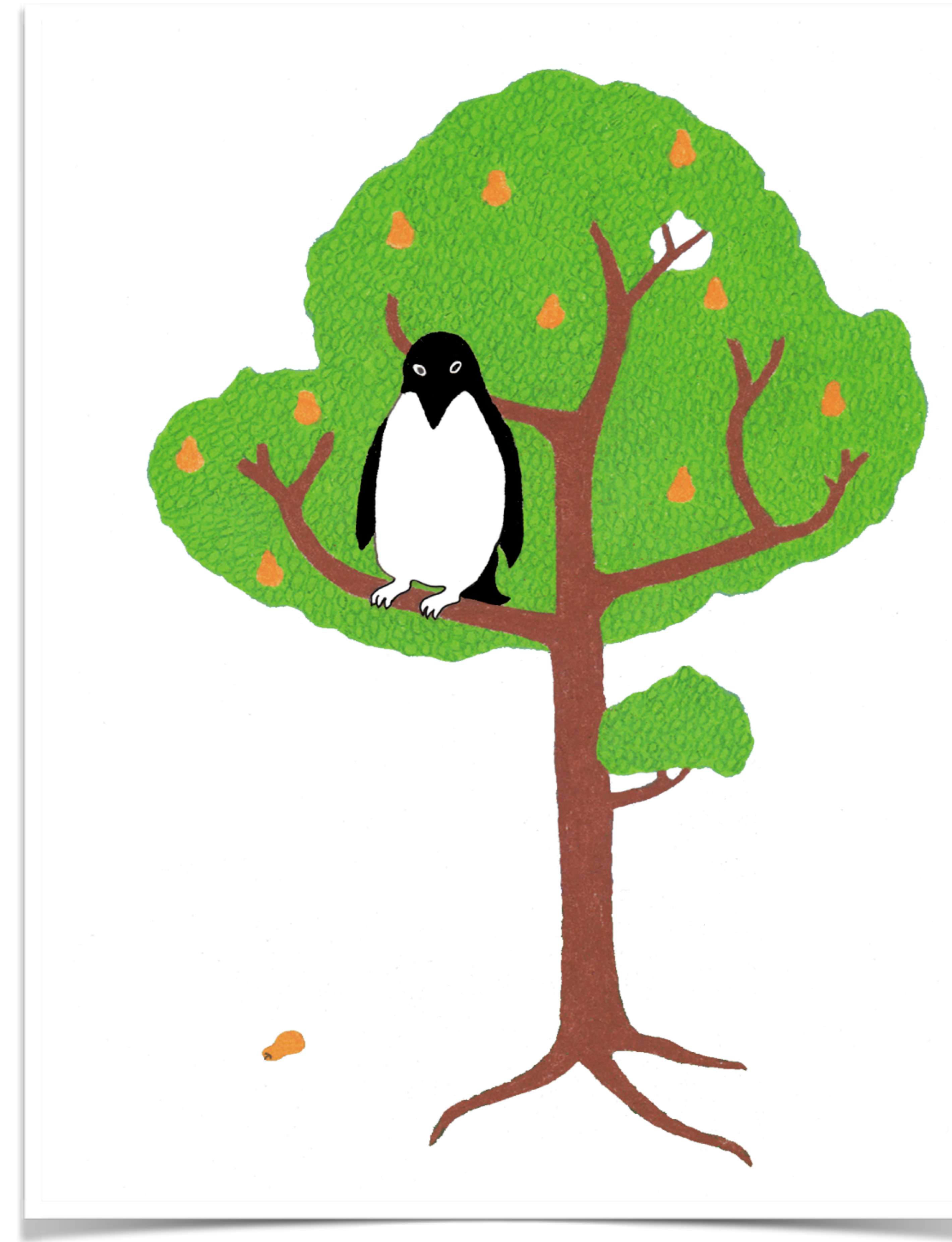
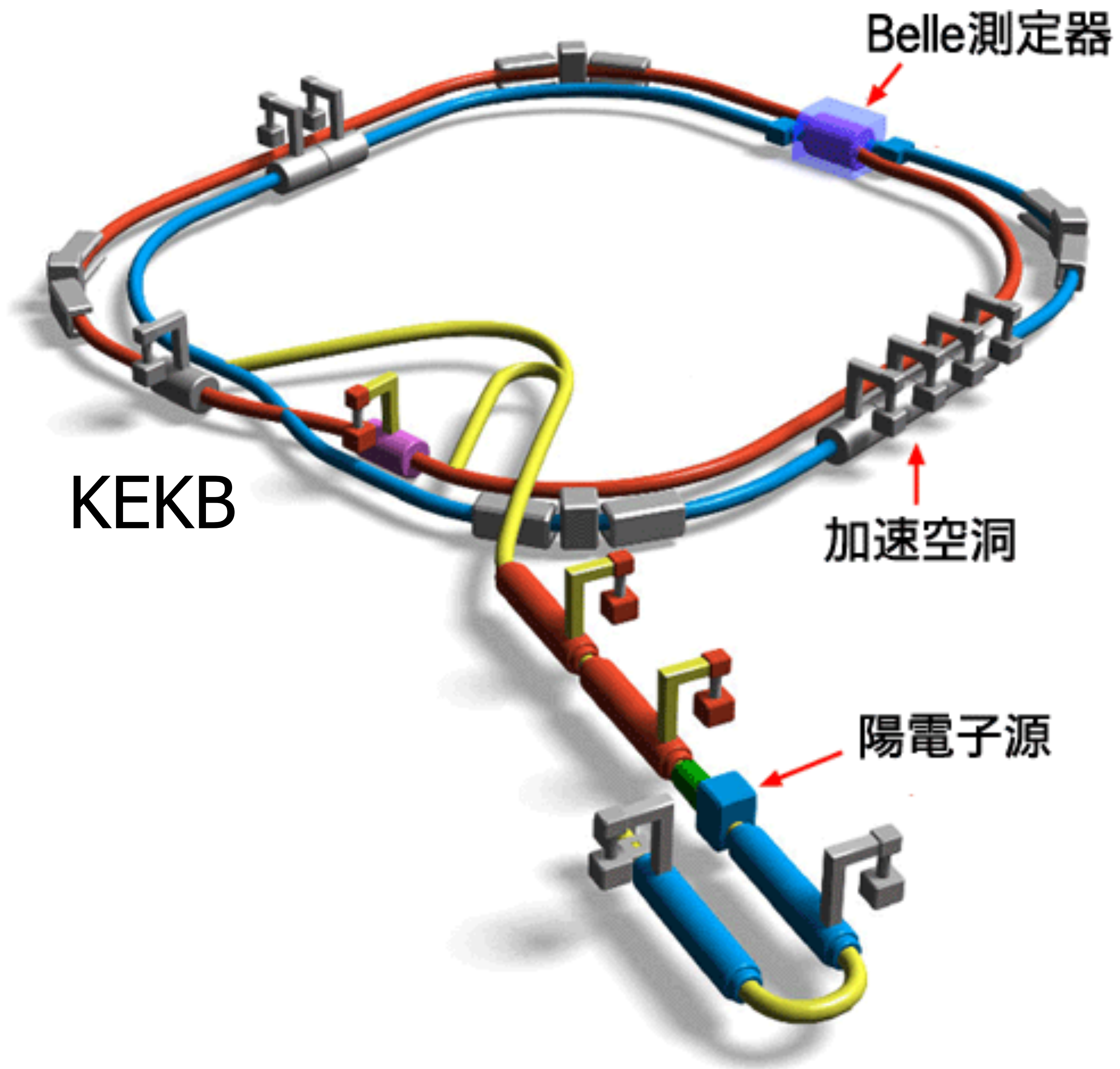
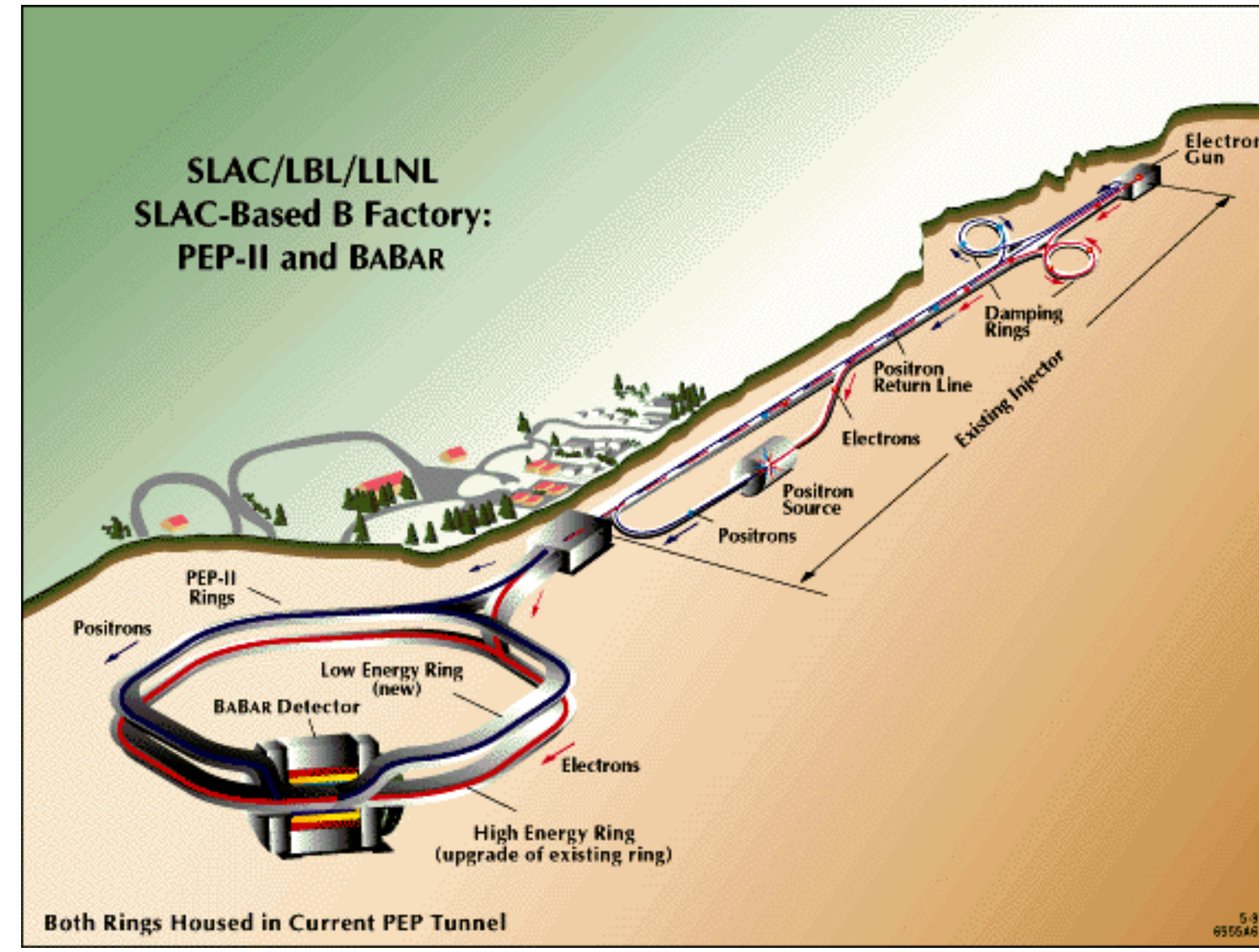
Now the main part for the grown-ups!



Asymmetric B factories: flavour physics at the luminosity frontier





$\sqrt{s}=10.58$ GeV

$e^+ \rightarrow \Upsilon(4s) \leftarrow e^-$

$\Upsilon(4s) \rightarrow B\,\bar{B}$

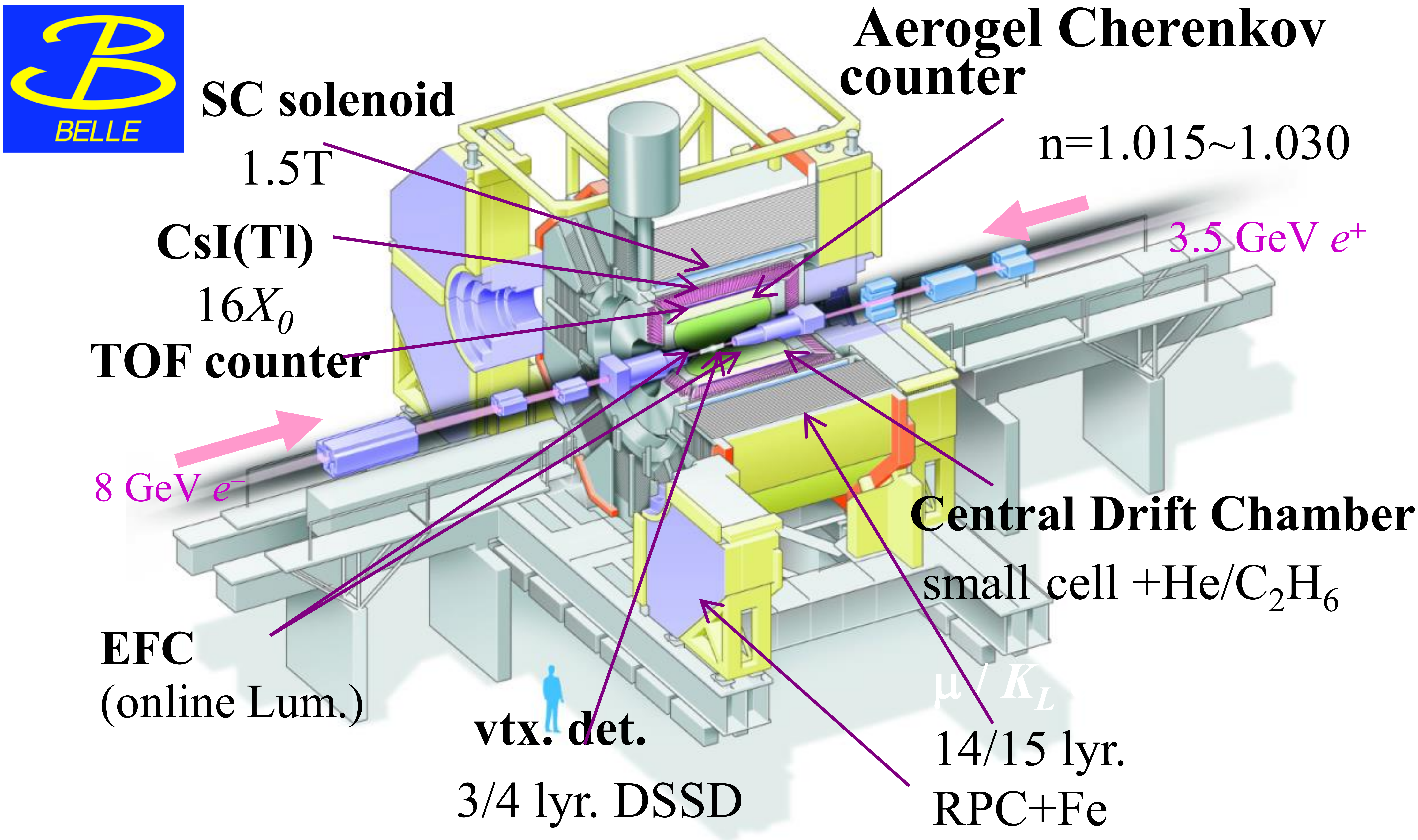
$\Delta z \sim c\beta\gamma\tau_B$

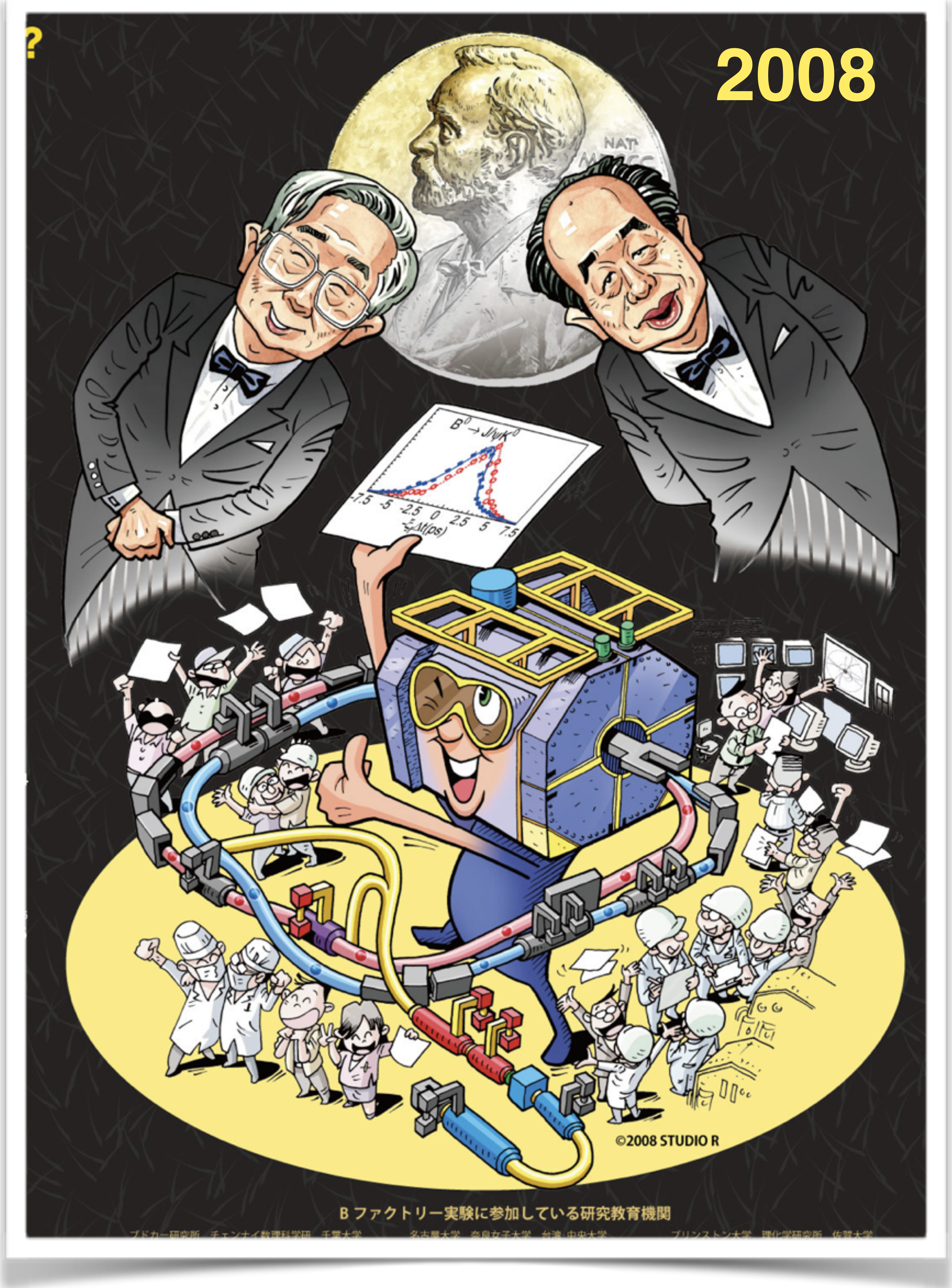
$\sim 200\mu m$

BaBar $p(e^-)=9$ GeV $p(e^+)=3.1$ GeV $\beta\gamma=0.56$

Belle $p(e^-)=8$ GeV $p(e^+)=3.5$ GeV $\beta\gamma=0.42$

To a large degree shaped flavour physics in the previous decade

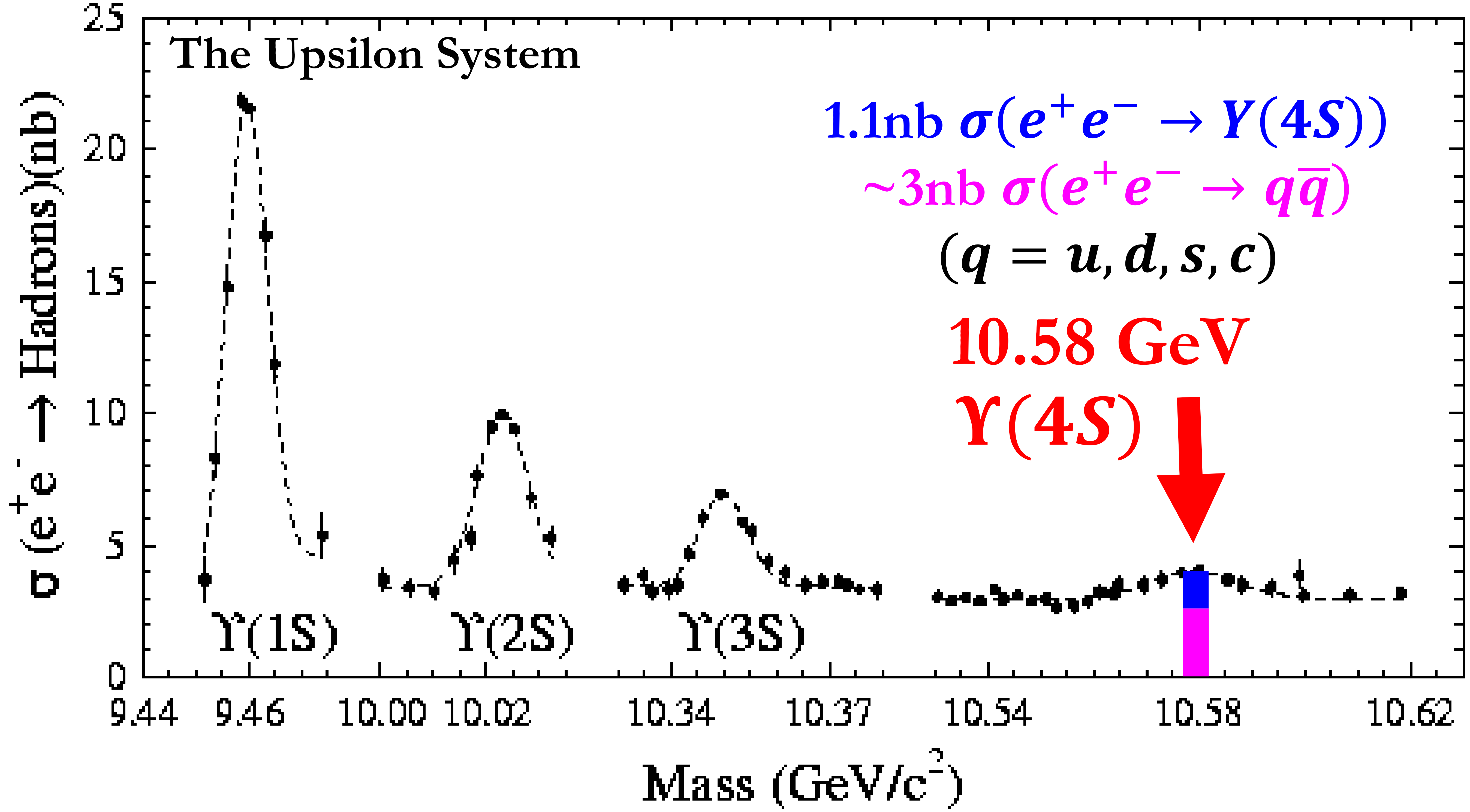

BELLE
SC solenoid
1.5T
CsI(Tl)
16X_0
TOF counter
Aerogel Cherenkov counter
n=1.015~1.030
3.5 GeV e^+
8 GeV e^-
Central Drift Chamber
small cell +He/C_2H_6
EFC
(online Lum.)
vtx. det.
3/4 lyr. DSSD
μ / K_L
14/15 lyr.
RPC+Fe



Belle (and BaBar, too) achievements include:

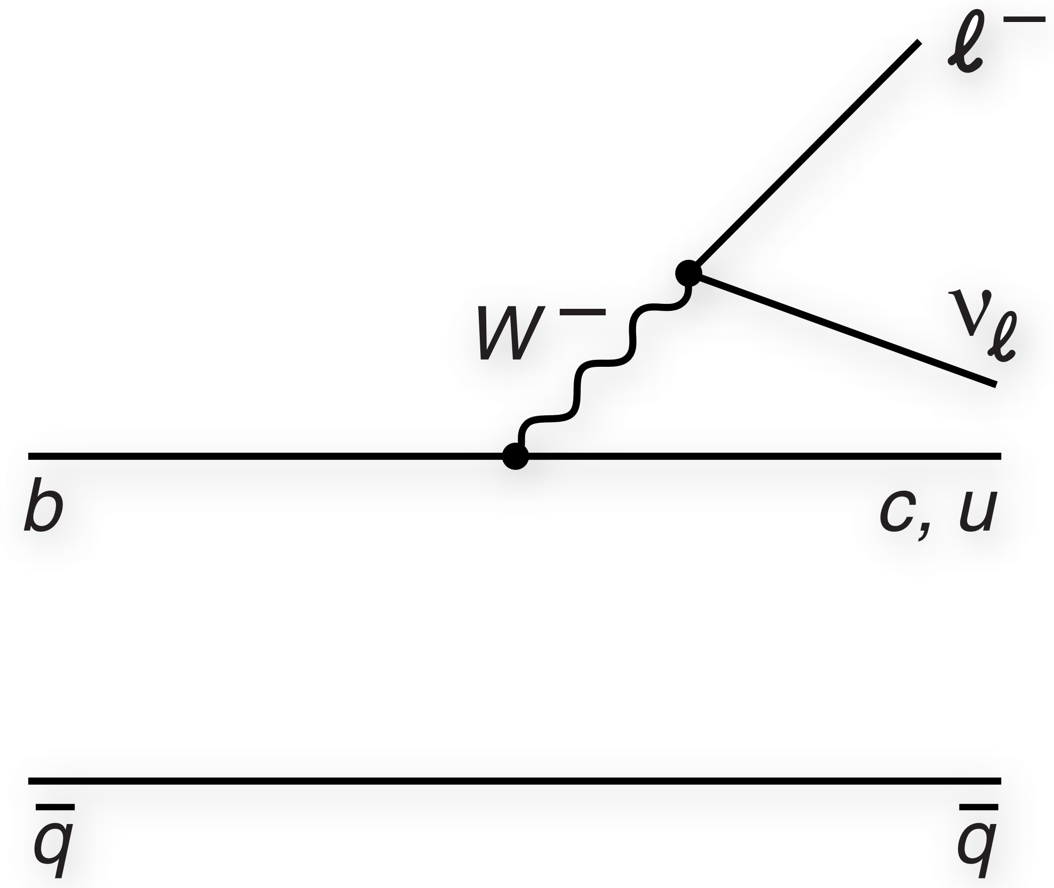
- CPV, CKM, and rare decays of B (and B_s, too)
- Mixing, CP, and spectroscopy of charm hadrons
- Quarkonium spectroscopy and discovery of (*many*) exotic states, e.g. $X(3872)$
- Studies of τ and 2γ

$e^+e^- \to \Upsilon(4S)$ 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

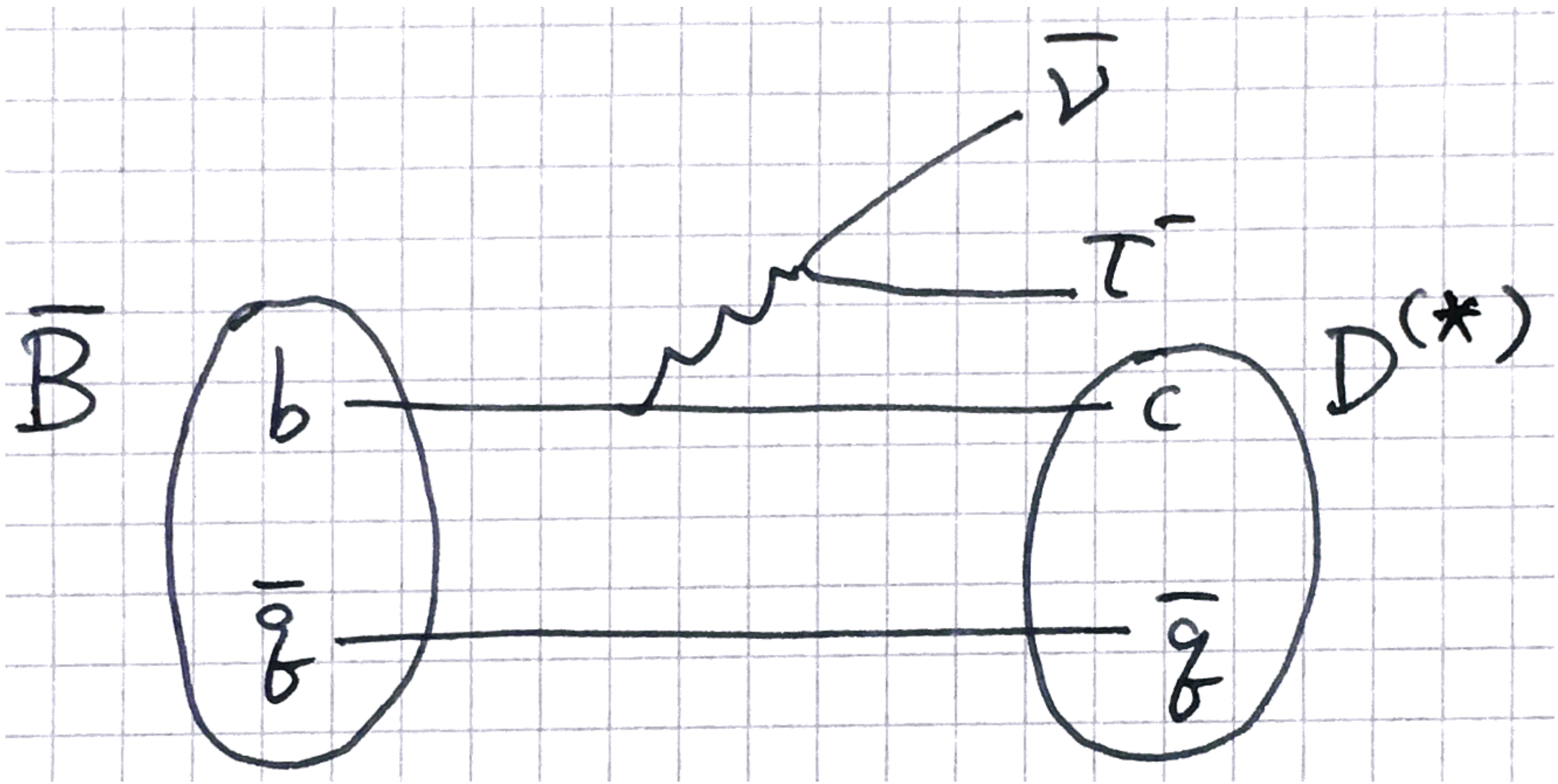
  $\therefore$ if we know $(E, \vec{p})$ of one B, the other B is also constrained



(b) Semileptonic

Semileptonic decays

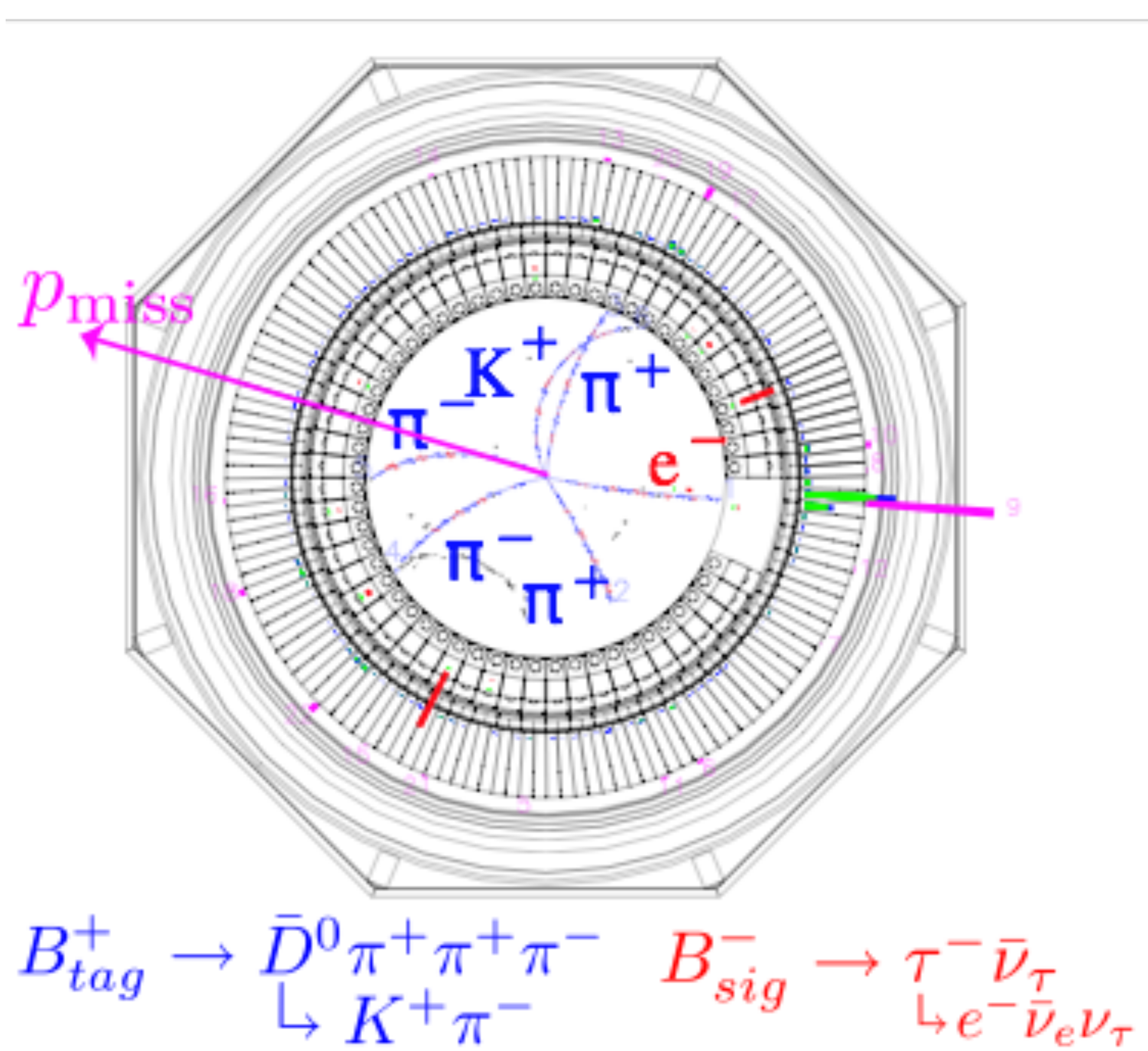
$B \rightarrow D^* \tau \nu$

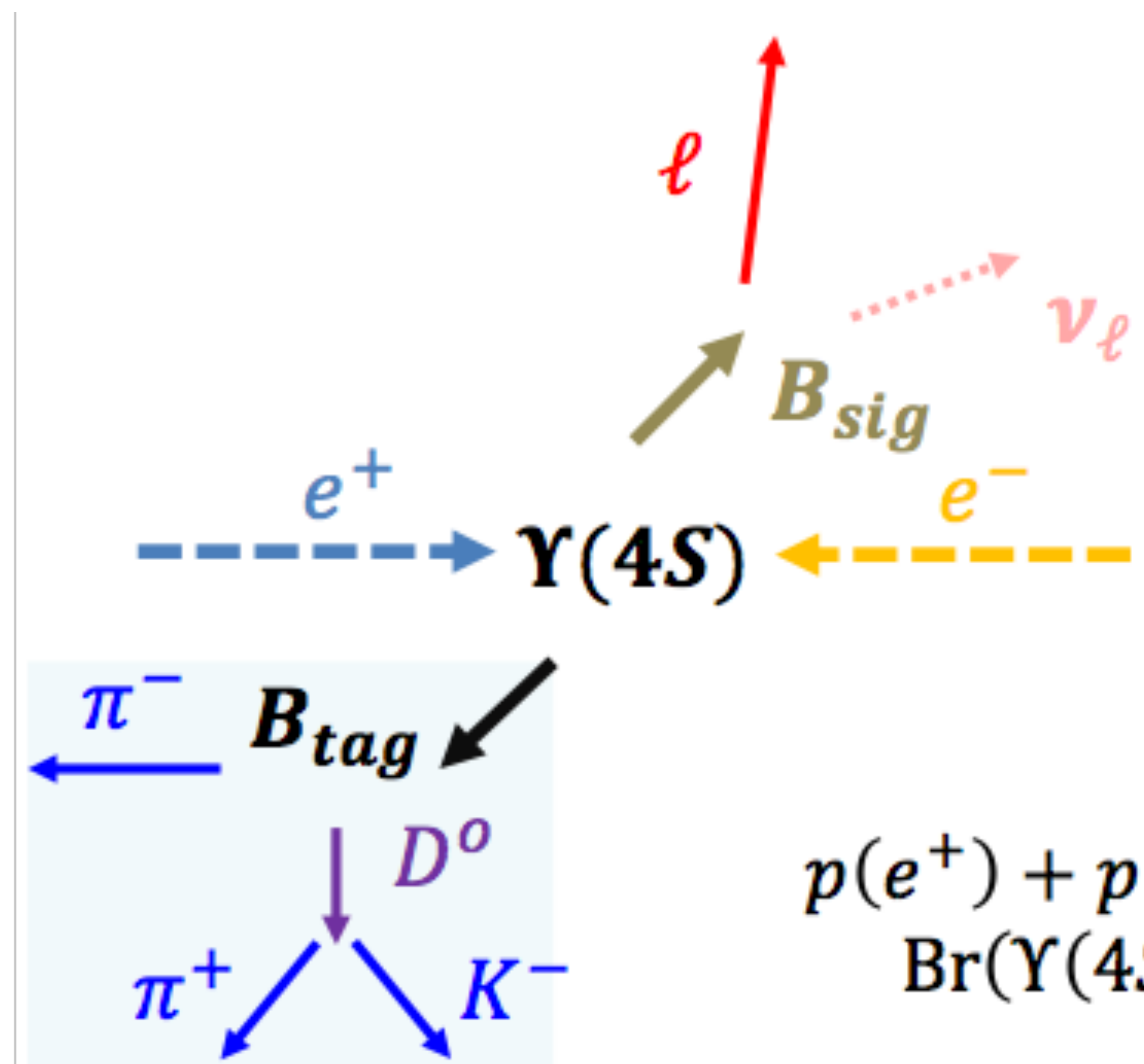


$\bar{\nu}$
τ^-
$D^{(*)}$
$\bar{B}$
b
c
$\bar{q}$
$\bar{q}$

How to study decays with invisible particles

- (Ex) $B \to X_u \ell^+ \nu_\ell$, $B^+ \to \tau^+ \nu_\tau$ and other exotic kinds (e.g. $B^0 \to \nu\bar{\nu}$)
- hadronic tagging method
  - * full reconstruction of B_{tag} in $\Upsilon(4S) \to B_{\mathrm{sig}} B_{\mathrm{tag}}$
    $\Rightarrow$ constrain the charge, flavor, & $(E, \vec{p})$ of B_{sig}
    $\Rightarrow$ resulting in very high-purity, but with low-efficiency ($\sim \mathcal{O}(0.1\%)$)
  - * need an algorithm for improved full-reconstruction of B mesons

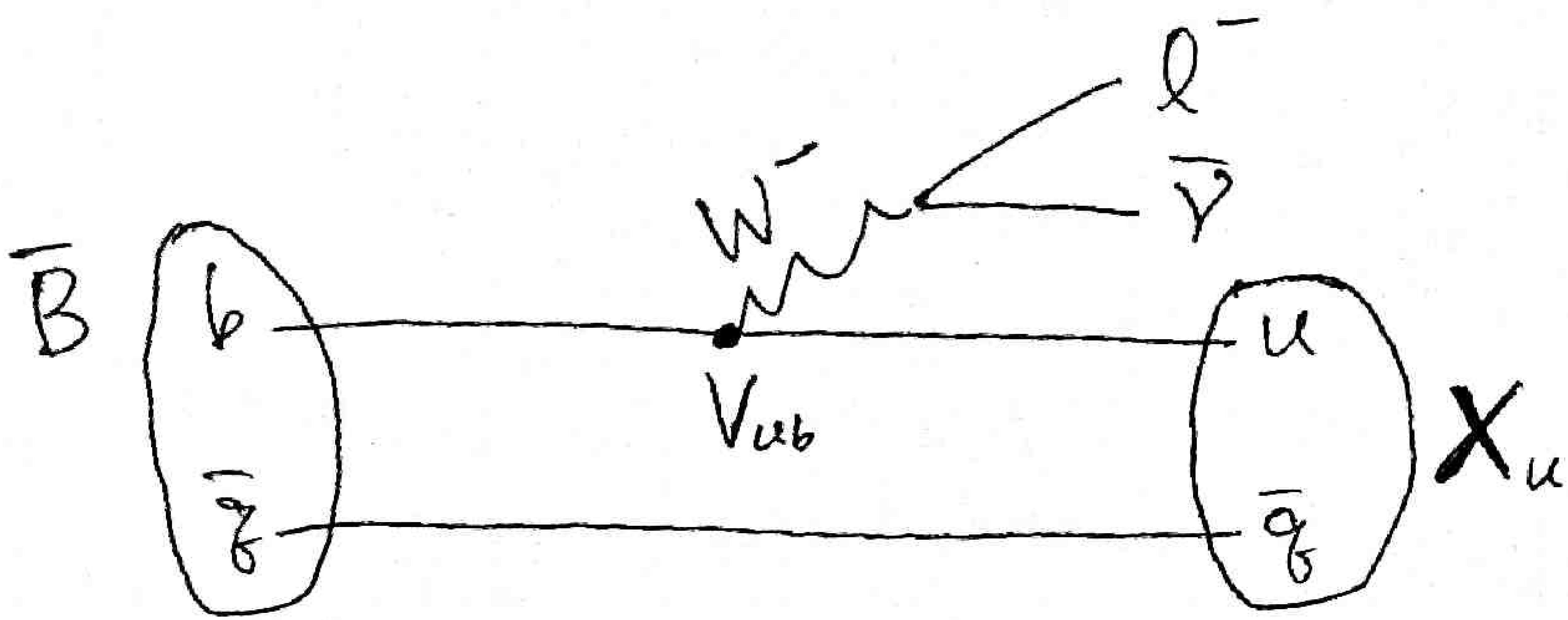




$p(e^+) + p(e^-) = p(B) + p($

$\mathrm{Br}(\Upsilon(4S) \to B\bar{B}) > 96\%$

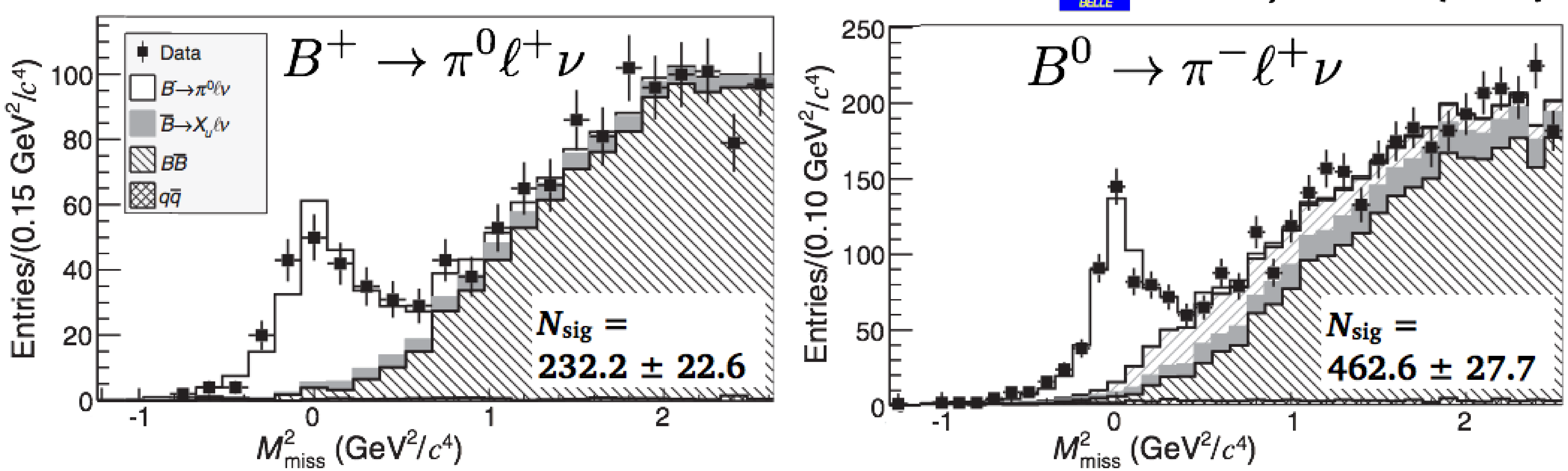
Proof of principle with $B \to X_u \ell \nu$



$B \to \pi \ell^+ \nu_\ell$ (hadronic tagging)

- analysis with full data set ($N_{B\bar{B}} = 772 \times 10^6$)
- hadronic tagging method (NeuroBayes)
- signal yield is extracted by max.-likelihood fit on M^2_{miss}

PRD 88, 032005 (2013)



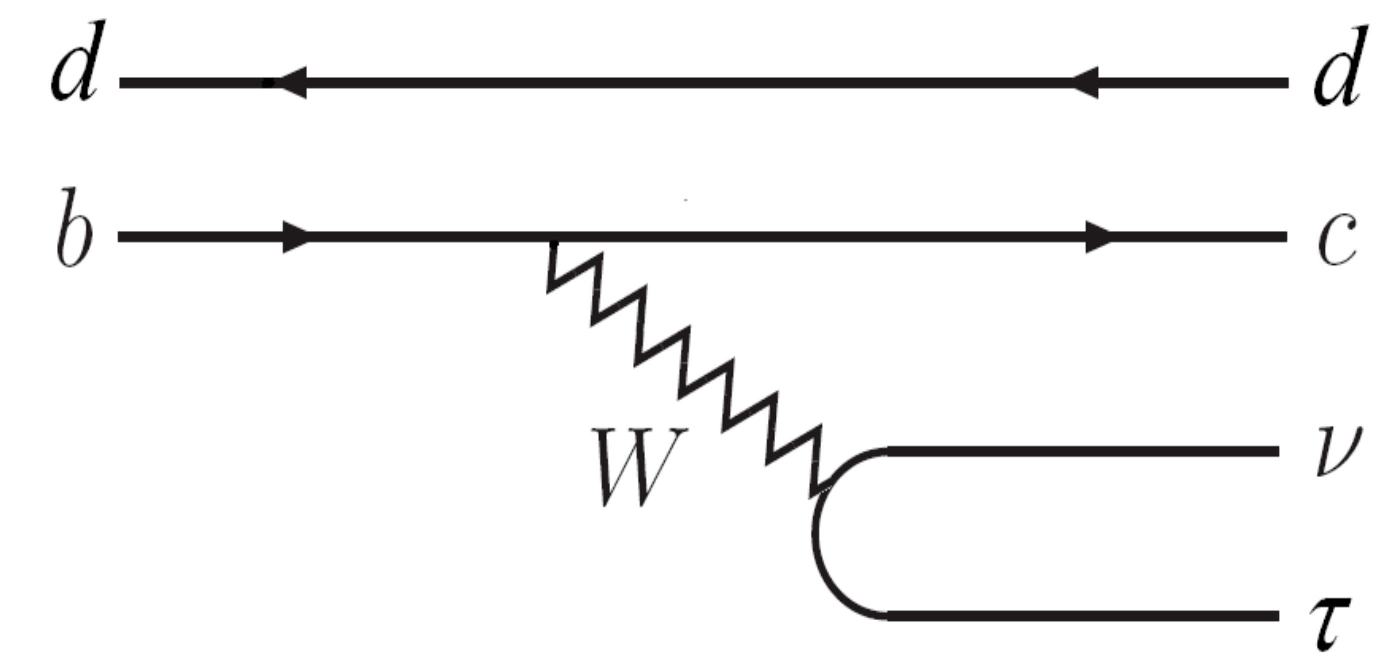
stat. error only for N_{sig}

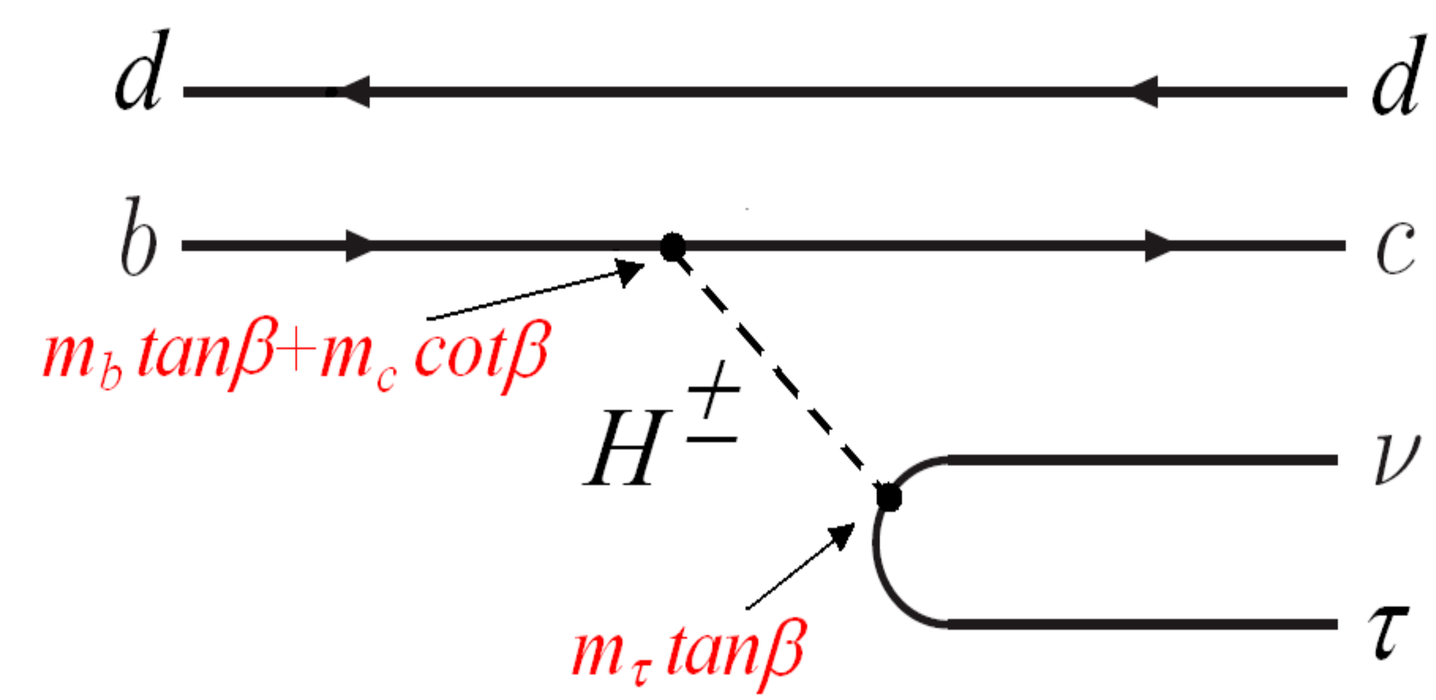
$$\mathcal{B}(B^+ \to \pi^0 \ell^+ \nu_\ell) = (0.80 \pm 0.08 \pm 0.04) \times 10^{-4}$$
$$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu_\ell) = (1.49 \pm 0.09 \pm 0.07) \times 10^{-4}$$

Major systematic error is from the full-recon tag efficiency, checked with $B \to D^{(*)} \ell^+ \nu_\ell$ decays
$\Rightarrow$ 4.2% (4.7%) for B^+ (B^0)

$B \to D^* \tau \nu$

- missing piece of B semileptonic decays
- good features
  - due to heavy m_τ, sensitive to H^+
  - $\mathcal{B}(B \to \overline{D}^{(*)}\tau^+\nu) \gg \mathcal{B}(B^+ \to \tau^+\nu)$
  - access to more dynamical info. through τ polarization
- but, very difficult for analysis
  - multiple ν's
  - large background from $B \to DX\ell^+\nu$
- $B \to \overline{D}^{(*)}\tau^+\nu$ depends on form-factor
  - but, it can be deduced from $B^+ \to \overline{D}^{(*)}\ell^+\nu$

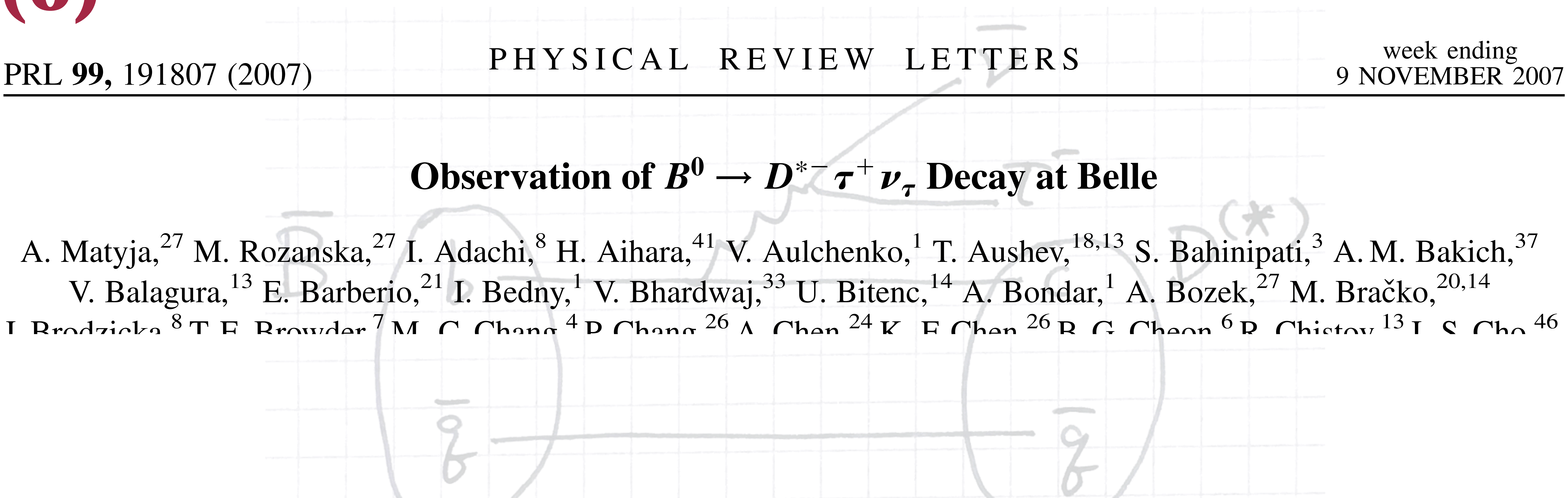




(SM) $\mathcal{B}(B \to \overline{D}^*\tau^+\nu) \approx 1.4\%$, $\mathcal{B}(B \to \overline{D}\tau^+\nu) \approx 0.7\%$

$B \rightarrow D^* \tau \nu$

(0)


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

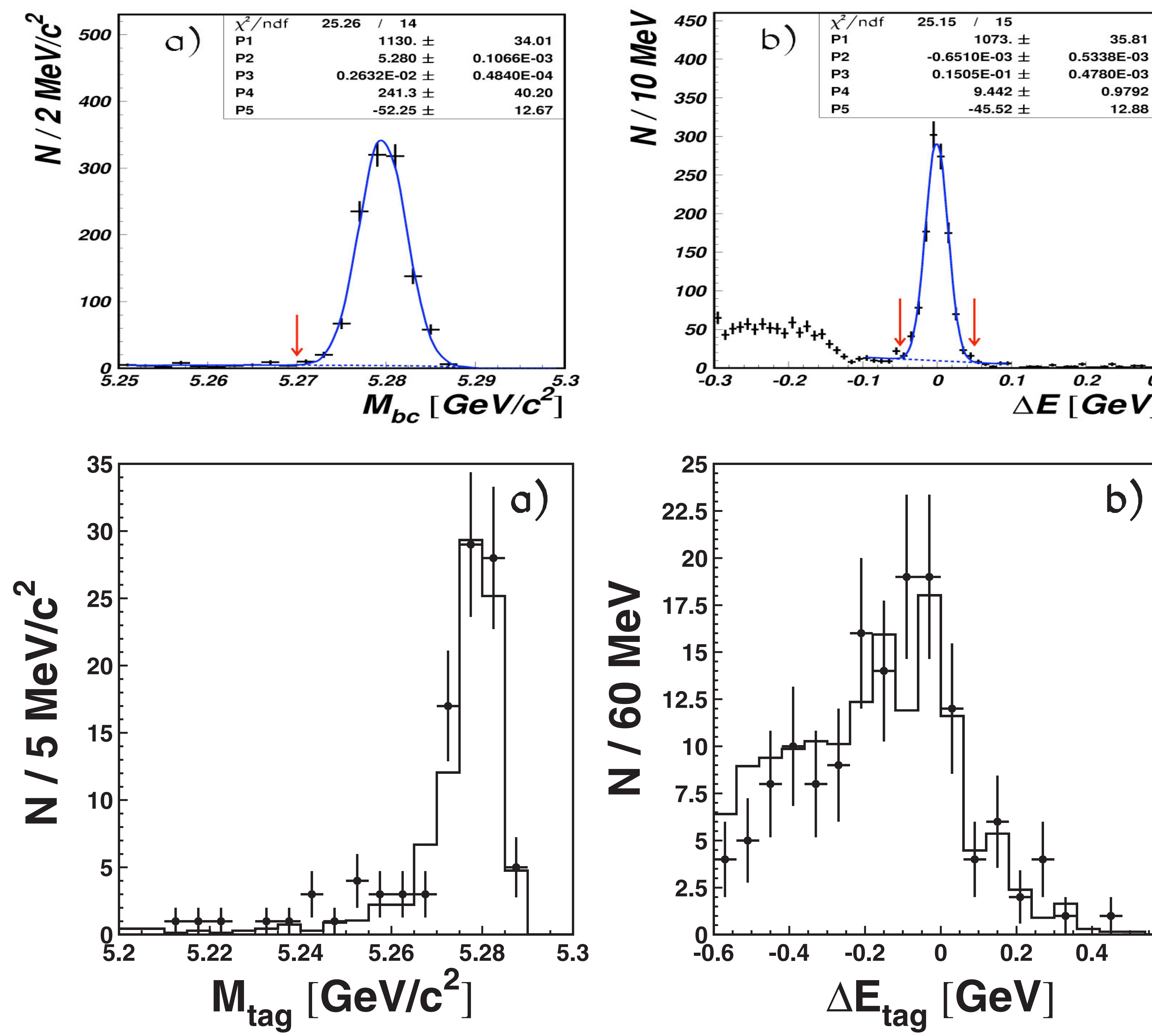
Observation of $B^0 \rightarrow D^{*-} \tau^+ \nu_\tau$ Decay at Belle

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] I.-S. Cho,[46]

First observed by Belle (2007)

$(B^0 \to D^{*-}\tau^+\nu)$ first observation

- full-recon tagging (á la $B^+ \to \tau^+\nu$)
- but a different implementation – **‘inclusive recon’**
  - not pay attention to any specific sub-resonance, but just collect particles to make a “B”
  - use all remaining particle after selecting candidate particles for $B_{\rm sig}$
- increased effic’y compared to exclusive full-recon
- $M_{\rm tag}$, $\Delta E_{\rm tag}$ as useful variables



calibration: $B^0 \to D^{*-}\pi^+$

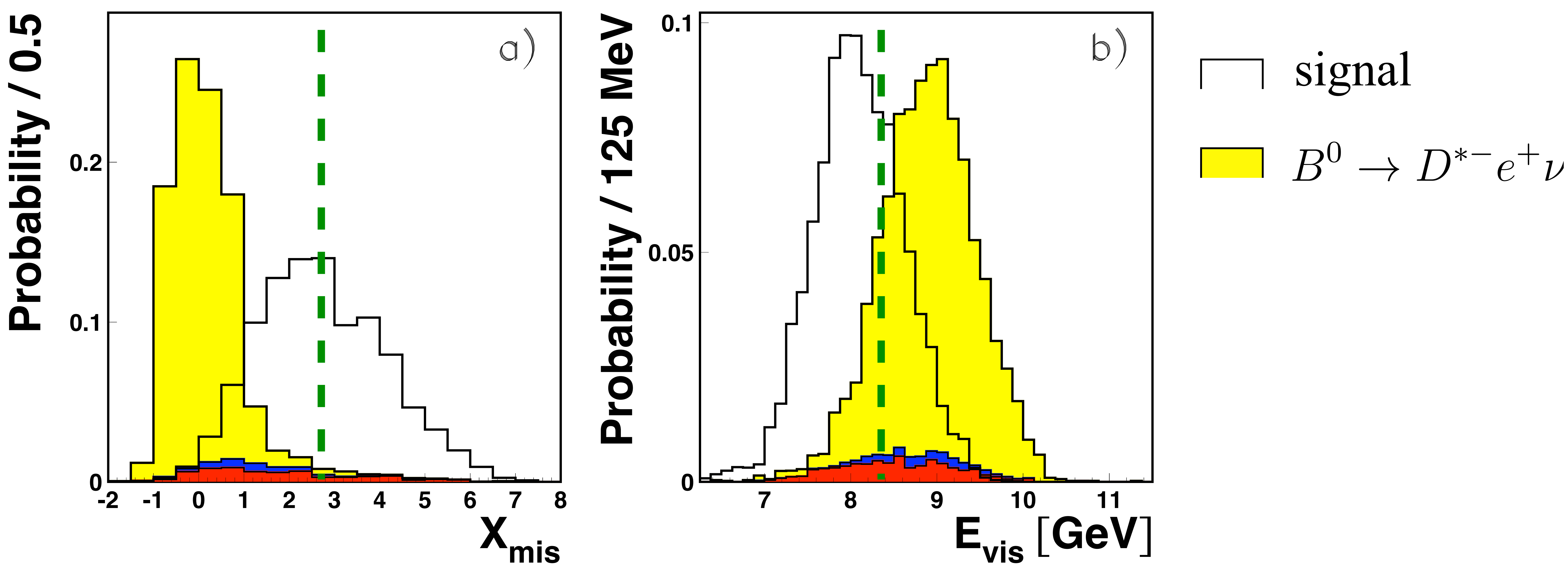
$(B^0 \to D^{*-}\tau^+\nu)$ first observation

Background suppression

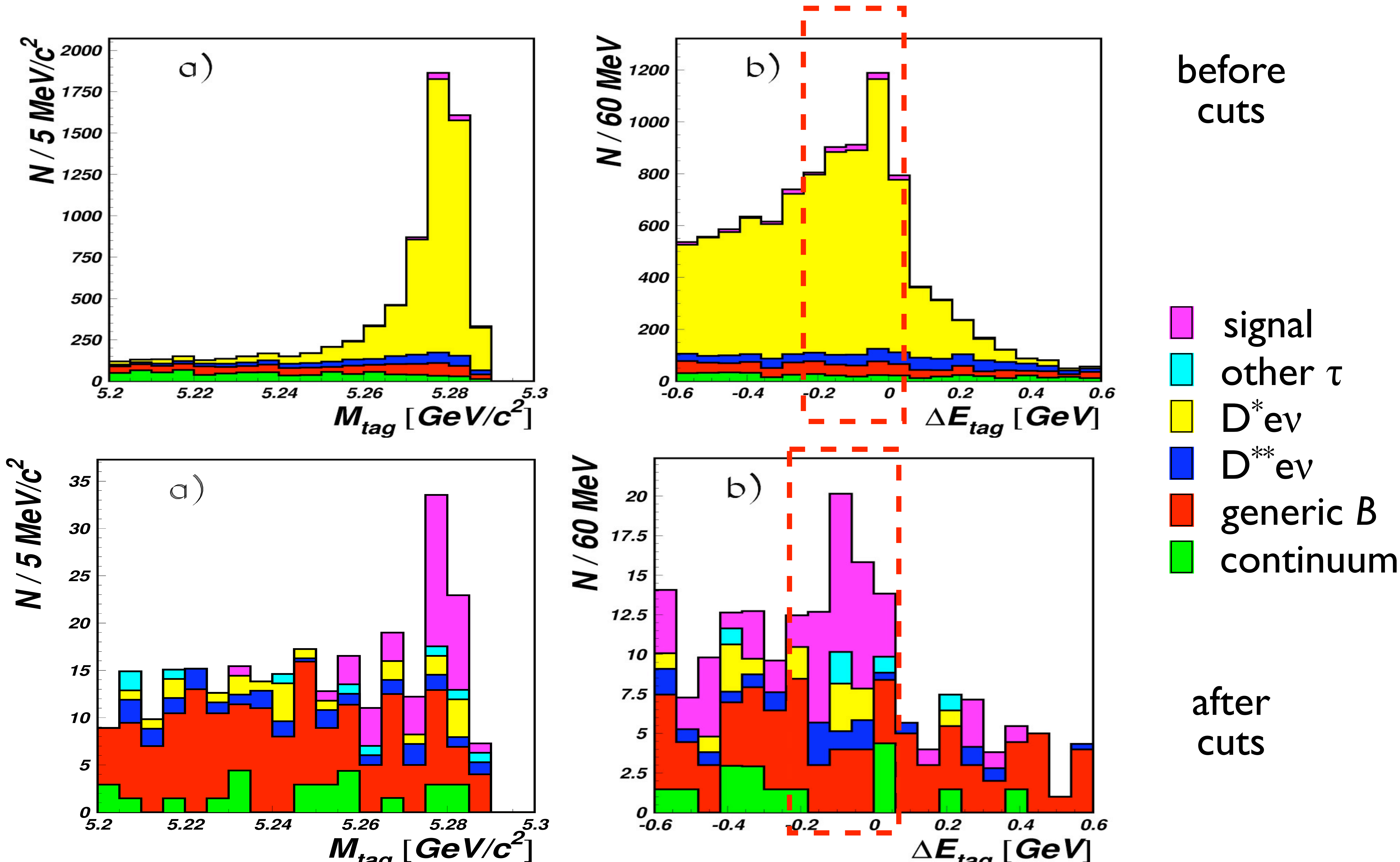
- Need to suppress huge backg'd from $B \to D^* e\nu$
- Useful variables
  - $X_{\rm mis}$: similar to $M^2_{\rm mis}$; most powerful
  - $E_{\rm vis}$ $(\equiv \sum_i E_i)$ is useful, too

$$E_{\rm mis} = E_{\rm beam} - E_{D^*} - E_{e/\pi}$$

$$X_{\rm mis} = \frac{E_{\rm mis} - \left|\vec{p}_{D^*} + \vec{p}_{e/\pi}\right|}{\sqrt{E^2_{\rm beam} - M^2_B}}$$



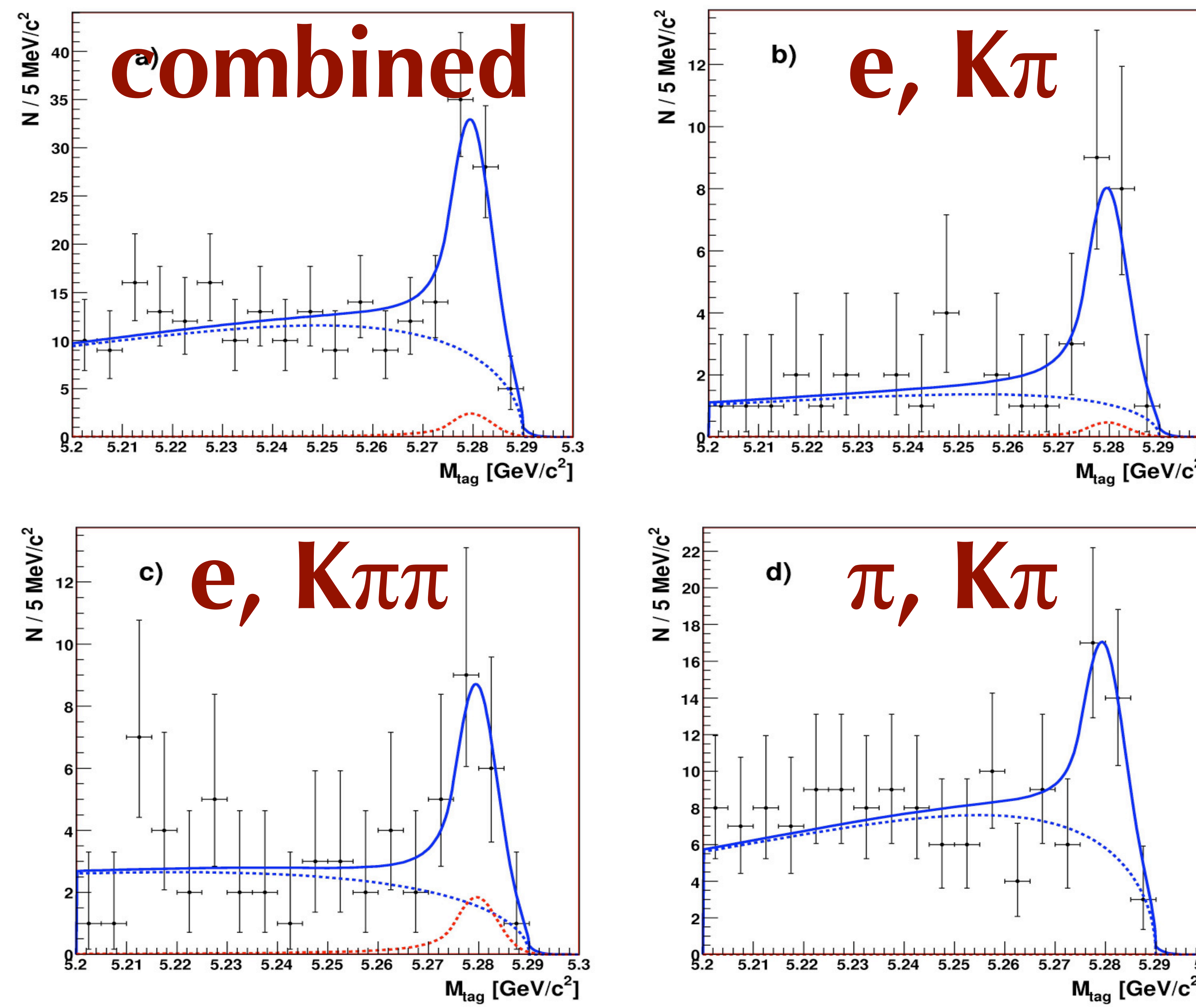
Background suppression



$(B^0 \to D^{*-}\tau^+\nu)$ first observation

Signal extraction

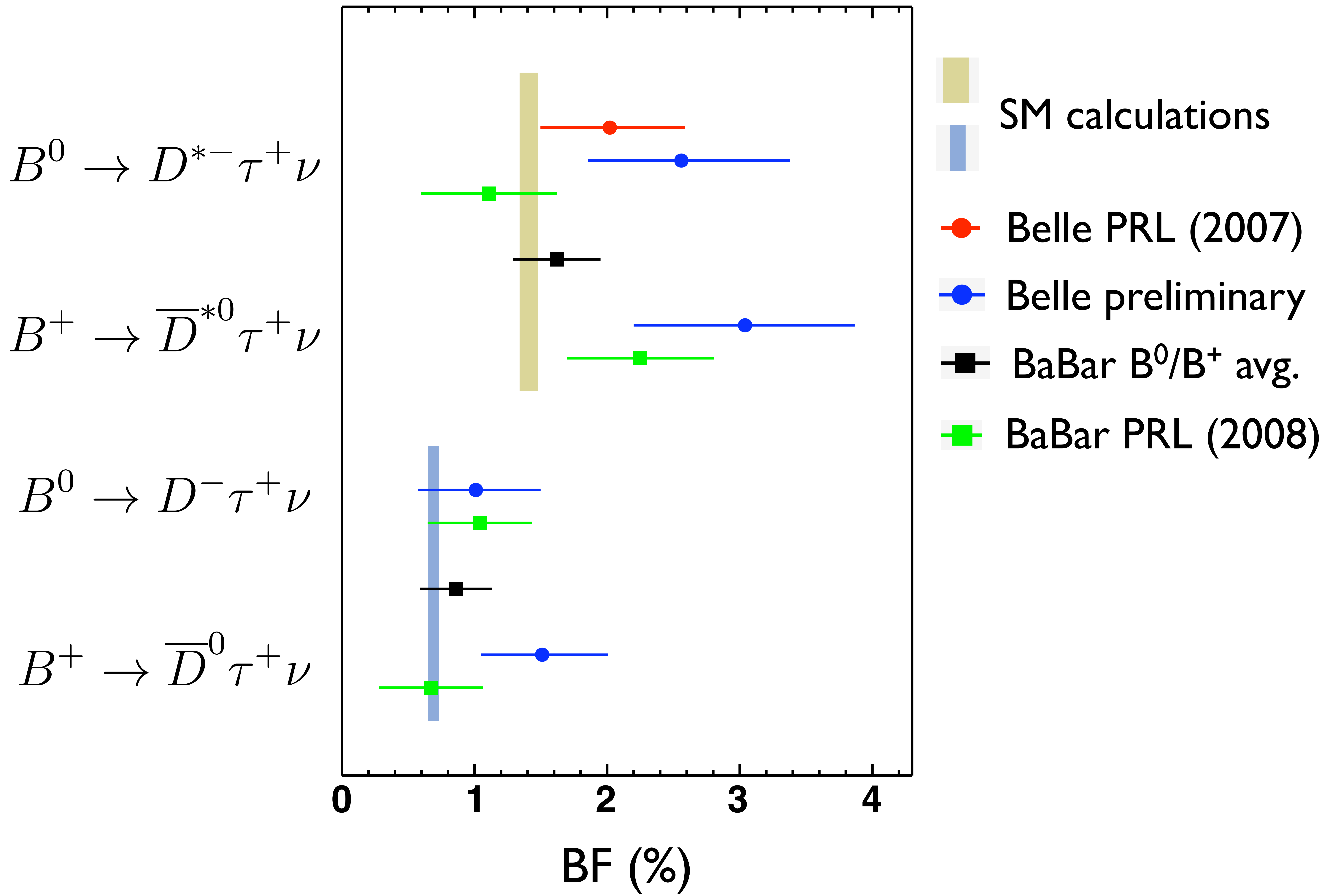
- Max. likelihood fit to M_{tag}
- signal shape from MC
- non-peaking bkgd. – weighted sum of various comp'nts
- peaking bkgd. – fixed by MC



subchannel	N_b^{MC}	N_p	N_s	N_b	N_{obs}	$\epsilon \times 10^{-4}$	$\mathcal{B}(\%)$	Σ
$D^0 \to K^-\pi^+, \tau \to e\bar{\nu}_e\nu_\tau$	$26.3^{+5.4}_{-3.7}$	$1.2^{+1.6}_{-1.5}$	$19.5^{+5.8}_{-5.0}$	$19.4^{+5.8}_{-5.0}$	40	3.25 ± 0.11	$2.44^{+0.74}_{-0.65}$	5.0σ
$D^0 \to K^-\pi^+\pi^0, \tau \to e\bar{\nu}_e\nu_\tau$	$50.8^{+5.5}_{-5.1}$	$5.0^{+2.6}_{-2.2}$	$11.9^{+6.0}_{-5.2}$	$43.1^{+8.0}_{-7.2}$	60	0.78 ± 0.07	$1.69^{+0.84}_{-0.74}$	2.6σ
$D^0 \to K^-\pi^+, \tau \to \pi^-\nu_\tau$	$138.0^{+9.2}_{-8.8}$	$-1.0^{+3.6}_{-3.2}$	$29.9^{+10.0}_{-9.1}$	$118.0^{+14.0}_{-13.0}$	148	$1.07^{+0.17}_{-0.15}$	$2.02^{+0.68}_{-0.61}$	3.8σ
Combined	215^{+12}_{-11}	$6.2^{+4.7}_{-4.2}$	60^{+12}_{-11}	182^{+15}_{-14}	248	$1.17^{+0.10}_{-0.08}$	$2.02^{+0.40}_{-0.37}$	6.7σ

$$\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau) = (2.02^{+0.40}_{-0.37} \pm 0.37)\% \text{ with } 5.2\sigma$$

B → D(*)τν as of 2008



(1)

BaBar (2012)

Featured in Physics | Editors' Suggestion

Evidence for an Excess of $\overline{B} \to D^{(*)}\tau^- \bar{\nu}_\tau$ Decays

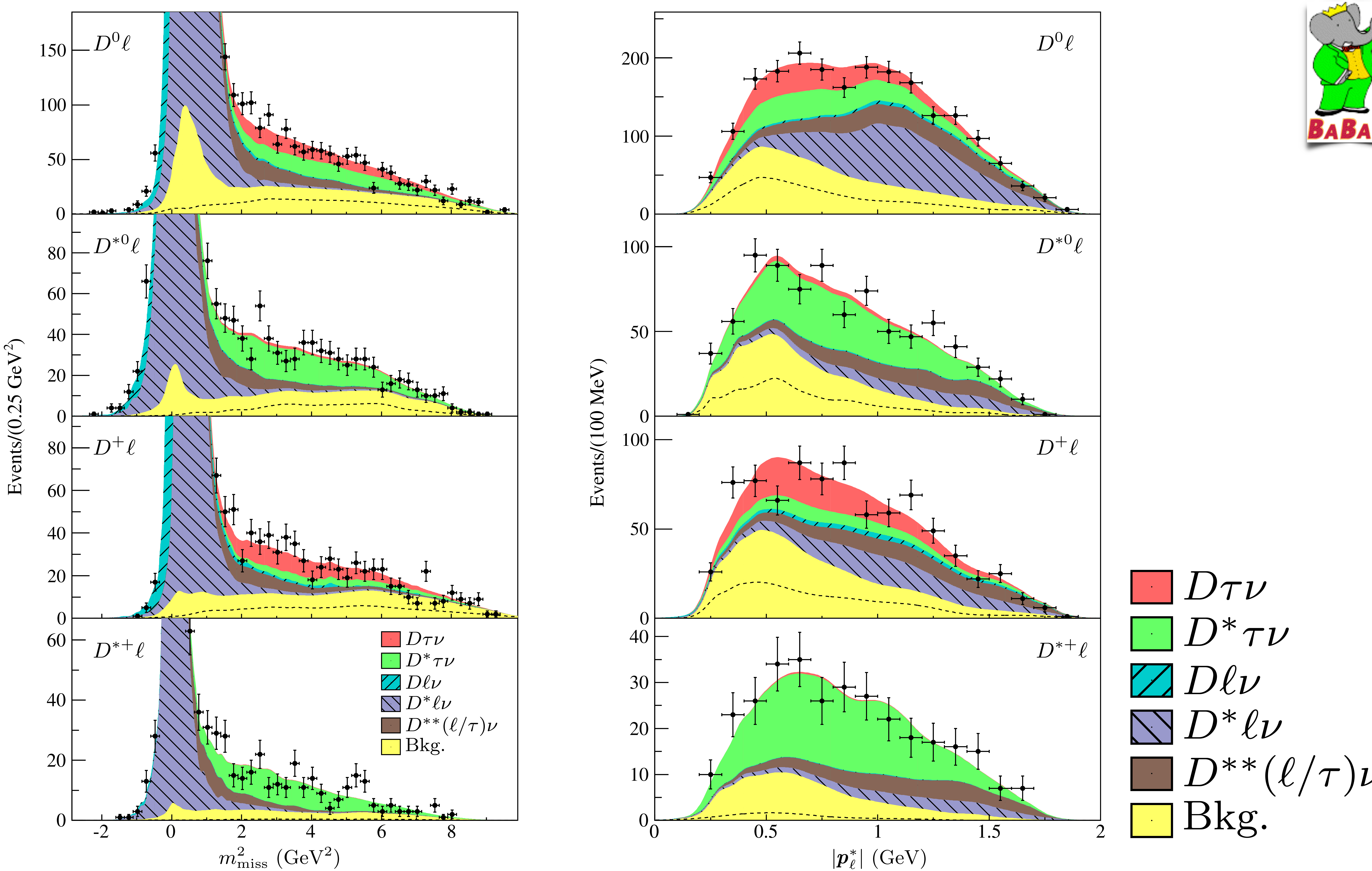
J. P. Lees *et al.* (BABAR Collaboration)
Phys. Rev. Lett. **109**, 101802 – Published 6 September 2012

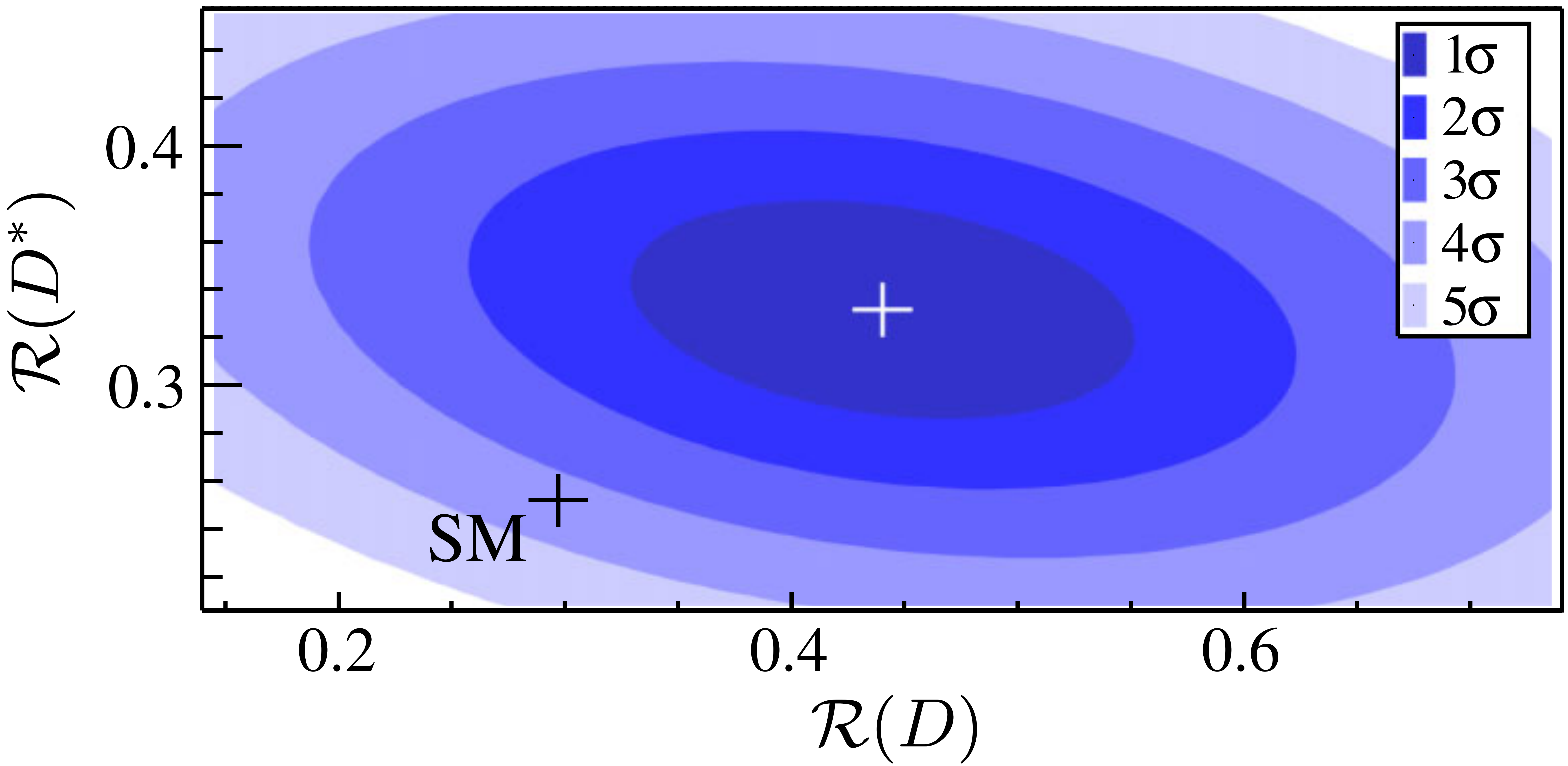
Physics See Synopsis: More tau leptons than expected

PHYSICAL REVIEW D **88,** 072012 (2013)

Measurement of an excess of $\bar{B} \to D^{(*)}\tau^- \bar{\nu}_\tau$ decays and implications for charged Higgs bosons

J. P. Lees,[1] V. Poireau,[1] V. Tisserand,[1] E. Grauges,[2] A. Palano,[3a,3b] G. Eigen,[4] B. Stugu,[4] D. N. Brown,[4]
L. T. Kerth,[5] Yu. G. Kolomensky,[5] M. Lee,[5] G. Lynch,[5] H. Koch,[6] T. Schroeder,[6] C. Hearty,[7] T. S. Mattison,[7]


$D^0\ell$
$D^{*0}\ell$
$D^+\ell$
$D^{*+}\ell$
Events/(0.25 GeV^2)
$m^2_{\rm miss}$ (GeV^2)
Events/(100 MeV)
$|\boldsymbol{p}^*_\ell|$ (GeV)
$D\tau\nu$
$D^*\tau\nu$
$D\ell\nu$
$D^*\ell\nu$
$D^{**}(\ell/\tau)\nu$
Bkg.



$$R(D) = \frac{\mathcal{B}(\bar{B} \to D\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D\ell^-\bar{\nu}_\ell)},$$

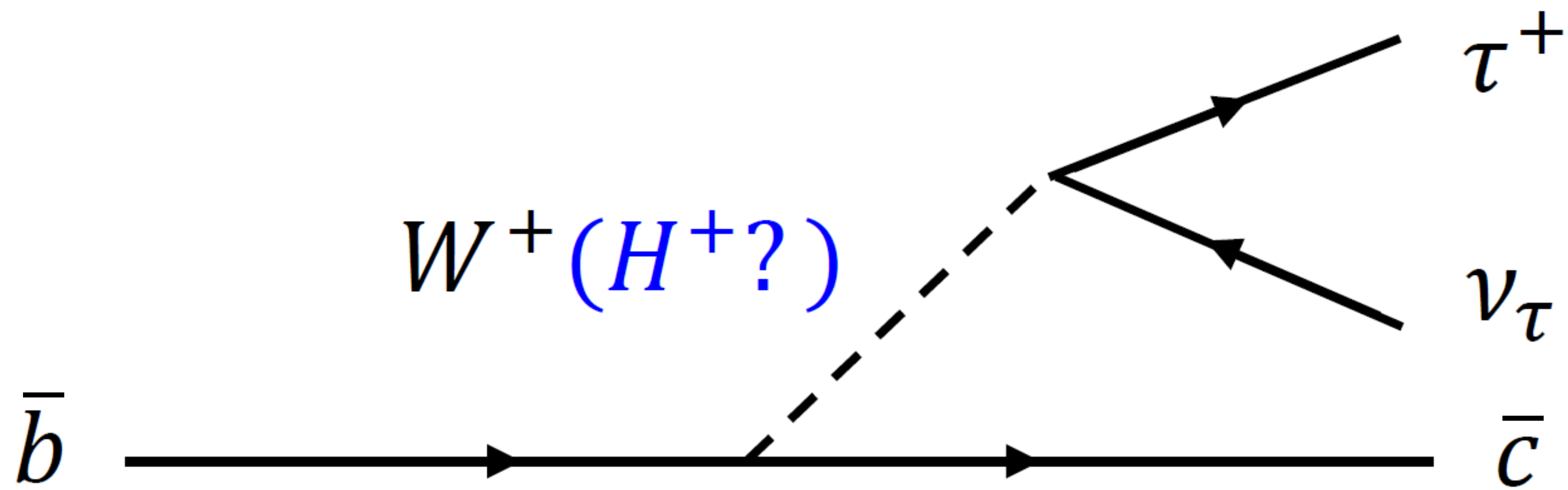
$$R(D^*) = \frac{\mathcal{B}(\bar{B} \to D^*\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^*\ell^-\bar{\nu}_\ell)},$$

$$\mathcal{R}(D) = 0.440 \pm 0.058 \pm 0.042,$$

$$\mathcal{R}(D^*) = 0.332 \pm 0.024 \pm 0.018,$$

testing new physics

- New physics may show up $\because m_\tau \gg m_\mu,\ m_e$



testing new physics

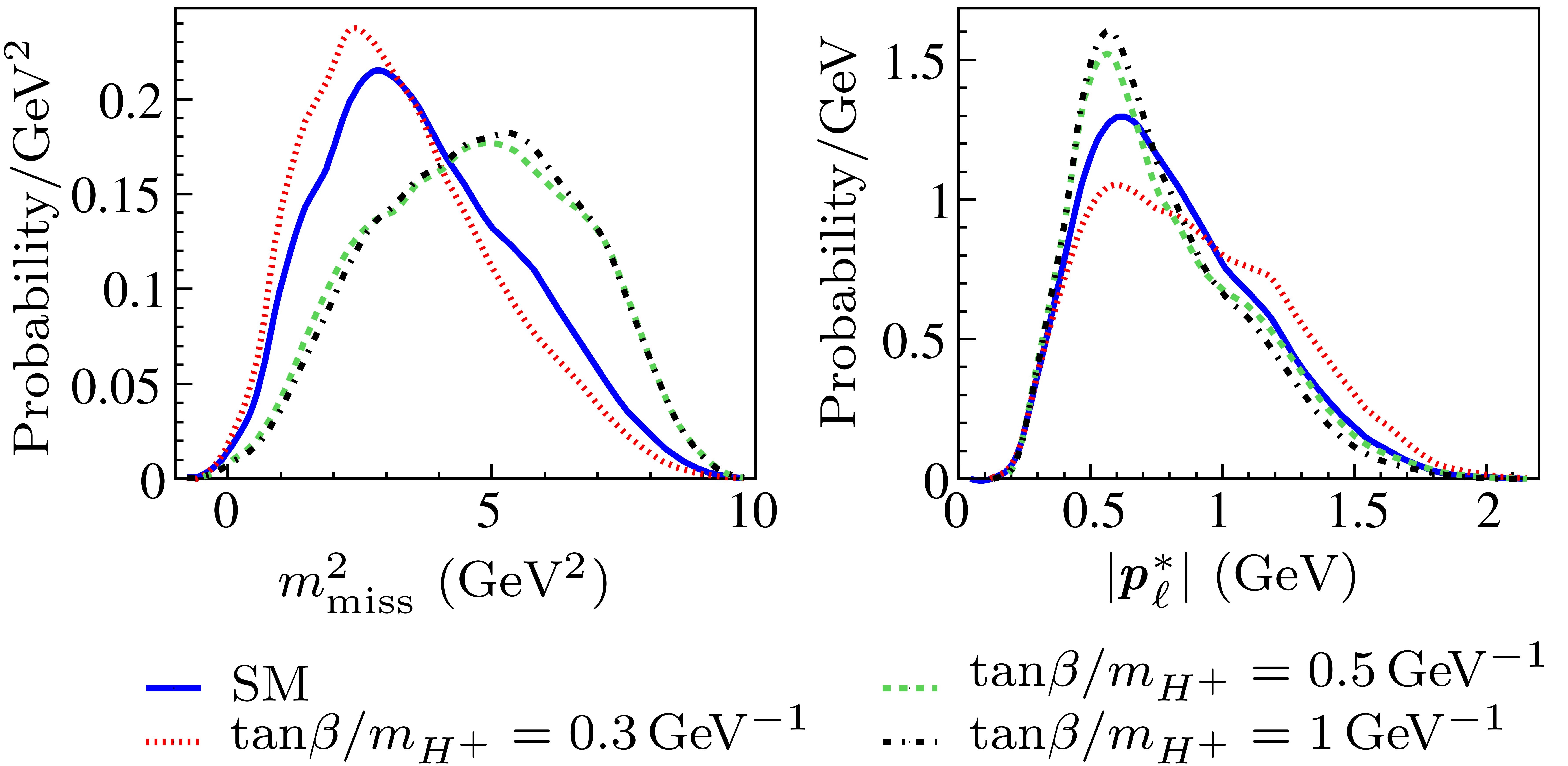
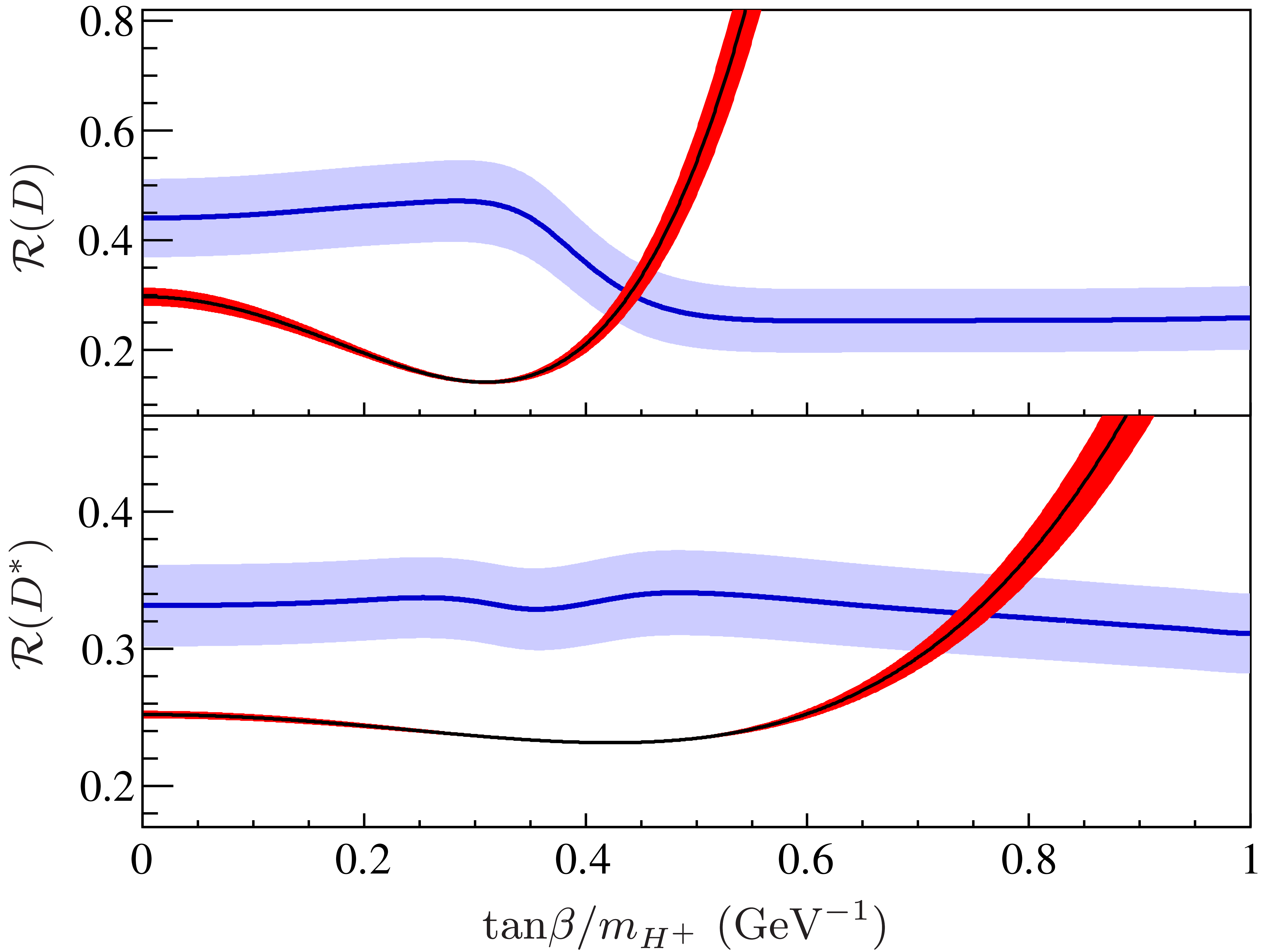


FIG. 18 (color online). m^2_{miss} and $|\boldsymbol{p}^*_\ell|$ projections of the $D^0\tau\nu \Rightarrow D^0\ell$ PDF for various values of $\tan\beta/m_{H^\pm}$.

testing new physics



(2)

BELLE

$B \rightarrow D^* \tau \nu$
by hadronic *B*-tag

PHYSICAL REVIEW D **92,** 072014 (2015)

Measurement of the branching ratio of $\bar{B} \rightarrow D^{(*)}\tau^-\bar{\nu}_\tau$ relative to $\bar{B} \rightarrow D^{(*)}\ell^-\bar{\nu}_\ell$ decays with hadronic tagging at Belle

M. Huschle,[26] T. Kuhr,[35] M. Heck,[26] P. Goldenzweig,[26] A. Abdesselam,[61] I. Adachi,[15,12] K. Adamczyk,[48] H. Aihara,[67] S. Al Said,[61,29] K. Arinstein,[4,51] D. M. Asner,[53] T. Aushev,[41,23] R. Ayad,[61] T. Aziz,[62] I. Badhrees,[61,28] A. M. Bakich,[60] V. Bansal,[53] E. Barberio,[39] V. Bhardwaj,[58] B. Bhuyan,[17] J. Biswal,[24] A. Bobrov,[4,51] A. Bozek,[48] M. Bračko,[37,24]

Hadronic B tagging for $B \to \overline{D}^{(*)}\tau^+\nu_\tau$

Belle, PRD 92, 072014 (2015)

- Exploit the unique feature of the e^+e^- B-factories

$$e^+e^- \to \Upsilon(4S) \to B_{\rm sig}B_{\rm tag}$$

- Full reconstruction of $B_{\rm tag}$ in hadronic B decay modes

  $\Rightarrow$ constrain the charge, flavor, & $(E,\vec{p})$ of $B_{\rm sig}$

  $\Rightarrow$ resulting in very high-purity, but with low-efficiency ($\sim \mathcal{O}(0.1\%)$)

- Signal side ($B_{\rm sig}$): reconstructed in $D^{(*)}\ell$ ($\ell = e, \mu$) [$\tau \to e\nu\bar{\nu}, \mu\nu\bar{\nu}$ only]

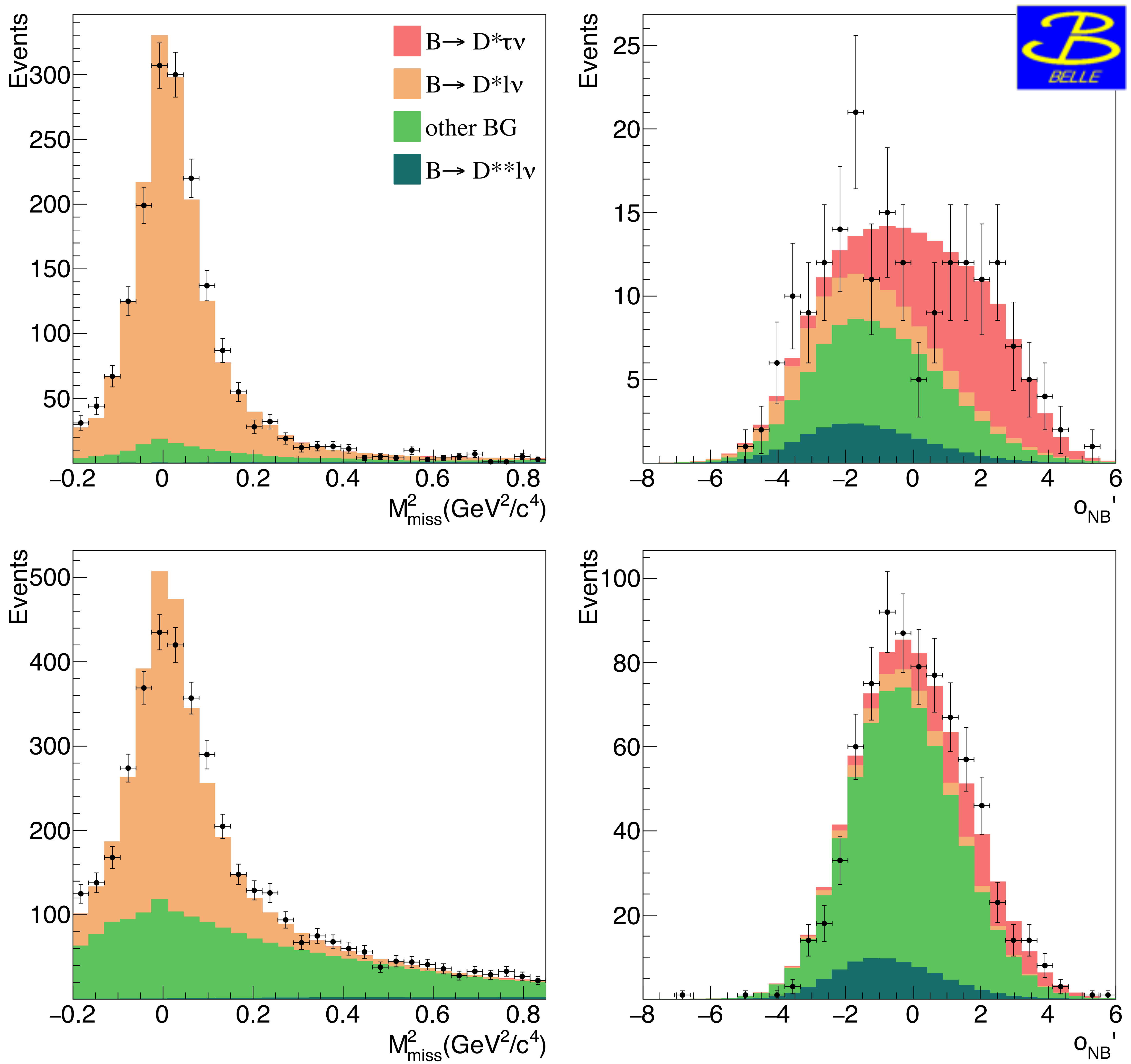
  * no extra tracks or π^0; total charge = 0

- Signal fitting in split regions

  * $M^2_{\rm miss} < 0.85$ GeV^2 — mostly $B \to D^{(*)}\ell\nu$ ($\ell = e, \mu$); fit $M^2_{\rm miss}$
  * $M^2_{\rm miss} > 0.85$ GeV^2 — $B \to \overline{D}^{(*)}\tau^+\nu_\tau$ enhanced; fit neural-net variable, $o'_{\rm NB}$

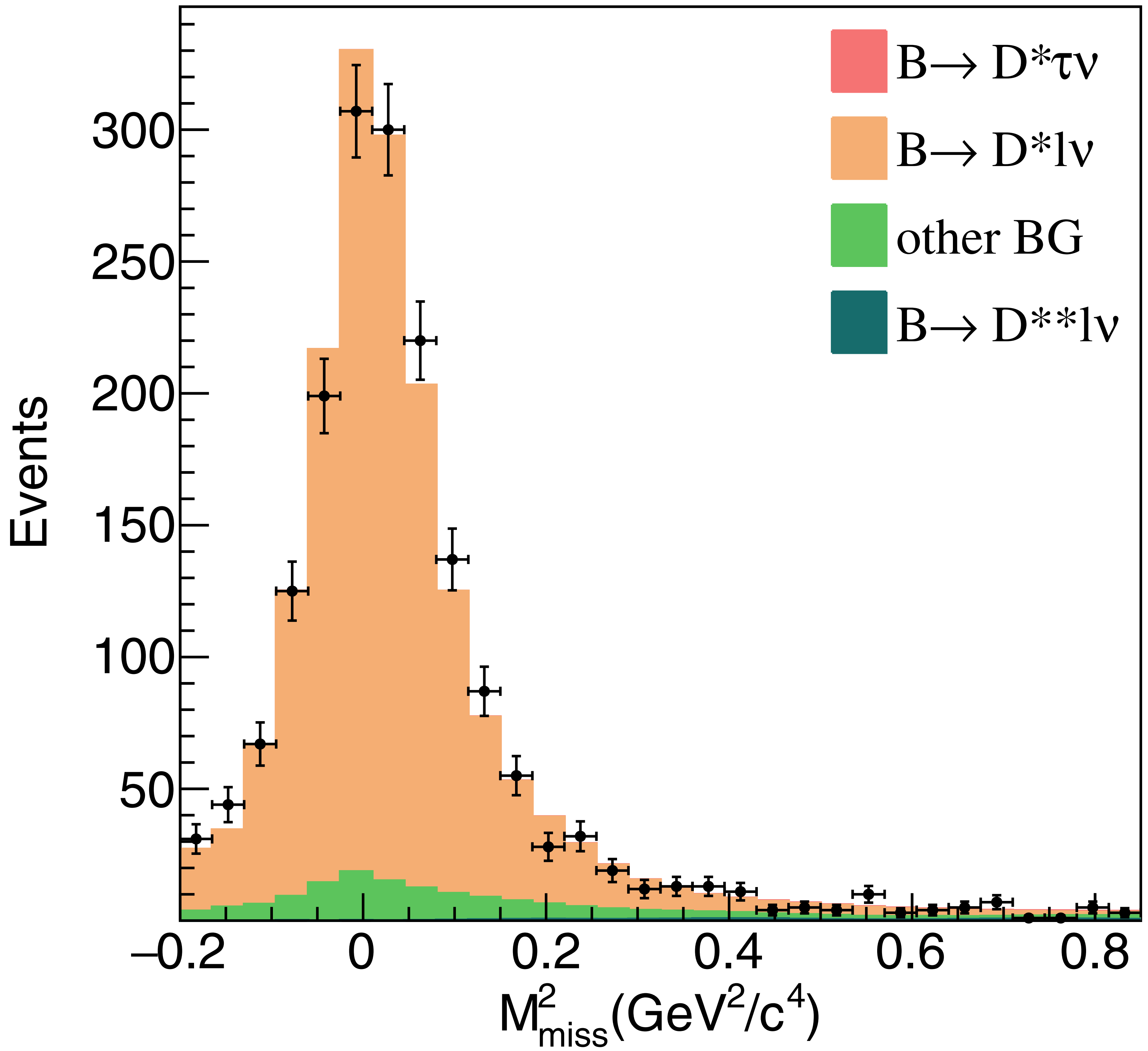
- Measure relative ratios $R(D)$, $R(D^*)$ — $R(D^{(*)}) \equiv \mathcal{B}(B \to D^{(*)}\tau\nu)/\mathcal{B}(B \to D^{(*)}\ell\nu)$

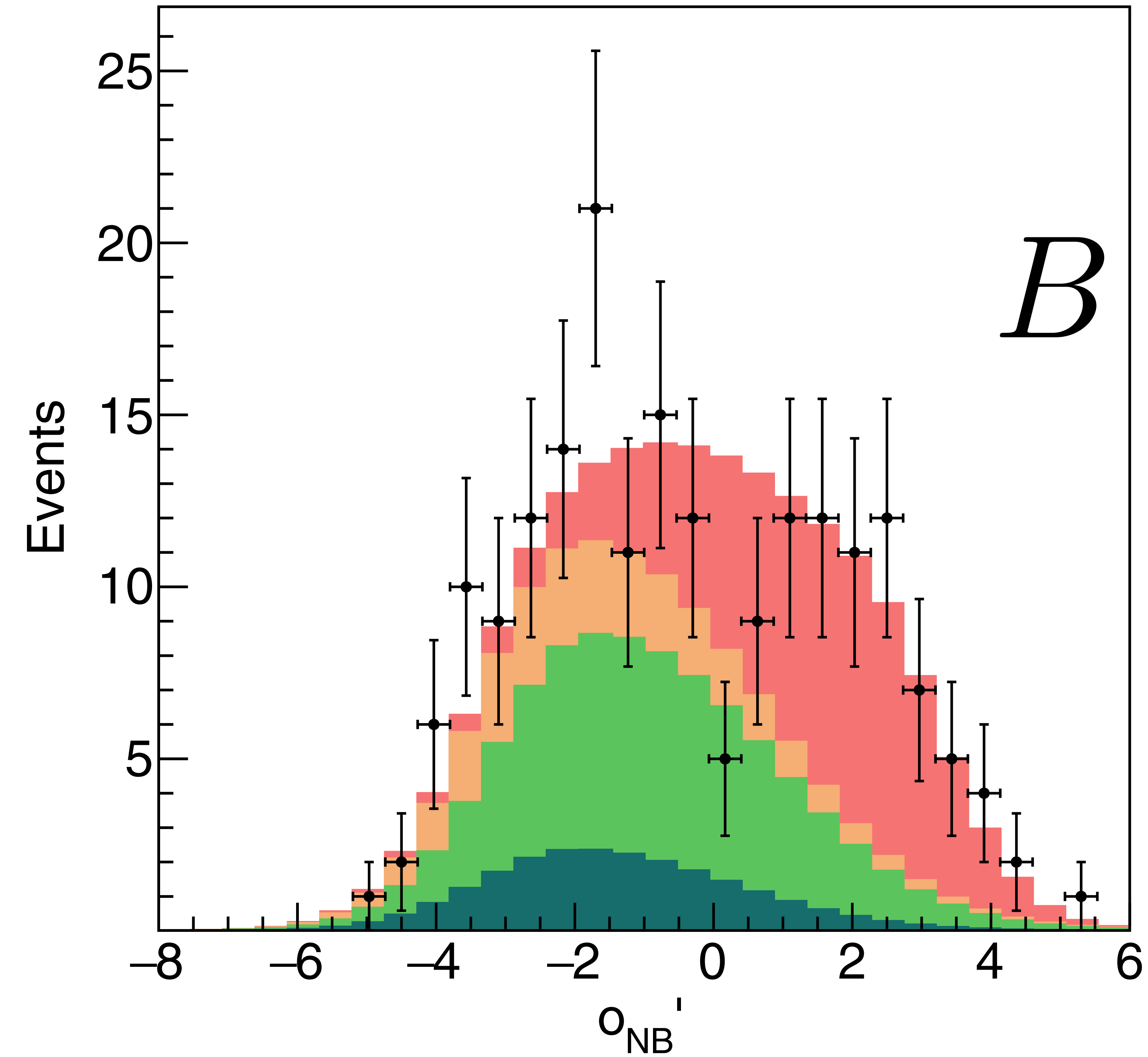
Fits for $B \to D^* \ell(X)$ final states

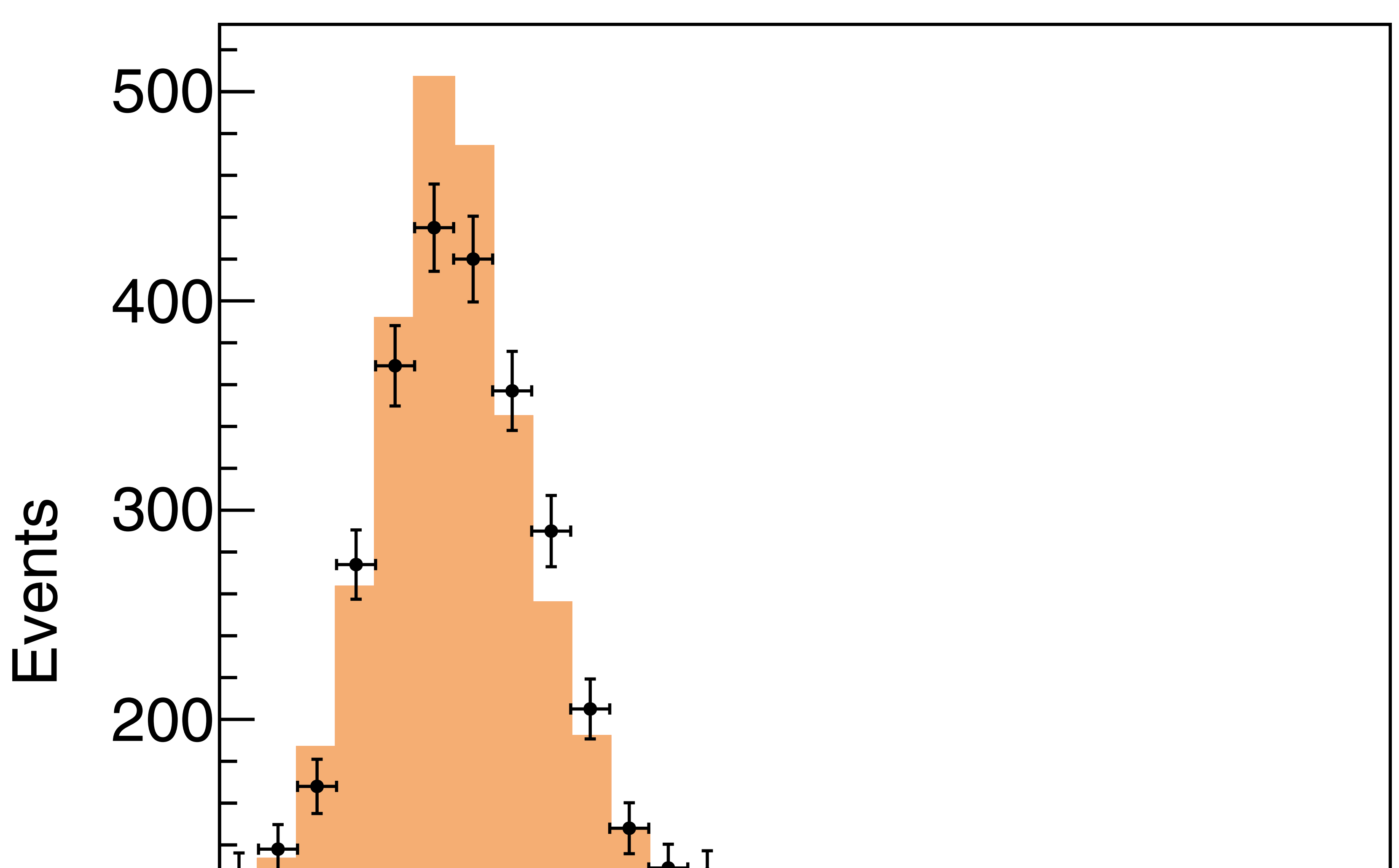


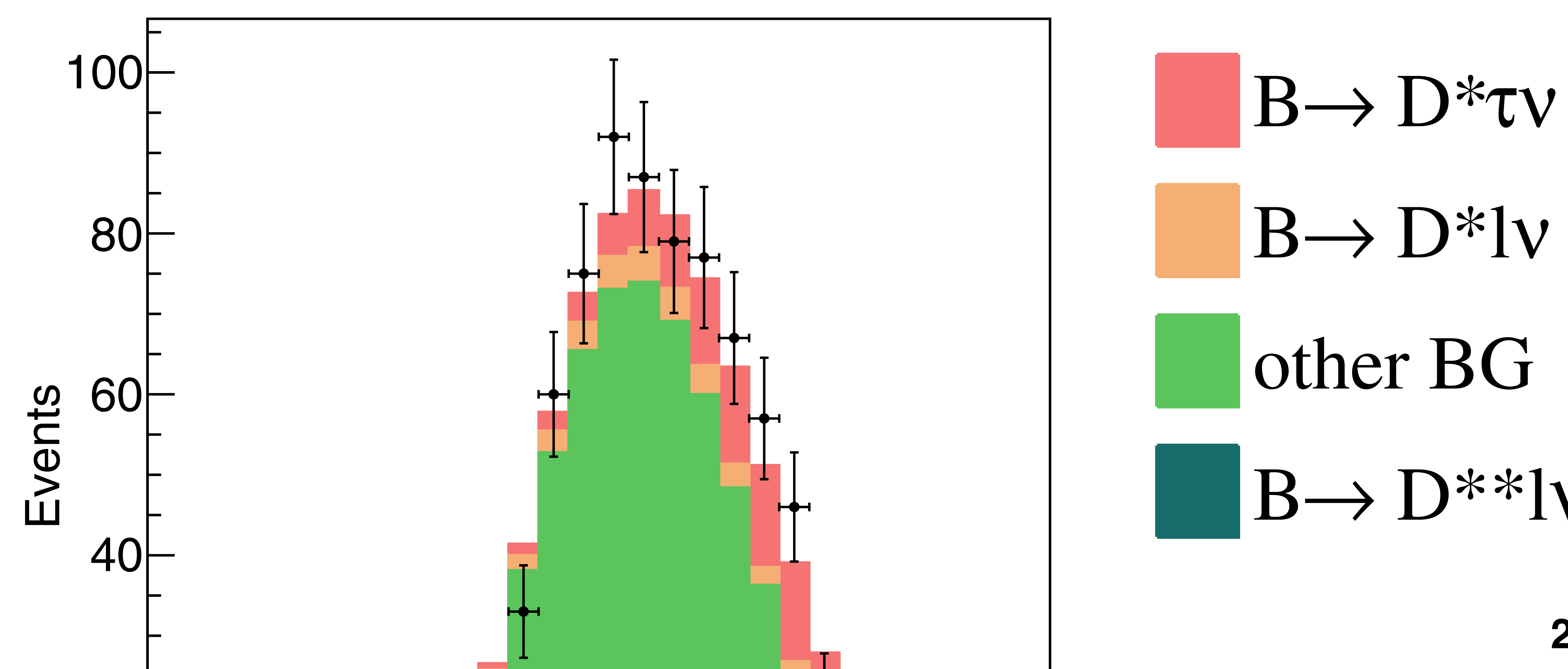
- (top) $D^{*+}\ell^-$
  (bottom) $D^{*0}\ell^-$
- (left) $M^2_{\text{miss}} < 0.85\ \text{GeV}^2$
  - $B \to D^*\ell\nu$ dominant
  - fit M^2_{miss} for backgr'd normalization
- (right) $M^2_{\text{miss}} > 0.85\ \text{GeV}^2$
  - $B \to D^*\tau\nu$ enhanced
  - fit o'_{NB}

$$B \to D^* \ell X$$

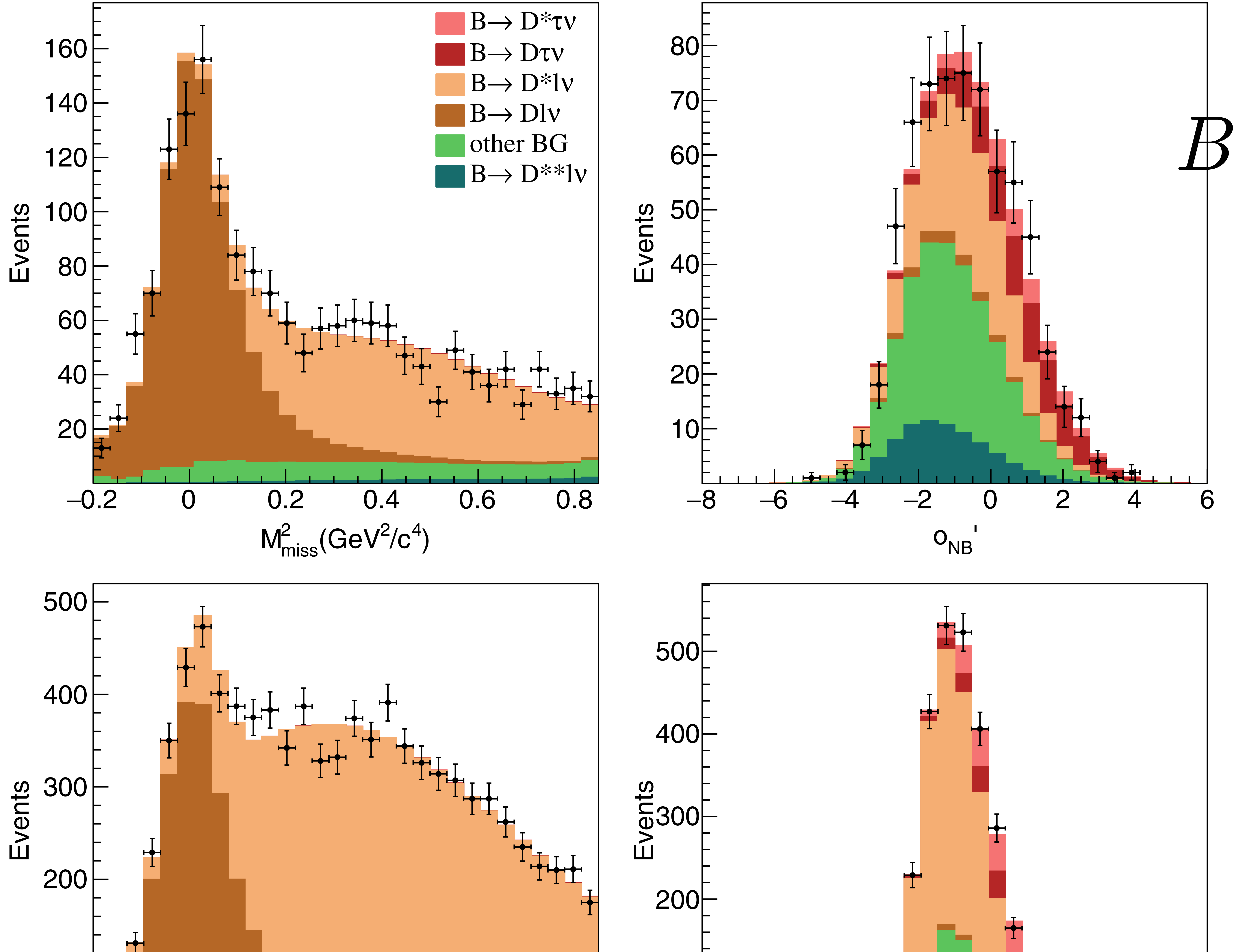

Events
300
250
200
150
100
50
−0.2
0
0.2
0.4
0.6
0.8
$M^2_{miss}(GeV^2/c^4)$
B→ D*τν
B→ D*lν
other BG
B→ D**lν

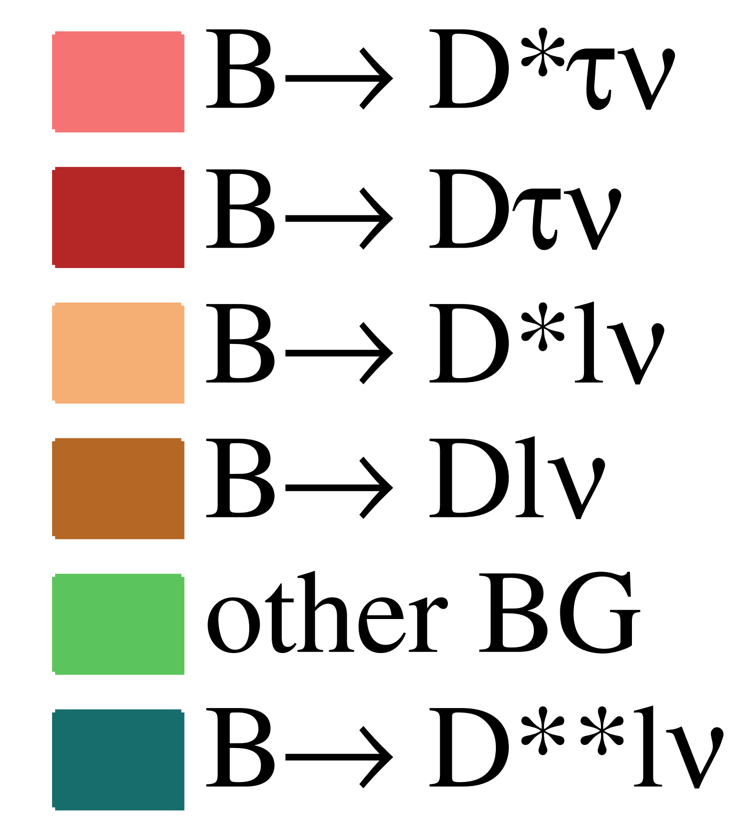

Events
25
20
15
10
5
−8
−6
−4
−2
0
2
4
6
o_{NB}'


Events
500
400
300
200


Events
100
80
60
40
B→ D*τν
B→ D*lν
other BG
B→ D**lν

$$B \to D\ell X$$


B→ D*τν
B→ Dτν
B→ D*lν
B→ Dlν
other BG
B→ D**lν
Events
M^2_{miss}(GeV^2/c^4)
o_{NB}'

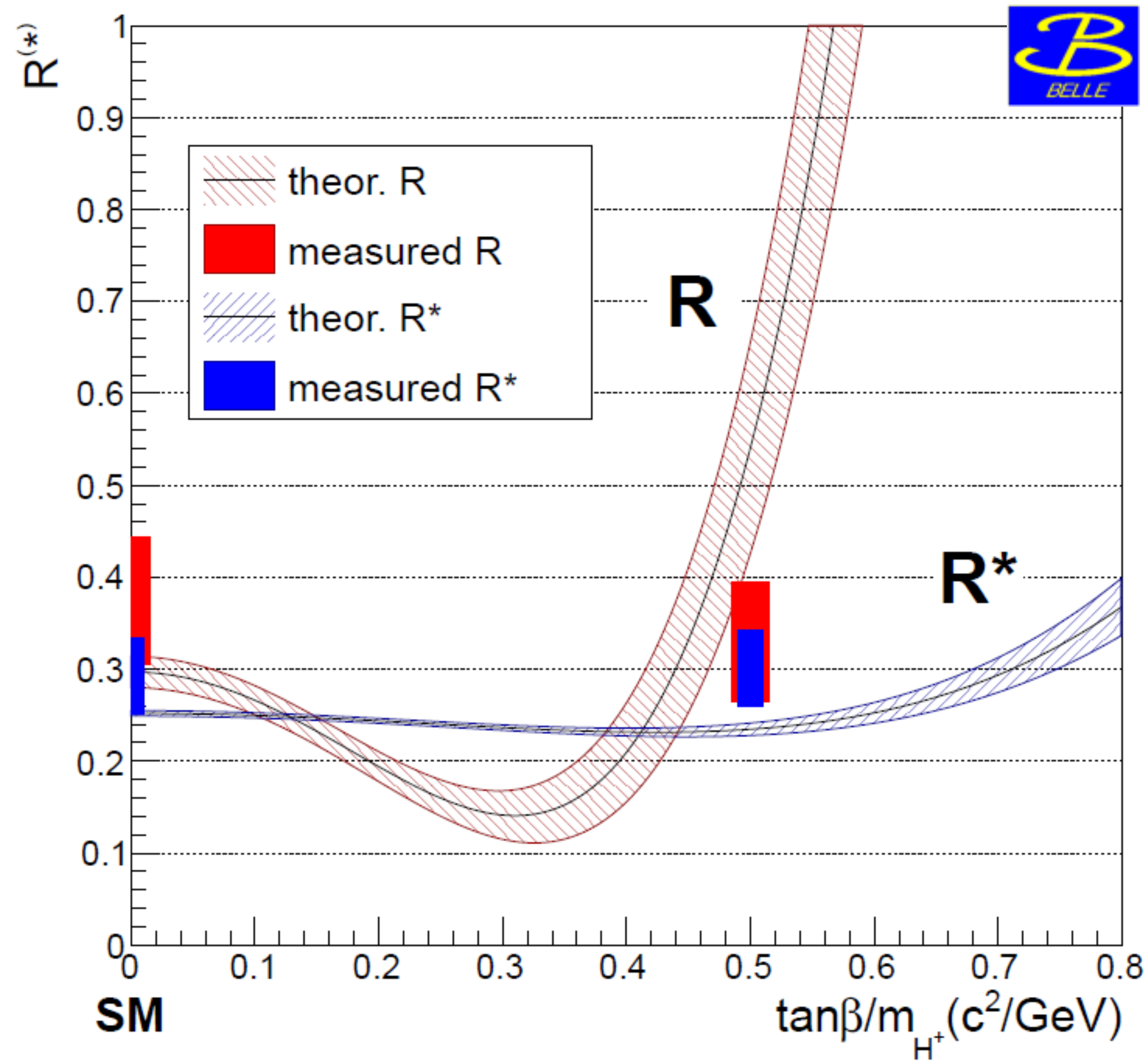

B→ D*τν
B→ Dτν
B→ D*lν
B→ Dlν
other BG
B→ D**lν

Hadronic B tagging for $B \to \overline{D}^{(*)}\tau^+\nu_\tau$

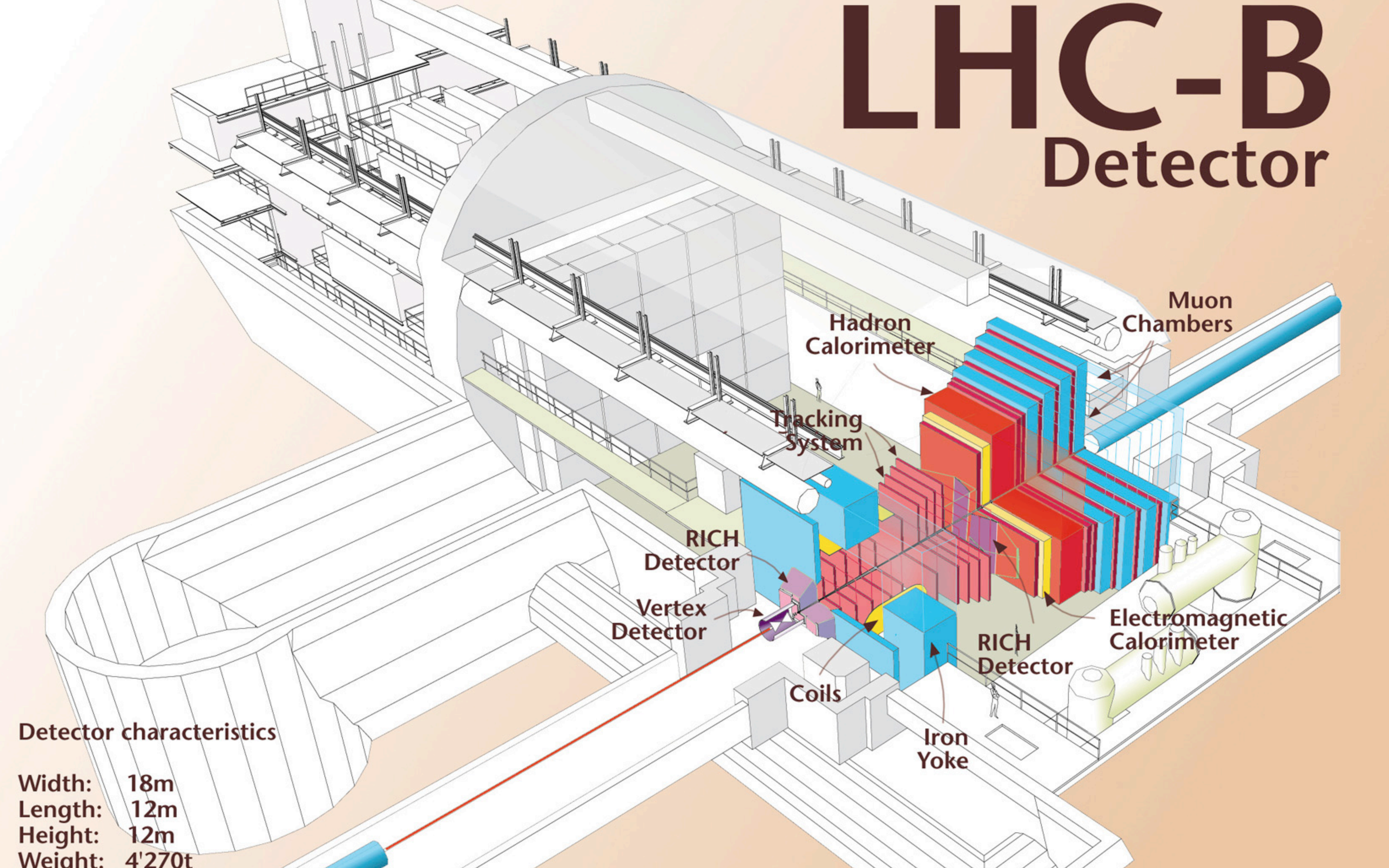
Belle, PRD 92, 072014 (2015)

Belle, had.-tag results

$$R(D) = 0.375 \pm 0.064 \pm 0.026$$
$$R(D^*) = 0.293 \pm 0.038 \pm 0.015$$



[Belle, had.-tag] consistent with 2HDM(II) for $0 < \tan\beta/m_{H^+} \lesssim 0.45\ \mathrm{GeV}^{-1}$

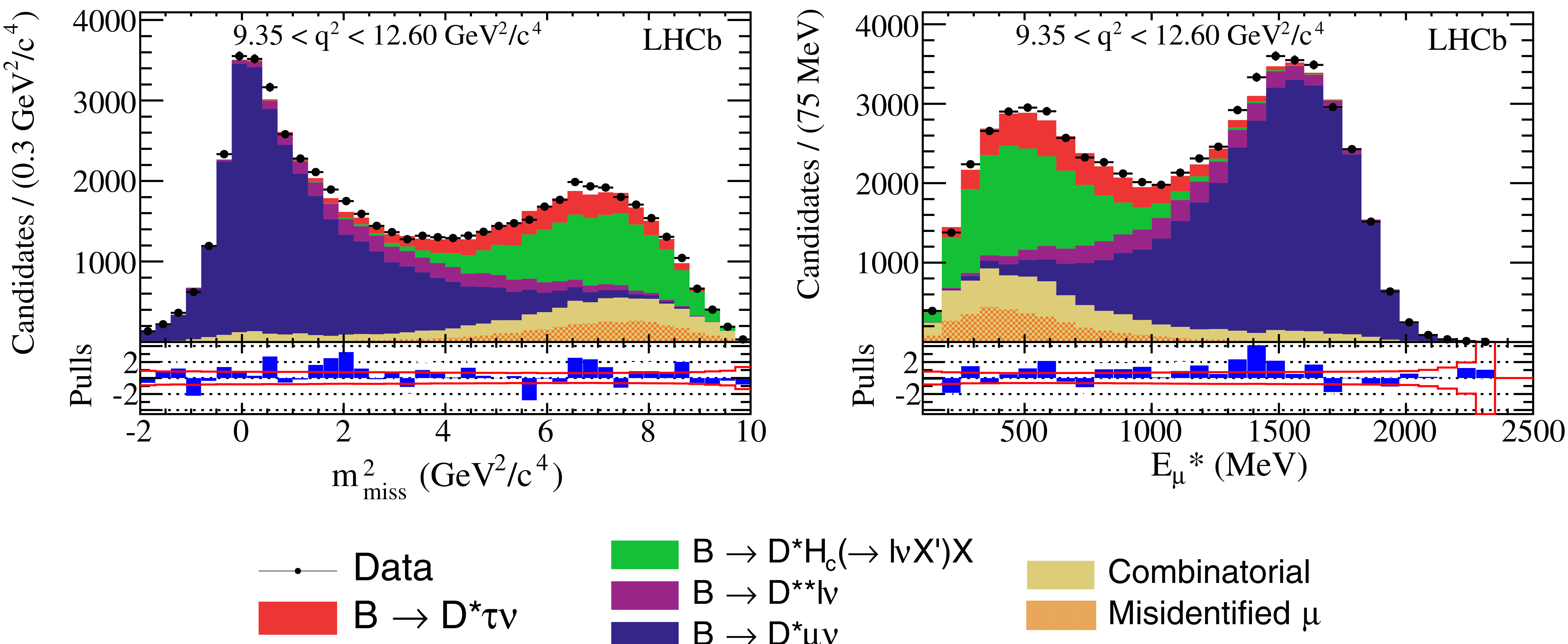

LHC-B
Detector
Muon
Chambers
Hadron
Calorimeter
Tracking
System
RICH
Detector
Vertex
Detector
Coils
Iron
Yoke
RICH
Detector
Electromagnetic
Calorimeter
Detector characteristics
Width: 18m
Length: 12m
Height: 12m
Weight: 4'270t

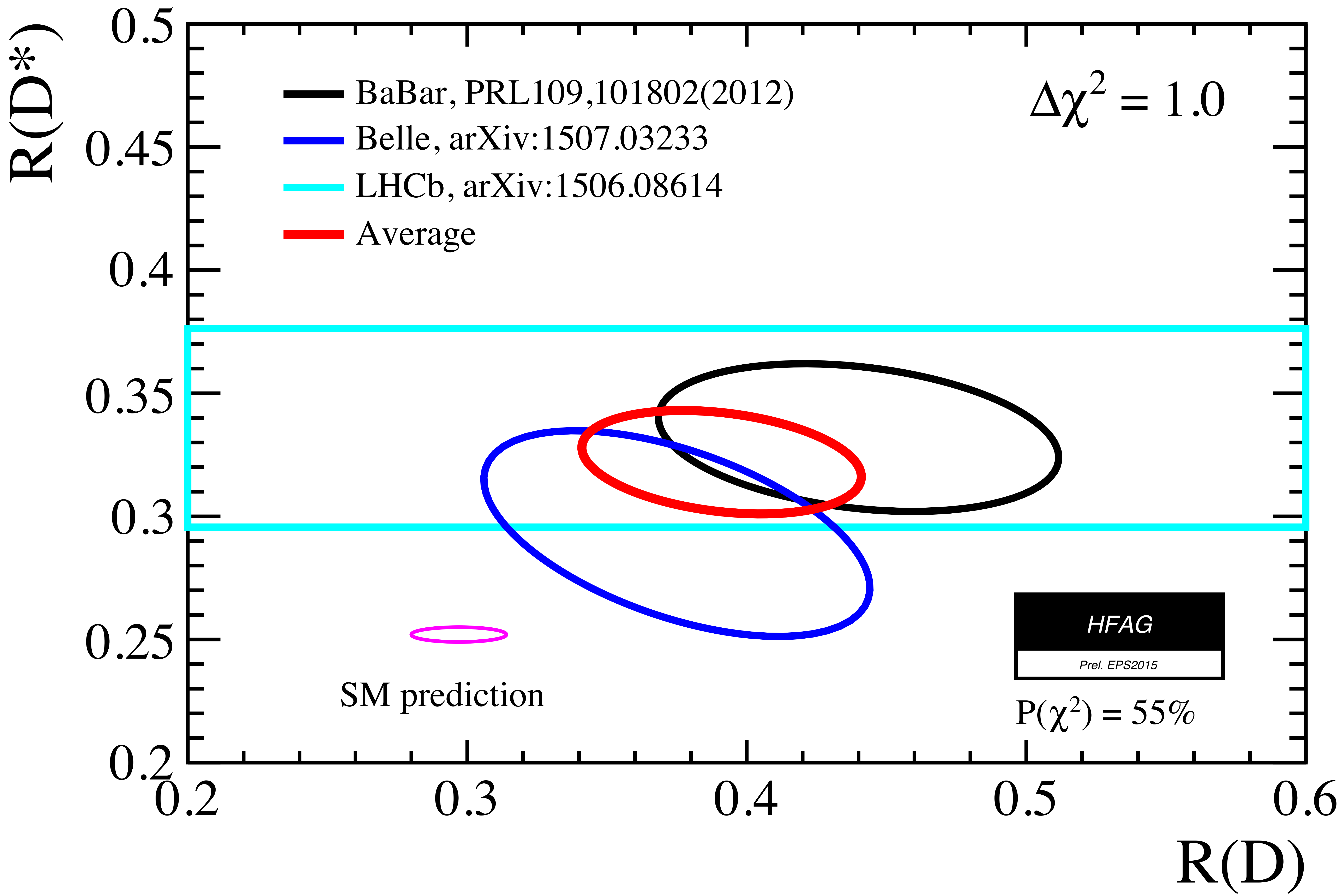
Measurement of the Ratio of Branching Fractions $\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)$

(3)

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

(Received 30 June 2015; published 9 September 2015; corrected 14 September 2015)





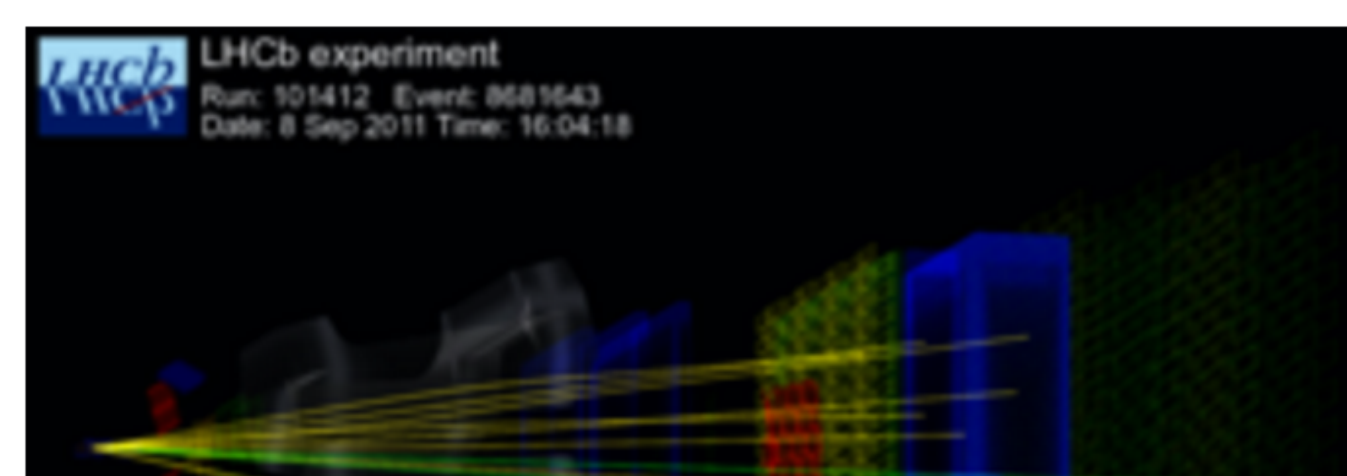
It's really amazing that LHCb also was able to measure this! For details, please come to KIAS workshop on July 18, 2017 and listen to Karim Trabelsi's talk.

SCIENTIFIC AMERICAN™

2 Accelerators Find Particles That May Break Known Laws of Physics

The LHC and the Belle experiment have found particle decay patterns that violate the Standard Model of particle physics, confirming earlier observations at the BaBar facility

By Clara Moskowitz | September 9, 2015 | Véalo en español



At the smallest scales, everything in the universe can be broken down into fundamental morsels called particles. The Standard Model of particle physics—the scitation.aip.org/content/aip/magazine/physicstoday/news/10.1063/PT.5.7203;jsessionid=e5h98jj9k0151.x-aip-live-03

Democracy suffers a blow—in particle physics

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

Steven K. Blau 17 September 2015

PREVIOUS POST | PHYSICS UPDATE | NEXT POST (1)

Upon learning of the discovery of the muon, I. I. Rabi famously quipped, “Who ordered that?” After all, the muon appeared to be identical to the electron except for its mass. Indeed, in the standard model of particle physics, the charged leptons—electron, muon, and tau—interact in the same way with the model’s gauge bosons, the particles that transmit force. As a consequence of that lepton democracy, the standard model prescribes the relative probabilities, or branching ratios, for a heavy particle to decay into one or another of the charged leptons plus other particles in common. Three years ago the BaBar collaboration at SLAC measured the branching ratios for B-meson decay to produce either a muon or a tau. For two slightly different decays, they found 2σ or greater deviations from the democratic standard-model expectation. Now the LHCb collaboration at CERN has confirmed the BaBar result for one of the decays. In a preprint, the Belle group at KEK in Japan has also announced

Physics Upc

History matters fo

A two-in-a-million nuclear decay

Enceladus’s subs wraps the moon

A study in contras surface frost

(4)

BELLE

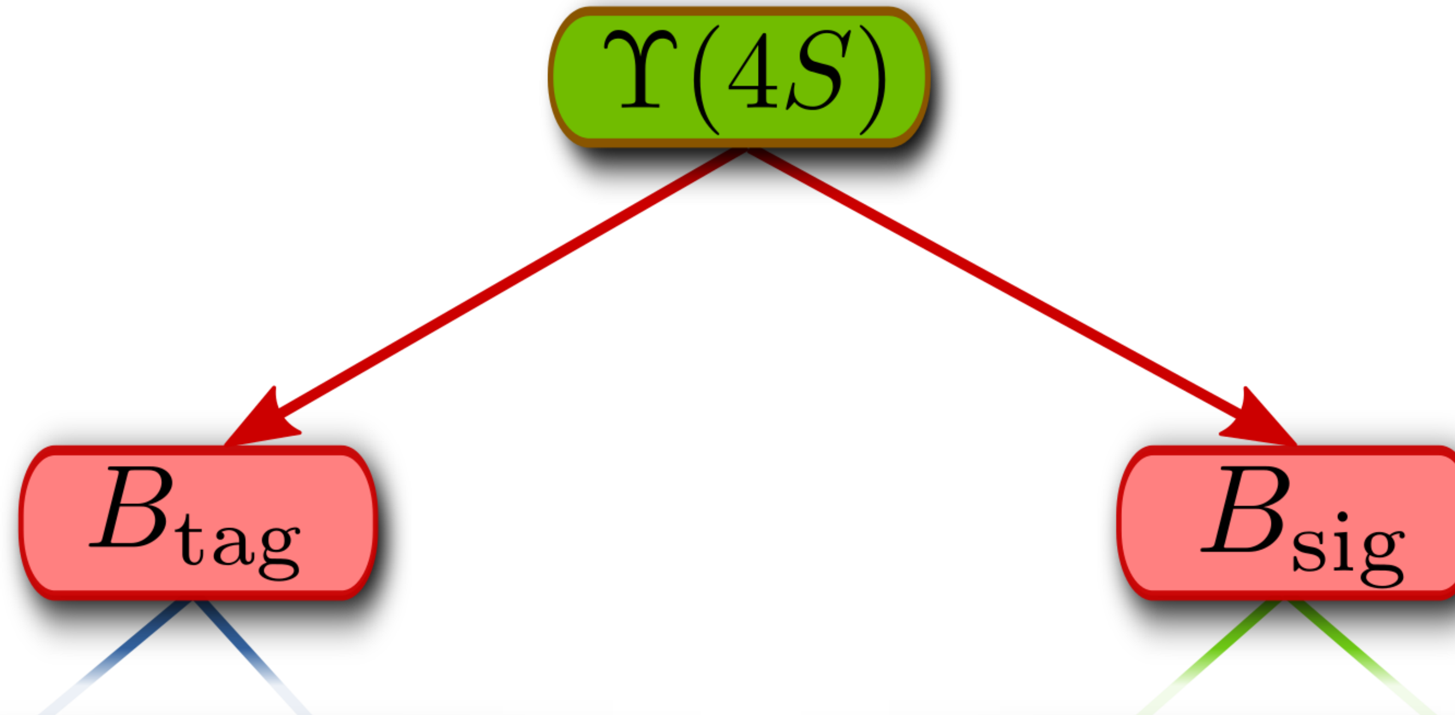
B → D* τ ν

by semileptonic *B*-tag

PHYSICAL REVIEW D **94,** 072007 (2016)

Measurement of the branching ratio of $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$ relative to $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ decays with a semileptonic tagging method

Y. Sato,[45,14] T. Iijima,[45,44] K. Adamczyk,[50] H. Aihara,[74] D. M. Asner,[56] H. Atmacan,[40] T. Aushev,[43] R. Ayad,[67] T. Aziz,[68] V. Babu,[68] J. Badhrees,[67,28] A. M. Bakich,[66] V. Bansal,[56] P. Behera,[20] V. Bhardwaj,[17] B. Bhuyan,[19] J. Biswal,[24]



Tagging techniques

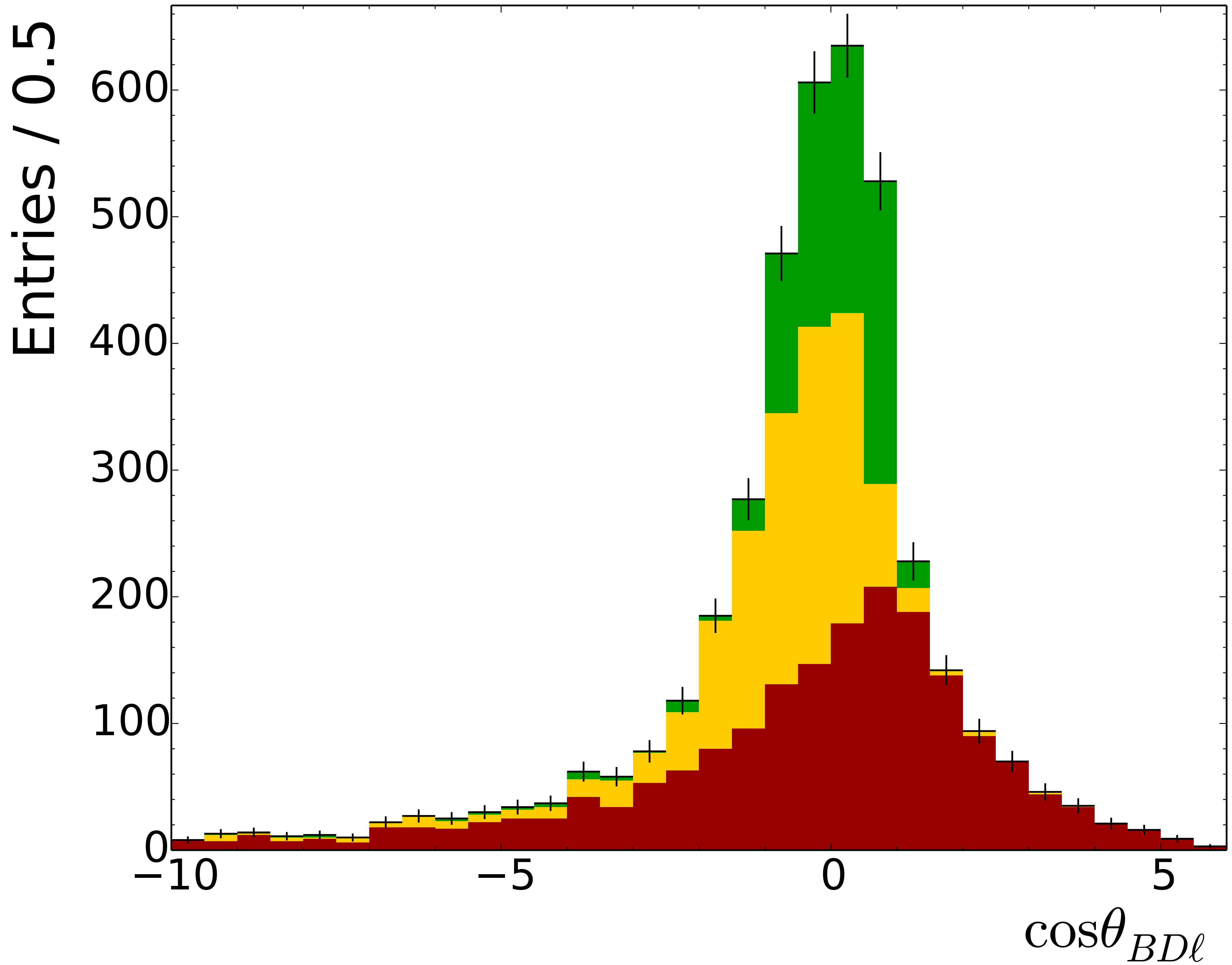
Purity →

← Efficiency

Inclusive	**Semileptonic**	**Hadronic**
$B \to$ anything	$B \to D^{(*)}\ell\nu_\ell$	$B \to$ hadrons
$\epsilon \approx \mathcal{O}(2\%)$	$\epsilon \approx \mathcal{O}(0.2\%)$	$\epsilon \approx \mathcal{O}(0.1\%)$

Inclusive:
very high statistics
very large background

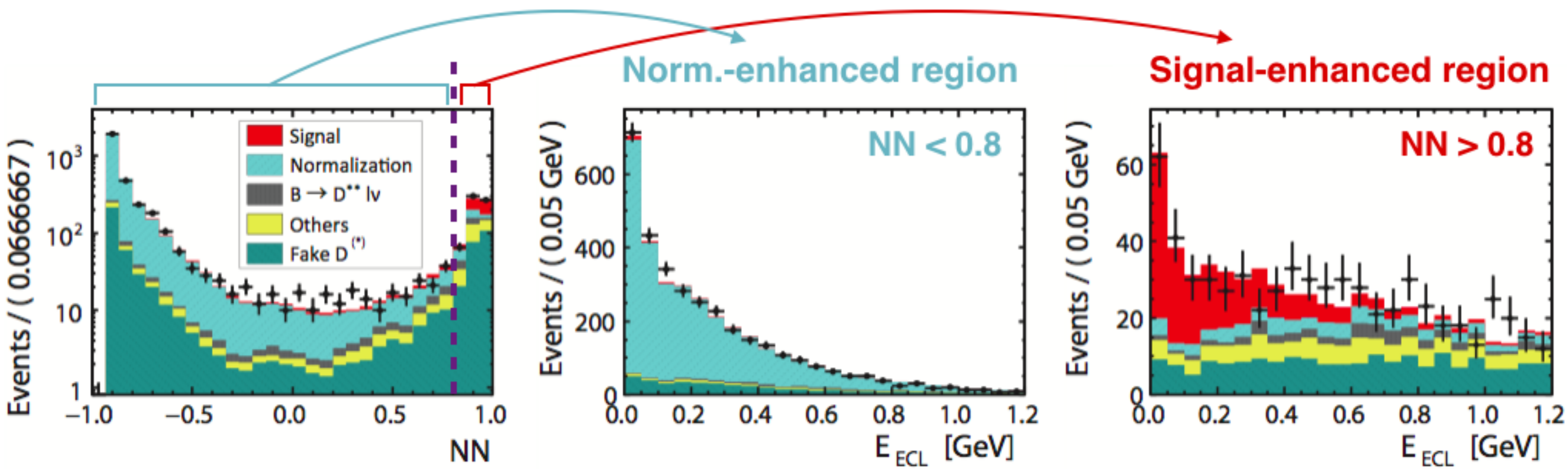
Hadronic:
super clean
w/ info. on $p^\mu(B_{\rm sig})$
very low statistics



$$\cos\theta_{B,D^{(*)}\ell} = \frac{2E_{\text{beam}}E_{D^{(*)}\ell} - M_B^2 - M_{D^{(*)}\ell}^2}{2p_B^* p_{D^{(*)}\ell}^*}$$

$\mathcal{R}(D^*)$ SL-tag – Results

2D fit to NN and E_{ECL}:

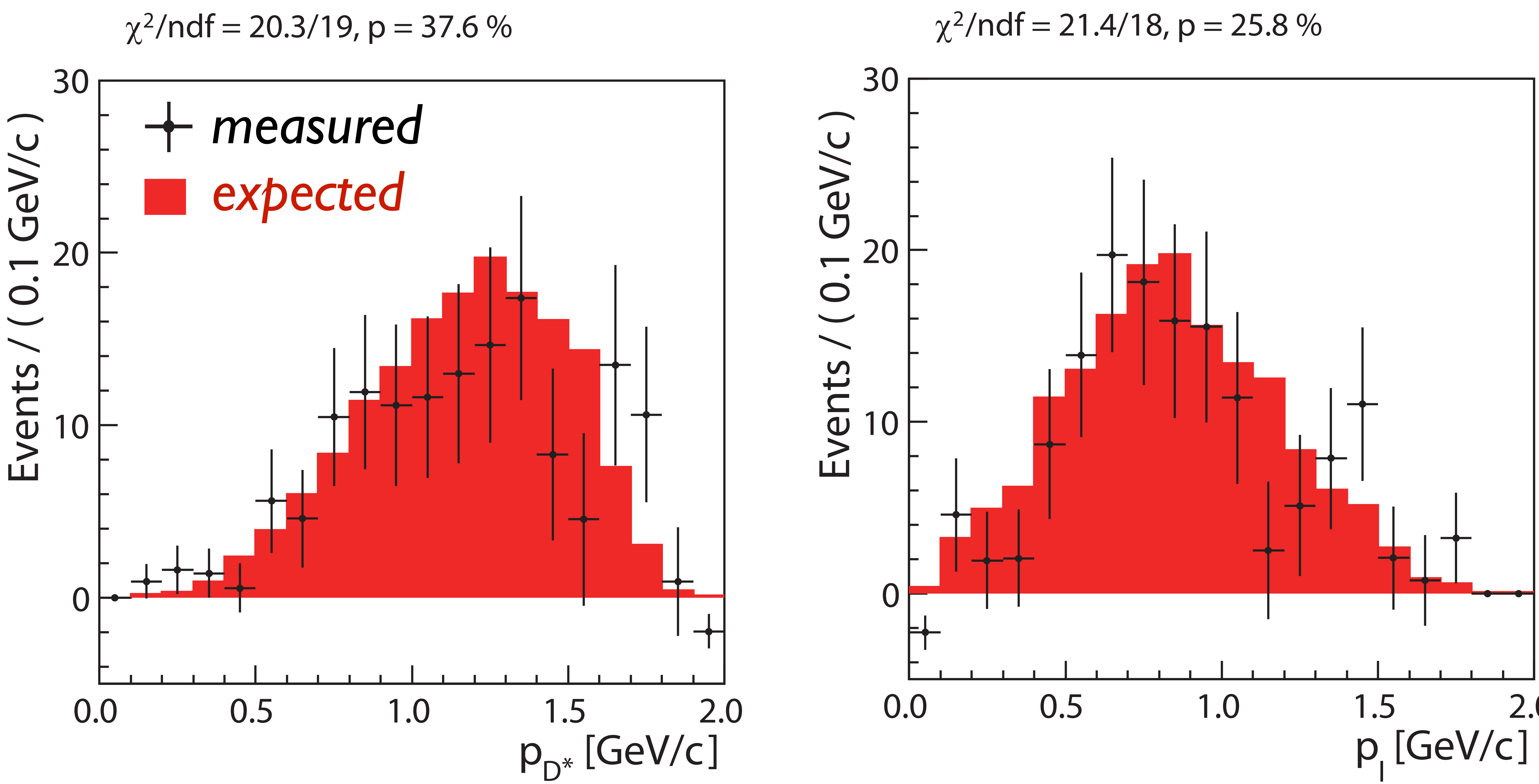


NN ∋ (M^2_{miss}, E_{vis}, $\cos\theta_{B\text{-}Dl}$), $\cos\theta_{B\text{-}D^*\ell} \equiv \frac{2E_{\mathrm{beam}}E_{D^*\ell} - m_B^2 - M_{D^*\ell}^2}{2|\vec{p}_B|\cdot|\vec{p}_{D^*\ell}|}$

$$\mathcal{R}(D^*) = \frac{1}{2\mathcal{B}(\tau^+ \to \ell^+\nu_\ell\bar{\nu}_\tau)} \frac{\varepsilon_{\mathrm{norm}}}{\varepsilon_{\mathrm{sig}}} \frac{N_{\mathrm{sig}}}{N_{\mathrm{norm}}} \qquad [\varepsilon_{\mathrm{norm}}/\varepsilon_{\mathrm{sig}} = 1.289 \pm 0.015]$$

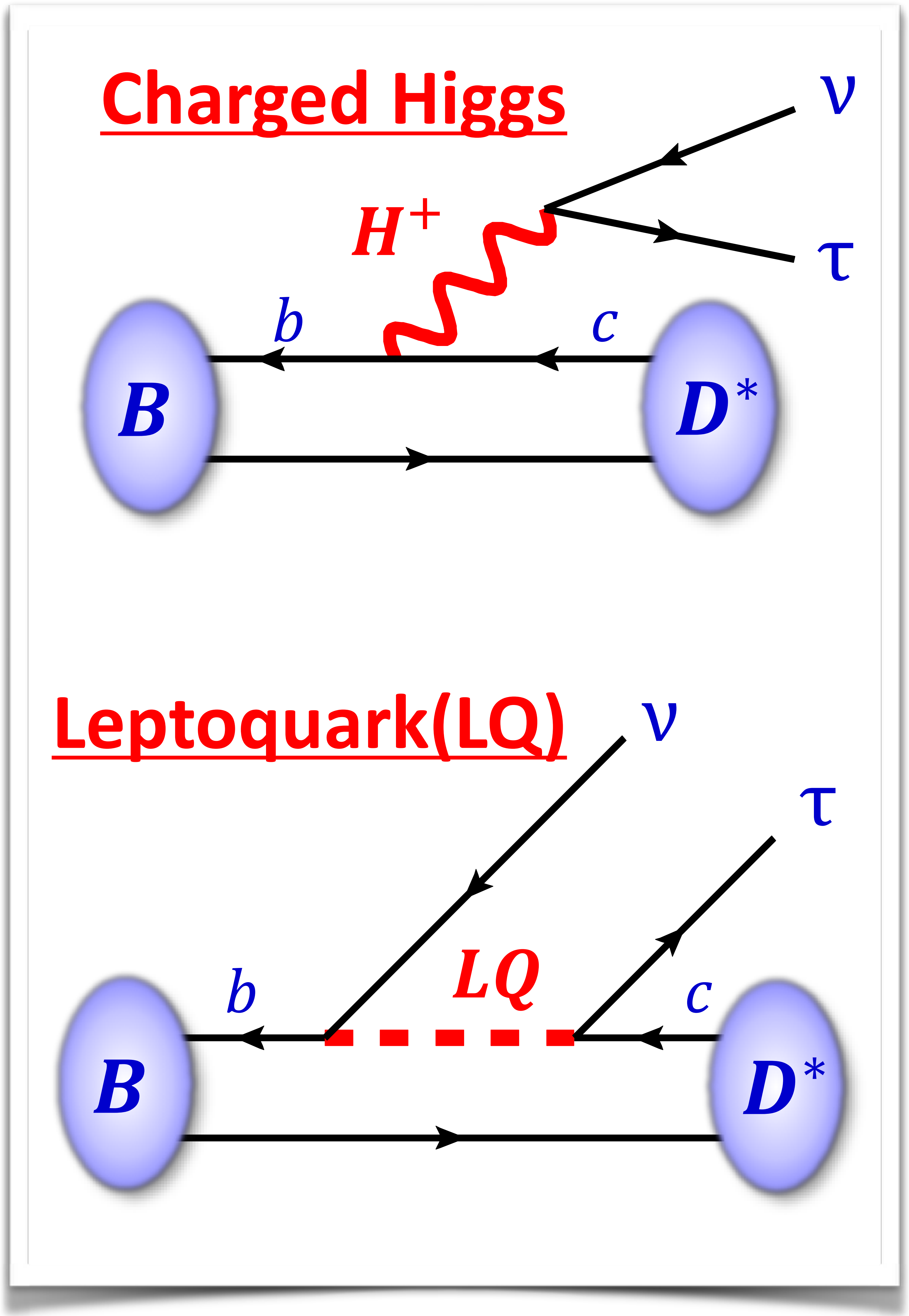
$$\mathcal{R}(D^*) = 0.302 \pm 0.030 \pm 0.011 \quad (13.8\sigma)$$

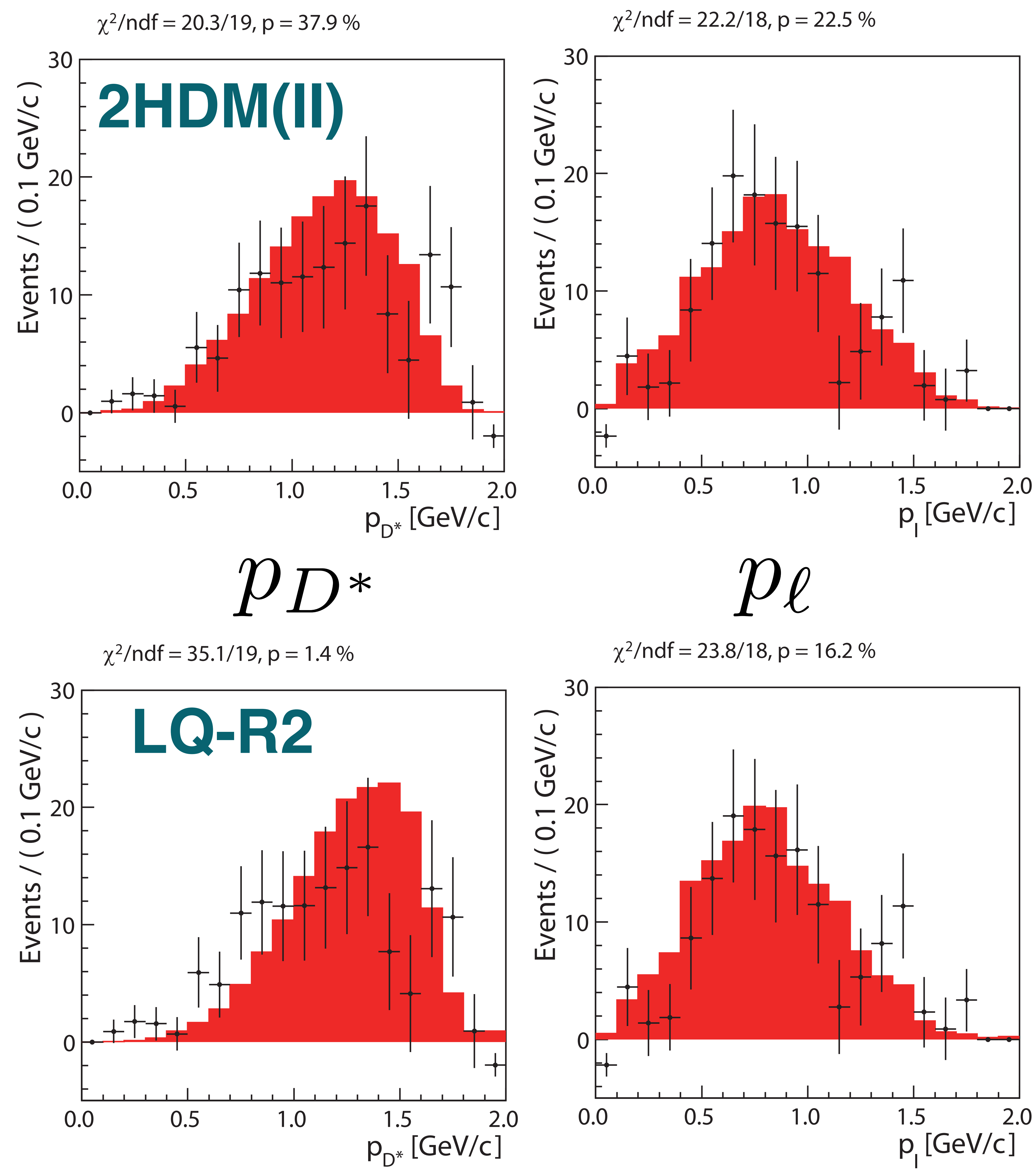
$\mathcal{R}(D^*)$ SL-tag – compared with SM



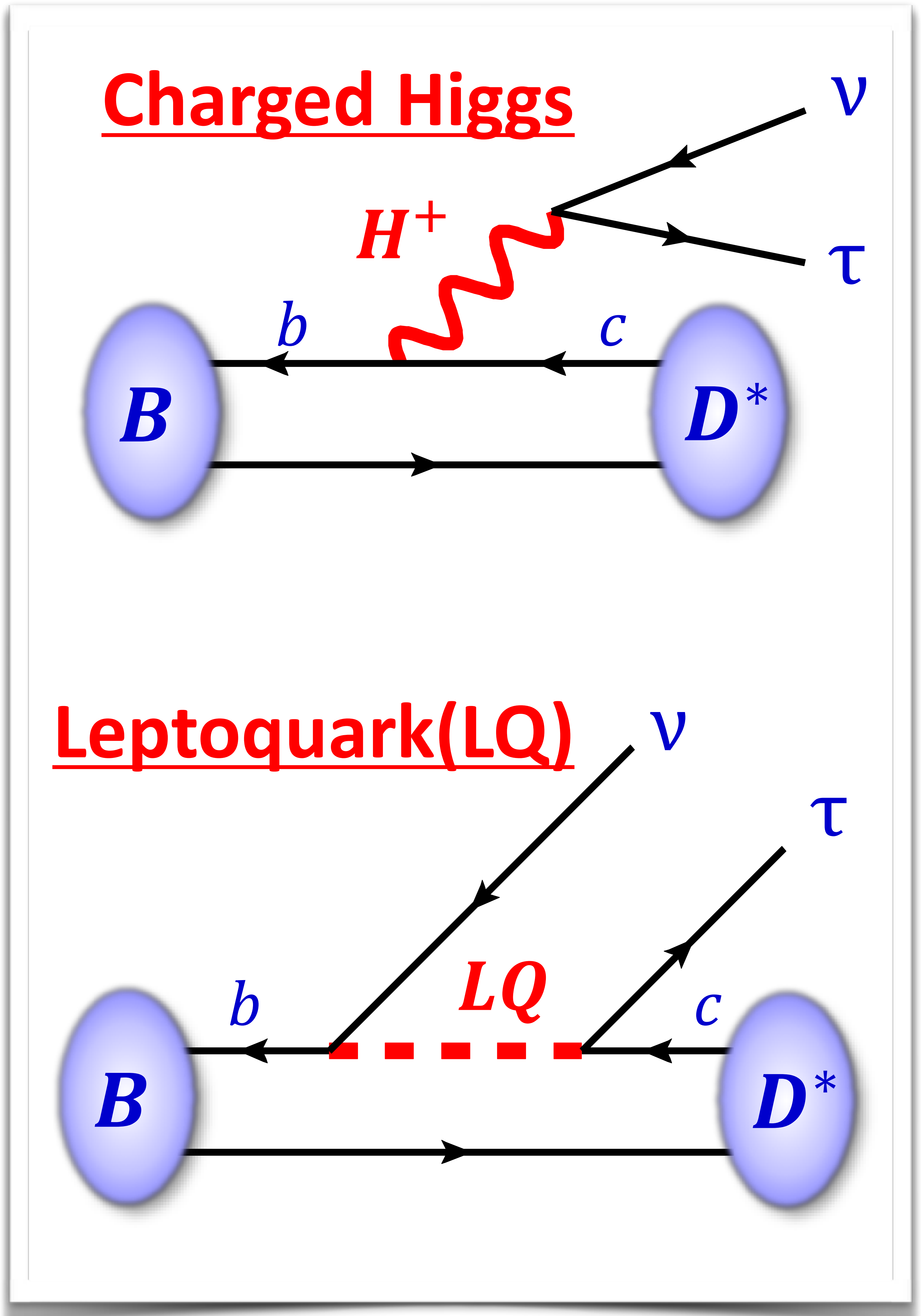
for signal-enhanced region: NN > 0.8, E_{ECL} < 0.5

Testing NP models





Testing NP models



2HDM(II)

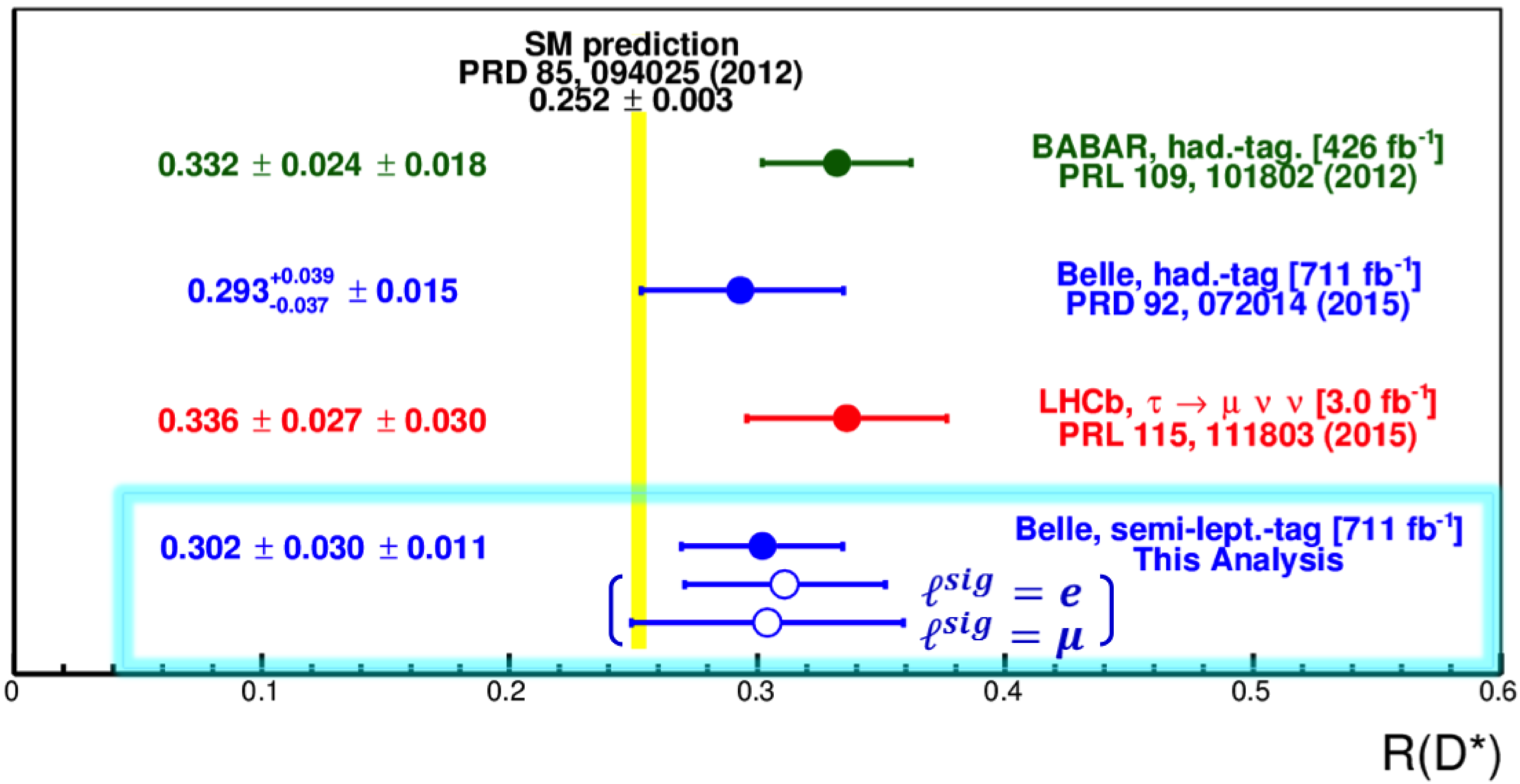
- scan for tan $\beta/m_H \in [0,1]$ and re-measure $R(D^*)$
- best match with data at tan $\beta/m_H = 0.7$ GeV^{-1}

LQ-R2

- Choose R_2 type leptoquark model# as a benchmark
- scan for C_T (for tensor op.) $\in [-0.15, +0.40]$ and re-measure $R(D^*)$
- best match for $C_T = -0.03$ and $+0.36$
- $C_T = +0.36$ doesn't fit p_{D^*} ($p = 1.4\%$), hence is disfavored

Doršner et al., JHEP 11, 084 (2013)

$\mathcal{R}(D^*)$ Comparison



more precise than Belle (had.-tag) and LHCb

(5)

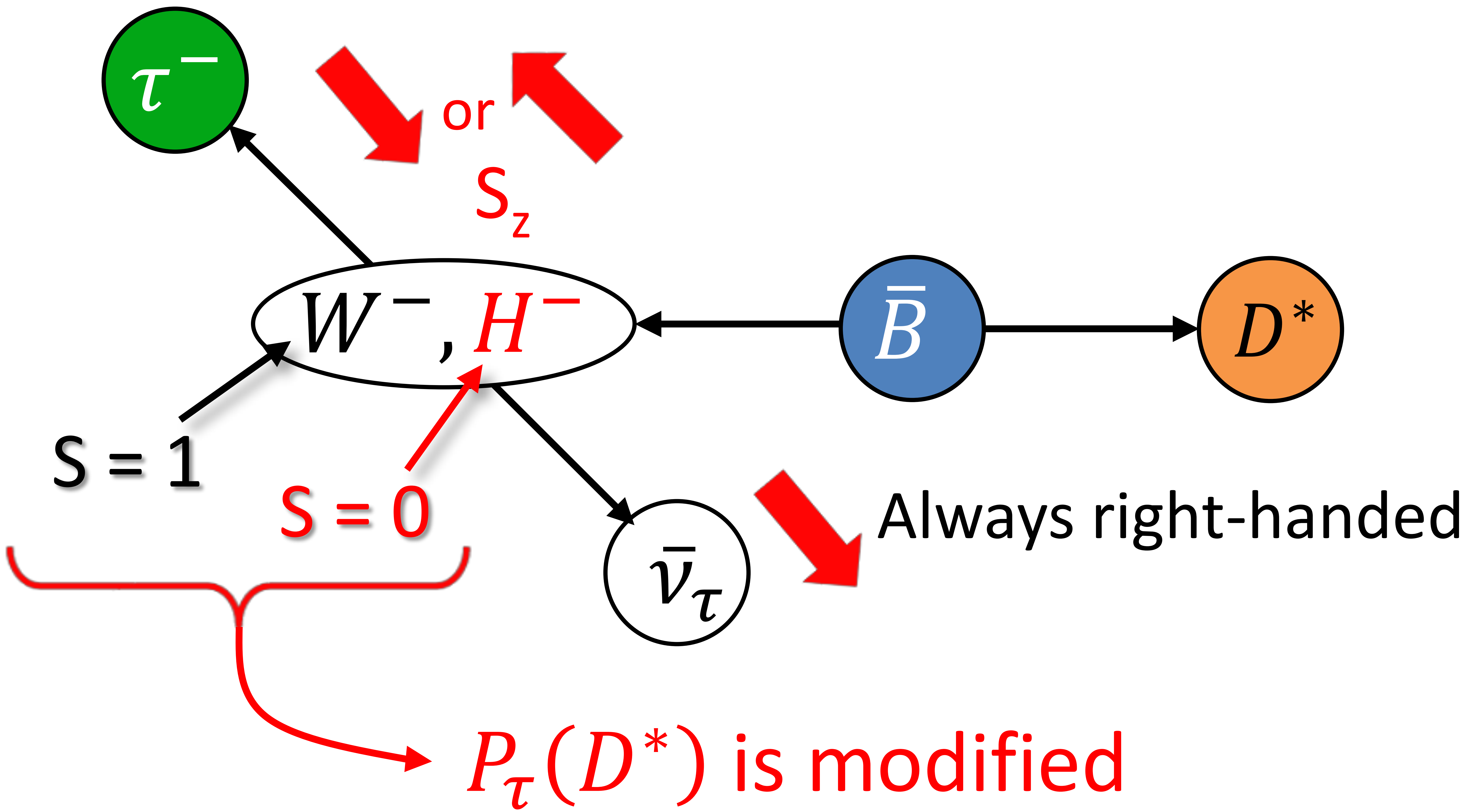
$B \rightarrow D^* \tau \nu$
polarization of τ

PRL **118,** 211801 (2017) PHYSICAL REVIEW LETTERS week ending 26 MAY 2017

Measurement of the τ Lepton Polarization and $R(D^*)$ in the Decay $\bar{B} \rightarrow D^* \tau^- \bar{\nu}_\tau$

S. Hirose,[47] T. Iijima,[48,47] I. Adachi,[14,11] K. Adamczyk,[53] H. Aihara,[74] S. Al Said,[67,31] D. M. Asner,[57] H. Atmacan,[43] V. Aulchenko,[4,56] T. Aushev,[46] R. Ayad,[67] V. Babu,[68] I. Badhrees,[67,30] A. M. Bakich,[66] V. Bansal,[57] E. Barberio,[42]

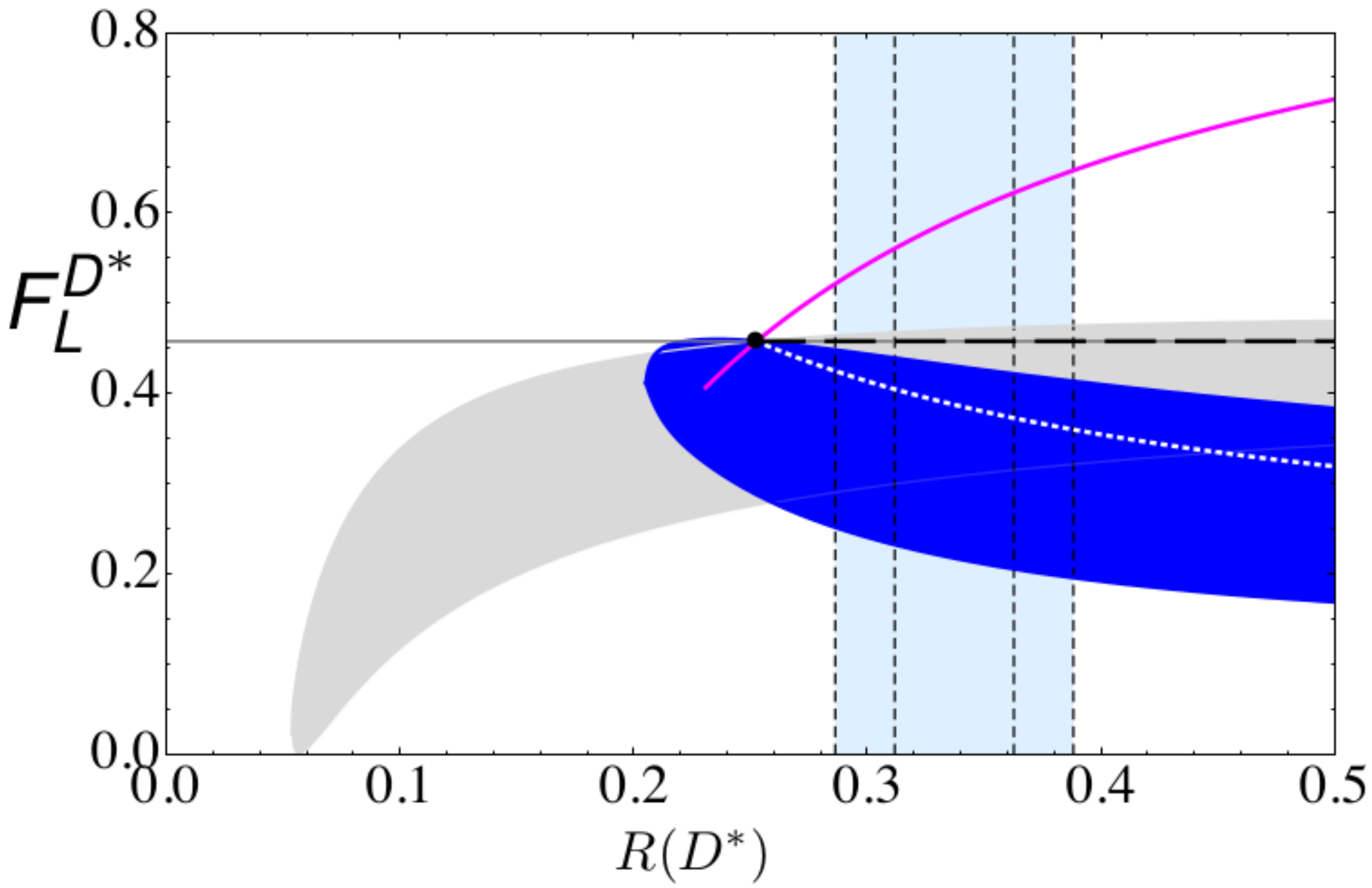
$\mathcal{R}(D^*)$ & $\mathcal{P}_\tau$ w/ 2-body τ decays (had. B-tag)

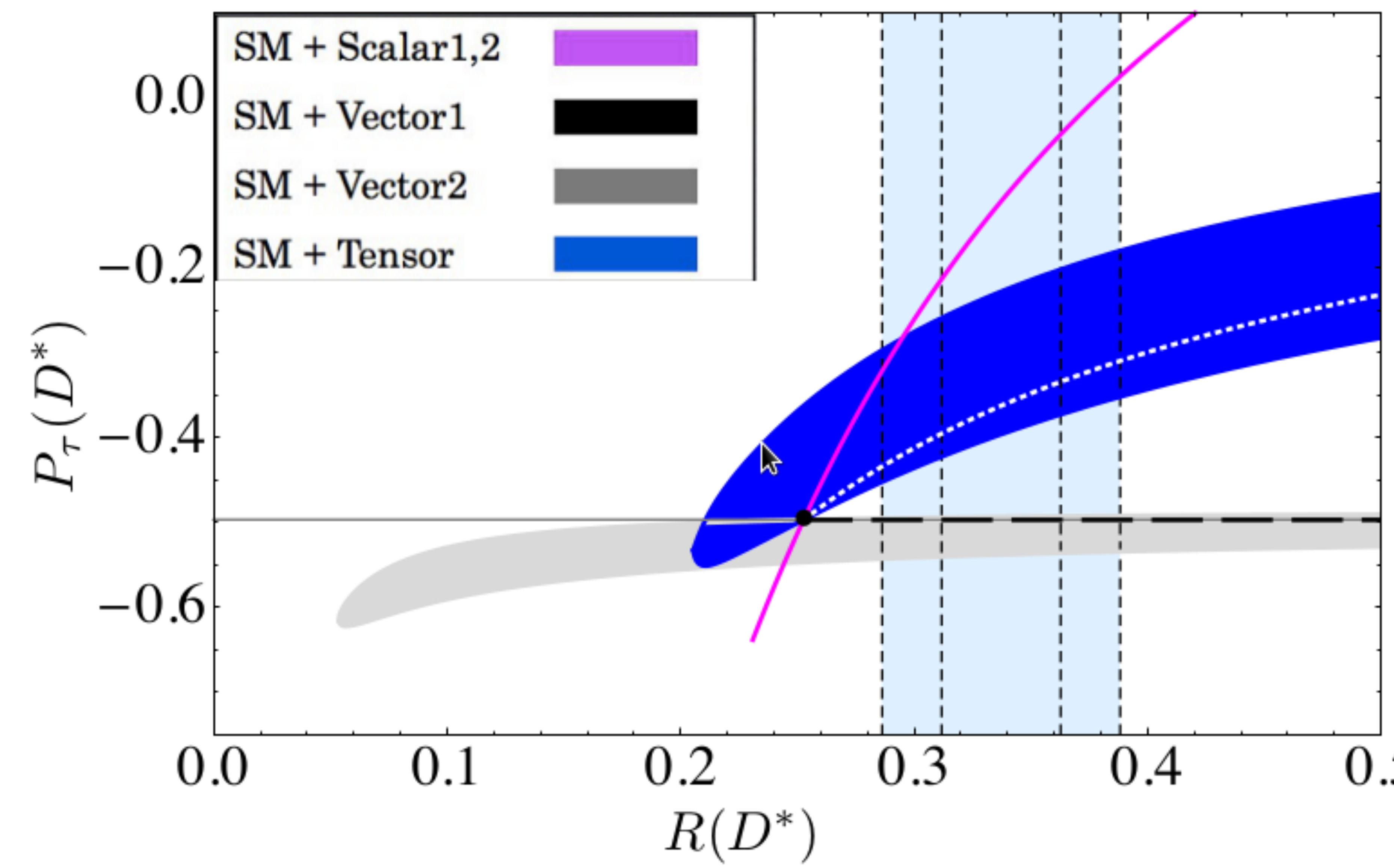


Two hadronic τ modes for $\mathcal{P}_\tau$

$\tau^- \to \pi^-\nu$ and $\rho^-(\to \pi^-\pi^0)\nu$

M. Tanaka and R. Watanabe, Phys. Rev. D 87, 034028 (2013)





$$F_L^{D^*} = \frac{\Gamma(D_L^*)}{\Gamma(D_L^*) + \Gamma(D_T^*)}$$

$F_L^{D^*}$: fraction of longitudinal polarization of D^*

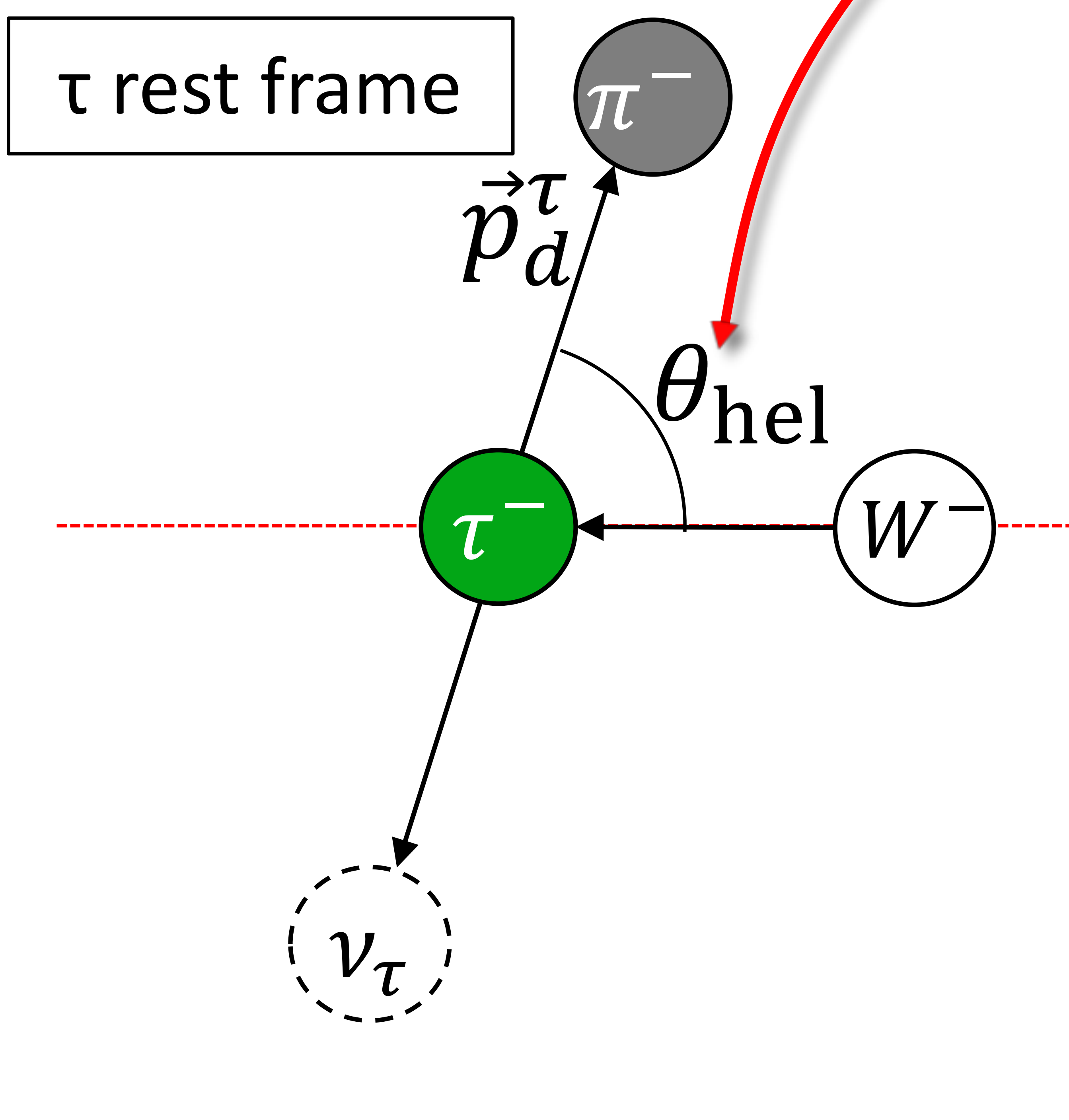
SM: $F_L^{D^*} = 0.46 - 0.53$

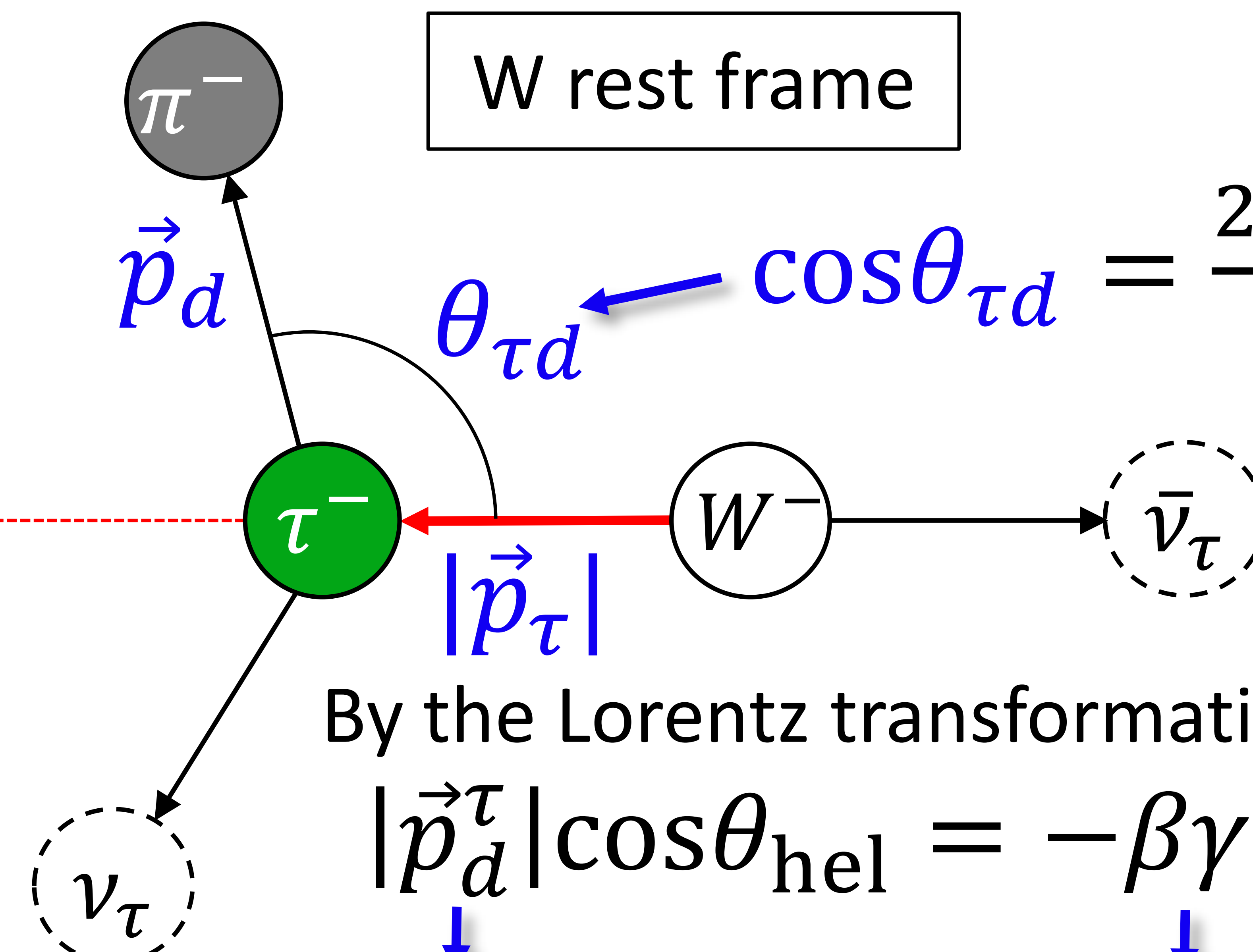
$$P_\tau = \frac{\Gamma(\lambda_\tau = +1/2) - \Gamma(\lambda_\tau = -1/2)}{\Gamma(\lambda_\tau = +1/2) + \Gamma(\lambda_\tau = -1/2)}$$

SM: $P_\tau(D^*) \approx -0.5$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\text{hel}}} = \frac{1}{2}\left(1 + \alpha P_\tau(D^*)\cos\theta_{\text{hel}}\right)$$

$$\alpha = \begin{cases} 1 & \text{for } \tau^- \to \pi^-\nu_\tau \\ \sim 0.45 & \text{for } \tau^- \to \rho^-\nu_\tau \end{cases}$$





$$\cos\theta_{\tau d} = \frac{2E_\tau E_d - m_\tau^2 - m_d^2}{2|\boldsymbol{p}_\tau||\boldsymbol{p}_d|}$$

By the Lorentz transformation,

$$|\vec{p}_d^{\,\tau}|\cos\theta_{\text{hel}} = -\beta\gamma E_d + \gamma|\vec{p}_d|\cos\theta_{\tau d}$$

$$|\vec{p}_d^{\,\tau}| \to \frac{m_\tau^2 - m_d^2}{m_\tau^2}, \quad \beta\gamma \to \frac{|\vec{p}_\tau|}{m_\tau}, \quad \gamma \to \frac{E_\tau}{m_\tau}$$

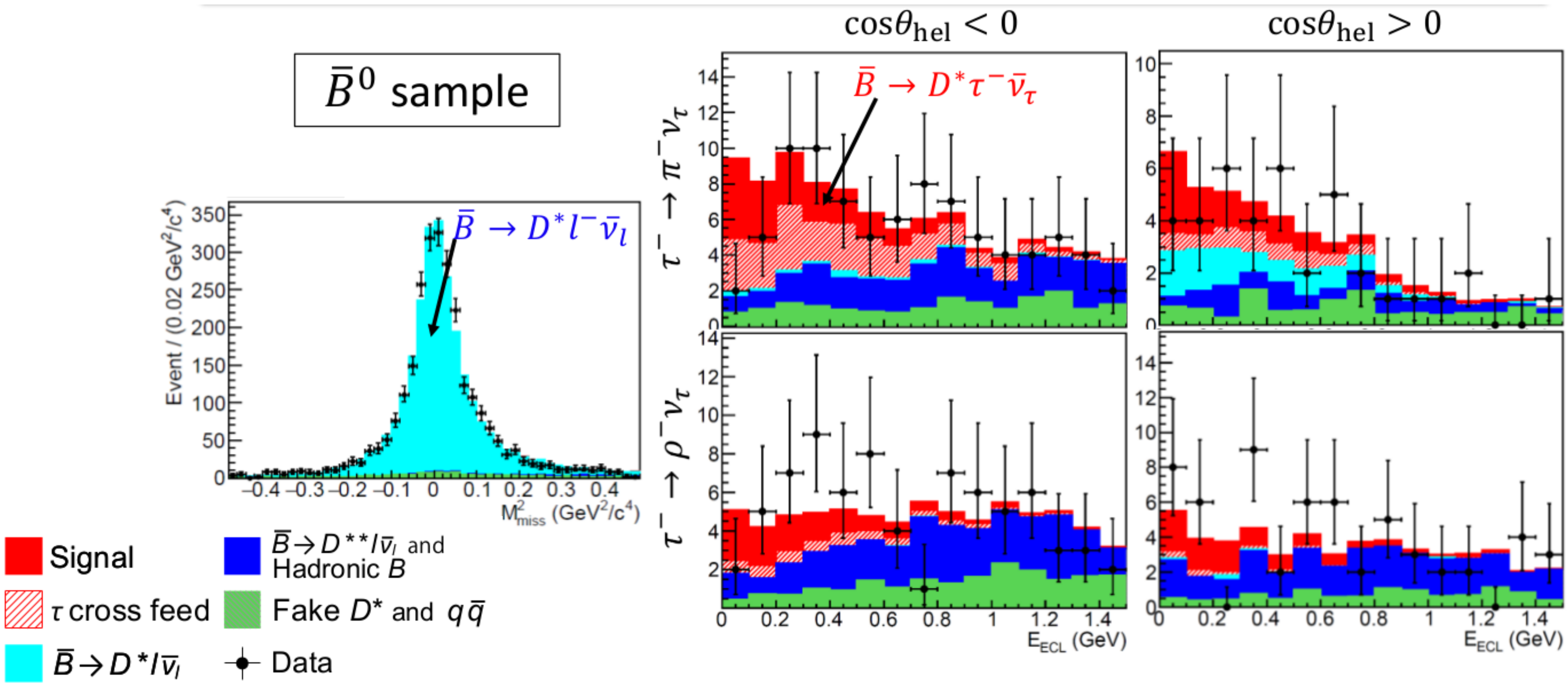
measure $\cos\theta_{\tau d} \Rightarrow$ obtain $\cos\theta_{\text{hel}}$

$\mathcal{R}(D^*)$ & $\mathcal{P}_\tau$ w/ 2-body τ decays (had. B-tag)

BELLE

- Simultaneous fitting of E_{ECL} (in 8 sub-samples)

  [B^0, B^+] ⊗ [$\pi\nu$, $\rho\nu$] ⊗ [Forward, Backward] in $\cos\theta_h$



Dominant Bkgd. from hadronic B decays (e.g. $B \to D^*(n\pi)$) is calibrated by requiring additional particles and reconstructing these modes

$\mathcal{R}(D^*)$ & $\mathcal{P}_\tau$ w/ 2-body τ decays (had. B-tag)

- Simultaneous fitting of E_{ECL} (in 8 sub-samples)
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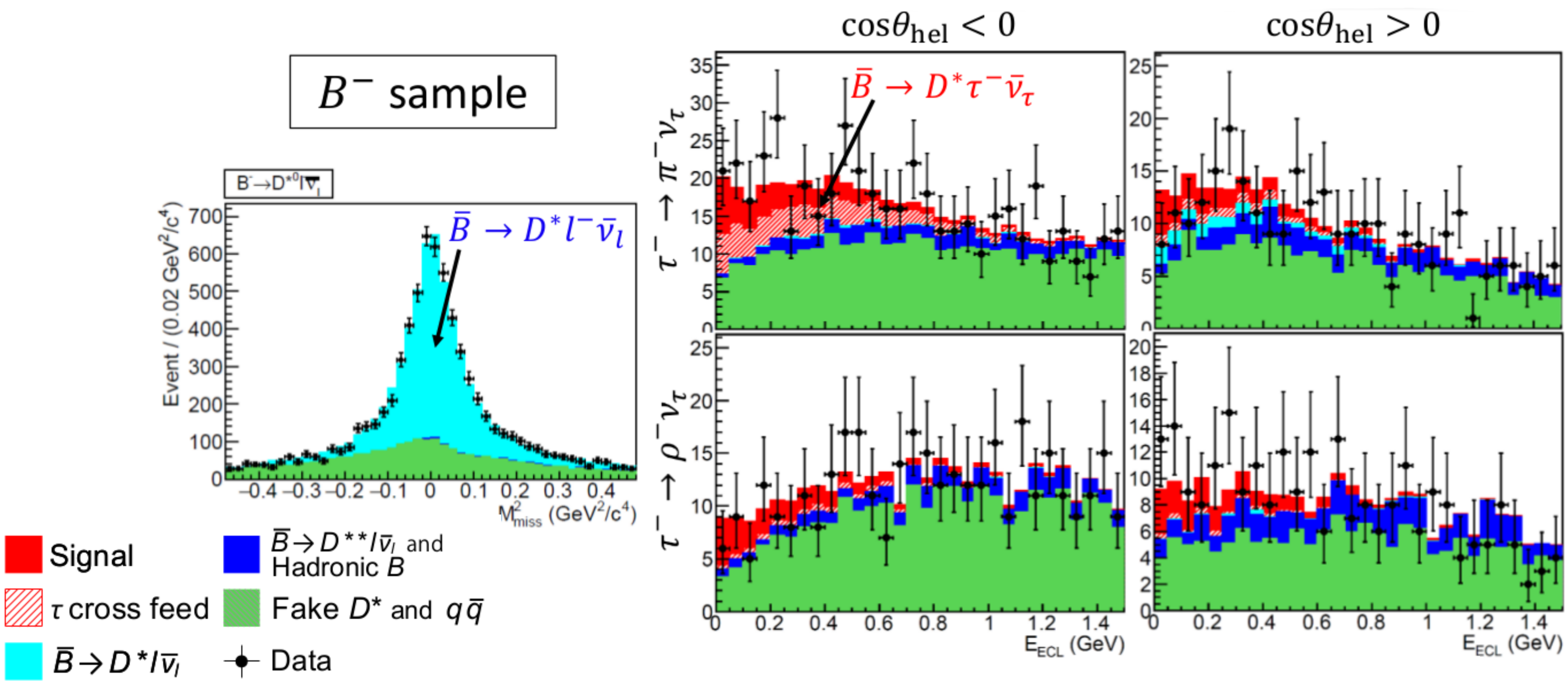
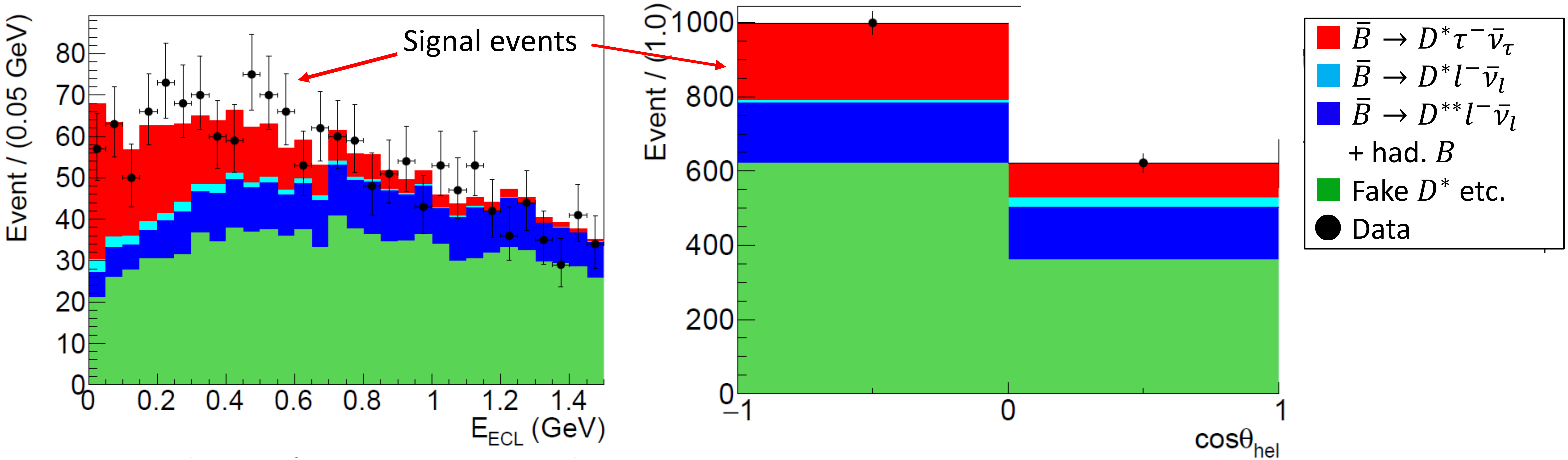


Dominant Bkgd. from hadronic B decays (e.g. $B \to D^*(n\pi)$) is calibrated by requiring additional particles and reconstructing these modes

$\mathcal{R}(D^*)$ & $\mathcal{P}_\tau$ w/ 2-body τ decays (had. B-tag)



$$R(D^*) = 0.270 \pm 0.035(\text{stat.})\,{}^{+0.028}_{-0.025}(\text{syst.})$$

$$P_\tau(D^*) = -0.38 \pm 0.51(\text{stat.})\,{}^{+0.21}_{-0.16}(\text{syst.})$$

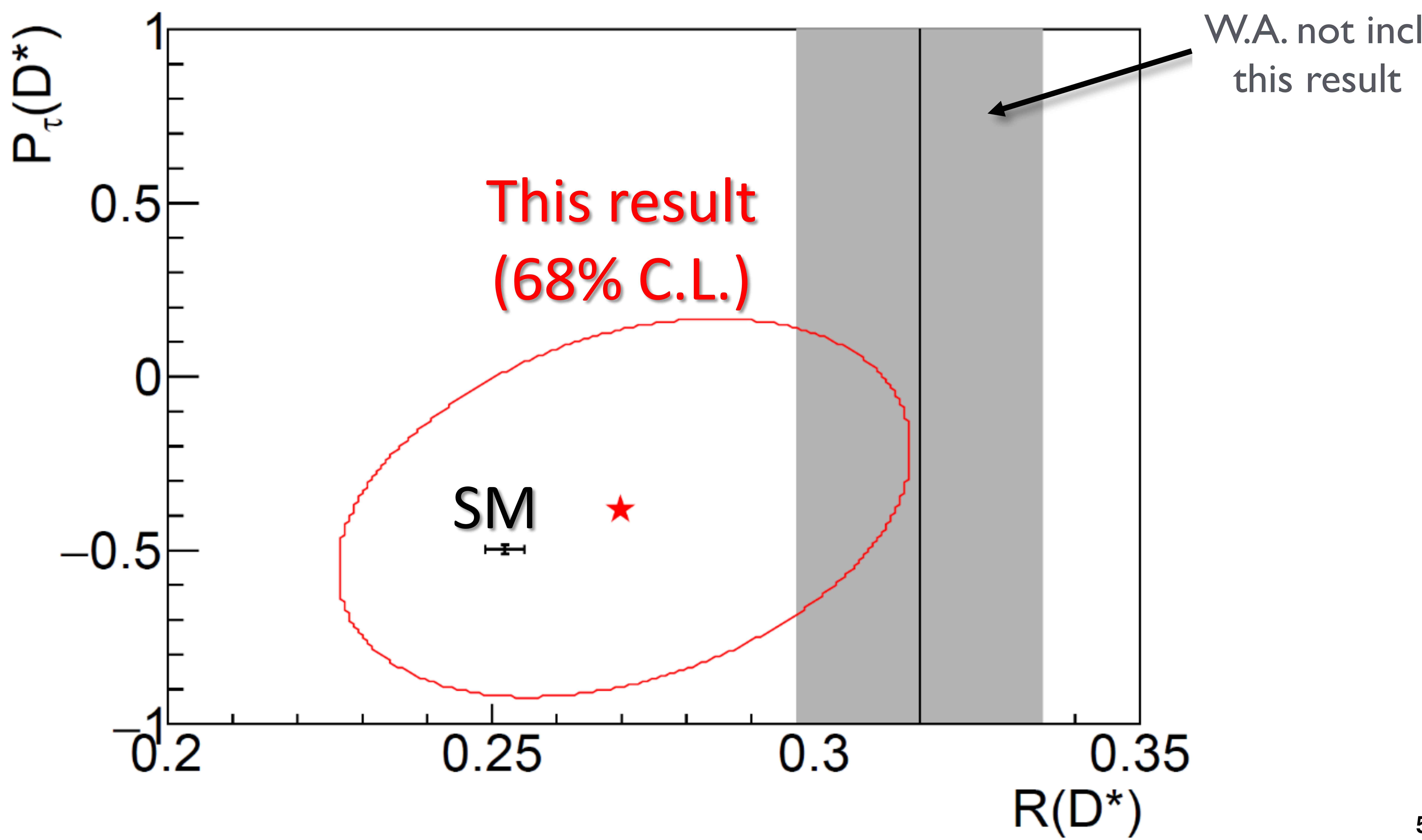
- **7.1σ including systematic uncertainty**
- **consistent with SM and other measurements**

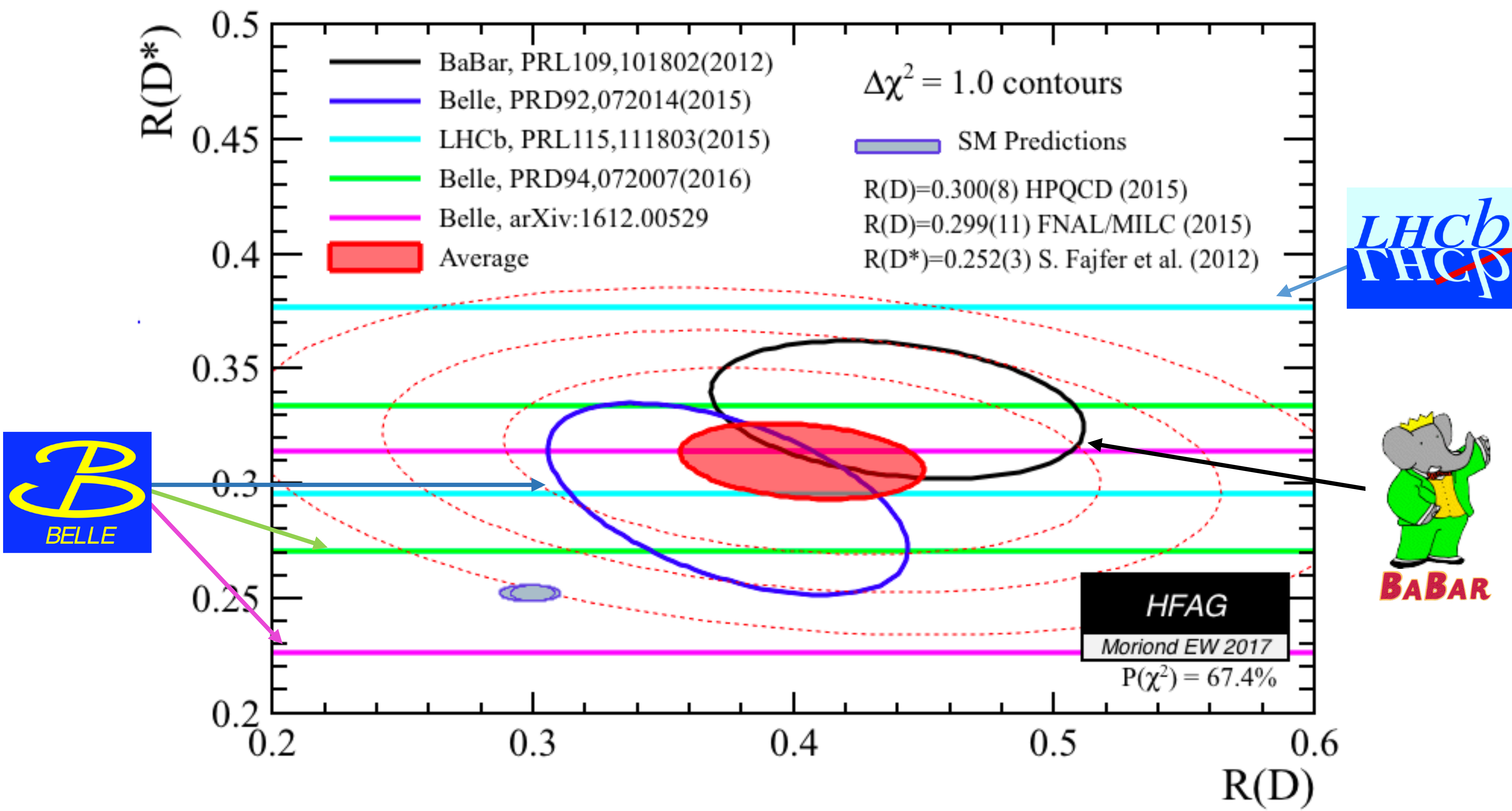
- **First measurement of P_τ**

$$\mathcal{P}_\tau^{\rm SM} = -0.497 \pm 0.014$$

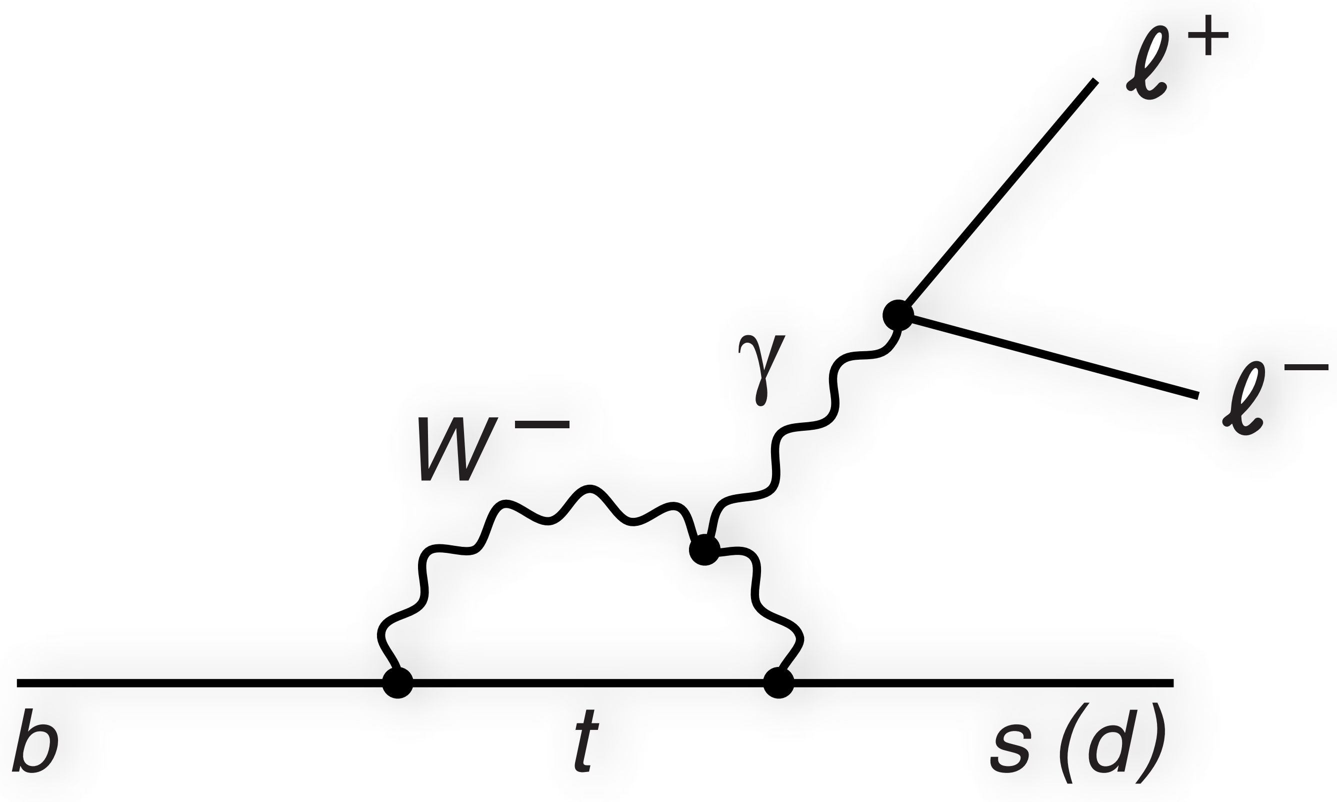
by M. Tanaka \& R. Watanabe, PRD 87, 034028 (2013)}

$\mathcal{R}(D^*)$ & $\mathcal{P}_\tau$ w/ 2-body τ decays (had. B-tag)





R(D*)
R(D)
BaBar, PRL109,101802(2012)
Belle, PRD92,072014(2015)
LHCb, PRL115,111803(2015)
Belle, PRD94,072007(2016)
Belle, arXiv:1612.00529
Average
Δχ² = 1.0 contours
SM Predictions
R(D)=0.300(8) HPQCD (2015)
R(D)=0.299(11) FNAL/MILC (2015)
R(D*)=0.252(3) S. Fajfer et al. (2012)
HFAG
Moriond EW 2017
P(χ²) = 67.4%
BELLE
LHCb
BABAR

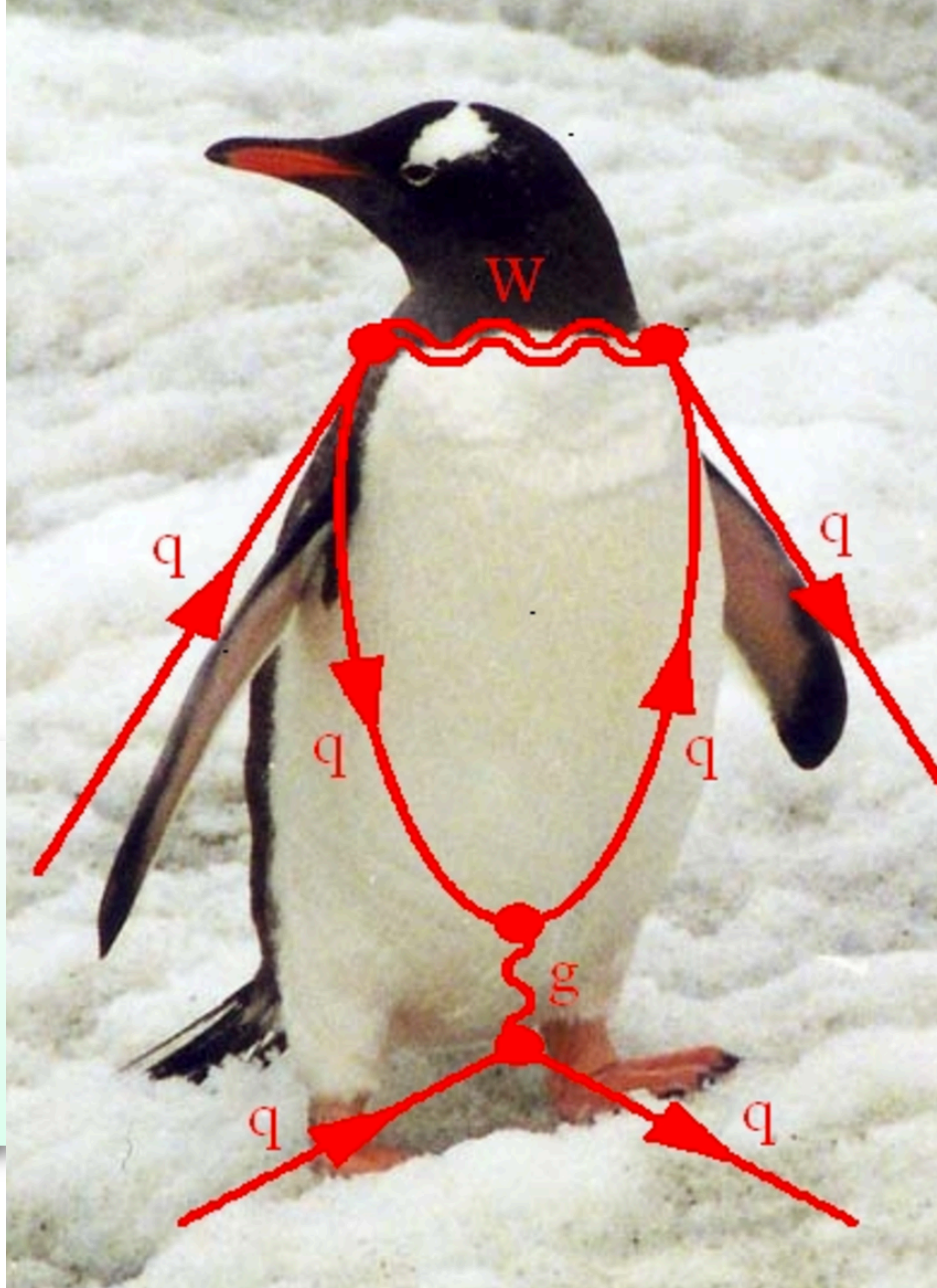


(g) EM penguin

Angular analysis of $B \rightarrow K^* l^+ l^-$

BELLE

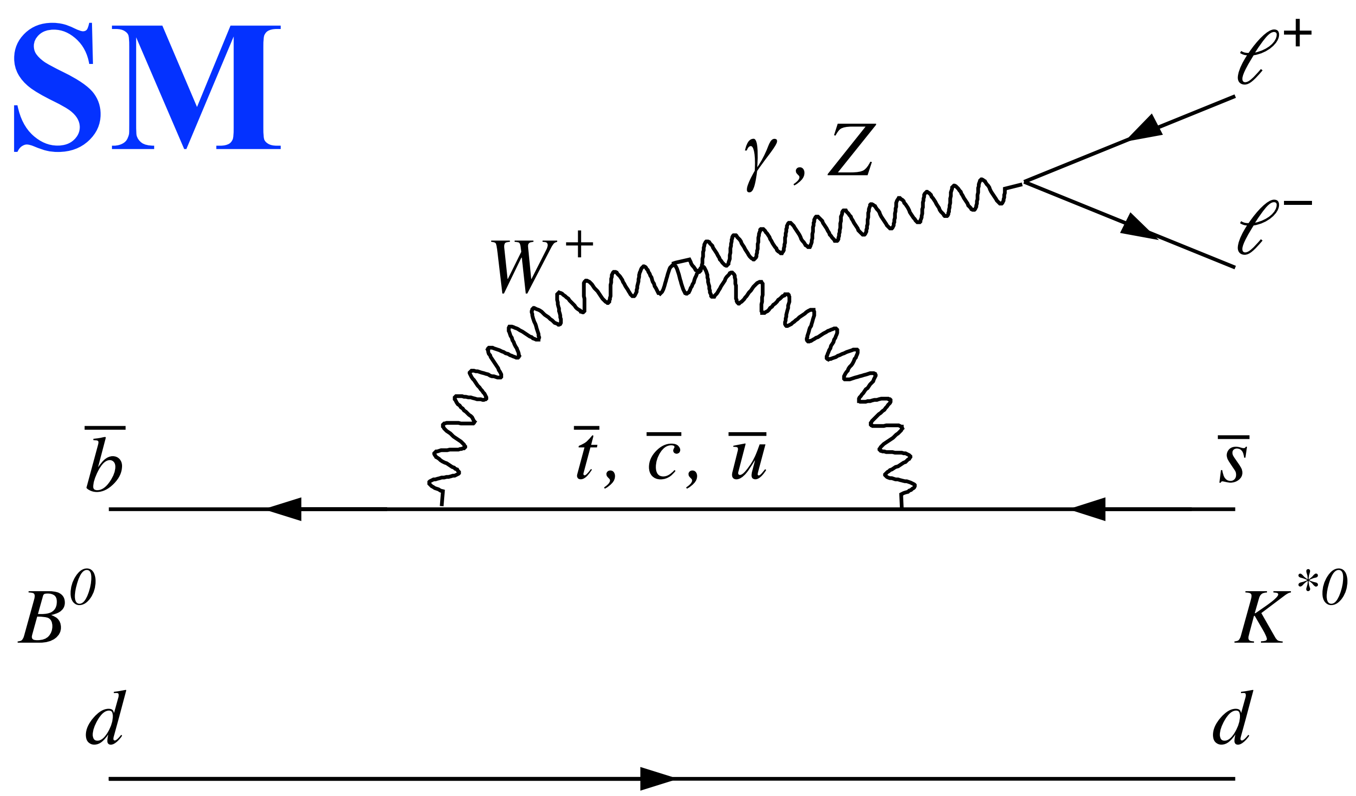
PRL 118, 111801 (2017)

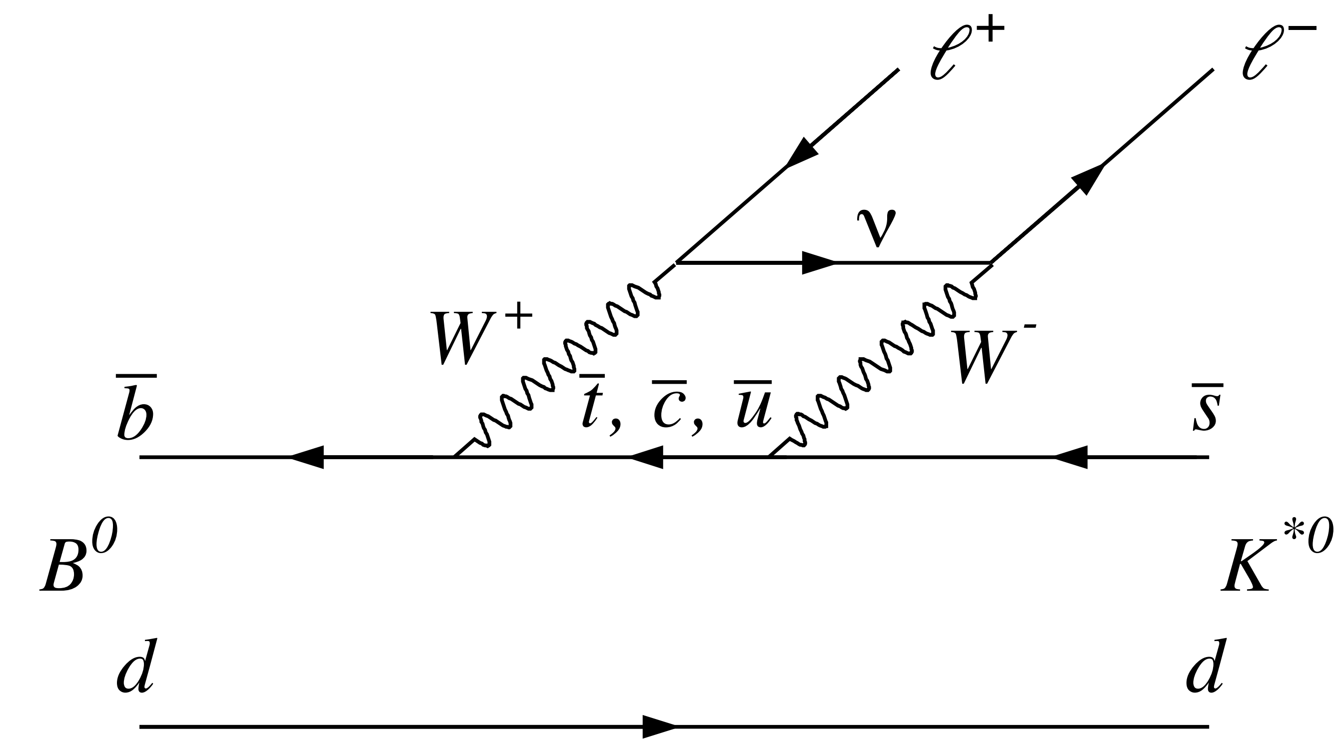


Why electro-weak penguin?

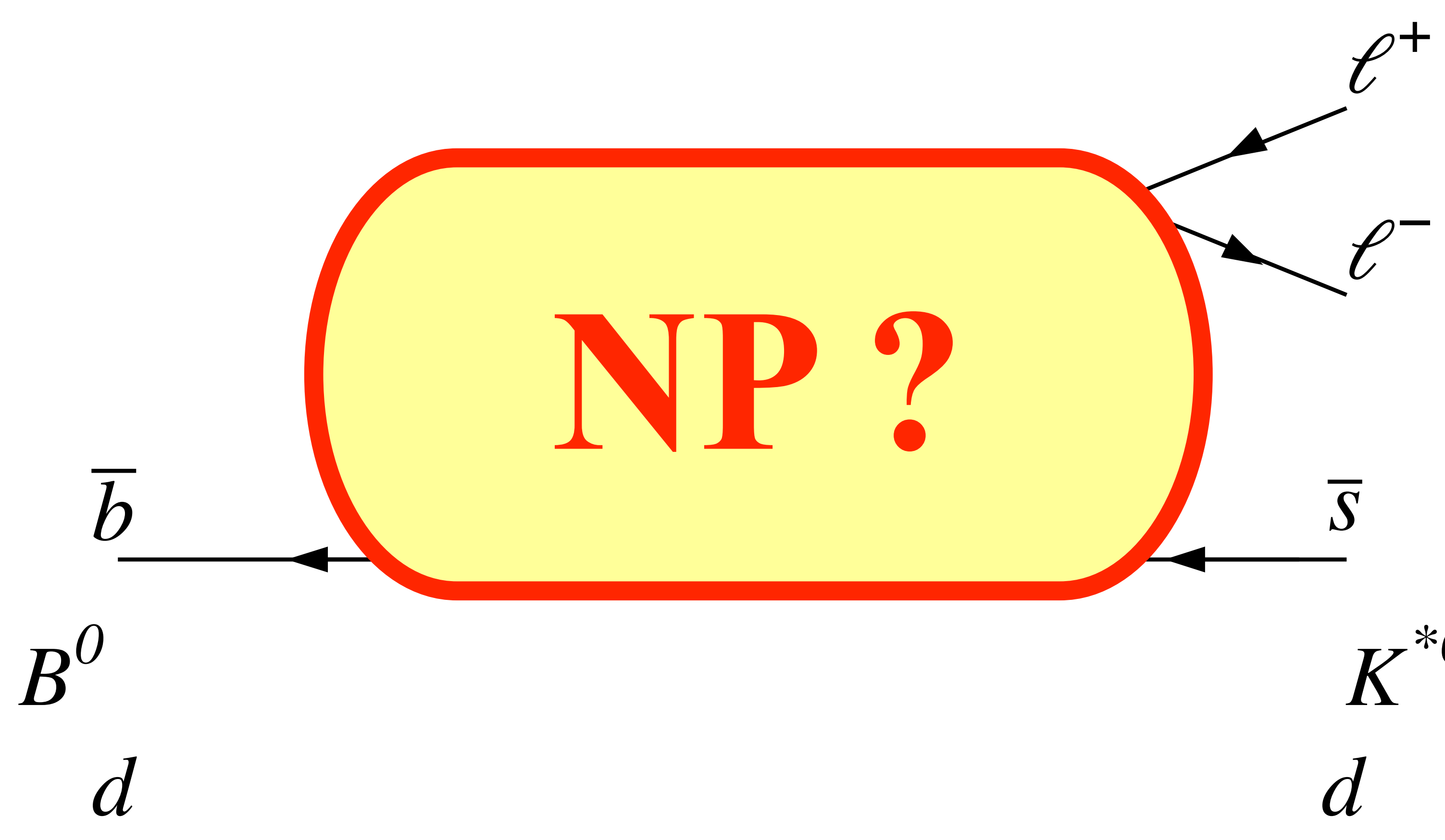
- FCNC that occurs only at loop level in the SM

SM

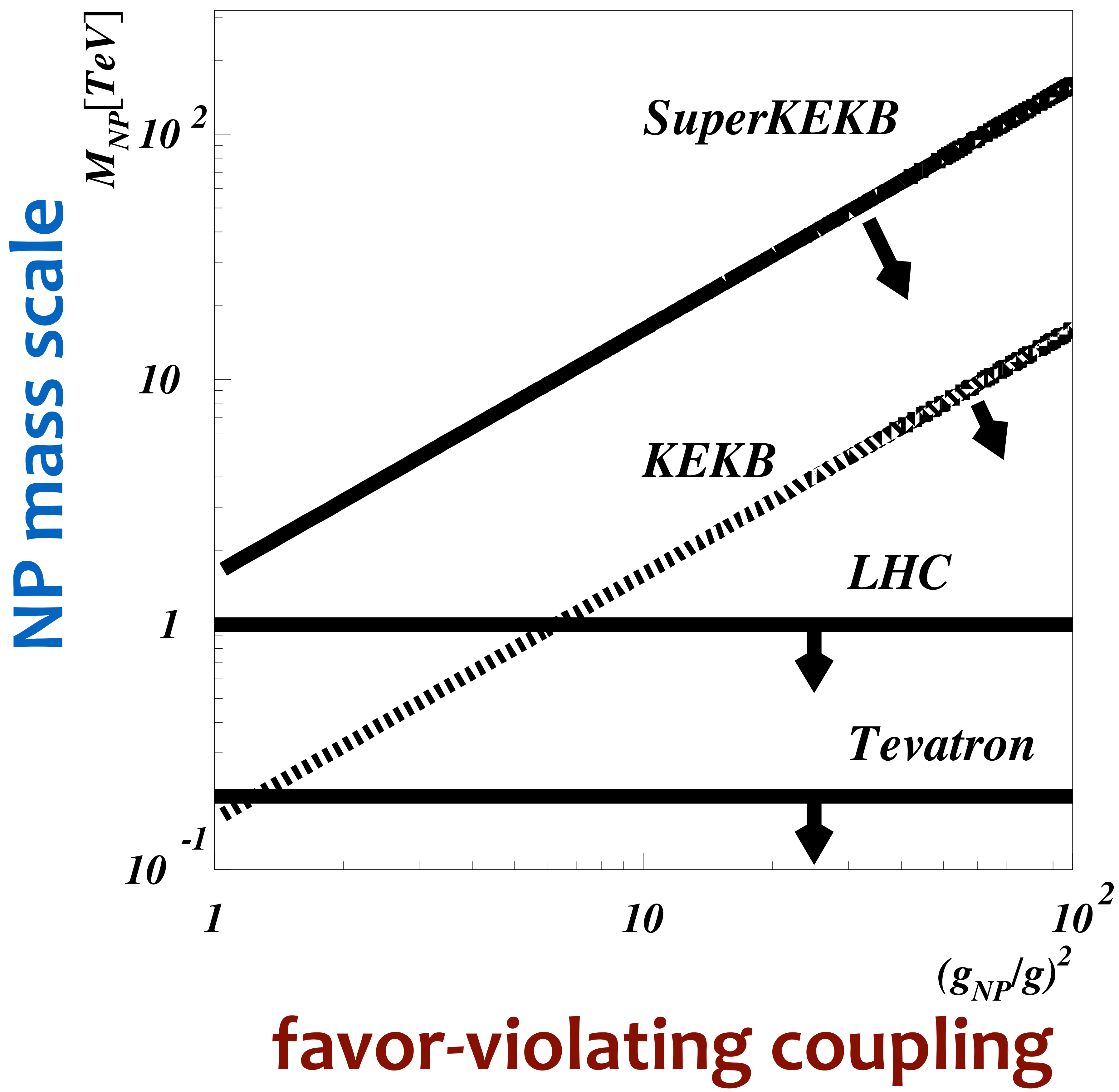




- Particles of new physics may enter the loop and affect the measured results



Energy vs. Intensity Frontiers



- Intensity Frontier is **complementary** to the Energy Frontier
- If LHC finds NP
  - * precision flavor input is essential to further clarify those discoveries
- Even if no new NP is found
  - * high-statistics flavor sector measurements (on b, c, and τ) can provide beyond-TeV-scale probe for NP

Belle's legacy on EWP

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

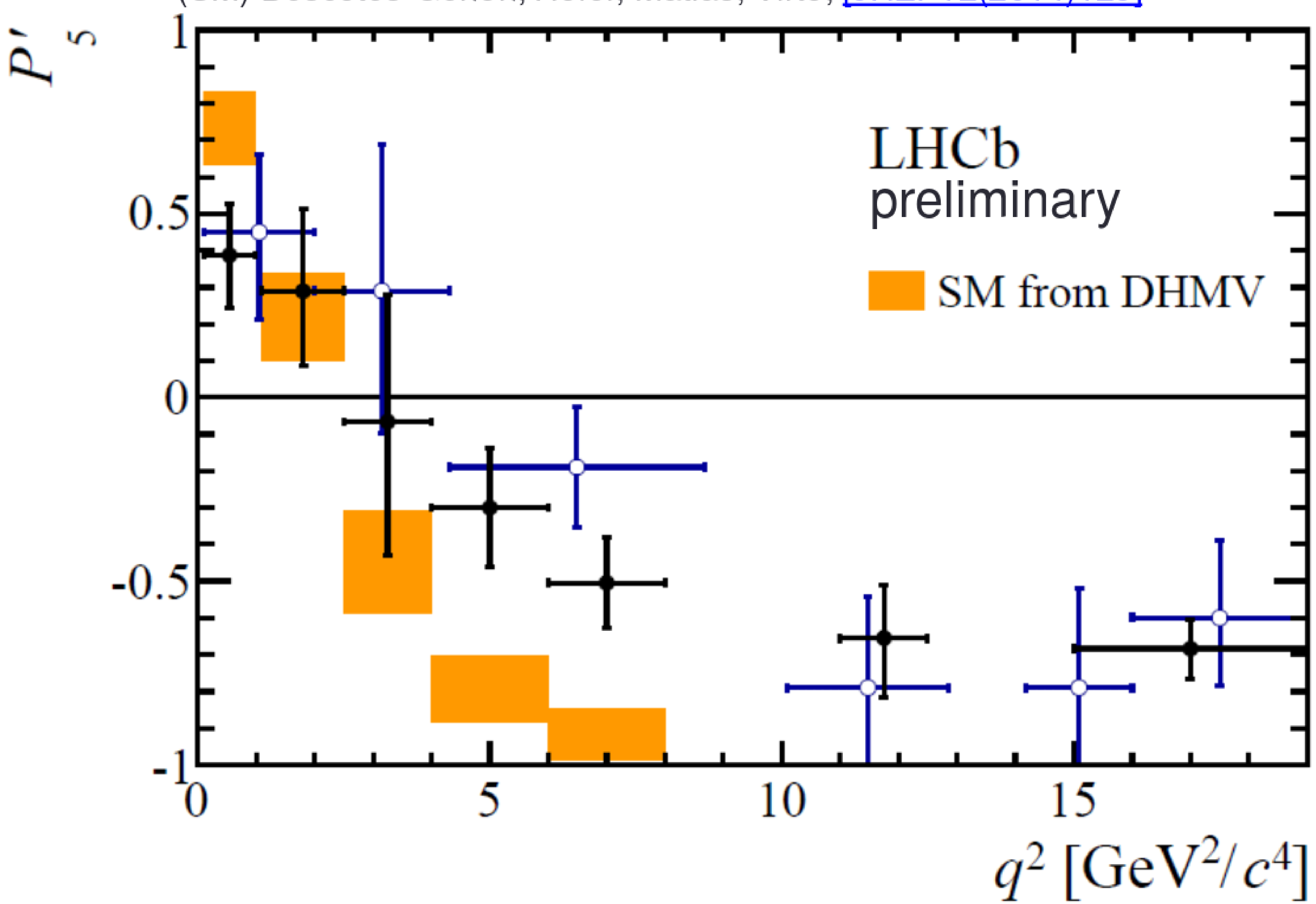
- First observations of several radiative modes, $\phi K\gamma$, $K_1\gamma$, etc.
- First observation of $B \to (\rho, \omega)\gamma$ PRL **96**, 221601 (2006)
- Most precise measurement of $B \to X_s\gamma$ covering the widest E_γ range PRL **103**, 241801 (2009)
- *and many more published results*

Hints of anomaly in $B \to K^* \ell^+ \ell^-$ (LHCb)

$$R_K \equiv \frac{\mathcal{B}(B^+ \to K^+ \mu\mu)}{\mathcal{B}(B^+ \to K^+ ee)}$$ by LHCb $\to 2.6\sigma$

P_5-anomaly by LHCb Measuerements $\to 3.4\sigma$

(SM) Descotes-Genon, Hofer, Matias, Virto, [JHEP12(2014)125]



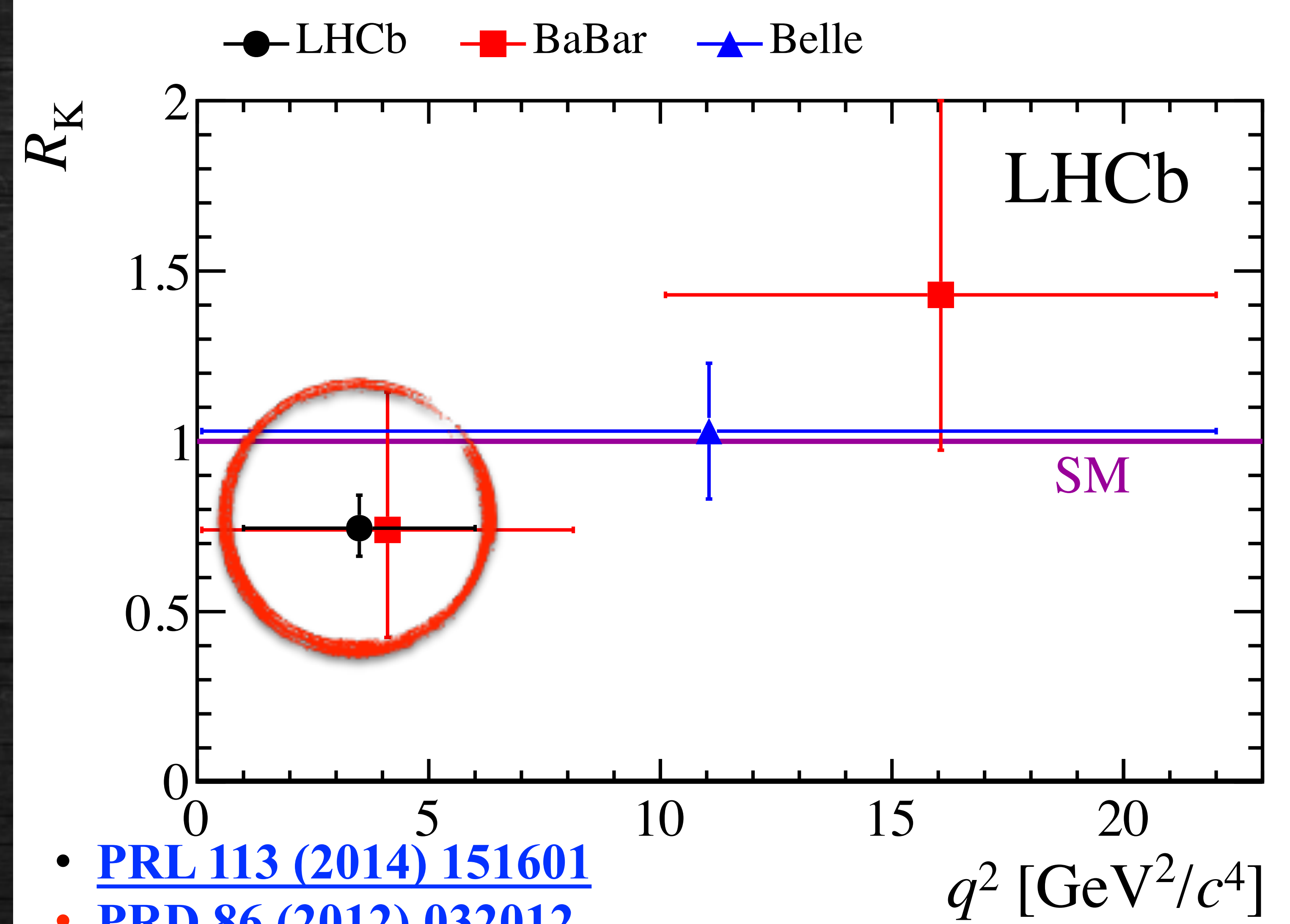
$$P'_5 = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

Once again, for details of the LHCb results, please come to KIAS workshop on July 18, 2017 and listen to Karim Trabelsi's talk.

Once upon a time …

- LHCb tested Lepton Universality using **$B^+ \to K^+ ll$** decays and observed a **tension with the SM at 2.6σ**

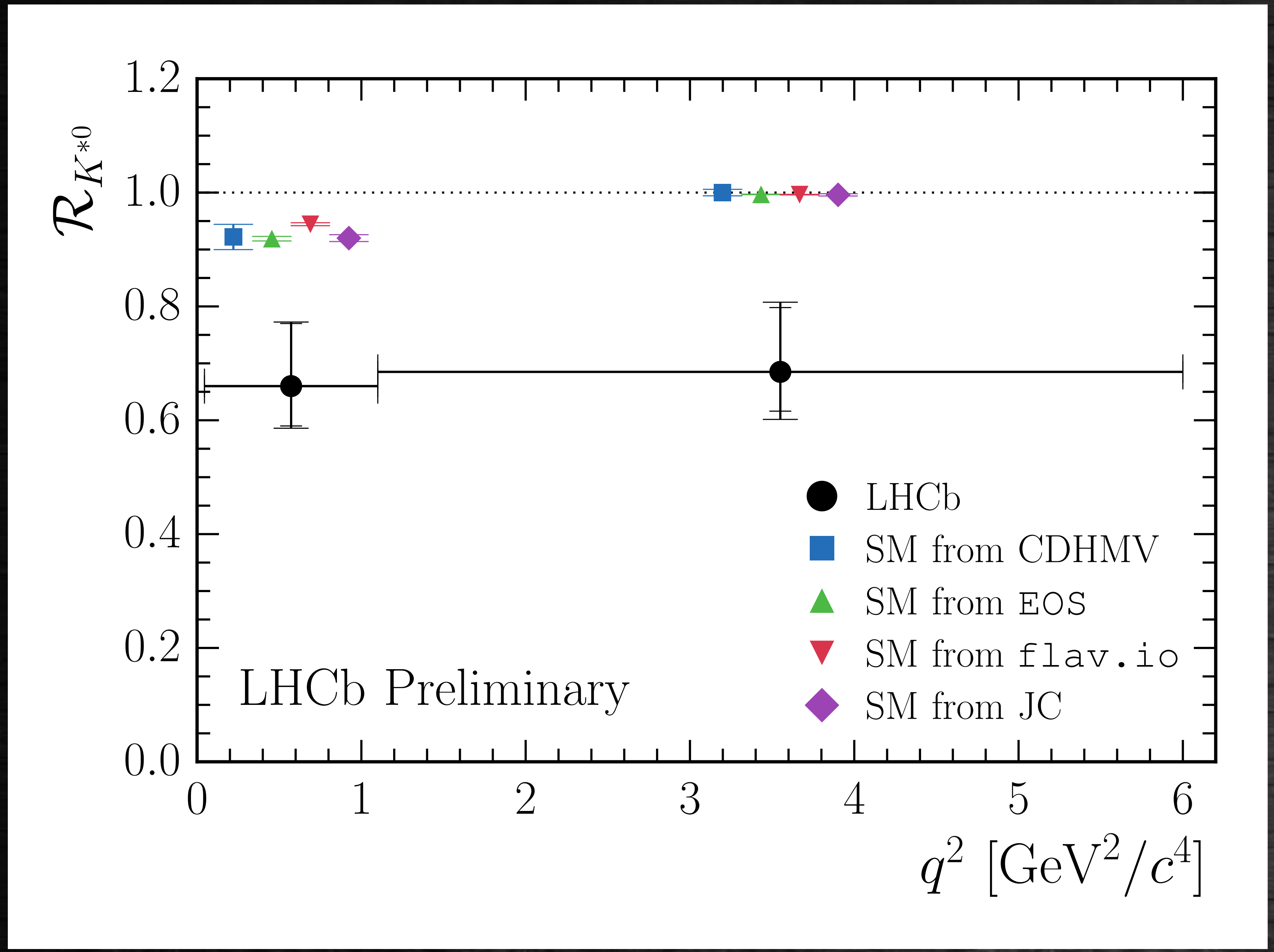
$$\mathcal{R}_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ J/\psi (\to \mu^+ \mu^-))} \Big/ \frac{\mathcal{B}(B^+ \to K^+ e^+ e^-)}{\mathcal{B}(B^+ \to K^+ J/\psi (\to e^+ e^-))}$$

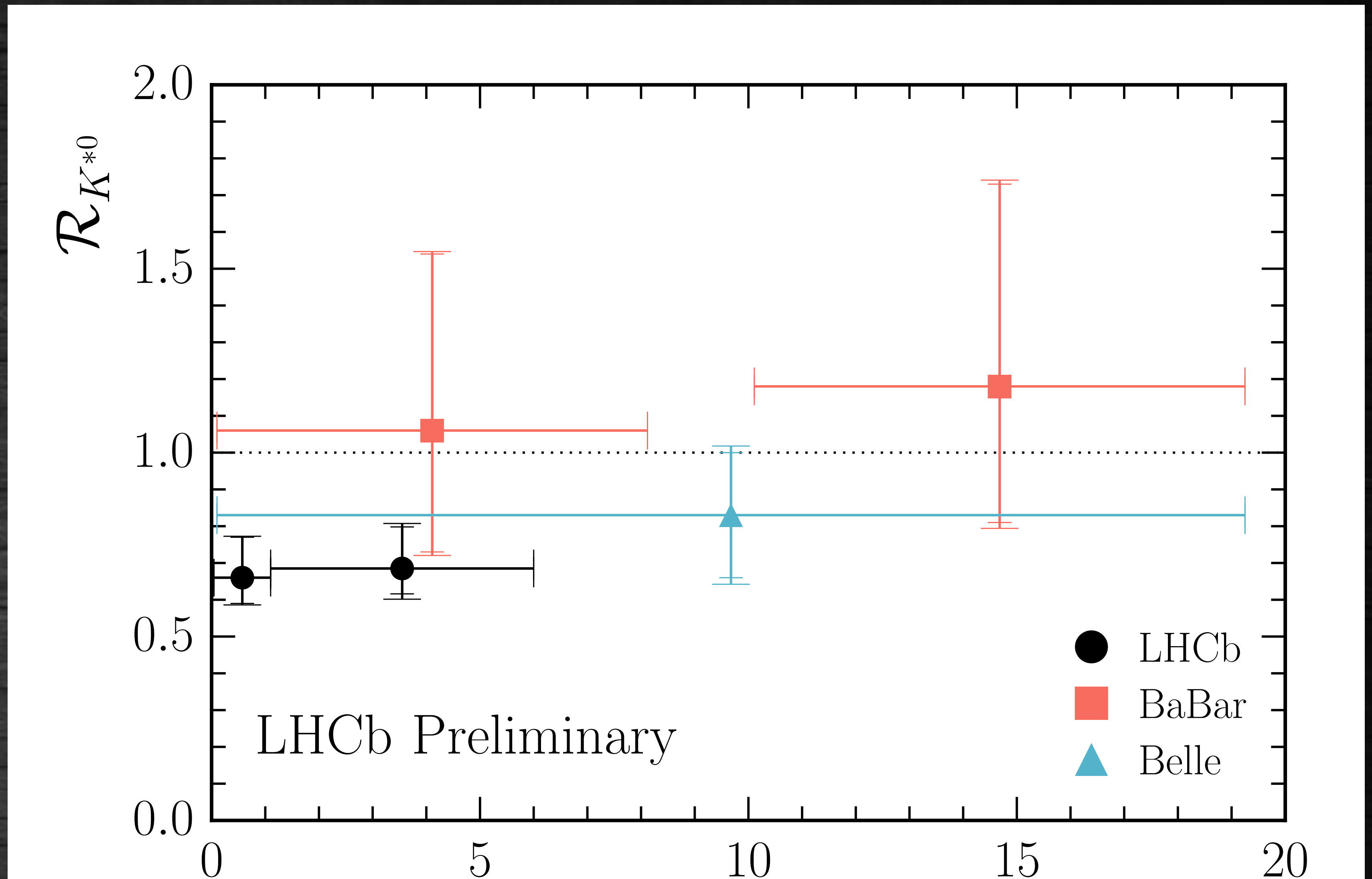


- PRL 113 (2014) 151601
- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

- Consistent with observed BR($B^+ \to K^+ \mu\mu$) if NP does not couple to electrons
- **Observation of LFU violations would be a clear sign of NP**

Results – II



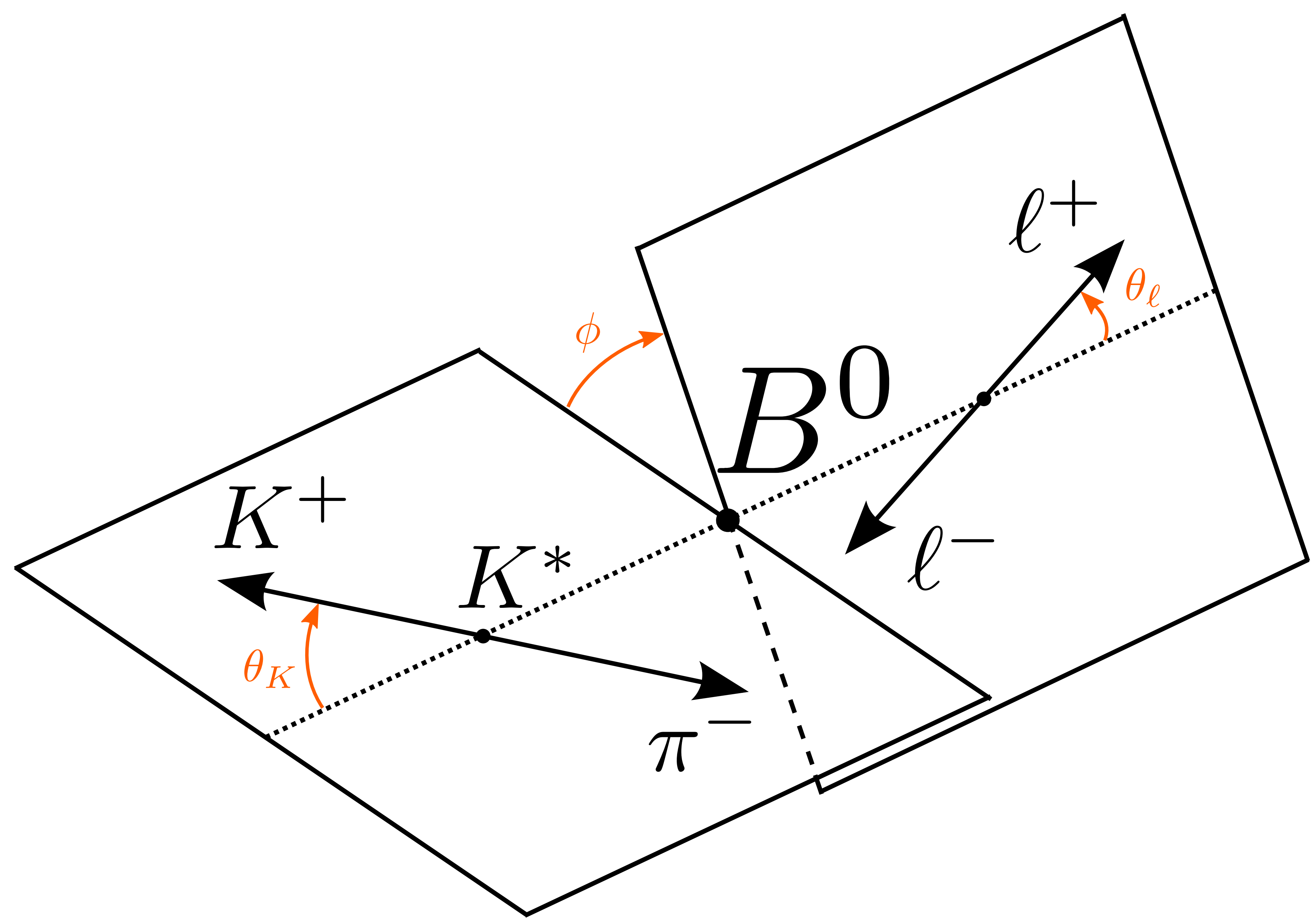


- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

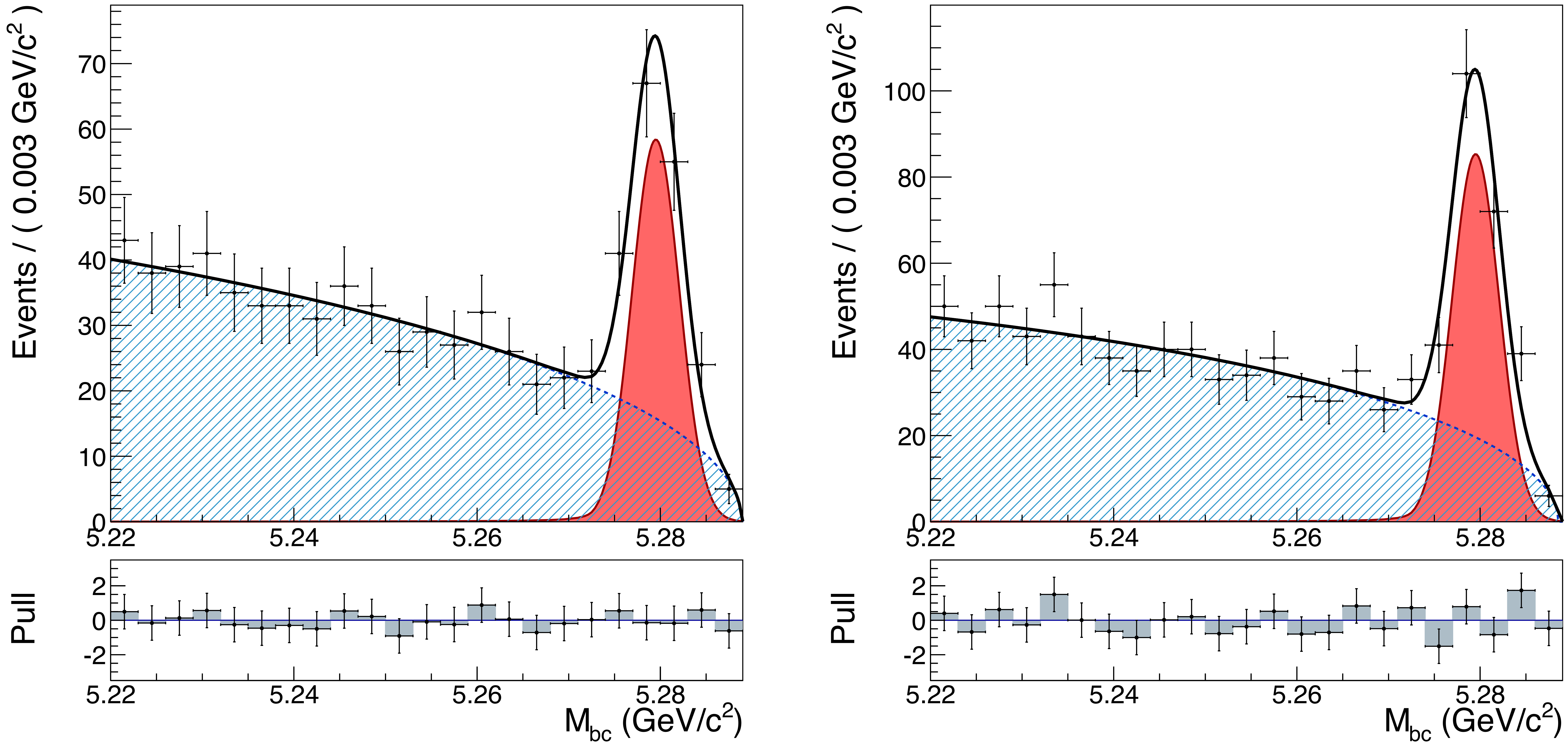
- The compatibility of the result in the **low-q^2** with respect to the SM prediction(s) is of **2.2-2.4** standard deviations
- The compatibility of the result in the **central-q^2** with respect to the SM prediction(s) is of **2.4-2.5** standard deviations

$B \to K^* \ell^+ \ell^-$ – basic features

- $\mathcal{B} \sim 10^{-7}$ – expect $\mathcal{O}(100)$ events from Belle
- $\exists$ irreducible background from J/ψ and ψ' – some q^2 regions are vetoed
- For robust fitting,
  $\Rightarrow$ employ 'folding' method developed by LHCb [PRL 111, 191801 (2013)]
- The decay is completely described by θ_ℓ, θ_K, ϕ and $q^2 = M^2_{\ell^+\ell^-}$.



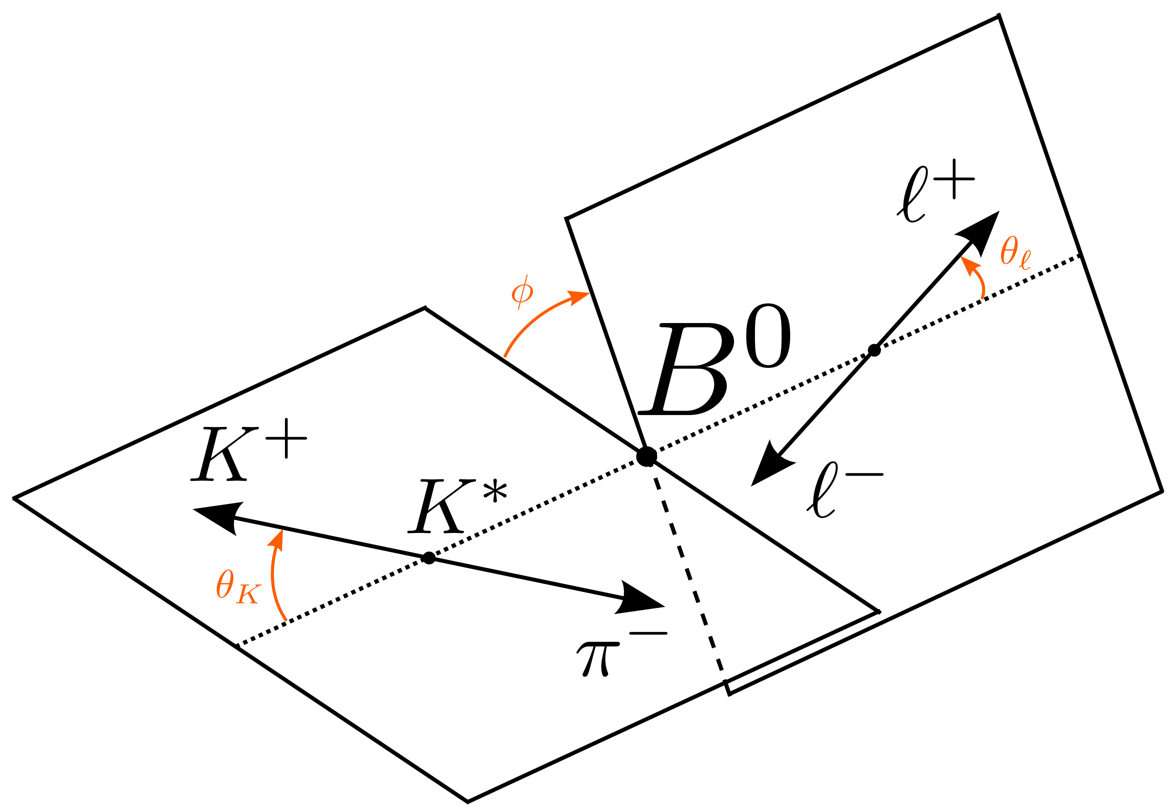
$B \to K^* \ell^+ \ell^-$ – signal yields



$N_{\mathrm{sig}} = 127 \pm 15$ $N_{\mathrm{sig}} = 185 \pm 17$

$B \to K^* \ell^+ \ell^-$ – angular analysis

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



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

considered to be largely free from form-factor uncertainties

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

$B \to K^* \ell^+ \ell^-$ – angular analysis

- 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,

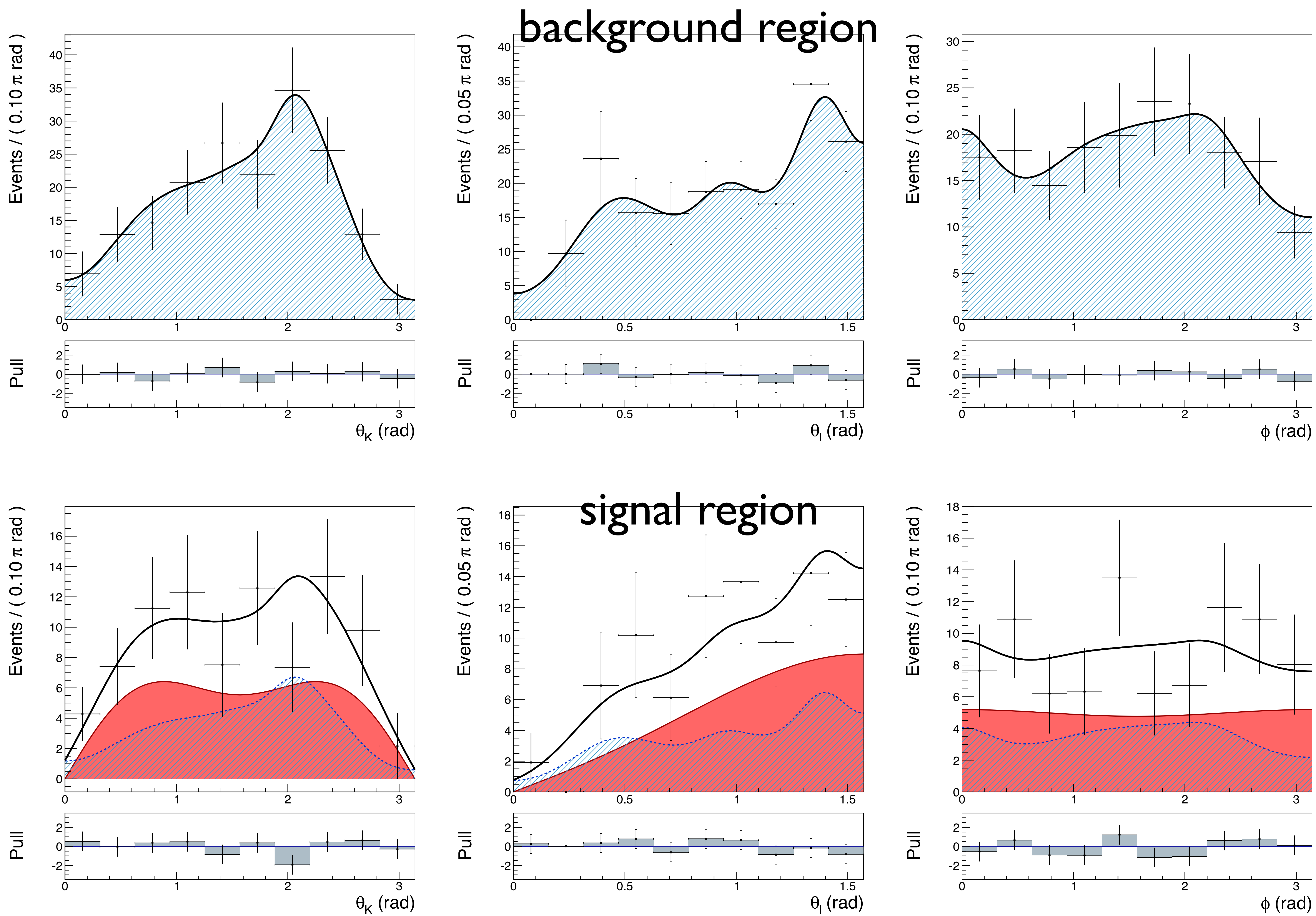
$$P_4', S_4 : \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \phi \to \pi - \phi & \text{for } \theta_\ell > \pi/2 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2, \end{cases} \qquad P_5', S_5 : \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2 \end{cases}$$

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

$B \to K^* \ell^+ \ell^-$ – fit procedure

- Signal and background fractions are determined from fits to $M_{\rm bc}$
- Background shapes for angular distributions are estimated by $M_{\rm bc} < 5.27$ GeV$/c^2$ (“side-band”)
  - (Note) Angular observables are uncorrelated with $M_{\rm bc}$ for background.
- Angular observables are obtained by 3D unbinned max. likelihood fit, in four bins of q^2

Fit projections for P_5'

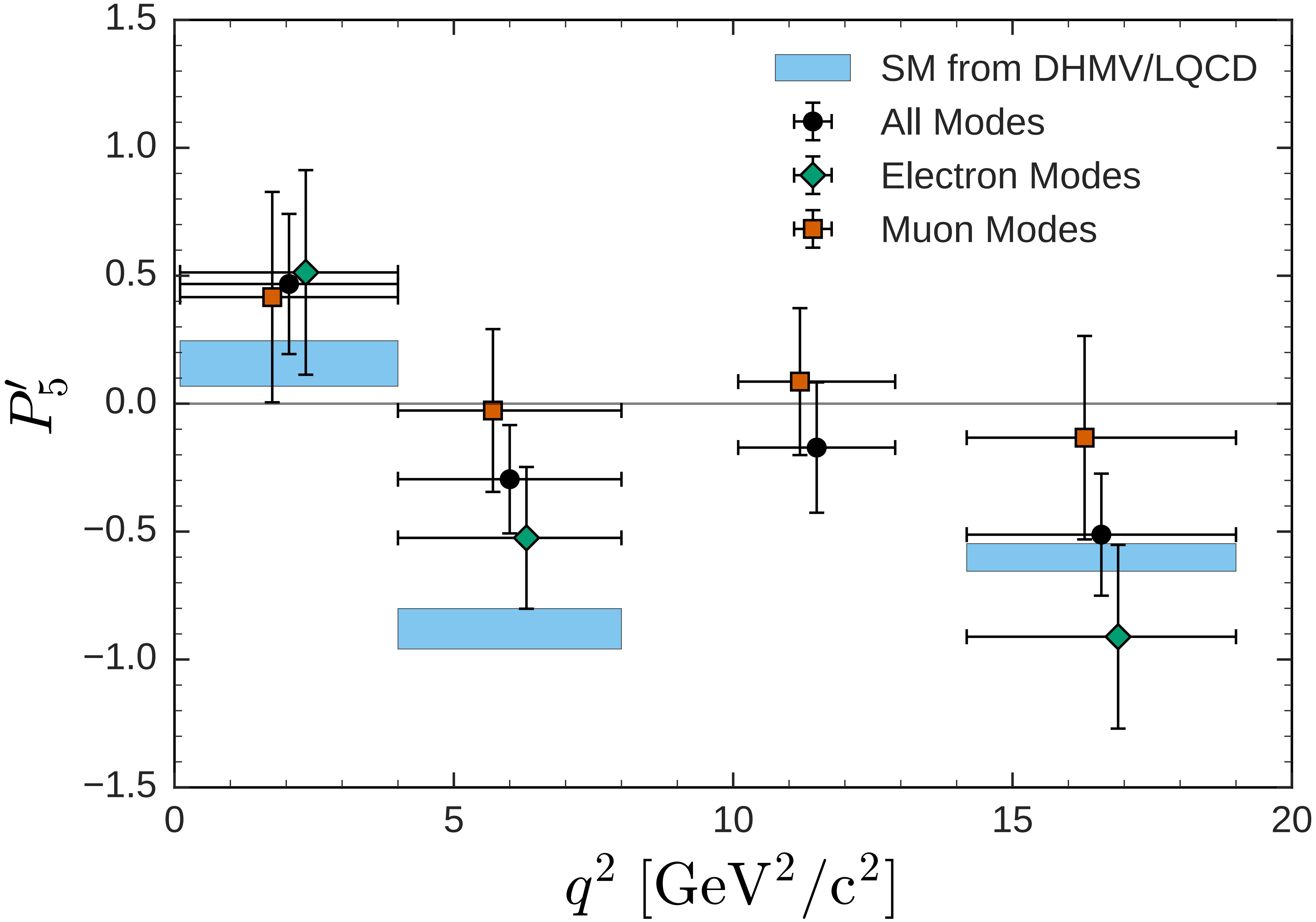


Bin #2

$4.0 < q^2 < 8.0$

- bkgd.
- signal
- total

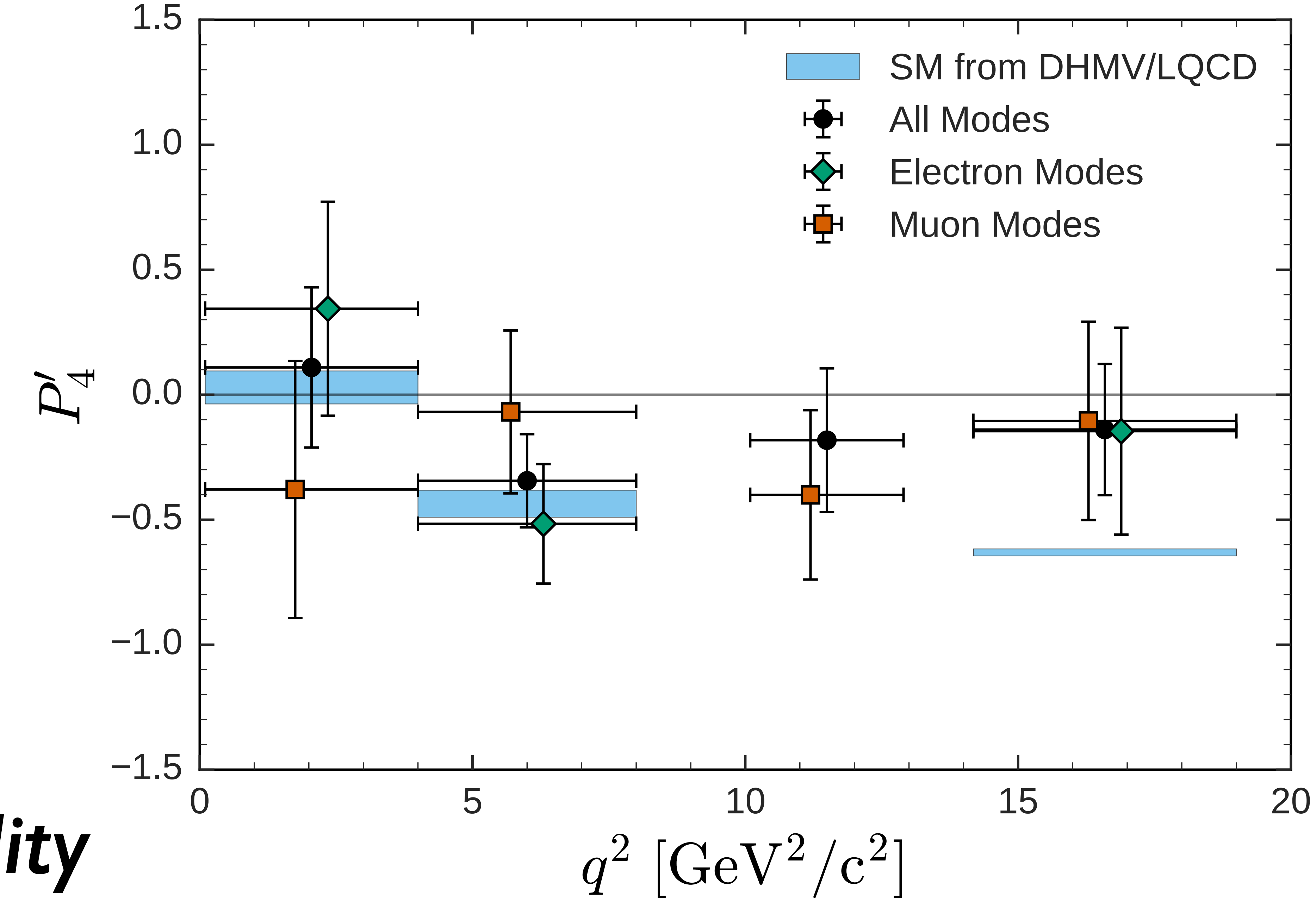
Result for P'_5



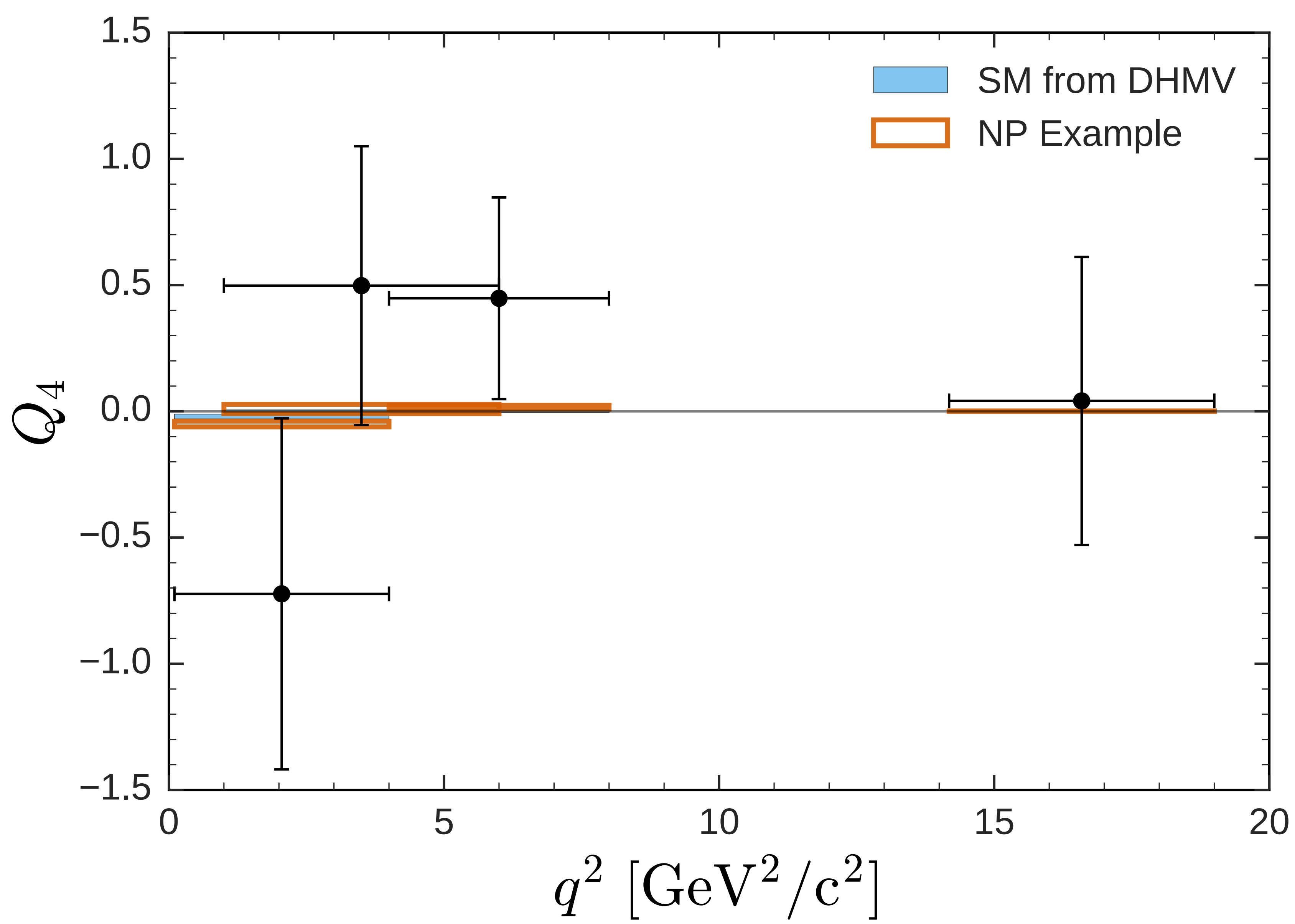
- compatible with both SM and LHCb
- 2.6σ in μ mode
  1.3σ in e mode

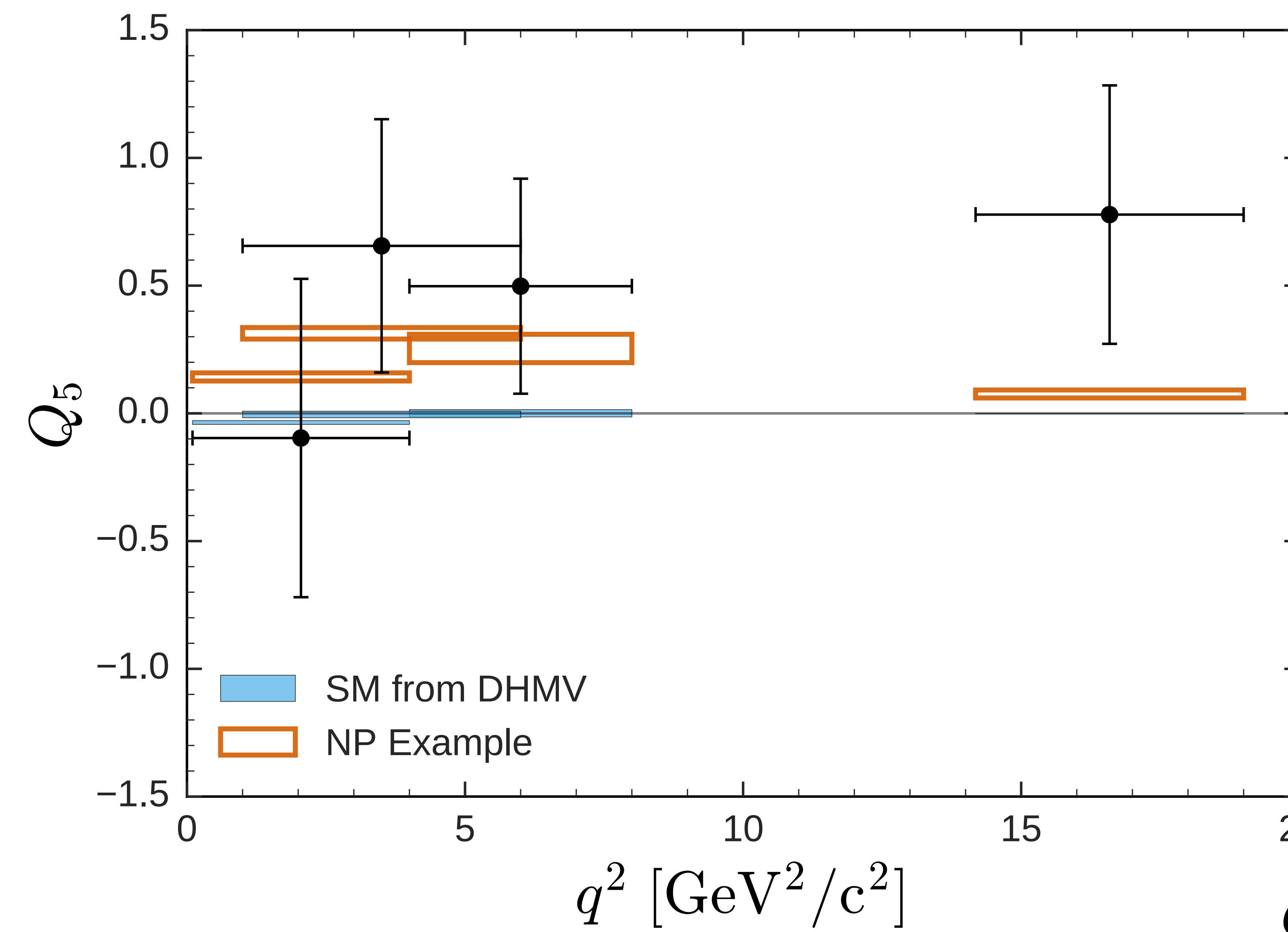
tension from SM is in the same direction as in LHCb

Other observables

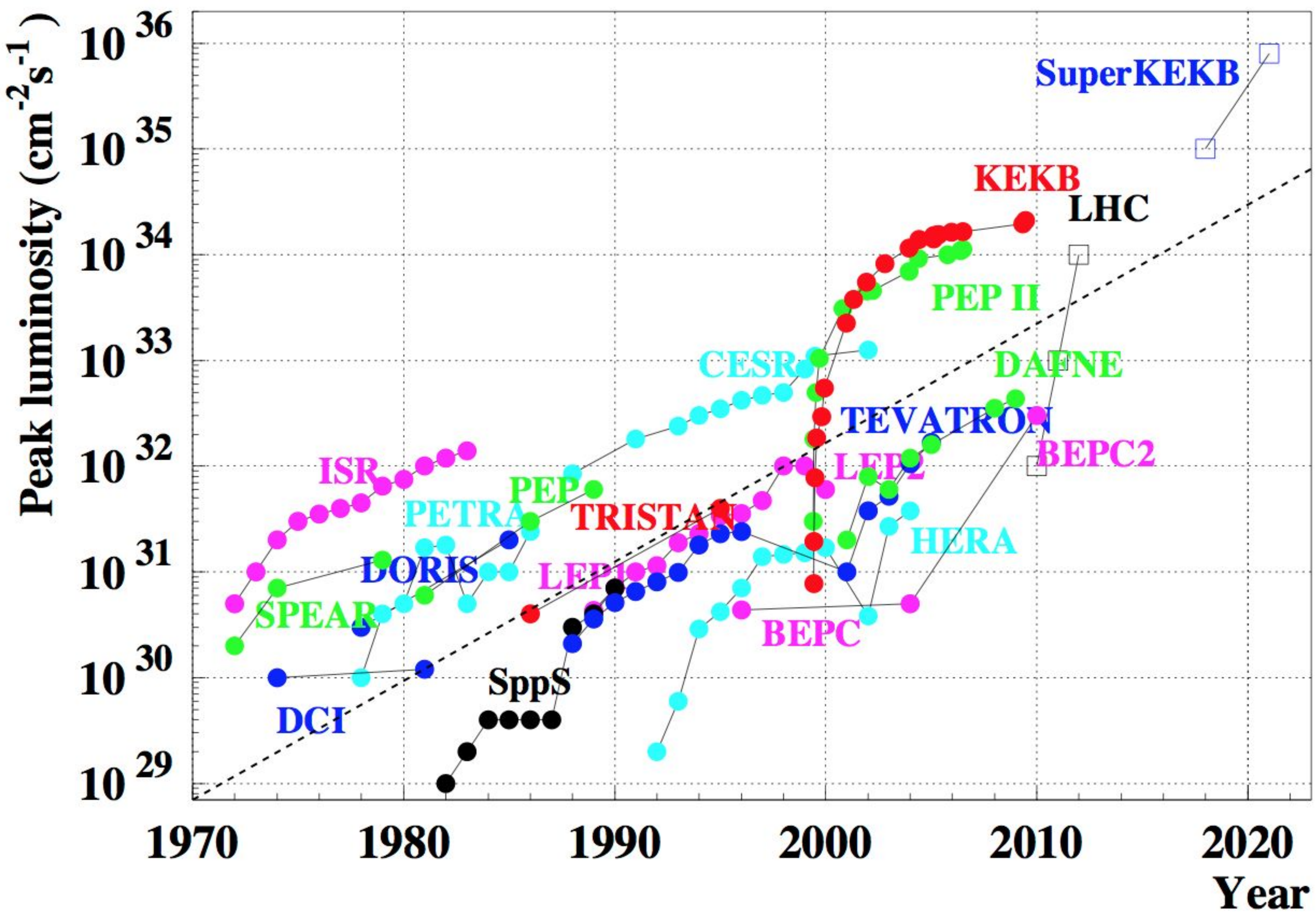


$$Q_i \equiv P_i^{\mu} - P_i^{e}$$ ***for lepton universality***

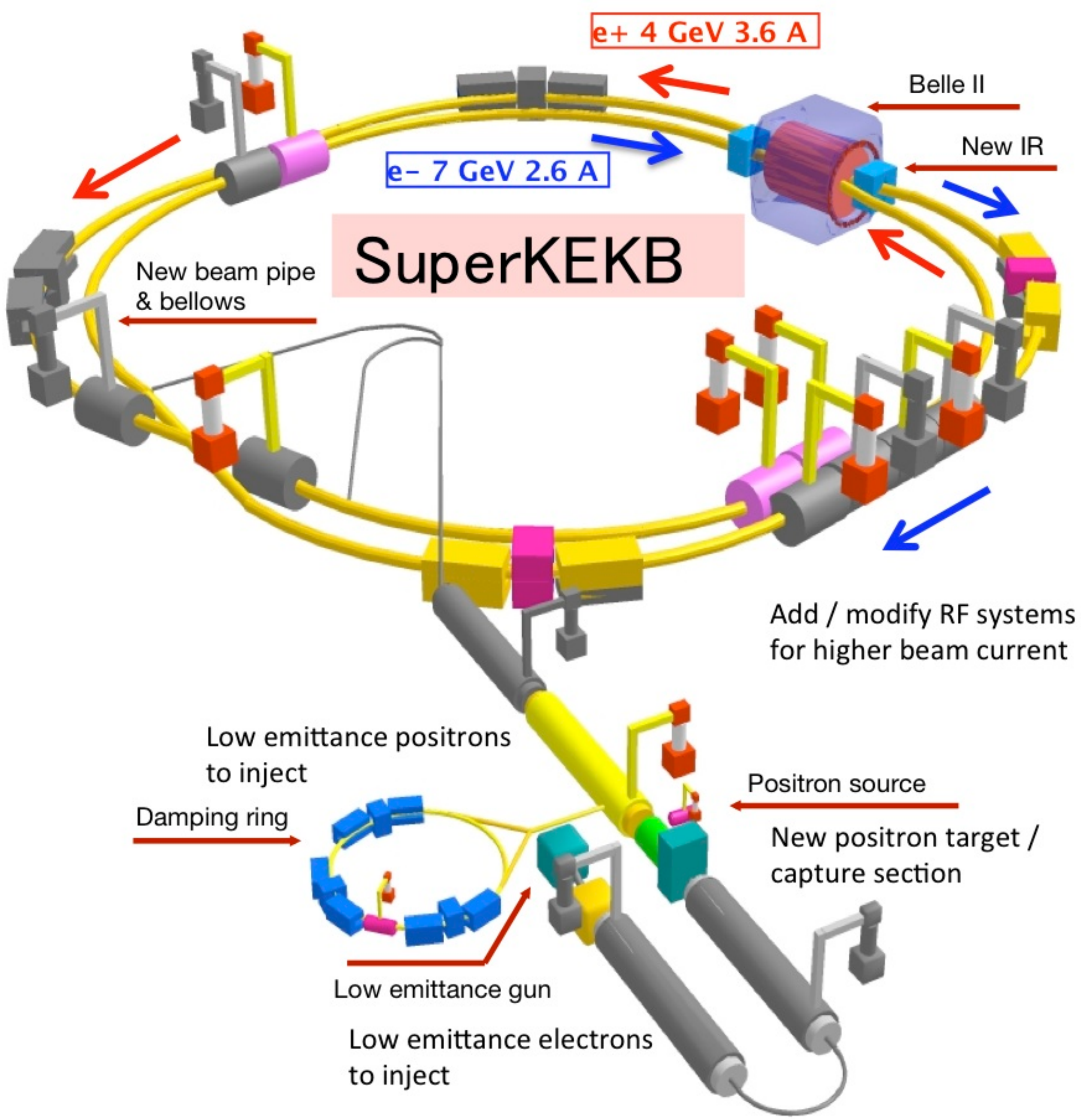


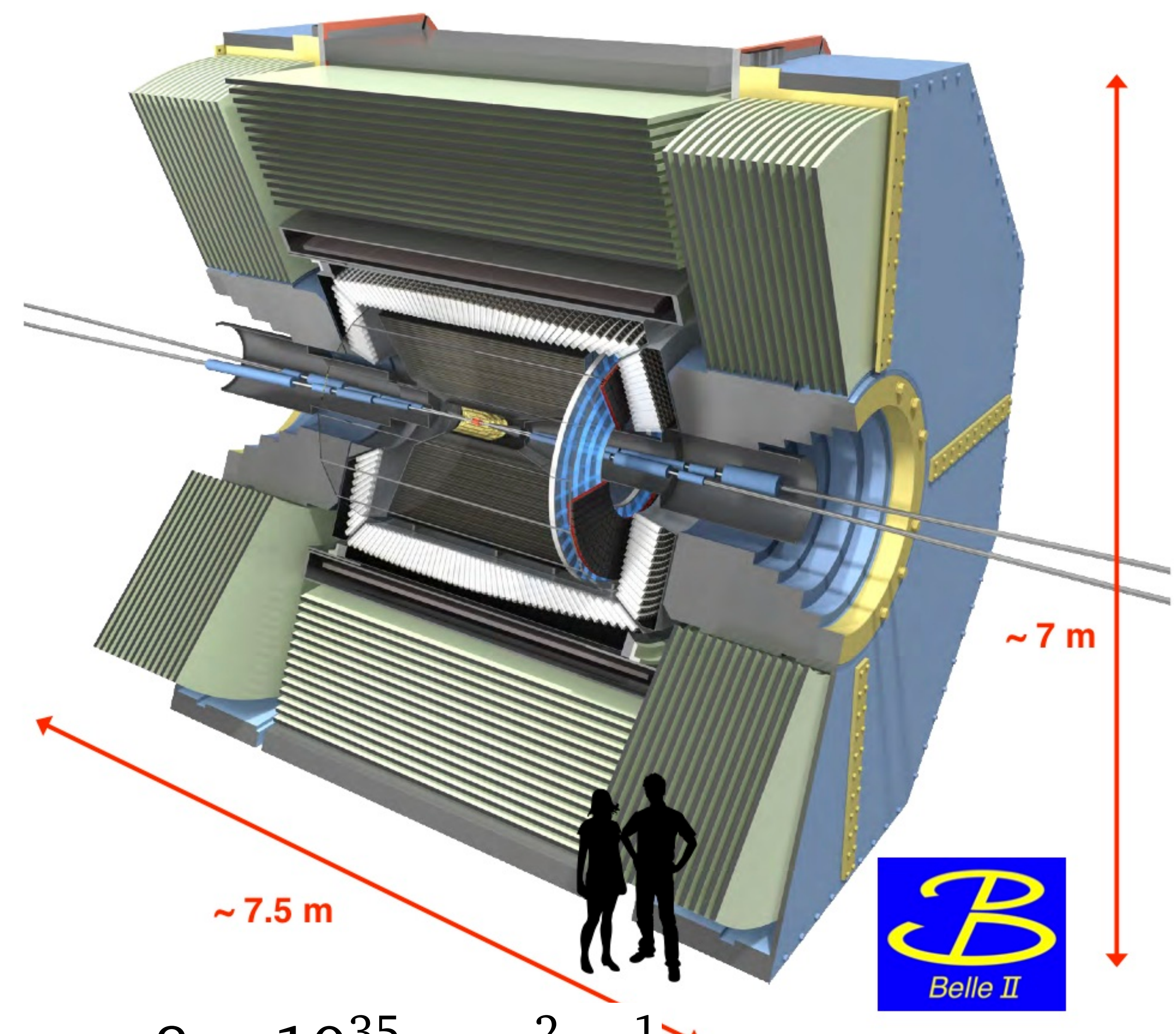


What's next? Luminosity Upgrade!



SuperKEKB & Belle II





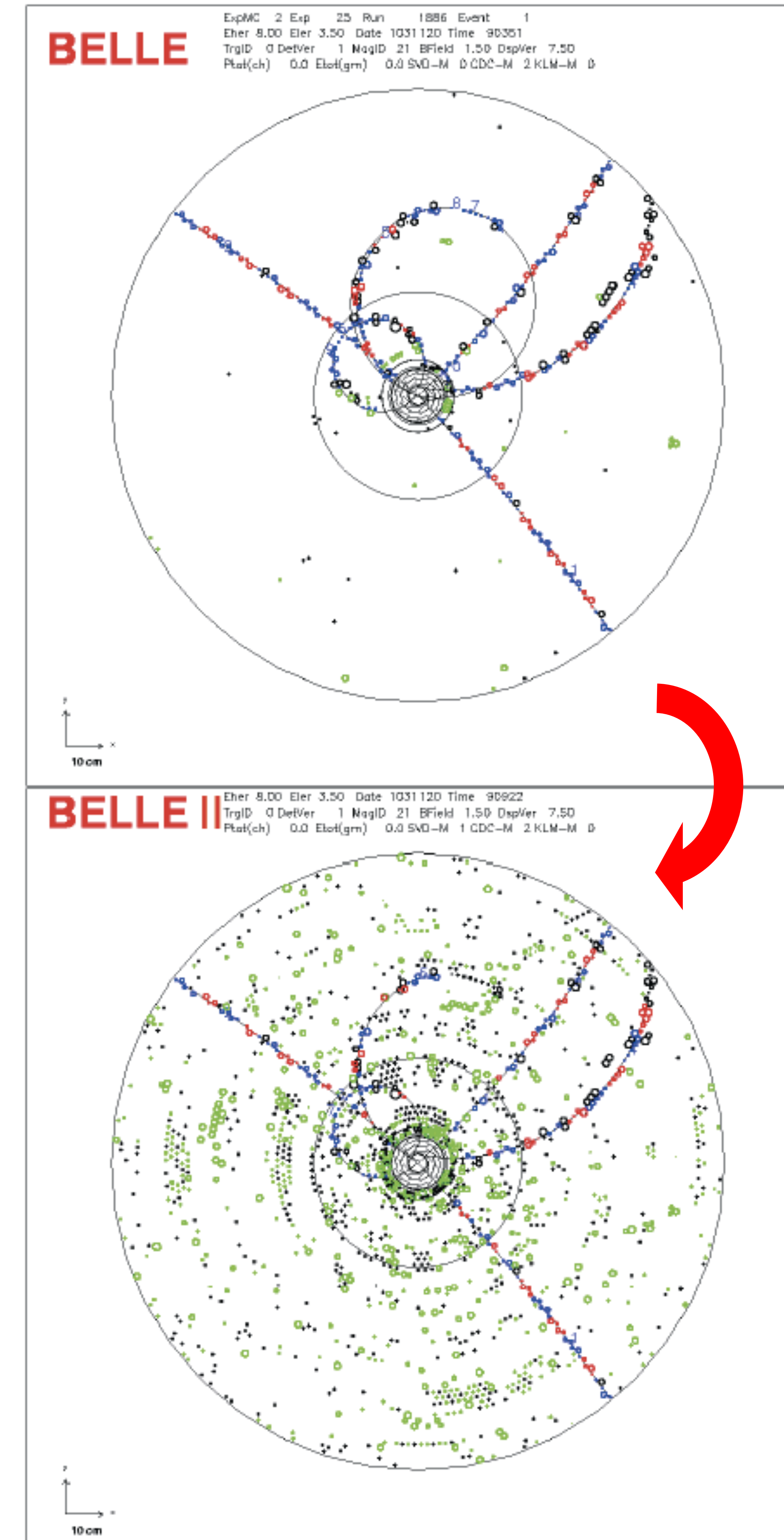
$$e^- \xrightarrow{\text{7 GeV}} (\star) \xleftarrow{\text{4 GeV}} e^+$$

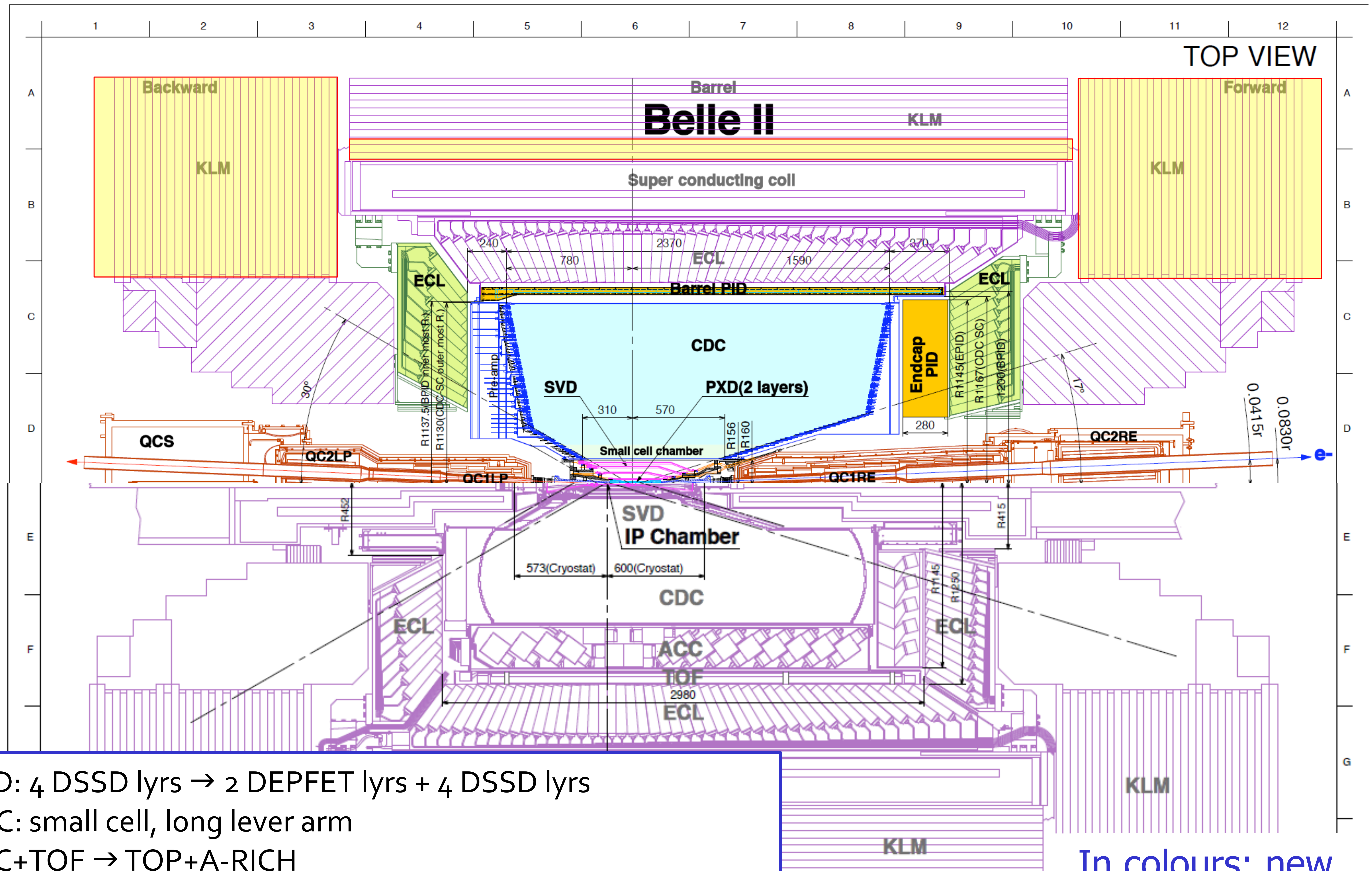
$$\mathcal{L}_{\text{peak}} = 8 \times 10^{35} \text{cm}^{-2}\text{s}^{-1}$$

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

Challenges & responses for Belle II

- Severe beam background
  - due to ×40 increase in $\mathcal{L}_{\text{peak}}$
  - fine segmentation and fast readout ➔ reduce occupancy
  - replace detector components
- Some big changes
  - vertex: SVD (4 layers) ➔ **PXD (2) + SVD (4)**
  - hadron identification: binary Cherenkov ➔ **iTOP** ("imaging Time-of-Propagation")



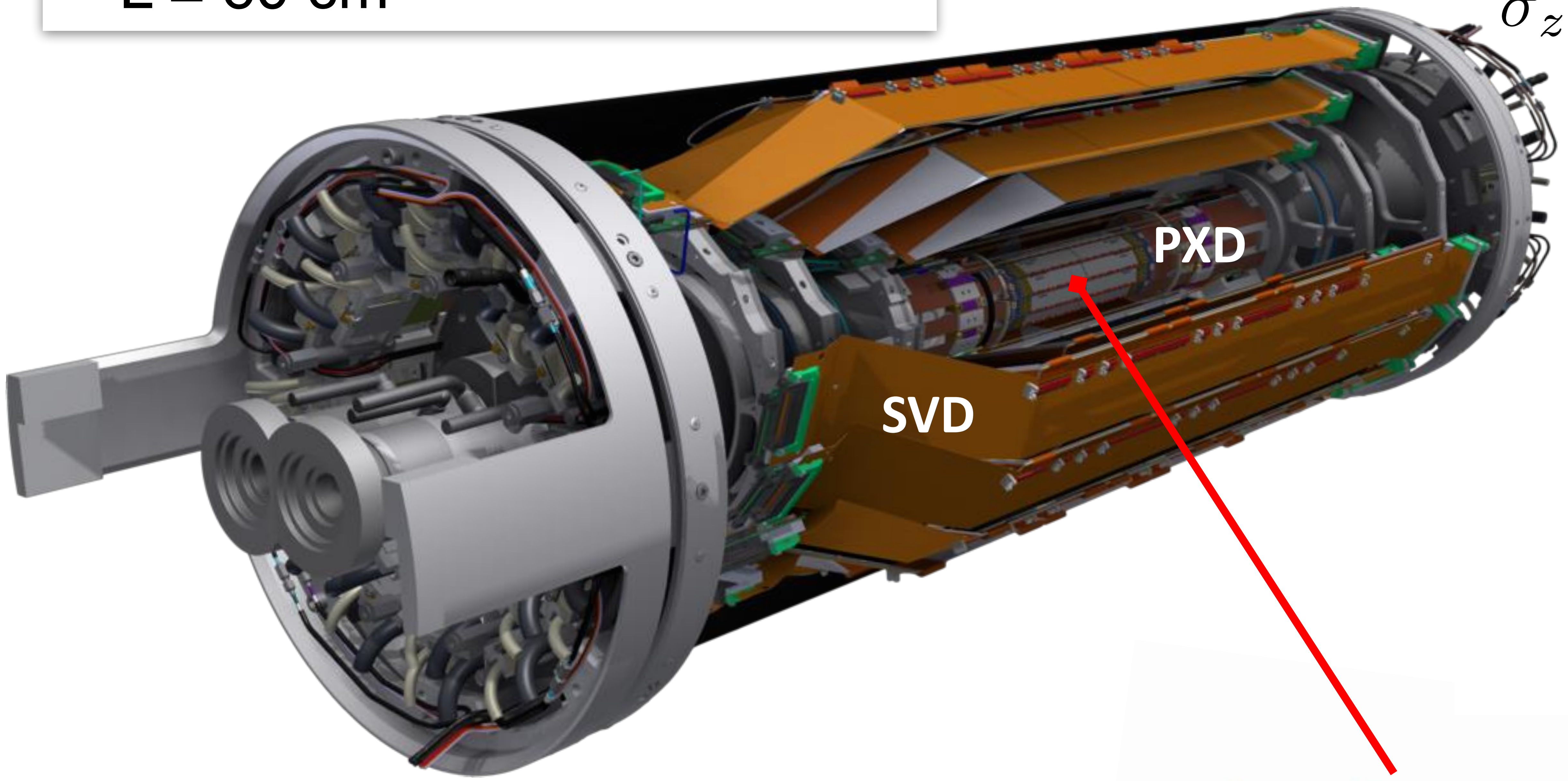


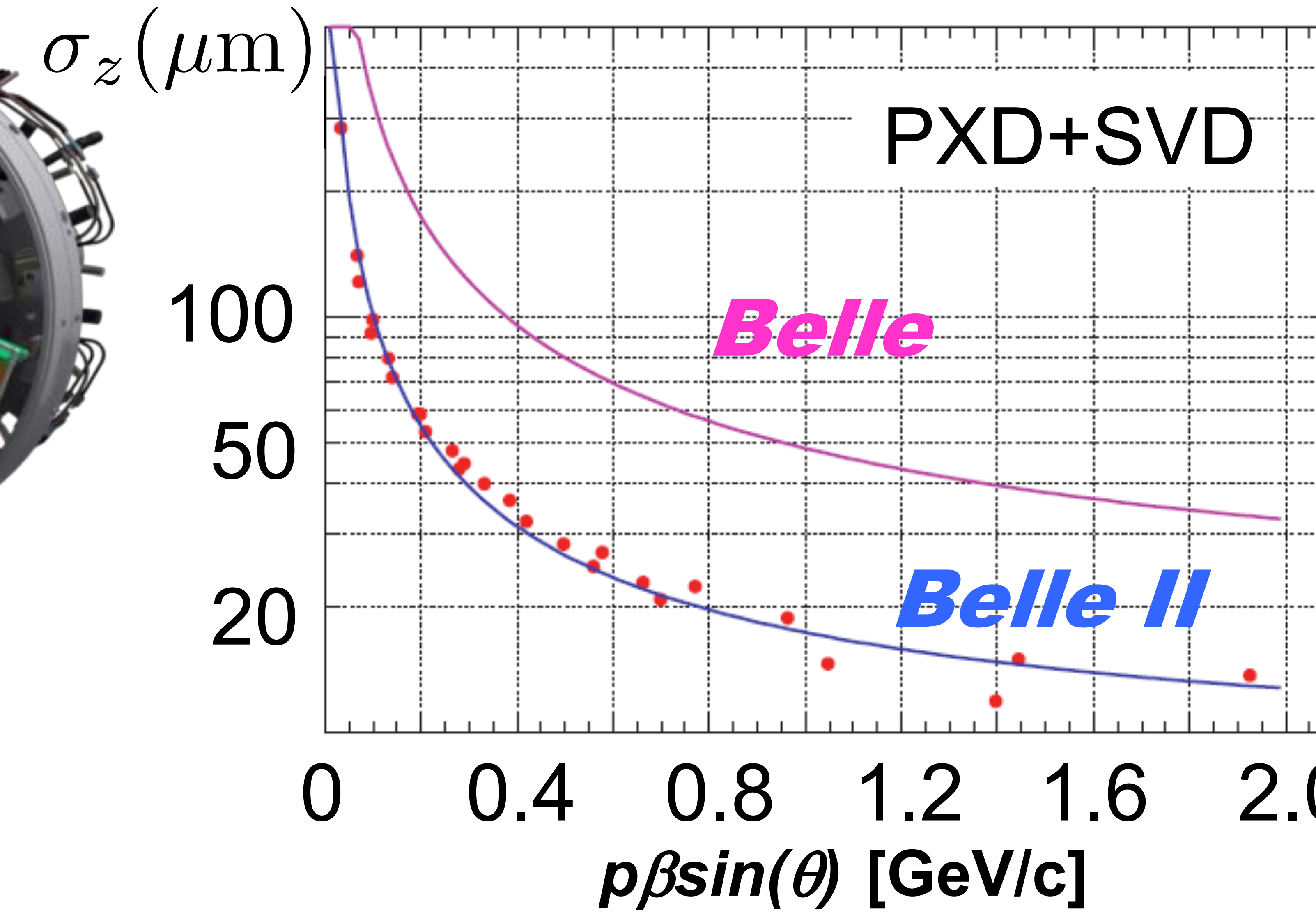
SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling (+pure CsI for endcaps)
KLM: RPC → Scintillator +MPPC (endcaps, barrel inner 2 lyrs)

In colours: new components

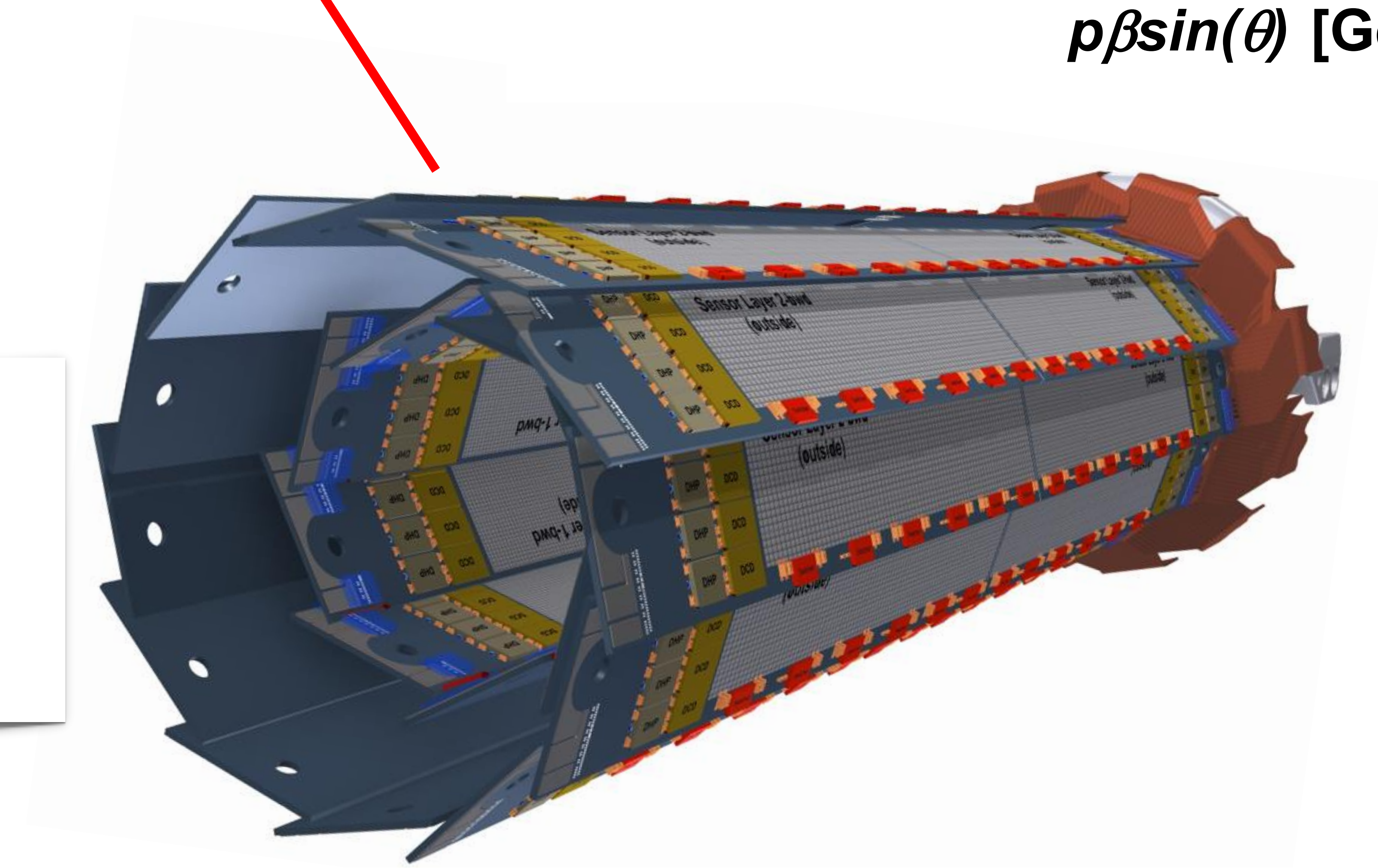
Vertexing for Belle II

SVD
- 4 layers of DSSD
- r = 3.8, 8.0, 11.5, 14.0 (cm)
- L = 60 cm

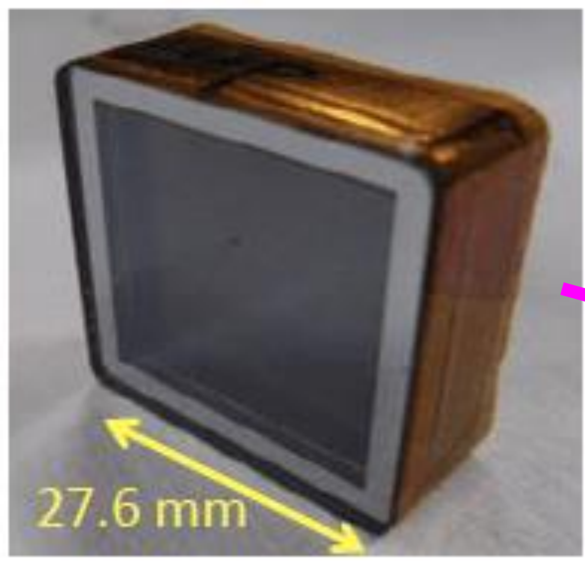




PXD (pixel detector)
- 2 layers of DEPFET
- r = 1.4, 2.2 (cm)
- L = 12 cm

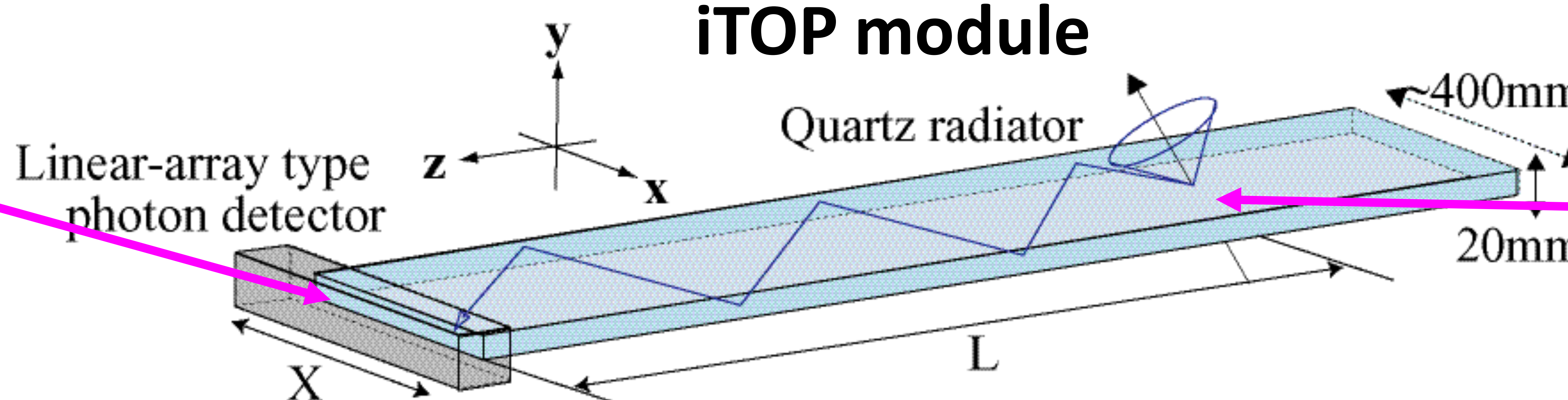


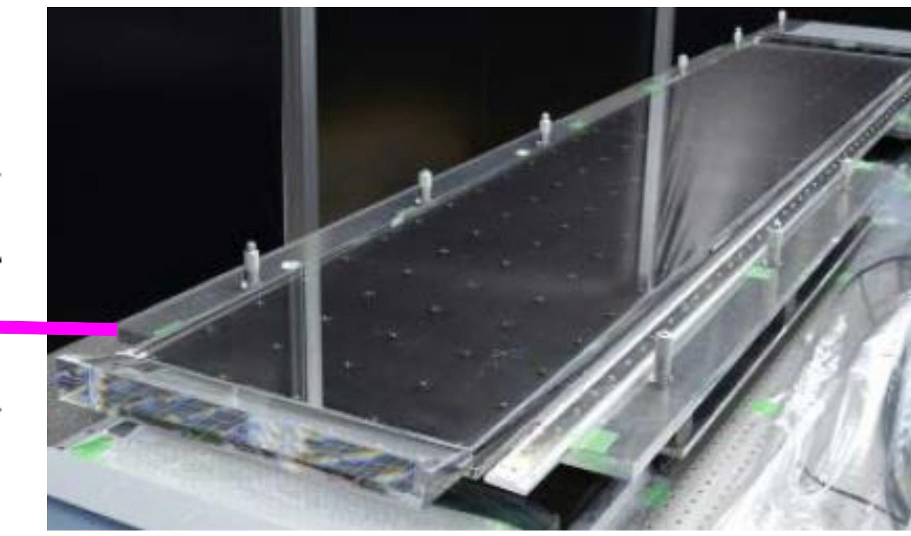
hadron ID for Belle II



512 Hamamatsu 4 x 4 MCP-PMT

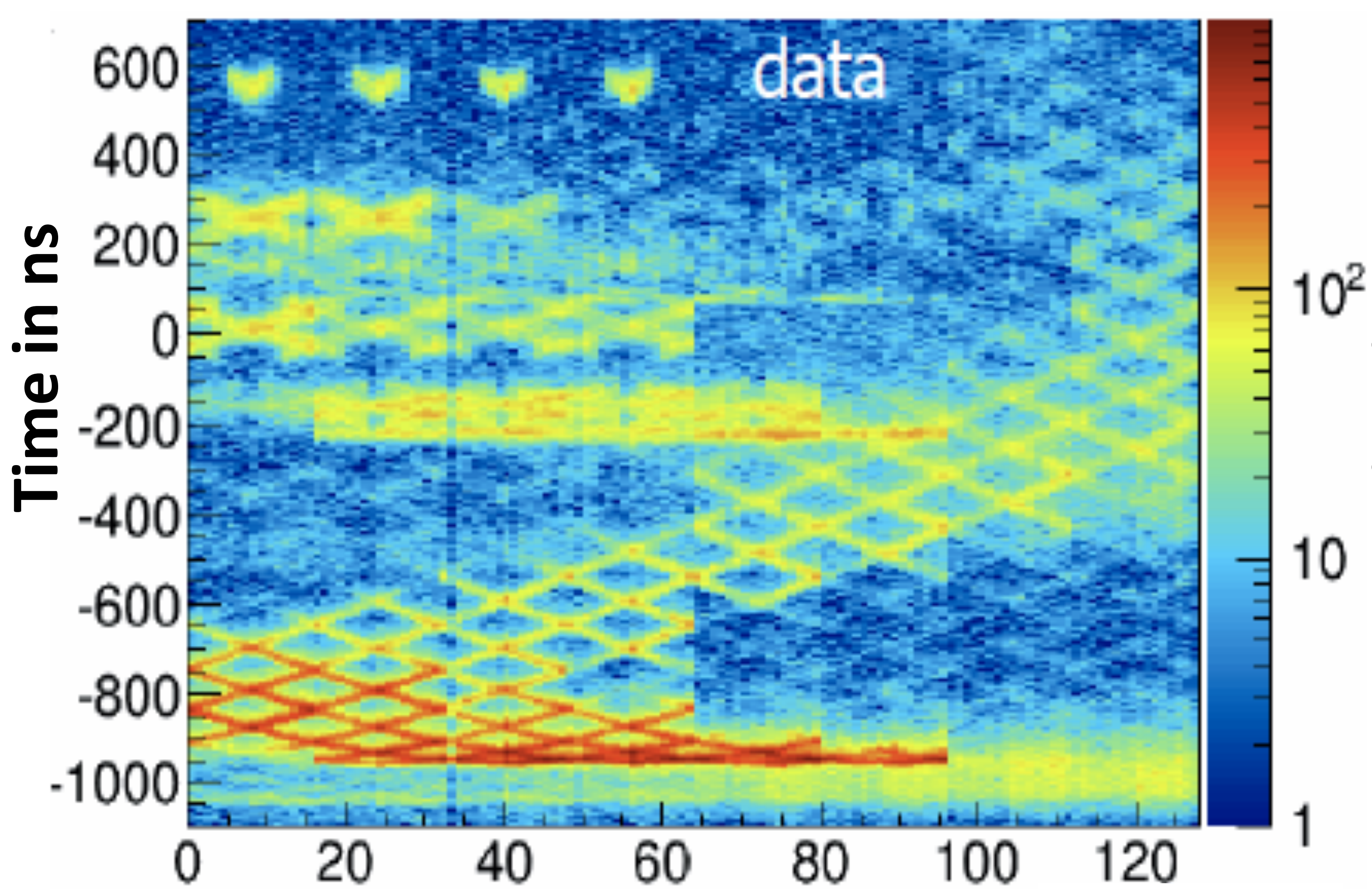
iTOP module

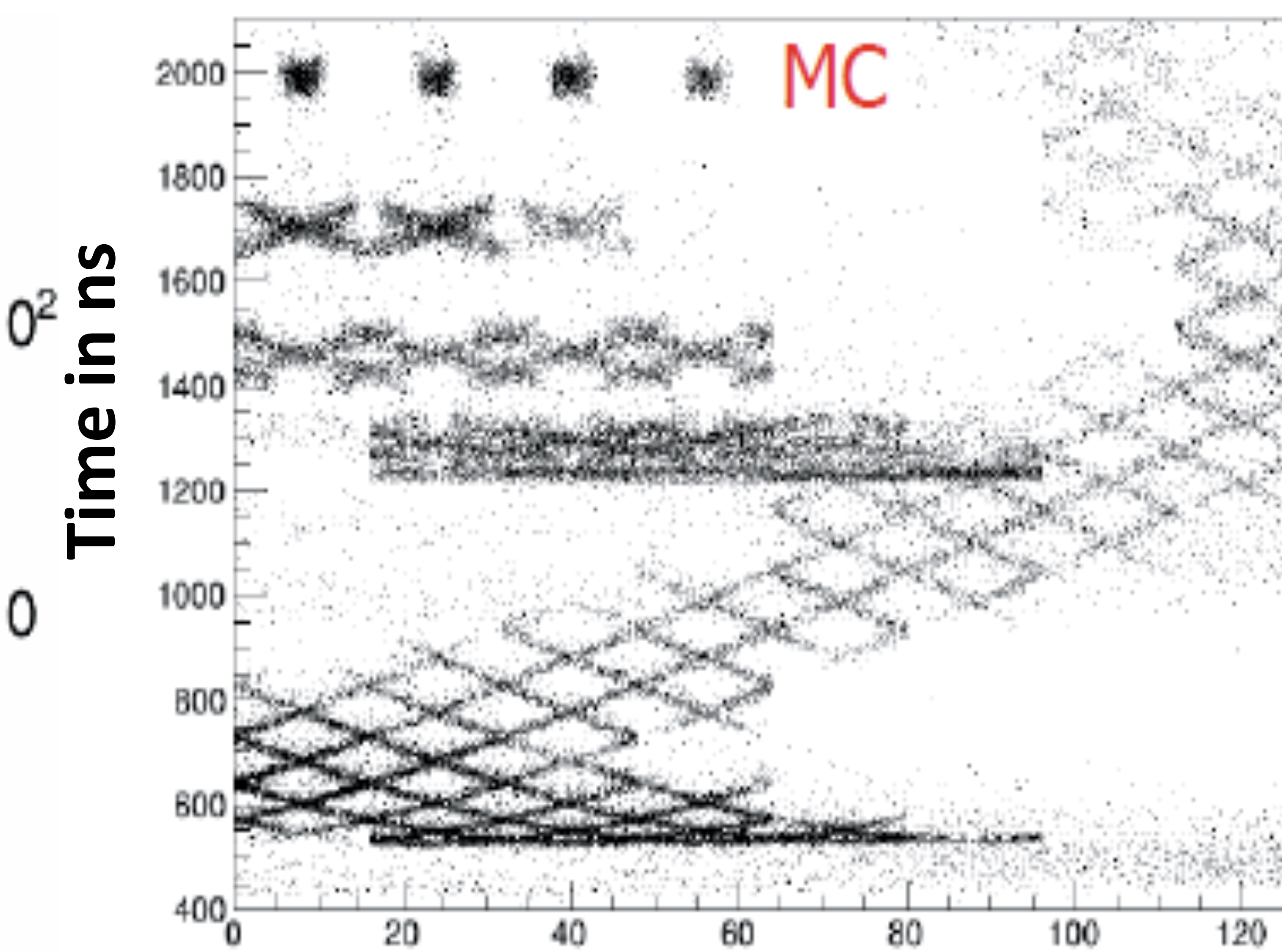




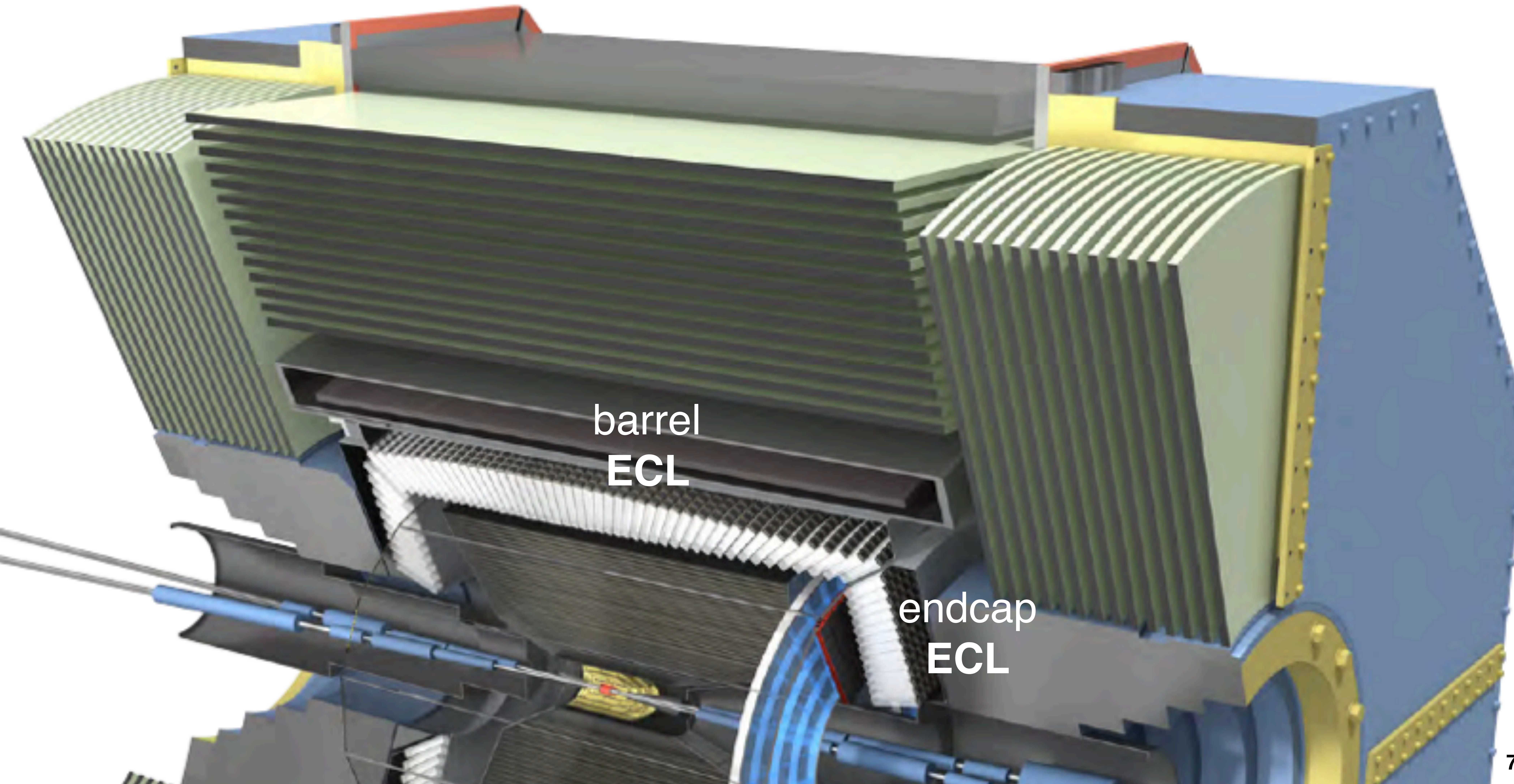
Quartz radiator

TOP test beam data





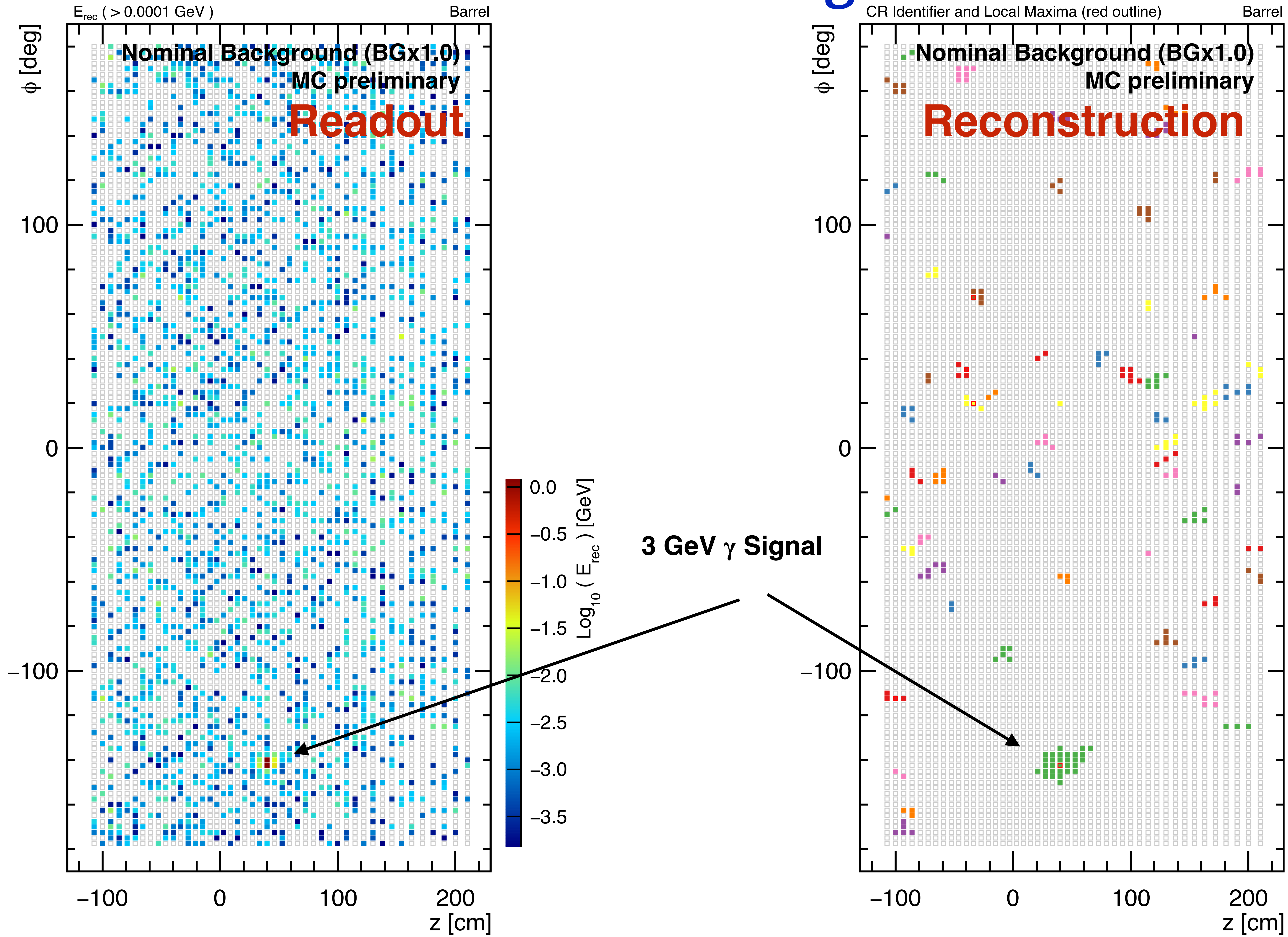
Challenges & responses: ECL



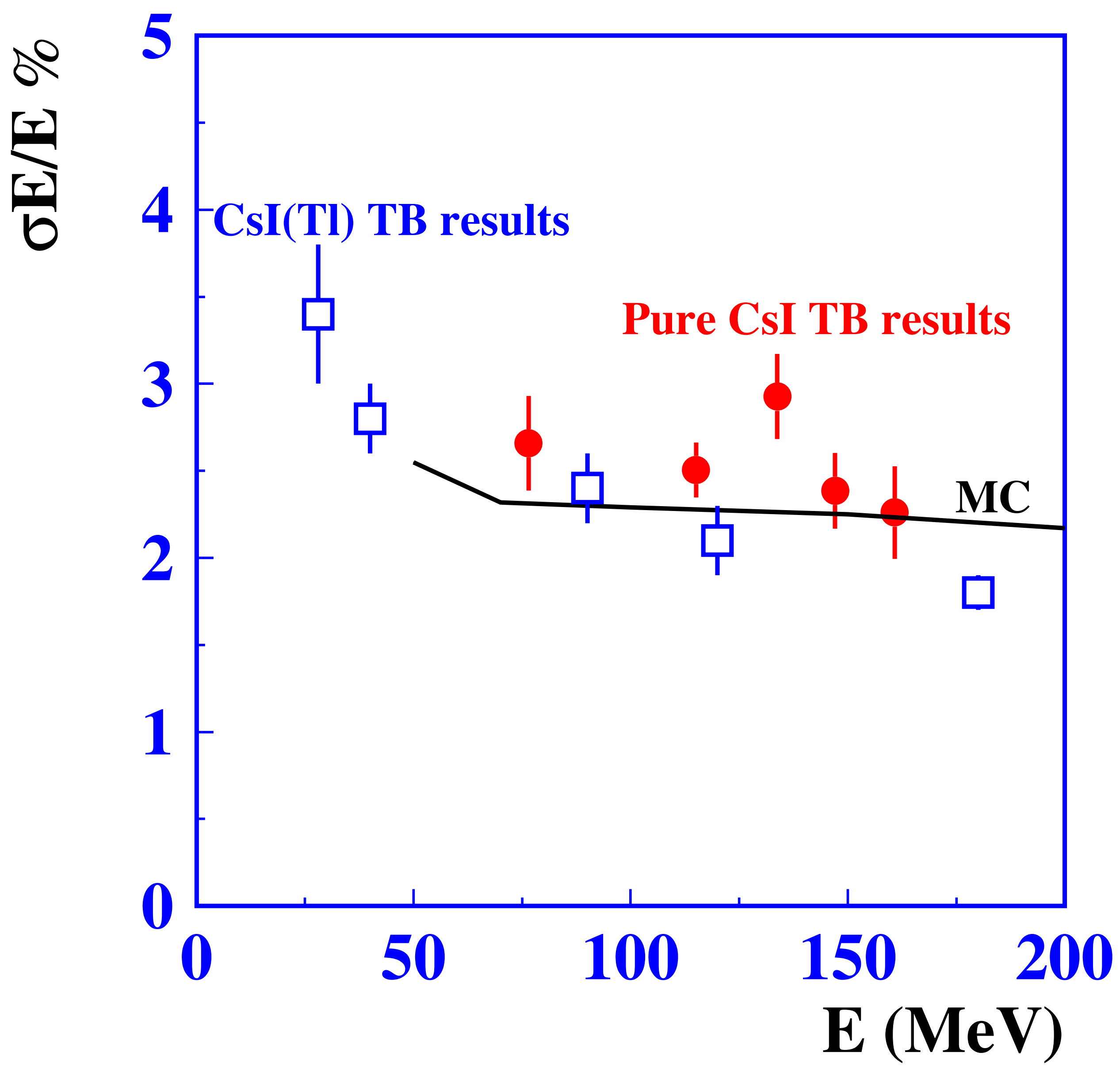
Challenges & responses: ECL

- ECL is essential for γ and $e^{\pm}$ detection
  - hence indispensable for τ LFV ($\tau^{\pm} \to e^{\pm}\gamma,\ \ell^{\pm}\ell^{+}\ell^{-}$ etc.)
- Belle ECL
  - CsI(Tl) crystals with PIN photodiode
- Belle II ECL
  - upgrade is needed due to higher rates & radiation load
  - waveform sampling in new readout electronics
    - timing resolution < 4.5 ns in cosmic-ray test of barrel ECL
  - use of pure-CsI for endcap crystals being considered

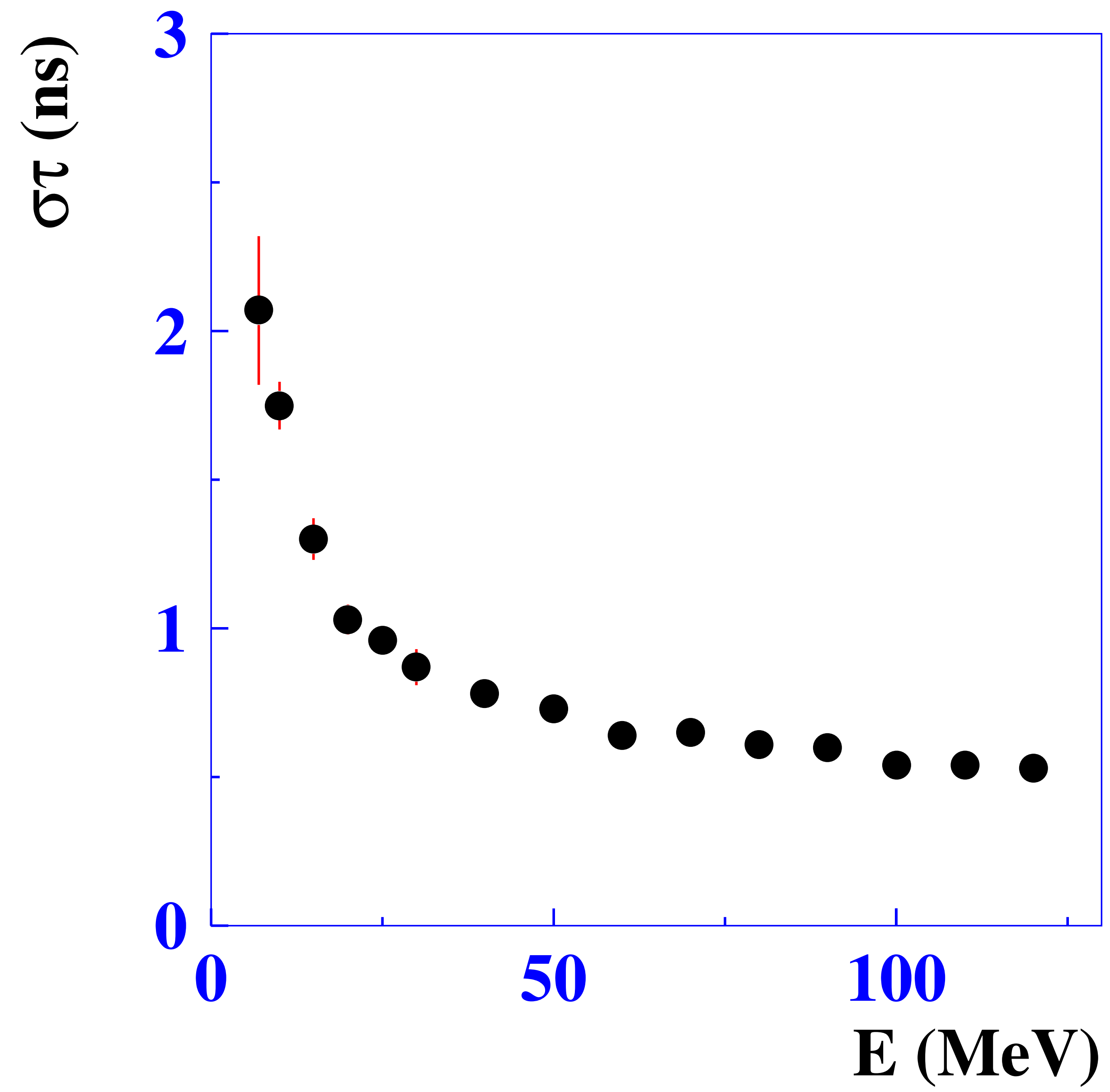
Belle II ECL with background



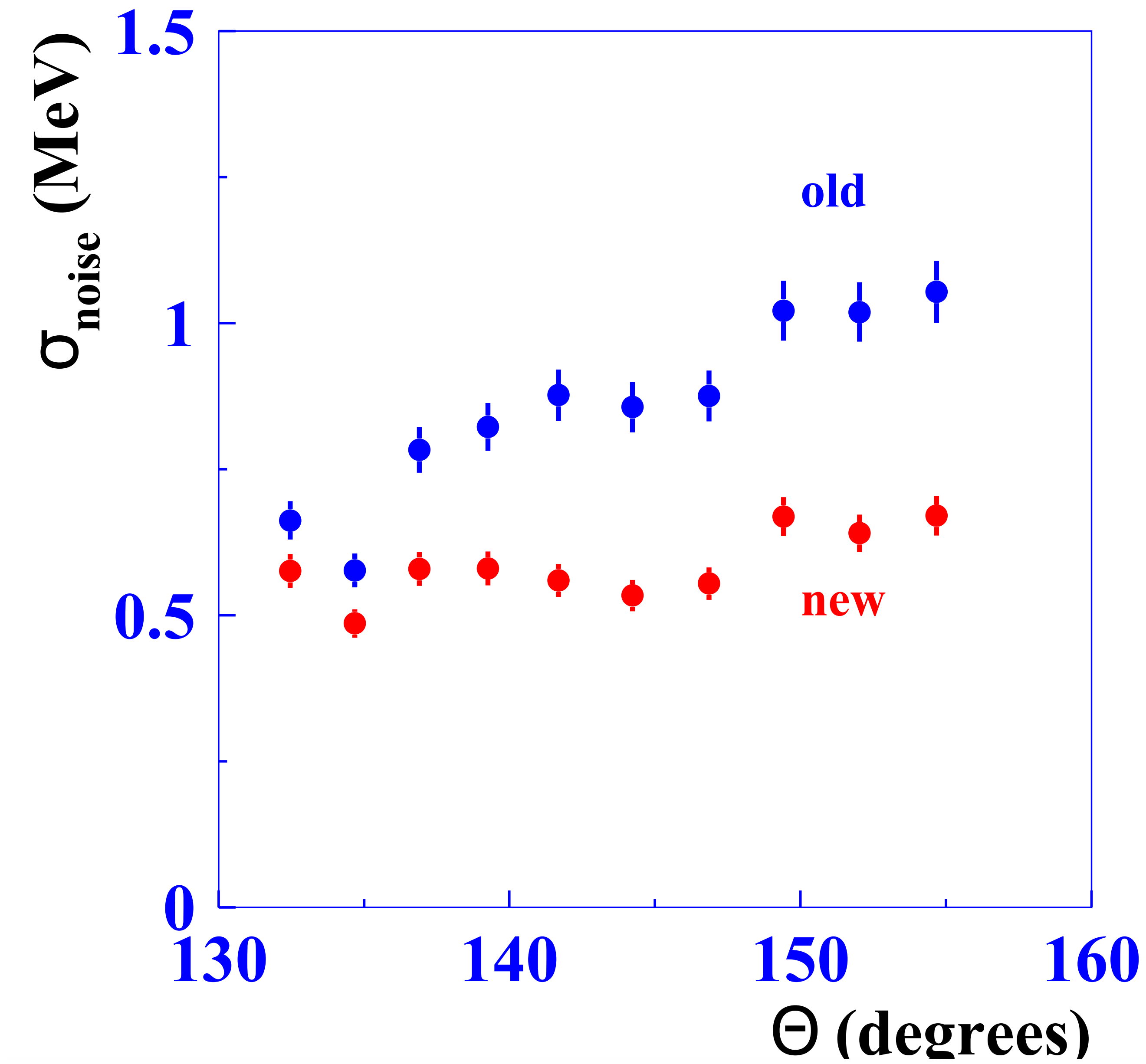
Belle II ECL performances (TB)



energy resolution

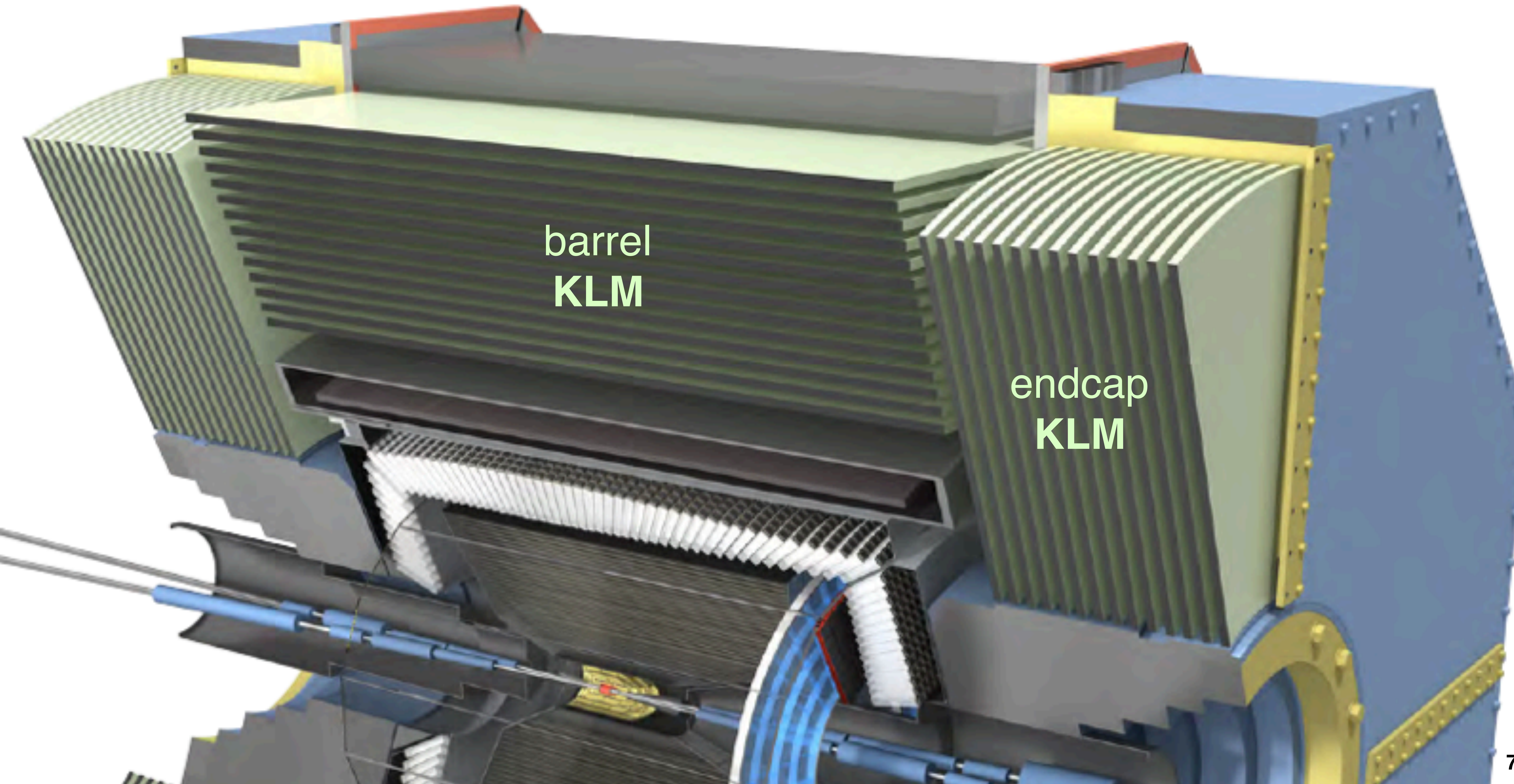


timing resolution



pile-up noise suppression
w/ new electronics

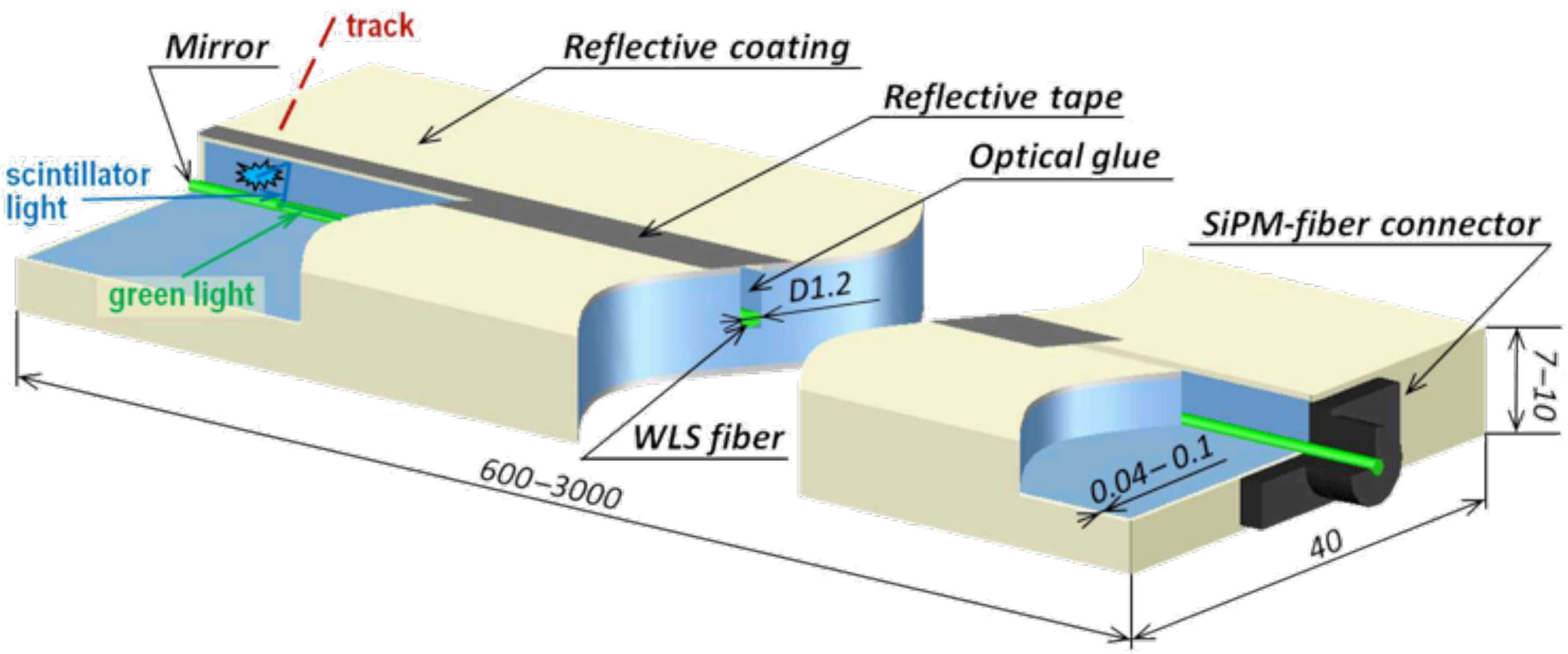
Challenges & responses: KLM

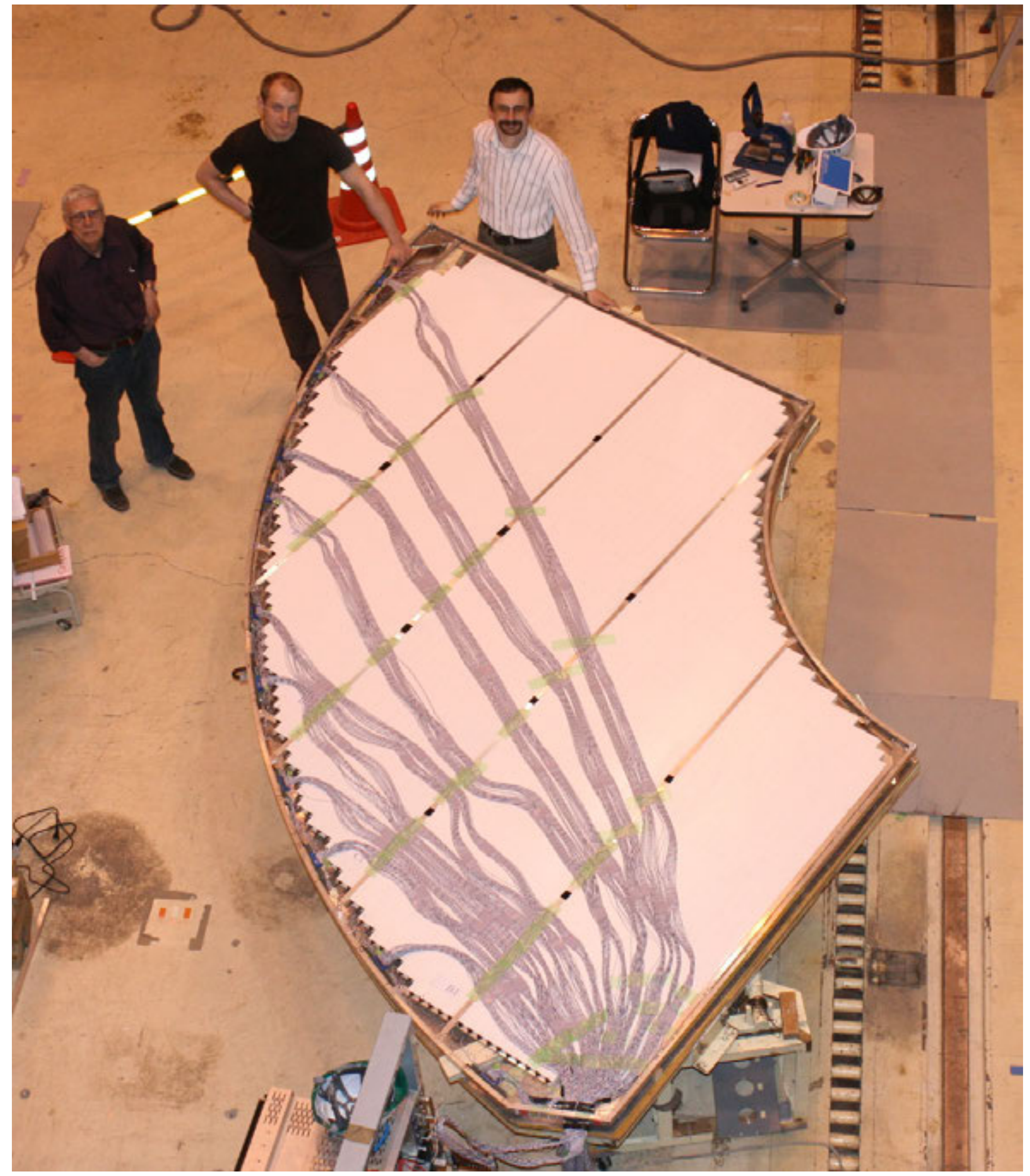


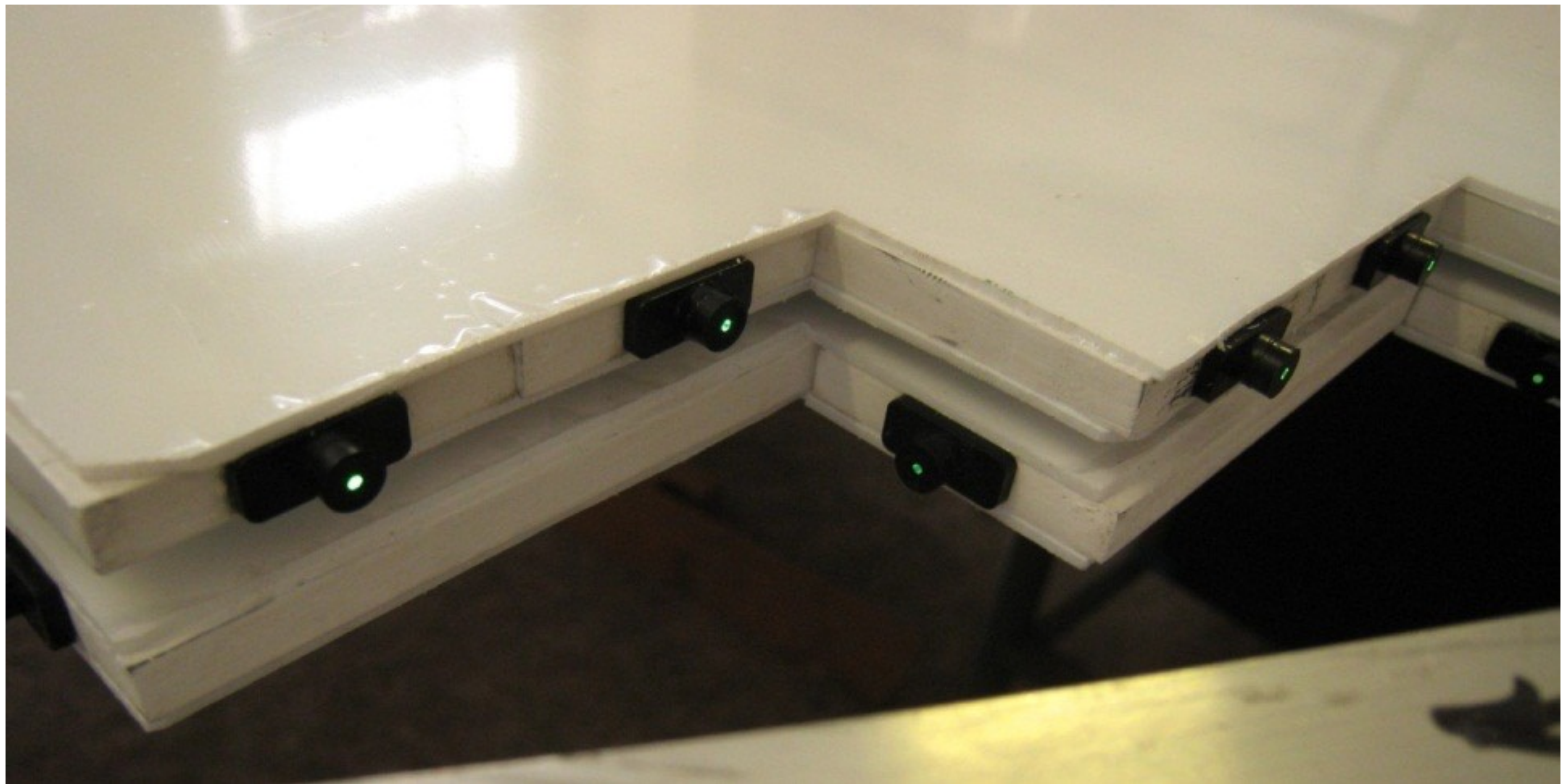
Challenges & responses: KLM

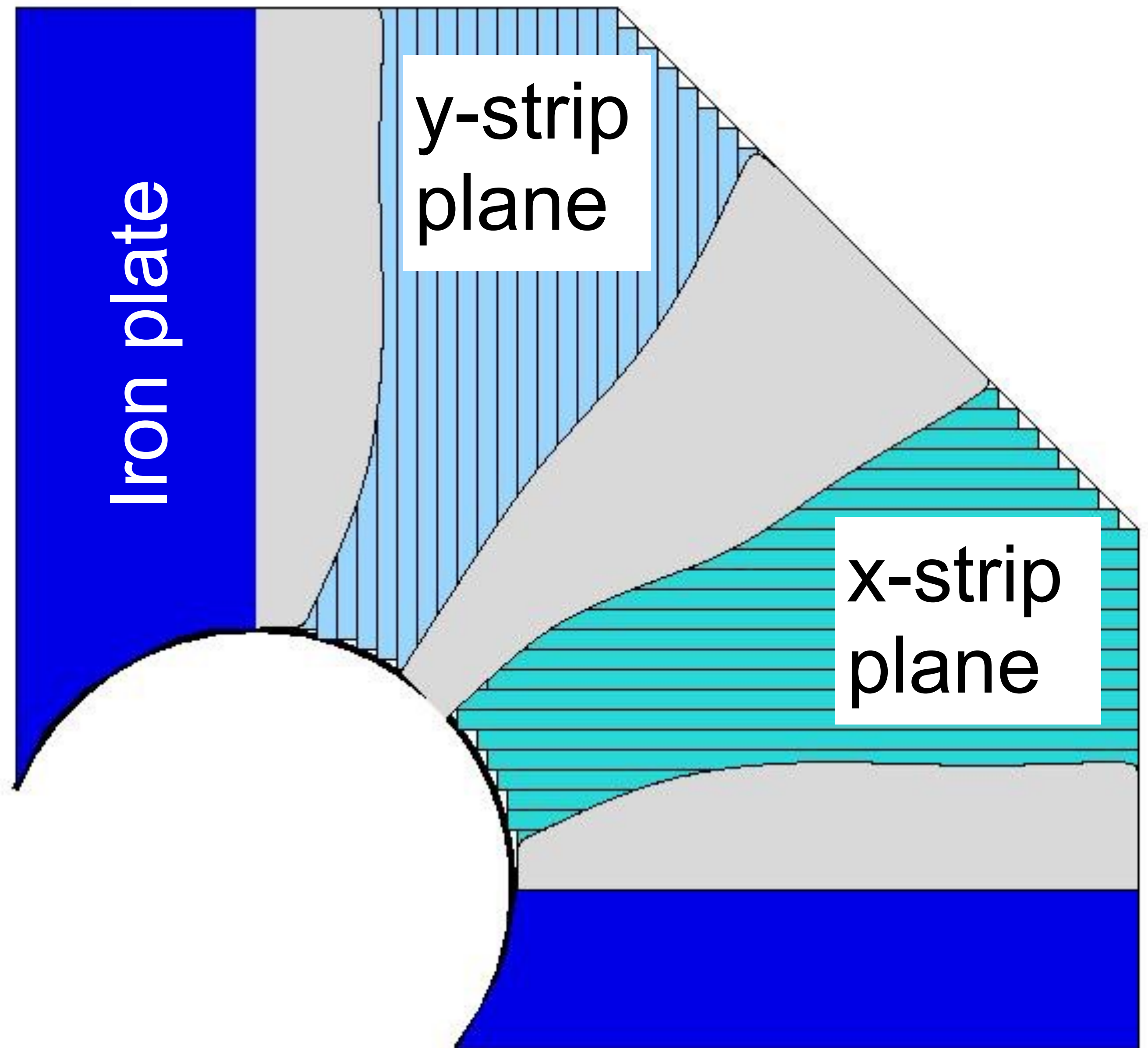
- KLM is essential for $\mu^{\pm}$ detection
  - hence indispensable for τ LFV ($\tau^{\pm} \to \mu^{\pm}\gamma,\ \ell^{\pm}\ell^{+}\ell^{-}$ etc.)
- Belle KLM
  - alternating layers of iron plates (partly for flux return) and RPC
- Belle II KLM
  - Belle's RPC system cannot handle high background rates
  - all RPC's in endcaps and 2 innermost barrel layers are replaced with scintillators
  - readout electronic under production (will be ready by summer 2017)

Scintillator-KLM (Belle II)





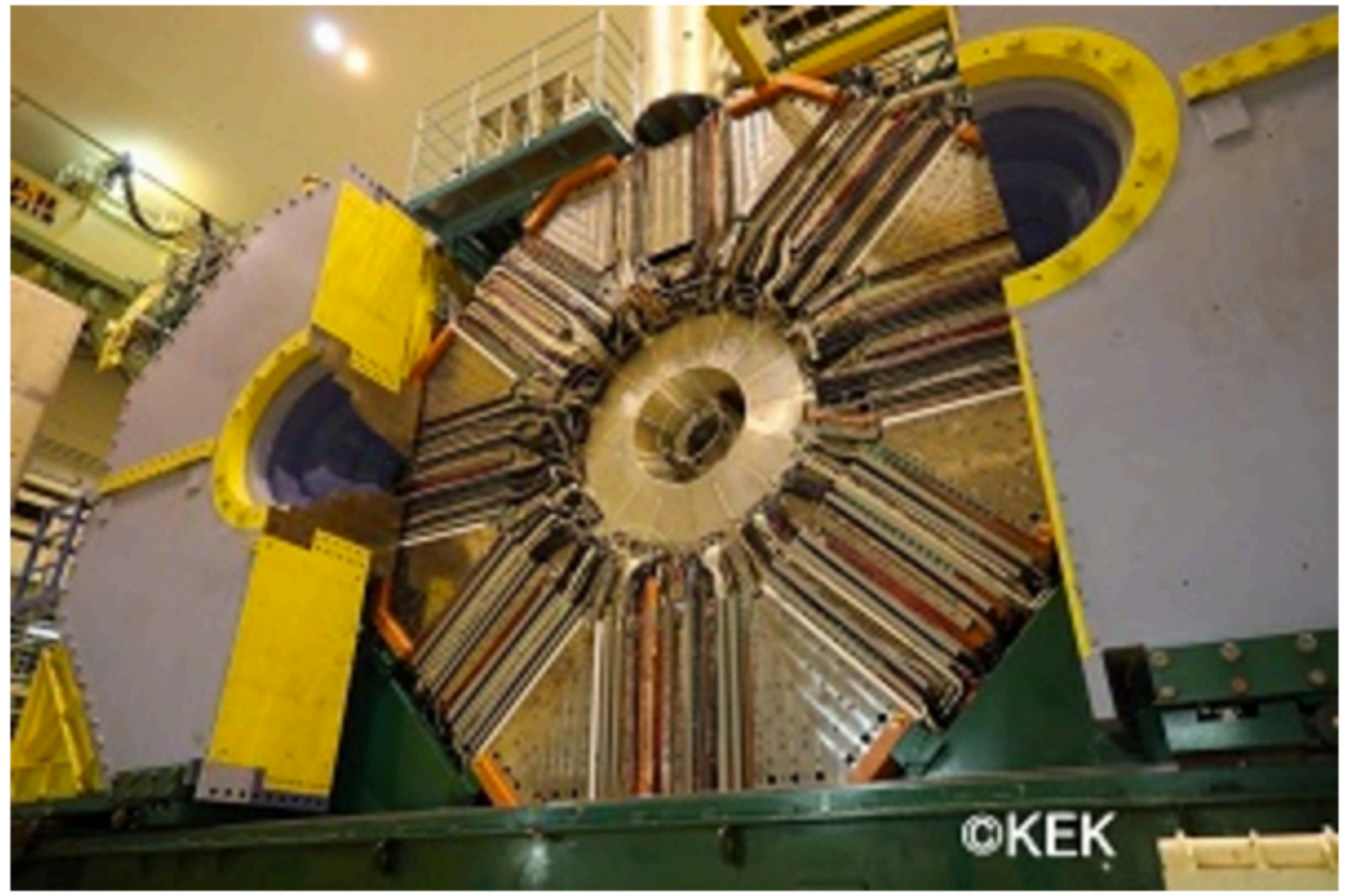




Belle II milestones

- Phase 1 (Feb. 2016): beam commissioning + beam background measurements
  - ✓ circulate beams; no collision
  - ✓ BEAST II (in place of Belle II) as a commissioning detector
- Recent highlights
  - ✓ Final Quads installed in Feb. 2017
  - ✓ Belle II roll-in on Apr. 11, 2017
- Phase 2 (Dec. 2017): Detector in place without SVD + PXD
  - ✓ *Dark-sector search can start!*
- Phase 3 (Nov. 2018): Start physics run with full Belle II detector

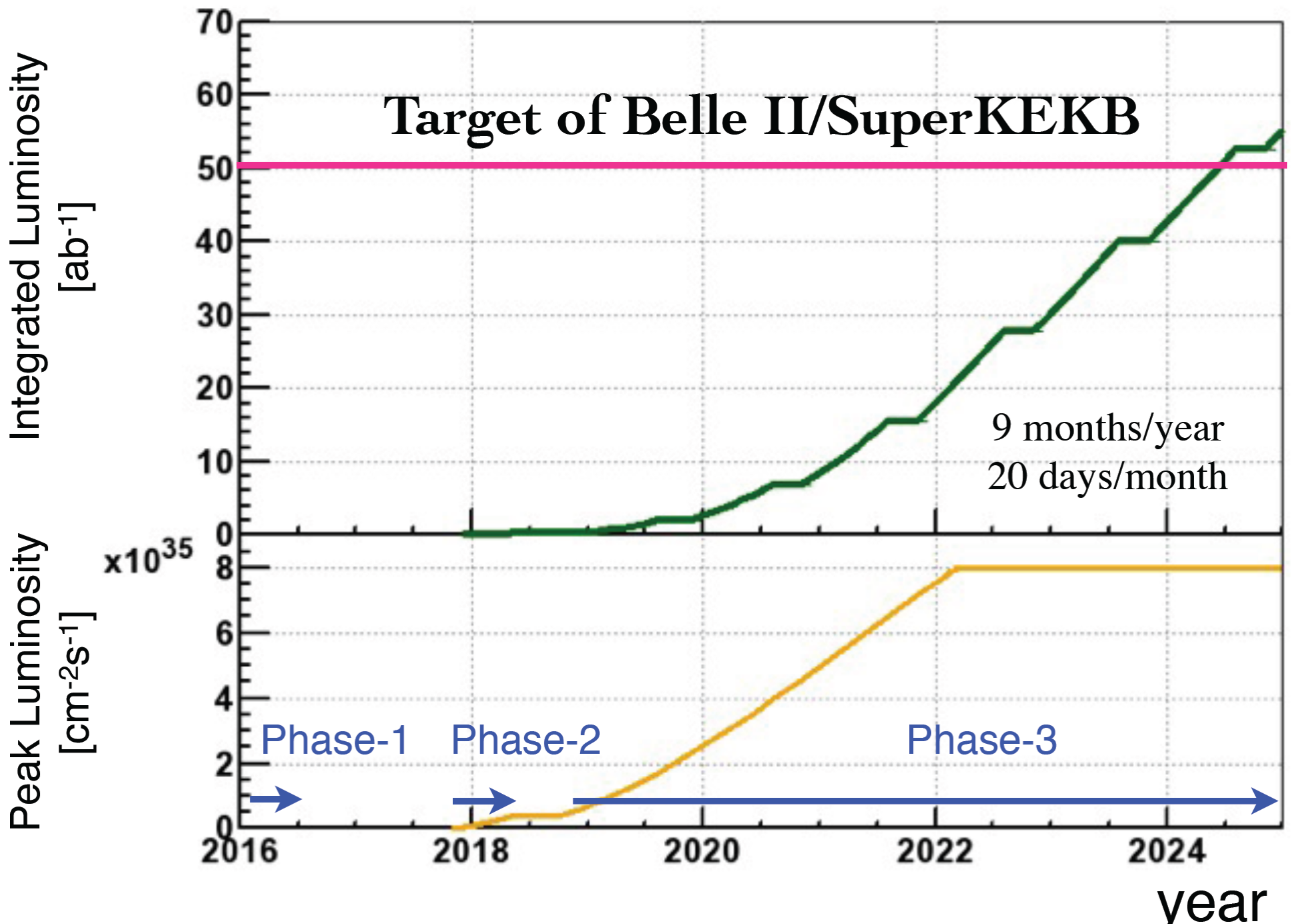
「BelleII測定器」が世界最強加速器とついに合体！
宇宙の謎に迫る素粒子実験の建設現場を8時間独占生中継

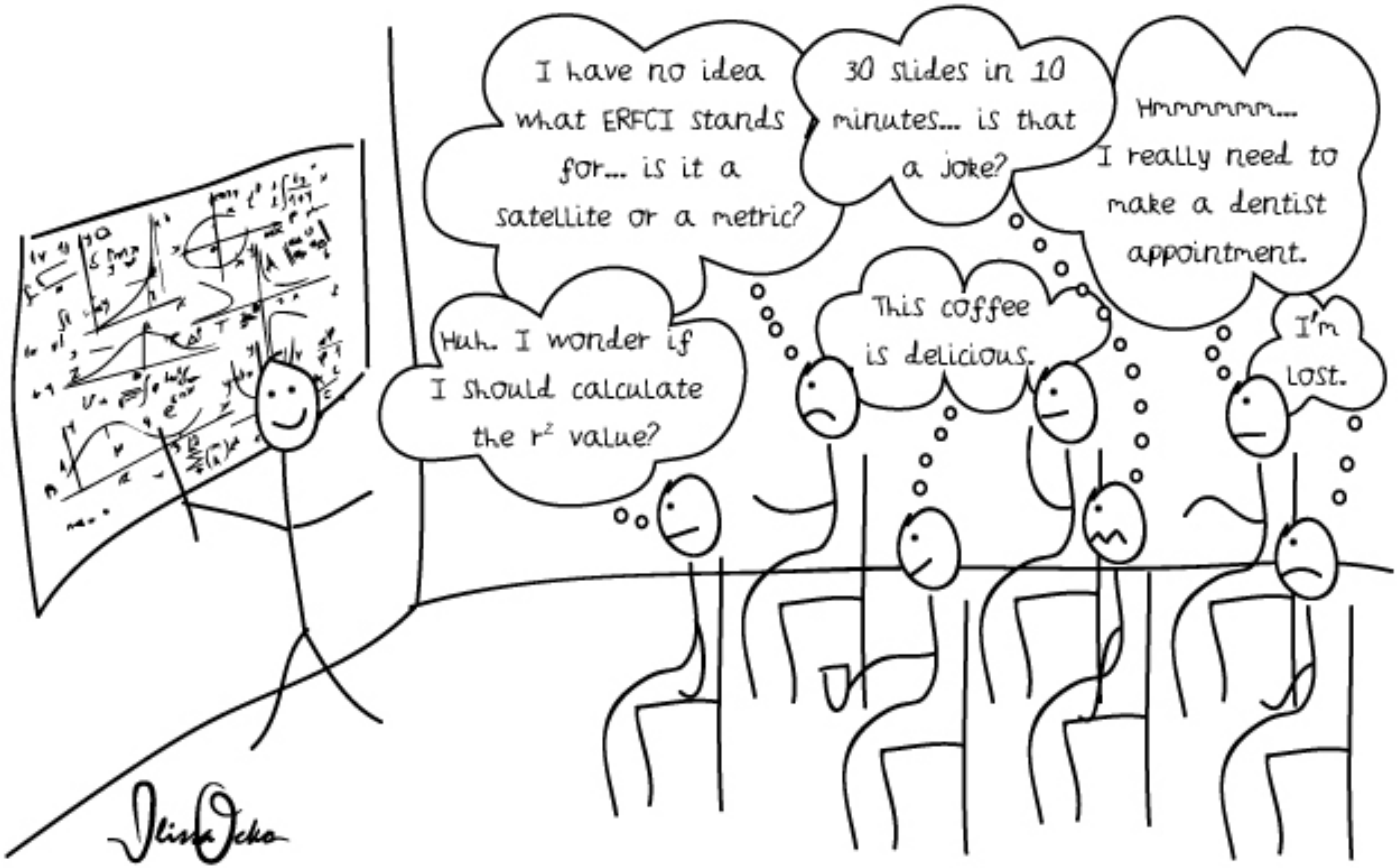


高エネルギー加速器研究機構（KEK/つくば市）で建設中の世界最強加速器SuperKEKBと
その心臓部であるBelleII測定器を合体させるロールイン作業が4月11日（火）に行われます。
BelleII測定器は、加速器で人工的に作り出した素粒子反応を精密に観測することで
宇宙の成り立ちの謎に迫ろうとする最先端の実験装置で、
世界中の研究者と協力しながらKEKで建設が進められています。

ロールインとは、1400トンの巨大なBelleII測定器を実験エリアまで
13メートルゆっくり移動させる作業で、
実験開始に向けた重要なマイルストーンの一つです。

SuperKEKB luminosity projection




I have no idea what ERFCI stands for... is it a satellite or a metric?
30 slides in 10 minutes... is that a joke?
Hmmmmmm... I really need to make a dentist appointment.
Huh. I wonder if I should calculate the r² value?
This coffee is delicious.
I'm lost.

Thank you!