LFV, LNV, LUV at Belle (II)

Youngjoon Kwon
Yonsei University

Muon Anomalies Workshop @ SNU, May 21, 2021

Belle & Belle II

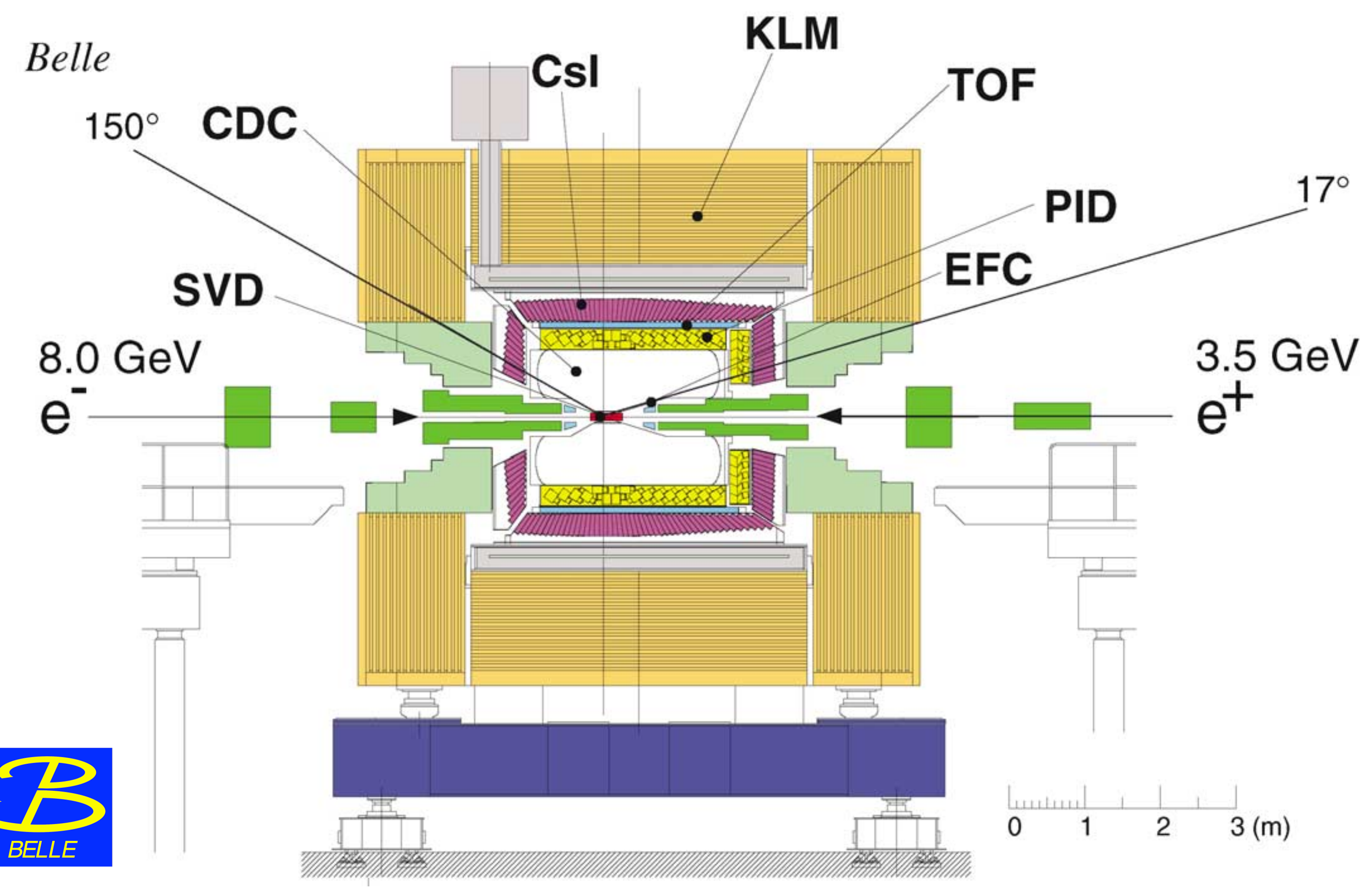
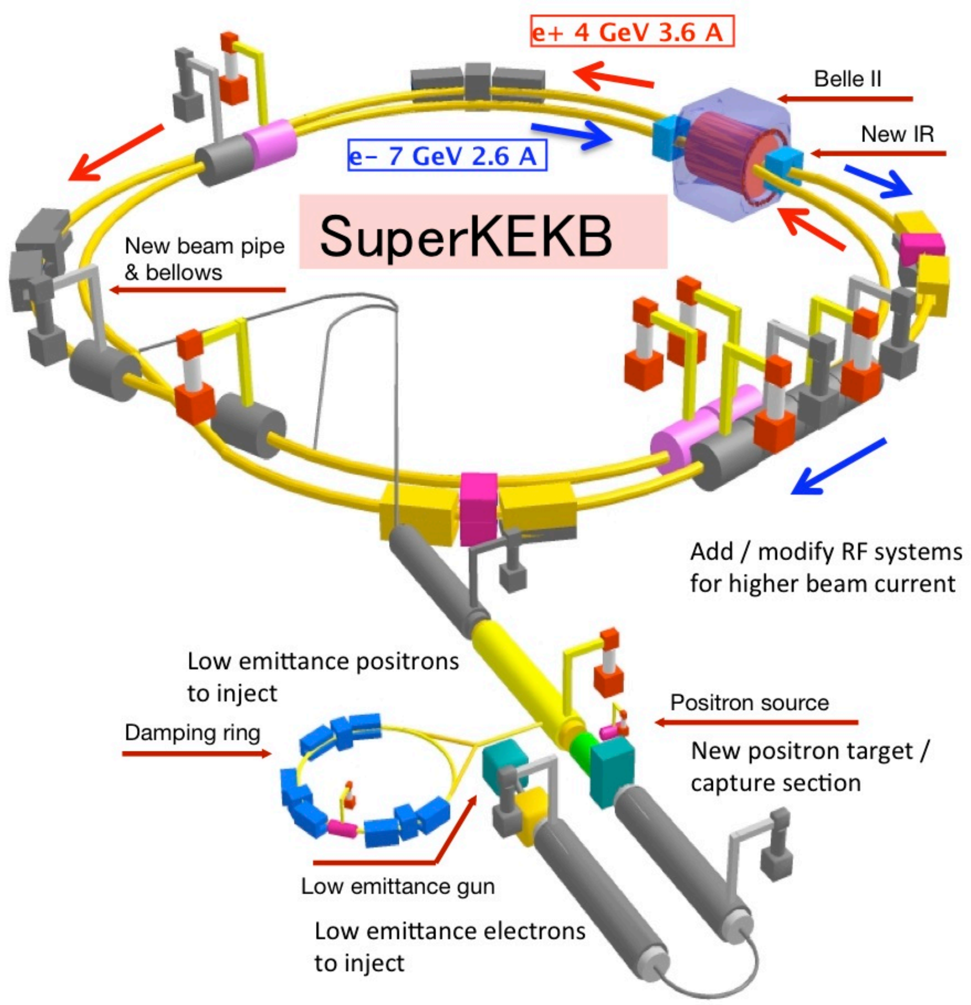
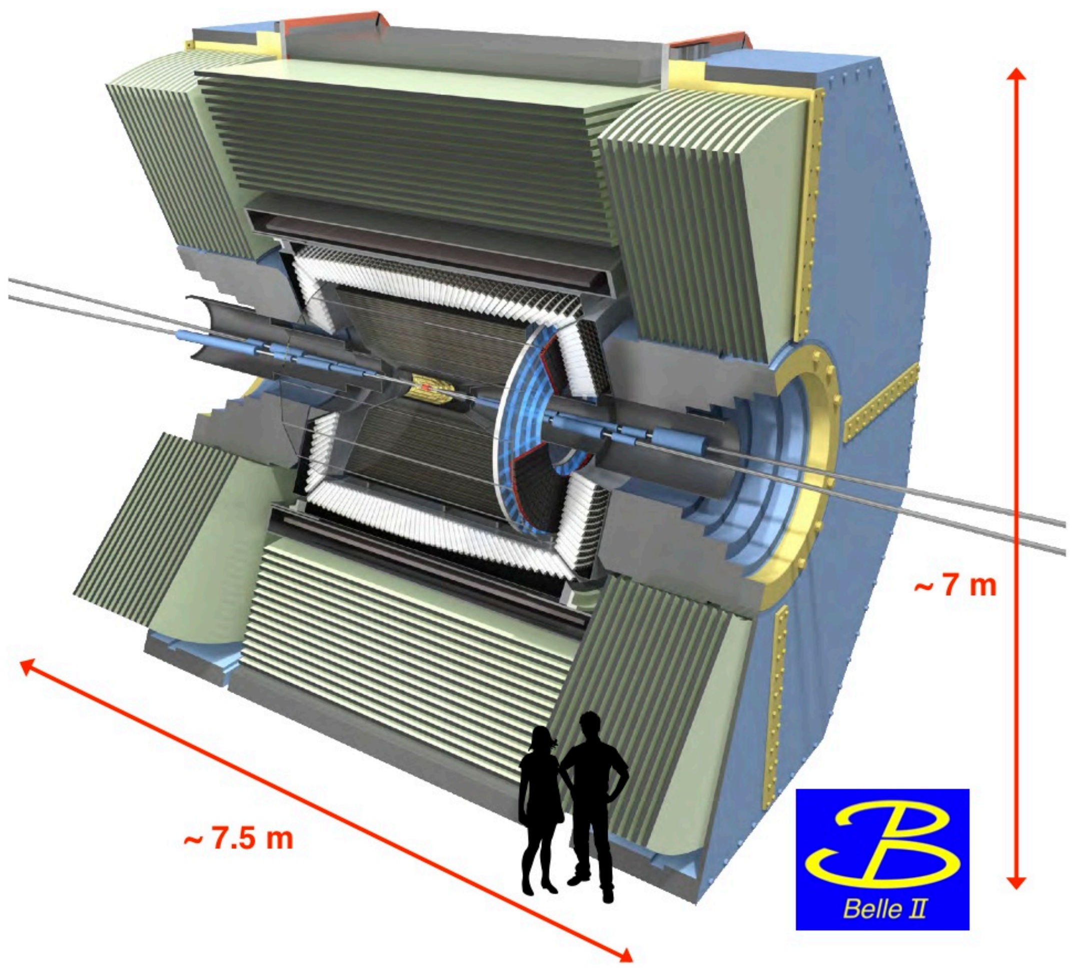


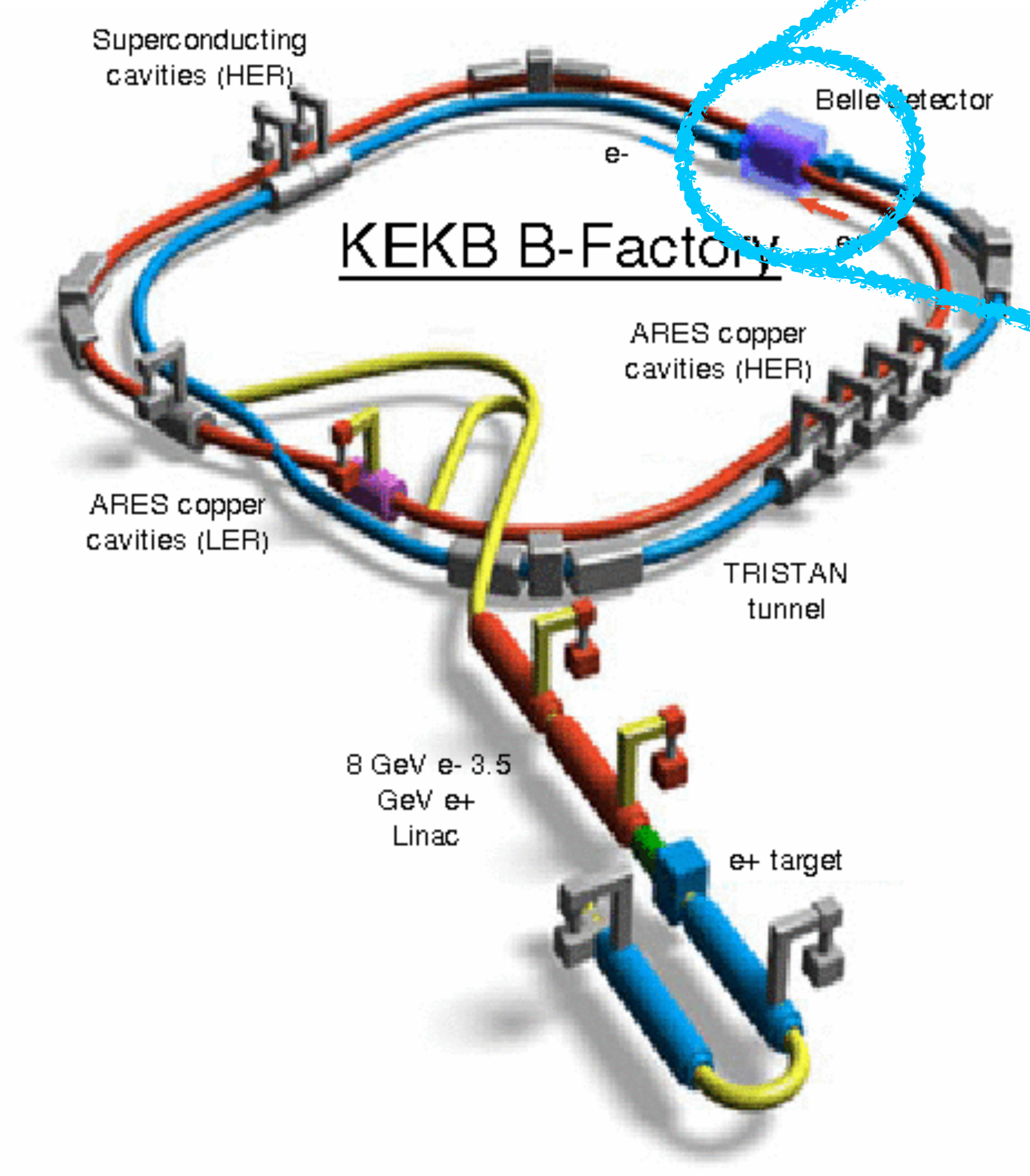
Fig. 1. Side view of the Belle detector.

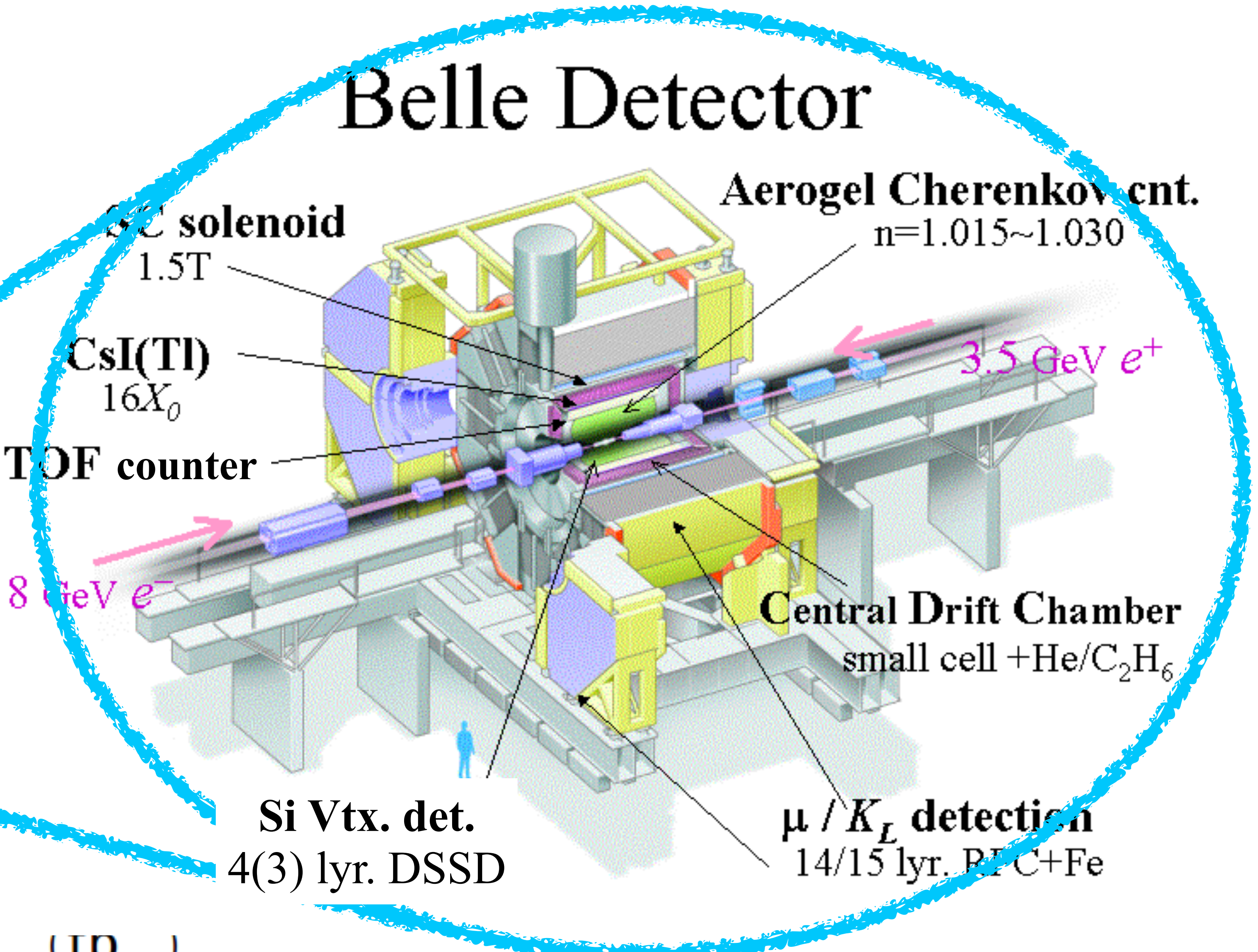




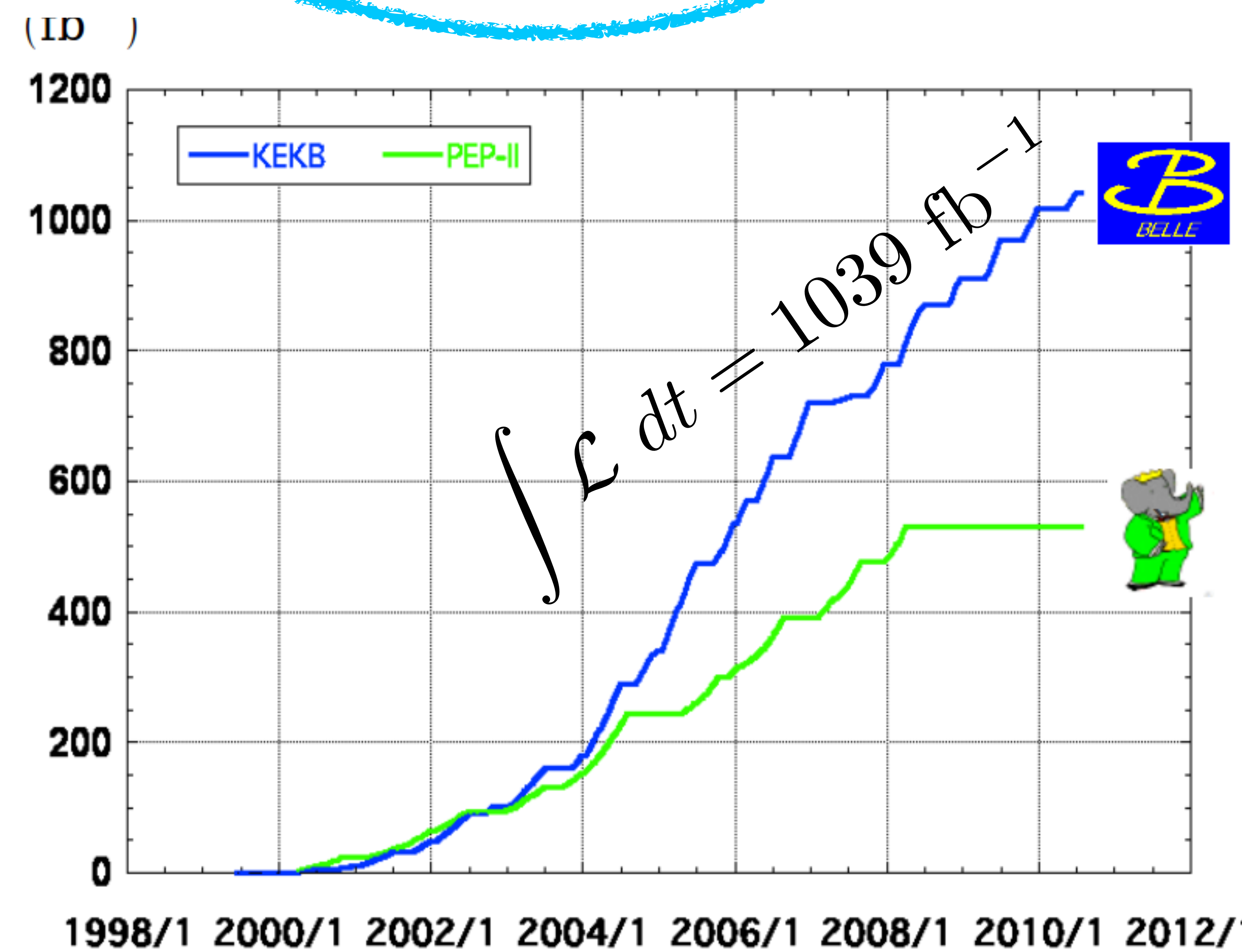
22 countries
100 institutions
~450 members

$$\mathcal{L}_{\rm peak} = 21.1\ {\rm nb}^{-1}{\rm s}^{-1}$$





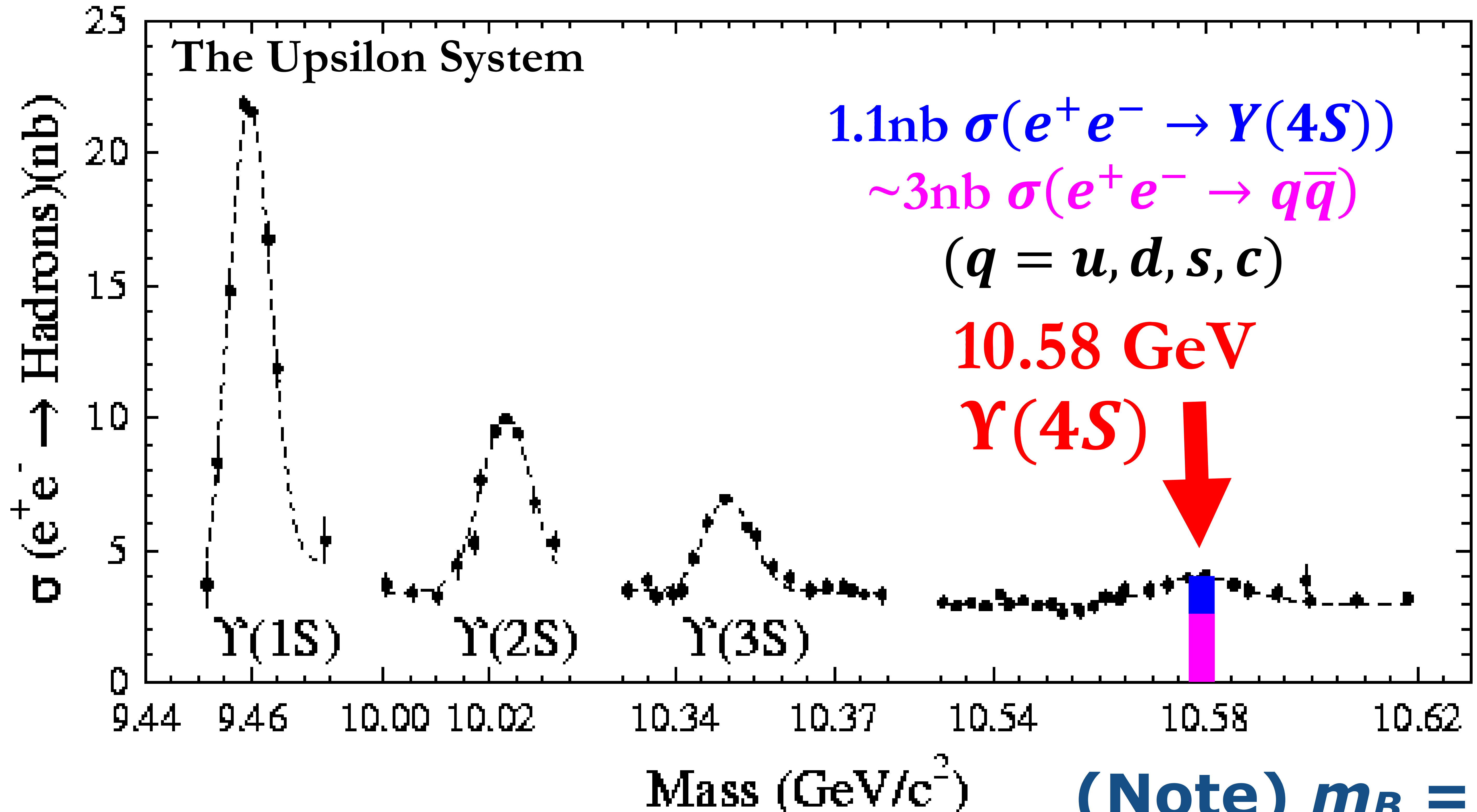
$$e^- \xrightarrow{\text{8 GeV}} (\star) \xleftarrow{\text{3.5 GeV}} e^+$$



> 1 ab^{-1}
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 25 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

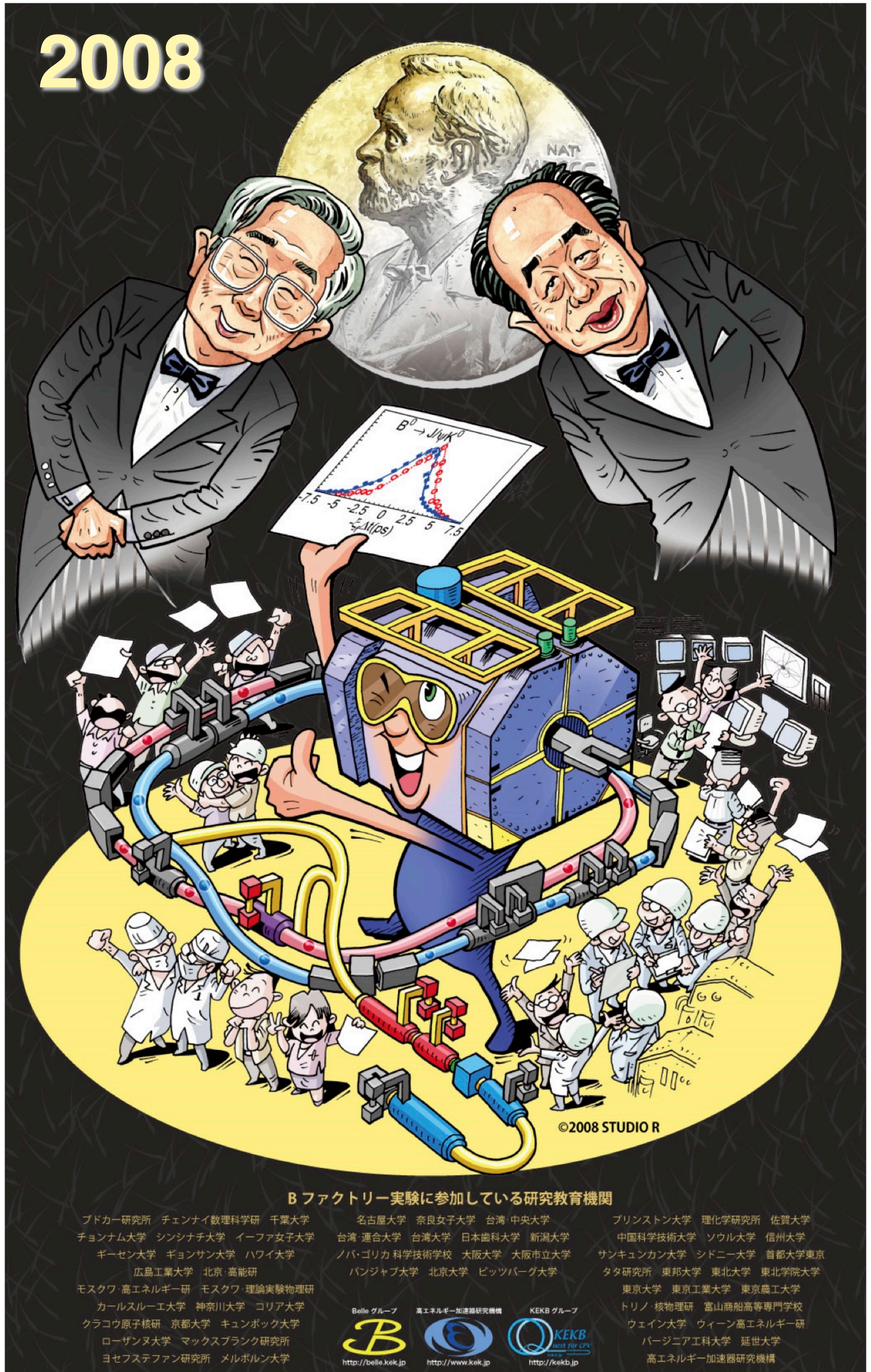
~ 550 fb^{-1}
On resonance:
$\Upsilon(4S)$: 433 fb^{-1}
$\Upsilon(3S)$: 30 fb^{-1}
$\Upsilon(2S)$: 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}

$e^+e^- \to \Upsilon(4S)$ as a B-factory



(Note) m_B = 5.28 GeV

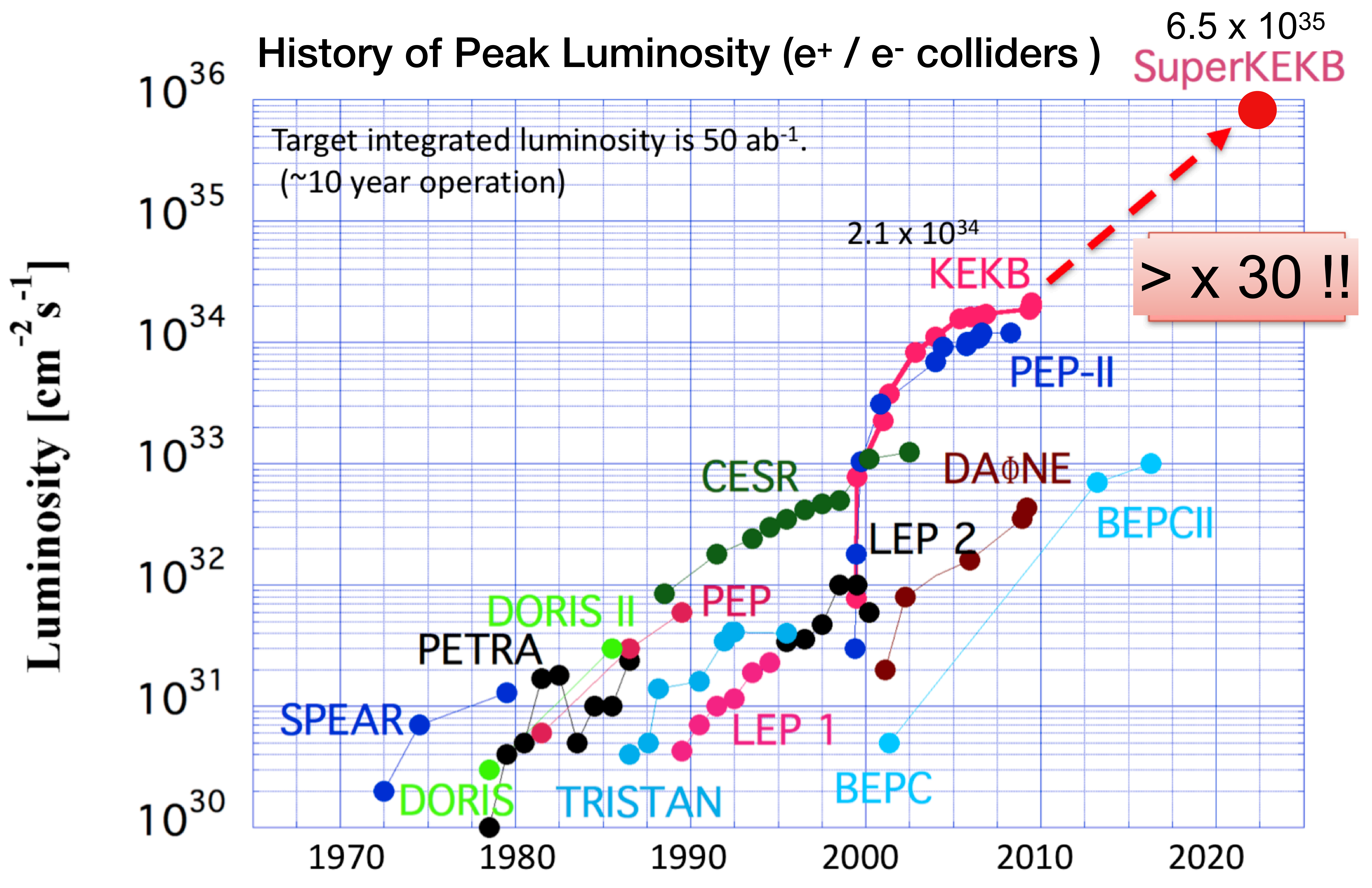
- $\mathcal{B}(\Upsilon(4S) \to B\bar{B}) > 96\%$, with $p_B^{CM} \sim 0.35$ GeV/c
- nothing else but $B\bar{B}$ in the final state
  $\therefore$ if we know $(E, \vec{p})$ of one B, the other B is also constrained



Belle (and BaBar, too) achievements include:

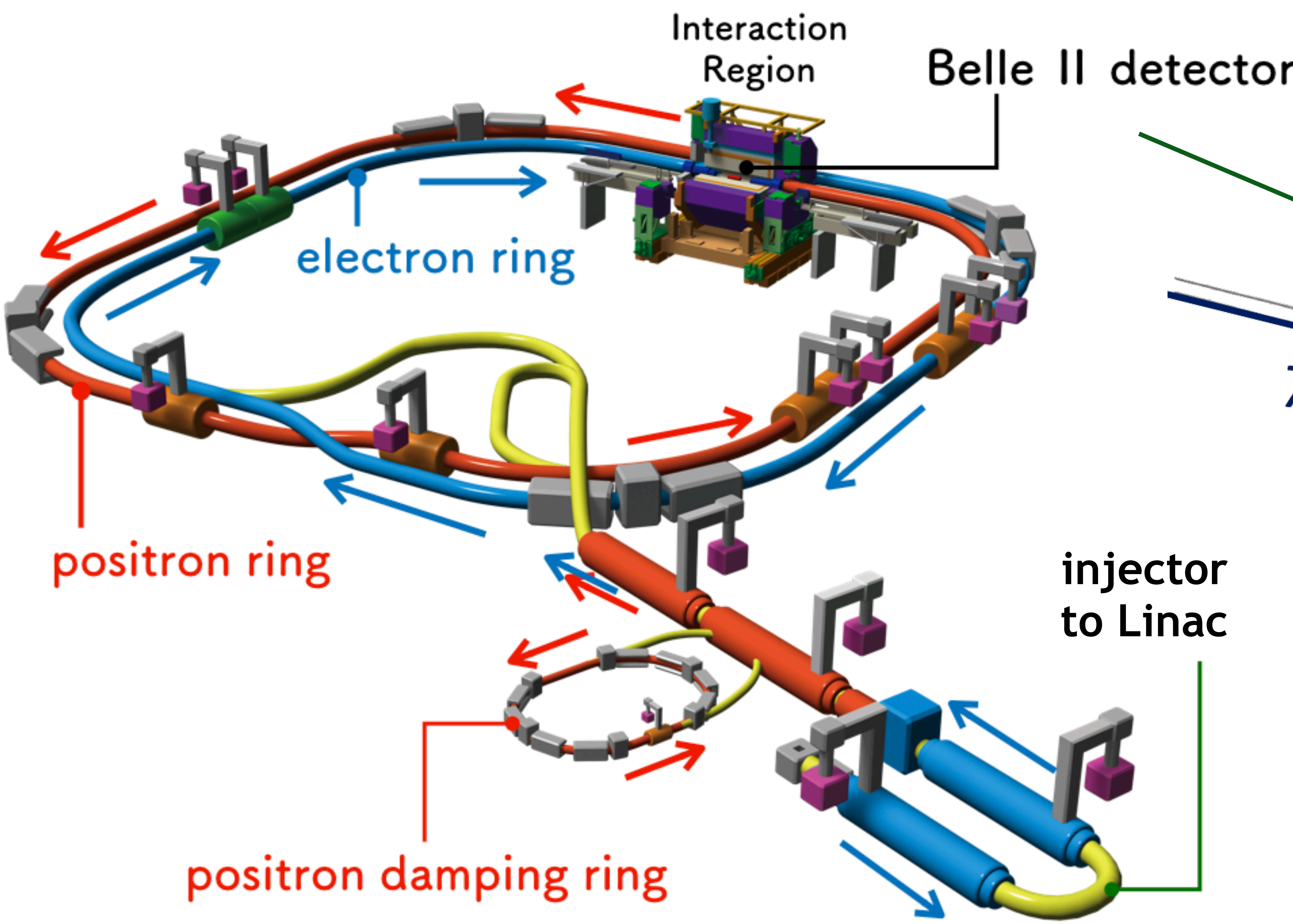
- CPV, CKM, and rare decays of B mesons (and B_s, too)
- Mixing, CP, and spectroscopy of charmed hadrons
- Quarkonium spectroscopy and discovery of (*many*) exotic states, e.g. $X(3872)$, $Z_c(4430)^+$
- Studies of τ and 2γ

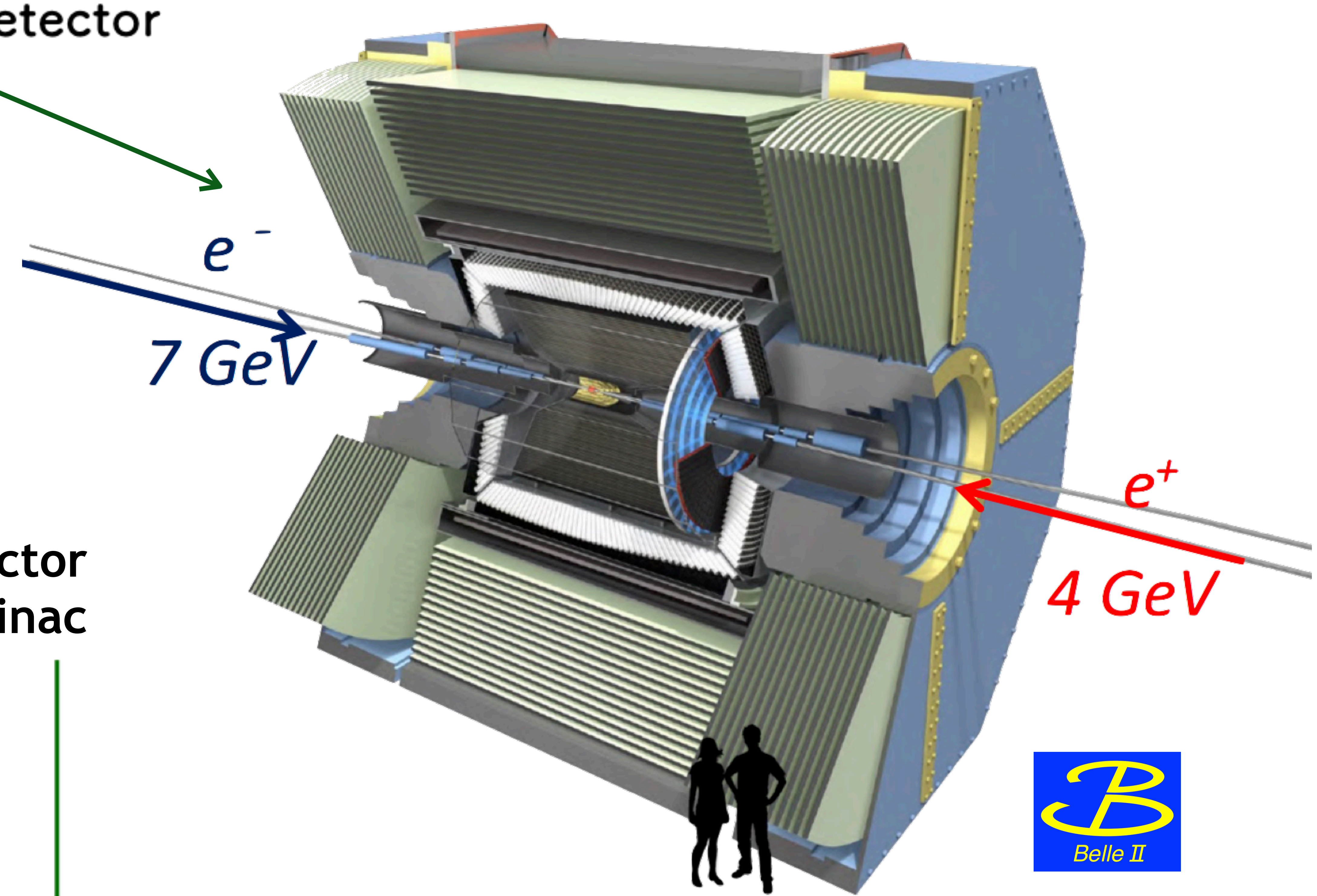
The next Luminosity Frontier



SuperKEKB

Belle II





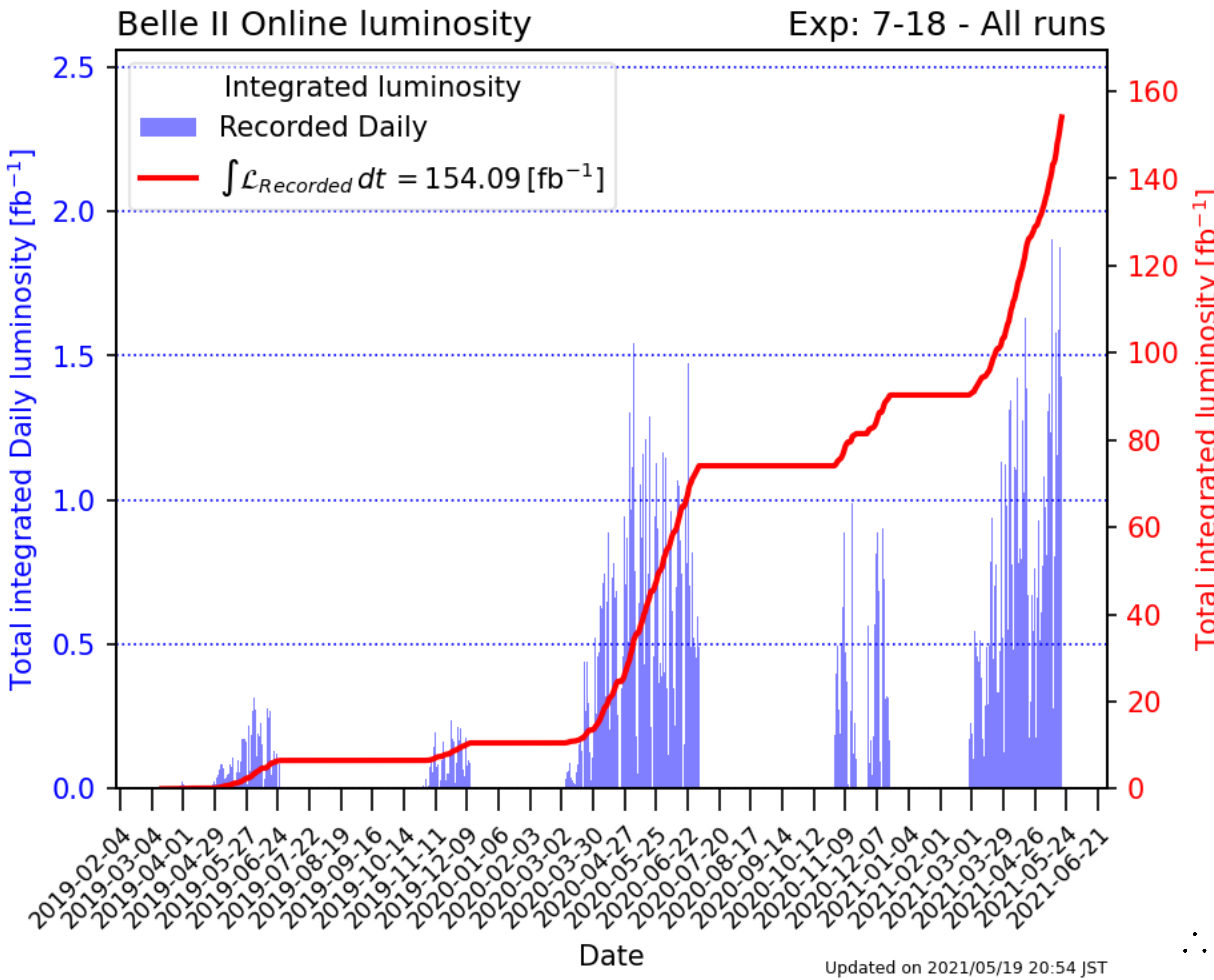
$$e^- \xrightarrow{7\text{ GeV}} (\star) \xleftarrow{4\text{ GeV}} e^+$$

$$\mathcal{L} = 6.5 \times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

$$\int^{\mathrm{goal}} \mathcal{L}\, dt = 50\ \mathrm{ab}^{-1}$$

The Belle II Collaboration

26 countries/regions, ~120 institutions, ~1000 collaborators



$$\sigma \int \mathcal{L}\; dt = N(\text{events})$$

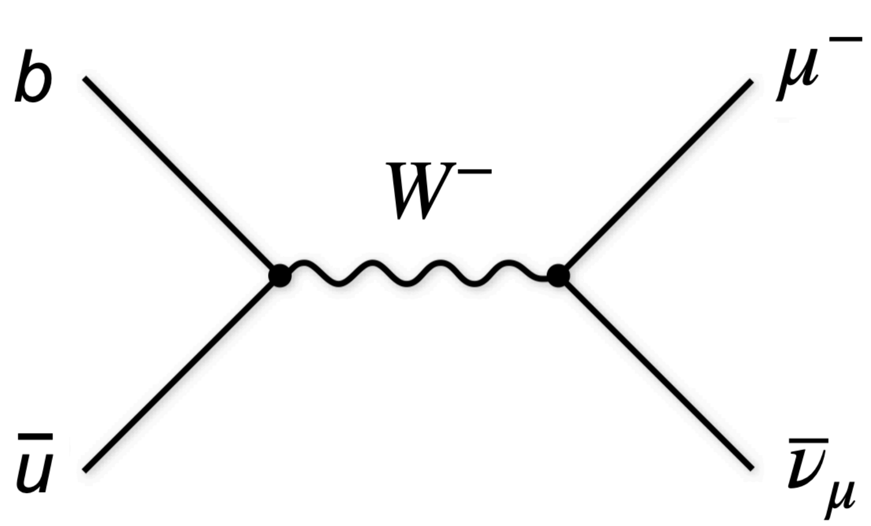
$$\sigma_{B\overline{B}} \simeq 1 \text{ nb}$$

$$\therefore 1 \text{ fb}^{-1} \sim 10^6 \; B\overline{B} \text{ events}$$

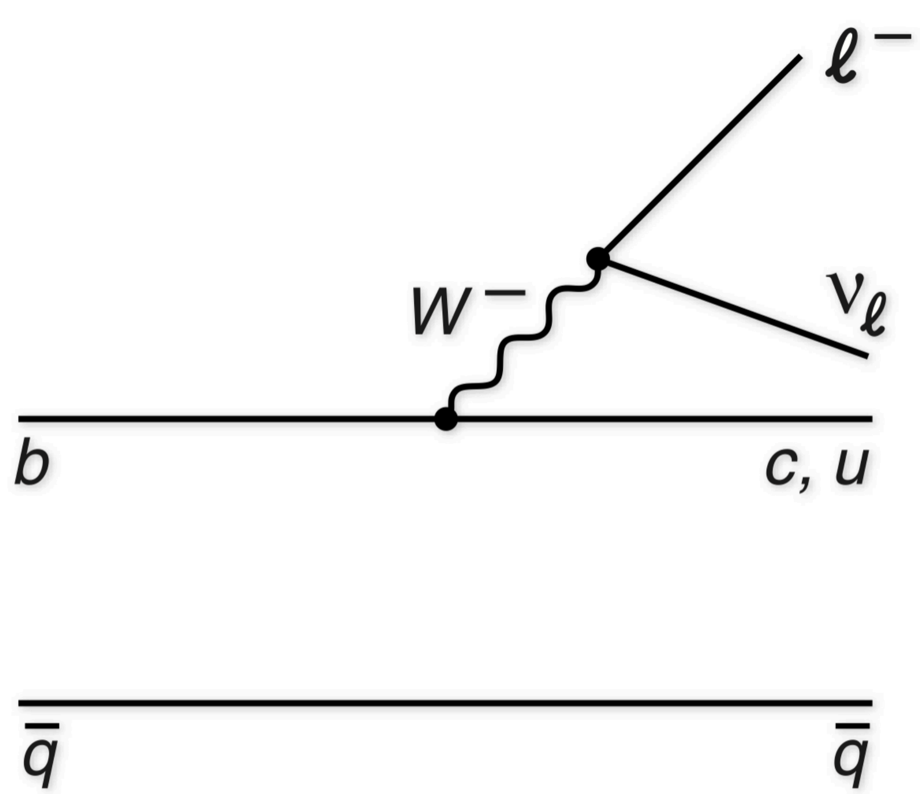
Processes with $W^+ \to \ell^+ \nu_\ell$

(a) $B^+ \to \ell^+ \nu_\ell$ and beyond ("leptonic")

(b) $B^+ \to X_q \ell^+ \nu_\ell$ ("semileptonic")



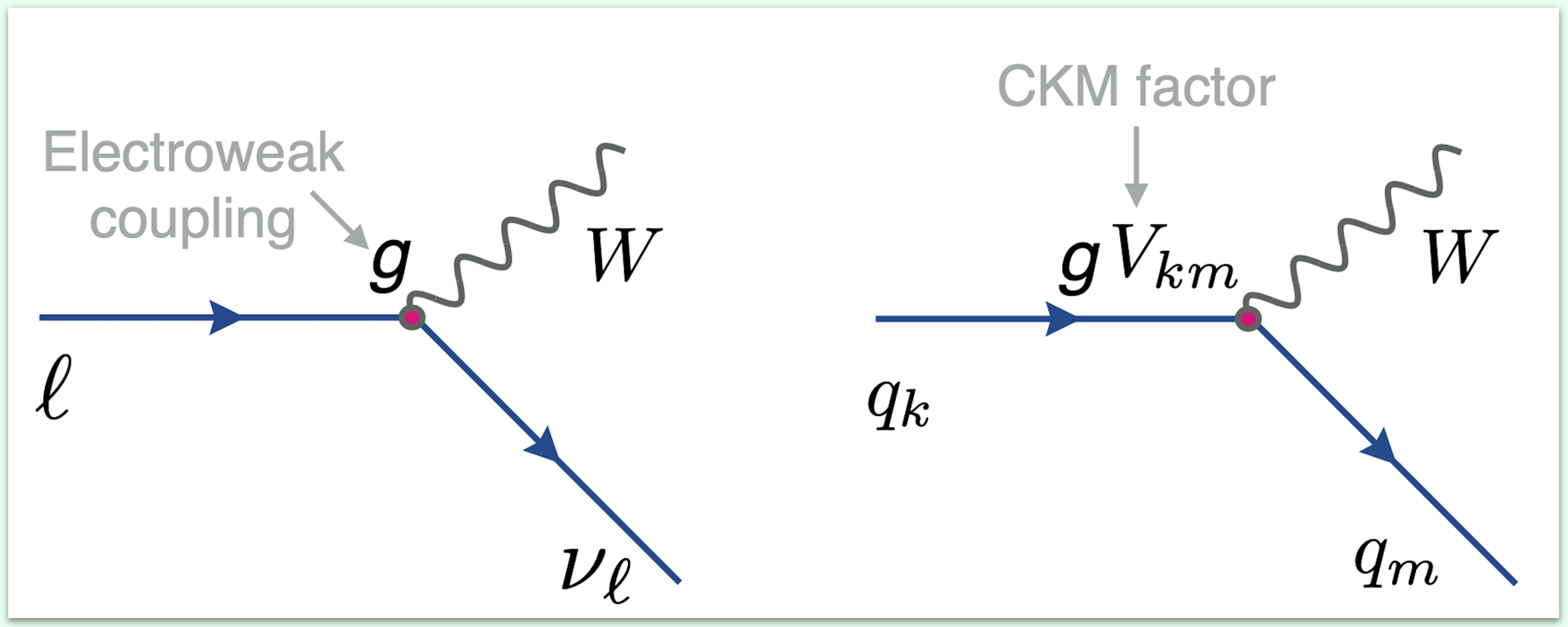
(a) Leptonic

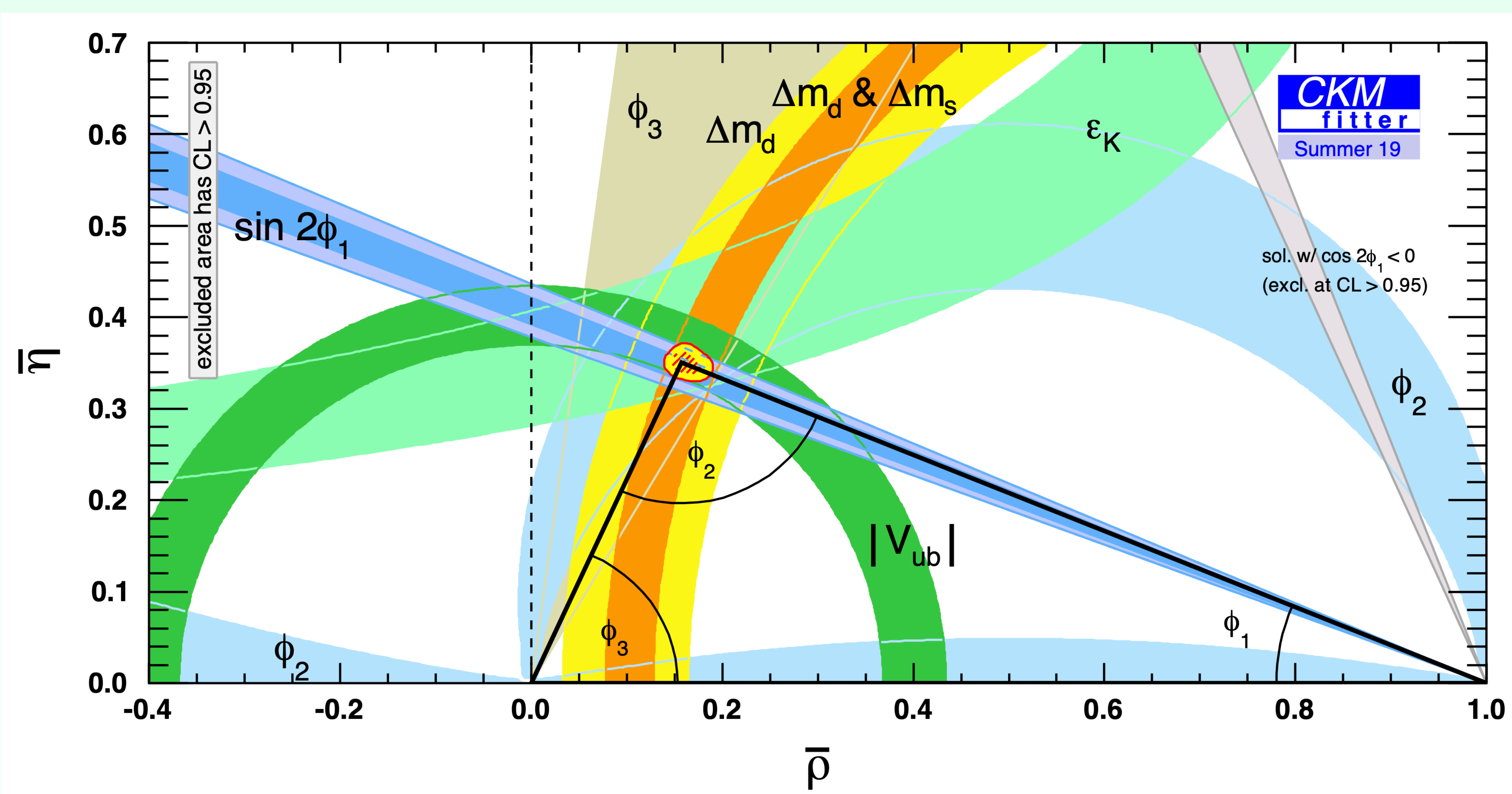


(b) Semileptonic

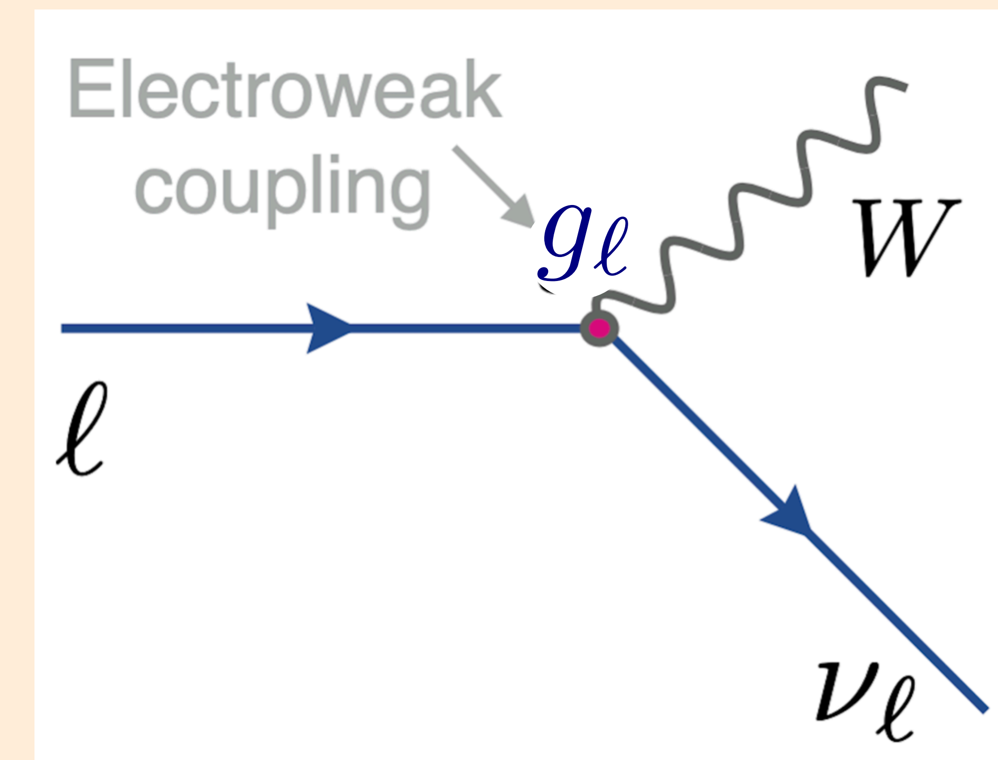
1-page summary of semileptonic decays

- Precision measurements of CKM UT





- Test of lepton universality in $R(D^{(*)})$



$$g_\ell \ (\ell = e, \ \mu, \ \tau)$$

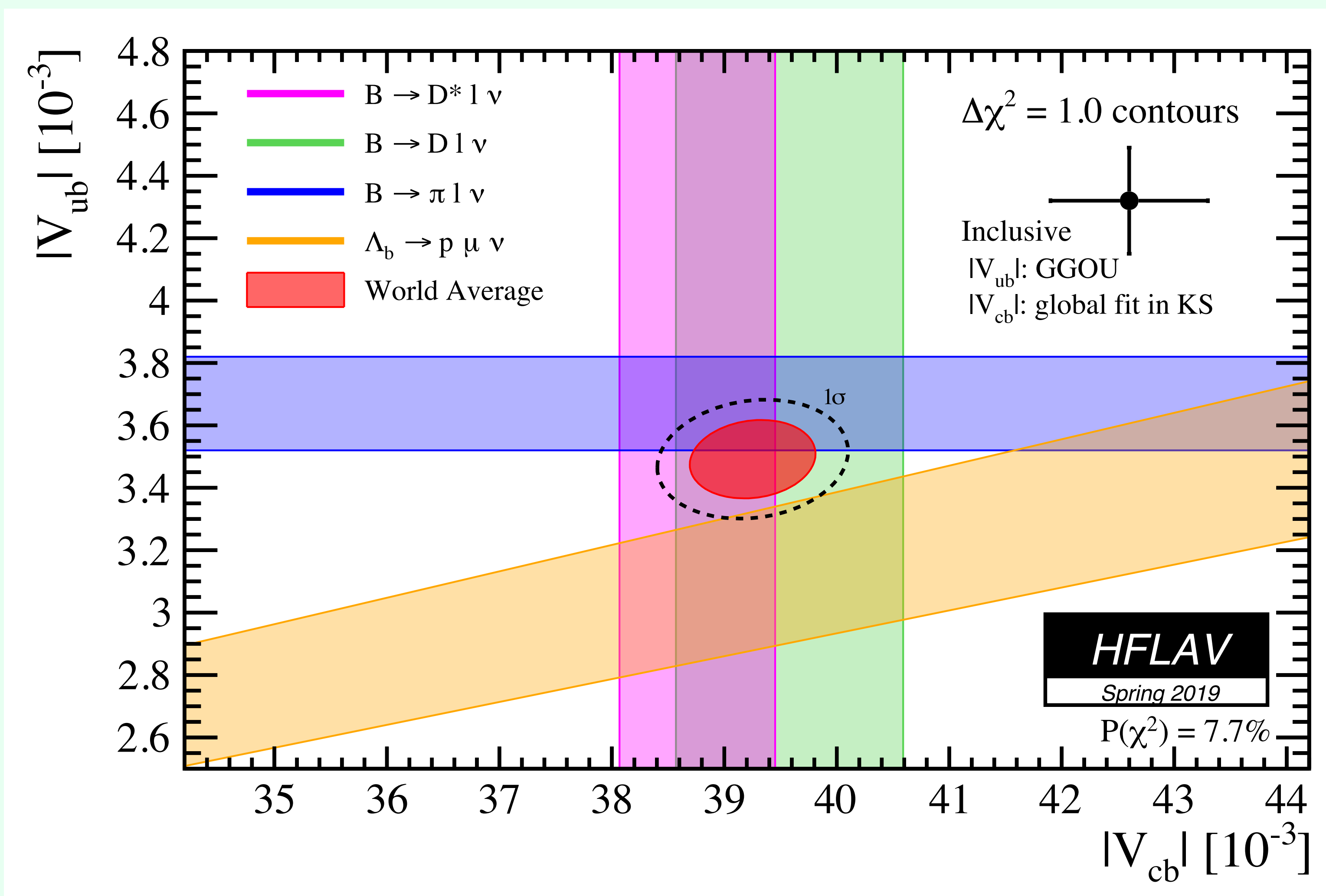
Is $g_\tau = g_\mu$, and/or g_e?

$$R(D^{(*)}) \equiv \frac{\mathscr{B}(B \to D^{(*)}\tau^+\nu)}{\mathscr{B}(B \to D^{(*)}\ell^+\nu)}$$

1-page summary of semileptonic decays

Precision measurements of CKM UT

- a tension of Inclusive vs. Exclusive?



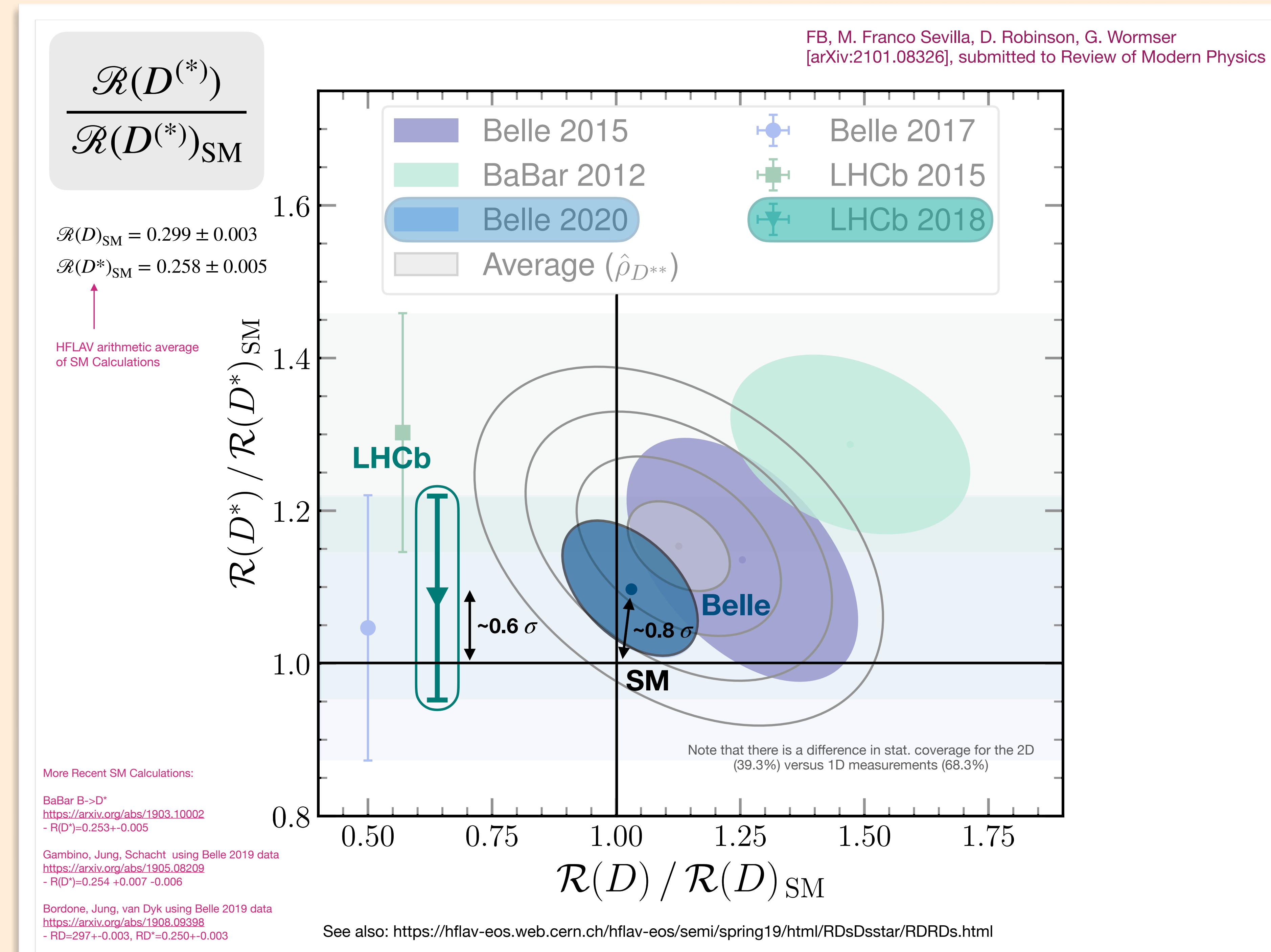
- **arXiv:2101.00020** for $|V_{ub}|$ inclusive

  a "*Belle masterpiece*" by Uni. Bonn group

Youngjoon Kwon
February 19 ·

gave a journal club seminar @ KIAS today,
presenting a most recent Belle masterpiece by the respected colleagues, Florian Bernlochner et al.
https://arxiv.org/abs/2102.00020

Test of lepton universality in $R(D^{(*)})$



from Florian Bernlochner's talk @ APS 2021

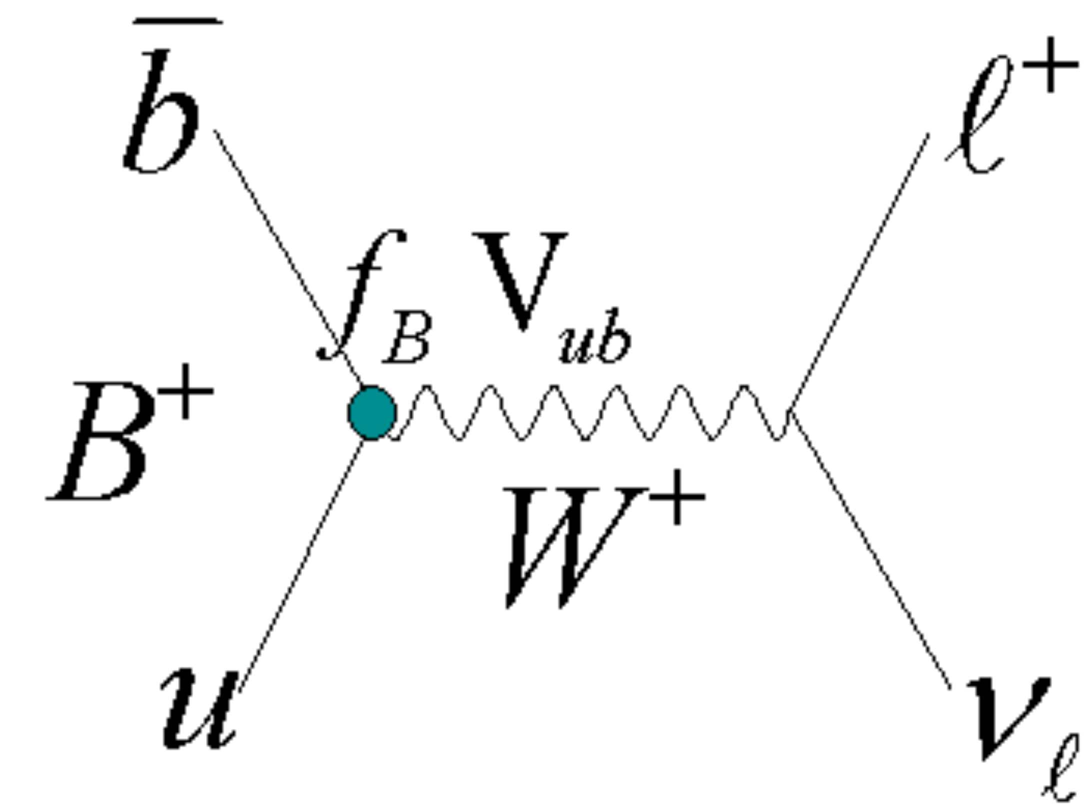
FB, M. Franco Sevilla, D. Robinson, G. Wormser
[arXiv:2101.08326], submitted to Review of Modern Physics

$B^+ \to \ell^+\nu_\ell$, features & motivations

- SM predictions

$$\Gamma(B^+ \to \ell^+\nu) = \frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2$$

$$\mathcal{B}(B^+ \to \tau^+\nu) \sim 10^{-4}$$
$$\mathcal{B}(B^+ \to \mu^+\nu) \sim \mathcal{B}(B^+ \to \tau^+\nu)/300$$
$$\mathcal{B}(B^+ \to e^+\nu) \sim \mathcal{B}(B^+ \to \tau^+\nu)/10^7$$



- Experimental features
  - $B^+ \to \tau^+\nu_\tau$ large BF, but multiple ν's
  - $B^+ \to \ell^+\nu_\ell$ $(\ell \neq \tau)$ $E_\ell \sim m_B/2$, but very small BF

$B^+ \to \ell^+\nu_\ell$, features & motivations

- SM predictions

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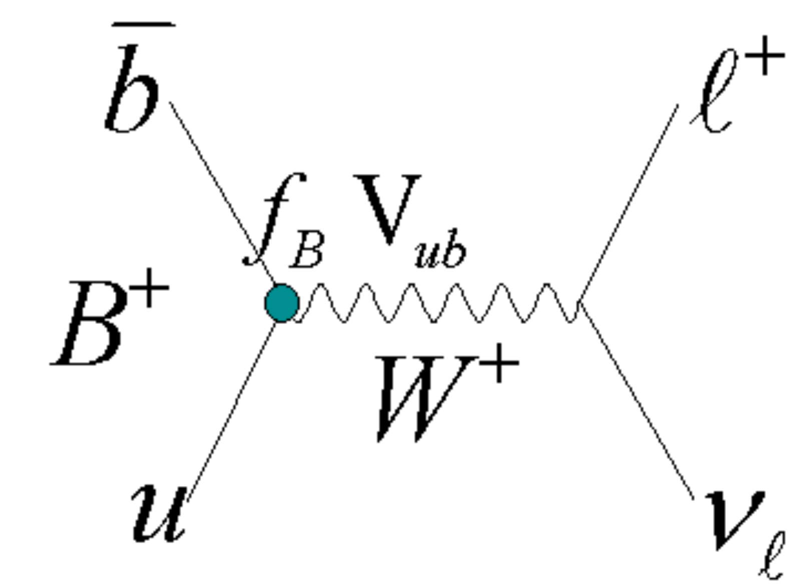


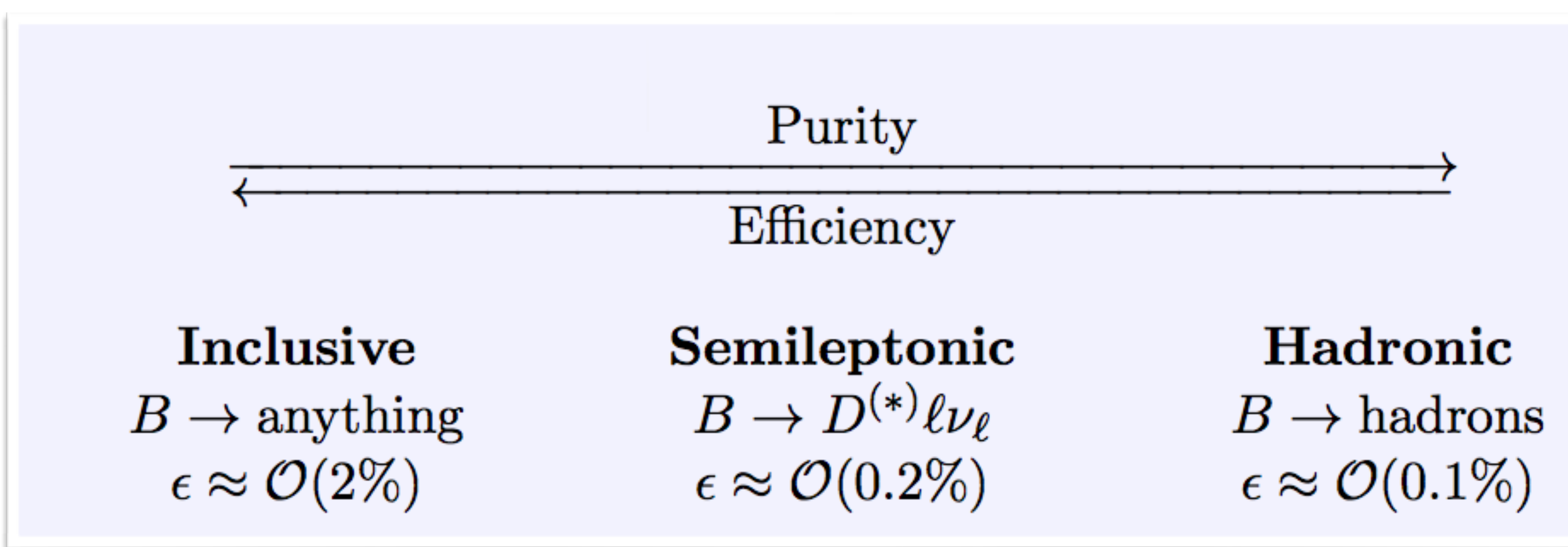
- Motivations
  - very clean place to measure $f_B|V_{ub}|$, and/or search for new physics (e.g. H^+ or LQ)
  - ultimate test of LUV $\frac{\Gamma(B^+ \to \ell^+\nu)}{\Gamma(B^+ \to \tau^+\nu)} = f(m_\ell^2, m_\tau^2)$ *and all other parameters cancel!*
  - Belle has measured $B^+ \to e^+\nu$, $\mu^+\nu$ with both inclusive tag [PLB 647, 67 (2007)] and hadronic tag [PRD 91, 052016 (2015)] and updated $B^+ \to \mu^+\nu$ with inclusive tagging [PRL 121, 031801 (2018), and PRD 101, 032007 (2020)].

$B^+ \to \ell^+\nu_\ell$, 'to Tag or not to Tag'

- Why bother?
  - missing ν(s) in the final state
  - need extra kinematic constraints to improve sensitivity
  - exploit $\Upsilon(4S)$ producing $B\overline{B}$ and nothing else

$$e^+e^- \to \Upsilon(4S) \to B_{\text{sig}}\overline{B}_{\text{tag}}$$

- How to tag?
  - "hadronic tagging" — reconstruction of the full decay chain of B_{tag} in hadronic modes
  - "semileptonic tagging" — use semileptonic B_{tag} decays, e.g. $B_{\text{tag}} \to \overline{D}^{(*)}\ell^+\nu$



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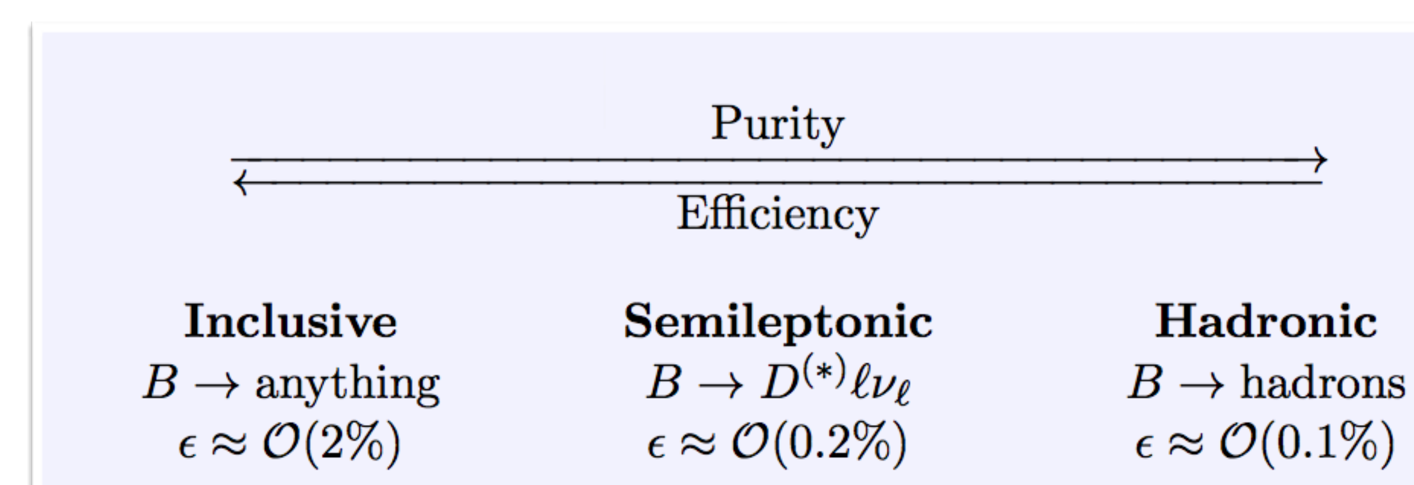
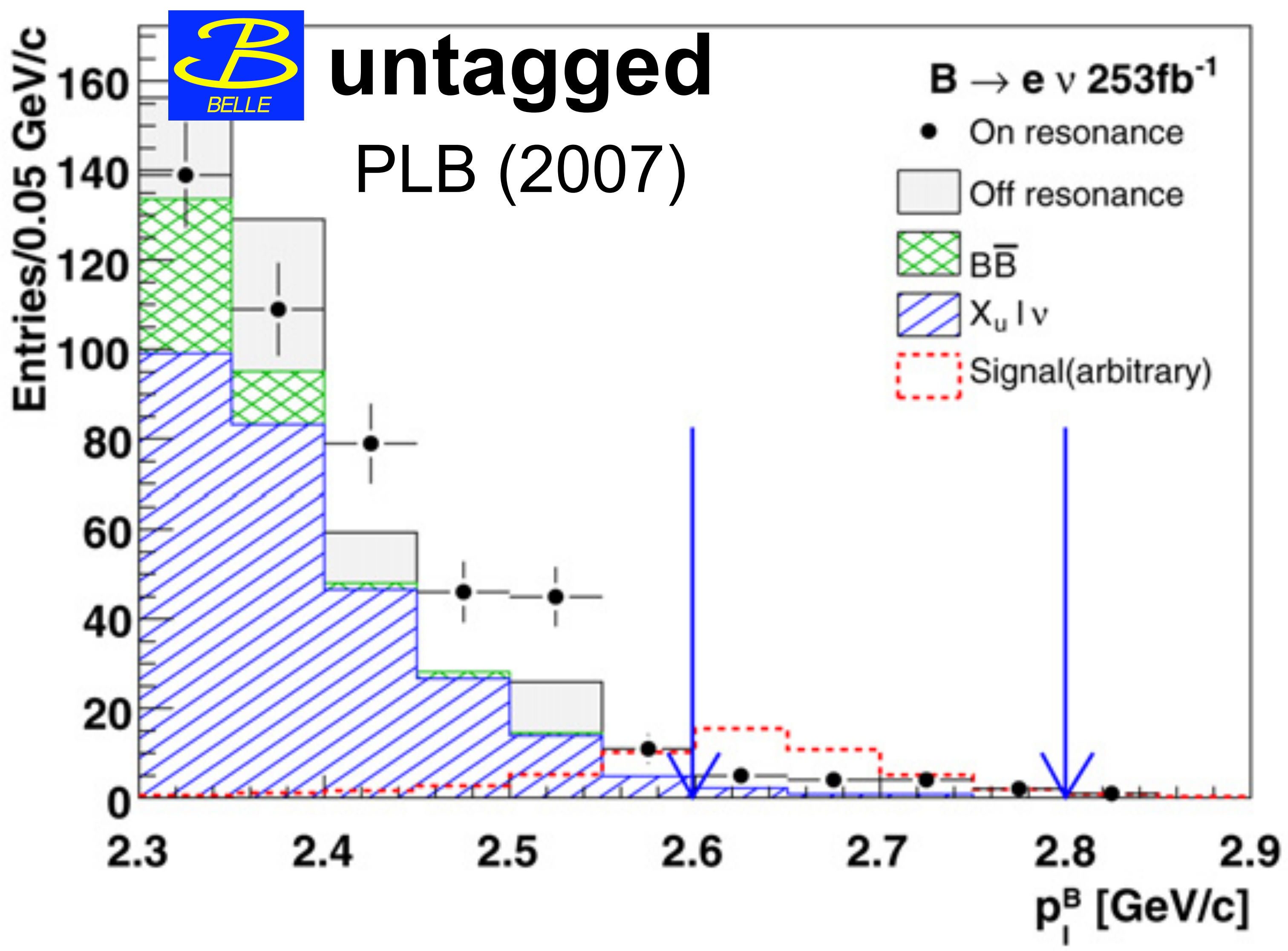
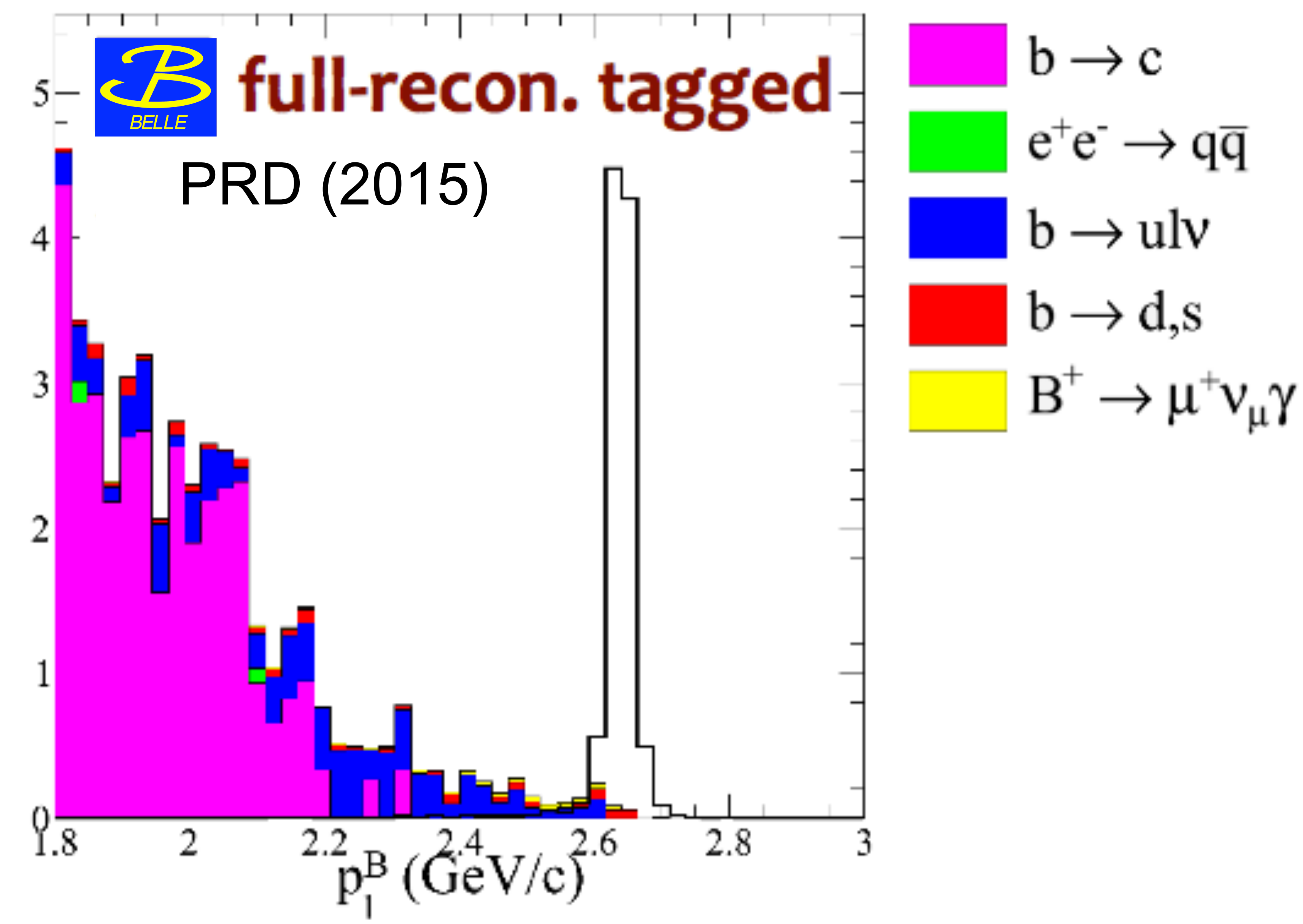
- Tagged vs. Untagged for $B^+ \to \ell^+\nu_\ell$ $(\ell \neq \tau)$
  - tagging is not really necessary $\because$ mono-energetic ℓ^+ in the final state
  - Nonetheless, analyses with tagging have also been tried



$B^+ \to \ell^+\nu_\ell$, why bother with tagging?

signal lepton candidate's momentum in the $B_{\rm sig}$ rest frame





- much better resolution of p_ℓ^B with the full-recon. tagging
- But, does it make a case for 'full-recon tagging' analysis of $B^+ \to \ell^+\nu_\ell$?

$B^+ \to \ell^+\nu_\ell$, why bother with tagging?

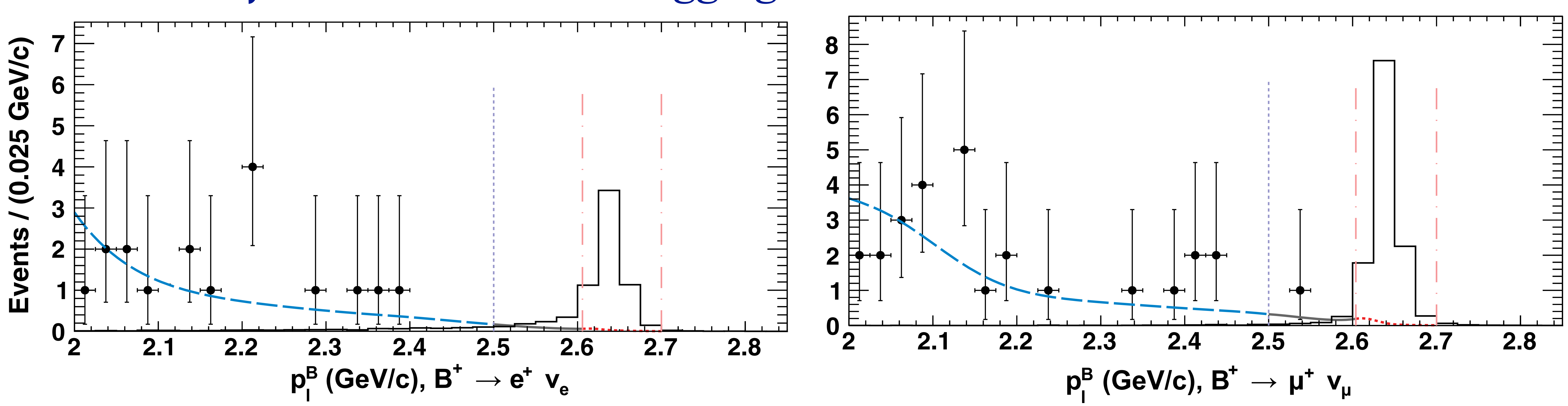
- Note: $\mathcal{B}_{SM}(B^+ \to e^+\nu_e) \sim 10^{-11}$ and $\mathcal{B}_{SM}(B^+ \to \mu^+\nu_\mu) \sim 3\times 10^{-7}$
  ➔ any signal for $B^+ \to e^+\nu_e$ at the Belle (II) sensitivity is way beyond the SM
- In that case, are we *sure* what we see is really $B^+ \to e^+\nu_e$?
  What about $B^0 \to e^+\tau^-$? Or, $B^+ \to e^+X^0$ where X^0 is any invisible particle from NP, e.g. sterile ν?
- With full-recon, we can use p_ℓ^B to discern many such cases

PHYSICAL REVIEW D **91,** 052016 (2015)

Search for $B^+ \to e^+\nu_e$ and $B^+ \to \mu^+\nu_\mu$ decays using hadronic tagging

Y. Yook,[70] Y.-J. Kwon,[70] A. Abdesselam,[58] I. Adachi,[12] S. Al Said,[58,27] K. Arinstein,[4] D. M. Asner,[49] V. Aulchenko,[4]
T. Aushev,[22] R. Ayad,[58] S. Bahinipati,[15] A. M. Bakich,[57] A. Bala,[50] V. Bansal,[49] V. Bhardwaj,[41] B. Bhuyan,[16] A. Bondar,[4]

Belle analysis with hadronic *B*-tagging



Mode	ε [%]	N	N^{bkg}	$\mathcal{B}$ (in 10^{-6})

$B^+ \to \ell^+\nu_\ell$, why bother with tagging?

- Note: $\mathscr{B}_{\rm SM}(B^+ \to e^+\nu_e) \sim 10^{-11}$ and $\mathscr{B}_{\rm SM}(B^+ \to \mu^+\nu_\mu) \sim 3 \times 10^{-7}$
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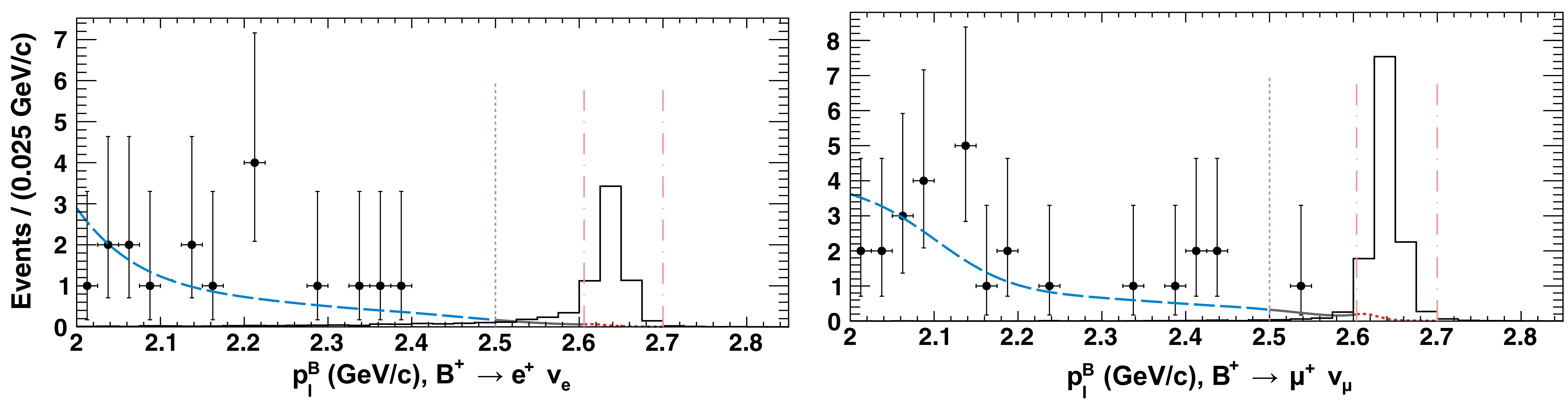
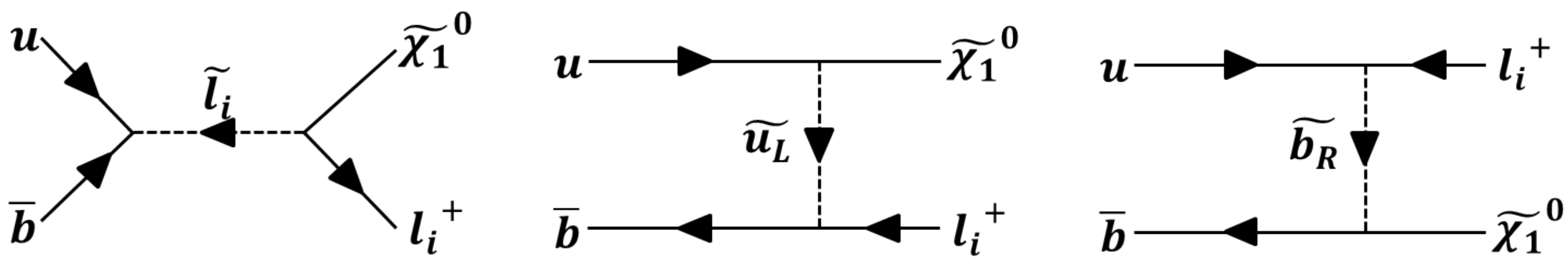
Belle analysis with hadronic B-tagging

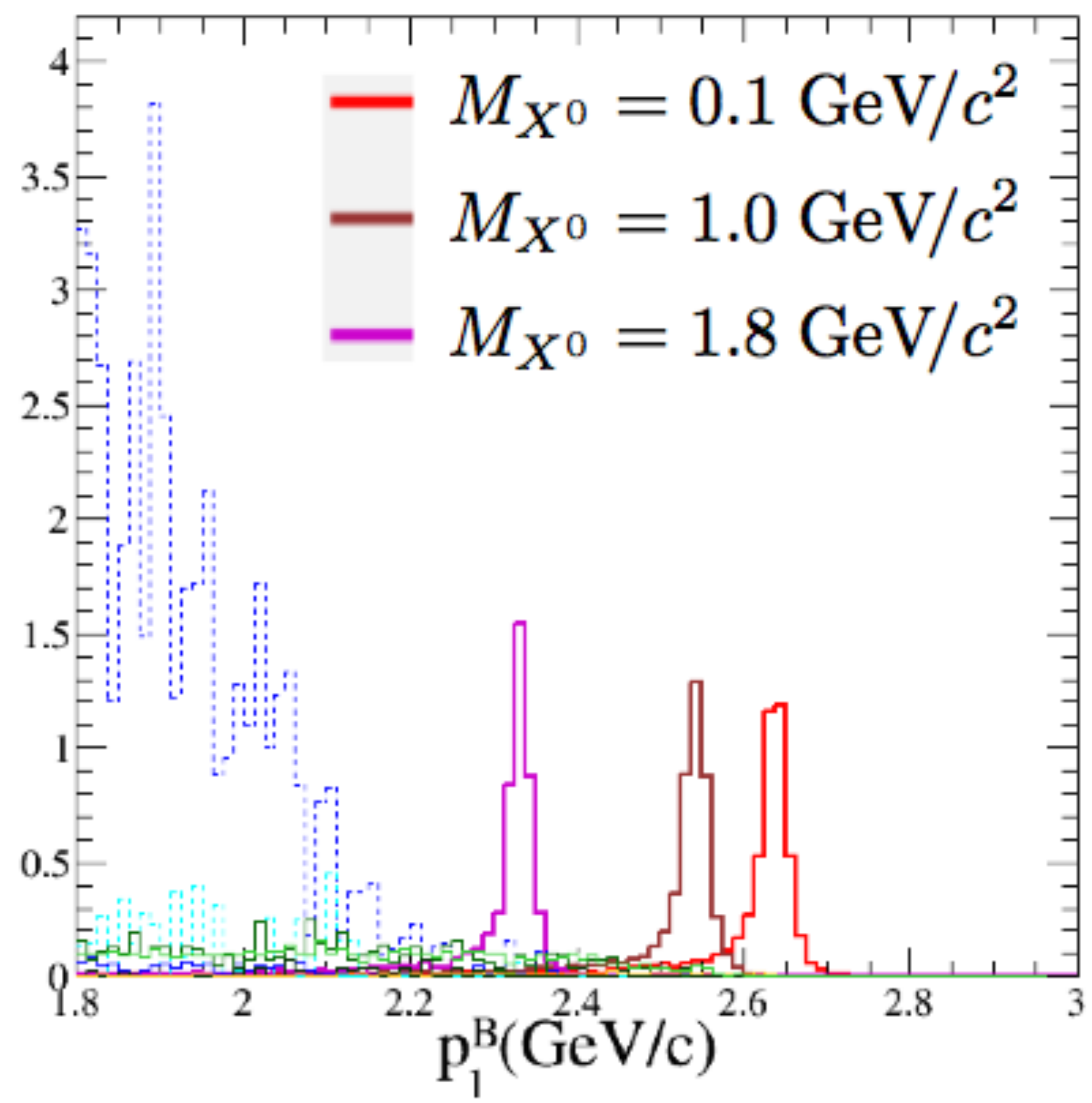
PRD 91, 052016 (2015)



Mode	$\epsilon_{\rm s}$ [%]	$N_{\rm obs}$	$N_{\rm exp}^{\rm bkg}$	$\mathcal{B}$ (in 10^{-6})
$B^+ \to e^+\nu_e$	0.086 ± 0.007	0	0.10 ± 0.04	**< 3.5**
$B^+ \to \mu^+\nu_\mu$	0.102 ± 0.008	0	$0.26^{+0.09}_{-0.08}$	**< 2.7**

$B^+ \to \ell^+ X^0$, why not?





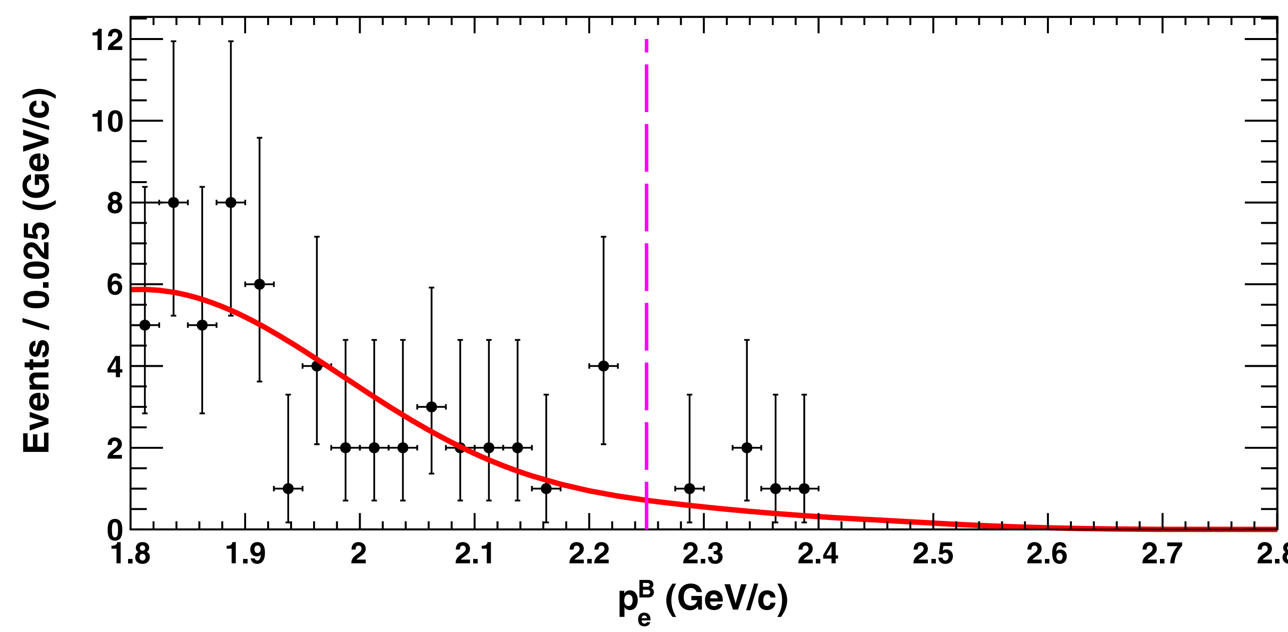
- Search for massive neutral invisible fermion "X^0"
  a heavy neutrino, or an LSP in RPV models, or whatever
- Experimental signature, very similar to $B^+ \to \ell^+ \nu_\ell$
- But, p_ℓ^B provides a handle on m_{X^0}

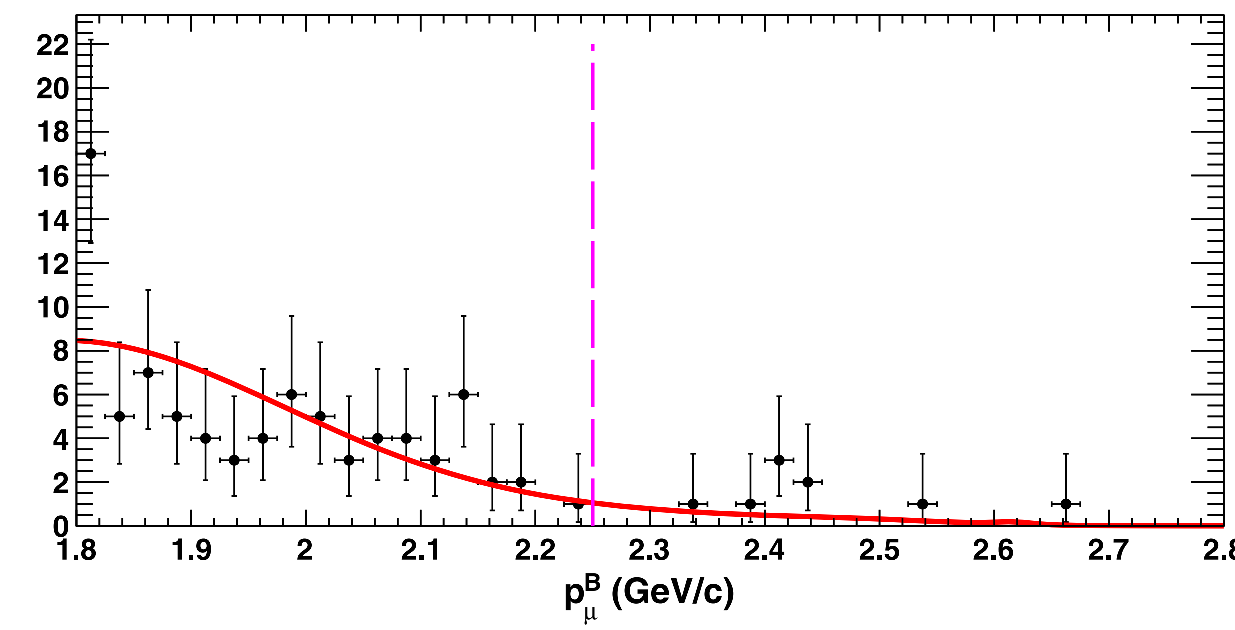
$B^+ \to \ell^+ X^0$ search at Belle

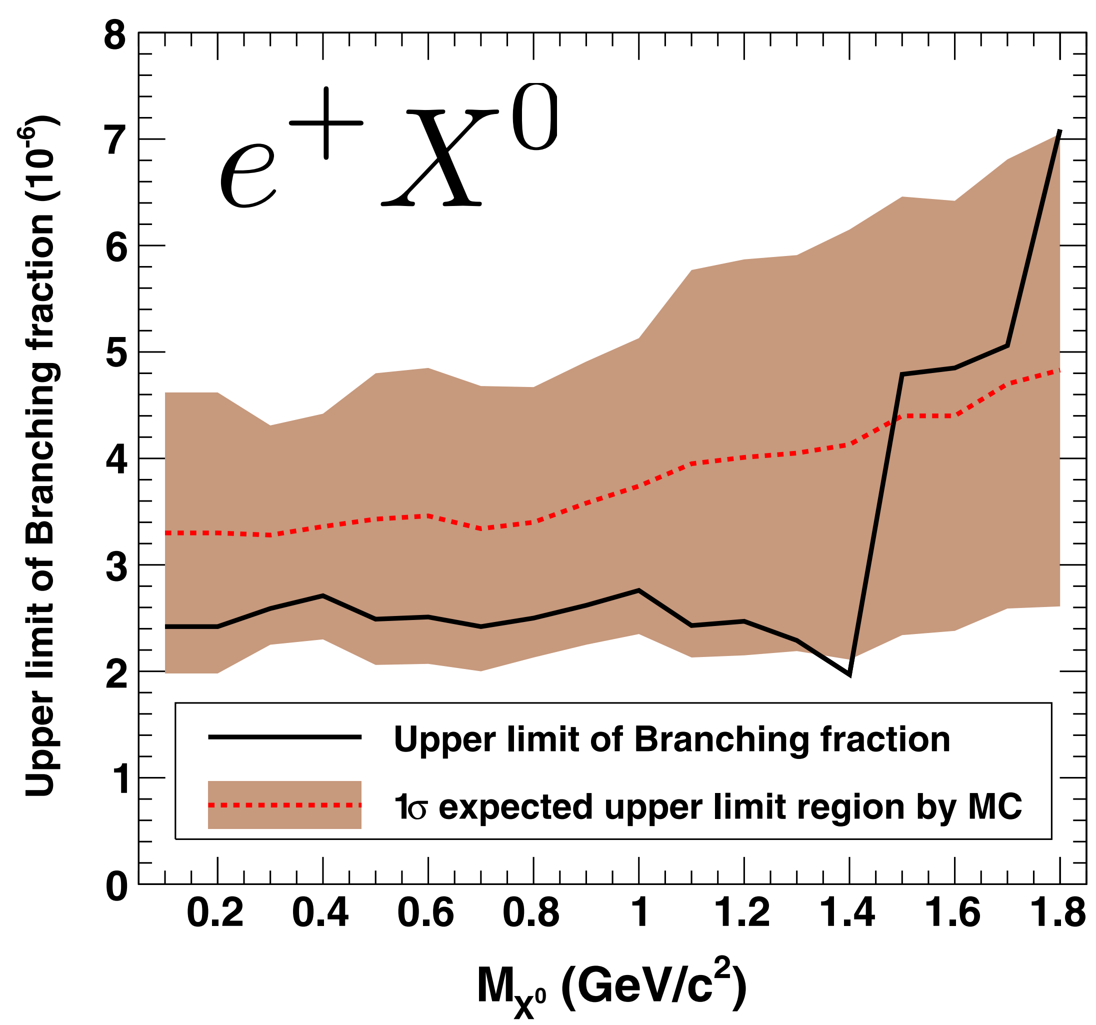
PHYSICAL REVIEW D **94,** 012003 (2016)

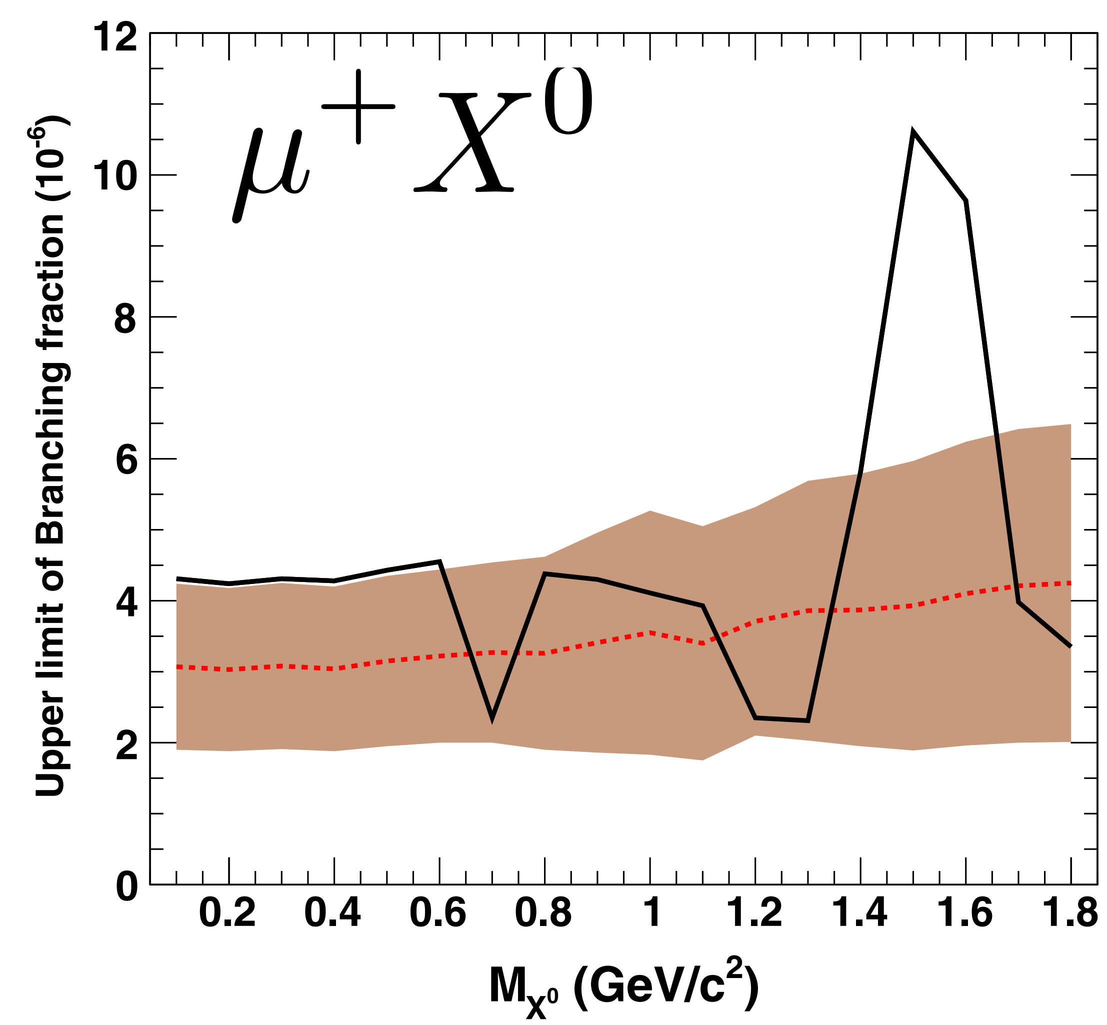
Search for a massive invisible particle X^0 in $B^+ \to e^+X^0$ and $B^+ \to \mu^+X^0$ decays

C.-S. Park,[69] Y.-J. Kwon,[69] I. Adachi,[12,9] H. Aihara,[61] D. M. Asner,[47] T. Aushev,[35] V. Babu,[55] I. Badhrees,[54,24]
A. M. Bakich,[53] E. Barberio,[33] P. Behera,[16] V. Bhardwaj,[51] J. Biswal,[21] G. Bonvicini,[67] A. Bozek,[42] M. Bračko,[31,21]









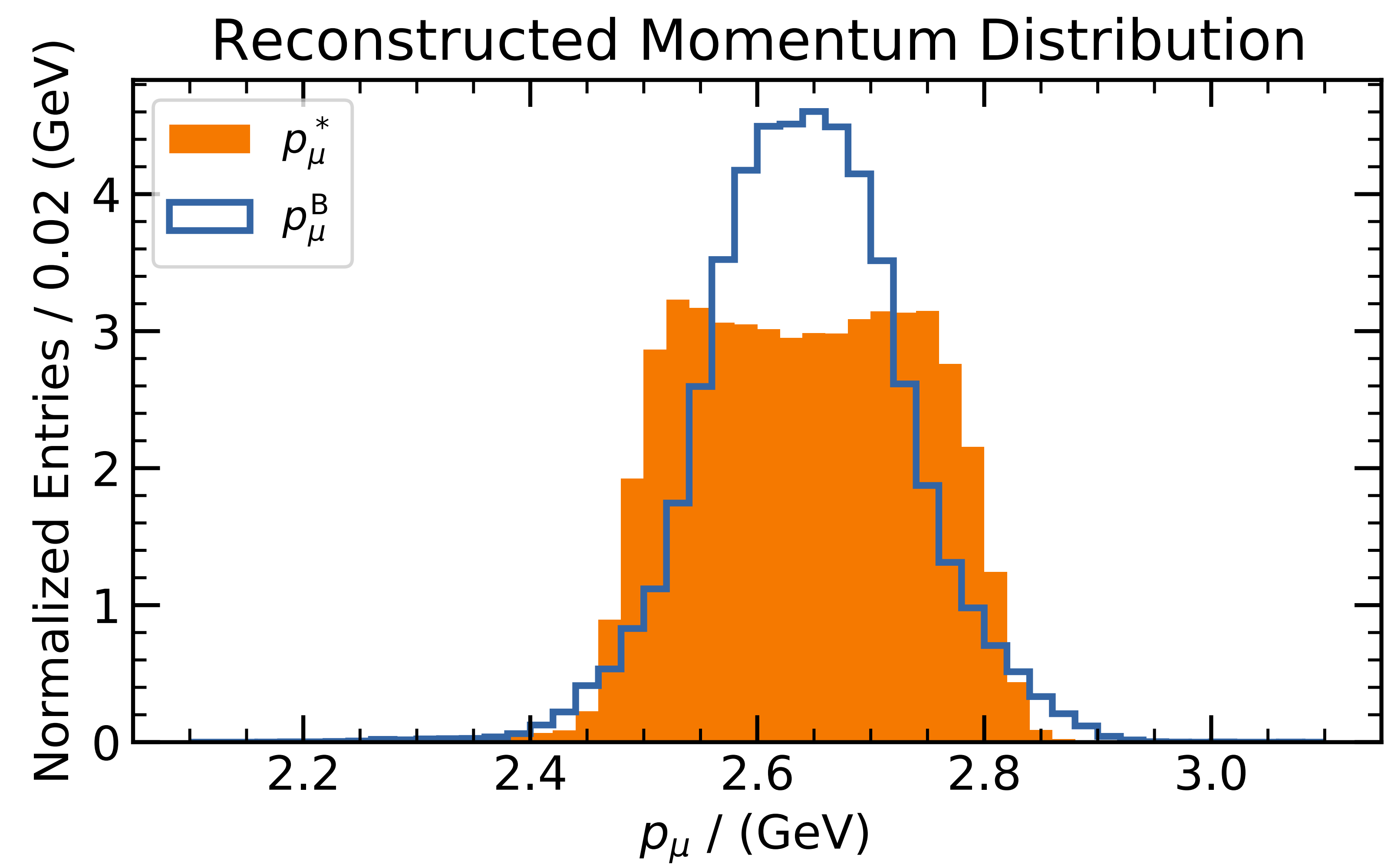
PRD 101, 032007 (2020)

$B^+ \to \mu^+\nu_\mu$ and $B^+ \to \mu^+ N$

N = an unknown neutral fermion (e.g. a sterile ν)

Features

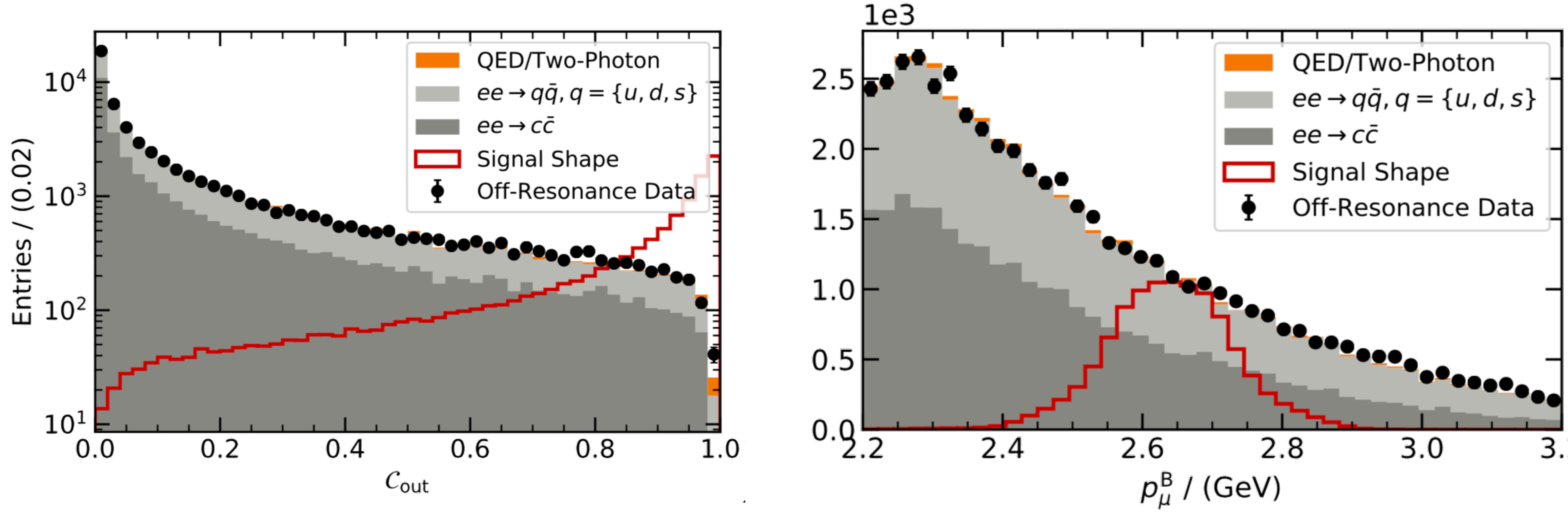
- an improved search over Belle's 2018 result (PRL 121, 031801)
  - ✓ modeling of $b \to u\ell^+\nu$ and continuum background
  - ✓ use inclusive B tagging to maximize signal selection efficiency ($\Leftarrow$ $BF_{SM} \sim 4 \times 10^{-7}$)
- carry out the analysis in the signal B rest frame
  - ✓ exploit $p_\mu^B \simeq 2.64$ GeV
  - ✓ achieve better resolution and sensitivity than using p_μ^* (CM frame)
  - ✓ sensitive to $B^+ \to \mu^+ N$ search, for $m_N \in [0, 1.5)$ GeV



$B^+ \to \mu^+\nu_\mu$ and $B^+ \to \mu^+ N$

Signal extraction

✓ by binned max. likelihood fit to p_μ^B in kinematic/BDT categories



Category	C_{out}	$\cos\Theta_{B\mu}$	Signal Efficiency
I	[0.98,1.00)	[-0.13,1.00)	6.5 %
II	[0.98,1.00)	[-1.00,-0.13)	5.9 %
III	[0.93,0.98)	[0.04,1.00)	7.1 %
IV	[0.93,0.98)	[-1.00,0.04)	8.3 %

PRD 101, 032007 (2020)

$B^+ \to \mu^+ \nu_\mu$ and $B^+ \to \mu^+ N$

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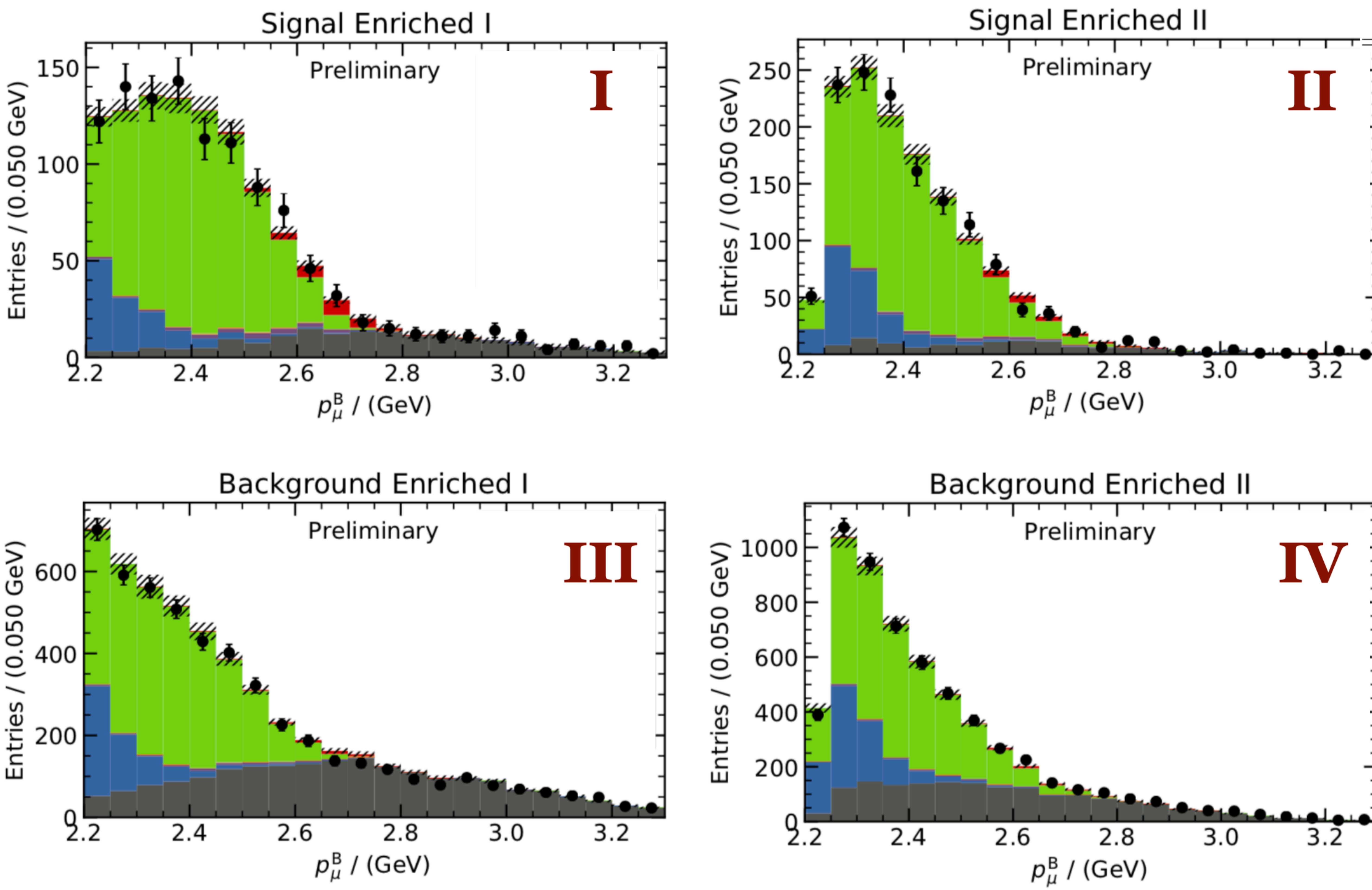
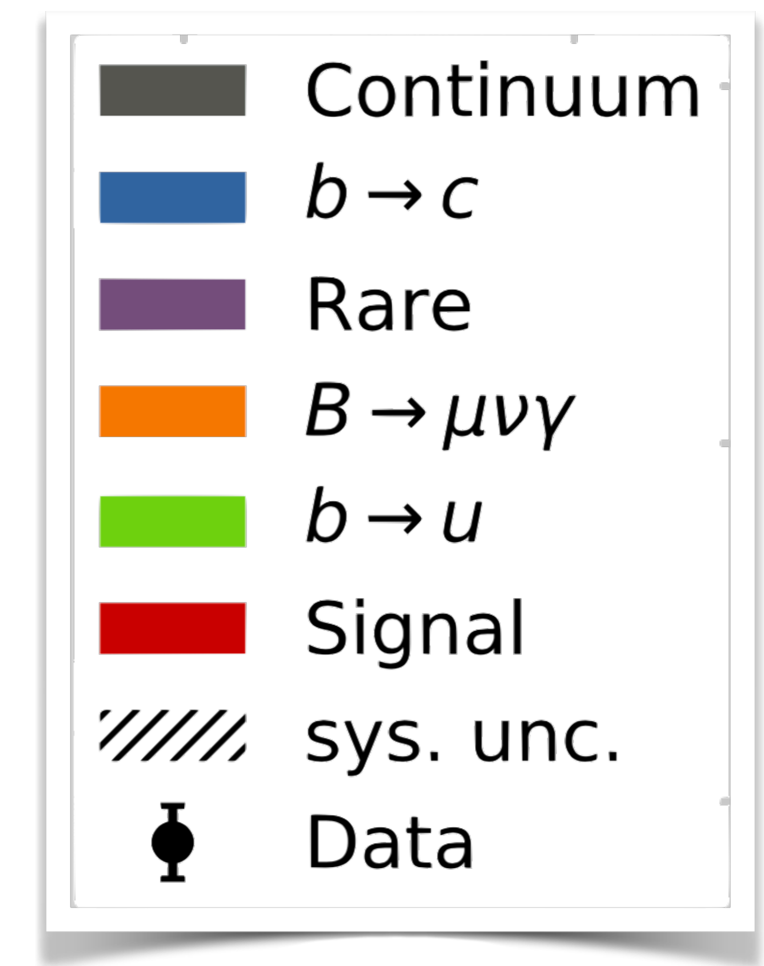
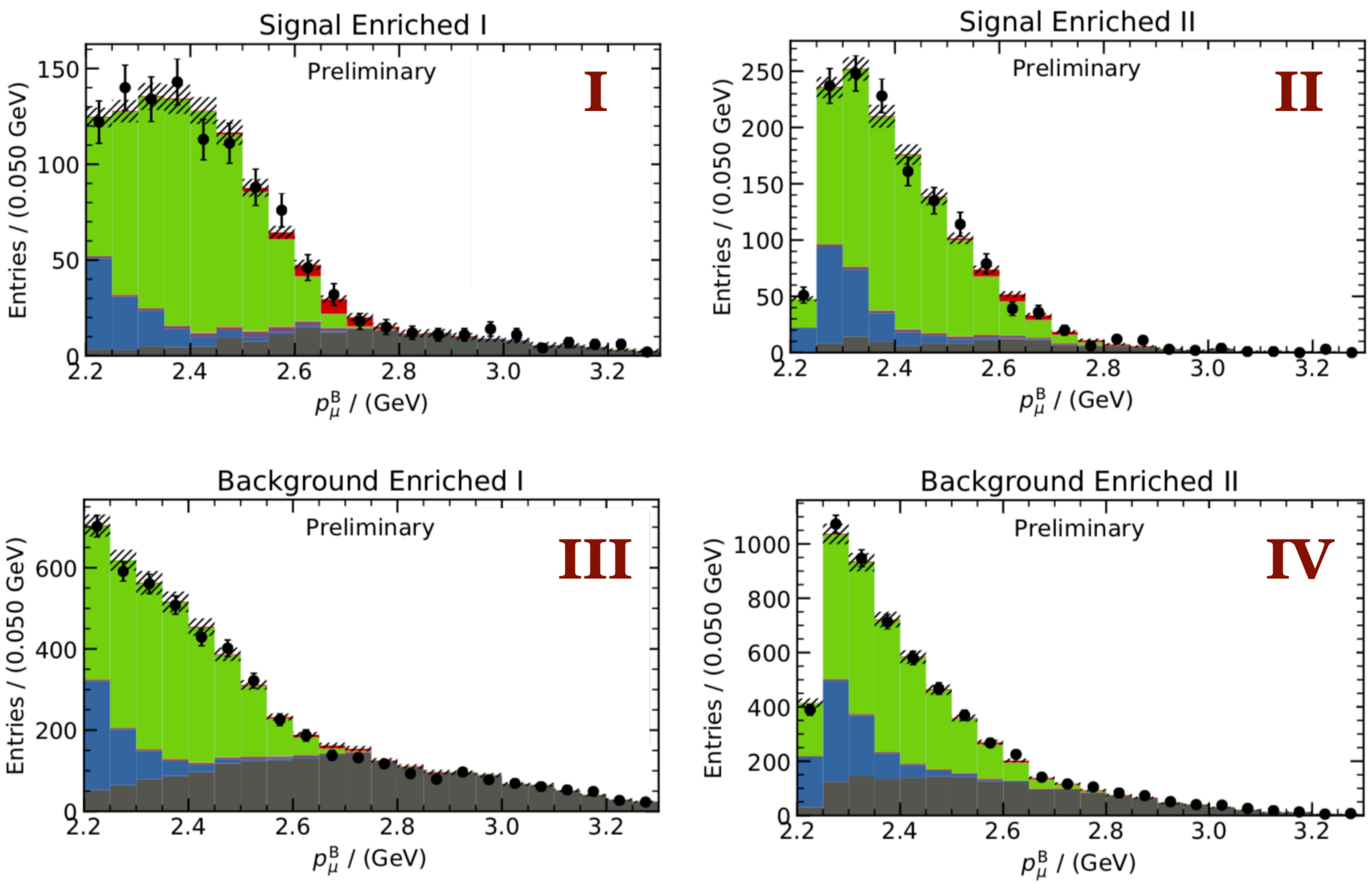
Signal extraction

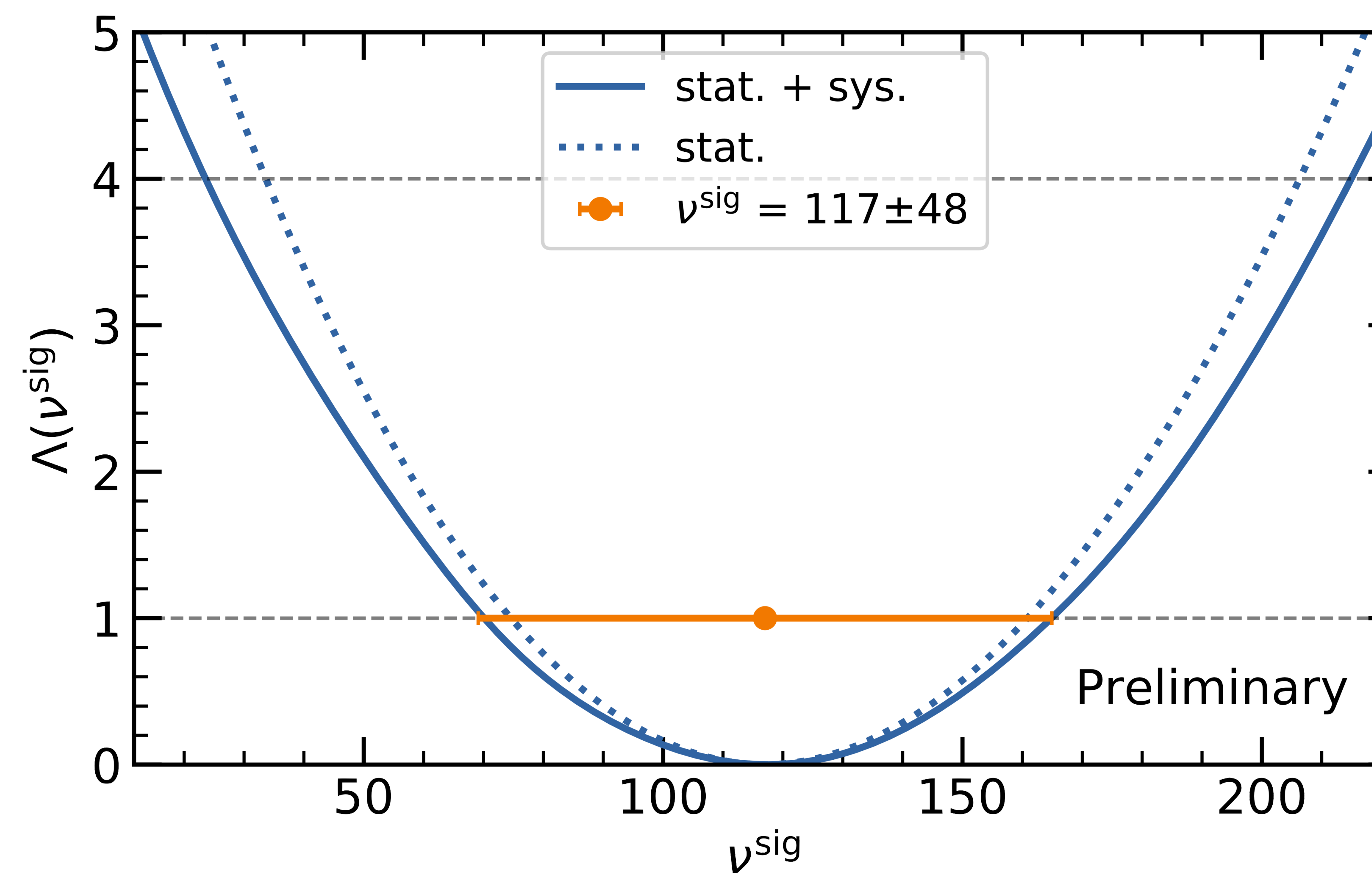




PRD 101, 032007 (2020)

$B^+ \to \mu^+\nu$ Result





- $\mathcal{B}(B^+ \to \mu^+\nu) = (5.3 \pm 2.0 \pm 0.9) \times 10^{-7}$ @ 2.8σ

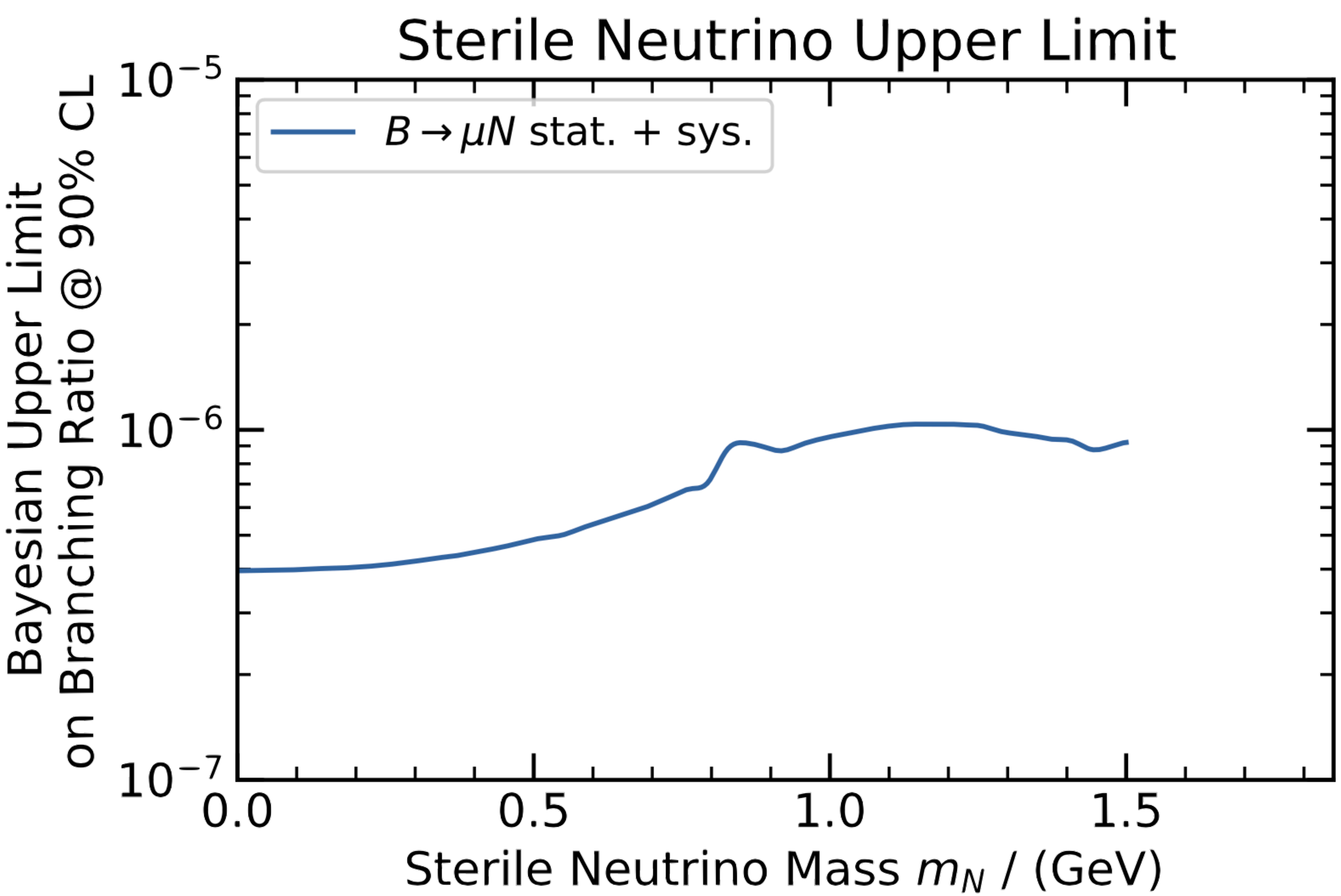
$\mathcal{B}(B^+ \to \mu^+\nu) < 8.6 \times 10^{-7}$ **Frequentist**

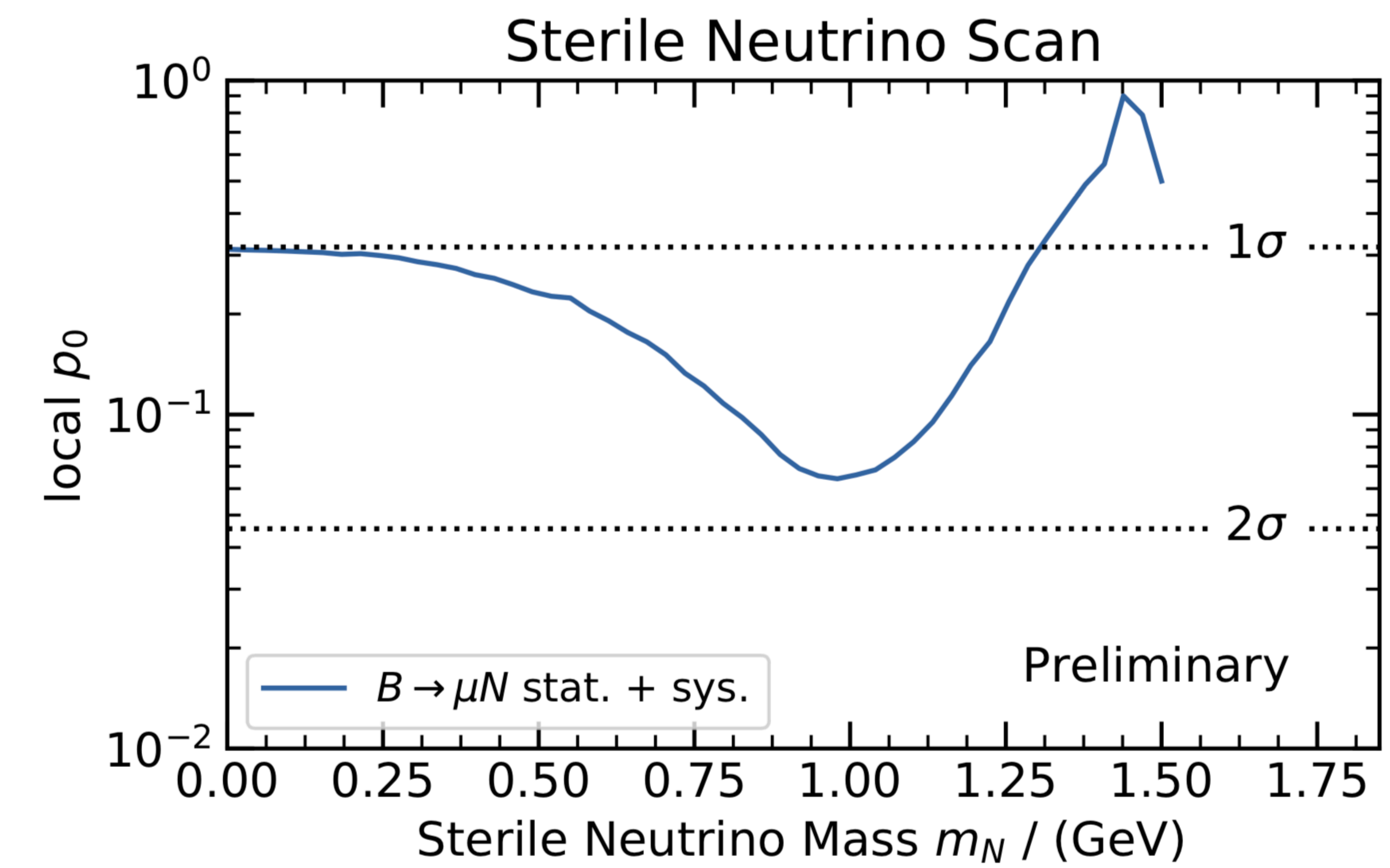
$< 8.9 \times 10^{-7}$ **Bayesian**

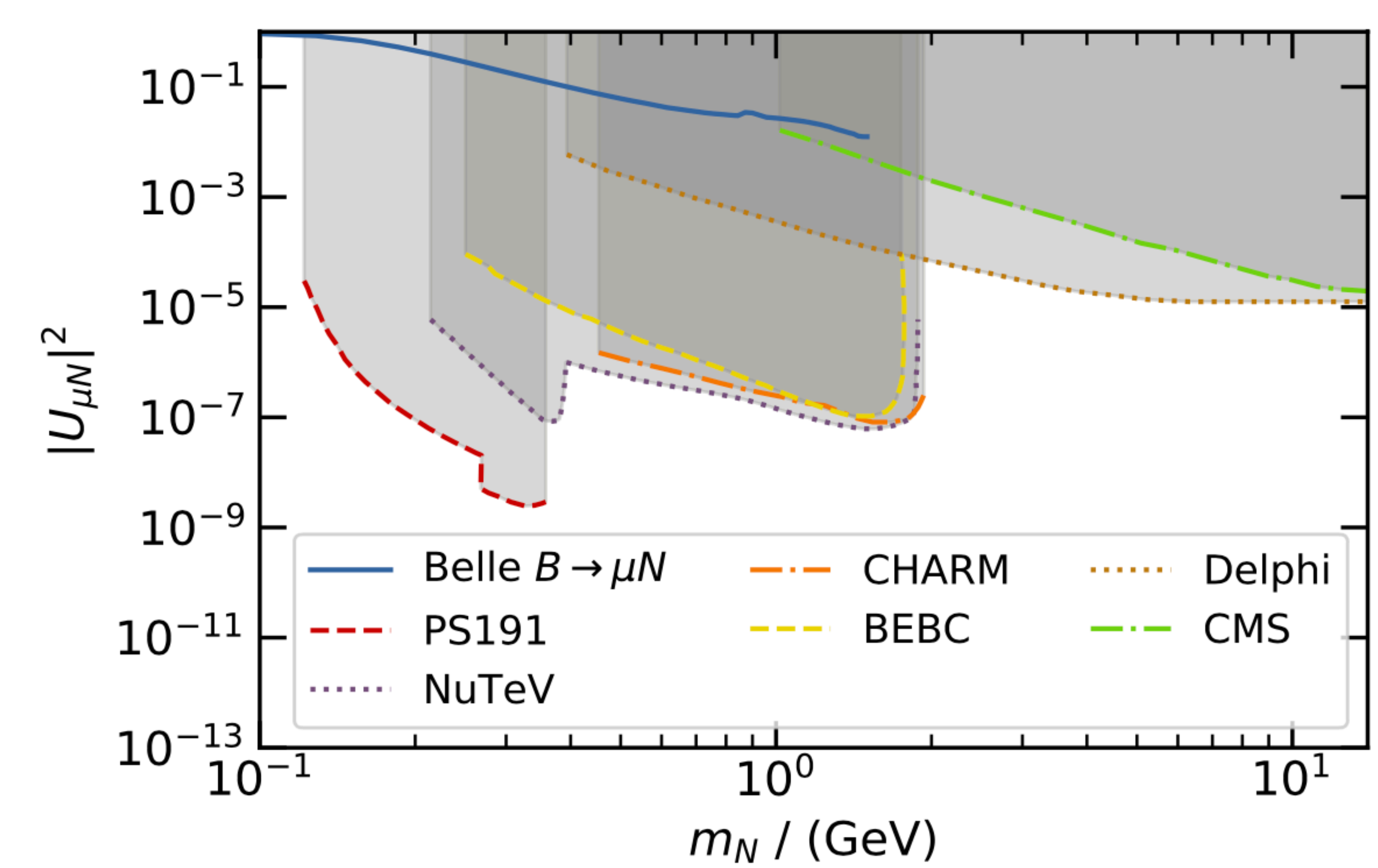
See back-up slide for New Physics implication!

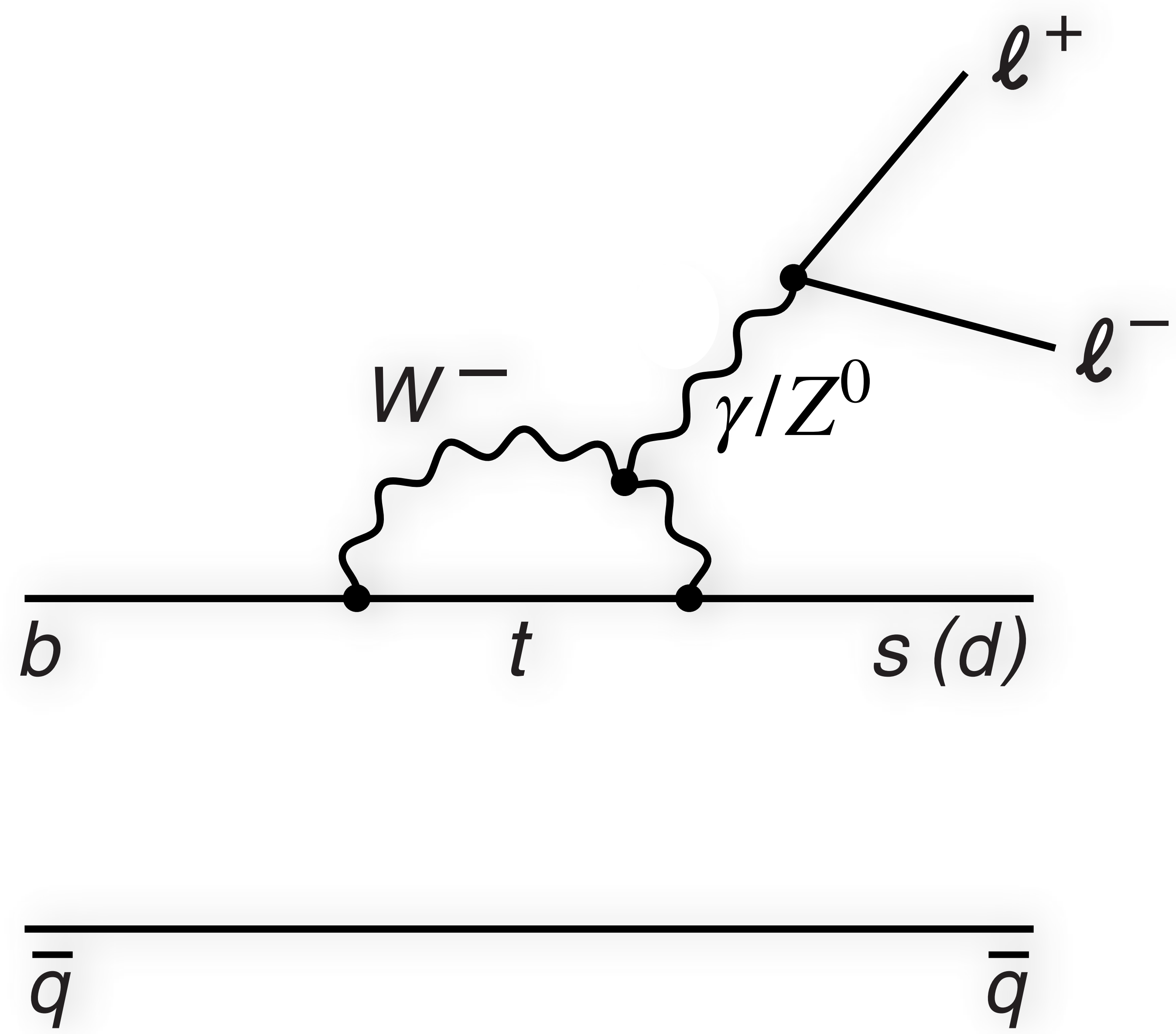
PRD 101, 032007 (2020)

$B^+ \to \mu^+ N$ search



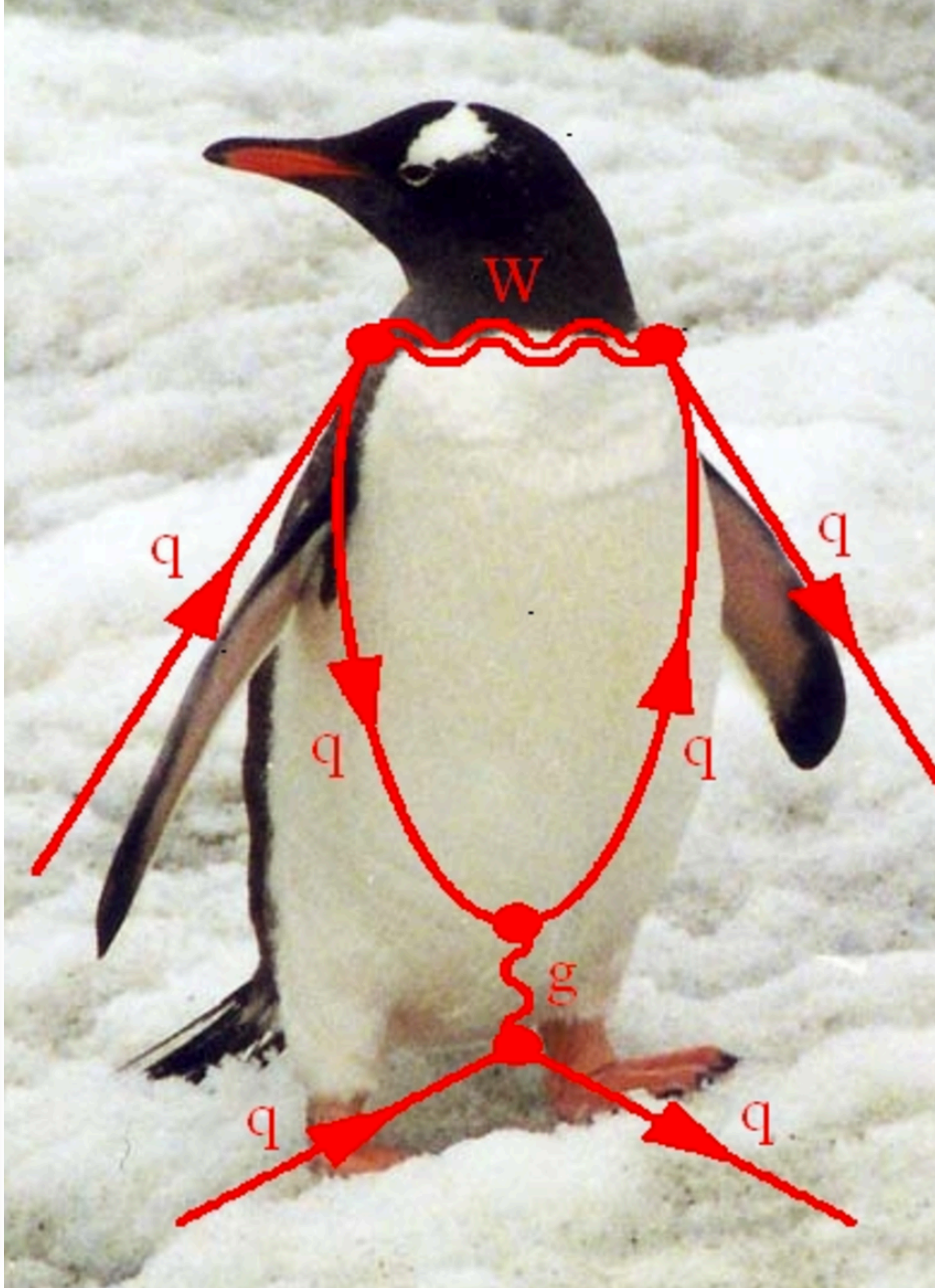






EW penguin

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



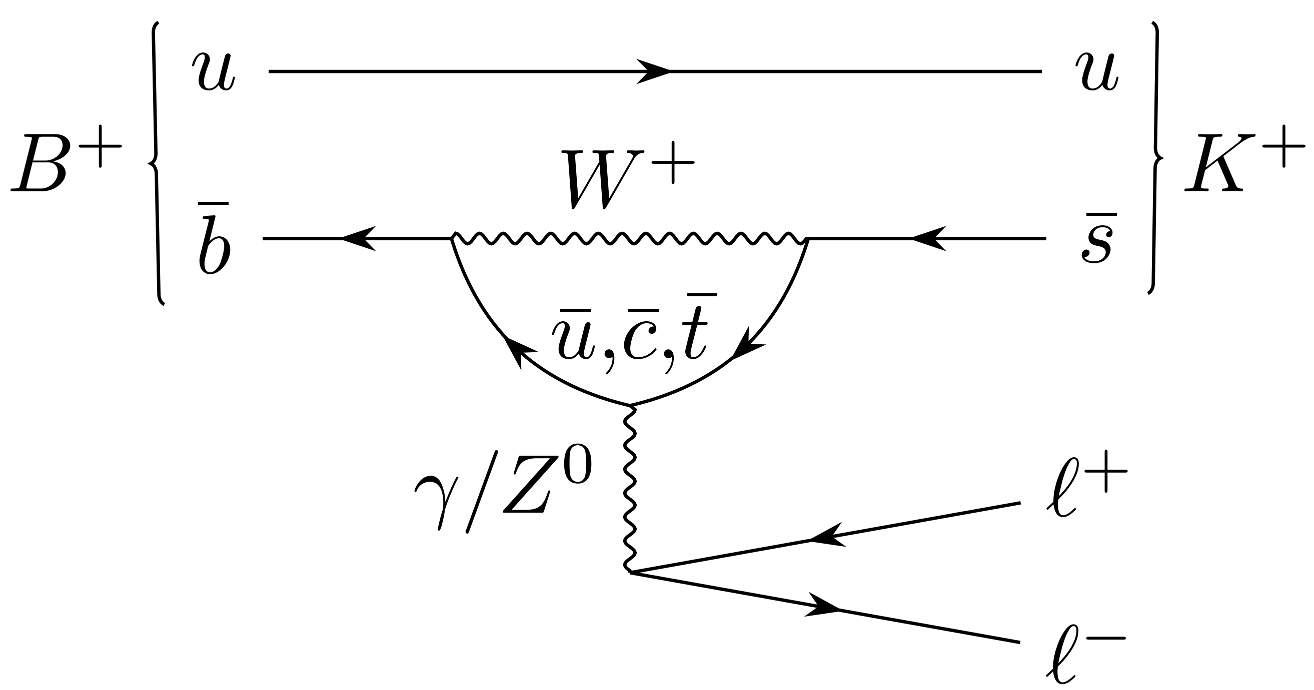
Belle's legacy on EW penguins

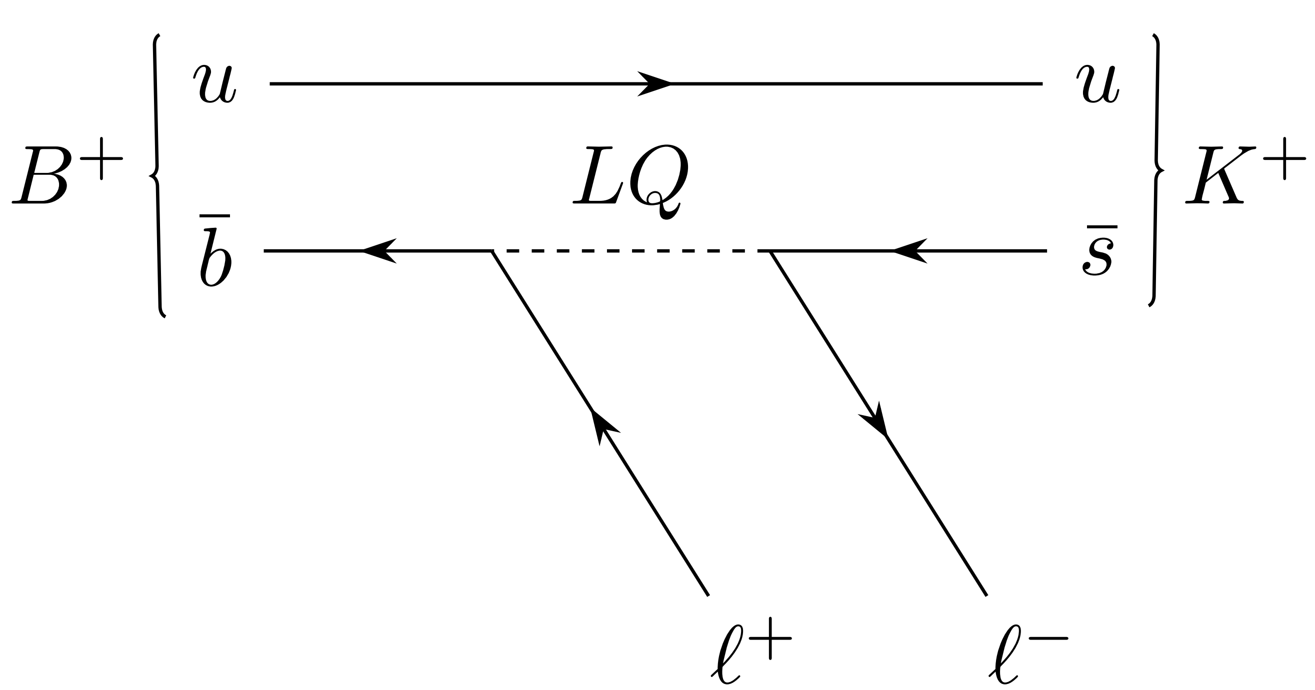
- First observation of $B \to K\ell^+\ell^-$ PRL **88**, 021801 (2002)
- First observation of $B \to K^*\ell^+\ell^-$ PRL **91**, 261601 (2003)
- First observation of $B \to X_s\ell^+\ell^-$ PRL **90**, 021801 (2003)
- First measurement of $A_{\rm FB}$ of $B \to K^*\ell^+\ell^-$ PRL **96**, 251801 (2006)

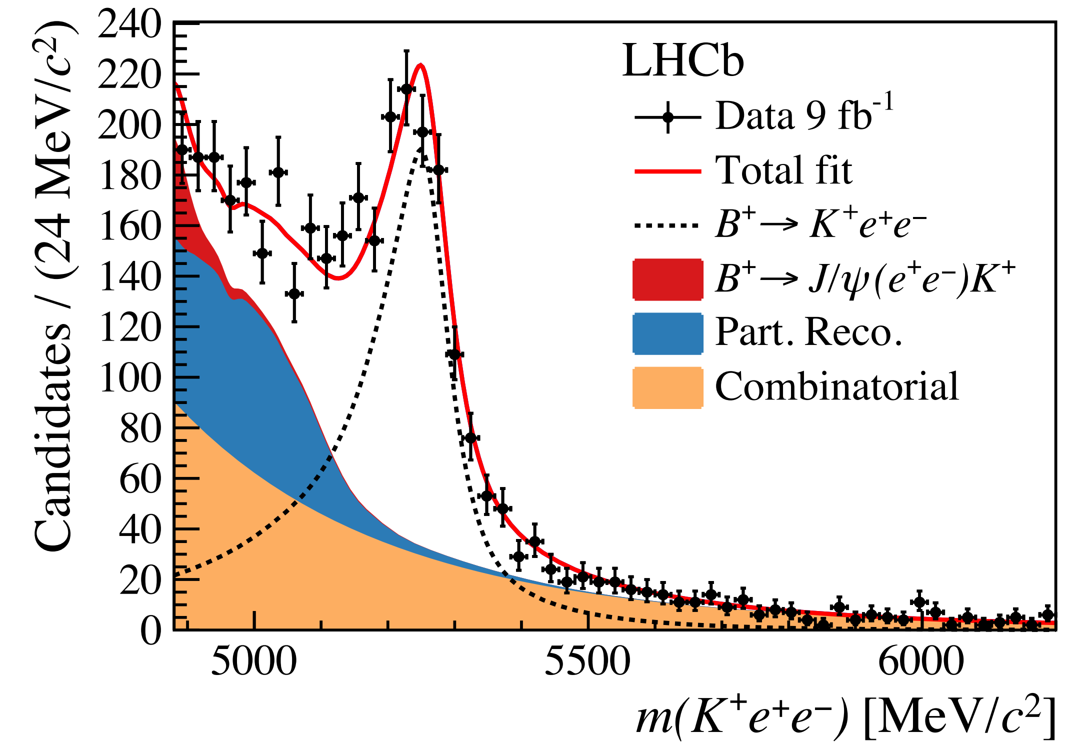
- First observations of several radiative modes, $\phi K\gamma$, $K_1\gamma$, etc.
- First observation of $B \to (\rho, \omega)\gamma$ PRL **96**, 221601 (2006)
- Most precise measurement of $B \to X_s\gamma$ covering the widest E_γ range PRL **103**, 241801 (2009)
- *and many more published results*

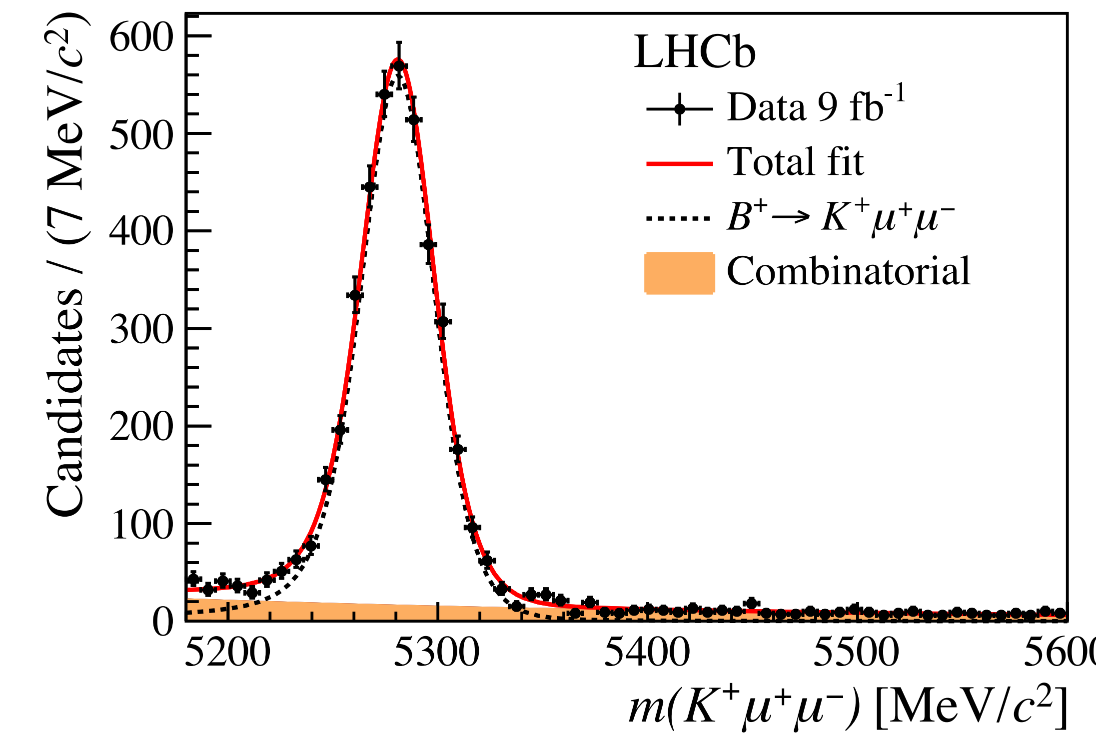
arXiv:2103.11769

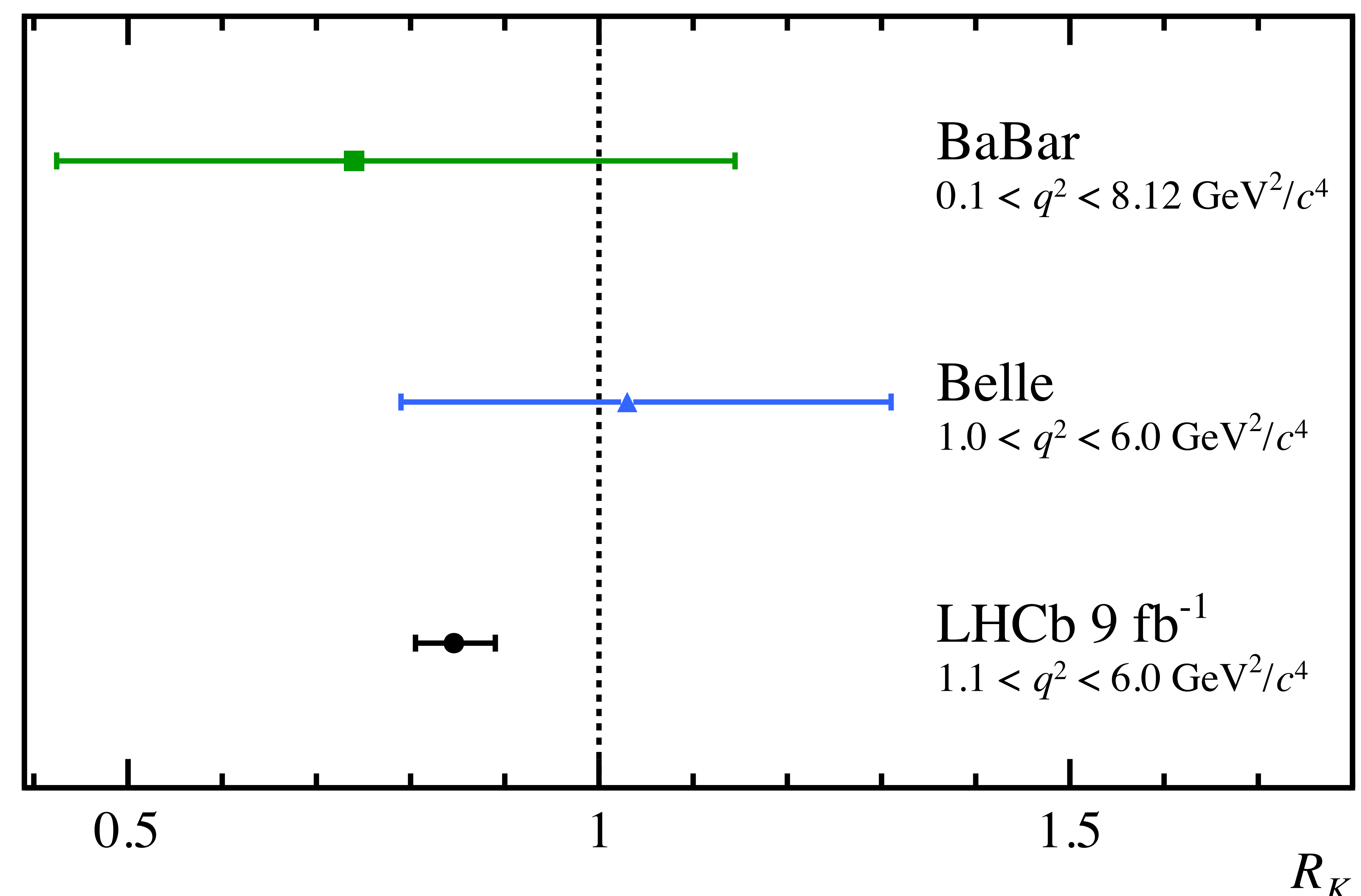
$$R_H \equiv \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\mathcal{B}(B \to H\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\mathcal{B}(B \to He^+e^-)}{dq^2} dq^2}$$









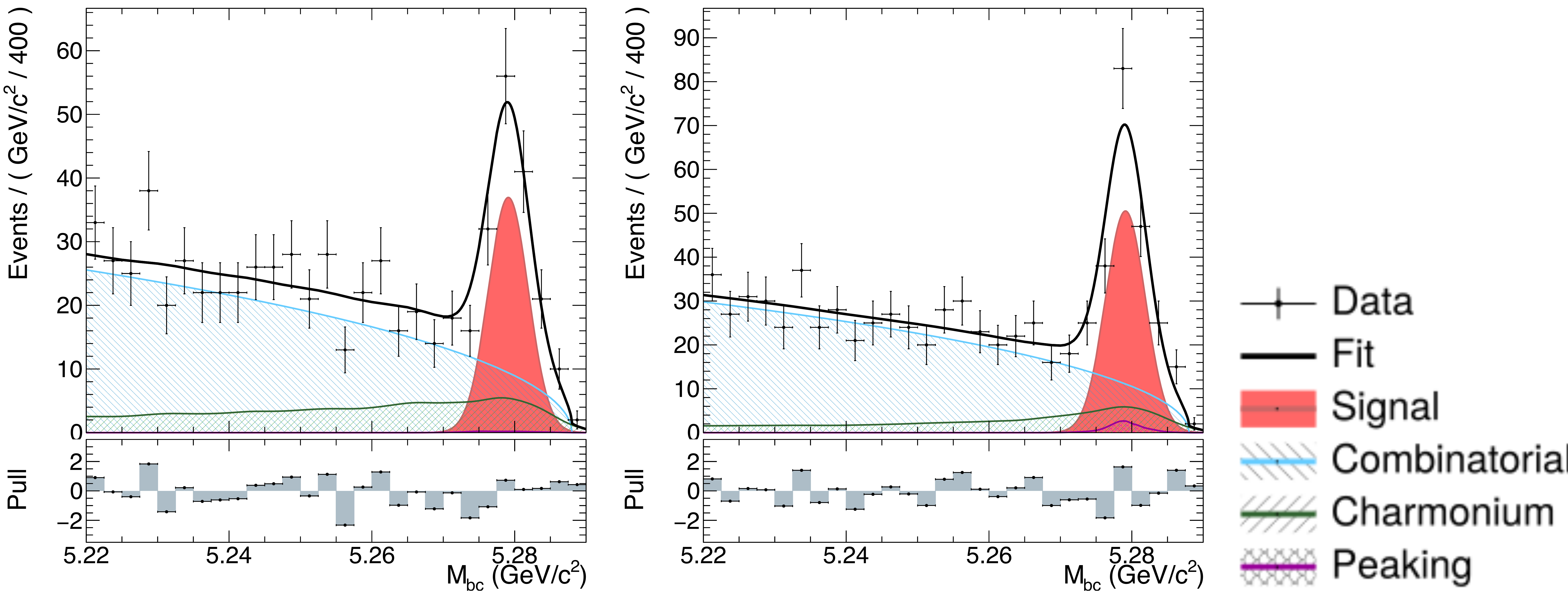


$$R_K(1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4) = 0.846\,^{+0.042}_{-0.039}\,^{+0.013}_{-0.012}$$

PRL 126, 161801 (2021)

R_{K^*} from Belle

- Use both B^0 and B^+ modes
  - K^* modes: $K^+\pi^-$, $K^+\pi^0$, $K^0_S\pi^+$

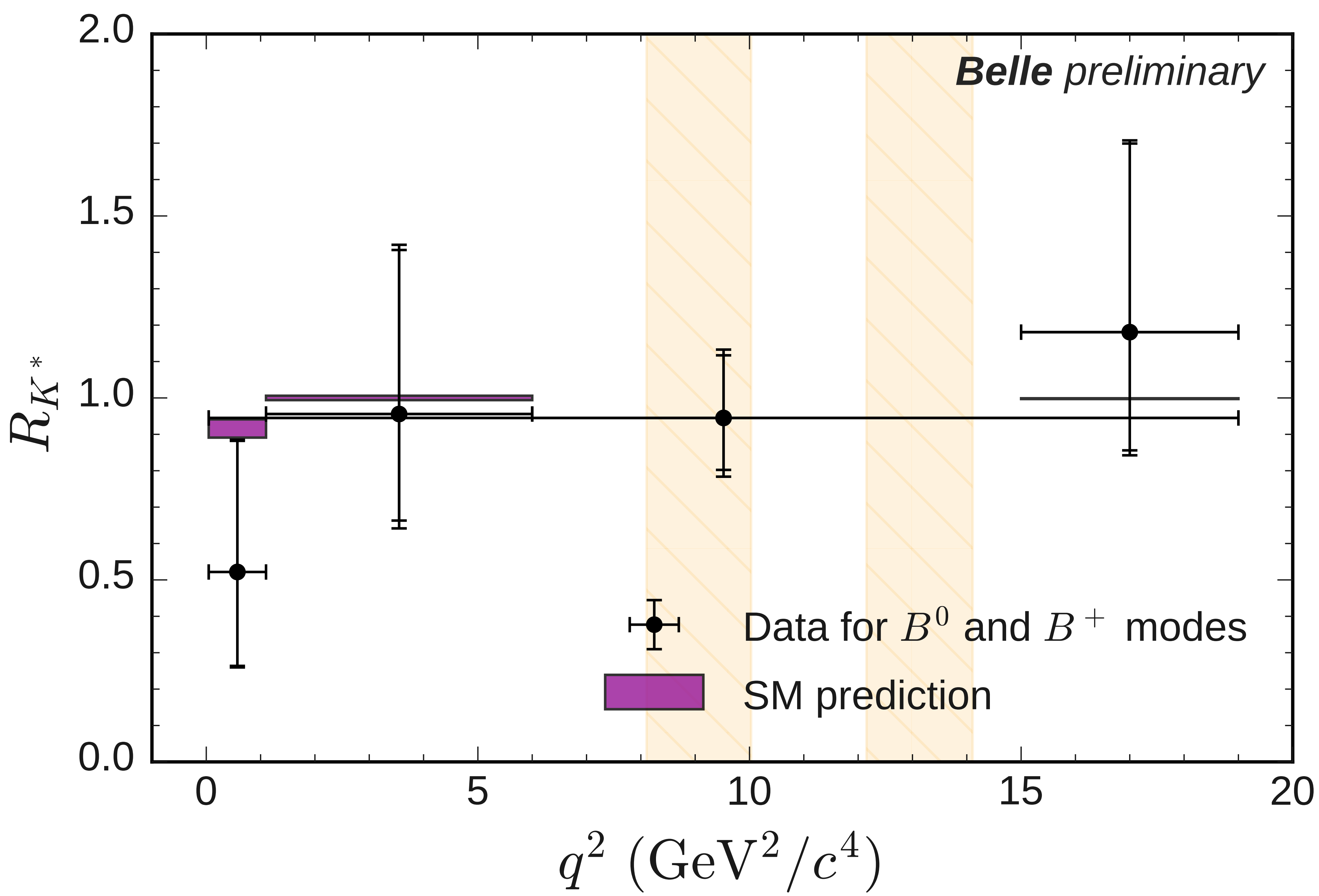


- example fit for $q^2 > 0.045\ \mathrm{GeV}^2$
- $103.0^{+13.4}_{-12.7}$ $(139.0^{+16.0}_{-15.4})$ events in the e (μ) modes

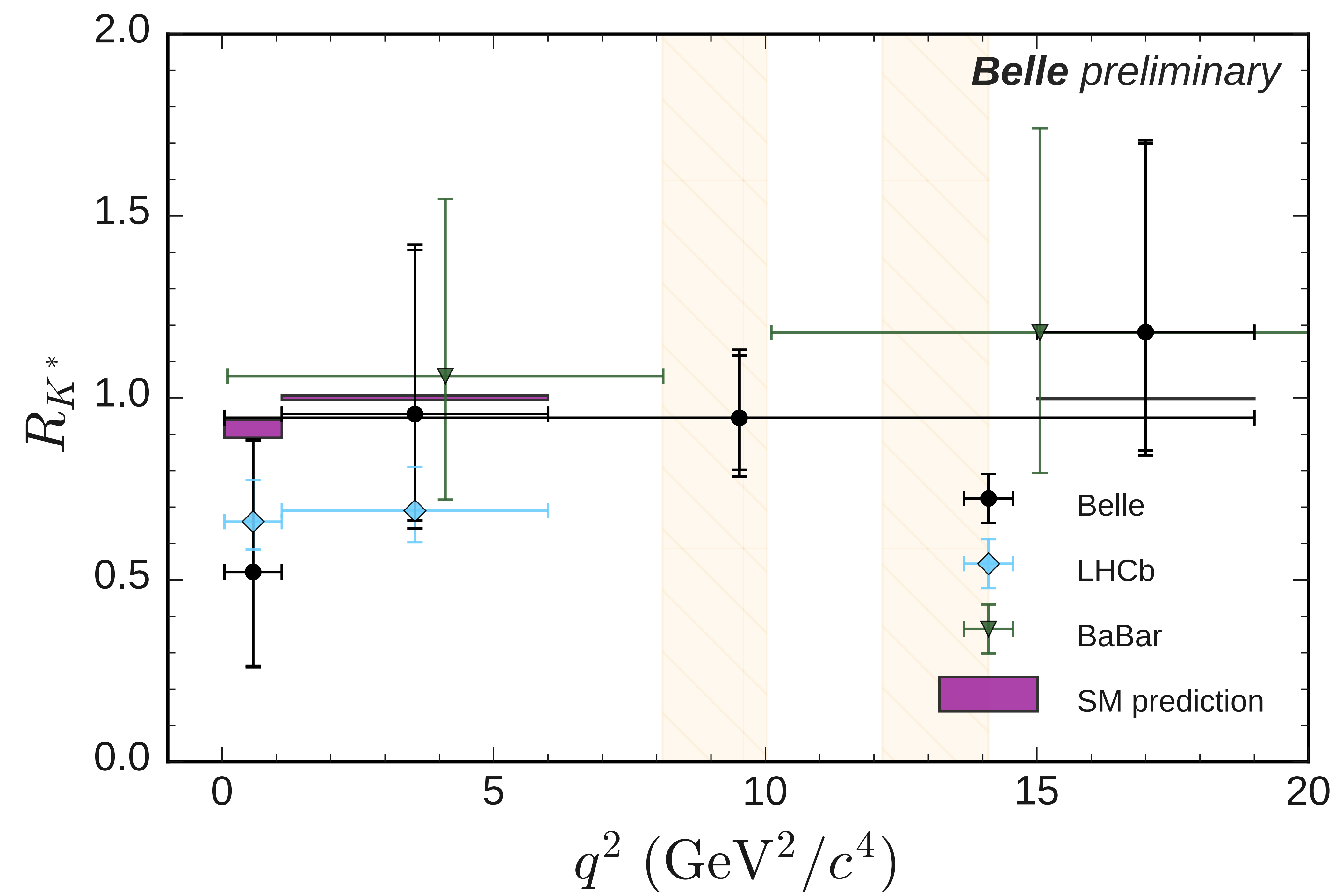
PRL 126, 161801 (2021)

R_{K^*} from Belle

R_{K^*} (Belle)



R_{K^*} (all)

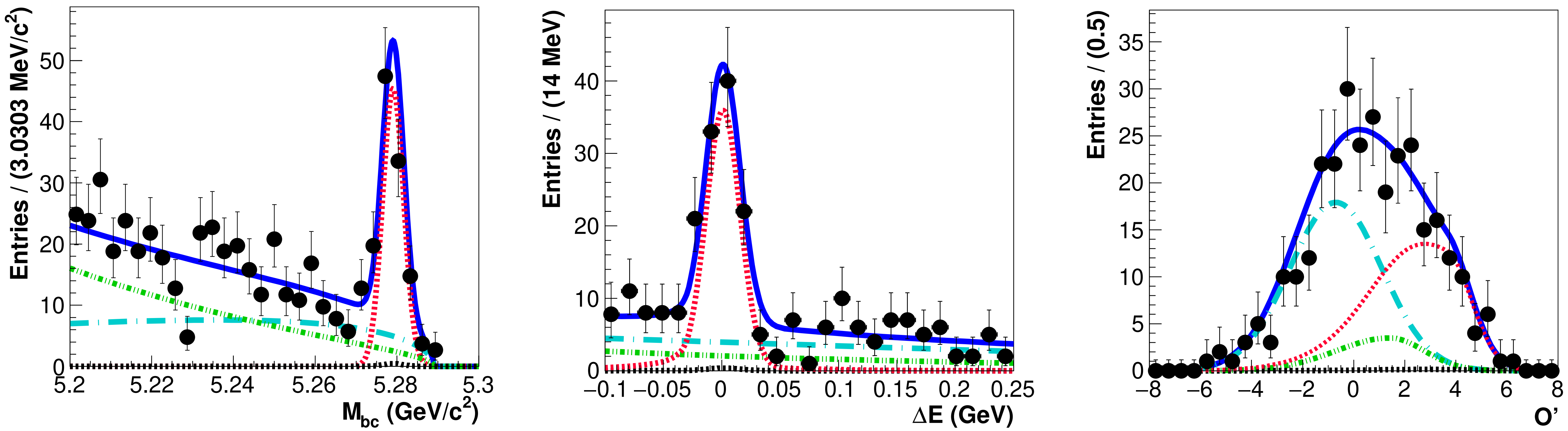


JHEP 03 (2021) 105

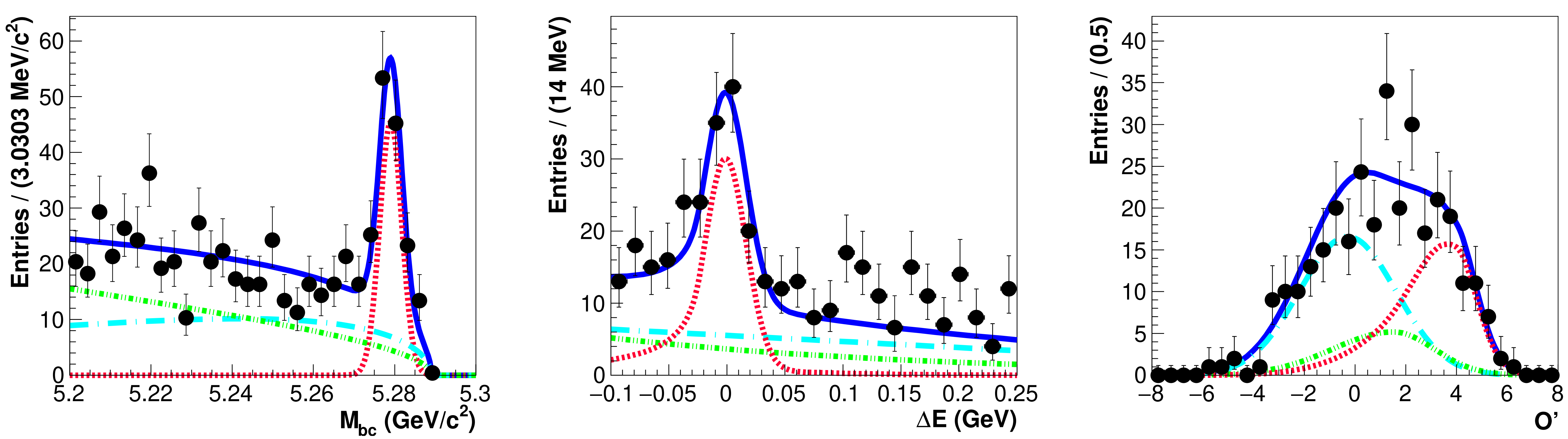
R_K from Belle

- Use both B^0 and B^+ modes

$q^2(\mu\mu) \in [(0.1,8.75),(10.2,13),(>14.18)]$



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

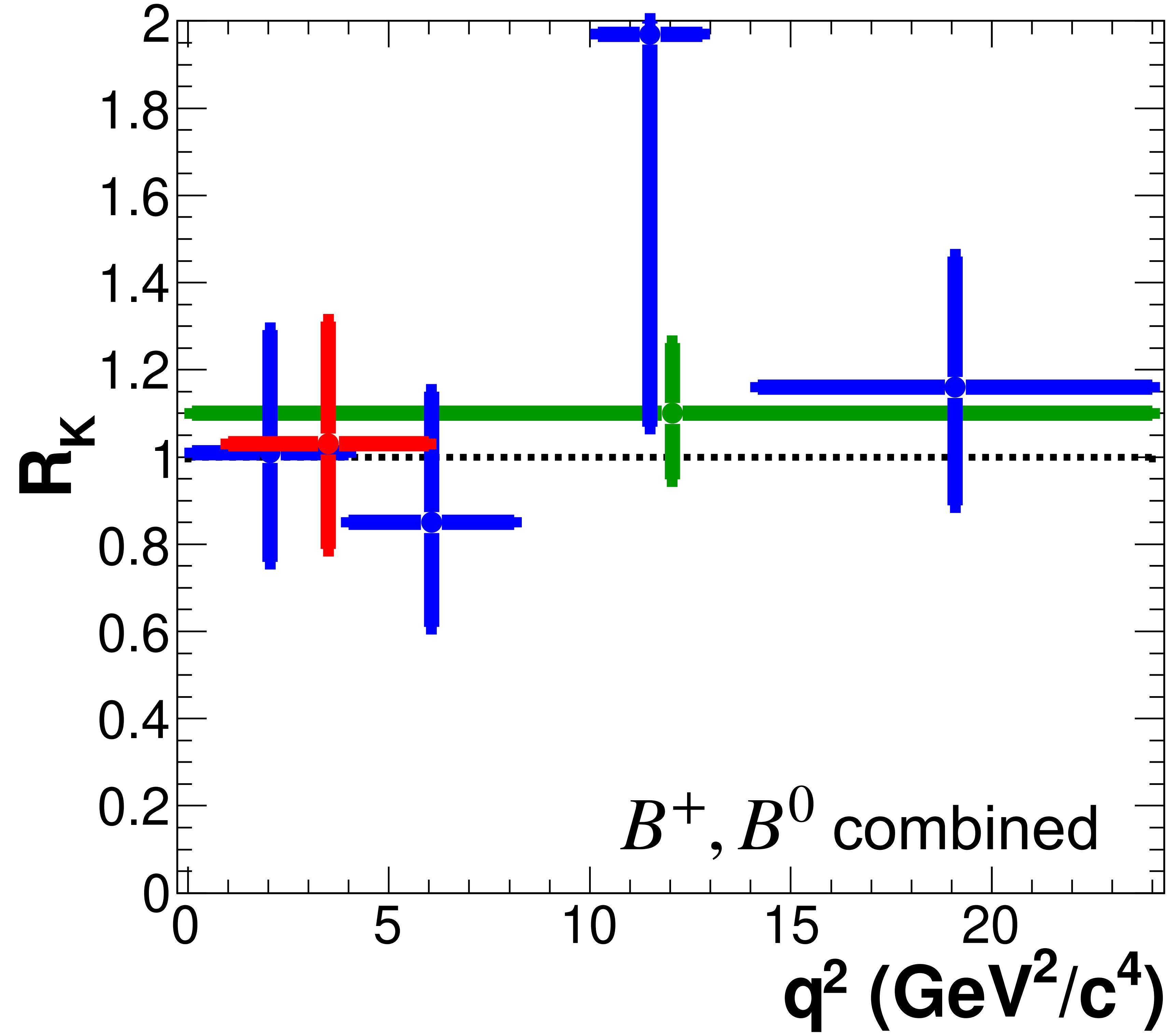


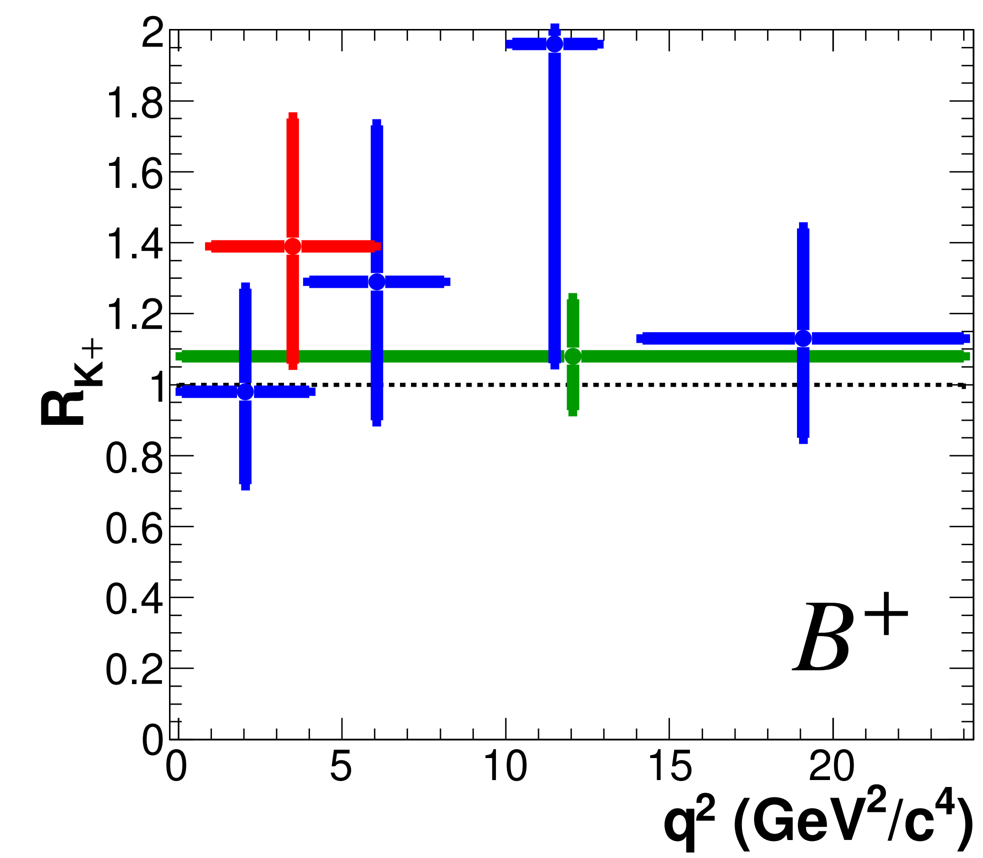
$B^+ \to K^+e^+e^-$

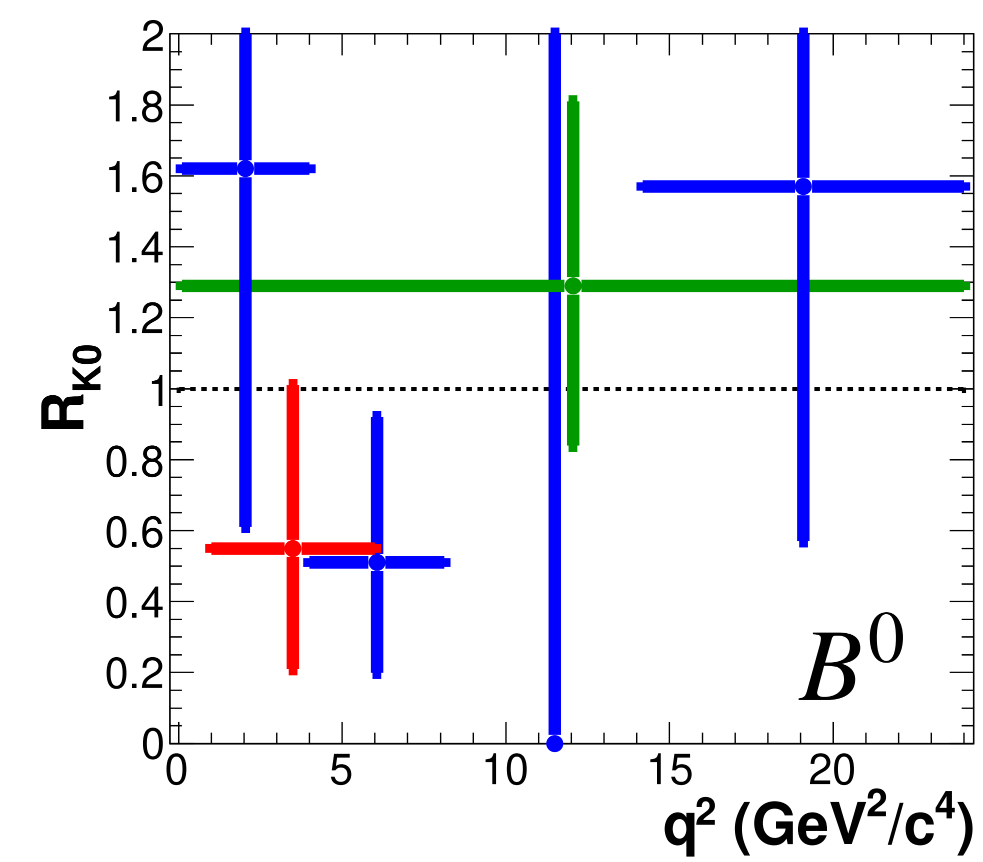
$q^2(ee) \in [(0.1,8.12),(10.2,12.8),(>14.18)]$

- $137 \pm 14(138 \pm 15)$ events in the $B^+ \to K^+\mu^+\mu^-$ $(K^+e^+e^-)$
- $27.3^{+6.6}_{-5.8}$ $(21.8^{+7.0}_{-6.1})$ events in the $B^0 \to K^0_S\mu^+\mu^-$ $(K^0_Se^+e^-)$

R_K from Belle







$$R_K = \begin{cases} 1.01 \ {}^{+0.28}_{-0.25} \pm 0.02 & q^2 \in (0.1, 4.0) \ \ \mathrm{GeV}^2/c^4 \,, \\ 0.85 \ {}^{+0.30}_{-0.24} \pm 0.01 & q^2 \in (4.00, 8.12) \ \ \mathrm{GeV}^2/c^4 \,, \\ 1.03 \ {}^{+0.28}_{-0.24} \pm 0.01 & q^2 \in (1.0, 6.0) \ \ \mathrm{GeV}^2/c^4 \,, \\ 1.97 \ {}^{+1.03}_{-0.89} \pm 0.02 & q^2 \in (10.2, 12.8) \ \ \mathrm{GeV}^2/c^4 \,, \\ 1.16 \ {}^{+0.30}_{-0.27} \pm 0.01 & q^2 > 14.18 \ \ \mathrm{GeV}^2/c^4 \,. \end{cases}$$

LFV in $B \to K^{(*)}\ell^+\ell^-$

- Much renewed interests in $B \to K^{(*)}\ell^+\ell^-$ for $R_{K^{(*)}}$ anomalies and potential interpretations in LUV

- LUV accompanied by LFV

  "However, any departure from lepton universality is necessarily associated with the violation of lepton flavor conservation. *No known symmetry principle can protect the one in the absence of the other.*"*

- So, why not search for $B \to K^{(*)}\ell^+\ell'^-$ $(\ell' \neq \ell)$?

* *Lepton Flavor Violation in B Decays?* Glashow, Guadagnoli, Lane, PRL 114, 091801 (2015)

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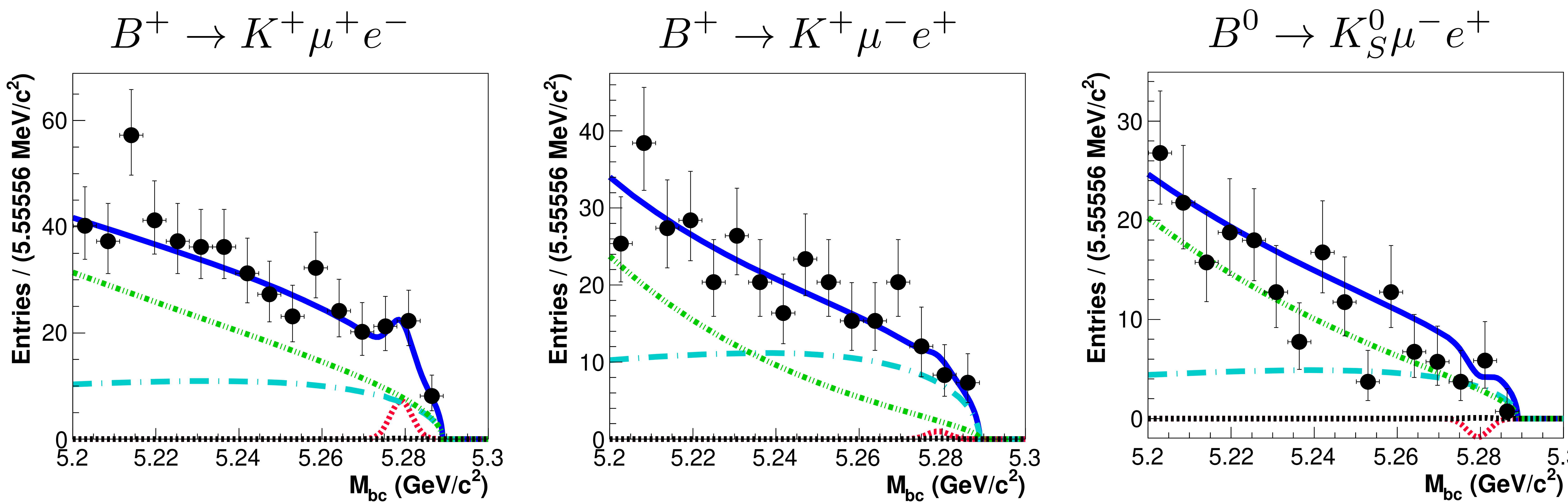
LFV in $B \to K\ell^+\ell^-$



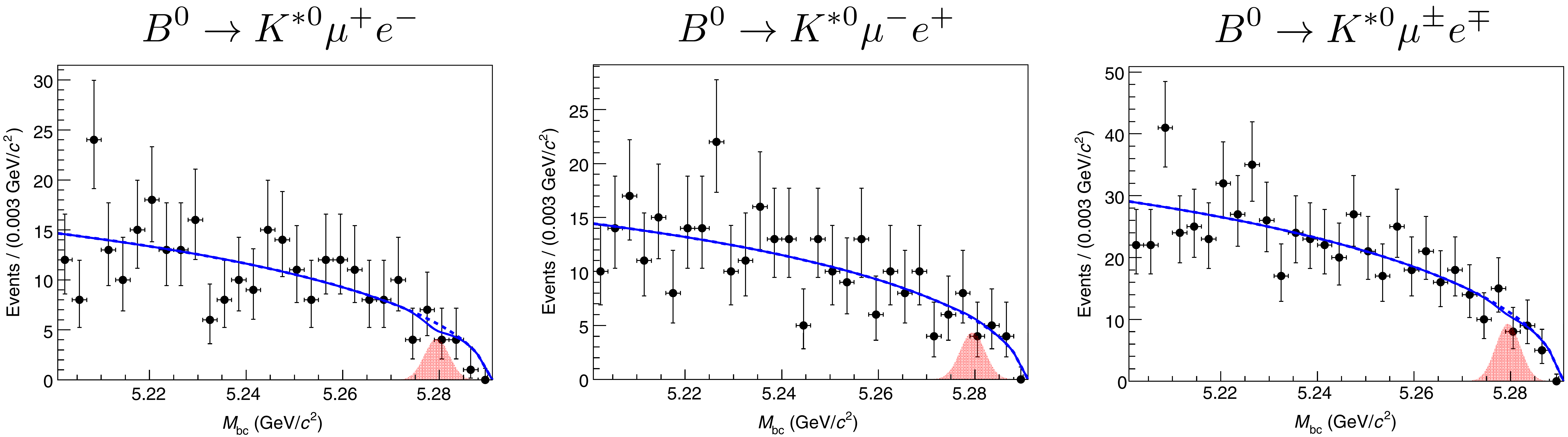
$\mathscr{B}(B^+ \to K^+\mu^+e^-) < 8.5 \times 10^{-8}$

$\mathscr{B}(B^+ \to K^+\mu^-e^+) < 3.0 \times 10^{-8}$

$\mathscr{B}(B^0 \to K_S^0\mu^-e^+) < 3.8 \times 10^{-8}$

Rapid Communications

Search for the lepton-flavor-violating decay $B^0 \to K^{*0}\mu^\pm e^\mp$



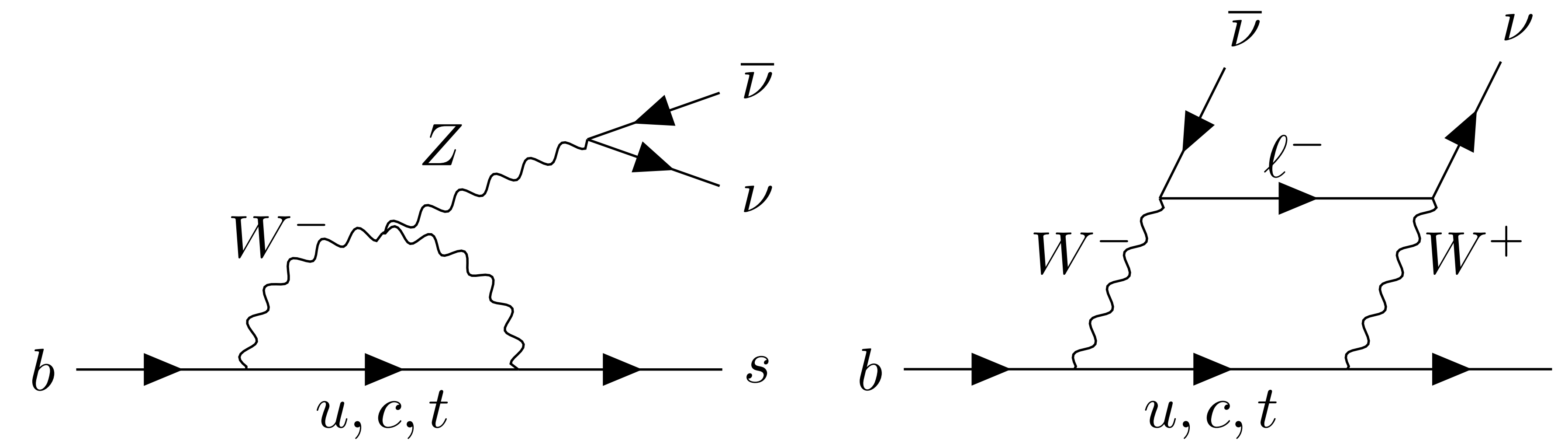
Mode	ε (%)	N_{sig}	N_{sig}^{UL}	$\mathcal{B}^{UL}$ (10^{-7})	BaBar (2006)
$B^0 \to K^{*0}\mu^+e^-$	8.8	$-1.5^{+4.7}_{-4.1}$	5.2	1.2	5.3
$B^0 \to K^{*0}\mu^-e^+$	9.3	$0.4^{+4.8}_{-4.5}$	7.4	1.6	3.4
$B^0 \to K^{*0}\mu^\pm e^\mp$ (combined)	9.0	$-1.2^{+6.8}_{-6.2}$	8.0	1.8	5.8

Invisible final states

- $B^+ \to K^+\nu\overline{\nu}$ (Belle II)
- $B^0 \to \nu\overline{\nu}(\gamma)$

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

- In the SM,
  - $\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = (4.6 \pm 0.5) \times 10^{-6}$ [4]
- sensitive to new physics BSM, e.g.
  - leptoquarks,
  - axions,
  - DM particles, etc.



(a) Penguin diagram (b) Box diagram

[4] T. Blake, G. Lanfranchi, and D. M. Straub, Prog. Part. Nucl. Phys. **92**, 50 (2017).

- existing measurements (upper limits)

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

$\Gamma(B^+ \to K^+\bar{\nu}\nu)/\Gamma_{total}$

Test for ΔB=1 weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT	Tagging
$< 1.6 \times 10^{-5}$	90	1, 2 LEES	2013I	BABR	$e^+ e^- \to \Upsilon(4S)$	hadronic + SL
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$< 1.9 \times 10^{-5}$	90	3, 1 GRYGIER	2017	BELL	$e^+ e^- \to \Upsilon(4S)$	semileptonic
$< 5.5 \times 10^{-5}$	90	1 LUTZ	2013	BELL	$e^+ e^- \to \Upsilon(4S)$	hadronic

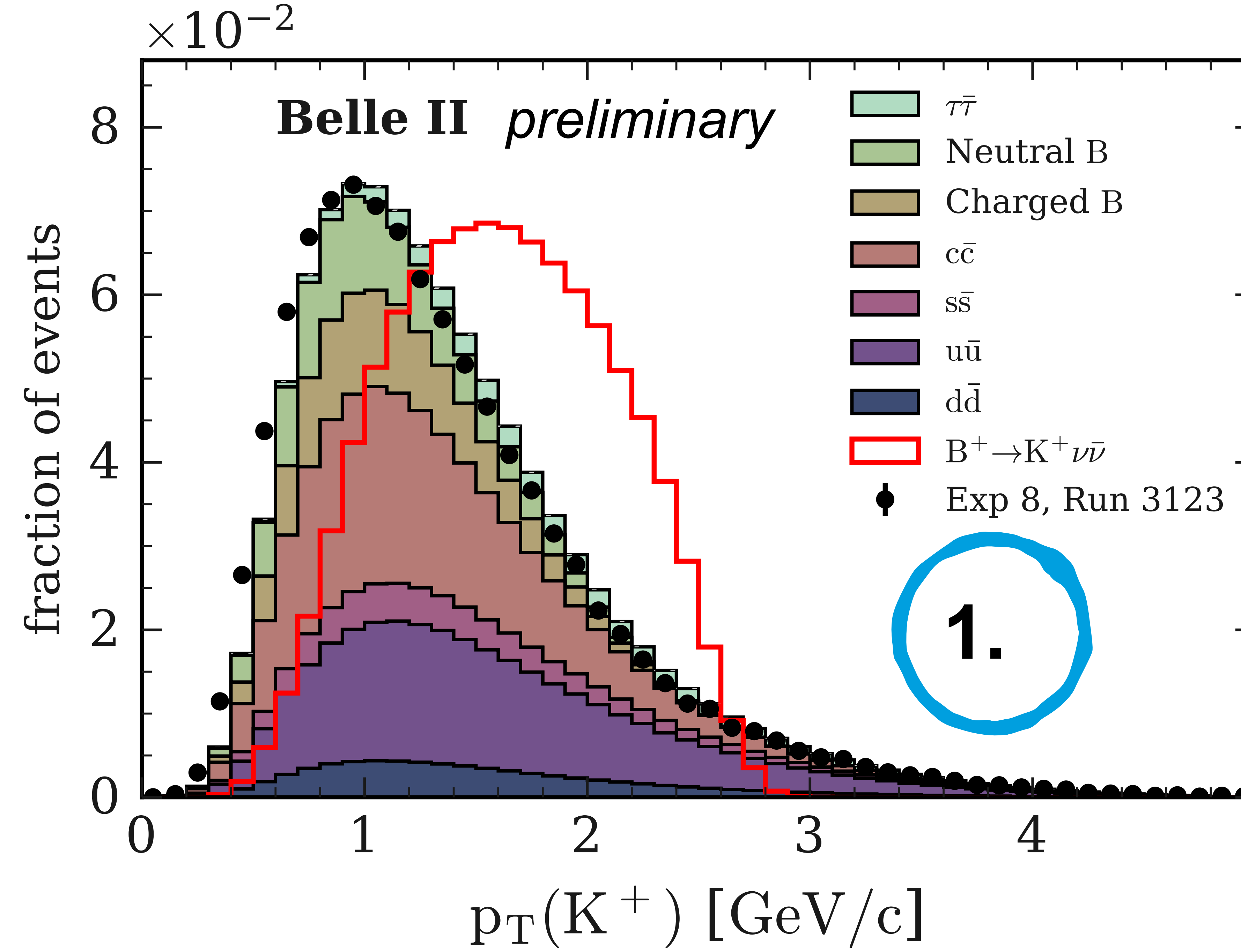
$B^+ \to K^+ \nu \bar{\nu}$ at Belle II

1. signal K^+ — track of highest p_T w/ at least 1 PXD hit ($\varepsilon \sim 80\,\%$)
2. all other tracks & clusters ⇒ “ROE” (rest of t
3. BDT for signal discrimination

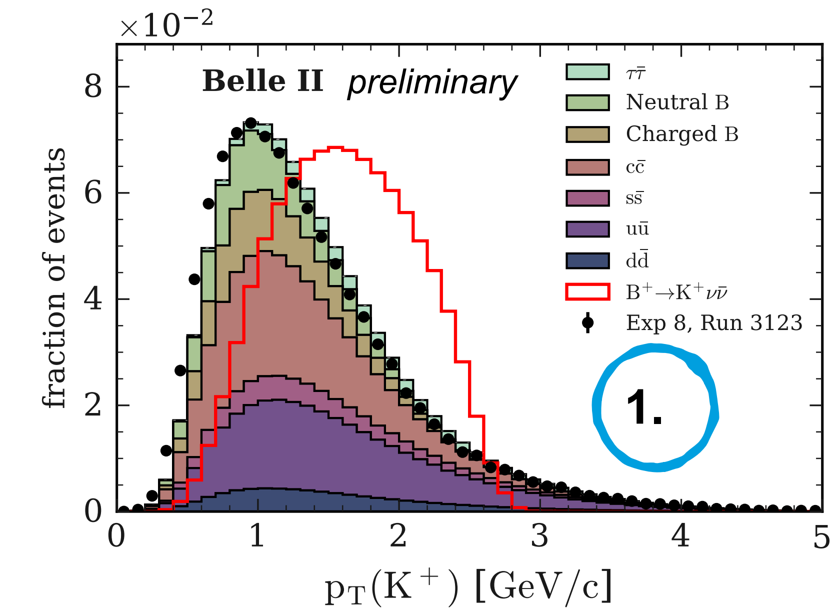
   use event-shape, ROE dynamics, B_{sig} kinematics, v
4. BDT₁ & BDT₂ (consecutive applications)

   ∵ to suppress two different bkgds : BB and contin
5. signal region in 2D (BDT₂ vs. $p_T(K^+)$)
6. check BDT output with $B^+ \to J/\psi K^+$ sampl

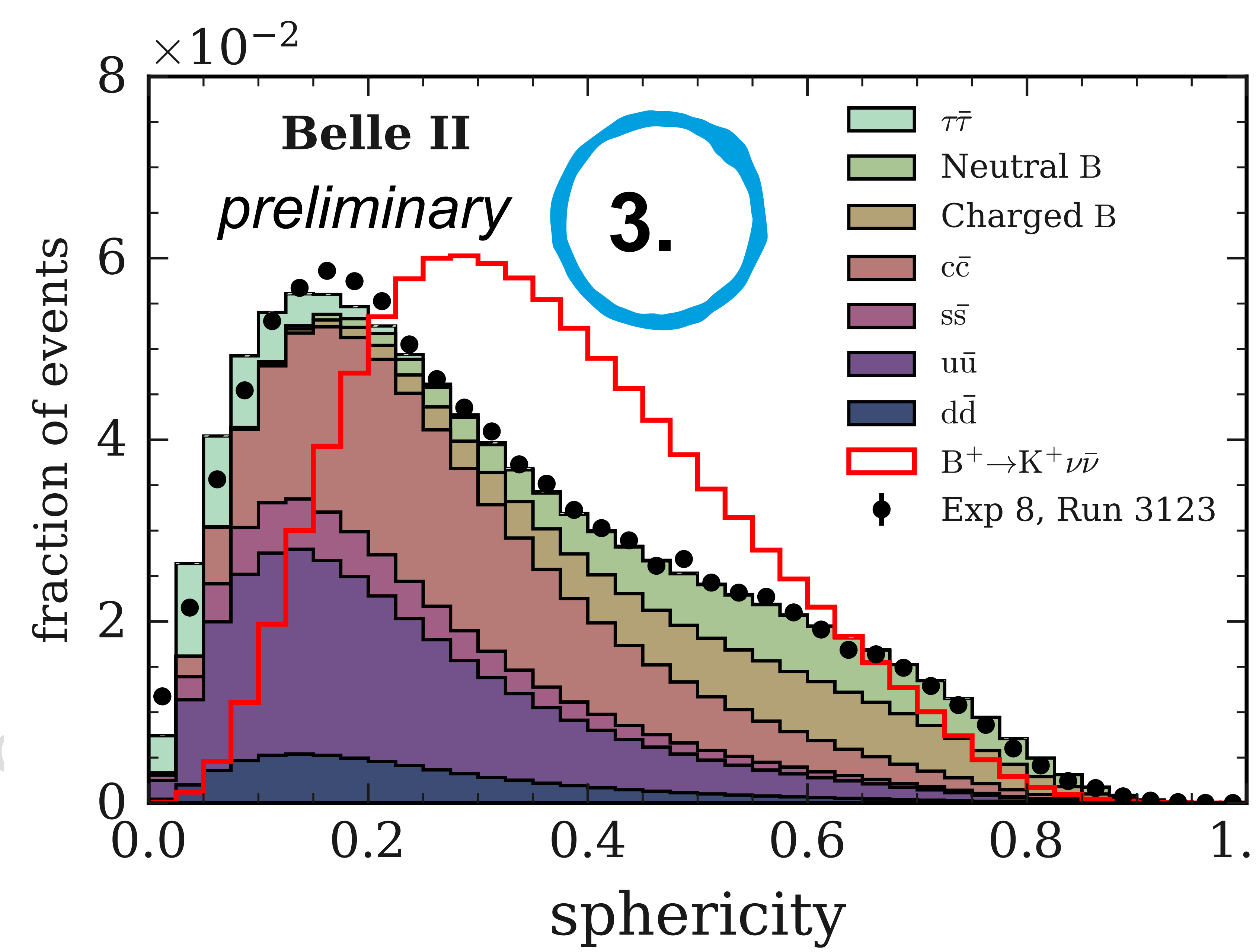
   for both signal and bkgd (see *back-up slide for deta*
7. check Data/MC agreement using Off-resonance data



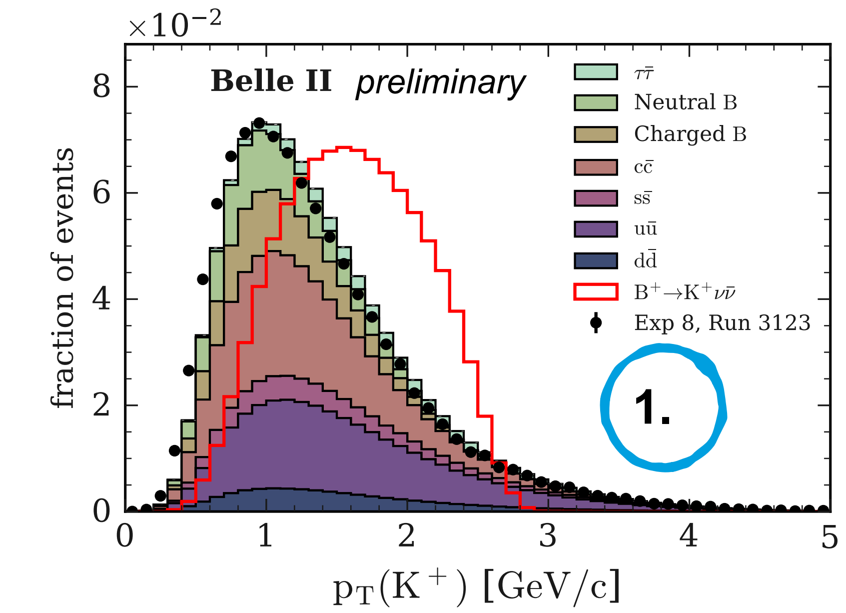
$B^+ \to K^+ \nu\bar{\nu}$ at Belle II



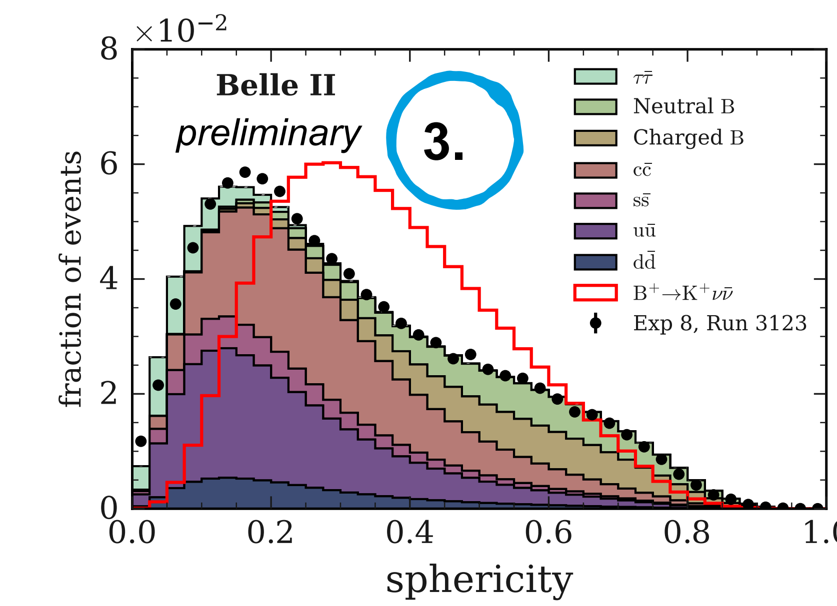
1. signal K^+ — track of highest p_T w/ at least 1 PXD hit ($\varepsilon \sim 80\,\%$)
2. all other tracks & clusters ⇒ "ROE" (rest of the event)
3. BDT for signal discrimination
   use event-shape, ROE dynamics, B_{sig} kinematics, vertexing info.
4. BDT₁ & BDT₂ (consecutive applications)
   ∵ to suppress two different bkgds : BB and continuum
5. signal region in 2D (BDT₂ vs. $p_T(K^+)$)
6. check BDT output with $B^+ \to J/\psi K^+$ samples
   for both signal and bkgd (*see back-up slide for details*)
7. check Data/MC agreement using Off-resonance



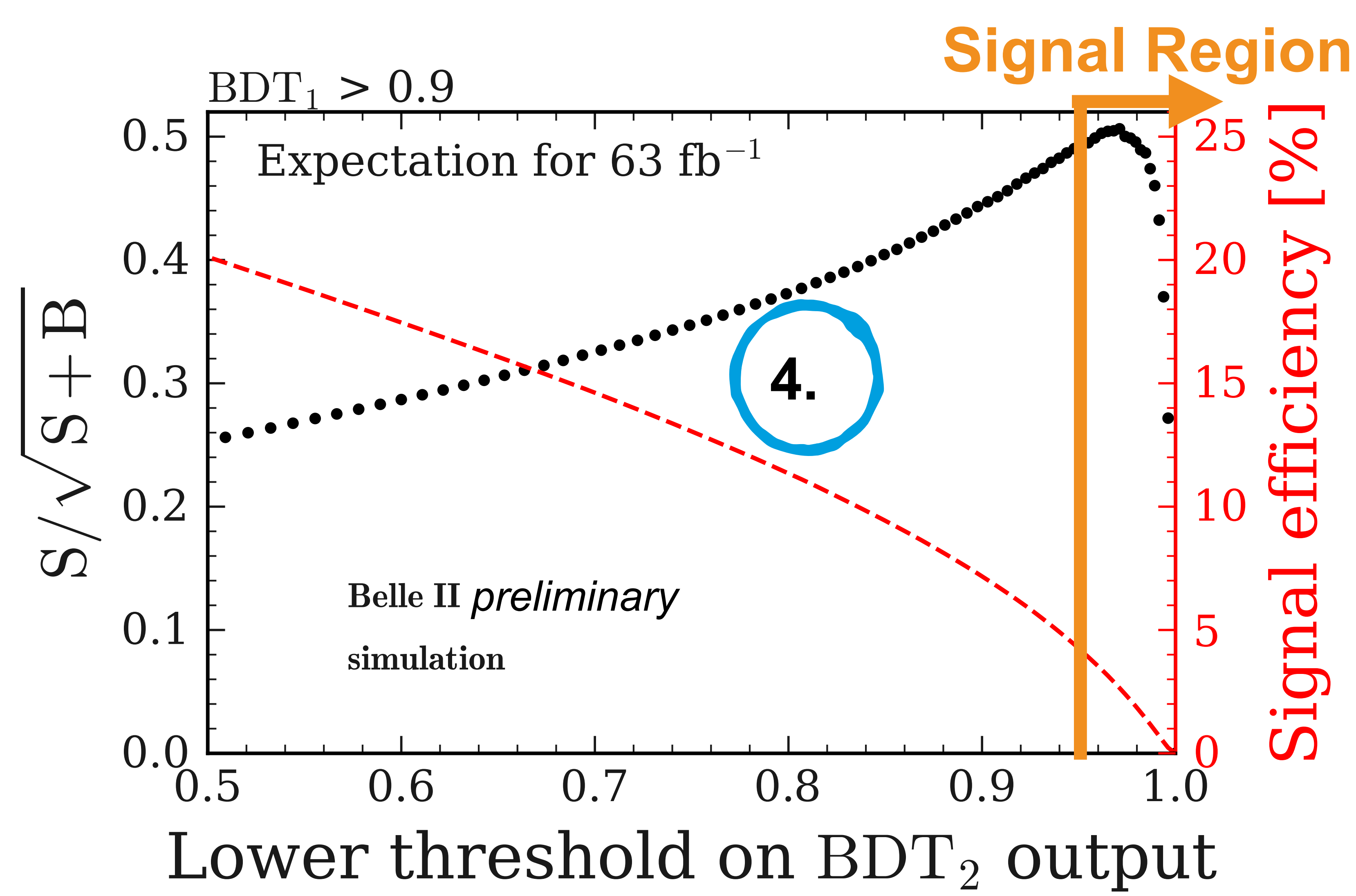
$B^+ \to K^+ \nu \bar{\nu}$ at Belle II



1. signal K^+ — track of highest p_T w/ at least 1 PXD hit ($\varepsilon \sim 80\,\%$)
2. all other tracks & clusters ⇒ "ROE" (rest of the event)
3. BDT for signal discrimination
   use event-shape, ROE dynamics, B_{sig} kinematics, vertexing info.

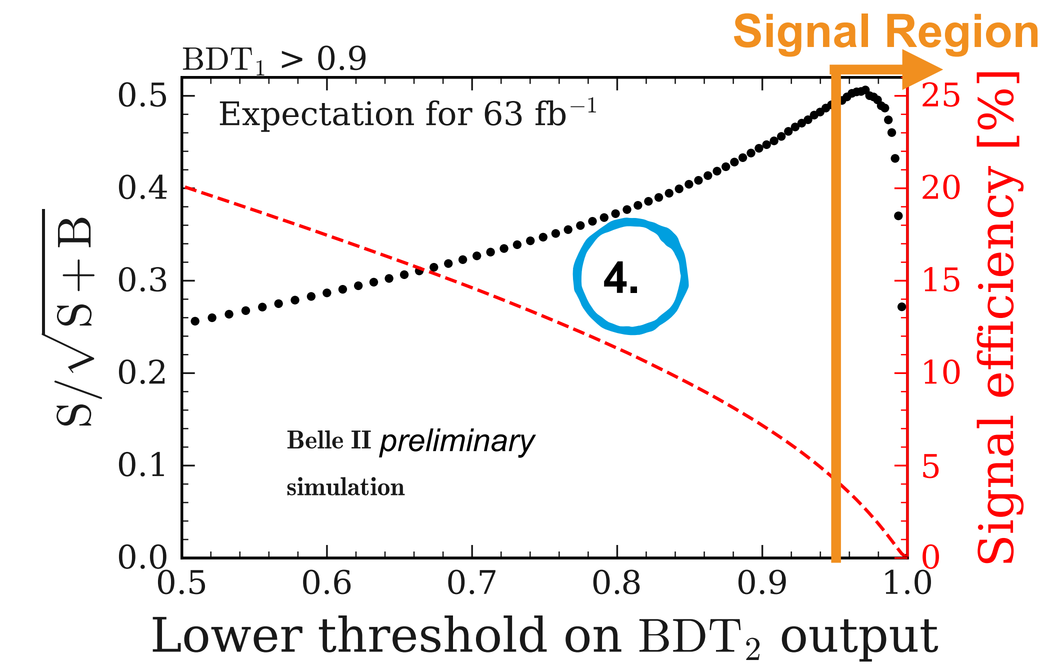


4. BDT_1 & BDT_2 (consecutive applications)
   ∵ to suppress two different bkgds : BB and continuum
5. signal region in 2D (BDT_2 vs. $p_T(K^+)$)
6. check BDT output with $B^+ \to J/\psi K^+$ samples
   for both signal and bkgd (*see back-up slide for details*)
7. check Data/MC agreement using Off-resonance d

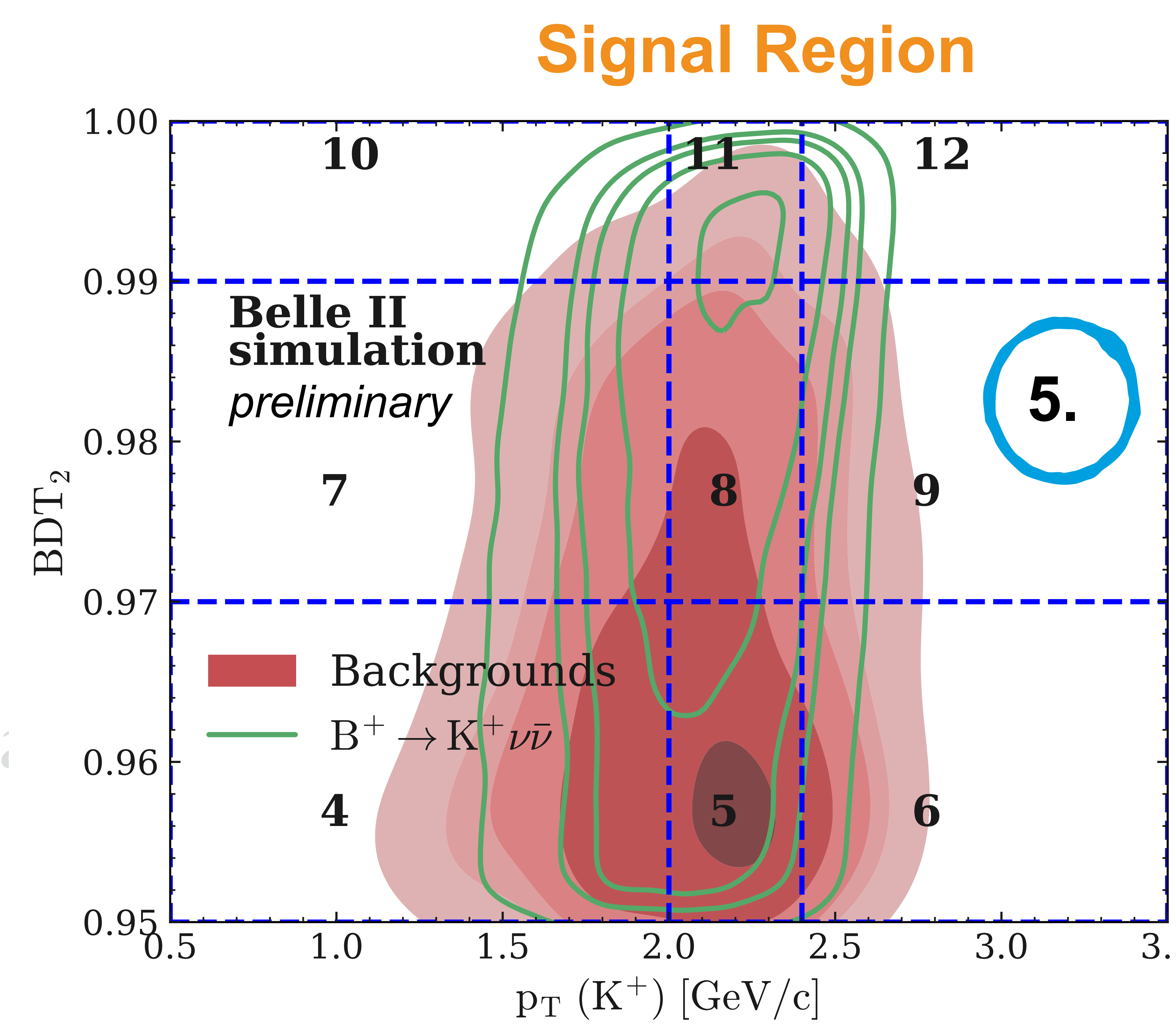


arXiv:2104.12624
submitted to PRL

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



1. signal K^+ — track of highest p_T w/ at least 1 PXD hit ($\varepsilon \sim 80\,\%$)
2. all other tracks & clusters ⇒ “ROE” (rest of the event)
3. BDT for signal discrimination
   use event-shape, ROE dynamics, B_{sig} kinematics, vertexing info.
4. BDT$_1$ & BDT$_2$ (consecutive applications)
   ∵ to suppress two different bkgds : BB and continuum
5. signal region in 2D (BDT$_2$ vs. $p_T(K^+)$)
6. check BDT output with $B^+ \to J/\psi K^+$ samples
   for both signal and bkgd (see *back-up slide for details*)
7. check Data/MC agreement using Off-resonance d



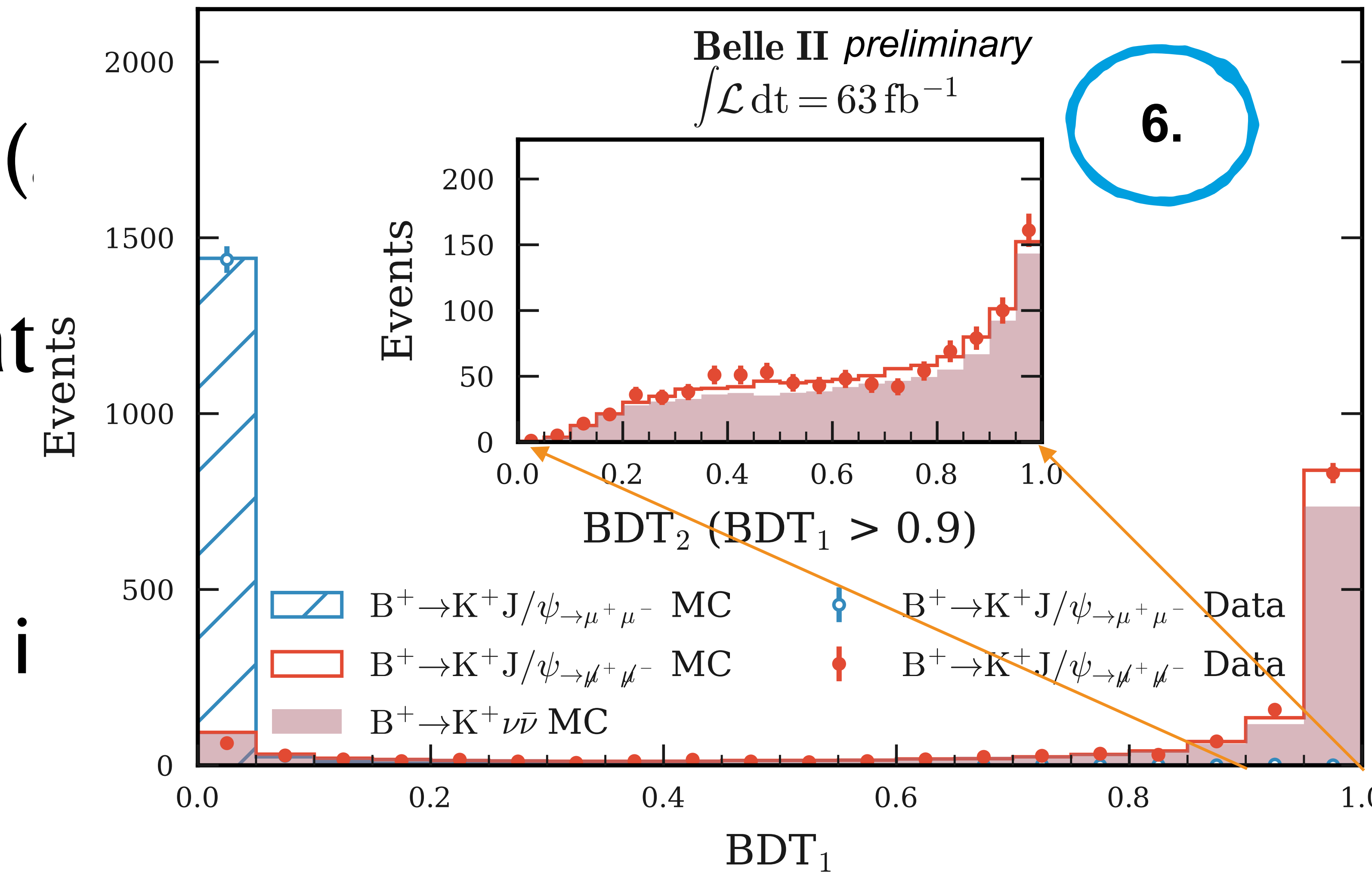
$B^+ \to K^+\nu\bar{\nu}$ at Belle II

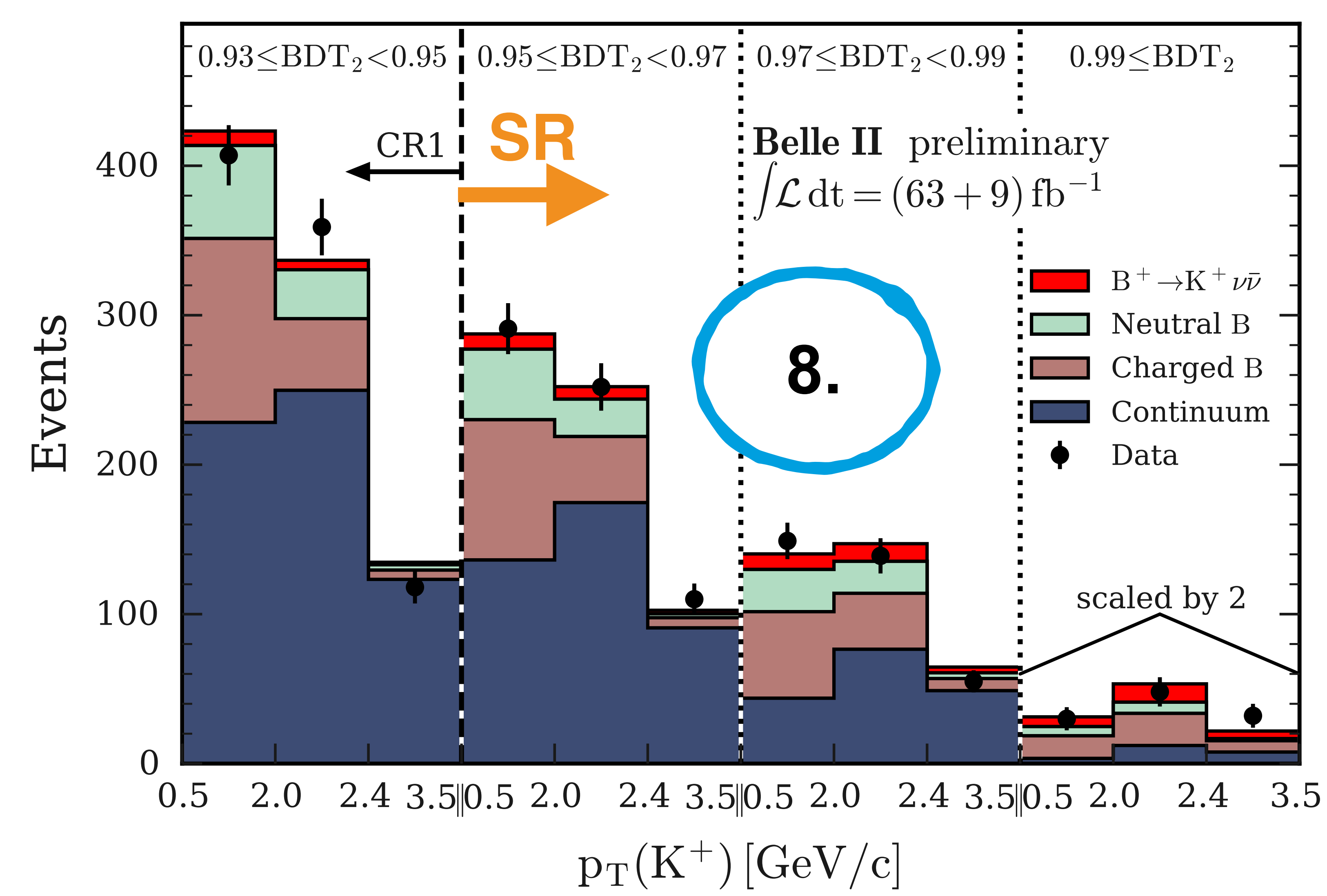
1. signal K^+ — track of highest p_T w/ at least 1 PXD hit (
2. all other tracks & clusters ⇒ "ROE" (rest of the event
3. BDT for signal discrimination

   use event-shape, ROE dynamics, B_{sig} kinematics, vertexing i
4. BDT_1 & BDT_2 (consecutive applications)

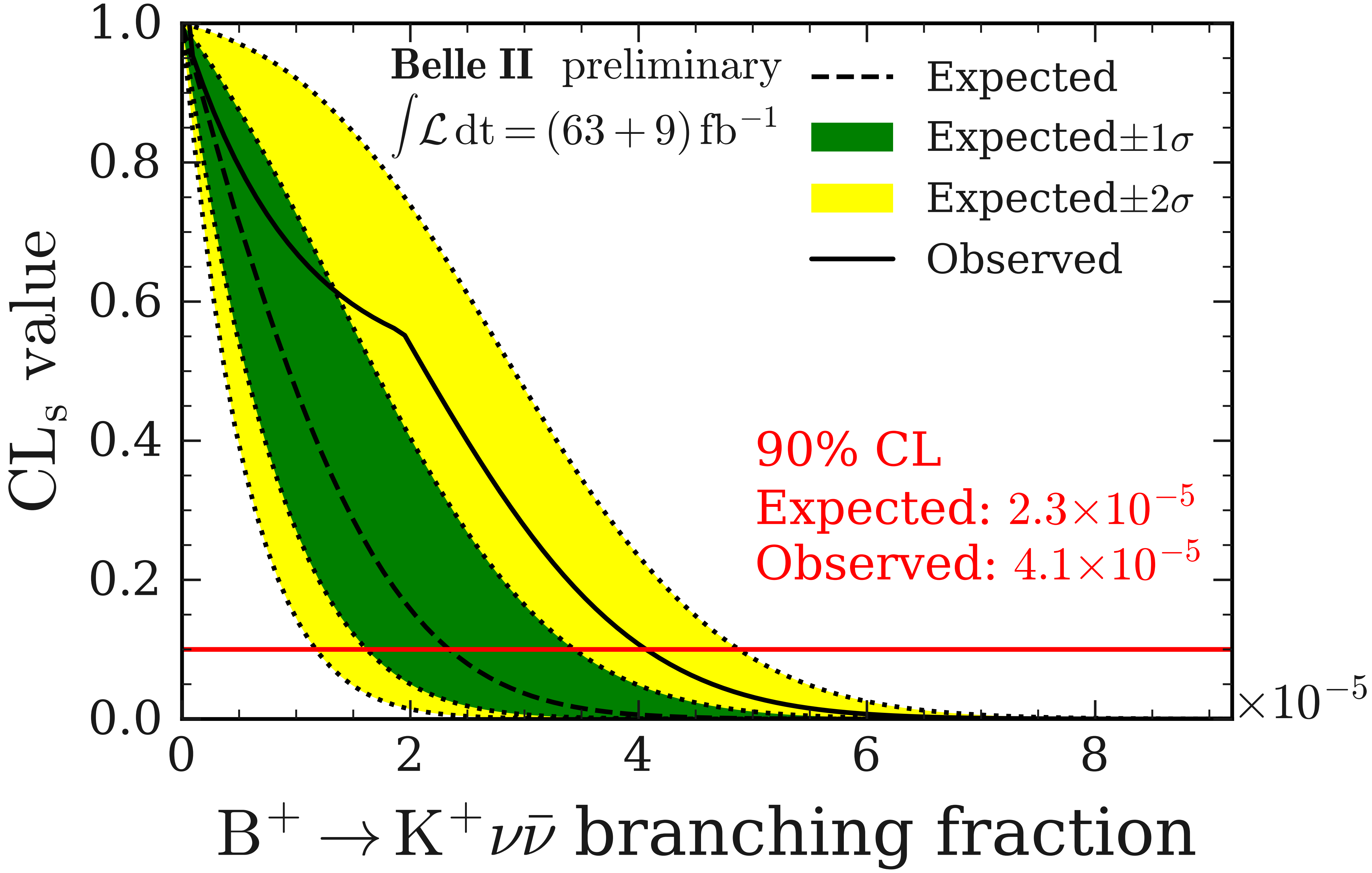
   ∵ to suppress two different bkgds : BB and continuum
5. signal region in 2D (BDT_2 vs. $p_T(K^+)$)
6. check BDT output with $B^+ \to J/\psi K^+$ samples

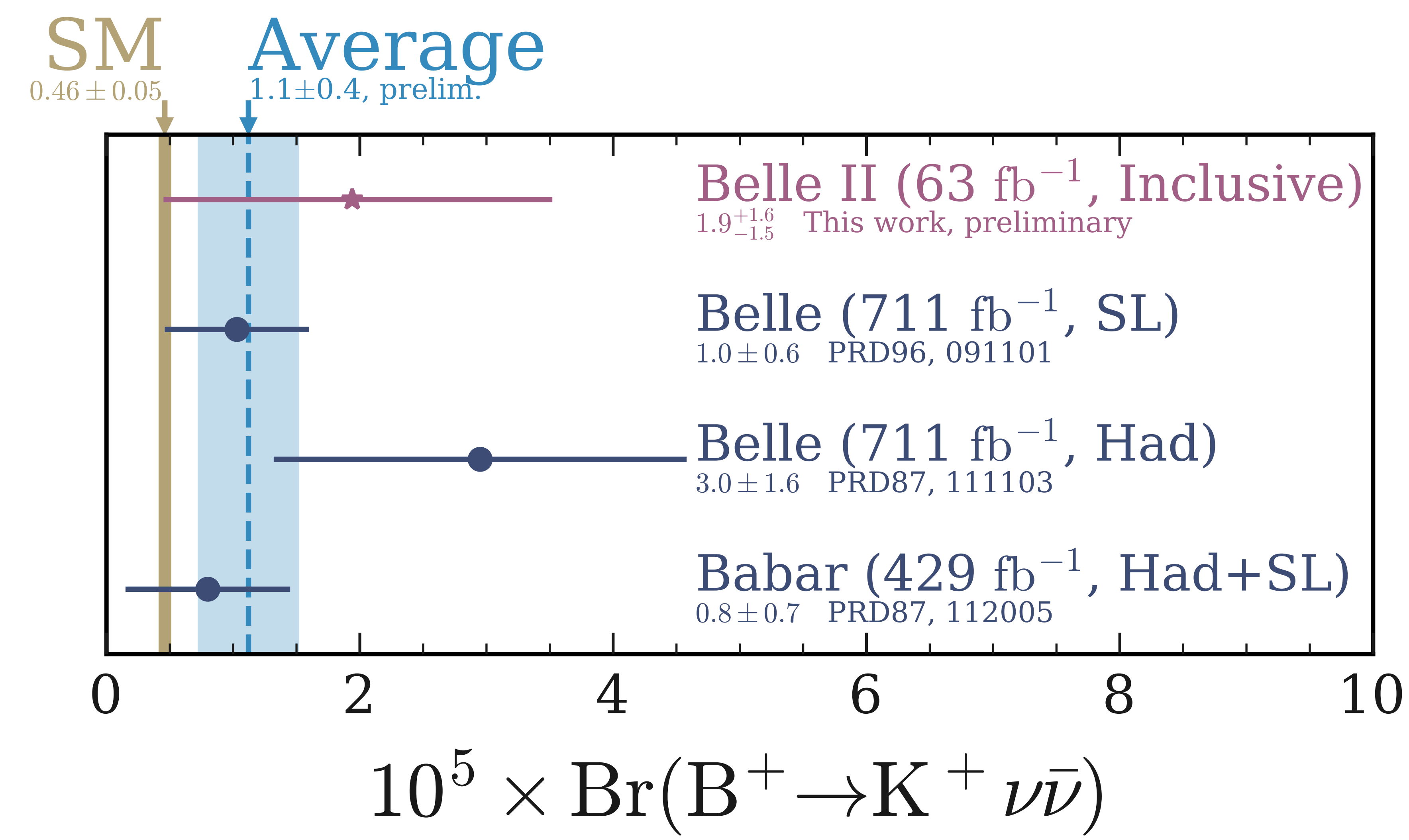
   for both signal and bkgd (*see the paper for details*)
7. Data/MC agreement using OFF-resonance data
8. simultaneous ML fit to ON- & OFF-resonance data





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





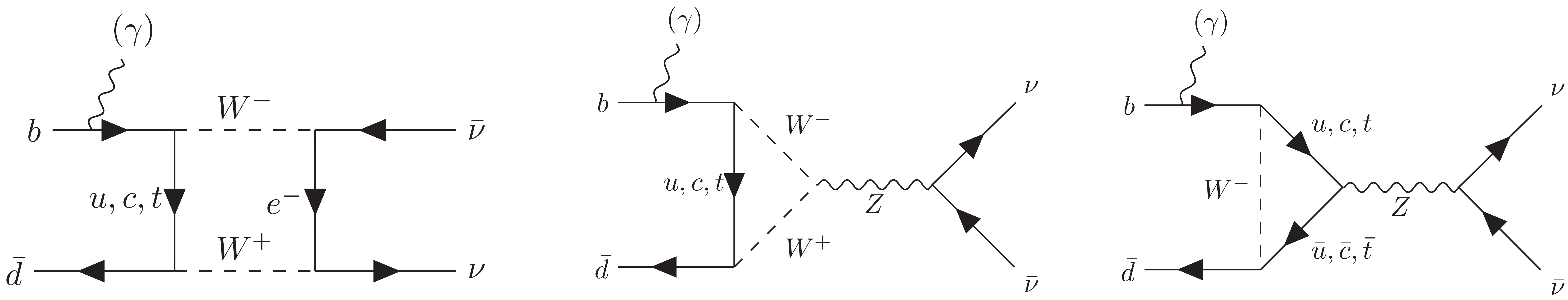
$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = (1.9^{+1.3+0.8}_{-1.3-0.7}) \times 10^{-5}$$

$$< 4.1 \times 10^{-5} \quad \text{@ 90\% CL}$$

PRD 102, 012003 (2020)

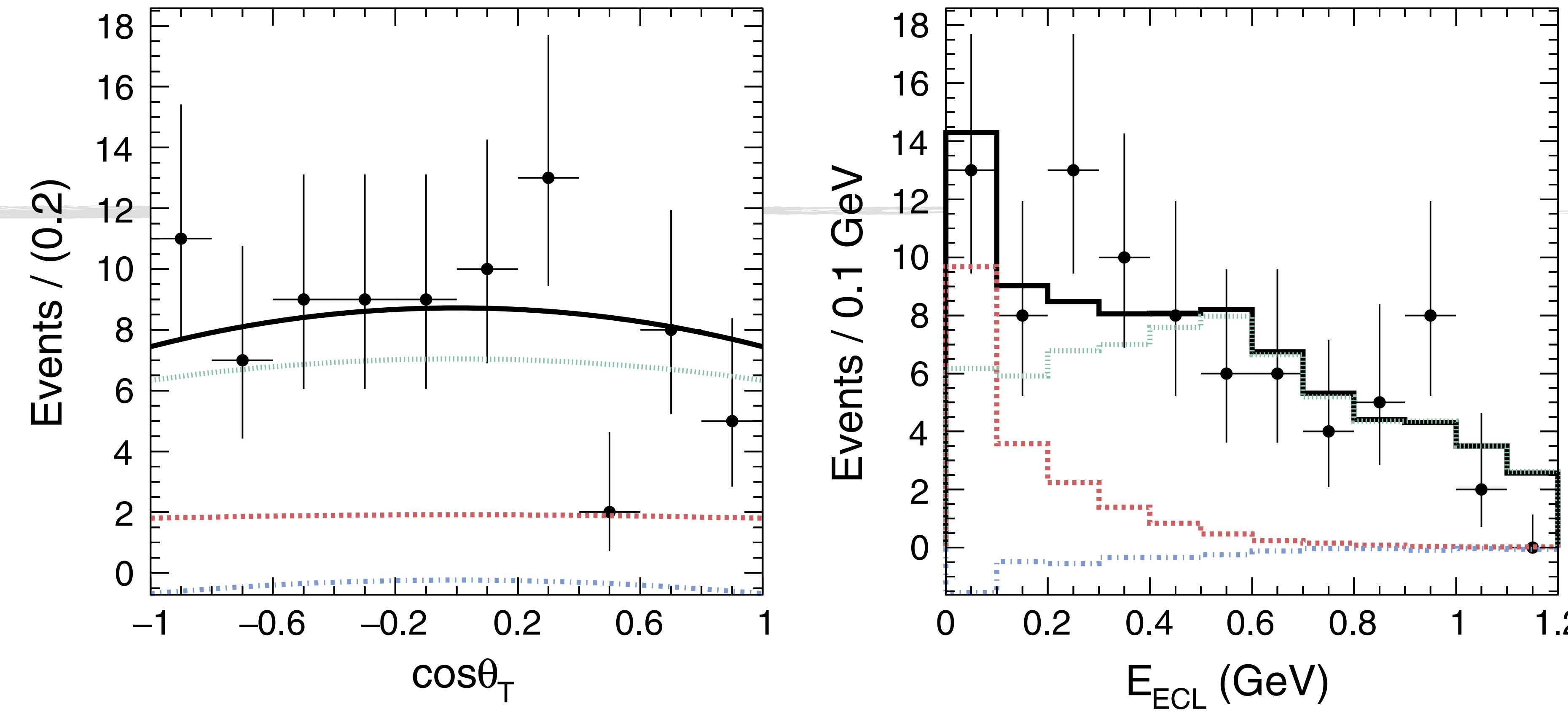
$B^0 \to$ *invisible* $(+\gamma)$

- In the SM
  - $\mathscr{B}(B^0 \to \nu\bar{\nu}) \sim 10^{-25}$, $\mathscr{B}(B^0 \to \nu\bar{\nu}\nu\bar{\nu}) \sim 10^{-16}$, $\mathscr{B}(B^0 \to \gamma\nu\bar{\nu}) \sim 10^{-9}$
- sensitive to new physics BSM, e.g.
  - R-parity-violating models
  - dark matter contributions
  - some models predict $\mathscr{B} \lesssim \mathscr{O}(10^{-6} - 10^{-7})$



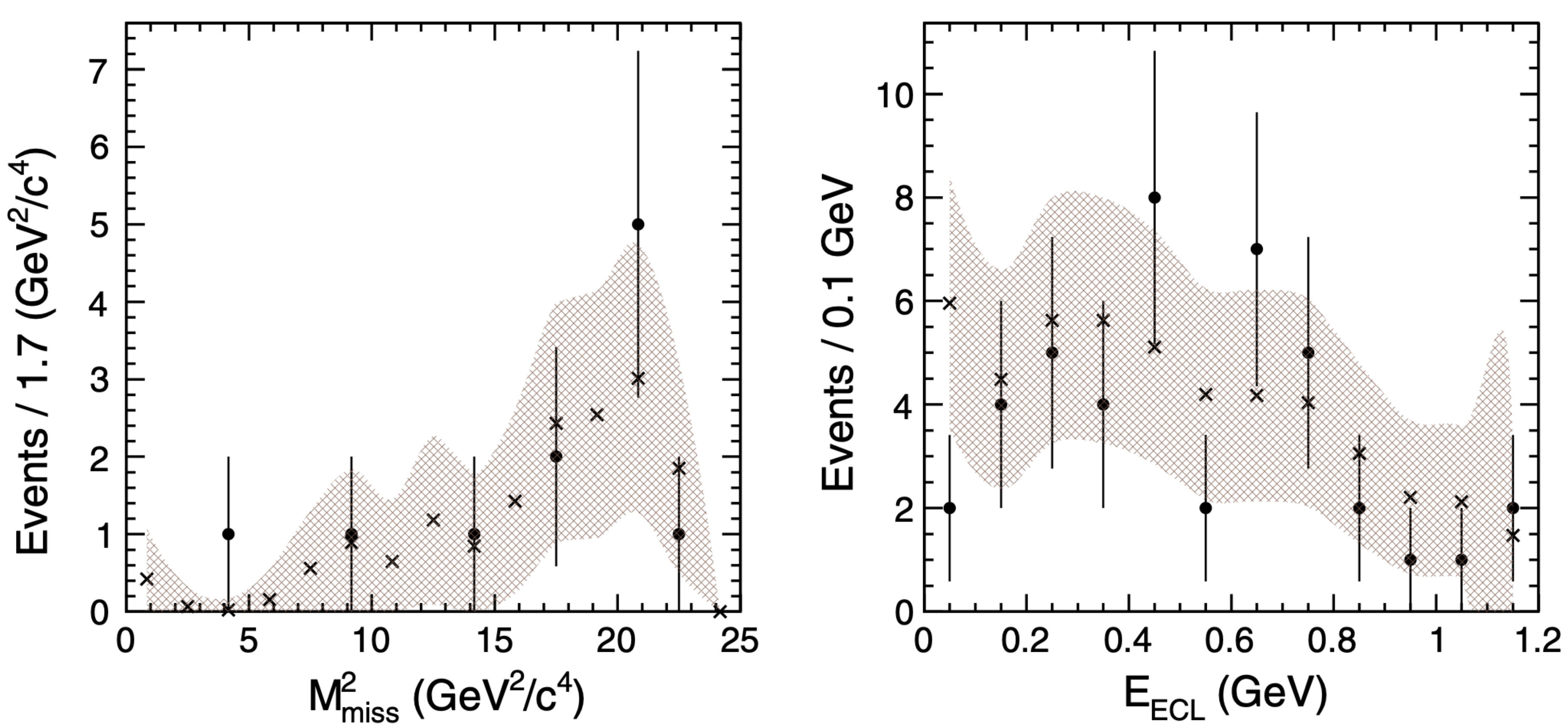
$B^0 \to invisible\ (+\gamma)$

- $B^0 \to \text{inv. signal extraction}$
  - by 2D fit to $(E_{\mathrm{ECL}},\ \cos\theta_T)$
  - $N_{\mathrm{sig}} = 18.8^{+15.3}_{-14.5}$



$\mathscr{B}(B^0 \to \text{invisible}) < 7.8 \times 10^{-5}$ @ 90% CL

- $B^0 \to \text{inv.} + \gamma$ signal extraction
  - counting in E_{ECL} with bkgd. subtraction
  - study M^2_{miss} for bkgd. evaluation using control mode, $B^0 \to D^- \ell^+ \nu$



$\mathscr{B}(B^0 \to \text{invisible} + \gamma) < 1.6 \times 10^{-5}$ @ 90% CL

LFV, LNV & BNV searches in τ decays

$\tau^- \to \mu^- \gamma$ $\tau^- \to e^- \gamma$

preliminary, to be submitted to JHEP

PRD 102, 111101 (2020)

$\tau^- \to \bar{p} e^+ e^-$

$\tau^- \to p e^- e^-$

$\tau^- \to \bar{p} e^+ \mu^-$

$\tau^- \to \bar{p} e^- \mu^+$

$\tau^- \to p \mu^- \mu^-$

$\tau^- \to \bar{p} \mu^- \mu^+$

New physics (NP) search with τ

- the τ lepton
  - the heaviest charged lepton
  - highly sensitive to NP
- Unique lab to look for NP
  - **LFV**
  - EDM, g-2, CPV
  - B (D) decays to τ
  - BNV, too $(m_\tau > m_\Lambda, m_p, ...)$

	electron	muon	tau
	e	μ	τ
Gen.	I	II	III
Mass [MeV]	0.511	106	1780
Life	∞	2.20μs	0.291ps

Lepton-flavor-violating (LFV) τ decay

- In the Standard Model with non-zero ν mass, τ LFV can happen, but the rate is really tiny.

$$\mathcal{B}(\tau \to l\gamma) = \frac{3\alpha}{32\pi} \left| \sum_i U^*_{\tau i} U_{\mu i} \frac{\triangle^2_{3i}}{m^2_W} \right|^2 \leq 10^{-53} \sim 10^{-49}$$

- However, in many new physics models it can become large enough to be within sensitivity of Belle (or Belle-II)

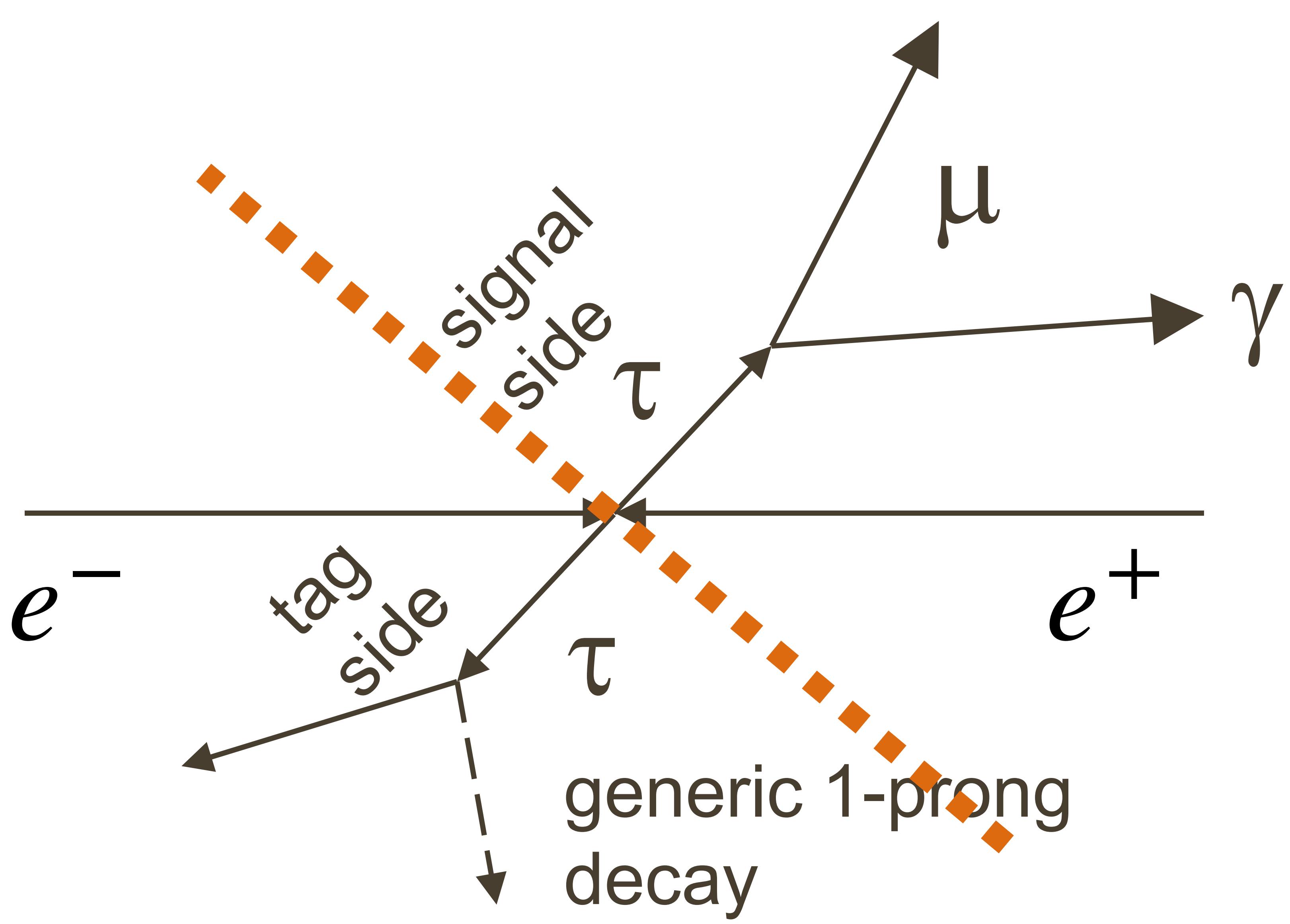
  - For example, with SUSY-GUT,

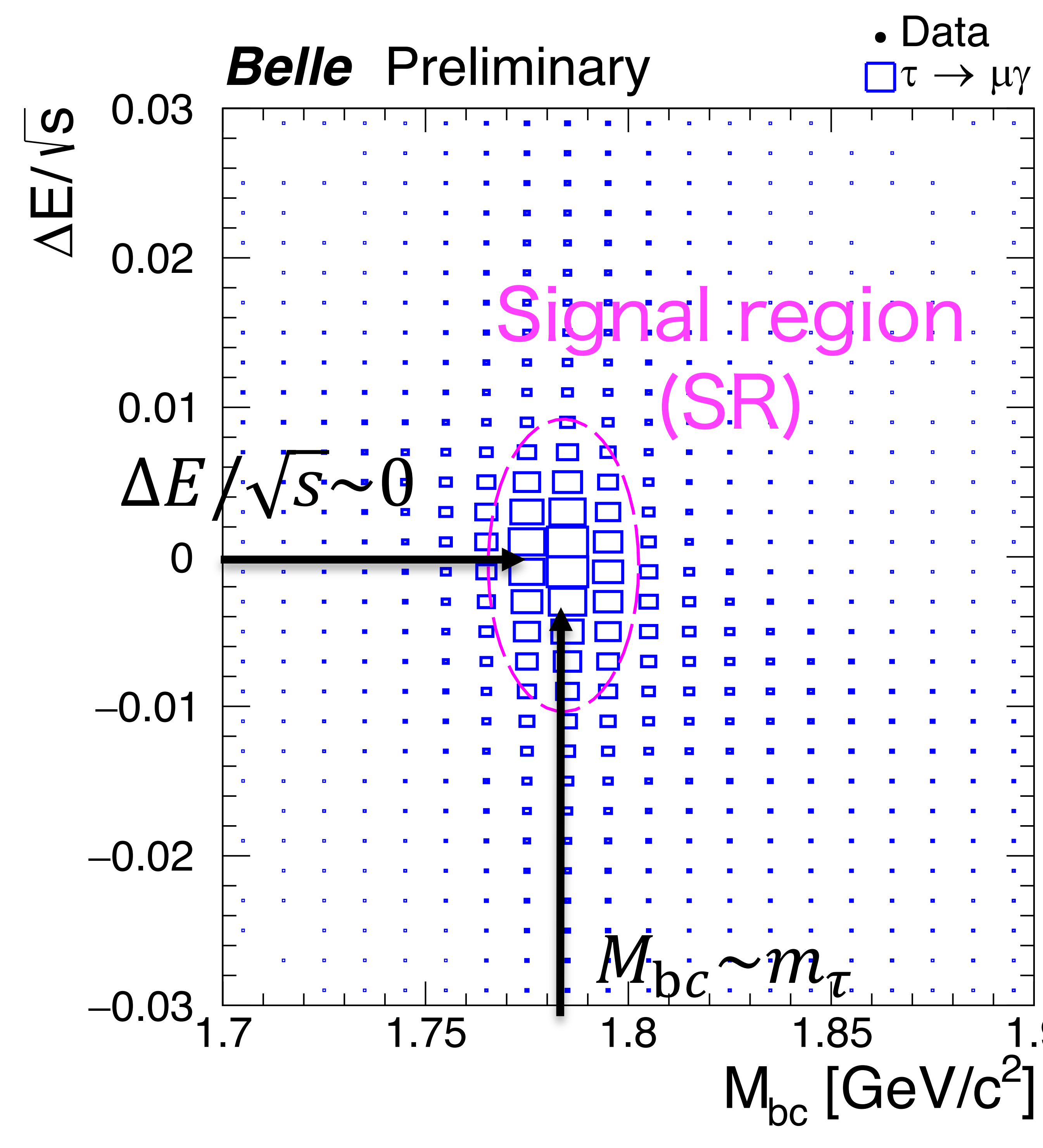
Calibbi et al., PRD 74, 116002 (2006)

$$\mathcal{B}(\tau \to \mu\gamma) \simeq (4.5 \times 10^{-6}) |(\delta_{LL})_{32}|^2 \left(\frac{500 \text{ GeV}}{m_{\text{SUSY}}}\right)^4 \left(\frac{\tan\beta}{10}\right)^2$$

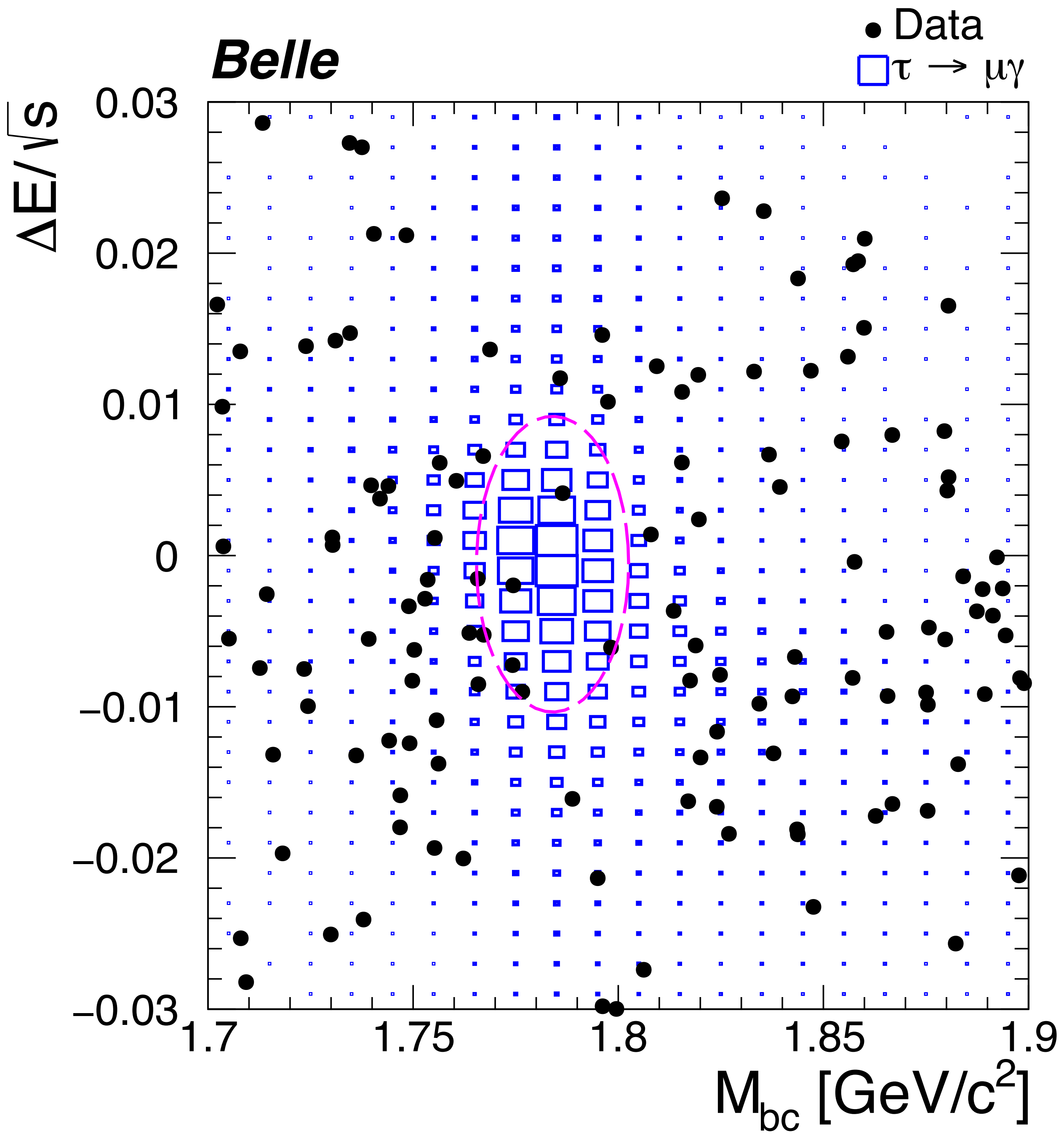
Search for $\tau^+ \to \ell^+\gamma$

- $\sigma(e^+e^- \to \tau^+\tau^-) = (0.919 \pm 0.003)$ nb $\approx \sigma_{b\bar{b}}$, at $\sqrt{s} \approx 10.58$ GeV
  $\therefore e^+e^-$ B-factory is, at the same time, a τ-factory, too!
- tag-side and signal-side τ decays are cleanly separated
- signal extraction by $M_{\rm bc}$ and $\Delta E/\sqrt{s}$

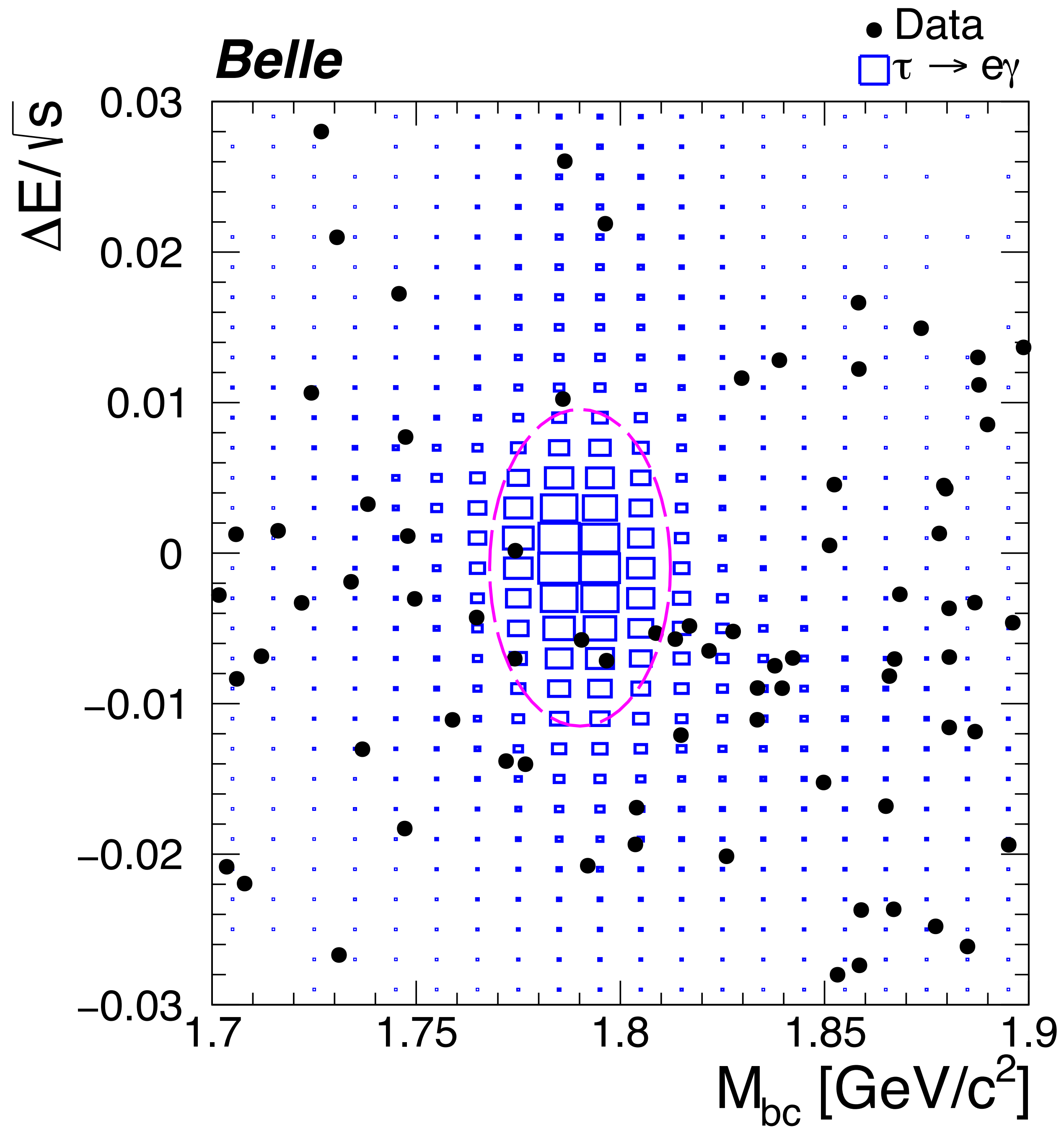




Search for $\tau^+ \to \ell^+\gamma$



(a) $\tau^\pm \to \mu^\pm\gamma$



(b) $\tau^\pm \to e^\pm\gamma$

- use $\int \mathcal{L} dt = 988\ \mathrm{fb}^{-1}$ Belle data $\Rightarrow N_{\tau\tau} = 912 \times 10^6$

$$\mathcal{B}(\tau^\pm \to \mu^\pm\gamma) < \frac{\tilde{s}_{90}}{2\epsilon N_{\tau\tau}} = 4.2 \times 10^{-8}$$

$$\mathcal{B}(\tau^\pm \to e^\pm\gamma) < \frac{\tilde{s}_{90}}{2\epsilon N_{\tau\tau}} = 5.6 \times 10^{-8}$$

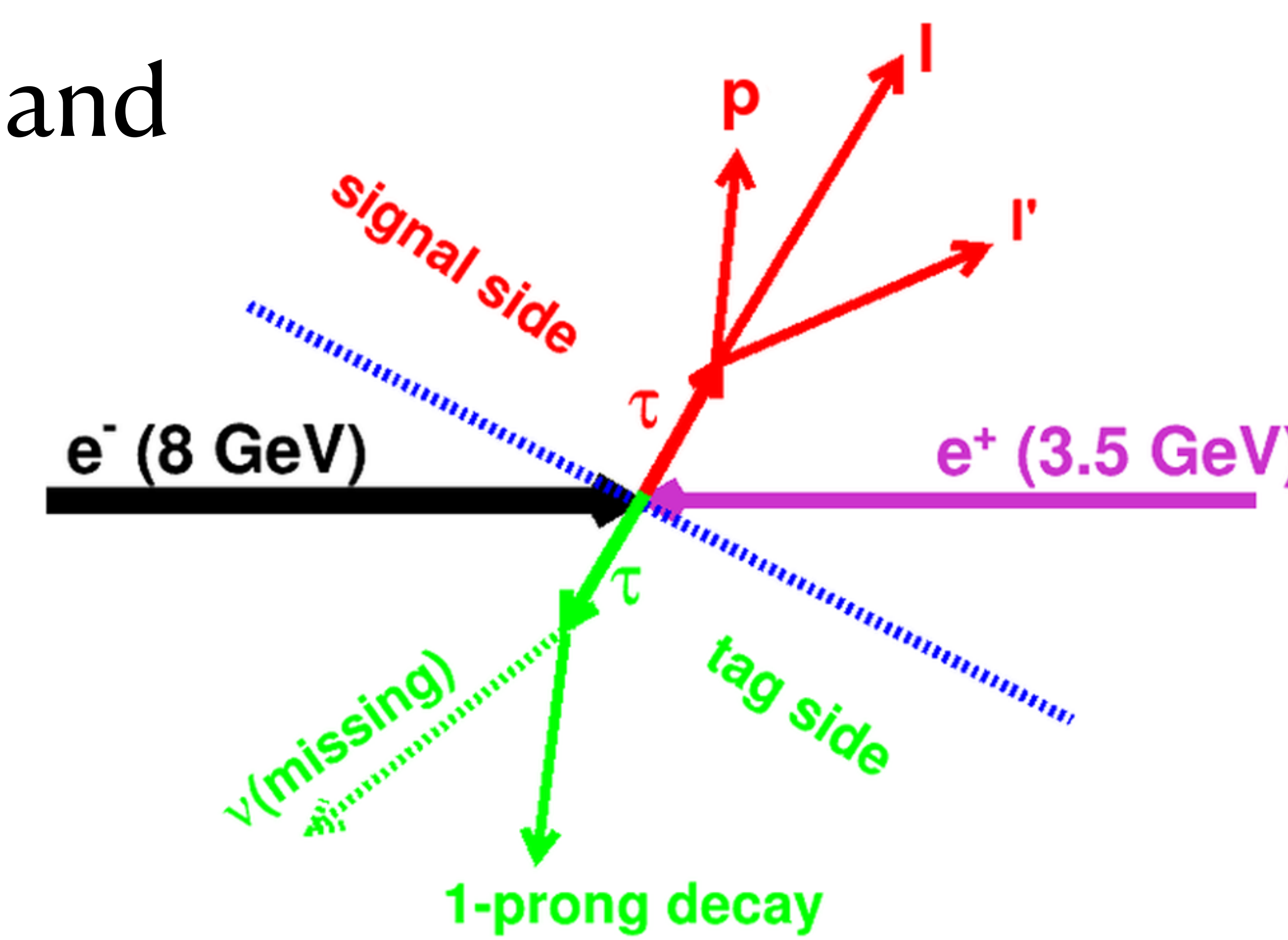
UL (90% CL)	Luminosity	Reference	$\tau \to \mu\gamma$	$\tau \to e\gamma$
Belle	535 fb^{-1}	PLB 666, 16 (2008)	4.5×10^{-8}	12.0×10^{-8}
BaBar	515 fb^{-1}	PRL 104, 021802 (2010)	4.4×10^{-8}	3.3×10^{-8}

τ LNV, BNV search — motivations

- Baryogenesis of our Universe has been unknown
- Lepton #, Baryon # — accidental symmetries of SM
- Baryon number violation — a crucial element of baryogenesis
- Signals of LNV, BNV could be a clear signal of BSM
- Selection rules : $|\Delta(B-L)| = 0$ or 2
  - $\Delta B = \Delta L = 0$ for standard β-decay
  - $\Delta B = \Delta L = \pm 1$
  - $\Delta B = -\Delta L = 1$, e.g. p decay
  - $\Delta B = 2$ ($n\bar{n}$ oscil.) or $\Delta L = 2$ ($0\nu 2\beta$), etc.

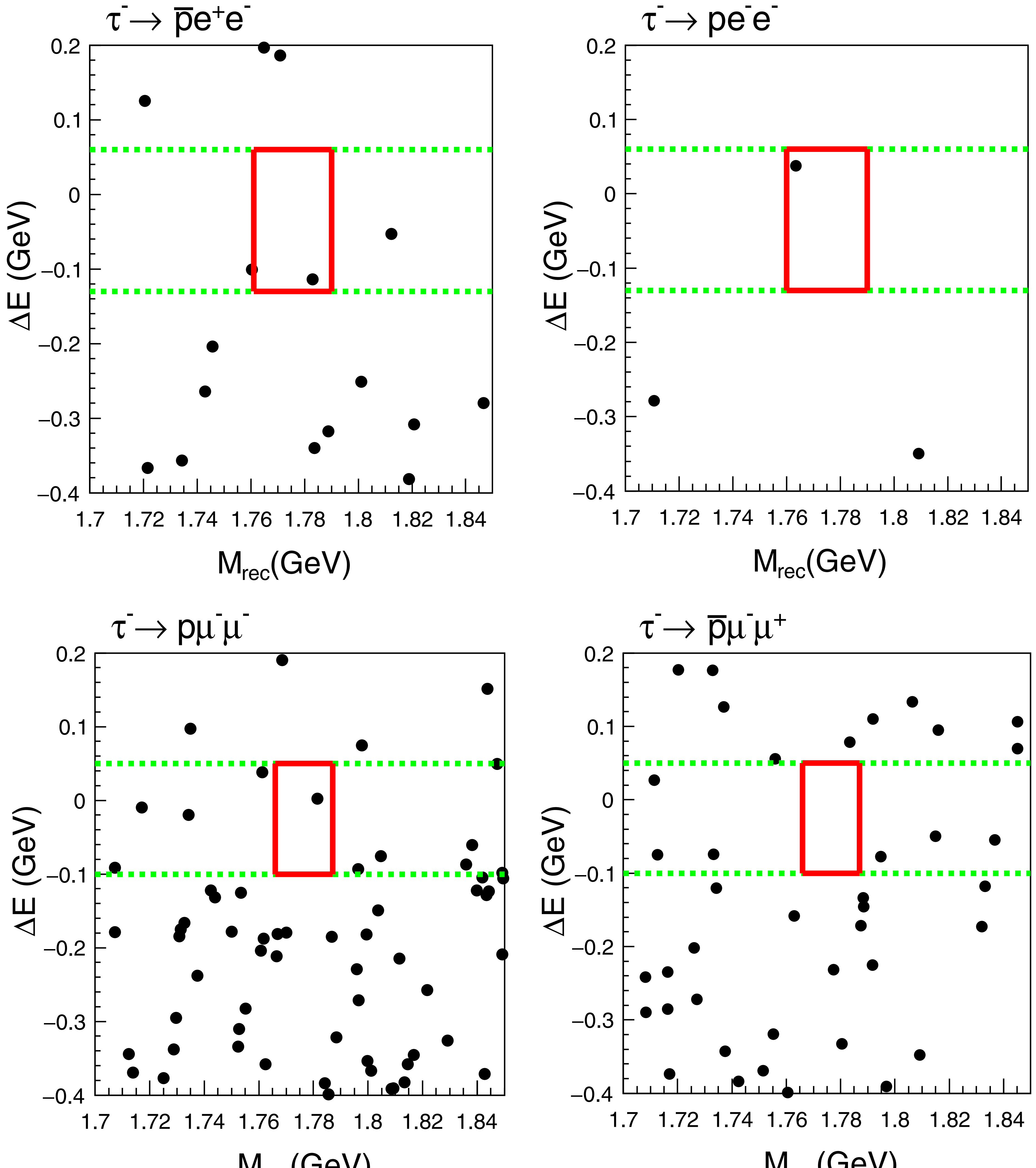
τ LNV, BNV search at Belle

- We search for various LNV, BNV τ decays
- $\exists$ LHCb limits for $\tau^- \to \bar{p}\mu^+\mu^-, p\mu^-\mu^- : \mathscr{B} < \mathcal{O}(10^{-7})$
- Theory calculations using p lifetime bound: $\mathscr{B} \lesssim 10^{-30} - 10^{-48}$
- Search using full $\Upsilon(4S)$ (**on**- and **off**-resonance) and $\Upsilon(5S)$ data from Belle



τ LNV, BNV

- Signal yield in $(M_{rec}, \Delta E)$



Channel	$\epsilon(\%)$	N_{bkg}	N_{obs}	N_{sig}^{UL}	$\mathcal{B}(\times 10^{-8})$
$\tau^- \to \bar{p}e^+e^-$	7.8	0.50 ± 0.35	1	3.9	< 3.0
$\tau^- \to pe^-e^-$	8.0	0.23 ± 0.07	1	4.1	< 3.0
$\tau^- \to \bar{p}e^+\mu^-$	6.5	0.22 ± 0.06	0	2.2	< 2.0
$\tau^- \to \bar{p}e^-\mu^+$	6.9	0.40 ± 0.28	0	2.1	< 1.8
$\tau^- \to p\mu^-\mu^-$	4.6	1.30 ± 0.46	1	3.1	< 4.0
$\tau^- \to \bar{p}\mu^-\mu^+$	5.0	1.14 ± 0.43	0	1.5	< 1.8

- an order-of-mag. improvement from LHCb in $p\mu^-\mu^-, \bar{p}\mu^+\mu^-$
- first limits in the other four modes

Epilogue

- Ever since the *B*-factories (Belle & BaBar) started taking data in 1999, we have learned a lot, e.g. CP violations in *B* systems and confirmation of CKM mechanism, discoveries of many rare decays, and many exotic hadrons.
- But we have not found answers to fundamental questions of 'flavor' in the SM. Moreover, we are most sure that SM is not a complete description of the Nature, and we definitely need New Physics beyond the SM.
- In this talk, we went through a few examples of such on-going efforts, searching for LFV, LNV, and LUV with Belle (II).

"*There must be something in the flavors. We just don't know where we can find it and what its scale is.*"*

"We shall not cease from exploration"†

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* In a private conversation with Tao Han

† T. S. Eliot

Thank you!