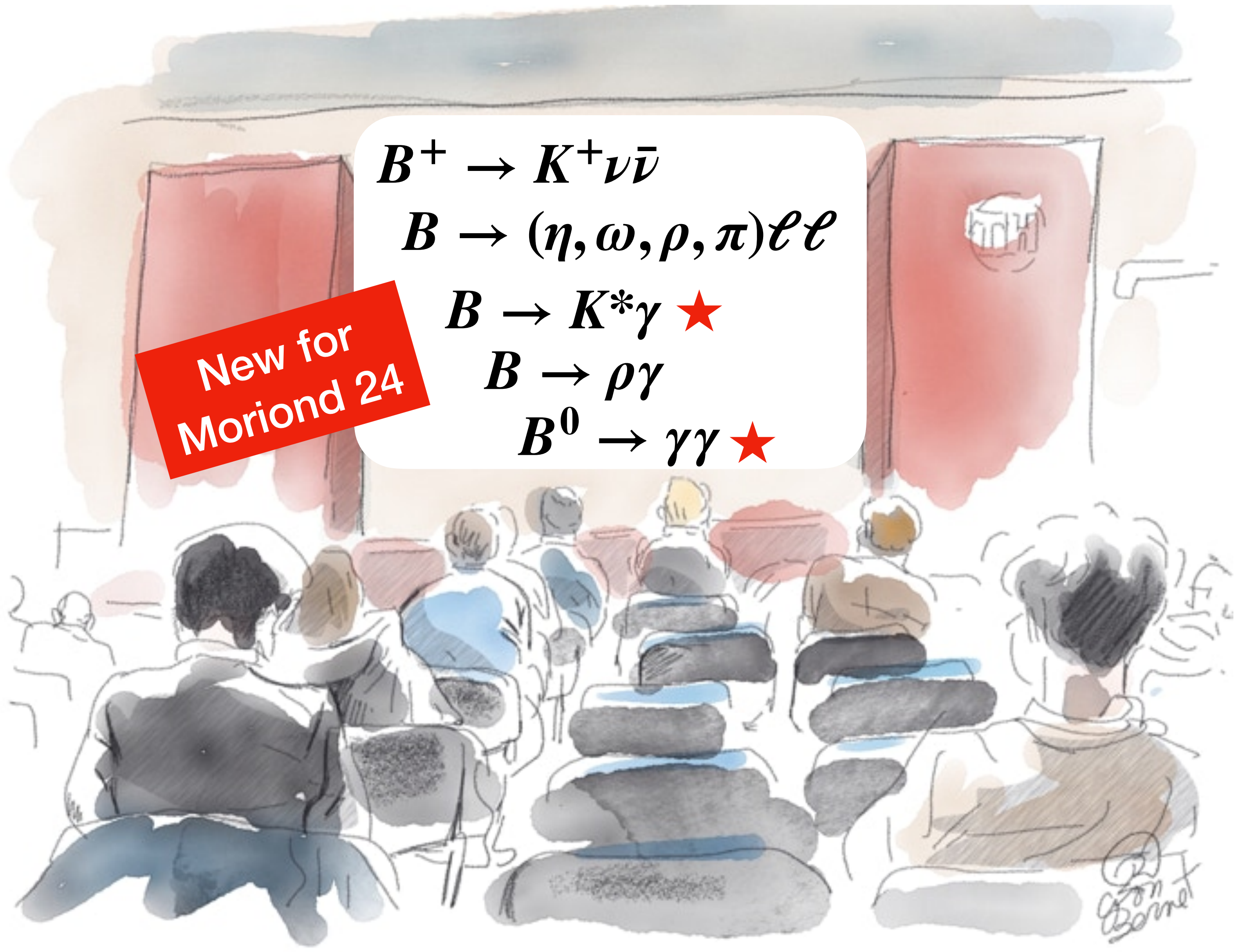
Radiative and electroweak penguin results from Belle and Belle II

Pablo Goldenzweig

On behalf of the Belle & Belle II Collaborations



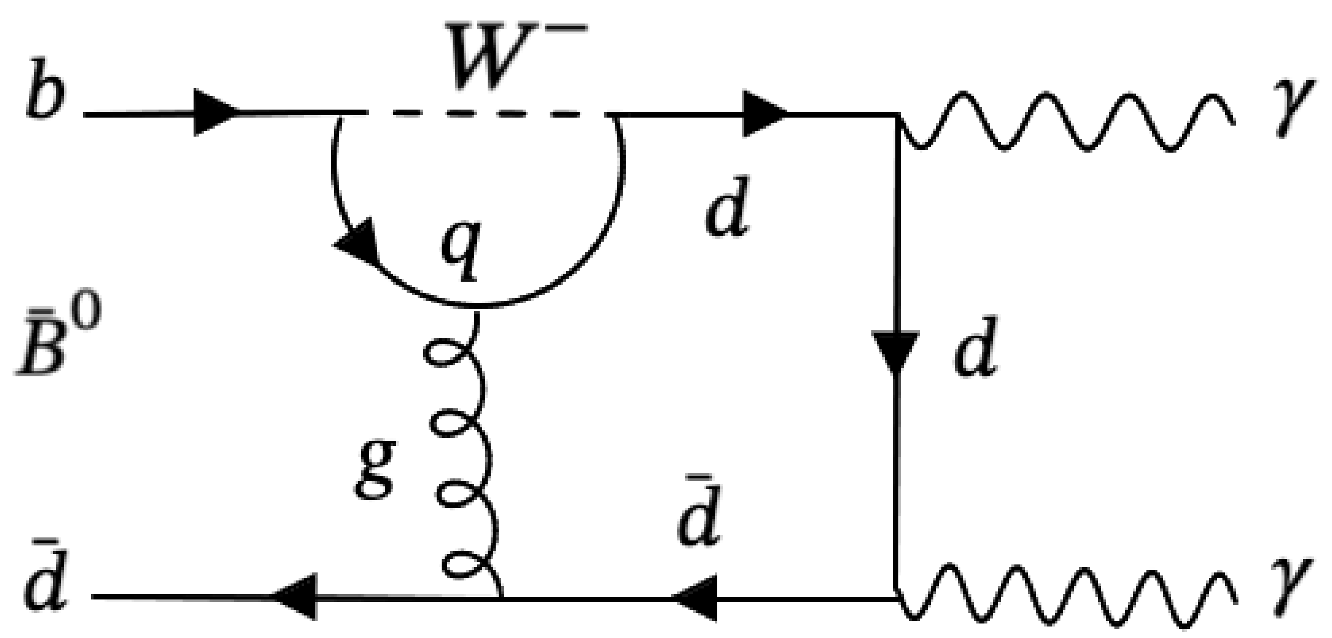
Moriond EW

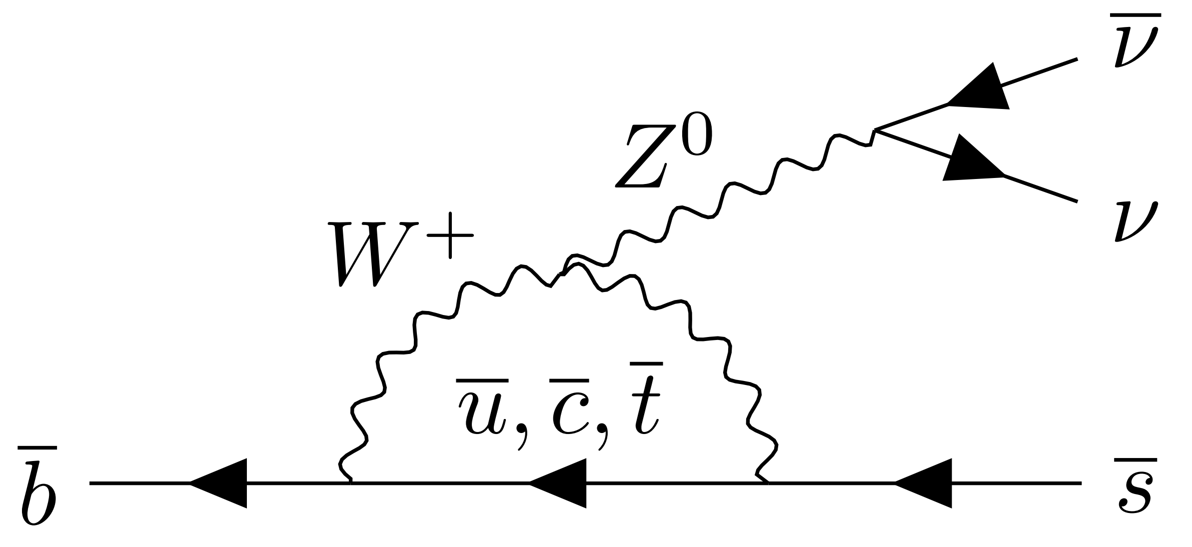
24-31 March 2024

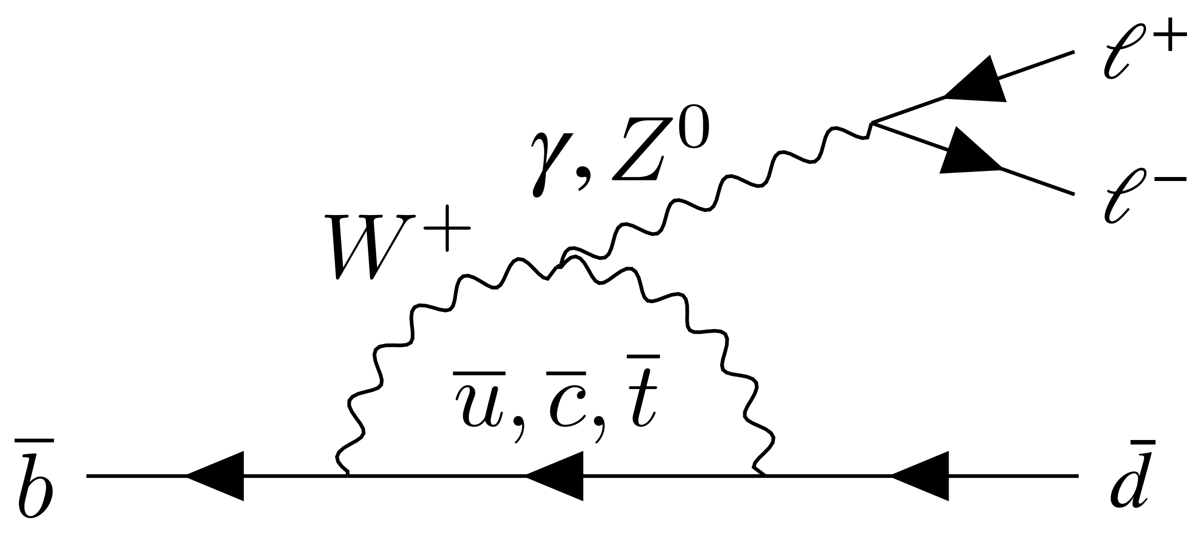
La Thuile

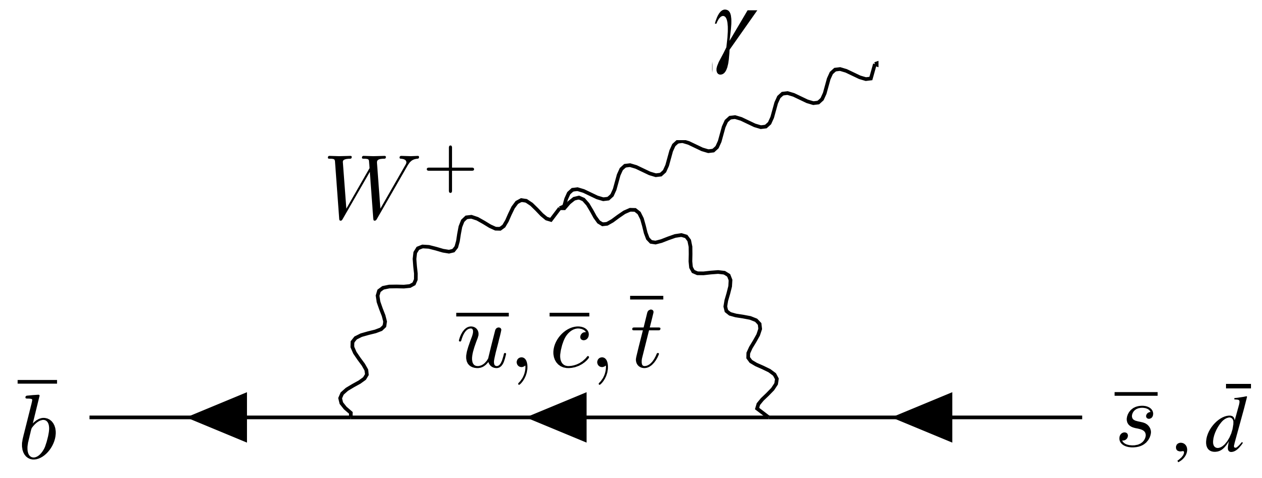
Introduction

- Flavor-changing neutral-current transitions are **excluded** in the SM at **tree-level** due to the GIM mechanism.
- Excellent place to **search for New Physics** that could interfere with radiative and electroweak penguin loops.
- In addition to $b \to s\nu\bar{\nu}$, $b \to d\ell\ell$, and $b \to (s,d)\gamma$, decays, we will report on the **first Belle + Belle II search for $B^0 \to \gamma\gamma$**:
    - *No direct interaction between the b and d quarks;*
    - *An effective FCNC is induced by a 1-loop or penguin diagram.*



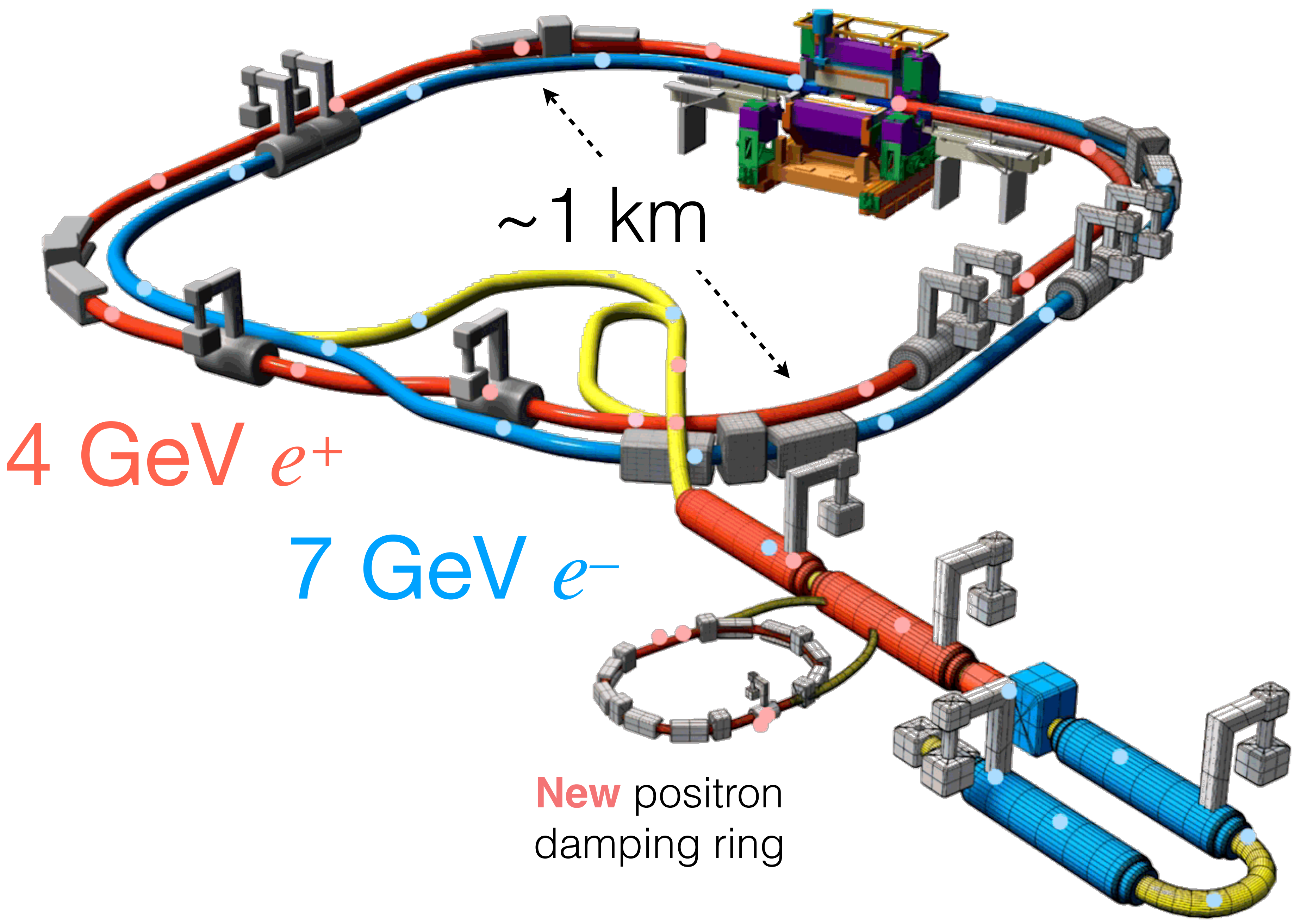




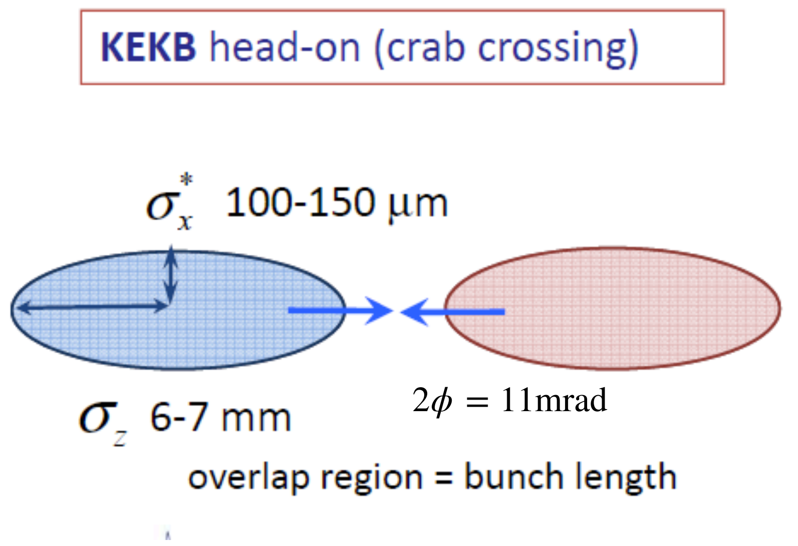


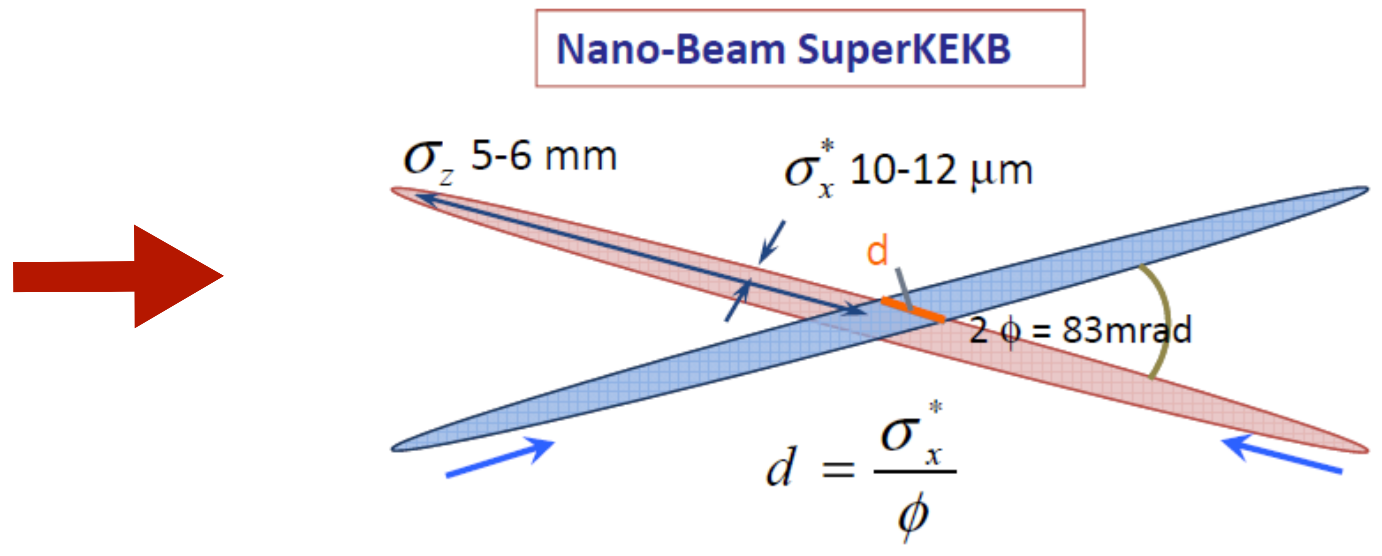
SuperKEKB and Belle II

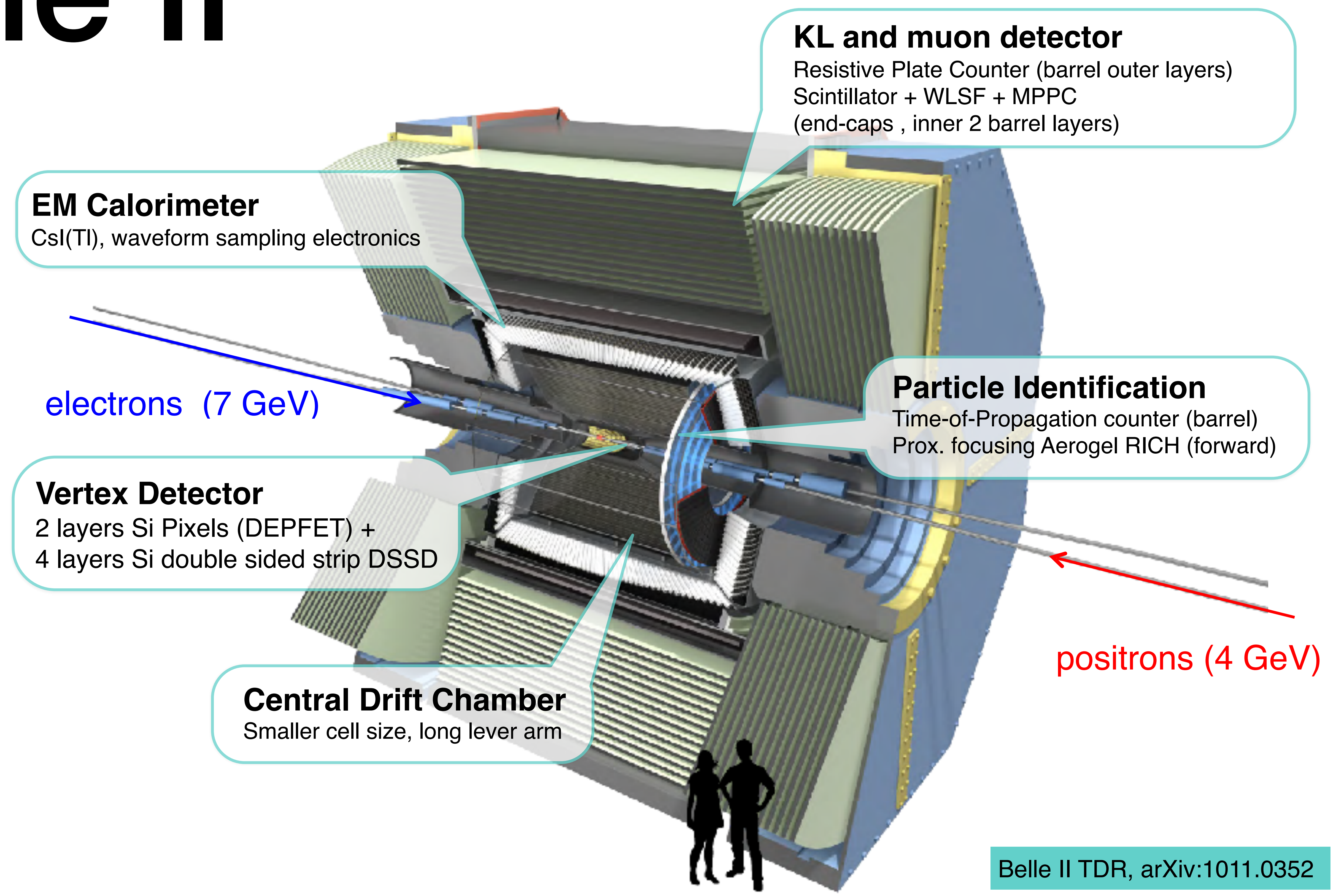
*Upgrade of KEKB and Belle to achieve **30x peak $\mathscr{L}$***



Animation © KEK





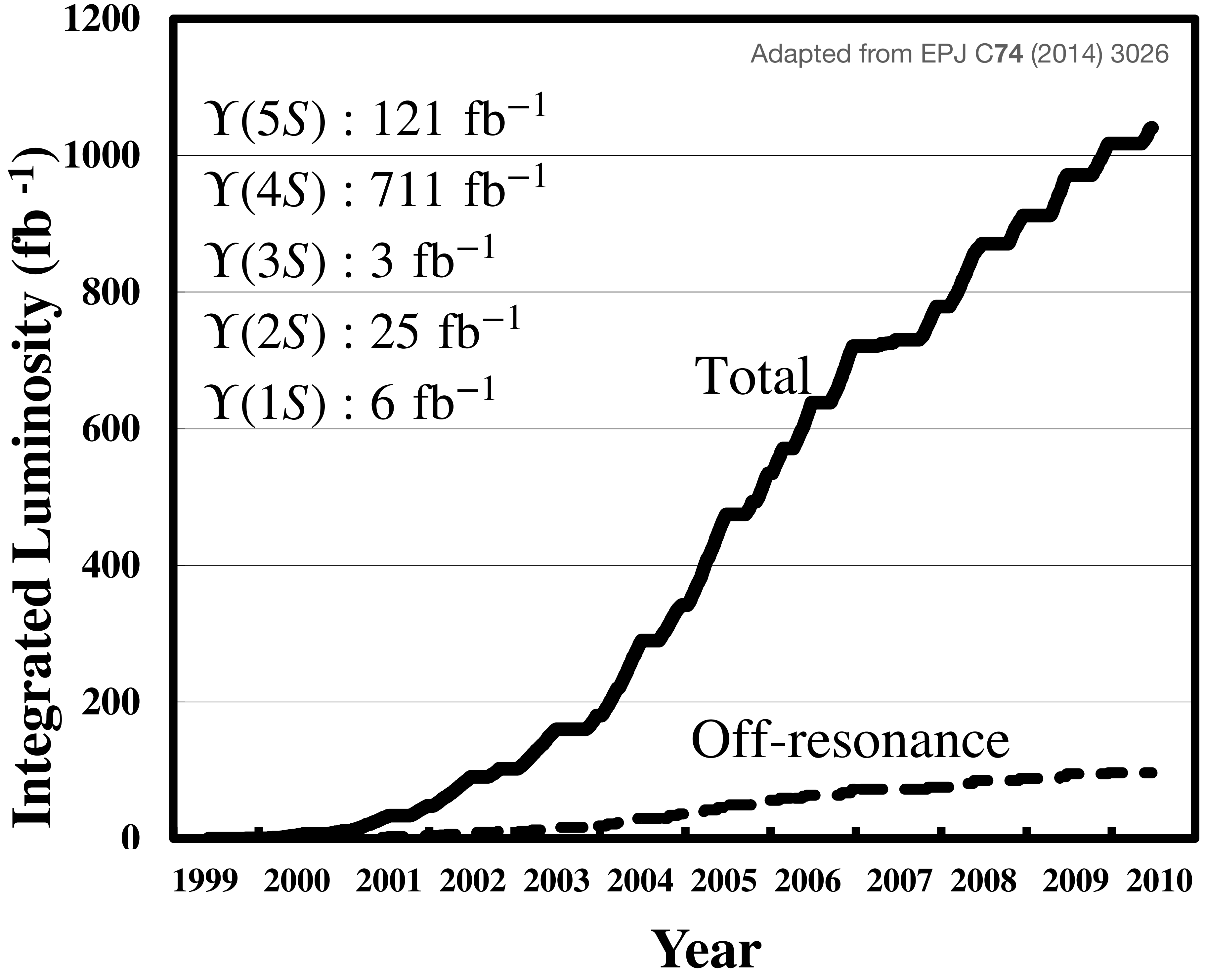


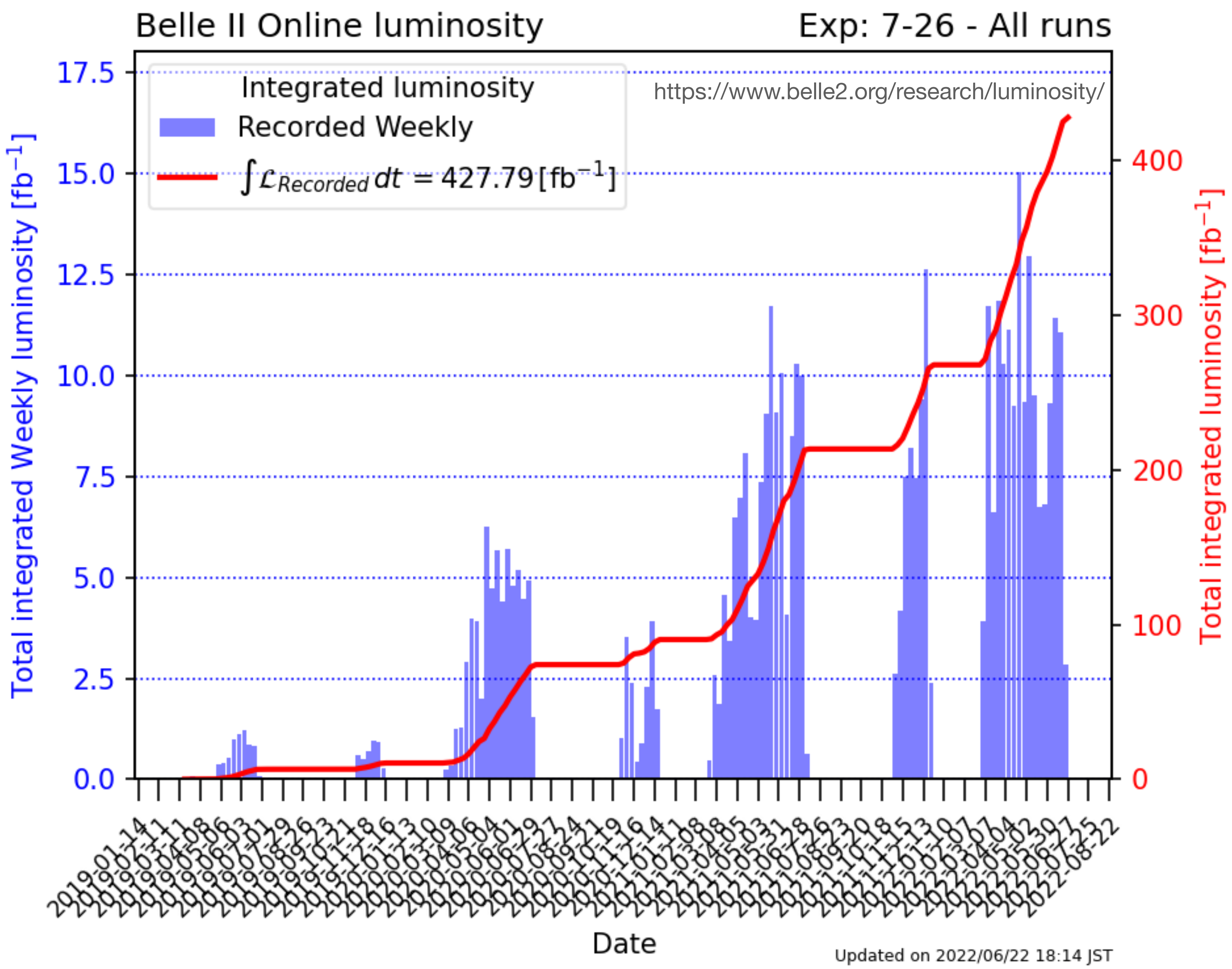
- *High resolution hermetic detector.*
- *Efficient reconstruction of neutrals (γ, π^0, η).*
- *World record* $\mathscr{L}_{\rm inst} = 4.7 \times 10^{34} {\rm cm}^{-2}{\rm s}^{-1}$ *(with $\beta_y^* = 1$mm).*

Datasets

BELLE

Belle II





Analysis presented today use Belle &/or Belle II datasets

BELLE $B \to (\eta, \omega, \rho, \pi)\ell\ell$

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

$B \to K^*\gamma$

BELLE + Belle II $B^0 \to \gamma\gamma$

$B \to \rho\gamma$

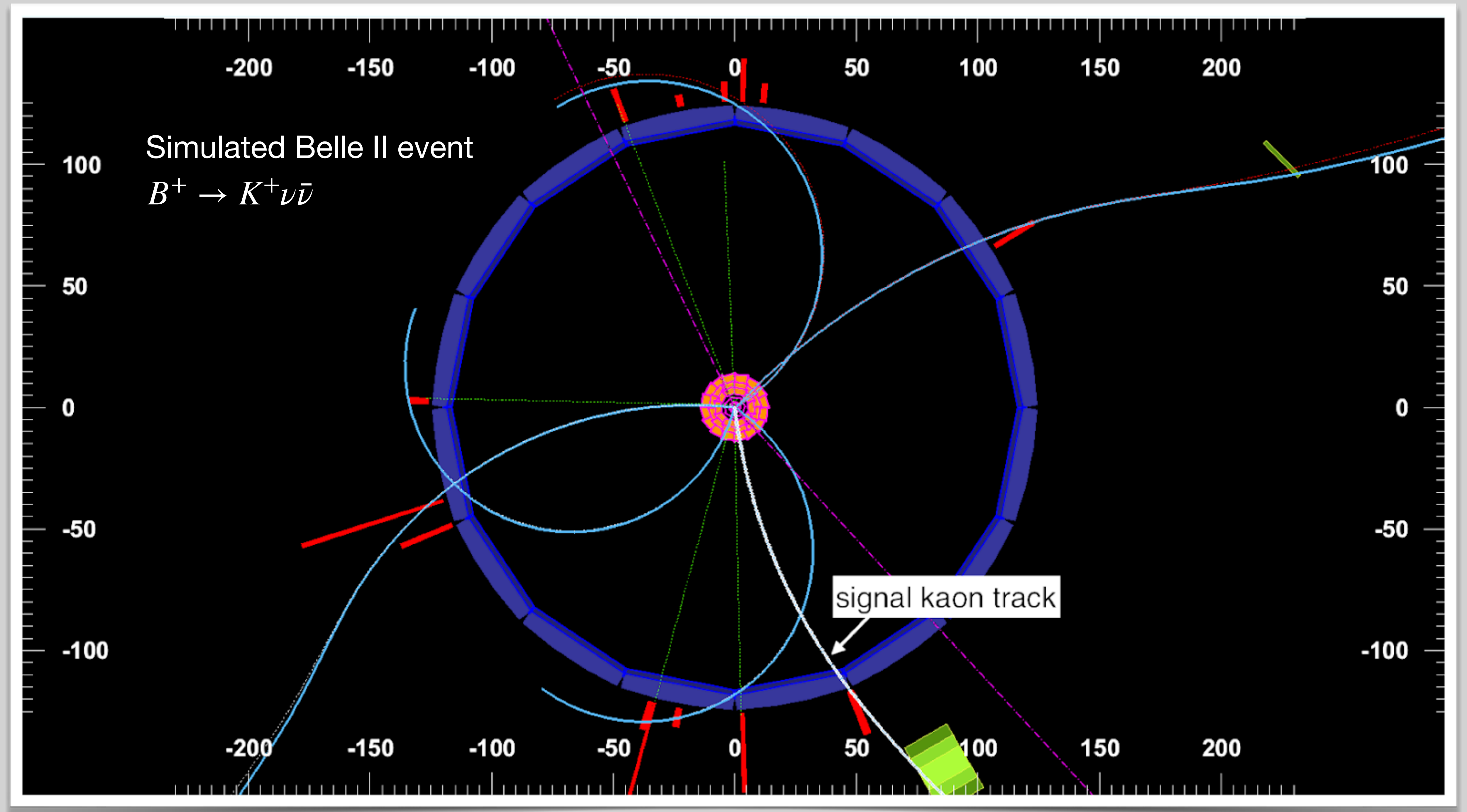
Evidence for $B^+ \to K^+\nu\bar{\nu}$

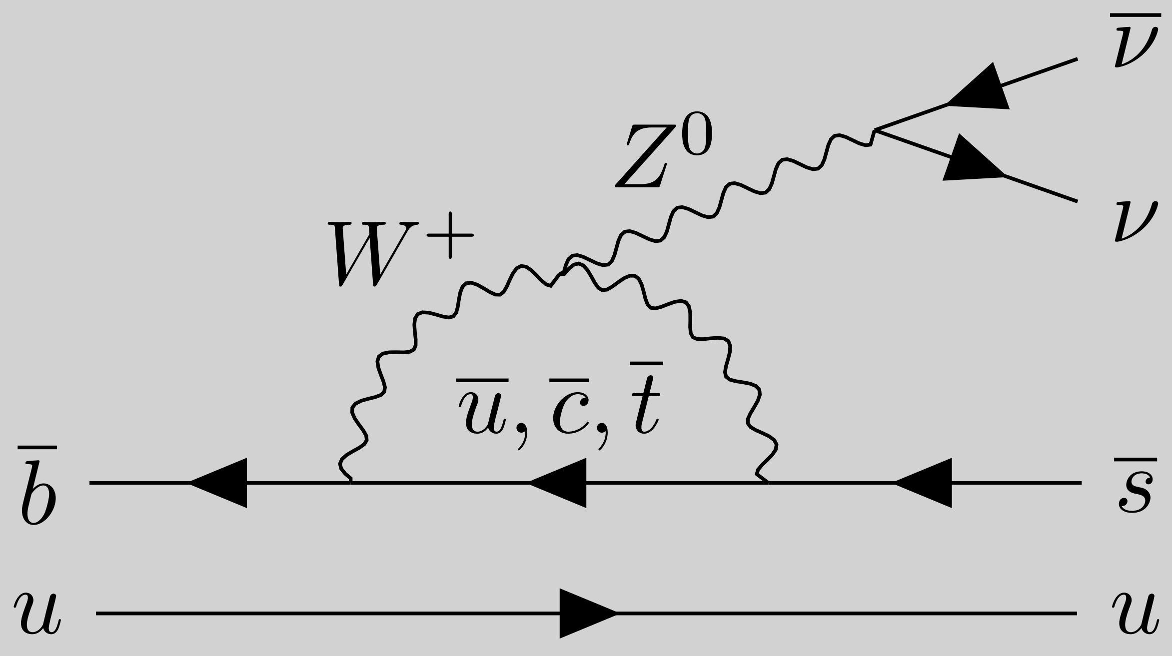
362 fb^{-1}

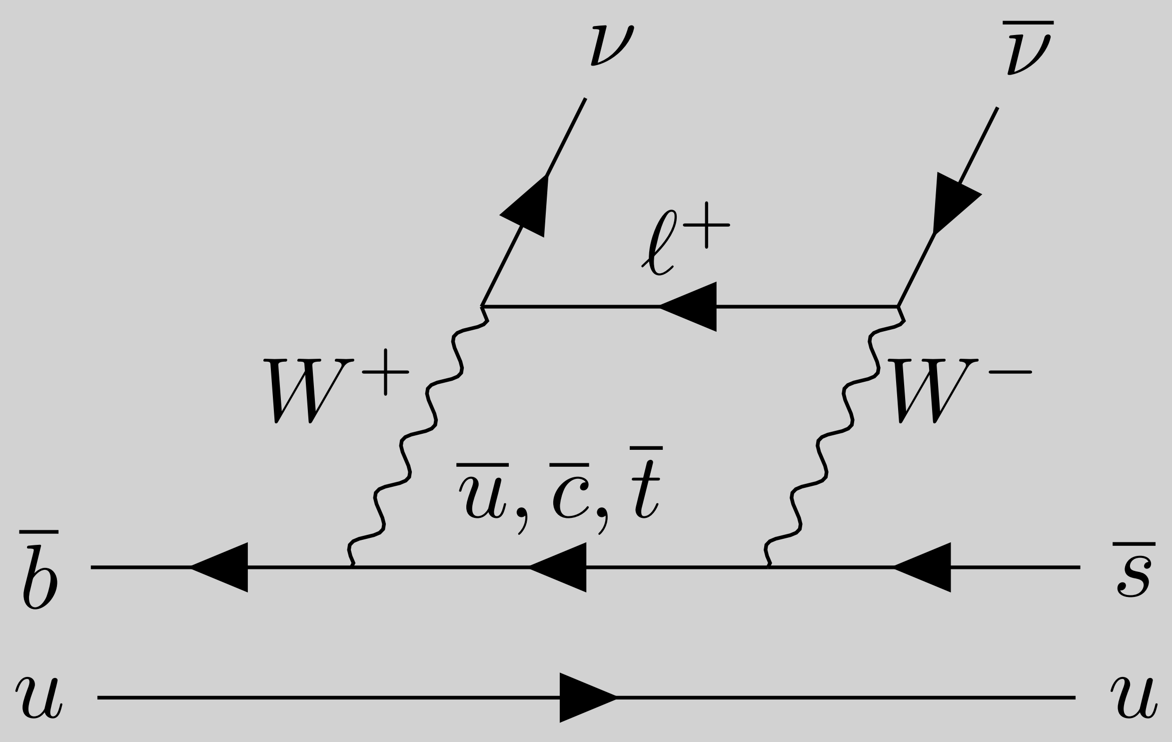
- **FCNC transition with precise SM prediction:**
  $\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = (5.58 \pm 0.37) \times 10^{-6}$.

*Including long-distance double charged current decay**
PRD **107**, 014511 (2023)

- **Belle II is ideally suited to measure B-decays with significant E_{miss}:**
  - Constraints from well-known initial state kinematics;
  - Lower average multiplicity at the $\Upsilon(4S)$ compared to hadronic collisions.







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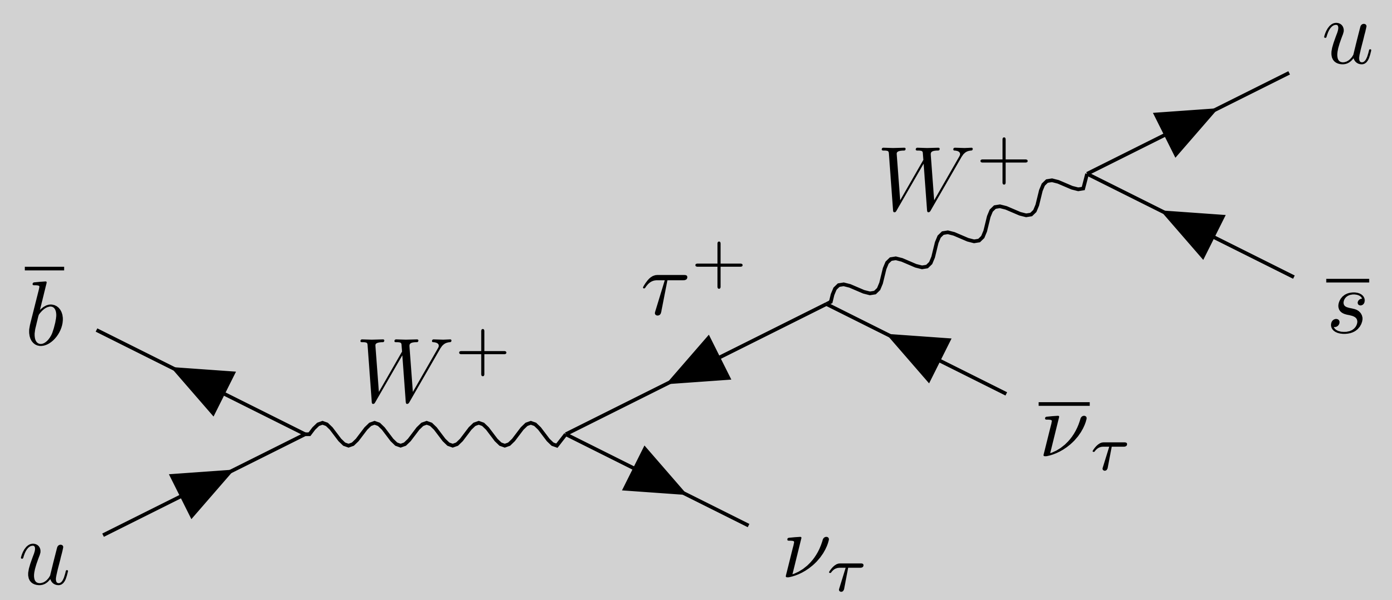

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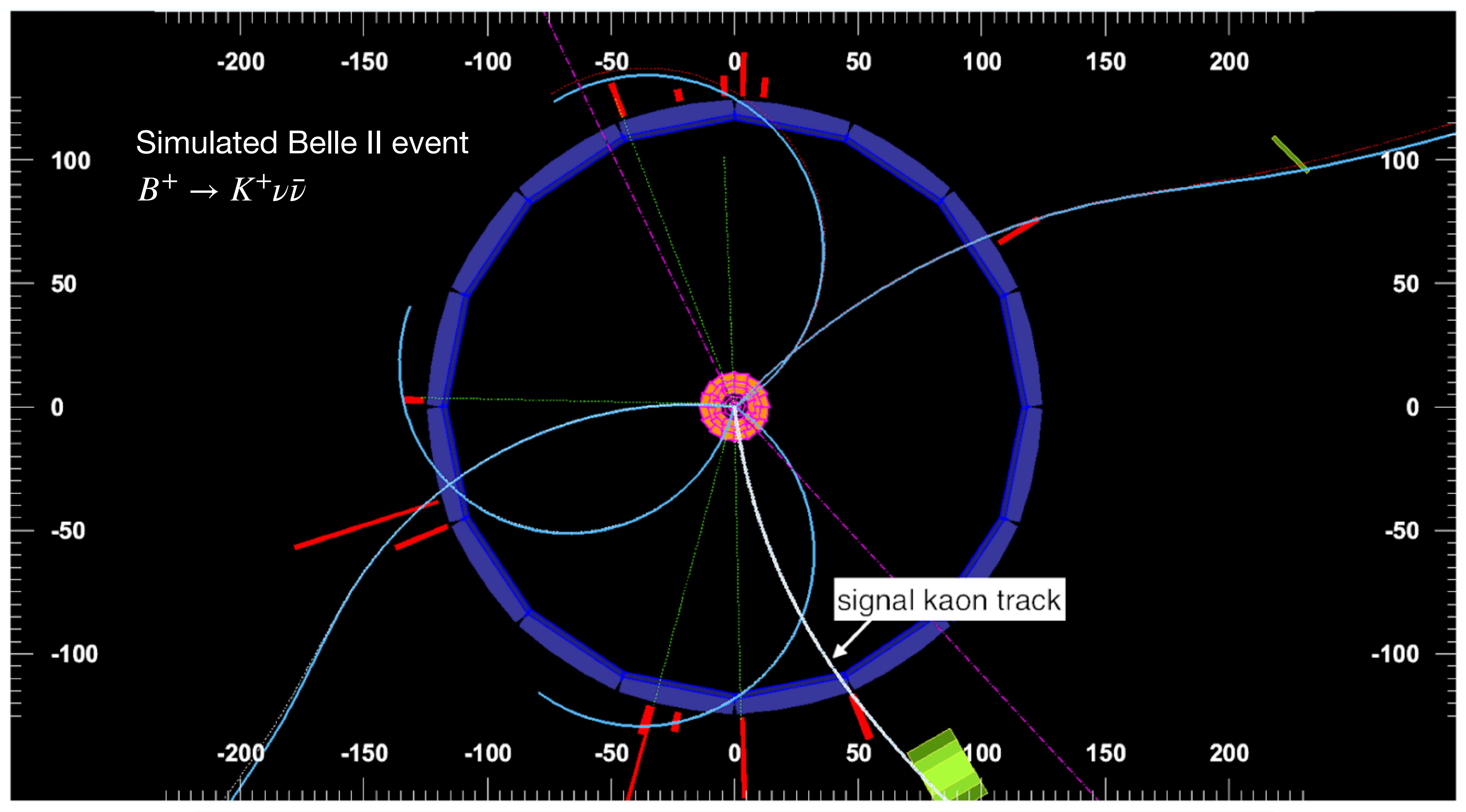
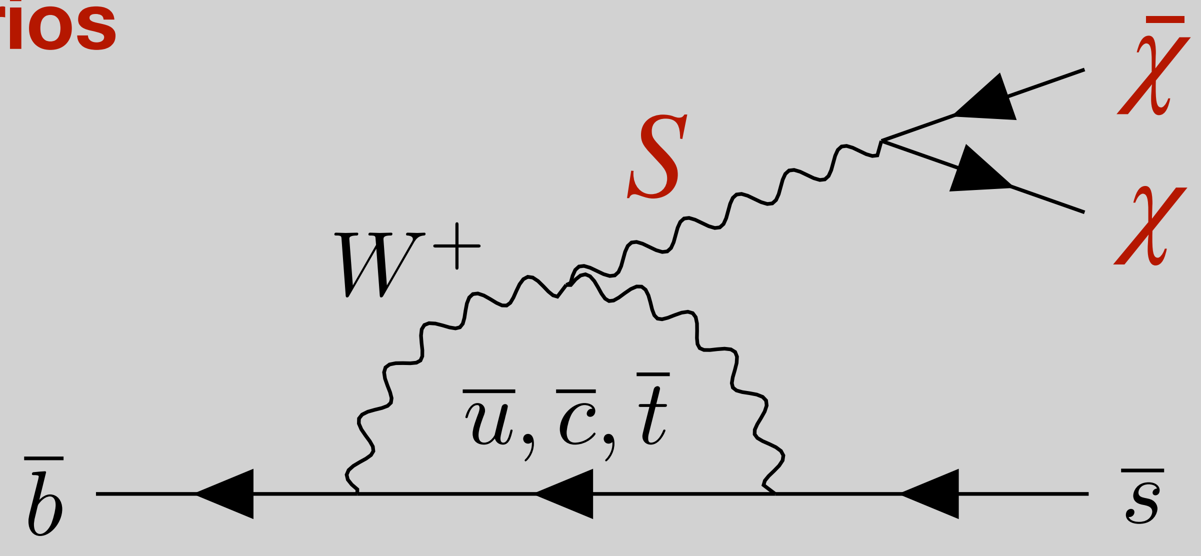
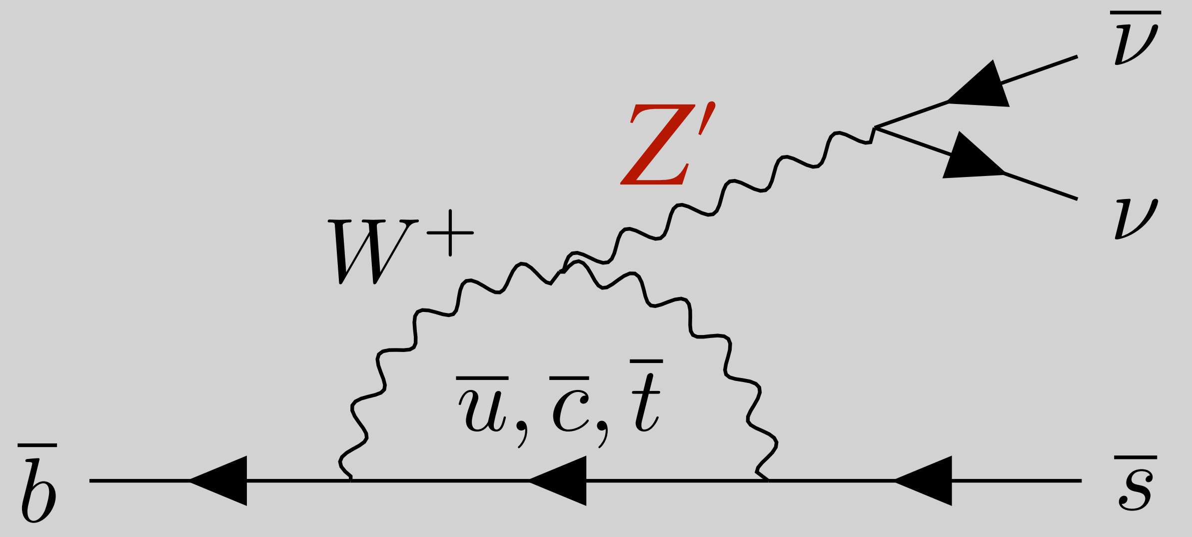


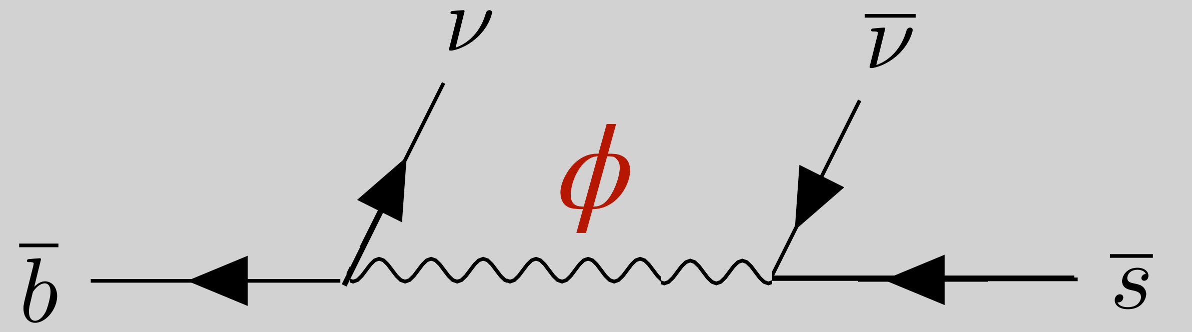
Decay rate can be significantly modified in models with BSM particles

NP Scenarios



Light:
- Axions PRD 102, 015023 (2020)
- ALPs JHEP 04, 131 (2023)
- Dark Scalars PRD 101, 095006 (2020)

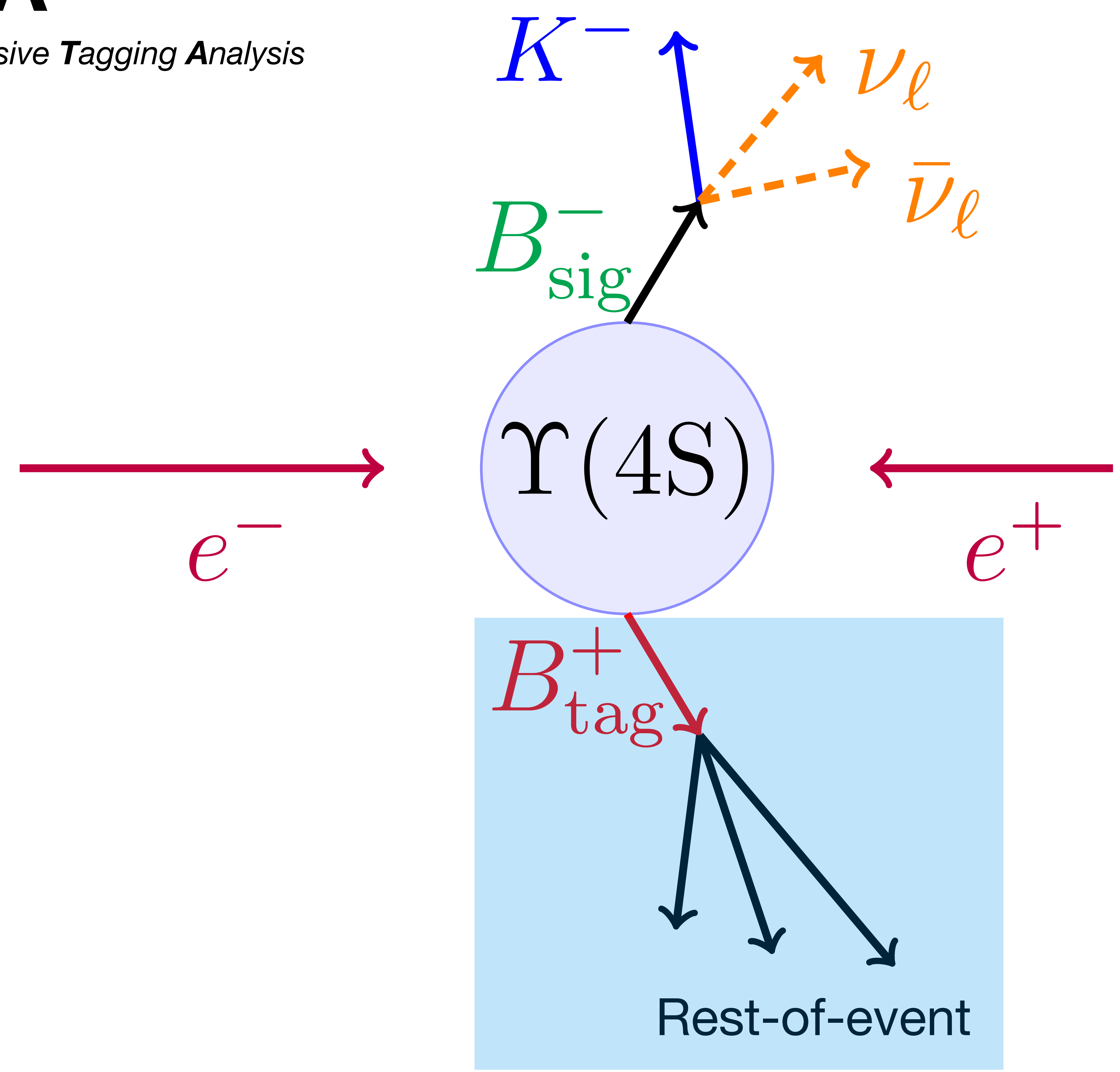




Heavy:
- Z' PLB 821, 13607 (2021)
- Leptoquarks PRD 98, 055003 (2018)

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

ITA
Inclusive Tagging Analysis

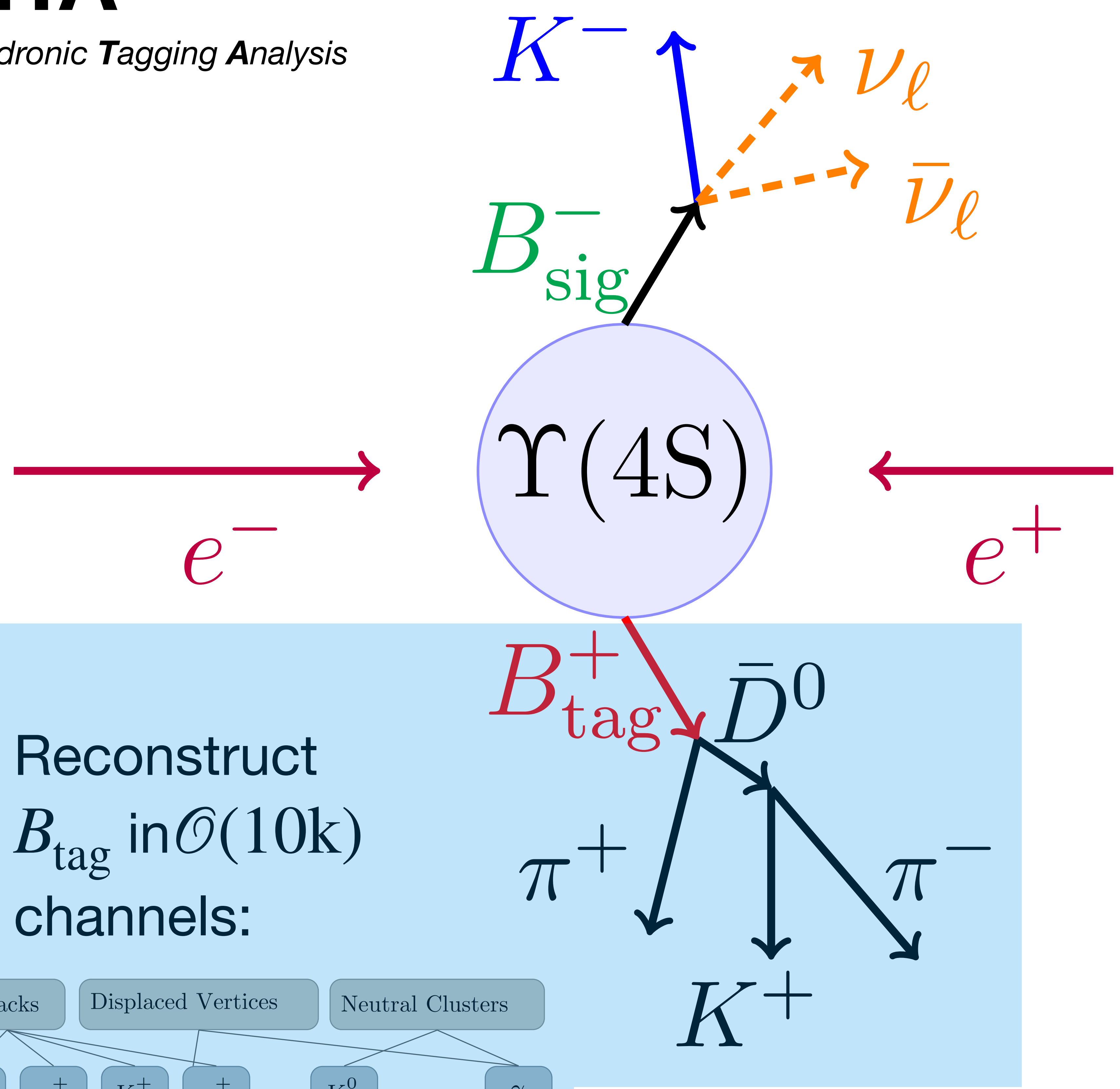


1) Select signal $K^\pm$ that minimizes $q^2_{\rm rec}$ ($K^\pm$ recoil).

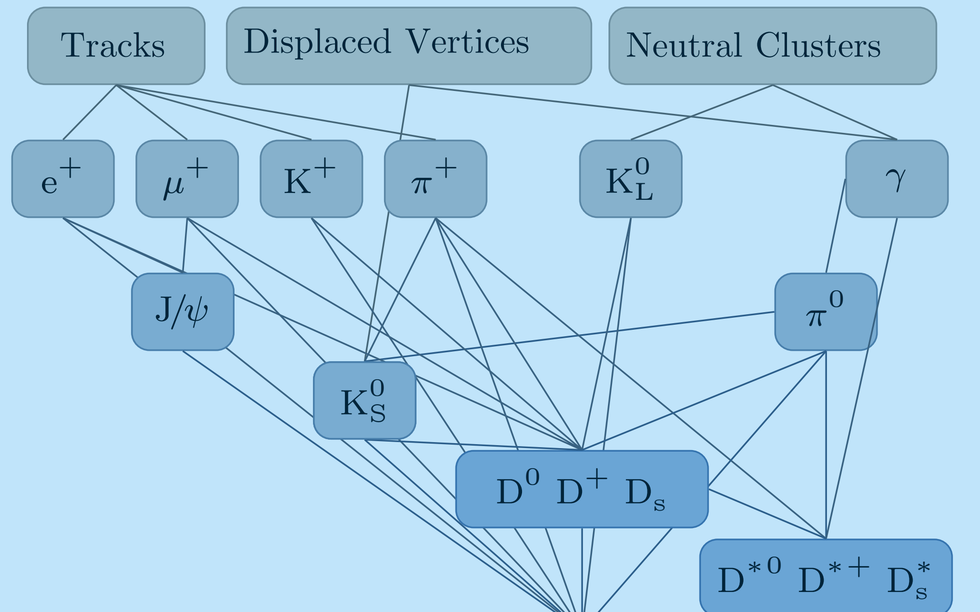
2) Identify rest-of-event object (includes all $E_{\rm miss}$).

Low purity (0.8%), high efficiency (8%)

HTA
Hadronic Tagging Analysis



1) Reconstruct $B_{\rm tag}$ in $\mathcal{O}(10{\rm k})$ channels:



Comput Softw Big Sci 3, 6 (2019)

2) Select signal $K^\pm$.

High purity (3.5%), low efficiency (0.4%)

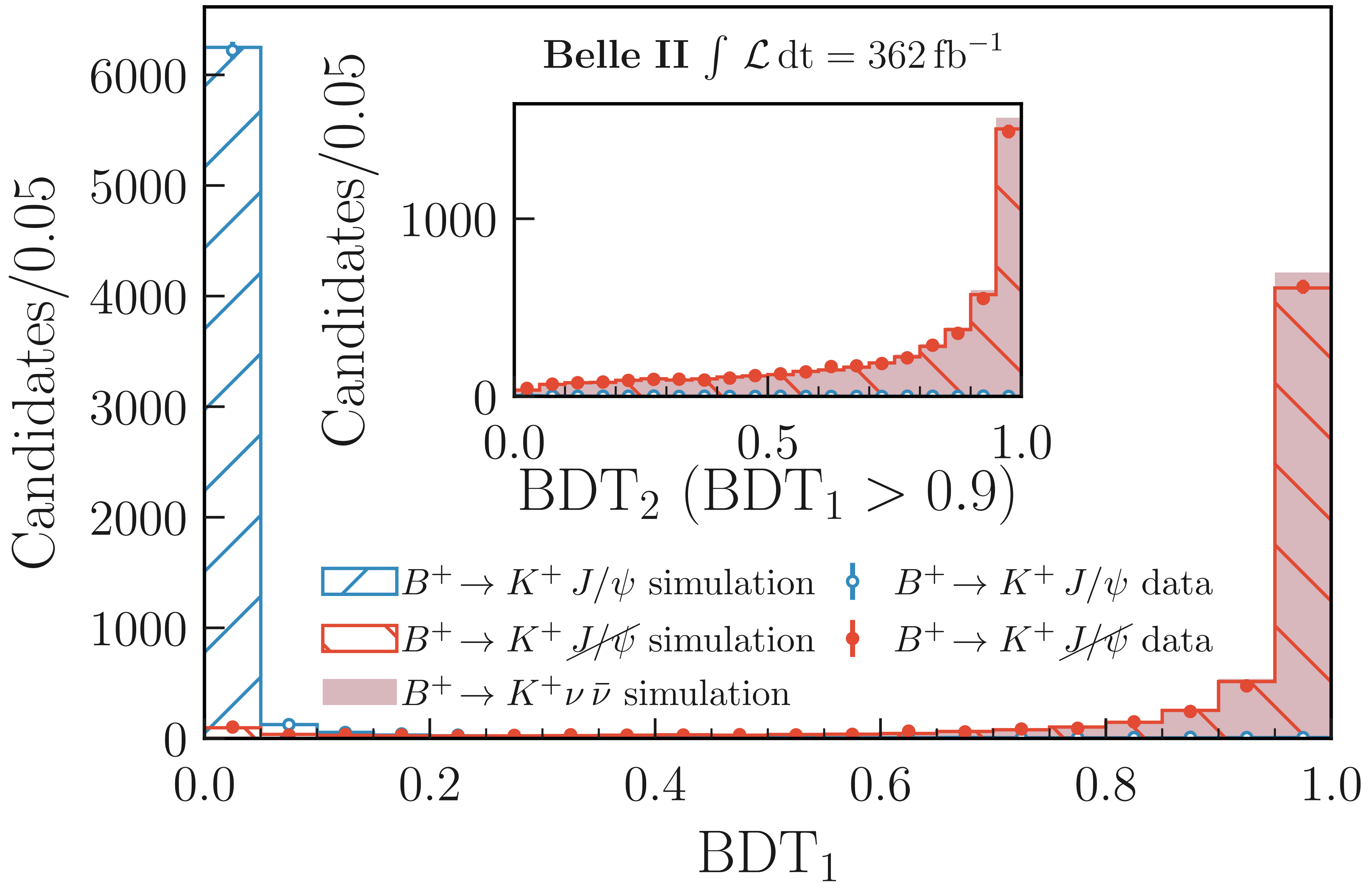
Small size of overlap results in 10% increase in precision over the ITA result alone.

See talk by S. Moneta for HTA result.

arXiv:2311.14647 [Accepted by PRD]

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

- Train two consecutive BTDs. Signal efficiency checked with $B^+ \to J/\psi K^+$ decays:
  - *Remove J/ψ and correct K^+ kinematics to match $K^+\nu\bar{\nu}$.*

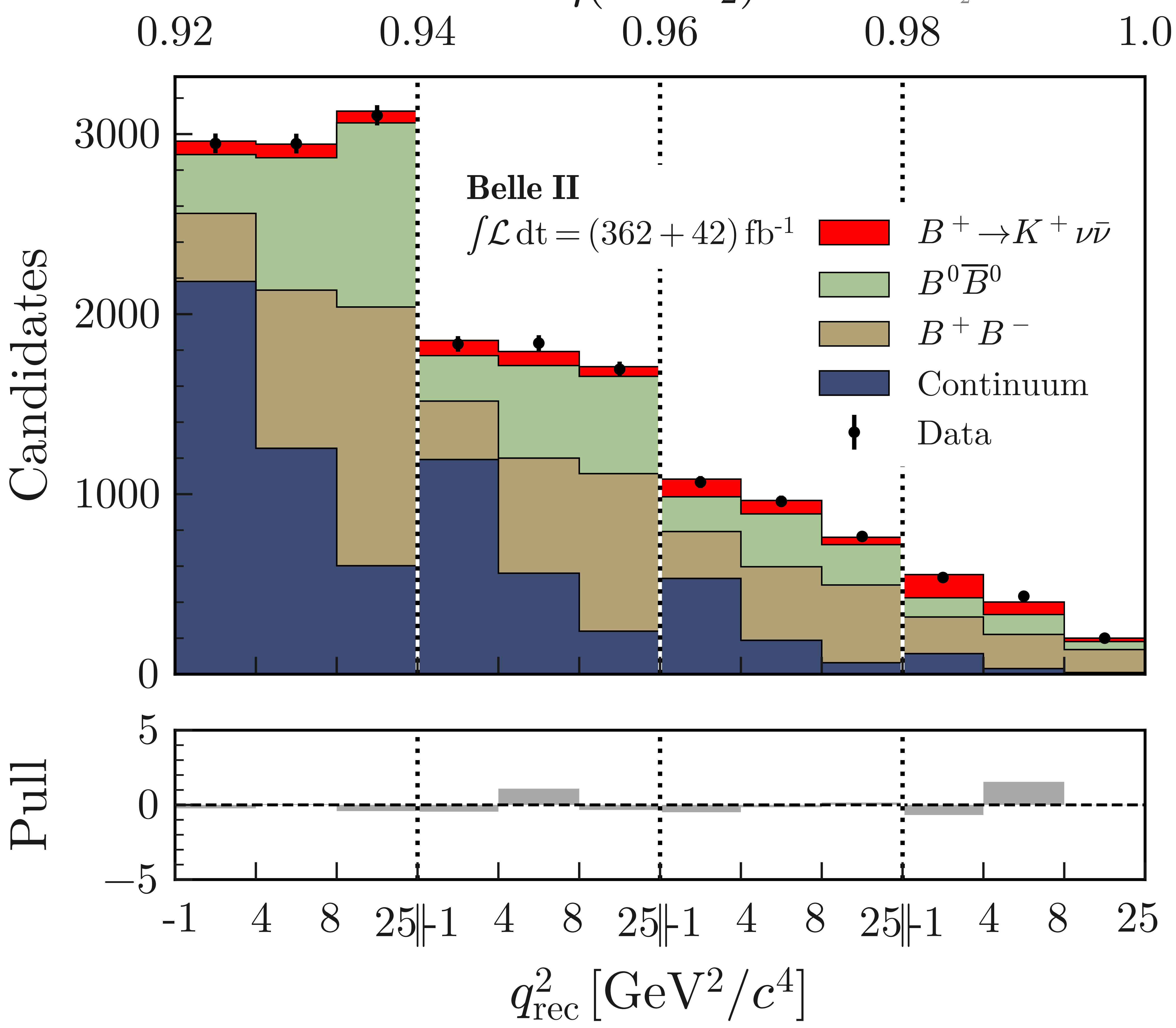


Detailed studies described in arXiv

- Contribution of $B \to X_c(K_L^0 X)$ corrected using π-enriched SB.
- Modeling of $\epsilon^{K_L^0}_{\text{detection}}$ in the calorimeter corrected using $e^+e^- \to \gamma\phi(\to K_S^0 K_L^0)$.
- Closure test: $\mathscr{B}(B^+ \to \pi^+ K_S^0) = (2.5 \pm 0.5) \times 10^{-5}$. *Compatible with PDG:* $(2.38 \pm 0.08) \times 10^{-5}$

Signal-selection ϵ density for $\mathrm{BDT}_2(b)$

$$\eta(\mathrm{BDT}_2) = 1 - \int_{\mathrm{BDT}_2}^{1} \epsilon(b)\,\mathrm{d}b$$



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

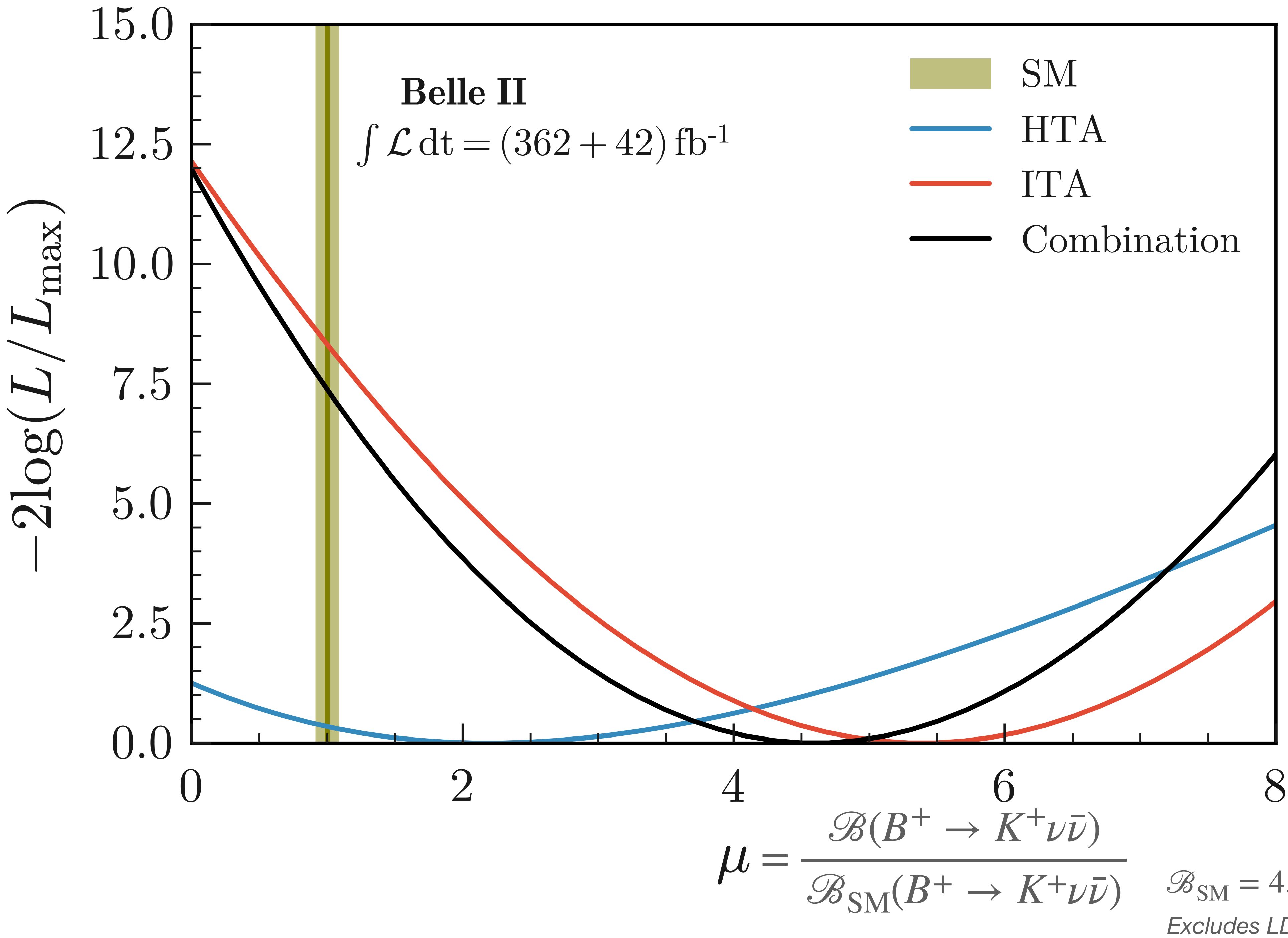
Bins follow theoretical predictions JHEP **02**, 184

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

arXiv:2311.14647 [Accepted by PRD]

ITA
- $\mathscr{B} = [2.7 \pm 0.5 \pm 0.5] \times 10^{-5}$
- Significance of the excess 3.5σ
- 2.9σ deviation from SM

HTA
- $\mathscr{B} = [1.1^{+0.9+0.8}_{-0.8-0.5}] \times 10^{-5}$
- Significance of the excess 1.1σ
- 0.6σ deviation from SM



$\mathscr{B}_{SM} = 4.97 \times 10^{-6}$

Excludes LD diagram

- Perform likelihood-level combination:
  - *Include correlations among common systematic uncertainties;*
  - *Common data events excluded from ITA sample.*

Compatibility between ITA and HTA results at 1.2σ

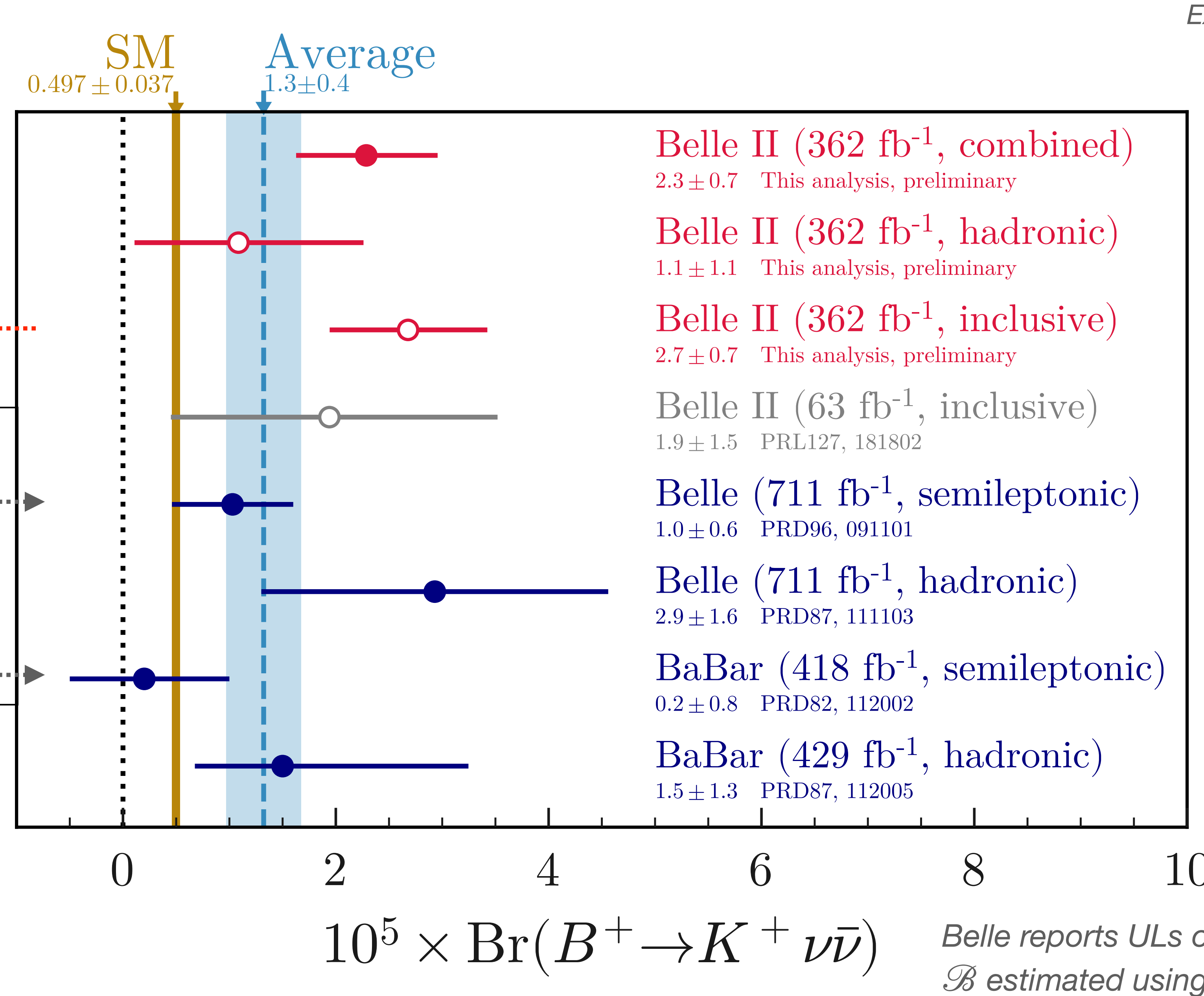
$$\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = [2.3 \pm 0.5(\text{stat})^{+0.5}_{-0.4}(\text{syst})] \times 10^{-5}$$

Significance of the excess is 3.5σ

2.7σ deviation from the SM prediction

HTA
In agreement with all previous measurements

ITA
1.8σ tension with Belle
2.3σ tension with BaBar

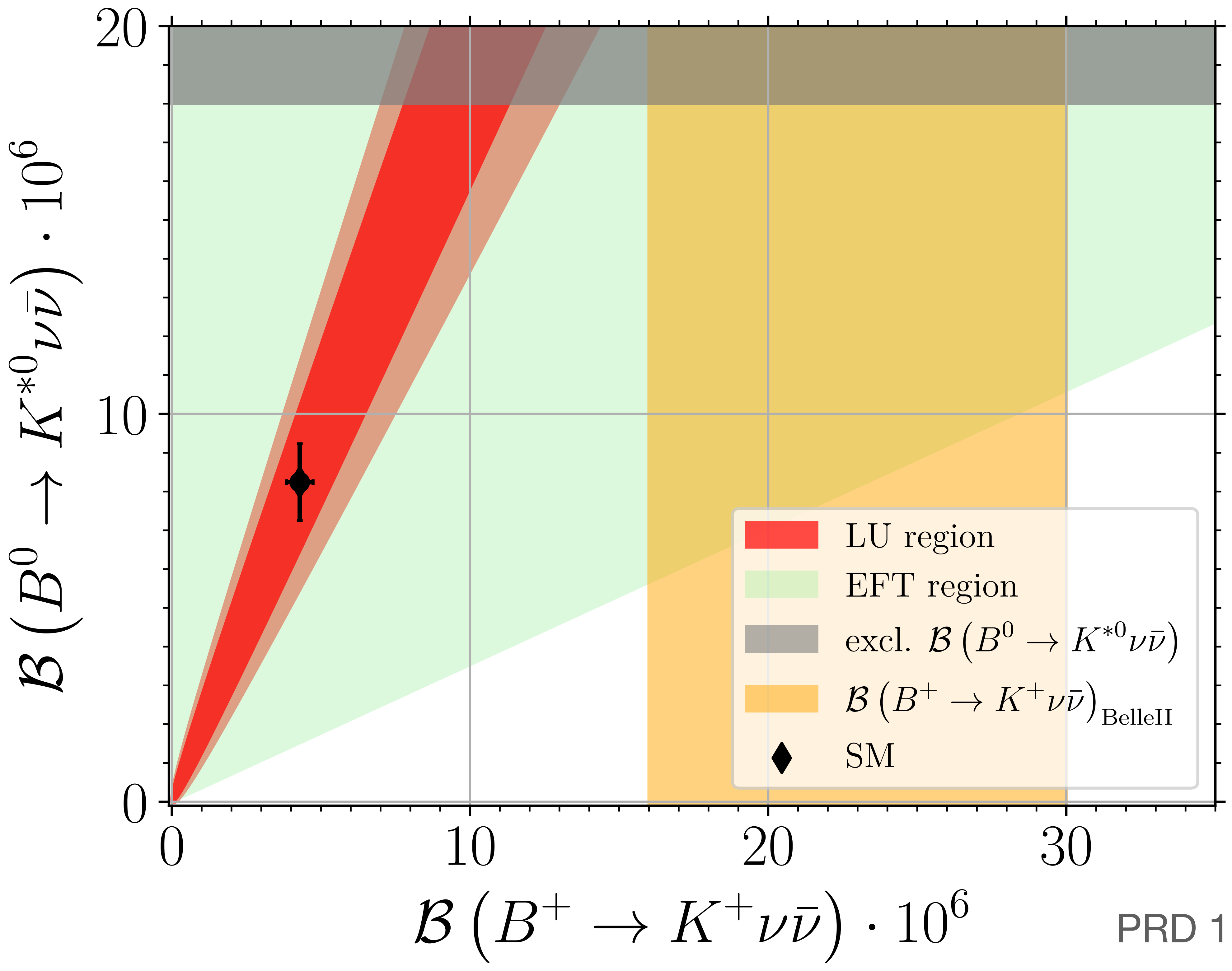


Overall compatibility
$\chi^2/\mathrm{ndf} = 5.6/5$

Belle reports ULs only; $\mathscr{B}$ estimated using published # of events & ϵ.

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

Many papers have been written to interpret this result



PRD 109, 015006 (2024)

- Lepton [flavor] universality (red) does not intersect with Belle II data (yellow) below the grey band (90% CL excluded).

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

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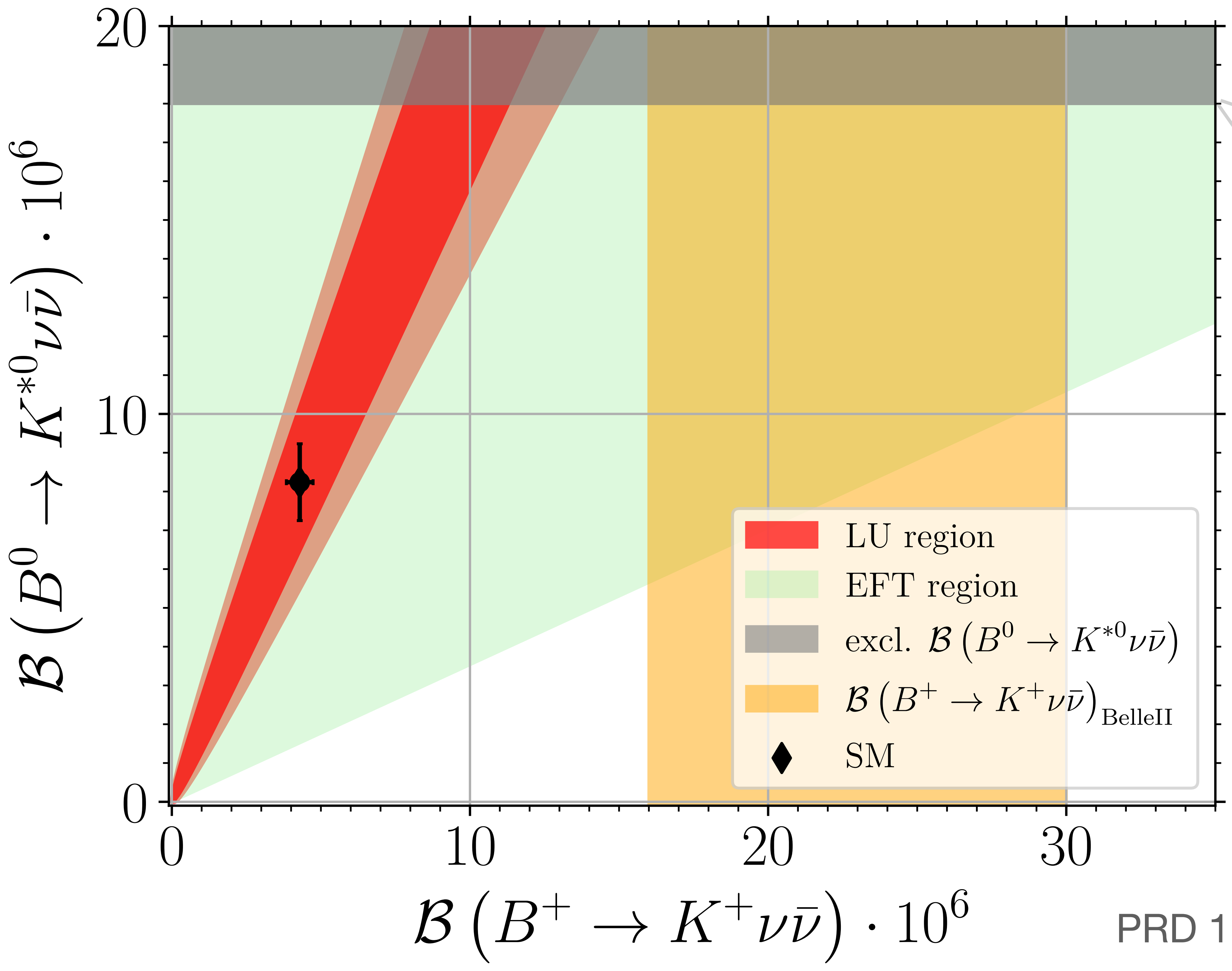


PRD 109, 015006 (2024)

- Lepton [flavor] universality (red) does not intersect with Belle II data (yellow) below the grey band (90% CL excluded).

Very active effort within Belle II to provide results for other $b \to s\nu\bar{\nu}$ channels.

Belle SL tag PHYSICAL REVIEW D **96,** 091101(R) (2017)

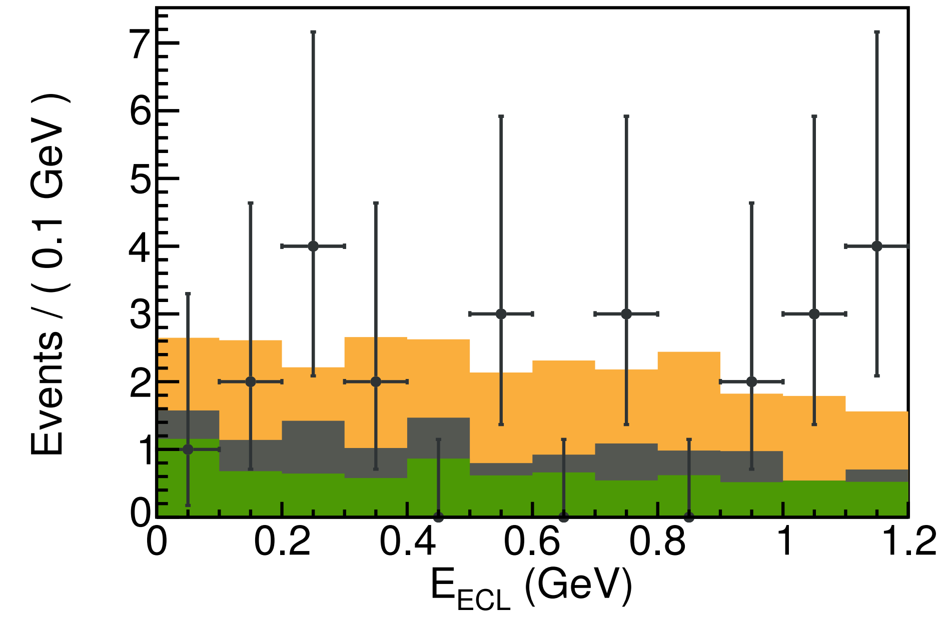
TABLE I. Results

(a) Observed signal yield (corrected for fitting bias) in each channel. The first error is statistical and the second is systematic.

Channel	Observed signal yield	Significance
$K^+\nu\bar{\nu}$	$17.7 \pm 9.1 \pm 3.4$	1.9σ
$K^0_S\nu\bar{\nu}$	$0.6 \pm 4.2 \pm 1.4$	0.0σ
$K^{*+}\nu\bar{\nu}$	$16.2 \pm 7.4 \pm 1.8$	2.3σ
$K^{*0}\nu\bar{\nu}$	$-2.0 \pm 3.6 \pm 1.8$	0.0σ
$\pi^+\nu\bar{\nu}$	$5.6 \pm 15.1 \pm 5.9$	0.0σ
$\pi^0\nu\bar{\nu}$	$0.2 \pm 5.6 \pm 1.6$	0.0σ
$\rho^+\nu\bar{\nu}$	$6.2 \pm 12.3 \pm 2.4$	0.3σ
$\rho^0\nu\bar{\nu}$	$11.9 \pm 9.0 \pm 3.6$	1.2σ

(b) Expected (median) and observed upper limits on the branching fraction at 90% C.L. The observed limits include the systematic uncertainties.

Channel	Efficiency	Expected limit	Observed limit
$K^+\nu\bar{\nu}$	2.16×10^{-3}	0.8×10^{-5}	1.9×10^{-5}
$K^0_S\nu\bar{\nu}$	0.91×10^{-3}	1.2×10^{-5}	1.3×10^{-5}
$K^{*+}\nu\bar{\nu}$	0.57×10^{-3}	2.4×10^{-5}	6.1×10^{-5}
$K^{*0}\nu\bar{\nu}$	0.51×10^{-3}	2.4×10^{-5}	1.8×10^{-5}
$\pi^+\nu\bar{\nu}$	2.92×10^{-3}	1.3×10^{-5}	1.4×10^{-5}
$\pi^0\nu\bar{\nu}$	1.42×10^{-3}	1.0×10^{-5}	0.9×10^{-5}
$\rho^+\nu\bar{\nu}$	1.11×10^{-3}	2.5×10^{-5}	3.0×10^{-5}
$\rho^0\nu\bar{\nu}$	0.82×10^{-3}	2.2×10^{-5}	4.0×10^{-5}



(d) $B^0 \to K^{*0}\nu\bar{\nu}$

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

711 fb^{-1}

- FCNC processes with multiple charged particles in final state with $\mathcal{B}(b \to d\ell^+\ell^-) \leq \mathcal{O}(10^{-8})$.

- $b \to d\ell^+\ell^-$ **suppressed** relative to $b \to s\ell^+\ell^-$ by $\frac{|V_{td}|^2}{|V_{ts}|^2} \sim 0.04$.

- NP signature may be **uniquely observed** in $b \to d\ell^+\ell^-$ if sensitive to quark flavors.

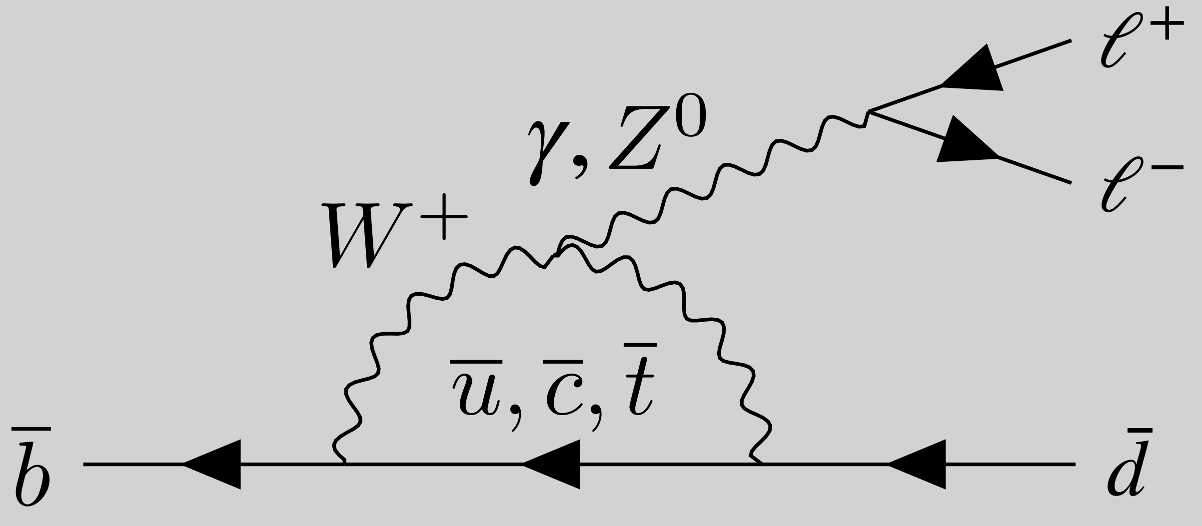
- LHCb has observed final states with muons and $\pi^\pm$ but none with **neutral mesons** (3 fb^{-1}):

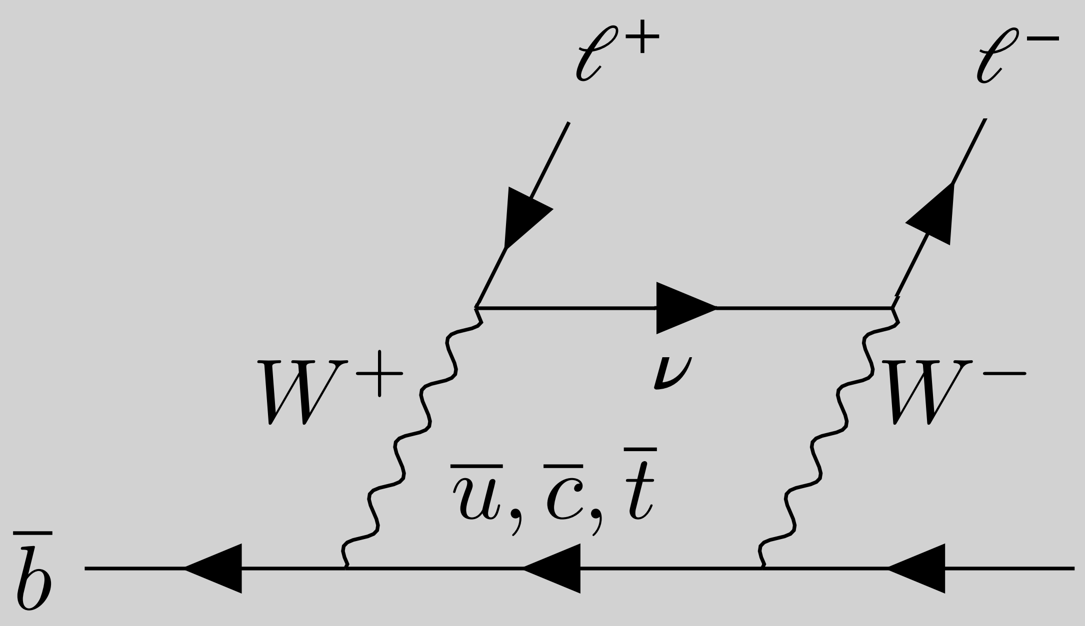
$$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-) = (1.78 \pm 0.23) \times 10^{-8},$$
$$\mathcal{B}(B^0 \to \rho^0\mu^+\mu^-) = (1.98 \pm 0.53) \times 10^{-8},$$
$$\mathcal{B}(B^0 \to \pi^+\pi^-\mu^+\mu^-) = (2.11 \pm 0.52) \times 10^{-8}.$$

No hint of any discrepancy so far…

JHEP **10** (2015) 34, PLB **743** (2015) 46

- ***Probe of LFU*** *in $b \to d\ell^+\ell^-$ possible with results from e and μ final states.*





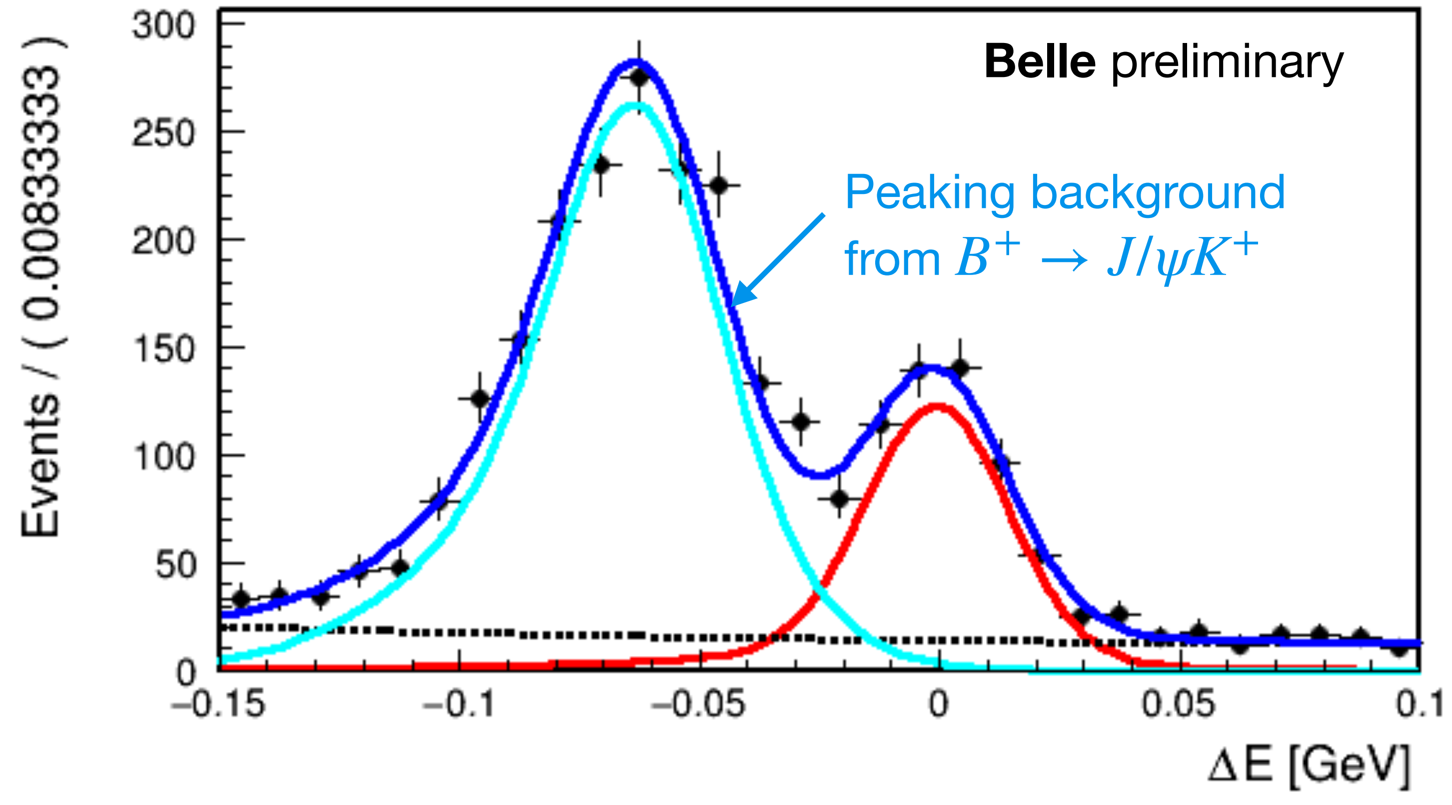
Today

$$B^{\pm,0} \to \left(\eta, \omega, \pi^{\pm,0}\rho^{\pm,0}\right) ee$$
$$B^{\pm,0} \to \left(\eta, \omega, \pi^{0}\rho^{\pm}\right) \mu\mu$$

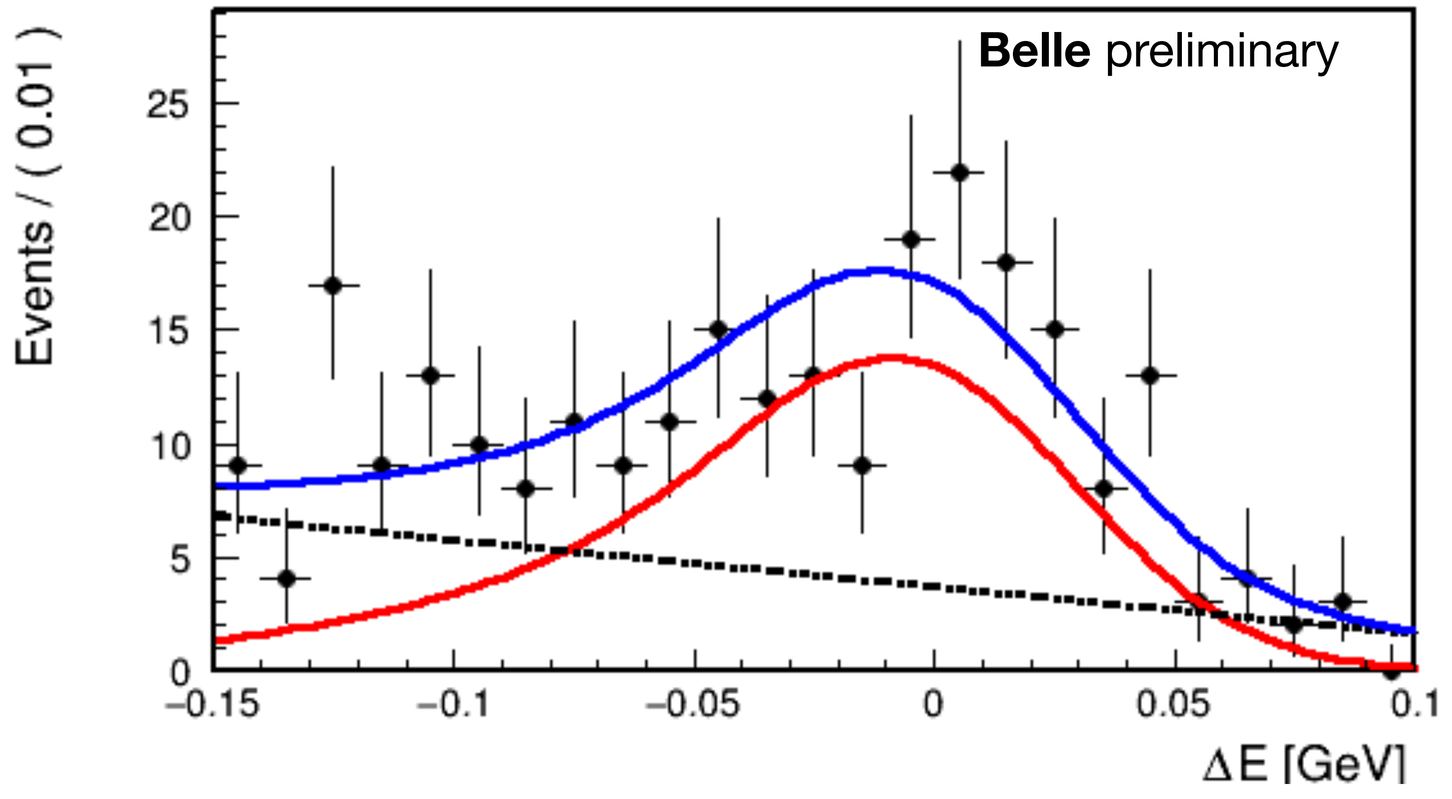
$b \to d\ell^+\ell^-$ Analysis strategy

- BDT trained to suppress dominant $e^+e^- \to q\bar{q}$ background:
  - Trained separately for each decay channel and optimized using Punzi's FOM.
- Suppression of peaking B backgrounds:
  - J/ψ and $\psi(2S)$ mass veto;
  - Photon conversions and π^0_{Dalitz} decays suppressed with $q^2_{ee} > 0.045\ \text{GeV}^2$.
- Control channel $B \to J/\psi(\ell^+\ell^-)\pi$ used to calibrate signal:

$B^+ \to J/\psi(\mu^+\mu^-)\pi^+$



$B^0 \to J/\psi(\mu^+\mu^-)\pi^0$



Measured $\mathscr{B}$ consistent within PDG uncertainty

channel	$\mathcal{B}$	PDG $\mathcal{B}$
$B^0 \to J/\psi(\mu\mu)\pi^0$	$(0.975 \pm 0.090) \times 10^{-6}$	0.990×10^{-6}
$B^0 \to J/\psi(ee)\pi^0$	$(1.091 \pm 0.119) \times 10^{-6}$	0.991×10^{-6}
$B^+ \to J/\psi(\mu\mu)\pi^+$	$(2.397 \pm 0.118) \times 10^{-6}$	2.337×10^{-6}
$B^+ \to J/\psi(ee)\pi^+$	$(2.140 \pm 0.174) \times 10^{-6}$	2.340×10^{-6}

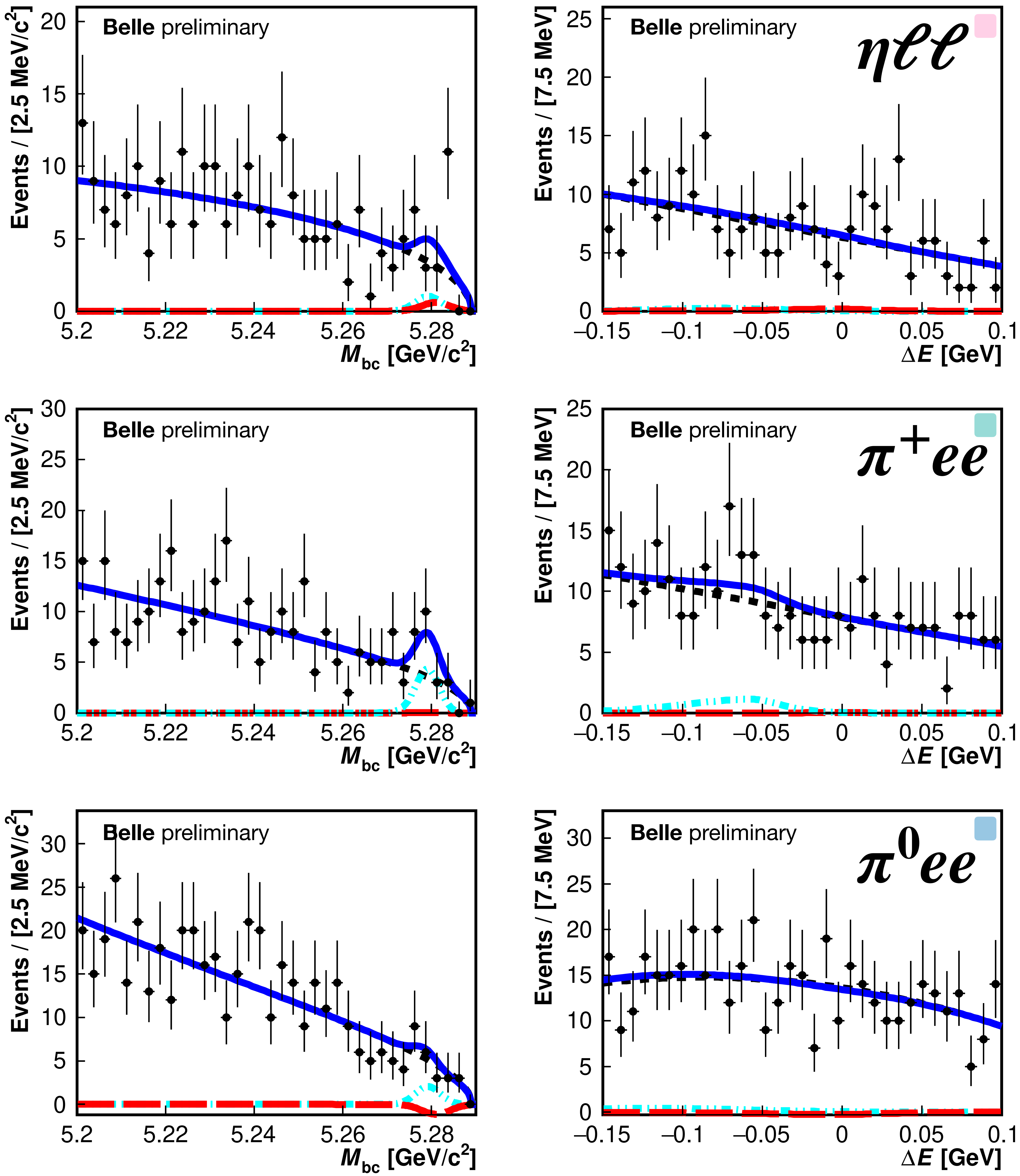
$\Delta E \equiv E^{\text{c.m.}}_{B^0} - E^{\text{c.m.}}_{\text{beam}}$

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

- 2D fit to ΔE & M_{bc} to extract signal yield.
- World's **best limits** for all $b \to d\ell^+\ell^-$ channels: $\mathscr{B} < (3.8 - 47) \times 10^{-8}$.

	N_{sig}	$\mathcal{B}^{UL}$ (10^{-8})	$\mathcal{B}$ (10^{-8})
$B^0 \to \eta\ell^+\ell^-$	$0.5^{+1.0}_{-0.8}$	< 4.8	$1.3^{+2.8}_{-2.2} \pm 0.1$
$B^0 \to \eta e^+e^-$	$0.0^{+1.4}_{-1.0}$	< 10.5	$0.0^{+4.9}_{-3.4} \pm 0.1$
$B^0 \to \eta\mu^+\mu^-$	$0.8^{+1.5}_{-1.1}$	< 9.4	$1.9^{+3.4}_{-2.5} \pm 0.2$
$B^+ \to \pi^+e^+e^-$	$0.1^{+2.5}_{-1.6}$	< 5.4	$0.1^{+2.7}_{-1.8} \pm 0.1$
$B^0 \to \pi^0\ell^+\ell^-$	$-1.8^{+1.6}_{-1.1}$	< 3.8	$-2.3^{+2.1}_{-1.5} \pm 0.2$
$B^0 \to \pi^0e^+e^-$	$-2.9^{+1.8}_{-1.4}$	< 7.9	$-5.8^{+3.6}_{-2.8} \pm 0.5$
$B^0 \to \pi^0\mu^+\mu^-$	$-0.5^{+3.6}_{-2.7}$	< 5.9	$-0.4^{+3.5}_{-2.6} \pm 0.1$

Statistically limited but consistent with $B^+ \to \pi^+\mu^+\mu^-$ from LHCb



$$M_{bc} \equiv \sqrt{\left(E^{c.m.}_{beam}\right)^2 - \left(p^{c.m.}_{B^0}\right)^2}$$

$$\Delta E \equiv E^{c.m.}_{B^0} - E^{c.m.}_{beam}$$

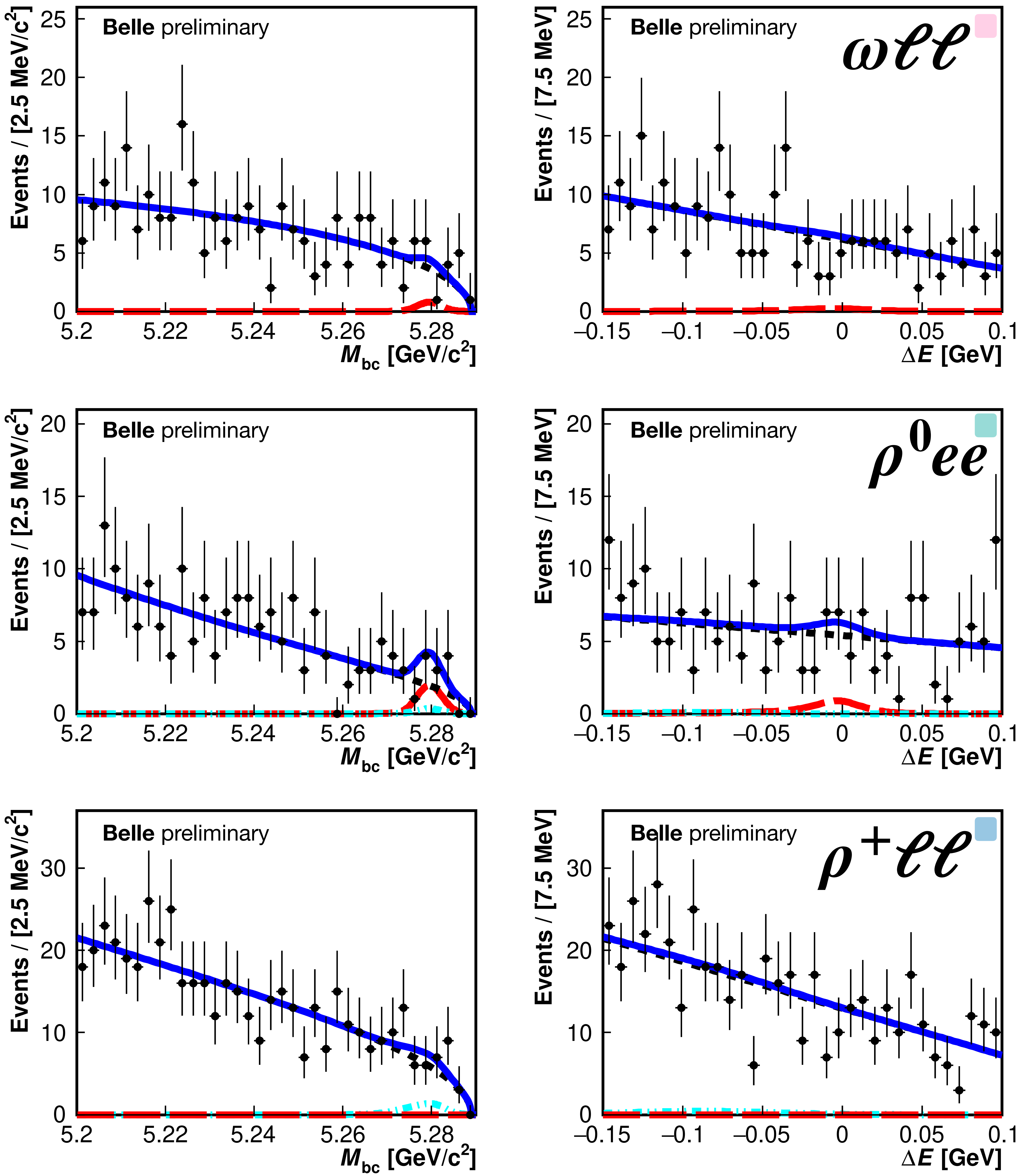
$b \to d\ell^+\ell^-$ Results

- World's **first limits** for $\omega\ell^+\ell^-$, $\rho^+\ell^+\ell^-$, and $\rho^0 e^+e^-$.

	$N_{\rm sig}$	$\mathcal{B}^{\rm UL}$ (10^{-8})	$\mathcal{B}$ (10^{-8})
$B^0 \to \omega\ell^+\ell^-$	$1.0^{+1.8}_{-1.3}$	< 22.0	$6.4^{+10.7}_{-7.8} \pm 0.5$
$B^0 \to \omega e^+e^-$	$-0.3^{+3.2}_{-2.5}$	< 30.7	$-2.1^{+26.5}_{-20.8} \pm 0.2$
$B^0 \to \omega\mu^+\mu^-$	$1.7^{+2.3}_{-1.6}$	< 24.9	$7.7^{+10.8}_{-7.5} \pm 0.6$
$B^0 \to \rho^0 e^+e^-$	$5.6^{+3.5}_{-2.7}$	< 45.5	$23.6^{+14.6}_{-11.2} \pm 1.1$
$B^+ \to \rho^+\ell^+\ell^-$	$0.4^{+2.3}_{-1.8}$	< 18.9	$2.5^{+14.6}_{-11.8} \pm 0.2$
$B^+ \to \rho^+e^+e^-$	$-4.4^{+2.3}_{-2.0}$	< 46.7	$-38.2^{+24.5}_{-17.2} \pm 3.4$
$B^+ \to \rho^+\mu^+\mu^-$	$3.0^{+4.0}_{-3.0}$	< 38.1	$13.0^{+17.5}_{-13.3} \pm 1.1$

- ***Additional information provided with first measurements of neutral and electron final states.***
- ***Approaching SM values.***
- ***No sign of lepton non-universality.***

Statistically limited but consistent with $B^0 \to \rho^0\mu^+\mu^-$ from LHCb



$$M_{\rm bc} \equiv \sqrt{\left(E^{\rm c.m.}_{\rm beam}\right)^2 - \left(p^{\rm c.m.}_{B^0}\right)^2}$$

$$\Delta E \equiv E^{\rm c.m.}_{B^0} - E^{\rm c.m.}_{\rm beam}$$

Measurement of $B \to K^*\gamma$

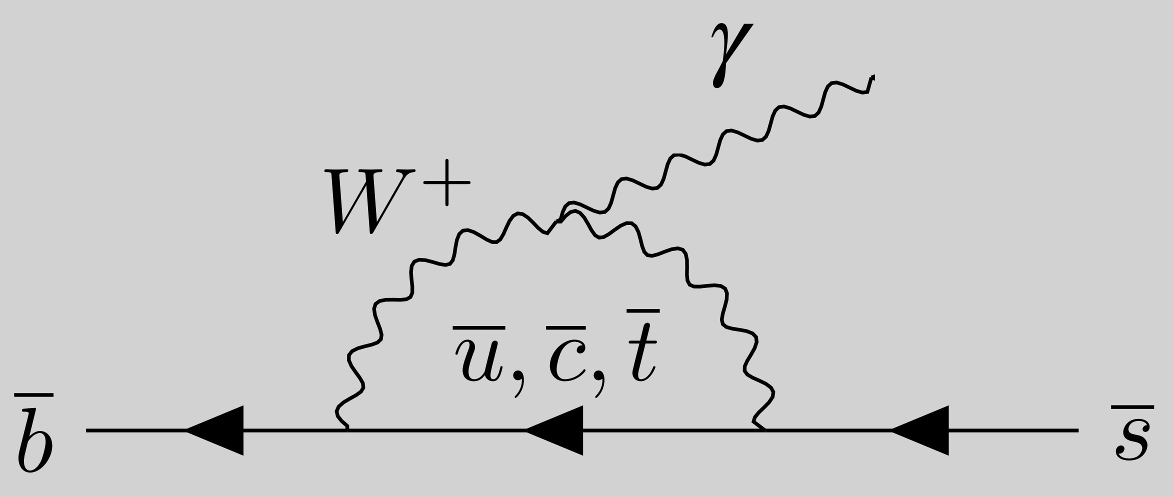
New for Moriond 24

BELLE

Belle II

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

- The **first** radiative penguin decay. Now a **precision** measurement.
- SM $\mathcal{B}$ predictions have **large uncertainties** (30%) related to form factors.
- ***CP*** and **isospin asymmetries** are theoretically **clean** due to cancelation of form factor uncertainties.
- SM prediction of A_{CP} is small (~1%) and those for Δ_{0+} range from 2-8% with an uncertainty ~2%.
- Belle observed **evidence of isospin violation** at 3.1σ. PRL **119**, 191802 (2017)



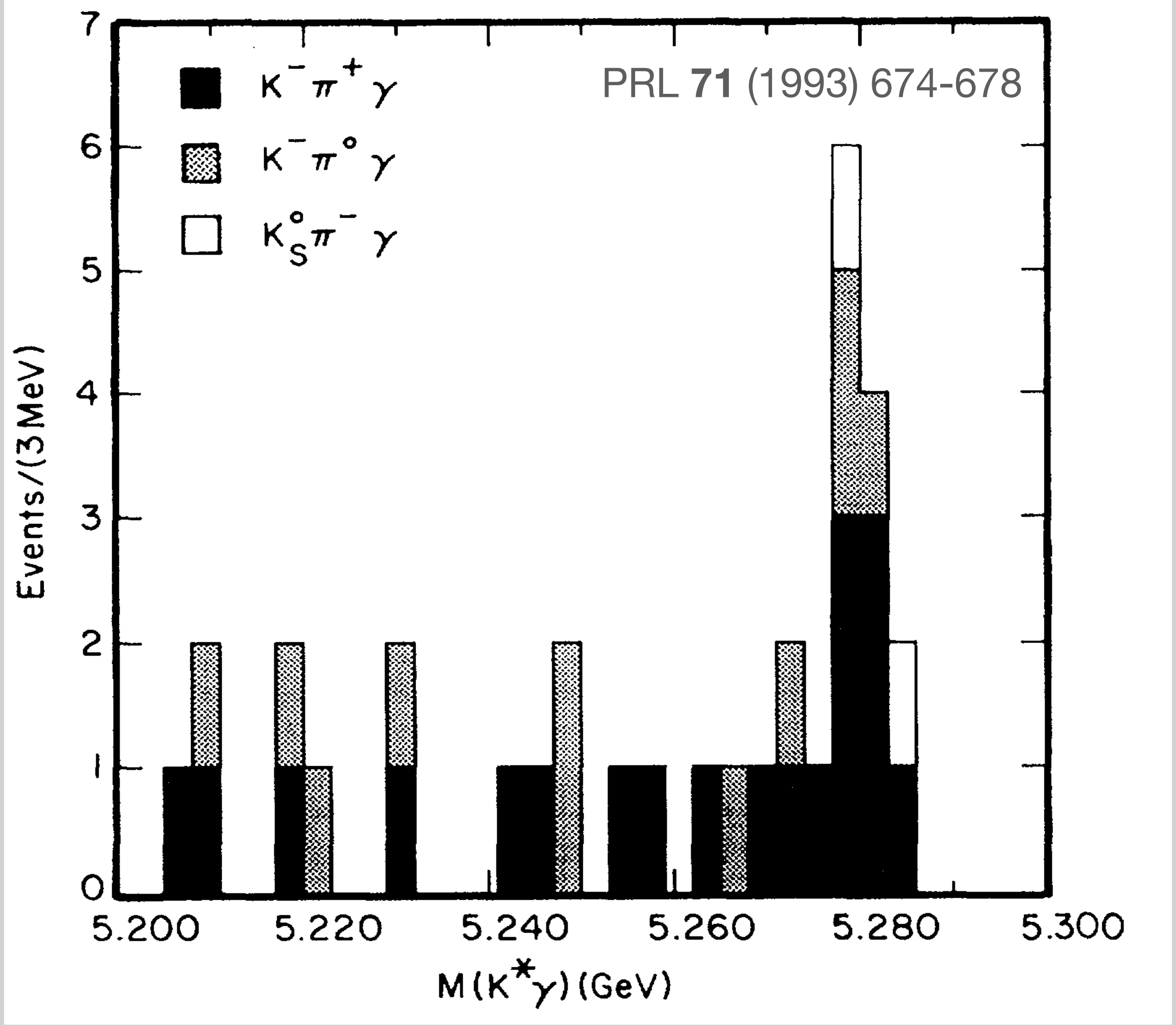
In addition to $\mathcal{B}$,
***targets** include:*

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

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

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

Long way since the first CLEO result in 1993



$B \to K^*\gamma$ Analysis strategy

- Reconstruct $K^* \to K^+\pi^-, K_S^0\pi^0, K^+\pi^0, K_S^0\pi^+$.
- Classifiers to reject boosted photons from asymmetric $\pi^0 \to \gamma\gamma$ and $\eta \to \gamma\gamma$ decays, and continuum events.
- Fit to M_{bc} and ΔE to extract yields.

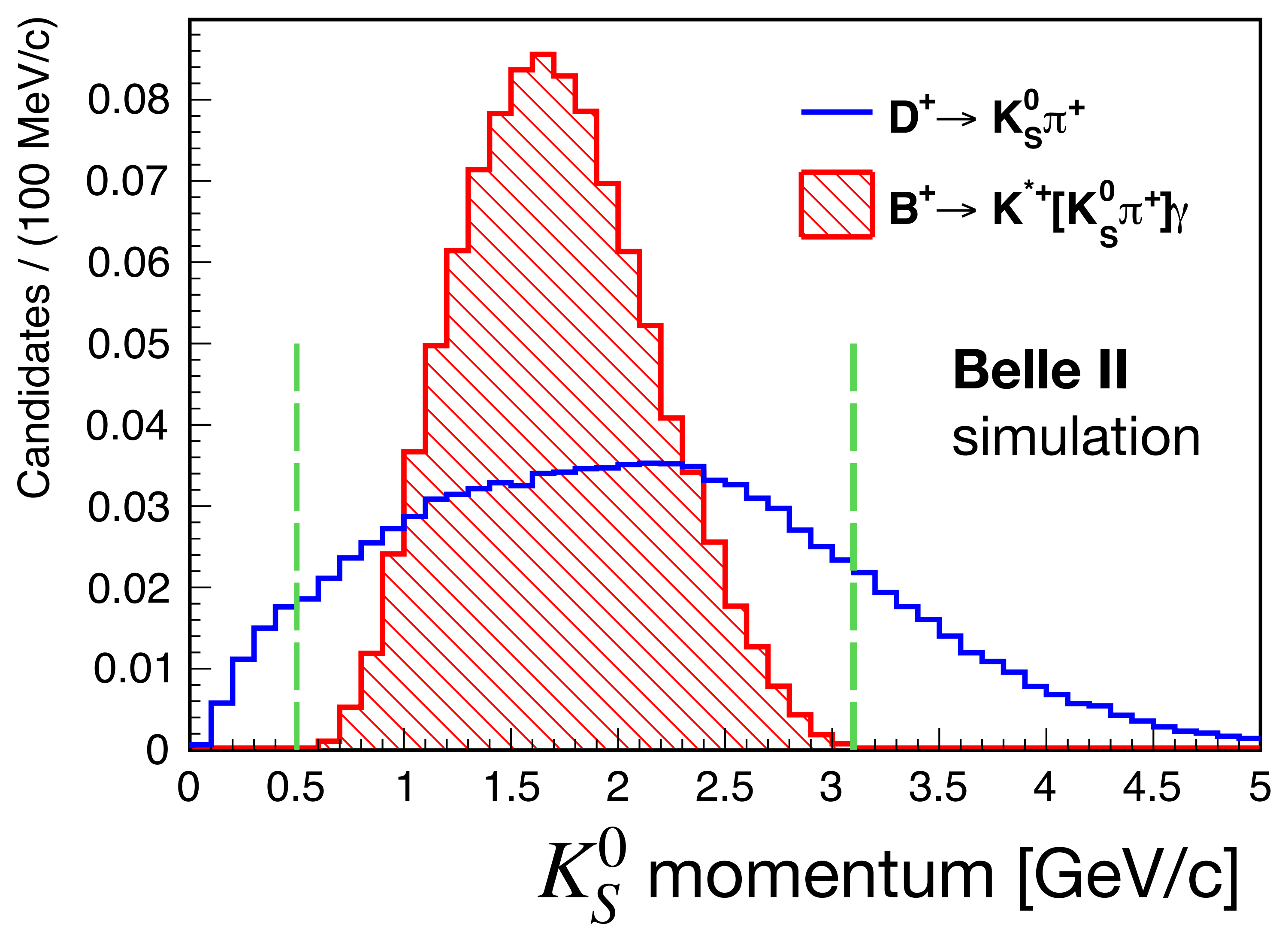
See Niharika Rout's talk on Hadronic B Decays at Belle and Belle II for details

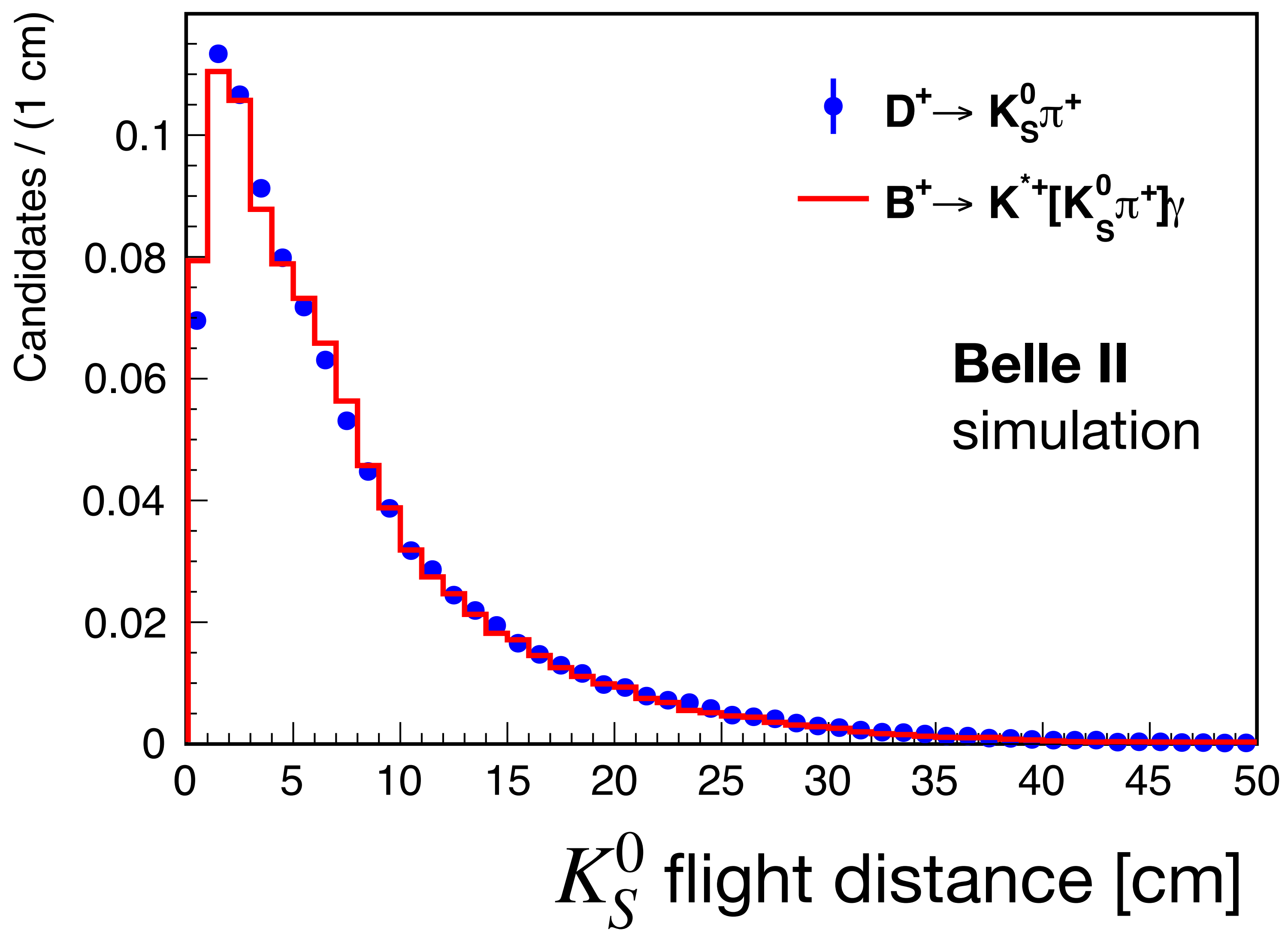
Significant effort at Belle II to improve K_S^0 reconstruction and systematics:

- Studied using $D^+ \to K_S^0\pi^+$ decays:
  - Kinematic region of the signal well covered.
  - Determine systematic error (1.4%) in bins of K_S^0 flight length for signal range of $p \in (0.5, 3.1)$ [GeV/c].

K_S^0 kinematics between signal and control mode in simulation

(Normalized to unit area)





$B \to K^*\gamma$ Results

$$\mathcal{B}[B^0 \to K^{*0}\gamma] = (4.16 \pm 0.10 \pm 0.11) \times 10^{-5}$$

$$\mathcal{B}[B^+ \to K^{*+}\gamma] = (4.04 \pm 0.13 \pm 0.13) \times 10^{-5}$$

$$\mathcal{B}[B \to K^*\gamma] = (4.12 \pm 0.08 \pm 0.11) \times 10^{-5}$$

$$A_{CP}[B^0 \to K^{*0}\gamma] = (-3.2 \pm 2.4 \pm 0.4)\,\%$$

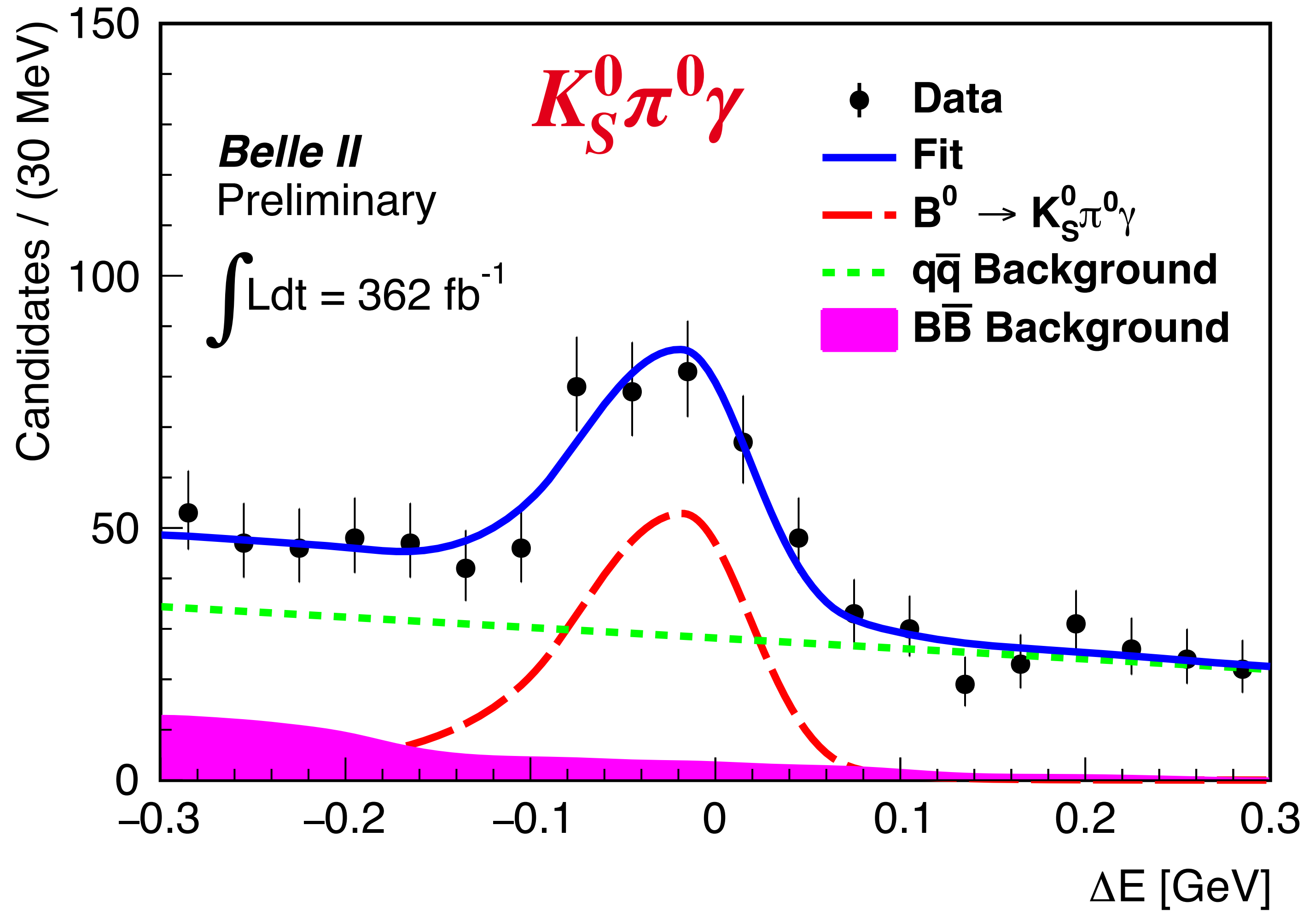
$$A_{CP}[B^+ \to K^{*+}\gamma] = (-1.0 \pm 3.0 \pm 0.6)\,\%$$

$$A_{CP}[B \to K^*\gamma] = (-2.3 \pm 1.9 \pm 0.3)\,\%$$

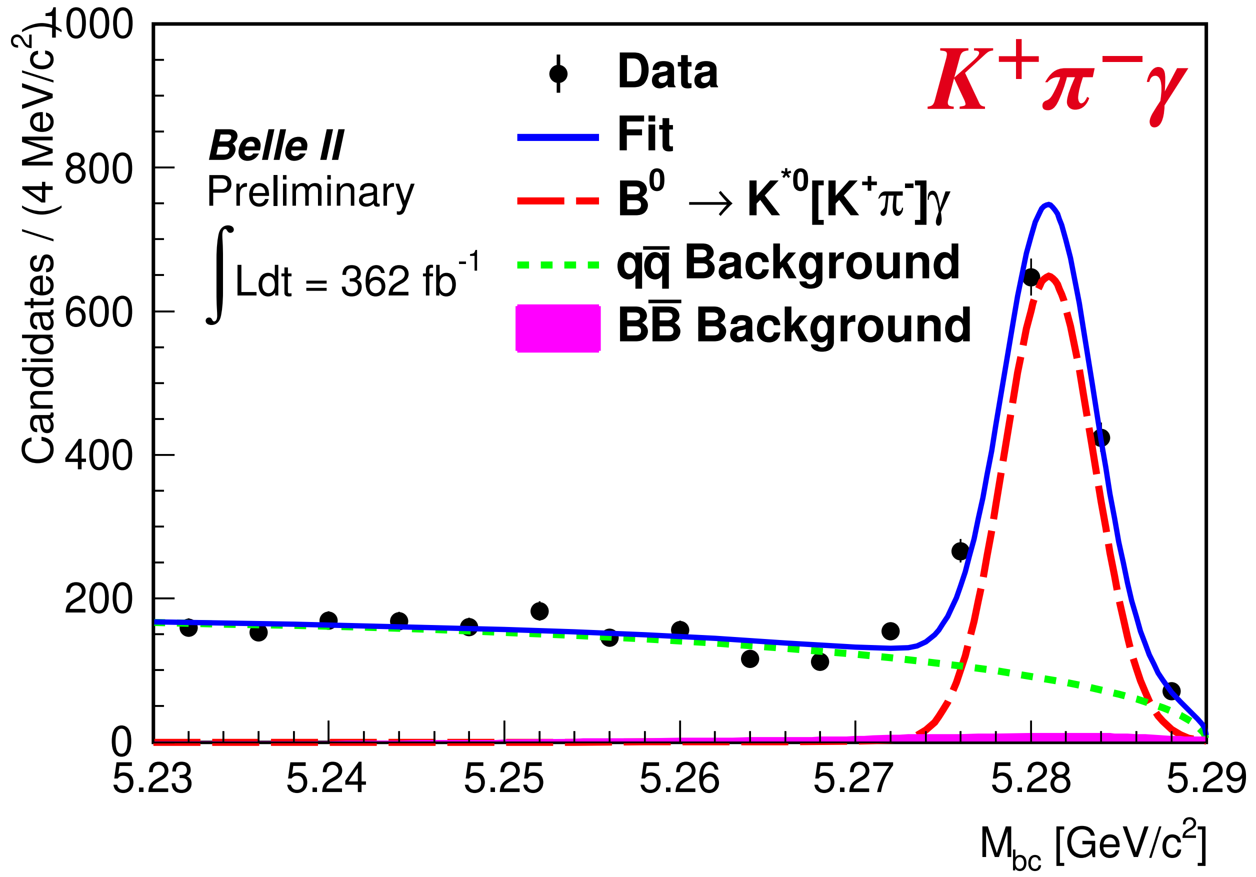
$$\Delta A_{CP} = (2.2 \pm 3.8 \pm 0.7)\,\%$$

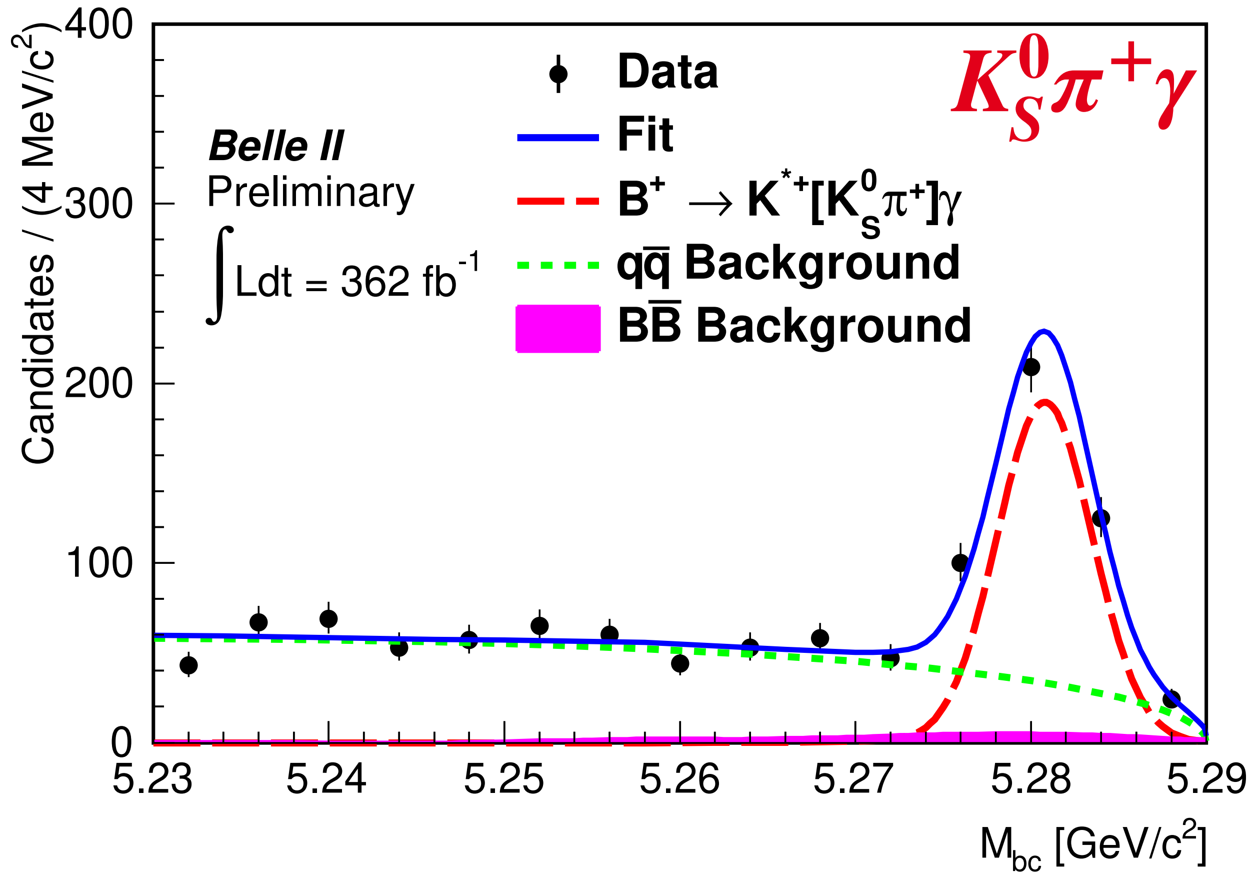
$$\Delta_{0+} = (5.1 \pm 2.0 \pm 1.0 \pm 1.1)\,\%$$

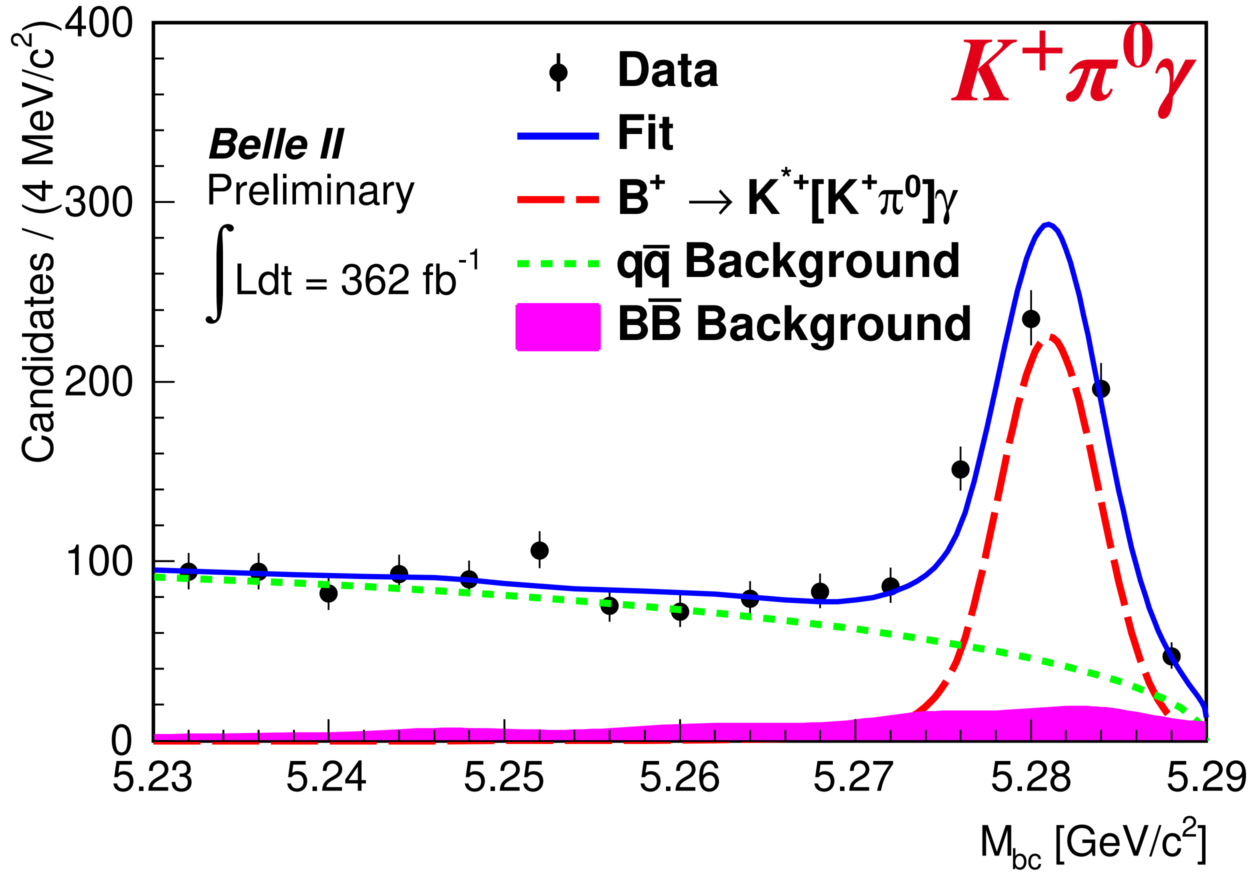
- ***Consistent with WA and SM.***
- ***Similar sensitivity wrt Belle due to improved K_S^0 efficiency and ΔE resolution.***



B^0, B^+







Measurement of $B \to \rho\gamma$

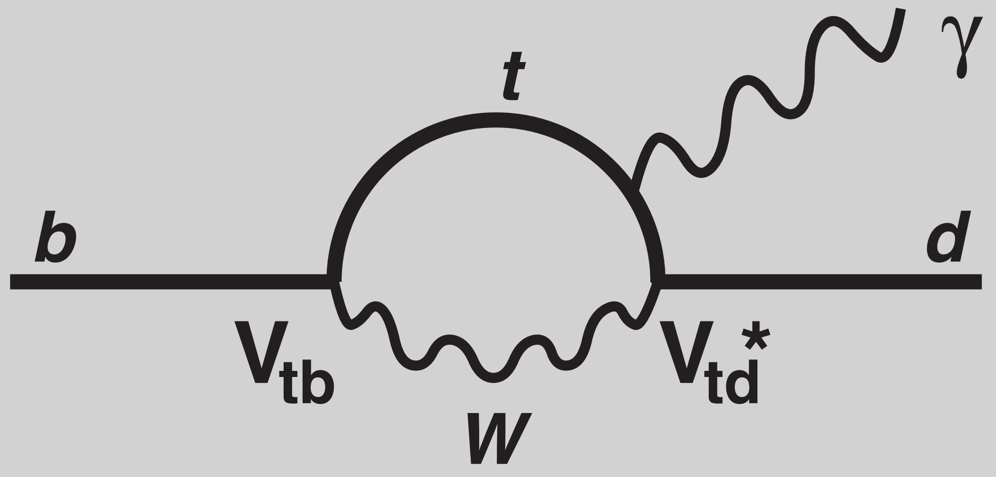
Full Belle & run 1 Belle II datasets:

BELLE $711\ \mathrm{fb}^{-1}$

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

Previous Belle result used $657\ \mathrm{fb}^{-1}$
PRL **101**, 111801 (2008)

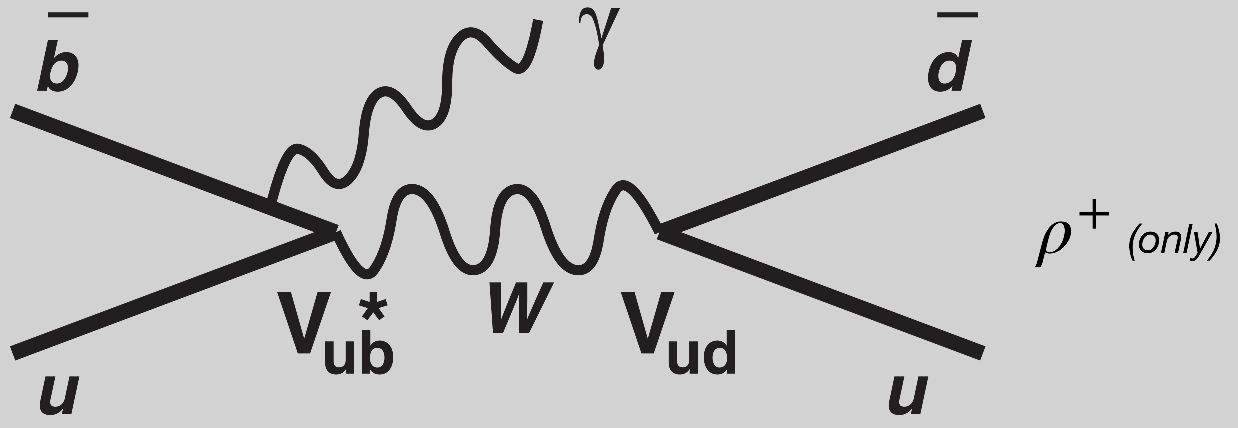
Suppressed relative to $b \to s\gamma$ by $\dfrac{|V_{td}|^2}{|V_{ts}|^2} \sim 0.04.$



Targets:

- $\mathscr{B}(B^{+,0} \to \rho^{+,0}\gamma)$, A_{CP}, and the isospin asymmetry with *CP*-averaged $\mathscr{B}$'s:

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



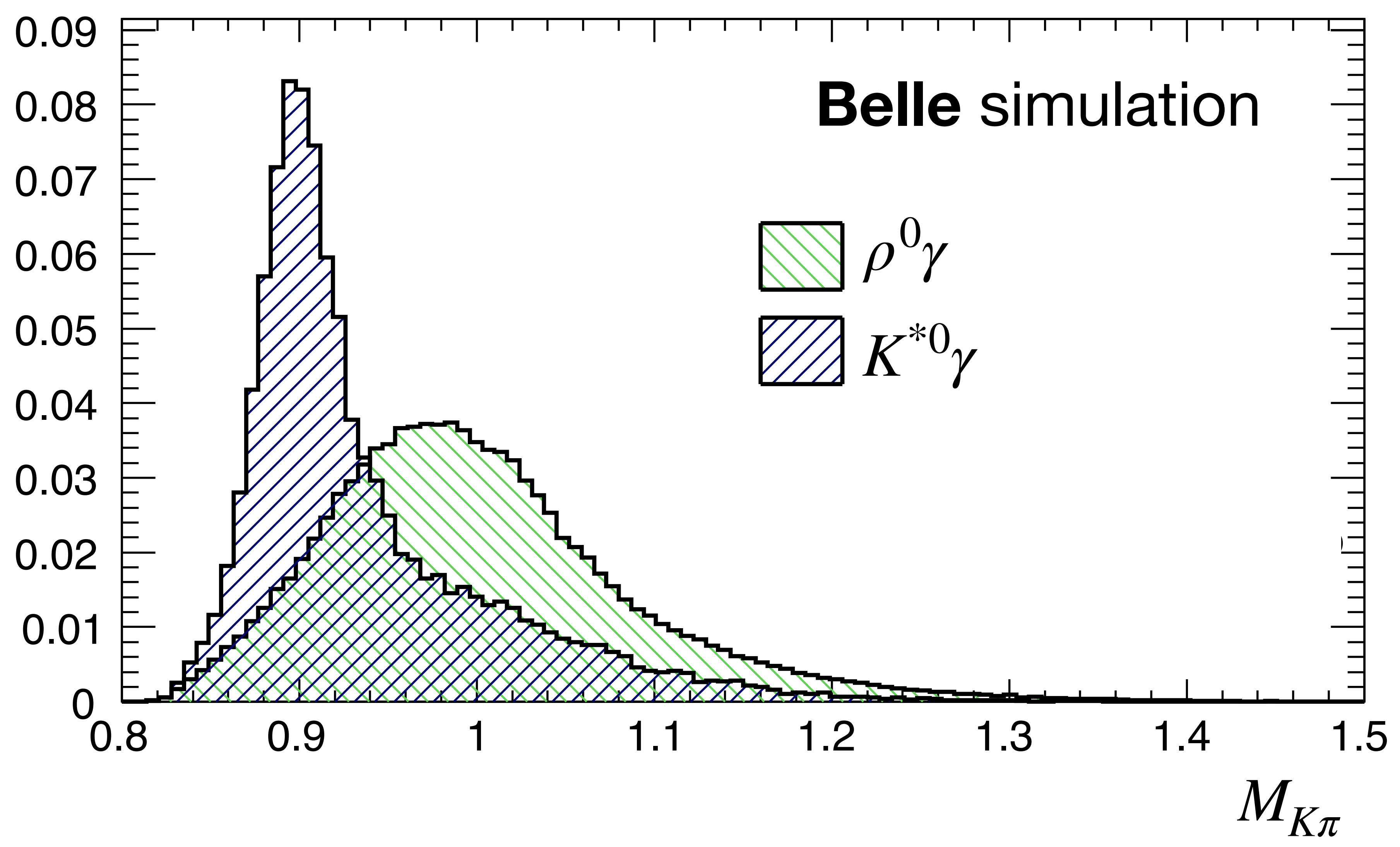
2σ tension between WA and SM prediction

$A_\mathrm{I}^\mathrm{WA} = (30^{+16}_{-13})\,\%$ $\qquad A_\mathrm{I}^\mathrm{SM} = (5.2 \pm 2.8)\,\%$

PRD **88**, 094004 (2013)

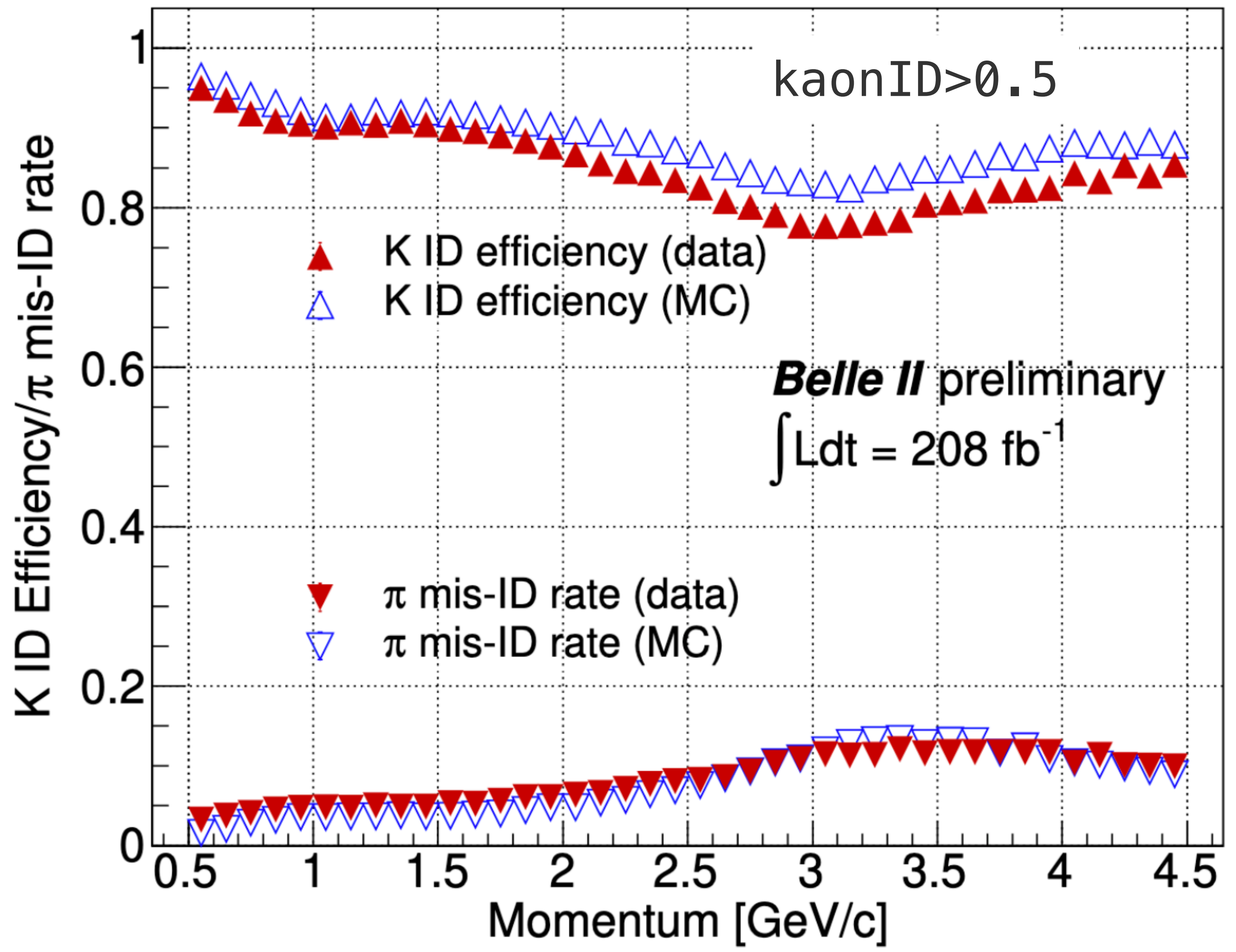
$B \to \rho\gamma$ Analysis strategy

- Challenge due to large backgrounds from continuum:
  - Driven by $\pi^0(\eta) \to \gamma\gamma$, where one γ has asymmetrically large energy.
- Train 2 MVA classifiers to veto π^0/η and to further reduce continuum.



- Large background from $B \to K^*\gamma$ decays ($K \to \pi$ mis-identified):
  - For $\rho^0 \to \pi^+\pi^-$, the π with the larger kaon identification is redefined as a K.
  - Include $M_{K\pi}$ as a fitting variable, along with ΔE and M_{bc}, to extract the signal.

*Improved performance at **Belle II** with TOP and ARICH detectors*



High Kaon identification efficiency and low $\pi \to K$ fake rate in full momentum range

$B \to \rho\gamma$ Results

- World's **most precise** measurements.
- $A_{\rm I}$ **consistent with SM** at 0.6σ.

$$\mathscr{B}\left(B^+ \to \rho^+\gamma\right) = \left(12.87^{+2.02+1.00}_{-1.92-1.17}\right) \times 10^{-7}$$

$$\mathscr{B}\left(B^0 \to \rho^0\gamma\right) = \left(7.45^{+1.33+1.00}_{-1.27-0.80}\right) \times 10^{-7}$$

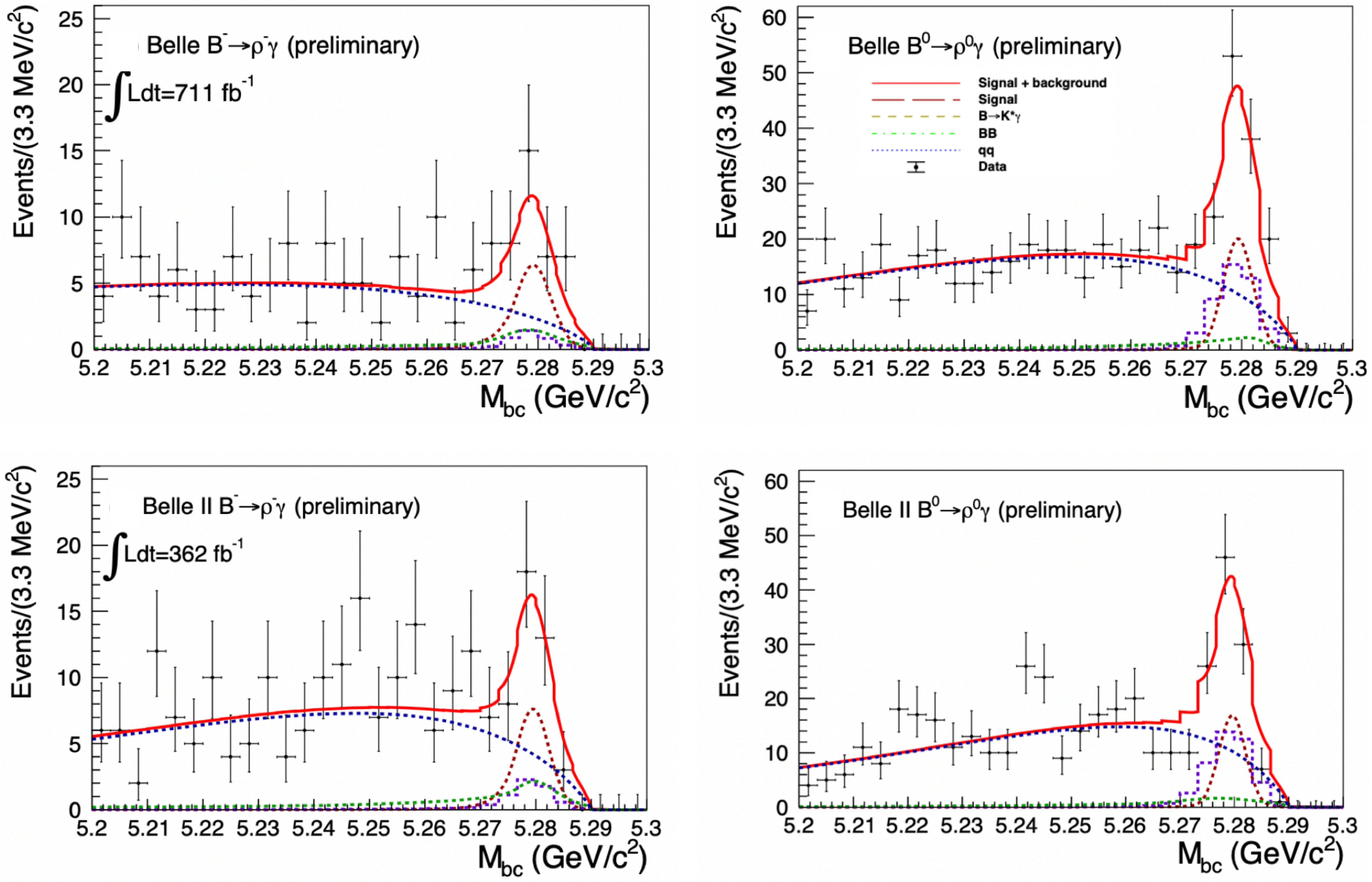
$$A_{CP}\left(B^+ \to \rho^+\gamma\right) = \left(-8.4^{+15.2+1.3}_{-15.3-1.4}\right)\ \%$$

$$A_{\rm I}\left(B \to \rho\gamma\right) = \left(14.2^{+11.0+8.9}_{-11.7-9.1}\right)\ \%$$

Dominant systematics:

- $\mathscr{B}$: Selection, peaking $K^*\gamma$ yield
- A_{CP}: Peaking $B\bar{B}$ A_{CP}
- A_I: Uncertainty from f_{+-}/f_{00} and lifetime ratio of B^+ to B^0.

PRD **107** L031102 (2023), PTEP **2022**, 083C01 (2022)

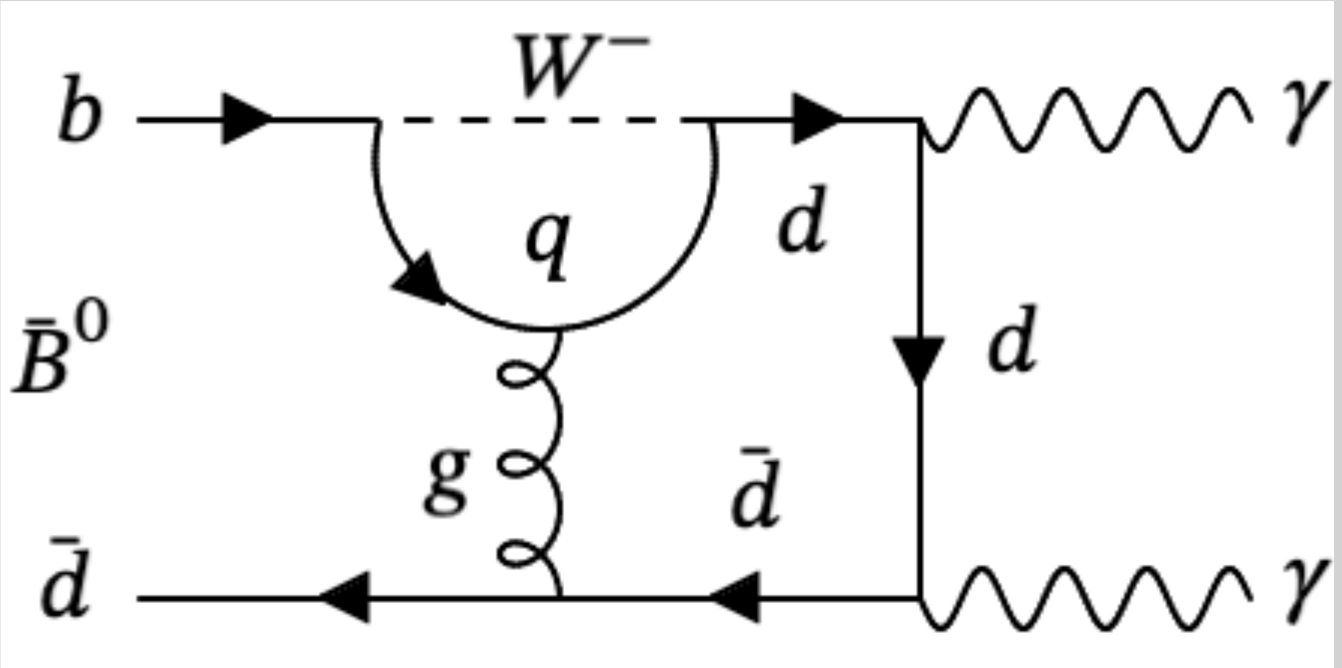


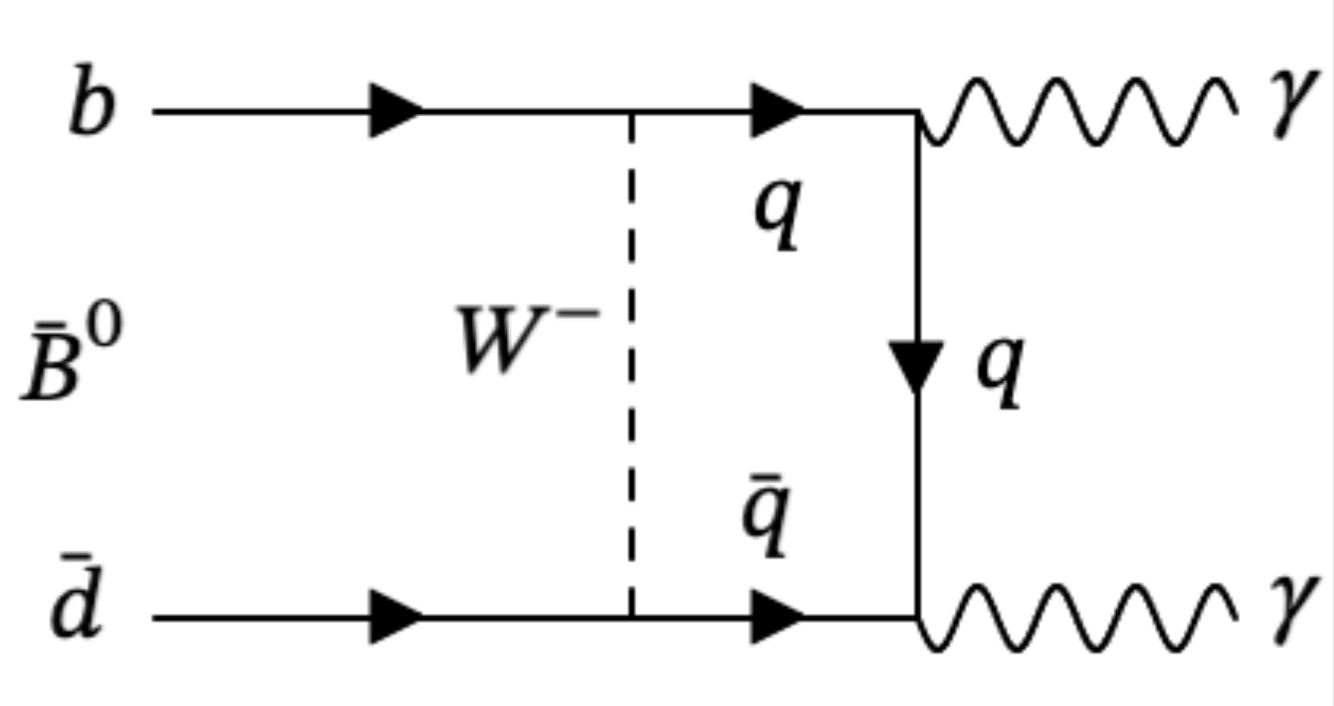
Search for $B^0 \to \gamma\gamma$

New for Moriond 24

Full Belle & run 1 Belle II datasets: BELLE $694\ \text{fb}^{-1}$, Belle II $362\ \text{fb}^{-1}$

- Very rare decay with $\mathscr{B}_{\text{SM}} = (1.4^{+1.4}_{-0.8}) \times 10^{-8}$.
  JHEP **12**, 169 (2020)
- Highly CKM suppressed relative to $B_s \to \gamma\gamma$.
- Challenging due to 2γ final state; large backgrounds.



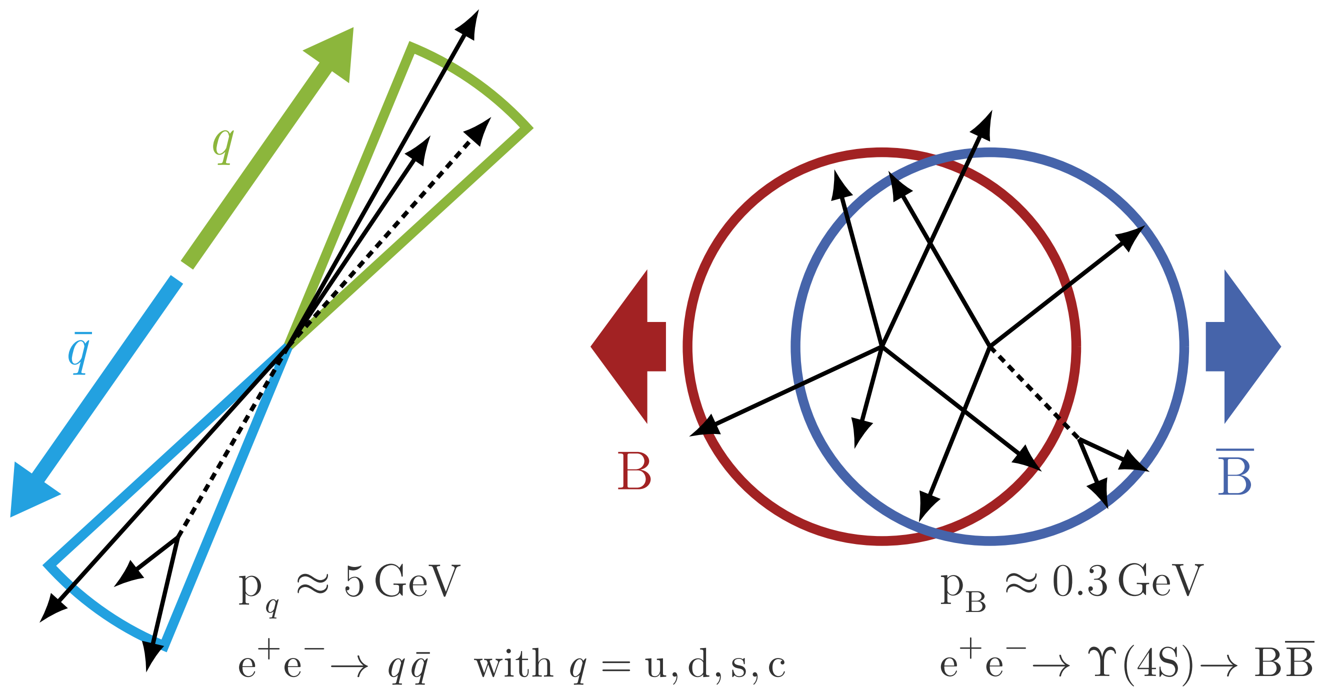


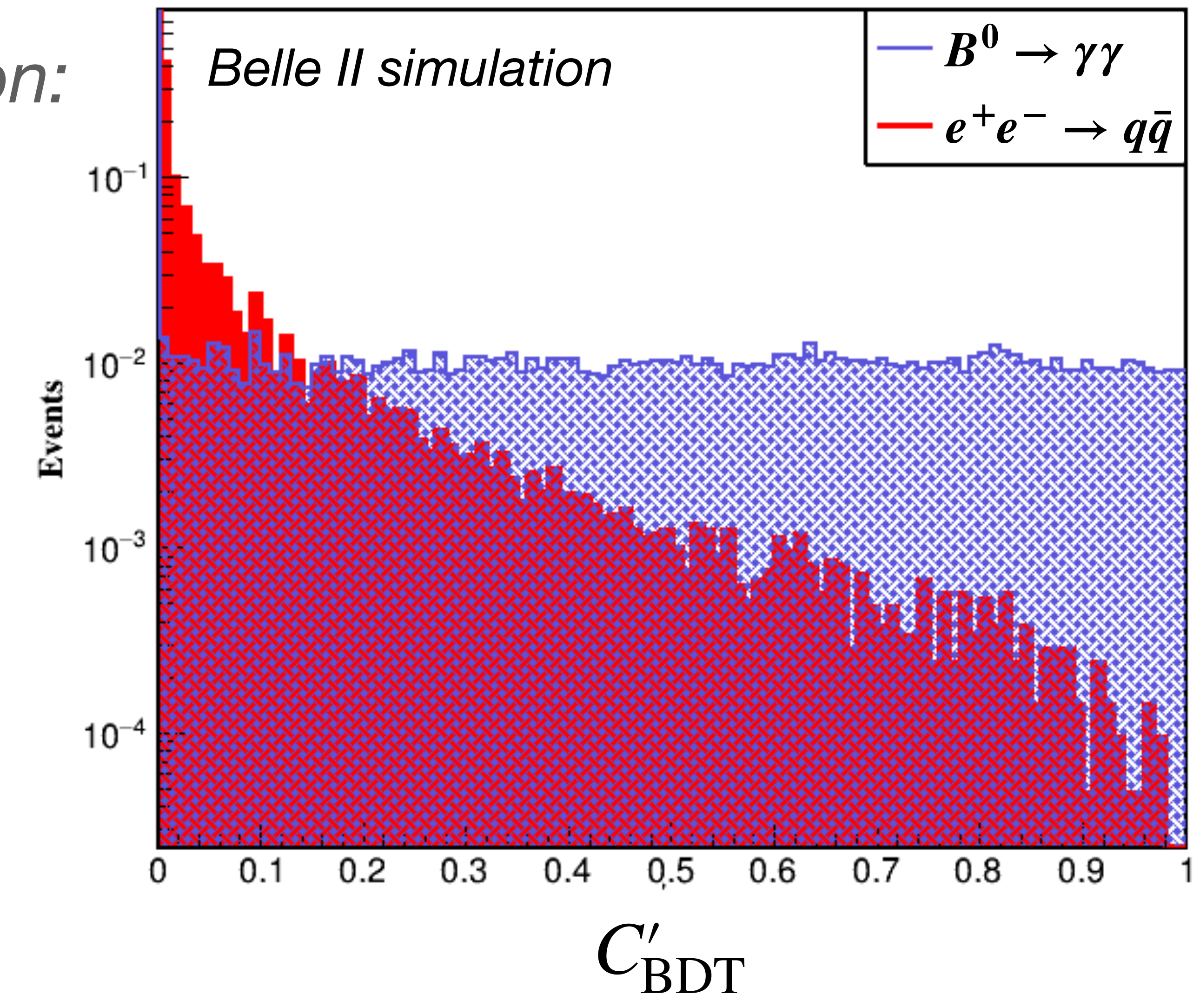
Previous searches	Limits
L3 $(73\ \text{pb}^{-1})$	$< 3.9 \times 10^{-5}$
Belle $(104\ \text{fb}^{-1})$	$< 6.2 \times 10^{-7}$
BaBar $(426\ \text{fb}^{-1})$	$< 3.2 \times 10^{-7}$

$B^0 \to \gamma\gamma$ Analysis strategy

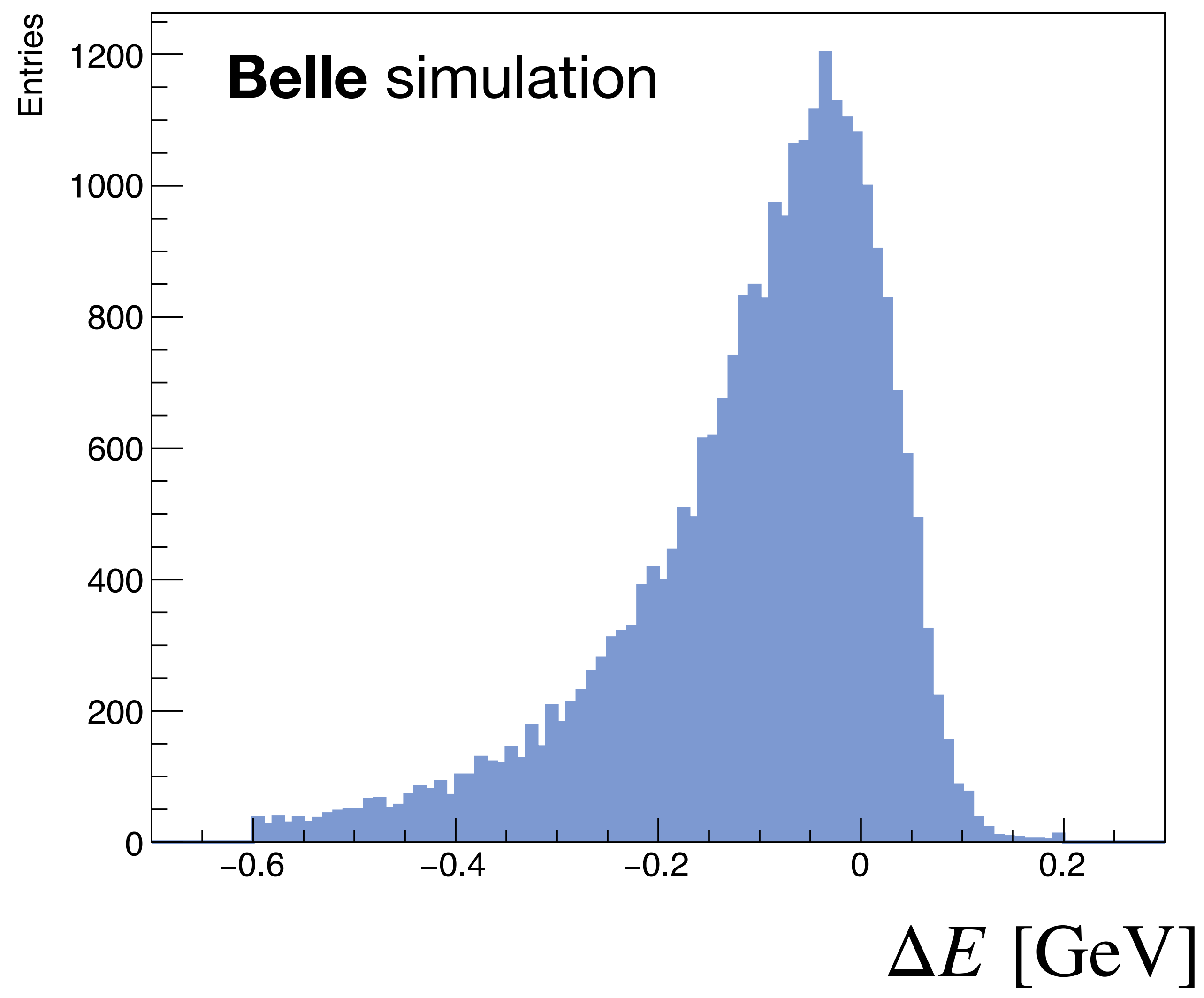
- Signal reconstructed from 2 highly energetic photons with $E_\gamma \in (1.4,\ 3.4)$ GeV.
- Peaking background in $M_{\rm bc}$ from combinations of back-to-back off-time photons → *suppressed using photon timing cuts.*
- Veto candidates from asymmetric π^0 and η decays.
- Dominant (90%) background contamination from $e^+e^- \to q\bar{q}$.
- Event shape variables used in a BDT for discrimination.

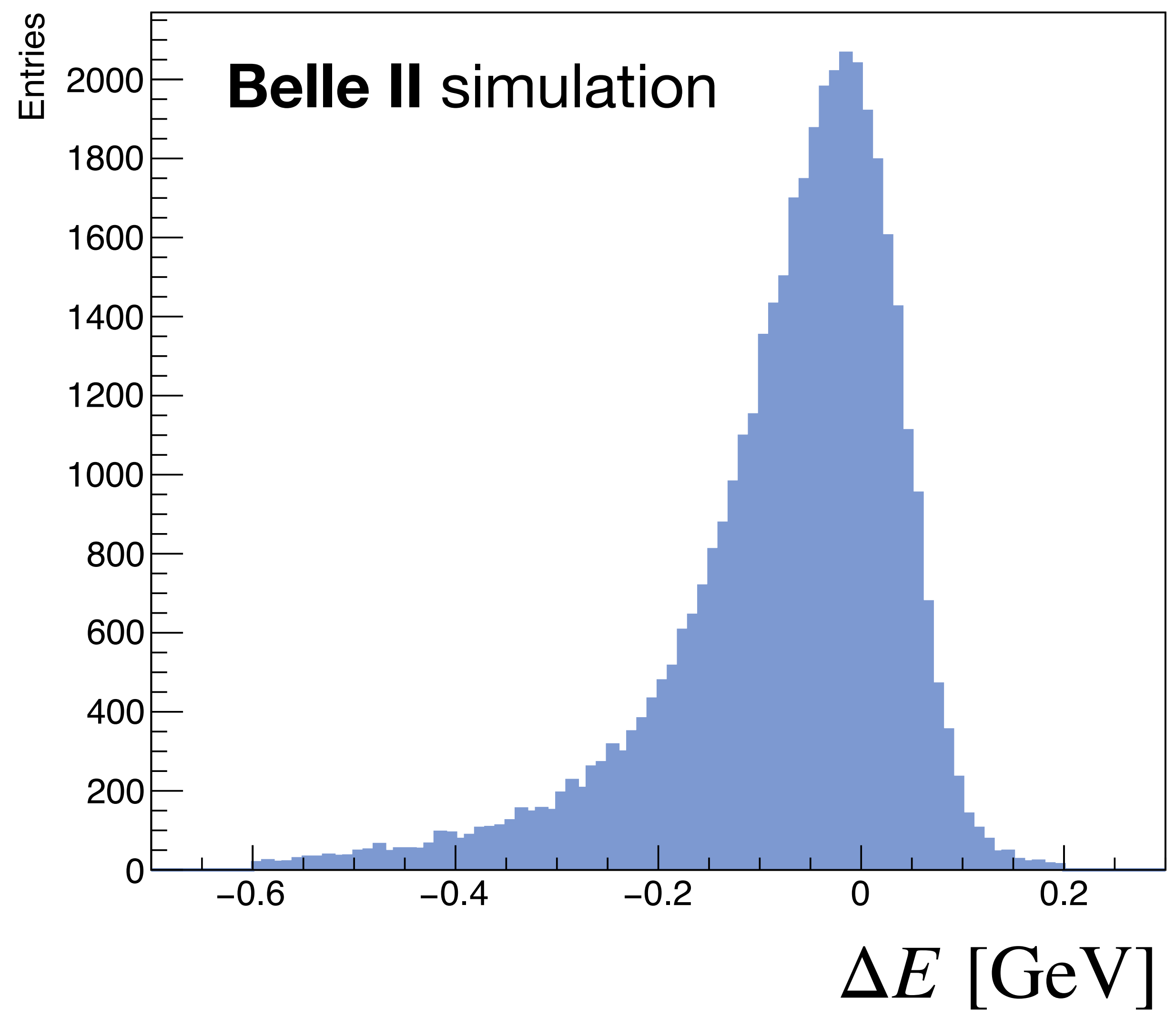
➡ *Probability integral transformation:*





Significant improvement in ΔE resolution in Belle II





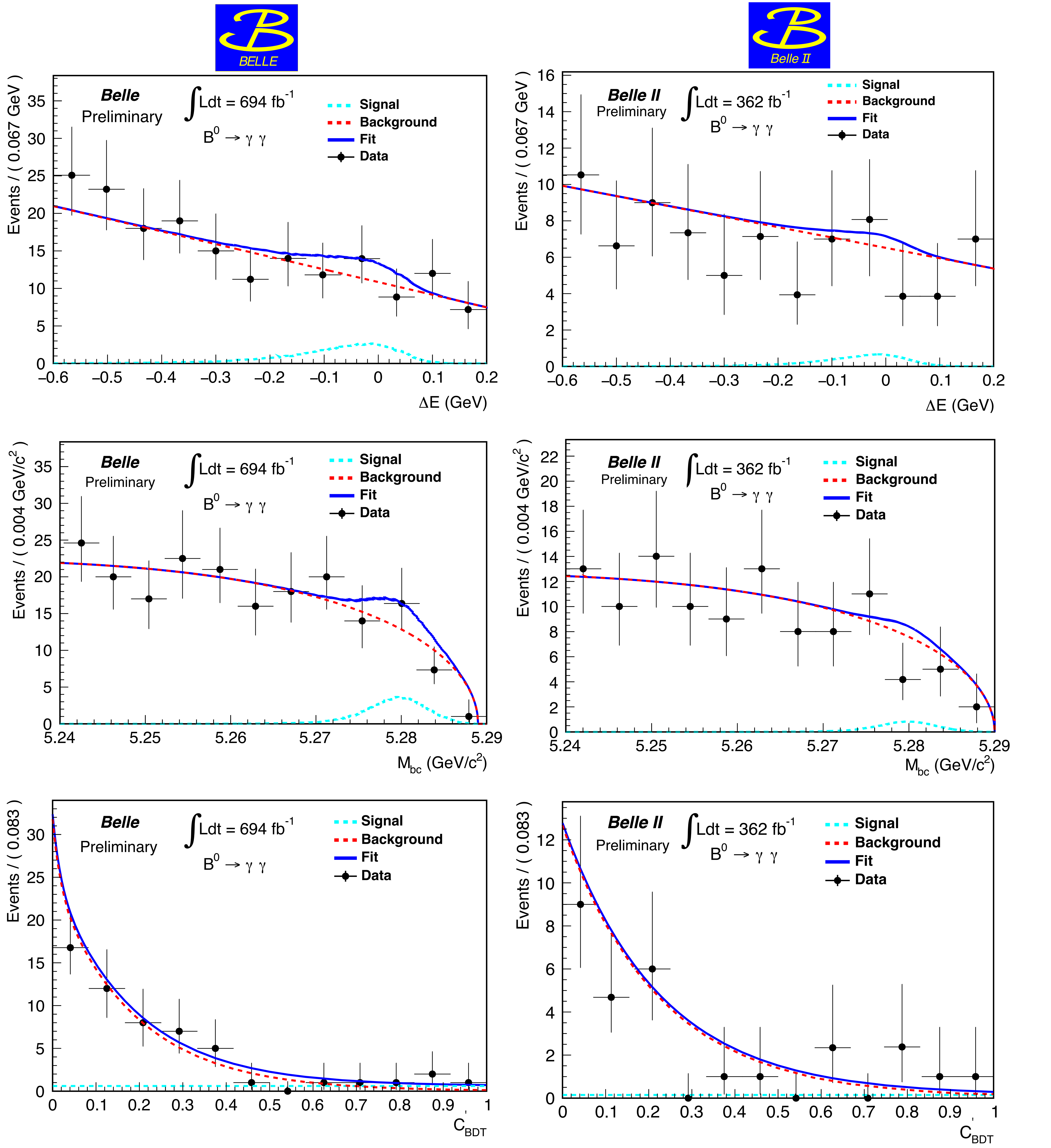
$B^0 \to \gamma\gamma$ Results

- Simultaneous 3D unbinned ML fit to $M_{\rm bc}$, ΔE and $C'_{\rm BDT}$.
  - Combined signal yield $= 11.0^{+6.5}_{-5.5}$.
  - 2.5σ significance.

	$\mathcal{B}(B^0 \to \gamma\gamma)$	$\mathcal{B}(B^0 \to \gamma\gamma)$ (at 90% CL)
Belle	$(5.4^{+3.3}_{-2.6} \pm 0.5) \times 10^{-8}$	$< 9.9 \times 10^{-8}$
Belle II	$(1.7^{+3.7}_{-2.4} \pm 0.3) \times 10^{-8}$	$< 7.4 \times 10^{-8}$
Combined	$(3.7^{+2.2}_{-1.8} \pm 0.7) \times 10^{-8}$	$< 6.4 \times 10^{-8}$

Expected
$\mathcal{B} < 4.4 \times 10^{-8}$

- ***Higher observed significance than expected (1.2σ).***
- ***Sensitivity approaching SM prediction.***
- ***Uncertainties are comparable between Belle and Belle II even though smaller dataset.***
- ***5x improvement over previous best UL.***



Outlook

- Robust radiative and electroweak penguin program exploiting the **full Belle and Run 1 Belle II datasets**.

- Many **more** analyses in the pipeline.

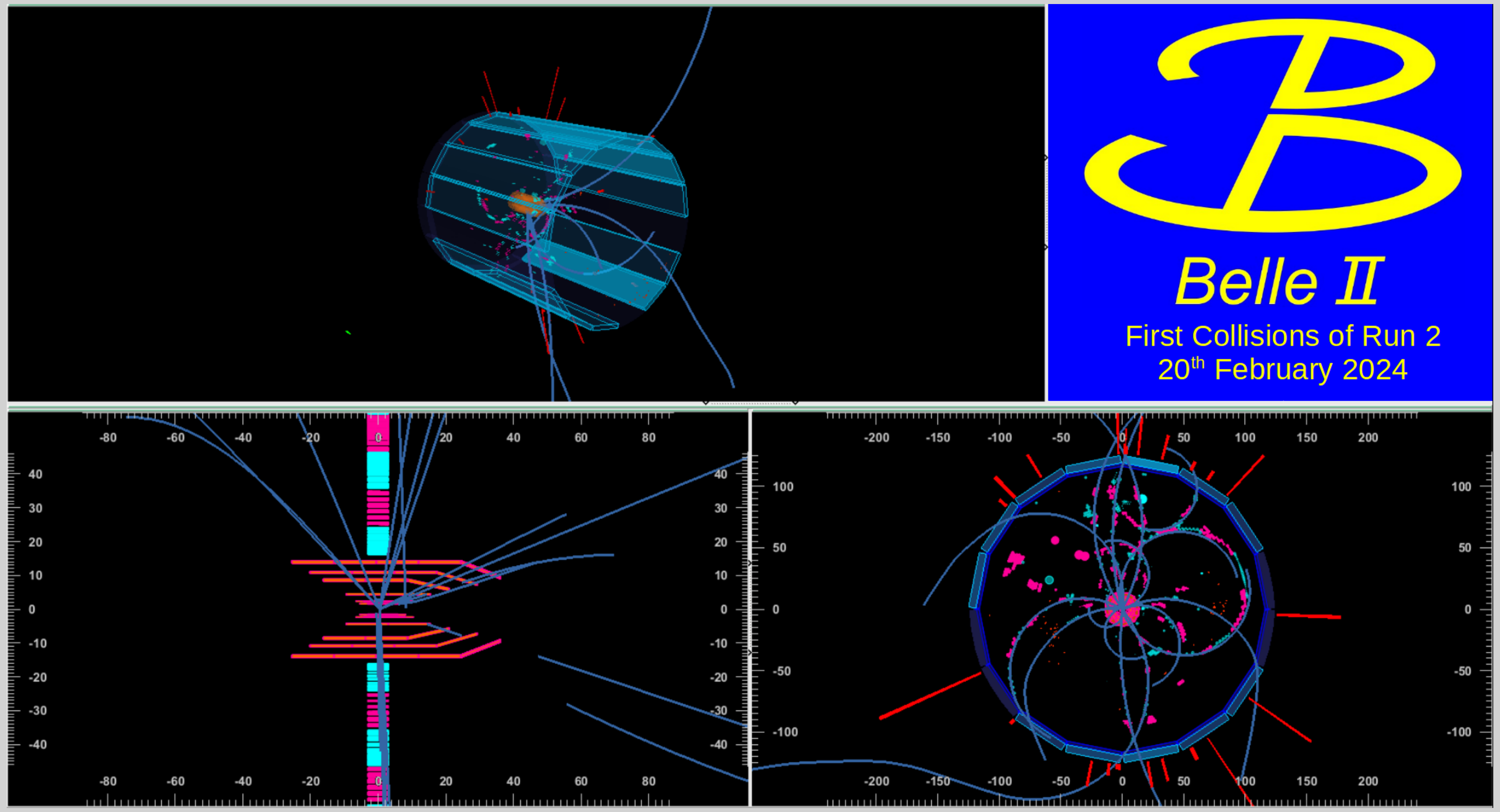
Expectations for the uncertainties on the signal strength μ (relative to the SM strength)

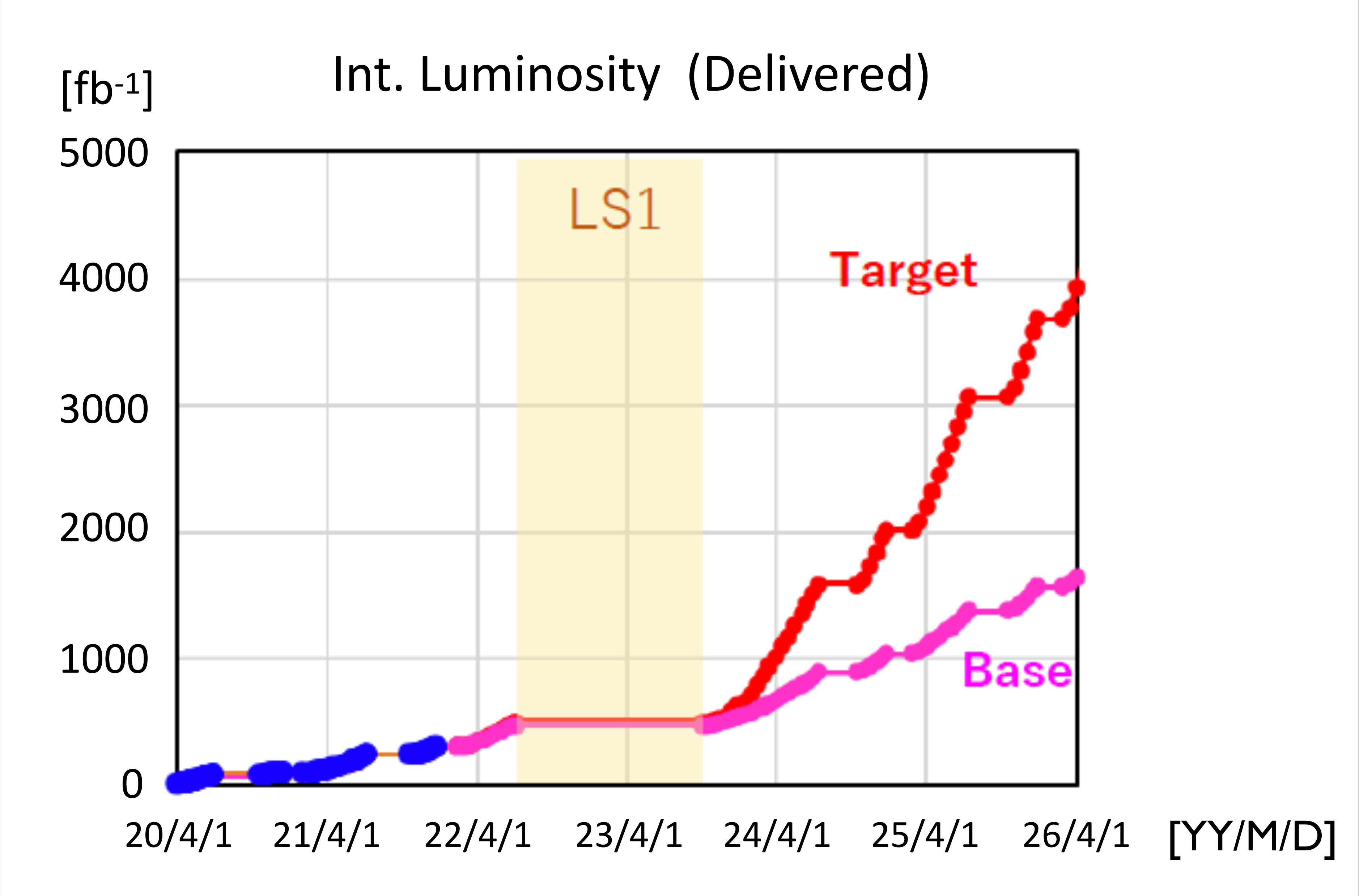
Decay	$1\,\mathrm{ab}^{-1}$	$5\,\mathrm{ab}^{-1}$	$10\,\mathrm{ab}^{-1}$	$50\,\mathrm{ab}^{-1}$
$B^+ \to K^+\nu\bar{\nu}$	0.55 (0.37)	0.28 (0.19)	0.21 (0.14)	0.11 (0.08)
$B^0 \to K^0_S\nu\bar{\nu}$	2.06 (1.37)	1.31 (0.87)	1.05 (0.70)	0.59 (0.40)
$B^+ \to K^{*+}\nu\bar{\nu}$	2.04 (1.45)	1.06 (0.75)	0.83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

Base (Target)

Snowmass submission *(most up-to-date prospects document)*

Run 2 is underway





Extra material

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

arXiv:2311.14647 [Accepted by PRD]

Belle II
362 fb^{-1}

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 type, parameters	Uncertainty size	Impact on σ_μ
Normalization of $B\bar{B}$ background	—	Global, 2	50%	0.90
Normalization of continuum background	—	Global, 5	50%	0.10
Leading B-decay branching fractions	—	Shape, 5	$O(1\%)$	0.22
Branching fraction for $B^+ \to K^+K^0_L K^0_L$	q^2 dependent $O(100\%)$	Shape, 1	20%	0.49
p-wave component for $B^+ \to K^+K^0_S K^0_L$	q^2 dependent $O(100\%)$	Shape, 1	30%	0.02
Branching fraction for $B \to D^{**}$	—	Shape, 1	50%	0.42
Branching fraction for $B^+ \to K^+n\bar{n}$	q^2 dependent $O(100\%)$	Shape, 1	100%	0.20
Branching fraction for $D \to K^0_L X$	+30%	Shape, 1	10%	0.14
Continuum-background modeling, BDT$_c$	Multivariate $O(10\%)$	Shape, 1	100% of correction	0.01
Integrated luminosity	—	Global, 1	1%	< 0.01
Number of $B\bar{B}$	—	Global, 1	1.5%	0.02
Off-resonance sample normalization	—	Global, 1	5%	0.05
Track-finding efficiency	—	Shape, 1	0.3%	0.20
Signal-kaon PID	p, θ dependent $O(10-100\%)$	Shape, 7	$O(1\%)$	0.07
Photon energy	—	Shape, 1	0.5%	0.08
Hadronic energy	−10%	Shape, 1	10%	0.37
K^0_L efficiency in ECL	−17%	Shape, 1	8%	0.22
Signal SM form-factors	q^2 dependent $O(1\%)$	Shape, 3	$O(1\%)$	0.02
Global signal efficiency	—	Global, 1	3%	0.03
Simulated-sample size	—	Shape, 156	$O(1\%)$	0.52

$B \to K^*\gamma$ Systematics

New for Moriond 24

Belle II

362 fb^{-1}

Preliminary

$\mathscr{B}$

Source	$K^{*0}[K^+\pi^-]\gamma$	$K^{*0}[K^0_S\pi^0]\gamma$	$K^{*+}[K^+\pi^0]\gamma$	$K^{*+}[K^0_S\pi^+]\gamma$
B counting	1.5	1.5	1.5	1.5
$f^{\pm}/f^{00}$	1.6	1.6	1.6	1.6
γ selection	0.9	0.9	0.9	0.9
π^0 veto	0.7	0.7	0.7	0.7
η veto	0.2	0.2	0.2	0.2
Tracking efficiency	0.5	0.5	0.2	0.7
π^+ selection	0.2	–	–	0.2
K^+ selection	0.4	–	0.4	–
K^0_S reconstruction	–	1.4	–	1.4
π^0 reconstruction	–	3.9	3.9	–
χ^2 selection	0.2	1.0	0.2	1.0
CSBDT selection	0.3	0.4	0.4	0.3
Candidate selection	0.1	1.0	0.6	0.2
Fit bias	0.1	0.9	0.5	0.2
Signal PDF model	0.1	0.4	0.3	0.2
KDE PDF model	0.1	0.8	0.6	0.2
Simulation sample size	0.2	0.8	0.4	0.5
Misreconstructed signal	–	1.0	1.0	–
Total	2.6	5.4	4.9	3.2

A_{CP}

Source	$K^{*0}[K^+\pi^-]\gamma$	$K^{*+}[K^+\pi^0]\gamma$	$K^{*+}[K^0_S\pi^+]\gamma$
Fit bias	0.1	0.2	0.2
Signal PDF model	0.1	0.1	0.1
KDE modelling	0.1	0.4	0.2
BCS	0.1	0.5	0.2
K^+ asymmetry	–	0.6	–
π^+ asymmetry	–	–	0.6
$K^+\pi^-$ asymmetry	0.3	–	–
Total	0.4	0.9	0.7

$B^0 \to \gamma\gamma$ Systematics

New for Moriond 24

BELLE
694 fb^{-1}

Belle II
362 fb^{-1}

Preliminary

Signal yield

Source	Belle (%)	Belle II (%)
Photon Detection Efficiency	4.0	2.7
Reconstruction Efficiency (ϵ_{rec})	0.6	0.5
Number of $B\overline{B}$	1.3	1.5
f^{00}	2.5	2.5
$C_{\rm BDT}$ requirement	0.4	0.9
π^0/η veto	0.3	0.4
Timing requirement efficiency	2.8	–
Total (sum in quadrature)	5.7	4.1

Signal efficiencies

Source	Belle (events)	Belle II (events)
Fit bias	+0.16	+0.12
PDF parameterization	$^{+0.56}_{-0.48}$	$^{+0.30}_{-0.32}$
Shape Modeling	+0.06	+0.04
Total (sum in quadrature)	$^{+0.58}_{-0.48}$	$^{+0.30}_{-0.32}$