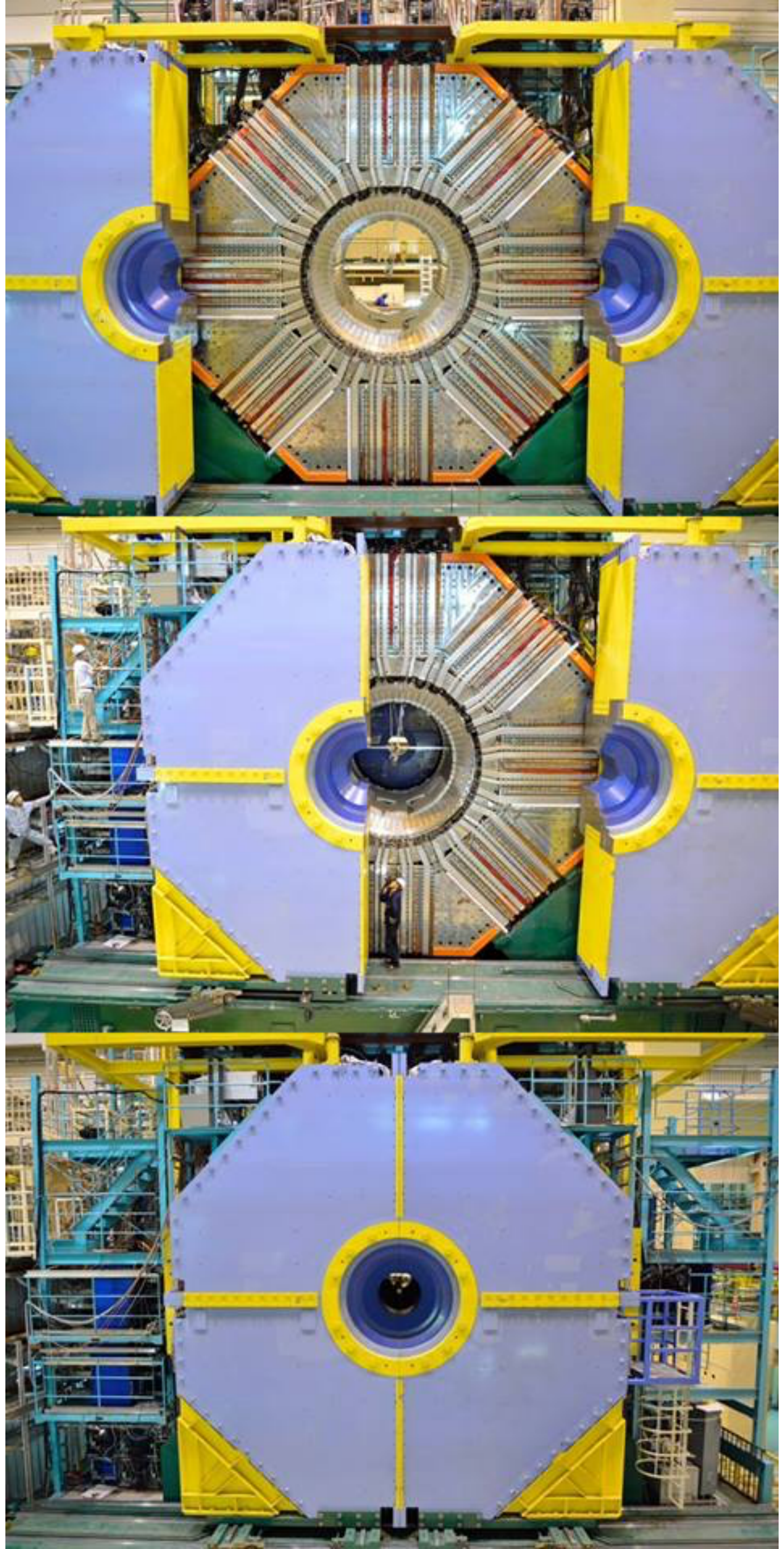


Semileptonic B decays at Belle II

Phillip Urquijo

Lyon LIO "From flavour to new physics"

April 2018

On behalf of the Belle II Collaboration

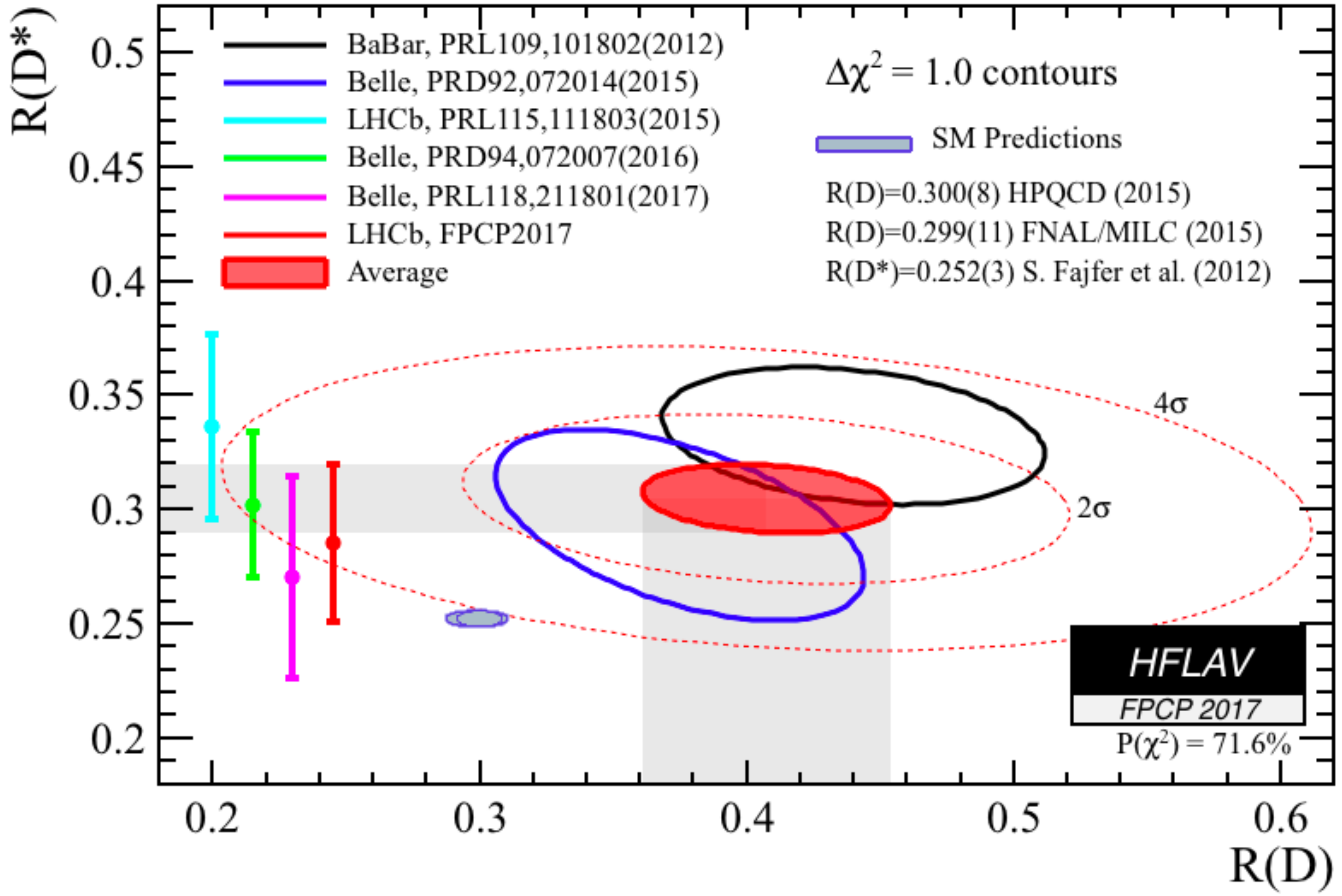
Super KEKB

Belle II

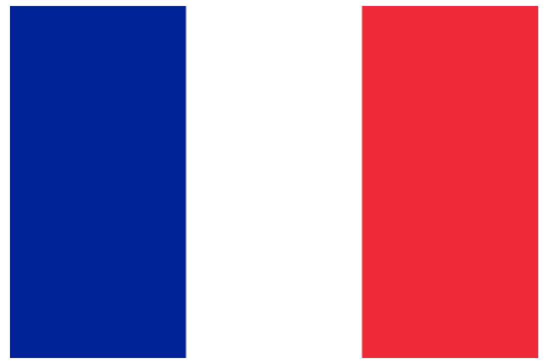
POSTERA CRESCAM LAUDE
THE UNIVERSITY OF MELBOURNE

Tree and Loop

- Belle II status and performance
- Lepton flavour universality and lepton ID
- **Tree Level B decays** (recent results)
  - **B → τ ν X, X= D, D*, π** : D* SemiLep tag 2016 PRD, D* Hadronic tag 2017 PRL&PRD, π 2016 PRD
  - **B → l ν X, X = D, D*** : B→D 2016 PRD, D* 2017 Preliminary, D** 2018 sub. to PRD
  - **B→ l ν, l = τ, μ**: B→ μν 2018 sub. to PRL
- **Loop level B decays** (recent results)
  - **B→ l l X, X = X_s, K, K*:** K(*) 2017 PRL, X_s 2016 PRL
  - **B→ τ l X & B→ X ν ν, X = K, K***: K(*) 2017 PRD



- ***Note: France joined Belle II in 2017! (25th country to join)***



Belle II Upgrades

Central beam pipe: decreased diameter from 3cm to 2cm (Beryllium)

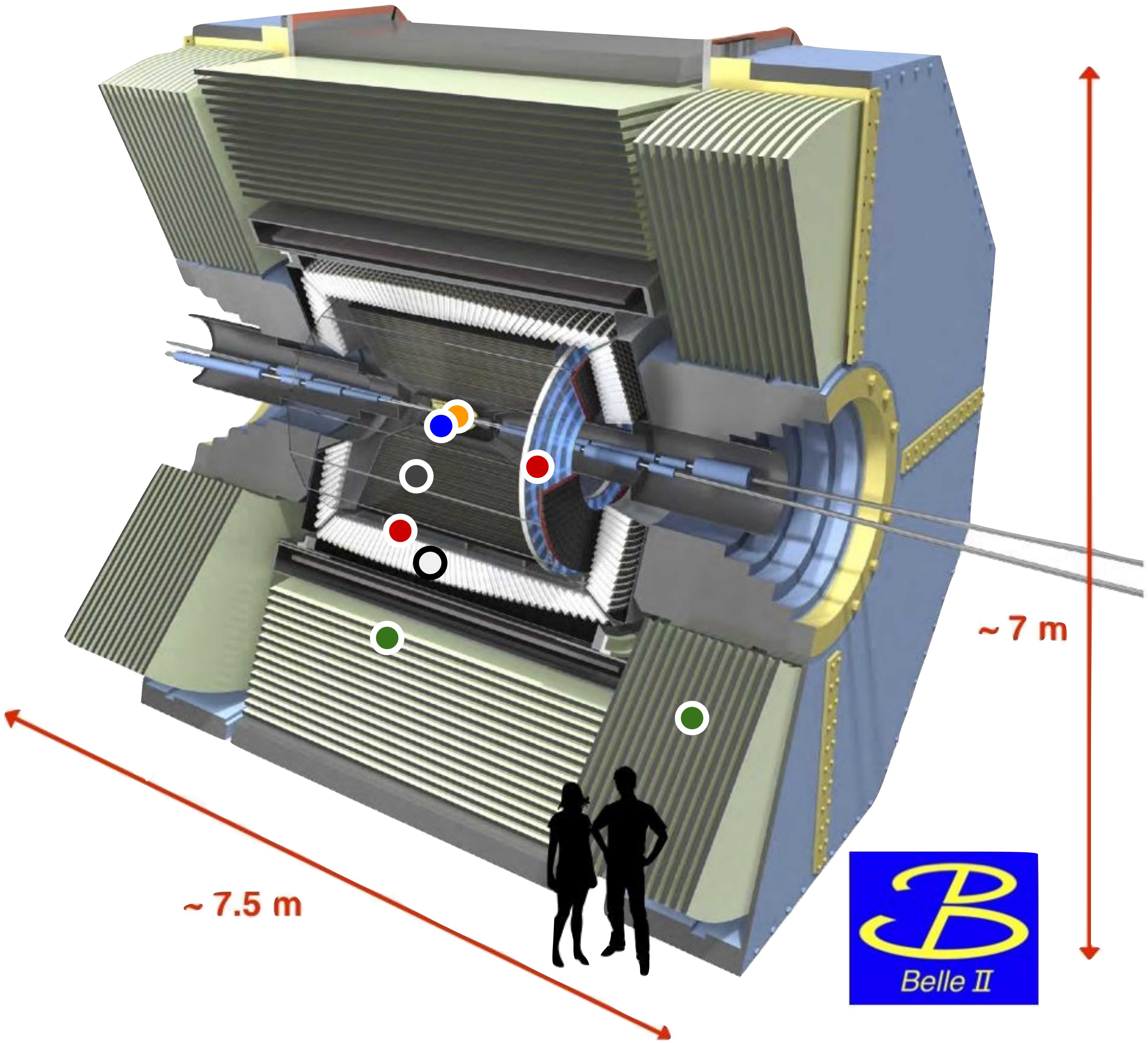
Vertexing: new 2 layers of pixels, upgraded 4 double-sided layers of silicon strips

Tracking: drift chamber with smaller cells, longer lever arm, faster electronics

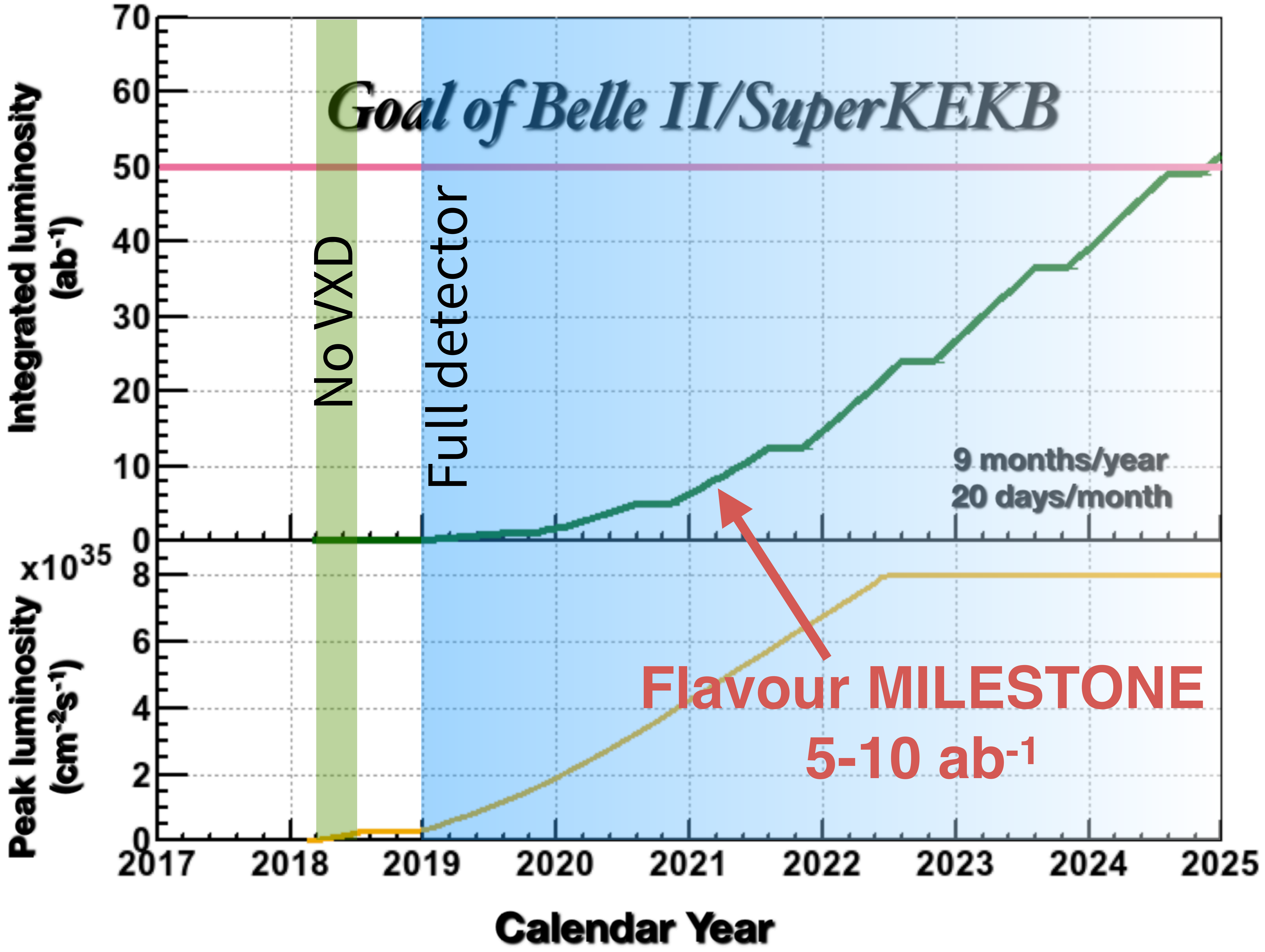
PID: new time-of-flight (barrel) and proximity focusing aerogel (endcap) Cherenkov detectors

EM calorimetry: upgrade of electronics and processing with legacy CsI(Tl) crystals

K_L and μ: scintillators replace RPCs (endcap and inner two layers of barrel)



SuperKEKB / Belle II Luminosity projections



Phase 2:
Peak luminosity reaches
1×10^{34} cm^{-2}s^{-1} (Belle)
20 fb^{-1} for physics near Y(4S)

March 2018: First beams.

April 2018: First collisions

July 2018: End of commissioning run.

Verification of nano-beam scheme
understand beam bkg in VXD volume

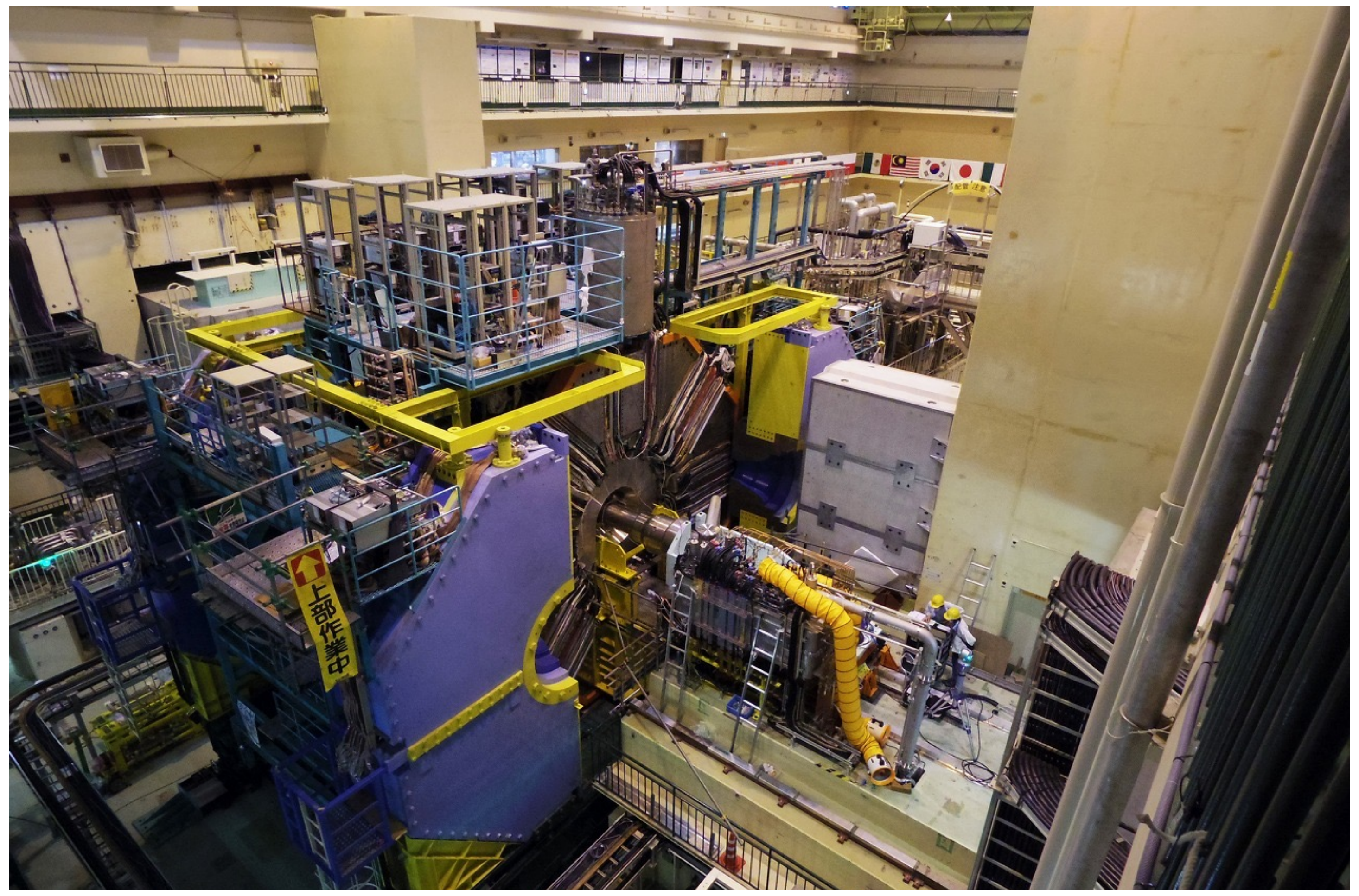
Phase 3:
50 ab^{-1} by 2025
50x Belle, 100x Babar

Early 2019: "**Phase 3**"

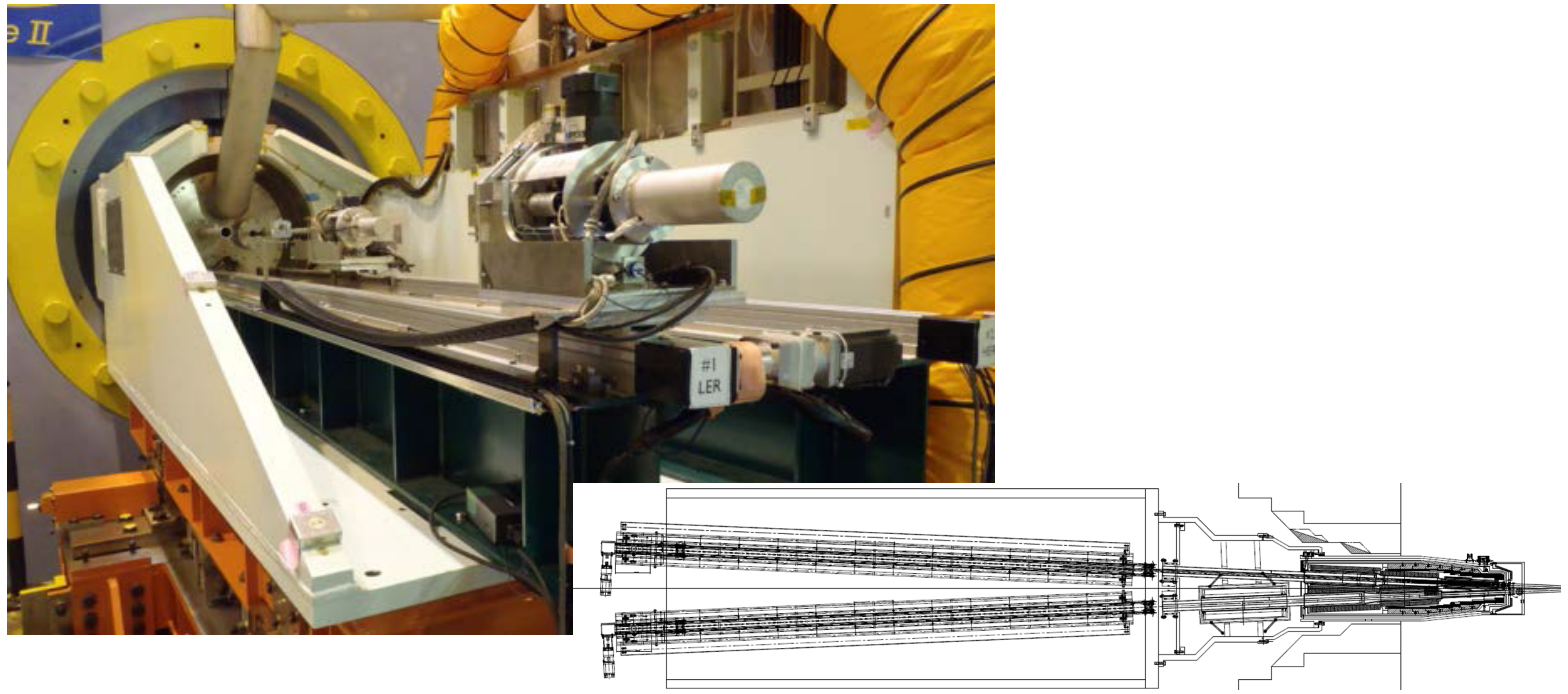
All 2018 dates are tentative

Detector installation activities

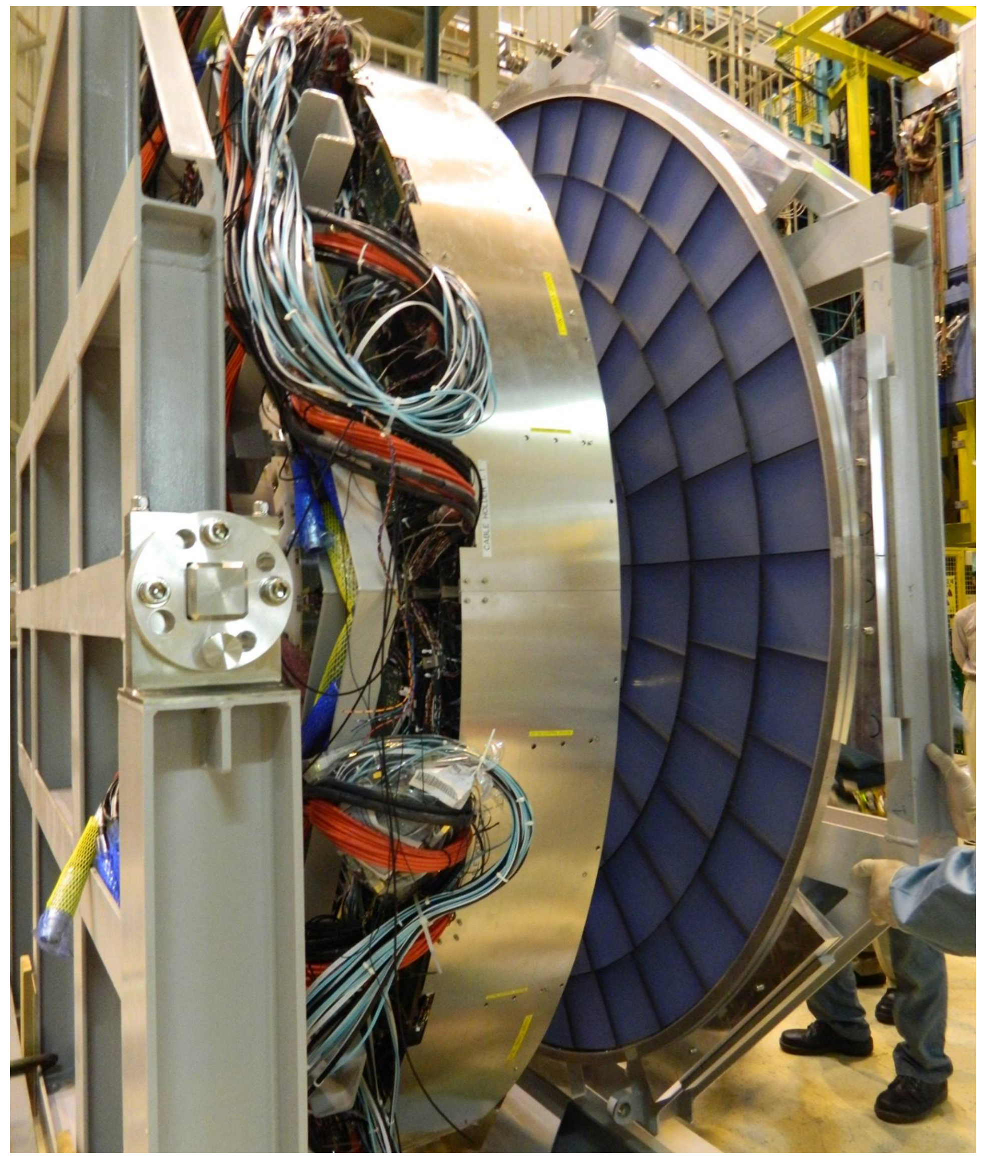
Belle II Roll-in



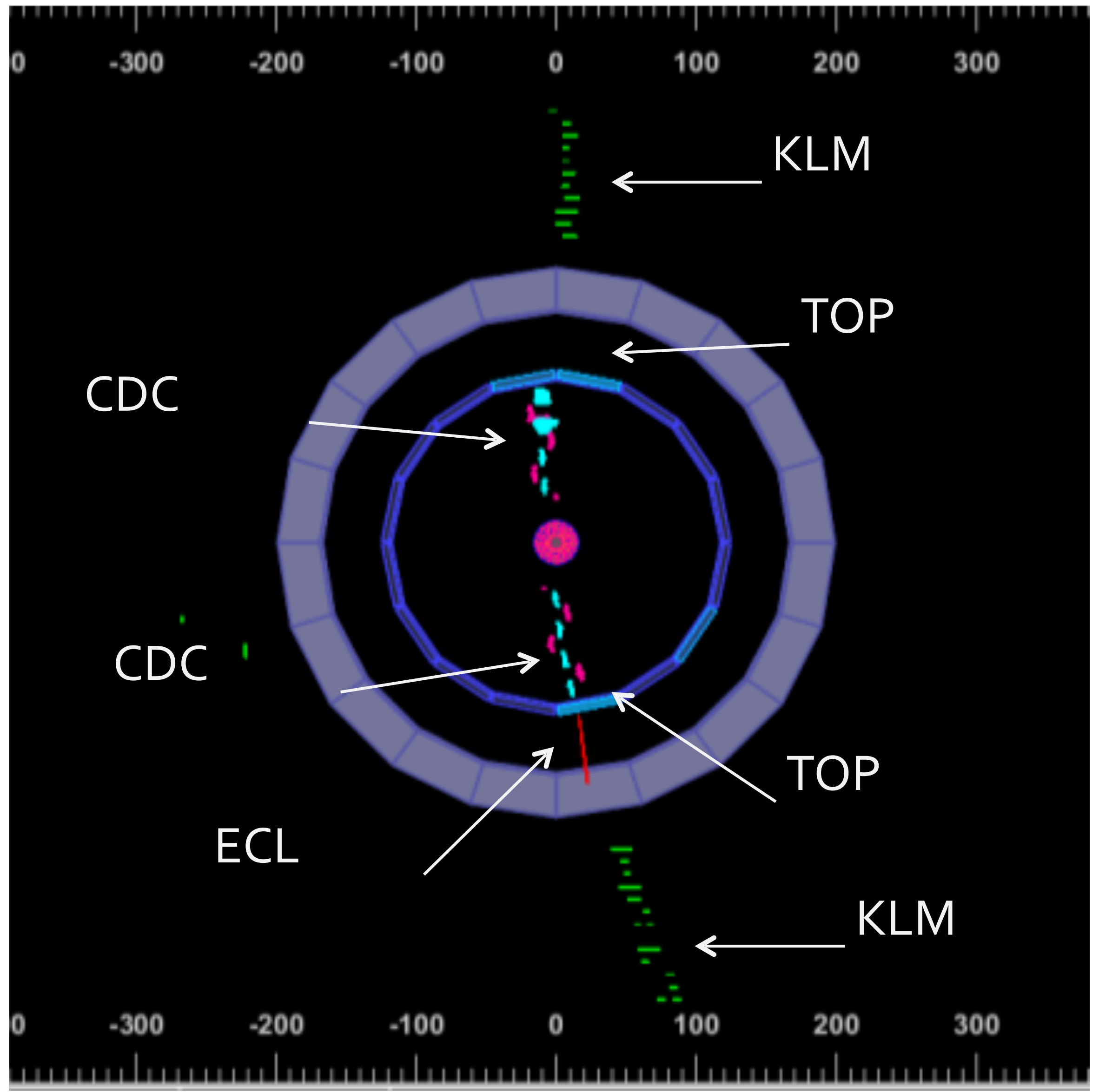
QCS solenoid



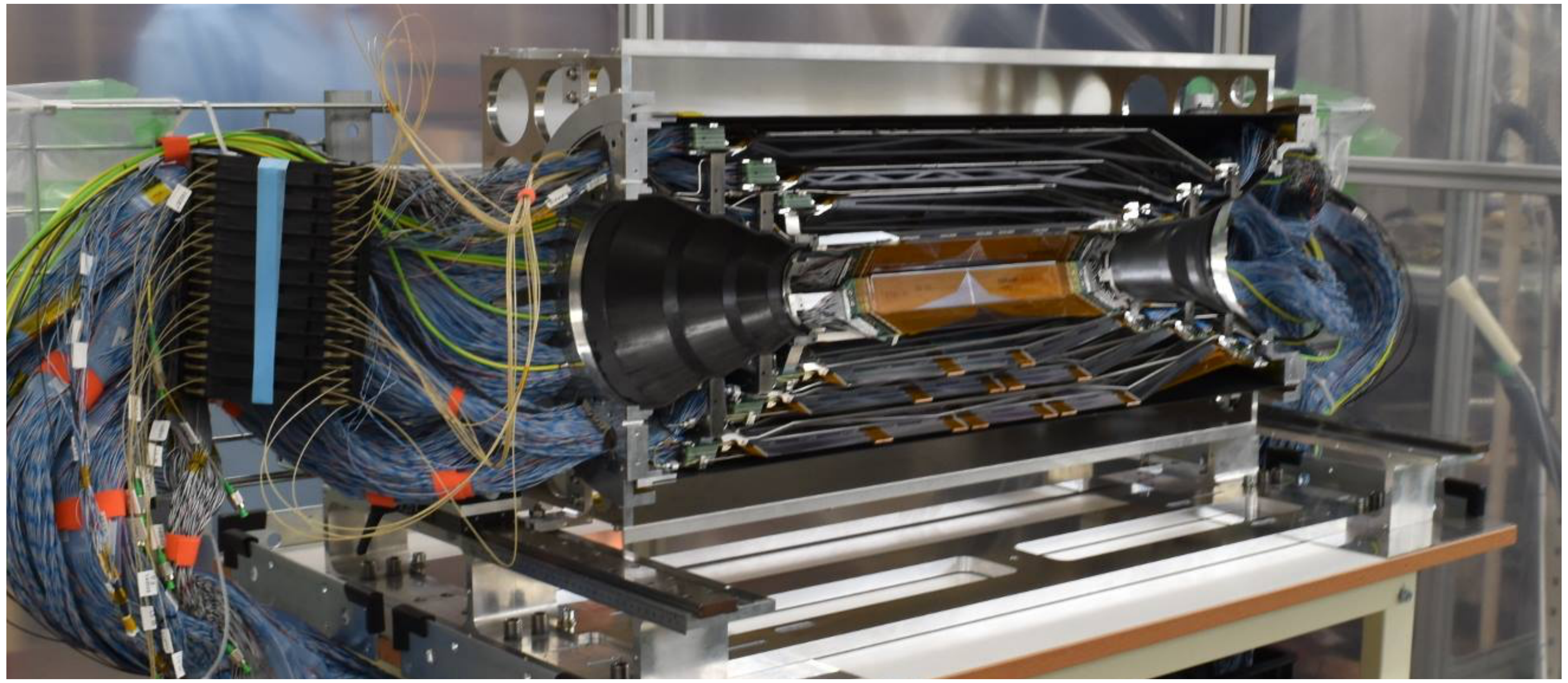
ARICH installation



Readout integration: cosmic



SVD Ladder mount



Start of Phase II

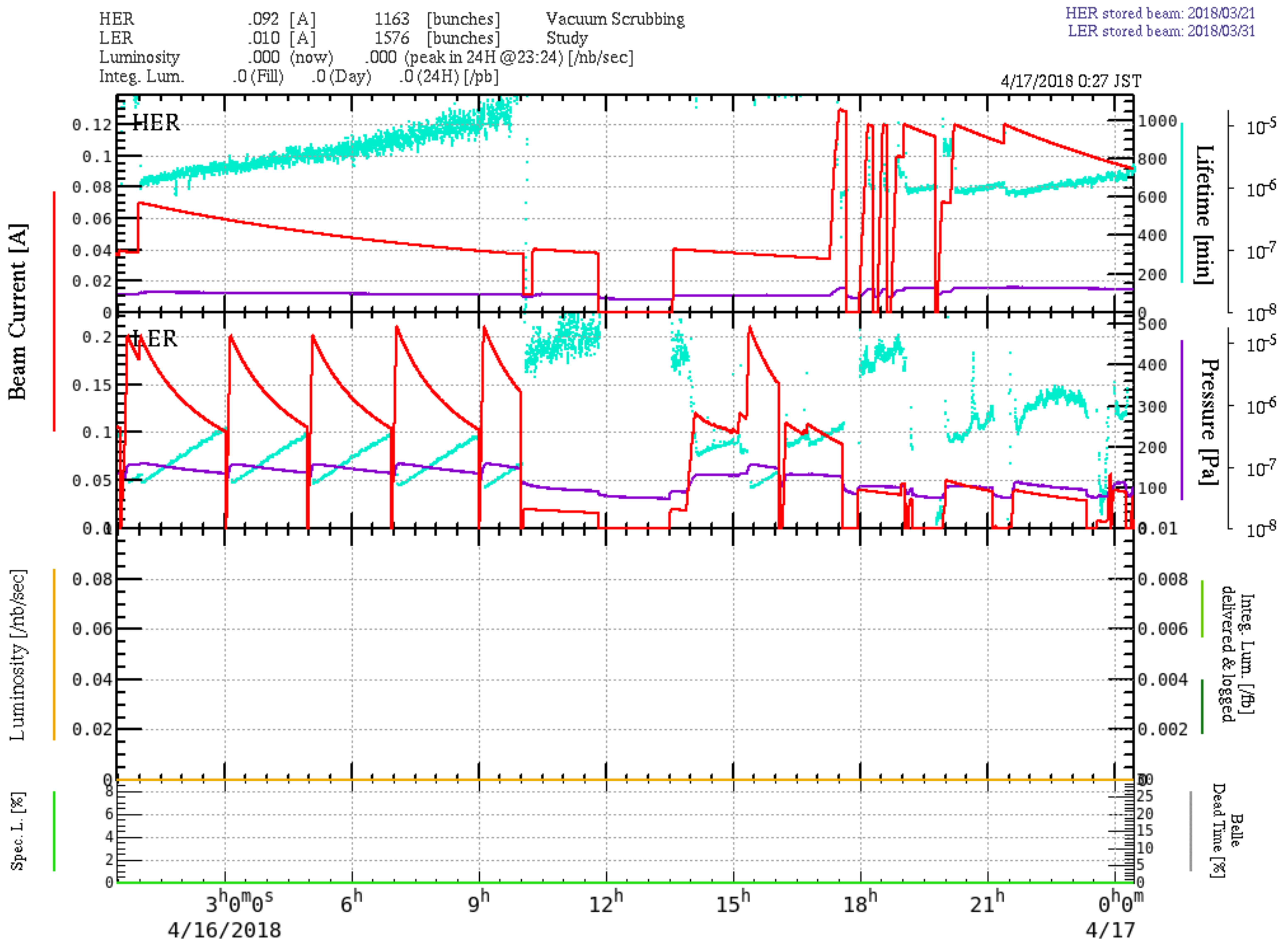
Control room, 14/2/2018

LER and HER current: 16 April 2018

HER

LER

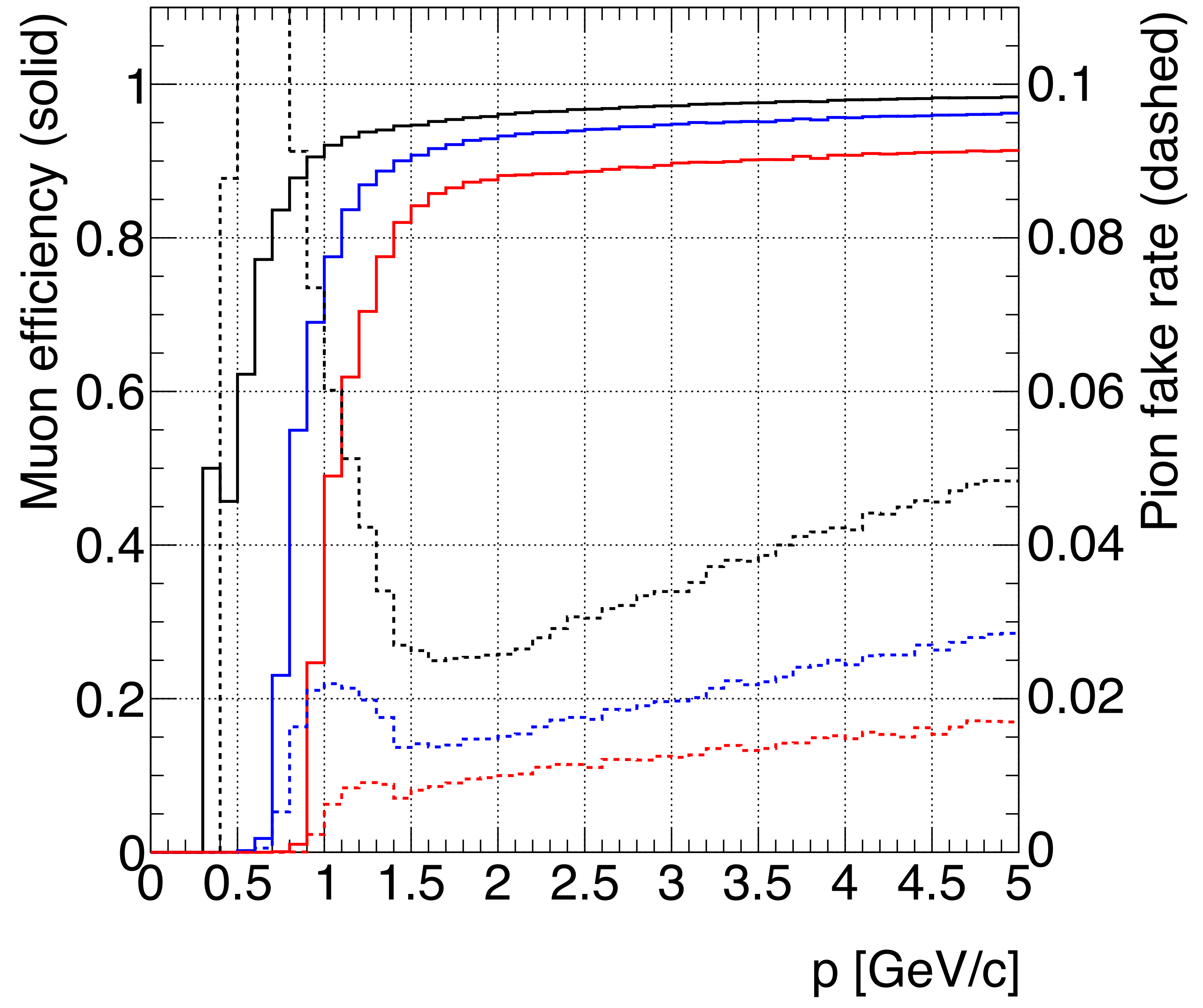
http://www-linac.kek.jp/skekb/snapshot/ring.html

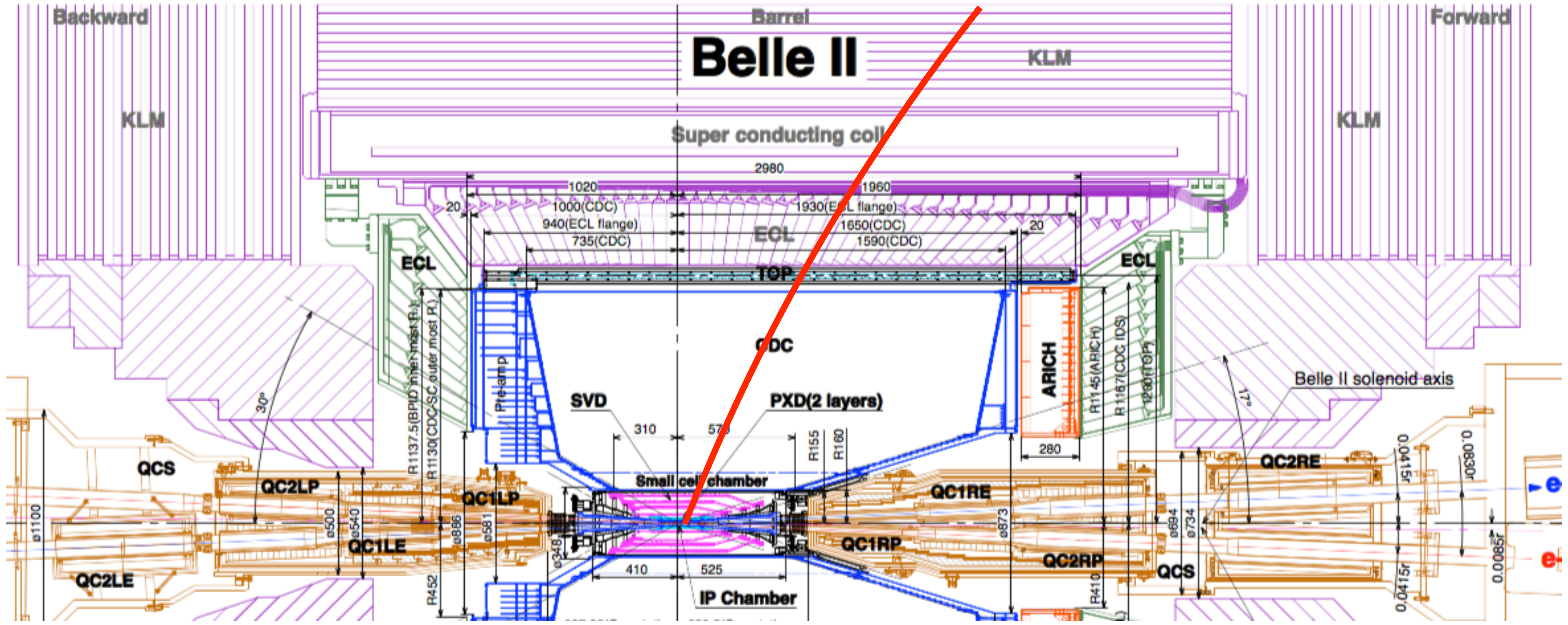


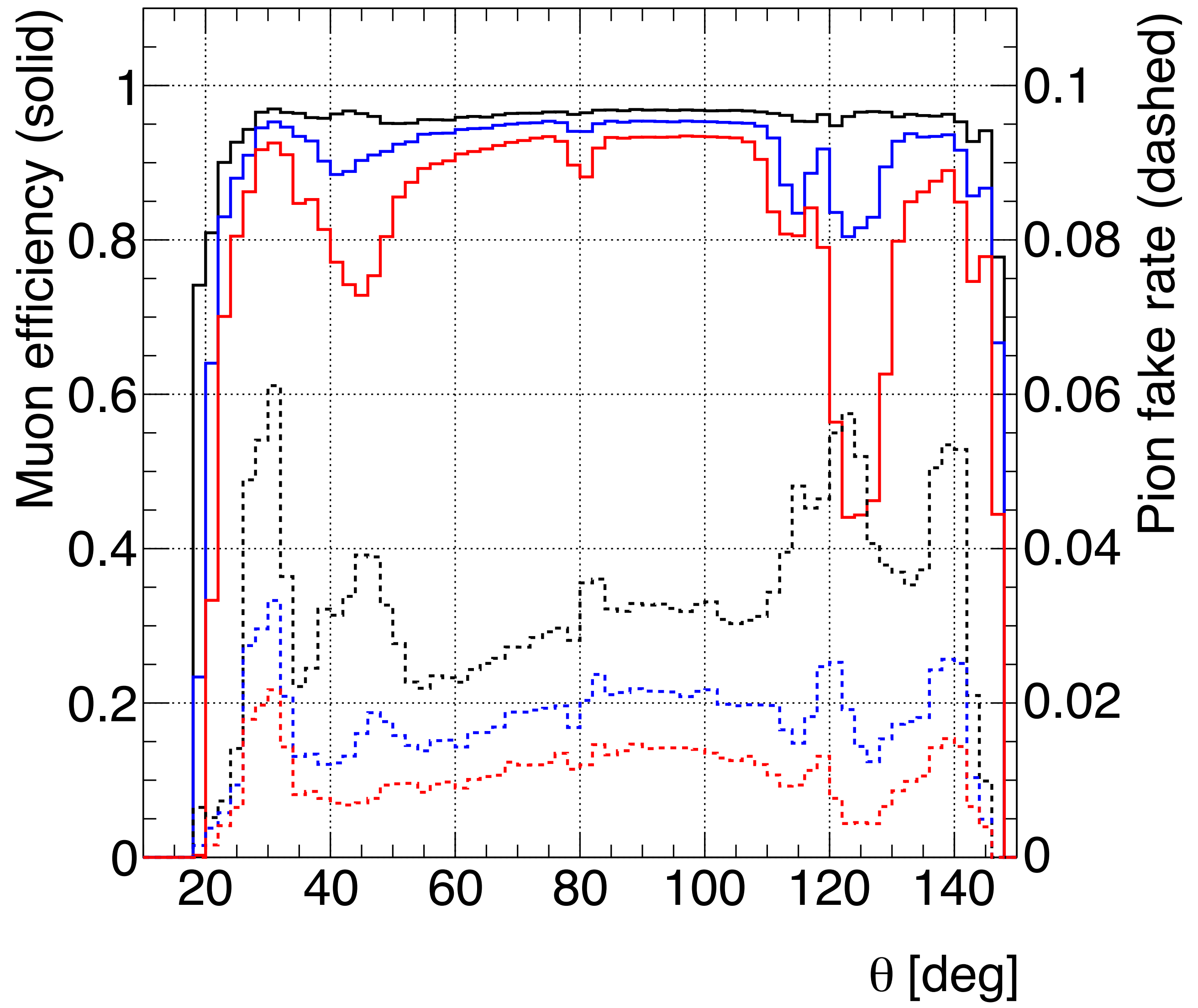
Muon identification

- Muons are the easiest to identify
  - Little to **no radiation** (heavy)
  - **Stable** within particle detectors
  - No strong interactions in absorber material
  - In B-factories, need p > 700 MeV/c to reach muon detectors
- ECL not used for μID at Belle → to be used in Belle II.

μID

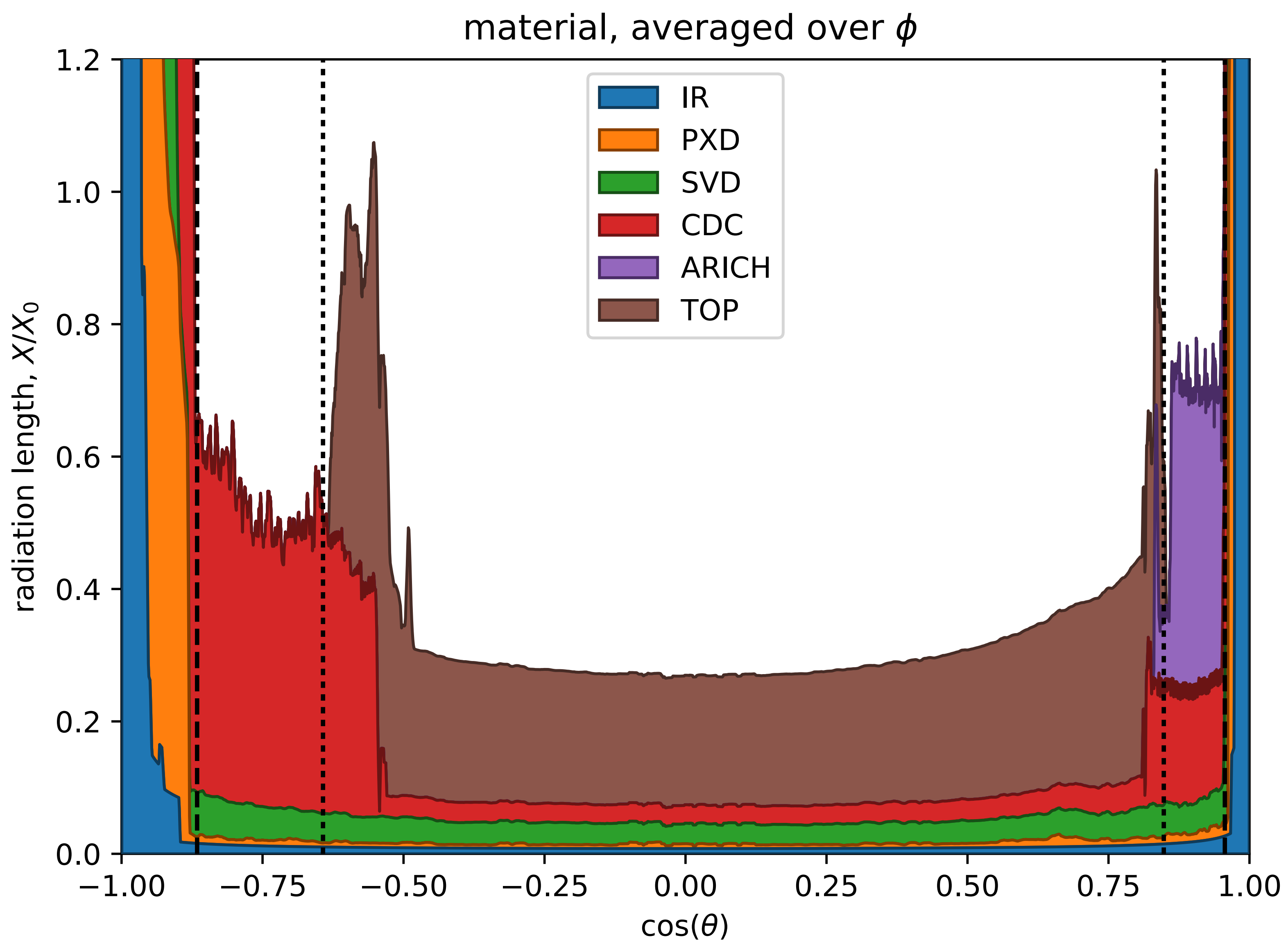


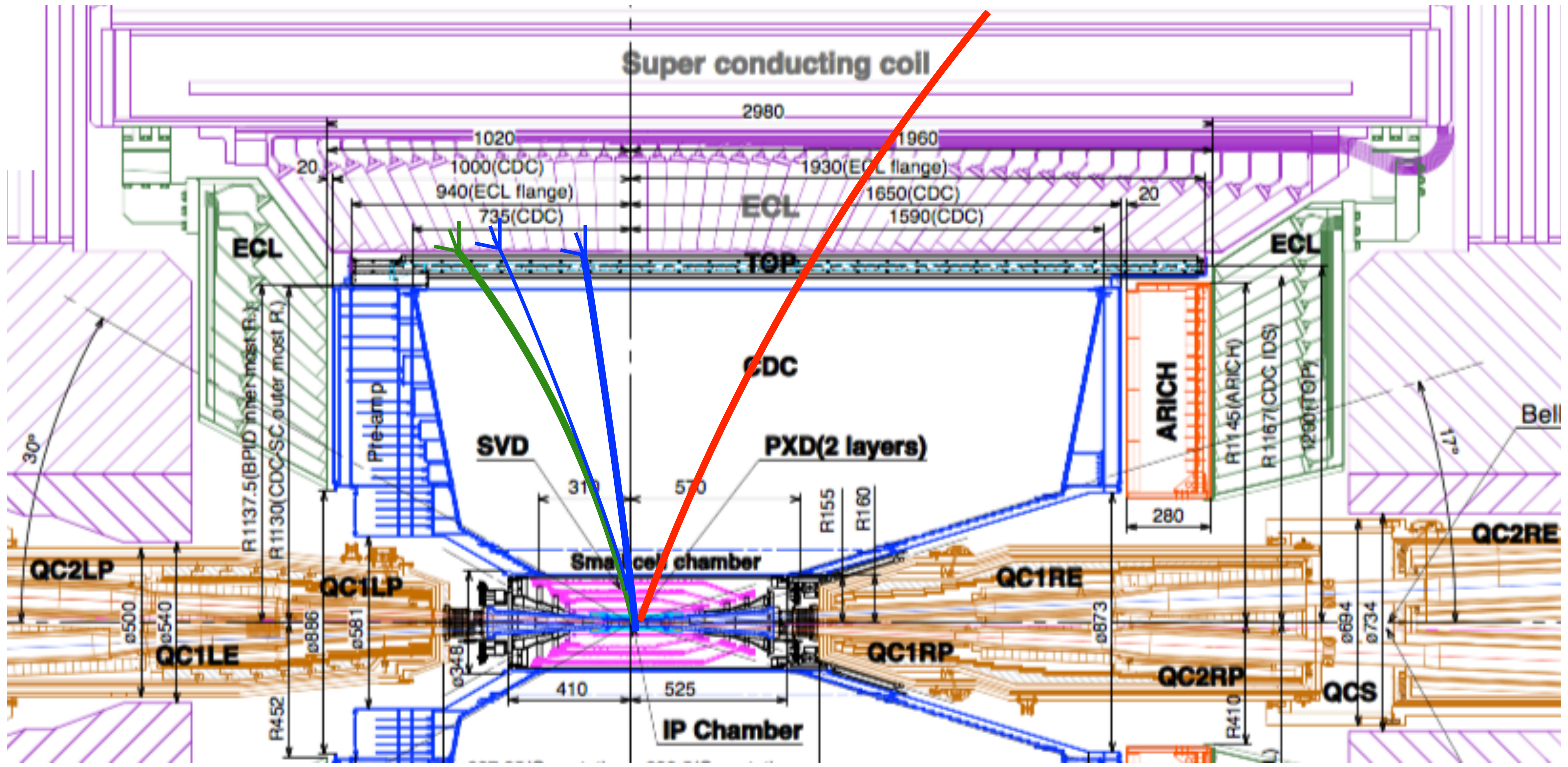


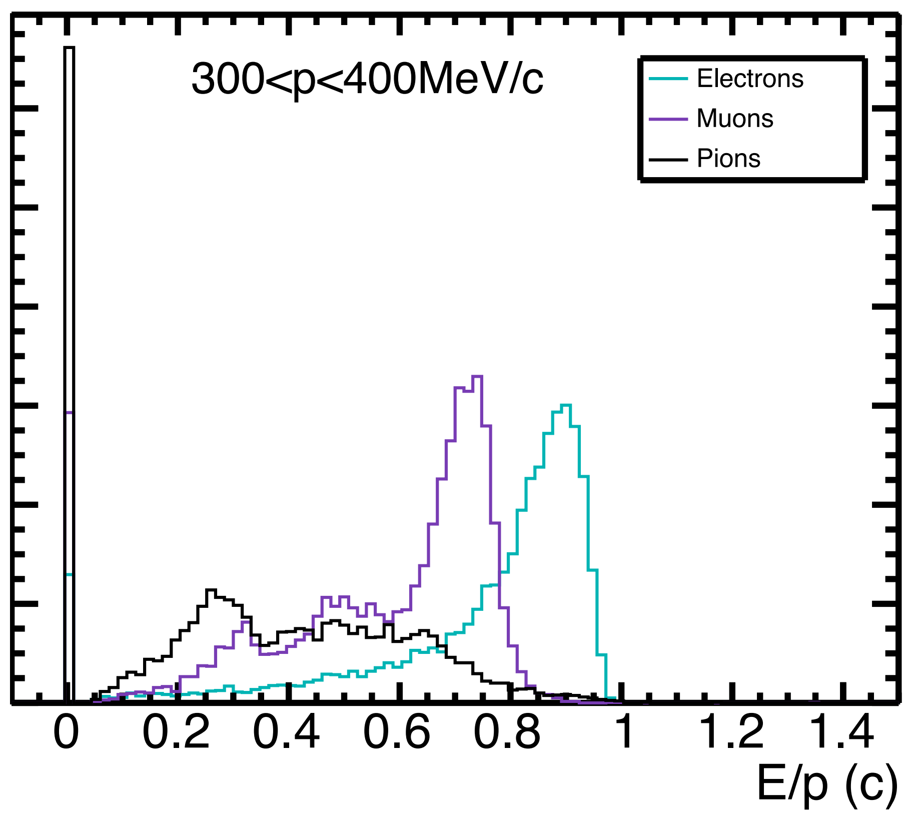


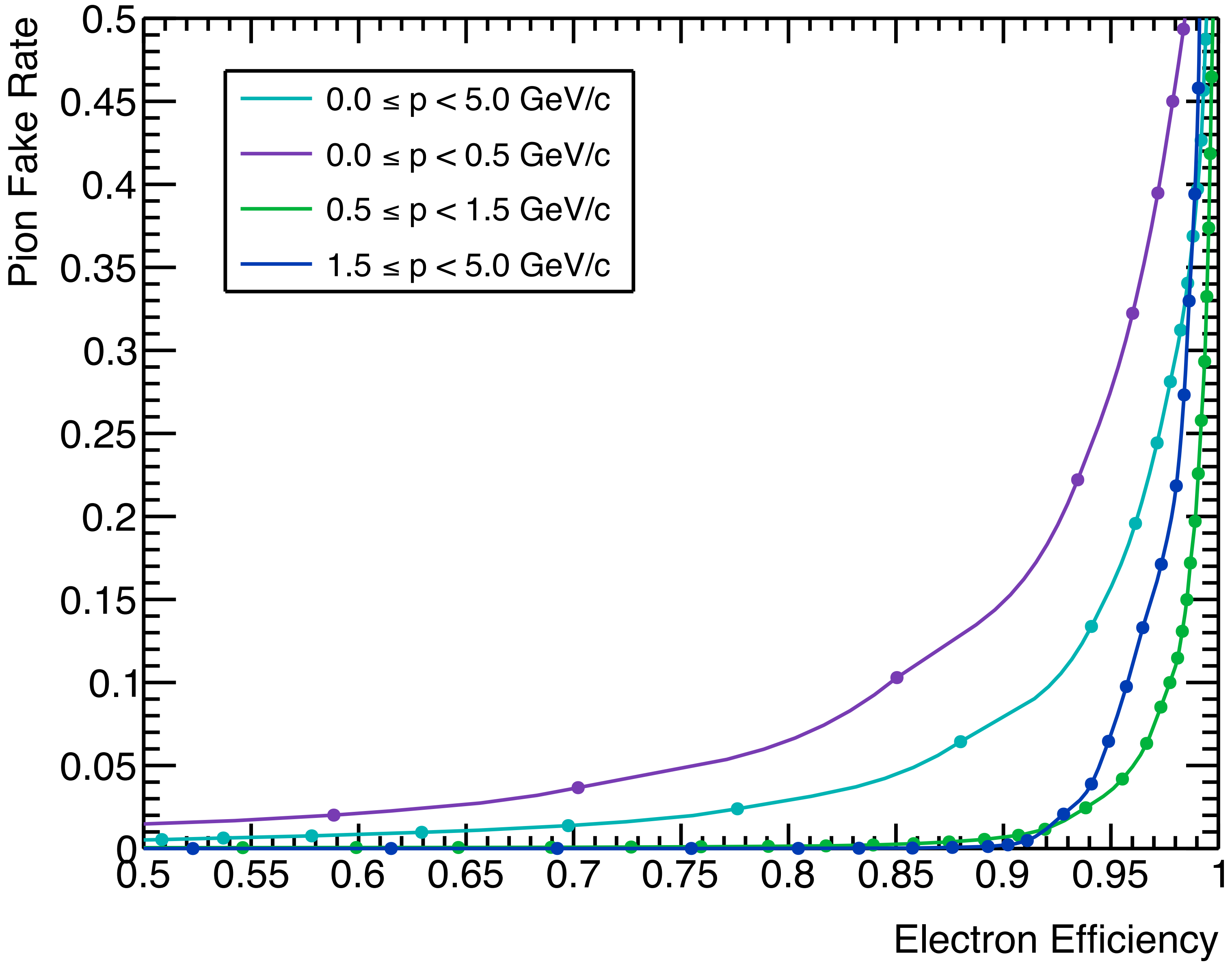
Electron identification

- Electrons are light: **Final state radiation**
  - **Bremsstrahlung** in material is likely
    - Measure too low momentum, Too low energy in calorimeter
    - **Bremsstrahlung recovery** partial fixes this
- Belle II: TOP, ARICH, dE/dx, ECL-shower profile
  → **development for low momentum in progress.**



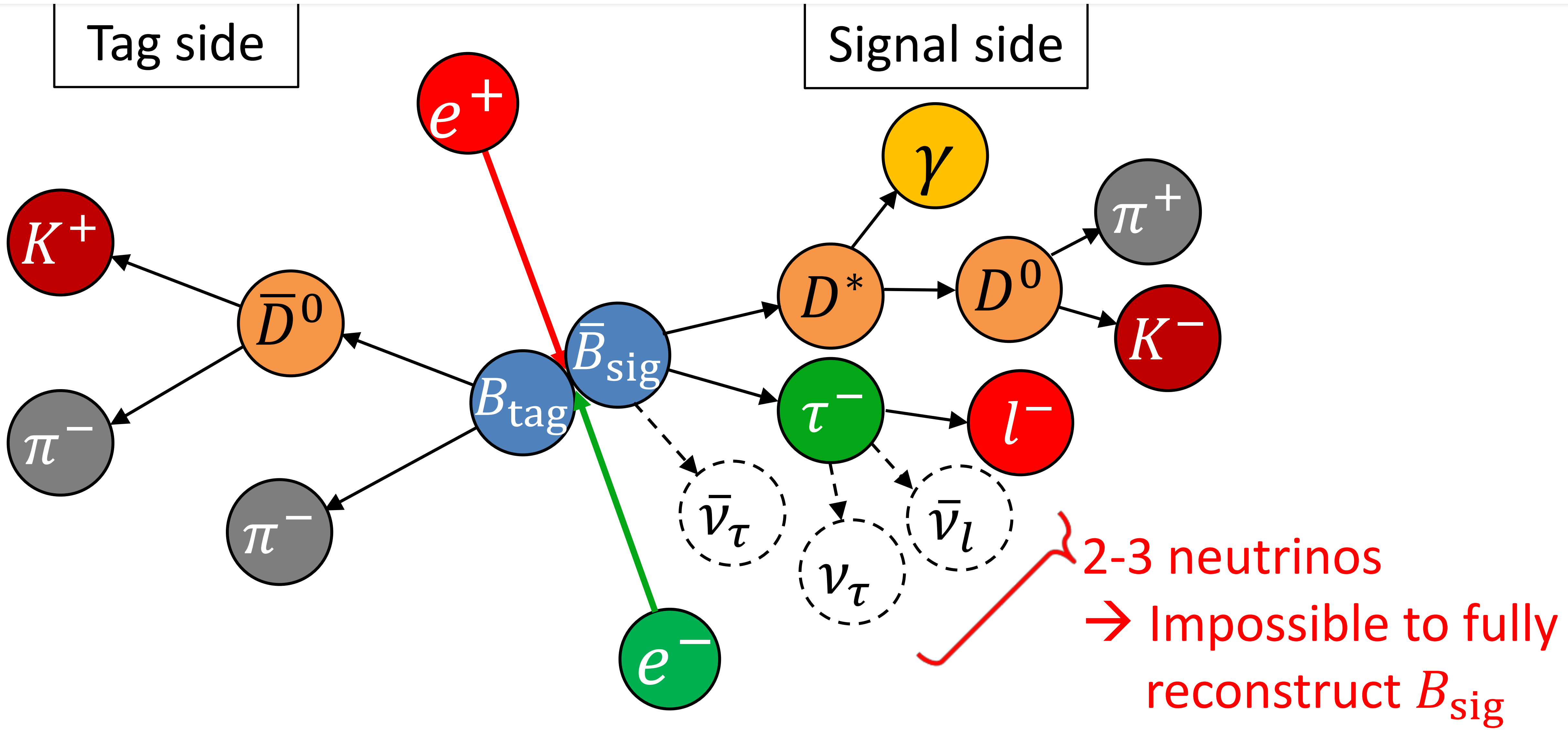


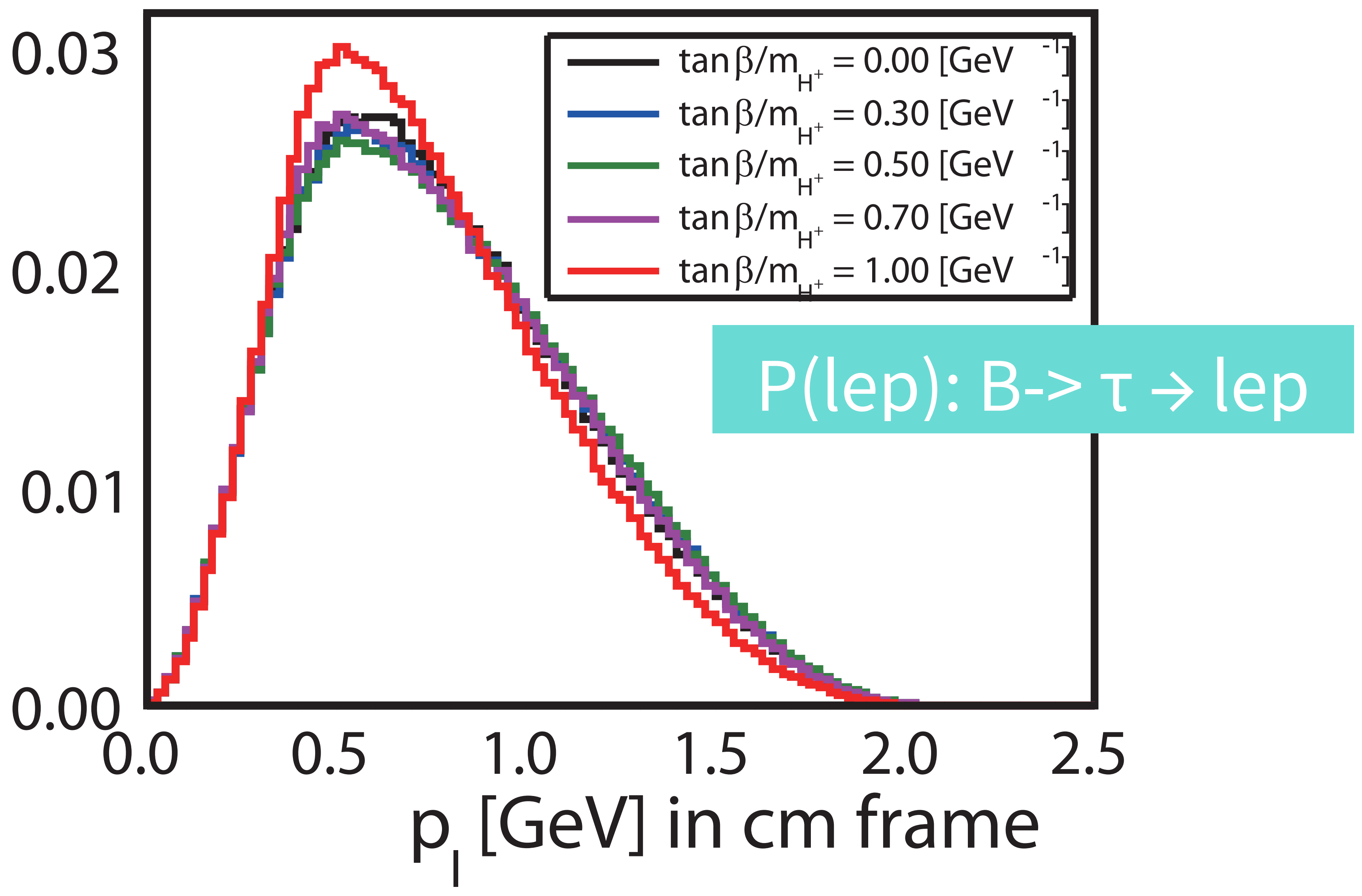




Tau identification (reconstruction)

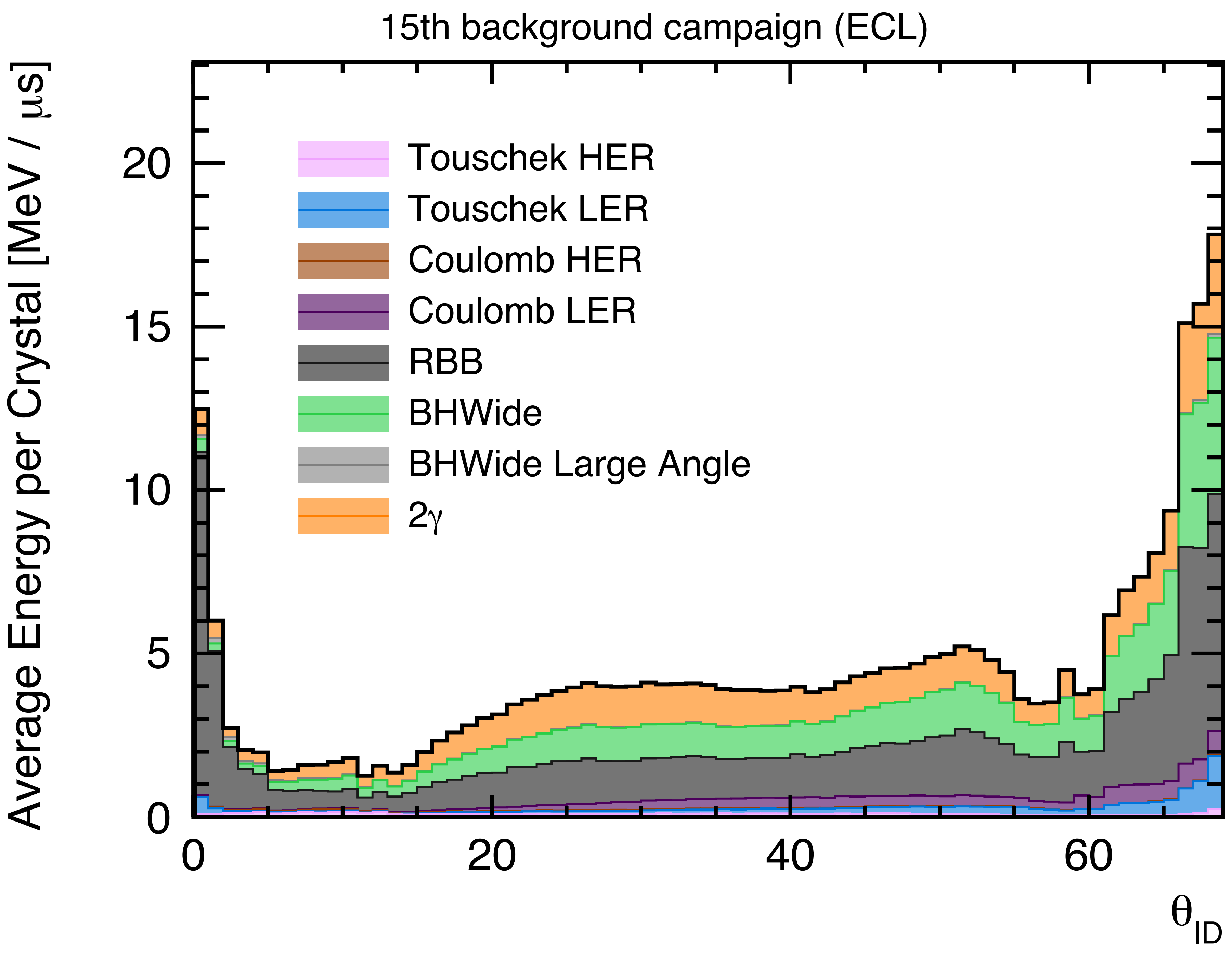
- Identification / reconstruction of τ leptons is very challenging
  - **Short lifetime** of 10^{-12} s
  - Hadronic decay with **π's and 1 ν**
  - Leptonic decay with **e/μ and 2 ν**
  - Lack of full reconstruction implies **background mimics the the signal where some daughters are lost e.g. K_L, π^0**. Often difficult to constrain with "sideband" data.

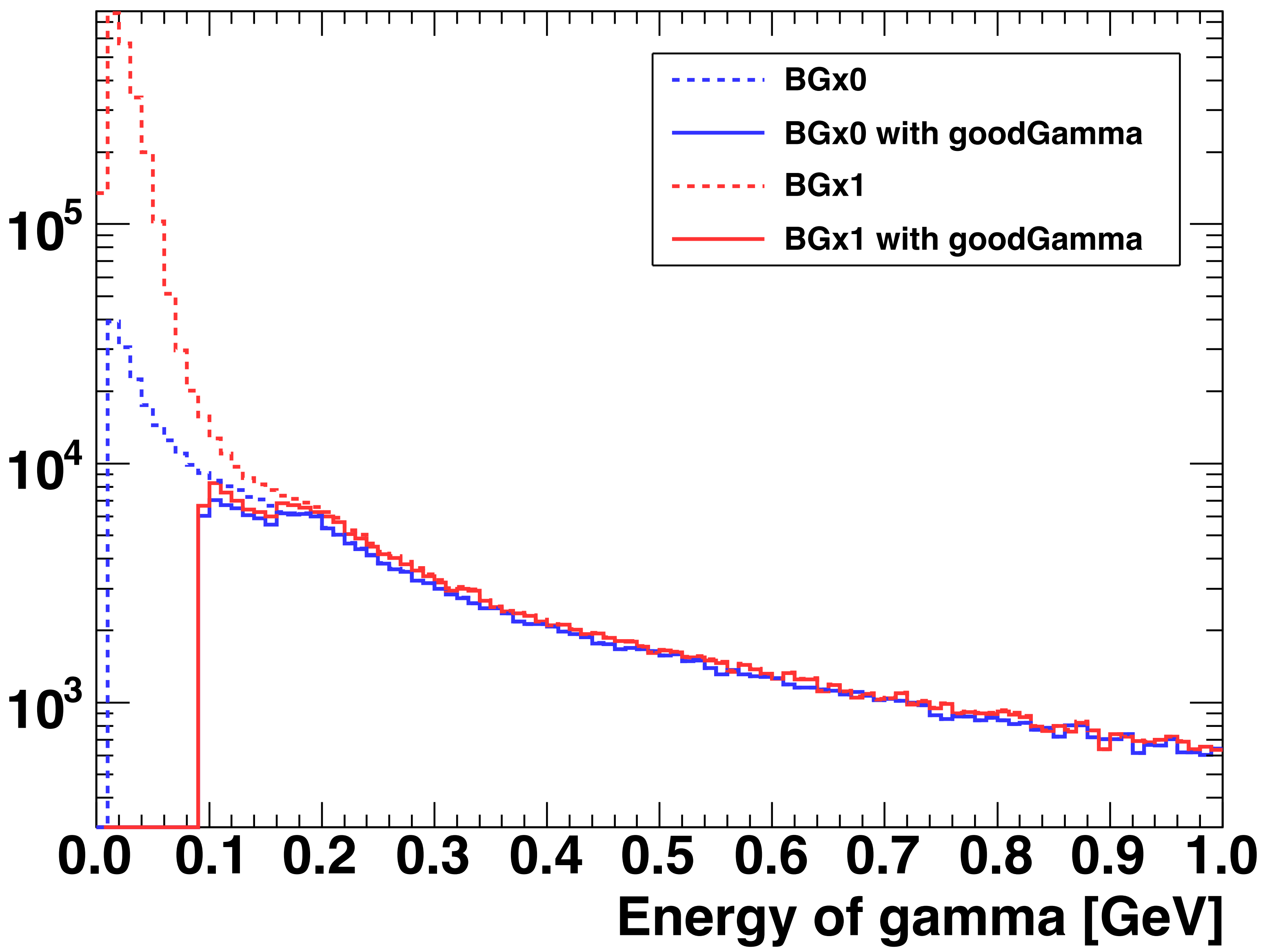


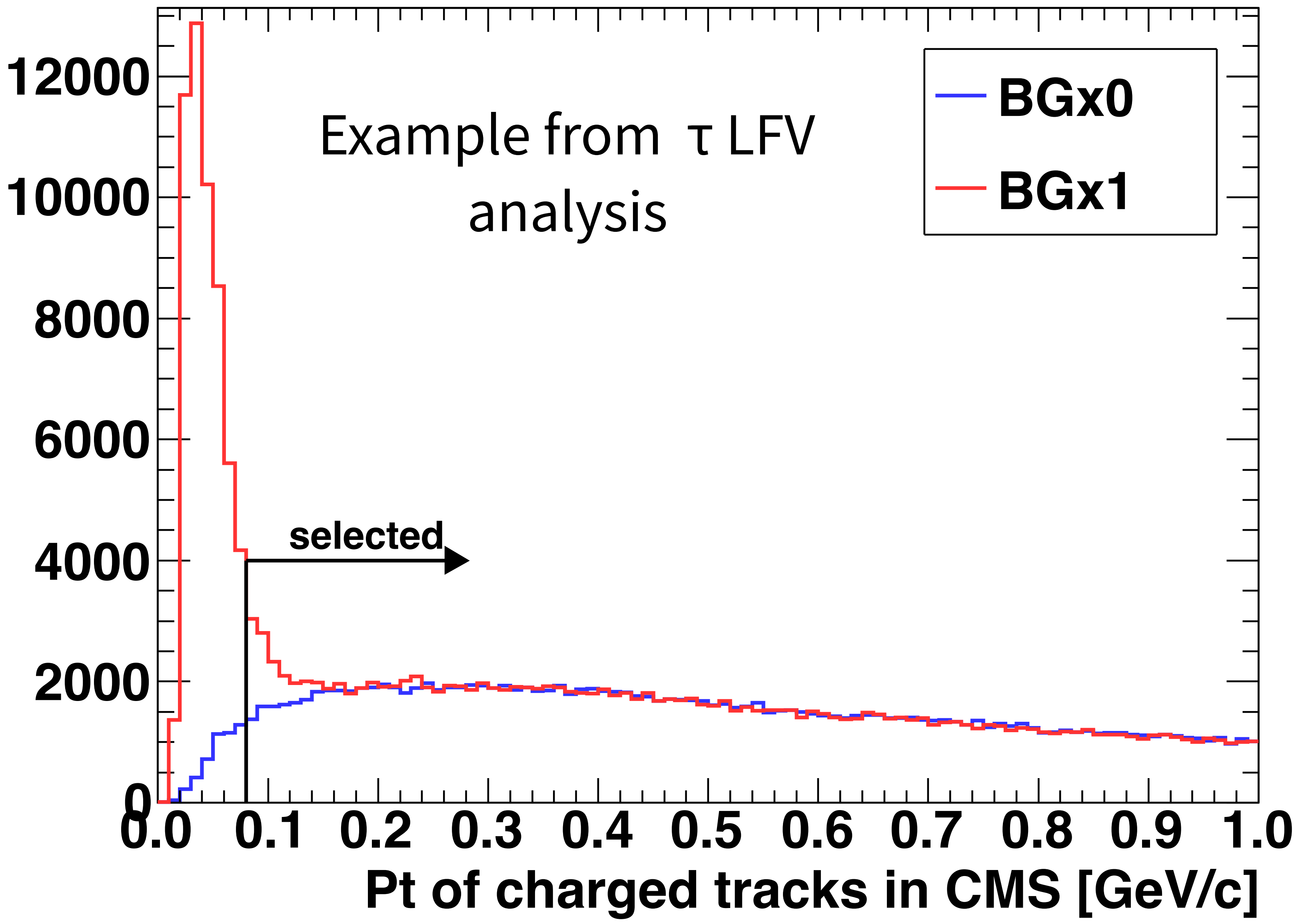


Beam background (MC 2017)

- **20x more beam induced background than KEKB!**
- Touschek (intrabunch scattering), Radiative Bhabhba, QED/2γ, Synchrotron radiation.
- Increases occupancy in inner Si layers - can degrade tracking.
- Increases background at low energy in the calorimeter.



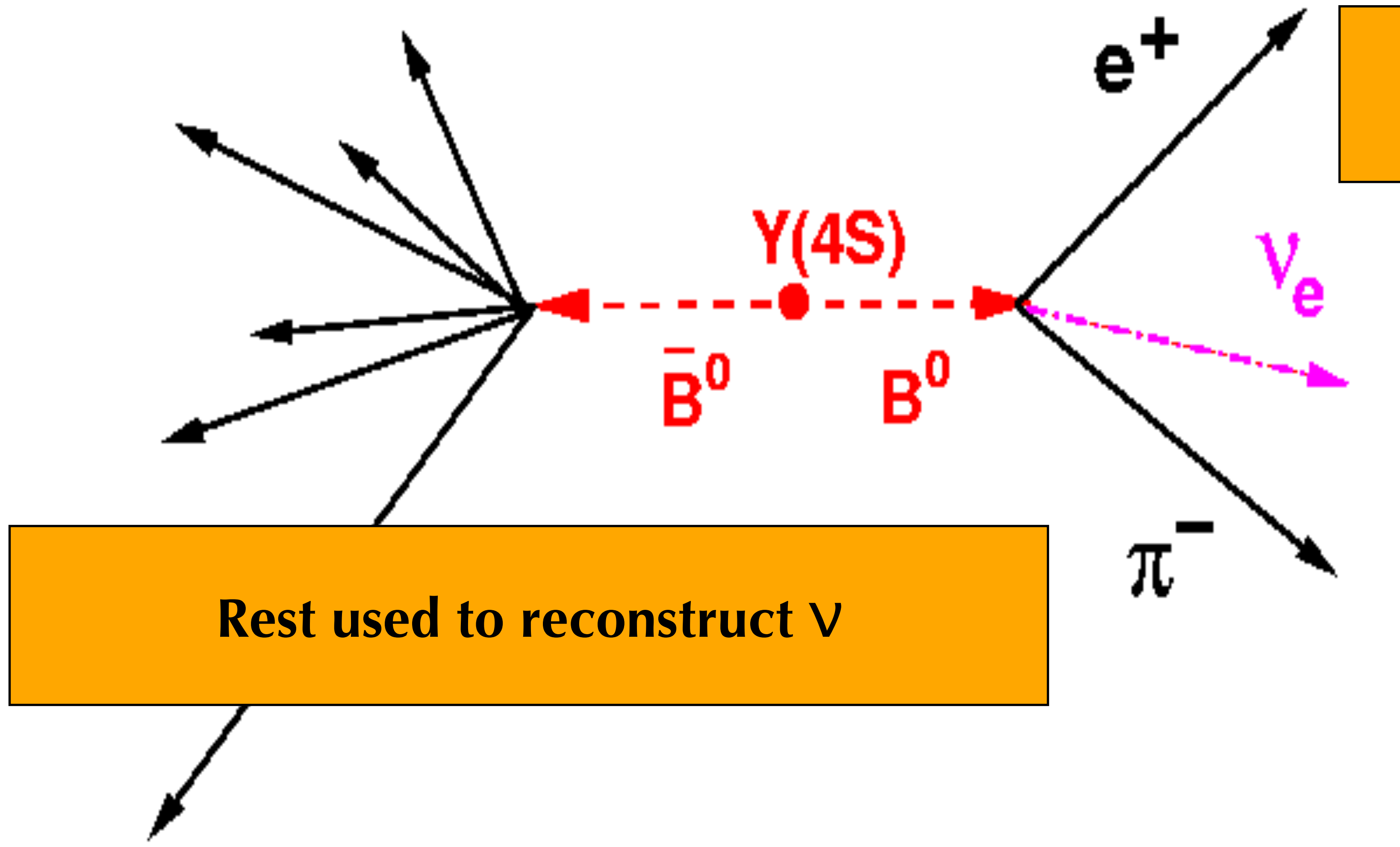




B-factory Approaches to Measuring B → X l ν

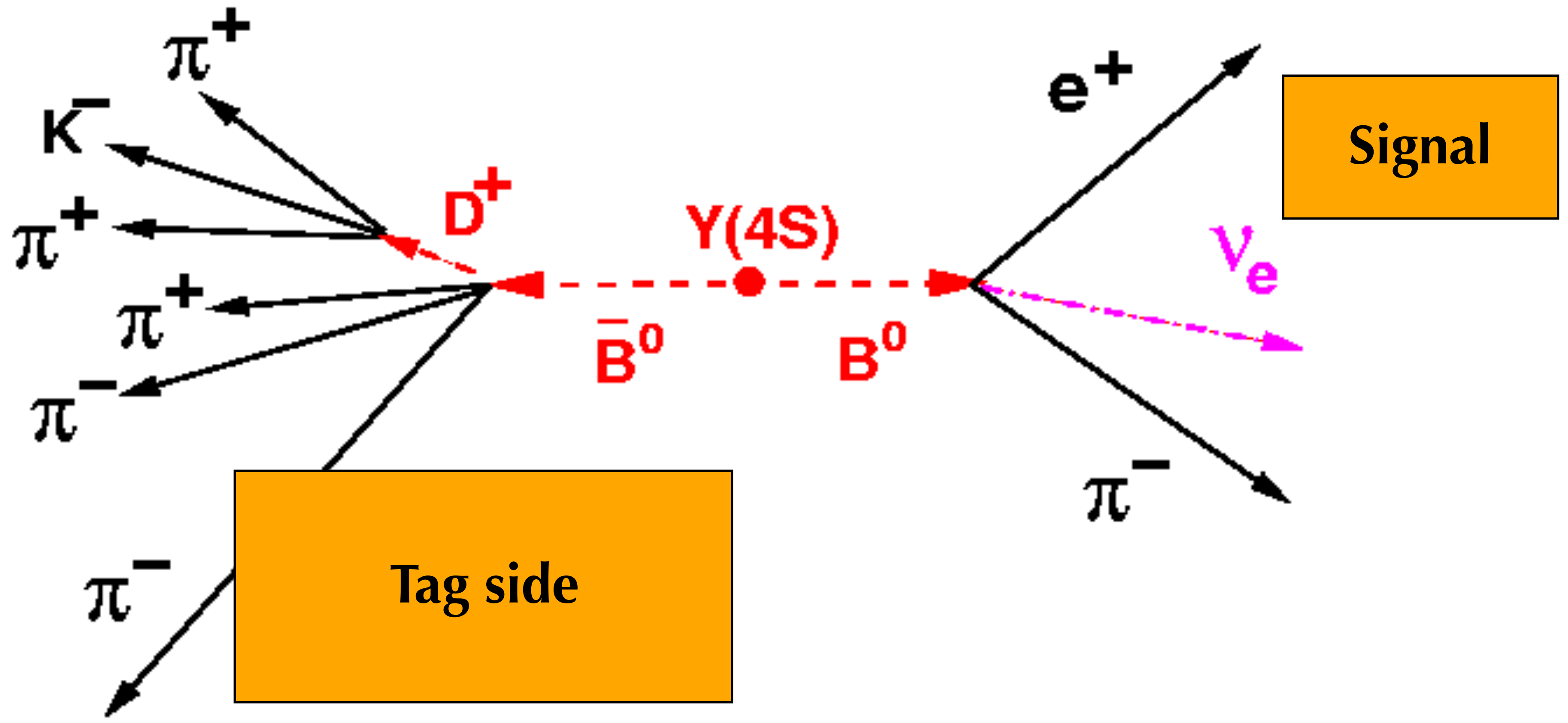
Untagged

initial 4-momentum known
missing 4-momentum = ν
Reconstruct B → X_q l ν
Use other side to constrain B flight direction.



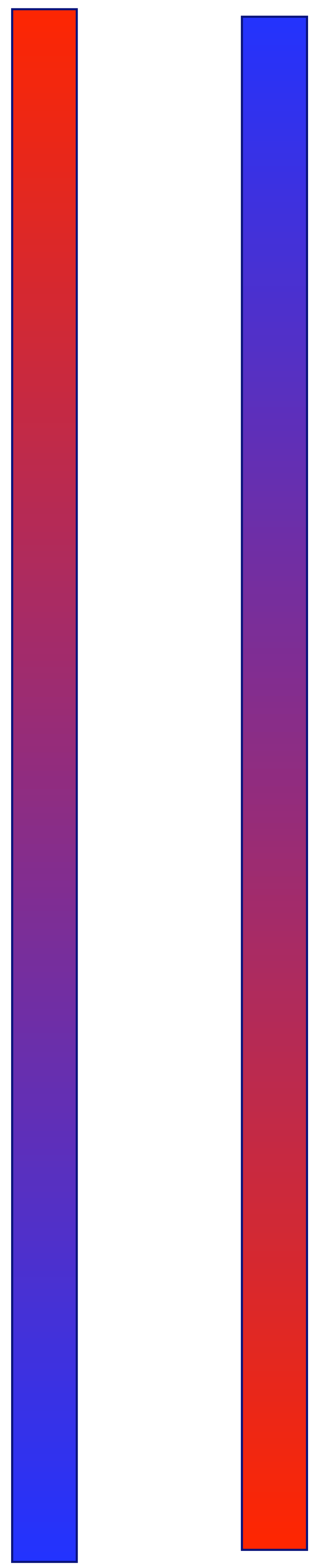
Fully Reconstructed Tag

One B reconstructed completely in a known b → c mode without ν.
“B-meson Beam”



Eff. **Purity**

High Low

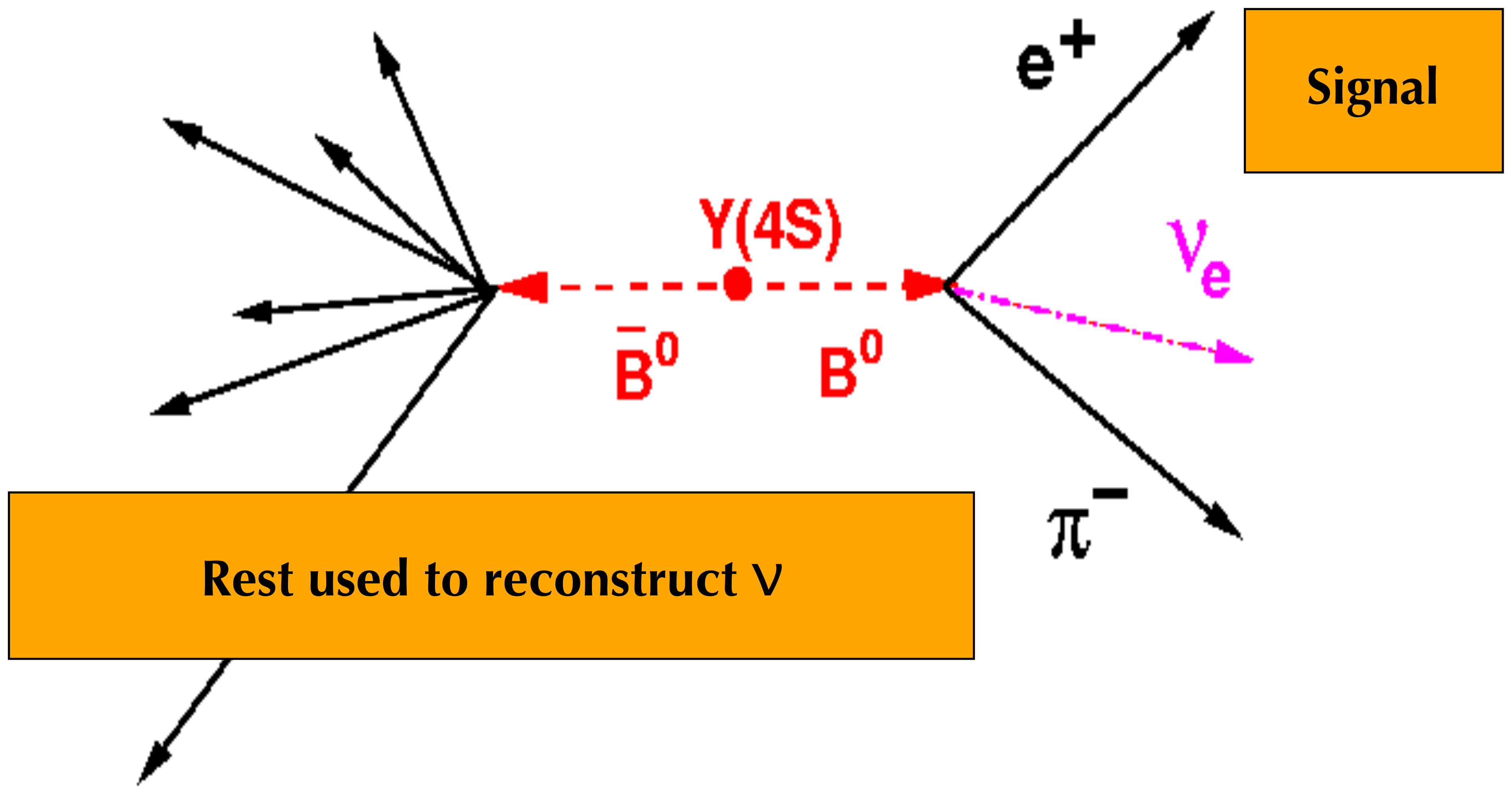


Low High

B-factory Approaches to Measuring B → X l ν

Untagged

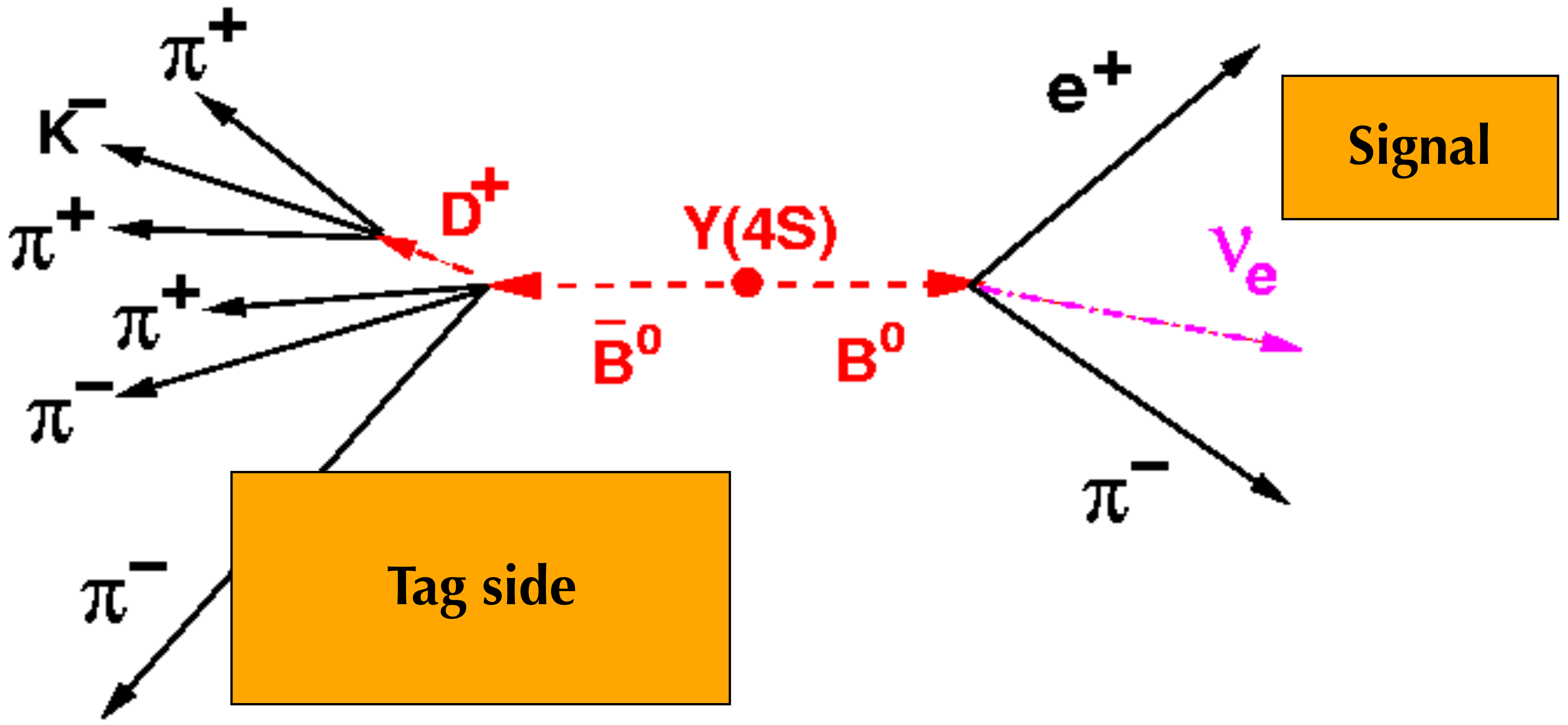
initial 4-momentum known
missing 4-momentum = ν
Reconstruct B → X_q l ν
Use other side to constrain B flight direction.



Fully Reconstructed Tag

One B reconstructed completely in a known b → c mode without ν.
"B-meson Beam"

$$\left(p_{e^+e^-} - p^B_{\text{tag}} - p^{D^*} - p_\ell\right)^2 = (p_\nu)^2 = m^2_{\text{miss}} \backsim 0$$



Eff.	Purity
High	Low
Low	High

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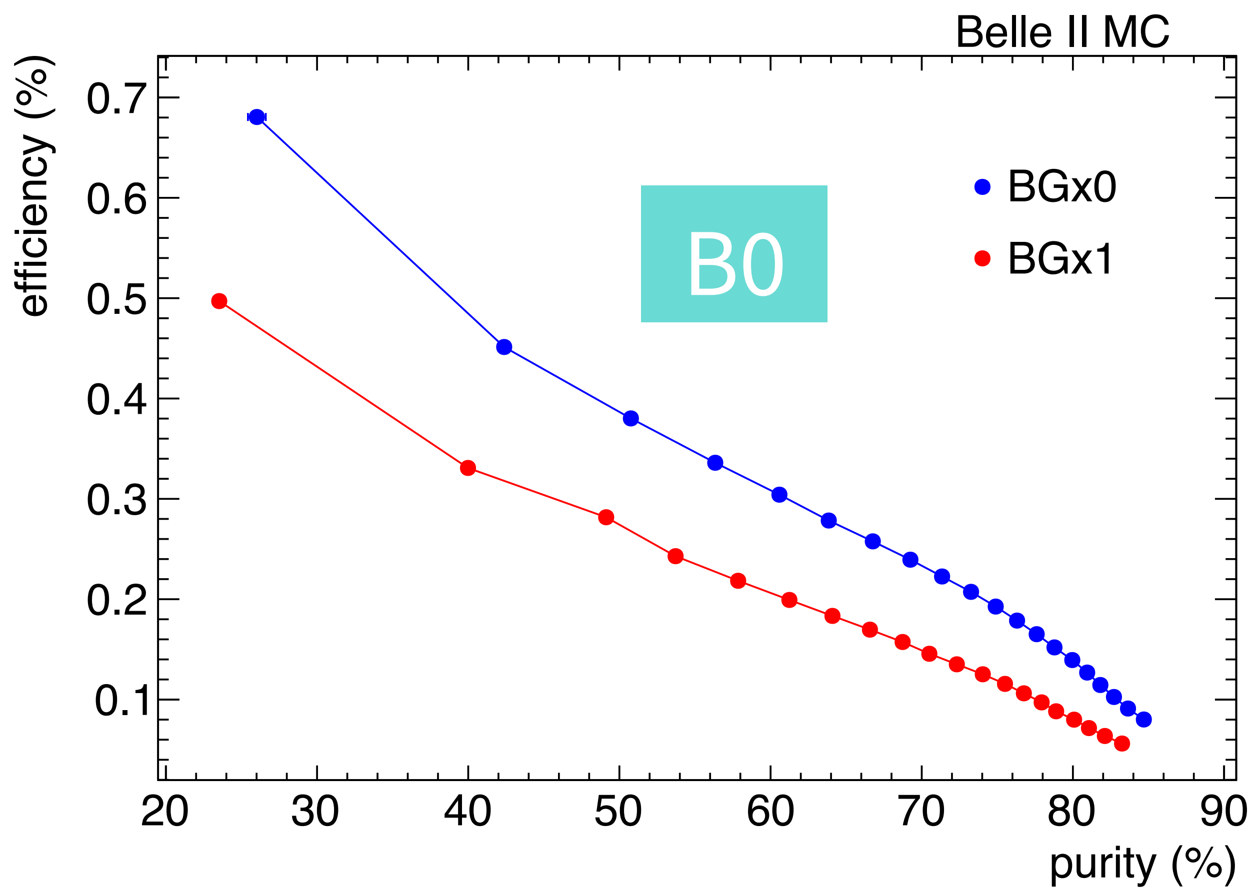
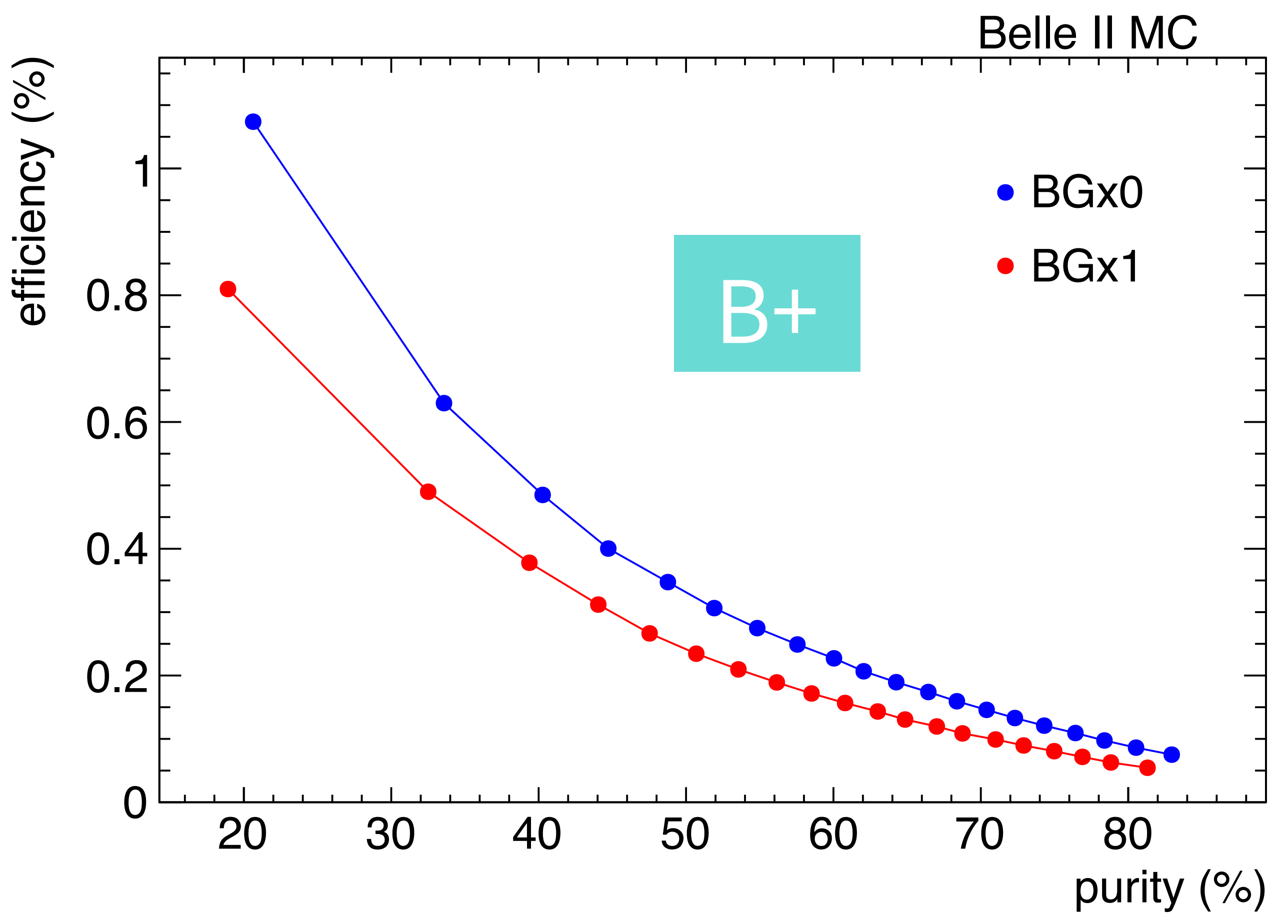
Hadronic tagging

Tag algorithm date	MVA	Efficiency	Purity
Belle v1 (2004)	Cut-based (Vcb)	-	-
Belle v3 (2007)	Cut-based	0.1	0.25
Belle NB (2011)	**Neurobayes**	**0.2**	**0.25**
Belle II FEI (2017)	Fast BoostedDecisionTree	0.5	0.25





- + NEW FEI method based on semileptonic tag Fast BDT tag in B → D(*) l ν + B → D(*)π l ν.

B^+ modes	B^0 modes
$B^+ \to \overline{D}^0\pi^+$	$B^0 \to D^-\pi^+$
$B^+ \to \overline{D}^0\pi^+\pi^0$	$B^0 \to D^-\pi^+\pi^0$
$B^+ \to \overline{D}^0\pi^+\pi^0\pi^0$	$B^0 \to D^-\pi^+\pi^+\pi^-$
$B^+ \to \overline{D}^0\pi^+\pi^+\pi^-$	$B^0 \to D_s^+ D^-$
$B^+ \to D_s^+\overline{D}^0$	$B^0 \to D^{*-}\pi^+$
$B^+ \to \overline{D}^{*0}\pi^+$	$B^0 \to D^{*-}\pi^+\pi^0$
$B^+ \to \overline{D}^{*0}\pi^+\pi^0$	$B^0 \to D^{*-}\pi^+\pi^+\pi^-$
$B^+ \to \overline{D}^{*0}\pi^+\pi^+\pi^-$	$B^0 \to D^{*-}\pi^+\pi^+\pi^-\pi^0$
$B^+ \to \overline{D}^{*0}\pi^+\pi^+\pi^-\pi^0$	$B^0 \to D_s^{*+} D^-$
$B^+ \to D_s^{*+}\overline{D}^0$	$B^0 \to D_s^+ D^{*-}$
$B^+ \to D_s^+\overline{D}^{*0}$	$B^0 \to D_s^{*+} D^{*-}$
$B^+ \to \overline{D}^0 K^+$	$B^0 \to J/\psi K_S^0$
$B^+ \to D^-\pi^+\pi^+$	$B^0 \to J/\psi K^+\pi^+$
$B^+ \to J/\psi K^+$	$B^0 \to J/\psi K_S^0\pi^+\pi^-$
$B^+ \to J/\psi K^+\pi^+\pi^-$	
$B^+ \to J/\psi K^+\pi^0$	
$B^+ \to J/\psi K_S^0\pi^+$	

$B^+ \to D^-\pi^+\pi^+\pi^0$	$B^0 \to D^-\pi^+\pi^0\pi^0$
$B^+ \to \overline{D}^0\pi^+\pi^+\pi^-\pi^0$	$B^0 \to D^-\pi^+\pi^+\pi^-\pi^0$
$B^+ \to \overline{D}^0 D^+$	$B^0 \to \overline{D}^0\pi^+\pi^-$
$B^+ \to \overline{D}^0 D^+ K_S^0$	$B^0 \to D^- D^0 K^+$
$B^+ \to \overline{D}^{*0} D^+ K_S^0$	$B^0 \to D^- D^{*0} K^+$
$B^+ \to \overline{D}^0 D^{*+} K_S^0$	$B^0 \to D^{*-} D^0 K^+$
$B^+ \to \overline{D}^{*0} D^{*+} K_S^0$	$B^0 \to D^{*-} D^{*0} K^+$
$B^+ \to \overline{D}^0 D^0 K^+$	$B^0 \to D^- D^+ K_S^0$
$B^+ \to \overline{D}^{*0} D^0 K^+$	$B^0 \to D^{*-} D^+ K_S^0$
$B^+ \to \overline{D}^0 D^{*0} K^+$	$B^0 \to D^- D^{*+} K_S^0$
$B^+ \to \overline{D}^{*0} D^{*0} K^+$	$B^0 \to D^{*-} D^{*+} K_S^0$
$B^+ \to \overline{D}^{*0}\pi^+\pi^0\pi^0$	$B^0 \to D^{*-}\pi^+\pi^0\pi^0$

D^+,D^{*+},D_s^+ modes	D^0,D^{*0} modes
$D^+ \to K^-\pi^+\pi^+$	$D^0 \to K^-\pi^+$
$D^+ \to K^-\pi^+\pi^+\pi^0$	$D^0 \to K^-\pi^+\pi^0$
$D^+ \to K^-K^+\pi^+$	$D^0 \to K^-\pi^+\pi^+\pi^-$
$D^+ \to K^-K^+\pi^+\pi^0$	$D^0 \to \pi^-\pi^+$
$D^+ \to K_S^0\pi^+$	$D^0 \to \pi^-\pi^+\pi^0$
$D^+ \to K_S^0\pi^+\pi^0$	$D^0 \to K_S^0\pi^0$
$D^+ \to K_S^0\pi^+\pi^+\pi^-$	$D^0 \to K_S^0\pi^+\pi^-$
$D^{*+} \to D^0\pi^+$	$D^0 \to K_S^0\pi^+\pi^-\pi^0$
$D^{*+} \to D^+\pi^0$	$D^0 \to K^-K^+$
$D_s^+ \to K^+K_S^0$	$D^0 \to K^-K^+K_S^0$
$D_s^+ \to K^+\pi^+\pi^-$	$D^{*0} \to D^0\pi^0$
$D_s^+ \to K^+K^-\pi^+$	$D^{*0} \to D^0\gamma$
$D_s^+ \to K^+K^-\pi^+\pi^0$	
$D_s^+ \to K^+K_S^0\pi^+\pi^-$	
$D_s^+ \to K^-K_S^0\pi^+\pi^+$	
$D_s^+ \to K^+K^-\pi^+\pi^+\pi^-$	
$D_s^+ \to \pi^+\pi^+\pi^-$	
$D_s^{*+} \to D_s^+\pi^0$	

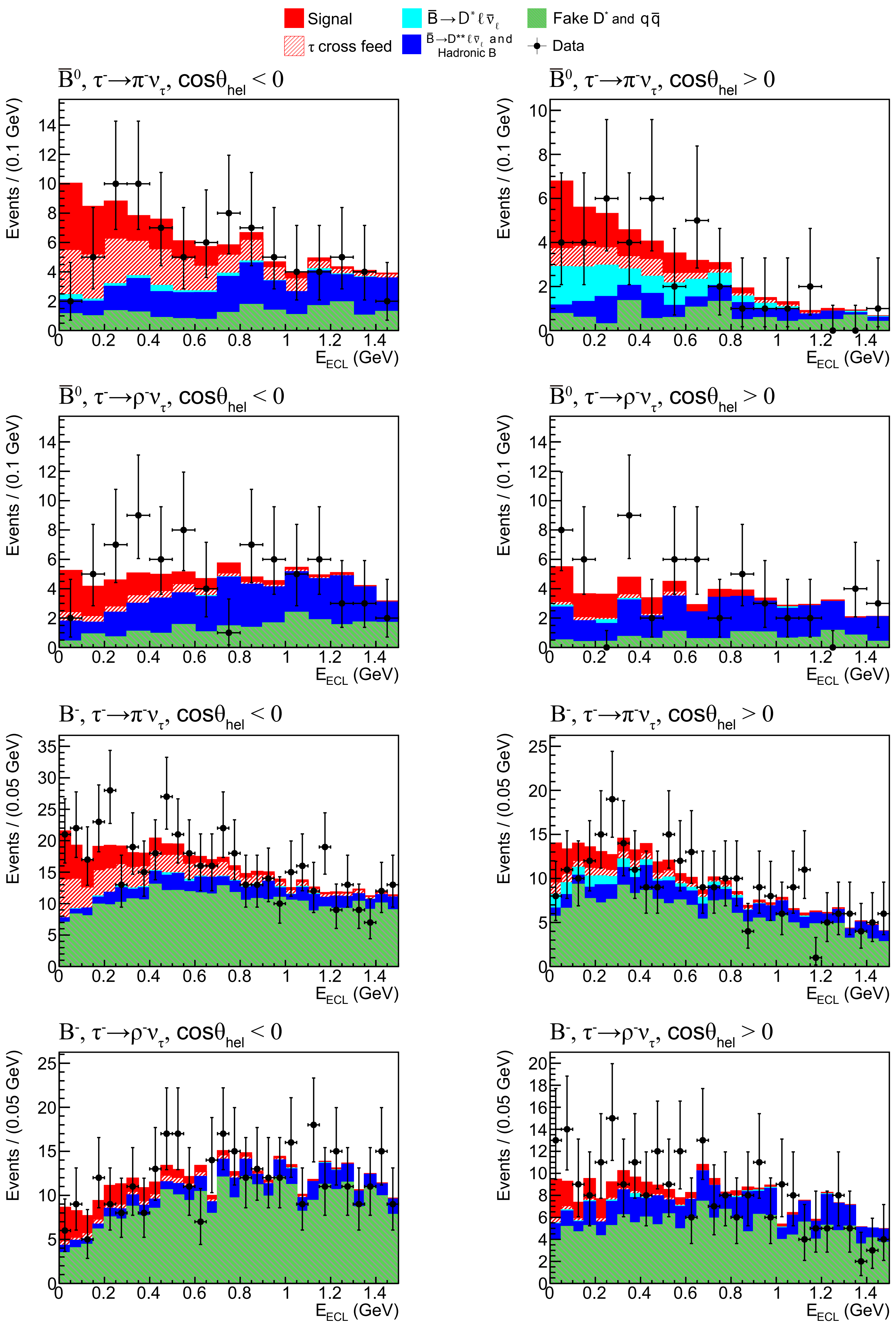
$D^+ \to \pi^+\pi^0$	$D^0 \to K^-\pi^+\pi^0\pi^0$
$D^+ \to \pi^+\pi^+\pi^-$	$D^0 \to K^-\pi^+\pi^+\pi^-\pi^0$
$D^+ \to \pi^+\pi^+\pi^-\pi^0$	$D^0 \to \pi^-\pi^+\pi^+\pi^-$
$D^+ \to K^+K_S^0K_S^0$	$D^0 \to \pi^-\pi^+\pi^0\pi^0$
$D^{*+} \to D^+\gamma$	$D^0 \to K^-K^+\pi^0$
$D_s^+ \to K_S^0\pi^+$	
$D_s^+ \to K_S^0\pi^+\pi^0$	
$D_s^{*+} \to D_s^+\pi^0$	

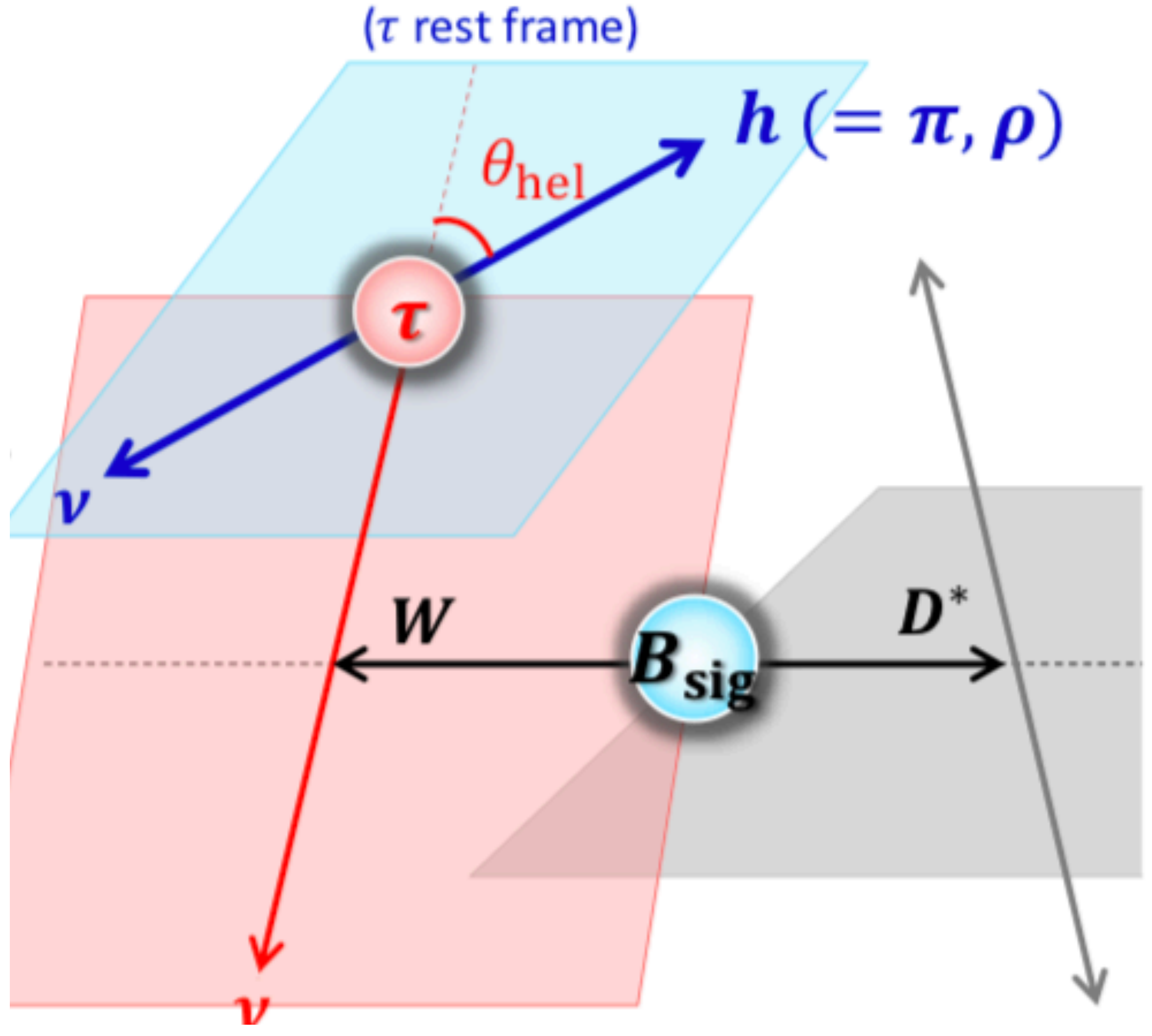
- Below line: not used in Belle NB tag.

B-> D* τ ν: τ Polarisation with τ → π ν, hadronic tag

Belle PRL 118, 211801 (2017)
Belle PRD 97, 012004 (2018)

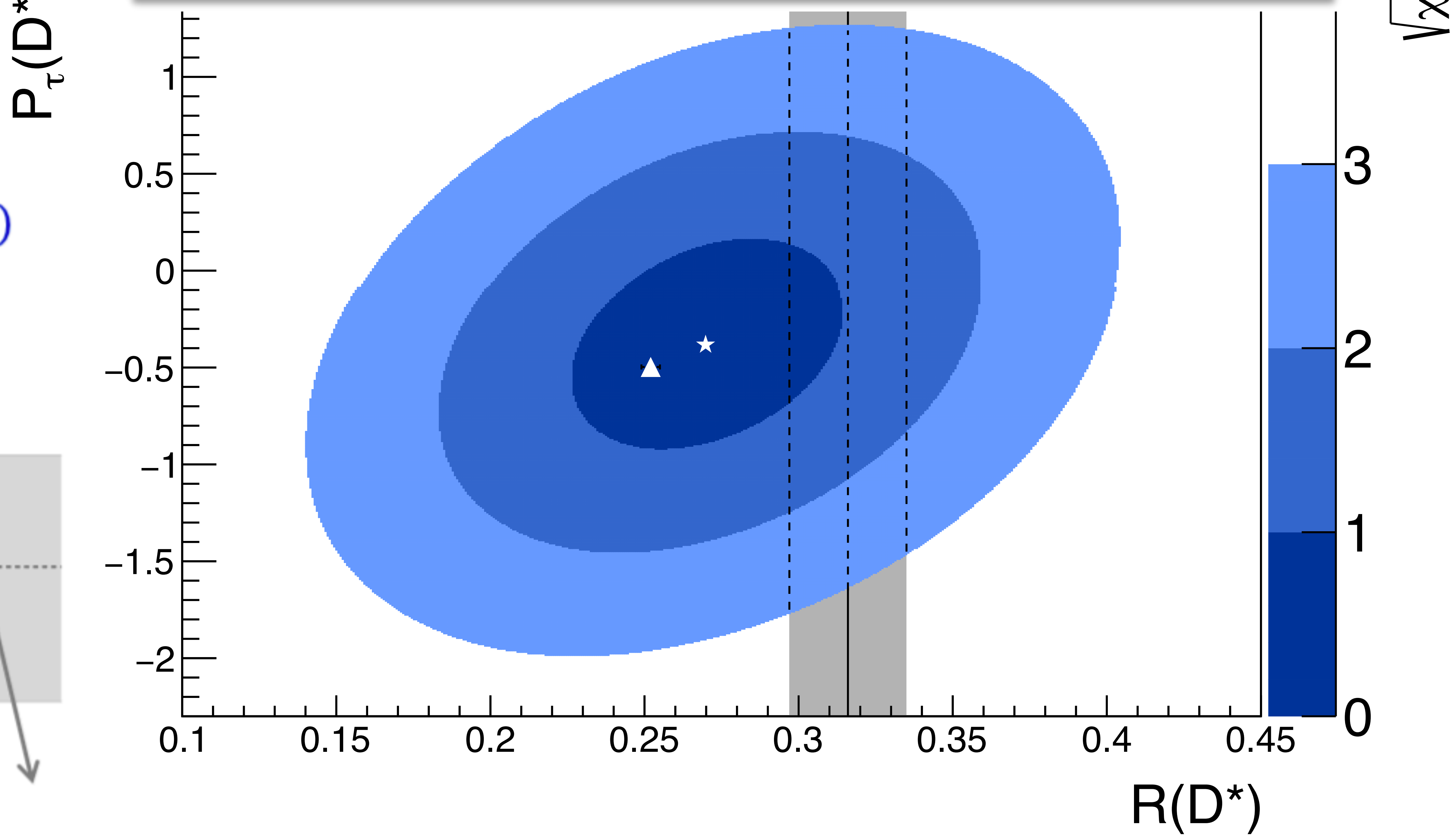
- First measurement, consistent with SM.





- B± → D* τ+ ν : 210±27(stat) events
  B± → D* l+ ν: 4711 ±57(stat.)
- B0 → D* τ+ ν : 88±11(stat) events
  B0 → D* l+ ν: 2502 ± 52 (stat.)

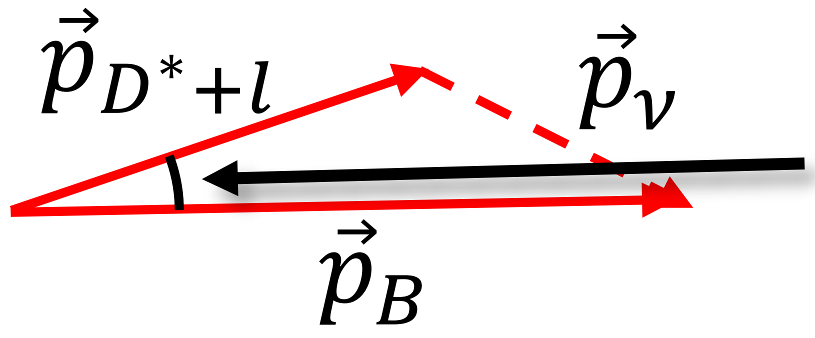
$$R(D^*) = 0.270 \pm 0.035(\text{stat.})\,^{+0.028}_{-0.025}(\text{syst.})$$
$$P_\tau(D^*) = -0.38 \pm 0.51(\text{stat.})\,^{+0.21}_{-0.16}(\text{syst.})$$



$B \rightarrow D^* \tau \nu$ with semi leptonic tag, $\tau \rightarrow l \nu \nu$

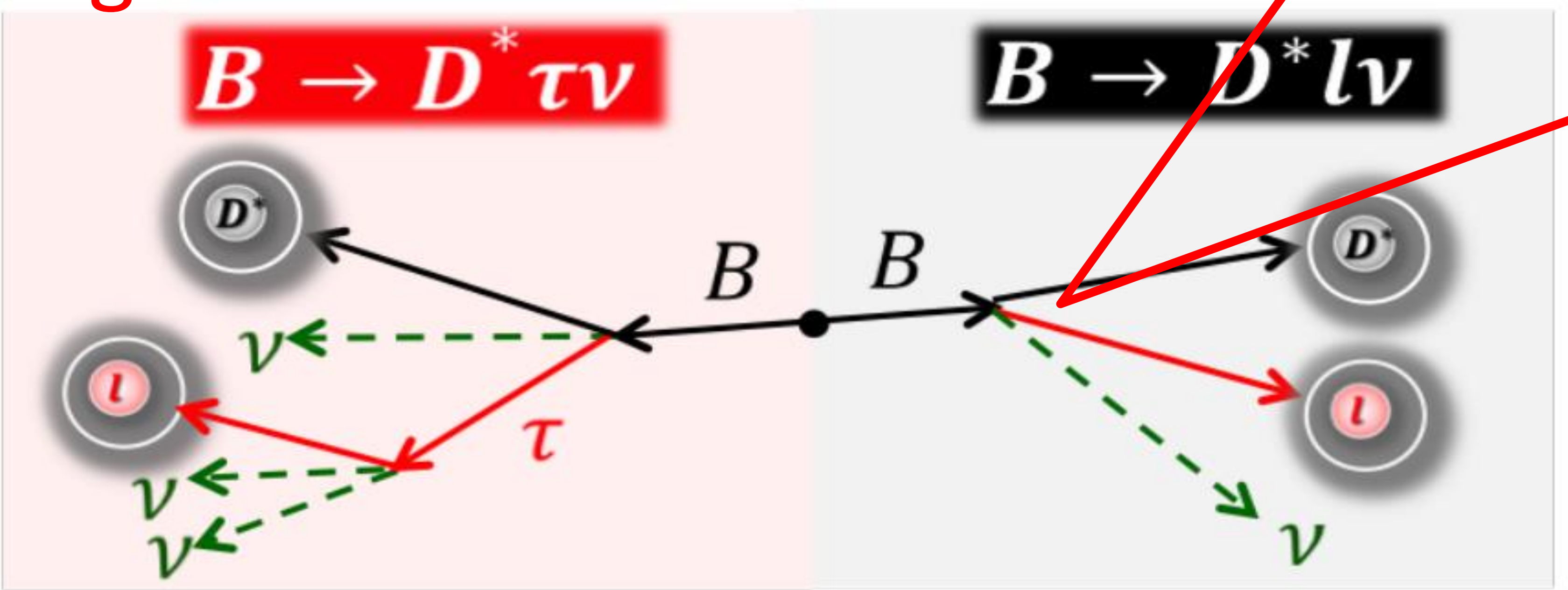
- Signal/Normalisation separation based on $\cos \theta_{B\text{-}D^*l}$

Belle PRD 94, 072007 (2016)

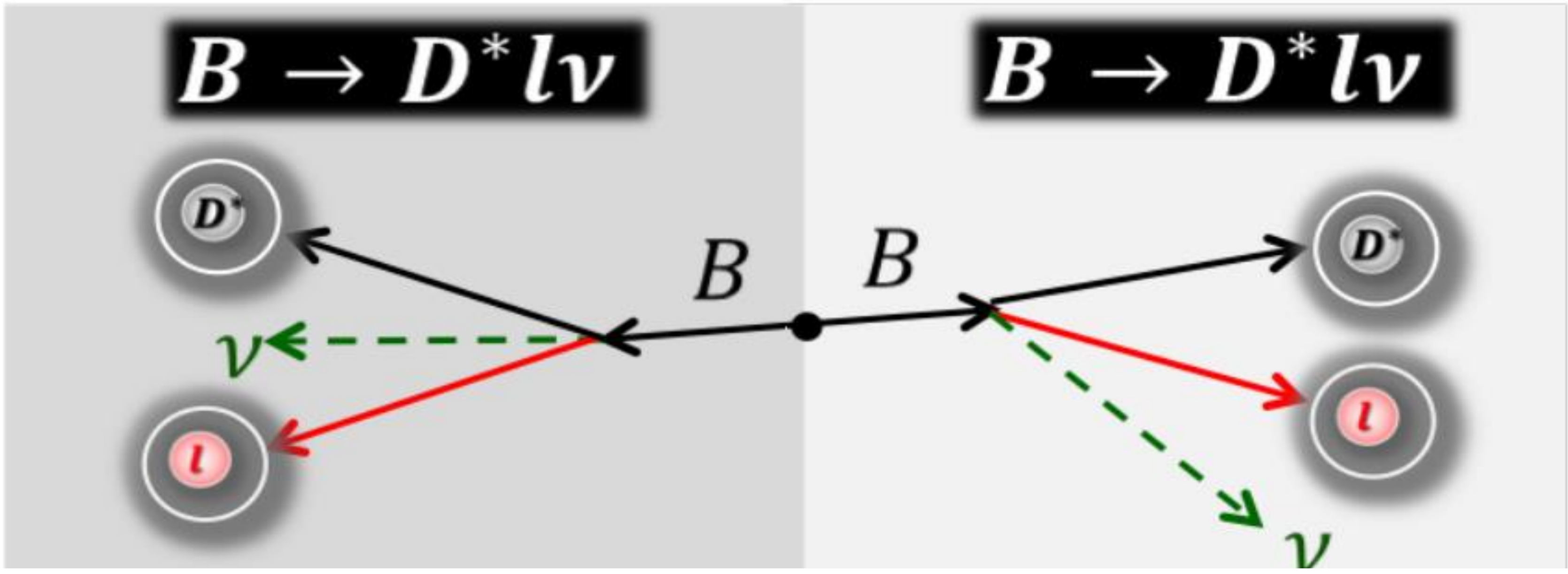


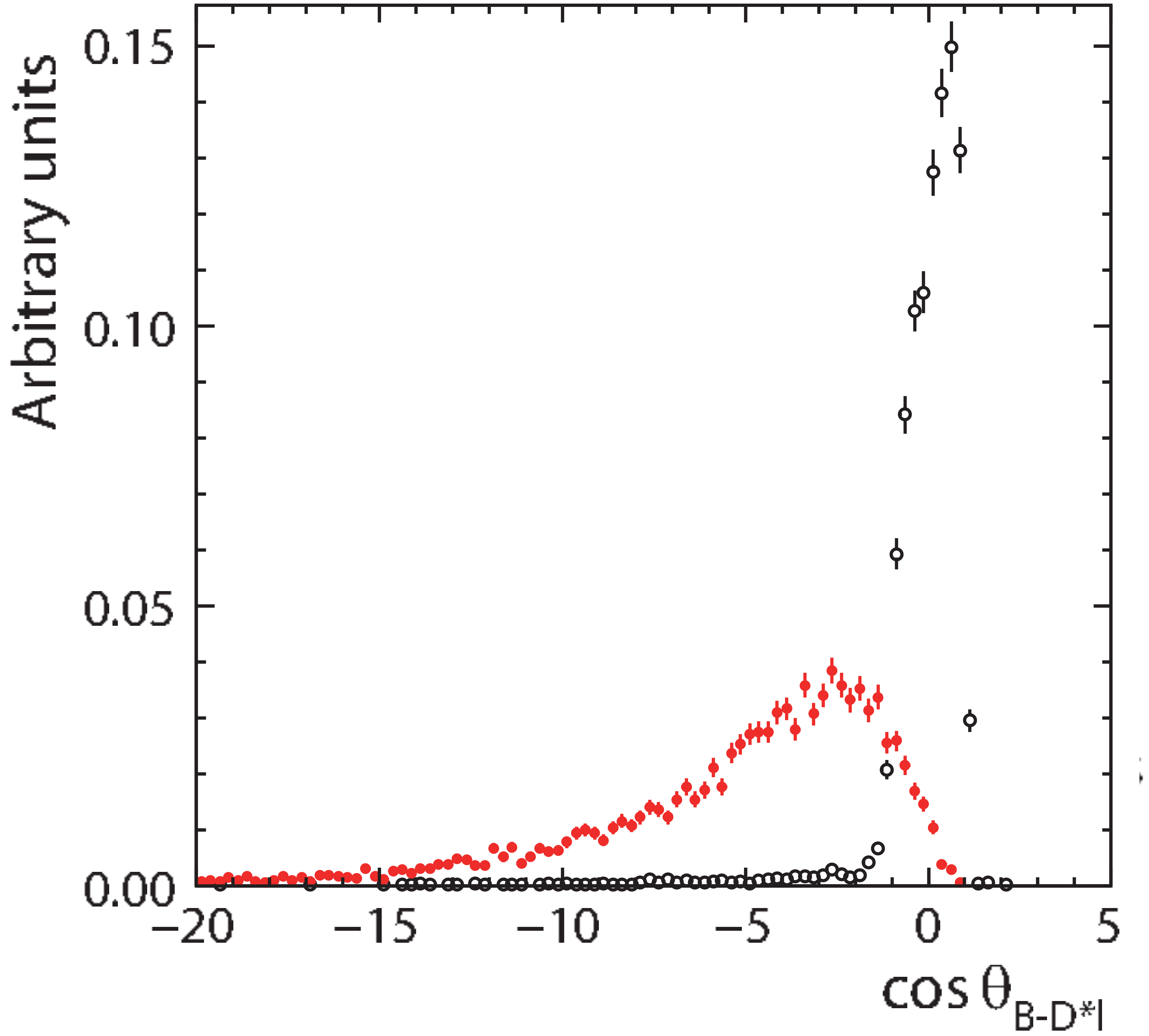
$$\cos\theta_{B-D^*l} = \frac{E^*_{\text{beam}} E^*_{D^*l} - m_B^2 - m_{D^*l}^2}{2|p^*_{\text{beam}}||p^*_{D^*l}|}$$

Signal event



Normalization event



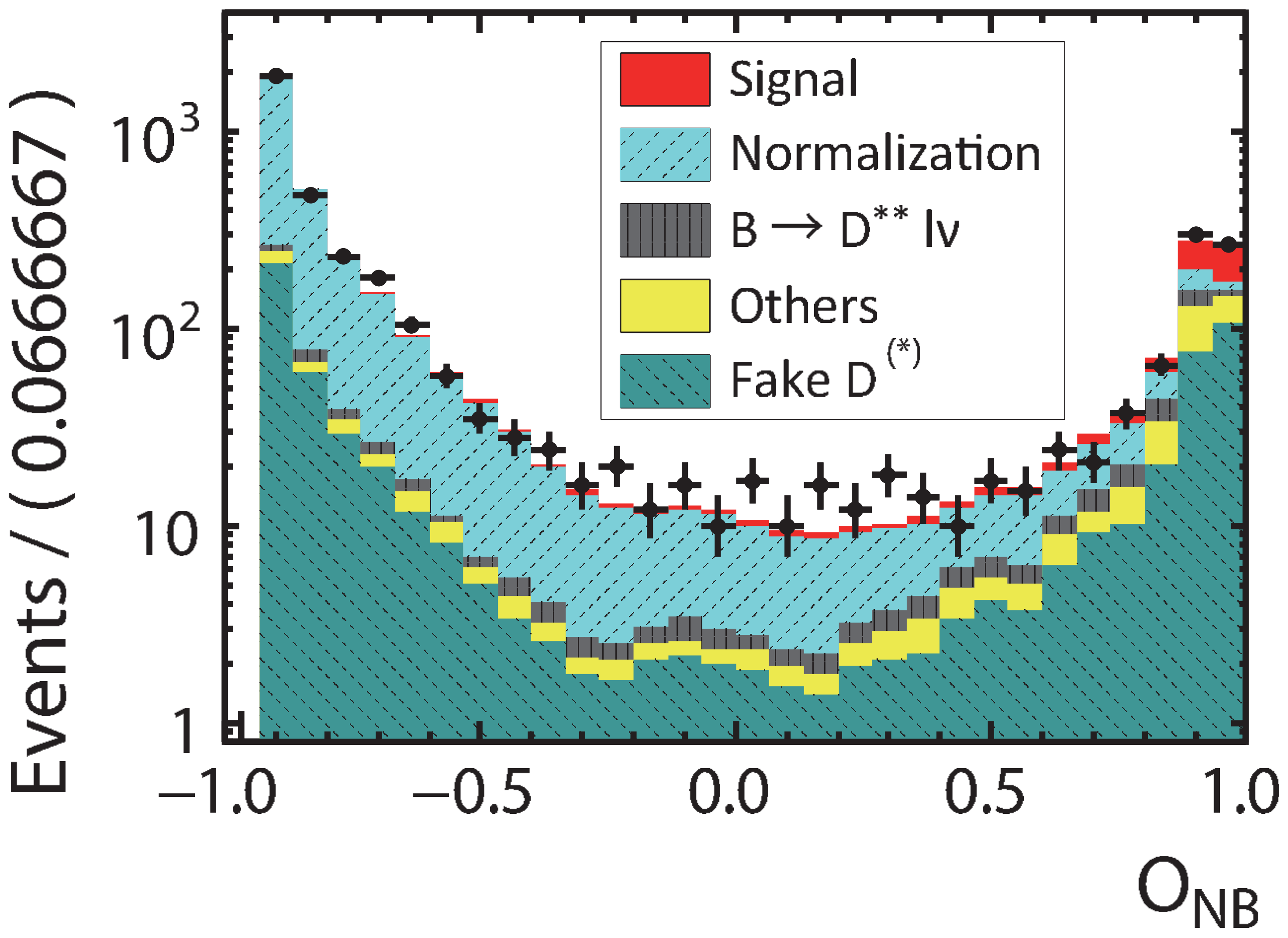


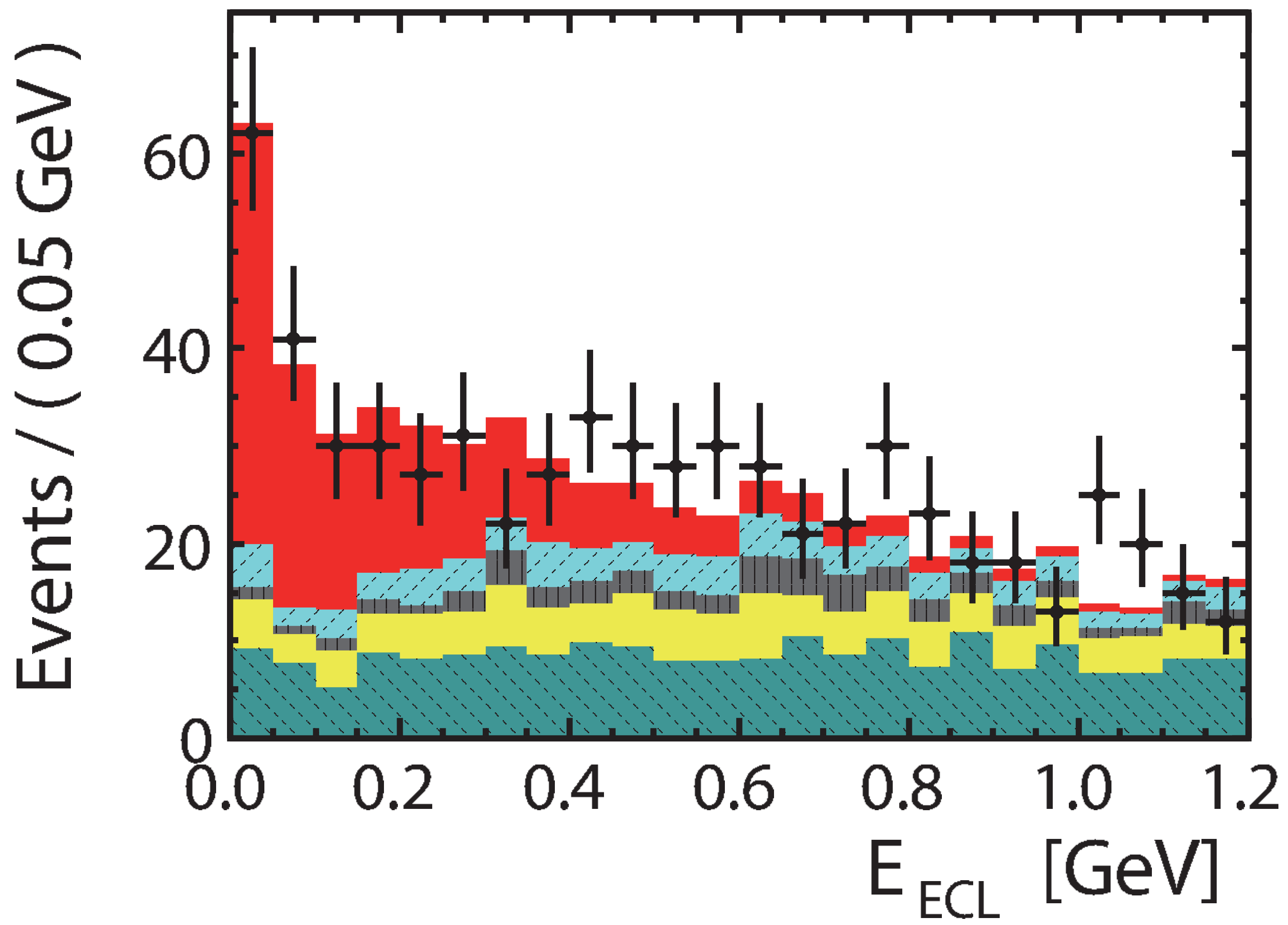
B → D* τ ν with semi leptonic tag, τ → l ν ν

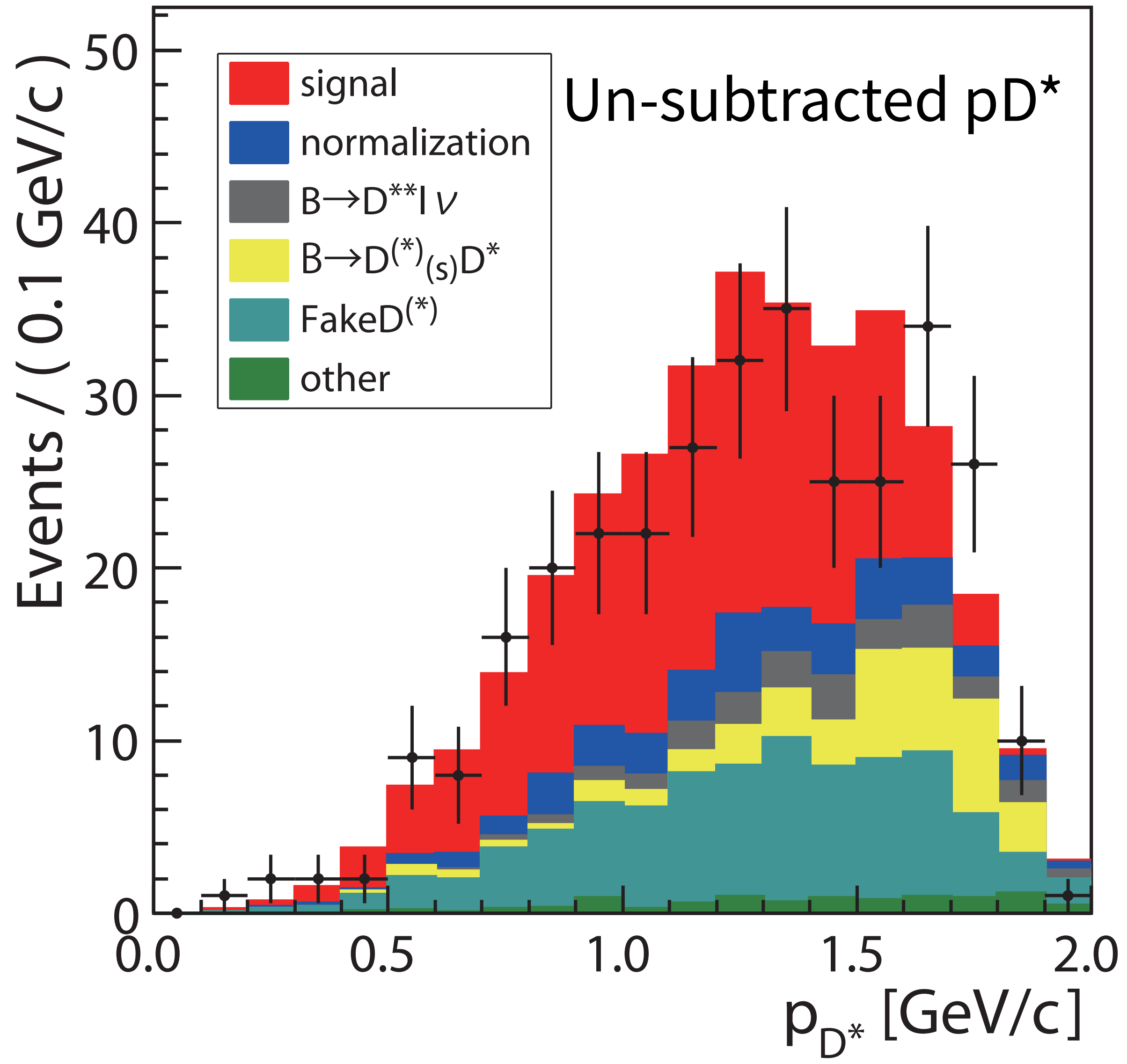
Belle PRD 94, 072007 (2016)

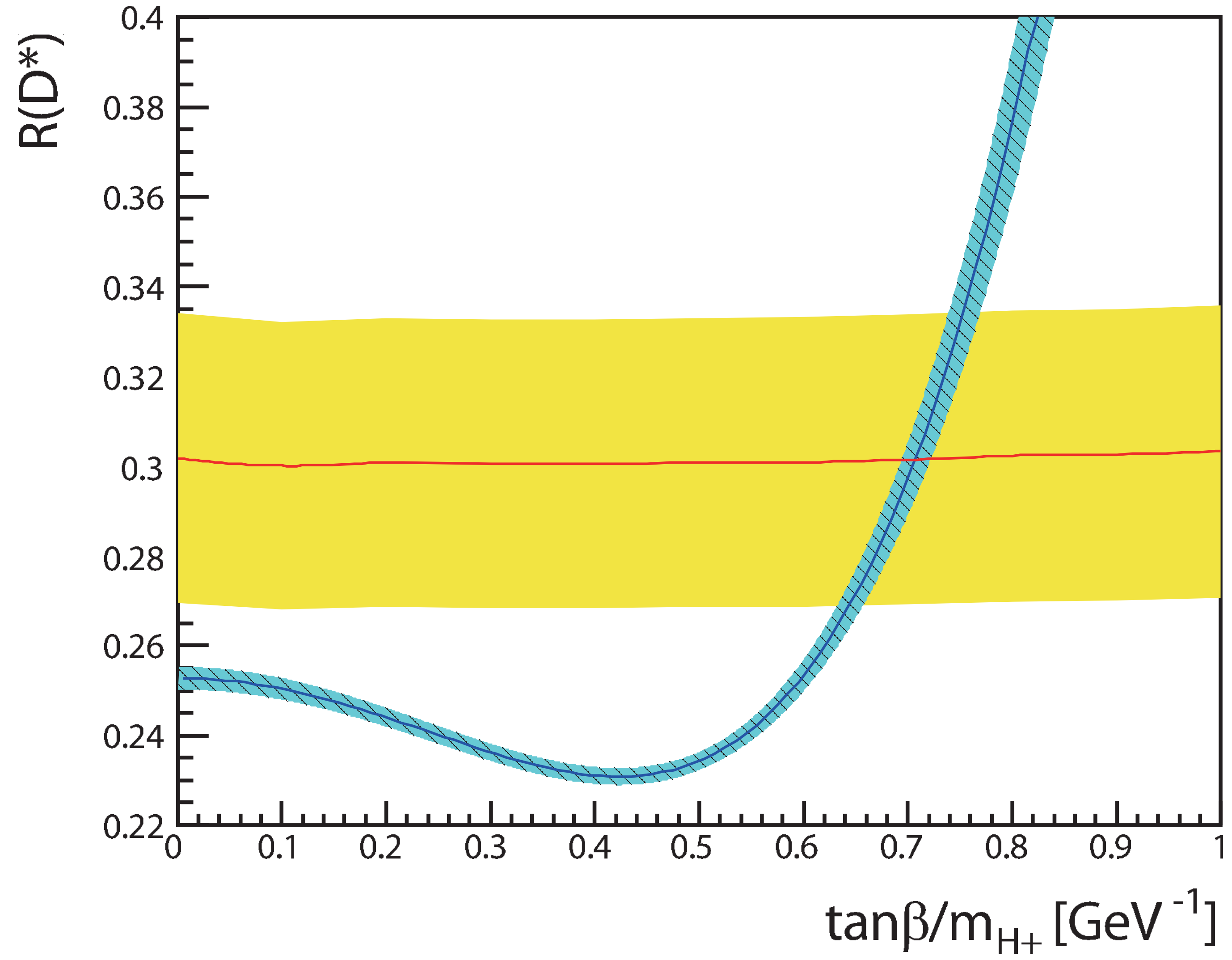
- 772M B$\bar{B}$ pairs
- 2D binned fit to E_{ECL} and O_{NB}
  - B0 → D*- τ+ ν : 231±23(stat) events
    B0 → D*- l+ ν: 2800±57(stat.) events.
- R(D*) = 0.302±0.030±0.011

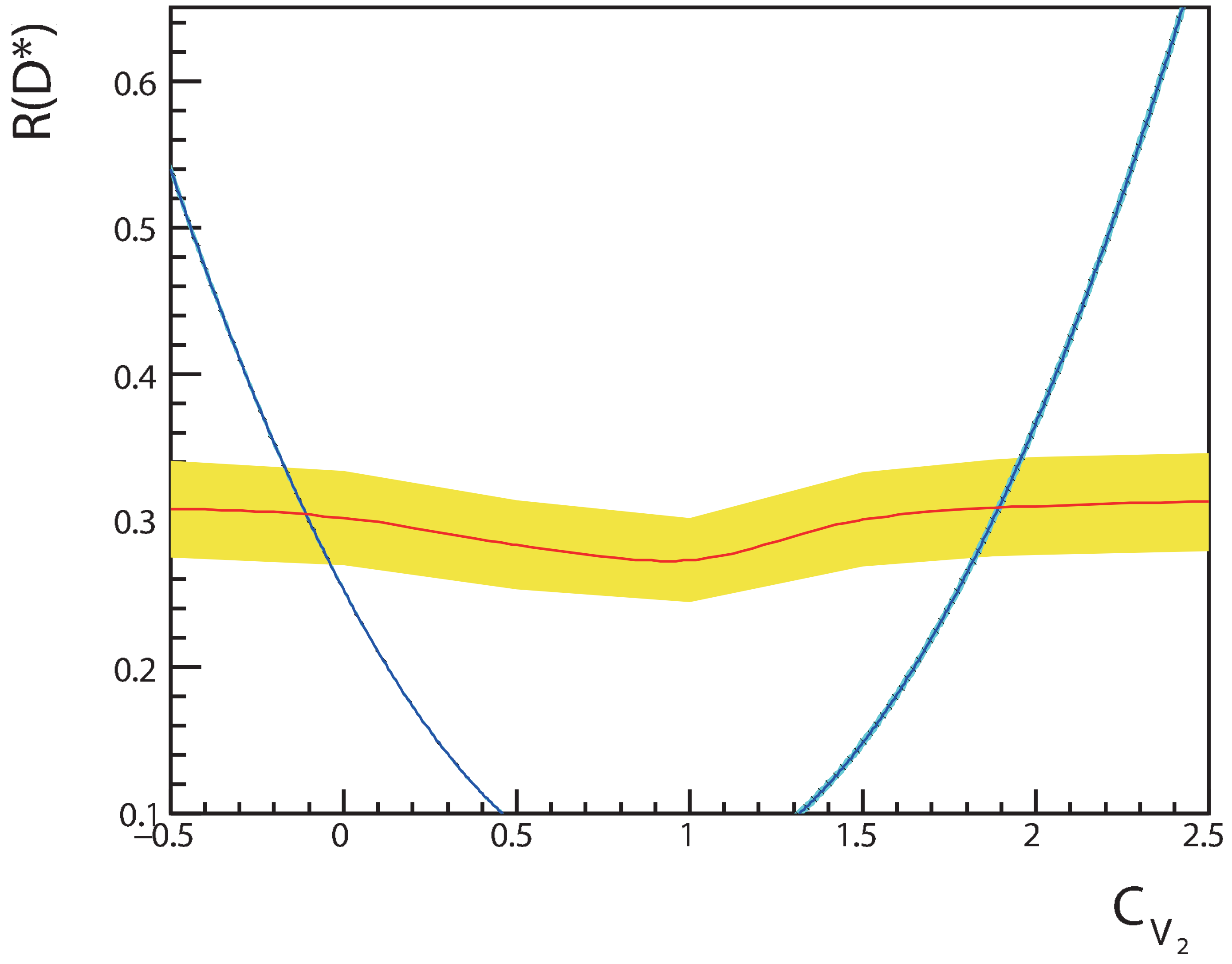
$\cos\theta^{sig}_{B-D^*l}$
M^2_{miss}
Total energy of $B_{tag} + B_{sig}$











$B \to D^{(*)} \tau \nu$ measurements @ Υ(4S)

- Target measurements
  - R_{D^*}, R_D, $P(\tau)$, $P(D^*)$, $d\Gamma/dq^2$, $d\Gamma/dp_D$, $d\Gamma/dp_l$

Experiment	Tag method	τ mode	R_D	R_{D^*}	ρ
Belle 07*	Inclusive	e ν ν, π ν	0.38±0.11	0.34±0.08	-
Belle 10*	Inclusive	l ν ν, π ν			
Babar 12	Hadronic	l ν ν	0.440±0.058±0.042	0.332±0.024±0.018	-0.27
Belle 15	**Hadronic**	**l ν ν**	**0.375±0.064±0.026**	**0.293±0.038±0.015**	**-0.32**
Belle 16	**Semileptonic**	**l ν ν**	**IN PROGRESS**	**0.302±0.030±0.011**	**-**
Belle 17	**Hadronic**	**π ν, ρ ν**	**-**	**0.270±0.035±0.027**	**-**
LHCb 16	-	l ν ν	-	0.336±0.027±0.030	-
LHCb 17		3 π ν	-	0.286±0.019±0.033	-
Belle ave.	**SL+Had**	**-**	**0.374±0.061**	**0.292±0.020±0.012**	**-0.29**

Belle inclusive not in average (cannot accurately account for correlations). I symmetrised some errors for this table.

Leading systematic uncertainties (Belle)

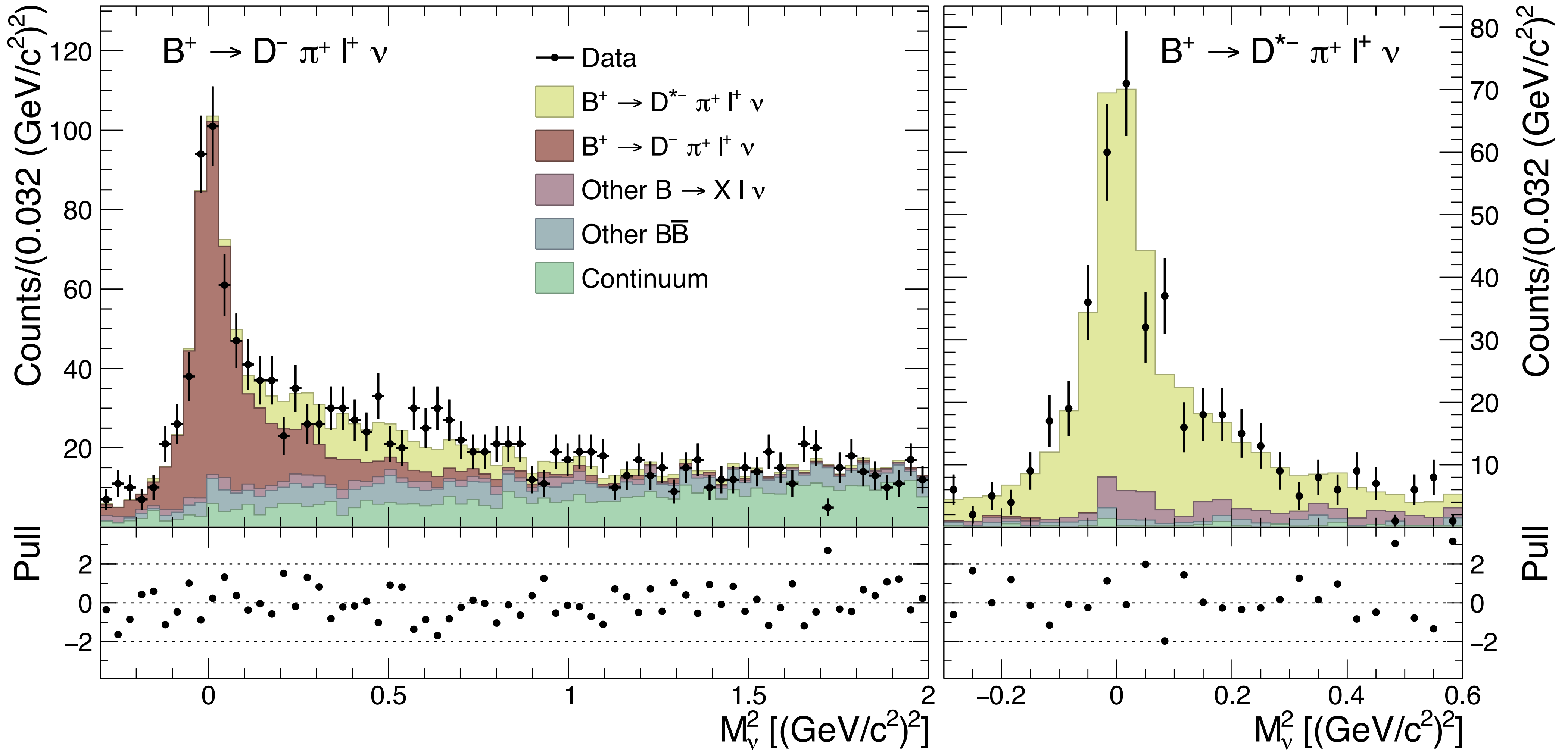
Belle, arXiv:1803.06444

- Must better understand B→ D** l ν background

	Experiment	SL tag R_{D^*}	Had tag R_{D^*}, τ→h ν	Had tag R_{D^*}, τ→l ν ν	Had tag R_D, τ→l ν ν
1	MC statistics	2.2	3.5	-	-
2	**B → D** l ν modelling**	**+1, -1.7**	**2.4**	**1.5**	**4.2**
3	B → D* l ν	+1.3, -0.2	2.3	-	-
4	**D** decay modes**	**(in 2)**	**(in 2)**	**1.3**	**3.0**
5	**Hadronic B decays**	**1.1**	**7.3**	**-**	**-**
6	**B → D** τ ν**	**(in 2)**	**(in 2)**	**-**	**-**
7	Fake $D^{(*)}$	1.4	0.2	0.3	0.5
8	Fake lepton	-	-	0.6	0.5
9	Lepton ID	1.2	1.8	0.5	0.5
10	τ Br	0.2	0.3	0.2	0.2
11	Other	-	2.3	-	-
	Total	3.5	9.9	5.2	7.1

- NEW hadronic tag analysis
  - $B^+ \to D^{(*)} \pi^+ l \nu$ (1.4k signal)
  - $B^0 \to D^{(*)} \pi^+ l \nu$ (1.1k signal)

- $\mathcal{B}(B^+ \to D^- \pi^+ \ell^+ \nu) = [4.55 \pm 0.27\ (\text{stat.}) \pm 0.39\ (\text{syst.})] \times 10^{-3}$,
- $\mathcal{B}(B^0 \to \bar{D}^0 \pi^- \ell^+ \nu) = [4.05 \pm 0.36\ (\text{stat.}) \pm 0.41\ (\text{syst.})] \times 10^{-3}$,
- $\mathcal{B}(B^+ \to D^{*-} \pi^+ \ell^+ \nu) = [6.03 \pm 0.43\ (\text{stat.}) \pm 0.38\ (\text{syst.})] \times 10^{-3}$,
- $\mathcal{B}(B^0 \to \bar{D}^{*0} \pi^- \ell^+ \nu) = [6.46 \pm 0.53\ (\text{stat.}) \pm 0.52\ (\text{syst.})] \times 10^{-3}$.

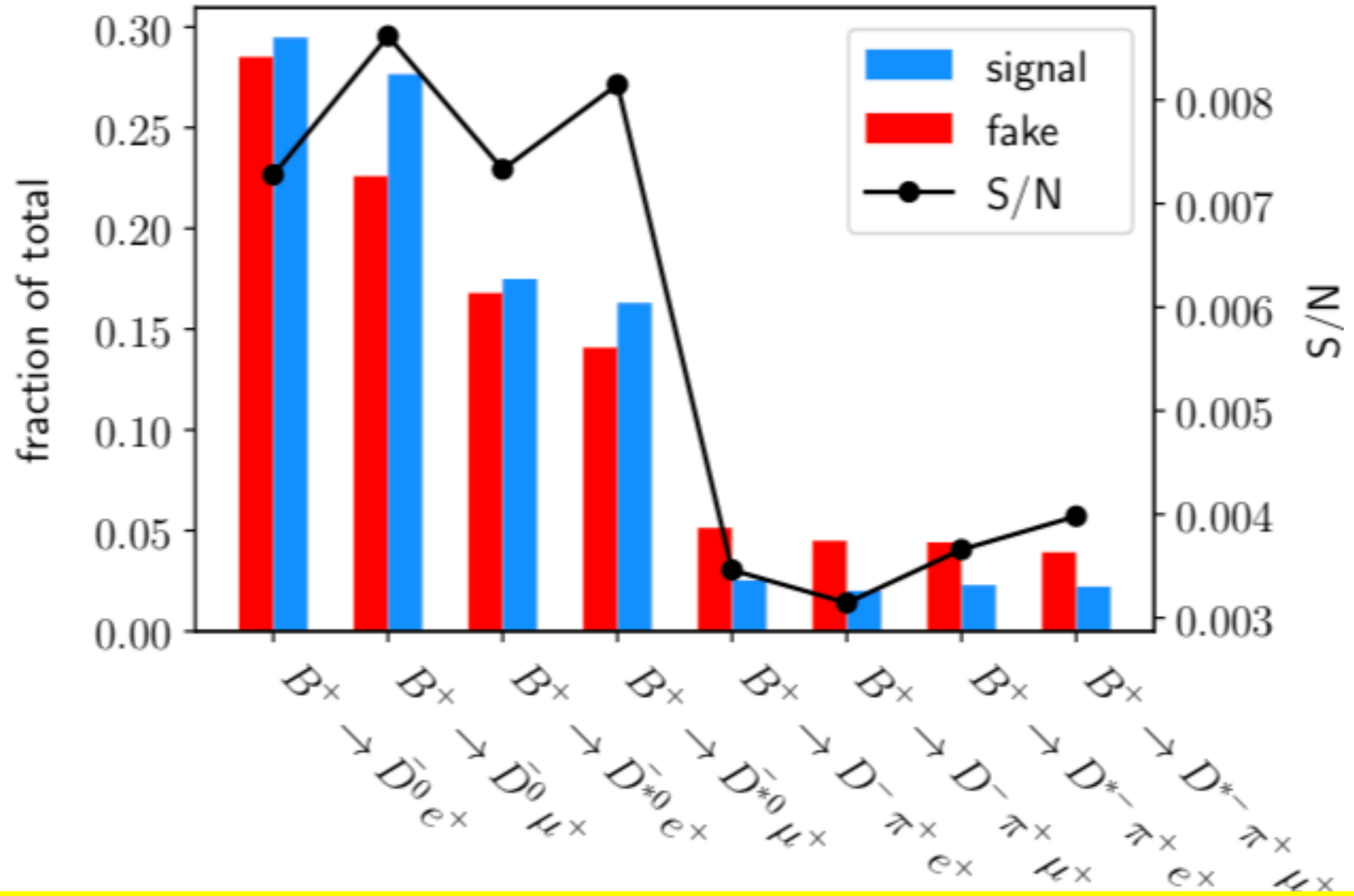


THE UNIVERSITY OF MELBOURNE

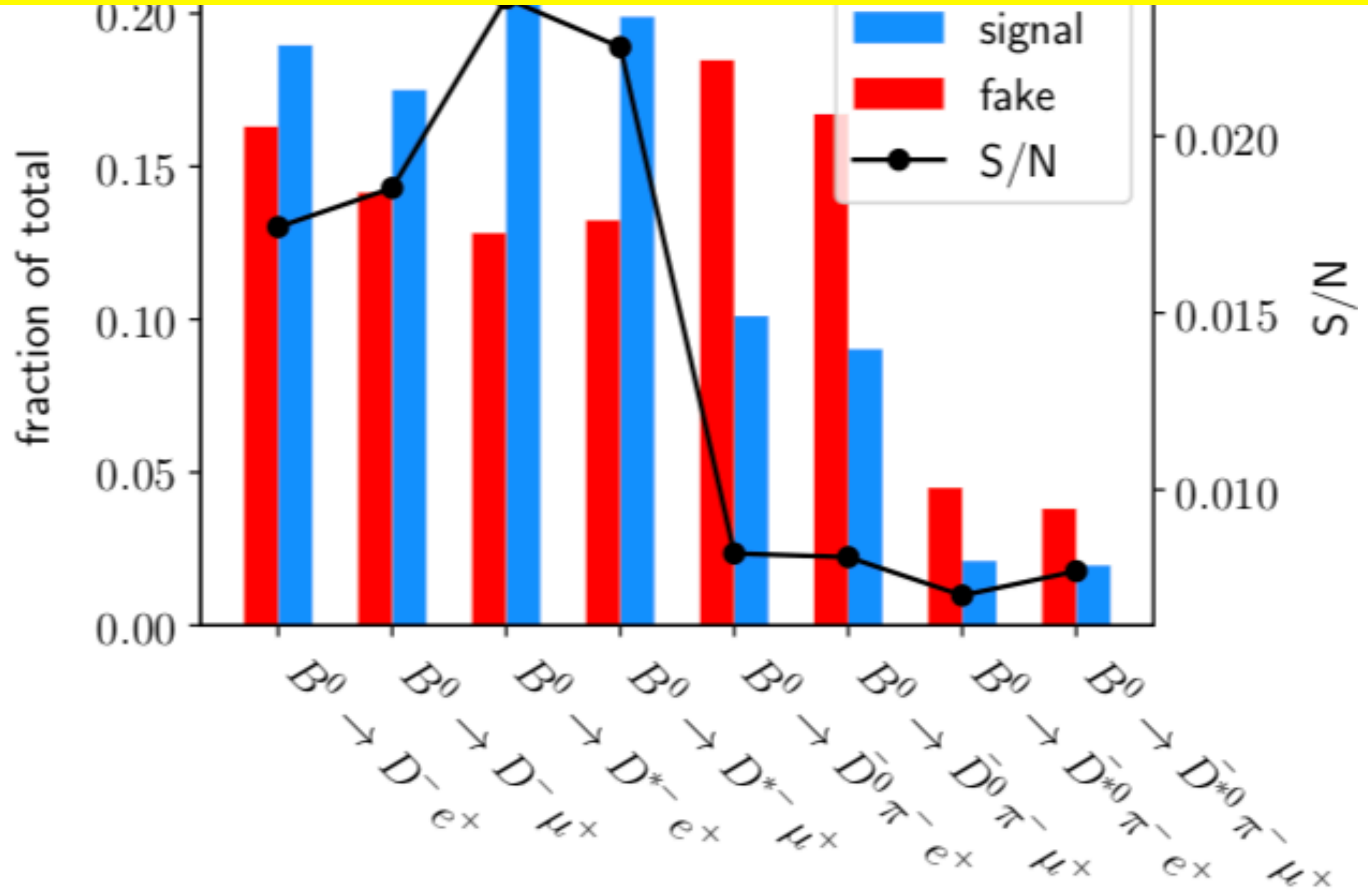
Novel measurements (not yet done at Belle)

- Measurements
  - Full differential measurements with systematics.
  - R(D) with semileptonic tag ** (Belle).
  - Inclusive-tag measurements (revisited with improved sys. errors).
  - Channels with $\tau \to 3\pi\nu$.
  - $B \to D^{**} \tau \nu$.
  - (Inclusive) $B \to X \tau \nu$,
  - CP violation with triple product
  - More effort to directly discriminate VL, VL, SL, SR, T-LQ scenarios.

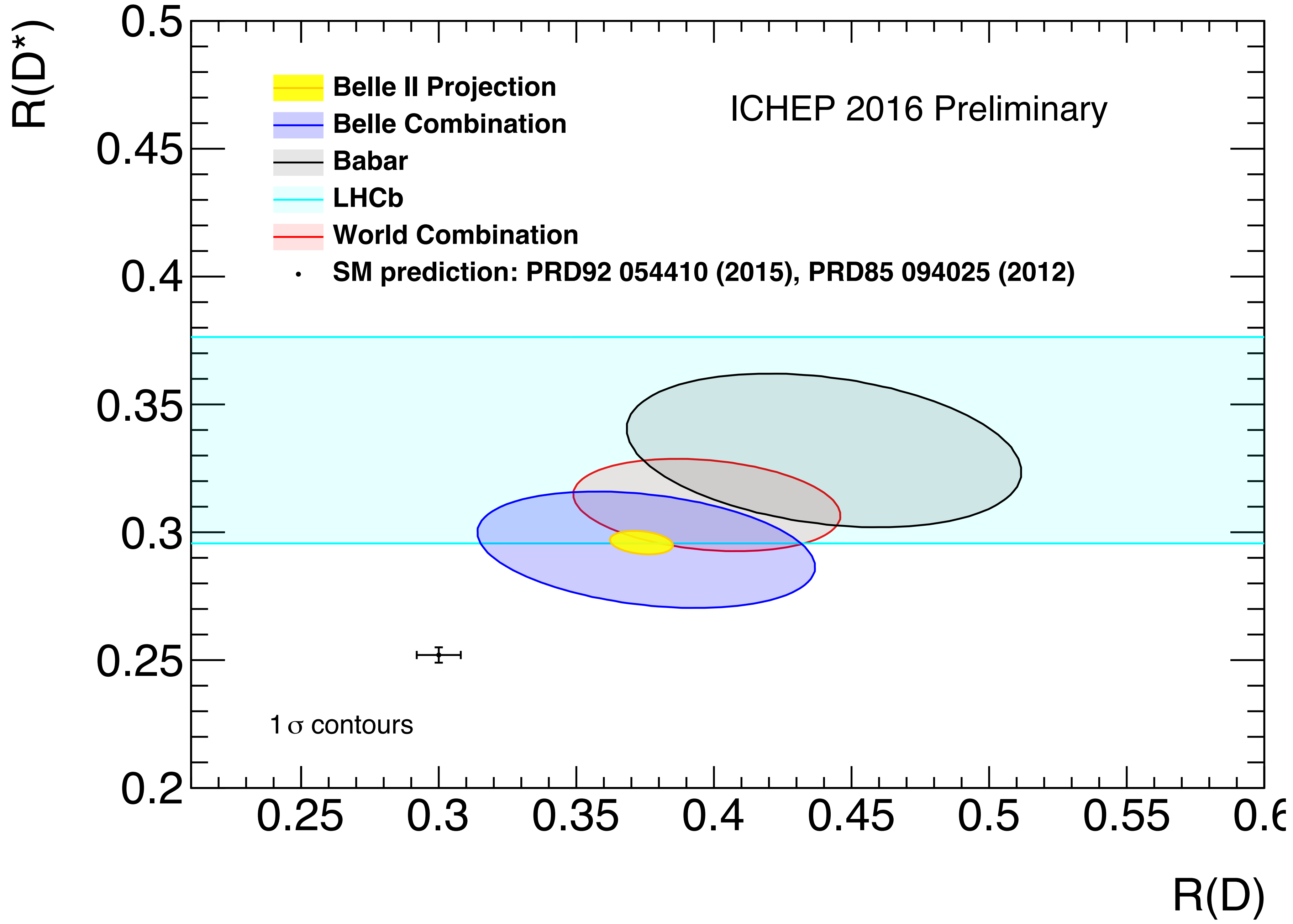
- Complementary Measurements
  - (B_s) $Bs \to Ds^{**}\, l\, \nu$, $Bs \to Ds\, \tau\, \nu$,
  - (D^{**}) Many more $B \to D^{**}\, l\, \nu$ measurements
  - (b→u) $B \to \pi \tau \nu$, $\rho \tau \nu$ - studied but not yet 3 σ.

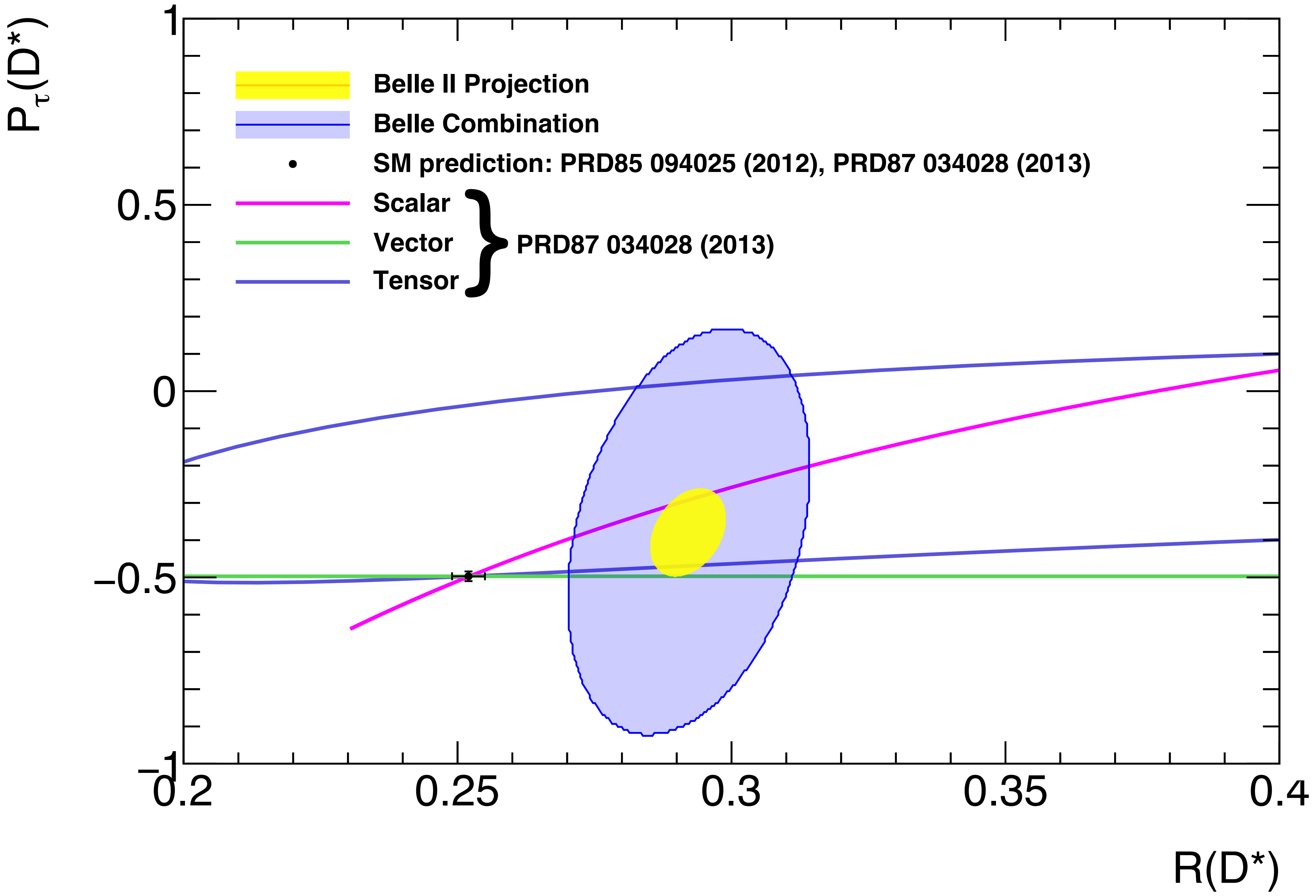


Semileptonic B-reco modes (preliminary)

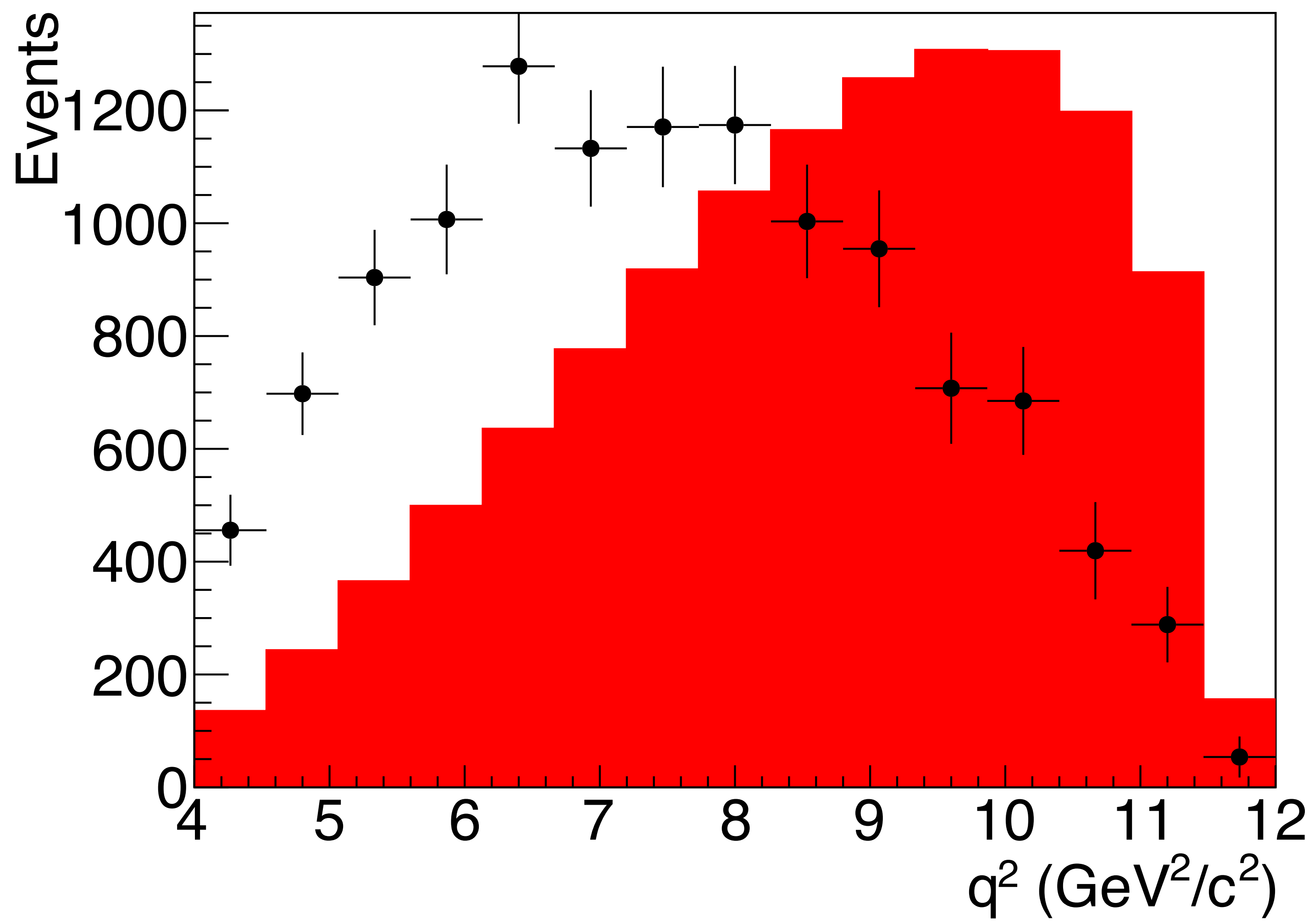


Belle II Projections





NP H±



50 ab-1 projection of the subtracted q^2 spectrum in $B \to D^* \tau \nu$ (HT)

	ΔR(D) [%]			ΔR(D*) [%]		
	Stat	Sys	Total	Stat	Sys	Total
Belle 0.7 ab^{-1}	14	6	16	6	3	7
Belle II 5 ab^{-1}	5	3	6	2	2	3
Belle II 50 ab^{-1}	2	3	3	1	2	2

- Full sim sensitivity studies in progress.
- Projections based on Belle + assumed $R(D)_{SL}$ precision
- Background modelling will dominate error @ 50 ab^{-1}.

LFUV in e/μ, and Model Independent SL Form Factors

$$\frac{d\Gamma}{dw}(B \to D\ell\nu) \sim (\text{Phase Space})|V_{cb}|^2 G(w)^2$$

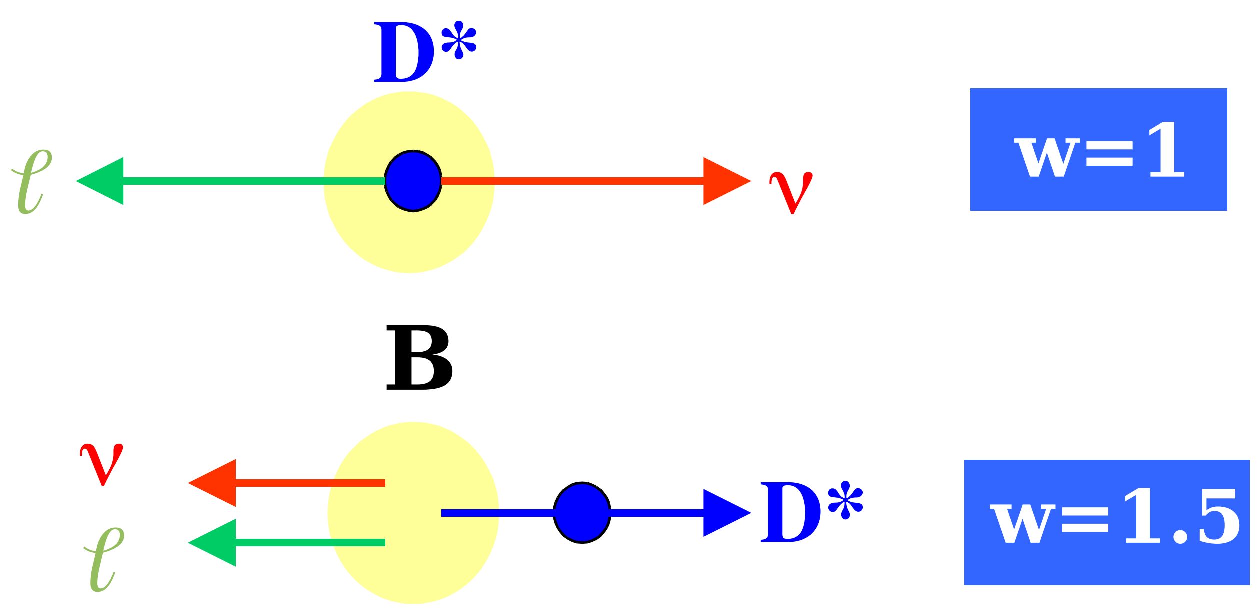
$$\frac{d\Gamma}{dw}(B \to D^*\ell\nu) \sim (\text{Phase Space})|V_{cb}|^2 F(w)^2 \sum_{i=+,0,-} |H_i(w)|^2$$

$$w = \frac{m_B^2 + m_D^2 - q^2}{2m_B m_d}$$

BGL, Boyd, Grinstein, Lebed Phys.Rev.Lett 74, 4603 (1995)

$$F_i(w) = \frac{p_i(w)}{B_i(z)\phi_i(z)} \sum_{n=0}^{N} a_n^{(i)} z^n \qquad z = (\sqrt{w+1} - \sqrt{2})/(\sqrt{w+1} + \sqrt{2})$$

Normalisation:
(heavy quark limit) $\xi(w=1)=1$



CLN, Caprini, Lellouch, Neubert Nucl.Phys.B530, 153 (1998)

$$G(w) = G(1)[1 - 8\rho^2 z + (51\rho^2 - 10)z^2 - (252\rho^2 - 84)z^3]$$

HFLAV (CLN)

$$|V_{cb}| = (42.19 \pm 0.78) \cdot 10^{-3} \quad \text{from} \quad B \to X_c l\nu$$

$$|V_{cb}| = (39.05 \pm 0.47_{\text{exp}} \pm 0.58_{\text{th}}) \cdot 10^{-3} \quad \text{from} \quad B \to D^* l\nu$$

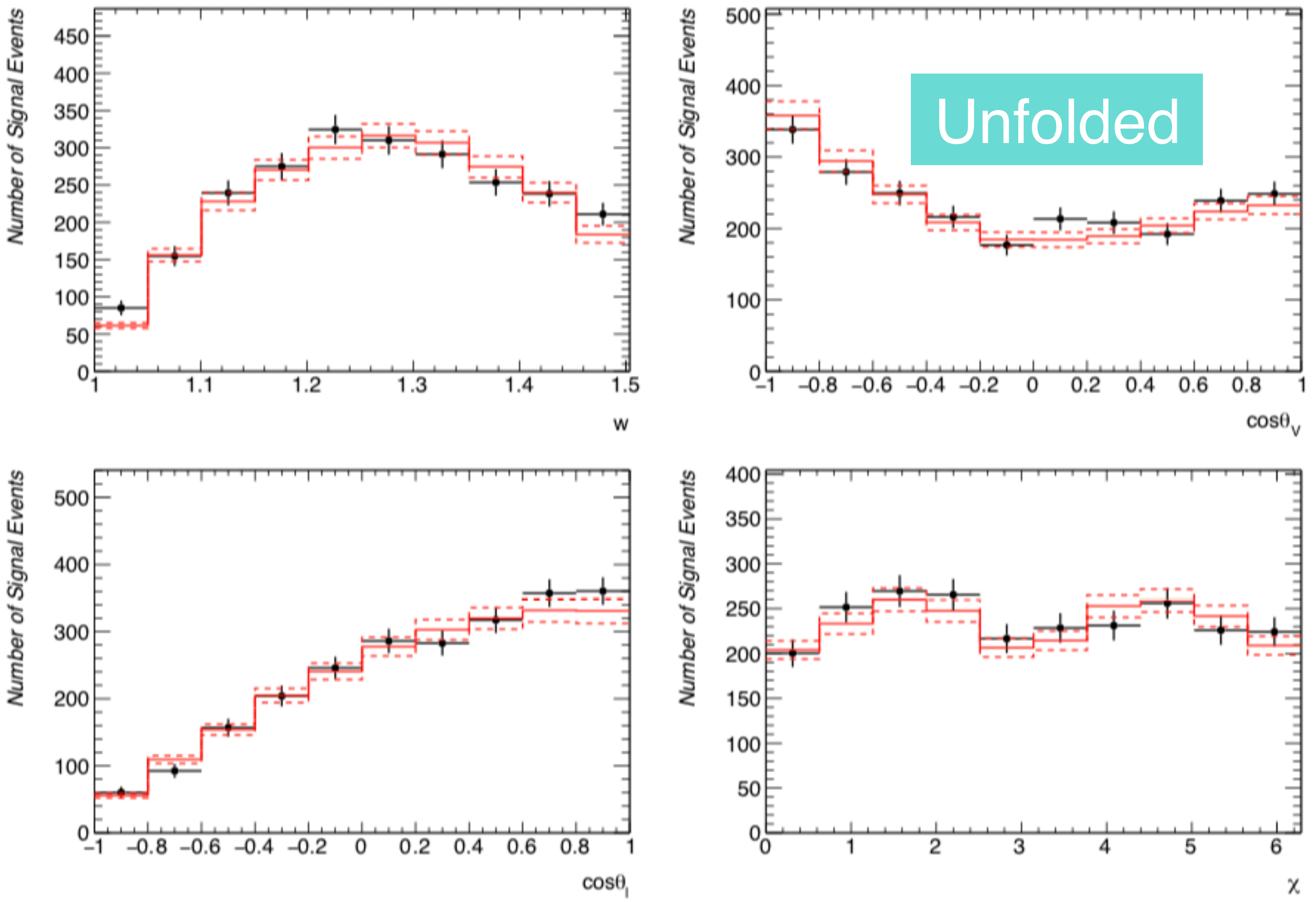
$$|V_{cb}| = (39.18 \pm 0.94_{\text{exp}} \pm 0.36_{\text{th}}) \cdot 10^{-3} \quad \text{from} \quad B \to D l\nu$$

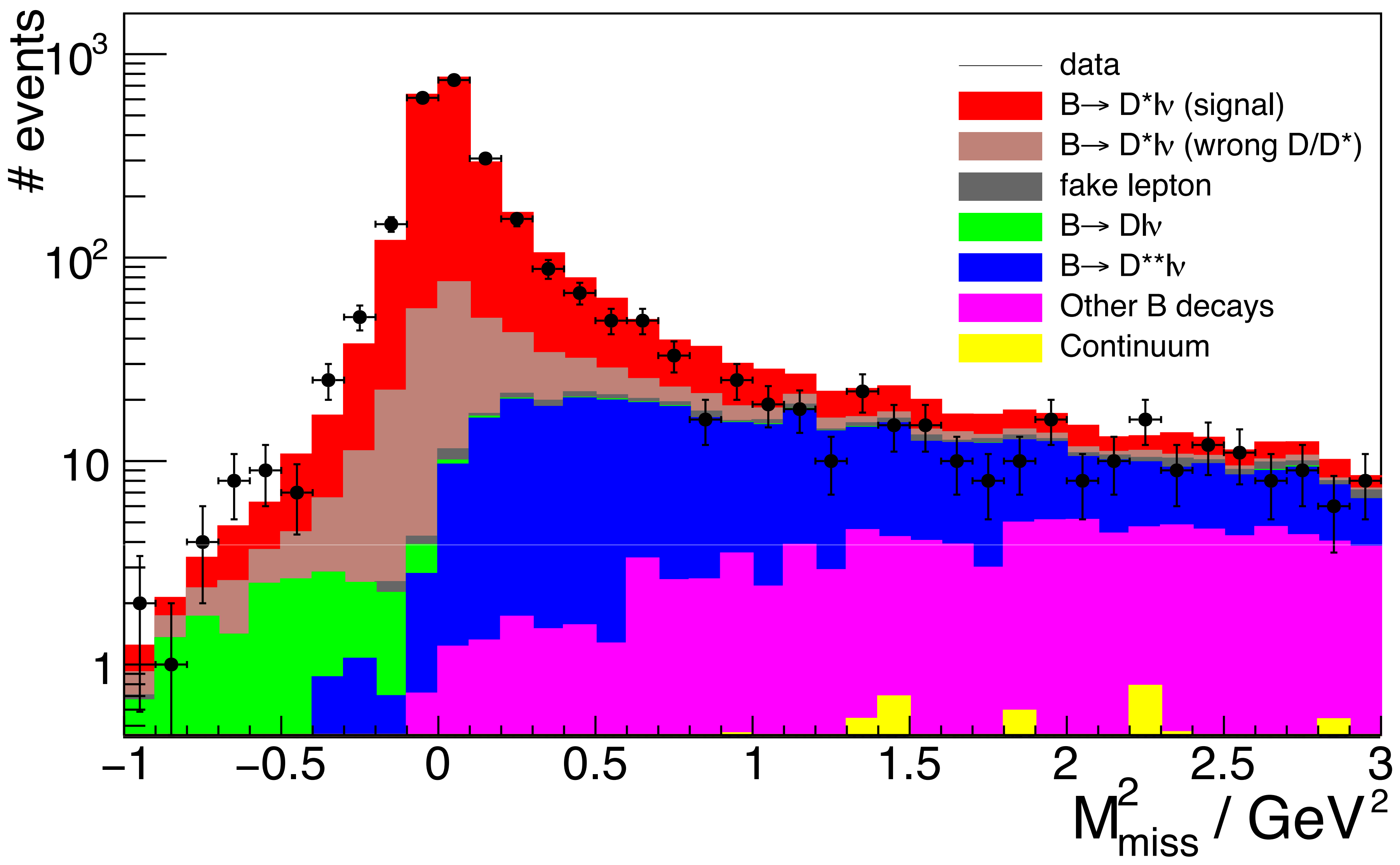
Model independent measurements

Belle arXiv:1702.01521
Bigi et al., arXiv:1703.06124

- Hadronic tag, tag calibration with B→X l ν
- Signal from un-binned maximum likelihood fit to M^2_{miss}.

ℓ	ν^{sig}	ν^{sig}_{MC}	$\epsilon_{reco}\epsilon_{tag}$
$e+\mu$	2374 ± 53	2310.1	3.19×10^{-5}
e	1306 ± 40	1248.8	3.45×10^{-5}
μ	1066 ± 34	1061.3	2.93×10^{-5}





$$\mathcal{B}(\bar{B}^0 \to D^{*+} e^- \bar{\nu}_e) = (5.04 \pm 0.15 \pm 0.23) \times 10^{-2}$$

$$\mathcal{B}(\bar{B}^0 \to D^{*+} \mu^- \bar{\nu}_\mu) = (4.84 \pm 0.15 \pm 0.22) \times 10^{-2}$$

BGL Fit:	Data + lattice	Data + lattice + LCSR
χ^2/dof	27.9/32	31.4/35
$\lvert V_{cb}\rvert$	$0.0417\,(^{+20}_{-21})$	$0.0404\,(^{+16}_{-17})$

CLN Fit:	Data + lattice	Data + lattice + LCSR
χ^2/dof	34.3/36	34.8/39
$\lvert V_{cb}\rvert$	0.0382 (15)	0.0382 (14)

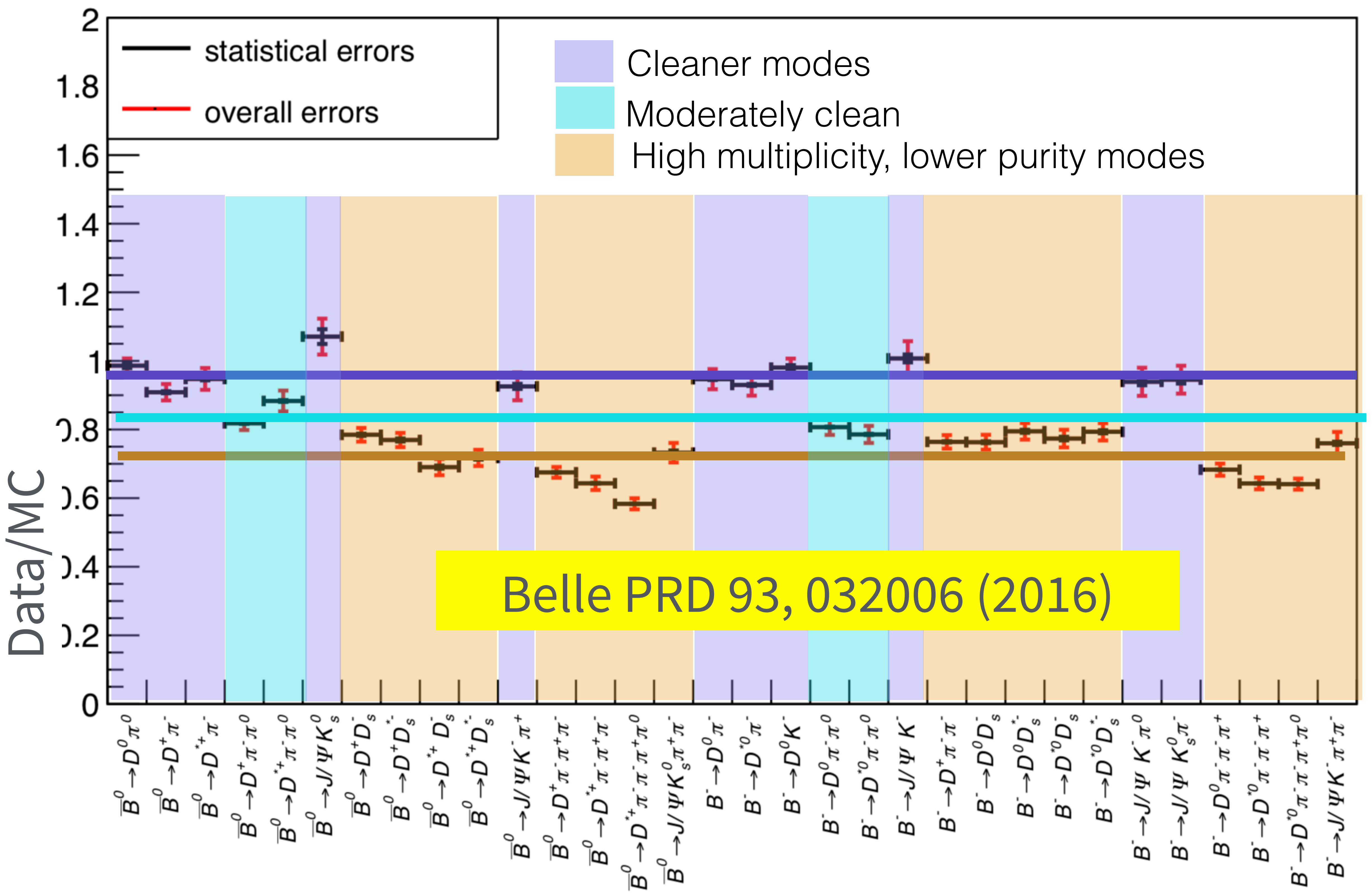
- **New form factor measurements reduce R(D*) tension from ~3.5 σ to around ~3.0 σ.**

Towards ultimate precision for B → D(*) l ν

Tag Method	D l ν	D* l ν
Br [10^{-2}]	**2.31**	**4.95**
Errors	%	%
Track	1.60	1.6
Slow track		0.1
eID	1.00	0.2 (in tag)
μID		0.1 (in tag)
fake leptons	<0.1	<0.1
B→D**lν, FF	0.70	<0.1
B→D**lν, Bfs	0.80	0.2
$D^{(*)}$ Bfs	1.80	0.5
PDFs	0.50	0.9
Tag calibration	**3.30**	**3.6**
N_{BB}	1.40	1.4
f_{+0}		1.1
τ_B	0.20	0
π^0 efficiency	0.60	0.5
Total	**4.6**	**4.5**
Stat	**1.3**	**2.2**

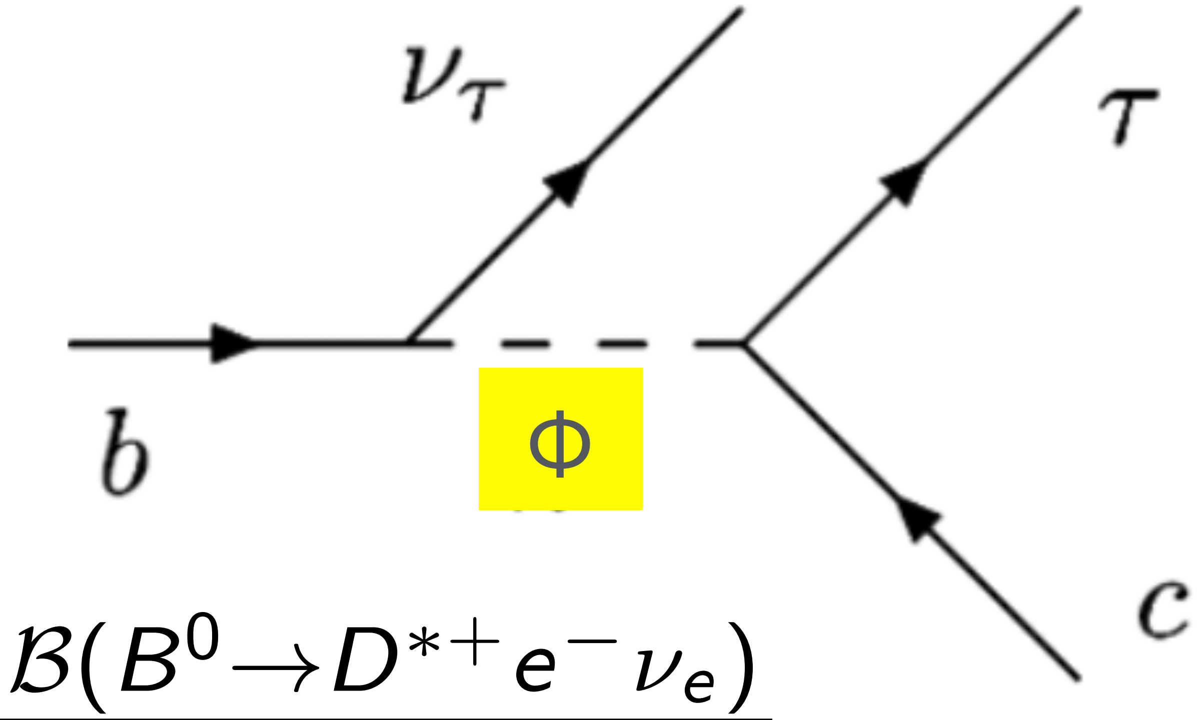
- How do we improve B→D(*) l ν further?
  - Errors on tracking, PID, π^0 efficiencies are data driven.
  - D* Slow pion Tracking in Belle II ~2x efficient < 100 MeV.

- Full B reco. calibration error can be improved by choosing cleaner modes (low stat. modes).



Naive Belle II projections

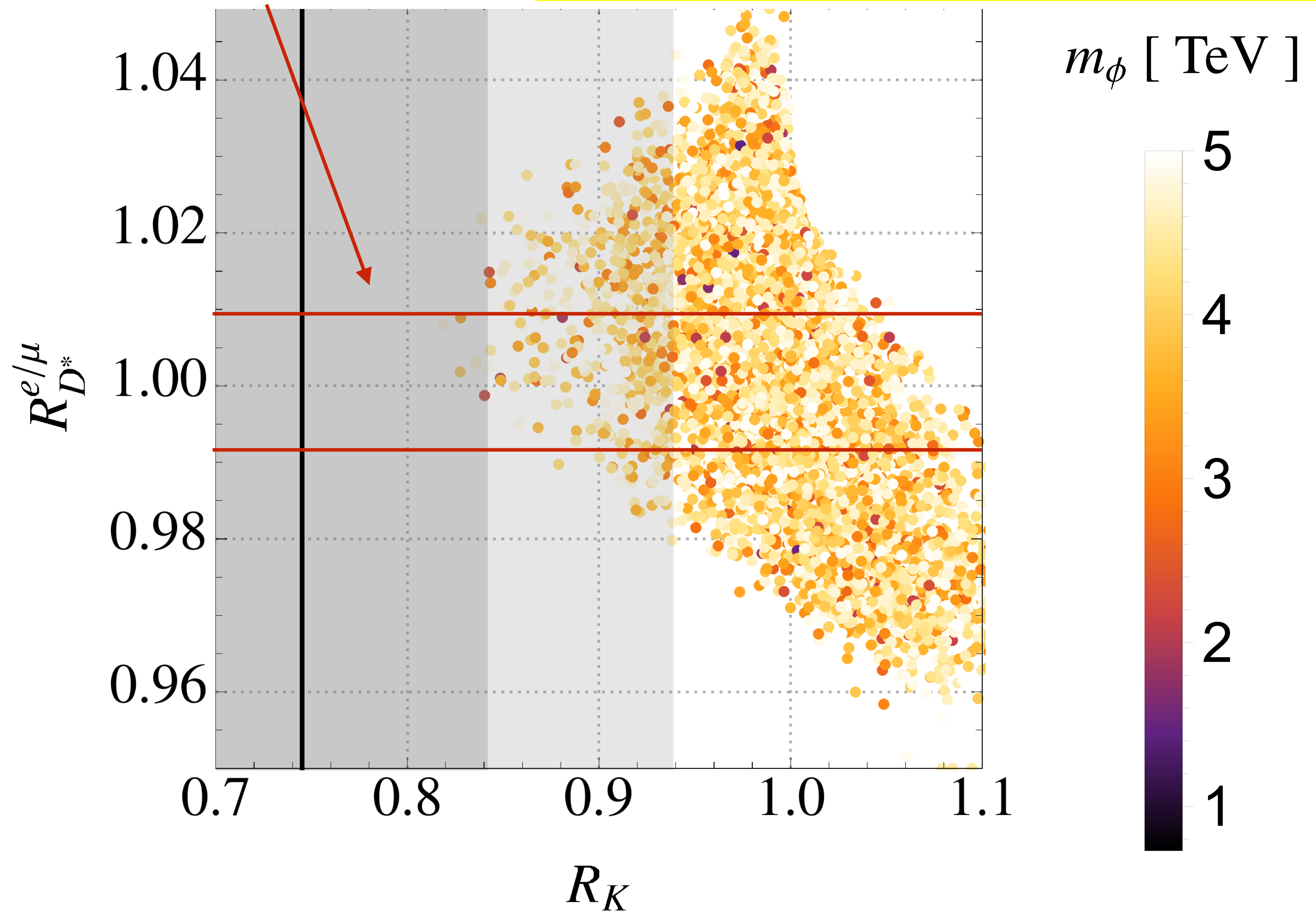
- Most errors cancel in LFUV measurement, except for eID, μID [data driven errors]
- B→ D* l ν ,
  - |Vcb| Experiment Error : 3% → 1%
  - **Re/μ : 5% approx. → ~1%**
- B→ D l ν ,
  - |Vcb| Experiment Error 3% → 1%
  - **Re/μ : (6% approx.) → ~1%**
- B → D** l ν
  - Exclusive modes never done comprehensively at B-factories. A long way to go to eliminate this as bias on B → D(*) τ ν.



$$\mathcal{R}_{e/u} = \frac{\mathcal{B}(B^0 \to D^{*+} e^- \nu_e)}{\mathcal{B}(B^0 \to D^{*+} \mu^- \nu_\mu)}$$

Belle II expectation

Cai, et al. JHEP 1710 (2017) 047



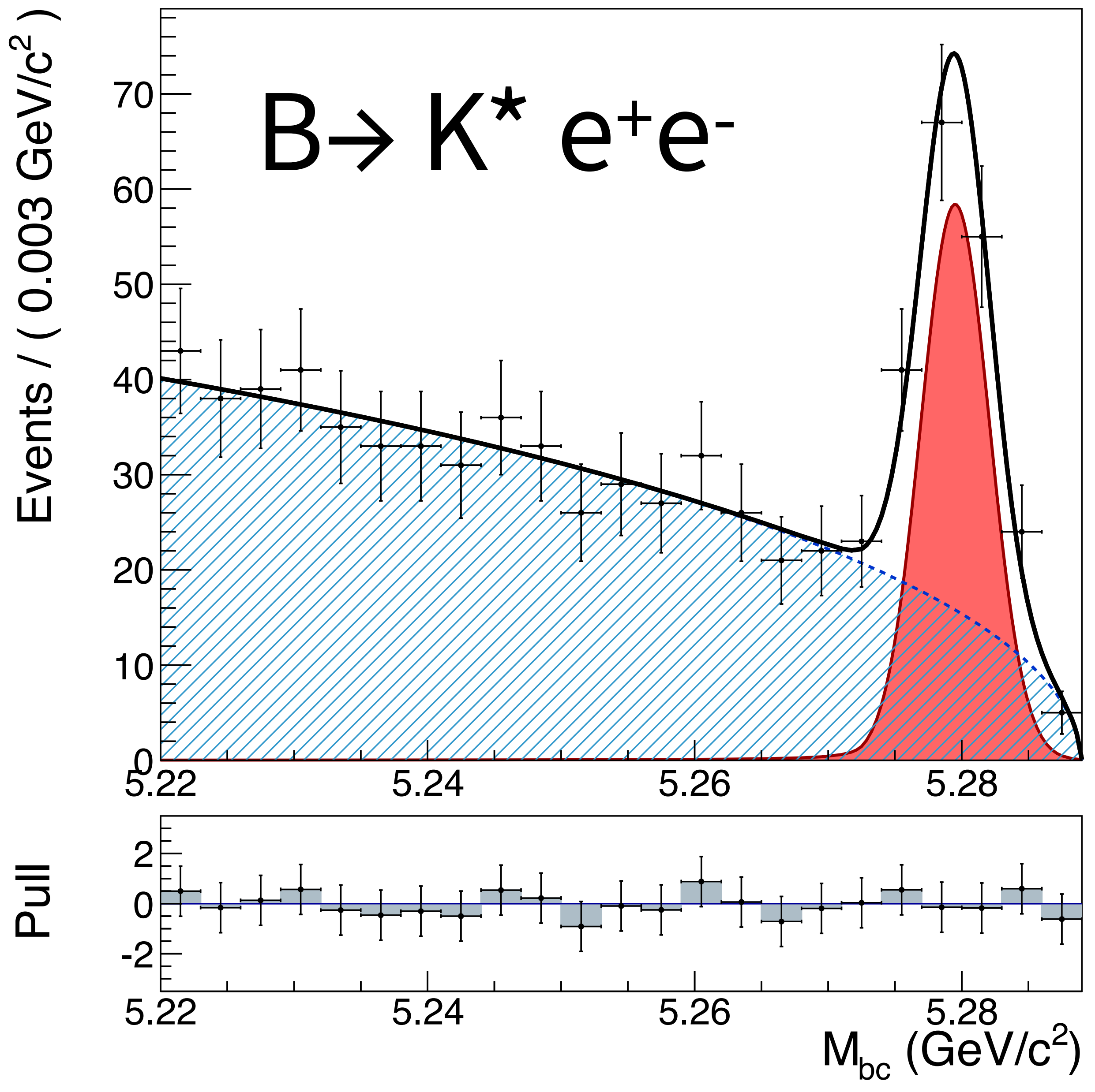
$b \to s\, l\, l$

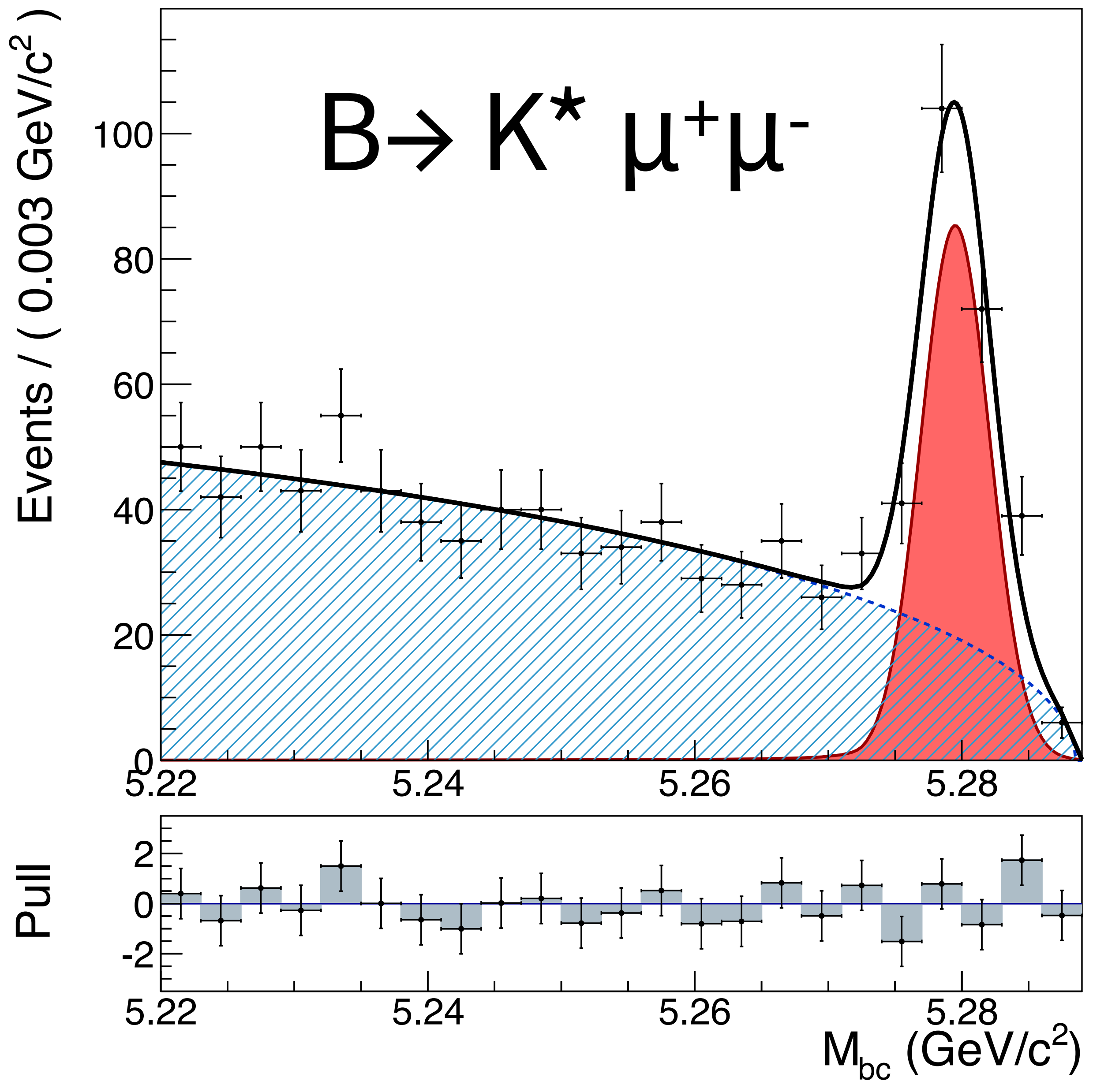
- **LHCb excellent for $B \to K^{*0}\, \mu^+\, \mu^-$ and $B \to K^+\, \mu^+\, \mu^-$ but what can we learn from Belle II?**
- BRs, direct CPV, differentials, isospin asymmetries, angular analyses, **time dependent CPV**, same sign (Majorana).
  - $B \to K^{(*)}\, l\, l$
    - $l = e, \mu, \tau$ [particularly good for electrons]
    - $K^{*+} \to K^+\pi^0, K_S\pi^+, K_L\pi^+$
      $K^{*0} \to K^+\pi^-, K_S\pi^0, K_L\pi^0$ [CP eigenstates]
      $K = K^\pm, K_S, K_L$
  - $B \to K^{(*)}\, l\, l'$, $l(') = e, \mu, \tau$
  - $B \to X_s\, l\, l$ via sum of exclusive modes, and B-tagged fully inclusive
- Additional constraints from $B \to X_s\, \gamma$, $K^*\, \gamma$

$B \to K^*ll$, efficiencies of modes with neutrals

- $B \to K^+\pi^- l^+ l^-$ dominates
- Other modes used for A_I, A_{CP}, ΔA_{CP}
  - **$B \to K^*(892)ee$ 200 events/ab^{-1}**
  - **$B \to K^*(892)\mu\mu$ 280 events/ab^{-1}**
- **Note: excellent m_{bc} resolution!**

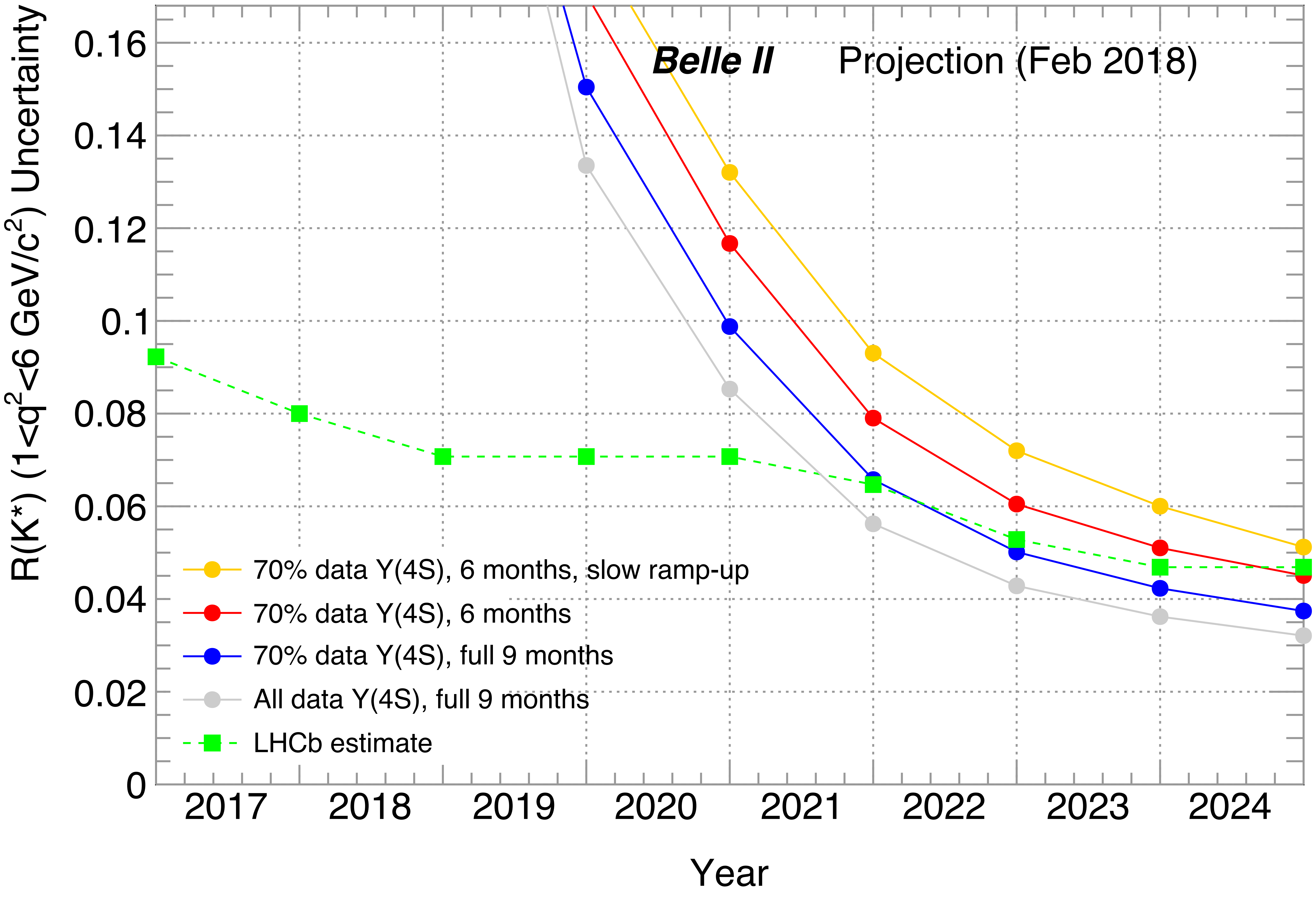
Belle, Phys. Rev. Lett 119, 171801 (2017)





Efficiencies	combined
$B^+ \to (K^+\pi^0)e^+e^-$	4.595 ±0.001
$B^+ \to (K^0\pi^+)e^+e^-$	3.951 ±0.001
$B^+ \to (K^+\pi^0)\mu^+\mu^-$	4.884 ±0.001
$B^+ \to (K^0\pi^+)\mu^+\mu^-$	4.203 ±0.001
$B^+ \to K^*(892)^+e^+e^-$	4.161 ±0.001
$B^+ \to K^*(892)^+\mu^+\mu^-$	4.426 ±0.001
$B^0 \to (K^+\pi^-)e^+e^-$	13.934 ±0.002
$B^0 \to (K^0\pi^0)e^+e^-$	1.333 ±0.001
$B^0 \to (K^+\pi^-)\mu^+\mu^-$	23.207 ±0.002
$B^0 \to (K^0\pi^0)\mu^+\mu^-$	2.606 ±0.001
$B^0 \to K^*(892)^0e^+e^-$	9.693 ±0.001
$B^0 \to K^*(892)^0\mu^+\mu^-$	16.335 ±0.001

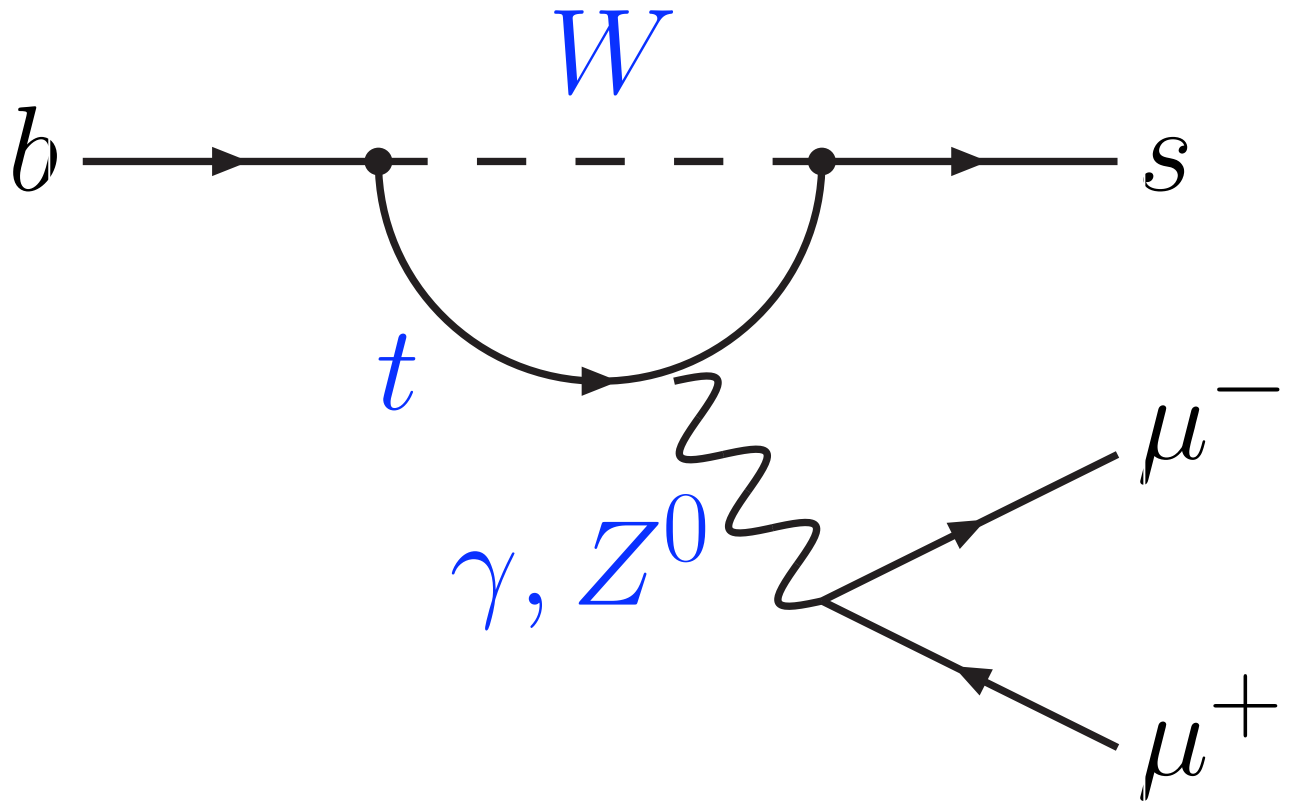
Projection

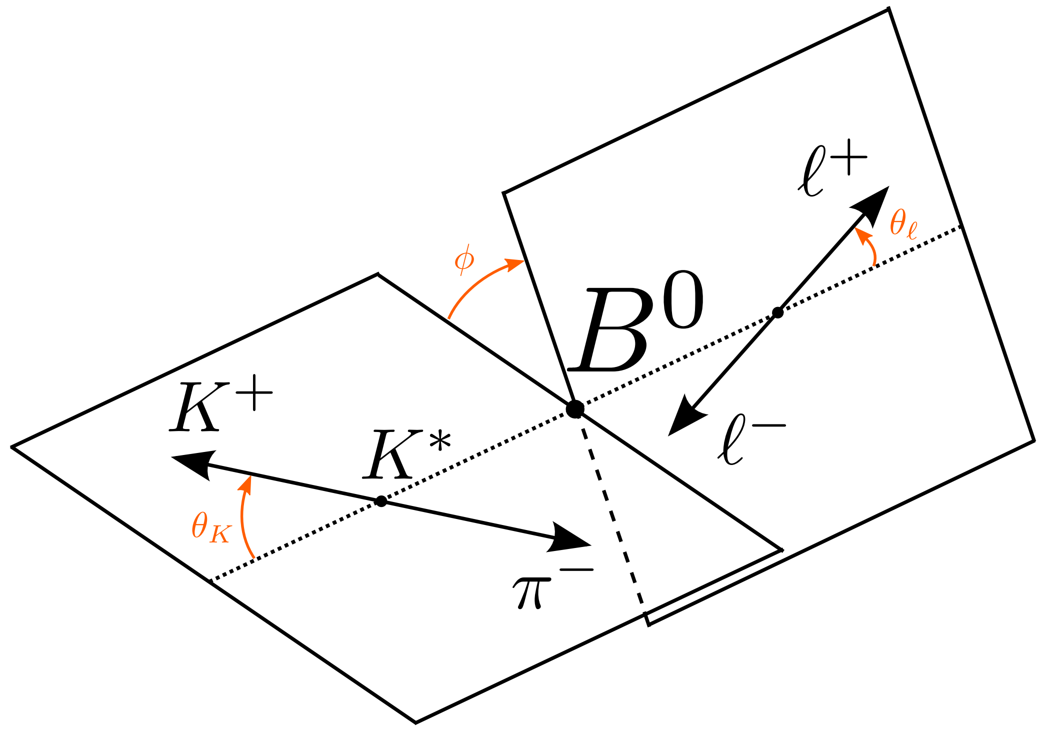


LHCb values based on naive run-1 extrapolation (not official)
Belle II scenarios due to operating conditions at KEK

** Consider it as a sketch to show Belle II can provide confirmation of any persistent anomaly.

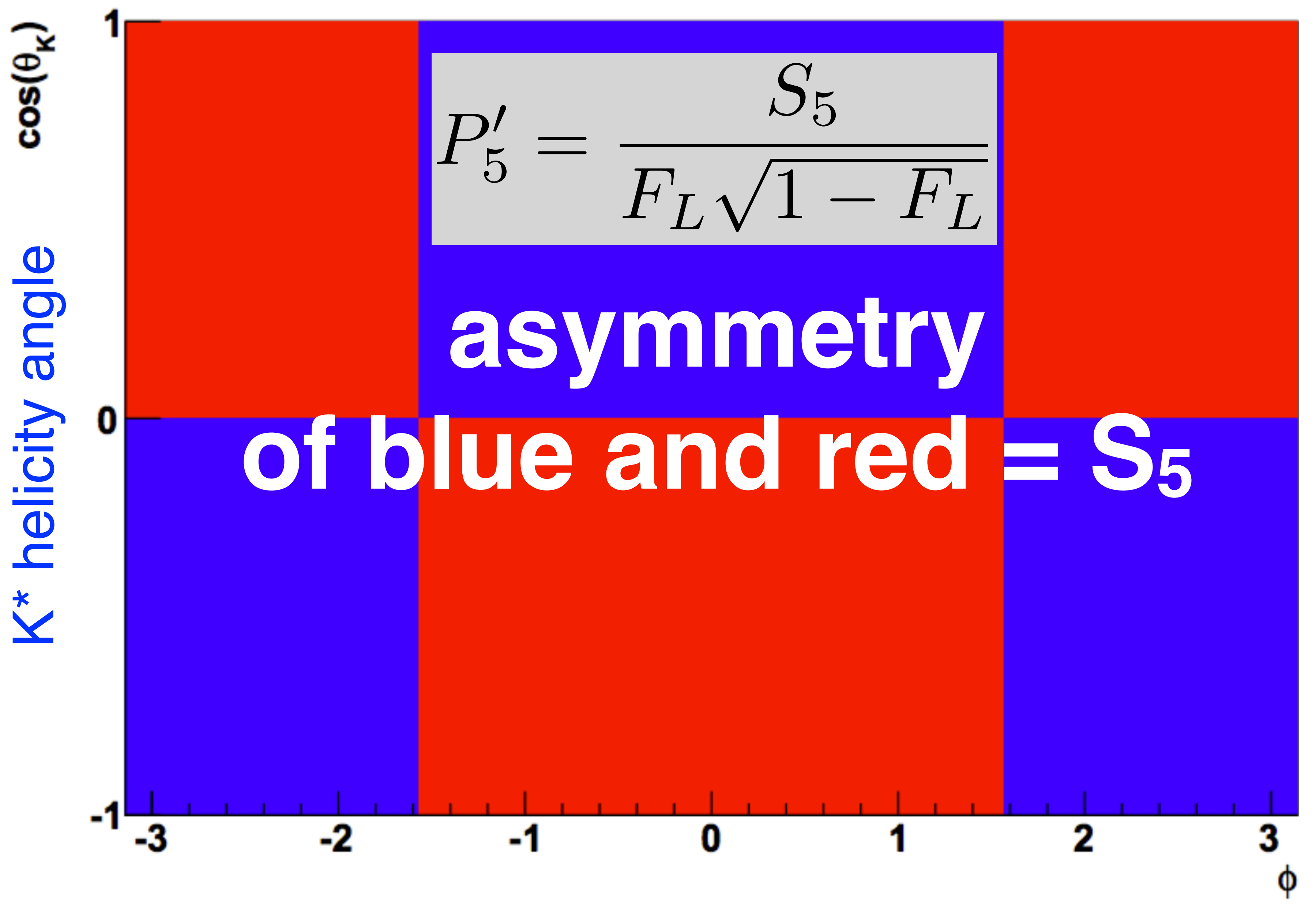
B → K$^{(*)}$ μ μ, B → K$^{(*)}$ e e





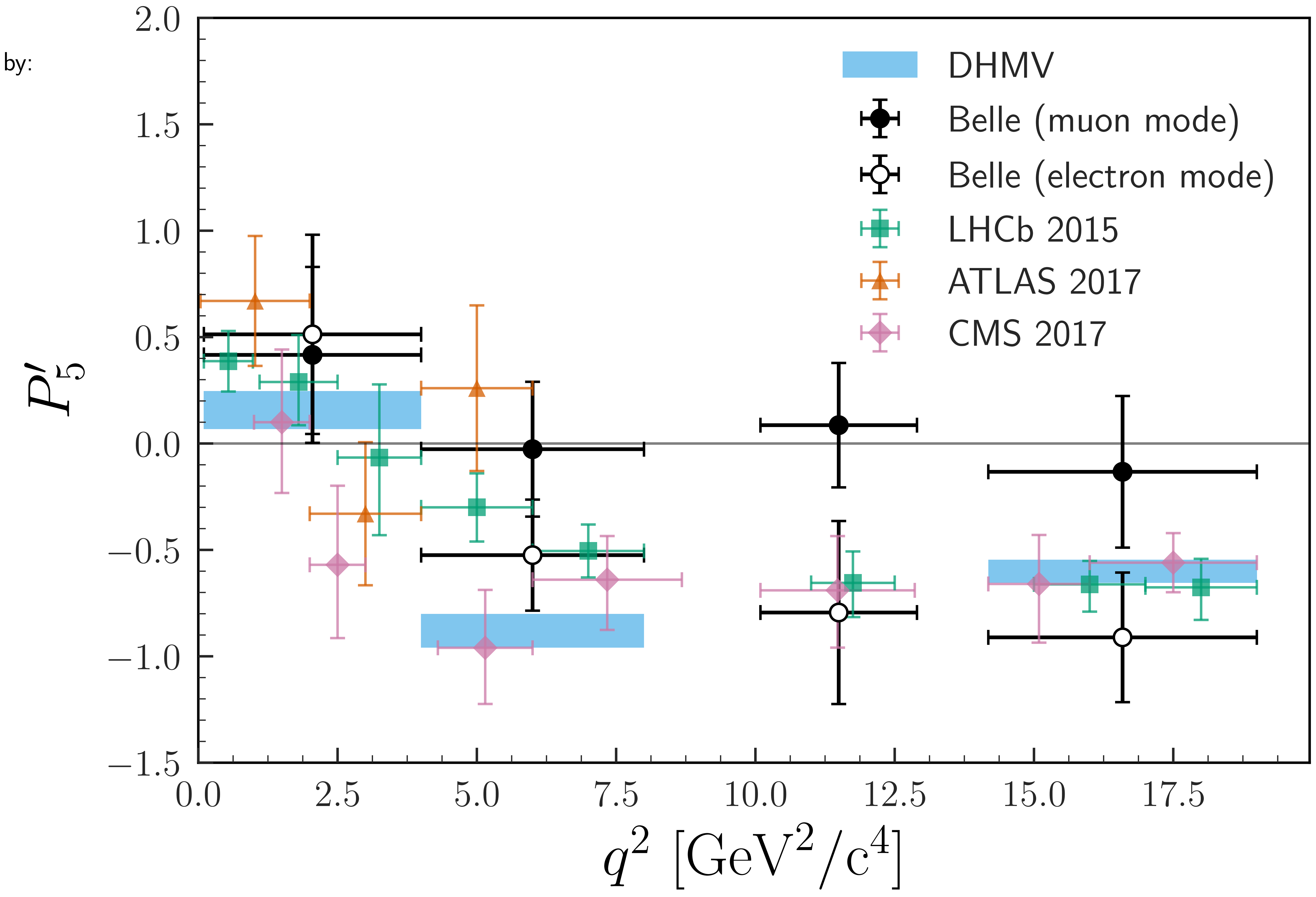
The decay is completely described by: θ_ℓ, θ_K, ϕ and $q^2 = M^2_{\ell^+\ell^-}$

Belle, Phys. Rev. Lett 119, 171801 (2017)



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

asymmetry of blue and red = S_5

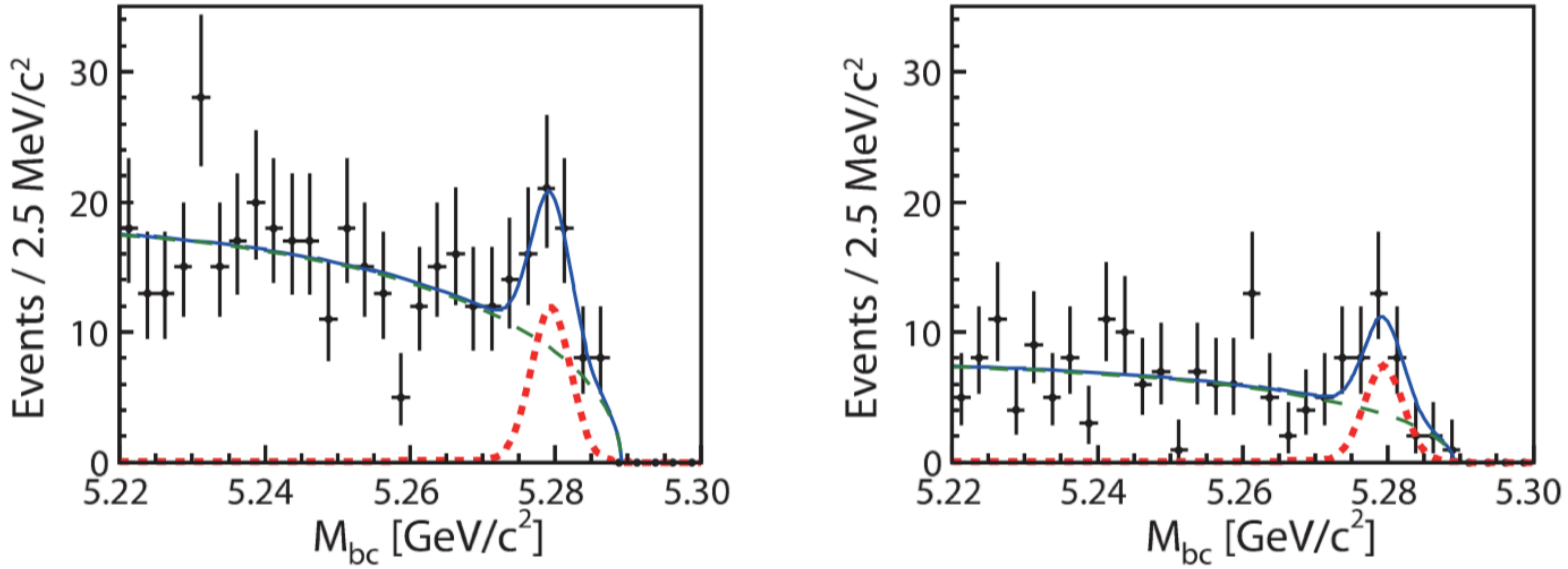


Inclusive analyses

Belle, Phys.Rev. D93 032008 (2016)

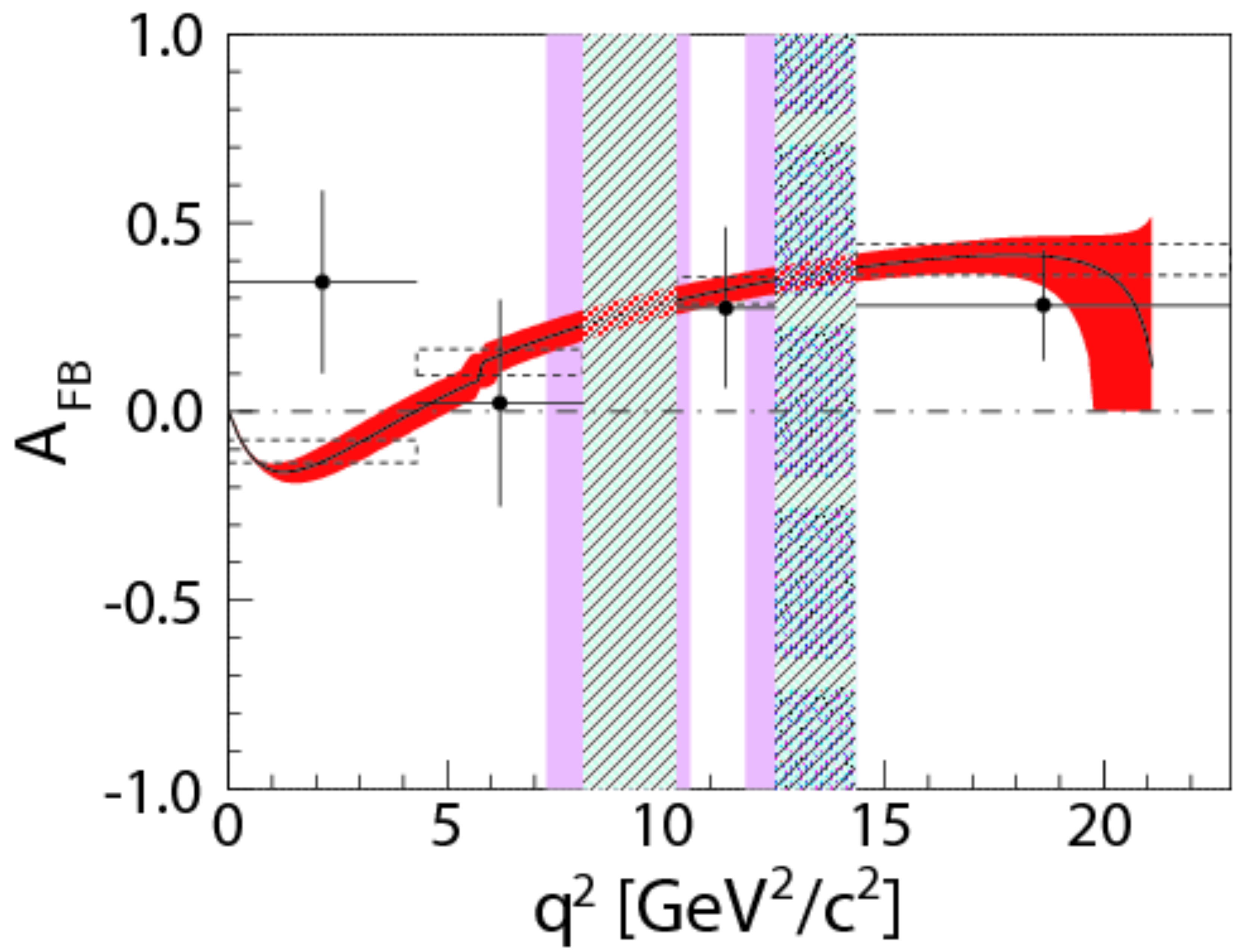
- $B \to X_s\, l^+ l^-$: 50% of rate

$\bar{B}^0$ decays		B^- decays	
	(K_S^0)	K^-	
$K^-\pi^+$	$(K_S^0\pi^0)$	$K^-\pi^0$	$K_S^0\pi^-$
$K^-\pi^+\pi^0$	$(K_S^0\pi^-\pi^+)$	$K^-\pi^+\pi^-$	$K_S^0\pi^-\pi^0$
$K^-\pi^+\pi^-\pi^+$	$(K_S^0\pi^-\pi^+\pi^0)$	$K^-\pi^+\pi^-\pi^0$	$K_S^0\pi^-\pi^+\pi^-$
$(K^-\pi^+\pi^-\pi^+\pi^0)$	$(K_S^0\pi^-\pi^+\pi^-\pi^+)$	$(K^-\pi^+\pi^-\pi^+\pi^-)$	$(K_S^0\pi^-\pi^+\pi^-\pi^0)$



(a) $B \to X_s e^+e^-$ candidates with $\cos\theta > 0$ (b) $B \to X_s e^+e^-$ candidates with $\cos\theta < 0$

- **$B \to X_s ee$ 200 events/ab^{-1}**
- **$B \to X_s \mu\mu$ 280 events/ab^{-1}**
- We can increase the number of exclusive modes in sum of exclusives.
- Investigating fully inclusive approach - only examining dilepton system.



$B \to X_s\, l^+ l^-$ inclusive

B2TiP, Belle II Physics book

Table 5: The Belle II sensitivities of the observables for the inclusive $B \to X_s \ell\ell$.

Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathcal{B}(B \to X_s\ell^+\ell^-)$ $(1.0 < q^2 < 3.5\ \mathrm{GeV}^2)$	29%	13%	6.6%
$\mathcal{B}(B \to X_s\ell^+\ell^-)$ $(3.5 < q^2 < 6.0\ \mathrm{GeV}^2)$	24%	11%	6.4%
$\mathcal{B}(B \to X_s\ell^+\ell^-)$ $(q^2 > 14.4\ \mathrm{GeV}^2)$	23%	10%	4.7%
$A_{CP}(B \to X_s\ell^+\ell^-)$ $(1.0 < q^2 < 3.5\ \mathrm{GeV}^2)$	26%	9.7 %	3.1 %
$A_{CP}(B \to X_s\ell^+\ell^-)$ $(3.5 < q^2 < 6.0\ \mathrm{GeV}^2)$	21%	7.9 %	2.6 %
$A_{CP}(B \to X_s\ell^+\ell^-)$ $(q^2 > 14.4\ \mathrm{GeV}^2)$	21%	8.1 %	2.6 %
$A_{FB}(B \to X_s\ell^+\ell^-)$ $(1.0 < q^2 < 3.5\ \mathrm{GeV}^2)$	26%	9.7%	3.1%
$A_{FB}(B \to X_s\ell^+\ell^-)$ $(3.5 < q^2 < 6.0\ \mathrm{GeV}^2)$	21%	7.9%	2.6%
$A_{FB}(B \to X_s\ell^+\ell^-)$ $(q^2 > 14.4\ \mathrm{GeV}^2)$	19%	7.3%	2.4%
$\Delta_{CP}(A_{FB})$ $(1.0 < q^2 < 3.5\ \mathrm{GeV}^2)$	52%	19%	6.1%
$\Delta_{CP}(A_{FB})$ $(3.5 < q^2 < 6.0\ \mathrm{GeV}^2)$	42%	16%	5.2%
$\Delta_{CP}(A_{FB})$ $(q^2 > 14.4\ \mathrm{GeV}^2)$	38%	15%	4.8%

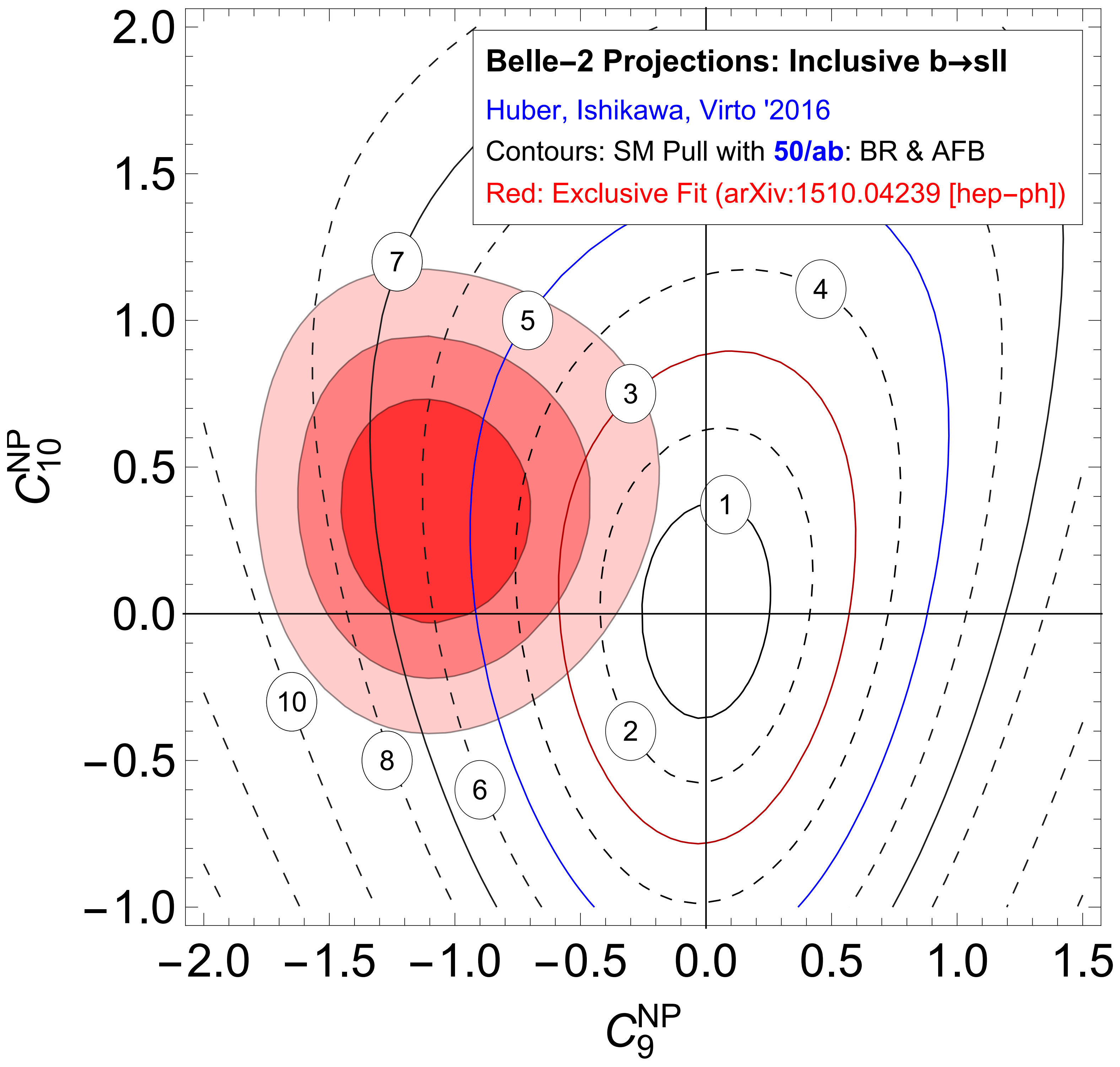


Table 8: Belle II sensitivities of angular observables for the $B \to K^*\ell^+\ell^-$ decay. Some numbers at Belle are extrapolated to 0.71 ab^{-1}. The number for each bin is needed for a global fit.

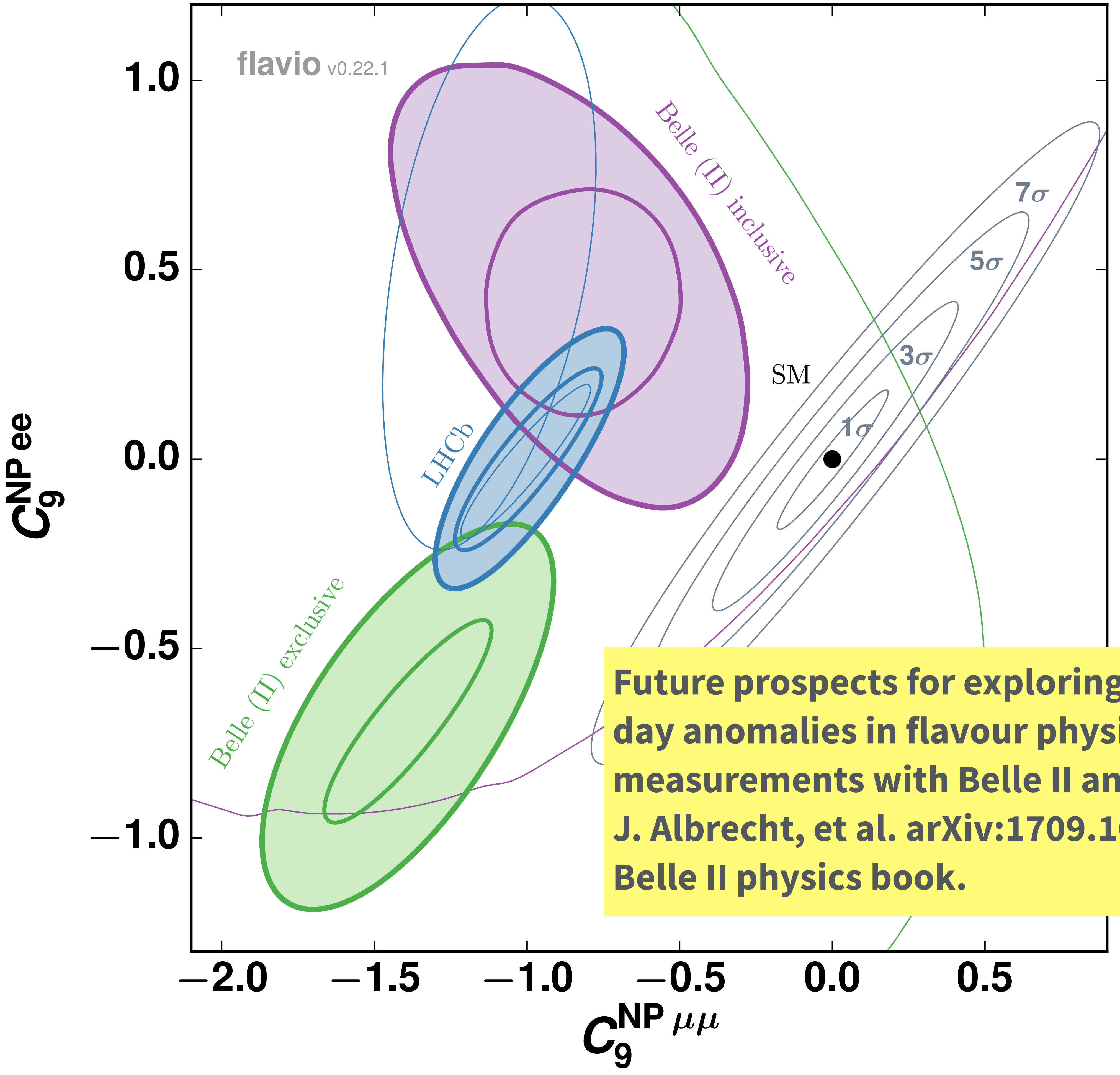
Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
R_K $(1 < q^2 < 6\ \mathrm{GeV}^2)$	28%	11%	3.6%
R_K $(q^2 > 14.4\ \mathrm{GeV}^2)$	30%	12%	3.6%
R_{K^*} $(1 < q^2 < 6\ \mathrm{GeV}^2)$	26%	10%	3.2%
R_{K^*} $(q^2 > 14.4\ \mathrm{GeV}^2)$	24%	9.2%	2.8%
R_{X_s} $(1 < q^2 < 6\ \mathrm{GeV}^2)$	32%	12%	4.0%
R_{X_s} $(q^2 > 14.4\ \mathrm{GeV}^2)$	28%	11%	3.4%

Belle II: b → s Loop Rare

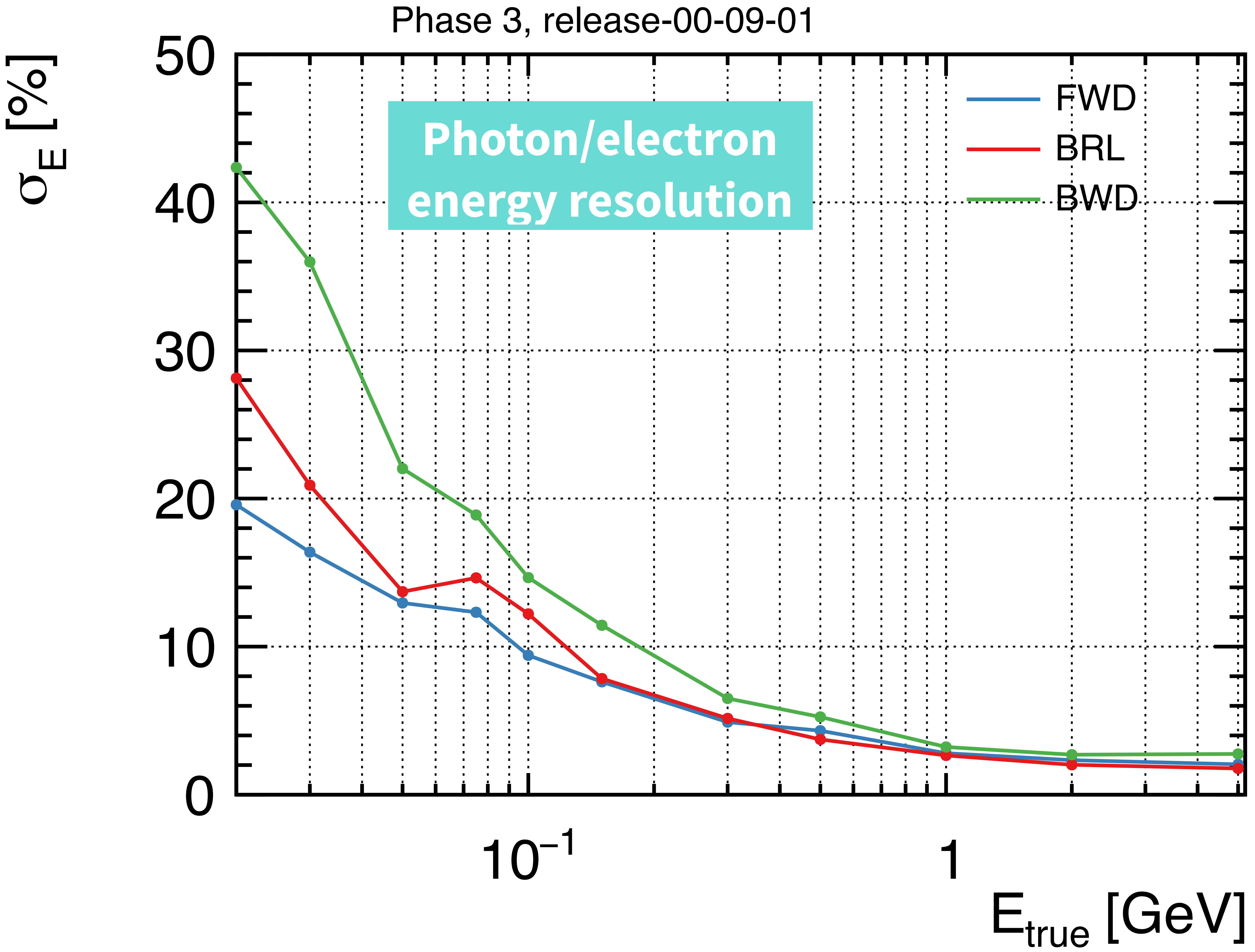
- Wilson coefficients can be done with competitive precision to LHCb over exclusive & inclusive.

$$\mathcal{H}_{\rm eff} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i (C_i O_i + C_i' O_i') + \text{h.c.}$$

$$O_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,,$$
$$O_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,,$$

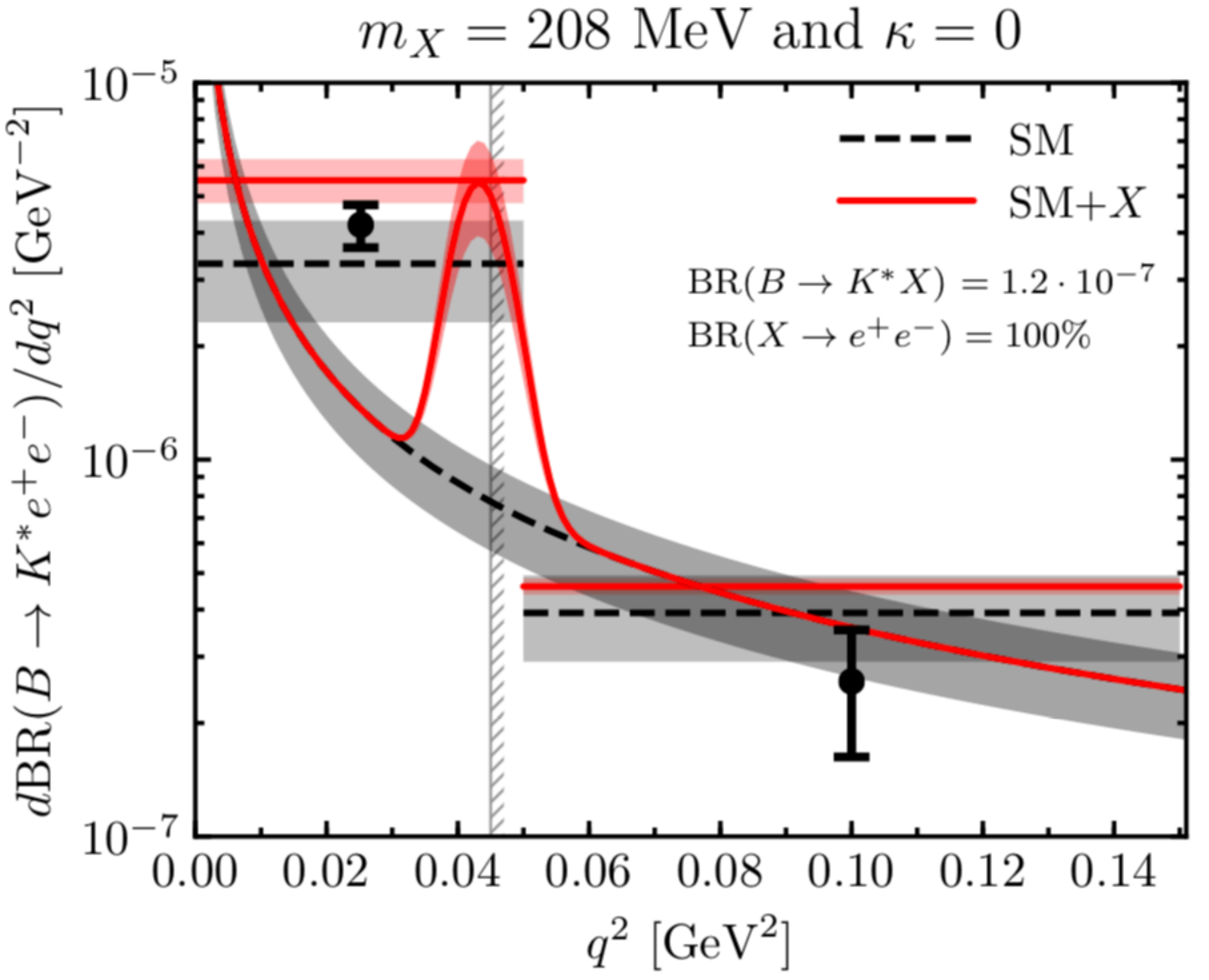


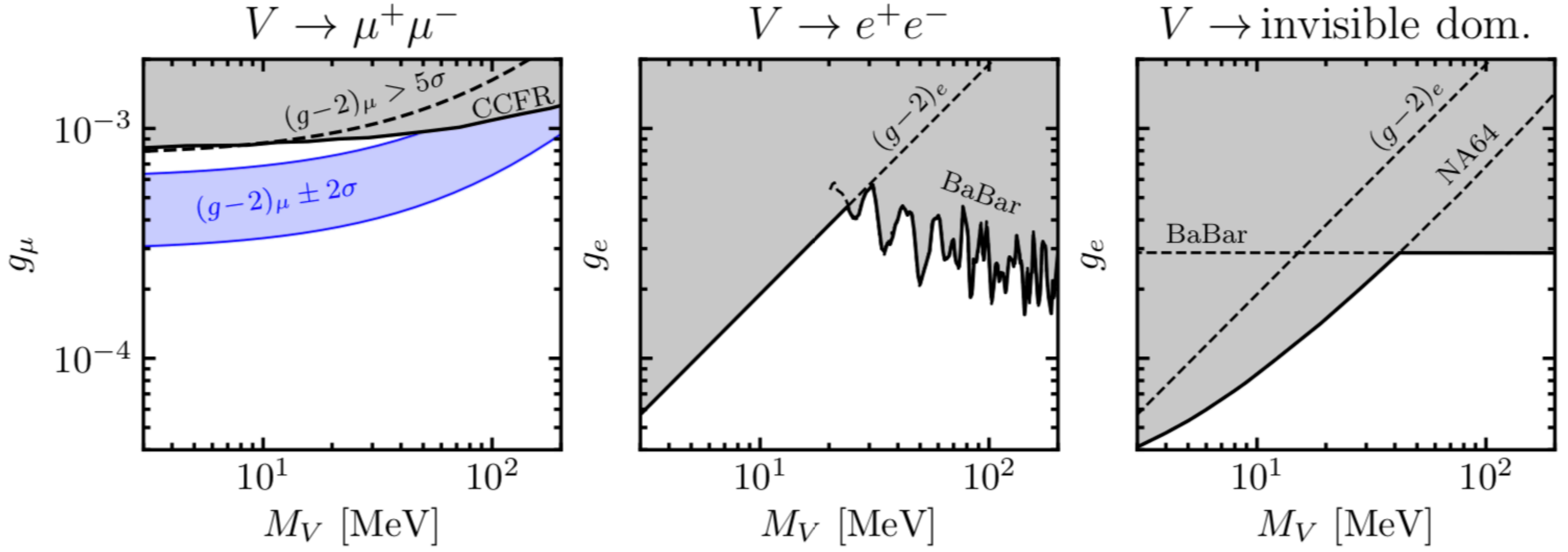
Future prospects for exploring present day anomalies in flavour physics measurements with Belle II and LHCb , J. Albrecht, et al. arXiv:1709.10308 & Belle II physics book.

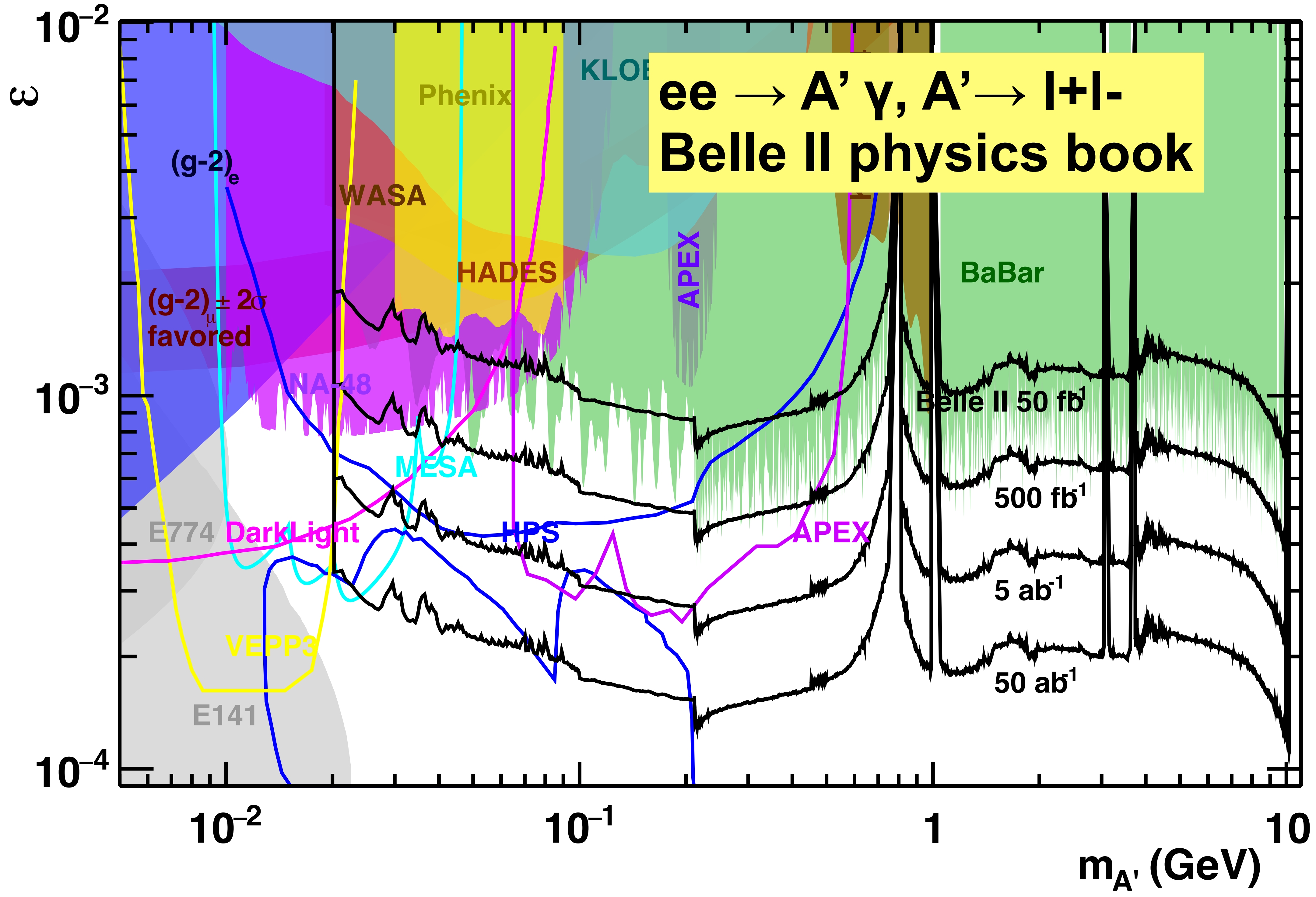


Exotic B → K*A', A' → e+e-

W. Altmannshofer, arXiv:1711.07494

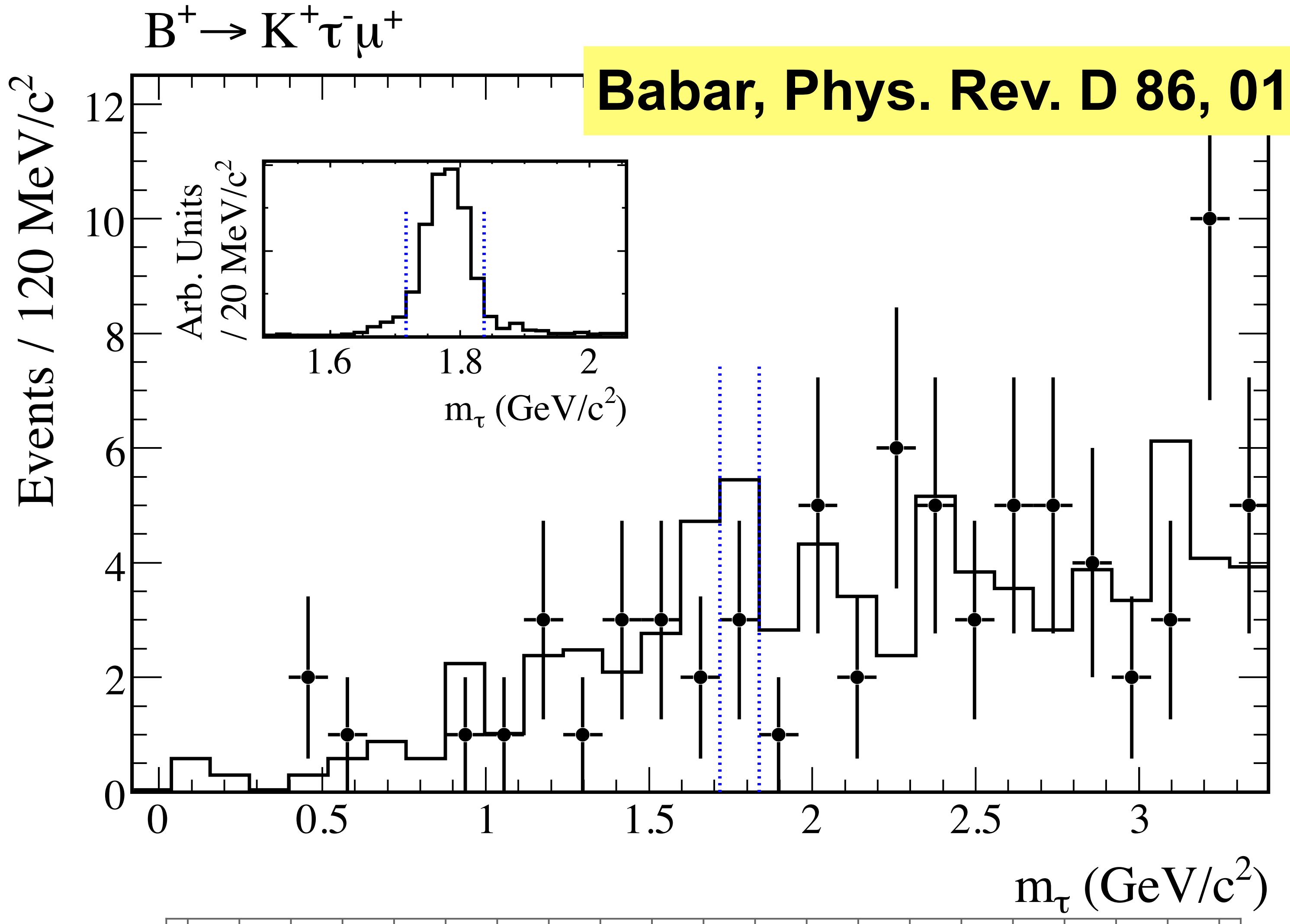






$b \to s\tau\tau$, $b \to s\tau l$, $b \to s\mu e$

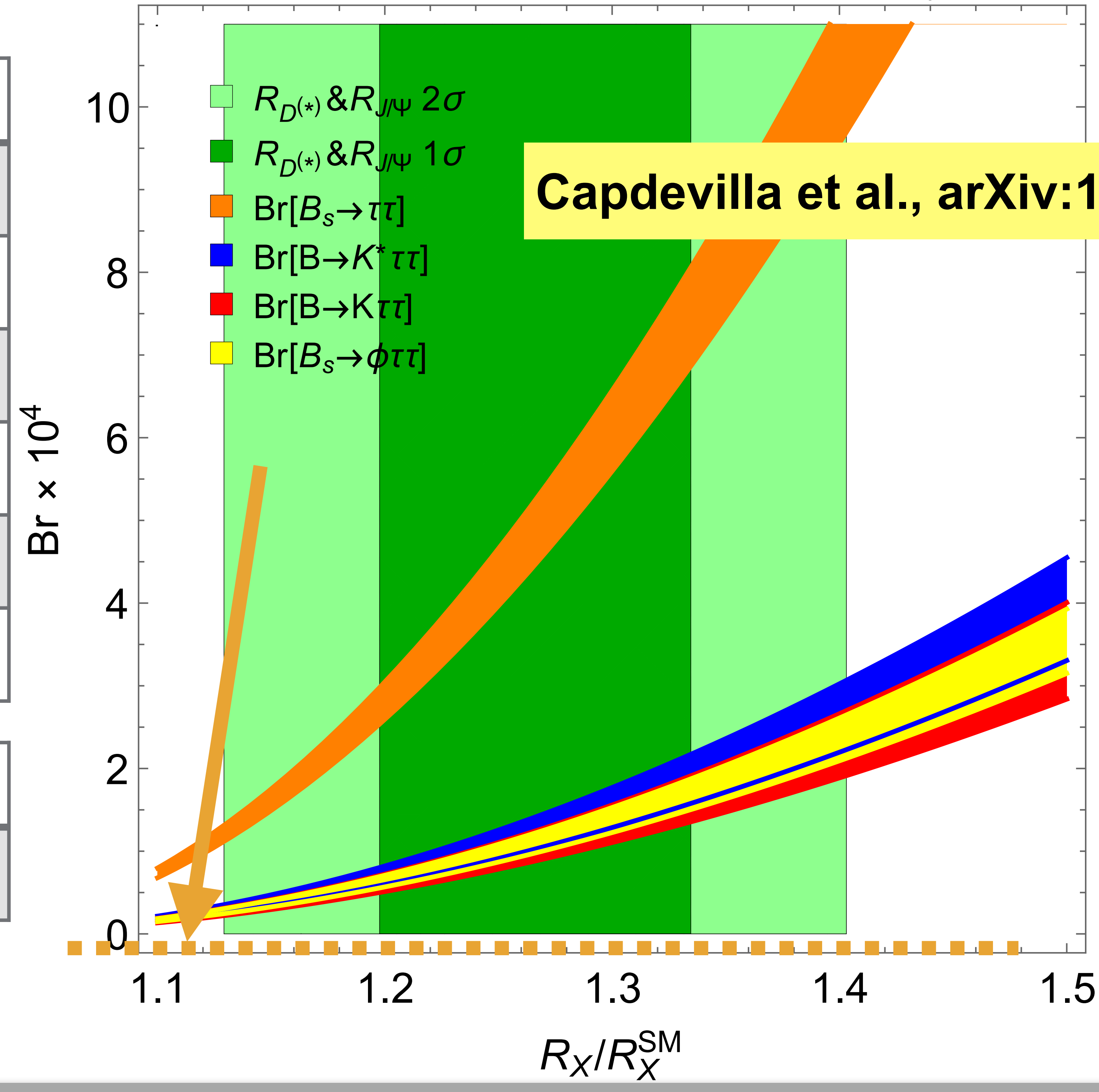
- $b \to s\tau\tau$: Extract from $E_{ECL/extra}$ Fit in B-tagged analysis.
- $b \to s\tau l$: Use B-tag, reconstruct $K^{(*)}$ and l, remaining mass is a τ.
- $b \to s e \mu$: Naively expect LHCb to dominate.



Babar, Phys. Rev. D 86, 012004 (2012)

Branching fraction	Belle 0.7 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}	SM
$B^+ \to K^+\tau^+\tau$	$<32\times10^{-5}$	$<6.5\times10^{-5}$	$<2.0\times10^{-5}$	0.0122×10^{-5}
$B^0 \to \tau^+\tau$	$<140\times10^{-5}$	$<30\times10^{-5}$	$<9.6\times10^{-5}$	0.0022×10^{-5}
$B^+ \to K^+\tau^+e^-$			$<2.1\times10^{-6}$	
$B^+ \to K^+\tau^+\mu^-$			$<3.3\times10^{-6}$	
$B^0 \to \tau^+e^-$			$<1.6\times10^{-5}$	
$B^0 \to \tau^+\mu^-$			$<1.3\times10^{-5}$	

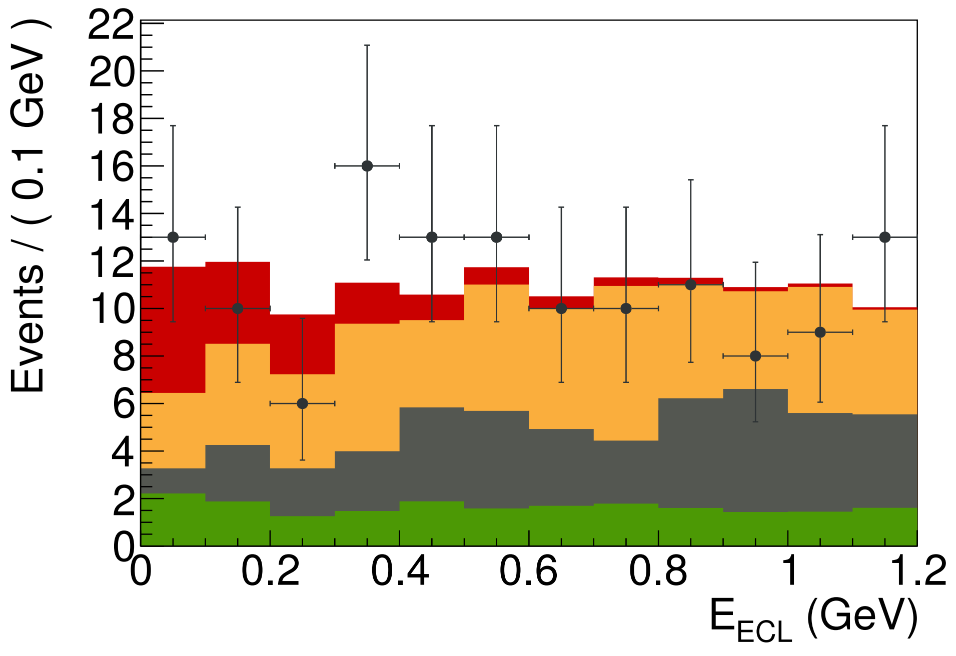
Branching fraction	Belle 0.12 ab^{-1}	Belle II 0.5 ab^{-1}	Belle II 5 ab^{-1}	SM
$B_s \to \tau^+\tau^-$	$<70\times10^{-4}$	$<24\times10^{-4}$	$<8.1\times10^{-4}$	0.00773×10^{-4}



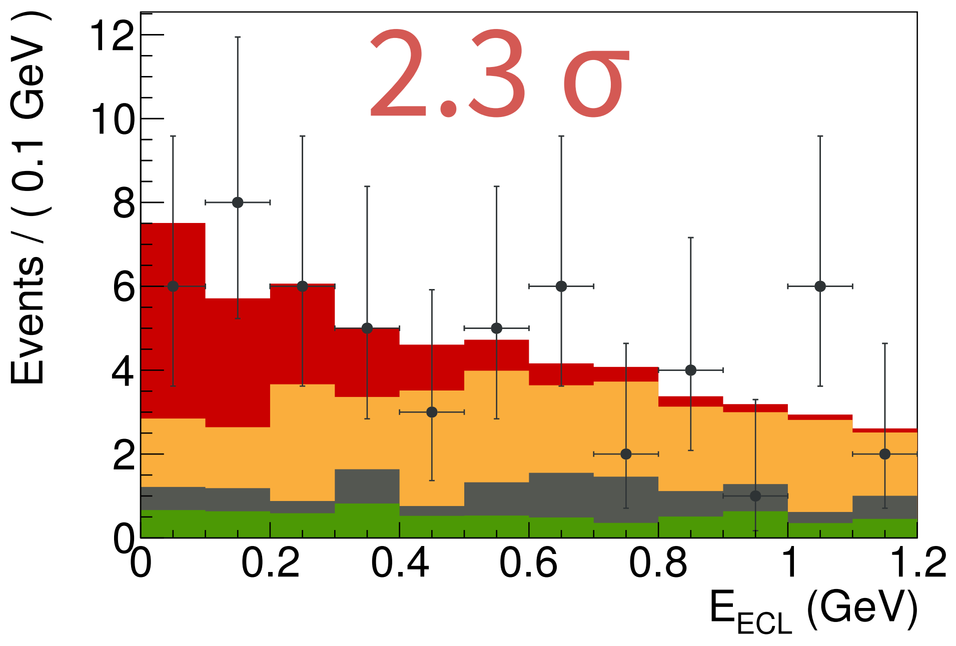
Capdevilla et al., arXiv:1712.01919

B → $K^{(*)} \nu \nu$

- Best limits on B → $K^{(*)} \nu \nu$ set by Belle semileptonic tag BR. Could be greatly enhanced in NP scenarios.

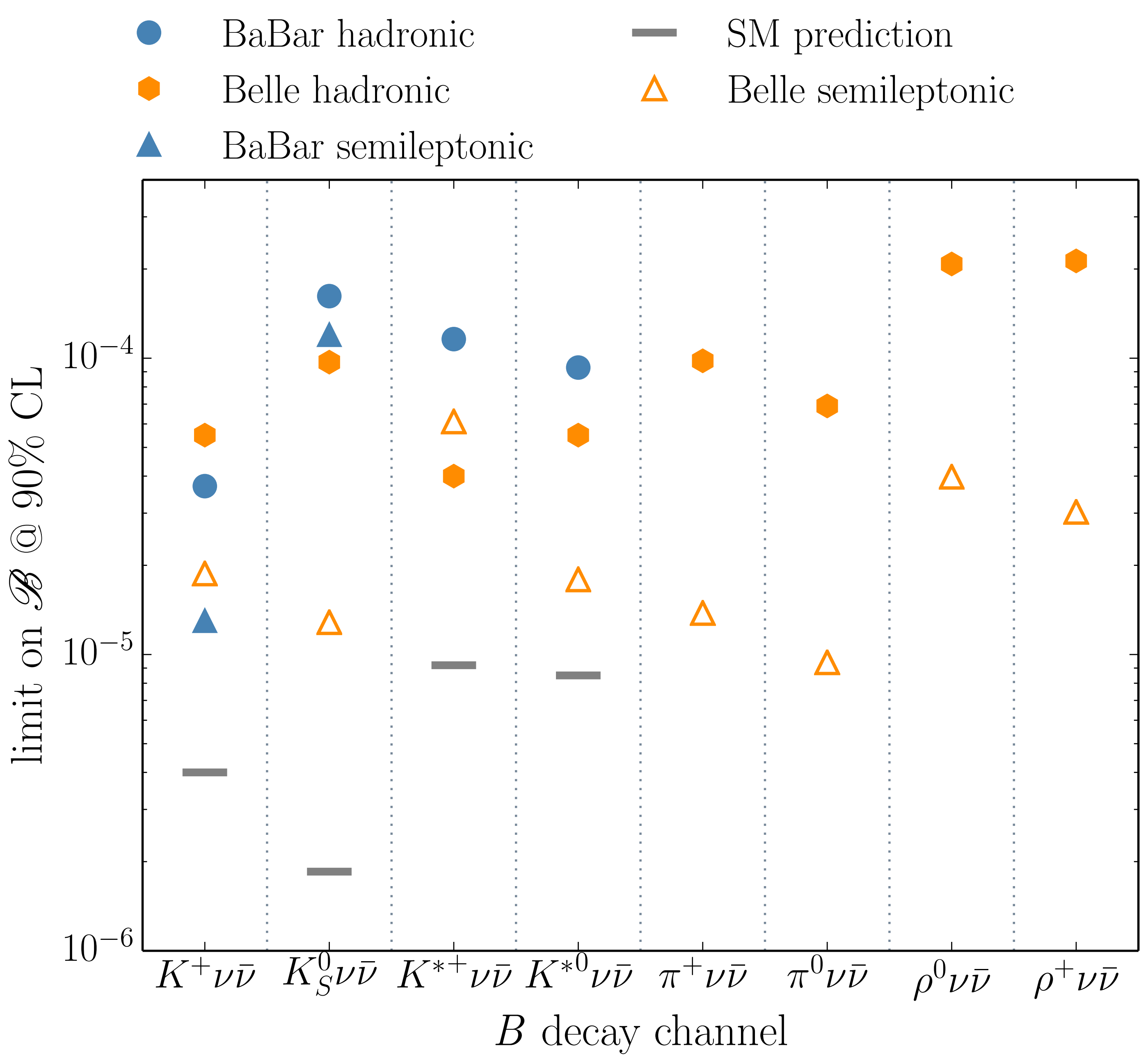


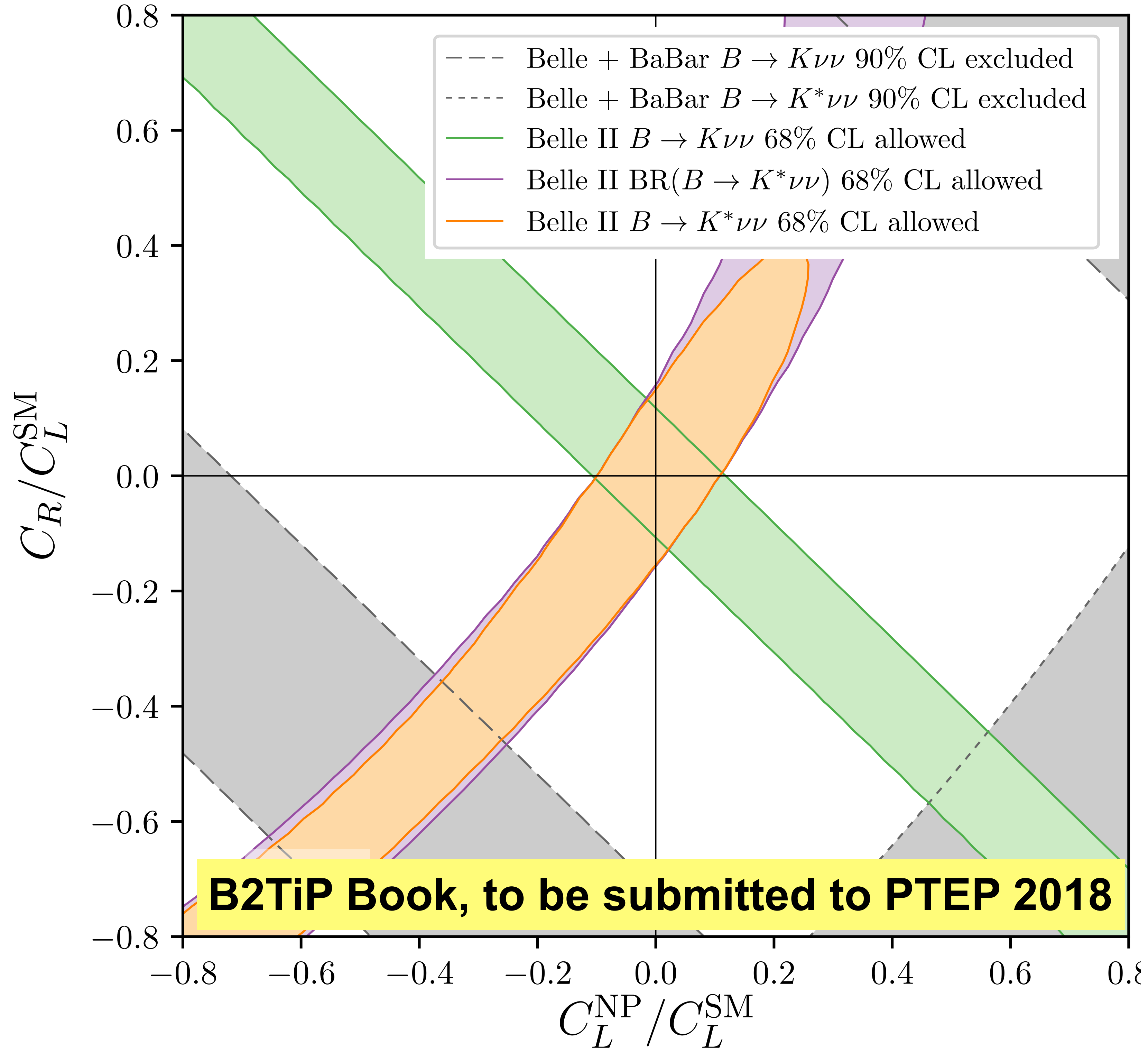
(a) $B^+ \to K^+ \nu\bar{\nu}$



(c) $B^+ \to K^{*+} \nu\bar{\nu}$

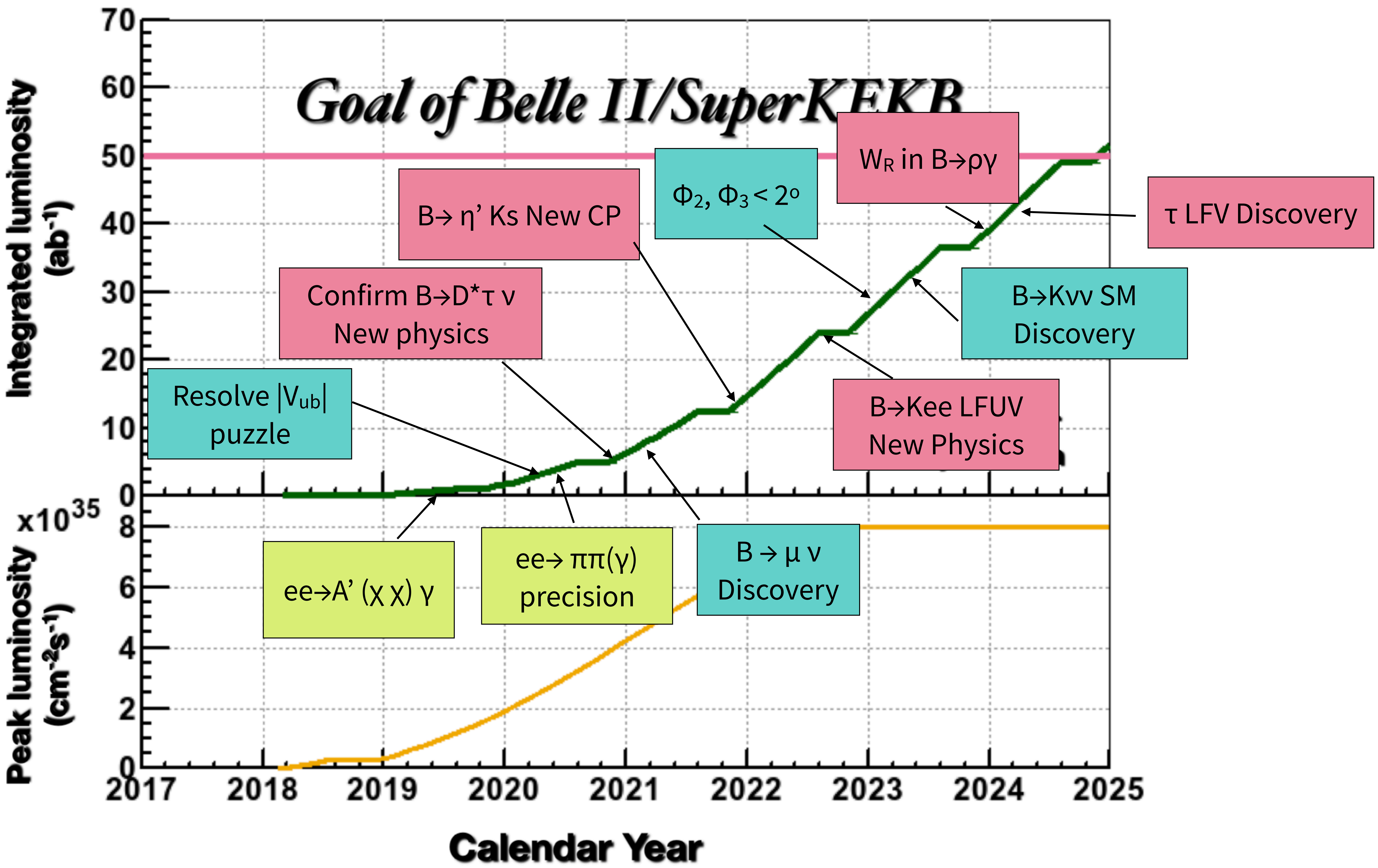
Belle PRD(R) 96, 091101 (2017)





Observables	Belle 0.71 ab^{-1} (0.12 ab^{-1})	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$Br(B^+ \to K^+\nu\bar{\nu})$	$< 450\%$	30%	11%
$Br(B^0 \to K^{*0}\nu\bar{\nu})$	$< 180\%$	26%	9.6%
$Br(B^+ \to K^{*+}\nu\bar{\nu})$	$< 420\%$	25%	9.3%
$F_L(B^0 \to K^{*0}\nu\bar{\nu})$	–	–	0.079
$F_L(B^+ \to K^{*+}\nu\bar{\nu})$	–	–	0.077
$Br(B^0 \to \nu\bar{\nu}) \times 10^6$	< 14	< 5.0	< 1.5
$Br(B_s \to \nu\bar{\nu}) \times 10^5$	< 9.7	< 4.5	< 1.5

Roadmap


Goal of Belle II/SuperKEKB
Integrated luminosity (ab^{-1})
Peak luminosity (cm^{-2}s^{-1})
x10^{35}
Calendar Year
70
60
50
40
30
20
10
0
8
6
4
2
0
2017
2018
2019
2020
2021
2022
2023
2024
2025
W_R in B→ργ
Φ$_2$, Φ$_3$ < 2°
B→ η' Ks New CP
τ LFV Discovery
Confirm B→D*τ ν New physics
B→Kνν SM Discovery
Resolve $|V_{ub}|$ puzzle
B→Kee LFUV New Physics
ee→A' (χ χ) γ
ee→ ππ(γ) precision
B → μ ν Discovery

Summary

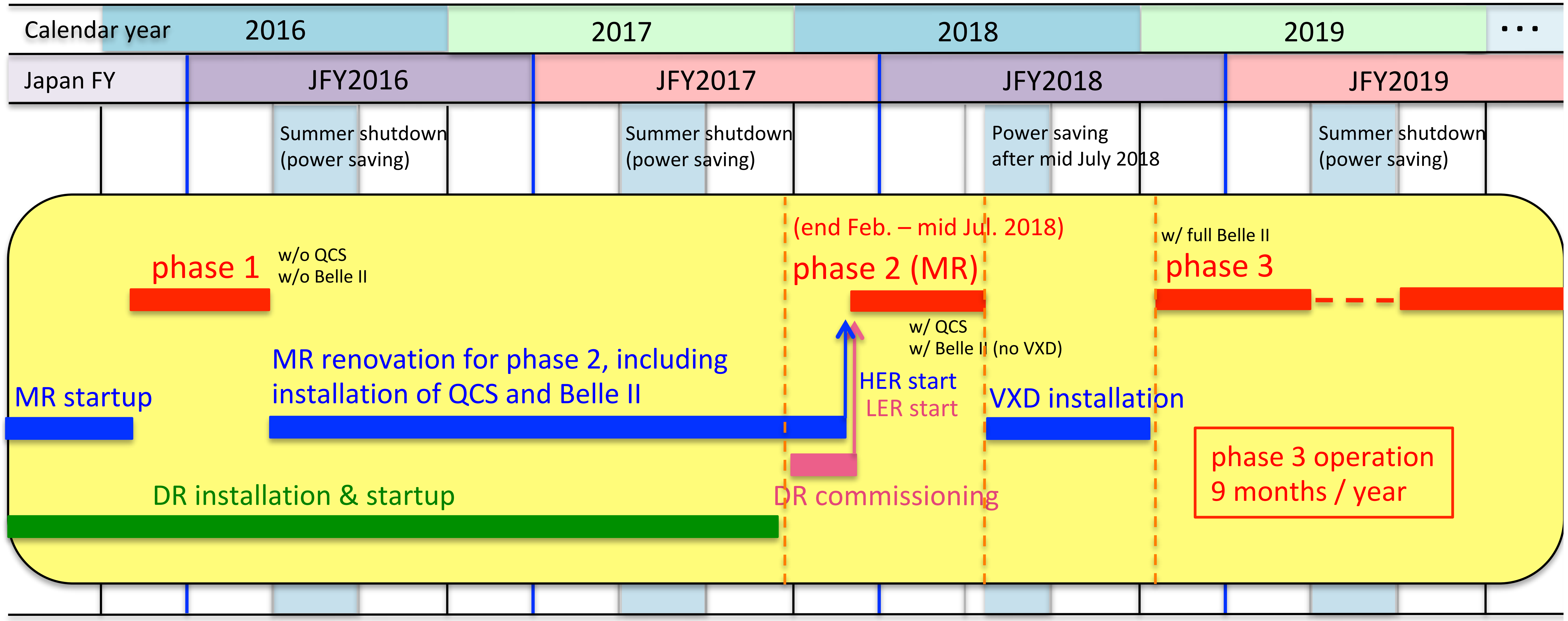
- Anomalous behaviour in semileptonic B decays observed by multiple experiments - **violations of lepton flavour universality.**
  - Belle II equally good efficiency and resolution for e and μ - and good for τ decay.
    - B→D(*) τ ν LFUV tested to 2-3%, B→D(*) l ν to <1%: will measure differential spectra.
    - B→K/K*/Xs l l 3% LFUV accuracy exclusive & inclusive: better E_{e-} resolution than LHCb.
- **Expect first collisions in April/May 2018 ~ 2 weeks!**
- **Belle II physics book to appear on arXiv in May.**

Belle II

https://www.facebook.com/belle2collab
https://twitter.com/belle2collab
http://live.nicovideo.jp/gate/lv312372695 (Live broadcast from April 20)

Backup

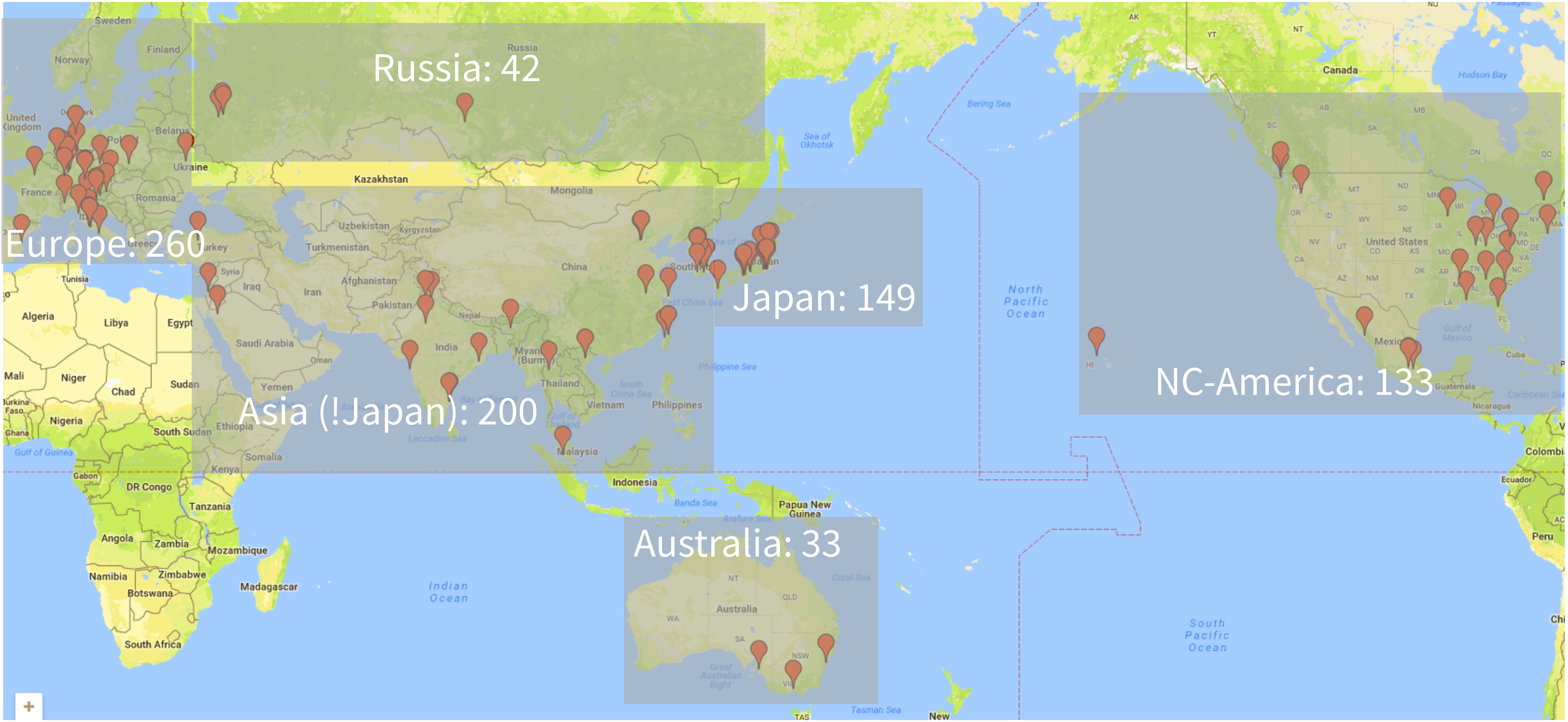
Belle II General Status and Timeline



- Phase 2 (w/final focusing Q, w/Belle II, w/ partial Si configuration & background monitors)
- Verification of nano-beam scheme
  - Target L> 10^{34} cm-2s-1
- Understand beam background and its luminosity scaling - particularly in VXD volume.

Belle II Collaboration

- 784 collaborators, 106 institutions, 25 countries/regions

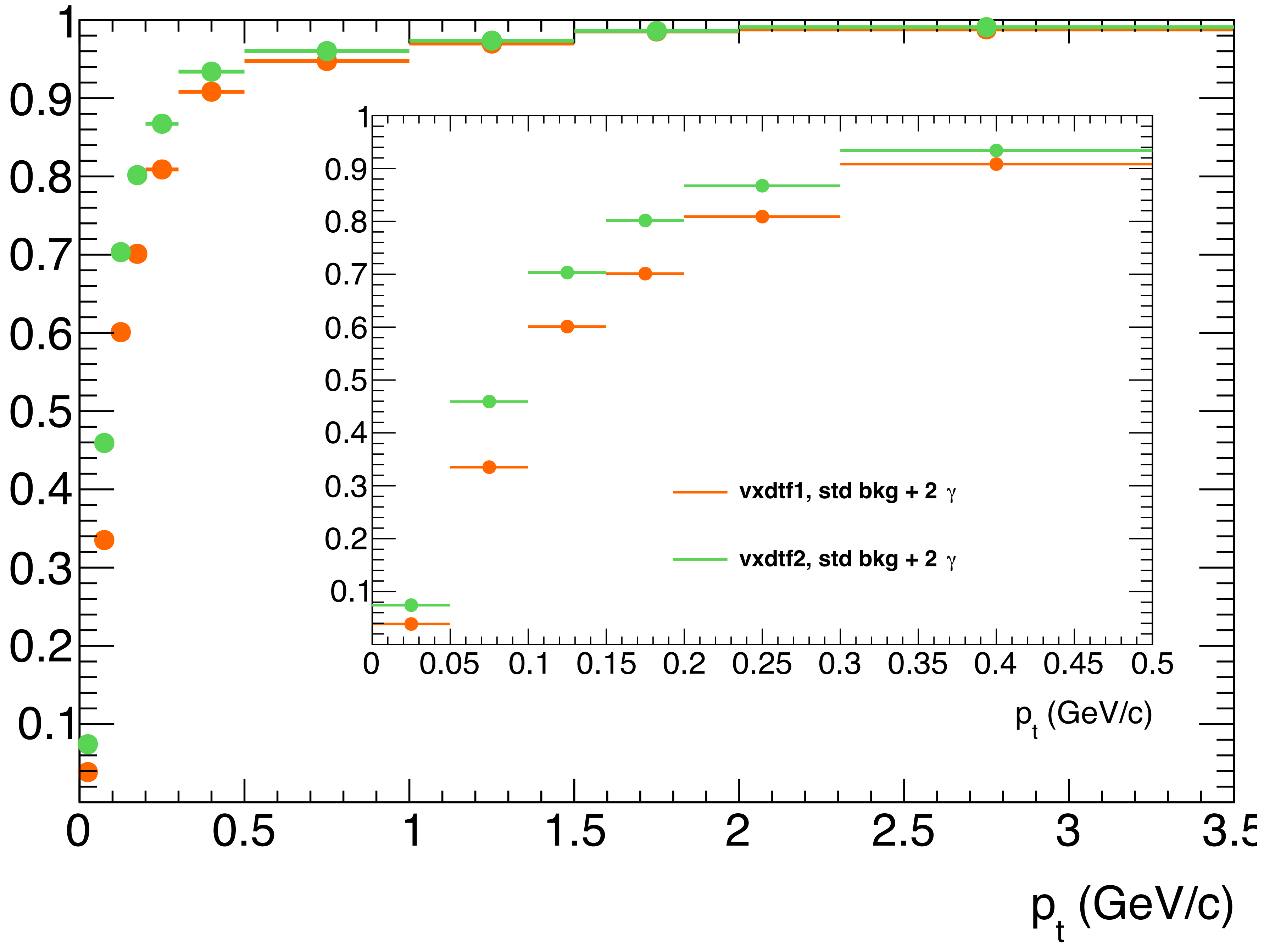


Track reconstruction

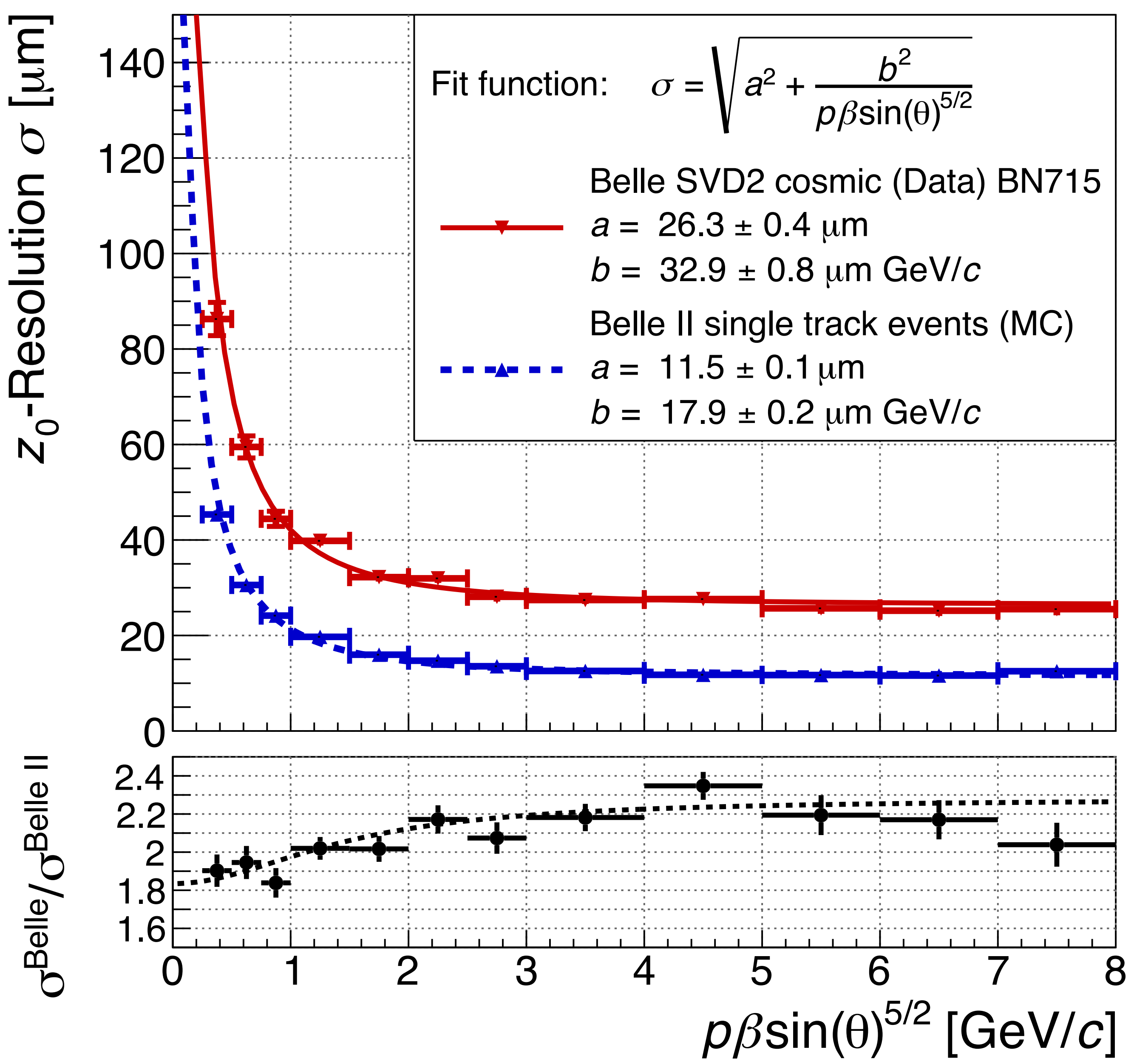
Discussed in Luigi's talk

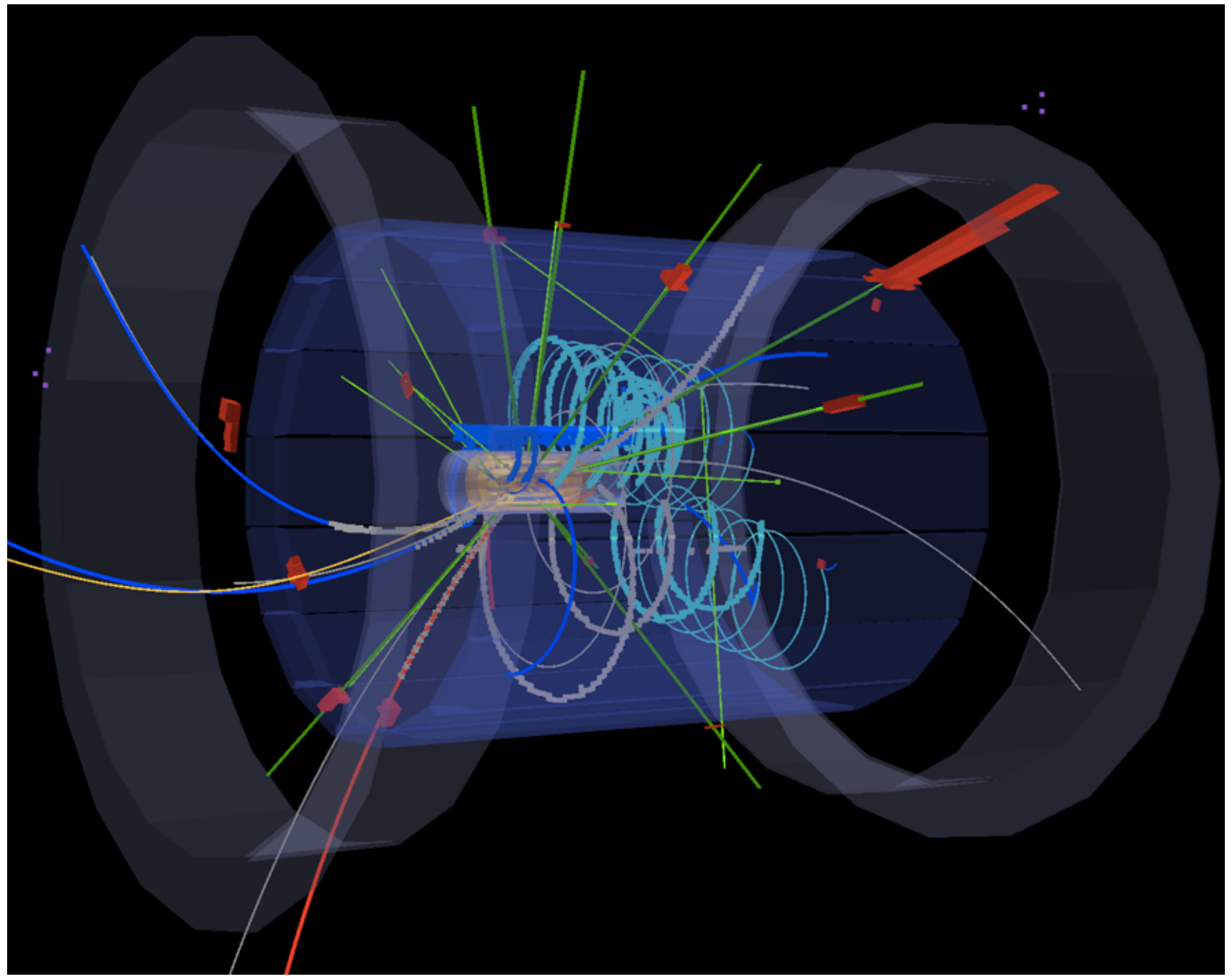
- Impact parameters: σ_{d0} Belle II ~ 0.5 x σ_{d0} Babar
- Vertex: σ_z Belle II ~ 0.5 x σ_z Belle
- Mass: σ_M Belle II ~ 0.7 x σ_M Belle
- Novel silicon—dedicated tracking. Good for D* efficiencies <$p_{\pi\text{-slow}}$> ~ 100 MeV.

Track efficiency



IP resolution



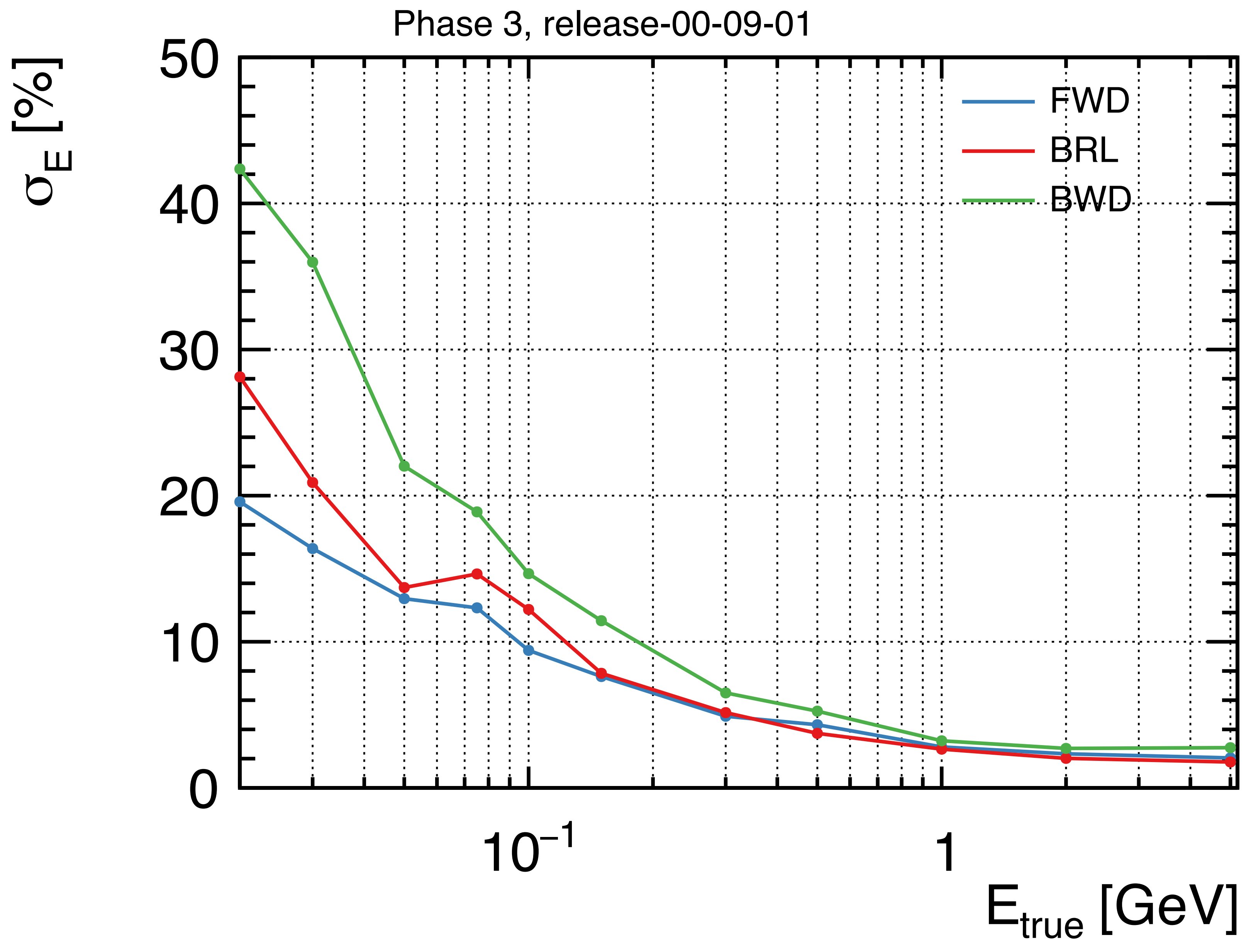


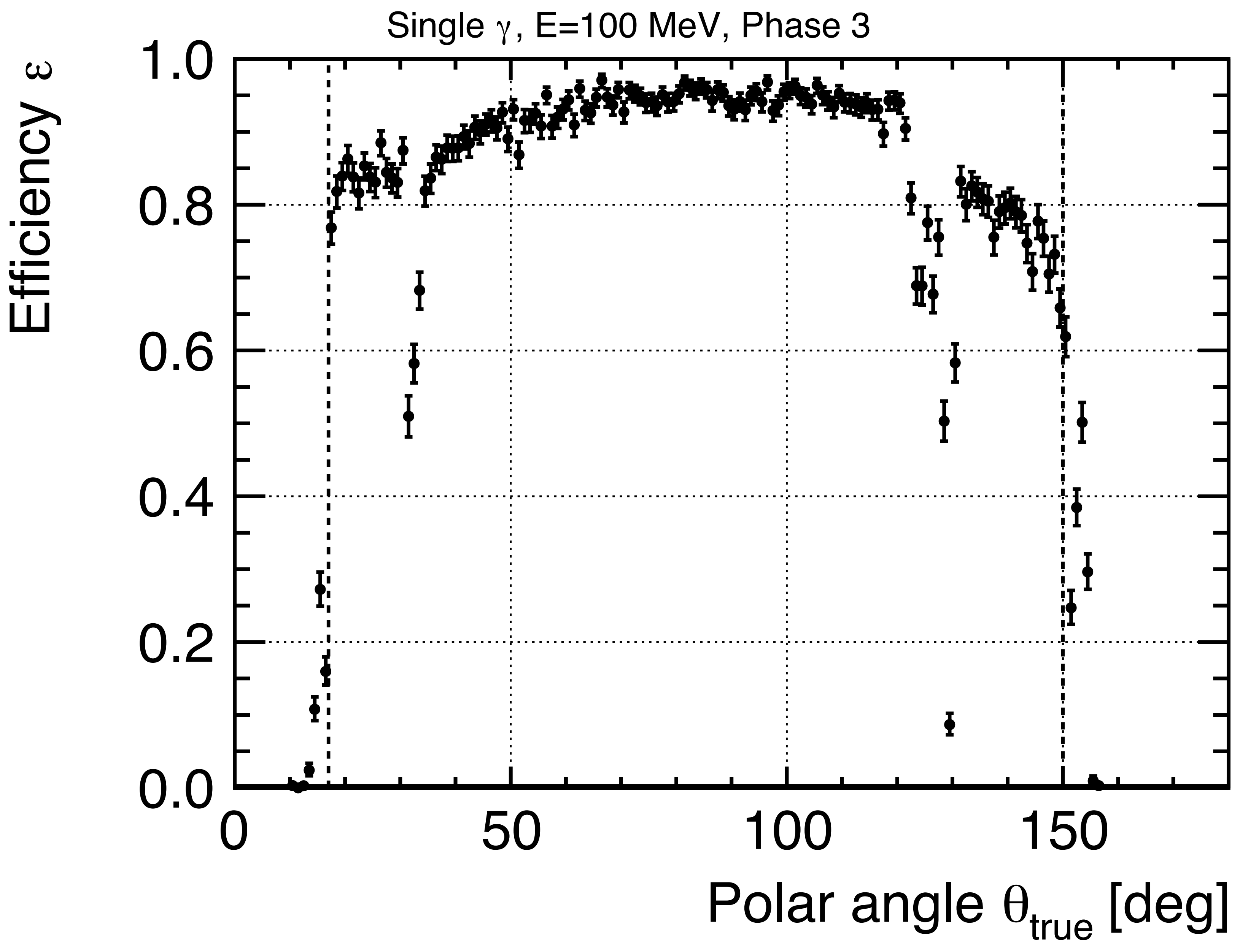
Photons reconstruction

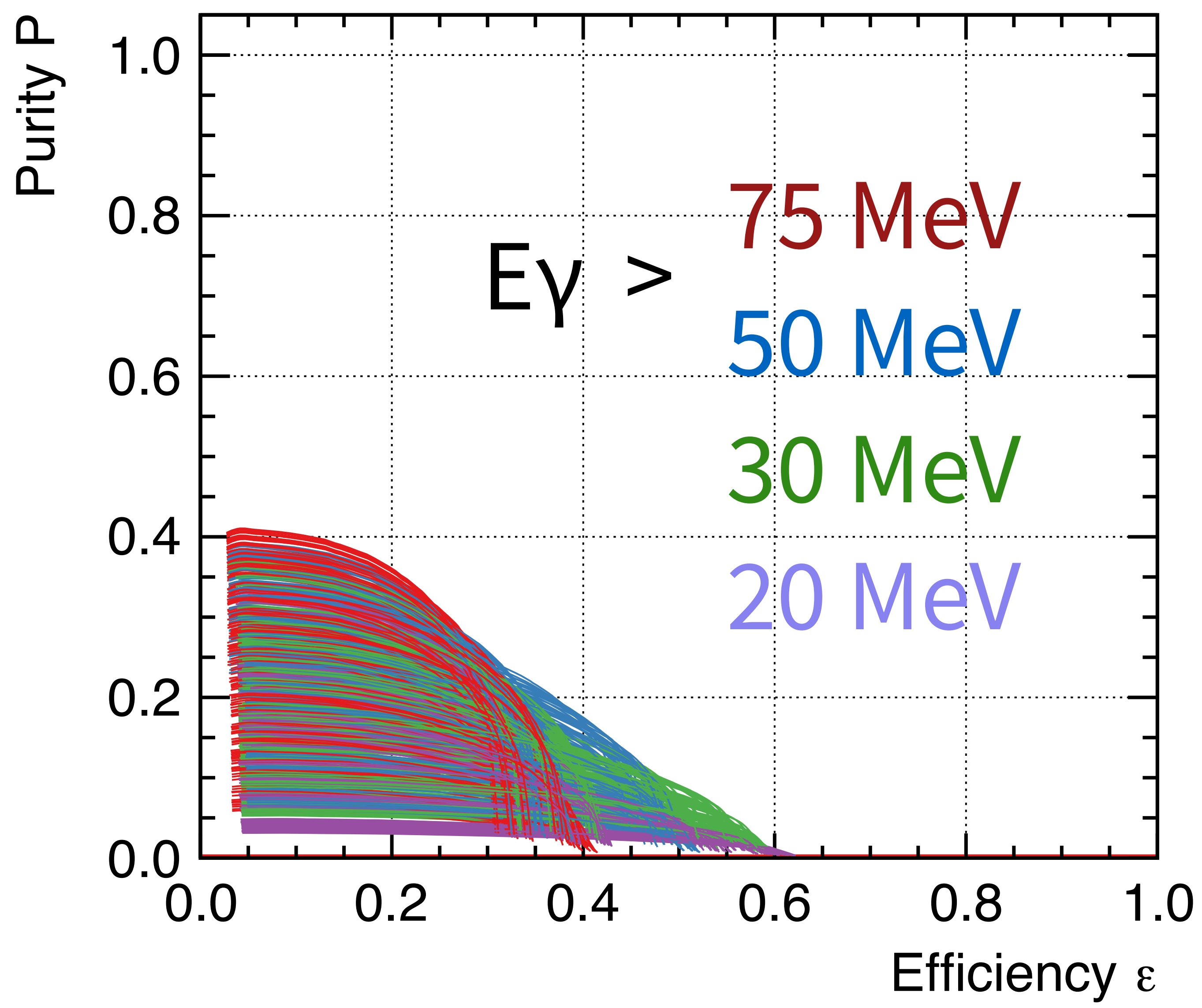
- Beam background mitigated with wave form sampling, timing.

ECL resolution

Photon and π^0 efficiencies



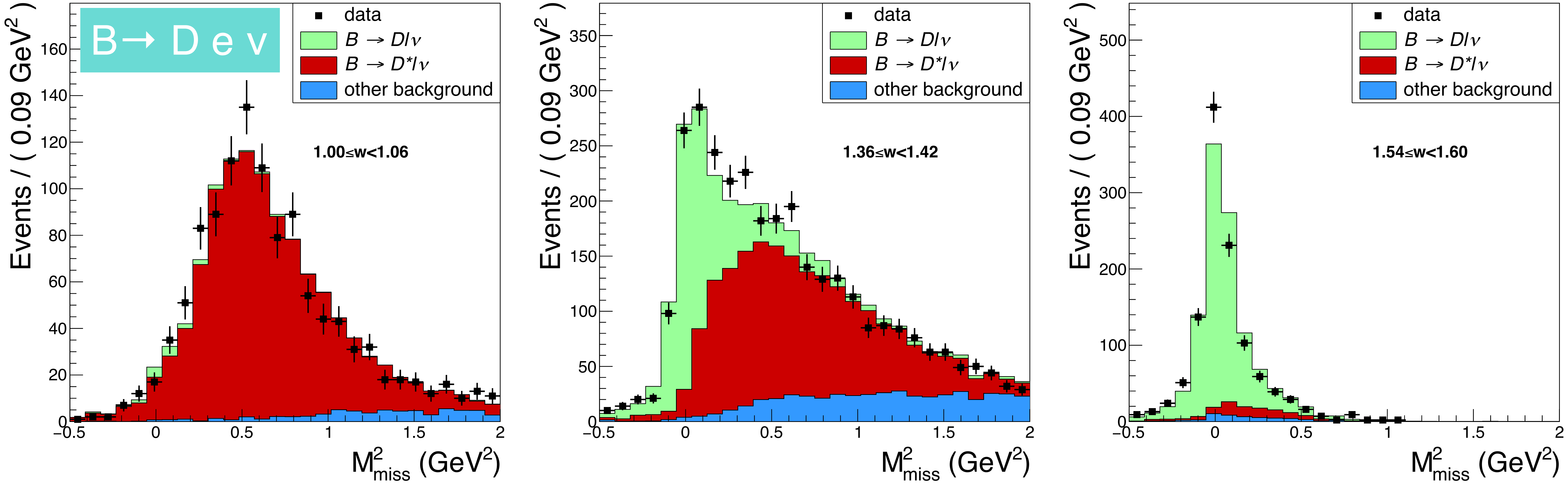




B → D l ν tagged

Belle PRD 93, 032006 (2016)

- Signal extract in 10 bins of w from M_{miss}^2
- Fit ~17000 signal events, use hadron B tag
- Largest background B→D* l ν
- First BGL analysis of b → c l ν



	$N = 4$
$a_{+,0}$	0.0126 ± 0.0001
$a_{+,1}$	-0.094 ± 0.003
$a_{+,2}$	0.34 ± 0.04
$a_{+,3}$	-0.1 ± 0.6
$a_{+,4}$	0.0 ± 1.0
$a_{0,0}$	0.0115 ± 0.0001
$a_{0,1}$	-0.057 ± 0.002
$a_{0,2}$	0.12 ± 0.04
$a_{0,3}$	0.4 ± 0.7
$a_{0,4}$	0.0 ± 1.0
$\eta_{\mathrm{EW}}\lvert V_{cb}\rvert$	41.10 ± 1.14
χ^2/n_{df}	$11.3/16$
Prob.	0.787

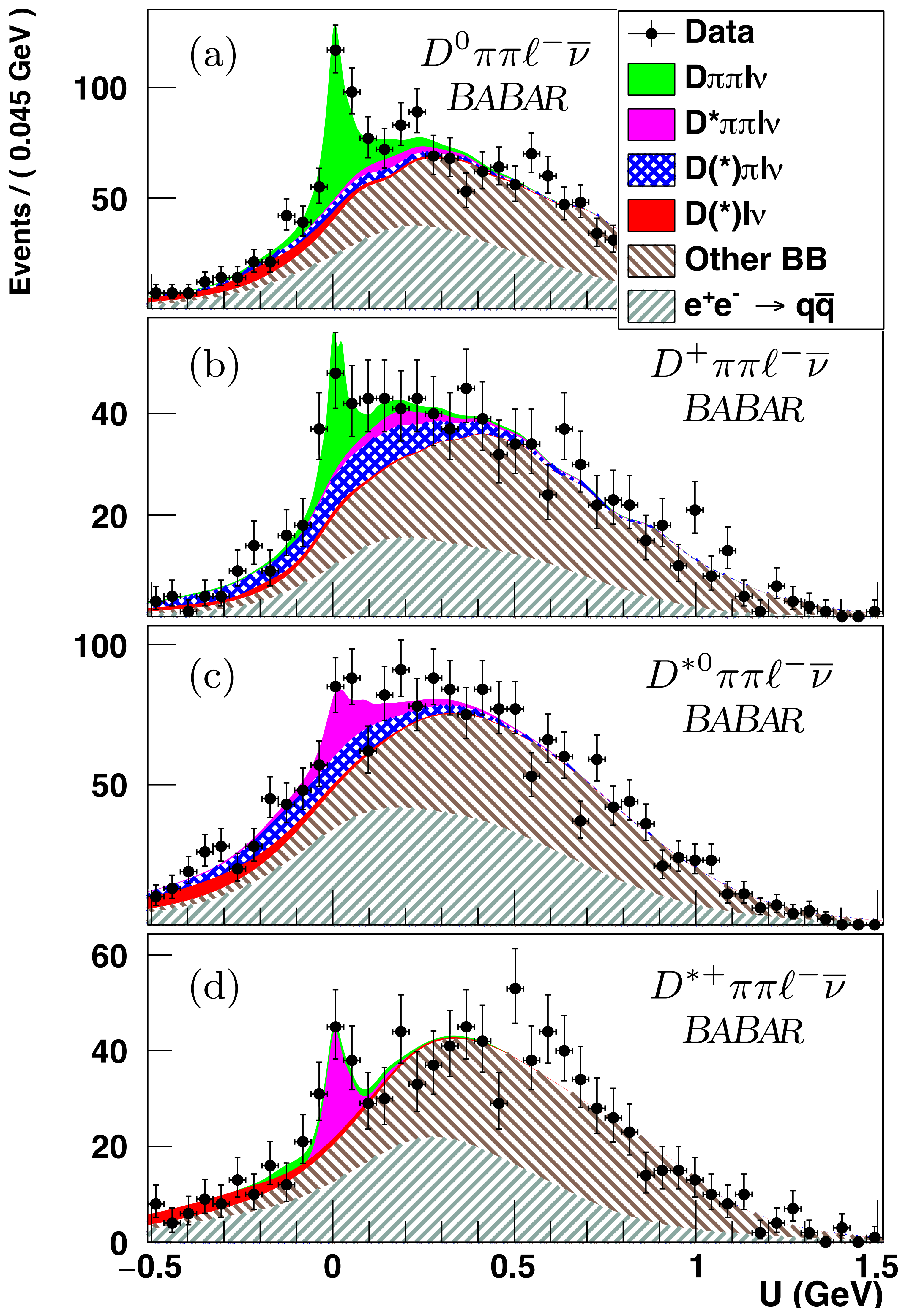
- Consistent results between the existing measurements.
- **Challenge is that a lot of information comes from w=1 but d Γ/dw → 0 at this point**

B → $D^{(*)} \pi\pi l \nu$

Babar PRL 116, 041801 (2016)

- Gap between inclusive B → Xc lν sum of known exclusive decays
- Good candidates: B → D(*)ππ(X)lν (could also be B → D(*)ηlν)
- Hadronic tag, normalise to B → D(*) l ν
- Unbinned ML fit
- Closes exclusive-inclusive gap to about 1% (10% of SL rate).

$$U \equiv E_{\rm miss} - |\vec{p}_{\rm miss}|c$$



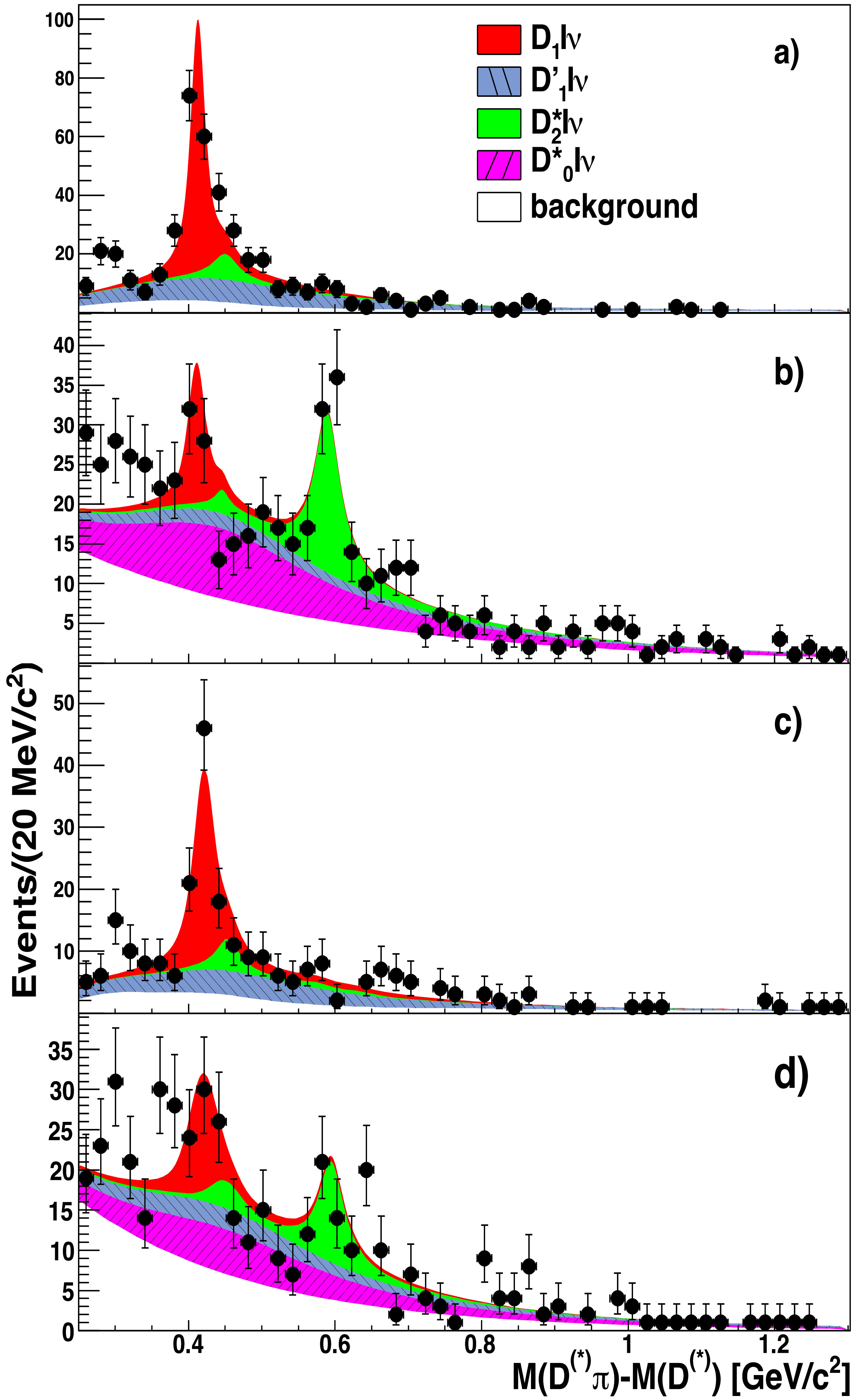
Channel	$R^{(*)}_{\pi^+\pi^-} \times 10^3$	$\mathcal{B} \times 10^5$
$D^0\pi^+\pi^-\ell^-\overline{\nu}$	$71 \pm 13 \pm 8$	$161 \pm 30 \pm 18 \pm 8$
$D^+\pi^+\pi^-\ell^-\overline{\nu}$	$58 \pm 18 \pm 12$	$127 \pm 39 \pm 26 \pm 7$
$D^{*0}\pi^+\pi^-\ell^-\overline{\nu}$	$14 \pm 7 \pm 4$	$80 \pm 40 \pm 23 \pm 3$
$D^{*+}\pi^+\pi^-\ell^-\overline{\nu}$	$28 \pm 8 \pm 6$	$138 \pm 39 \pm 30 \pm 3$
$D\pi^+\pi^-\ell^-\overline{\nu}$	$67 \pm 10 \pm 8$	$152 \pm 23 \pm 18 \pm 7$
$D^*\pi^+\pi^-\ell^-\overline{\nu}$	$19 \pm 5 \pm 4$	$108 \pm 28 \pm 23 \pm 4$

$B \to D^{**} l \nu$

Babar PRL 101:261802 (2008)

- Reconstruct $B \to D(^*)\pi^{\pm} l\nu$ in events tagged with hadronic B decays
- Simultaneous fit to $M(D(^*)\pi)$ or $M(D(^*)\pi)$ -$M(D(^*))$, including cross- feeds
- Background yield constrained from fit to B_{tag} mass. Shapes checked on wrong-sign data combinations
- Large rate for broad states!

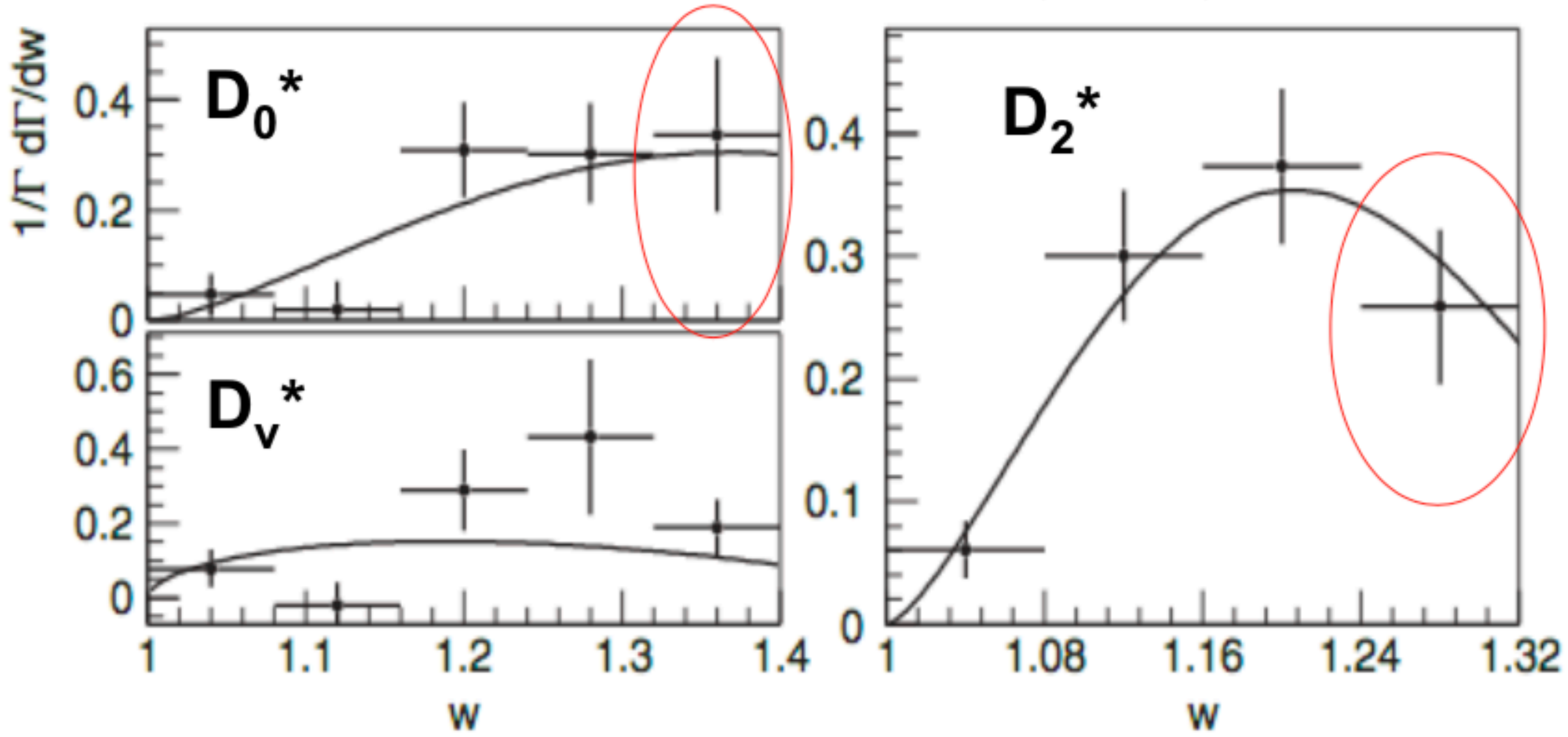
Decay Mode	Yield	$\epsilon_{\rm sig}(\times 10^{-4})$	$\mathcal{B}\ (\overline{B} \to D^{**}\ell^-\bar{\nu}_\ell\ ) \times \mathcal{B}(D^{**} \to D^{(*)}\pi^{\pm})$ %
$B^- \to D_1^0\ell^-\bar{\nu}_\ell$	165 ± 18	1.24	$0.29 \pm 0.03 \pm 0.03$
$B^- \to D_2^{*0}\ell^-\bar{\nu}_\ell$	97 ± 16	1.44	$0.15 \pm 0.02 \pm 0.01$
$B^- \to D_1^{\prime 0}\ell^-\bar{\nu}_\ell$	142 ± 21	1.13	$0.27 \pm 0.04 \pm 0.05$
$B^- \to D_0^{*0}\ell^-\bar{\nu}_\ell$	137 ± 26	1.15	$0.26 \pm 0.05 \pm 0.04$
$\overline{B}^0 \to D_1^+\ell^-\bar{\nu}_\ell$	88 ± 14	0.70	$0.27 \pm 0.04 \pm 0.03$
$\overline{B}^0 \to D_2^{*+}\ell^-\bar{\nu}_\ell$	29 ± 13	0.91	$0.07 \pm 0.03 \pm 0.01$ (< 0.11 @90% CL)
$\overline{B}^0 \to D_1^{\prime +}\ell^-\bar{\nu}_\ell$	86 ± 18	0.60	$0.31 \pm 0.07 \pm 0.05$
$\overline{B}^0 \to D_0^{*+}\ell^-\bar{\nu}_\ell$	142 ± 26	0.70	$0.44 \pm 0.08 \pm 0.06$



$B \to D^{**} l \nu$ exclusive measurements

Babar PRL 101:261802 (2008)
Babar PRL 103:051803 (2009)
Belle PRD 77:091503 (2008)

- $B \to D^{(*)} \pi l \nu$ - ultimately want to measure form factors
- Normalised with $D l \nu$ or $X l \nu$
- Strong model dependence in systematics - particularly broad J=1/2 modes.
- **Highly stats limited** (modelling errors can be overcome by measuring differentials)



	Belle tagged J=3/2 & 1/2	Babar tagged J=3/2 & 1/2
N_{BB} [10^6]	657	460
Error	%	%
Tracking		1.8-2.4
Particle ID	2	1.2-1.6
π^0 & γ Eff.		0.2-4.8
MC stats.	in stat.	-
Comb.&Cont.	-	0.2-10.4
Helicity corr.		**4.5-13.8**
Signal model	**12-22**	
PDFs		**0.2-8.7**
N_{BB}	-	-
D(*) Bfs	10	3-4.5
Norm		4-6
Bkg	6	-
total sys	**14-25**	**5.5-17**
total stat	**14-40**	**10-20**

B → D* τ⁻ ν with hadronic tag, τ → l ν ν

M. Huschle, PhD Thesis (2015)
Belle PRD 92, 072014 (2015)

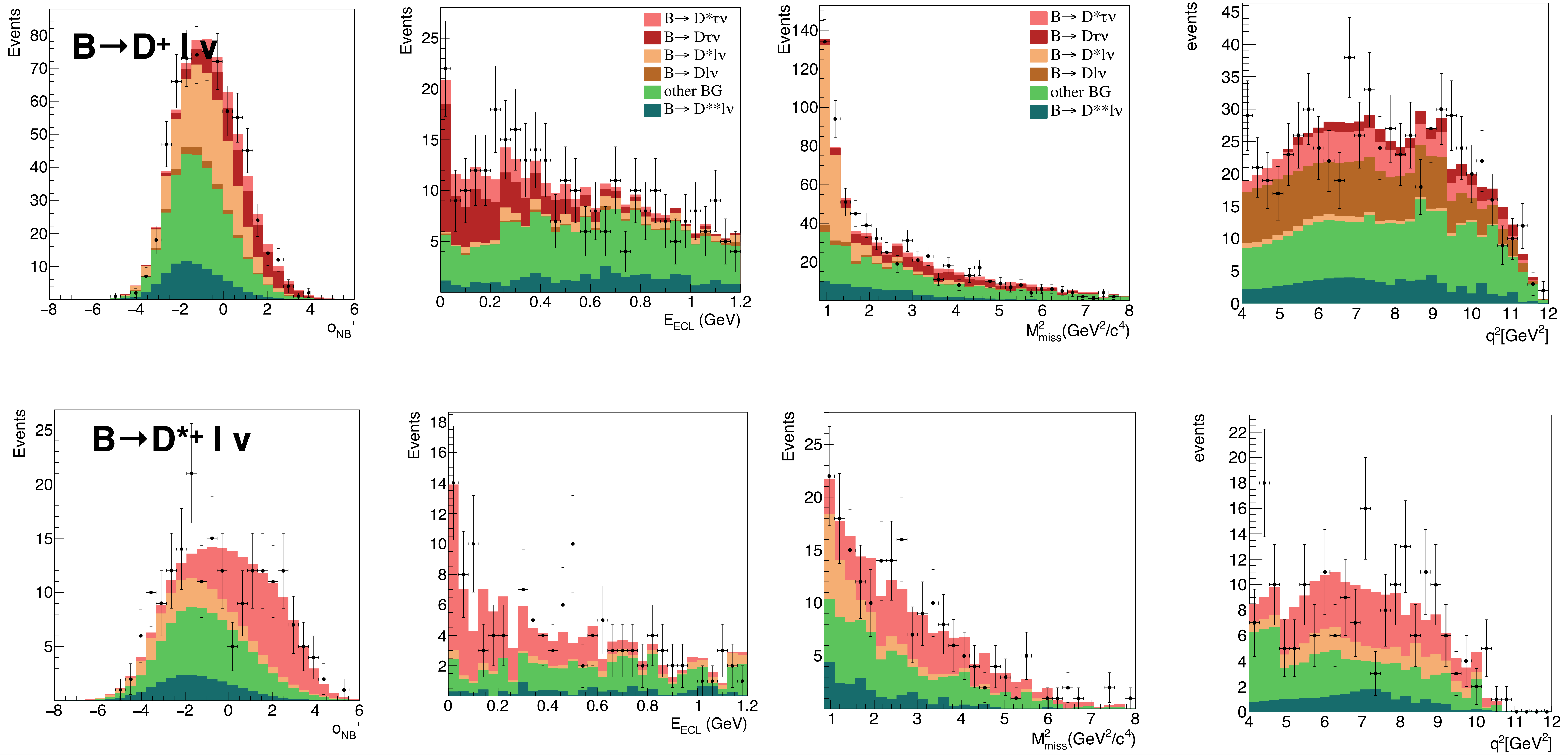
- Signal/Normalisation separation based on NB classifier and M^2_{Miss}
- B→D** l ν not directly constrained.

- B→ D τ⁺ ν : 320 ± 50(stat. - approx.) events
- B → D* τ⁺ ν : 503 ± 65 (stat. approx.) events (includes feed-down to D channel)

M^2_{miss}> 0.85 GeV

M^2_{miss}> 2 GeV

Un-subtracted q^2 distributions



Background calibration in $B \to D^* \tau \nu$, $\tau \to \pi \nu$

Phys. Rev. Lett. 118, 211801

- Hadronic modes where one particle is lost, mimics signal ν
  - Analyse B_{tag} + B_{signal} in hadronic mode & compared to MC (table)
  - Highly statistics limited - largest systematic error in τ→π ν analysis.
- K_L Modes e.g. $B \to D^* \pi K_L$ and $D^* K K_L$ are large background, corrected with MC. Better KL_{ID} at Belle II may help.

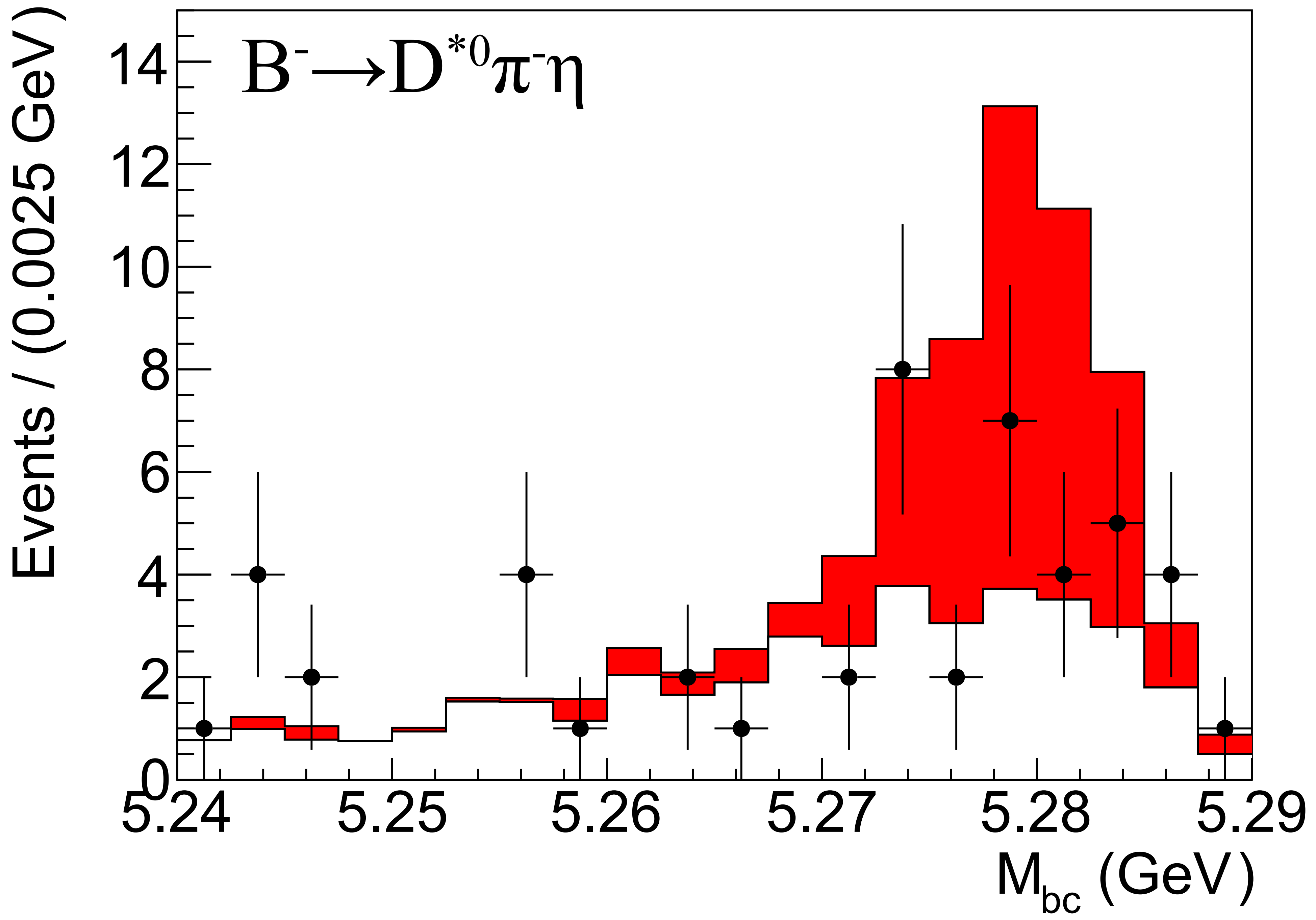


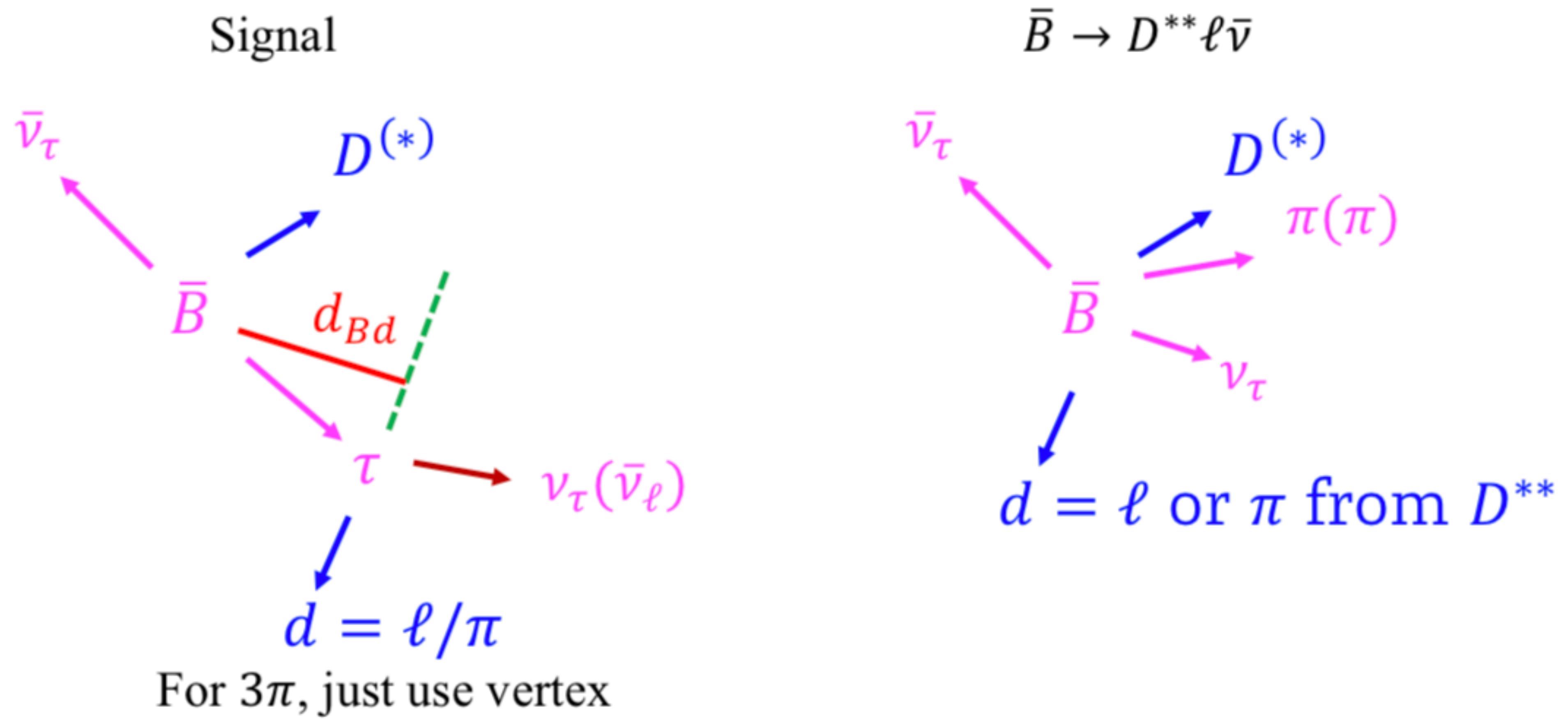
TABLE I. Calibration factors used to correct the hadronic B background rates in the MC simulation. The errors arise from the calibration sample statistics.

B decay mode	B^-	$\bar{B}^0$
$D^*\pi^-\pi^-\pi^+$	< 0.51	$0.62^{+0.67}_{-0.49}$
$D^*\pi^-\pi^-\pi^+\pi^0$	$0.31^{+0.43}_{-0.40}$	$0.59^{+0.45}_{-0.39}$
$D^*\pi^-\pi^-\pi^+\pi^0\pi^0$	$2.15^{+1.70}_{-1.60}$	$2.60^{+6.95}_{-2.24}$
$D^*\pi^-\pi^0$	$0.06^{+0.33}_{-0.28}$	< 0.47
$D^*\pi^-\pi^0\pi^0$	$0.09^{+1.04}_{-0.98}$	$1.63^{+0.74}_{-0.69}$
$D^*\pi^-\eta$	$0.24^{+0.21}_{-0.18}$	$0.15^{+0.16}_{-0.10}$
$D^*\pi^-\eta\pi^0$	$0.74^{+0.79}_{-0.75}$	$0.89^{+1.04}_{-0.88}$

$\tau \to 3\,\pi\,\nu$

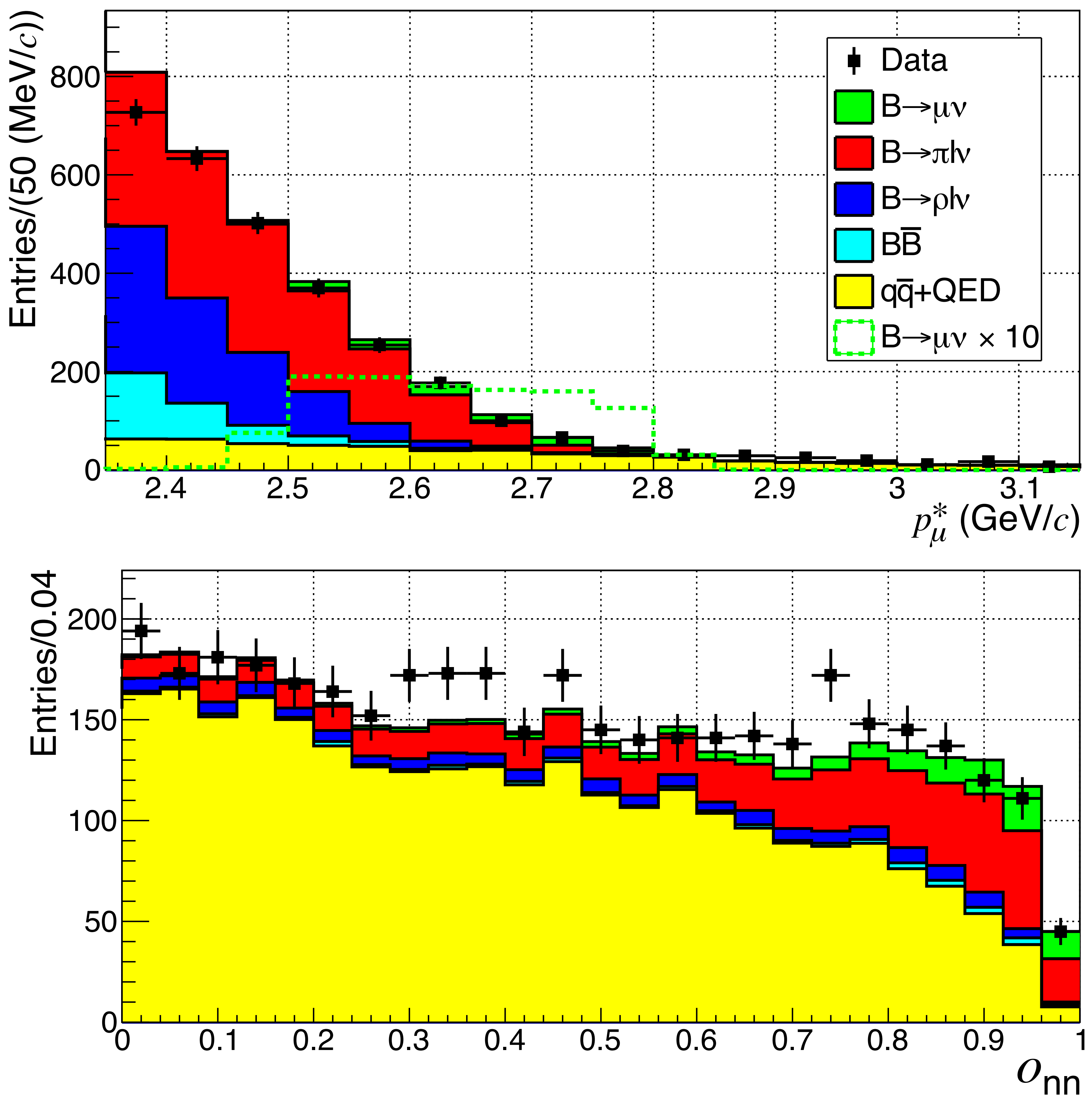
- At Belle we did an analysis of 1-prong τ decays
- We didn't try τ → 3 π ν because
  - Br(τ → π ν + ρ ν) = 36%
  - Br(τ → 3 π ν) = 9%
  - Analysis of τ → π ν was already low in purity.
  - τ → 3 π ν is less sensitive to Pτ(D*) which was the main motivation τ → π ν
- However τ → 3 π ν may be more interesting at Belle II
  - Belle II has better vertex separation - expect O(40 μm) precision on τ Vtx.
  - Access CP-odd observables.

M. Duraisamy and A. Datta, J. High Energ. Phys. 09 (2013) 059
K. Hagiwara et al., Phys. Rev. D 89, 094009 (2014)



B → μ ν (Light lepton LFUV tests)

- B → μ ν untagged result finds 2.4 σ significance, compatible with SM



SM prediction

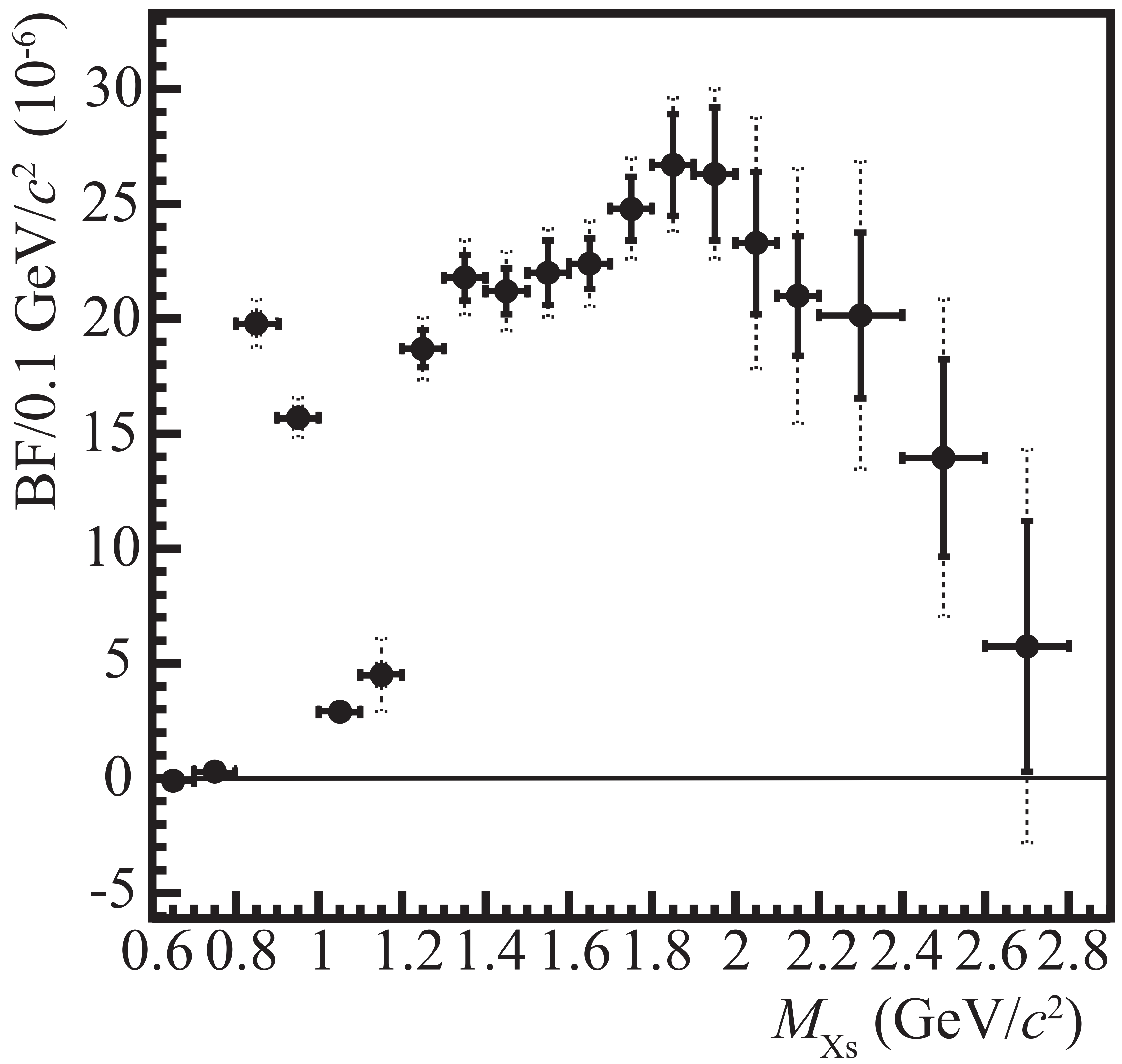
$$\mathcal{B}(B \to \mu\nu) = (3.80 \pm 0.31) \cdot 10^{-7}$$

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

$$\mathcal{B}(B^- \to \mu^- \bar{\nu}_\mu) = (6.46 \pm 2.22 \pm 1.60) \times 10^{-7}$$

Fragmentation challenge, c.f. B → X_s γ

- Rely on PYTHIA for inclusive modelling - requires large in situ corrections.
- X_s mass distribution is different in B → X_s γ and B → X_s l+l-
  - But we can use B → X_s γ data to measure fragmentation as a function of M_{Xs} and feed back to B → X_s l+l-



Belle, Phys. Rev. D 91, 052004 (2015)

Mode Category	Definition	Data	Default MC
1	$K\pi$ without π^0	4.2±0.4	10.3 (+17)
2	$K\pi$ with π^0	2.1±0.2	5.4 (+19)
3	$K2\pi$ without π^0	14.5±0.5	12.9 (−3.1)
4	$K2\pi$ with π^0	24.0±0.7	15.2 (−12)
5	$K3\pi$ without π^0	8.3±0.8	5.9 (−3.3)
6	$K3\pi$ with π^0	16.1±1.8	15.7 (−0.2)
7	$K4\pi$	11.1±2.8	12.3 (+0.4)
8	$K2\pi^0$	14.4±3.5	14.4 (−0.0)
9	$K\eta$	3.2±0.8	4.9 (+2.3)
10	$3K$	2.0±0.3	3.0 (+3.3)