Gaetano de Marino
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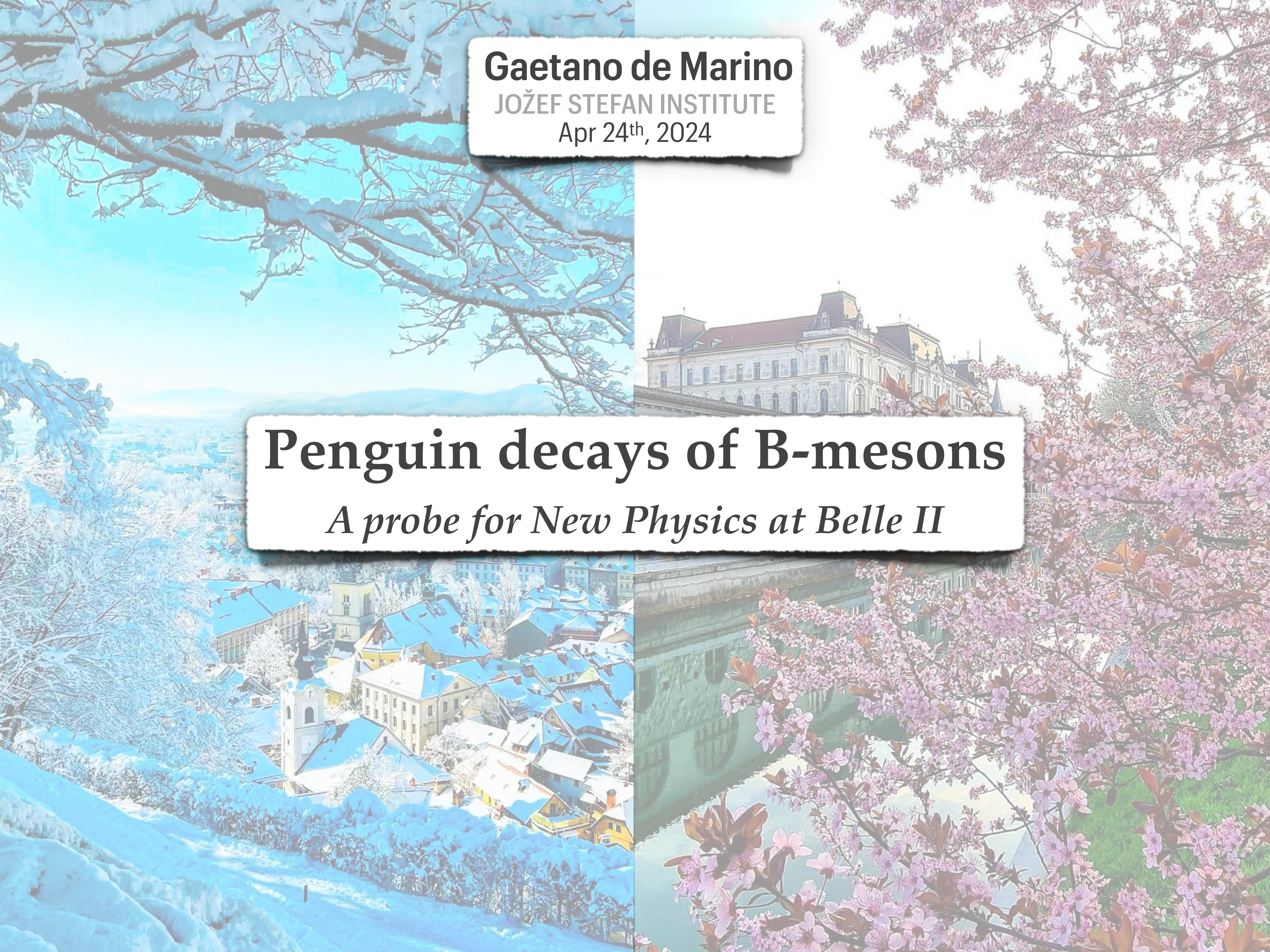
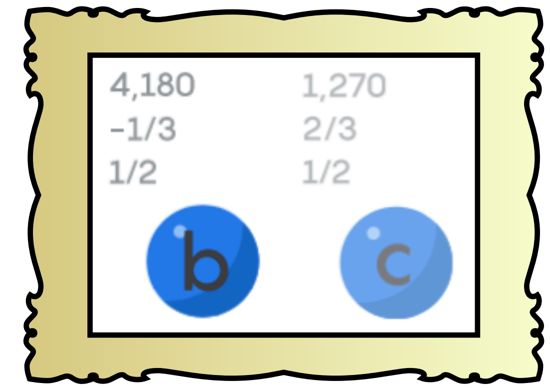
Apr 24th, 2024

Penguin decays of B-mesons

A probe for New Physics at Belle II



B-PHYSICS

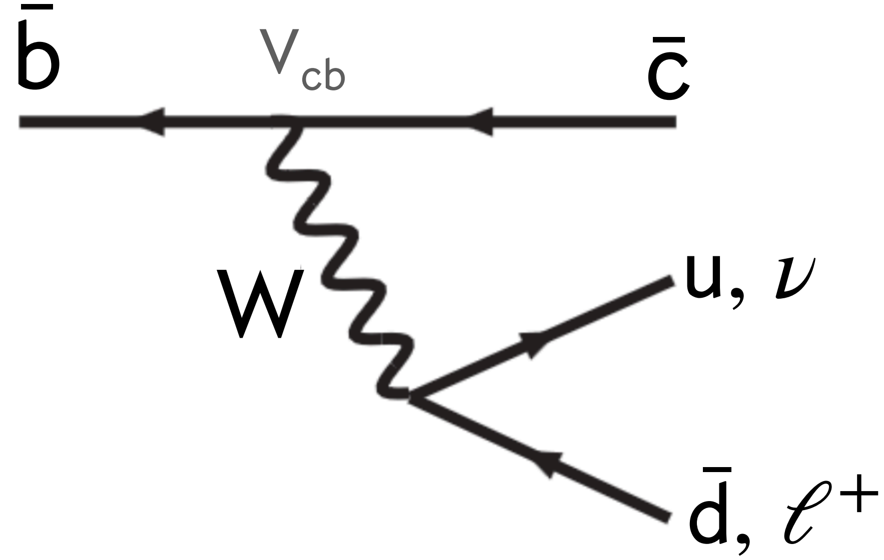


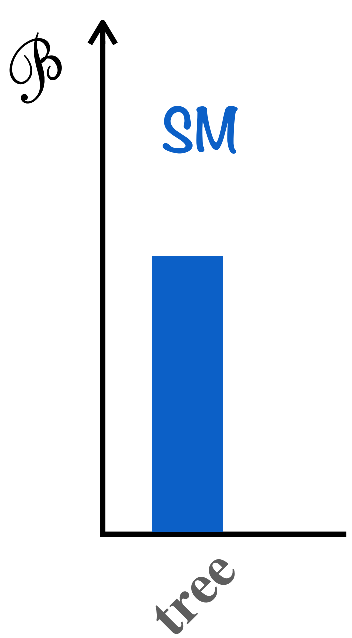
B-mesons

- **Relatively light** → Can be produced abundantly
- **Relatively heavy** → Thousands of decay modes $M(B) - M(D) \sim 3\ \text{GeV}$

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

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





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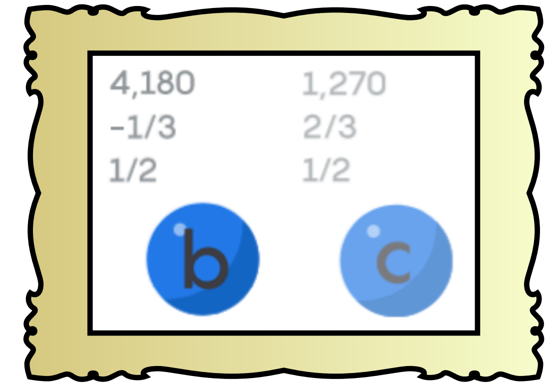

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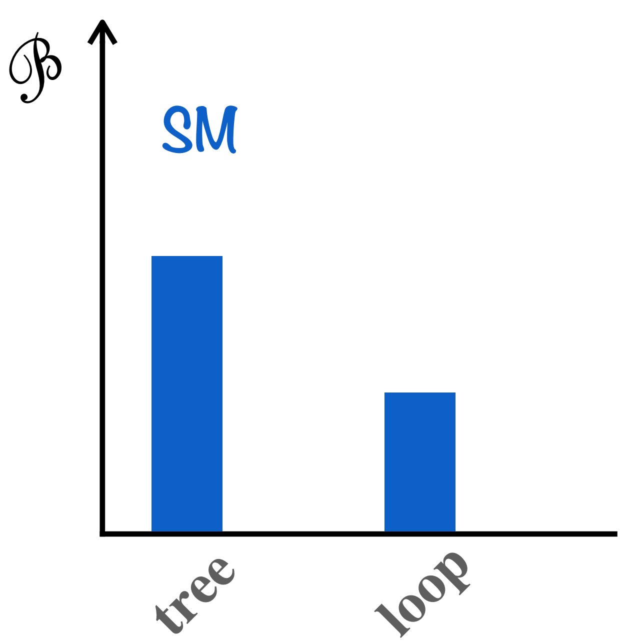
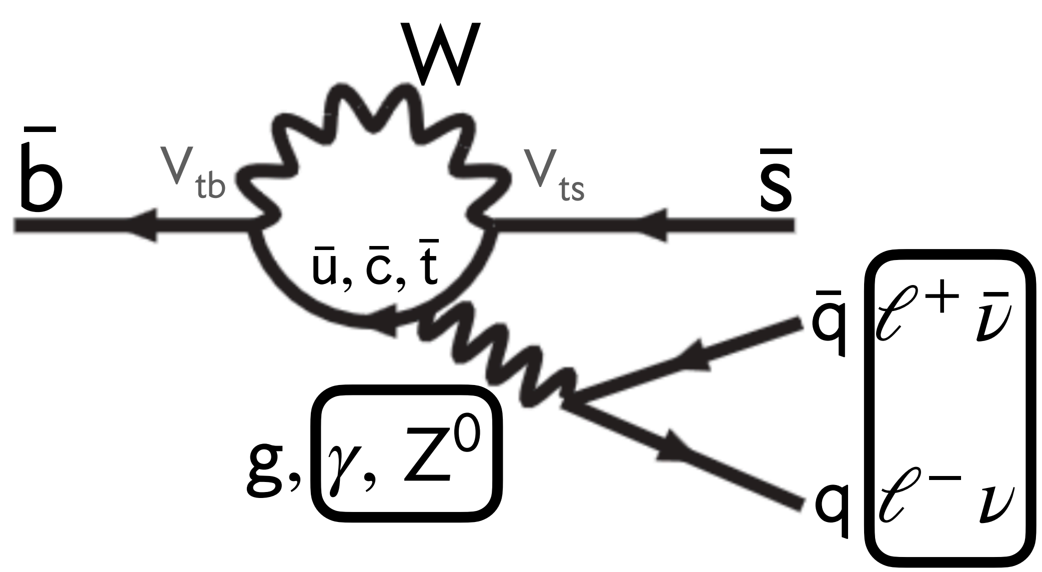
- **Decays with low/zero branching ratio** →Searches for rare/forbidden decays $\mathcal{B} < 5 \times 10^{-5}$

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

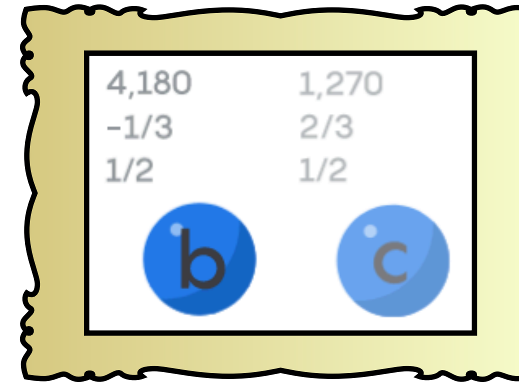
They occur at **loop level** in the SM





Loop, GIM and CKM suppressed !

RARE B DECAYS



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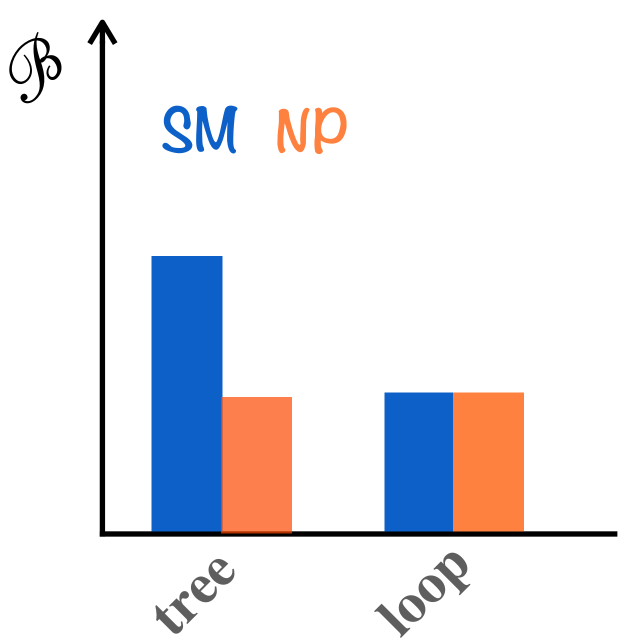
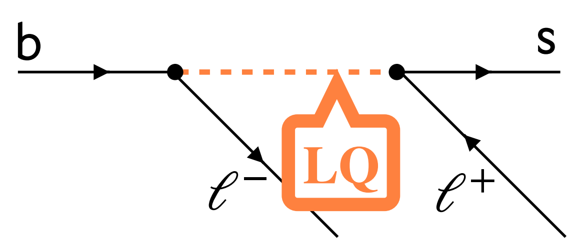
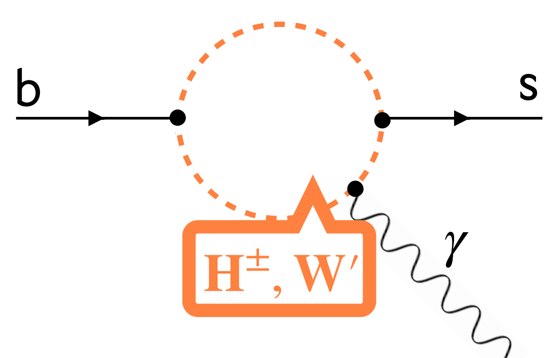
Alterations/enhancements in FCNC due to NP contributions:





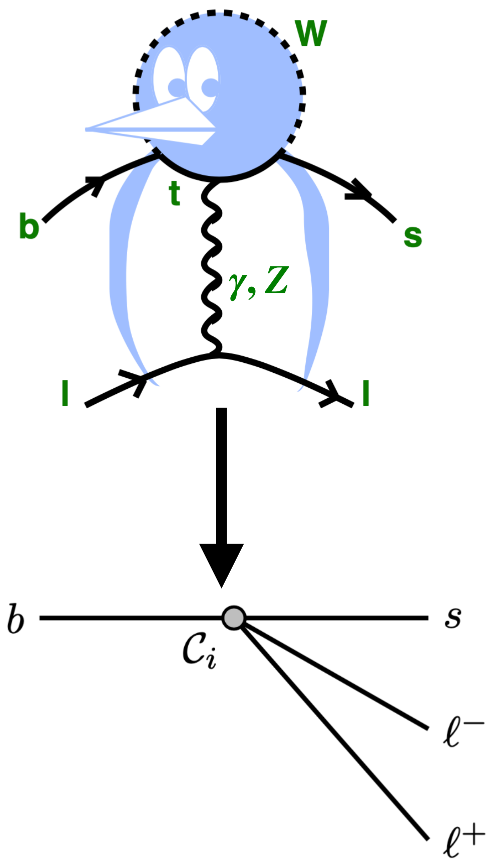
- New interactions at tree level



- Weaker GIM cancellations due to new particles in loop corrections

THE FLAVOR 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**



Full theory

Effective description

$$\mathcal{L}_{\mathrm{eff}} = \frac{4G_F}{\sqrt{2}}\lambda_t \sum_i \left(C_i\,\mathcal{O}_i\right) + \mathrm{h.c.}$$

Wilson Coefficients (C_i)

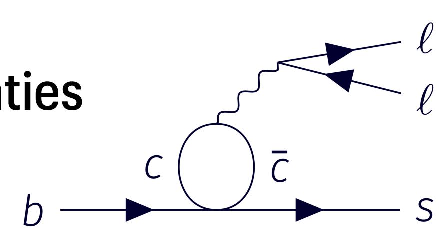
Effective operator ($\mathcal{O}_i$)

NP can manifest through

- Alterations of SM couplings $\mathbf{C_9^{eff} = C_9^{SM} + C_9^{NP}}$
- Additional operators $\mathcal{O}'^{\ell\ell}_{9,10}$ $\mathcal{O}^{\nu_i\nu_j}_{R}$ $\mathcal{O}'_7$

Theoretical uncertainties arise from

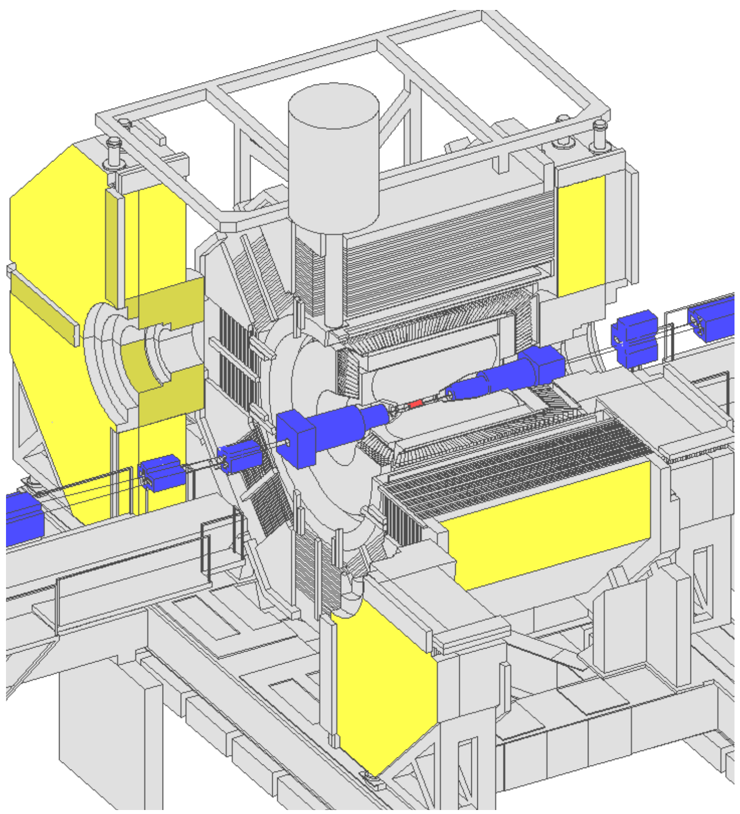
- WC and constants (e.g. V_{CKM}) → **small uncertainties** $|\lambda_t| = |V_{tb}V^*_{ts}| = |V_{cb}|(1 + \mathcal{O}(\lambda^2))$
- Local hadronic ME → **Moderate uncertainties (3-15%)** $\langle K^{(*)}|\mathcal{O}_{7,9,10}|B\rangle$ $\mathcal{O}_{7,9,10} = (\bar{s}\Gamma b)$
- Non-local hadronic ME → **Large uncertainties** $i\int d^4x\, e^{iq\cdot x}\langle K^{(*)}|T\{j^{em}_\mu(x)\mathcal{O}^c_{1,2}(0)\}|B\rangle$ $\mathcal{O}_{1,2} = (\bar{s}\Gamma b)(\bar{c}\Gamma c)$



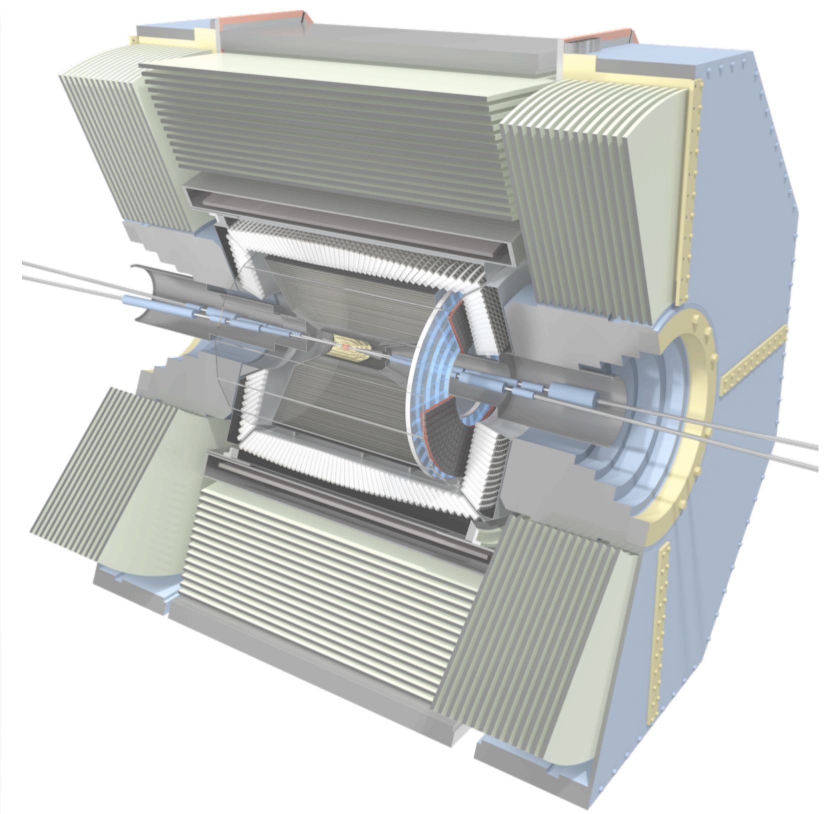
Use ratios for (partial) cancellation of uncertainties — both theoretical and experimental

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

THE BELLE&BELLE II EXPERIMENTS



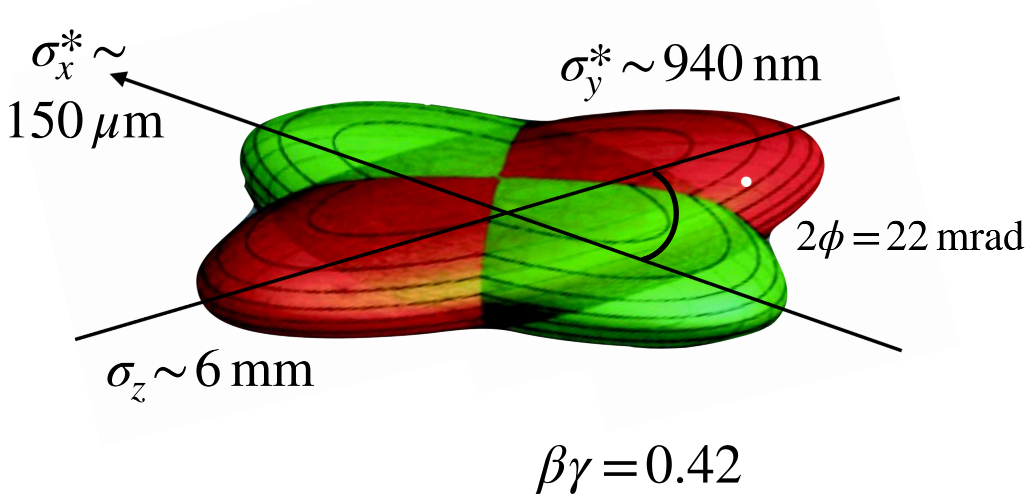
- High resolution (momentum, vertex) hermetic detectors
- Efficient reconstruction of neutrals (γ, π^0, η)
- Clean environment and low background
- World luminosity records



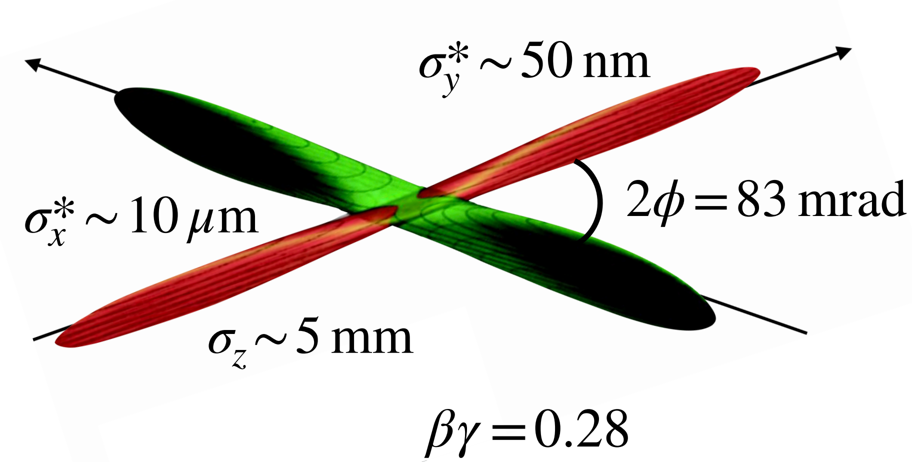
WR Luminosity of x 2.1×10^{34} cm^{-2} s^{-1} (Currents 1.2/1.6 A) (June 2009)

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

KEKB



SuperKEKB



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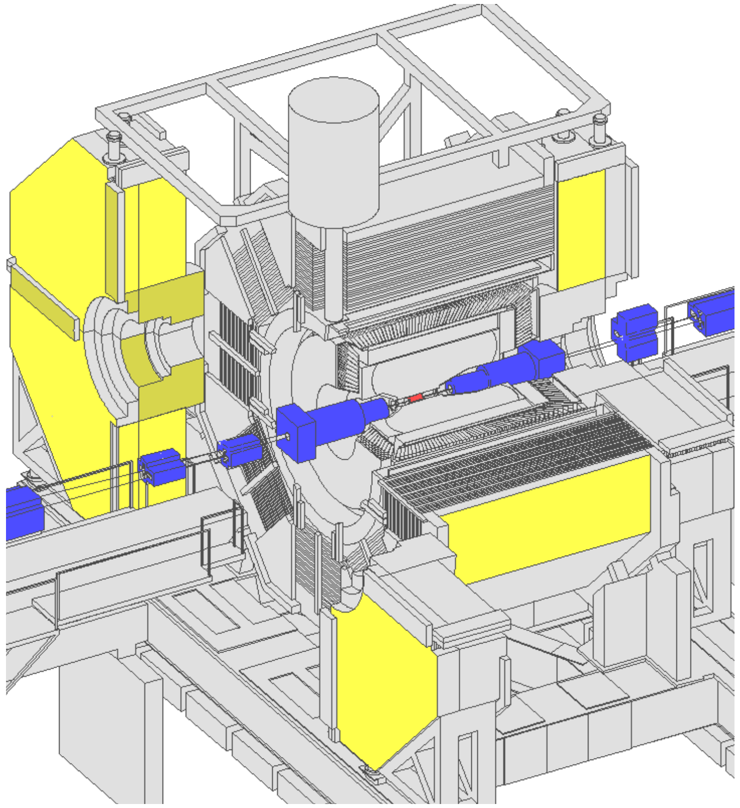

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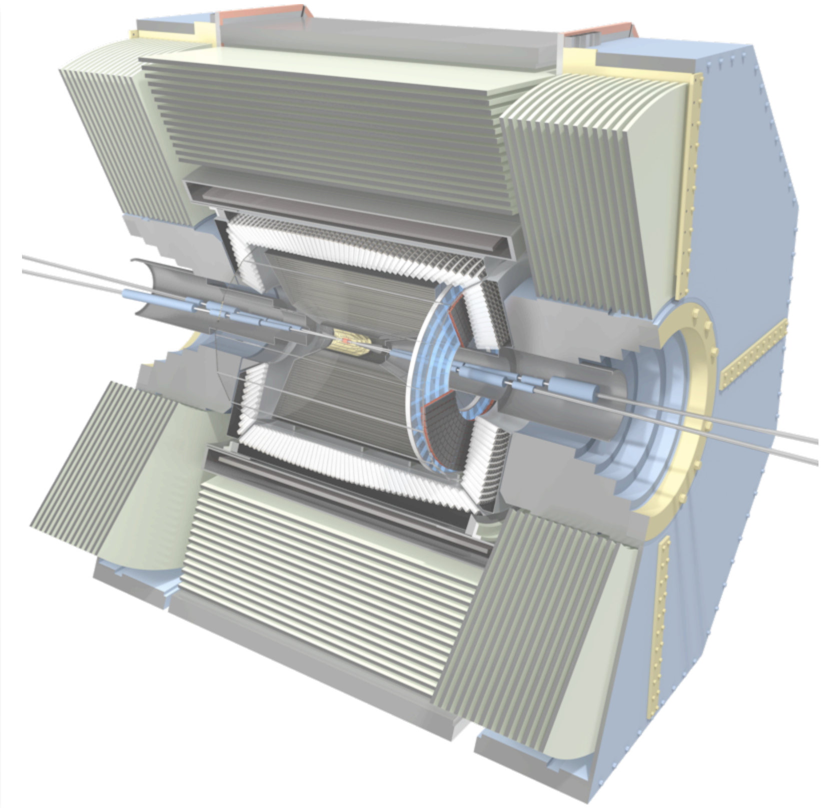
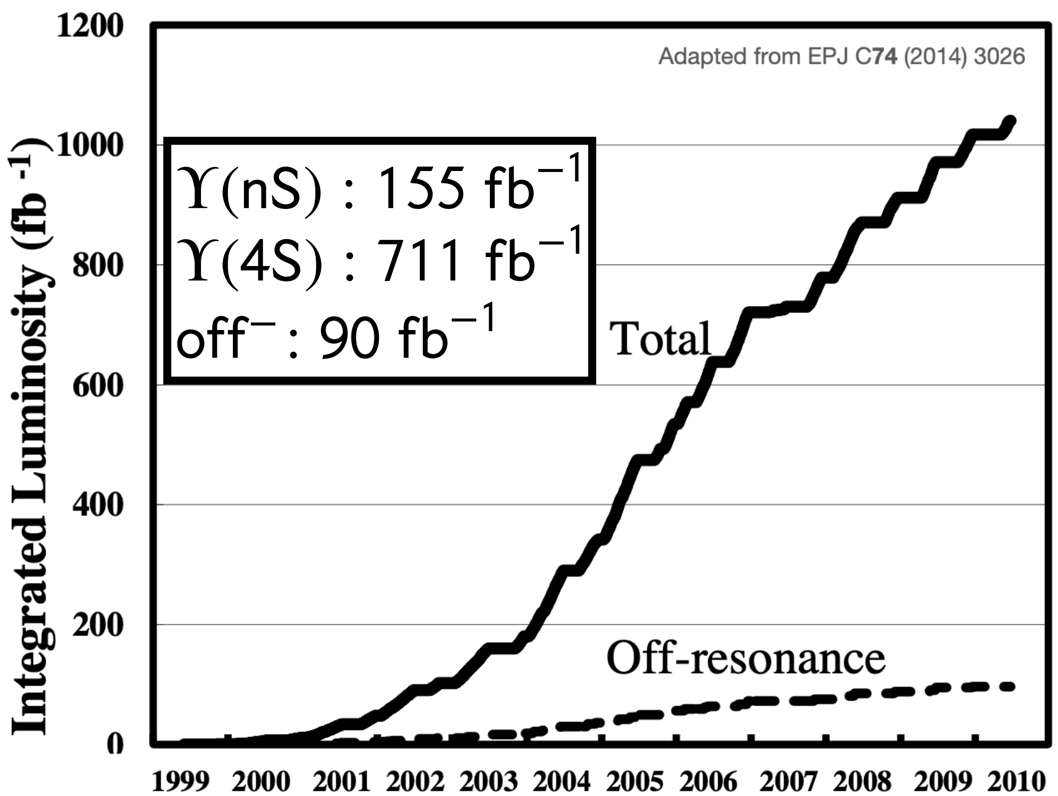
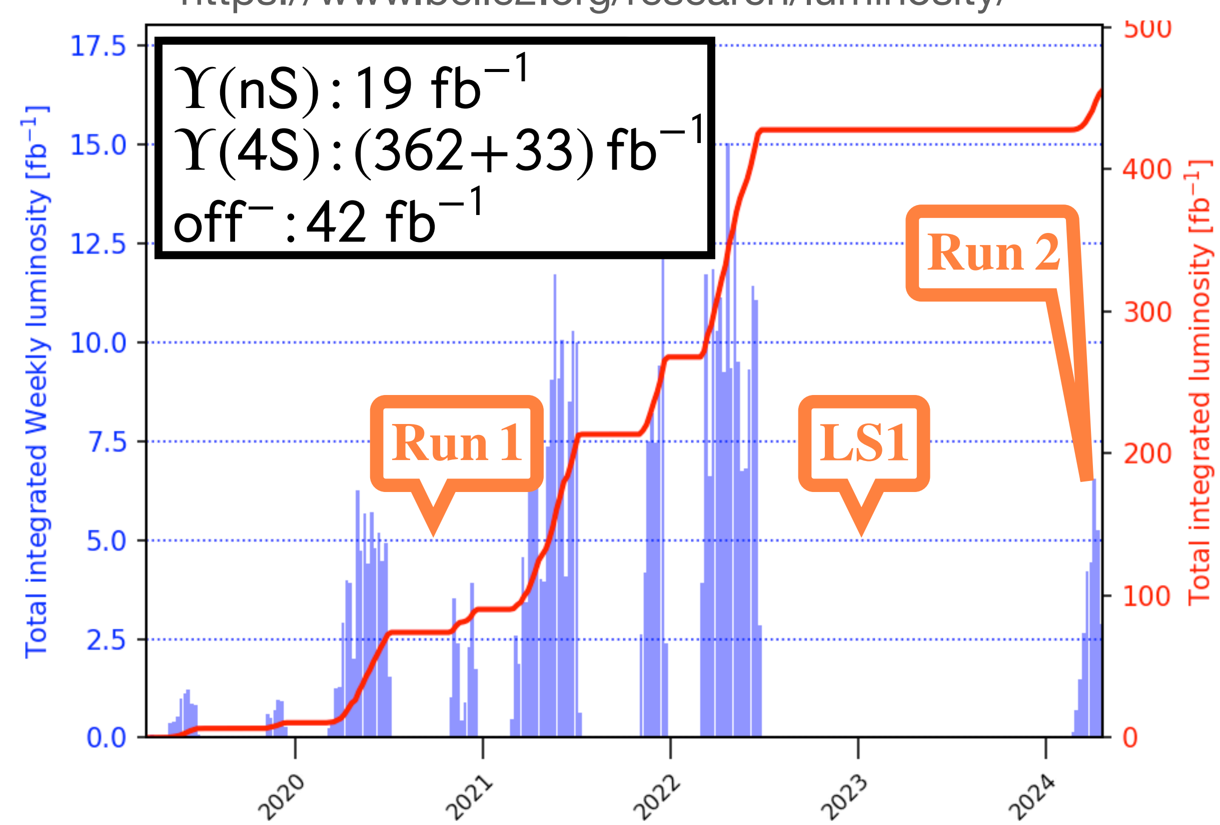




https://www.belle2.org/research/luminosity/



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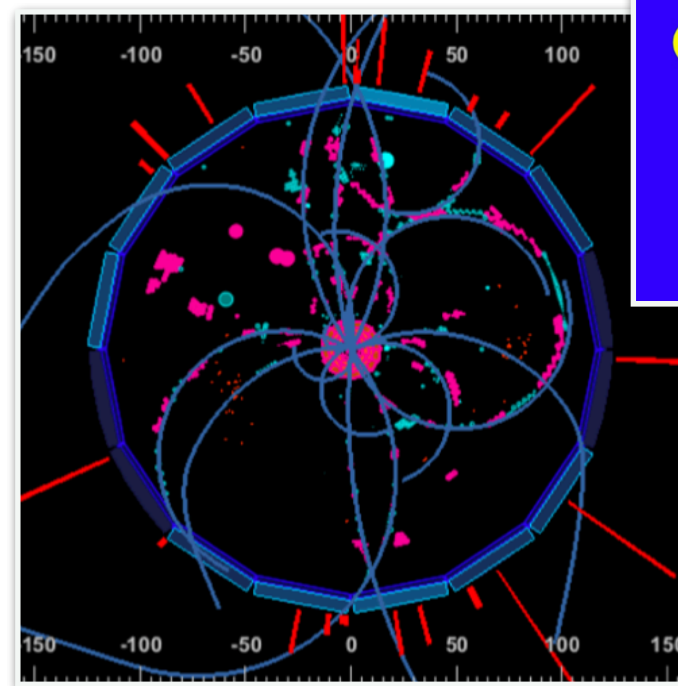

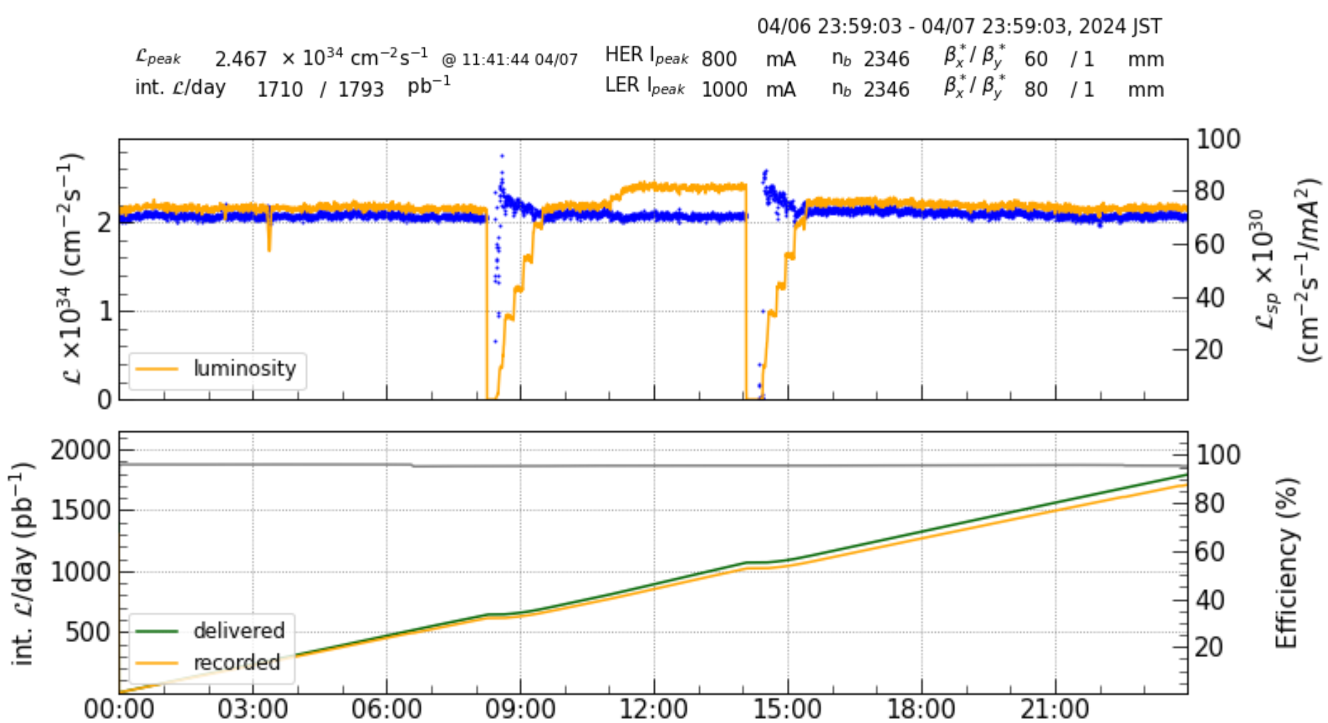

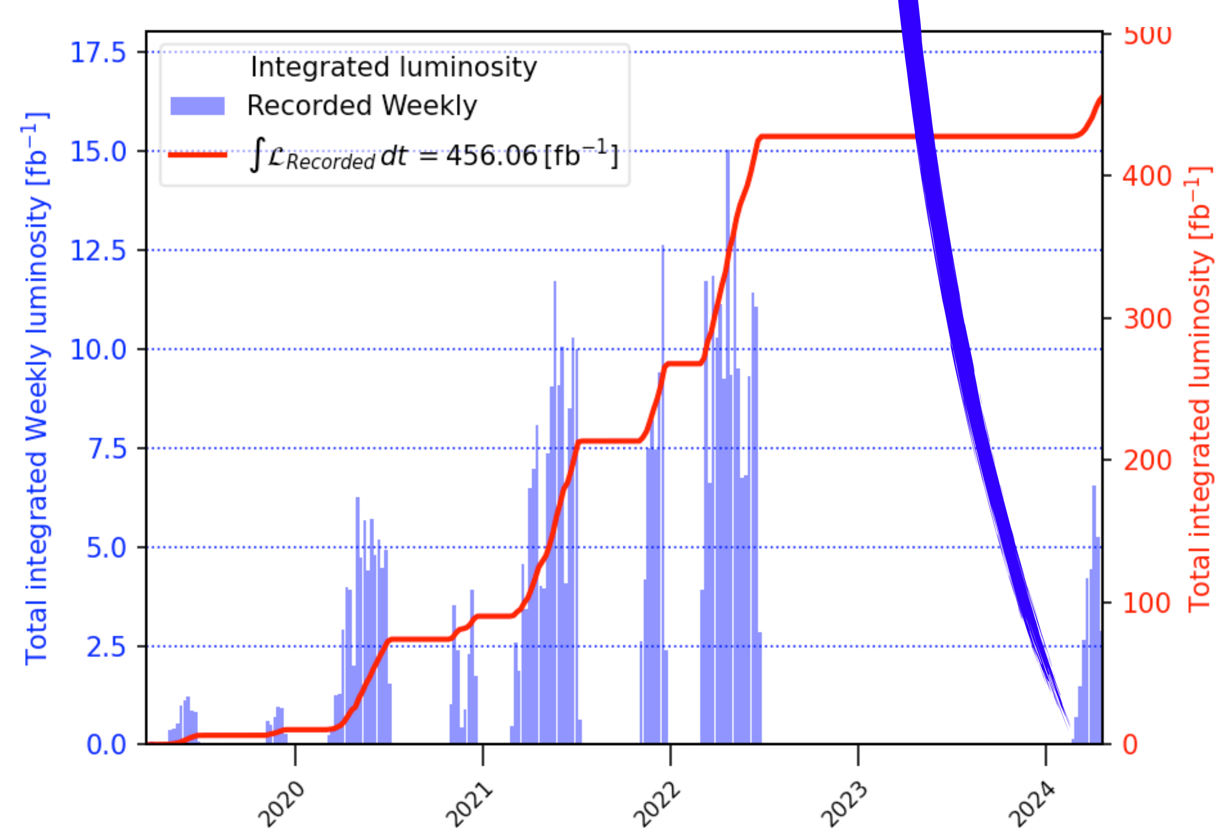

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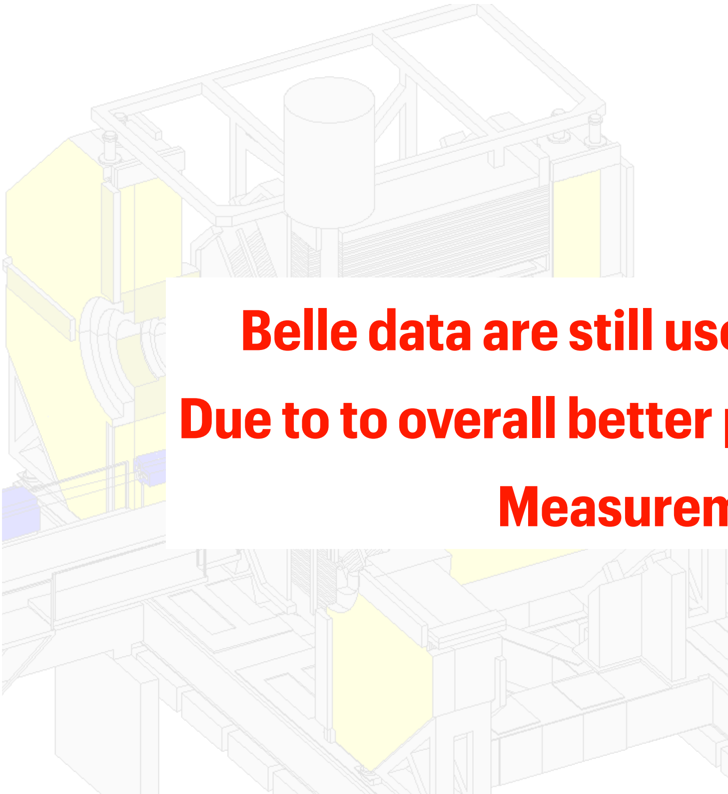
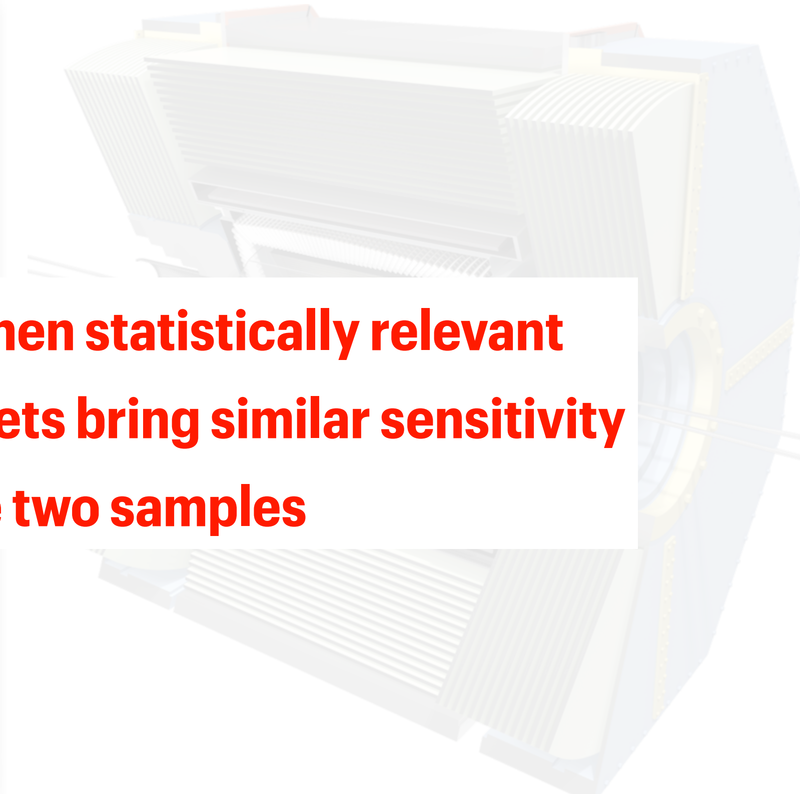


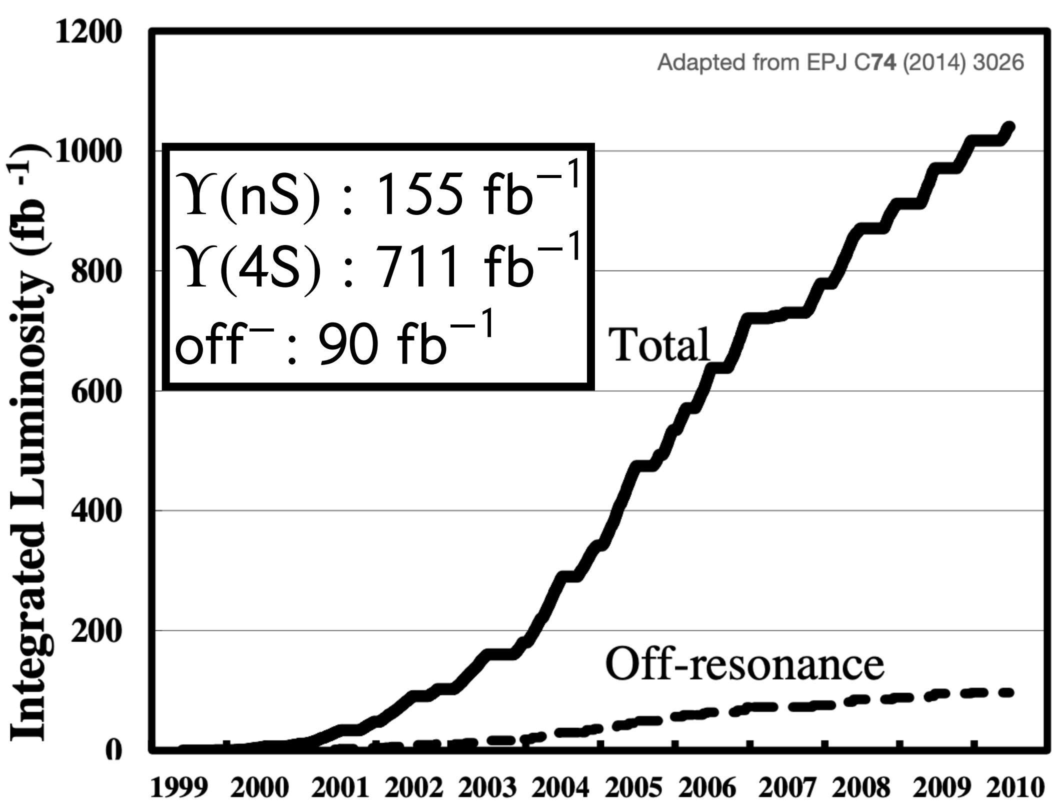
- High resolution (momentum, vertex) hermetic detectors
- Efficient reconstruction of
- background
- World luminosity records

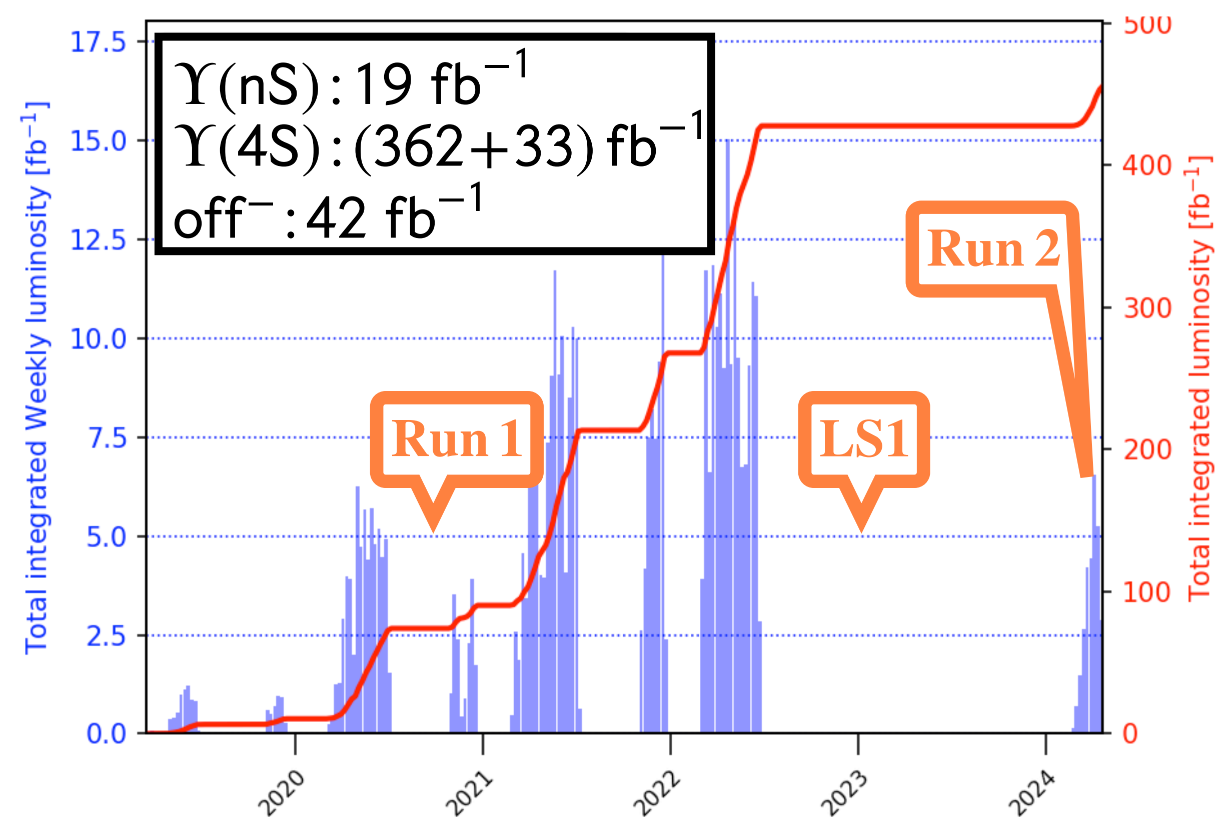


Belle data are still used and often combined with Belle II when statistically relevant

Due to to overall better performance at Belle II, the two datasets bring similar sensitivity

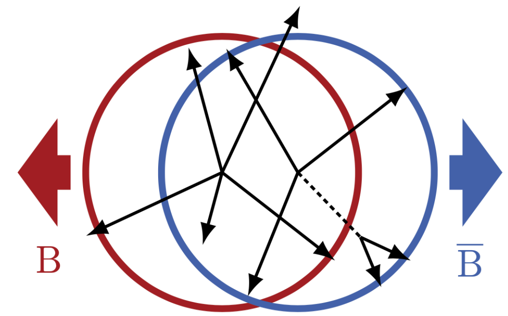
Measurements are separately optimised for the two samples

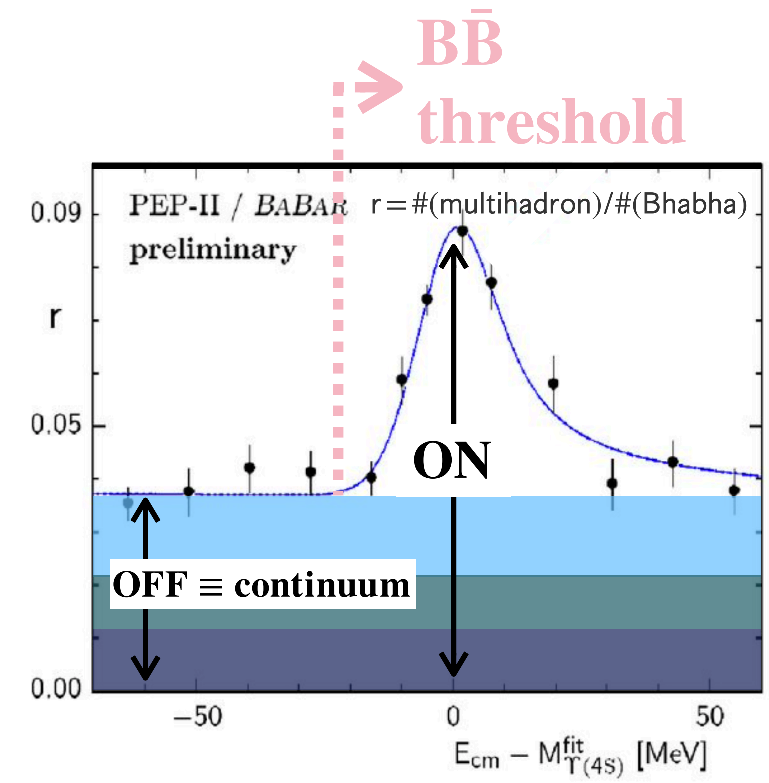




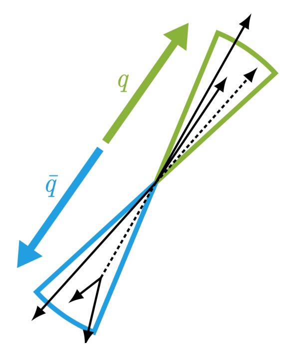
B-PHYSICS AT B-FACTORIES

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



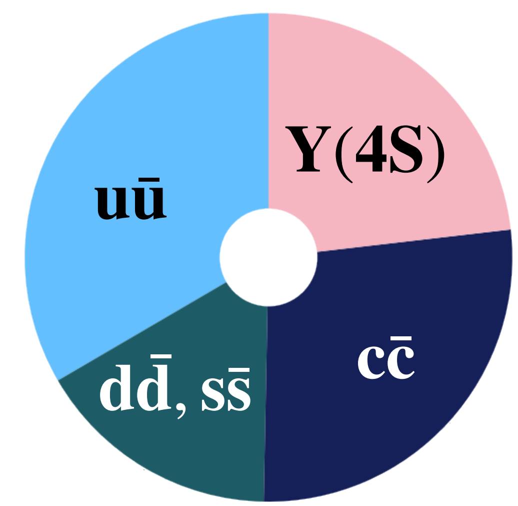


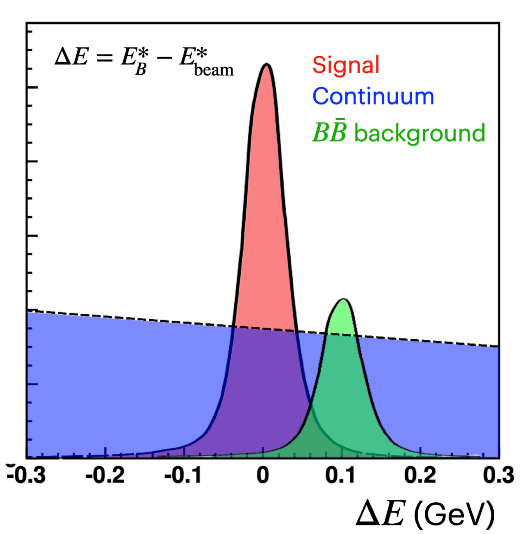
- Known initial kinematics + almost-4π detector coverage → reconstruct final states with neutrinos

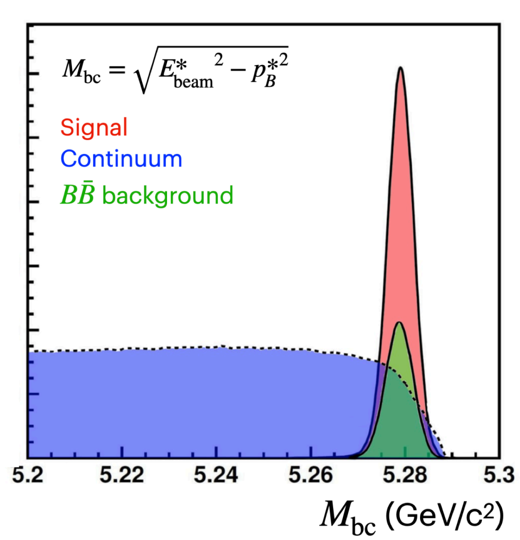


- OFF-resonance data → $B\bar{B}$-free sample

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





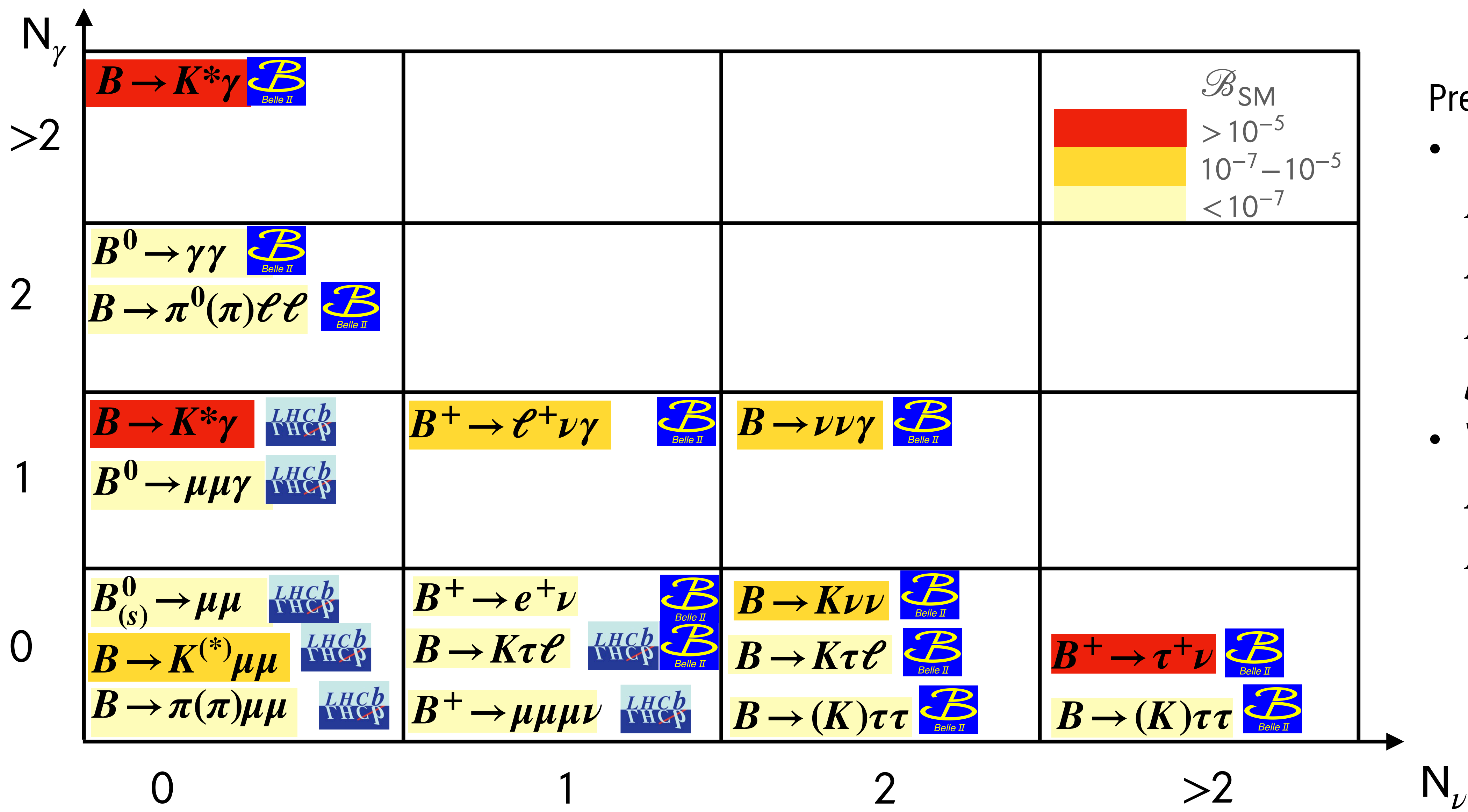


- Beam-constrained mass M_{bc} and energy difference ΔE as discriminative variables against combinatorial and peaking backgrounds

BELLE II STRENGTHS

LHCb: Better with muons/charged particles that can be vertexed

Belle II: Better with γ and ν

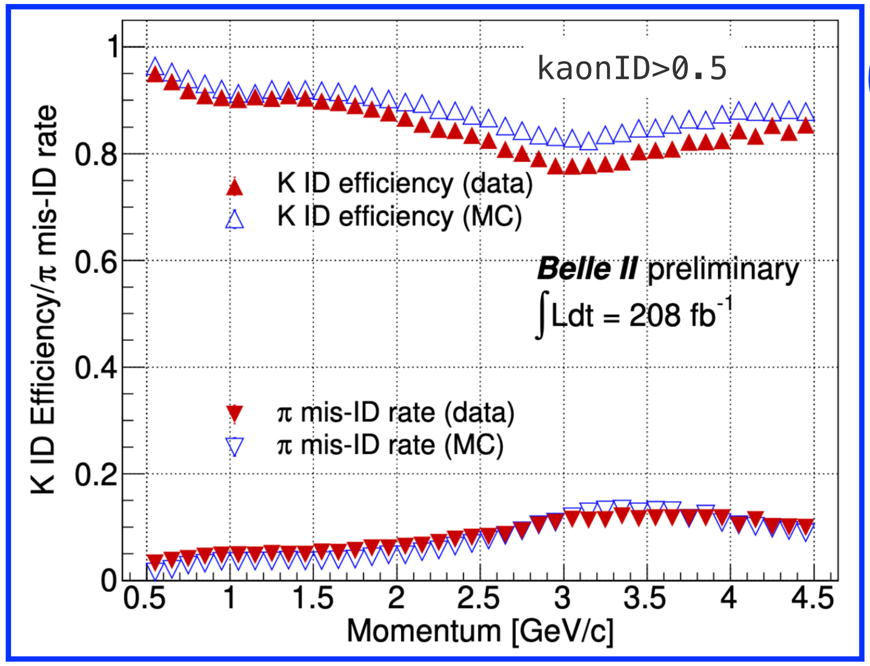


Presented today

- No neutrinos
  - $B^0 \to \gamma\gamma$
  - $B \to \{K^*, \rho\}\gamma$
  - $B \to K^*ee$
  - $b \to d\ell\ell$
- With neutrinos
  - $B \to K\nu\nu$
  - $B \to K\tau\{\ell, \tau\}$

Belle II TDR, arXiv: 1011.0352

KEY-PERFORMANCES AT BELLE II

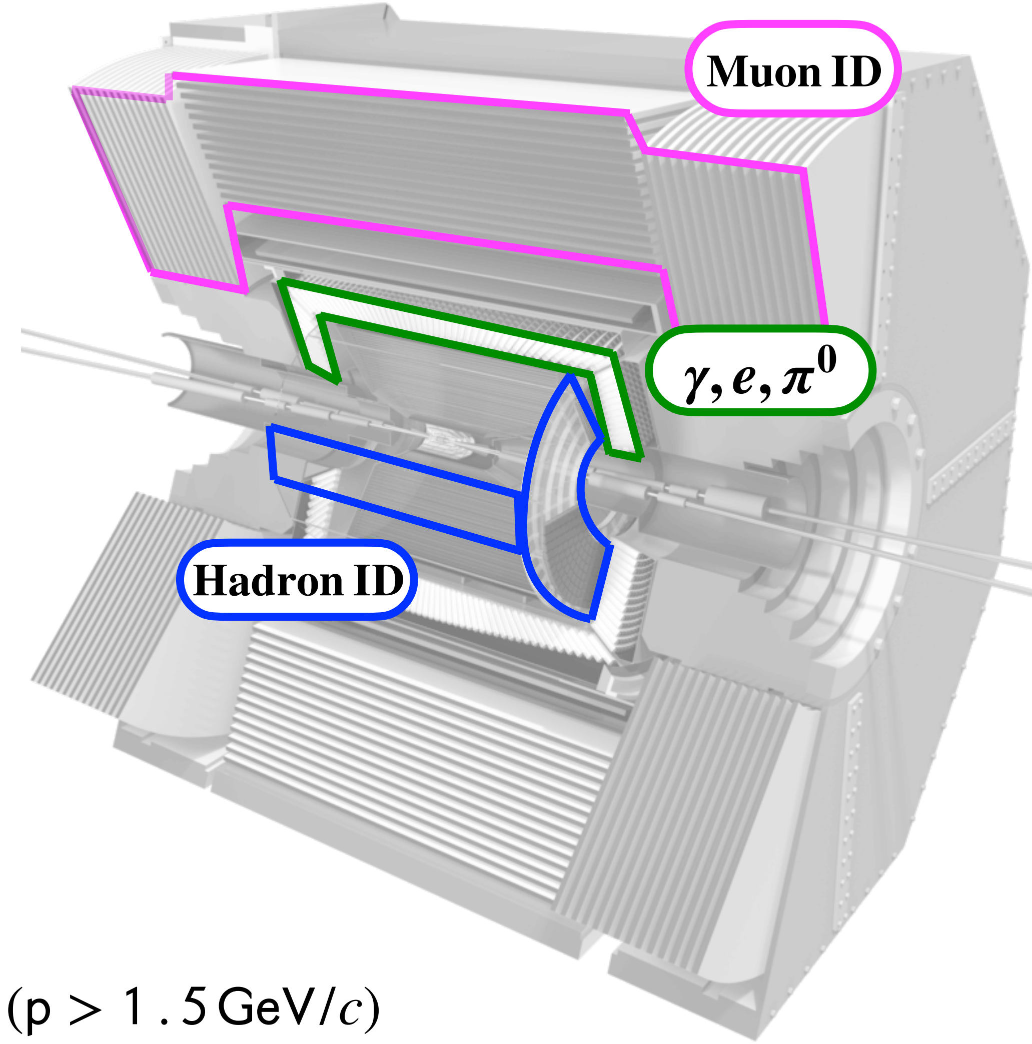


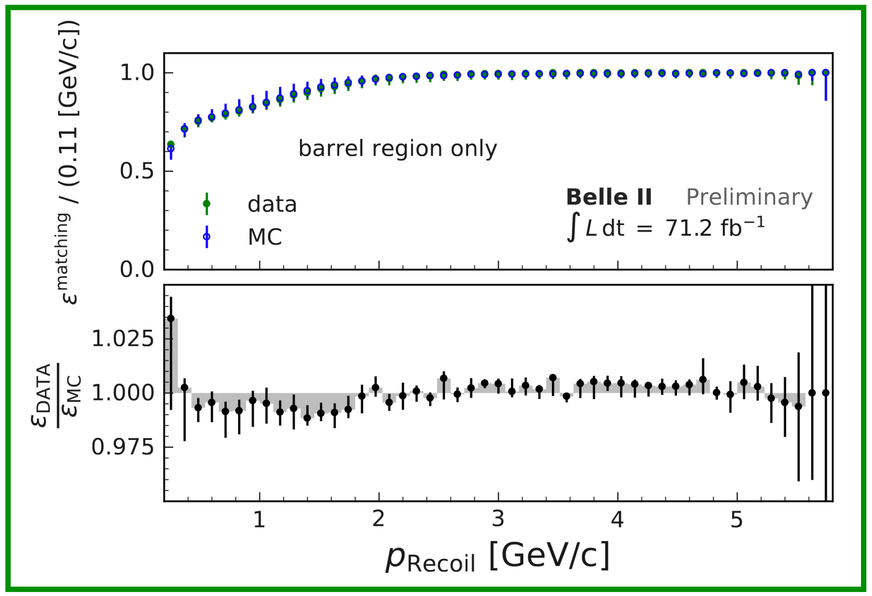
K ID

$\varepsilon \sim 90\,\%$

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

Good kaon identification in full momentum range

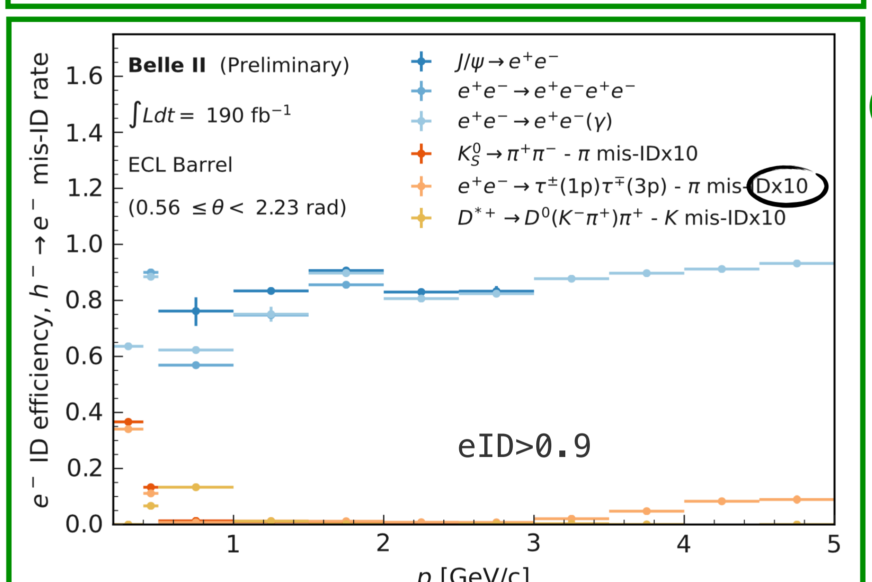




γ, π^0

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

Belle-like resolution on π^0 mass



e ID

$\varepsilon \sim 86\,\%$

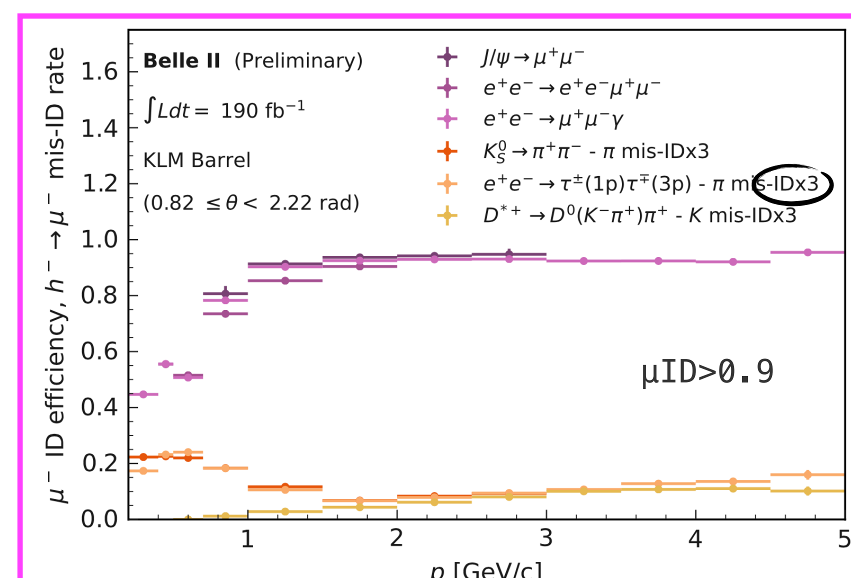
$\pi \to e \sim 0.4\,\%$

μ ID

$\varepsilon \sim 90\,\%$

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

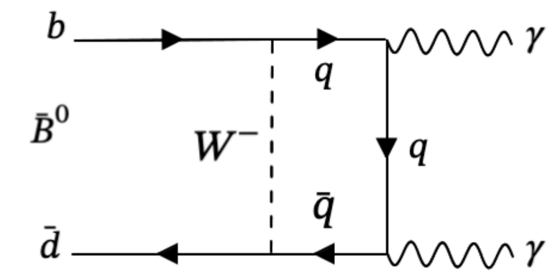
Good lepton ID performance



B → VISIBLE

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

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



Rarest decay searched at Belle II so far

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

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

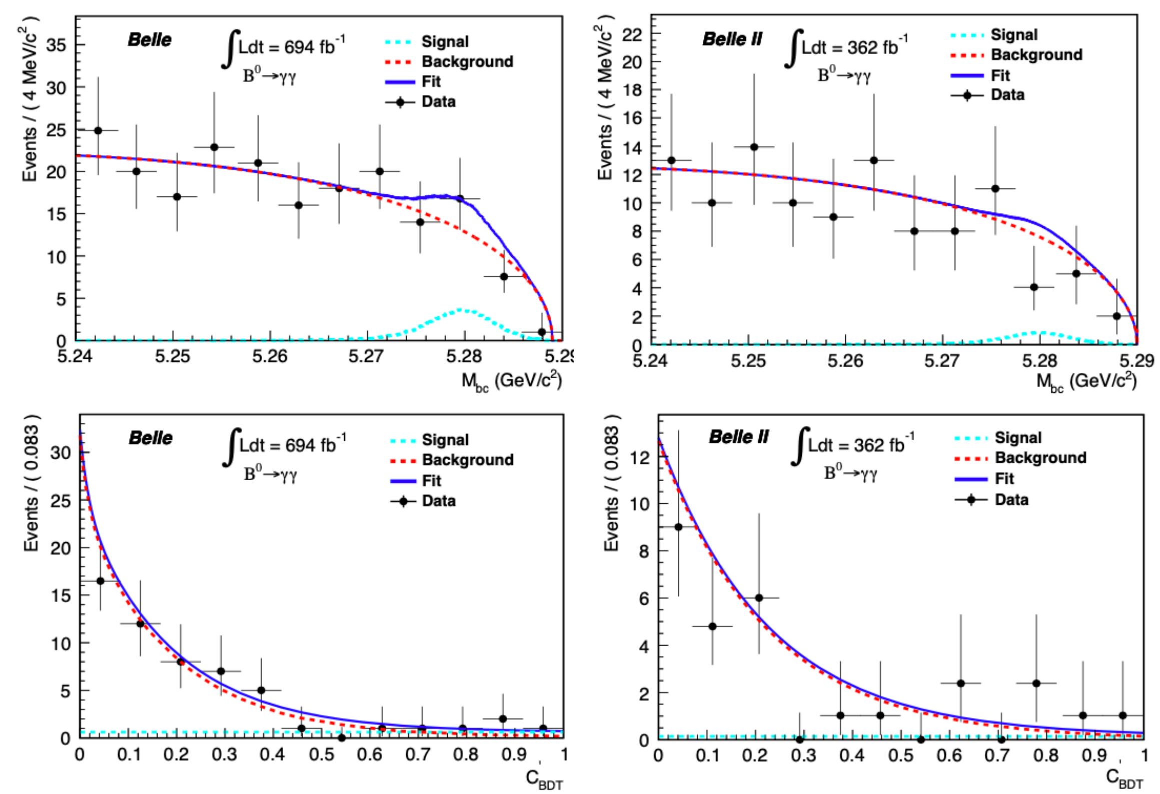
Require good quality high energy γ

Reject photon candidates form asymmetric η and π^0 decays

90% qq + $B^0 \to \pi^0\pi^0$

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

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



$N_{sig} = 11.0^{+6.5}_{-5.5}$ 2.5σ

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

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

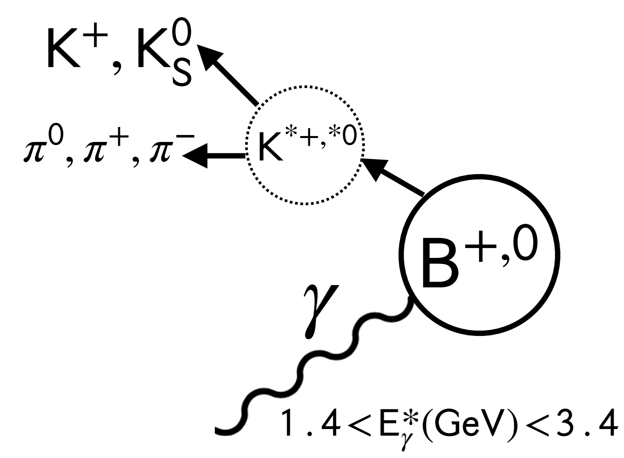
- **Sensitivity approaching the SM prediction**
- **5x improvement over previous best UL (BaBar)** [PRD 83 032006 (2011)]

$B \to K^*\gamma$ MEASUREMENT

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

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

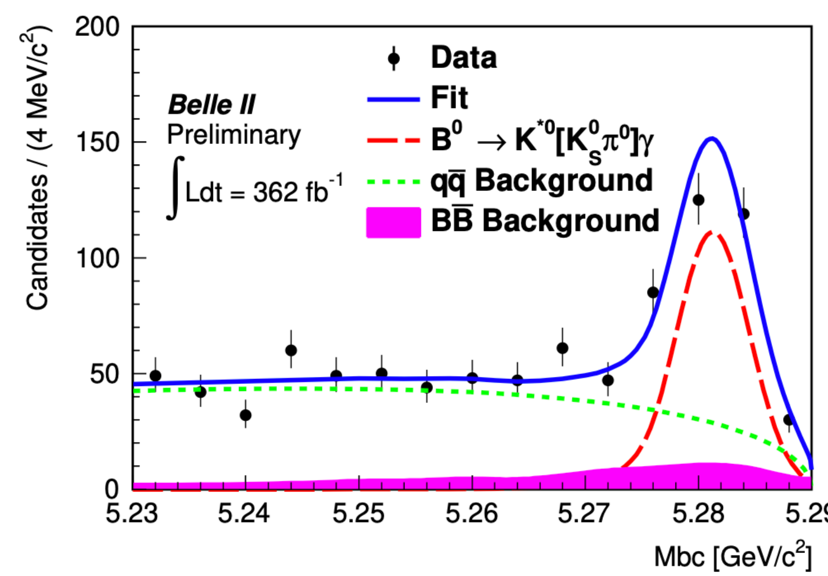
$$\Delta\mathcal{A}_{CP} = \mathcal{A}_{CP}(B^+ \to K^{*+}\gamma) - \mathcal{A}_{CP}(B^0 \to K^{*0}\gamma)$$

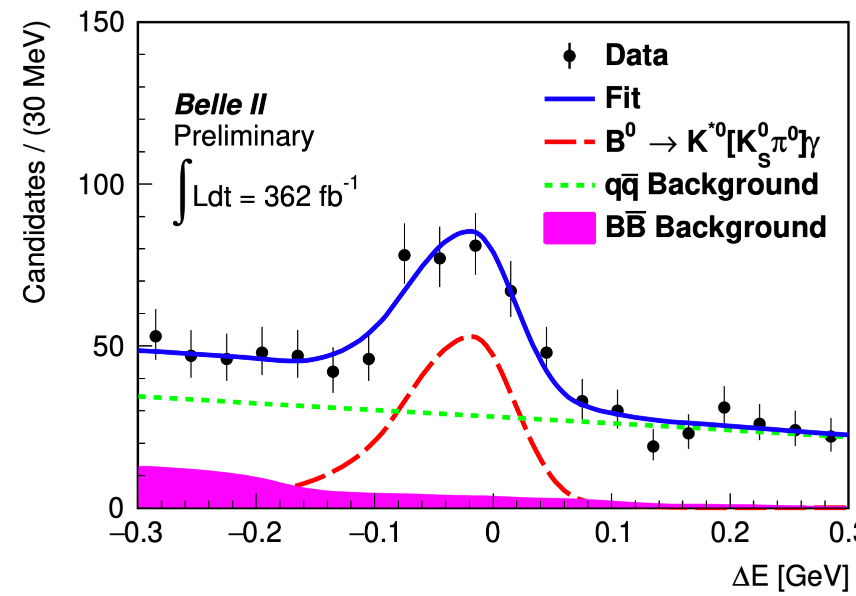


Measure $\mathscr{B}$, $\mathscr{A}_{CP}$ and isospin asymmetry

- 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 $\Delta_{0+} = [+6.2 \pm 1.5(\text{stat}) \pm 0.6(\text{syst}) \pm 1.2(f_{+-}/f_{00})]\%$,

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

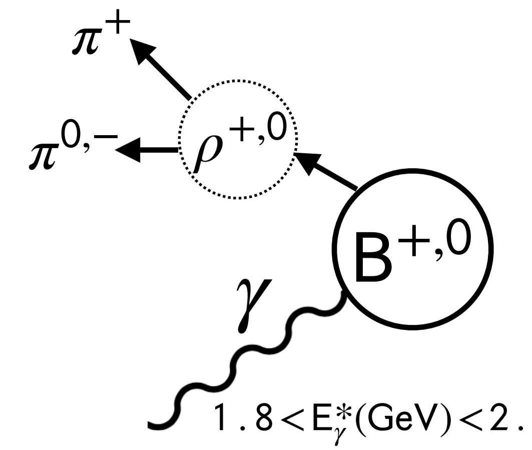
[1] 1411.3161
[2] PRD 88, 094004 (2013)

$B \to \rho\gamma$ MEASUREMENT

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

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

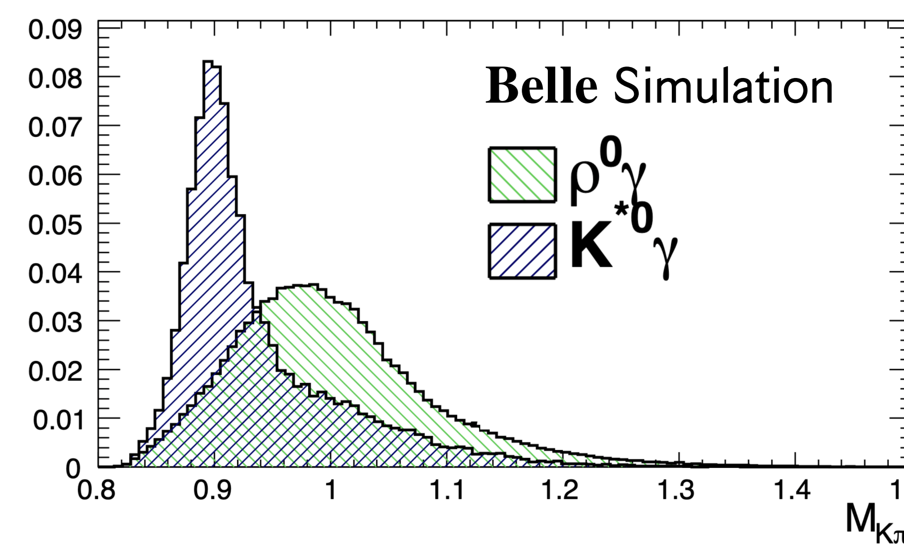
BELLE 711 fb^{-1} | Belle II 362 fb^{-1}



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

Sensitive to NP related to C_7
NP search independent from $b \to s$ counterpart
$\mathscr{A}_I$ WA shows a slight tension

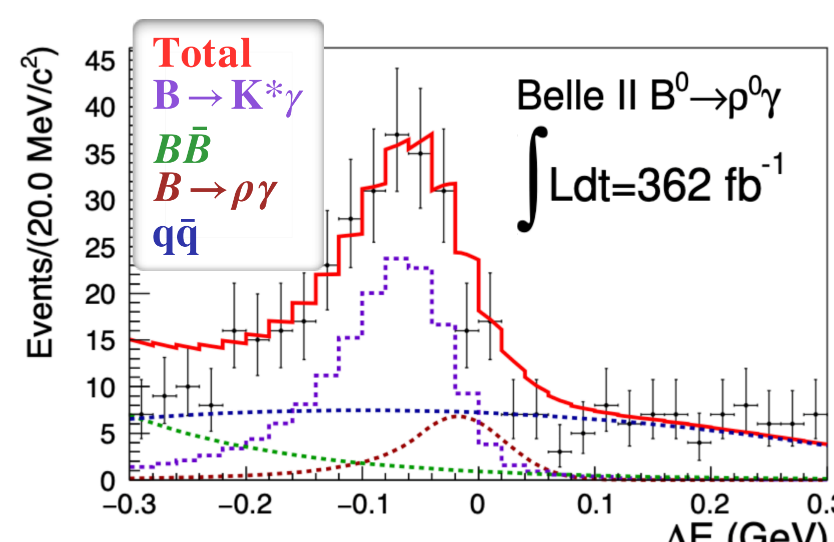
Challenge Low BF, large backgrounds from
- **Continuum events:** photon from largely asymmetric $\pi^0/\eta \to \gamma\gamma$ decays
  → 2 MVA classifiers, one for π^0/η veto, the other for generic $q\bar{q}$
- ***$B \to K^*\gamma$***: $K \to \pi$ misID and much larger BF $|V_{td}/V_{ts}|^2 \simeq 0.04$
  → $M(\pi^*\pi)$, 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	$0.75 \pm 0.13^{+0.10}_{-0.08}$
$\mathscr{A}_I$	$0.30^{+0.16}_{-0.13}$	$0.14^{+0.11}_{-0.12} \pm 0.09$
$\mathscr{A}_{CP}(B^+ \to \rho^+\gamma)$	-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)]



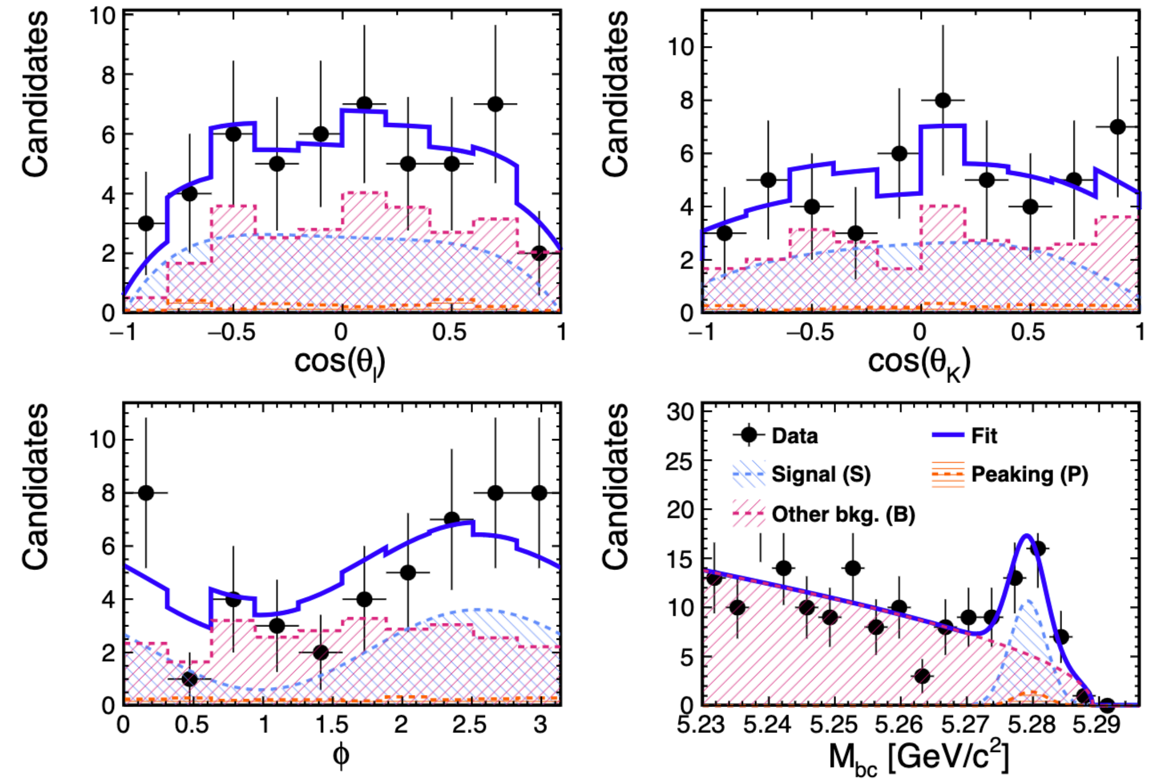
$B \to K^{(*)}\ell\ell$

BELLE $711\ fb^{-1}$

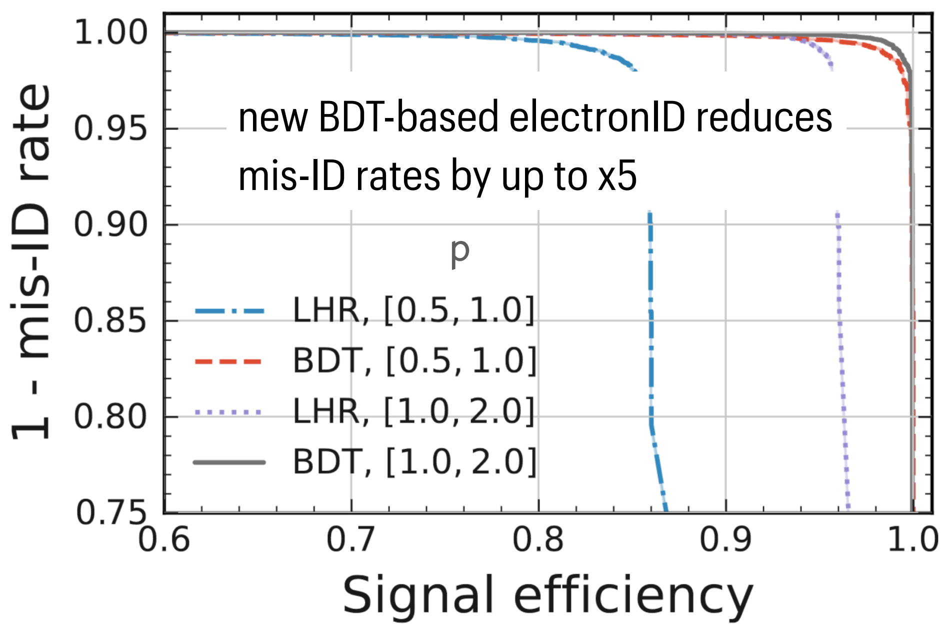
In the $K\ell\ell$ sector, Belle(II) can:

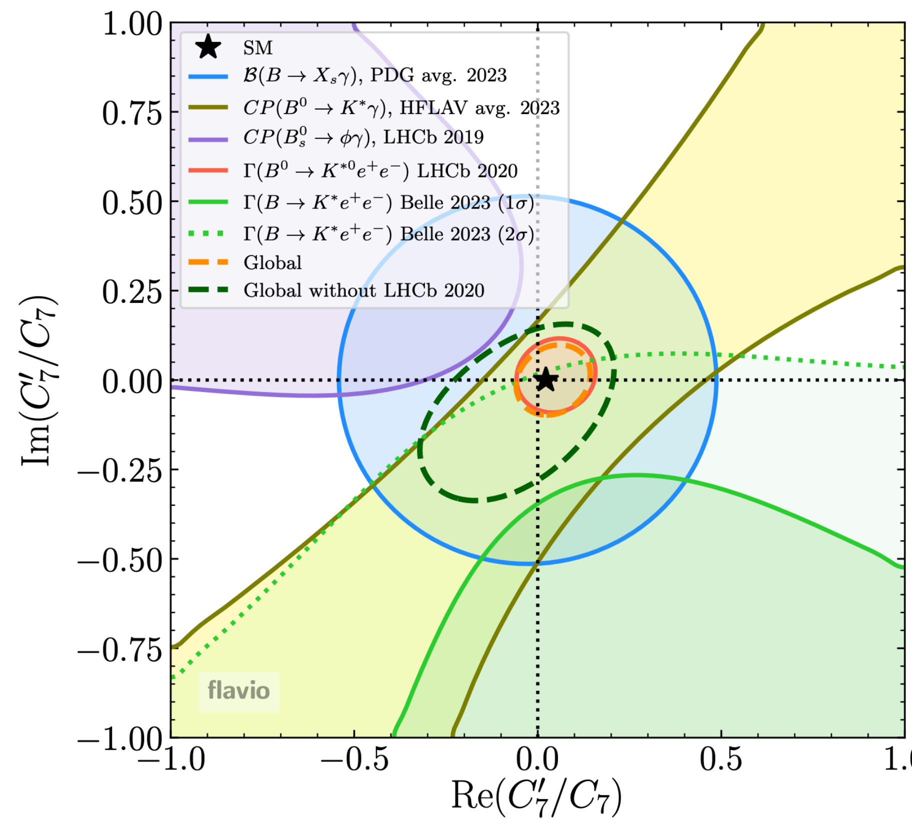
- Provide unique insight for
  Inclusive $\mathscr{B}(B \to X_s\ell\ell)$ - 10% accuracy @ 5 ab^{-1} expected
- Be redundant with LHCb for
  LFU test $R_{K^{(*)}}$ 1808.10567
  Independent measurement of $R_{K^{(*)}}$ at Belle II with 5-10 ab^{-1}
  3% precision at 50 ab^{-1}

$C_7^{(\prime)}$ constraints → $B \to K^*ee$ (low q^2) 2404.00201



$q^2 \in [0.0008, 1.1200]\ GeV^2/c^4$





The value of C_7' is

- in agreement with the SM within 2**σ** (this result only)
- consistent with the SM (combined without LHCb)

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

BELLE
711 fb^{-1}

Better sensitivity to NP than $b \to s\ell^+\ell^-$?

Previous results:

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

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

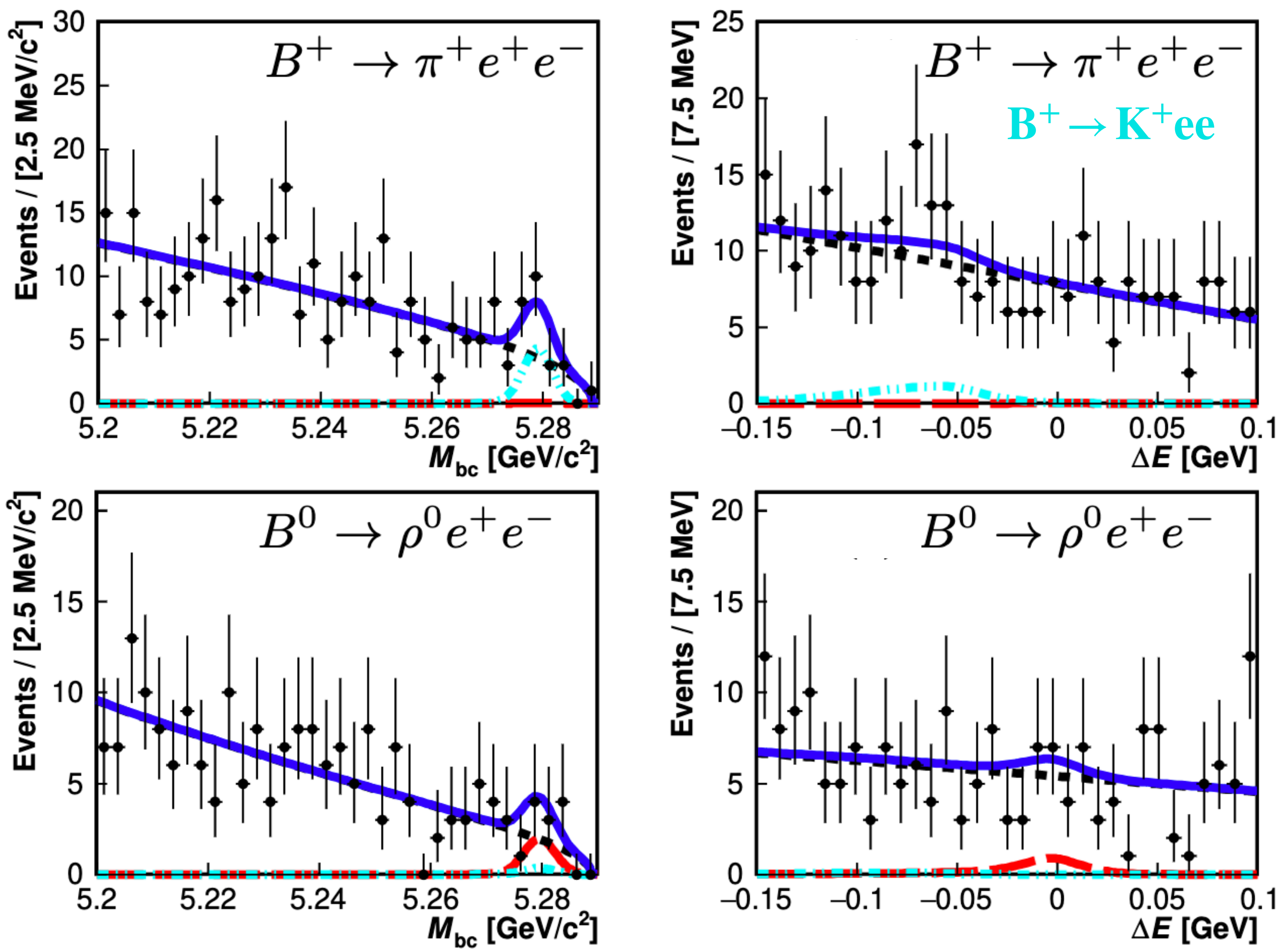
LHCb (3 fb^{-1}) observed $B^+ \to \pi^+ \mu^+ \mu^-$, $B^0 \to \pi^+ \pi^- \mu^+ \mu^-$ [JHEP 10 (2015) 034, PLB 743 (2015) 46-55]

Many unexplored modes with

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

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

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

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

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

Previous results:

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

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

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

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

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

First search for $B^0 \to \omega \ell^+ \ell^-$, $B^0 \to \rho^0 e^+ e^-$, $B^\pm \to \rho^\pm \ell^+ \ell^-$ ❀

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

No sign of LUV

Approaching SM

90% CL upper limits

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

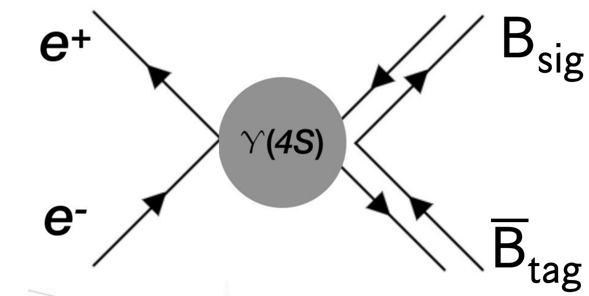
B → VISIBLE + MISSING ENERGY

CHALLENGES FOR MISSING-ENERGY MODES

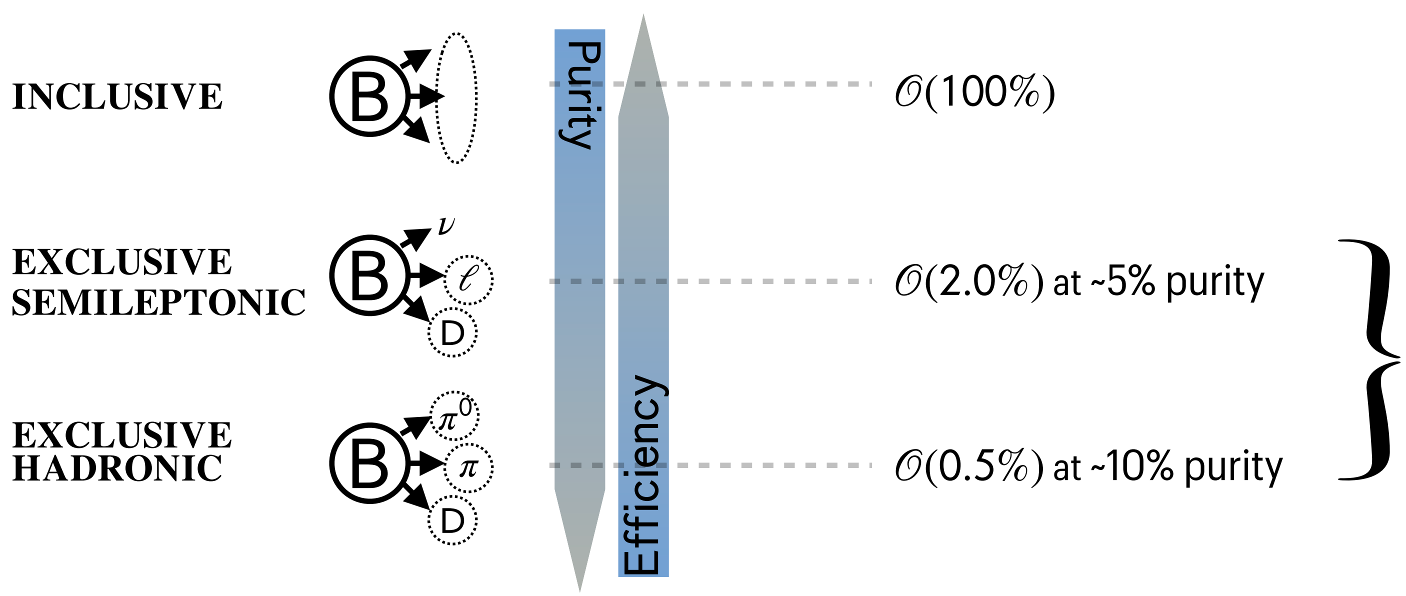
B-tagging

- The reconstruction of the B_{tag} allows to infer the properties of the signal-side with missing energy - $B_{sig} \to D\tau\nu$, $K\nu\bar{\nu}$... and to have a handle on backgrounds

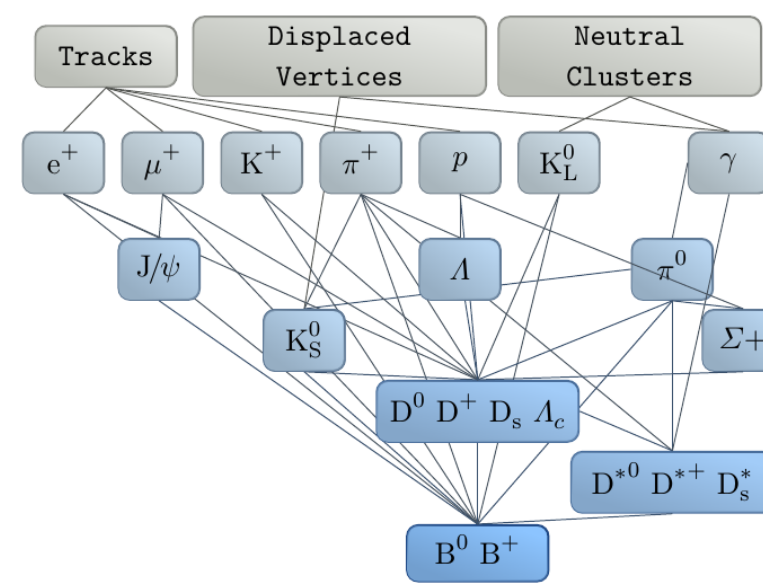
$$p_{e^+} + p_{e^-} = p_B + p_{\bar{B}}$$



Typical $B\bar{B}$ **events:**
10 tracks and ~10 photons



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



36 (32) hadronic B^+(B^0)-modes

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

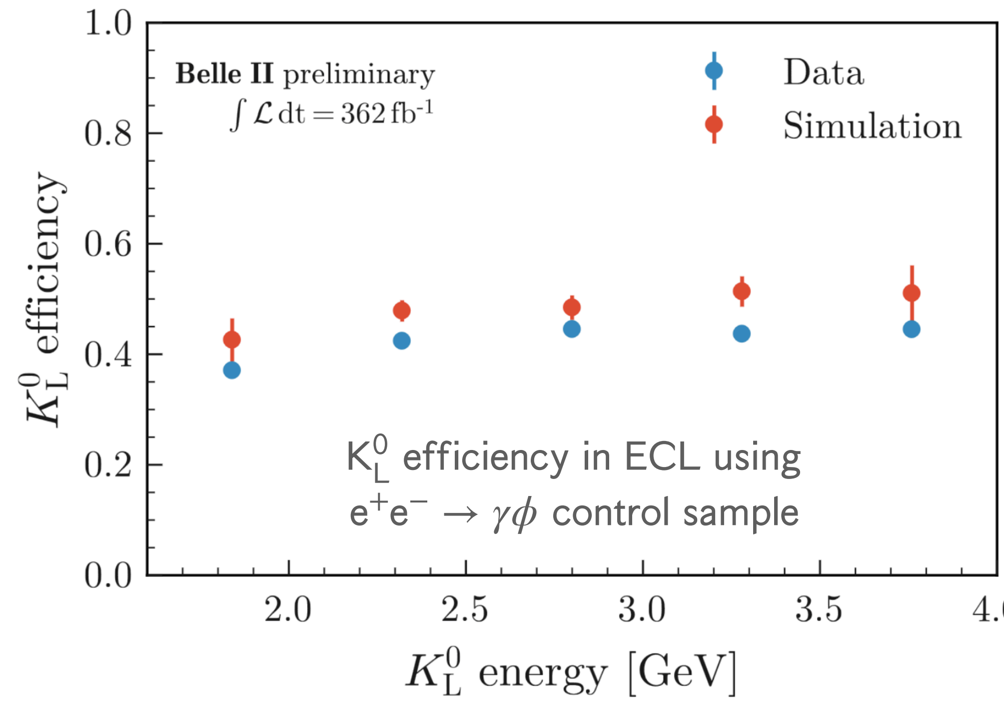
Large data/MC efficiency corrections
Hadronic B-tagging: pure but very low efficiency

[1] Comput Softw Big Sci 3, 6 (2019) [2] Nucl.Instrum.Meth.A 654 (2011) 432-440

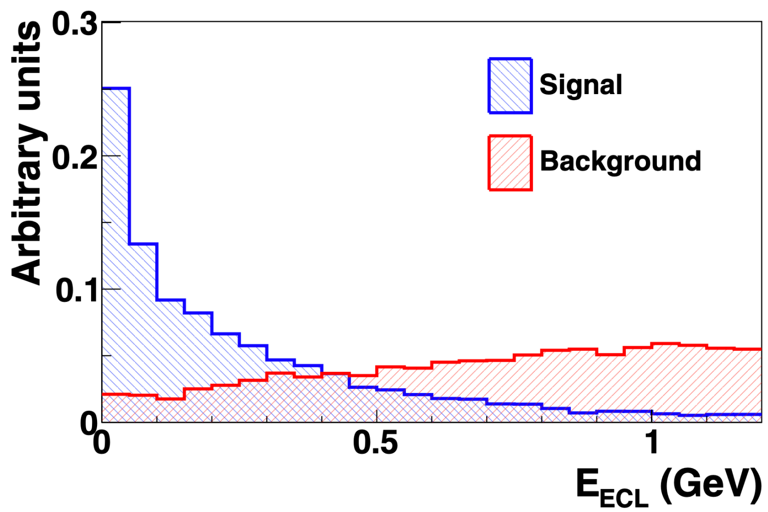
CHALLENGES FOR MISSING-ENERGY MODES

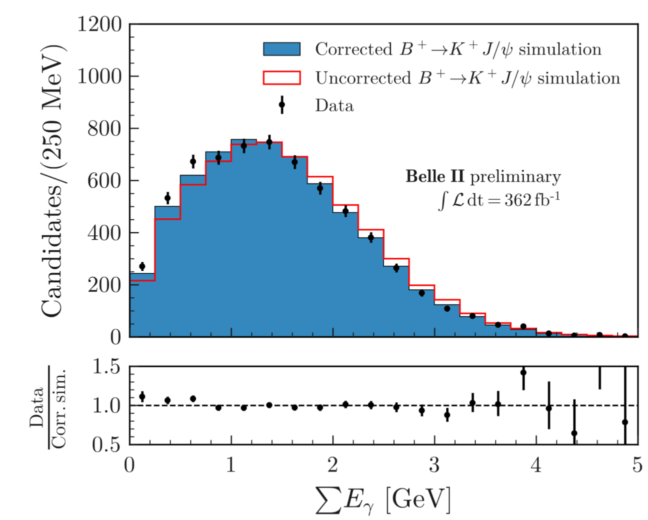
Neutrals reconstruction

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



E_{ECL}: Sum of the energy deposits in the calorimeter that cannot be directly associated with the reconstructed daughters of the B_{tag} or the B_{sig}





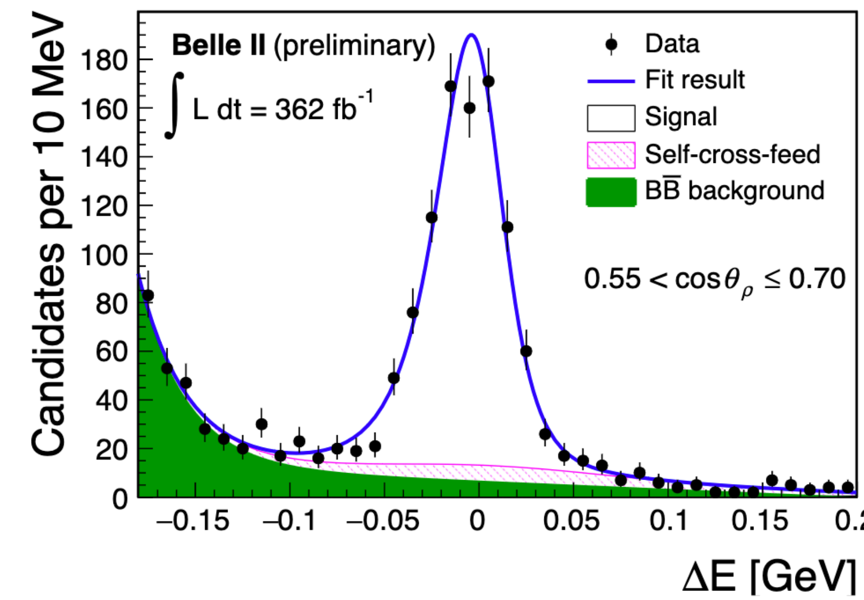
Hadronic showers or track's deposits mistakenly reconstructed as photons
Differences between data and MC

CHALLENGES FOR MISSING-ENERGY MODES

MC modelling

$q\bar{q}$ background validated on off-resonance data. **Corrections needed in**

- **Normalisation**
- **Shape ↦ event-by-event data-driven correction**
  [J. Phys.: Conf. Ser. 368 012028]



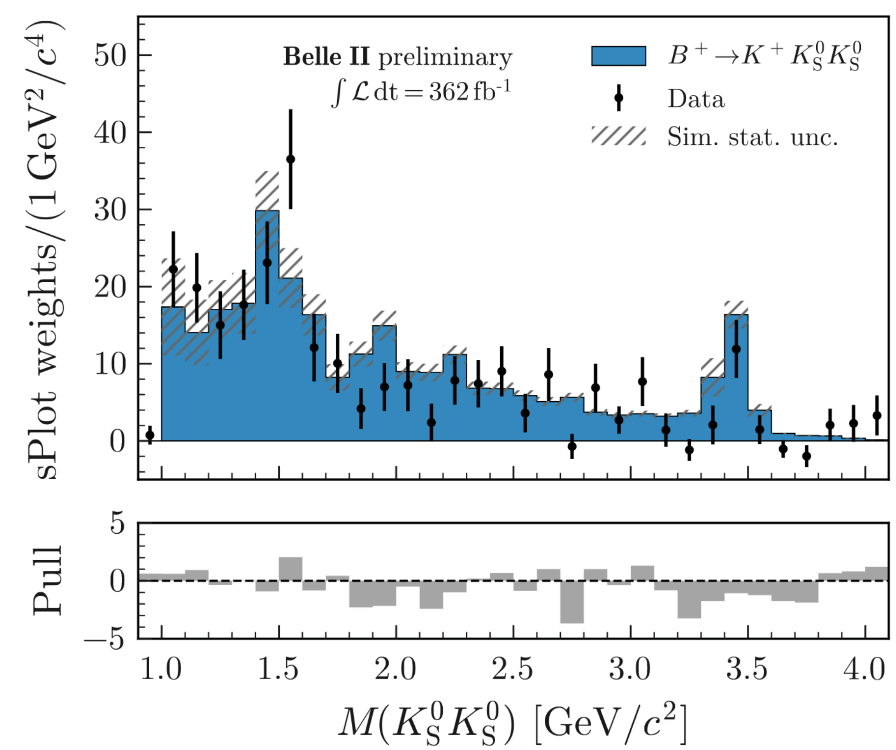
$B \to$ hadronic for B_{tag}

More precise measurements for better B-tagging

- $B \to D^{(*)} K^0_S K$ (Possible new mode for FEI) [2305.01321]
- $B^+ \to D^{(*)-} \pi^+ \pi^+ \pi^0$ (Ongoing at IJS)
- $B^- \to D^0 \rho^-$ **NEW** (FEI calibration factor was 0.75) [2404.10874]

$\mathscr{B}_{\text{PDG}} = (1.34 \pm 0.18)\,\%$

$\mathscr{B}_{\text{Belle II}} = (0.939 \pm 0.05)\,\%$



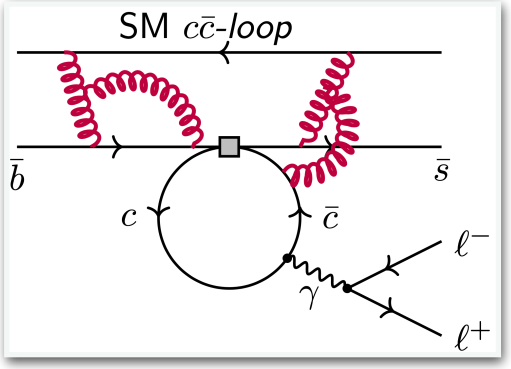
$B \to$ hadronic for B_{sig}

Measurements + isospin assumptions

Improved modelling of rare decays like $B \to K n\bar{n}$, $K K^0 K^0$
(not only BF but also decay model)

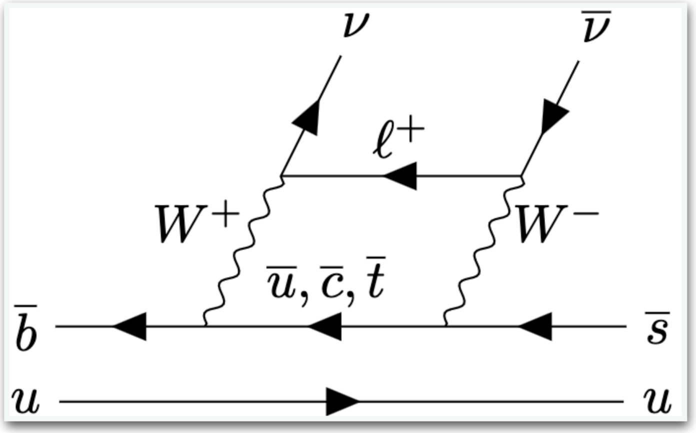
$B \to$ SL (for B_{sig}) ...

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



Precise SM prediction — no hadronic uncertainties for charm annihilation like in $B \to K^{(*)}\ell^+\ell^-$

$BF_{SM} = (5.6 \pm 0.4) \times 10^{-6}$ [PRD 107 014511 (2023)]



Short-distance contribution
(Long distance: 10% of the total BF)

NP in $b \to s\nu\bar{\nu}$ does not necessarily show up in $b \to s\ell^+\ell^-$ too
Interplay with other anomalies [2309.02246, 2401.10112, 2401.11552]

Axions: PRD 102, 015023 (2020)
ALPs: JHEP 04, 131 (2023)
Dark scalars: PRD 101, 095006 (2020)
Z′: PLB 821, 13607 (2021)
Leptoquarks PRD 98, 055003 (2018)

<u>Unique to experiments at e^+e^- machines</u>

Challenges

- Low BF
- 2 neutrinos in the final state + 3-body (no kinematic constraints)
- Large backgrounds

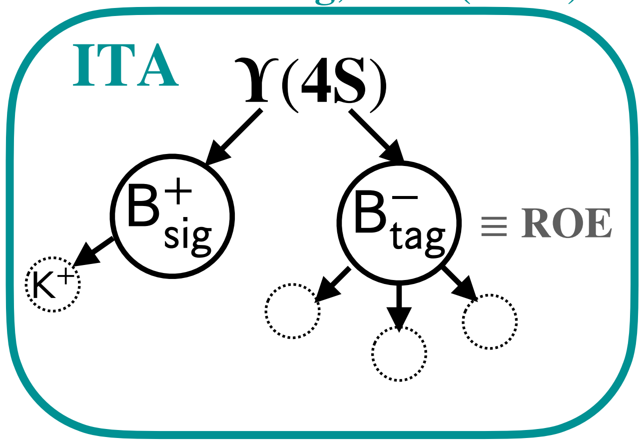
$B^+ \to K^+ \nu\bar{\nu}$ SEARCH WITH BELLE II

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

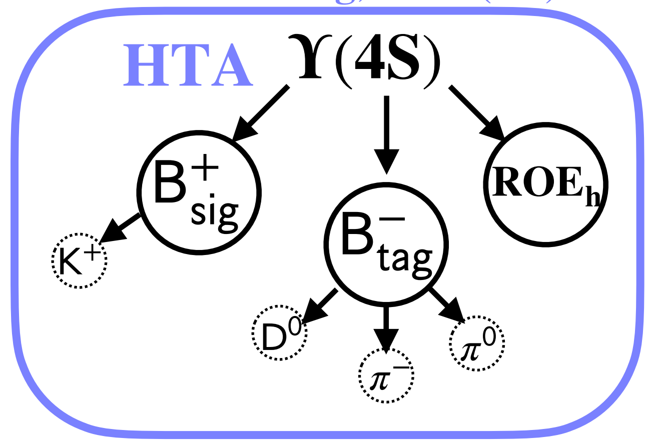
2311.14647 (Accepted PRD)

Two tagging approaches leading to almost statistically independent samples

Inclusive Tag, $\varepsilon = \mathcal{O}(100\%)$



Hadronic Tag, $\varepsilon = \mathcal{O}(1\%)$



ROE: Rest Of Event
(remaining charged and neutral particles)

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

- **Approach leading the final sensitivity**
- Two consecutive MVA classifiers
  basic filter (BDT_1)
  \+ main background suppression (BDT_2)
- Total efficiency ~8%, purity ~0.8%
- Fit to $q^2_{rec} \times \eta(BDT_2)$ simultaneously for ON and OFF resonance data

- **Less sensitive but well-established approach, used for consistency check**
- Single classifier BDT_h
- Total efficiency ~0.4%, purity ~3.5%
- Fit to $\eta(BDT_h)$ for ON resonance data

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

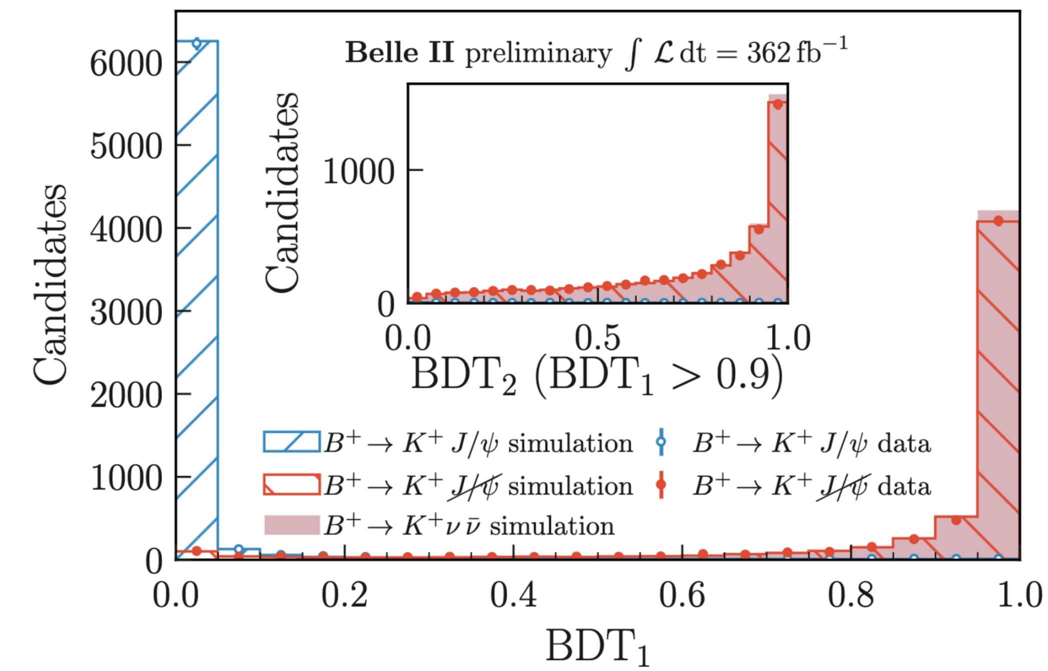
$BDT_{2,h}$: uses information of signal kaon, ROE and event topology

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

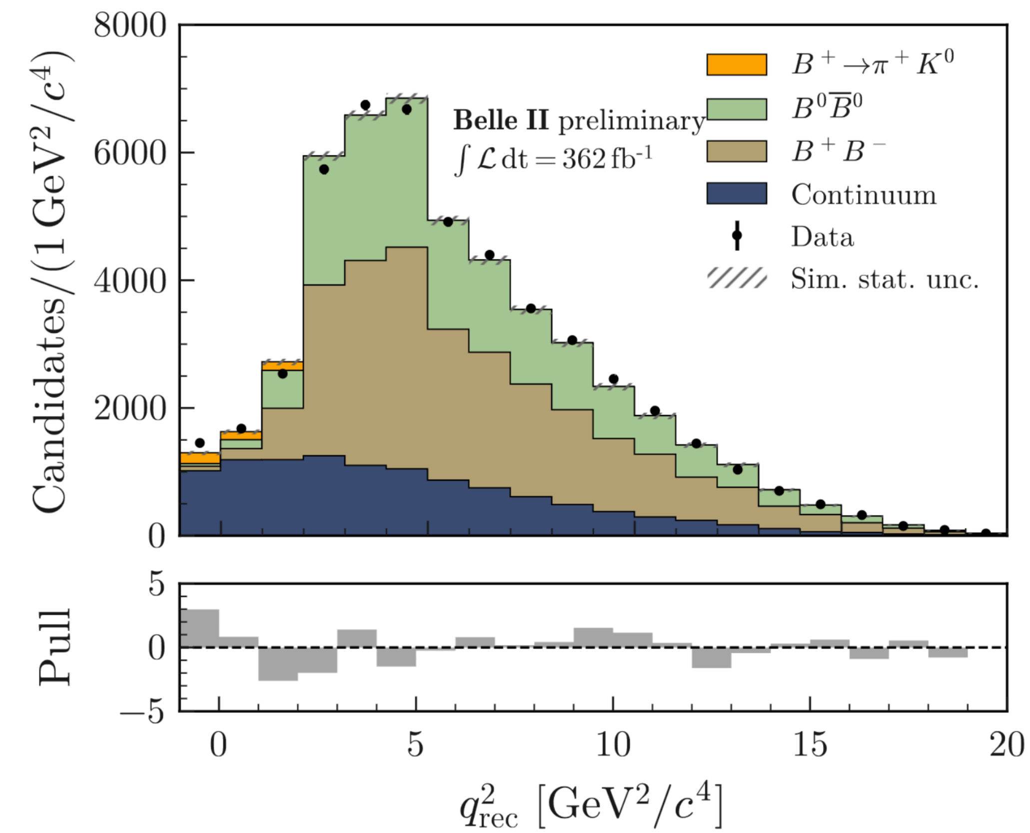
2311.14647 (Accepted PRD)

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 $B^+ \to K^+\nu\bar{\nu}$
- $\mathbf{B \to X_c(K^0_L X)K^+}$ **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
$\mathcal{B}(B^+ \to \pi^+ K^0) = (2.5 \pm 0.5) \times 10^{-5}$, consistent with PDG



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

$\mu = BF_{meas}/B_{SM,short\ dist} = BF_{meas}/(4.97\times10^{-6})$

ITA

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

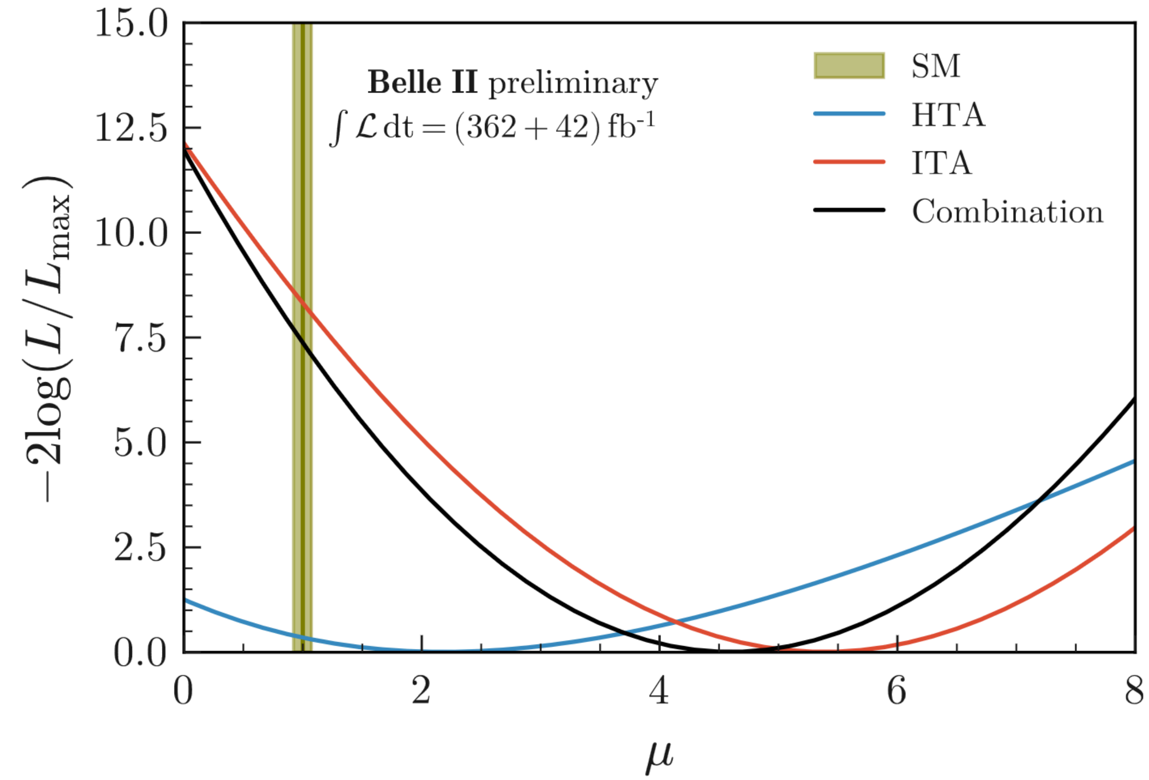
2.9σ deviation from SM exp

HTA

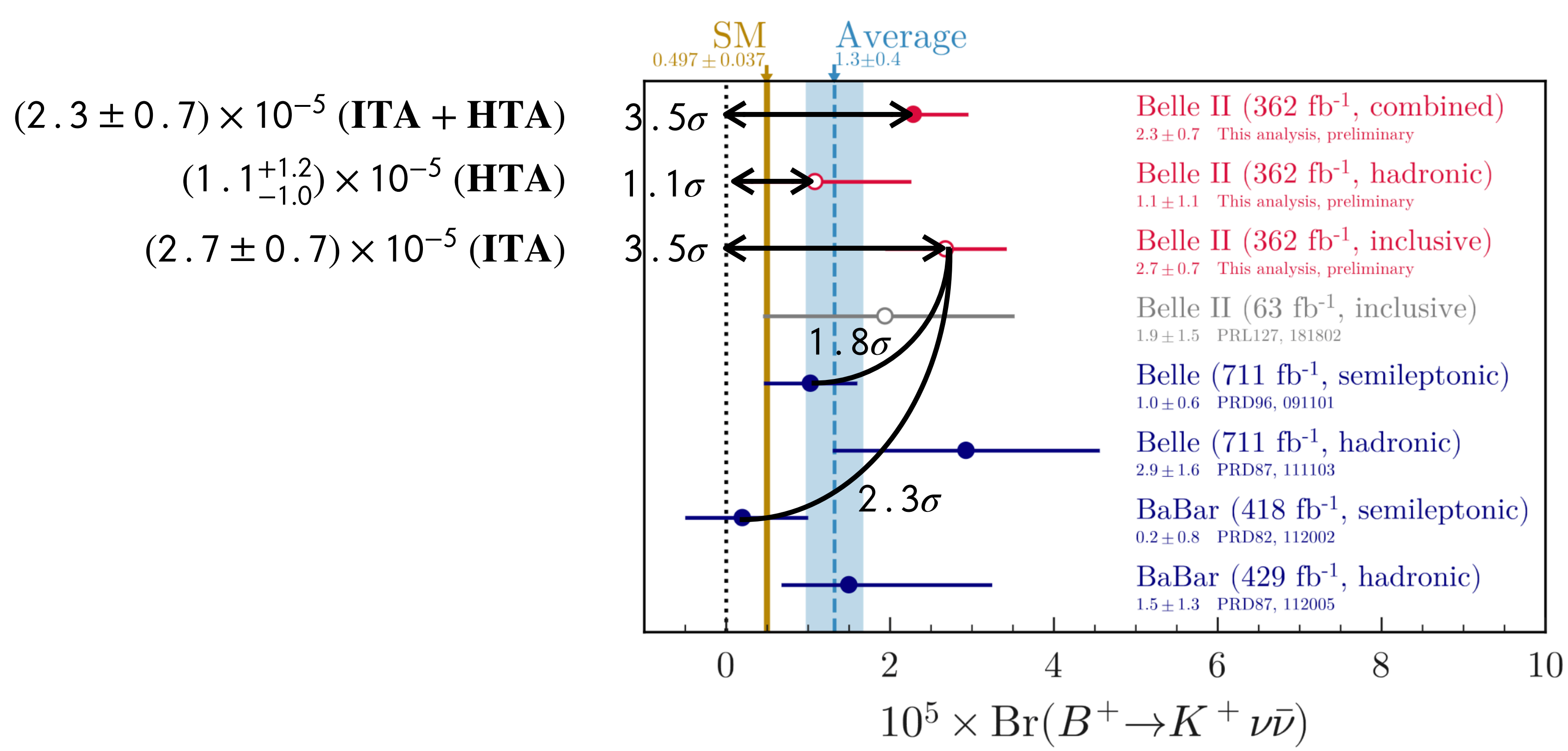
$\mu = 2.2^{+1.8}_{-1.7}(\text{stat})^{+1.6}_{-1.1}(\text{syst})$

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



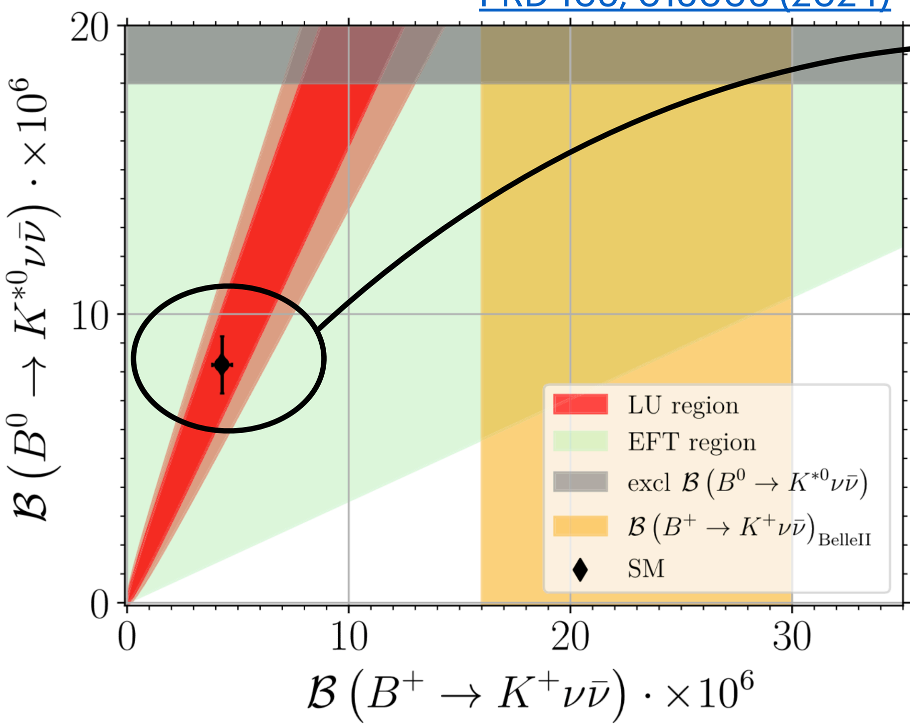
First evidence of $B^+ \to K^+\nu\bar{\nu}$

$3.5\,\sigma$ deviation from background-only hyp

$2.7\,\sigma$ deviation from SM exp

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

PRD 109, 015006 (2024)



B → K

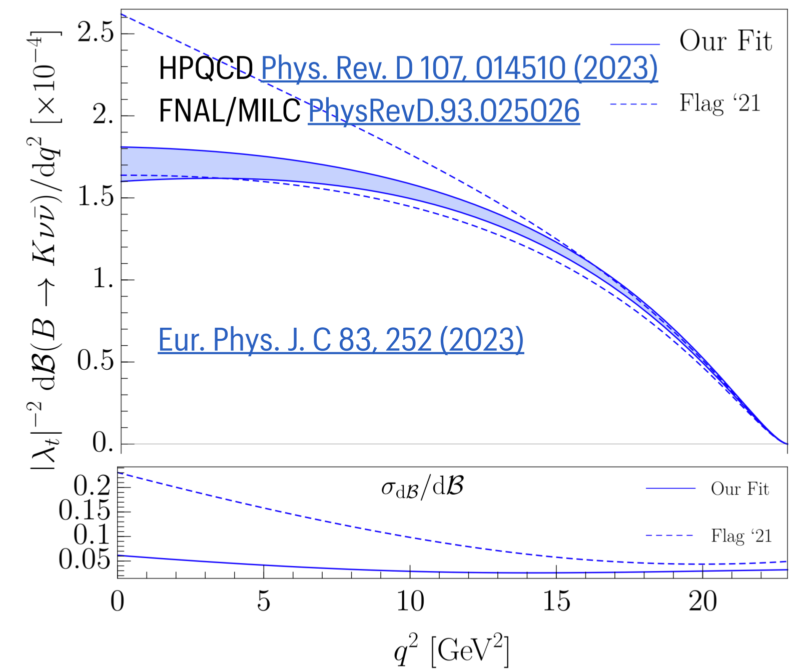
LQCD Phys. Rev. D 107, 014510 (2023)

LCSR JHEP 01 (2019) 150

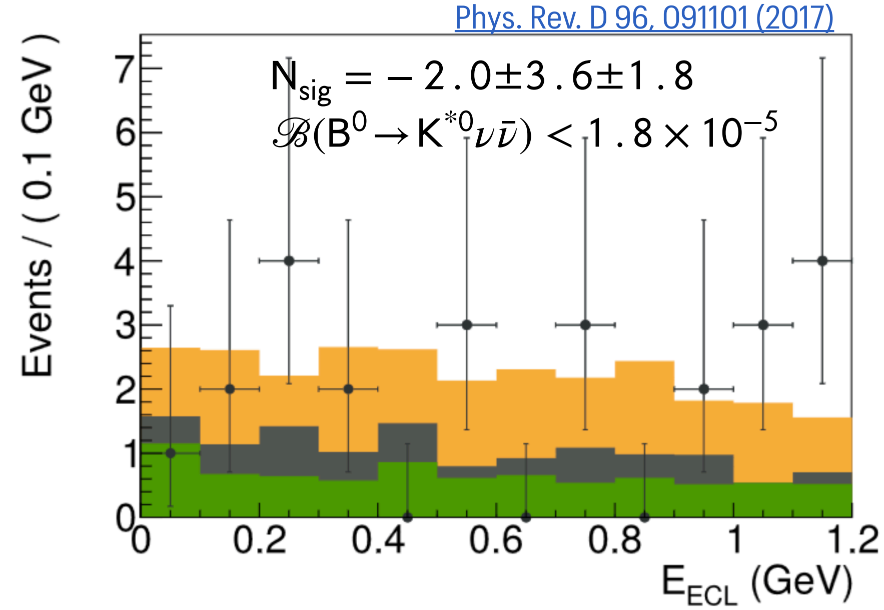
B → K* — less precise (15% vs 3% of K+)

LQCD 1501.00367

LCSR JHEP 01 (2019) 150

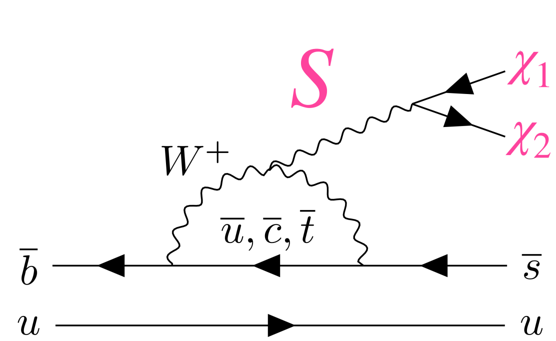


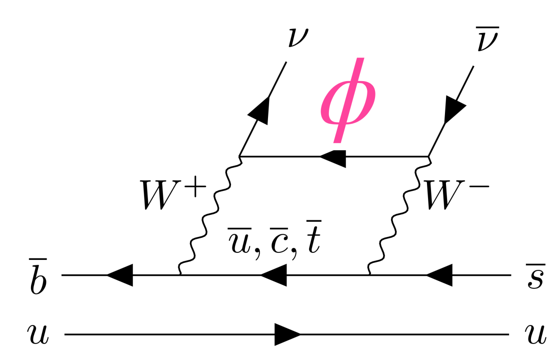
Phys. Rev. D 96, 091101 (2017)



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

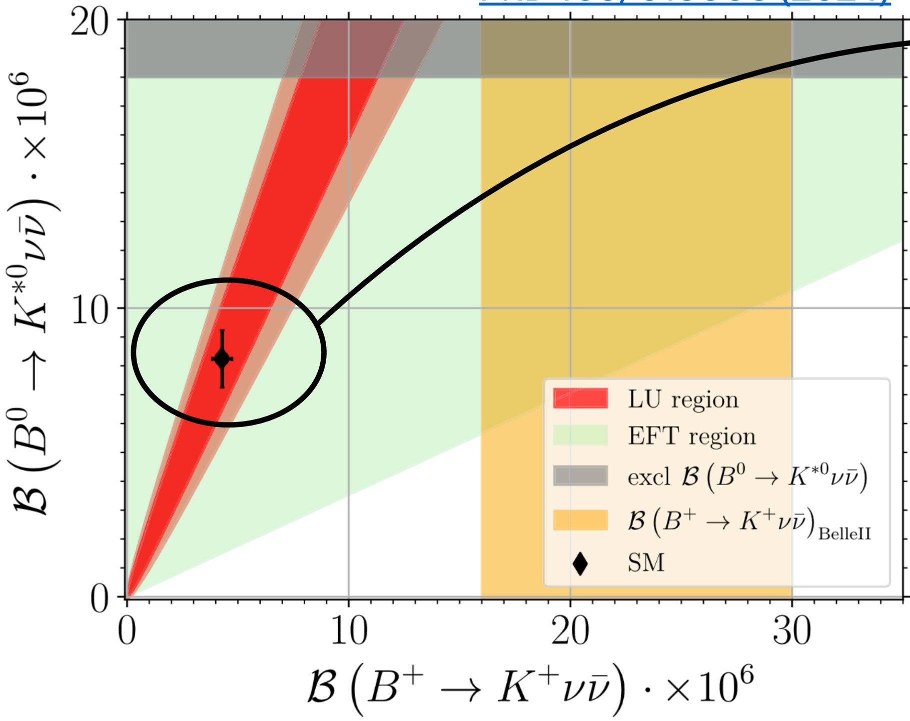
Lepton flavor universality is violated?
multi-TeV-scale?
light new physics?





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

PRD 109, 015006 (2024)



$B \to K$

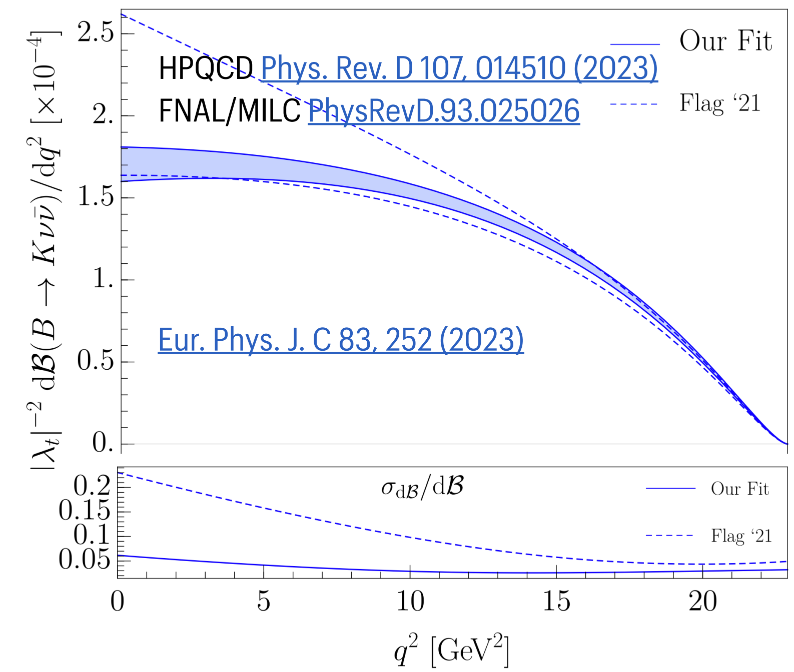
LQCD Phys. Rev. D 107, 014510 (2023)

LCSR JHEP 01 (2019) 150

$B \to K^*$ — less precise (15% vs 3% of K+)

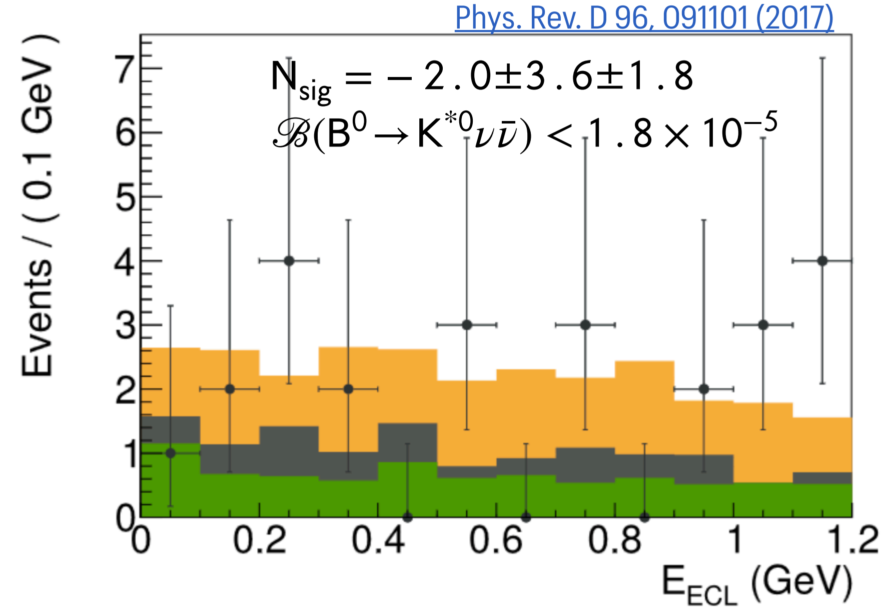
LQCD 1501.00367

LCSR JHEP 01 (2019) 150



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

Phys. Rev. D 96, 091101 (2017)



Lepton flavor universality is violated?

multi-TeV-scale?

light new physics?

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*)

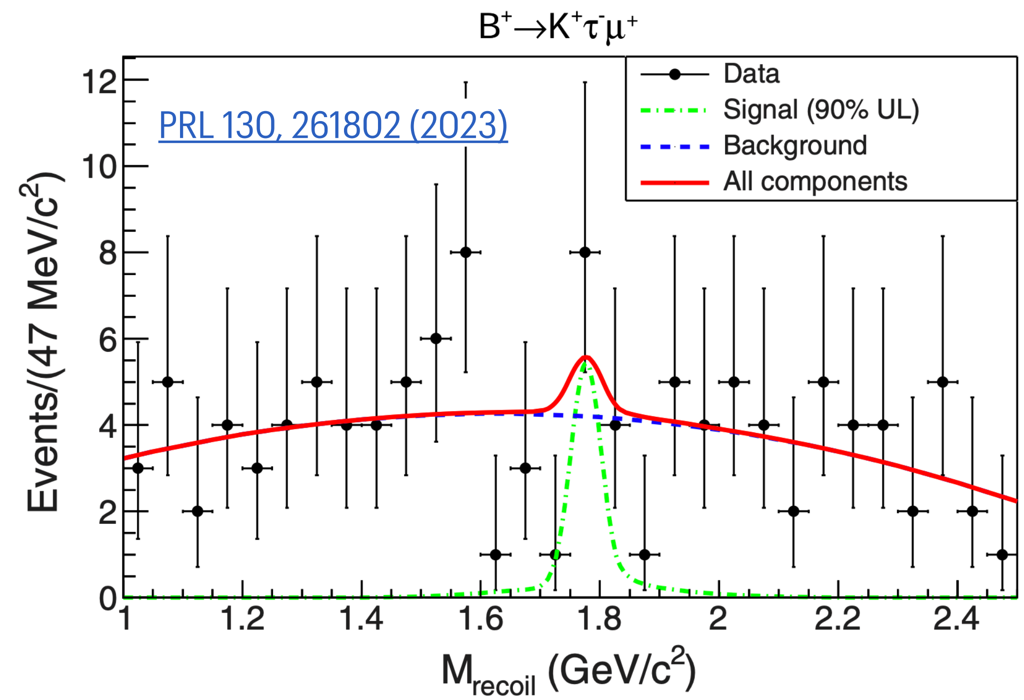
- **Additional tagging approaches**

(uncertainty SL~ITA)

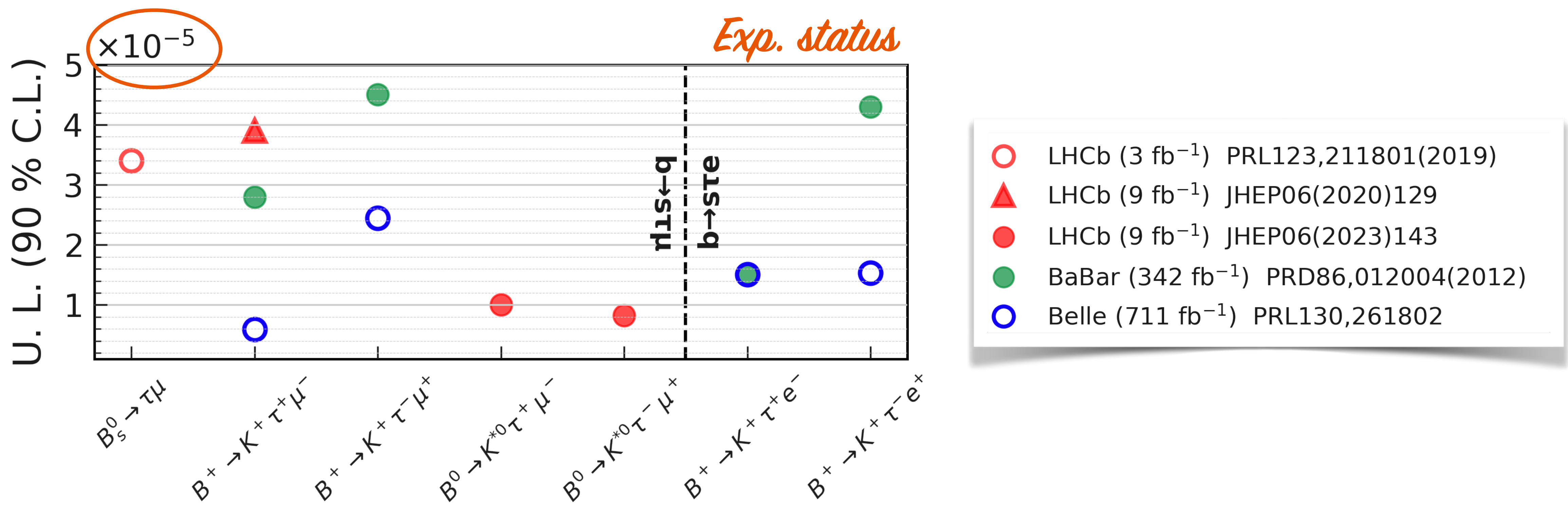
LFV SEARCHES WITH $B \to K\tau\ell$

- Forbidden in SM
- $b \to s\nu\bar{\nu}$: $K^+\nu\bar{\nu}$ observation + $K^*\nu\bar{\nu}$ UL compatible $\mathscr{B}(B \to K\mu\tau) \in [2, 3] \times 10^{-6}$ PLB 848, 138411 (2023)

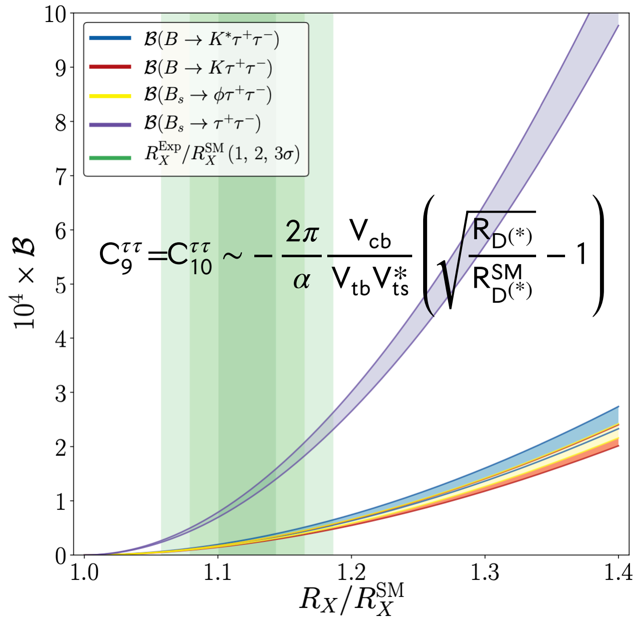
  - τ bump hunting in M_{recoil}
  - Current sensitivity has entered the 10^{-6} regime (LHCb and Belle-ONLY!)
  - Further modes are being explored



$$M_{recoil} = \left[m_B^2 + m_{K\ell}^2 - 2\left(E_B^* E_{K\ell}^* + |\vec{p}_B^*||\vec{p}_{K\ell}^*|\cos\theta\right)\right]^{0.5}$$



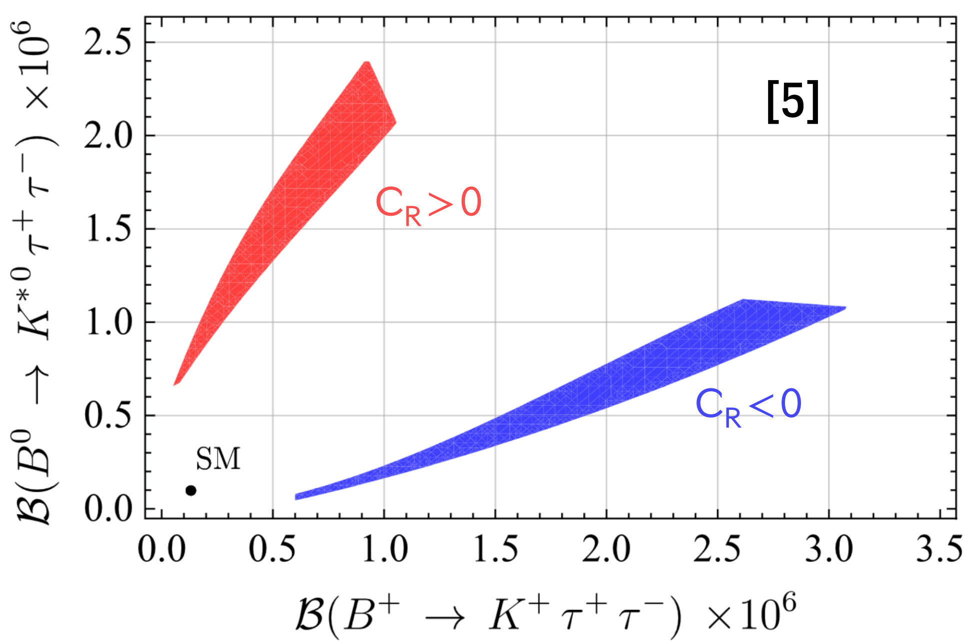
MOTIVATION FOR $b \to s\tau\tau$ SEARCHES

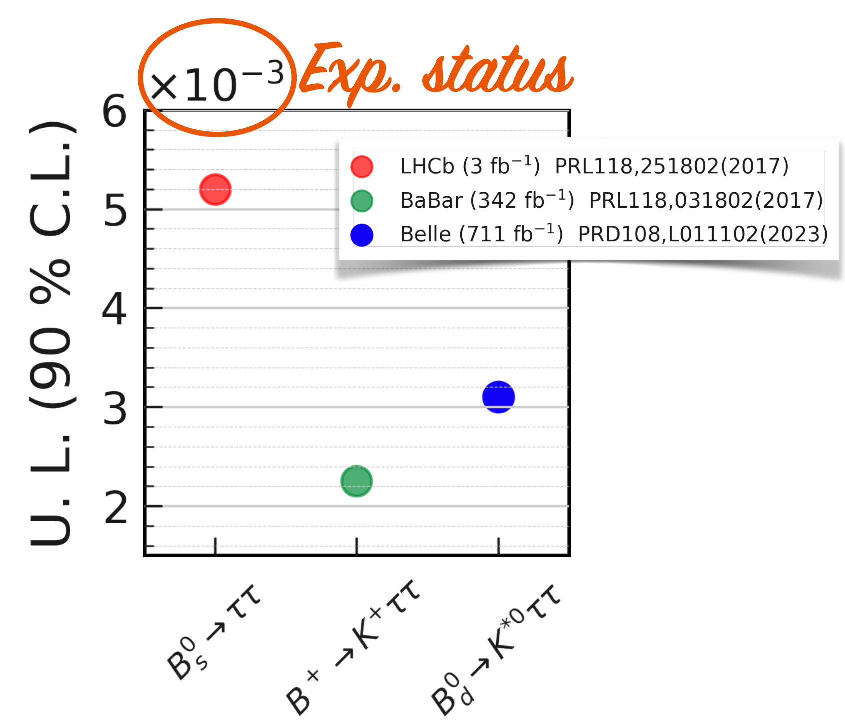


- $\mathcal{B}_{SM} \sim \mathcal{O}(10^{-7})$ [1]
- Correlation with $R_{D^{(*)}}$ [2] → Large enhancements to SM BF $\mathcal{O}(10^2 - 10^3)$ [3]
- Recent $B^+ \to K^+\nu\bar{\nu}$ excess, combined with R_{K*} constraints, suggest LUV in τ's [4,5]

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

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

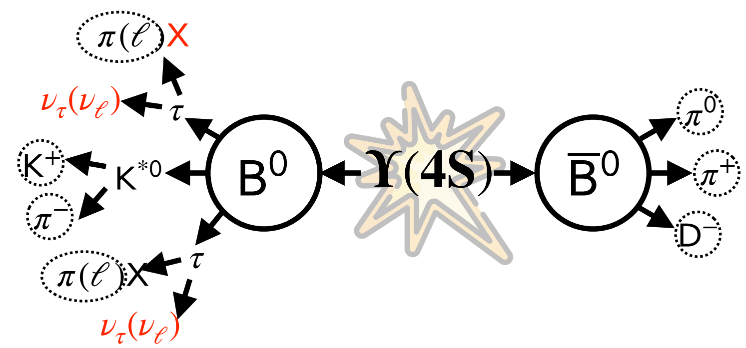


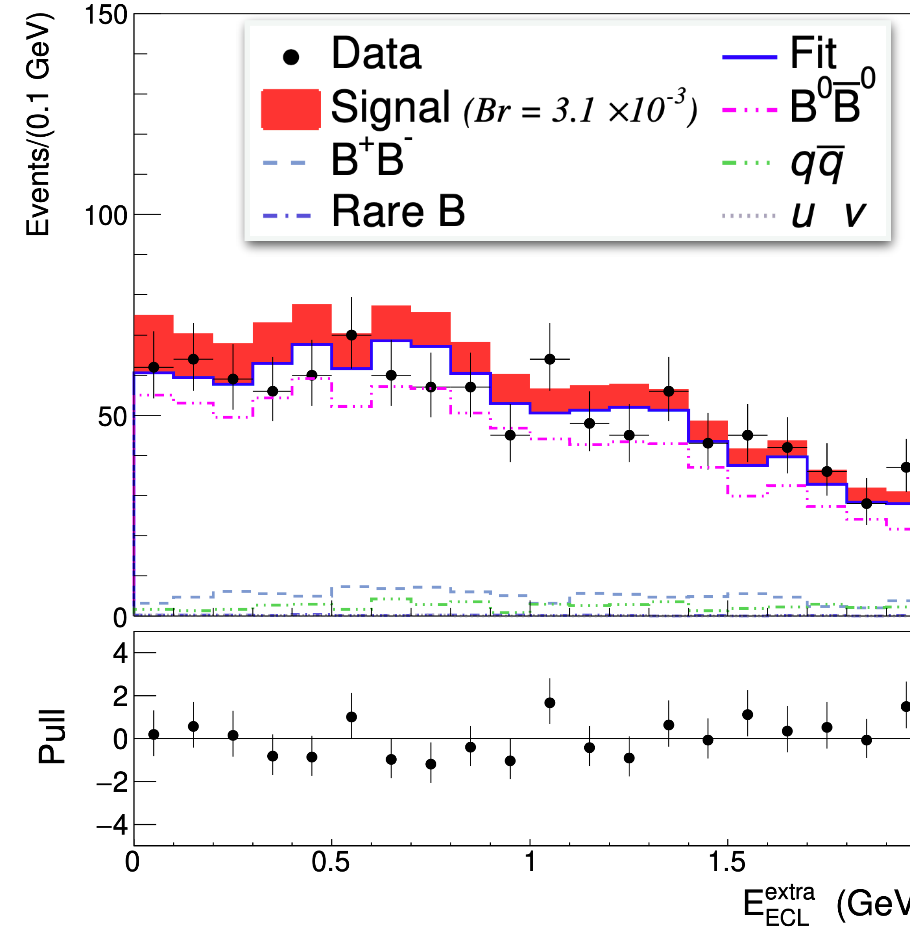


Many unexplored modes, unique opportunity for Belle II

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

$B \to K\tau\tau$ AT BELLE II: THE CHALLENGE



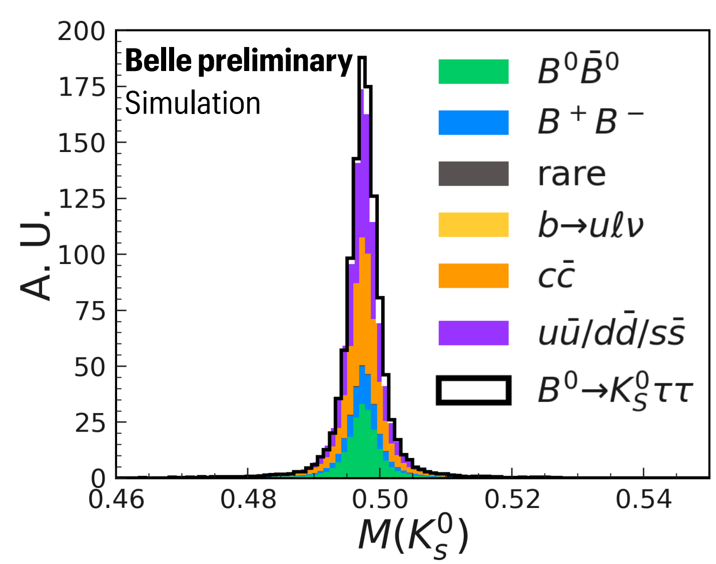


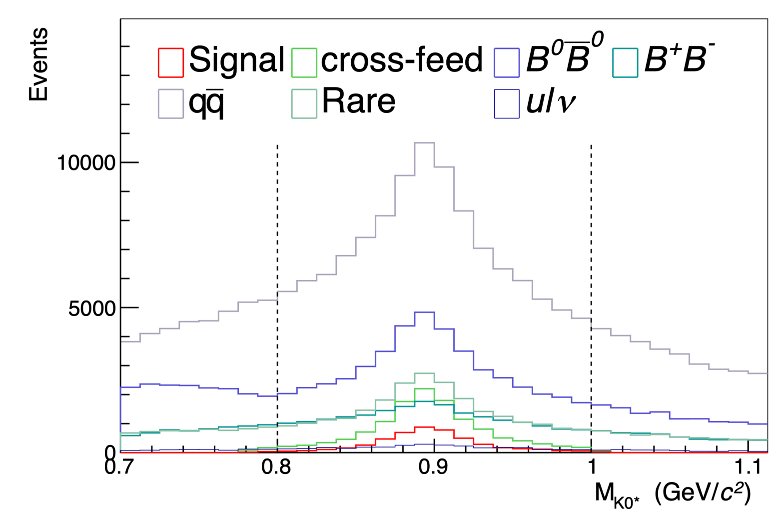
Search at Belle

- Hadronic B-tagging Belle algorithm (Neurobayes FR)
- $\tau \to \ell\nu\bar{\nu}, \pi\nu$ modes considered
- Cut&count analysis
- $\mathscr{B}(B^0 \to K^{*0}\tau\tau) < 3.1 \times 10^{-3}$ (90 % CL)

Improvements at Belle II

- **~2x hadronic B-tagging efficiency** FR → FEI
- **Multivariate analysis**
- **Add $\tau \to \rho\nu$ modes** $\mathscr{B}(\tau \to \rho\nu) \sim 25\,\%$





At IJS: Search for $B^0 \to K^0_S\tau\tau$ decays (never searched for)

Compared to K^{*0} narrower resonance and cleaner signature but even lower efficiency

CONCLUSION

Belle (II) producing world-leading results in rare B decays

Best precision

$B \to \rho\gamma$

First Belle II(+ Belle) measurement of b → d. Most precise on B → $\rho\gamma$ parameters

Best UL

$B \to \gamma\gamma$

$b \to d\ell^+\ell^-$

Approaching $\mathscr{B}_{\mathrm{SM}}$

First observation

$B^+ \to K^+\nu\nu$

Tension wrt SM at 2.7σ for the combined (inclusive+hadronic) result

OUTLOOK

Belle (II) producing world-leading results in rare B decays

Best precision

$B \to \rho\gamma$ — First Belle II(+ Belle) measurement of b → d. Most precise on $B \to \rho\gamma$ parameters

Best UL

$B \to \gamma\gamma$

$b \to d\ell^+\ell^-$

Approaching $\mathscr{B}_{SM}$ — More data needed

First observation

$B^+ \to K^+\nu\nu$ — Tension wrt SM at 2.7σ for the combined (inclusive+hadronic) result

Thank you for your attention

me!

$B \to K^*\gamma$ | $B \to K\tau\ell$ | $B \to K_S^0\nu\nu$ | $B \to K\tau\tau$ | $B \to K\ell\ell$ | $B \to K^{*0}\nu\nu$