Electroweak and radiative penguin B meson decays at Belle and Belle II

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on behalf of the
Belle & Belle II collaborations

LAKE LOUISE WINTER INSTITUTE
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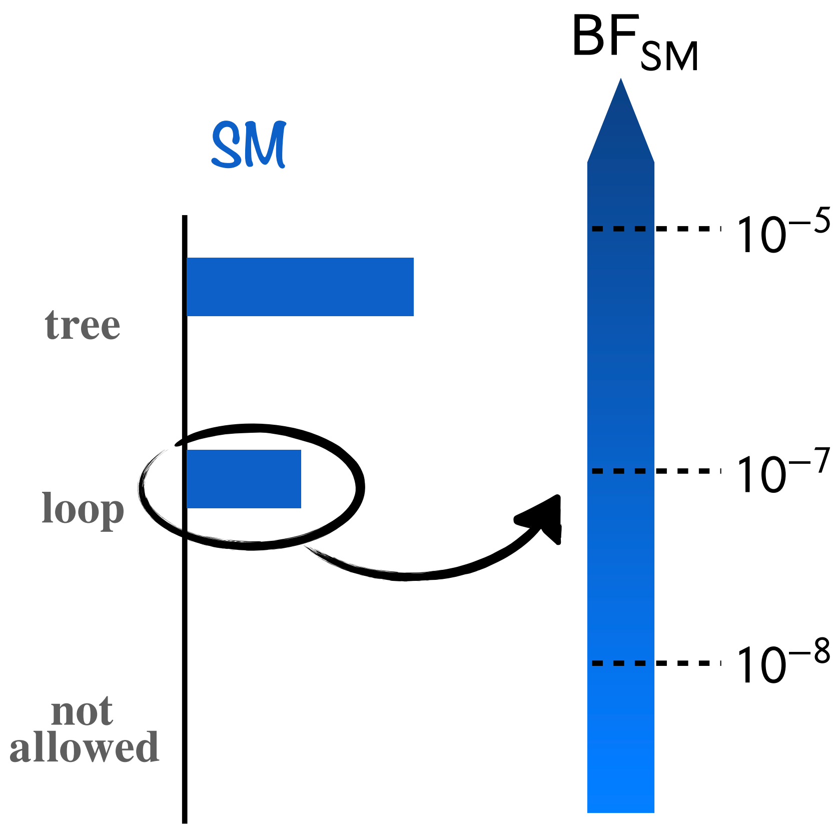
RARE B DECAYS

$$\mathscr{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V^*_{td(s)} \sum_i C_i^{(\prime)} \mathcal{O}_i$$

Effective coupling: $C_i^{(\prime)}$ — Local operator: $\mathcal{O}_i$

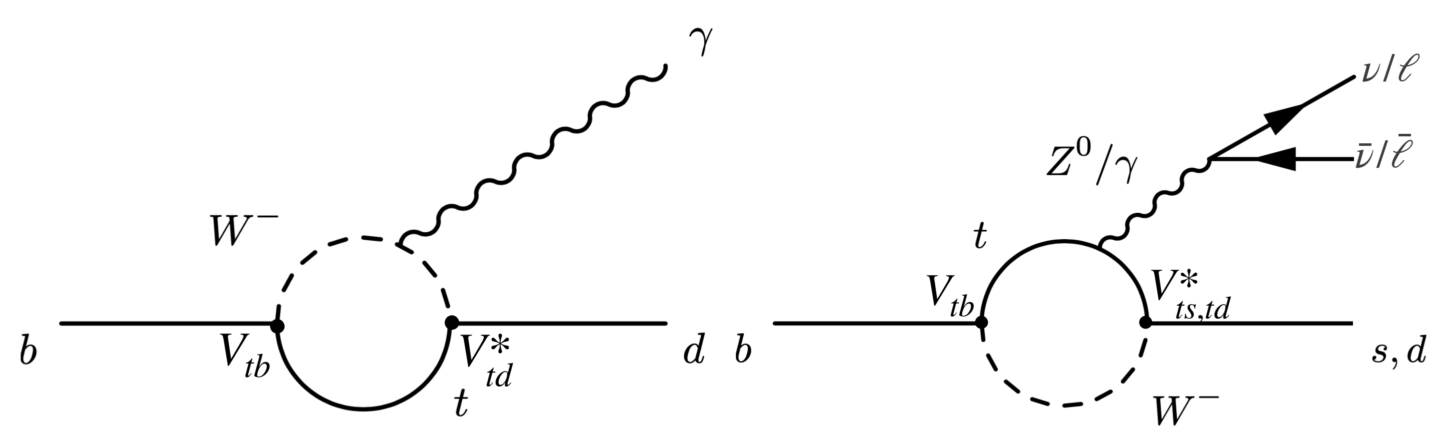


$b \to s\nu\bar{\nu}$
$B^+ \to K^+\nu\bar{\nu}$ — **First observation** — $C_L^{\nu_i\nu_j}$

$b \to d\gamma$
$B \to \rho\gamma$ — C_7

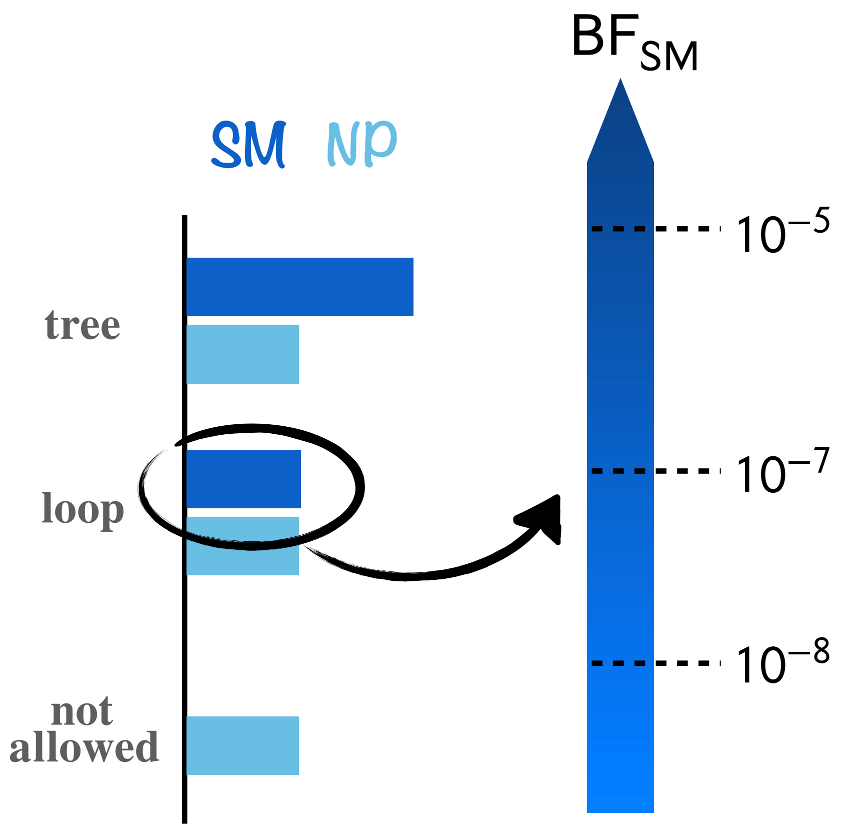
$b \to d\ell^+\ell^-$
$B \to \{\pi, \rho, \eta, \omega\}\ell^+\ell^-$ — **New!** — C_9^ℓ C_{10}^ℓ

Flavor changing neutral currents **FCNC** $b \to s/d$
- They occur at **loop level** in the **SM**
- **Low BF's** due to CKM and GIM suppression



RARE B DECAYS

$$\mathscr{L}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V^*_{td(s)} \sum_i C_i^{(\prime)} \mathcal{O}_i + \sum_{i=1}^{n_d} \frac{1}{\Lambda^{d-4}} C_i^{(d)} \mathcal{O}_i^{(d)}$$



$b \to s\nu\bar{\nu}$
$B^+ \to K^+\nu\bar{\nu}$ **First observation** $C_L^{\nu_i\nu_j}$ $C_R^{\nu_i\nu_j}$

$b \to d\gamma$
$B \to \rho\gamma$ $C_7^{(\prime)}$

$b \to d\ell^+\ell^-$
$B \to \{\pi, \rho, \eta, \omega\}\ell^+\ell^-$ **New!** $C_9^{(\prime)\ell}$ $C_{10}^{(\prime)\ell}$

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

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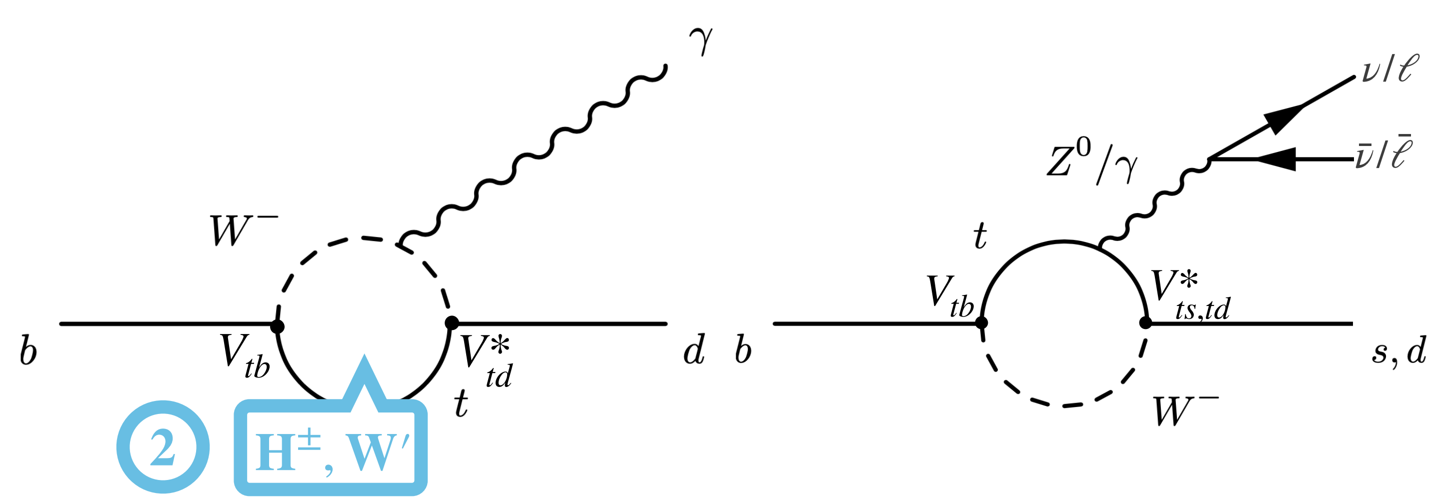
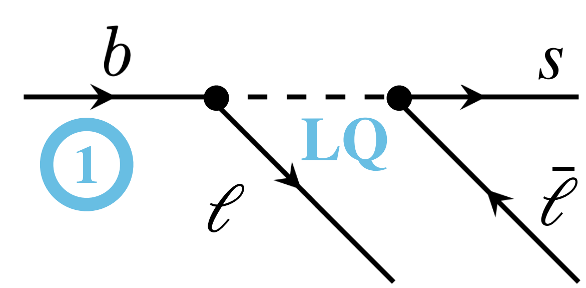
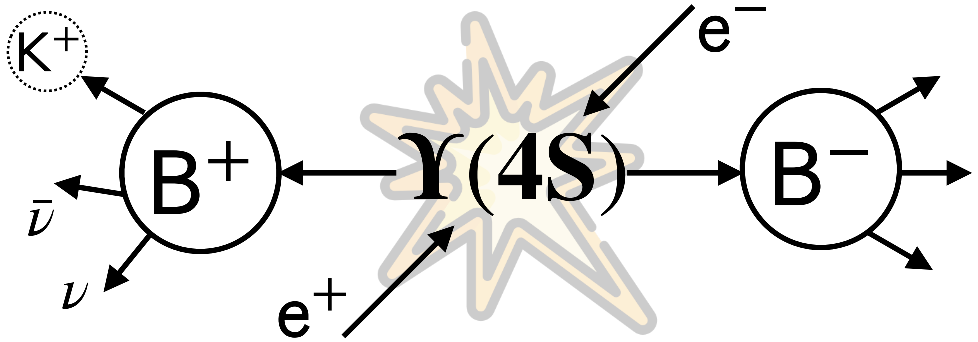


Look for alterations/enhancements in FCNC due to NP contributions

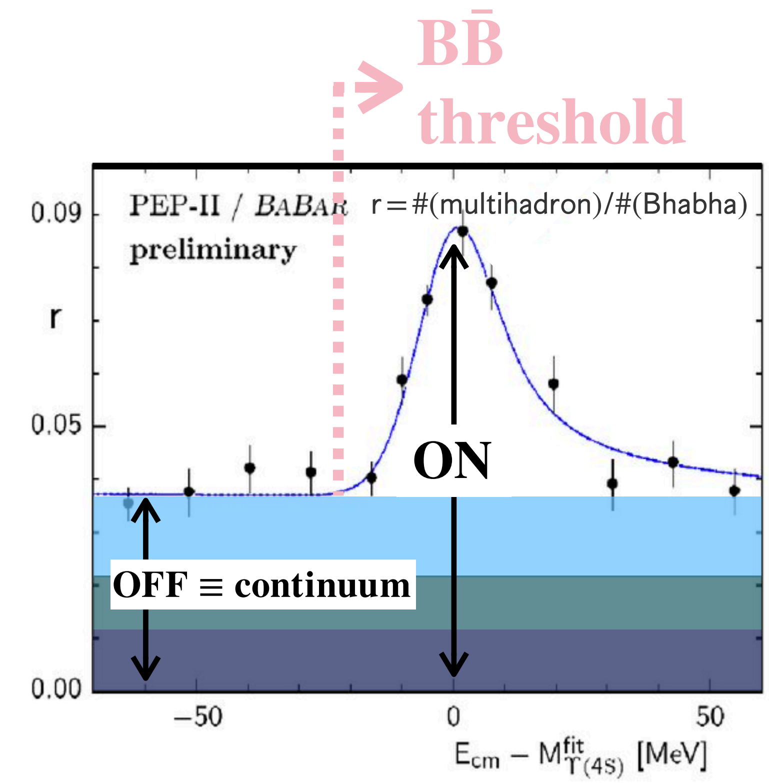
- New interactions at tree level (1)
- Weaker GIM cancellations due to new particles in loop corrections (2)

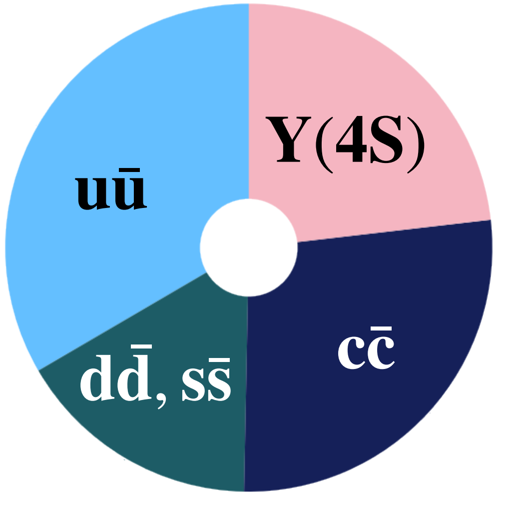


PENGUINS AT BELLE&BELLE II



- 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





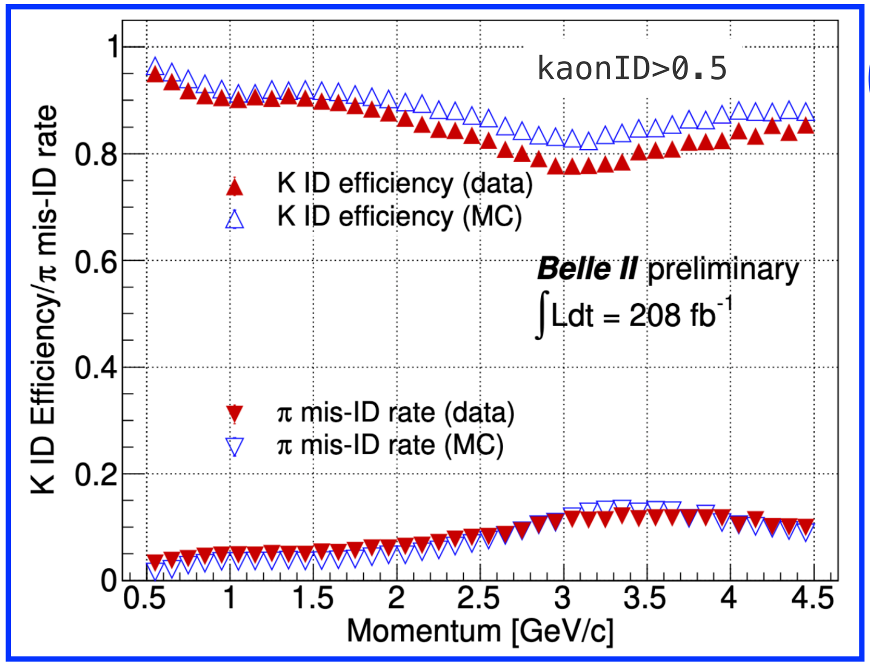
Hadronic cross-section
@ $\sqrt{s} = 10.58$ GeV

Today's results are based on the datasets

	ON	OFF
Belle	711 fb^{-1}	90 fb^{-1}
Belle II	362 fb^{-1}	42 fb^{-1}

KEY-PERFORMANCES AT BELLE II

Belle II TDR, arXiv: 1011.0352

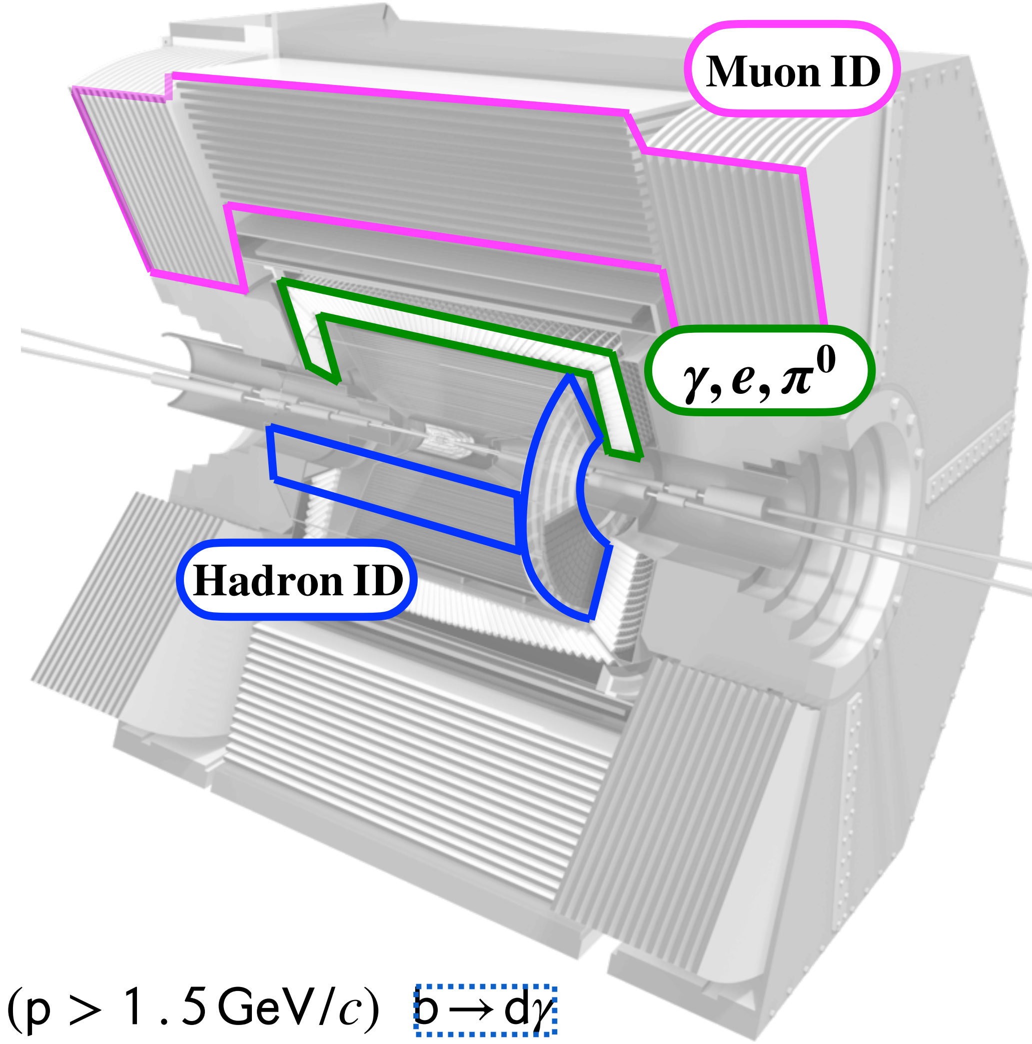


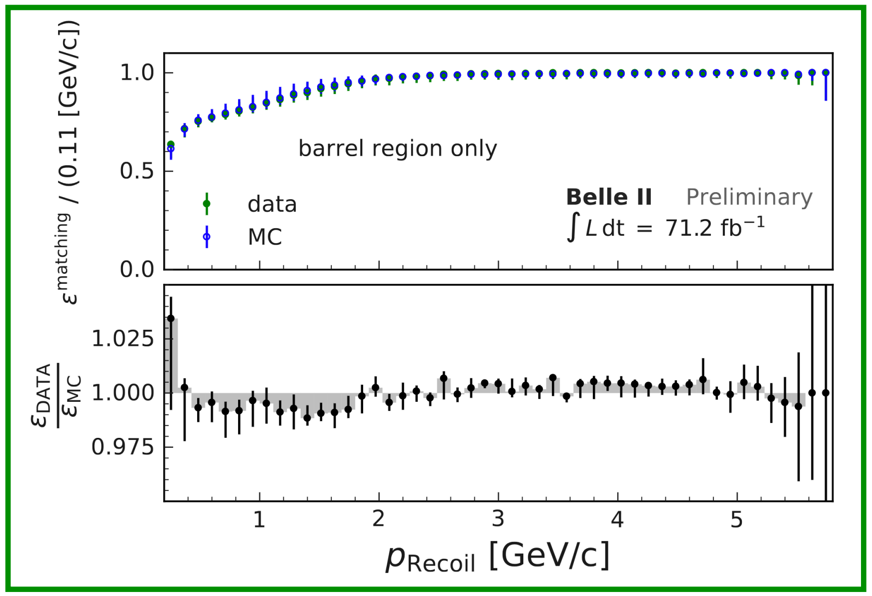
K ID

$\varepsilon \sim 90\,\%$ $b \to s\nu\bar{\nu}$

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

Good kaon identification in full momentum range

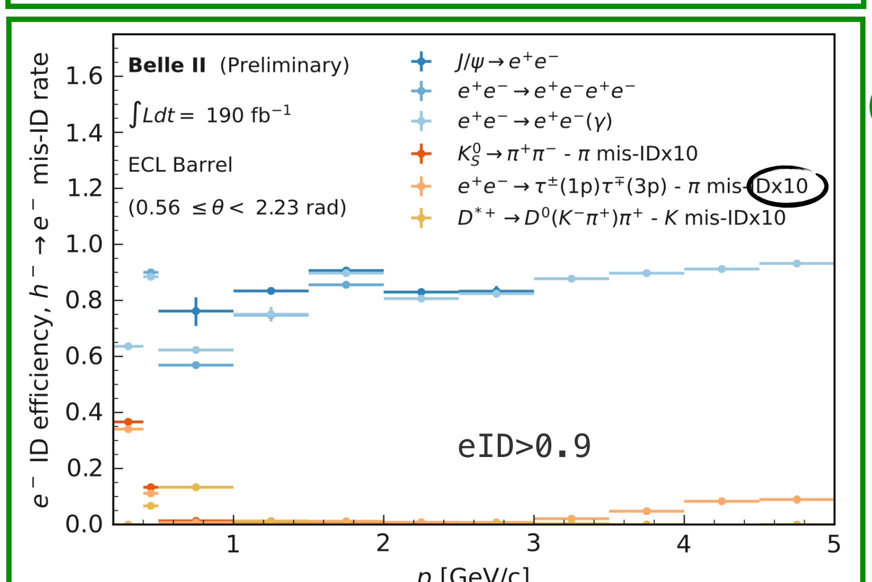




γ, π^0

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

Belle-like resolution on π^0 mass $b \to d\ell^+\ell^-$



e ID

$\varepsilon \sim 86\,\%$

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

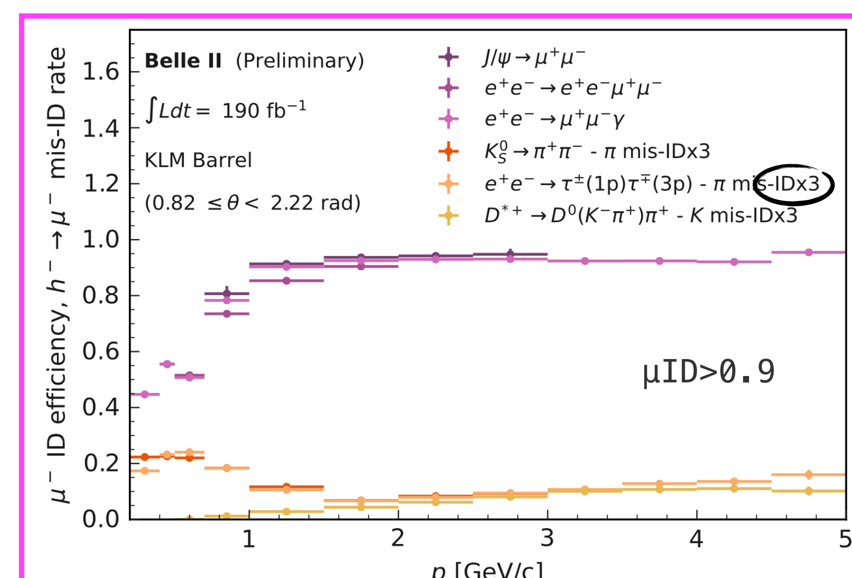
μ ID

$\varepsilon \sim 90\,\%$

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

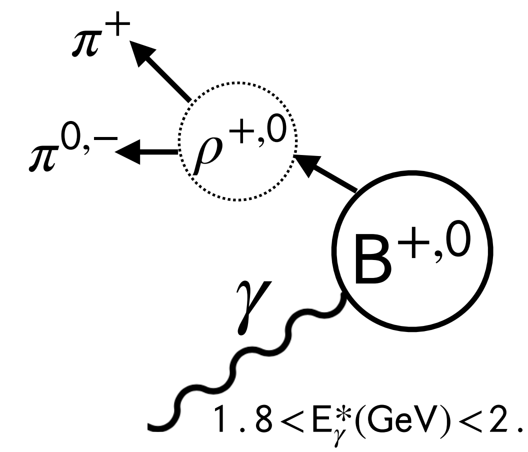
Good lepton ID performance

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



$B \to \rho\gamma$ MEASUREMENT WITH BELLE+BELLE II

BELLE
Belle II



$B \to \rho\gamma$ 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

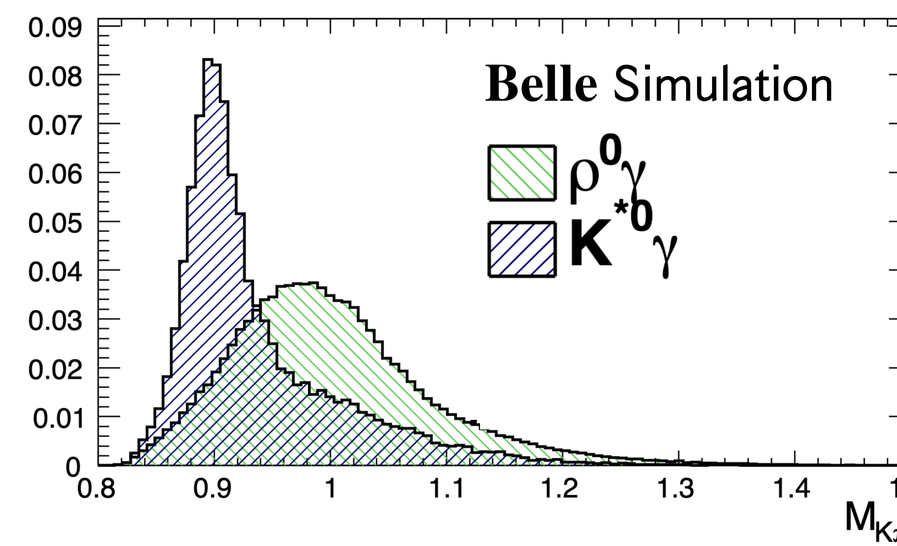
$\mathscr{A}_I$ W.A. shows a slight tension

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

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

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



	Belle 2008	BaBar 2008	W.A.
$\mathscr{B}(B^+ \to \rho^+\gamma) \times 10^6$	$0.87^{+0.29+0.09}_{-0.27-0.11}$	$1.20^{+0.42}_{-0.37} \pm 0.20$	0.98 ± 0.25
$\mathscr{B}(B^0 \to \rho^0\gamma) \times 10^6$	$0.78^{+0.17+0.09}_{-0.16-0.10}$	$0.97^{+0.24}_{-0.22} \pm 0.06$	0.86 ± 0.15
$\mathscr{A}_I$			$0.30^{+0.16}_{-0.13}$
$\mathscr{A}_{CP}(B^+ \to \rho^+\gamma)$	$-0.11 \pm 0.32 \pm 0.09$		-0.11 ± 0.33

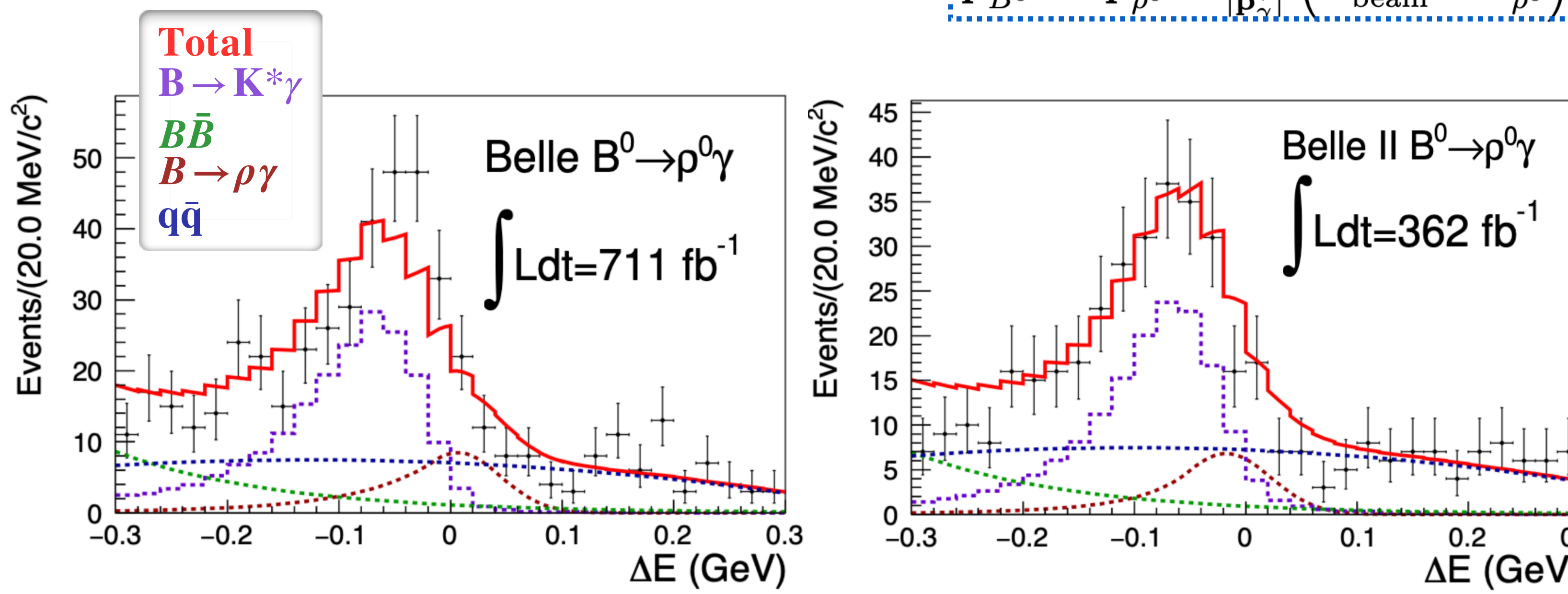
$B \to \rho\gamma$ MEASUREMENT WITH BELLE+BELLE II

BELLE
Belle II

$$M_{\rm bc} = \sqrt{(E^*_{\rm beam}/c^2)^2 - (p^*_B/c)^2}$$
$$\Delta E = E^*_B - E^*_{\rm beam}$$
$$\mathbf{p}^*_{B^0} \to \mathbf{p}^*_{\rho^0} + \frac{\mathbf{p}^*_\gamma}{|\mathbf{p}^*_\gamma|}\left(E^*_{\rm beam} - E^*_{\rho^0}\right)/c$$

Simultaneous fit to M_{bc}, ΔE, and $M(\pi^*\pi)$ distributions of six independent datasets: $(B^+, B^-, B^0/\bar{B}^0) \times$ (Belle, Belle II)

Belle II has comparable sensitivity to Belle despite the lower luminosity !



The dominant sources of **systematic uncertainties**:

Full breakdown in BACKUP

- Selection, peaking $K^*\gamma$ yield — $\mathscr{B}(B \to \rho\gamma)$
- Peaking $B\bar{B}$ $\mathscr{A}_{CP}$ — $\mathscr{A}_{CP}$
- $B^+B^-/B^0\bar{B}^0$ production — $\mathscr{A}_I$

	Belle 2008	BaBar 2008	W.A.	B+BII 2023
$\mathscr{B}(B^+ \to \rho^+\gamma) \times 10^6$	$0.87^{+0.29+0.09}_{-0.27-0.11}$	$1.20^{+0.42}_{-0.37} \pm 0.20$	0.98 ± 0.25	$1.29^{+0.20+0.10}_{-0.19-0.12}$
$\mathscr{B}(B^0 \to \rho^0\gamma) \times 10^6$	$0.78^{+0.17+0.09}_{-0.16-0.10}$	$0.97^{+0.24}_{-0.22} \pm 0.06$	0.86 ± 0.15	$0.75 \pm 0.13^{+0.10}_{-0.08}$
$\mathscr{A}_I$			$0.30^{+0.16}_{-0.13}$	$0.14^{+0.11}_{-0.12} \pm 0.09$
$\mathscr{A}_{CP}(B^+ \to \rho^+\gamma)$	$-0.11 \pm 0.32 \pm 0.09$		-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)]

EXCLUSIVE $b \to d\ell^+\ell^-$ WITH BELLE

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)]

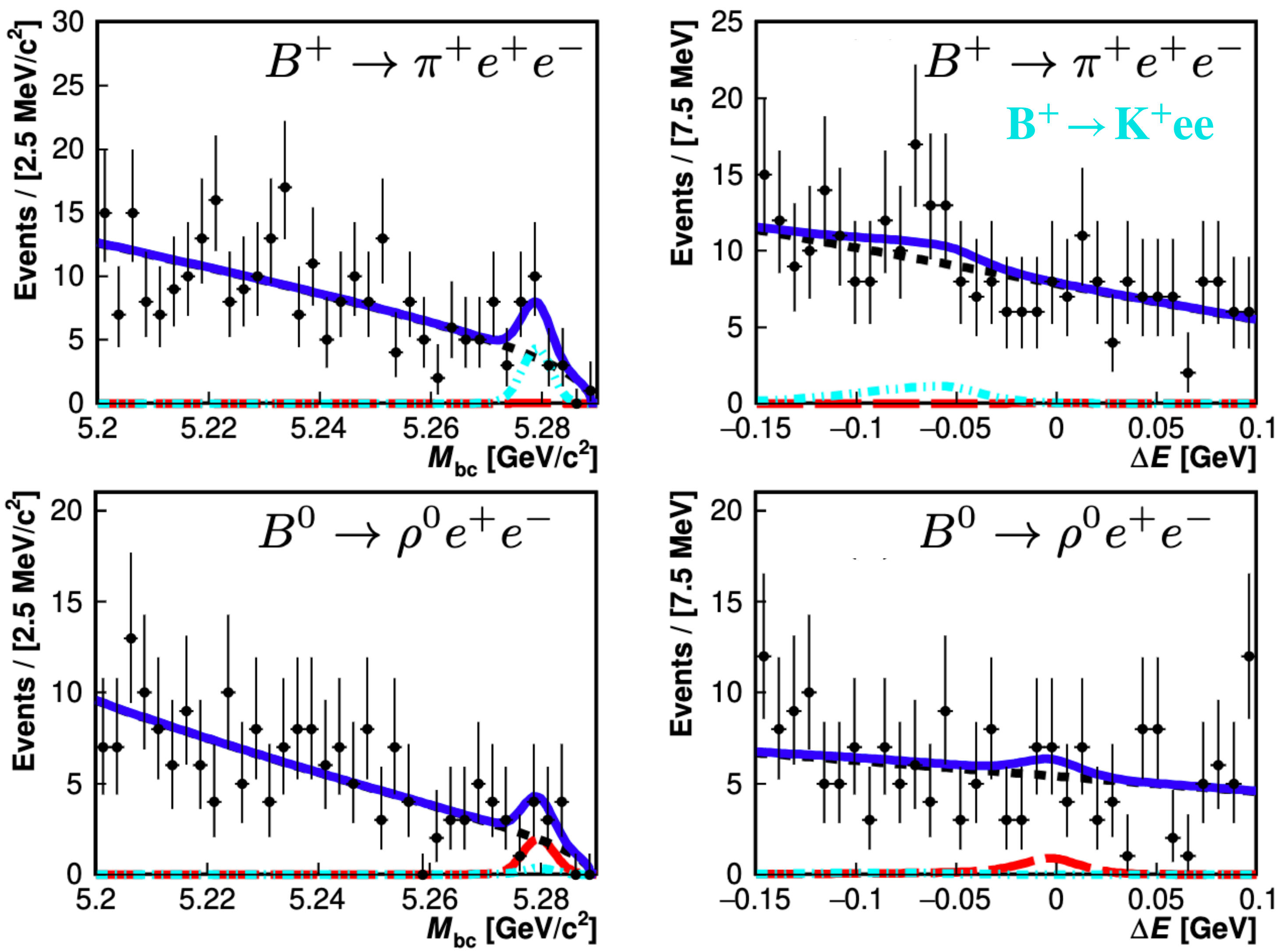
LHCb (3 fb^{-1}) observed $B^+ \to \pi^+\mu^+\mu^-$, $B^0 \to \pi^+\pi^-\mu^+\mu^-$ [Phys.Lett.B 743 (2015) 46-55, JHEP 10 (2015) 034]

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

Combinatorial bg → Dominated by continuum events

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

EXCLUSIVE $b \to d\ell^+\ell^-$ WITH BELLE

BELLE

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[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 $(3.8 - 47) \times 10^{-7}$

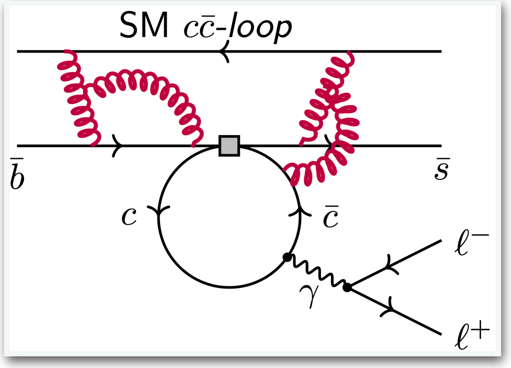
World best limits for all the searched decay modes

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

90% CL upper limits

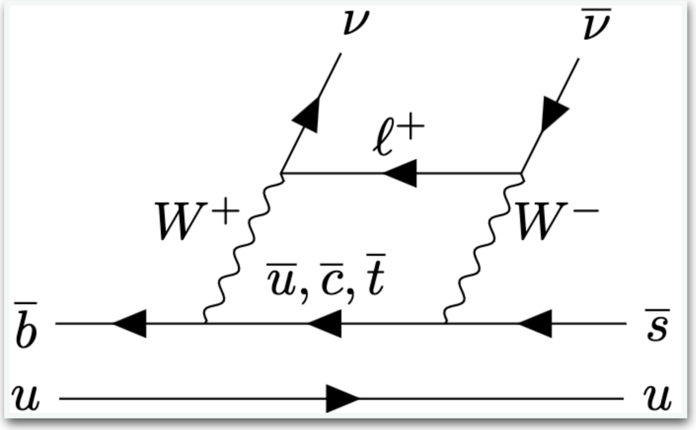
channel		N_{sig}	N_{sig}^{UL}	ε (%)	$\mathcal{B}^{UL}$ (10^{-8})	$\mathcal{B}$ (10^{-8})
$B^0 \to \eta e^+e^-$		$0.0^{+1.4}_{-1.0}$	3.1	3.9	< 10.5	$0.0^{+4.9}_{-3.4} \pm 0.1$
$B^0 \to \eta\mu^+\mu^-$		$0.8^{+1.5}_{-1.1}$	4.2	5.9	< 9.4	$1.9^{+3.4}_{-2.5} \pm 0.2$
$B^0 \to \eta\ell^+\ell^-$		$0.5^{+1.0}_{-0.8}$	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	$2.5^{+14.6}_{-11.8} \pm 0.2$

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



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 necessary show up in $b \to s\ell^+\ell^-$ too
Interplay with $B \to K^*\nu\bar{\nu}/K^{(*)}\tau\tau/K^{(*)}\tau\ell$ and other anomalies [2309.02246, 2401.10112, 2401.11552]

Unique to experiments at e^+e^- machines

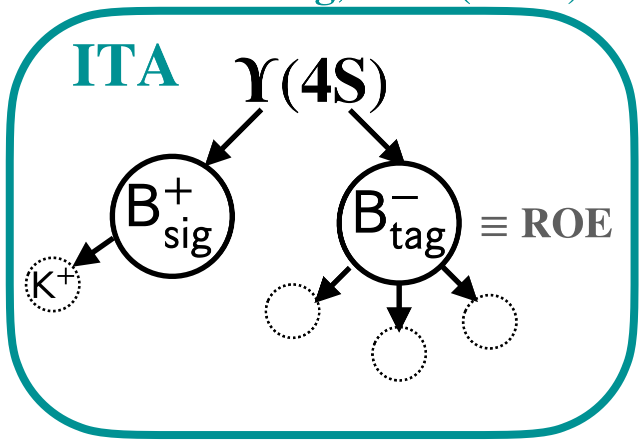
Challenges
- Low BF
- 2 neutrinos in the final state + 3-body kinematics (no good kinematic constraints)
- Large backgrounds

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

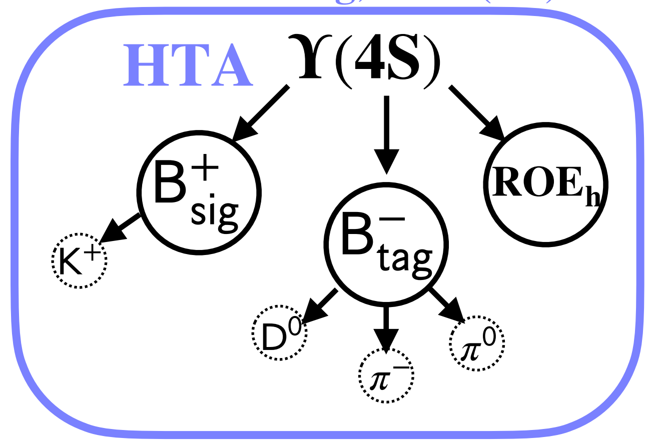
Two tagging approaches leading to almost statistically independent samples

arXiv:2311.14647 **(Submitted to PRD)**

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

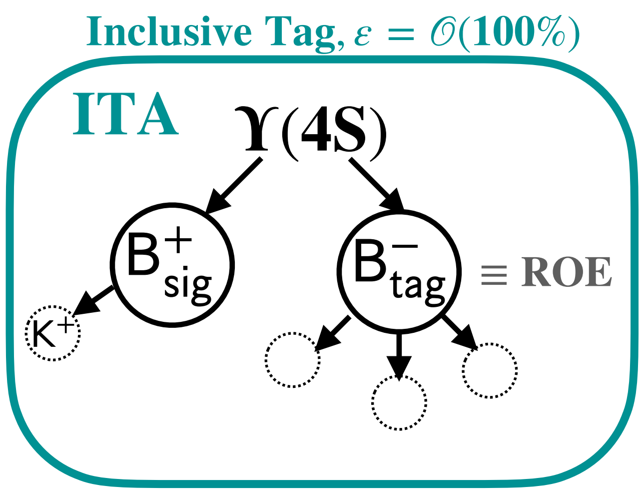
$$\mathbf{q^2_{rec}} = s/(4c^4) + M_K^2 - \sqrt{s}E_K^*/c$$

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

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

Belle II

arXiv:2311.14647 (Submitted to PRD)



- Approach leading the final sensitivity
- Two consecutive MVA classifiers

  basic filter (BDT_1)

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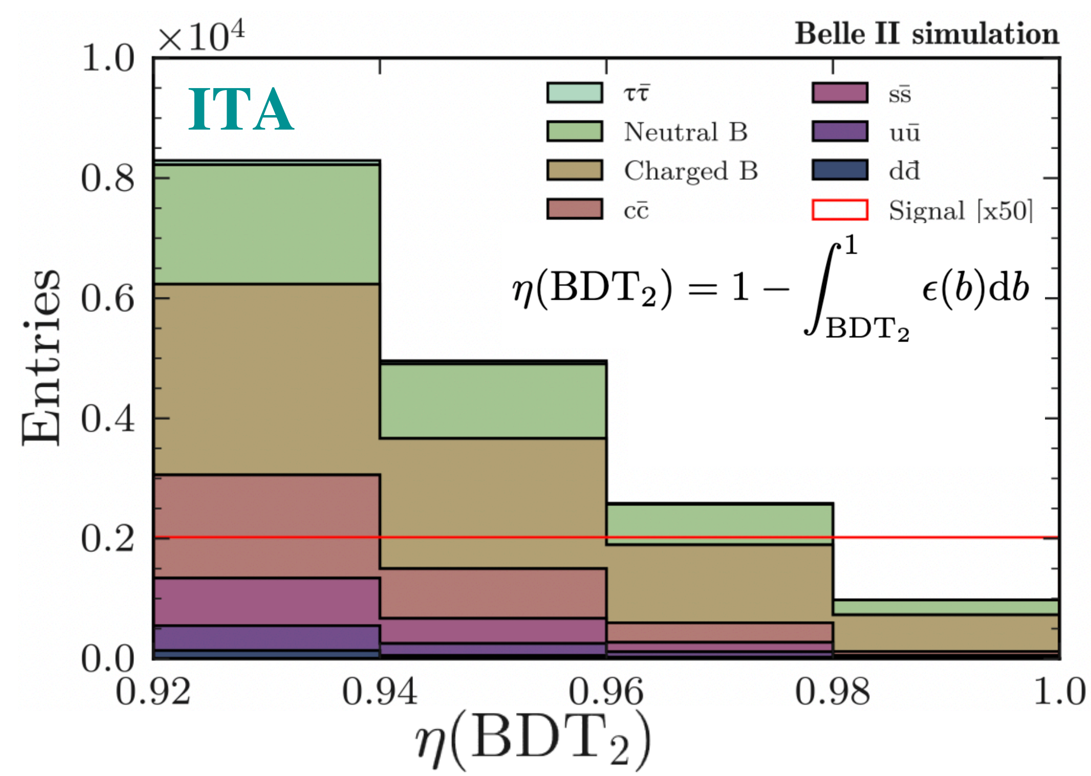
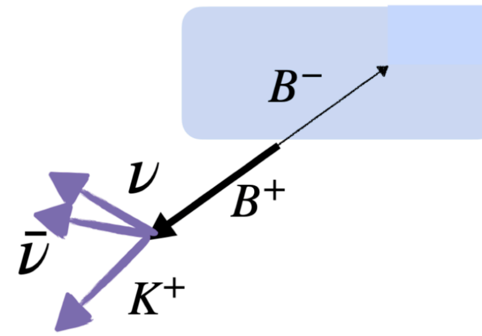
- Total efficiency ~8%, purity ~0.8%
- **Fit to $q^2_{rec} \times \eta(BDT_2)$ simultaneously for ON and OFF resonance data**

FOCUS ON ITA



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

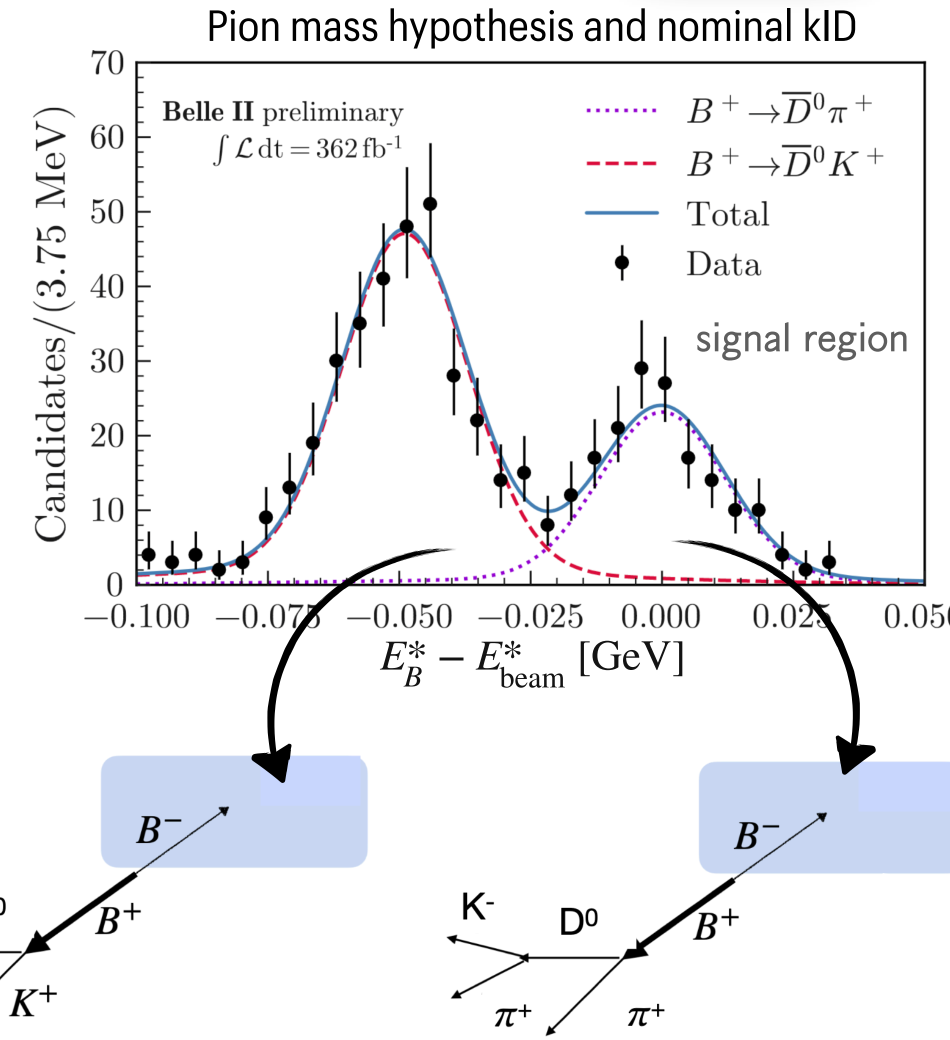
VALIDATION ITA (I)



- **Kaon ID selection**

  The data/MC corrections are validated for the signal region using a $B^+ \to \bar{D}^0(\to K^+\pi^-)h^+$, $h = \{\pi, K\}$ sample

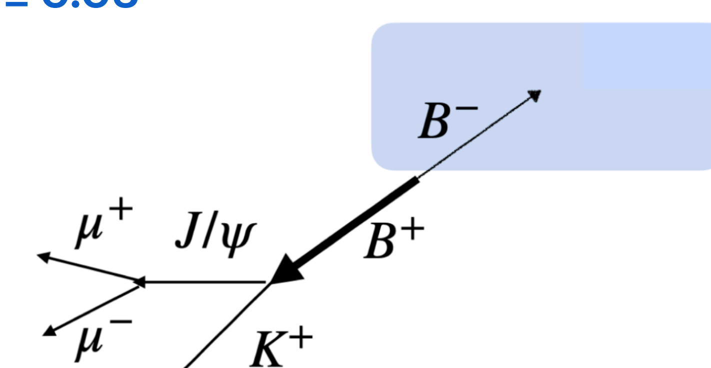
  Data/MC ratio of relative abundance of B→DK and B→Dπ: 1.03±0.09

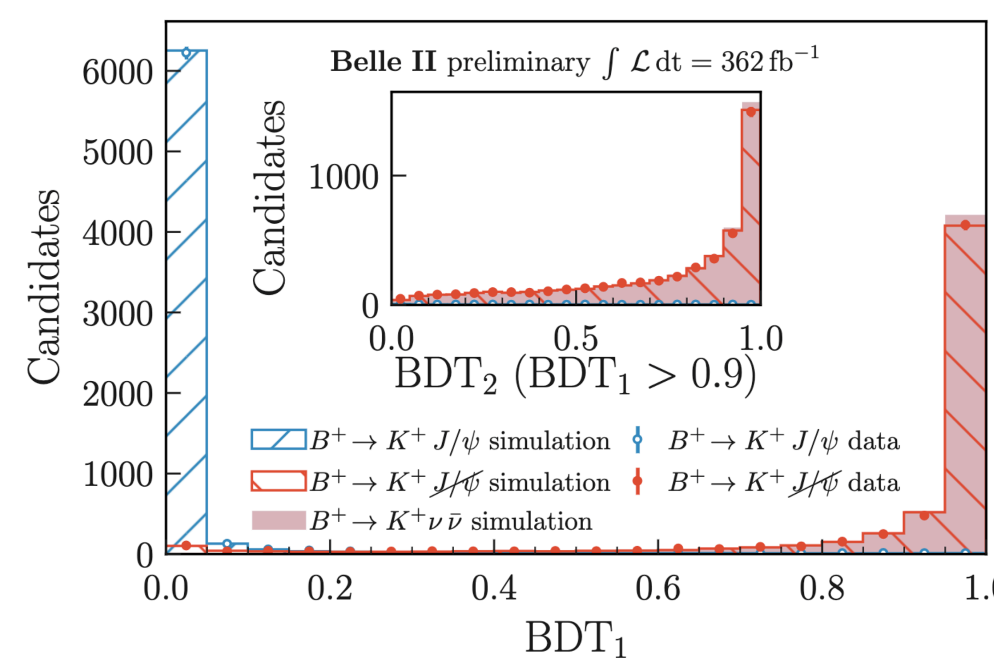


- **Signal efficiency**

  $B^+ \to J/\psi(\mu\mu)K^+$ control channel where muons are removed to mimic the neutrinos and the Kaon kinematics are corrected to match the signal one

  Data/MC efficiency ratio: 1.00 ± 0.03



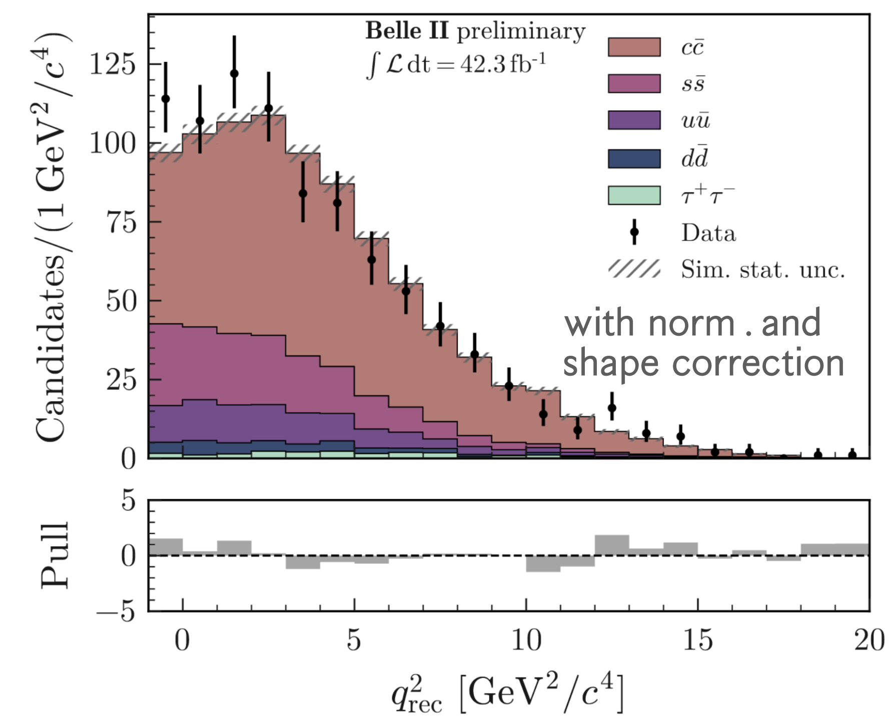


VALIDATION ITA (II)

Validation of background composition for ITA in signal region

- **$q\bar{q}$ events**

  Off-resonance data to correct for data/MC differences in
  - normalisation ↦ **40% discrepancy**
  - shape ↦ **event-by-event data-driven correction** [J. Phys.: Conf. Ser. 368 012028]



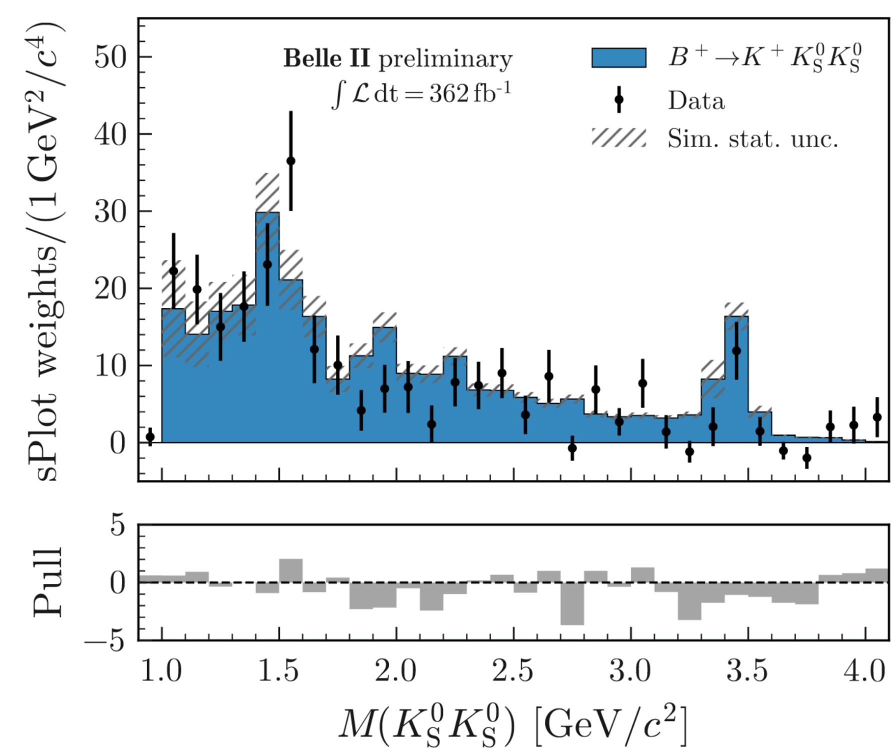
!! Undetected K^0_L's in EM calorimeter can mimic neutrinos

- **$B \to D^{(*)}K^+$ events**

  Modelling of K^0_L detection efficiency in the calorimeter corrected using $e^+e^- \to \gamma\phi(K^0_S K^0_L)$ sample

  Size of $B \to X_c(K^0_L X)$ corrected using pion-enriched sideband (lepton-enriched samples for validation) ↦ **30% rescaling**

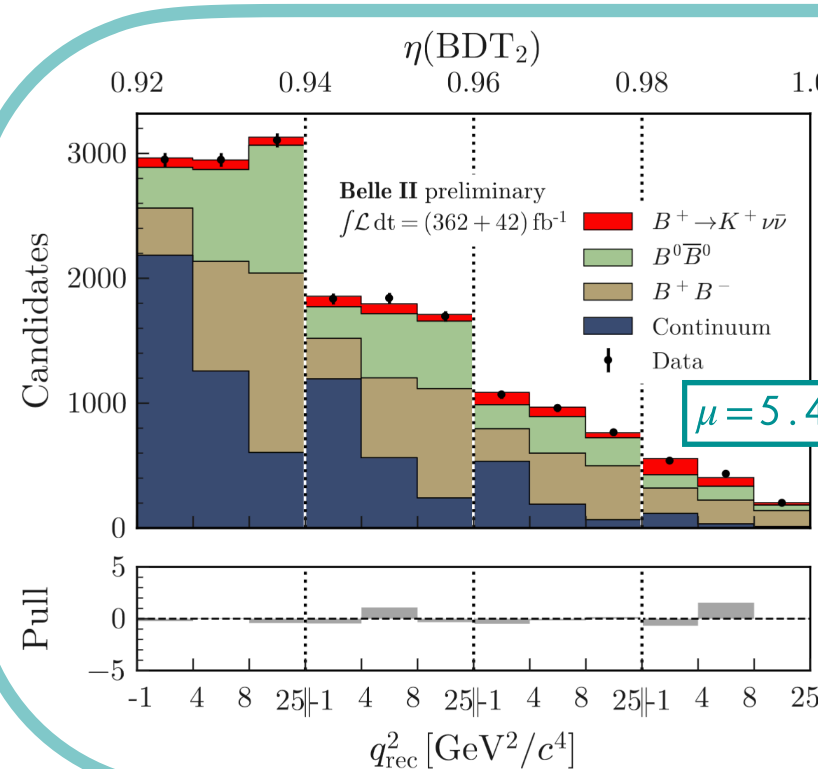
- **$B^+ \to K^+ K^0_L K^0_L$ events**
  - Use BaBar [PRD85, 112010 (2012)] $B^+ \to K^+ K^0_S K^0_S$ measurement as input from to model $B^+ \to K^+ K^0_L K^0_L$
  - Good agreement in shape and normalisation for $B^+ \to K^+ K^0_S K^0_S$
  - Similar study for $B^+ \to K^+ K^0_S K^0_L$ and $B^+ \to K^+ n\bar{n}$ (smaller contribution)



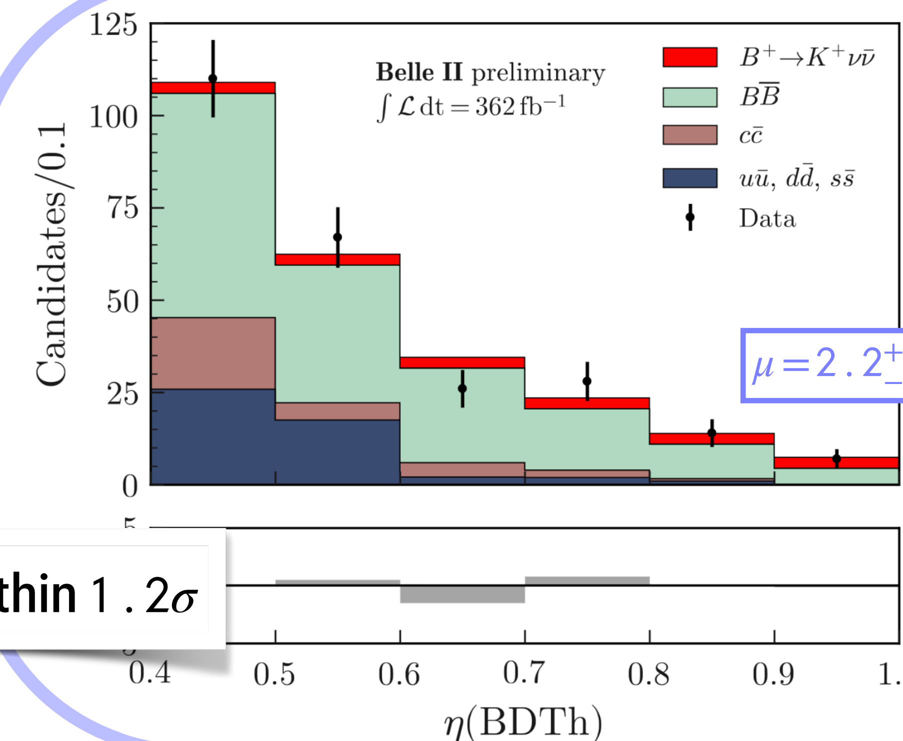
$B^+ \to K^+ \nu\bar{\nu}$ RESULTS

$\mu = BF_{meas}/B_{SM,short\ dist} = BF_{meas}/(4.97 \times 10^{-6})$

Full breakdown of syst. unc. in BACKUP



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



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

Consistent within 1.2σ

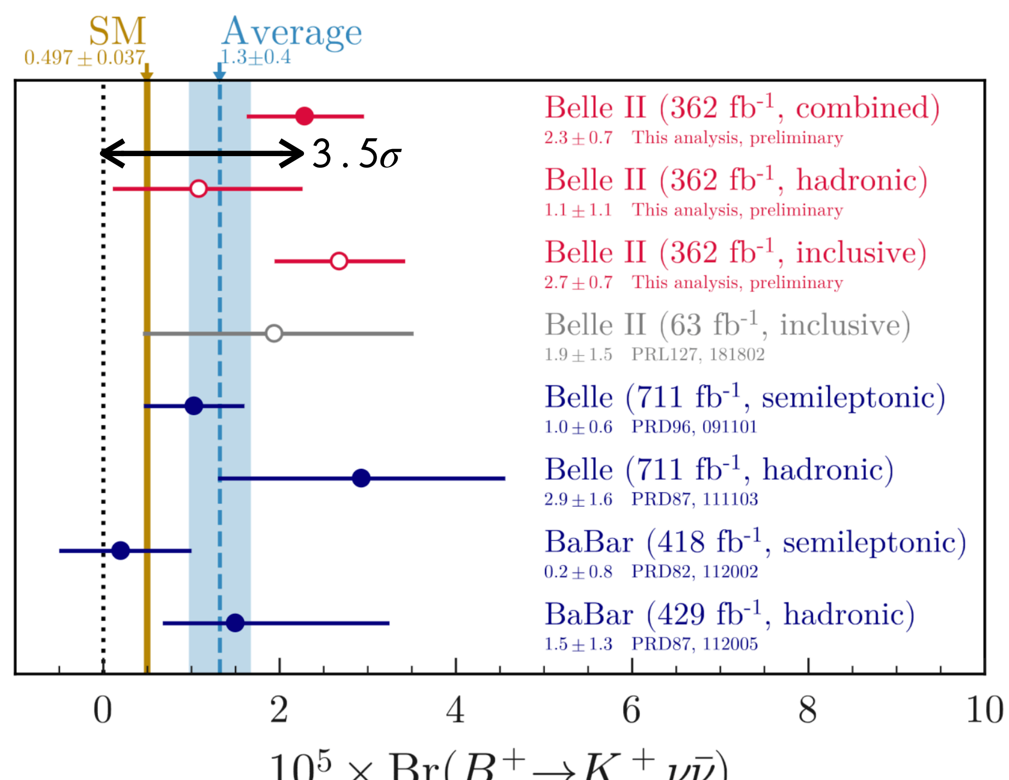
ITA
- 3.5σ deviation from background-only hyp
- 2.9σ deviation from SM exp

HTA
- 1.1σ deviation from background-only hyp
- 0.6σ deviation from SM exp

$(2.3 \pm 0.7) \times 10^{-5}$ (**ITA + HTA**)

$(1.1^{+1.2}_{-1.0}) \times 10^{-5}$ (**HTA**)

$(2.7 \pm 0.7) \times 10^{-5}$ (**ITA**)



ITA + HTA
- 3.5σ deviation from background-only hyp
- 2.7σ deviation from SM exp

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

SUMMARY

Three new results since last LLWI: First evidence on $B^+ \to K^+ \nu\bar{\nu}$ **and studies of** $b \to d$ **transitions**

$b \to d\gamma$

First Belle II(+ Belle) measurement of $b \to d$. Best precision on $B \to \rho\gamma$ parameters

Future: Time-dependent CPV ($B^0 \to \rho^0\gamma$)

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

Most stringent UL's on several $B \to \{\pi, \rho, \eta, \omega\}\ell^+\ell^-$ BFs with Belle (only!) data

$b \to s\nu\bar{\nu}$

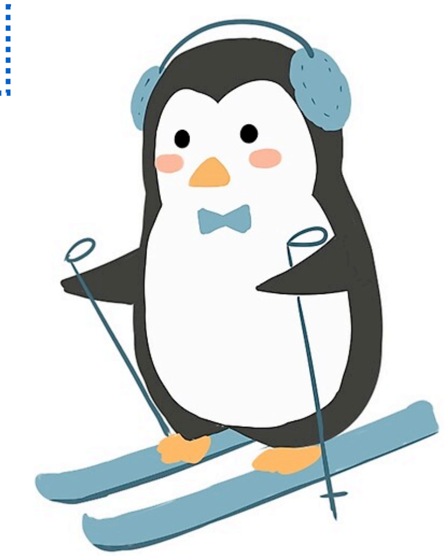
Inclusive *B*-tagging approach has proved to be the most sensitive to $B^+ \to K^+ \nu\bar{\nu}$ decays

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

Future: Search for $B \to K^* \nu\bar{\nu}$ and explore the semileptonic *B*-tagging approach

arXiv: 2311.14647

Thank you for your attention



ADDITIONAL MATERIAL

$B \to \rho\gamma$ - ASYMMETRY

Our results for $B \to \rho ll$, including breakdowns of operator dependence, are shown in Figs. 7 and 9, and tabulated data is given in Appendix F 1 in Table XI. The experimental measurement of the isospin asymmetry is defined differently to the K^* case, as [47]

$$\Delta(\rho\gamma) = \frac{\tau_{B^0}}{2\tau_{B^+}} \frac{\mathcal{B}(B^+ \to \rho^+\gamma)}{\mathcal{B}(B^0 \to \rho^0\gamma)} - 1 = \frac{-2\bar{a}_I(\rho\gamma)}{1 + \bar{a}_I(\rho\gamma)} \overset{a_I(\rho\gamma)\ll 1}{\approx} -2\bar{a}_I(\rho\gamma) \qquad (68)$$

$[a_I(\rho\gamma) = -\Delta(\rho\gamma)/(2 + \Delta(\rho\gamma))]$ where a CP-averaged branching fraction is used. In this normalization, our result compares with the experimental result as [3]

$$\Delta(\rho\gamma)_{\mathrm{HFAG}} = -46(17)\%, \qquad \Delta(\rho\gamma)_{\mathrm{LZ}} = -10(6)\%. \qquad (69)$$

We shall quote Δ in percentage even though, contrary to $-1 \leq a_I \leq 1$, Δ is not bounded when $a_I \to -1$. For completeness we further quote our result for the CP-averaged isospin asymmetry in $B \to \rho\gamma$ in the SM as

$$\bar{a}_I(\rho\gamma)_{\mathrm{HFAG}} = 30\binom{-13}{+16}\%, \qquad \bar{a}_I(\rho\gamma)_{\mathrm{LZ}} = 5.2(2.8)\%, \qquad (70)$$

$$\bar{a}_I = (\mathscr{A}^{\bar{0}-} + \mathscr{A}^{0+})/2$$

$$\mathscr{A}^{\bar{0}-} = \frac{2\Gamma(\bar{B}^0 \to \rho^0\gamma) - \Gamma(B^- \to \rho^-\gamma)}{2\Gamma(\bar{B}^0 \to \rho^0\gamma) + \Gamma(B^- \to \rho^-\gamma)}$$

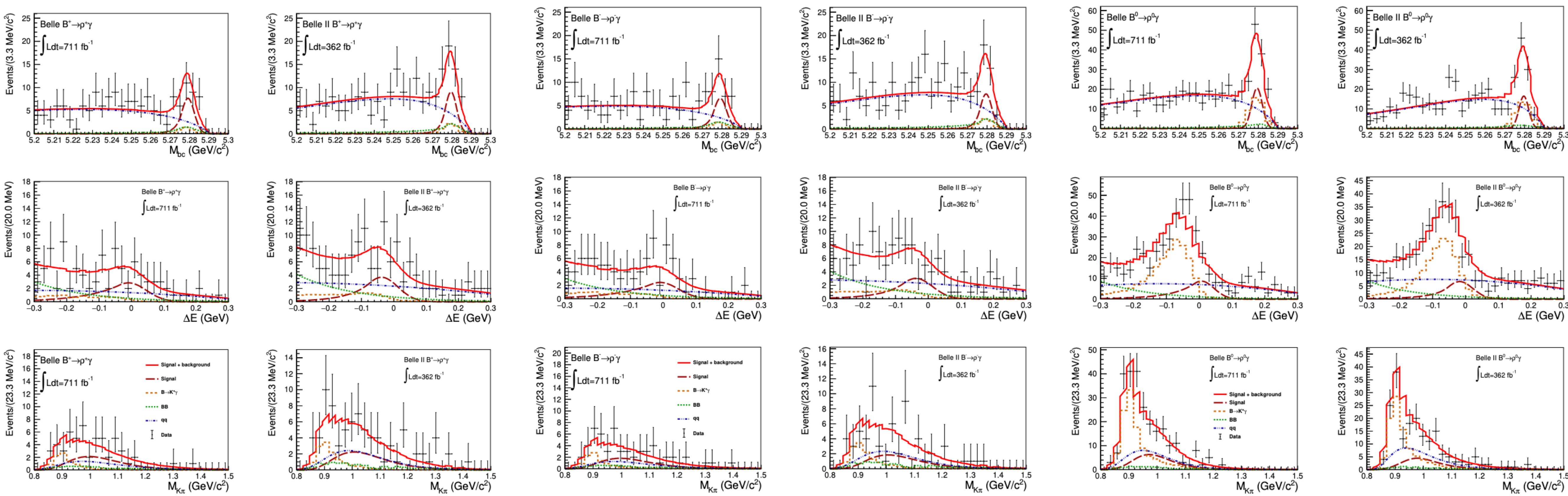
$$\mathscr{A}^{0+} = \mathrm{CP}(\mathscr{A}^{\bar{0}-})$$

$B \to \rho\gamma$ - SYSTEMATIC UNCERTAINTIES

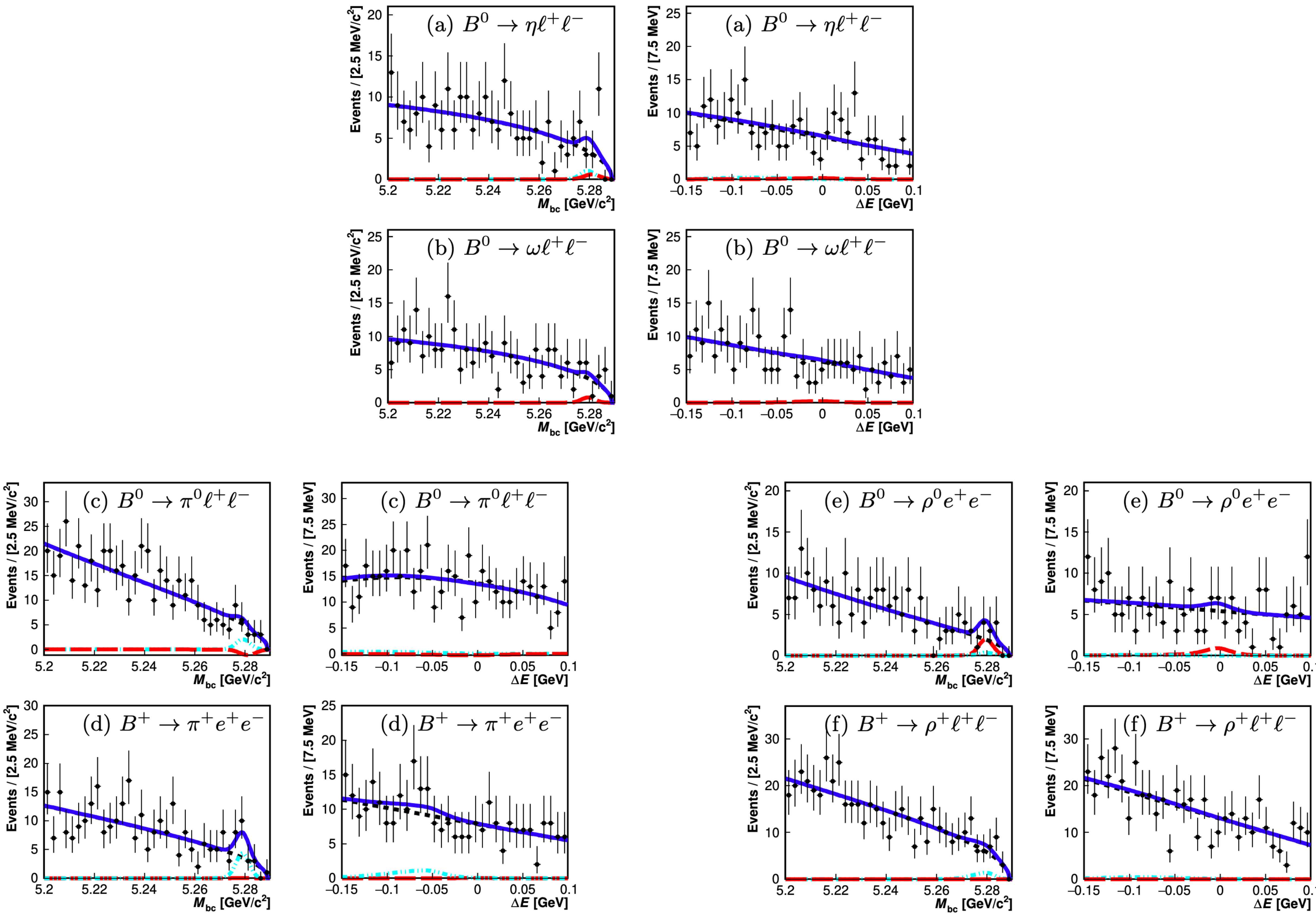
Source	$\mathcal{B}_{\rho^+\gamma} \times 10^8$	$\mathcal{B}_{\rho^0\gamma} \times 10^8$	A_I	A_{CP}
reconstruction eff.	4.1	1.2	1.5%	0.4%
cut eff.	8.9	3.3	4.0%	0.6%
Fixed PDF parameters	1.1	2.6	1.8%	0.2%
Signal shape	4.6	2.9	3.1%	0.5%
Histogram PDF	1.0	0.6	0.6%	0.2%
$K^*\gamma$ yield	3.4	5.4	3.2%	0.1%
$B\overline{B}$ peaking yield	2.2	0.7	0.9%	0.2%
A_{CP} of peaking	0.2	0.0	0.1%	1.0%
Number of $B\overline{B}$	1.7	1.4	0.3%	0.1%
Other parameters	4.0	3.6	6.3%	0.0%
Total	12.6	8.8	9.0%	1.3%

Other parameters includes number

$B \to \rho\gamma$ - 3D FITS



$b \to d\ell\ell$ - BELLE 2024



$b \to d\ell\ell$ - BABAR

[428 fb^{-1}, PRD 88 032012 (2013)]

TABLE III: $B \to \pi\ell^+\ell^-$ and $B^0 \to \eta\ell^+\ell^-$ efficiencies, yields, branching fractions, and branching fraction upper limits at the 90% CL. The error on the yield is statistical. The first error quoted on the branching fractions is statistical while the second is systematic. Branching fraction upper limits include systematic uncertainties.

Mode	ε	Yield	$\mathcal{B}\,(10^{-8})$	Upper Limit (10^{-8})
$B^+ \to \pi^+e^+e^-$	0.199	$4.2^{+5.7}_{-4.6}$	$4.3^{+5.9}_{-4.7} \pm 2.0$	12.5
$B^0 \to \pi^0e^+e^-$	0.163	$1.0^{+3.2}_{-1.1}$	$1.2^{+5.4}_{-4.0} \pm 0.2$	8.4
$B^0 \to \eta e^+e^-$			$-4.0^{+10.0}_{-8.0} \pm 0.6$	10.8
$B^0 \to \eta_{\gamma\gamma}e^+e^-$	0.164	$-1.2^{+3.1}_{-2.4}$		
$B^0 \to \eta_{3\pi}e^+e^-$	0.115	$-0.5^{+1.2}_{-1.0}$		
$B^+ \to \pi^+\mu^+\mu^-$	0.140	$-0.5^{+3.1}_{-2.3}$	$-0.6^{+4.4}_{-3.2} \pm 0.9$	5.5
$B^0 \to \pi^0\mu^+\mu^-$	0.115	$-0.2^{+2.0}_{-0.7}$	$-1.0^{+5.0}_{-3.4} \pm 0.6$	6.9
$B^0 \to \eta\mu^+\mu^-$			$-2.0^{+9.7}_{-6.6} \pm 0.4$	11.2
$B^0 \to \eta_{\gamma\gamma}\mu^+\mu^-$	0.102	$-0.4^{+1.7}_{-1.3}$		
$B^0 \to \eta_{3\pi}\mu^+\mu^-$	0.063	$-0.1^{+0.7}_{-0.4}$		
$B \to \pi e^+e^-$			$4.0^{+5.1}_{-4.2} \pm 1.6$	11.0
$B \to \pi\mu^+\mu^-$			$-0.9^{+3.9}_{-3.0} \pm 1.2$	5.0
$B^+ \to \pi^+\ell^+\ell^-$			$2.5^{+3.9}_{-3.3} \pm 1.2$	6.6
$B^0 \to \pi^0\ell^+\ell^-$			$1.2^{+3.9}_{-3.3} \pm 0.2$	5.3
$B^0 \to \eta\ell^+\ell^-$			$-2.8^{+6.6}_{-5.2} \pm 0.3$	6.4
$B \to \pi\ell^+\ell^-$			$2.5^{+3.3}_{-3.0} \pm 1.0$	5.9

$b \to d\ell\ell$ - PEAKING BG

- Charmless peaking background is found for the modes with muons in the final state
- Peaking background is studied in rareMC

channel	background	MC ($\mathcal{B}$)	$N_{\rm peak}$ (50×)	$N_{\rm peak}$ (Belle)	status
$B^0 \to \eta\mu\mu$	$B^0 \to \eta K\pi$	1.15×10^{-5}	14	0.28	**included in PDF**
	$B^0 \to \eta\pi\pi$	0.62×10^{-5}	4	0.08	negligible
$B^0 \to \omega\mu\mu$	$B^0 \to \omega K\pi$	0.30×10^{-5}	2	0.04	negligible
	$B^0 \to \omega\pi\pi$	0.10×10^{-5}	0	0	no contribution
$B^+ \to \rho^+\mu\mu$	$B^+ \to \rho^+ K\pi$	0.80×10^{-5}	7	0.14	negligible
$B^0 \to \pi^0\mu\mu$	$B^0 \to \pi^0 K\pi$	0.94×10^{-5}	13	0.26	**included in PDF**
	$B^0 \to \pi^0\pi\pi$	0.95×10^{-5}	3	0.06	negligible
	$B^0 \to \pi^0 KK$	1.89×10^{-5}	24	0.48	**included in PDF**

channel	source
$B^0 \to \eta\mu\mu$	$B^0 \to \eta K\pi$
$B^0 \to \pi^0\mu\mu$	$B^0 \to \pi^0 K\pi$ & $B^0 \to \pi^0 KK$
$B^+ \to \pi^+ ee$	$B^+ \to K^+ ee$
$B^0 \to \rho^0 ee$	$J/\psi \to e$ & $K^* \to K \leftrightarrow e$
$B^+ \to \rho^+\mu\mu$	$J/\psi \to \mu$ & $K^* \to K \leftrightarrow \mu$, $\rho^+\overline{D^0}(K^+\pi^-)$

- Peaking backgrounds are either vetoed or included in the fit by:
  - applying invariant mass vetoes by assigning faking particle mass hypothesis to correct particle
  - studying high statistics inclusive J/ψ sample
  - generating signalMC for peaking contribution

arXiv: 2311.14647

$B \to K\nu\bar{\nu}$ - SYSTEMATIC UNCERTAINTIES - ITA

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

arXiv: 2311.14647

$B \to K\nu\bar{\nu}$ - SYSTEMATIC UNCERTAINTIES - HTA

	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

arXiv: 2311.14647

$B \to K\nu\bar{\nu}$ - COMBINATION

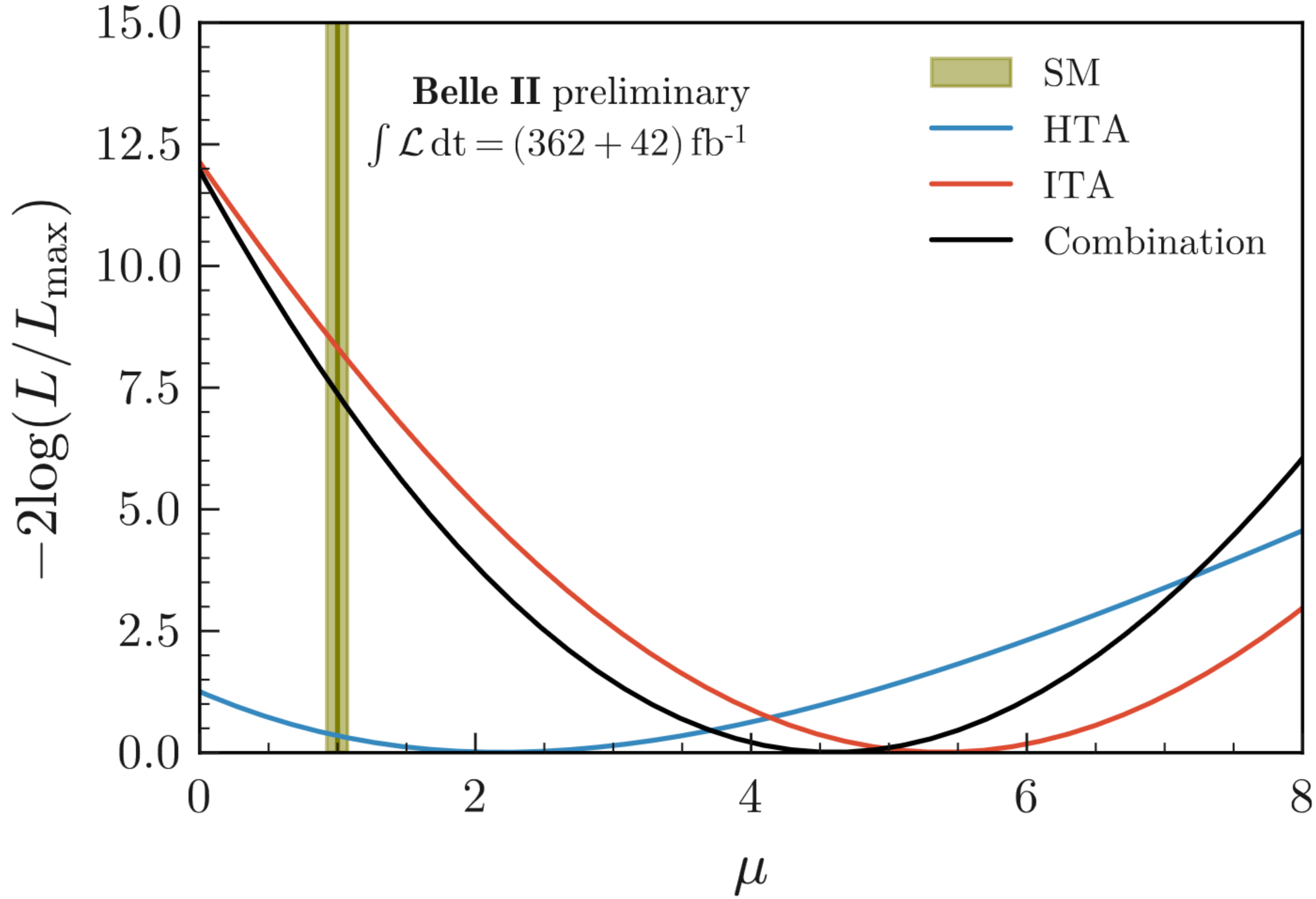
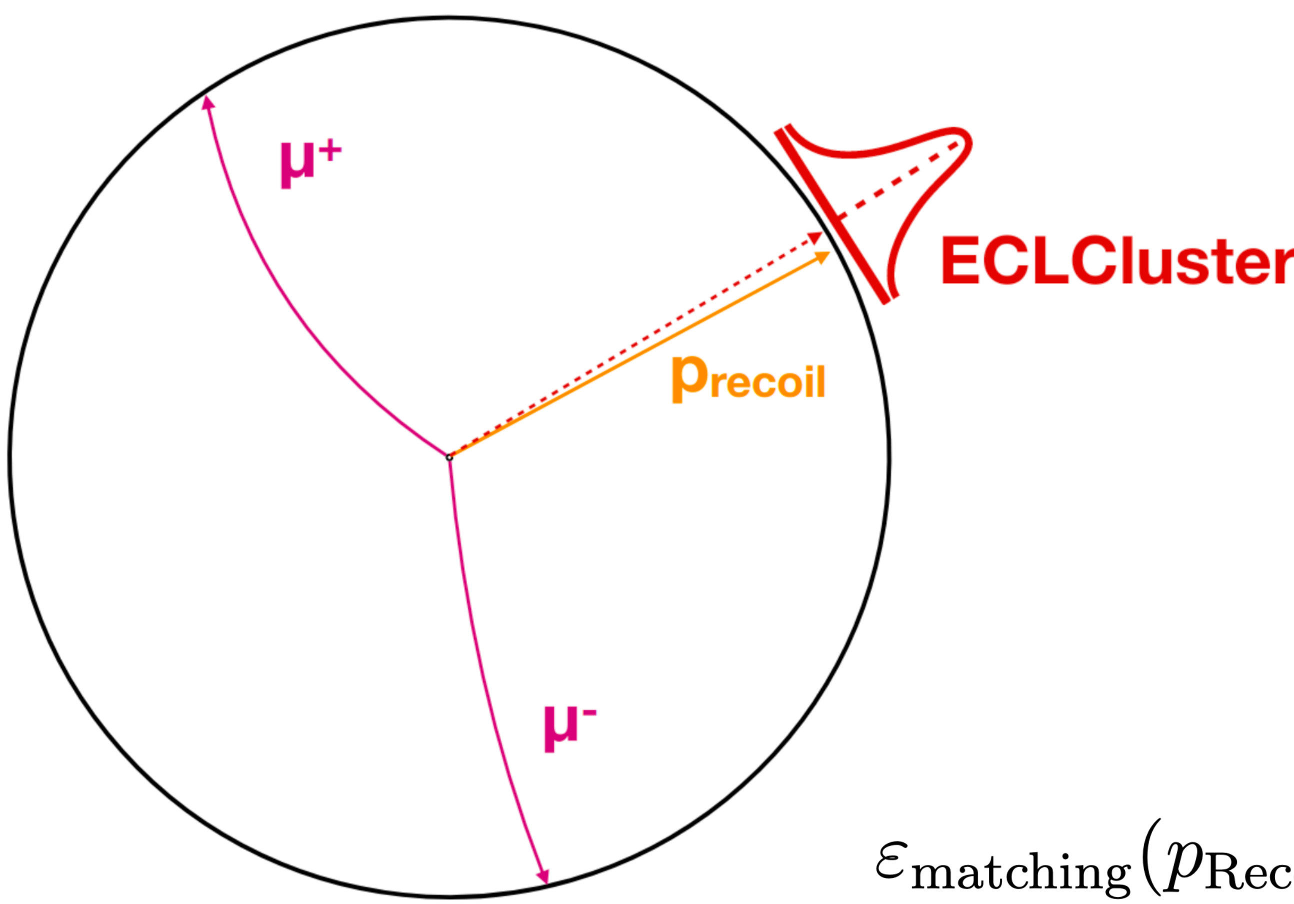


FIG. 16. Twice the negative profile log-likelihood ratio as a function of the signal strength μ for the ITA, HTA, and the combined result. The value for each scan point is determined by fitting the data, where all parameters but μ are varied.

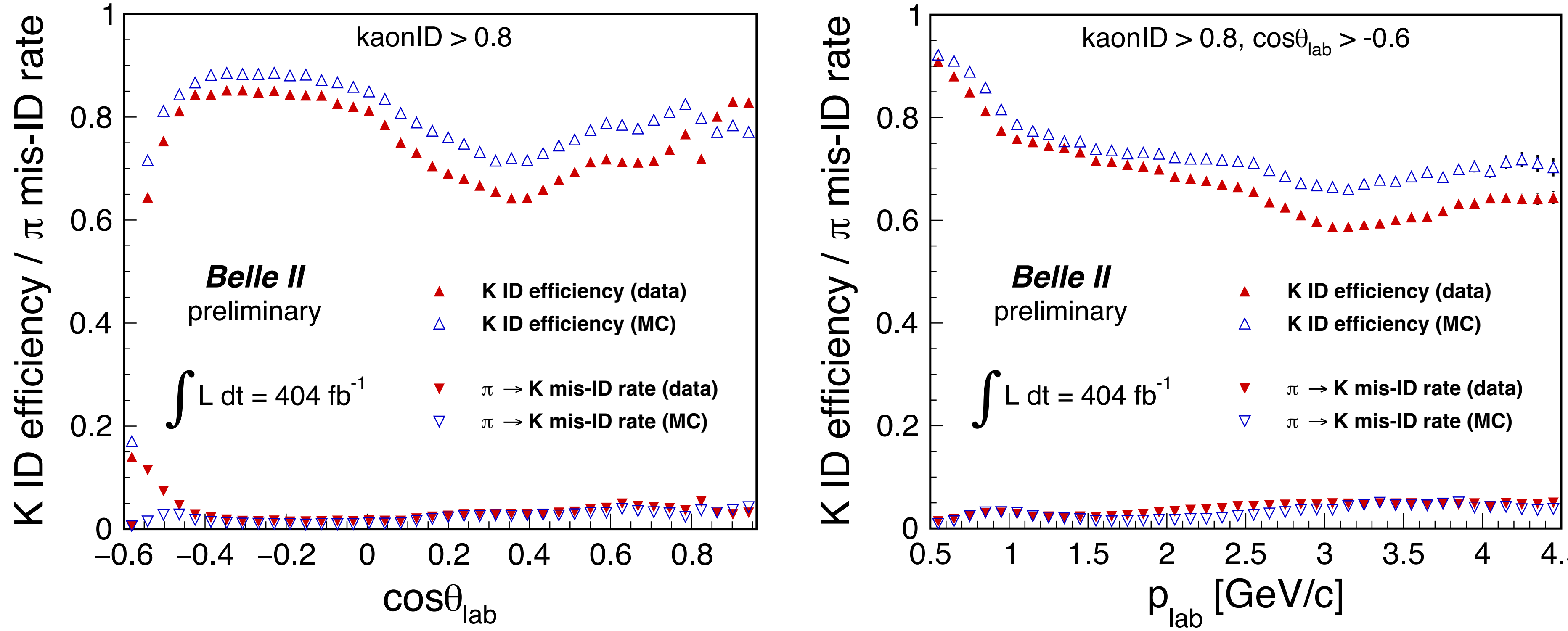
BELLE II NEUTRALS

The measurement selects $e^+e^- \to \mu^+\mu^- (\gamma_{\text{ISR}})$ events, where γ_{ISR} is a photon radiated from the initial e^+e^- state. The schematic representation of the measurement is illustrated in Fig. 1. Employing constraints derived from the precisely defined initial e^+e^- state, the photon energy and directions can be obtained from the missing momentum of the dimuon system. The missing momentum is termed as the "recoil" momentum, with its magnitude indicated by p_{Recoil}. Its direction is expressed through θ_{Recoil} and ϕ_{Recoil}, corresponding to the polar and azimuthal angles, respectively. The invariant mass linked to the recoil is denoted as m_{Recoil}.



$$\varepsilon_{\text{matching}}(p_{\text{Recoil}}, \theta_{\text{Recoil}}, \phi_{\text{Recoil}}) = \frac{\text{N}_{\text{matched}}}{\text{N}_{\text{selected}}}$$

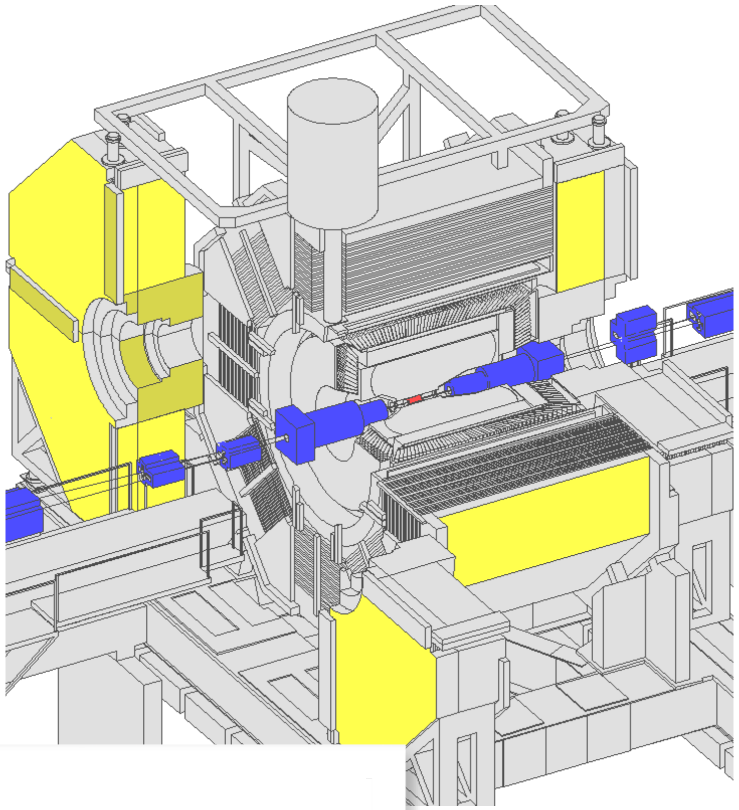
PARTICLE ID



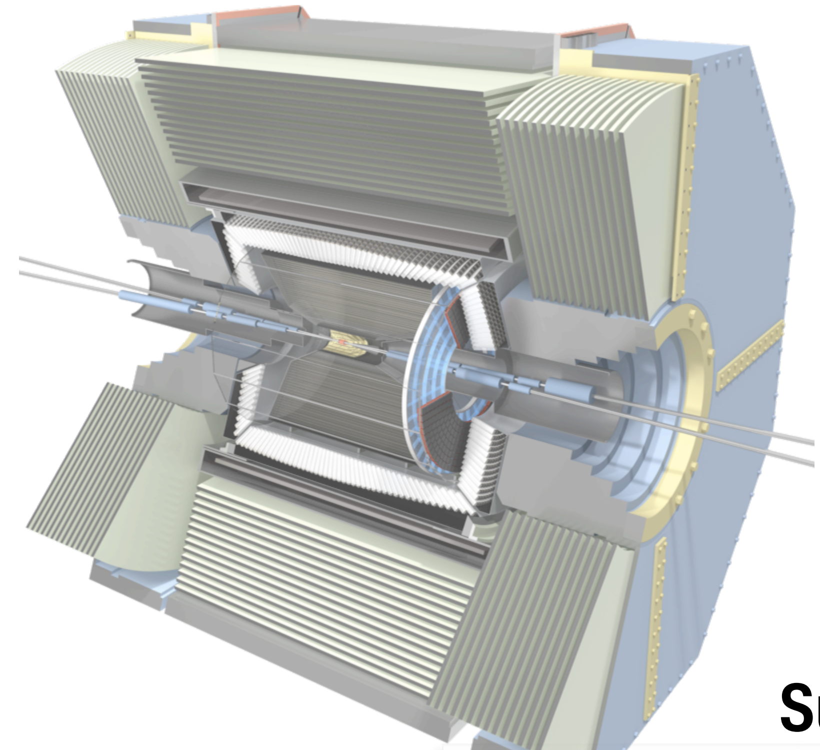
	Definition	Cut	Range	Efficiency	Fake rate
e	$L_{\text{eid}} = \frac{\Pi_{i=1}^{N} L_e^i}{\Pi_{i=1}^{N} L_e^i + \Pi_{i=1}^{N} L_{\bar{e}}^i}$	> 0.5	$p \in (1,3)$ GeV/c	$(92.4 \pm 0.4)\%$	$\pi: (0.25 \pm 0.02)\%$ $K: (0.43 \pm 0.07)\%$
μ	$\mathcal{L}_\mu = \frac{prob_\mu}{prob_\mu + prob_\pi + prob_K}$	> 0.9	$p \in (1,3)$ GeV/c	$(88.8 \pm 0.9)\%$	$\pi: (1.35 \pm 0.07)\%$ $K: (1.7 \pm 0.4)\%$
K	$\text{Prob}(K:\pi)$	> 0.6	$p \in (0.5, 4.0)$ GeV/c	$(87.99 \pm 0.12)\%$	$\pi: (8.53 \pm 0.10)\%$

https://doi.org/10.1016/S0168-9002(02)01510-3

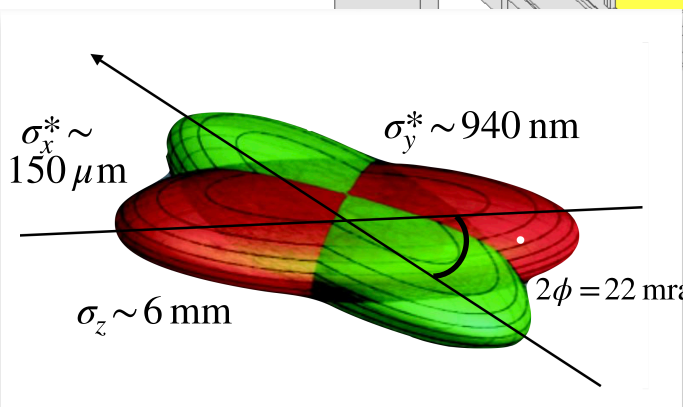
THE BELLE&BELLE II EXPERIMENTS



UPGRADE

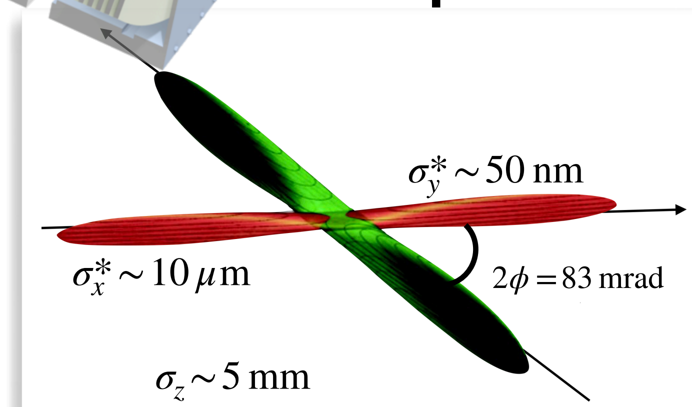


KEKB

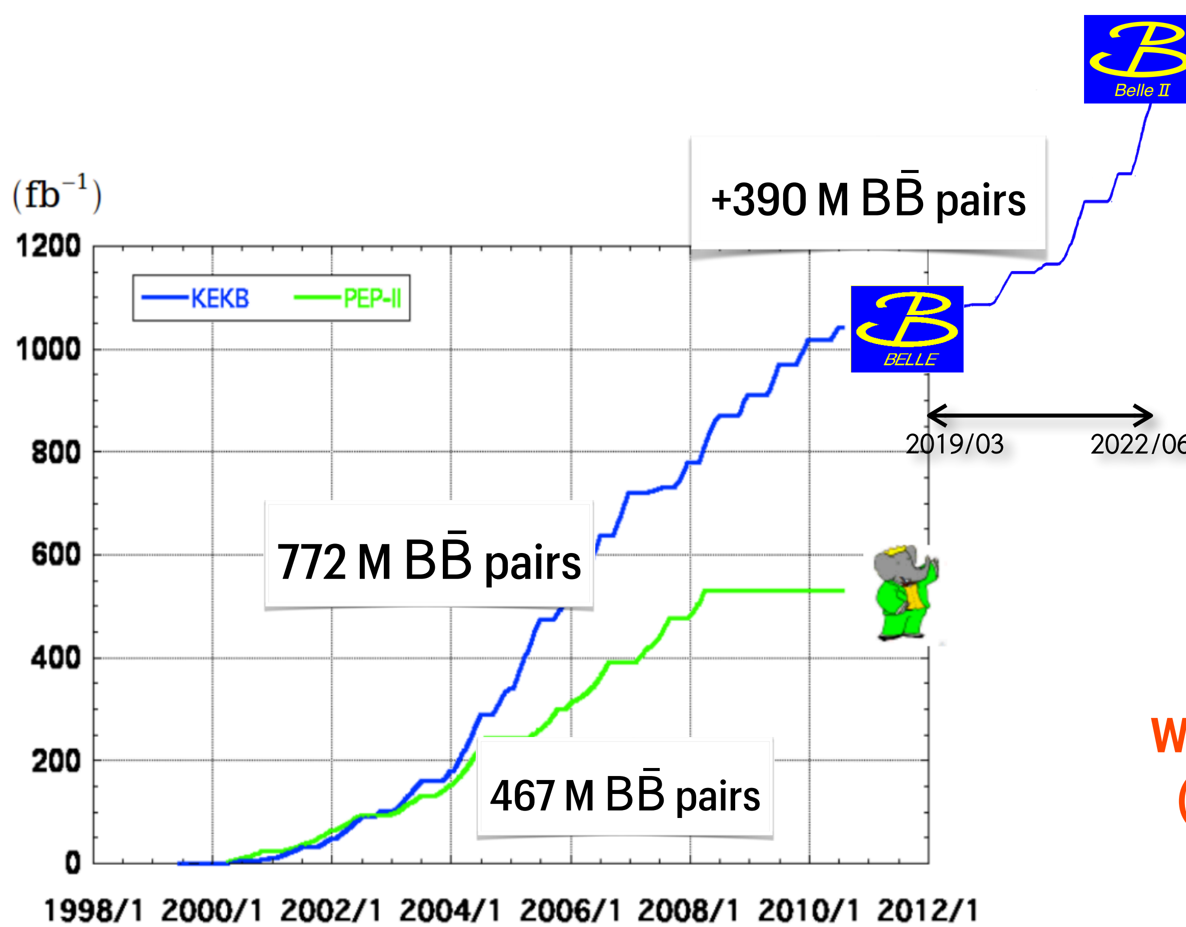


$\beta\gamma = 0.42$

SuperKEKB



$\beta\gamma = 0.28$



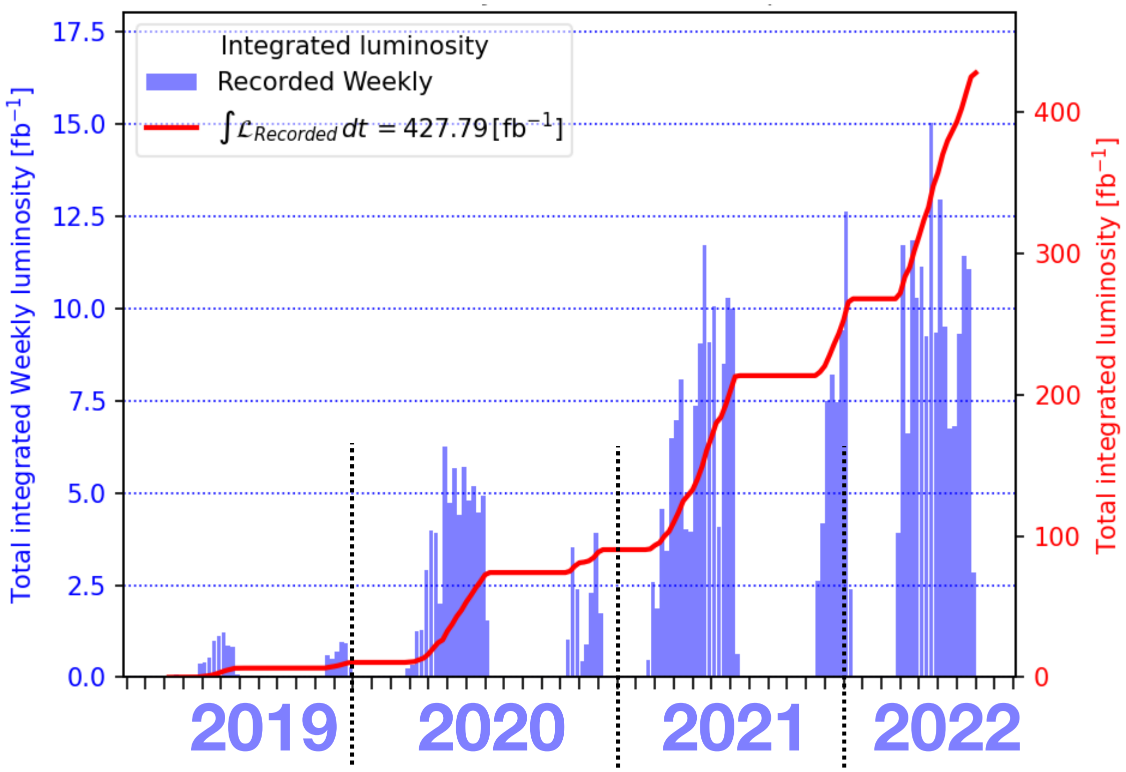
WR Luminosity of x 2.1×10^{34} cm^{-2} s^{-1}
(Currents 1.2/1.6 A) (June 2009)

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

Belle TDR, S0168-9002(01)02013-7

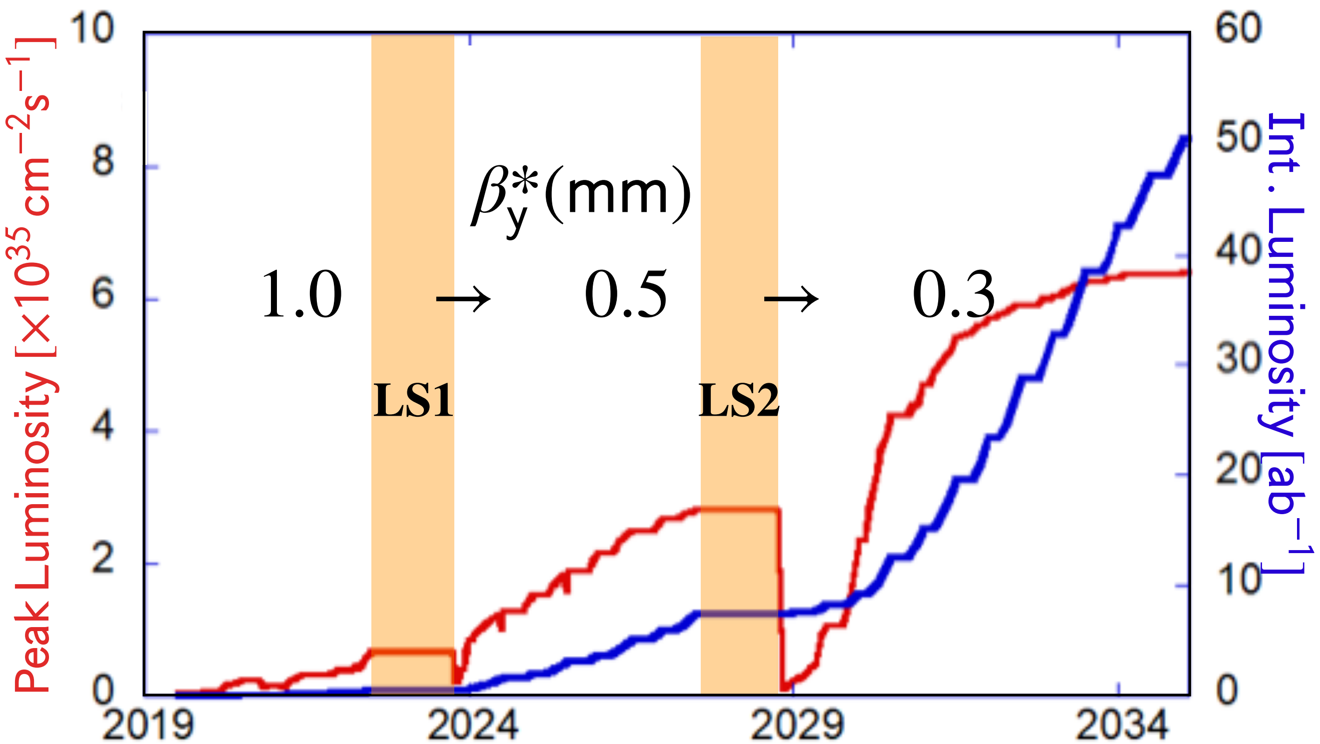
DATA TAKING SCHEDULE

Kodai Matsuoka, Rencontres du Vietnam Flavour Physics Conference 2022



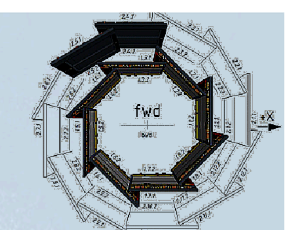
Recorded 424 fb^{-1}

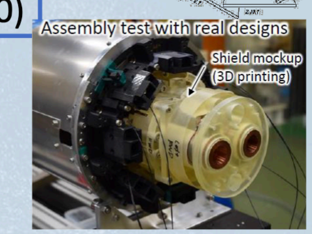
- 362 fb^{-1} at $\Upsilon(4S)$ cf. BaBar: 424 fb^{-1} at $\Upsilon(4S)$
- 42 fb^{-1} at $\Upsilon(4S)$ – 60 MeV
- 19 fb^{-1} around 10.75 GeV in 2021 autumn to study new structure $\Upsilon(10753)$ observed by Belle in $\pi^+\pi^-\Upsilon(nS)$ transition



Belle II detector upgrade

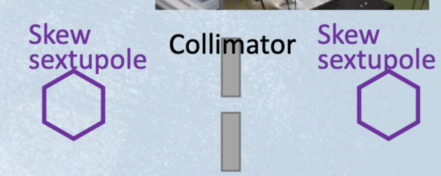
- Exchange of PXD (pixel detector) with the full 2nd layer
- TOP conventional MCP-PMT replacement (TBD)
- Migration to new back-end readout (COPPER → PCIe40)





Beam background mitigation

- Additional shield on the QCS(*) bellows
- Additional shield for neutron background
- Installation of a non-linear collimator



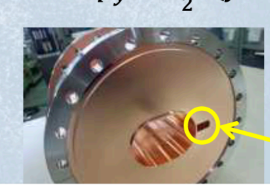
Beam kick by skew sextupole: $\Delta p_y = \frac{SK_2}{2}(y^2 - x^2)$, $\Delta p_x = SK_2 xy$

Protection of machine and Belle II

- Collimator heads of more robust material
- Faster beam abort system

Improvement of beam injection

- Enlarged beam pipe at the HER injection
- Pulse-by-pulse beam control for Linac



Beam channel for injection

QCS: Final focusing system

BELLE II, LHCB

Property	LHCb	Belle II
$\sigma_{\bar{b}b}(nb)$	~150,000	~**1**
$\int Ldt\ (fb^{-1})\ by\ 2027$	~**25**	~50,000
Background level	**High**	Low
Typical efficiency	**Low**	High
π^0, K_s efficiency	**Low**	High
Initial state	**Not well known**	Well known
Decay-time resolution	Excellent	**Good**
Collision spot size	**Large**	Tiny
Heavy bottom hadrons	B_s, B_c, b-baryons	**Partly B_s**
τ physics capability	**Limited**	Excellent
B-flavor tagging efficiency	**3.5-6%**	36%

Reference: Abi Soffer, Intensity Frontier in Particle Physics, October 2019, Taipei