Probing new physics with rare B decays at Belle II

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University of Liverpool - 2025.01.22

HEP Seminars

FLAVOUR

Flavour →species of Standard Model fermions

Flavour physics → investigates the properties of **quarks** & leptons

SU(3) × U(1)$_{\text{em}}$

$3_{2/3}: \quad u, c, t,$

$3_{-1/3}: d, s, b,$

$1_{-1}: \quad e, \mu, \tau,$

$1_0: \quad \nu_e, \nu_\mu, \nu_\tau$

10.23730/CYRSP-2019-006.181

Quark flavour physics → SM parameters

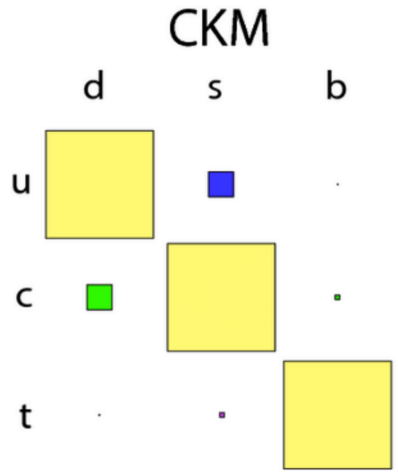
couplings, CKM params., masses

Symmetries

C, P, CP, CPT, flavour, CPV sources

QCD

dynamics, spectroscopy



Flavour physics allows to probe well above the electroweak scale

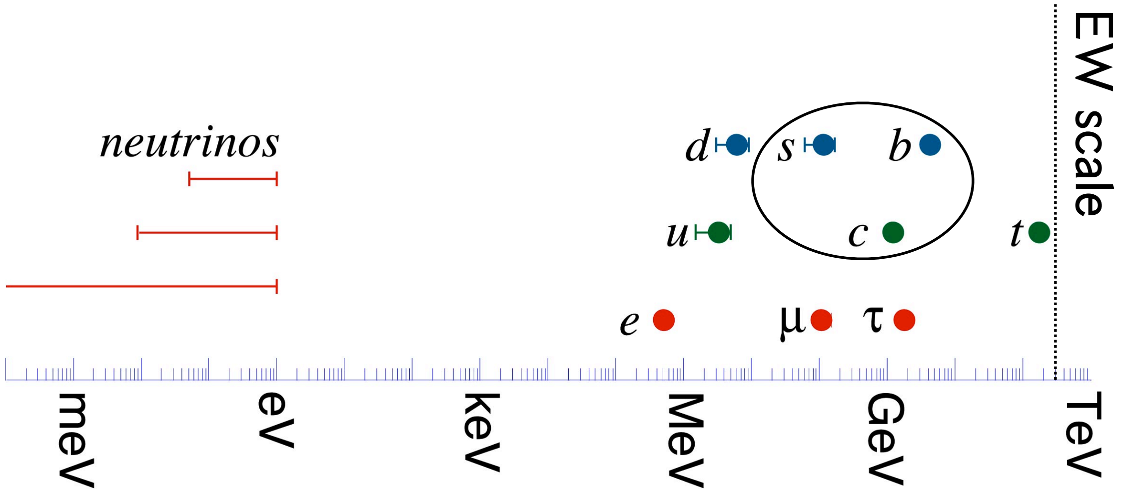
Flavour observables can provide constraints on New Physics

Main players (flavor quark physics)

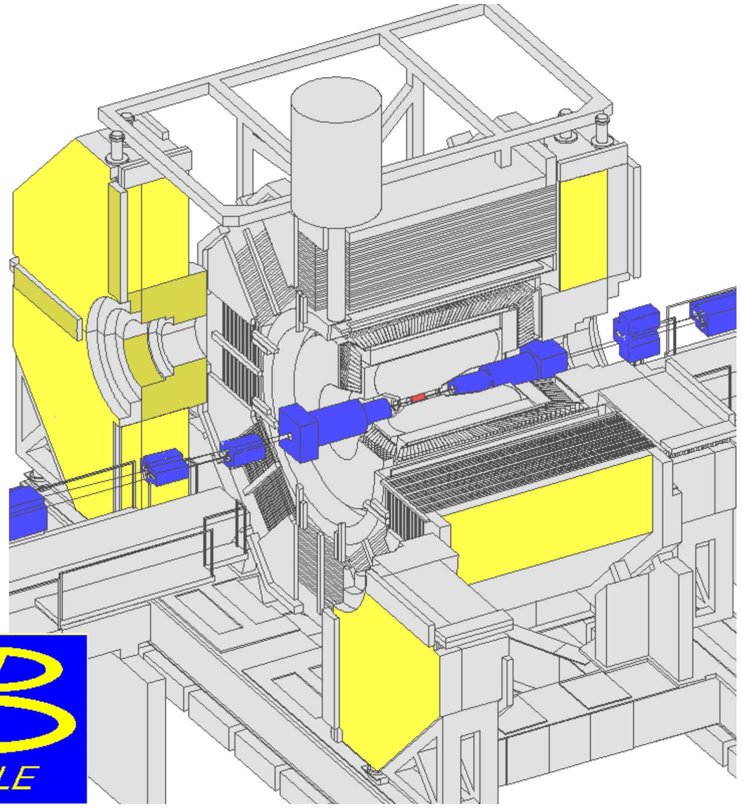
s — NA62, KOTO

c — BESIII

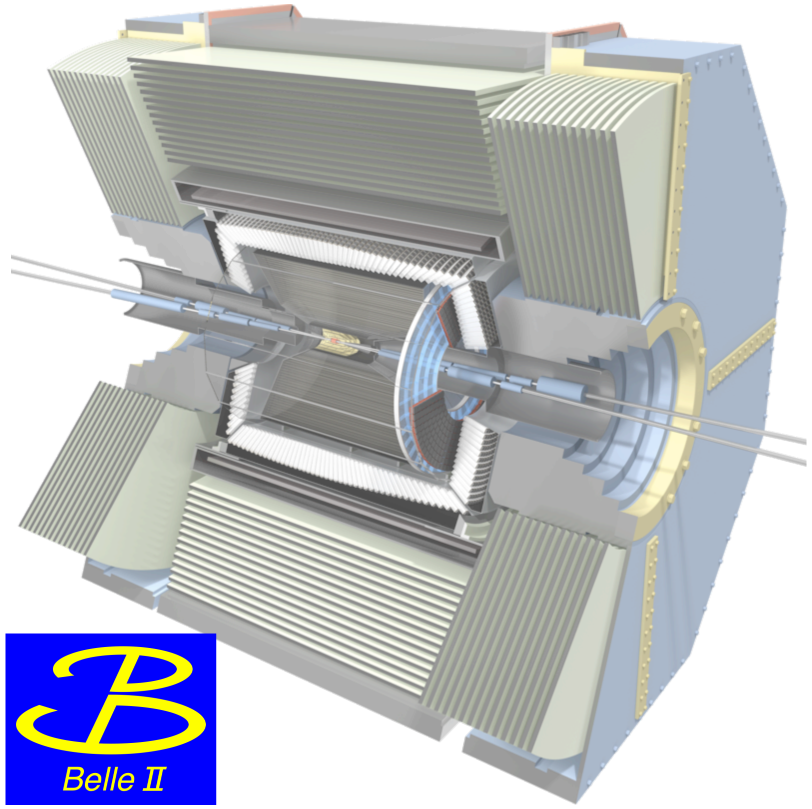
b — LHCb, **Belle II**

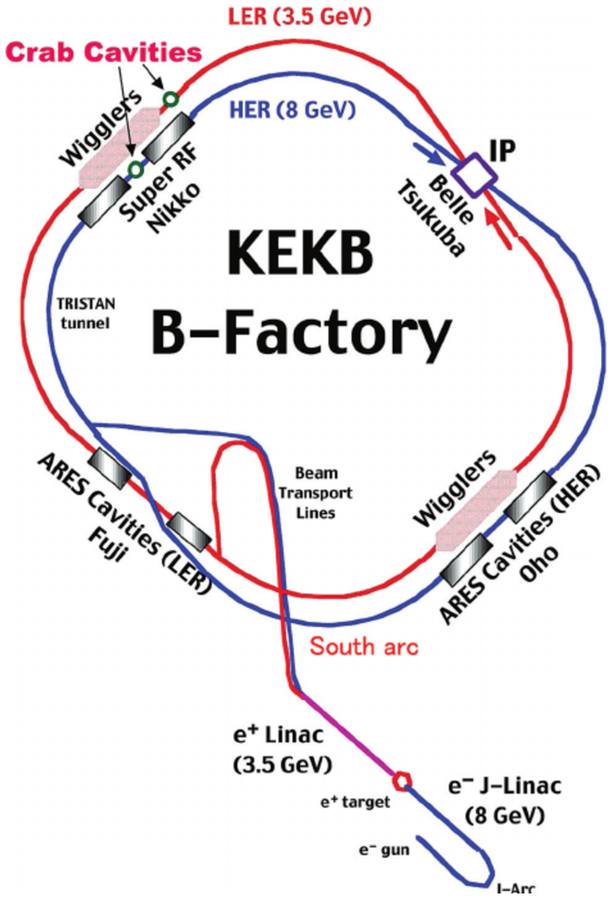


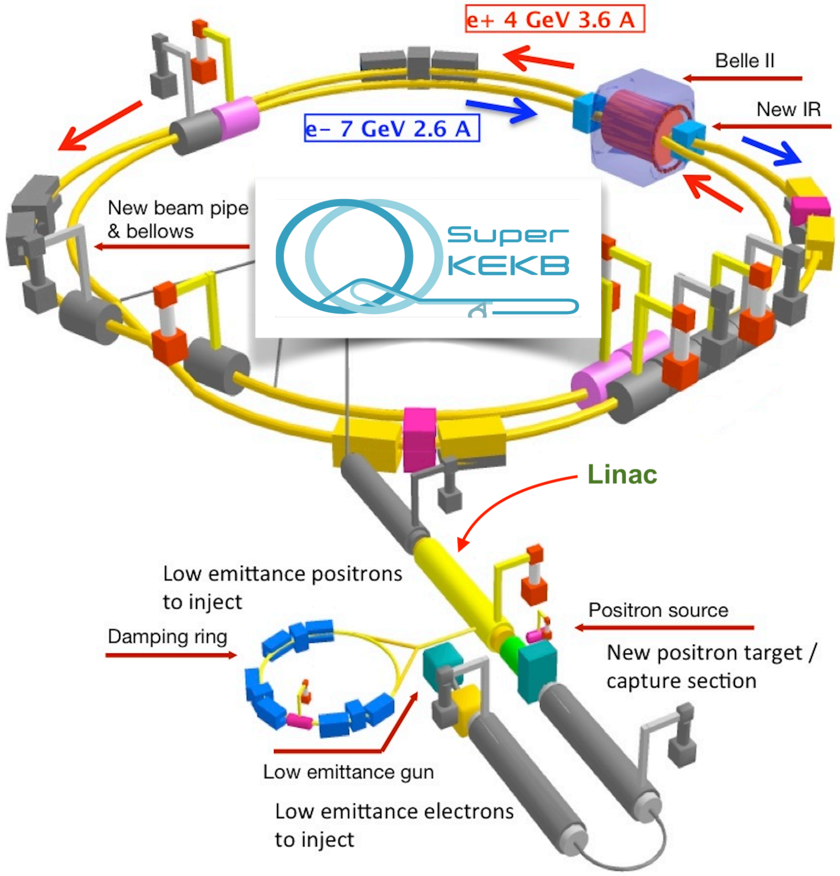
THE BELLE&BELLE II EXPERIMENTS



- High resolution (momentum, vertex) hermetic detectors
- Efficient reconstruction of neutrals (γ, π^0, η)
- Clean environment and low background
- World luminosity records







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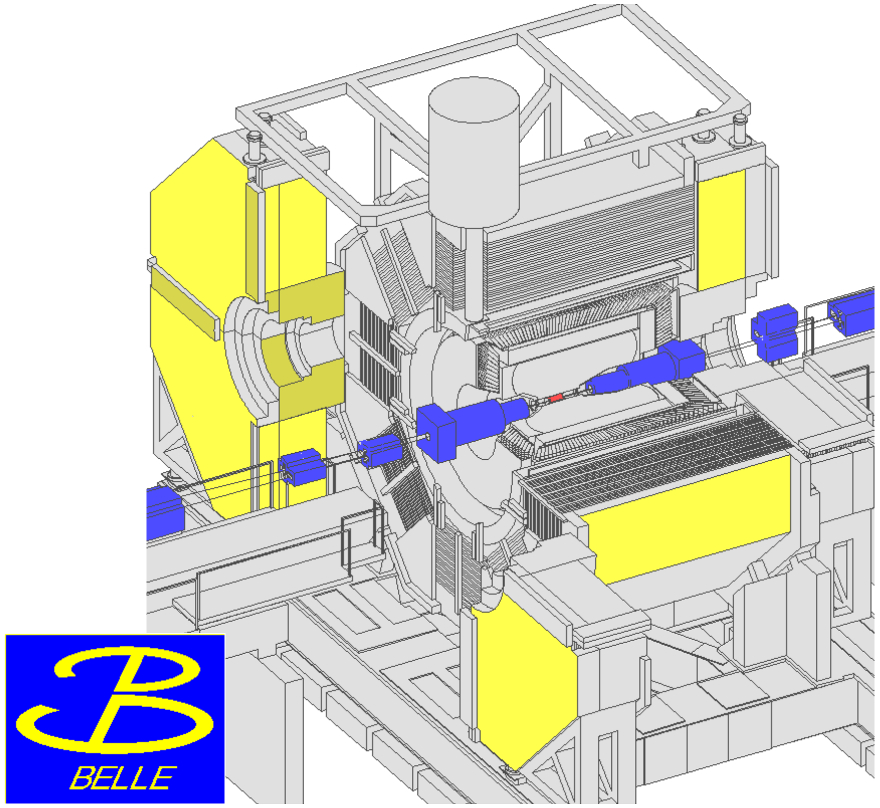

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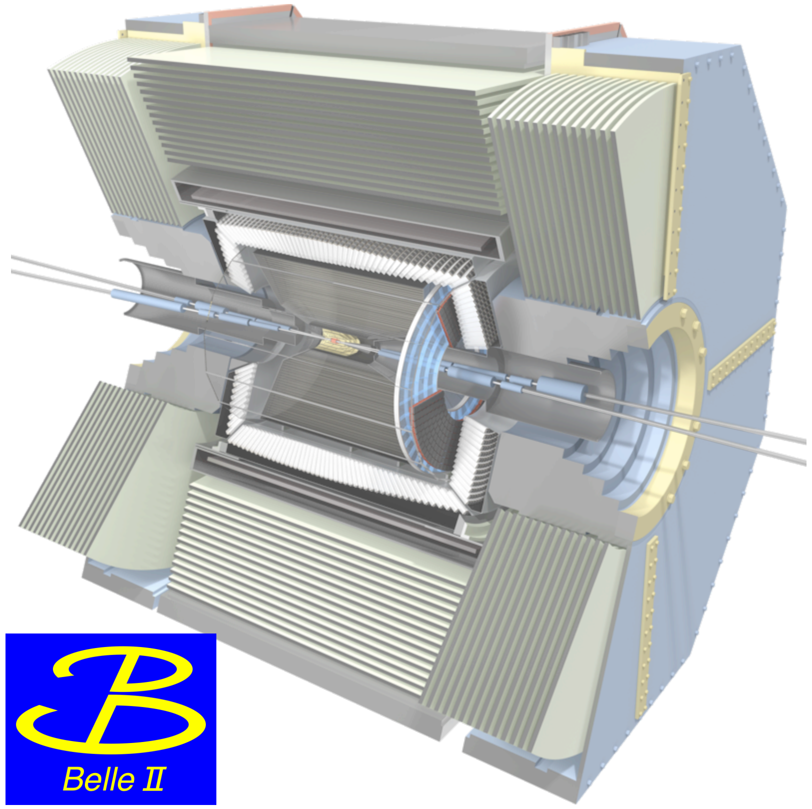
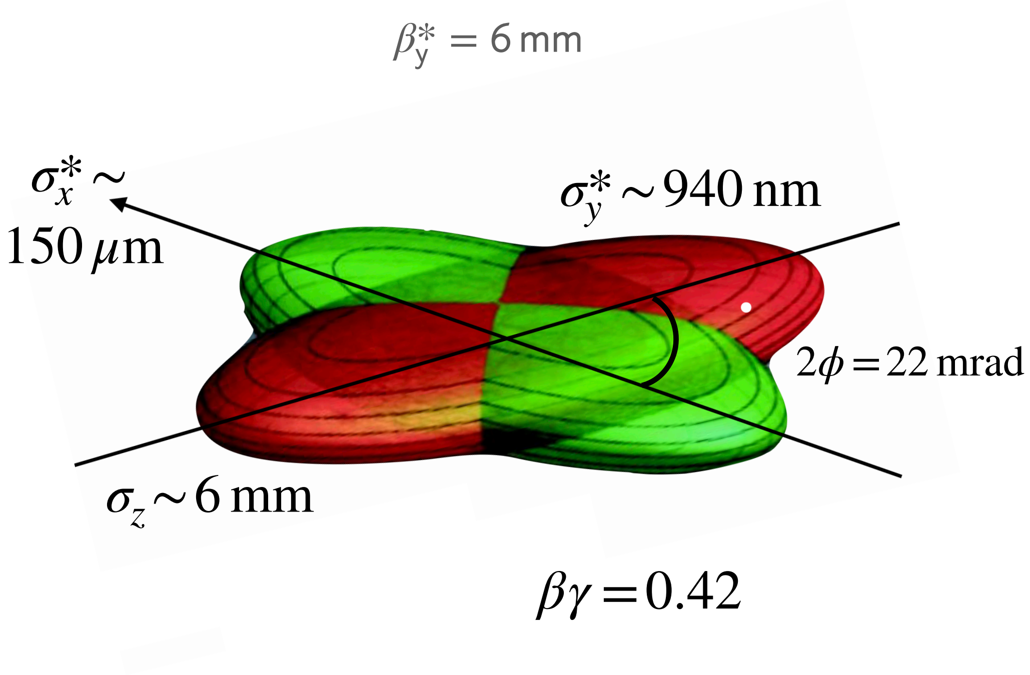


WR Luminosity of 2.1×10^{34} cm^{-2} s^{-1} (Currents 1.2/1.6 A) (June 2009)

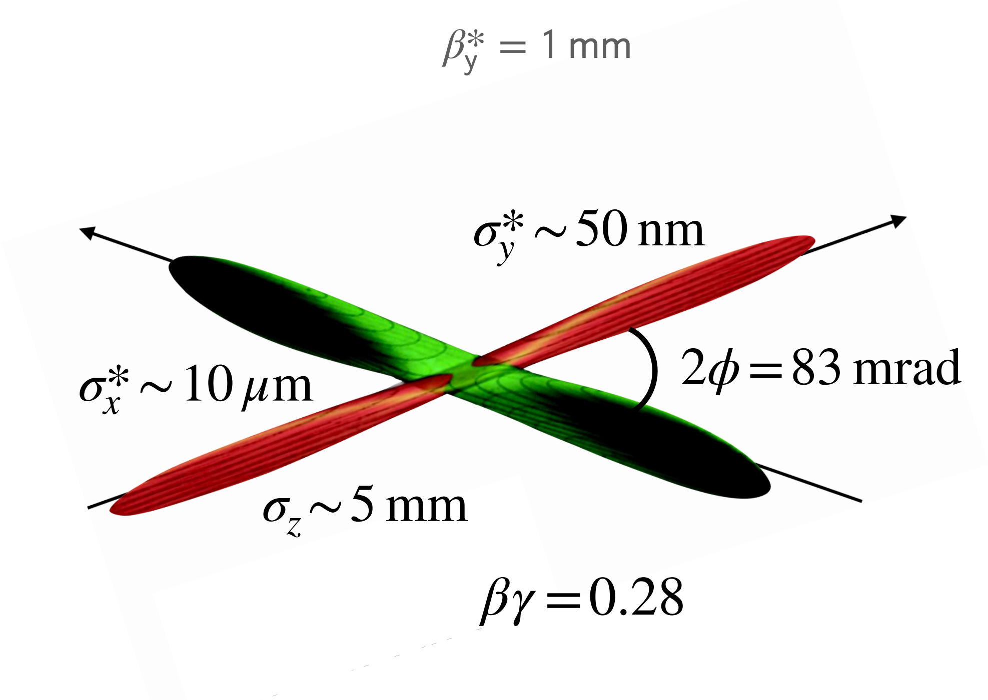
$$\mathscr{L} = \frac{\gamma_\pm}{2 e r_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \, \xi_{y\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_{y\pm}}}\right)$$

WR Luminosity of 4.7×10^{34} cm^{-2} s^{-1} (Currents 1.1/1.5 A) (June 2022)

$\beta_y^* = 6$ mm



$\beta_y^* = 1$ mm



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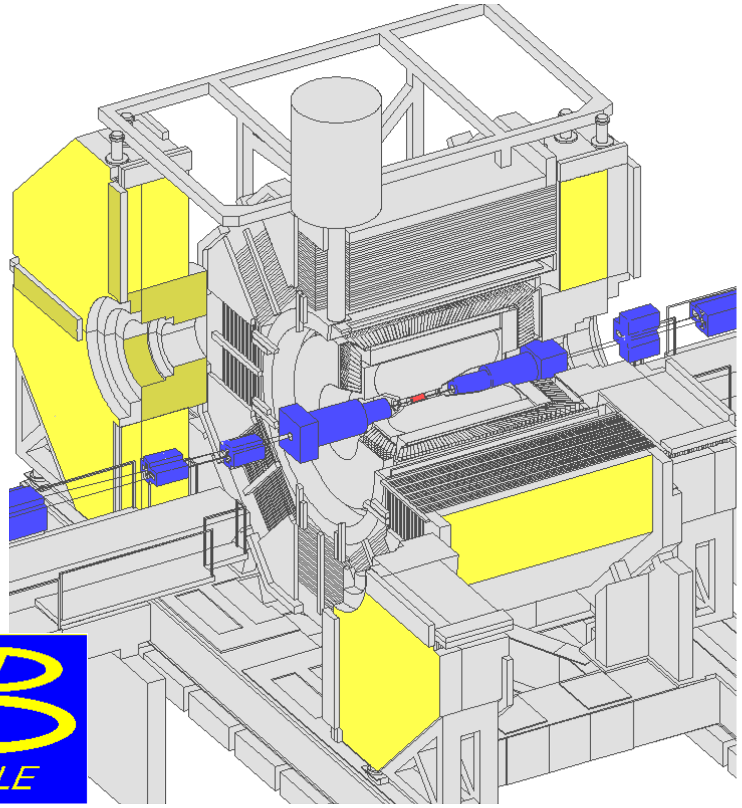

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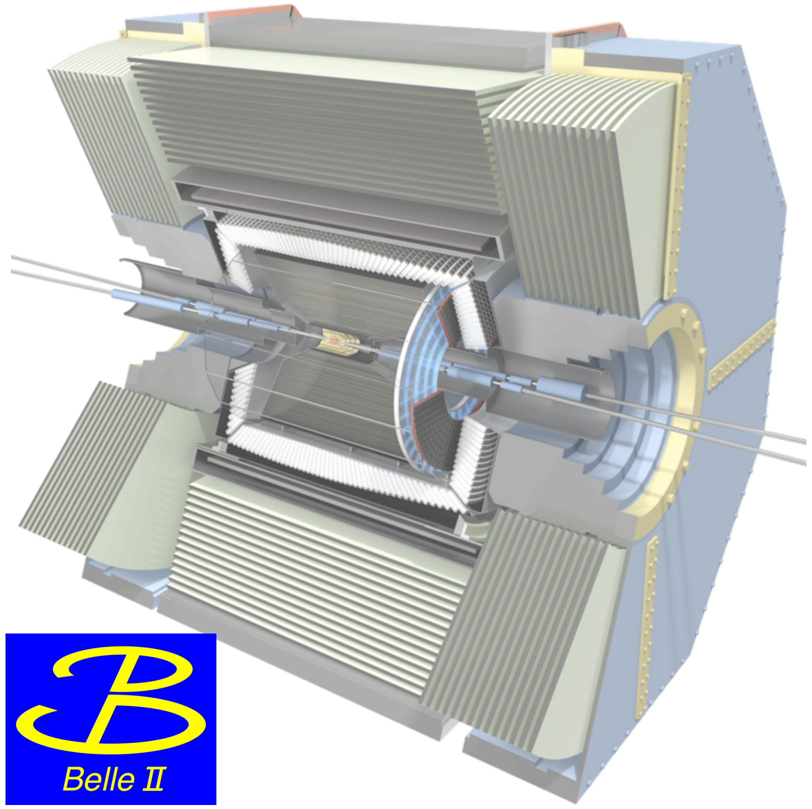
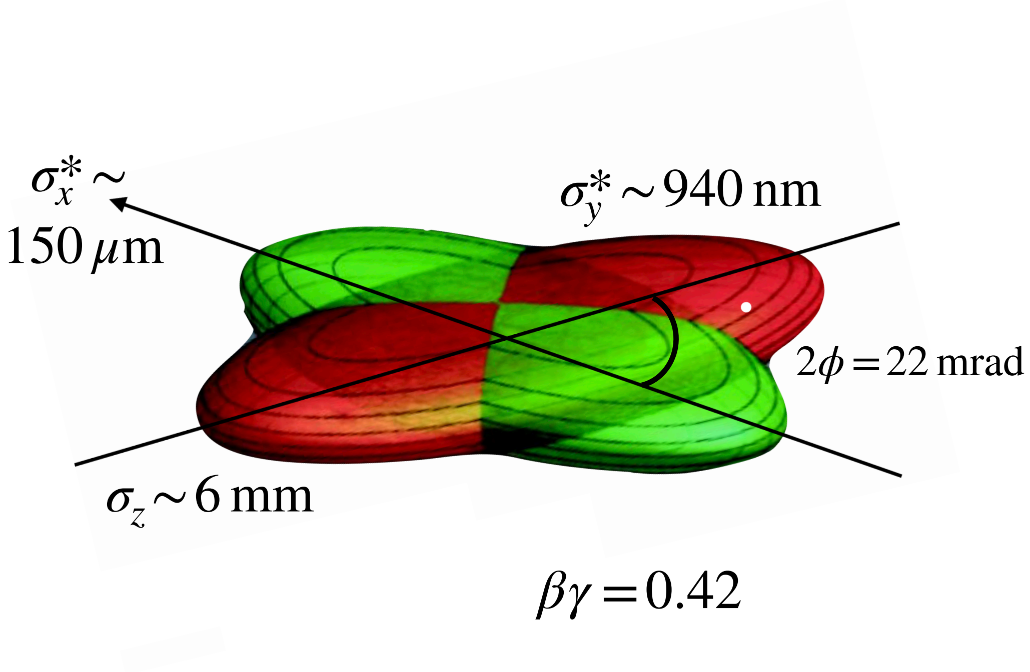
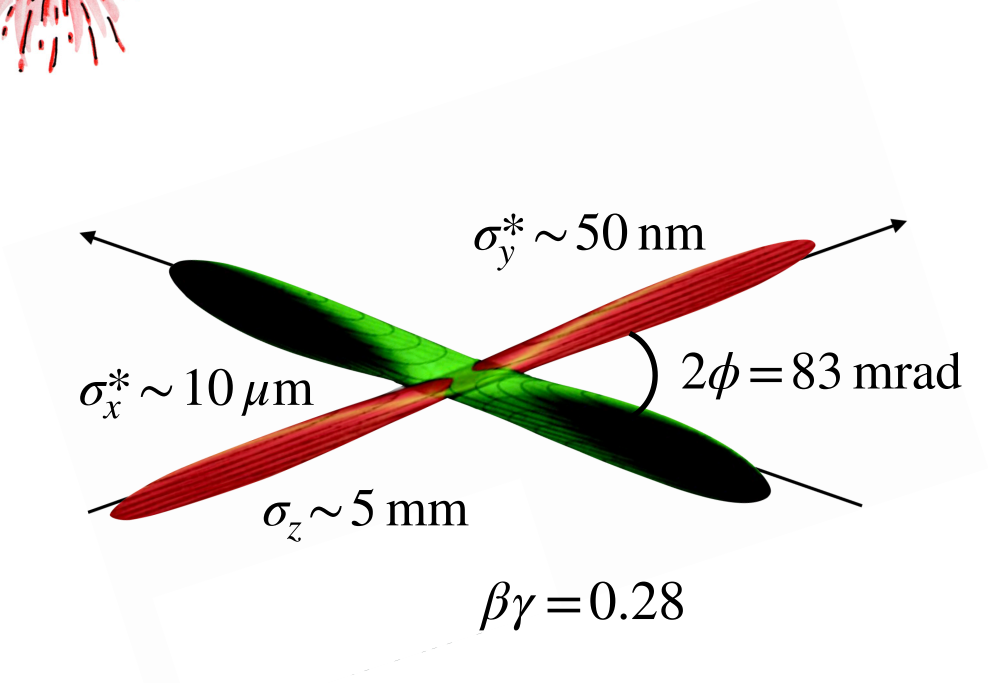


WR Luminosity of 2.1×10^{34} cm^{-2} s^{-1} (Currents 1.2/1.6 A) (June 2009)

WR Luminosity of 5.1×10^{34} cm^{-2} s^{-1} (Currents 1.3/1.7 A) (Dec 2024)





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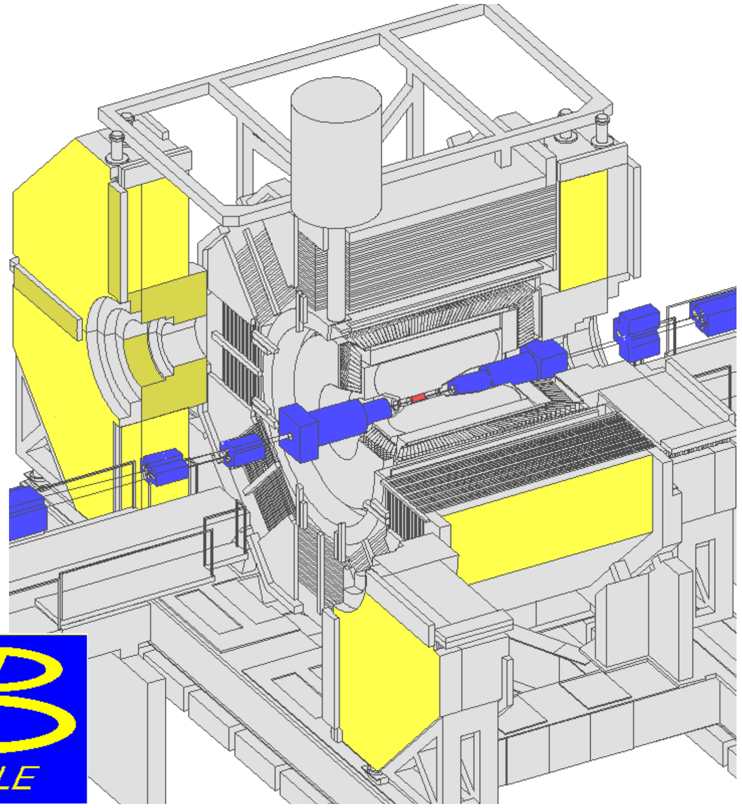
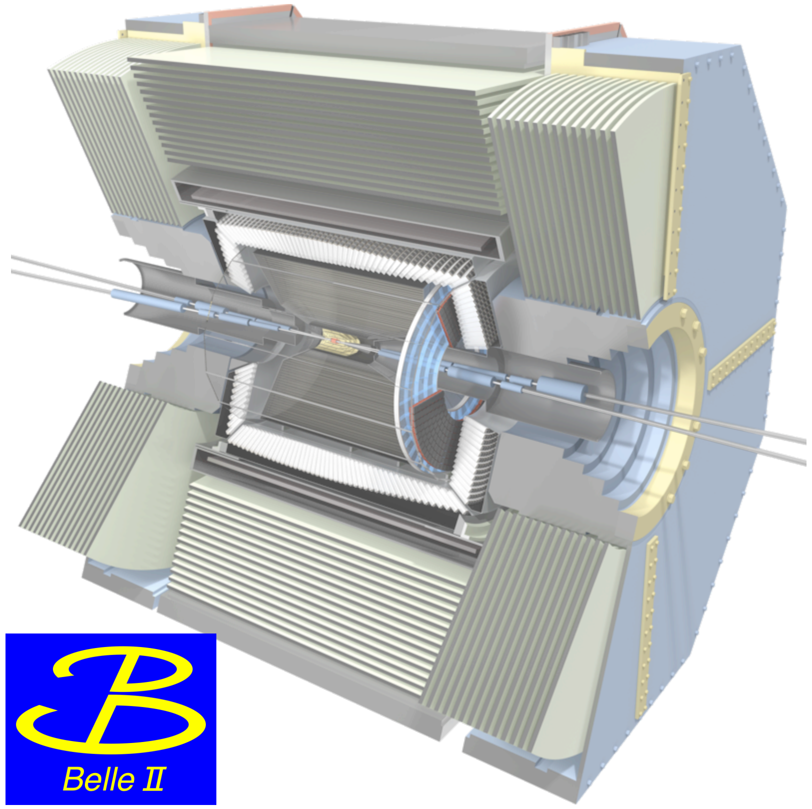
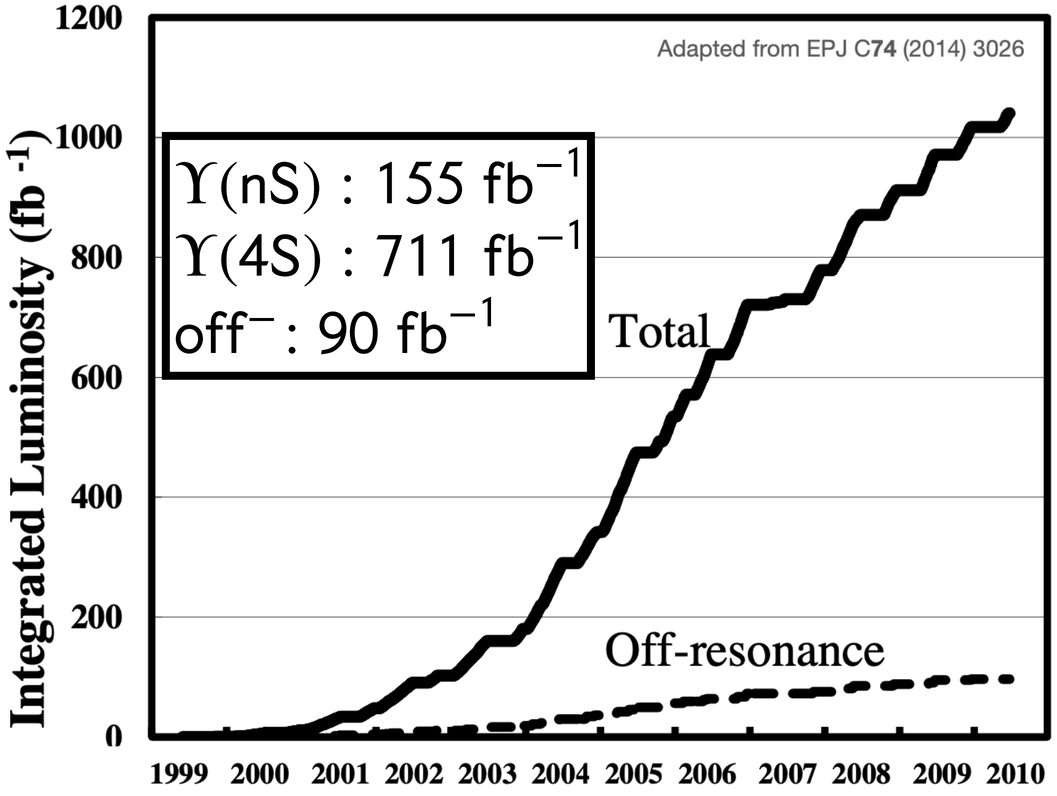


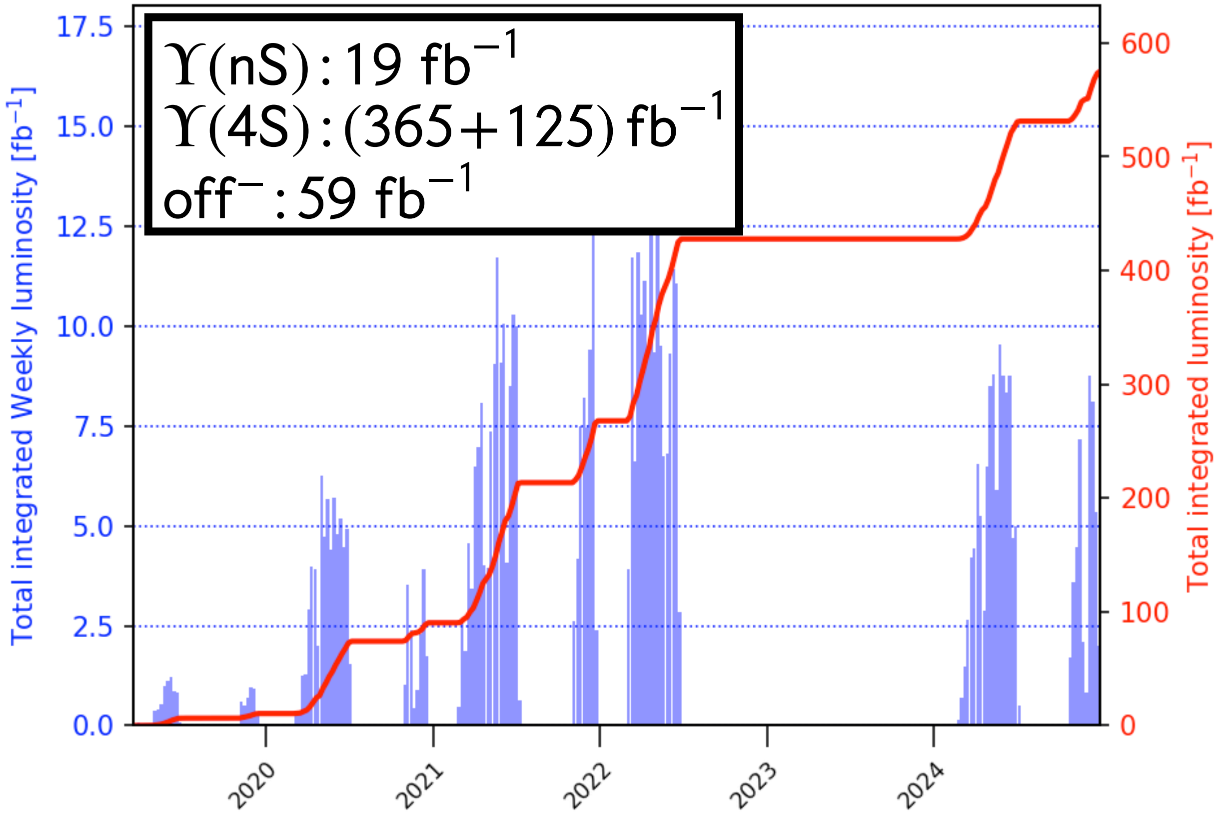
BELLE



Belle II



https://www.belle2.org/research/luminosity/



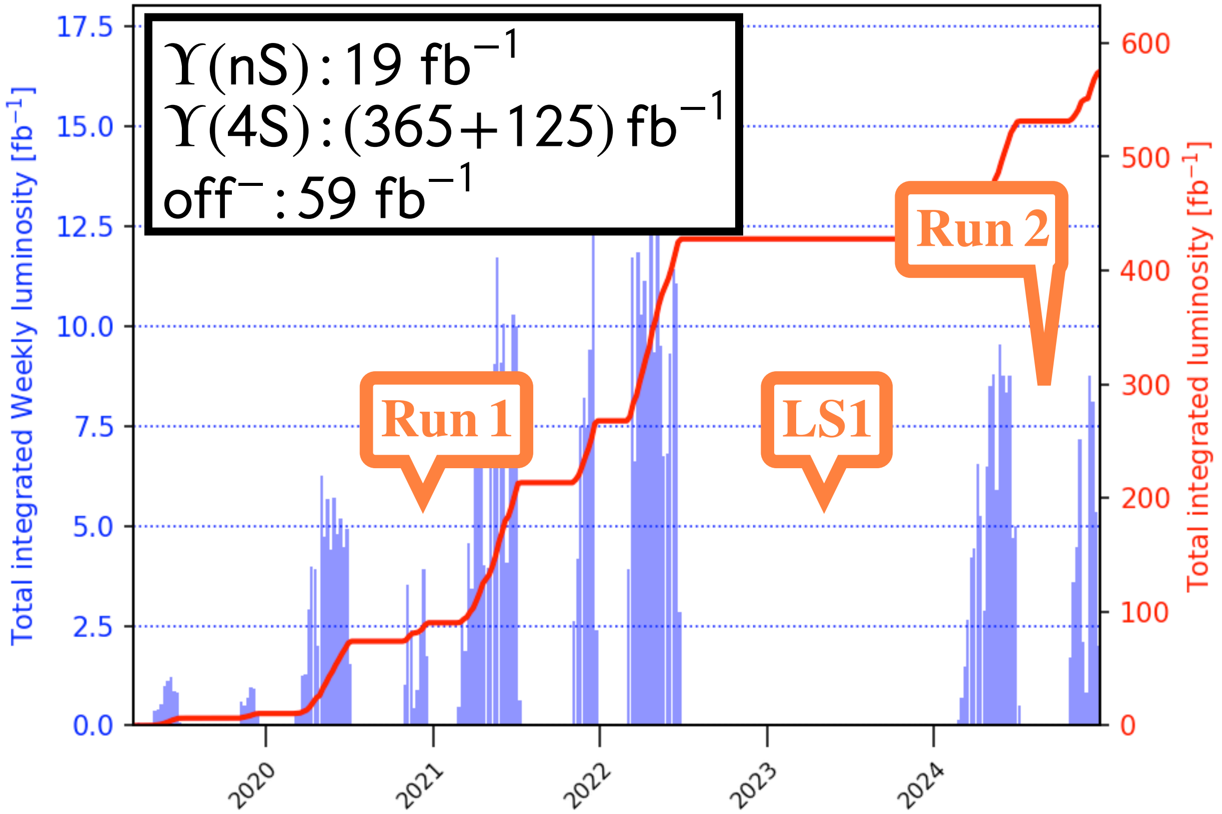
THE BELLE&BELLE II EXPERIMENTS

- Belle II control room, start of Run2

- SuperKEKB control room, last 2024 collisions

Belle2collab

https://www.belle2.org/research/luminosity/



LS1 goals

- **Detector upgrade**
  PXD, TOP, backend readout COPPER→PCIe40
- **Background mitigation**
  Shields, non-linear collimator
- **Protection of machine and Belle II**
  collimator heads, abort systems
- **Improvement of beam injection**

EVENTS AT THE B-FACTORIES

Products of e^+e^- collisions at $\sqrt{s} \approx 10.58$ GeV:

- **Low multiplicity** Bhabha+QED, $\mu^+\mu^-$, $\tau^+\tau^-$
- **Continuum** $u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$
- **$\Upsilon(4S) \to B\overline{B}$** $B^+B^-, B^0\overline{B}^0$

Process	$\sigma(e^+e^- \to X)$ [nb]
$\sigma[\Upsilon(4S)]$	1.11
$\sigma[u\bar{u}(\gamma)]$	1.61
$\sigma[d\bar{d}(\gamma)]$	0.40
$\sigma[s\bar{s}(\gamma)]$	0.38
$\sigma[c\bar{c}(\gamma)]$	1.30
$\sigma[\tau^+\tau^-(\gamma)]$	0.919
$\sigma[e^+e^-(\gamma)]$	300
$\sigma[\gamma\gamma(\gamma)]$	4.99
$\sigma[\mu^+\mu^-(\gamma)]$	1.148
$\sigma[e^+e^-e^+e^-]$	39.7
$\sigma[e^+e^-\mu^+\mu^-]$	18.9
$\sigma[\nu\bar{\nu}(\gamma)]$	0.00025

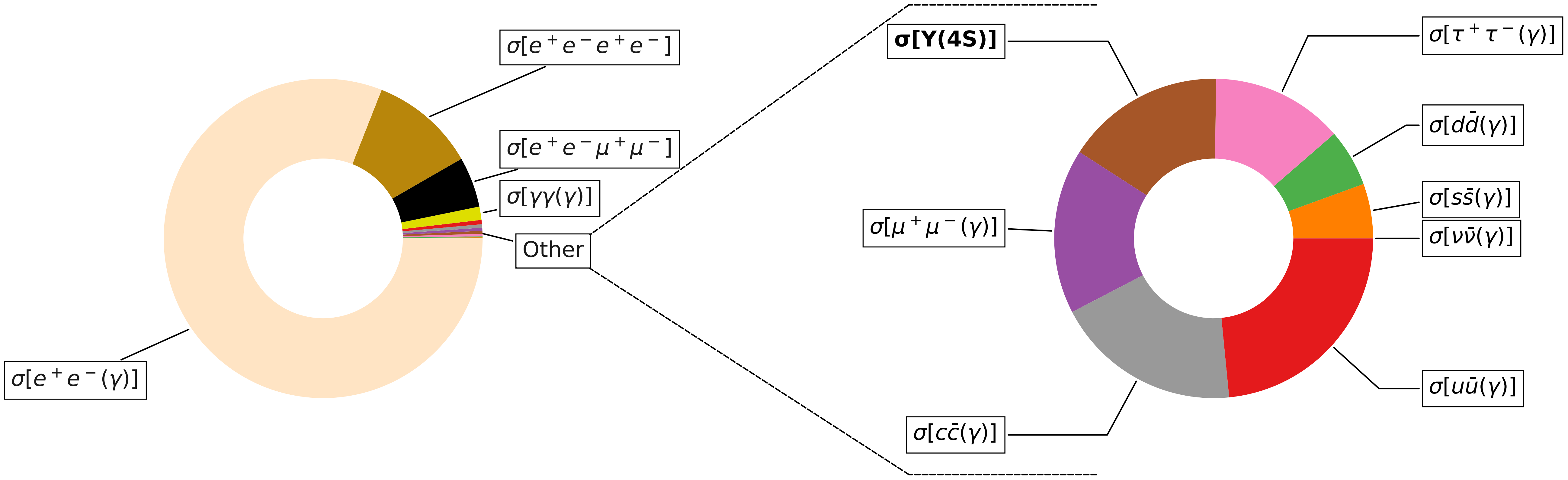
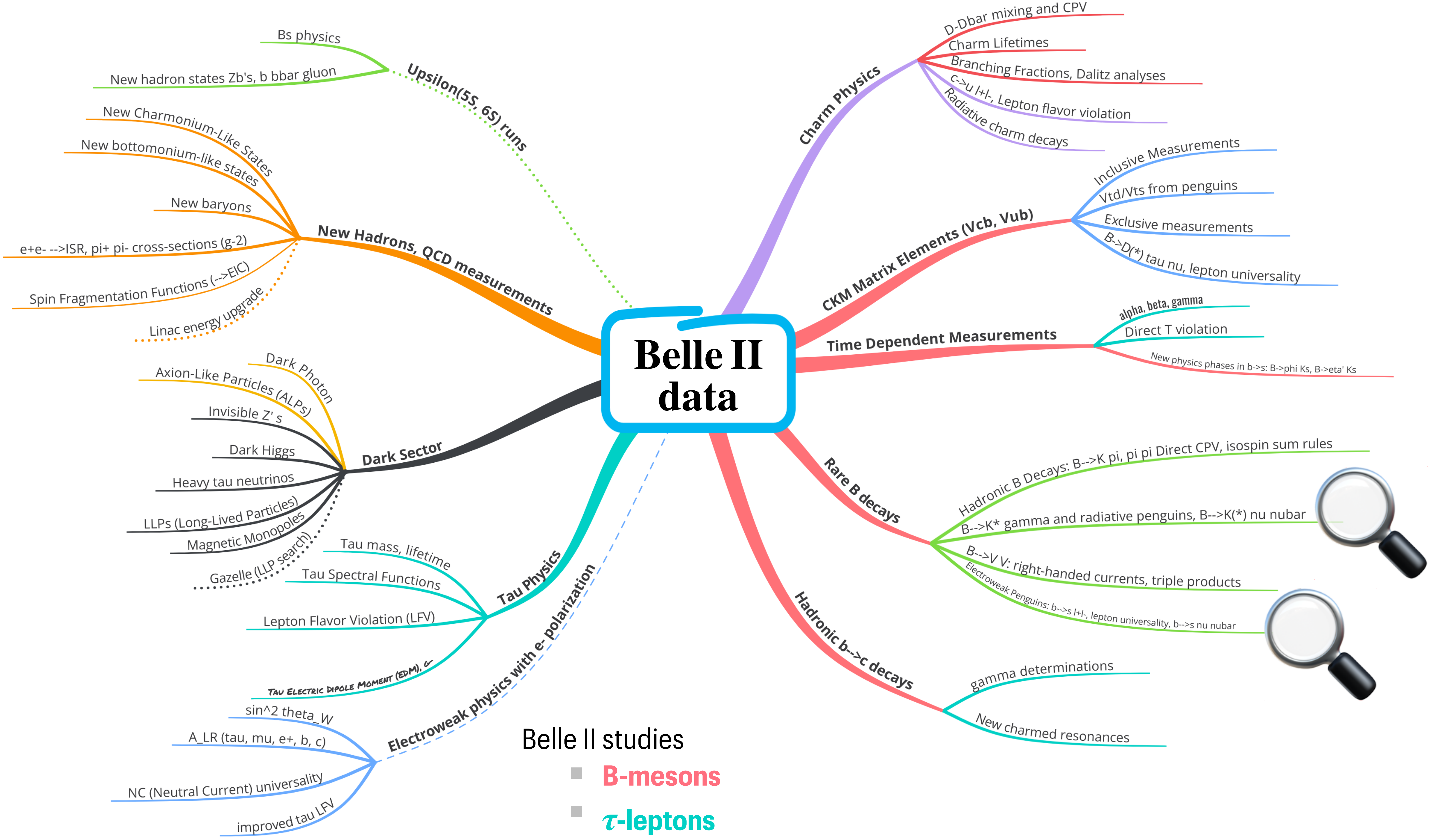


Image credit: H. Svidras (BELLE2-PTHESIS-2023-005)

A RICH PHYSICS PROGRAMME

>50 publications (see here)



Belle II data

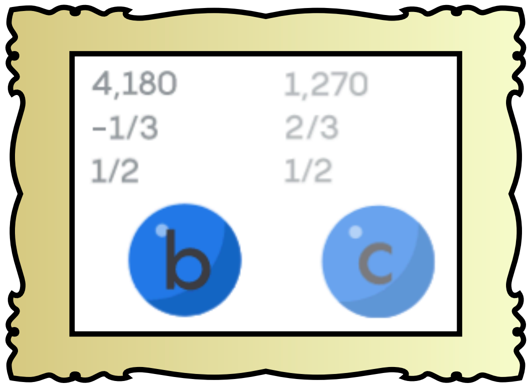
- **Upsilon(5S, 6S) runs**
  - Bs physics
  - New hadron states Zb's, b bbar gluon
- **New Hadrons, QCD measurements**
  - New Charmonium-Like States
  - New bottomonium-like states
  - New baryons
  - e+e- -->ISR, pi+ pi- cross-sections (g-2)
  - Spin Fragmentation Functions (-->EIC)
  - Linac energy upgrade
- **Dark Sector**
  - Dark Photon
  - Axion-Like Particles (ALPs)
  - Invisible Z' s
  - Dark Higgs
  - Heavy tau neutrinos
  - LLPs (Long-Lived Particles)
  - Magnetic Monopoles
  - Gazelle (LLP search)
- **Tau Physics**
  - Tau mass, lifetime
  - Tau Spectral Functions
  - Lepton Flavor Violation (LFV)
  - TAU ELECTRIC DIPOLE MOMENT (EDM), G-
- **Electroweak physics with e- polarization**
  - sin^2 theta_W
  - A_LR (tau, mu, e+, b, c)
  - NC (Neutral Current) universality
  - improved tau LFV
- **Charm Physics**
  - D-Dbar mixing and CPV
  - Charm Lifetimes
  - Branching Fractions, Dalitz analyses
  - c->u l+l-, Lepton flavor violation
  - Radiative charm decays
- **CKM Matrix Elements (Vcb, Vub)**
  - Inclusive Measurements
  - Vtd/Vts from penguins
  - Exclusive measurements
  - B->D(*) tau nu, lepton universality
- **Time Dependent Measurements**
  - alpha, beta, gamma
  - Direct T violation
  - New physics phases in b->s: B->phi Ks, B->eta' Ks
- **Rare B decays**
  - Hadronic B Decays: B-->K pi, pi pi Direct CPV, isospin sum rules
  - B-->K* gamma and radiative penguins, B-->K(*) nu nubar
  - B-->V V: right-handed currents, triple products
  - Electroweak Penguins: b-->s l+l-, lepton universality, b-->s nu nubar
- **Hadronic b-->c decays**
  - gamma determinations
  - New charmed resonances

Belle II studies

- B-mesons
- τ-leptons
- Charmed mesons/baryons
- Dark sector
- Etc.

Today I will cover only two branches

B-PHYSICS



b-quark

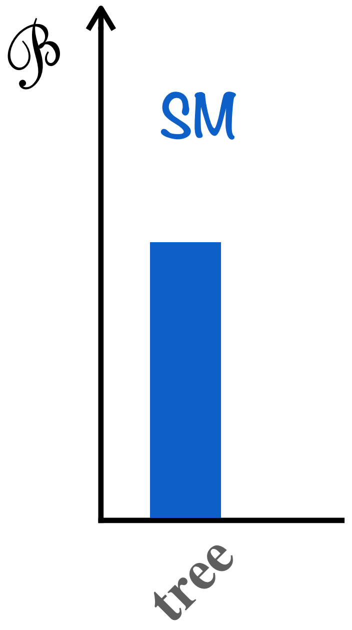
- heaviest fermion forming bound states
- lighter than the *t*-quark ⟹ decays to quarks of other generations

b-hadrons

- Thousands of decay modes $M(B)-M(D)\sim 3\,\mathrm{GeV}$

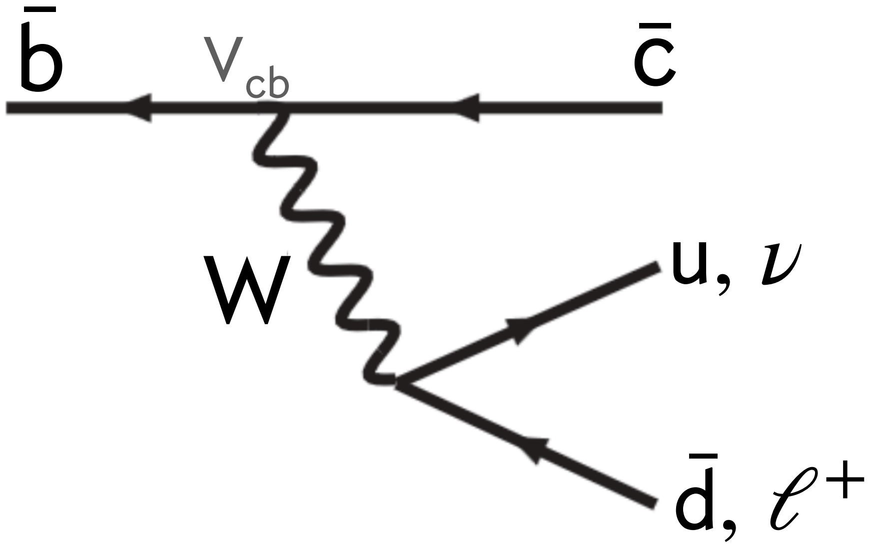
B-factories (like Belle II) have a rich program related to B-mesons

- **Decays with large branching ratio →** Precision measurement of SM observables $\mathcal{B}\sim\mathcal{O}(10^{-3}-10^{-2})$

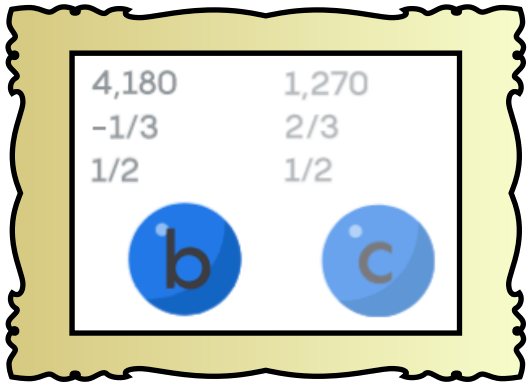


Flavour changing **charged** currents **FCCC** $b\to c$

They occur at **tree level** in the **SM**



B-PHYSICS



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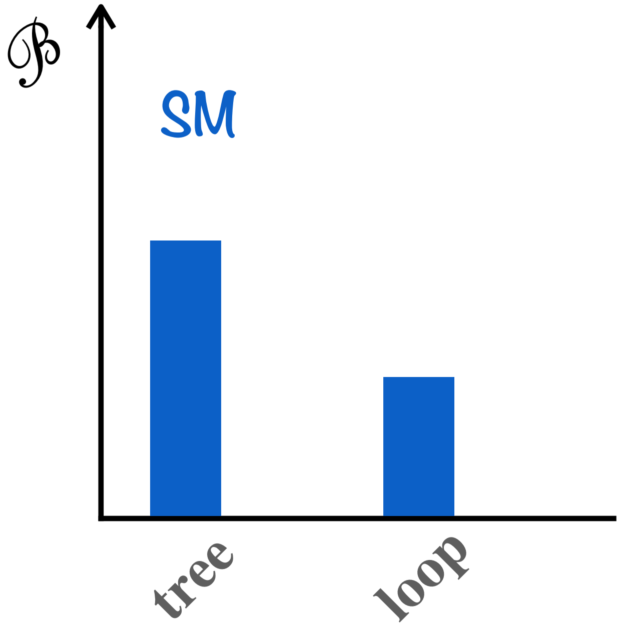
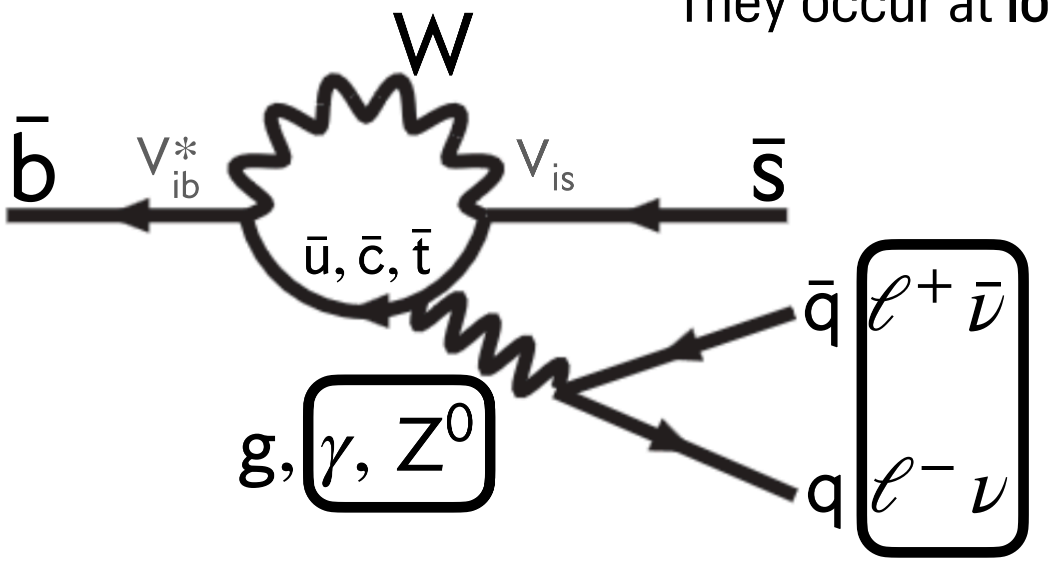
- **Decays with large branching ratio →** Precision measurement of SM observables $\mathscr{B} \sim \mathcal{O}(10^{-3} - 10^{-2})$
- **Decays with low/zero branching ratio →**Searches for rare/forbidden decays $\mathscr{B} < 5 \times 10^{-5}$



Flavour changing **neutral** currents **FCNC** $b \to s/d$

They occur at **loop level** in the **SM**

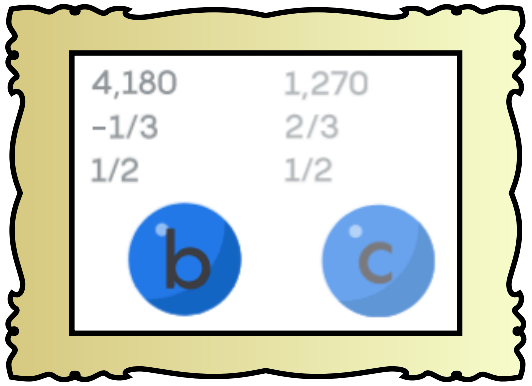


Suppressed by

GIM m_i^2/m_W^2

CKM $V_{ib}V^*_{is}$

B-PHYSICS



b-quark

- heaviest fermion forming bound states
- lighter than the *t*-quark $\Longrightarrow$ decays to quarks of other generations

b-hadrons

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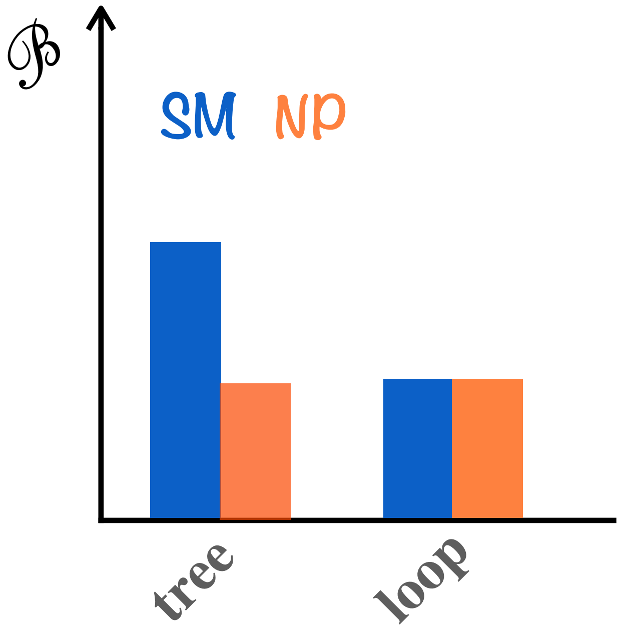
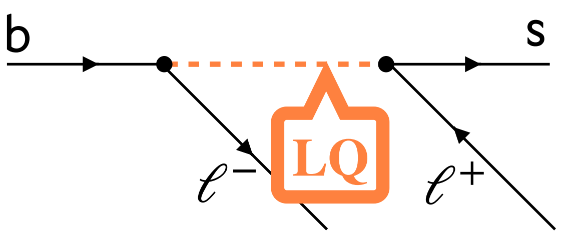
B-factories (like Belle II) have a rich program related to B-mesons

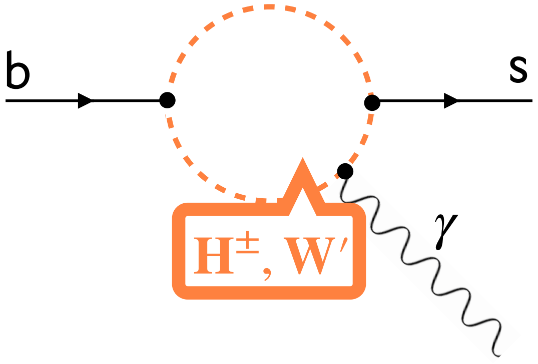
- **Decays with large branching ratio →** Precision measurement of SM observables $\mathscr{B} \sim \mathcal{O}(10^{-3} - 10^{-2})$
- **Decays with low/zero branching ratio →** Searches for rare/forbidden decays $\mathscr{B} < 5 \times 10^{-5}$

Alterations/enhancements in FCNC due to NP contributions:





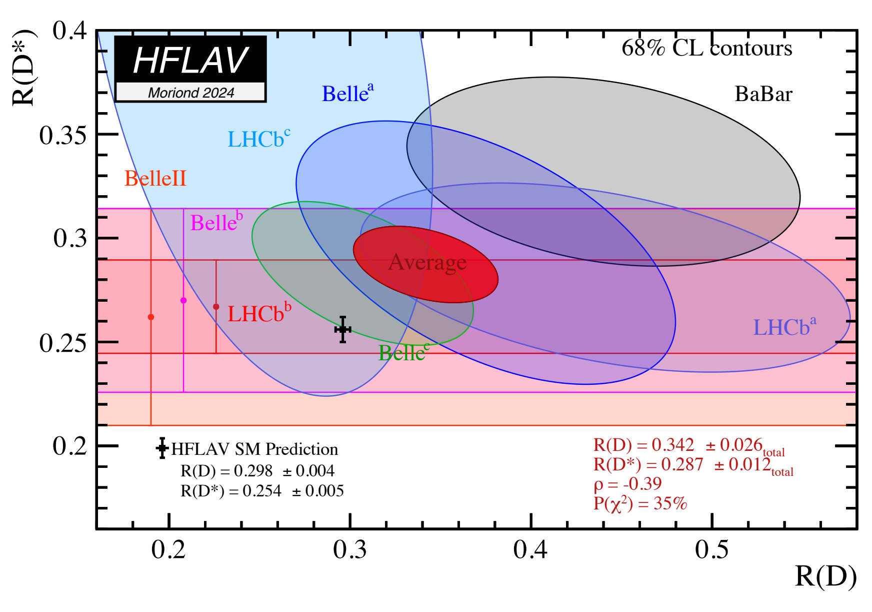
- New interactions at tree level



- Weaker GIM cancellations due to new particles in loop corrections

B-ANOMALIES

$b \to c\tau\nu$

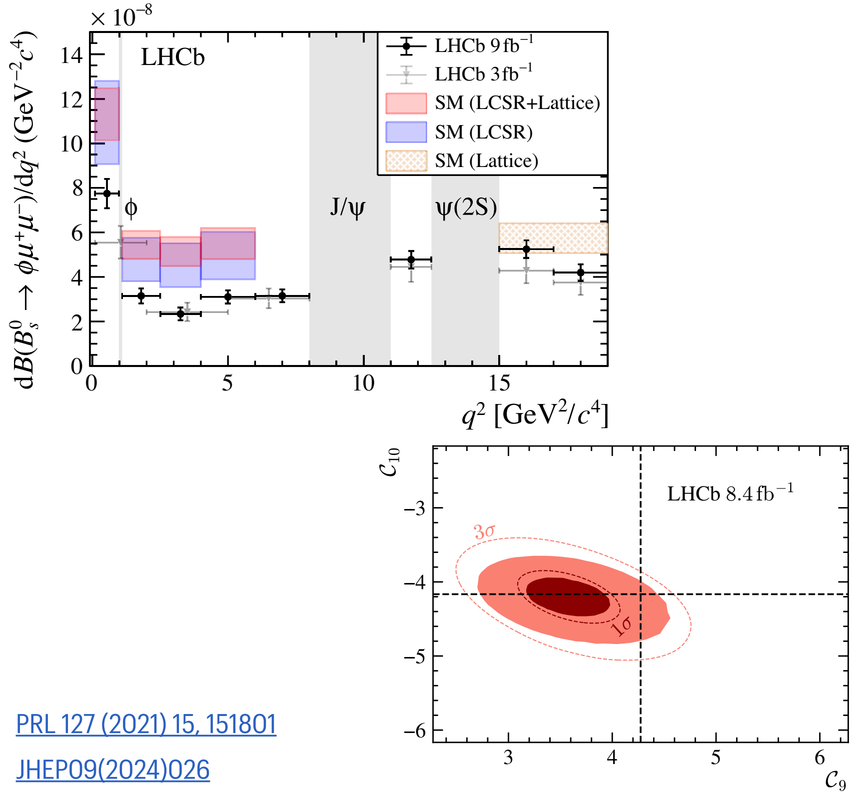


HFLAV

3.31σ for R(D) – R(D*)

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

$b \to s\mu\mu$

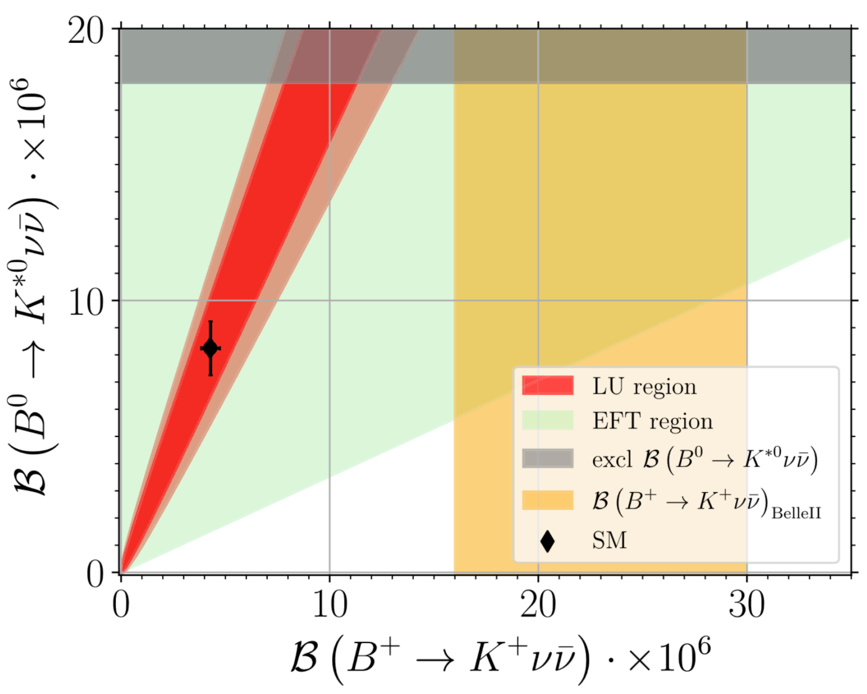


PRL 127 (2021) 15, 151801

JHEP09(2024)026

1-3σ tensions in several observables

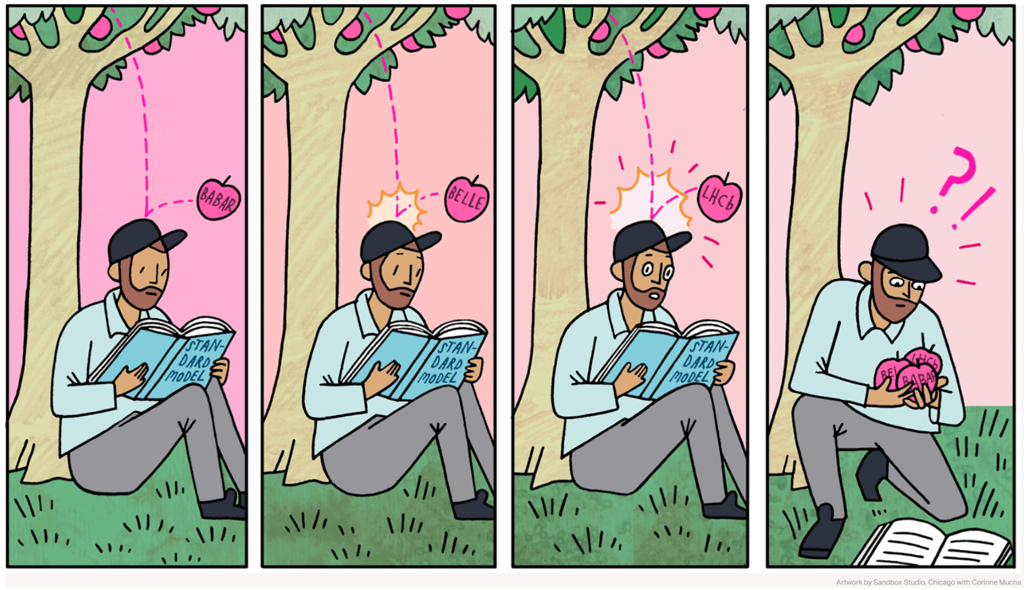
$b \to s\nu\nu$



PRD 109, 015006 (2024)

$$\frac{\mathcal{B}(B \to K\nu\nu)}{\mathcal{B}(B \to K\nu\nu)^{SM}} = 5.4 \pm 1.5\ (2.7\sigma)$$

Is there a joint explanation?

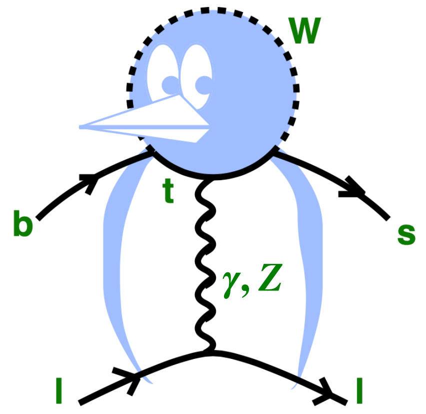


THE FLAVOUR WAY

Rare decays: more sensitive to NP and less limited by collision energy

but

- harder to interpret compared to a bump

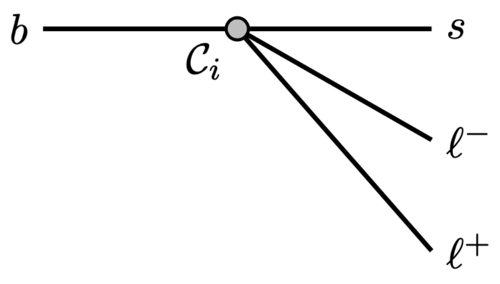


Full theory

EW scale

>>

m_b



Wilson Coefficients

$$\mathscr{L}_{\text{eff}} = \frac{4G_F}{\sqrt{2}}\lambda_t \sum_i \left(\boxed{C_i(\mu)}\,\boxed{\mathcal{O}_i(\mu)}\right)$$

Effective operators

Effective description

SM operators

Dipole operator $$\mathcal{O}_7^{ij} = \frac{e\, m_{d_j}}{(4\pi)^2}(\bar{d}_i\, \sigma_{\mu\nu}\, P_R\, d_j)\, F^{\mu\nu}$$

SL operators $$\mathcal{O}_9^{ij;\ell\ell'} = \frac{e^2}{(4\pi)^2}(\bar{d}_i\, \gamma^\mu\, P_L\, d_j)(\bar{\ell}\, \gamma_\mu\, \ell') \qquad \mathcal{O}_{10}^{ij;\ell\ell'} = \frac{e^2}{(4\pi)^2}(\bar{d}_i\, \gamma^\mu\, P_L d_j)(\bar{\ell}\, \gamma_\mu\, \gamma_5\, \ell')$$

(pseudo)scalar operator $$\mathcal{O}_P^{ij;\ell\ell'} = \frac{e^2}{(4\pi)^2}(\bar{d}_i\, P_R\, d_j)(\bar{\ell}\, \gamma_5\, \ell') \qquad \mathcal{O}_S^{ij;\ell\ell'} = \frac{e^2}{(4\pi)^2}(\bar{d}_i\, P_R\, d_j)(\bar{\ell}\, \ell')$$

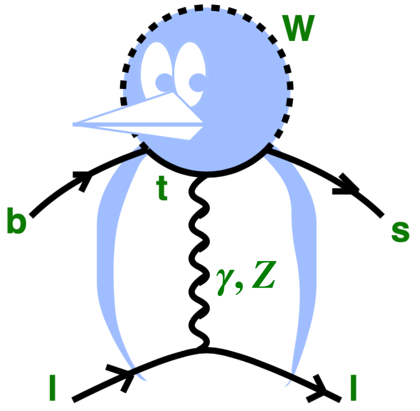
$$P_{L/R} = \frac{1}{2}(1 \mp \gamma_5)$$

THE FLAVOUR WAY

Rare decays: more sensitive to NP and less limited by collision energy

but

- harder to interpret compared to a bump



Full theory

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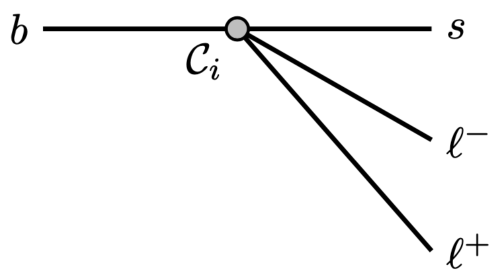
$>>$

m_b



Wilson Coefficients

$$\mathscr{L}_{\rm eff} = \frac{4G_F}{\sqrt{2}}\lambda_t \sum_i \left(\boxed{C_i(\mu)}\boxed{\mathcal{O}_i(\mu)}\right)$$

Effective operators

Effective description

NP can manifest through

- Alterations of SM couplings $\mathbf{C_9^{eff} = C_9^{SM} + C_9^{NP}}$
- Additional operators

$\mathcal{O}'^{\ell\ell}_{\mathbf{9,10}}$

$\mathcal{O}^{\nu_i\nu_j}_{\mathbf{R}}$

$\mathcal{O}'_{\mathbf{7}}$

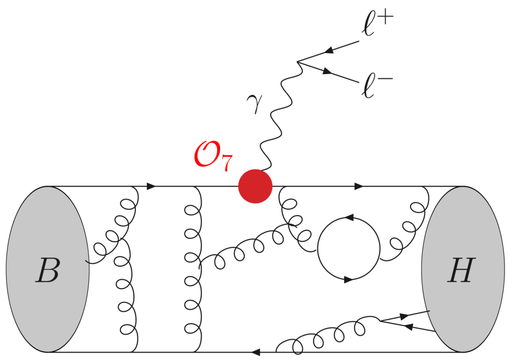
$\mathcal{O}^{(\prime)}_{\mathbf{C,P}}$

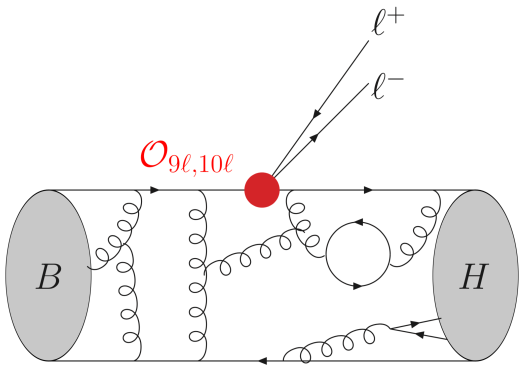
THE FLAVOUR WAY

Rare decays: more sensitive to NP and less limited by collision energy

but

- harder to interpret compared to a bump
- **predictions for SM observables must be well-known**





Theoretical uncertainties arise from

- WC and constants (e.g. V_{CKM})
  → **small uncertainties**

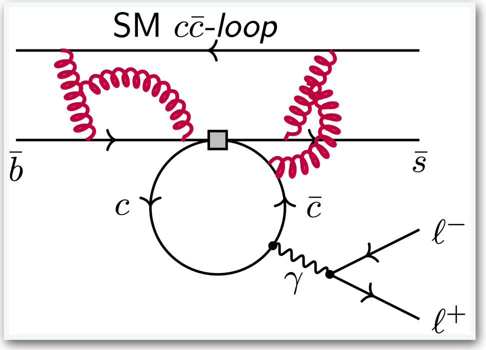
$$|\lambda_t| = |V_{tb}V_{ts}^*| = |V_{cb}|(1+\mathcal{O}(\lambda^2))$$

- Local hadronic ME
  → **Moderate uncertainties (3-15%)**

$$\langle H|\mathcal{O}_{7,9,10}|B\rangle$$

$\mathcal{O}_{7,9,10} = (\bar{s}\Gamma b)$

- Non-local hadronic ME
  → **Large uncertainties**



$$i\int d^4x\, e^{iq\cdot x}\left\langle K^{(*)}\middle|T\{j_\mu^{em}(x)\mathcal{O}^c_{1,2}(0)\}\middle|B\right\rangle$$

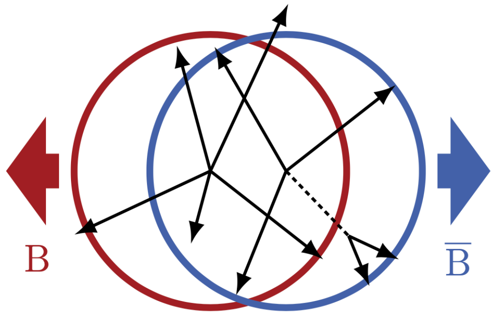
$\mathcal{O}_{1,2} = (\bar{s}\Gamma b)(\bar{c}\Gamma c)$

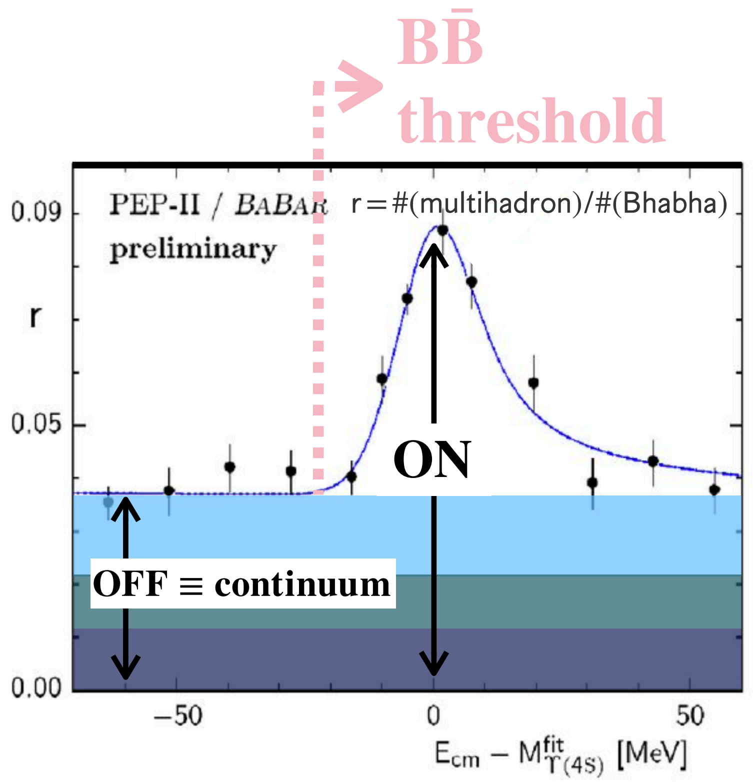
Use ratios for (partial) cancellation of uncertainties — both theoretical and experimental

$$\frac{\mathcal{B}(B\to K\mu\mu)}{\mathcal{B}(B\to Kee)} \qquad \frac{\mathcal{B}(\bar{b}\to\bar{f}) - \mathcal{B}(b\to f)}{\mathcal{B}(\bar{b}\to\bar{f}) + \mathcal{B}(b\to f)}$$

B-PHYSICS AT B-FACTORIES

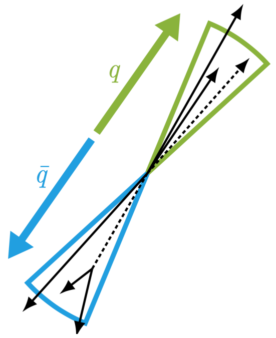
- **Threshold $B\bar{B}$ production** → Relatively low backgrounds



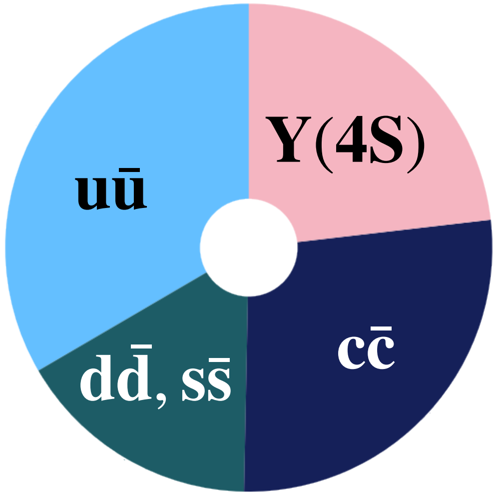


- **Known initial kinematics + almost-4π detector coverage** → reconstruct final states with neutrinos

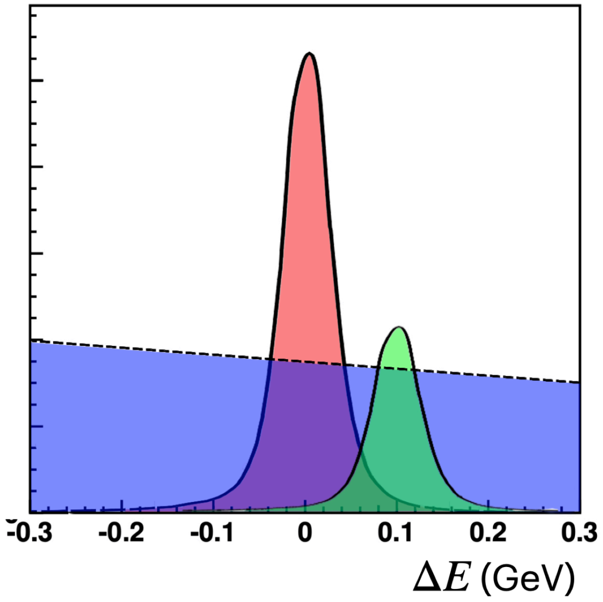
- **OFF-resonance data** → $B\bar{B}$-free sample



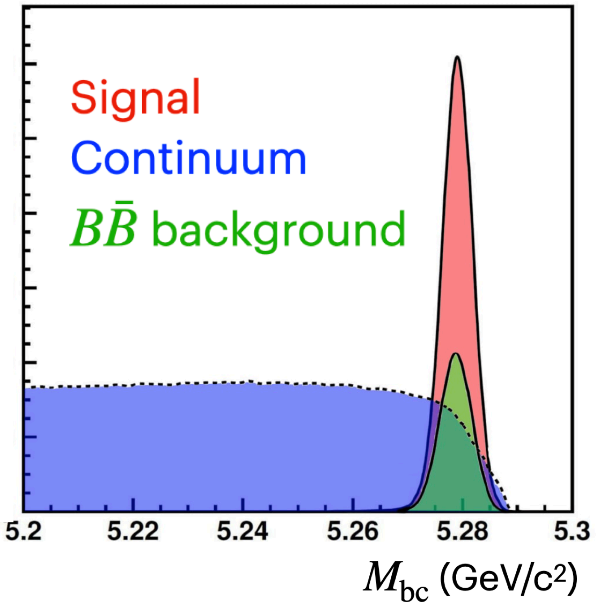
Hadronic cross-section @ $\sqrt{s} = 10.58$ GeV



$$\Delta E = E^*_B - E^*_{beam}$$



$$M_{bc} = \sqrt{(E^*_{beam}/c^2)^2 - (p^*_B/c)^2}$$



- **Energy difference ΔE and beam-constrained mass M_{bc} and as discriminative variables against combinatorial and peaking backgrounds**

$\mathrm{B\bar{B}}$ EVENT DISPLAY

What we need for a $\mathrm{B\bar{B}}$ event

- Identify charged particles
- Distinguish different species (e, μ, π, K)
- Reconstruct neutrals (γ, $\mathrm{K_L^0}$)
- Overcome the presence of missing energy - ν's

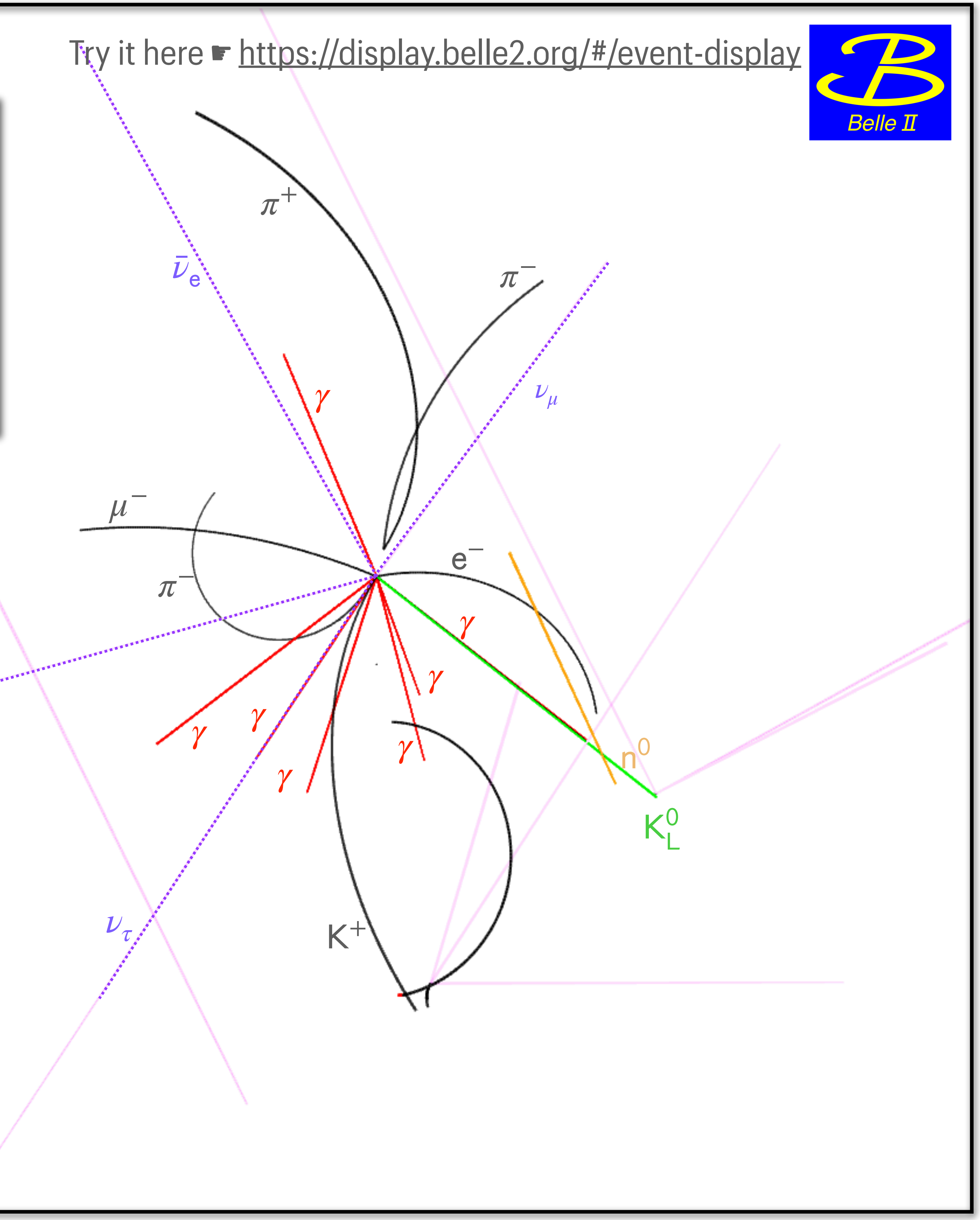
$$\Upsilon(4S) \to \bar{\mathrm{B}}^0 \ \mathrm{B}^0$$

$$\bar{\mathrm{B}}^0 \to \mathrm{K_S^0}(\pi^+\pi^-)\tau^-(\mathrm{e}^-\bar{\nu}_\mathrm{e}\nu_\tau\gamma)\tau^+(\mathrm{K}^+\pi^0\bar{\nu}_\tau)$$

$$\mathrm{B}^0 \to \mathrm{D}^{*-}(\mathrm{D}^-\pi^0)\mu^+\nu_\mu$$

$$\mathrm{D}^- \to \mathrm{K_L^0}\pi^-\pi^0$$

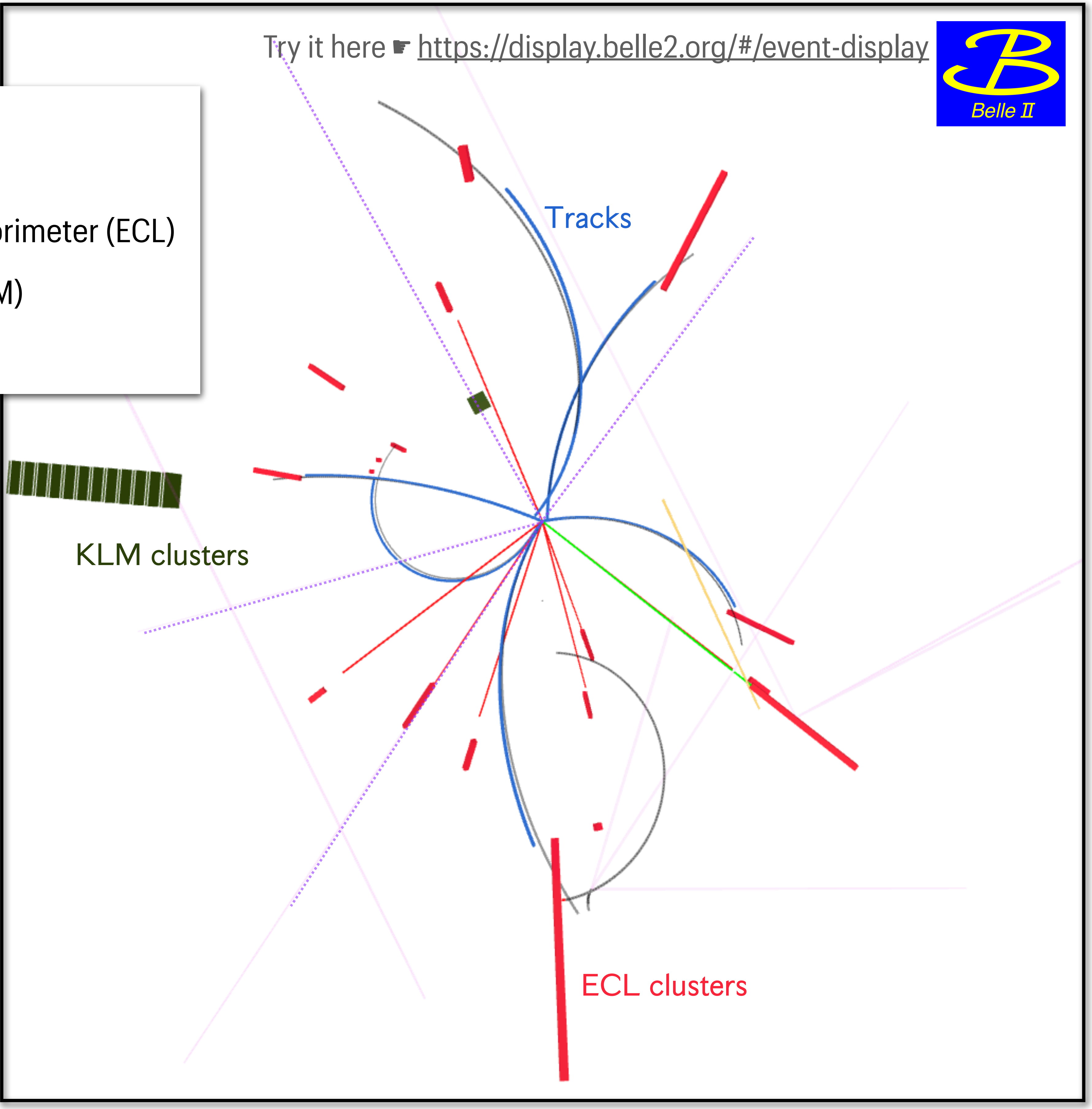
Try it here ☛ https://display.belle2.org/#/event-display



$B\bar{B}$ EVENT DISPLAY

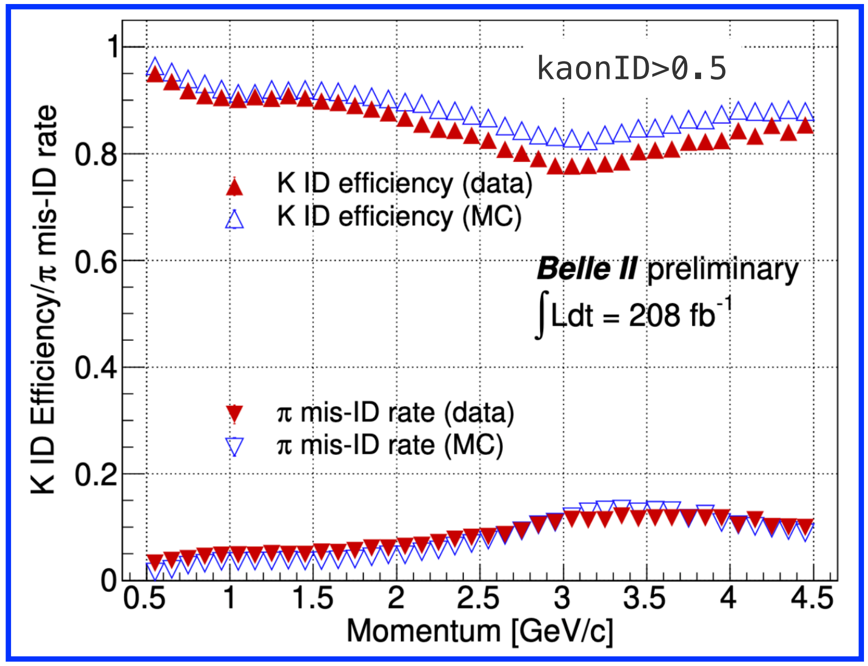
What we get

- Tracks
- Clusters in the electromagnetic calorimeter (ECL)
- Clusters in the $\mu + K^0_L$ detector (KLM)
- (+ PID objects: see next slide)



Try it here ☛ https://display.belle2.org/#/event-display

KEY-PERFORMANCE AT BELLE II



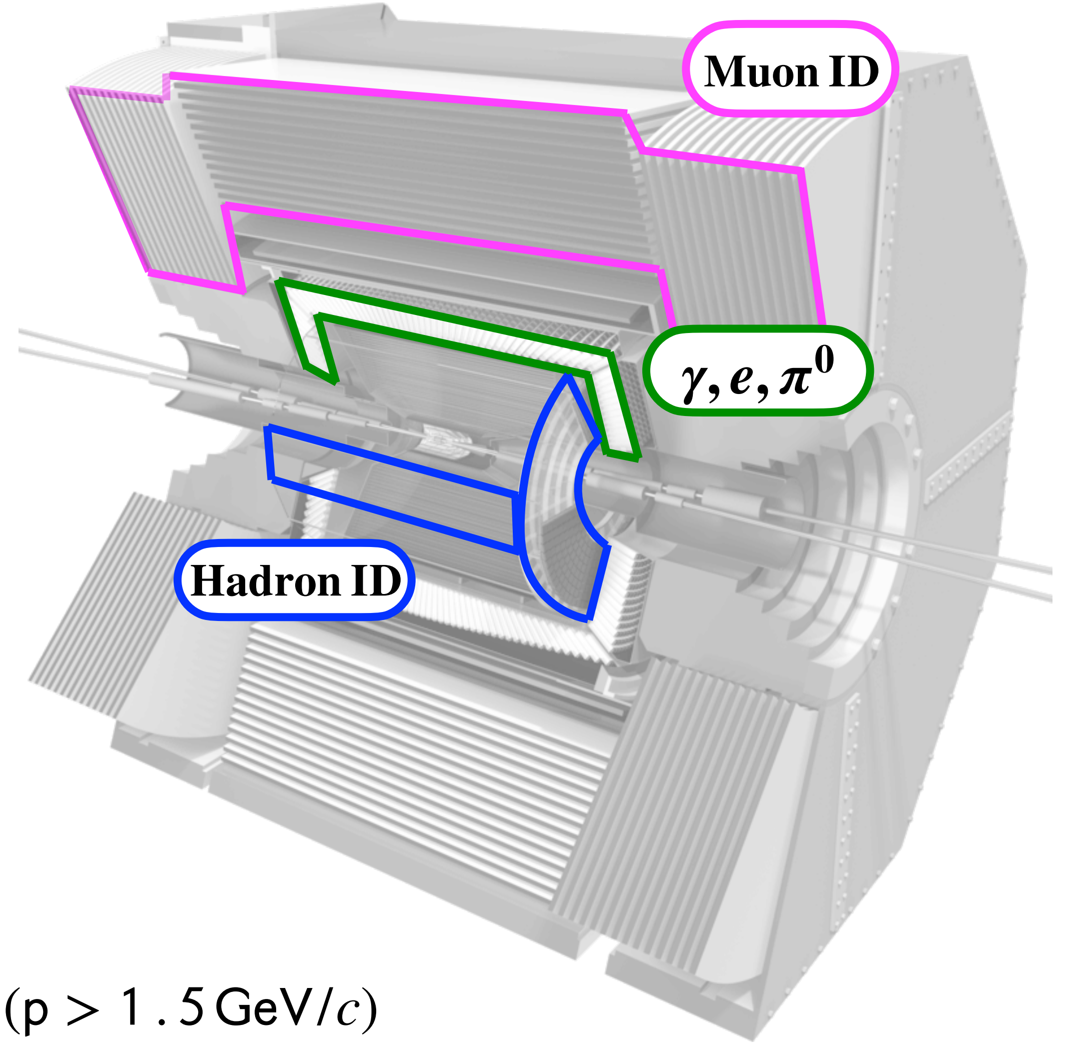
K ID

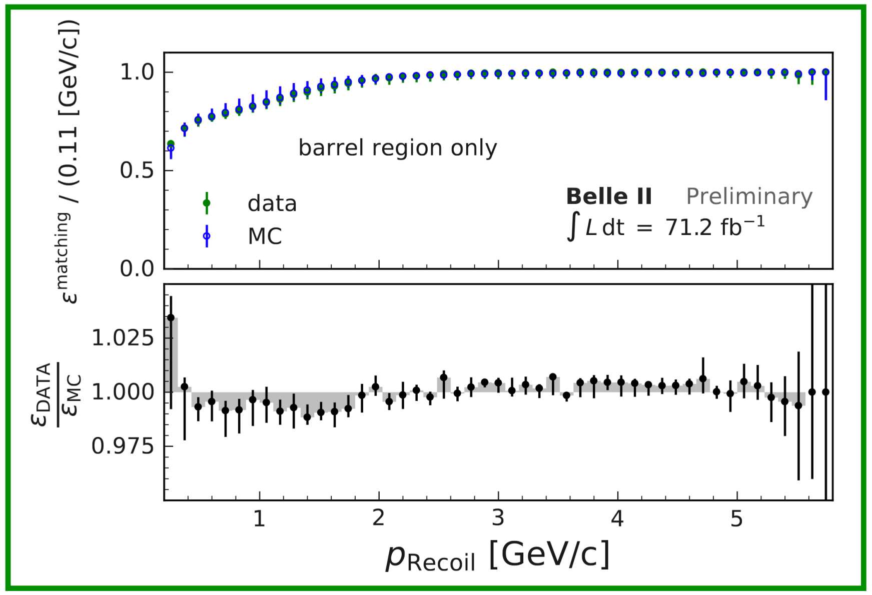
$\varepsilon \sim 90\,\%$

$\pi \rightarrow K \sim 6\,\%$

Good kaon identification in full momentum range

Belle II TDR, arXiv: 1011.0352

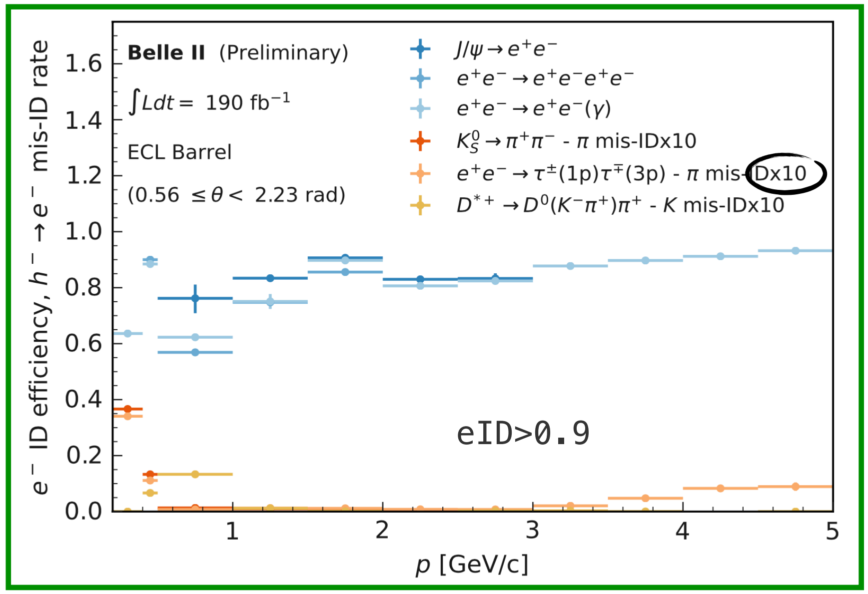




γ, π^0

High photon efficiency $\varepsilon > 90\,\%$ ($p > 1.5\,\mathrm{GeV}/c$)

Belle-like resolution on π^0 mass



e ID

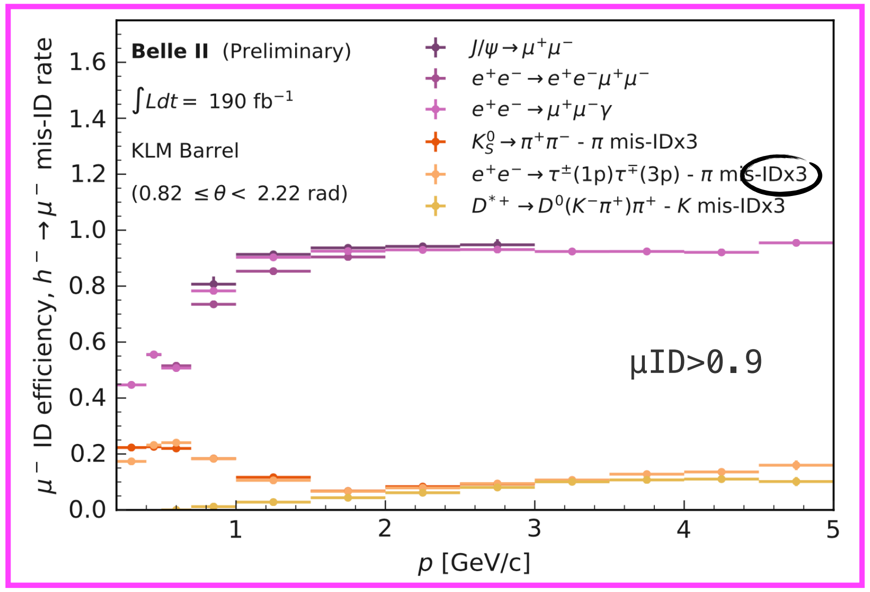
$\varepsilon \sim 86\,\%$

$\pi \rightarrow e \sim 0.4\,\%$

μ ID

$\varepsilon \sim 90\,\%$

$\pi \rightarrow \mu \sim 7\,\%$

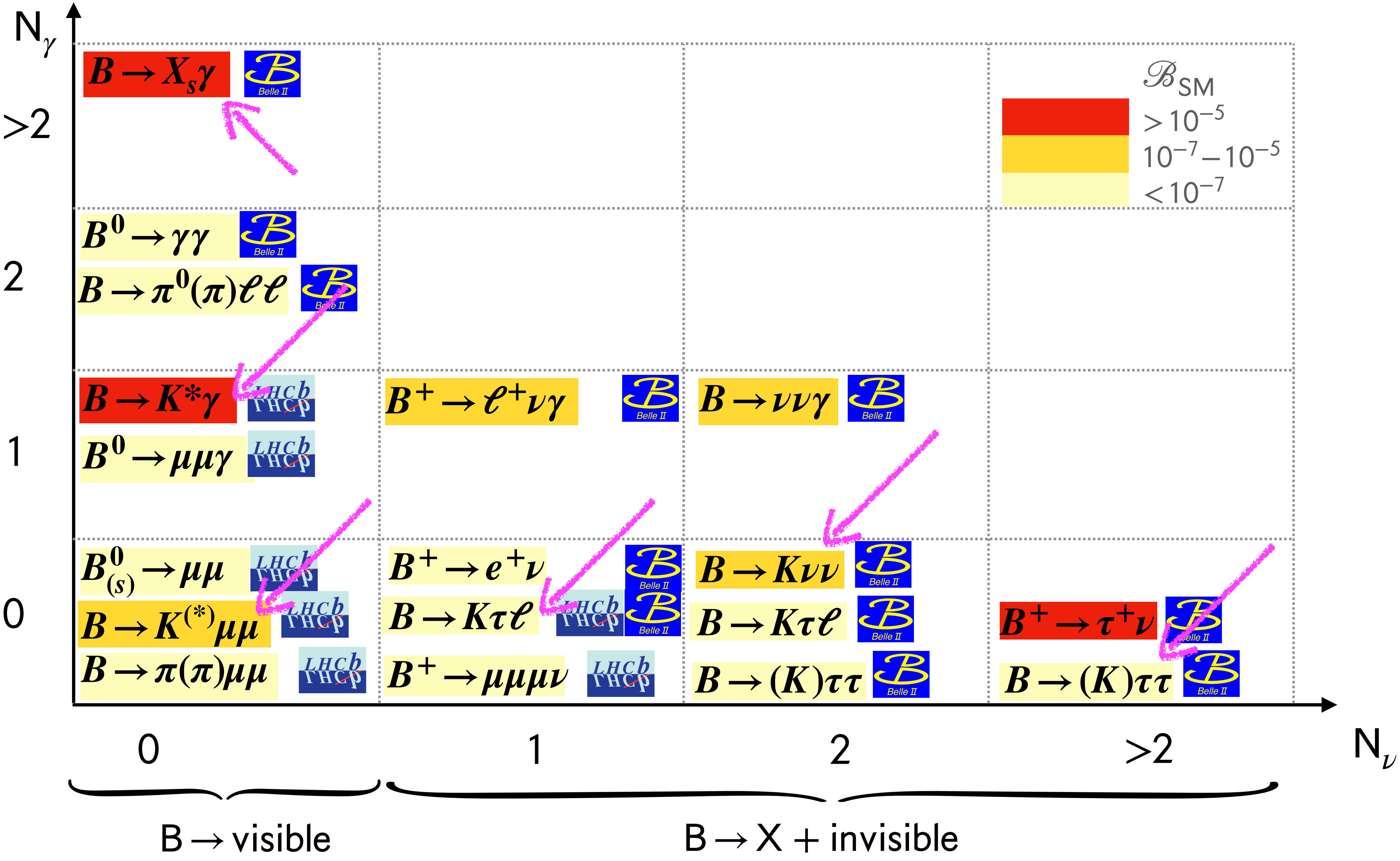


Good lepton ID and similar $e - \mu$ performance

PLENTY OF DECAYS

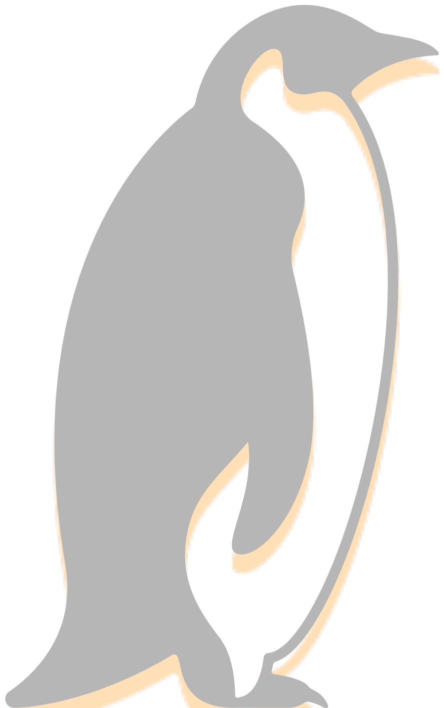
Many decay modes to measure/search for at *B*-flavour experiments

- **LHCb** Better with muons/charged particles that can be vertexed
- **Belle II** Better with e, γ and ν



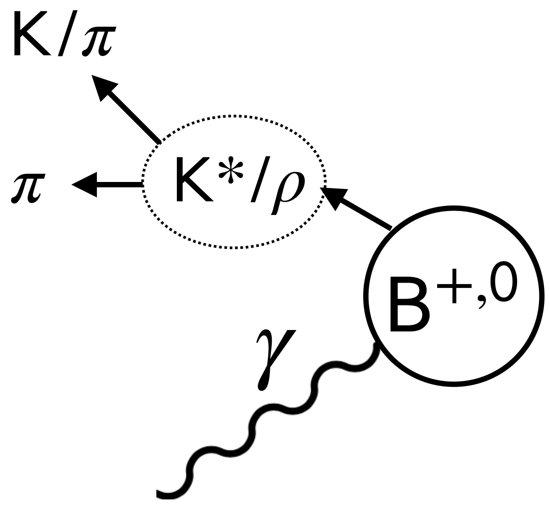
N_γ \ N_ν	0	1	2	>2
>2	$B \to X_s\gamma$ Belle II			
2	$B^0 \to \gamma\gamma$ Belle II $B \to \pi^0(\pi)\ell\ell$ Belle II			
1	$B \to K^*\gamma$ LHCb $B^0 \to \mu\mu\gamma$ LHCb	$B^+ \to \ell^+\nu\gamma$ Belle II	$B \to \nu\nu\gamma$ Belle II	
0	$B^0_{(s)} \to \mu\mu$ LHCb $B \to K^{(*)}\mu\mu$ LHCb $B \to \pi(\pi)\mu\mu$ LHCb	$B^+ \to e^+\nu$ Belle II $B \to K\tau\ell$ LHCb Belle II $B^+ \to \mu\mu\mu\nu$ LHCb	$B \to K\nu\nu$ Belle II $B \to K\tau\ell$ Belle II $B \to (K)\tau\tau$ Belle II	$B^+ \to \tau^+\nu$ Belle II $B \to (K)\tau\tau$ Belle II

B → VISIBLE



- Radiative B-decays
- $b \to (s, d)\ell\ell$ decays

RADIATIVE B-DECAYS



Exclusive measurements

✓ Study specific dynamics of hadronisation
Explore photon properties/asymmetries that could reveal NP effects

✗ Predictions suffer from large theoretical uncertainties (form factors estimation)

Observables

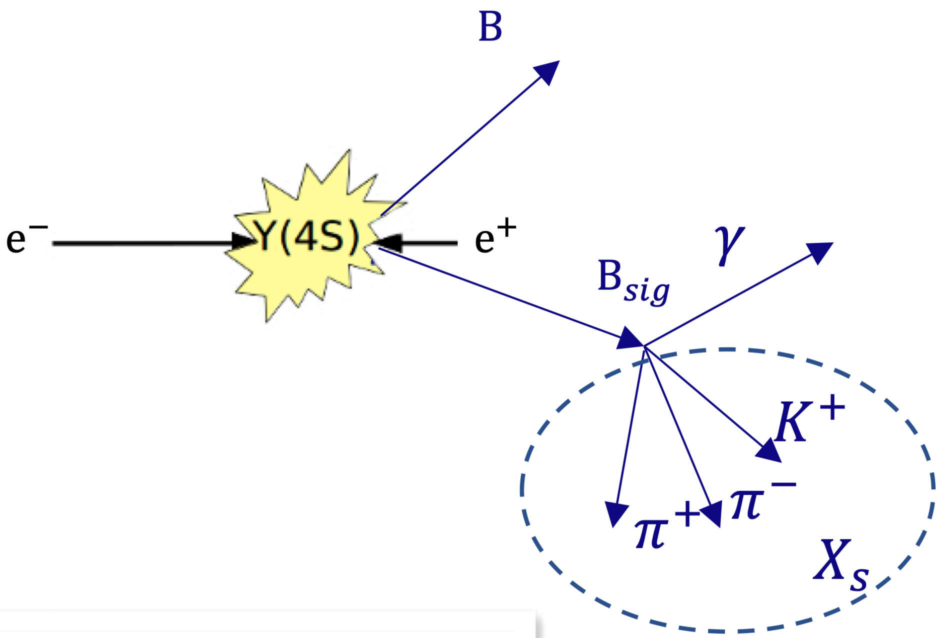
- ○ Exclusive BF b→(s/d)γ
- ○ CP, isospin asymmetry
- ○ Photon up-down asymmetry
- ○ ...

$$\mathscr{A}_{\mathrm{CP}} = \frac{\Gamma(\bar{B}\to\bar{V}\gamma) - \Gamma(B\to V\gamma)}{\Gamma(\bar{B}\to\bar{V}\gamma) + \Gamma(B\to V\gamma)} \qquad \mathscr{A}_{\mathrm{I}} = \frac{\Gamma(B^0\to V^0\gamma) - \Gamma(B^+\to V^+\gamma)}{\Gamma(B^0\to V^0\gamma) + \Gamma(B^+\to V^+\gamma)}$$

Inclusive measurements

✓ Test the SM predictions for the total b→sγ branching fraction and probe the underlying quark-level process with minimal hadronic uncertainties

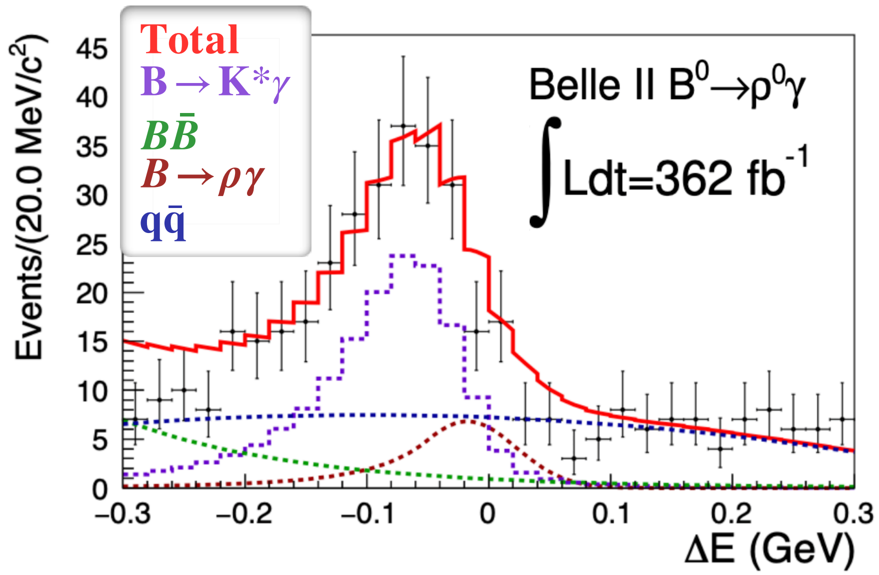
✗ Experimentally more challenging but **only possible in the clean environment of B factories**



For E_γ > 1.6 GeV:

$BF_{HFLAV} = (3.49 \pm 0.19) \times 10^{-4}$
$BF_{th} = (3.40 \pm 0.17) \times 10^{-4}$ JHEP06(2020)175

RADIATIVE B-DECAYS



Exclusive measurements

✓ Study specific dynamics of hadronisation
Explore photon properties/asymmetries that could reveal NP effects

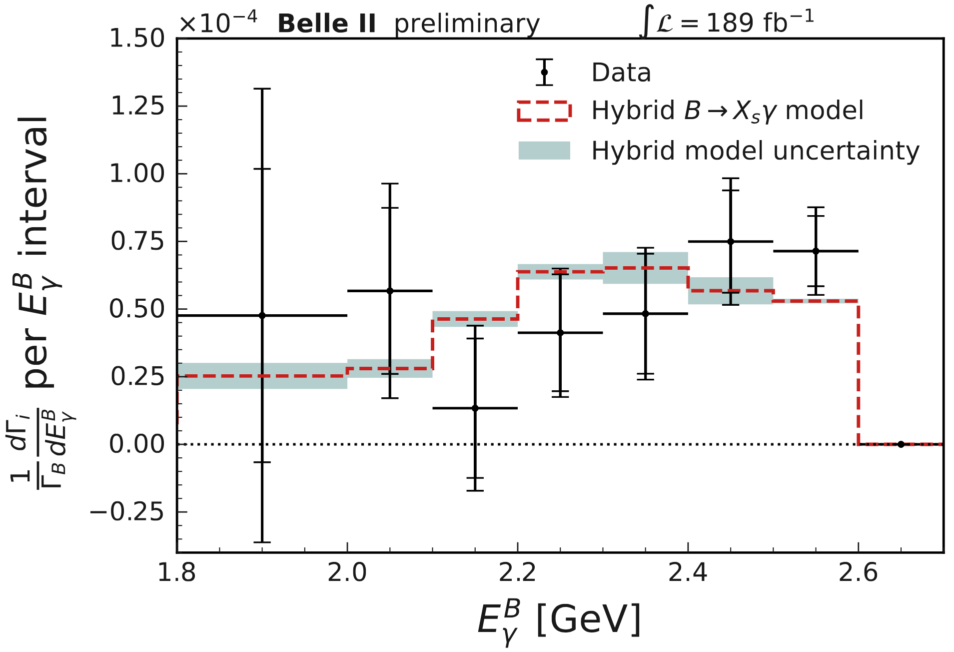
✗ Predictions suffer from large theoretical uncertainties (form factors estimation)

Observables

- Exclusive BF b→(s/d)γ
- CP, isospin asymmetry
- Photon up-down asymmetry
- …

$B \to \rho\gamma$: Belle+Belle II (Preliminary) 2407.08984 **Most precise measurement!**

$B \to K^*\gamma$: Belle II (Preliminary) 2411.10127 **Need more data!**



Inclusive measurements

✓ Test the SM predictions for the total b→sγ branching fraction and probe the underlying quark-level process with minimal hadronic uncertainties

✗ Experimentally more challenging but **only possible in the clean environment of B factories**

$B \to X_s\gamma$: Belle II 2210.10220 **Need more data!**

$b \to (s,d)\ell\ell$

In the $b \to (s,d)\ell\ell$ sector, Belle II can:

- Provide **unique insight** for

  Inclusive $\mathscr{B}(B \to X_s\ell\ell)$ - 10% accuracy @ 5 ab^{-1} expected [1808.10567](https://arxiv.org/abs/1808.10567)

- Be redundant with LHCb for

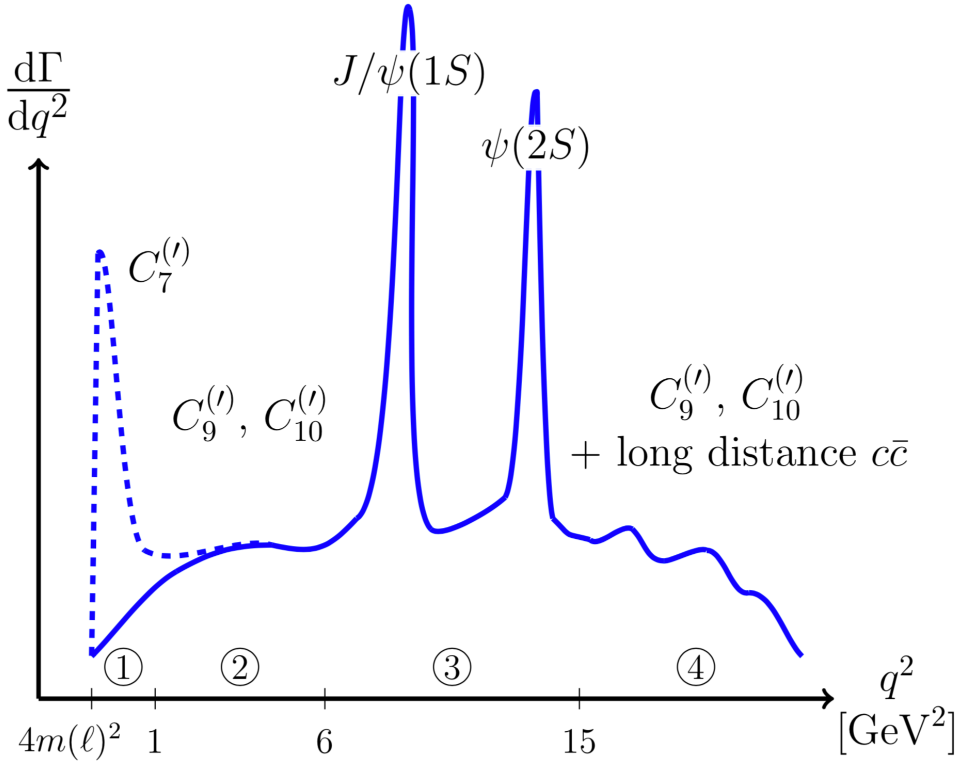
  LFU test $R_{K^{(*)}}$

  Independent measurement of $R_{K^{(*)}}$ at Belle II with 5-10 ab^{-1}

  3% precision at 50 ab^{-1}

  $C_7^{(\prime)}$ constraints → $B \to K^*ee$ (low q²)

  Search for rarer $b \to d\ell\ell$ decays

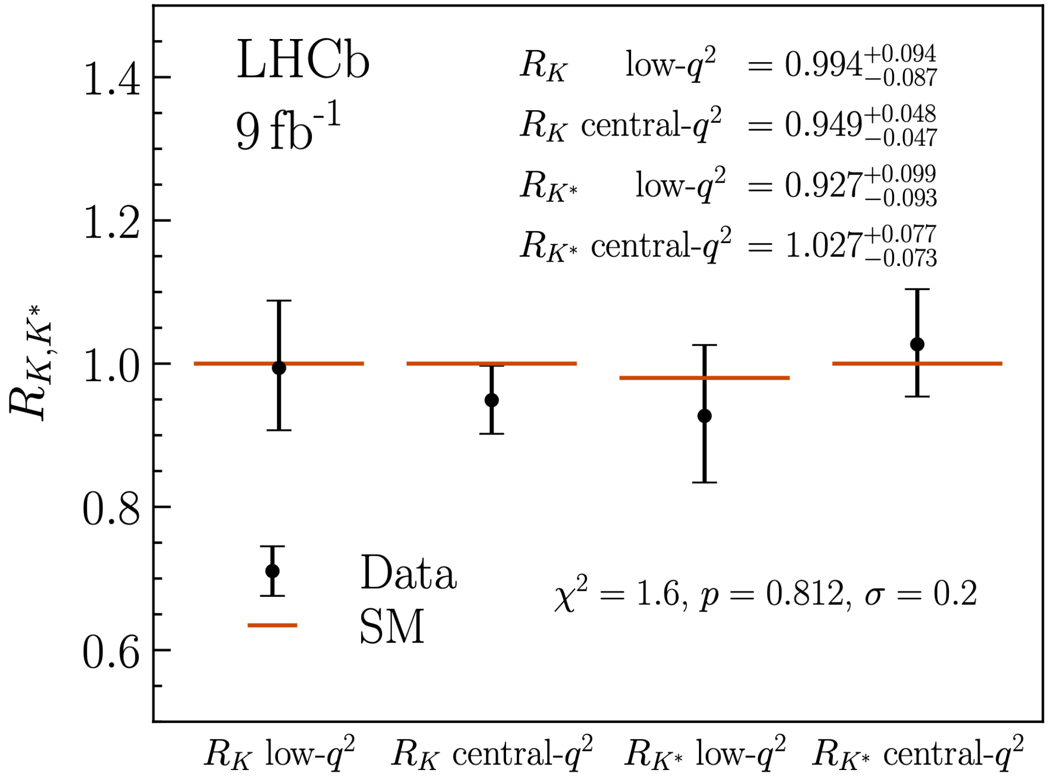


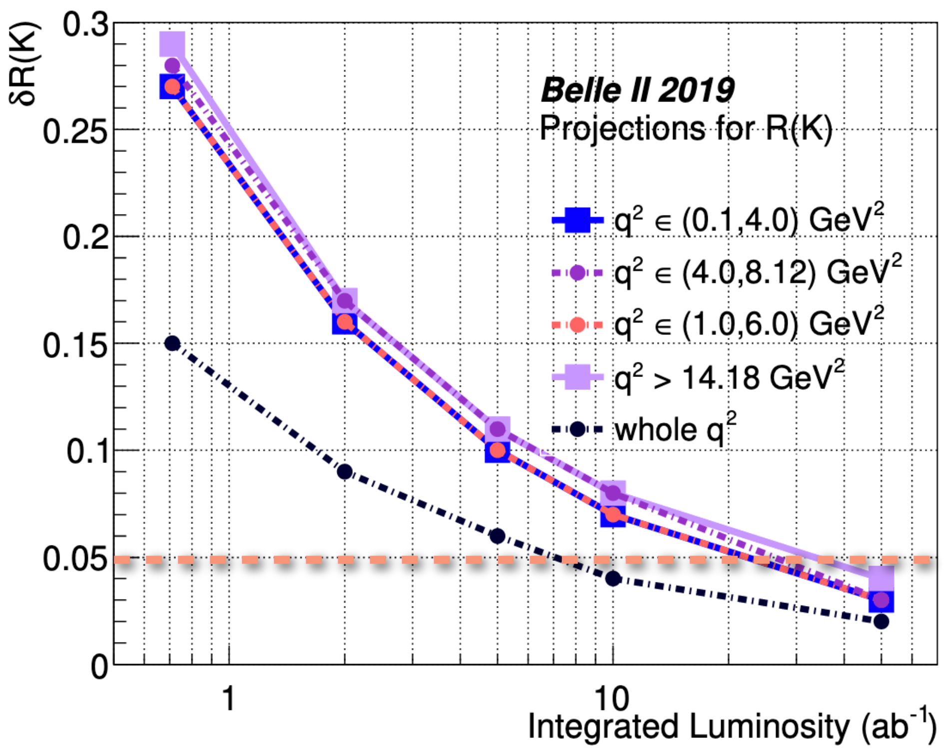
***low-q^2* : [0.1,1.1] GeV^2/c^4**

***central-q^2*: [1.1,6.0] GeV^2/c^4**

[PRD 108 (2023) 032002](https://doi.org/10.1103/PhysRevD.108.032002)
[PRL 131 (2023) 051803](https://doi.org/10.1103/PhysRevLett.131.051803)

$$\mathscr{R}_{K^{(*)}} = \frac{\mathscr{B}(B \to K^{(*)}\mu\mu)}{\mathscr{B}(B \to K^{(*)}ee)}$$





Precisely predicted to be ~1 in the SM - unc $\mathcal{O}(1\%)$

[EPJC 76, 440 (2016)](https://doi.org/10.1140/epjc/s10052-016-4274-7)
[JHEP12(2020)104](https://doi.org/10.1007/JHEP12(2020)104)
[JHEP10(2022)146](https://doi.org/10.1007/JHEP10(2022)146)

b → (s, d)$\ell\ell$

In the b → (s, d)$\ell\ell$ sector, Belle II can:

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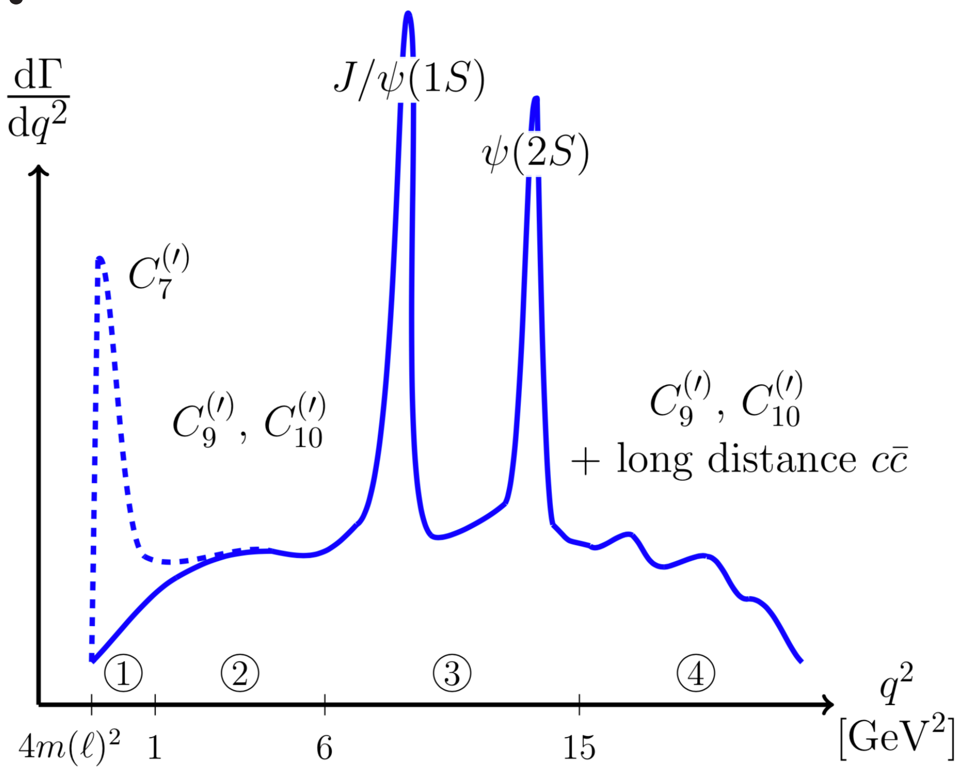
    Independent measurement of $R_{K^{(*)}}$ at Belle II with 5-10 ab^{-1}

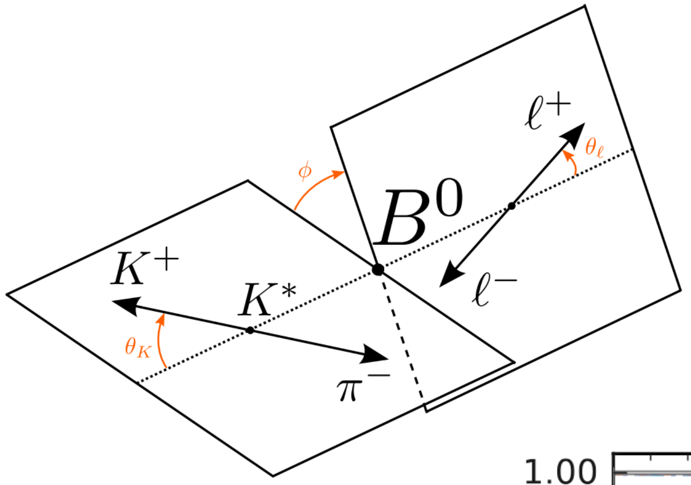
    3% precision at 50 ab^{-1}

  $C_7^{(\prime)}$ constraints → B → K*ee (low q^2) **Belle,** PRD 110 (2024) 7, 072005

  Search for rarer b → d$\ell\ell$ decays

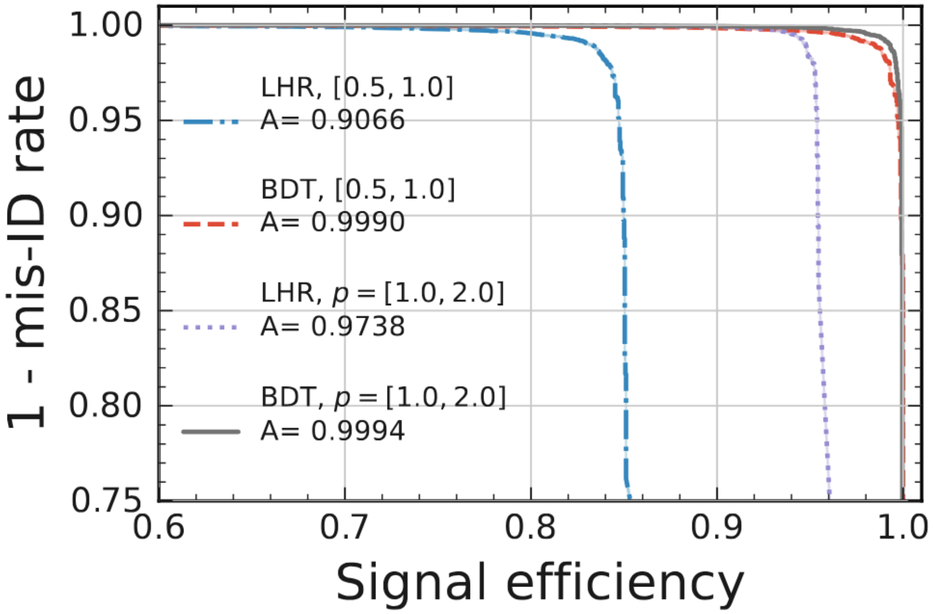


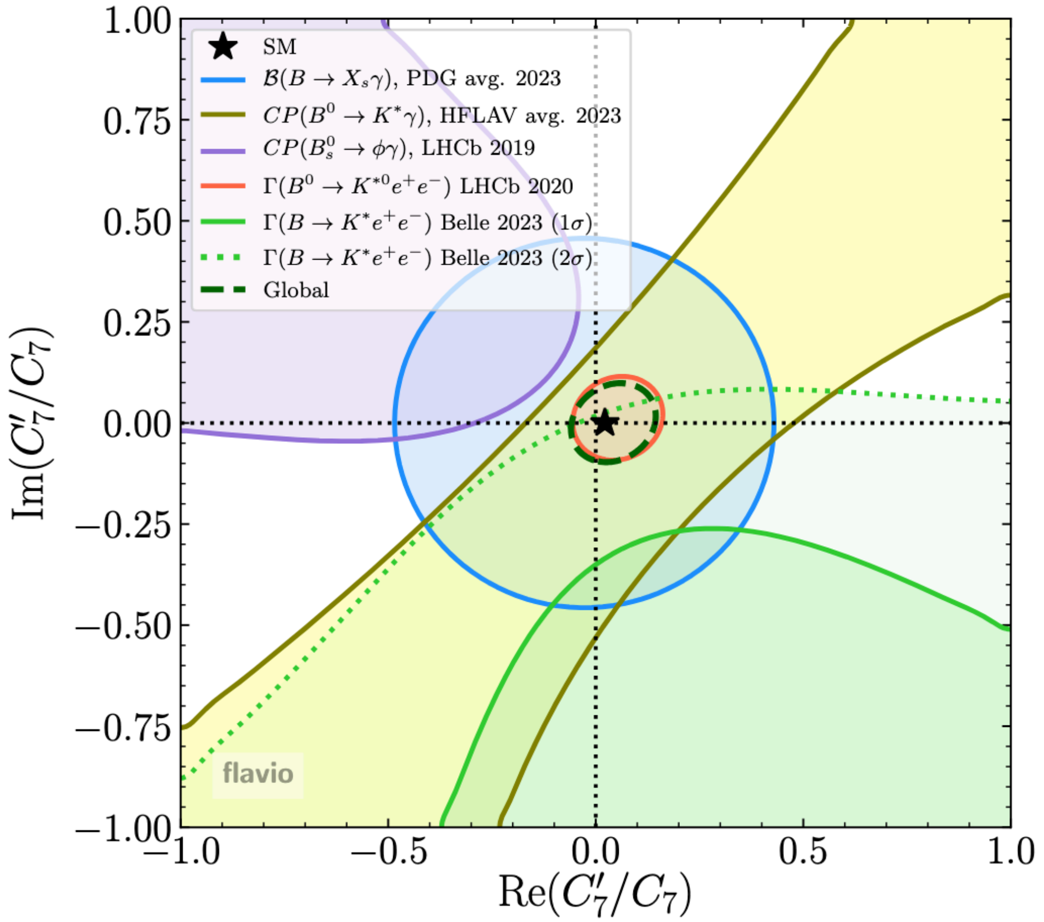
$$\boldsymbol{q^2 \in [0.0008, 1.1200]\ \mathrm{GeV}^2/c^4}$$



$$A_T^{\mathrm{Im}}(q^2=0) = \frac{2\mathrm{Im}(\mathcal{C}_7^{\mathrm{eff}}\mathcal{C}_7^{\prime\mathrm{eff}*})}{|\mathcal{C}_7^{\mathrm{eff}}|^2+|\mathcal{C}_7^{\prime\mathrm{eff}}|^2}$$

$$A_T^{(2)}(q^2=0) = \frac{2\mathrm{Re}(\mathcal{C}_7^{\mathrm{eff}}\mathcal{C}_7^{\prime\mathrm{eff}*})}{|\mathcal{C}_7^{\mathrm{eff}}|^2+|\mathcal{C}_7^{\prime\mathrm{eff}}|^2}$$





b$\rightarrow$ (s, d)$\ell\ell$

In the b$\rightarrow$(s, d)$\ell\ell$ sector, Belle II can:

- Provide **unique insight** for

  Inclusive $\mathscr{B}$(B$\rightarrow$X$_s\ell\ell$) - 10% accuracy @ 5 ab^{-1} expected
- Be redundant with LHCb for

  LFU test R$_{K^{(*)}}$

    Independent measurement of R$_{K^{(*)}}$ at Belle II with 5-10 ab^{-1}

    3% precision at 50 ab^{-1}

  C$_7^{(')}$ constraints → B$\rightarrow$K*ee (low q^2)

  Search for rarer b$\rightarrow$d$\ell\ell$ decays Belle, PRL 133, 101804 (2024)

Channel	UL or BR	Collaboration
$B^0 \rightarrow \eta ee$	$< 10.8 \times 10^{-8}$	BaBar
$B^0 \rightarrow \eta\mu\mu$	$< 11.2 \times 10^{-8}$	BaBar
$B^0 \rightarrow \pi^0 ee$	$< 8.4 \times 10^{-8}$	BaBar
$B^0 \rightarrow \pi^0\mu\mu$	$< 6.9 \times 10^{-8}$	BaBar
$B^+ \rightarrow \pi^+ ee$	$< 8.0 \times 10^{-8}$	Belle
$B^+ \rightarrow \pi^+\mu\mu$	$(1.78 \pm 0.22 \pm 0.03) \times 10^{-8}$	LHCb
$B^0 \rightarrow \rho^0\mu\mu$	$(1.98 \pm 0.53) \times 10^{-8}$	LHCb

Obtained $\mathscr{B}^{\text{UL}}$ in the range $(3.8 - 47) \times 10^{-7}$

First search

$B^0 \rightarrow \omega\ell^+\ell^-$

$B^0 \rightarrow \rho^0 e^+e^-$

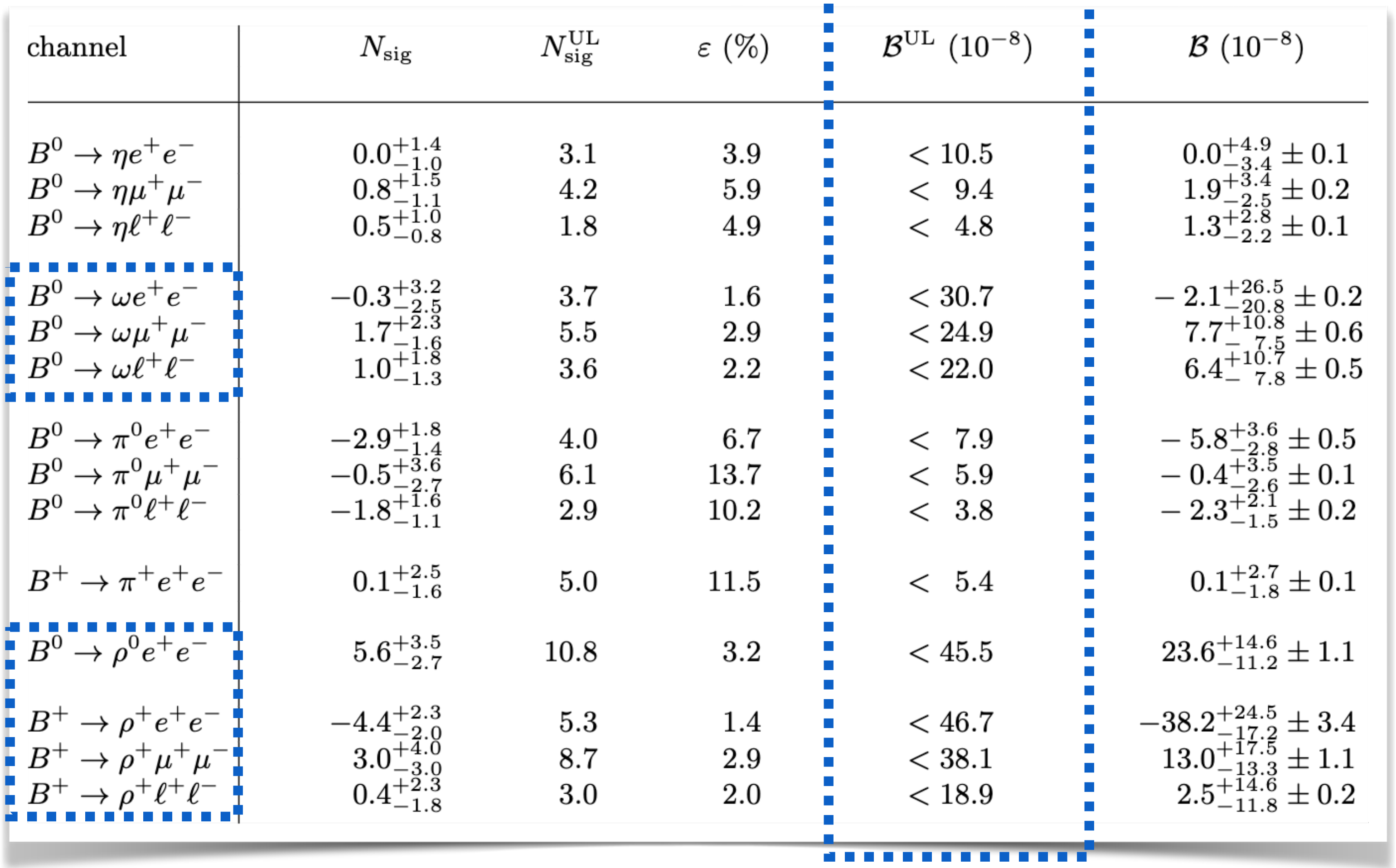
$B^\pm \rightarrow \rho^\pm\ell^+\ell^-$

$\pi^+/\rho^0 ee$ stat limited but consistent with $\pi^+/\rho^0\mu\mu$ from LHCb

No sign of LFUV

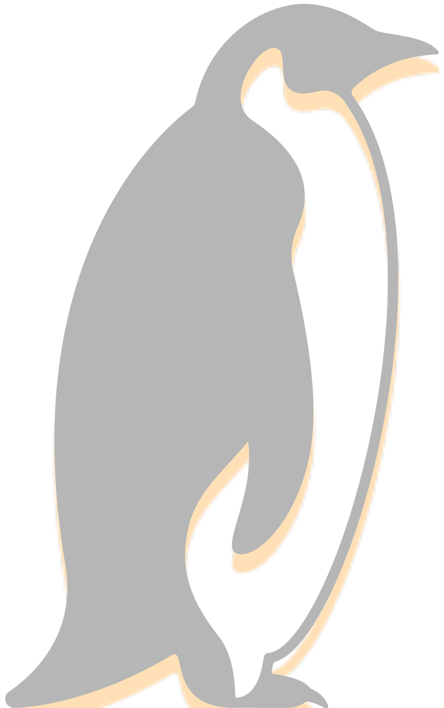
Approaching SM!

90% CL upper limits



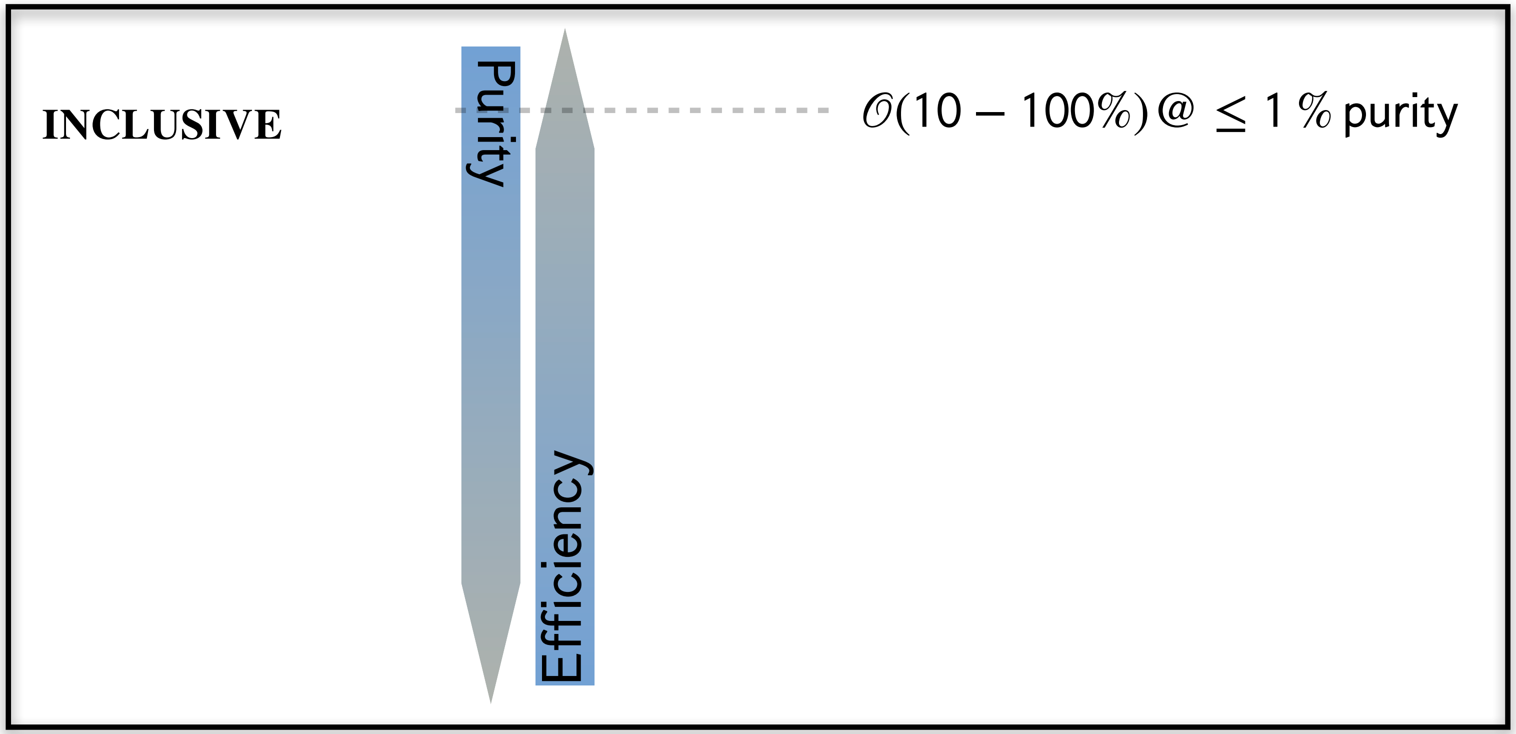
channel	N_{sig}	$N_{\text{sig}}^{\text{UL}}$	ε (%)	$\mathcal{B}^{\text{UL}}$ (10^{-8})	$\mathcal{B}$ (10^{-8})
$B^0 \rightarrow \eta e^+e^-$	$0.0^{+1.4}_{-1.0}$	3.1	3.9	< 10.5	$0.0^{+4.9}_{-3.4} \pm 0.1$
$B^0 \rightarrow \eta\mu^+\mu^-$	$0.8^{+1.5}_{-1.1}$	4.2	5.9	< 9.4	$1.9^{+3.4}_{-2.5} \pm 0.2$
$B^0 \rightarrow \eta\ell^+\ell^-$	$0.5^{+1.0}_{-0.8}$	1.8	4.9	< 4.8	$1.3^{+2.8}_{-2.2} \pm 0.1$
$B^0 \rightarrow \omega e^+e^-$	$-0.3^{+3.2}_{-2.5}$	3.7	1.6	< 30.7	$-2.1^{+26.5}_{-20.8} \pm 0.2$
$B^0 \rightarrow \omega\mu^+\mu^-$	$1.7^{+2.3}_{-1.6}$	5.5	2.9	< 24.9	$7.7^{+10.8}_{-7.5} \pm 0.6$
$B^0 \rightarrow \omega\ell^+\ell^-$	$1.0^{+1.8}_{-1.3}$	3.6	2.2	< 22.0	$6.4^{+10.7}_{-7.8} \pm 0.5$
$B^0 \rightarrow \pi^0 e^+e^-$	$-2.9^{+1.8}_{-1.4}$	4.0	6.7	< 7.9	$-5.8^{+3.6}_{-2.8} \pm 0.5$
$B^0 \rightarrow \pi^0\mu^+\mu^-$	$-0.5^{+3.6}_{-2.7}$	6.1	13.7	< 5.9	$-0.4^{+3.5}_{-2.6} \pm 0.1$
$B^0 \rightarrow \pi^0\ell^+\ell^-$	$-1.8^{+1.6}_{-1.1}$	2.9	10.2	< 3.8	$-2.3^{+2.1}_{-1.5} \pm 0.2$
$B^+ \rightarrow \pi^+ e^+e^-$	$0.1^{+2.5}_{-1.6}$	5.0	11.5	< 5.4	$0.1^{+2.7}_{-1.8} \pm 0.1$
$B^0 \rightarrow \rho^0 e^+e^-$	$5.6^{+3.5}_{-2.7}$	10.8	3.2	< 45.5	$23.6^{+14.6}_{-11.2} \pm 1.1$
$B^+ \rightarrow \rho^+ e^+e^-$	$-4.4^{+2.3}_{-2.0}$	5.3	1.4	< 46.7	$-38.2^{+24.5}_{-17.2} \pm 3.4$
$B^+ \rightarrow \rho^+\mu^+\mu^-$	$3.0^{+4.0}_{-3.0}$	8.7	2.9	< 38.1	$13.0^{+17.5}_{-13.3} \pm 1.1$
$B^+ \rightarrow \rho^+\ell^+\ell^-$	$0.4^{+2.3}_{-1.8}$	3.0	2.0	< 18.9	$2.5^{+14.6}_{-11.8} \pm 0.2$

B → VISIBLE + MISSING ENERGY



- B-tagging strategies
- $B^+ \rightarrow K^+\nu\bar{\nu}$ observation
- $B \rightarrow K\tau\tau$ searches
- LFV in B

B-TAGGING FOR MISSING-ENERGY MODES

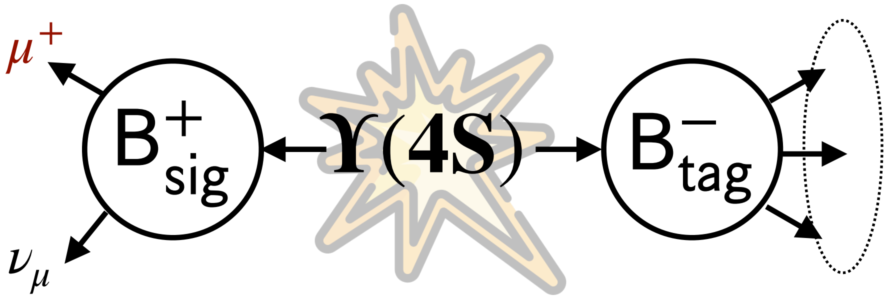


INCLUSIVE

Purity

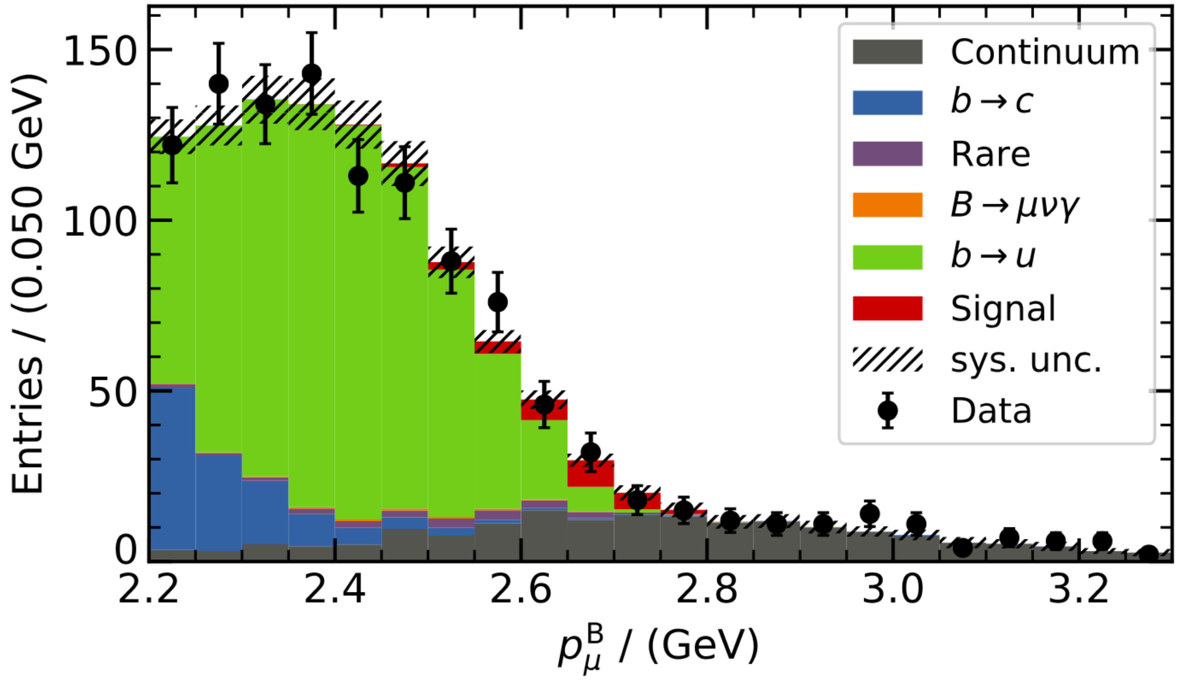
Efficiency

$\mathcal{O}(10-100\%)$ @ $\leq 1\,\%$ purity



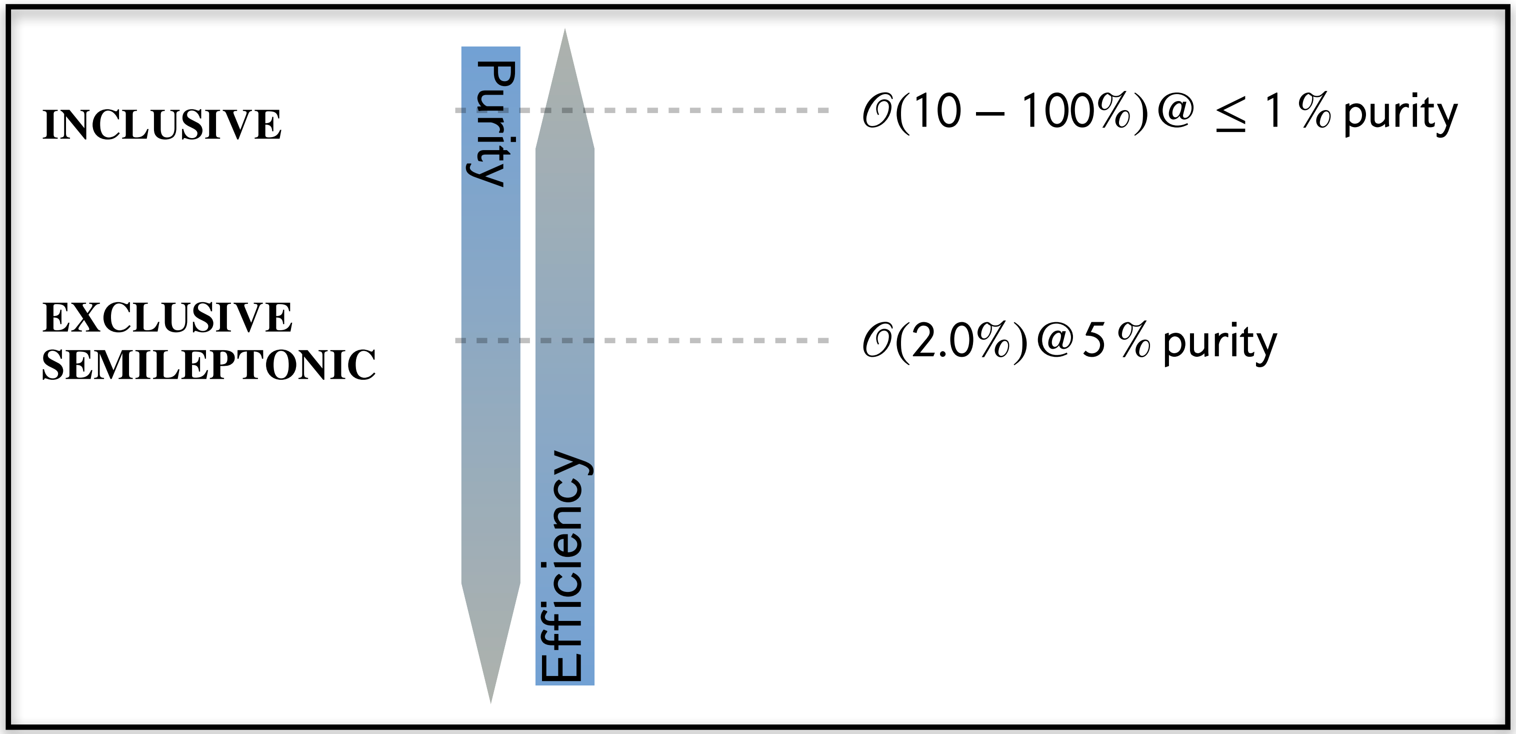
B-tagging used for
- Background filtering
- Partial kinematic info

[PRD 101, 032007 (2020)](PRD 101, 032007 (2020))



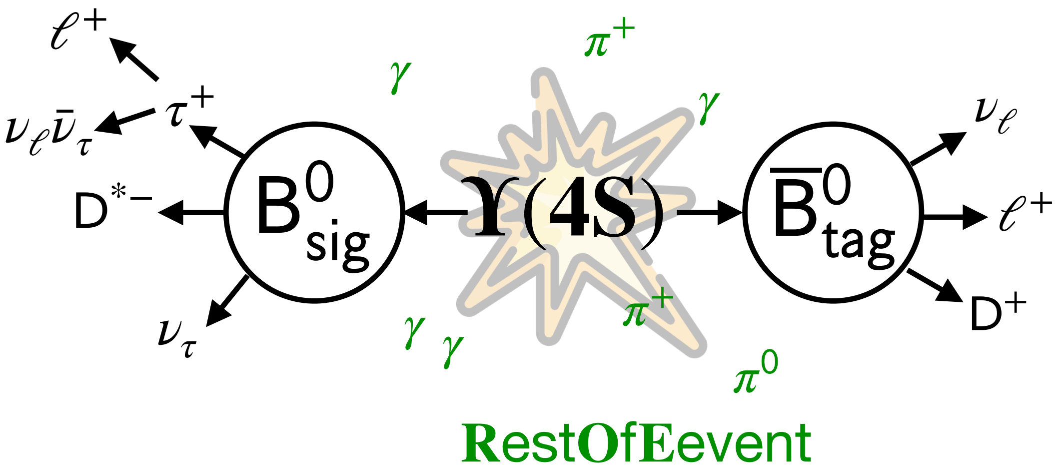
- Maximise sensitivity for decays with specific signatures (e.g. single track)
- The directional information from the B_{tag}, despite the poor experimental resolution, is used to boost the $\mu^\pm$ into the signal B_{sig} rest-frame

B-TAGGING FOR MISSING-ENERGY MODES



INCLUSIVE $\mathcal{O}(10-100\%)$ @ $\leq 1\,\%$ purity

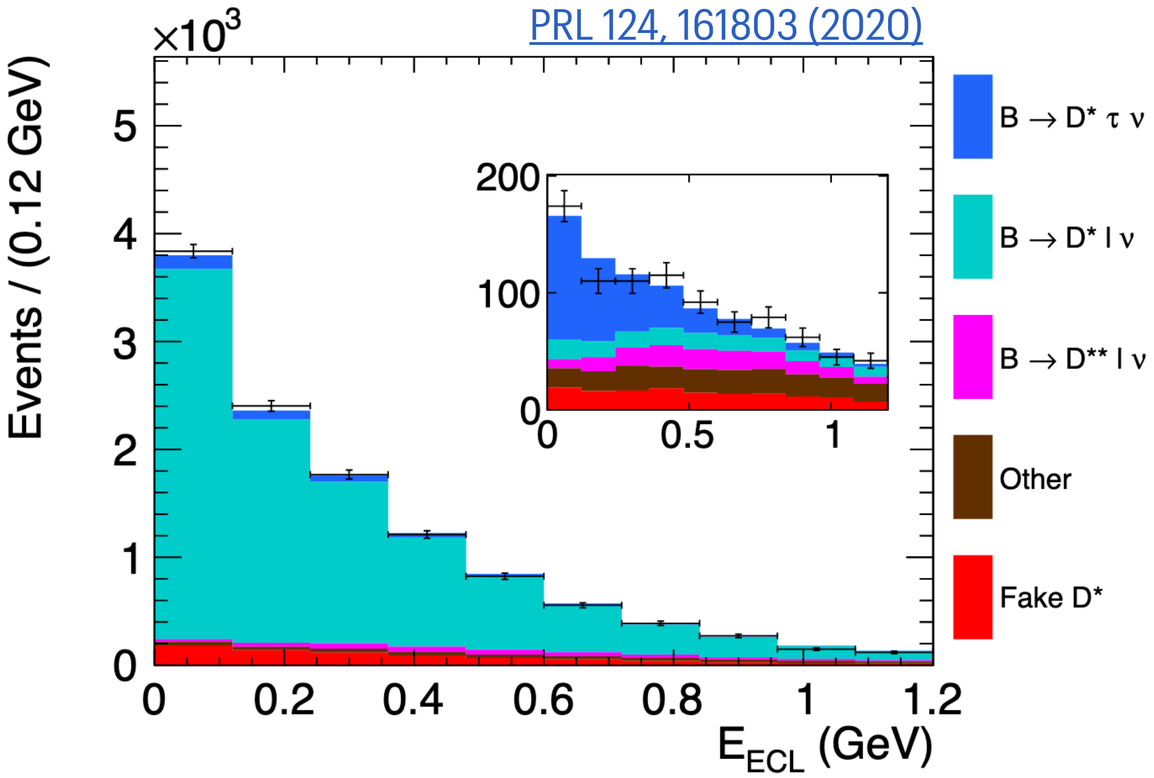
EXCLUSIVE SEMILEPTONIC $\mathcal{O}(2.0\%)$ @ $5\,\%$ purity



B-tagging used for

- Background filtering
- Partial kinematic info
- Flavour info

PRL 124, 161803 (2020)

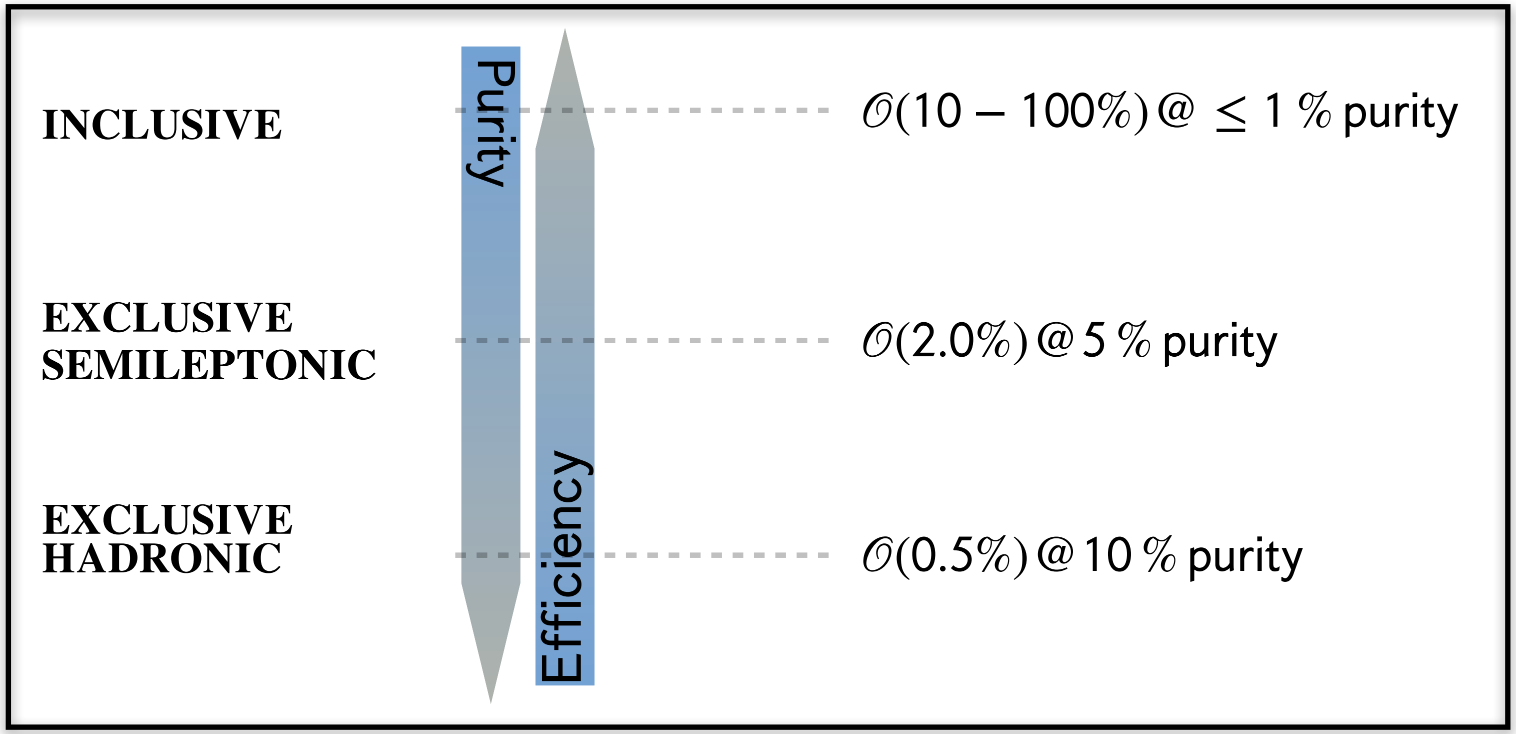


$\mathbf{E_{ECL}}$ → Sum of the energy deposits in the calorimeter that cannot be associated with the reconstructed daughters of the B_{tag} or the B_{sig}

Signal events → $\mathbf{E_{ECL}} \sim 0$

Background events → Additional neutral clusters from unreconstructed particles

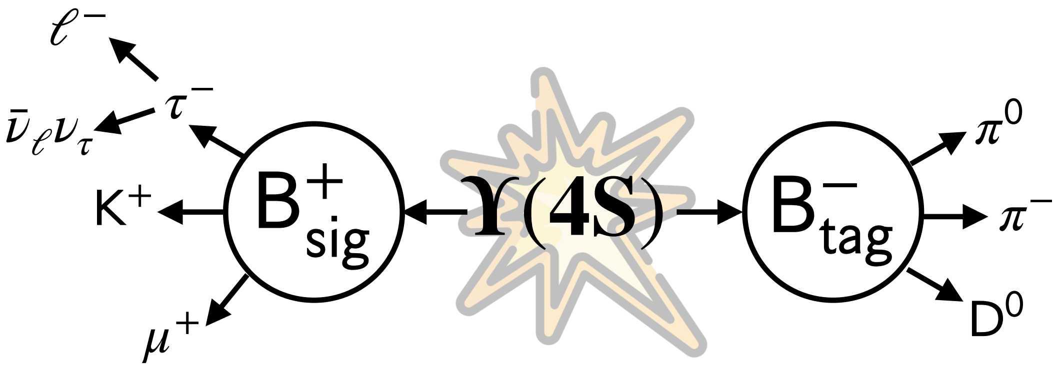
B-TAGGING FOR MISSING-ENERGY MODES



INCLUSIVE — $\mathcal{O}(10-100\%)$ @ $\leq 1\,\%$ purity

EXCLUSIVE SEMILEPTONIC — $\mathcal{O}(2.0\%)$ @ $5\,\%$ purity

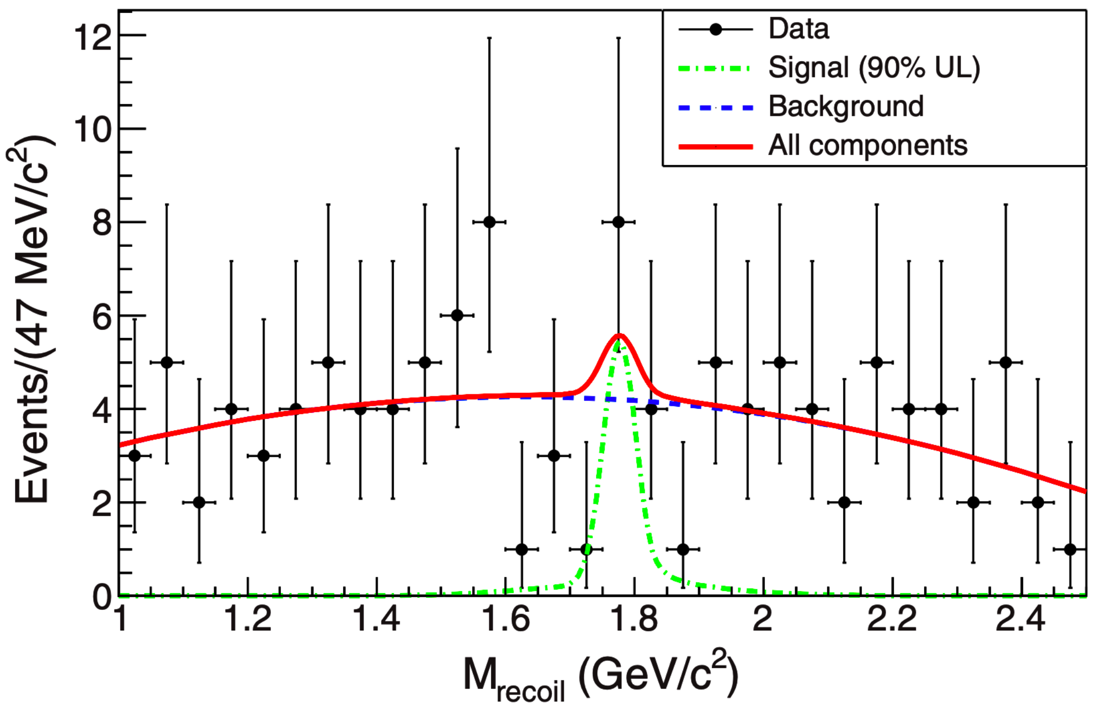
EXCLUSIVE HADRONIC — $\mathcal{O}(0.5\%)$ @ $10\,\%$ purity



B-tagging used for

- Background filtering
- Flavour info
- Full kinematic info

PRL 130, 181803 (2023)



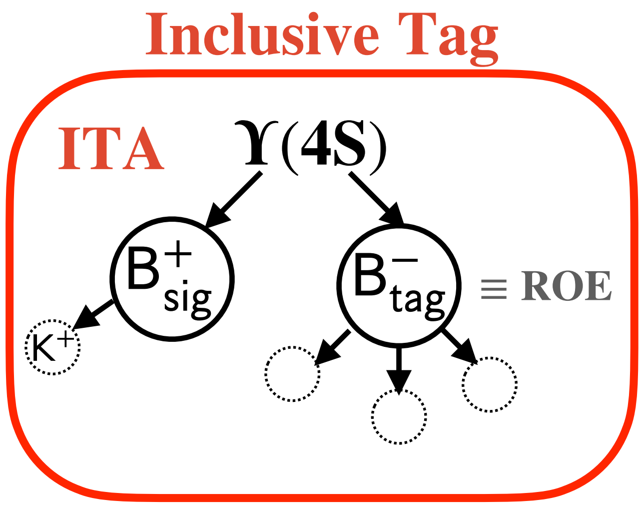
The two B's are produced back-to-back in the CM frame $\leftrightarrow$ the reconstruction of the B_{tag} allows to know the 3-momentum of the B_{tag} on an event-by-event basis with excellent resolution

$$M_{recoil} = \left[m_B^2 + m_{K\ell}^2 - 2(E^*_{beam} E^*_{K\ell} + |\vec{p}^{\,*}_{B_{tag}}| |\vec{p}^{\,*}_{K\ell}| \cos\theta) \right]^{1/2}$$

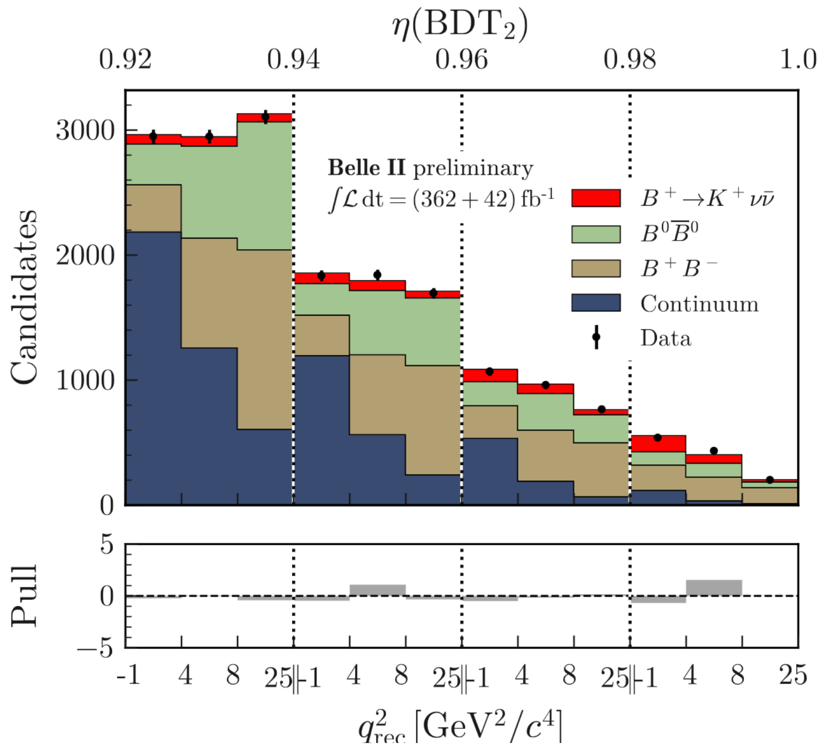
$B^+ \to K^+ \nu\bar{\nu}$ SEARCH WITH BELLE II

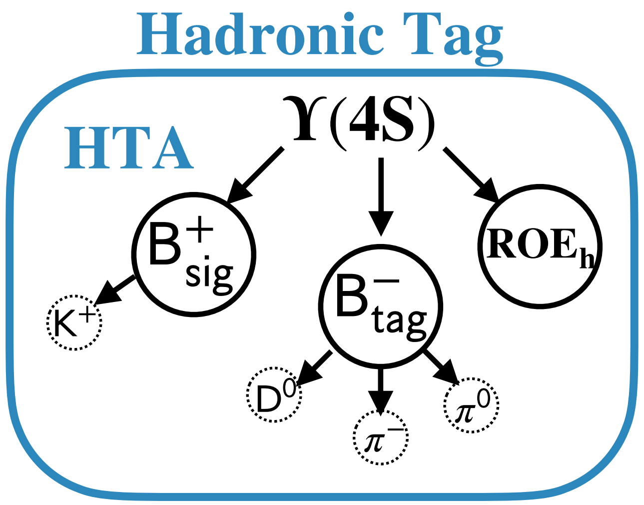
PRD 109, 112006 (2024)

Two tagging approaches leading to almost statistically independent samples

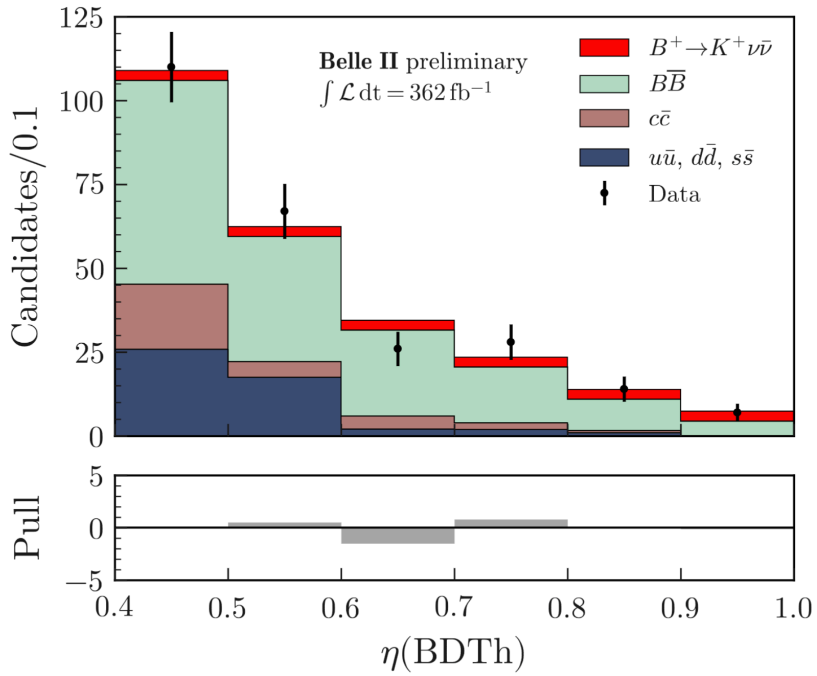


- **Leading the final sensitivity**
- Two classifiers pre-filter (BDT_1) + BDT_2
- Fit to $q^2_{rec} \times \eta(BDT_2)$ (ON+OFF data)





- **Less sensitive, used for consistency check**
- Single classifier BDT_h
- Fit to $\eta(BDT_h)$ for ON resonance data



$\mathbf{K^+_{sig}}$: reconstructed applying kaon-enriching selection

$\mathbf{q^2_{rec}} = s/(4c^4) + M_K^2 - \sqrt{s}E_K^*/c$

$BDT_{2,h}$: uses information of signal kaon, ROE and event topology

$B \to K^+\nu\bar{\nu}$ COMBINATION

ITA

$\mu = 5.4 \pm 1.0(\text{stat}) \pm 1.1(\text{syst})$

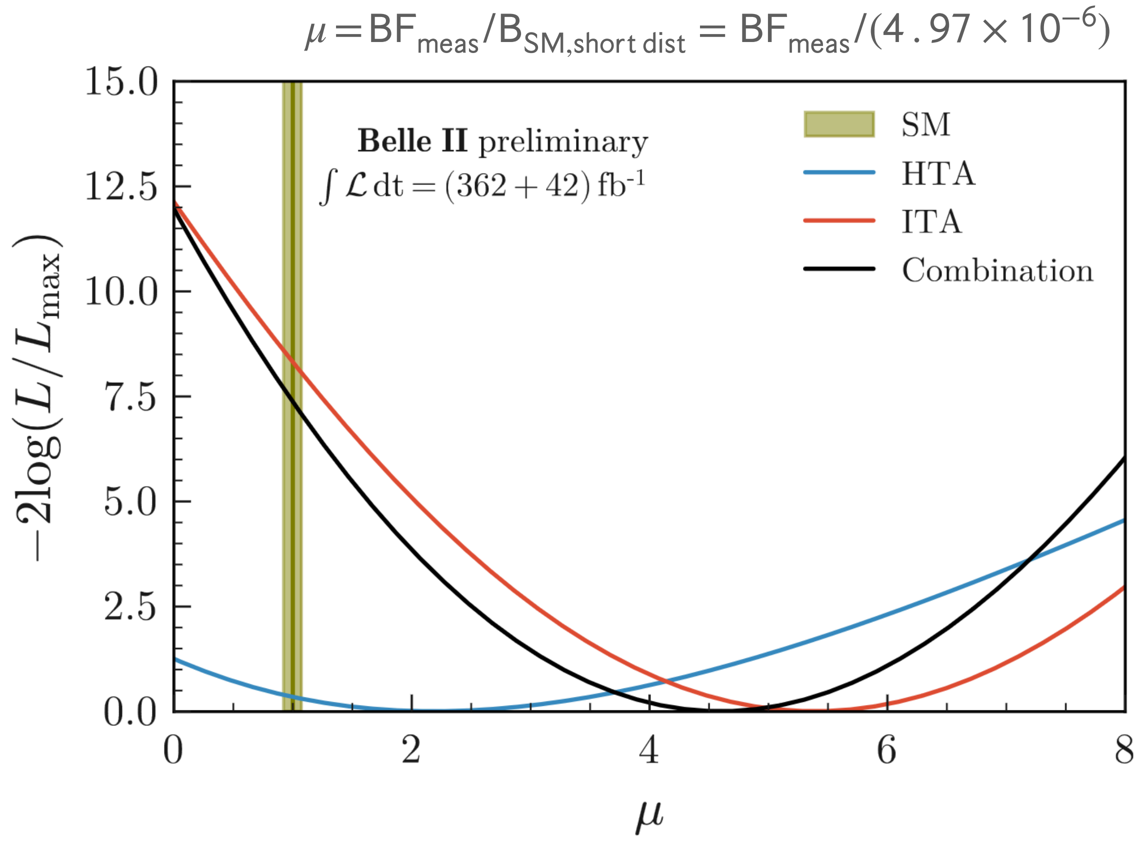
2.9σ deviation from SM exp

HTA

$\mu = 2.2^{+1.8}_{-1.7}(\text{stat})^{+1.6}_{-1.1}(\text{syst})$

0.6σ deviation from SM exp

Consistent within 1.2σ



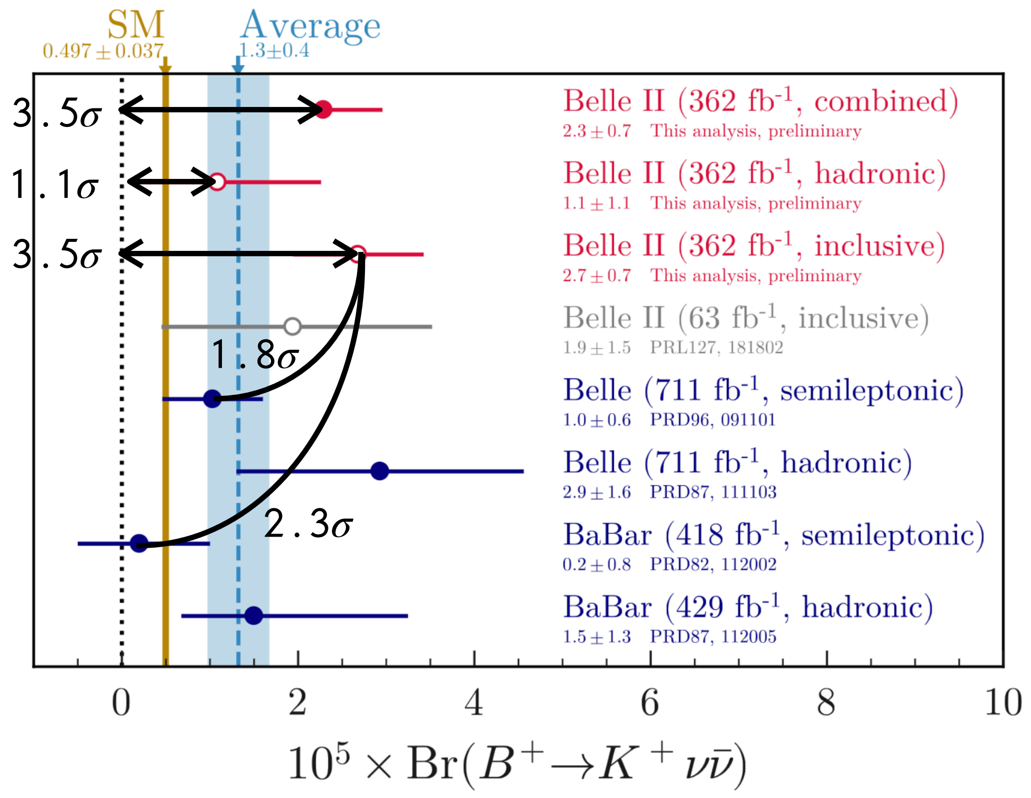
ITA + **HTA** Likelihood-level combination:

- Include correlations among common syst unc.
- Common data events excluded from ITA sample

$(2.3 \pm 0.7)\times10^{-5}$ (**ITA + HTA**)

$(1.1^{+1.2}_{-1.0})\times10^{-5}$ (**HTA**)

$(2.7 \pm 0.7)\times10^{-5}$ (**ITA**)

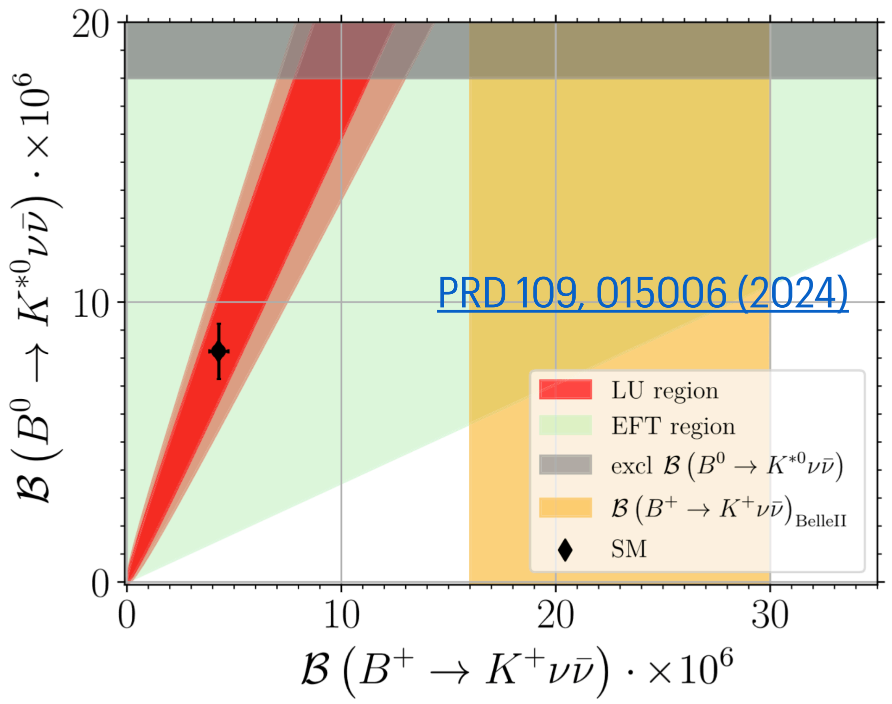


First evidence of $B^+ \to K^+\nu\bar{\nu}$

3.5 σ deviation from background-only hypothesis

2.7 σ deviation from SM exp

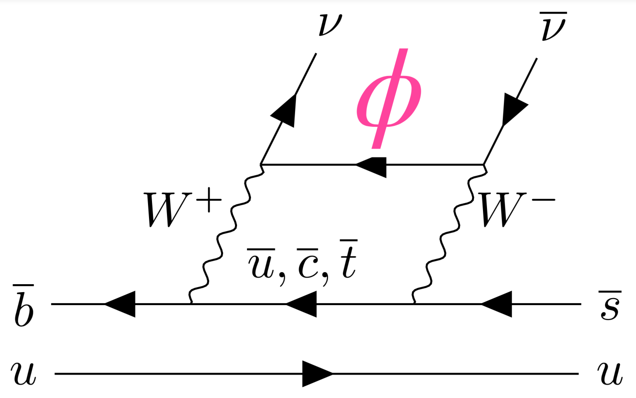
WHAT FOLLOWS $B^+ \to K^+\nu\bar{\nu}$



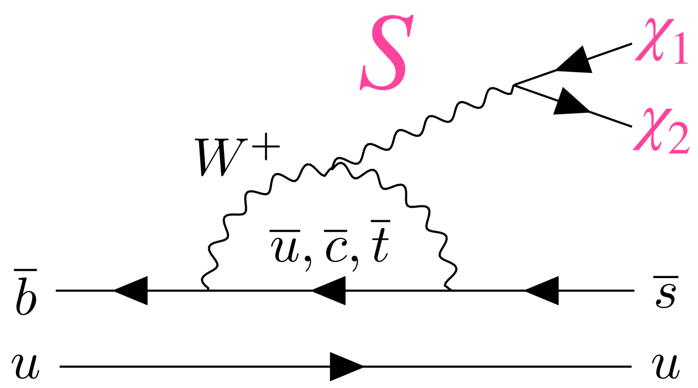
PRD 109, 015006 (2024)

Lepton flavour universality does not intersect with Belle II data below the excluded region from Belle

Is lepton flavour universality violated?
Multi-TeV-scale? Light new physics?



LQ, PRD 98, 055003 (2018)

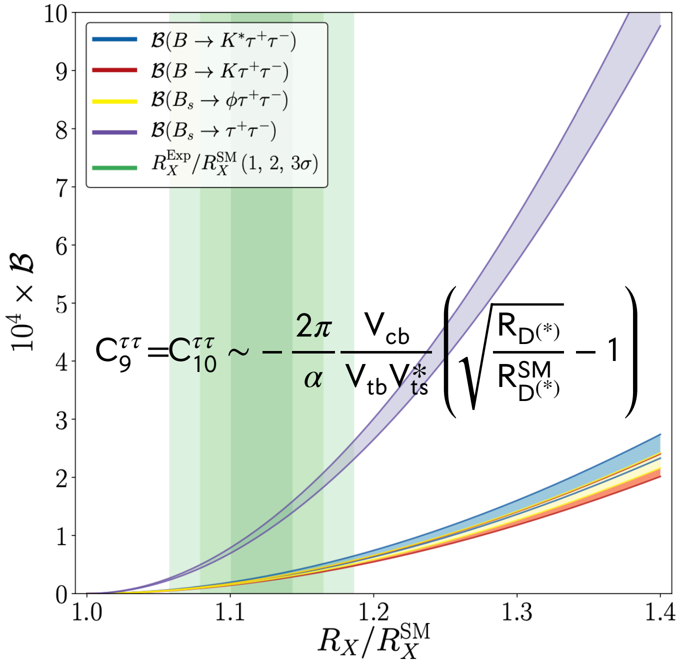


ALPs, EPJC 79 (2019) 5, 369

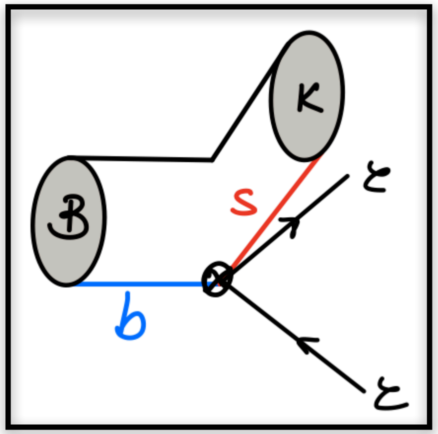
Important to corroborate the 2023 result

- **More data** (ITA: stat~syst, with some syst being statistical in nature)
- **Additional $b \to s\nu\bar{\nu}$ channels** (NP can couple differently to K, K*)
- **Additional tagging approaches** (uncertainty SL~ITA)

MOTIVATION FOR $b \to s\tau\tau$ SEARCHES



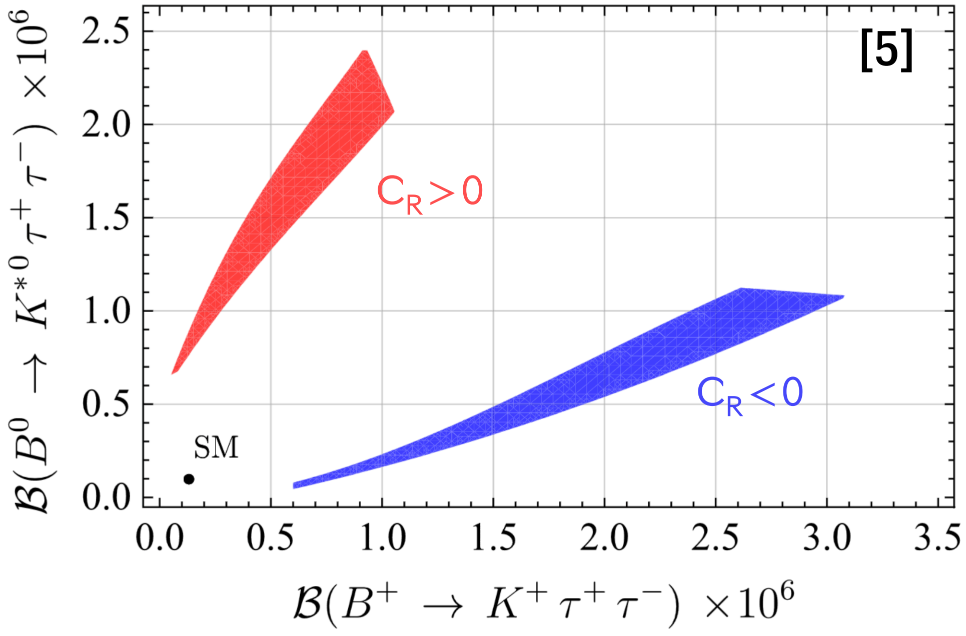
$$C_9^{\tau\tau} = C_{10}^{\tau\tau} \sim -\frac{2\pi}{\alpha}\frac{V_{cb}}{V_{tb}V_{ts}^*}\left(\sqrt{\frac{R_{D^{(*)}}}{R_{D^{(*)}}^{SM}}} - 1\right)$$

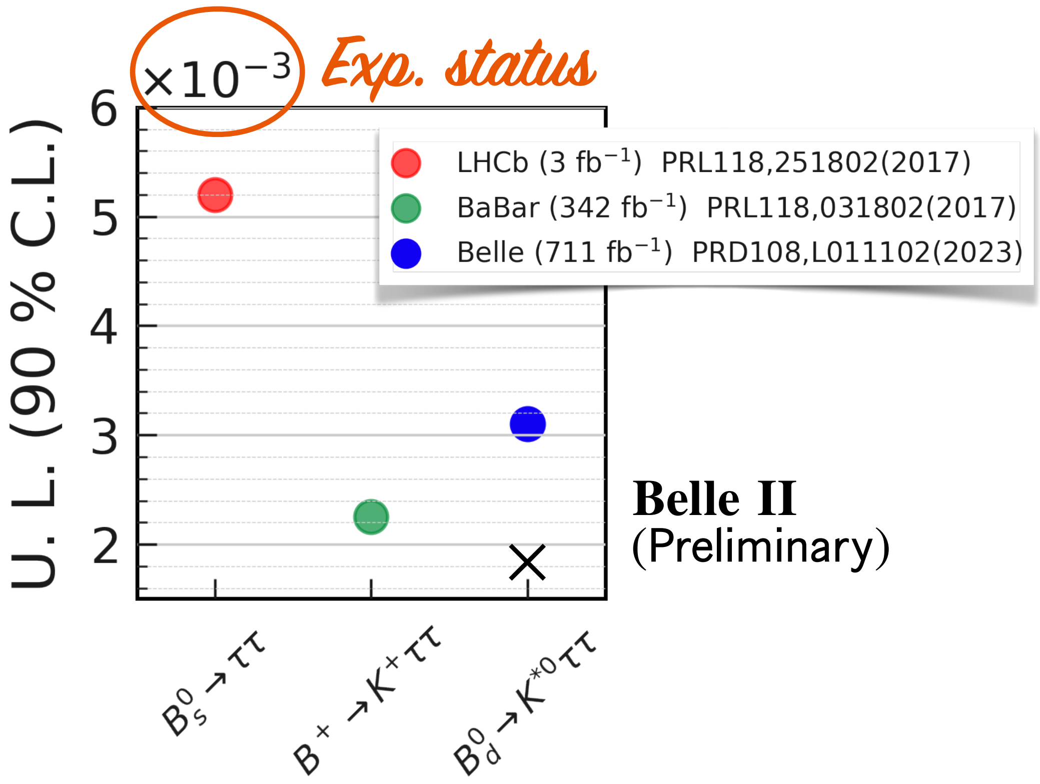


- $\mathscr{B}_{SM} \sim \mathcal{O}(10^{-7})$ [1]
- Correlation with $R_{D^{(*)}}$ [2] → Large enhancements to SM BF $\mathcal{O}(10^2 - 10^3)$ [3]
- Recent $B^+ \to K^+\nu\bar{\nu}$ excess, combined with R_{K^*} constraints, suggest LFUV in τ's [4,5]

$$\frac{\mathscr{B}(B \to K\nu\nu)}{\mathscr{B}(B \to K\nu\nu)^{SM}} = 5.4 \pm 1.5 \text{ (Belle II)}$$

$$\frac{\mathscr{B}(B \to K\tau\tau)}{\mathscr{B}(B \to K\tau\tau)^{SM}} = \frac{\mathscr{B}(B \to K^*\tau\tau)}{\mathscr{B}(B \to K^*\tau\tau)^{SM}} \in [16, 48]$$





Unique opportunity for Belle II

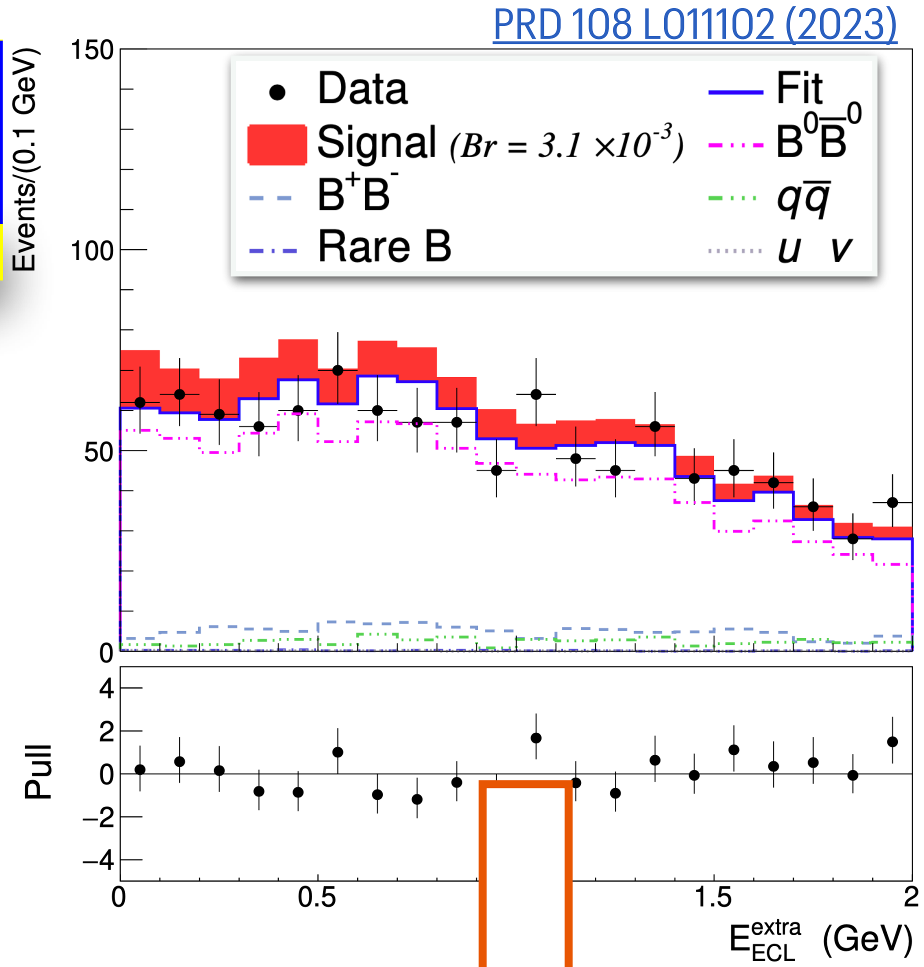
[1] PRD 107, 014511 (2023) [2] PRL 120, 181802 (2018) [3] PRD 105,113007 (2022) [4] PLB 848, 138411 (2023) [5] 2309.00075

$B \to K^{*0}\tau\tau$ AT BELLE (II)

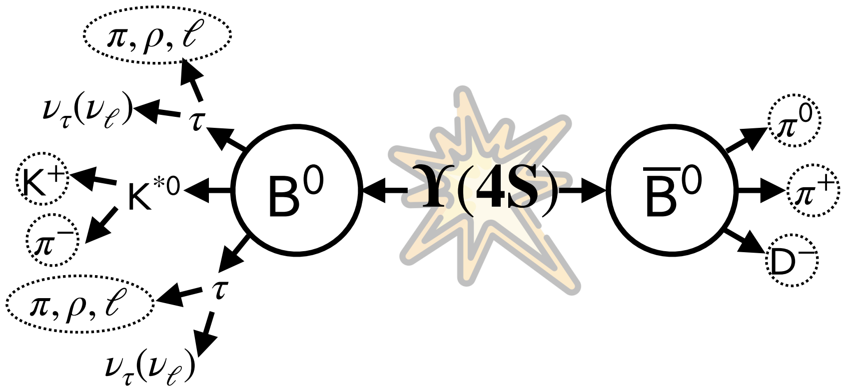
BELLE

711 fb^{-1}

PRD 108 L011102 (2023)

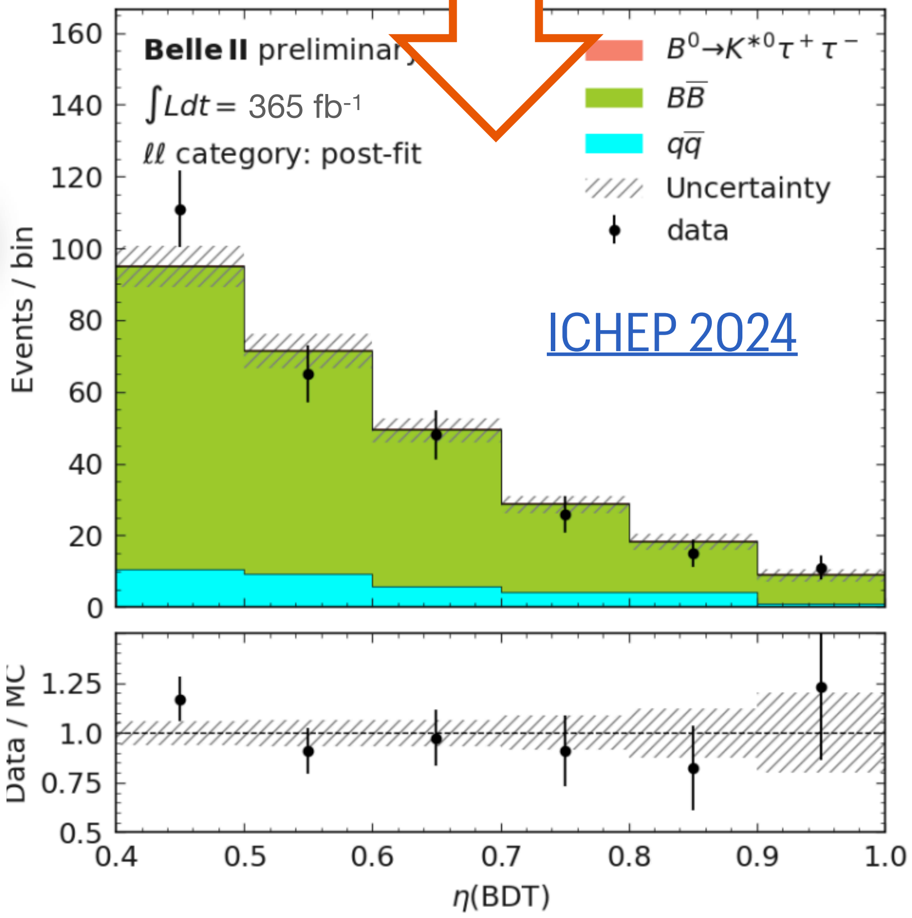


- Hadronic B-tagging Belle neurobayes-based algorithm
- Cut-based analysis
- $\tau \to \ell\nu\bar{\nu}, \pi\nu$ combined template fit in E$_{ECL}$
- $\mathscr{B}(B^0 \to K^{*0}\tau\tau) < 3.1 \times 10^{-3}$ (90 % CL)



Belle II

365 fb^{-1}



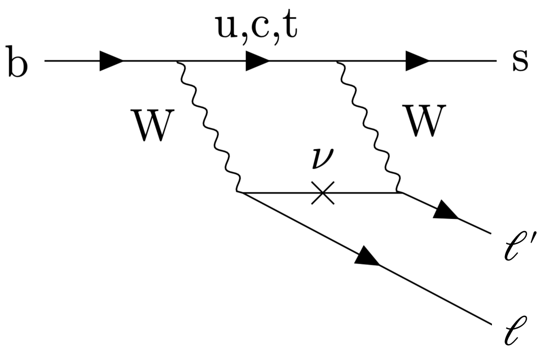
ICHEP 2024

- Hadronic B-tagging Belle II BDT-based algorithm × 2 eff .
- Multivariate analysis
- Simultaneous fit for $\ell\ell, \ell\pi, \pi\pi, \rho X$ in BDT output $\mathscr{B}(\tau \to \rho\nu) \sim 25\,\%$
- $\mathscr{B}(B^0 \to K^{*0}\tau\tau) < 1.8 \times 10^{-3}$ (90 % CL)

Better UL with less data!

CHARGED LEPTON FLAVOUR VIOLATION IN B DECAYS

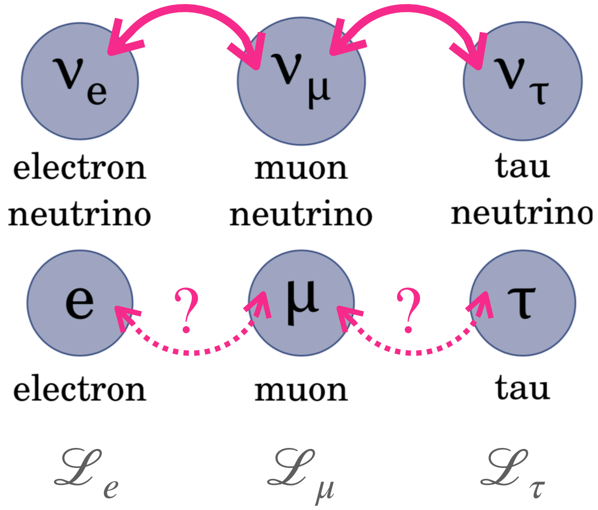
- Lepton Flavour Violating (LFV) decays can occur in the SM via ν mixing but are highly suppressed (m_ν^2/m_W^2) – well beyond any experimental sensitivity



- Extensions to the SM explaining the B-anomalies can connect the LFUV to the LFV

$$\boxed{\mathrm{L\cancel{F}U} \overset{\mathrm{BSM}}{\longleftrightarrow} \mathrm{\cancel{LF}}}$$

PRL 114, 091801 (2015)



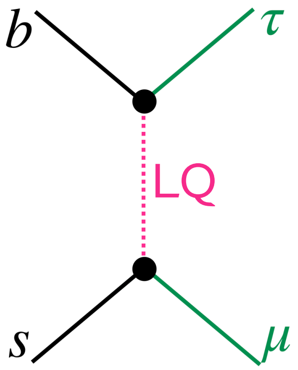
- Enhanced decay rates in, for example, $b \to s\tau\ell$ transitions

$$\boxed{\mathscr{B}(B\to K\mu\tau)\in[2,3]\times 10^{-6}}$$

PLB 848, 138411 (2023)

- The specific NP models that can lead to LFV must obey the constraints from other flavour observables $B_{(c)}/W\to\tau\nu,\ B^0-\overline{B}^0,\ \tau\to\mu\gamma(\phi)\ \ldots$

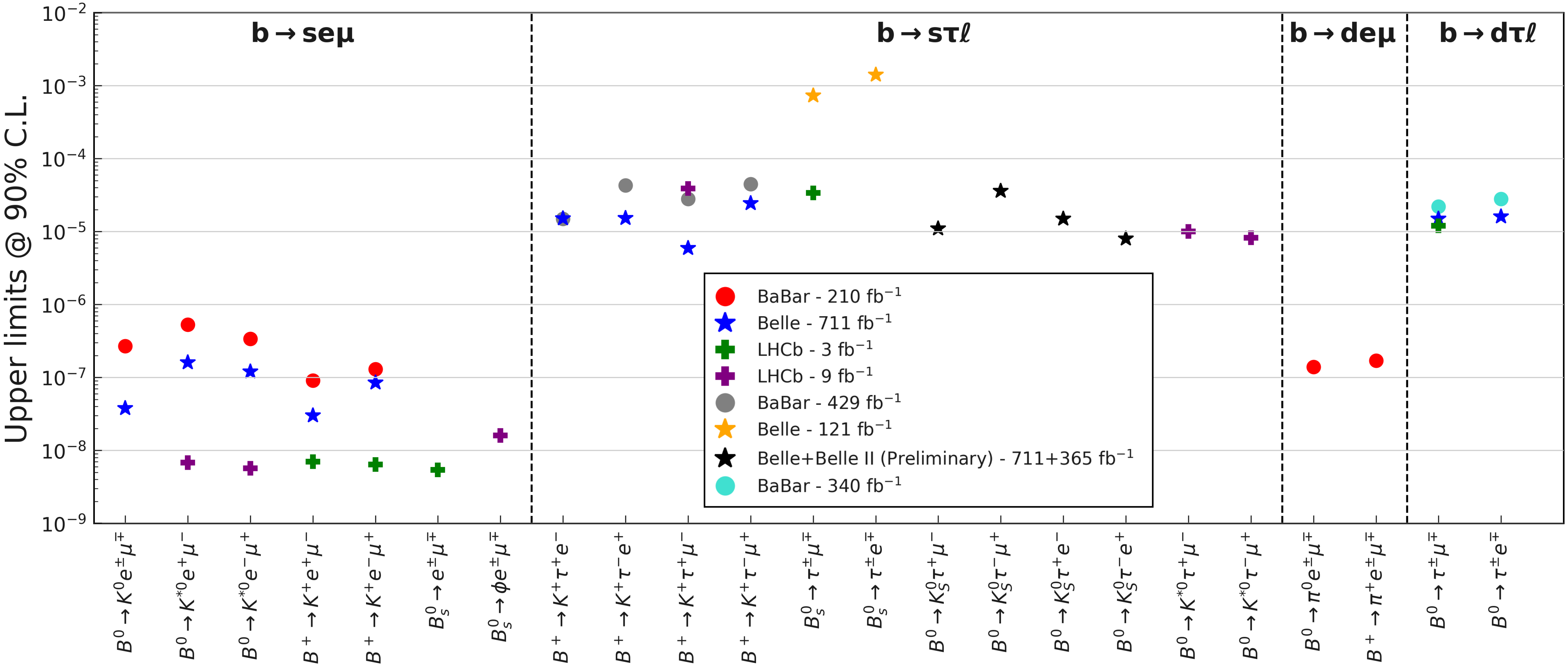
[1602.00881, 1606.00524, 1611.06676, 1806.05689, 2103.16558, 2206.09717, …]



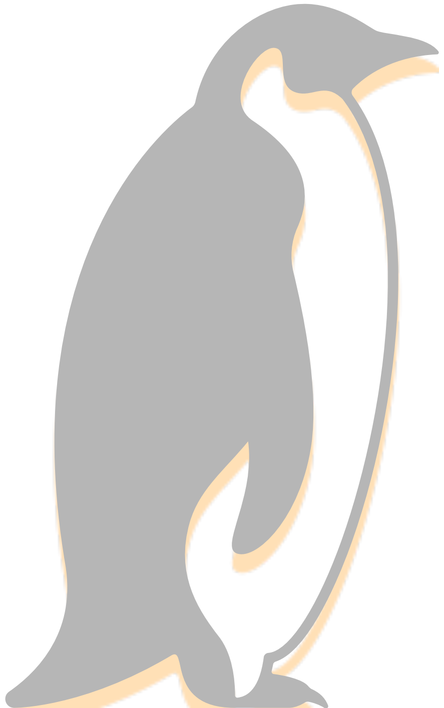
The observation of LFV in the charged sector would be a clear sign of physics beyond the Standard Model!

EXPERIMENTAL STATUS

- Searches of $\mathrm{b} \to \mathrm{s}e\mu$ decays are dominated by LHCb and UL's are $\mathcal{O}(10^{-8} - 10^{-9})$
- $\mathrm{b} \to \mathrm{s}\tau\ell$ are the most searched for, given the connection with the *B*-anomalies
  - UL are $\mathcal{O}(10^{-5})$ and Belle(II) and LHCb have similar sensitivities
- *B*-factories perform better with $\mathrm{b} \to (\mathrm{s}, \mathrm{d})\tau\mathrm{e}$ modes

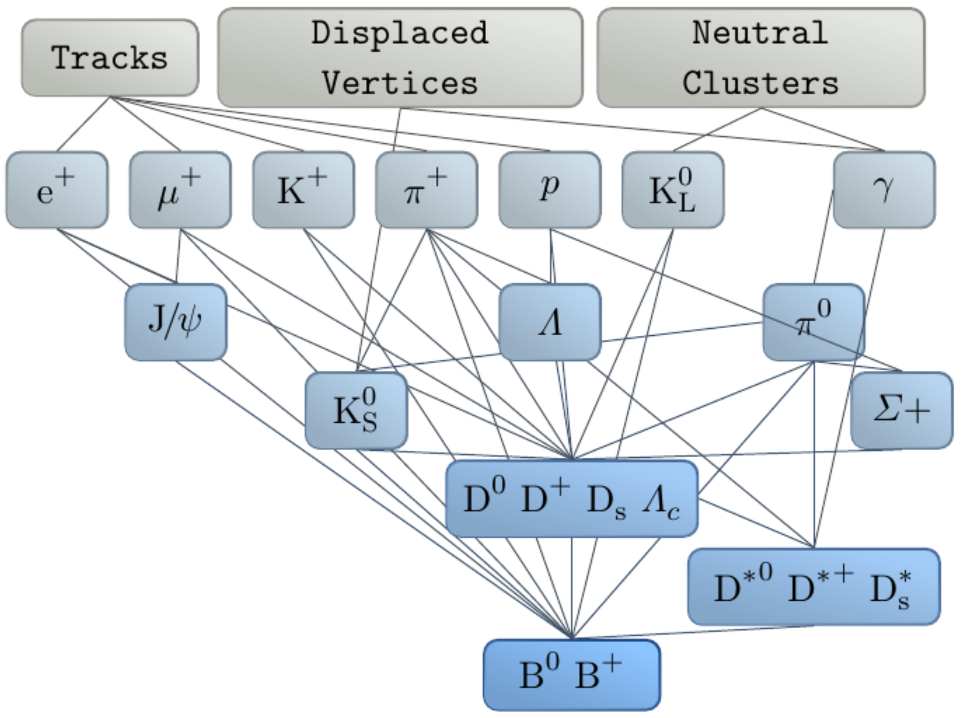


THE CHALLENGES



- Modelling of $b \to c\bar{u}d$
- Modelling of (signal-like) backgrounds
- Neutrals reconstruction

EXCLUSIVE B-TAGGING AT BELLE II



Full **E**vent **I**nterpretation (**FEI**)

FEI is the algorithm for HAD B_{tag} reconstruction at Belle II [1]

- Mostly $B \to D^{(*)} m\pi^{\pm} n\pi^0$
- ~2x higher efficiency wrt previous algorithms [2]
- Employs BDTs trained on MC $\Upsilon(4S) \to B\bar{B}$ events
- $\mathscr{P}_{FEI}$ used to select best B_{tag}

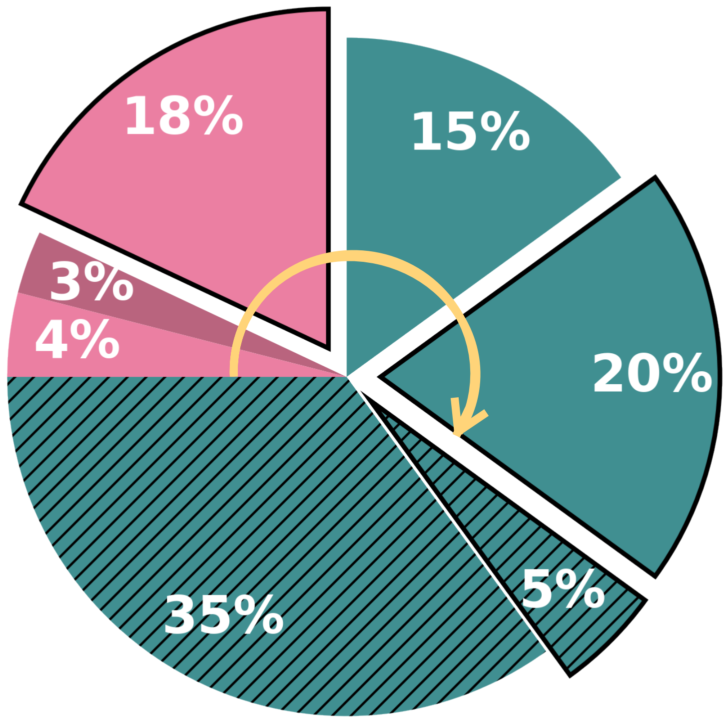
Main challenges

1. Large data/MC efficiency discrepancies
→ **Improve the modelling of B-decays**

2. Hadronic B-tagging: pure but very low efficiency
→ Add more decay modes
→ New algorithms: Graph Neural Network FEI ACAT2022

[1] Comput Softw Big Sci 3, 6 (2019) [2] NIMA 654 (2011) 432-440

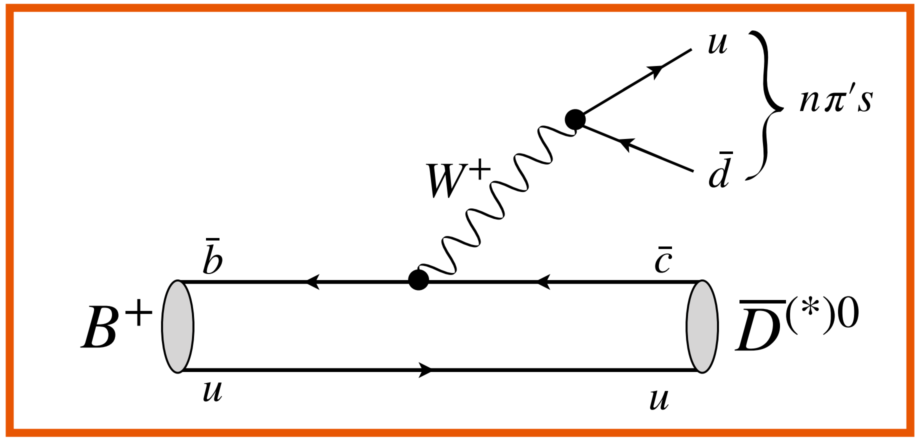
B-MESON DECAYS

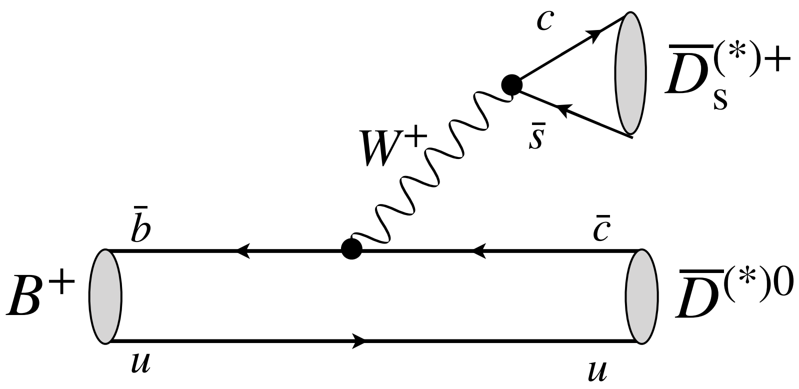


- ● **Semileptonic** $(\ell = \{e, \mu\})$
- ● **Semileptonic** $(\ell = \tau)$
- ● **Hadronic**
- ☐ **Covered by FEI**
- ☐ **EvtGen**
- ▨ **PYTHIA**

From
- PDG (i.e. measurements, though most are performed with small data sets → large statistical uncertainties, some poorly implemented in the simulation)
- symmetry principles

Quark fragmentation (i.e. no control over the final states and their BF, difficult to tune)





A. Lenz, 0011258

- $\bar{\mathtt{b}} \to \mathtt{c}\mathtt{W}^{*+}(\to \bar{\mathtt{u}}\mathtt{d})$ (~60% of had B)
- $\bar{\mathtt{b}} \to \bar{\mathtt{c}}\mathtt{W}^{*+}(\to \mathtt{c}\bar{\mathtt{s}})$ (~30% of had B)

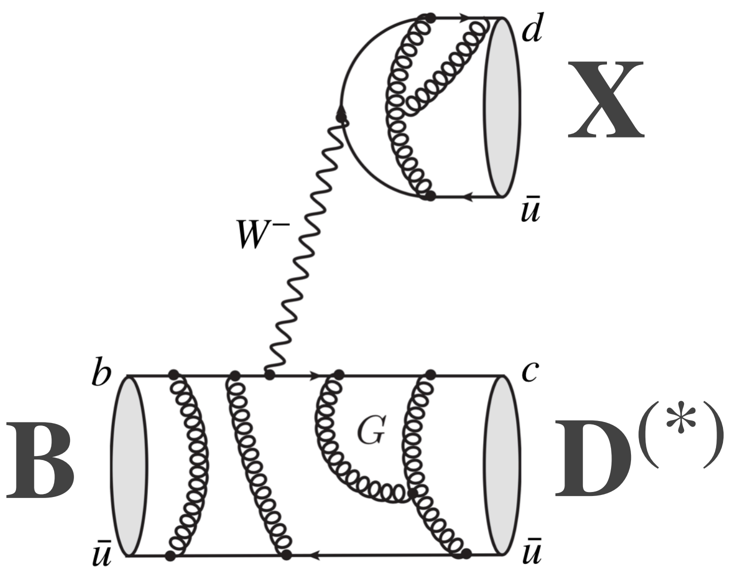
Poor knowledge of hadronic $B \to Dn\pi$ decays

⇒ Poor MC

⇒ Poor hadronic B-tagging

⇒ Limits our reach to exciting physics 🙁

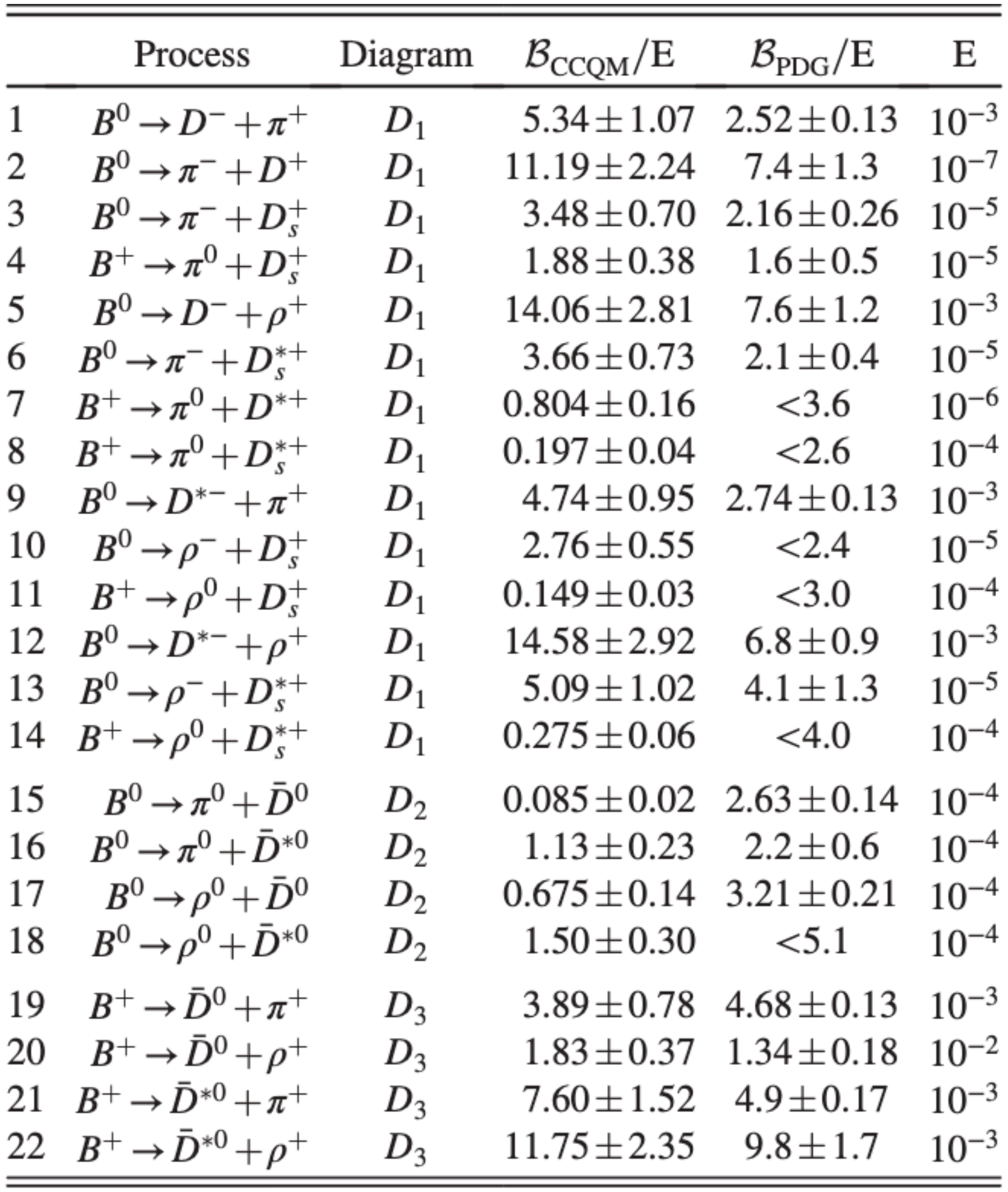
$\mathrm{B \to D^{(*)}h}$ DECAYS



- ‘Simplest’ decays: two-body with $\mathrm{W}^{*-} \to \pi^+/\rho^+/\mathrm{a}_1^+$
- Rates can be obtained by a product of 2 currents (factorisation):
  - $\mathrm{B \to D}$
  - $\mathrm{W^* \to X}$
- The corrections to this model due to perturbative QCD effects grow at higher $\mathrm{q^2 \equiv m_X^2}$

Discrepancies between measurements and expectations

[PRD 106 (2022) 3, 033006 (Table), JHEP 09 (2016) 112]



	Process	Diagram	$\mathcal{B}_{\mathrm{CCQM}}/\mathrm{E}$	$\mathcal{B}_{\mathrm{PDG}}/\mathrm{E}$	E
1	$B^0 \to D^- + \pi^+$	D_1	5.34 ± 1.07	2.52 ± 0.13	10^{-3}
2	$B^0 \to \pi^- + D^+$	D_1	11.19 ± 2.24	7.4 ± 1.3	10^{-7}
3	$B^0 \to \pi^- + D_s^+$	D_1	3.48 ± 0.70	2.16 ± 0.26	10^{-5}
4	$B^+ \to \pi^0 + D_s^+$	D_1	1.88 ± 0.38	1.6 ± 0.5	10^{-5}
5	$B^0 \to D^- + \rho^+$	D_1	14.06 ± 2.81	7.6 ± 1.2	10^{-3}
6	$B^0 \to \pi^- + D_s^{*+}$	D_1	3.66 ± 0.73	2.1 ± 0.4	10^{-5}
7	$B^+ \to \pi^0 + D^{*+}$	D_1	0.804 ± 0.16	<3.6	10^{-6}
8	$B^+ \to \pi^0 + D_s^{*+}$	D_1	0.197 ± 0.04	<2.6	10^{-4}
9	$B^0 \to D^{*-} + \pi^+$	D_1	4.74 ± 0.95	2.74 ± 0.13	10^{-3}
10	$B^0 \to \rho^- + D_s^+$	D_1	2.76 ± 0.55	<2.4	10^{-5}
11	$B^+ \to \rho^0 + D_s^+$	D_1	0.149 ± 0.03	<3.0	10^{-4}
12	$B^0 \to D^{*-} + \rho^+$	D_1	14.58 ± 2.92	6.8 ± 0.9	10^{-3}
13	$B^0 \to \rho^- + D_s^{*+}$	D_1	5.09 ± 1.02	4.1 ± 1.3	10^{-5}
14	$B^+ \to \rho^0 + D_s^{*+}$	D_1	0.275 ± 0.06	<4.0	10^{-4}
15	$B^0 \to \pi^0 + \bar{D}^0$	D_2	0.085 ± 0.02	2.63 ± 0.14	10^{-4}
16	$B^0 \to \pi^0 + \bar{D}^{*0}$	D_2	1.13 ± 0.23	2.2 ± 0.6	10^{-4}
17	$B^0 \to \rho^0 + \bar{D}^0$	D_2	0.675 ± 0.14	3.21 ± 0.21	10^{-4}
18	$B^0 \to \rho^0 + \bar{D}^{*0}$	D_2	1.50 ± 0.30	<5.1	10^{-4}
19	$B^+ \to \bar{D}^0 + \pi^+$	D_3	3.89 ± 0.78	4.68 ± 0.13	10^{-3}
20	$B^+ \to \bar{D}^0 + \rho^+$	D_3	1.83 ± 0.37	1.34 ± 0.18	10^{-2}
21	$B^+ \to \bar{D}^{*0} + \pi^+$	D_3	7.60 ± 1.52	4.9 ± 0.17	10^{-3}
22	$B^+ \to \bar{D}^{*0} + \rho^+$	D_3	11.75 ± 2.35	9.8 ± 1.7	10^{-3}

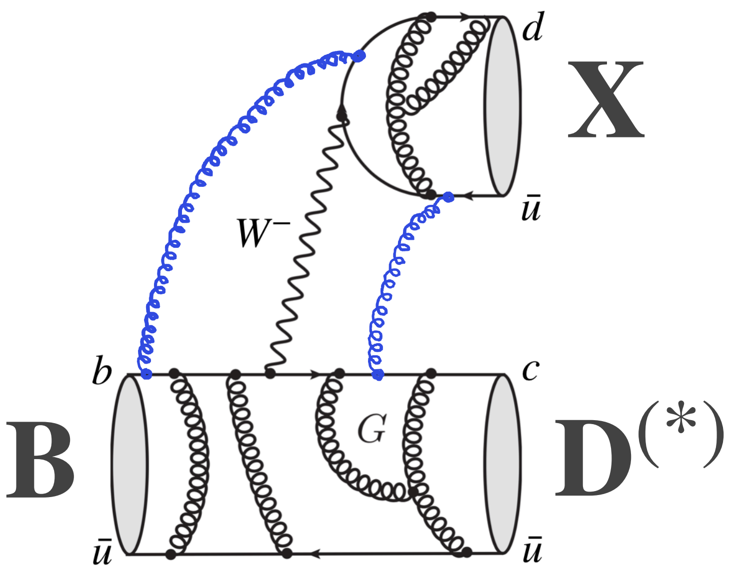
$\boldsymbol{B \to D\pi}$ (Belle) [PRD 105 (2022) 1, 012003 (1),
PRD 105 (2022) 7, 072007 (15, 19)]

$\boldsymbol{B^+ \to \bar{D}^0 \rho^+}$ (Belle II) PRD 109, 111103 (2024)

- $\mathscr{B}_{\text{Belle II}} = (0.939 \pm 0.021 \pm 0.05)\ \%$
- FEI calibration factor 0.75 → 1.07

$B \to D^{(*)}h$ DECAYS

- ‘Simplest’ decays: two-body with $W^{*-} \to \pi^+/\rho^+/a_1^+$
- Rates can be obtained by a product of 2 currents (factorisation):
  - $B \to D$
  - $W^* \to X$
- The corrections to this model due to perturbative QCD effects grow at higher $q^2 \equiv m_X^2$



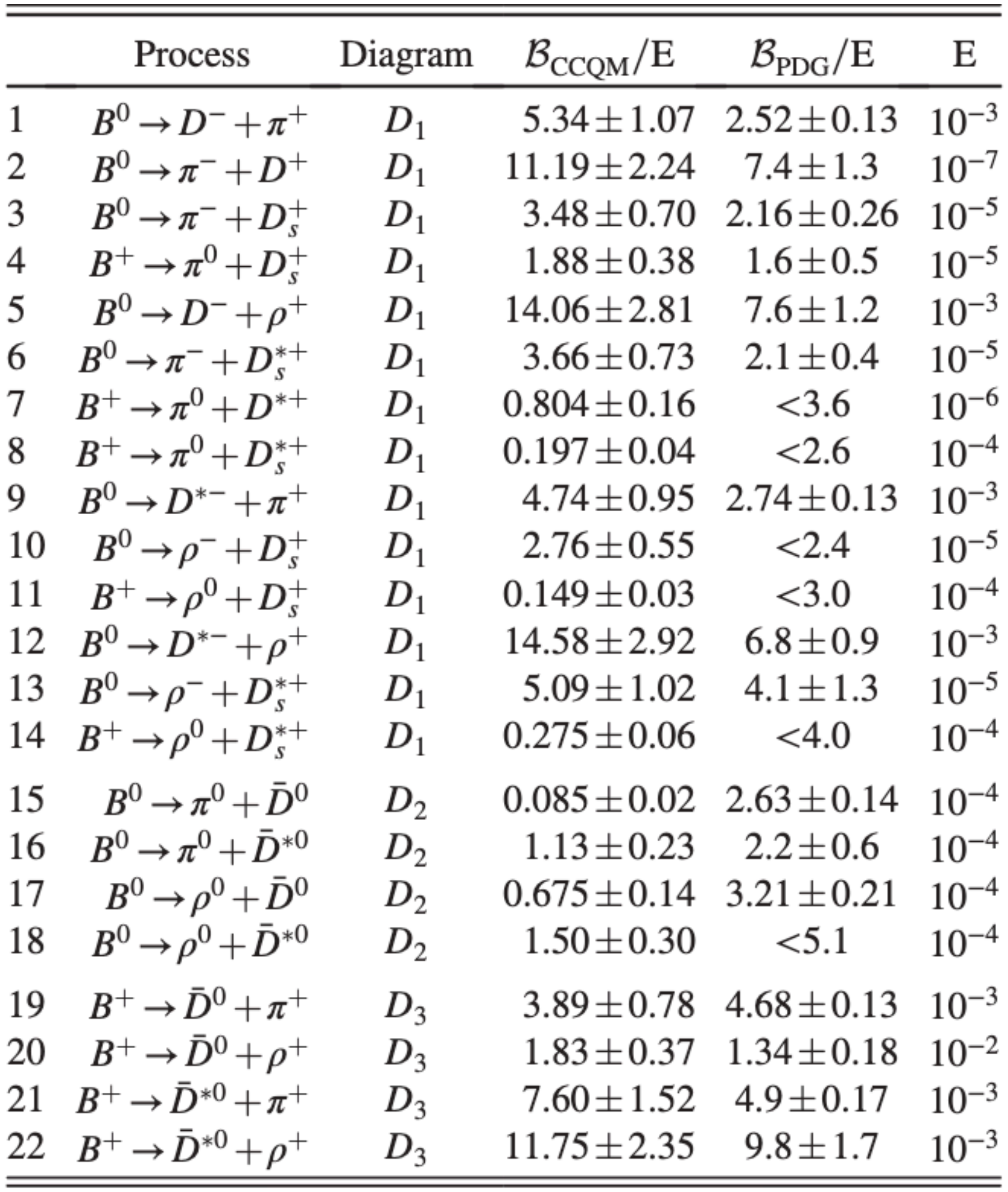
Discrepancies between measurements and expectations

[PRD 106 (2022) 3, 033006 (Table), JHEP 09 (2016) 112]

Failure of the factorisation?

**NP contributions? [JHEP 10 (2021) 235,
PRD 102.071701 (2020)]**

Things get even more complicated for $n\pi$, $n > 2$ ...
<u>Need more measurements!</u>



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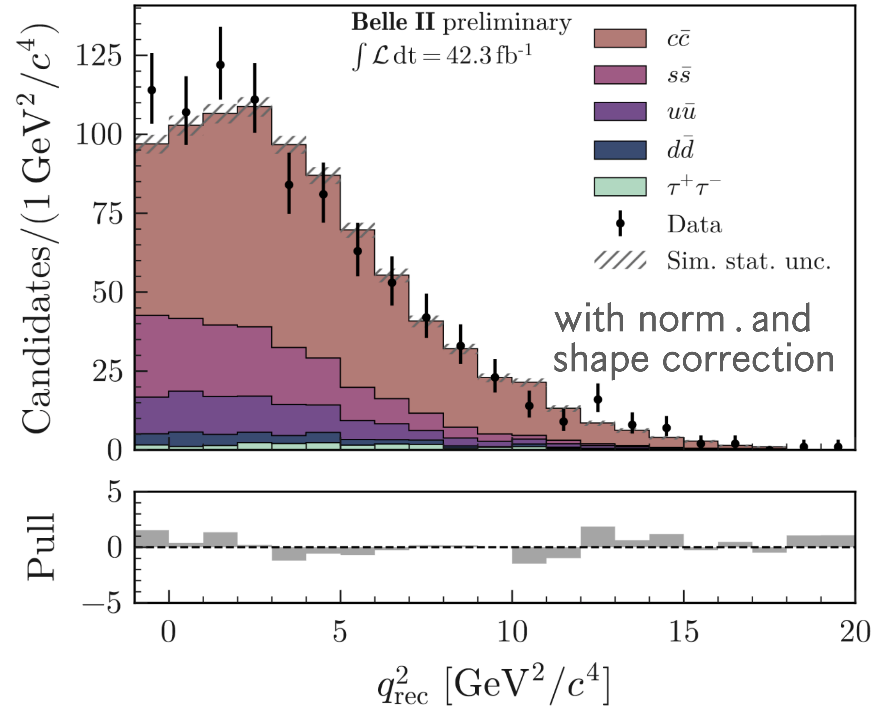
7	$B^+ \to \pi^0 + D^{*+}$	D_1	0.804 ± 0.16	<3.6	10^{-6}
8	$B^+ \to \pi^0 + D_s^{*+}$	D_1	0.197 ± 0.04	<2.6	10^{-4}
9	$B^0 \to D^{*-} + \pi^+$	D_1	4.74 ± 0.95	2.74 ± 0.13	10^{-3}
10	$B^0 \to \rho^- + D_s^+$	D_1	2.76 ± 0.55	<2.4	10^{-5}
11	$B^+ \to \rho^0 + D_s^+$	D_1	0.149 ± 0.03	<3.0	10^{-4}
12	$B^0 \to D^{*-} + \rho^+$	D_1	14.58 ± 2.92	6.8 ± 0.9	10^{-3}
13	$B^0 \to \rho^- + D_s^{*+}$	D_1	5.09 ± 1.02	4.1 ± 1.3	10^{-5}
14	$B^+ \to \rho^0 + D_s^{*+}$	D_1	0.275 ± 0.06	<4.0	10^{-4}
15	$B^0 \to \pi^0 + \bar{D}^0$	D_2	0.085 ± 0.02	2.63 ± 0.14	10^{-4}
16	$B^0 \to \pi^0 + \bar{D}^{*0}$	D_2	1.13 ± 0.23	2.2 ± 0.6	10^{-4}
17	$B^0 \to \rho^0 + \bar{D}^0$	D_2	0.675 ± 0.14	3.21 ± 0.21	10^{-4}
18	$B^0 \to \rho^0 + \bar{D}^{*0}$	D_2	1.50 ± 0.30	<5.1	10^{-4}
19	$B^+ \to \bar{D}^0 + \pi^+$	D_3	3.89 ± 0.78	4.68 ± 0.13	10^{-3}
20	$B^+ \to \bar{D}^0 + \rho^+$	D_3	1.83 ± 0.37	1.34 ± 0.18	10^{-2}
21	$B^+ \to \bar{D}^{*0} + \pi^+$	D_3	7.60 ± 1.52	4.9 ± 0.17	10^{-3}
22	$B^+ \to \bar{D}^{*0} + \rho^+$	D_3	11.75 ± 2.35	9.8 ± 1.7	10^{-3}

MC MODELLING

$q\bar{q}$ background

Validated on off-resonance data. **Corrections needed in**

- **Normalisation**
- **Shape ↦ event-by-event data-driven correction using OFF resonance data** [J.Phys.Conf.Ser. 368 (2012) 012028]

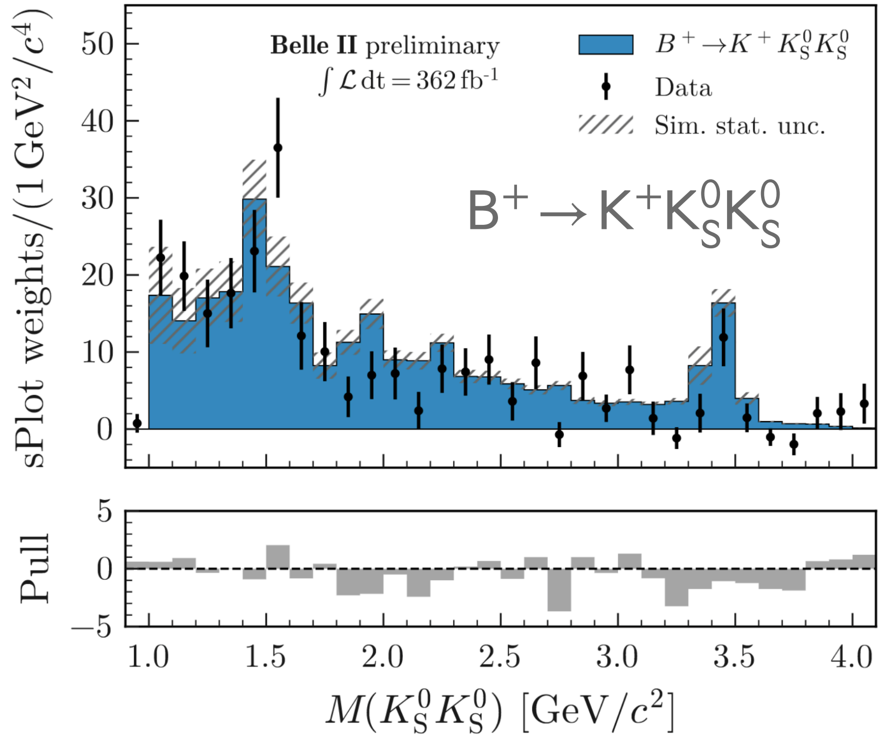


with norm . and shape correction

B → hadronic for B_{sig}

Improved simulation of rare decays like $B \to Kn\bar{n}$, KK^0K^0 (total BF and decay model)

- using experimental inputs and
- incorporating isospin assumptions



$B^+ \to K^+K^0_SK^0_S$

MC MODELLING

$q\bar{q}$ background

Validated on off-resonance data. **Corrections needed in**

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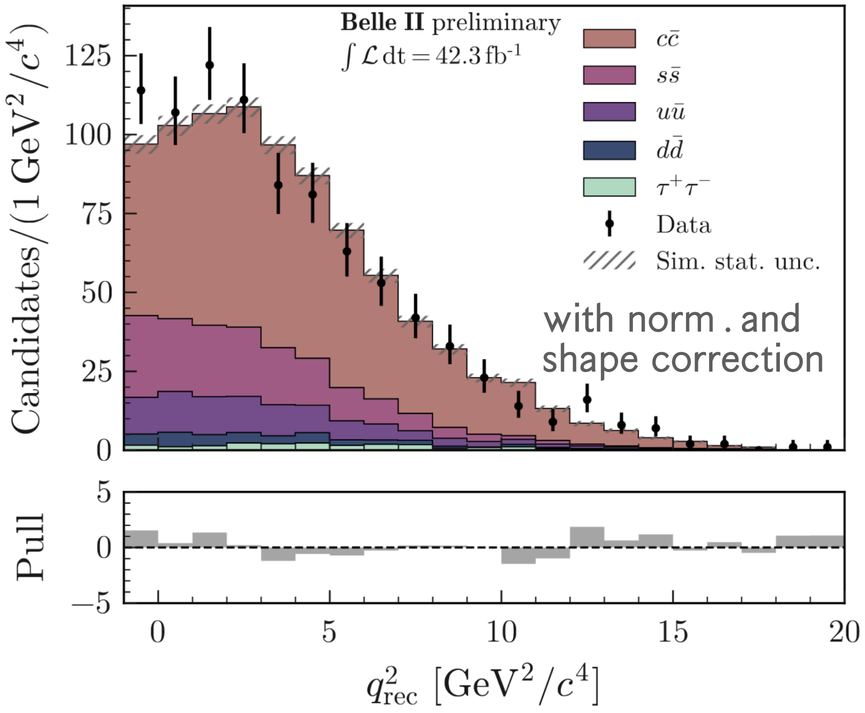
- Shape ↦ event-by-event data-driven correction using OFF resonance data [J.Phys.Conf.Ser. 368 (2012) 012028]



with norm . and shape correction

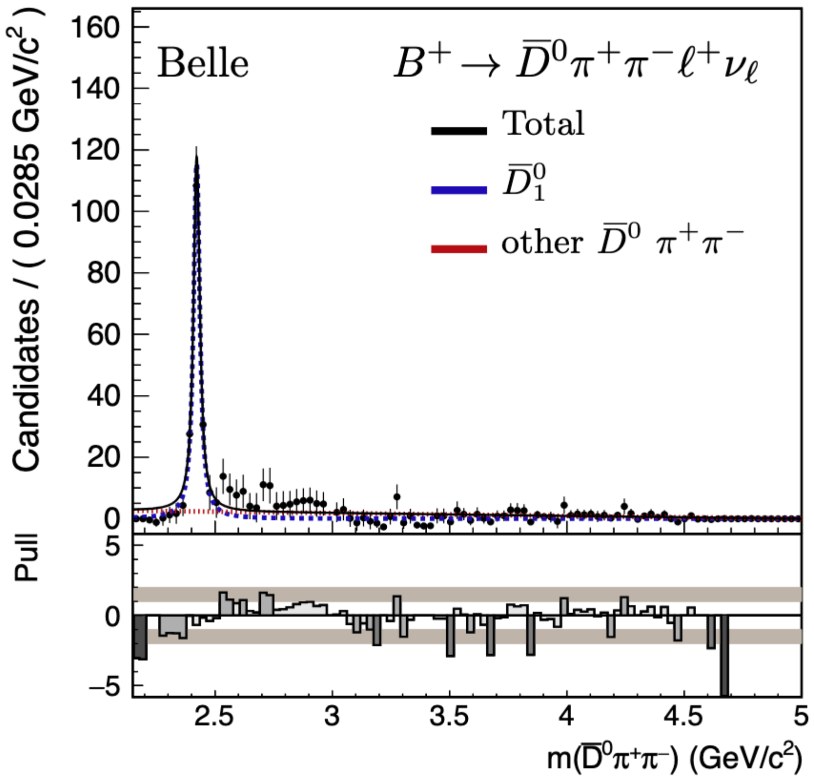
B → semileptonic for B_{sig}

$B \to D n\pi\ell\nu$ events are often a source of background

The BF's are not well known (see SL gap)

Effort in Belle (II) to measure those modes and improve the simulation

- $B \to D^{(*)}\pi(\pi)\ell\nu$ [Belle, PRD 107 (2023) 9, 092003]
- $B \to D^{(*)}\eta\ell\nu$ via $B \to D^{(*)}\eta\pi$

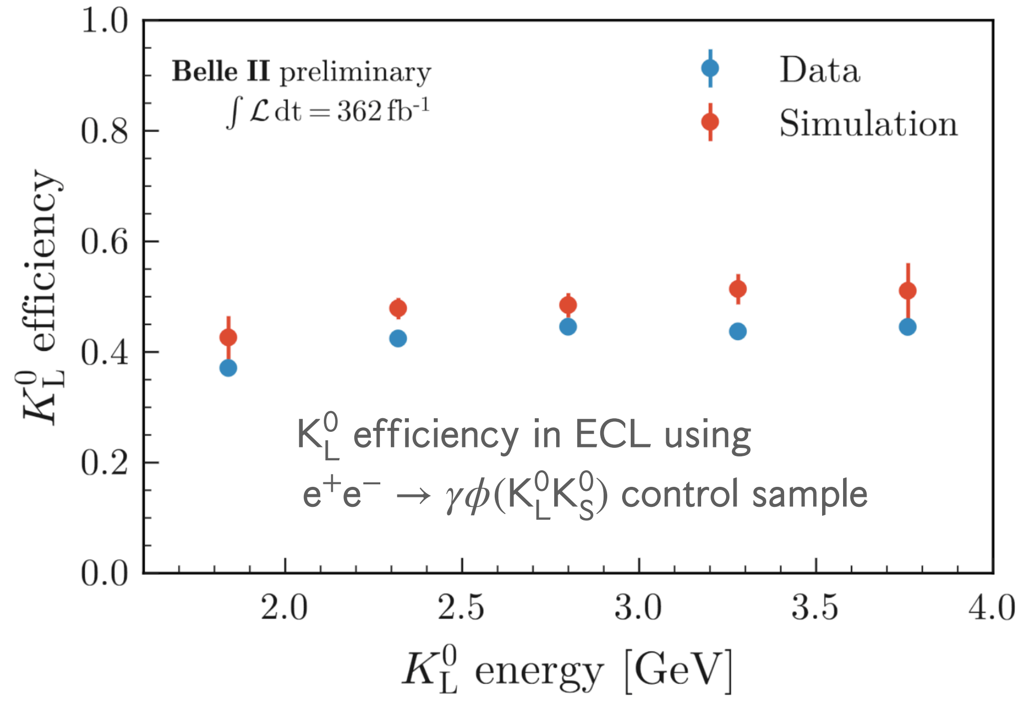


NEUTRALS

K_L^0 reconstruction and simulation

- K_L^0 escaping ECL can mimic neutrinos → prominent background in missing energy analyses
- Currently K_L^0 are not explicitly reconstructed due to modelling issues
- The impact is validated on a case-by-case basis

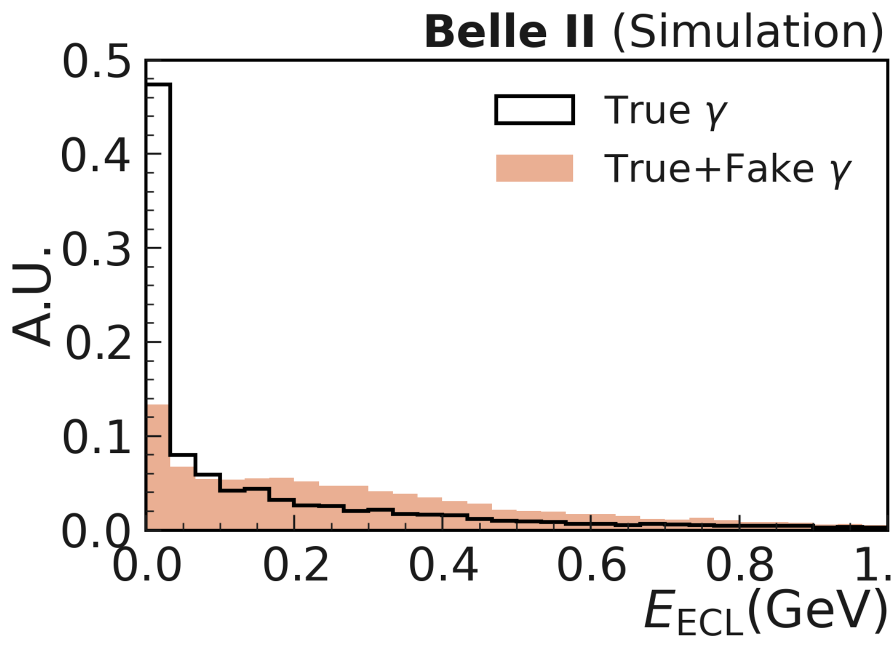
Improvements in K_L^0 reconstruction and better agreement with simulation will allow to veto on them



K_L^0 efficiency in ECL using $e^+e^- \to \gamma\phi(K_L^0 K_S^0)$ control sample

Fake photons

- Deposits from charged particles/hadrons in the calorimeter can be wrongly reconstructed as photons
- **This dilutes the separation power of E_{ECL} and degrades the precision of measurements with missing energy → ad-hoc MVA (needs calibration)**



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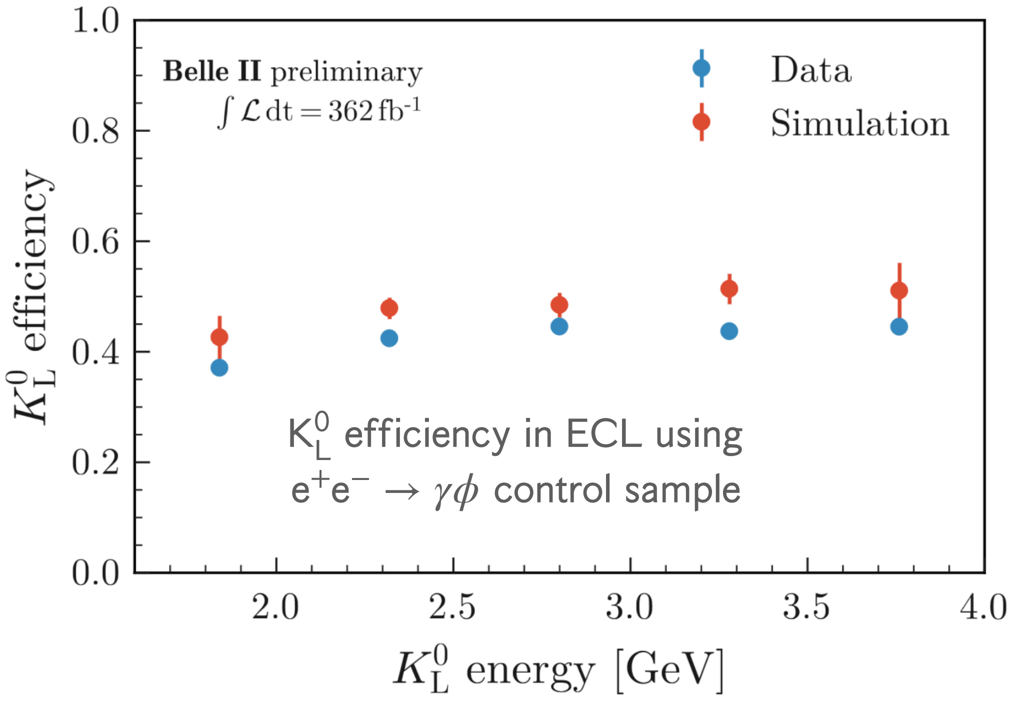

K_L^0 efficiency in ECL using $e^+e^- \to \gamma\phi$ control sample

Fake photons

- Deposits from charged particles/hadrons in the calorimeter can be wrongly reconstructed as photons
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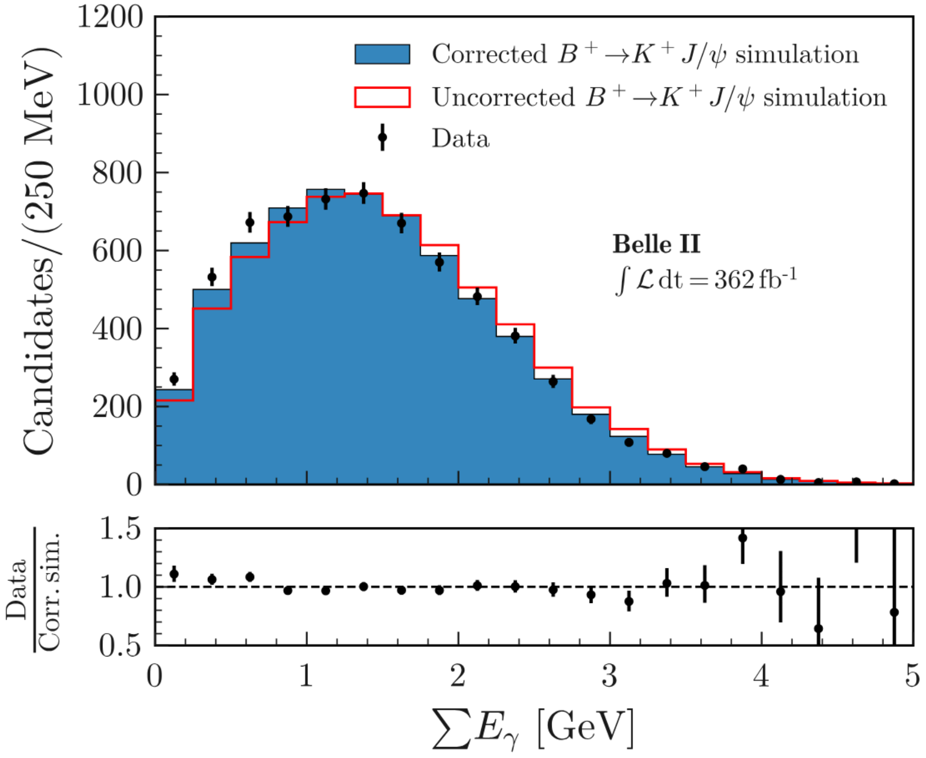
Rescaling of the fake photon component in MC needed!



CONCLUSION

- **Rare B decays allow to test SM and probe NP**
- **(Belle+)Belle II producing world-leading results**
  - **Best precision** $B\to\rho\gamma$ $B\to K\nu\bar{\nu}$
  - **Best UL** $b\to d\ell^+\ell^-$ $B^+\to K^+\tau\ell$ $B^0\to K^{*0}\tau\tau$
- **While waiting for more data, working on the tools to boost even further our sensitivity**
- **More to come** $B\to X_s\gamma, B^+\to K^+\tau\tau, B\to X\ell\ell, B\to(K^*/\rho)\nu\bar{\nu}, \ldots$

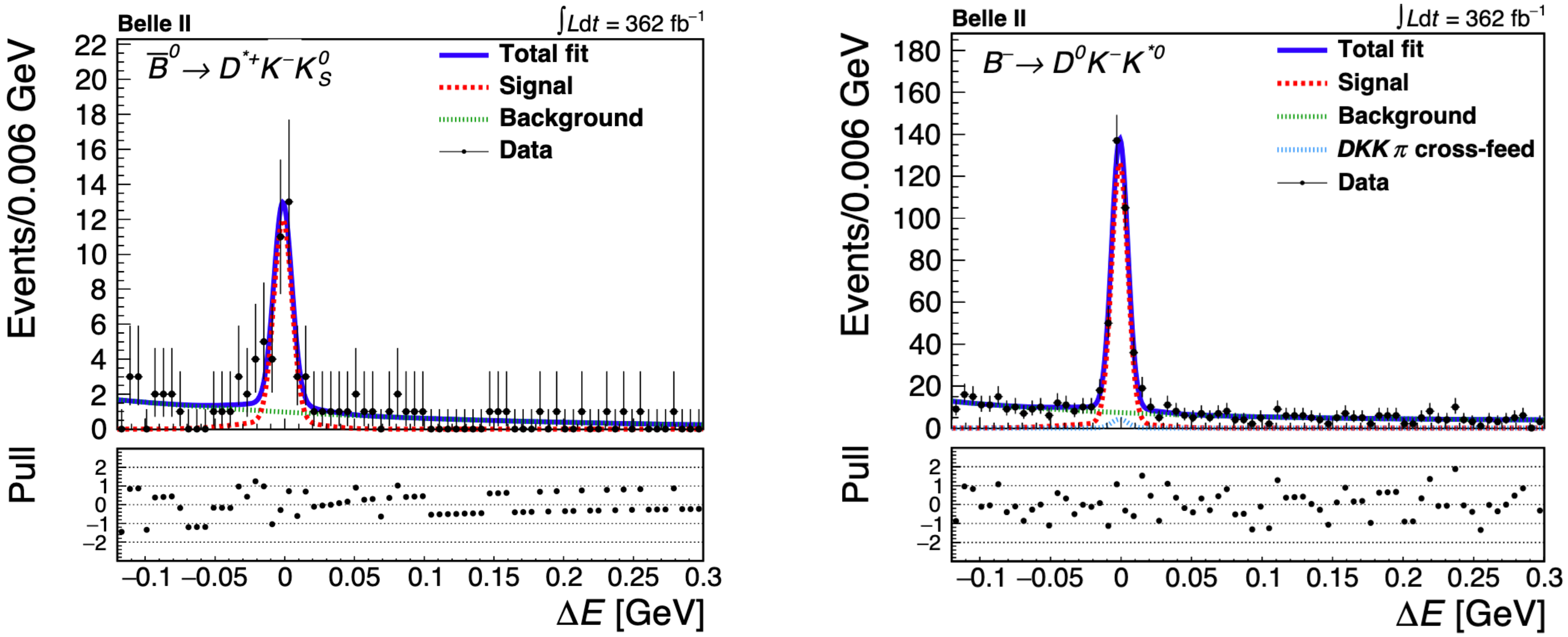
Thank you for
your attention

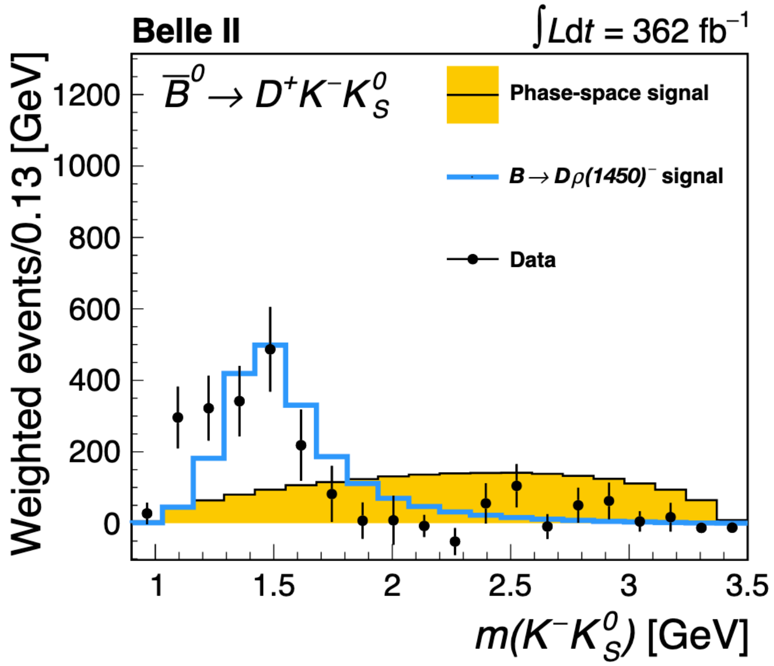
ADDITIONAL MATERIAL

ADDITIONAL MODES FOR FEI

PLB 542 (2002) 171

$B \rightarrow D^{(*)} K^- K^{(*)0}_{(S)}$ JHEP08(2024)206



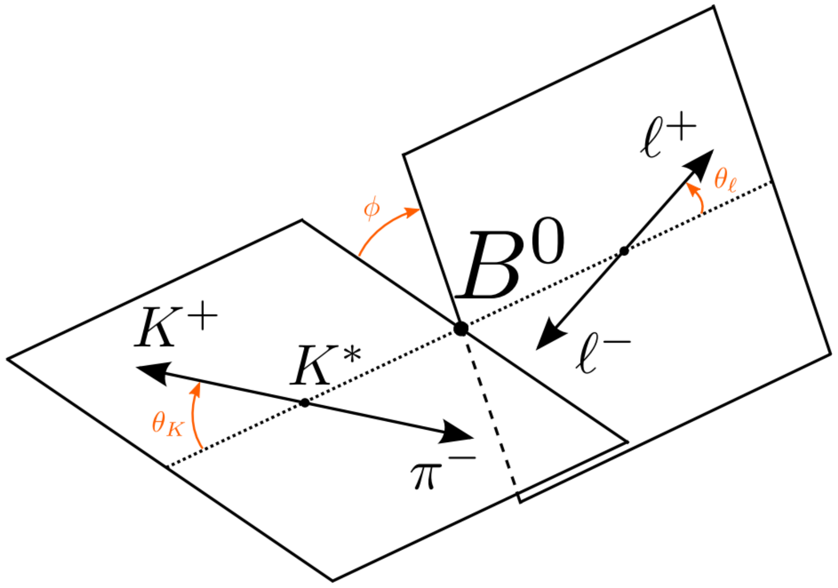


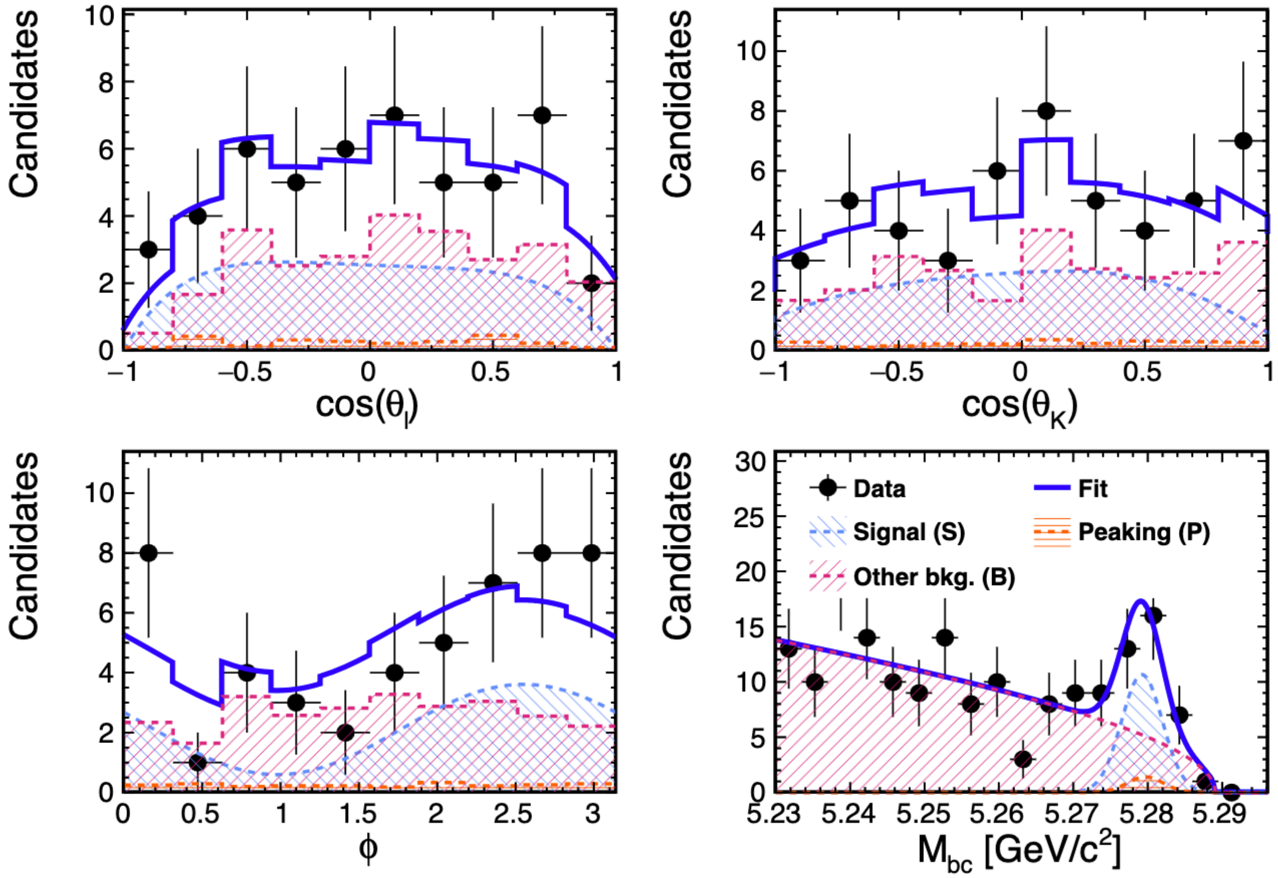
Low-mass enhancement of kaon pairs in $B \rightarrow D^{(*)} K K^0$ decays
Phys. Rev. D 109 (2024) 116009

Channel	Yield	Average ε	$\mathcal{B}$ $[10^{-4}]$	Stat. significance $[\sigma]$	
$B^- \rightarrow D^0 K^- K^0_S$	209 ± 17	0.098	$1.82 \pm 0.16 \pm 0.08$	> 10	
$\overline{B}^0 \rightarrow D^+ K^- K^0_S$	105 ± 14	0.048	$0.82 \pm 0.12 \pm 0.05$	10	*
$B^- \rightarrow D^{*0} K^- K^0_S$	51 ± 9	0.044	$1.47 \pm 0.27 \pm 0.10$	8	*
$\overline{B}^0 \rightarrow D^{*+} K^- K^0_S$	36 ± 7	0.046	$0.91 \pm 0.19 \pm 0.05$	9	*
$B^- \rightarrow D^0 K^- K^{*0}$	325 ± 19	0.043	$7.19 \pm 0.45 \pm 0.33$	> 10	
$\overline{B}^0 \rightarrow D^+ K^- K^{*0}$	385 ± 22	0.021	$7.56 \pm 0.45 \pm 0.38$	> 10	
$B^- \rightarrow D^{*0} K^- K^{*0}$	160 ± 15	0.019	$11.93 \pm 1.14 \pm 0.93$	> 10	
$\overline{B}^0 \rightarrow D^{*+} K^- K^{*0}$	193 ± 14	0.020	$13.12 \pm 1.21 \pm 0.71$	> 10	

* First observations

ANGULAR ANALYSIS OF $B \to K^* e^+ e^-$





$$
\begin{aligned}
&\frac{1}{d(\Gamma+\bar\Gamma)/dq^2}\,\frac{d^4(\Gamma+\bar\Gamma)}{dq^2\,d\cos\theta_\ell\,d\cos\theta_K\,d\phi} = \\
&\frac{9}{16\pi}\Big(\frac{3}{4}(1-\boxed{F_L})\sin^2\theta_K + F_L\cos^2\theta_K \\
&+ \big(\frac{1}{4}(1-F_L)\sin^2\theta_K - F_L\cos^2\theta_K\big)\cos 2\theta_\ell \\
&+ \frac{1}{2}(1-F_L)\boxed{A_T^{(2)}}\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi \\
&+ (1-F_L)\boxed{A_T^{\mathrm{Re}}}\sin^2\theta_K\cos\theta_\ell \\
&+ \frac{1}{2}(1-F_L)\boxed{A_T^{\mathrm{Im}}}\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big),
\end{aligned}
$$

floated

fixed

$$A_T^{(2)} = \frac{I_3}{2I_2^s} \overset{q^2\to 0}{=} \frac{2\Re(\mathcal{C}_7^{\mathrm{eff}}\mathcal{C}_7^{\prime\mathrm{eff}*})}{|\mathcal{C}_7^{\mathrm{eff}}|^2+|\mathcal{C}_7^{\prime\mathrm{eff}*}|^2}$$

$$A_T^{\mathrm{Im}} = \frac{I_9}{2I_2^s} \overset{q^2\to 0}{=} \frac{2\Im(\mathcal{C}_7^{\mathrm{eff}}\mathcal{C}_7^{\prime\mathrm{eff}*})}{|\mathcal{C}_7^{\mathrm{eff}}|^2+|\mathcal{C}_7^{\prime\mathrm{eff}*}|^2}$$

HADRONIC B-MESON DECAYS

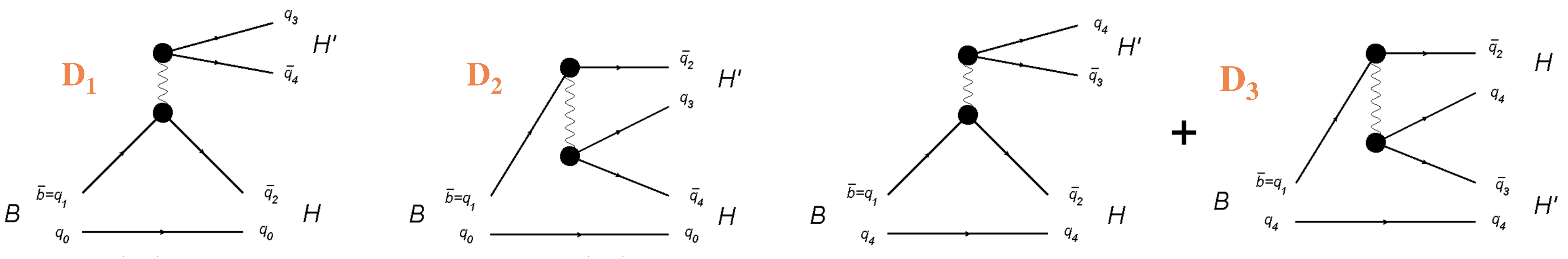
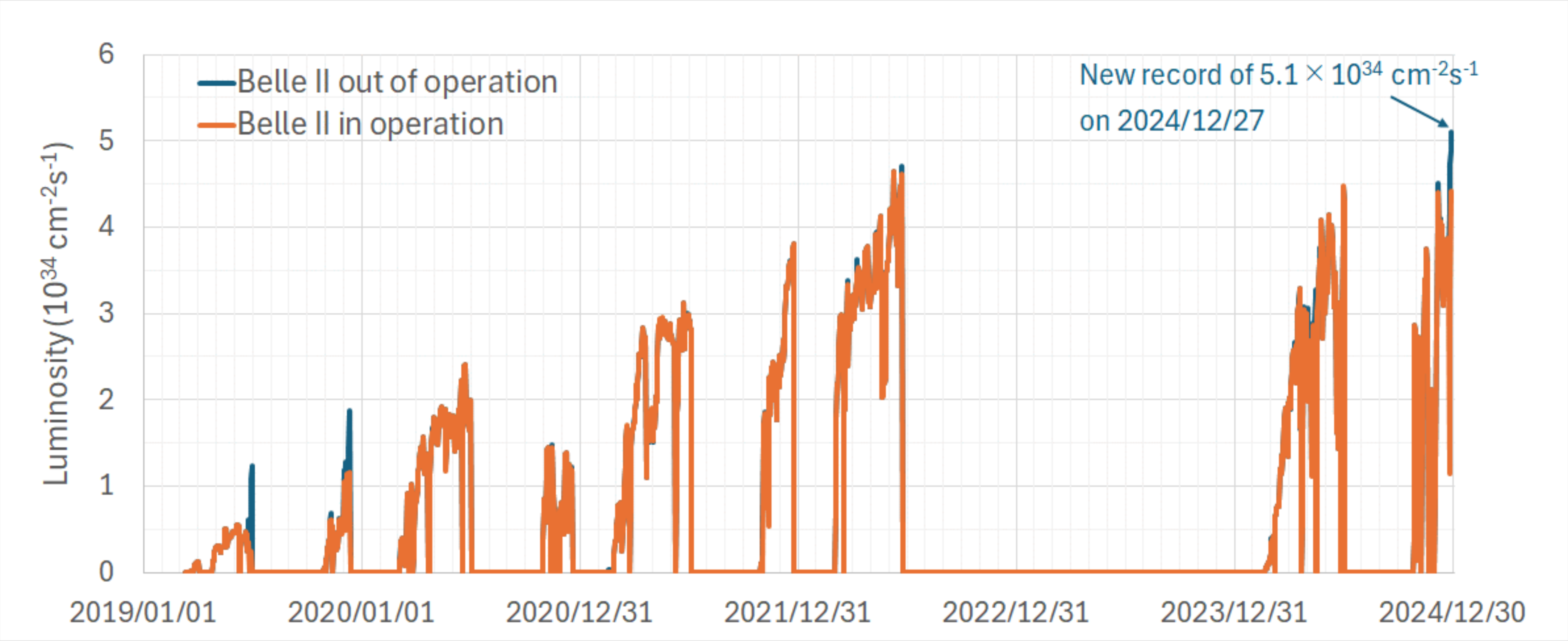


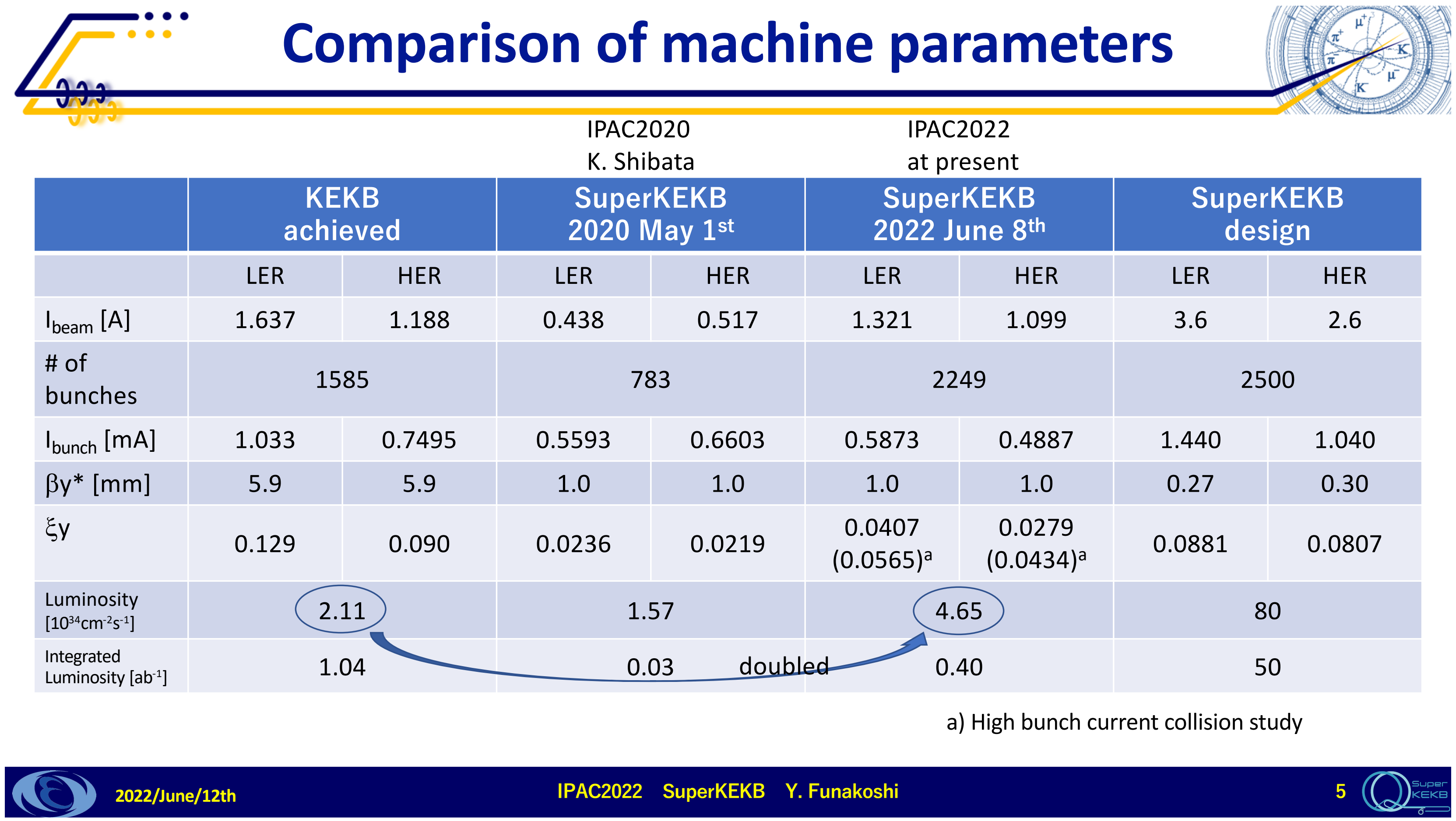
	Diagram type		
Spin structure	D_1	D_2	D_3
(A) $\underline{\boldsymbol{PS}\rightarrow\boldsymbol{PS}}+PS$	$\underline{B^0\rightarrow D^-}+\pi^+$ $\underline{B^0\rightarrow\pi^-}+D^+$ $\underline{B^0\rightarrow\pi^-}+D_s^+$ $\underline{B^+\rightarrow\pi^0}+D_s^+$	$\underline{B^0\rightarrow\pi^0}+\bar{D}^0$	$\underline{B^+\rightarrow\bar{D}^0}+\pi^+$
(B) $\underline{\boldsymbol{PS}\rightarrow\boldsymbol{PS}}+V$	$\underline{B^0\rightarrow D^-}+\varrho^+$ $\underline{B^0\rightarrow\pi^-}+D_s^{*+}$ $\underline{B^+\rightarrow\pi^0}+D^{*+}$ $\underline{B^+\rightarrow\pi^0}+D_s^{*+}$	$\underline{B^0\rightarrow\pi^0}+\overline{D^{*0}}$	$\underline{B^+\rightarrow\bar{D}^0}+\varrho^+$
(C) $\underline{\boldsymbol{PS}\rightarrow\boldsymbol{V}}+PS$	$\underline{B^0\rightarrow D^{*-}}+\pi^+$ $\underline{B^0\rightarrow\varrho^-}+D_s^+$ $\underline{B^+\rightarrow\varrho^0}+D_s^+$	$\underline{B^0\rightarrow\varrho^0}+\bar{D}^0$	$\underline{B^+\rightarrow\overline{D^{*0}}}+\pi^+$
(D) $\underline{\boldsymbol{PS}\rightarrow\boldsymbol{V}}+V$	$\underline{B^0\rightarrow D^{*-}}+\varrho^+$ $\underline{B^0\rightarrow\varrho^-}+D_s^{*+}$ $\underline{B^+\rightarrow\varrho^0}+D_s^{*+}$	$\underline{B^0\rightarrow\varrho^0}+\overline{D^{*0}}$	$\underline{B^+\rightarrow\overline{D^{*0}}}+\varrho^+$

SUPERKEKB LUMINOSITY PROFILE



10.1093/ptep/pts102

SUPERKEKB LUMINOSITY PROFILE



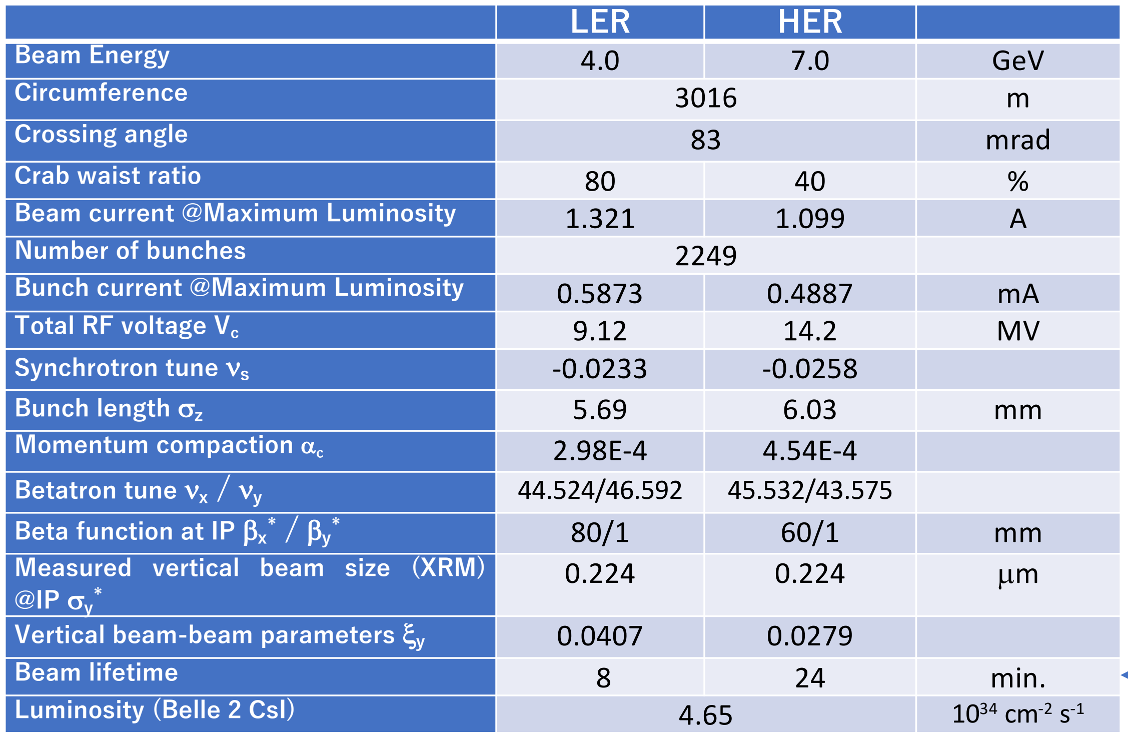
Comparison of machine parameters

	KEKB achieved		SuperKEKB 2020 May 1st (IPAC2020 K. Shibata)		SuperKEKB 2022 June 8th (IPAC2022 at present)		SuperKEKB design	
	LER	HER	LER	HER	LER	HER	LER	HER
I_{beam} [A]	1.637	1.188	0.438	0.517	1.321	1.099	3.6	2.6
# of bunches	1585		783		2249		2500	
I_{bunch} [mA]	1.033	0.7495	0.5593	0.6603	0.5873	0.4887	1.440	1.040
βy^* [mm]	5.9	5.9	1.0	1.0	1.0	1.0	0.27	0.30
ξy	0.129	0.090	0.0236	0.0219	0.0407 (0.0565)^a	0.0279 (0.0434)^a	0.0881	0.0807
Luminosity [10^{34}cm^{-2}s^{-1}]	2.11		1.57		4.65		80	
Integrated Luminosity [ab^{-1}]	1.04		0.03		0.40		50	

doubled

a) High bunch current collision study

2022/June/12th IPAC2022 SuperKEKB Y. Funakoshi 5



	LER	HER	
Beam Energy	4.0	7.0	GeV
Circumference	3016		m
Crossing angle	83		mrad
Crab waist ratio	80	40	%
Beam current @Maximum Luminosity	1.321	1.099	A
Number of bunches	2249		
Bunch current @Maximum Luminosity	0.5873	0.4887	mA
Total RF voltage V_c	9.12	14.2	MV
Synchrotron tune ν_s	-0.0233	-0.0258	
Bunch length σ_z	5.69	6.03	mm
Momentum compaction α_c	2.98E-4	4.54E-4	
Betatron tune ν_x / ν_y	44.524/46.592	45.532/43.575	
Beta function at IP β_x^* / β_y^*	80/1	60/1	mm
Measured vertical beam size (XRM) @IP σ_y^*	0.224	0.224	μm
Vertical beam-beam parameters ξ_y	0.0407	0.0279	
Beam lifetime	8	24	min.
Luminosity (Belle 2 CsI)	4.65		10^{34} cm^{-2} s^{-1}

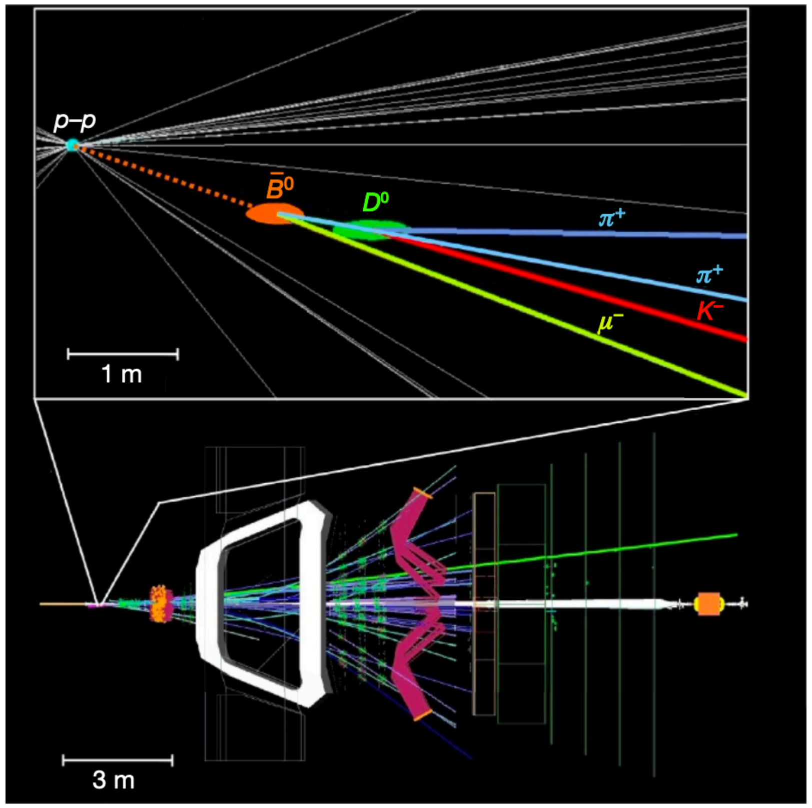
← Touschek dominant

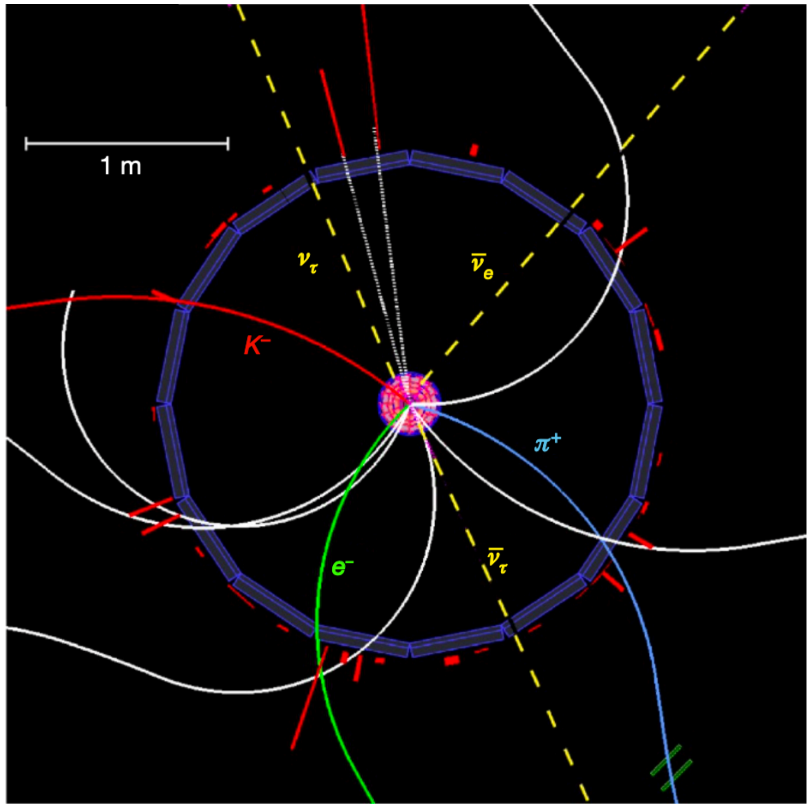
BELLE II AND LHCb : COMPARISON

Better with muons/charged particles that can be vertexed
Richer *b*-hadron program
high backgrounds / high σ_b

Properties	**LHCb**	**Belle II**
σ_b	$\mathscr{O}(100\mu b)$	~ 1 nb
$\int \mathscr{L}$dt (fb^{-1})	$18 \rightarrow 300$	$(1+)0.6 \rightarrow$ 30-50
Background level	~ 60 mb	~ 4 nb
Typical efficiency	Low	High
π^0, K_S^0 efficiency	Low	High
Initial state	Not well known	Well known
Decay-time resolution	Excellent	Good
Collision spot size	Large	Tiny
Heavy bottoms hadrons	$B_{u,d,s,c}$, $b-$baryons	$B_{u,d(,s)}$
B-flavour tagging capability	$\sim 5\%$	$\sim 35\%$
τ physics capability	Limited	Excellent

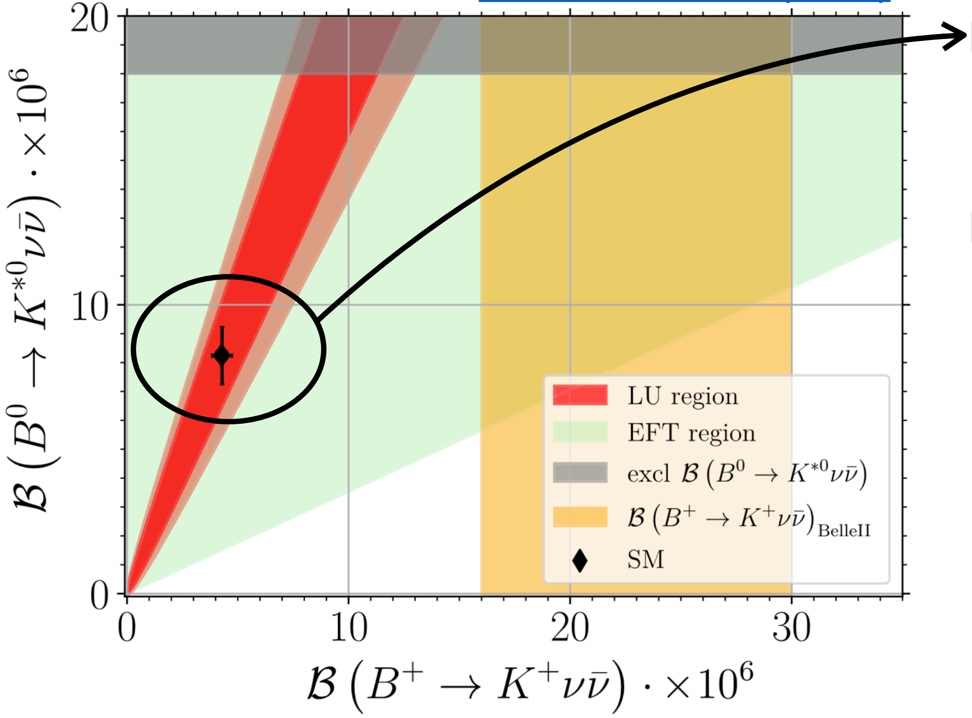
Better with γ and ν
Higher tagging efficiency
Low backgrounds / low σ_b





WHAT FOLLOWS $B^+ \to K^+\nu\bar{\nu}$ 2311.14647

PRD 109, 015006 (2024)



B → K

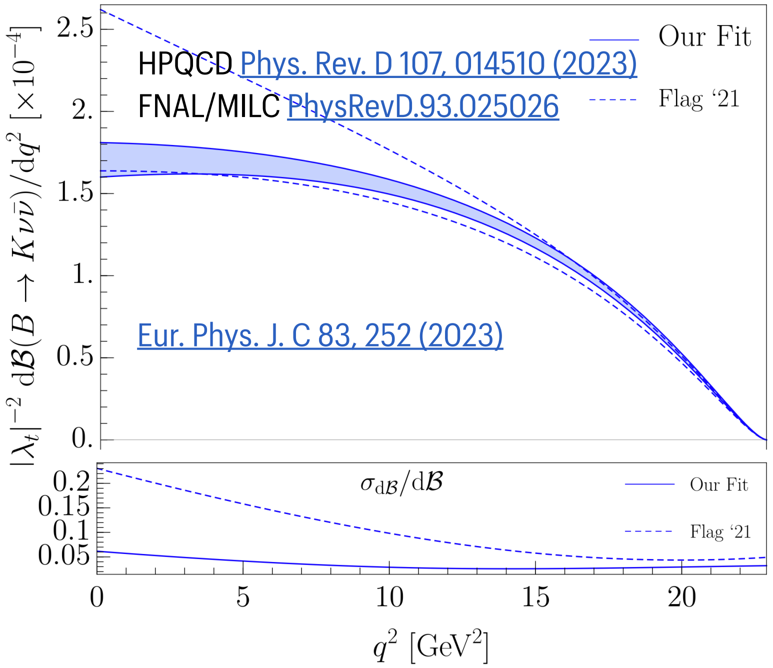
LQCD PRD 107, 014510 (2023)

LCSR JHEP01(2019)150

B → K* — less precise (15% vs 3% of K+)

LQCD 1501.00367

LCSR JHEP01(2019)150

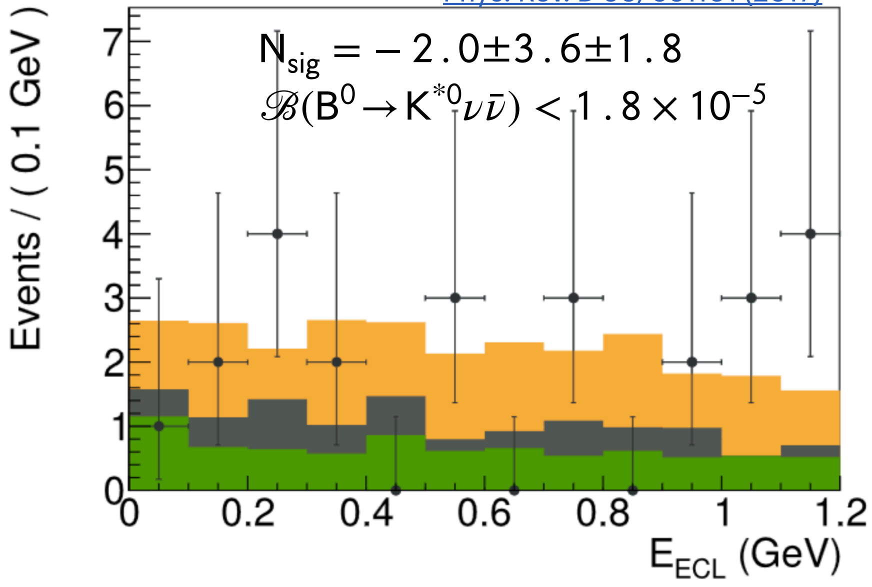


HPQCD Phys. Rev. D 107, 014510 (2023)

FNAL/MILC PhysRevD.93.025026

Eur. Phys. J. C 83, 252 (2023)

Phys. Rev. D 96, 091101 (2017)

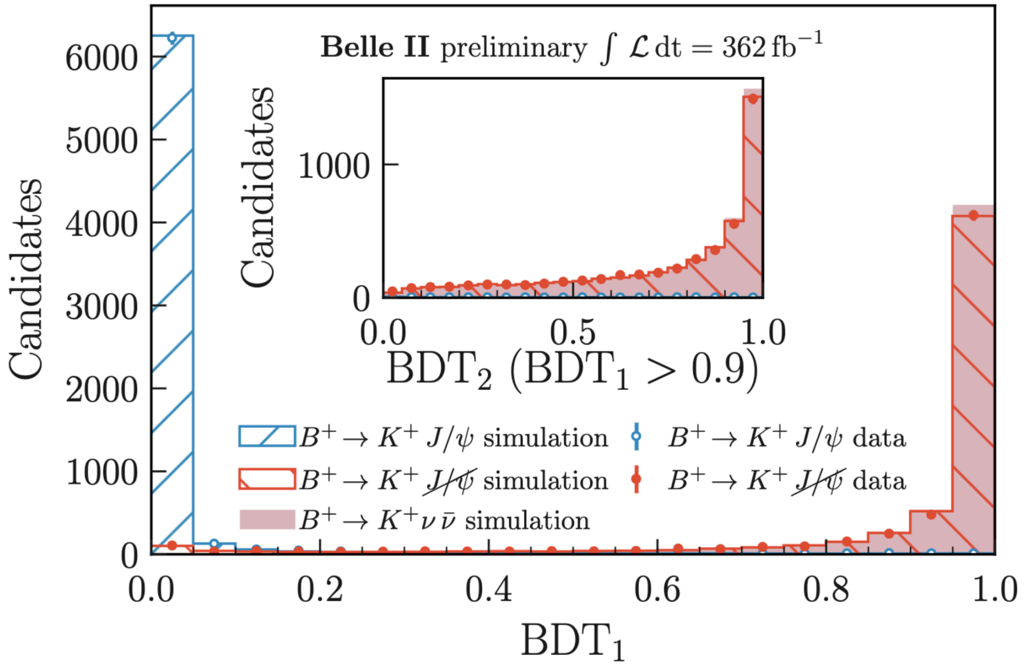


$\mathbf{B \to K^+ \nu \bar{\nu}}$ ITA

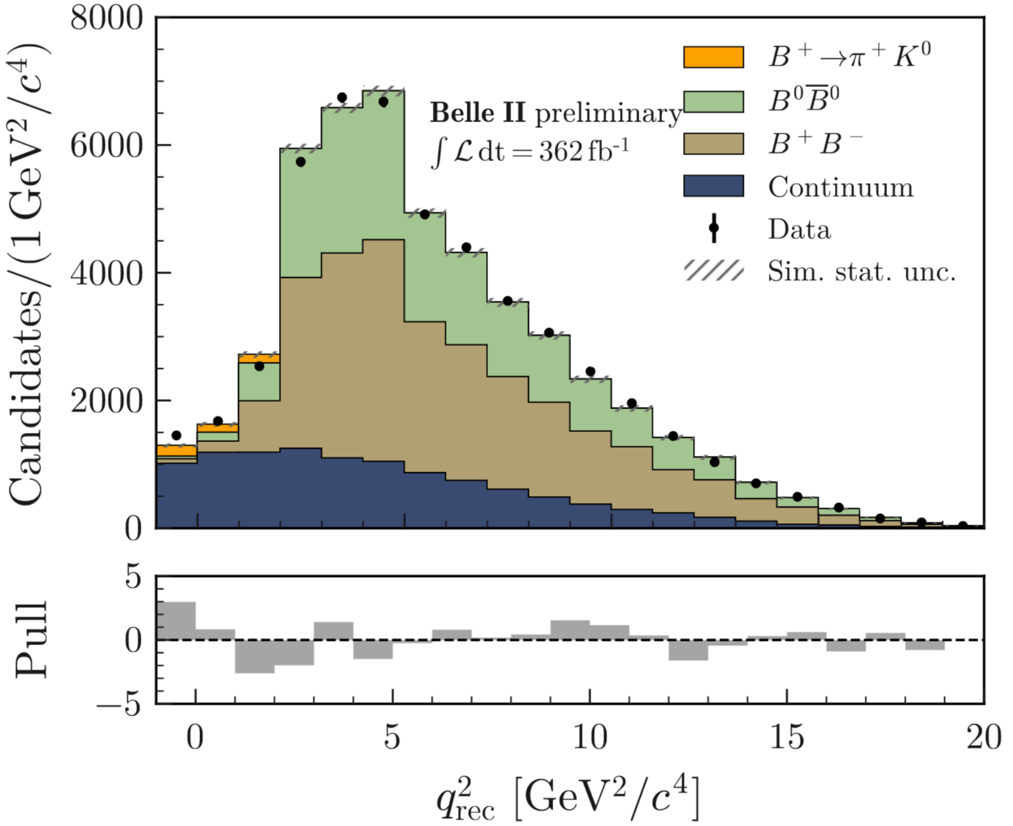
Belle II
362 fb^{-1}

Analysis relies on simulation for background suppression and fitting (sample-composition fit)
The quality of simulation and corrections is validated via several control channels on data

- **Kaon ID selection with** $B^+ \to \bar{D}^0(\to K^+\pi^-)h^+$, $h = \{\pi, K\}$
- **Signal efficiency with** $B^+ \to K^+ J/\psi$
  Remove $B^+ \to K^+ J/\psi$ and correct K^+ kinematics to match $B^+ \to K^+\nu\bar{\nu}$
- $\mathbf{B \to X_c(K_L^0 X)K^+}$ **background**
  corrected/validated using pion/lepton-enriched sidebands



Measuring a known and rare mode with similar BF to $B^+ \to K^+\nu\bar{\nu}$ to further validate the inclusive analysis strategy
pion-ID instead of K-ID
$\mathscr{B}(B^+ \to \pi^+ K^0) = (2.5 \pm 0.5) \times 10^{-5}$, consistent with PDG

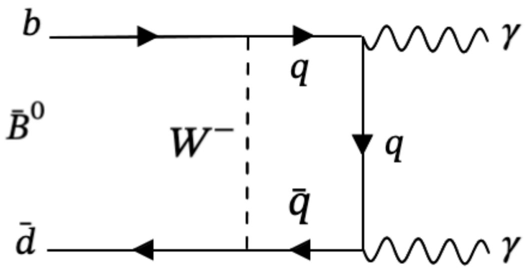


$\mathbf{B} \to \gamma\gamma$ SEARCH

BELLE $694\ \mathrm{fb}^{-1}$ **Belle II** $362\ \mathrm{fb}^{-1}$

Rarest decay searched at Belle II so far

$\mathscr{B}_{\mathrm{SM}}(\mathrm{B}^0 \to \gamma\gamma) = (1.43^{+1.35}_{-0.80}) \times 10^{-8}$ [JHEP12(2020)169]



Sensitive to heavy NP [PRD 58, 095014 (1998)]

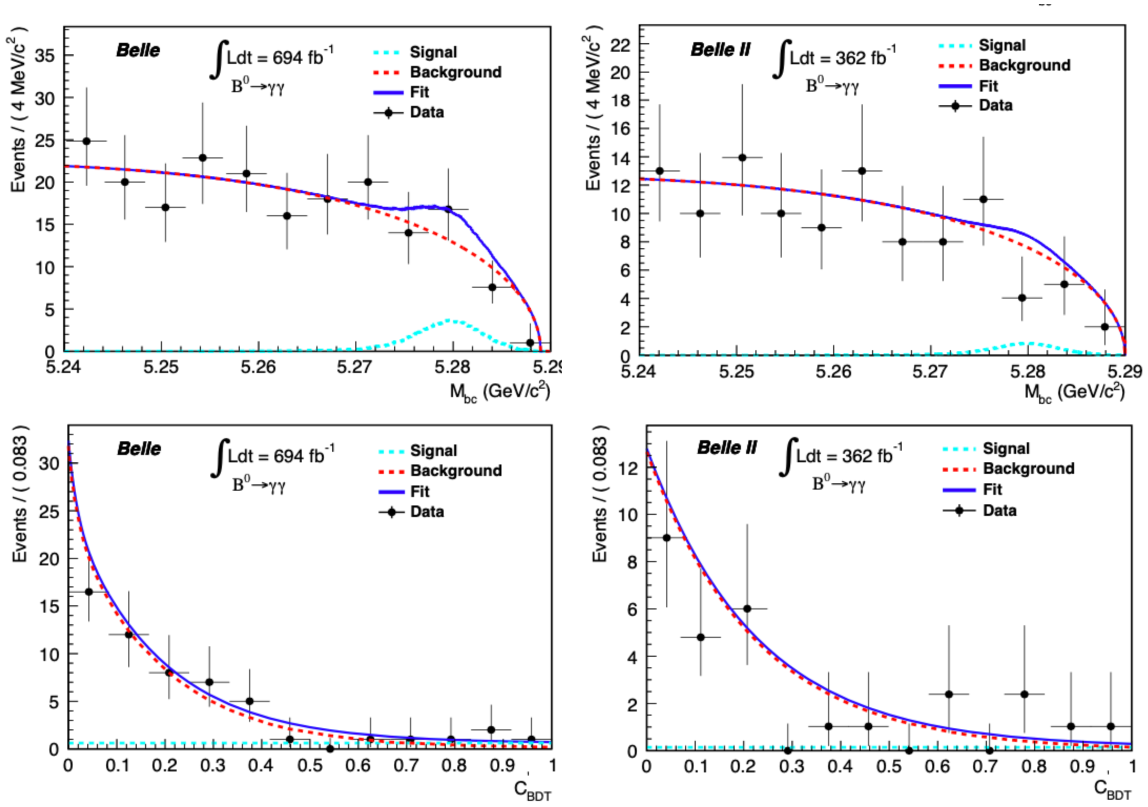
Require good quality high energy γ

Reject photon candidates form asymmetric η and π^0 decays

90% qq + $\mathrm{B}^0 \to \pi^0\pi^0$

Main syst uncertainties: Photon eff (3%), f^{00} (2.5%)

Signal efficiency for Belle (II) is 23(31)% for ~0.8 bkg/fb^{-1}



$\mathrm{N}_{\mathrm{sig}} = 11.0^{+6.5}_{-5.5}\quad 2.5\sigma$

$\mathscr{B}(\mathrm{B}^0 \to \gamma\gamma) = (3.7^{+2.2}_{-1.8}(\mathrm{stat}) \pm 0.5(\mathrm{syst})) \times 10^{-8}$

$\mathscr{B}(\mathrm{B}^0 \to \gamma\gamma) < 6.4 \times 10^{-8}$ @ 90 % CL (exp 4.4×10^{-8})

- **Sensitivity approaching the SM prediction**
- **5x improvement over previous best UL (BaBar)** [PRD 83 032006 (2011)]

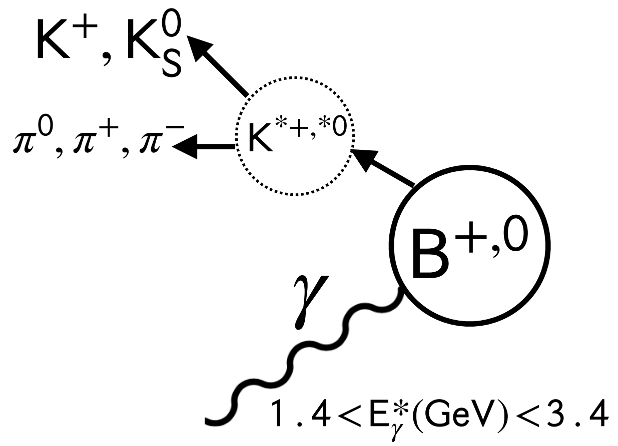
$B \to K^*\gamma$ MEASUREMENT

Belle II
$362\ \mathrm{fb}^{-1}$

$$\mathcal{A}_{CP} = \frac{\Gamma(\overline{B} \to \overline{K}^*\gamma) - \Gamma(B \to K^*\gamma)}{\Gamma(\overline{B} \to \overline{K}^*\gamma) + \Gamma(B \to K^*\gamma)}$$

$$\Delta_{0+} = \frac{\Gamma(B^0 \to K^{*0}\gamma) - \Gamma(B^+ \to K^{*+}\gamma)}{\Gamma(B^0 \to K^{*0}\gamma) + \Gamma(B^+ \to K^{*+}\gamma)}$$

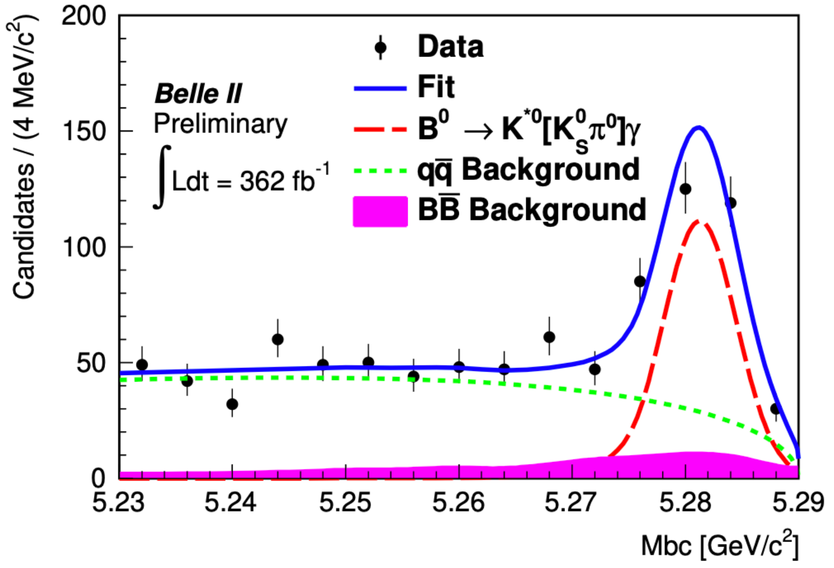
$$\Delta\mathcal{A}_{CP} = \mathcal{A}_{CP}(B^+ \to K^{*+}\gamma) - \mathcal{A}_{CP}(B^0 \to K^{*0}\gamma)$$

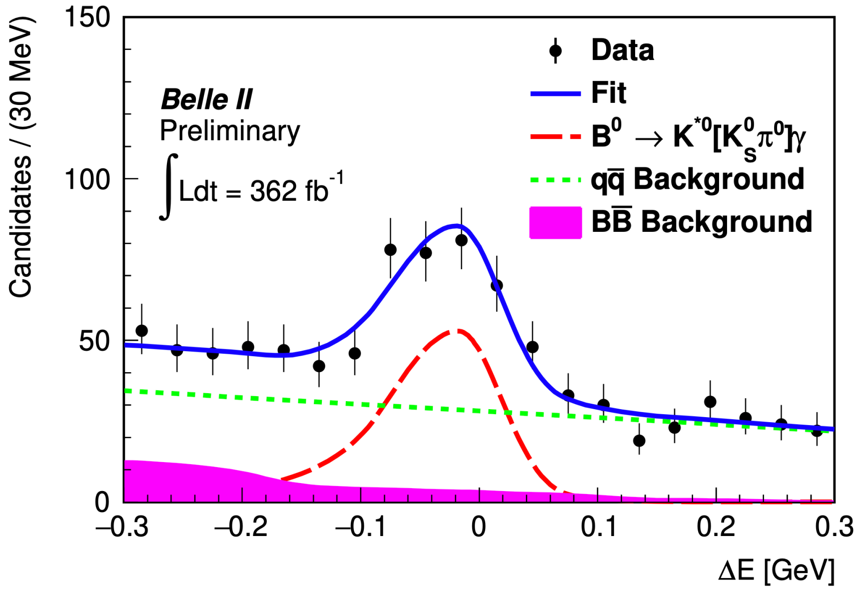


Measure $\mathscr{B}$, $\mathscr{A}_{CP}$ and isospin asymmetry

- Uncertainty on BF ~ 4%, close to Belle results [PRL 119.191802]
- stat ~ syst errors ($\mathscr{B}$)
- stat > syst errors ($\mathscr{A}$, Δ_{0+})
- Belle had observed the isospin violation at 3.1 σ $\Delta_{0+} = [+6.2 \pm 1.5(\mathrm{stat}) \pm 0.6(\mathrm{syst}) \pm 1.2(f_{+-}/f_{00})]\%$,

Channel	$\mathcal{A}_{CP}$ (%)	$\mathcal{B}$ (10^{-5})	
$B^0 \to K^{*0}[K^+\pi^-]\gamma$	$-3.2 \pm 2.4 \pm 0.4$	$4.15 \pm 0.10 \pm 0.11$	
$B^0 \to K^{*0}[K^0_S\pi^0]\gamma$	–	$4.24 \pm 0.37 \pm 0.23$	
$B^0 \to K^{*0}\gamma$	$-3.2 \pm 2.4 \pm 0.4$	$4.16 \pm 0.10 \pm 0.11$	SM: (4.21±0.68)10^{-5} [1]
$B^+ \to K^{*+}[K^+\pi^0]\gamma$	$1.5 \pm 4.2 \pm 0.9$	$3.91 \pm 0.18 \pm 0.19$	
$B^+ \to K^{*+}[K^0_S\pi^+]\gamma$	$-3.5 \pm 4.3 \pm 0.7$	$4.13 \pm 0.19 \pm 0.13$	
$B^+ \to K^{*+}\gamma$	$-1.0 \pm 3.0 \pm 0.6$	$4.04 \pm 0.13 \pm 0.13$	SM: (4.42±0.73)10^{-5} [1]
$B \to K^*\gamma$	$-2.3 \pm 1.9 \pm 0.3$	$4.12 \pm 0.08 \pm 0.11$	
	$\Delta\mathcal{A}_{CP}$(%)	Δ_{0+}(%)	SM: (4.9±2.6)% [2]
$B \to K^*\gamma$	$2.2 \pm 3.8 \pm 0.7$	$5.1 \pm 2.0 \pm 1.5$	



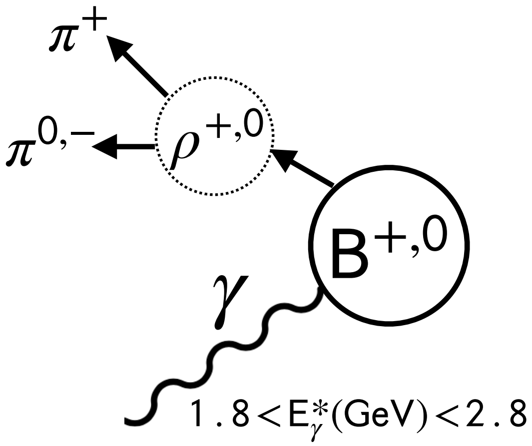


- Consistent with WA and SM
- Similar sensitivity wrt Belle due to improved K_S efficiency and ΔE resolution

[1] 1411.3161
[2] PRD 88, 094004 (2013)

$B \to \rho\gamma$ MEASUREMENT

BELLE $711\ \text{fb}^{-1}$ **Belle II** $362\ \text{fb}^{-1}$



$B \to \rho\gamma$ decays previously observed at Belle (605 fb^{-1}) [PRL 101 (2008) 129904] and BaBar (428 fb^{-1}) [PRD 78 (2008) 112001]

$$A_{\text{CP}}(B \to \rho\gamma) = \frac{\Gamma\left(\overline{B} \to \overline{\rho}\gamma\right) - \Gamma\left(B \to \rho\gamma\right)}{\Gamma\left(\overline{B} \to \overline{\rho}\gamma\right) + \Gamma\left(B \to \rho\gamma\right)}$$

$$A_{\text{I}} = \frac{2\Gamma(\overset{(-)}{B^0} \to \rho^0\gamma) - \Gamma(B^\pm \to \rho^\pm\gamma)}{2\Gamma(\overset{(-)}{B^0} \to \rho^0\gamma) + \Gamma(B^\pm \to \rho^\pm\gamma)}$$

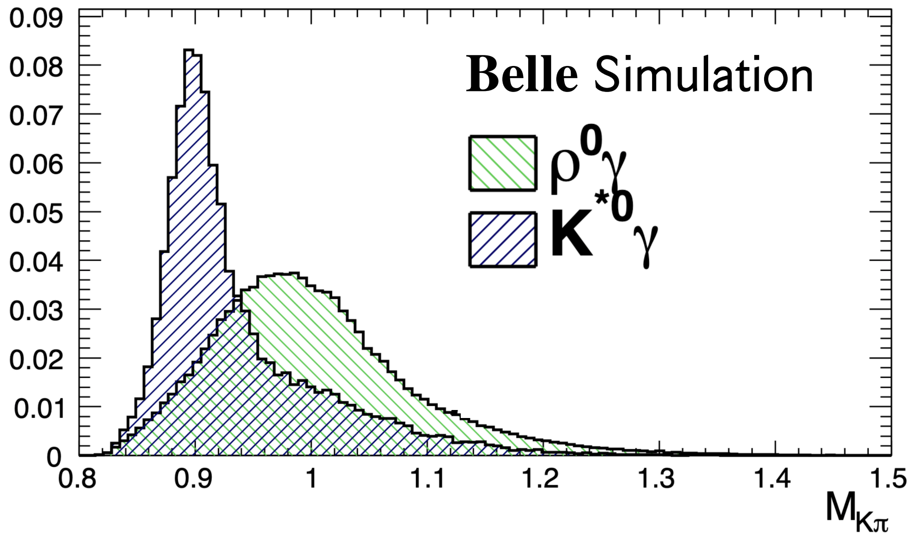
Sensitive to NP related to C_7

NP search independent from $b \to s$ counterpart

$\mathscr{A}_I$ **WA shows a slight tension**

Challenge Low BF, large backgrounds from

- **Continuum events:** photon from largely asymmetric $\pi^0/\eta \to \gamma\gamma$ decays
  → 2 MVA classifiers, one for π^0/η veto, the other for generic $q\bar{q}$
- $B \to K^*\gamma$: $K \to \pi$ misID and much larger BF $|V_{td}/V_{ts}|^2 \simeq 0.04$
  → $M(\pi^*\pi)$, π^* : kaon hyp. for the pion candidate with highest kaonID

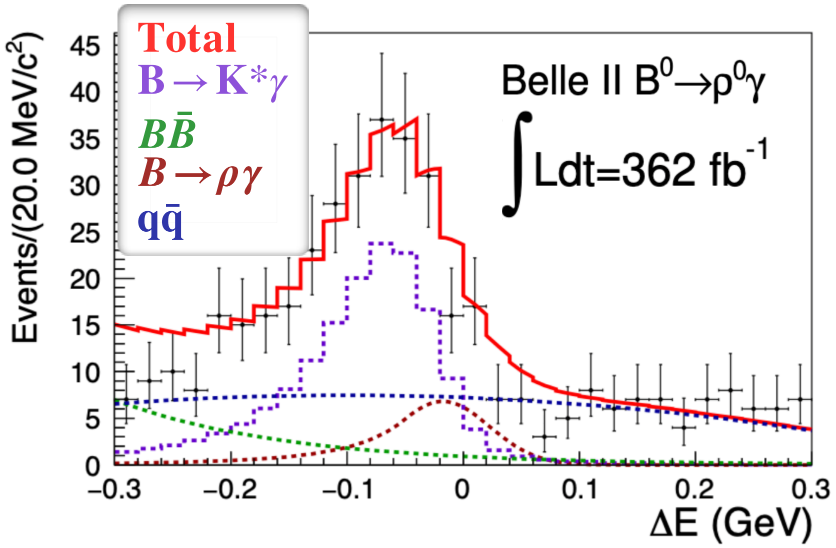


	WA	B+BII 2023
$\mathscr{B}(B^+ \to \rho^+\gamma) \times 10^6$	0.98 ± 0.25	$1.29^{+0.20+0.10}_{-0.19-0.12}$
$\mathscr{B}(B^0 \to \rho^0\gamma) \times 10^6$	0.86 ± 0.15	$0.75 \pm 0.13^{+0.10}_{-0.08}$
$\mathscr{A}_I$	$0.30^{+0.16}_{-0.13}$	$0.14^{+0.11}_{-0.12} \pm 0.09$
$\mathscr{A}_{\text{CP}}(B^+ \to \rho^+\gamma)$	-0.11 ± 0.33	$-0.08^{+0.15+0.01}_{-0.15-0.01}$

→ **Consistent with SM**

0.052 ± 0.028

[PRD 88, 094004 (2013)]



BELLE
711 fb^{-1}

$\mathbf{b \rightarrow d\ell\ell}$

Better sensitivity to NP than b→sℓ+ℓ−?

Previous results:

Belle (605 fb^{-1}) $B \rightarrow \pi\ell^+\ell^-$ [PRD 78 011101 (2008)]

BaBar (428 fb^{-1}) $B \rightarrow \{\pi, \eta\}\ell^+\ell^-$ [PRD 88 032012 (2013)]

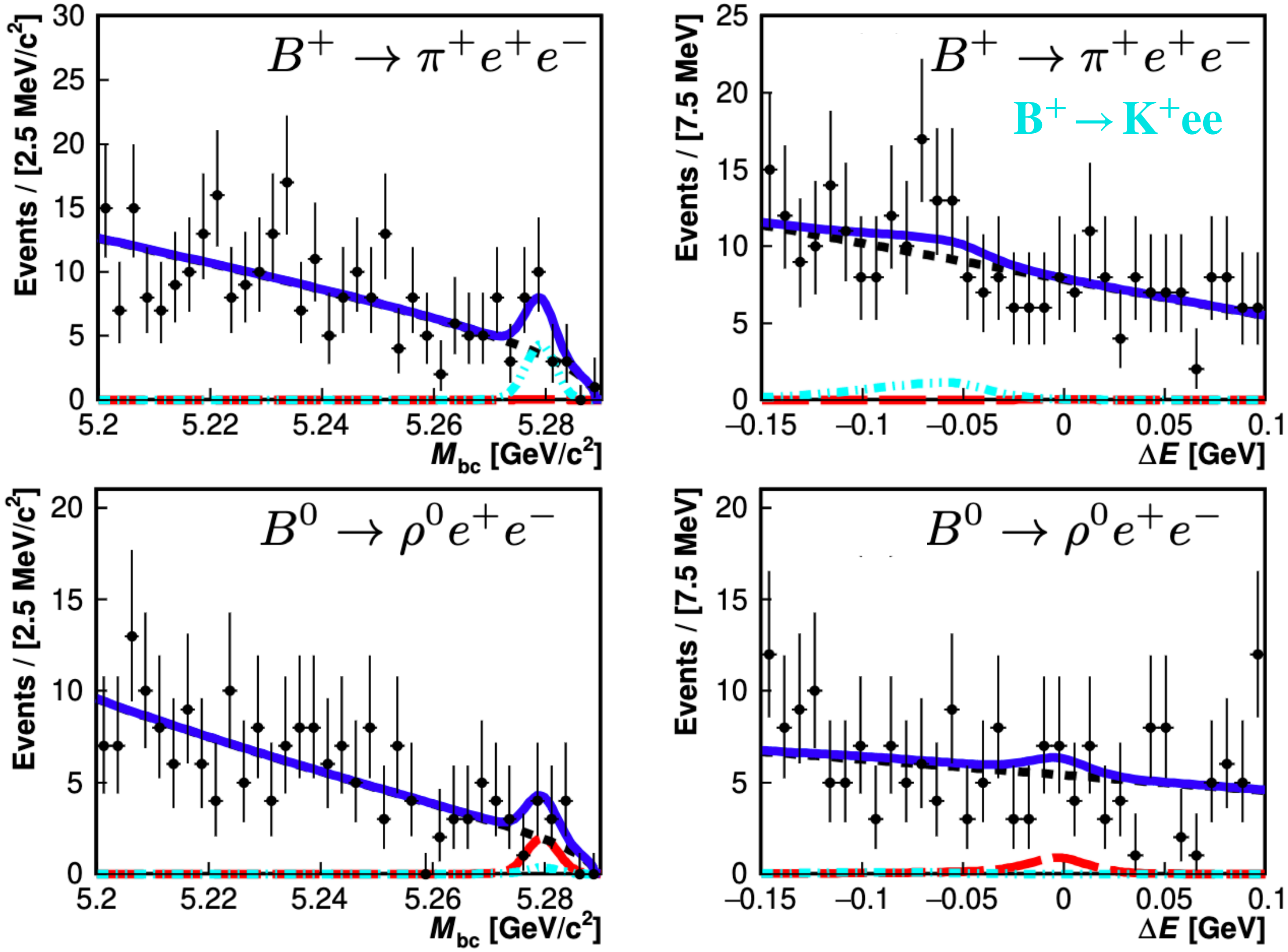
LHCb (3 fb^{-1}) observed $B^+ \rightarrow \pi^+\mu^+\mu^-$, $B^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ [JHEP 10 (2015) 034, PLB 743 (2015) 46-55]

Many unexplored modes with

- Electrons
  - → lepton-flavour universality in $b \rightarrow d$ transitions
- Neutrals
  - → First search for $B^0 \rightarrow \omega\ell\ell$, $B^0 \rightarrow \rho^0 ee$, $B^\pm \rightarrow \rho^\pm\ell\ell$

$$B \rightarrow \{\pi, \rho, \eta, \omega\}\ell\ell \quad \begin{cases} \rho^{+,0} \rightarrow \pi^+\pi^{0,-} \\ \eta \rightarrow \gamma\gamma, \pi^+\pi^-\pi^0 \\ \omega \rightarrow \pi^+\pi^-\pi^0 \end{cases}$$

Two-dimensional ML fits

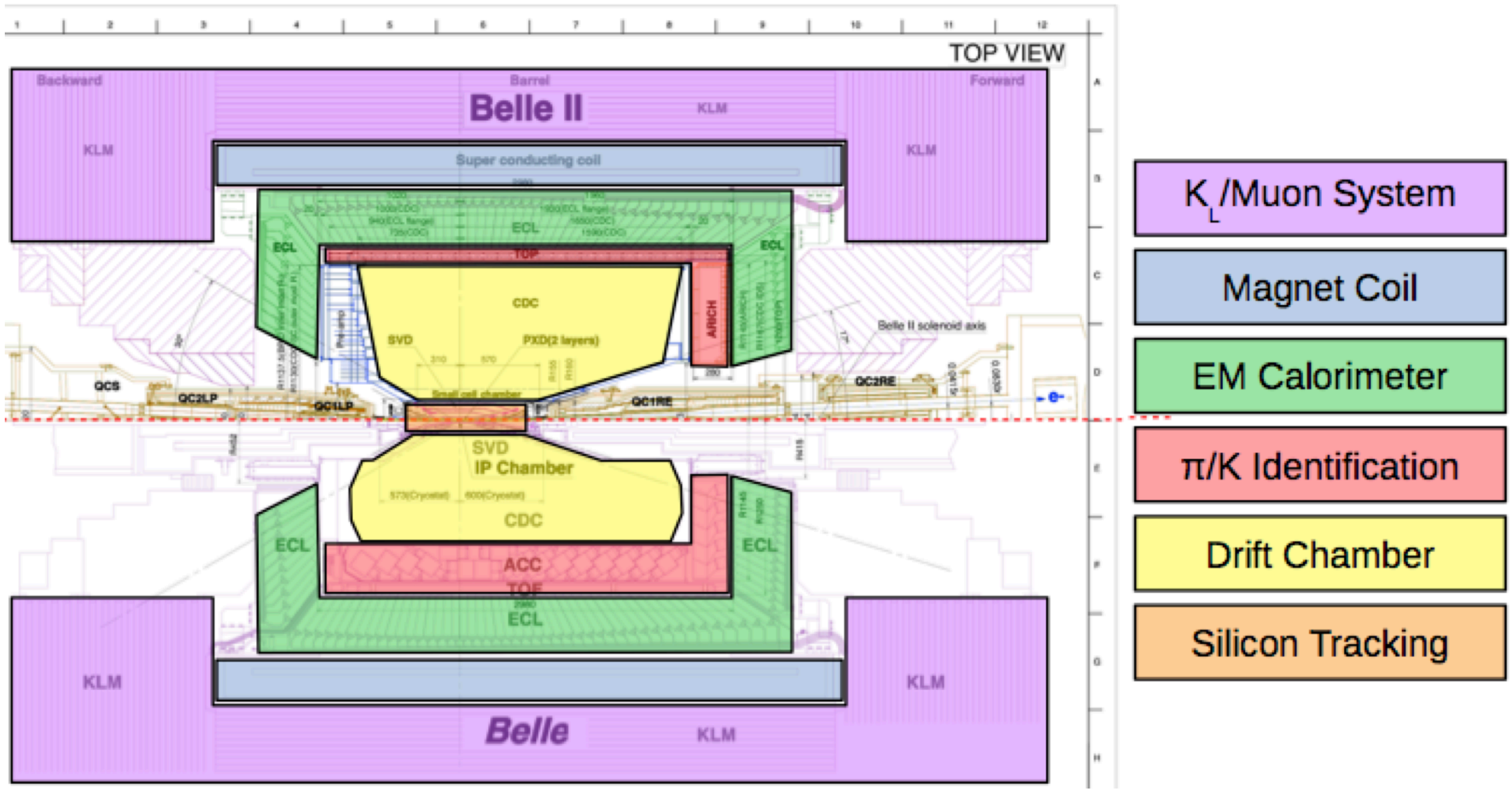


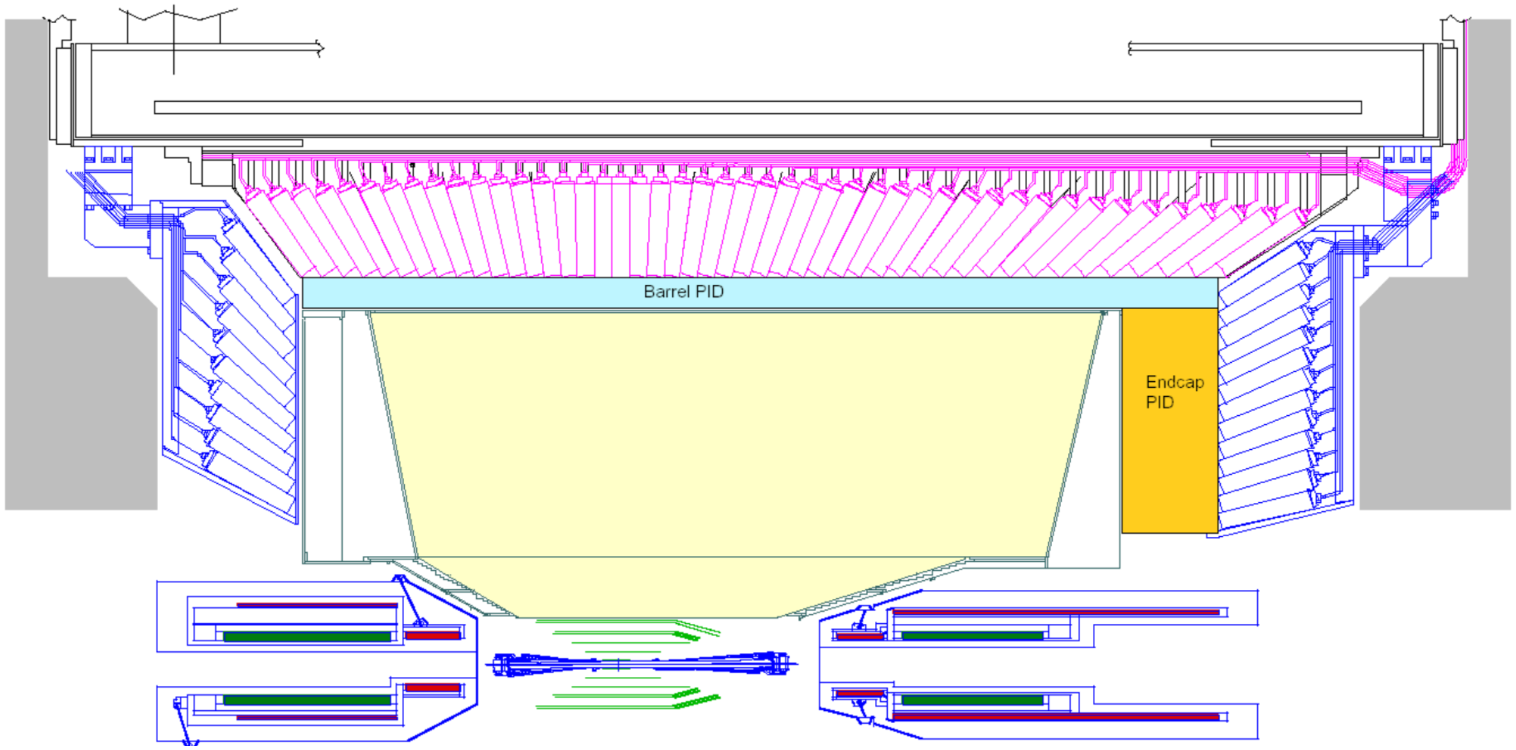
Total
Combinatorial bg
Peaking bg
Signal

Dominated by continuum events

Peaking BB backgrounds charmless/$K^{(*)}\ell\ell$/$K^{(*)}c\bar{c}(\ell\ell)$ are either vetoed or included in the fit

BELLE II SECTION

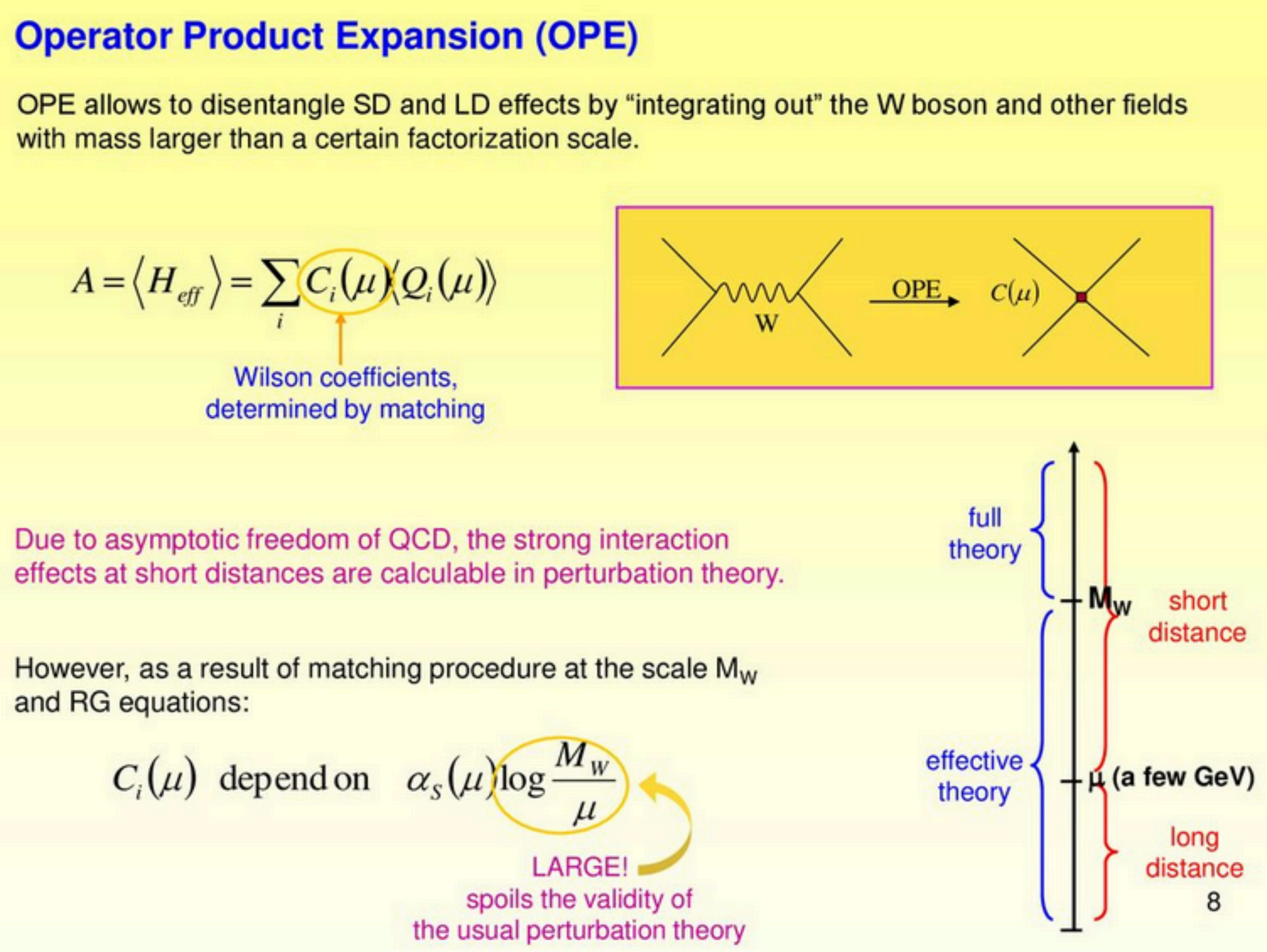




OPE I

MW>>mb>>LambdaQCD(QCD scale)

Operator Product Expansion
Long-distance physics at scale lower than mu is contained in operator matrix elements
O_i are local effective operators renormalised at the scale mu=mb
Short-distance physics at scale higher than mu is described by the Wilson coefficients



Operator Product Expansion (OPE)

OPE allows to disentangle SD and LD effects by "integrating out" the W boson and other fields with mass larger than a certain factorization scale.

$$A=\langle H_{eff}\rangle=\sum_i \boxed{C_i(\mu)}\langle Q_i(\mu)\rangle$$

Wilson coefficients,
determined by matching

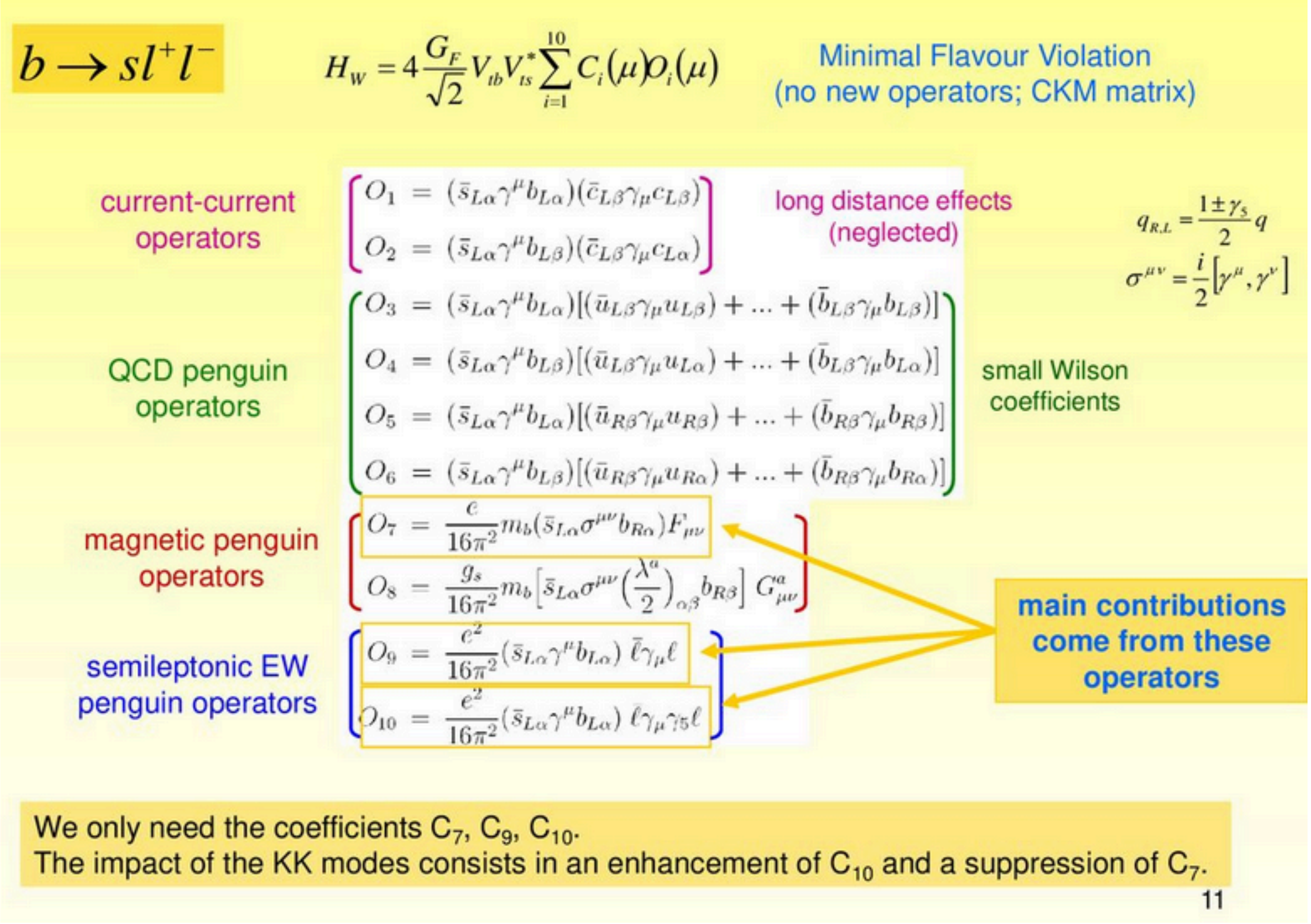
Due to asymptotic freedom of QCD, the strong interaction effects at short distances are calculable in perturbation theory.

However, as a result of matching procedure at the scale M_W and RG equations:

$$C_i(\mu)\ \text{depend on}\ \alpha_s(\mu)\boxed{\log\frac{M_W}{\mu}}$$

LARGE!
spoils the validity of
the usual perturbation theory

OPE II



$b \to s l^+ l^-$

$$H_W = 4\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1}^{10} C_i(\mu) O_i(\mu)$$

Minimal Flavour Violation
(no new operators; CKM matrix)

current-current operators

$$O_1 = (\bar{s}_{L\alpha}\gamma^\mu b_{L\alpha})(\bar{c}_{L\beta}\gamma_\mu c_{L\beta})$$
$$O_2 = (\bar{s}_{L\alpha}\gamma^\mu b_{L\beta})(\bar{c}_{L\beta}\gamma_\mu c_{L\alpha})$$

long distance effects
(neglected)

$$q_{R,L} = \frac{1 \pm \gamma_5}{2} q$$
$$\sigma^{\mu\nu} = \frac{i}{2}\left[\gamma^\mu, \gamma^\nu\right]$$

QCD penguin operators

$$O_3 = (\bar{s}_{L\alpha}\gamma^\mu b_{L\alpha})[(\bar{u}_{L\beta}\gamma_\mu u_{L\beta}) + \dots + (\bar{b}_{L\beta}\gamma_\mu b_{L\beta})]$$
$$O_4 = (\bar{s}_{L\alpha}\gamma^\mu b_{L\beta})[(\bar{u}_{L\beta}\gamma_\mu u_{L\alpha}) + \dots + (\bar{b}_{L\beta}\gamma_\mu b_{L\alpha})]$$
$$O_5 = (\bar{s}_{L\alpha}\gamma^\mu b_{L\alpha})[(\bar{u}_{R\beta}\gamma_\mu u_{R\beta}) + \dots + (\bar{b}_{R\beta}\gamma_\mu b_{R\beta})]$$
$$O_6 = (\bar{s}_{L\alpha}\gamma^\mu b_{L\beta})[(\bar{u}_{R\beta}\gamma_\mu u_{R\alpha}) + \dots + (\bar{b}_{R\beta}\gamma_\mu b_{R\alpha})]$$

small Wilson coefficients

magnetic penguin operators

$$\boxed{O_7 = \frac{e}{16\pi^2} m_b (\bar{s}_{L\alpha}\sigma^{\mu\nu} b_{R\alpha}) F_{\mu\nu}}$$
$$O_8 = \frac{g_s}{16\pi^2} m_b \left[\bar{s}_{L\alpha}\sigma^{\mu\nu}\left(\frac{\lambda^a}{2}\right)_{\alpha\beta} b_{R\beta}\right] G^a_{\mu\nu}$$

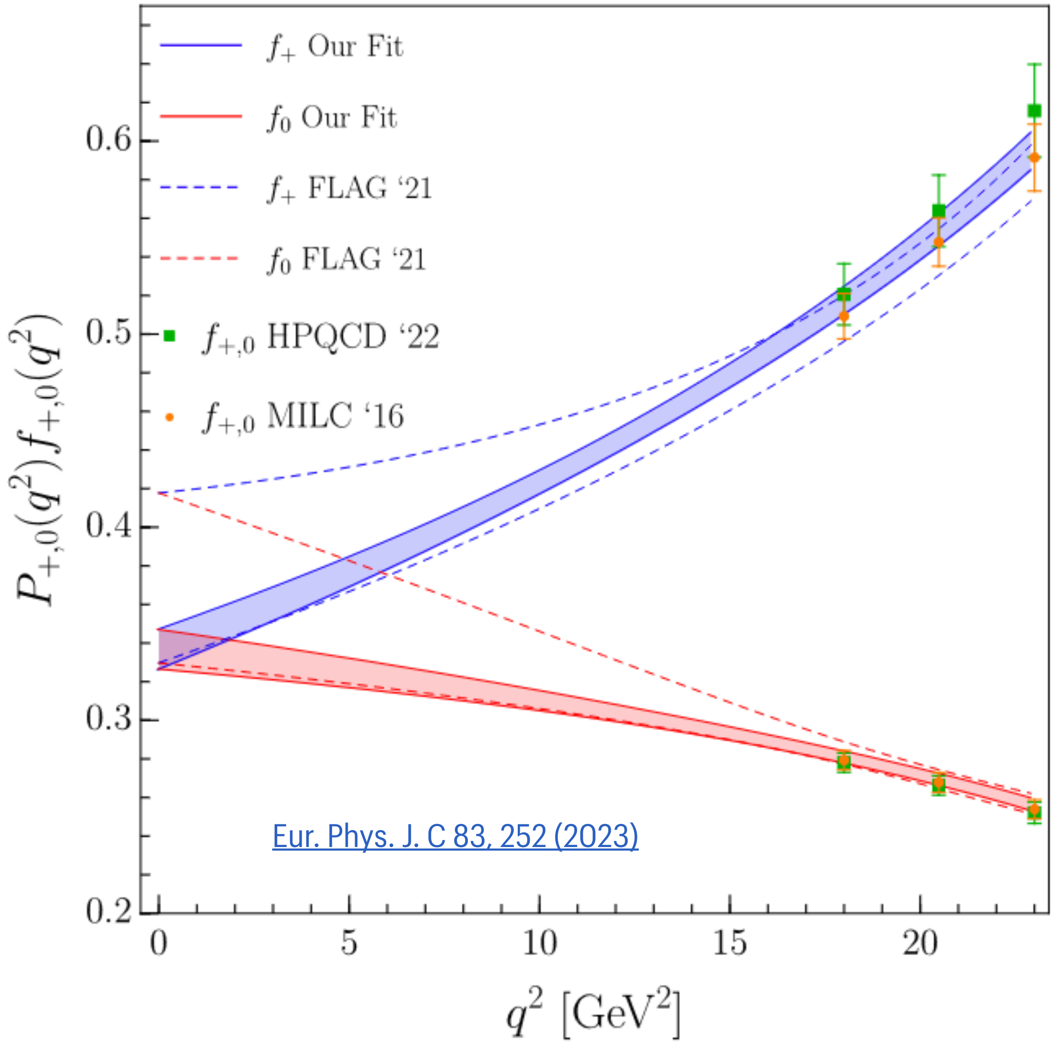
semileptonic EW penguin operators

$$\boxed{O_9 = \frac{e^2}{16\pi^2}(\bar{s}_{L\alpha}\gamma^\mu b_{L\alpha})\, \bar{\ell}\gamma_\mu \ell}$$
$$\boxed{O_{10} = \frac{e^2}{16\pi^2}(\bar{s}_{L\alpha}\gamma^\mu b_{L\alpha})\, \bar{\ell}\gamma_\mu\gamma_5 \ell}$$

main contributions come from these operators

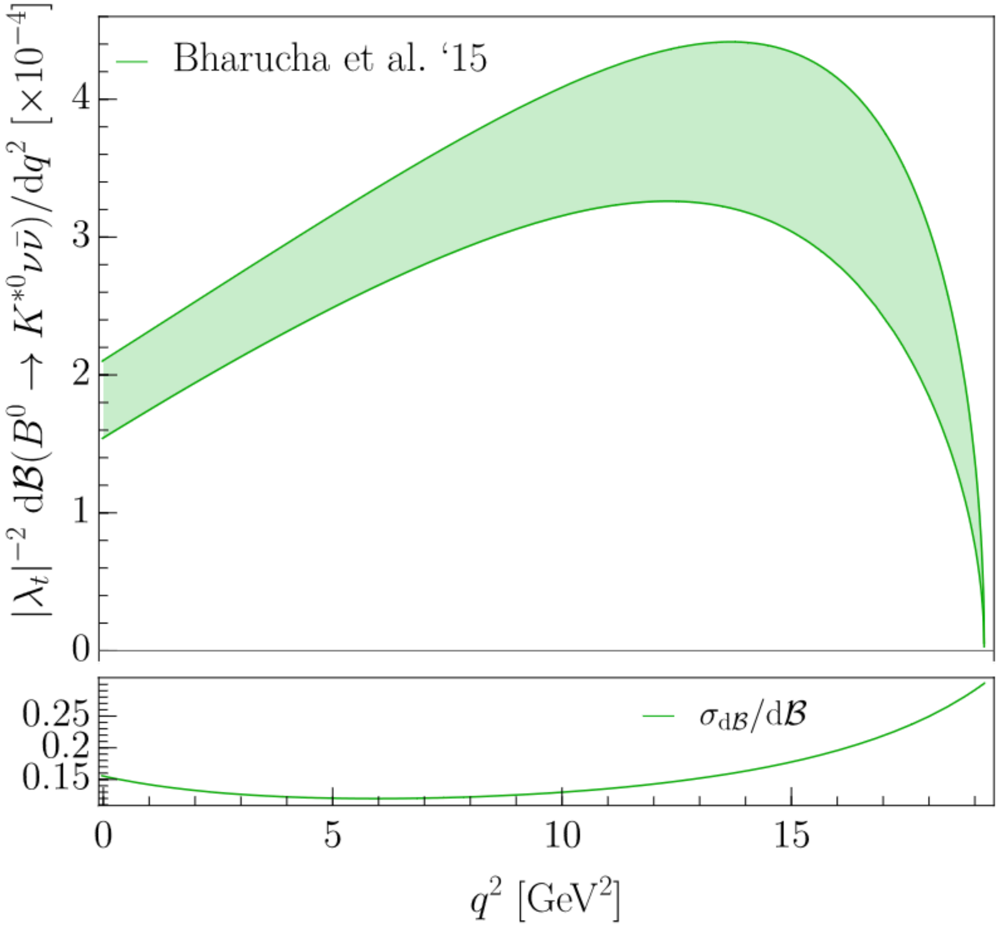
We only need the coefficients C_7, C_9, C_{10}.
The impact of the KK modes consists in an enhancement of C_{10} and a suppression of C_7.

FF

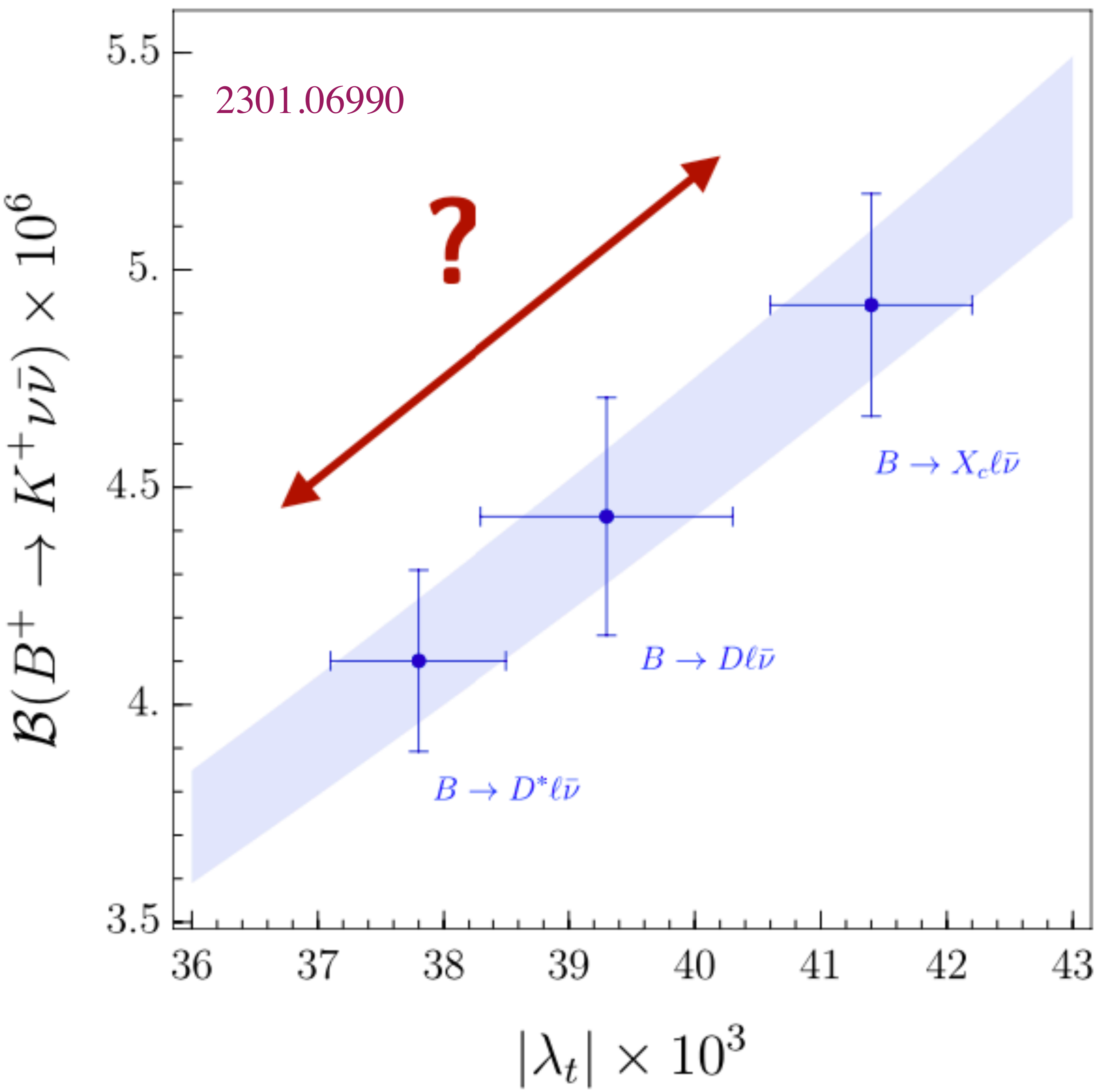


Eur. Phys. J. C 83, 252 (2023)

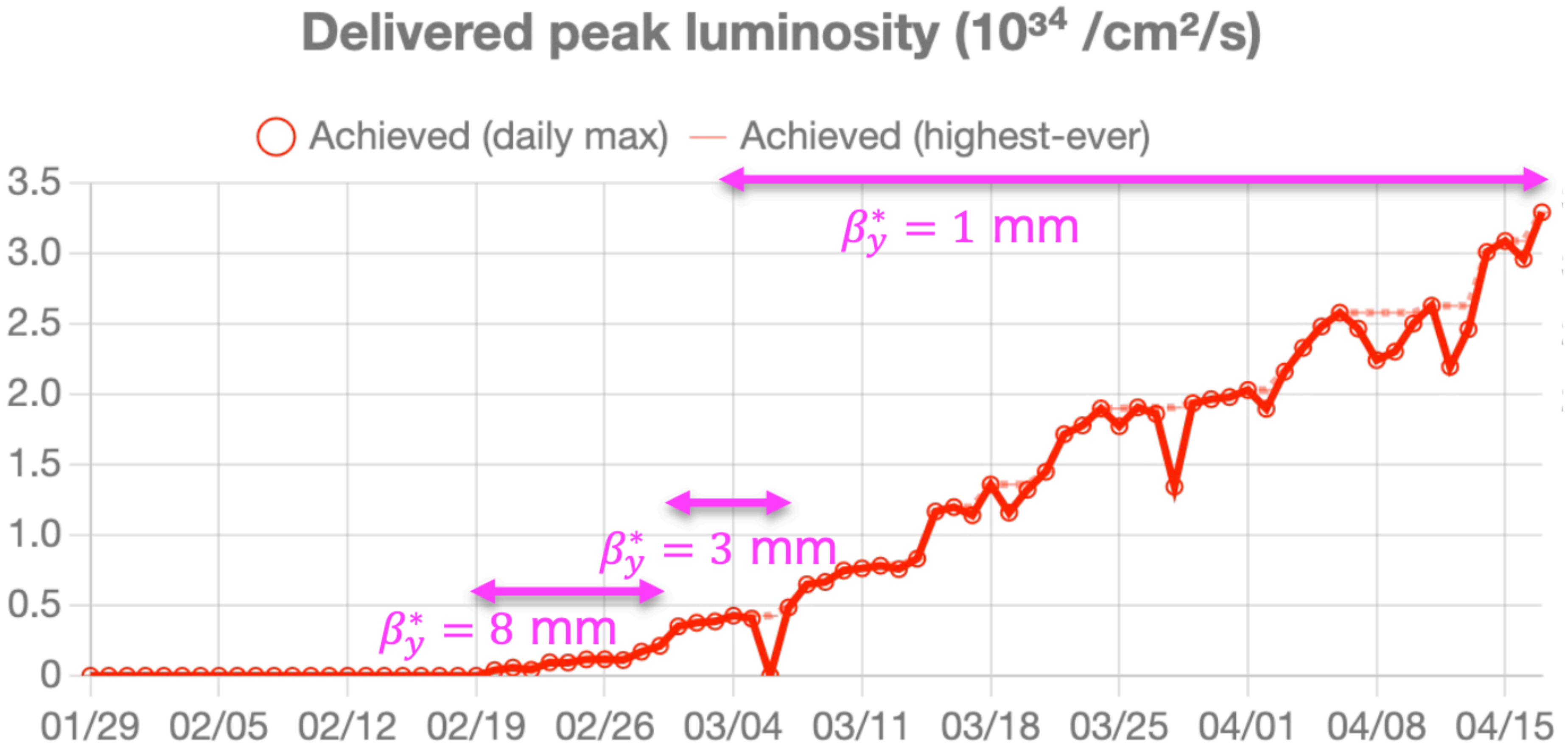
FIG. 1. *The results of our fit for $f_+(q^2)$ and $f_0(q^2)$ form factors are depicted by the blue and red solid curves respectively. The dashed lines correspond to the results reported by FLAG [29]. The synthetic data points by HPQCD (green) [27] and by FNAL/MILC (orange) [28] are also shown for comparison. $P_{+,0}(q^2)$ are the inverse pole terms defined in Eq.* (A5).



CKM


2301.06990
?
$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) \times 10^6$
5.5
5.
4.5
4.
3.5
36
37
38
39
40
41
42
43
$|\lambda_t| \times 10^3$
$B \to X_c\ell\bar{\nu}$
$B \to D\ell\bar{\nu}$
$B \to D^*\ell\bar{\nu}$

RUN2 β_y^*


Delivered peak luminosity (10^{34} /cm²/s)
○ Achieved (daily max)
— Achieved (highest-ever)
$\beta_y^* = 1$ mm
$\beta_y^* = 3$ mm
$\beta_y^* = 8$ mm
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
01/29
02/05
02/12
02/19
02/26
03/04
03/11
03/18
03/25
04/01
04/08
04/15

$B \to K\nu\bar{\nu}$ SYST ITA

arXiv: 2311.14647

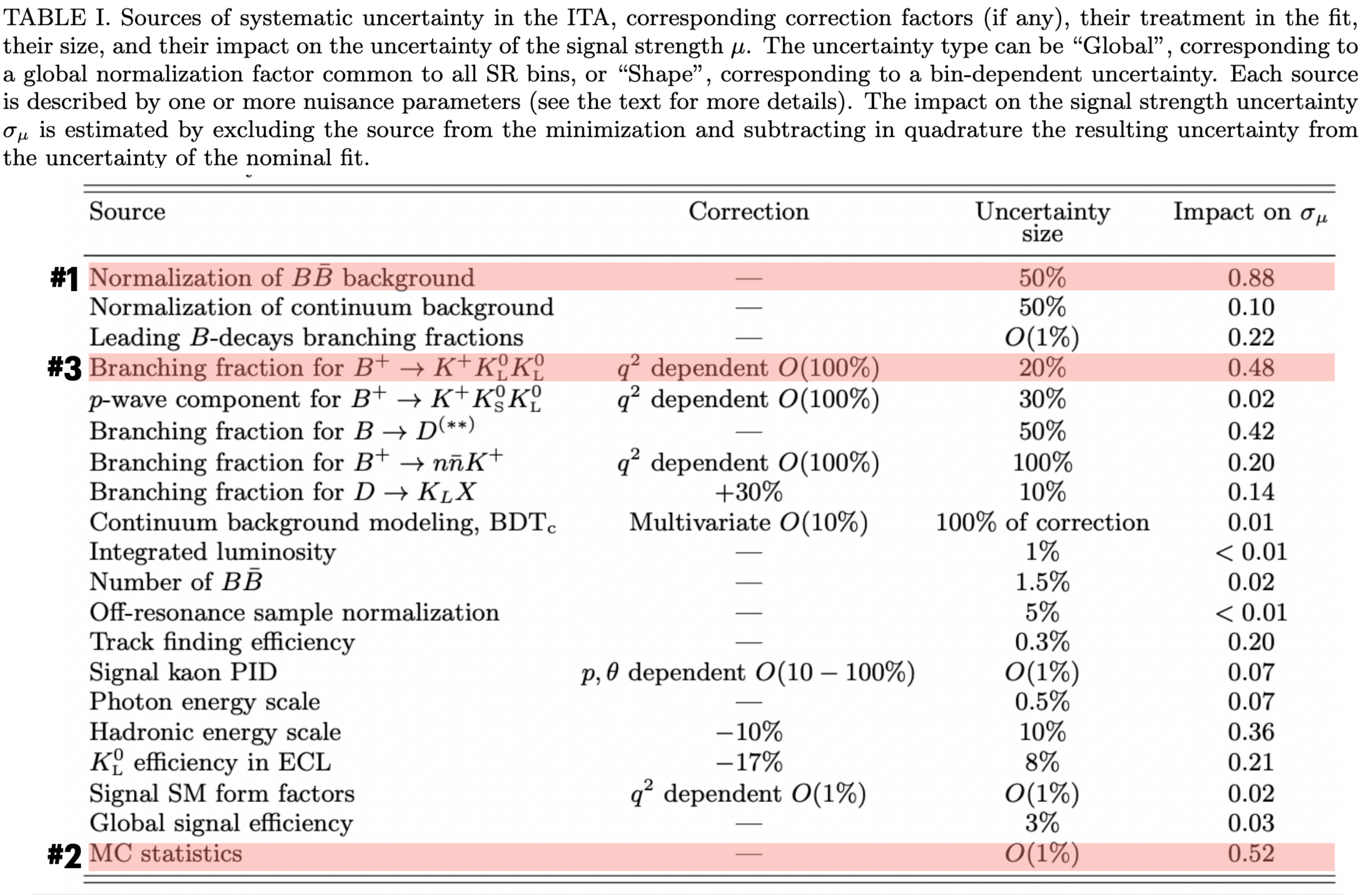
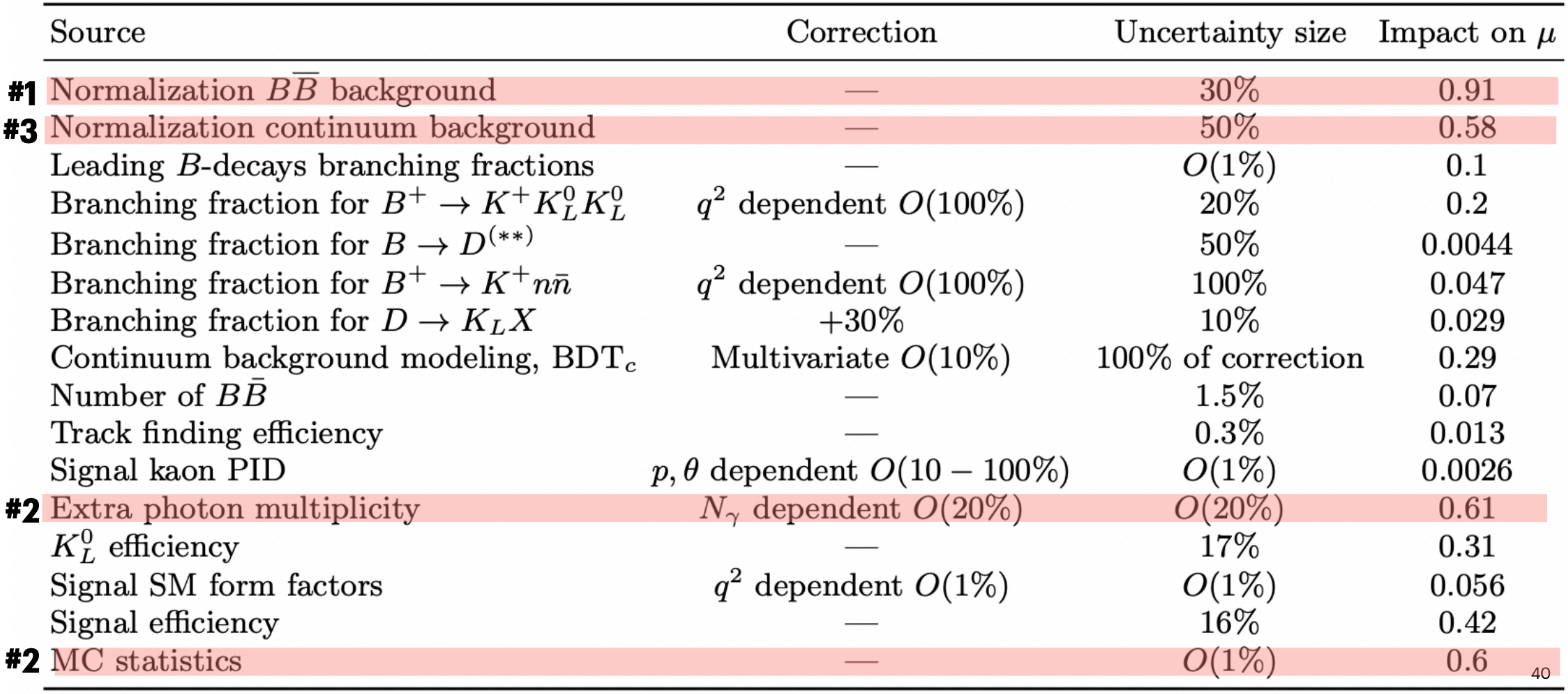


TABLE I. Sources of systematic uncertainty in the ITA, corresponding correction factors (if any), their treatment in the fit, their size, and their impact on the uncertainty of the signal strength μ. The uncertainty type can be "Global", corresponding to a global normalization factor common to all SR bins, or "Shape", corresponding to a bin-dependent uncertainty. Each source is described by one or more nuisance parameters (see the text for more details). The impact on the signal strength uncertainty σ_μ is estimated by excluding the source from the minimization and subtracting in quadrature the resulting uncertainty from the uncertainty of the nominal fit.

	Source	Correction	Uncertainty size	Impact on σ_μ
#1	Normalization of $B\bar{B}$ background	—	50%	0.88
	Normalization of continuum background	—	50%	0.10
	Leading B-decays branching fractions	—	$O(1\%)$	0.22
#3	Branching fraction for $B^+ \to K^+ K^0_L K^0_L$	q^2 dependent $O(100\%)$	20%	0.48
	p-wave component for $B^+ \to K^+ K^0_S K^0_L$	q^2 dependent $O(100\%)$	30%	0.02
	Branching fraction for $B \to D^{(**)}$	—	50%	0.42
	Branching fraction for $B^+ \to n\bar{n}K^+$	q^2 dependent $O(100\%)$	100%	0.20
	Branching fraction for $D \to K_L X$	+30%	10%	0.14
	Continuum background modeling, BDT$_c$	Multivariate $O(10\%)$	100% of correction	0.01
	Integrated luminosity	—	1%	< 0.01
	Number of $B\bar{B}$	—	1.5%	0.02
	Off-resonance sample normalization	—	5%	< 0.01
	Track finding efficiency	—	0.3%	0.20
	Signal kaon PID	p, θ dependent $O(10-100\%)$	$O(1\%)$	0.07
	Photon energy scale	—	0.5%	0.07
	Hadronic energy scale	−10%	10%	0.36
	K^0_L efficiency in ECL	−17%	8%	0.21
	Signal SM form factors	q^2 dependent $O(1\%)$	$O(1\%)$	0.02
	Global signal efficiency	—	3%	0.03
#2	MC statistics	—	$O(1\%)$	0.52

$B \to K\nu\bar{\nu}$ SYST ITA

arXiv: 2311.14647



	Source	Correction	Uncertainty size	Impact on μ
#1	Normalization $B\bar{B}$ background	—	30%	0.91
#3	Normalization continuum background	—	50%	0.58
	Leading B-decays branching fractions	—	$O(1\%)$	0.1
	Branching fraction for $B^+ \to K^+K^0_L K^0_L$	q^2 dependent $O(100\%)$	20%	0.2
	Branching fraction for $B \to D^{(**)}$	—	50%	0.0044
	Branching fraction for $B^+ \to K^+n\bar{n}$	q^2 dependent $O(100\%)$	100%	0.047
	Branching fraction for $D \to K_L X$	+30%	10%	0.029
	Continuum background modeling, BDT$_c$	Multivariate $O(10\%)$	100% of correction	0.29
	Number of $B\bar{B}$	—	1.5%	0.07
	Track finding efficiency	—	0.3%	0.013
	Signal kaon PID	p, θ dependent $O(10-100\%)$	$O(1\%)$	0.0026
#2	Extra photon multiplicity	N_γ dependent $O(20\%)$	$O(20\%)$	0.61
	K^0_L efficiency	—	17%	0.31
	Signal SM form factors	q^2 dependent $O(1\%)$	$O(1\%)$	0.056
	Signal efficiency	—	16%	0.42
#2	MC statistics	—	$O(1\%)$	0.6

Systematic uncertainties

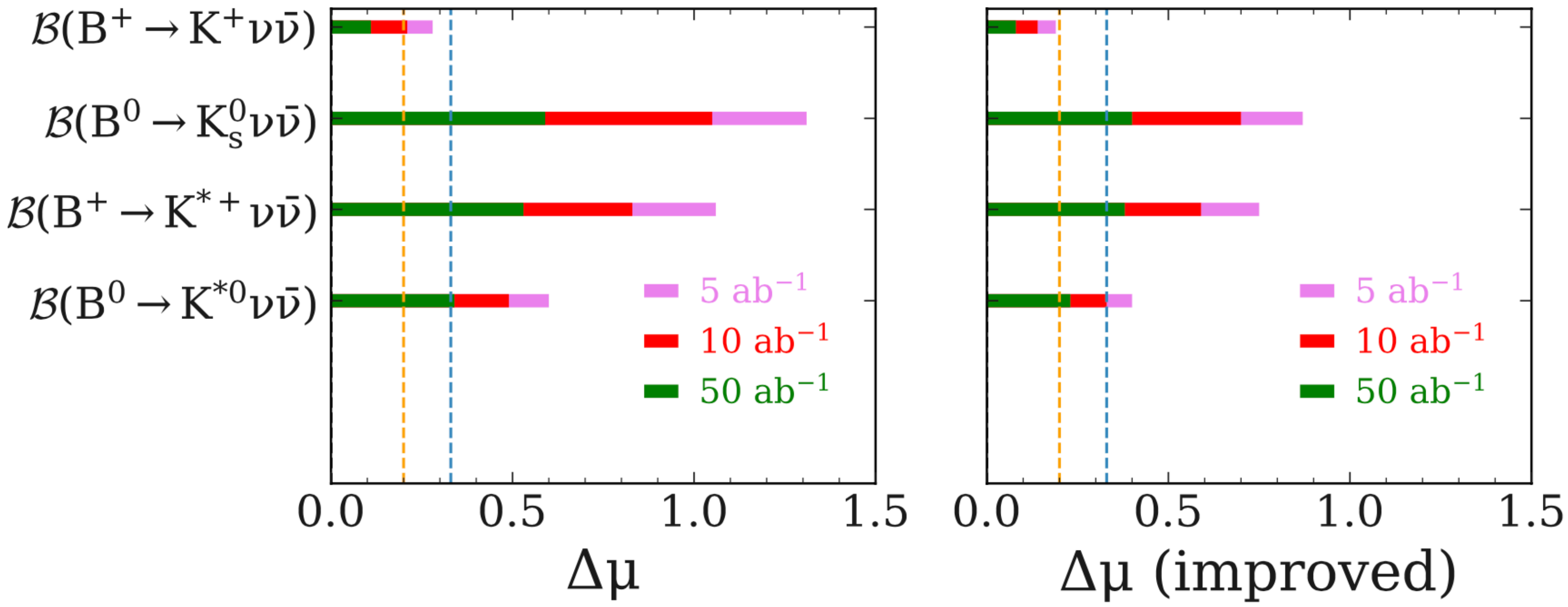
Incorporated in the fit as nuisance parameters

- Background normalisation $B\bar{B}$ (HTA, ITA)
- Limited size of simulation sample for the fit model (HTA, ITA)
- Knowledge of $B^+ \to K^+K^0_L K^0_L$ BF and modelling of $B^+ \to D^{**}\ell\nu$ decays (HTA)
- ROE photon multiplicity mis-modeling (ITA)

$B \to K\nu\bar{\nu}$ PROJECTIONS

Belle II Snowmass paper : 2 scenarios baseline (improved*)

3σ (5σ) for SM $B^+ \to K^+\nu\bar{\nu}$ decays with 5 ab^{-1}

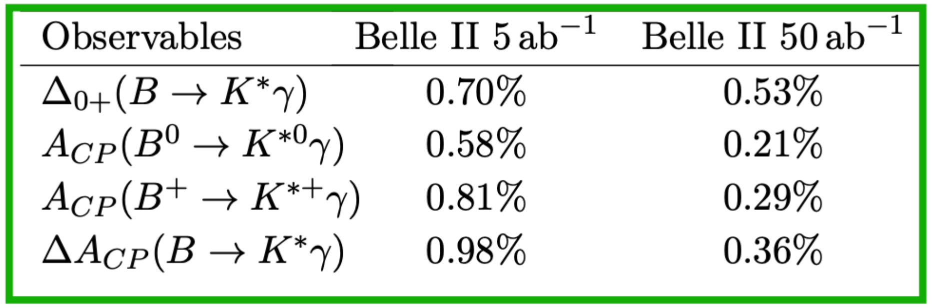


*The "improved" scenario assumes a 50% increase in signal efficiency for the same background level

PROJECTIONS

$B \to K^*\gamma$

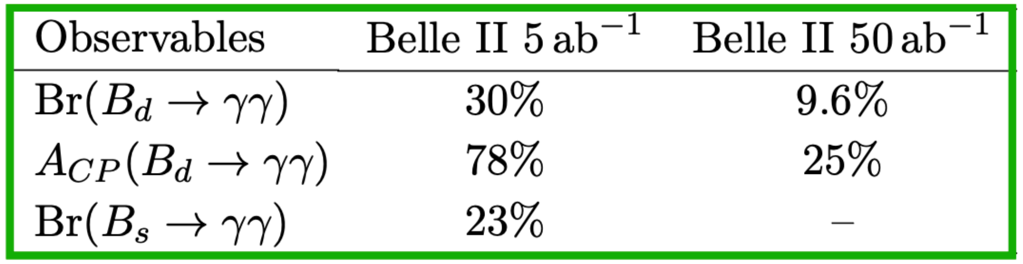
Belle II Physics Book



Observables	Belle II $5\,\mathrm{ab}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
$\Delta_{0+}(B \to K^*\gamma)$	0.70%	0.53%
$A_{CP}(B^0 \to K^{*0}\gamma)$	0.58%	0.21%
$A_{CP}(B^+ \to K^{*+}\gamma)$	0.81%	0.29%
$\Delta A_{CP}(B \to K^*\gamma)$	0.98%	0.36%

$B^0 \to \gamma\gamma$

Belle II Physics Book



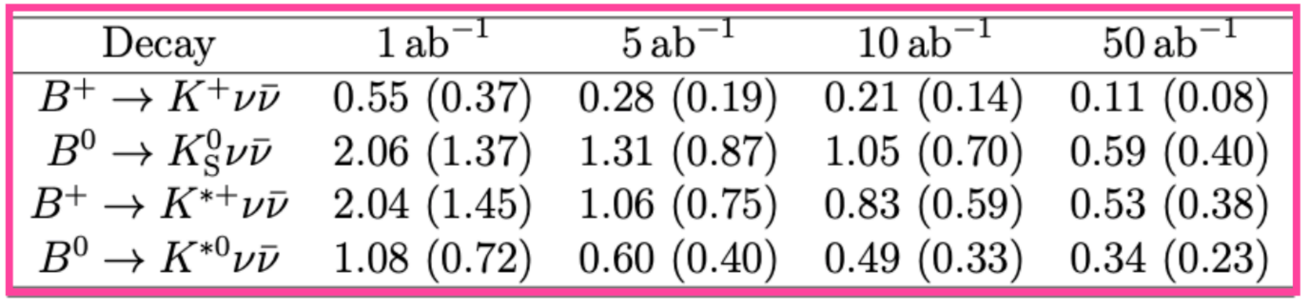
Observables	Belle II $5\,\mathrm{ab}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
$\mathrm{Br}(B_d \to \gamma\gamma)$	30%	9.6%
$A_{CP}(B_d \to \gamma\gamma)$	78%	25%
$\mathrm{Br}(B_s \to \gamma\gamma)$	23%	–

$B_s^0 \to \mu\mu\gamma$

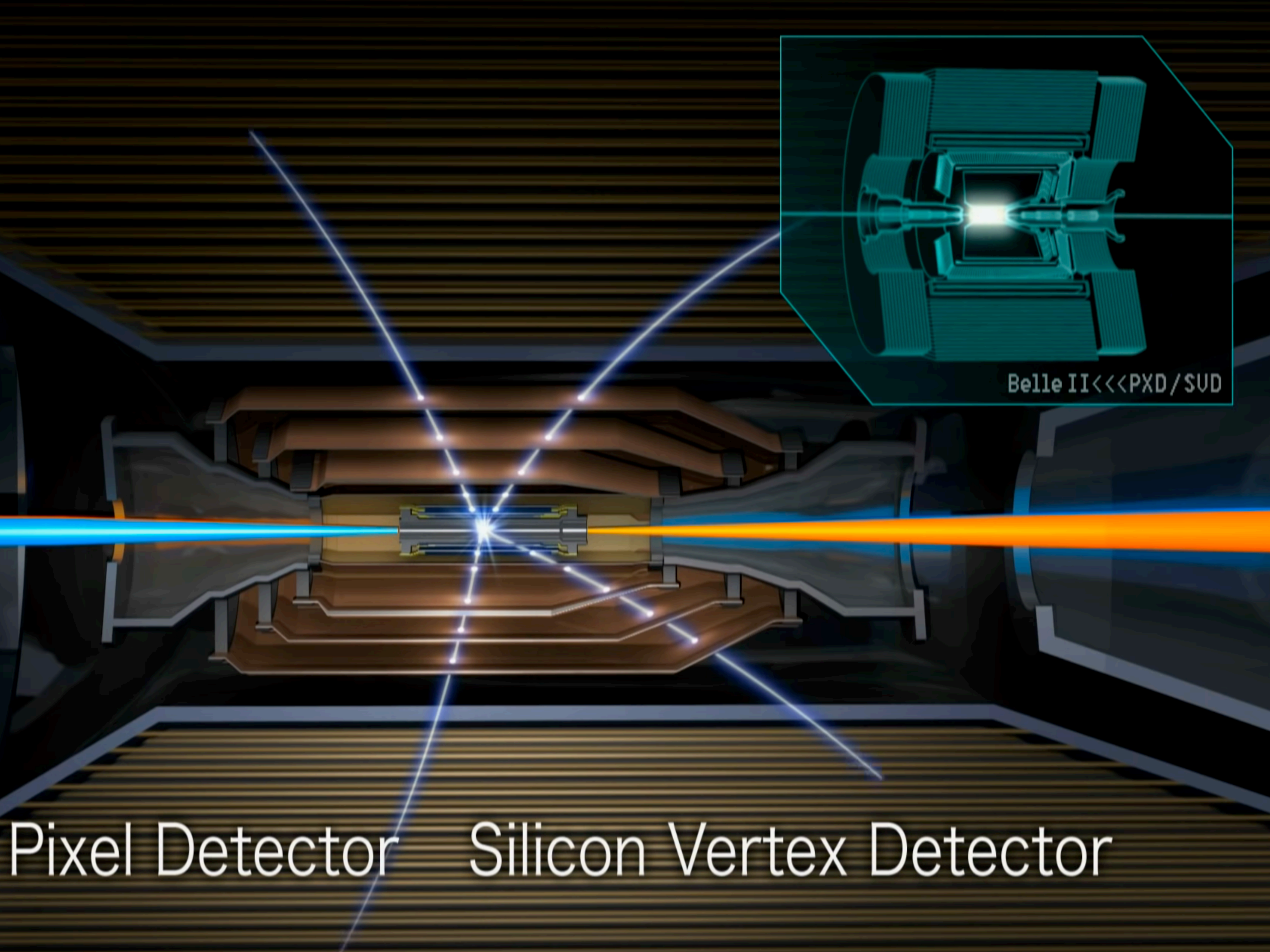
more data will result in a observation of this decay

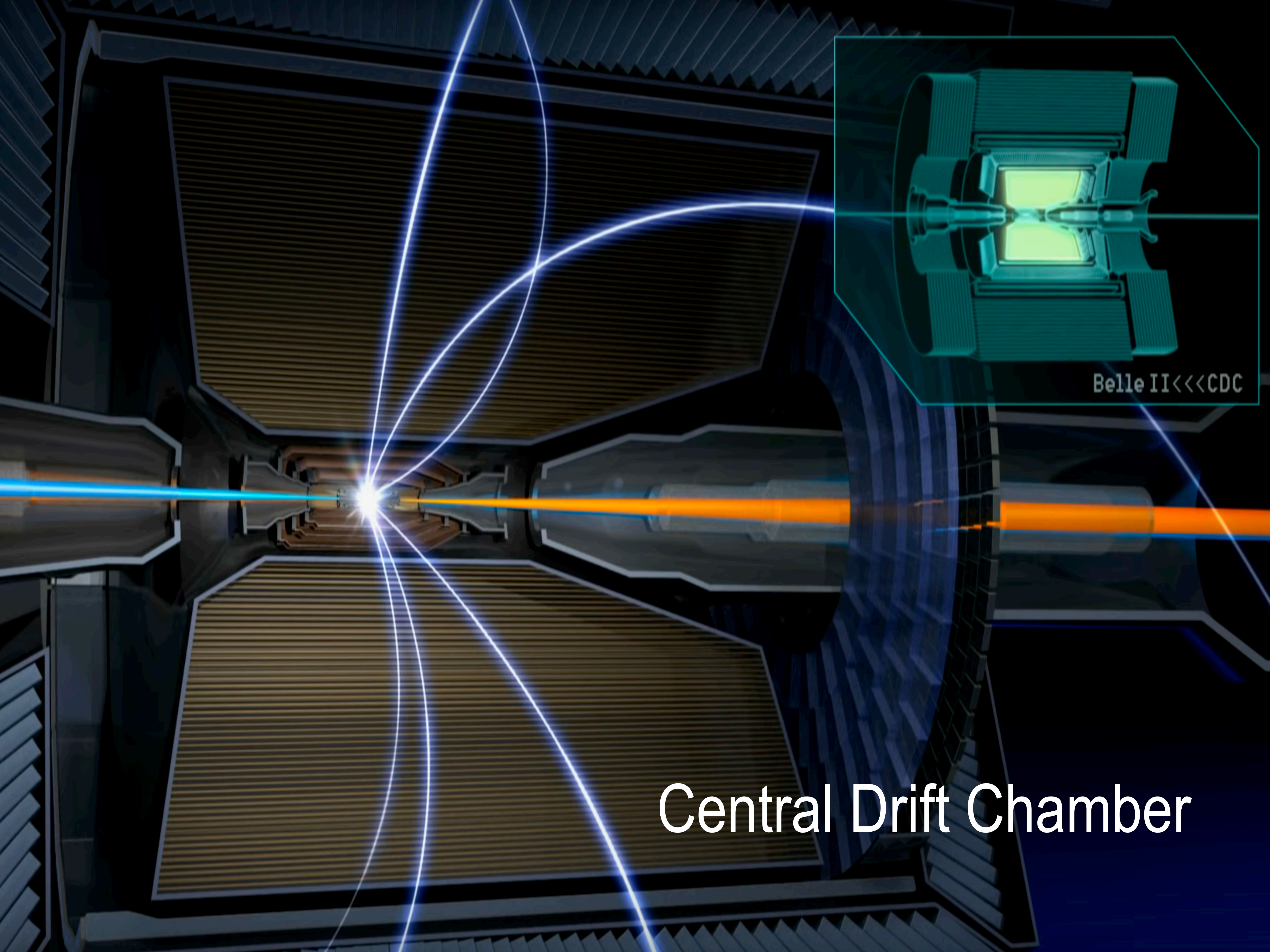
$B^+ \to K^+\nu\bar{\nu}$

Belle II snowmass paper : 2 scenarios baseline (improved*) assuming SM



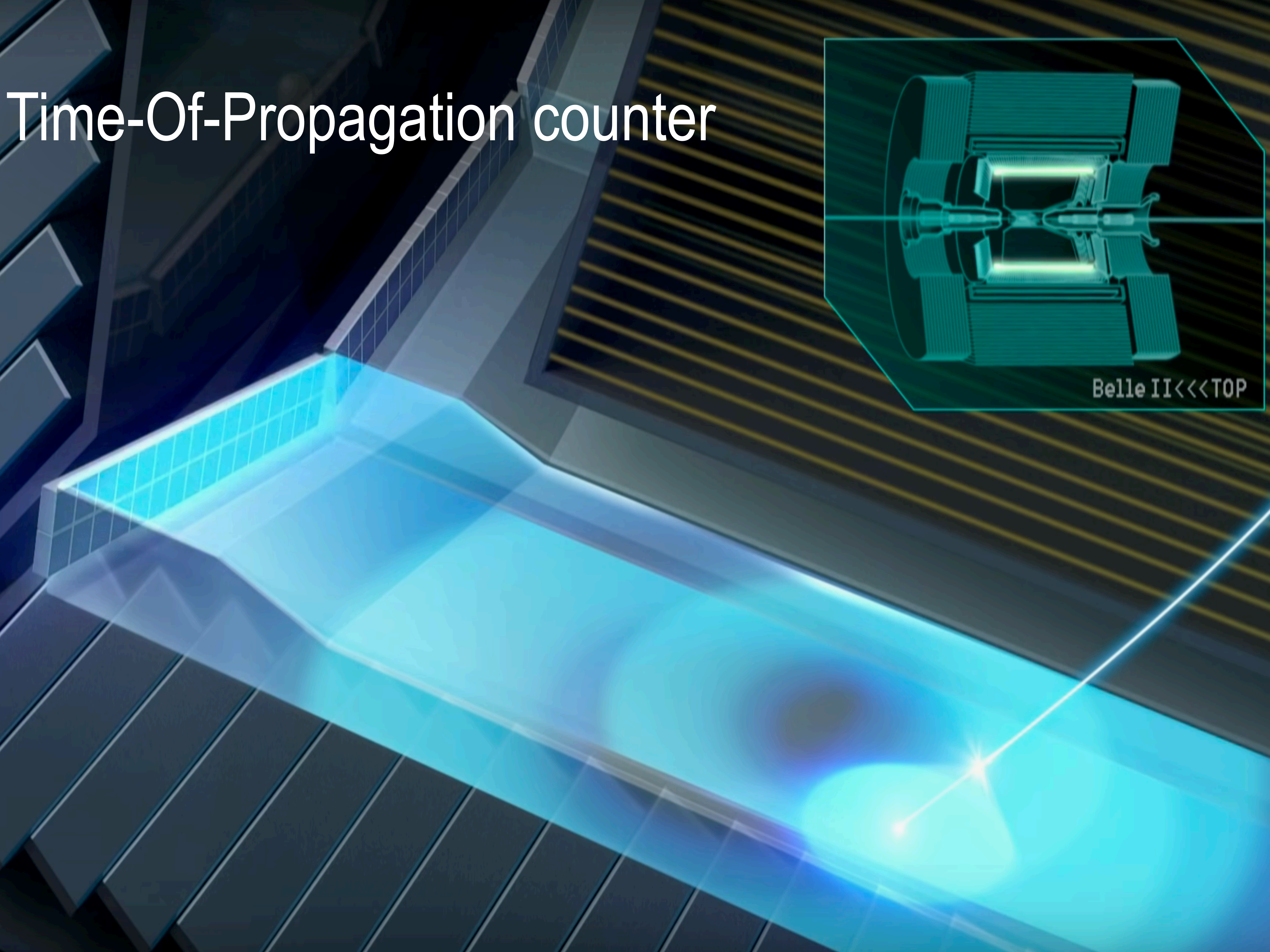
Decay	$1\,\mathrm{ab}^{-1}$	$5\,\mathrm{ab}^{-1}$	$10\,\mathrm{ab}^{-1}$	$50\,\mathrm{ab}^{-1}$
$B^+ \to K^+\nu\bar{\nu}$	0.55 (0.37)	0.28 (0.19)	0.21 (0.14)	0.11 (0.08)
$B^0 \to K_S^0\nu\bar{\nu}$	2.06 (1.37)	1.31 (0.87)	1.05 (0.70)	0.59 (0.40)
$B^+ \to K^{*+}\nu\bar{\nu}$	2.04 (1.45)	1.06 (0.75)	0.83 (0.59)	0.53 (0.38)
$B^0 \to K^{*0}\nu\bar{\nu}$	1.08 (0.72)	0.60 (0.40)	0.49 (0.33)	0.34 (0.23)


Belle II<<<PXD/SVD
Pixel Detector
Silicon Vertex Detector

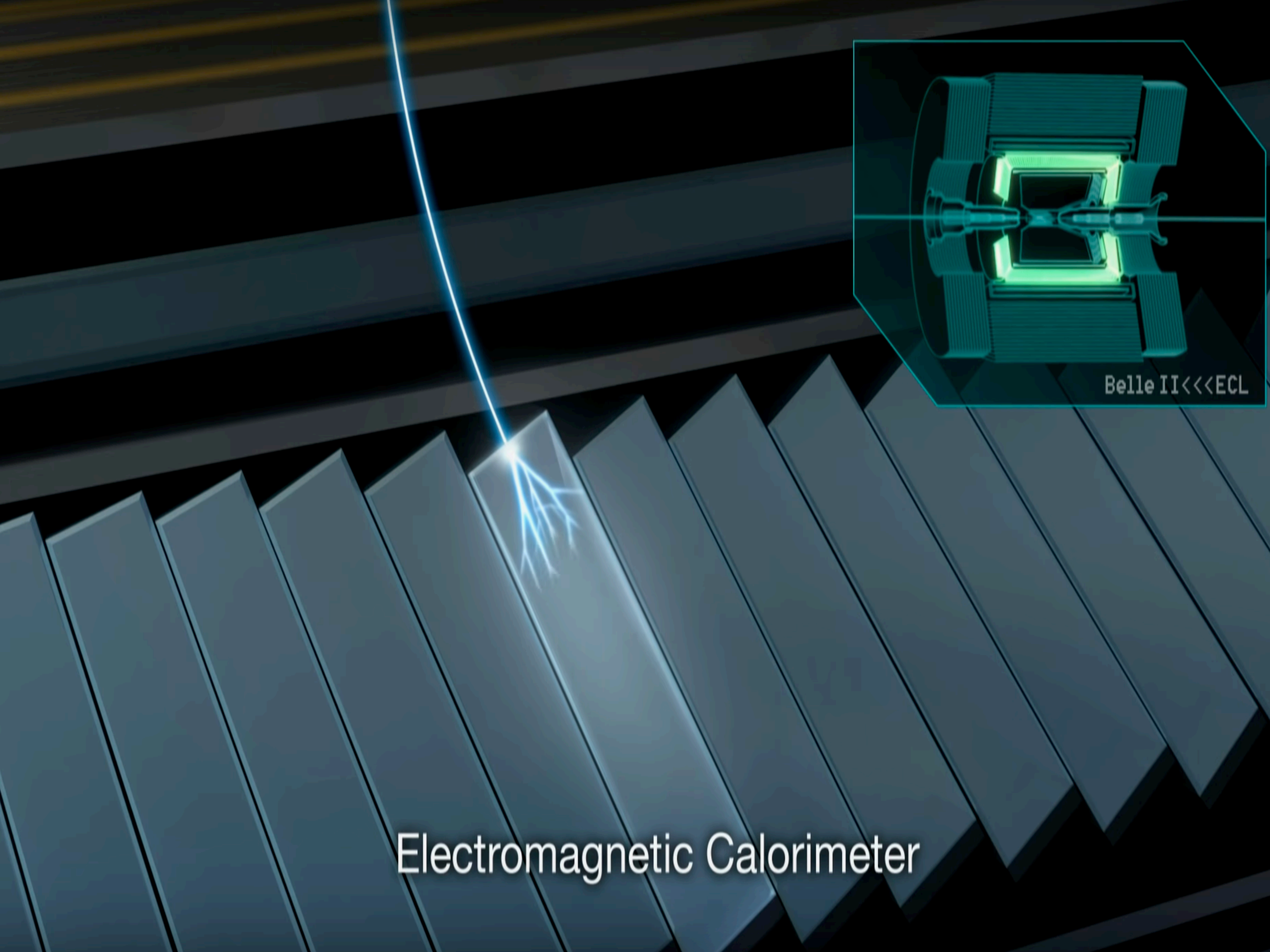


Central Drift Chamber

Time-Of-Propagation counter



Aerogel Ring-Imaging Cherenkov detector



Electromagnetic Calorimeter

K_L and Muon detector