B-anomalies (experimental)

Youngjoon Kwon
Yonsei University

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REVIEW

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A challenge to lepton universality in *B*-meson decays

Gregory Ciezarek[1], Manuel Franco Sevilla[2], Brian Hamilton[3], Robert Kowalewski[4], Thomas Kuhr[5], Vera Lüth[6] & Yutaro Sato[7]

One of the key assumptions of the standard model of particle physics is that the interactions of the charged leptons, namely electrons, muons and taus, differ only because of their different masses. Whereas precision tests comparing processes

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Model of particle physics, confirr

By Clara Moskowitz | September 9, 2

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Democracy suffers a blow—in particle physics

Three independent B-meson experiments suggest that the charged leptons may not be so equal after all.

Outline

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

Mini-workshop on missing particle signatures and new physics at Belle II and LHCb

Jul 5 – 6, 2021

Europe/Berlin timezone

Overview
Timetable
Contribution List
Registration
Participant List
Organizing committee

Participant List

185 participants

First Name		
Abhijit		
Abner		
Alessandra		
Alessandro		
Alexander	Ward	Warwick, Monash, LHCb
Alexey	Petrov	Wayne State University

The organizers

Abi Soffer (Belle II)

Patrick Koppenburg (LHCb)

Youngjoon Kwon (Belle II)

Pyungwon Ko (theory)

Sebastien Descotes-Genon (theory)

Belle II Physics Mind-map

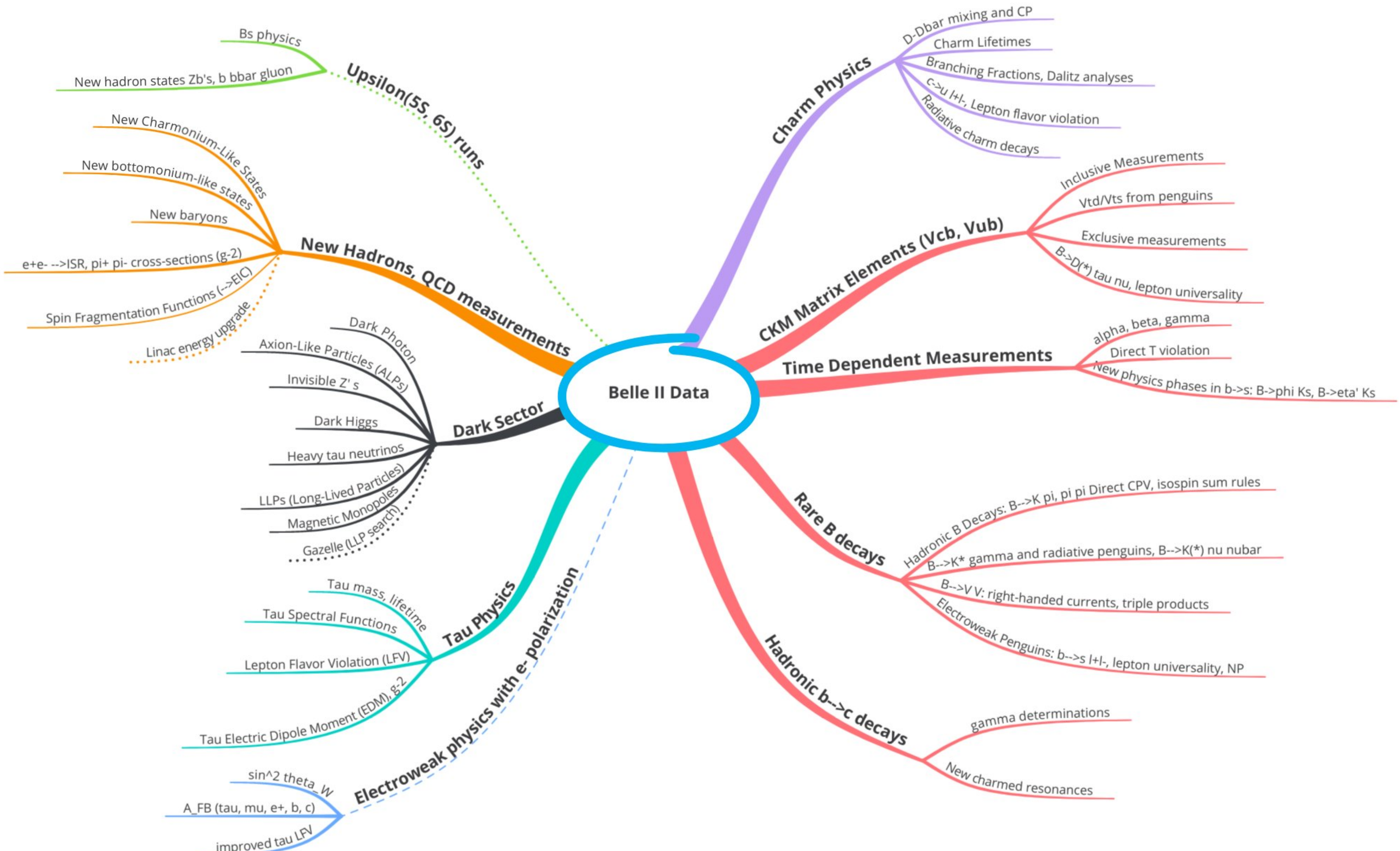


Image courtesy of Tom Browder

Belle II Physics Mind-map

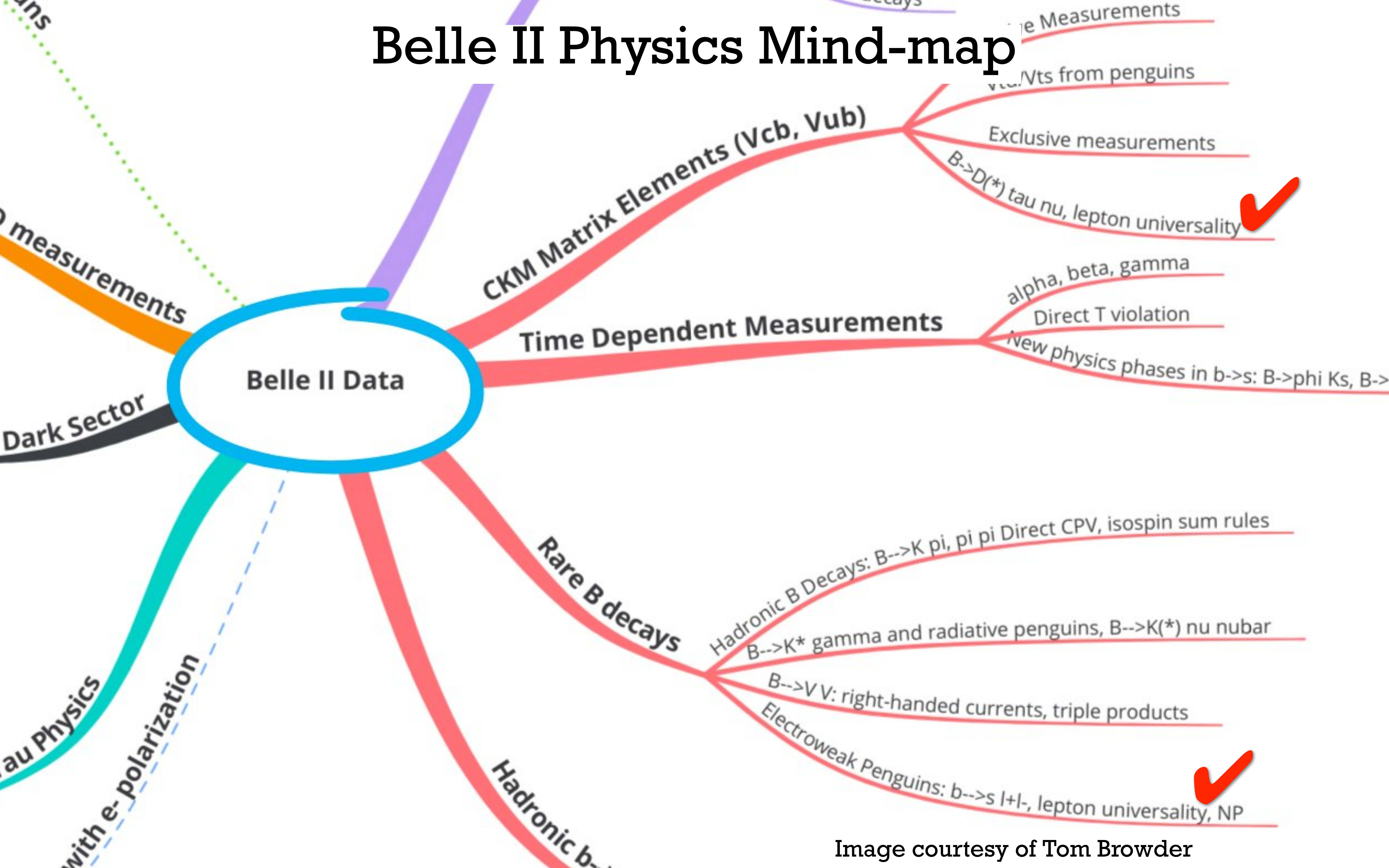
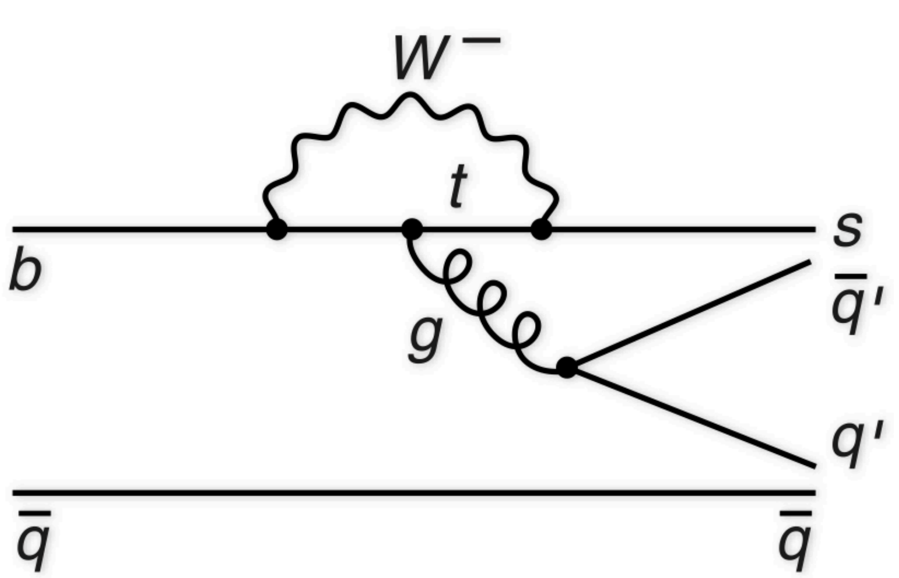
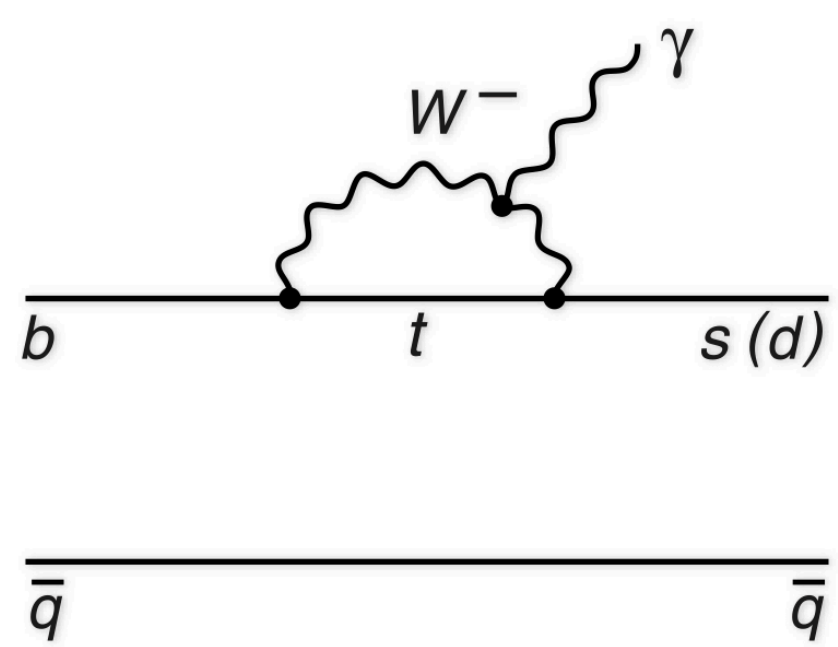


Image courtesy of Tom Browder

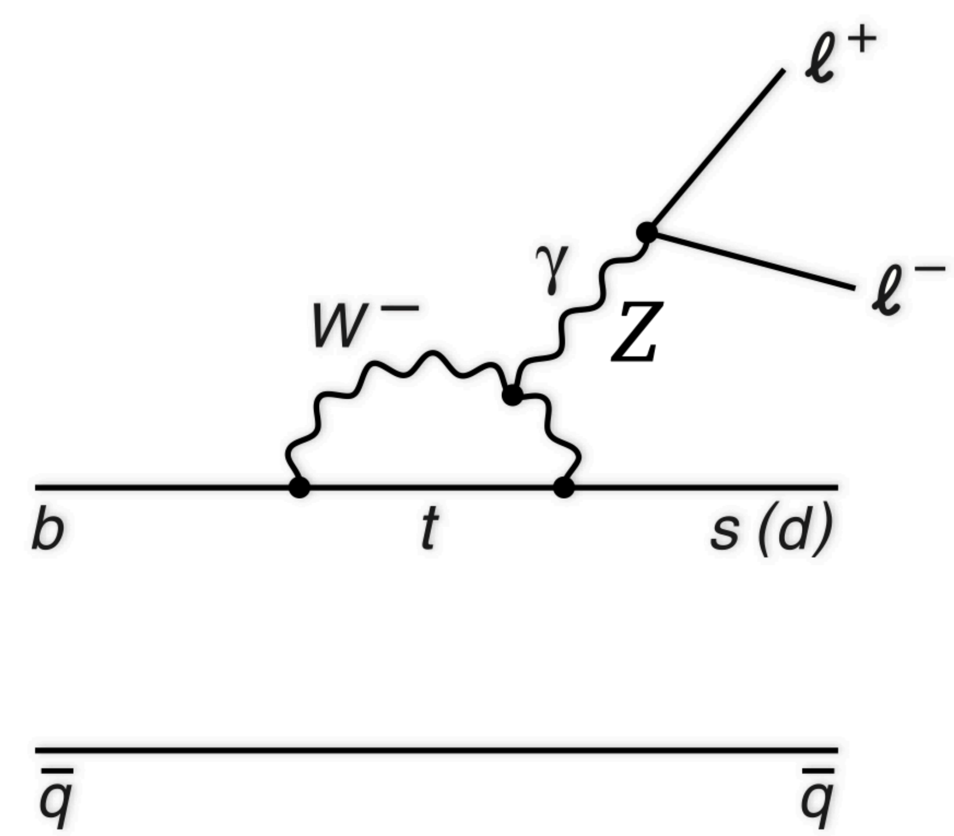
B-anomaly in EWP



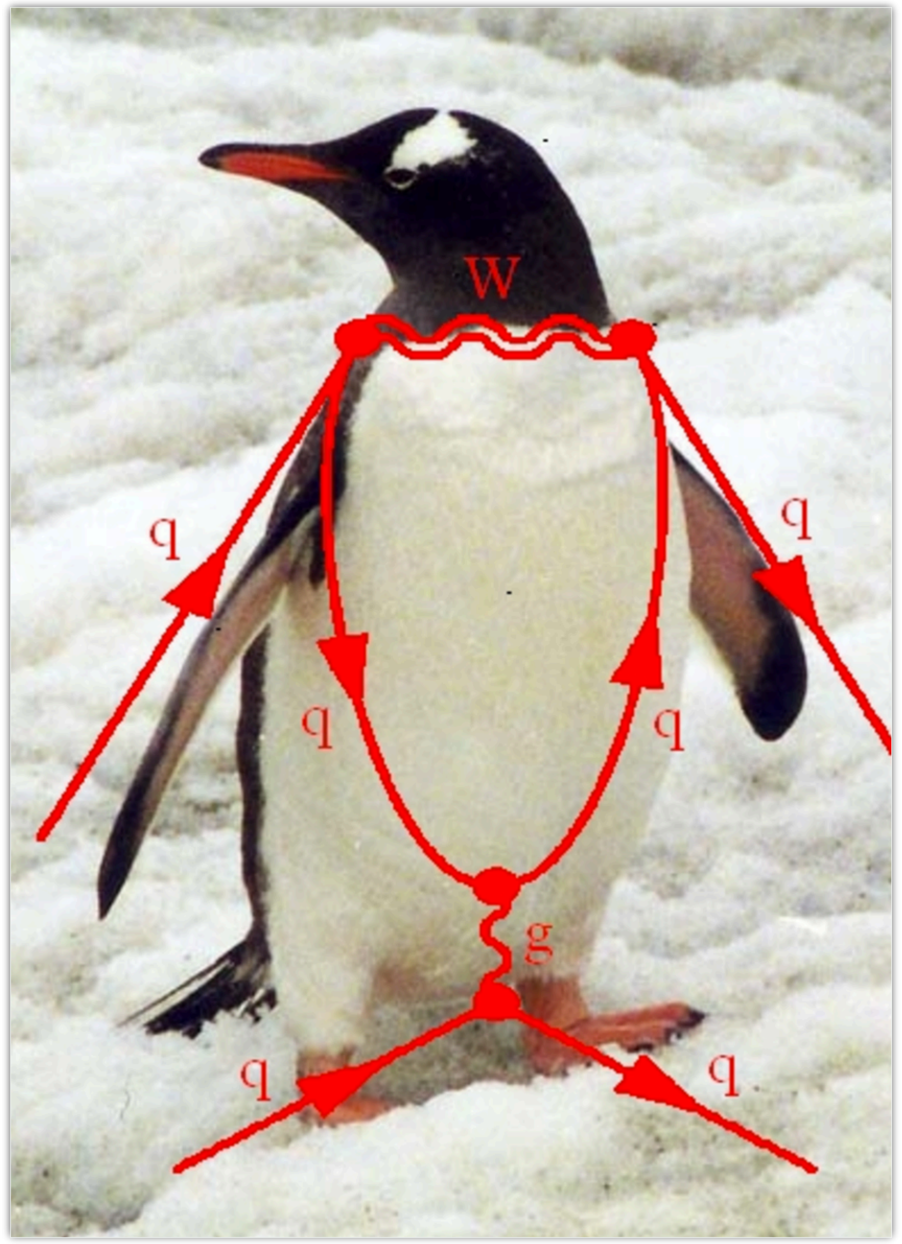
(e) Gluonic penguin



(f) EM penguin



(g) EW penguin



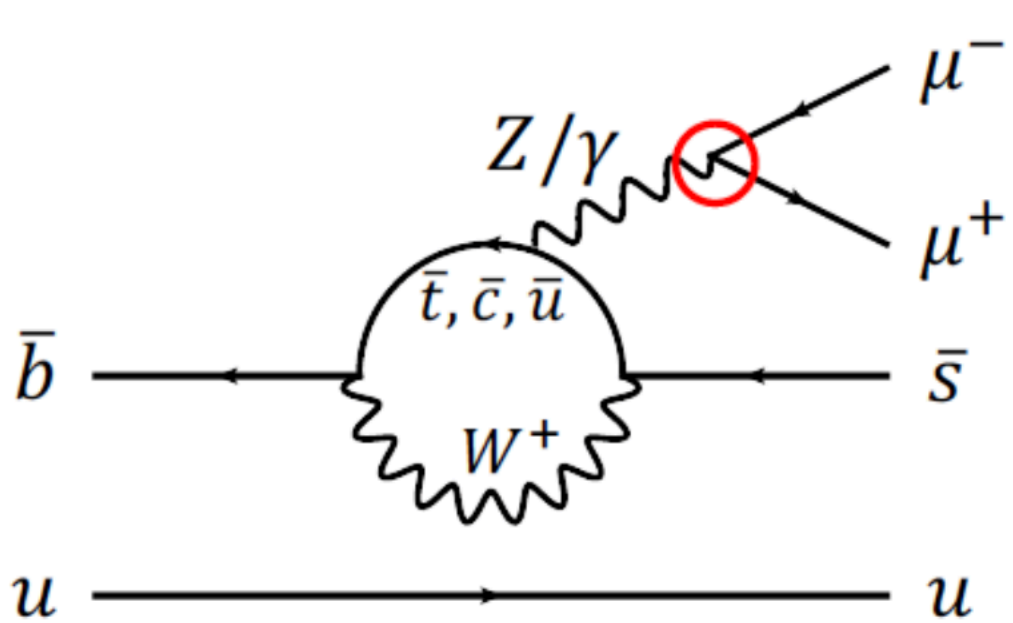
The *B*-anomalies in EWP

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

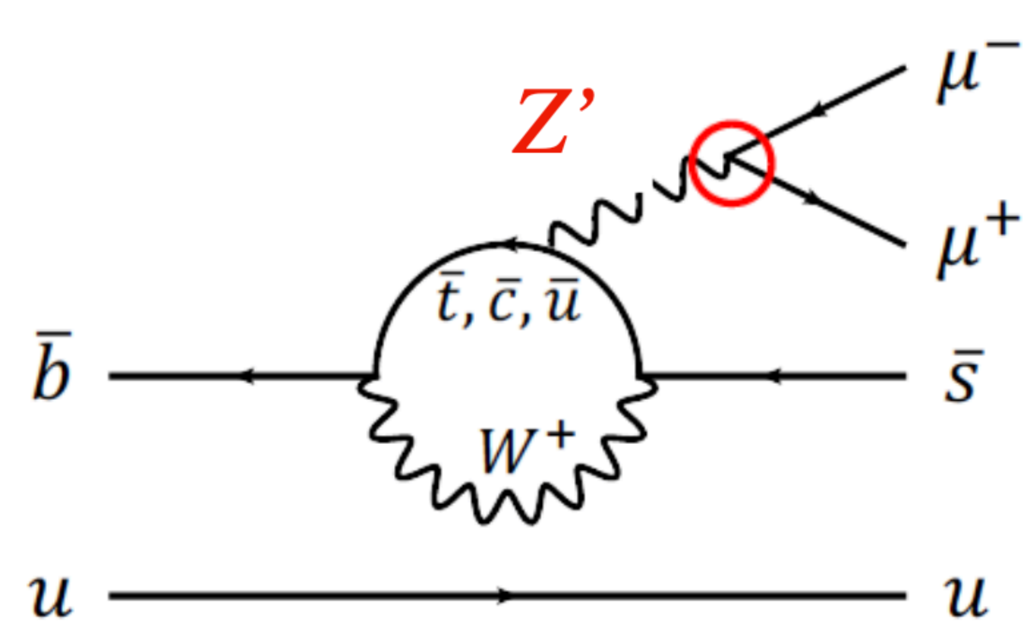
$$\Rightarrow R_{K^{(*)}}^{\text{SM}} \equiv \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \approx 1$$

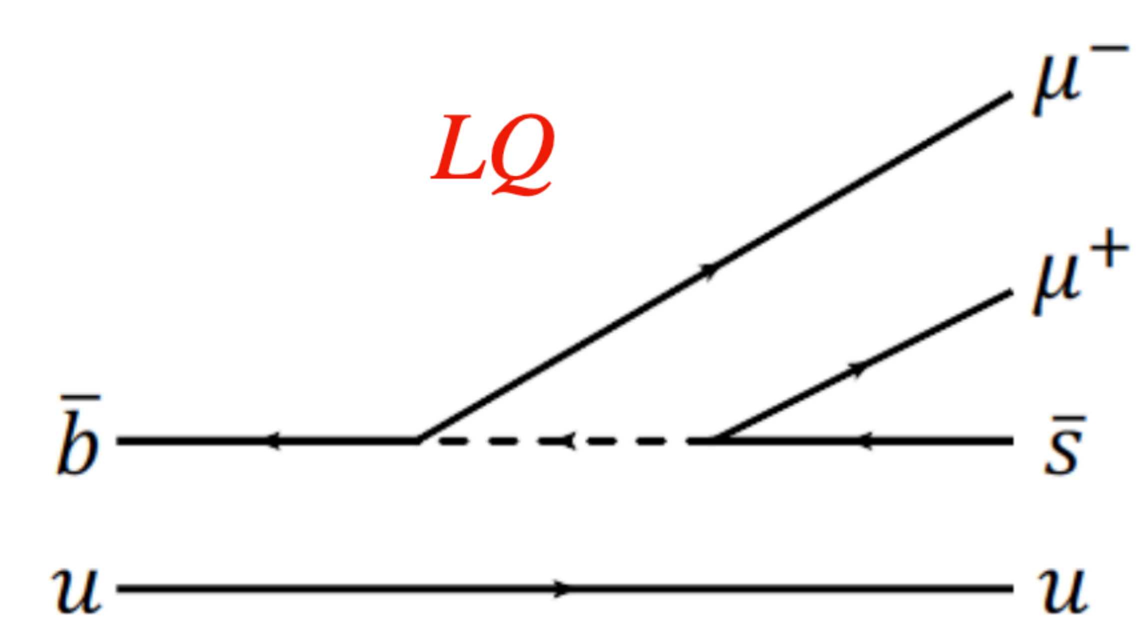
- *B*-anomalies in EWP
  - R_K and R_{K*}, measured by LHCb, seem to be far less than 1
  - a discrepancy (with the SM) in some angular observable

SM



Possible NP interpretations

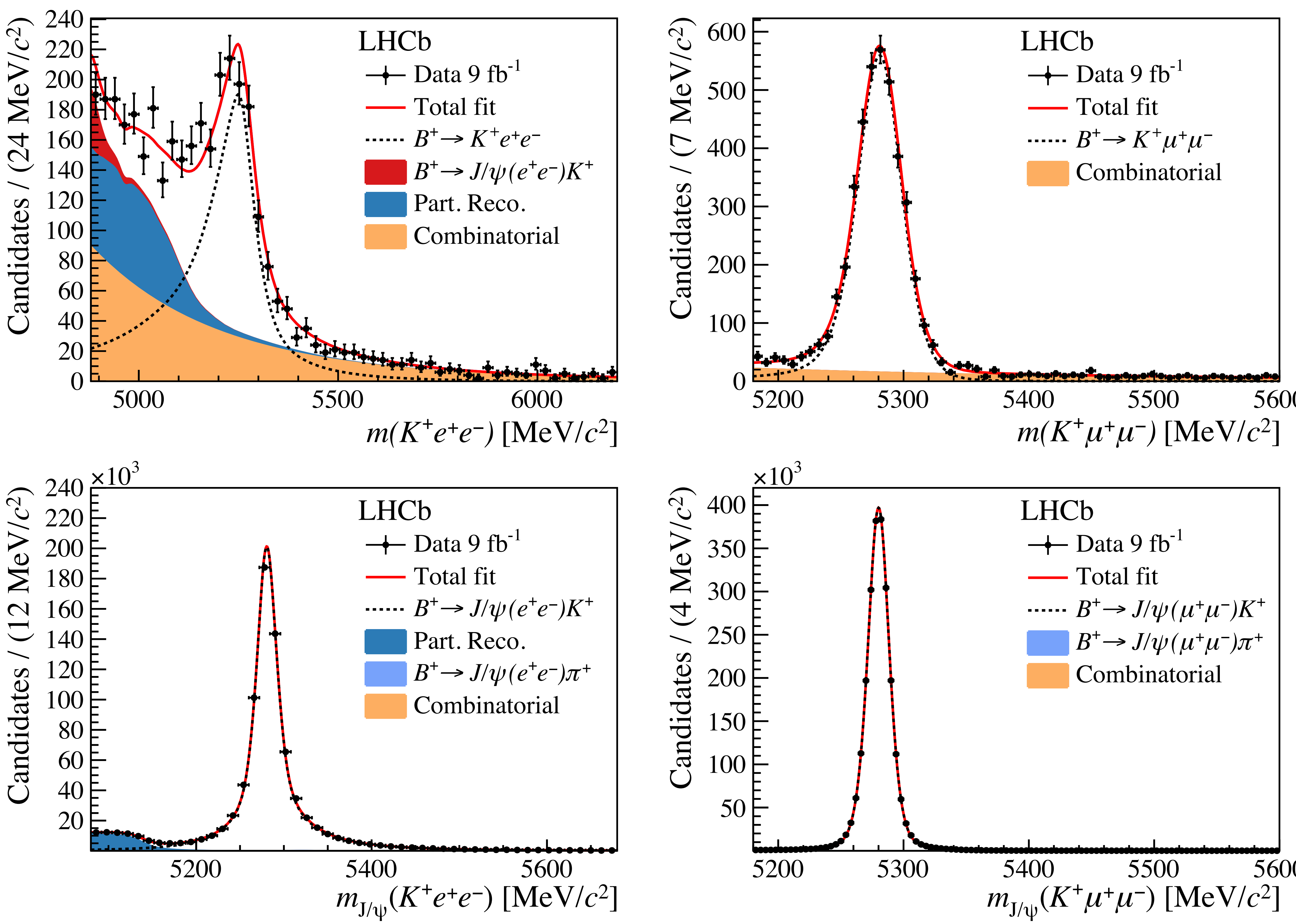


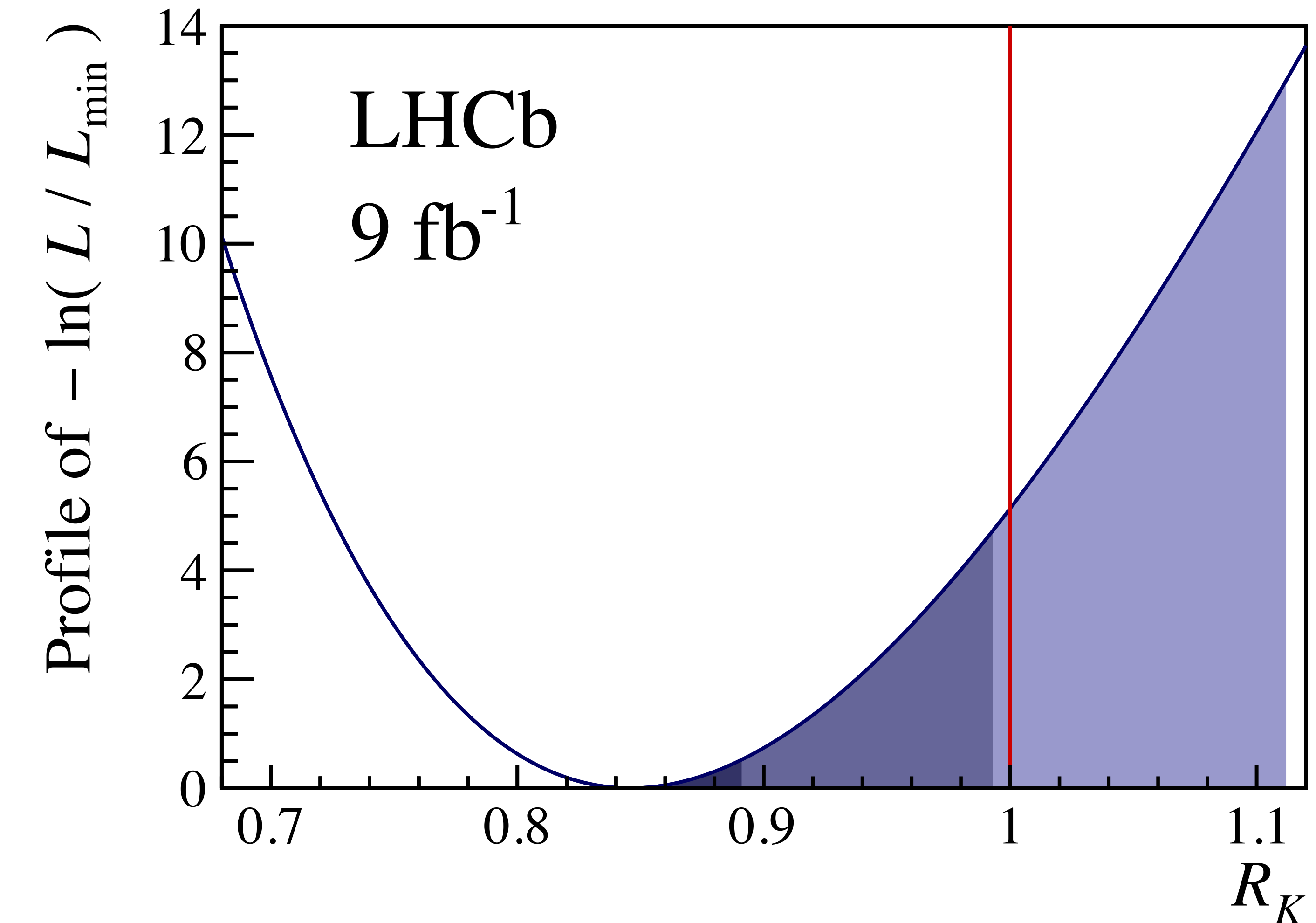


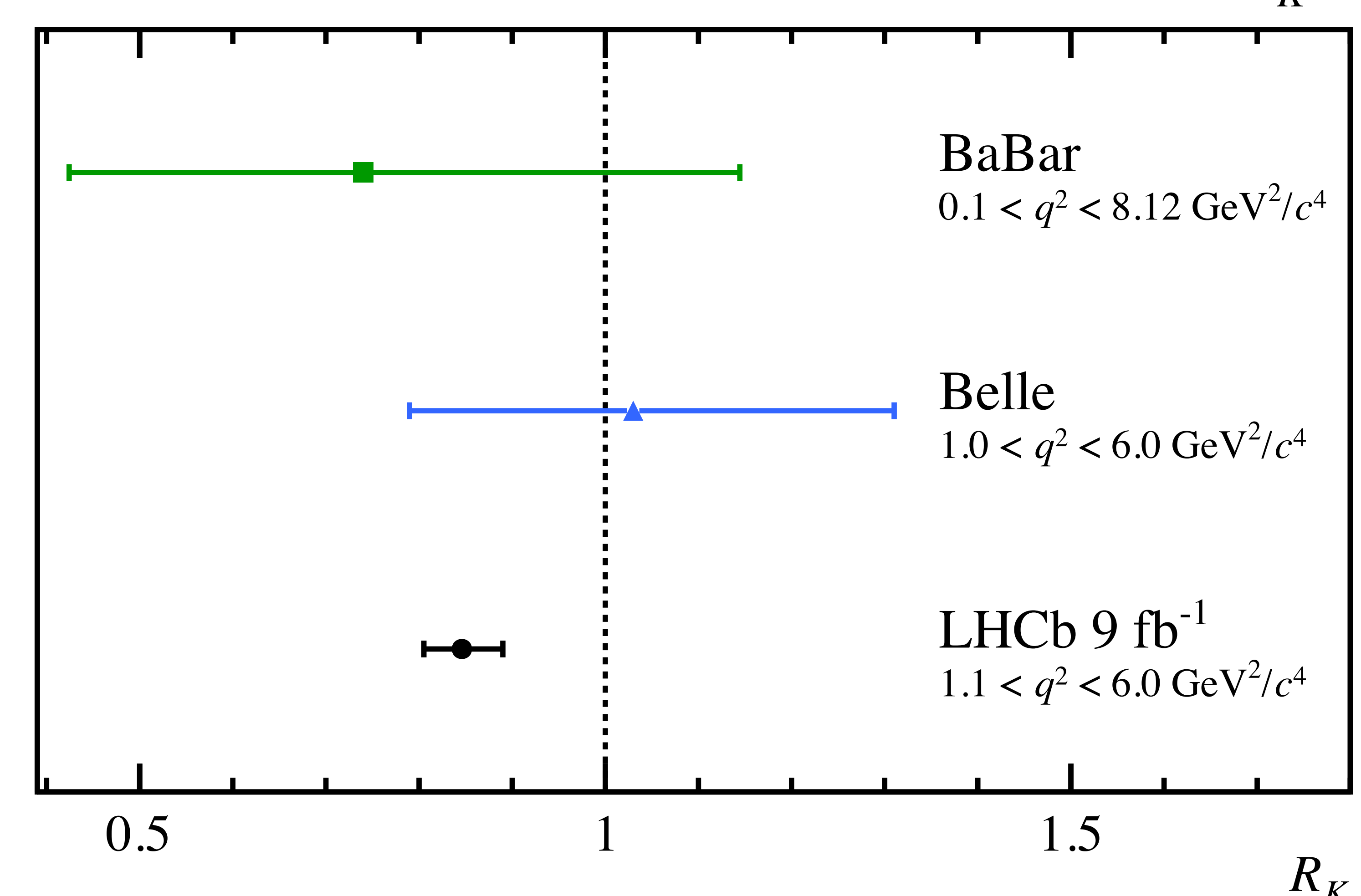
arXiv:2103.11769
submitted to Nature Physics

R_K (LHCb)

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



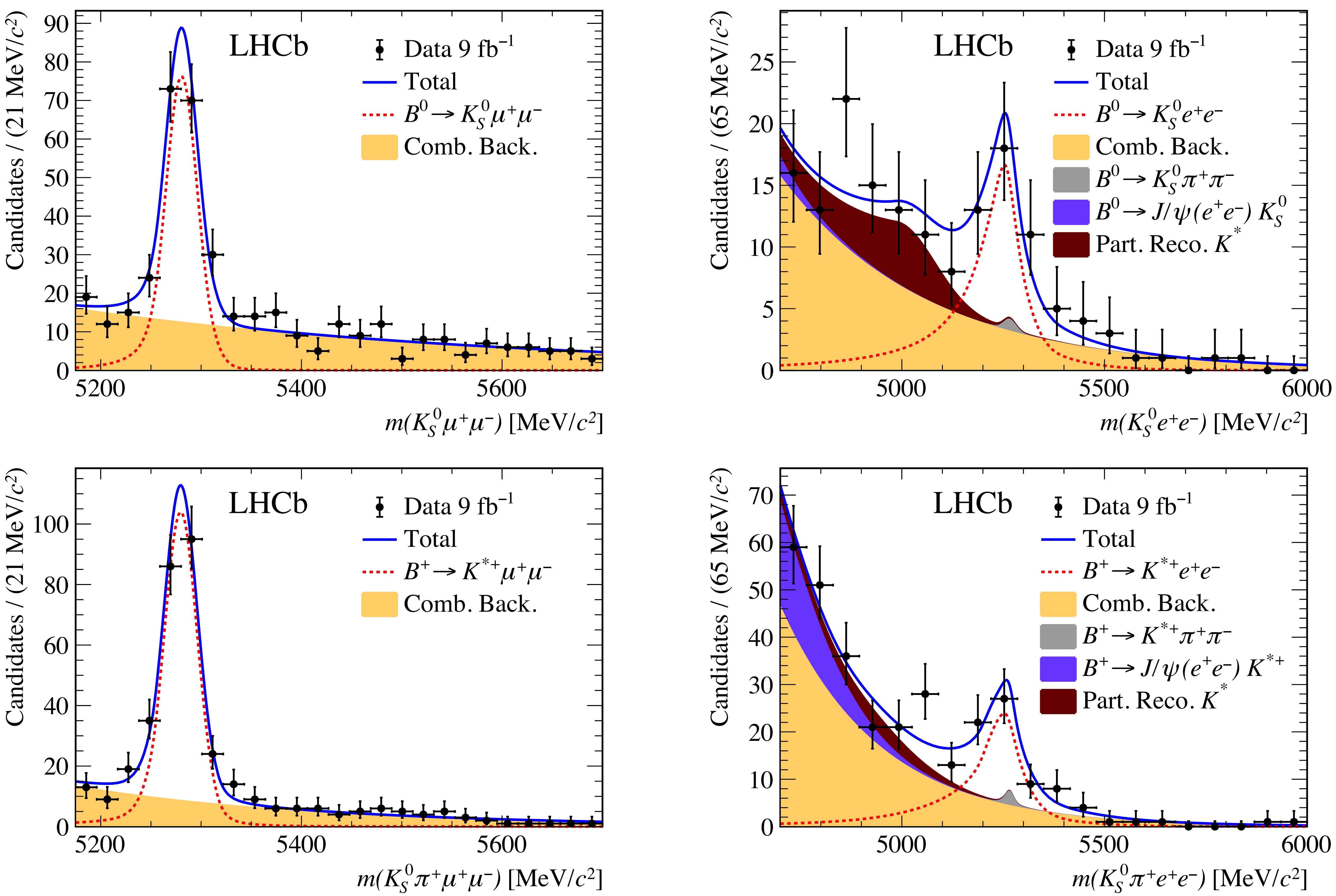


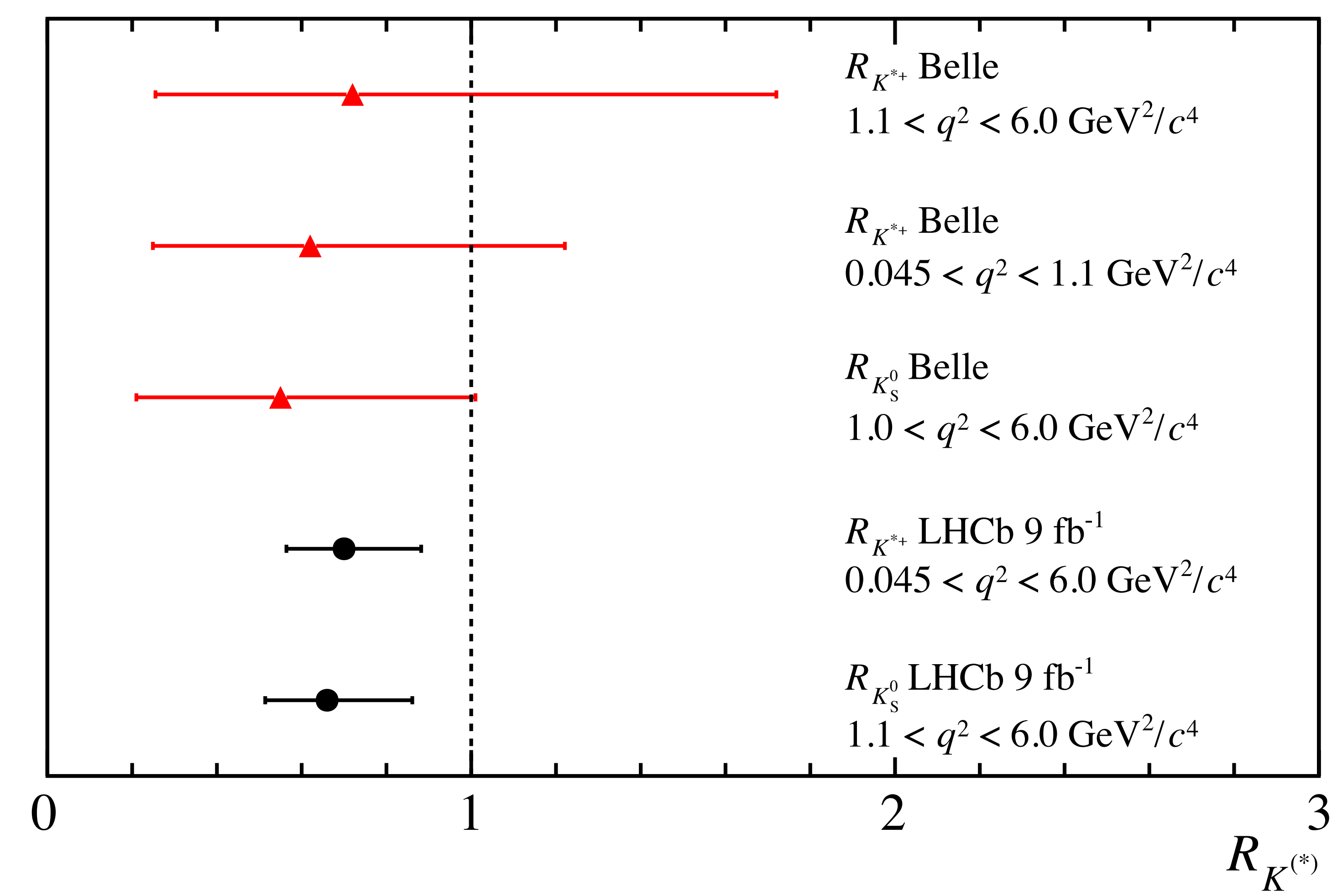


arXiv:2110.08501
submitted to PRL

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

$$R^{-1}_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)} e^+ e^-)}{\mathcal{B}(B \to J/\psi\,(e^+ e^-)\,K^{(*)})} \Big/ \frac{\mathcal{B}(B \to K^{(*)} \mu^+ \mu^-)}{\mathcal{B}(B \to J/\psi\,(\mu^+ \mu^-)\,K^{(*)})}$$



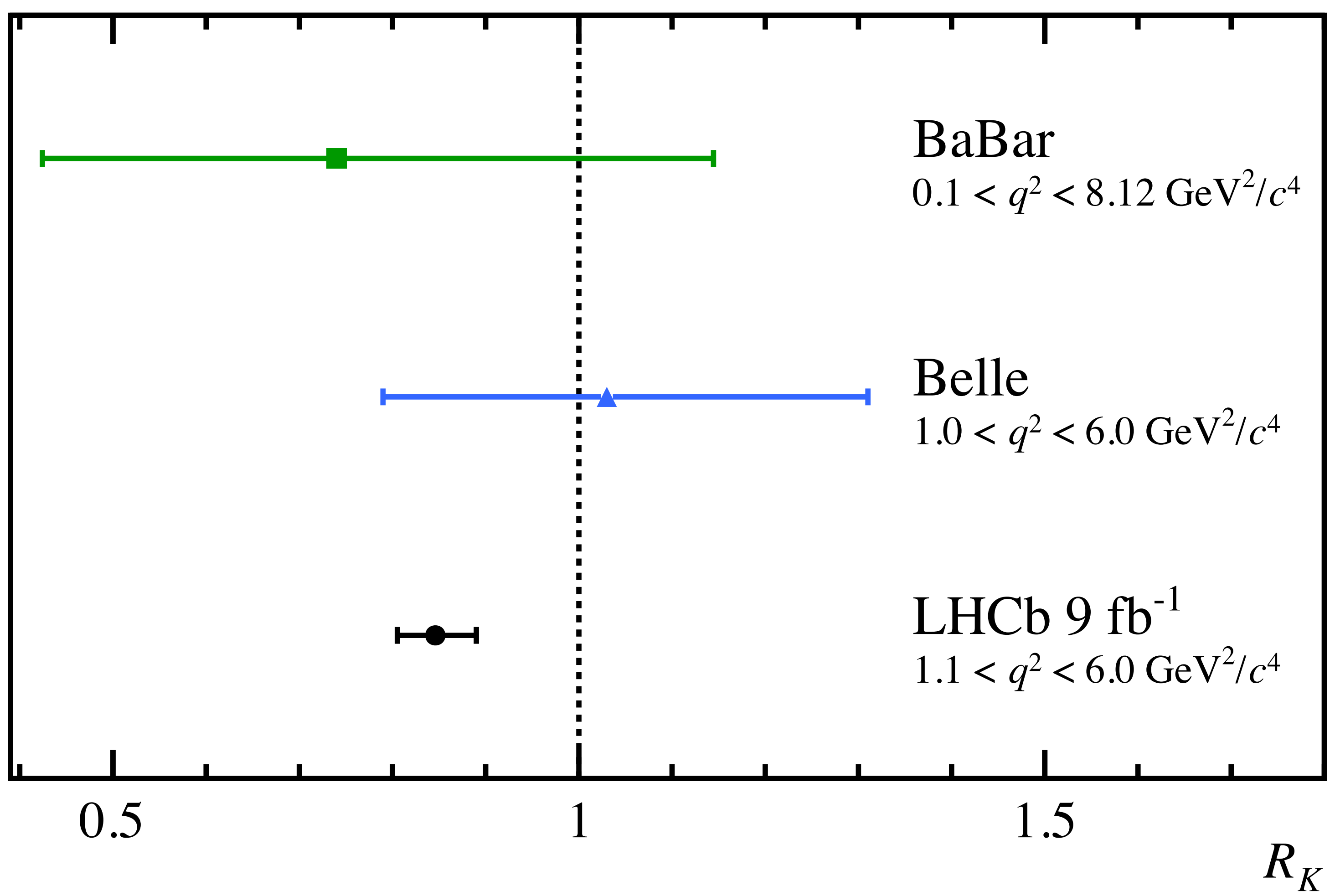


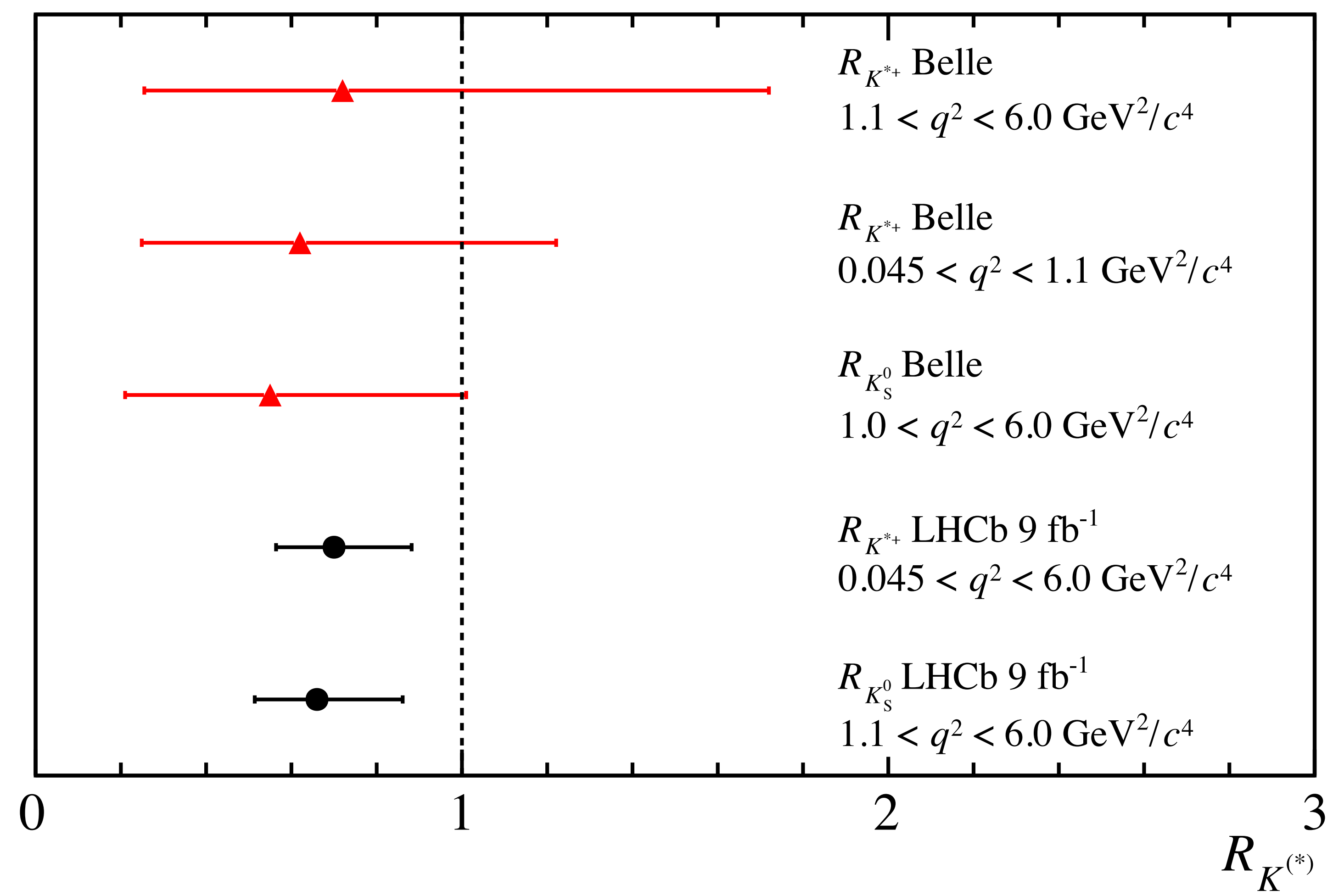
$$R_{K^0_S} = 0.66\,^{+0.20}_{-0.14}\,(\text{stat.})\,^{+0.02}_{-0.04}\,(\text{syst.})$$

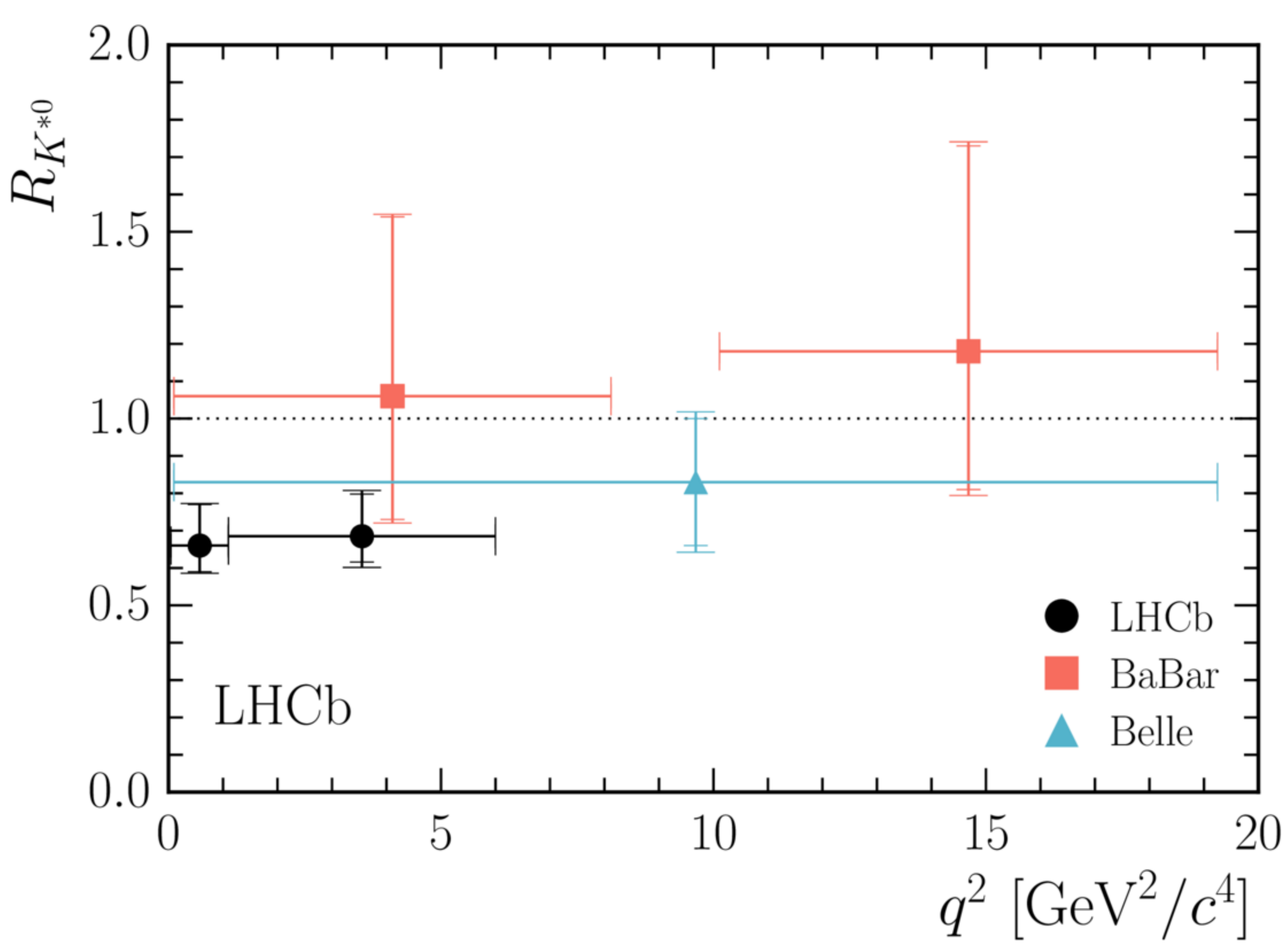
$$R_{K^{*+}} = 0.70\,^{+0.18}_{-0.13}\,(\text{stat.})\,^{+0.03}_{-0.04}\,(\text{syst.})$$

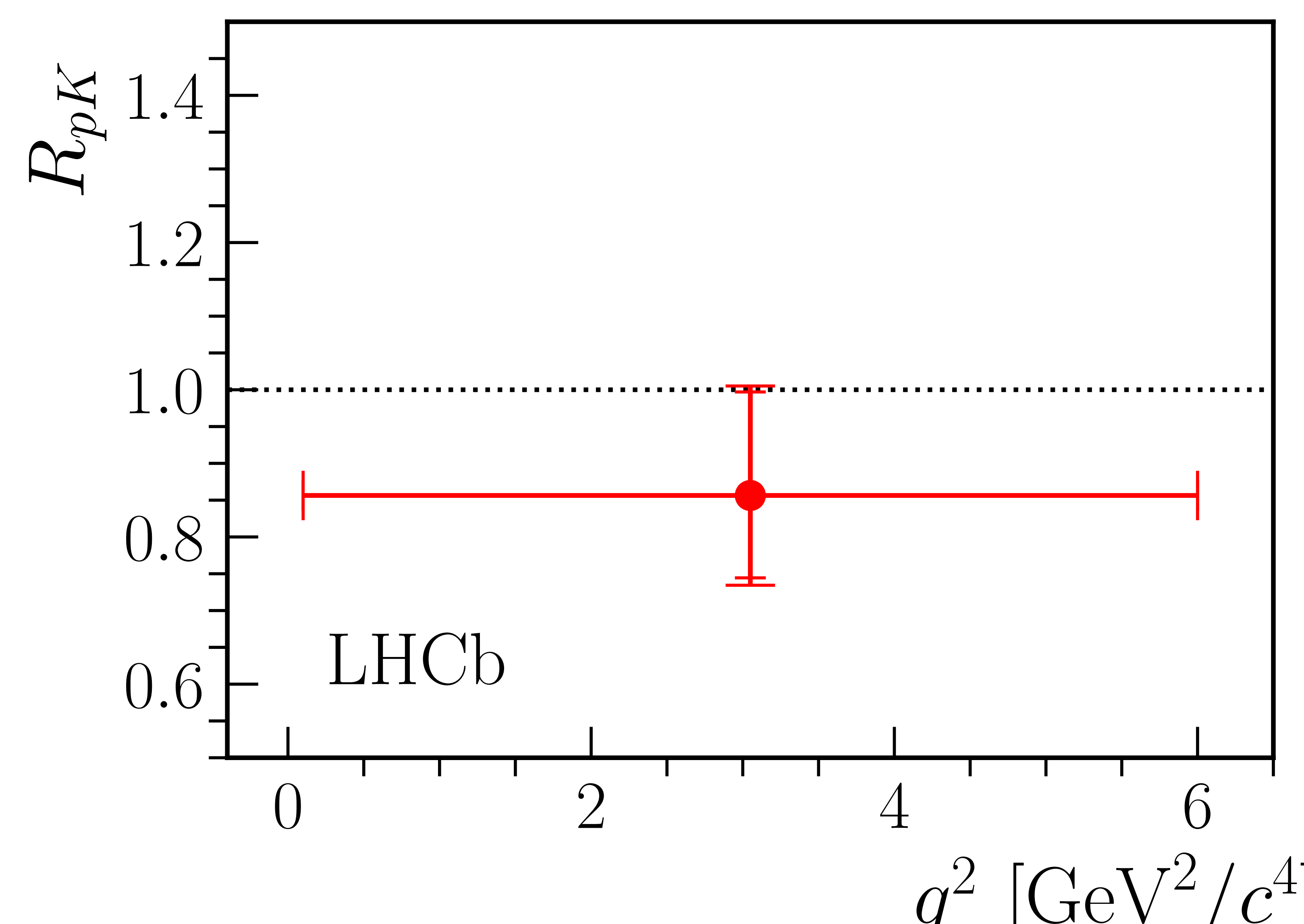
2σ for combined significance

LHCb results, collected





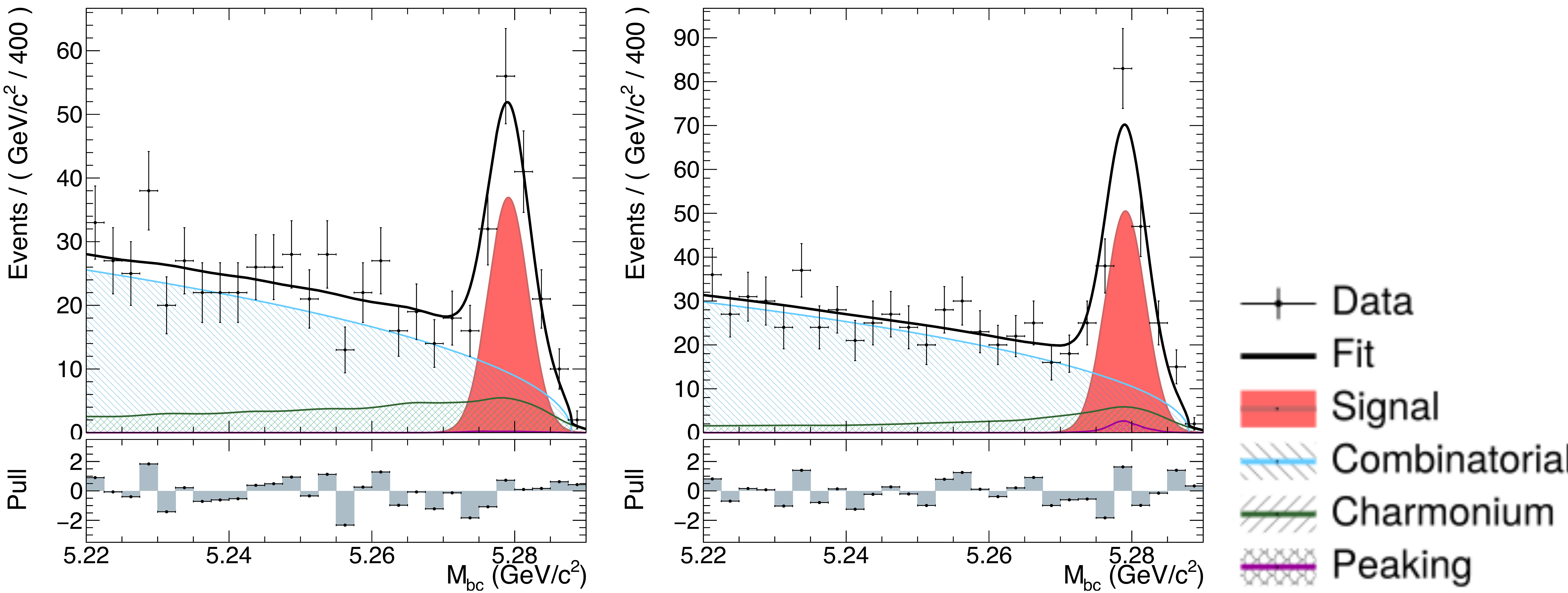




PRL 126, 161801 (2021)

R_{K^*} from Belle

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

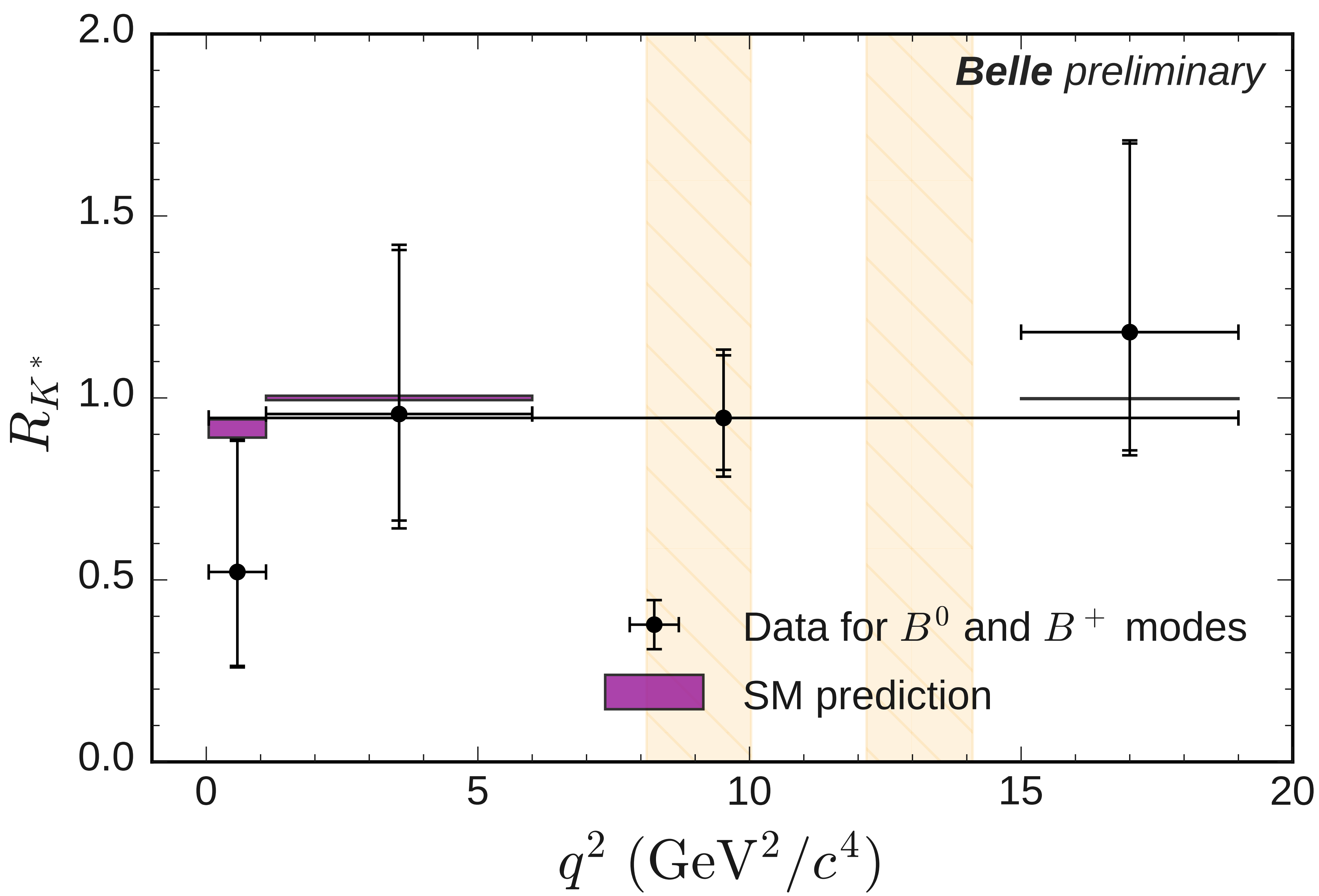


- example fit for $q^2 > 0.045\ \mathrm{GeV}^2$
- $103.0^{+13.4}_{-12.7}$ $(139.0^{+16.0}_{-15.4})$ events in the e (μ) modes

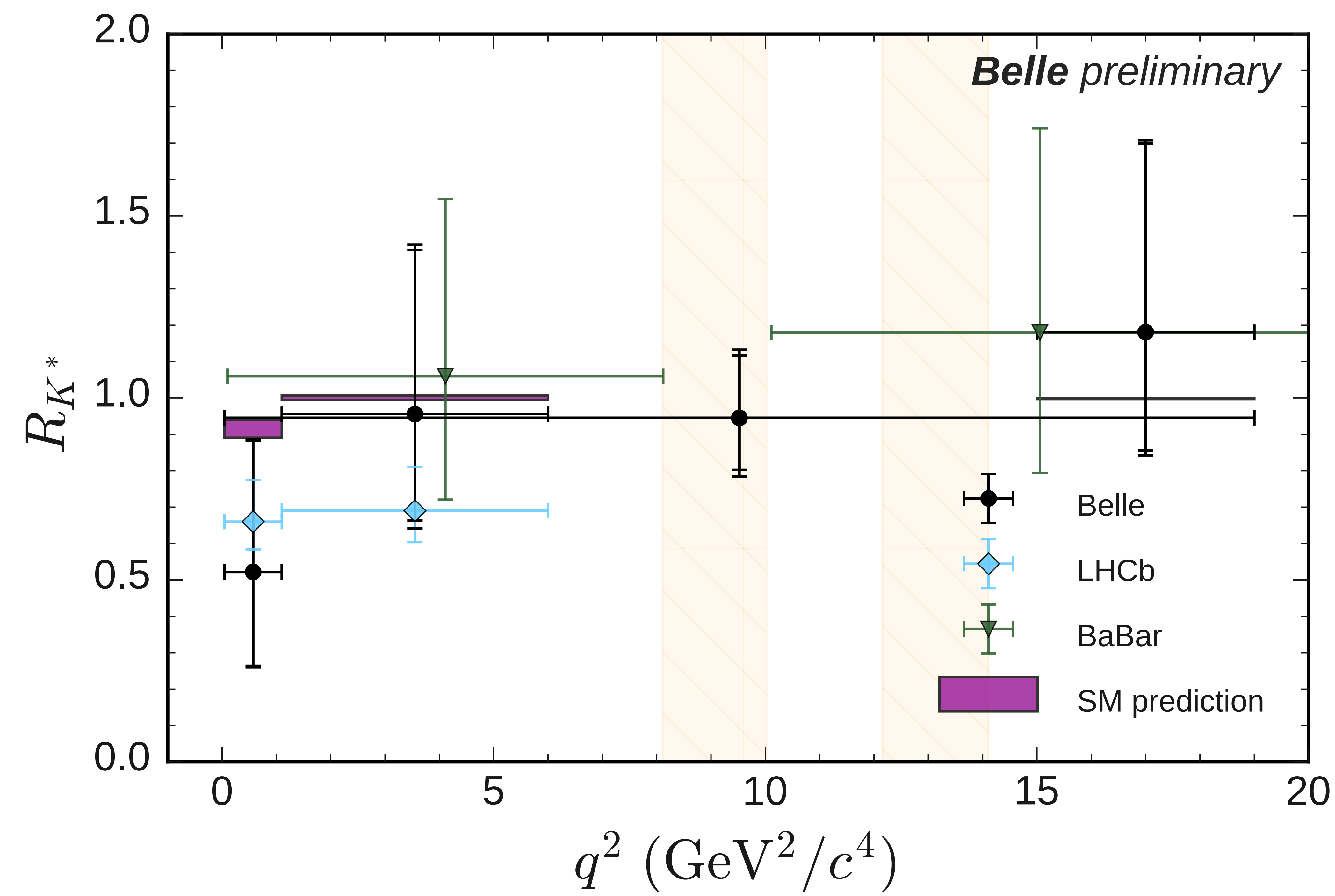
PRL 126, 161801 (2021)

R_{K^*} from Belle

R_{K^*} (Belle)



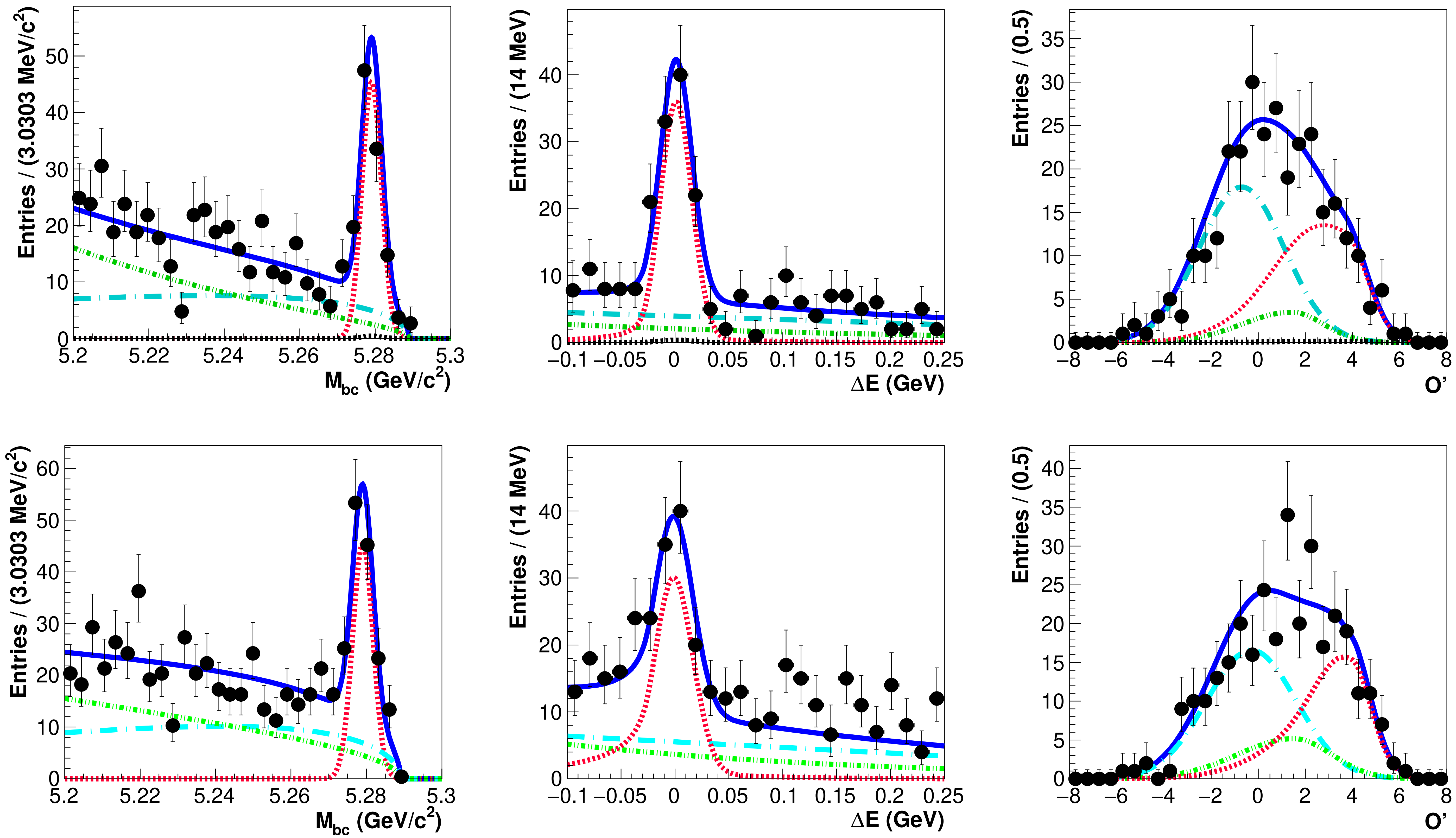
R_{K^*} (all)



R_K from Belle

- Use both B^0 and B^+ modes

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



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

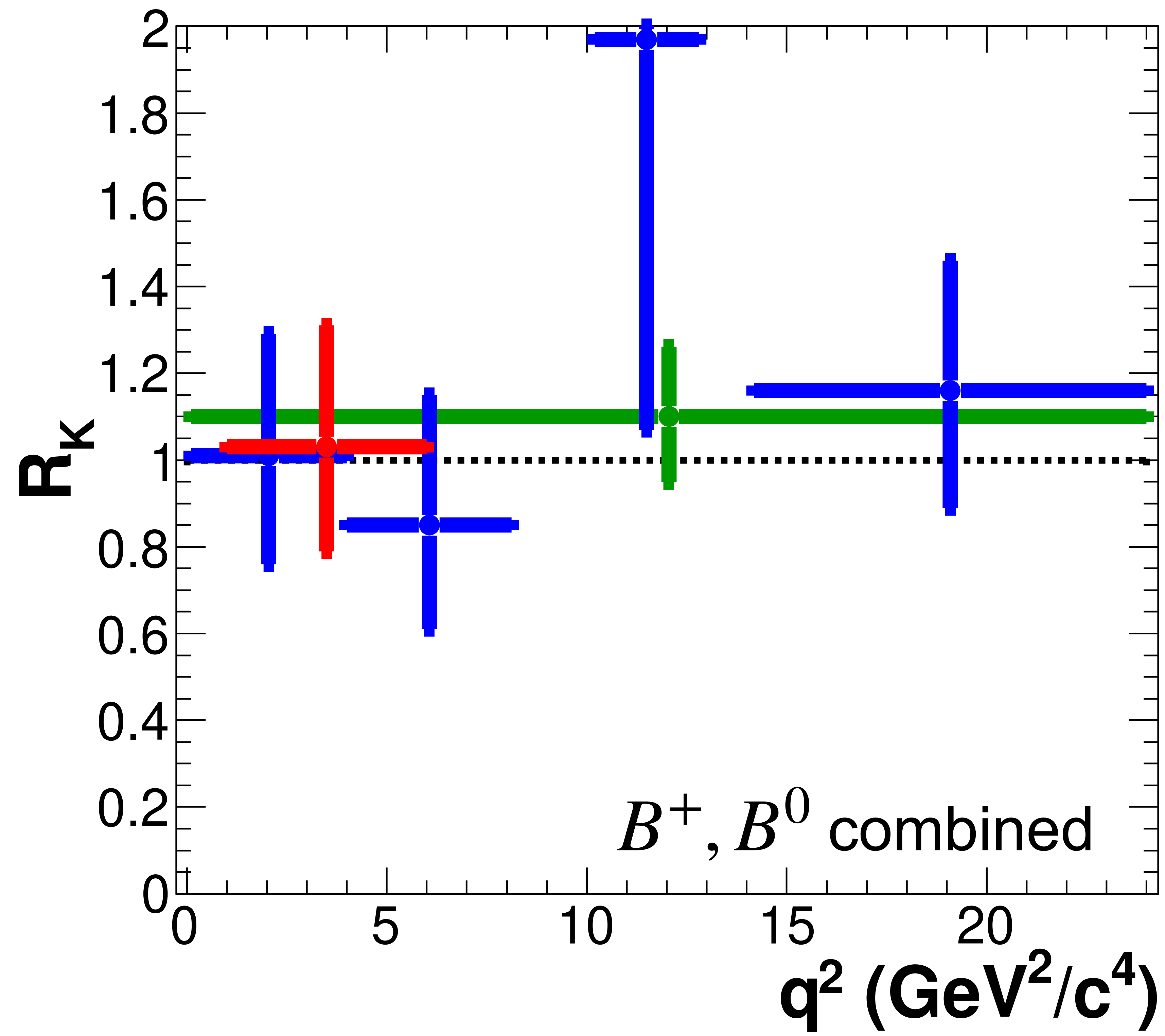
$B^+ \to K^+e^+e^-$

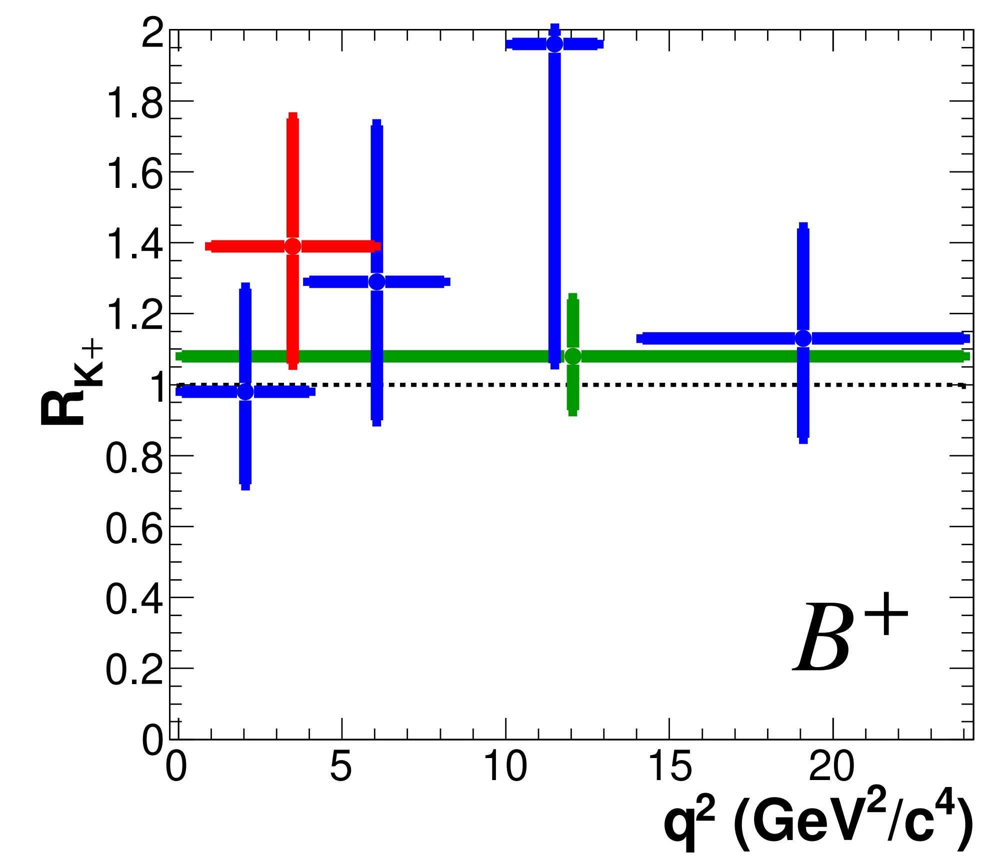
$q^2(ee) \in [(0.1,8.12),(10.2,12.8),(>14.18)]$

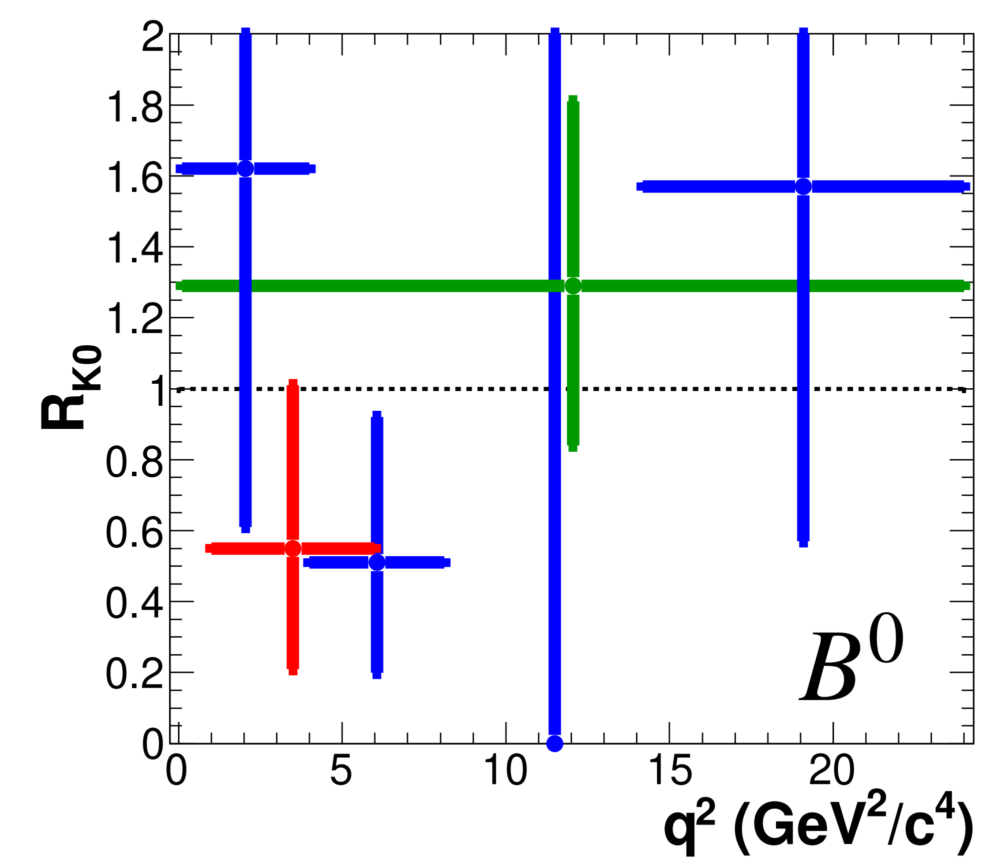
- $137 \pm 14 (138 \pm 15)$ events in the $B^+ \to K^+\mu^+\mu^-$ $(K^+e^+e^-)$
- $27.3^{+6.6}_{-5.8}$ $(21.8^{+7.0}_{-6.1})$ events in the $B^0 \to K^0_S\mu^+\mu^-$ $(K^0_S e^+e^-)$

JHEP 03 (2021) 105

R_K from Belle







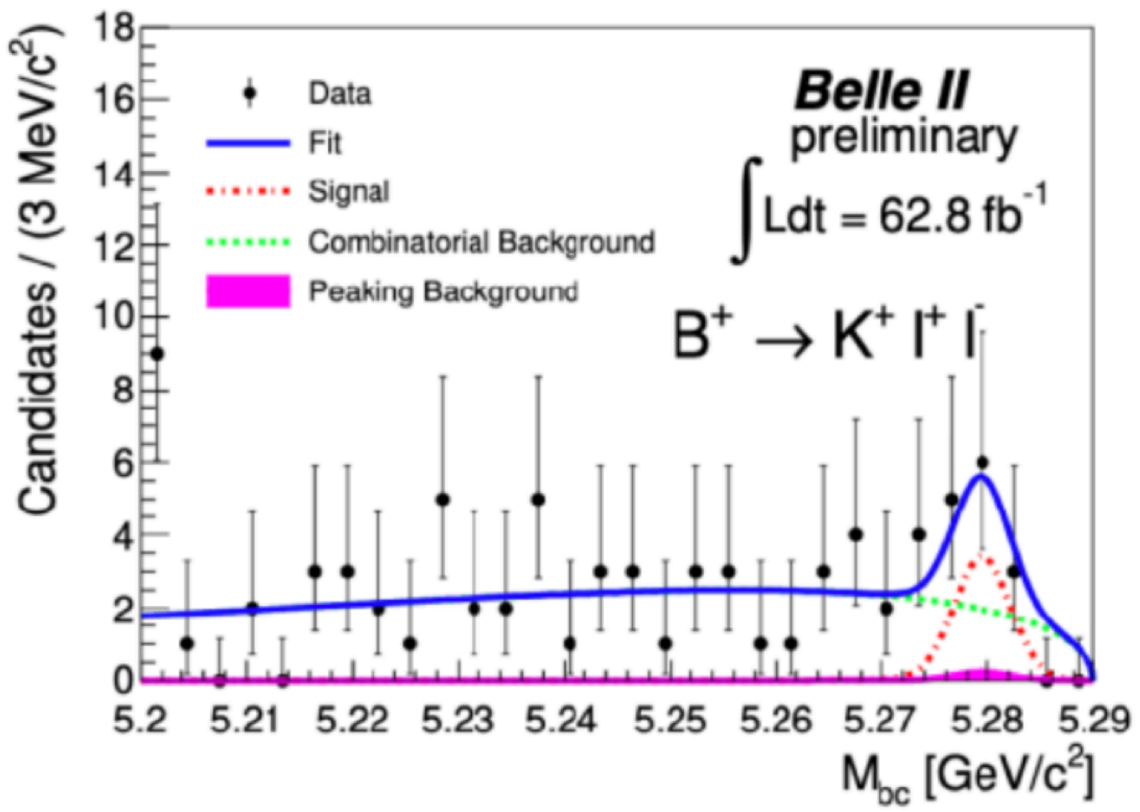
$$R_K = \begin{cases} 1.01 \, ^{+0.28}_{-0.25} \pm 0.02 & q^2 \in (0.1, 4.0) \quad \mathrm{GeV}^2/c^4 \,, \\ 0.85 \, ^{+0.30}_{-0.24} \pm 0.01 & q^2 \in (4.00, 8.12) \quad \mathrm{GeV}^2/c^4 \,, \\ 1.03 \, ^{+0.28}_{-0.24} \pm 0.01 & q^2 \in (1.0, 6.0) \quad \mathrm{GeV}^2/c^4 \,, \\ 1.97 \, ^{+1.03}_{-0.89}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

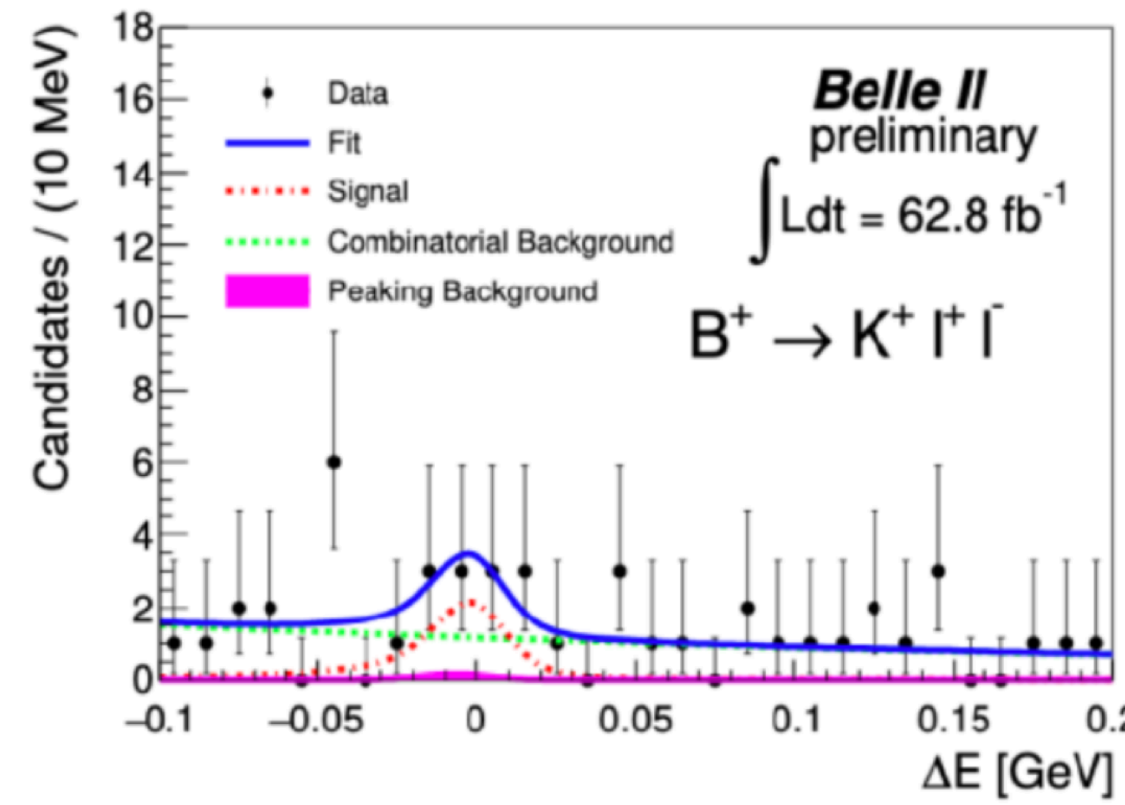
See the Belle II talk by B. Cheon on Dec.17 of this meeting

Progress in Belle II

Exclusive EWP

- preliminary measurements using 62.8 fb^{-1} of Belle II data



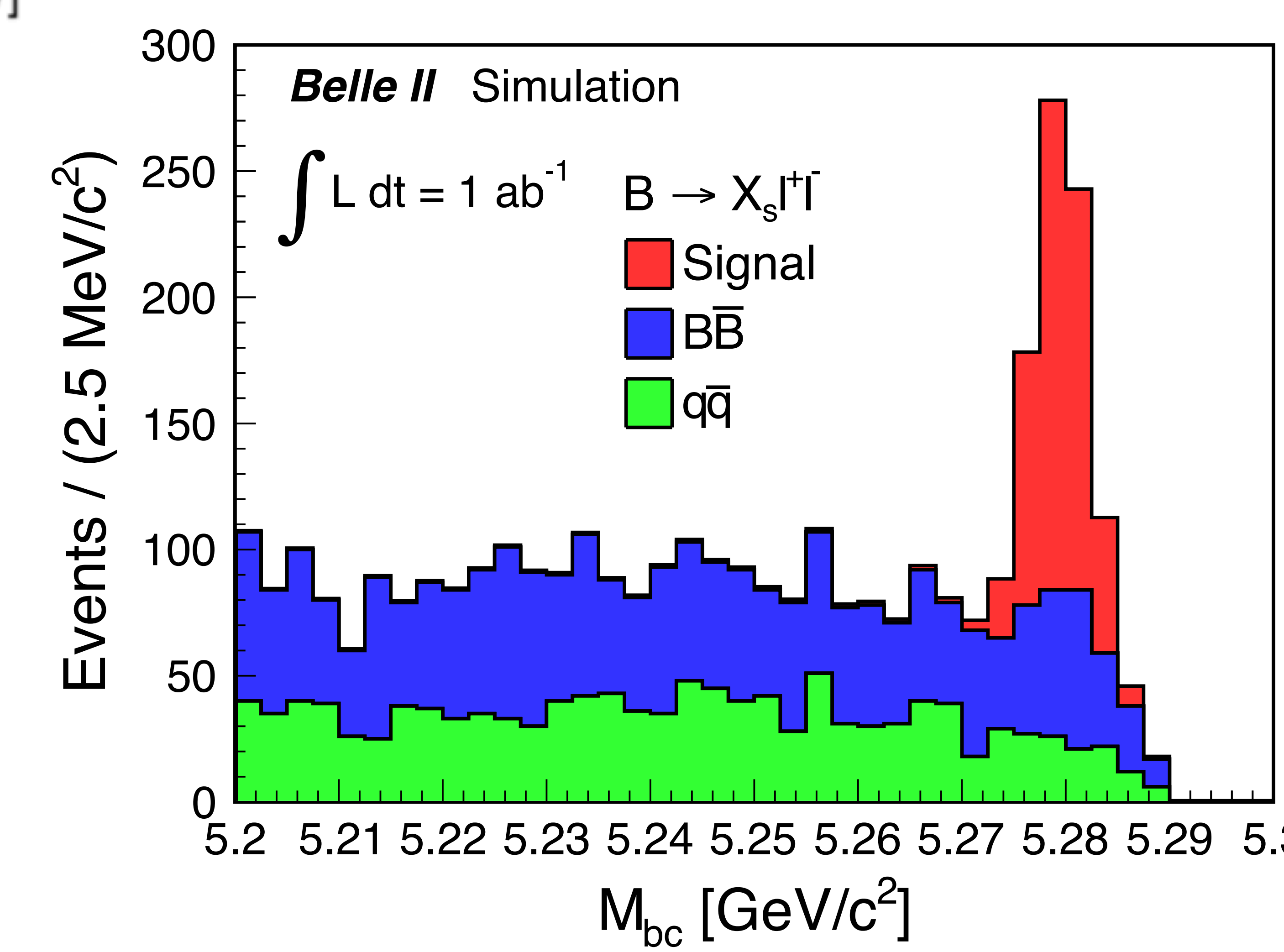


$N_{\mathrm{sig}} = 9.6^{+4.3}_{-3.9} \pm 0.4 \ (2.7\sigma)$

not yet for $R_{K^{(*)}}$

Inclusive $B \to X_s \ell^+ \ell^-$

- complementary to $B \to K^{(*)} \ell^+ \ell^-$ w/ different hadronic uncertainty
- (fig. MC) sum-of-exclusive method



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

See the Belle II talk by B. Cheon on Dec.17 of this meeting

- 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

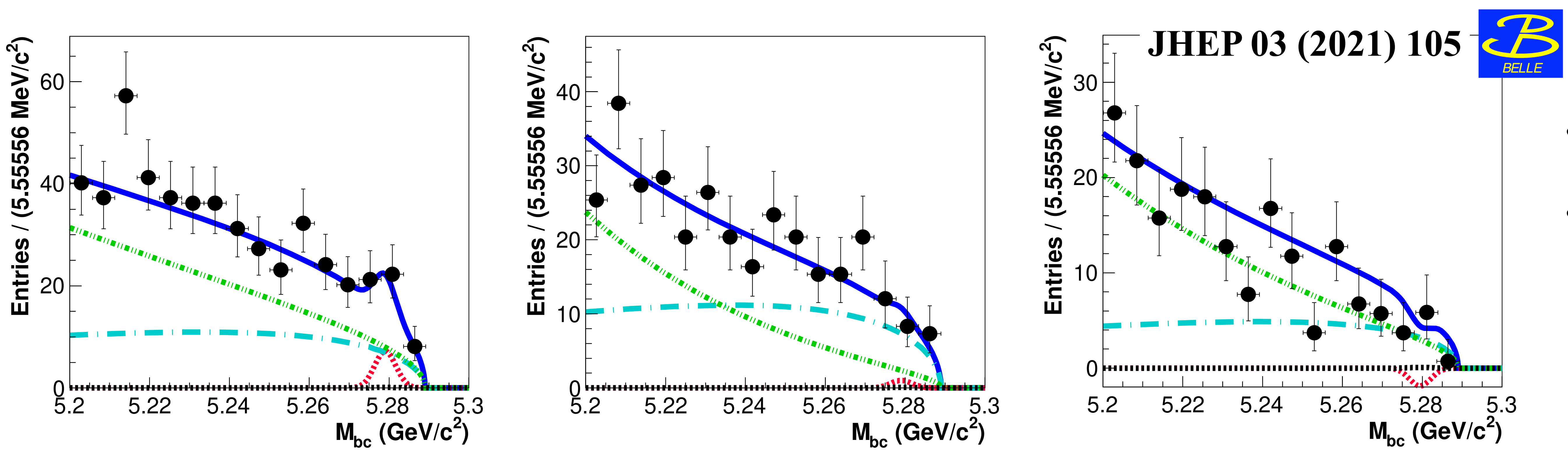
Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
R_K ([1.0, 6.0] GeV^2)	28%	11%	3.6%
R_K (>14.4 GeV^2)	30%	12%	3.6%
R_{K^*} ([1.0, 6.0] GeV^2)	26%	10%	3.2%
R_{K^*} (>14.4 GeV^2)	24%	9.2%	2.8%
R_{X_s} ([1.0, 6.0] GeV^2)	32%	12%	4.0%
R_{X_s} (>14.4 GeV^2)	28%	11%	3.4%

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



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

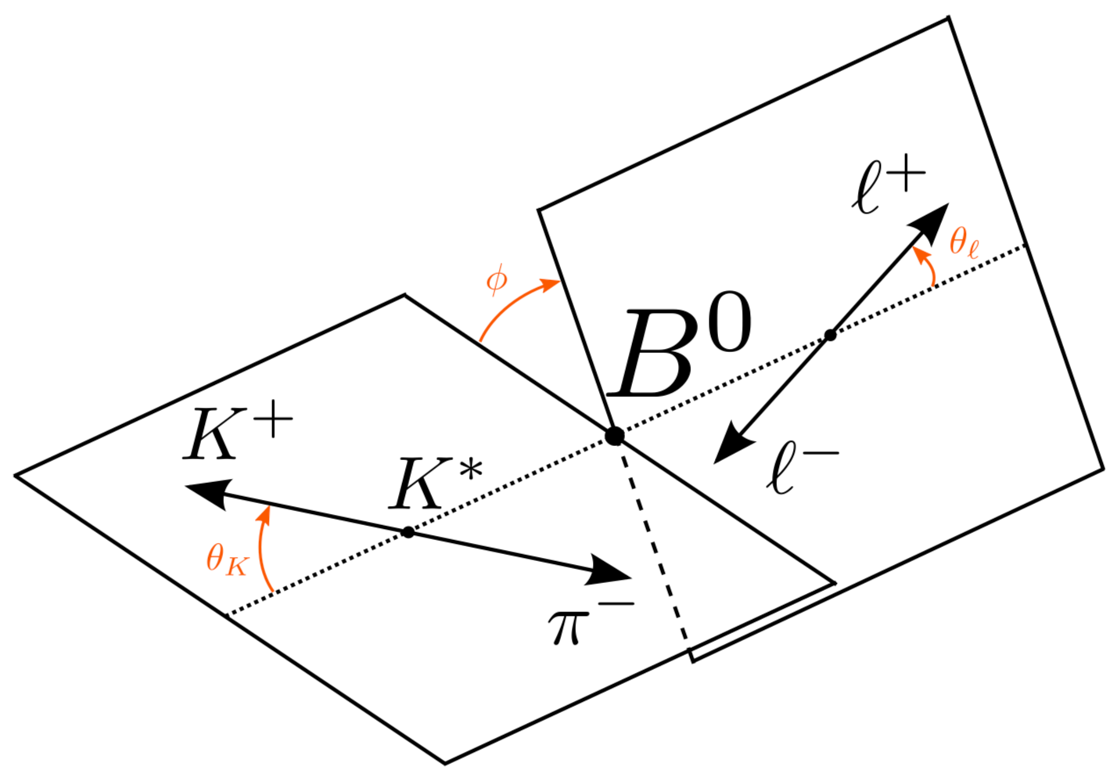
$\mathcal{B}(B^+ \to K^+\mu^-e^+) < 3.0 \times 10^{-8}$

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

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

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

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



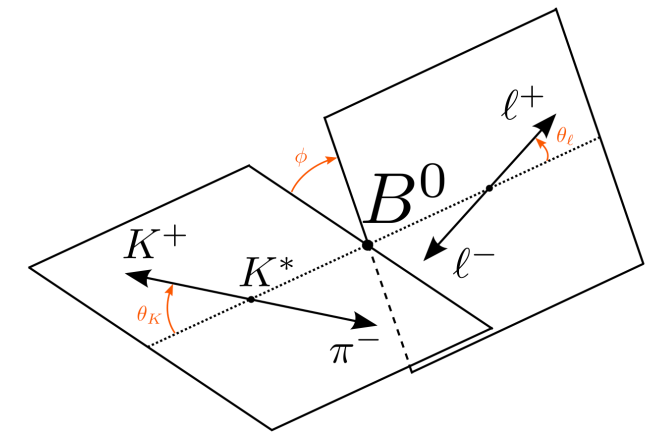
$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

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

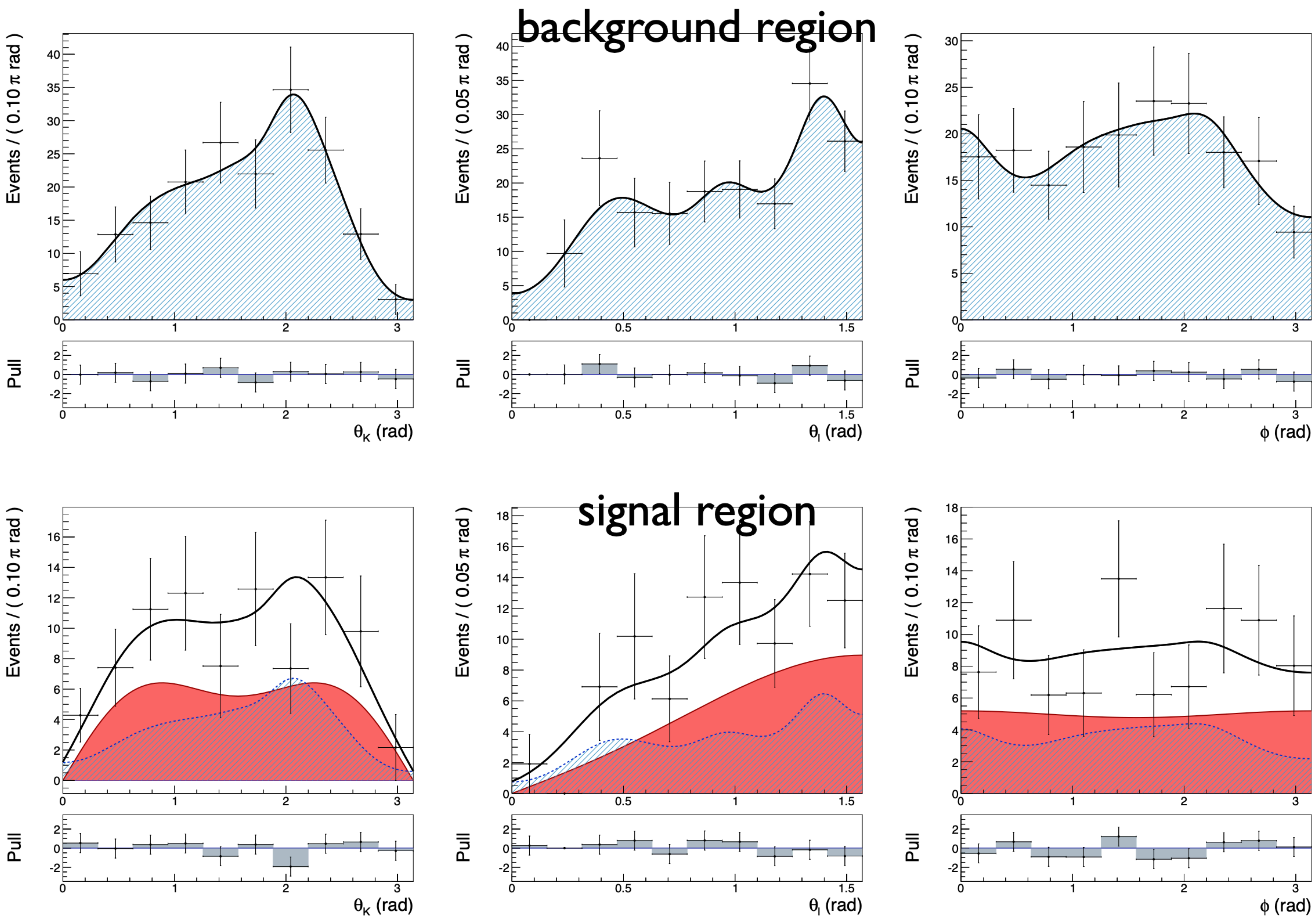
Extract transverse polarization asymmetry $A_T^{(2)} = 2S_3/(1-F_L)$

- 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: $8 \to 3$

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

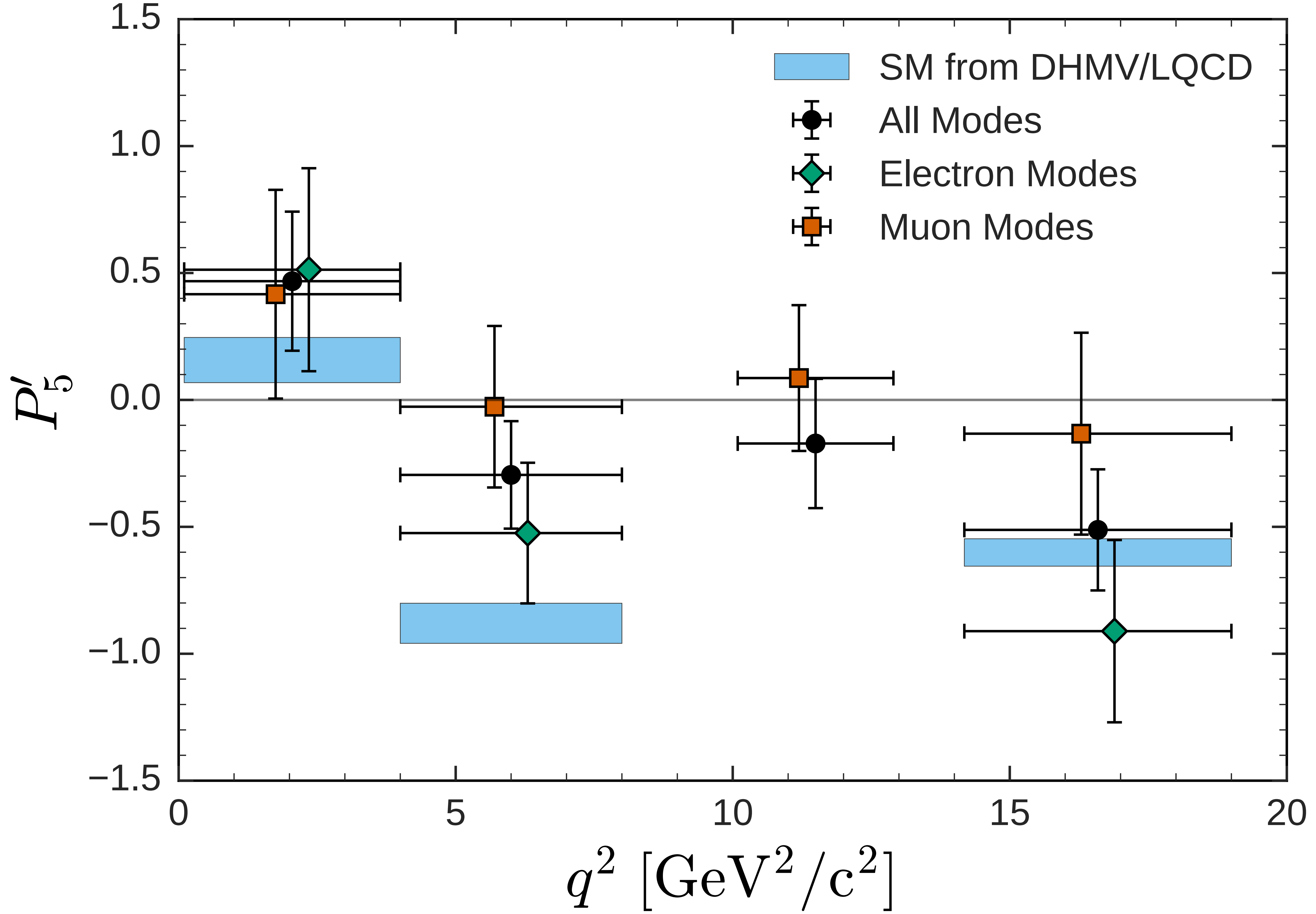


Bin #2

$4.0 < q^2 < 8.0$

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

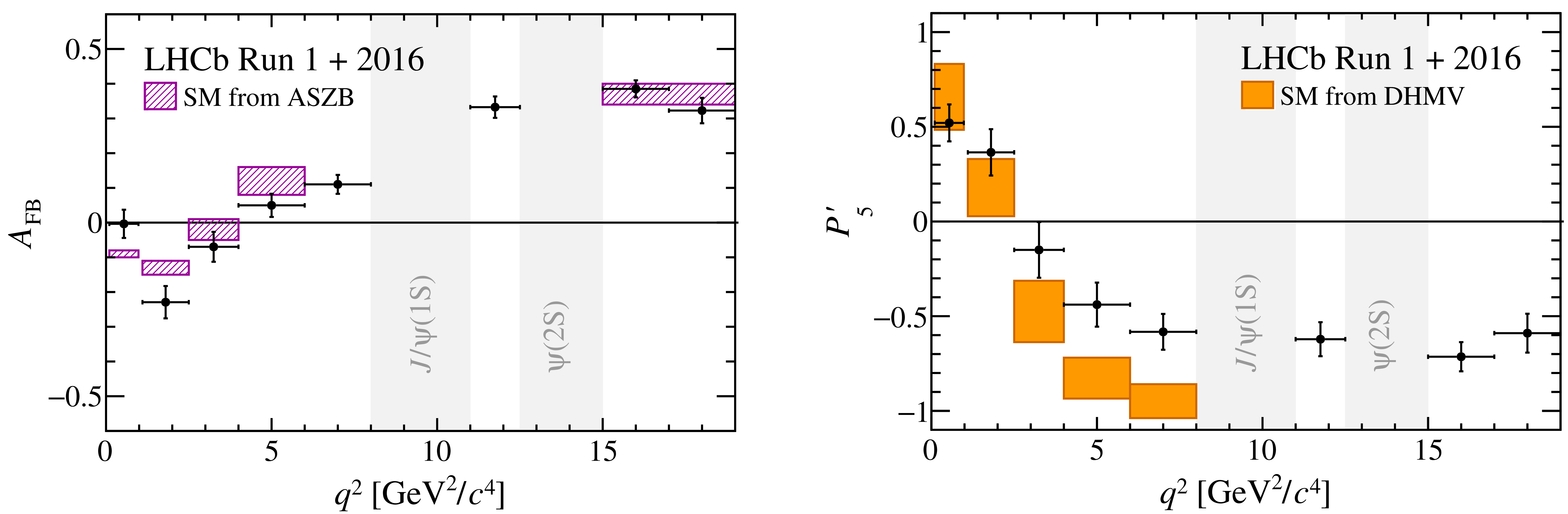
PHYSICAL REVIEW LETTERS **125,** 011802 (2020)

Editors' Suggestion | Featured in Physics

Measurement of *CP*-Averaged Observables in the $B^0 \to K^{*0}\mu^+\mu^-$ Decay

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

$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$



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

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

[77] W. Altmannshofer and D. M. Straub, Eur. Phys. J. C **75**, 382 (2015).
[78] A. Bharucha, D. M. Straub, and R. Zwicky, J. High Energy

[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.

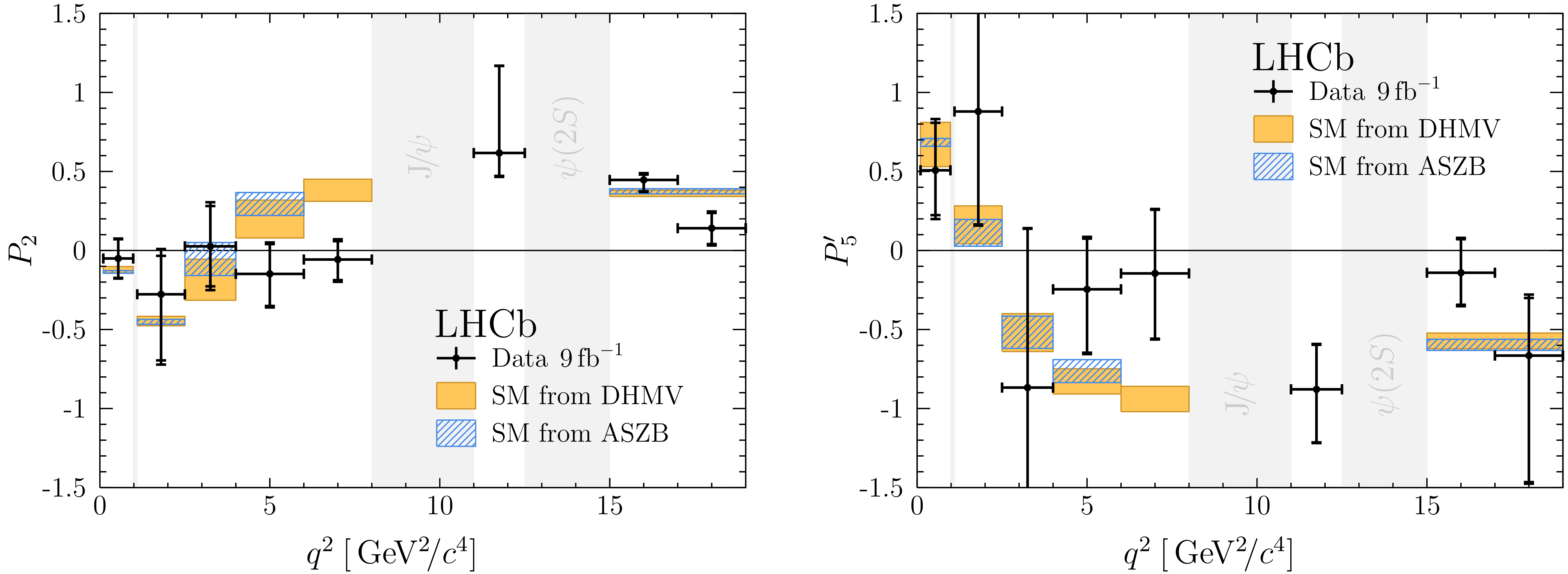
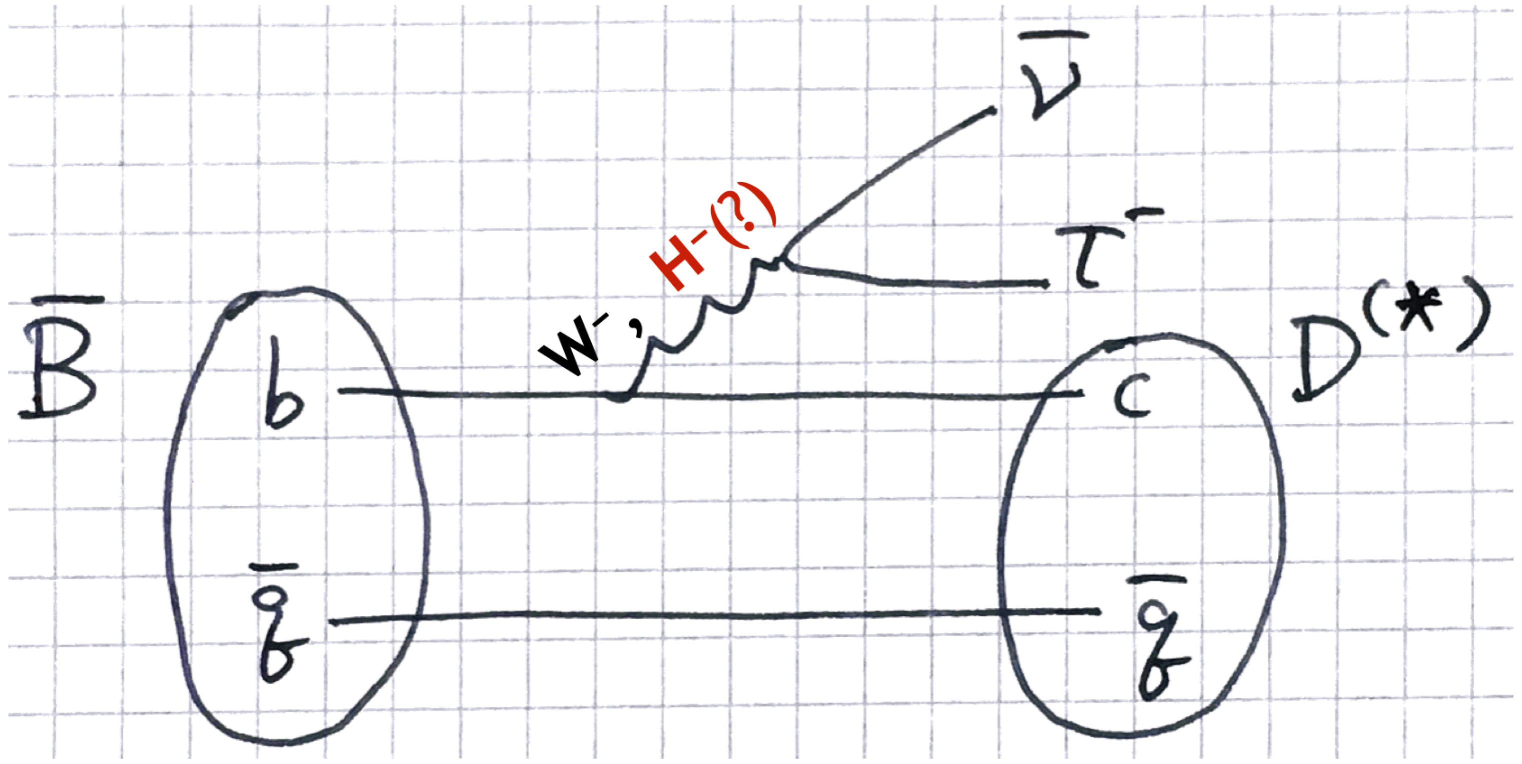


FIG. 2. The CP-averaged observables (left) P_2 and (right) P_5' in intervals of q^2. The first (second) error bars represent the statistical (total) uncertainties. The theoretical predictions in blue are based on Ref. [77] with hadronic form factors taken from Refs. [78–80] and are obtained with the 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.

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

- $m_\tau \gg m_e, m_\mu$ $\quad\therefore$ B ➔ D* τ ν can be more sensitive to NP, e.g. from H⁺
- B ➔ D* τ ν 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]

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

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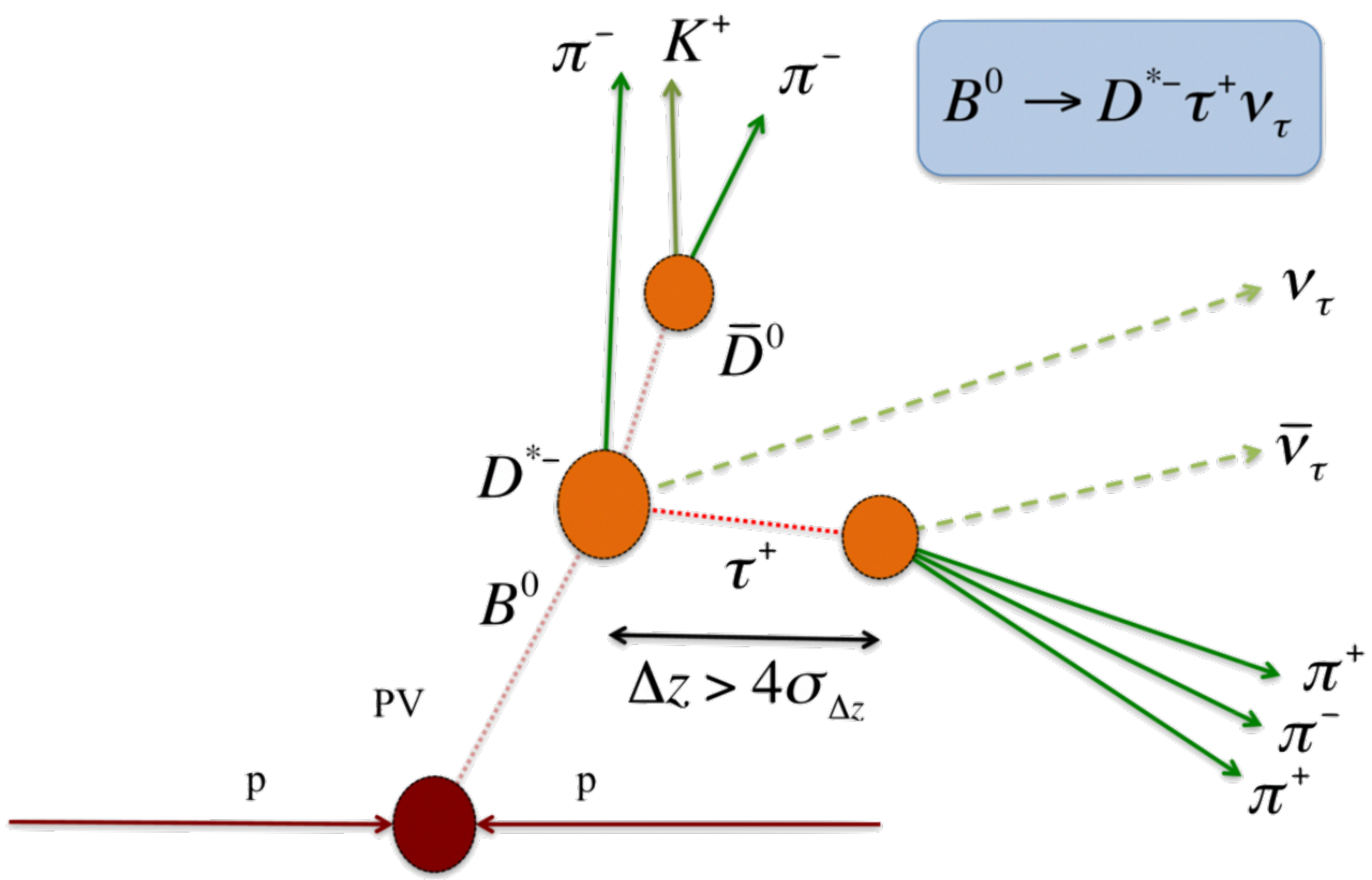
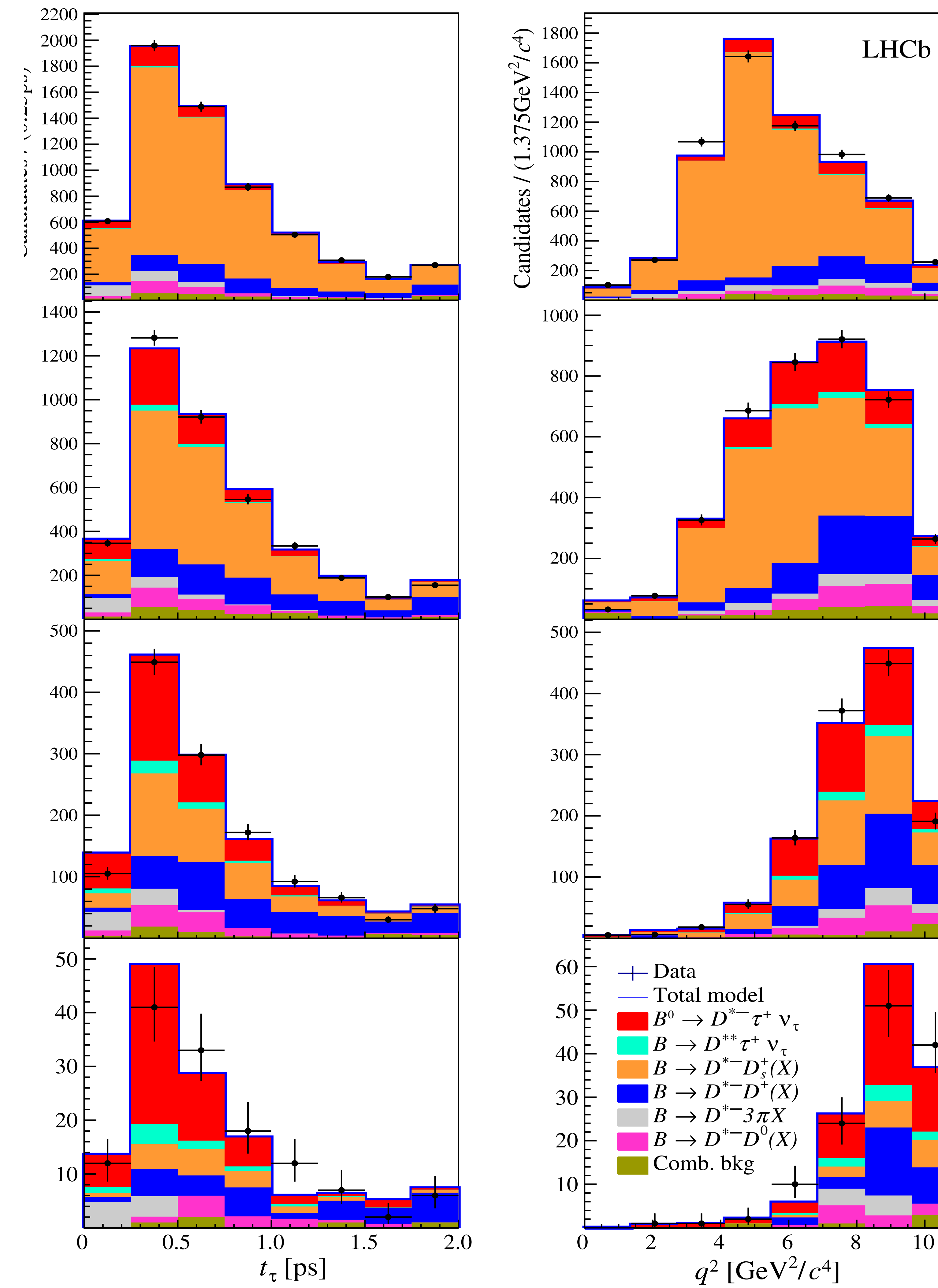
LHCb $R(D^*)$ with $\tau \to 3\pi(\pi^0)\nu$

- Background suppression
  - $B^0 \to D^{*-}\pi^+\pi^-\pi^+(X)$ by $\Delta z > 4\sigma_{\Delta z}$
  - $B \to D^{*-}D_s^+(X)$ by BDT

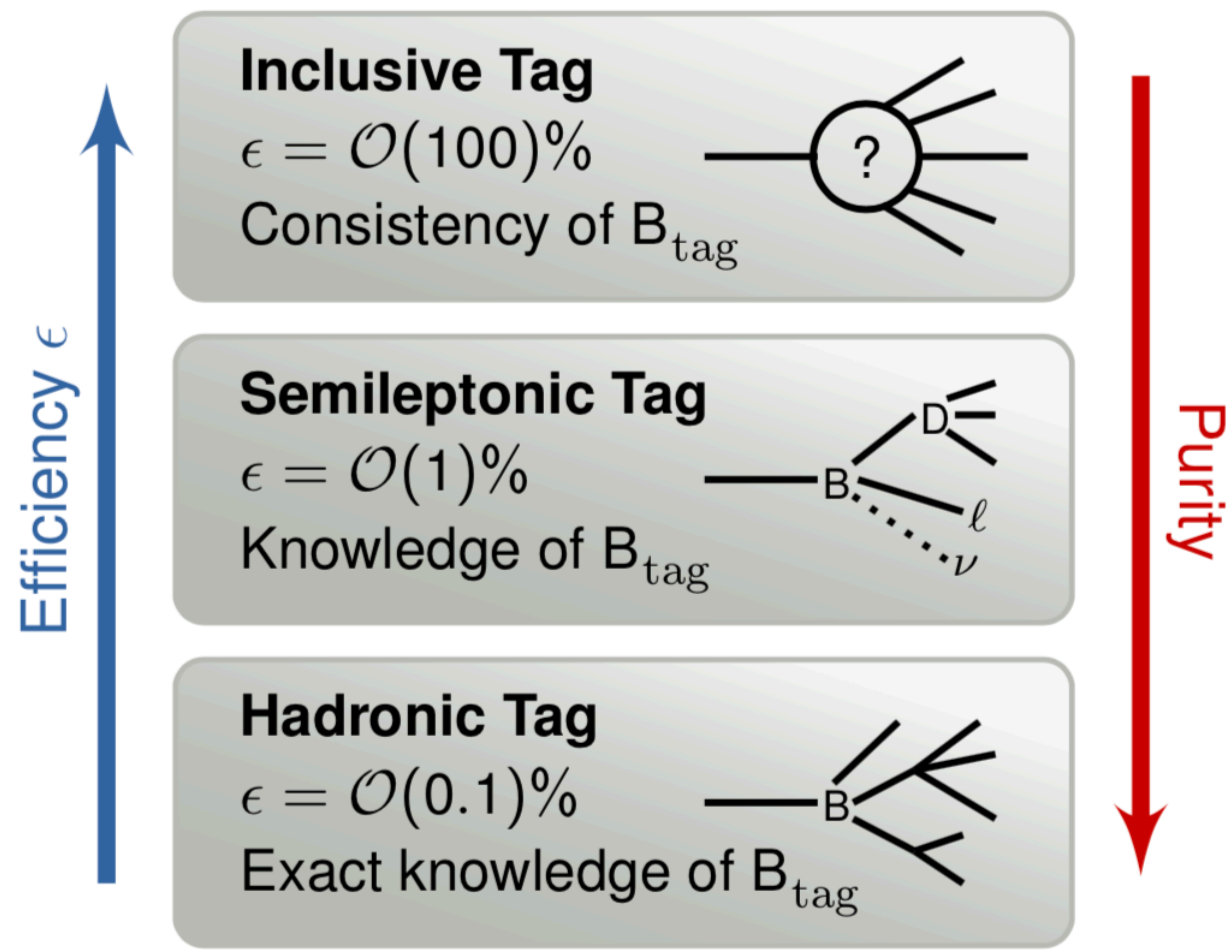


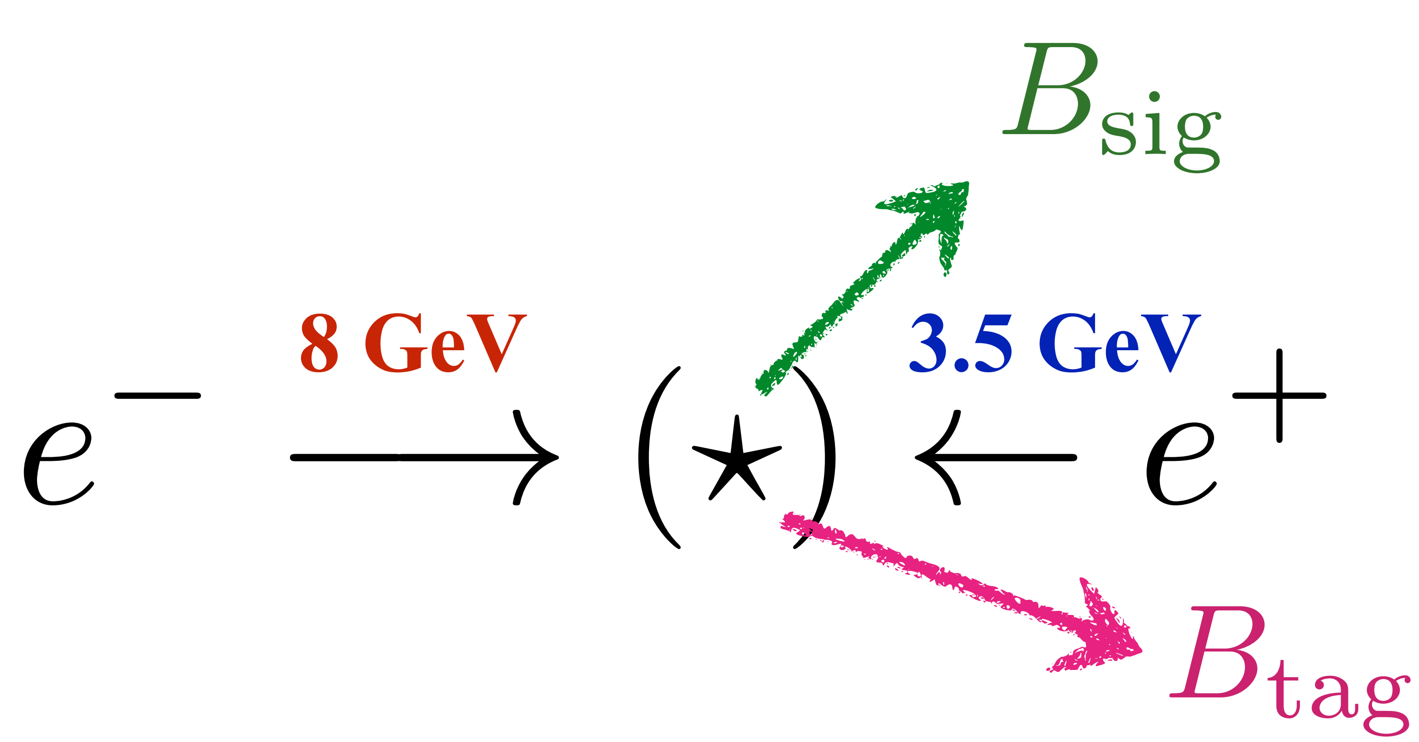
- Signal extraction
  - by 3D binned fit to $(q^2,\ t_\tau,\ O_{\rm BDT})$
  - fits to $\tau \to 3\pi\nu$ and $3\pi\pi^0\nu$ modes are summed by fixing the relative ratio

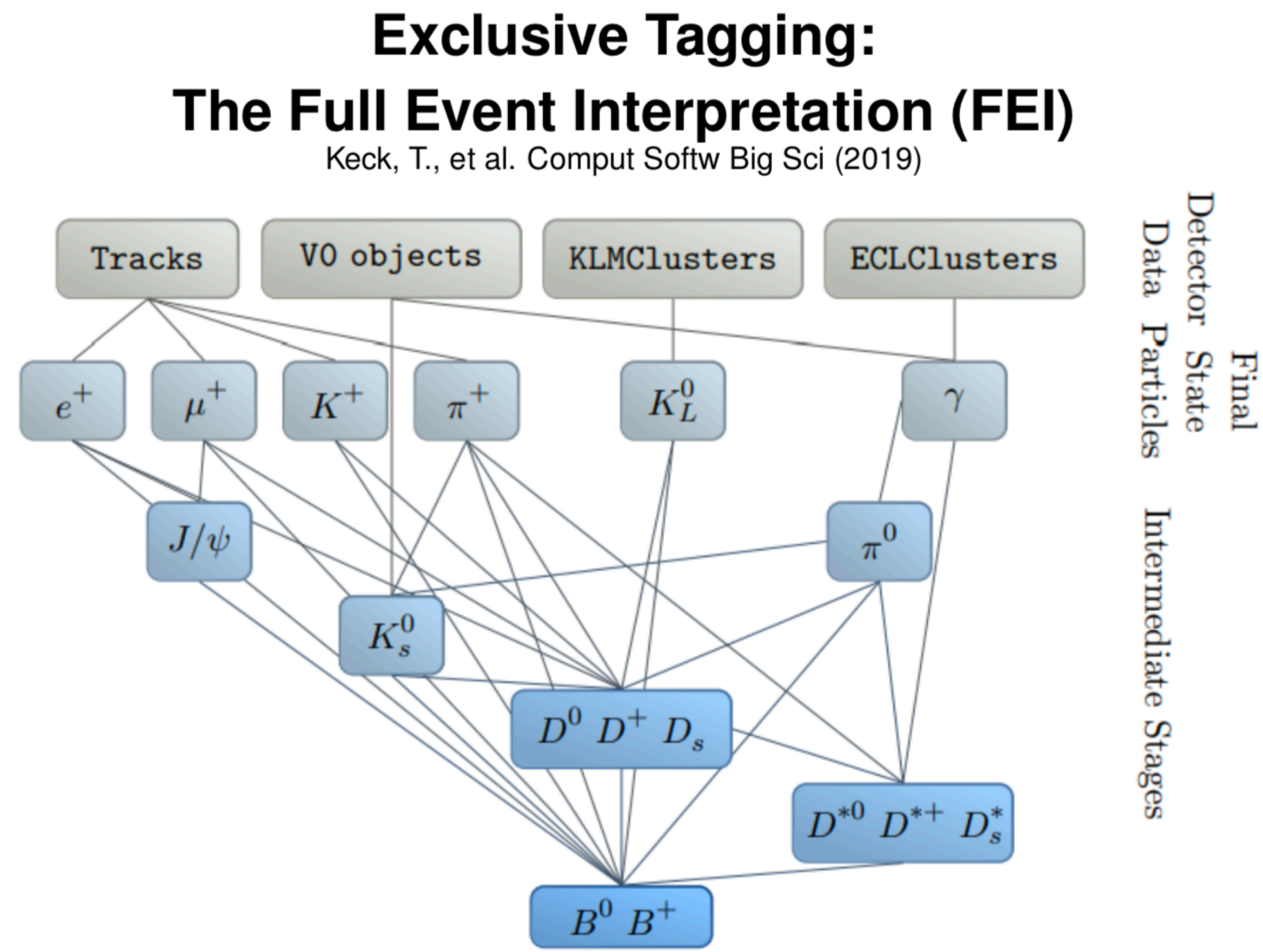


$$\mathcal{R}(D^{*-}) = 0.291 \pm 0.019(\text{stat}) \pm 0.026(\text{syst}) \pm 0.013(\text{ext})$$

B-tagging and FEI







FEI

- the most evolved version of B-tagging S/W
- developed for Belle II; used in several Belle studies

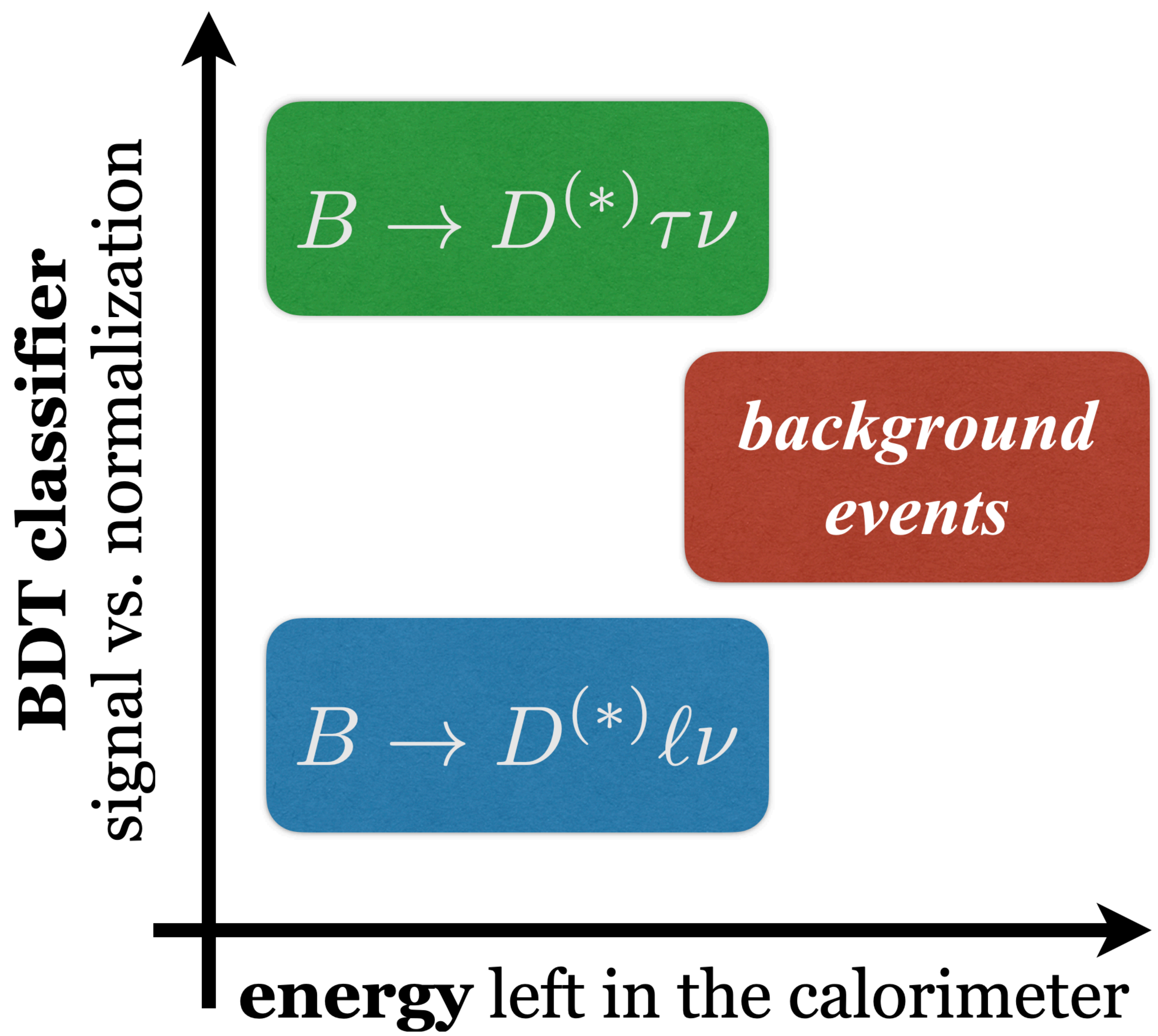
$R(D)$ and $R(D^*)$ with SL tagging

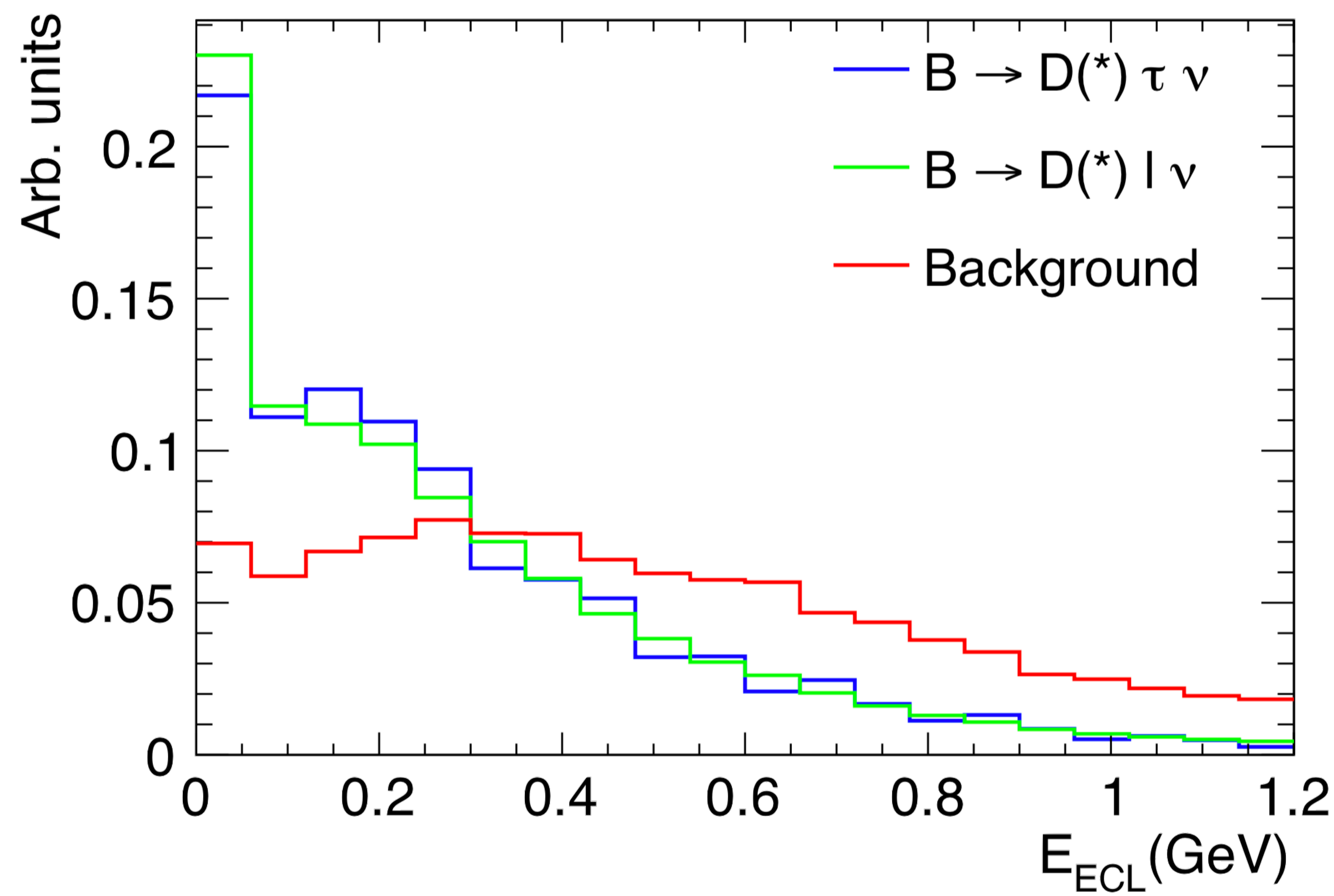
Features of the analysis

- improved over the Belle's old SL-tagged analysis
  Phys. Rev. D 94, 072007 (2016)
  - ✓ $R(D^*)$ only $\Rightarrow$ $R(D)$ and $R(D^*)$, simultaneously
  - ✓ for $R(D^*)$, B^0 only $\Rightarrow$ B^0 and B^+
  - ✓ better B-tagging (FEI, a Belle II s/w)
- on the tag-side, exploit the observable
  - ✓ $\cos\theta_{B,D^{(*)}\ell}$ = angle between B and $D^{(*)}\ell$ in $\Upsilon(4S)$ frame

$$\cos\theta_{B,D^{(*)}\ell} = \frac{2E_{\mathrm{beam}}E_{D^{(*)}\ell} - m_B^2 - m_{D^{(*)}\ell}^2}{2|p_B||p_{D^{(*)}\ell}|}$$

$R(D)$ and $R(D^*)$ with SL tagging





- E_{ECL} to suppress generic background
- BDT classifier to distinguish *Signal* from $D^{(*)}\ell\nu$
  - ✓ based on XGBoost package
  - ✓ uses m^2(miss), E(vis), cos $\theta(B, D^{(*)}\ l\ )$
- 2D fit to (BDT class, E_{ECL})

E_{ECL} = extra energy left in the EM calorimeter

$R(D)$ and $R(D^*)$ with SL tagging

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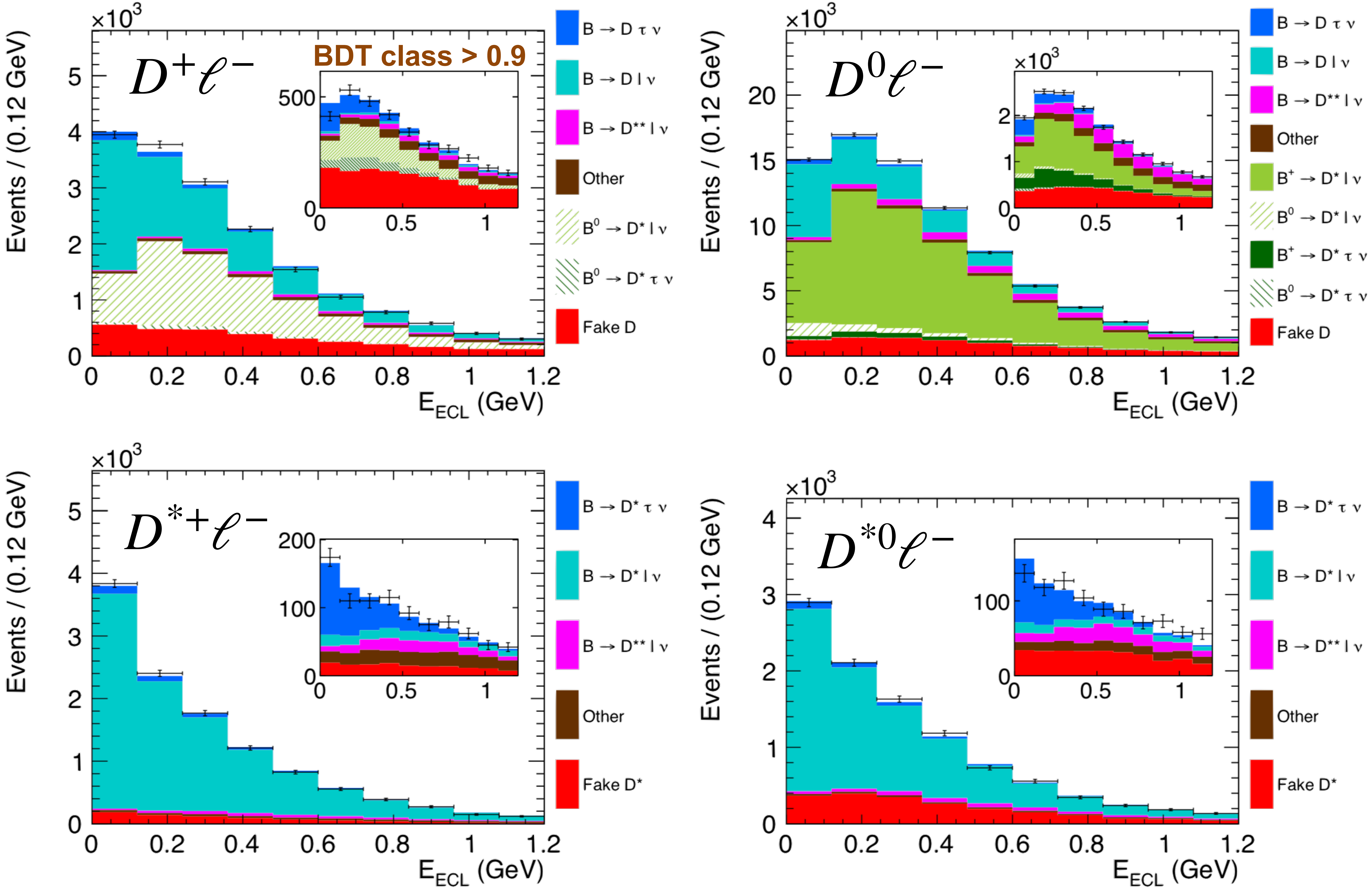
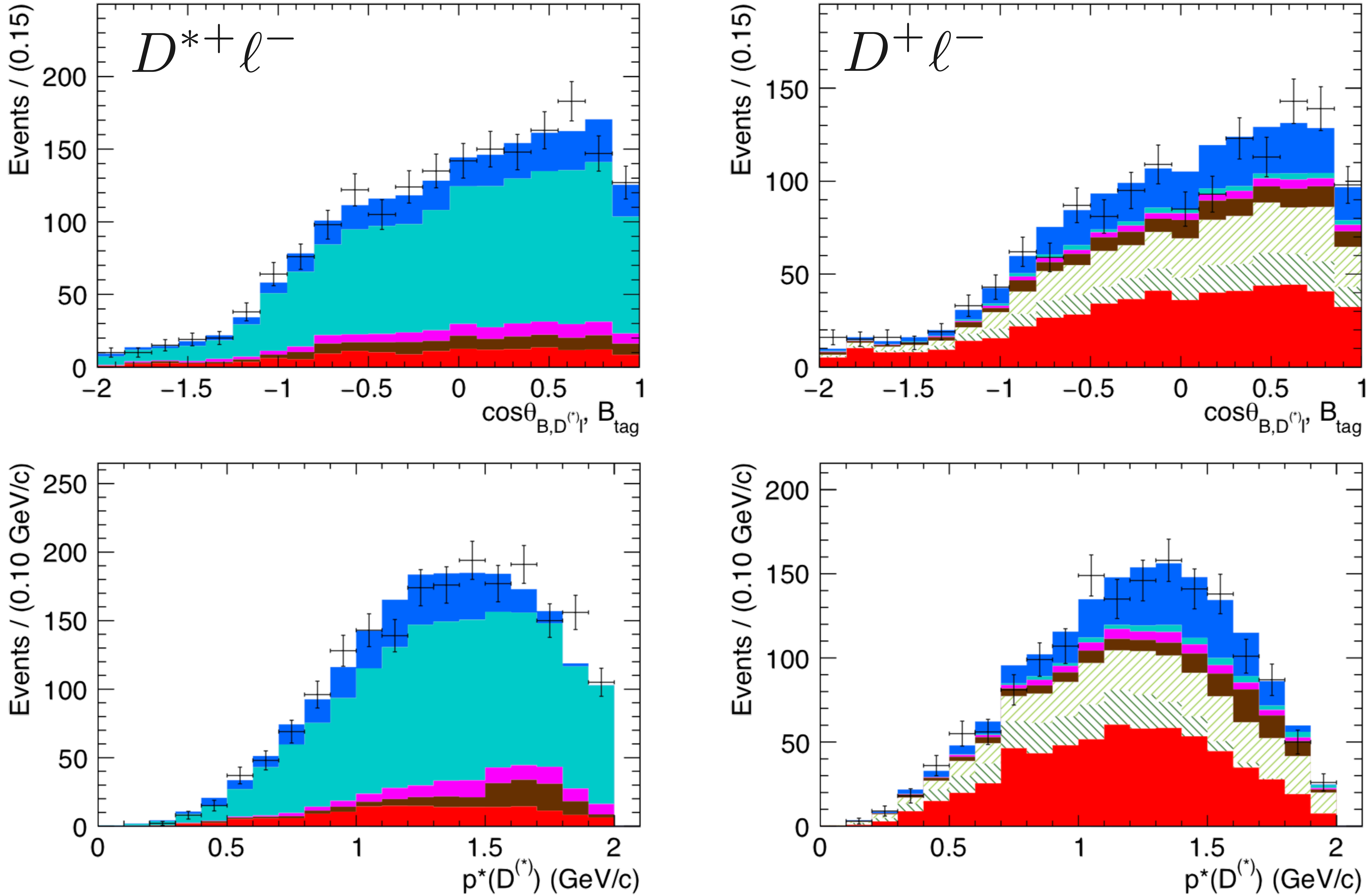


$R(D)$ and $R(D^*)$ with SL tagging

PRL **124**, 161803 (2020)



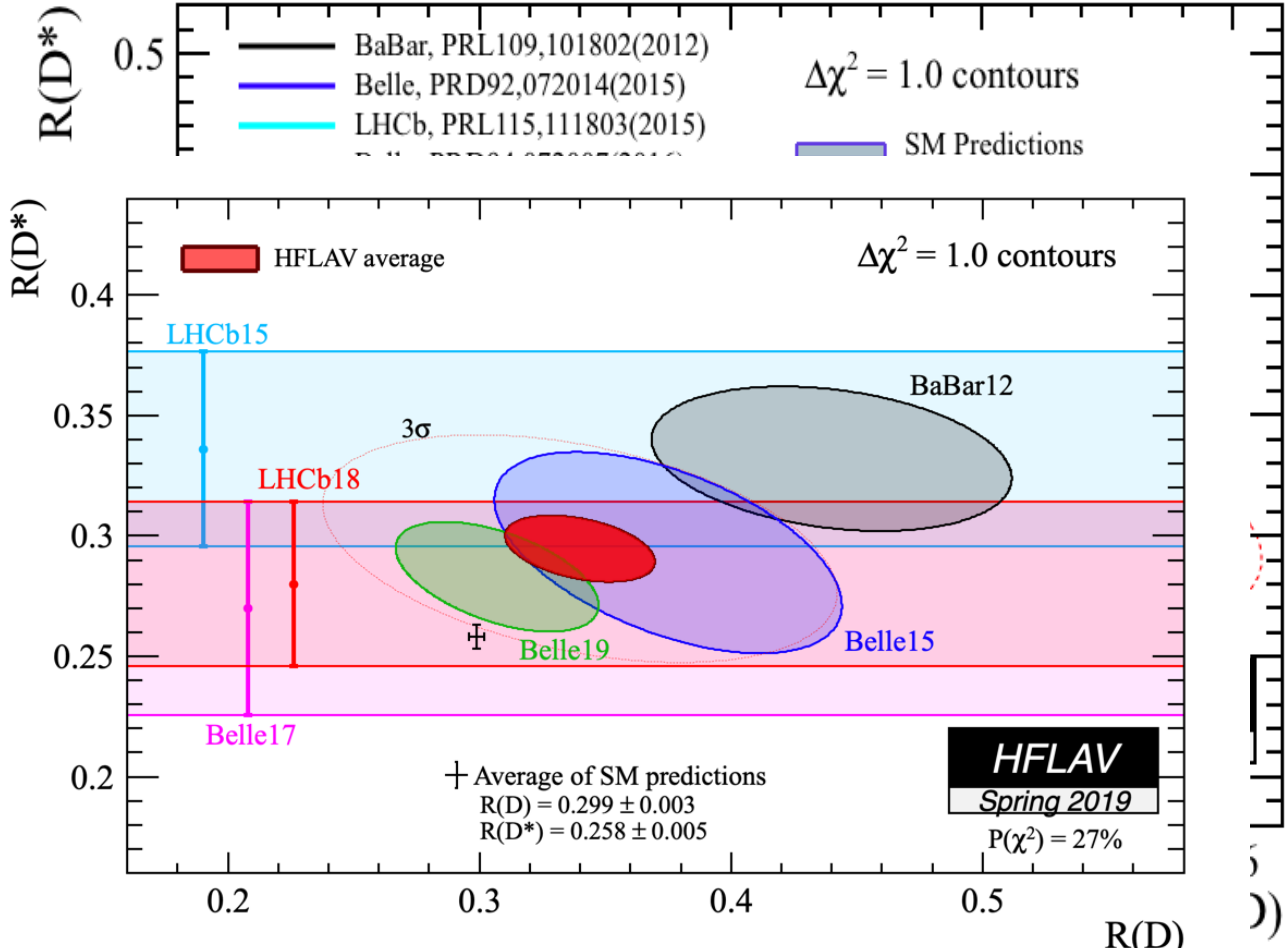
other views of the signal yields

Experiment	Tag method	τ mode	**R(D)**	R(D*)	
Babar '12	Hadronic	ℓ ν ν	**0.440 ± 0.058 ± 0.042**	0.332 ± 0.024 ± 0.018	
Belle '15	Hadronic	ℓ ν ν	**0.375 ± 0.064 ± 0.026**	0.293 ± 0.038 ± 0.015	
LHCb '15	-	ℓ ν ν	-	0.336 ± 0.027 ± 0.030	
Belle '16	Semileptonic	ℓ ν ν	-	0.302 ± 0.030 ± 0.011	B^0
Belle '17	Hadronic	π ν, ρ ν	-	0.270 ± 0.035 ± 0.027	
LHCb '18	-	π π π ν	-	0.291 ± 0.019 ± 0.029	
Belle '19	Semileptonic	ℓ ν ν	0.307 ± 0.037 ± 0.016	0.283 ± 0.018 ± 0.014	B^0, B^+
Average (2018)	-	-	*0.407 ± 0.039 ± 0.024*	*0.306 ± 0.013 ± 0.007*	
Average (2019)	**-**	**-**	**0.340 ± 0.027 ± 0.013**	**0.295 ± 0.011 ± 0.008**	
SM			0.299 ± 0.003	0.258 ± 0.005	

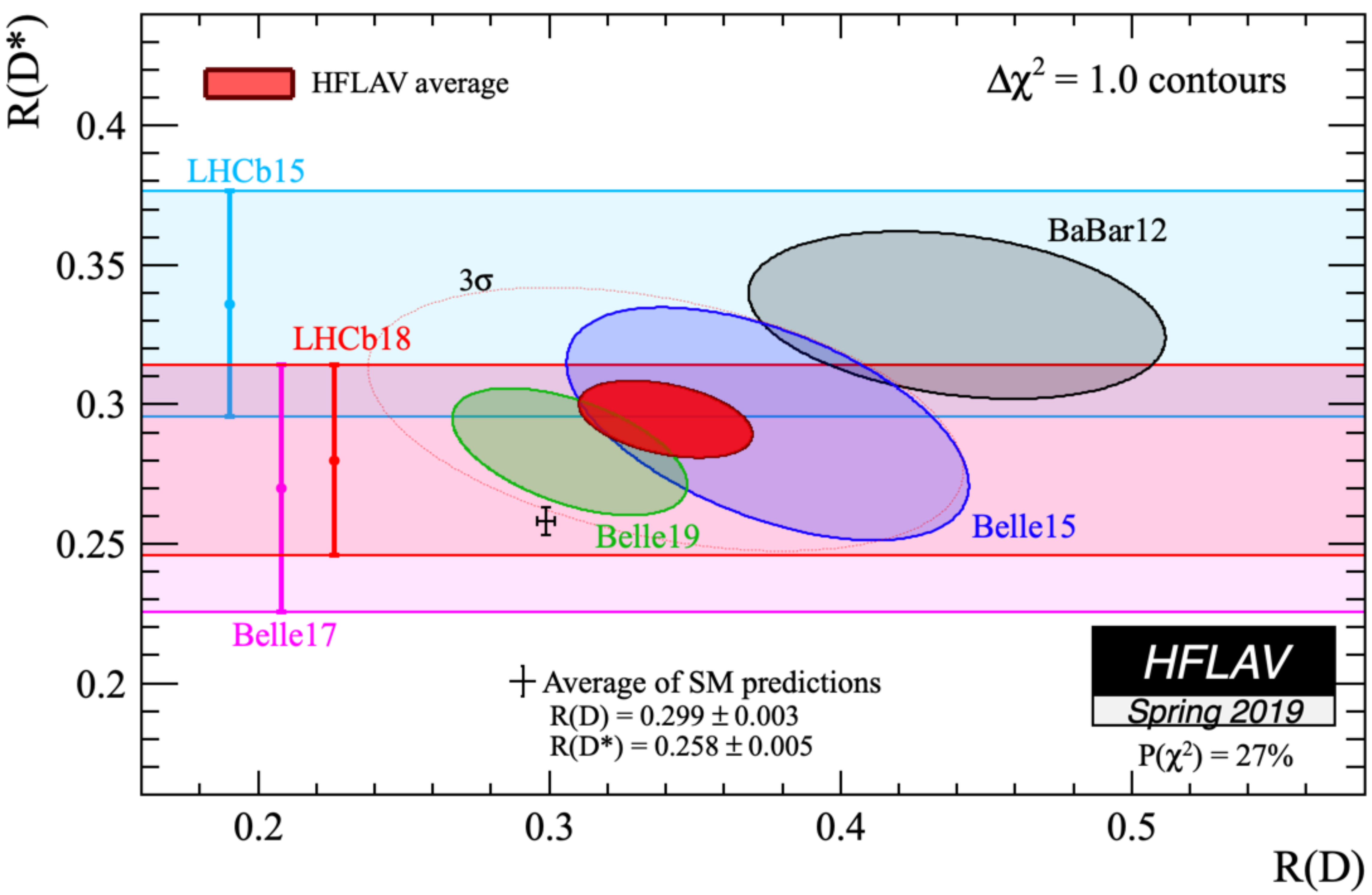
averages from HFLAV

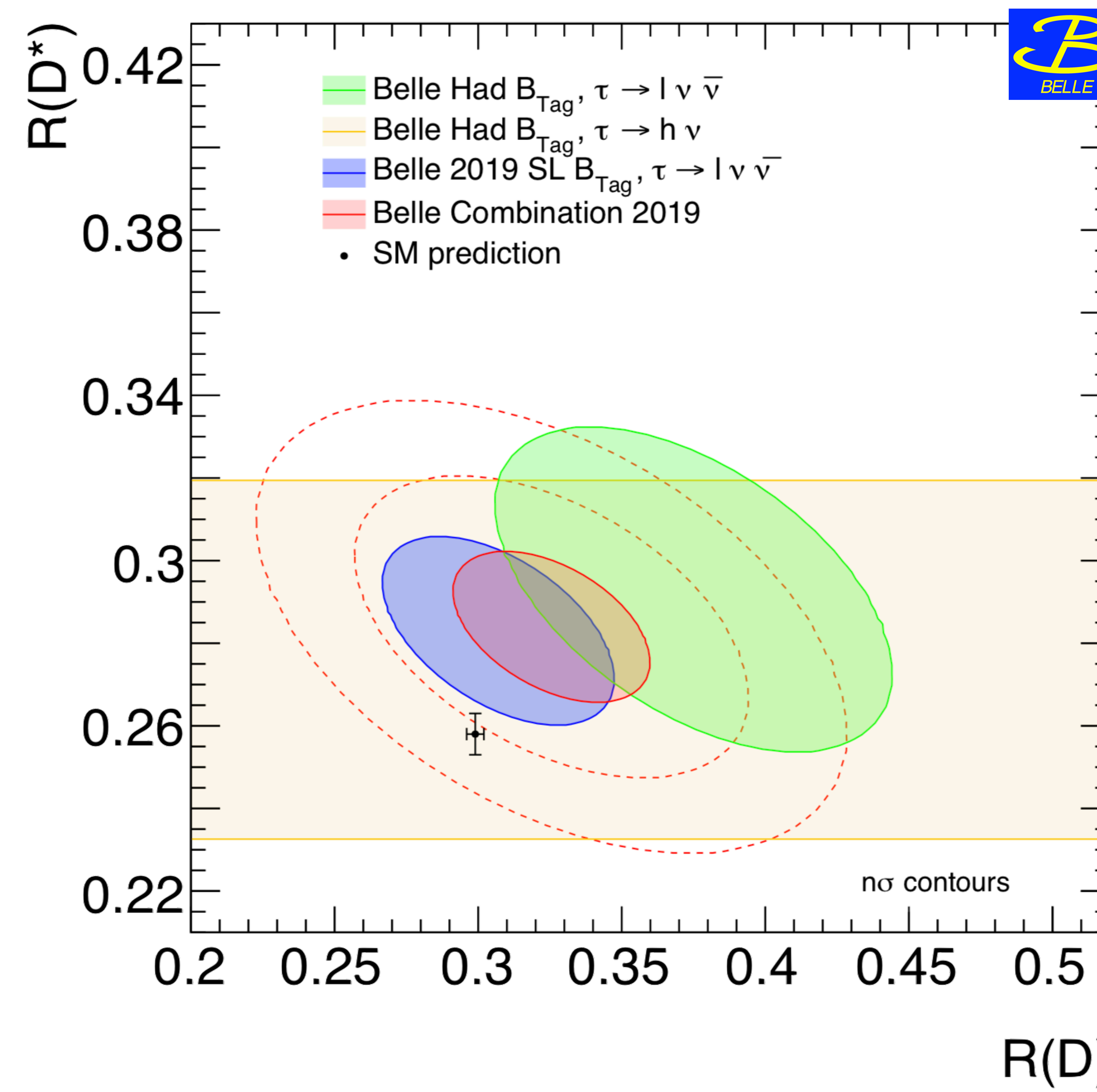
$R(D)$ and $R(D^*)$ updated

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



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





- 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 (was 3.8σ)

Closing remarks

- The B-anomalies in $b \to s\ell^+\ell^-$ (EWP) and in $b \to c\tau^+\nu$ decays are tantalizing, but many questions remain:
  - Are they real (NP)?
  - Are they from a single NP source, or two (or more)?
  - Can it be also related to $(g-2)_\mu$?
- LHCb made impressive series of $R_{K^{(*)}}$ measurements
  - and more b-hadron states are being covered
- Belle has also accomplished an excellent series of $R(D^{(*)})$ measurements
  - Belle's $R_{K^{(*)}}$ are short of statistics, but Belle II is coming
  - and Belle (II) can cover whole q^2 region with ~equal significance

"We shall not cease from exploration"†

† T. S. Eliot