Recent Belle and Belle II results on radiative and EWP decays

31st Lepton Photon Conference 2023
MELBOURNE CONVENTION & EXHIBITION CENTRE
17 - 21 JULY

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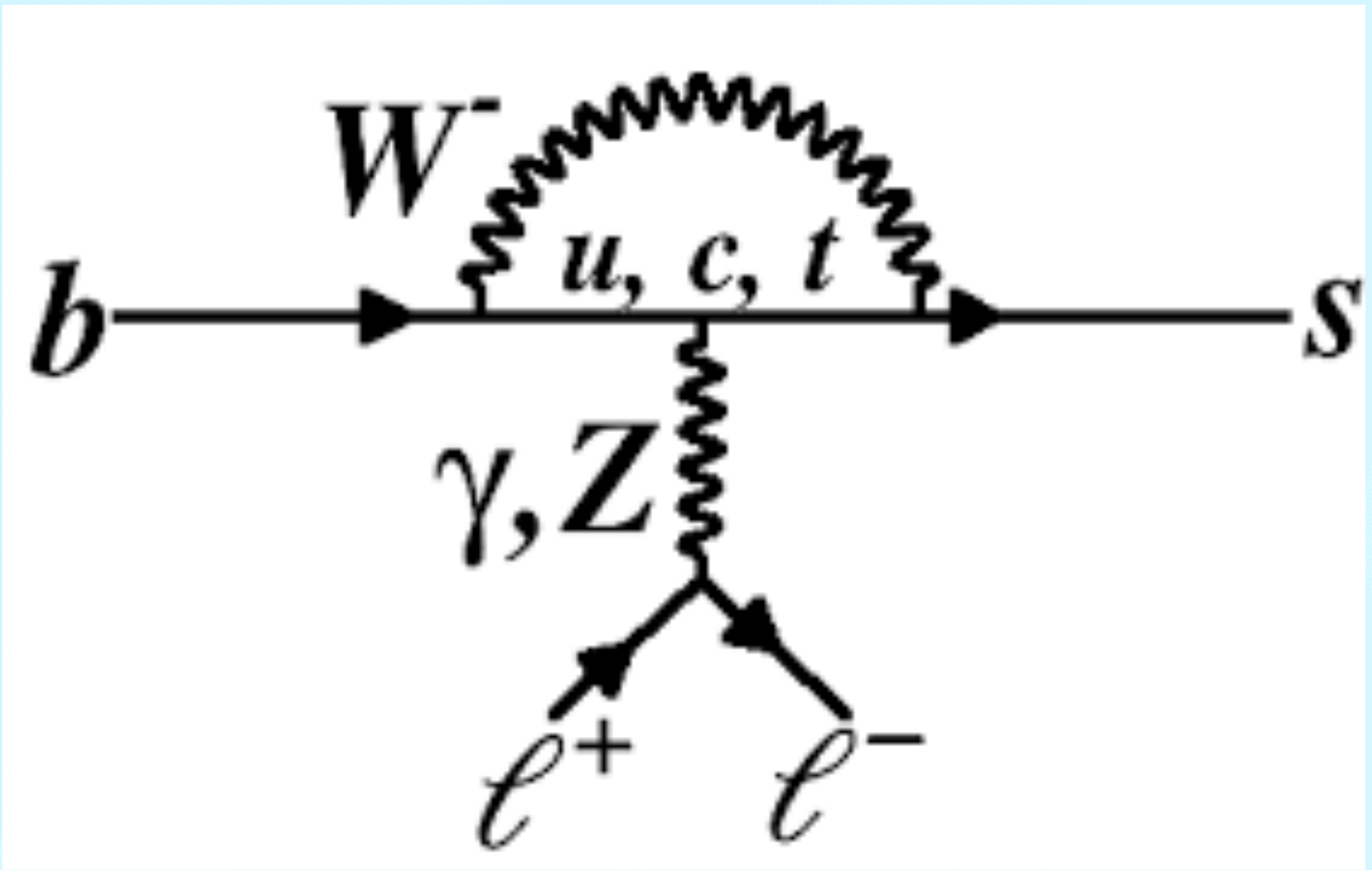
(On behalf of the Belle II collaboration)

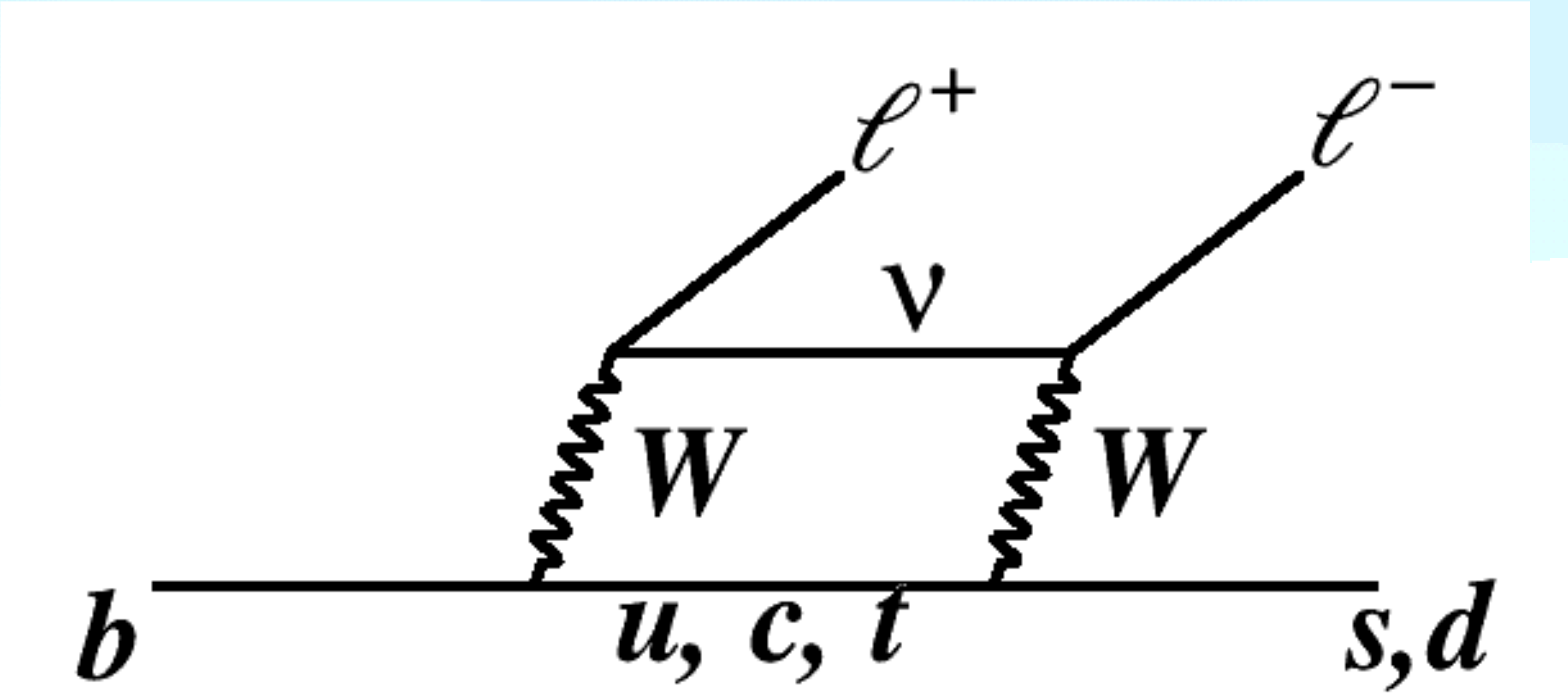
INFN TRIESTE

Belle II

Motivation

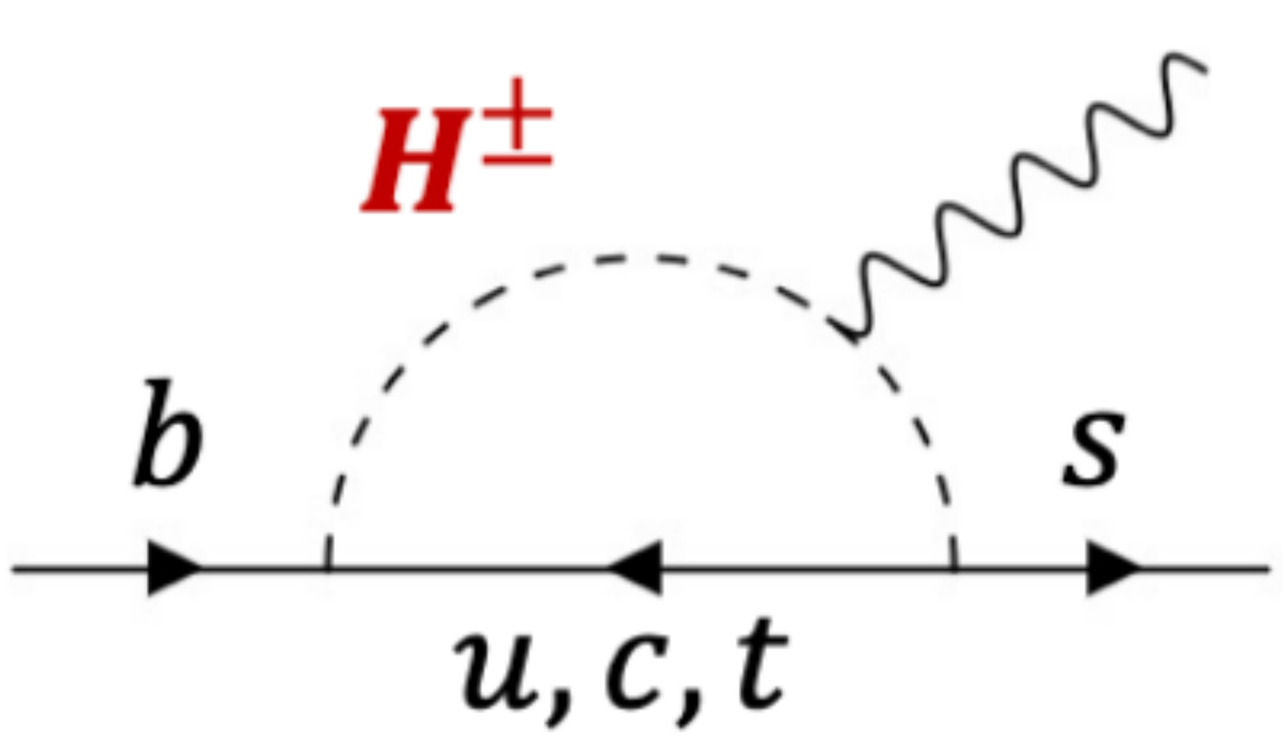
- $b \to s(d)$ flavour changing neutral current (FCNC) transitions **forbidden at tree level** in the Standard Model (SM)
  - Mediated by loop/box diagrams
  - Resulting B decays are rare $\mathscr{B}_{SM} = \mathcal{O}(10^{-7} - 10^{-4})$
- Precise predictions for ratios, angular observables and asymmetries





Look for variations/enhancements in FCNC due to BSM contributions Nature Phys. 18, 3 (2022) 277

- New interactions at tree level diagrams
- New particles in loop corrections



Many opportunities to probe the SM and explore BSM physics

Belle II at SuperKEKB

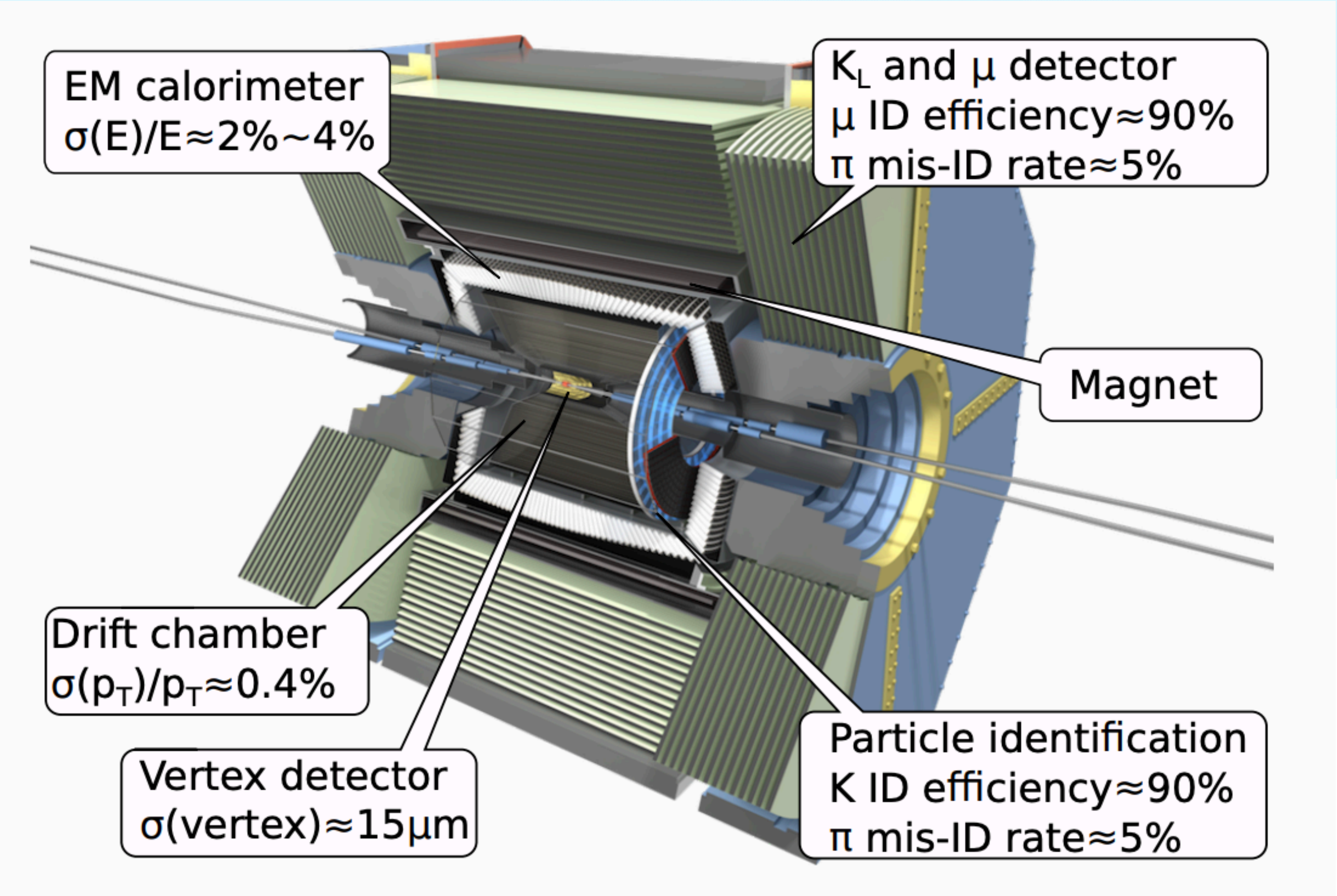
Asymmetric e^+e^- collisions at SuperKEKB accelerator at Japan

Collected 424 fb^{-1} of dataset so far (363 fb^{-1} on $\Upsilon(4S)$ resonance and 61 fb^{-1} below/above)

- Close to full solid-angle (~4π) coverage
- Low background
- Known initial kinematics
- Good charged particle reconstruction

★ *Similar advantages for Belle as well*

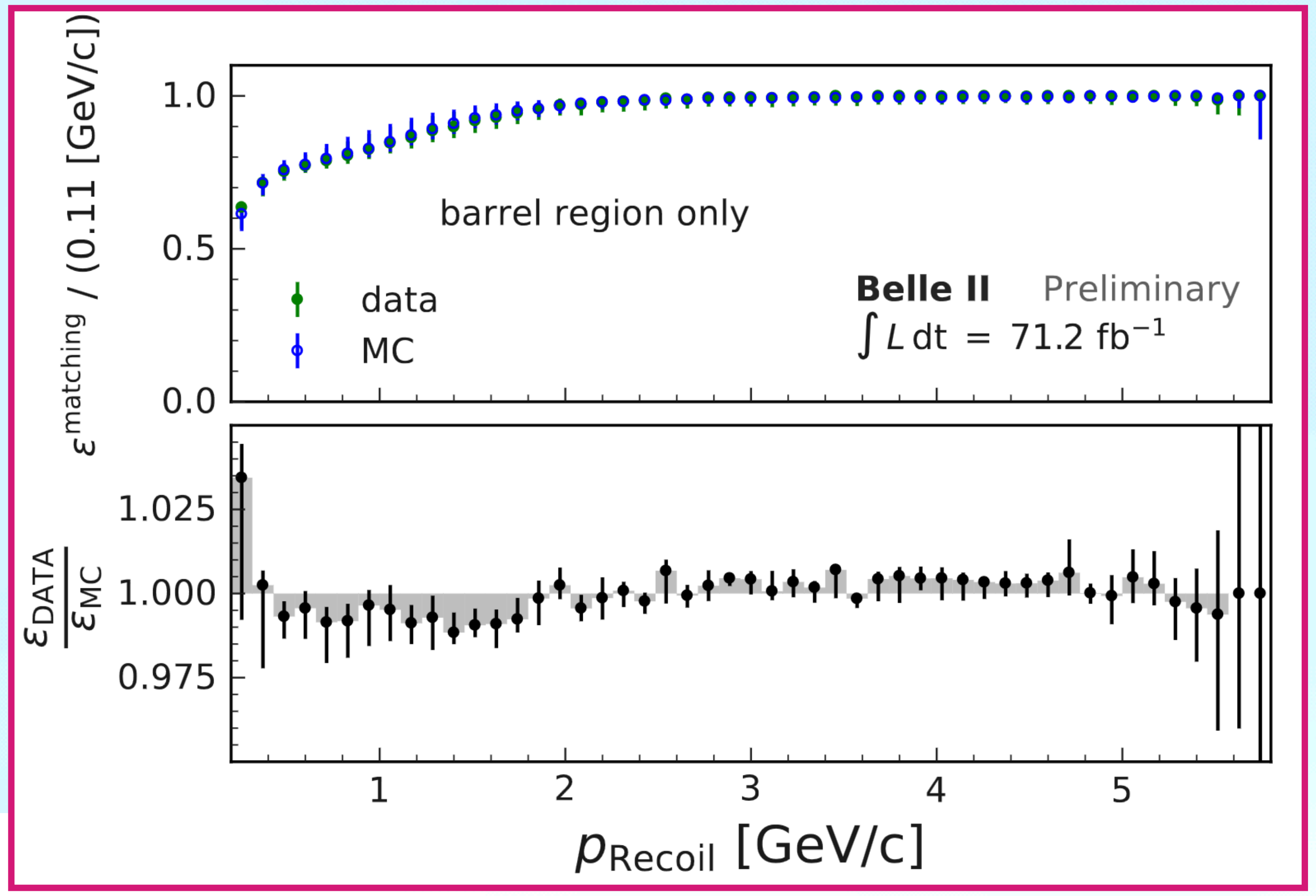
Instantaneous luminosity world record:
$4.7 \times 10^{34} \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ (June 2022)



Promising with multiple neutral particles and missing energy in the final state

Belle II: advantage for radiative and EWP

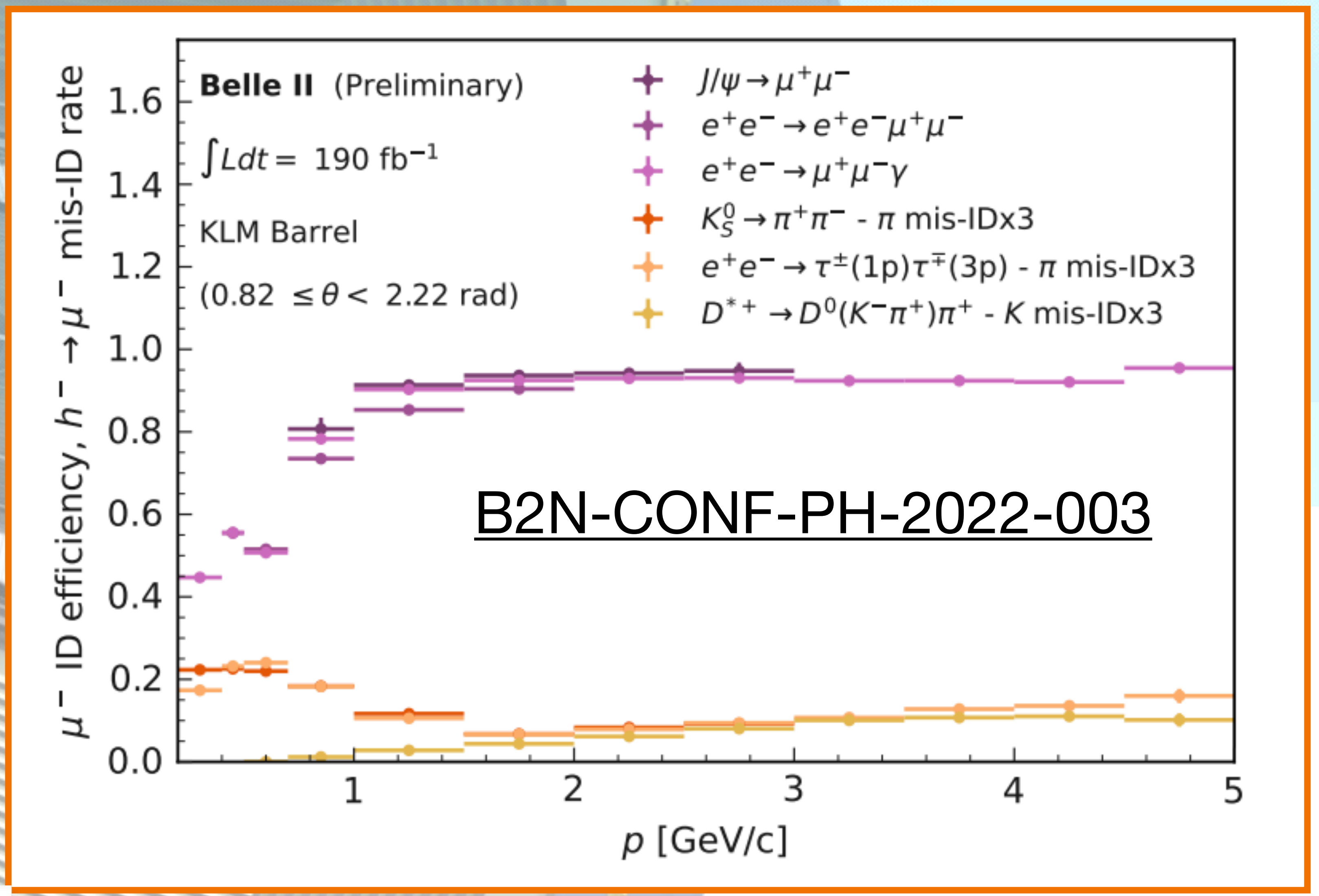
B2N-PL-2021-008



ECL
$\gamma = \sigma_E/E = 2\,\%\,(E > 1\ \text{GeV})$
eID: 85% at 0.1% π fake

KLM
muID: 90% at 5-10% π fake

High photon detection efficiency and good electron and muon identification efficiency



B2N-CONF-PH-2022-003

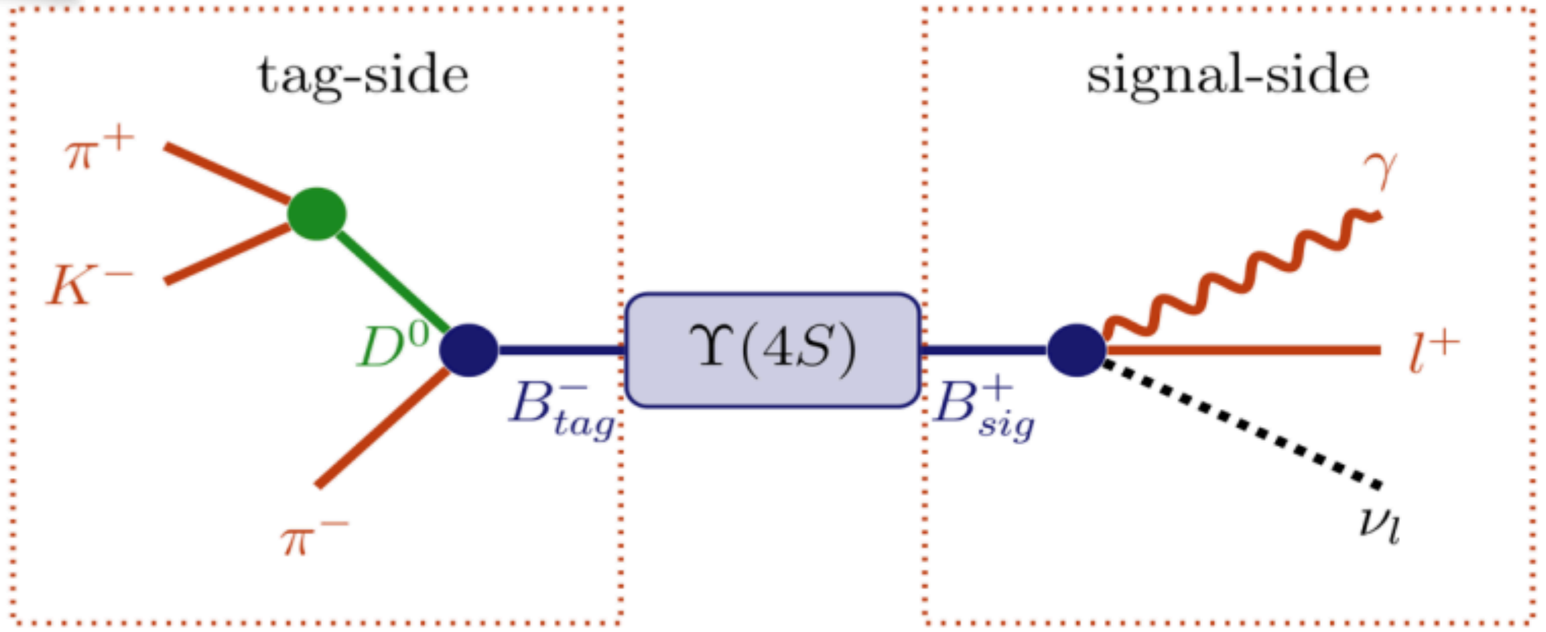
Inclusive and missing energy decays

$\mathcal{O}(1\%)$ Tagging efficiencies, achievable yields $\mathcal{O}(100\%)$

$\mathcal{O}(10\%)$ Purities of the tagged samples

Hadronic tagging
$B \to D^{(*)}n\pi$

Fully inclusive, no tagging
$B \to$ anything



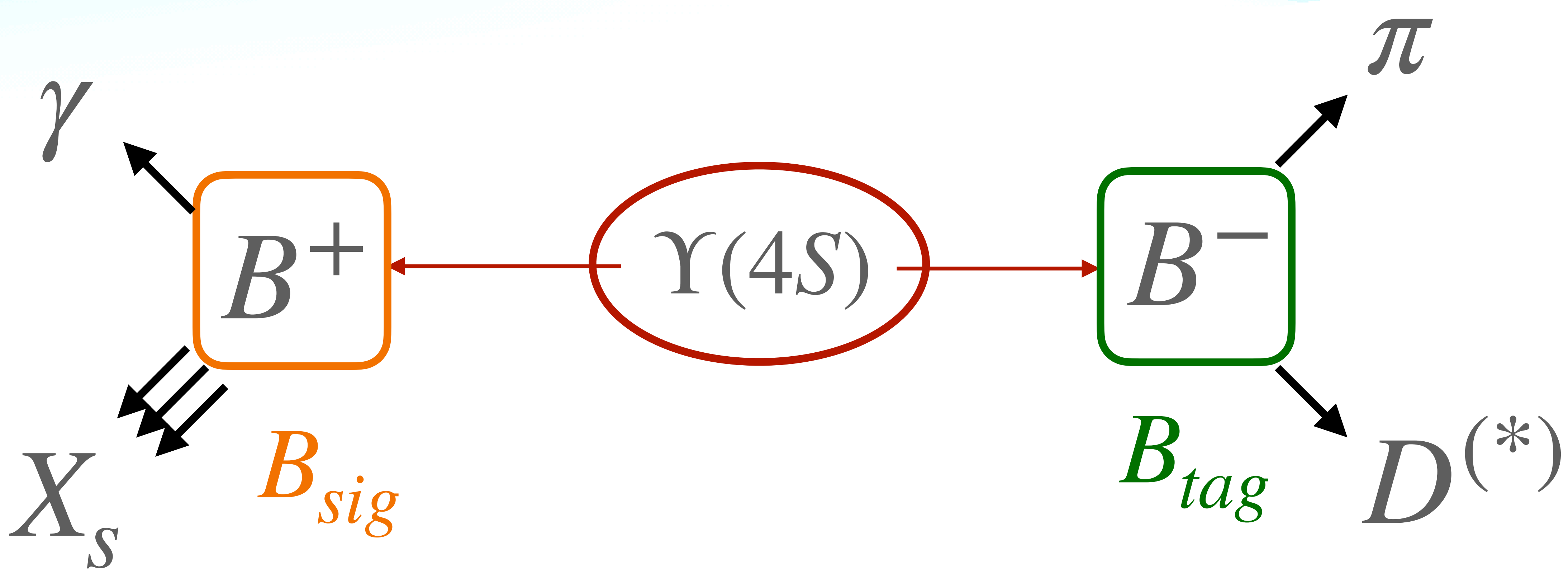
Let’s start with….

Fully inclusive $\mathrm{B} \to \mathrm{X_s}\gamma$: Belle II

arXiv:2210.10220

- $\mathscr{B}(B \to X_S\gamma)$ measurement as the most effective way to search for or constrain NP in $b \to s\gamma$
  - **Only possible in the clean environment of B-factories**

- Fully inclusive $\mathscr{B}(B \to X_S\gamma)$ measurement at Belle II using 189 fb^{-1} of dataset in bins of E_γ^B
- Partner B (tag) meson reconstruction in the event via **hadronic tagging**
  - Lower background, isolated X_S system, access to E_γ^B
  - Reduced statistics (efficiency < 1%)



E_γ^B: photon energy in B_{sig} rest frame

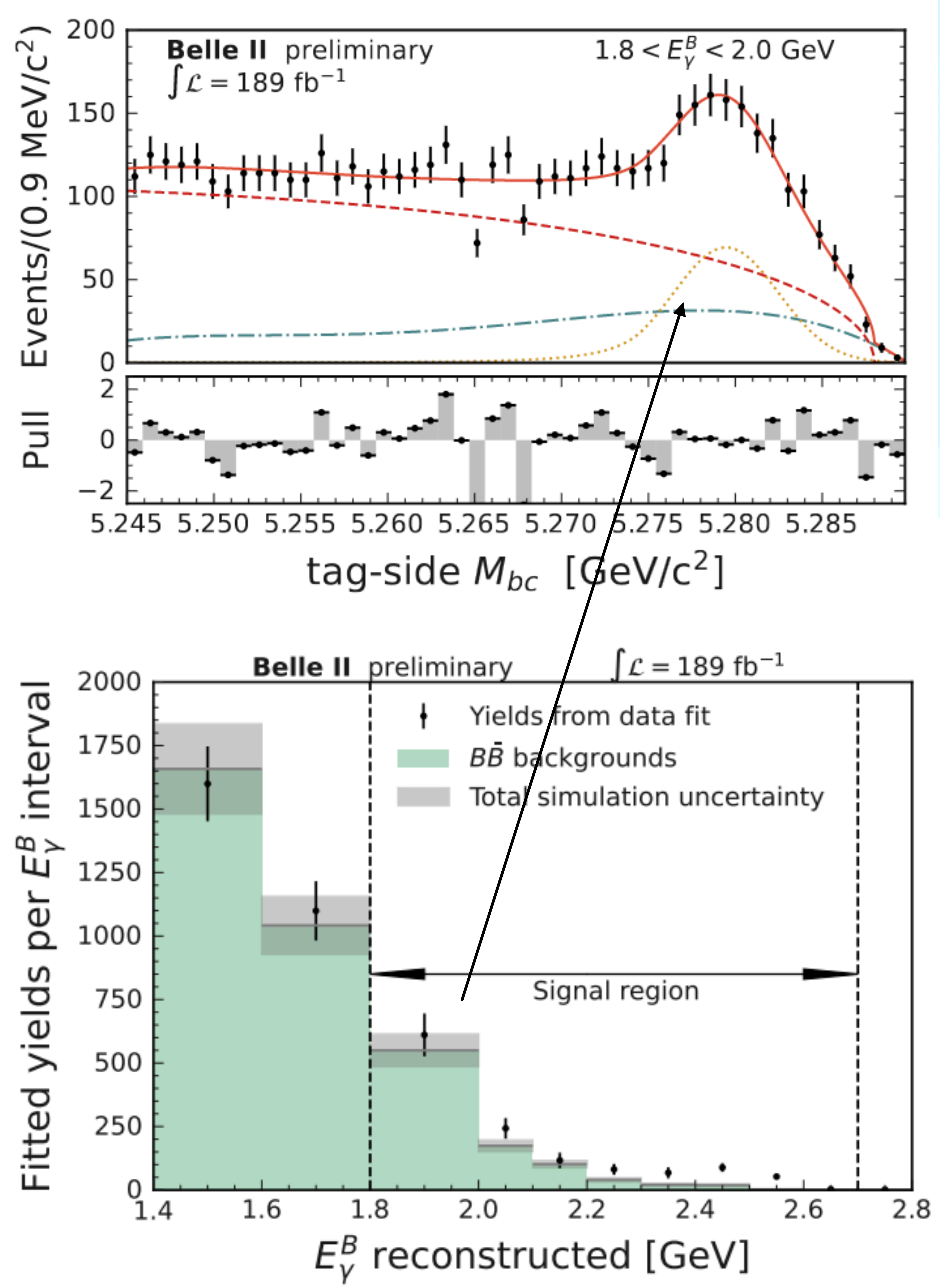
$\mathbf{B \to X_s\gamma}$: Selection and signal extraction strategy

arXiv:2210.10220

- Background suppression:
  - Veto γ from π^0 and η in signal region
  - Other backgrounds using boosted decision tree (BDT) classifier
- Simultaneous **fit to tag-side B mass in bins of E_γ^B**

$$M_{bc} = \sqrt{E_{beam}^2 - |\overrightarrow{p_B}|^2}$$

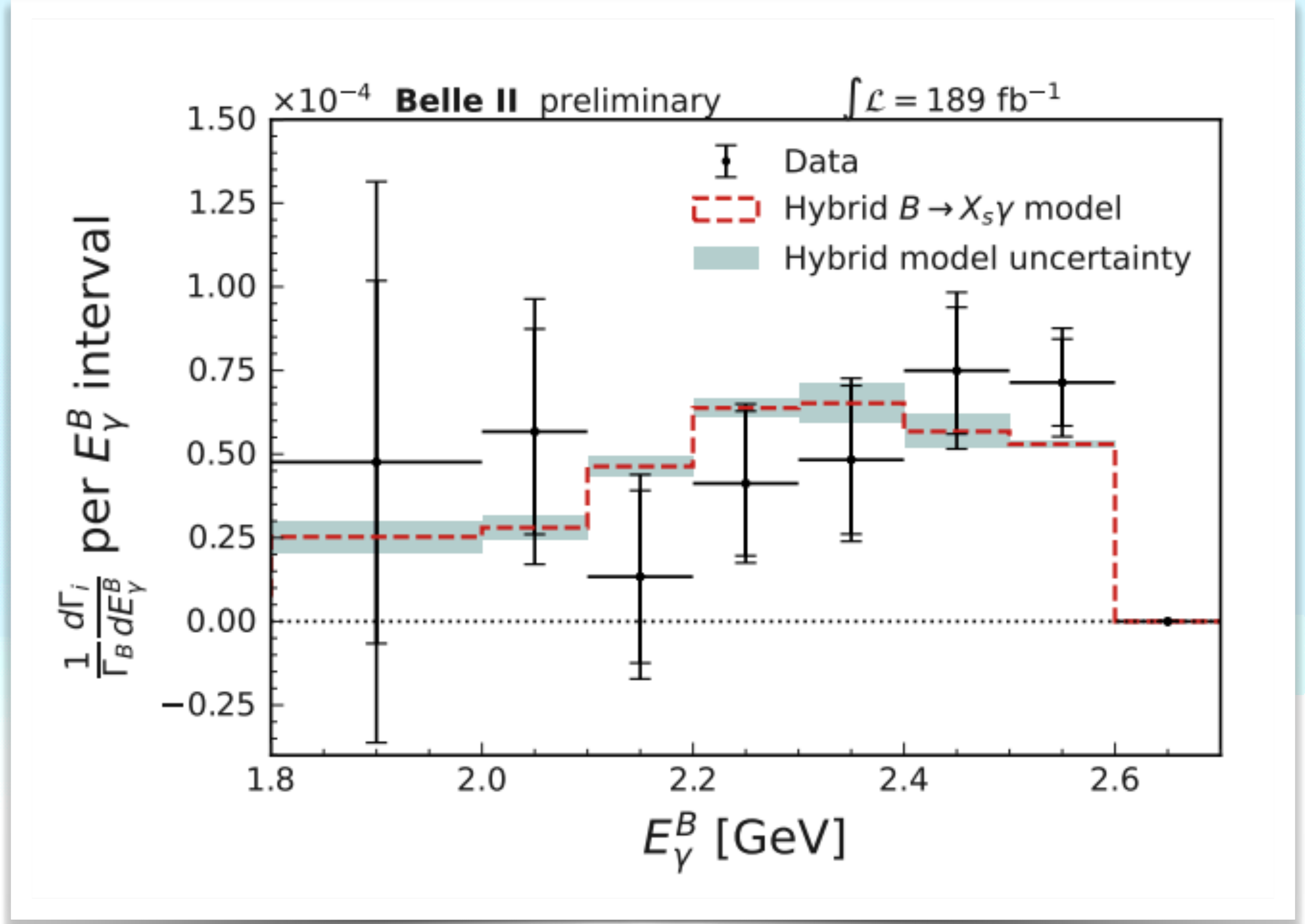
- Non-signal B subtracted using simulation
- $b \to d\gamma$ contribution removed assuming same shape and selection efficiency as $B \to X_S\gamma$



$\mathbf{B \to X_s\gamma}$: results

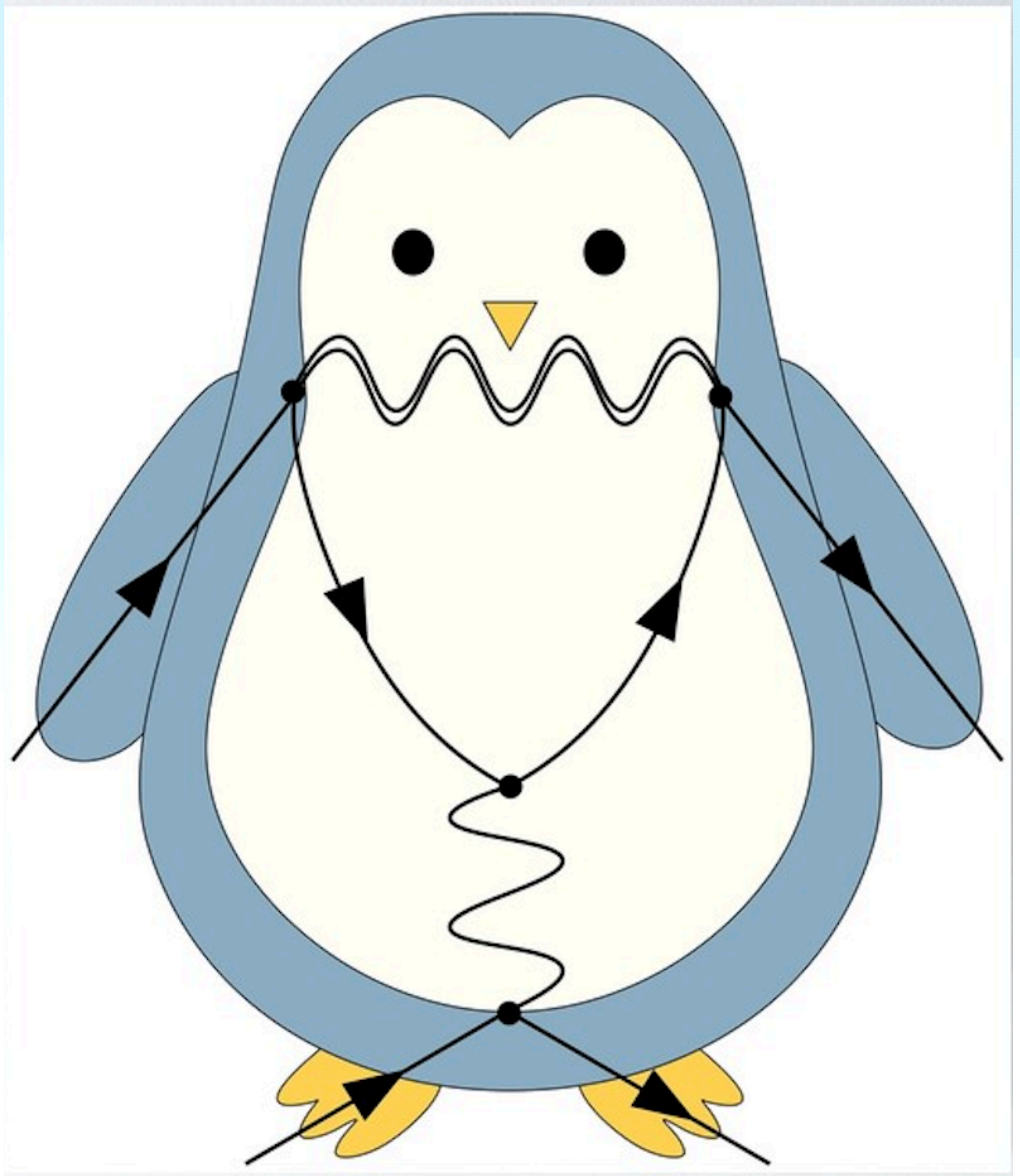
arXiv:2210.10220

E_γ^B threshold (GeV)	$\mathscr{B}(B \to X_s\gamma)(10^{-4})$
1.8	$3.54 \pm 0.78 \pm 0.83$
2.0	$3.06 \pm 0.56 \pm 0.47$
2.1	$2.49 \pm 0.46 \pm 0.35$



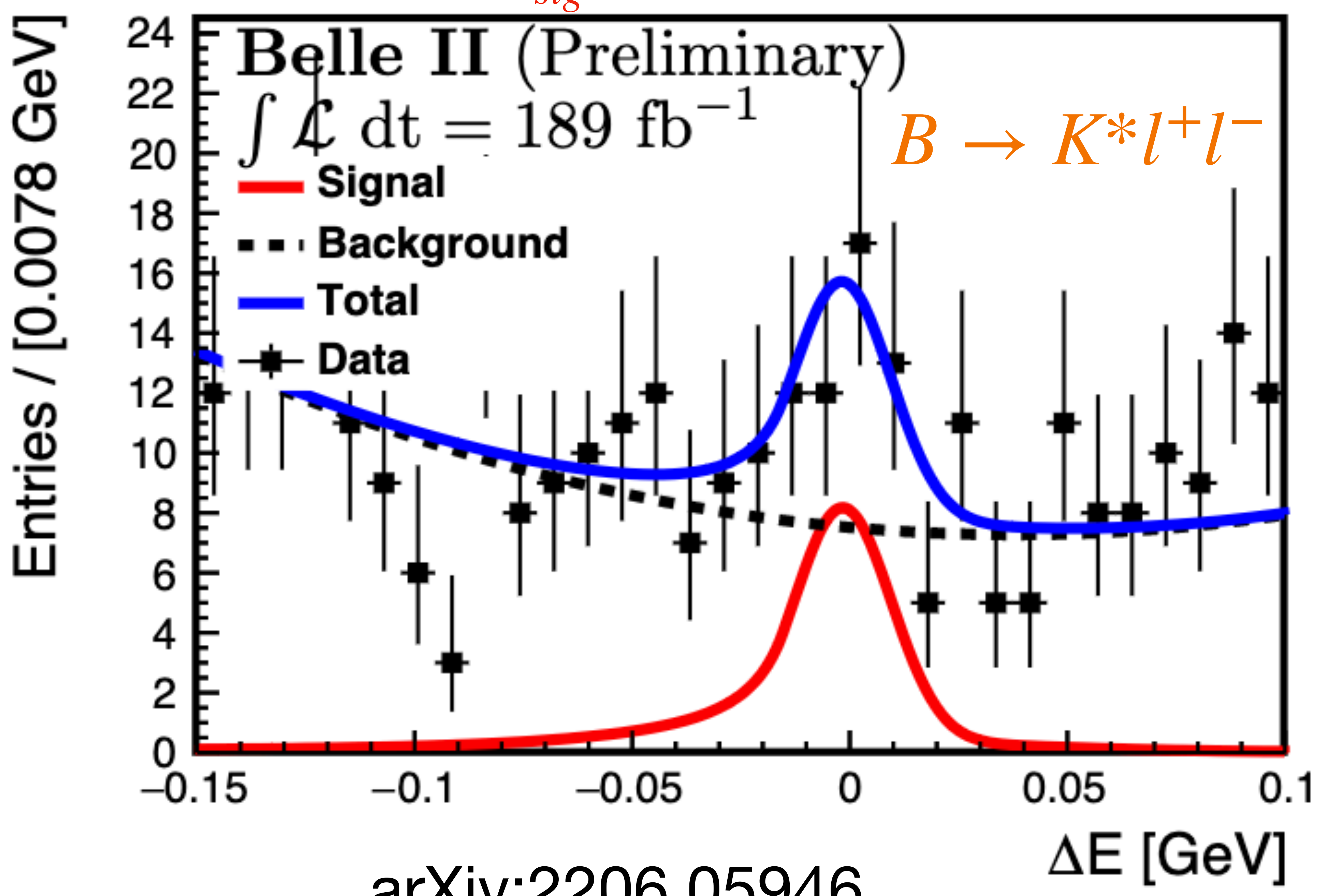
- Provided partial branching fractions in bins of E_γ^B
- We are already **competitive with BaBar results with 10% less data**
  - BaBar hadronic tag result for $E_\gamma^B > 1.9$ GeV (210 fb^{-1}): $(3.66 \pm 0.85 \pm 0.60) \times 10^{-4}$ PRD77.051103
- Dominant systematics comes from background modelling (limited size of the simulation propagated) and fit assumptions

Moving towards……



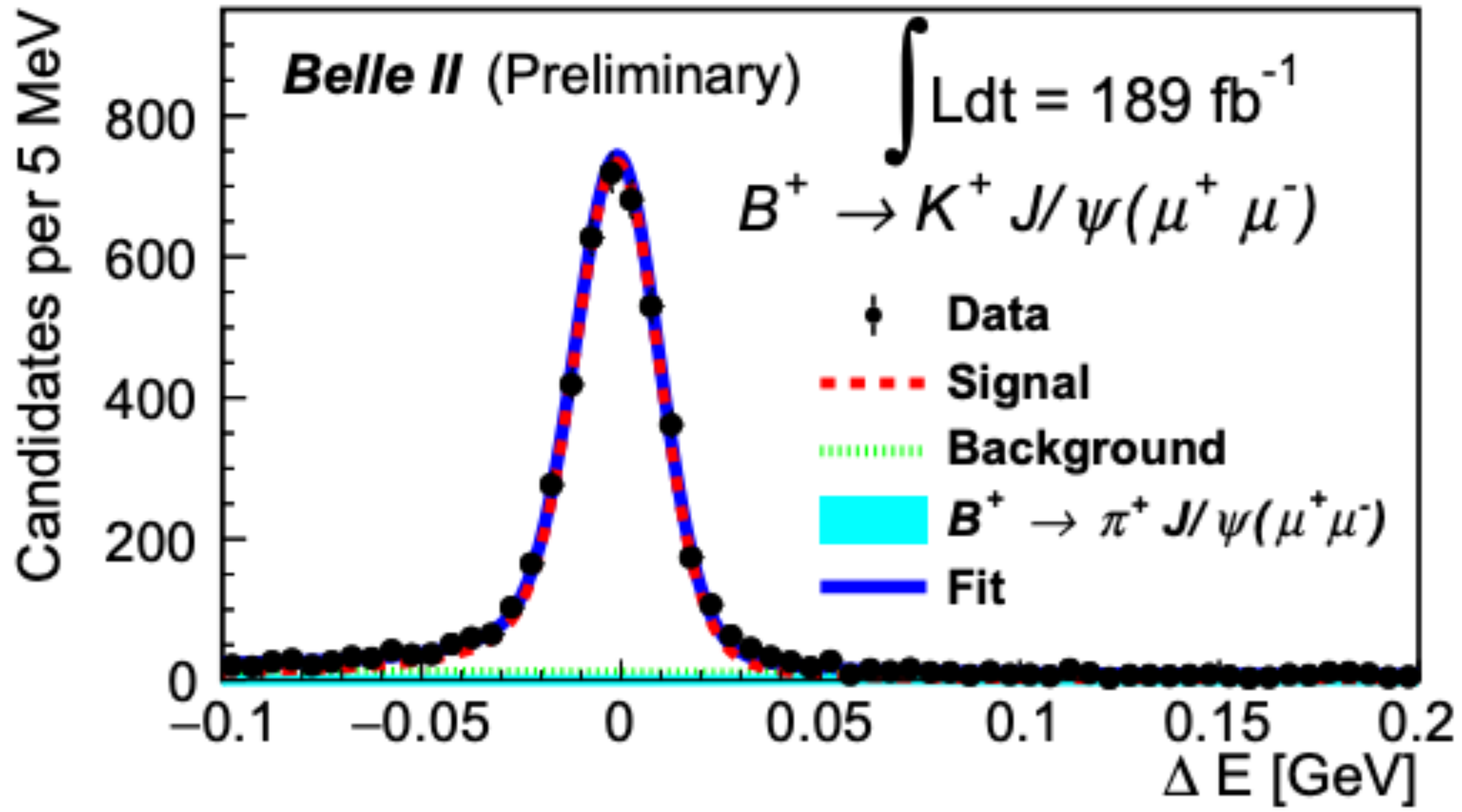
Preparatory work towards $R_{K^{(*)}}$: Belle II

$N_{sig} = 38 \pm 9$



arXiv:2206.05946

$N_{sig} = 4578 \pm 62$



arXiv:2207.11275

$$\mathscr{B}(B \to K^* l^+ l^-) = (1.25 \pm 0.30^{+0.08}_{-0.07}) \times 10^{-6}$$

$$R_{K^+}(J/\psi) = 1.009 \pm 0.022 \pm 0.008$$
$$R_{K^0}(J/\psi) = 1.042 \pm 0.042 \pm 0.008$$

$$\Delta E = E_B - E_{beam}$$

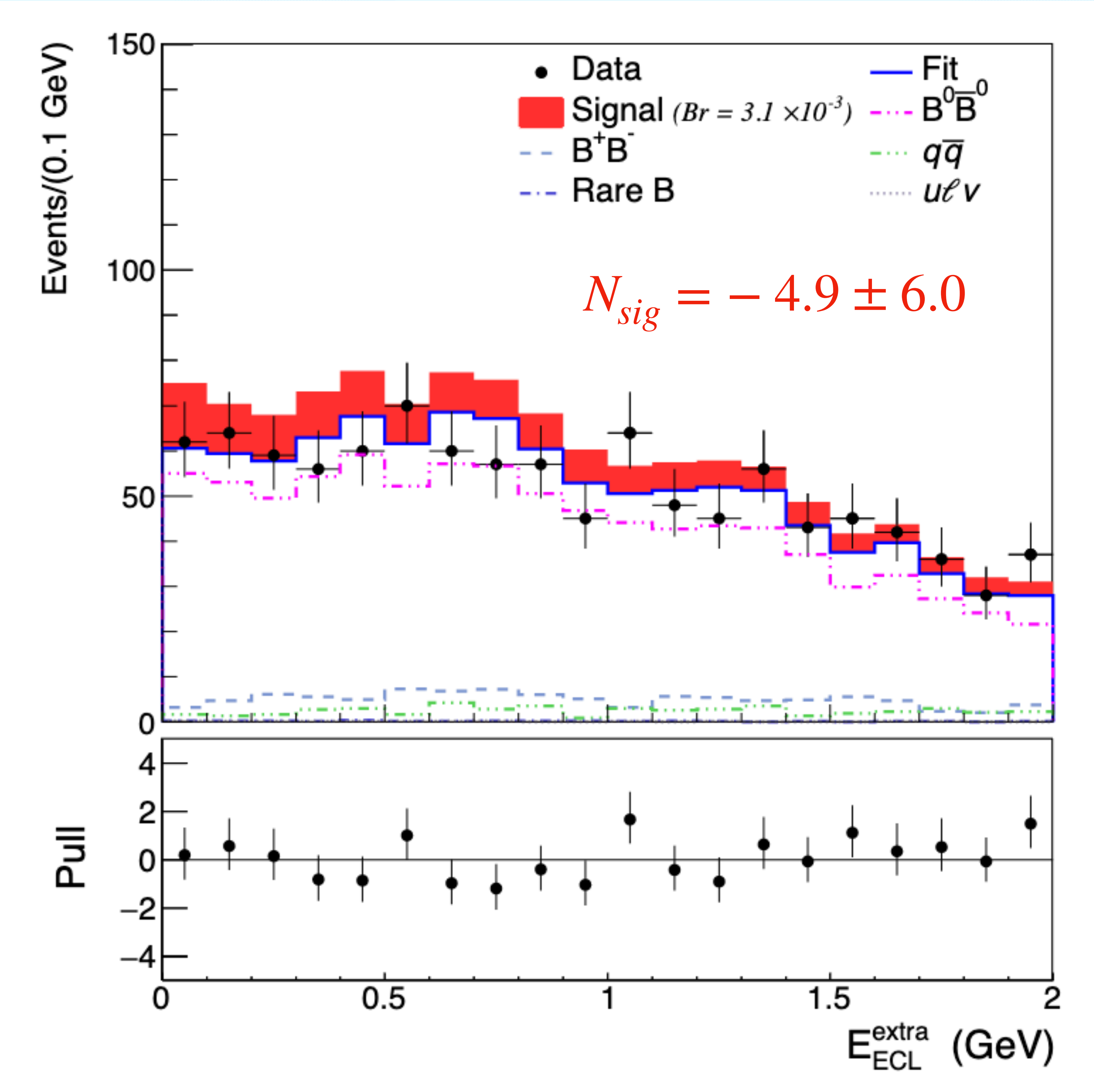
- Similar performance for e and μ channels
- Belle II predicts 3% precision of $R_{K^{(*)}}$ at 50 ab-1, it would provide a crucial clarification in a different experimental environment compared to LHCb

Search for $\mathbf{B} \to \mathbf{K}^{*0}\tau\tau$ decays: Belle

arXiv:2110.03871

- SM expected BF $\mathcal{O}(10^{-7})$
- Current sensitivity is far from $\mathscr{B}_{\rm SM}$

Decay	BF U.L. @90% CL		
$B_S \to \tau\tau$	5.2×10^{-3}	LHCb	3 fb-1
$B^+ \to K\tau\tau$	2.3×10^{-3}	BABAR	424 fb-1
$B^0 \to K^{*0}\tau\tau$	3.1×10^{-3}	Belle	711 fb-1



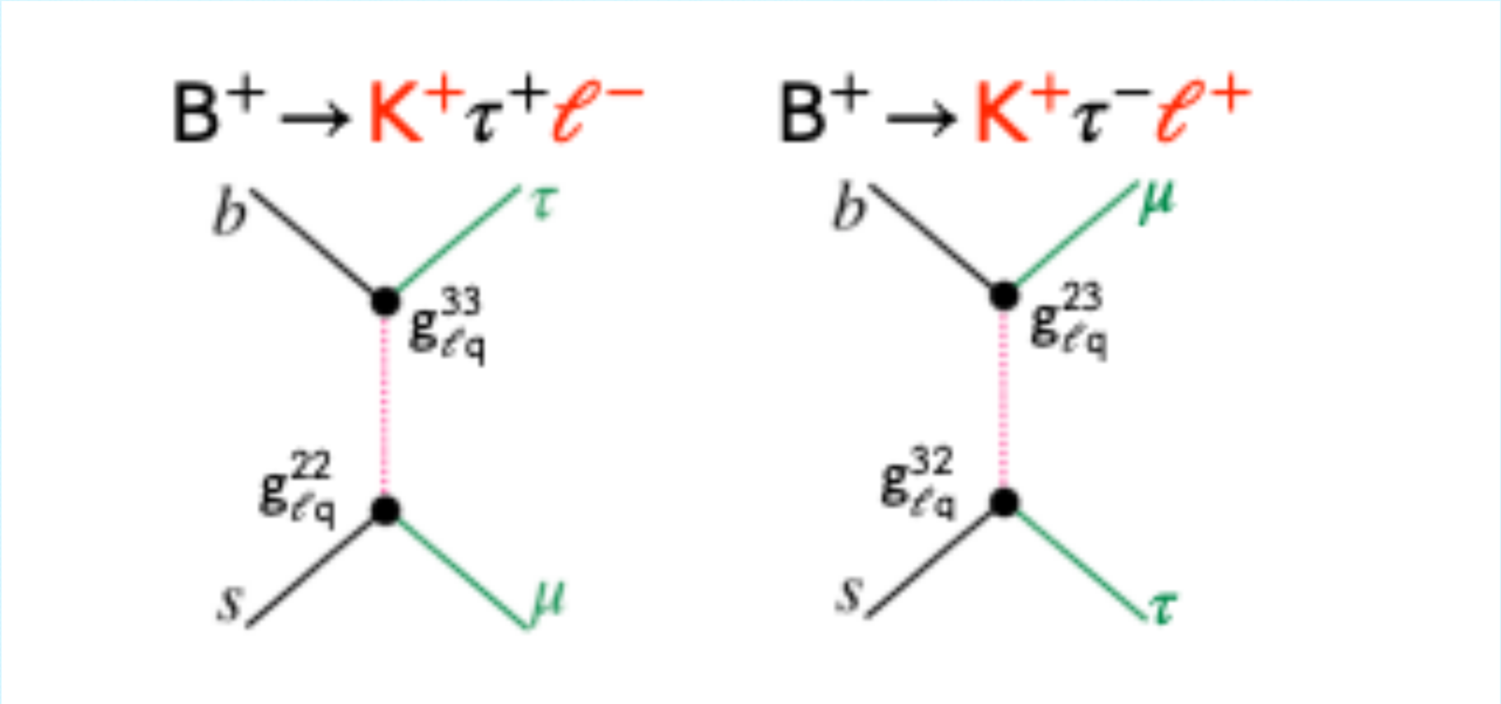
- Tag-side B decays hadronic ally
- $\tau \to l\nu\bar{\nu}, \pi\nu$ modes are considered
- Signal extraction from fit to the $E_{\rm ECL}^{extra}$: gives peak at zero for signal events

$$\boxed{\mathscr{B}(\mathbf{B^0} \to \mathbf{K^{*0}}\tau\tau) < \mathbf{3.1 \times 10^{-3}}}$$

No signal observed, UL is provided at 90% CL

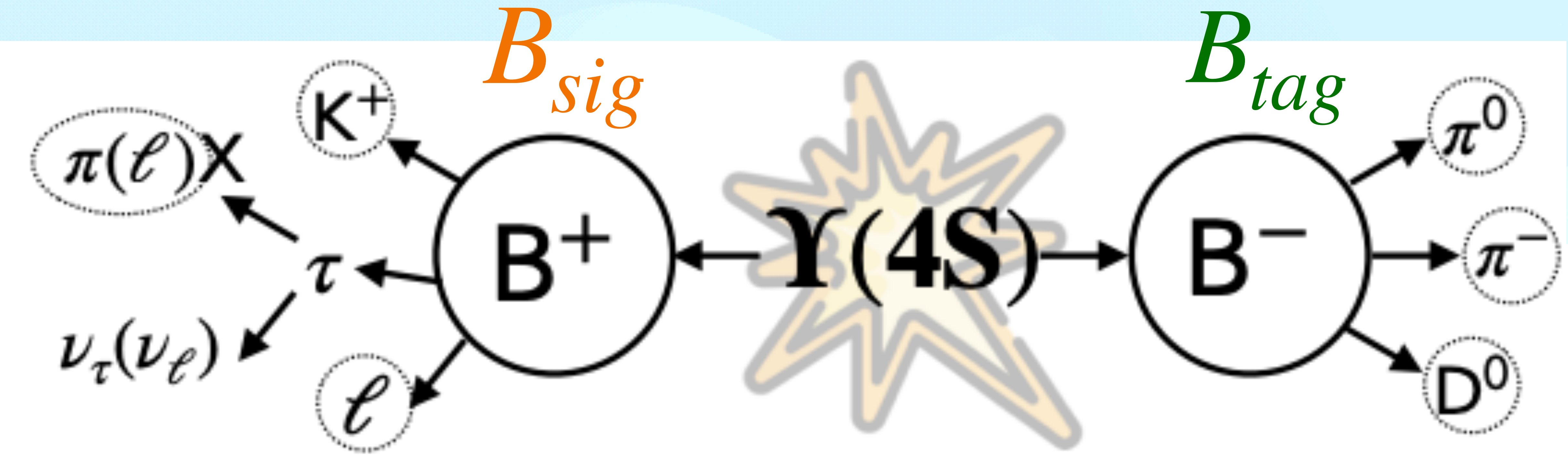
$\mathrm{B} \to \mathrm{K}\tau l$ search: Belle

PRL130(2023)261802



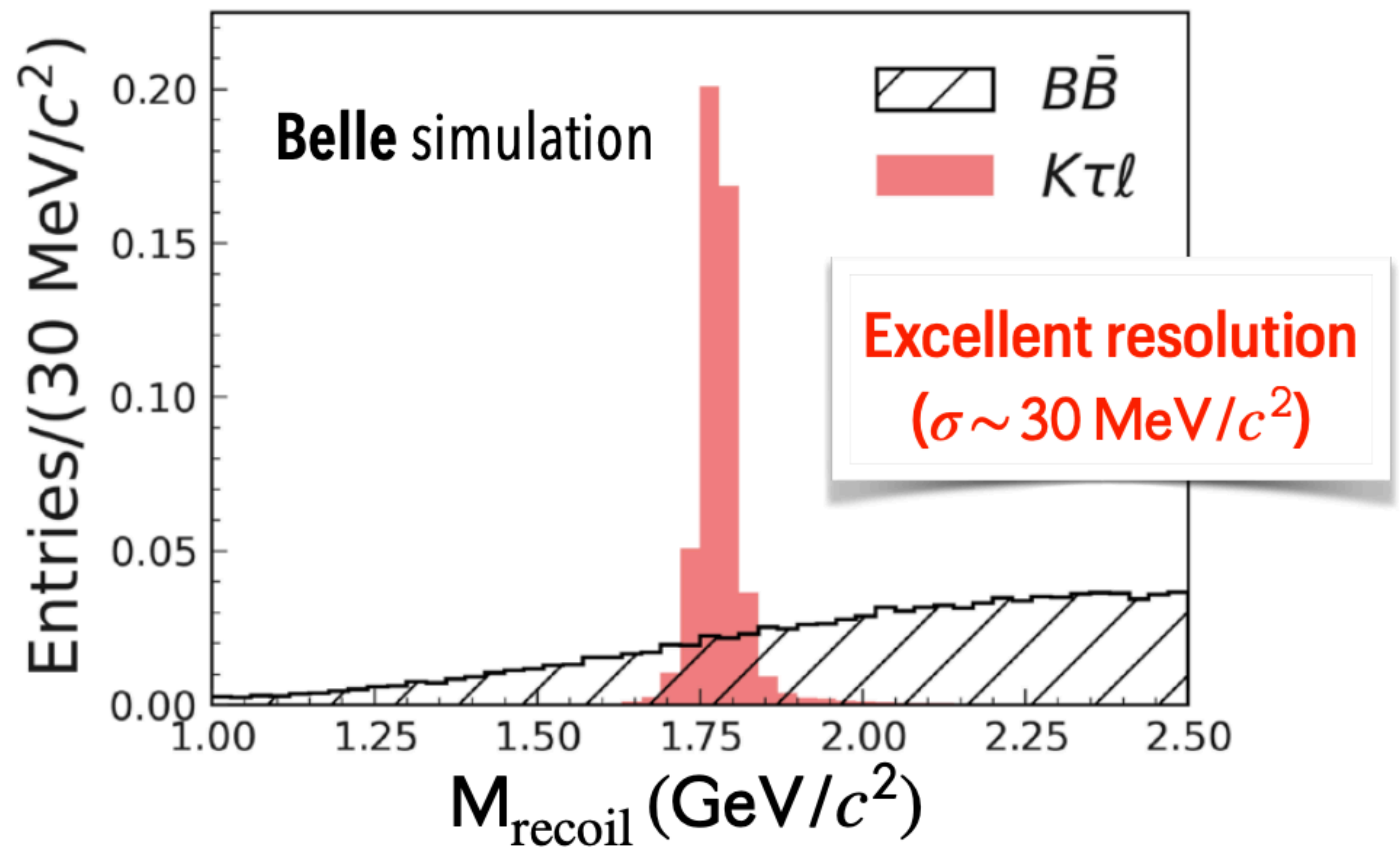
- LFV $B \to K\tau l$ decays are more interesting to simultaneously explain $R_{K^{(*)}}$ and $R_{D^{(*)}}$ anomalies

  - Sensitivity is entering now the 10^{-6} regime



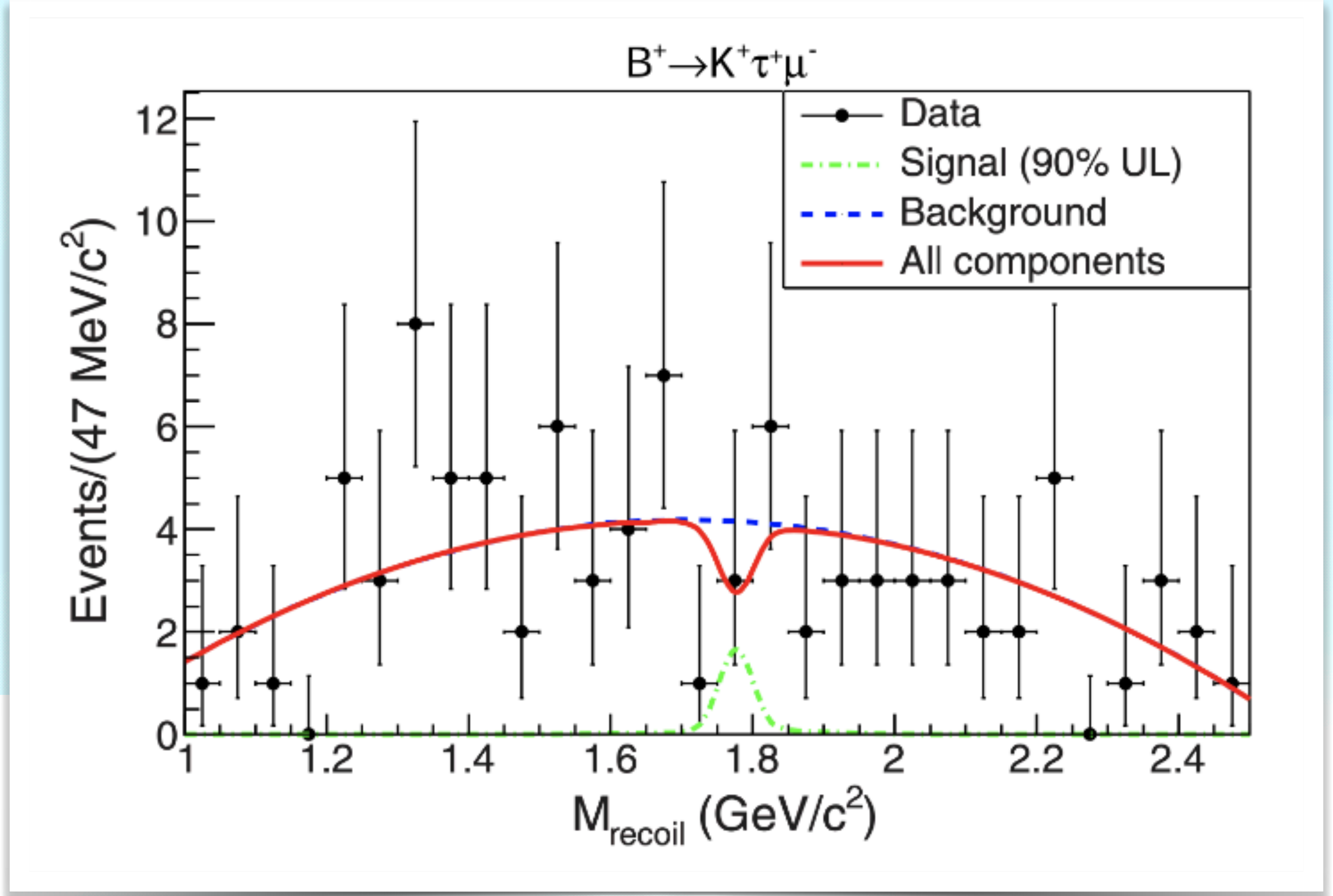
Search at Belle

- Uses full 711 fb-1 of Belle dataset
- Tag-side B decays hadronically
- Signal B reconstruction from K and lepton (e, μ)
- Signal extraction from the **recoil-mass** of B_{sig} and B_{tag}: should give a peak at τ mass for signal events
- Background is suppressed using BDT



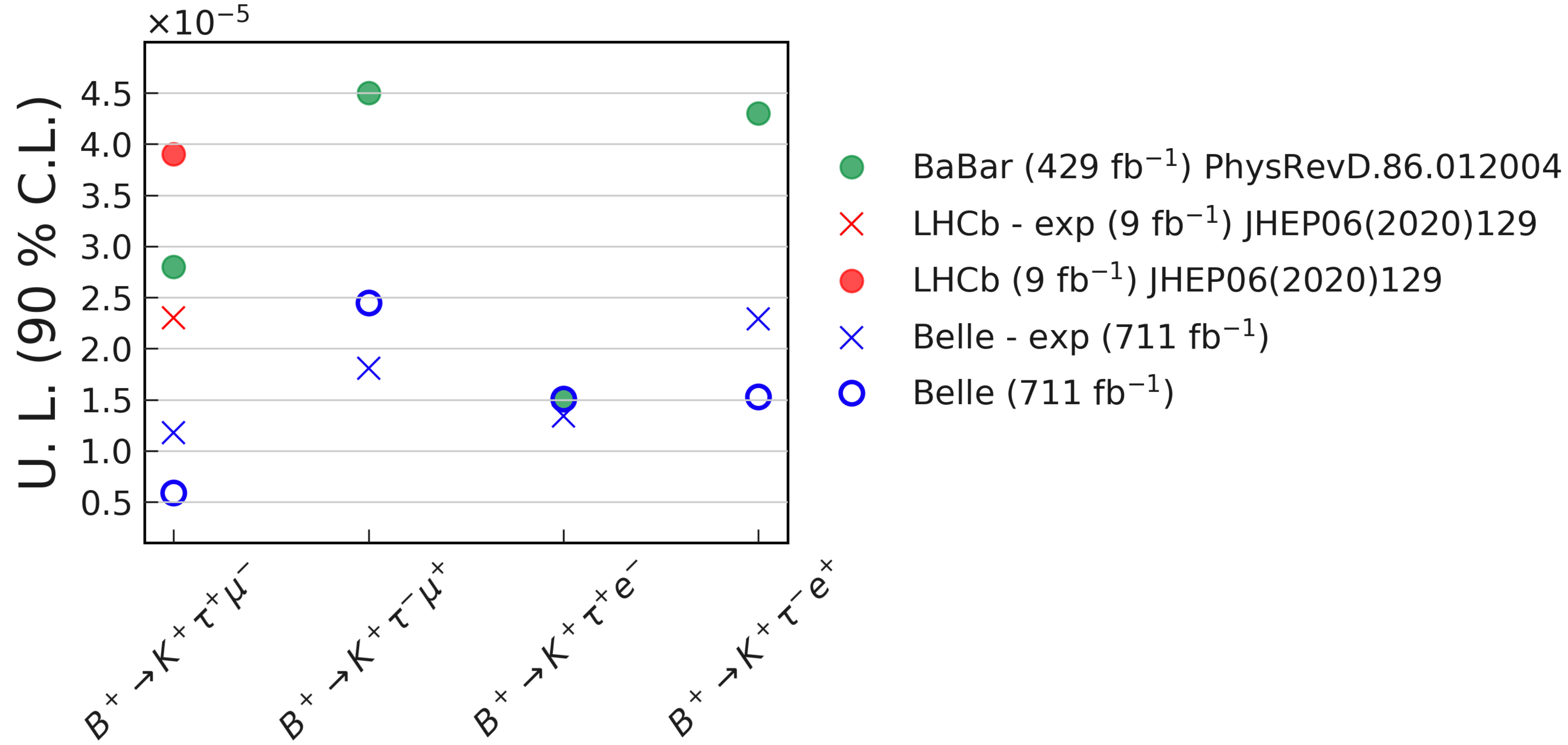
$\mathbf{B \to K\tau l}$ search: results

PRL130(2023)261802



Four different modes (2 charge configurations x 2 flavours)

Mode	ε (%)	$\varepsilon^{\mathrm{NP}}$ (%)	N_{sig}	$\mathcal{B}^{\mathrm{UL}}$ (10^{-5})
$B^+ \to K^+\tau^+\mu^-$	0.064	0.058	-2.1 ± 2.9	0.59 (0.65)
$B^+ \to K^+\tau^+e^-$	0.084	0.074	1.5 ± 5.5	1.51 (1.71)
$B^+ \to K^+\tau^-\mu^+$	0.046	0.038	2.3 ± 4.1	2.45 (2.97)
$B^+ \to K^+\tau^-e^+$	0.079	0.058	-1.1 ± 7.4	1.53 (2.08)



- No significant signal is observed, UL is provided at 90% CL
- **World's best limit on $B \to K\tau l$ decays**

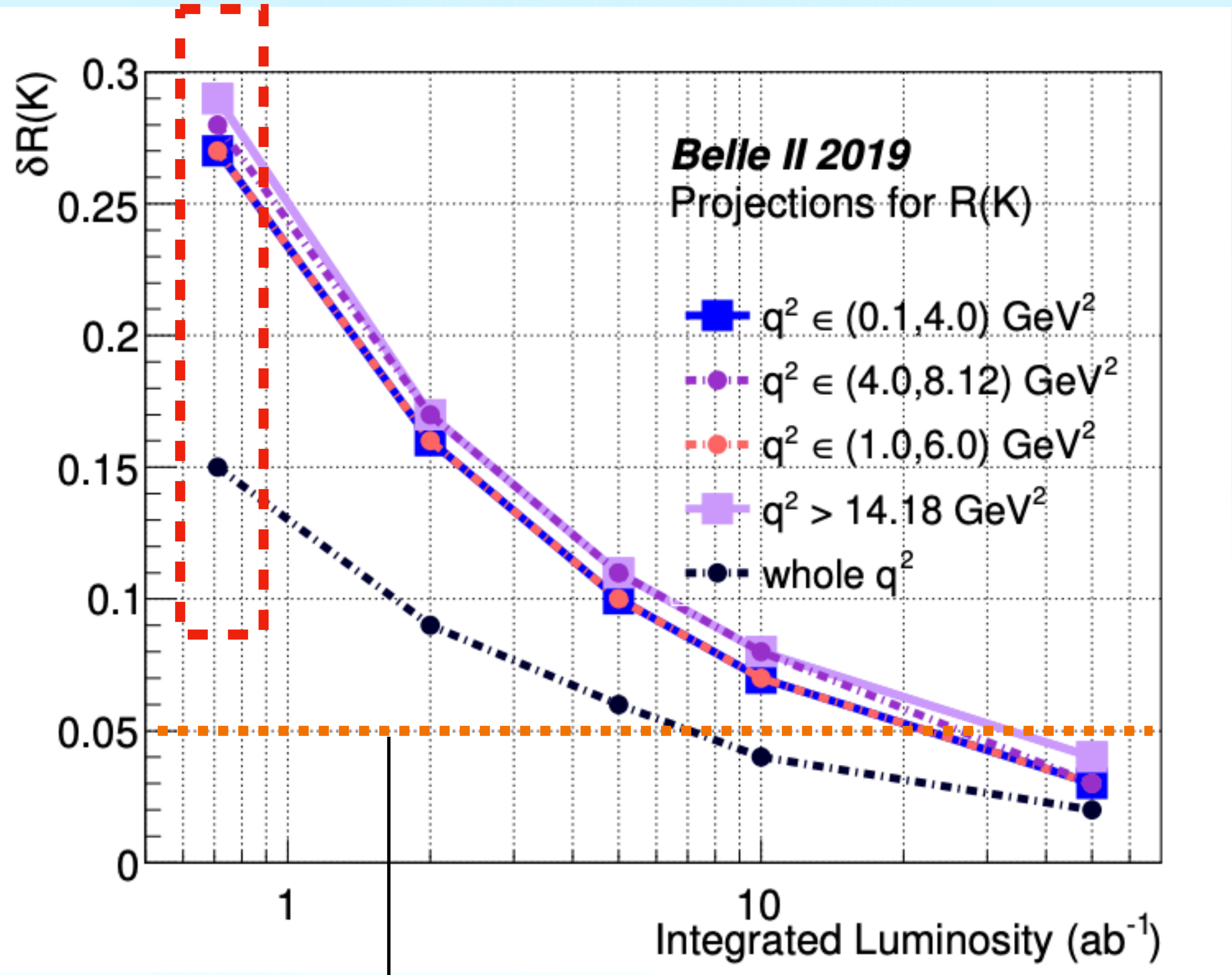
Summary

- $b \to s$ transitions offer powerful probe of the SM and physics beyond
- $b \to s$ studies are important part of Belle II physics program
  - Unique access to radiative and missing energy modes
- Measurements with 189 fb^{-1} Belle II dataset were presented today
  - BF of inclusive $B \to X_s\gamma$ decays and preparatory measurements for LFU test
- Measurements with 711 fb^{-1} Belle dataset were also presented
  - Search for $B^0 \to K^{*0}\tau\tau$: no signal observed, provided UL at 90% CL
  - Search of LFV decay $B \to K\tau l$ decays: **currently provides world's best limits**

Belle II: twice the dataset already available, data taking will restart in early 2024. Many exciting results are coming, stay tuned!

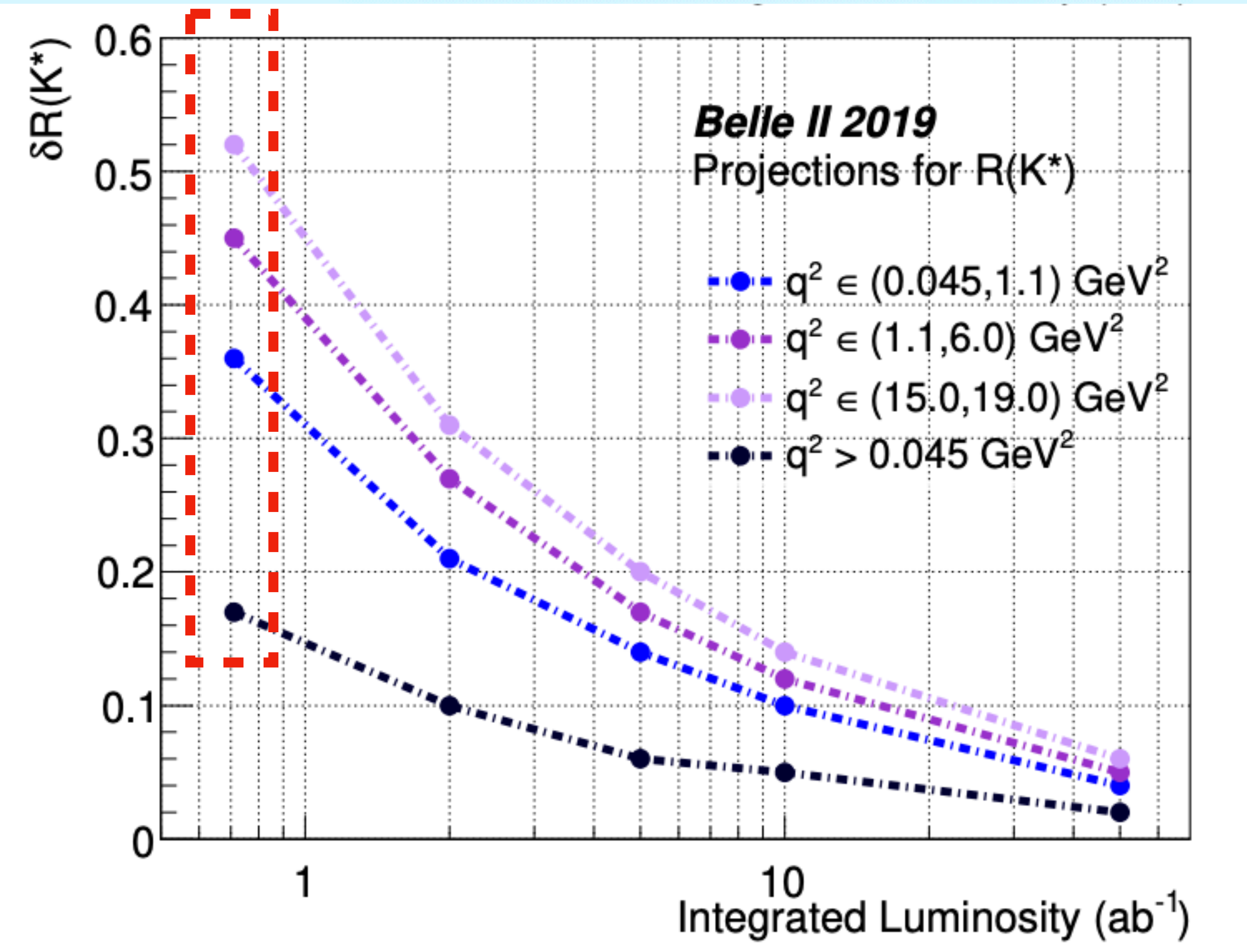
Belle II prospects for $\mathrm{R}_{\mathrm{K}^{(*)}}$

Uncertainties are from:
Belle JHEP 03 105 (2021)



Current LHCb precision for $q^2 \in [1,6]\ \mathrm{GeV}/c^2$ (9 fb-1): stat. dominated

Uncertainties are from:
Belle PRL 126, 161801 (2021)



Belle II can provide 3% precision at 50 ab-1

$B \to K^*(892) l^+ l^-$: results

arXiv:2206.05946

$$\mathscr{B}(B \to K^* \mu^+ \mu^-) = (1.19 \pm 0.31^{+0.08}_{-0.07}) \times 10^{-6}$$
$$\mathscr{B}(B \to K^* e^+ e^-) = (1.42 \pm 0.48 \pm 0.09) \times 10^{-6}$$

- **Results are consistent with the W.A., but precision is limited by the sample size**
- Performance is similar between muon and electron channels
- Main systematics sources are:
  - Total number of $B\bar{B}$ pair: 2.9%
  - Data-MC differences in π^0 reconstruction efficiency: 3.4%

$B \to J/\psi(l^+l^-)K$: results

arXiv:2207.11275

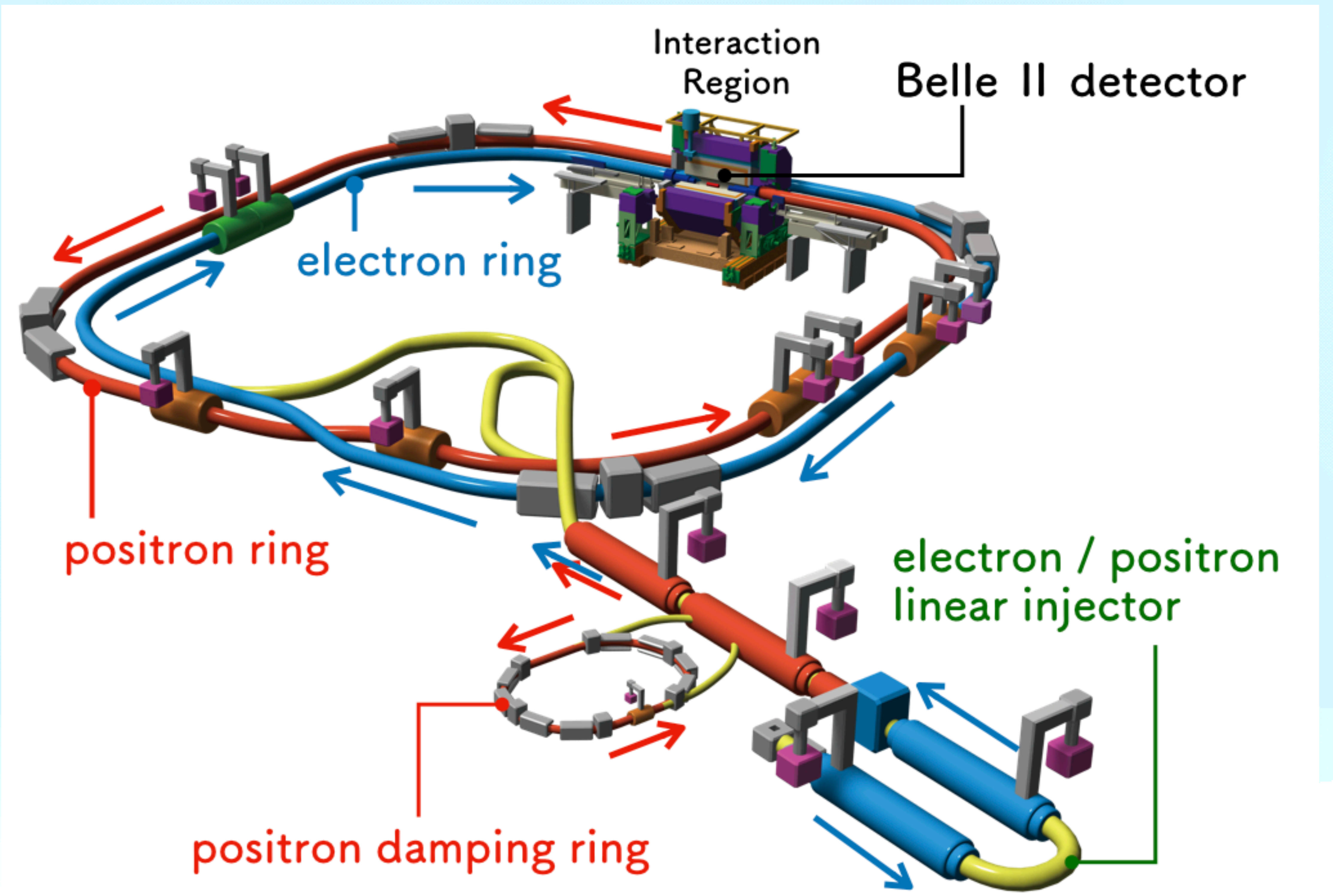
$$A_I(B \to J/\psi(\mu^+\mu^-)K) = -0.006 \pm 0.015 \pm 0.030$$
$$A_I(B \to J/\psi(e^+e^-)K) = -0.022 \pm 0.016 \pm 0.030$$
$$R_{K^+}(J/\psi) = 1.009 \pm 0.022 \pm 0.008$$
$$R_{K^0}(J/\psi) = 1.042 \pm 0.042 \pm 0.008$$

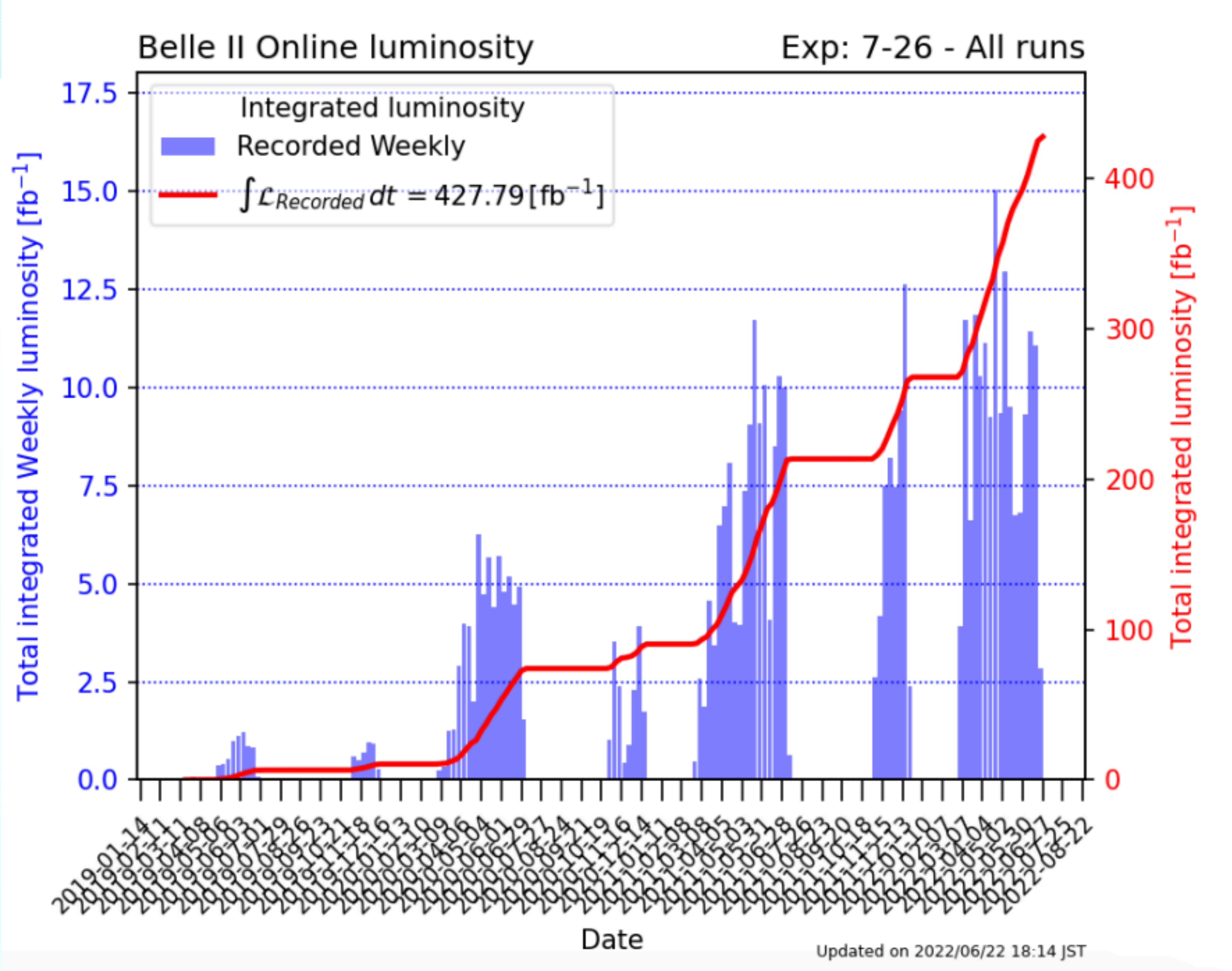
- **Results are consistent with the W.A.**
- Similar efficiencies for muon and electron modes: uncertainty on R_K will be equally contributed by the these flavour modes
- Main systematics sources are:
  - BF of $\Upsilon(4S) \to B^0\bar{B}^0, B^+B^-$: 2.6%
  - Data-MC differences in K_S^0 reconstruction efficiency: 3.0%

Belle II at SuperKEKB

- Asymmetric e^+e^- collisions at centre-of-mass energy 10.58 GeV corresponding to $\Upsilon(4S)$ resonance mass

- $B\bar{B}$ at threshold production: $\mathscr{B}(\Upsilon(4S) \to B\bar{B}) > 96\,\%$





- Instantaneous luminosity world record: $4.7 \times 10^{34}\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ (June 2022)

- Target instantaneous luminosity: $6 \times 10^{35}\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

- Collected 428 fb^{-1} of dataset so far (362 fb^{-1} on $\Upsilon(4S)$ resonance and 66 fb^{-1} below)

- Target dataset: 50 ab^{-1}

Measurement of $\mathbf{B \to J/\psi(l^+l^-)K}$

arXiv:2207.11275

- Not an EW penguin process but a control channel for $B \to Kl^+l^-$

- $R_K(J/\psi) = \dfrac{\mathscr{B}(B \to J/\psi(\to \mu^+\mu^-)K)}{\mathscr{B}(B \to J/\psi(\to e^+e^-)K)}$

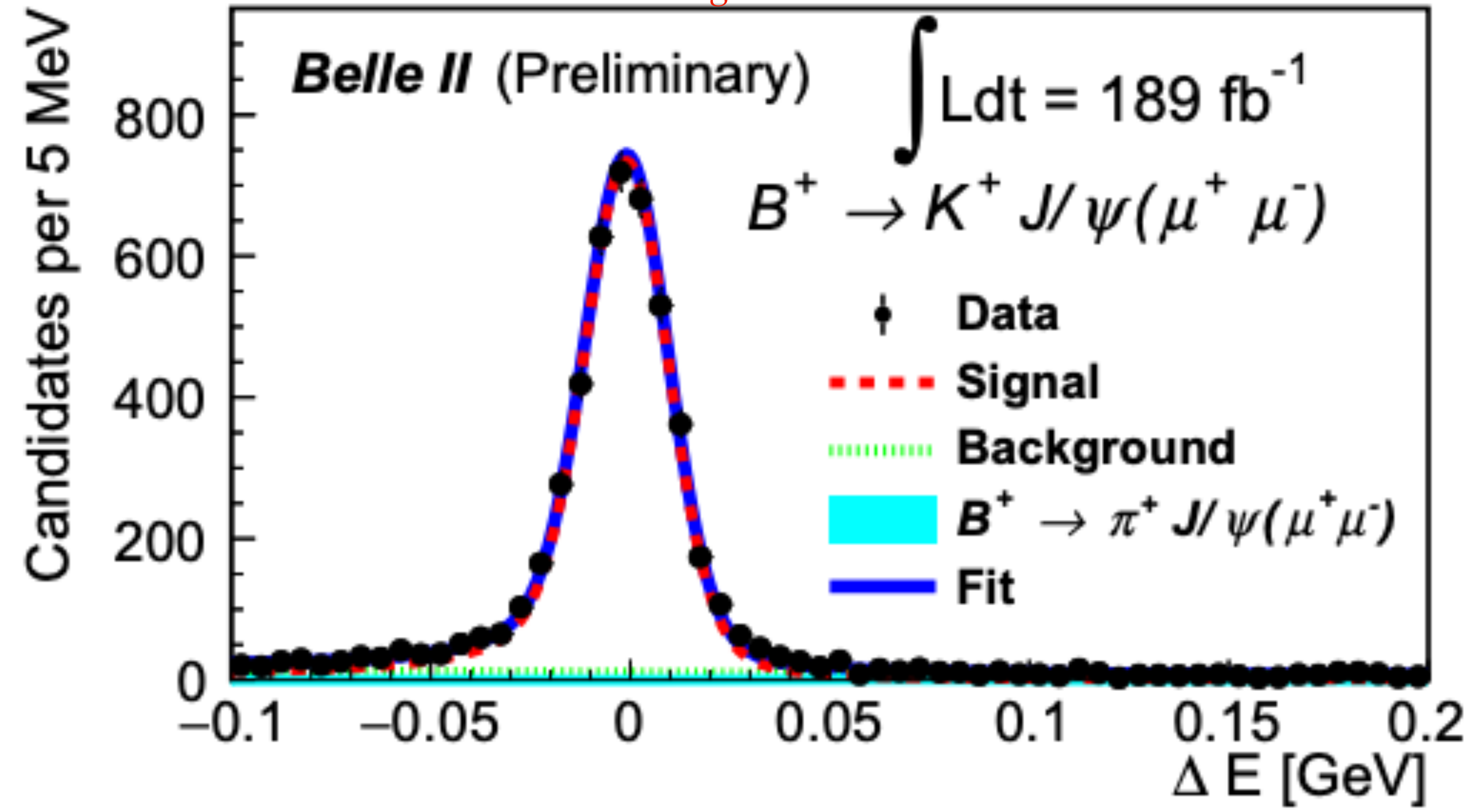
- Reconstructed four channels: $B^+ \to J/\psi(l^+, l^-)K^+$ and $B^0 \to J/\psi(l^+l^-)K_S^0;\ l = e, \mu$

$$\Delta E = E_B - \sqrt{S}/2$$

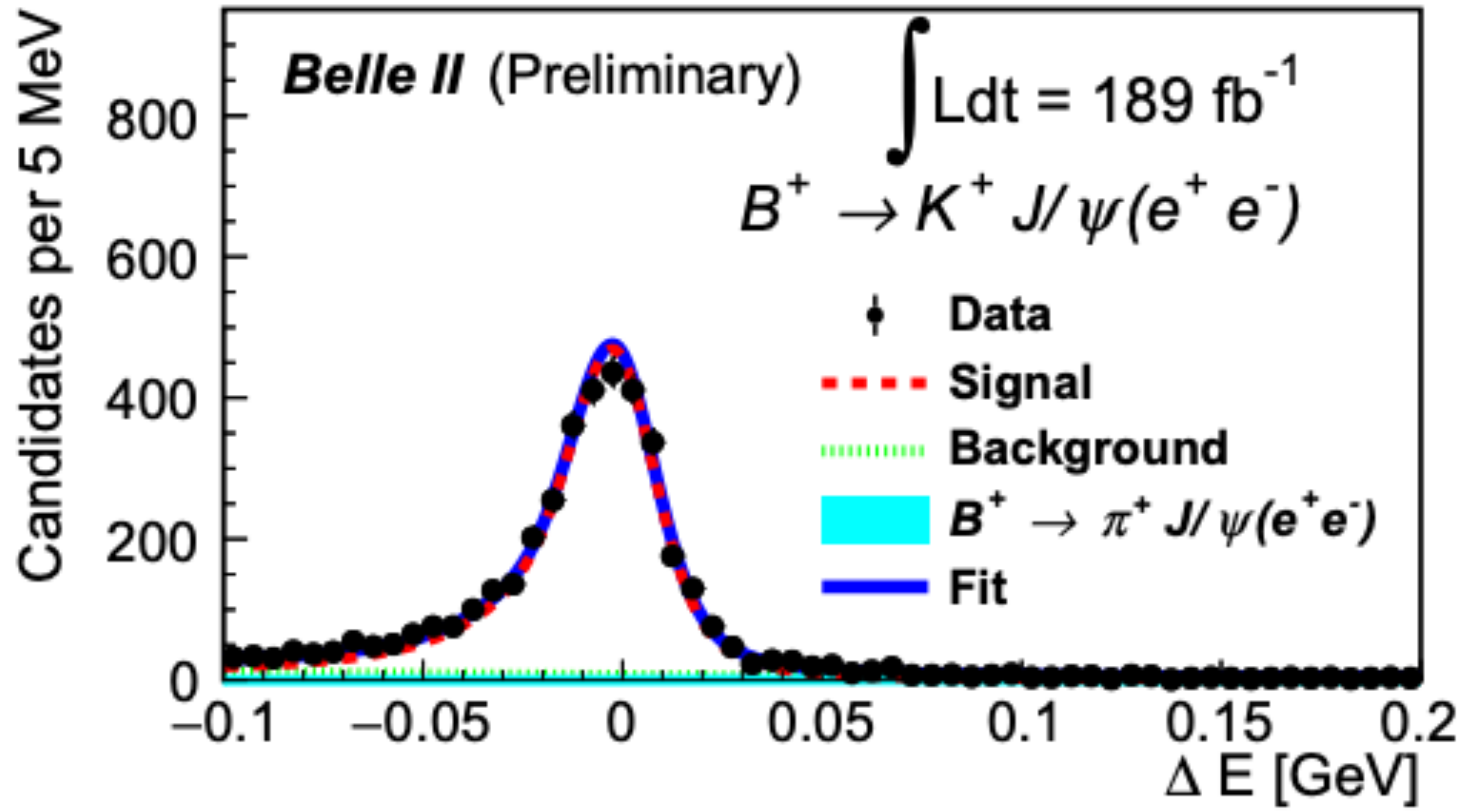
$$\boxed{\begin{array}{l} \mathbf{R_{K^+}(J/\psi) = 1.009 \pm 0.022 \pm 0.008} \\ \mathbf{R_{K^0}(J/\psi) = 1.042 \pm 0.042 \pm 0.008} \end{array}}$$

- Systematics uncertainties have been reduced compared to most precise measurements from Belle *(JHEP03(2021)105)*

$N_{sig} = 4578 \pm 62$



$N_{sig} = 3706 \pm 62$



Preparatory work towards $\mathrm{R}_{\mathrm{K}^{(*)}}$ measurement

- Following decays are reconstructed ($l = e, \mu$) with 189 fb^{-1} of dataset
  - $B^+ \to K^{*+} l^+ l^-$ with $K^{*+} \to K_S^0 \pi^+, K^+ \pi^0$
  - $B^0 \to K^{*0} l^+ l^-$ with $K^{*0} \to K^+ \pi^-$

arXiv:2206.05946

- Background suppression:
  - Veto γK^* and q^2 regions containing $B \to J/\psi K^*, \psi(2S) K^*$
  - Remaining background with BDT

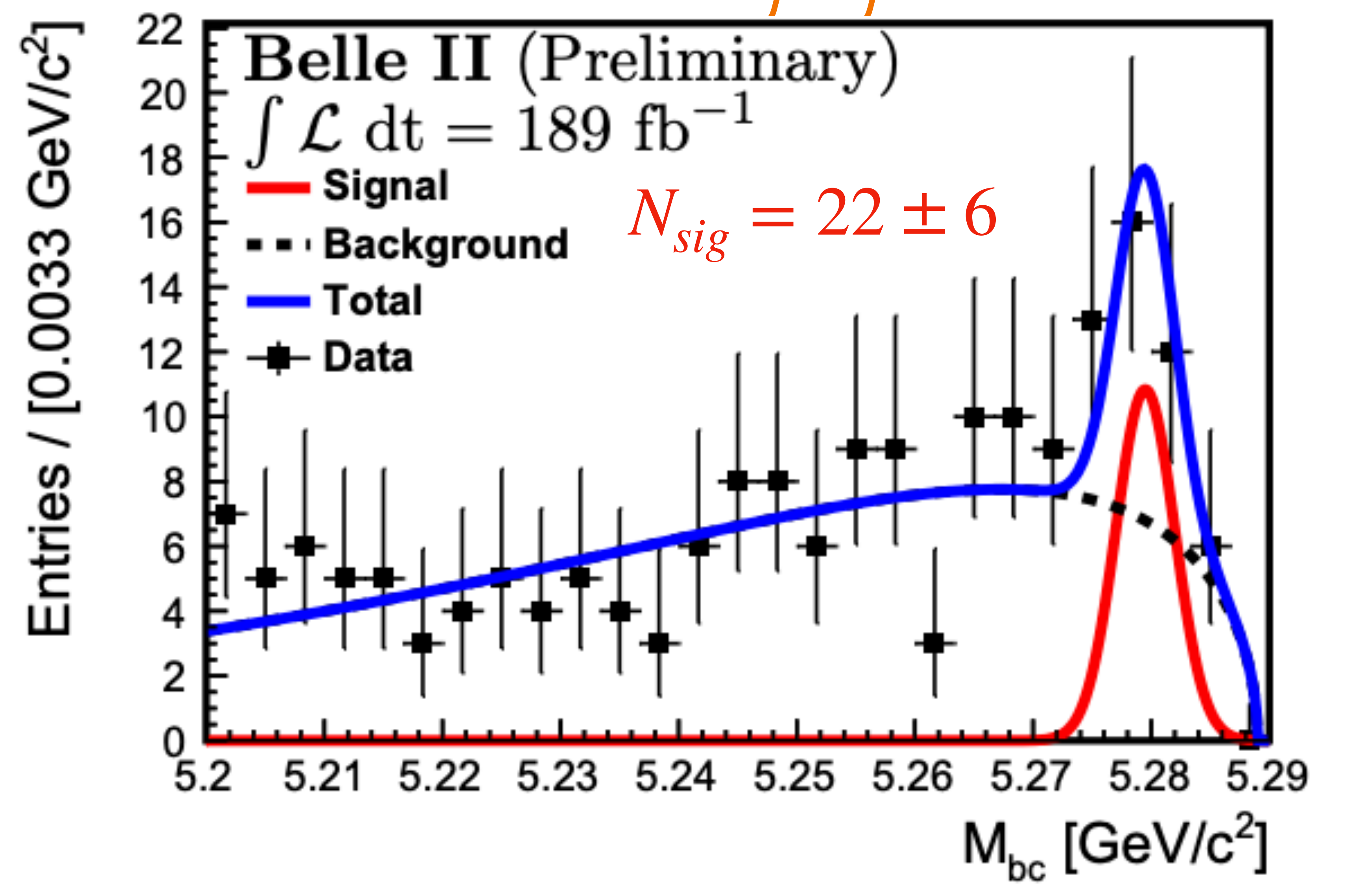
$$\boxed{\mathscr{B}(\mathrm{B} \to \mathrm{K}^* \mathrm{l}^+ \mathrm{l}^-) = (1.25 \pm 0.30^{+0.08}_{-0.07}) \times 10^{-6}}$$

- Result is consistent with the W.A., but precision is limited by the sample size

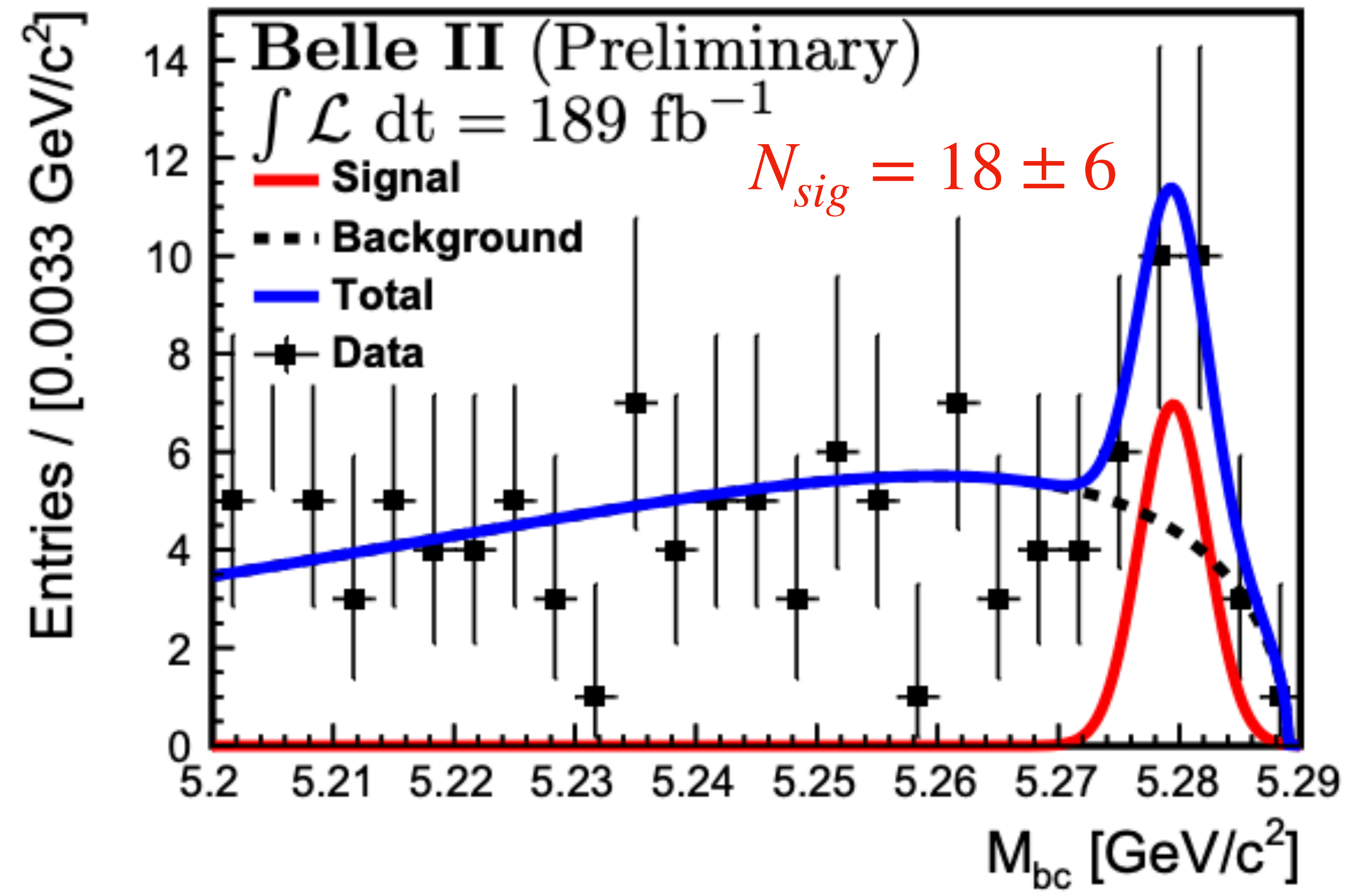
$$\mathscr{B}(B \to K^* \mu\mu)_{WA} = (1.06 \pm 0.09) \times 10^{-6}$$
$$\mathscr{B}(B \to K^* ee)_{WA} = (1.19 \pm 0.20) \times 10^{-6}$$

- Observation of these decays is the first step towards LFU test (R_{K^*})

$B \to K^* \mu^+ \mu^-$



$B \to K^* e^+ e^-$

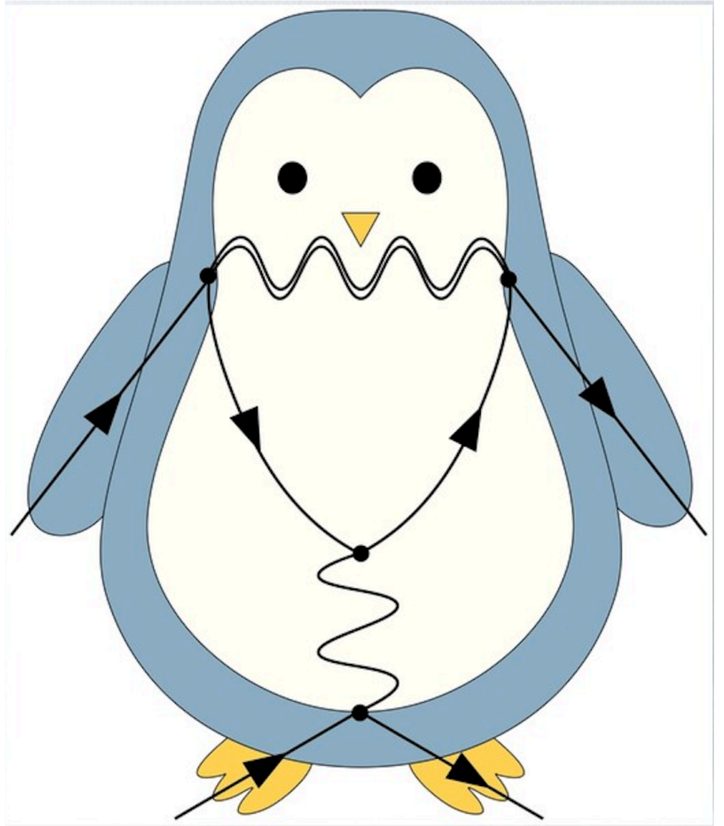


Today's focus

- Inclusive branching fraction (BF) measurement of $B \to X_s\gamma$

Requires good photon detection efficiency

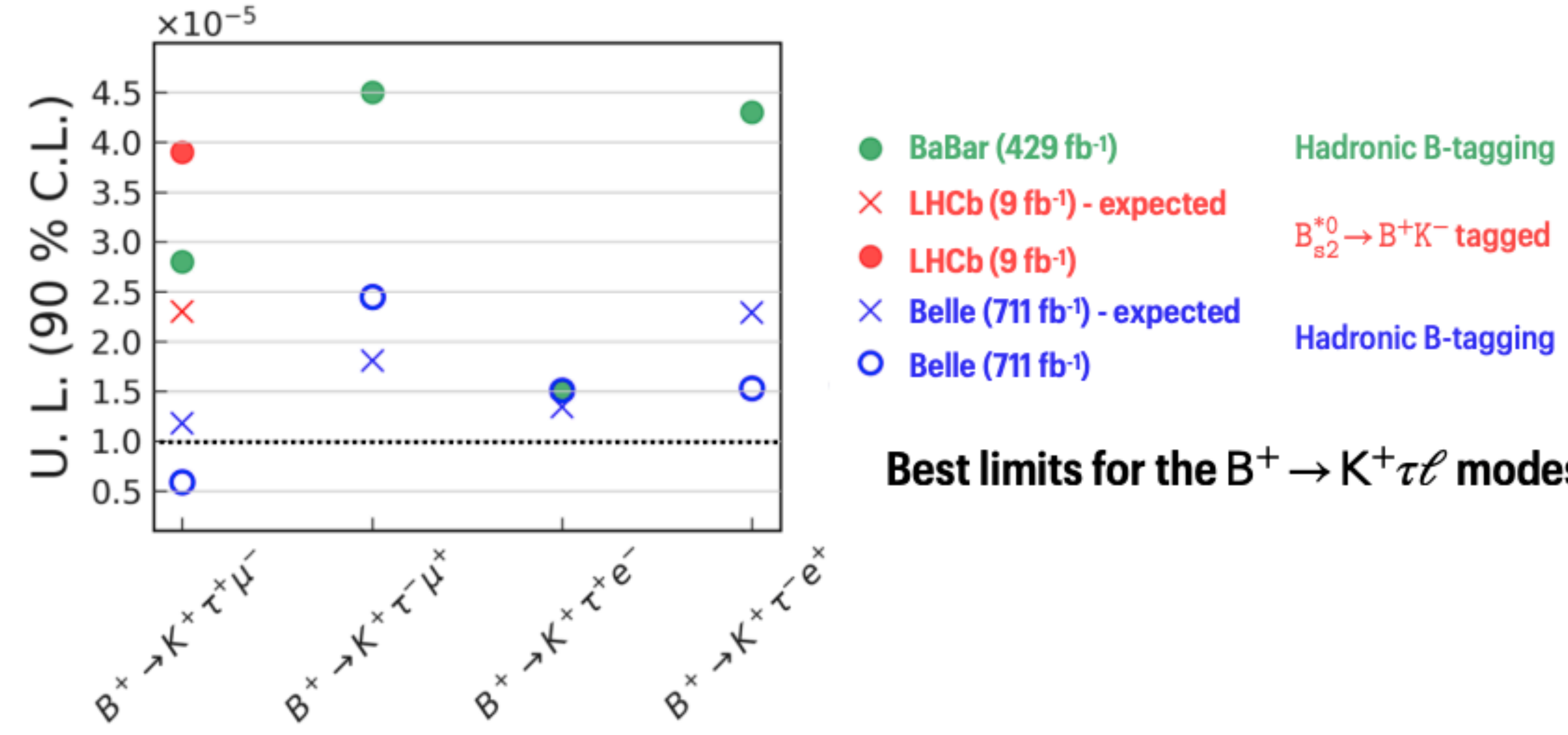
- Towards $R_{K^{(*)}}$ measurement
  - BF of $B \to K^*(892)l^+l^-$ decays
  - Study of control mode $B \to J/\psi(l^+l^-)K$
- Search for LFV $B \to K\tau l$ decays at Belle



Requires good e and μ identification

$B \to K\tau l$ search at Belle: results

PRL130(2023)261802

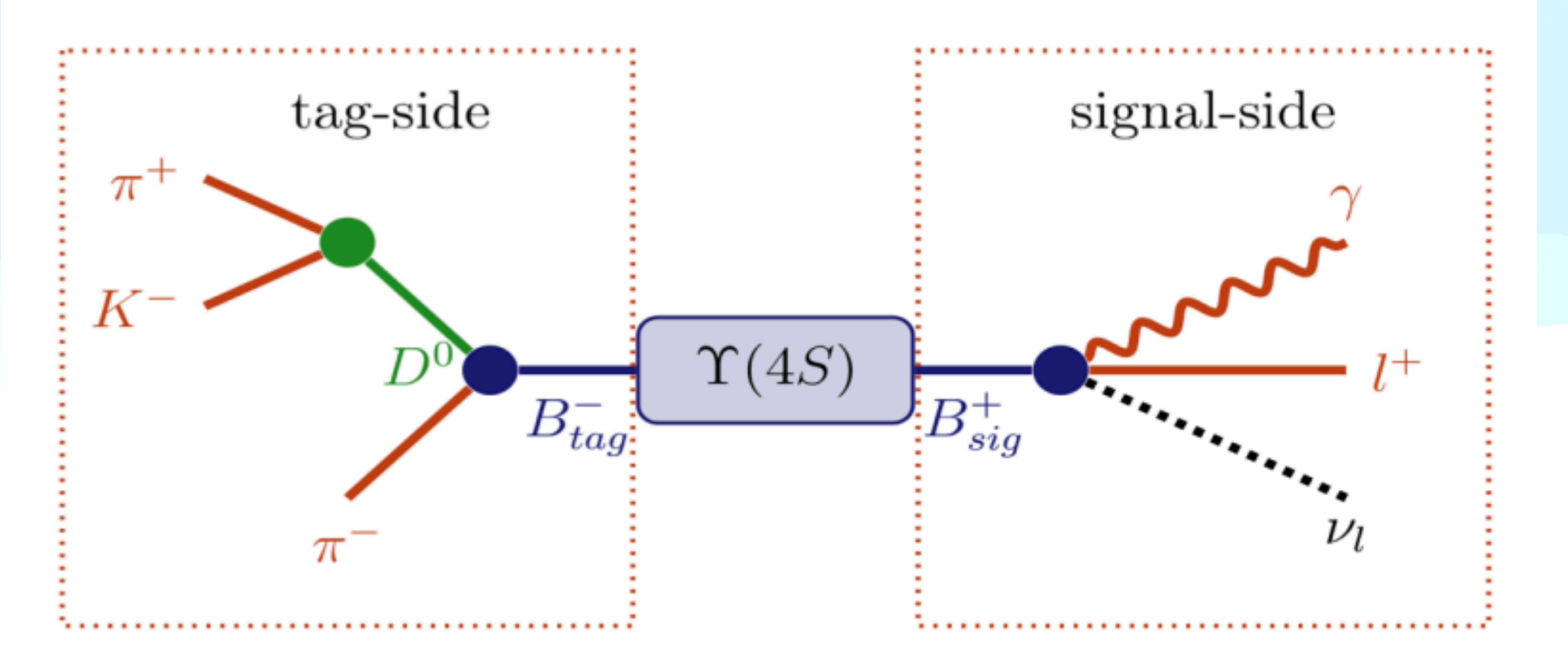


Best limits for the $B^+ \to K^+\tau\ell$ modes!

No significant signal is observed for any of the 4 modes!

Reconstruction techniques at B factories

- A typical $B\bar{B}$ event generates ~10 tracks and ~10 photons
- Measurement of inclusive decays or decays with ν in the final state suffer from missing kinematic information
- **B-factory advantage: information from partner B (tag) provides insight of signal B**



$\mathcal{O}(1\%)$ Tagging efficiencies, achievable yields $\mathcal{O}(100\%)$

$\mathcal{O}(10\%)$ Purities of the tagged samples, physics observables

Hadronic tagging
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Fully inclusive, no tagging
$B \to$ anything