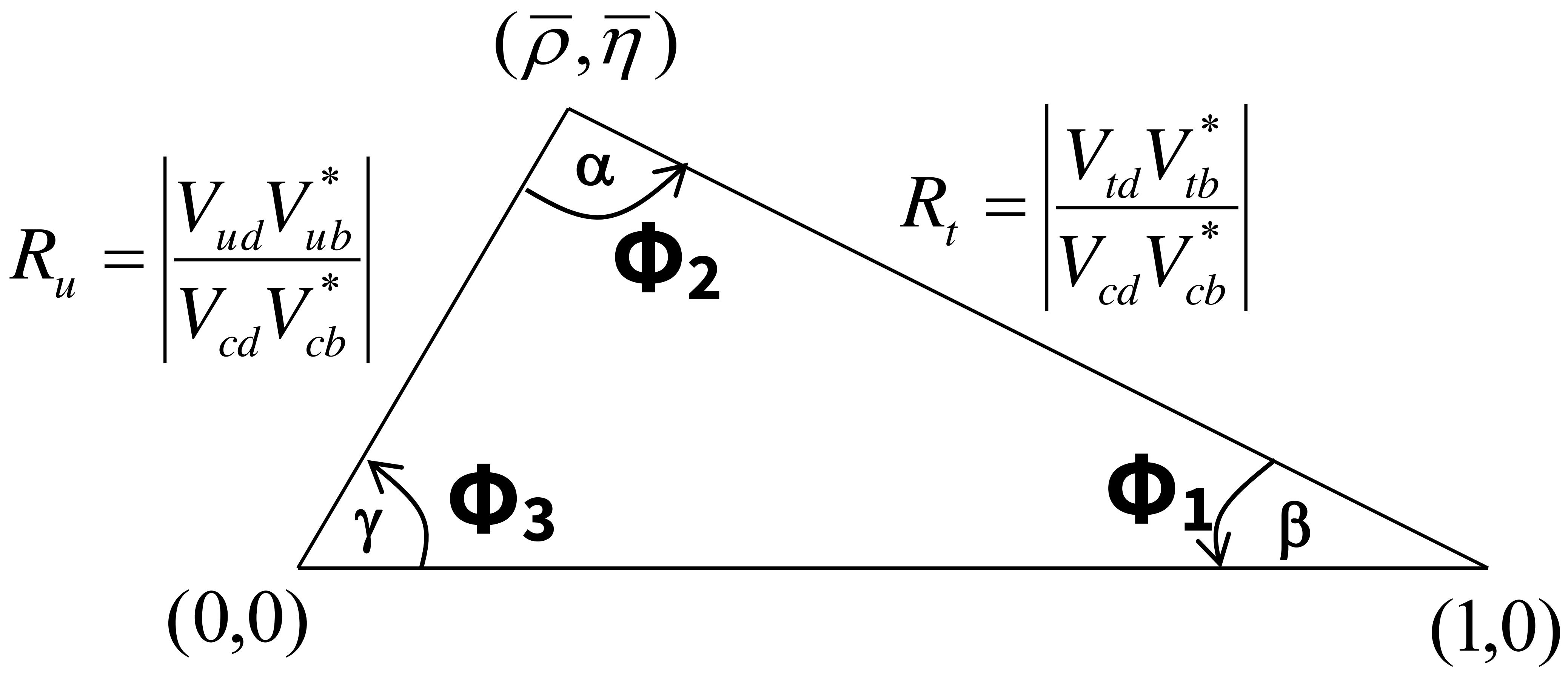
Wolfenstein parameterisation: Phase invariant, conserving CKM matrix unitarity at any order in λ.

WA HFLAV

$\sin 2\Phi_1 = 0.70 \pm 0.02$

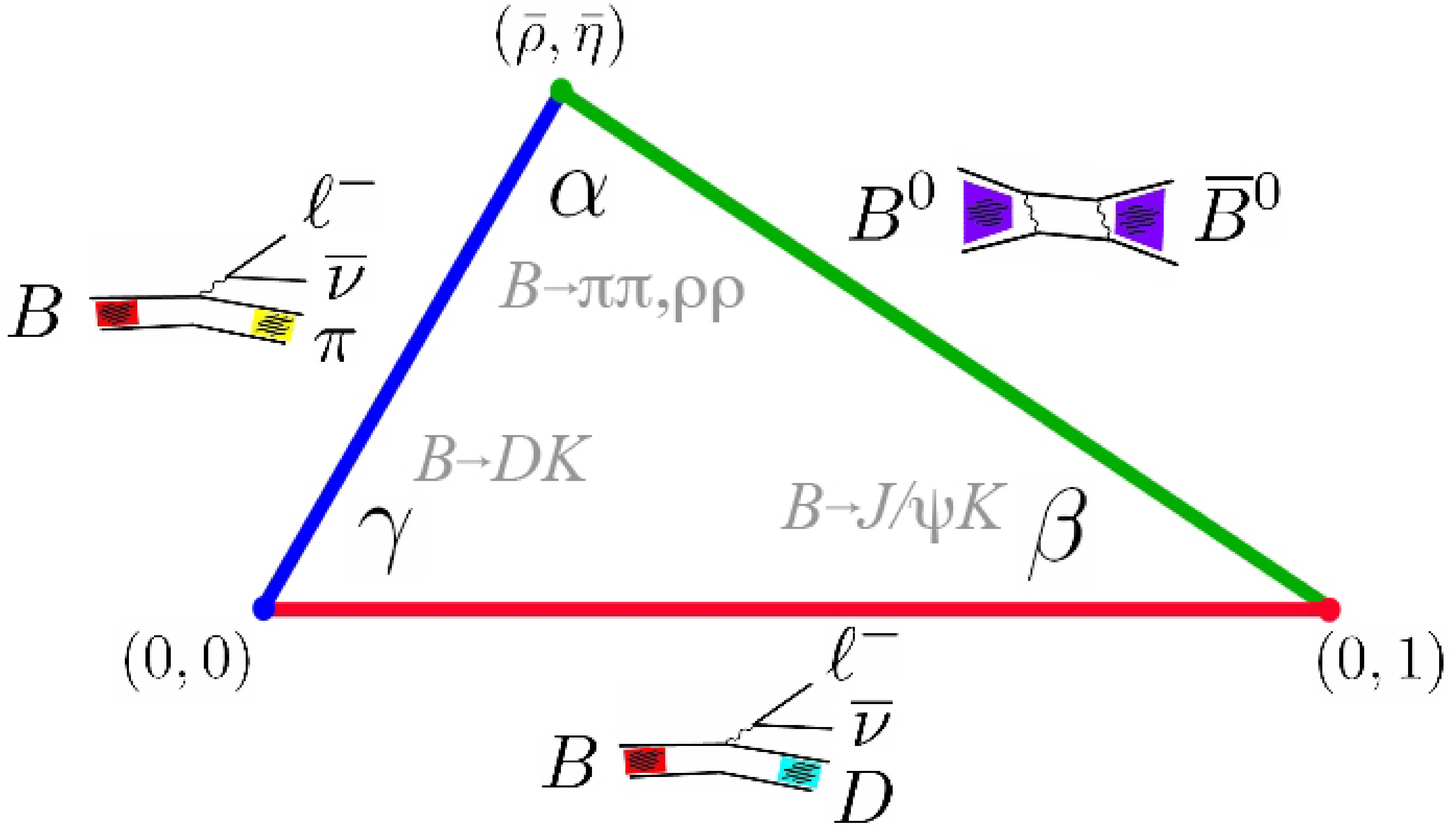
$\Phi_2 = (84.9^{+5.1}_{-4.5})^\circ$

$\mathbf{\Phi_3 = (73.5^{+4.2}_{-5.1})^\circ}$

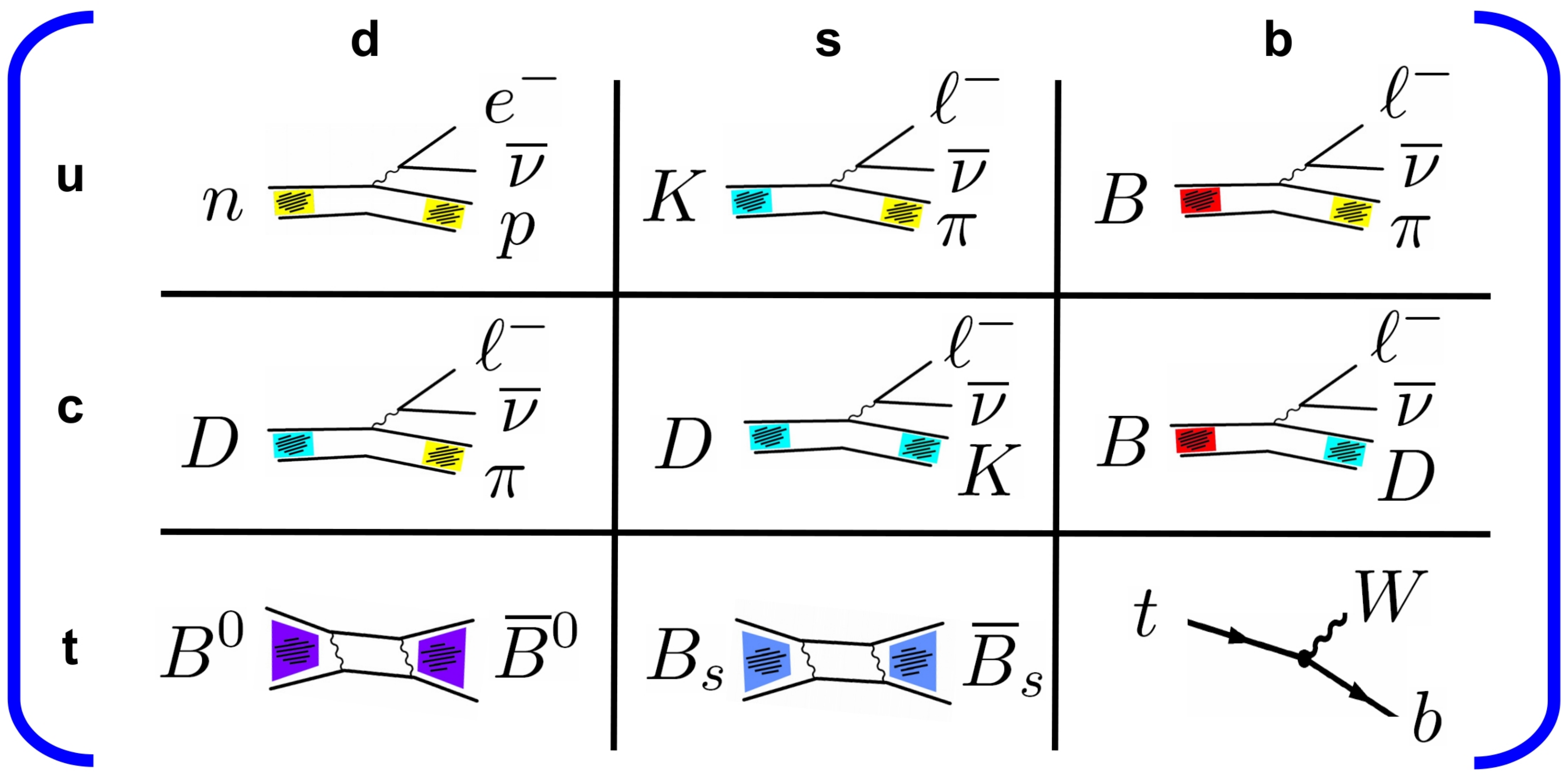


$$\lambda^2 \equiv \frac{|V_{us}|^2}{|V_{ud}|^2+|V_{us}|^2} \qquad A^2\lambda^4 \equiv \frac{|V_{cb}|^2}{|V_{ud}|^2+|V_{us}|^2} \qquad \bar\rho + i\bar\eta = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

Important Decays in the Combination



V =



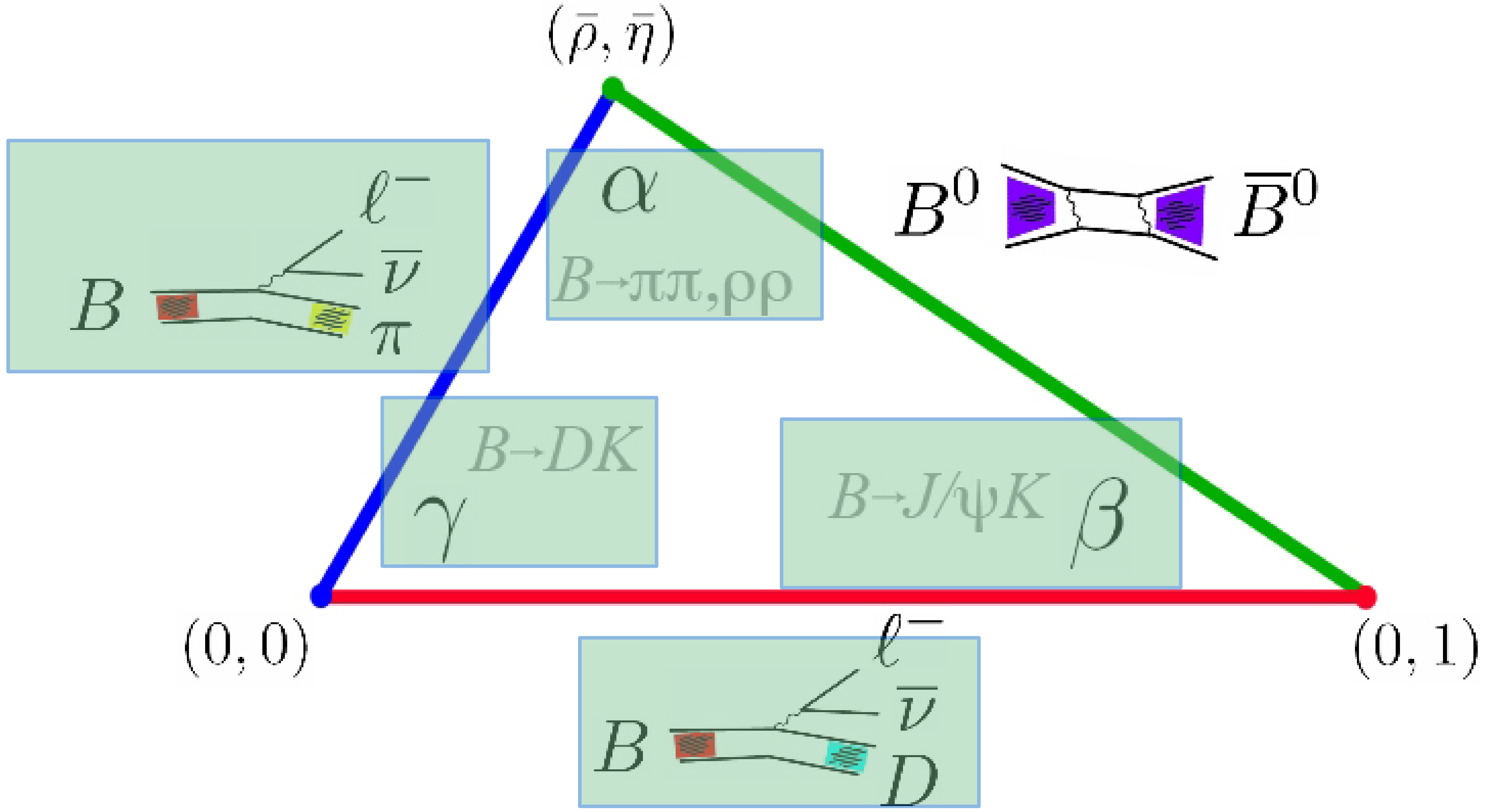
$B \to \pi\pi, \rho\rho$	Φ_2	$B \to D\, l\, \nu / b \to c\, l\, \nu$	$\lvert V_{cb} \rvert$ via Form factor / OPE
$B \to D^{(*)} K^{(*)}$	Φ_3	$B \to \pi\, l\, \nu / b \to u\, l\, \nu$	$\lvert V_{ub} \rvert$ via Form factor / OPE
$B \to J/\psi K_s$	Φ_1	$M \to l\, \nu\, (\gamma)$	$\lvert V_{UD} \rvert$ via Decay constant f_M
$B_s \to J/\psi \Phi$	β_s	ε_K	(ρ, η) via B_K
$K \to \pi\, \nu$ anti-ν	ρ, η	$\Delta m_d, \Delta m_s$	$\lvert V_{tb} V_{t\{d,s\}} \rvert$ via Bag factor B_B
		$B_{(s)} \to \mu+ \mu-$	$\lvert V_{t\{d,s\}} \rvert$ via Decay constant f_B

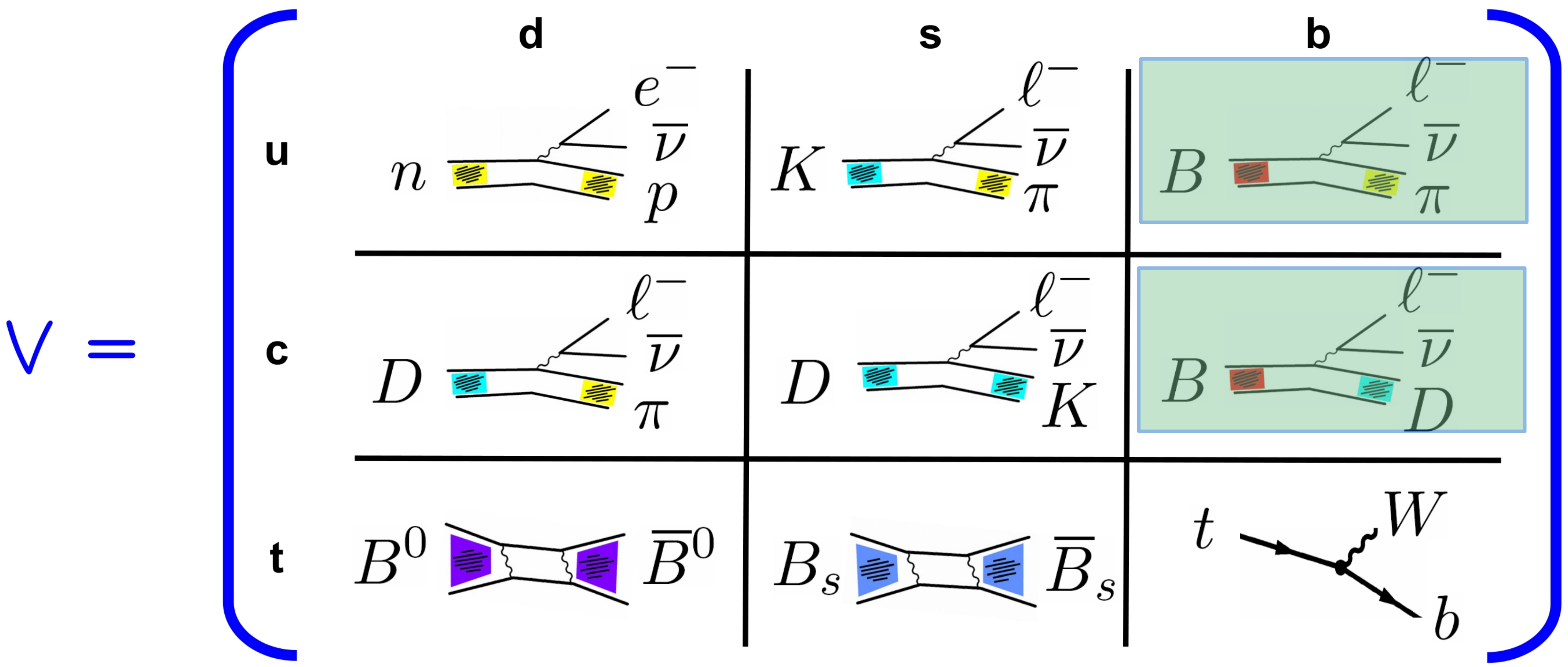
Observables with very different properties

Tree: e.g., $\lvert V_{ub} \rvert$, Φ3
Loop: e.g., Δm_d, Δm_s, ε_K, sin(2β)
CP-*conserving*: e.g., $\lvert V_{ub} \rvert$, Δm_d, Δm_s
CP-*violating*: e.g., γ, ε_K, sin(2β)

Exp. uncs.: e.g., α, sin(2β), γ
Syst. uncs.: e.g., $\lvert V_{ub} \rvert$, $\lvert V_{cb} \rvert$, ε_K, Δm_d, Δm_s

Important Decays in the Combination





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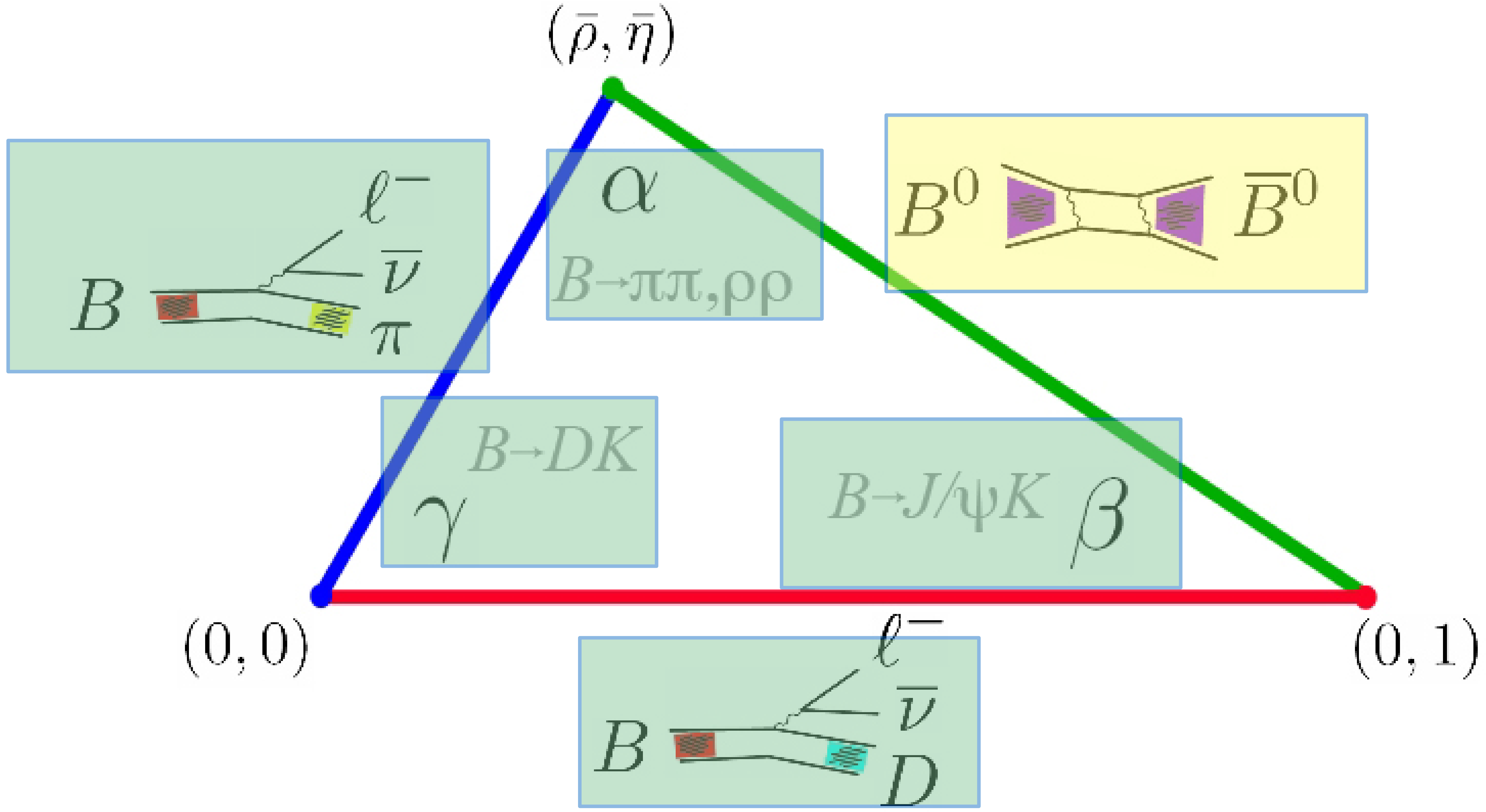
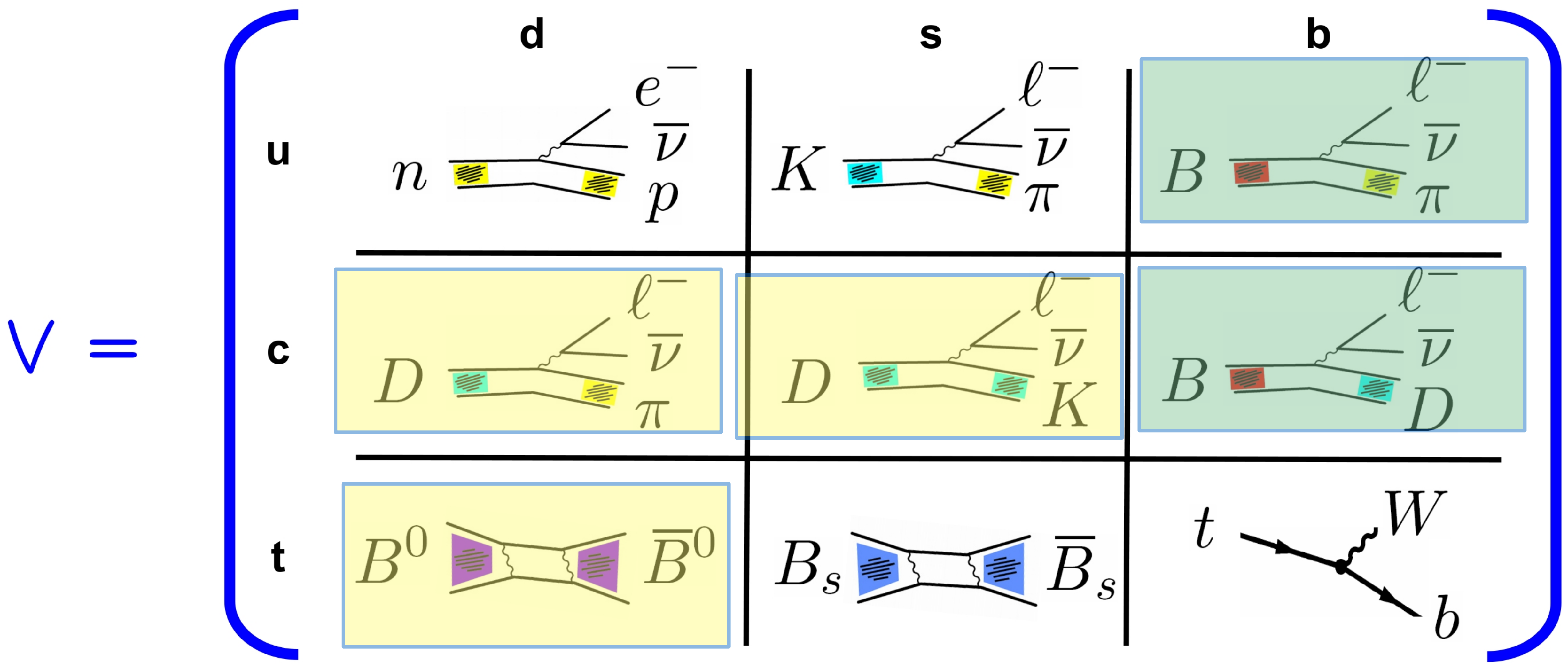
Important Decays in the Combination





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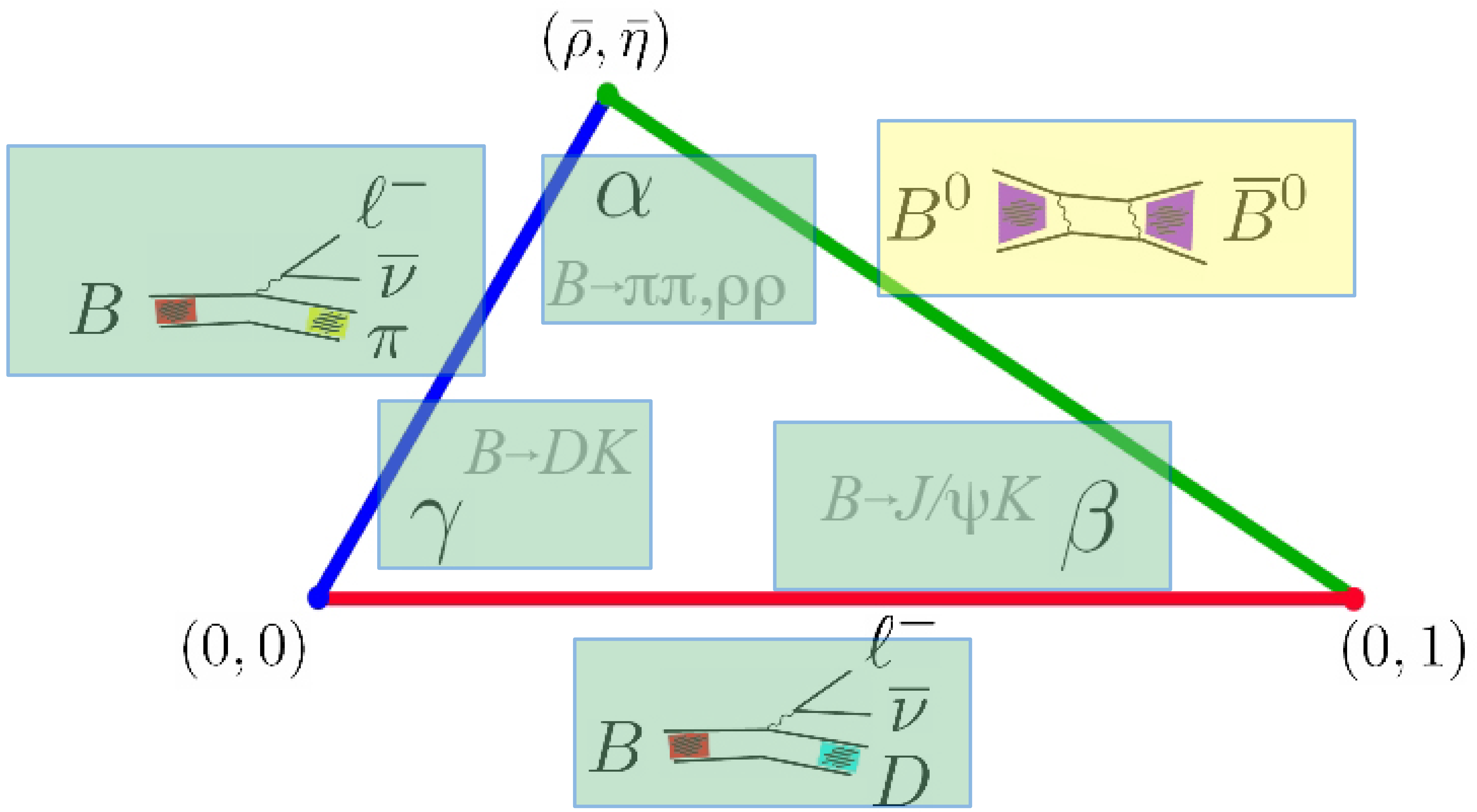
$B \to J/\psi\, K_S$	Φ_1	$M \to l\, \nu\, (\gamma)$	$\lvert V_{UD} \rvert$ via Decay constant f_M
$B_s \to J/\psi\, \Phi$	β_s	ε_K	(ρ, η) via B_K
$K \to \pi\, \nu$ anti-ν	ρ, η	$\Delta m_d, \Delta m_s$	$\lvert V_{tb}\, V_{t\{d,s\}} \rvert$ via Bag factor B_B
		$B_{(s)} \to \mu+\, \mu-$	$\lvert V_{t\{d,s\}} \rvert$ via Decay constant f_B

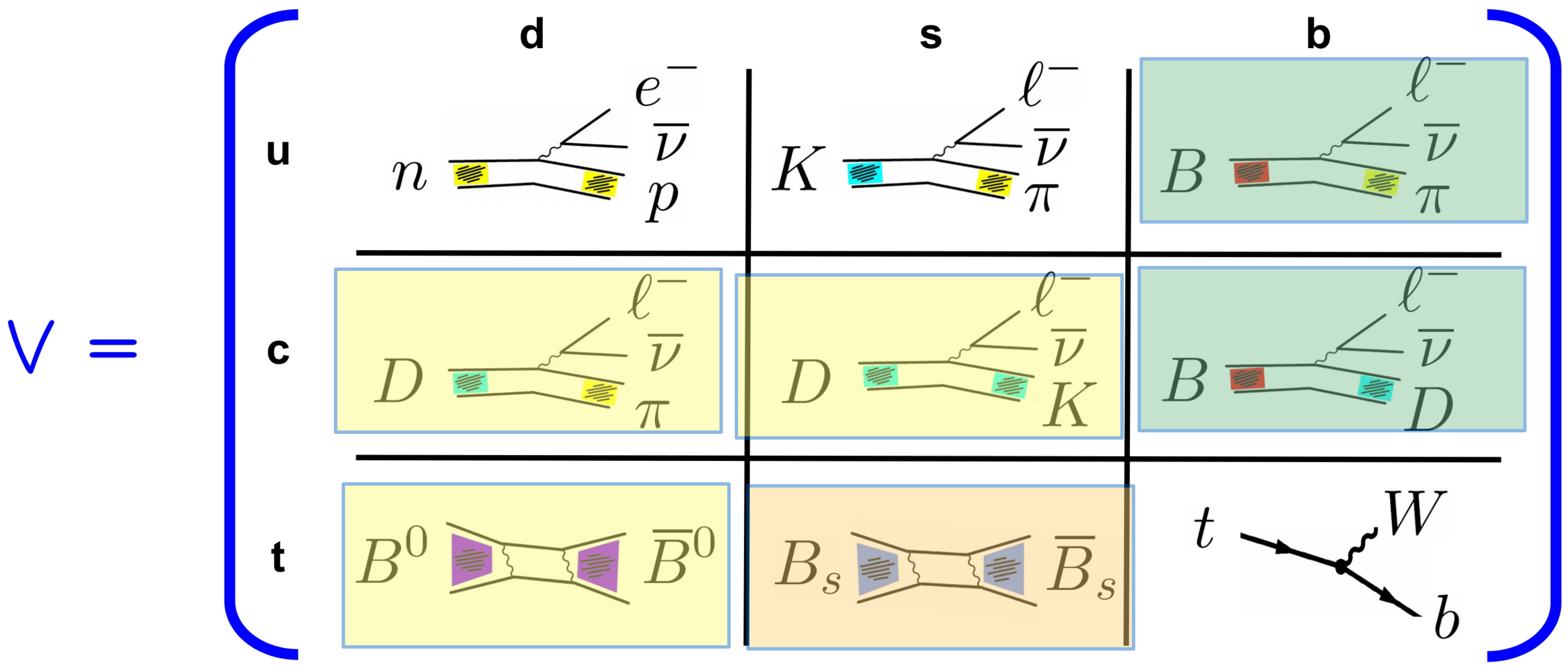
Observables with very different properties

Tree: e.g., $\lvert V_{ub} \rvert$, $\Phi 3$
Loop: e.g., Δm_d, Δm_s, ε_K, $\sin(2\beta)$
CP-*conserving*: e.g., $\lvert V_{ub} \rvert$, Δm_d, Δm_s
CP-*violating*: e.g., γ, ε_K, $\sin(2\beta)$

Exp. uncs.: e.g., α, $\sin(2\beta)$, γ
Syst. uncs.: e.g., $\lvert V_{ub} \rvert$, $\lvert V_{cb} \rvert$, ε_K, Δm_d, Δm_s

Important Decays in the Combination





B → ππ, ρρ	**Φ_2**	*B→D l ν / b → c l ν*	**$\lvert V_{cb}\rvert$** via Form factor / OPE
$B \to D^{(*)} K^{(*)}$	**Φ_3**	*B→π l ν / b → u l ν*	**$\lvert V_{ub}\rvert$** via Form factor / OPE
$B \to J/\psi K_s$	**Φ_1**	*M → l ν (γ)*	**$\lvert V_{UD}\rvert$** via Decay constant f_M
$B_s \to J/\psi\ \Phi$	**β_s**	*ε_K*	**(ρ, η)** via B_K
K → π ν anti-ν	**ρ, η**	*Δm_d, Δm_s*	**$\lvert V_{tb} V_{t\{d,s\}}\rvert$** via Bag factor B_B
		$B_{(s)} \to \mu+ \mu-$	**$\lvert V_{t\{d,s\}}\rvert$** via Decay constant f_B

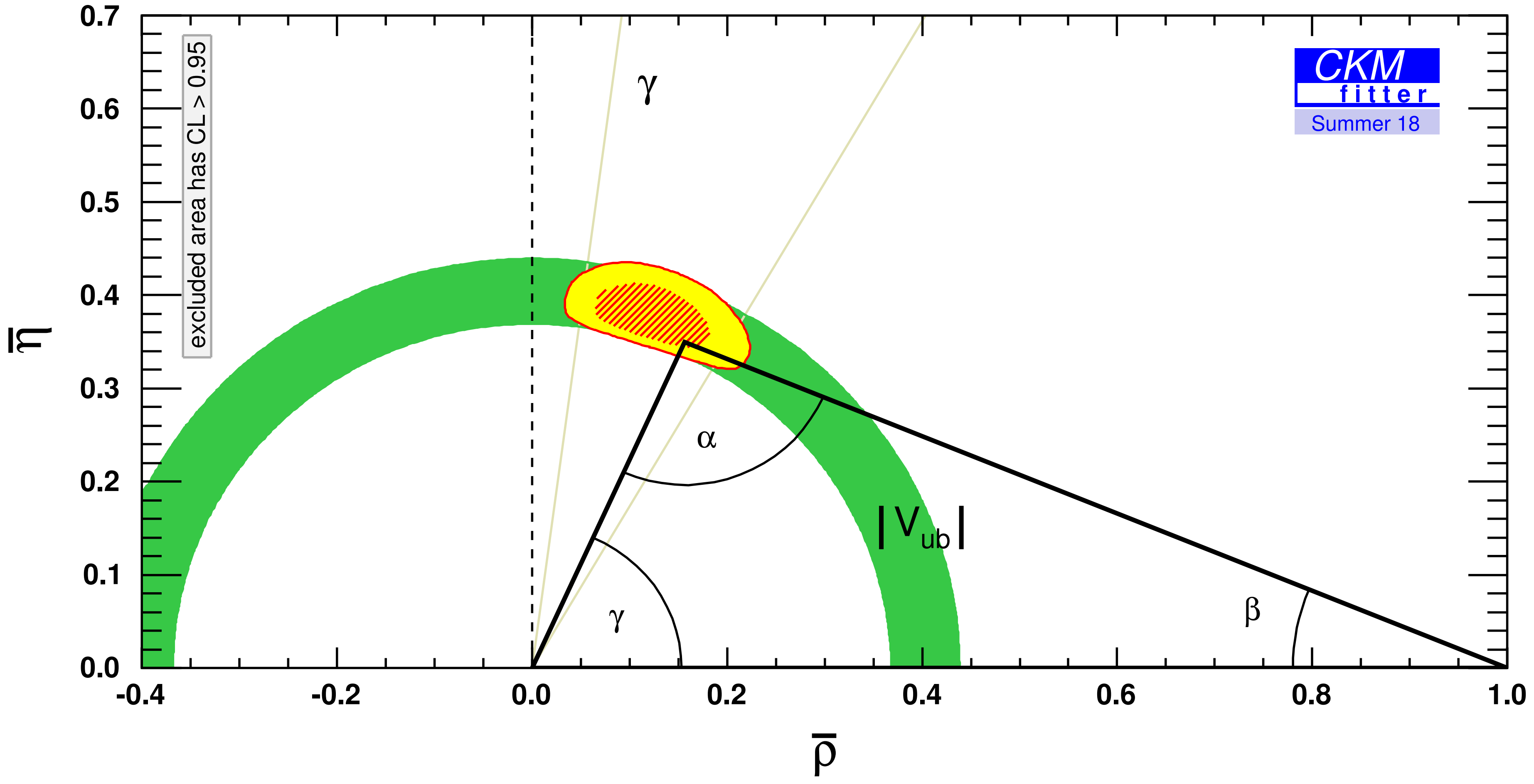
Observables with very different properties

Tree: e.g., $\lvert V_{ub}\rvert$, Φ3
Loop: e.g., Δm_d, Δm_s, ε_K, sin(2β)
CP-*conserving*: e.g., $\lvert V_{ub}\rvert$, Δm_d, Δm_s
CP-*violating*: e.g., γ, ε_K, sin(2β)

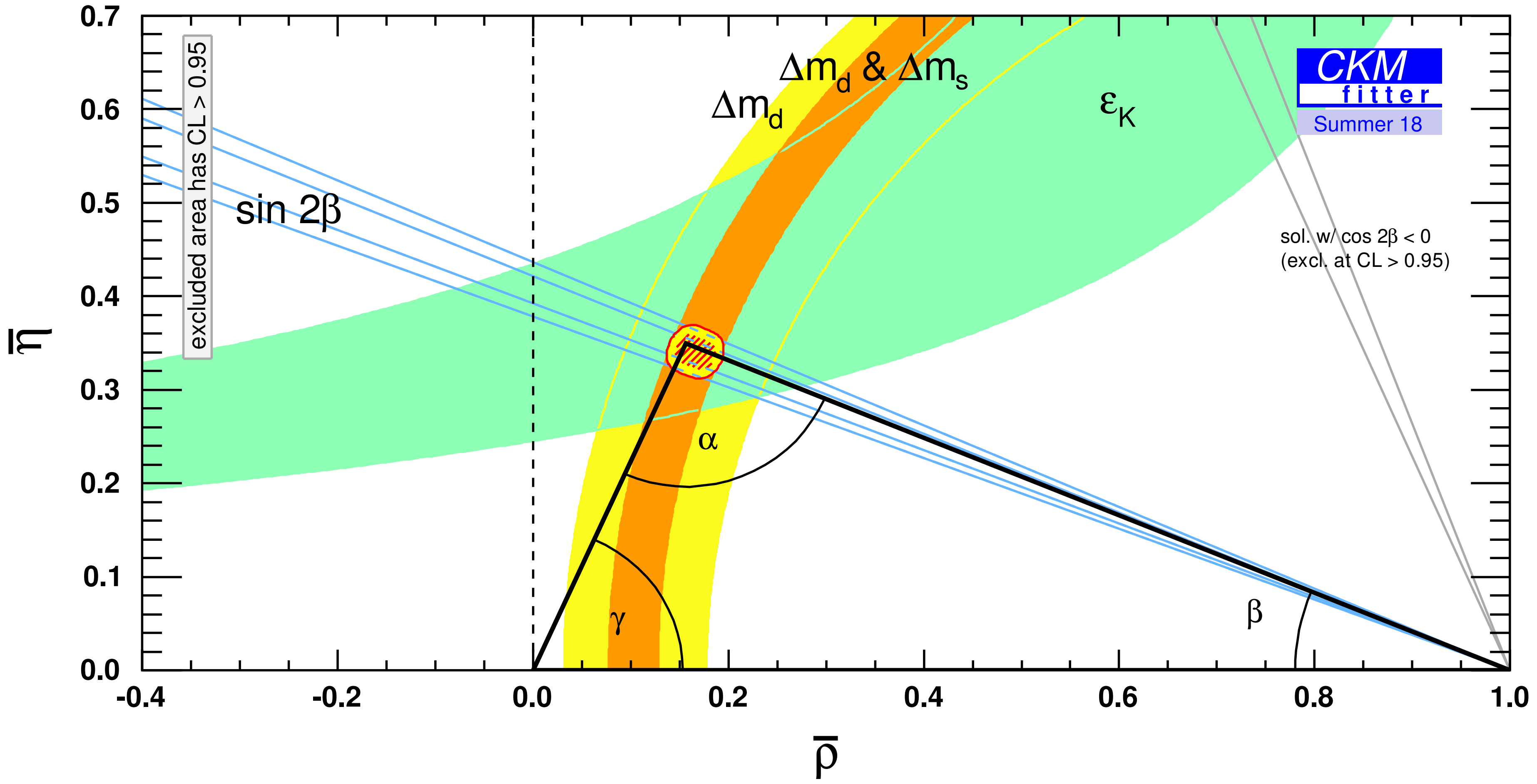
Exp. uncs.: e.g., α, sin(2β), γ
Syst. uncs.: e.g., $\lvert V_{ub}\rvert$, $\lvert V_{cb}\rvert$, ε_K, Δm_d, Δm_s

Consistency among classes of observables

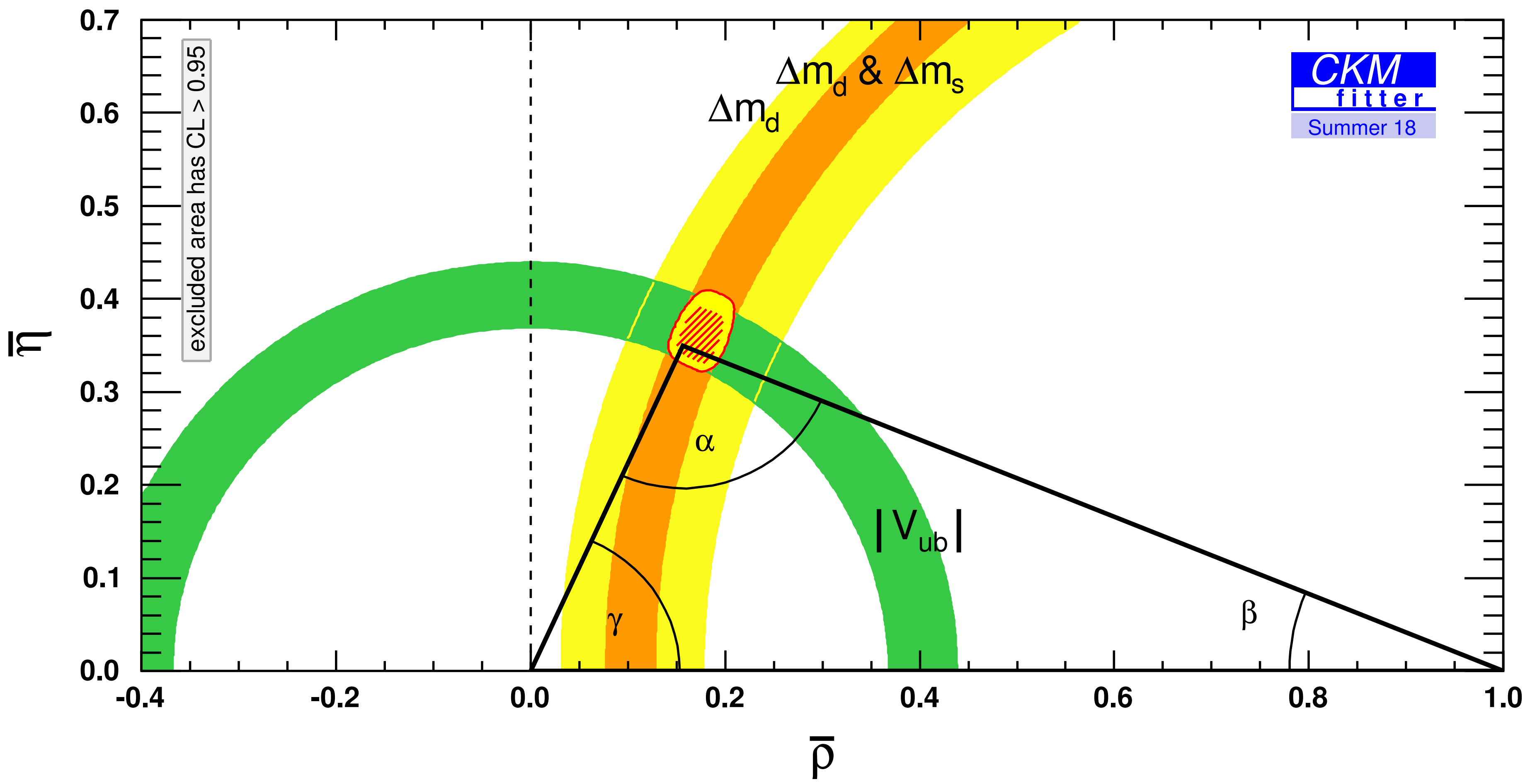
tree level



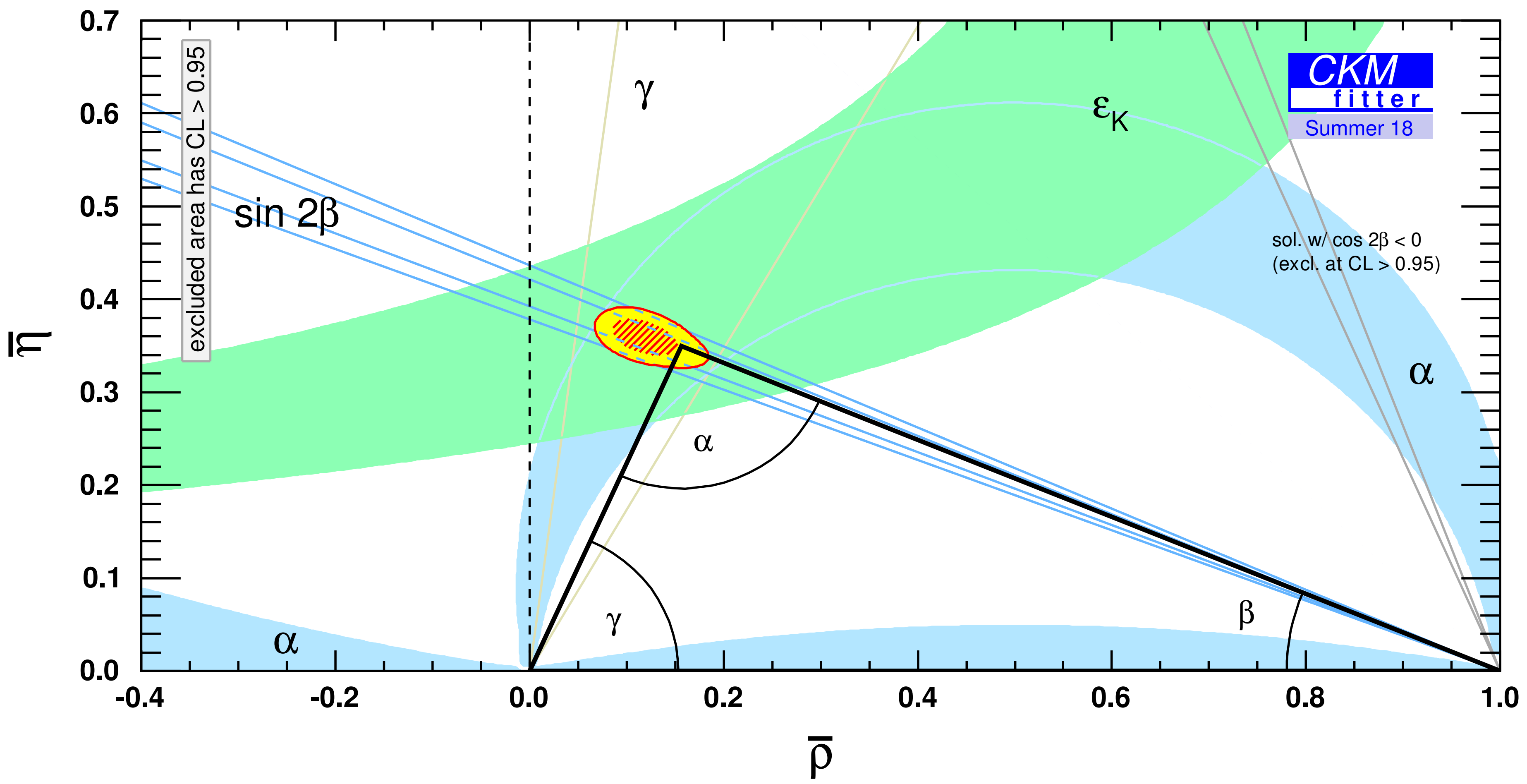
loop-induced



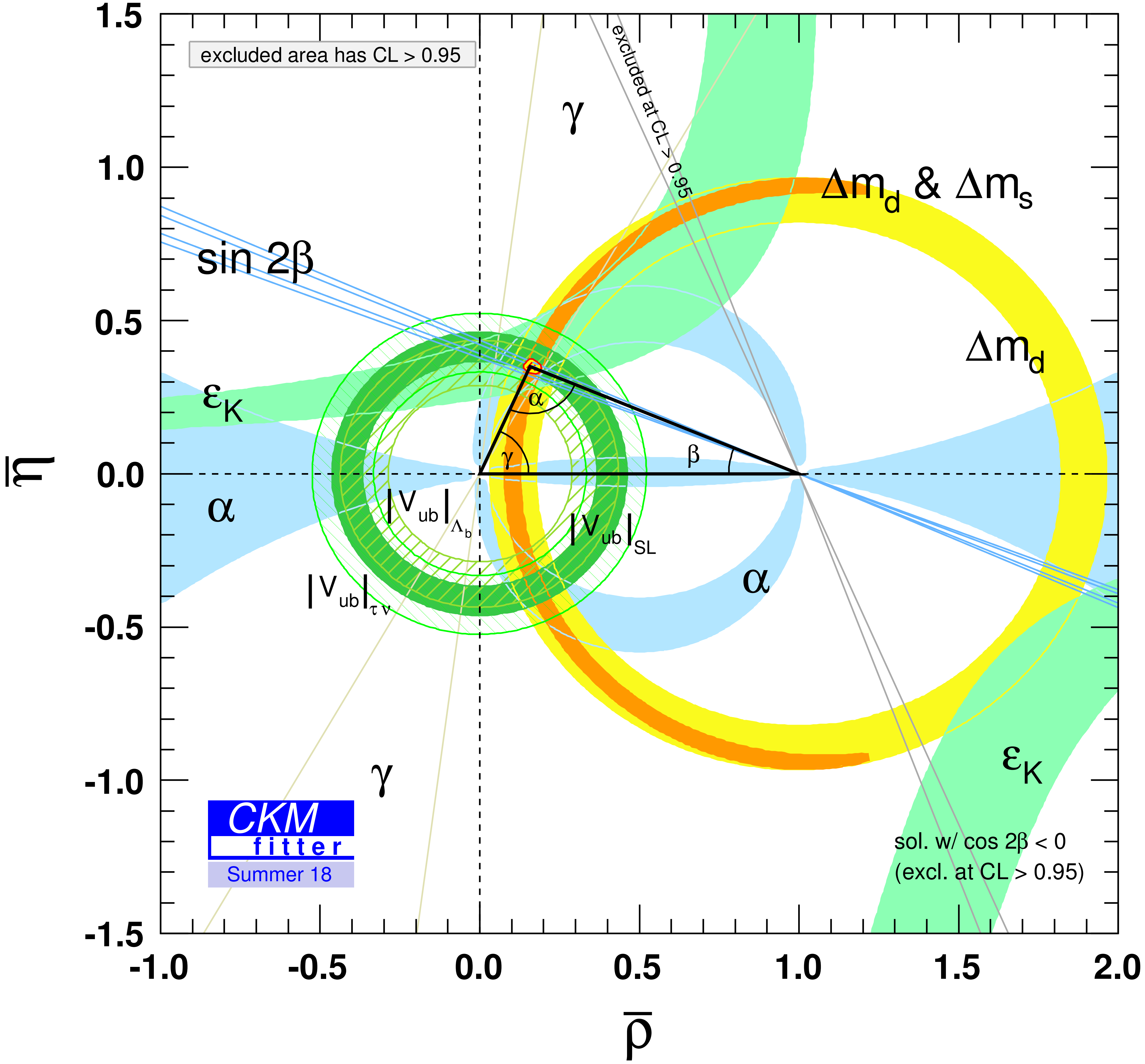
$\mathcal{CP}-$conserving



$\mathcal{CP}-$violating



Overall results from 2018



Global fit remains excellent:

ICHEP'16: p-value ~ 21% (1.3σ) →

CKM'18: p-value ~ 51% (0.7σ)

$$A = 0.8403^{+0.0056}_{-0.0201}\ (2\%\ \text{unc.})$$

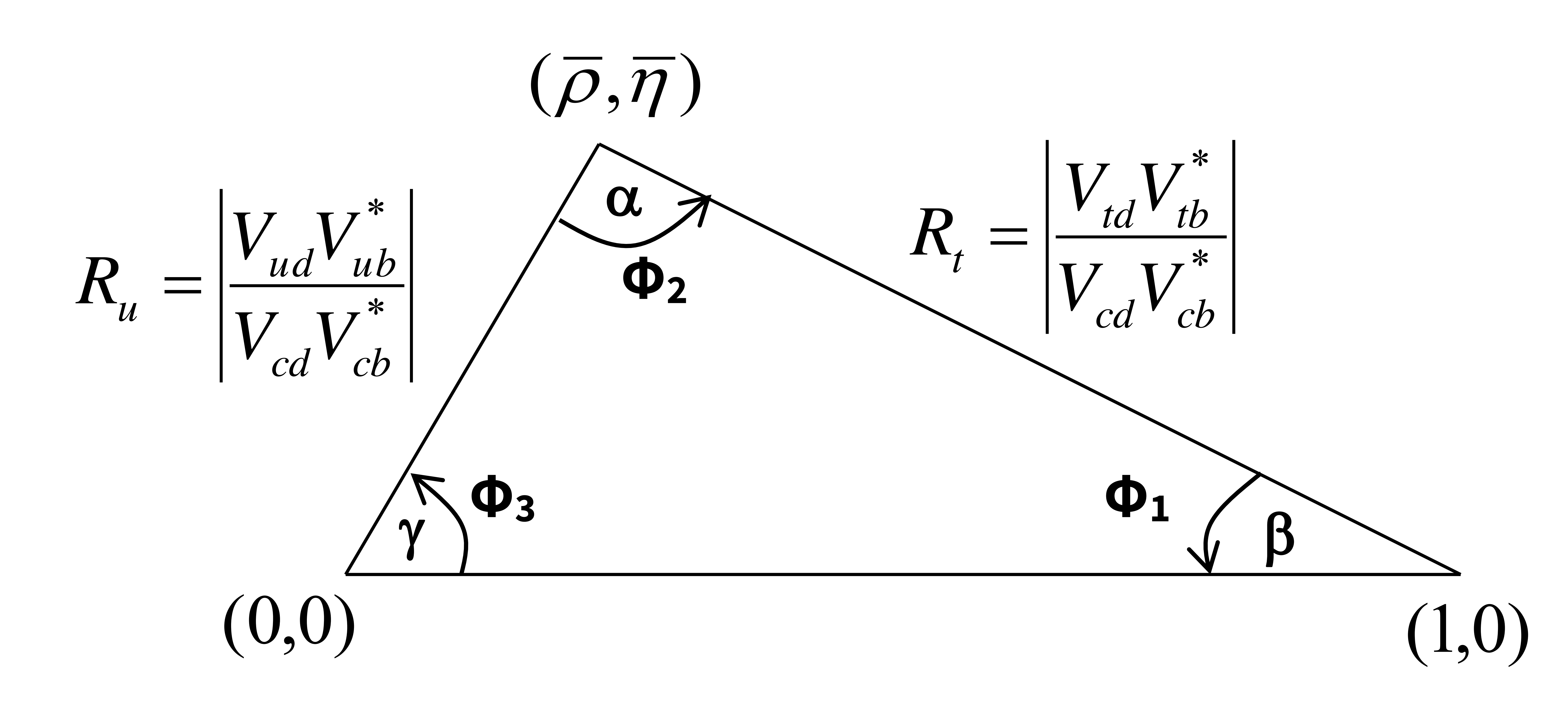
$$\lambda = 0.224747^{+0.000254}_{-0.000059}\ (0.07\%\ \text{unc.})$$

$$\bar{\rho} = 0.1577^{+0.0096}_{-0.0074}\ (5\%\ \text{unc.})$$

$$\bar{\eta} = 0.3493^{+0.0095}_{-0.0071}\ (2\%\ \text{unc.})$$

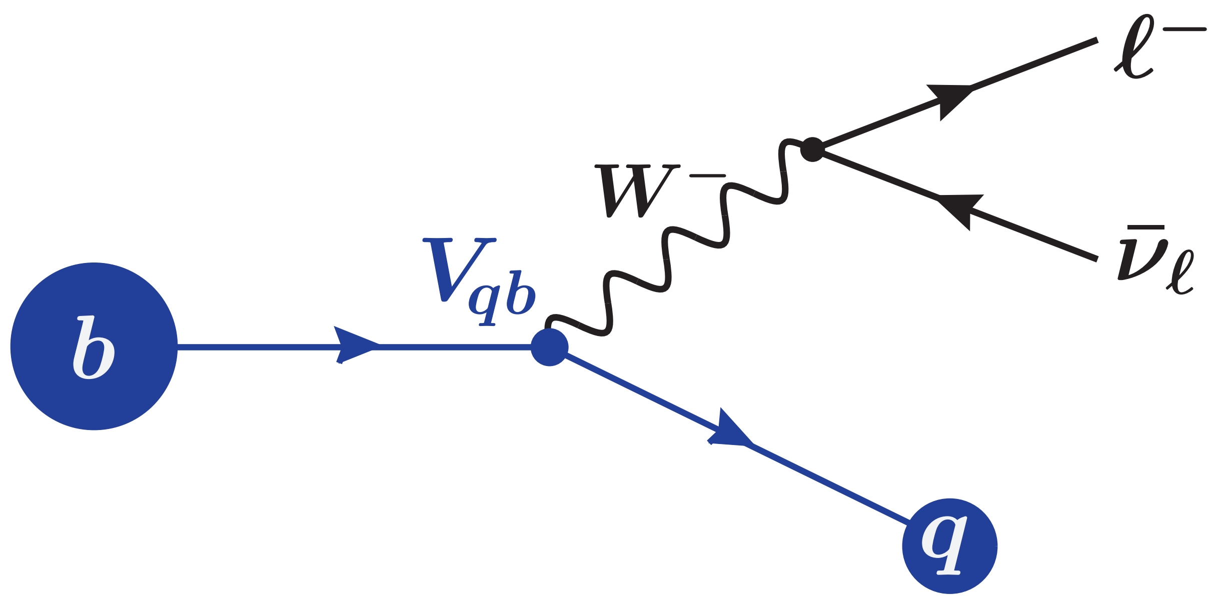
68% C.L. intervals

Determination of UT sides



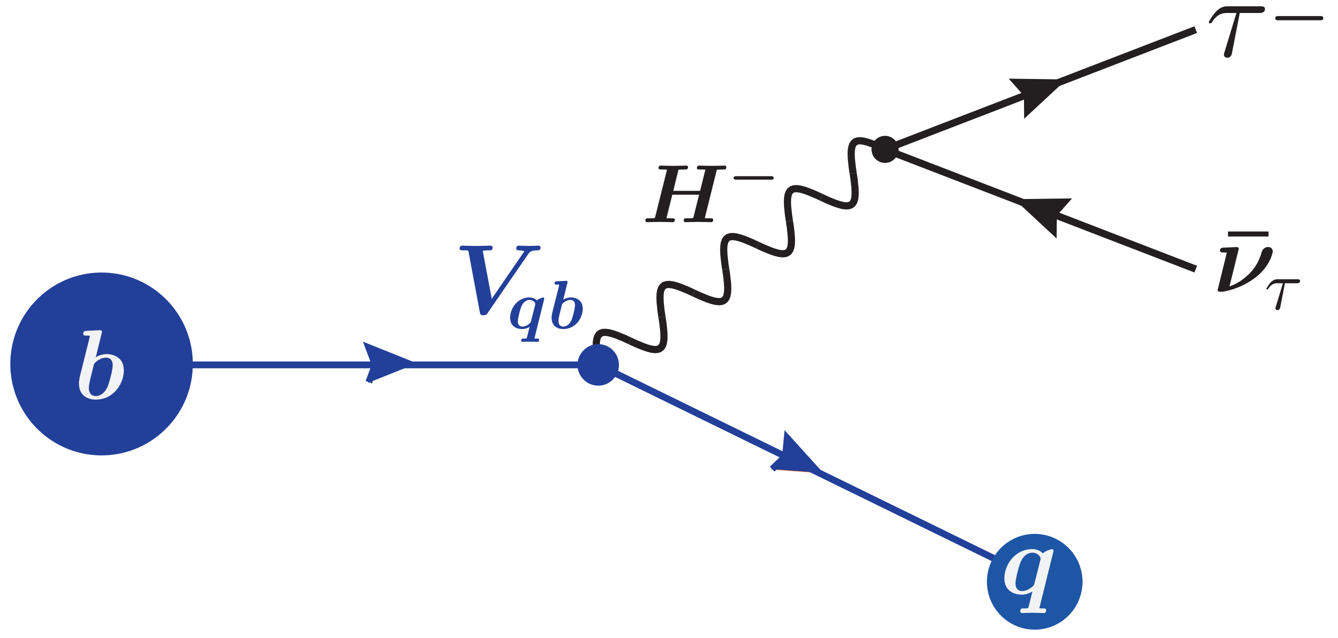
CKM matrix elements, Ru ~ |Vub|/|Vcb|

- 3-ways to measure $|V_{CKM}|$ with leptonic and semileptonic decays



- **Leptonic**: decay constant from LQCD

$$\Gamma(B \to \ell_1 \ell_2) = \frac{M_B}{4\pi} |G|^2 f_B^2 \zeta_{12} \frac{\lambda_{12}^{1/2}}{M_B^2} \qquad G = \frac{G_F}{\sqrt{2}} V_{ub}, \quad (m_{\nu_\ell} \to 0)$$



- **Exclusive semileptonic**: form factor parameterisation with normalisation from LQCD or Light Cone Sum Rules

$$\frac{d\Gamma}{dq^2} = C_q |\eta_{\mathrm{EW}}|^2 \frac{G_F^2 |V_{qb}|^2}{(2\pi)^3} \frac{\lambda^{1/2}}{4M_B^3} \frac{\lambda_{12}^{1/2}}{q^2} \left\{ q^2 \beta_{12} \left[|H_+|^2 + |H_-|^2 + |H_0|^2 \right] + \zeta_{12} |H_s|^2 \right\}$$

- **Inclusive semileptonic**: Heavy quark symmetry if you measure the full rate, described by heavy quark expansion

$$\Gamma(B \to X_c \ell \nu) = \frac{G_F^2 m_b^5}{192\pi^3} |V_{cb}|^2 [[1 + A_{ew}] A_{nonpert} A_{pert}]$$

$$\lambda_{12} = (M_B^2 - m_1^2 - m_2^2)^2 - 4m_1^2 m_2^2,$$

$$\zeta_{12} = m_1^2 + m_2^2 - \frac{(m_1^2 - m_2^2)^2}{M_B^2},$$

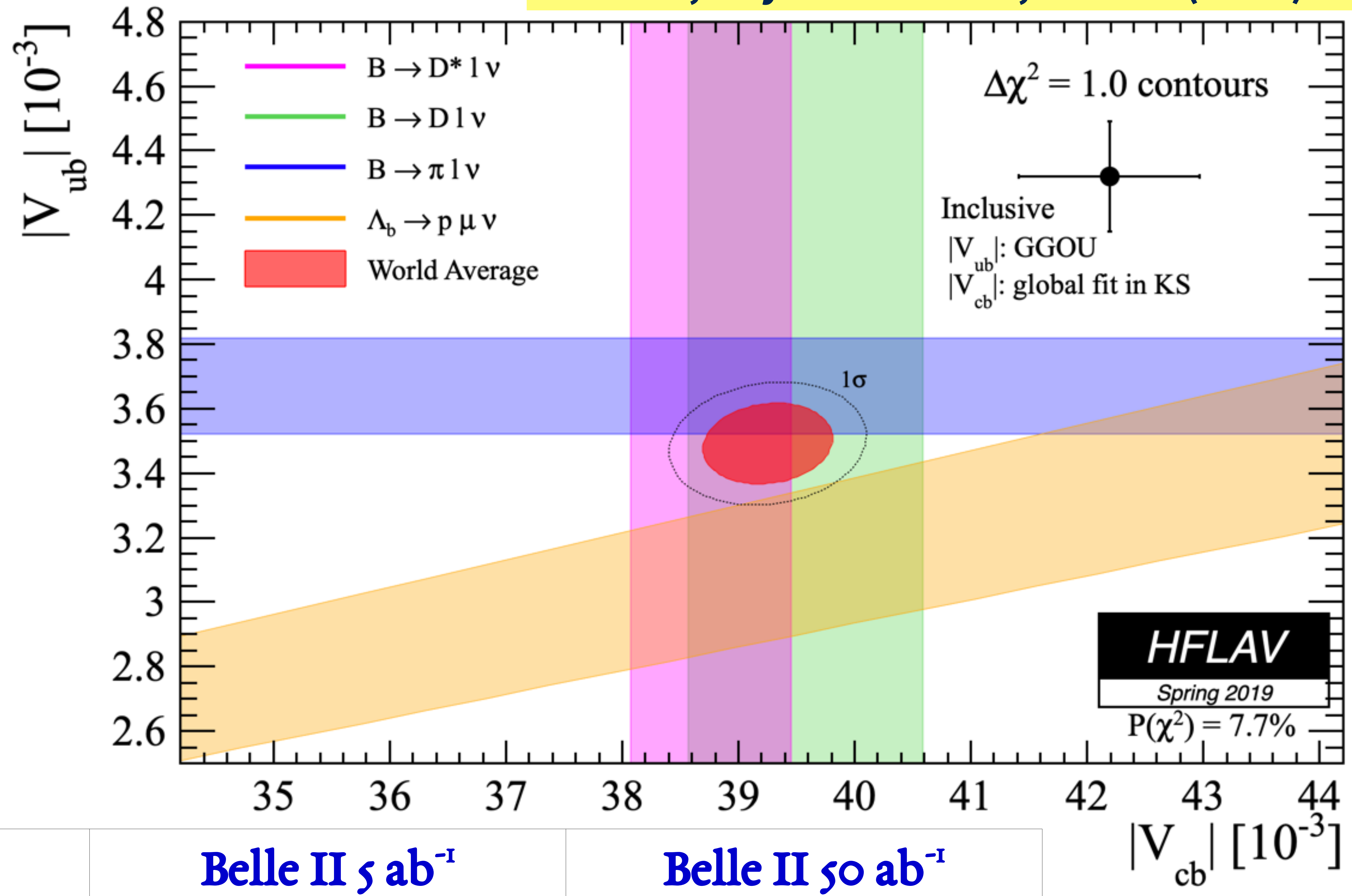
$$\beta_{12} = 1 - \frac{m_1^2 + m_2^2}{q^2} - \frac{\lambda_{12}}{q^2}$$

Status and prospects, Ru ~ Vub/Vcb

Recent $|V_{cb}|$ exclusive results
Babar, Phys. Rev. Lett. 123, 091801 (2019)
Belle, Phys. Rev. D 100, 052007 (2019)

- Current precision:
  2% for $|V_{cb}|$,
  5-6% for $|V_{ub}|$,
  but sizeable tension between exclusive and inclusive.

- Belle II should fully resolve this tension within 5 years (**inclusive, exclusive, leptonic**), combined with **LQCD** improvements.



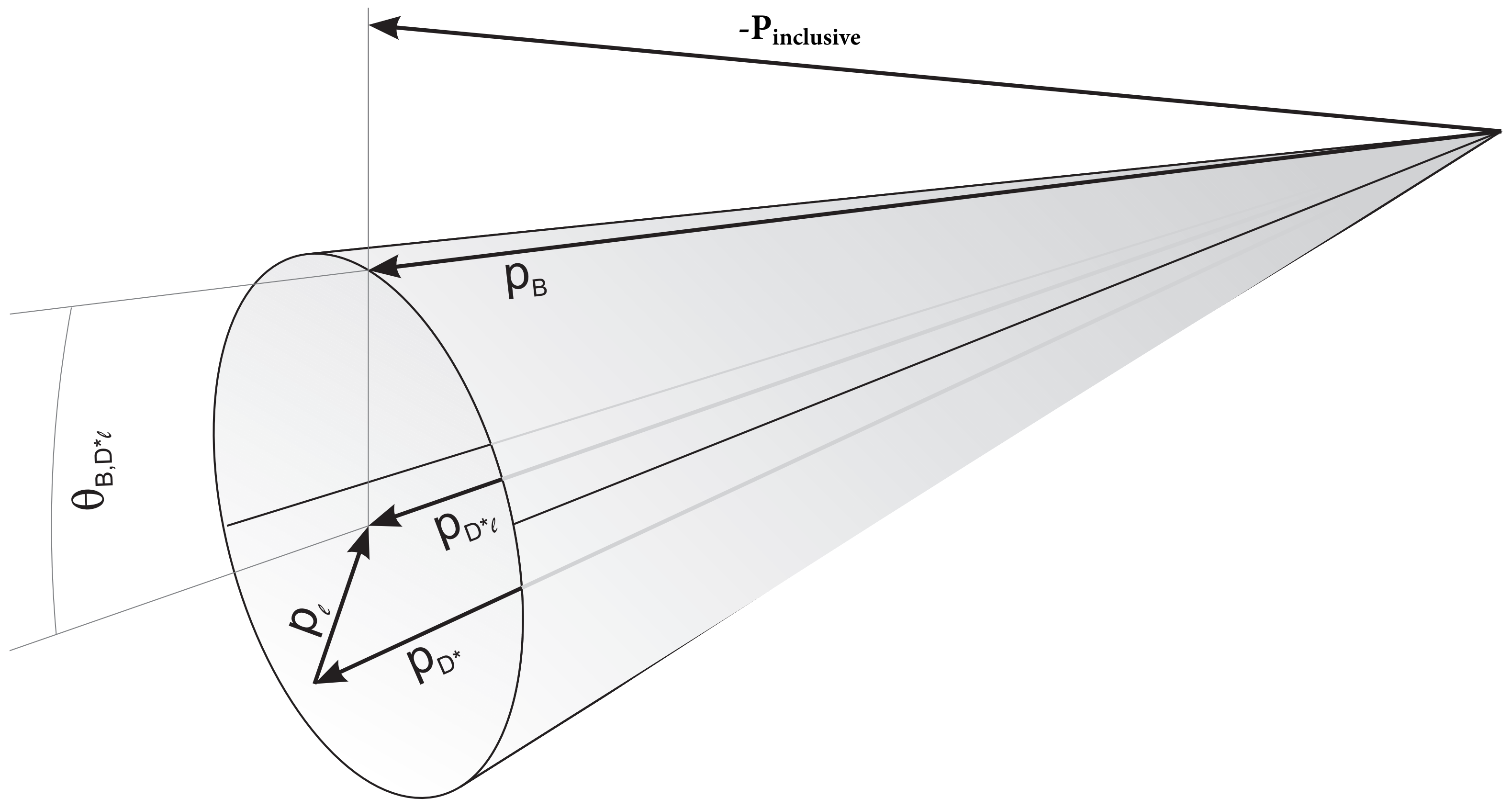
	Belle	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$|V_{ub}|$ exclusive (tagged)	$(3.8 \oplus 7.0)\%$	$(1.8 \oplus 1.7)\%$	$(1.2 \oplus 0.9)\%$
$|V_{ub}|$ exclusive (untagged)	$(2.7 \oplus 7.0)\%$	$(1.2 \oplus 1.7)\%$	$(0.9 \oplus 0.9)\%$
$|V_{ub}|$ inclusive	$(6.0 \oplus 2.5\text{-}4.5)\%$	$(2.3 \oplus 2.5\text{-}4.5)\%$	$(1.7 \oplus 2.5\text{-}4.5)\%$

Observation of B→D* l ν at Belle II

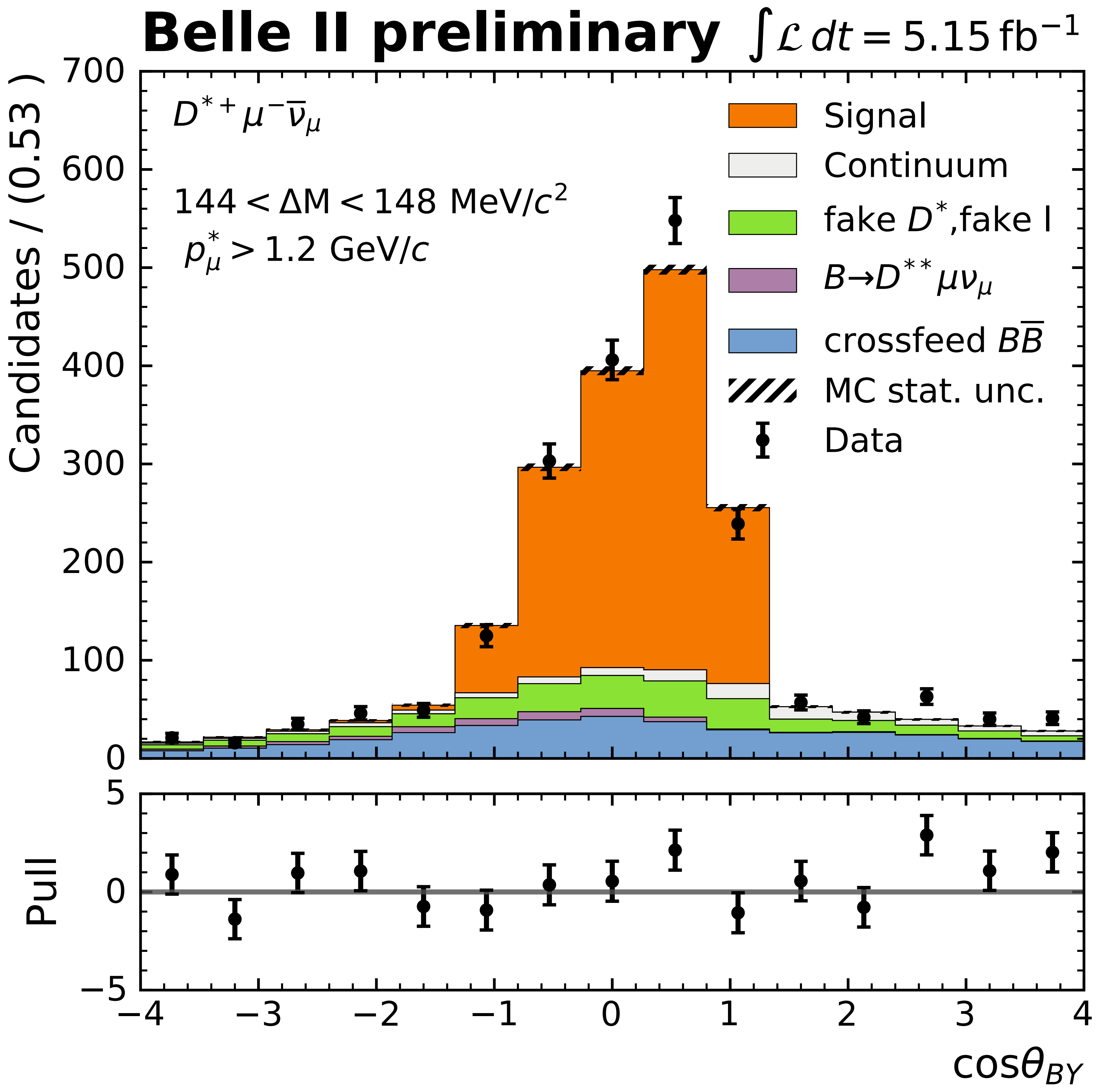
Signals for B→ D^{*+} l^- ν, D^{*+}→D^0 π^+ using $\cos\theta_{BD^*l}$ variable

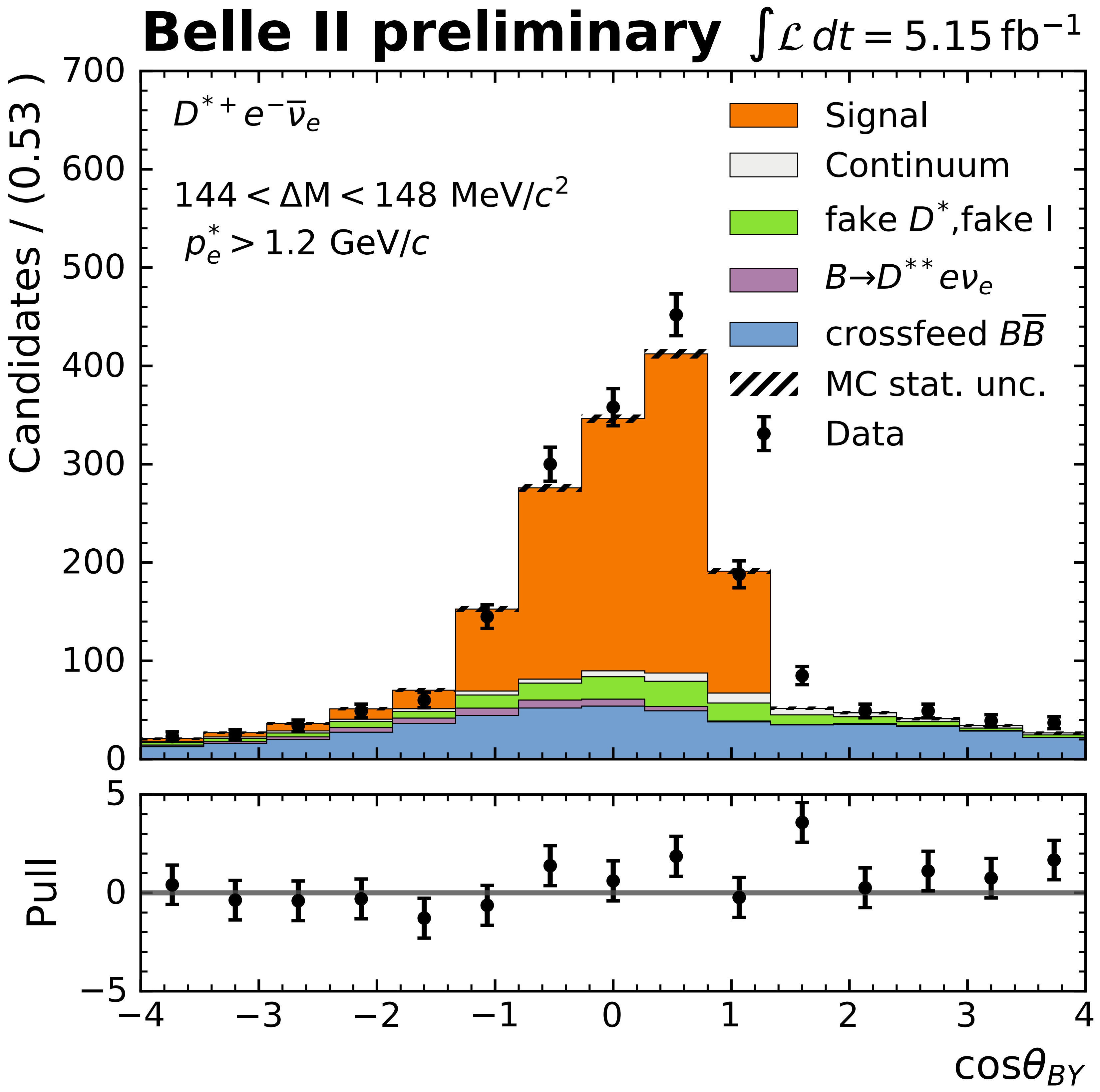
Clear signals are found in both the electron and muon modes.

Cosine of the angle between the B flight direction and the direction of the (D*l) system (Y):

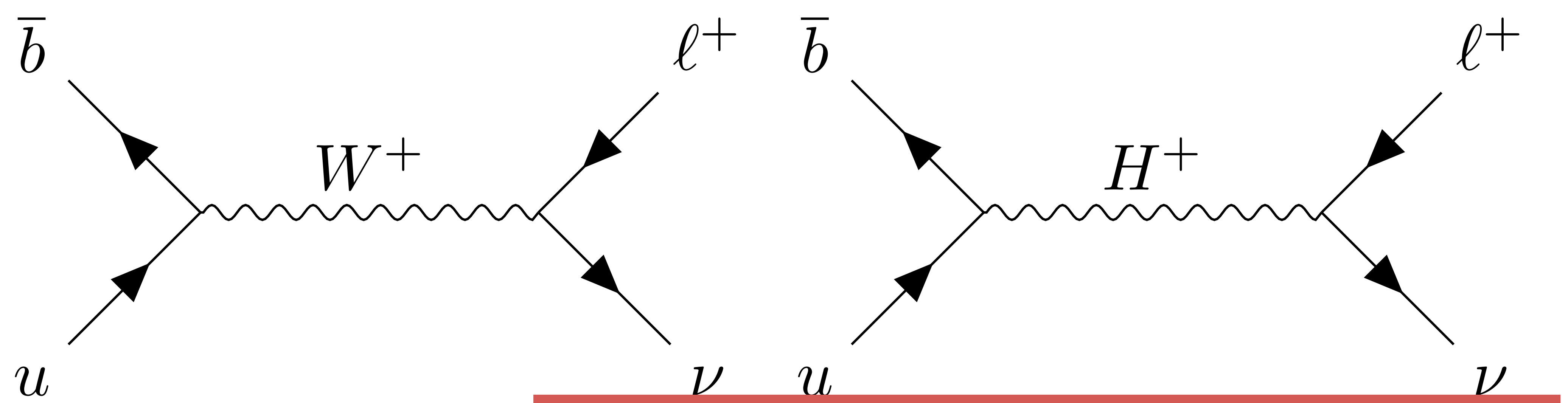


$$\cos\theta_{BY} = \frac{2E_B^* E_Y^* - M_B^2 - m_Y^2}{2p_B^* p_Y^*}$$



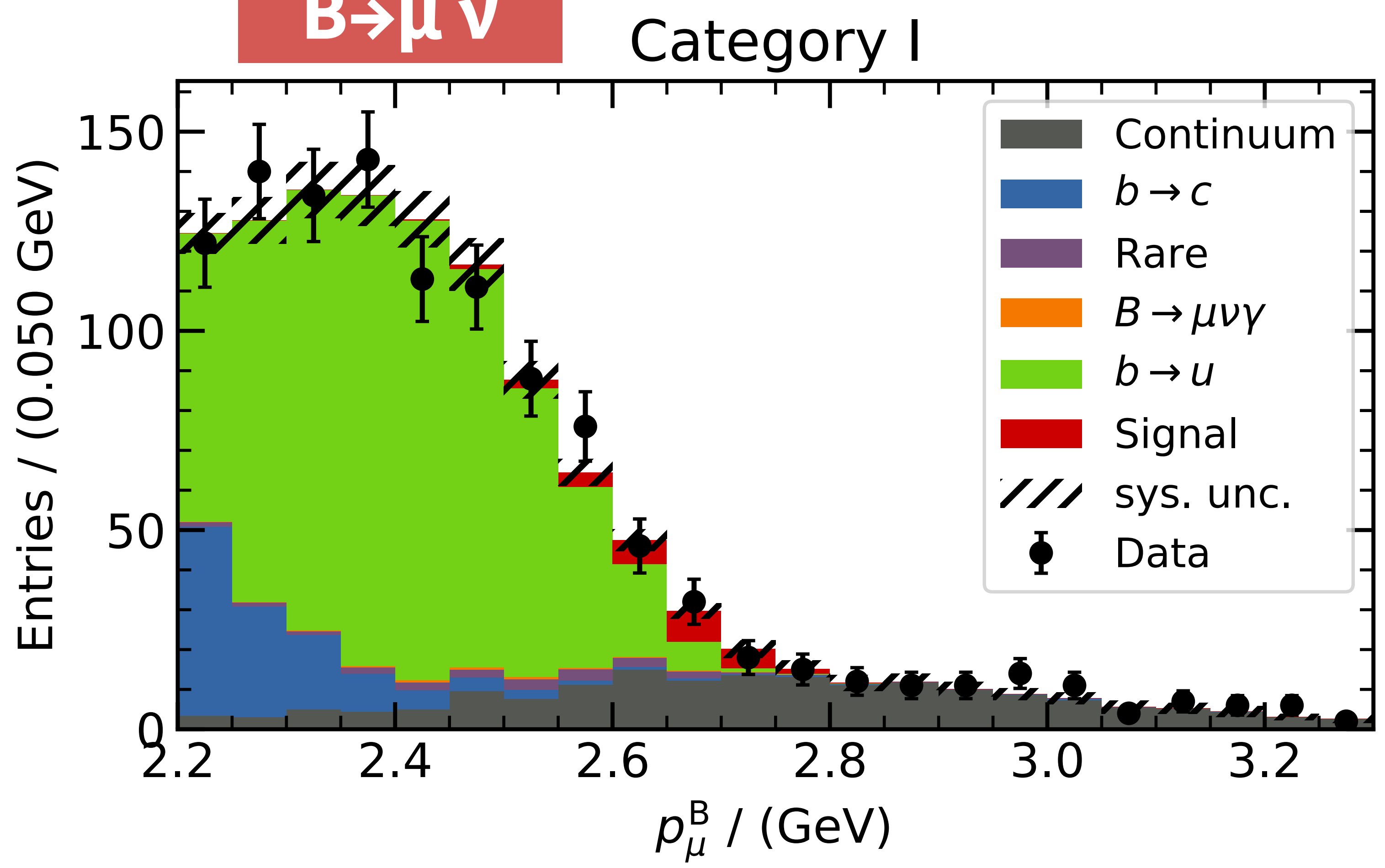


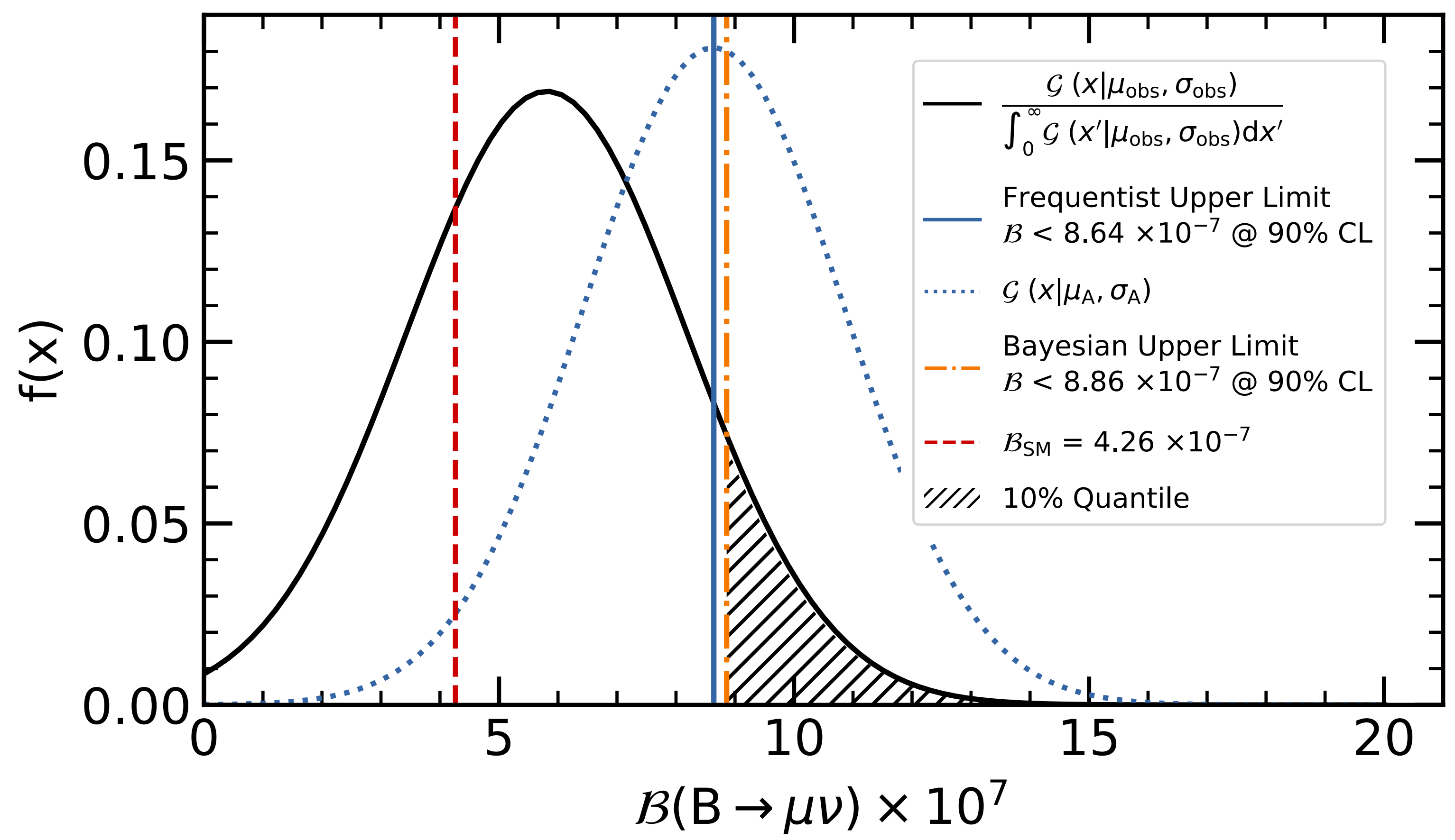
|V_{ub}| and LFU in B→lν



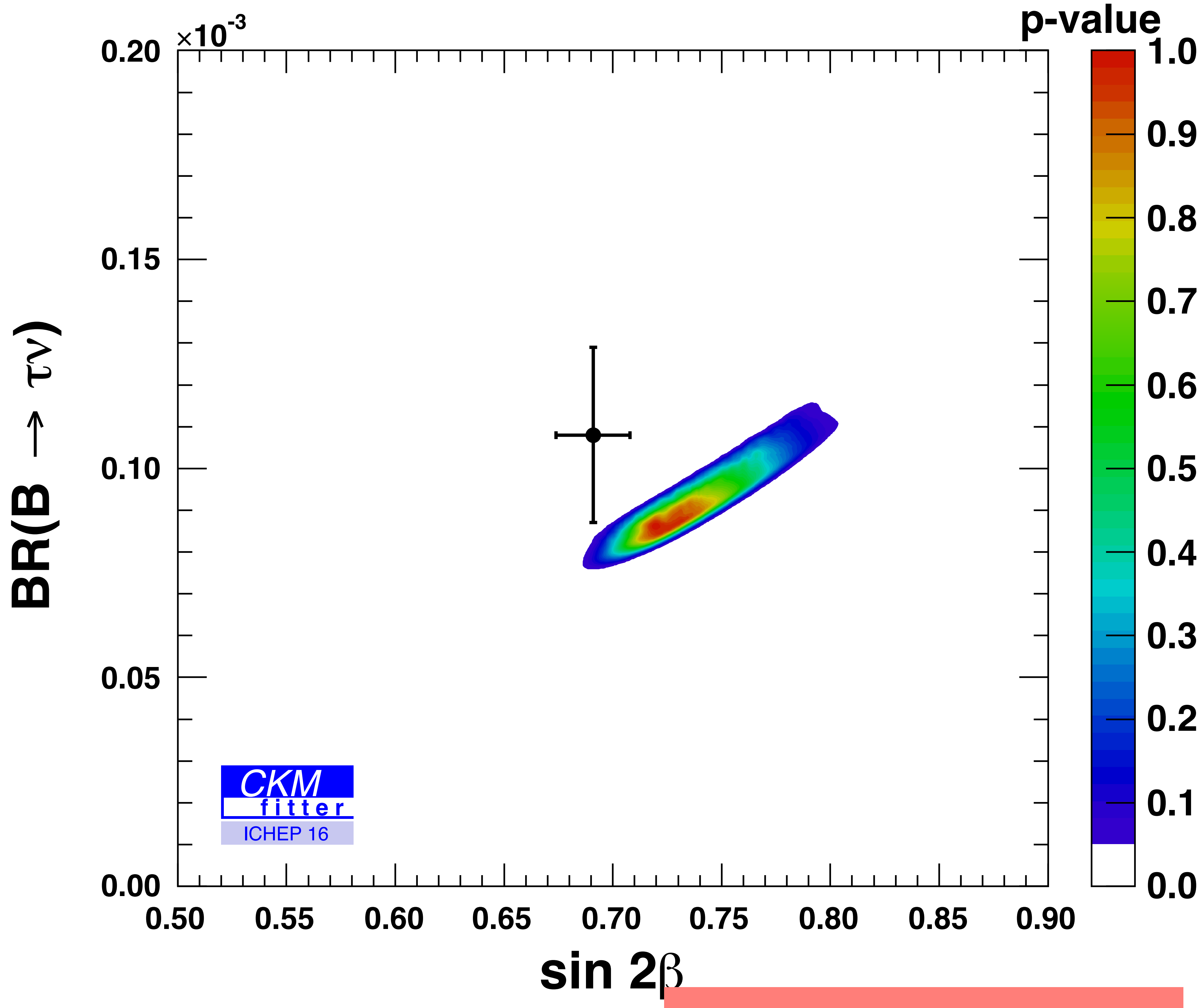
Belle, arXiv: 1911.03186
submitted to PRD

B→μ ν





- 5 σ discoveries of B→ τ ν and B→ μ ν expected with < 5 ab^{-1}.



Phase of Vtd

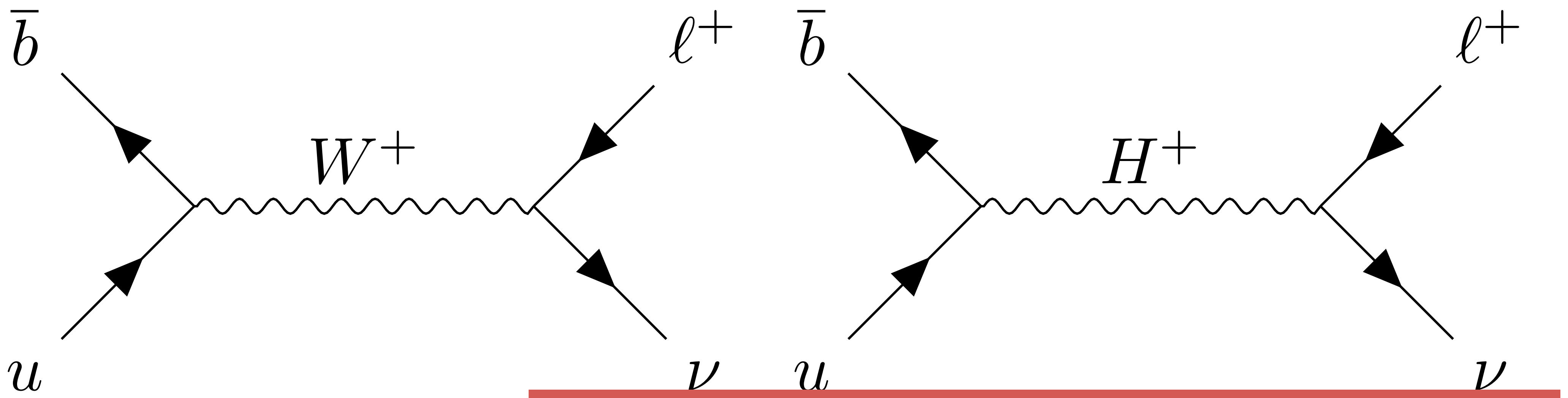
Total uncertainty

L [ab^{-1}]		σ |V_{ub}| [%]
5	B→ π l ν	2
	B→ τ ν	5
	B→ μ ν	>>5σ
50	B→ π l ν	1.2
	B→ τ ν	1.5 - 2
	B→ μ ν	5

LQCD projections on decay constants.

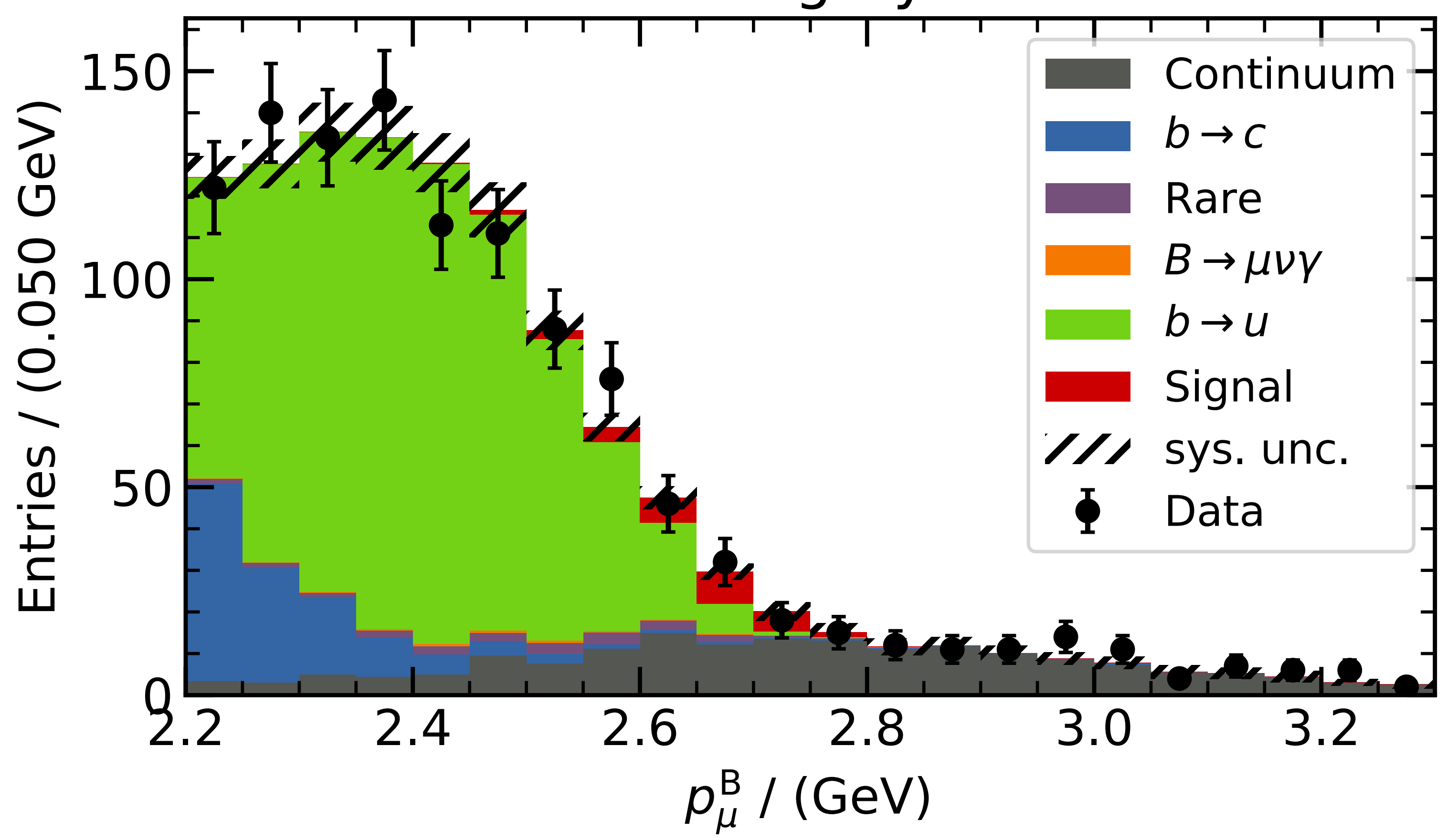
N_f	forecast	f_B[MeV]
	current (2017)	188(3)
2+1+1	5 yr w/o EM	188(1.5)
	5 yr w/ EM	188(2.4)
	10 yr w/o EM	188(0.60)
	10 yr w/ EM	188(2.0)

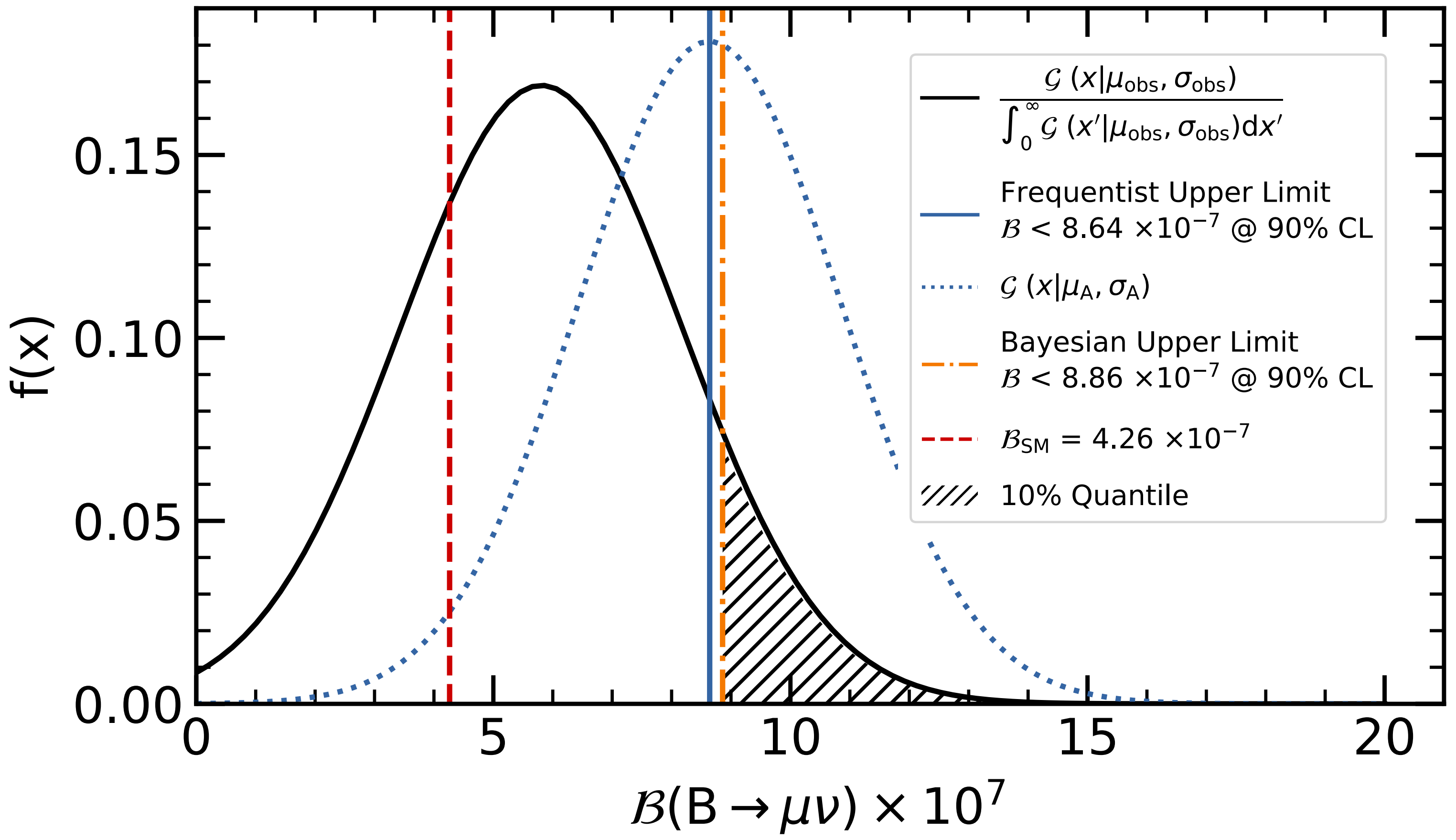
$|V_{ub}|$ and LFU in B→lν



Belle, arXiv: 1911.03186 submitted to PRD

B→μ ν





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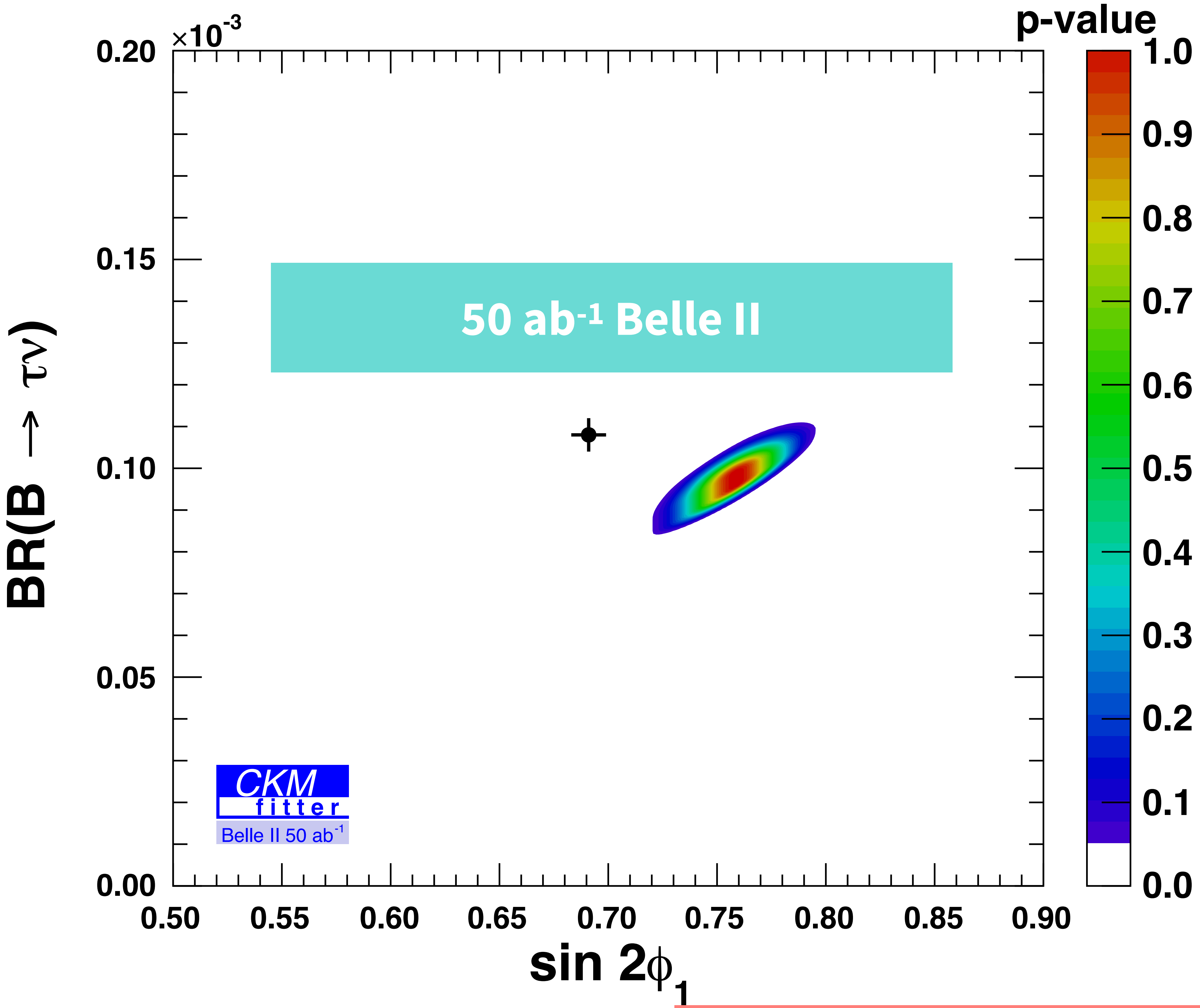

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LQCD projections on decay constants.

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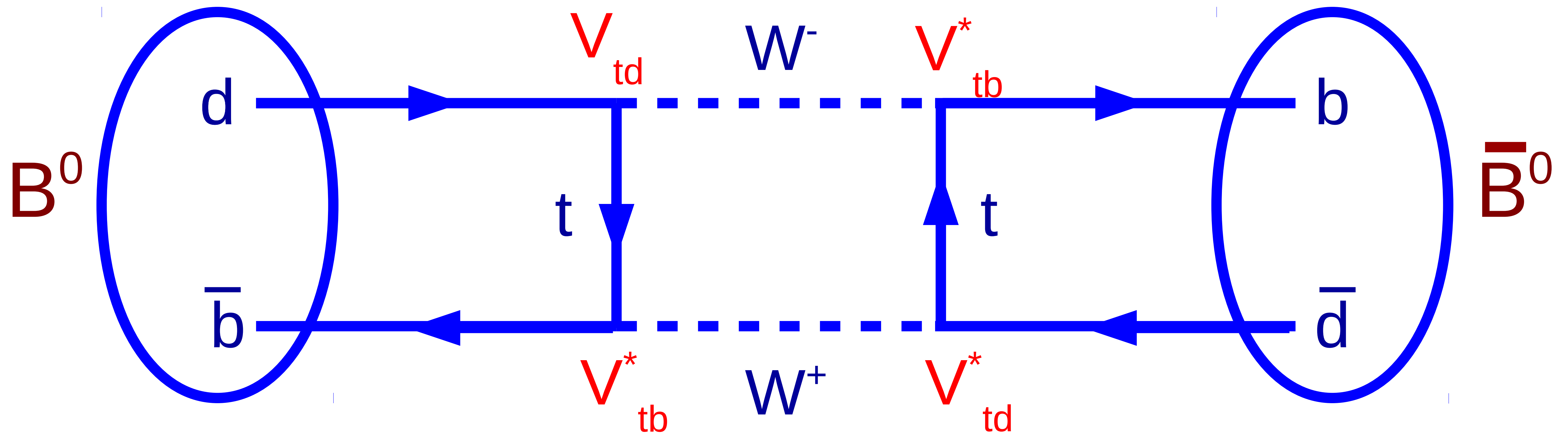
2+1+1	5 yr w/ EM	188(2.4)
	10 yr w/o EM	188(0.60)
	10 yr w/ EM	188(2.0)

Mixing measurements, Rt ~ |Vtd|/|Vts|

- Derived from the B anti-B oscillation frequencies **Δm_d/ Δm_s (LHCb dominated)** (systematics cancel in the ratio);
- Measurements close to systematics dominated,: focus is on Lattice QCD, which computes the relevant hadronic quantities;
- Some tension with CKM fit emerging!

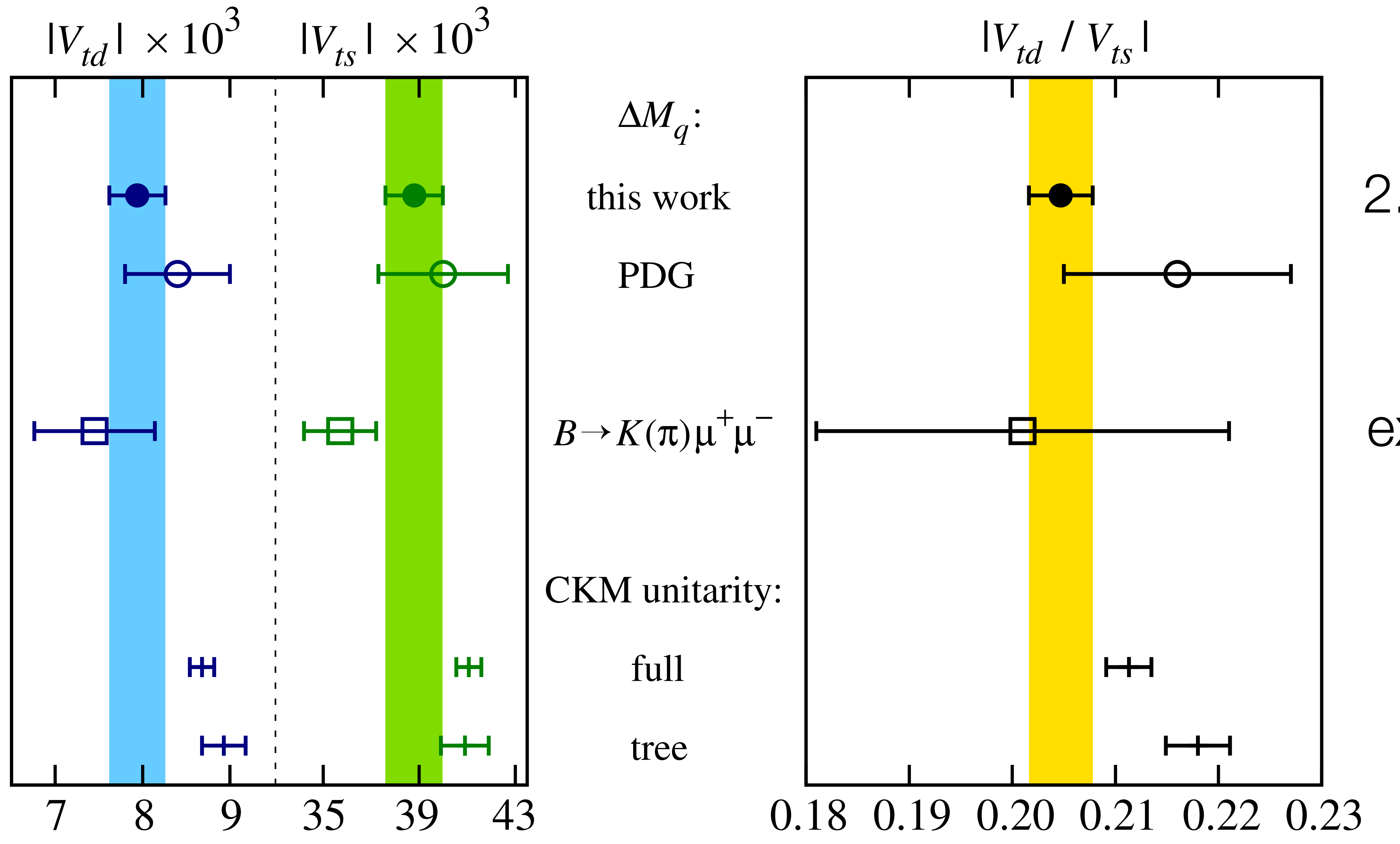


LQCD projections on mixing input, Belle II Physics book

N_f	forecast	$f_B\sqrt{B_B^{(1)}}$
	current (2017)	169(8)
	5 yr w/o EM	169(4.0)
2+1	5 yr w/ EM	169(4.3)
	10 yr w/o EM	169(1.6)
	10 yr w/ EM	169(2.3)

2.4σ, 1.3σ

2.0σ, 2.9σ

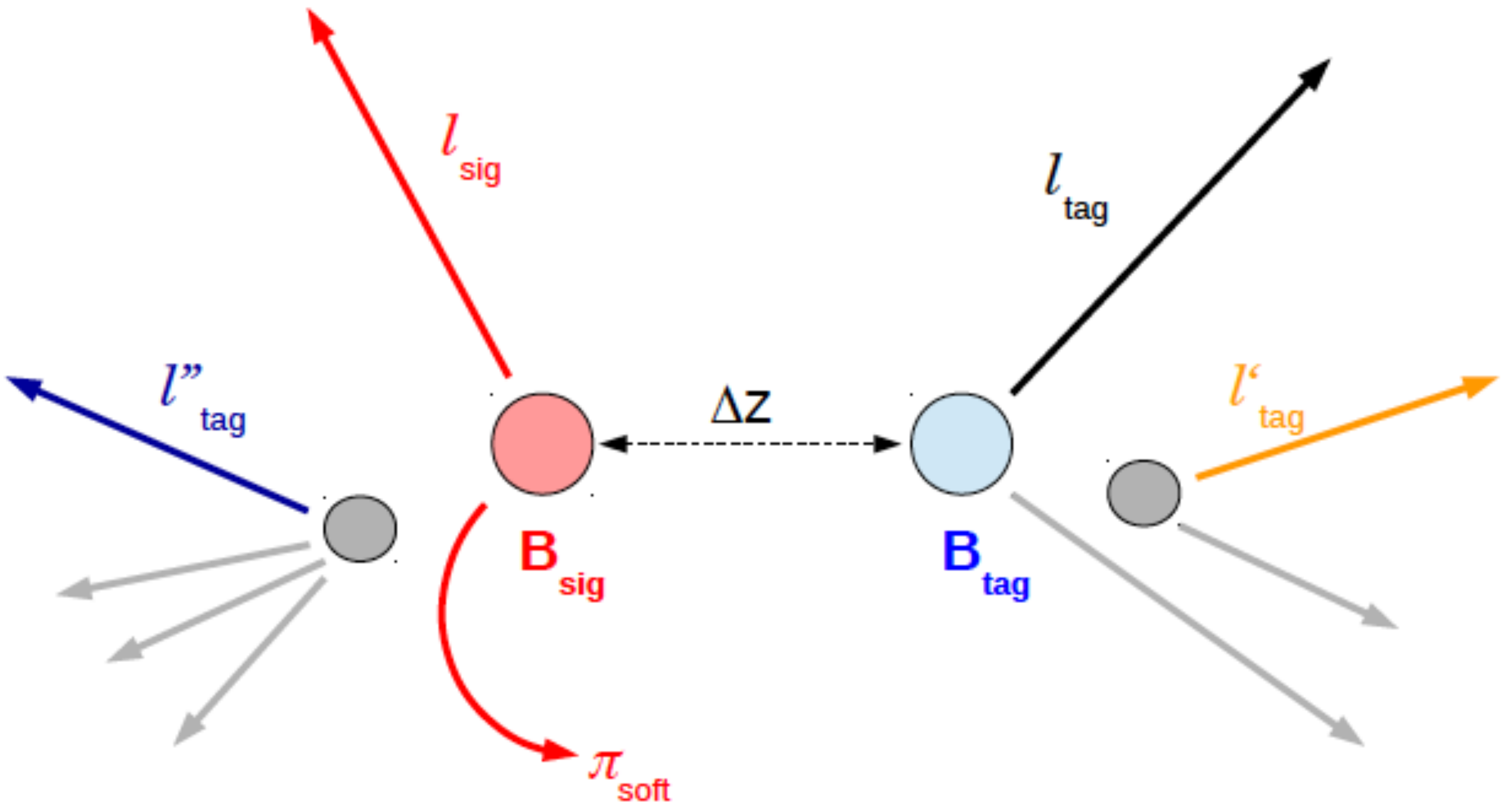


2.4σ

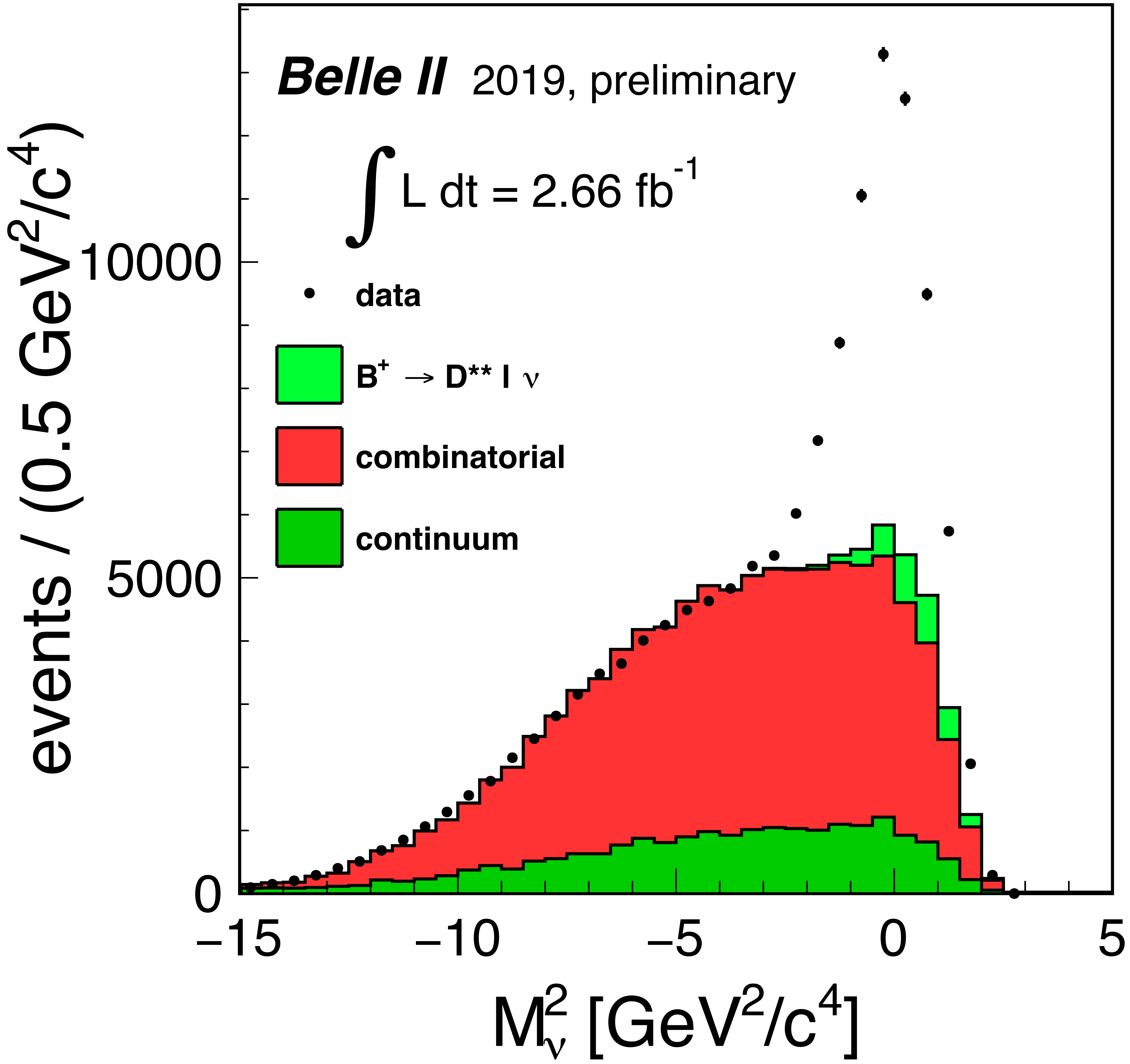
expt

B mixing at Belle II

Start with a B^0 (wait a while, ~a few x 10^{-12} sec).
There is a large probability that the B^0 will turn into its anti-particle, an anti-B^0 (discovered by ARGUS at DESY in 1987)
Use flavour specific final states but requires tagging. Verifies Belle II VXD capabilities for CP violation.



Large B→ D* l ν signal from partial reconstruction: 35492±2209

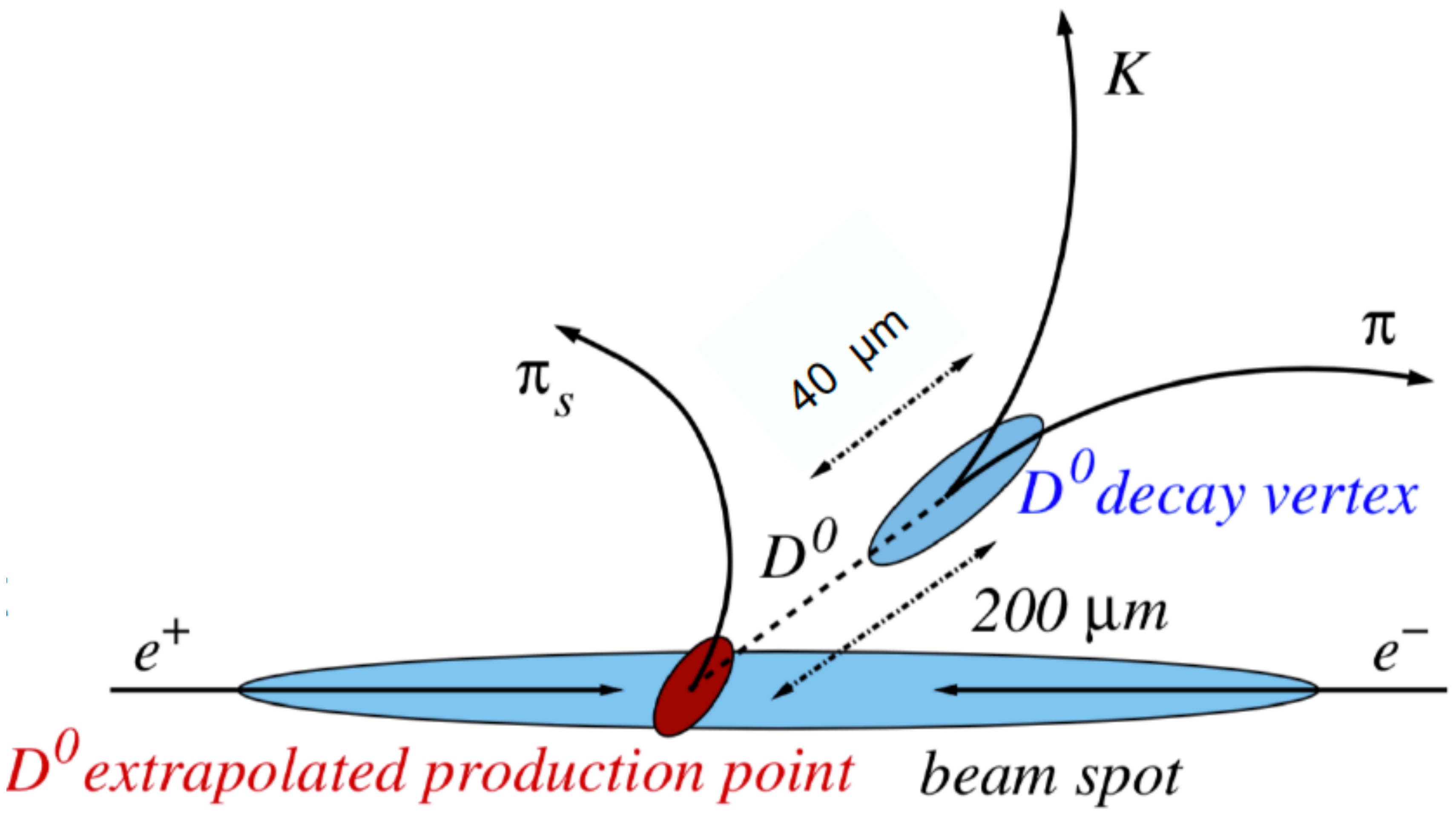


The leptons may come from the B weak decay or (primed case) from a cascade decay B→D→l ν decay.

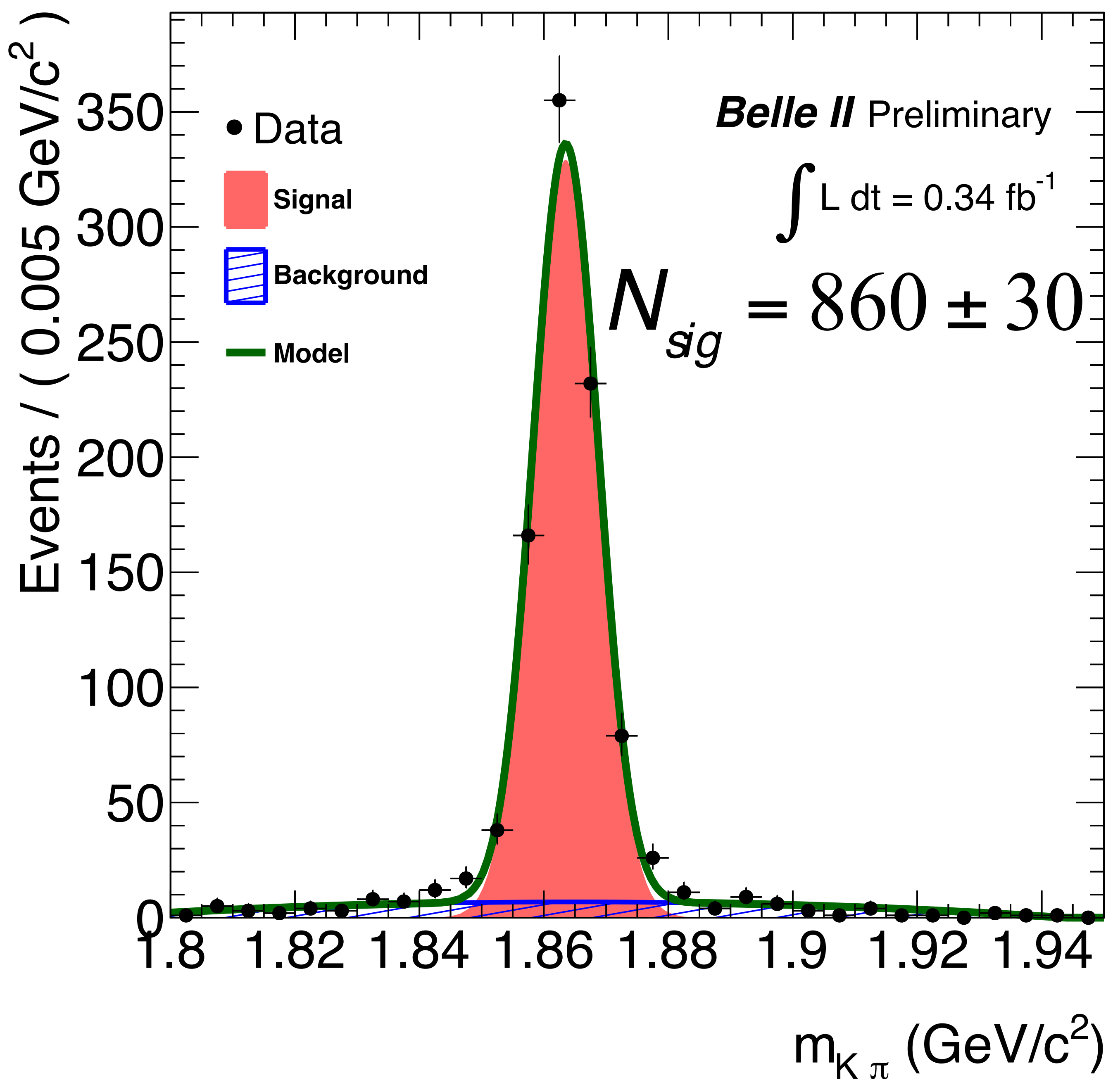
$D^0(\rightarrow K\pi)$ Lifetime in Belle II Phase 3 data

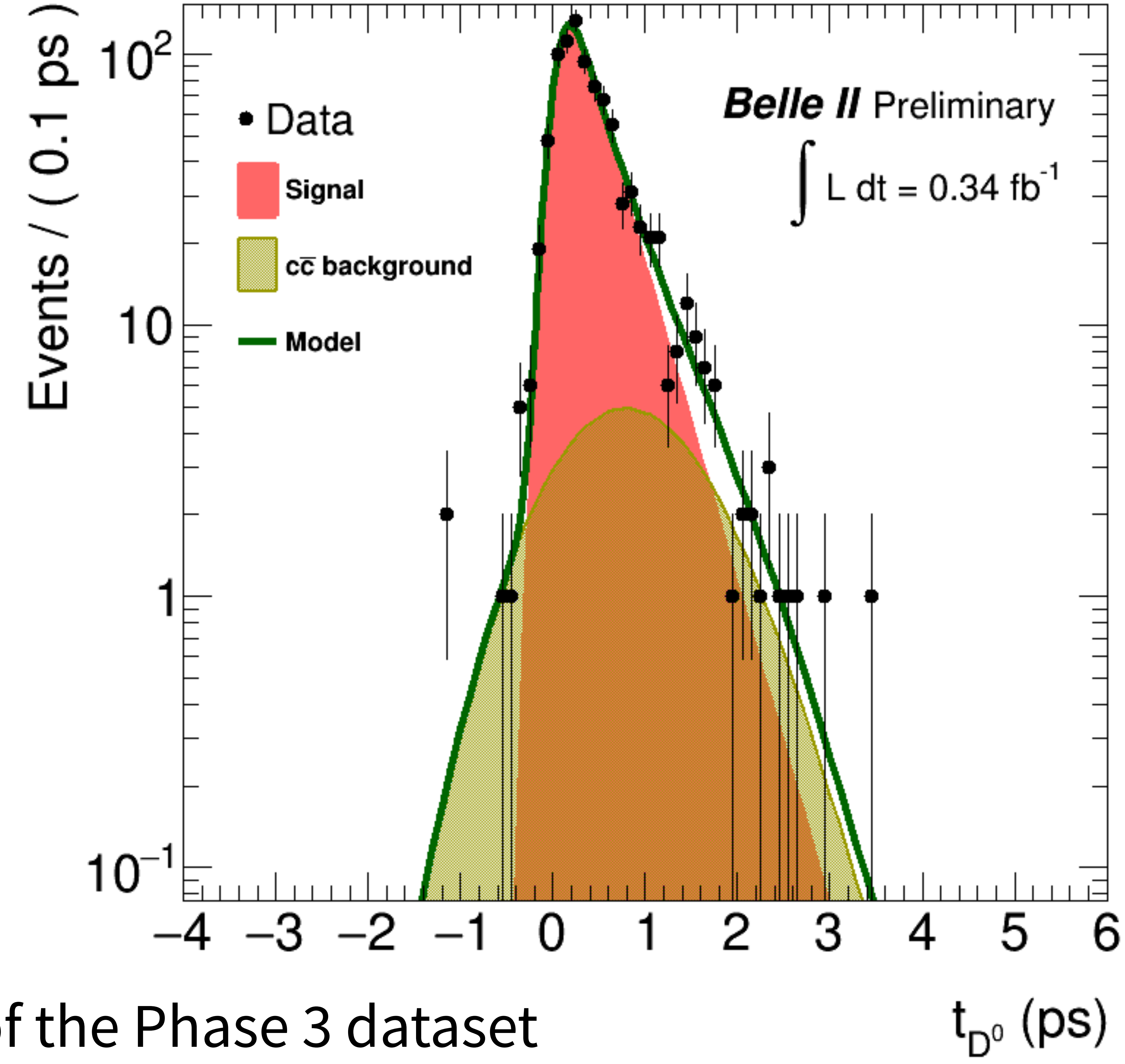
Use charm to demonstrate the combined performance of the PXD and SVD for time dependent measurements. *Accepted value 410 fs.*

$\tau_{D^0} = 370 \pm 40(stat)$ fs



J-F Krohn, PU (Belle II vertex fitting), submitted to NIMA, arXiv:1901.11198

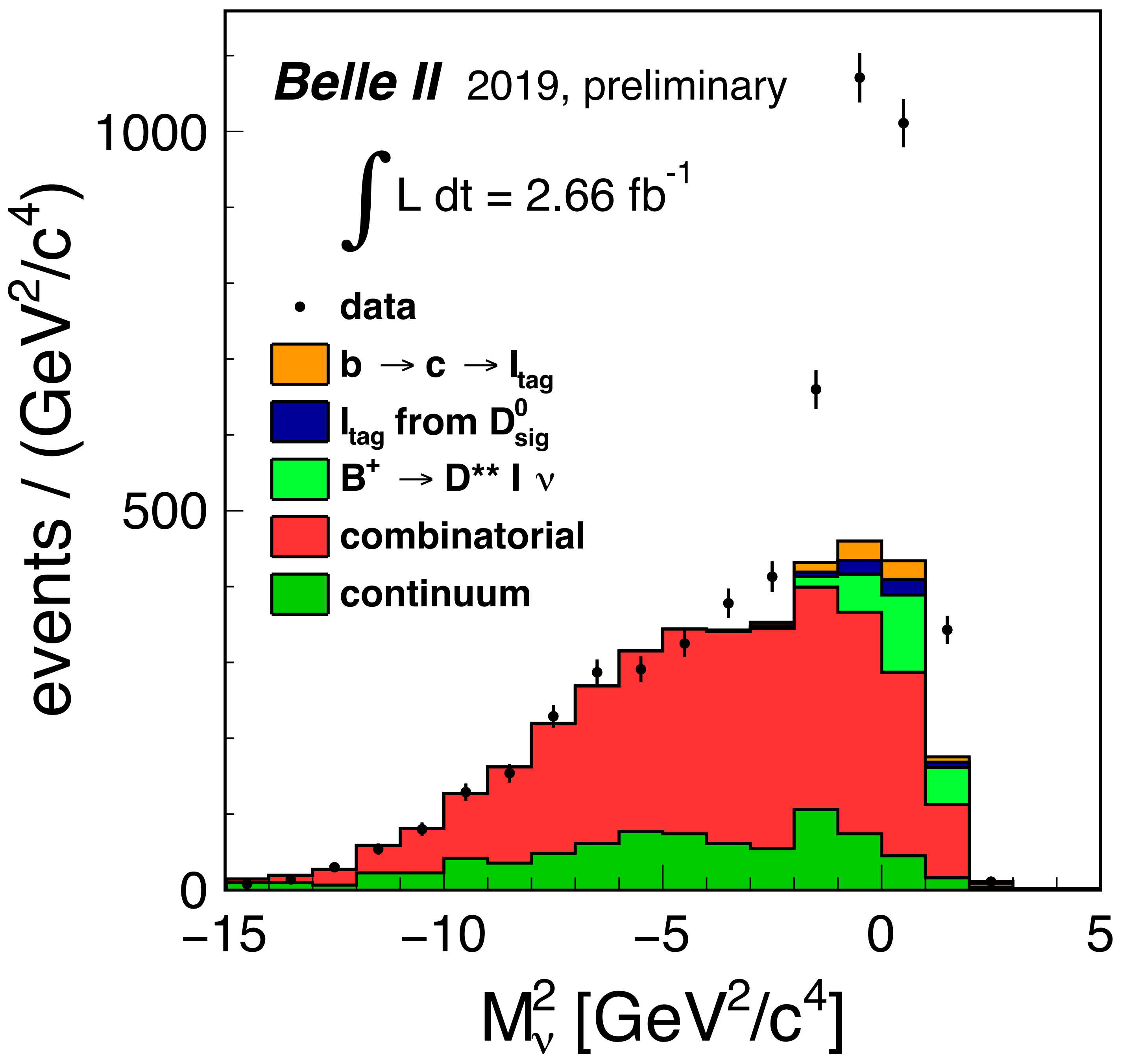




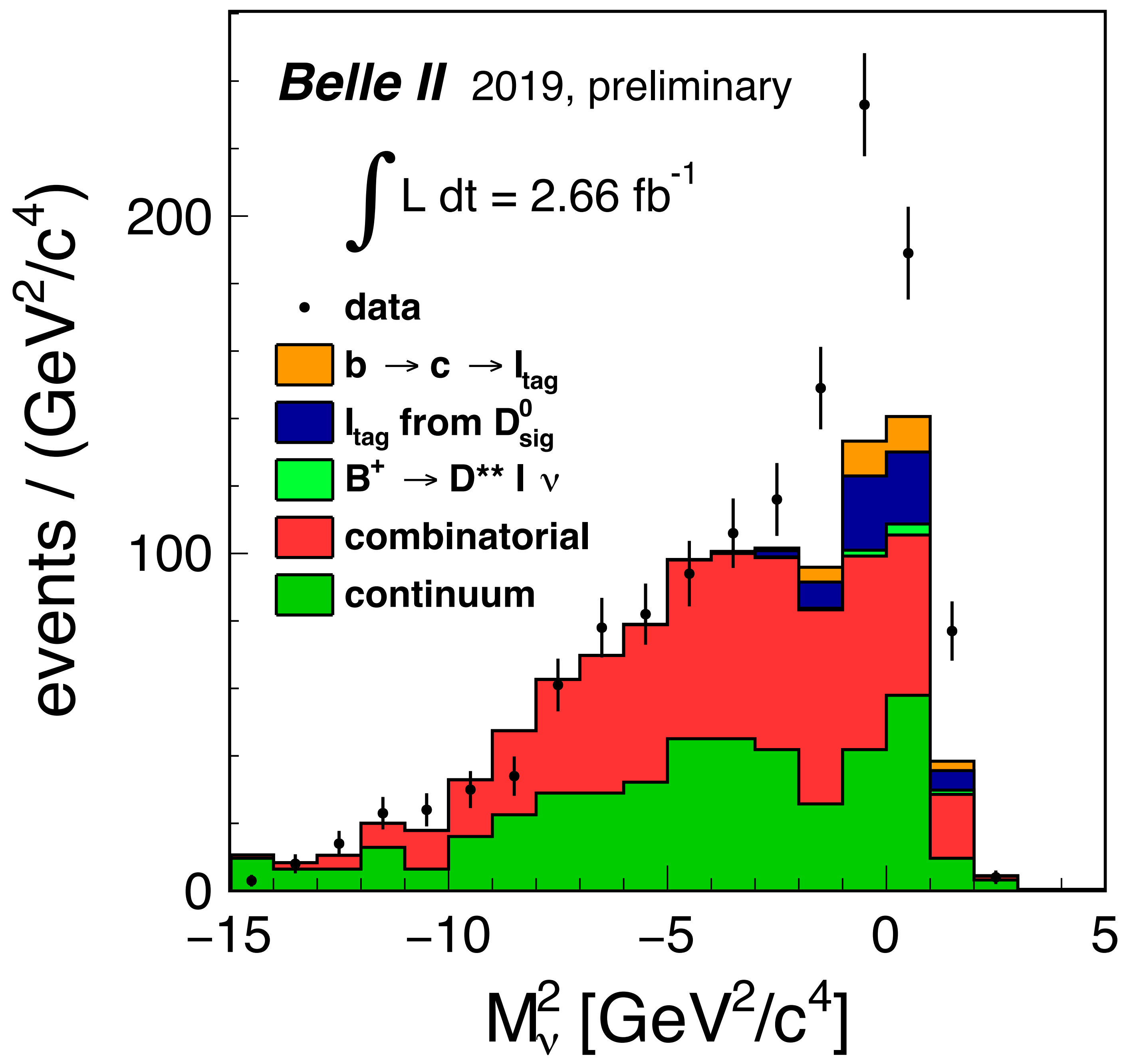
Uses 3% of the Phase 3 dataset

Observation of BB mixing at Belle II

Unmixed (l^+l^-)



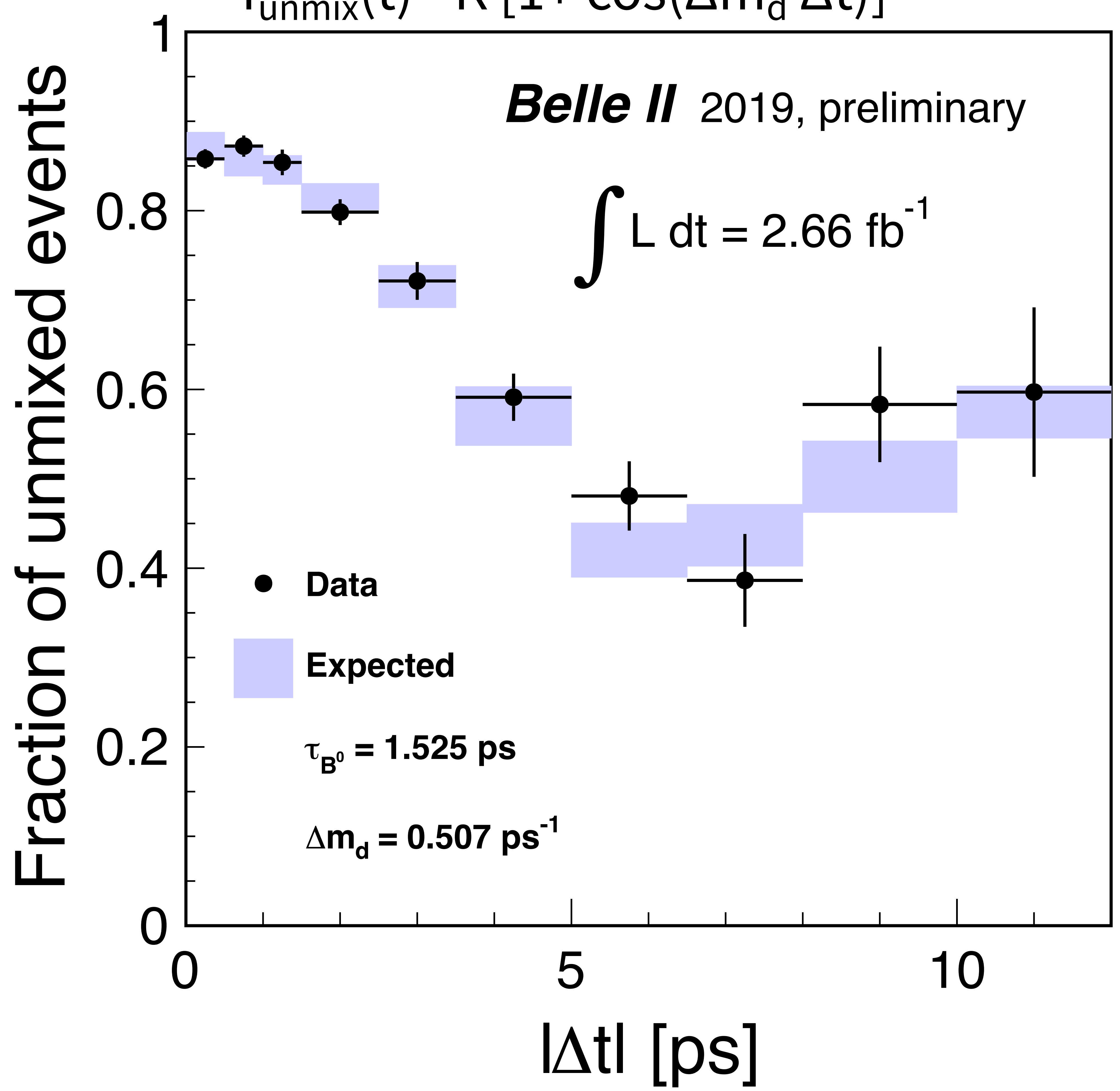
Mixed ($l^\pm l^\pm$)



Fraction of mixed events χd = (17.2 ± 3.6)% (WA = 18.6%)

Not CP violating:

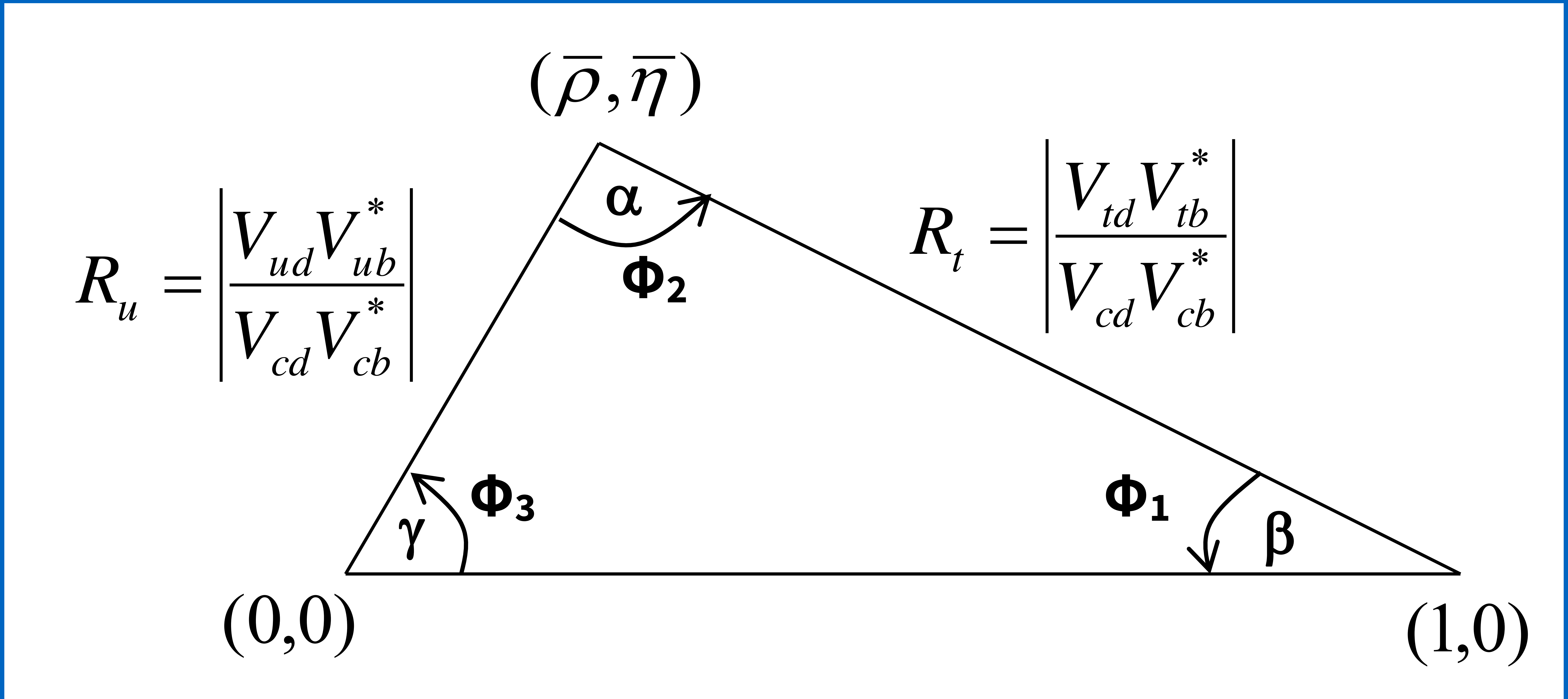
$f_{unmix}(t) = K\,[1 + \cos(\Delta m_d\,\Delta t)]$



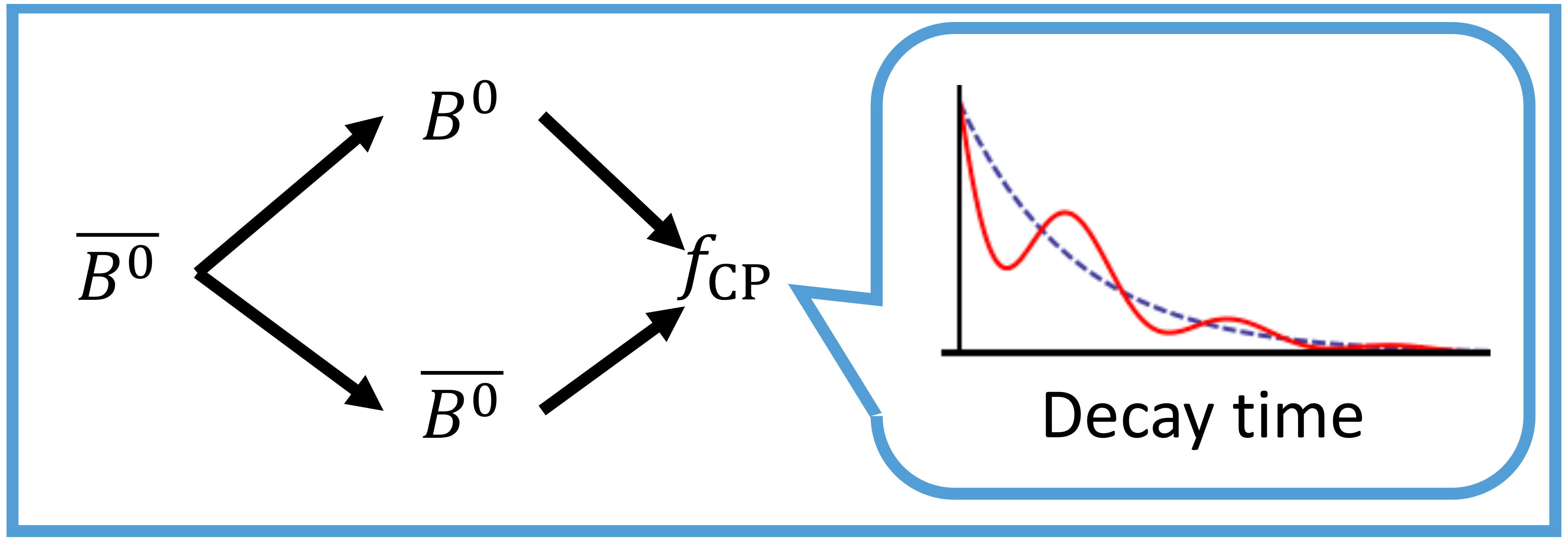
	Result (ps^{-1})	Dataset	Reference
Δm_d	$0.511 \pm 0.007 \pm 0.007$	$81\ fb^{-1}$	BaBar: Phys. Rev. D73 (2006) 012004
	$0.511 \pm 0.005 \pm 0.006$	$140\ fb^{-1}$	Belle: Phys. Rev. D71 (2005) 072003
	$0.5050 \pm 0.0021 \pm 0.0010$	$3.0\ fb^{-1}$	LHCb: Eur. Phys. J C76 (2016) 412
Δm_s	$17.768 \pm 0.023 \pm 0.006$	$1.0\ fb^{-1}$	LHCb: New J. Phys. 15 (2013) 053021

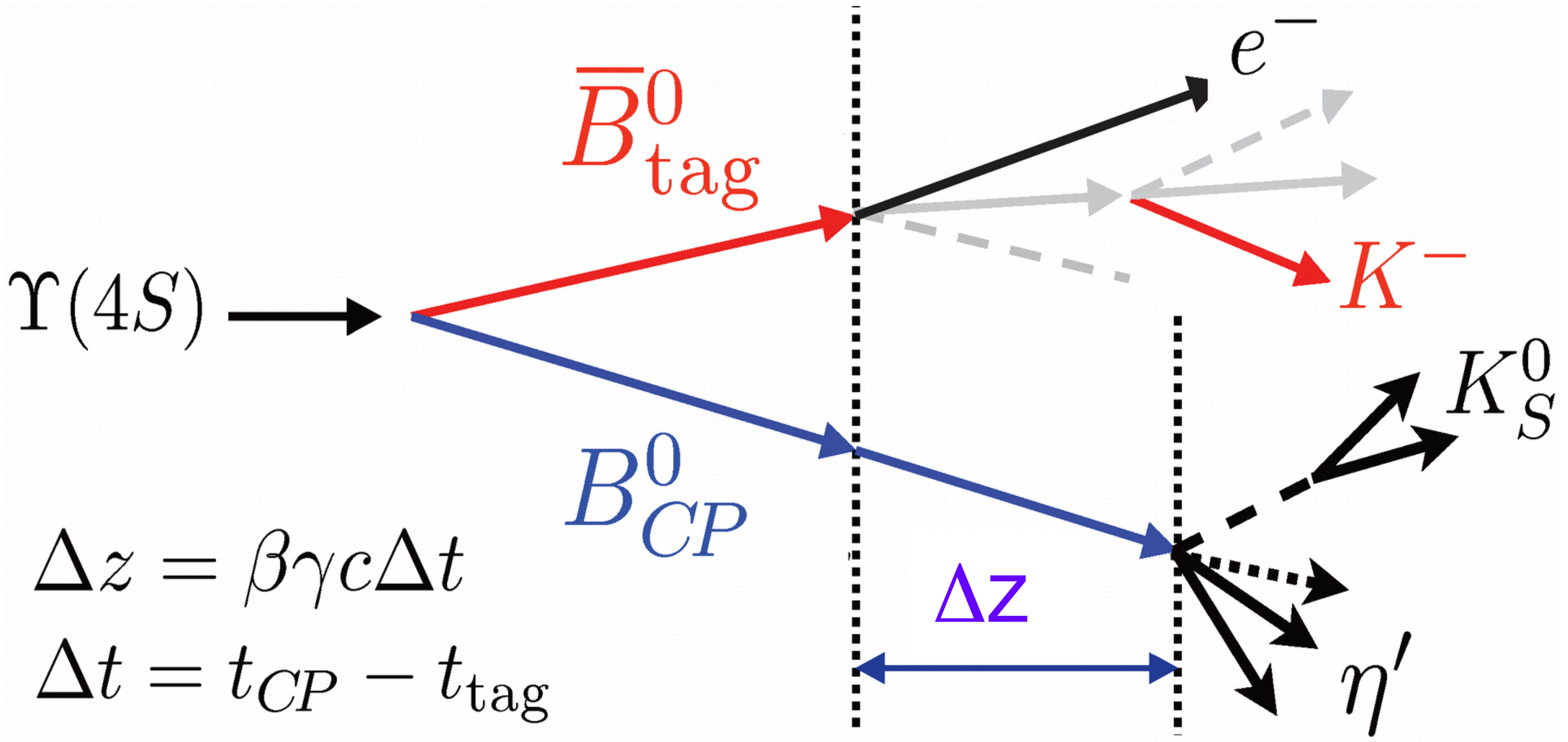
Belle result dominated by vertex resolution and D** l ν background - improved dramatically at Belle II and LHCb. CP violation in mixing (**D0 anomaly**) can also be tested.

Determination of UT angles & CPV in Hadronic Decays



Time dependent CP Violation (mixing+decay)





$$\Delta z = \beta\gamma c \Delta t$$
$$\Delta t = t_{CP} - t_{\rm tag}$$

$$\mathcal{A}_{CP}(t) = \frac{\Gamma\left(\overline{B}^0_q(t) \to f\right) - \Gamma\left(B^0_q(t) \to f\right)}{\Gamma\left(\overline{B}^0_q(t) \to f\right) + \Gamma\left(B^0_q(t) \to f\right)}$$
$$= \frac{\mathcal{S}_f \sin(\Delta m t) - \mathcal{C}_f \cos(\Delta m t)}{\cosh\left(\frac{\Delta\Gamma t}{2}\right) + \mathcal{A}_{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma t}{2}\right)}$$

Beam energies are asymmetric (7 on 4 GeV)

Decay distance is increased by around a factor ~7

Flavour tagging eff.

3-5% LHCb

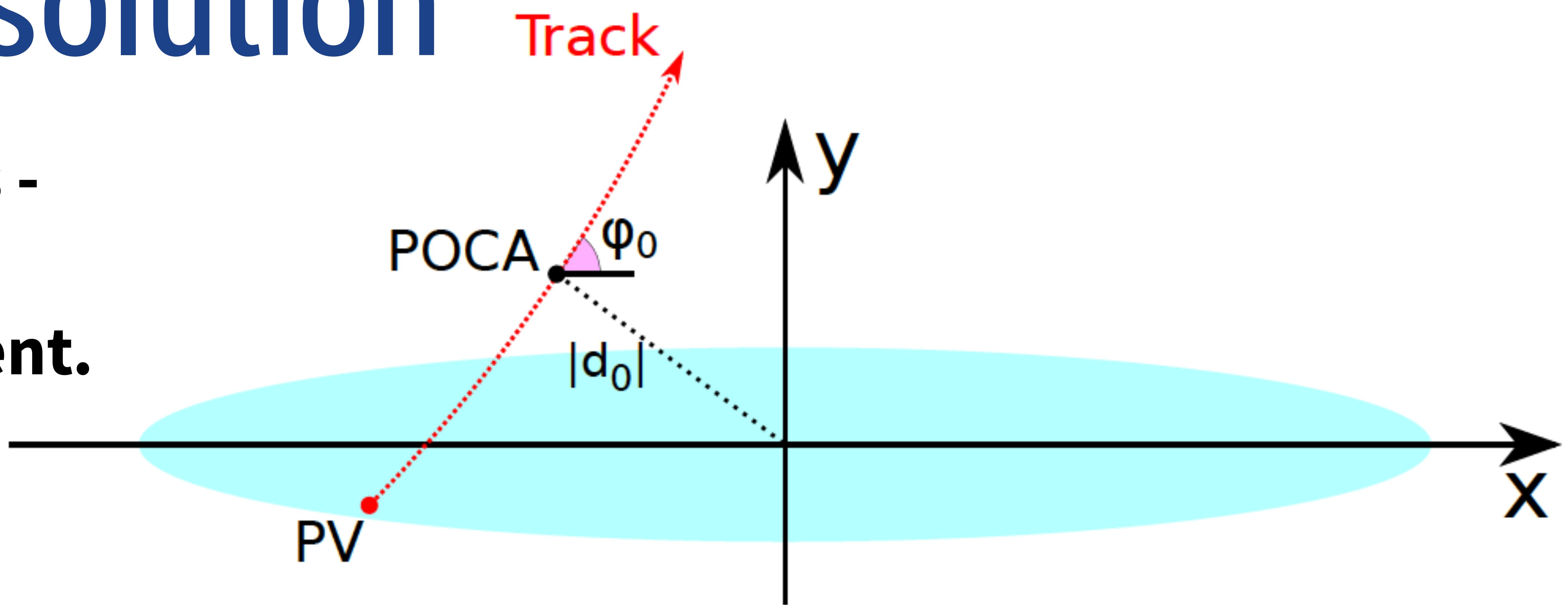
30% Belle

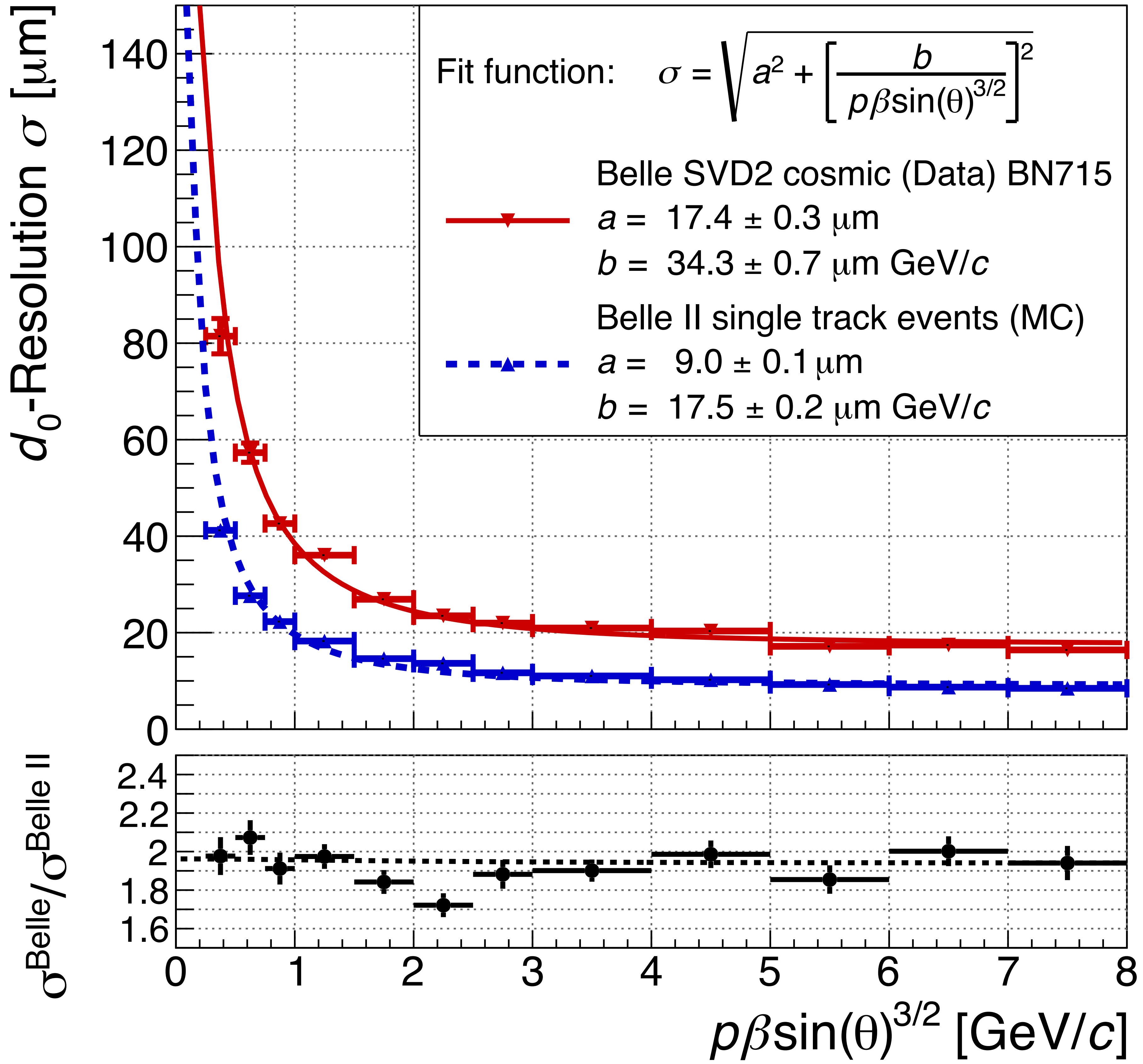
35% Belle II

- Requires: Vertex fitting and flavour tagging: Boost, IP resolution, hermetic coverage; Kaons (K_L, K_S) from CP eigenstate b→c anti-c s and b→s penguin decays

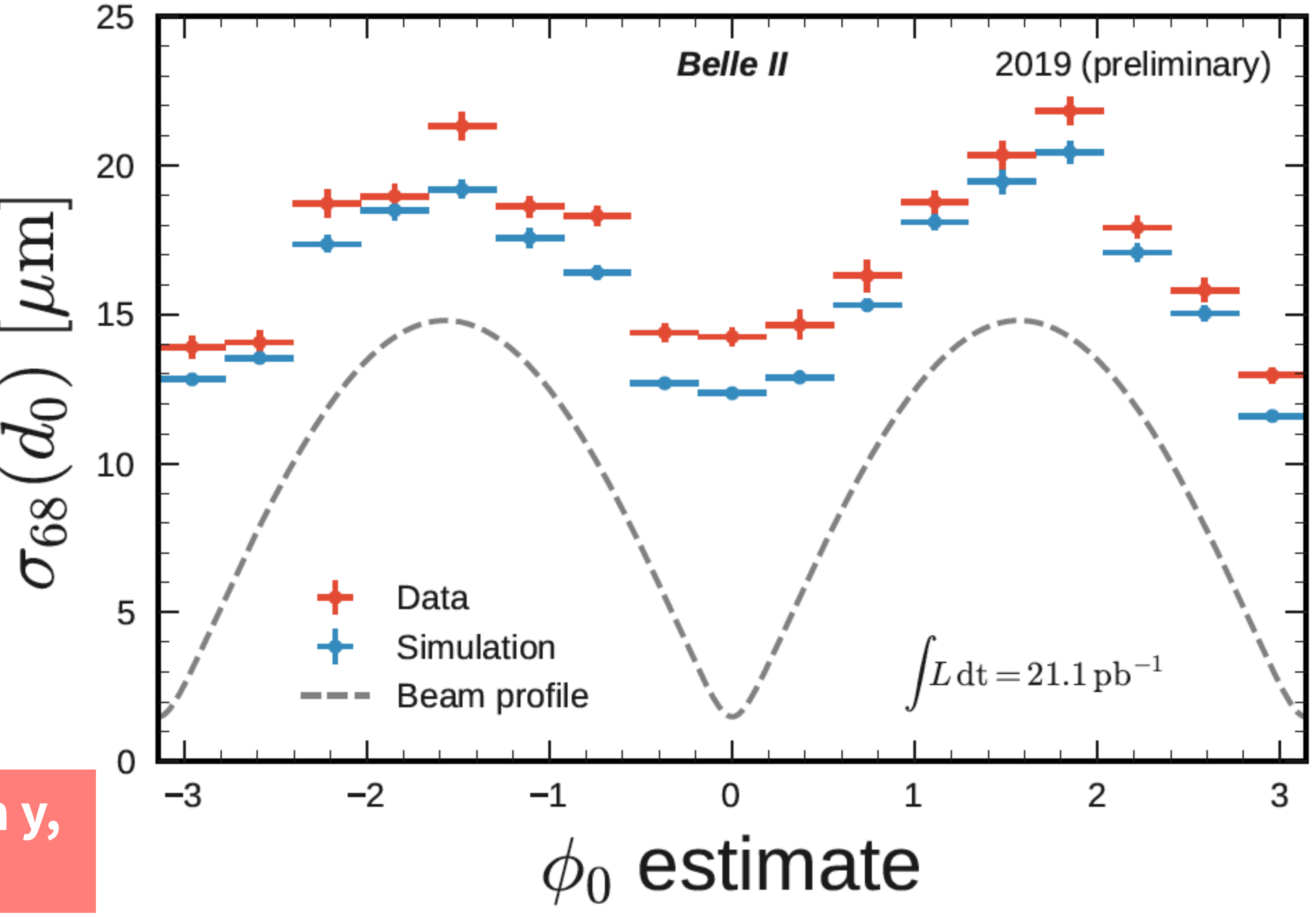
Track impact parameter resolution

VXD resolution in impact parameter ~14 microns - half that of Belle.
Key for time dependent CP violation measurement.





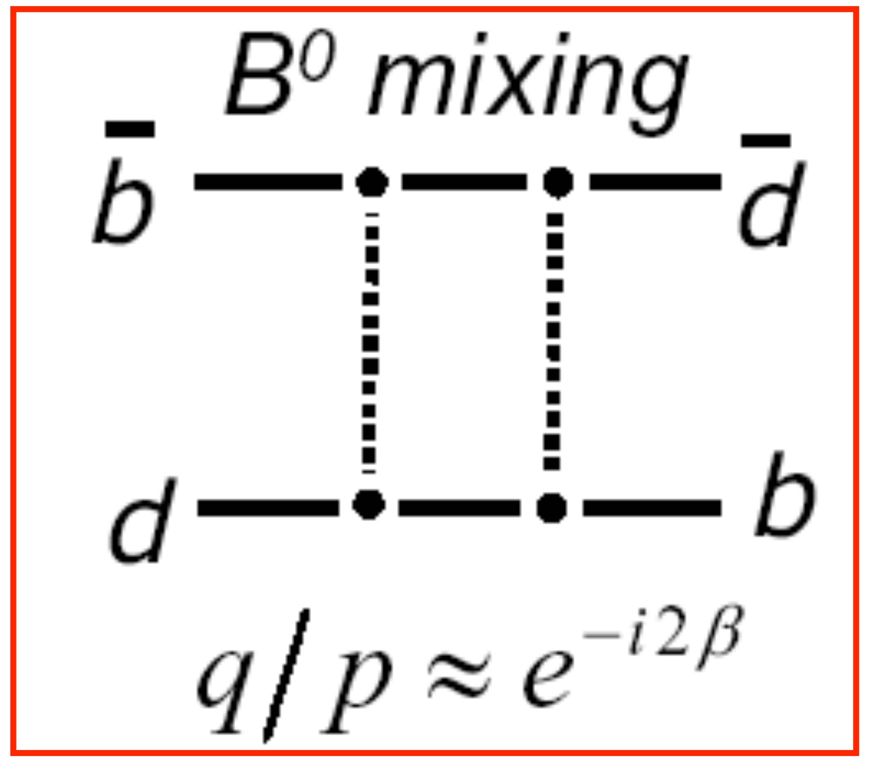
Impact parameter resolution from two-track events.
Alignment and calibration are working well.

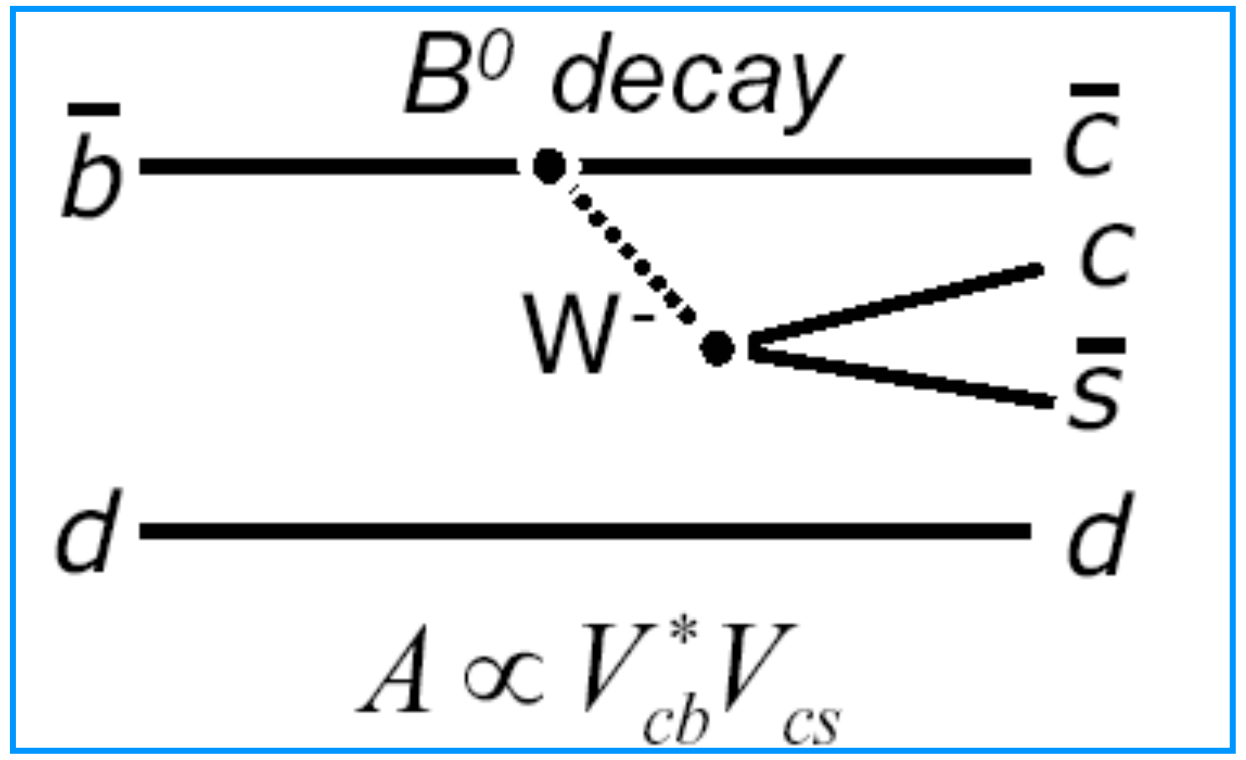


Belle II

Nano-beam in y, Φ=0, π

Φ_1/β (phase of V_{td}) with $B \to J/\psi K_S$

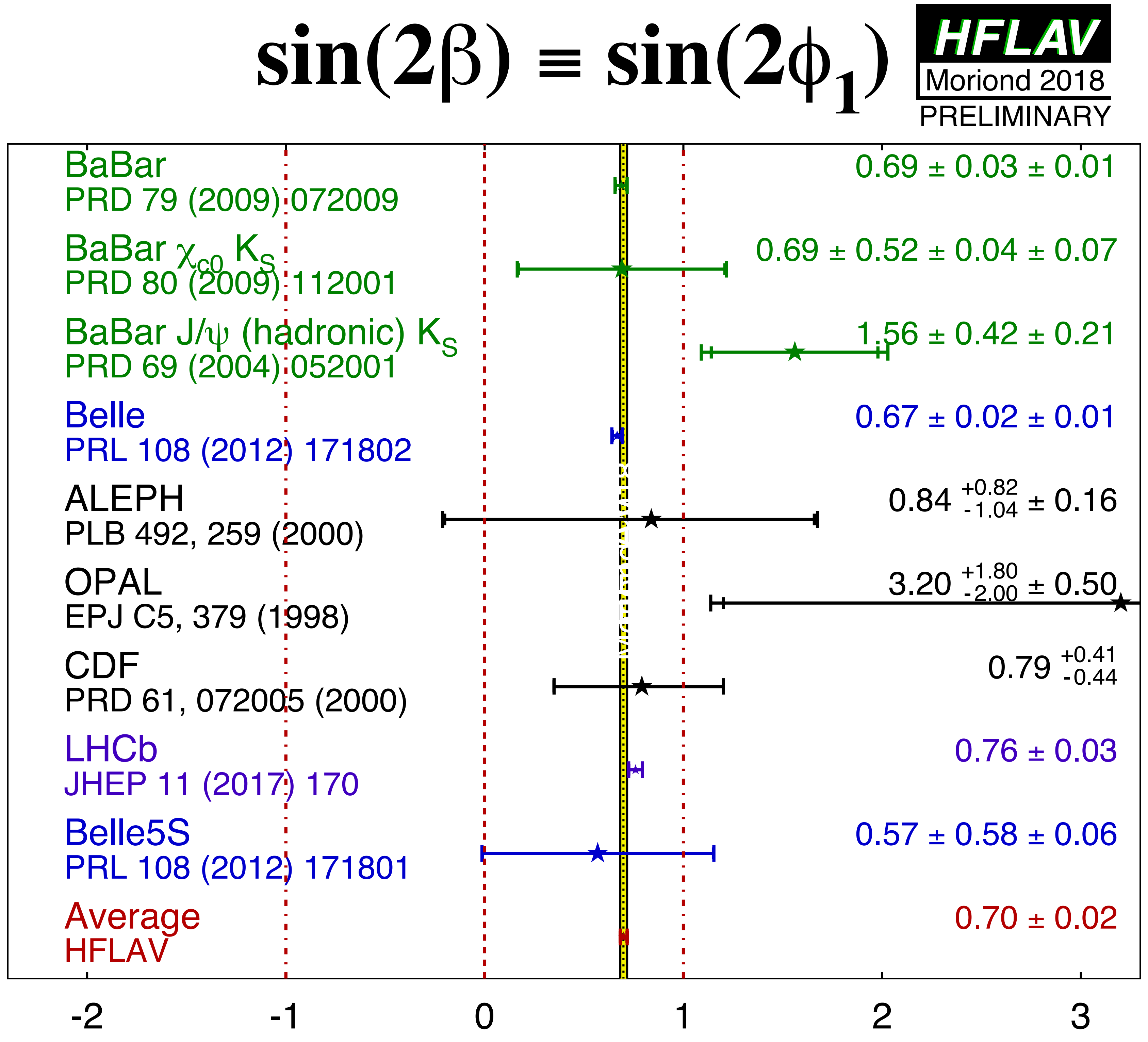


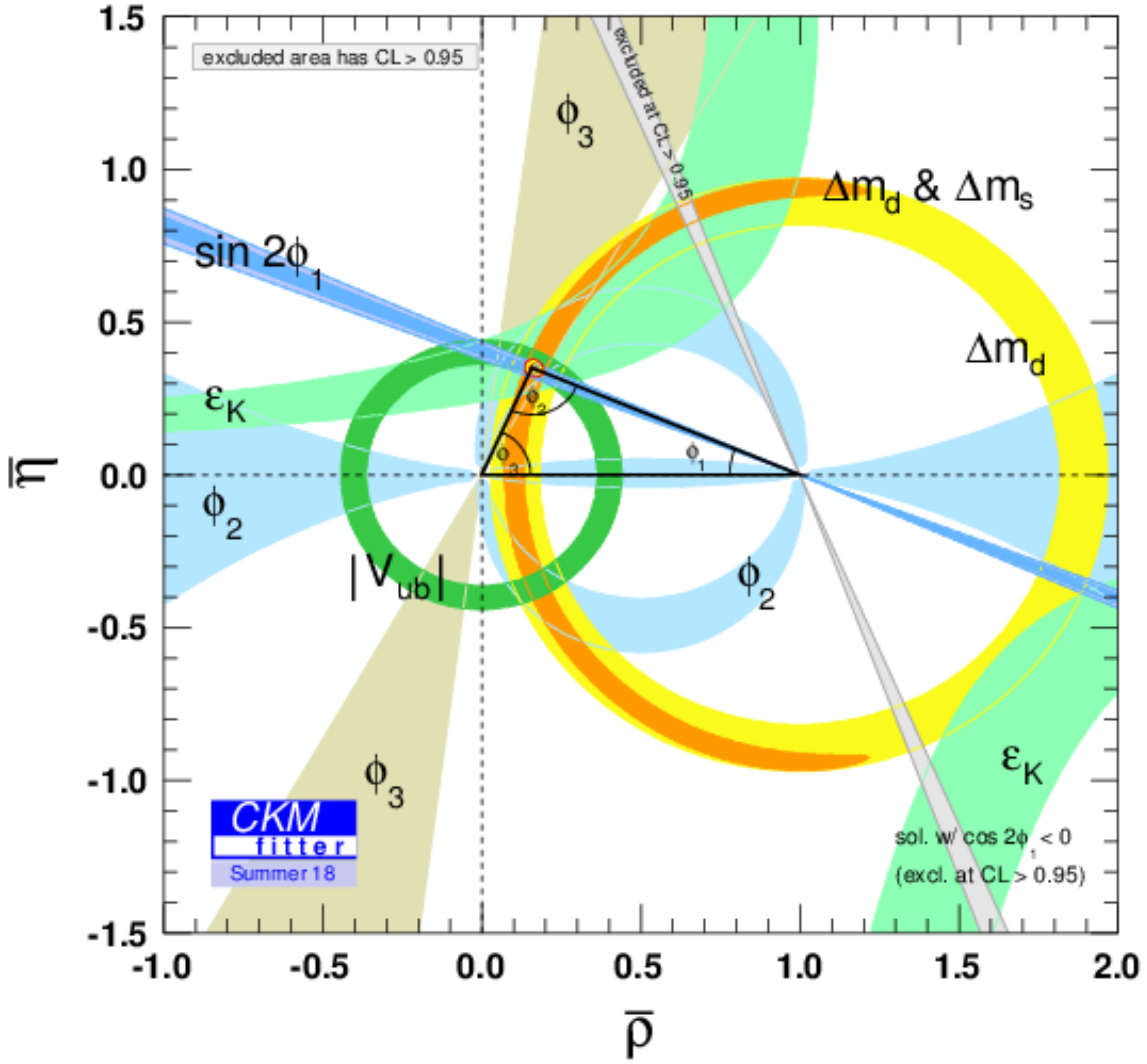


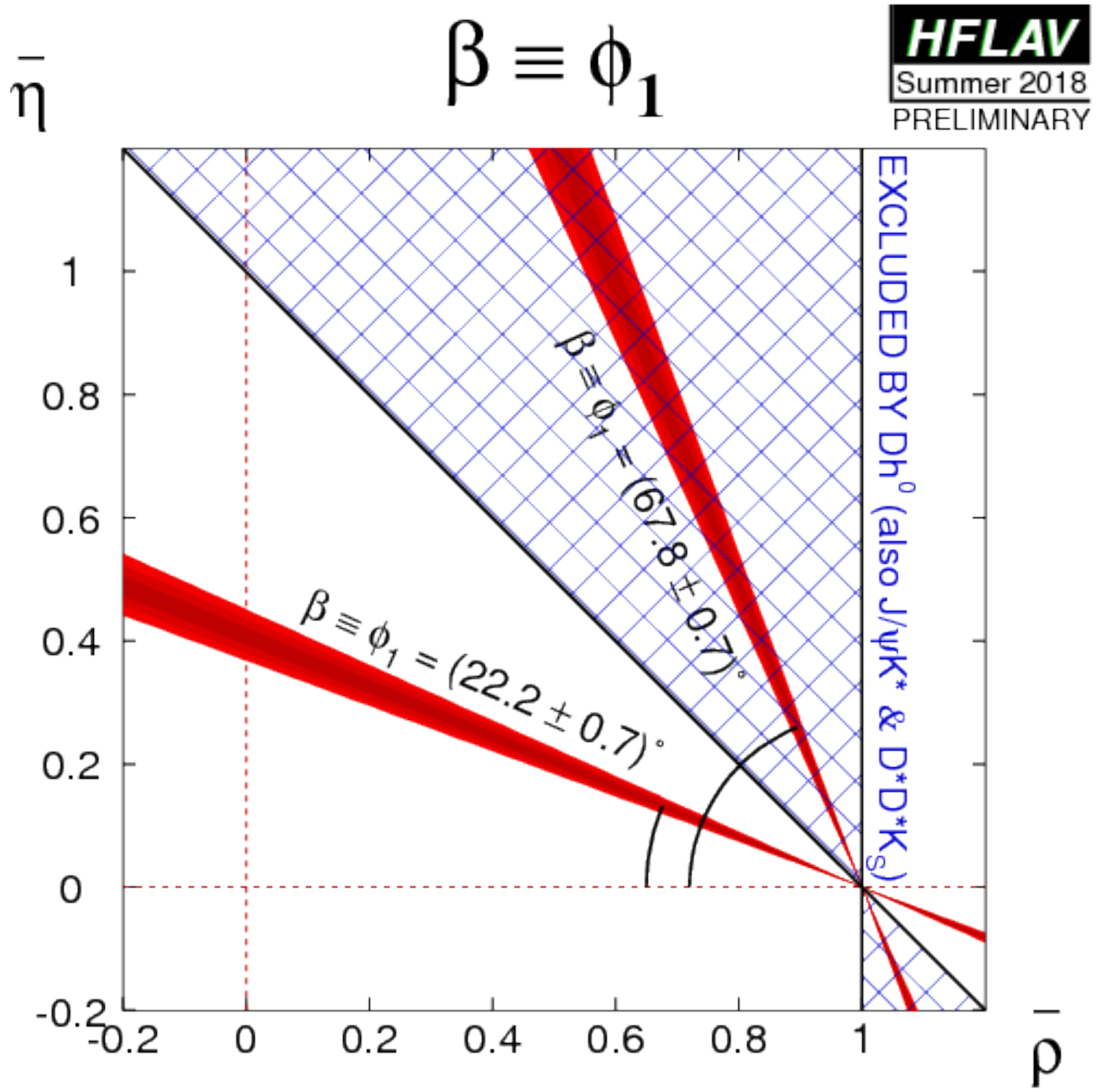
S_{CP} < 2 σ from SM UT fit

0.691±0.017 WA HFLAV

0.738 $^{+0.030}_{-0.027}$ Indirect CKMFitter

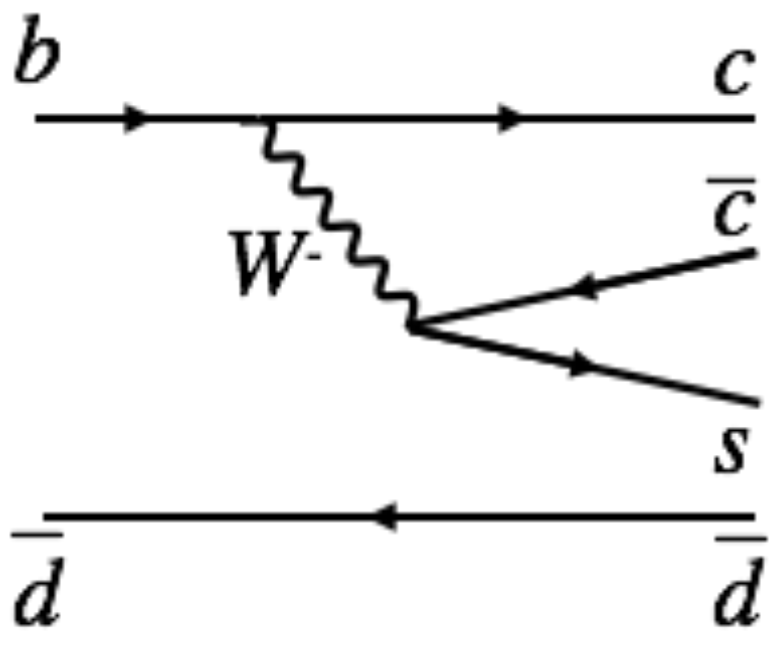




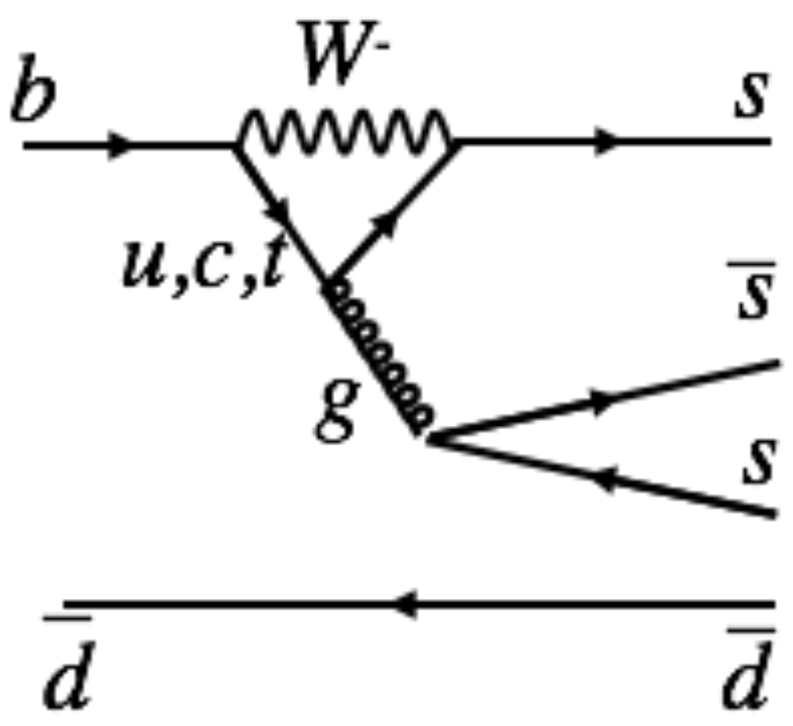


Time dependent CP Violation / Targets

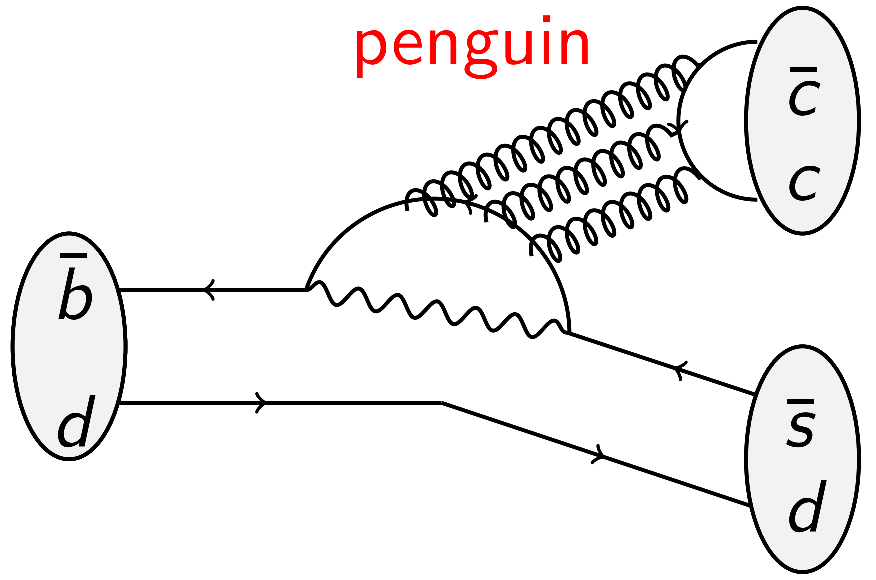
- Improving on $\sin 2\Phi_1$ will be a challenge:
  - for **experiments**: soon the measurement will be systematics limited: need to control them;
  - for **theory**: so far neglected the contributions from suppressed amplitudes carrying a different phase.
- TD CP violation measurements of $b \to qqs$ transitions (q = u, d, s) are a major target



- Tree



- Gluonic Penguin (NP sensitive)

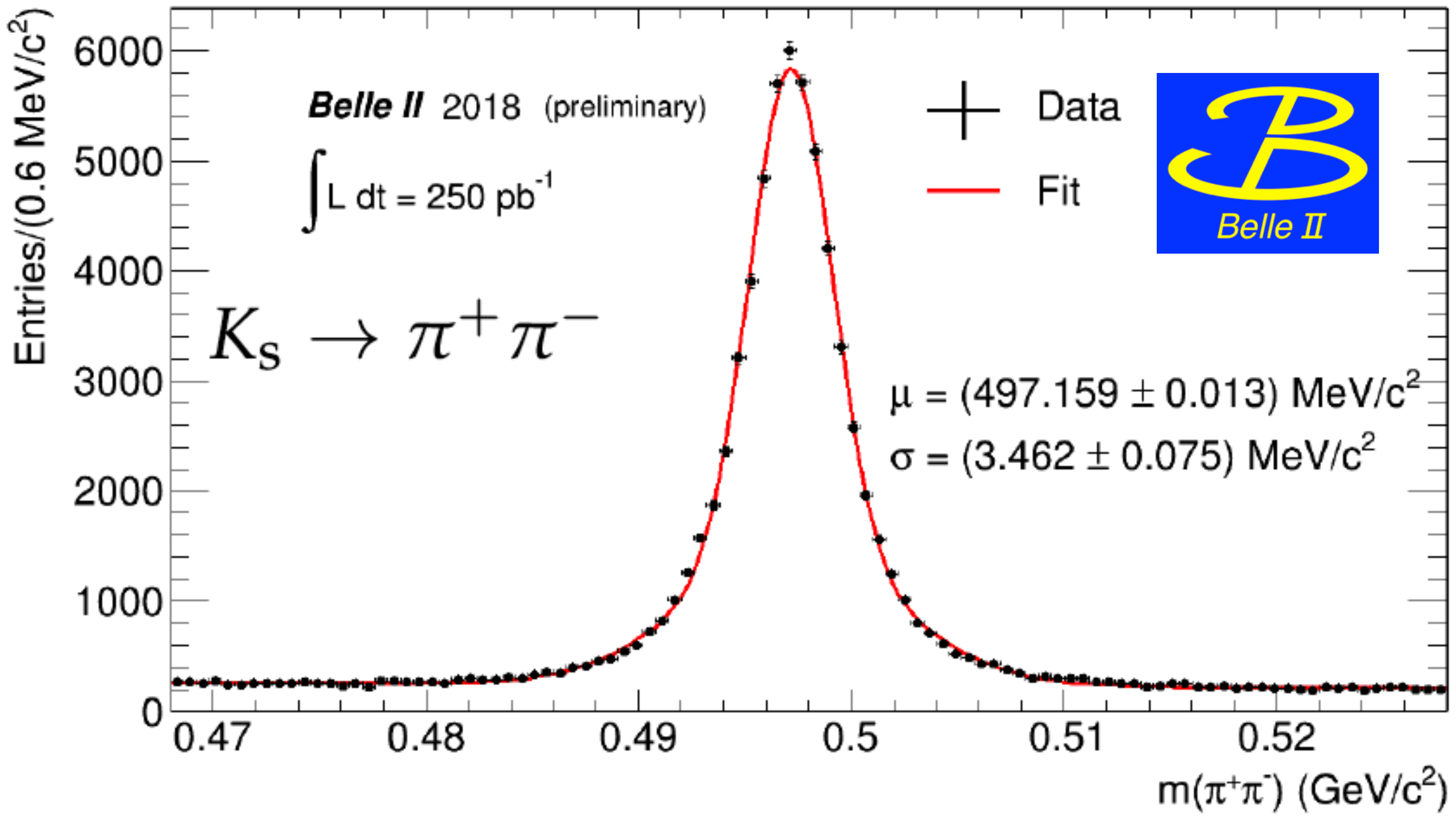


- Constrains penguin pollution

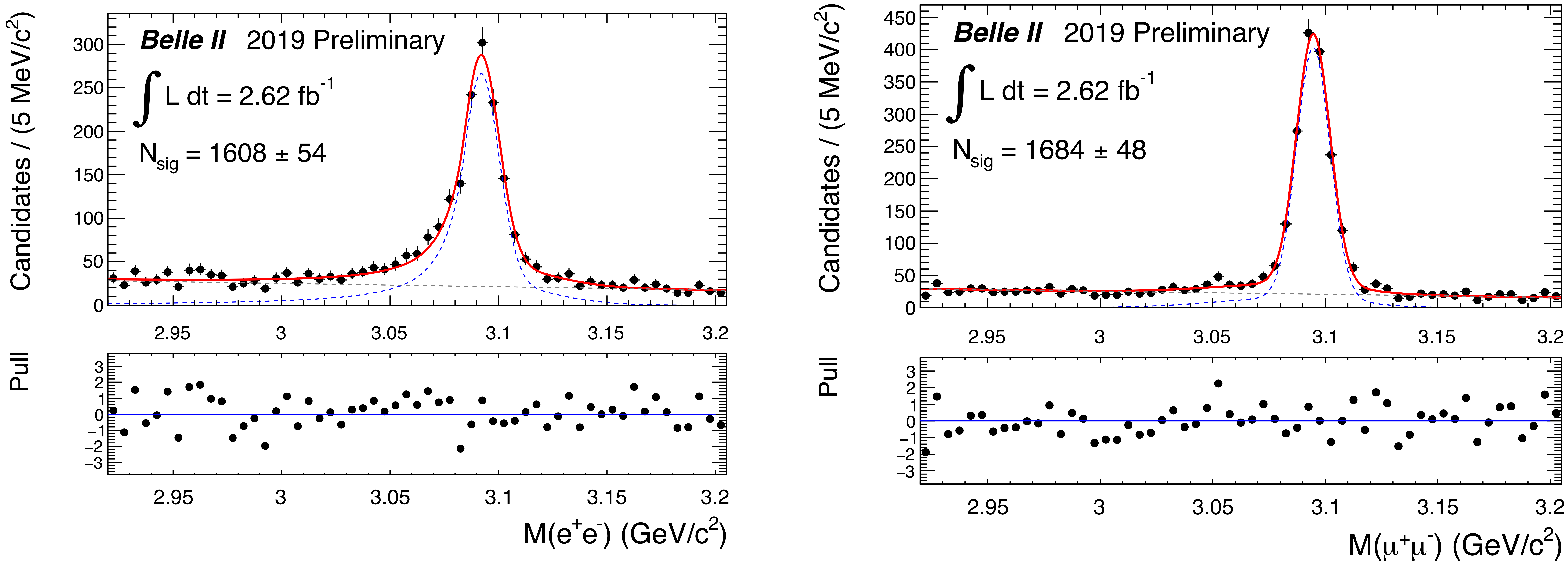
Belle II

arXiv: 1808.10567

Channel	WA (2017) $\sigma(S)$	WA (2017) $\sigma(A)$	$5\ \mathrm{ab}^{-1}$ $\sigma(S)$	$5\ \mathrm{ab}^{-1}$ $\sigma(A)$	$50\ \mathrm{ab}^{-1}$ $\sigma(S)$	$50\ \mathrm{ab}^{-1}$ $\sigma(A)$
$J/\psi K^0$	0.022	0.021	0.012	0.011	0.0052	0.0090
ϕK^0	0.12	0.14	0.048	0.035	0.020	0.011
$\eta' K^0$	0.06	0.04	0.032	0.020	0.015	0.008
ωK_S^0	0.21	0.14	0.08	0.06	0.024	0.020
$K_S^0 \pi^0 \gamma$	0.20	0.12	0.10	0.07	0.031	0.021
$K_S^0 \pi^0$	0.17	0.10	0.09	0.06	0.028	0.018



Signals for B→J/ψ X in Phase 3 data

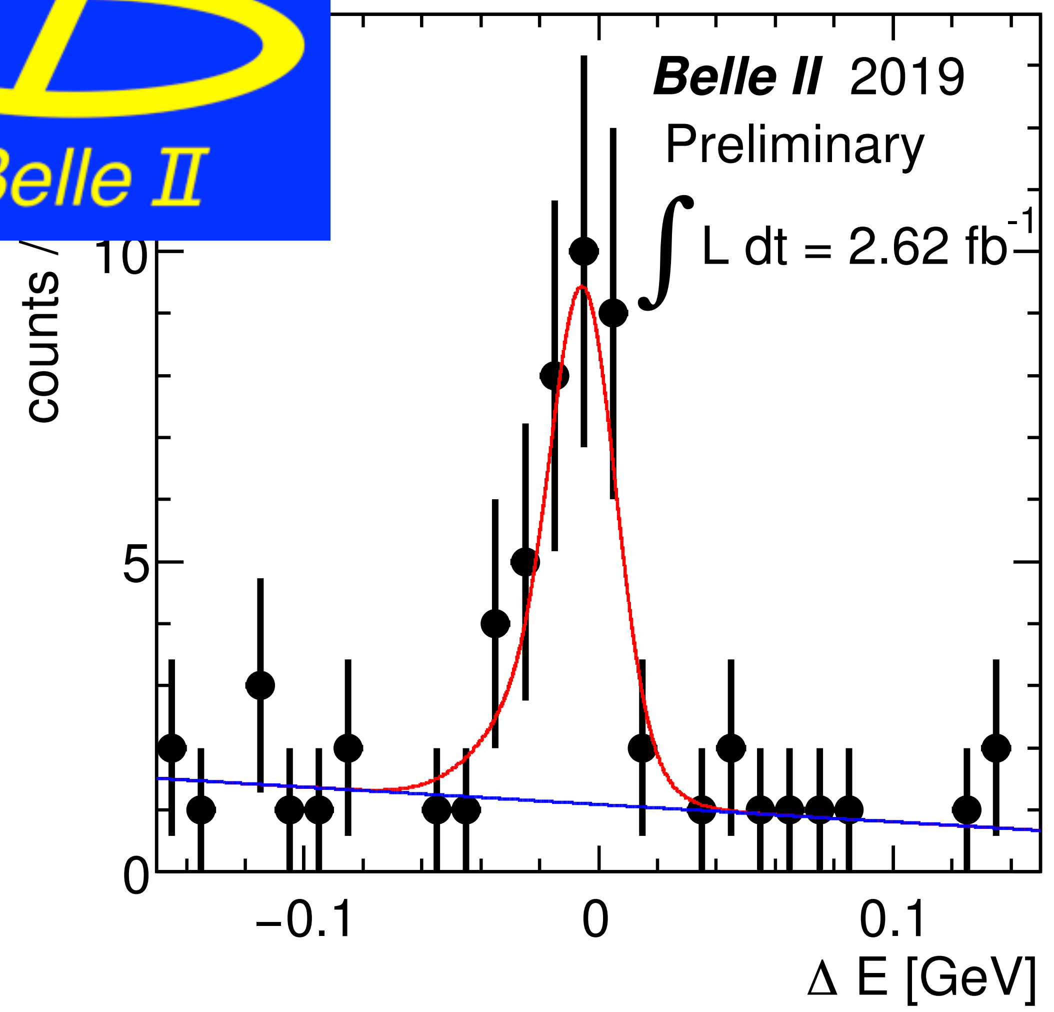


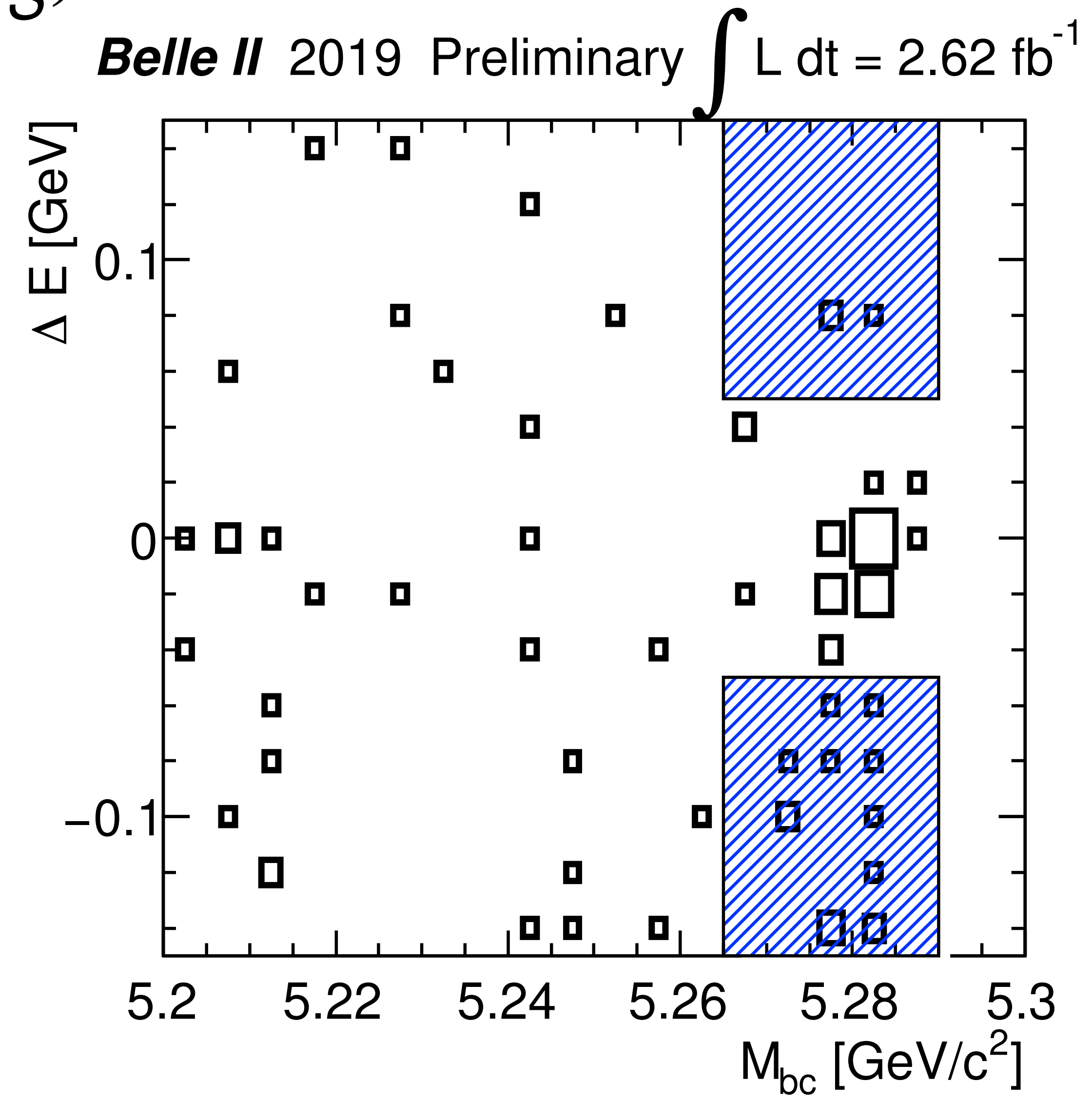
Clear signals for B→J/ψ X in ~1/4 of Phase 3 data. Note small radiative tail on the di-electrons (includes bremsstrahlung recovery).

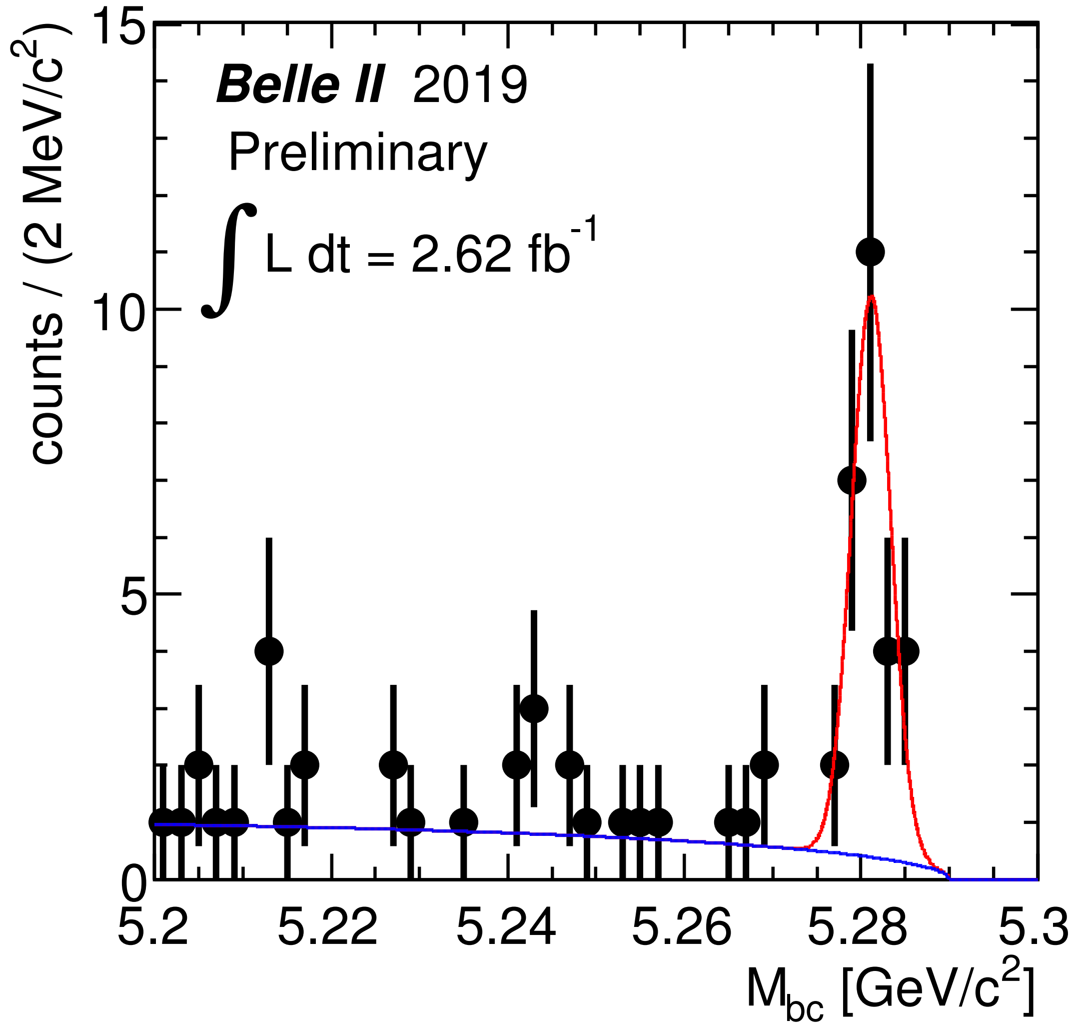
Belle II has equally strong capabilities for electrons and muons.

Observation of B→J/ψ K_S / Golden Mode

$N(B \to J/\psi\, K_S) = 26.9 \pm 5.2$



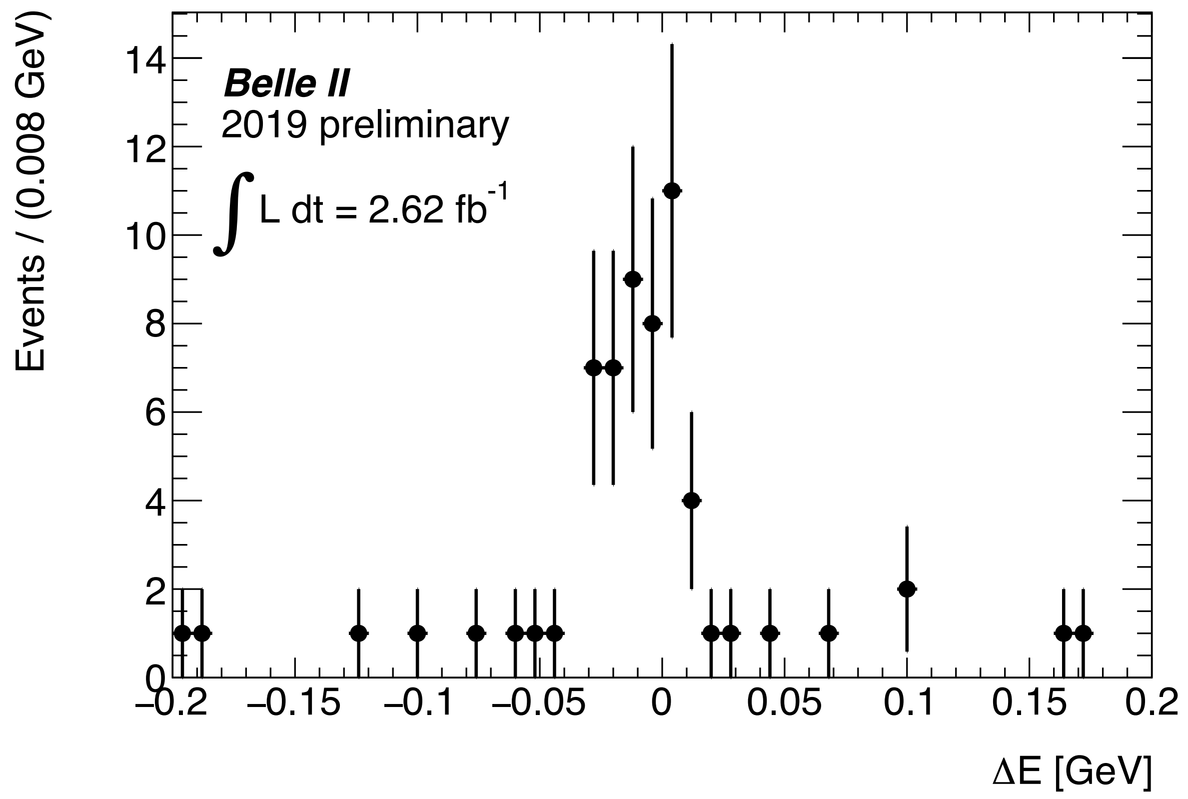


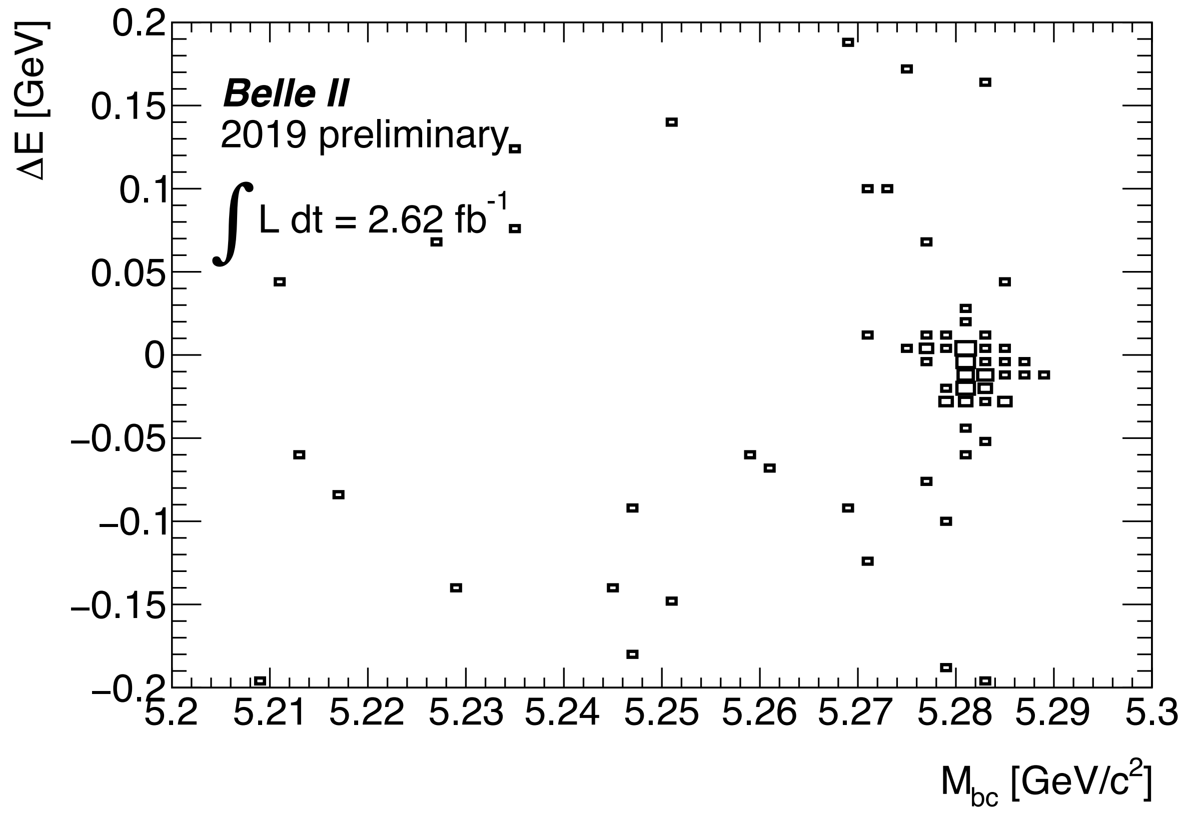


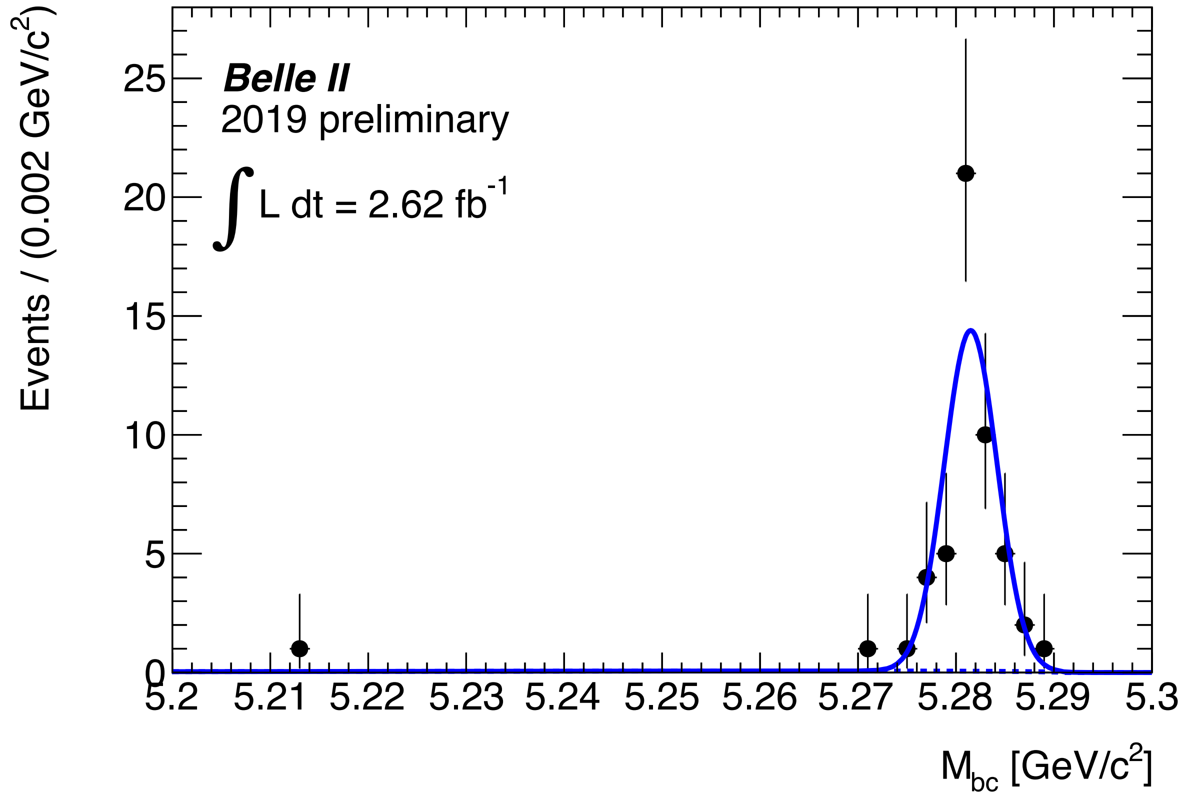
A Golden CP Eigenstate

About 1/4 of the Phase 3 data sample collected.

$N(B \to J/\psi\, K^{*0} \to J/\psi\ K^- \pi^+) = 48.6 \pm 7.0$







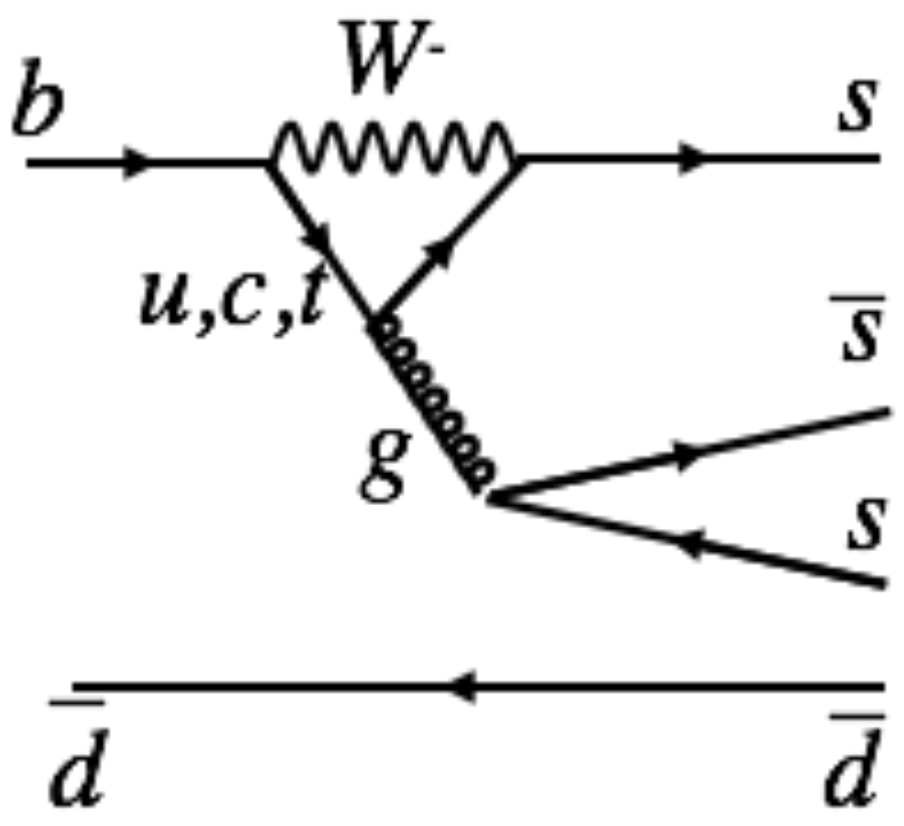
Not useful for measuring CP violation, but very useful to study vertex resolution (comparing the J/ψ and the K* vertices)

Time dependent CP Violation prospects

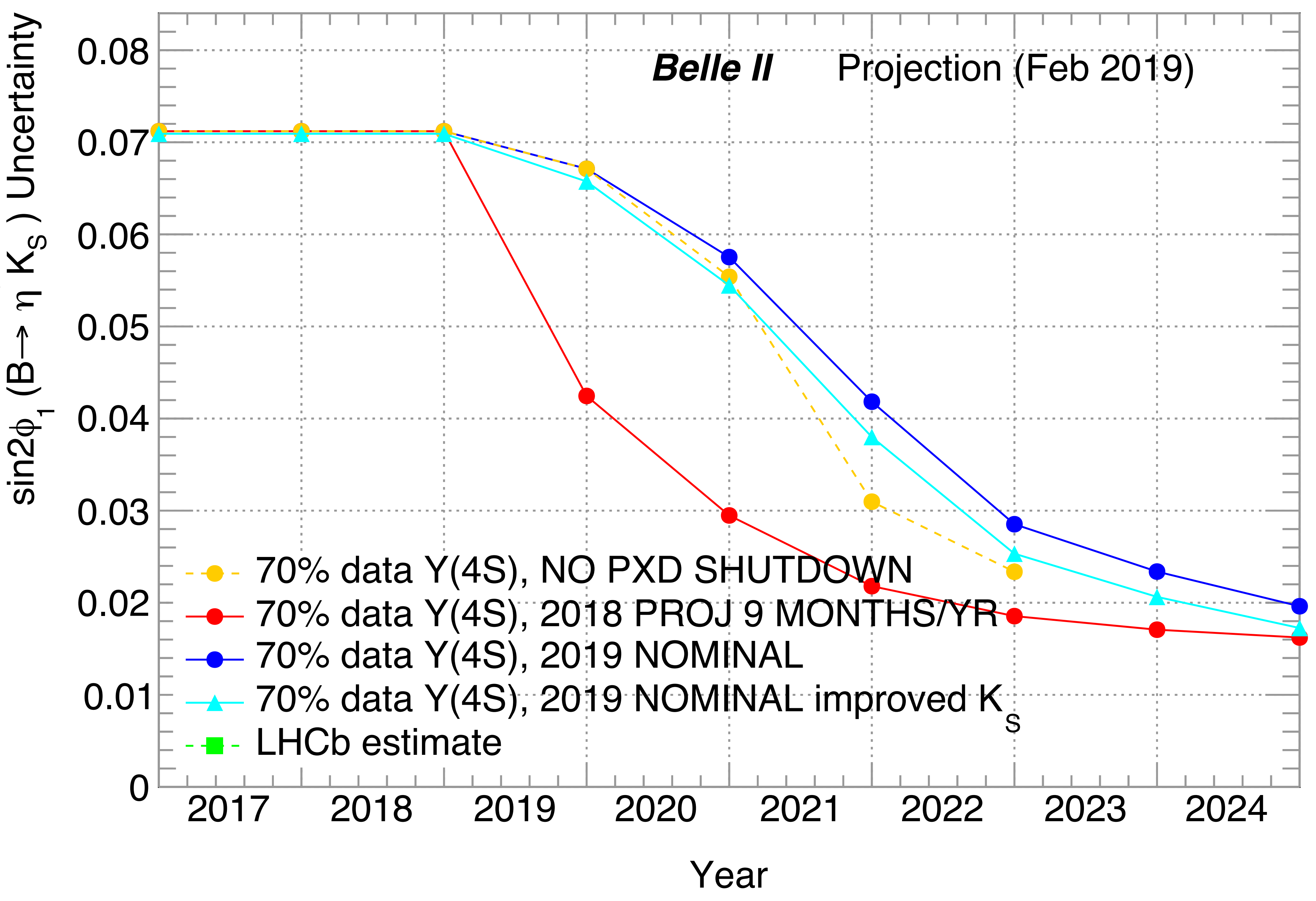
1. **UT angles - errors ~3x reduction within 5 years.**
2. **Searches for new phases in b→s gluon and EW penguins will hit few % precision.**

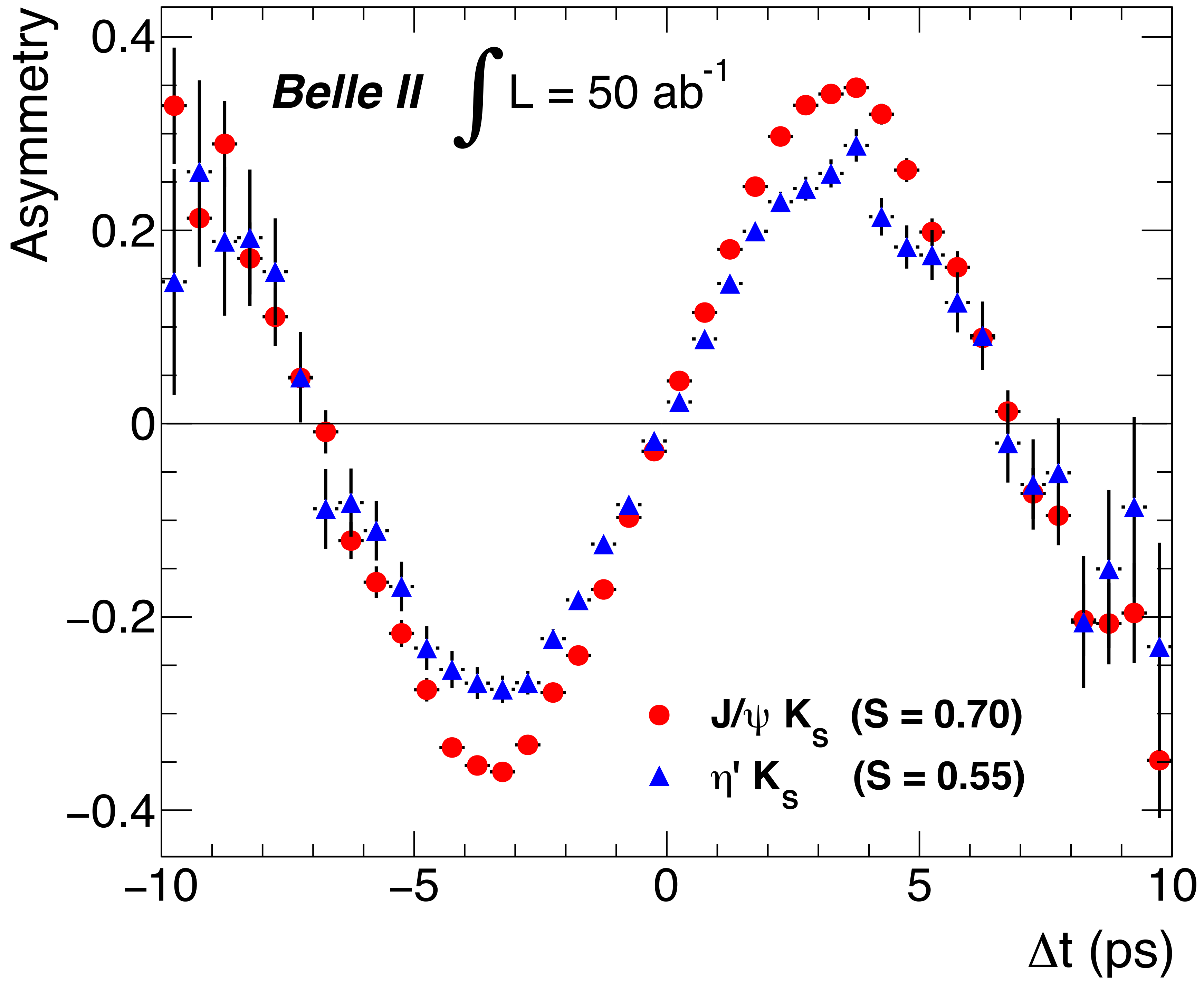
	Current	50 ab^{-1} projection
ϕ_1:		
Experimental:	0.7°	0.2°
Theoretical - QCDF & pQCD	0.1°	0.1°
Theoretical - SU(3)	1.7°	0.8°
ϕ_2:		
Experimental:	4.2°	0.6°
Theoretical:	1.2°	< 1.0°

(phase of V_{td}) - B→η' K_S - gluonic penguin



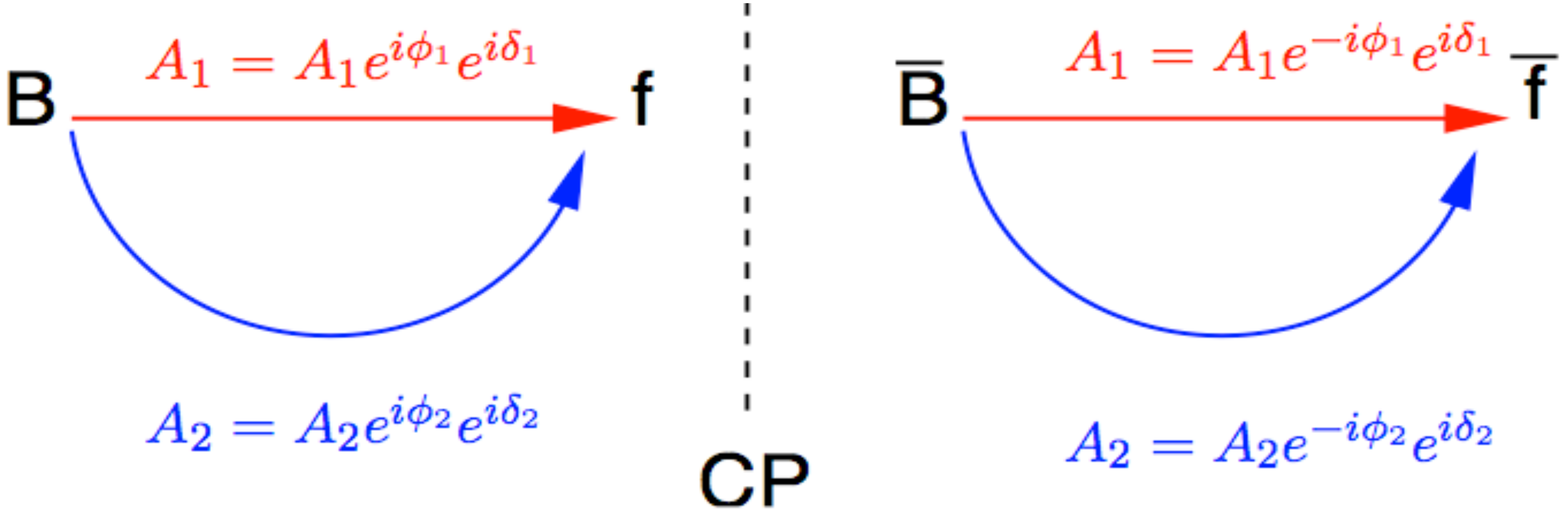
- *Gluonic Penguin (NP sensitive)*





Direct CP Violation, Φ_3

$\Phi_{1,2}$ rely on $\Delta F=2$ (mixing+decay), but we can also use $\Delta F=1$ (direct) as a precise probe



$$\text{CPV: } |A_f|^2 \neq |\bar{A}_{\bar{f}}|^2 \Rightarrow \Delta\phi \text{ and } \Delta\delta \neq 0$$

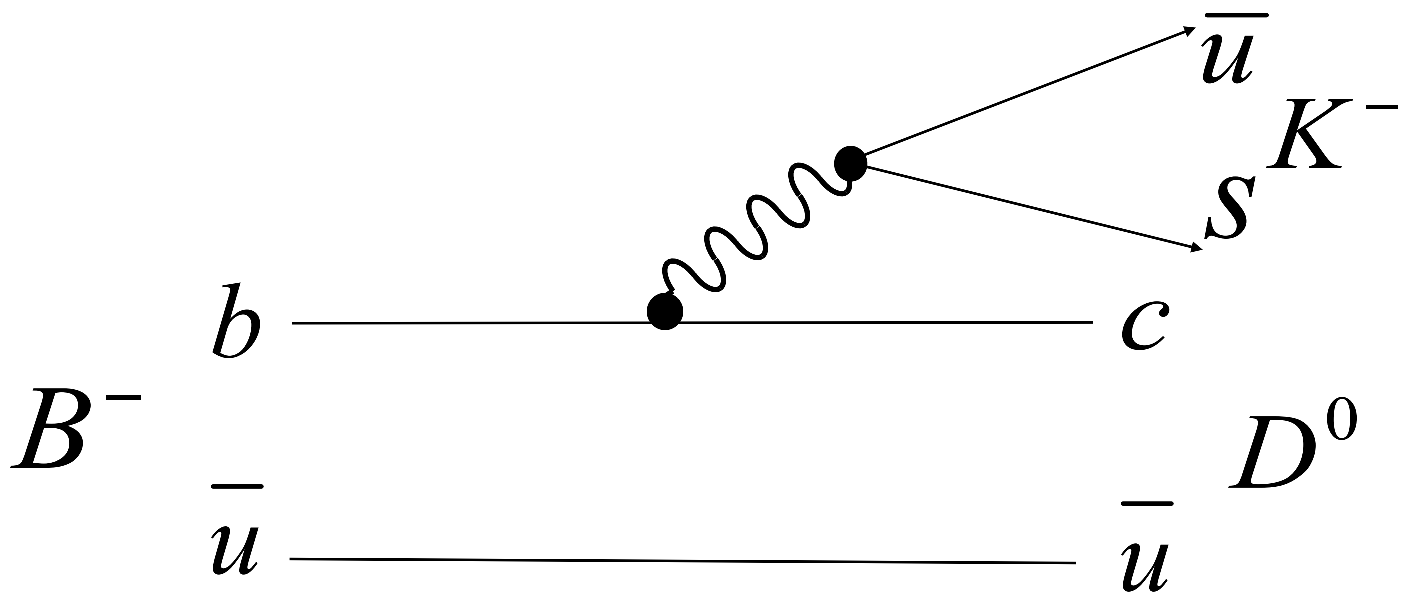
For CPV A_1 and A_2 need to have **different weak phases Φ** and different **CP invariant (e.g. strong) phases δ.**

To measure Φ you need to know δ, and ratio of amplitudes -

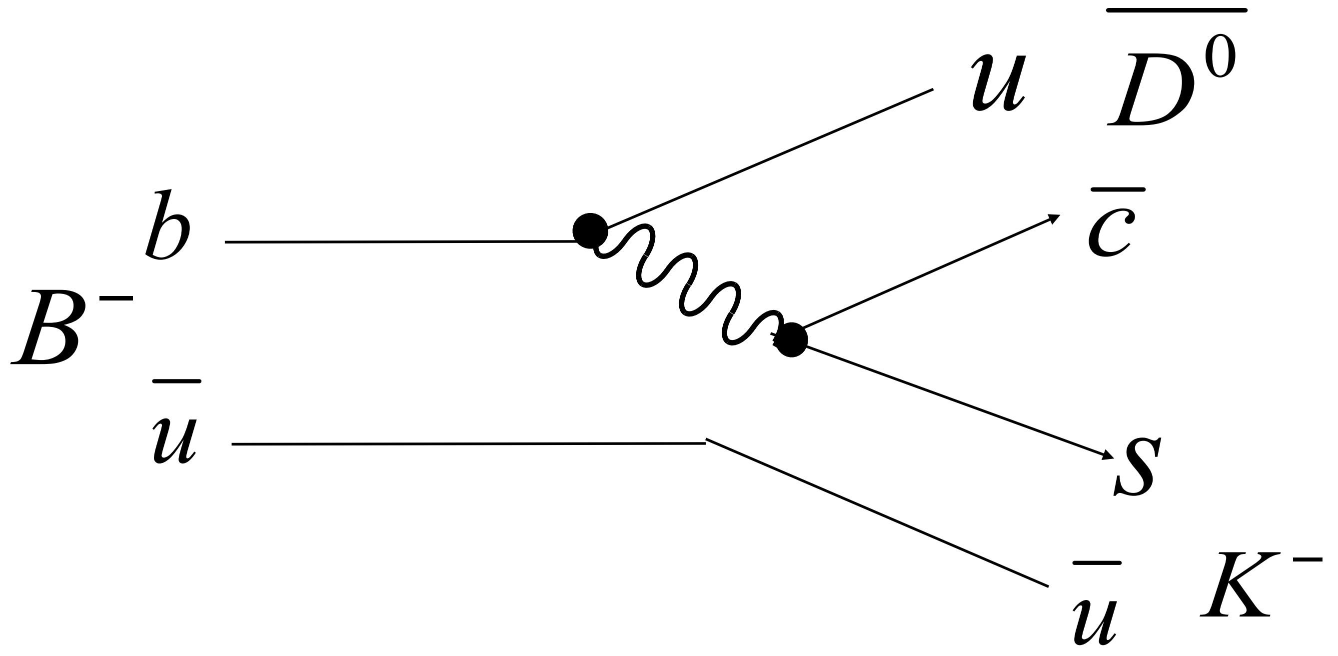
e.g. in γ/Φ_3 measurements the relative strength of V_{ub} and V_{cb} processes and colour suppression.

Φ_3/γ (phase of V_{ub}) Determination

- Theory is "pristine" in these approaches, << 1% on Φ_3



Favoured

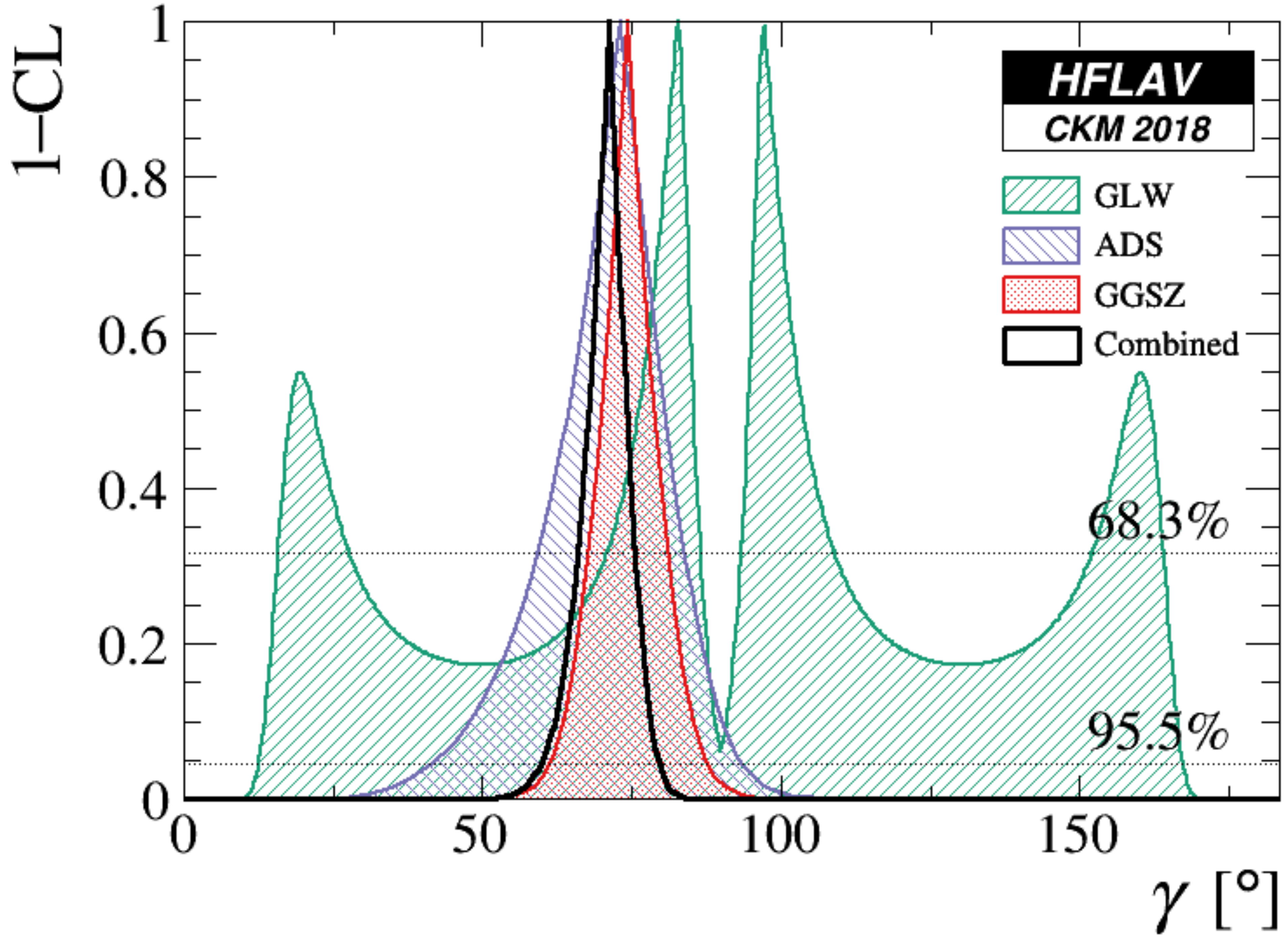


Suppressed

3 D^0 mode categories:

- D_{CP}, CP eigenstates [GLW]
- D_{sup}, Doubly cabibbo suppressed [ADS]
- **3-Body [GGSZ]**

$\gamma \equiv \Phi_3$	**$(71.1\,^{+4.6}_{-5.3})^\circ$**



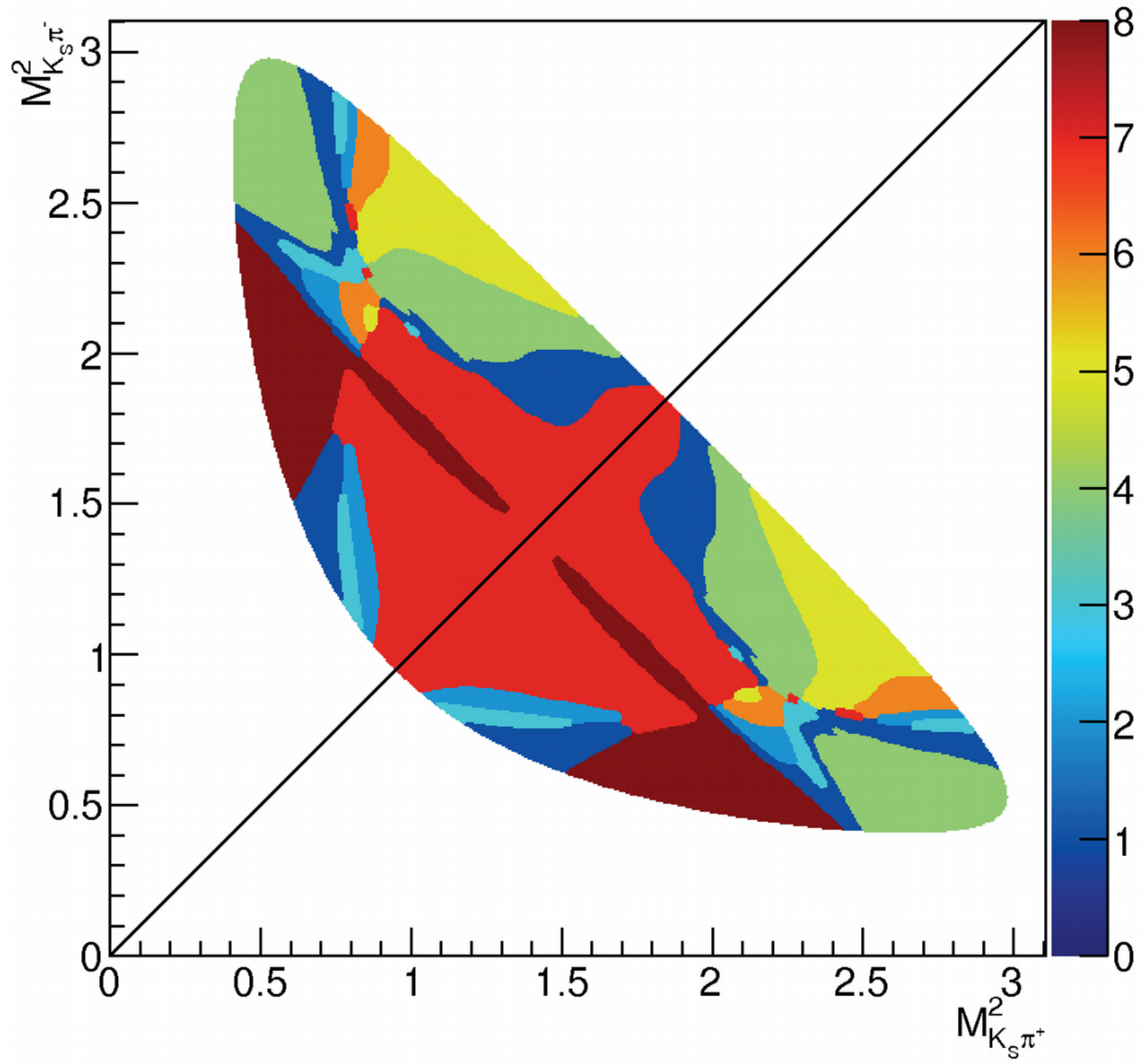
$$r_B = \frac{|A_{\text{suppressed}}|}{|A_{\text{favoured}}|} \approx \frac{V_{ub}V_{cs}^*}{V_{cb}V_{us}^*} \times [\text{colour supp.}] = 0.1 - 0.2$$

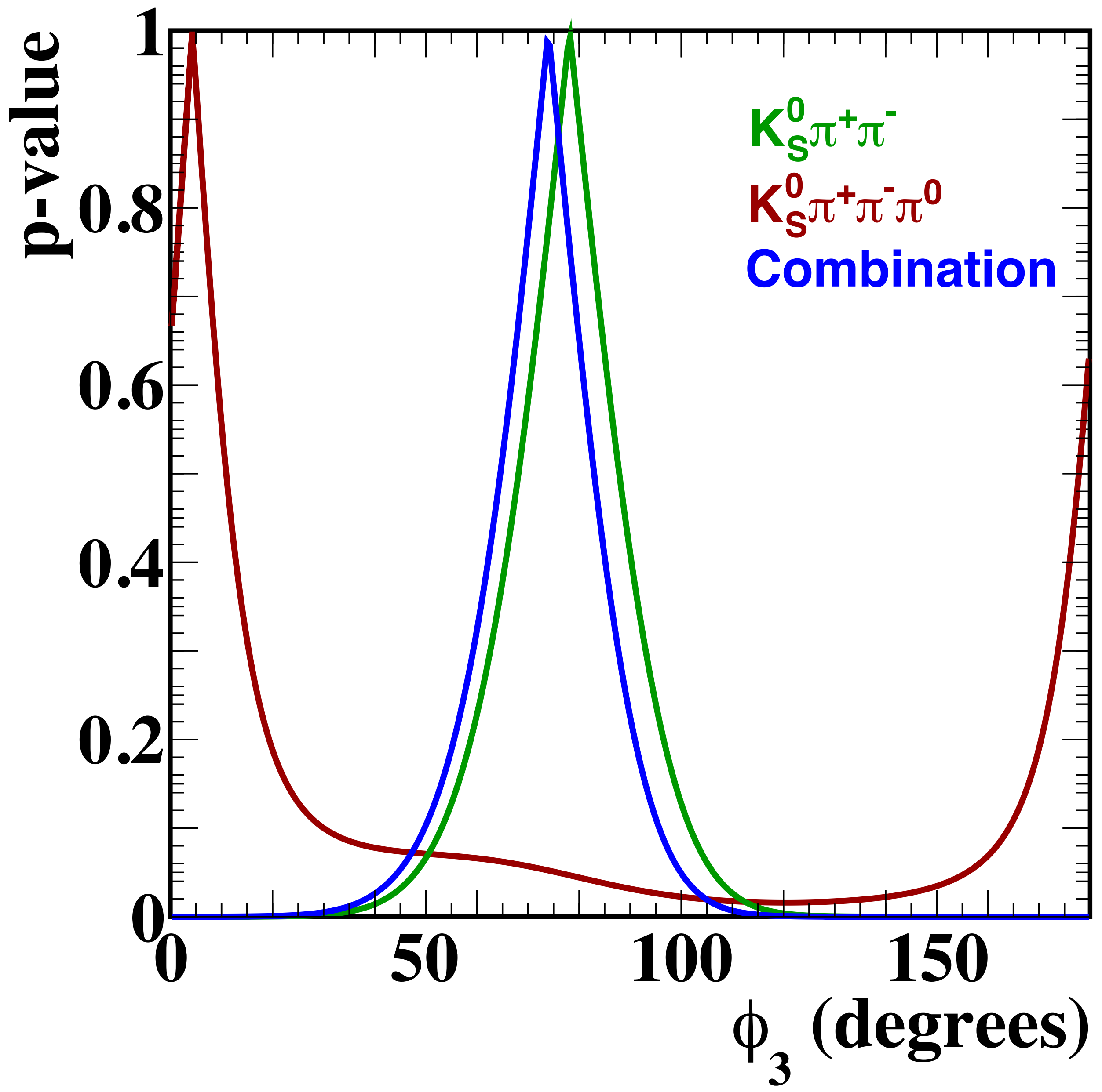
Relative weak phase is Φ_3, Relative strong phase is δ_R

A dream of Belle & Babar: difficult due to V_{ub} and colour suppression.
Many Direct CPV techniques developed at the B-factories.

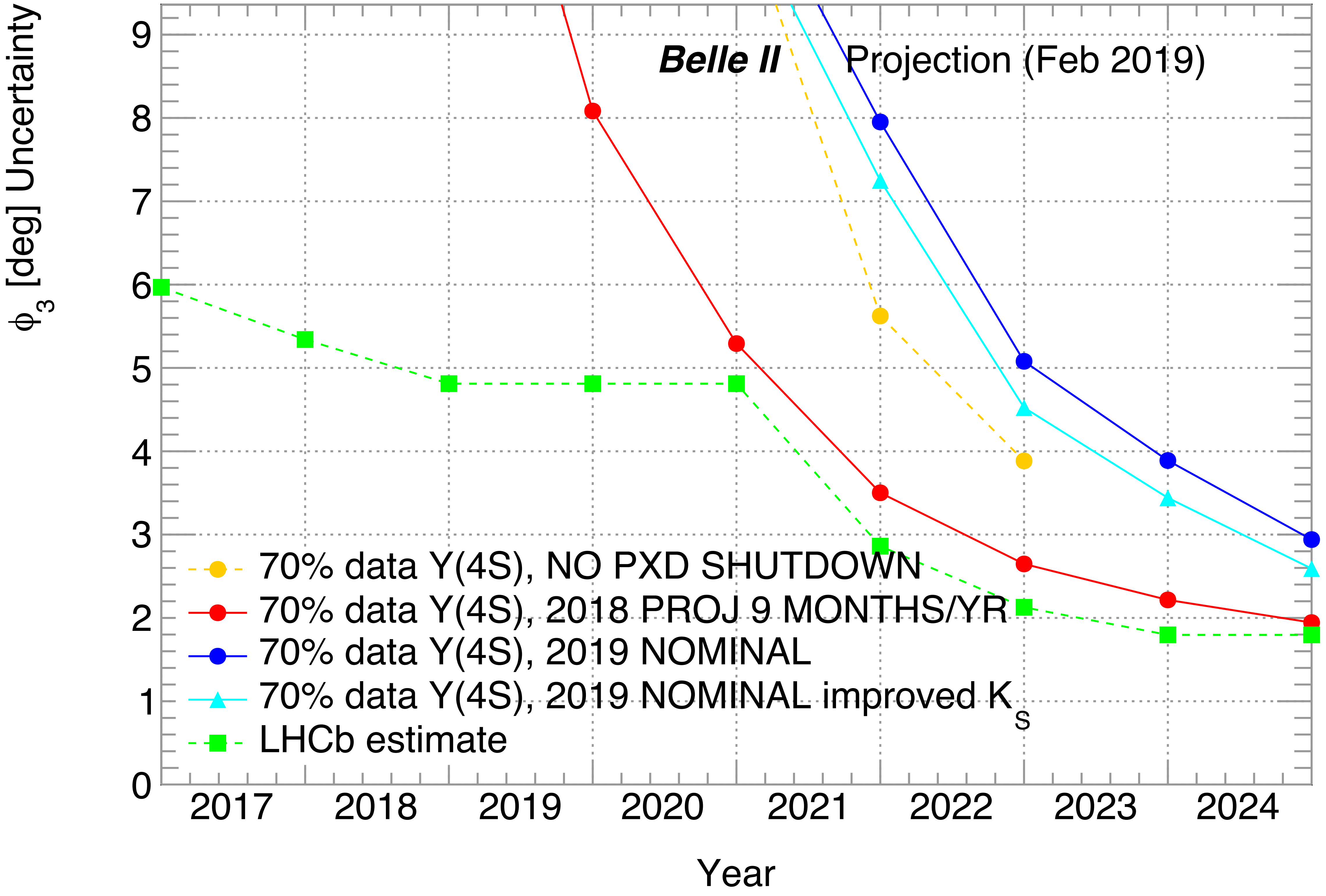
Φ_3 at Belle II

- Most sensitive method: GGSZ(*) analysis of the $D^0 \to$ **$K_S\pi^+\pi^-$ Dalitz Plot**, exploits large strong phases across the plane to enhance the sensitivity;
- Systematics overcome with model independent **DP**, with strong phase from BESIII;
- Enhanced by including $K^+K^-K_S$, **$K_S\pi^+\pi^-\pi^0$**, $K\pi^+\pi^-$ & $D^{*0} \to D^0\gamma$ and $D^{*0} \to D^0\pi^0$ modes.



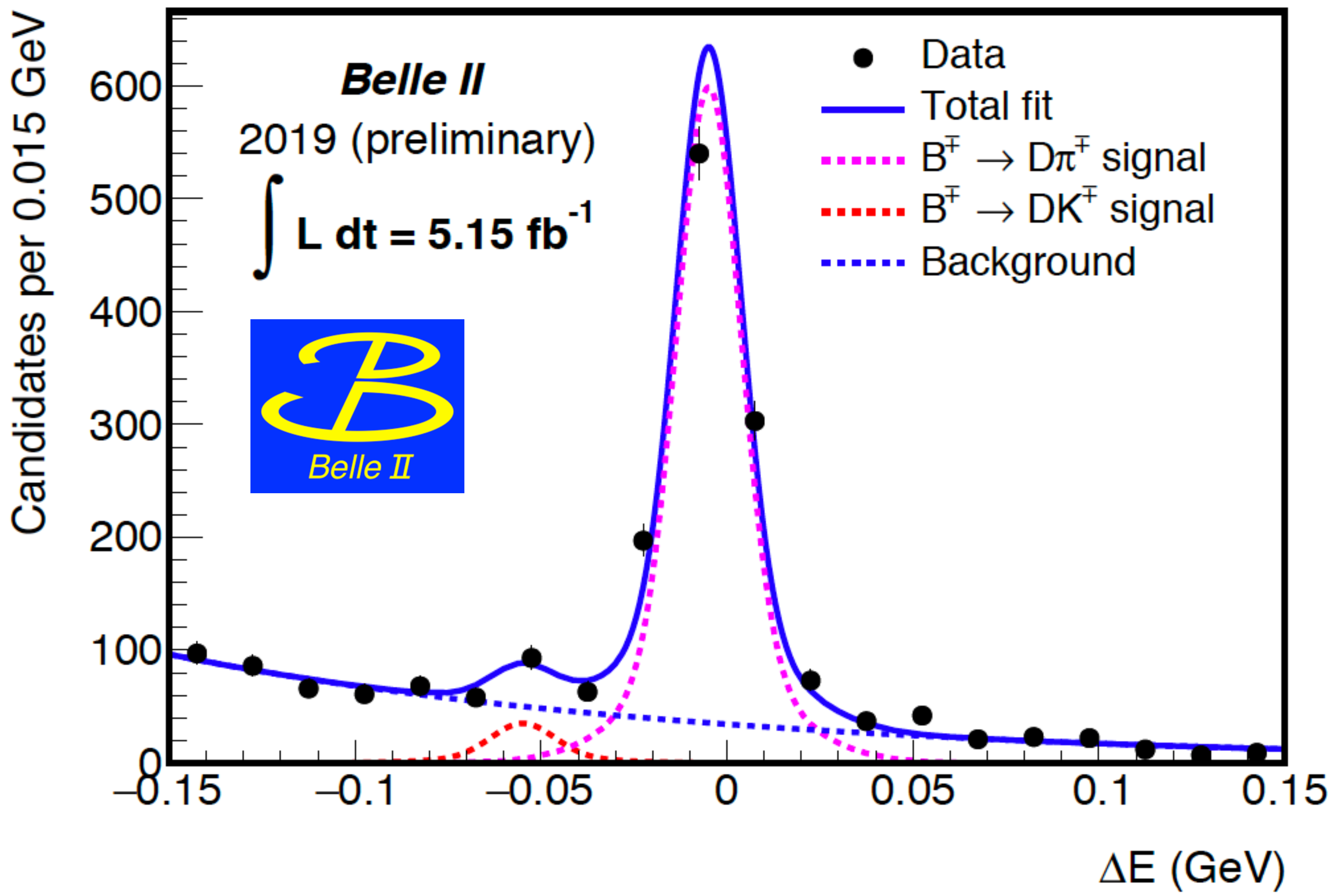


Belle, arXiv: 1908.09499
Method demonstration.

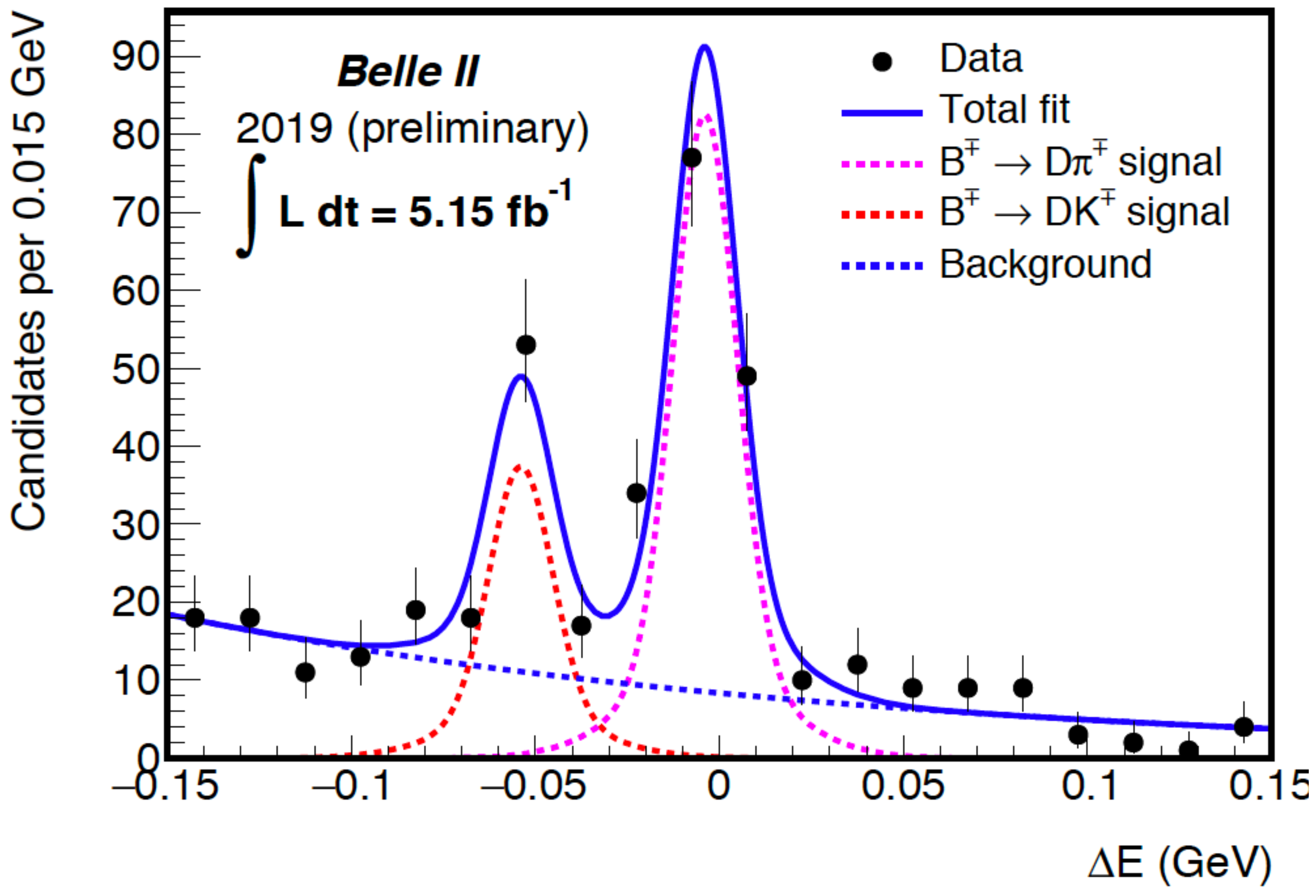


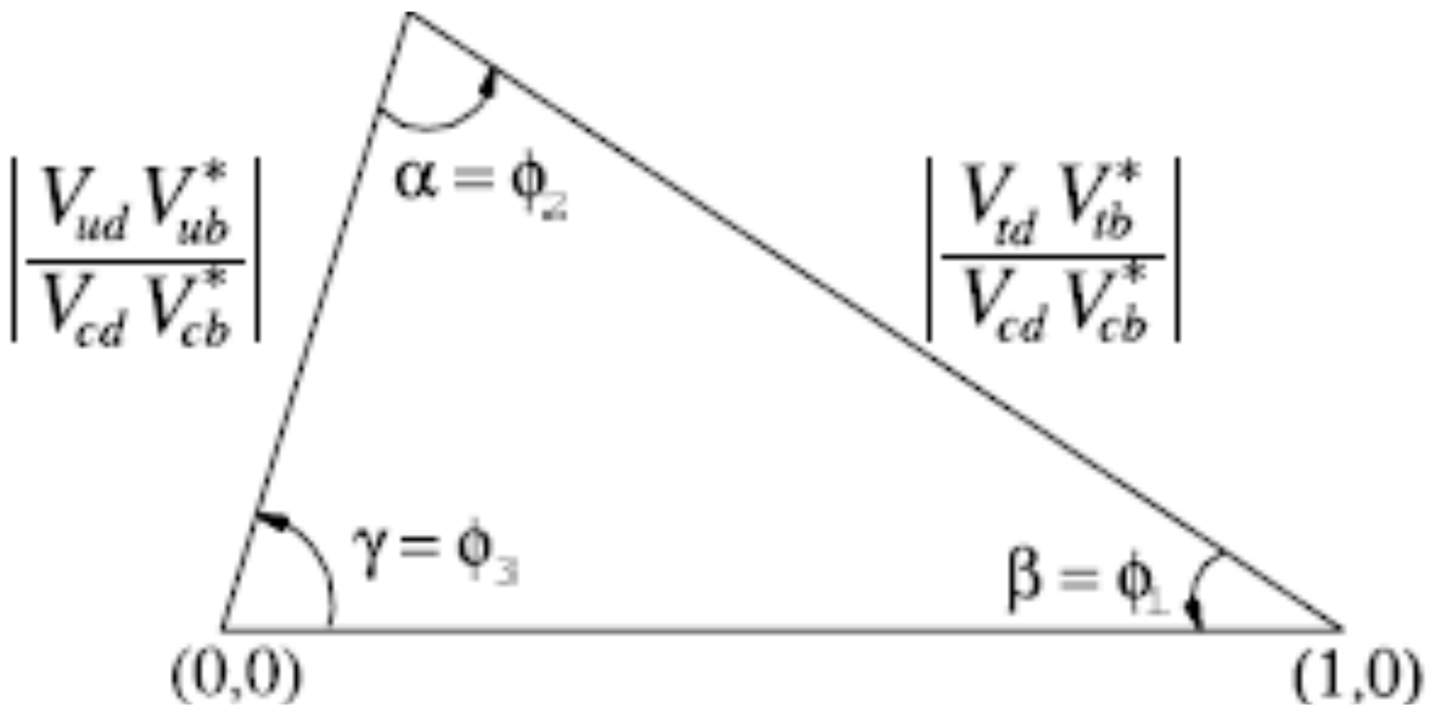
Observation of $B^- \to D^0 K^-$ at Belle II

No PID



With high momentum PID





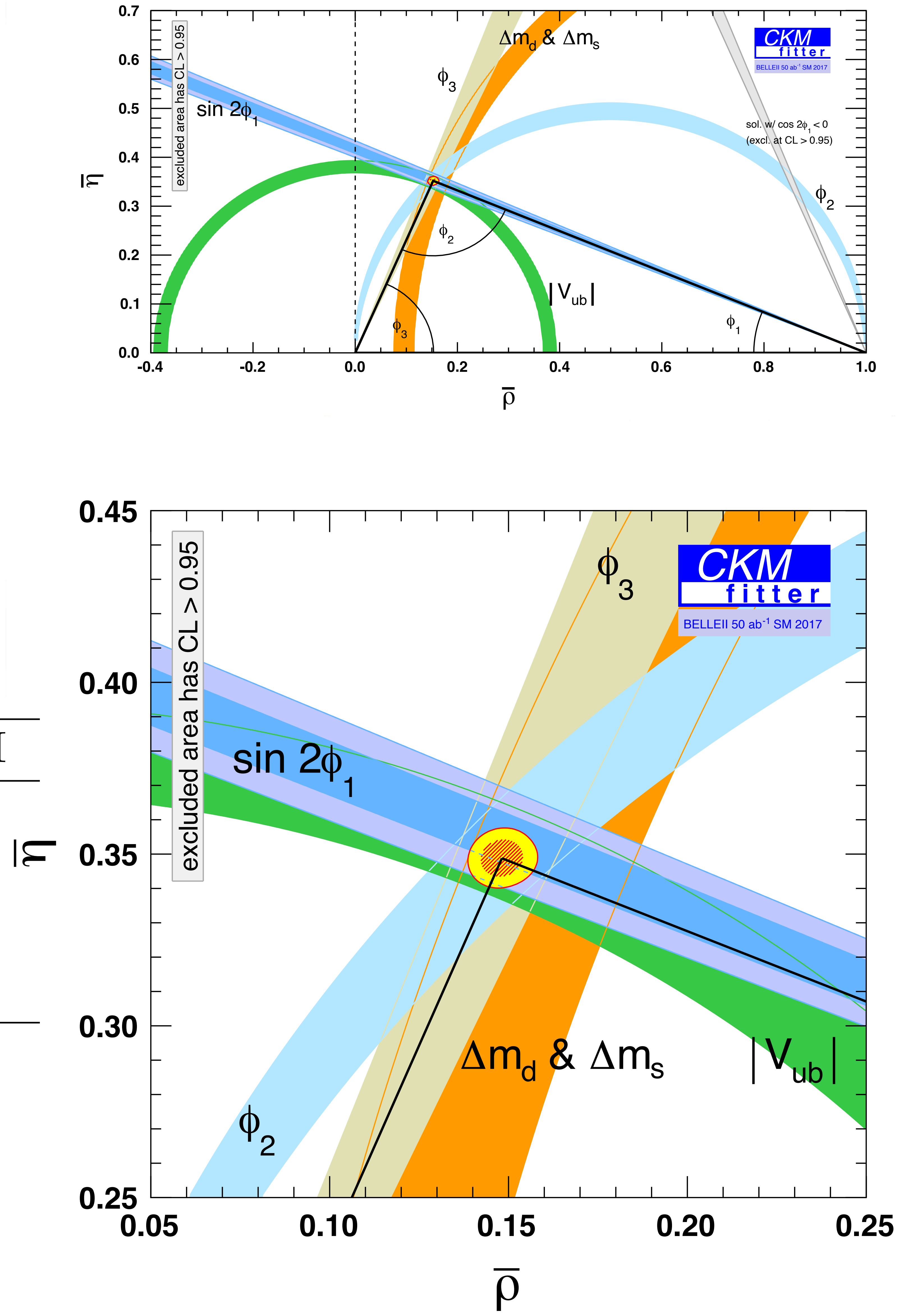
Demonstration of Belle II high momentum PID on a decay mode to be used for future determinations of the unitarity angle γ (a.k.a φ_3)

Belle II 50 ab^{-1}

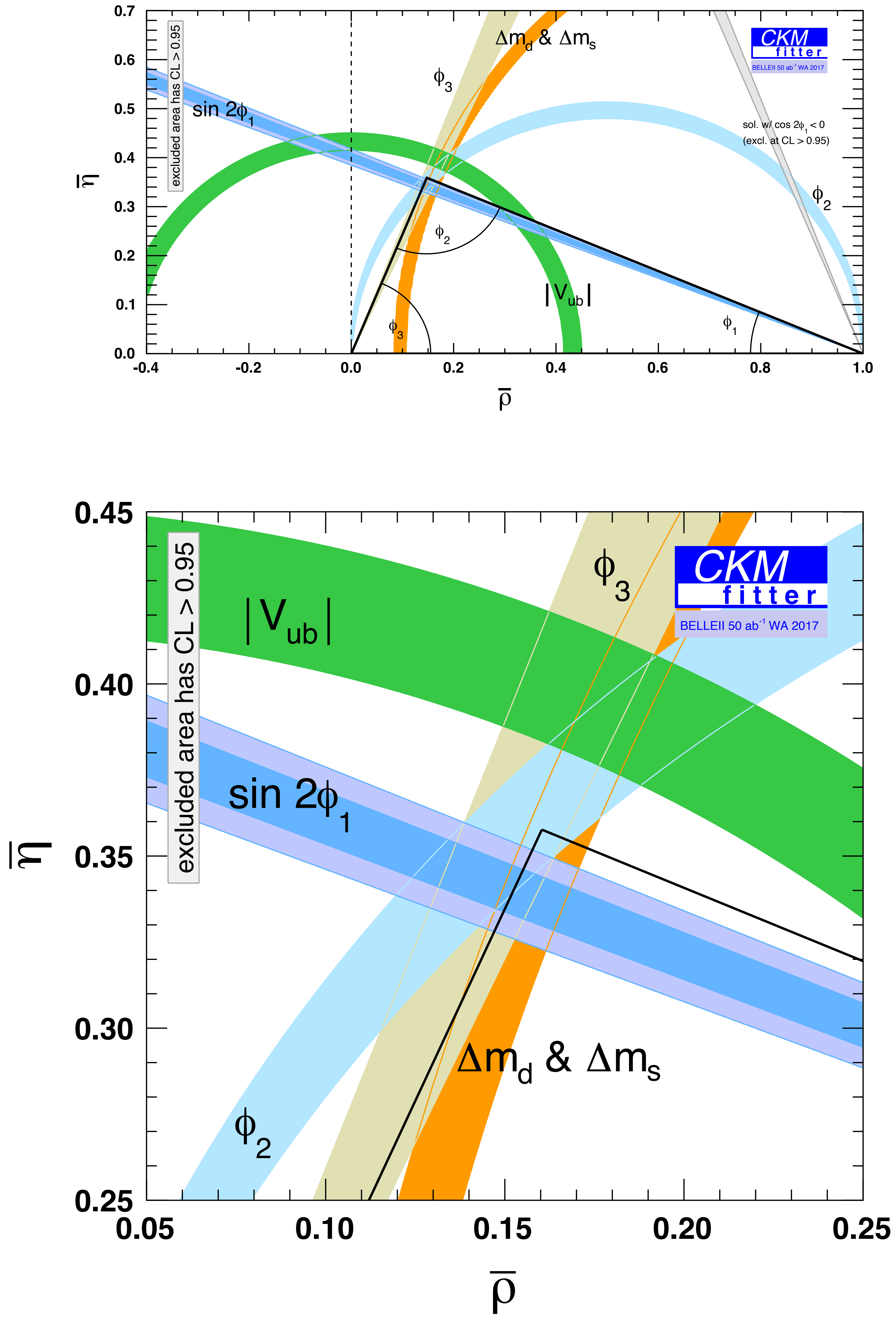
- Belle II+mixing from LHCb+LQCD
- Lots of space for new physics.
- Note: to get this far we rely on LQCD to make big advances in form factors, bag factors etc.

Input	Current WA	SM value Belle II
A	$0.8227^{+0.0066}_{-0.0136}$	$^{+0.0025}_{-0.0027}$
λ	$0.22543^{+0.00042}_{-0.00031}$	$^{0.00036}_{-0.00030}$
$\bar{\rho}$	$0.1504^{+0.0121}_{-0.0062}$	$^{+0.0054}_{-0.0044}$
$\bar{\eta}$	$0.3540^{+0.00069}_{-0.0076}$	$^{+0.0037}_{-0.00040}$

SM-like



New-physics

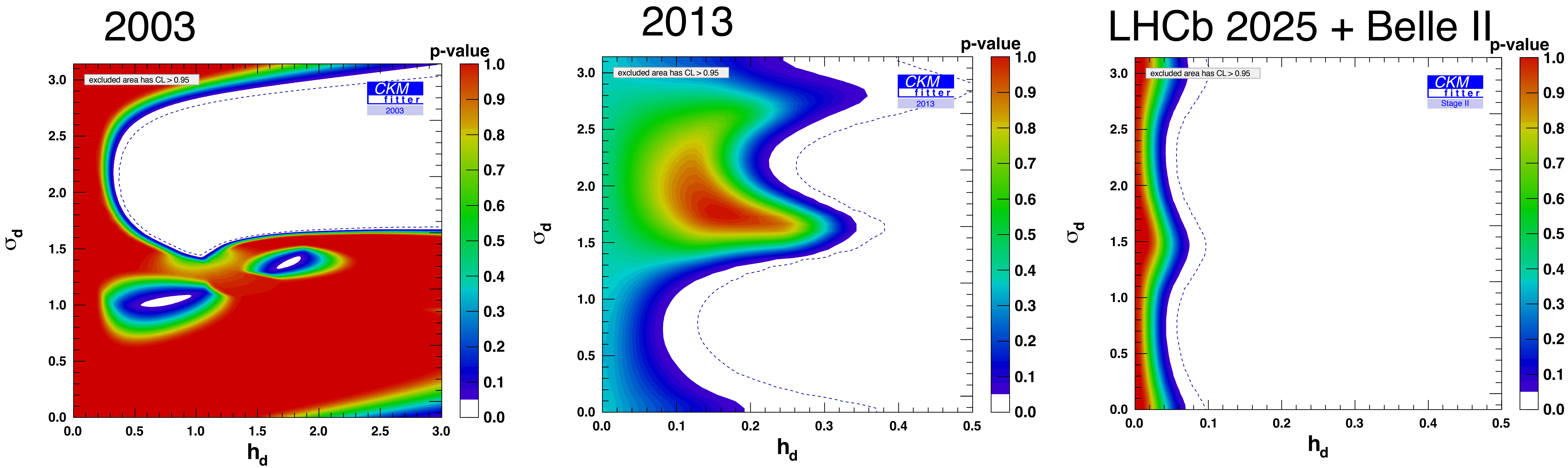


THE UNIVERSITY OF MELBOURNE

NP in B_d mixing: Fit results

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

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



- at 95% NP≲(many × SM) $\Longrightarrow$ NP≲(0.3 × SM) $\Longrightarrow$ 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

Beyond the Standard Model and Anomalies

Flavour physics anomalies

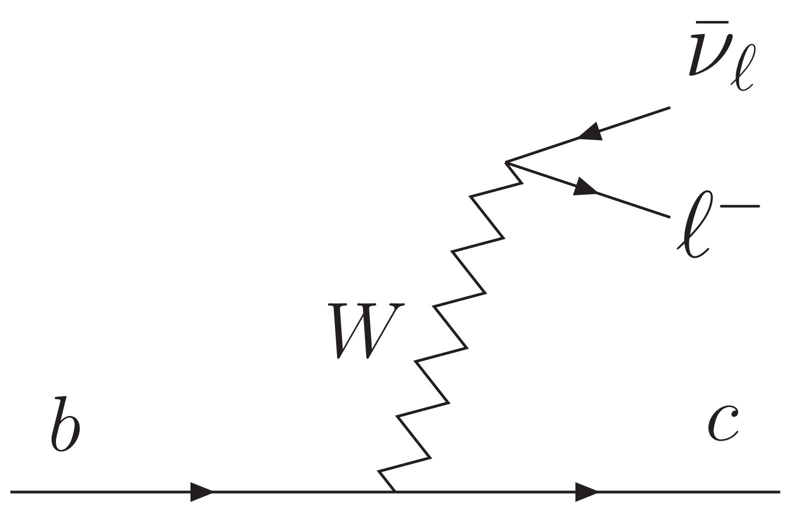
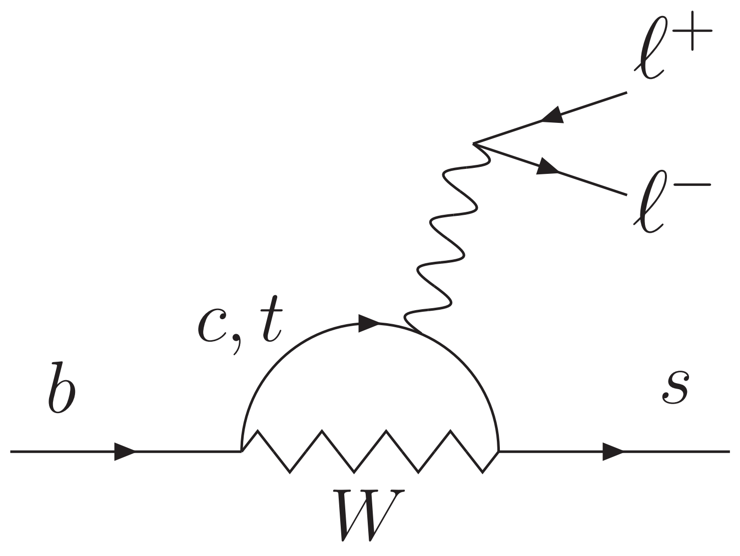
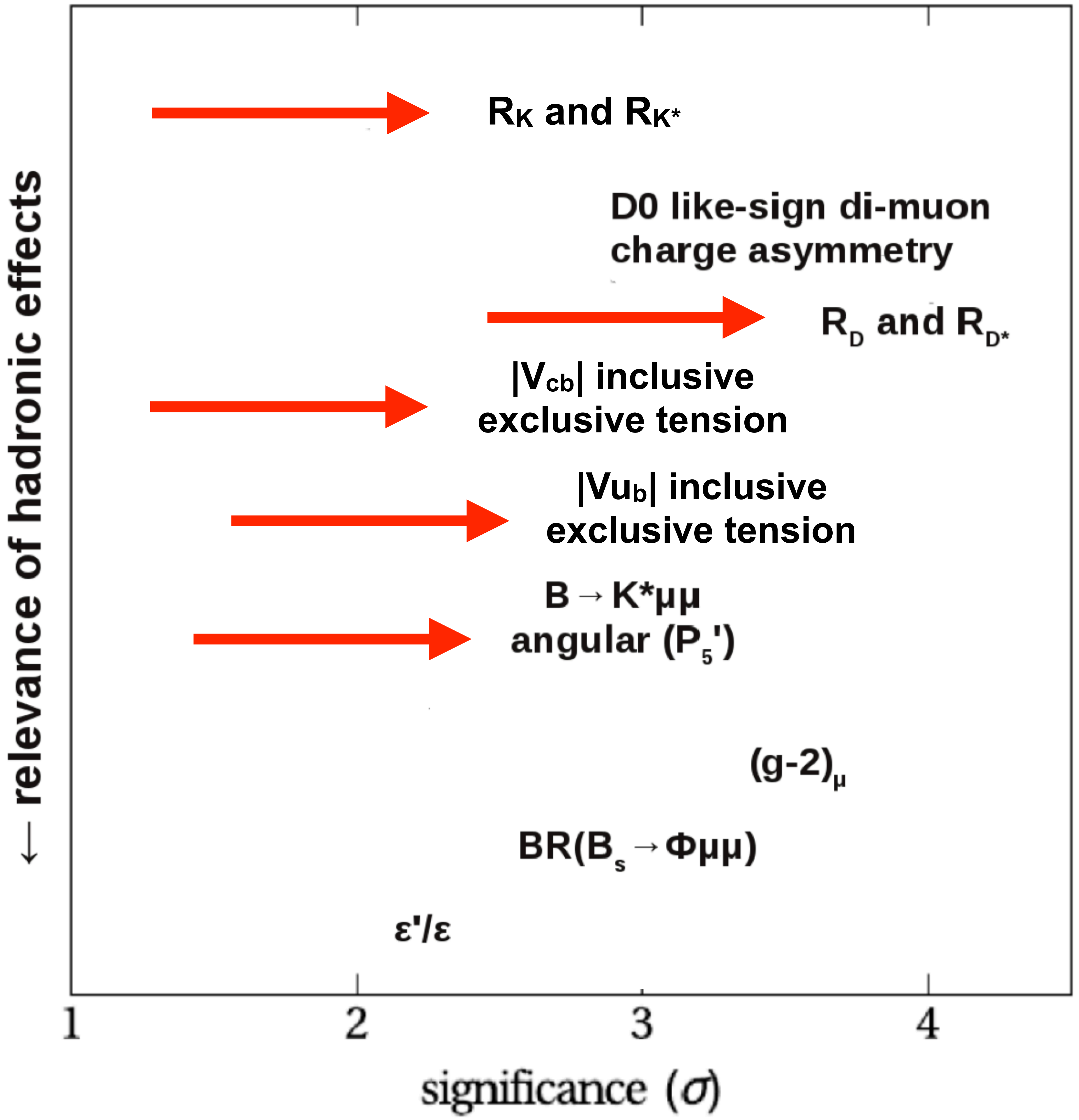
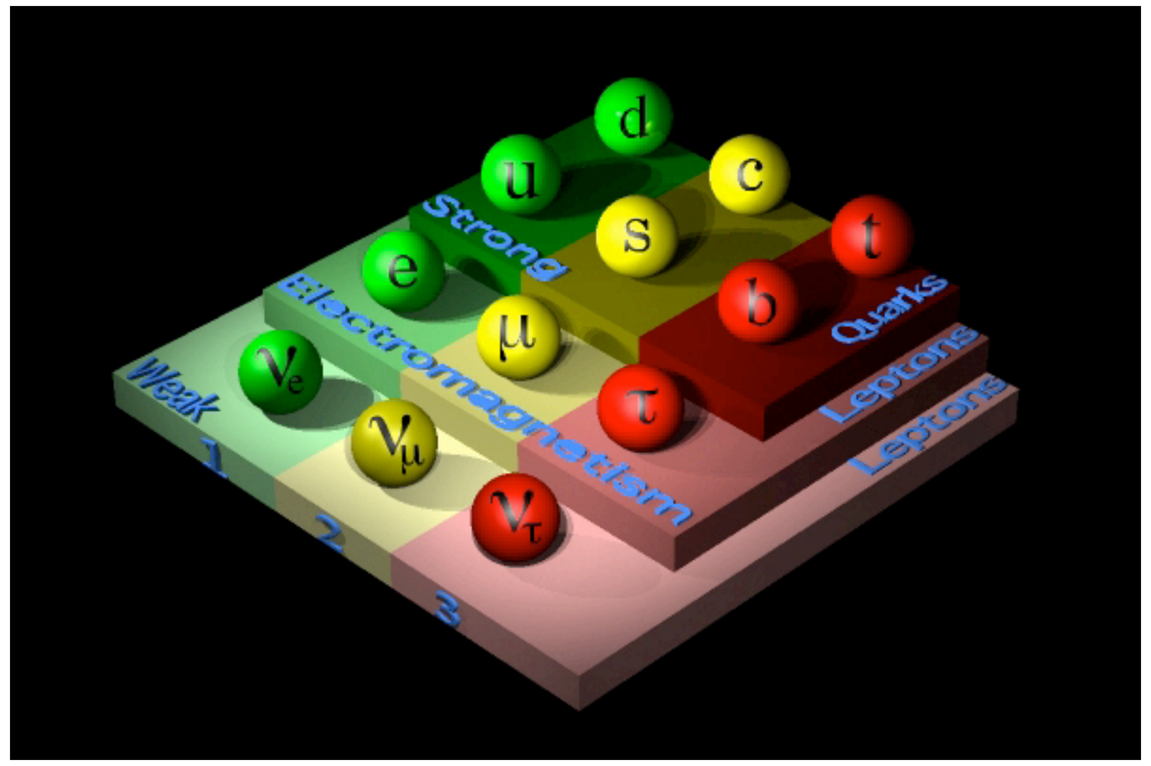
	$b \to c\ell\bar{\nu}_\ell$	$b \to s\ell^+\ell^-$
		
SM	tree (charged) $(V - A)$	loop (neutral)
Spin 0	$\overline{B} \to D\ell\bar{\nu}_\ell$	$B \to K\ell\ell$
Spin 1	$\overline{B} \to D^*\ell\bar{\nu}_\ell$	$B \to K^*\ell\ell$, $B_s \to \phi\ell\ell$
Observables	Total Br	$d\Gamma/dq^2$ + Angular obs
with	$\ell = \tau, \mu, e$	$\ell = \mu, e$
Tensions	$R_{D(*)} = \frac{Br(B \to D(*)\tau\nu)}{Br(B \to D(*)\ell\bar{\nu}_\ell)}$	$R_K = \frac{Br(B \to K\mu\mu)}{Br(B \to Kee)}$
	$\|V_{cb}\|$ & $\|V_{ub}\|$ inclusive-exclusive tension	$Br\ (K, K^*, \phi + \mu\mu)$ angular obs (e.g., P_5')

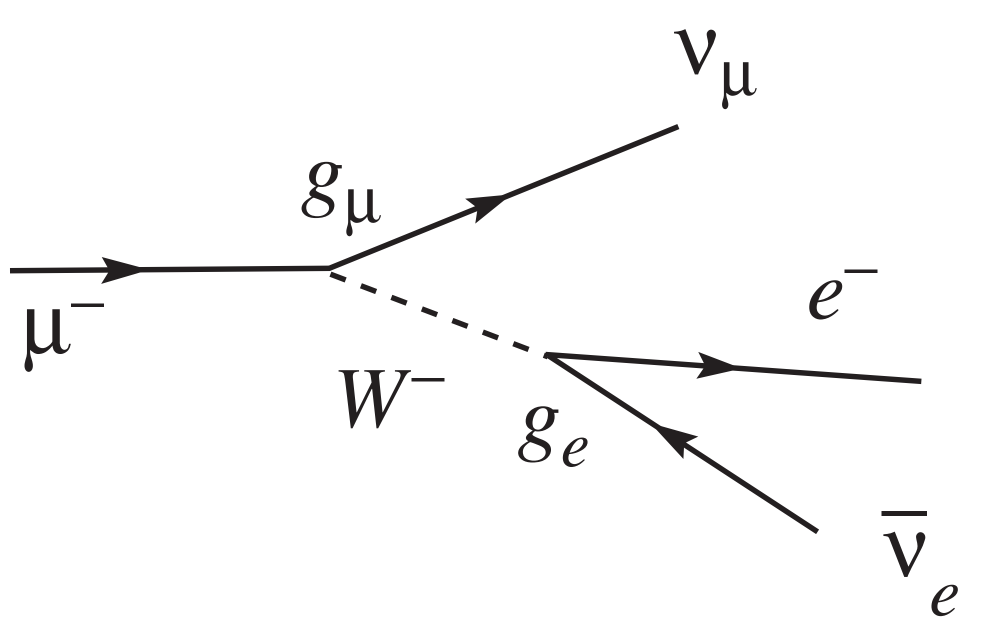
Table from S. Descotes-Genon

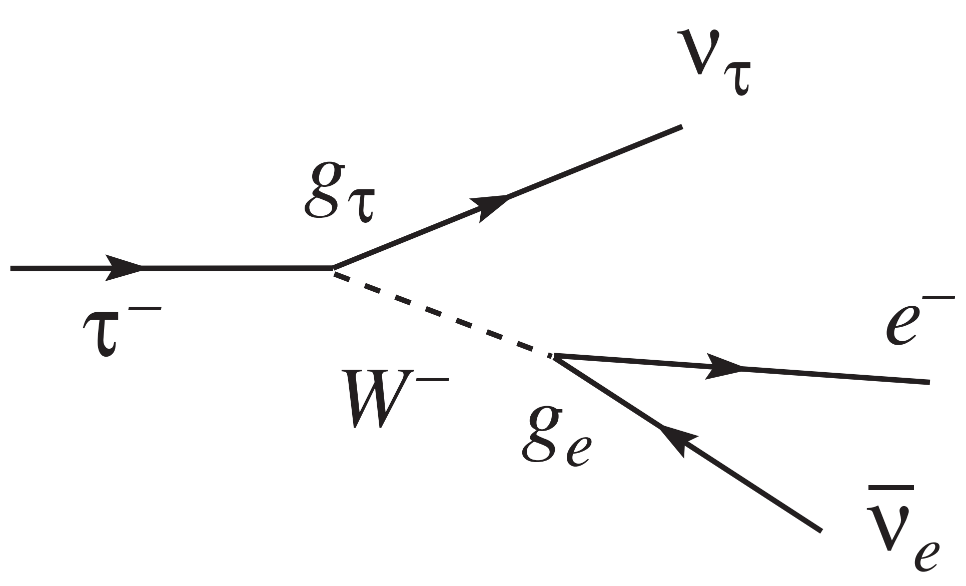


- ***Belle II STRATEGY: Improved ν reco / novel B-tagging, improved lepton identification (from τ).***

Lepton flavour universality



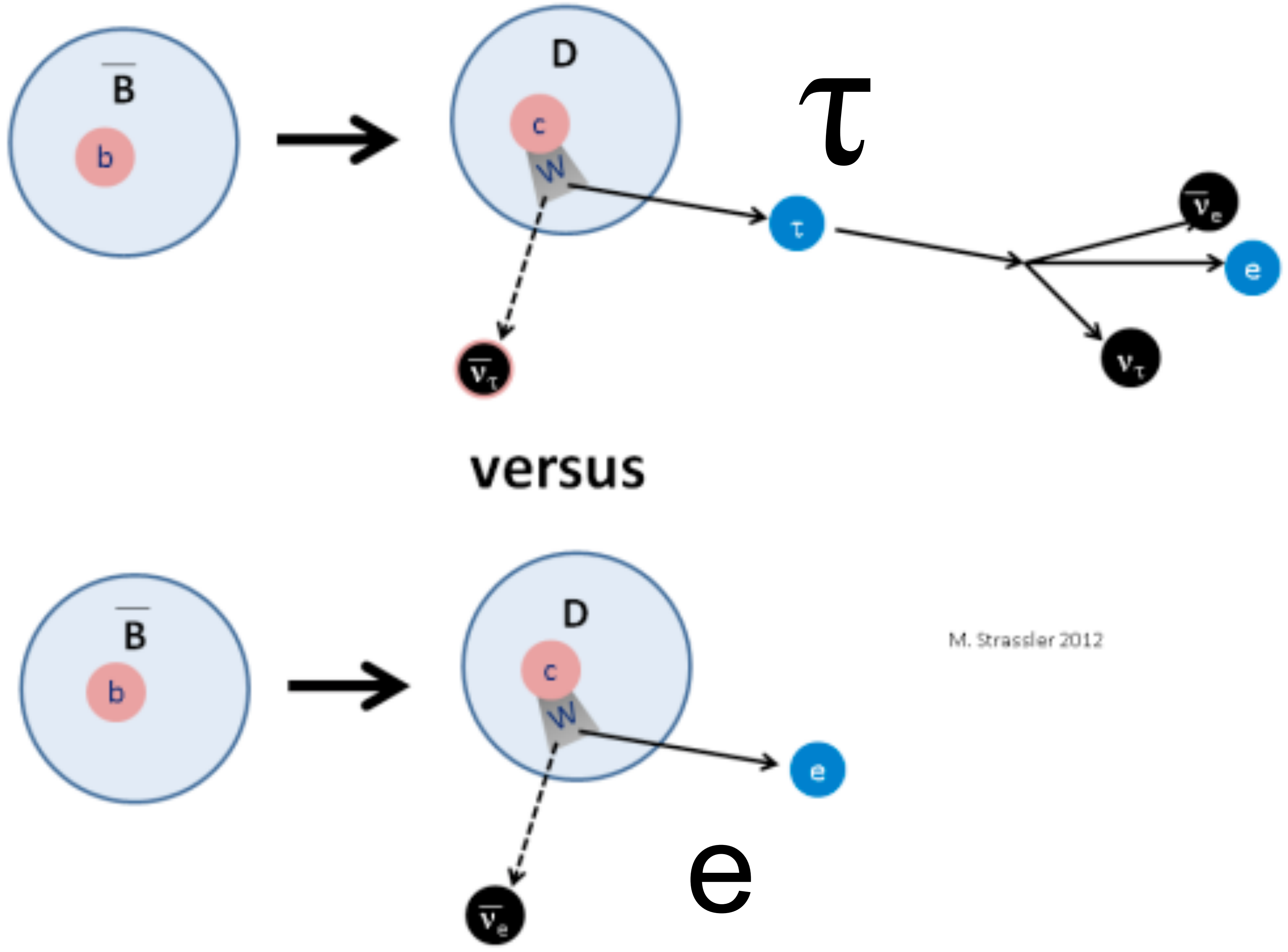




$$\frac{g_\mu^2}{g_\tau^2} = \frac{1}{\tau_\mu} \frac{\tau_\tau}{BR(\tau^- \to e^- \overline{\nu}_e \nu_\tau)} \frac{m_\tau^5}{m_\mu^5} \frac{\rho_\tau}{\rho_\mu}$$

$$\frac{g_\tau}{g_\mu} = 1.0000 \pm 0.0014$$

Experimentally good for leptonic decays to an accuracy much better than 1%.



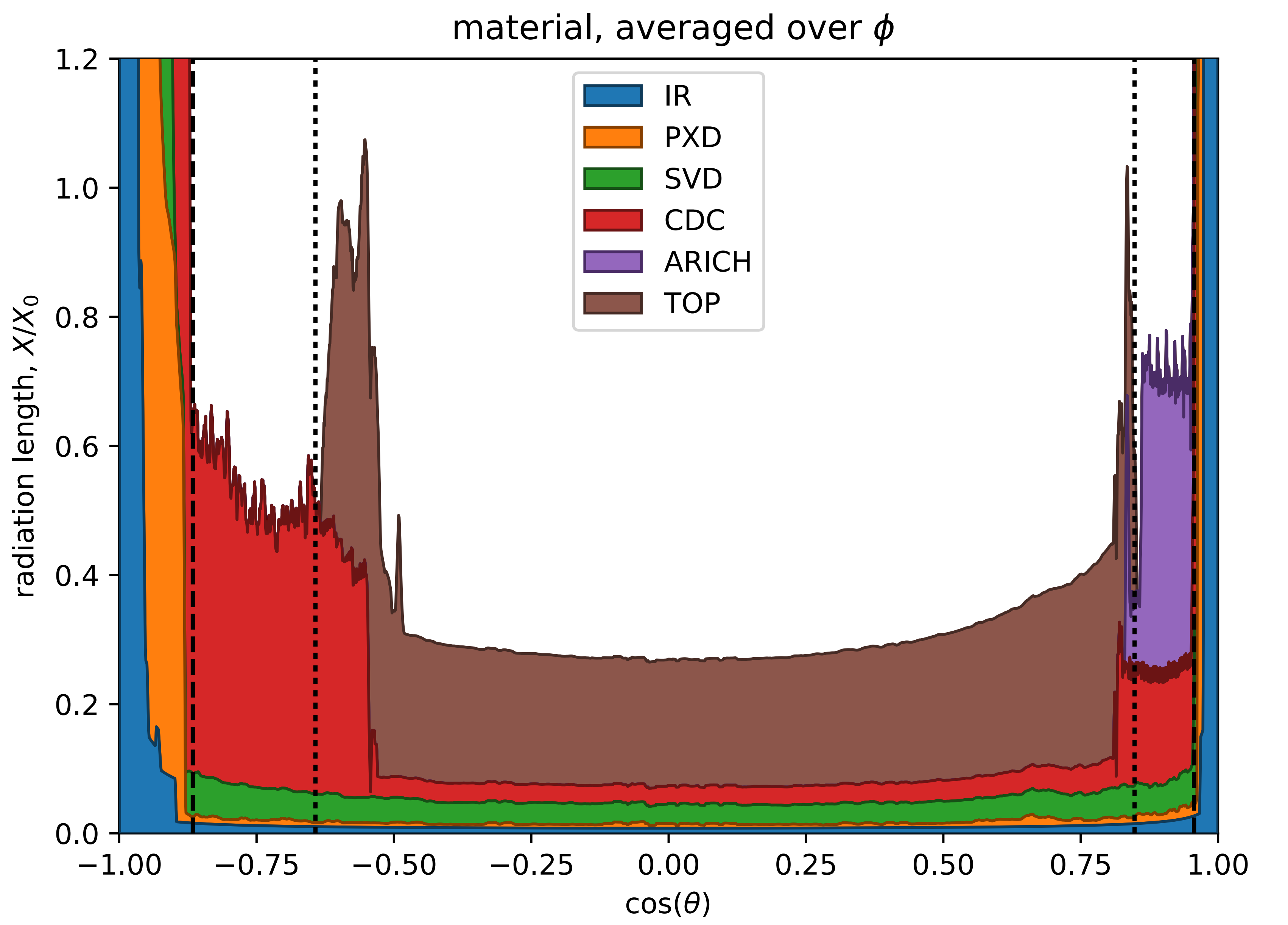
Now can access the 3rd generation of leptons and coupling to quarks!

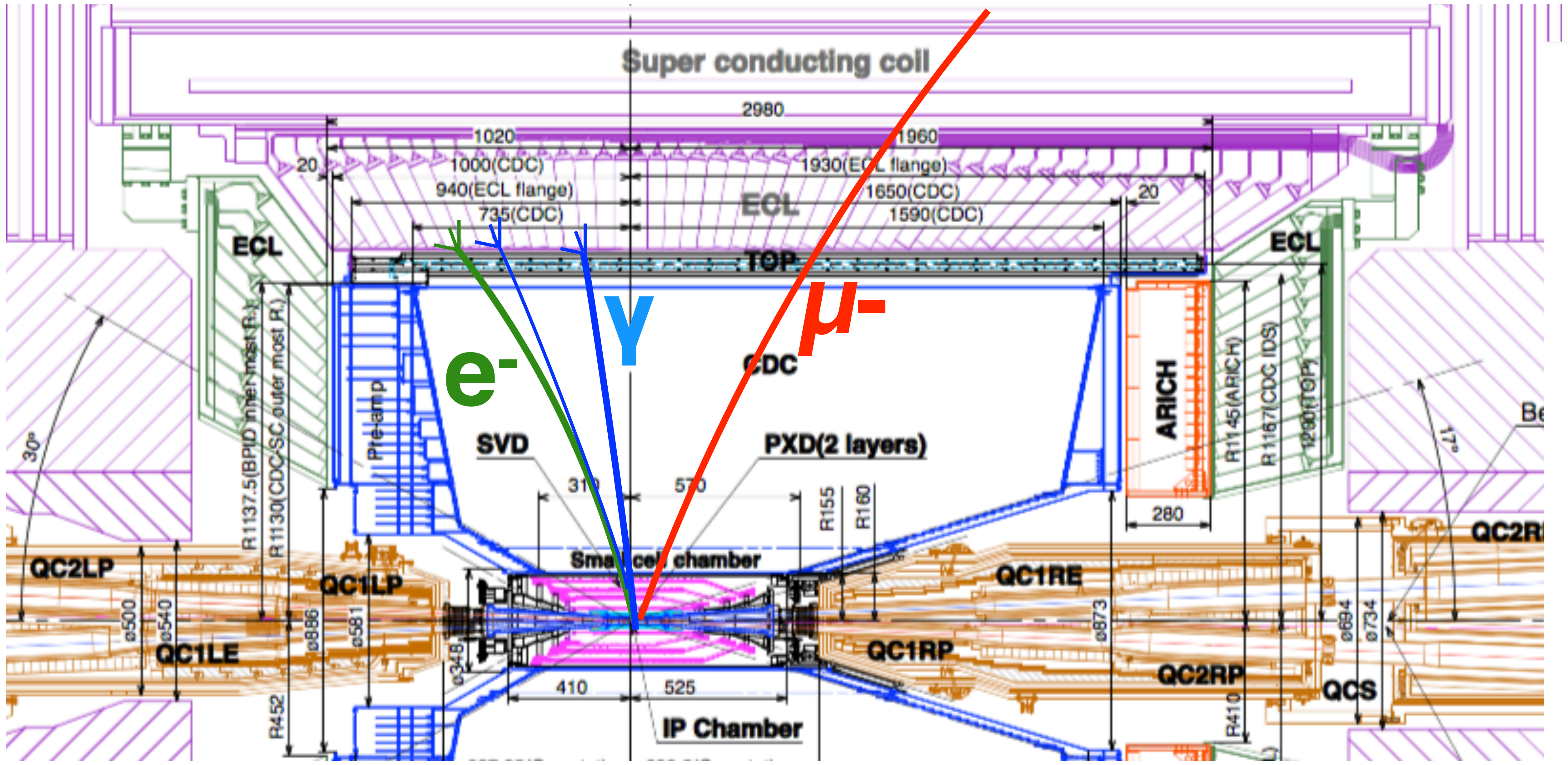
The only SM differences are are due to masses - easy* to calculate!

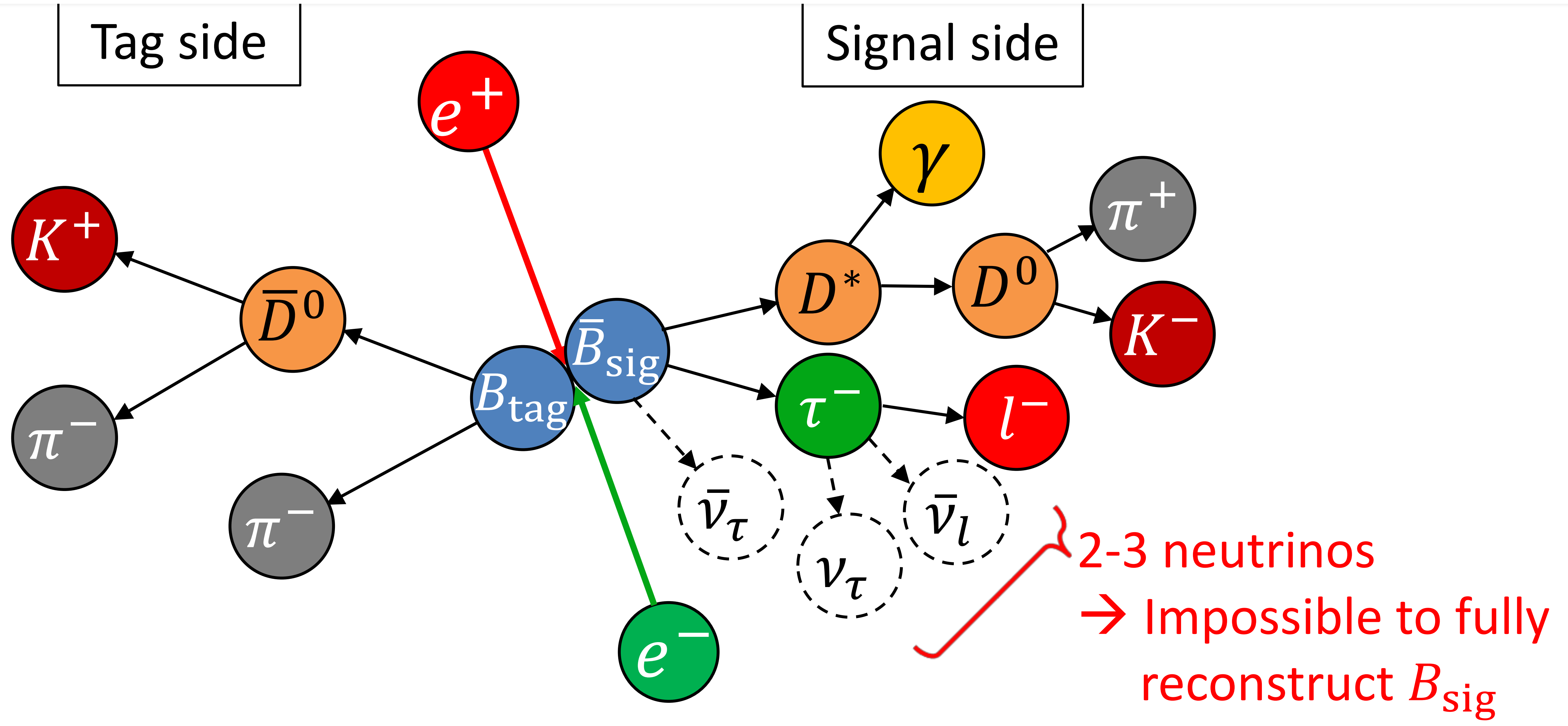
Any further difference would imply non-SM interaction.

Lepton reconstruction non-universality

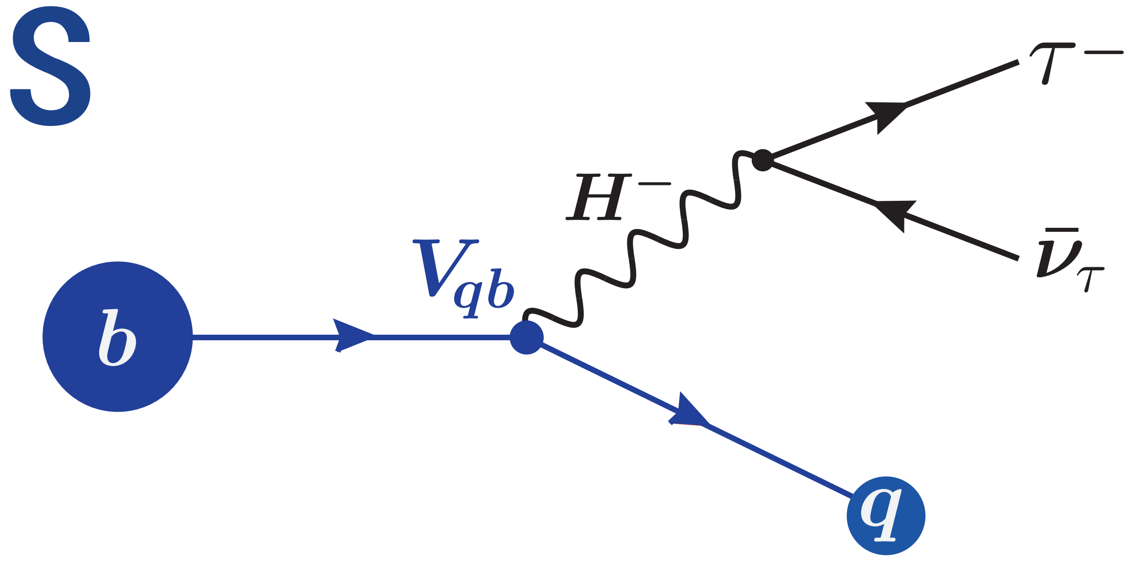
- **Muons**: Little to **no radiation** (heavy), **Stable** within particle detectors, no strong interactions
- **Electrons** are light: Final state radiation, Bremsstrahlung in material is likely (more material in LHC detectors).
- **Taus** lifetime is 10^{-12} s: background mimics signal where daughters are lost e.g. K_L, π^0.







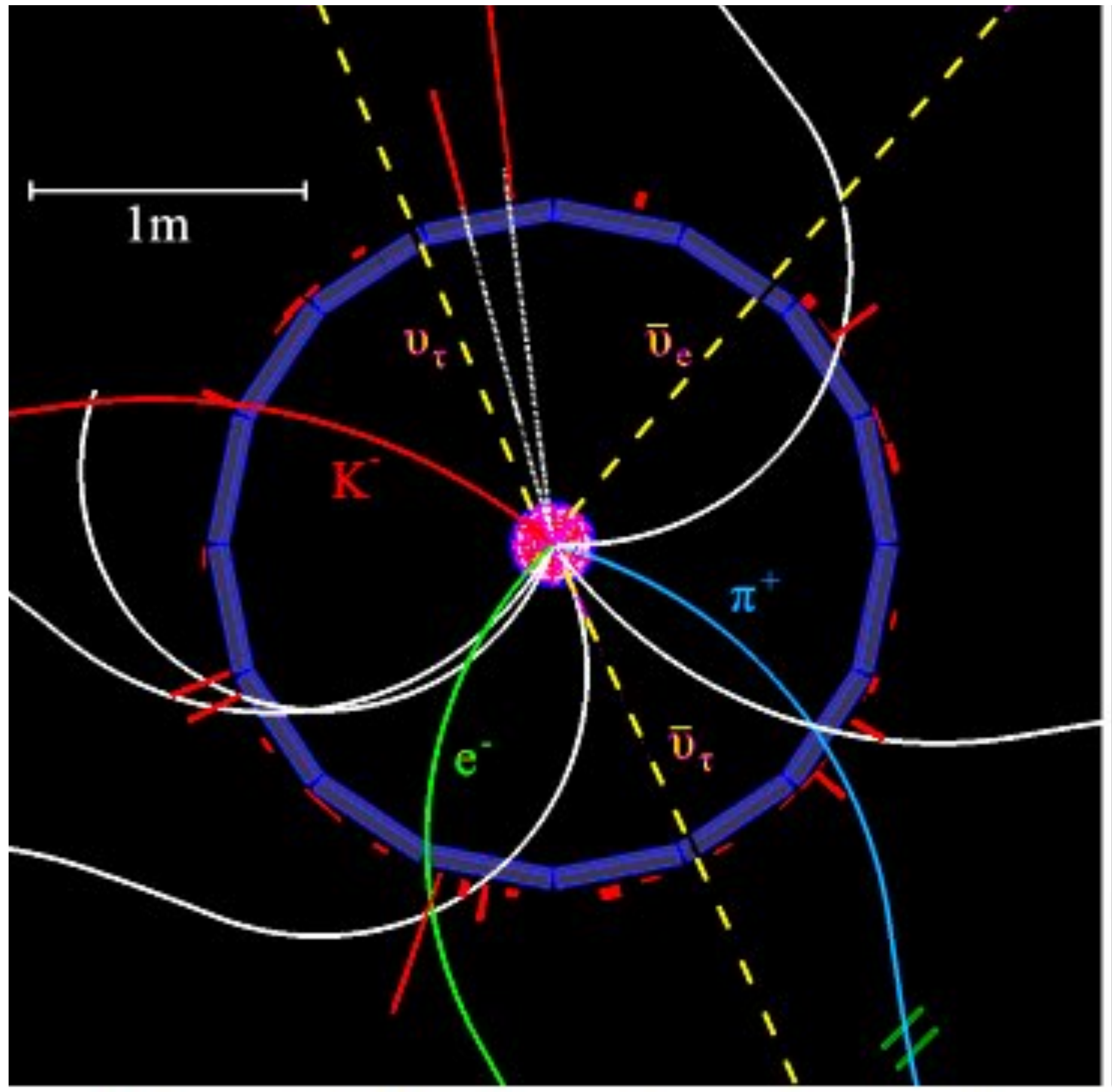
R(D) and R(D*) Tree anomalies



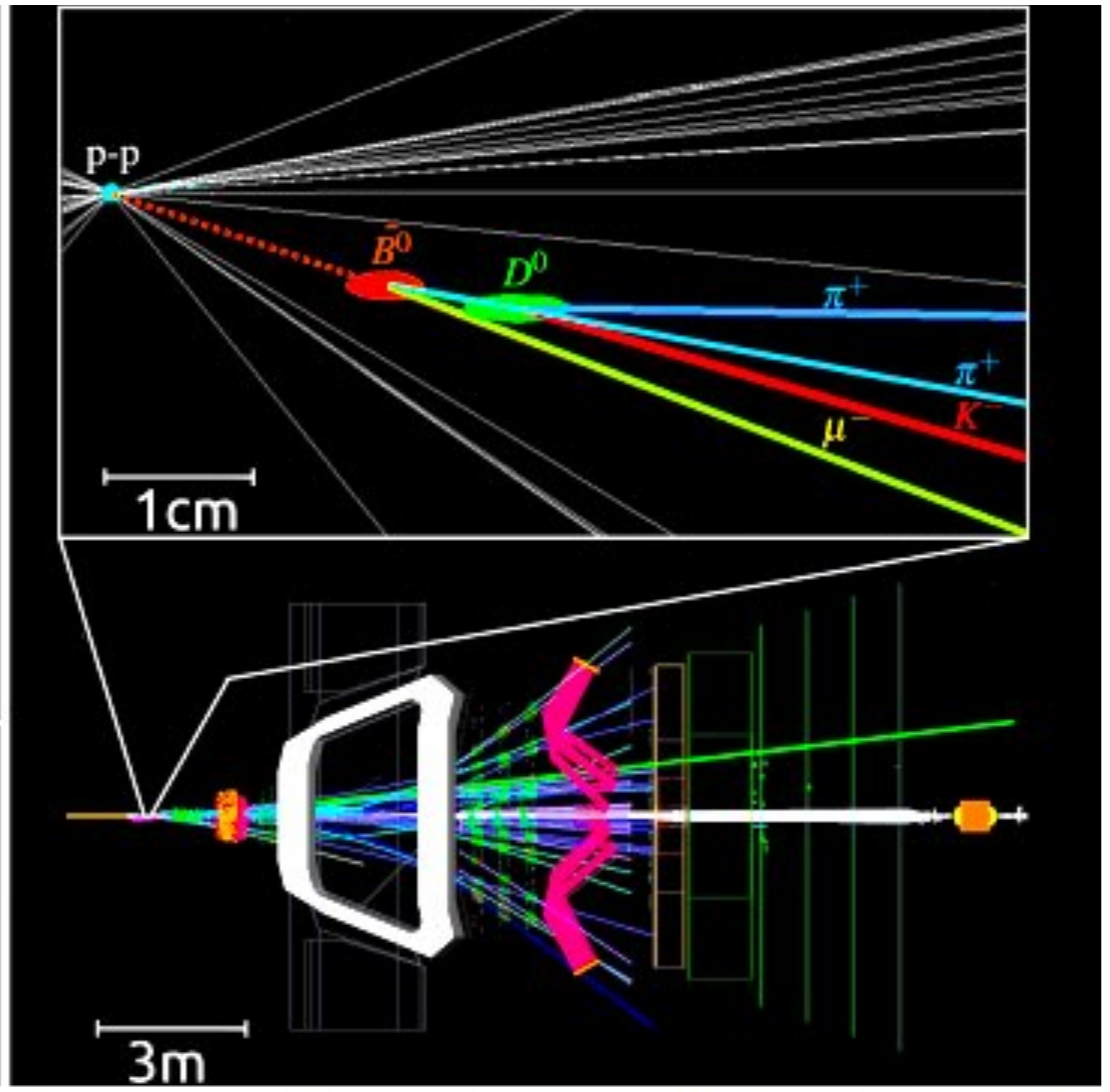
$$R = \frac{\mathcal{B}(b \to q\,\tau\,\bar{\nu}_\tau)}{\mathcal{B}(b \to q\,\ell\,\bar{\nu}_\ell)}$$

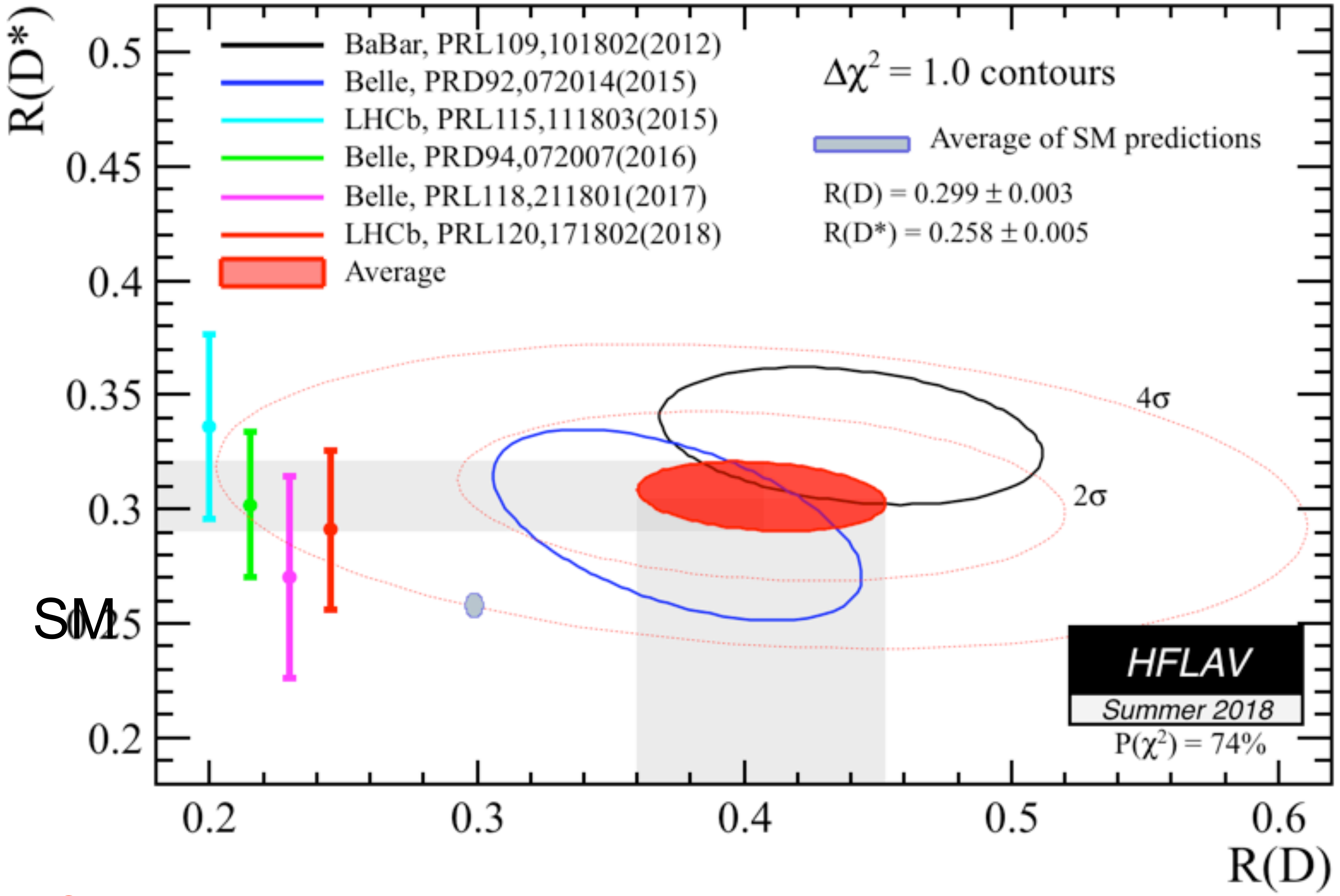
$\ell = e, \mu$

Belle



LHCb





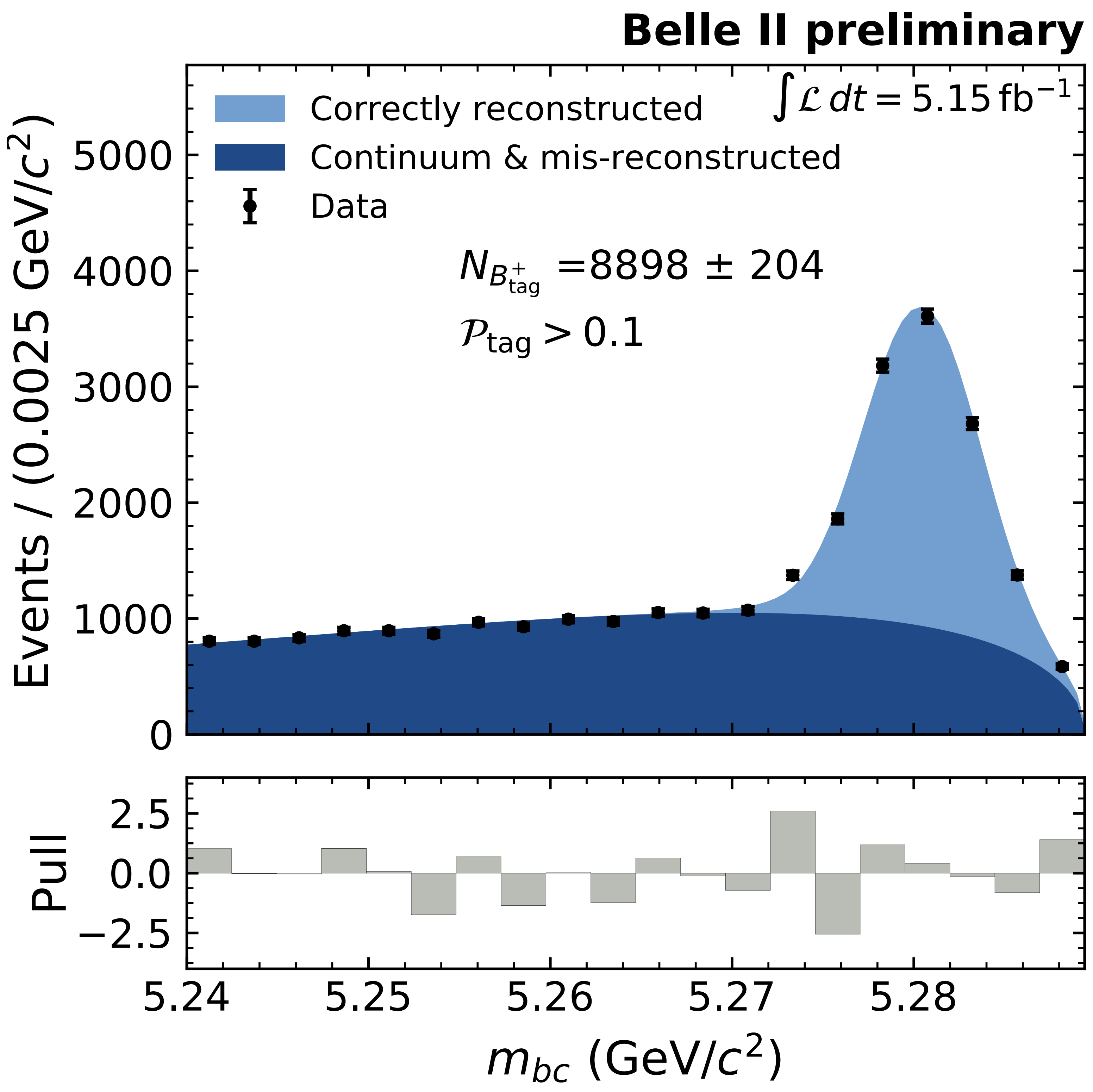
2018 World Average 4σ from the SM

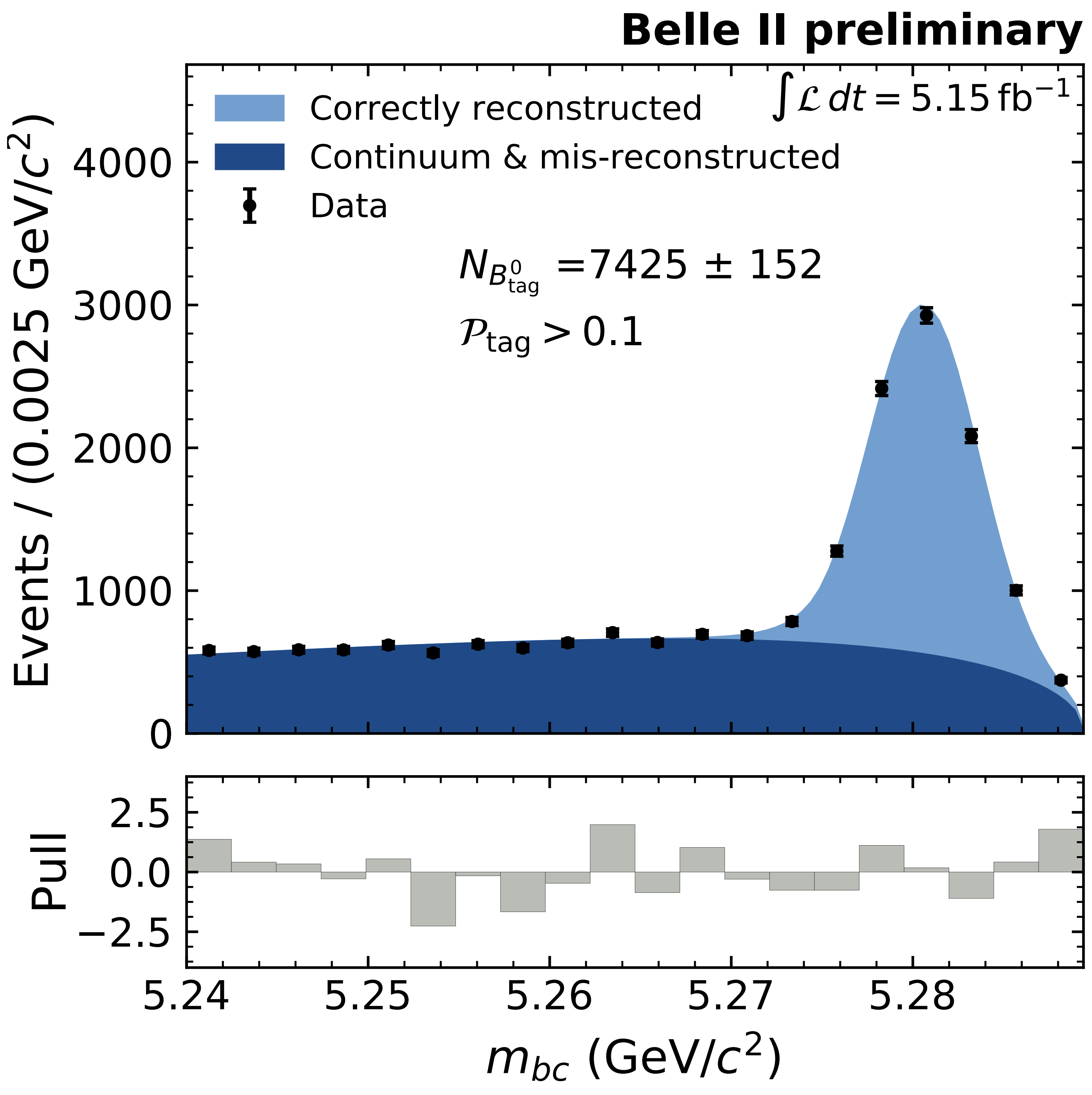
B→D* l ν, R(e/μ) by Belle agrees with SM at 3% precision.

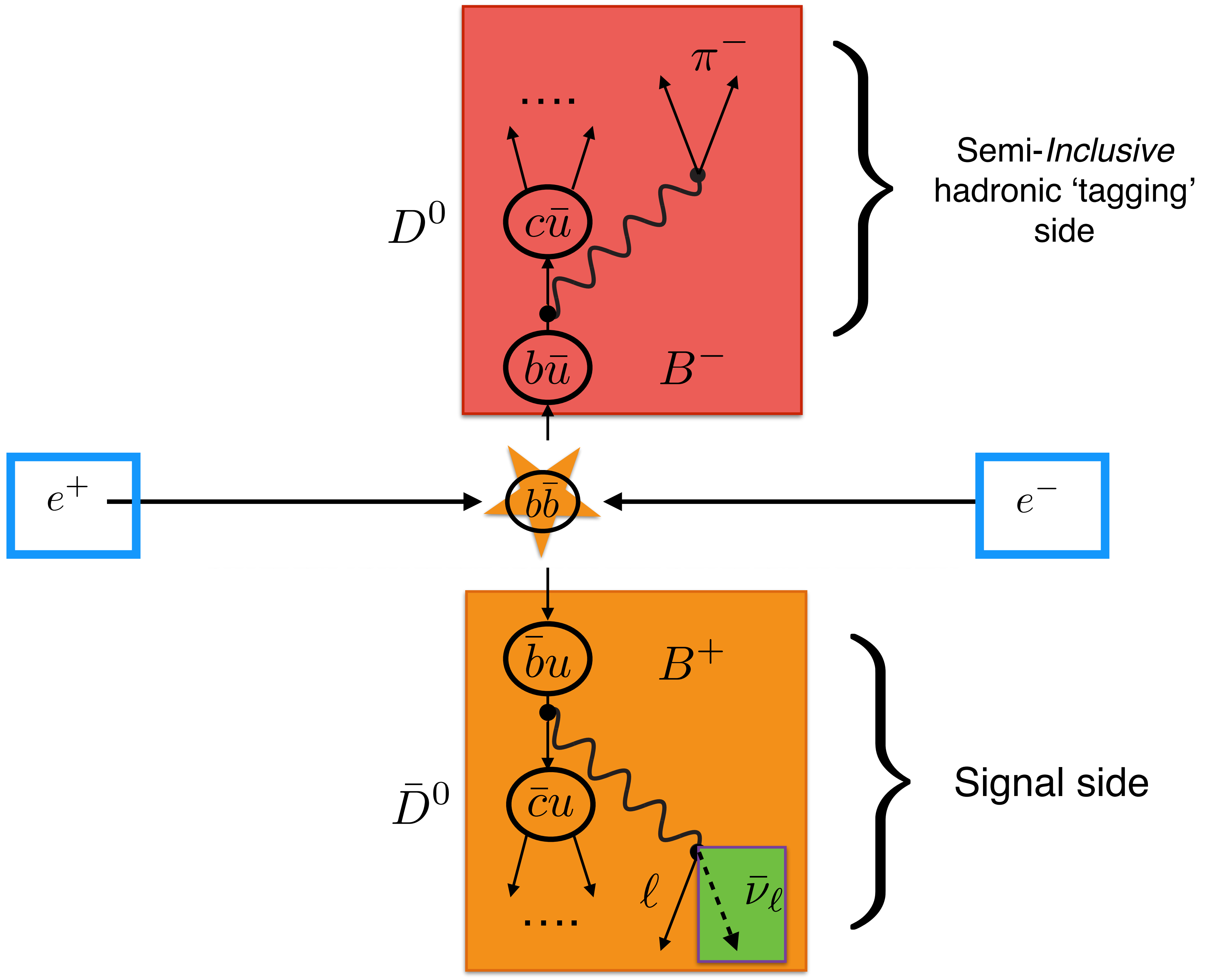
Belle, Phys. Rev. D 100, 052007 (2019)

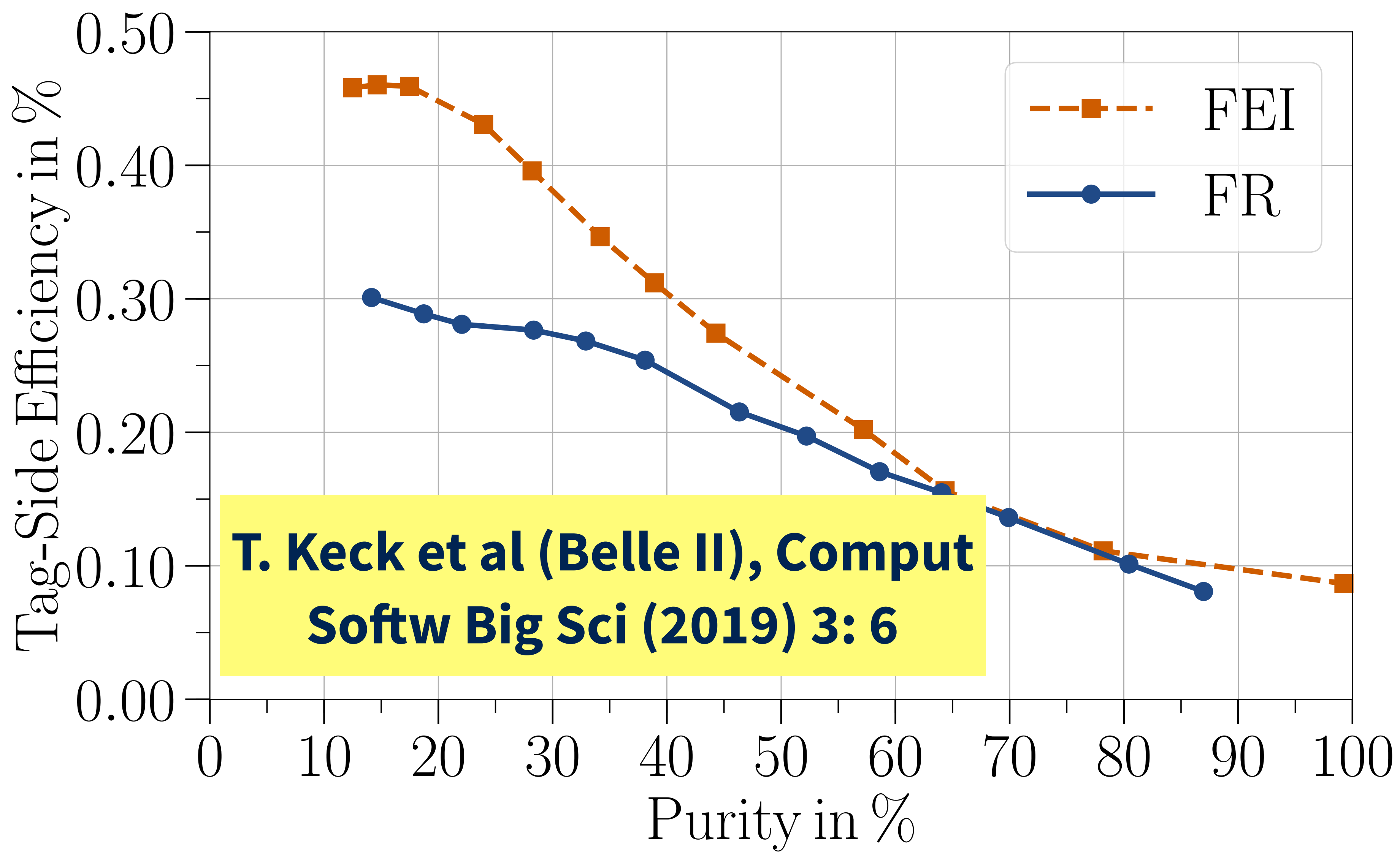
Belle II B-tag reconstruction

FEI = Full Event Interpretation using a machine learning technique, BDT (boosted decision trees) and 1000s of B decay modes.









T. Keck et al (Belle II), Comput Softw Big Sci (2019) 3: 6

New ML methods also being developed to improve lepton ID at low momentum, i.e. B→ τ → e/μ

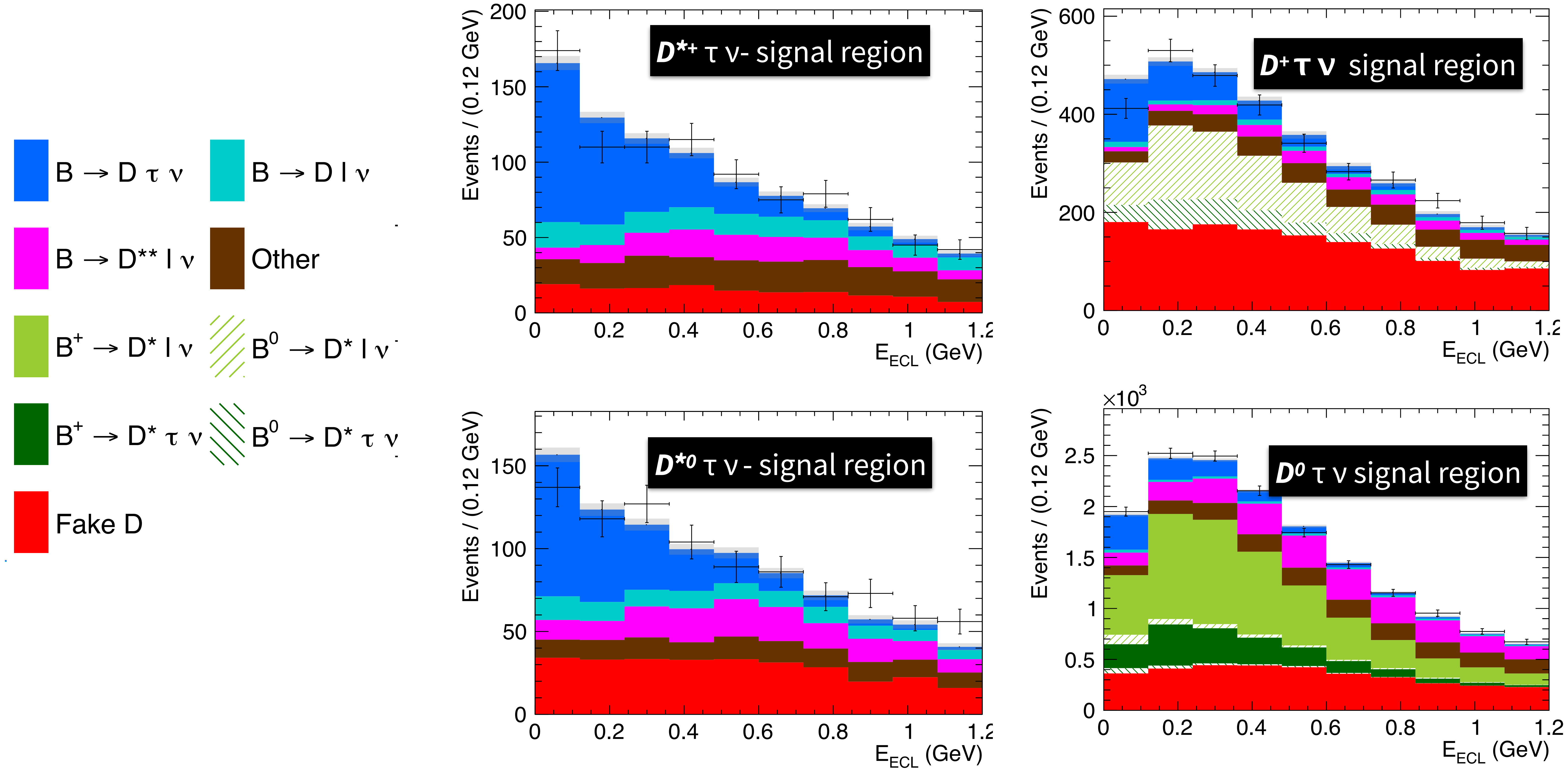
M. Milesi, CHEP 2019

Belle B → D$^{(*)}$ τ⁻ ν analysis / Converted Belle→Belle II Data

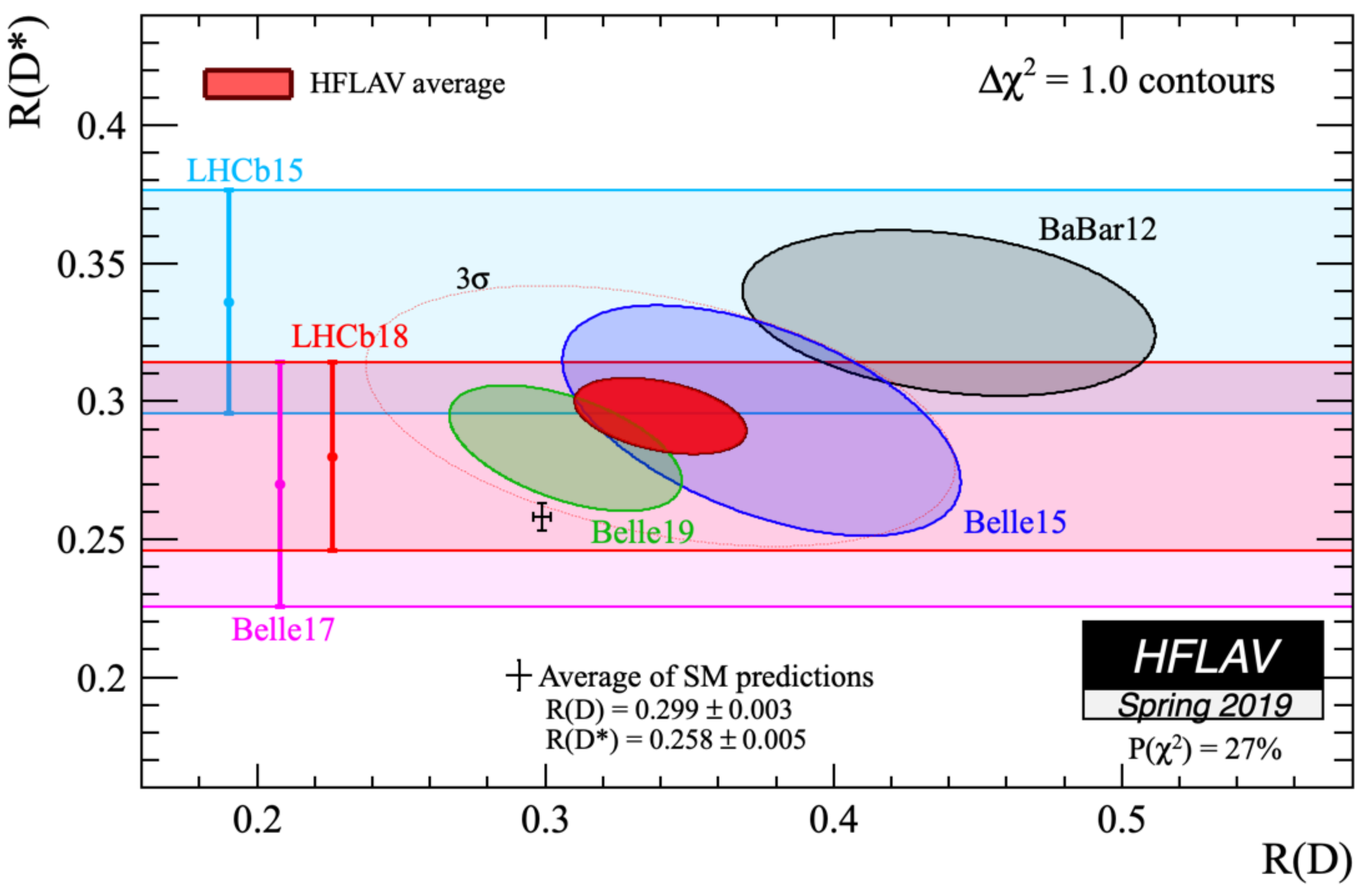
- Semileptonic tag / FEI BDT, B→D τ ν and B→D* τ ν *Simultaneously*
- 2D fit to 3-var. XG-boost BDT classifier and extra energy in EM calo.

Belle, arXiv:1910.05864
Submitted to PRL

$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014,$$



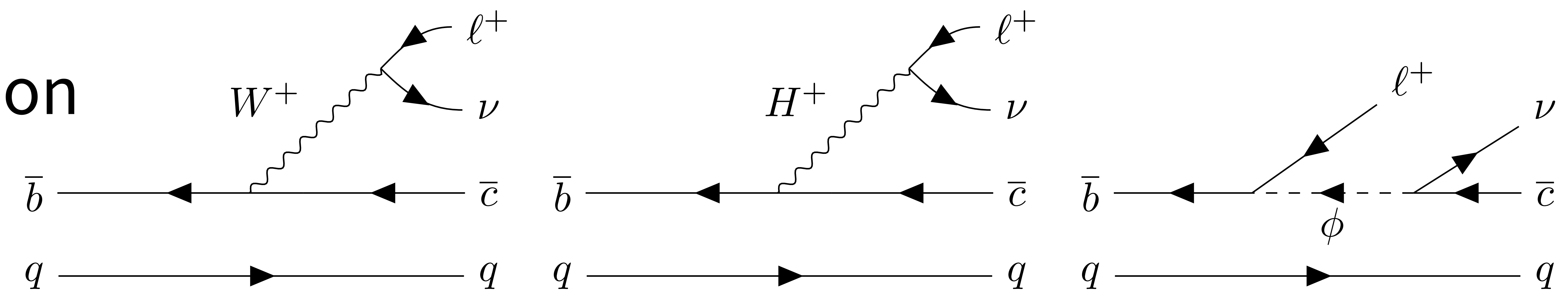
WA with new Belle result.

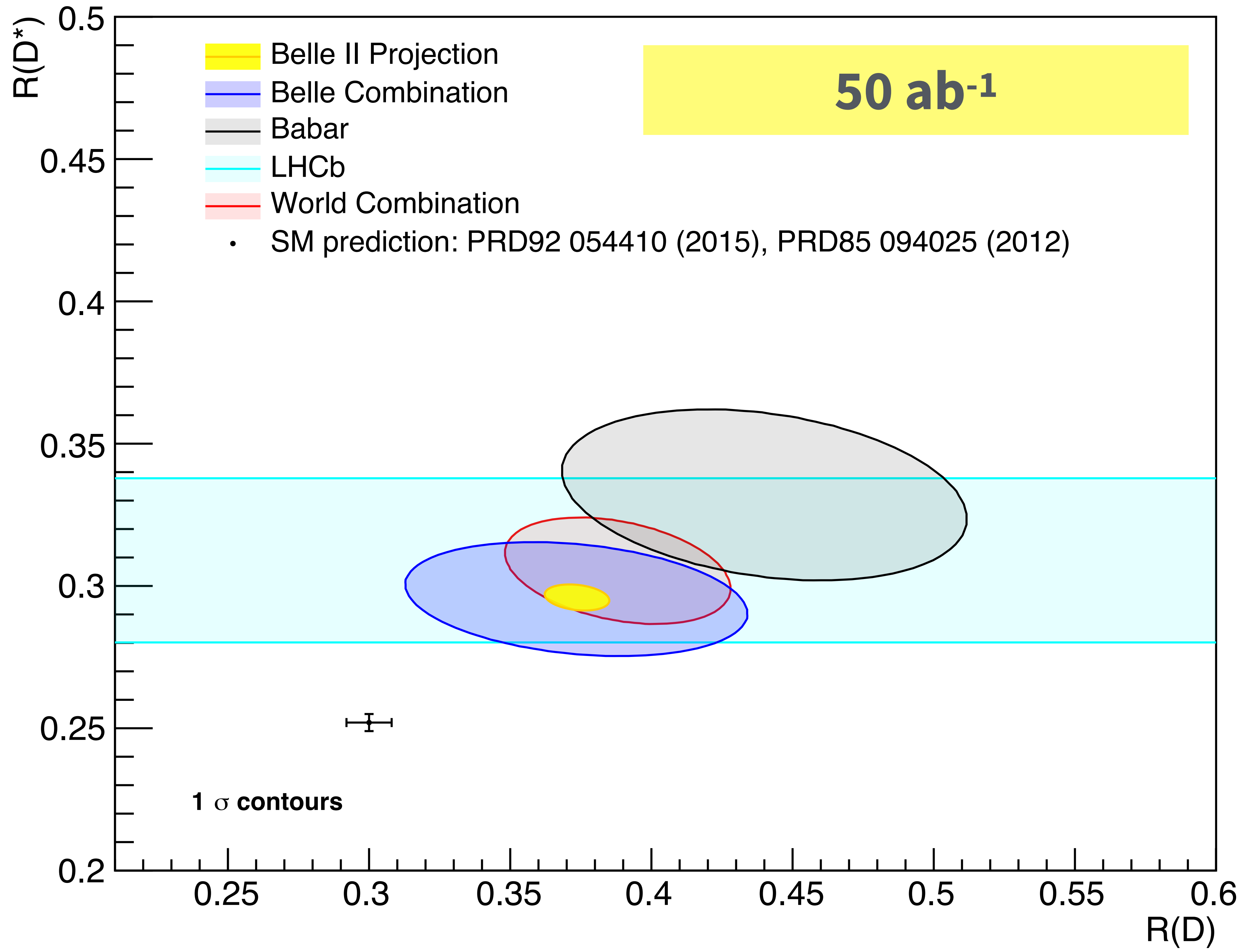


$B \rightarrow D^{(*)} \tau \nu$ @ Belle II

Belle II Physics Book, arXiv: 1808.10567

- $R(D/D^*)$ stat limited: Belle II should confirm/ deny anomaly with 5 ab^{-1}.(3-4x error reduction in 5 years)
- **Determine the type of mediator by analysis of kinematic spectra > 5 ab^{-1}**





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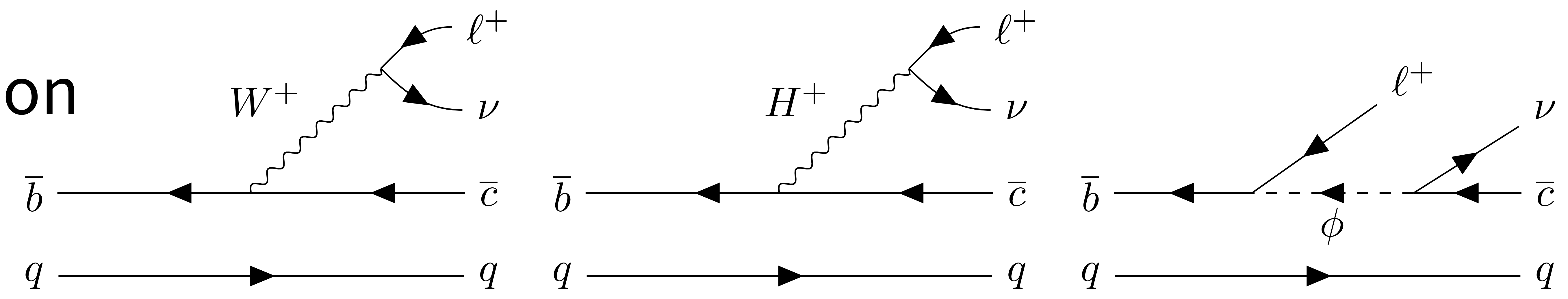
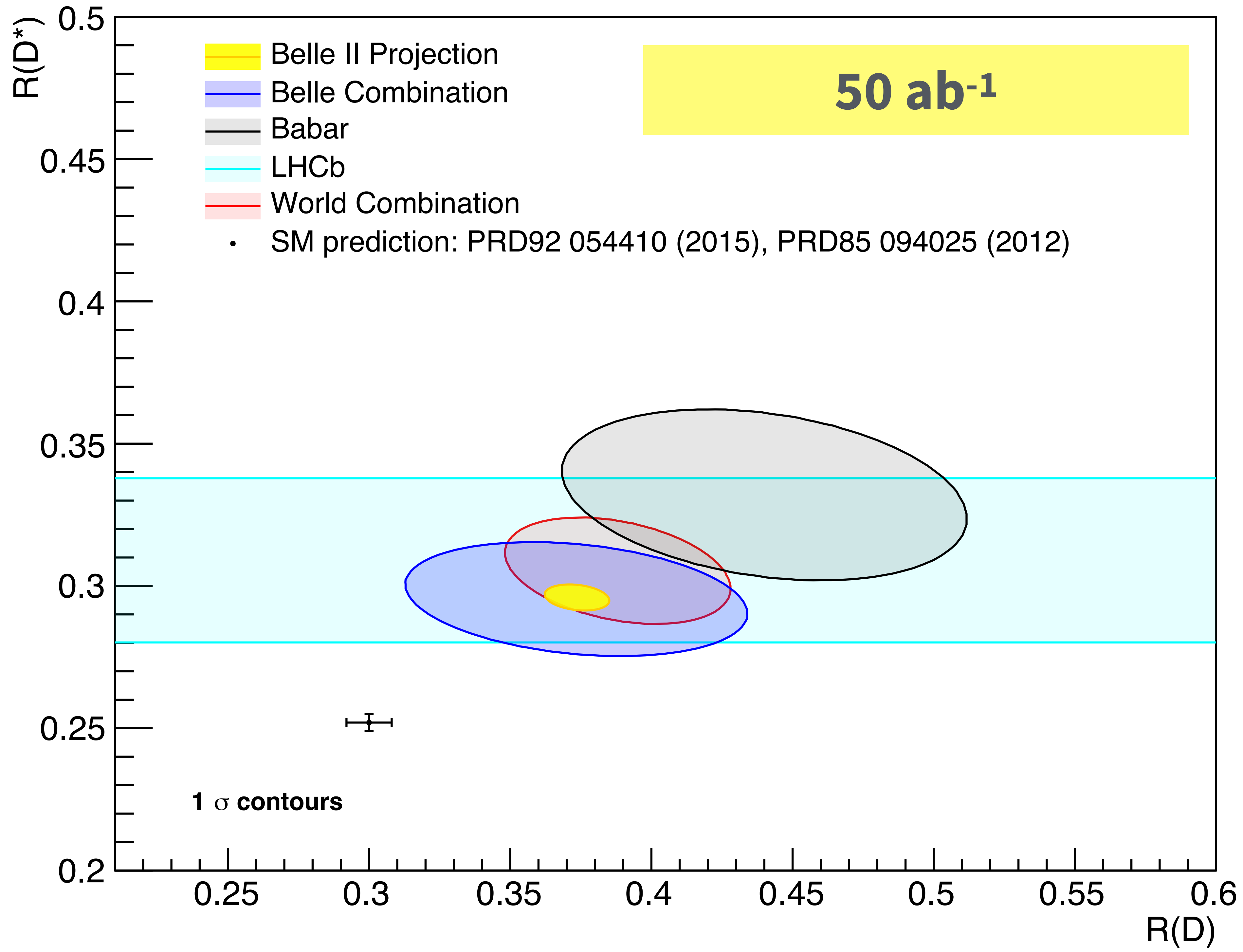
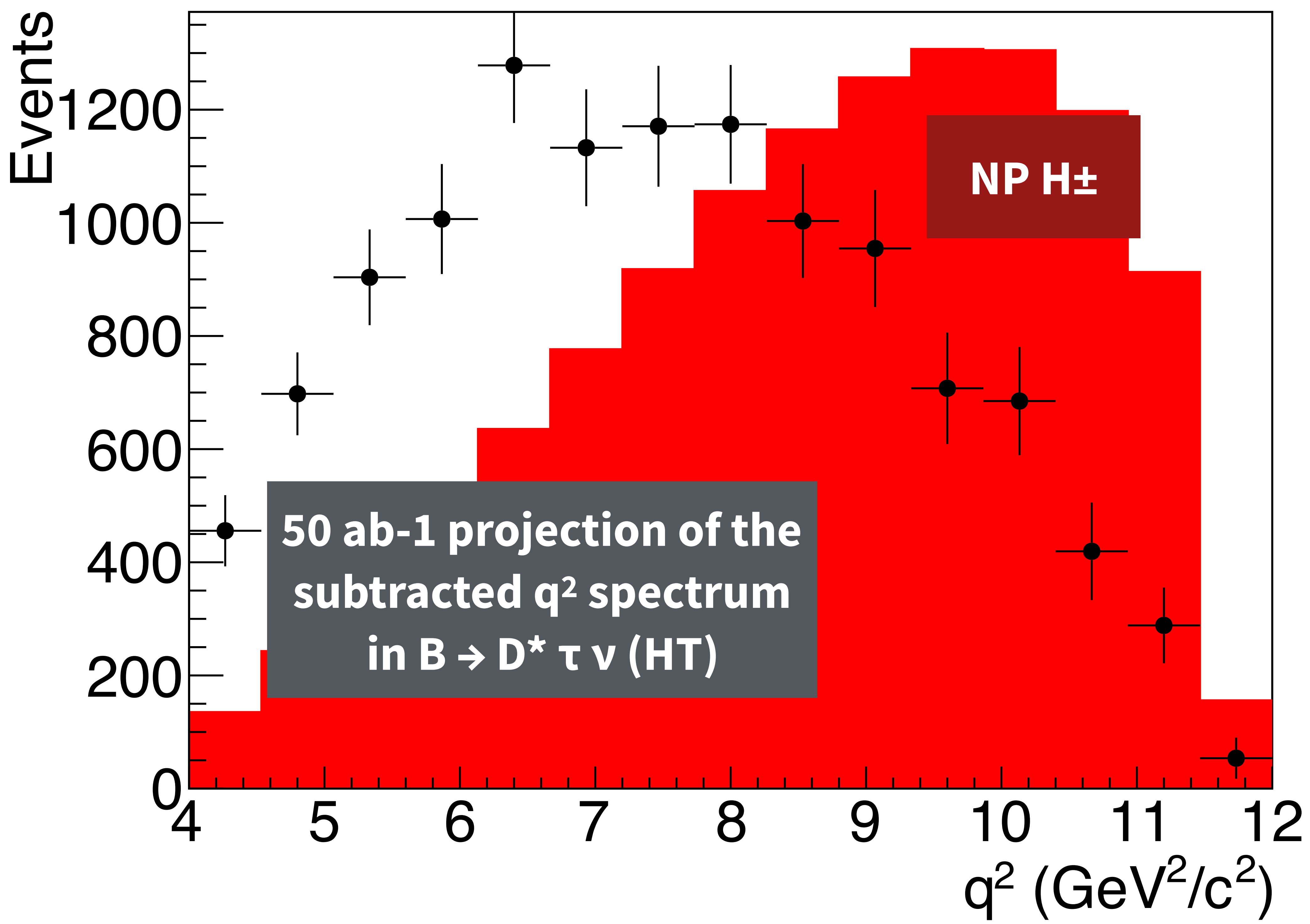




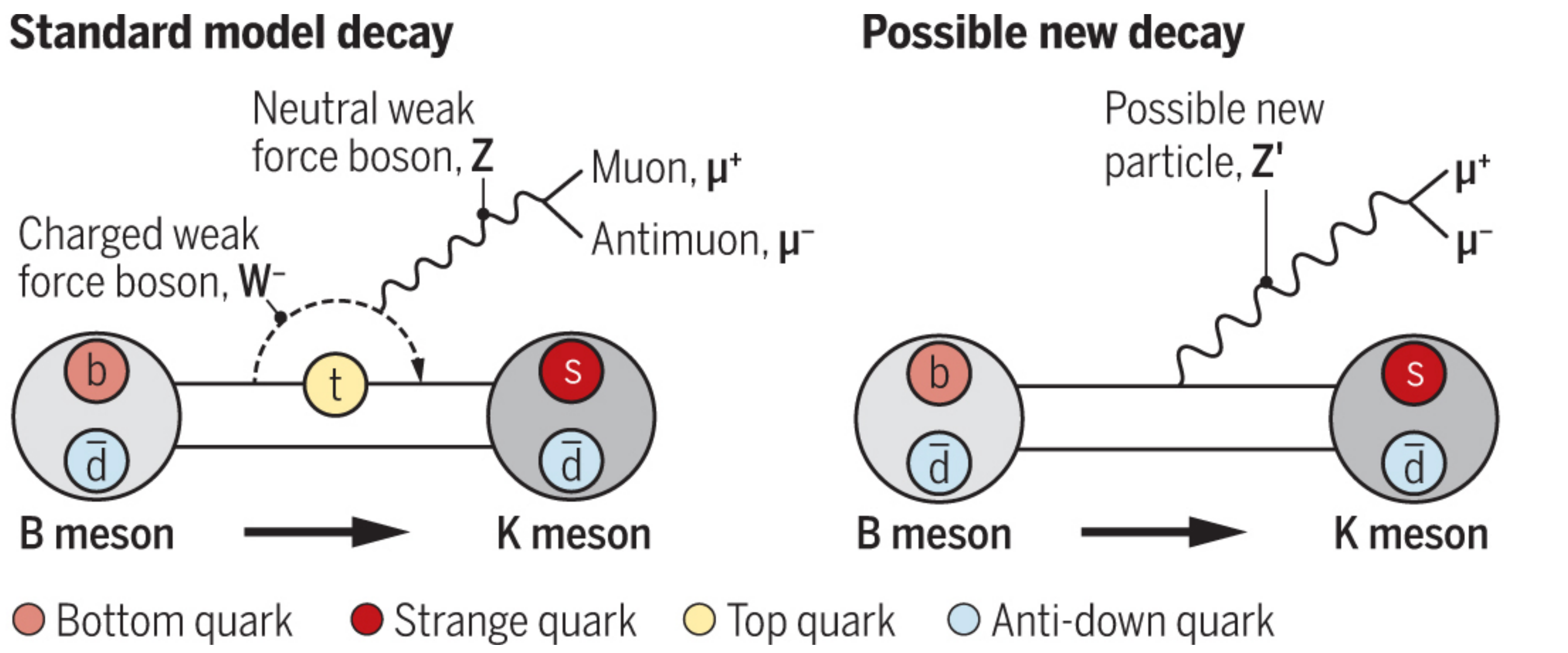


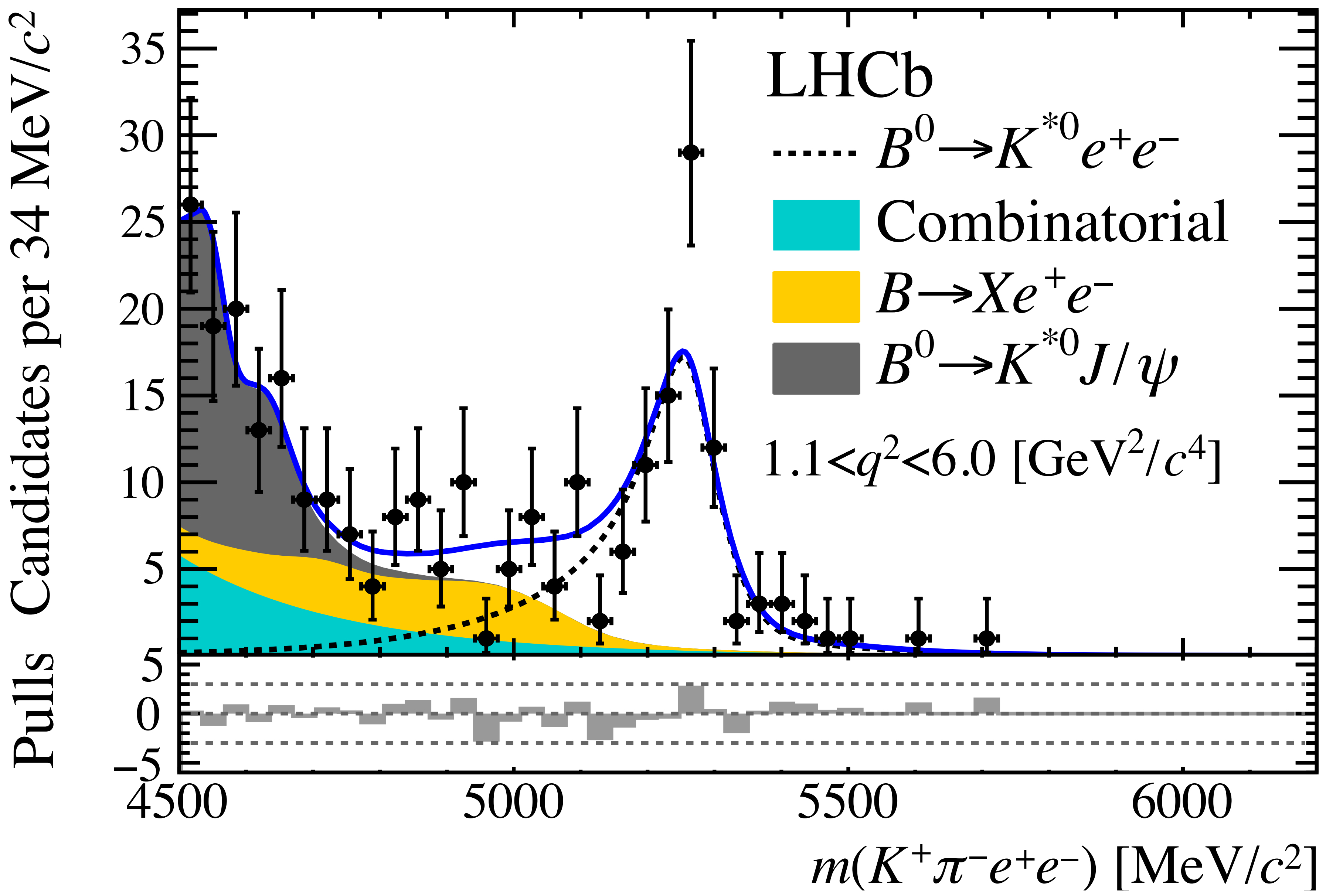
R(K*) LFUV Loop anomalies

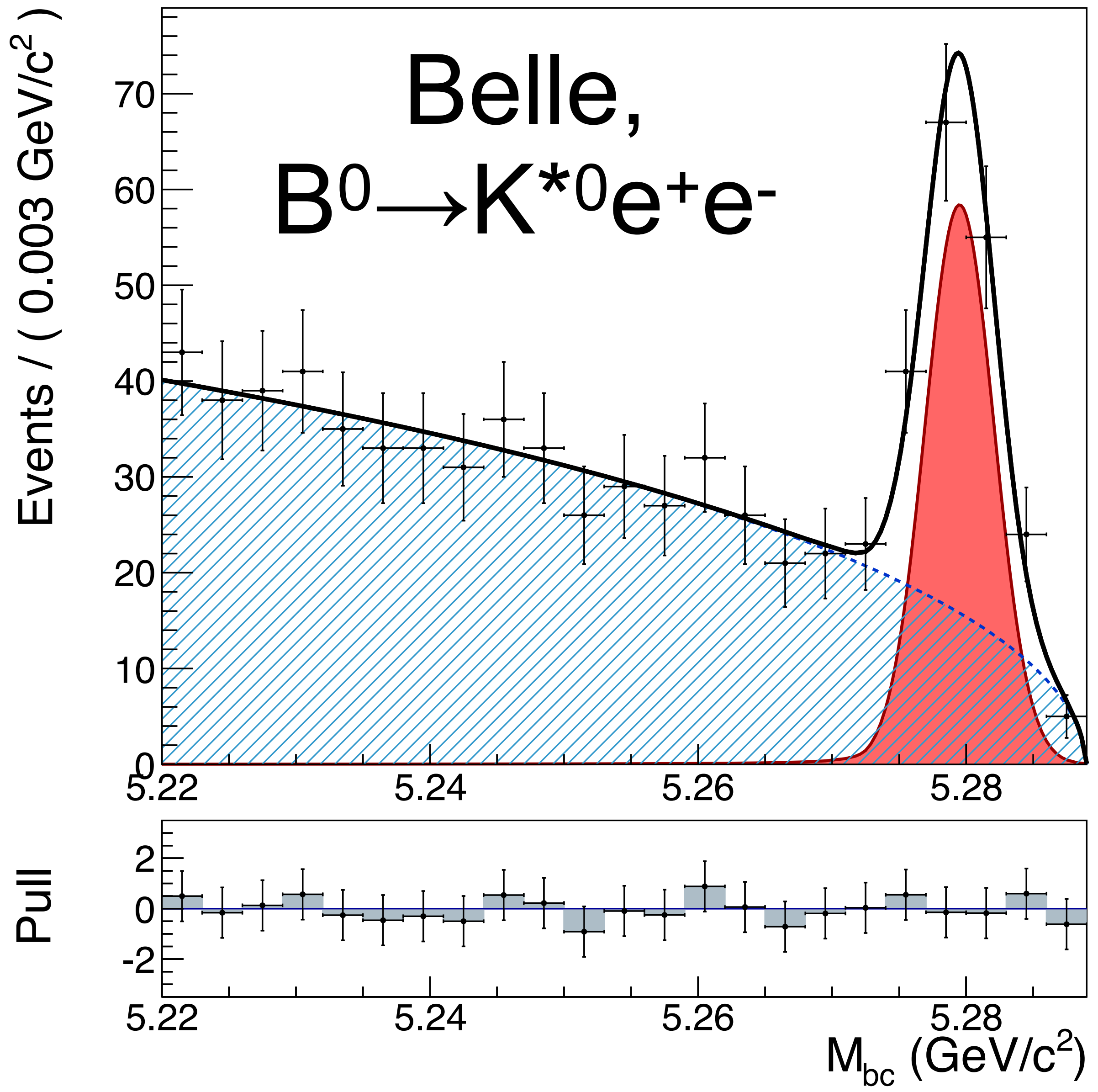
Belle, arXiv:1904.02440
LHCb, JHEP 08(2017) 055

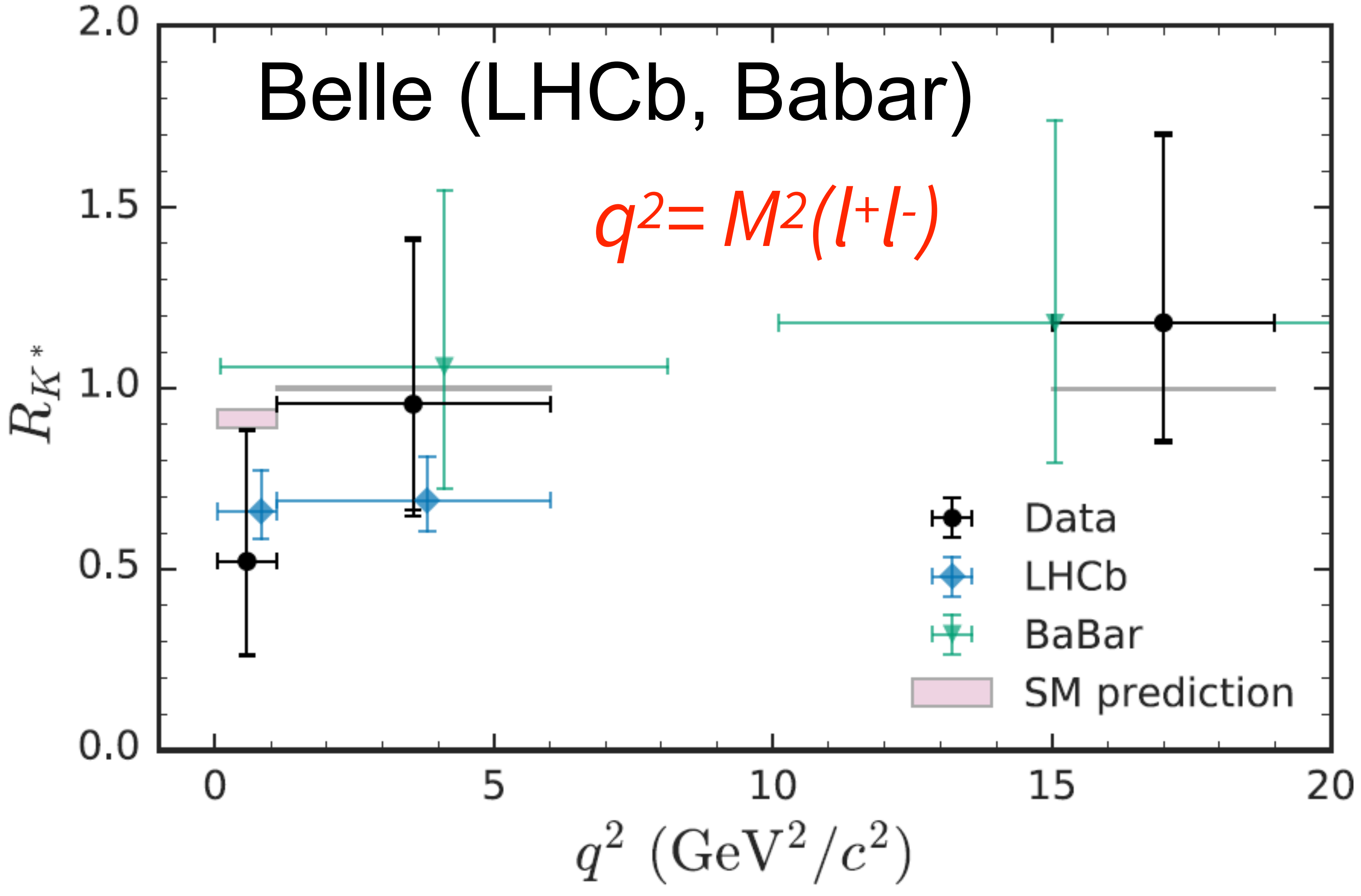
$$R_{K^{(*)}}(q^2) = \frac{BF(B \to K^{(*)}\mu^+\mu^-)}{BF(B \to K^{(*)}e^+e^-)}$$

Deviations from SM observed, primarily claimed by LHCb.
R_{K^*} ~2.1σ (low bin), 2.5σ (central bin)







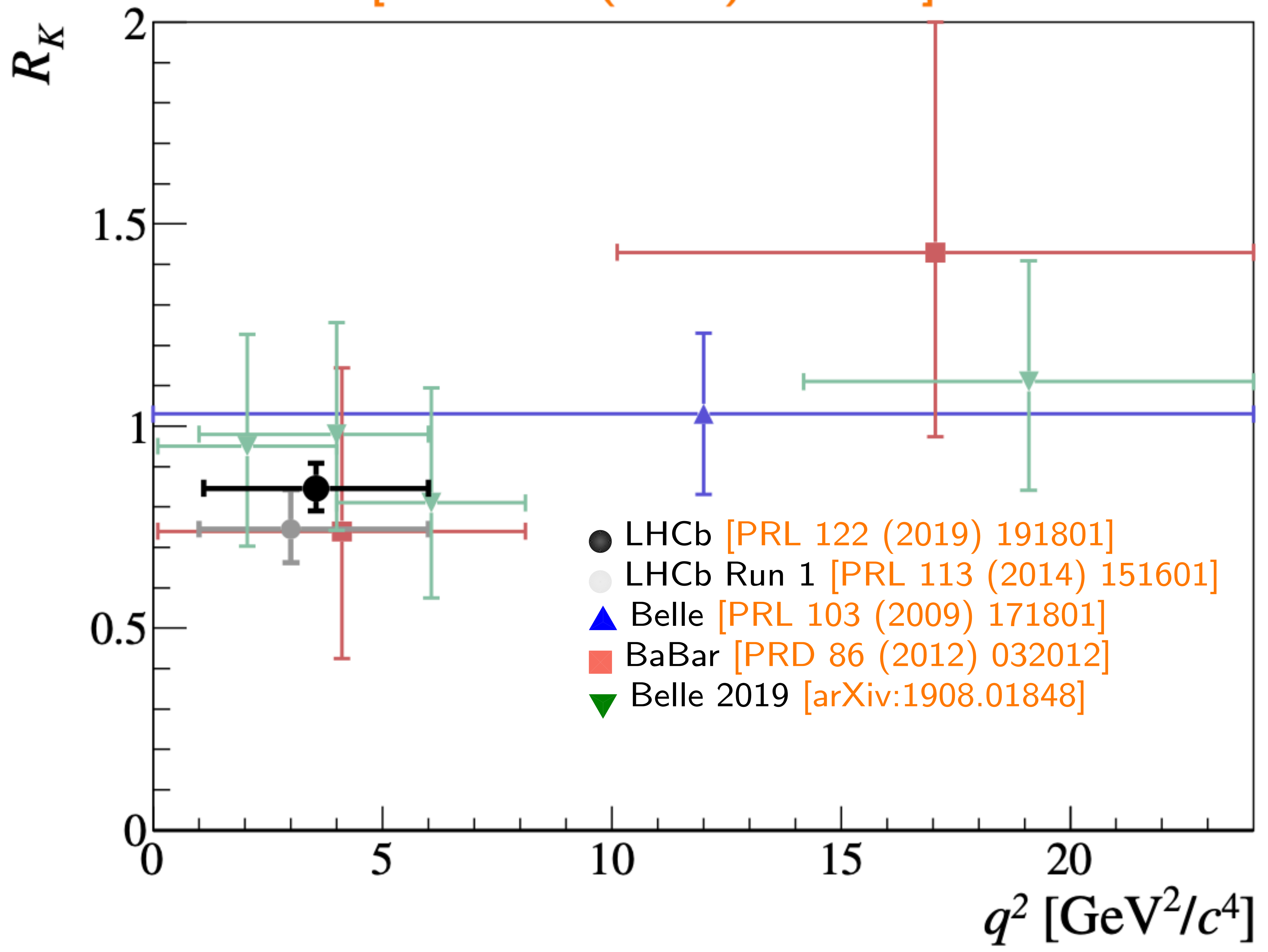


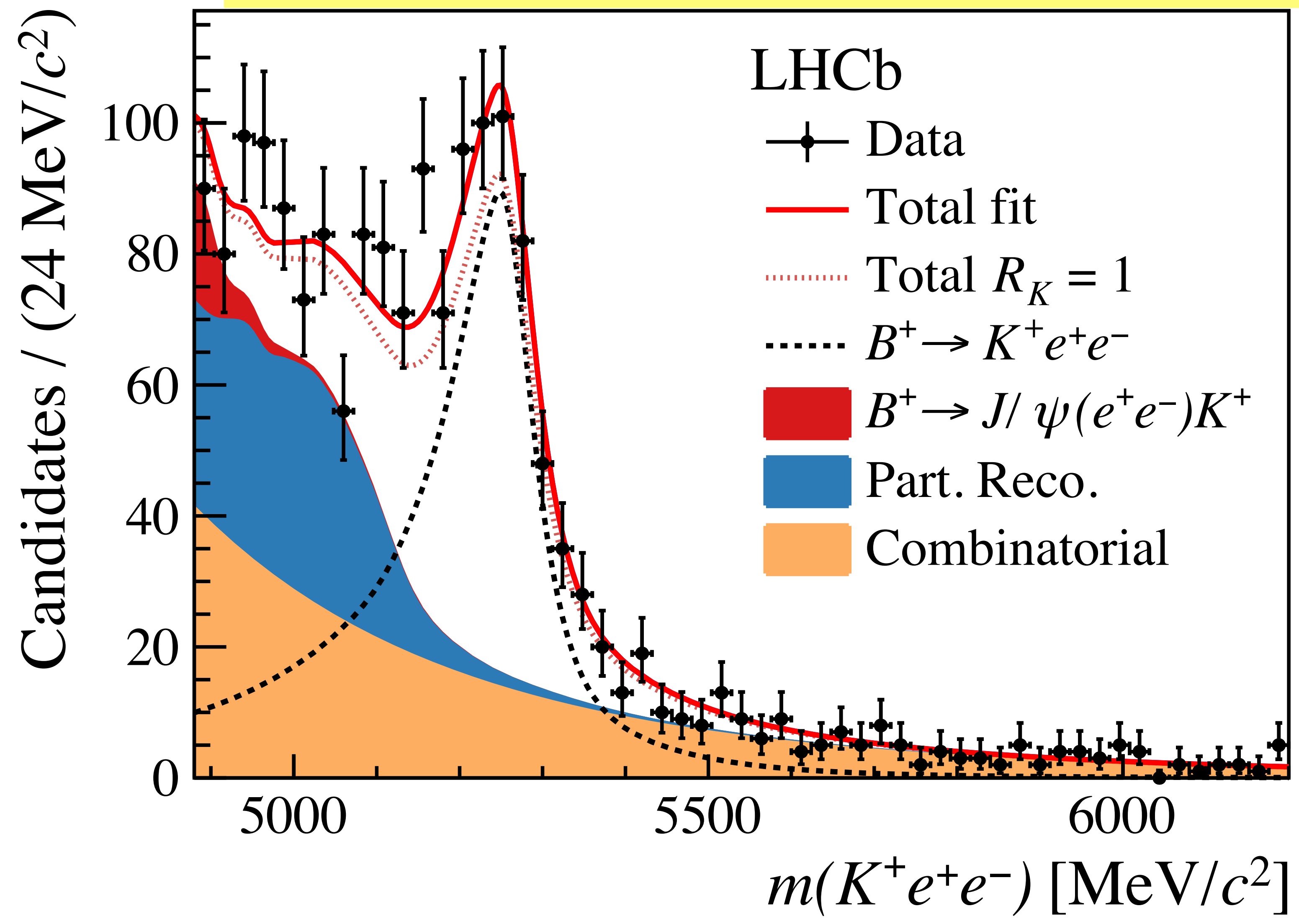
R(K) Loop anomalies

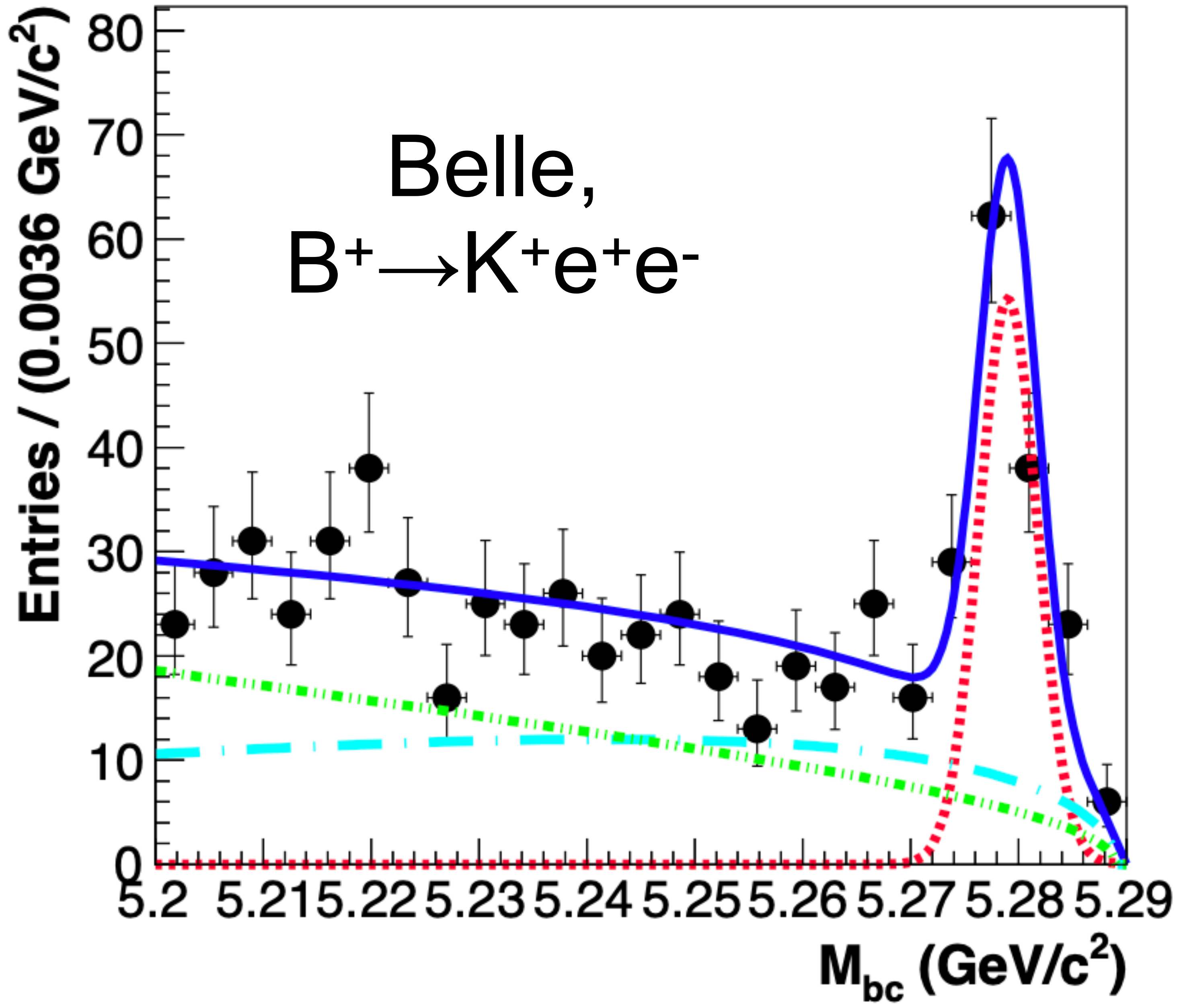
Belle, arXiv:1908.01848
LHCb, PRL 122(2019) 191801

R_K is ~2.5σ from the SM, primarily claimed by LHCb.
New Belle result compatible with SM but Belle II dataset needed.

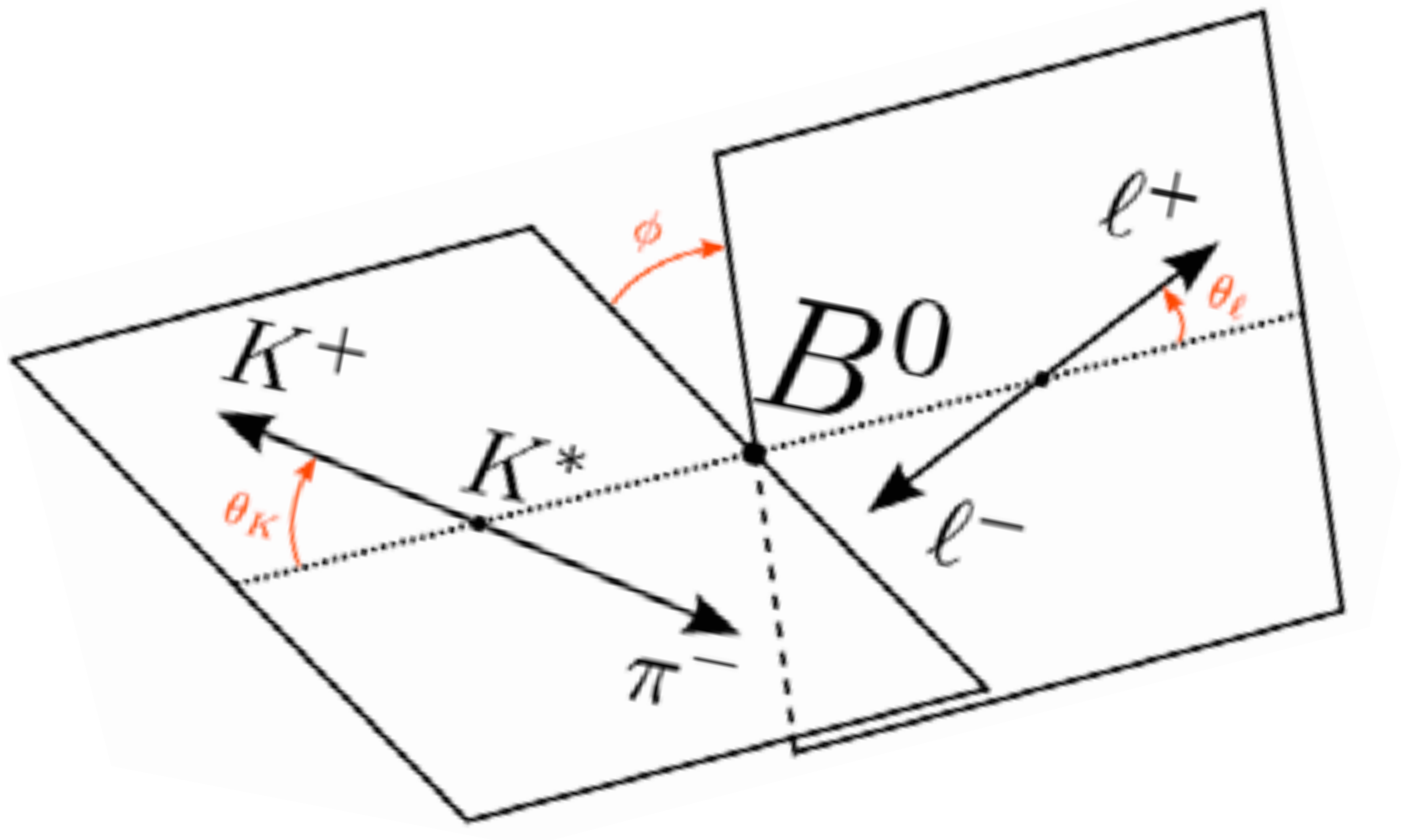
[PRL 122 (2019) 191801]



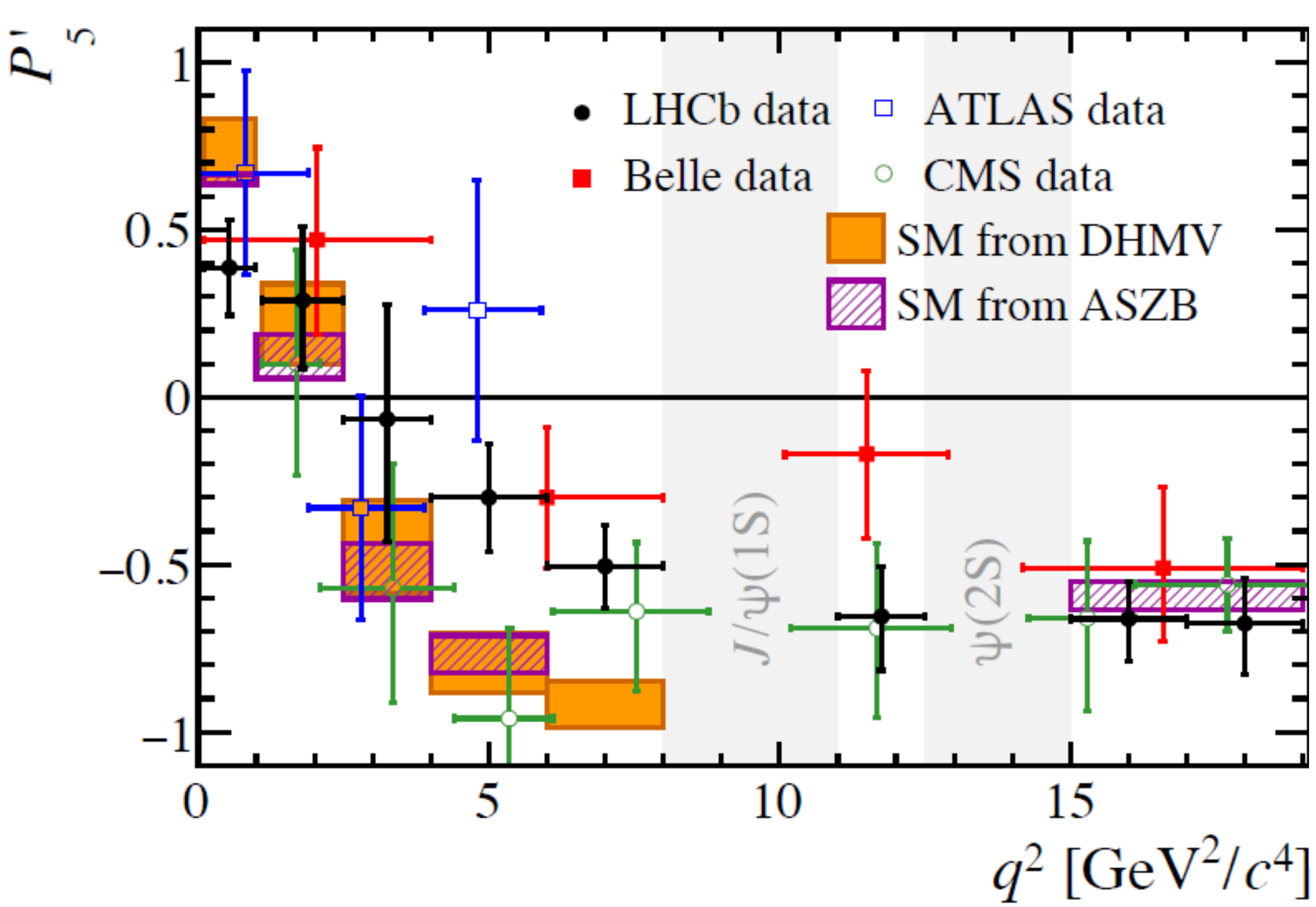


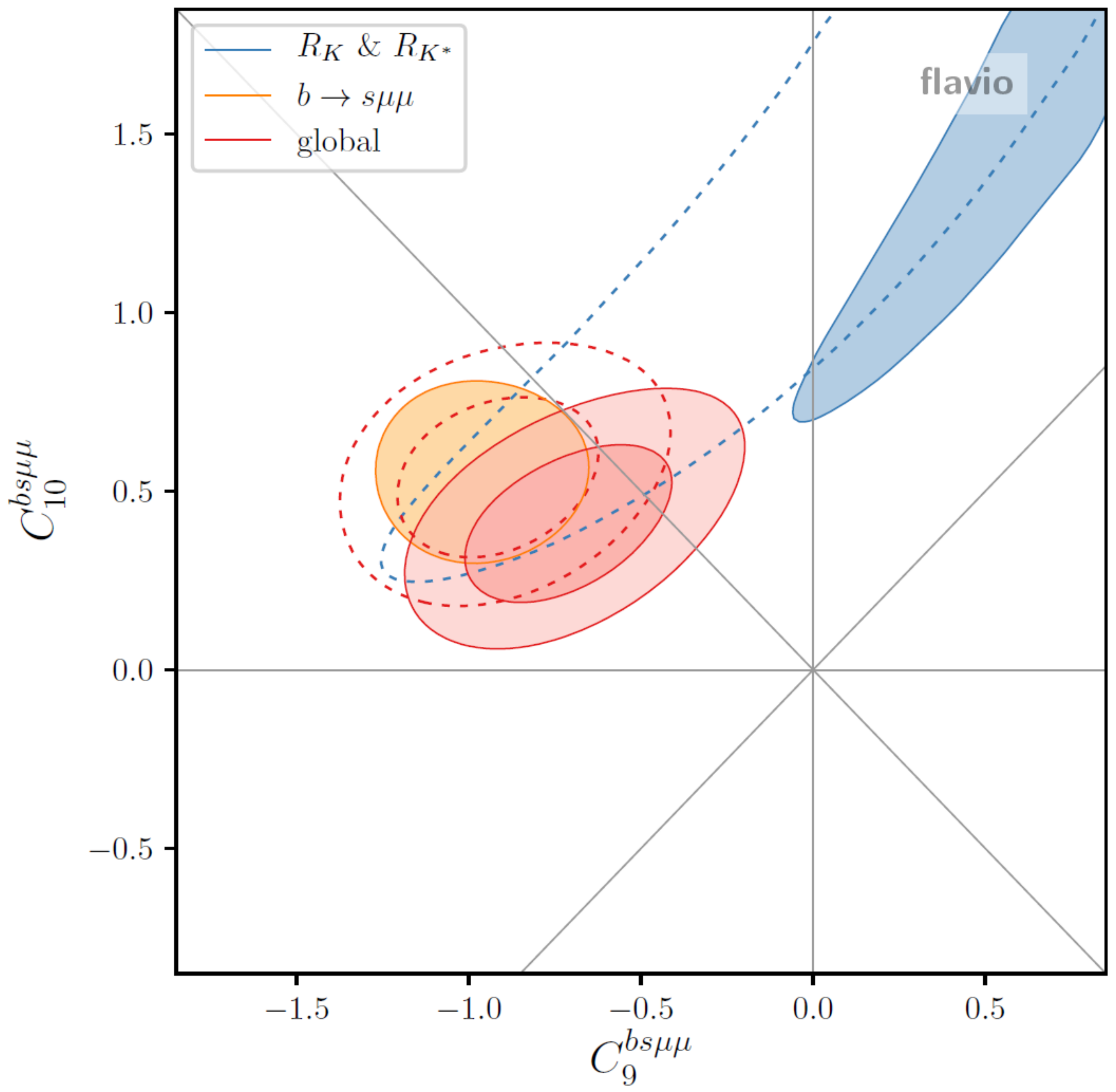


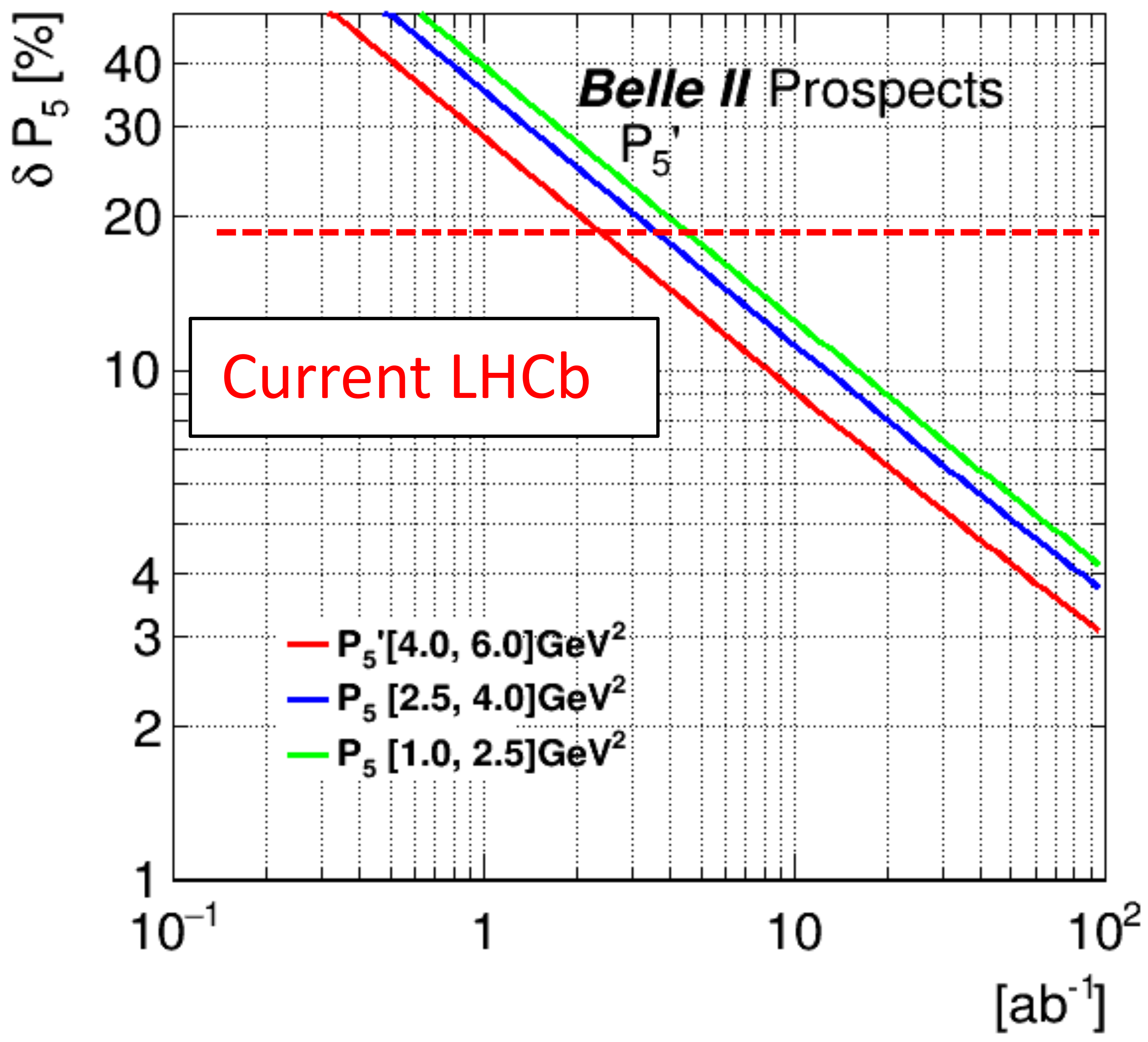
P5' Anomalies



- Deviations from SM also claimed in folded angular observables.
- Anomaly claimed by LHCb analysis.
  - Theoretically affected by charm loop effect.
  - About ~4σ deviation q^2=[4,8]GeV^2
- **In 2022, Belle II can reach current LHCb sensitivity and add neutral & inclusive modes.**







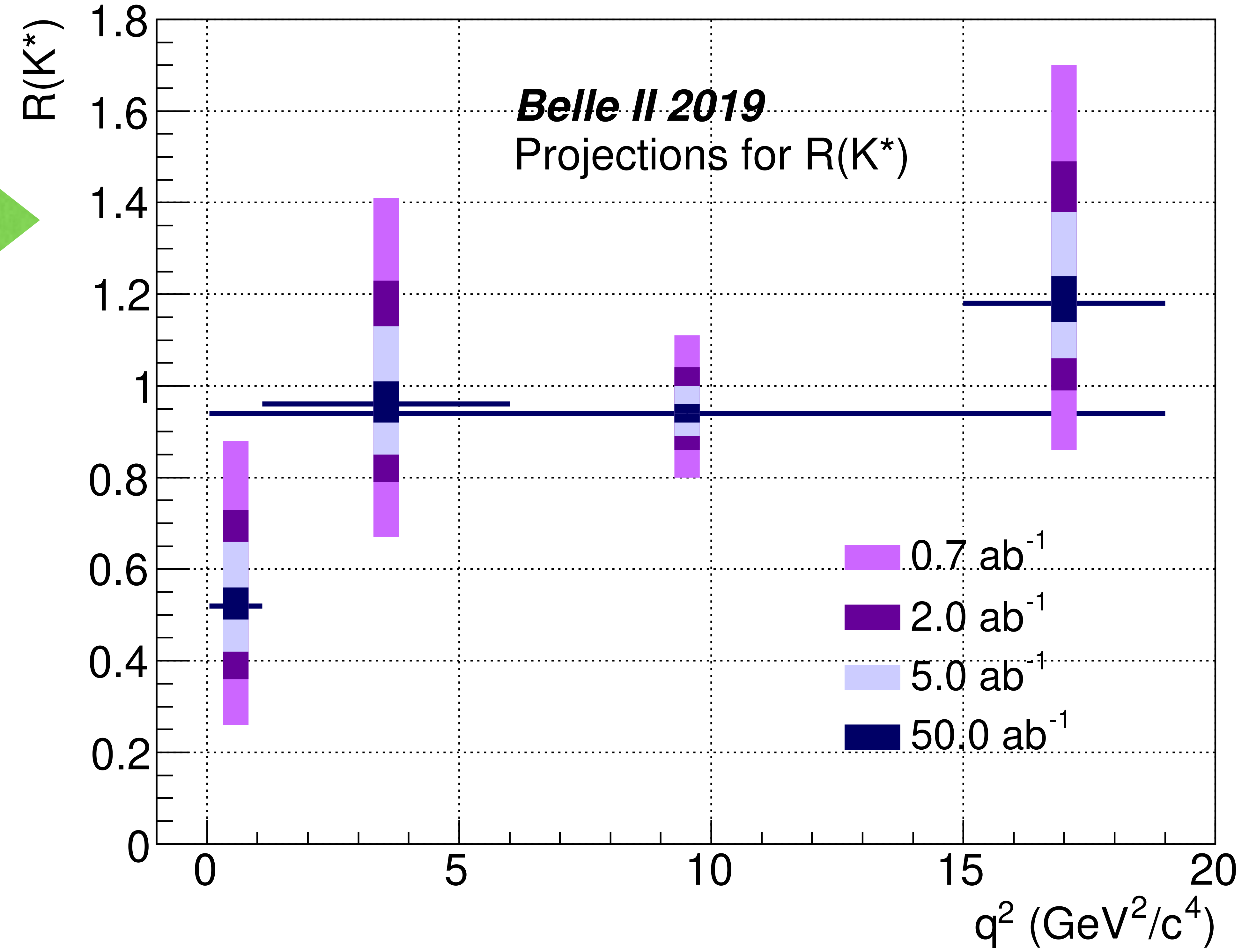
EW penguin B decays / Belle II Prospects

Belle Preliminary 2019, arXiv:1904.02440

q^2 in GeV^2/c^4	All modes	B^0 modes	B^+ modes
$[0.045, 1.1]$	$0.52^{+0.36}_{-0.26} \pm 0.05$	$0.46^{+0.55}_{-0.27} \pm 0.07$	$0.62^{+0.60}_{-0.36} \pm 0.10$
$[1.1, 6]$	$0.96^{+0.45}_{-0.29} \pm 0.11$	$1.06^{+0.63}_{-0.38} \pm 0.13$	$0.72^{+0.99}_{-0.44} \pm 0.18$
$[0.1, 8]$	$0.90^{+0.27}_{-0.21} \pm 0.10$	$0.86^{+0.33}_{-0.24} \pm 0.08$	$0.96^{+0.56}_{-0.35} \pm 0.14$
$[15, 19]$	$1.18^{+0.52}_{-0.32} \pm 0.10$	$1.12^{+0.61}_{-0.36} \pm 0.10$	$1.40^{+1.99}_{-0.68} \pm 0.11$
$[0.045,]$	$0.94^{+0.17}_{-0.14} \pm 0.08$	$1.12^{+0.27}_{-0.21} \pm 0.09$	$0.70^{+0.24}_{-0.19} \pm 0.07$

Belle II should refute/confirm deviations observed by LHCb within 5 years.

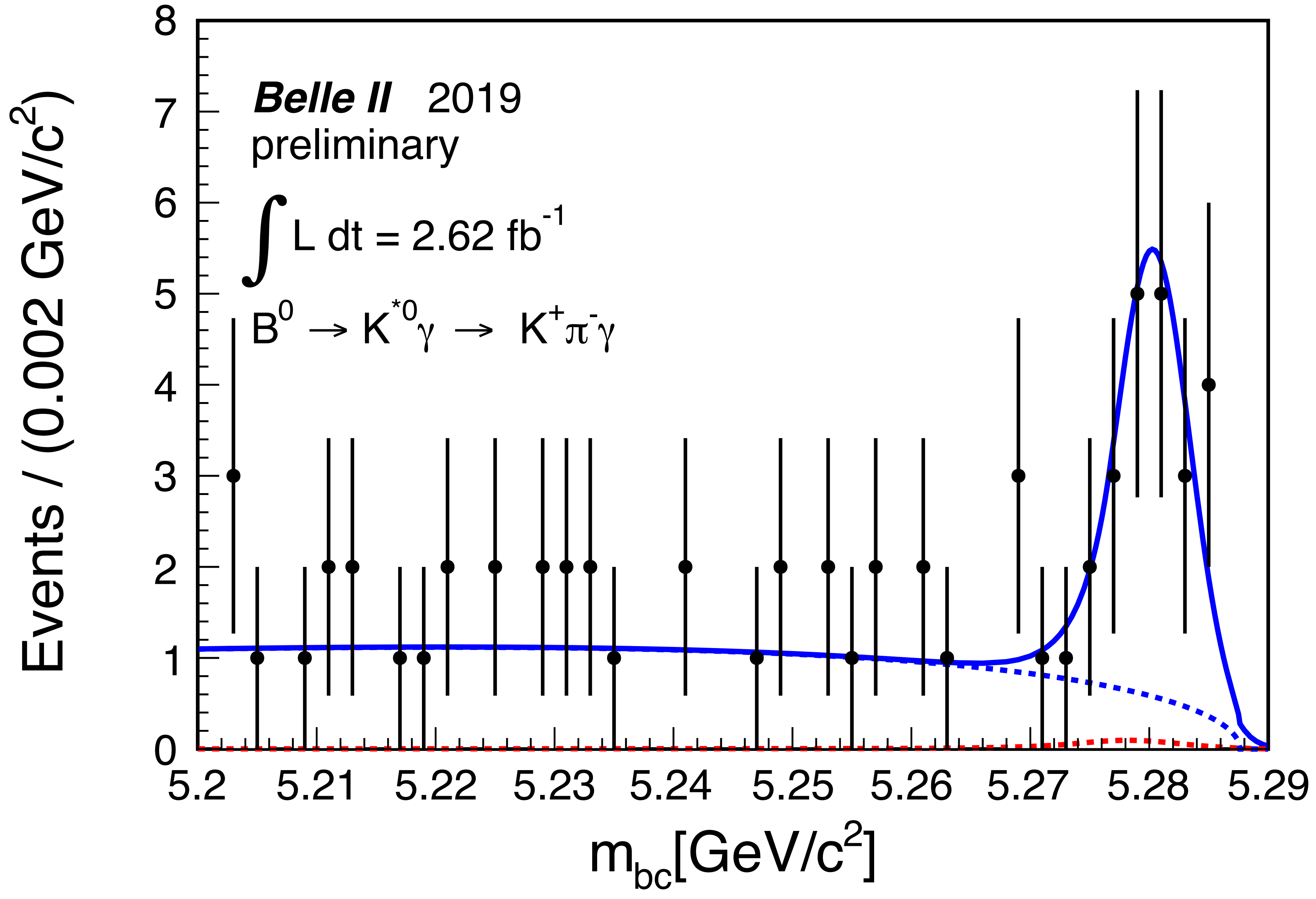
Large program of radiative decays CP violation -
New sources of CP violation in B→K*γ, ργ could reveal right handed currents.

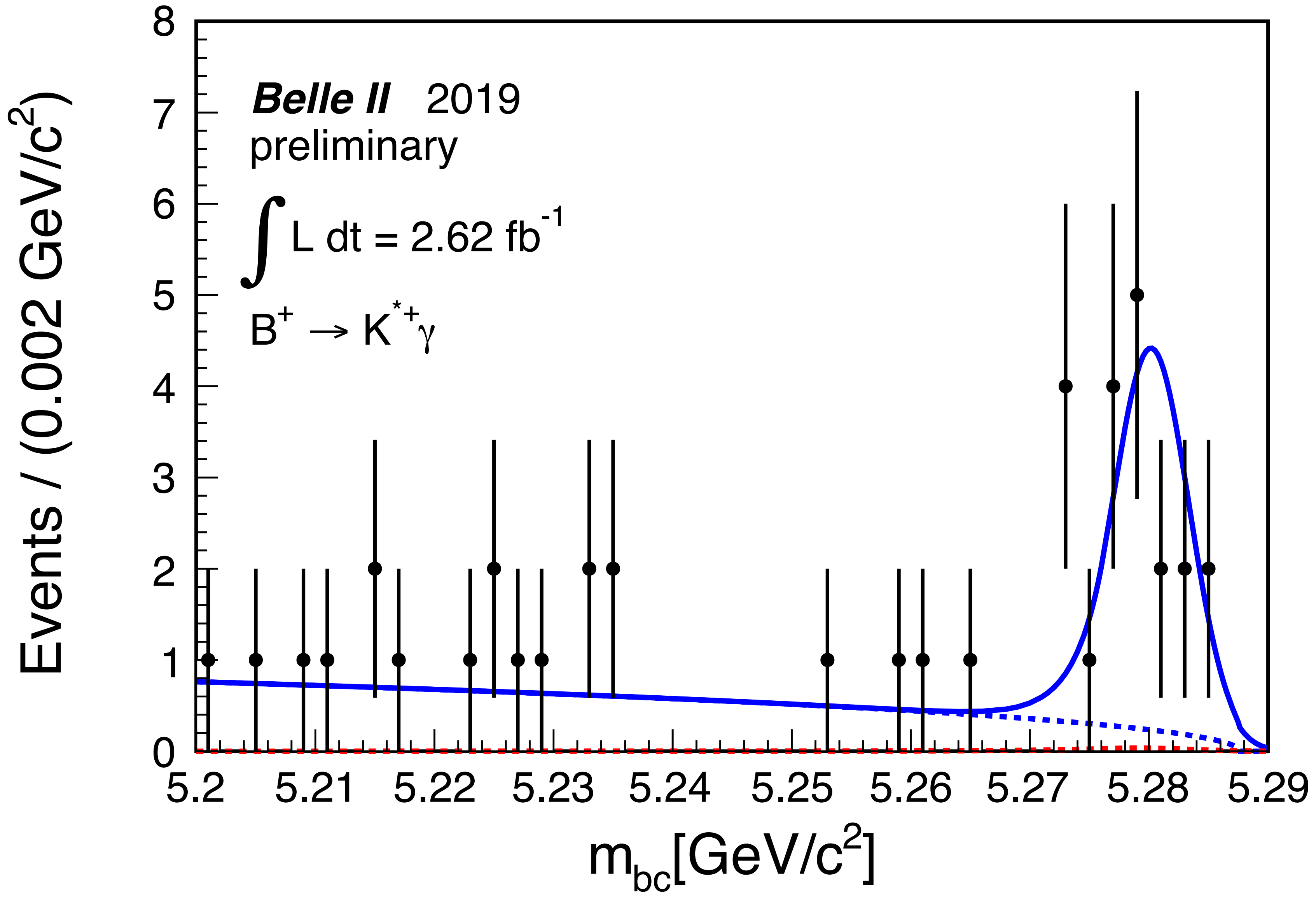


Observables	Belle (2017)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathcal{B}(B \to K^{*+}\nu\bar{\nu})$	$< 40 \times 10^{-6}$	25%	9%
$\mathcal{B}(B \to K^{+}\nu\bar{\nu})$	$< 19 \times 10^{-6}$	30%	11%
$A_{CP}(B \to X_{s+d}\gamma)$ $[10^{-2}]$	$2.2 \pm 4.0 \pm 0.8$	1.5	0.5
$S(B \to K^0_S\pi^0\gamma)$	$-0.10 \pm 0.31 \pm 0.07$	0.11	0.035
$S(B \to \rho\gamma)$	$-0.83 \pm 0.65 \pm 0.18$	0.23	0.07
$A_{FB}(B \to X_s\ell^+\ell^-)$ $(1 < q^2 < 3.5\ \mathrm{GeV}^2/c^4)$	26%	10%	3%
$Br(B \to K^+\mu^+\mu^-)/Br(B \to K^+e^+e^-)$ $(1 < q^2 < 6\ \mathrm{GeV}^2/c^4)$	28%	11%	4%
$Br(B \to K^{*+}(892)\mu^+\mu^-)/Br(B \to K^{*+}(892)e^+e^-)$ $(1 < q^2 < 6\ \mathrm{GeV}^2/c^4)$	24%	9%	3%
$\mathcal{B}(B_s \to \gamma\gamma)$	$< 8.7 \times 10^{-6}$	23%	–
$\mathcal{B}(B_s \to \tau\tau)$ $[10^{-3}]$	–	< 0.8	–

Belle II's 1st penguin: Observation of B→K* γ

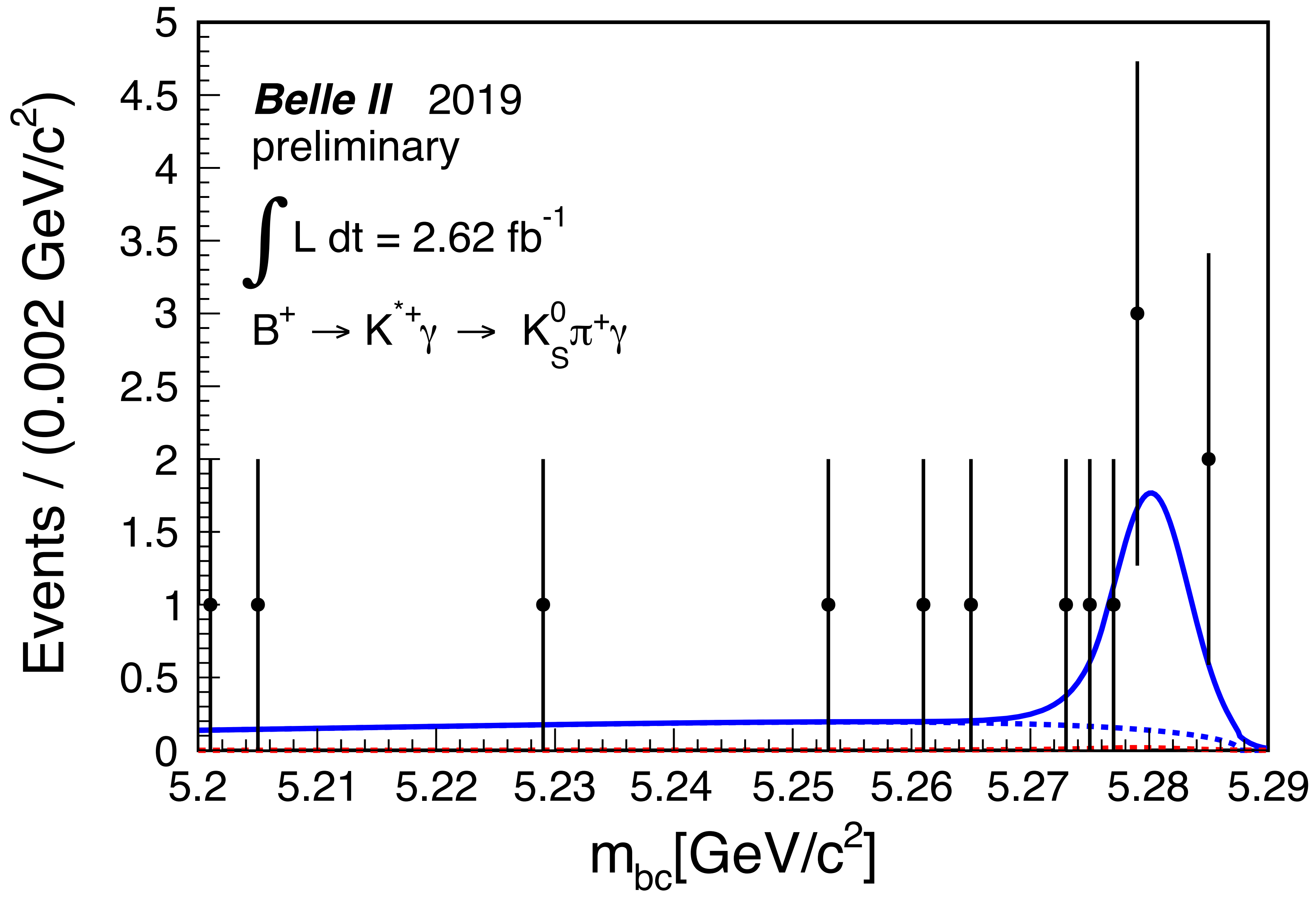
Yields consistent with WA branching fraction

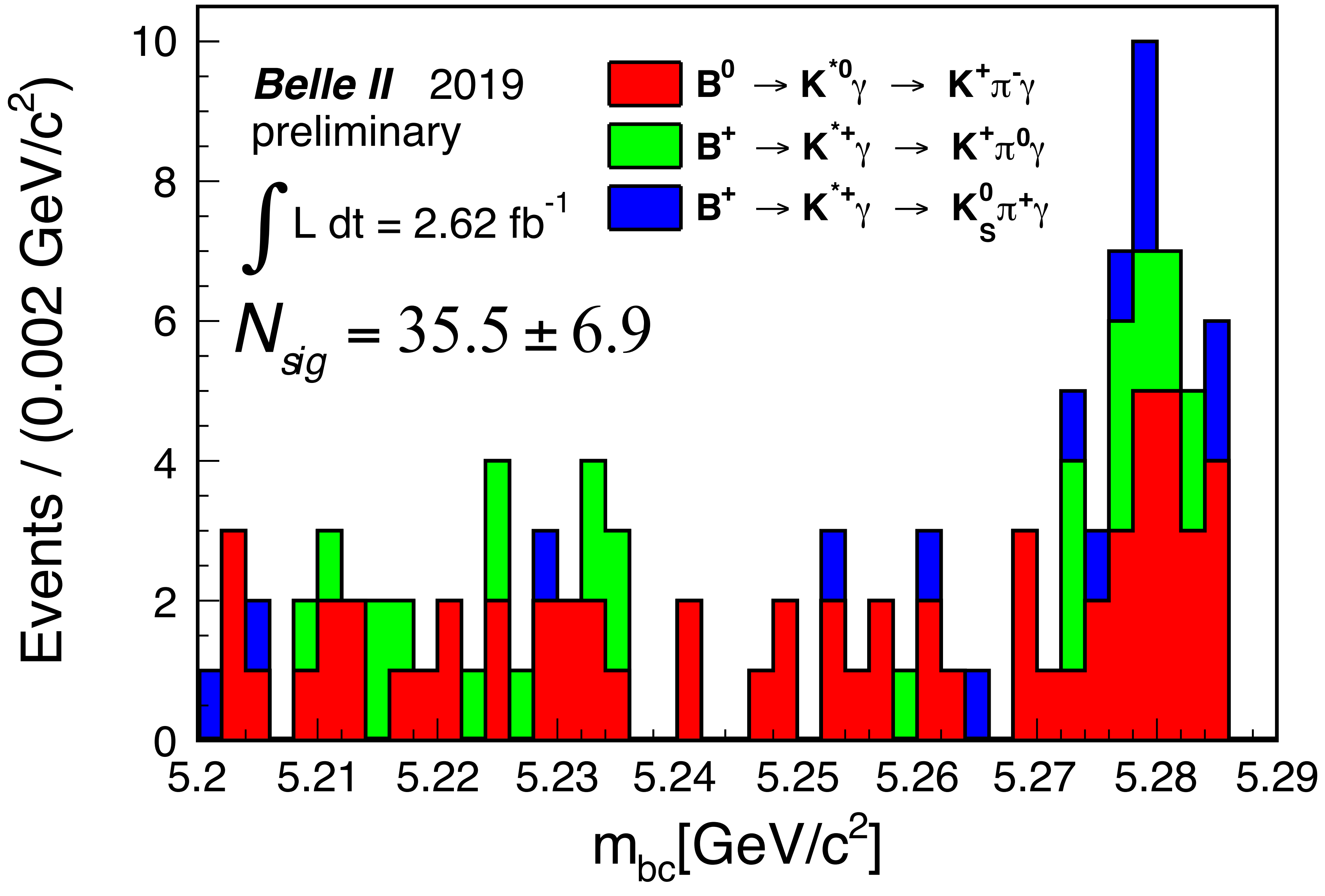




~1/4 of the Phase 3 dataset

B→K$_S$π^0 γ is the target for TDCPV analysis





Belle II Milestones in the next 5 years (B-physics oriented)

Modes highlighted as golden in the B2TiP (Belle II Physics) book (non exhaustive).

E. Kou, PU et al. arXiv: 1808.10567
Accepted to PTEP, printing in December

[ab^{-1}]	Group	Channel	Current precision (Belle)	Precision
0.05	LOWM	ee→ A' γ, A'→ invisible	-	Unique
	LOWM	ee→ a' γ, a' → γ γ	-	Unique
	LOWM	ee→ Z' μμ, Z'→ invisible	-	Unique
	LOWM	ee→ MM	-	Unique
2	SL	$R(B\to D^*\tau\nu)$	0.02	0.012
	SL	$R(B\to D\tau\nu)$	0.07 (0.04)	0.035 (0.024)
	SL	$\|V_{ub}\|$ (B→π l ν) +LQCD improvements	5%	2.5%
	TDCPV	$S_{CP}(B\to J/\psi K_S)$	0.023	0.012
6	SL	Br(B→τν)	21%	9%
	SL	Br(B →μν)	2 σ	> 5 σ
	SL	Br(B → Xu l ν) inclusive dΓ/dMx for $\|V_{ub}\|$	9%	4%
	EWP	R(K) e.g. $1<q^2<6$ GeV/c^2	28%	11%
	EWP	R(K*) e.g. $1<q^2<6$ GeV/c^2	26%	10%
	EWP	P(5') in B→ K*l+l- e.g. $4<q^2<6$ GeV/c^2	0.34	0.12
	TDCPV	$S_{CP}(B\to\eta' K_S)$	0.08	0.03
	TDCPV	$S_{CP}(B\to K^*\gamma)$	0.32	0.12
	HAD	Φ3 (B→DK)	15 deg	5 deg
15	EWP	$Br(B\to X_s l^+l^-)$, e.g. $3.5<q^2<6$ GeV/c^2	24%	8%
	TDCPV	$S_{CP}(B\to\rho\gamma)$	60	10
	TDCPV	$S_{CP}(B\to J/\psi\,\pi^0)$	0.22	0.10
	HAD	$A_{CP}(B\to K_S\,\pi^0)$	0.15	0.05
20+	EWP	Br(B→K ν ν)	~100%	11%
	EWP	$Br(B\to K^*\nu\nu)$	~100%	10%
	EWP	$Br(B_s\to\gamma\gamma)$	< 8.7 10^{-6}	0.3 10^{-6}
	TDCPV	$S_{CP}(B\to\pi^0\pi^0)$	-	0.06

Belle II - LHCb Comparison

Belle II
Higher sensitivity to decays with photons and neutrinos (e.g. $B \to K\nu\nu$, $\mu\nu$), inclusive decays, time dependent CPV in B_d, τ physics.

LHCb
Higher production rates for ultra rare B, D, & K decays, access to all b-hadron flavours (e.g. Λ_b), high boost for fast B_s oscillations.

Overlap in various key areas to verify discoveries.

Upgrades
Most key channels will be stats. limited (not theory or syst.).
LHCb scheduled major upgrades during LS3 and LS4.
Belle II formulating a 250 ab^{-1} upgrade program post 2028.

Observable	Current Belle/ Babar	Current LHCb	Belle II (50 ab^{-1})	LHCb (23 fb^{-1})	Belle II Upgrade (250 ab^{-1})	LHCb upgrade II (300 fb^{-1})
CKM precision, new physics in CP Violation						
$\sin 2\beta/\varphi_1$ ($B \to J/\psi K_S$)	0.03	0.04	0.005	0.011	0.002	0.003
γ/φ_3	13°	5.4°	1.5°	1.5°	0.4°	0.4°
α/φ_2	4°	–	0.6°	–	0.3°	–
$\lvert V_{ub}\rvert$ (Belle) or $\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ (LHCb)	4.5%	6%	1%	3%	<1%	1%
φ_s	–	49 mrad	–	14 mrad	–	4 mrad
$S_{CP}(B \to \eta' K_S$, gluonic penguin)	0.08	○	0.015	○	0.007	○
$A_{CP}(B \to K_S \pi^0)$	0.15	–	0.04	–	0.02	–
New physics in radiative & EW Penguins, LFUV						
$S_{CP}(B_d \to K^* \gamma)$	0.32	○	0.035	○	0.015	○
$R(B \to K^* l^+ l^-)$ ($1<q^2<6$ GeV$^2/c^2$)	0.24	0.1	0.03	0.03	0.01	0.01
$R(B \to D^* \tau\nu)$	6.4%	10%	1.5%	3%	<1%	1%
$Br(B \to \tau\nu)$, $Br(B \to K^*\nu\nu)$	24%, –	–	4%, 9%	–	1.7%, 4%	–
$Br(B_d \to \mu\mu)$	–	90%	–	34%	–	10%
Charm and τ						
$\Delta A_{CP}(KK-\pi\pi)$	–	8.5×10^{-4}	5.4×10^{-4}	1.7×10^{-4}	2×10^{-4}	0.3×10^{-4}
$A_{CP}(D \to \pi^+\pi^0)$	1.2%	–	0.2%	–	0.1%	–
$Br(\tau \to e\gamma)$	$<120\times10^{-9}$	–	$<12\times10^{-9}$	–	$<5\times10^{-9}$	–
$Br(\tau \to \mu\mu\mu)$	$<21\times10^{-9}$	$<46\times10^{-9}$	$<3\times10^{-9}$	$<16\times10^{-9}$	$<0.3\times10^{-9}$	$<5\times10^{-9}$

○ Possible in similar channels, lower precision
– Not competitive.

arXiv: 1808.08865 (Physics case for LHCb upgrade II), 1808.10567 (Belle II Physics Book)

Conclusions

- **CKM UT angles (CP violating) and sides (CP conserving) to improve everywhere by factor ~3x at least within 5 years: results from Belle II, LHCb, BESIII, LQCD.**
  - Most powerful tests will continue to be statistics limited, clean theoretically and systematically.
  - Many more BSM CPV searches to greatly improve with upgraded detectors + datasets (Belle II, LHCb), such as gluonic ($B\to \eta' K_S$) and EW penguin ($B\to\rho\gamma$).

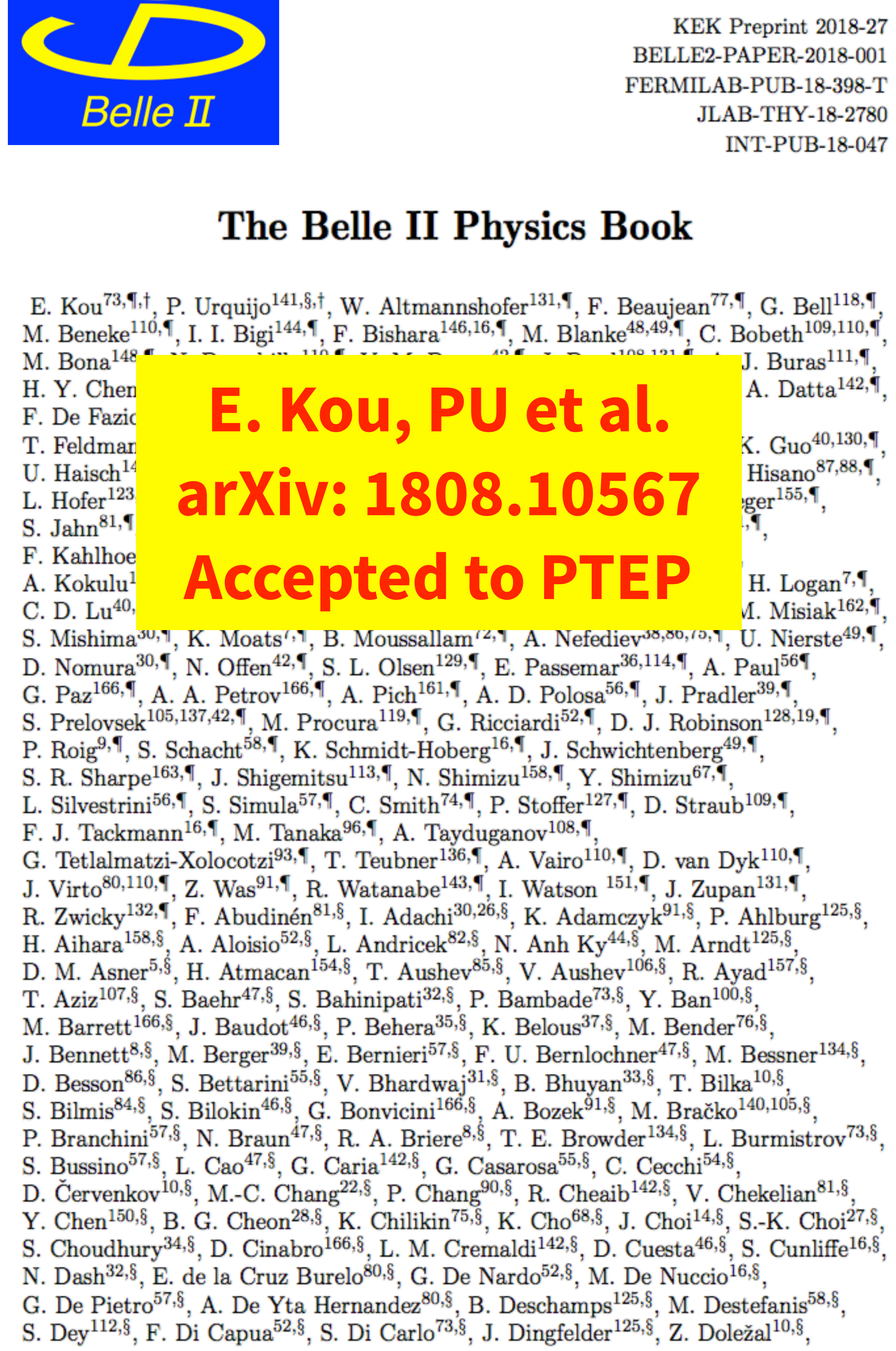
- **LFUV in leptonic and semileptonic theoretically clean but NOT always experimentally clean.** Material mapping, hermetic coverage, and lepton universality in triggering and DETECTION is critical. Belle II has a major role in next 5 years.

- **Belle II: First physics run in Super B Factory mode (Phase 3) began March 2019**.
  Integrated ~10 fb^{-1}, 10^{34} $/cm^2/s$ exceeded.
  5 year prospects are very promising on CP violation, UT precision tests and LFUV anomalies.

Backup

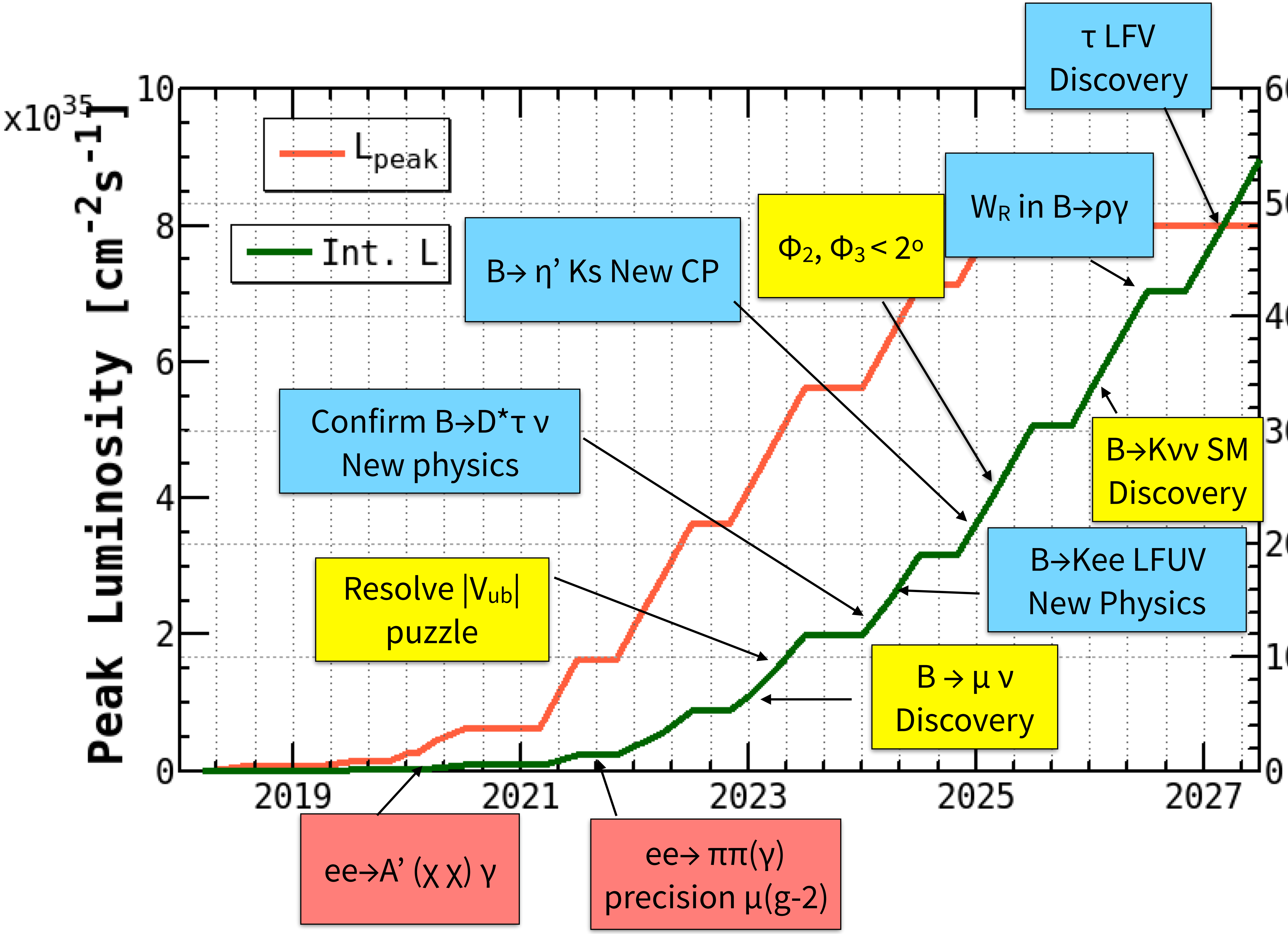
Roadmap

- Most powerful tests will continue to be statistics limited, clean theoretically and systematically.


KEK Preprint 2018-27
BELLE2-PAPER-2018-001
FERMILAB-PUB-18-398-T
JLAB-THY-18-2780
INT-PUB-18-047

The Belle II Physics Book

E. Kou, P. Urquijo, W. Altmannshofer, F. Beaujean, G. Bell, M. Beneke, I. I. Bigi, F. Bishara, M. Blanke, C. Bobeth, M. Bona, ... J. Buras, H. Y. Chen ... A. Datta, F. De Fazio ... T. Feldman ... K. Guo, U. Haisch ... Hisano, L. Hofer ..., S. Jahn ..., F. Kahlhoefer ..., A. Kokulu ... H. Logan, C. D. Lu ... M. Misiak, S. Mishima, K. Moats, B. Moussallam, A. Nefediev, U. Nierste, D. Nomura, N. Offen, S. L. Olsen, E. Passemar, A. Paul, G. Paz, A. A. Petrov, A. Pich, A. D. Polosa, J. Pradler, S. Prelovsek, M. Procura, G. Ricciardi, D. J. Robinson, P. Roig, S. Schacht, K. Schmidt-Hoberg, J. Schwichtenberg, S. R. Sharpe, J. Shigemitsu, N. Shimizu, Y. Shimizu, L. Silvestrini, S. Simula, C. Smith, P. Stoffer, D. Straub, F. J. Tackmann, M. Tanaka, A. Tayduganov, G. Tetlalmatzi-Xolocotzi, T. Teubner, A. Vairo, D. van Dyk, J. Virto, Z. Was, R. Watanabe, I. Watson, J. Zupan, R. Zwicky, F. Abudinén, I. Adachi, K. Adamczyk, P. Ahlburg, H. Aihara, A. Aloisio, L. Andricek, N. Anh Ky, M. Arndt, D. M. Asner, H. Atmacan, T. Aushev, V. Aushev, R. Ayad, T. Aziz, S. Baehr, S. Bahinipati, P. Bambade, Y. Ban, M. Barrett, J. Baudot, P. Behera, K. Belous, M. Bender, J. Bennett, M. Berger, E. Bernieri, F. U. Bernlochner, M. Bessner, D. Besson, S. Bettarini, V. Bhardwaj, B. Bhuyan, T. Bilka, S. Bilmis, S. Bilokin, G. Bonvicini, A. Bozek, M. Bračko, P. Branchini, N. Braun, R. A. Briere, T. E. Browder, L. Burmistrov, S. Bussino, L. Cao, G. Caria, G. Casarosa, C. Cecchi, D. Červenkov, M.-C. Chang, P. Chang, R. Cheaib, V. Chekelian, Y. Chen, B. G. Cheon, K. Chilikin, K. Cho, J. Choi, S.-K. Choi, S. Choudhury, D. Cinabro, L. M. Cremaldi, D. Cuesta, S. Cunliffe, N. Dash, E. de la Cruz Burelo, G. De Nardo, M. De Nuccio, G. De Pietro, A. De Yta Hernandez, B. Deschamps, M. Destefanis, S. Dey, F. Di Capua, S. Di Carlo, J. Dingfelder, Z. Doležal,

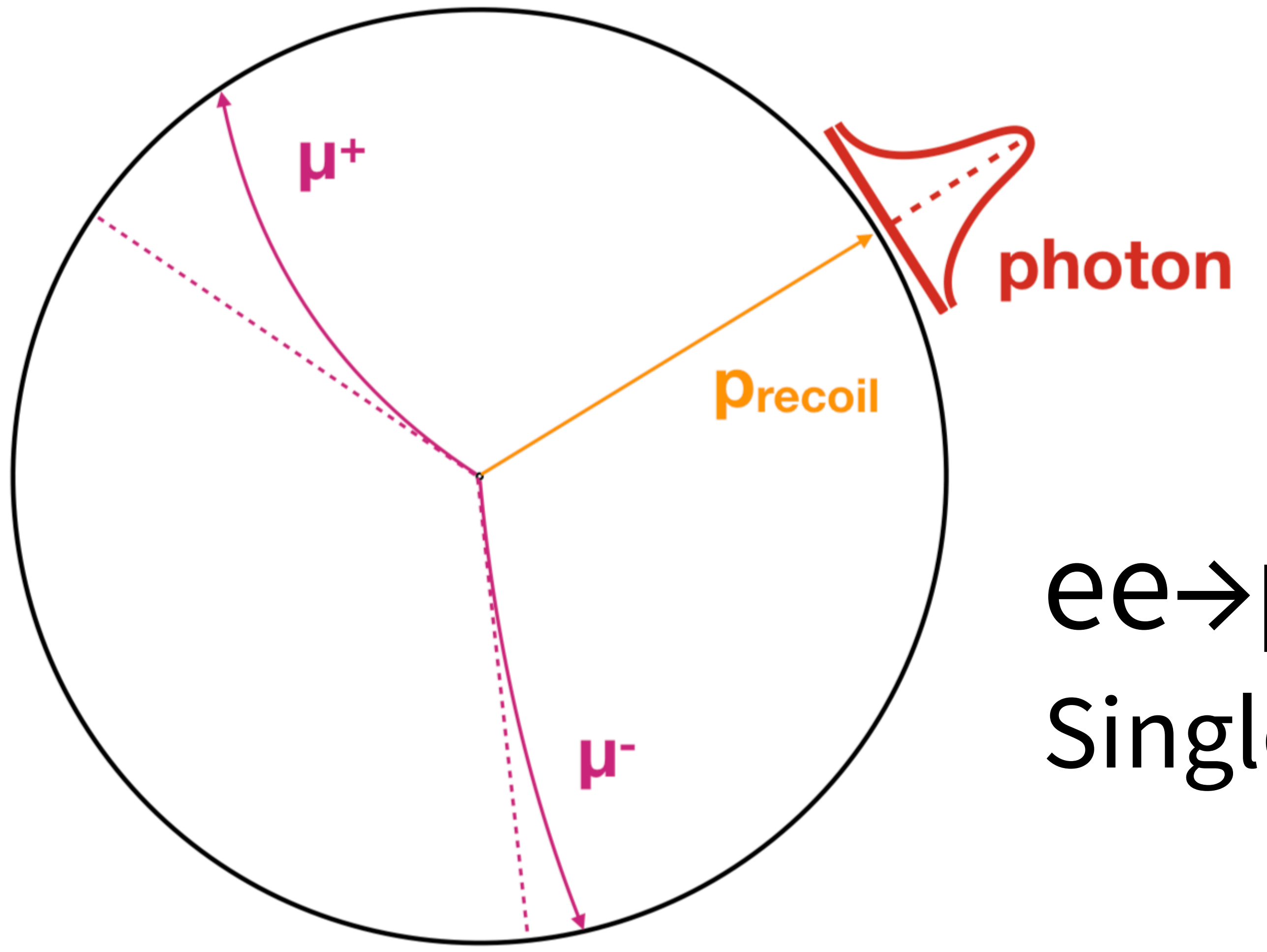


Belle II Physics Ultimate Precision, 50 ab^{-1}

Observables	Expected the. accuracy		Expected exp. uncertainty	Facility (2025)
UT angles & sides				
ϕ_1 [°]	***		0.4	Belle II
ϕ_2 [°]	**	CKM	1.0	Belle II
ϕ_3 [°]	***		1.0	LHCb/Belle II
$\|V_{cb}\|$ incl.	***		1%	Belle II
$\|V_{cb}\|$ excl.	***		1.5%	Belle II
$\|V_{ub}\|$ incl.	**		3%	Belle II
$\|V_{ub}\|$ excl.	**		2%	Belle II/LHCb
CPV				
$S(B \to \phi K^0)$	***		0.02	Belle II
$S(B \to \eta' K^0)$	***	CPV	0.01	Belle II
$\mathcal{A}(B \to K^0 \pi^0)[10^{-2}]$	***		4	Belle II
$\mathcal{A}(B \to K^+ \pi^-)$ $[10^{-2}]$	***		0.20	LHCb/Belle II
(Semi-)leptonic				
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**		3%	Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**	SL	7%	Belle II
$R(B \to D\tau\nu)$	***		3%	Belle II
$R(B \to D^*\tau\nu)$	***		2%	Belle II/LHCb

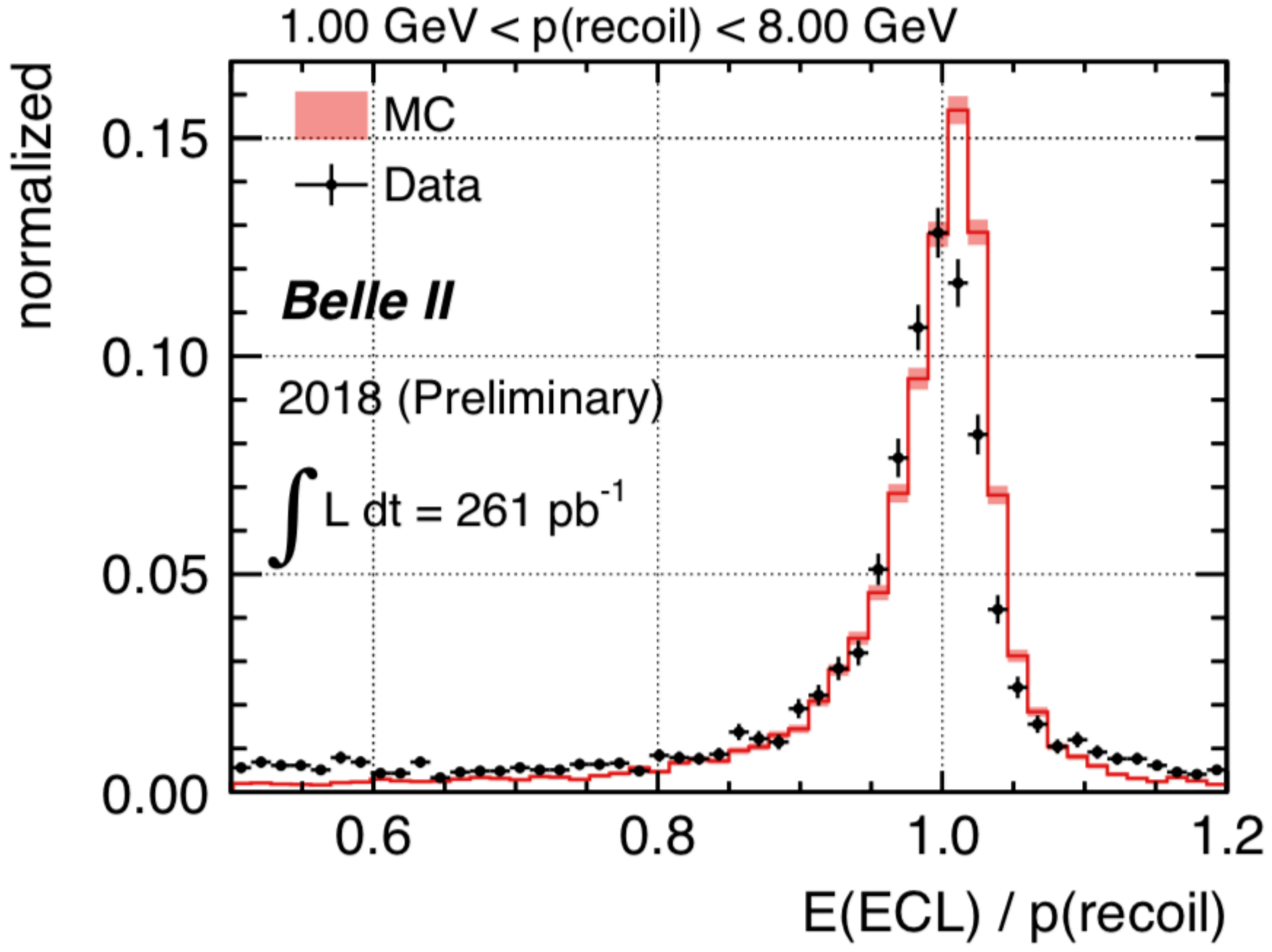
Radiative & EW Penguins				
$\mathcal{B}(B \to X_s\gamma)$	**		4%	Belle II
$A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	***		0.005	Belle II
$S(B \to K_S^0\pi^0\gamma)$	***		0.03	Belle II
$S(B \to \rho\gamma)$	**	EWP	0.07	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	**		0.3	Belle II
$\mathcal{B}(B \to K^*\nu\overline{\nu})$ $[10^{-6}]$	***		15%	Belle II
$\mathcal{B}(B \to K\nu\overline{\nu})$ $[10^{-6}]$	***		20%	Belle II
$R(B \to K^*\ell\ell)$	***		0.03	Belle II/LHCb
Charm				
$\mathcal{B}(D_s \to \mu\nu)$	***		0.9%	Belle II
$\mathcal{B}(D_s \to \tau\nu)$	***	D	2%	Belle II
$A_{CP}(D^0 \to K_S^0\pi^0)$ $[10^{-2}]$	**		0.03	Belle II
$\|q/p\|(D^0 \to K_S^0\pi^+\pi^-)$	***		0.03	Belle II
$\phi(D^0 \to K_S^0\pi^+\pi^-)$ [°]	***		4	Belle II
Tau				
$\tau \to \mu\gamma$ $[10^{-10}]$	***		< 50	Belle II
$\tau \to e\gamma$ $[10^{-10}]$	***	τ	< 100	Belle II
$\tau \to \mu\mu\mu$ $[10^{-10}]$	***		< 3	Belle II/LHCb

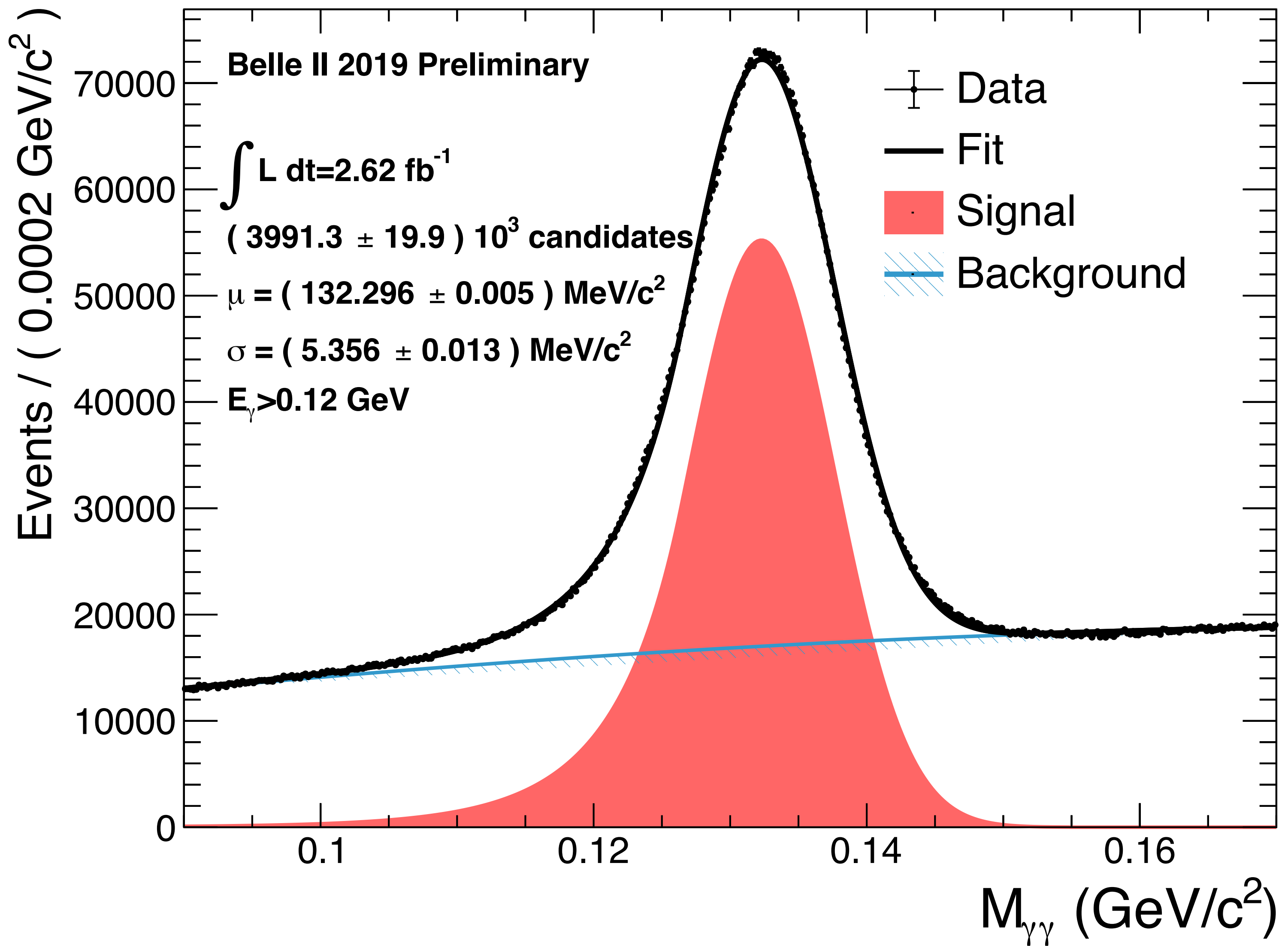
Dark Sector, expected sensitivity



ee→μμγ

Single Photon Lines

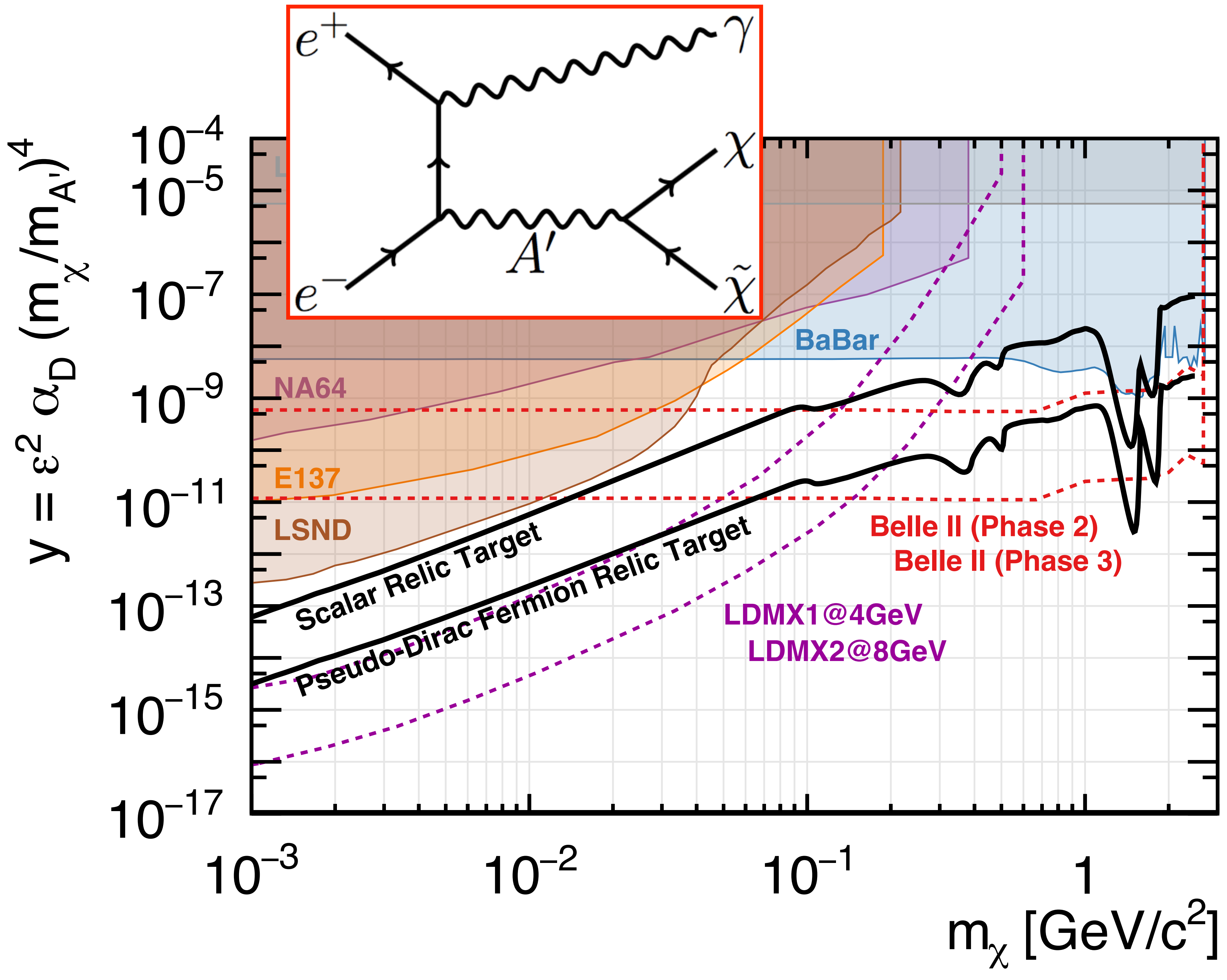


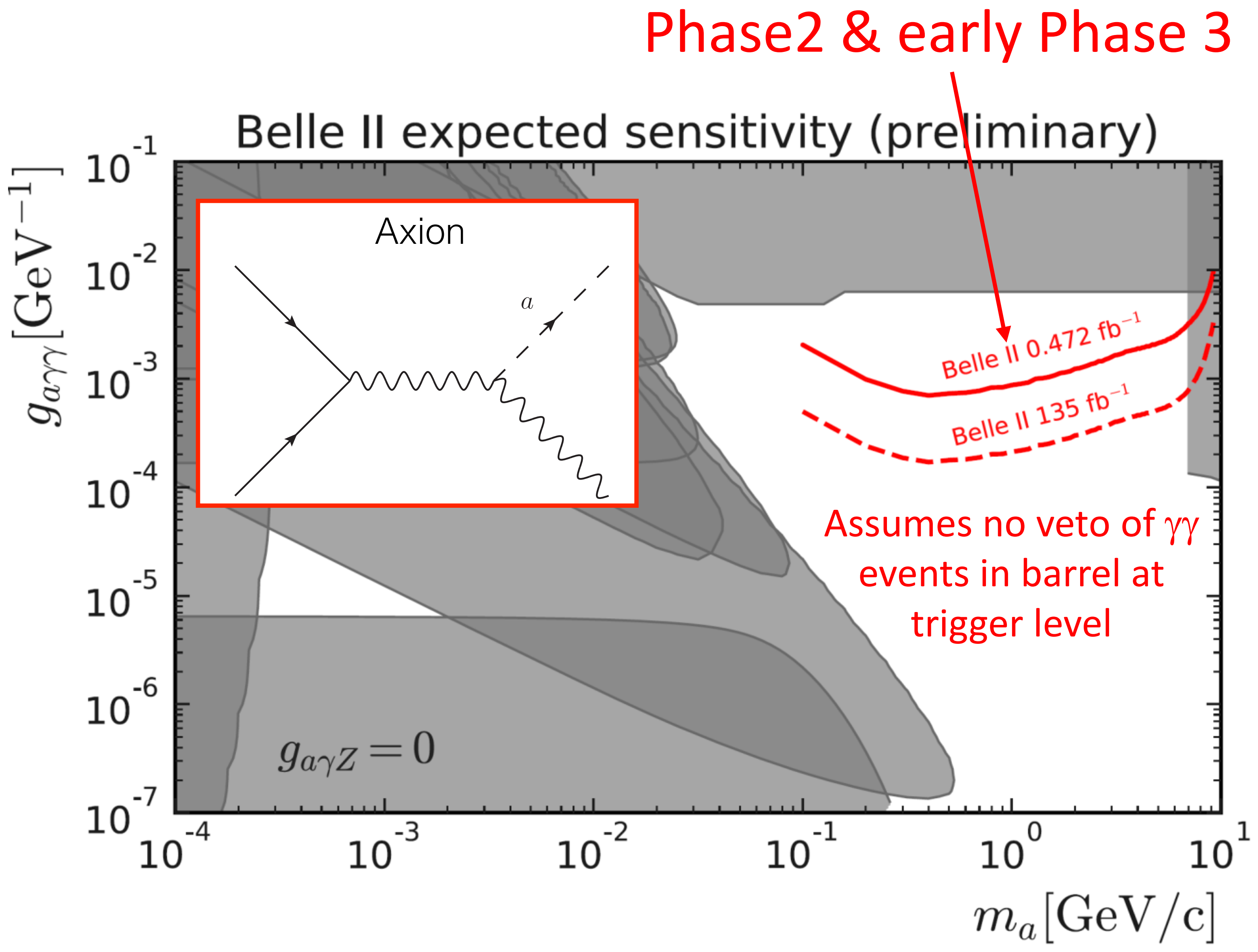


Dark sector results are the first to come from Belle II

- $e^+e^- \to \gamma X$
- $e^+e^- \to \gamma$ ALP ($\to\gamma\gamma$)
- $e^+e^- \to \gamma A'$ (dark photon)
- Dark Z', Magn. Monopoles

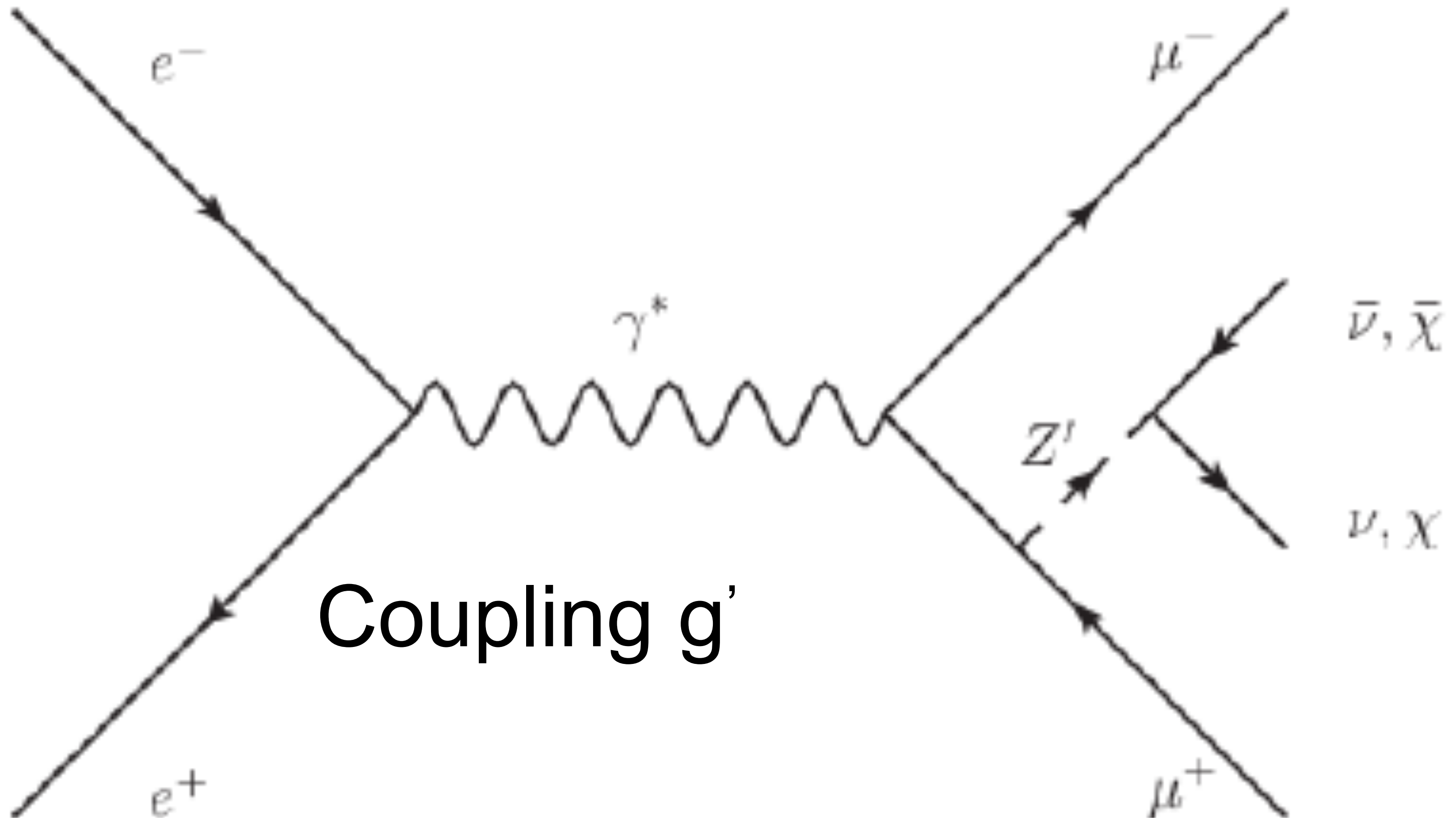
Can also access through flavour transitions.





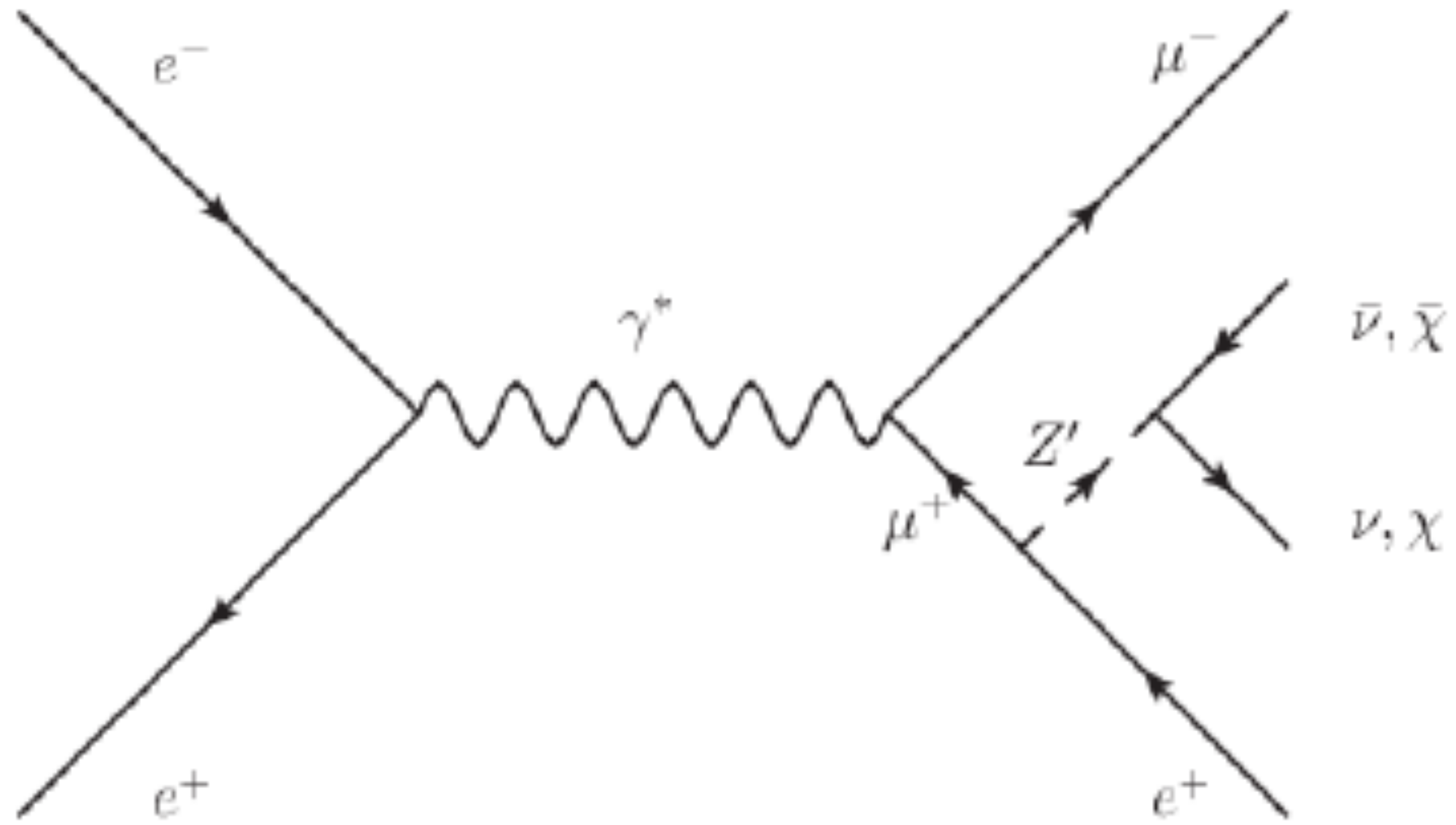
Leptophilic Dark Z'

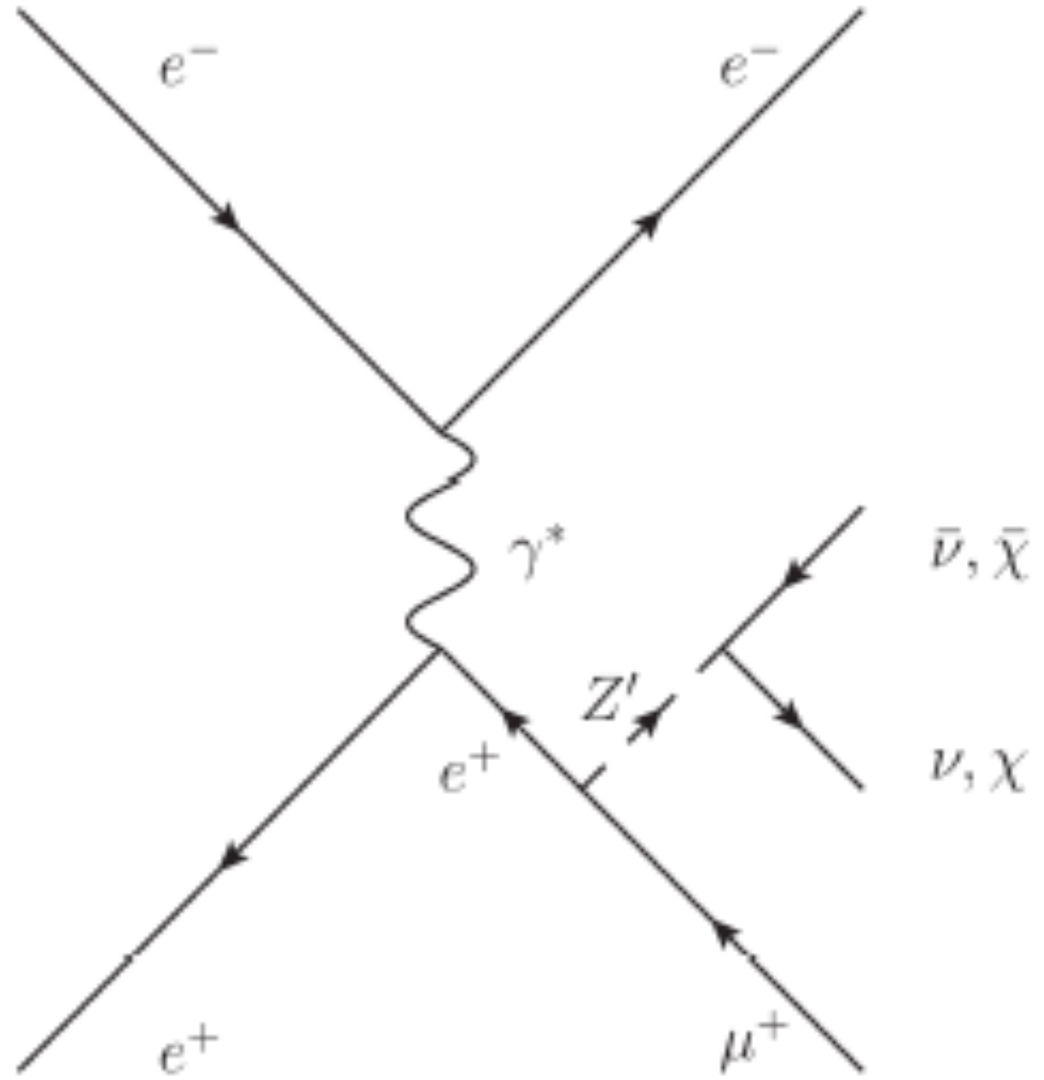
Previously limited by trigger, QED background and theoretical imagination. *Now new possibilities of triggering, more bandwidth.*



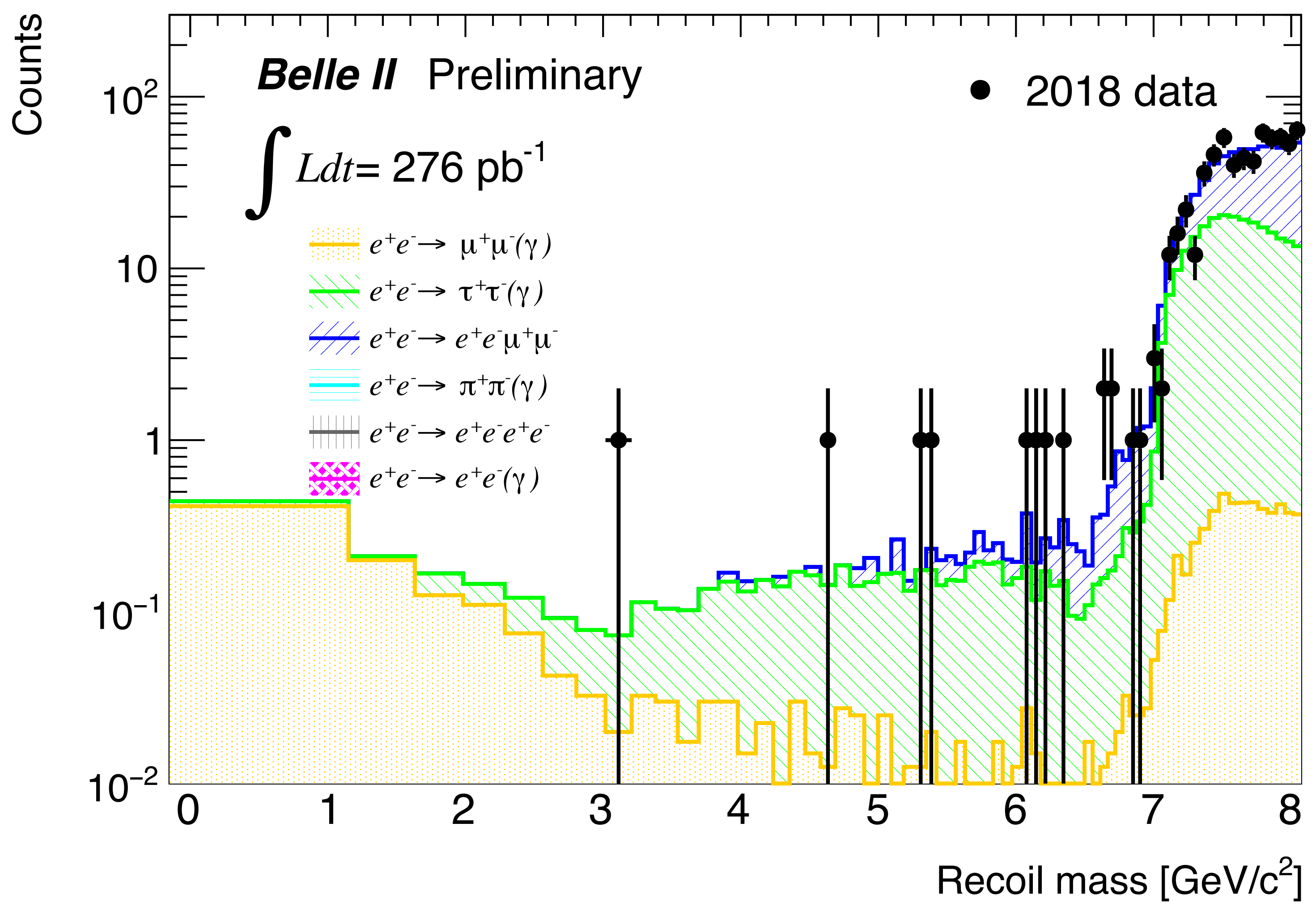
Belle II First Physics. A novel result on the dark sector (Z' → nothing) recoiling against μ-μ *or* e-μ pair. Both possibilities are poorly constrained at low Z' mass and in the first case, could explain μ g-2 anomaly.

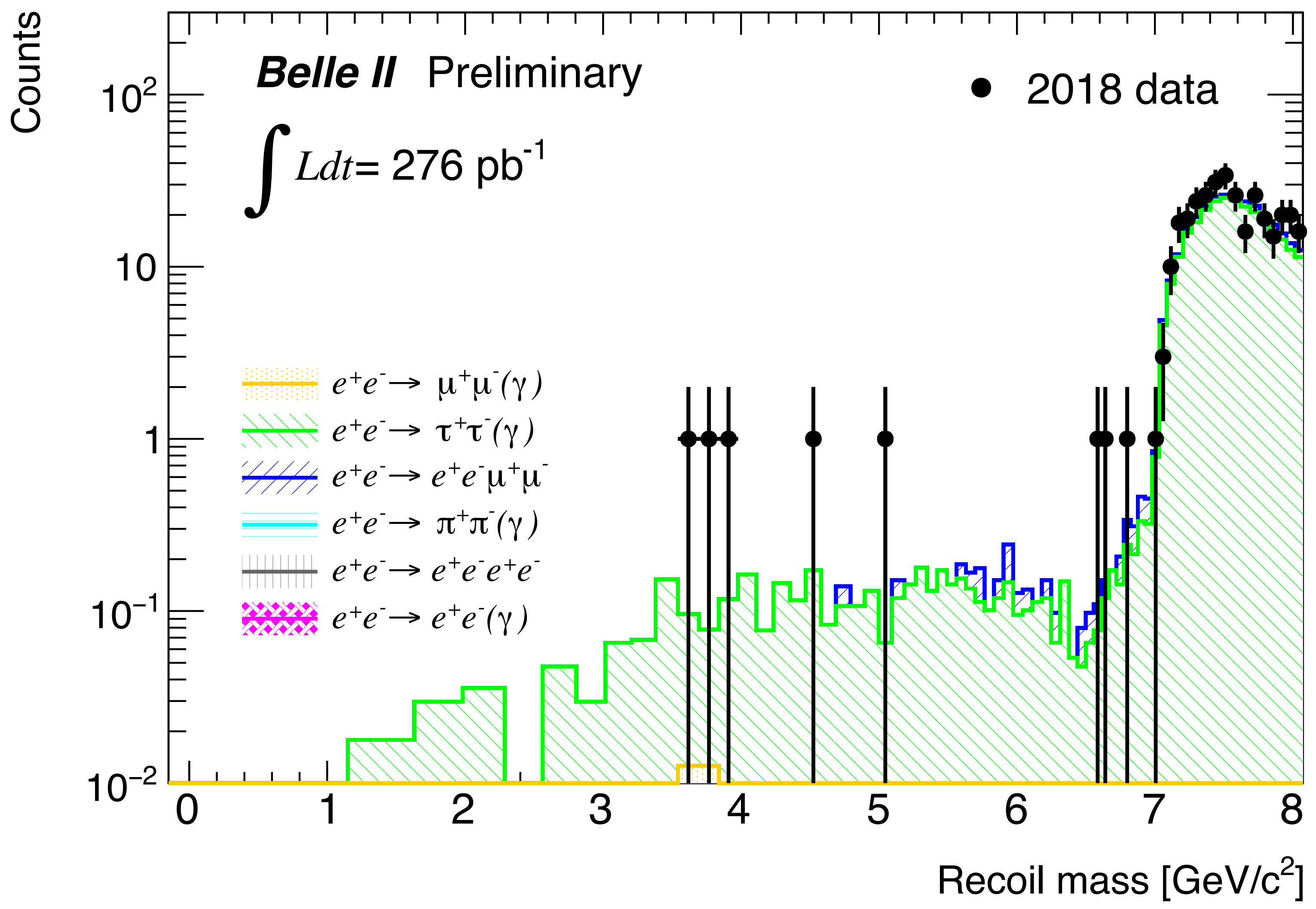
Also examine a lepton flavour violating NP signature in the dark sector

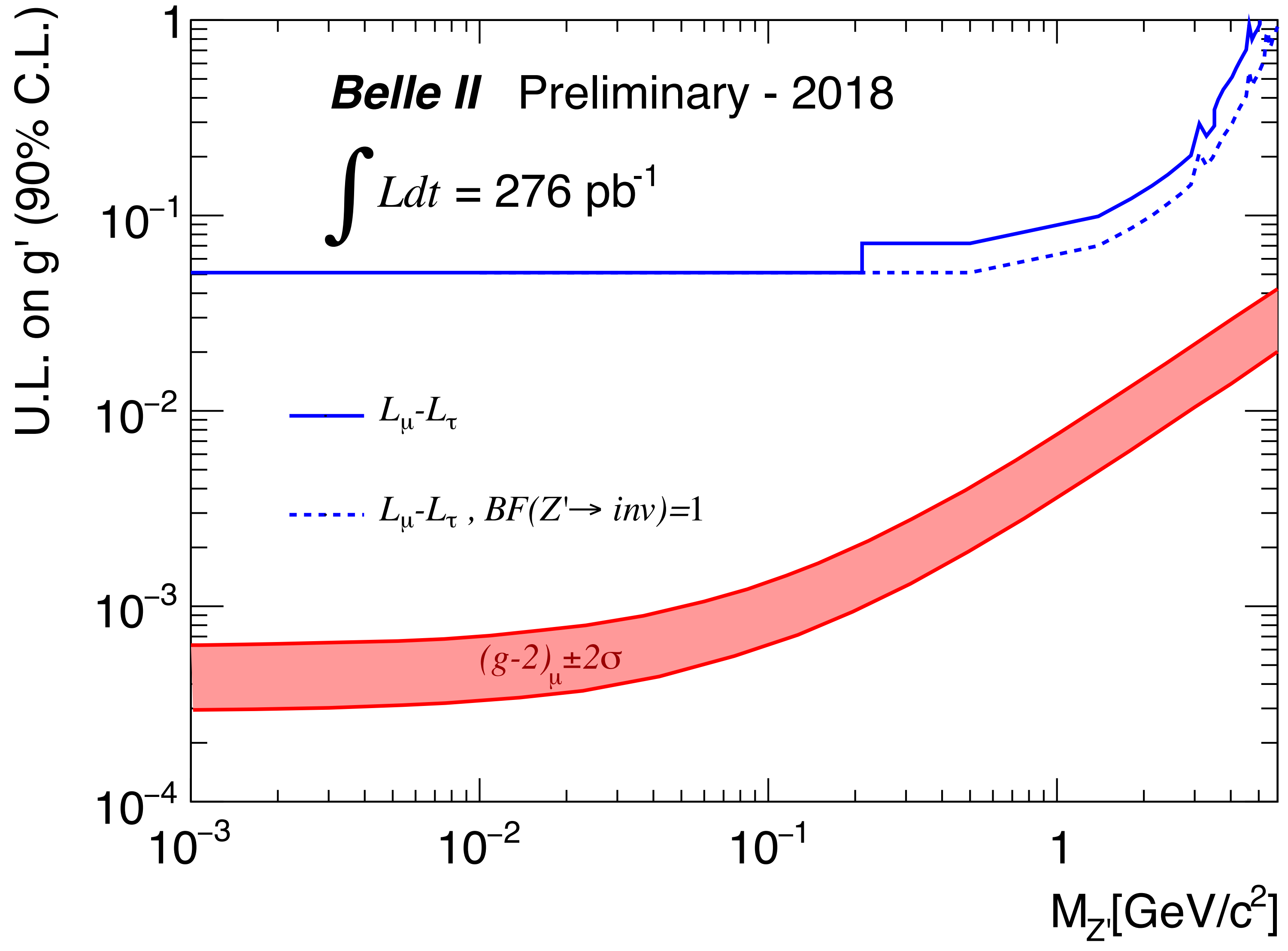


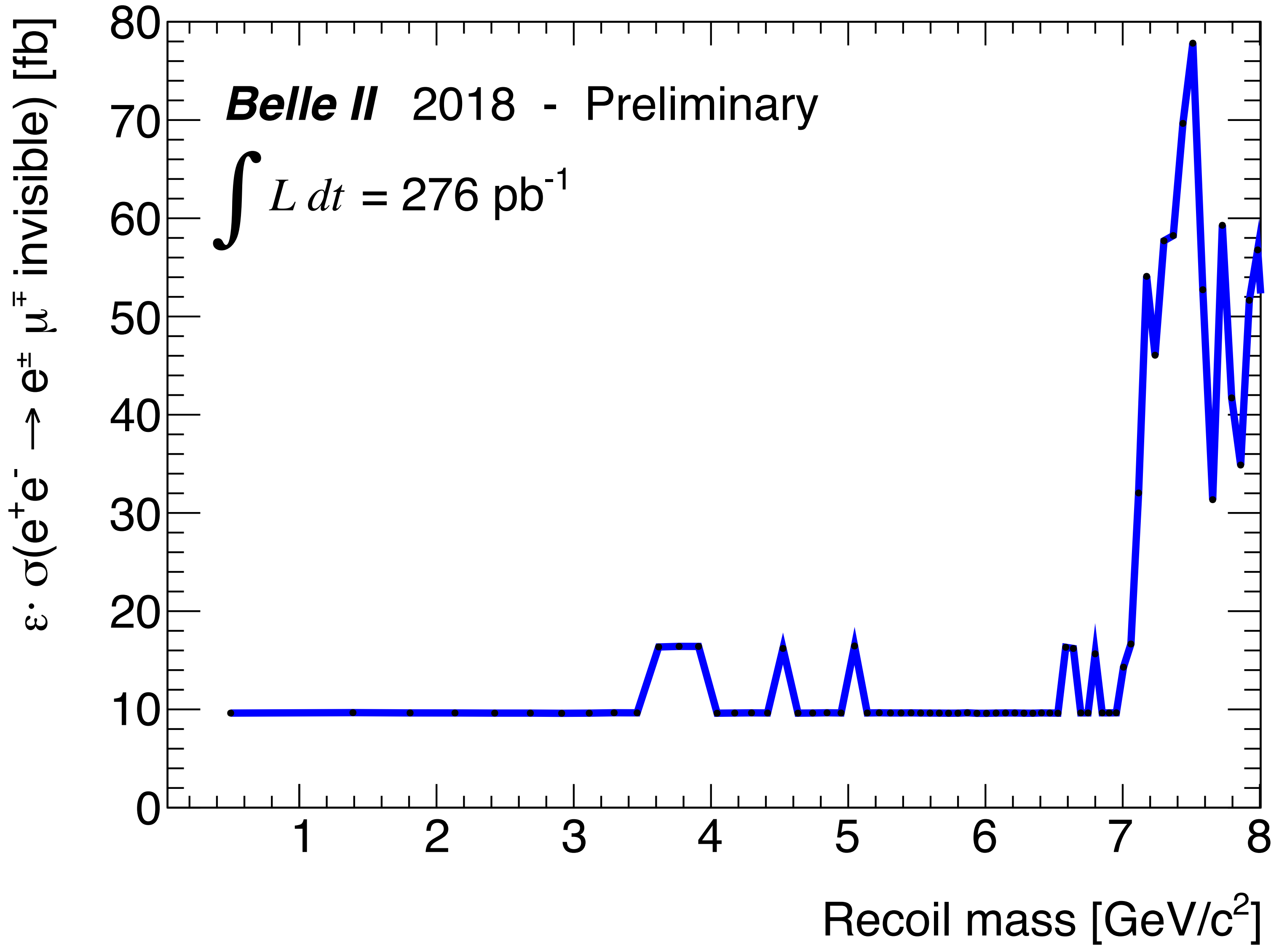


Search for ee→μμZ'/eμZ' (Z'→nothing)









Compatible with backgrounds, No excess above 3σ