Views beyond the SM from Belle (II)

on flavor anomalies and other related subjects

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(네가) 뭘 좋아할지 몰라
다 넣어봤어

I didn't know what you'd like, so I put them all in!

Belle II Physics Mind-map

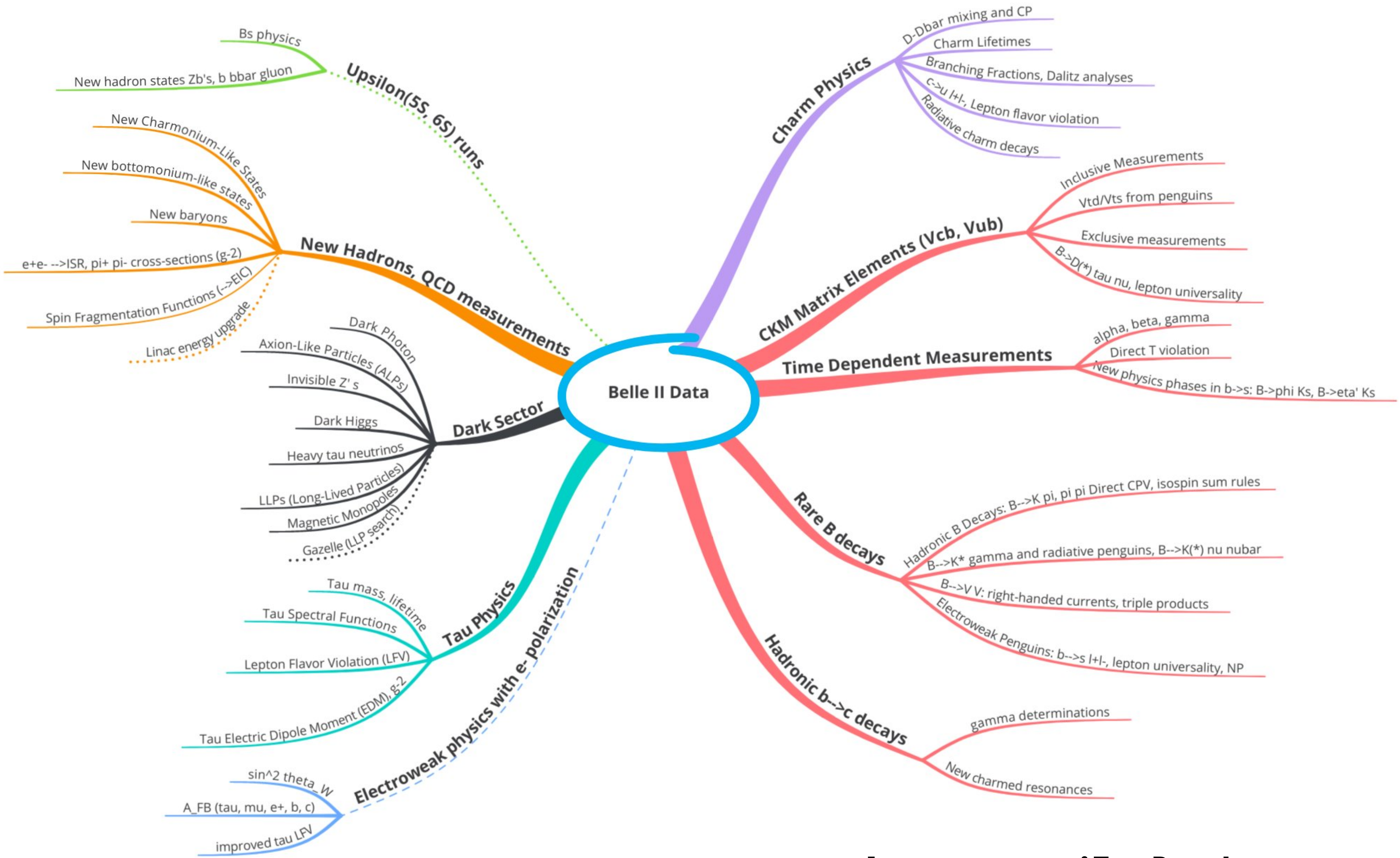


Image courtesy of Tom Browder

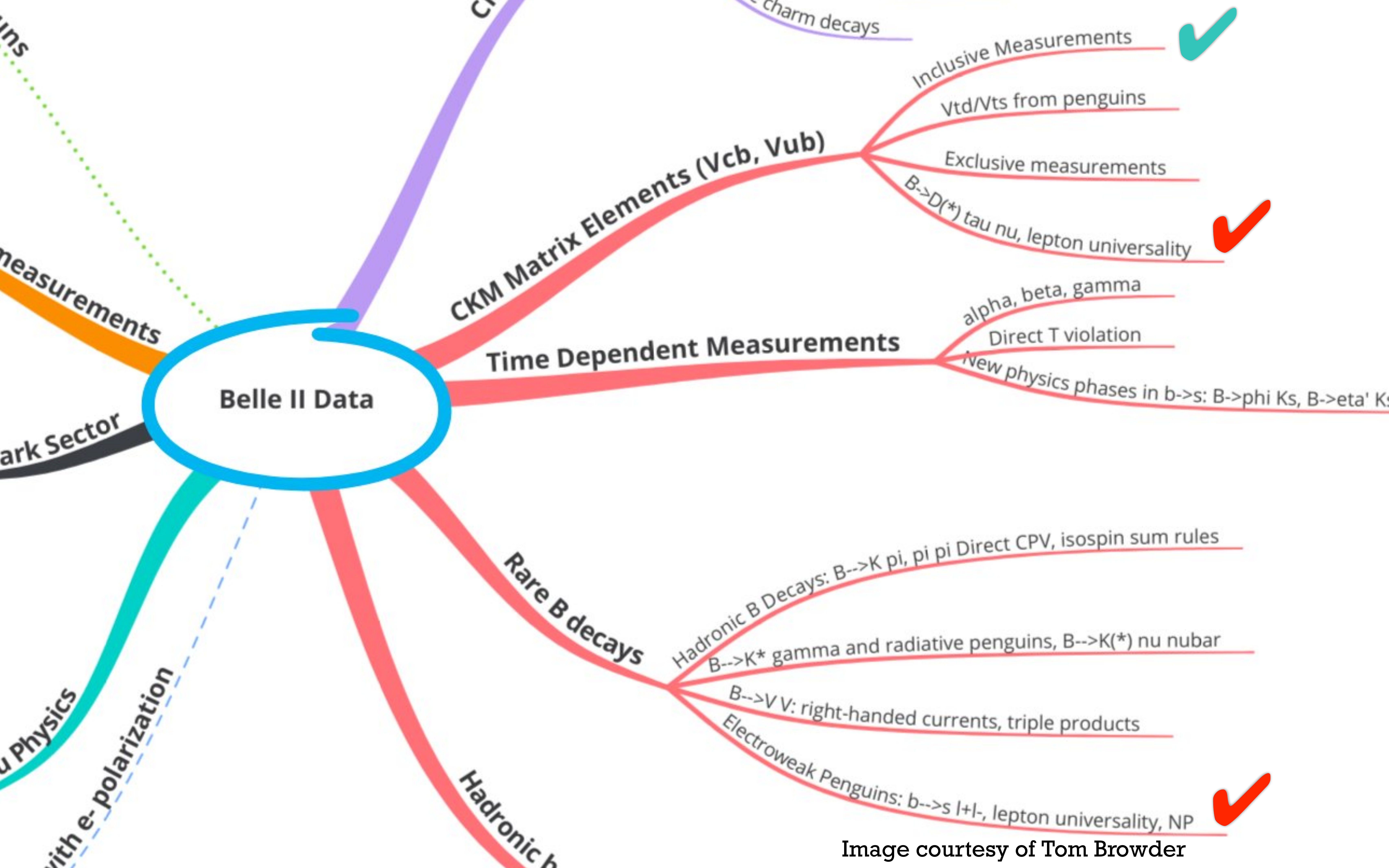


Image courtesy of Tom Browder

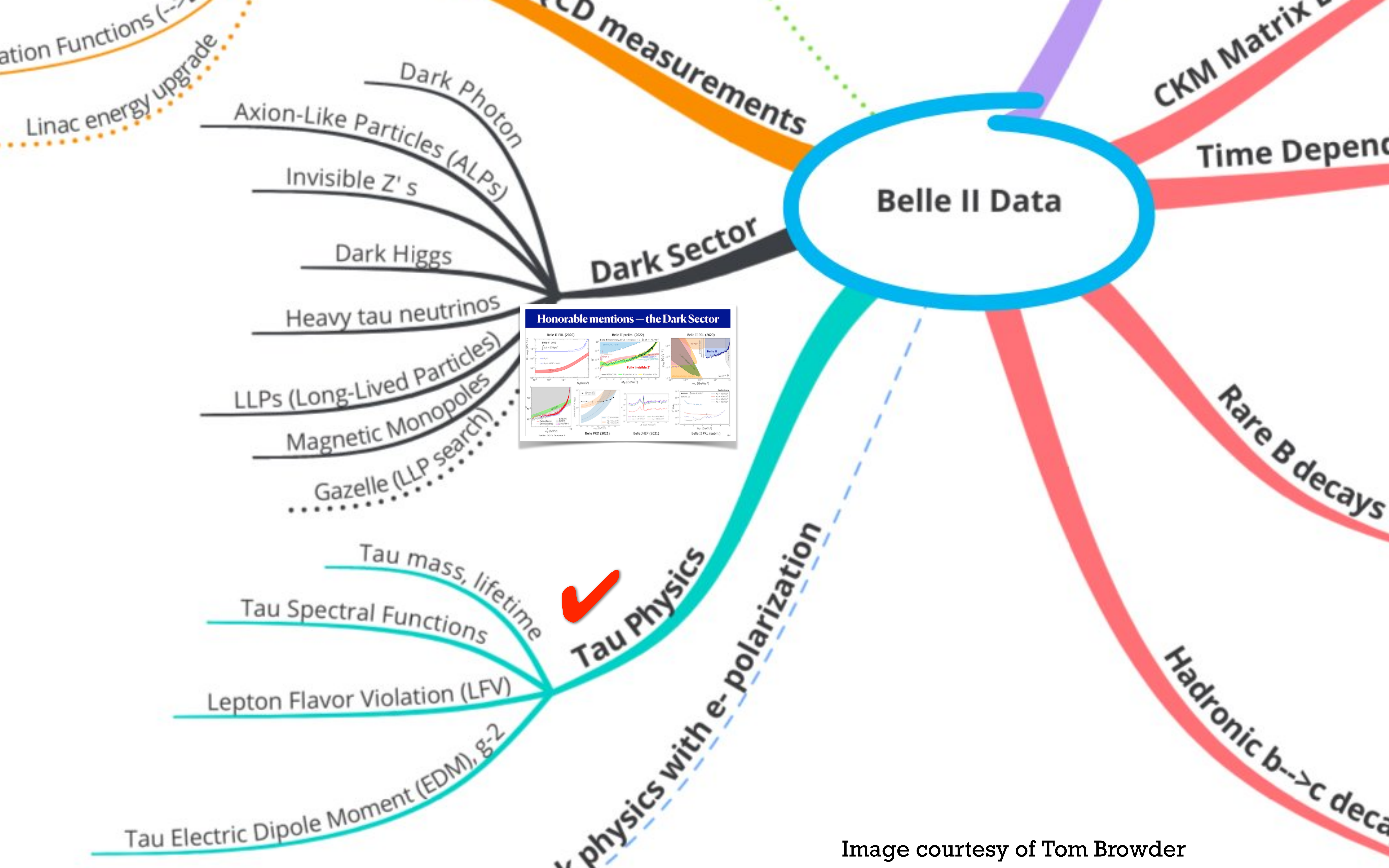


Image courtesy of Tom Browder

Overview

- Intro.
  - Belle & Belle II
- flavor anomalies in EWP B
- τ results from Belle, Belle II
- anomaly, tension in semileptonic B
- *closing, just with a short quote*

Belle & Belle II

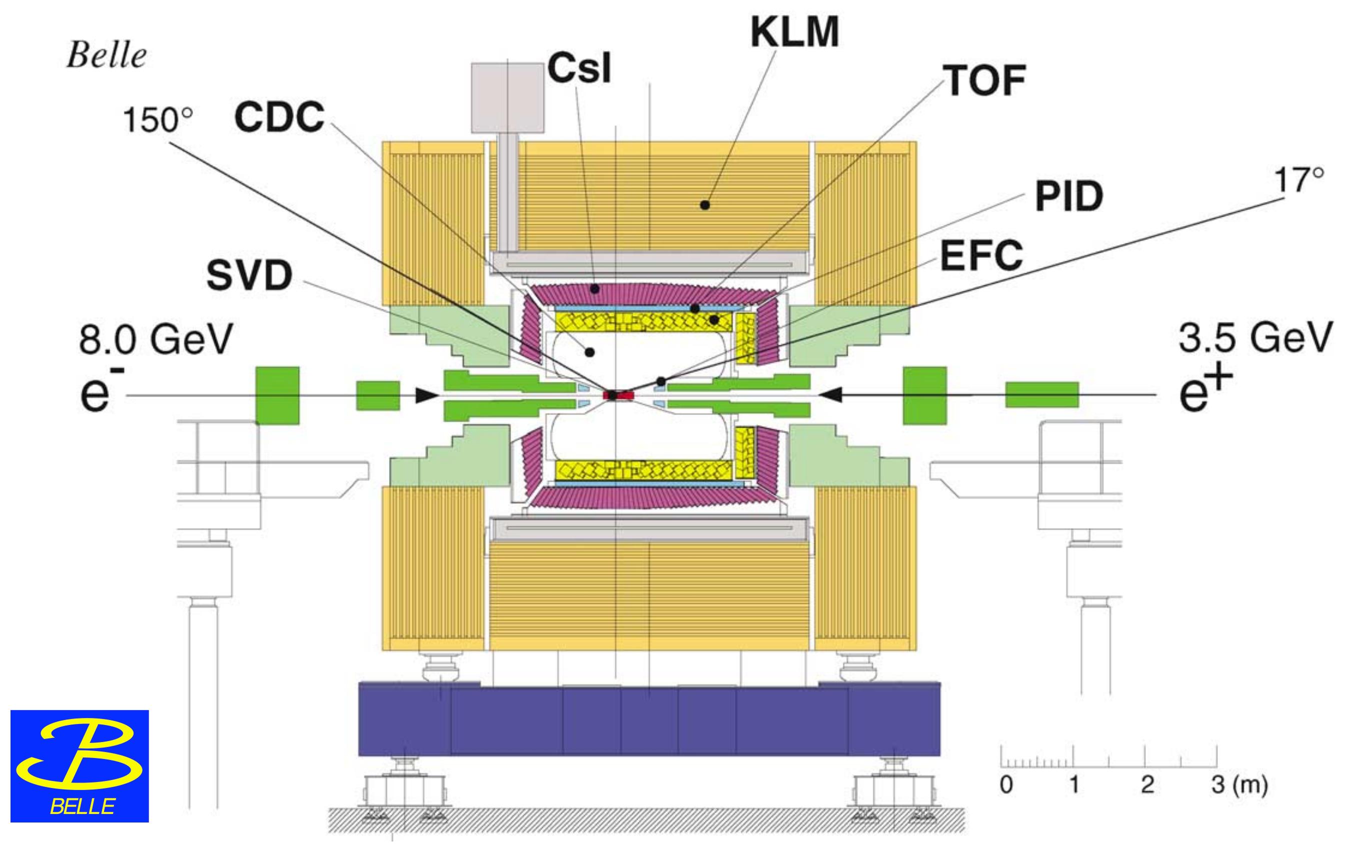
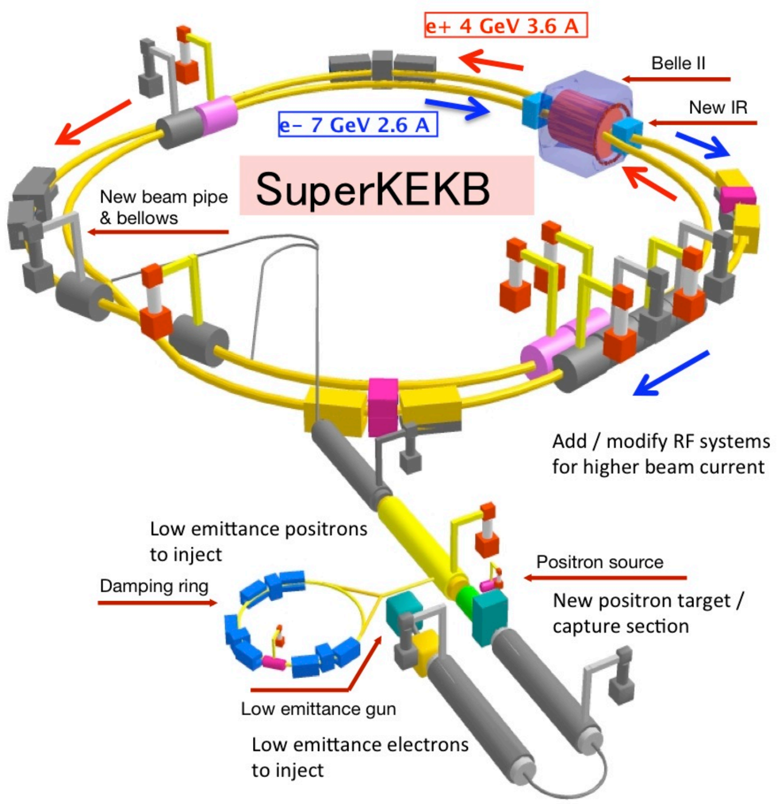
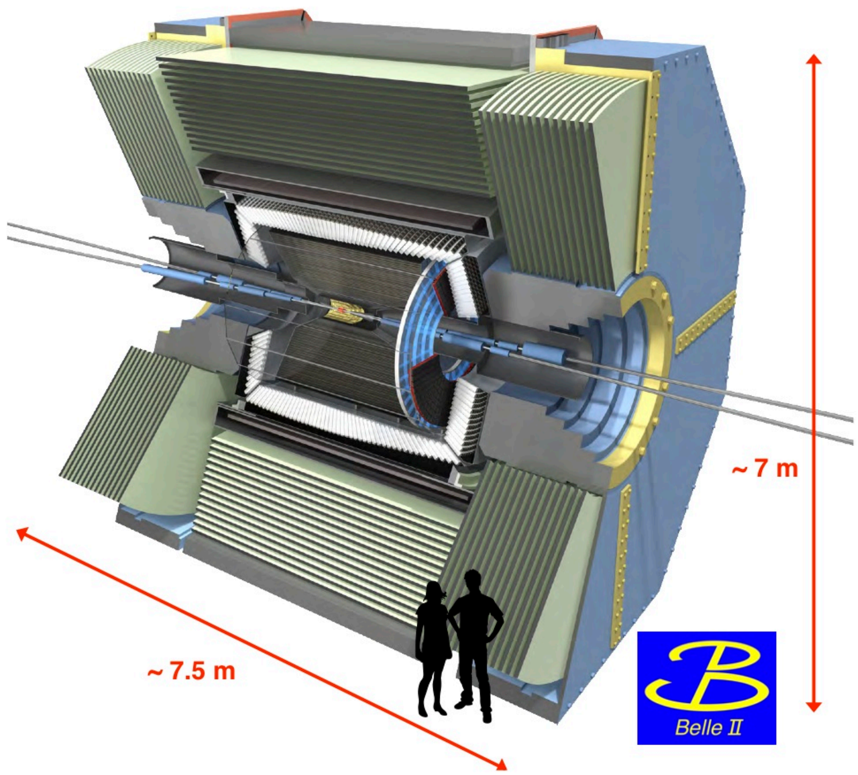


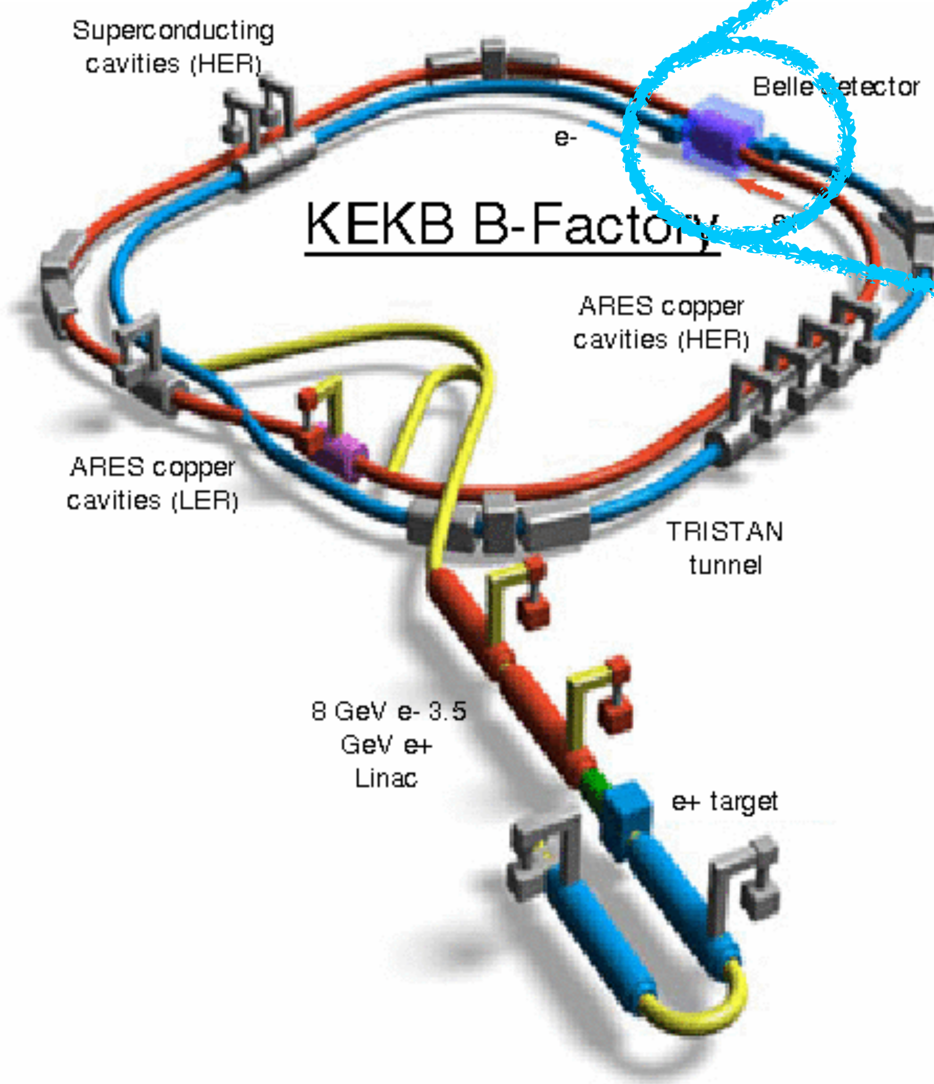
Fig. 1. Side view of the Belle detector.



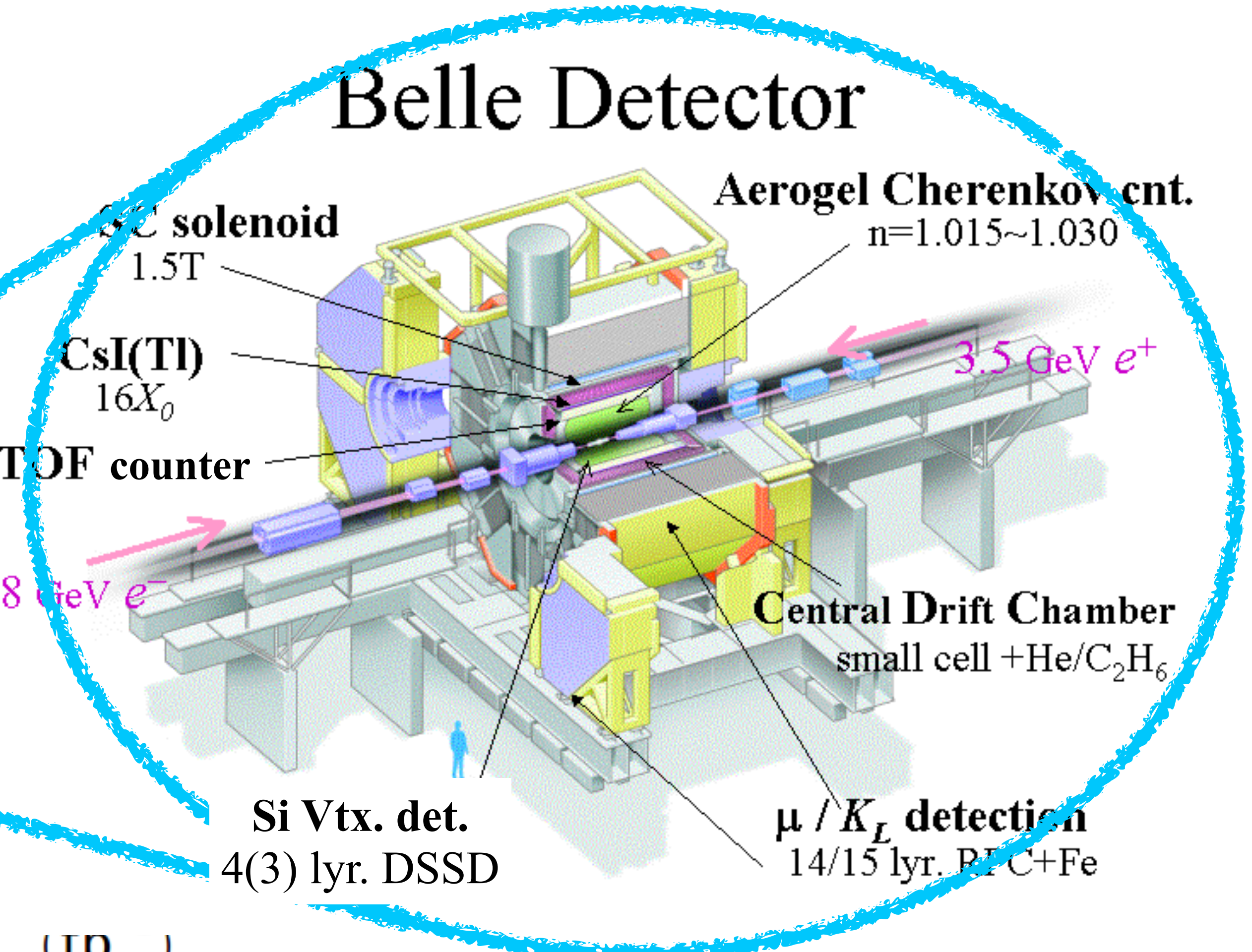


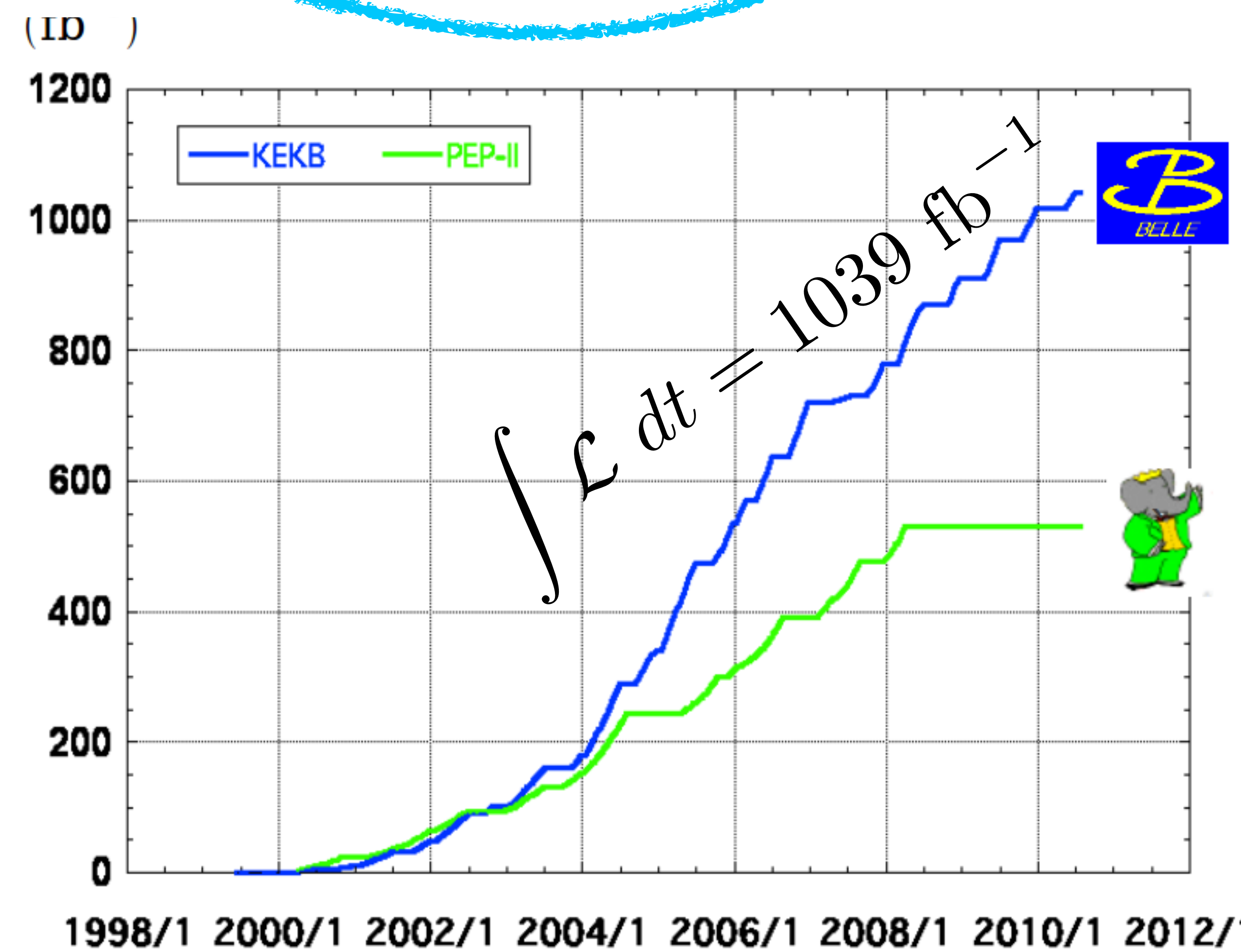
22 countries
100 institutions
~450 members

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



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





> 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:

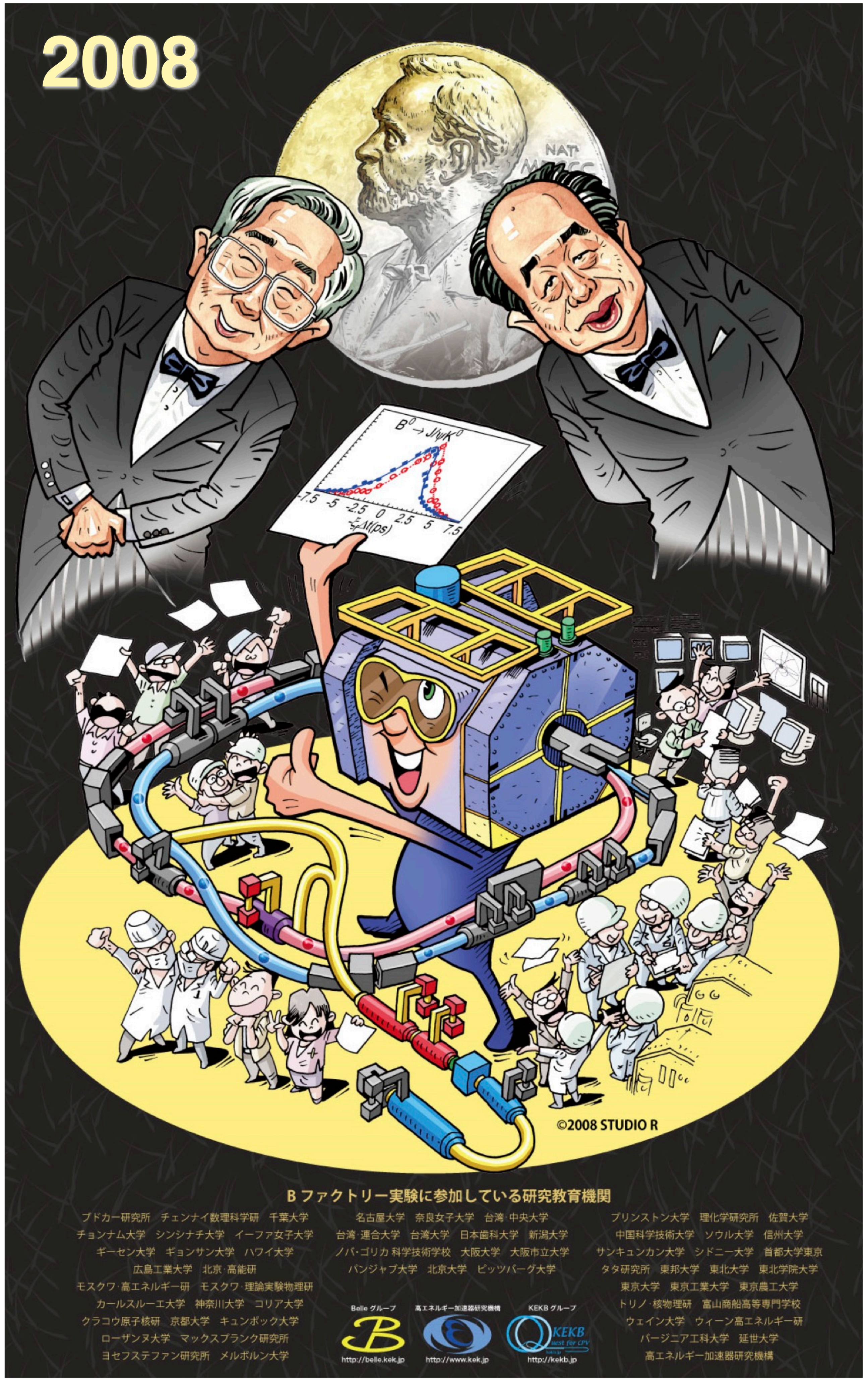
$\Upsilon(4S)$: 433 fb^{-1}

$\Upsilon(3S)$: 30 fb^{-1}

$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

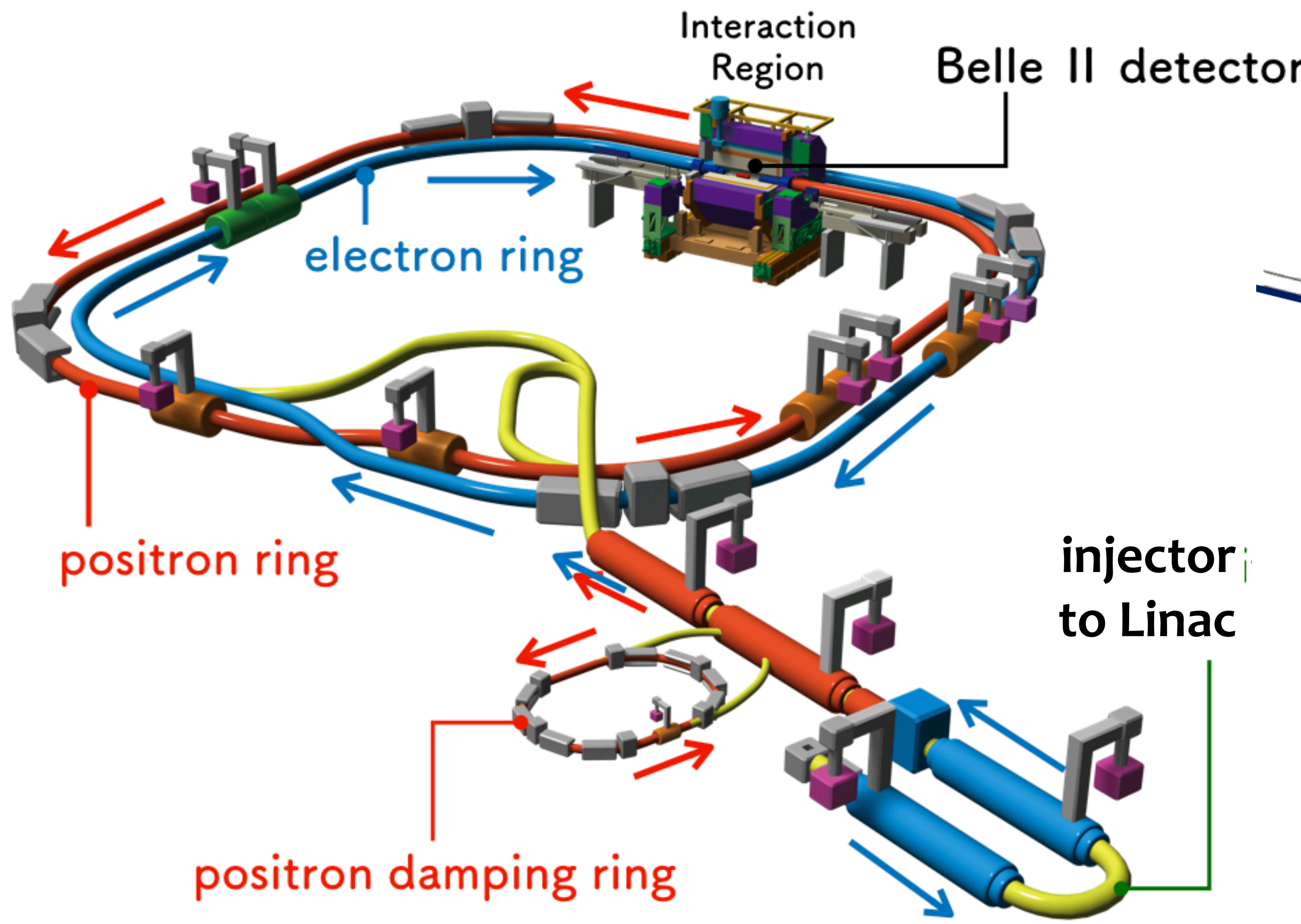
~ 54 fb^{-1}

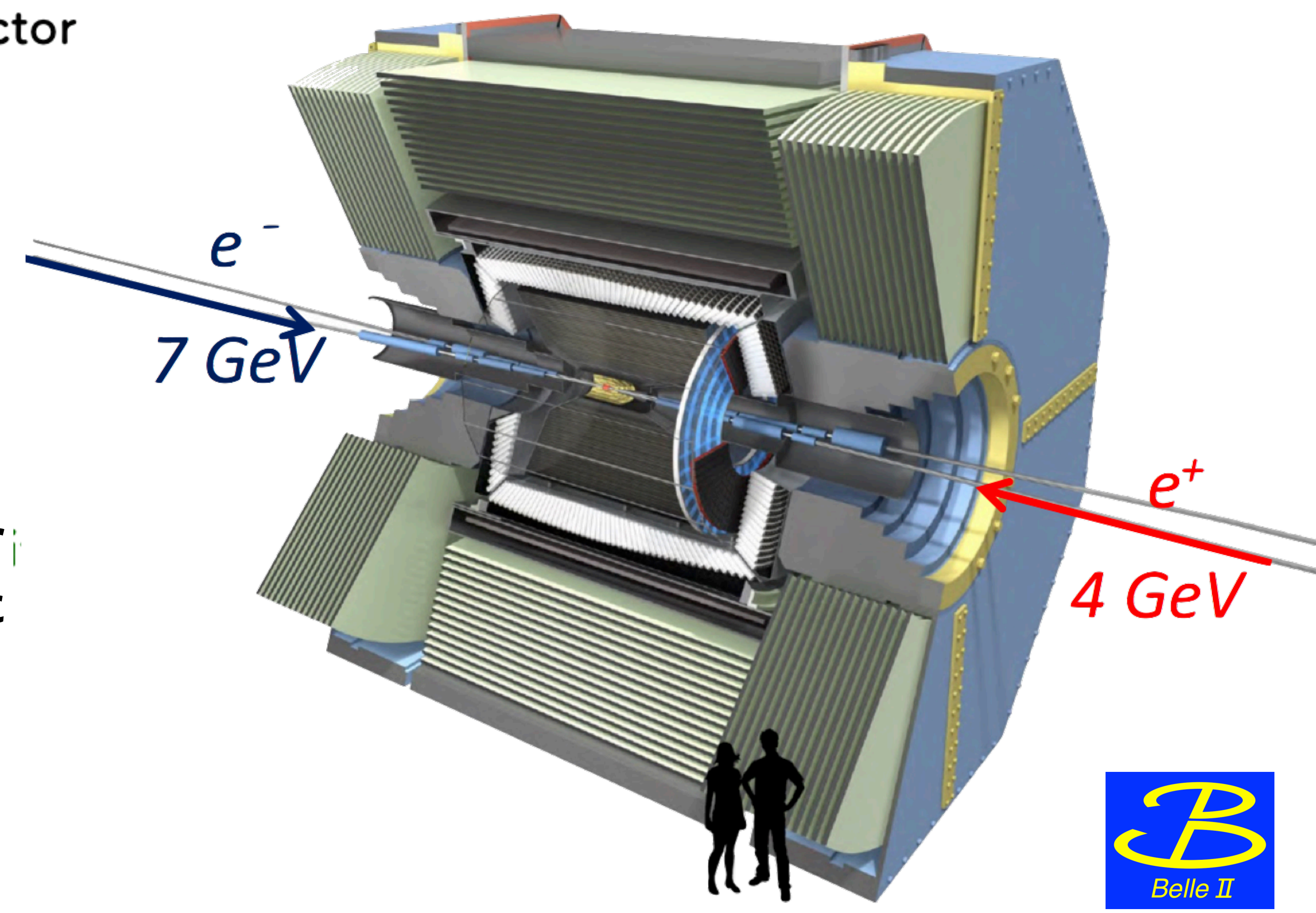


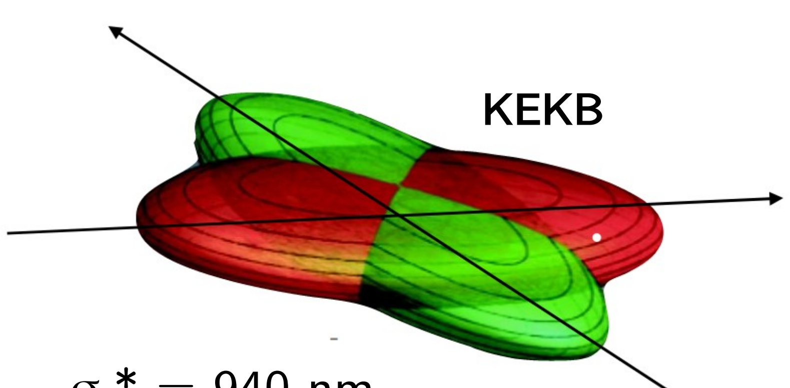
Belle (and BaBar, too) achievements include:

- CPV, CKM, and rare decays of B mesons (and B_s, too)
- Mixing, CP, and spectroscopy of charmed hadrons, e.g. $D^*_{s0}(2317)^+$
- Quarkonium spectroscopy and discovery of (*many*) exotic states, e.g. $X(3872)$, $Z_c(4430)^+$
- Studies of τ and 2γ

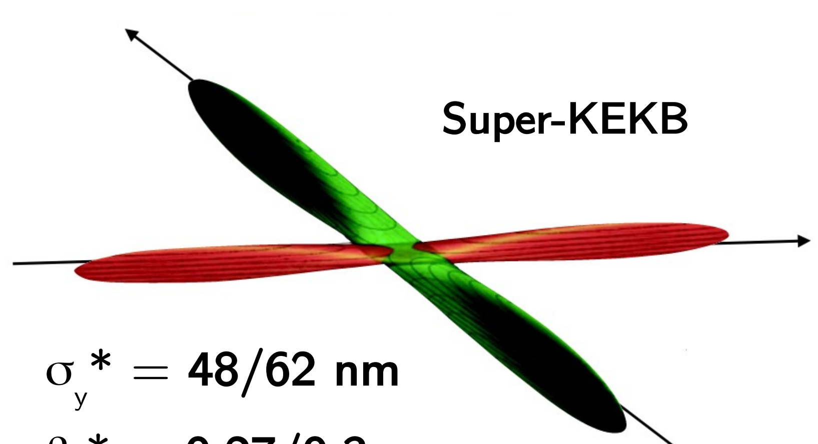
SuperKEKB $e^- \xrightarrow{7\text{ GeV}} (\star) \xleftarrow{4\text{ GeV}} e^+$ Belle II







$\sigma_y^* = 940$ nm
$\beta_y^* = 5.9$ mm
$\sigma_x^* = 147/170$ µm



$\sigma_y^* = 48/62$ nm
$\beta_y^* = 0.27/0.3$ mm
$\sigma_x^* = 10.1/10.7$ µm

$$\mathcal{L}_{\text{II}}^{\text{peak}} \approx 30 \times \mathcal{L}_{\text{I}}^{\text{peak}}$$

$$\int^{\text{goal}} \mathcal{L}_{\text{II}}\, dt = 50\ \text{ab}^{-1} \approx 50 \int \mathcal{L}_{\text{I}}\, dt$$

The Belle II Collaboration

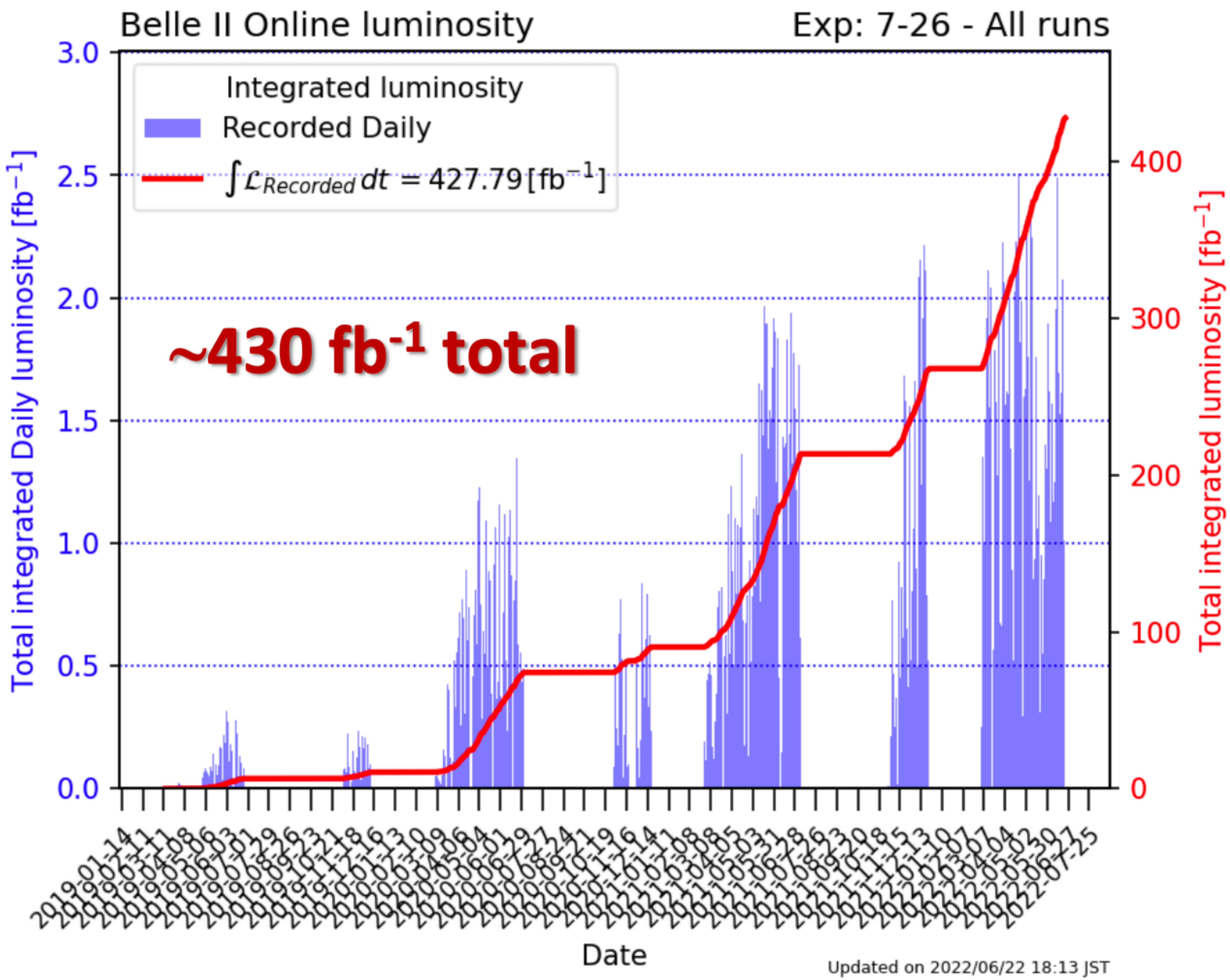
26 countries/regions, ~120 institutions, ~1000 collaborators

Belle II

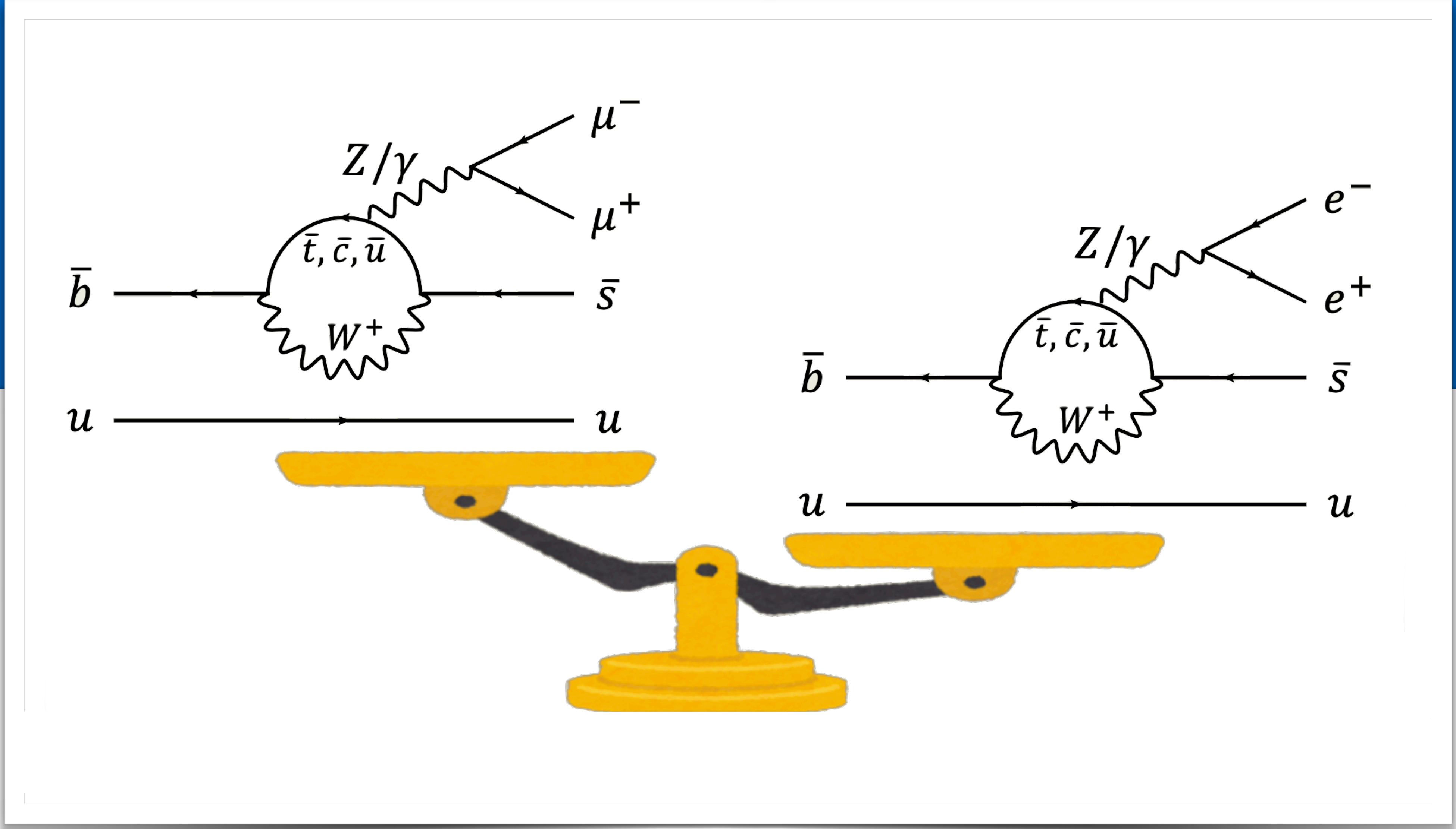
Collected luminosity up to now: 2019-2022

Belle II has been in operation through the Pandemic era, with modified working mode in accordance with the anti-pandemic policy.
(*See back-up slide!*)

peak luminosity world record
$4.7 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$



B-anomaly in EWP



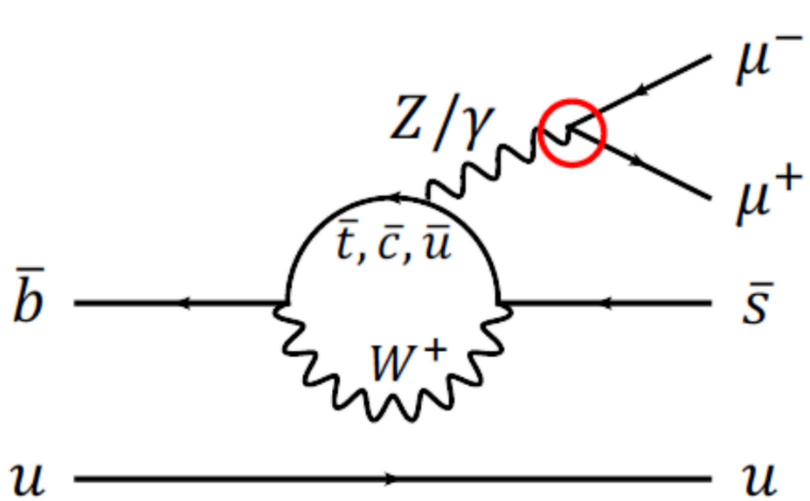
The *B*-anomalies in EWP

- In the SM, due to lepton flavor universality of Z/γ, we expect

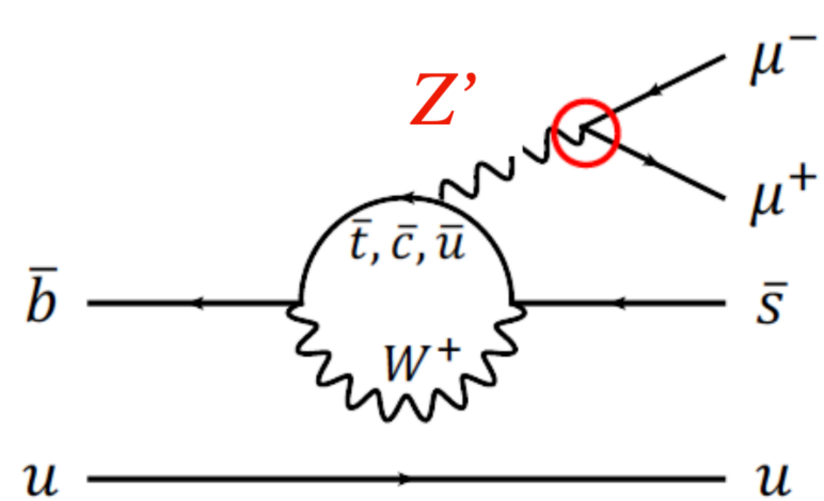
$$\Rightarrow R^{\rm SM}_{K^{(*)}} \equiv \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \approx 1$$

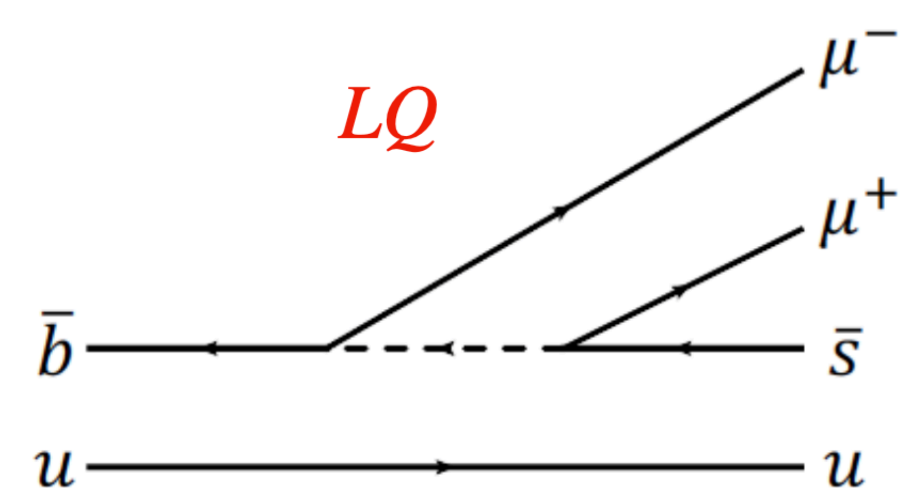
- *B*-anomalies in EWP
  - R_K and R_{K*}, measured by LHCb, seem to be far less than 1
  - a discrepancy (with the SM) in some angular observable

SM



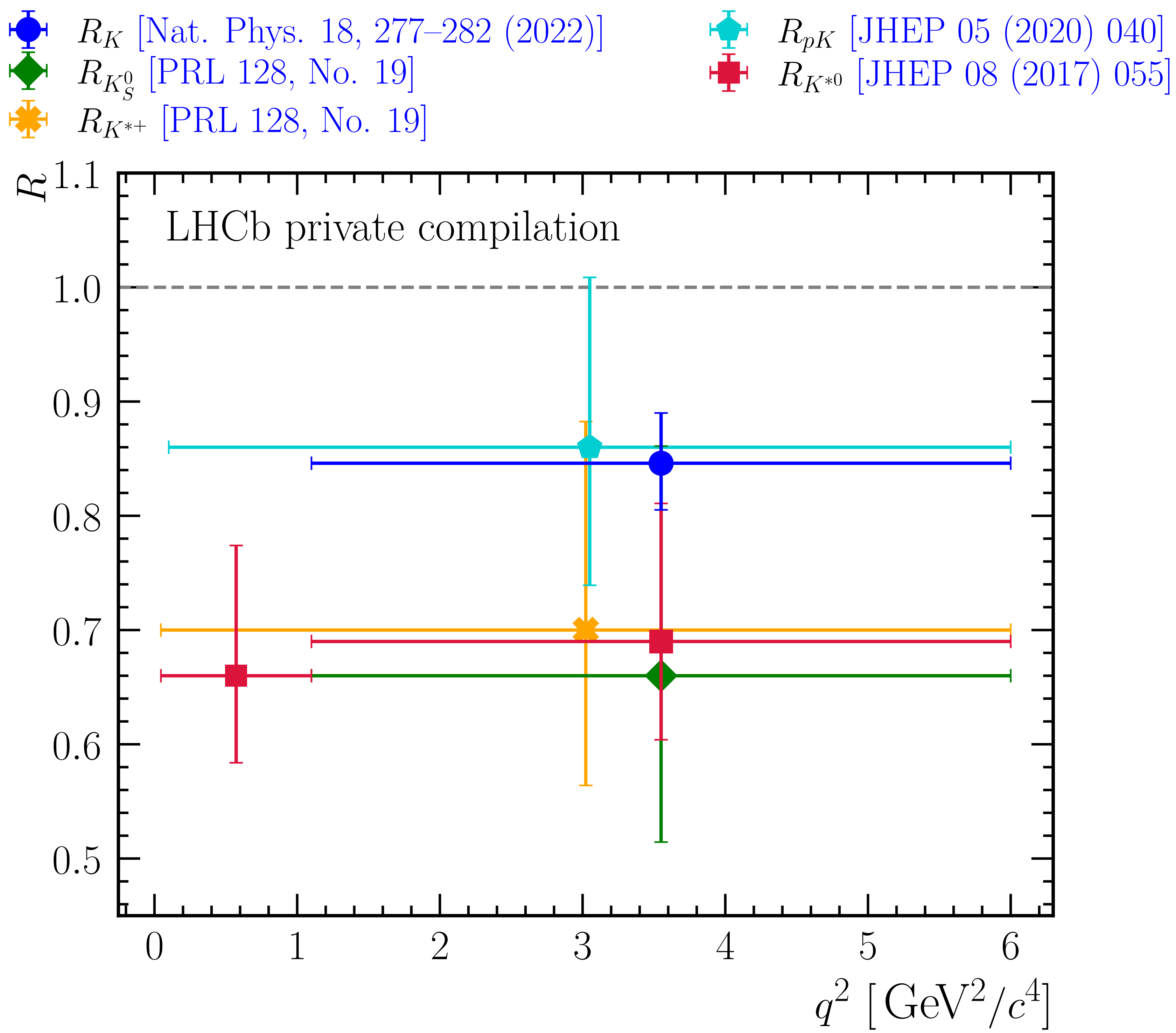
Possible NP interpretations

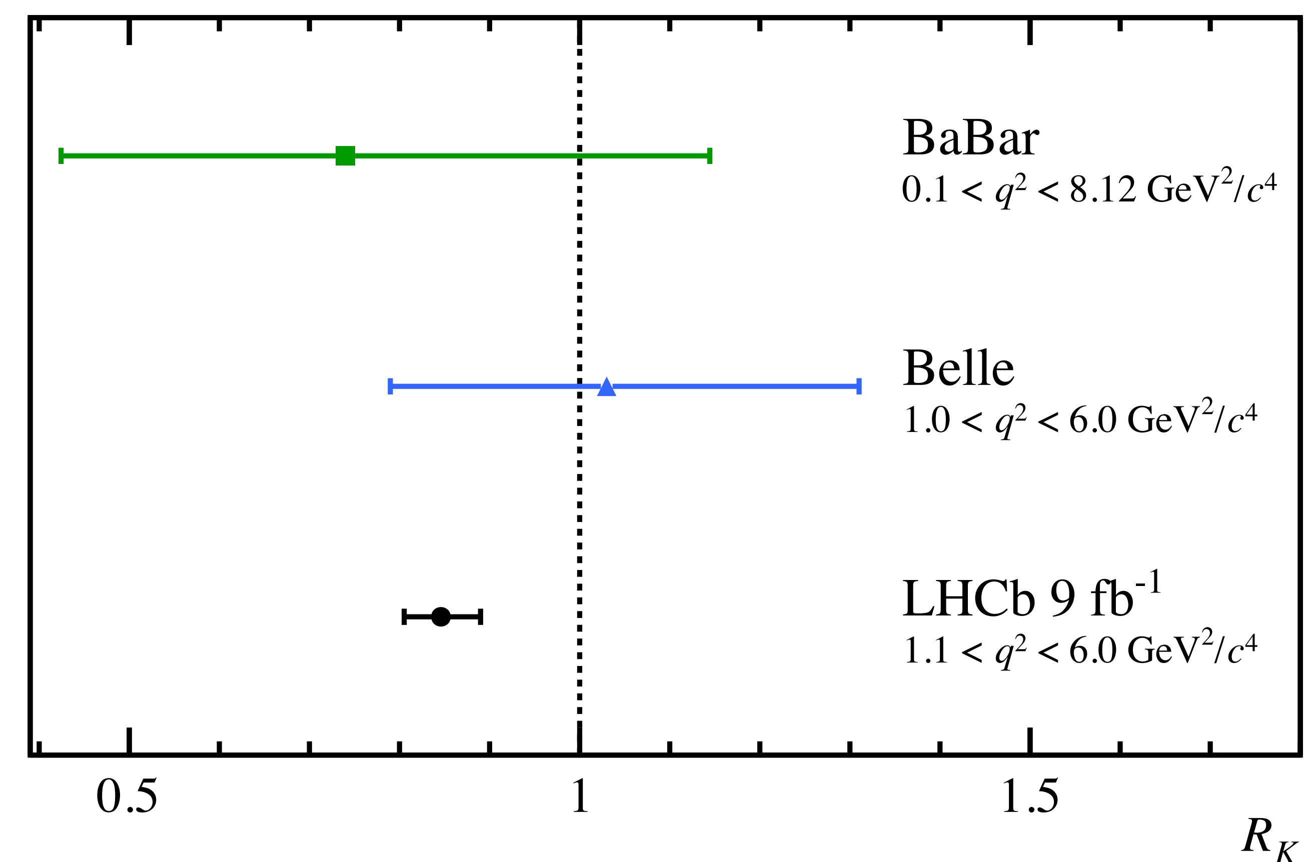




$R_{K^{(*)}}$ collection by LHCb

from the talk by Sebastian Schmitt

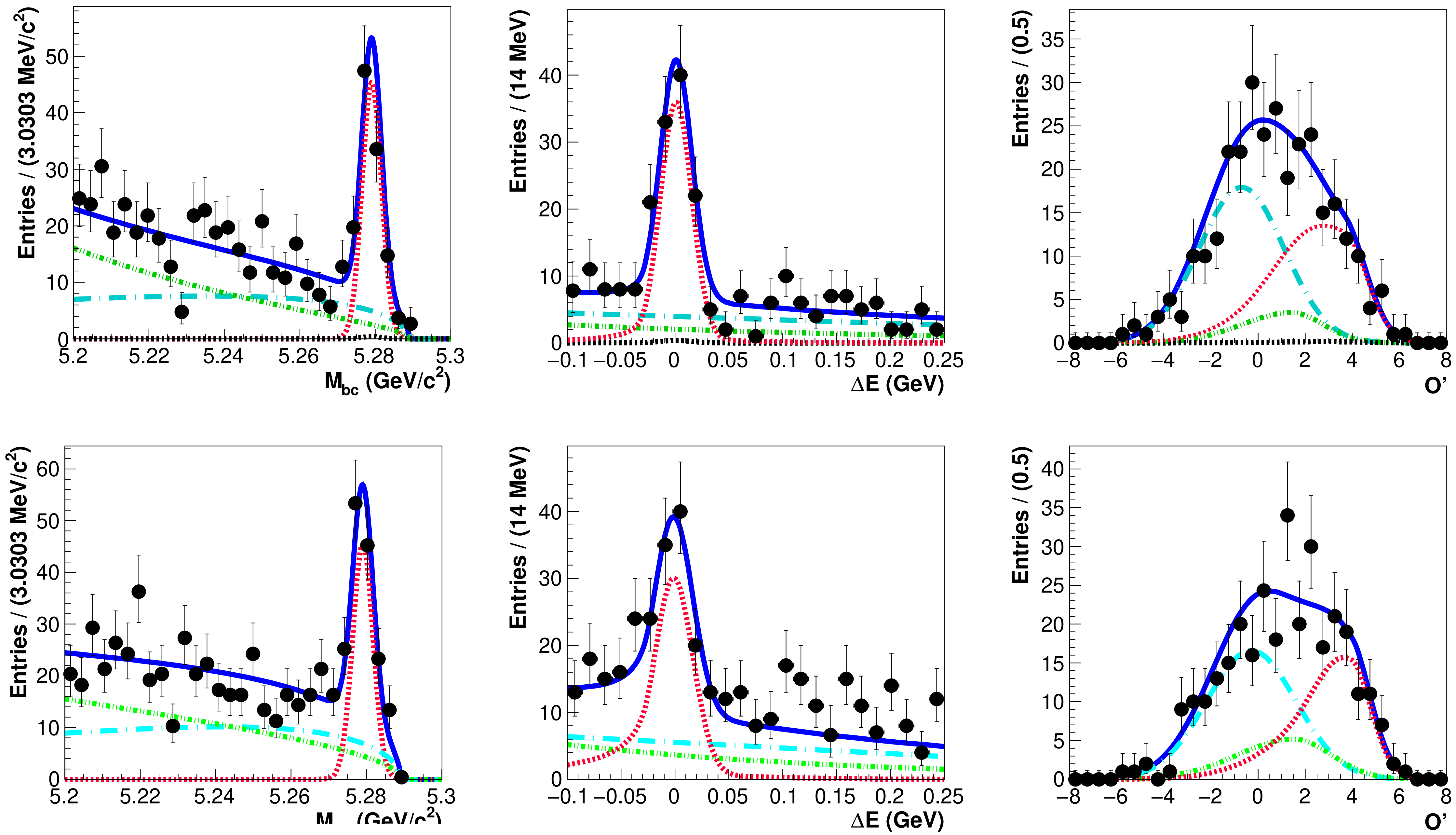




R_K from Belle

- Use both B^0 and B^+ modes

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



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

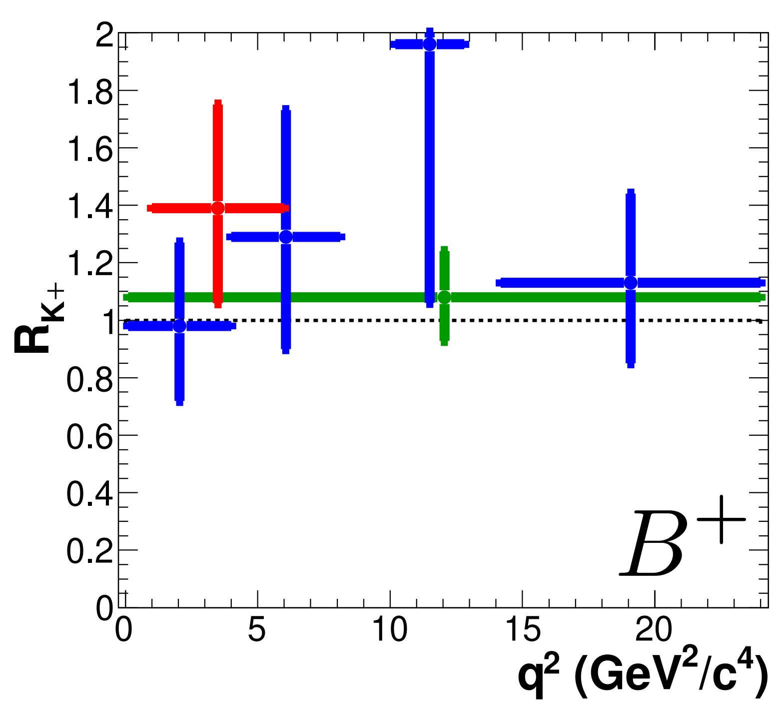
$B^+ \to K^+e^+e^-$

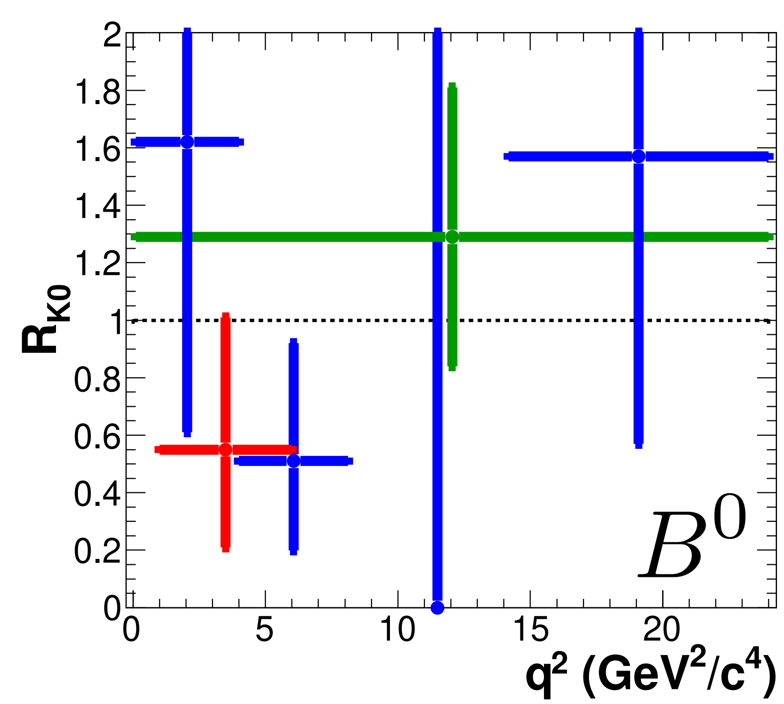
$q^2(ee) \in [(0.1, 8.12), (10.2, 12.8), (>14.18)]$

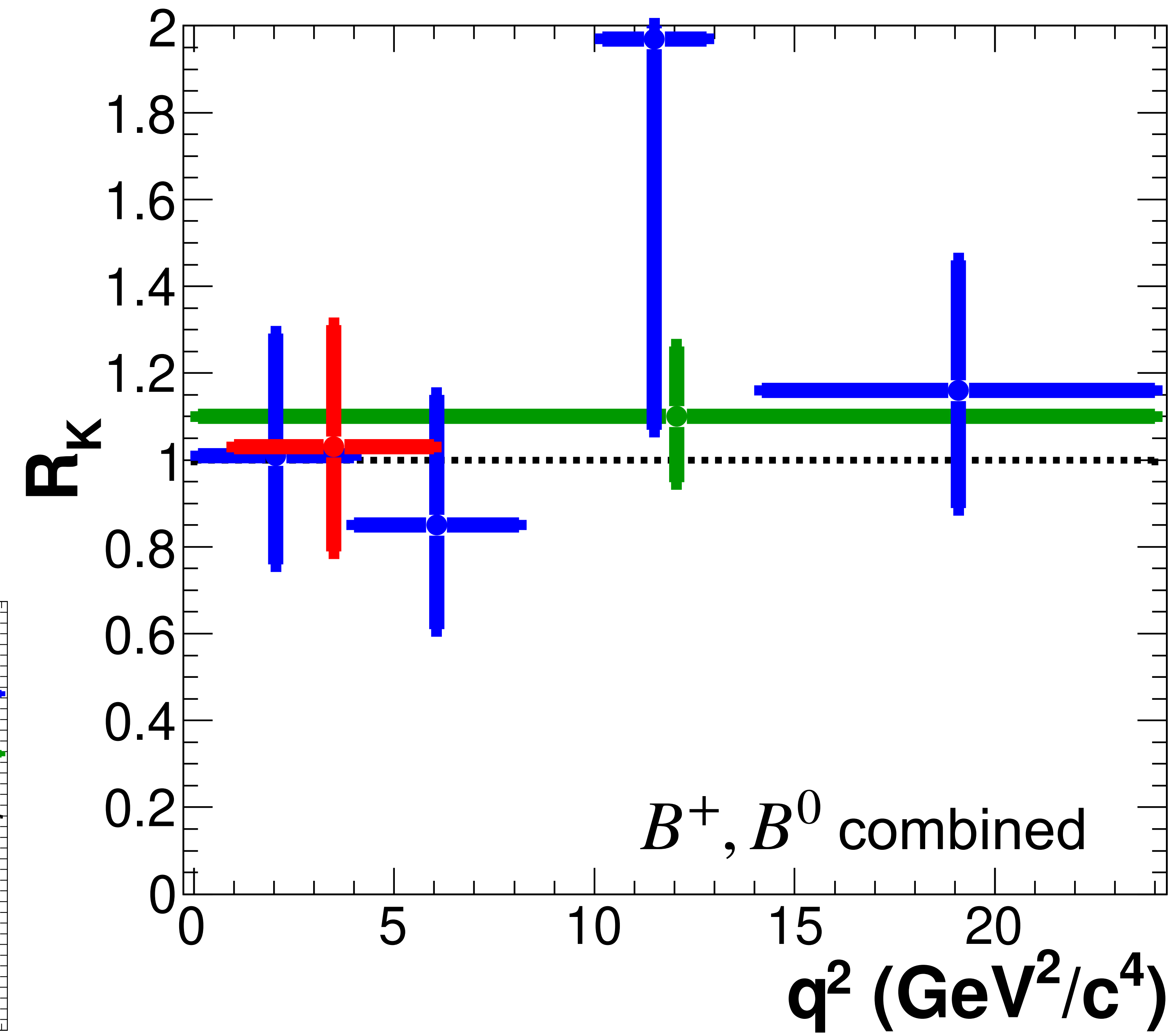
- $137 \pm 14 (138 \pm 15)$ events in the $B^+ \to K^+\mu^+\mu^-$ $(K^+e^+e^-)$
- $27.3^{+6.6}_{-5.8}$ $(21.8^{+7.0}_{-6.1})$ events in the $B^0 \to K^0_S\mu^+\mu^-$ $(K^0_Se^+e^-)$

R_K from Belle

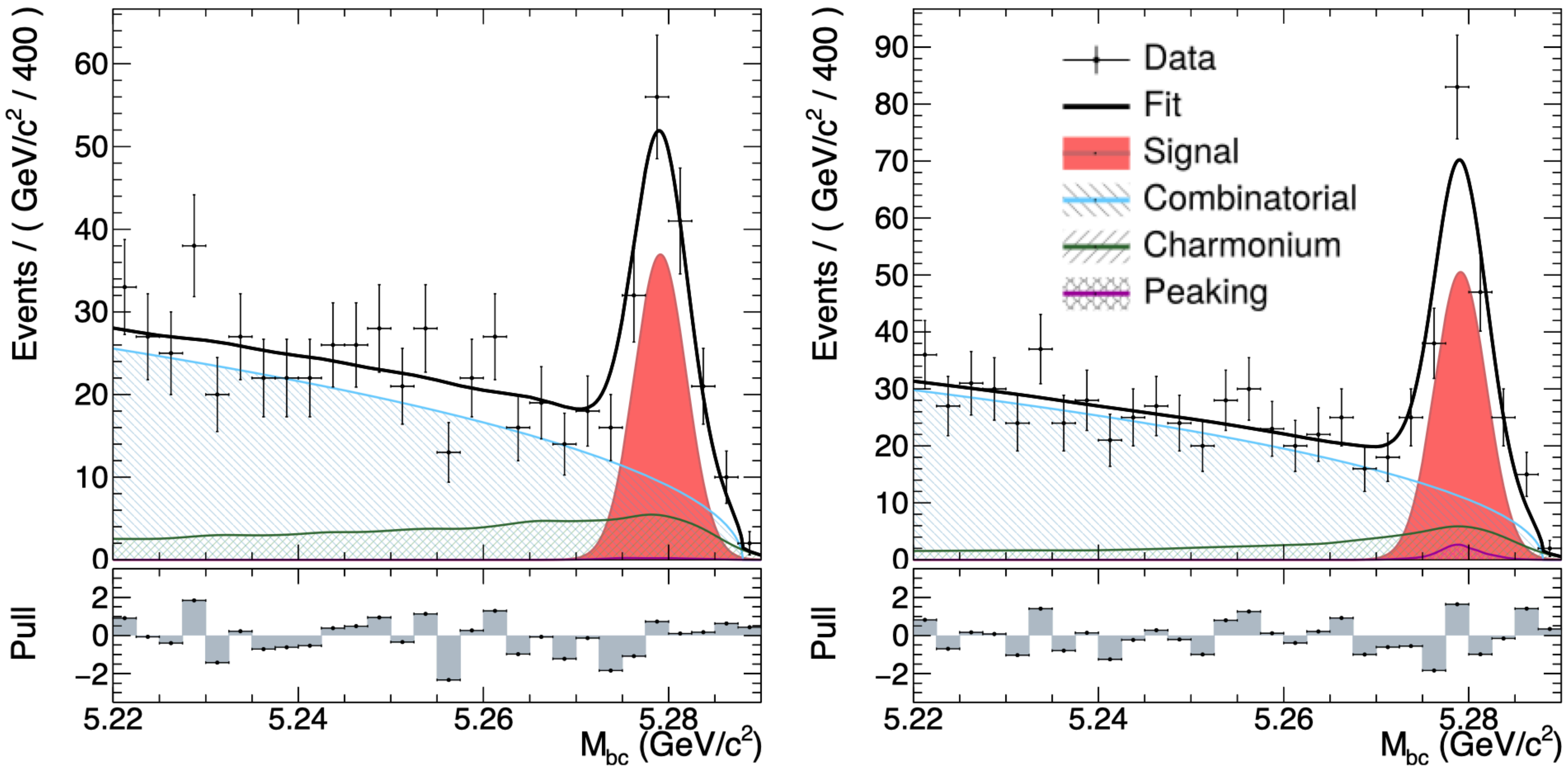
$$R_K = \begin{cases} 1.01\ ^{+0.28}_{-0.25} \pm 0.02 & q^2 \in (0.1, 4.0) \quad \mathrm{GeV}^2/c^4\,, \\ 0.85\ ^{+0.30}_{-0.24} \pm 0.01 & q^2 \in (4.00, 8.12) \quad \mathrm{GeV}^2/c^4\,, \\ 1.03\ ^{+0.28}_{-0.24} \pm 0.01 & q^2 \in (1.0, 6.0) \quad \mathrm{GeV}^2/c^4\,, \\ 1.97\ ^{+1.03}_{-0.89} \pm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



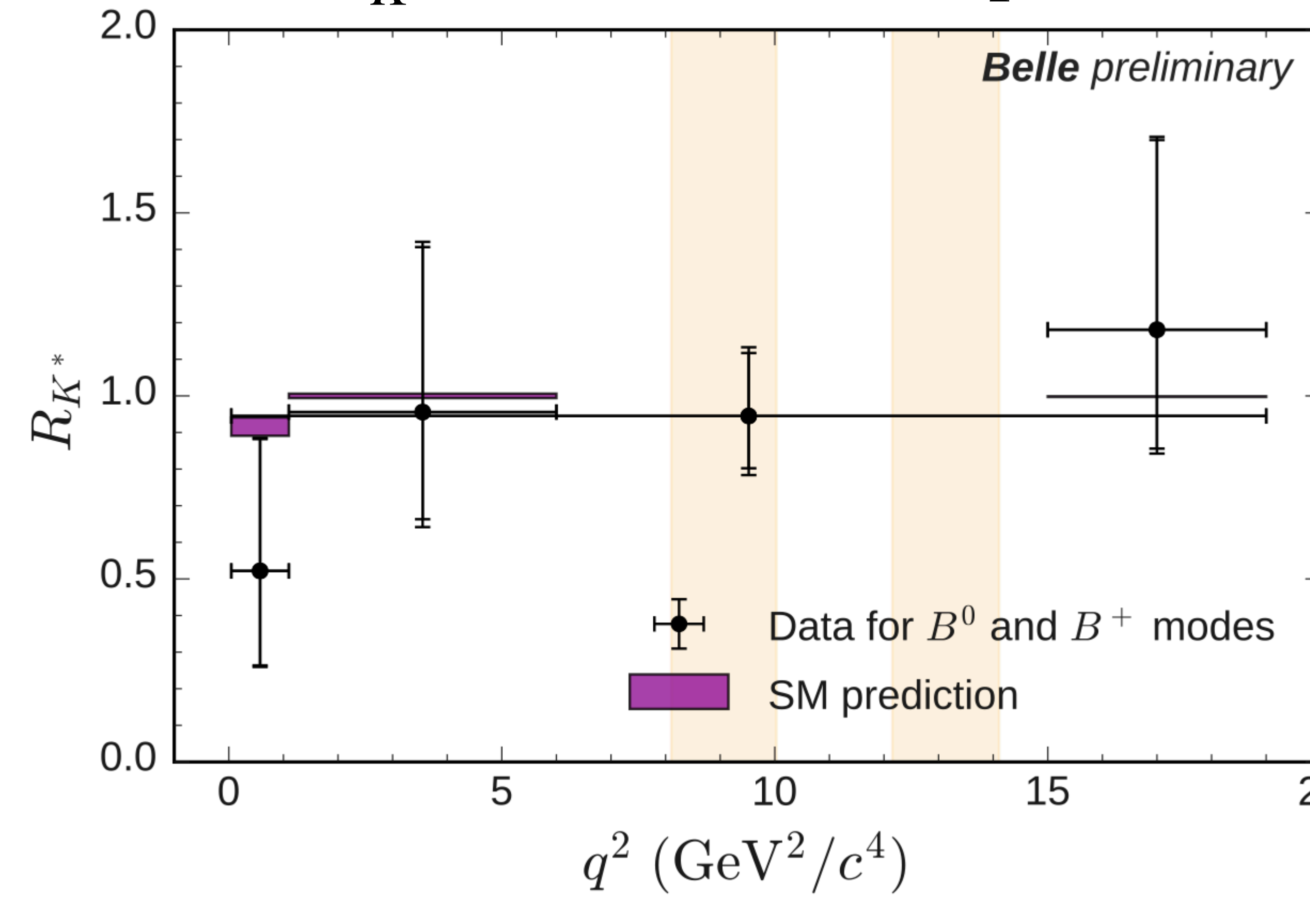




R_{K^*} from Belle



R_{K^*} (Belle) in bins of q^2



- 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

Prospects for R_{K,K^*,X_s} at Belle II

- with clean e^+e^- environment
  - easier Brems. recovery for $e^\pm$
  - wide q^2 range
  - inclusive measurements (R_{X_s})
- limited by statistics even at 50 ab^{-1}
  - major syst. error from lepton ID (~0.4%)
- Prospects for discovery
  - ~10 ab^{-1} for R_K & R_{K^*} combined
  - ~20 ab^{-1} for R_{X_s}
  - can study correlations among R_{K,K^*,X_s} and other observables (angular, etc.)

PTEP 2019, 123C01

Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
R_K ([1.0, 6.0] GeV^2)	28%	11%	3.6%
R_K (>14.4 GeV^2)	30%	12%	3.6%
R_{K^*} ([1.0, 6.0] GeV^2)	26%	10%	3.2%
R_{K^*} (>14.4 GeV^2)	24%	9.2%	2.8%
R_{X_s} ([1.0, 6.0] GeV^2)	32%	12%	4.0%
R_{X_s} (>14.4 GeV^2)	28%	11%	3.4%

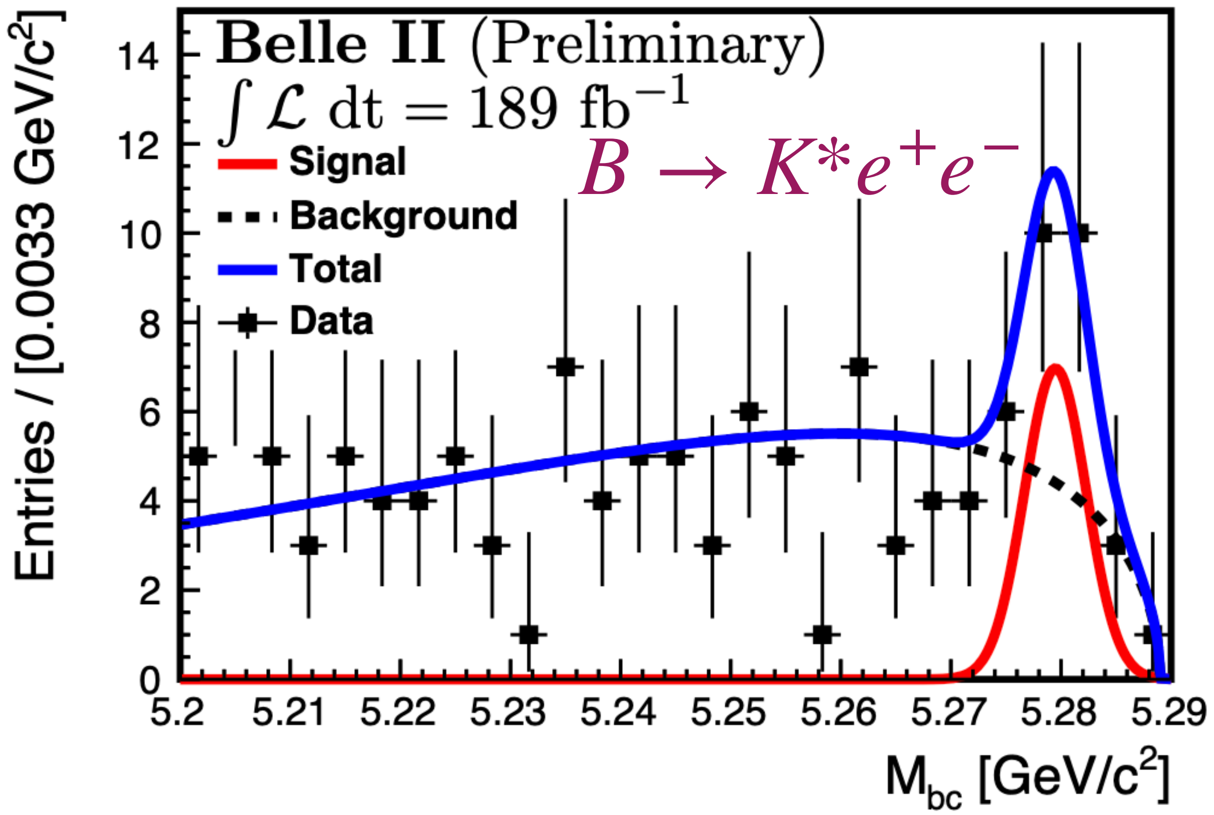
Progress in Belle II

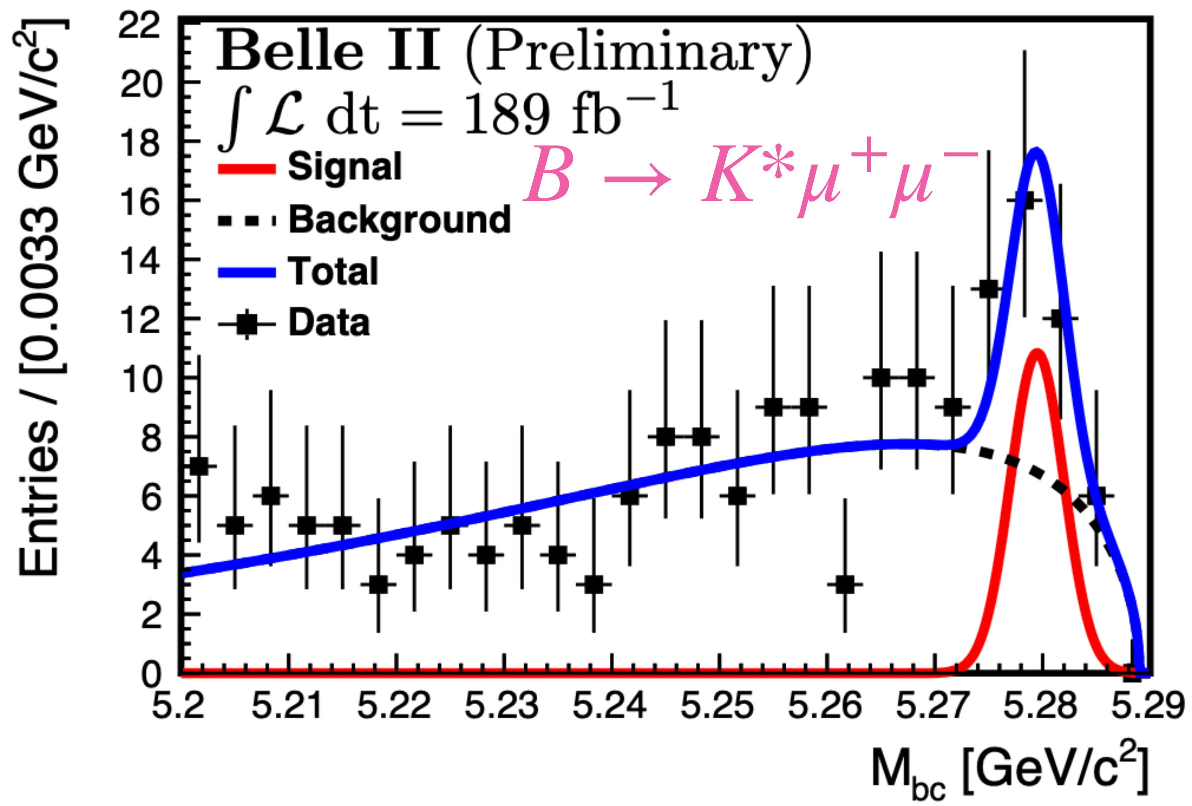
- Exclusive EWP
  - $B \to K^* \ell^+ \ell^-$
- Precision measurement
  - $B \to K J/\psi$
- Semi-invisible states
  - $B \to K \nu \bar{\nu}$

Exclusive EWP: $B \to K^*\ell^+\ell^-$

- Belle II can do independent check of $R_{K^{(*)}}$ with $\mathscr{L} \sim \mathcal{O}(1)$ ab^{-1}
- Measure $B \to K^*\ell^+\ell^-$ with 189 fb^{-1}
- charmonium veto; BDT for continuum ($e^+e^- \to q\bar{q}$) suppression
- similar precision for ee and $\mu\mu$ (unlike LHCb)

Decay	Belle II (10^{-6})	PDG (10^{-6})
$B \to K^*e^+e^-$	$1.42 \pm 0.48 \pm 0.09$	1.19 ± 0.20
$B \to K^*\mu^+\mu^-$	$1.19 \pm 0.31^{+0.08}_{-0.07}$	1.06 ± 0.09





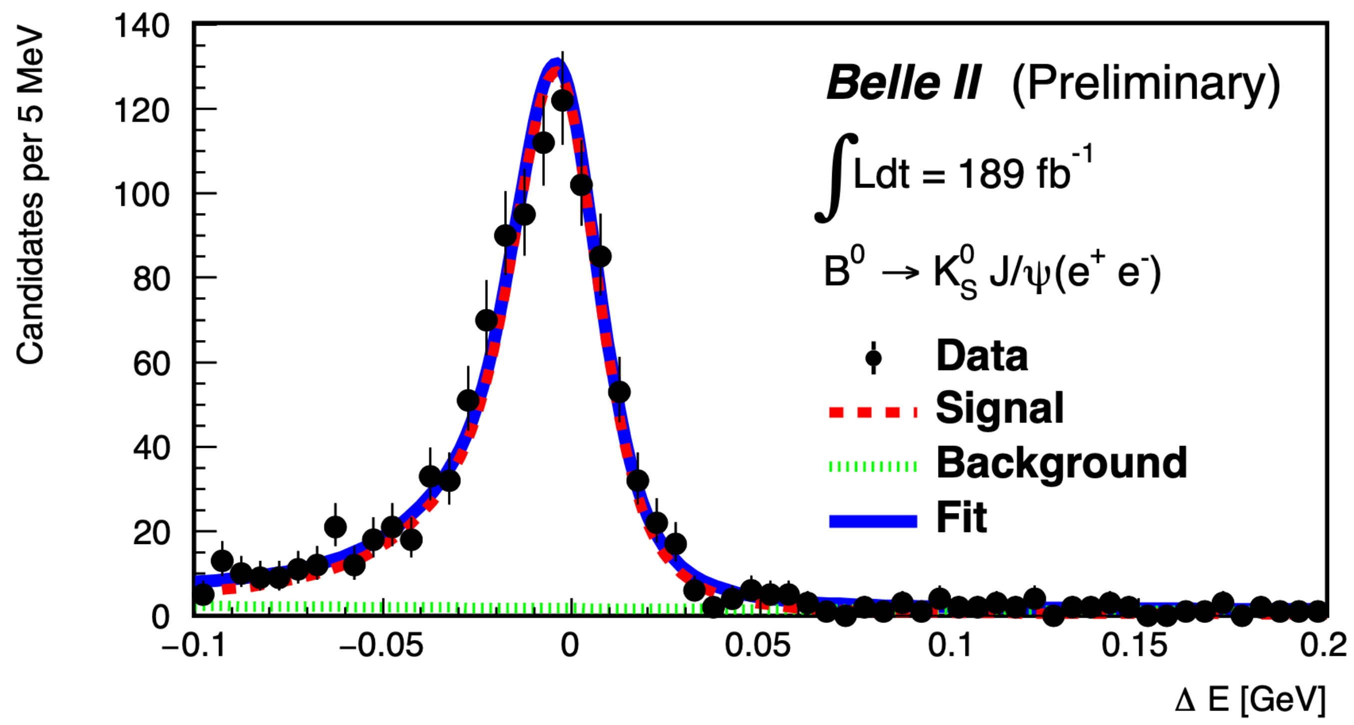
Precision measurement : $B \to K\,J/\psi$

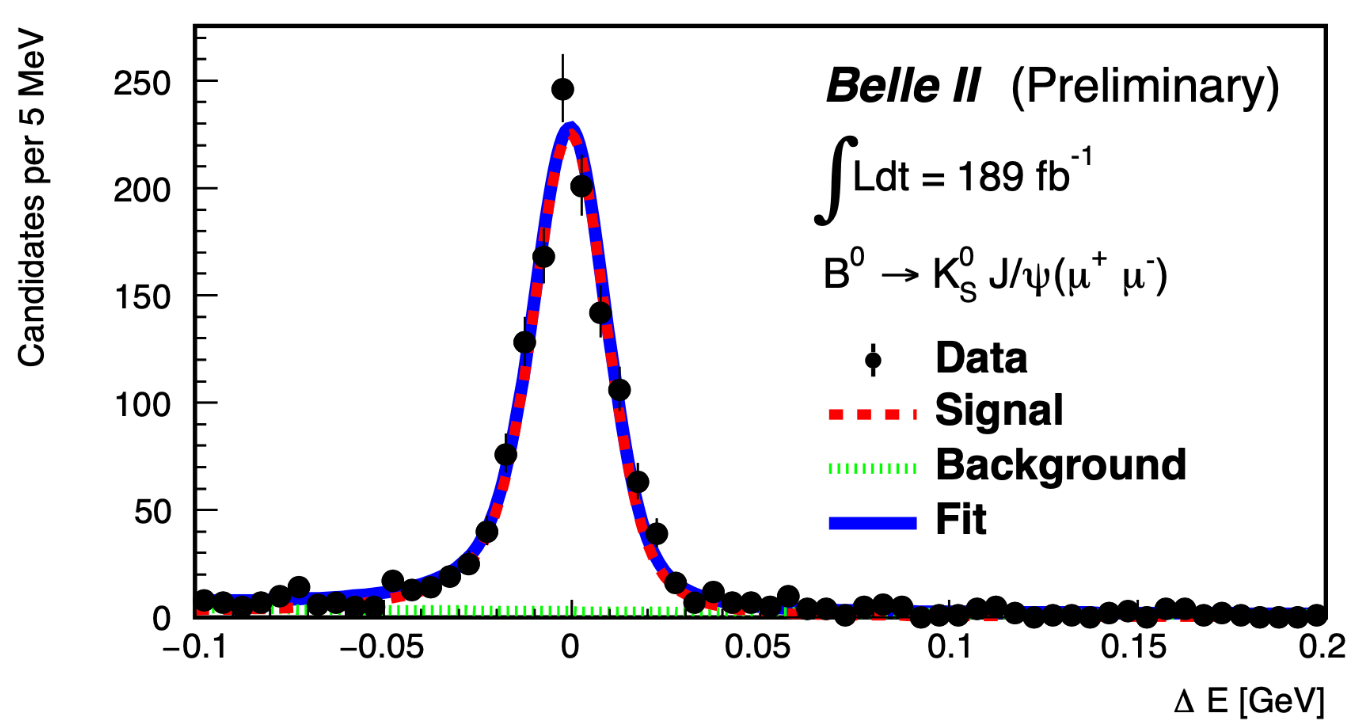
- Not EWP, but a control channel for $B \to K\ell^+\ell^-$
- Measure $R_K(J/\psi)$ with 189 fb^{-1}

$$R_K(J/\psi) = \frac{\mathcal{B}(B \to KJ/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B \to KJ/\psi(\to e^+e^-))}$$

Observable	Belle II	Belle (2021)
$R_{K^+}(J/\psi)$	$1.009 \pm 0.022 \pm 0.008$	$0.994 \pm 0.011 \pm 0.010$
$R_{K^0_S}(J/\psi)$	$1.042 \pm 0.042 \pm 0.008$	$0.993 \pm 0.015 \pm 0.010$

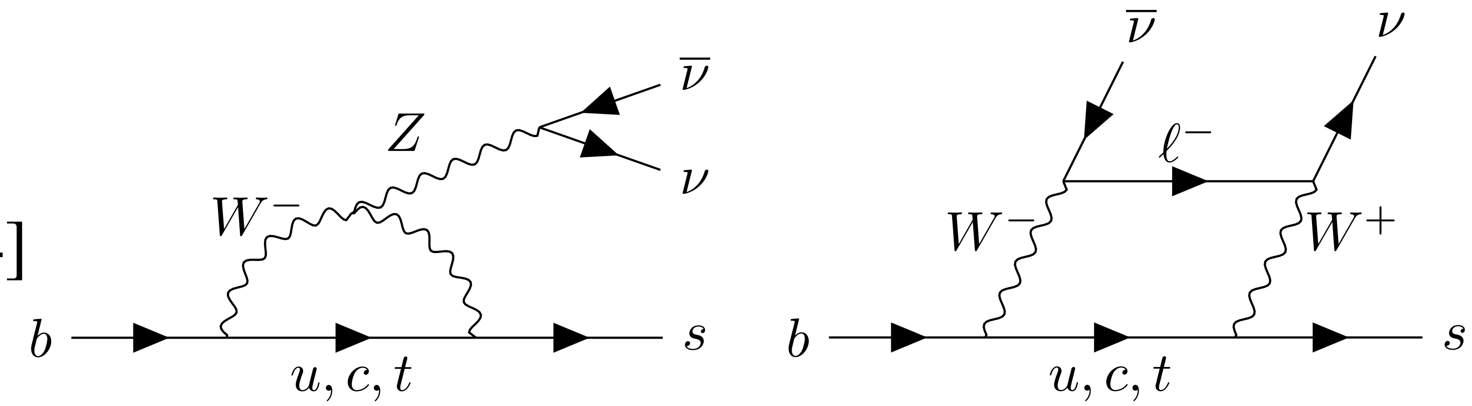
Lepton ID syst. uncertainty, improved over Belle





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 tl
3. BDT for signal discrimination

   use event-shape, ROE dynamics, B_{sig} kinematics, ve

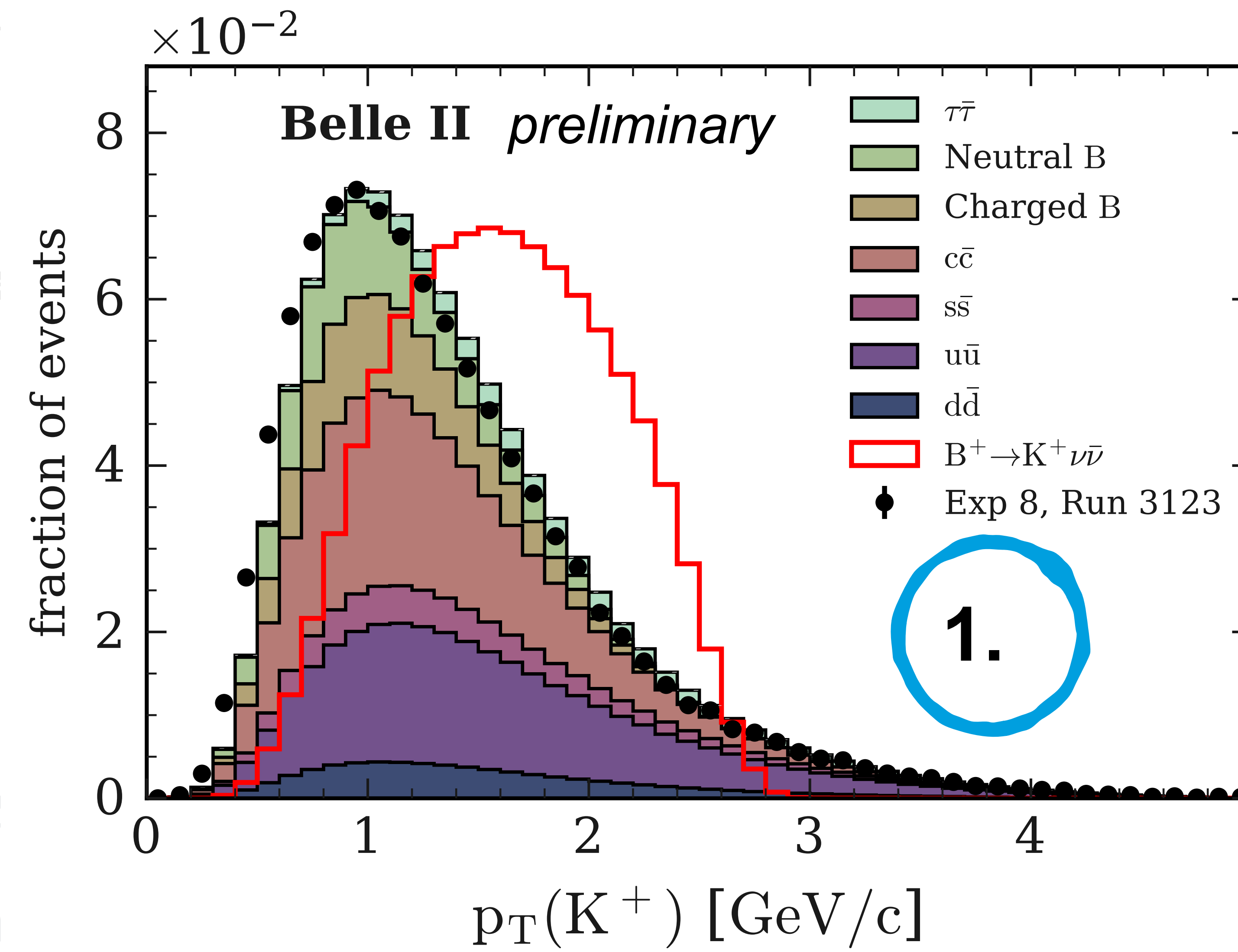
4. BDT_1 & BDT_2 (consecutive applications)

   ∵ to suppress two different bkgds : BB and contin

5. signal region in 2D (BDT_2 vs. $p_T(K^+)$)
6. check BDT output with $B^+ \to J/\psi K^+$ sample

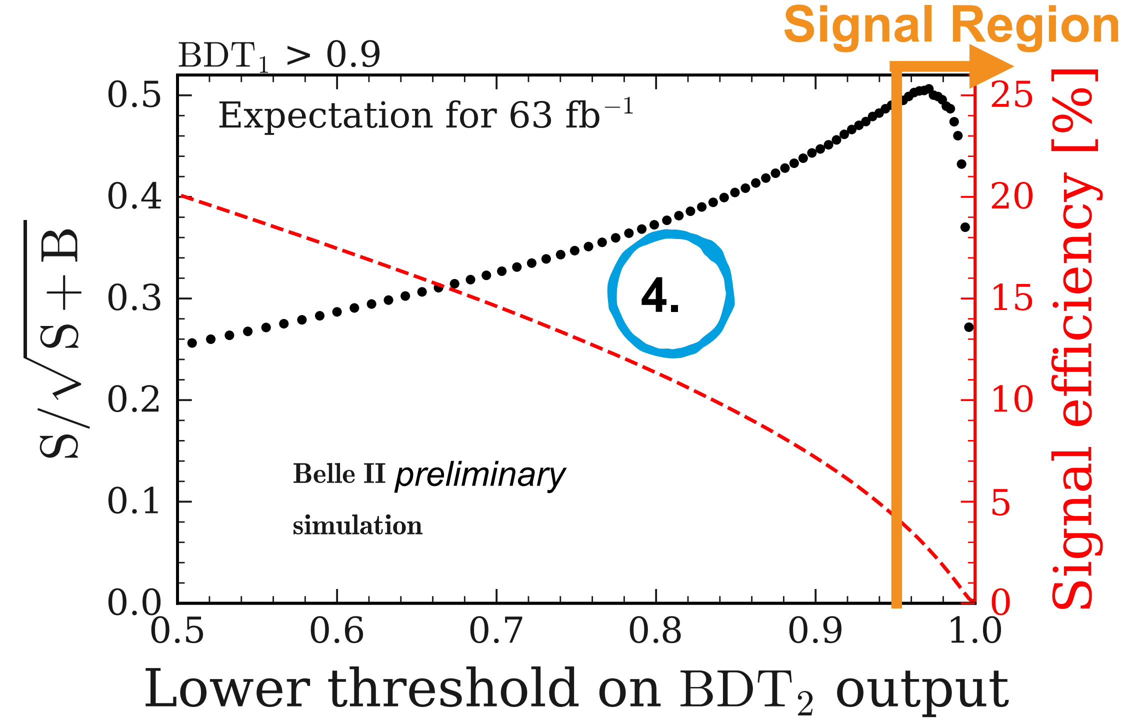
   for both signal and bkgd (see *back-up slide for deta*

7. check Data/MC agreement using Off-resonance data



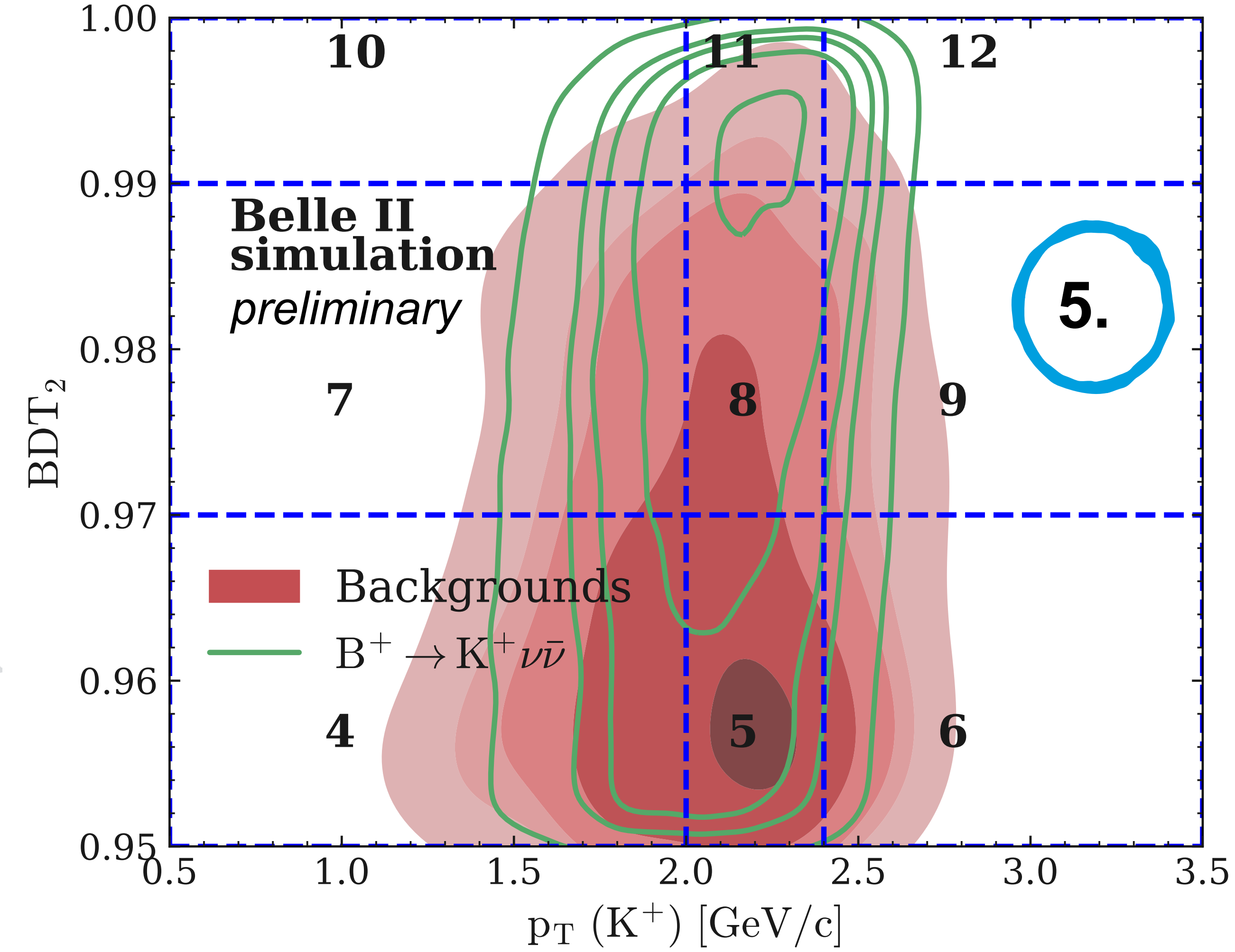
$B^+ \to K^+ \nu \bar{\nu}$ at Belle II

1. signal K^+ — track of highest p_T w/ at least 1 PXD hit ($\varepsilon \sim$
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.



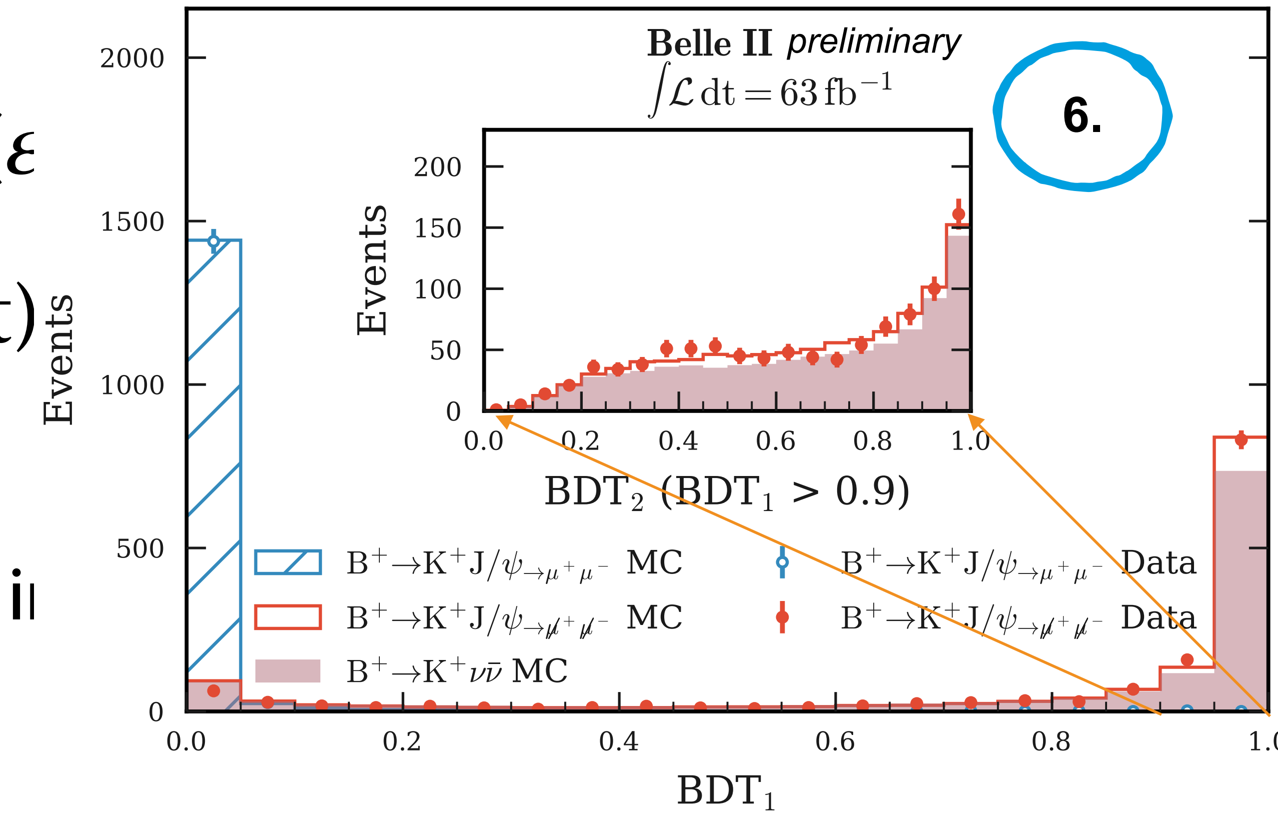
4. BDT$_1$ & BDT$_2$ (consecutive applications)
   ∵ to suppress two different bkgds : BB and continuum
5. signal region in 2D (BDT$_2$ vs. $p_T(K^+)$)
6. check BDT output with $B^+ \to J/\psi K^+$ samples
   for both signal and bkgd (see *back-up slide for details*)
7. check Data/MC agreement using Off-resonance da

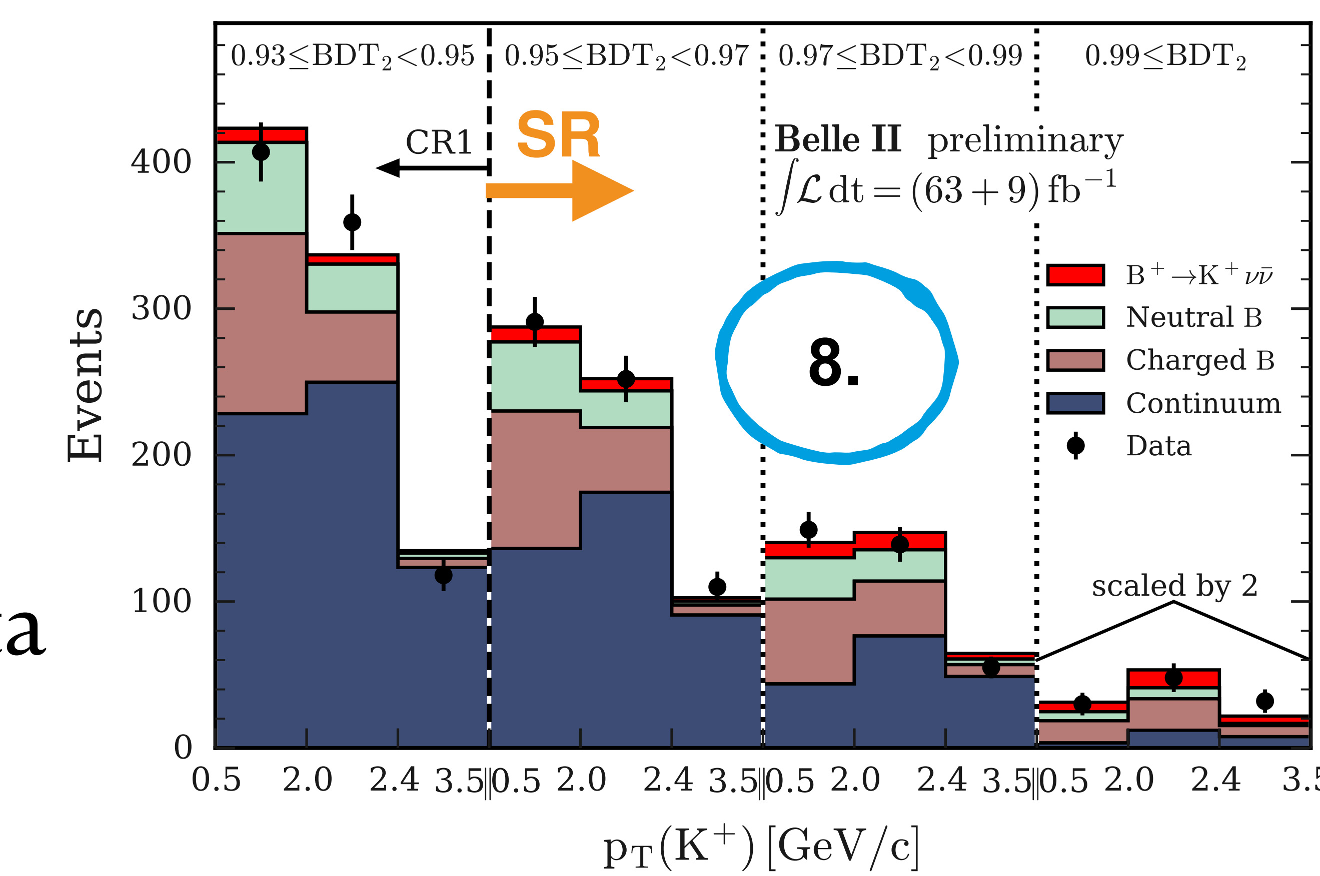
Signal Region



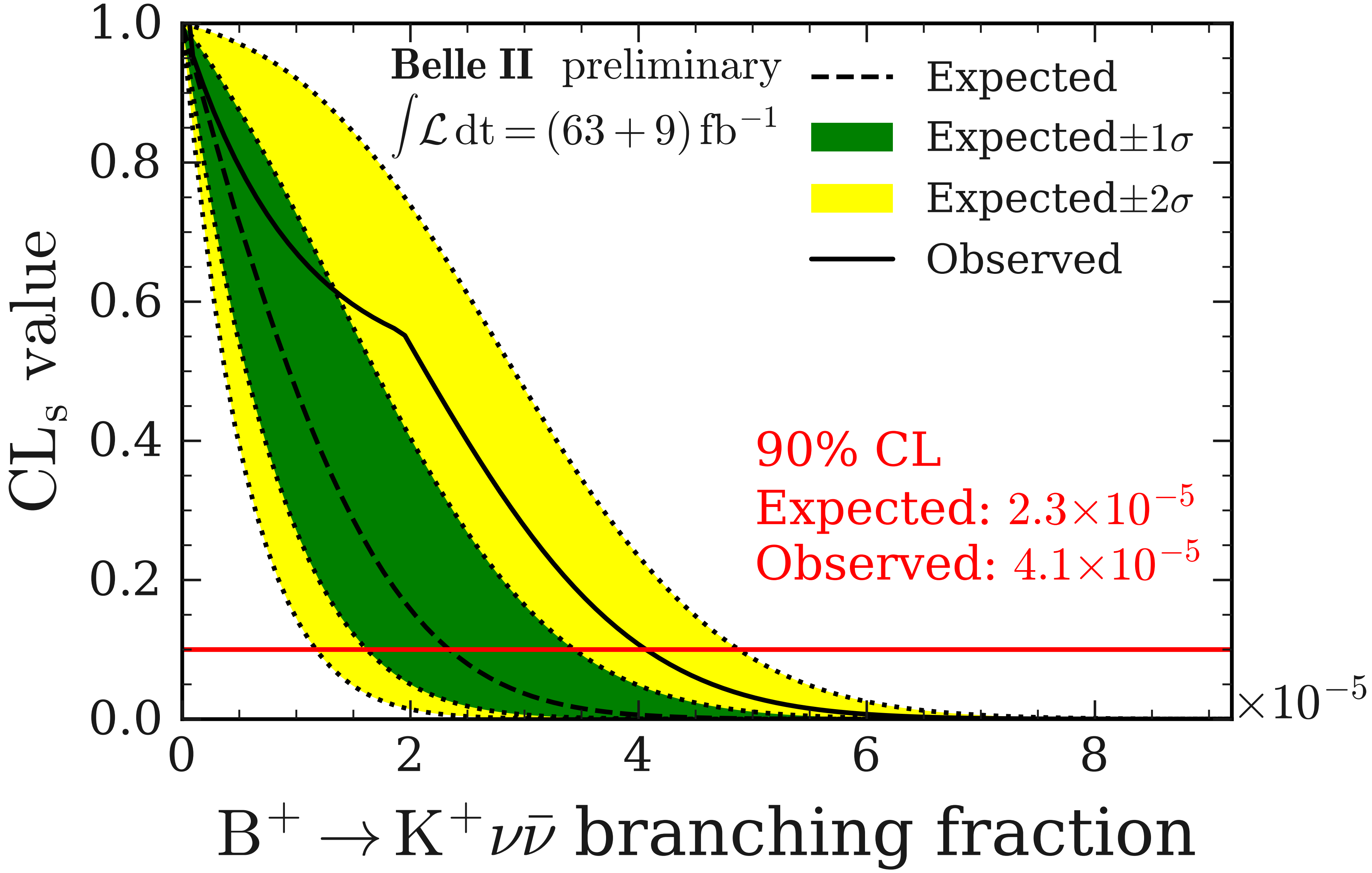
$B^+ \to K^+ \nu\bar{\nu}$ at Belle II

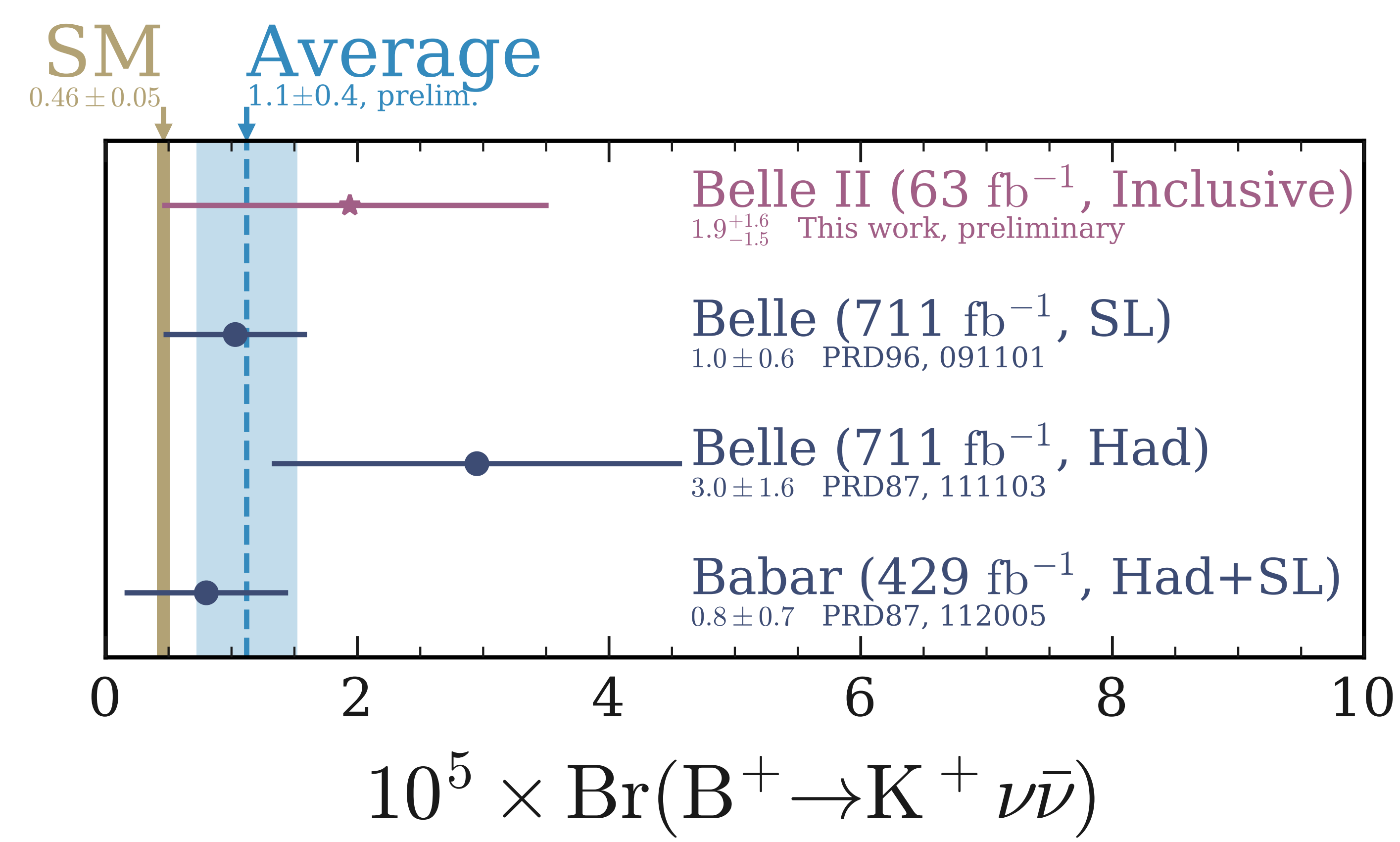
1. signal K^+ — track of highest p_T w/ at least 1 PXD hit (ε
2. all other tracks & clusters ⇒ "ROE" (rest of the event)
3. BDT for signal discrimination
   use event-shape, ROE dynamics, B_{sig} kinematics, vertexing i
4. BDT₁ & BDT₂ (consecutive applications)
   ∵ to suppress two different bkgds : 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 data
8. simultaneous ML fit to ON- & OFF-resonance data





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





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

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

other hints for anomaly in EWP?

[77] W. Altmannshofer and D. M. Straub, Eur. Phys. J. C **75**, 382 (2015).

Angular Analysis of the $B^+ \to K^{*+}\mu^+\mu^-$ Decay

R. Aaij *et al.*[*]
(LHCb Collaboration)

[81] S. Descotes-Genon, L. Hofer, J. Matias, and J. Virto, J. High Energy Phys. 06 (2016) 092.
[82] B. Capdevila, A. Crivellin, S. Descotes-Genon, J. Matias, and J. Virto, J. High Energy Phys. 01 (2018) 093.

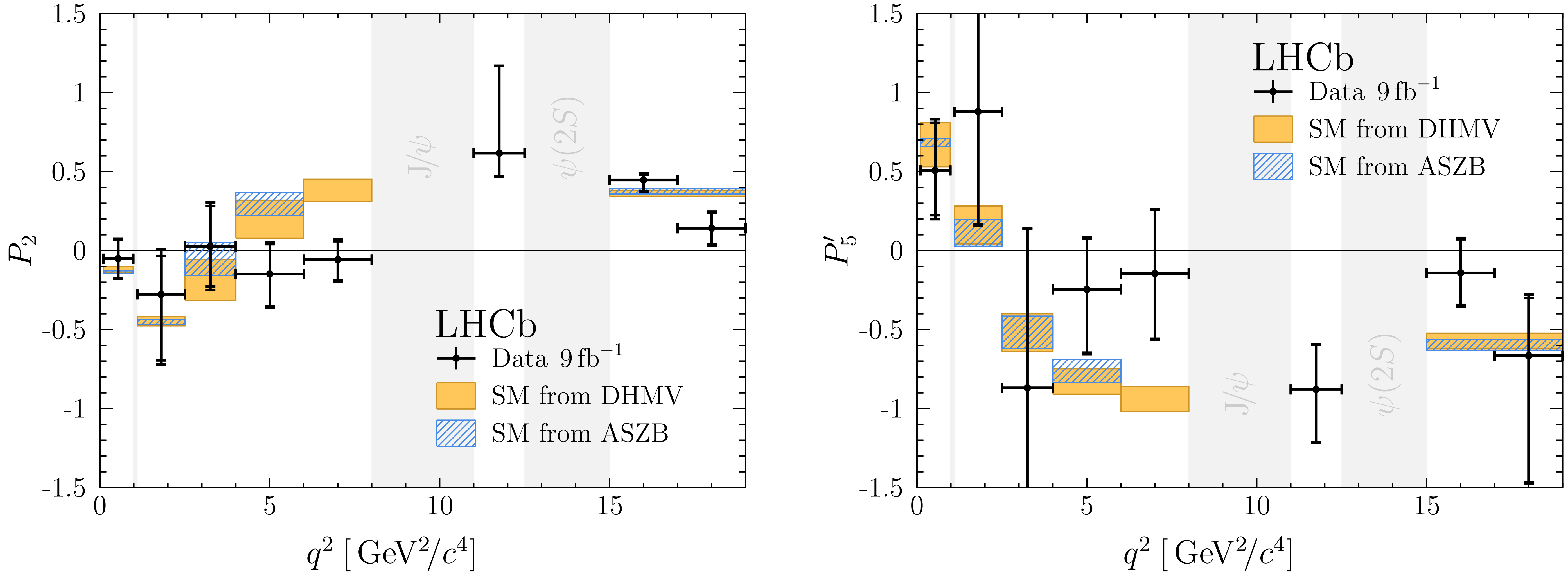
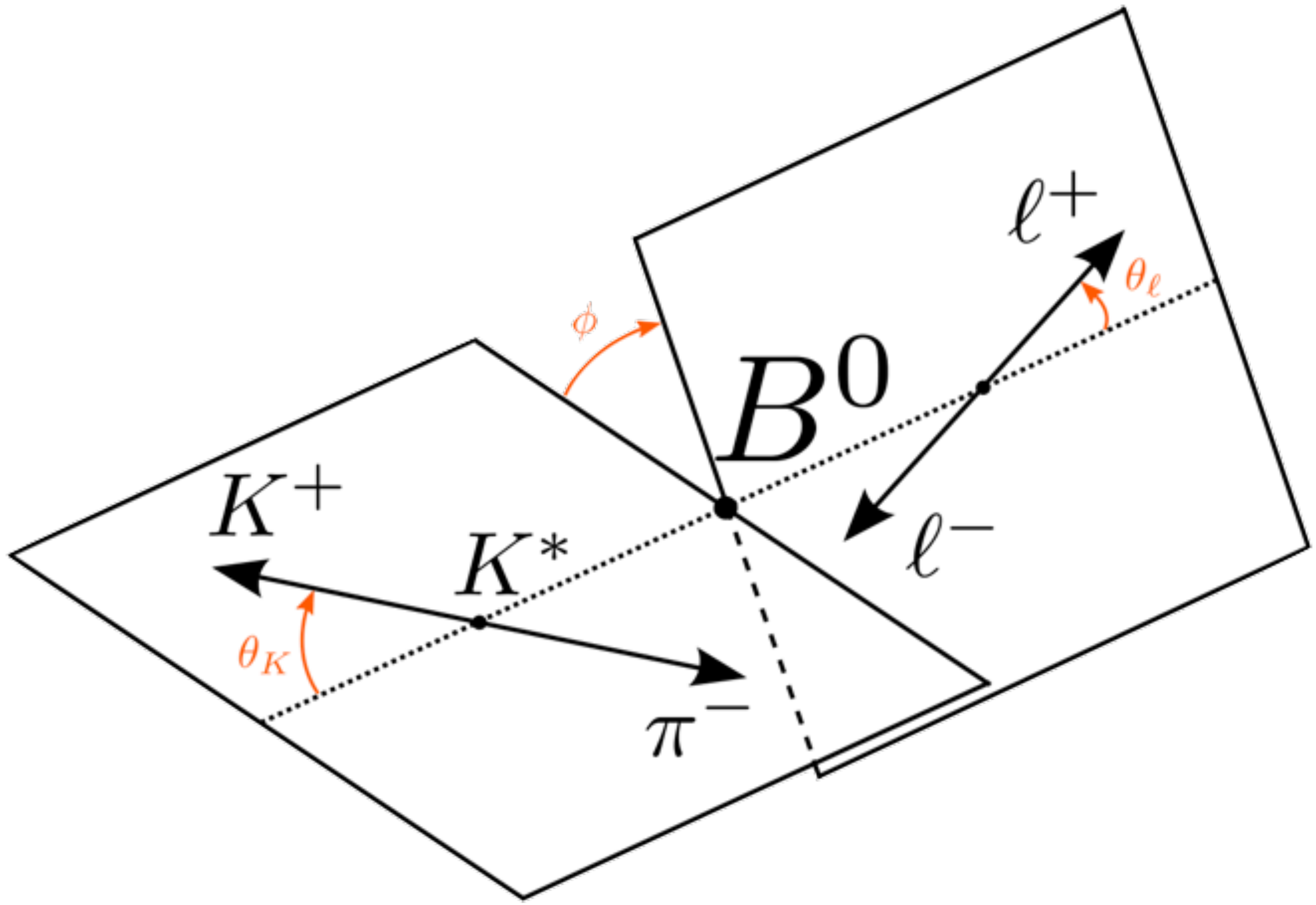


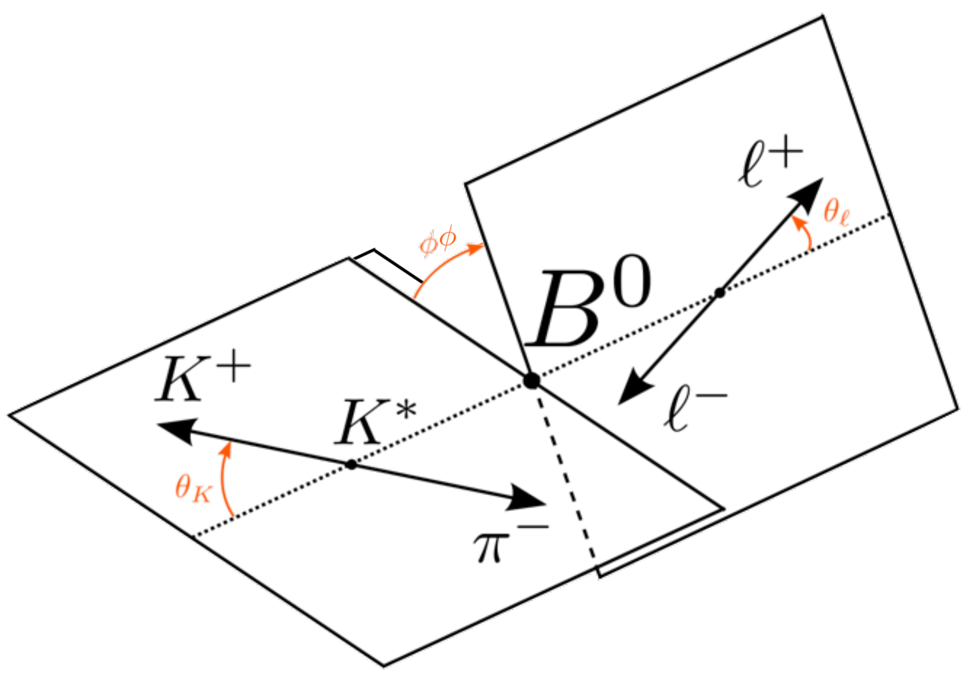
FIG. 2. The CP-averaged observables (left) P_2 and (right) P'_5 in intervals of q^2. The first (second) error bars represent the statistical (total) uncertainties. The theoretical predictions in blue are based on Ref. [77] with hadronic form factors taken from Refs. [78–80] and are obtained with the FLAVIO software package [84] (version 2.0.0). The theoretical predictions in orange are based on Refs. [81,82] with hadronic form factors from Ref. [83]. The gray bands indicate the regions of excluded $\phi(1020)$, J/ψ, and $\psi(2S)$ resonances.

Angular analysis of $B \to K^* \ell^+ \ell^-$



Angular analysis of $B \to K^*\ell^+\ell^-$

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$



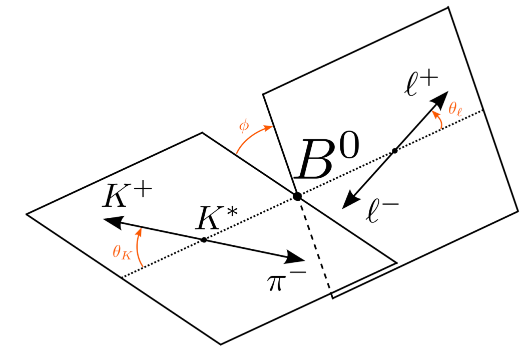
$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

considered to be largely free from form-factor uncertainties

Extract transverse polarization asymmetry $A_T^{(2)} = 2S_3/(1-F_L)$

Angular analysis of $B \to K^* \ell^+ \ell^-$

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$



$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

considered to be largely free from form-factor uncertainties

Extract transverse polarization asymmetry $A_T^{(2)} = 2S_3/(1-F_L)$

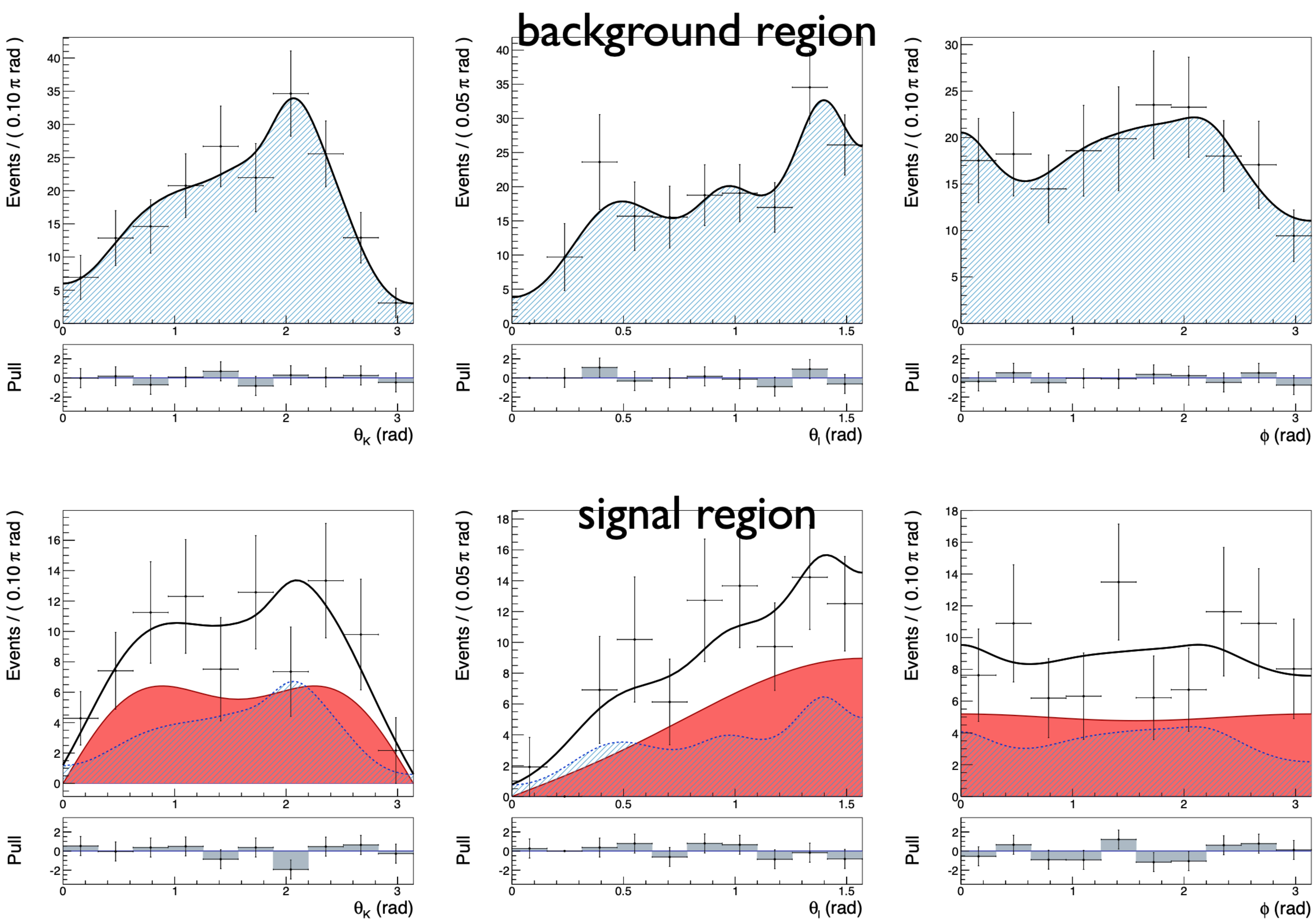
- not enough statistics to perform full 8-dim fit for angular analysis
- reduce the # of fit parameters (hence improve fit convergence) by 'folding' technique à la LHCb
- For example,

$$P'_4, S_4 : \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \phi \to \pi - \phi & \text{for } \theta_\ell > \pi/2 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2, \end{cases} \qquad P'_5, S_5 : \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2 \end{cases}$$

- Each of these foldings cause all the other S_i's (except for S_3) to vanish
  $\Rightarrow$ #(fit parameters) is reduced: $8 \to 3$

PRL 118, 111801 (2017)

Fit projections for P_5' of $B \to K^*\ell^+\ell^-$

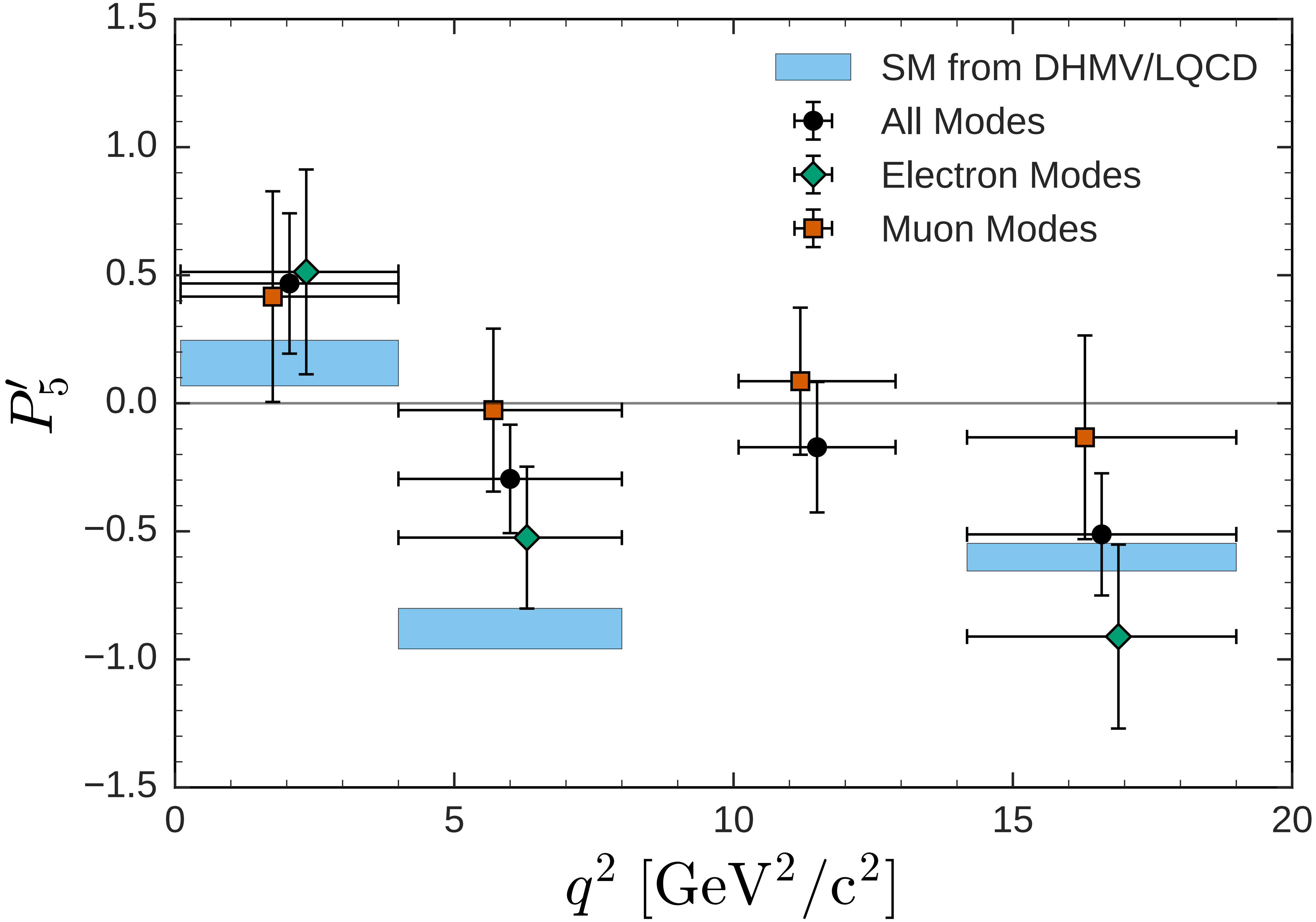


Bin #2

$4.0 < q^2 < 8.0$

bkgd.
signal
total

P'_5 of $B \to K^*\ell^+\ell^-$



- compatible with both SM and LHCb
- 2.6σ in μ mode
  1.3σ in e mode

tension from SM is in the same direction as in LHCb

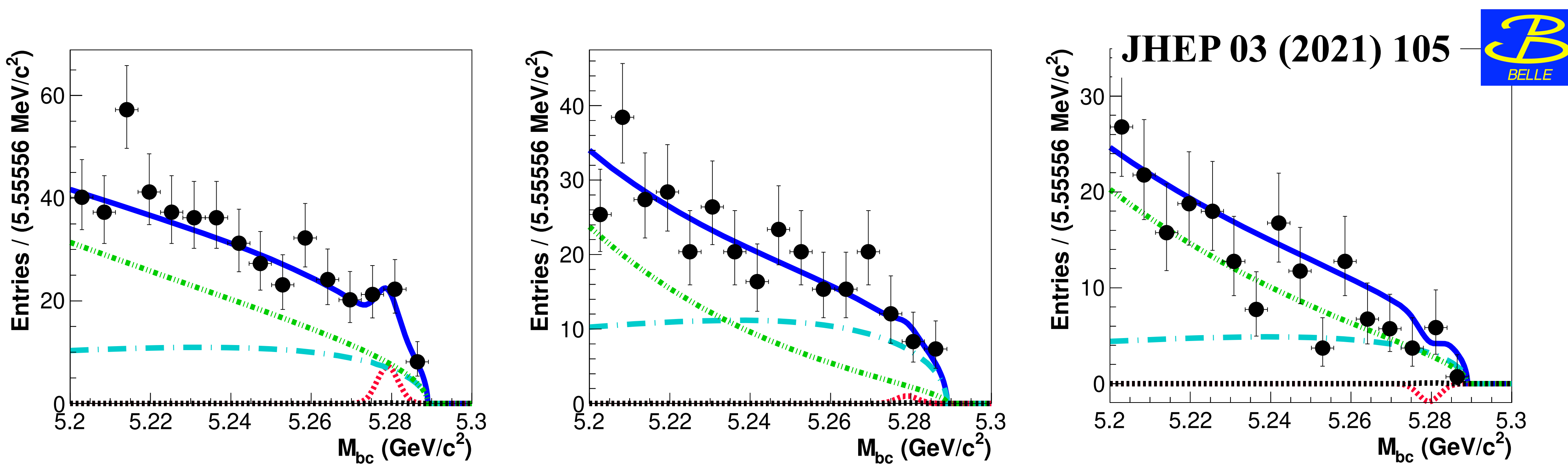
LFV in $B \to K^{(*)}\ell^+\ell'^-$

- 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 $B \to K^{(*)}\ell^+\ell'^-$ $(\ell' \neq \ell)$?

JHEP 03 (2021) 105



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

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

$\mathcal{B}(B^0 \to K^0_S\mu^-e^+) < 3.8 \times 10^{-8}$

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

$R(D^{(*)})$ & B decays to τ

- $B^0 \to \ell^\pm \tau^\mp$
- $B \to K^{*0} \tau^+ \tau^-$
- $B^+ \to K^+ \tau^\pm \ell^\mp$ *(not today)*
- $B \to D^{(*)} \tau^+ \nu_\tau$ and related

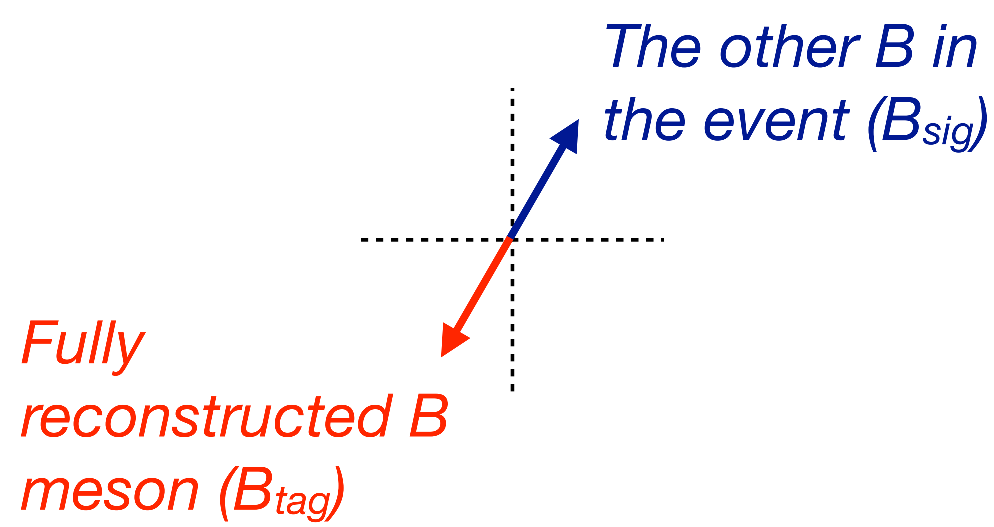
PRD 104, L091105 (2021)

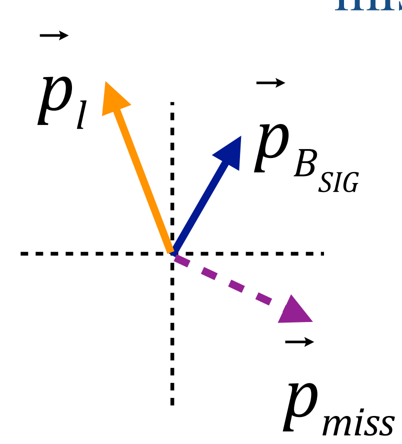
Search for $B^0 \to \ell^\pm \tau^\mp$ (intro.)

- LFV, hence forbidden in the SM
- can occur via ν-mixing, but very small $\sim\mathcal{O}(10^{-54})$[1]
- NP models (e.g. Pati-Salam LQ) can predict $\mathcal{B} \sim \mathcal{O}(10^{-9})$[11]
  - ✓ leptoquarks, SUSY See-saw models, etc.
- Existing limits
  - ✓ $\mathcal{B} \lesssim (1-2)\times 10^{-5}$ by BaBar, LHCb
- use hadronic B-tagging
- do not explicitly reconstruct τ; instead, look at recoil mass

[1] L. Calibbi and G. Signorelli, Charged lepton flavour violation: An experimental and theoretical introduction, Riv. Nuovo Cimento **41**, 71 (2018).

[11] A. D. Smirnov, Mod. Phys. Lett. A **33**, 1850019 (2018).



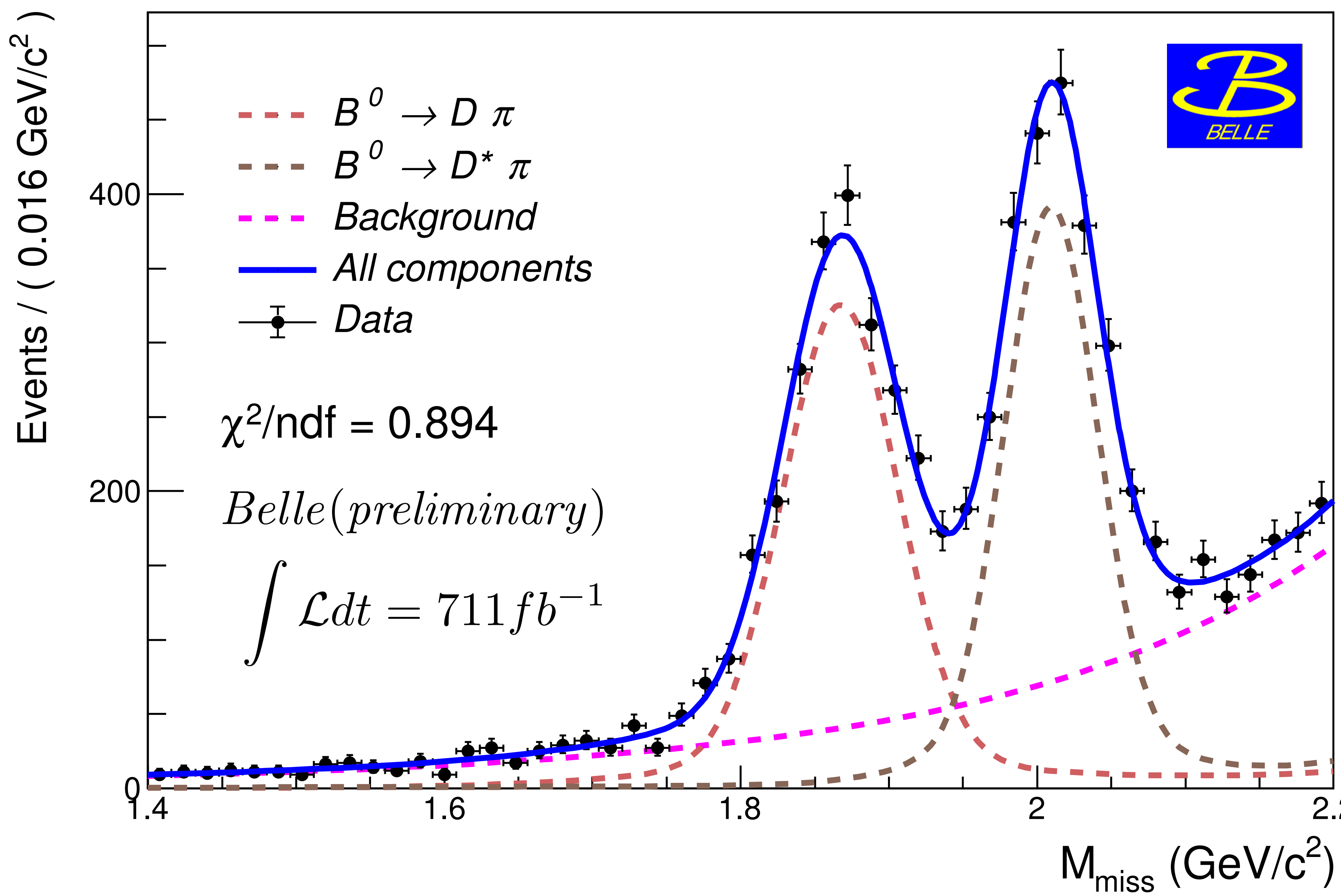


$$M_{\text{miss}} = \sqrt{E_{\text{miss}}^2 - |\vec{p}_{\text{miss}}|^2}$$

$$p^\mu_{\text{miss}} = p^\mu_{B\text{sig}} - p^\mu_\ell$$

Search for $B^0 \to \ell^\pm \tau^\mp$ (validation)

- Validation with $B \to D^{(*)}\pi$

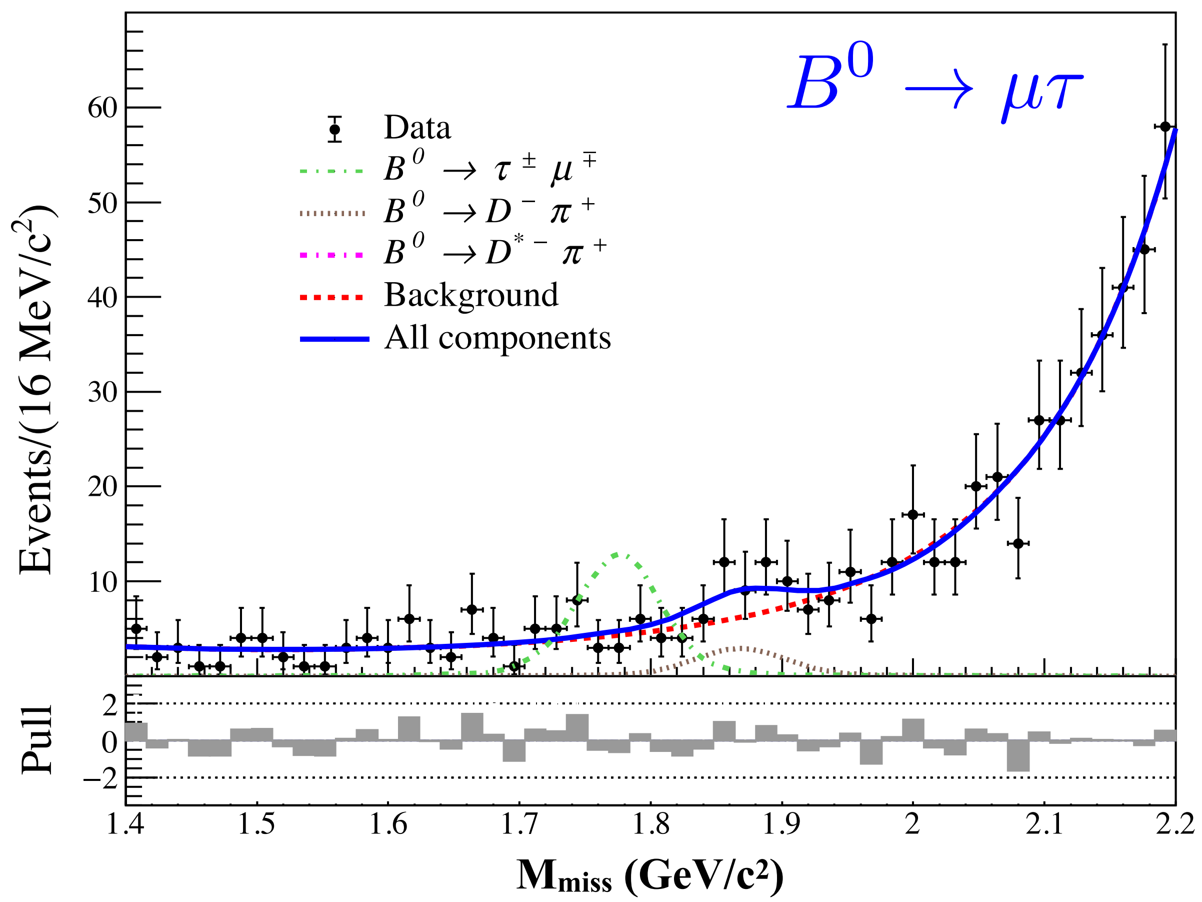


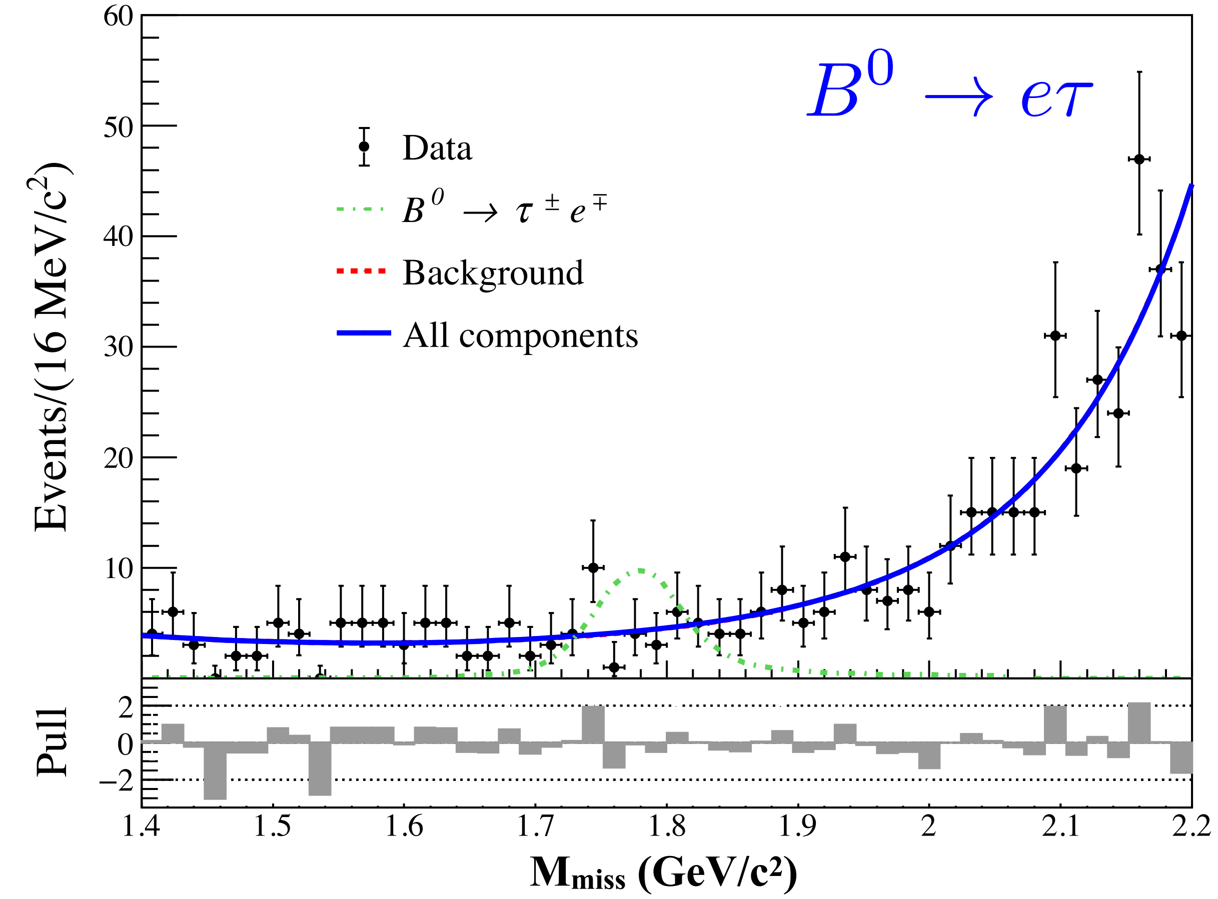
branching fractions in 10^{-3}

Mode	World average	This measurement
$B^0 \to D^-\ \pi^+$	2.52 ± 0.13 (stat+sys)	2.54 ± 0.11 (stat)
$B^0 \to D^{*-}\ \pi^+$	2.74 ± 0.13 (stat+sys)	2.67 ± 0.12 (stat)

Search for $B^0 \to \ell^\pm \tau^\mp$ (results)

- extract signal yield by unbinned extended max. likelihood fit





Signal Efficiency: 1.1 x 10^{-3}

$$N_{sig} = 1.8^{+8.2}_{-7.6}$$

$$\mathscr{B}(B^0 \to \mu\tau) < 1.5 \times 10^{-5}$$

Signal Efficiency: 1.0 x 10^{-3}

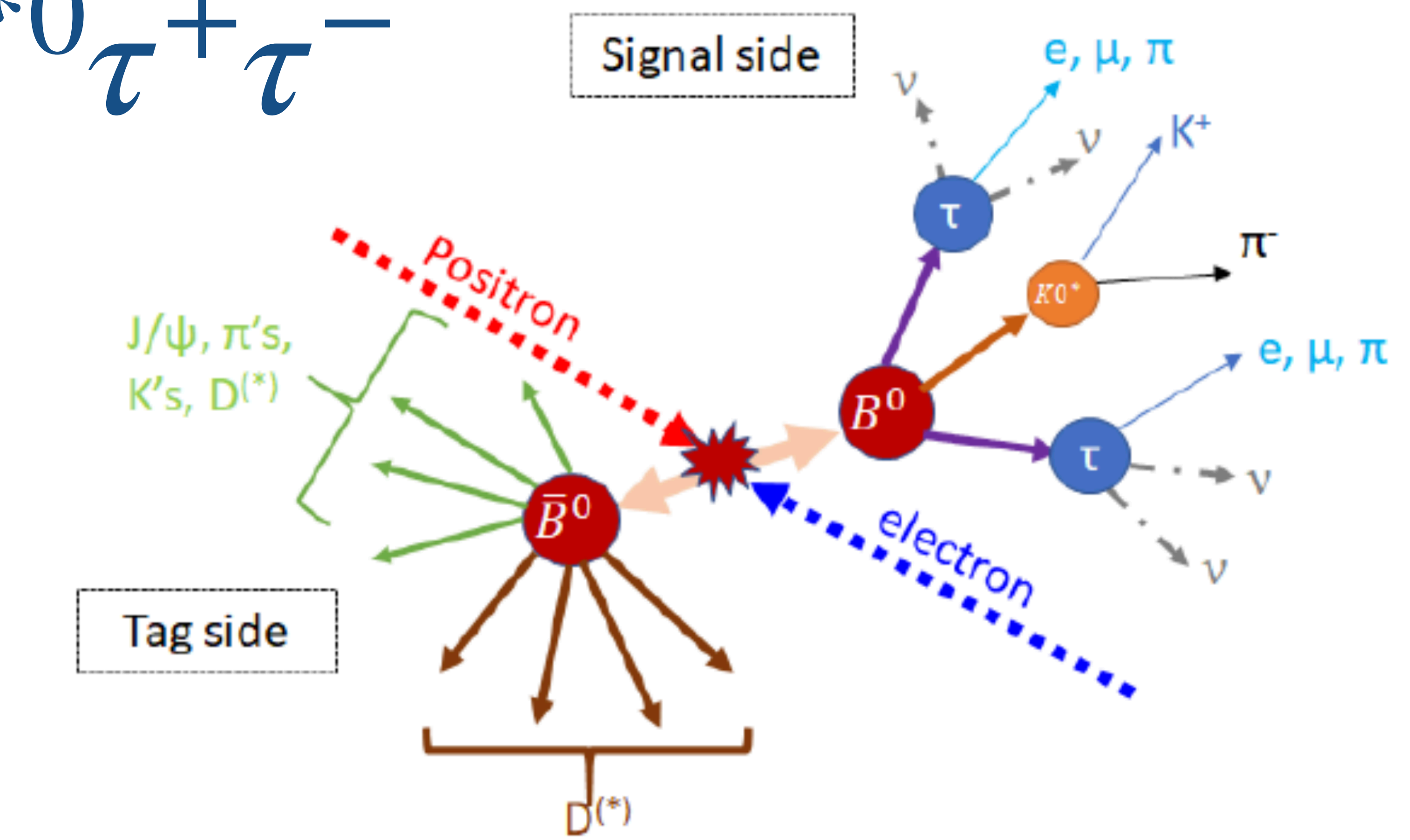
$$N_{sig} = 0.3^{+8.8}_{-8.2}$$

$$\mathscr{B}(B^0 \to e\tau) < 1.6 \times 10^{-5}$$

arXiv:2110.03871
submitted to PRD

Search for $B^0 \to K^{*0}\tau^+\tau^-$

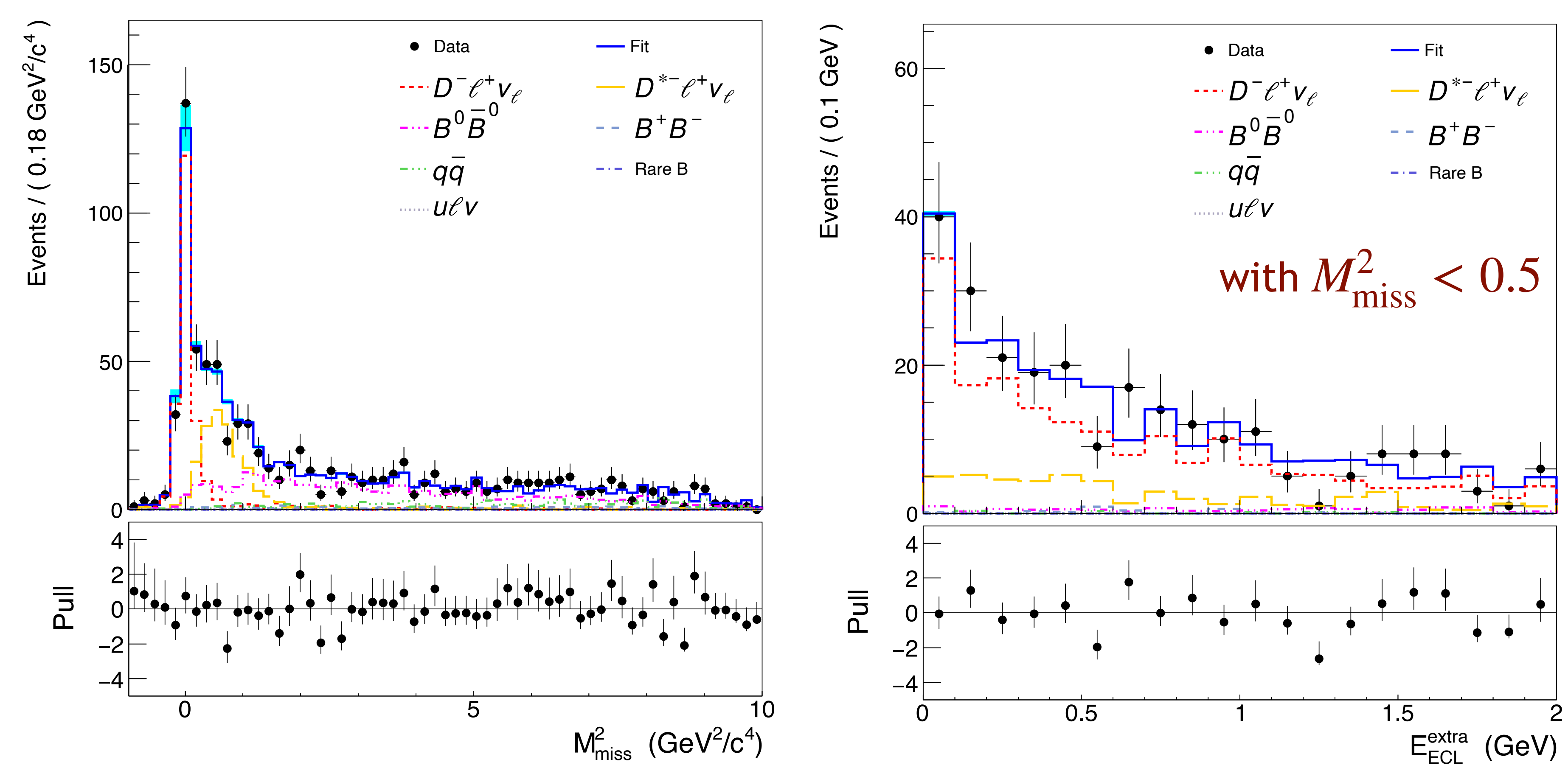
- Highly suppressed in SM : $\mathscr{B}_{SM} \sim \mathcal{O}(10^{-7})$
- Test of R_{K^*} with 3rd gen. lepton (τ)
  - potentially very sensitive to NP
- the only experimental result of $b \to s\tau^+\tau^-$:
  $\mathscr{B}(B^+ \to K^+\tau^+\tau^-) < 2.25 \times 10^{-3}$ (BaBar, 2017)



- use hadronic B-tagging
- Signal yield is extracted using E_{ECL}^{extra}
  - cross-check with $\mathscr{B}(B \to D^{(*)}\ell\nu)$

$$\mathscr{B} = (2.26 \pm 0.17)\,\% \text{ with } E_{ECL}^{extra}$$
$$= (2.19 \pm 0.15)\,\% \text{ with } M_{miss}^2$$

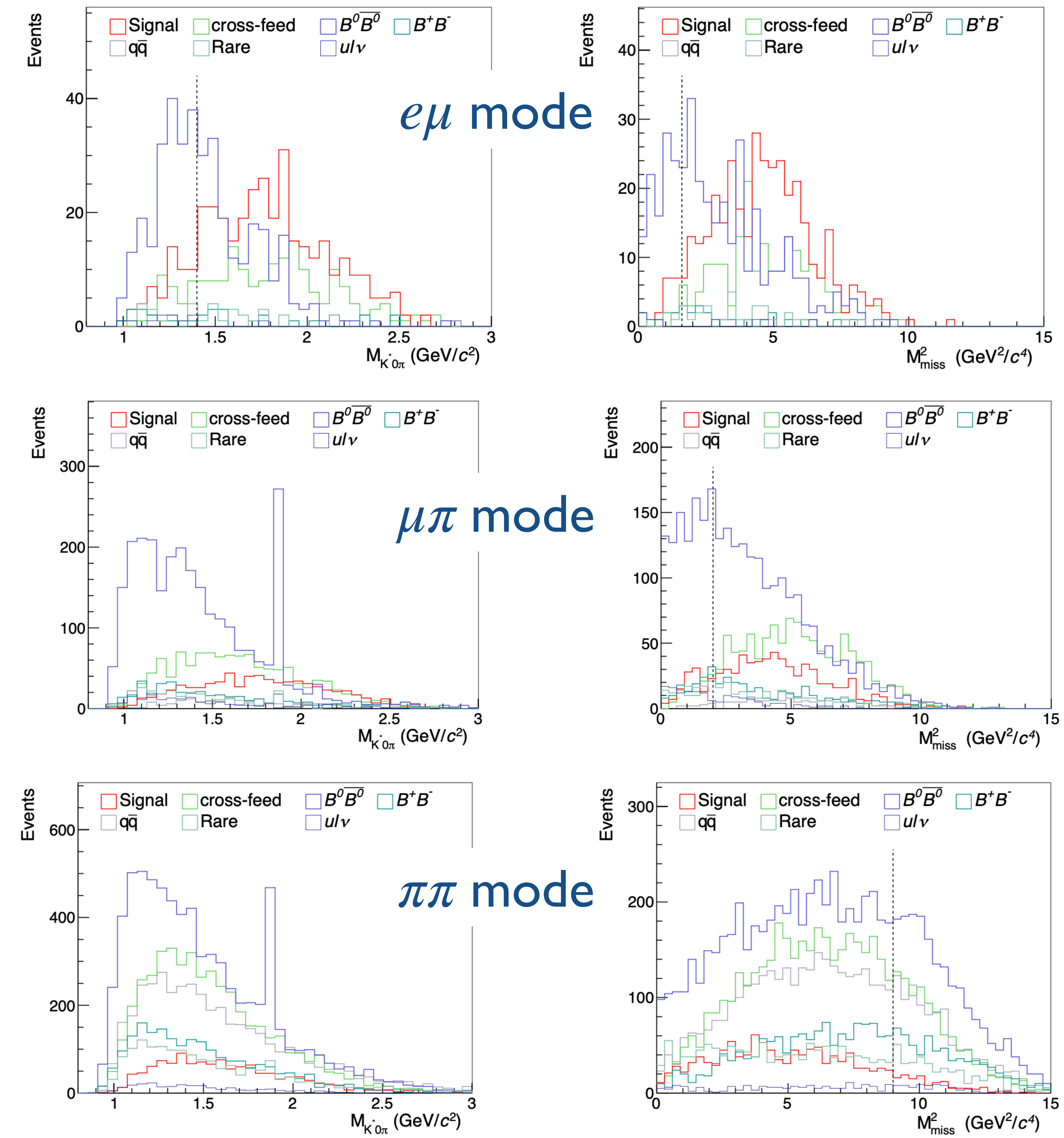
compare w/ $(2.31 \pm 0.10)\,\%$ W. Avg.



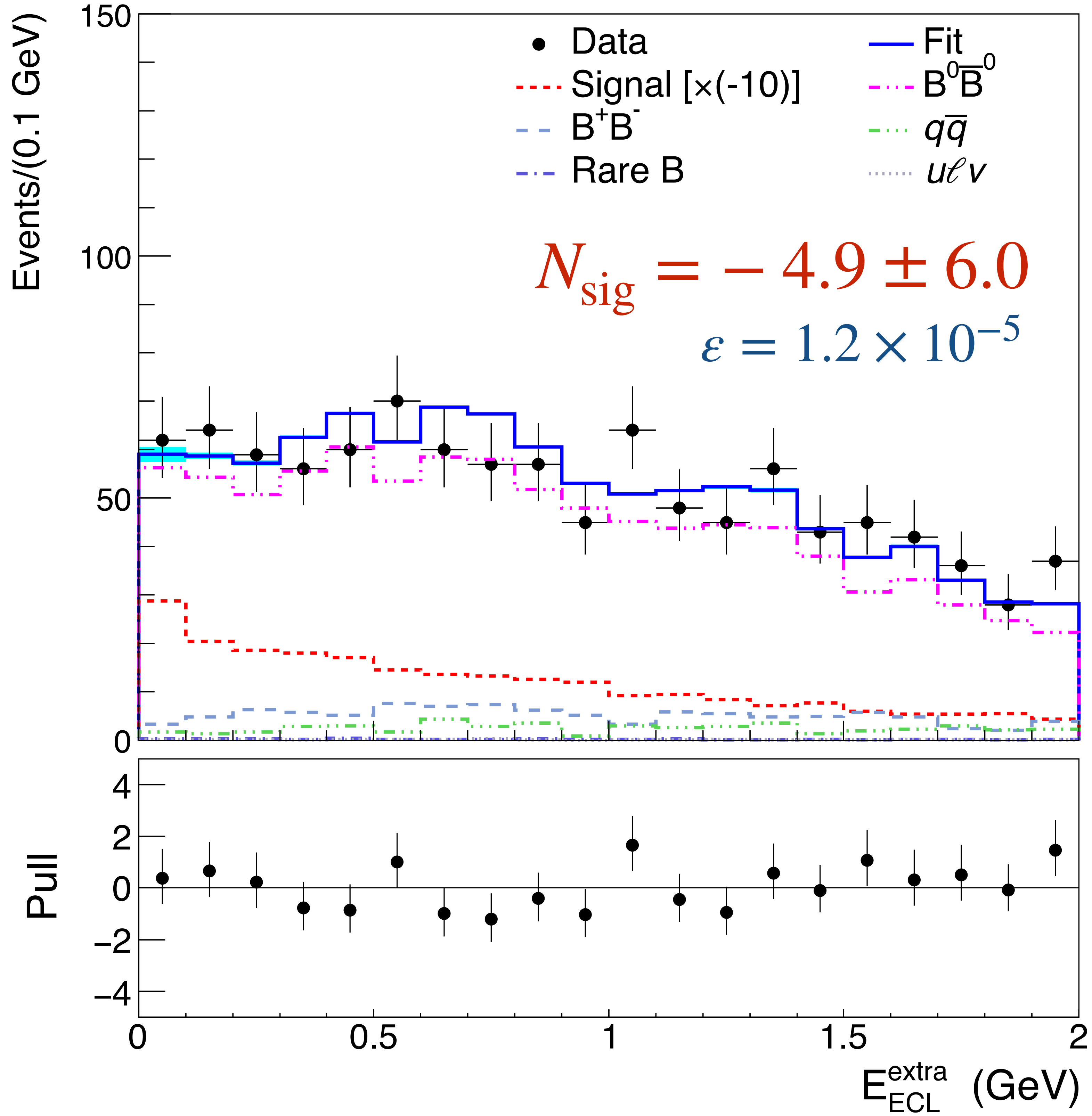
Search for $B^0 \to K^{*0}\tau^+\tau^-$

- Main backgrounds (*same final-state particles*)
  - $B^0 \to D^{(*)-}\ell^+\nu$, $D^- \to K^{*0}\ell^-\bar{\nu}$ (for ee, $e\mu$, $\mu\mu$ modes)
  - $B^0 \to D^{(*)-}X$, $D^- \to K^{*0}\pi^-$ (for $e\pi$, $\mu\pi$, $\pi\pi$ modes)
- Background suppression with $M^2_{\rm miss}$ & $M_{K^*\pi^-}$

Signal Mode	$M_{K^{*0}\pi^-}$ (GeV/c^2)	$M^2_{\rm miss}$ (GeV^2/c^4)
$K^{*0}e^+e^-$	> 1.4	> 3.2
$K^{*0}e^\mp\mu^\pm$	> 1.4	> 1.6
$K^{*0}\mu^+\mu^-$	> 1.6	> 1.6
$K^{*0}\pi^\mp e^\pm$	> 1.4	> 2.0
$K^{*0}\pi^\mp\mu^\pm$	> 1.4	> 2.0
$K^{*0}\pi^+\pi^-$	> 1.5	< 9



Search for $B^0 \to K^{*0}\tau^+\tau^-$



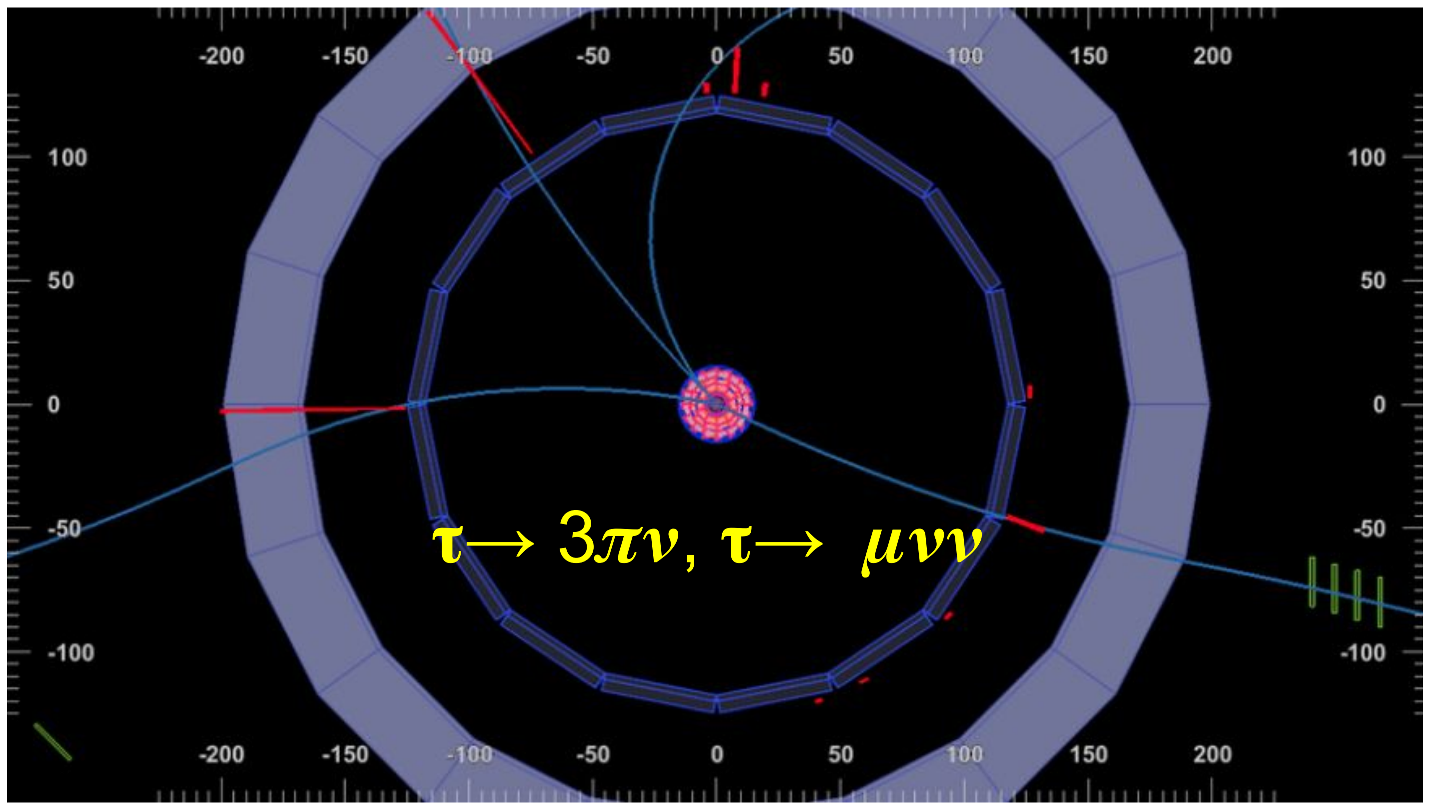
Source	error(%)
statistics	5.2
Number of $B^0\bar{B}^0$	1.8
Tag efficiency	4.6
Tracking	1.4
K-ID	1.25
π-ID	1.15
e-ID	1.66
μ-ID	0.93
K-short veto	0.17
π^0 veto	1.56
Sum	7.88

$$\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-) < 2.0 \times 10^{-3} \text{ @ } 90\% \text{ CL}$$

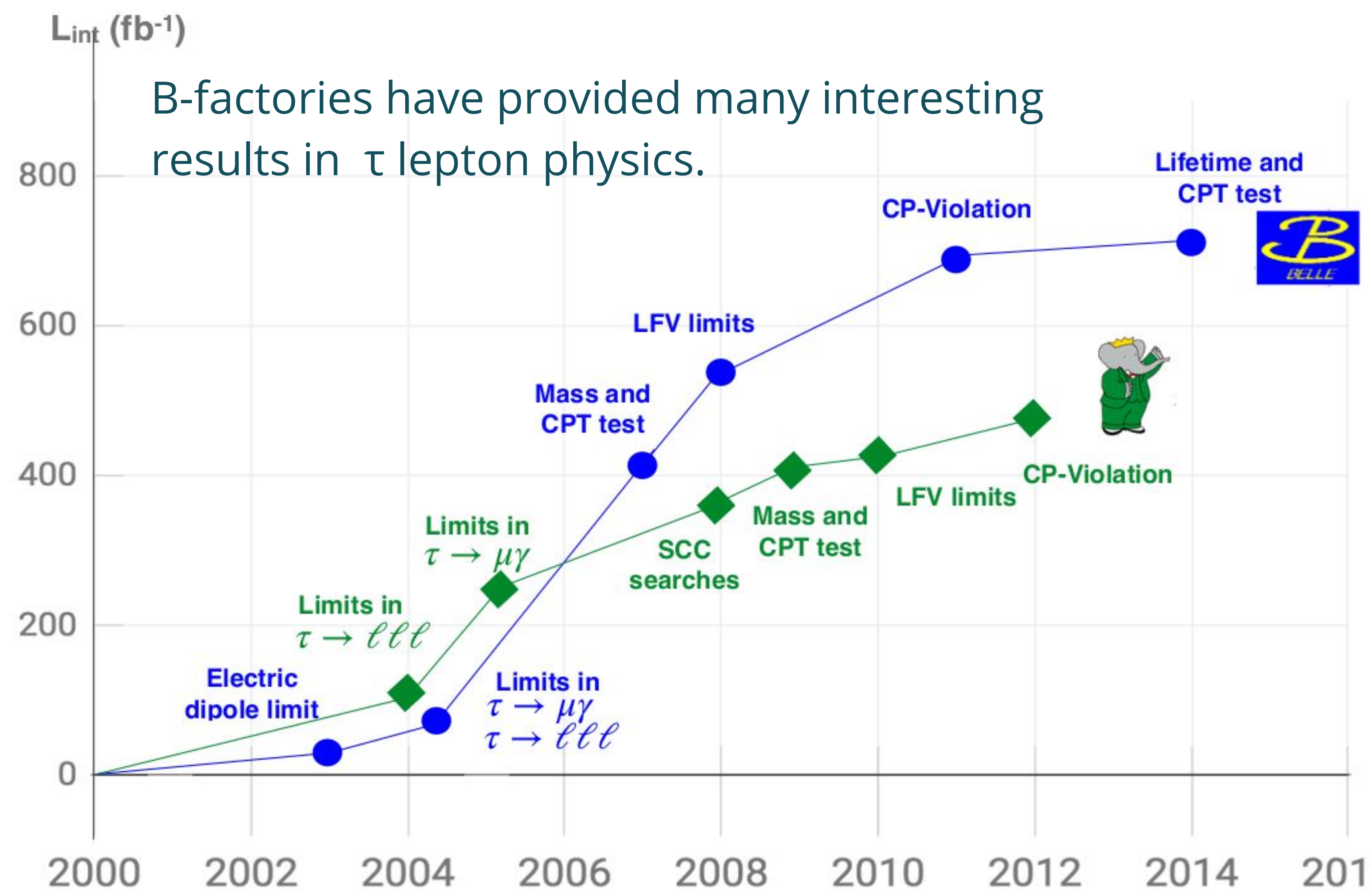
more on τ from Belle, Belle II

- $\tau^+ \to \ell^+\gamma$ (LFV)
- τ EDM

Why τ at a B-factory?



- $\sigma(ee \to \tau\tau) \simeq \sigma(ee \to b\bar{b})$
- low bkgd. & high resolution
- absolute BF



τ LFV in new physics beyond-SM

Ratios of τ LFV decay BF's allow one to discriminate between new physics models

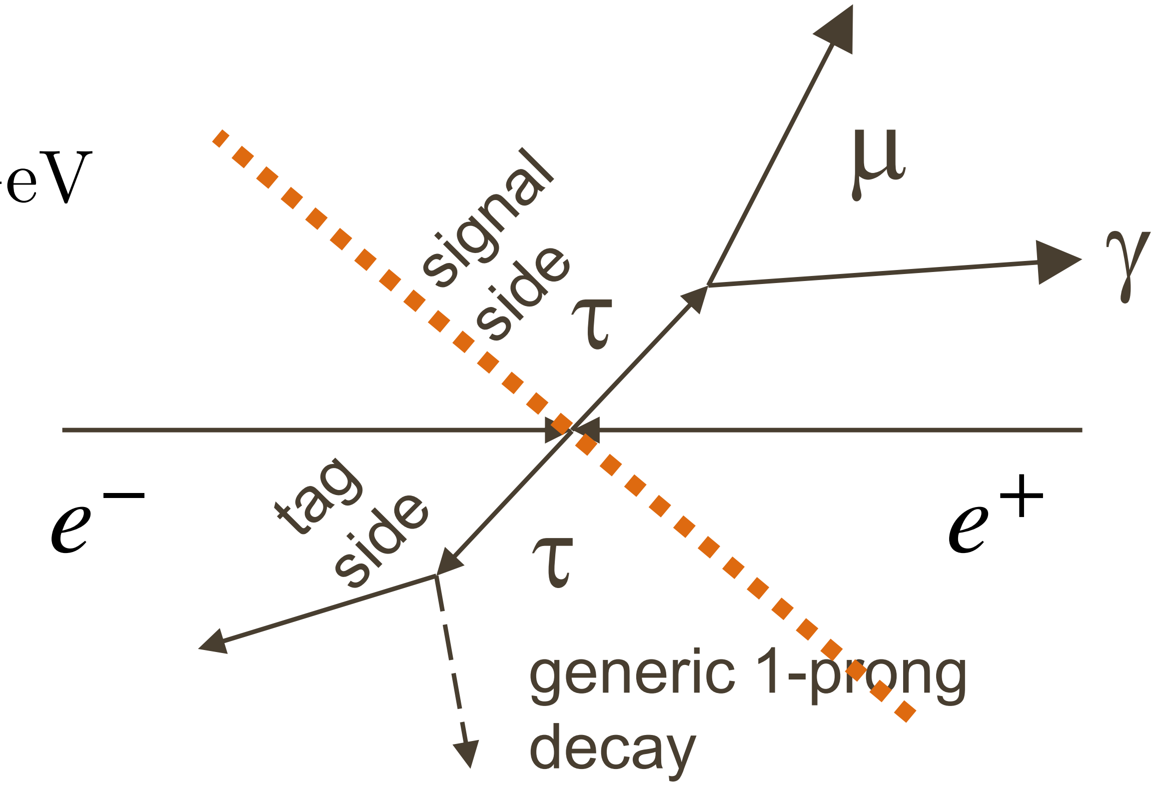
	SUSY+GUT (SUSY+Seesaw)	Higgs mediated	Little Higgs	non-universal Z'
$\frac{\mathcal{B}(\tau \to \mu\mu\mu)}{\mathcal{B}(\tau \to \mu\gamma)}$	~2 x 10^{-3}	0.06 - 0.1	0.4 - 2.3	~16
$\frac{\mathcal{B}(\tau \to \mu ee)}{\mathcal{B}(\tau \to \mu\gamma)}$	~1 x 10^{-2}	~1 x 10^{-2}	0.3 - 1.6	~16
$\mathcal{B}(\tau \to \mu\gamma)_{\max}$	$< 10^{-7}$	$< 10^{-10}$	$< 10^{-10}$	$< 10^{-9}$

JHEP 0705, 013 (2007); PLB 547, 252 (2002)

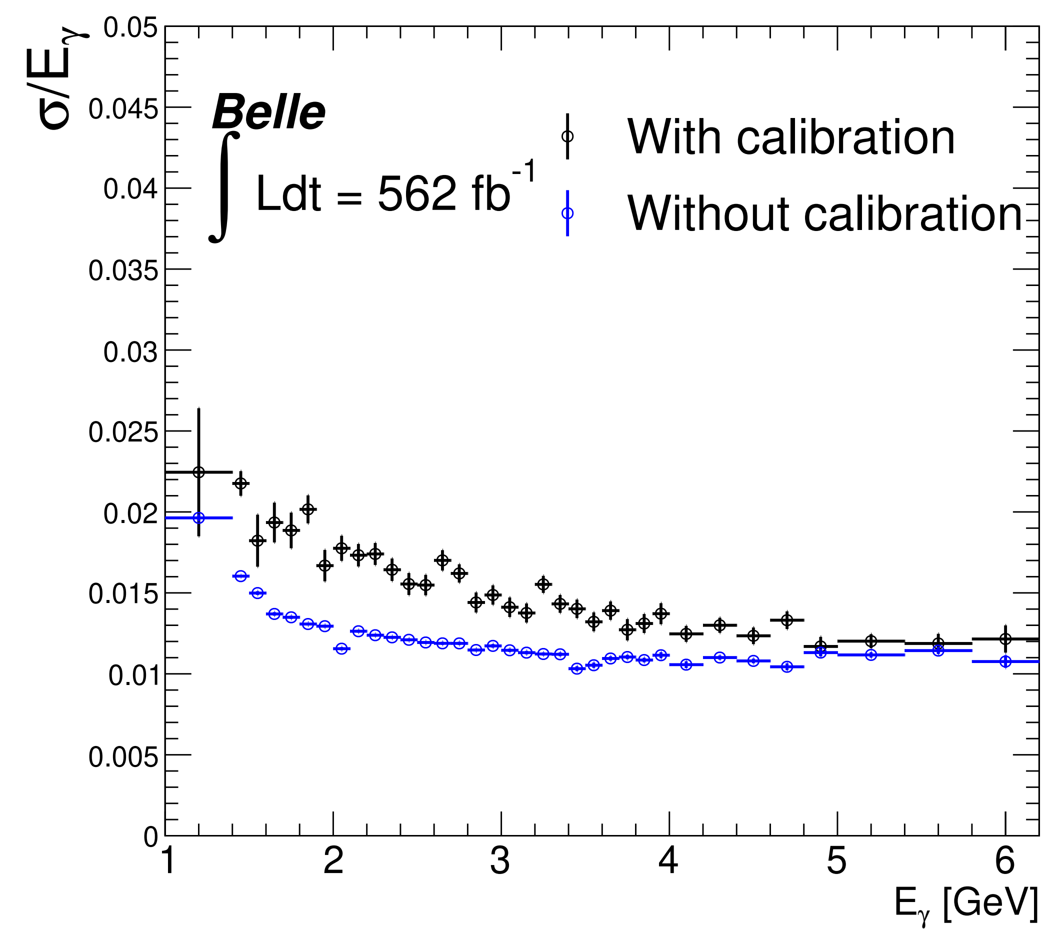
$\therefore$ Good to measure LFV in as many modes as possible!

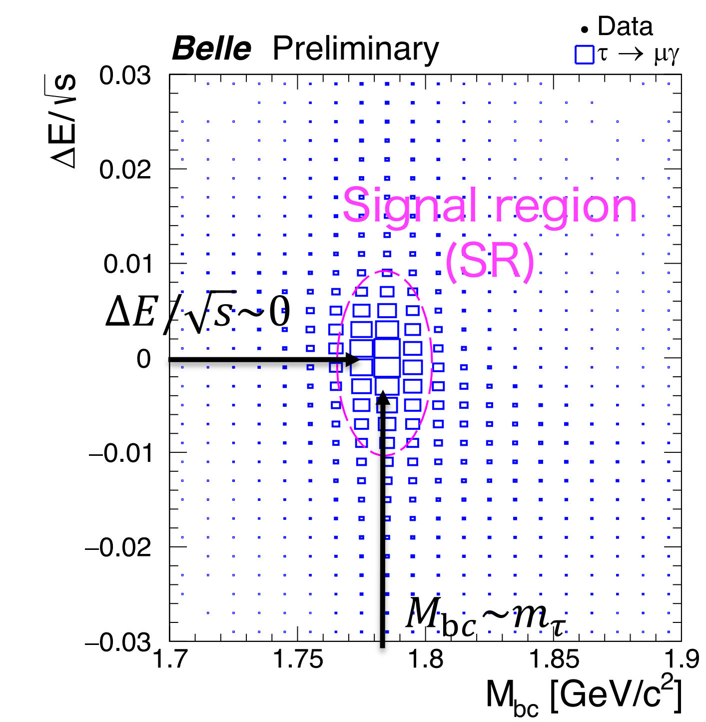
Search for $\tau^+ \to \ell^+ \gamma$

- $\sigma(e^+e^- \to \tau^+\tau^-) = (0.919 \pm 0.003)$ 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 $\Delta E/\sqrt{s}$



- Calibration of E_γ by $e^+e^- \to \mu^+\mu^-\gamma$ events
  - by comparing $E_\gamma - E_{\rm recoil}$ (data vs. MC), where $E_{\rm recoil} = \sqrt{s} - E_{\mu^+} - E_{\mu^-}$
  - calibrated resolution (for $1 < E_\gamma < 6$ GeV) agrees with data, and with test-beam result
  - performed for the first time at Belle; major improvement over the previous Belle result [PLB 666, 16 (2008)]

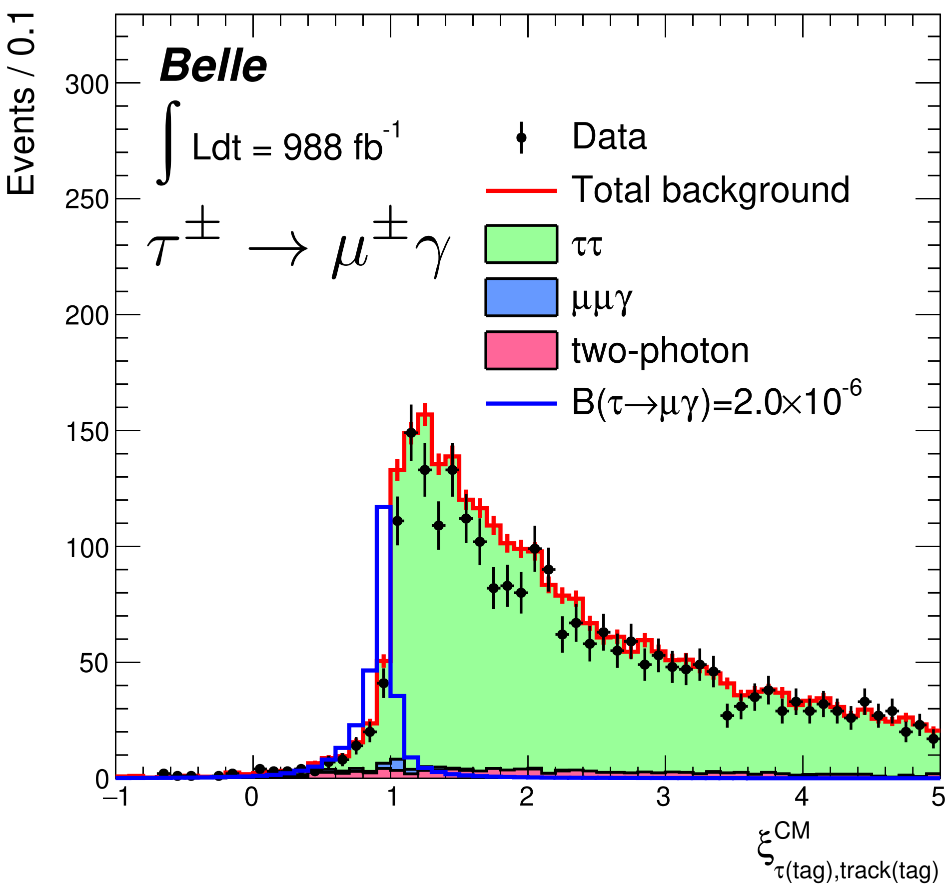




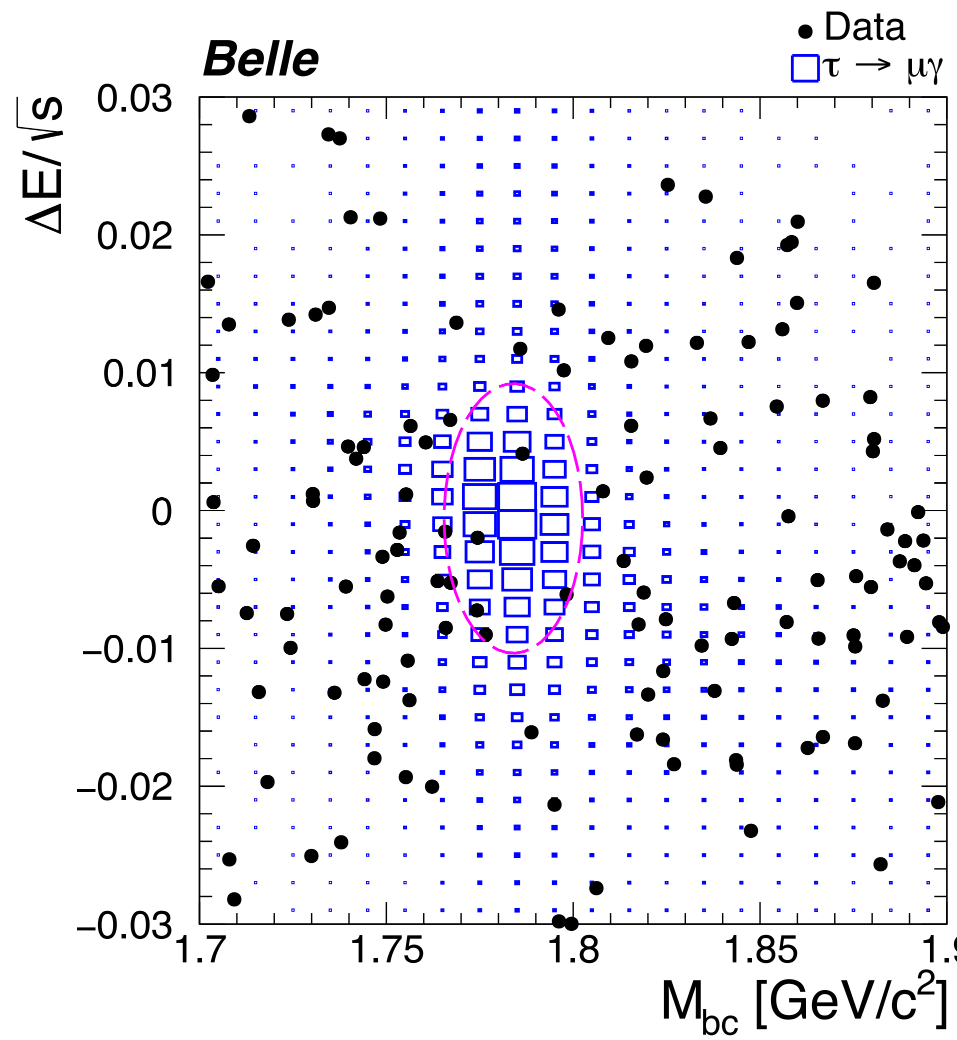
Search for $\tau^+ \to \ell^+\gamma$

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

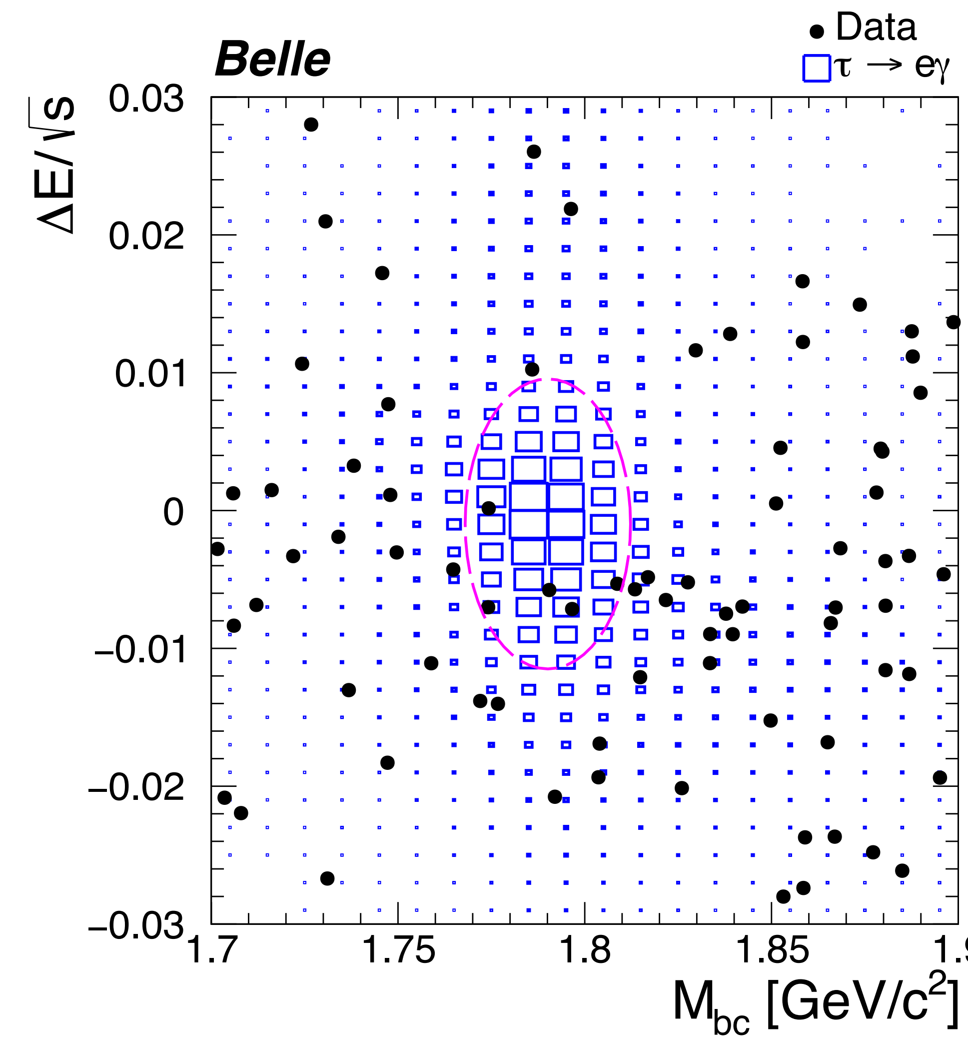
a new variable
to suppress $\tau\tau$ bkgd.



$$\xi^{\text{CM}}_{\tau(\text{tag}),\text{track(tag)}} = \frac{\vec{p}^{\,\text{CM}}_{\tau(\text{tag})} \cdot \vec{p}^{\,\text{CM}}_{\text{track(tag)}}}{|\vec{p}^{\,\text{CM}}_{\tau(\text{tag})}||\vec{p}^{\,\text{CM}}_{\text{track(tag)}}|}$$



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



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

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

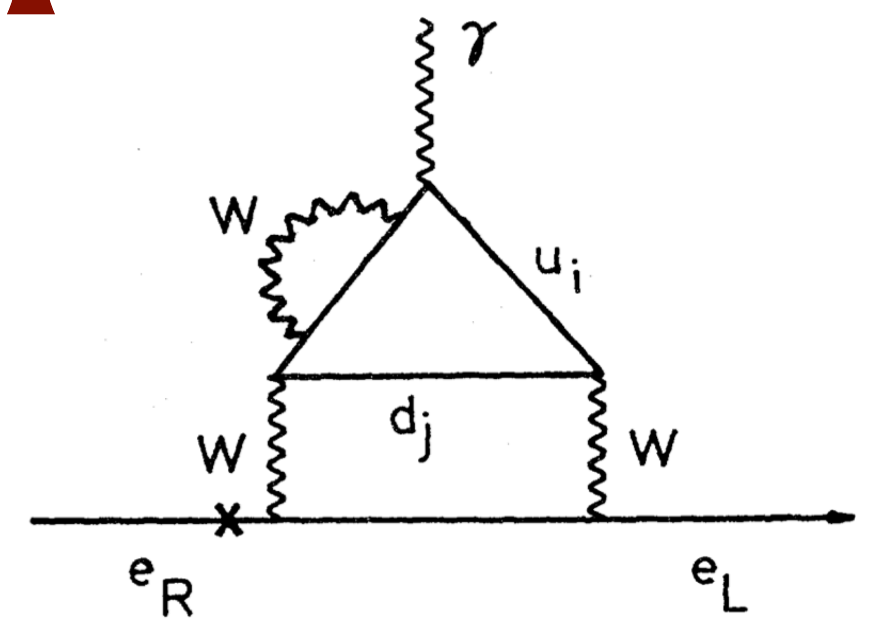
$$\mathcal{B}(\tau^\pm \to e^\pm\gamma) < \frac{\tilde{s}_{90}}{2\epsilon N_{\tau\tau}} = 5.6 \times 10^{-8}$$

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}

Search for τ EDM

EDM of τ

- charge asymmetry along the spin direction
- non-zero EDM ⇒ P , T violation
- CP violation parameter in the $\gamma\tau\tau$ vertex
- SM prediction: $|d_\tau| \sim \mathcal{O}(10^{-37})$ e cm
- a non-zero EDM at Belle (II) sensitivity ⇒ **a clear sign for NP**



from Bernreuther and Suzuki, Rev. Mod. Phys. 63, 313 (1991)

$\mathscr{L}_{\rm eff}$ for $\gamma\tau\tau$

$$\mathcal{L} = \bar{\tau}[-eQ\gamma^\mu A_\mu - id_\tau \sigma^{\mu\nu}\gamma_5 \partial_\mu A_\nu]\tau$$

$$\chi_{\rm prod} = \chi_{\rm SM} + {\rm Re}(d_\tau)\chi_{\rm Re} + {\rm Im}(d_\tau)\chi_{\rm Im} + |d_\tau|^2\chi_{d^2}$$

squared spin-density matrix for $\gamma\tau\tau$ in the process $e^+e^- \to \tau^+\tau^-$

$$\begin{aligned} {\rm Re}(d_\tau) &= (-0.62 \pm 0.63) \times 10^{-17}\ e{\rm cm} \\ {\rm Im}(d_\tau) &= (-0.40 \pm 0.32) \times 10^{-17}\ e{\rm cm} \end{aligned}$$

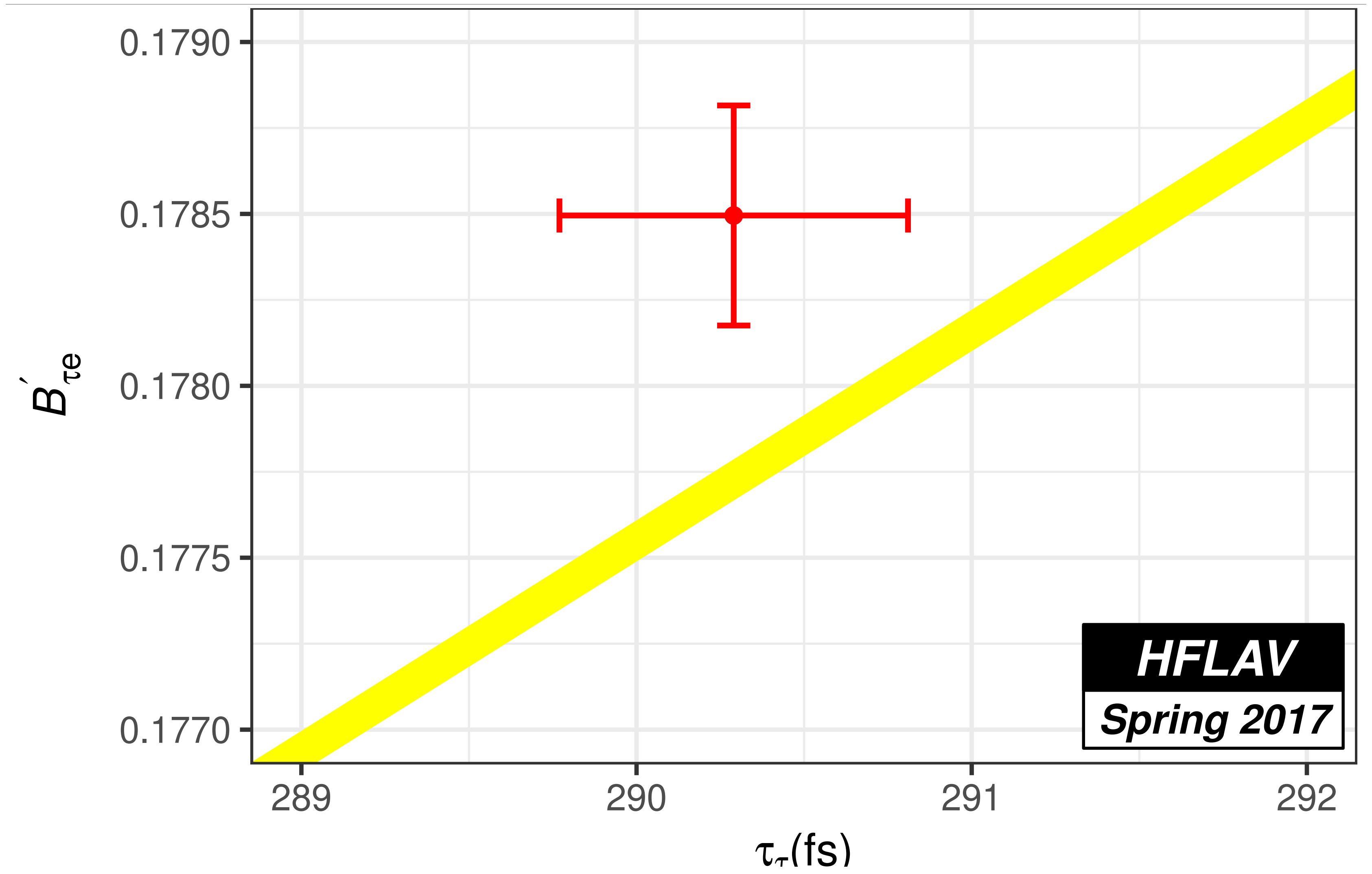
$$\begin{aligned} -1.85 \times 10^{-17} < {\rm Re}(d_\tau) < 0.61 \times 10^{-17}\ e{\rm cm} \\ -1.03 \times 10^{-17} < {\rm Im}(d_\tau) < 0.23 \times 10^{-17}\ e{\rm cm} \end{aligned}$$

- consistent with null τ-EDM
- precision improved by x2.7
- syst. err. ~ stat. err.

τ studies at Belle II

- τ mass
- $\tau^+ \to \ell^+ \alpha$
- *and one more thing!*

τ mass



- m_τ is a crucial element for a test of lepton universality

$$B_{\tau\ell} \propto B_{\mu e} \frac{\tau_\tau}{\tau_\mu} \frac{m_\tau^5}{m_\mu^5}$$

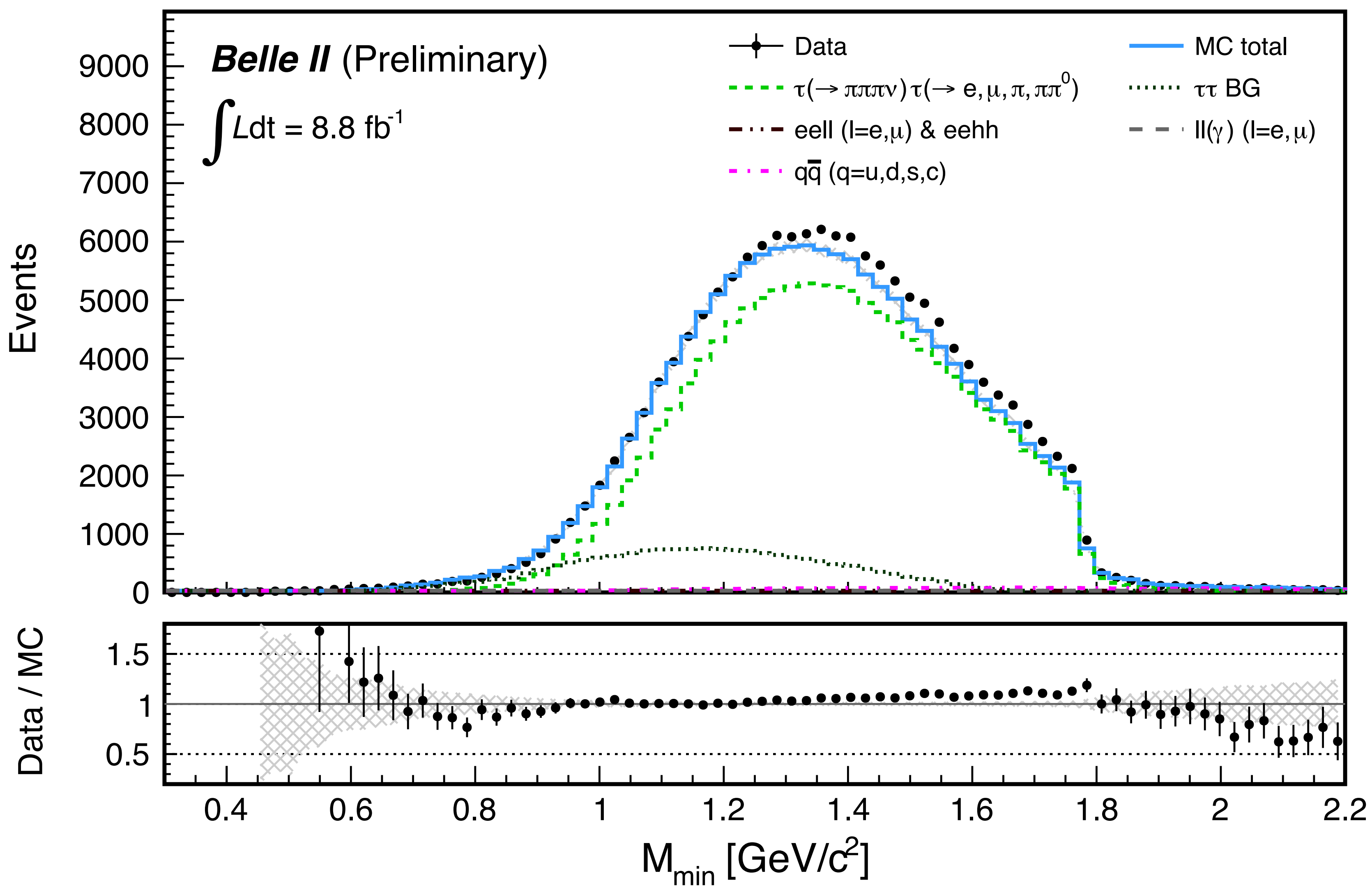
$$m_\tau^2 = (p_h + p_\nu)^2$$
$$= 2E_h(E_\tau - E_h) + m_h^2 - 2|\vec{p}_h|(E_\tau - E_h) \ \cos(\vec{p}_h, \vec{p}_\nu)$$

$\Leftarrow$ approx. $\cos(\mathbf{p}_\nu, \mathbf{p}_h)$

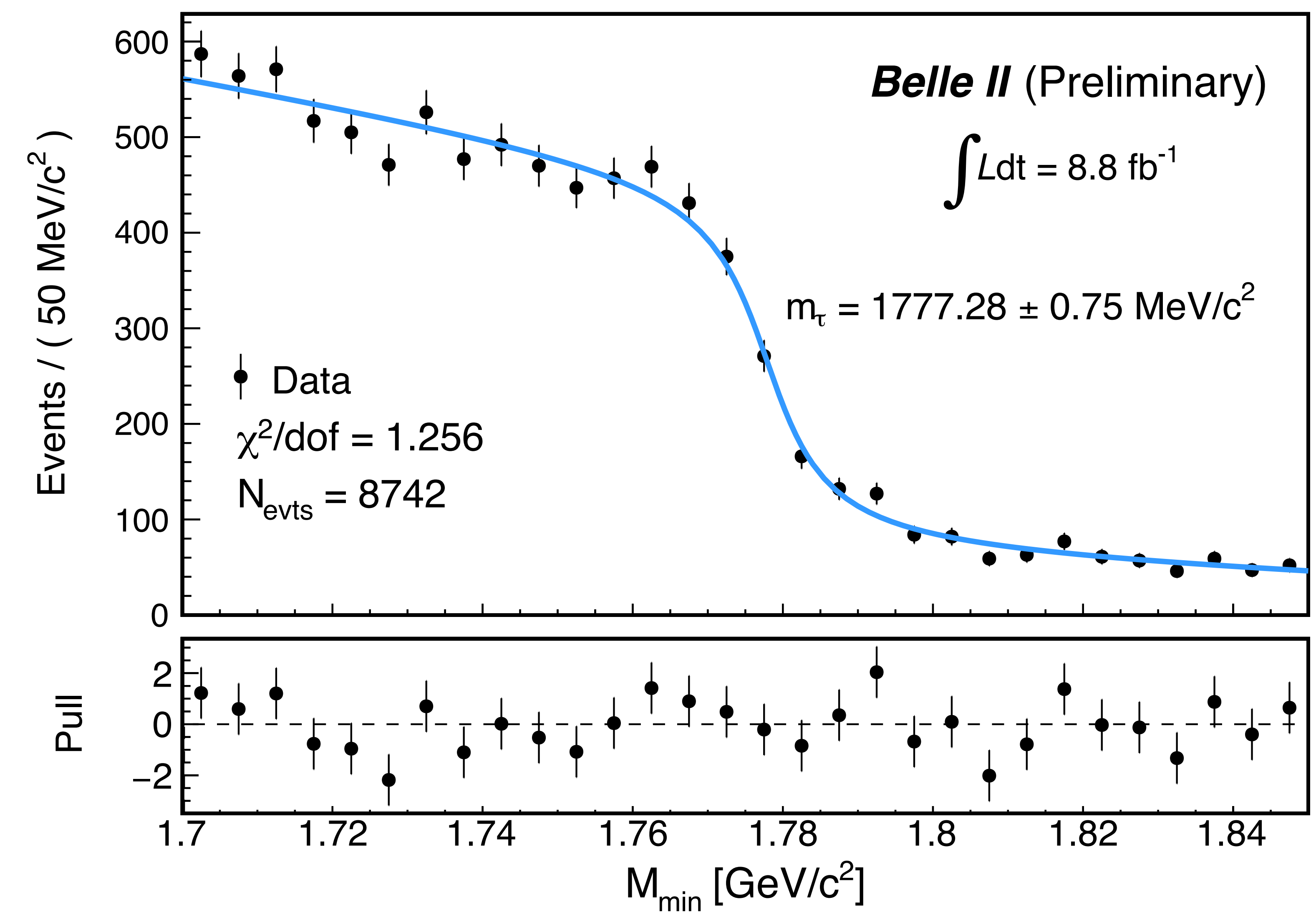
"pseudo-mass" $M_{\min}^2 = 2E_h(E_\tau - E_h) + m_h^2 - 2|\vec{p}_h|(E_\tau - E_h) \ < m_\tau^2$

τ mass

Pseudo mass dist. (data vs. MC)



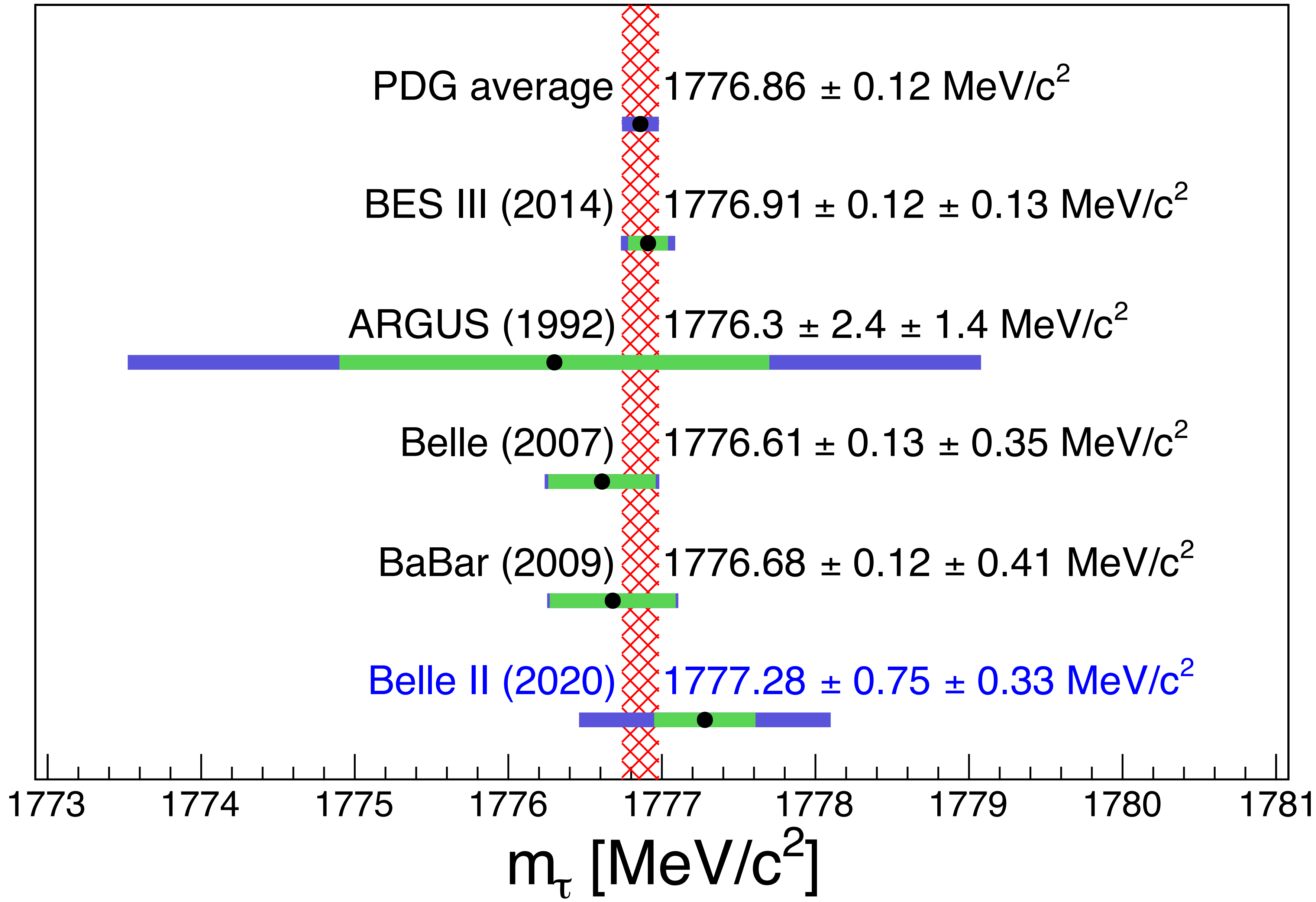
Fitting the edge of $M_{\rm min}$



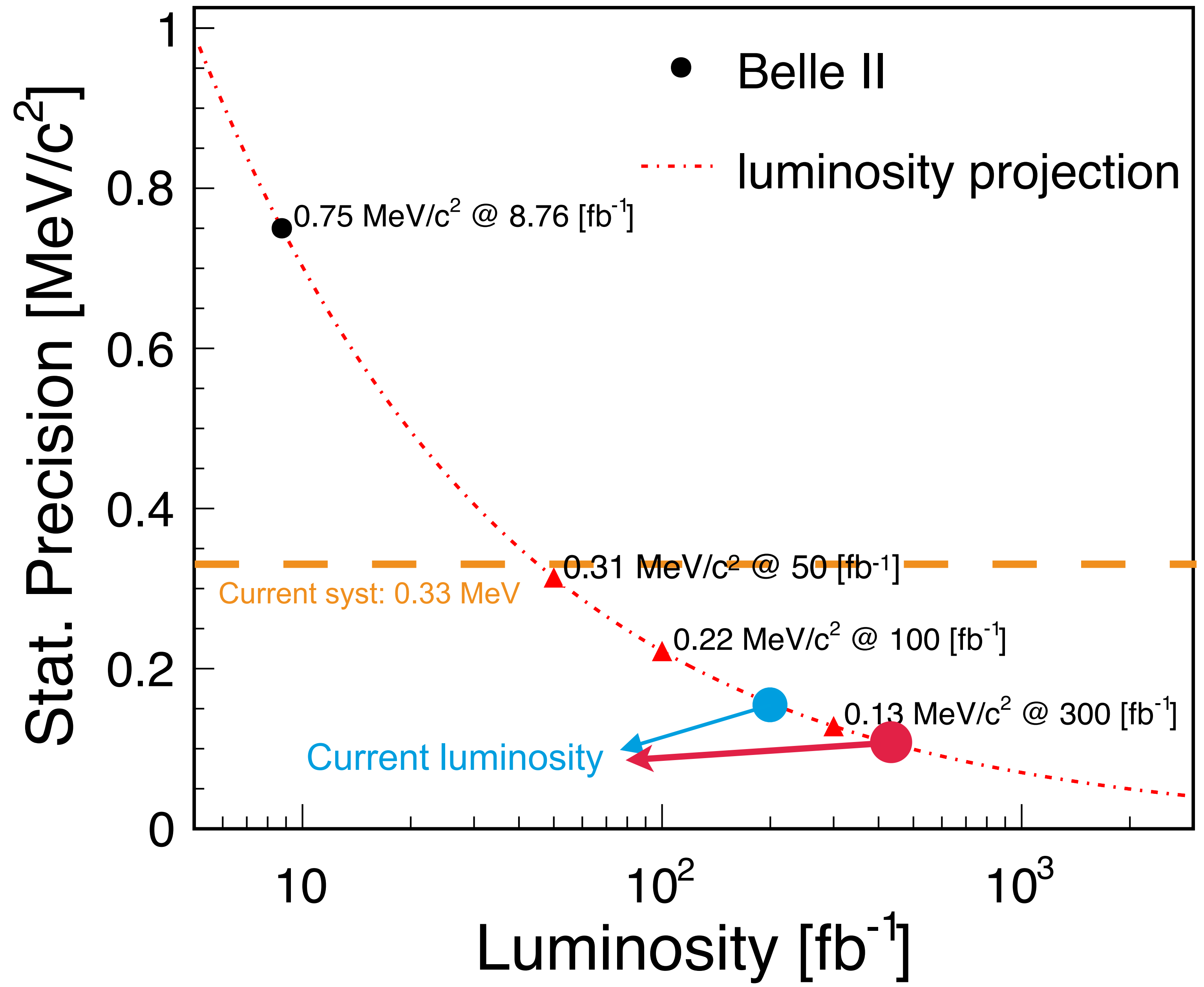
$$F(M, \vec{P}) = (P_3 + P_4 M) \cdot \tan^{-1}[(M - P_1)/P_2] + P_5 M + 1$$

bias corrections, etc. $\Rightarrow$ $m_\tau = 1777.28 \pm 0.75\ (\text{stat.}) \pm 0.33\ (\text{sys.})\ \text{MeV}/c^2$

τ mass



PDG average
1776.86 ± 0.12 MeV/c²
BES III (2014)
1776.91 ± 0.12 ± 0.13 MeV/c²
ARGUS (1992)
1776.3 ± 2.4 ± 1.4 MeV/c²
Belle (2007)
1776.61 ± 0.13 ± 0.35 MeV/c²
BaBar (2009)
1776.68 ± 0.12 ± 0.41 MeV/c²
Belle II (2020)
1777.28 ± 0.75 ± 0.33 MeV/c²
1773 1774 1775 1776 1777 1778 1779 1780 1781
m_τ [MeV/c²]

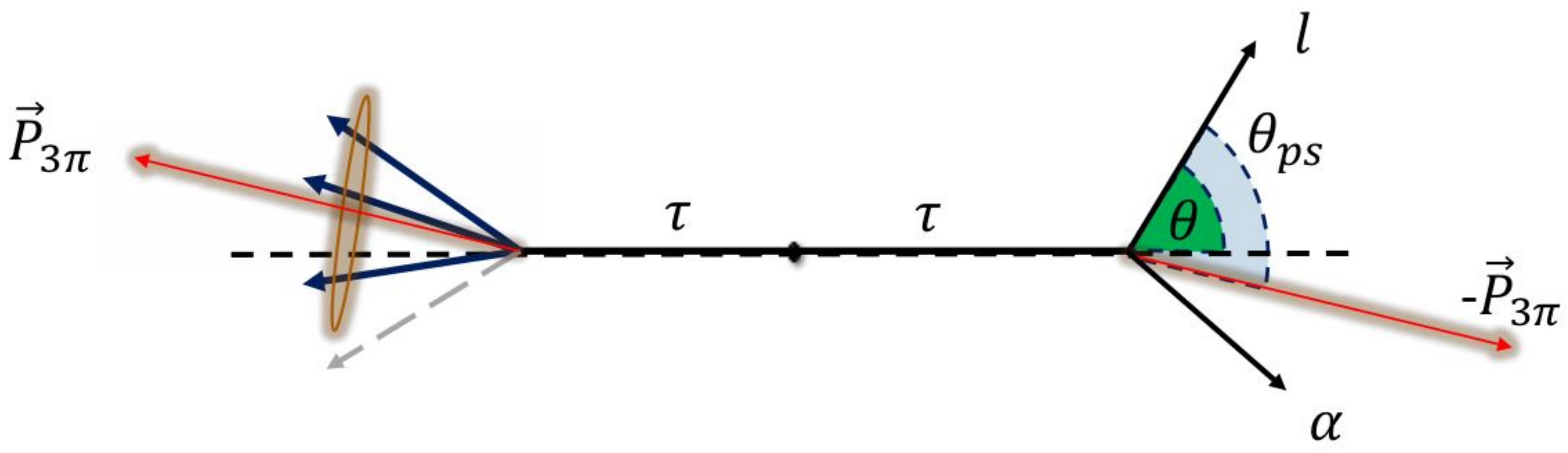


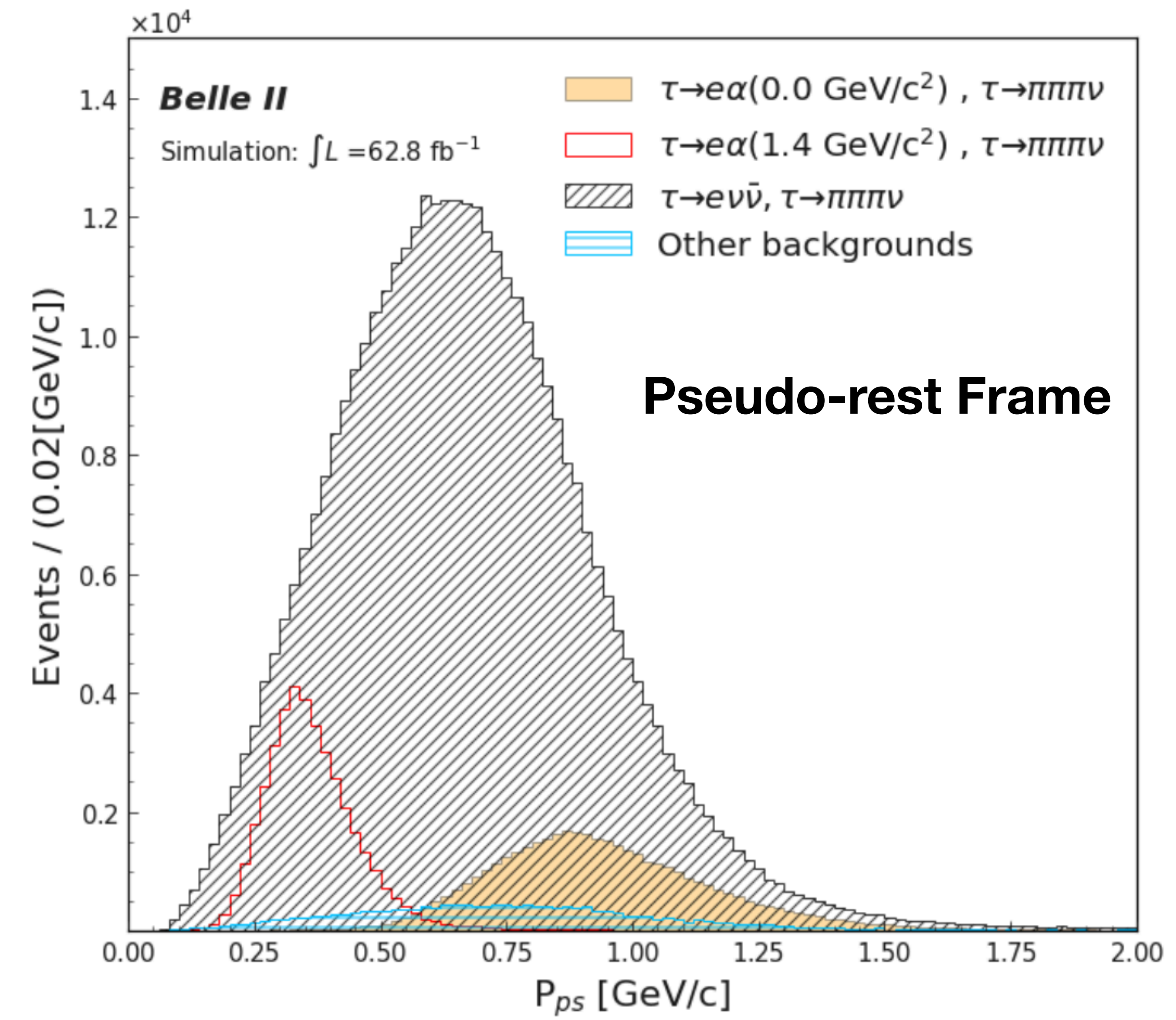
Belle II
luminosity projection
0.75 MeV/c² @ 8.76 [fb⁻¹]
0.31 MeV/c² @ 50 [fb⁻¹]
Current syst: 0.33 MeV
0.22 MeV/c² @ 100 [fb⁻¹]
0.13 MeV/c² @ 300 [fb⁻¹]
Current luminosity
Stat. Precision [MeV/c²]
Luminosity [fb⁻¹]

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

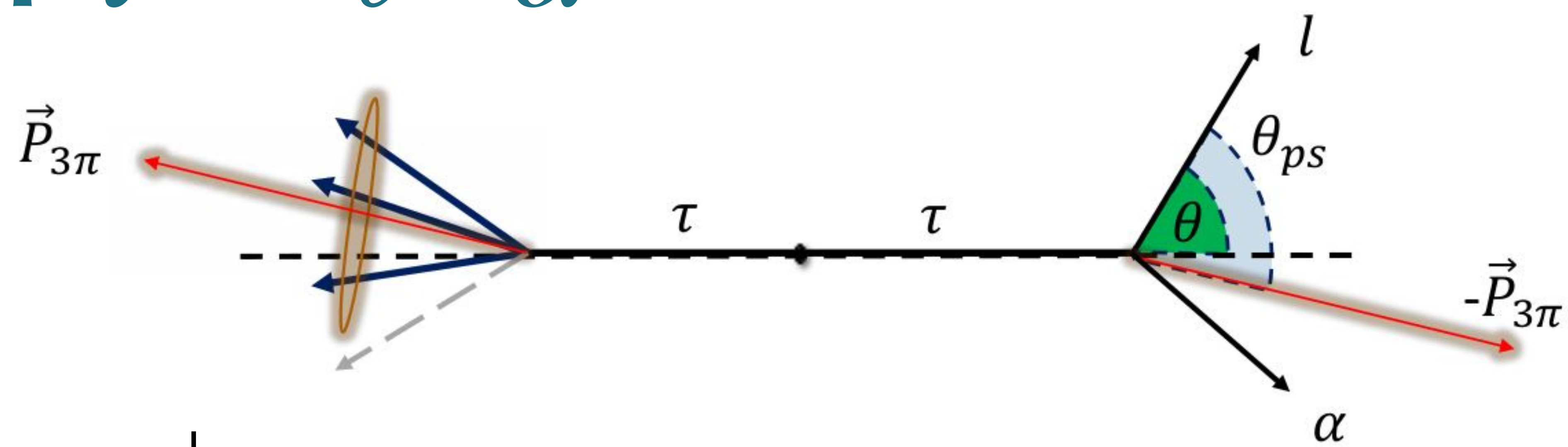
- for α being an ***invisible*** particle
- previous searches by Mark III (1985) and ARGUS (1995)
- event topology
  - ✓ 1-vs-3 (3-prong for tag side)
- τ pseudo-rest-frame by approx. $E_\tau^{CM} \simeq \sqrt{s}/2$

$$\hat{p}_\tau \approx -\frac{\vec{p}_{tag}}{|\vec{p}_{tag}|}, \quad E_\tau \approx \sqrt{s}/2$$

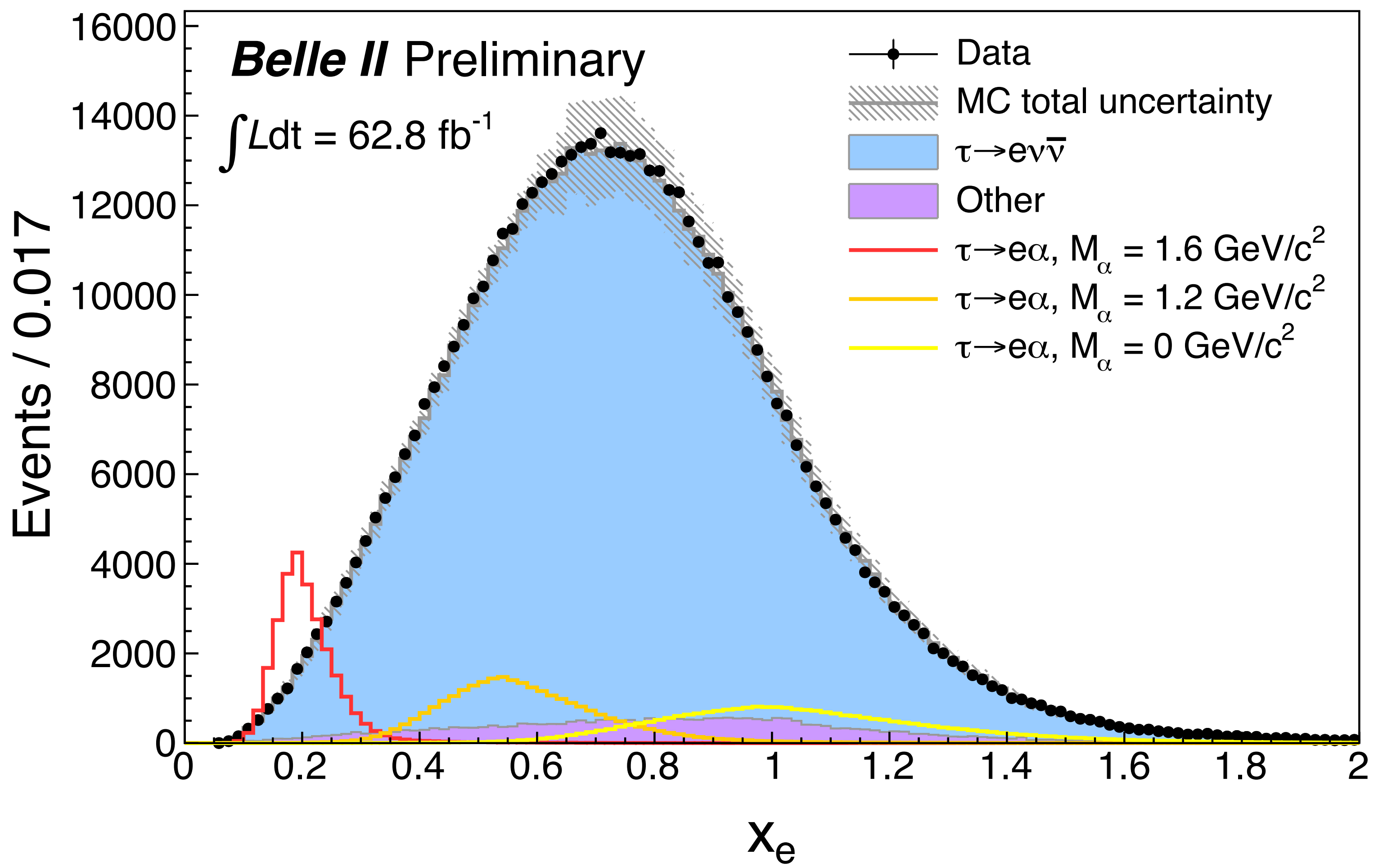




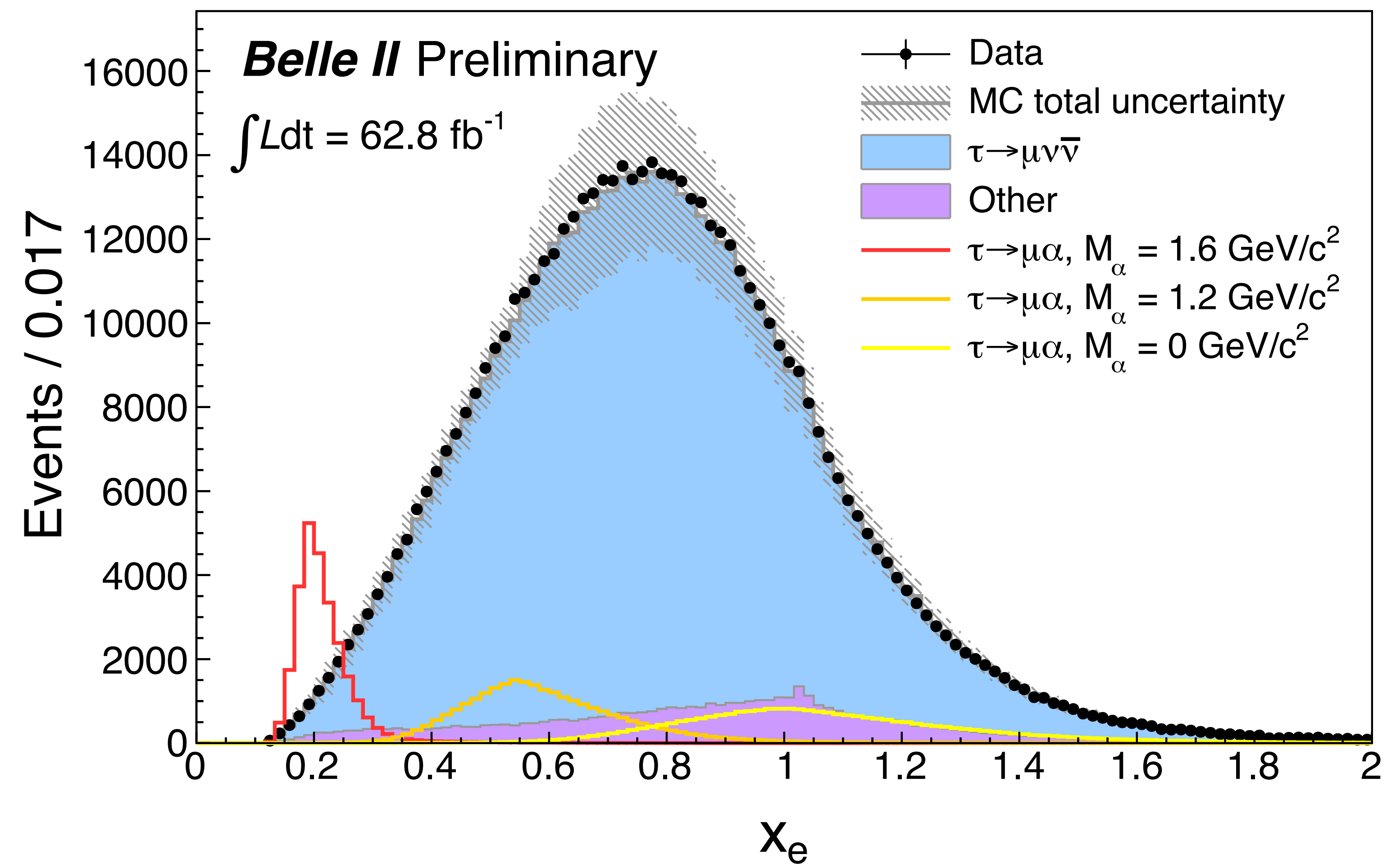
Search for $\tau \to \ell^+\alpha$



$\tau \to e^+\alpha$



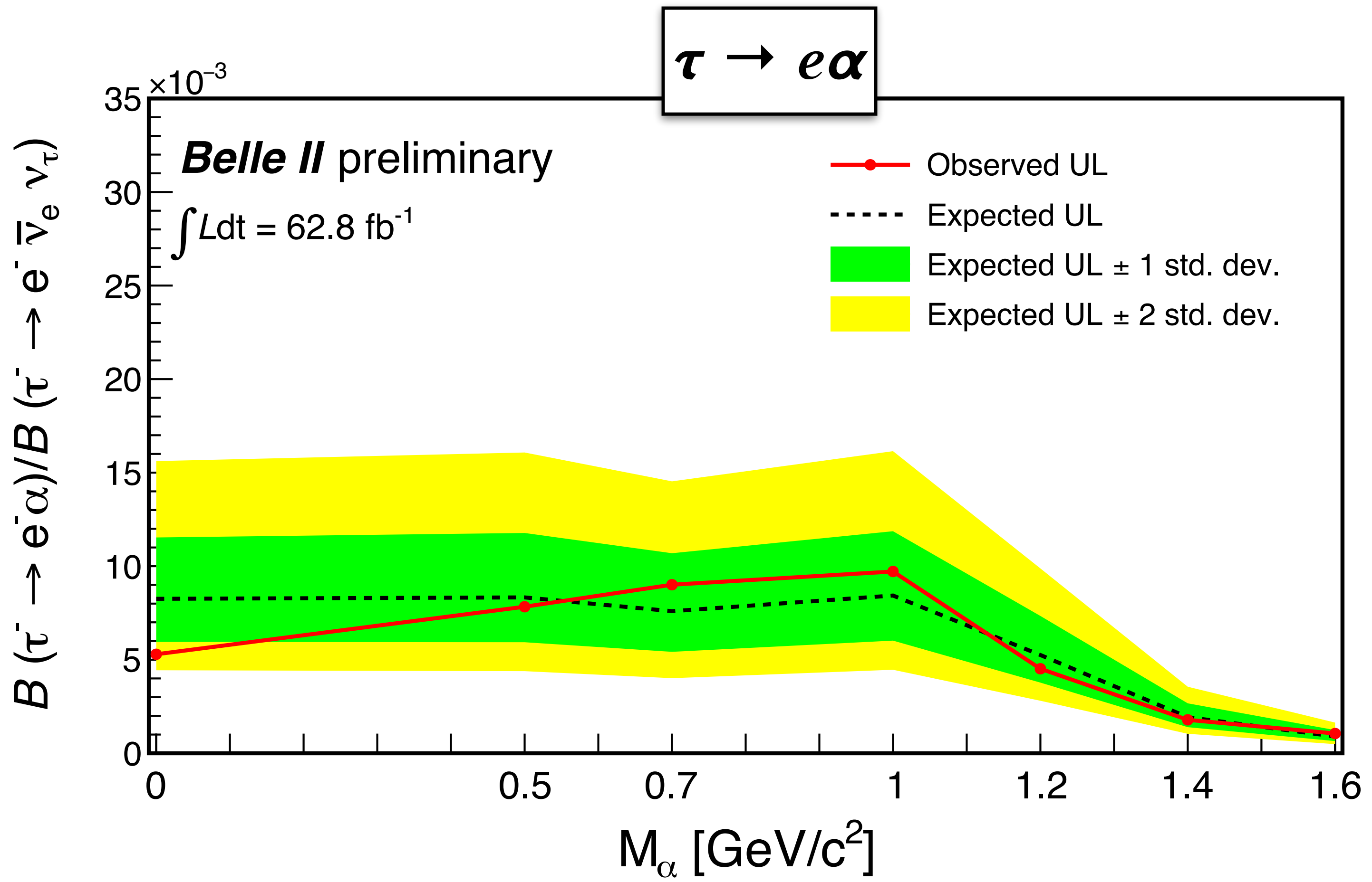
$\tau \to \mu^+\alpha$

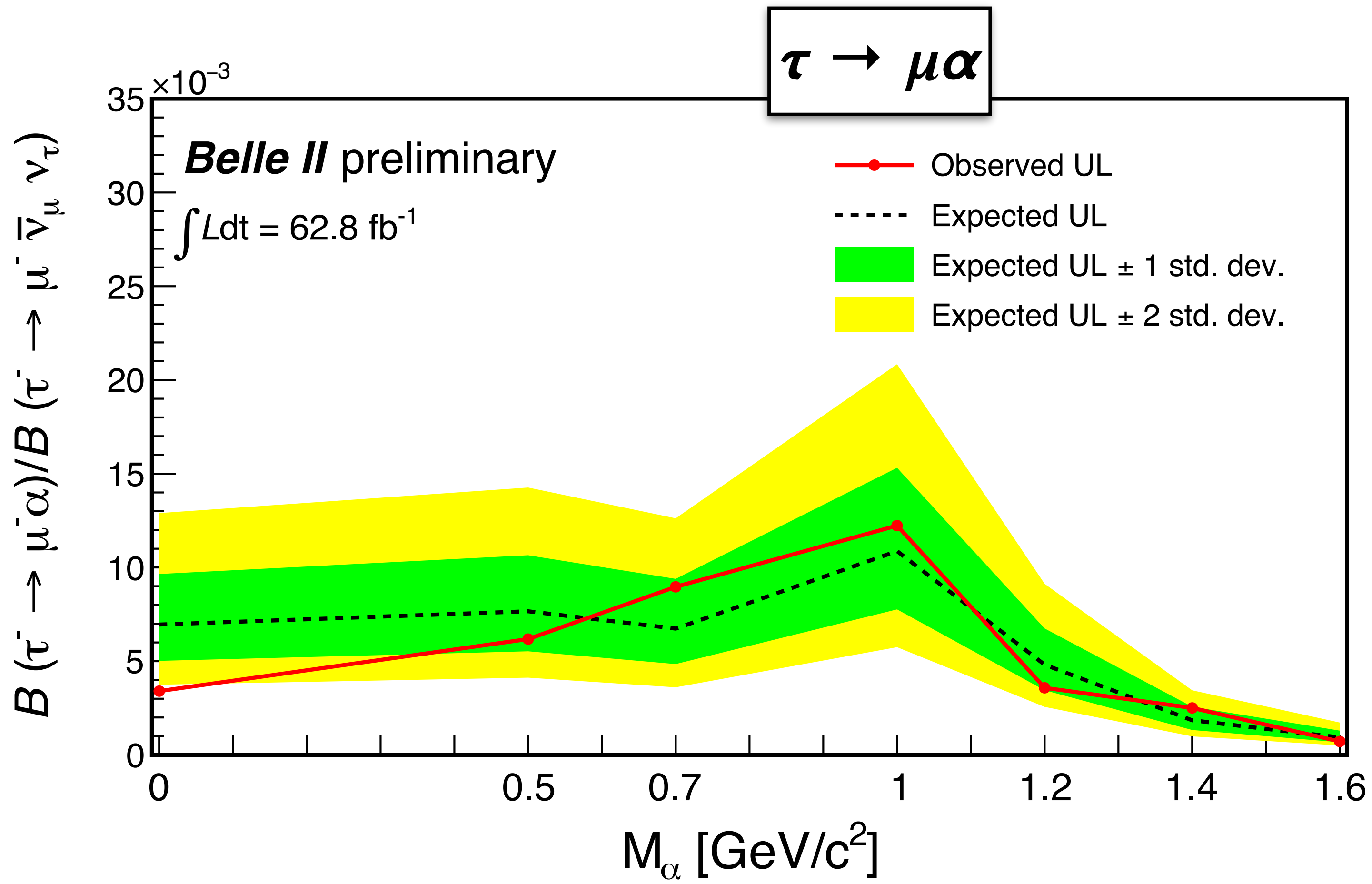


- $\boldsymbol{\tau \to \ell\alpha}$ channels shown normalised to a BF of 5%.

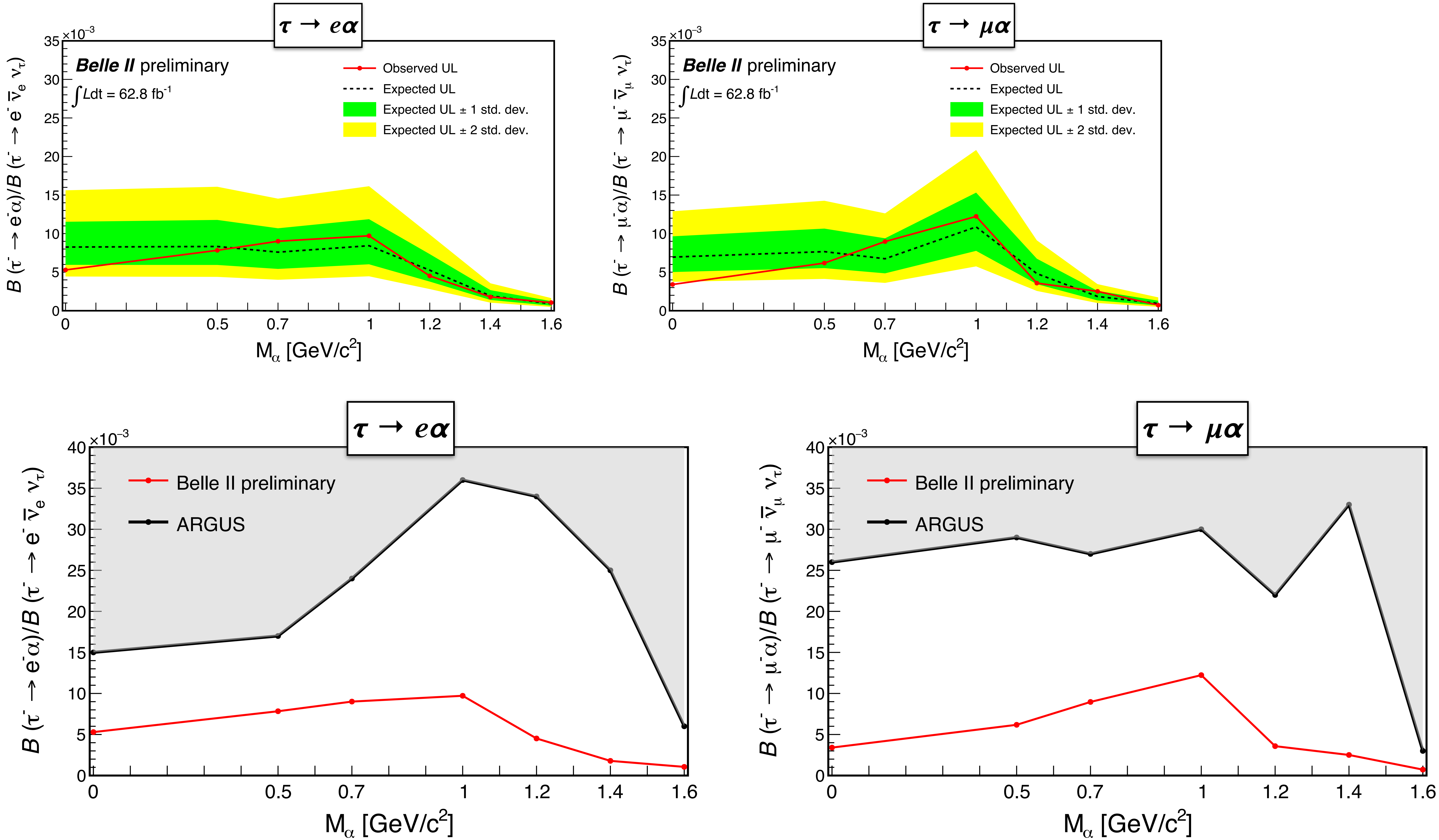
Results for $\tau \to \ell^+ \alpha$

- We find no signal excess and set 95% CL upper limits on $\mathscr{B}(\tau \to \ell\alpha)/\mathscr{B}(\tau \to \ell\nu\bar{\nu})$
- Most stringent limits in these channels to date



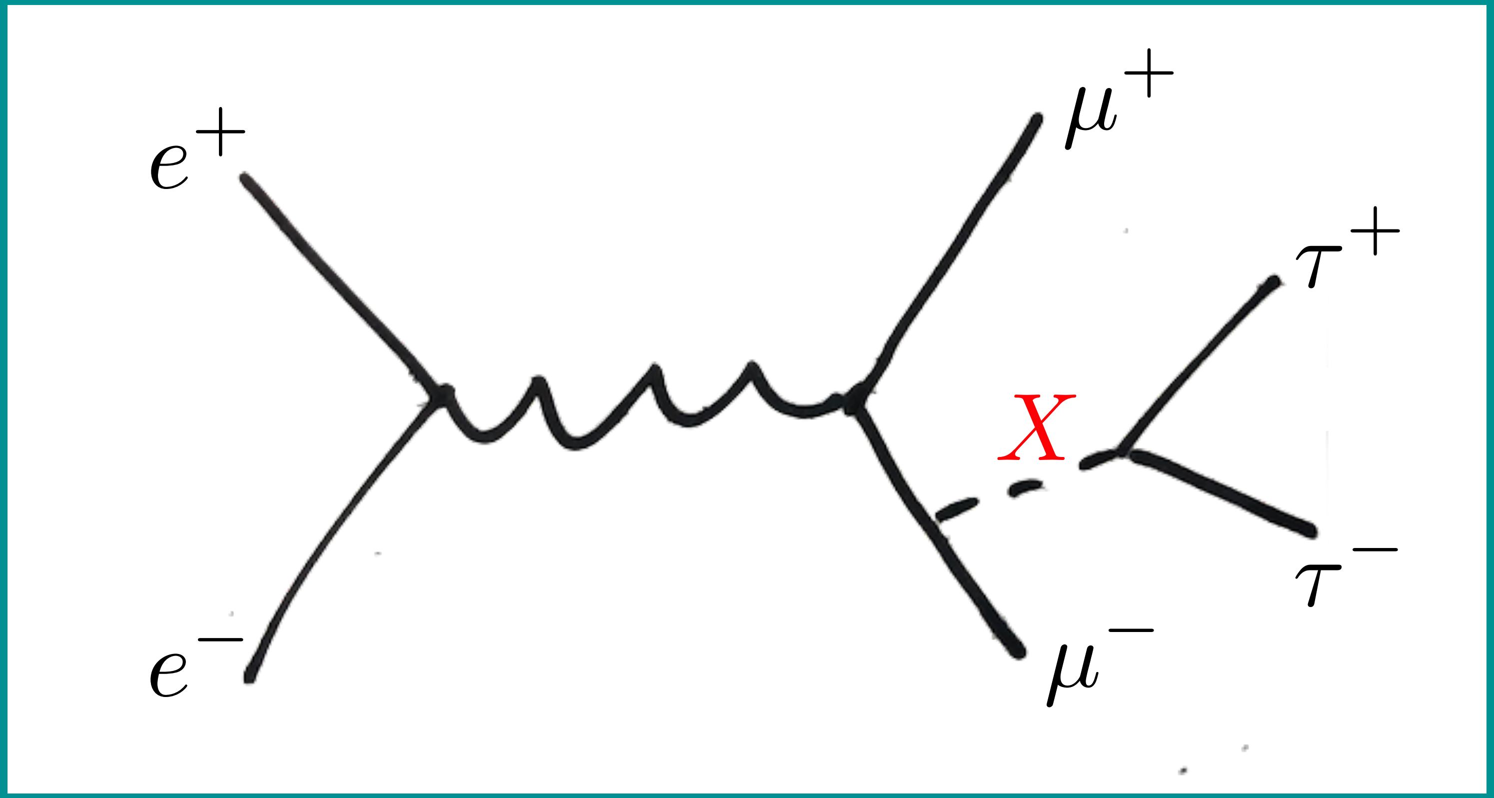


Results for $\tau \to \ell^+\alpha$



One more thing on τ (Belle II)*!*

$$e^+e^- \to \mu^+\mu^- X(\to \tau^+\tau^-)$$

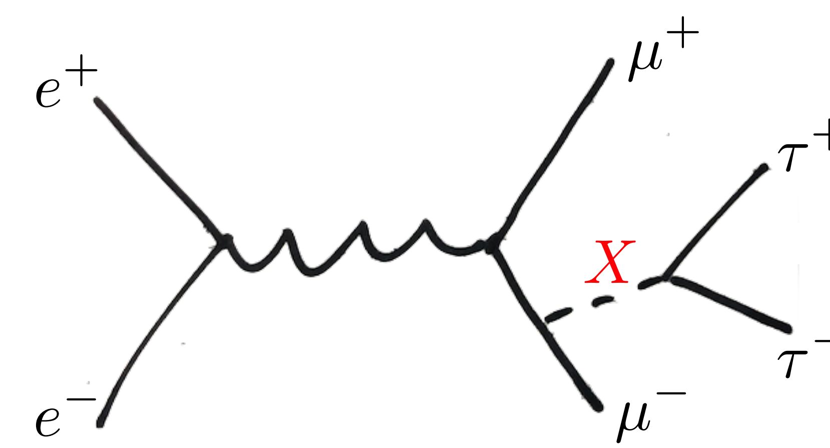


$X = Z', \ S, \ \text{ALP}$

$M_X = M_{\text{recoil}}(\mu\mu)$

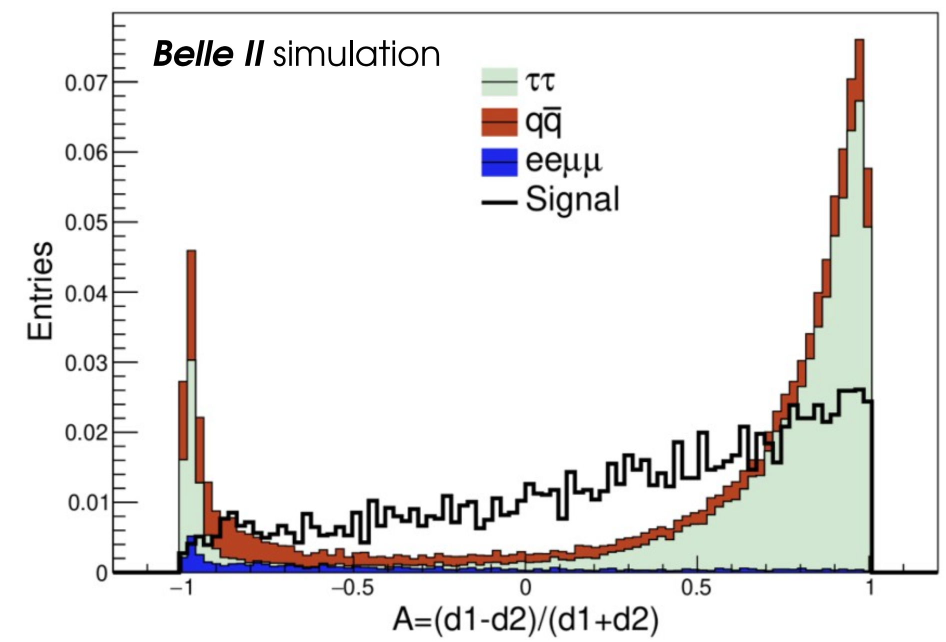
$e^+e^- \to \mu^+\mu^- X(\to \tau^+\tau^-)$

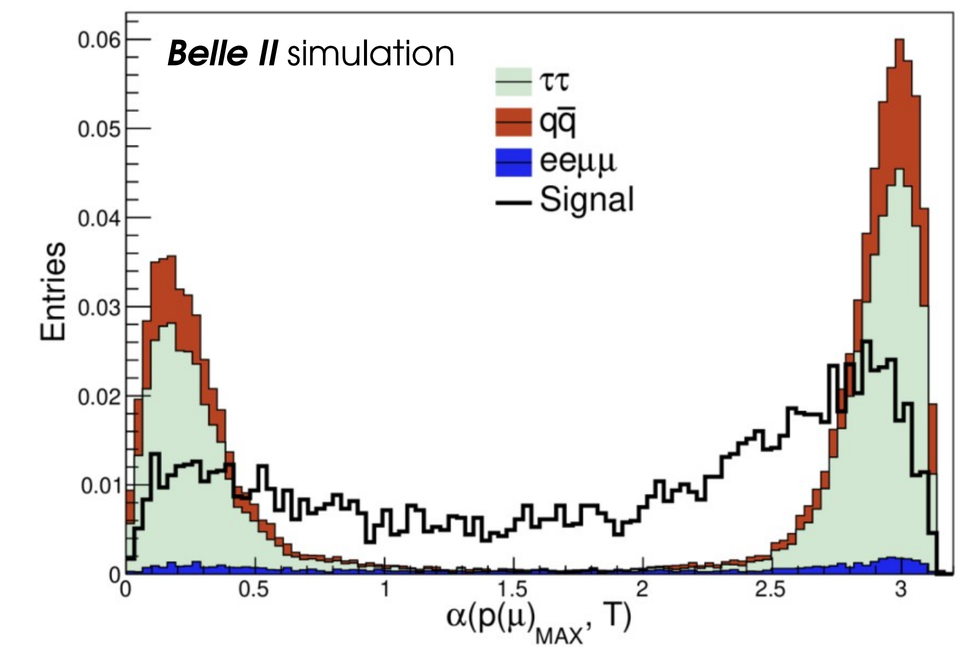
preliminary

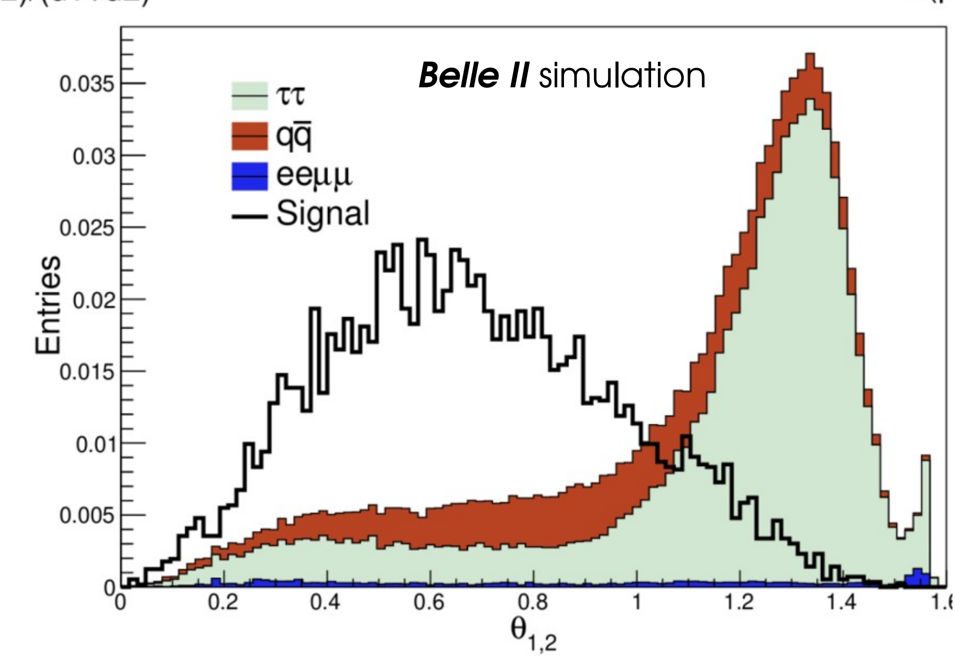


$X = Z',\ S,\ \mathrm{ALP}$

- Dataset: 62.8 fb^{-1}
- Signal selection
  - 1-prong τ only $\Rightarrow$ 4 charged tracks $[2\mu + 2(e/\mu/\pi)]$
  - M(4 tracks) < 9.5 GeV
  - scan $M_{\mathrm{recoil}}(\mu\mu)$
- Background sources
  - $\tau\tau(\gamma)$ [1+3 prongs]
  - $q\bar{q}$
  - $\ell^+\ell^-\ell'^+\ell'^-$ (no ISR in MC)
  - $\mu\mu\pi\pi$
  - $e^+e^-X_{\mathrm{had}}$ (no MC)
- Background suppression with ML
  - based on 14 input neurons & one hidden layer of 15 neurons
  - separately in 8 ranges of $M_{\mathrm{recoil}}(\mu\mu)$

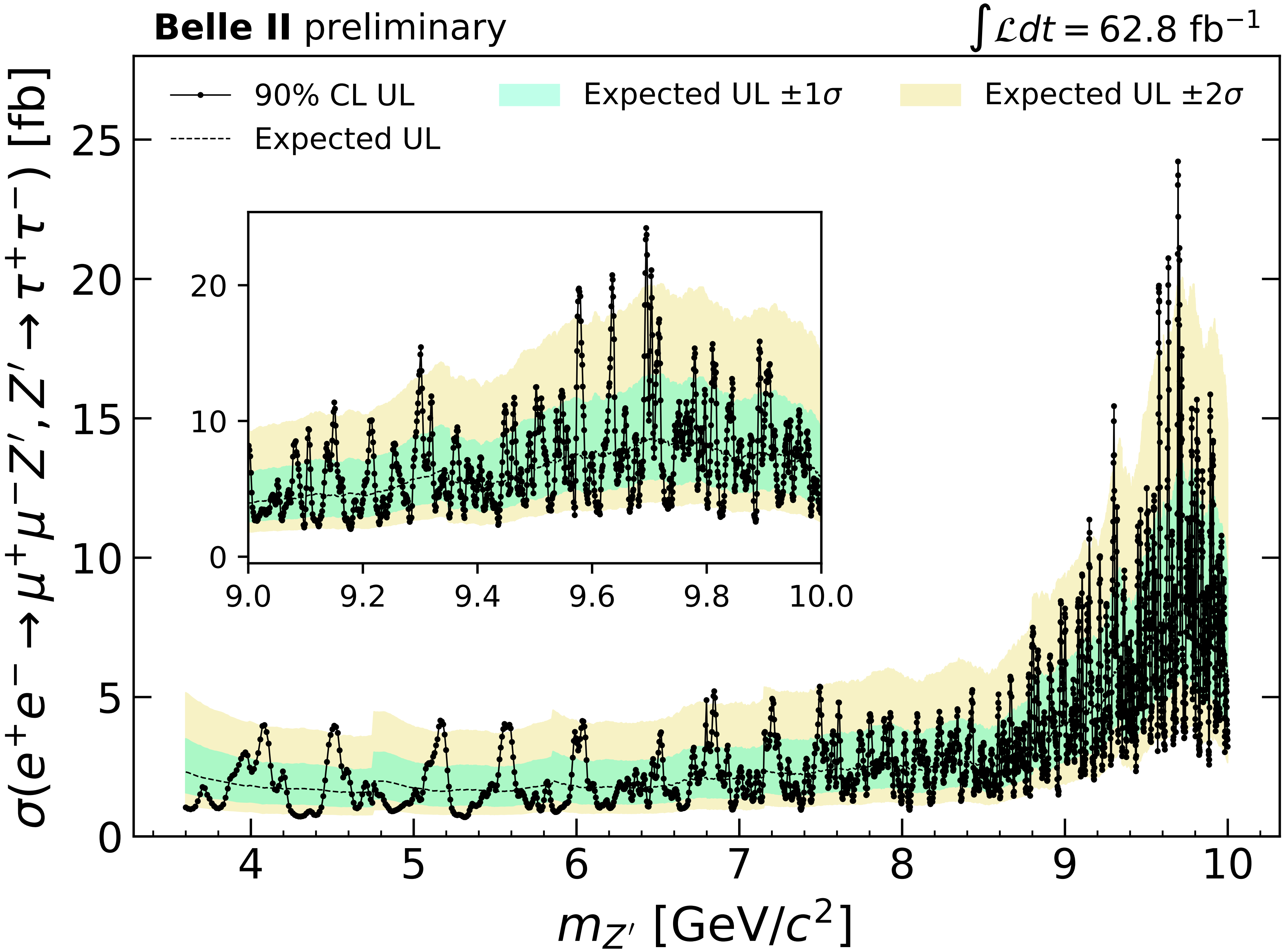


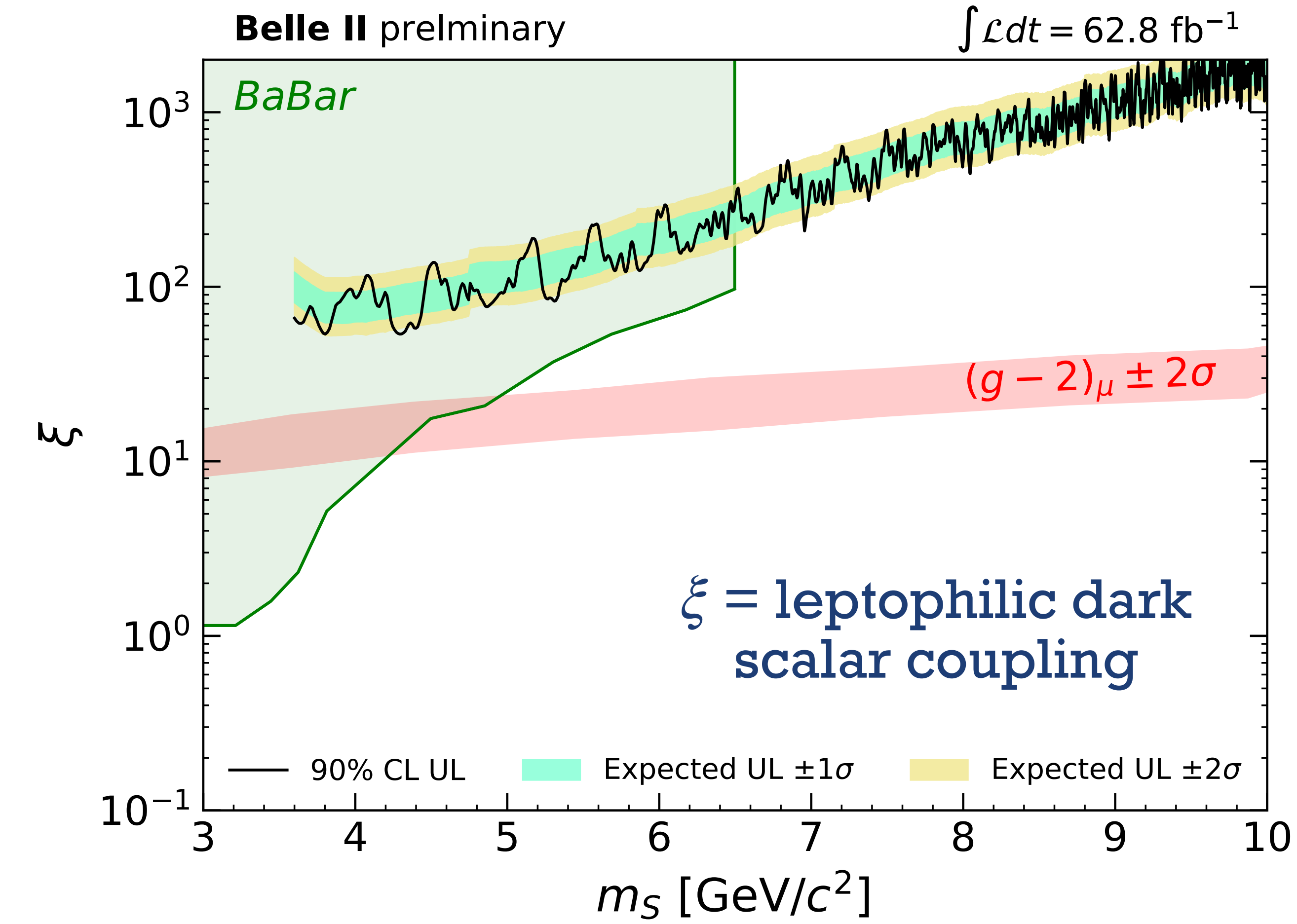


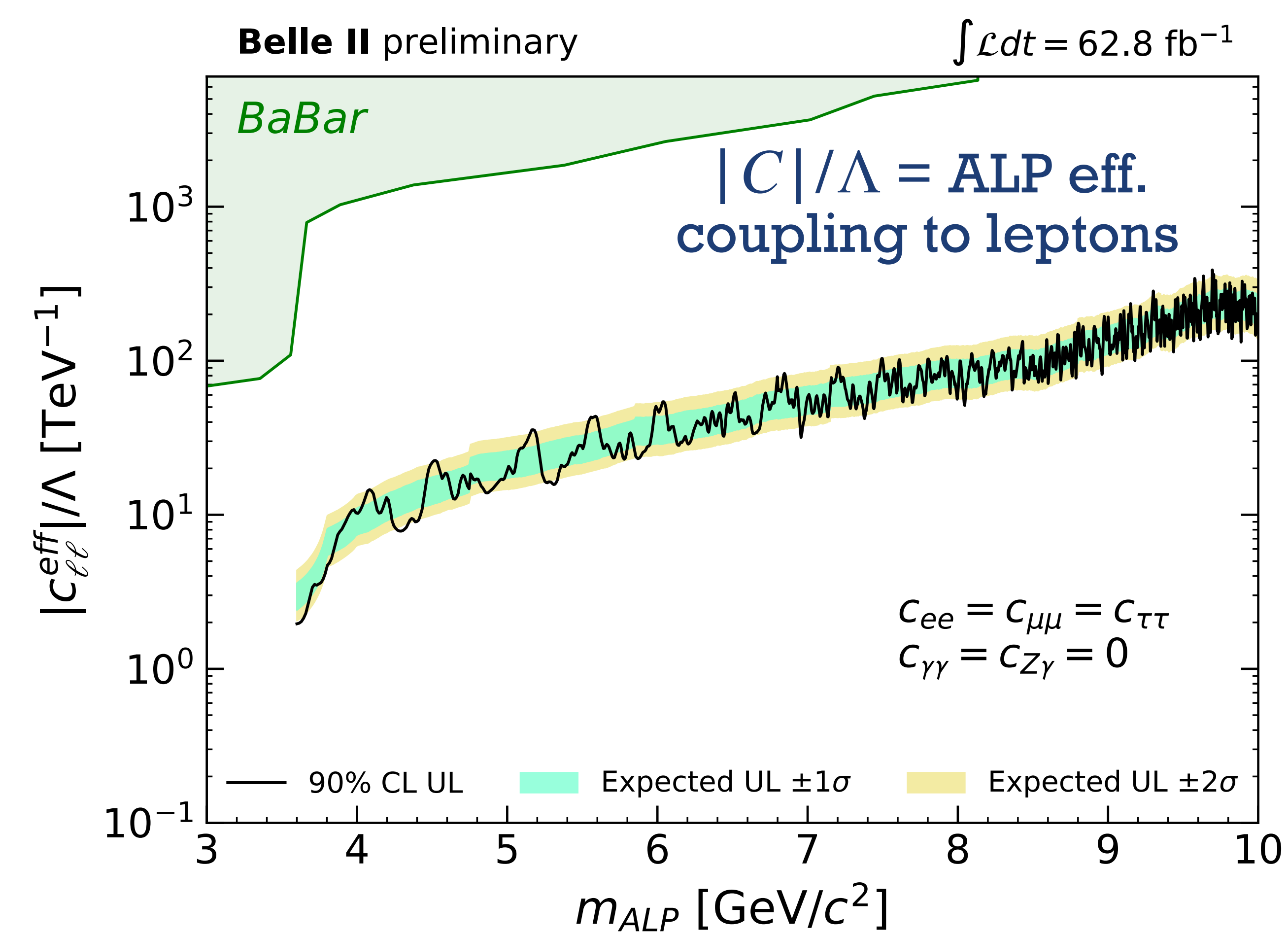


$$\theta_{1,2} = \tan^{-1}\left(p(\tau_0,\tau_1), M(\tau_0,\tau_1)\right)$$

$e^+e^- \to \mu^+\mu^- X(\to \tau^+\tau^-)$





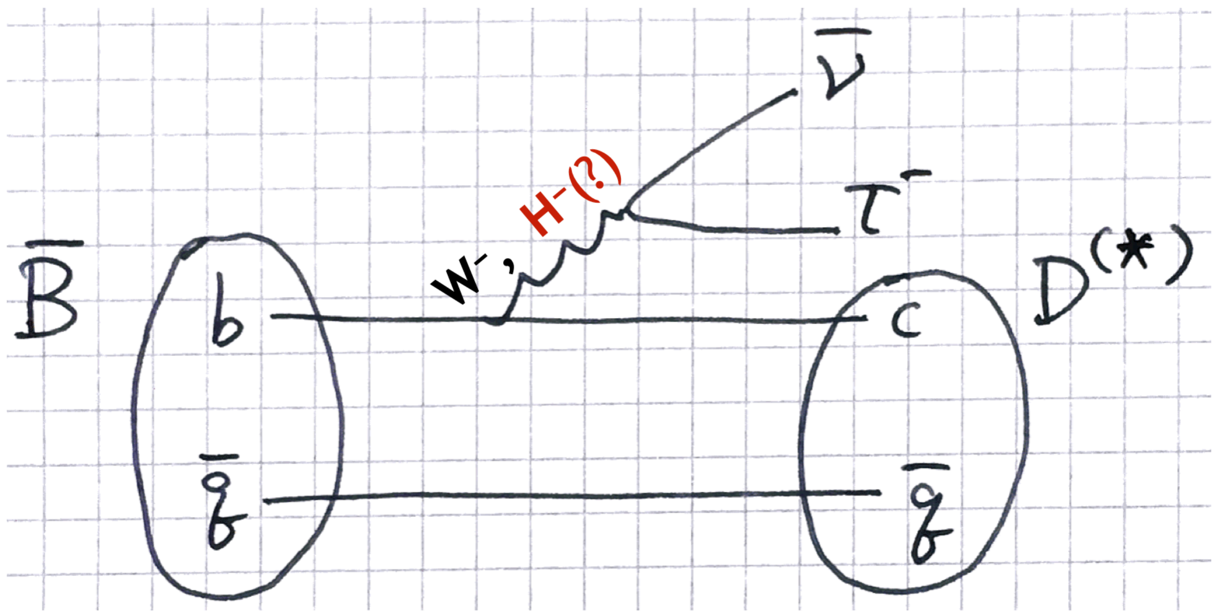


- no excess anywhere
- set 90% UL on cross-sections (L) & couplings (R)
  - 1st constraints on S (leptophilic dark scalar) for M > 6.5 GeV
  - 1st direct constraints on ALP $\to \tau^+\tau^-$

B-anomaly in $B \to D^{(*)}\tau^+\nu$

and related

- $m_\tau \gg m_e, m_\mu$ $\quad\therefore$ B ➔ $D^*\,\tau\,\nu$ can be more sensitive to NP, e.g. from H^+
- B ➔ $D^*\,\tau\,\nu$ was first observed by Belle
- ∃ hints for deviations of $R(D)$, $R(D^*)$ from SM; **LUV?**



PRL **99,** 191807 (2007) PHYSICAL REVIEW LETTERS week ending 9 NOVEMBER 2007

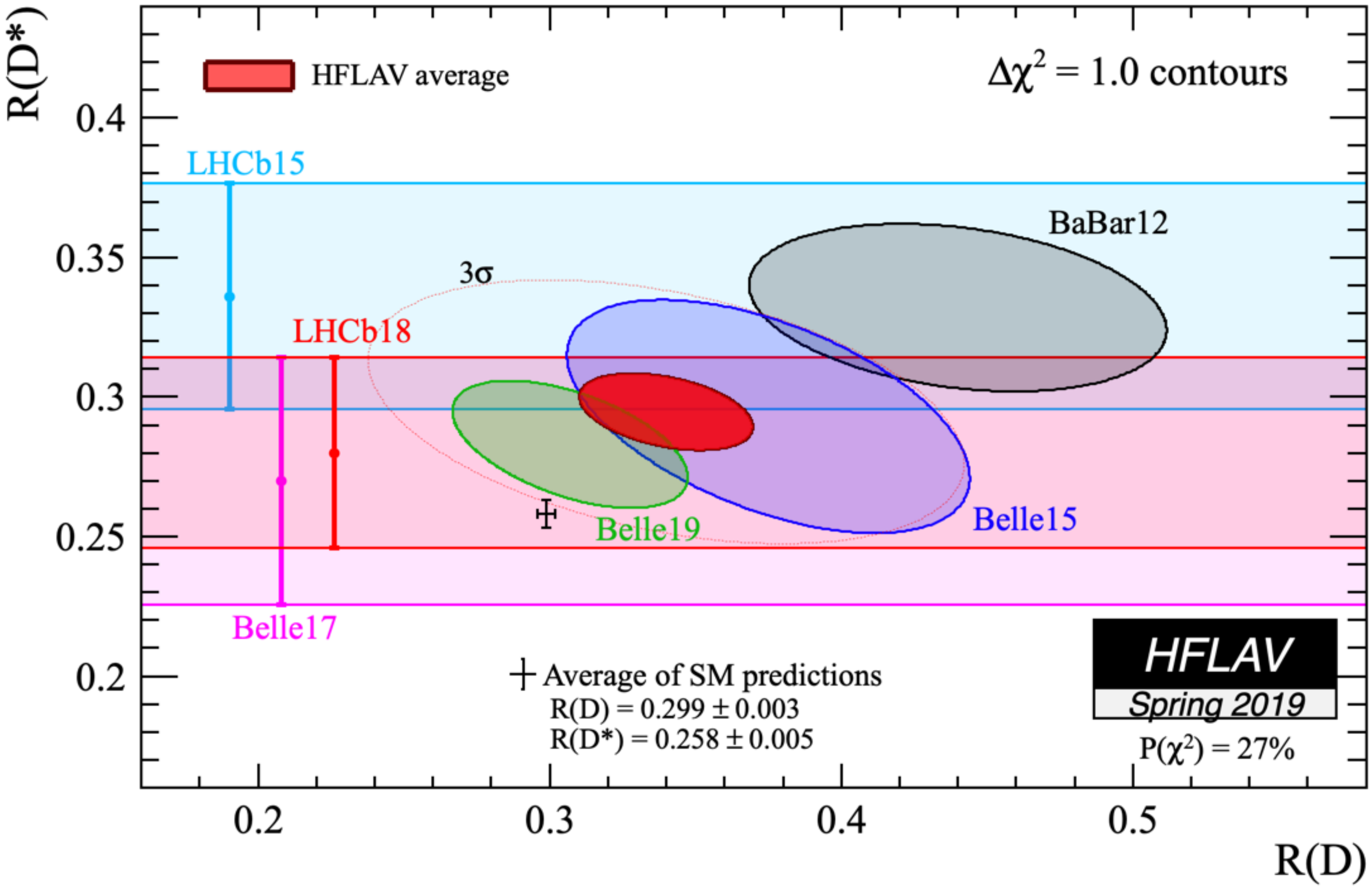
Observation of $B^0 \to D^{*-}\tau^+\nu_\tau$ Decay at Belle

A. Matyja,[27] M. Rozanska,[27] I. Adachi,[8] H. Aihara,[41] V. Aulchenko,[1] T. Aushev,[18,13] S. Bahinipati,[3] A. M. Bakich,[37] V. Balagura,[13] E. Barberio,[21] I. Bedny,[1] V. Bhardwaj,[33] U. Bitenc,[14] A. Bondar,[1] A. Bozek,[27] M. Bračko,[20,14] J. Brodzicka,[8] T. E. Browder,[7] M.-C. Chang,[4] P. Chang,[26] A. Chen,[24] K.-F. Chen,[26] B. G. Cheon,[6] R. Chistov,[13] J.-S. Cho,[46]

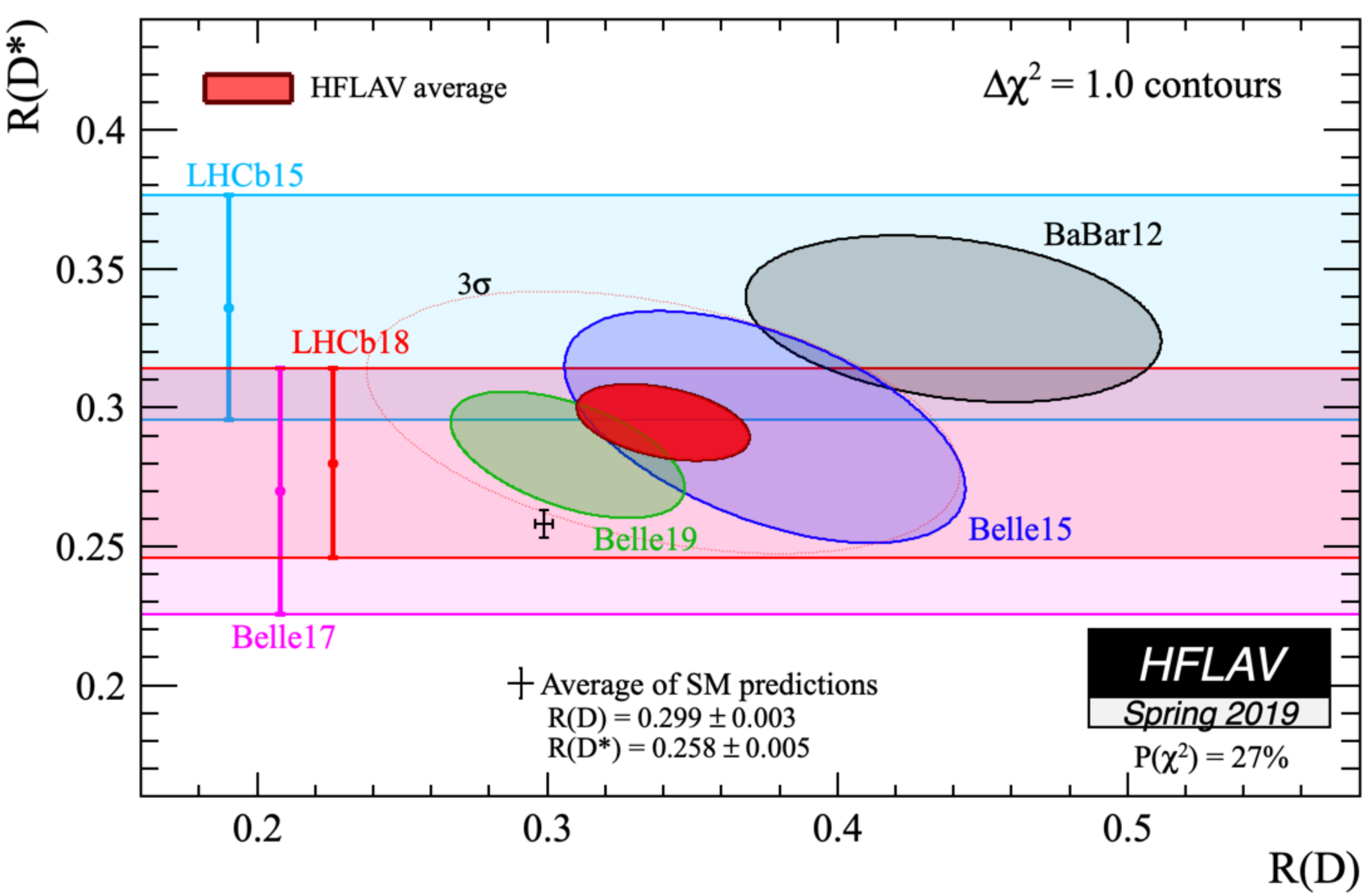
$$\mathcal{R}(D^{(*)}) \equiv \frac{\mathcal{B}(B \to D^{(*)}\tau^+\nu)}{\mathcal{B}(B \to D^{(*)}\ell^+\nu)}$$

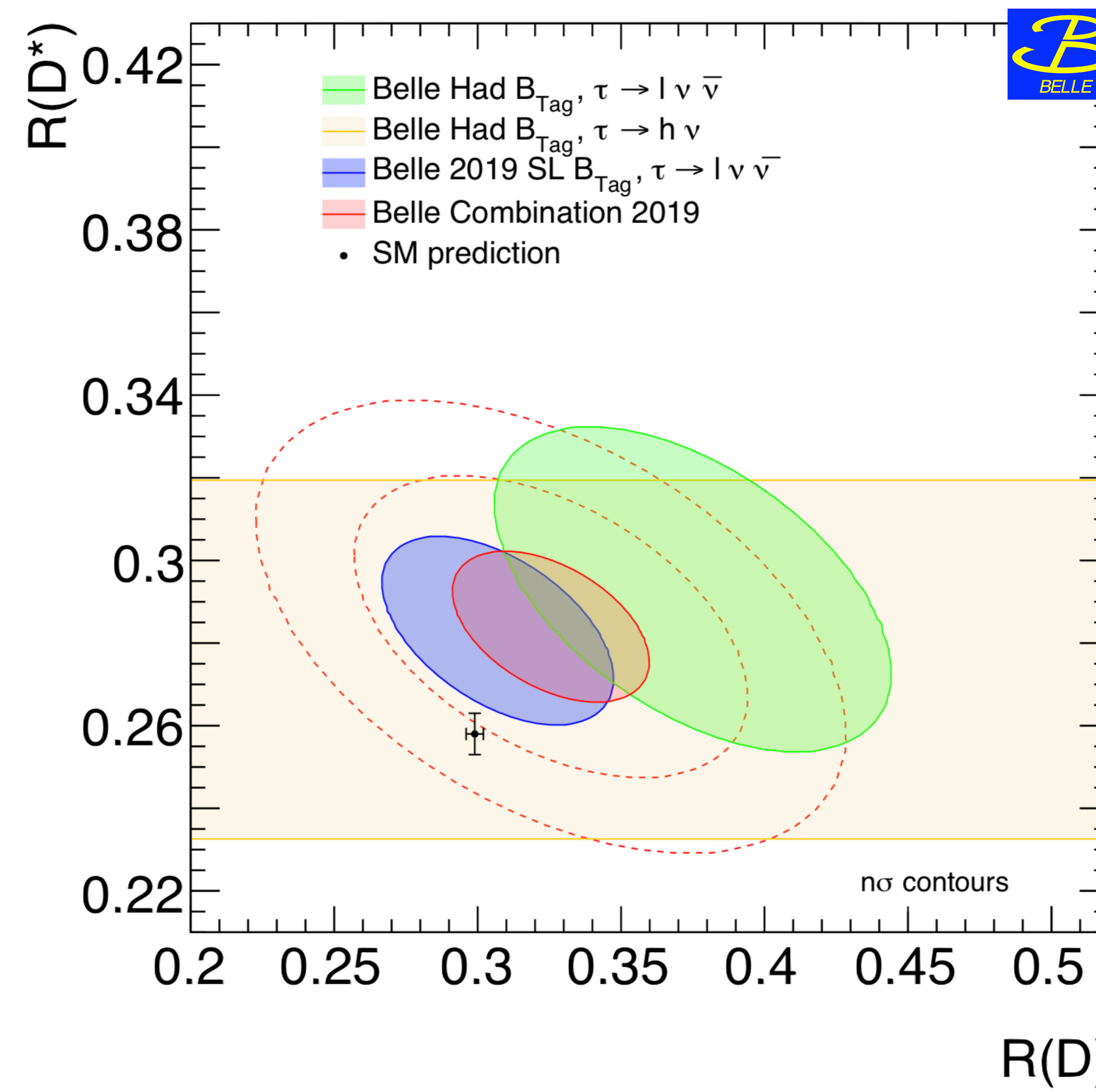
$R(D)$ and $R(D^*)$

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



$R(D)$ and $R(D^*)$



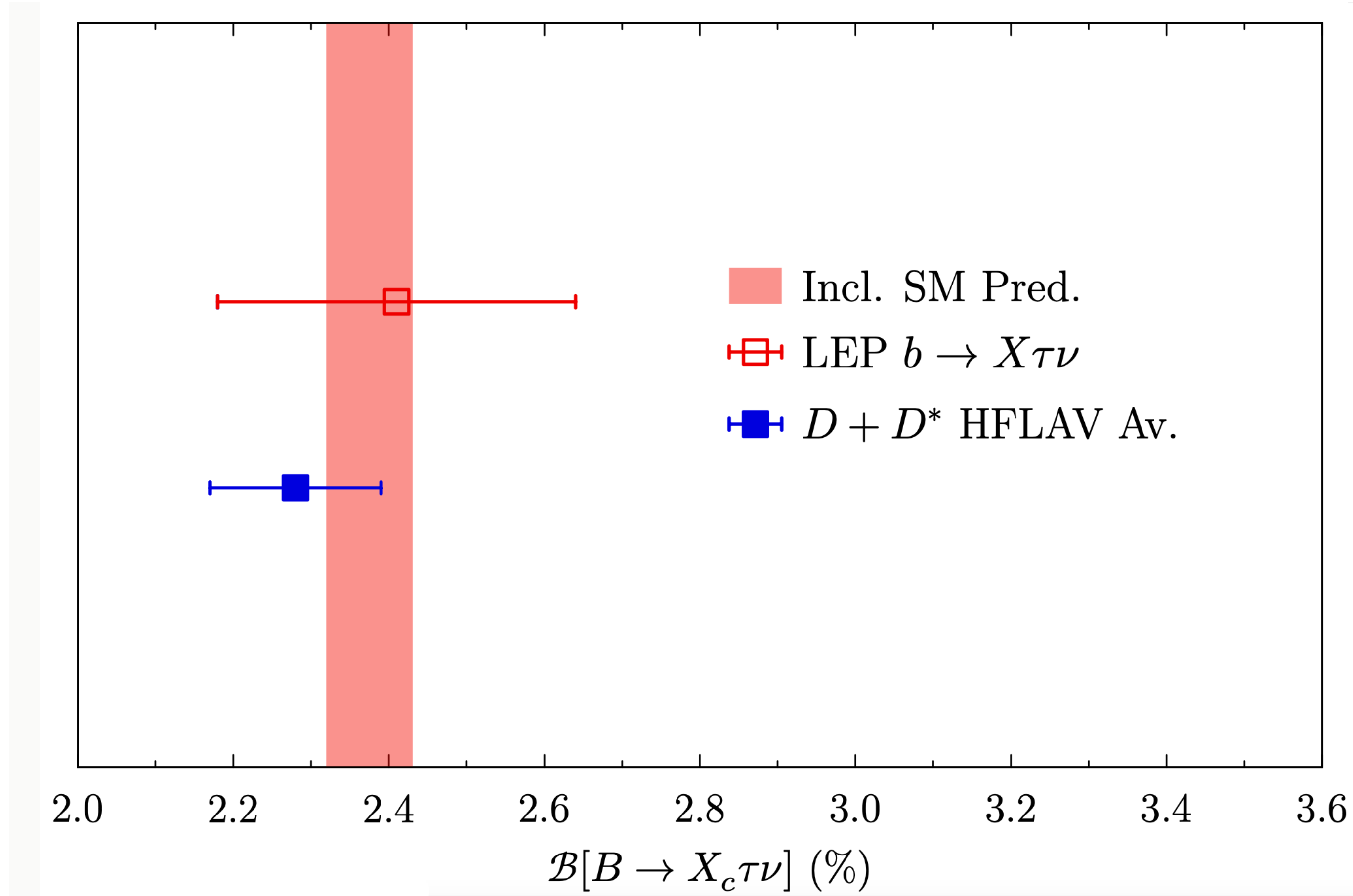


- Most precise $R(D)$, $R(D^*)$ to date
- First $R(D)$ with SL-tag
- 1.2σ from SM

- Belle average, now within 2σ from SM
- World average — tension with SM, now ~3.1σ

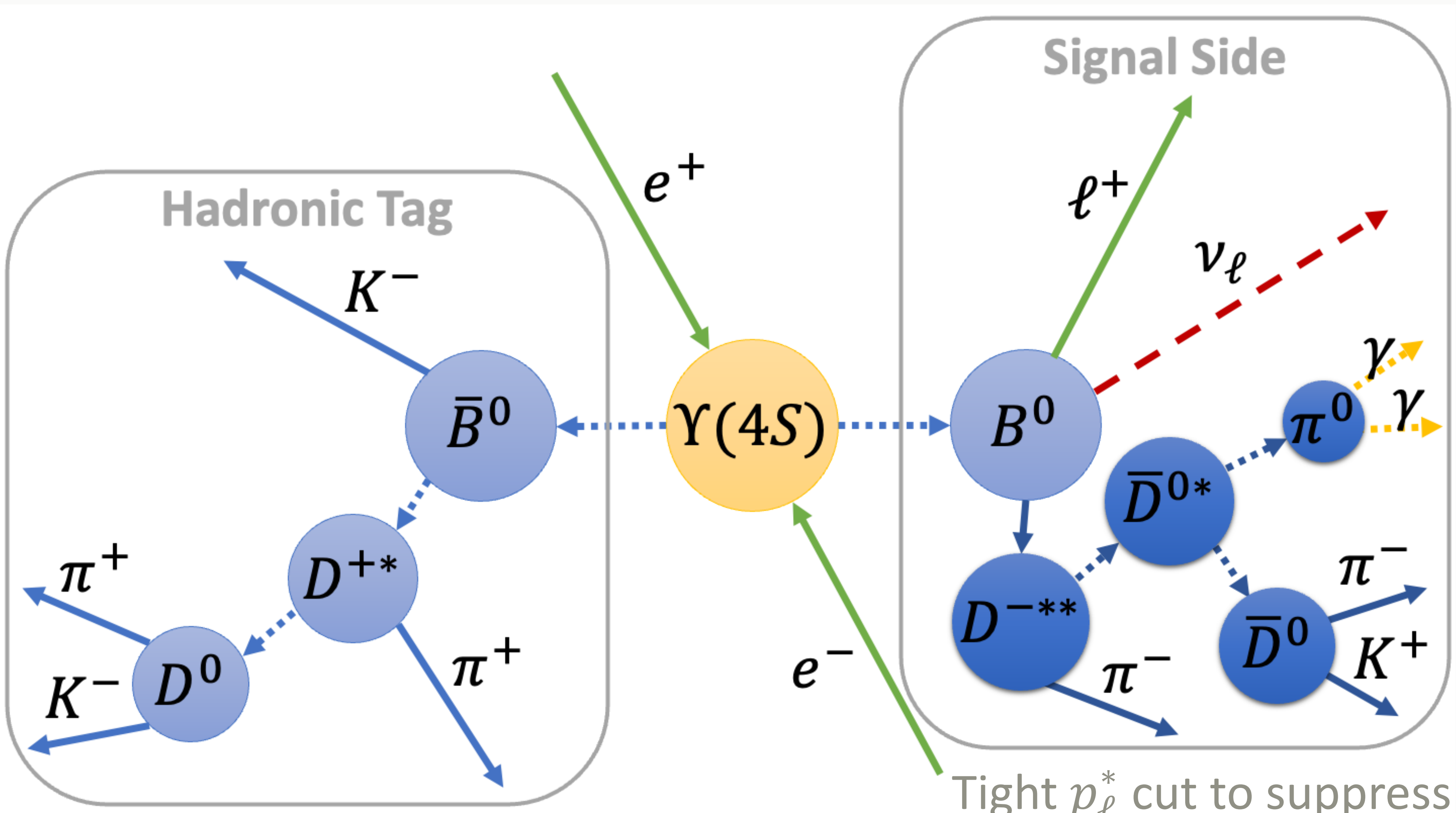
LFU test with inclusive $B \to X\ell\nu$

- ***inclusive*** study — complementary to ***exclusive*** studies
- one of the unique and high-profile goals of Belle II
- last measured by LEP (!)
- very challenging — larger bkgd. & much less constrained
- precise modeling of $B \to X\ell\nu$ is critical



- $\boldsymbol{R(X_{c,\tau/\ell})_{SM} = 0.223 \pm 0.004}$
  Phys. Rev. D 92, 054018 (2015)
- $\boldsymbol{R(X_{e/\mu})_{SM} = 1.006 \pm 0.001}$
  K. Vos, M. Rahimi, in progress

LFU test with inclusive $B \to X\ell\nu$



- **Reconstruct**
  $\Upsilon(4S) \to B^-_{\rm tag}\ell^+X$
  $\Upsilon(4S) \to \bar{B}^0_{\rm tag}\ell^+X$
- **$p^*_\ell > 1.3$ GeV**
- **Only basic quality cuts on tracks and calorimeter signals**
- **Tight constraints on tag quality**

$\epsilon = \mathcal{O}(0.1\%)$

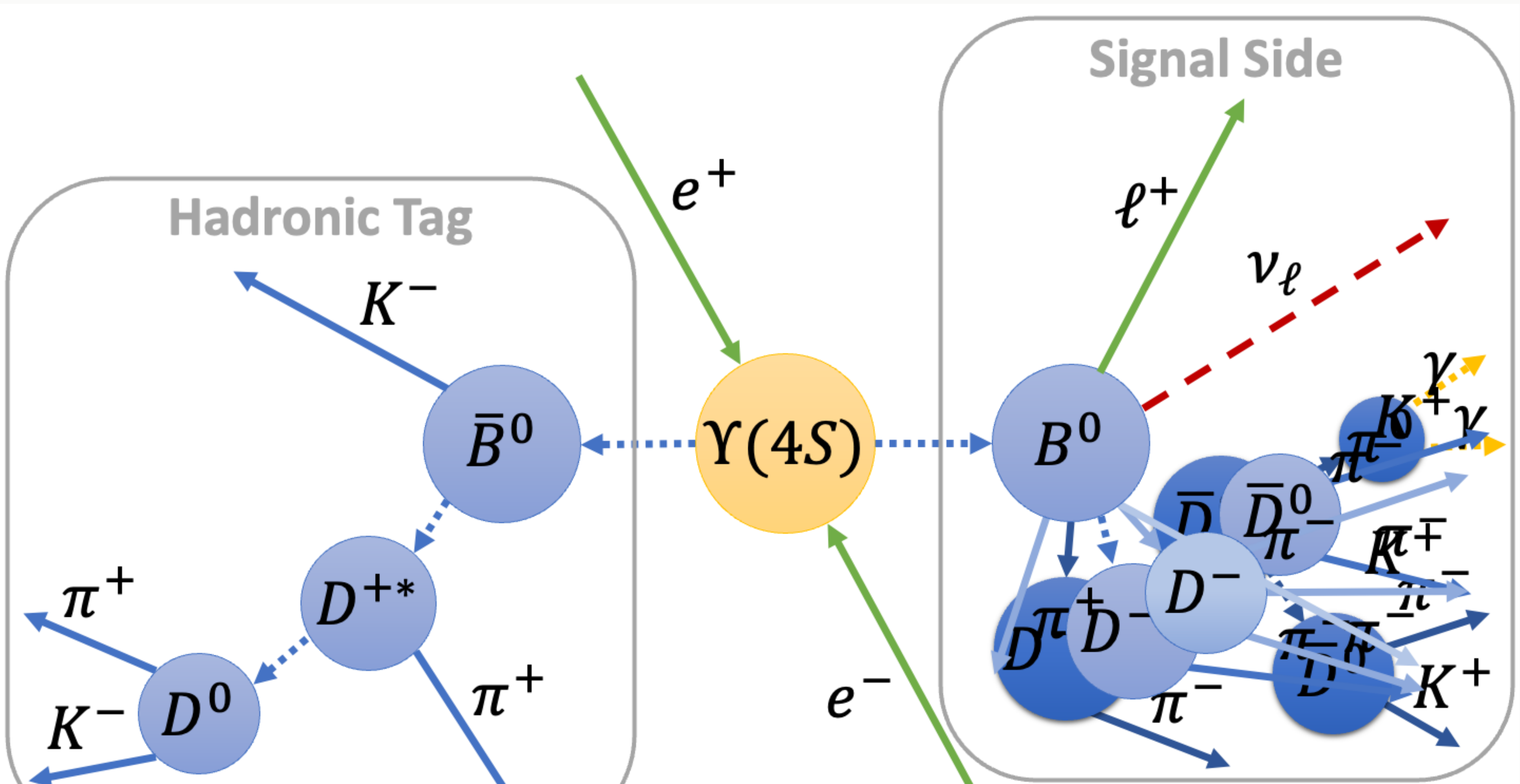
Precise knowledge of $B_{\rm tag}$ kinematics

Tight p^*_ℓ cut to suppress
- hadrons faking leptons (“**fakes**”)
- secondary leptons from $b \to c \to (\ell, s)$ cascades (“**secondaries**”)
- $B \to X\tau\nu$

[53% (e) / 66% (μ) of selected B $\to X\ell\nu$ is retained]

slide taken from Belle II ICHEP2022 talk by H. Junkerkalefeld

LFU test with inclusive $B \to X\ell\nu$



$\epsilon = \mathcal{O}(0.1\%)$

Precise knowledge of B_{tag} kinematics

Tight p_ℓ^* cut to suppress

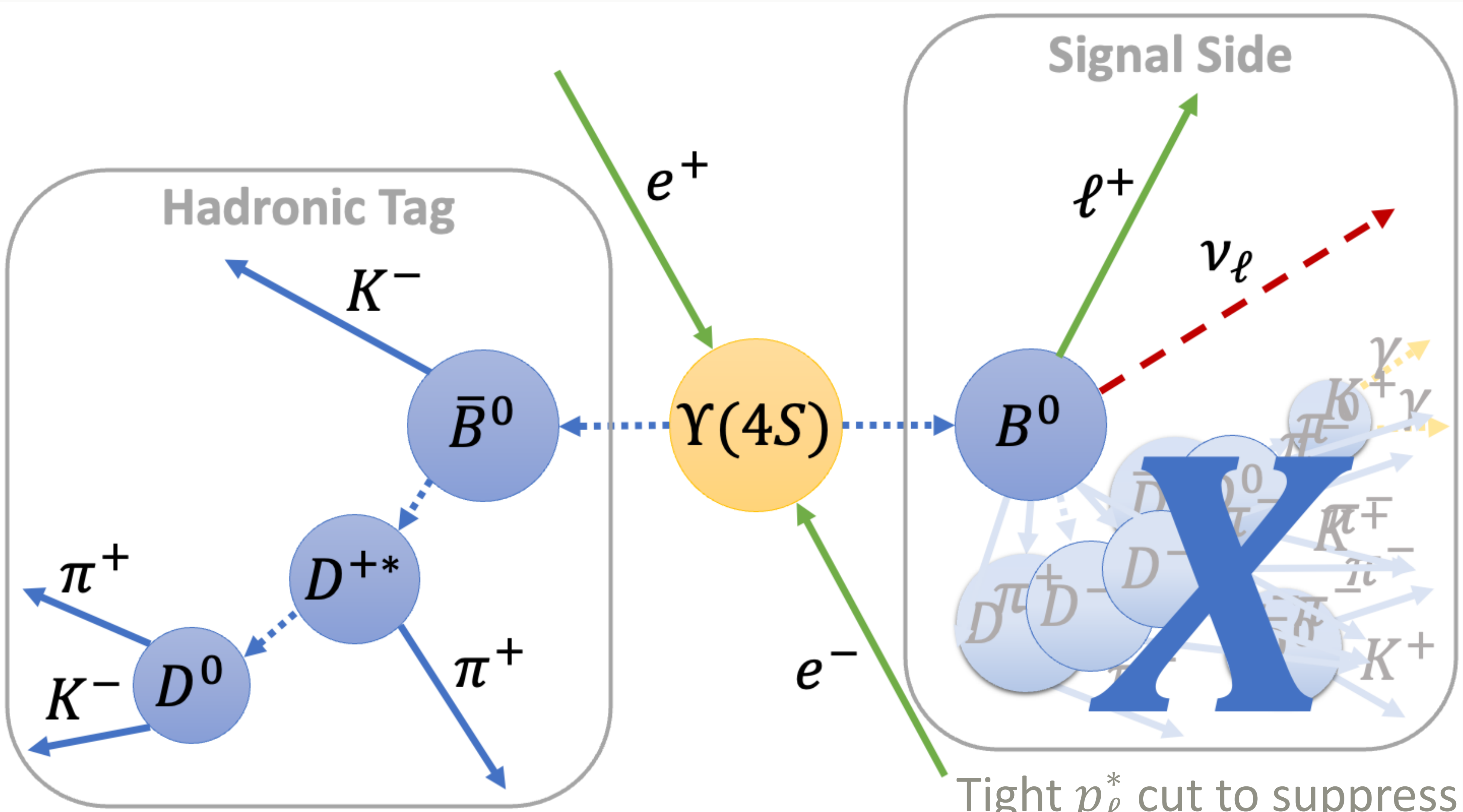
- hadrons faking leptons ("**fakes**")
- secondary leptons from $b \to c \to (\ell, s)$ cascades ("**secondaries**")
- $B \to X\tau\nu$

[53% (e) / 66% (μ) of selected B $\to X\ell\nu$ is retained]

- **Reconstruct** $\Upsilon(4S) \to B^-_{\text{tag}}\ell^+ X$ $\Upsilon(4S) \to \bar{B}^0_{\text{tag}}\ell^+ X$
- $p_\ell^* > 1.3$ **GeV**
- **Only basic quality cuts on tracks and calorimeter signals**
- **Tight constraints on tag quality**

slide taken from Belle II ICHEP2022 talk by H. Junkerkalefeld

LFU test with inclusive $B \to X\ell\nu$



- Reconstruct
  $\Upsilon(4S) \to B^-_{\text{tag}}\ell^+ X$
  $\Upsilon(4S) \to \bar{B}^0_{\text{tag}}\ell^+ X$
- $p^*_\ell > 1.3$ GeV
- Only basic quality cuts on tracks and calorimeter signals
- Tight constraints on tag quality

$\epsilon = \mathcal{O}(0.1\%)$

Precise knowledge of B_{tag} kinematics

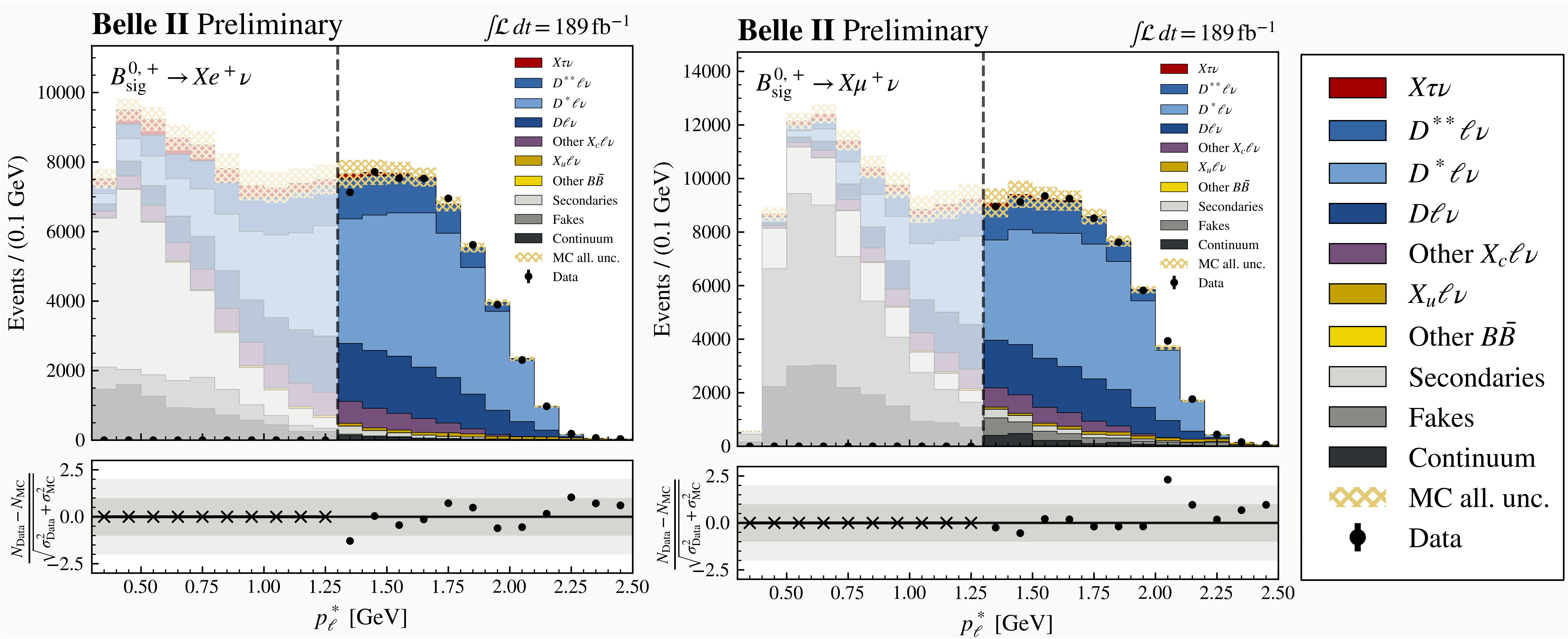
Tight p^*_ℓ cut to suppress

- hadrons faking leptons ("**fakes**")
- secondary leptons from $b \to c \to (\ell, s)$ cascades ("**secondaries**")
- $B \to X\tau\nu$

[53% (e) / 66% (μ) of selected B $\to X\ell\nu$ is retained]

slide taken from Belle II ICHEP2022 talk by H. Junkerkalefeld

LFU test with inclusive $B \to X\ell\nu$



Background is constrained by wrong-sign lepton charge samples (BU)

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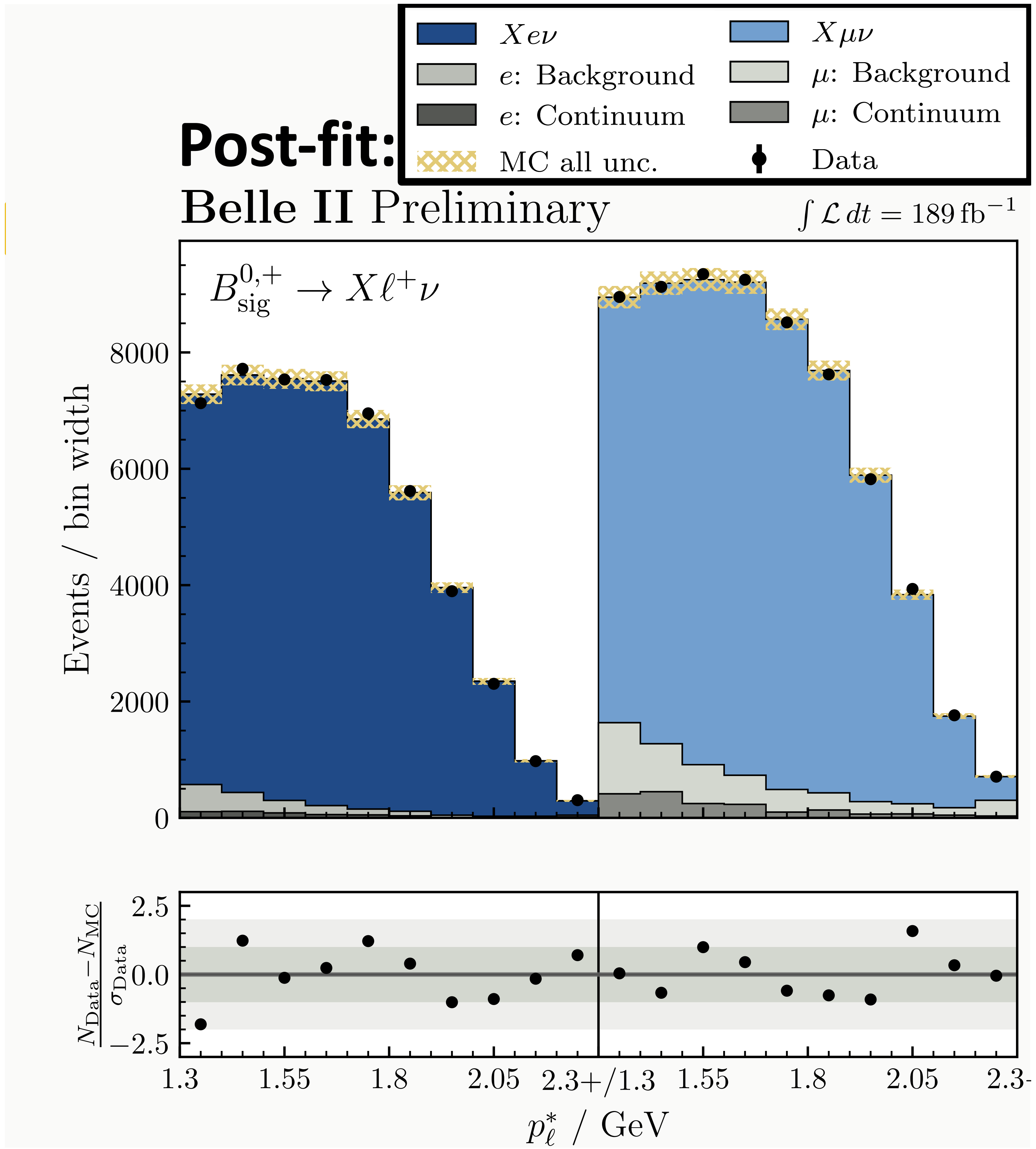
LFU test with inclusive $B \to X\ell\nu$

Post-fit:



$$R(X_{e/\mu}) = \frac{N_{Xe\nu}\cdot\epsilon_{X\mu\nu}}{N_{X\mu\nu}\cdot\epsilon_{Xe\nu}} \quad \text{with}$$

$$\epsilon_{X\ell\nu} = \frac{N^{\ell}_{sel}\cdot(\epsilon^{data}_{Btag}/\epsilon^{MC}_{Btag})}{2\cdot N_{BB}\cdot BR(B\to X\ell\nu)}$$

$$R(X_{e/\mu})^{p^*_\ell>1.3} = 1.033 \pm 0.010 \pm 0.020$$

Source of uncertainty	Lepton ID	$X_c\ell\nu$ BFs	$X_c\ell\nu$ FFs	Statistical	Total
Rel. unc. of $R(X_{e/\mu})$	1.8%	0.1%	0.2%	1.0%	2.2%

compatible within 0.6σ with exclusive Belle measurement:
$R(D^*_{e/\mu}) = 1.01 \pm 0.01 \pm 0.03$ [PRD 100, 052007 (2019)]

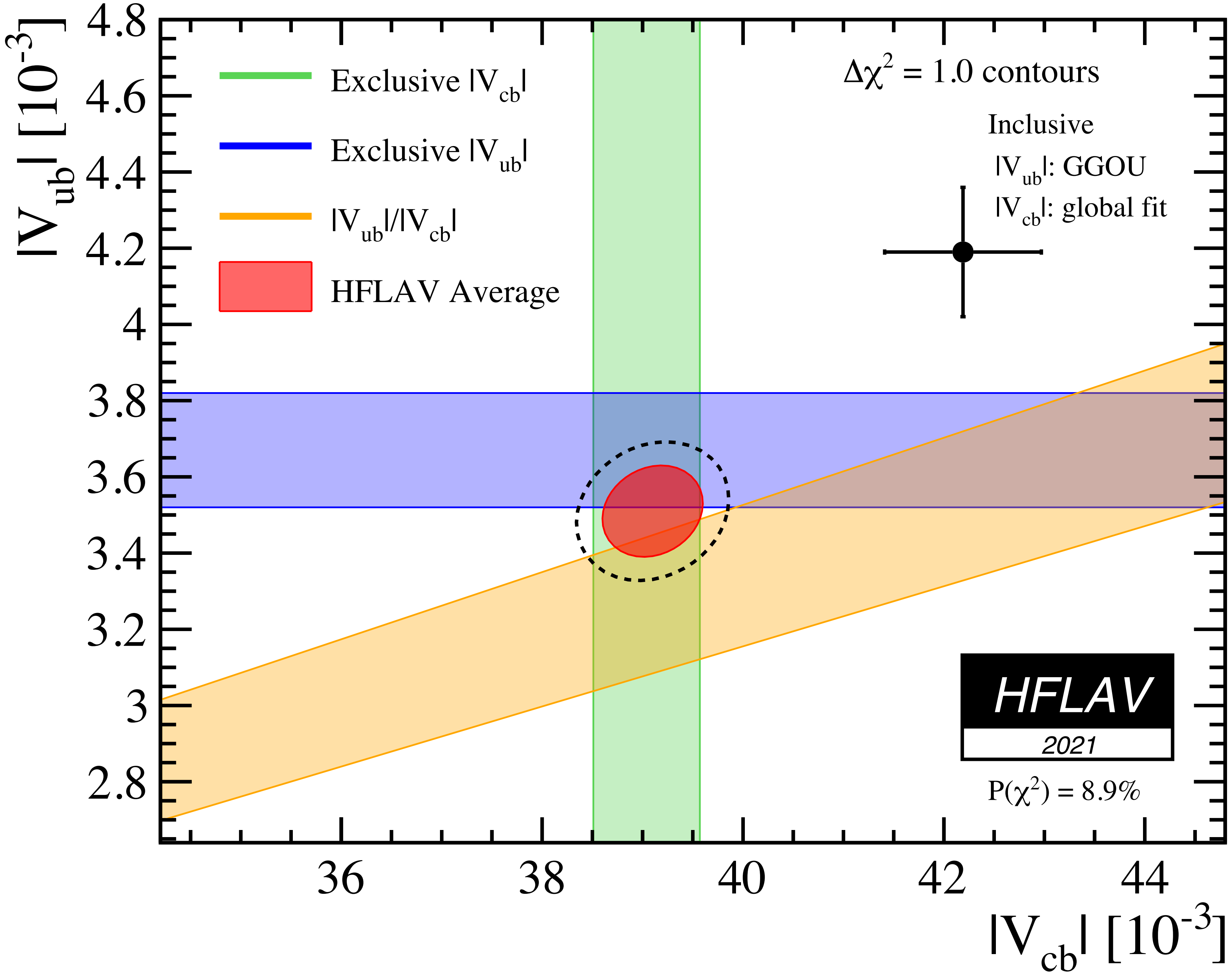
slide portion taken from Belle II ICHEP2022 talk by H. Junkerkalefeld

More on $B \to X\ell^+\nu$

- V_{cb}, V_{ub} — "inclusive vs. exclusive tension"
- V_{ub} efforts (quick summary)
- V_{cb} — a new method with q^2 moments (Belle, Belle II, hep-ph)

Inclusive vs. Exclusive Tension

in the measurements of $|V_{cb}|$, $|V_{ub}|$ between inclusive and exclusive approaches



$$|V_{ub}|_{\rm incl.} = (4.19 \pm 0.12^{+0.11}_{-0.12}) \times 10^{-3}$$

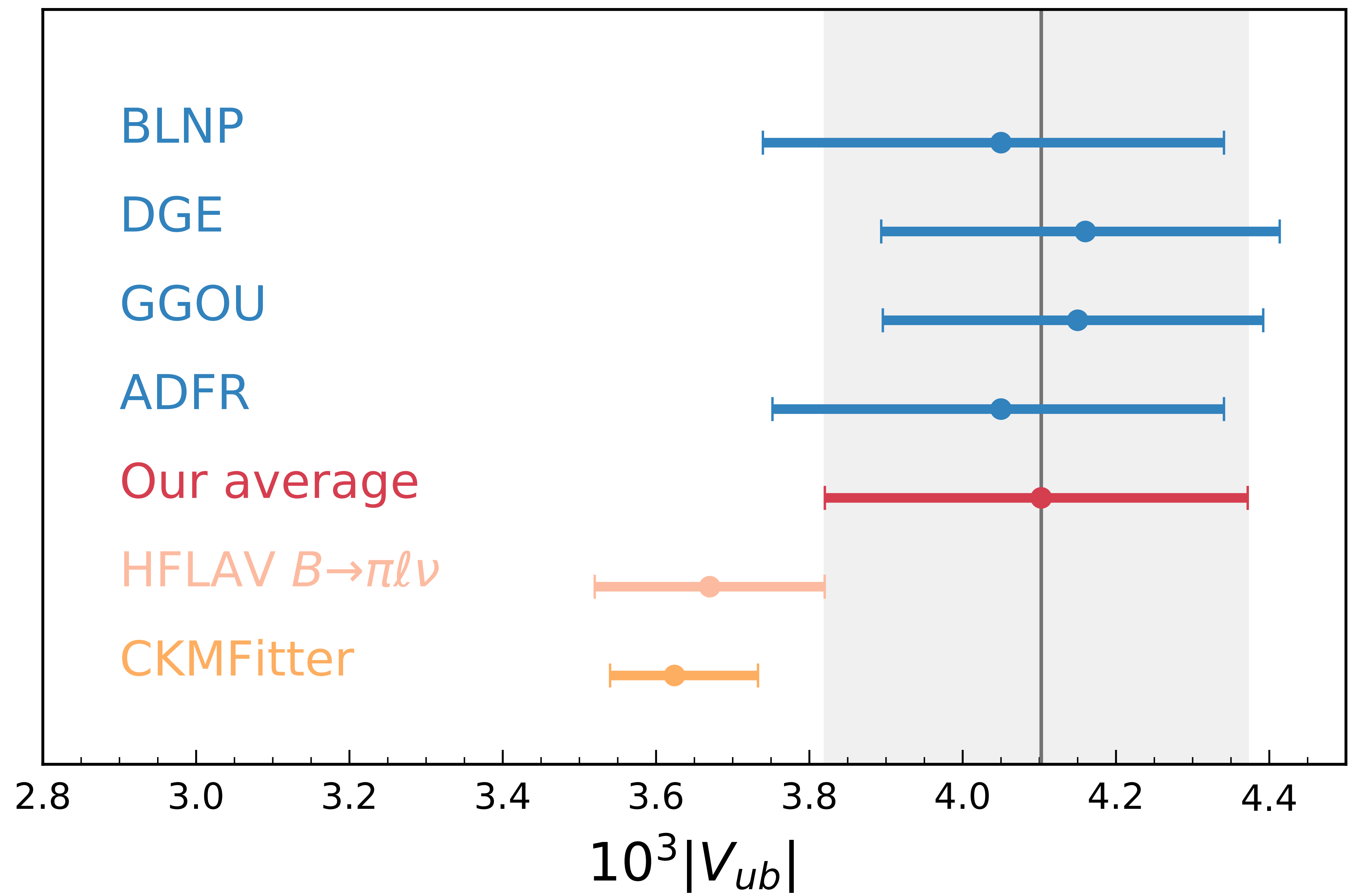
$$|V_{ub}|_{\rm excl.} = (3.51 \pm 0.12) \times 10^{-3}$$

$$|V_{cb}|_{\rm excl.} = (39.10 \pm 0.50) \times 10^{-3}$$

$$|V_{cb}|_{\rm incl.} = (42.19 \pm 0.78) \times 10^{-3}$$

$\sim 3\sigma$ tension for each ($|V_{cb}|$, $|V_{ub}|$)

Determination of $|V_{ub}|$



- $|V_{ub}|$ from inclusive $B \to X_u \ell^+ \nu_\ell$
- compatible with exclusive determination by 1.3σ
- compatibility with CKM unitarity[73] : 1.6σ
- differential shapes and other properties — left for future work

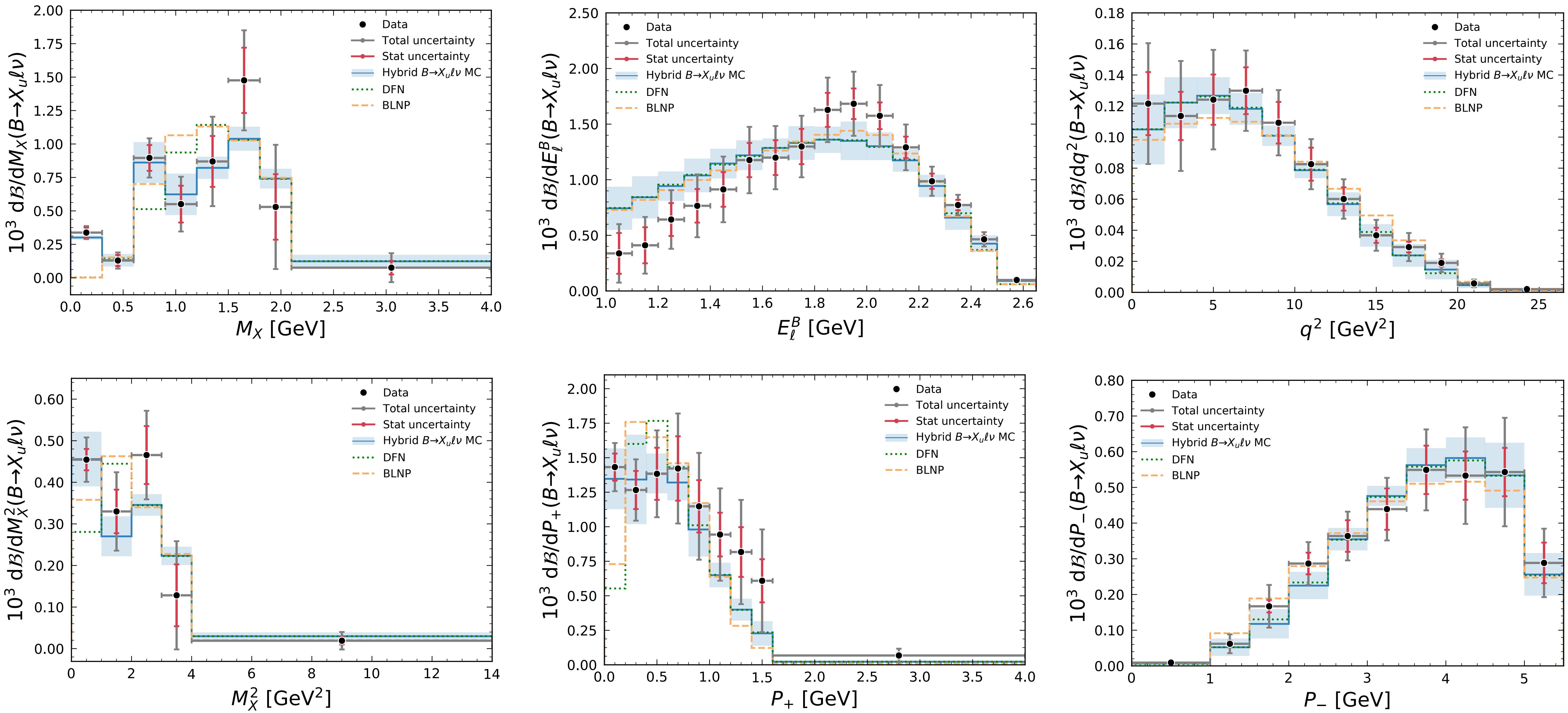
[73] J. Charles *et al.* (CKMfitter Group), Eur. Phys. J. C **41**, 1 (2005), arXiv:hep-ph/0406184.

$$|V_{ub}| = (4.10 \pm 0.09 \pm 0.22 \pm 0.15) \times 10^{-3}$$

to quote a single value, we take a simple arithmetic avg. of the most inclusive results (2D fits)

Differential $\Delta\mathscr{B}(B \to X_u \ell^+ \nu)$ – Results

- Measure differential $\Delta\mathscr{B}(B \to X_u \ell^+ \nu)$ with $E_\ell^B > 1$ GeV (Figs. below)
- All MC shapes are normalized to $\Delta\mathscr{B} = 1.59 \times 10^{-3}$
- Useful input for future model-independent determination of $|V_{ub}|$

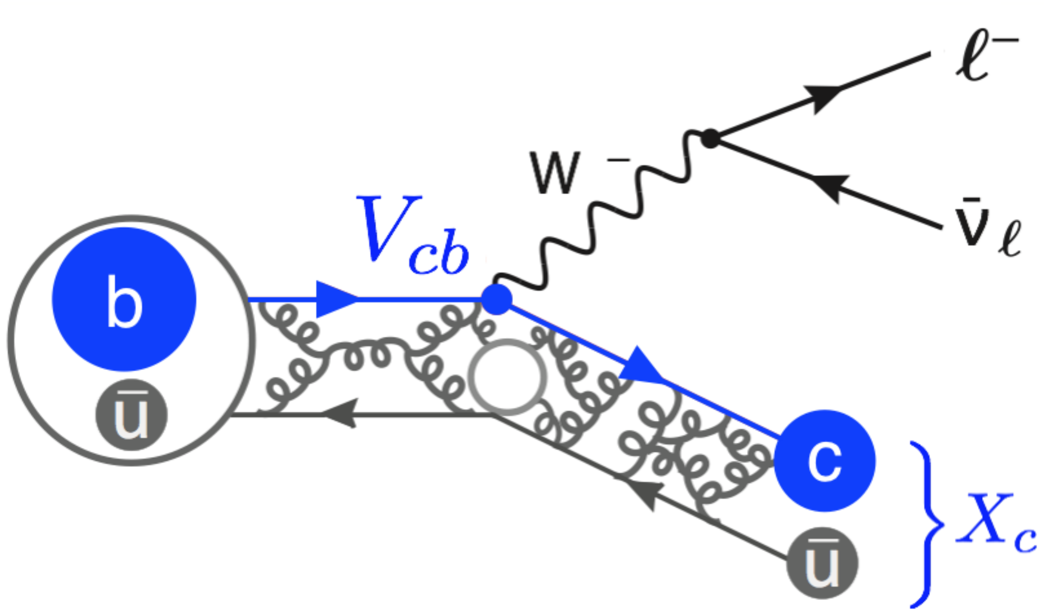


q^2 moments in $B \to X_c \ell^+ \nu_\ell$

Motivations

- $\exists$ tension between exclusive & inclusive measurements of $|V_{cb}|$
- inclusive approach for $|V_{cb}|$
  - free from uncertainties of form factor shape and normalization
  - exploits HQE — total decay rate and spectral moments can be expanded into a manageable number of non-perturbative matrix elements
- measure q^2 moments
  - a novel approach by Fael, Manel, Keri Vos [JHEP 02, 177 (2019)]
  - use "reparametrization invariance"
  - data-driven method for $|V_{cb}|$ up to $1/m_b^4$

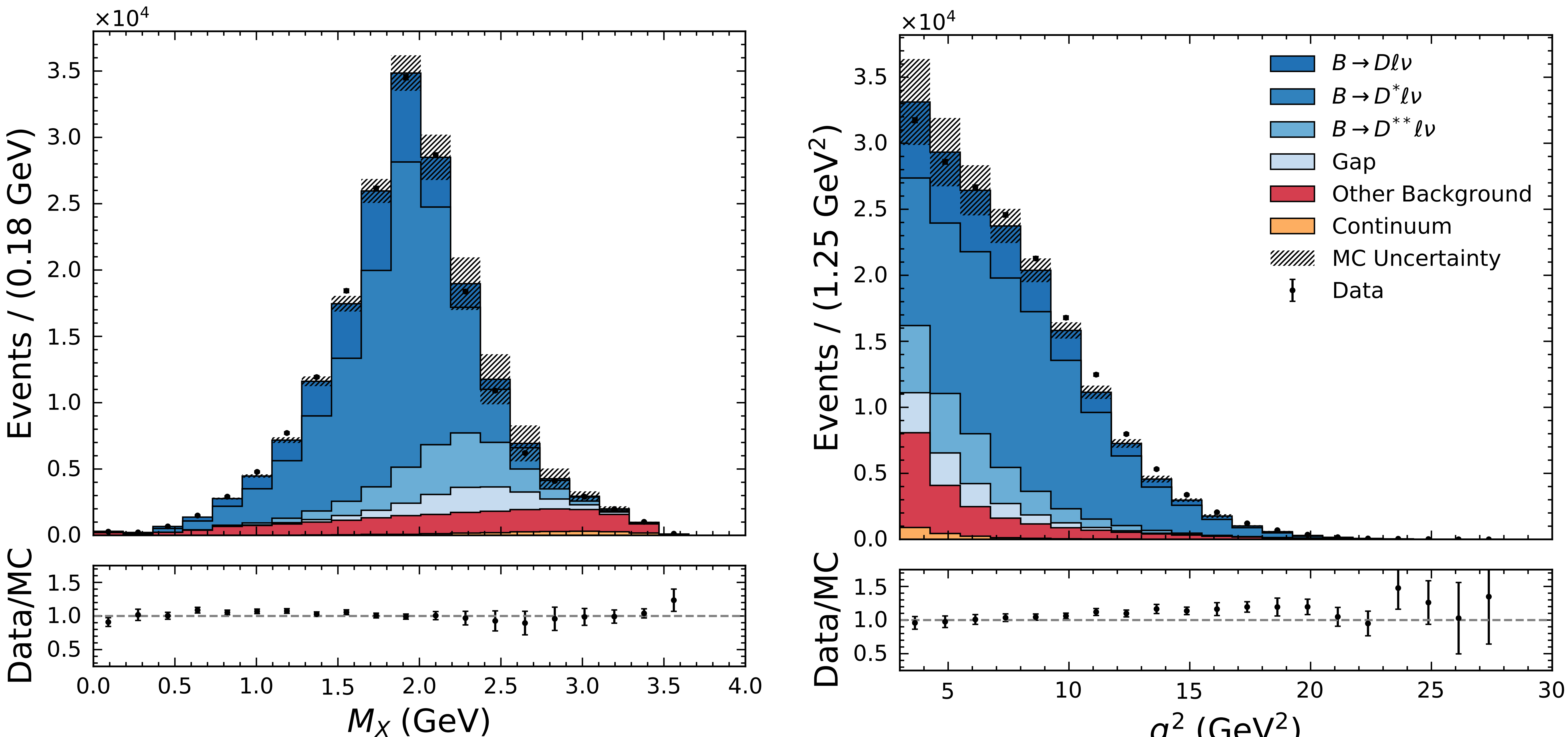
    reduce # of parameters $(13 \to 8)$



q^2 moments in $B \to X_c \ell^+ \nu_\ell$ (Belle)

Analysis features

- use full reconstruction tagging (of the accompanying B) — B_{tag}
- Remainder (after B_{tag}) of the signal event (ℓ^+, X_c and a missing ν) — measure M_X, q^2



q^2 moments in $B \to X_c \ell^+ \nu_\ell$ (Belle)

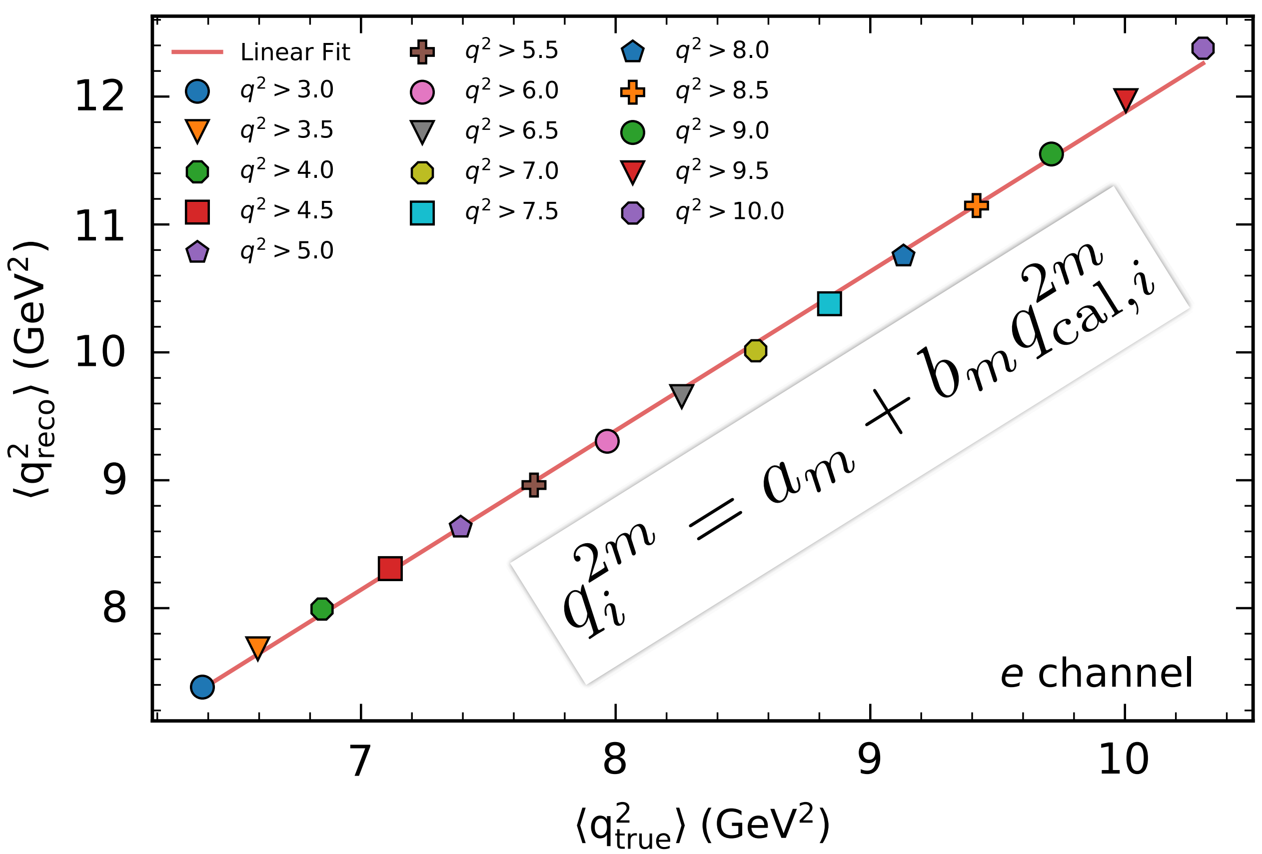
Analysis features

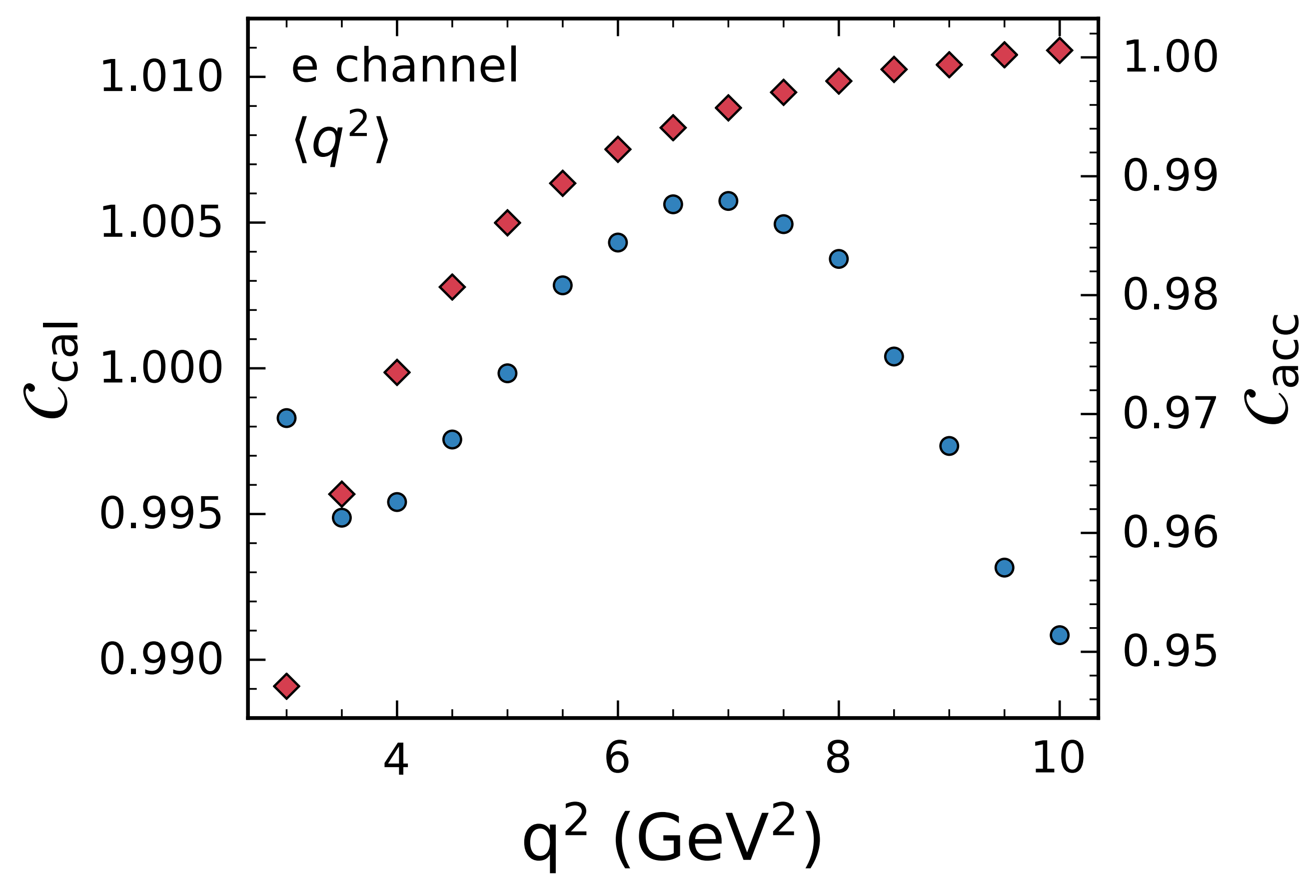
- use full reconstruction tagging (of the accompanying B) — B_{tag}
- Remainder (after B_{tag}) of the signal event (ℓ^+, X_c and a missing ν) — measure M_X, q^2

The moments — how to

$$\langle q^{2m} \rangle = \frac{C_{\rm cal} \cdot C_{\rm acc}}{\sum_i^{\rm events} w(q_i^2)} \times \sum_i^{\rm events} w(q_i^2) \cdot q_{{\rm cal}\, i}^{2m}$$

$C_{\rm cal}$: residual bias correction
$C_{\rm acc}$: acceptance correction





PRD 104, 112011 (2021)

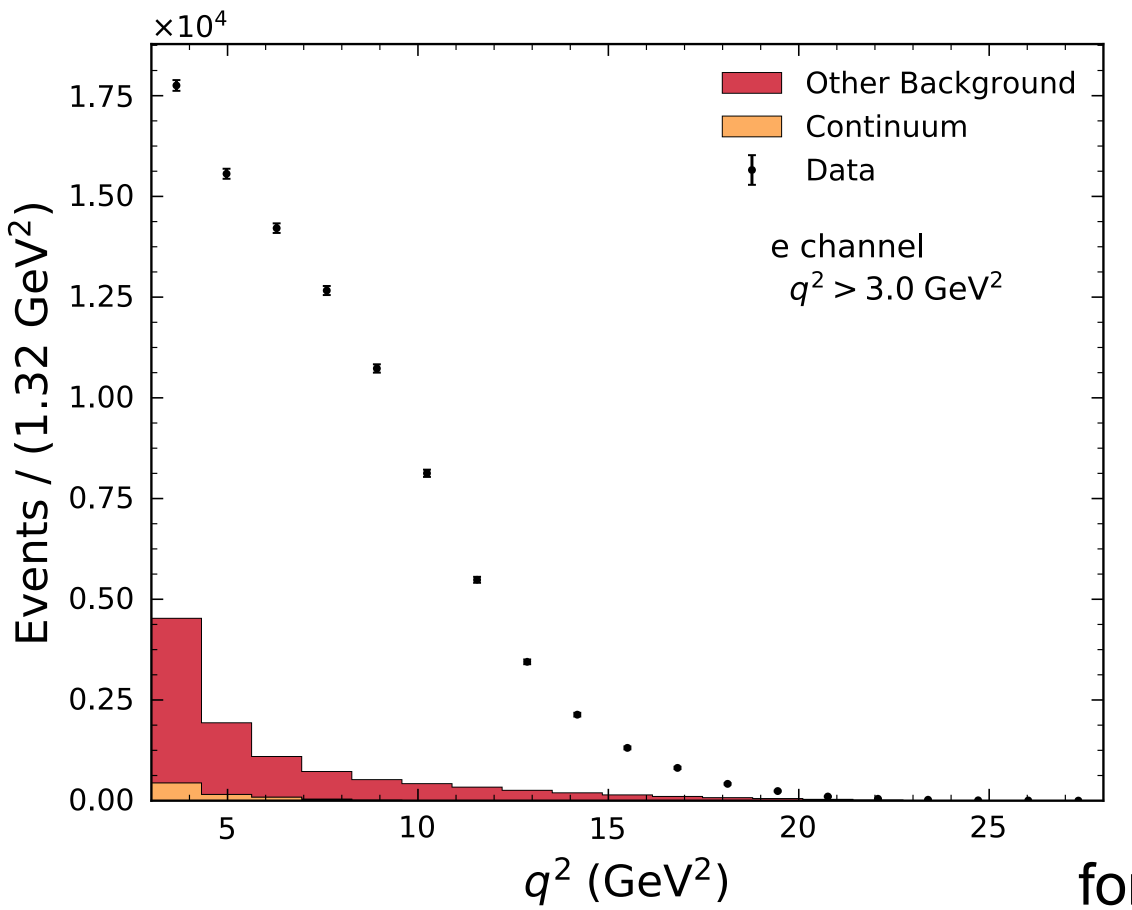
q^2 moments in $B \to X_c \ell^+ \nu_\ell$ (Belle)

Analysis features

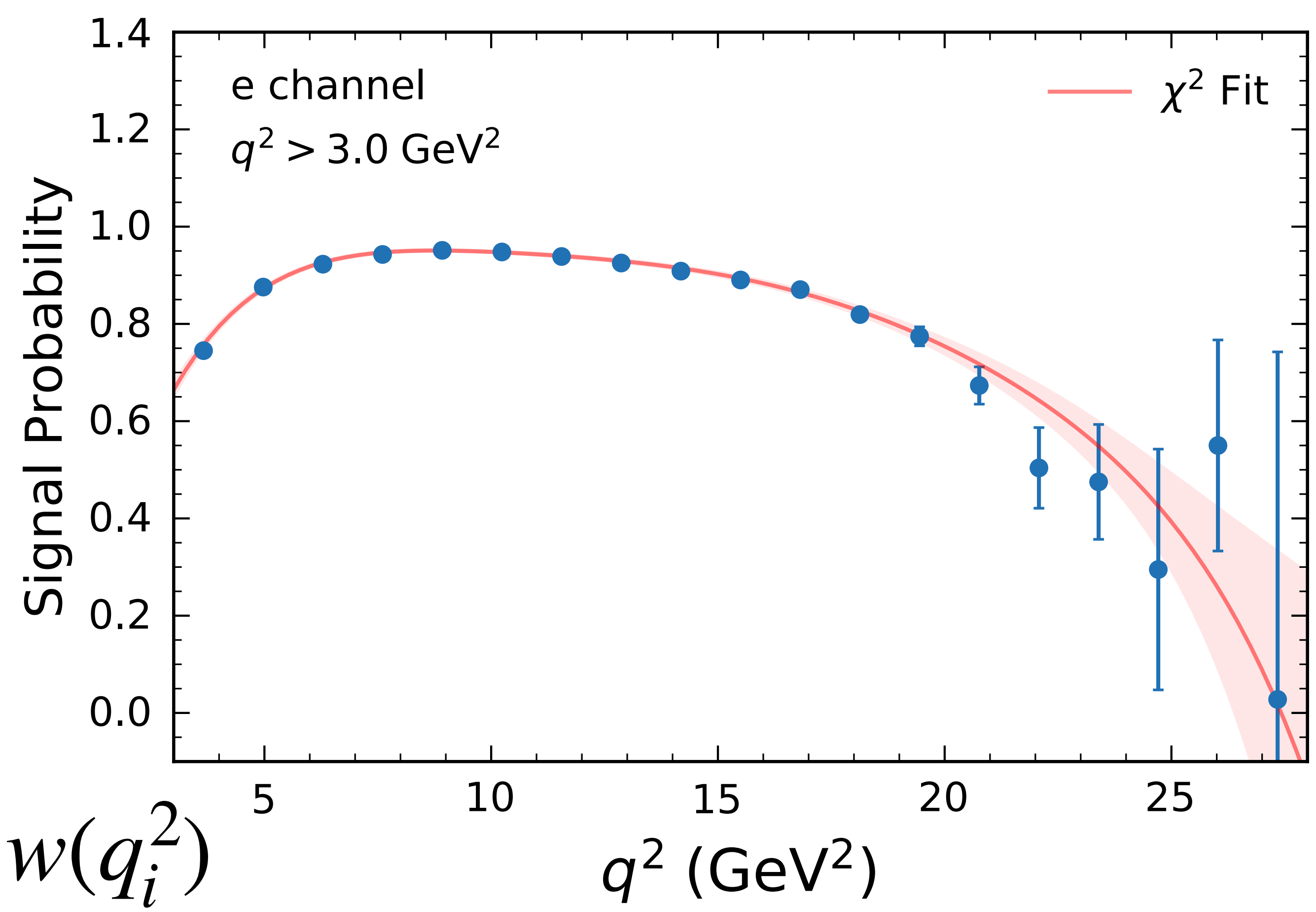
- use full reconstruction tagging (of the accompanying B) — B_{tag}
- Remainder (after B_{tag}) of the signal event (ℓ^+, X_c and a missing ν) — measure M_X, q^2

The moments — how to

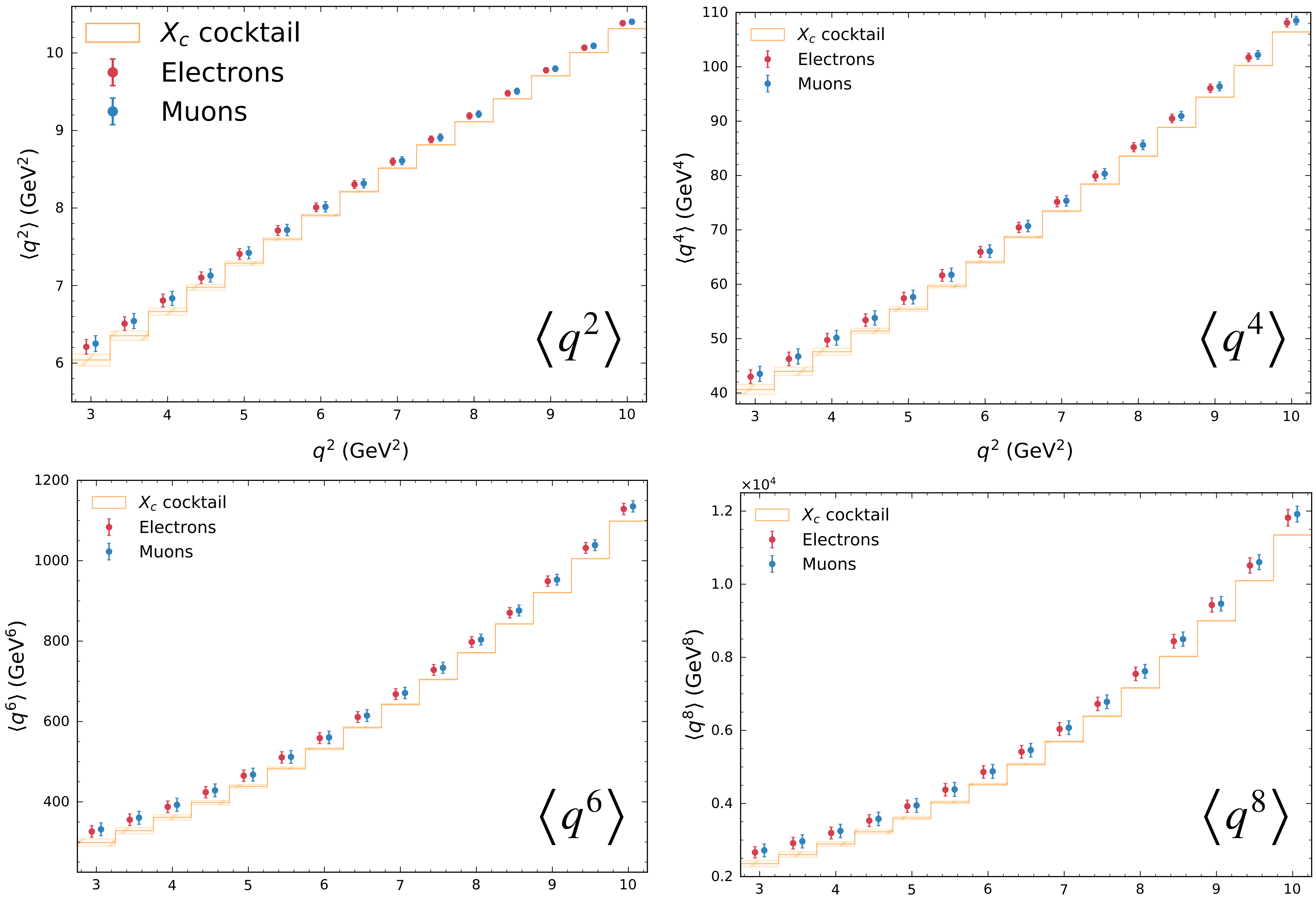
$$\langle q^{2m} \rangle = \frac{C_{\text{cal}} \cdot C_{\text{acc}}}{\sum_i^{\text{events}} w(q_i^2)} \times \sum_i^{\text{events}} w(q_i^2) \cdot q_{\text{cal}\, i}^{2m}$$



for $w(q_i^2)$

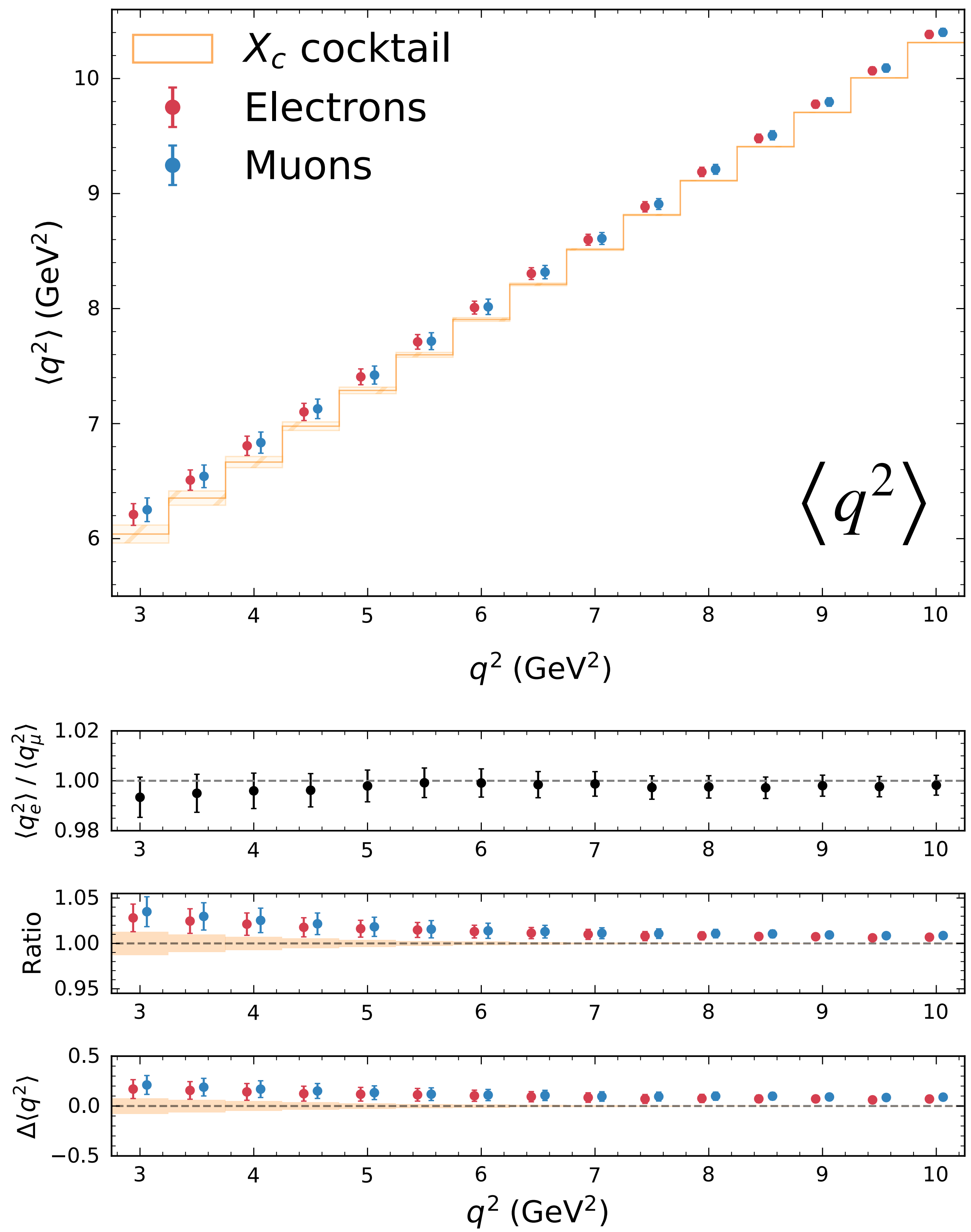


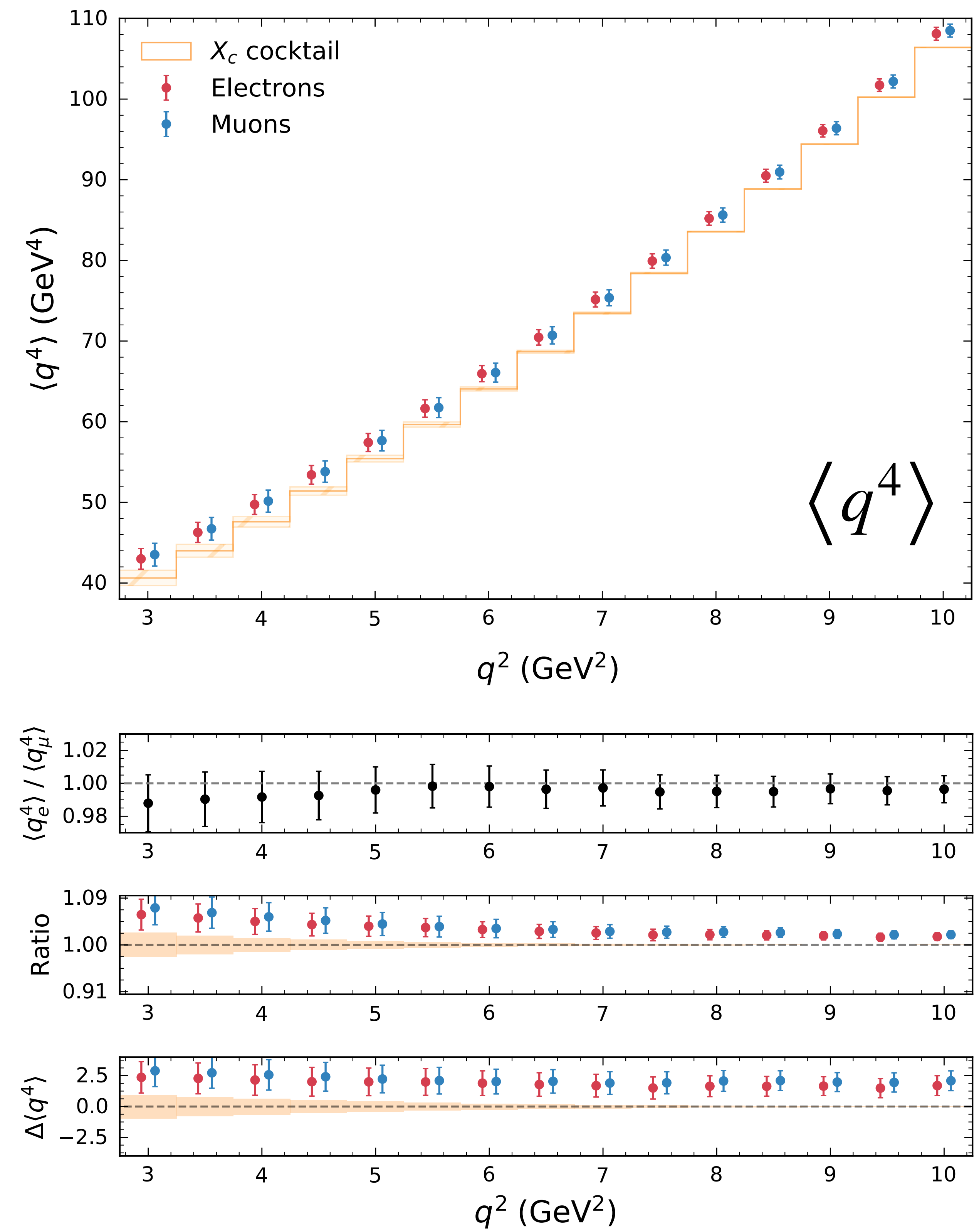
q^2 moments in $B \to X_c \ell^+ \nu_\ell$ (Belle)



PRD 104, 112011 (2021)

q^2 moments in $B \to X_c \ell^+ \nu_\ell$ (Belle)

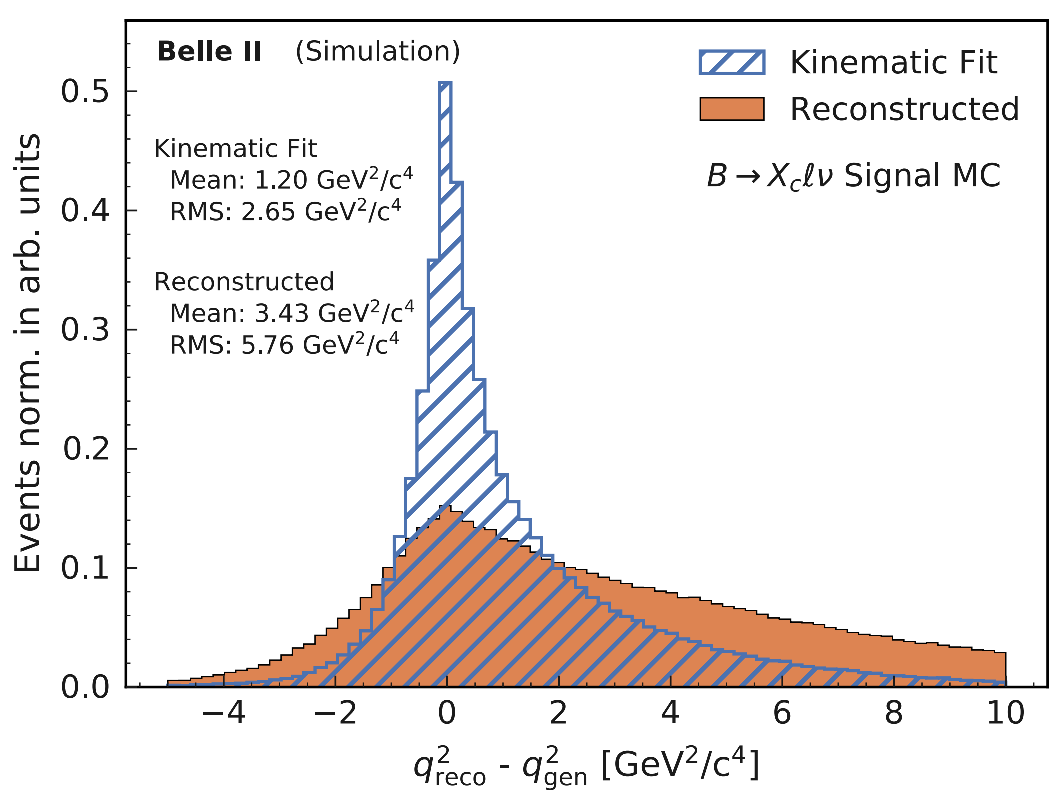


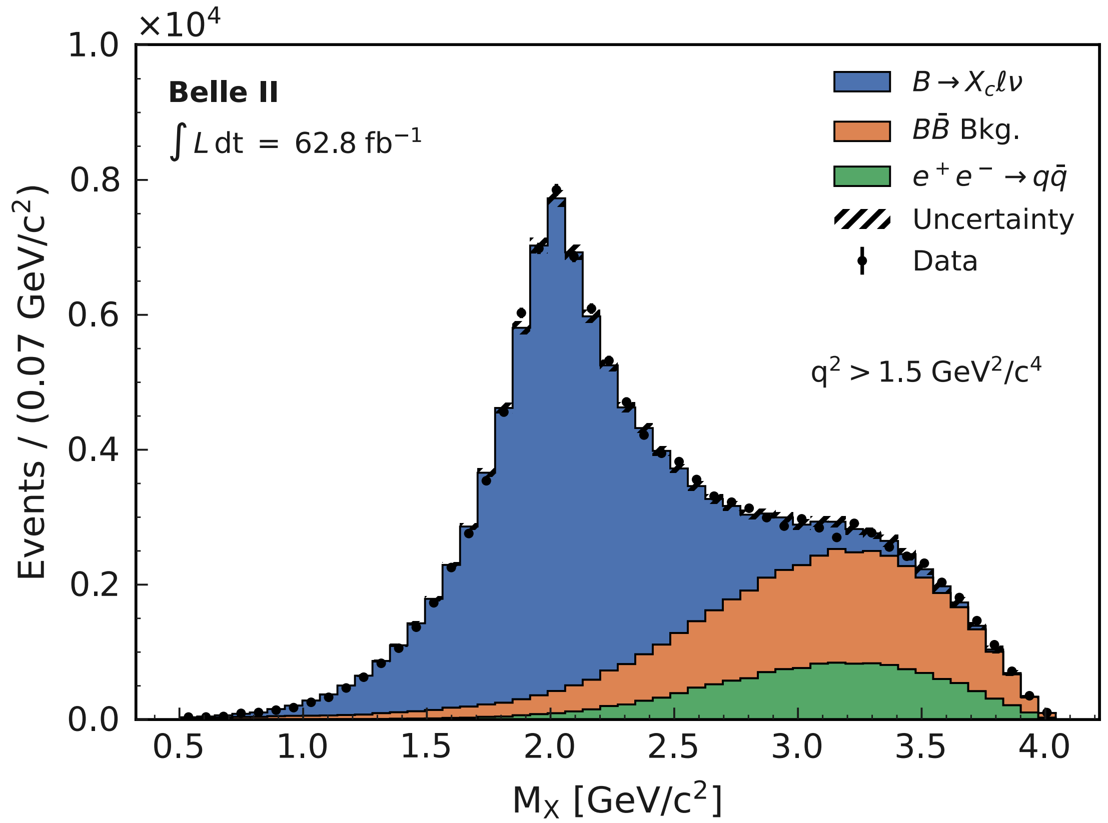


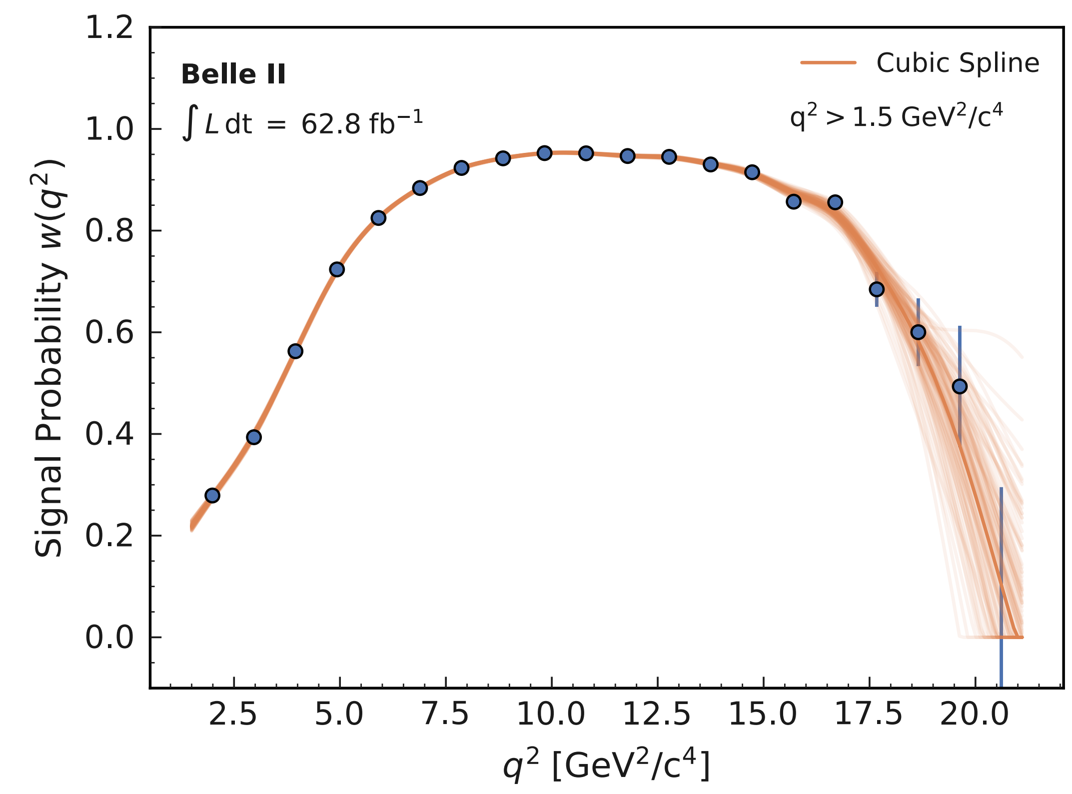
q^2 moments in $B \to X_c \ell^+ \nu_\ell$ (Belle II)

Analysis features

- exploit FEI for B_{tag}
- raw and central (variance) moments for $q^2 > 1.5\ \text{GeV}^2$ up to $q^2 > 8.5\ \text{GeV}^2$
- first $\langle q^{2n} \rangle$ measurement in range $[1.5,\ 2.5]\ \text{GeV}^2$ range
- kinematic fit improves q^2 resolution significantly
- signal probability in q^2 bin estimated by M_X fit; interpolated with cubic spline





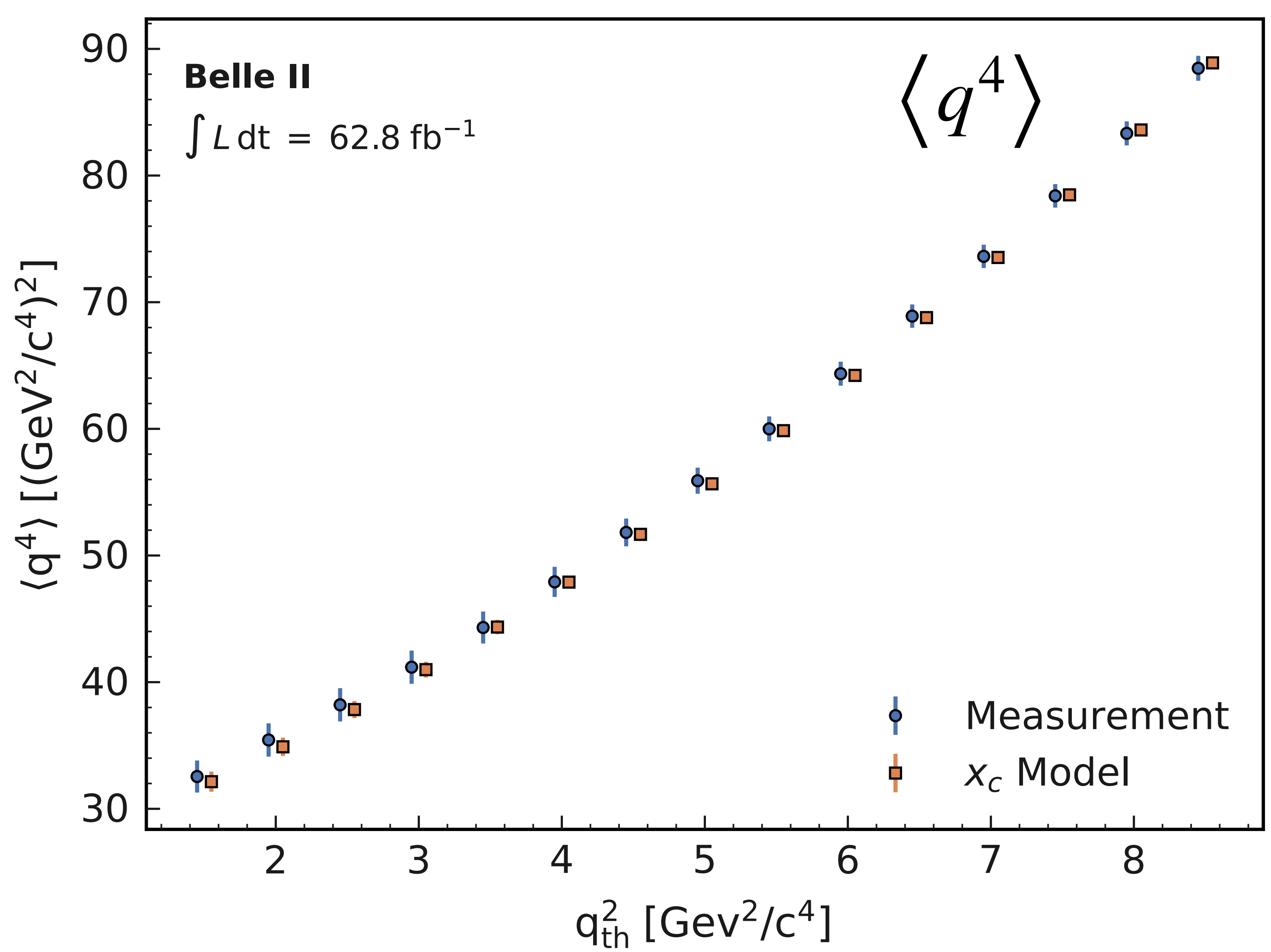


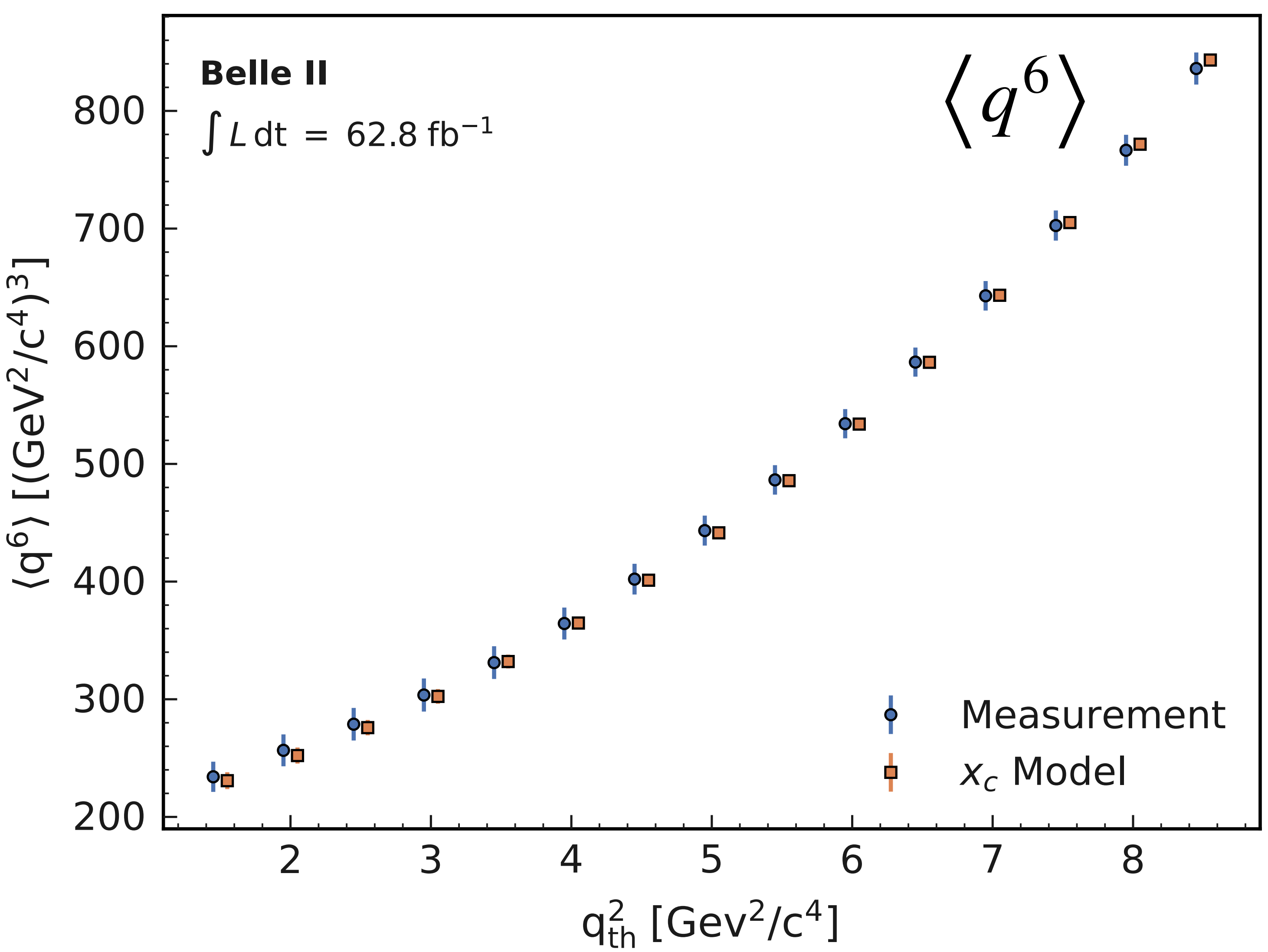
q^2 moments in $B \to X_c \ell^+ \nu_\ell$ (Belle II)

$\int \mathcal{L} dt = 62.8 \text{ fb}^{-1}$

Analysis features

- exploit FEI for B_{tag}
- raw and central (variance) moments for $q^2 > 1.5 \text{ GeV}^2$ up to $q^2 > 8.5 \text{ GeV}^2$
- first $\langle q^{2n} \rangle$ measurement in range $[1.5,\ 2.5]$ GeV^2 range





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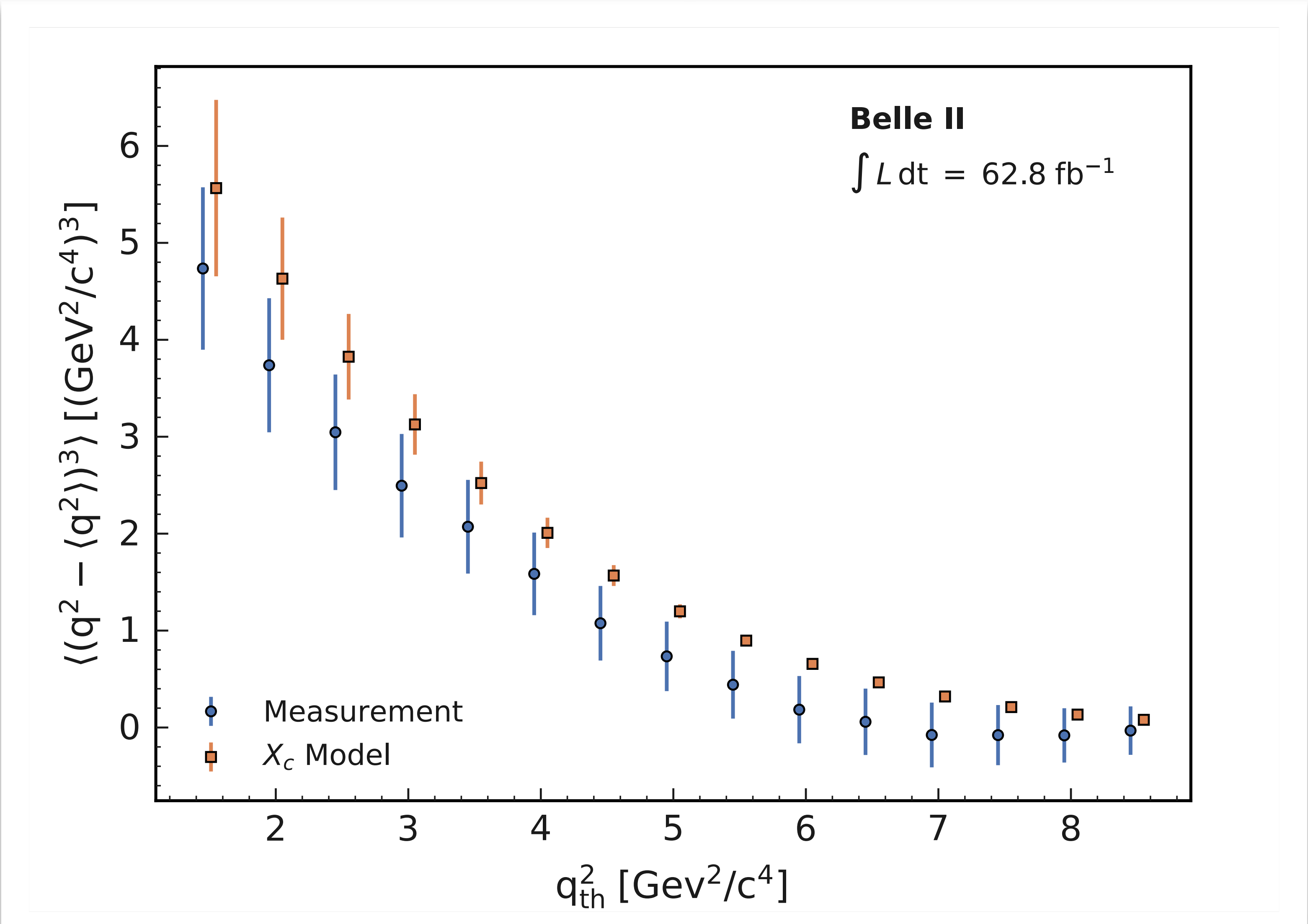
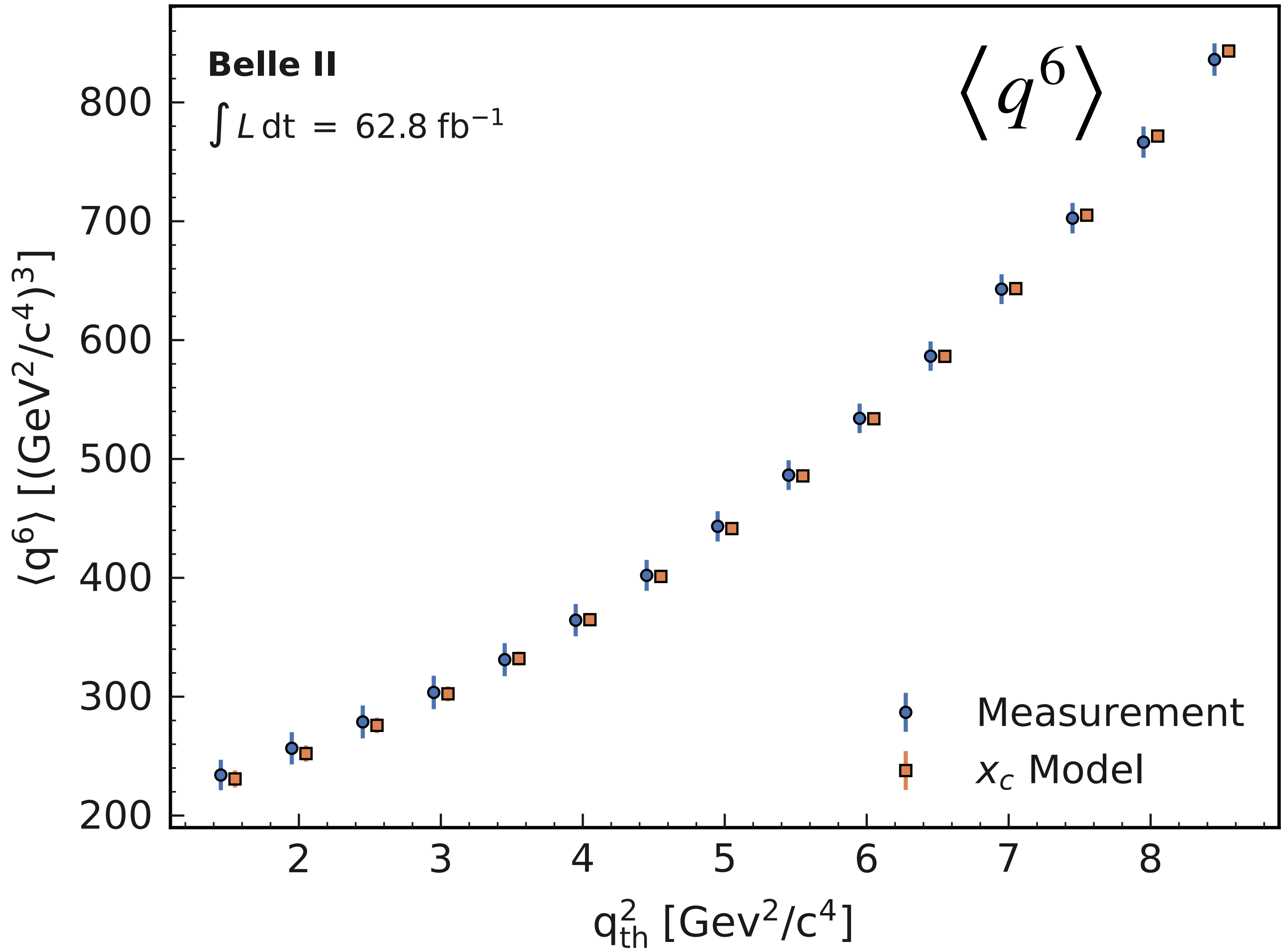




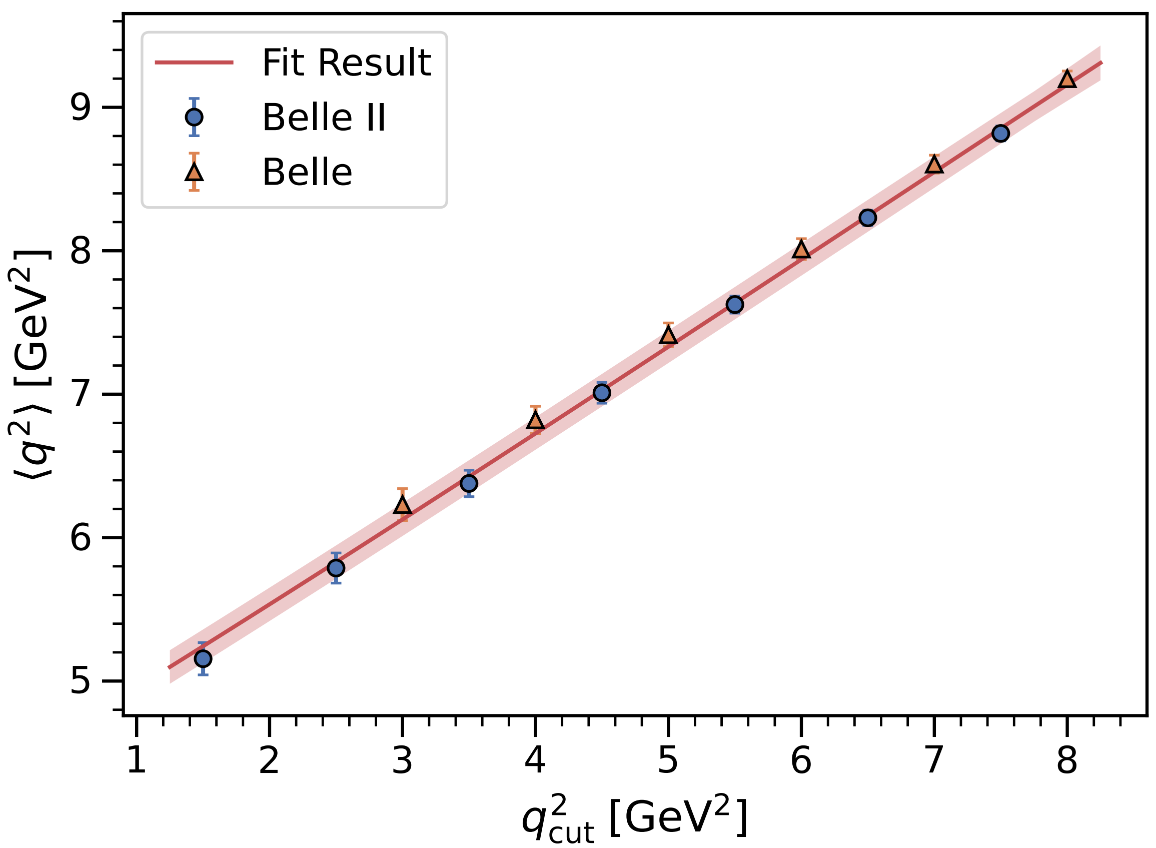
V_{cb} from q^2 moments in $B \to X_c \ell^+ \nu_\ell$

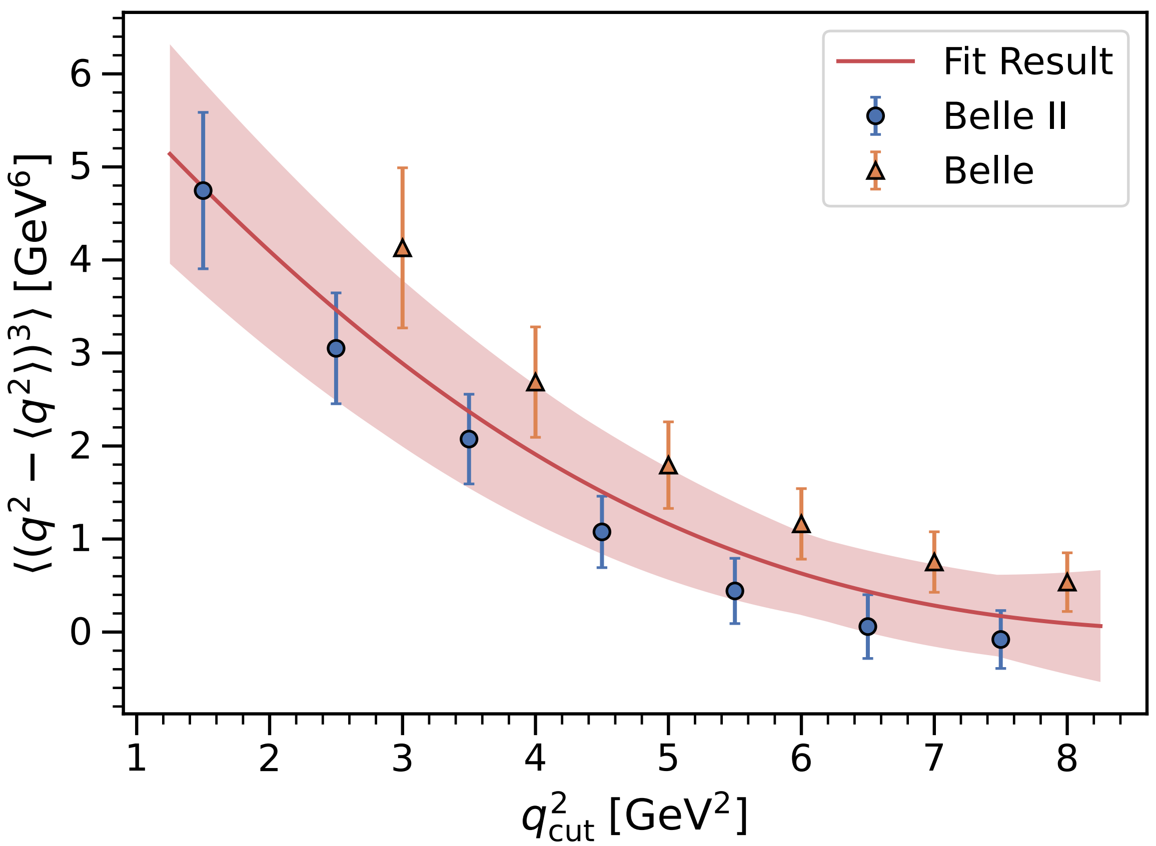
- a meta-analysis using q^2 moment spectra of Belle & Belle II (combined)
- use $\mathscr{B}(B \to X_c \ell^+ \nu) = (10.48 \pm 0.13)\,\%$
- HQE parameters and $|V_{cb}|$ by simultaneous χ^2 fit

First extraction of inclusive V_{cb} from q^2 moments

Florian Bernlochner[a], Matteo Fael[b], Kevin Olschewsky[c], Eric Persson[a], Raynette van Tonder[d], K. Keri Vos[e,f], Maximilian Welsch[a]

V_{cb} from q^2 moments in $B \to X_c \ell^+ \nu_\ell$





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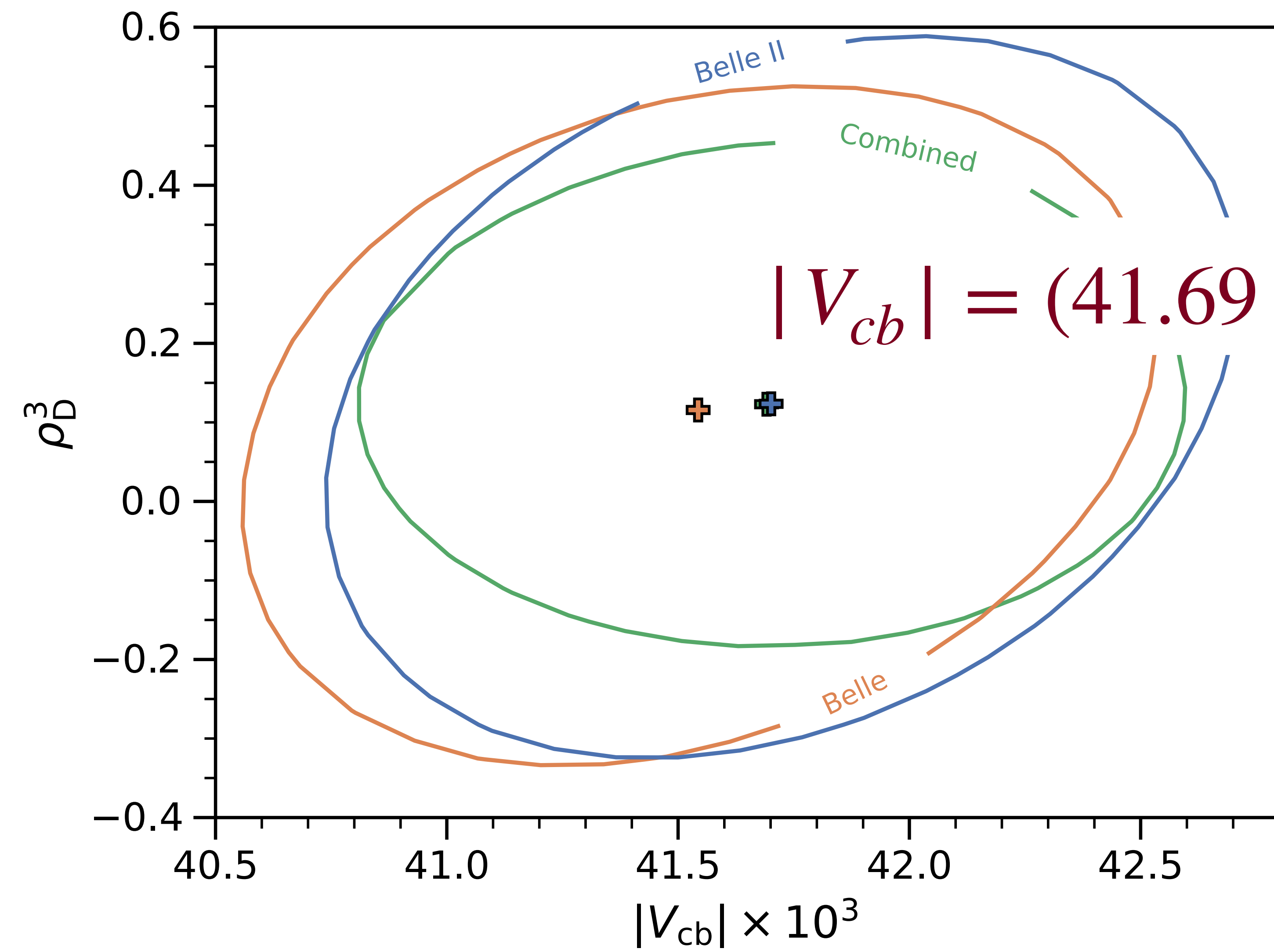
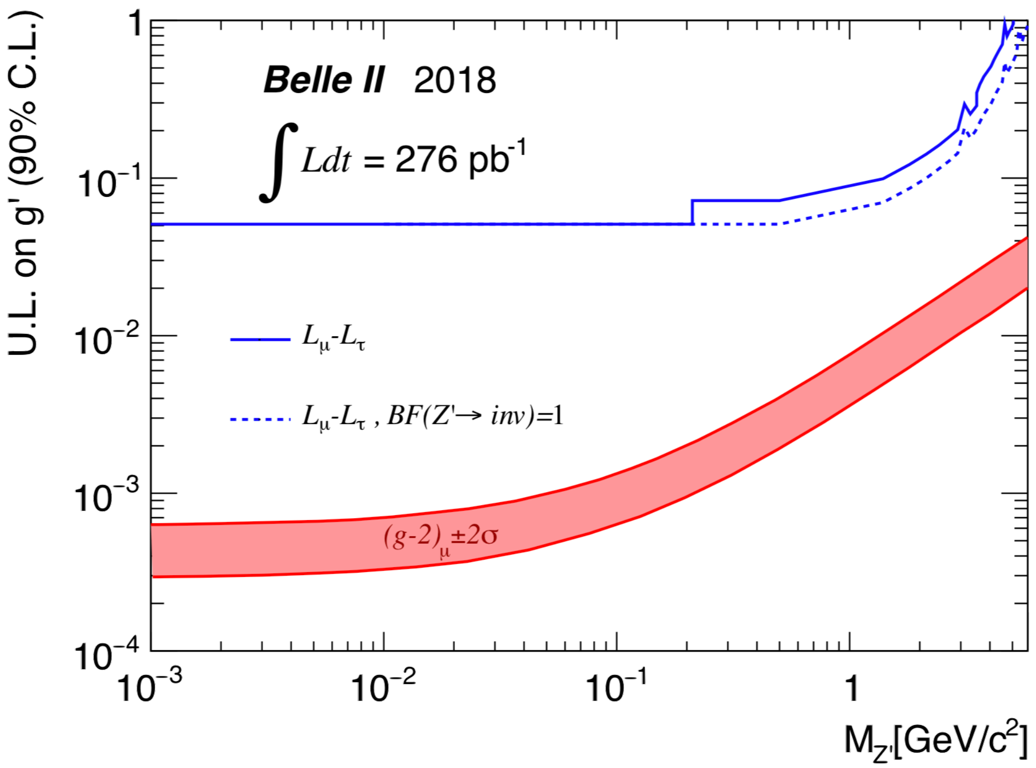


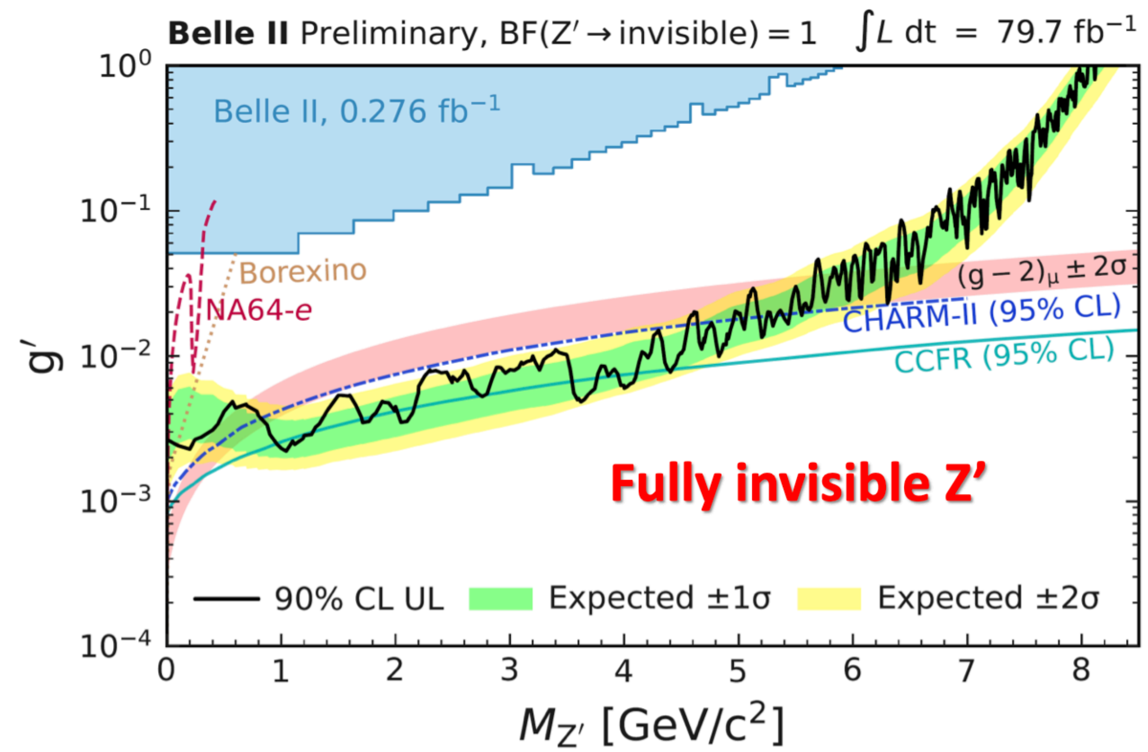
$|V_{cb}| = (41.69 \pm 0.63) \times 10^{-3}$

Honorable mentions — the Dark Sector

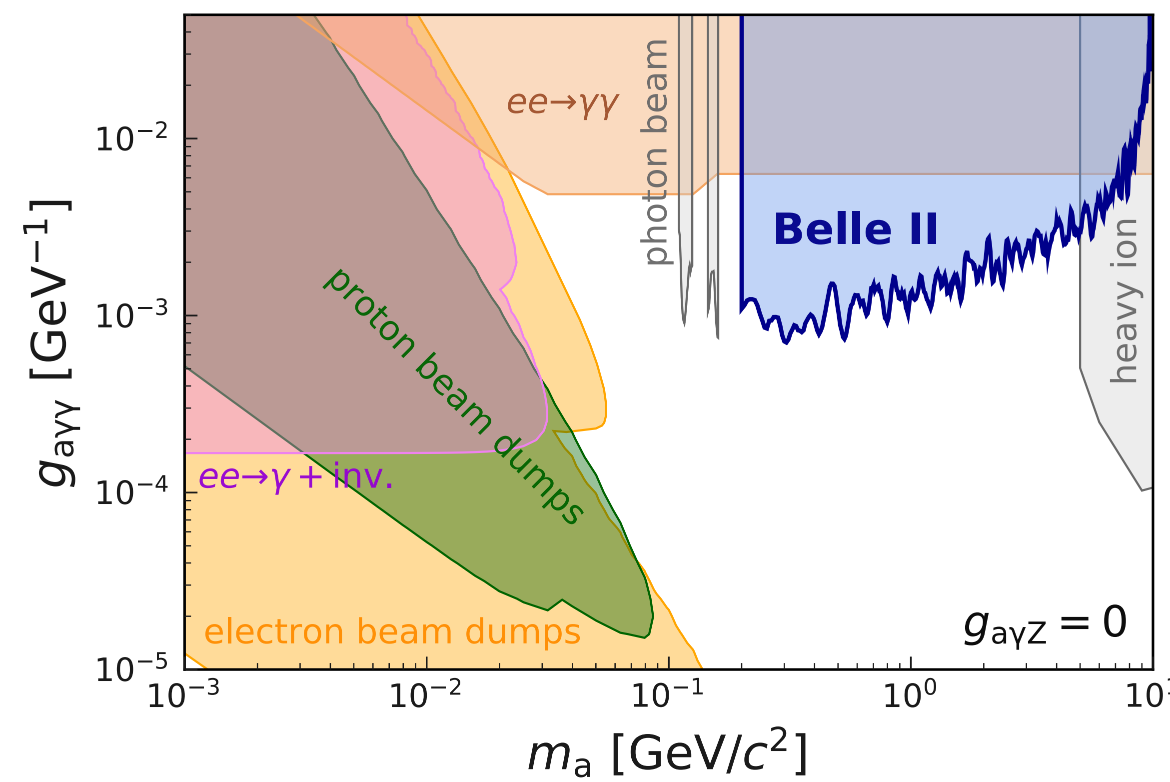
Belle II PRL (2020)

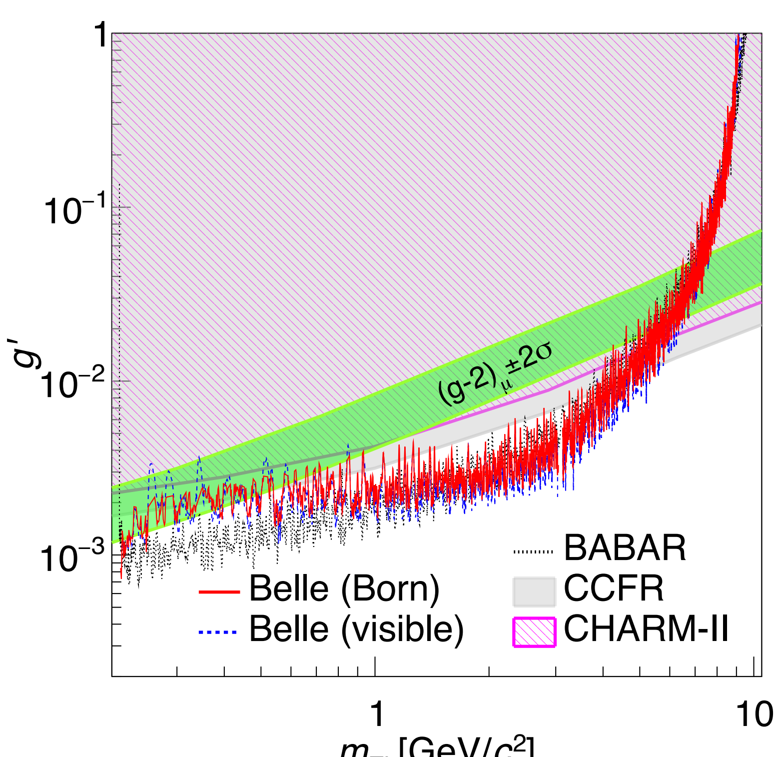


Belle II prelim. (2022)

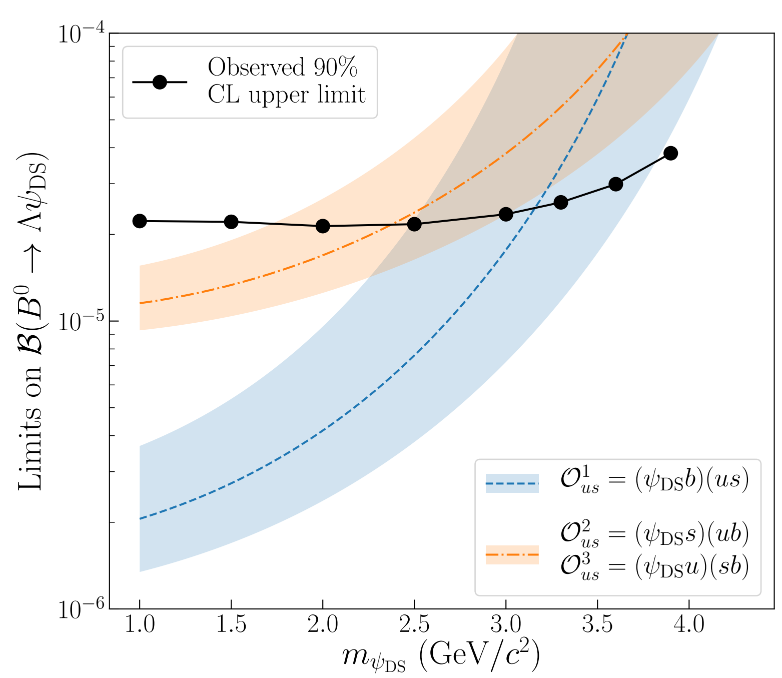


Belle II PRL (2020)

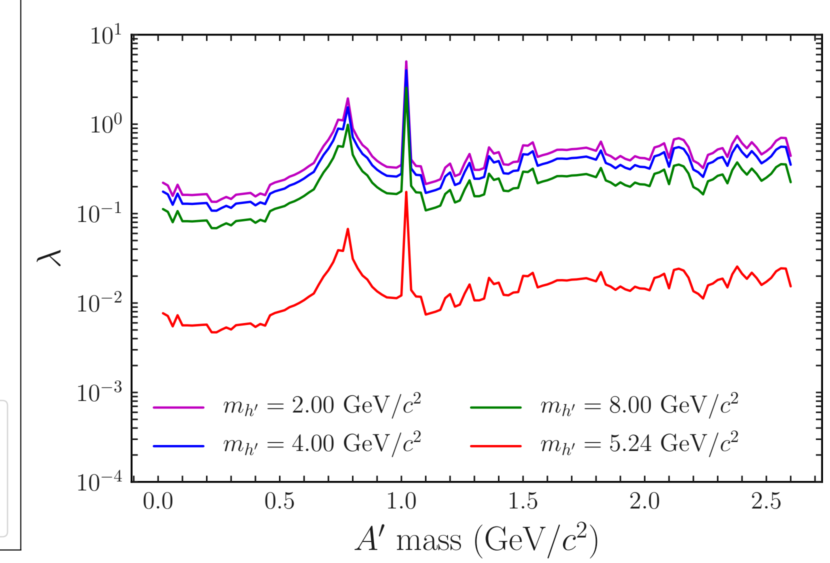




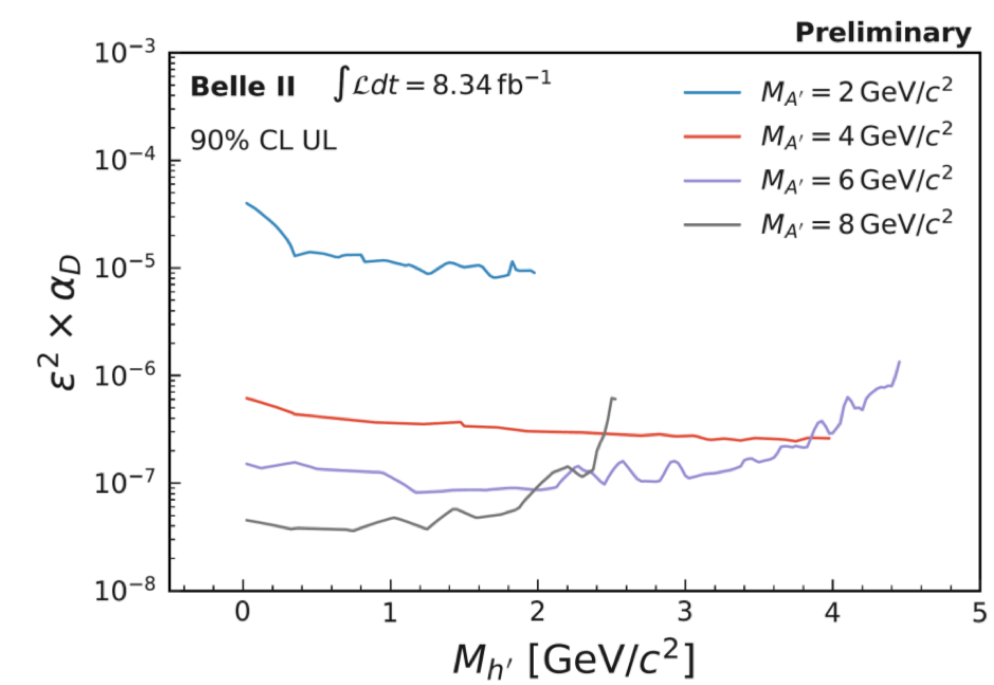
Belle PRD (accep.)



Belle PRD (2021)



Belle JHEP (2021)



Belle II PRL (subm.)

We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time.

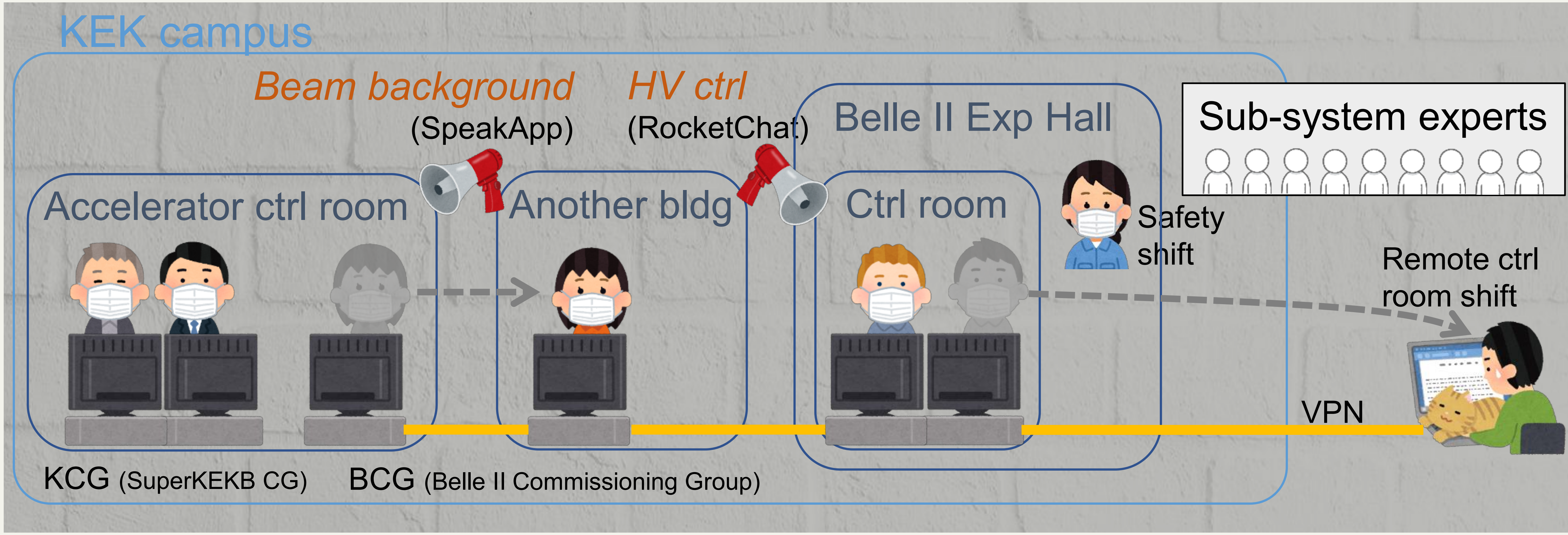
…

T. S. Eliot, from "Little Gidding"

Back-up slides

Belle II operations under Pandemic

- Minimize person-to-person contact and avoid 3C
  - Remote control room shifts and expert shifts
  - Travel restrictions (~40 Belle II colleagues on-site)
  - Online meetings



from ICHEP2020 talk by K. Matsuoka