Status of flavor anomalies with Belle & Belle II

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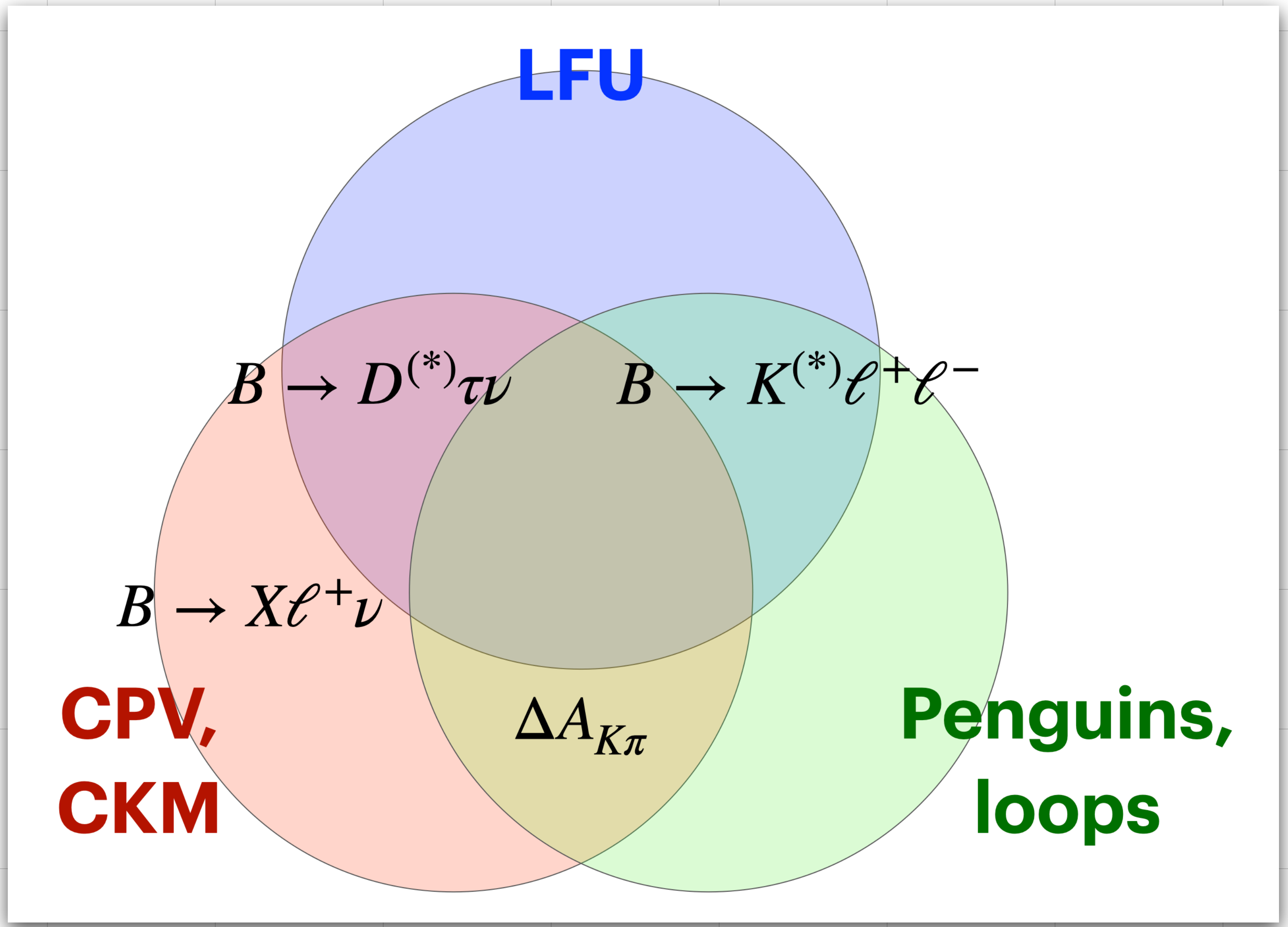
for PPC 2023 (June 12-16, 2023)

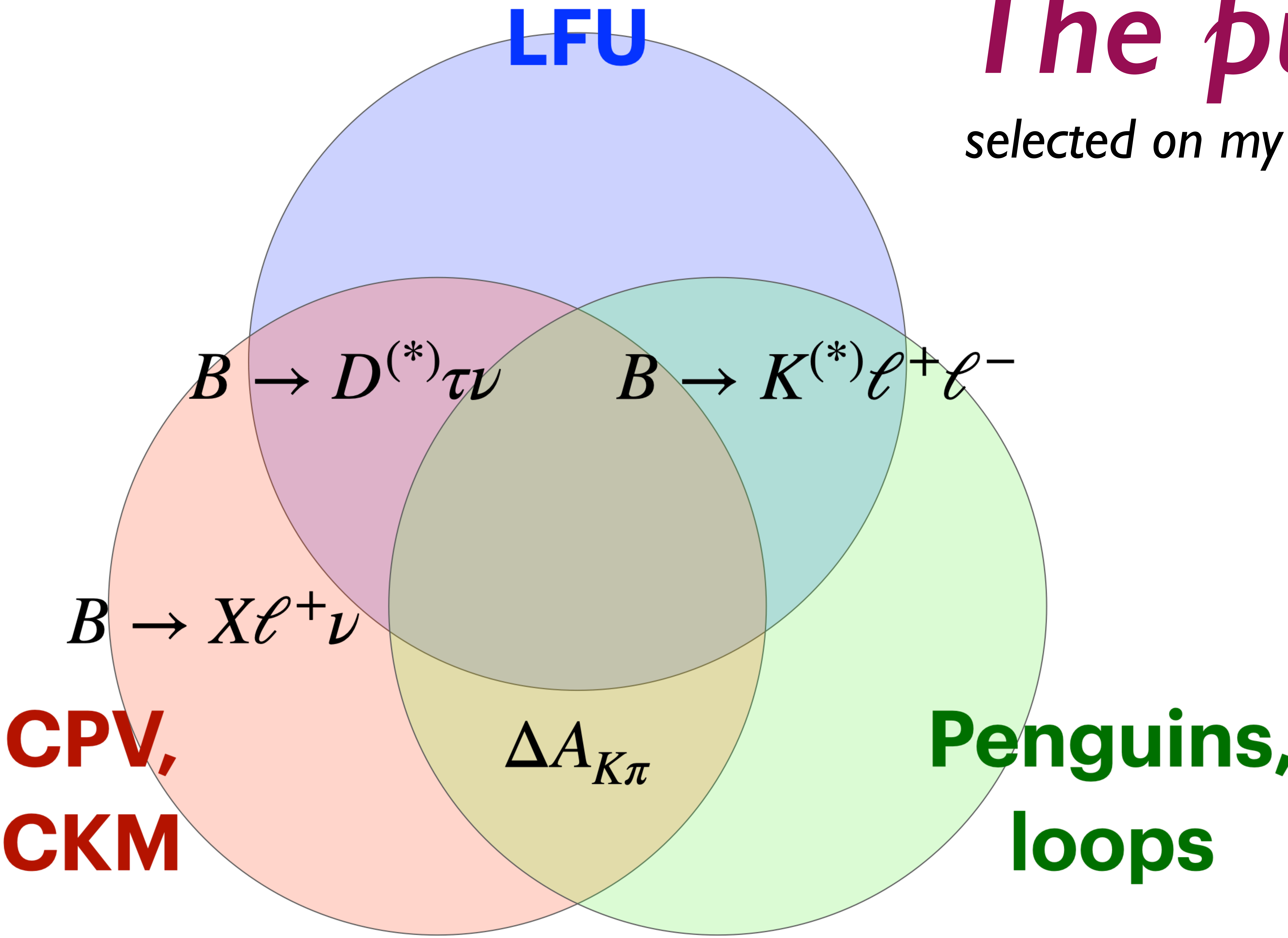
Outline

- The puzzles
  - Introduction
  - Cram course for B decays
- Results and status
  - $\Delta A_{K\pi}$
  - [CKM] Tension in $(V_{cb},\ V_{ub})$
  - [$R(D^{(*)})$] Inclusive test of LFU for μ vs. e
  - EWP B decays for studies related to $R_{K^{(*)}}$
- Honorable mentions
- Closing



The puzzles

selected on my personal taste



Belle II Physics Mind-map

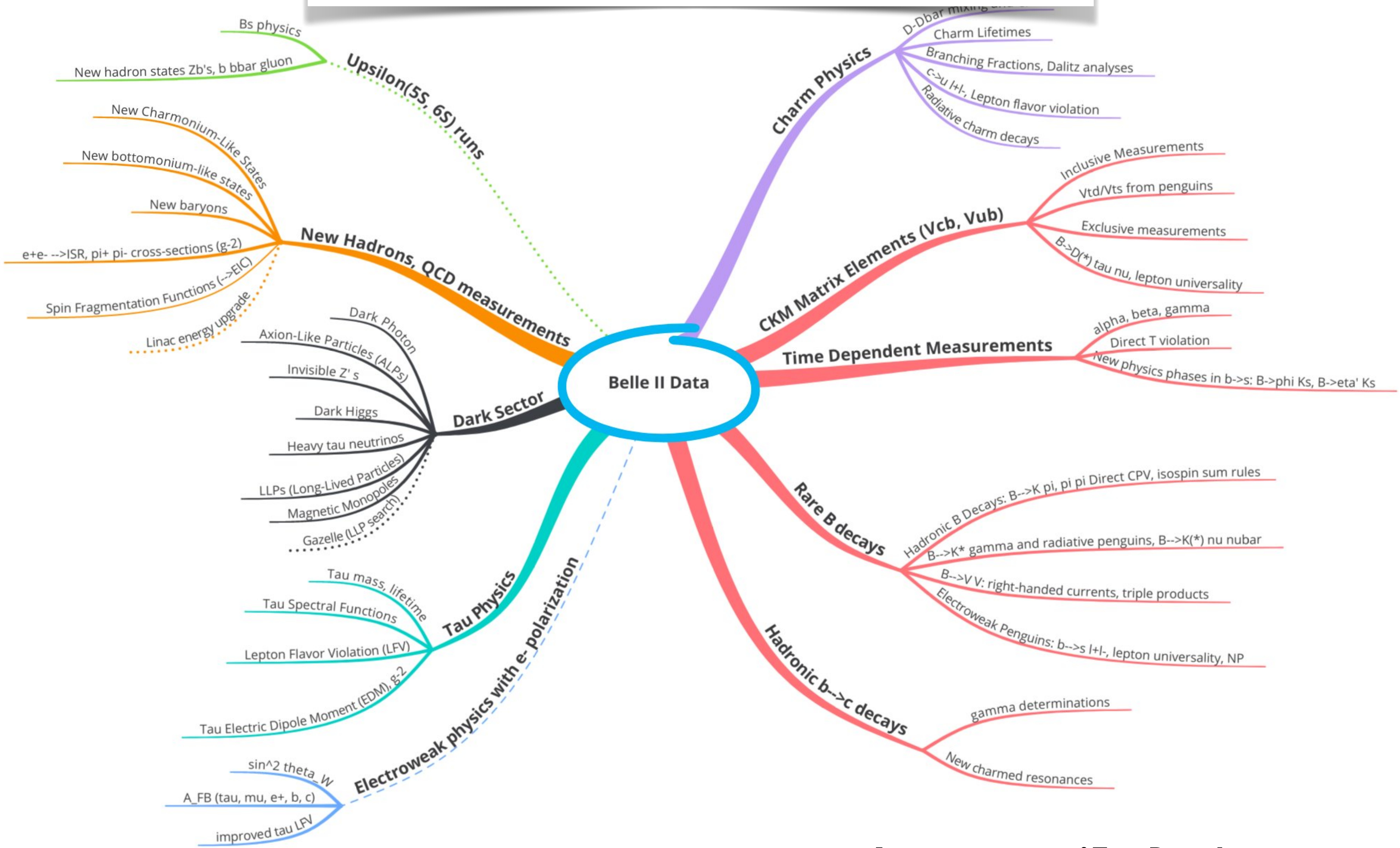


Image courtesy of Tom Browder

Belle II Physics Mind-map

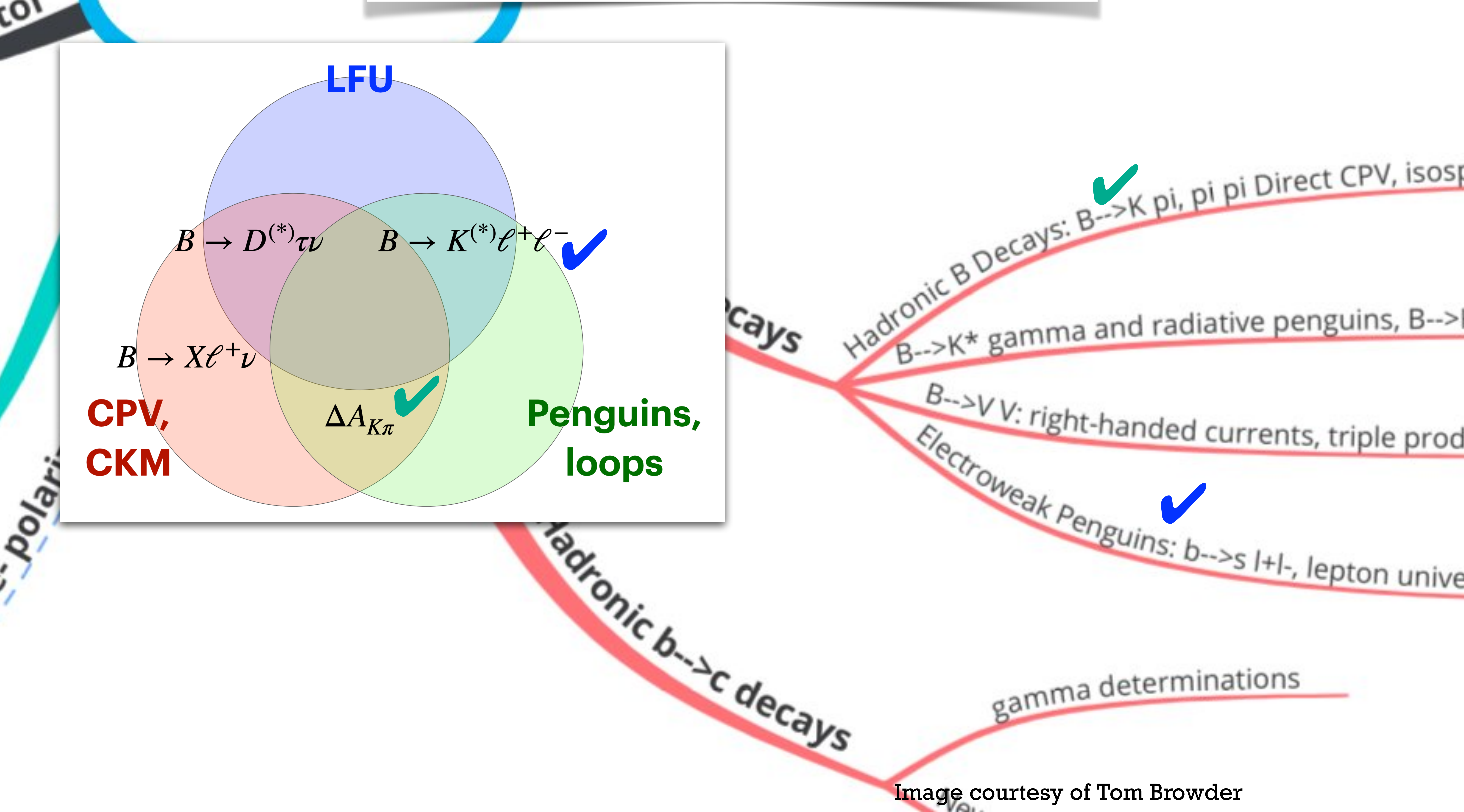


Image courtesy of Tom Browder

Belle II Physics Mind-map

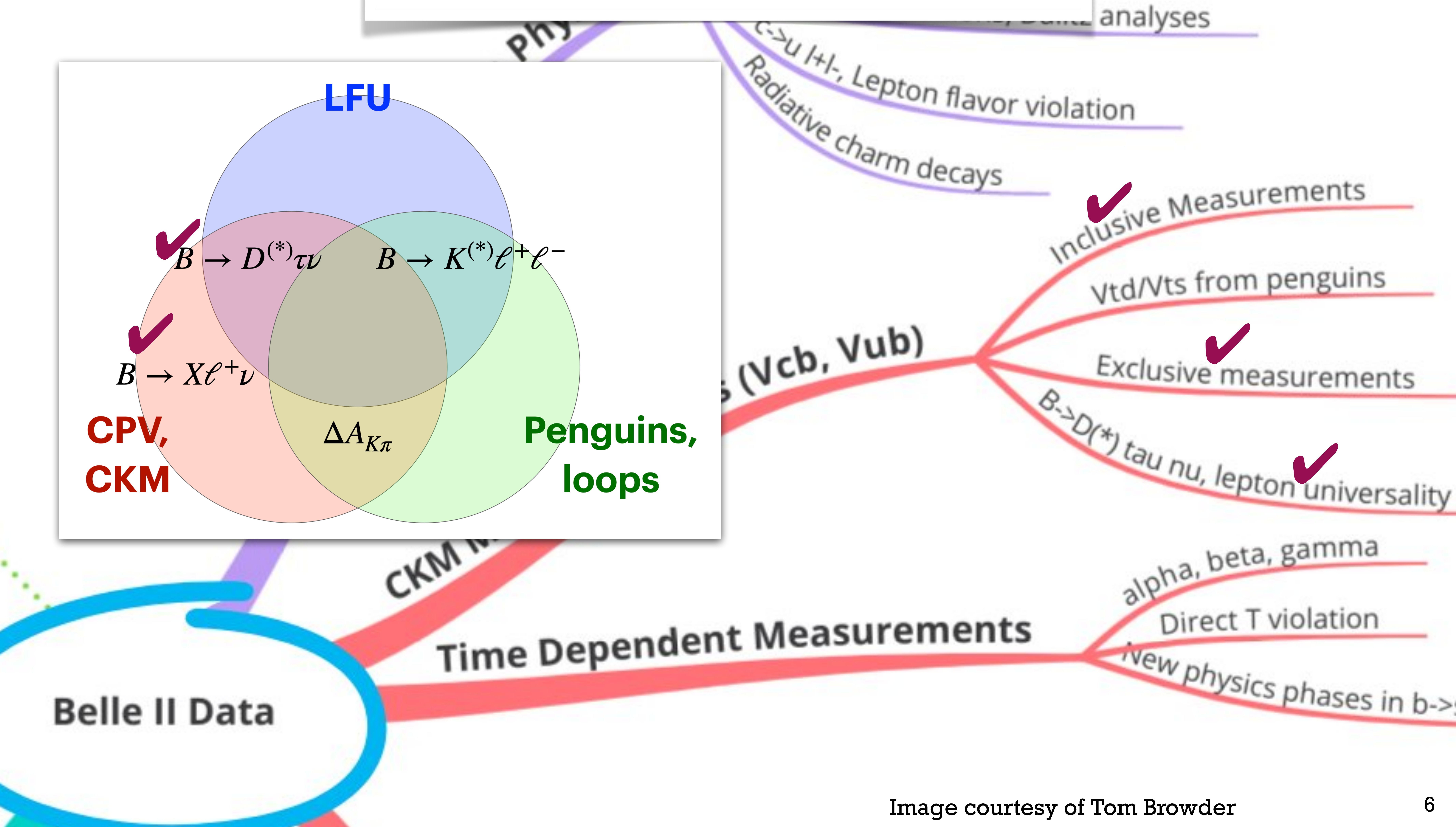


Image courtesy of Tom Browder

The cram course

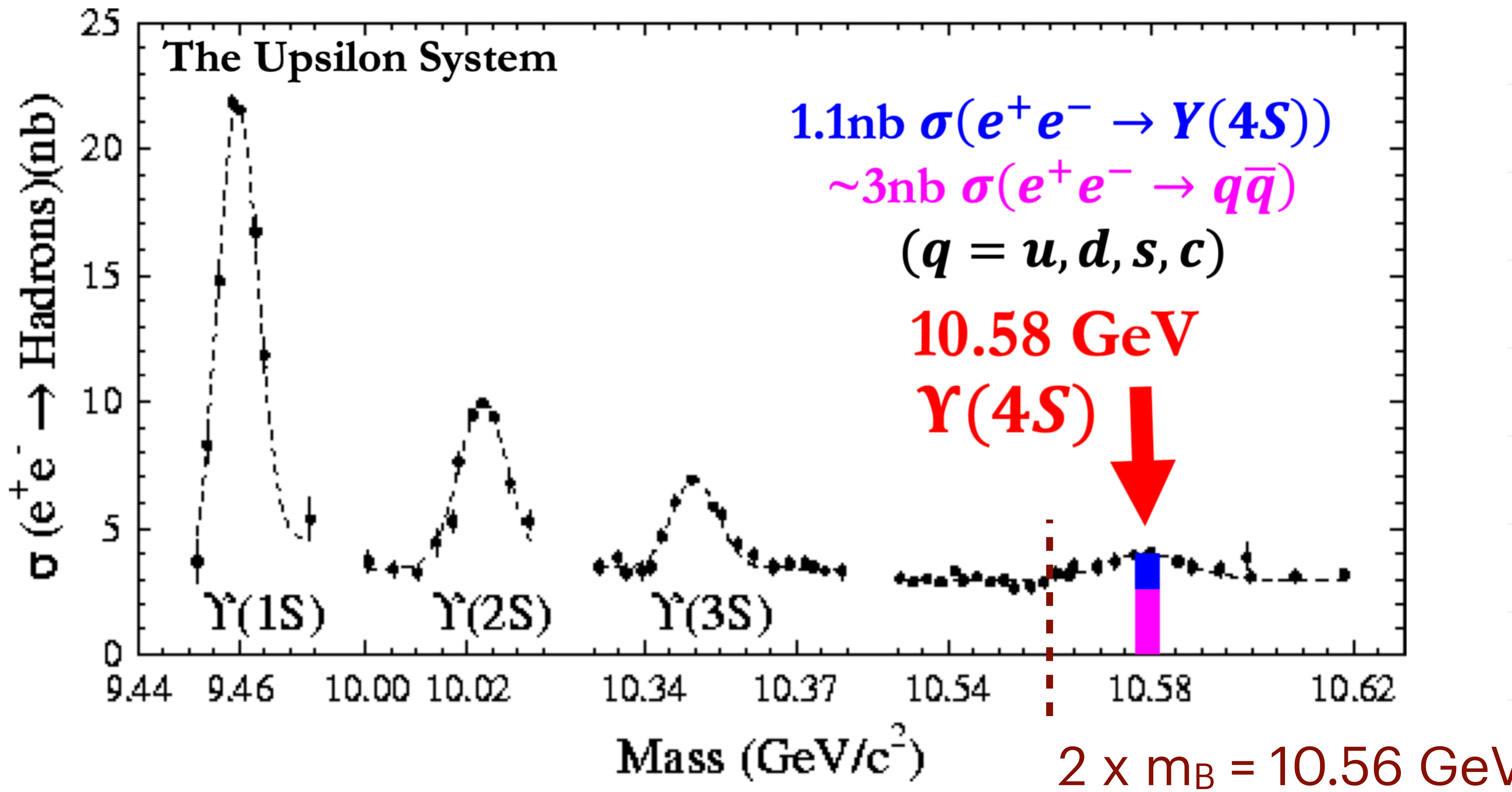
for B-mesons @ Belle (II)

$e^- \xrightarrow{\text{8 GeV}} (\star) \xleftarrow{\text{3.5 GeV}} e^+$ (1999-2010)

$e^- \xrightarrow{\text{7 GeV}} (\star) \xleftarrow{\text{4 GeV}} e^+$ (since 2019)

See Appendix 0 (p.45-47)

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

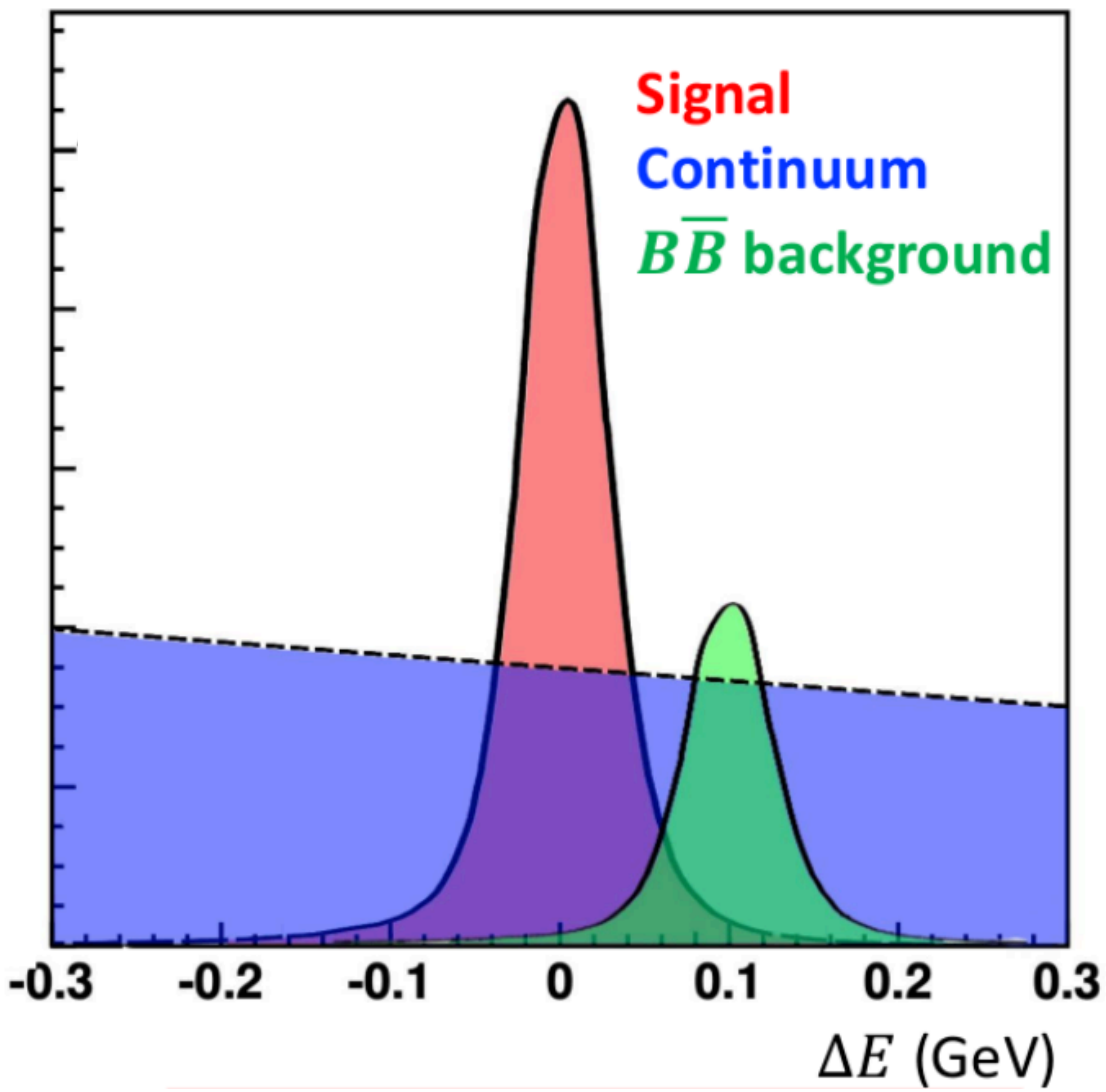


- $\mathcal{B}(\Upsilon(4S) \to B\bar{B}) > 96\%$, with $p_B^{CM} \sim 0.35$ GeV/c
- nothing else but $B\bar{B}$ in the final state

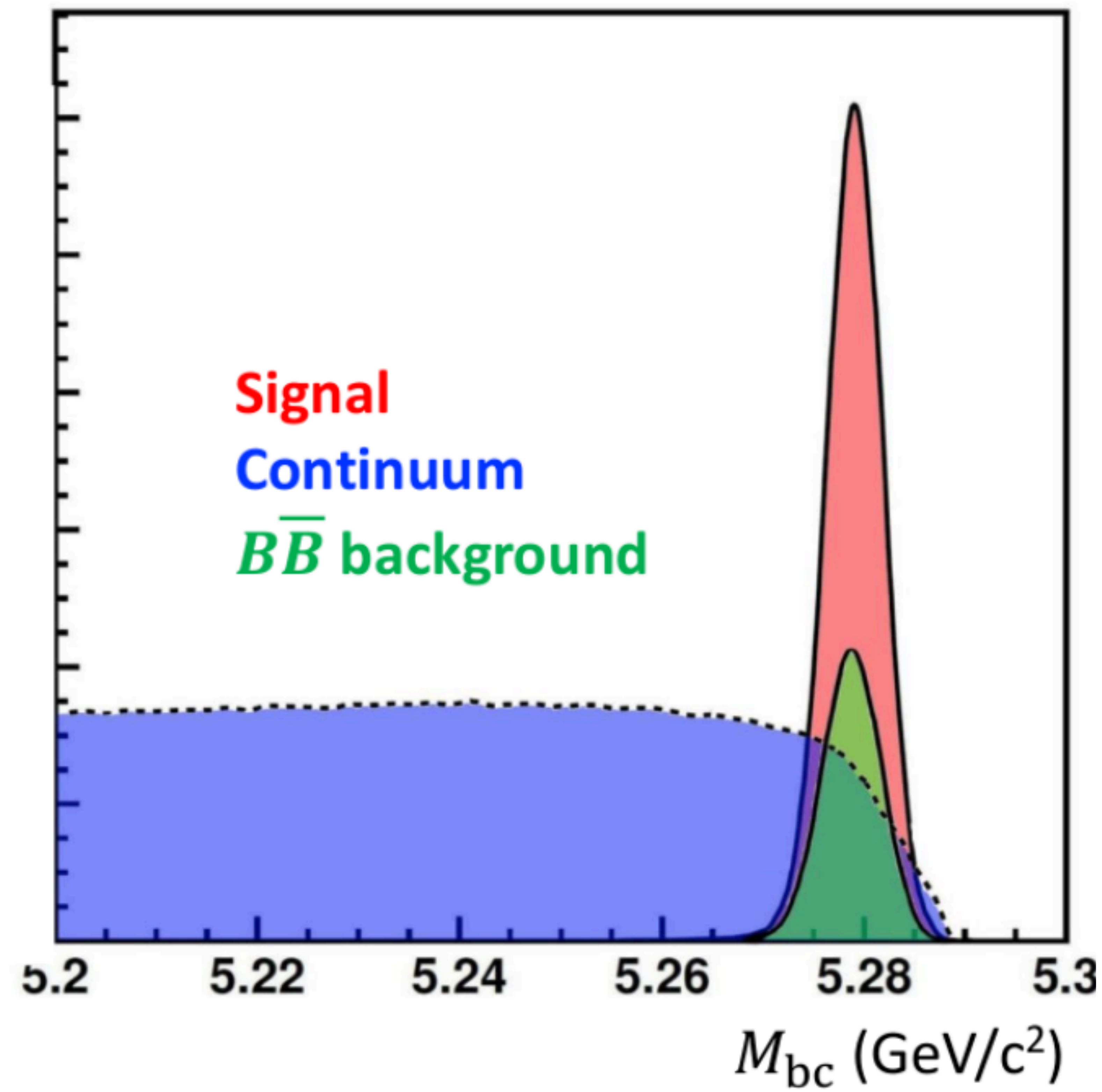
  $\therefore$ if we know $(E, \vec{p})$ of one B, the other B is also constrained

Key variables of B decays

$$\Delta E = E_B^* - \sqrt{s}/2$$

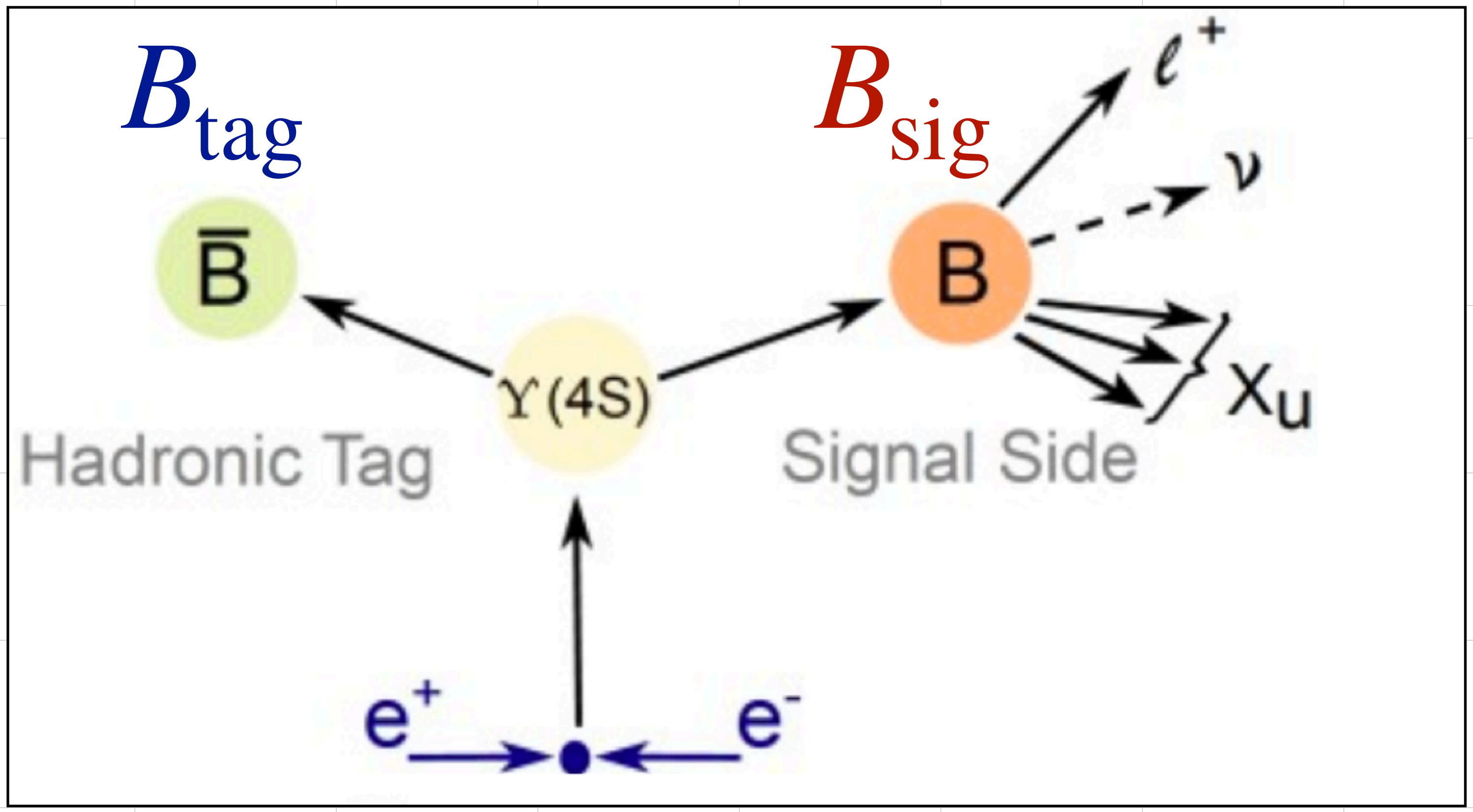


$$M_{bc} = \sqrt{(\sqrt{s}/2)^2 - \vec{p}_B^{\,*2}}$$

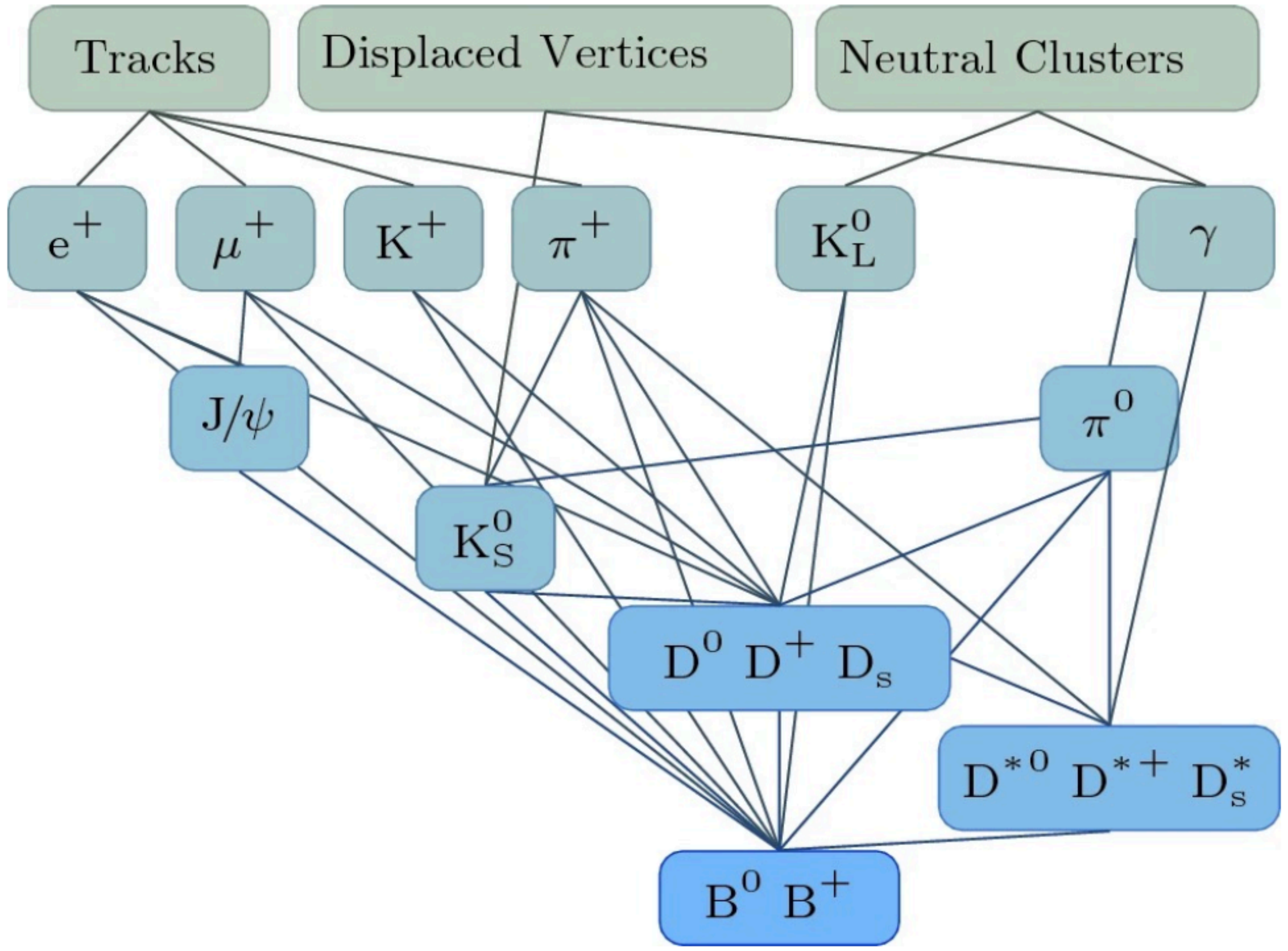


Full Event Interpretation (FEI)

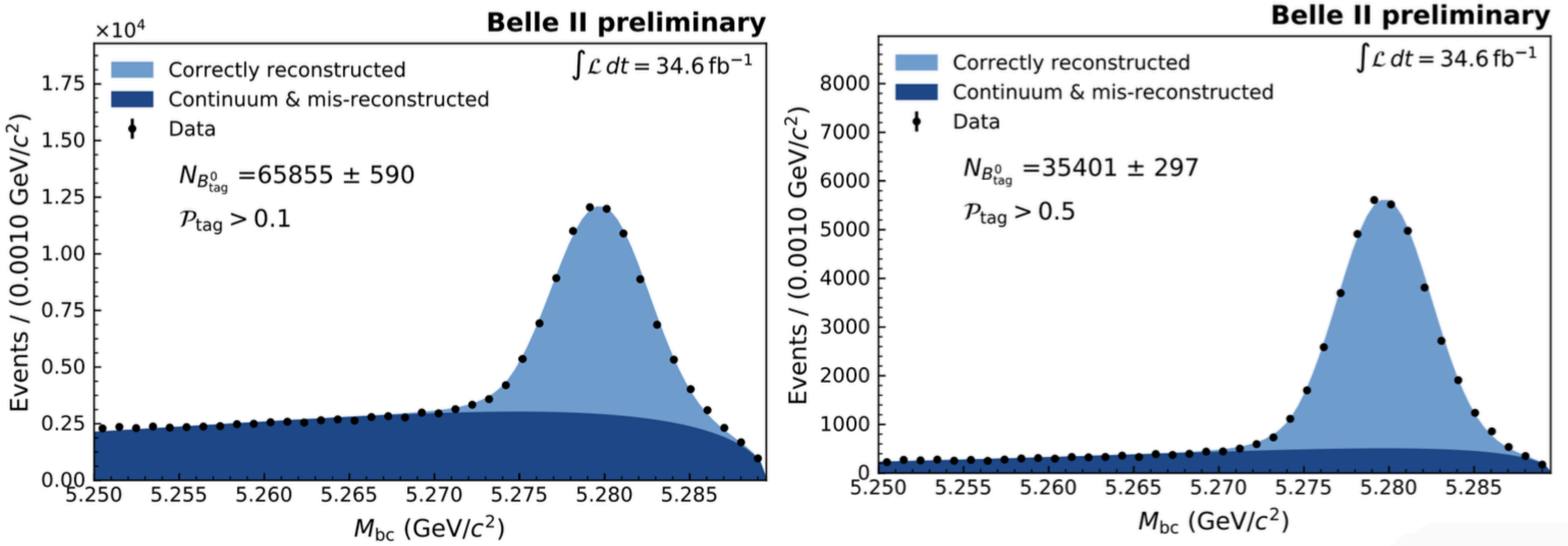
- FEI algorithm to reconstruct B_{tag}
  - uses ~200 BDT's to reconstruct $\mathcal{O}(10^4)$ different B decay chains
  - assign signal probability of being correct B_{tag}



Comput Softw Big Sci 3, 6 (2019)



arXiv:2008.060965



The $A_{K\pi}$ puzzle

— a historic tension

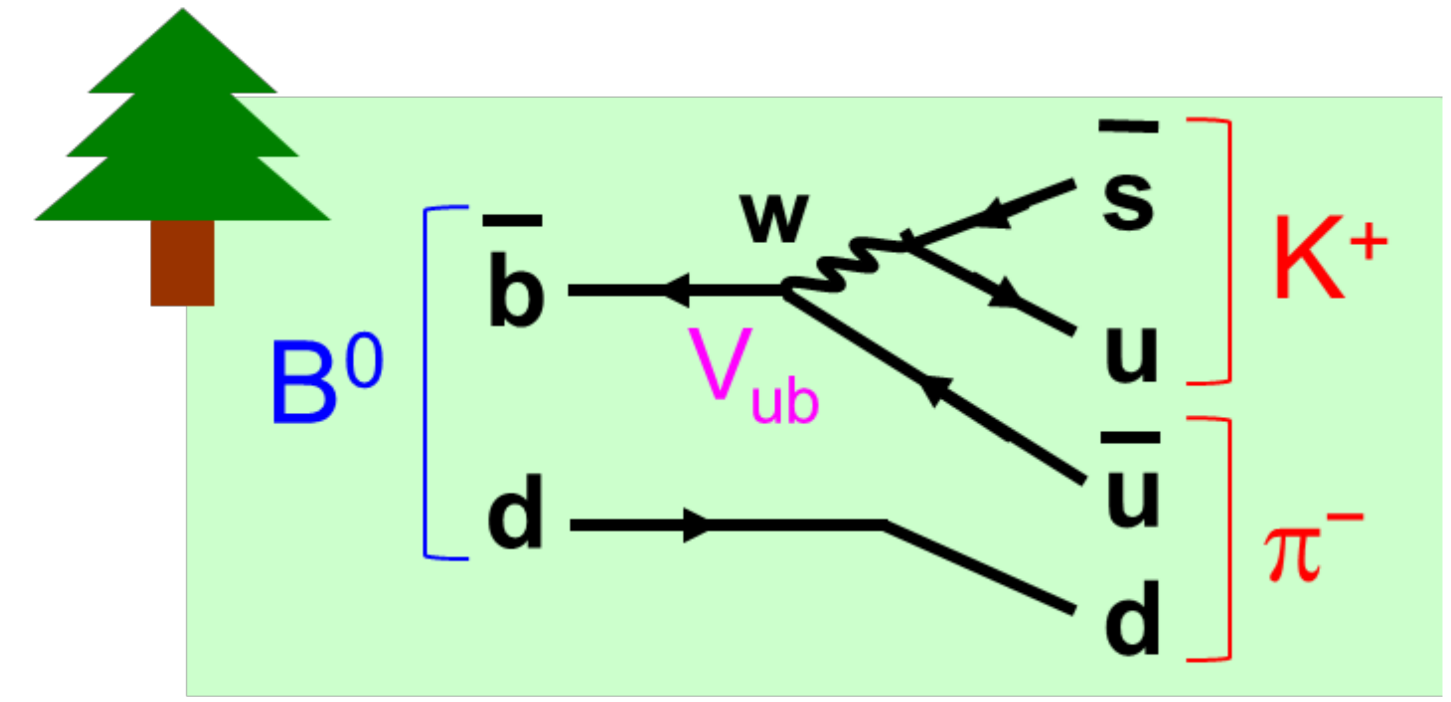
$B \to K\pi$

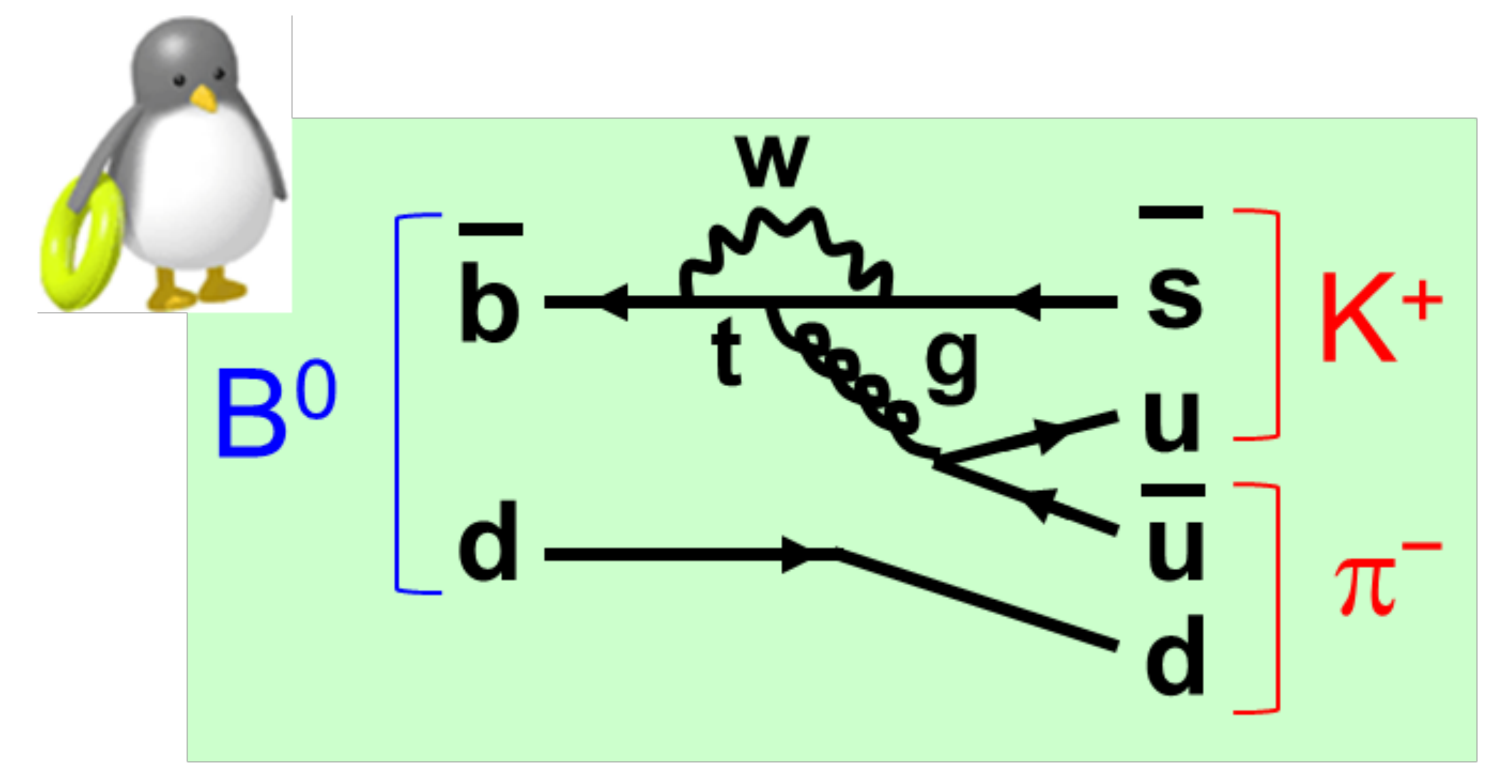
- charmless hadronic decays, with $\mathscr{B} \sim \mathscr{O}(10^{-5})$
- Tree (with V_{ub}) + Penguin ➔ "direct CPV"

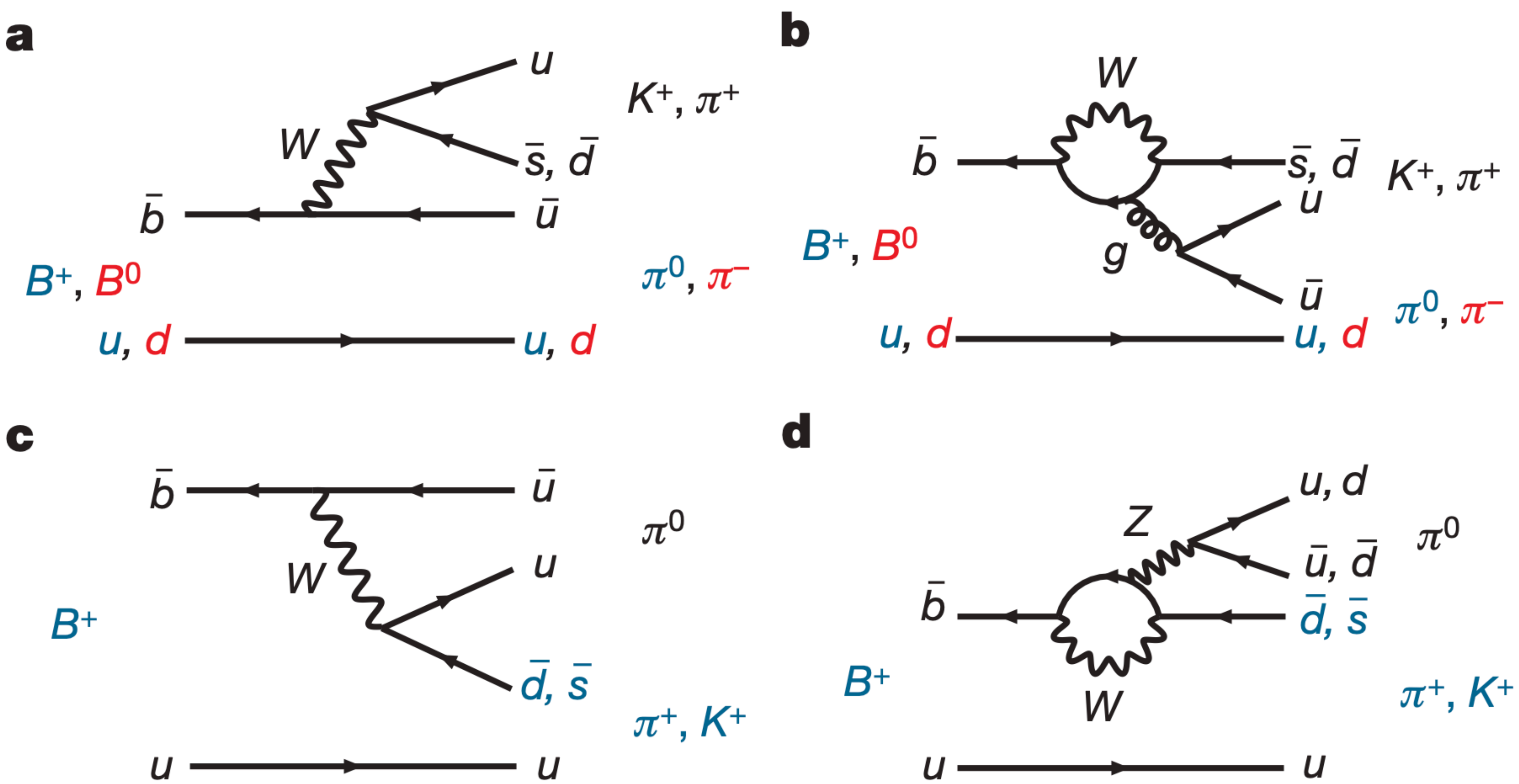
  $A_{CP} \neq 0$, observed for both B^+, B^0

- Not much difference in A_{CP} is expected for B^+ & B^0

  extra diagrams for B^+, but no new weak phase







nature Vol 452|20 March 2008|doi:10.1038/nature06827

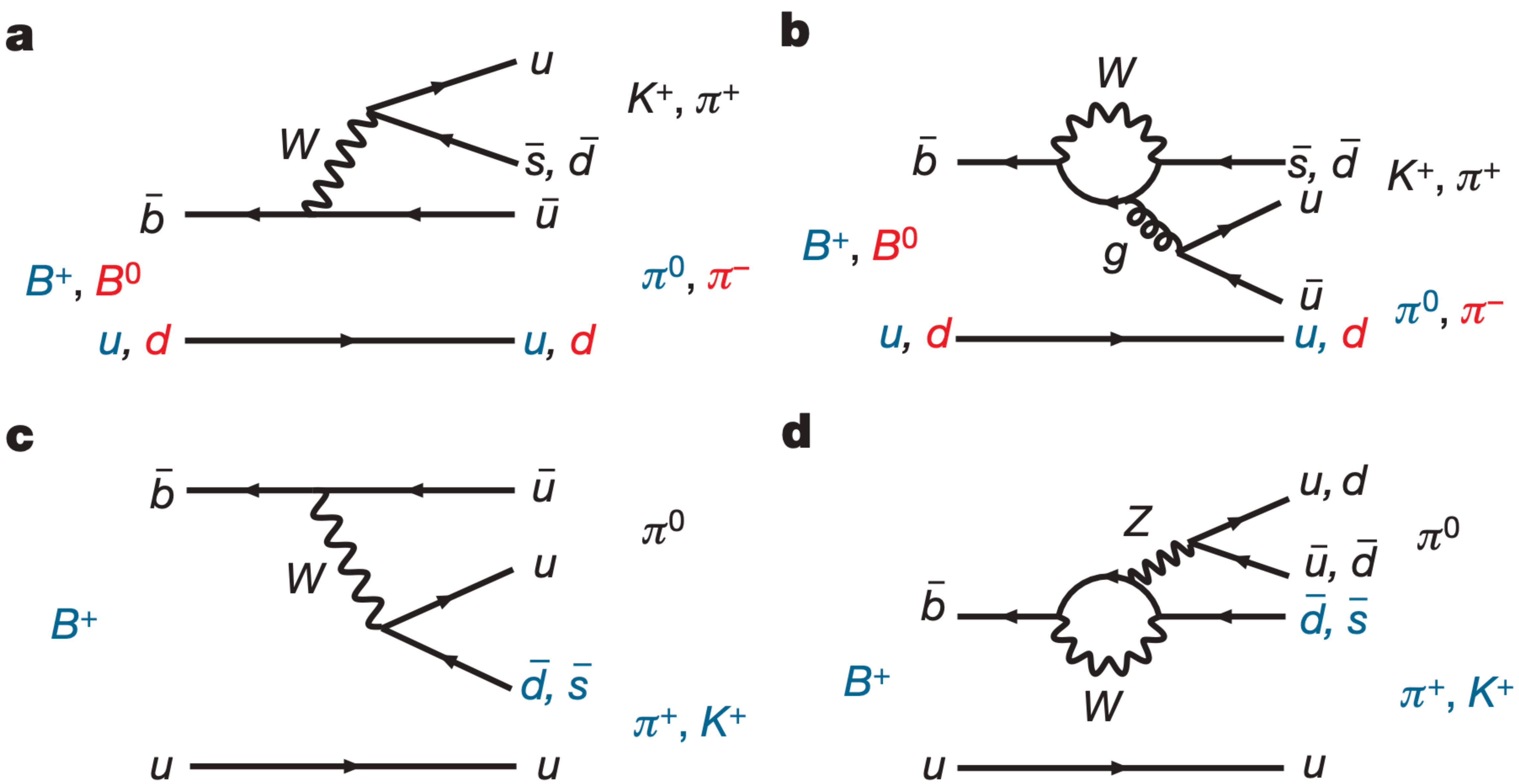
BELLE

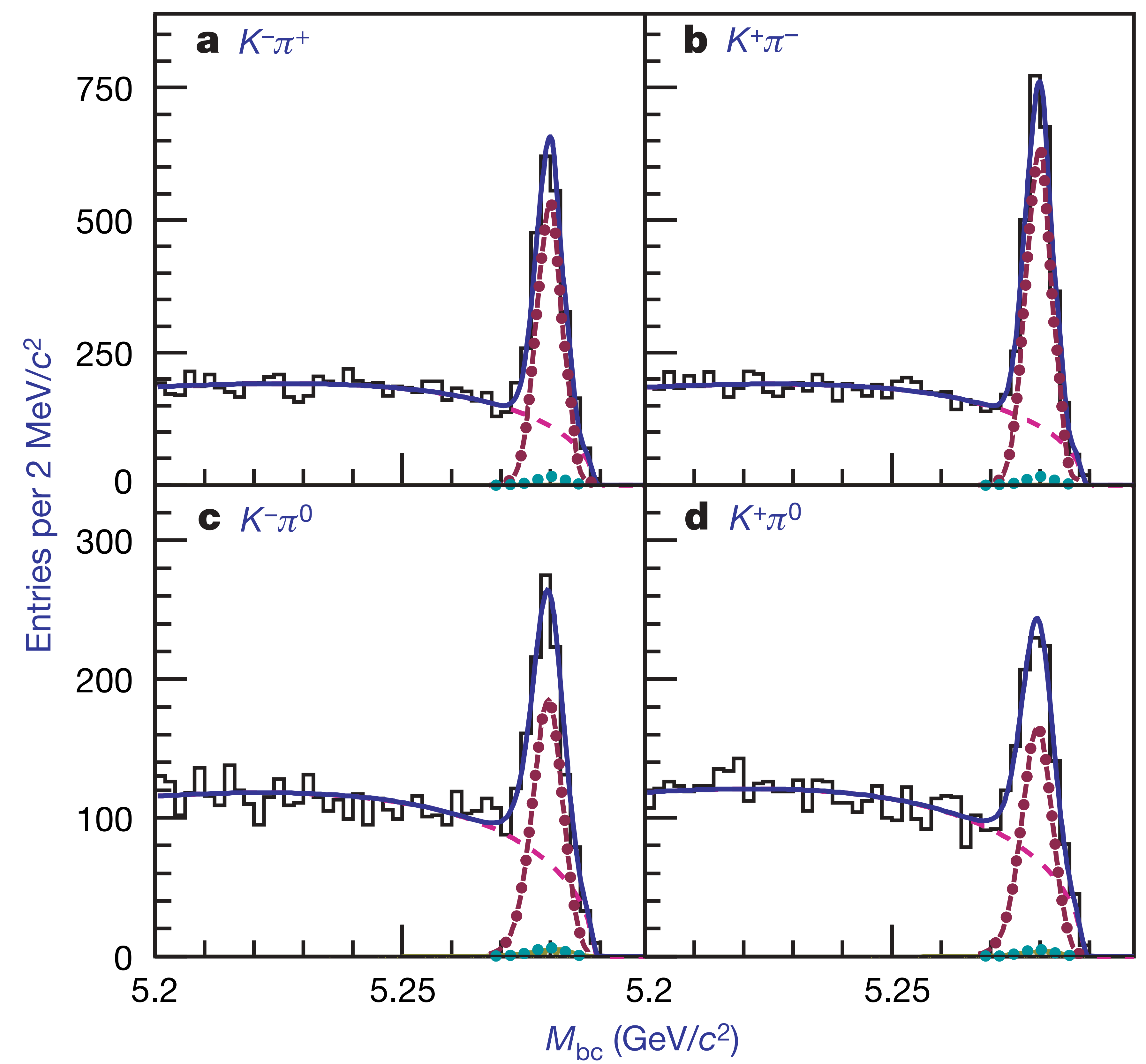
LETTERS

The "$A_{K\pi}$ puzzle"

Difference in direct charge-parity violation between charged and neutral *B* meson decays

The Belle Collaboration*





Current status of $\Delta A_{K\pi}$

A_{CP}			
Mode	BaBar	Belle	LHCb
$K^+\pi^-$	$-0.107 \pm 0.016^{+0.006}_{-0.004}$	$-0.069 \pm 0.014 \pm 0.007$	$-0.080 \pm 0.007 \pm 0.003$
$K^+\pi^0$	$0.030 \pm 0.039 \pm 0.010$	$0.043 \pm 0.024 \pm 0.002$	
$K^0\pi^+$	$-0.029 \pm 0.039 \pm 0.010$	$-0.011 \pm 0.021 \pm 0.006$	$-0.022 \pm 0.025 \pm 0.010$
$K^0\pi^0$	$-0.13 \pm 0.13 \pm 0.03$	$0.14 \pm 0.13 \pm 0.06$	

Sum rule test for $\Delta A_{K\pi}$

M. Gronau, PLB 627, 82 (2005)

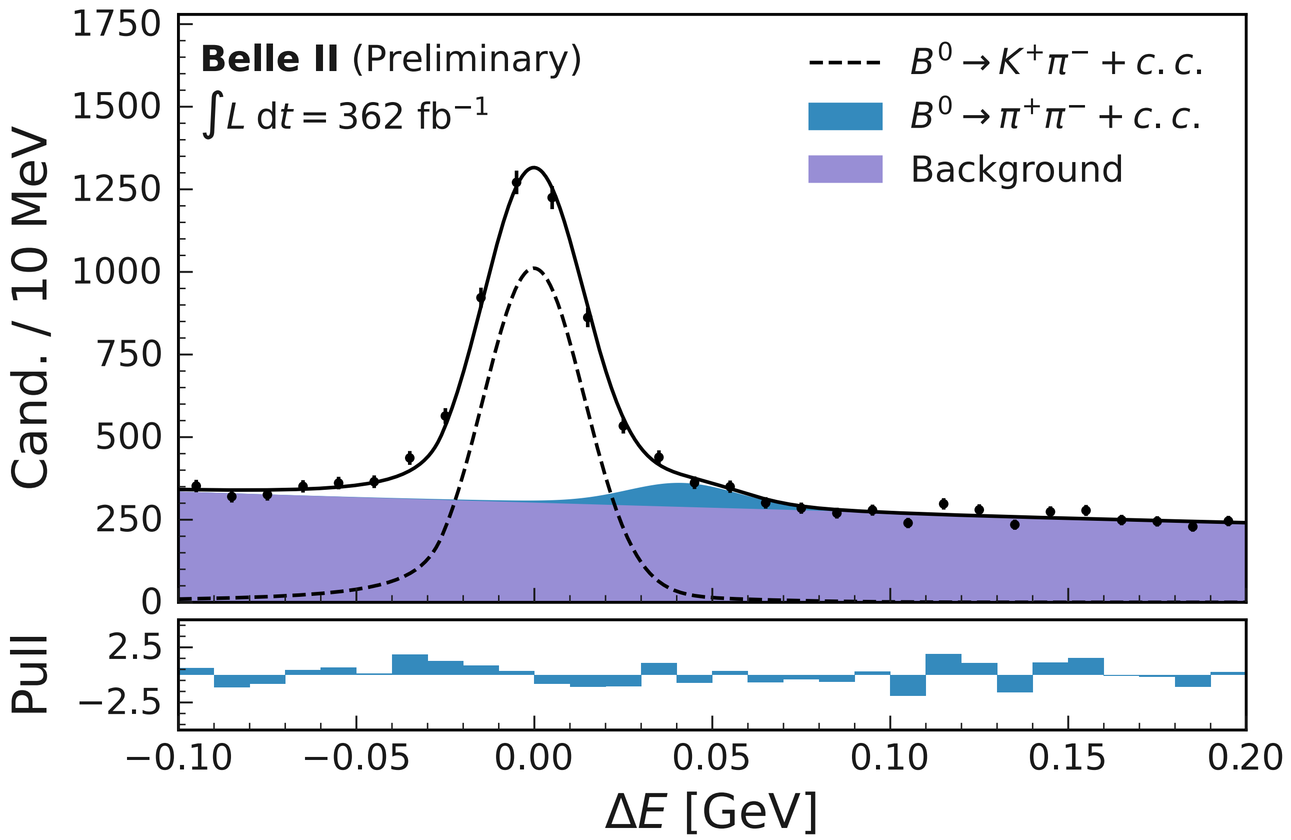
$$I_{K\pi} = \mathcal{B}(K^+\pi^-)\mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\mathcal{B}(K^0\pi^+)\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\mathcal{B}(K^+\pi^0)\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\mathcal{B}(K^0\pi^0)$$

$$I_{K\pi}^{\mathrm{SM}} = 0$$

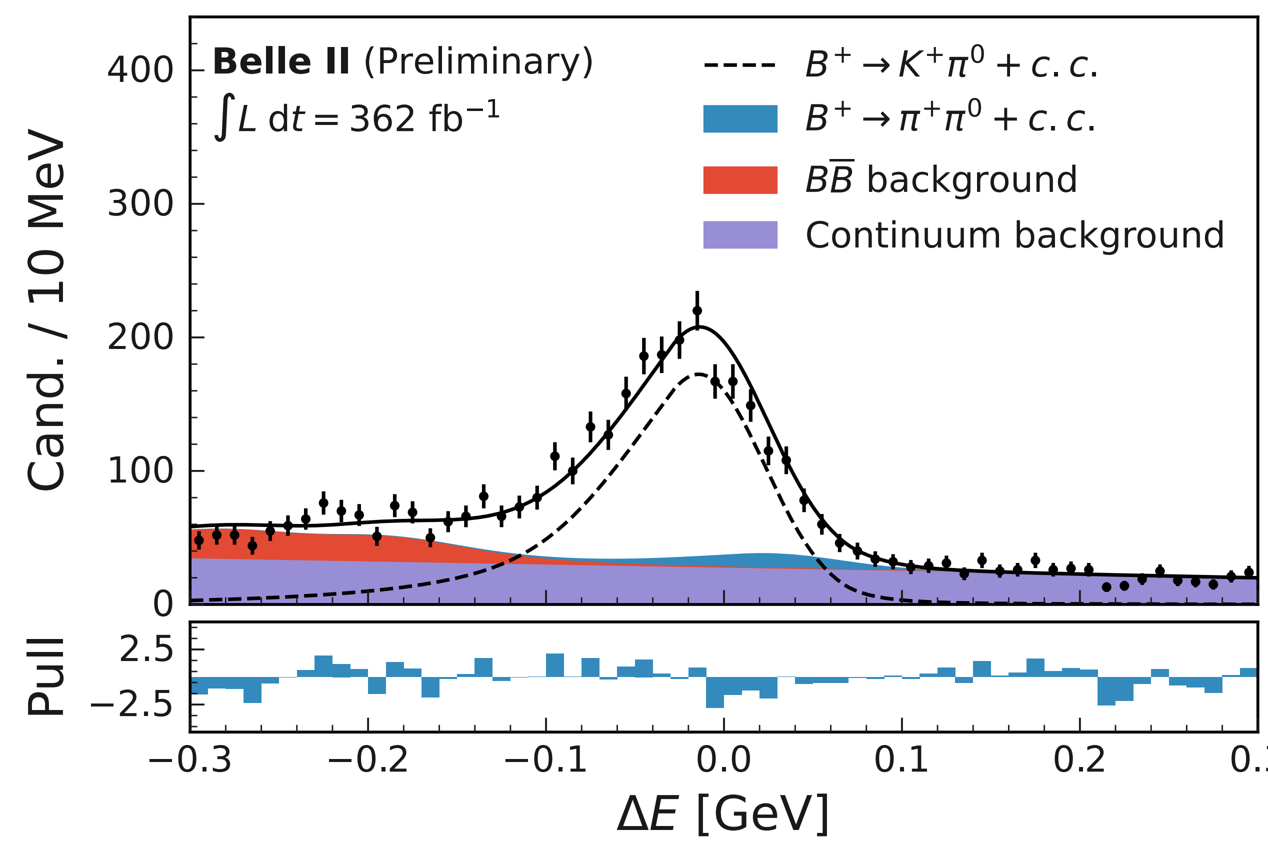
within 1%

Belle II for $A_{K\pi}$ sum rule test

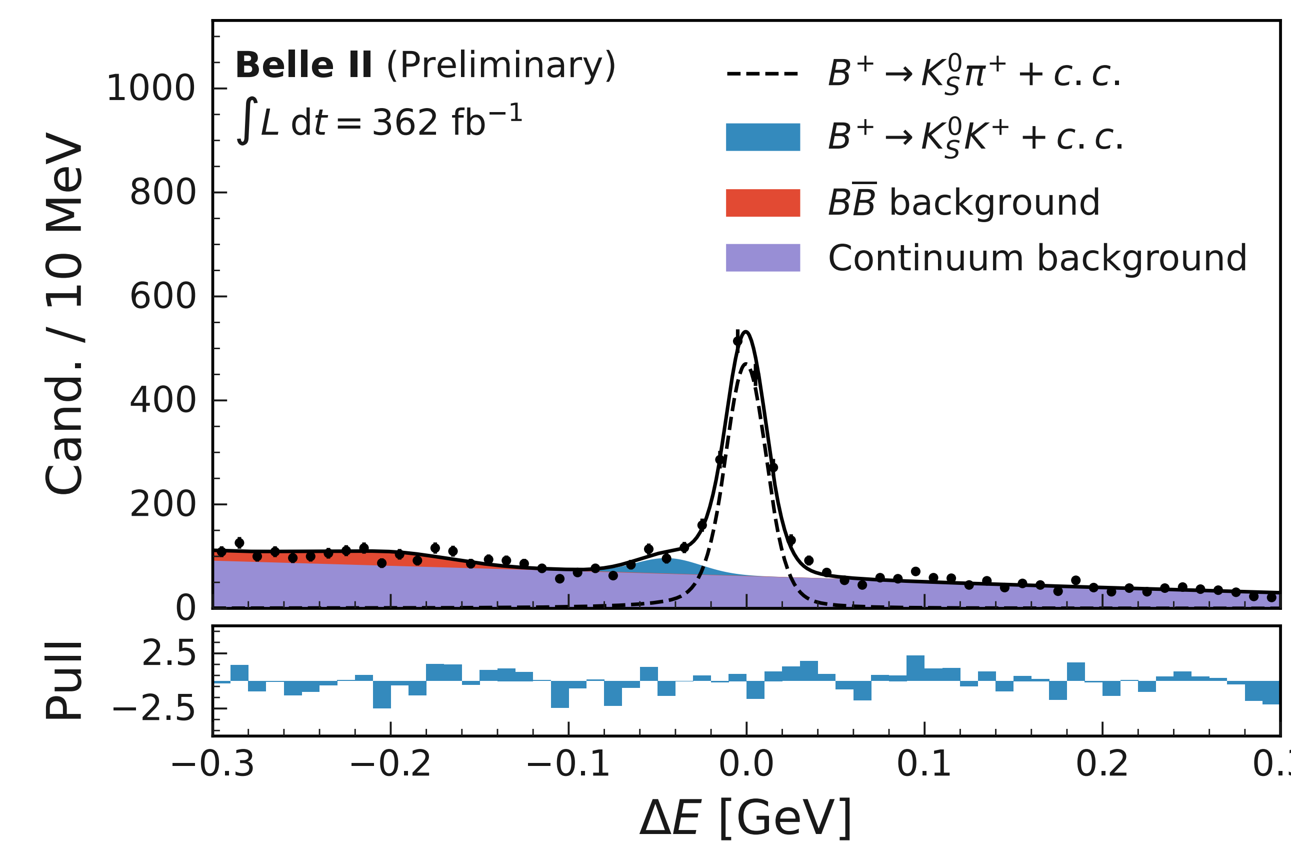
$B^0 \to K^+\pi^-$

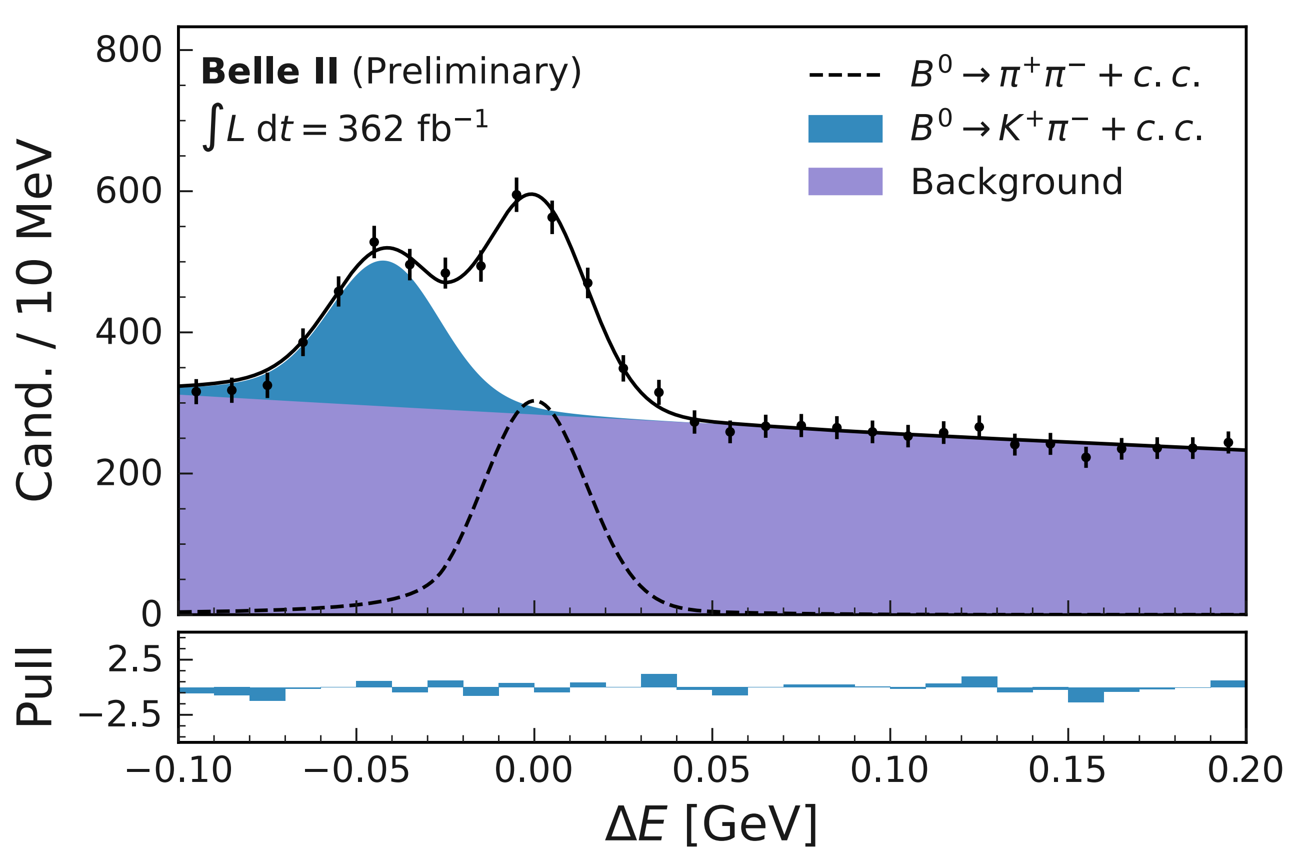


$B^+ \to K^+\pi^0$

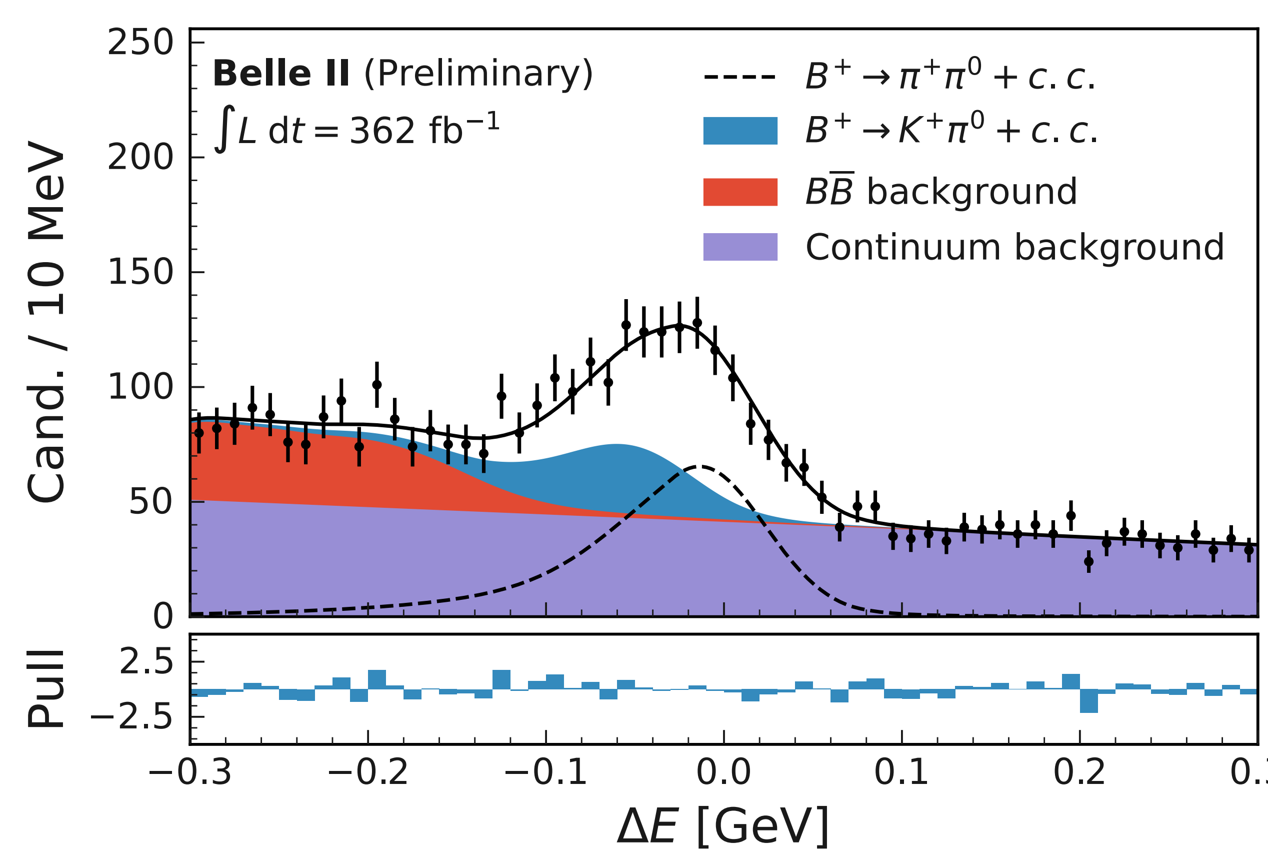


$B^+ \to K^0_S\pi^+$





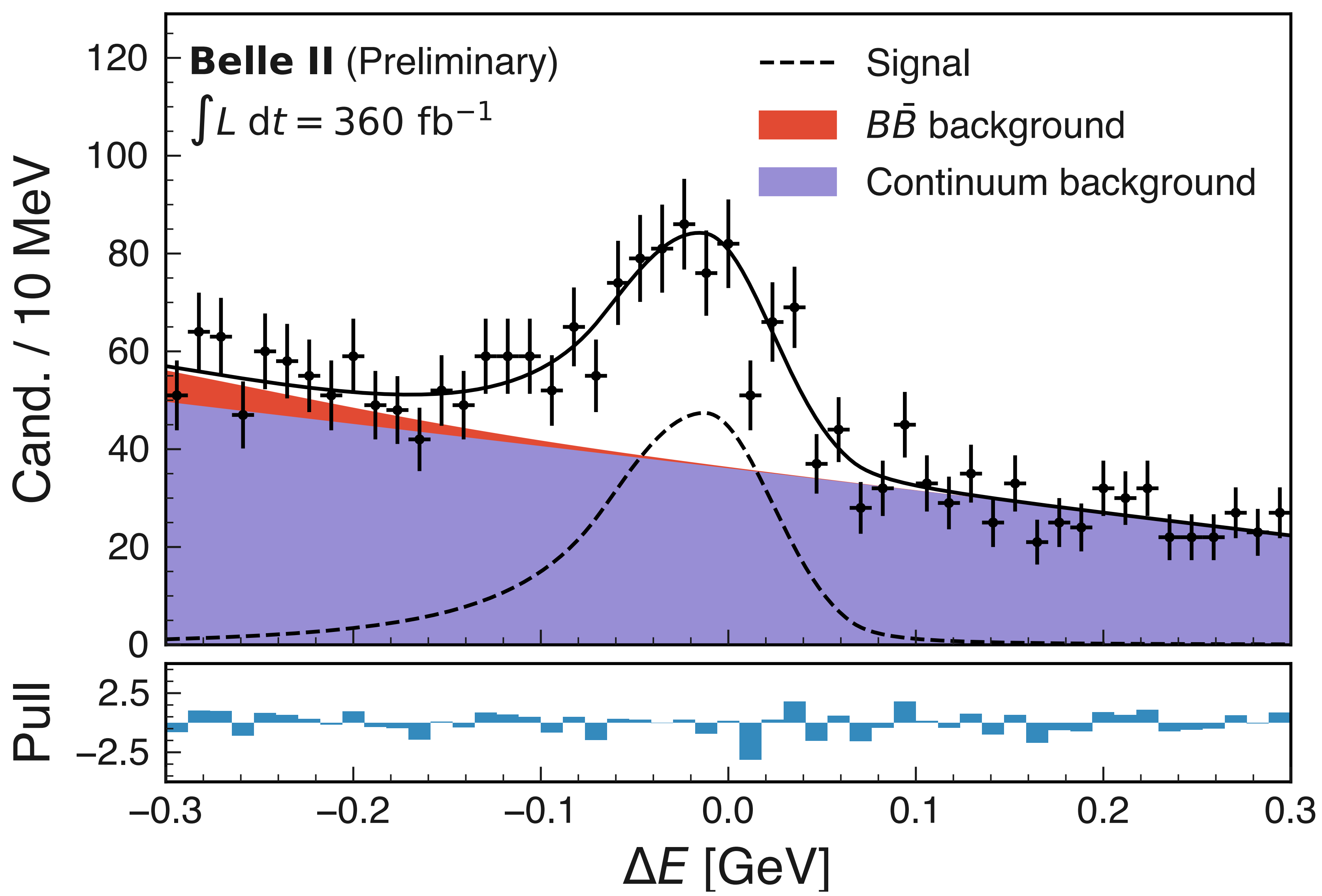
$B^0 \to \pi^+\pi^-$

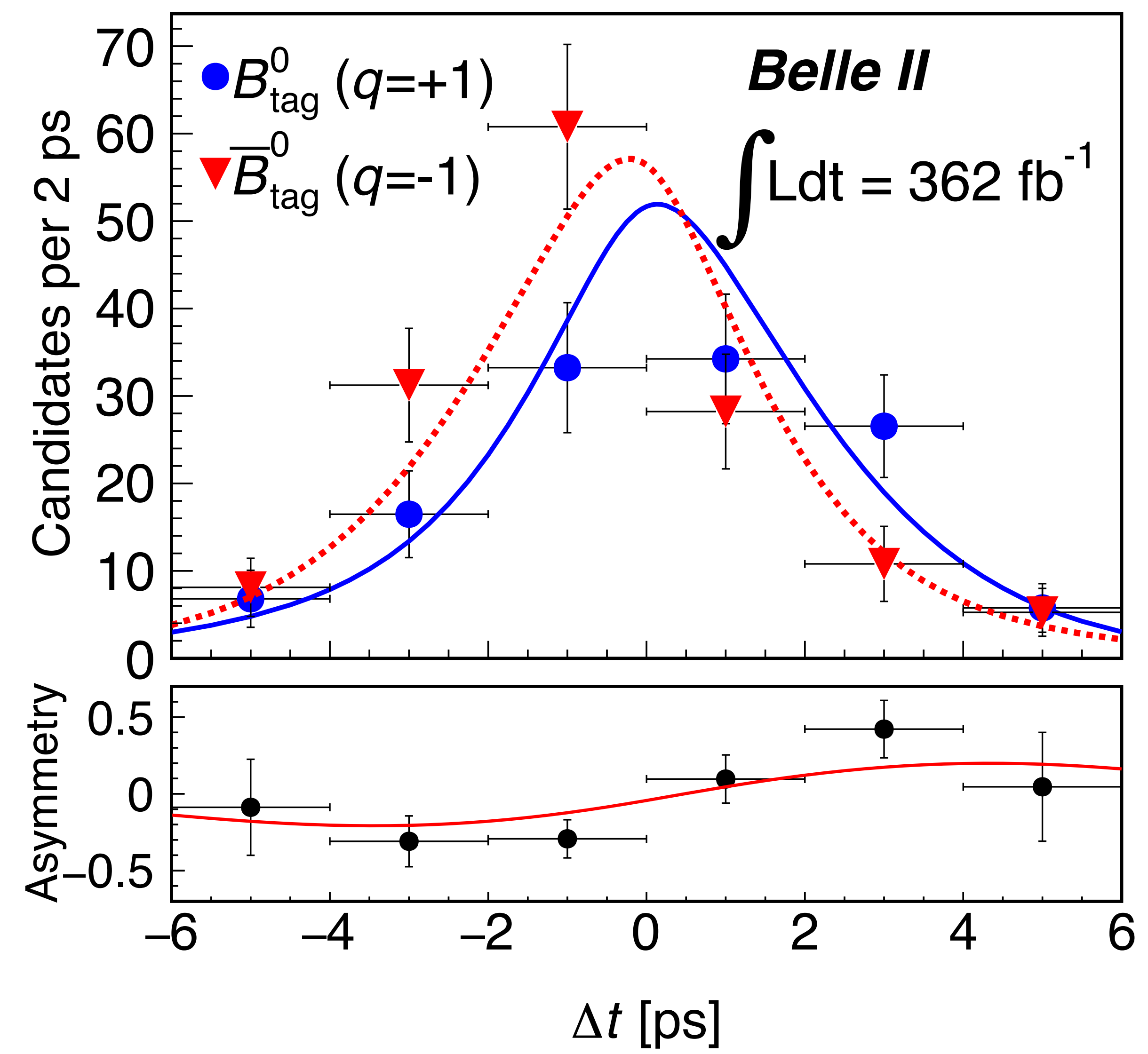


$B^+ \to \pi^+\pi^0$

What about $B^0 \to K^0_S\pi^0$?

$B^0 \to K_S^0\pi^0$ for sum rule test





$$S_{K_S^0\pi^0} = +0.75^{+0.20}_{-0.23} \pm 0.04$$

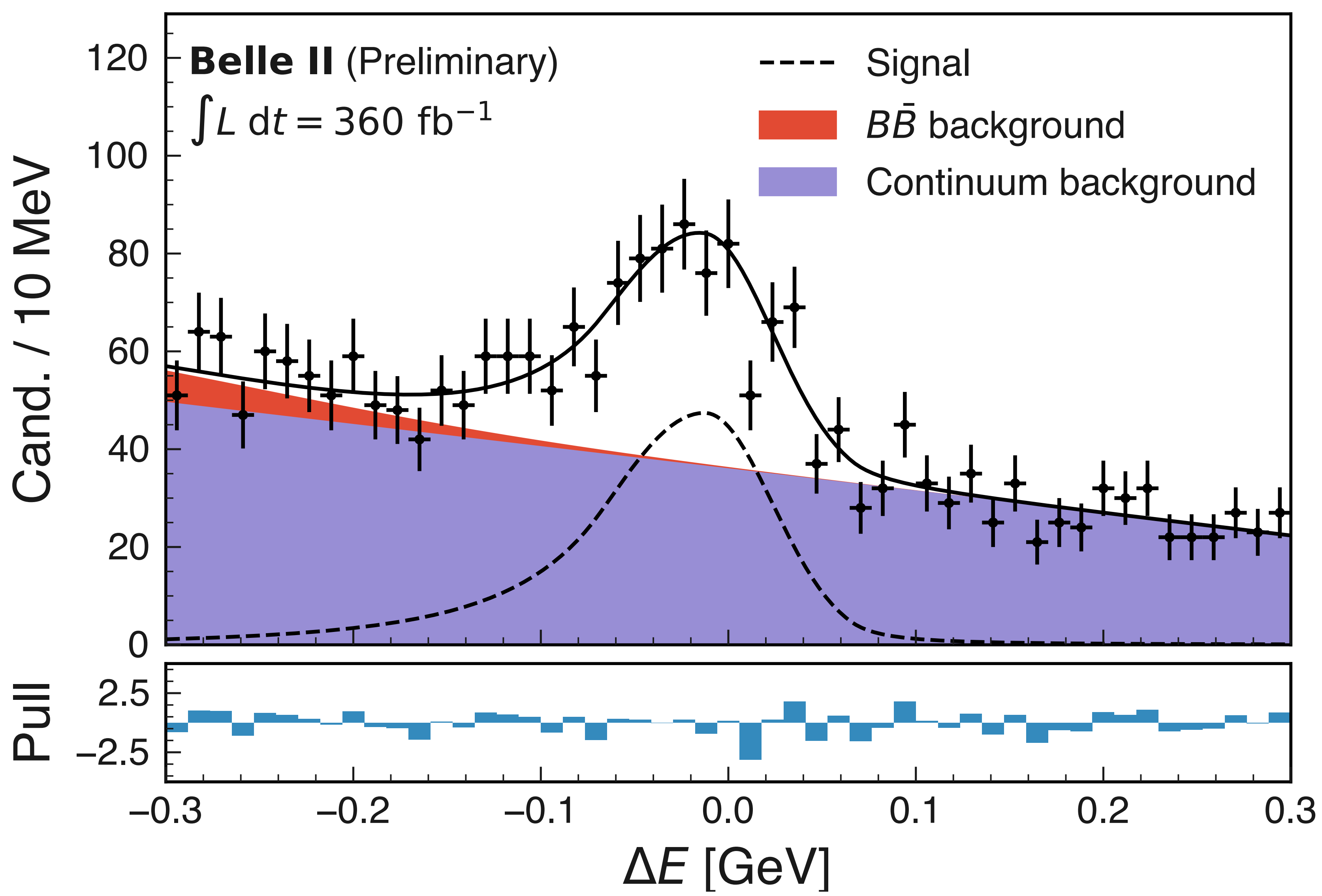
$$A_{K_S^0\pi^0} = +0.04 \pm 0.15 \pm 0.05$$

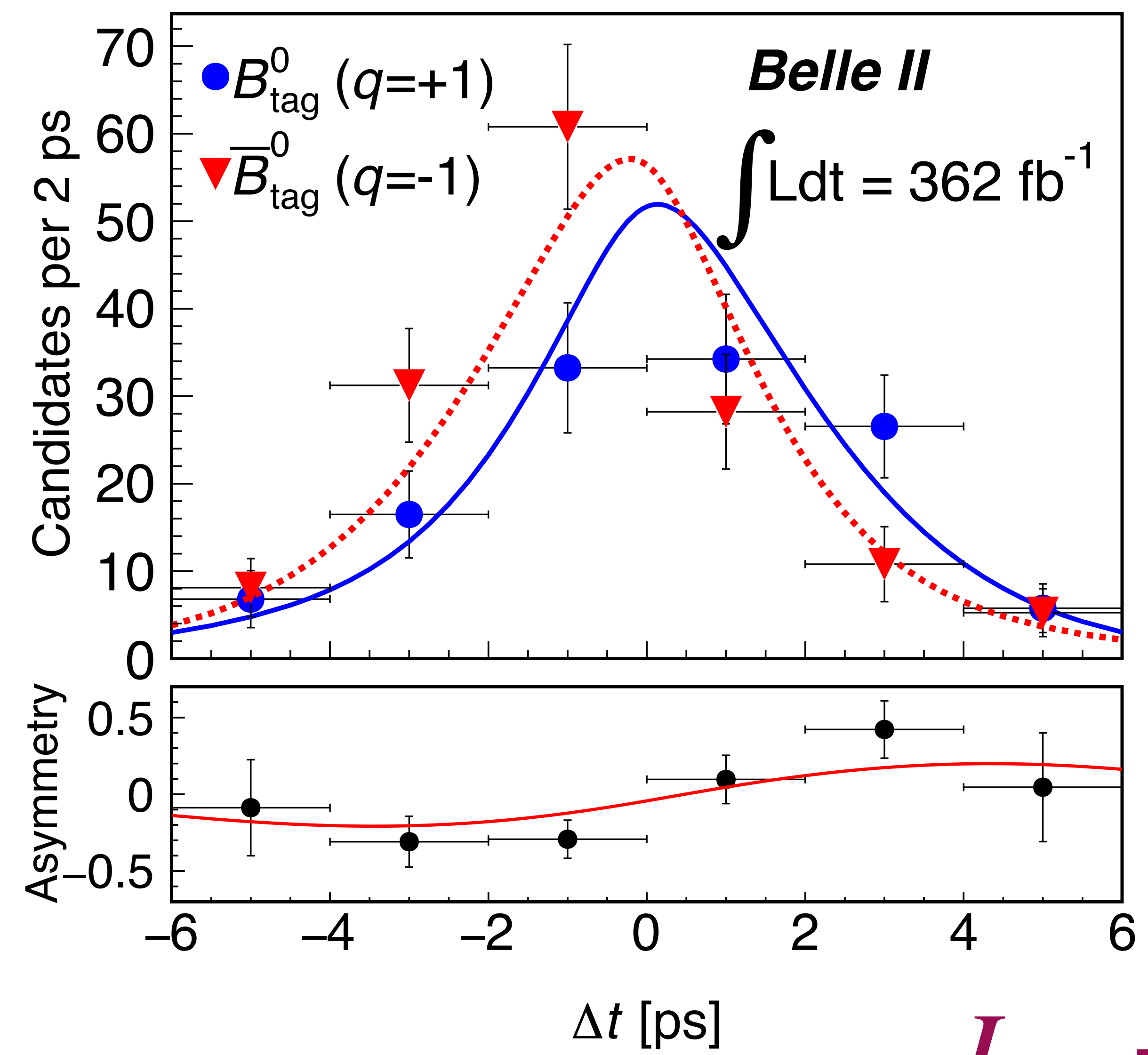
meaning of S,A, in the back-up slide, p.49

What about $B^0 \to K_S^0\pi^0$?

Decay	Signal yield	Feed-across yield	Signal ϵ [%]	Feed-across ϵ [%]	$\mathcal{B}$ $[10^{-6}]$	$\mathcal{A}_{CP}$
$B^0 \to K^+\pi^-$	3868 ± 71	880 ± 16	49.91	11.37	$20.67 \pm 0.37 \pm 0.62$	$-0.072 \pm 0.019 \pm 0.007$
$B^0 \to \pi^+\pi^-$	1187 ± 43	327 ± 8	54.31	14.94	$5.83 \pm 0.22 \pm 0.17$	–
$B^+ \to K^+\pi^0$	2052 ± 57	359 ± 10	36.91	6.46	$13.93 \pm 0.38 \pm 0.84$	$0.013 \pm 0.027 \pm 0.005$
$B^+ \to \pi^+\pi^0$	785 ± 44	136 ± 8	37.60	6.50	$5.10 \pm 0.29 \pm 0.32$	$-0.081 \pm 0.054 \pm 0.008$
$B^+ \to K^0\pi^+$	1547 ± 45	–	15.89	–	$24.4 \pm 0.71 \pm 0.86$	$0.046 \pm 0.029 \pm 0.007$
$B^0 \to K^0\pi^0$ **time-integrated**	502 ± 32	–	12.67	–	$10.16 \pm 0.65 \pm 0.67$	$-0.06 \pm 0.15 \pm 0.05$

$B^0 \to K_S^0\pi^0$ for sum rule test





$$S_{K_S^0\pi^0} = +0.75^{+0.20}_{-0.23} \pm 0.04$$

$$A_{K_S^0\pi^0} = +0.04 \pm 0.15 \pm 0.05$$

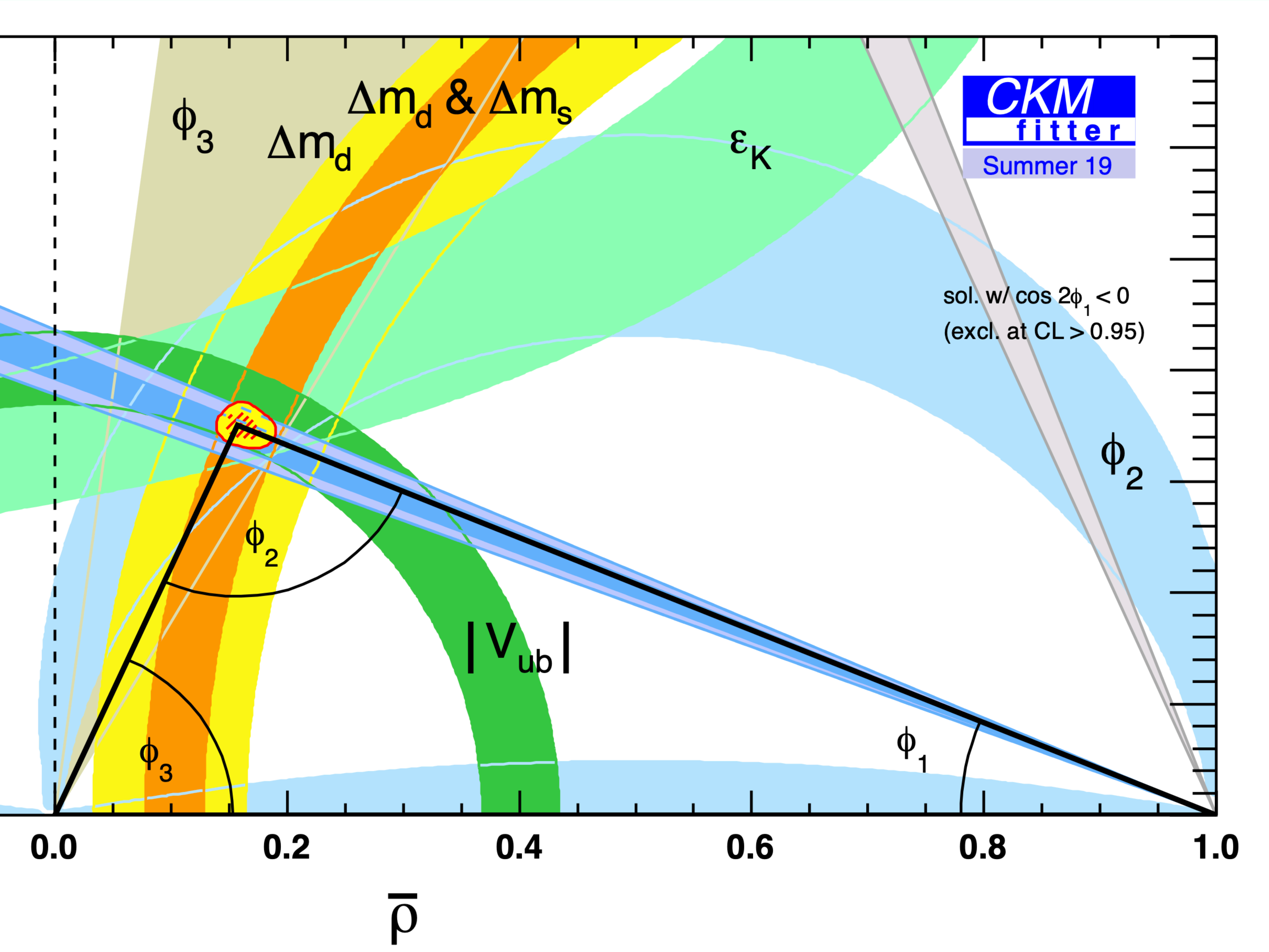
$$I_{K\pi} = -0.03 \pm 0.13 \pm 0.05$$

Decay	Signal yield	Feed-across yield	Signal ϵ [%]	Feed-across ϵ [%]	$\mathcal{B}$ $[10^{-6}]$	$\mathcal{A}_{CP}$
$B^0 \to K^0\pi^0$ **time-integrated**	502 ± 32	–	12.67	–	$10.16 \pm 0.65 \pm 0.67$	$-0.06 \pm 0.15 \pm 0.05$
$B^0 \to K^0\pi^0$ **time-dependent**	415 ± 26	–	9.95	–	11.00 ± 0.67	$0.04 \pm 0.15 \pm 0.05$
$B^0 \to K^0\pi^0$ **combined**	–	–	–	–	$10.50 \pm 0.62 \pm 0.69$	$-0.01 \pm 0.12 \pm 0.05$

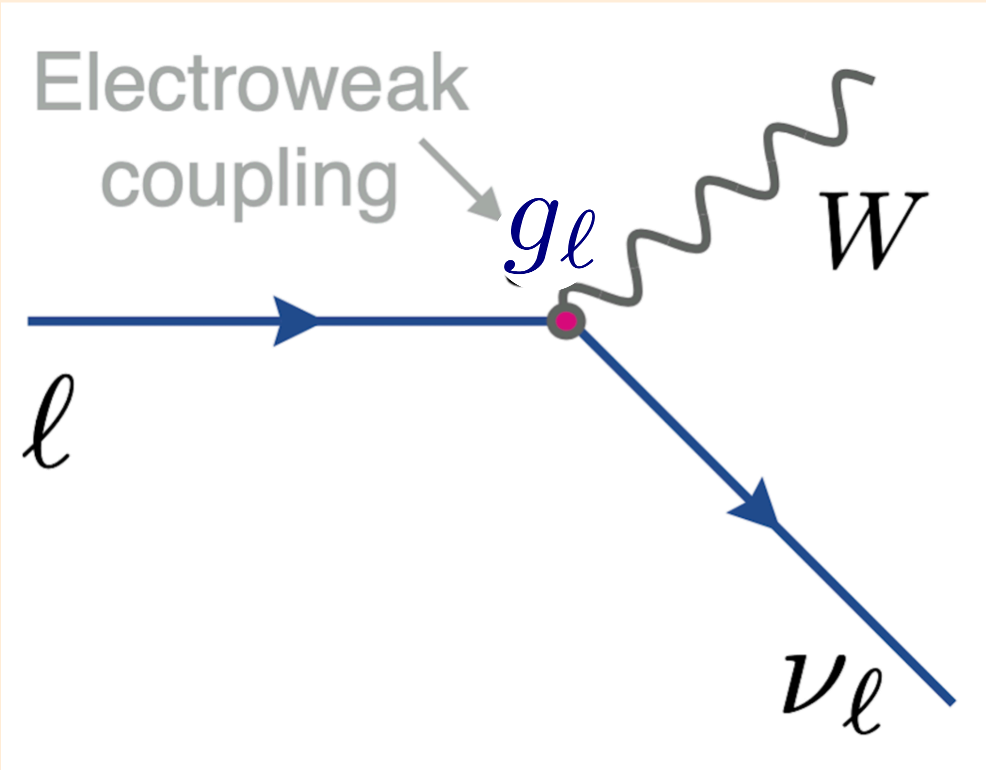
Tensions in
Semileptonic B decays

a quick summary of semileptonic B decays

- Precision measurements of CKM UT



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



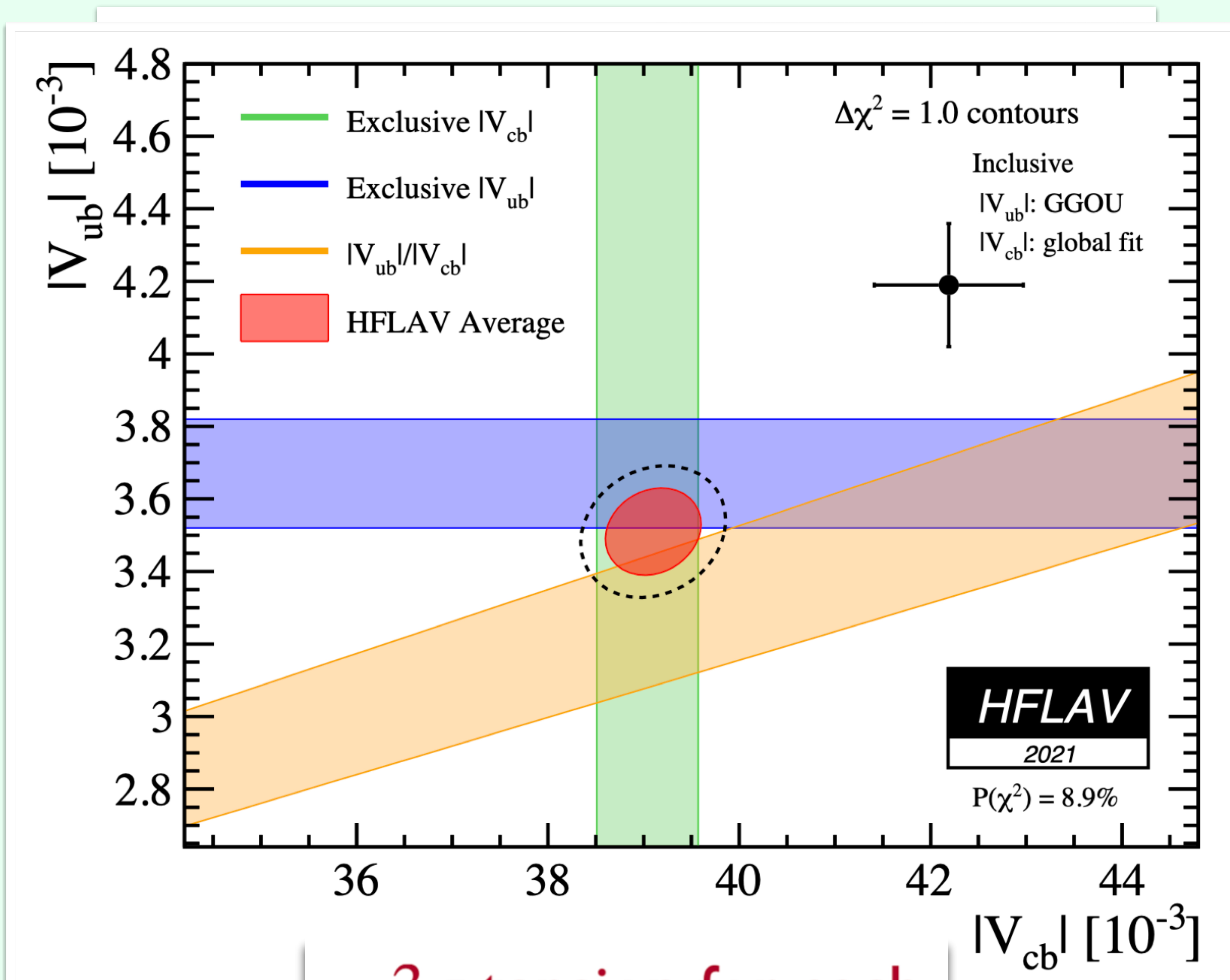
$$g_\ell \ (\ell = e,\ \mu,\ \tau)$$

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

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

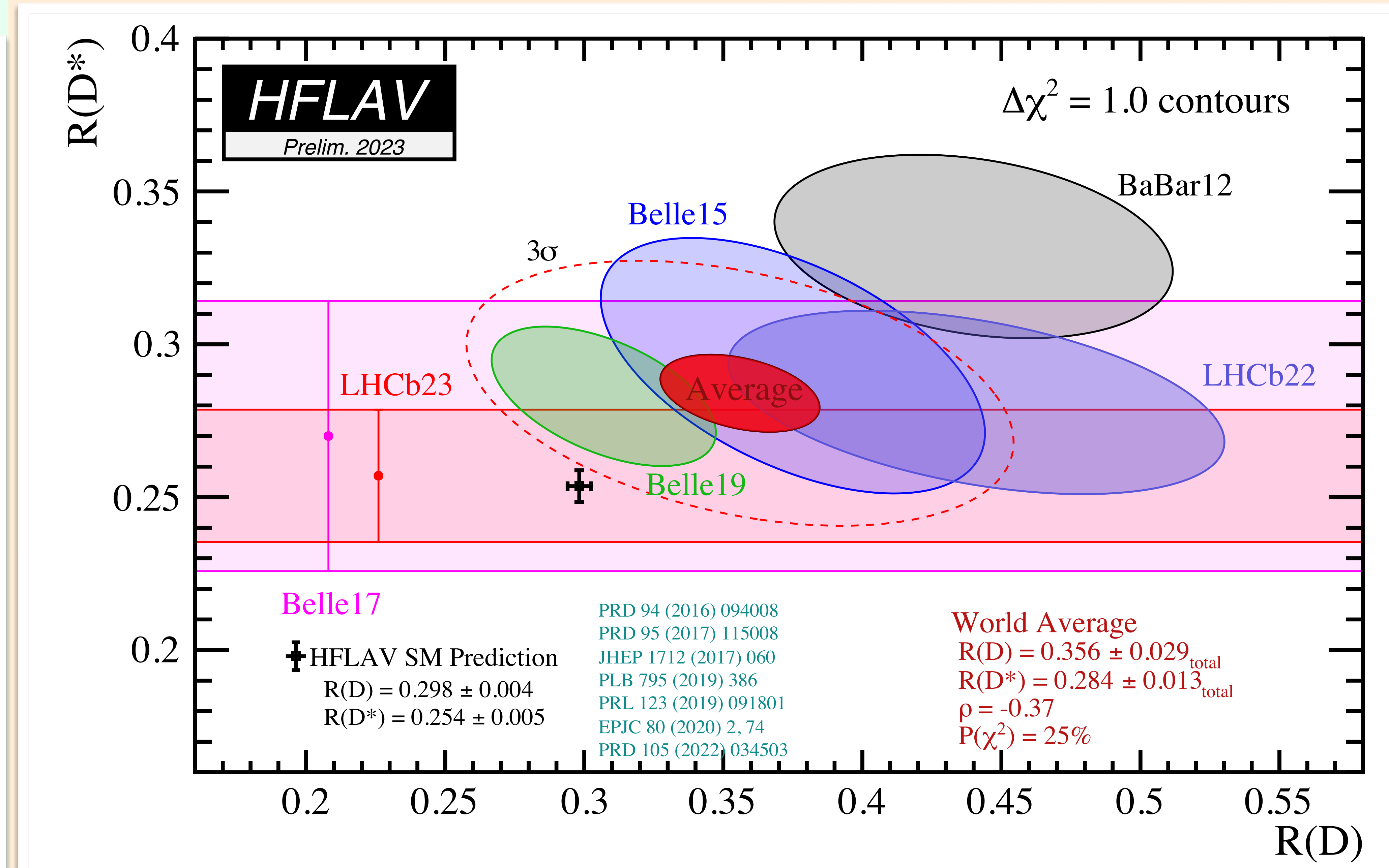
a quick summary of semileptonic B decays

- Precision measurements of CKM UT



~ 3σ tension for each $(|V_{cb}|, |V_{ub}|)$

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



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

Measurement of the ratios of branching fractions $\mathcal{R}(D^*)$ and $\mathcal{R}(D^0)$

arXiv:2302.02886, submitted to PRL

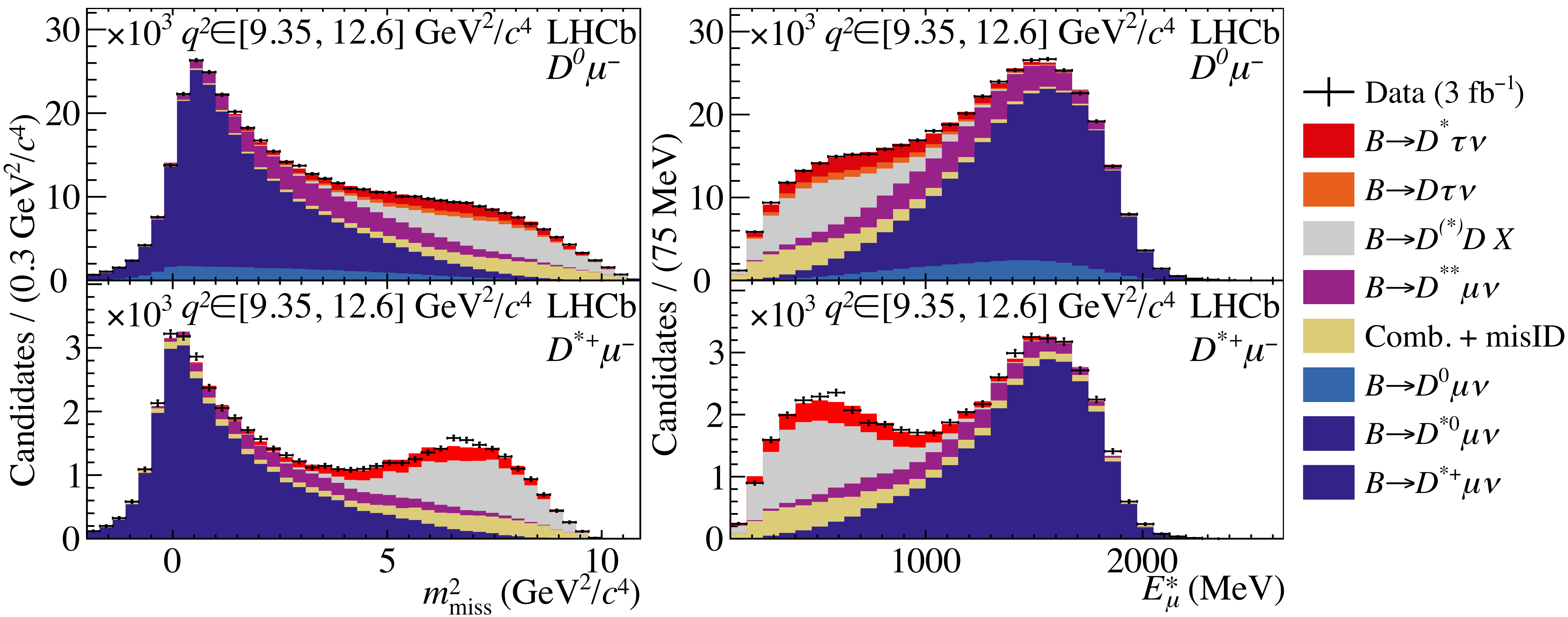


Figure 1: Distributions of (left) m^2_{miss} and (right) E^*_μ in the highest q^2 bin (above 9.35 GeV$^2/c^4$) of the (top) $D^0\mu^-$ and (bottom) $D^{*+}\mu^-$ signal data, overlaid with projections of the fit model.

- used $\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau$ mode
- $R(D^*) = 0.281 \pm 0.018 \pm 0.024, \quad R(D^0) = 0.441 \pm 0.060 \pm 0.066$
- 1.9σ away from SM

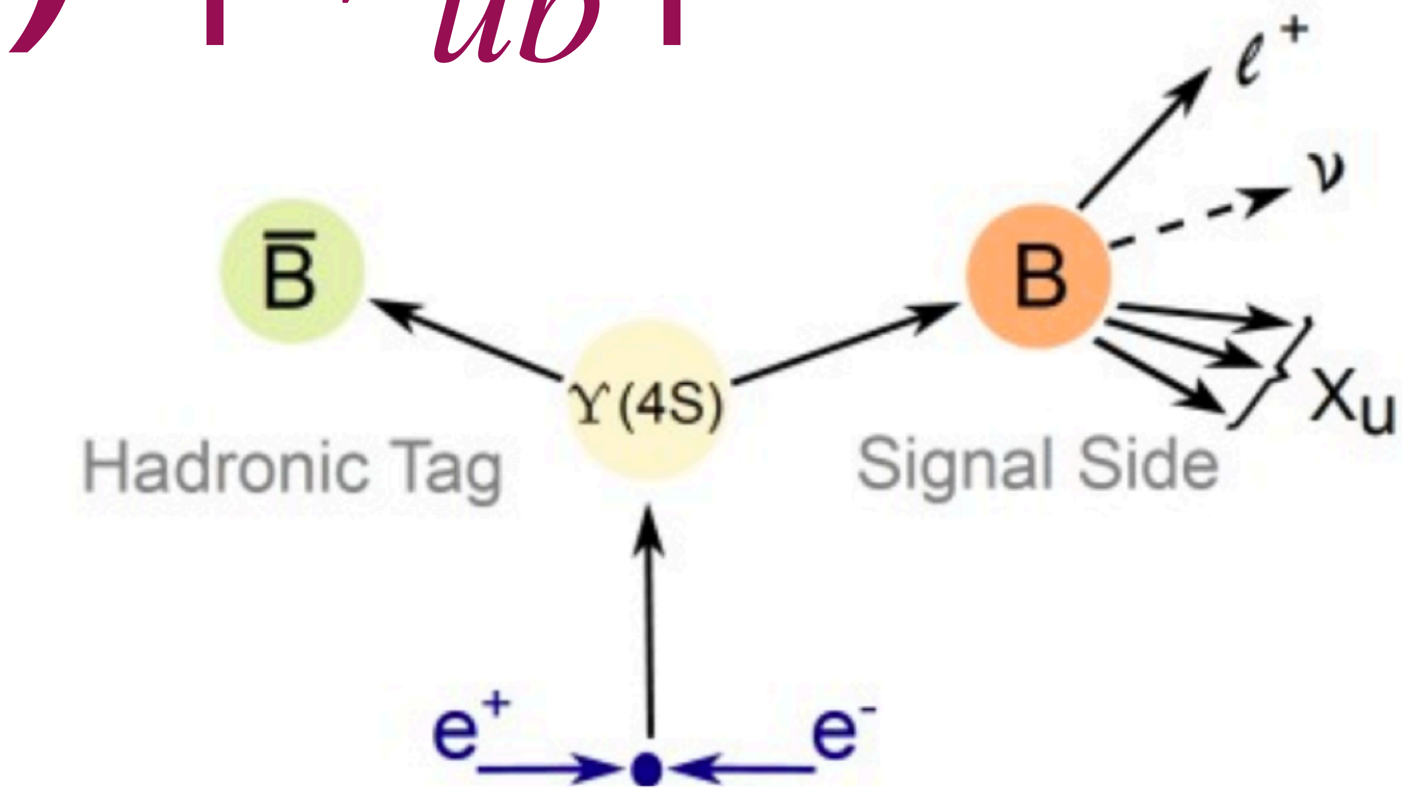
B semileptonic (1)

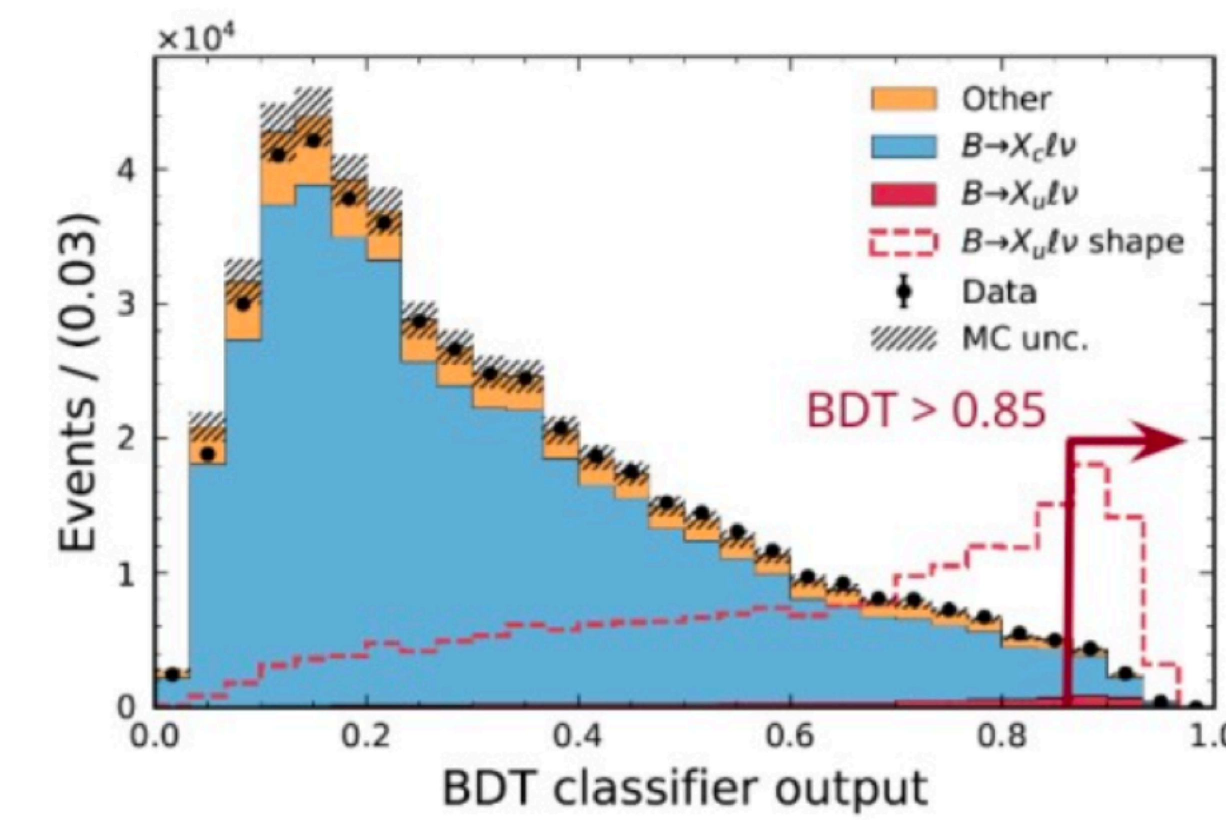
- $|V_{cb}|$ from exclusive B decays (Belle, Belle II)
  - by $B \to D^* \ell^+ \nu$ shape (Belle)
  - by $B \to D^* \ell^+ \nu$ shape (Belle II)
- Simultaneous (incl. & excl.) $|V_{ub}|$ (Belle)

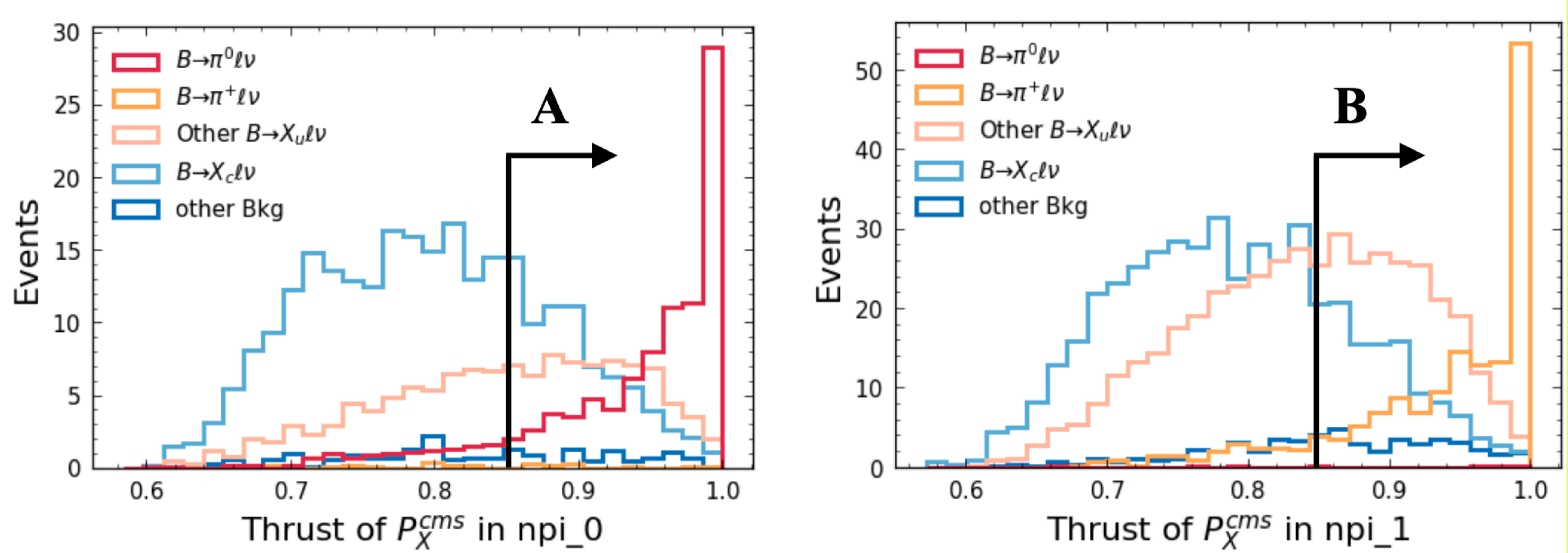
arXiv:2303.17309
submitted to PRL

Simultaneous (incl. & excl.) $|V_{ub}|$

- Full Belle dataset ($\mathscr{L}_{\text{int}} = 711\ \text{fb}^{-1}$)
- B-tagging by hadronic decays
  - ANN-based tagging
  - allows reconstruction of X_u in $B \to X_u \ell^+ \nu$
- $b \to c$ is suppressed using M_X, and further by BDT
  - 11 features for training (M^2_{m}, χ^2_{vtx}, $N(K'\text{s})$, etc.)
- use X_u thrust in the CM frame, for $B \to \pi \ell^+ \nu$ significance

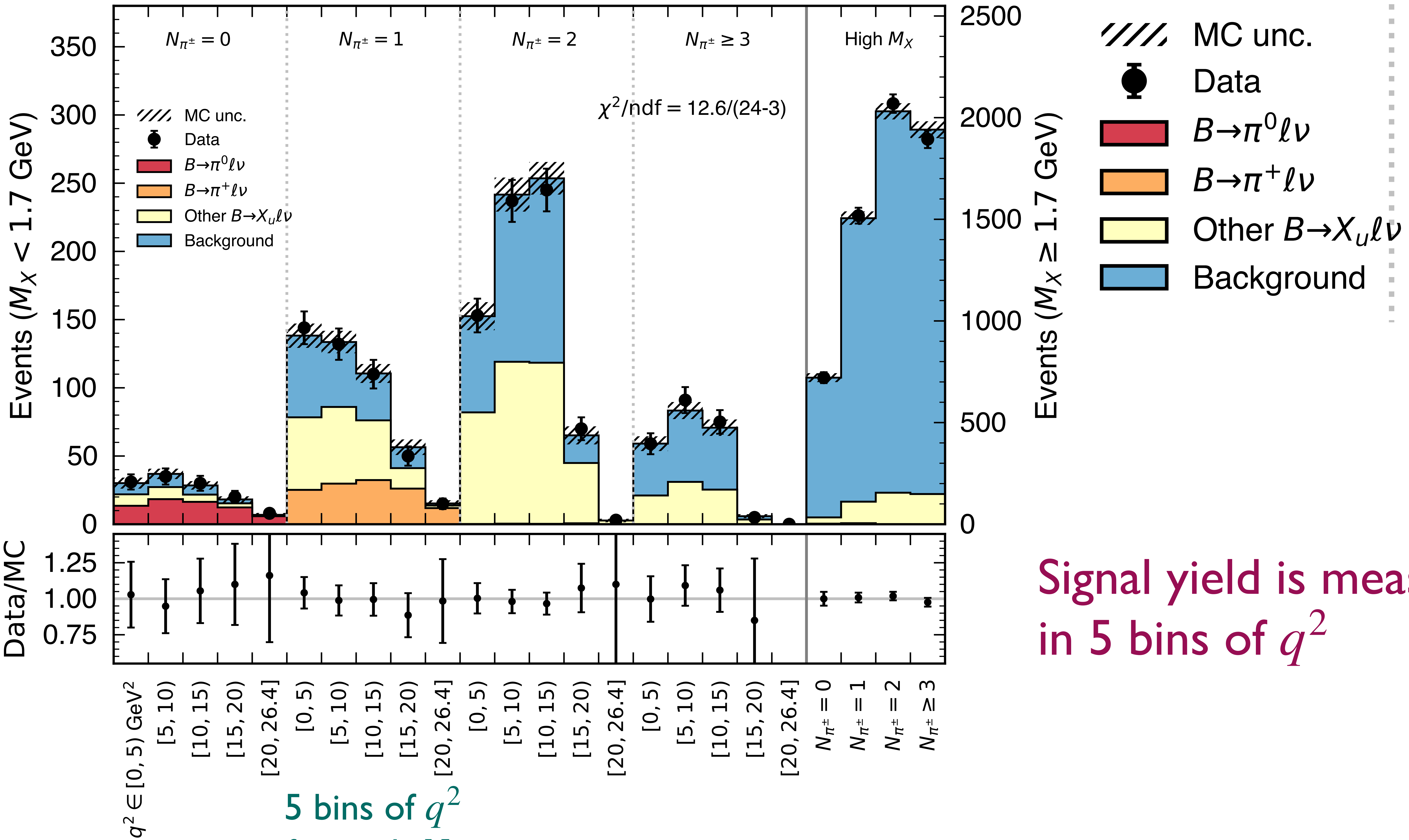






Simultaneous (incl. & excl.) $|V_{ub}|$

arXiv:2303.17309
submitted to PRL



Signal yield is measured in 5 bins of q^2

5 bins of q^2 for each N_π

Simultaneous (incl. & excl.) $|V_{ub}|$

arXiv:2303.17309
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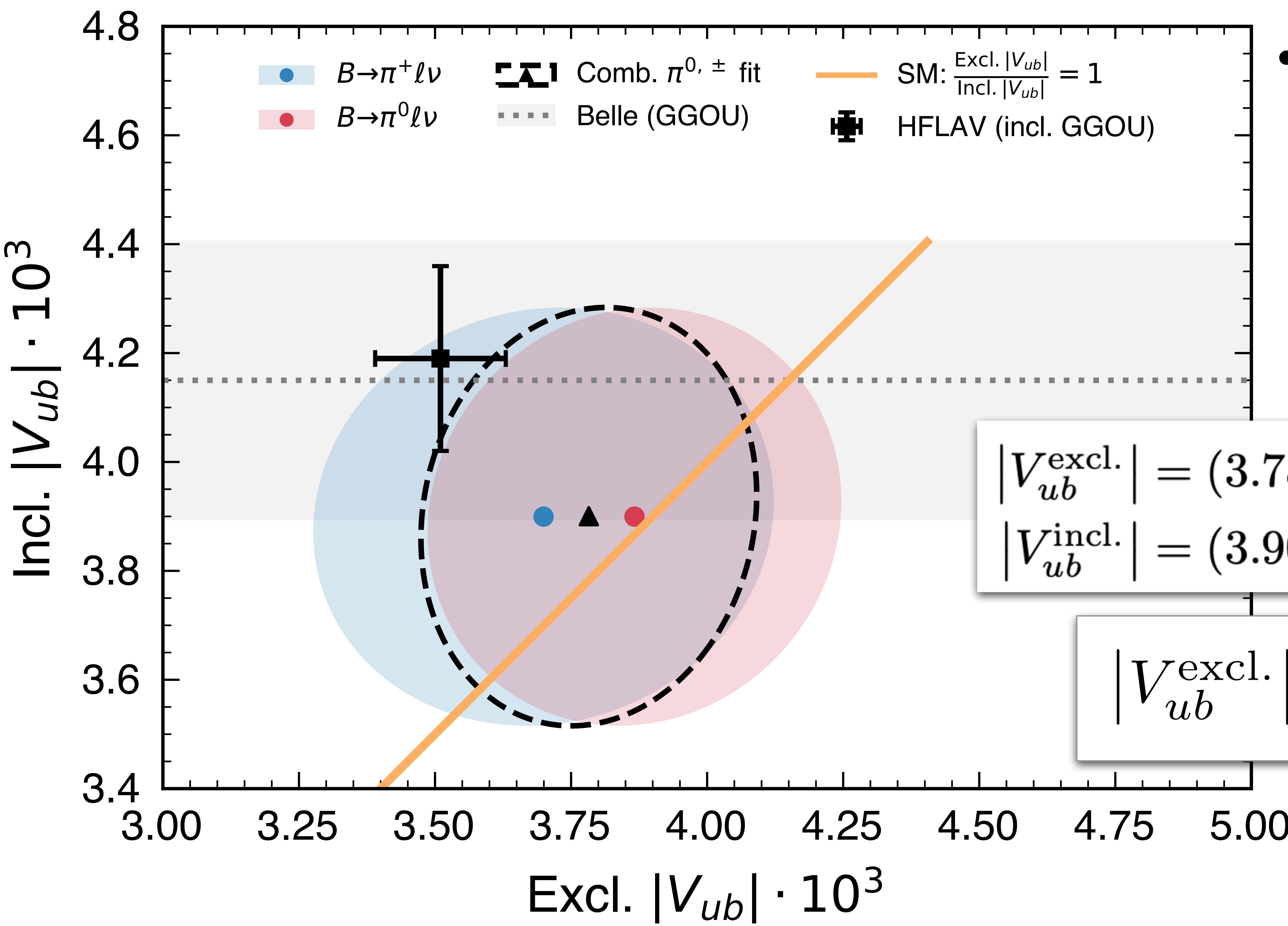


- $|V_{ub}|$ results from fits using LQCD and experimental constraints for the $B \to \pi^+ \ell \nu$ form-factor

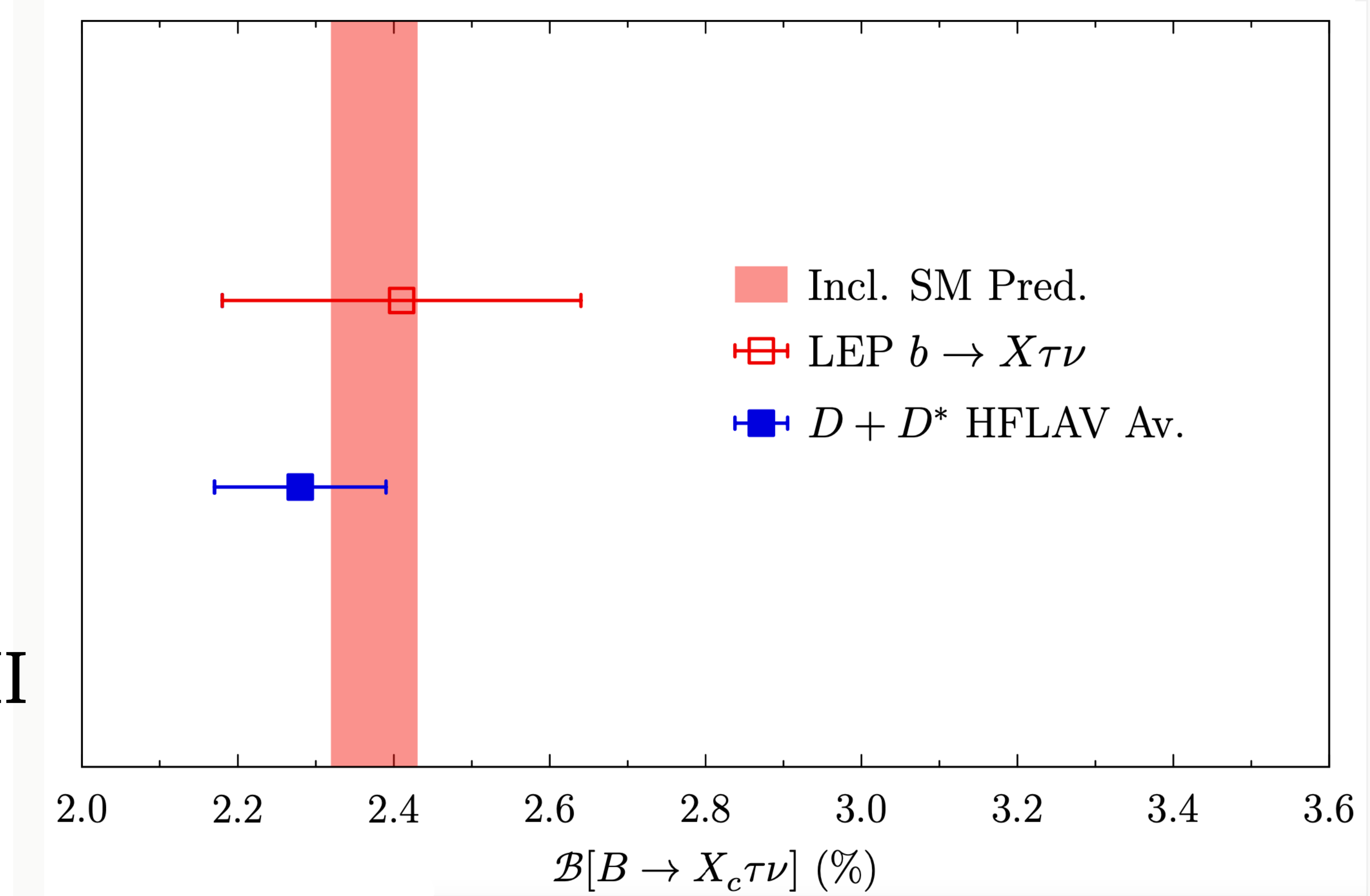
$$\left|V_{ub}^{\text{excl.}}\right| = (3.78 \pm 0.23 \pm 0.16 \pm 0.14) \times 10^{-3}$$
$$\left|V_{ub}^{\text{incl.}}\right| = (3.90 \pm 0.20 \pm 0.32 \pm 0.09) \times 10^{-3}$$

$$\left|V_{ub}^{\text{excl.}}\right| / \left|V_{ub}^{\text{incl.}}\right| = 0.97 \pm 0.12$$

B semileptonic (2)

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

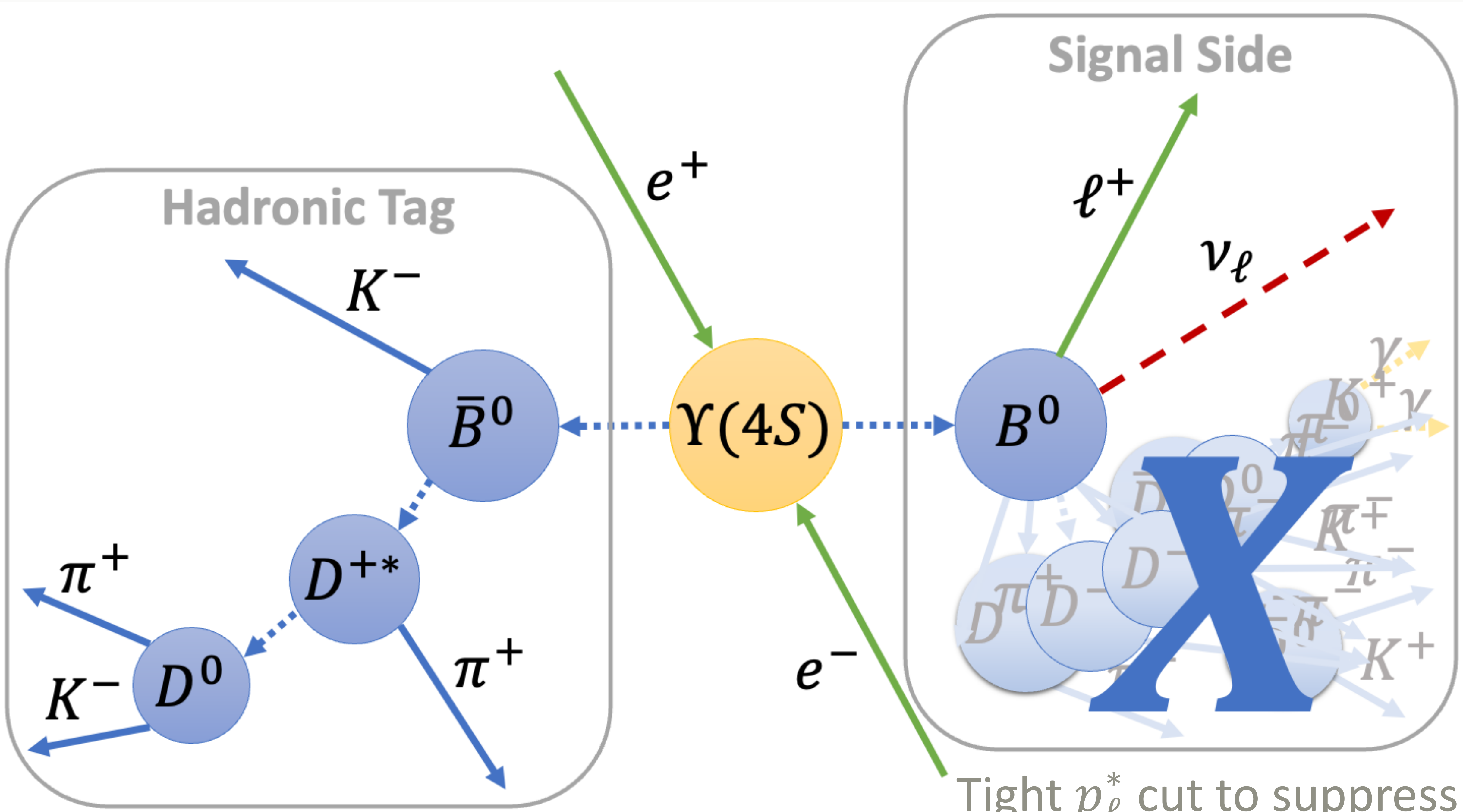
- ***inclusive*** study — complementary to ***exclusive*** studies
  - existing $R(D^{(*)})$ are all from exclusive analyses
- one of the unique and high-profile goals of Belle II
- last measured by LEP (!)
- very challenging — larger bkgd. & much less constrained
- precise modeling of $B \to X\ell\nu$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



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

arXiv:2301.08266
accepted to PRL

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**”)
- $B \to X\tau\nu$

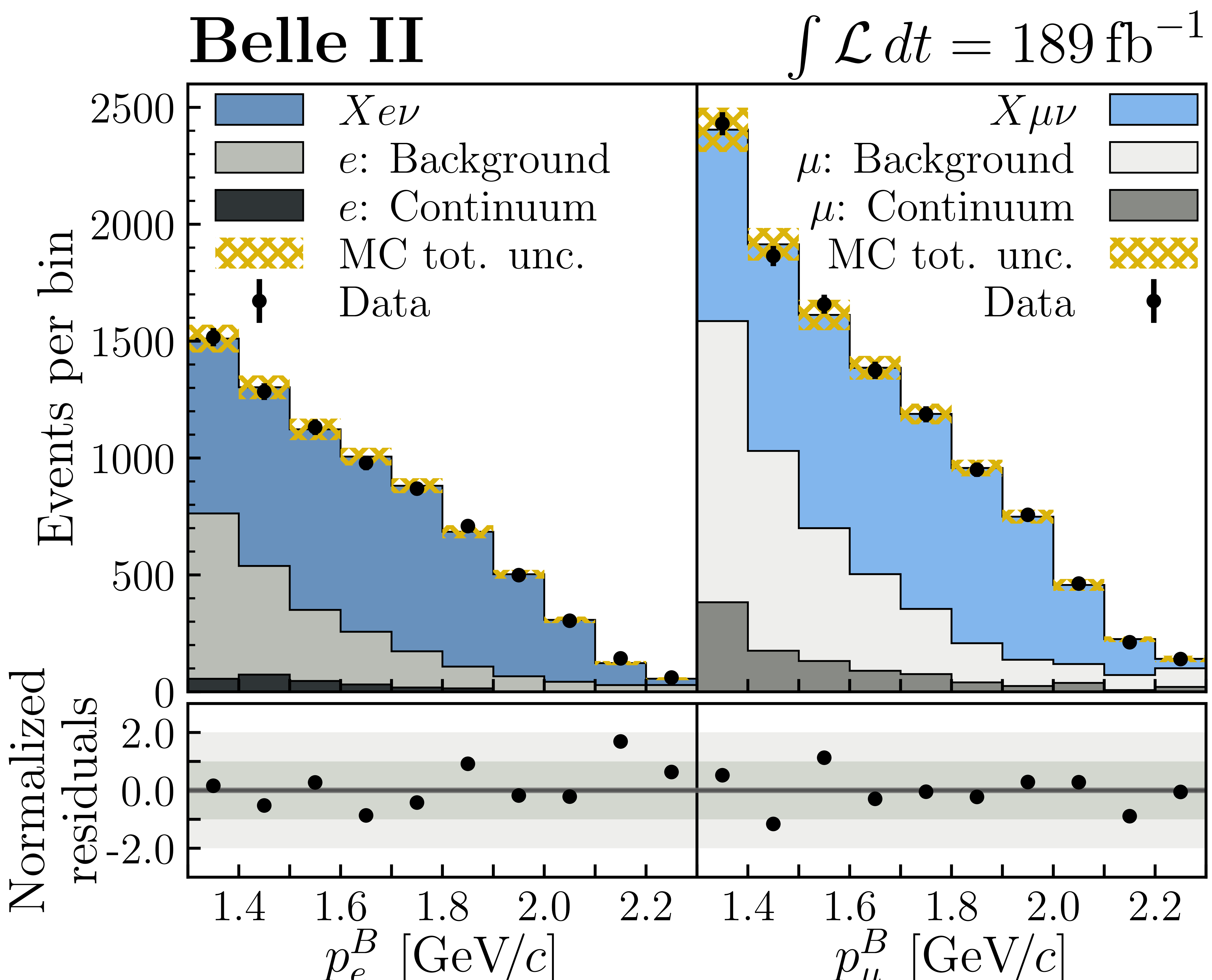
[53% (e) / 66% (μ) of selected B $\to X\ell\nu$ is retained]

- **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

arXiv:2301.08266
accepted to PRL

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

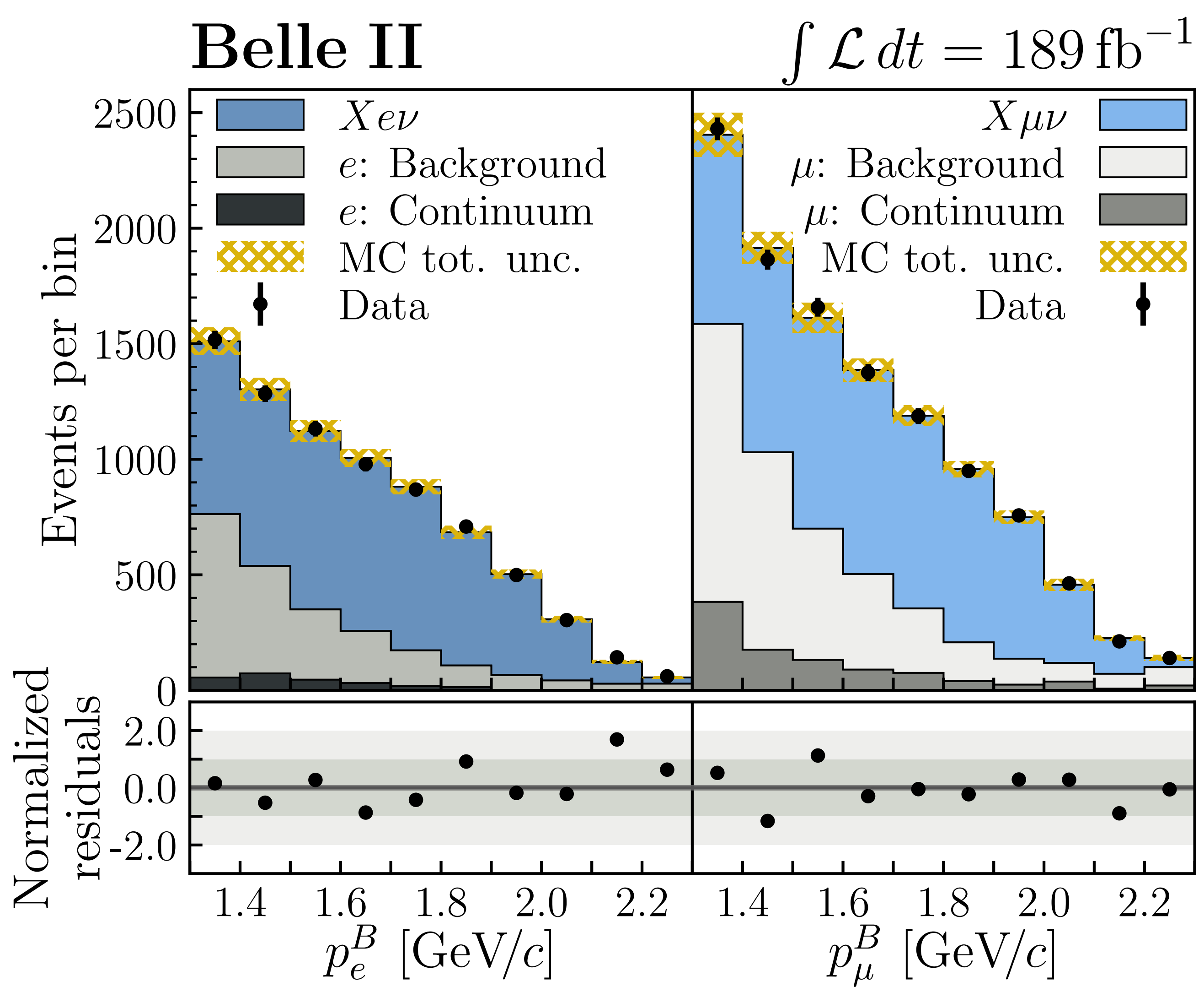


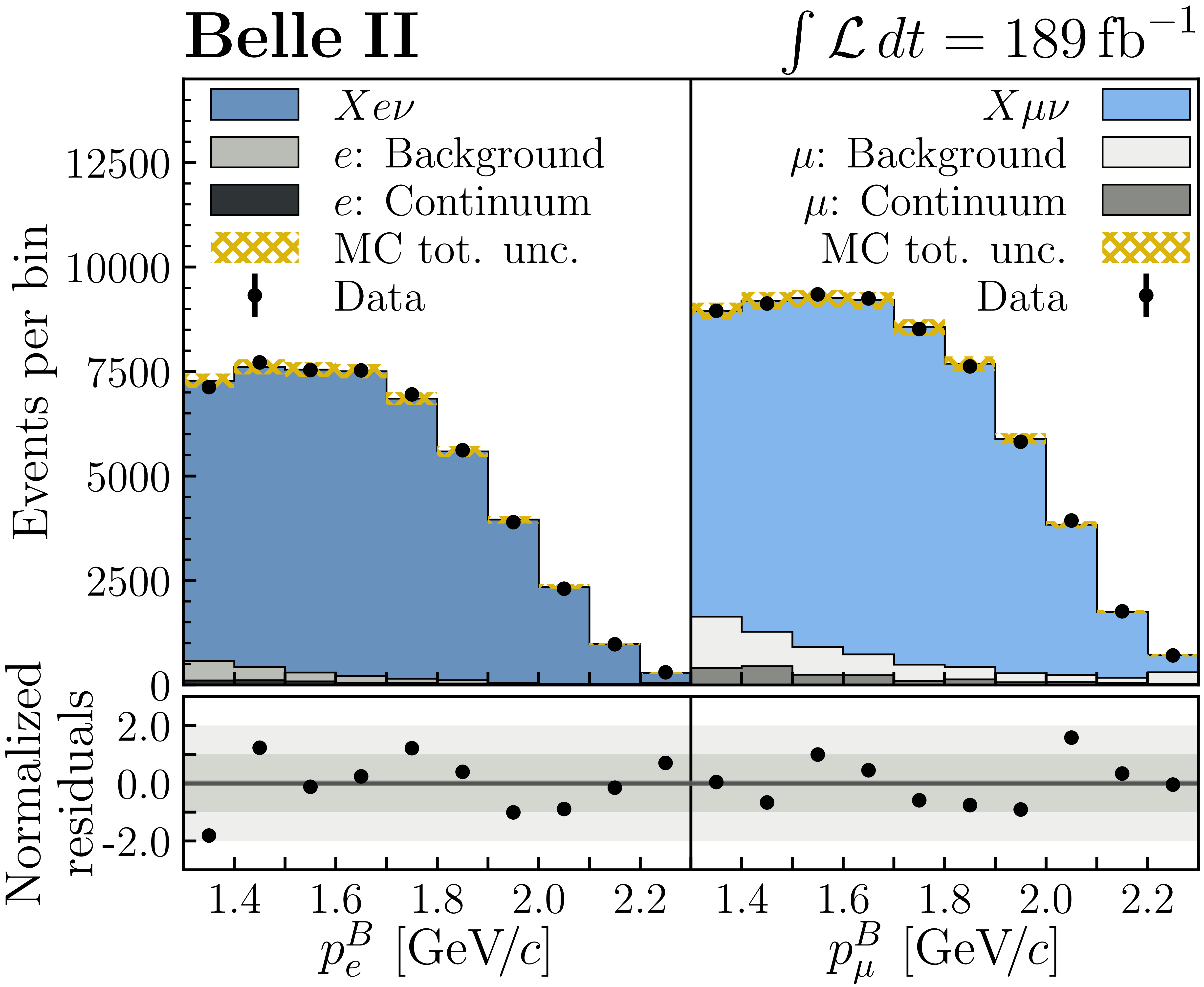
Signal extraction by fitting p_ℓ^B

- continuum bkgd. is Gaussian-constrained by off-resonance data
- fake & 2ndary leptons are Gaussian-constrained by simulatenously fitting the p_ℓ^B in same-charge sample

arXiv:2301.08266
accepted to PRL

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

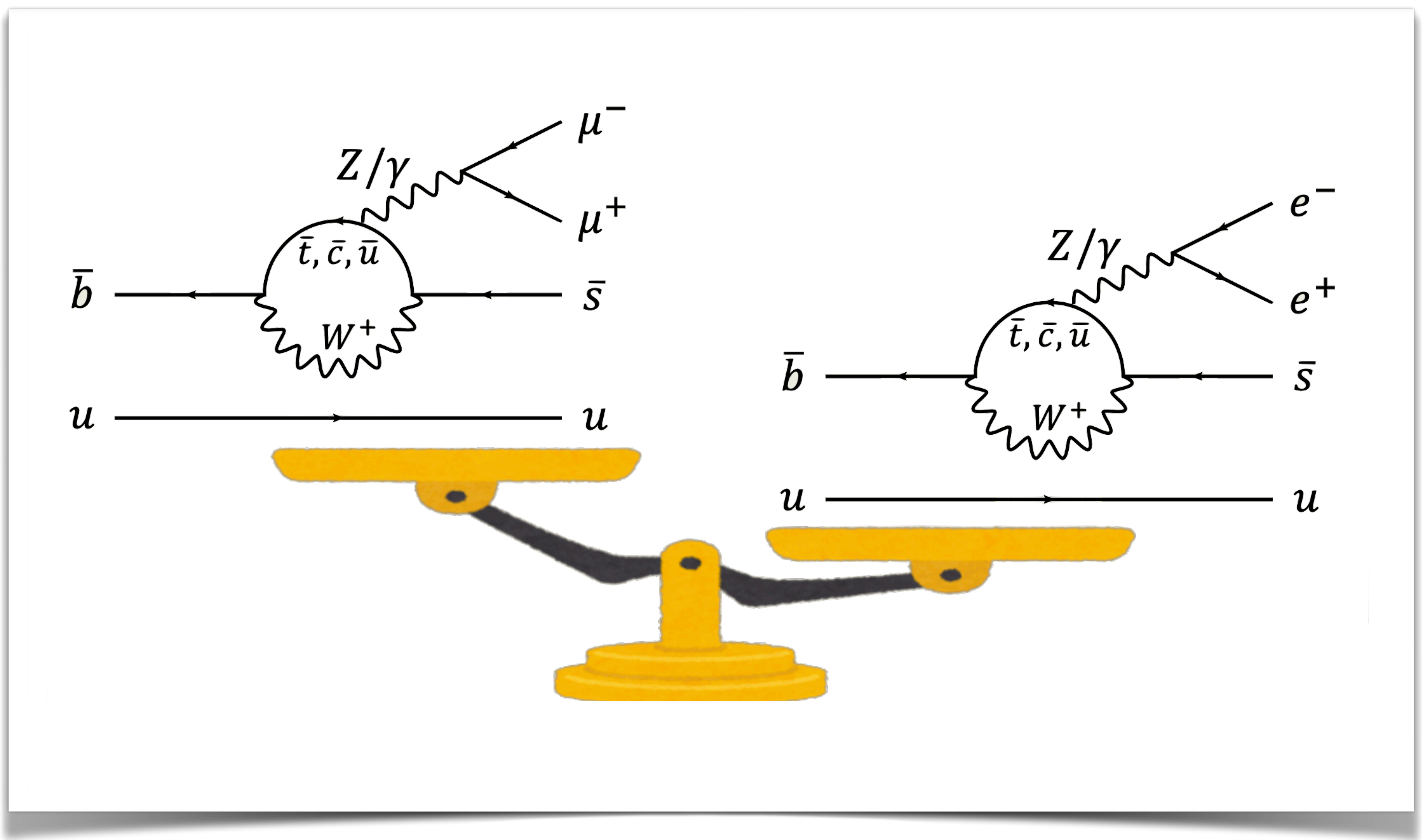


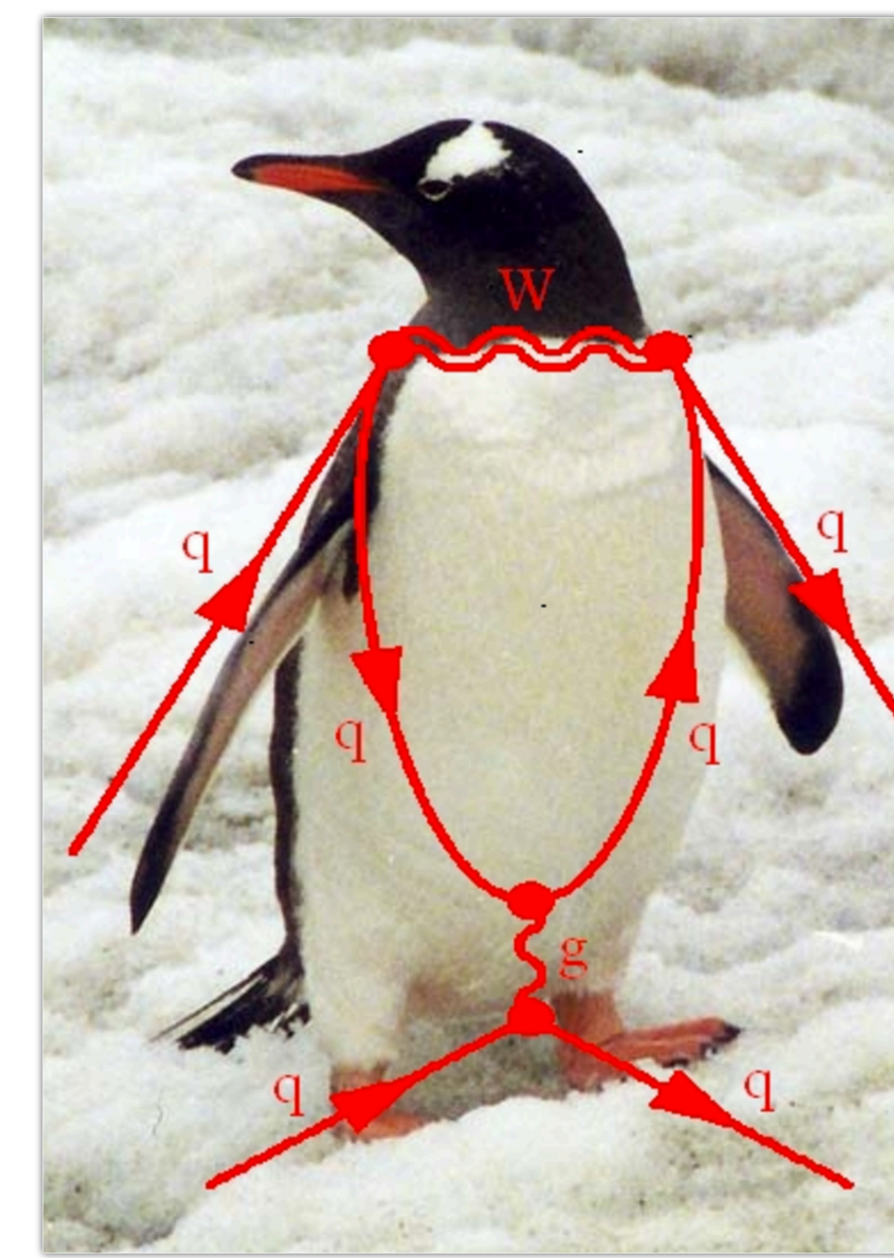


$$R(X_{e/\mu}\,|\,p_\ell^B > 1.3\ \mathrm{GeV}) = 1.007 \pm 0.009 \pm 0.019$$

the most precise BF-based LFU test, and consistent with SM

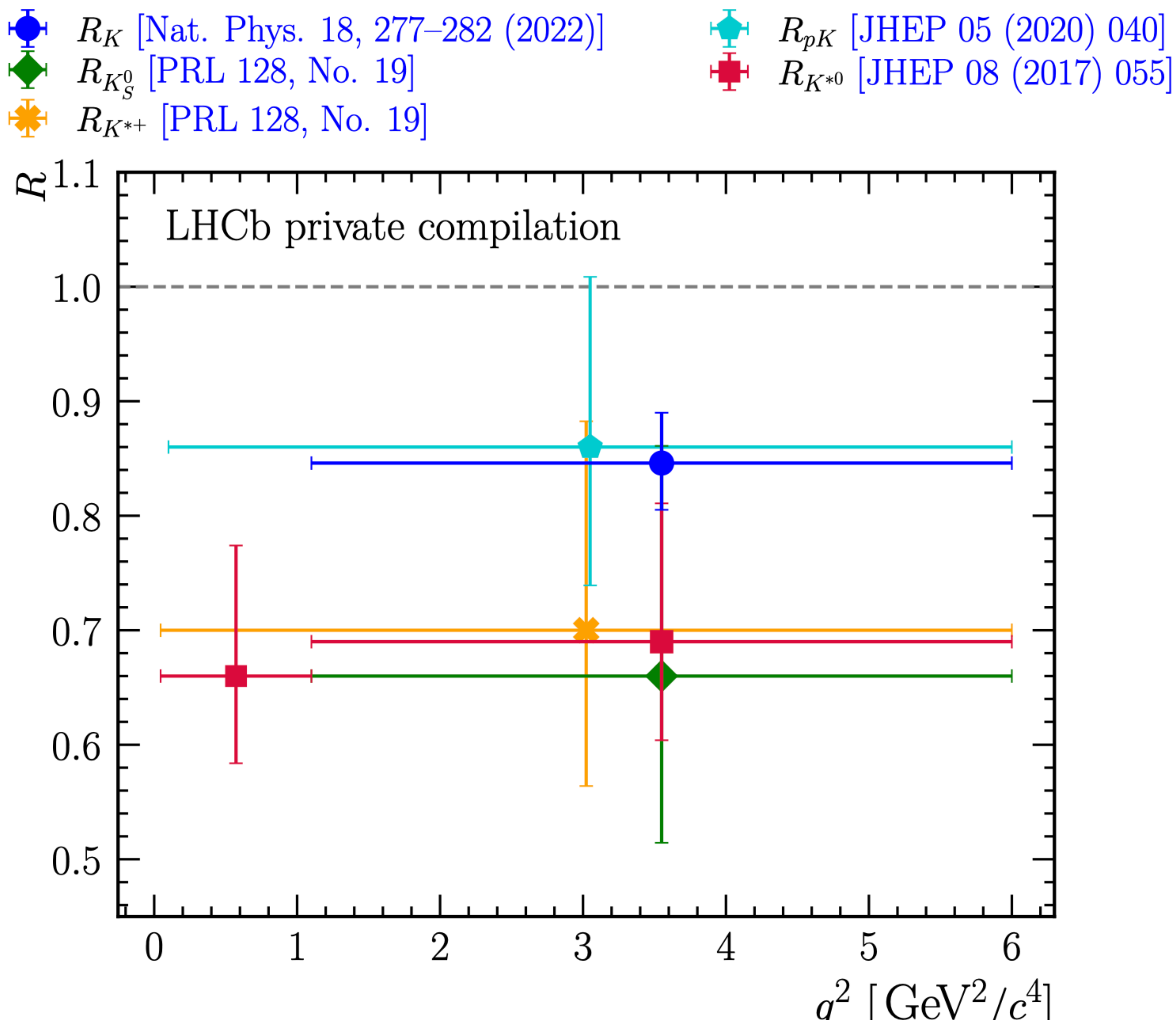
Status of $R_{K^{(*)}}$

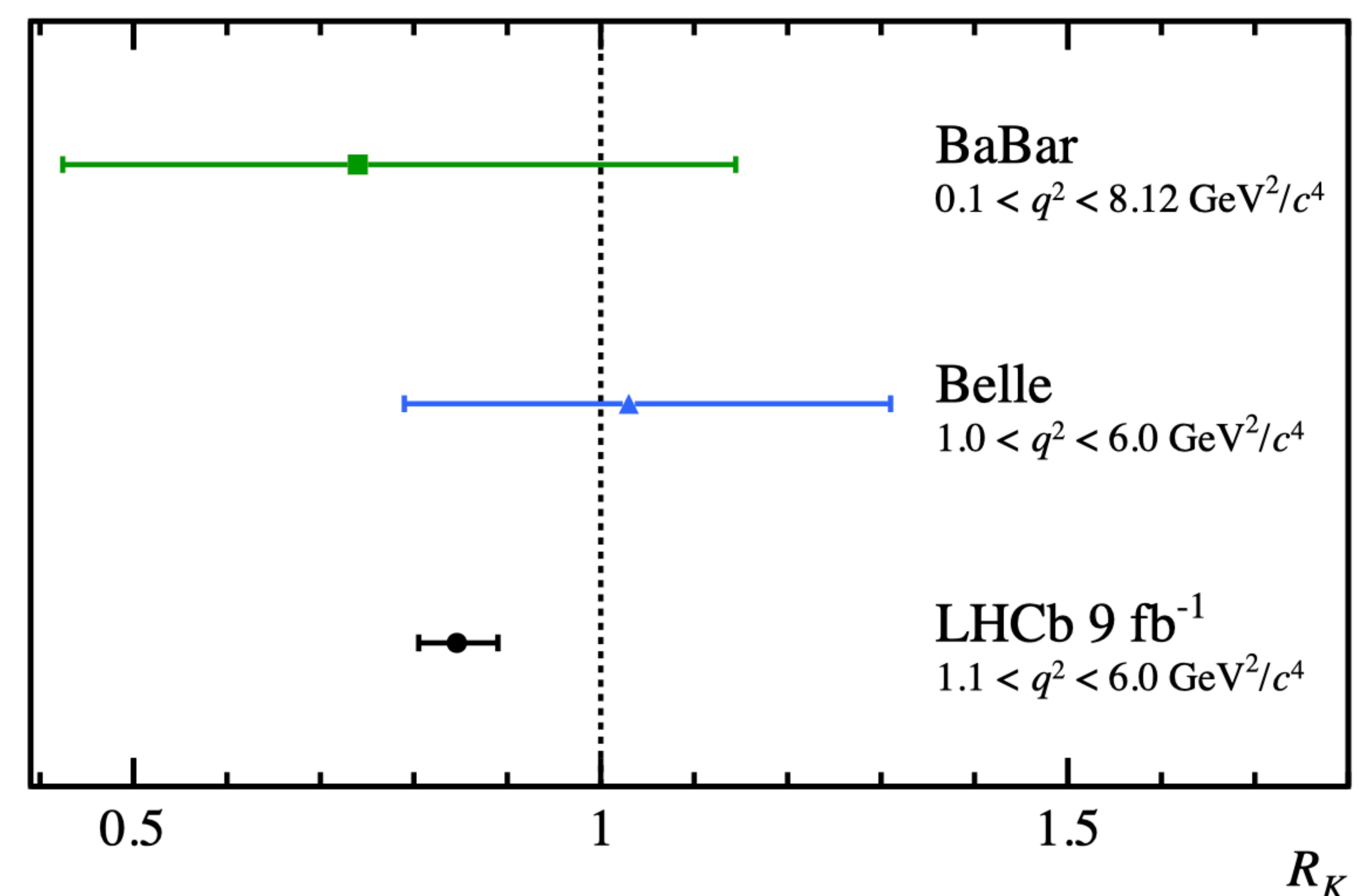




LFU test with $b \to s\ell^+\ell^-$ at LHCb

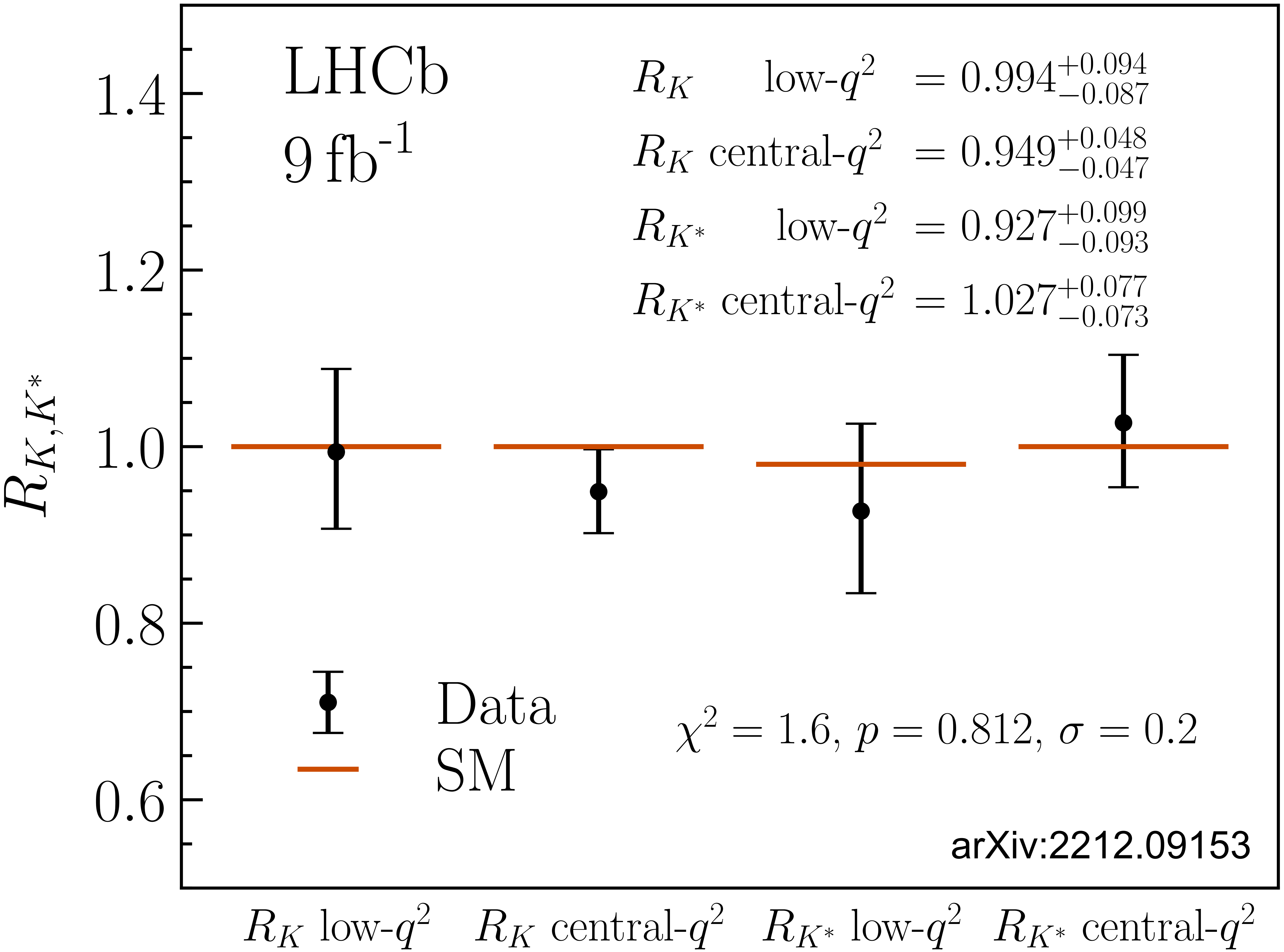
as of Fall, 2022



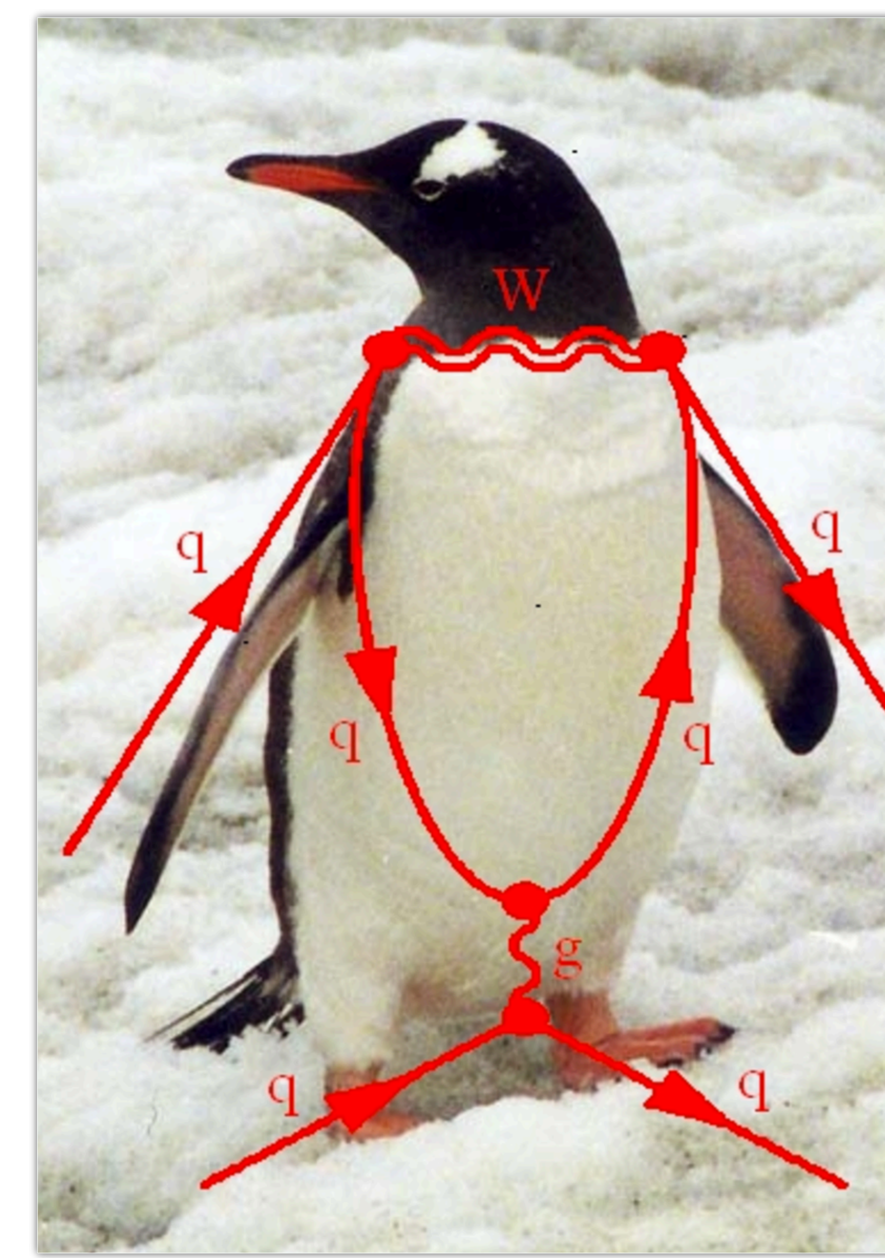


LFU test with $b \to s\ell^+\ell^-$ at LHCb

as of now (*updated* Dec. 2022)

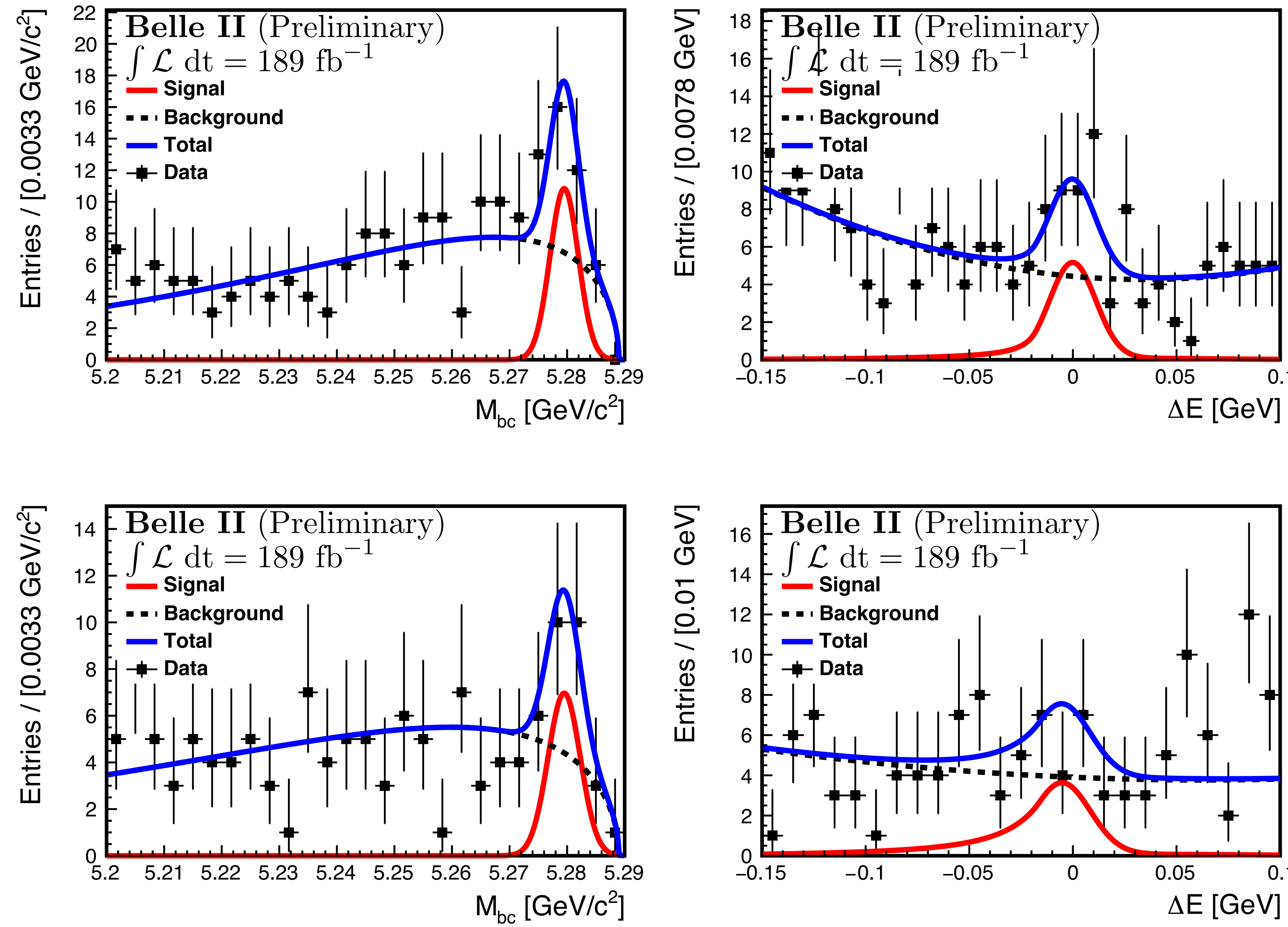


Other EW-penguin(-like) B decays



$B \to K^* \ell^+ \ell^-$ from Belle II

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



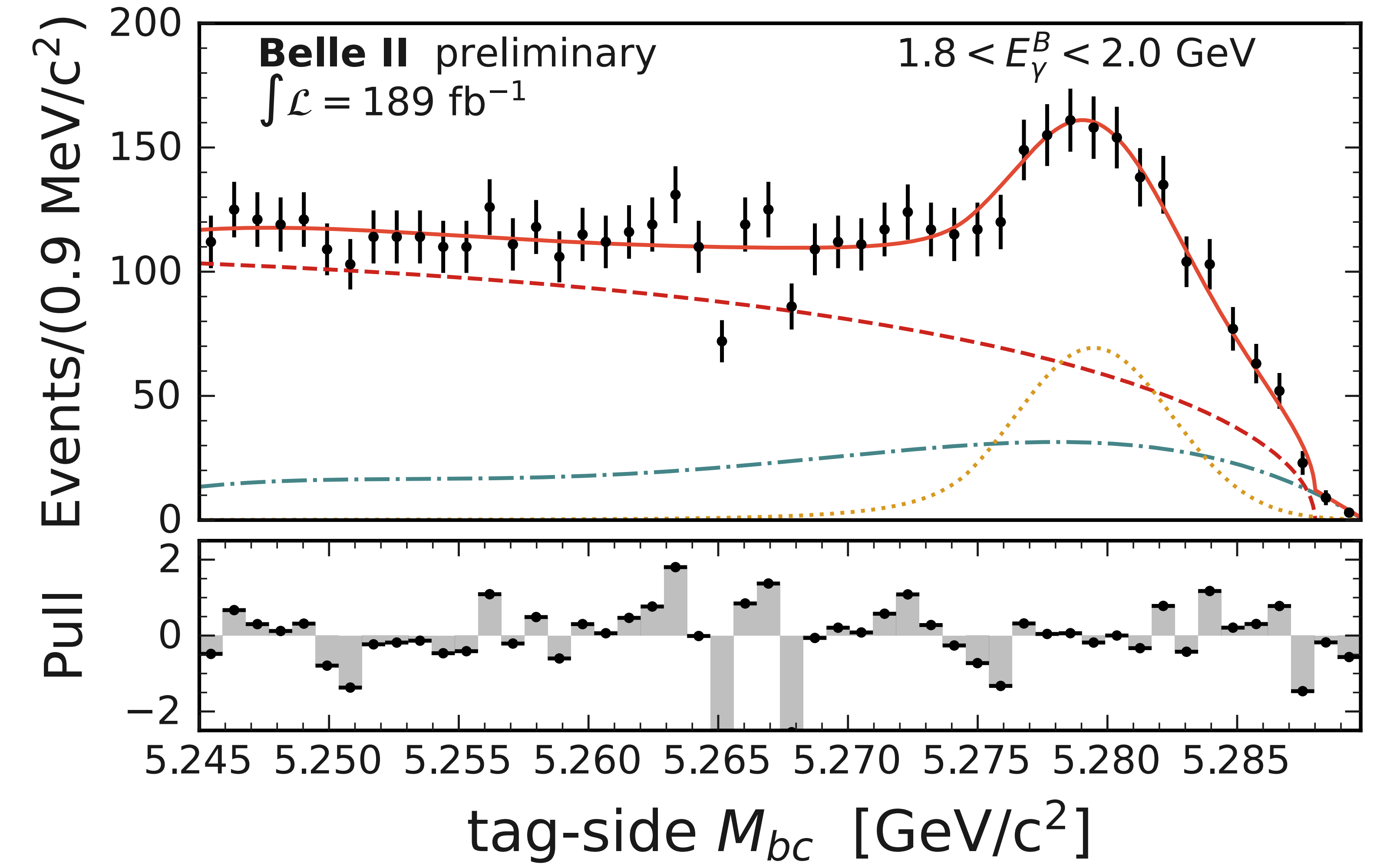
Decay	Belle II (10^{-6})	PDG (10^{-6})
$B \to K^* e^+ e^-$	$1.42 \pm 0.48 \pm 0.09$	1.19 ± 0.20
$B \to K^* \mu^+ \mu^-$	$1.19 \pm 0.31^{+0.08}_{-0.07}$	1.06 ± 0.09

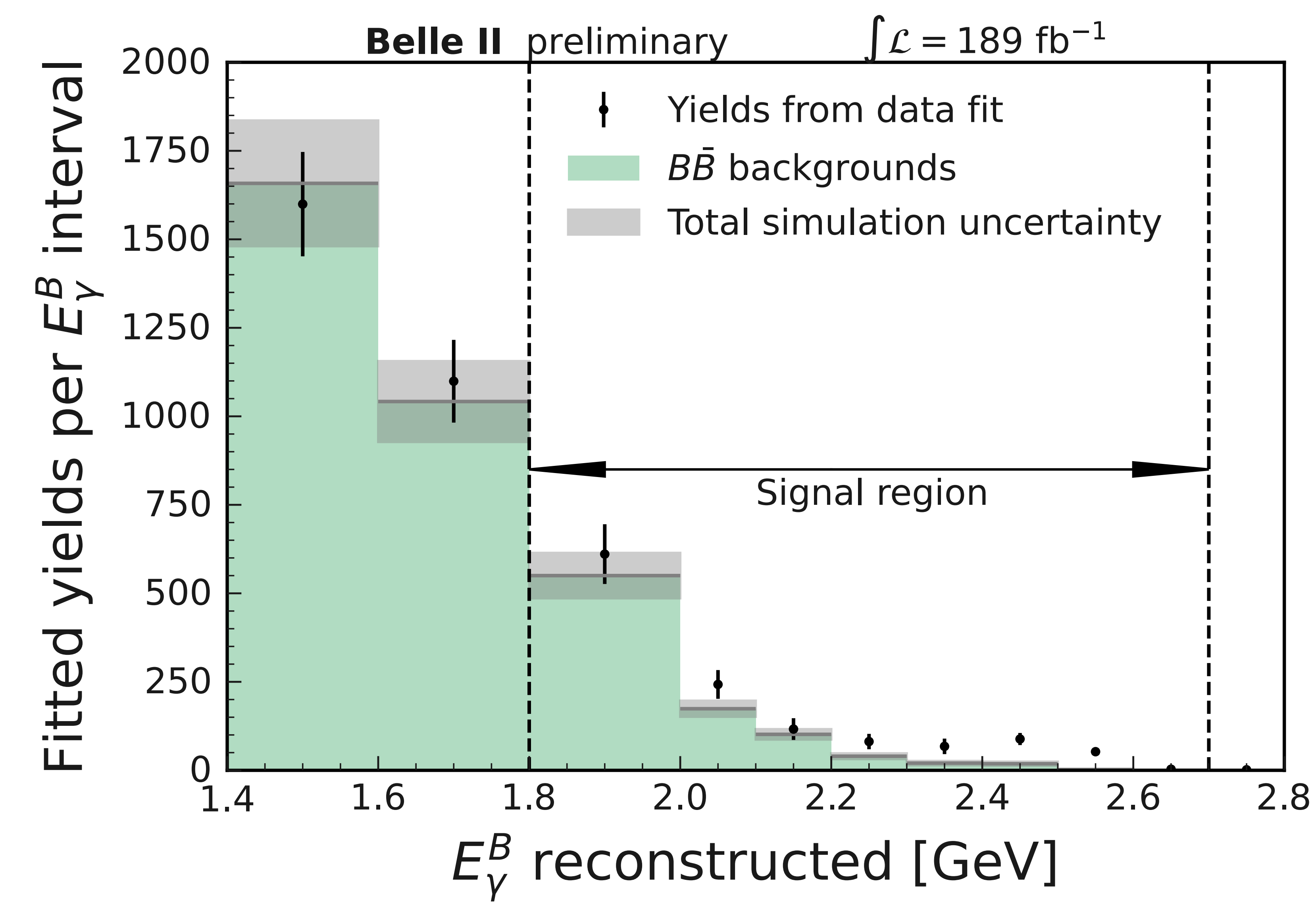
$$\mathcal{B}(B \to K^* \ell^+ \ell^-) = (1.25 \pm 0.30^{+0.08}_{-0.07}) \times 10^{-6}$$

arXiv:2210.10220

$B \to X_s\gamma$ (inclusive) from Belle II

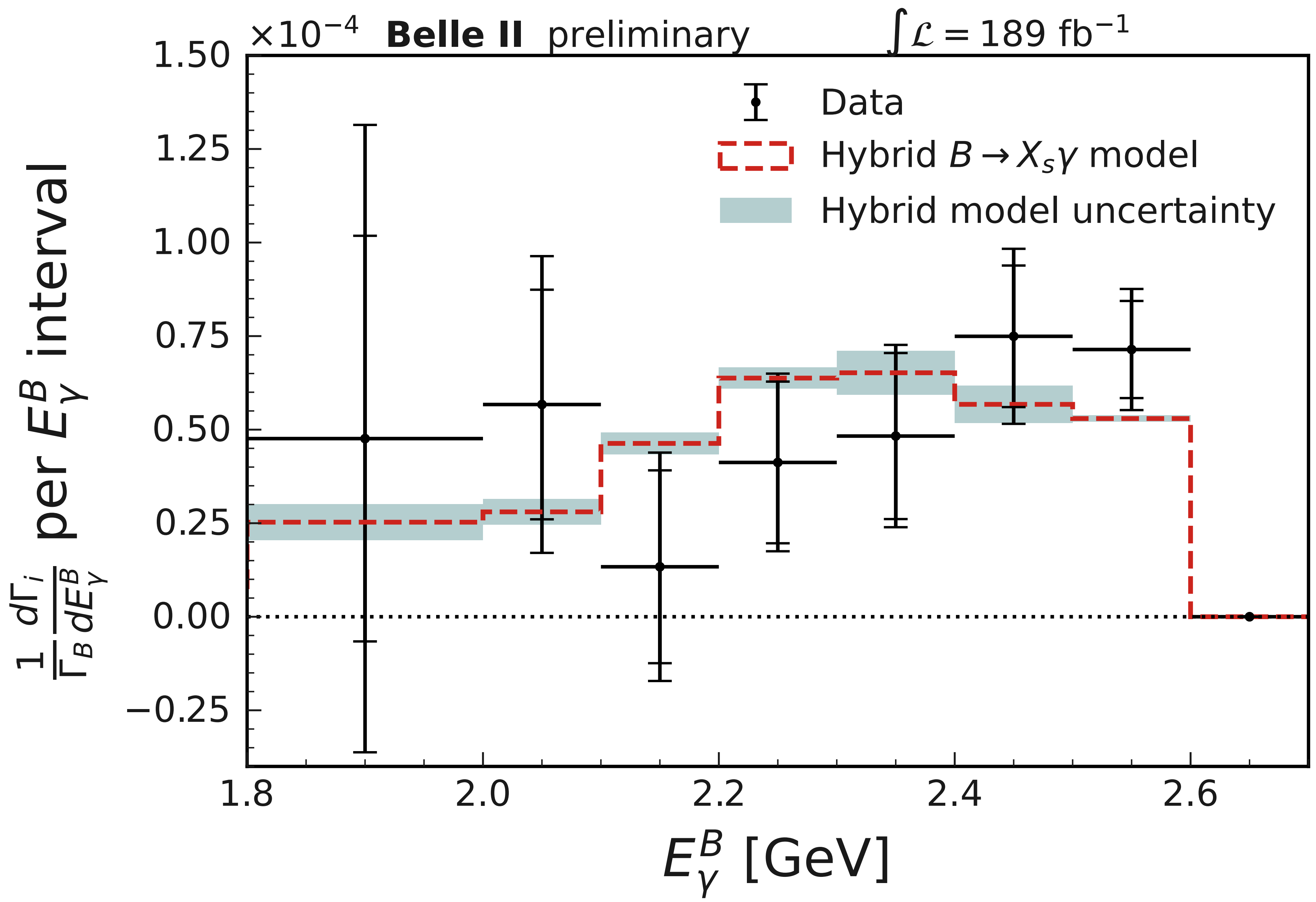
- measure $\mathscr{B}(B \to X_s\gamma)$ (inclusive) with $\int \mathscr{L} dt = 189\ \text{fb}^{-1}$
- FEI for hadronic B-tagging
  - fit M_{bc} (tag side) for signal yield in bins of E_γ
- dominant continuum bkgd. are suppressed with π^0/η veto (BDT)
- use MC to subtract leftover bkgd. in each E_γ bin
- $b \to d\gamma$ is subtracted using $|V_{td}/V_{ts}|$
- The measured E_γ spectrum is unfolded to correct for smearing, etc.





arXiv:2210.10220

$B \to X_s\gamma$ (inclusive) from Belle II



Compare with (for $E_\gamma > 1.6$ GeV)

$$\mathcal{B}_{\text{th}}(B \to X_s\gamma) = (3.40 \pm 0.17) \times 10^{-4}\ [1]$$

$$\mathcal{B}_{\text{exp}}(B \to X_s\gamma) = (3.49 \pm 0.19) \times 10^{-4}\ [2]$$

[1] M. Misiak, A. Rehman and M. Steinhauser, *Towards $\overline{B} \to X_s\gamma$ at the NNLO in QCD without interpolation in m_c*, *J. High Energy Phys.* **06** (2020) 175 [2002.01548].

[2] HFLAV 2022; experimental results are extrapolated to $E_\gamma > 1.6$ by Buchmuller & Flatter, PRD 73, 073008 (2006)

E_γ^B threshold [GeV]	$\mathcal{B}(B \to X_s\gamma)$ $[10^{-4}]$
1.8	3.54 ± 0.78 (stat.) $\pm$ 0.83 (syst.)
2.0	3.06 ± 0.56 (stat.) $\pm$ 0.47 (syst.)
2.1	2.49 ± 0.46 (stat.) $\pm$ 0.35 (syst.)

- The result is consistent with theory (SM, NNLO)
- and the uncertainty is compatible with the other hadronic B-tag analysis (BaBar, 2008)

arXiv:2212.04128
accepted to PRL

$B^+ \to K^+\tau^\pm\ell^\mp$

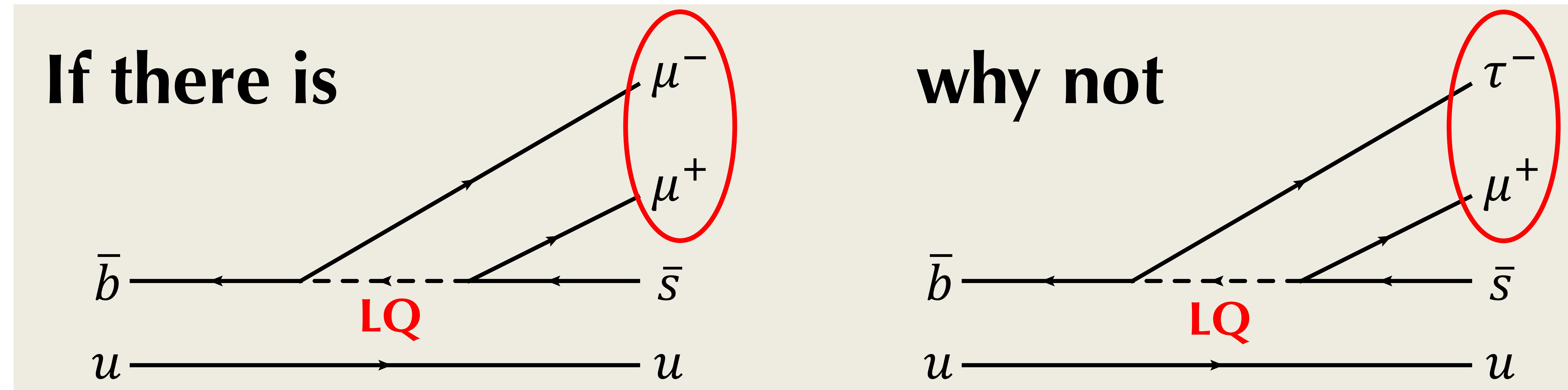
LFV in EWP-type *B* decays

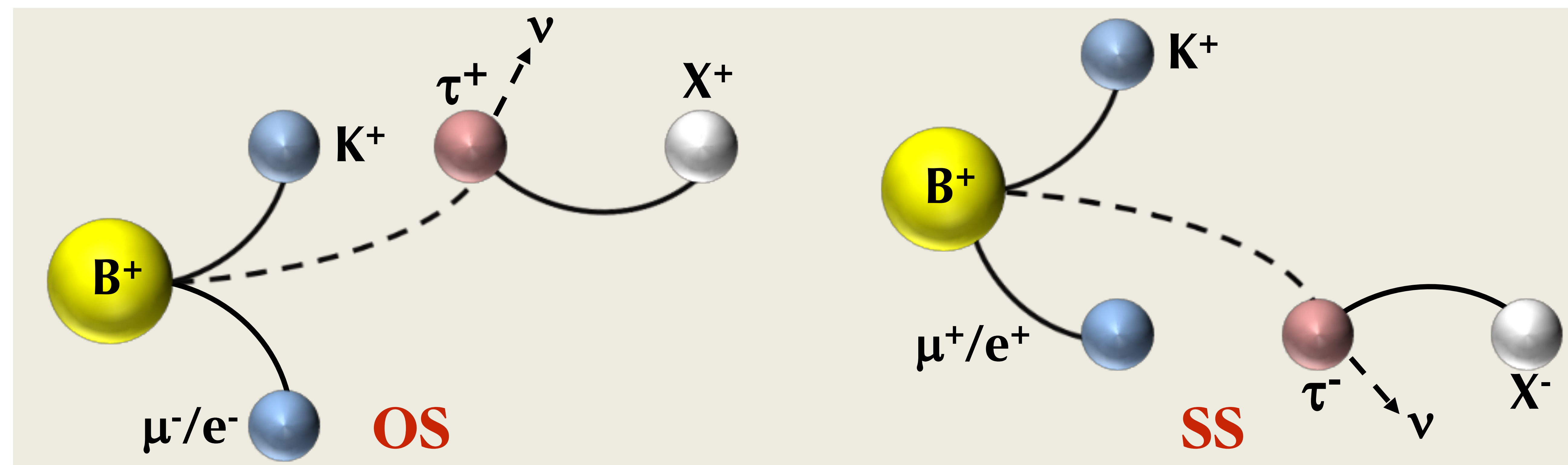
Motivation

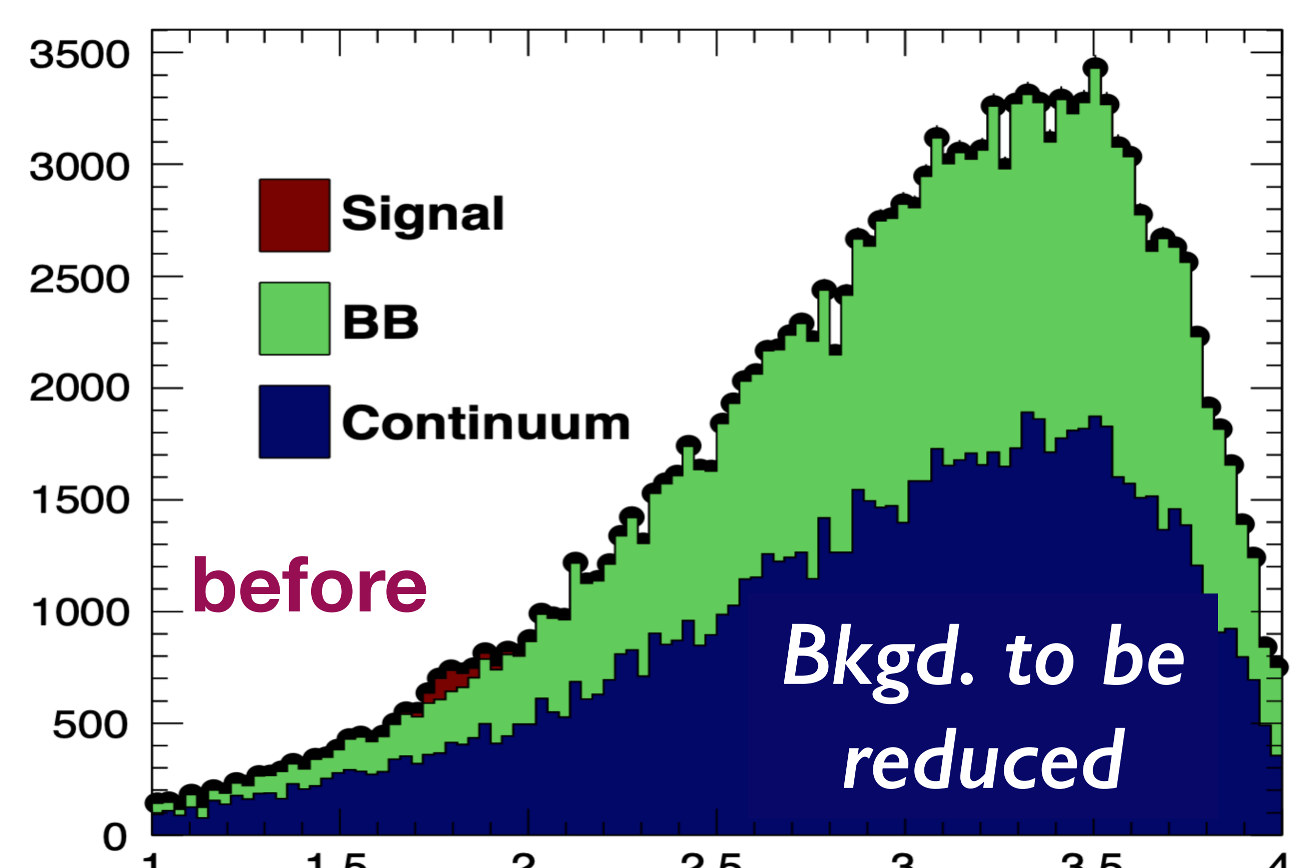
- If there is LUV, there is no natural mechanism to prevent LFV

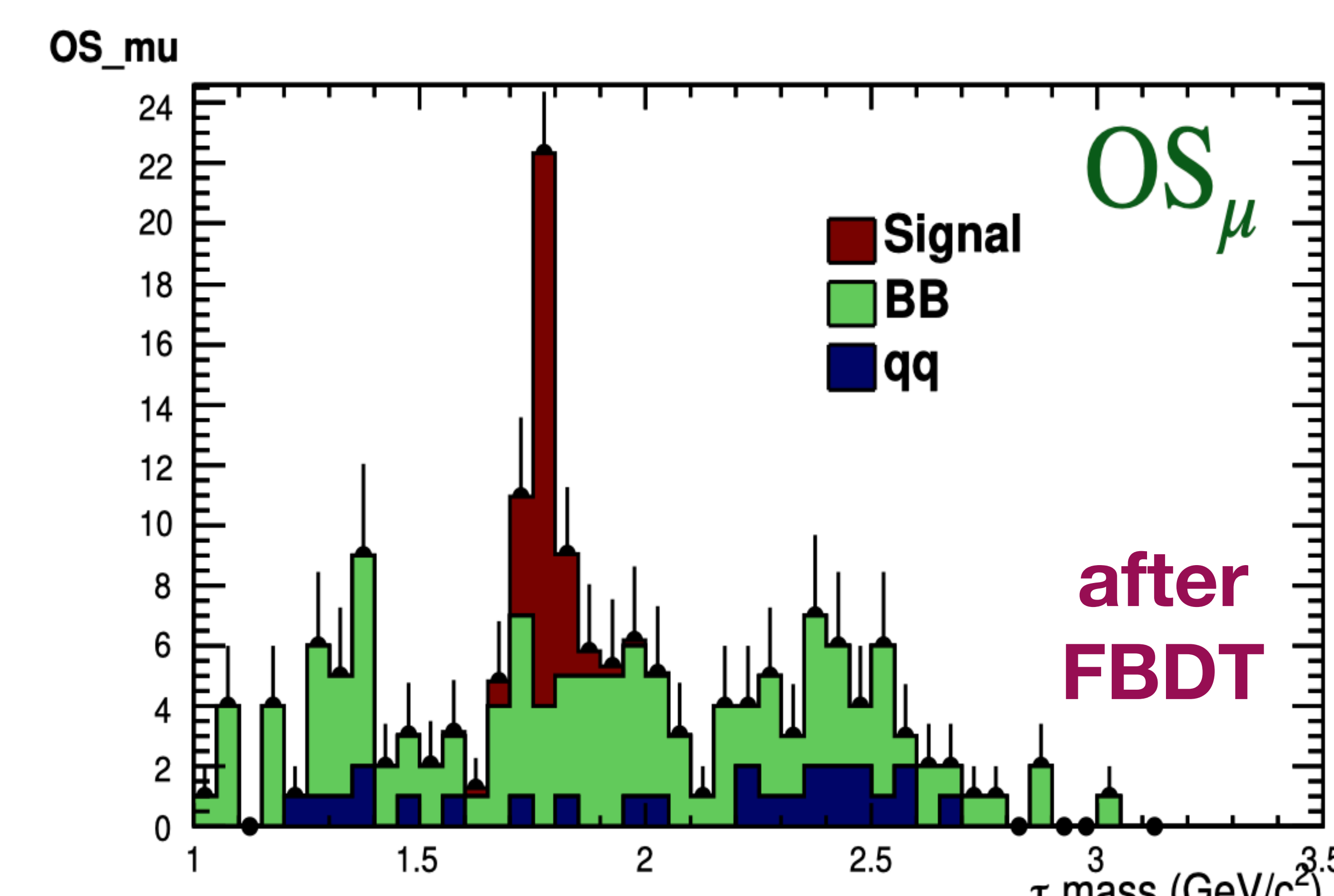
Analysis feature

- hadronic B-tagging (FEI[1])
- OS vs. SS (very different bkgd.)
- fit for recoil mass for M_τ
- use FBDT[2] to suppress bkgd.







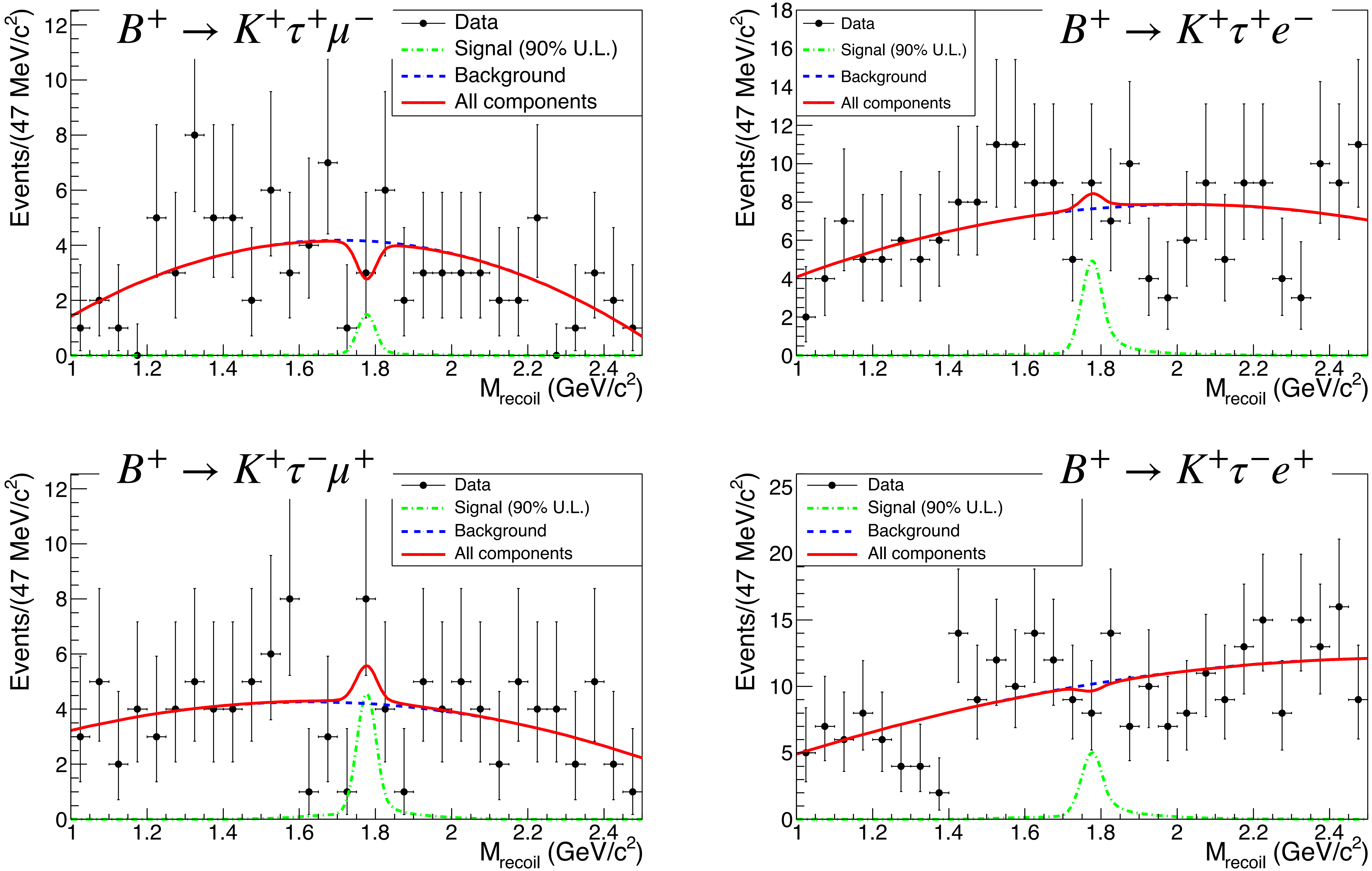


[1] Keck, T. et al., *The Full Event Interpretation*. Comput Softw Big Sci 3, 6 (2019).

[2] Keck, T., *FastBDT: A Speed-Optimized Multivariate Classification Algorithm for the Belle II Experiment*. Comput Softw Big Sci 1, 2 (2017).

$B^+ \to K^+\tau^\pm\ell^\mp$ Results

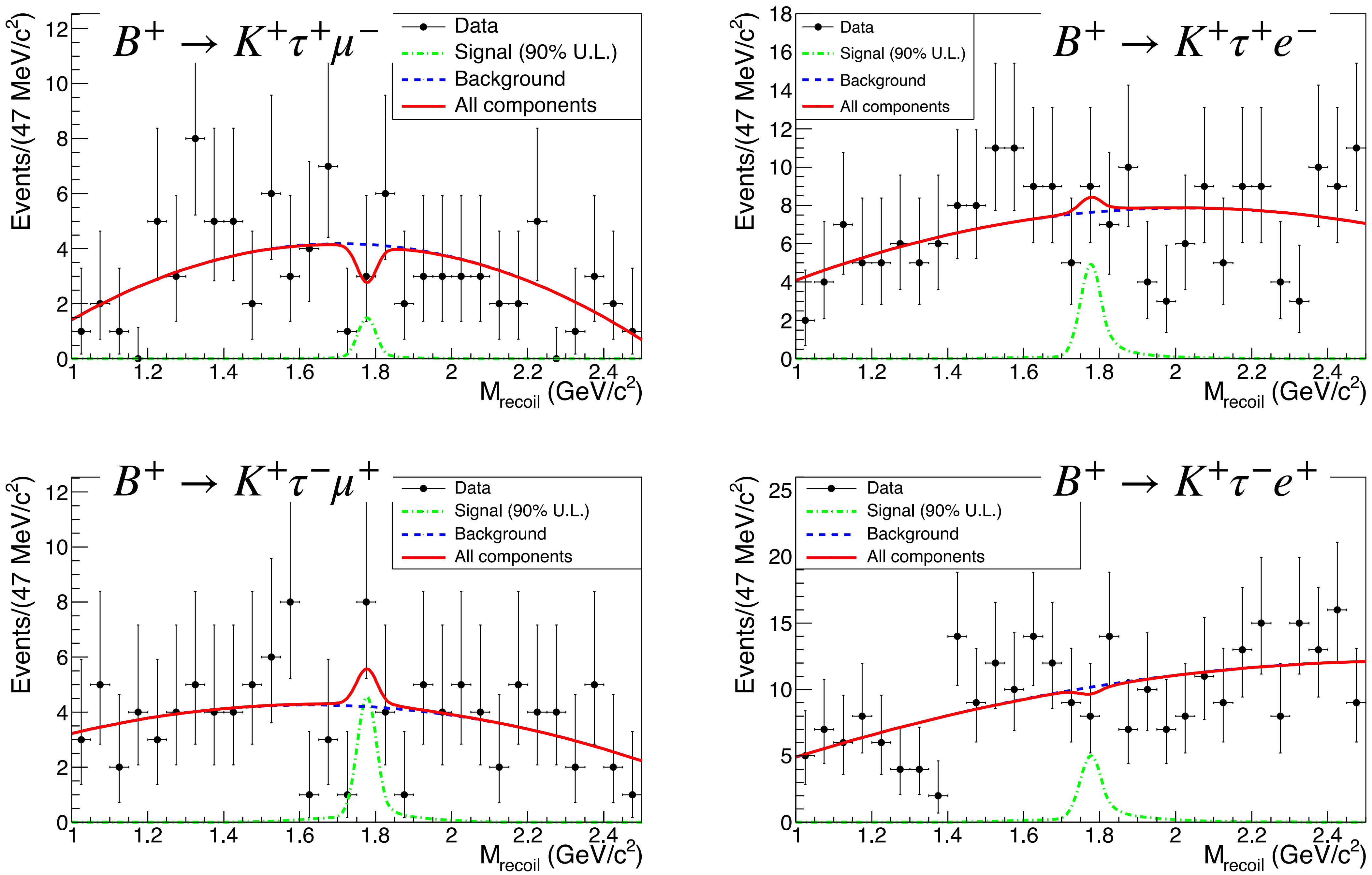
arXiv:2212.04128
accepted to PRL



No signal excess in any mode!

$B^+ \to K^+\tau^\pm\ell^\mp$ Results

arXiv:2212.04128
accepted to PRL



Mode	ε (%)	ε^{NP} (%)	N_{sig}
$B^+ \to K^+\tau^+\mu^-$	0.064	0.058	-2.1 ± 2.9
$B^+ \to K^+\tau^+e^-$	0.084	0.074	1.5 ± 5.5
$B^+ \to K^+\tau^-\mu^+$	0.046	0.038	2.3 ± 4.1
$B^+ \to K^+\tau^-e^+$	0.079	0.058	-1.1 ± 7.4

$$\mathcal{B}(B^+ \to K^+\tau^+\mu^-) < 0.59 \times 10^{-5}$$

$$\mathcal{B}(B^+ \to K^+\tau^+e^-) < 1.51 \times 10^{-5}$$

$$\mathcal{B}(B^+ \to K^+\tau^-\mu^+) < 2.45 \times 10^{-5}$$

$$\mathcal{B}(B^+ \to K^+\tau^-e^+) < 1.53 \times 10^{-5}$$

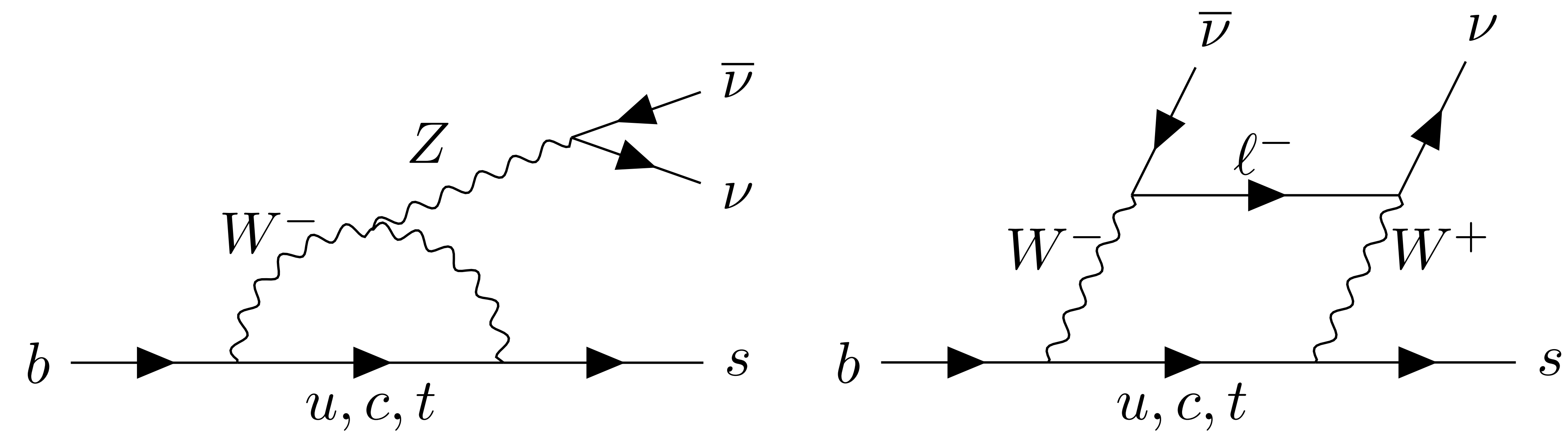
- The most stringent limit on $\mathscr{B}(B^+ \to K^+\tau\ell)$ in all four modes, based on PHSP model
- NP upper limits are also estimated for models that give lowest efficiency
- paper has been accepted to PRL

PRL 127, 181802 (2021)

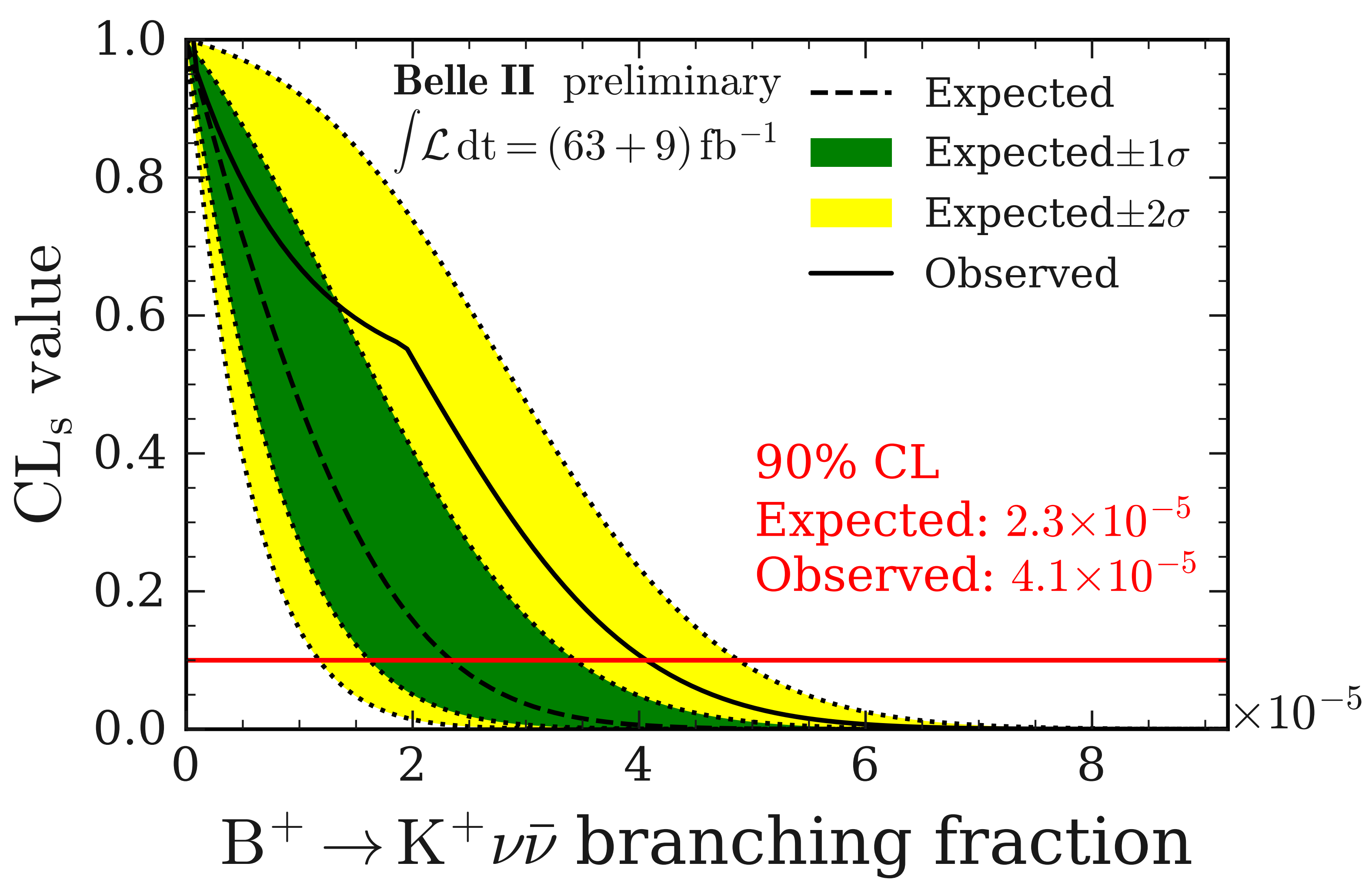
Search for $B^+ \to K^+\nu\bar{\nu}$ at Belle II

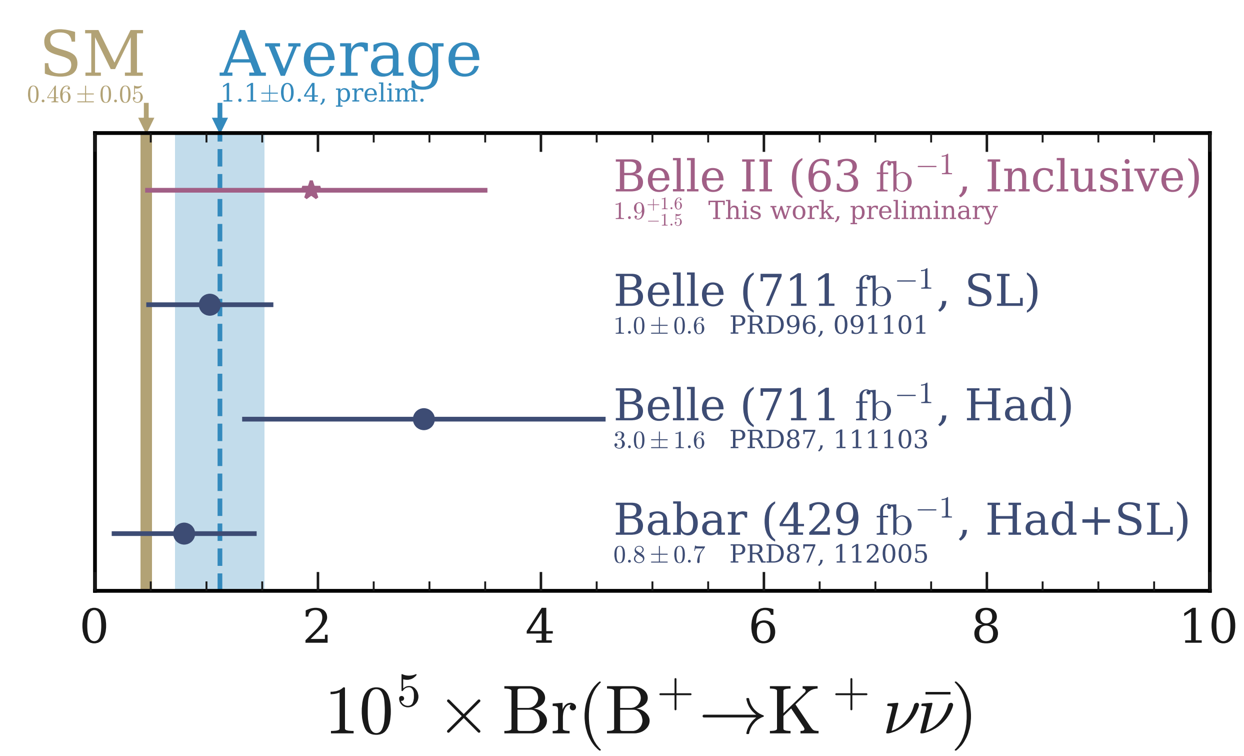
- In the SM,
  - $\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = (4.6 \pm 0.5) \times 10^{-6}$ [4]
- sensitive to new physics BSM, e.g.
  - leptoquarks,
  - axions,
  - DM particles, etc.

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



(a) Penguin diagram (b) Box diagram





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

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

Closing remarks

- With the original *B*-factories (Belle & BaBar), 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.
- Moreover, there have been several anomalies and/or tensions in B meson systems, some historic and others on-going.
- In this talk, we went through the current status of Belle II (and Belle as well) for some of these tensions/anomalies.
- With the Belle II experiment to resume operation around the end of this year, we expect much more to come, and it will be exciting.

https://mohamadalasadi.blogspot.com/2021/09/signs-you-should-quit-a-business.html

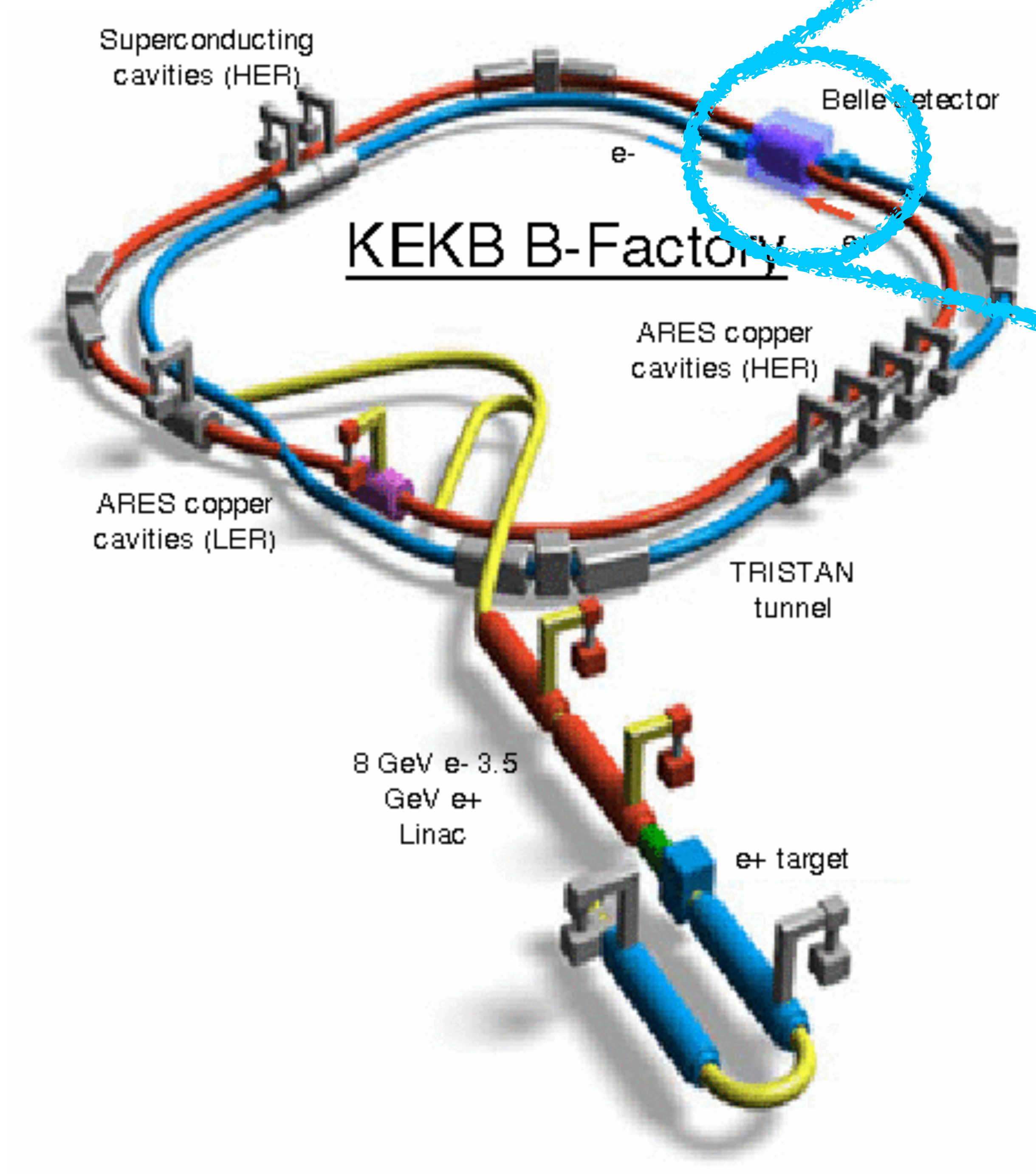
Thank you!

Appendices

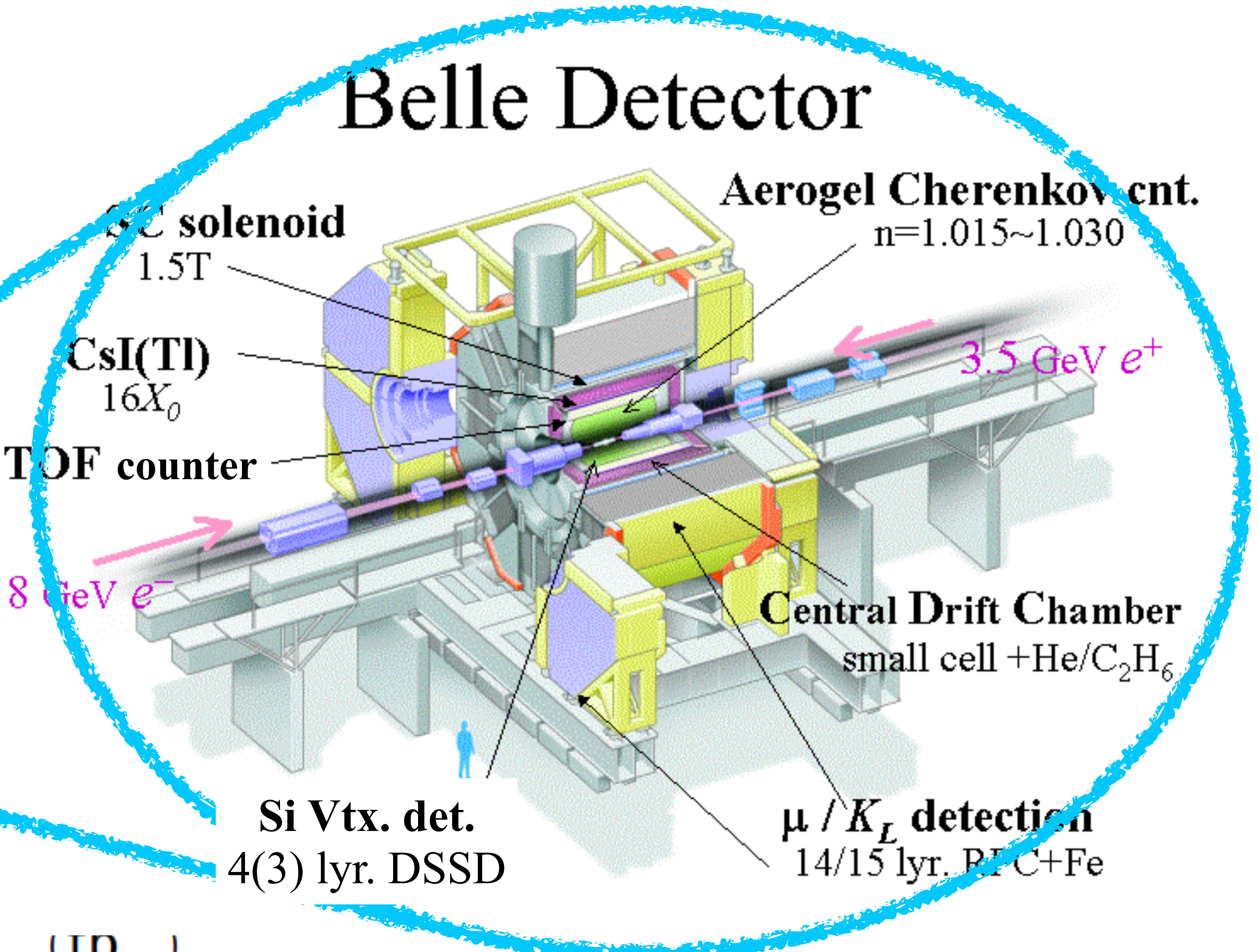
Appendix 0 The apparatuses

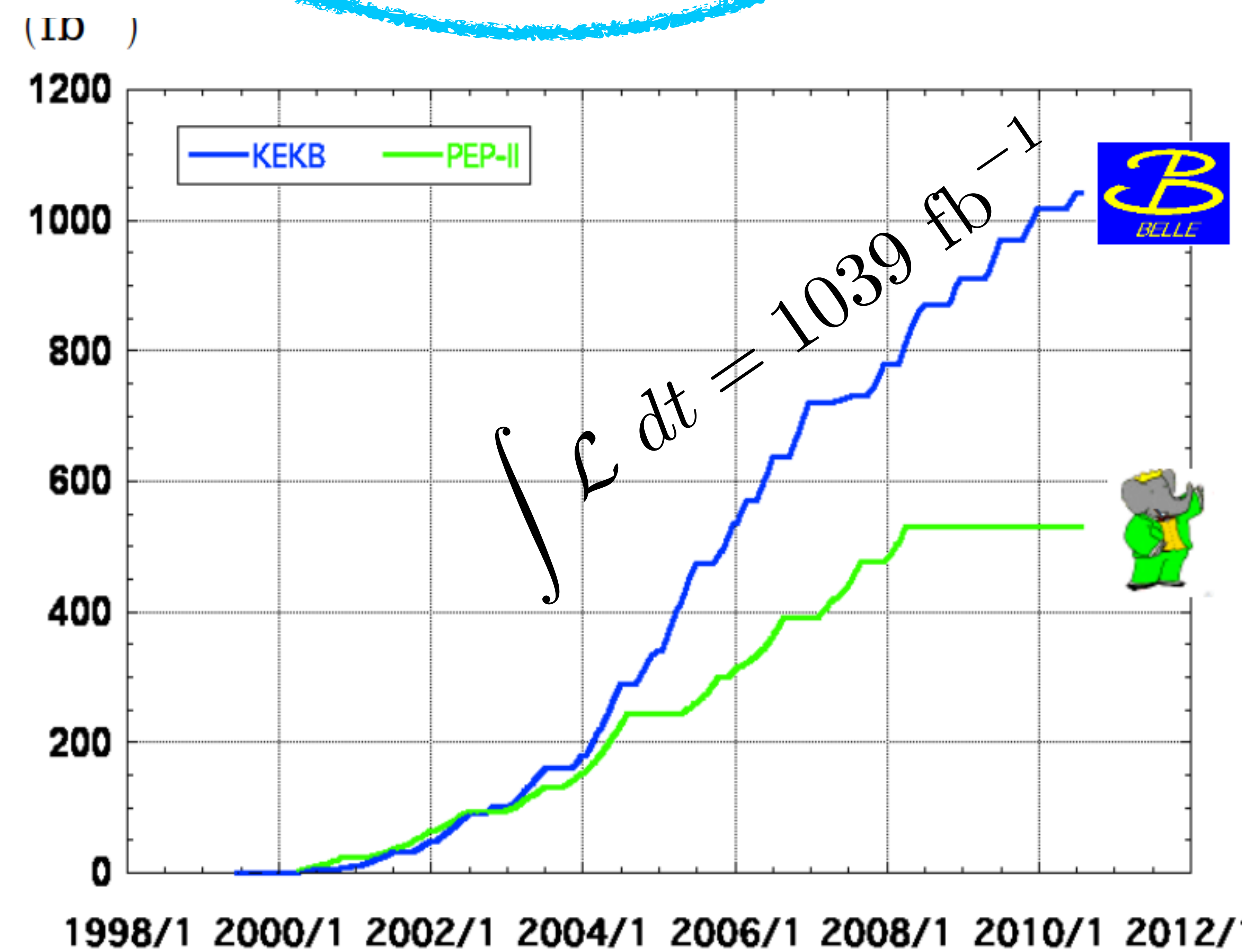
22 countries
100 institutions
~450 members

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



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



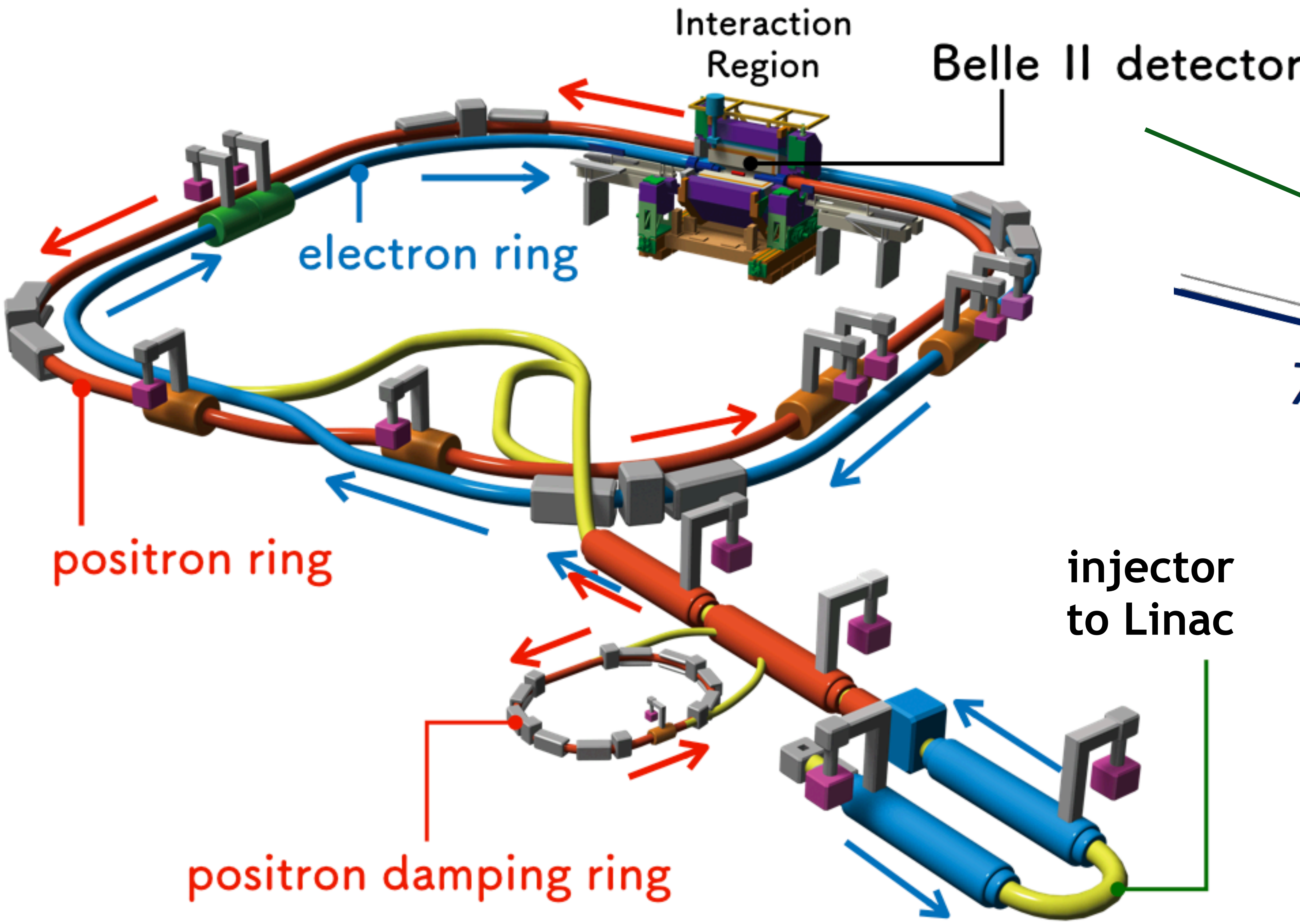


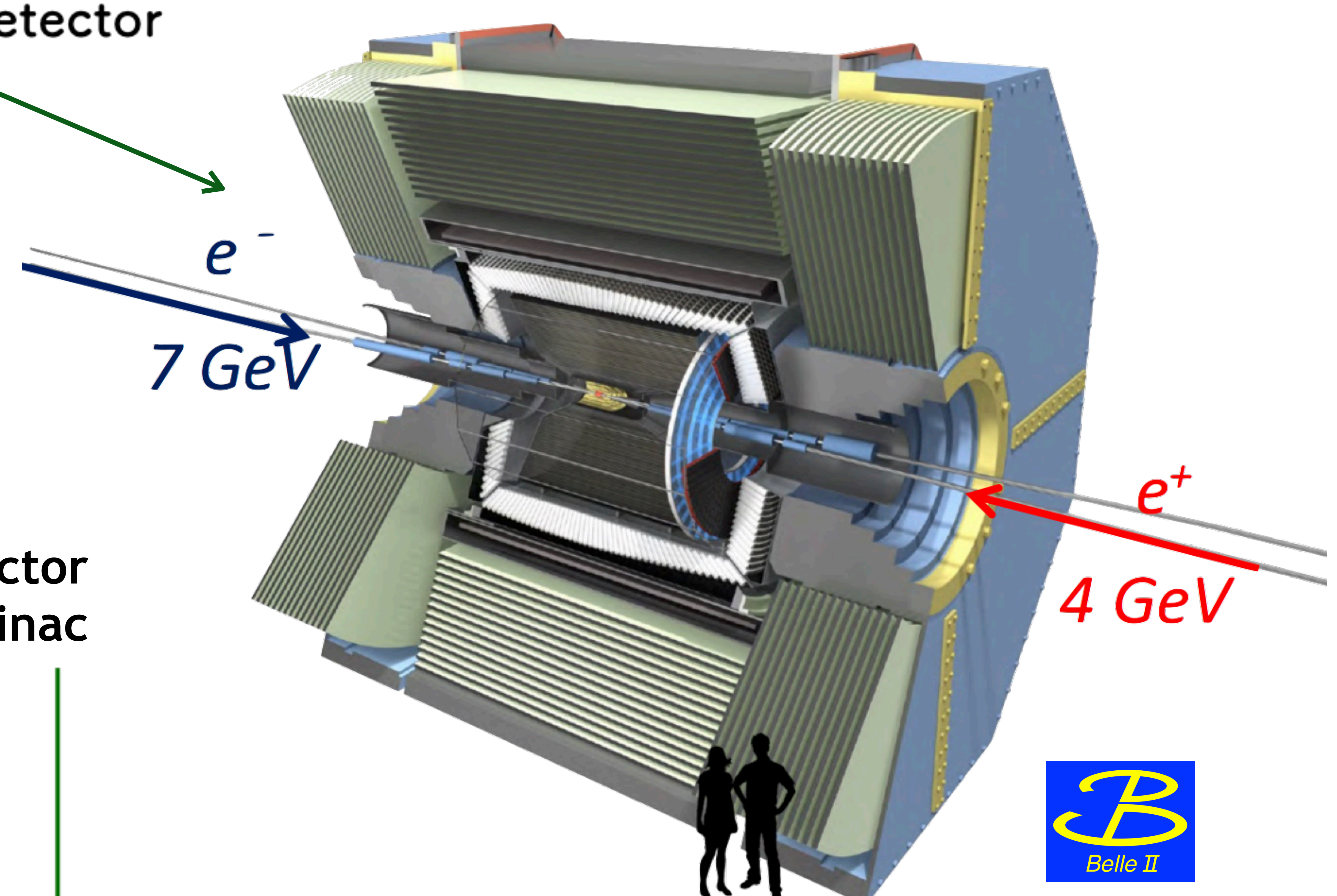
> 1 ab^{-1}
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 25 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

~ 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}

SuperKEKB

Belle II





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

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

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

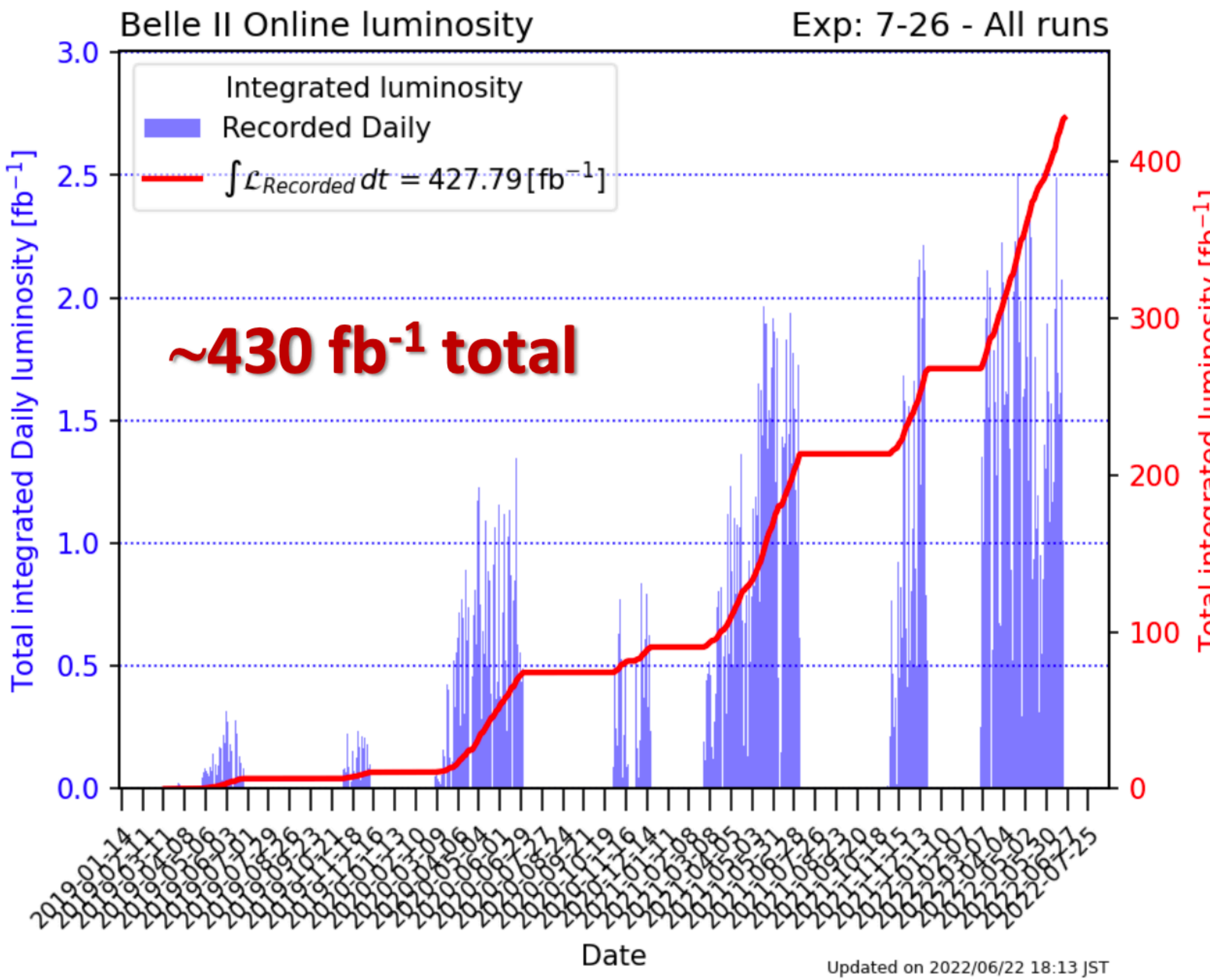
Belle II

Collected luminosity before LS1 (2019-2022)

Belle II has been in operation through the Pandemic era, with modified working mode in accordance with the anti-pandemic policy.

peak luminosity world record

$4.7 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

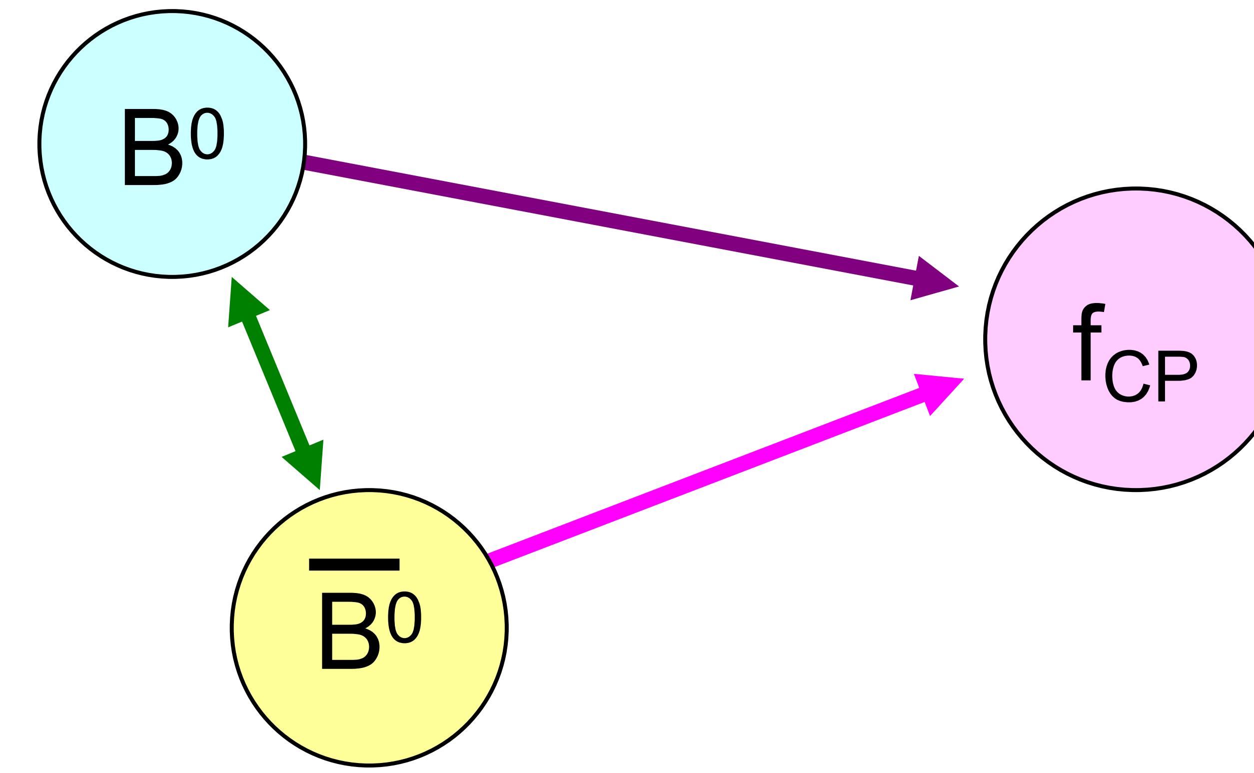


Appendix 1 time-dependent CPV in one slide

mixing-induced time-dependent CPV

Mixing-induced CP asymmetry of B mesons

- B^0 and $\overline{B}^0$ decay to a common CP eigenstate f_{CP}.
- CP violation appears as a decay time difference.



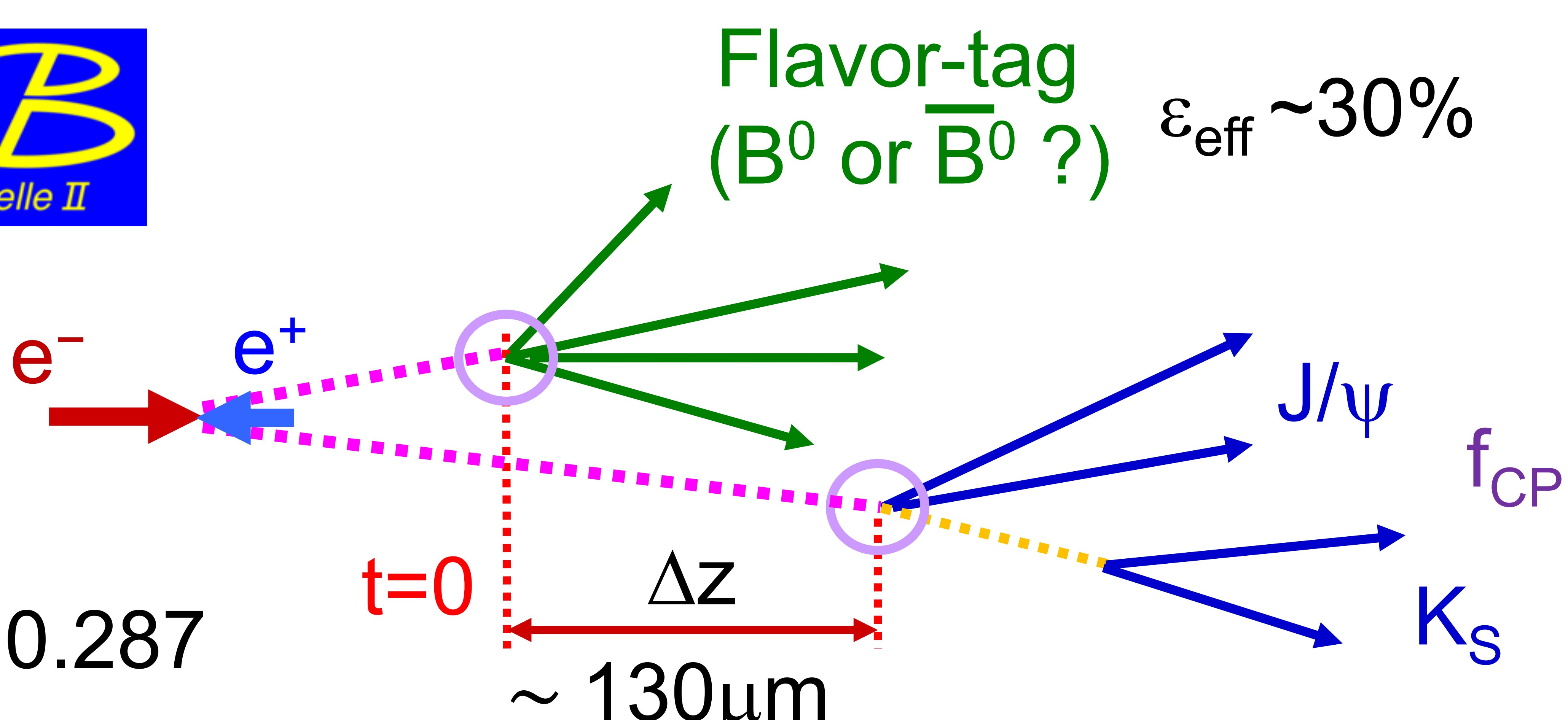
$$A_{CP}(\Delta t) = \frac{\Gamma(\overline{B}^0(\Delta t) \to f_{CP}) - \Gamma(B^0(\Delta t) \to f_{CP})}{\Gamma(\overline{B}^0(\Delta t) \to f_{CP}) + \Gamma(B^0(\Delta t) \to f_{CP})}$$

$$= S \sin(\Delta m \Delta t) + A \cos(\Delta m \Delta t)$$

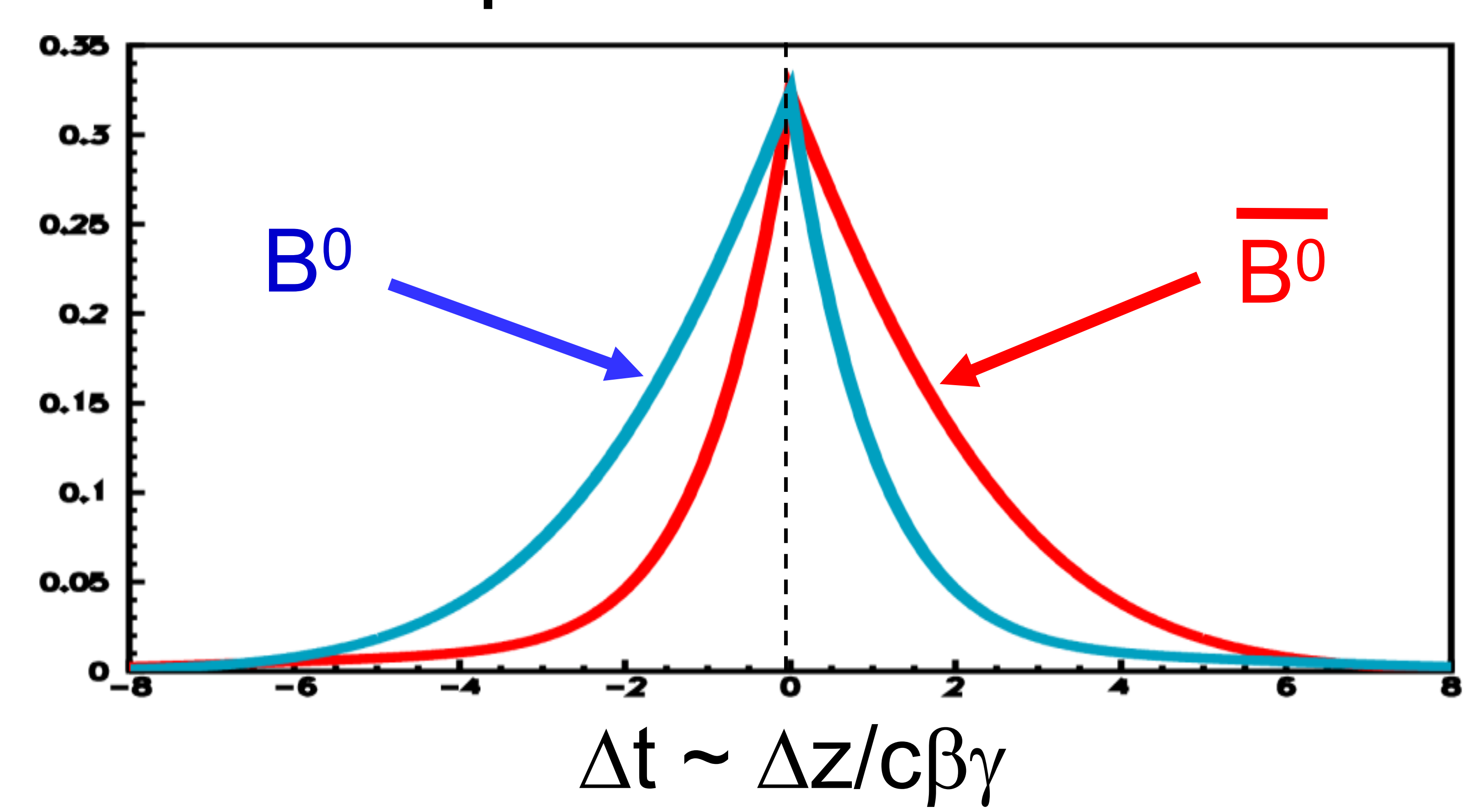
$S = -\xi \sin(2\phi_1)$ for $B \to J/\psi\, K_S$ $(\phi_1 = \beta)$

S : mixing induced CPV

A : direct CPV (=−C)



measure position instead of time



Appendix 2 Exclusive $B \to D^{(*)}\ell^+\nu$ for V_{cb}

$B \to D^* \ell^+ \nu$ shapes & $|V_{cb}|$

- Differential shapes (*normalized*) of $B \to D^* \ell^+ \nu$
  - as input to determine the non-perturbative form factor
  - once FF shape is known, it can be combined with L-QCD (or other methods) for the absolute normalization to determine $|V_{cb}|$

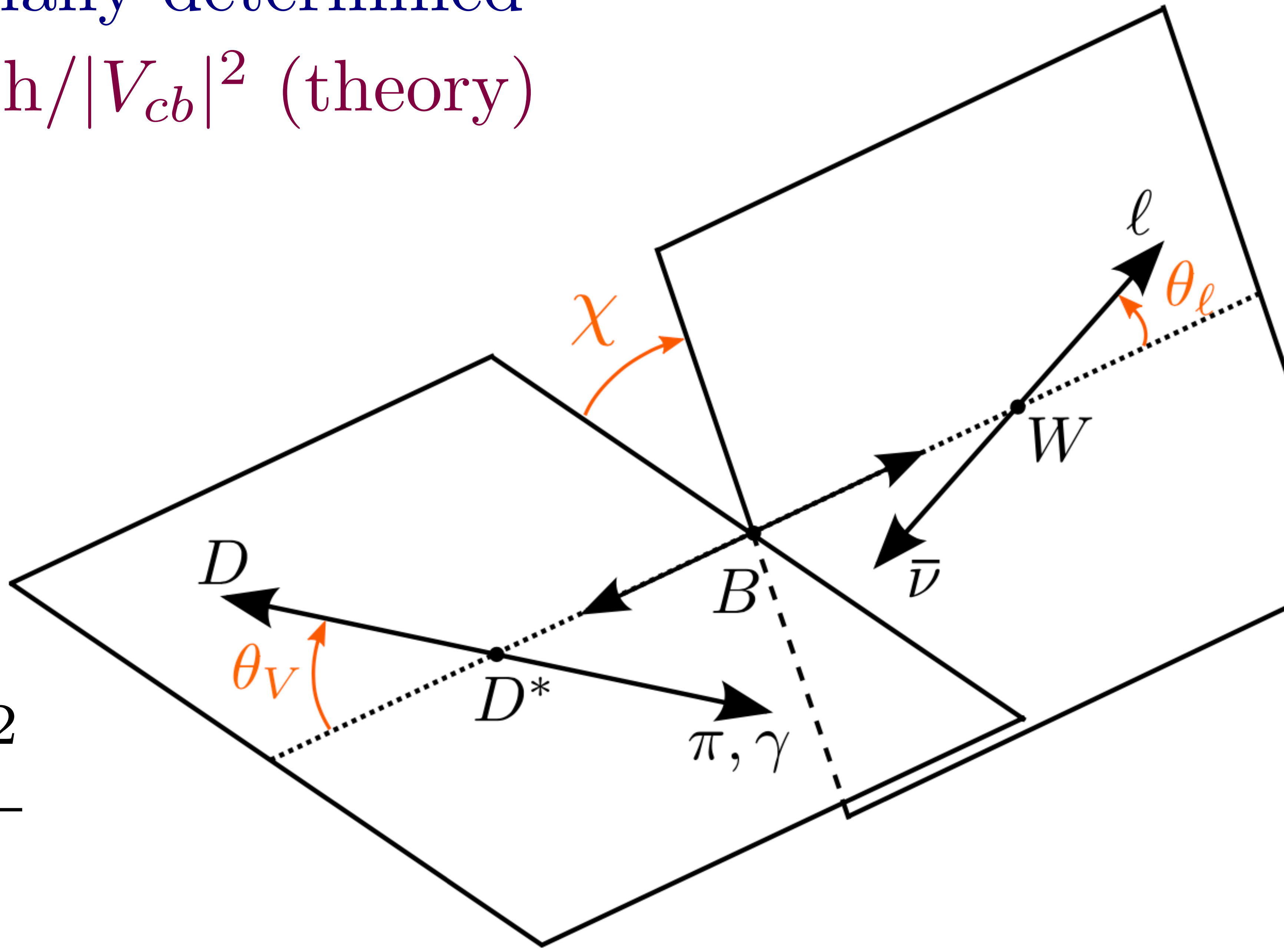
$$|V_{cb}| = \sqrt{\frac{\mathcal{B}(B \to D^* \ell \bar{\nu}_\ell)}{\tau_B \, \Gamma(B \to D^* \ell \bar{\nu}_\ell)}}$$

$\mathcal{B}$ – externally determined

Γ = decay width/$|V_{cb}|^2$ (theory)

  - use hadronic B-tagging via FEI
  - L-QCD at zero recoil ($w = 1$) is used for $|V_{cb}|$

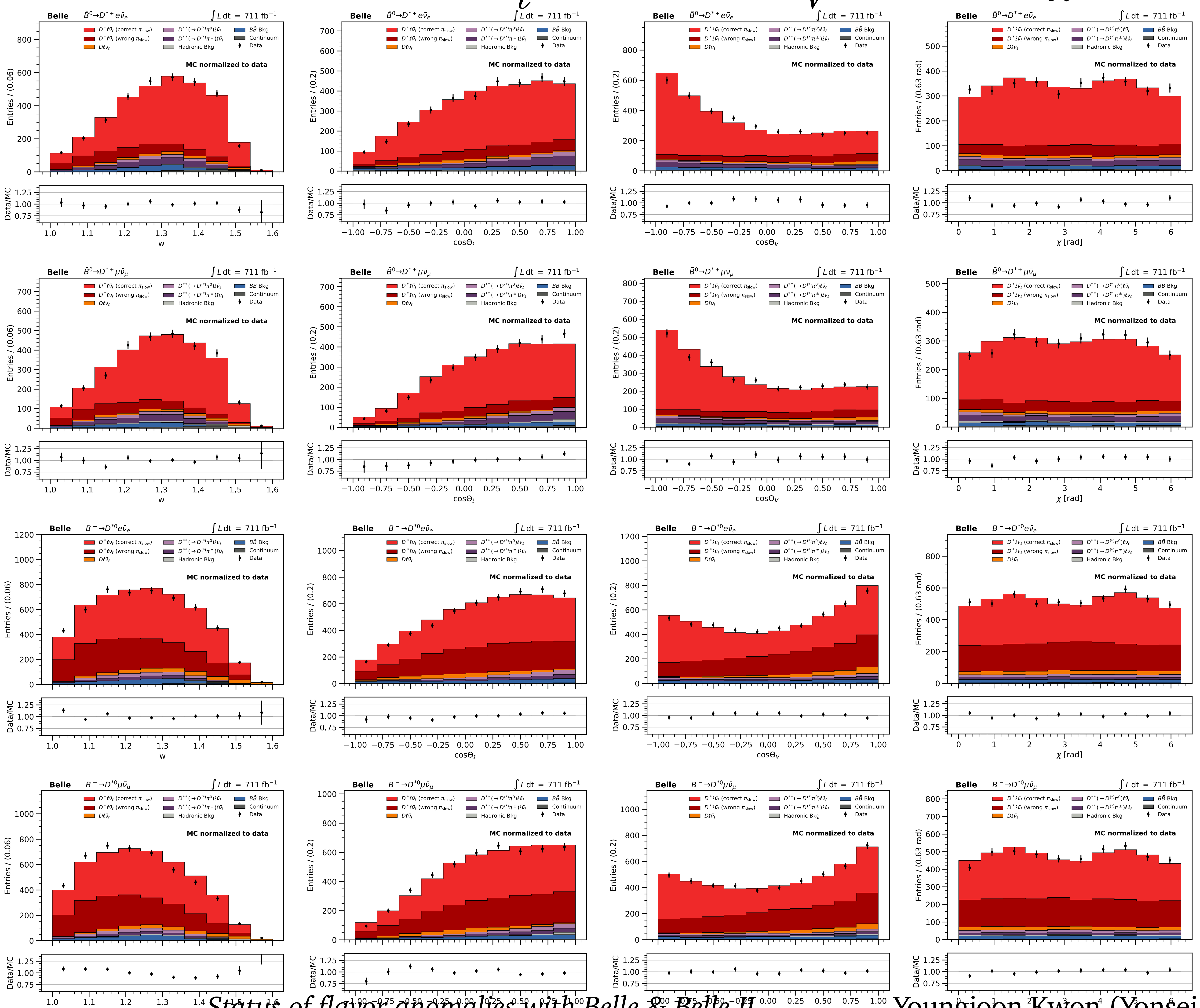
$$w = v \cdot v' = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$$



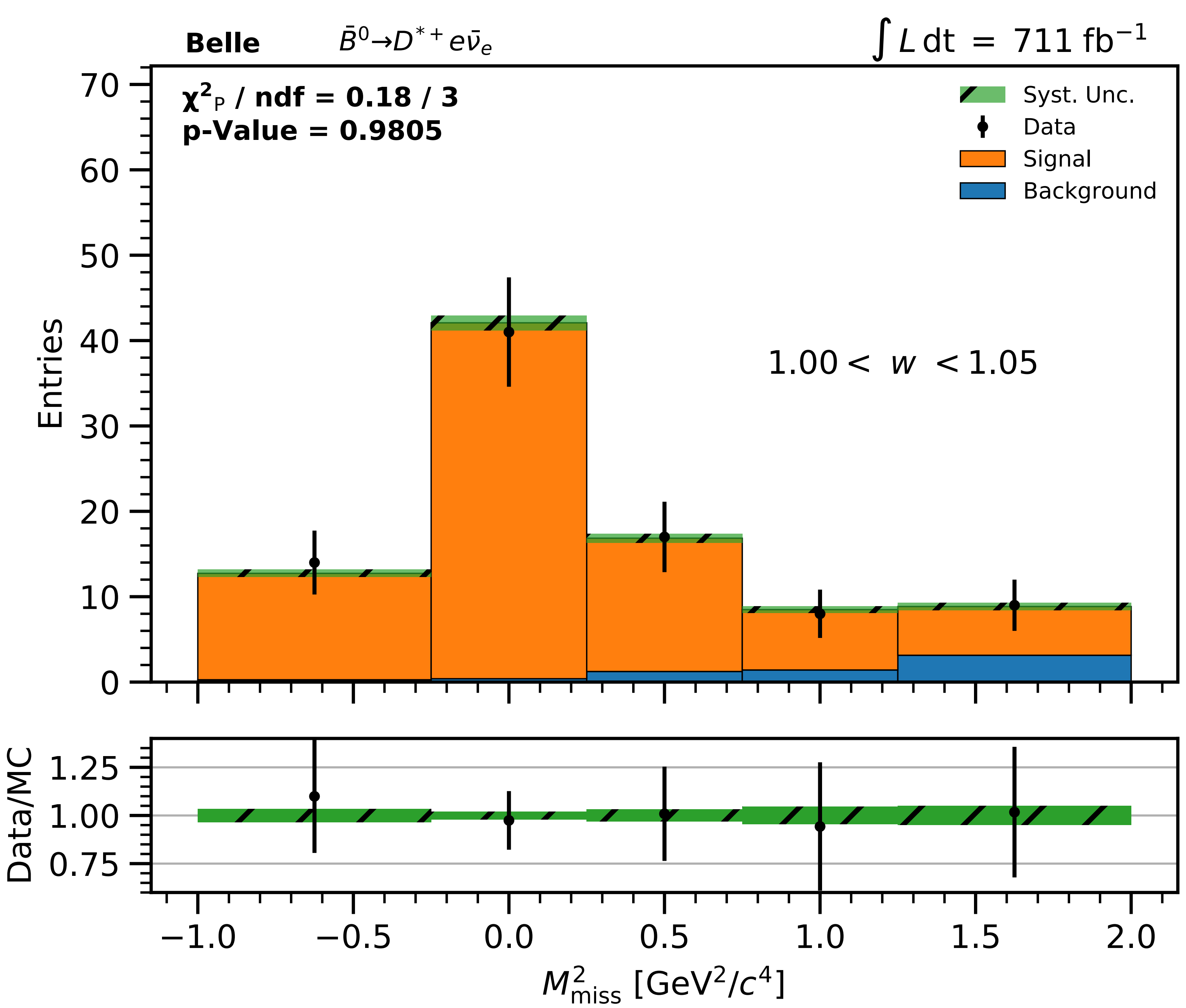
arXiv:2301.07529
submitted to PRD

$B \to D^* \ell^+ \nu$ shapes & $|V_{cb}|$

w | $\cos\theta_\ell$ | $\cos\theta_V$ | χ



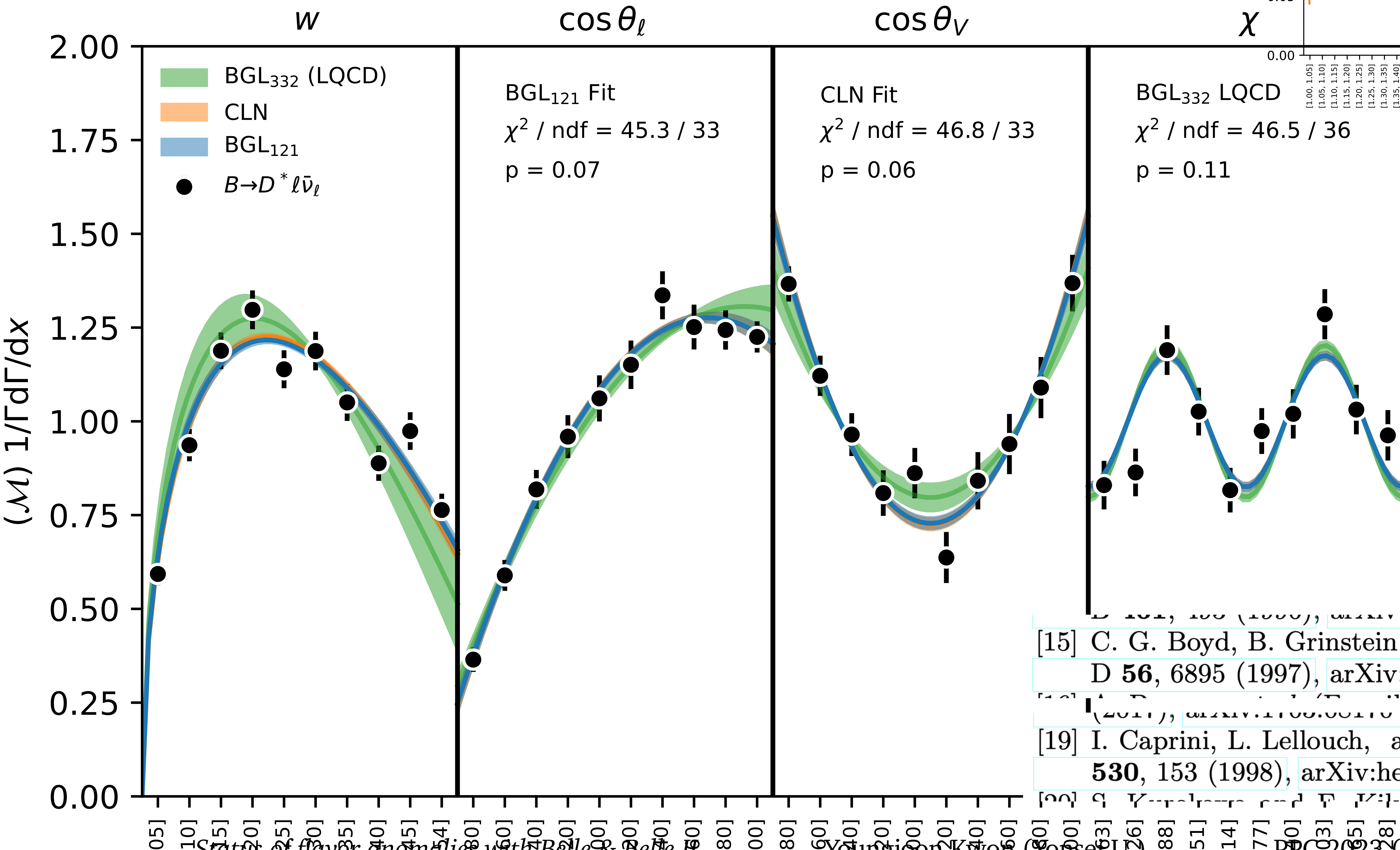
- Full correlations b/w the projections are also determined
- Bkgd. subtraction, with binned likelihood fits to $M^2_{\rm miss}$

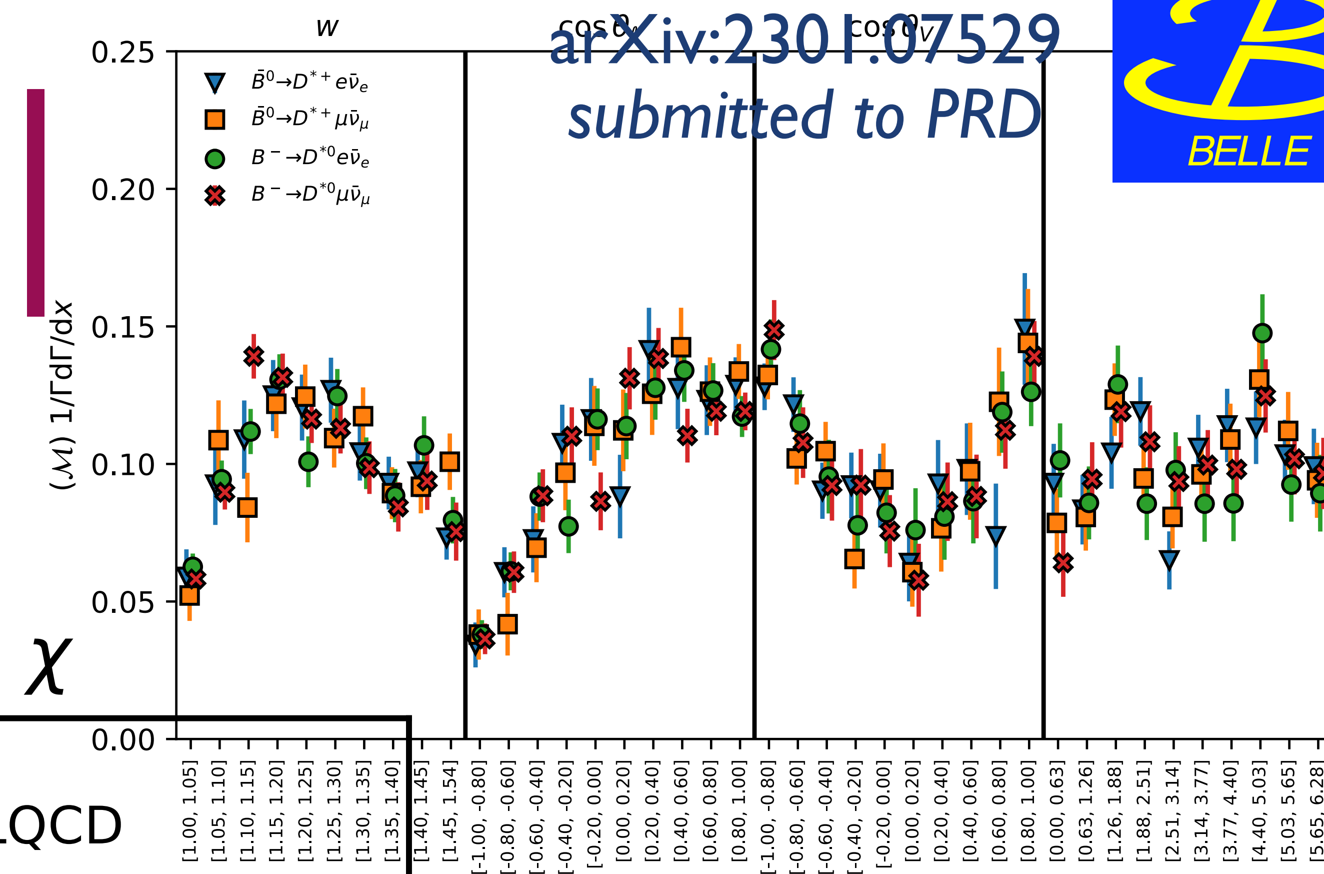


$B \to D^* \ell^+ \nu$ shapes & $|V_{cb}|$

arXiv:2301.07529
submitted to PRD

fitted shapes to BGL & CLN models



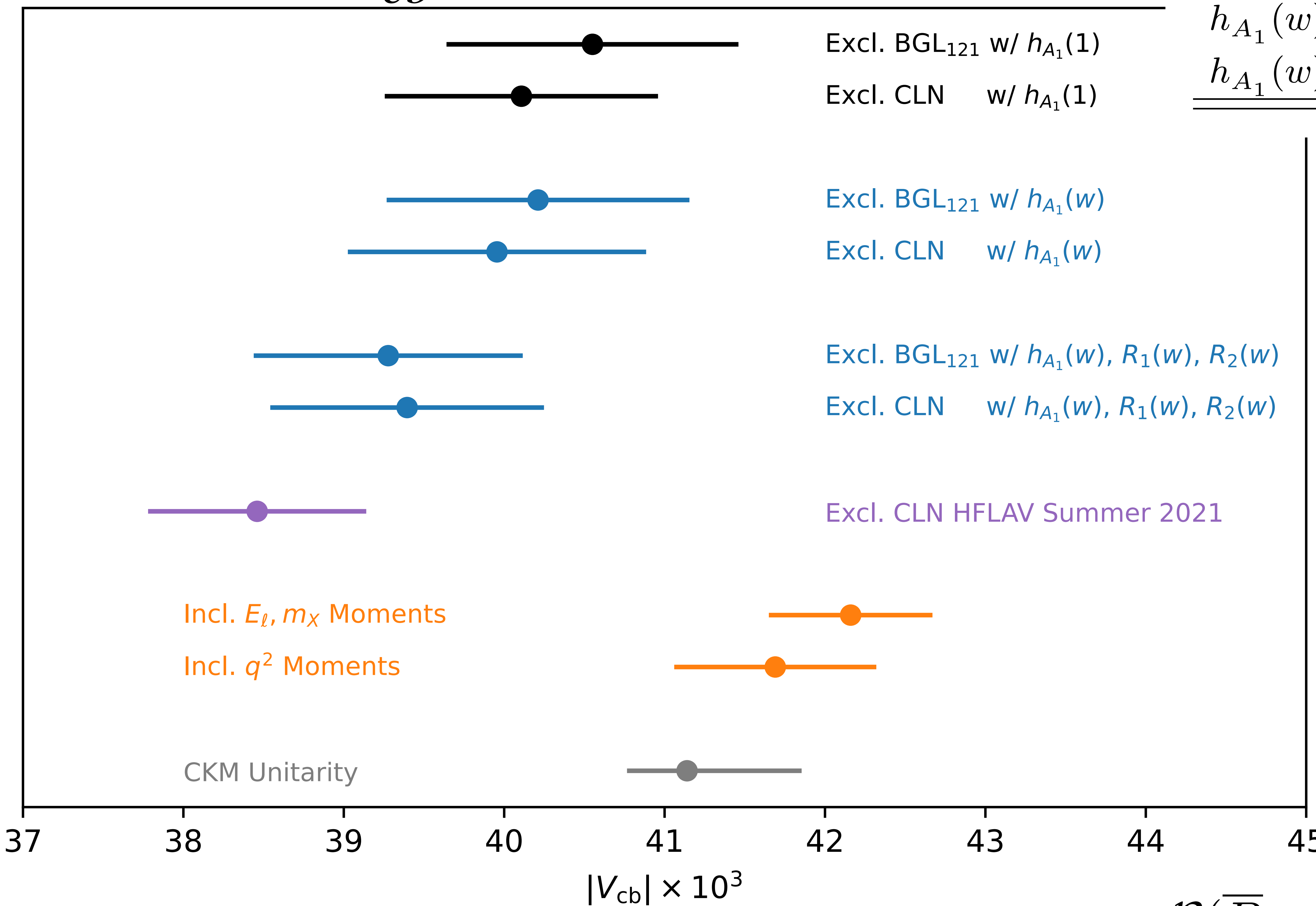


[15] C. G. Boyd, B. Grinstein, and R. F. Lebed, Phys. Rev. D **56**, 6895 (1997), arXiv:hep-ph/9705252.

[19] I. Caprini, L. Lellouch, and M. Neubert, Nucl. Phys. B **530**, 153 (1998), arXiv:hep-ph/9712417.

$B \to D^* \ell^+ \nu$ shapes & $|V_{cb}|$

$|V_{cb}|$ and other results



	BGL_{121}	CLN
$h_{A_1}(1)$	40.6 ± 0.9	40.1 ± 0.9
$h_{A_1}(w)$	40.2 ± 0.9	40.0 ± 0.9
$h_{A_1}(w),\ R_1(w),\ R_2(w)$	39.3 ± 0.8	39.4 ± 0.9

$$\Delta A_{\mathrm{FB}} = A_{\mathrm{FB}}^{\mu} - A_{\mathrm{FB}}^{e}$$

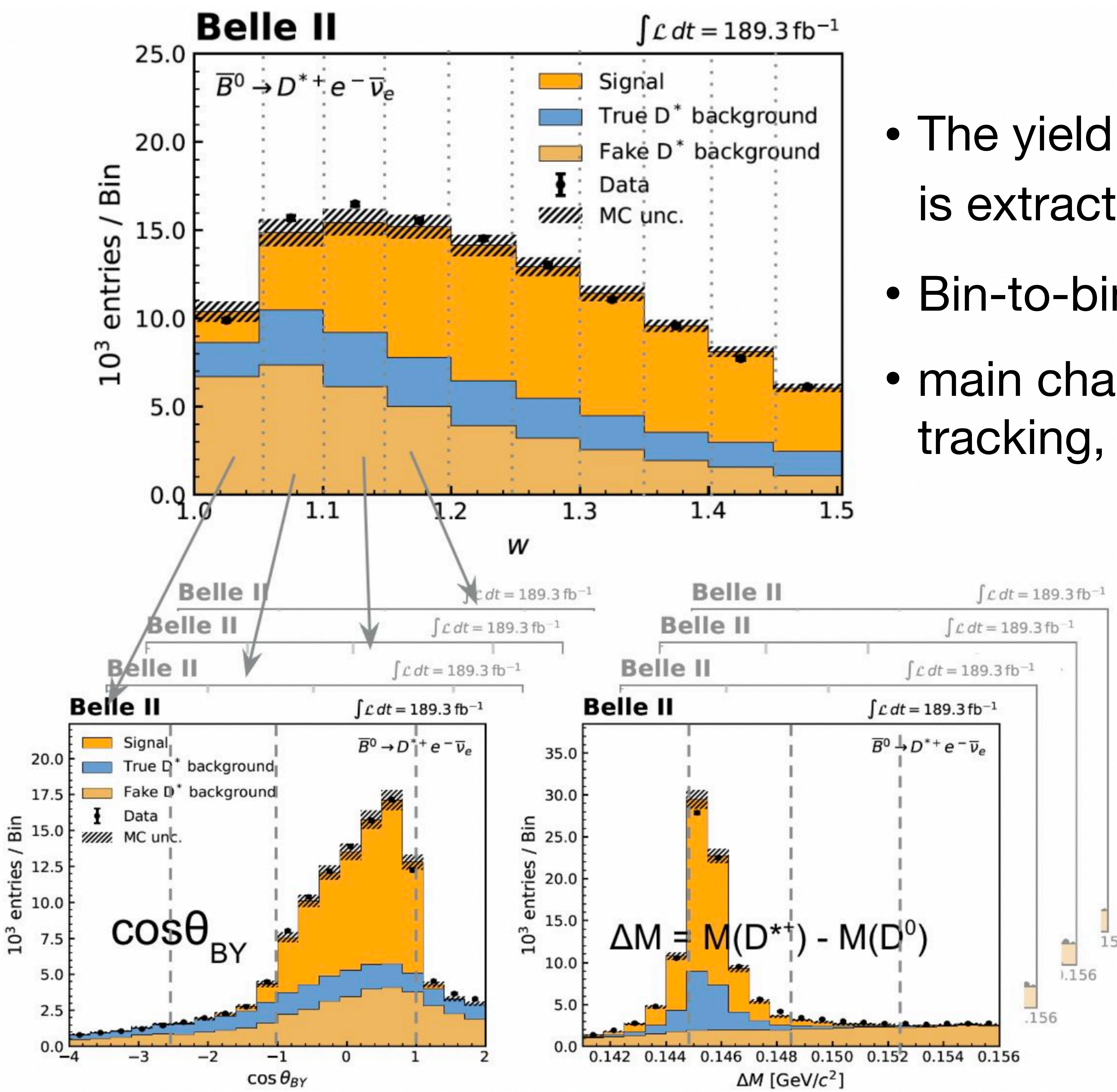
	ΔA_{FB}
$\bar{B}^0 \to D^{*+} \ell \bar{\nu}_\ell$	$0.062 \pm 0.044 \pm 0.011$
$B^- \to D^{*0} \ell \bar{\nu}_\ell$	$-0.003 \pm 0.033 \pm 0.009$
$B \to D^* \ell \bar{\nu}_\ell$	$0.022 \pm 0.026 \pm 0.007$

$$\Delta F_L = F_L^{\mu} - F_L^{e}$$

	$\Delta F_L^{D^*}$
$\bar{B}^0 \to D^{*+} \ell \bar{\nu}_\ell$	$0.032 \pm 0.033 \pm 0.010$
$B^- \to D^{*0} \ell \bar{\nu}_\ell$	$0.025 \pm 0.035 \pm 0.010$
$B \to D^* \ell \bar{\nu}_\ell$	$0.034 \pm 0.024 \pm 0.007$

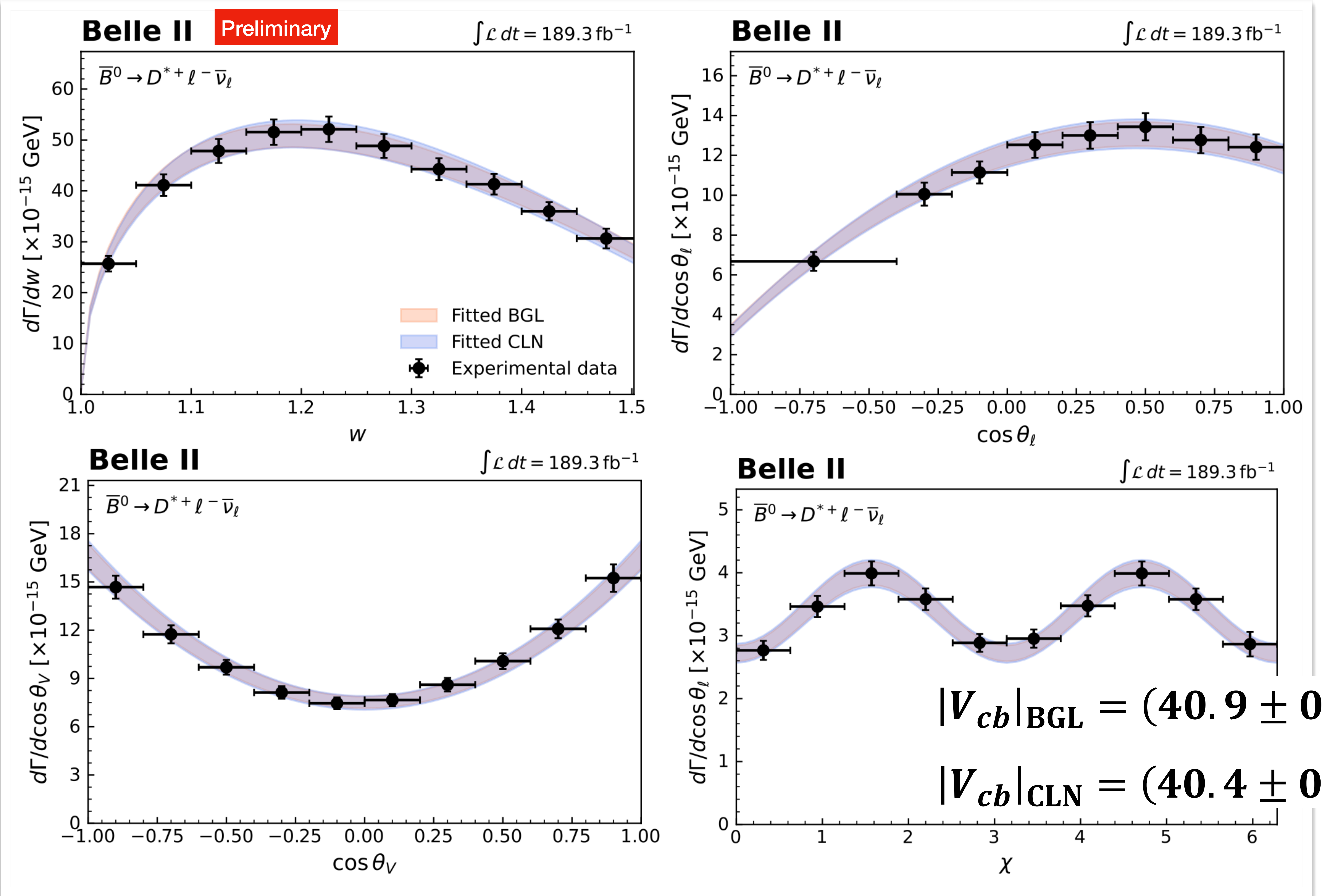
$$R_{e/\mu} = \frac{\mathcal{B}(\overline{B} \to D^* e \bar{\nu}_e)}{\mathcal{B}(\overline{B} \to D^* \mu \bar{\nu}_\mu)} = 0.990 \pm 0.021 \pm 0.023$$

$B \to D^* \ell^+ \nu$ shapes & $|V_{cb}|$ from Belle II



- The yield in 10 (8) bin of w and the three cosine angles is extracted by fitting $\cos\theta_{BY}$ and ΔM for D^*
- Bin-to-bin migration is corrected with SVD unfolding
- main challenges: background modeling, slow-pion tracking, and stat. correlations b/w bins

$B \to D^* \ell^+ \nu$ shapes & $|V_{cb}|$ from Belle II

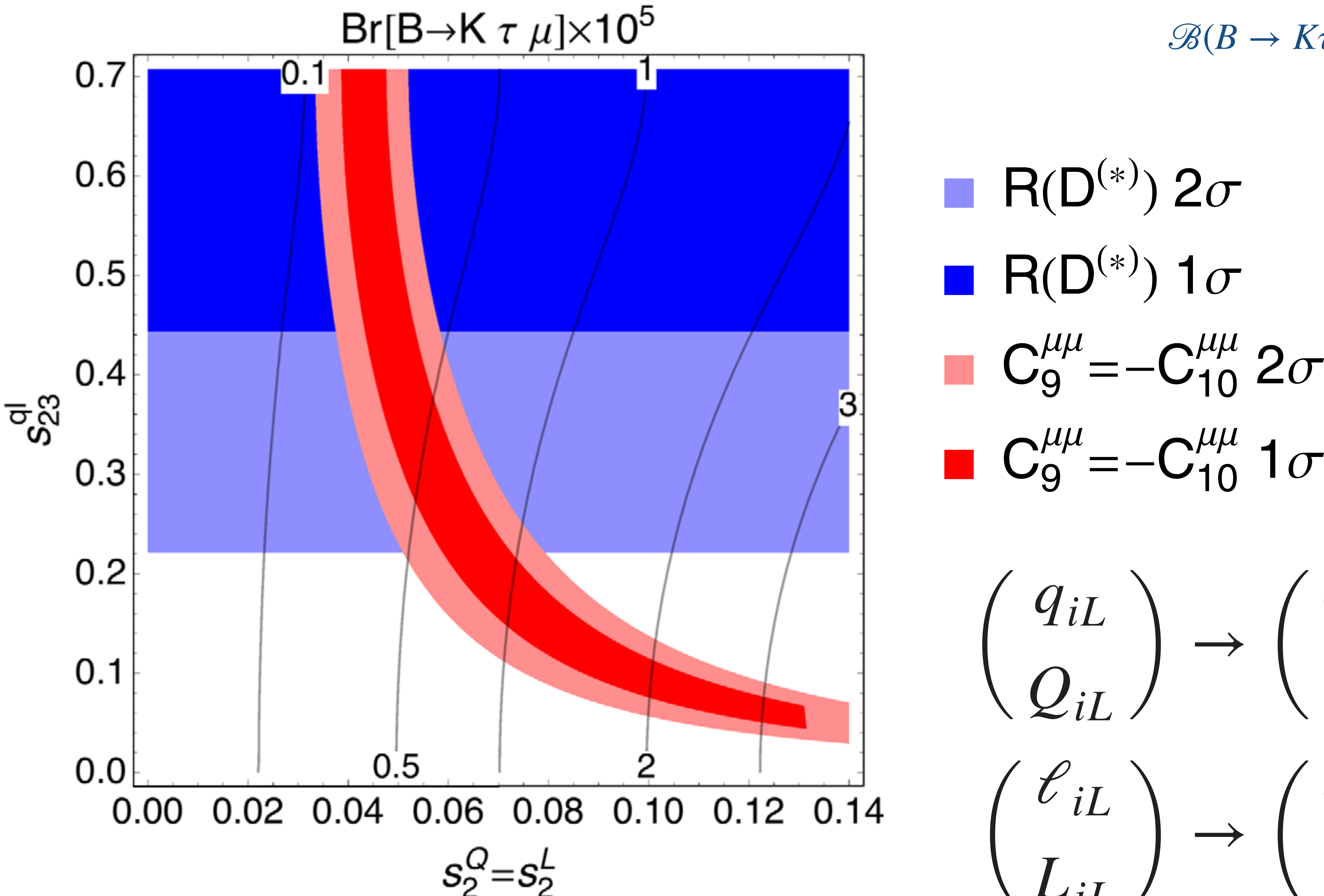


$$|V_{cb}|_{\mathrm{BGL}} = (40.9 \pm 0.3 \pm 1.0 \pm 0.6)\times 10^{-3}$$

(QCD input)

$$|V_{cb}|_{\mathrm{CLN}} = (40.4 \pm 0.3 \pm 1.0 \pm 0.6)\times 10^{-3}$$

$B^+ \to K^+\tau^\pm\ell^\mp$ theory motivation



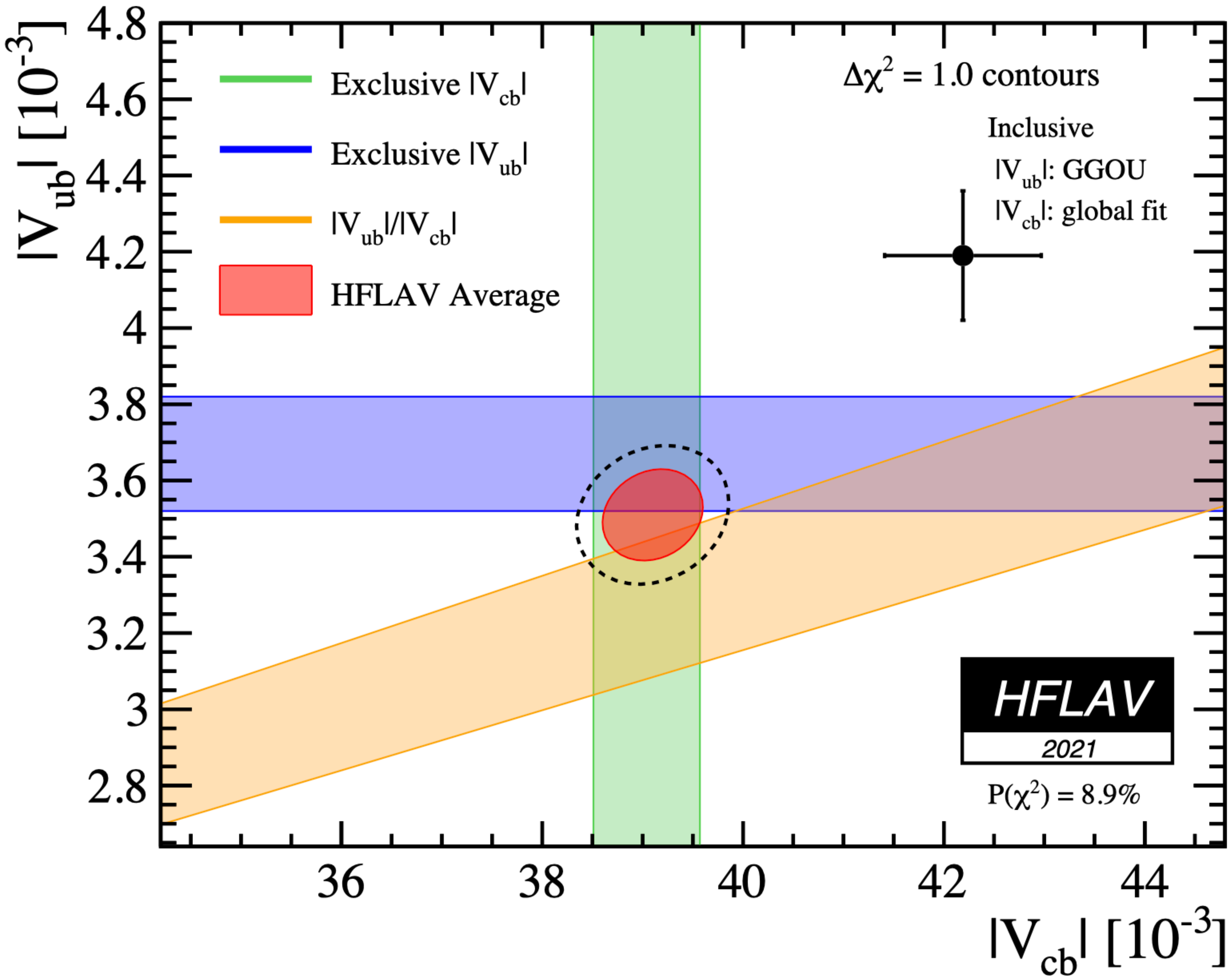
$\mathscr{B}(B \to K\tau\mu) \sim \mathscr{O}(10^{-6})$ is preferred in a certain VLQ model, for instance.

Calibbi, Crivellin, Li

PHYS. REV. D **98,** 115002 (2018)

$$\begin{pmatrix} q_{iL} \\ Q_{iL} \end{pmatrix} \to \begin{pmatrix} c_{iQ} & -s_{iQ} \\ s_{iQ} & c_{iQ} \end{pmatrix} \begin{pmatrix} q_{iL} \\ Q_{iL} \end{pmatrix}$$

$$\begin{pmatrix} \ell_{iL} \\ L_{iL} \end{pmatrix} \to \begin{pmatrix} c_{iL} & -s_{iL} \\ s_{iL} & c_{iL} \end{pmatrix} \begin{pmatrix} \ell_{iL} \\ L_{iL} \end{pmatrix}.$$



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

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

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

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

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