B-Decays with Missing Energy at Belle II

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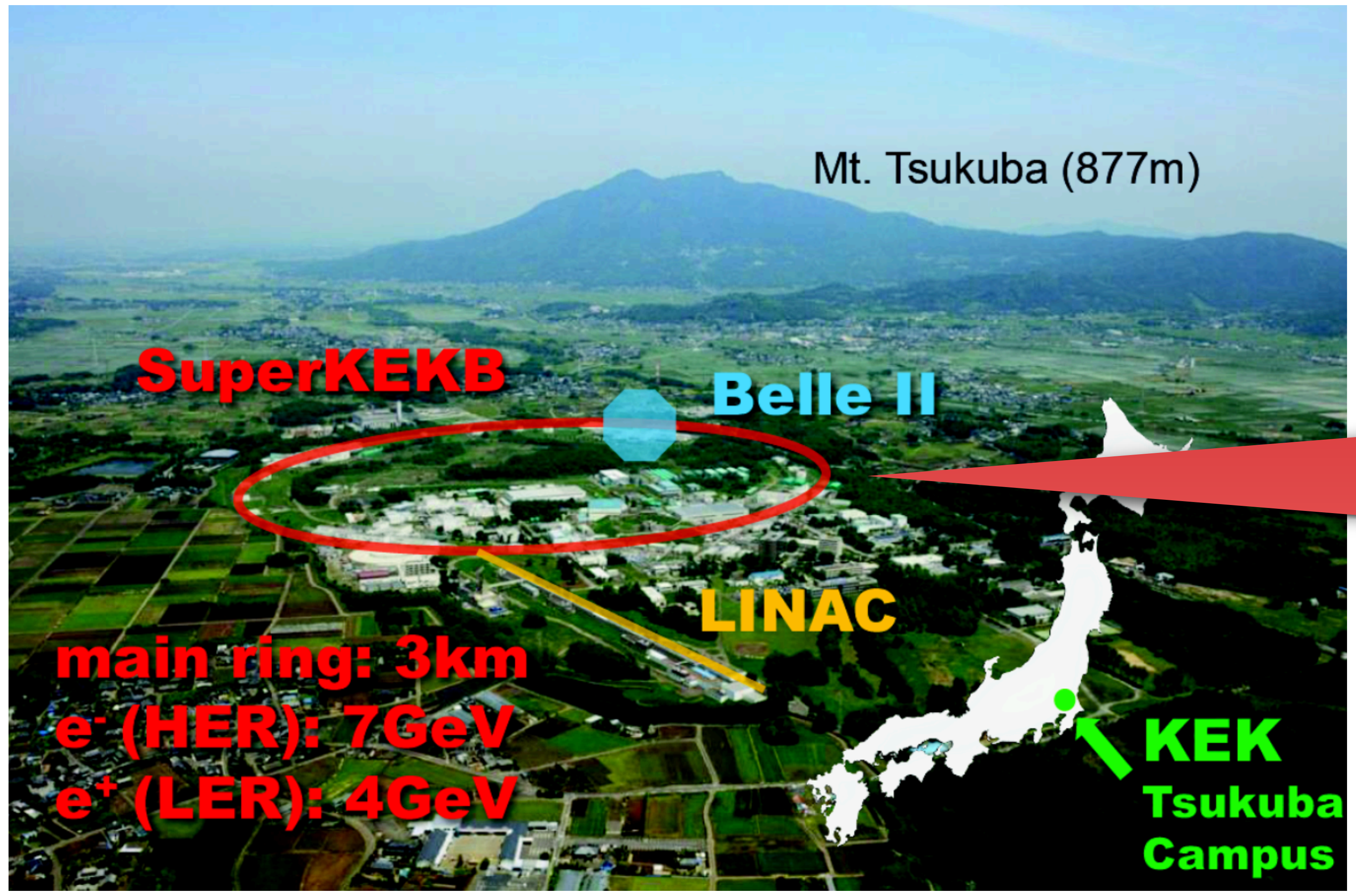
for the Belle II Collaboration

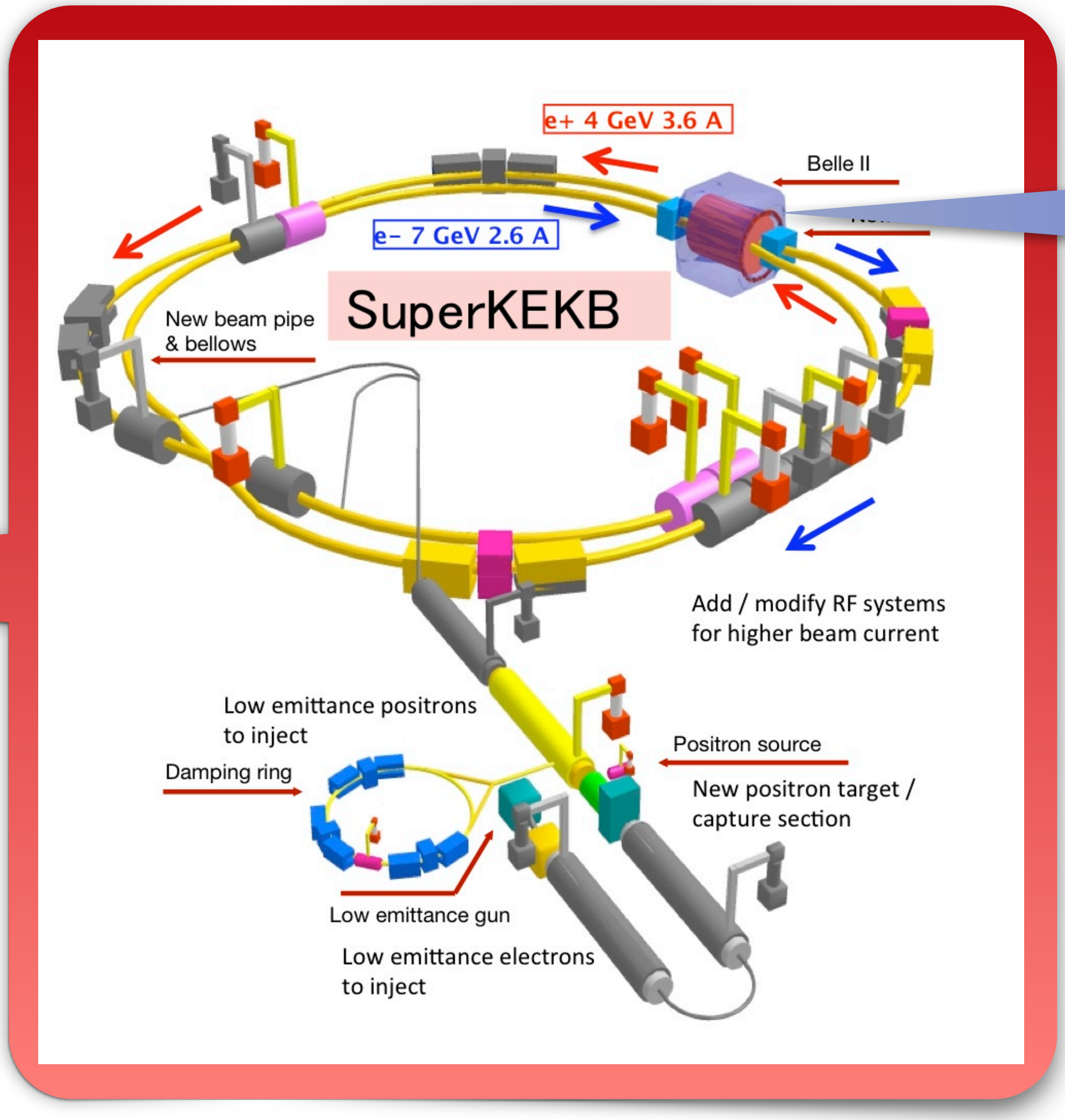
31 Jan. 2019 @ MITP, Mainz

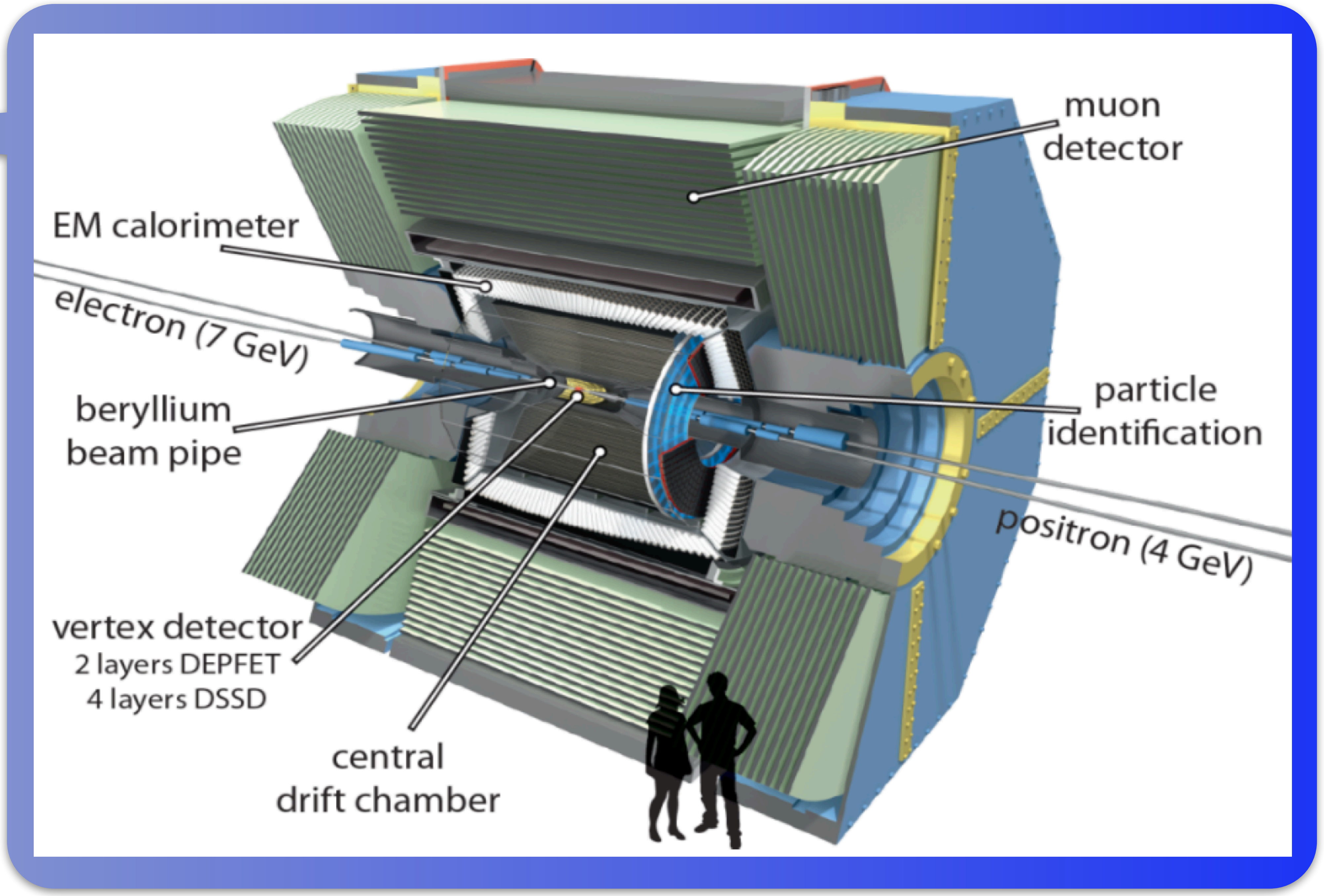
Belle II

Karlsruher Institut für Technologie

Belle II Experiment







- 40 times higher instantaneous luminosity from KEKB to SuperKEKB: $8 \times 10^{35} \mathrm{cm}^{-2} \mathrm{s}^{-1}$
- Detector upgraded for intenser particle multiplicity and tracking capacity
- Physics data taking with full detector will start soon

SuperKEKB/Belle II Schedule

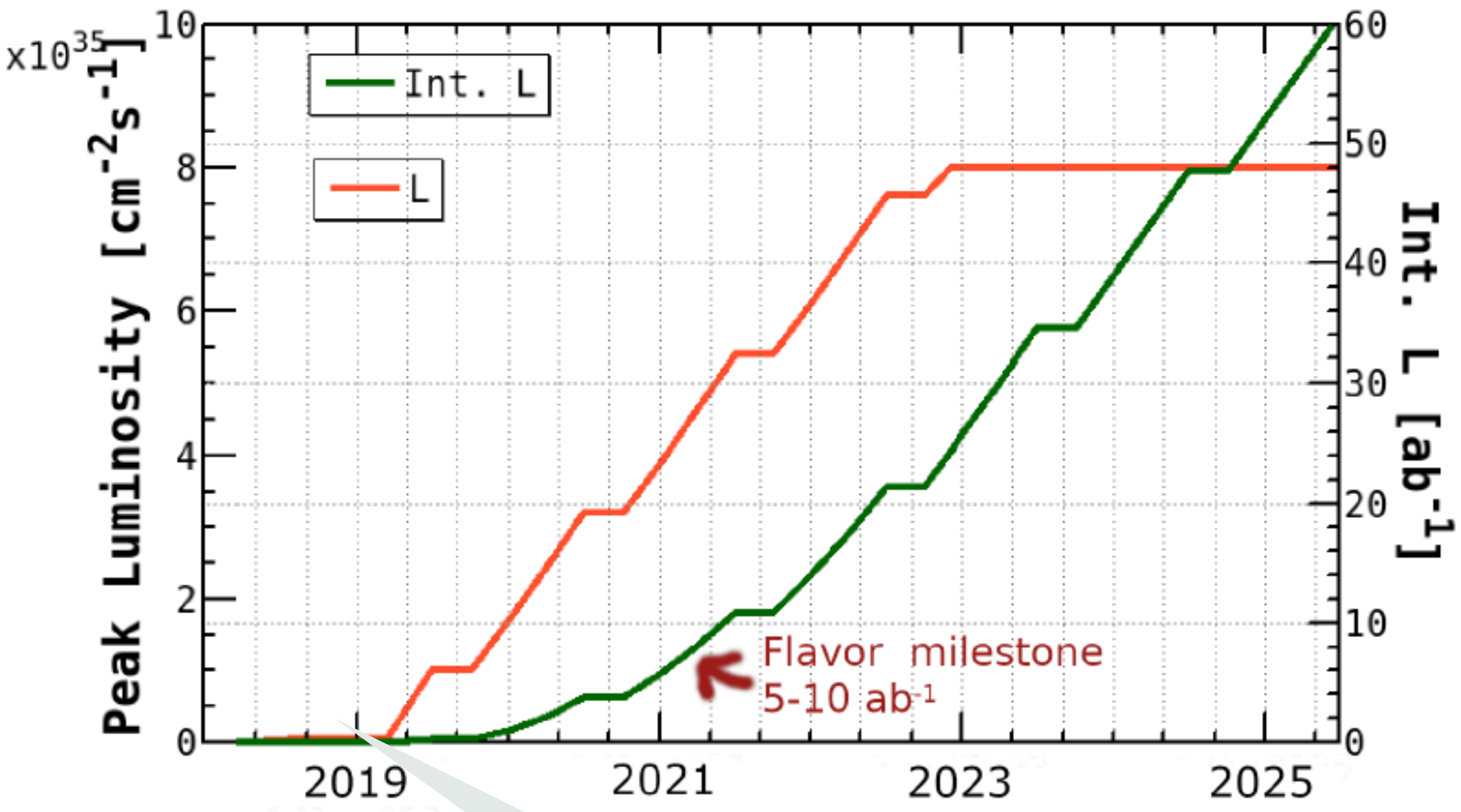
Phase 1: Bean operation run (2016) ✔

Phase 2: Commissioning run (2018) ✔

- With partial vertex detector
- Collected int. L = 0.5fb^{-1}

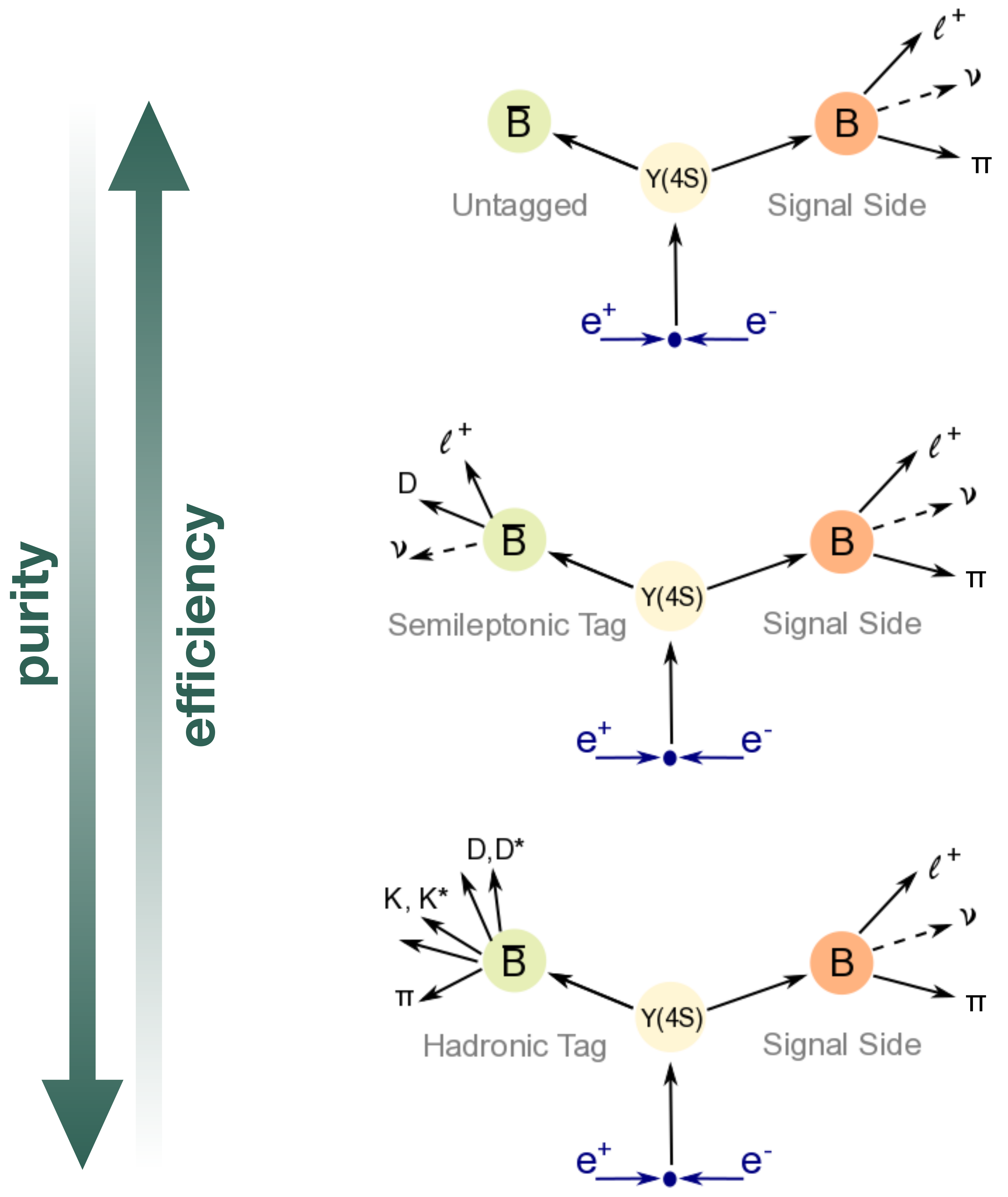
Phase 3: Physics run ⇐

- Will start in **March 2019**
- 9 months/year operation
- Will reach "**flavor milestone**" in two years
- will record integrated luminosity **50ab^{-1} by 2025**



Physics data is coming!!

Event Reconstruction with Tagging Techniques



- Untagged
  - Loose constraints on signal
  - Very large statistics, but also very large background
  - Efficiency $\epsilon \approx \mathcal{O}(100\%)$

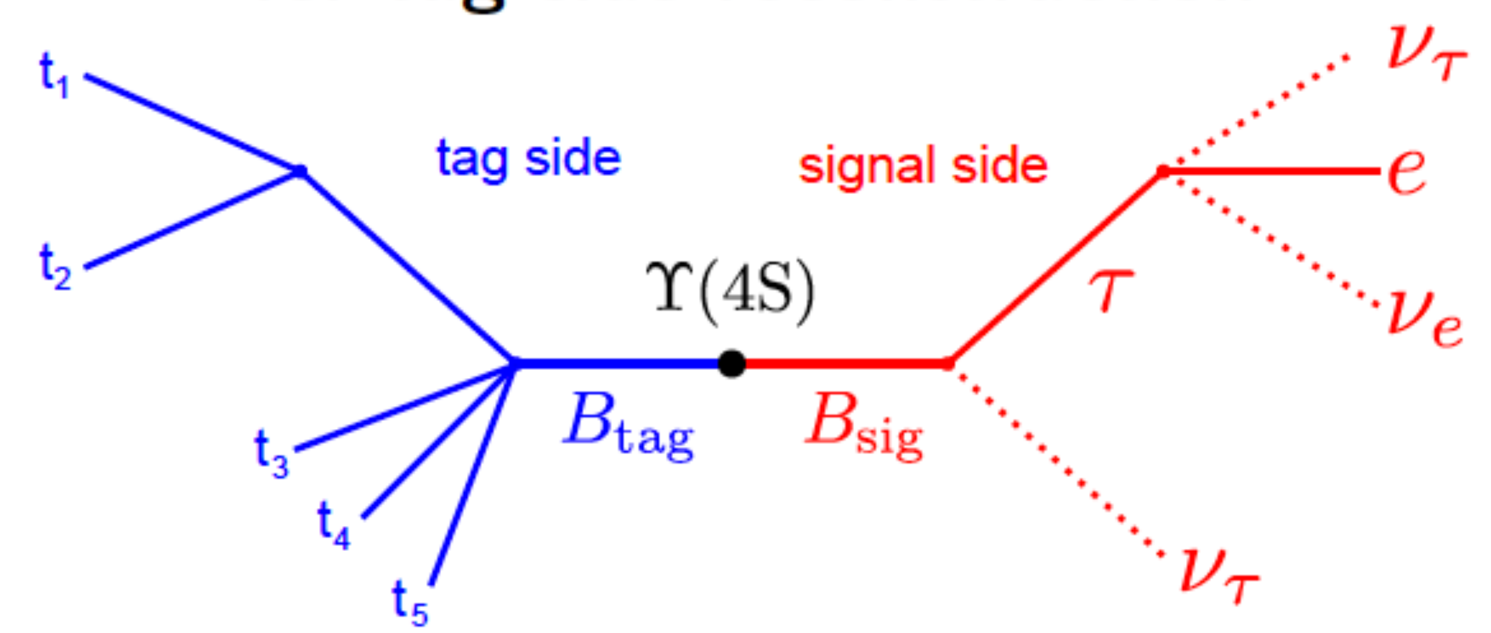
- Semileptonic tag
  - Mid-range reconstruction efficiency $\epsilon \approx \mathcal{O}(1\%)$
  - Due to multiple neutrinos, less information about B_{tag}

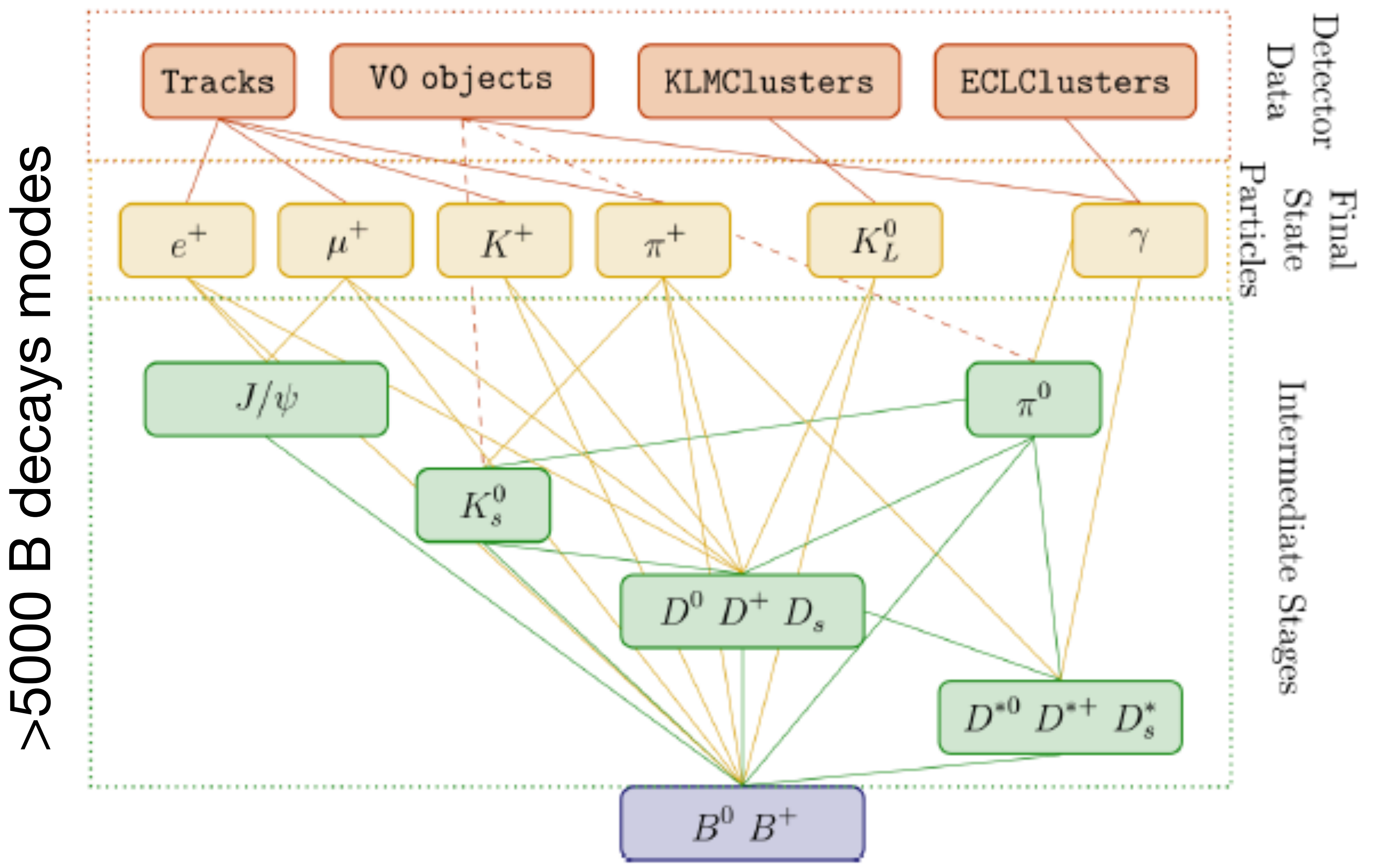
- Hadronic tag
  - Cleaner sample
  - Knowledge of $p(B_{sig})$
  - Low tag-side efficiency $\epsilon \approx \mathcal{O}(0.1\%)$

Improved Tagging Algorithms

Courtesy of W. Sutcliffe

New Full Event Interpretation (FEI) algorithm for tag-side reconstruction





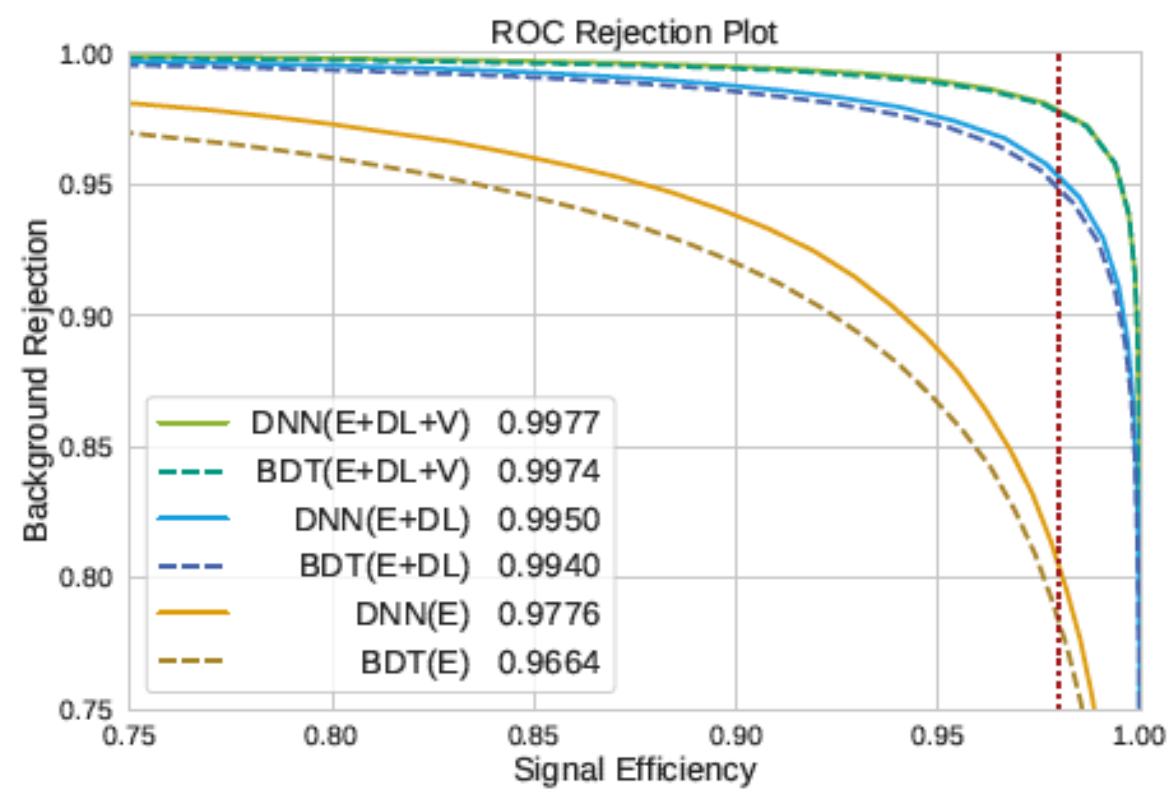
[1] T. Keck; [2] J. Gemmler; [2] D. Weyland

Tagging ε on MC

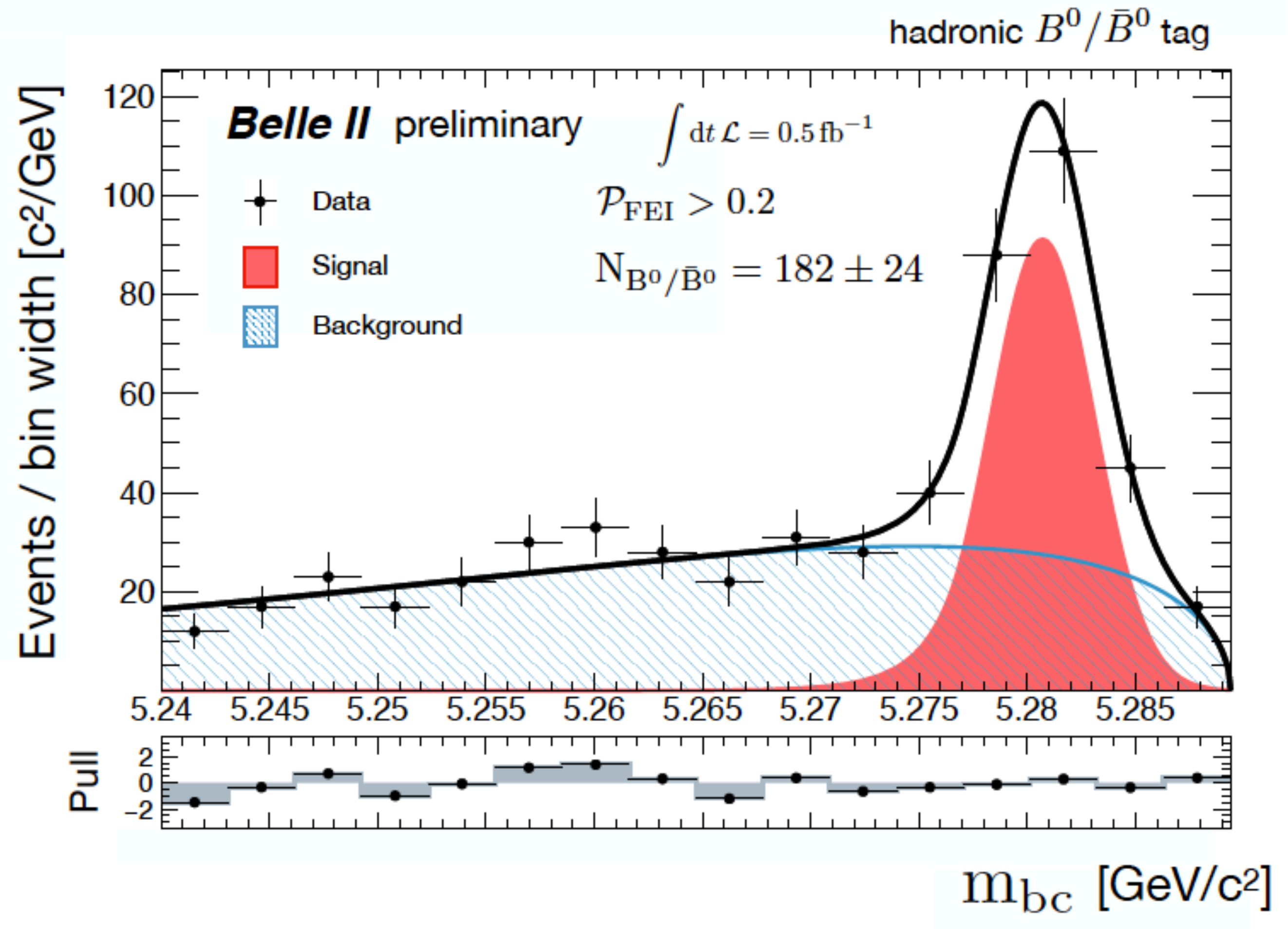
Tag	FR[1]	FEI Belle	FEI Belle II
Hadronic B^+	0.28%	0.76%	0.66%
SL B^+	0.67%	1.80%	1.45%
Hadronic B^0	0.18%	0.46%	0.38%
SL B^0	0.63%	2.04%	1.94%

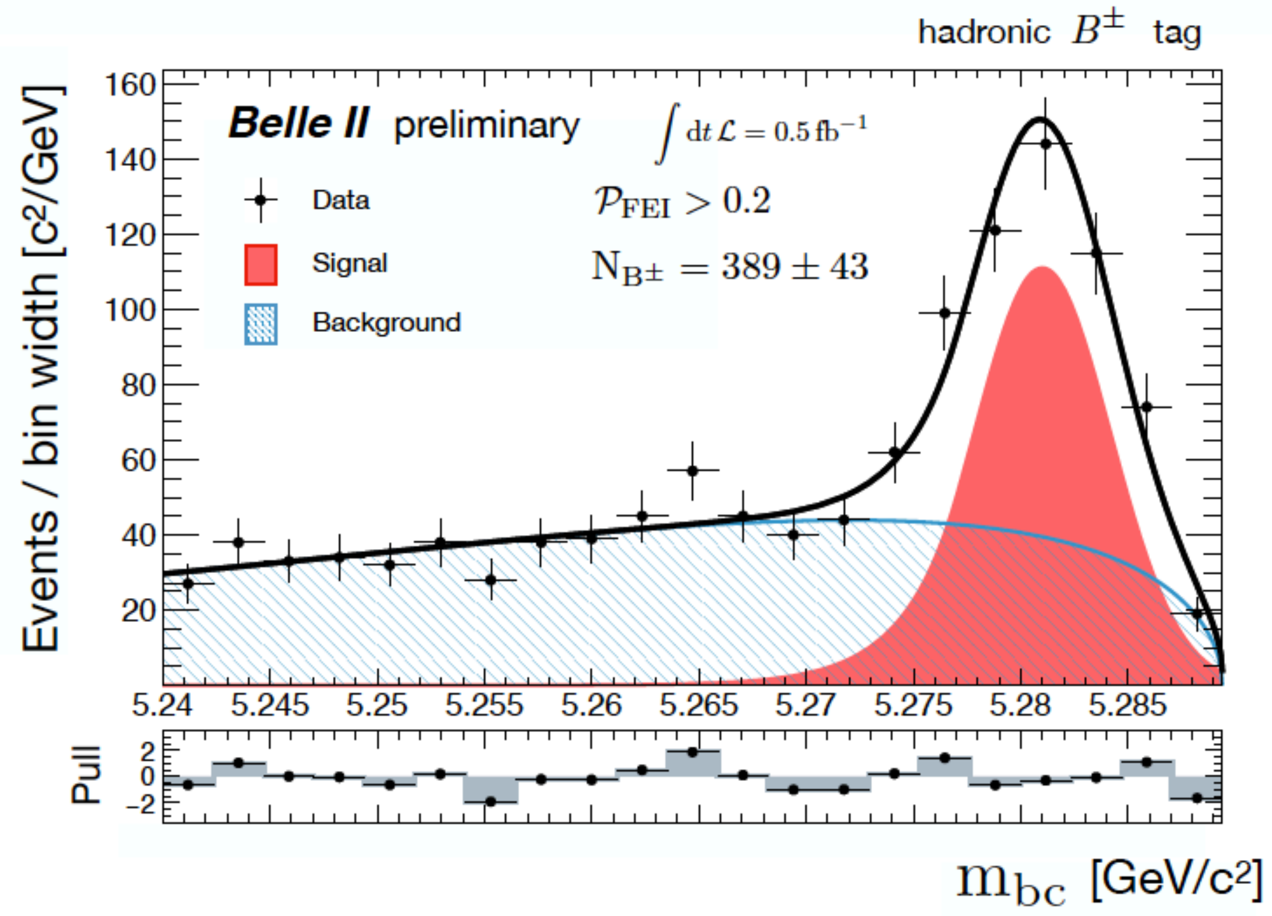
[1] Belle Full Reconstruction algorithm.

Deep NN based $e^+e^- \to q\bar{q}$ background suppression



Phase 2 data

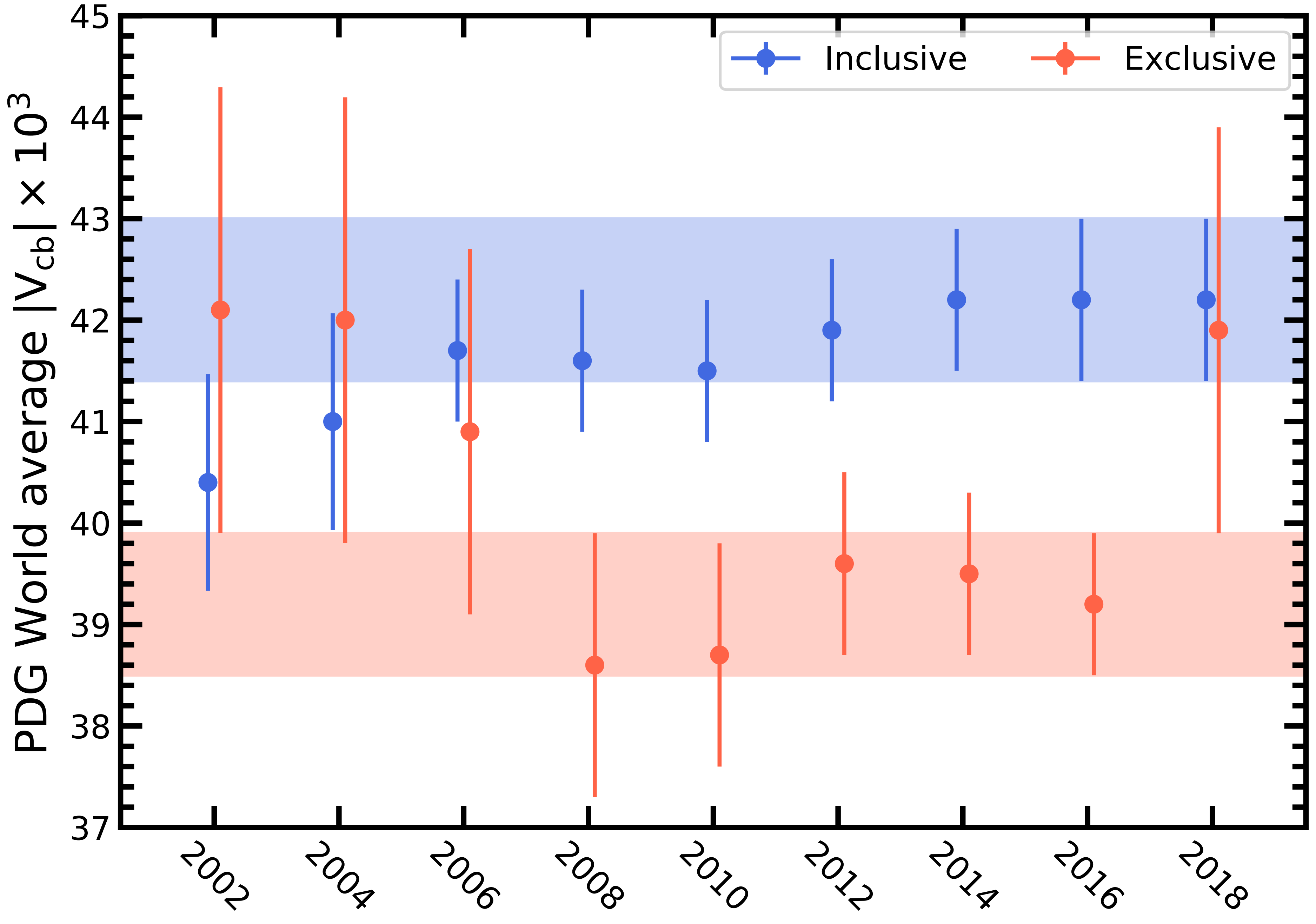




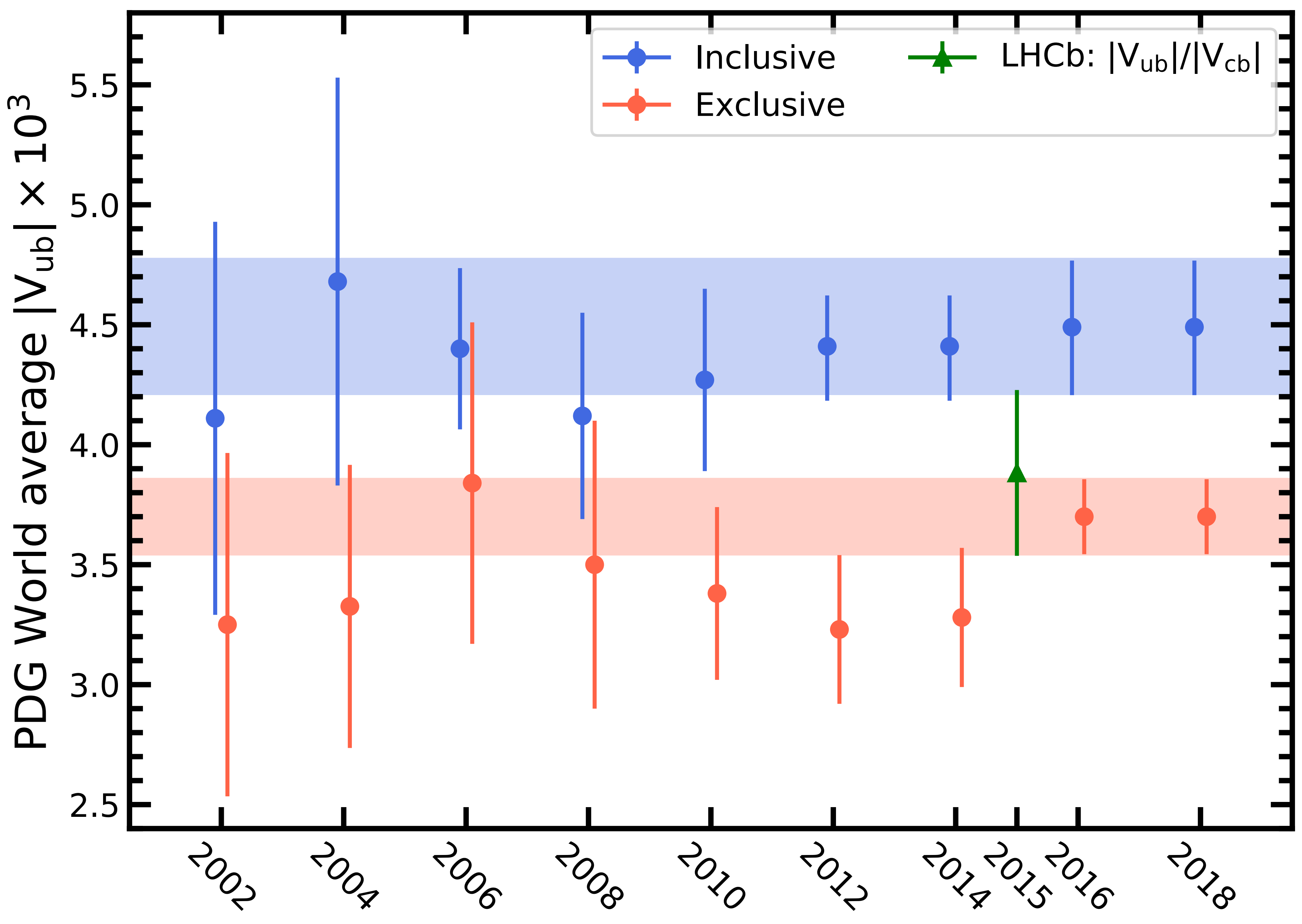
$$M_{bc} = \sqrt{(\sqrt{s}/2)^2 - \vec{p}^{\,2}_{B_{tag}}}$$

Long-Standing Puzzle: Inclusive vs. Exclusive $|V_{cb}|$ & $|V_{ub}|$

V_{cb}



V_{ub}



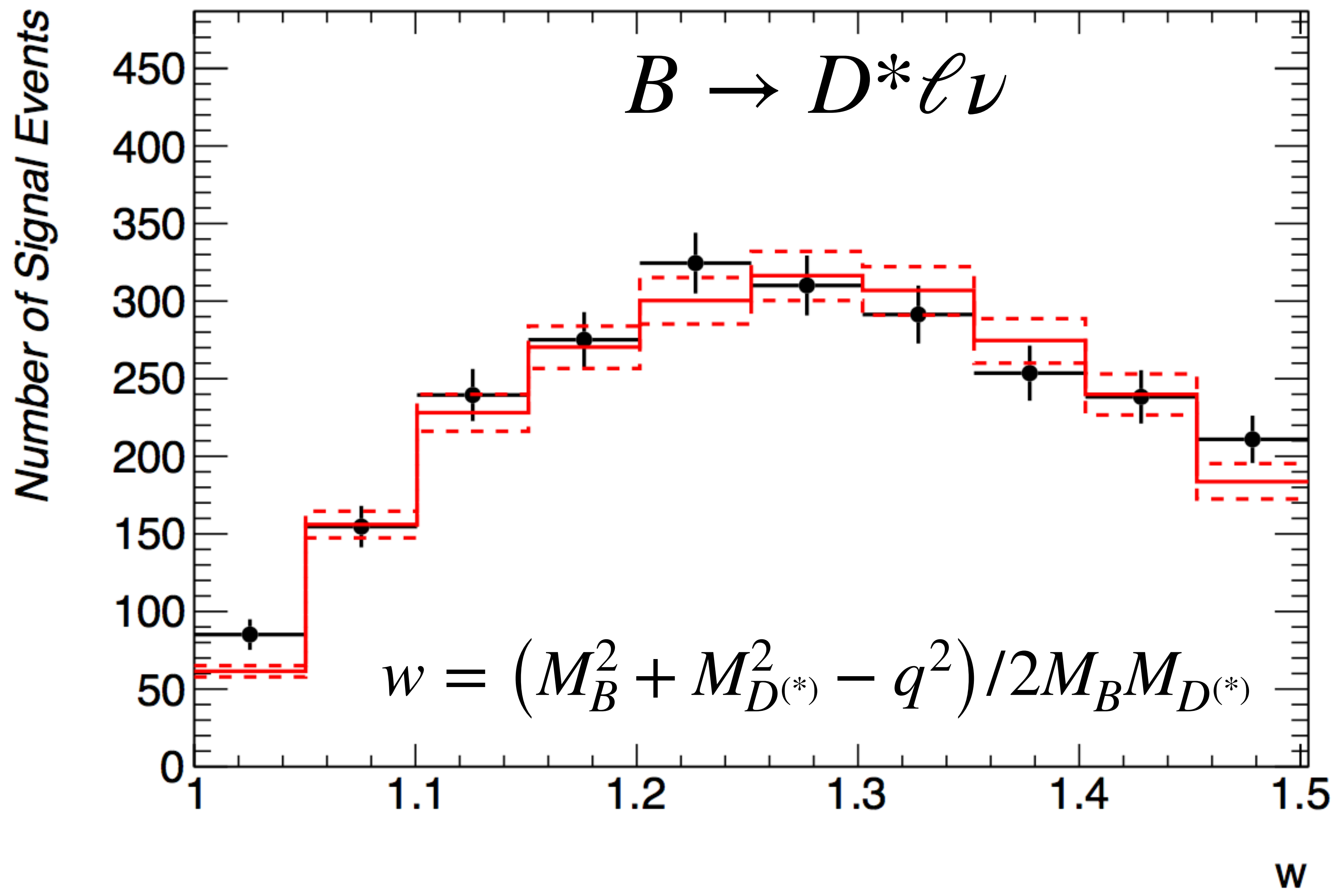
- 3σ deviation between excl. vs. incl.
- PDG2018 exclusive value based on only measured unfolded differential decay rates in $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_\ell$ from Belle using BGL parameterisation 1702.01521
- More unfolded results needed

- 3.5σ discrepancy between excl. vs. incl.
- LHCb provided ratio with baryonic b-decays (NP 2015)
- Leptonic measurements not precise enough, favours inclusive results
- More precise leptonic measurements needed

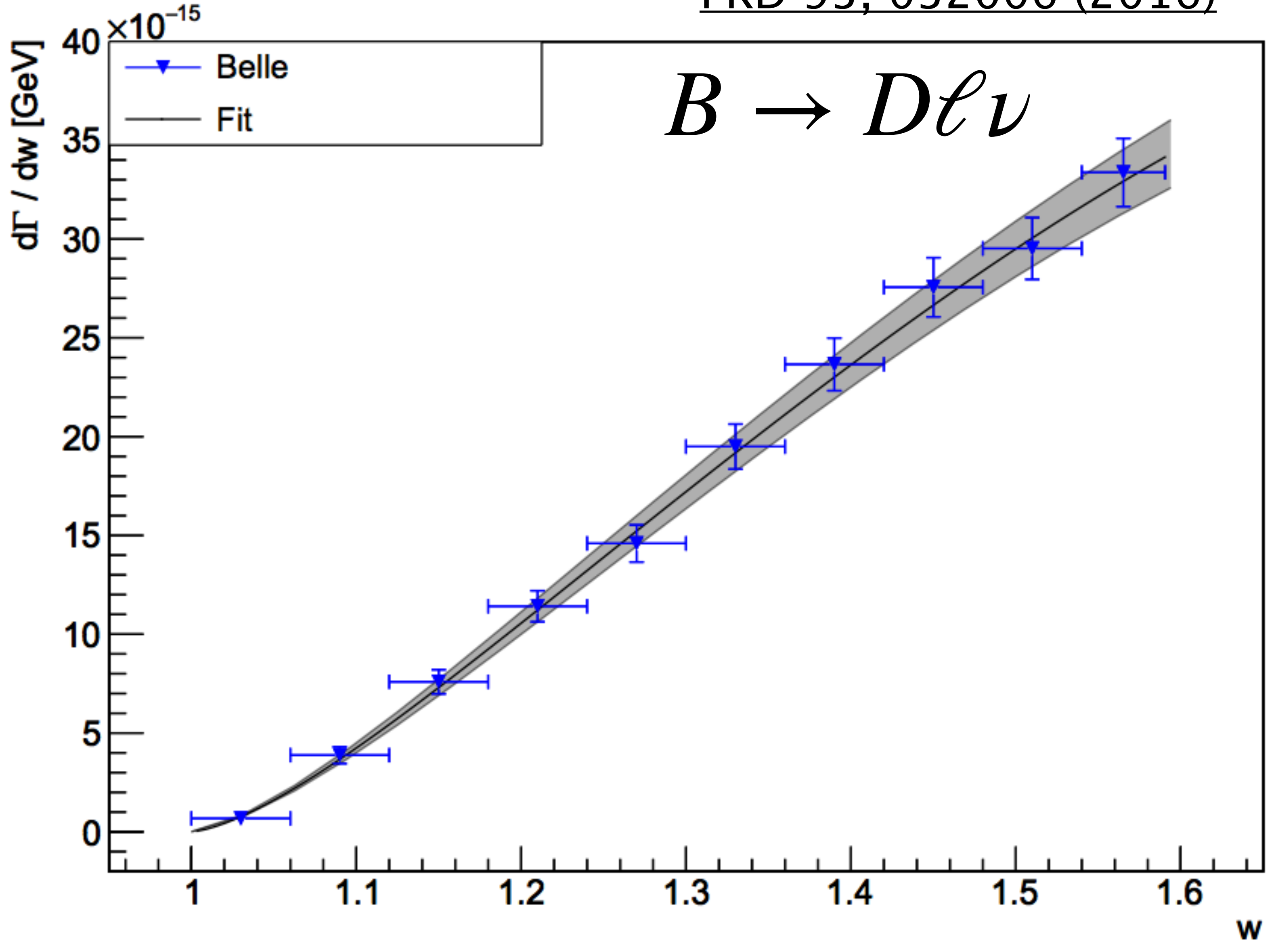
Exclusive |Vcb| in $B \to D^{(*)}\ell\nu$

- Recent two measurements from Belle (both provide unfolded differential decay rate)
- Hadronic tagging allows missing mass constraint on signal side $M^2_{\text{miss}} = \left(p_{e^+e^-} - p_{B_{\text{tag}}} - p_{D^{(*)}} - p_l\right)^2$
- Leading systematic uncertainty is from hadronic tag calibration (can be improved with FEI for Belle II)
- Extract $|V_{cb}|$ requires **form factor** parametrisation and LQCD input as normalisation
- Bonus: separating electron-muon to test lepton flavor universality via $R_{e/\mu}$

1702.01521



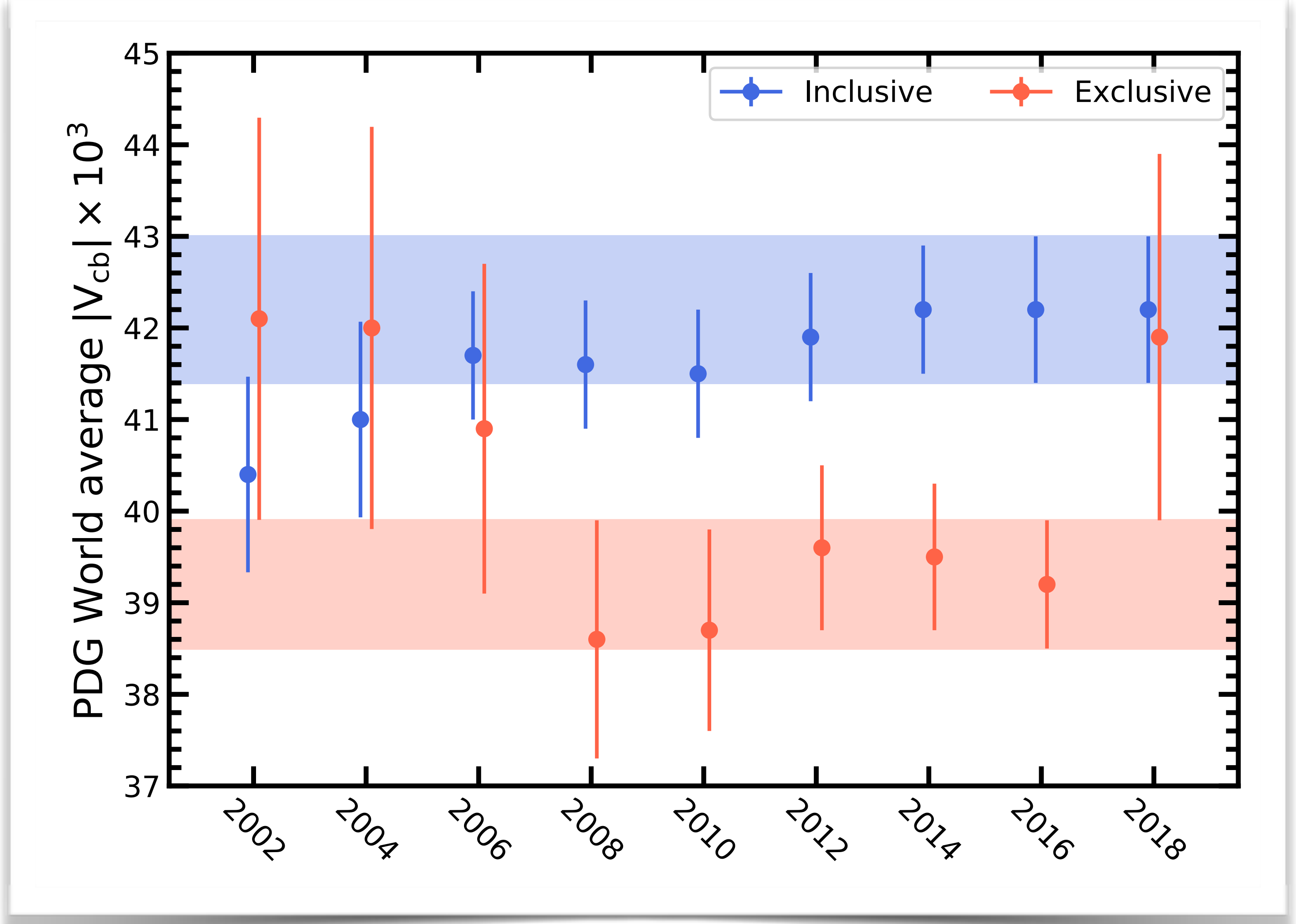
PRD 93, 032006 (2016)



Form Factor: CLN or BGL ?

Courtesy of F. Bernlochner

- Change from CLN to BGL lead to 10% discrepancy in $|V_{cb}|$ determination
- Might resolve inclusive vs. exclusive puzzle
- Full kinematic dependence of $B \to D^* \ell \nu$ f.f. from LQCD is underway



D* **unfolded** distributions analyzed by three groups

$\bar{B} \to D^* \ell \bar{\nu}_\ell$

CLN	*D**
$|V_{cb}| \times 10^3$	**38.2 ± 1.5**

CLN: Phys. Lett. B380, 376 (1996)

From unfolded data, slightly higher than 'folded' result of previous slide

→

Includes additional measurement & beyond zero recoil lattice constraints

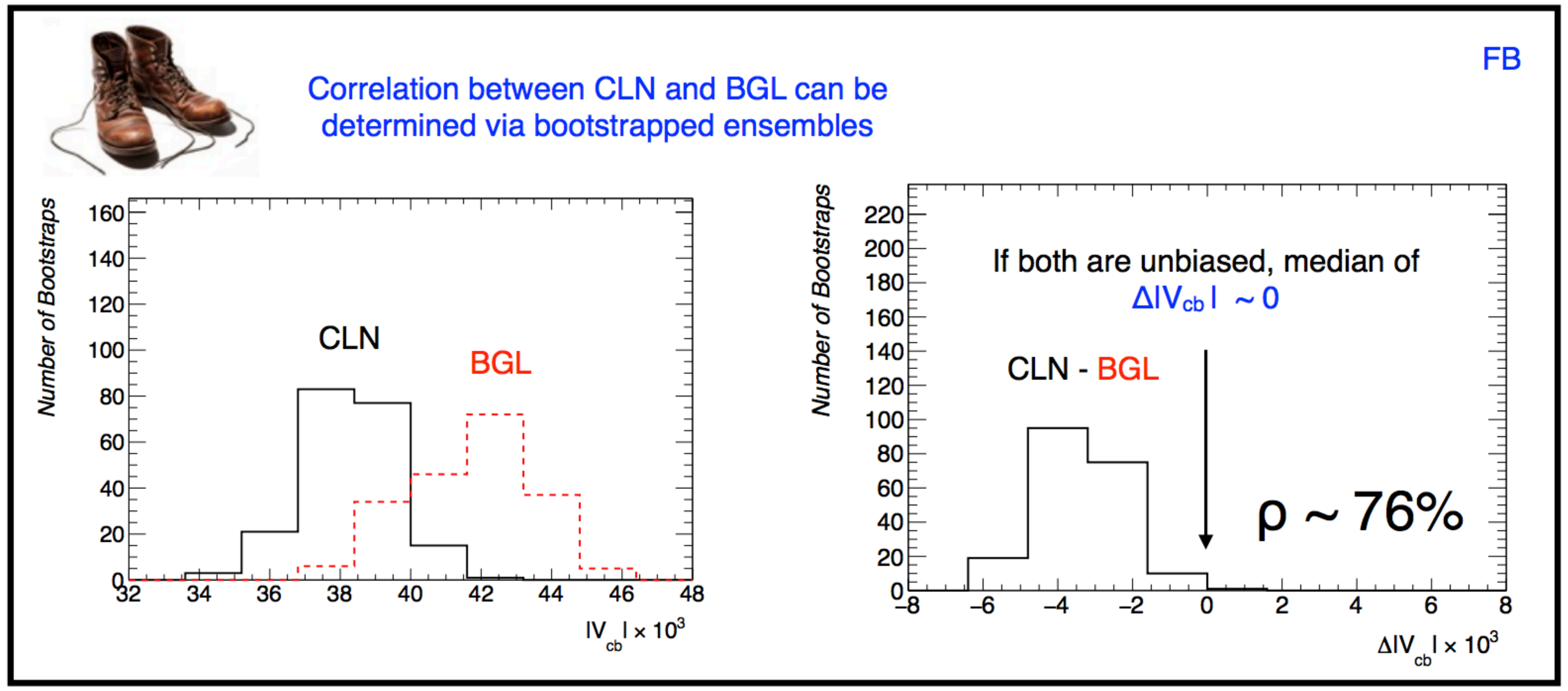
1703.06124, 1703.08170

BGL	*D**
$|V_{cb}| \times 10^3$	**41.9 ± 1.9**

BGL: Phys. Rev. Lett. 74, 4603 (1995)

1703.05330

CLN'	*D + D**
$|V_{cb}| \times 10^3$	**39.3 ± 1.0**



CLN ⟷ BGL
~3 σ

Naive estimate with ρ = 100% correlation gives a ~9σ tension

Similar results seen in PRL 109, 071802(2012) PRD 92(5), 054510(2015) PRD 94, 094008(2016) PLB 769, 441(2017)

Inclusive $B \to X_c l\nu$

$$\Gamma = \frac{G_F^2 m_b^5}{192\pi^3} \left| V_{cb} \right|^2 \left(1 + \frac{c_5(\mu)\langle O_5 \rangle(\mu)}{m_b^2} + \frac{c_6(\mu)\langle O_6 \rangle(\mu)}{m_b^3} + \mathcal{O}\left(\frac{1}{m_b^4}\right)\right)$$

- Latest measurement is from the year 2010!
- Current global fit based on measured moments of E_l, M_X^2
- 2% tot. uncertainty limited by theoretical uncertainty (1.2%~1.4% at Belle II 50ab^{-1})
- New method using q^2 moments has been proposed 1812.07472

Untagged $B \to \pi l \nu$ @ Belle II MC

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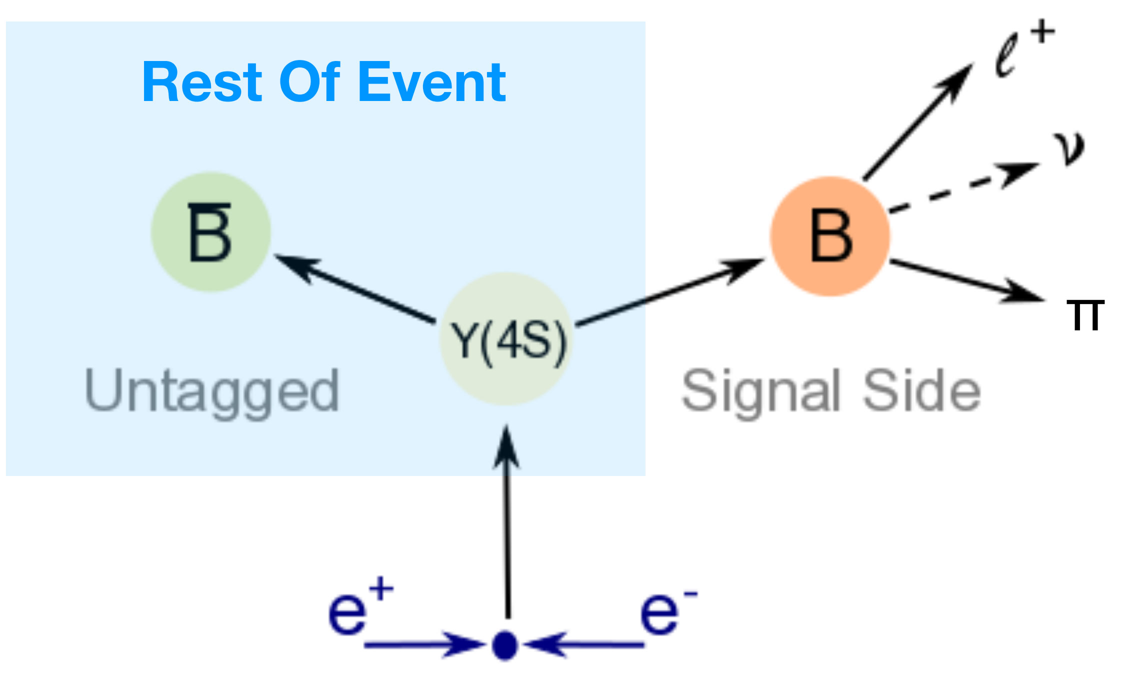
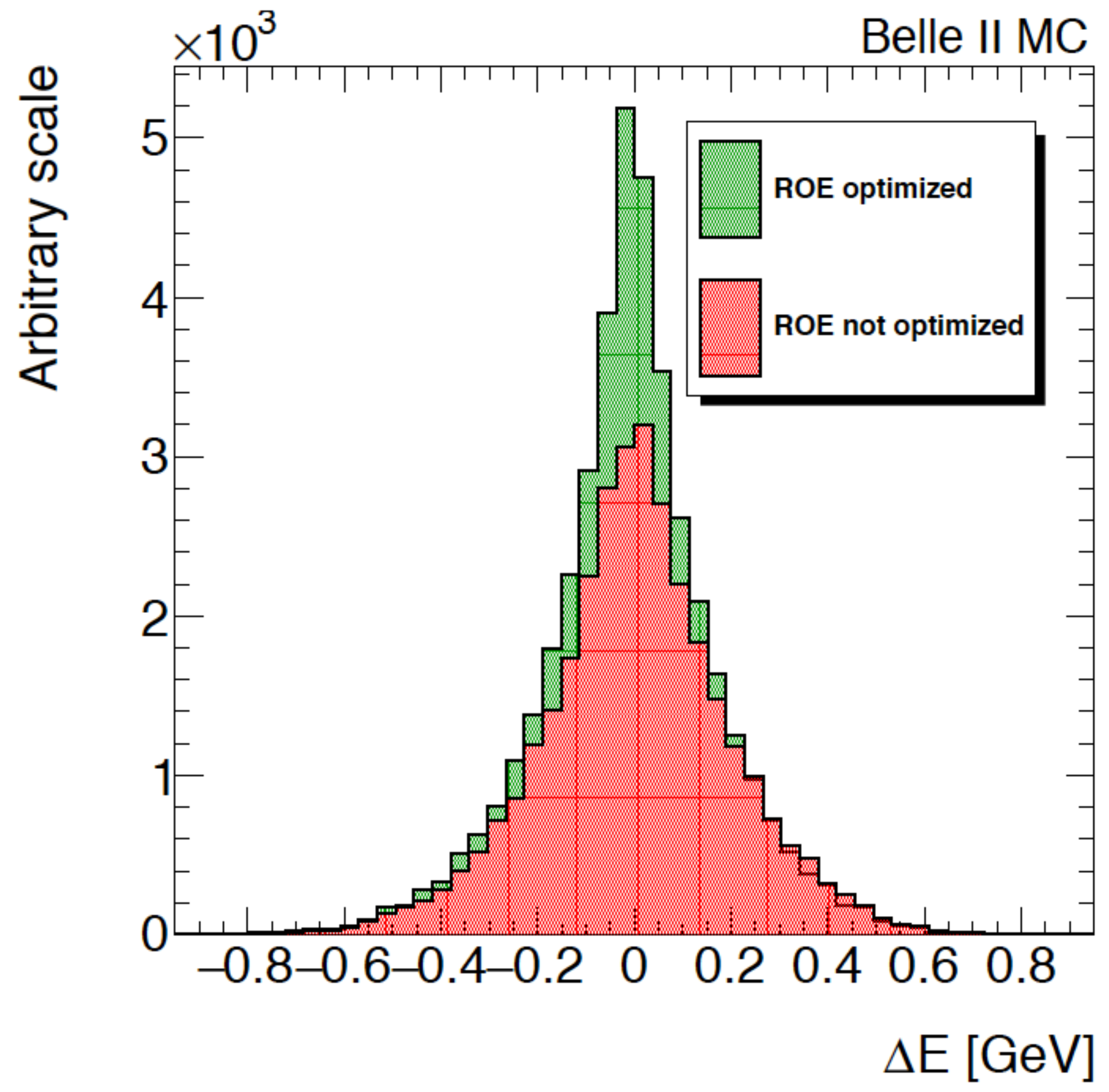
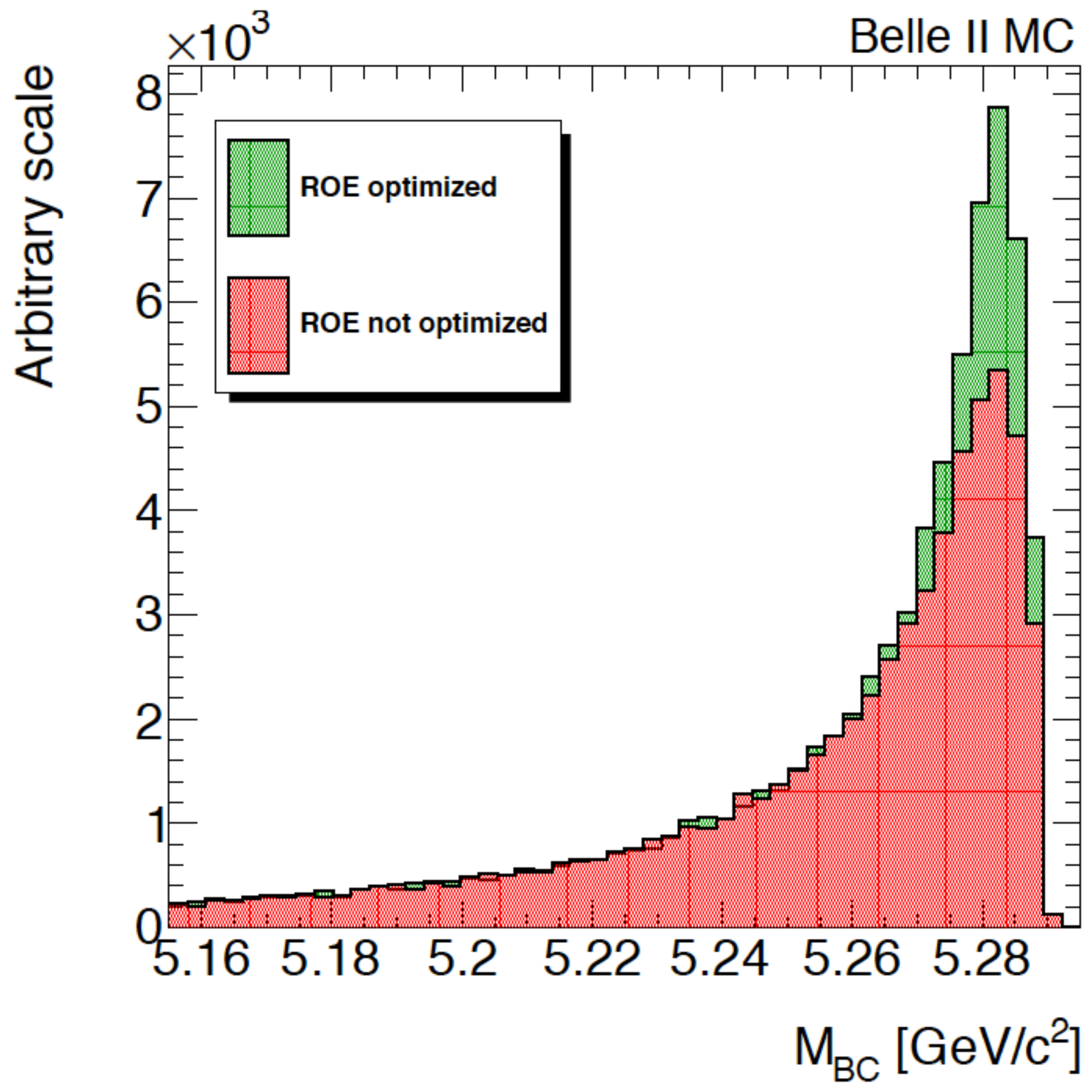
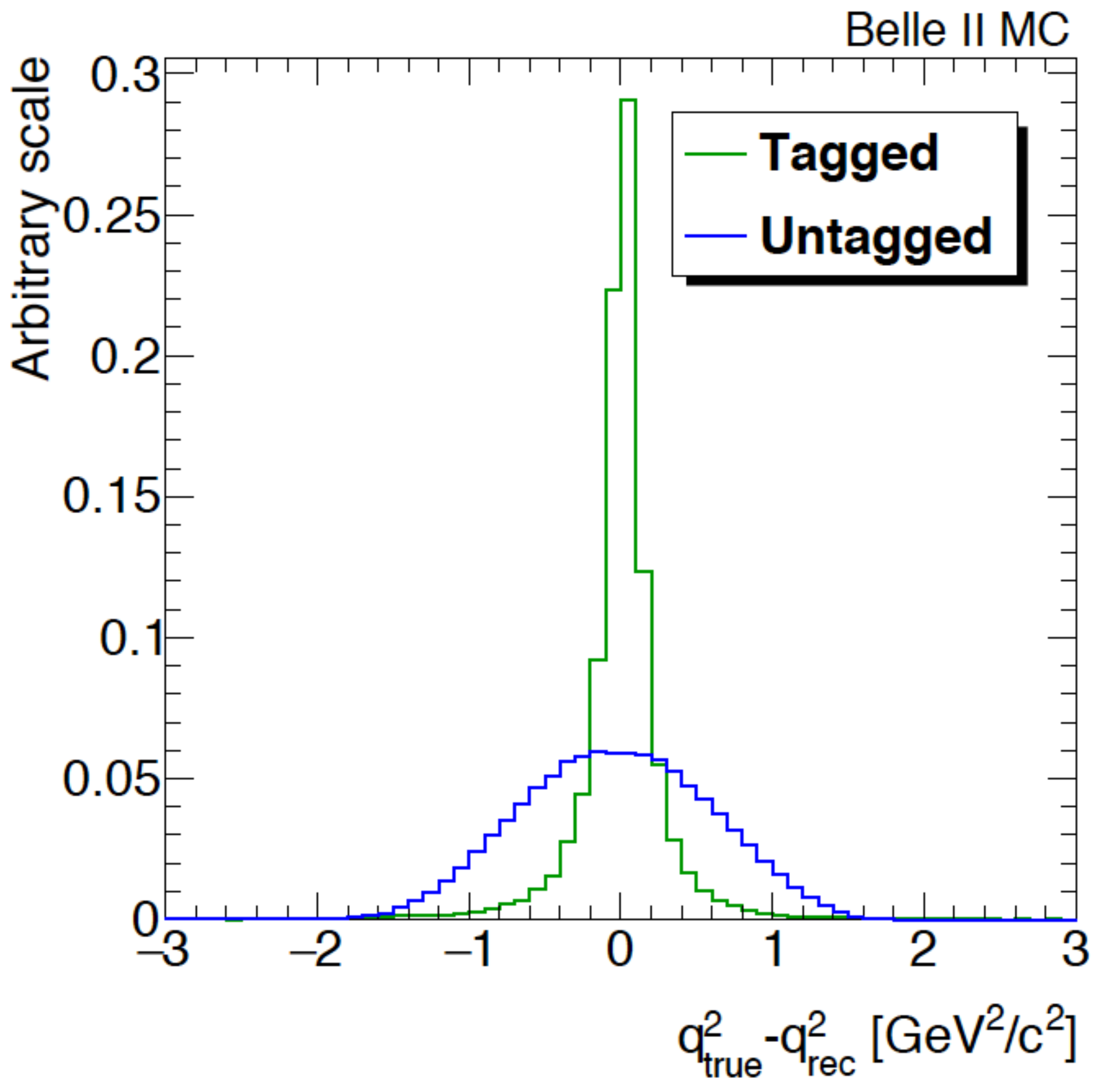


- Select good pion and lepton (>1 GeV/c)
- Assuming neutrino is the only missing particle
- Optimized BDT selection in ROE
- Background suppressed by $M^2_{miss}, \cos\theta_{BY}, M_{bc}, \Delta E$

$$M^2_{\rm miss} = \left(p_{e^+e^-} - p_\pi - p_l - p_{ROE}\right)^2 \quad \cos\theta_{BY} = \frac{2E^*_B E^*_Y - M^2_B - M^2_Y}{2p^*_B p^*_Y} \quad M_{\rm bc} = \sqrt{\frac{\left(s/2 + \mathbf{p}_B \cdot \mathbf{p}_{e^+e^-}\right)^2}{E^2_{e^+e^-}} - p^2_B} \quad \Delta E = \frac{\mathrm{p}_B \cdot \mathrm{p}_{e^+e^-} - s/2}{\sqrt{s}}$$







Tagged $B \to \pi l \nu$ @ Belle II MC

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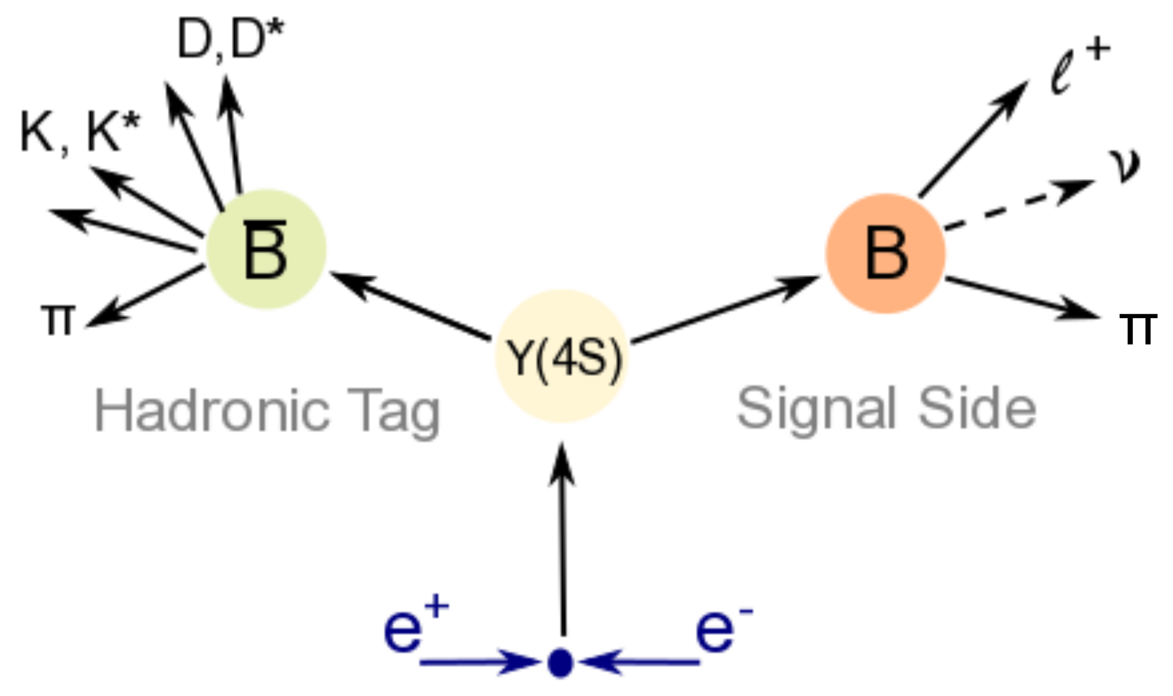
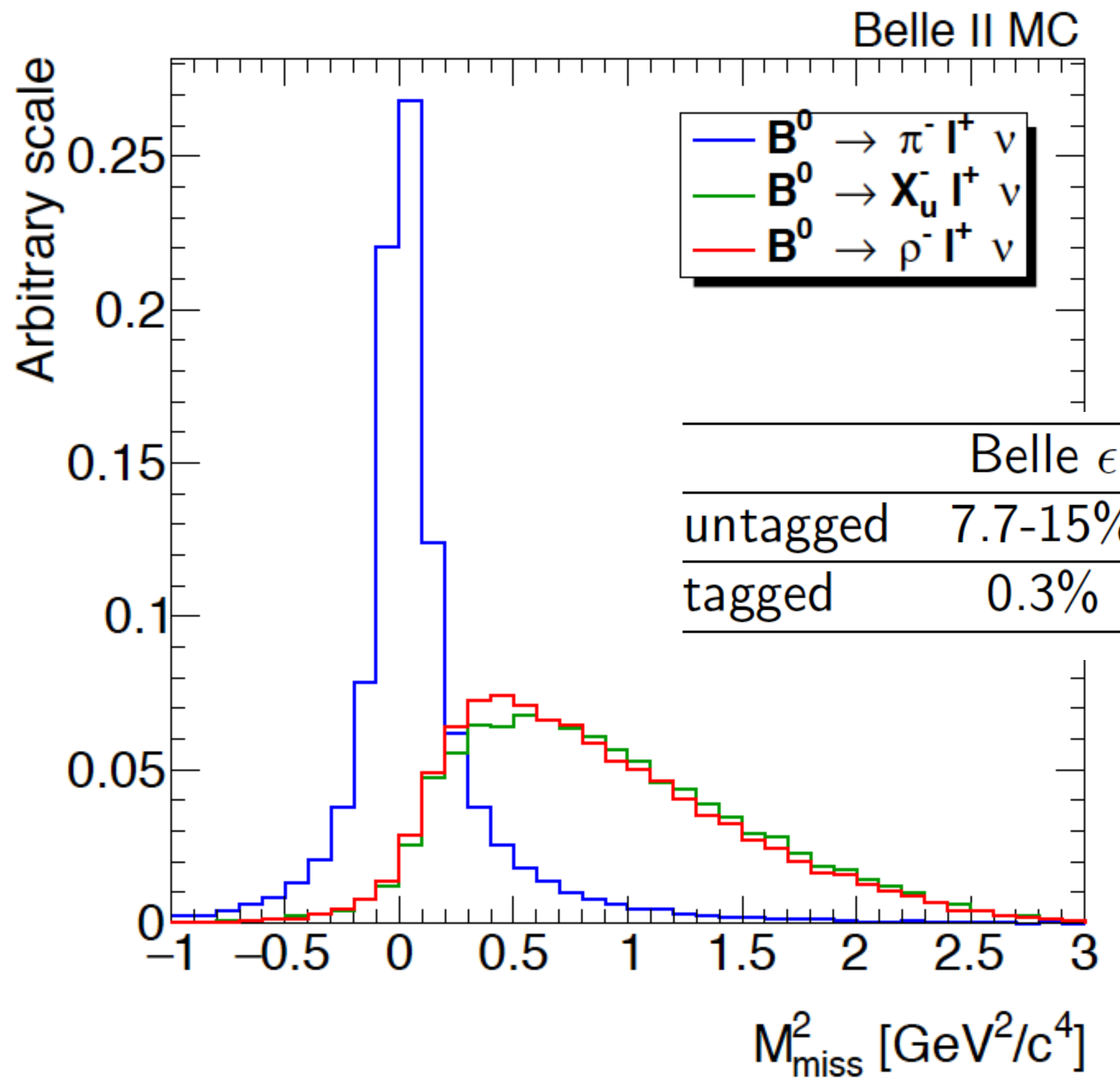
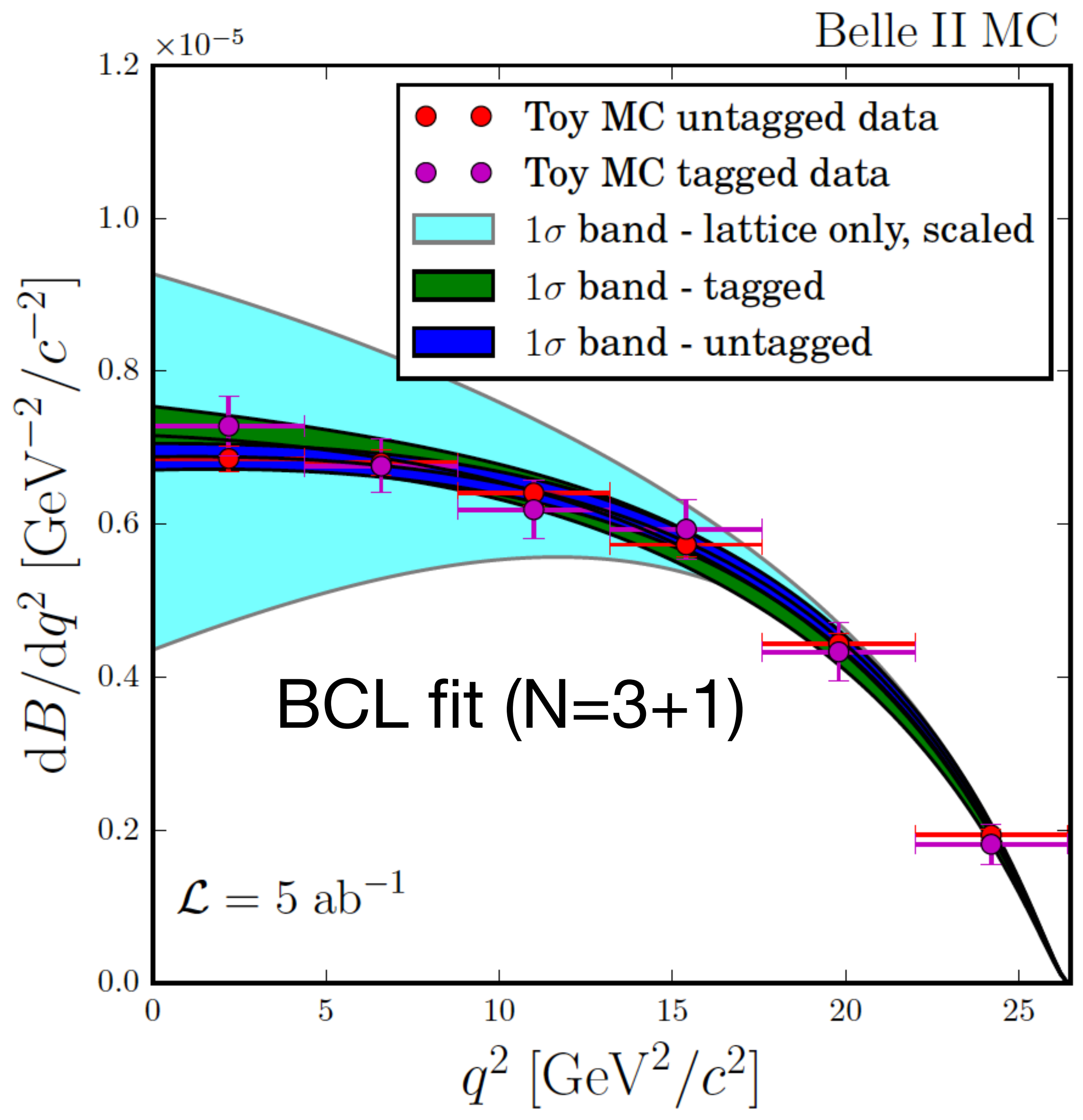
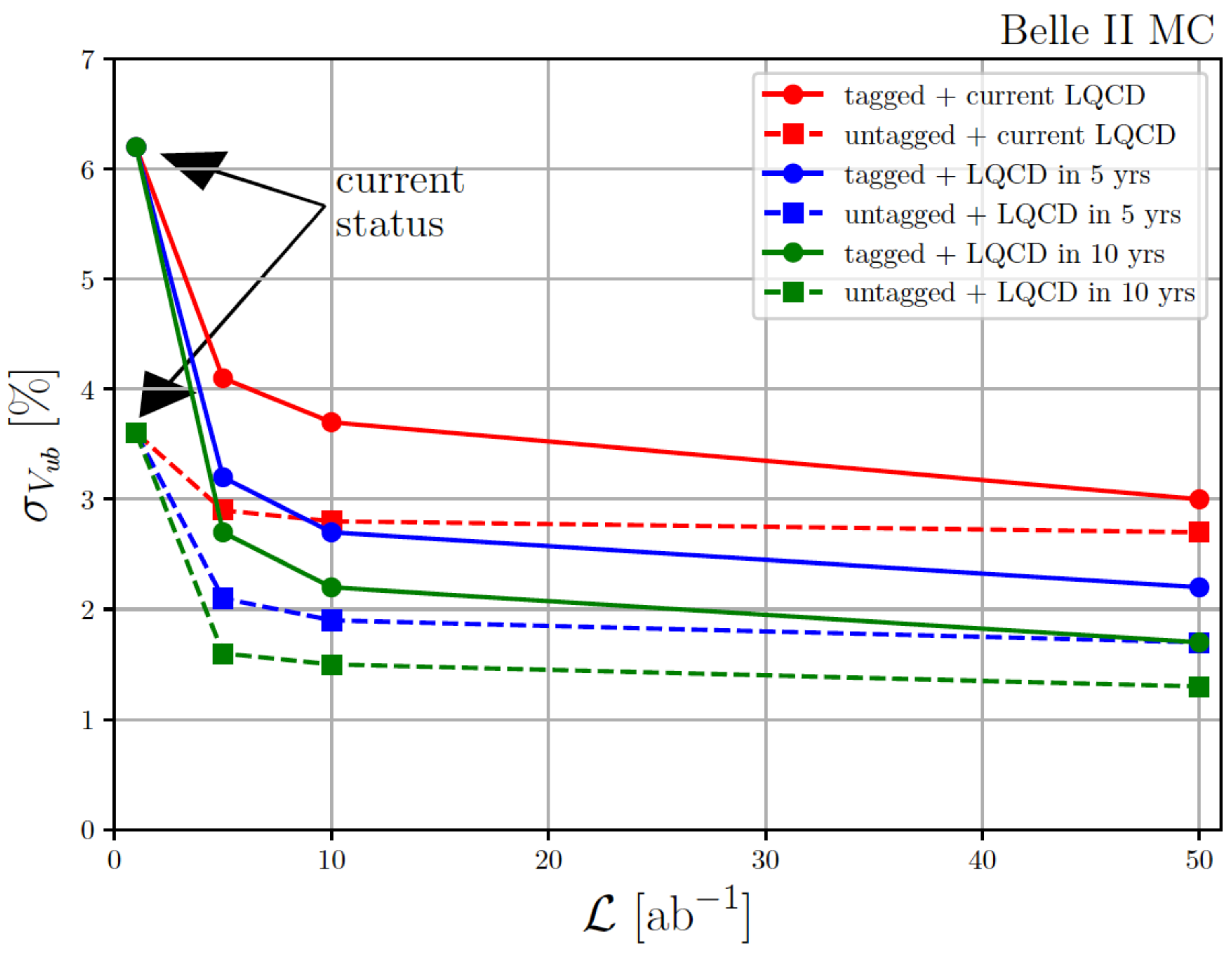


- Select good pion and lepton (>1 GeV/c)
- With new tagging algorithm FEI
- Precise tag knowledge $M^2_{\text{miss}} = \left(p_{e^+e^-} - p_{tag} - p_\pi - p_l\right)^2$
- Belle II aims at excl. $|V_{ub}|$ exp. σ ~4% (now 5%)

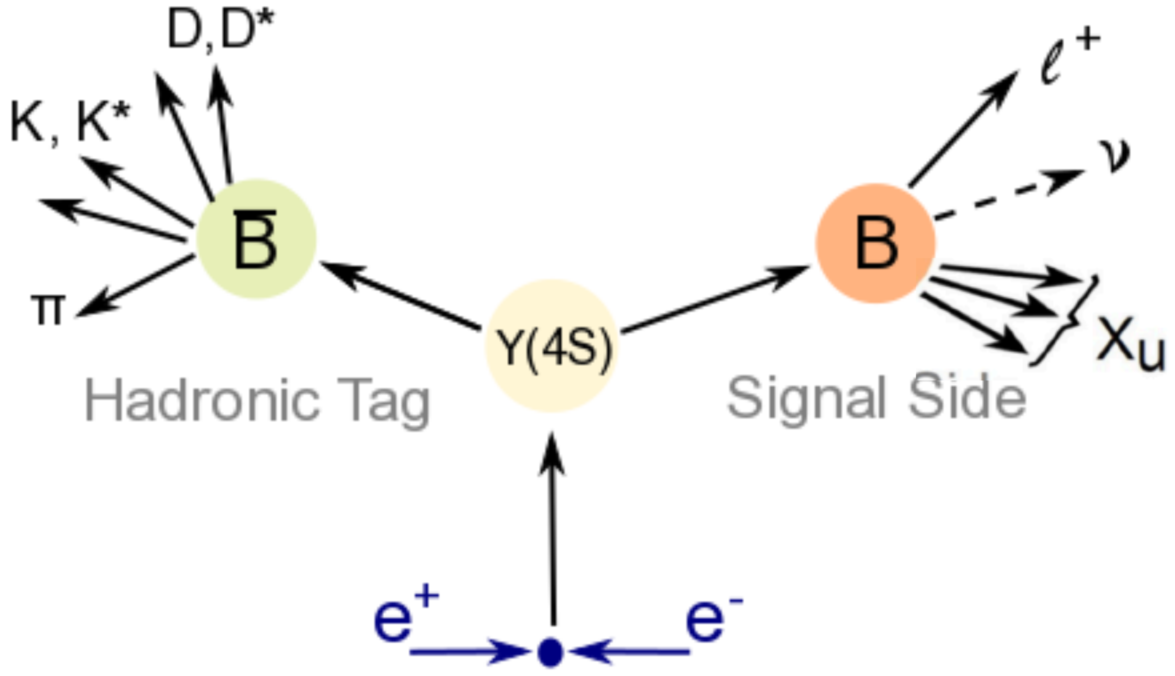


	Belle ϵ	Belle II ϵ
untagged	7.7-15%	20%
tagged	0.3%	0.55%

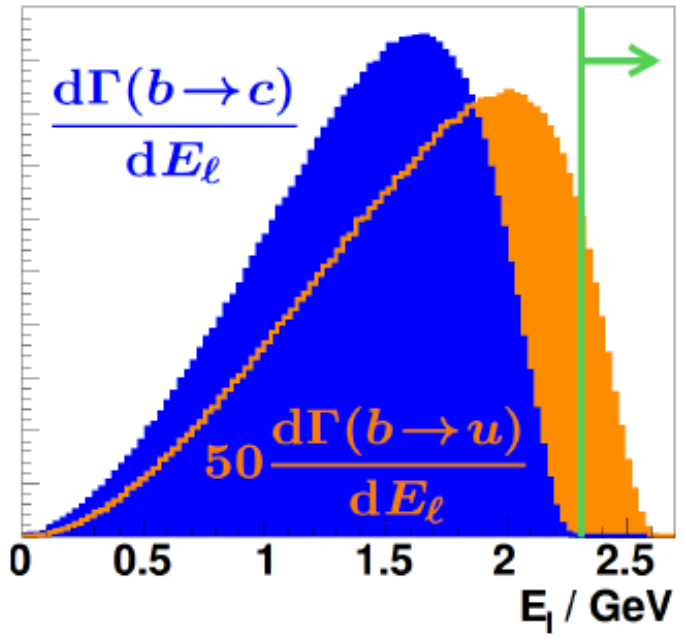


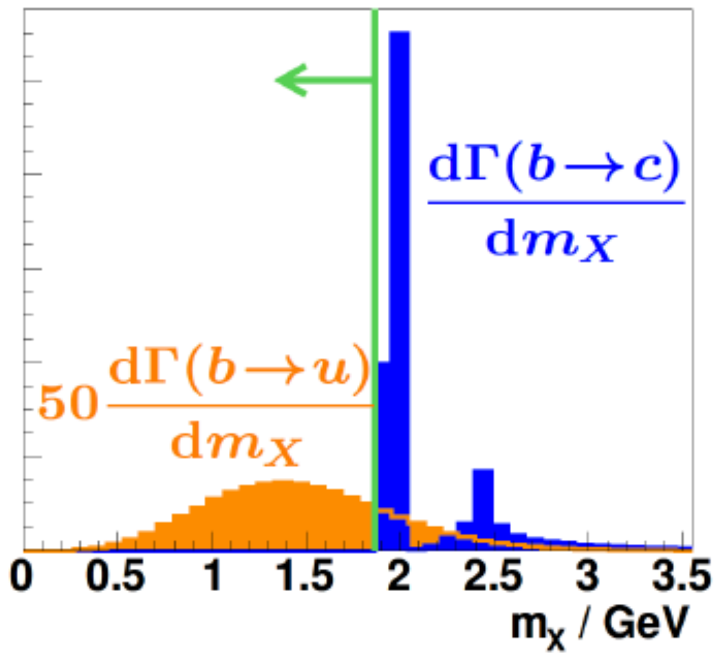


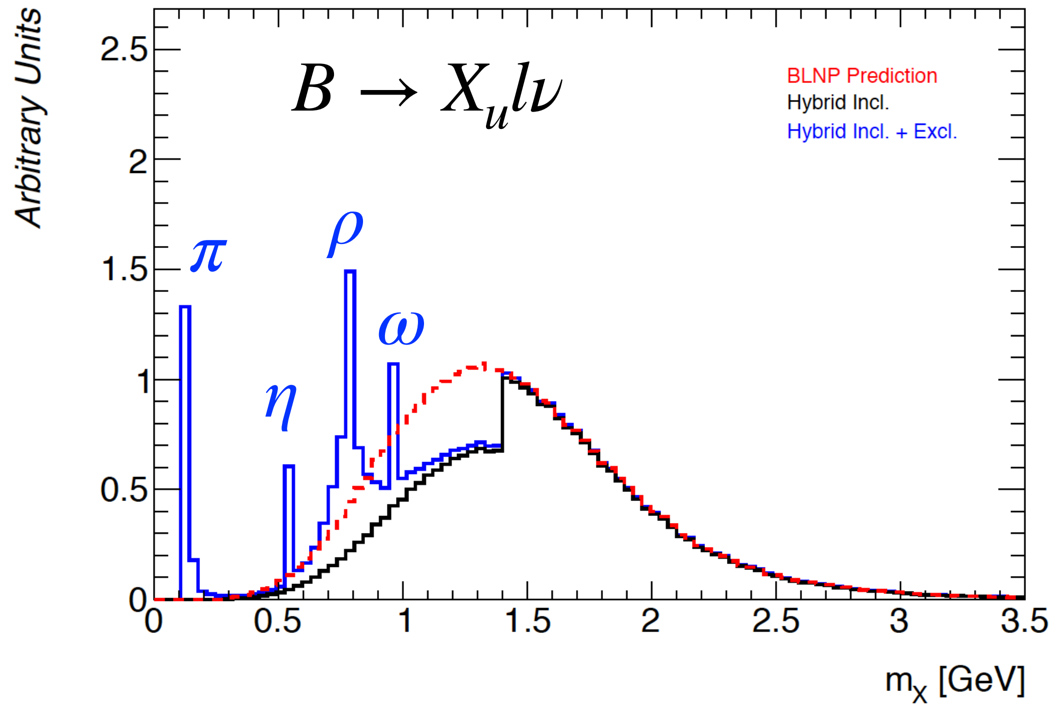
Inclusive $B \to X_u l \nu$

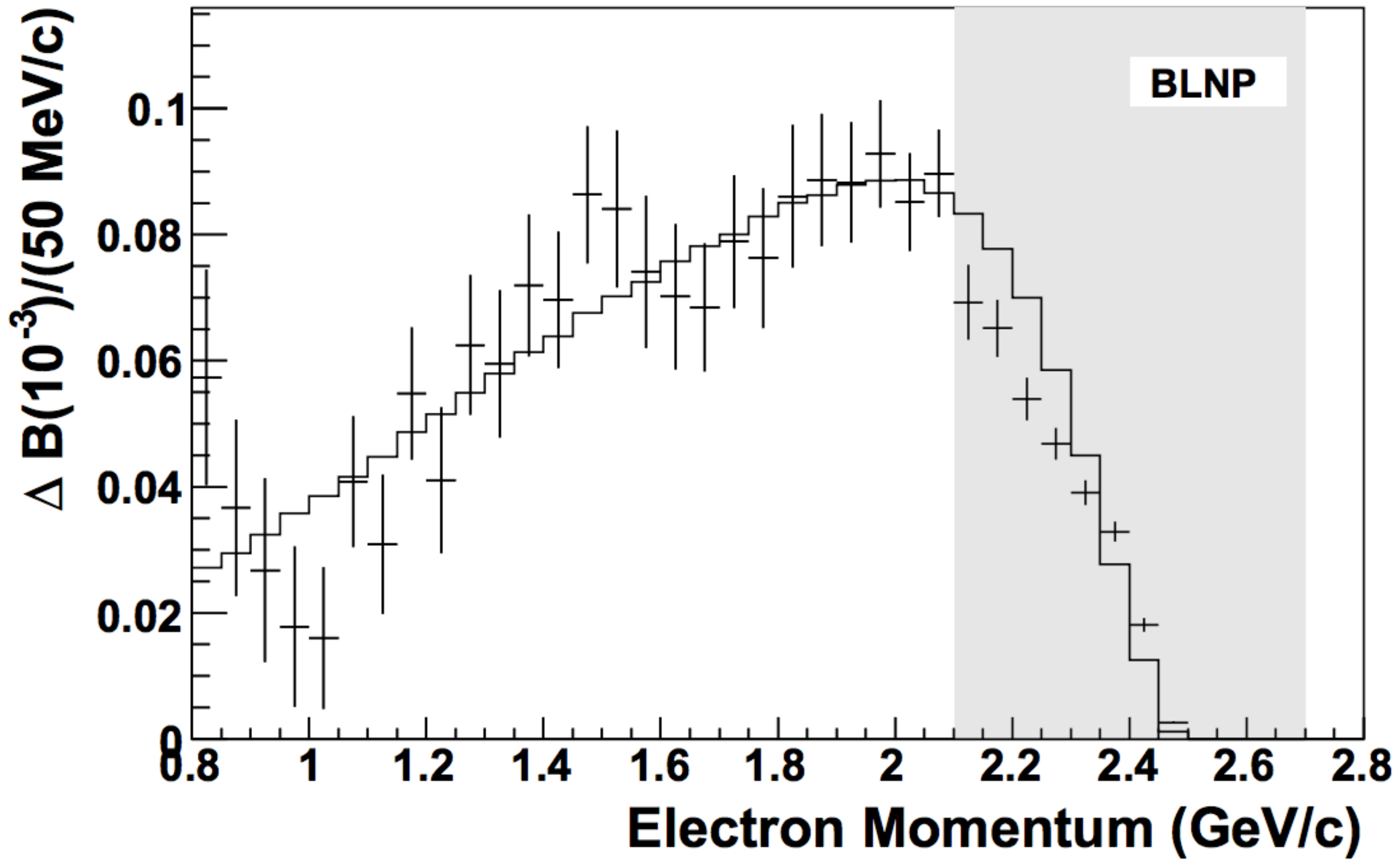


- Challenge in high b→c background
- Inclusive + exclusive hybrid modelling
- Large theoretical uncertainty close to end point
- Belle II aims at inclu. $|V_{ub}|$ exp. σ ~3% @50fb^{-1} (now 5%)
- Latest measurement based on electron energy spectrum fit BaBar 2017

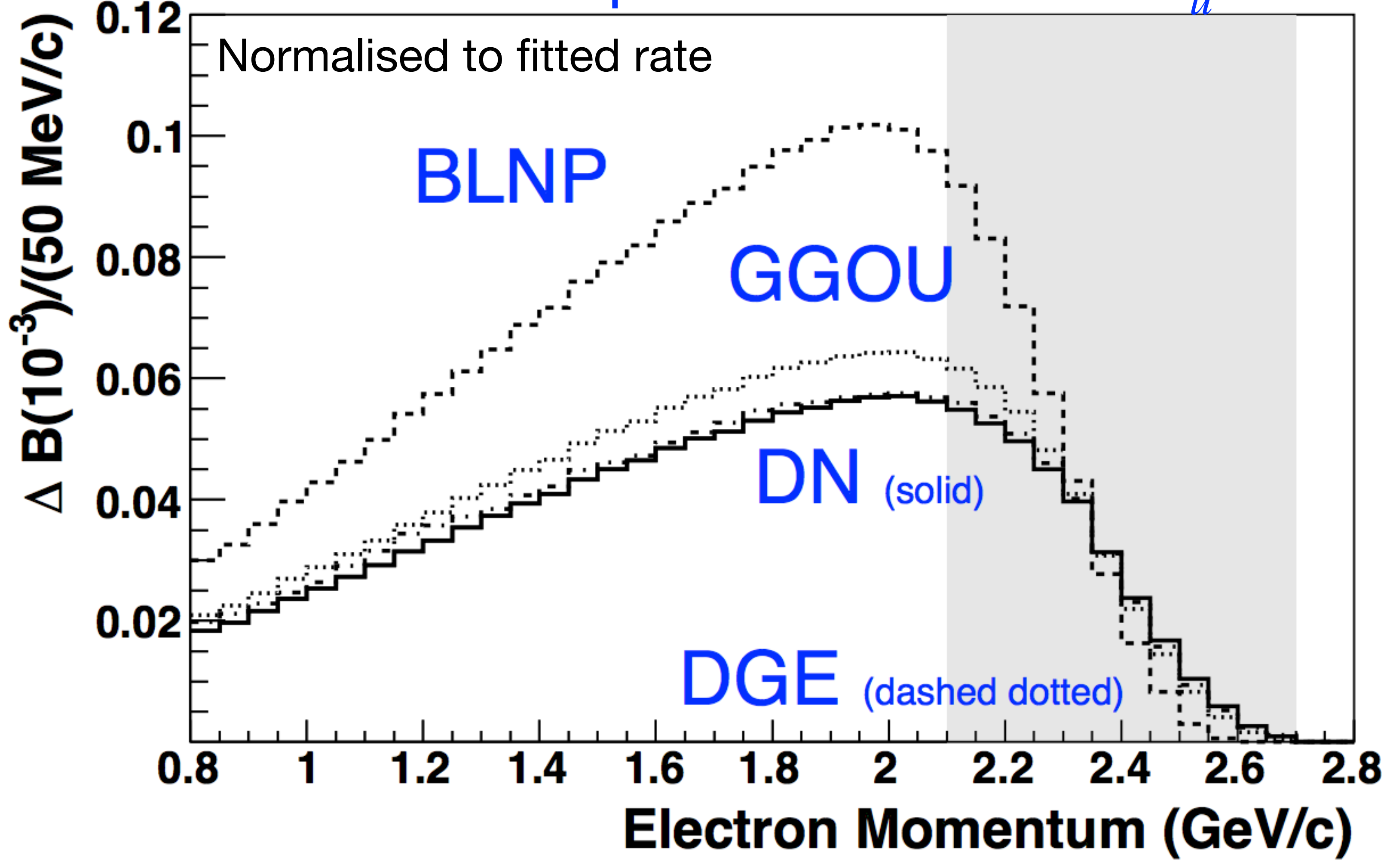








Theoretical prediction on $B \to X_u e \nu$



	BLNP	GGOU	DN	DGE
$\|V_{ub}\| \times 10^3$	4.6 ± 0.3	4.0 ± 0.3	3.8 ± 0.3	3.8 ± 0.1

A Global Fit Approach to Inclusive $|V_{ub}|$

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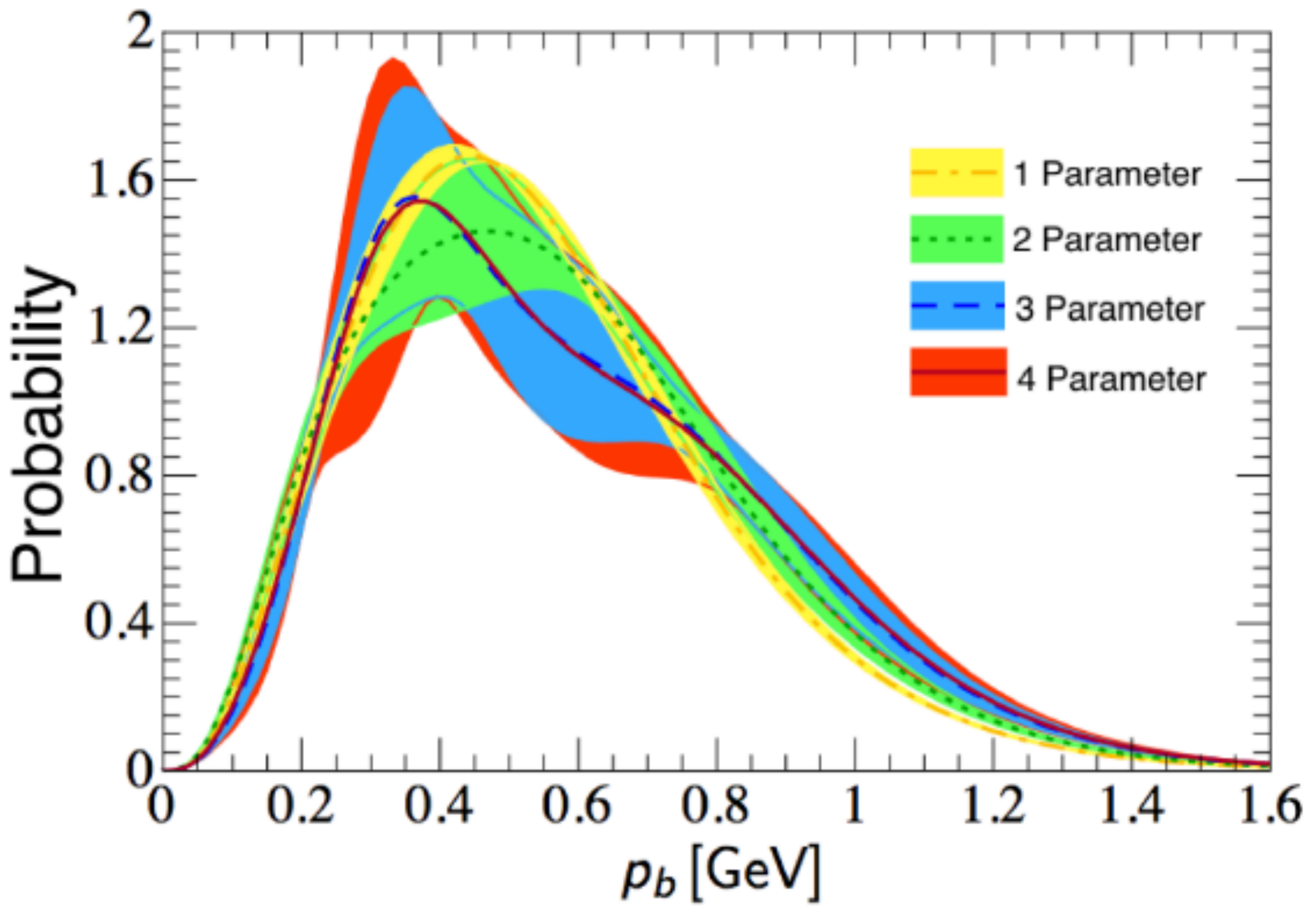
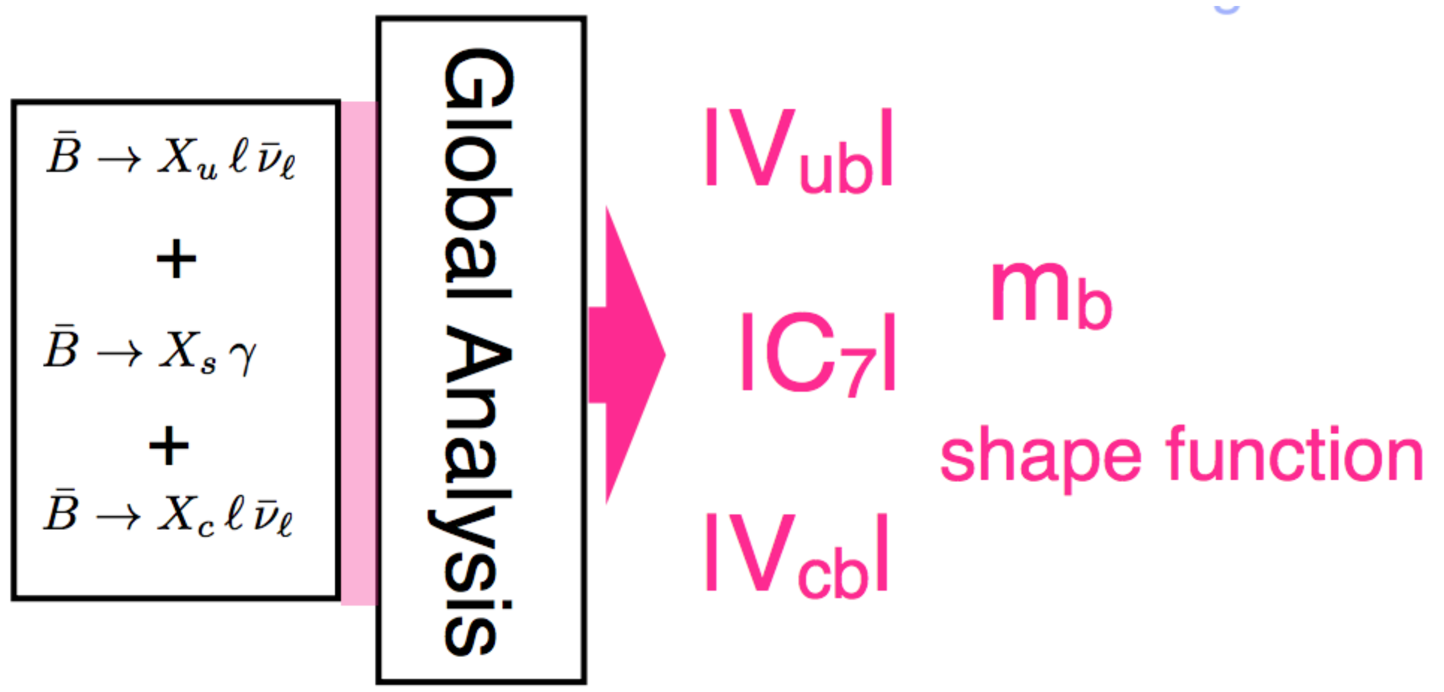
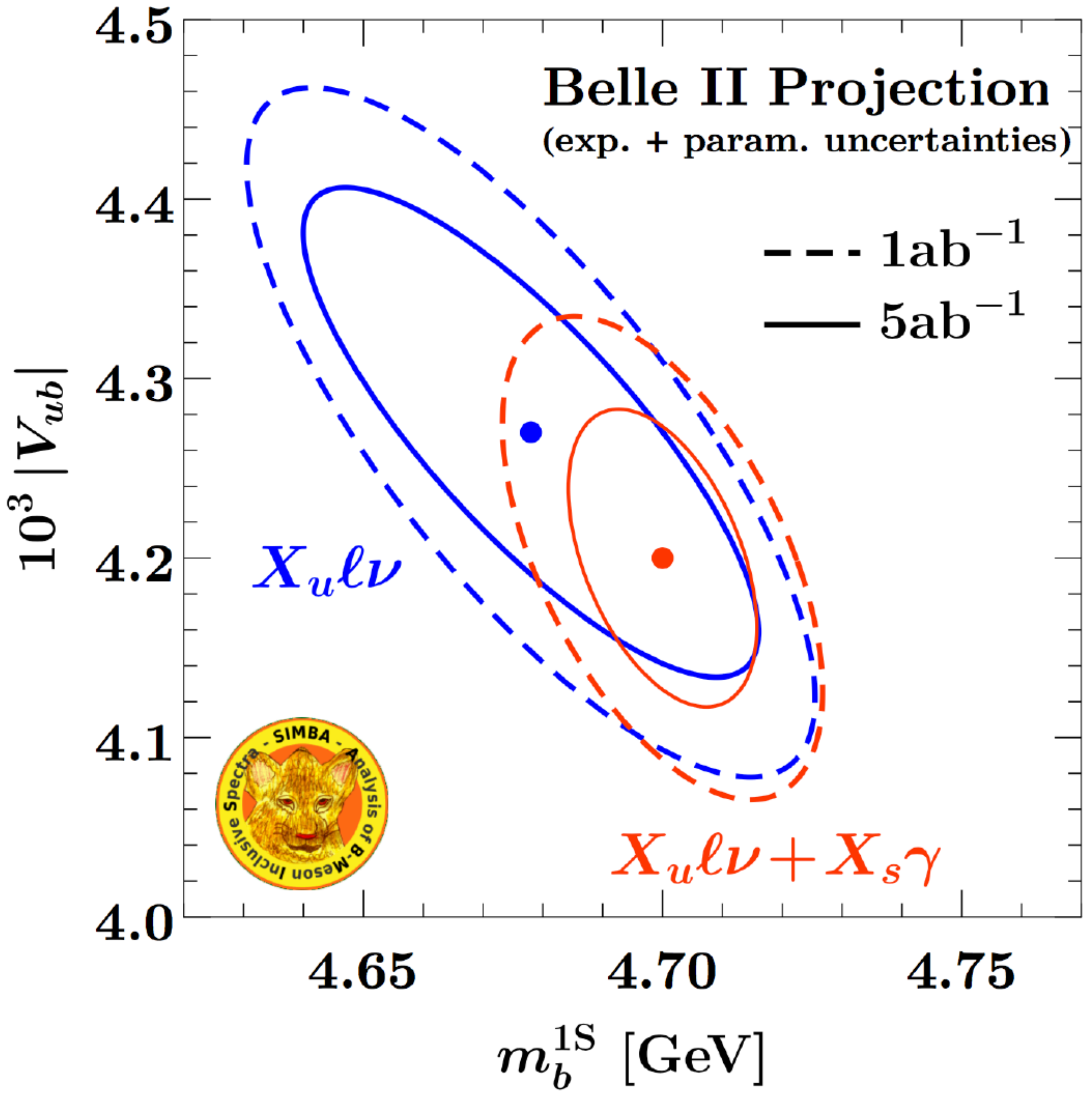
- Global model-independent fits for B meson shape function 1303.0958

$$F(k) = \sum_n (c_n f_n(k))^2$$







Leptonic: $B \to l\nu \quad (l = \mu, \tau)$

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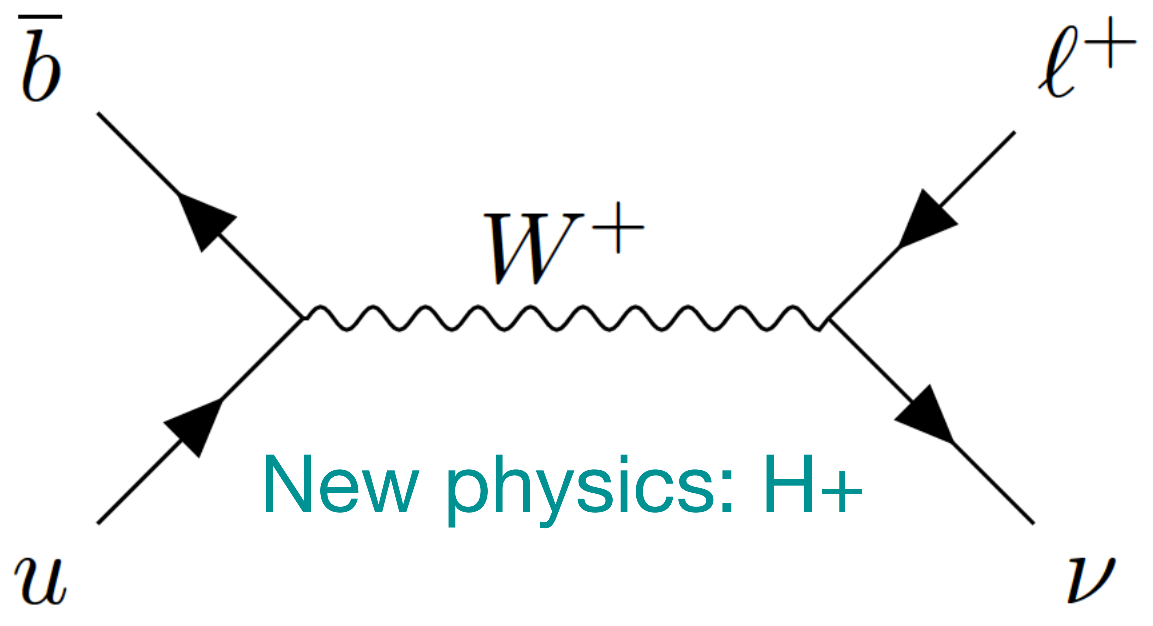


$$\mathcal{B}\left(B^- \to l^- \overline{\nu}_l\right) = \frac{G_F^2 m_B m_l^2}{8\pi}\left(1 - \frac{m_l^2}{m_B^2} f_B^2\right)\left|V_{ub}\right|^2 \tau_B$$

Expected data set

ℓ	$\mathcal{B}_{\text{SM}}$	711 fb^{-1}	5 ab^{-1}	50 ab^{-1}
τ	$(7.71 \pm 0.62) \times 10^{-5}$	61200 ± 5000	430000 ± 35000	4300000 ± 350000
μ	$(3.46 \pm 0.28) \times 10^{-7}$	275 ± 23	1930 ± 160	19300 ± 1600
e	$(0.811 \pm 0.065) \times 10^{-11}$	0.0064 ± 0.0005	0.0453 ± 0.0037	0.453 ± 0.037

- Branching fractions are hierarchical with lepton mass ue to helicity suppression
- Precise theoretical prediction in the SM
- Clean $|V_{ub}|$ measurement
- Probe of LFU and new physics

$B \to \mu\nu$

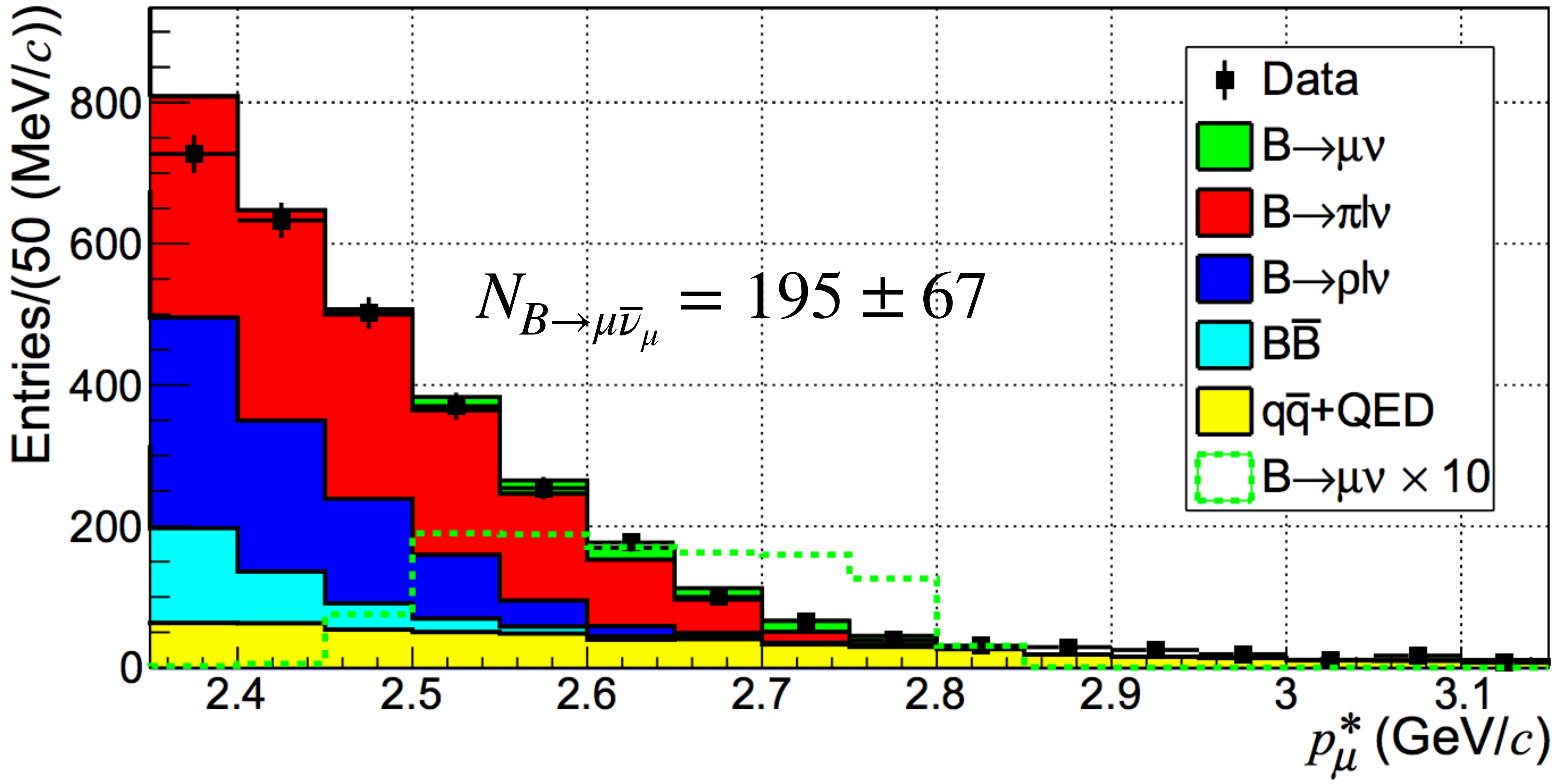
PRL 121, 031801 (2018)

- Latest measurement from Belle untagged analysis

Experiment	Upper limit @ 90% C.L.	Comment
Belle	2.7×10^{-6}	Fully reconstructed hadronic tag, 711 fb^{-1}
Belle	1.7×10^{-6}	Untagged analysis, 253 fb^{-1}
BaBar	1.0×10^{-6}	Untagged analysis, 468×10^6 $B\bar{B}$ pairs
Belle	2.9×10^{-7}	Untagged analysis, 711 fb^{-1}

$$\mathscr{B}\left(B^- \to \mu^- \overline{\nu}_\mu\right) \in [2.9,\ 10.7] \times 10^{-7}$$

@ 90% C.L. , agree with SM



$$\mathscr{B}_{SM}\left(B^- \to \mu^- \overline{\nu}_\mu\right) = (3.80 \pm 0.31) \times 10^{-7}$$

Expected uncertainty

50 ab^{-1}	$\mathcal{B}$Stat.	$\mathcal{B}$Syst.	$\lvert V_{ub}\rvert$
Belle II Untagged	$\sim$ 5%	$\sim$ 5%	3-4%
Belle II tagged	$\sim$ 13%	-	-

$B \to \tau\nu$

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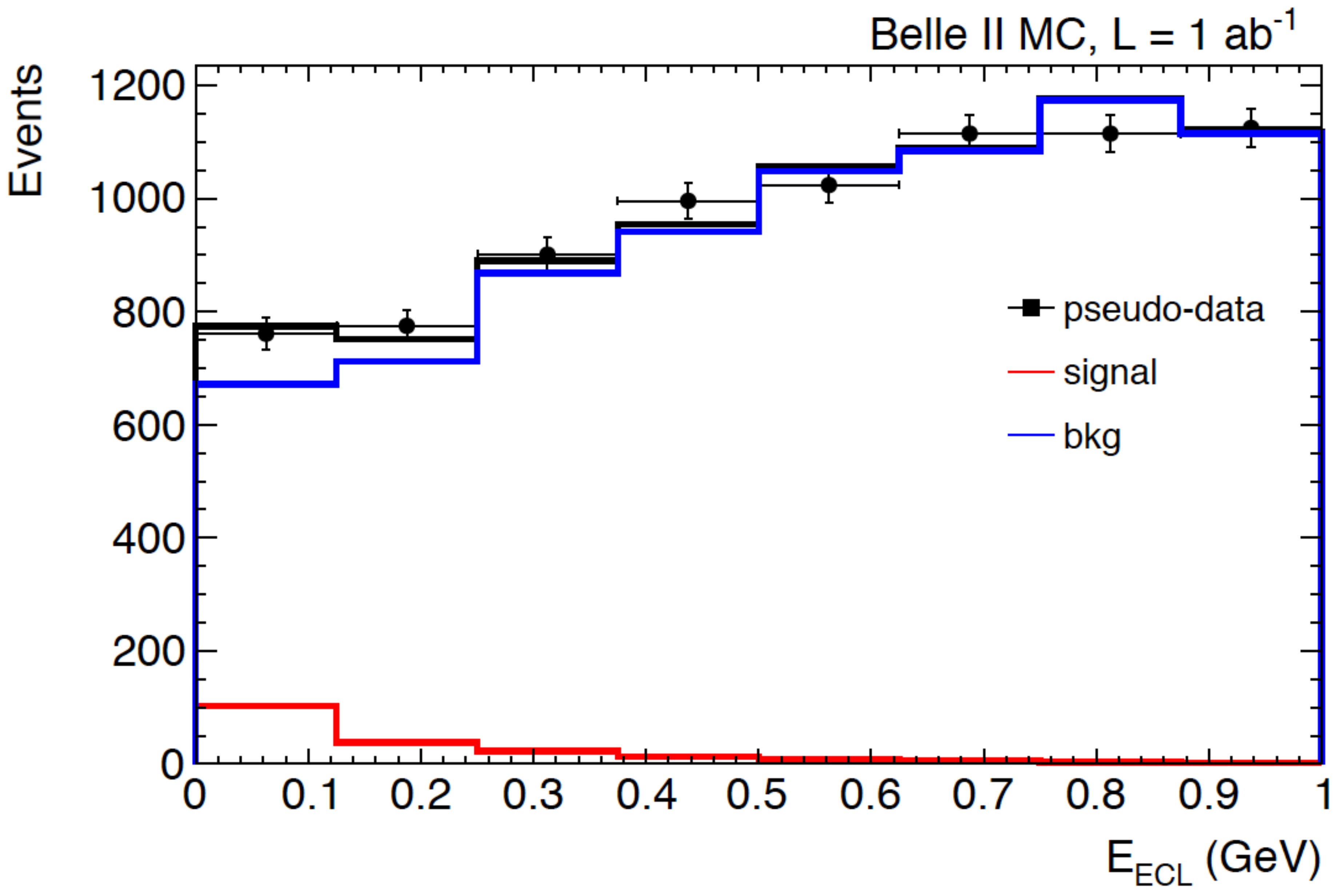
- Reconstruct B$_{tag}$ hadronically or semileptonic
- Due to tauon decay $e^-\nu_\tau\bar{\nu}_e, \mu^-\nu_\tau\bar{\nu}_\mu, \pi^-\bar{\nu}_\tau, \rho^-\bar{\nu}_\tau$, final $N_\nu \geq 1$
- Fit remaining energy on EM calorimeter (E$_{ECL}$)
- Expect to reach 5σ significancy with 2.6ab^{-1}



Expected yields @1 ab^{-1}

E_{ECL}		< 1 GeV	< 0.25 GeV
without background	Background yield [events]	12835	2062
	Signal yield [events]	332	238
	Signal efficiency (‰)	3.8	2.7
with background	Background yield [events]	7420	1348
	Signal yield [events]	188	136
	Signal efficiency (‰)	2.2	1.6

Expected uncertainty

	Integrated Luminosity (ab^{-1})	1	5	50
hadronic tag	statistical uncertainty (%)	29	13	4
	systematic uncertainty (%)	13	7	5
	total uncertainty (%)	32	15	6
semileptonic tag	statistical uncertainty (%)	19	8	3
	systematic uncertainty (%)	18	9	5
	total uncertainty (%)	26	12	5

Summary of $|V_{ub}|$ Projections

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	Statistical	Systematic (reducible, irreducible)	Total Exp	Theory	Total
$\|V_{ub}\|$ exclusive (had. tagged)					
711 fb^{-1}	3.0	(2.3, 1.0)	3.8	7.0	8.0
5 ab^{-1}	1.1	(0.9, 1.0)	1.8	1.7	3.2
50 ab^{-1}	0.4	(0.3, 1.0)	1.2	0.9	1.7
$\|V_{ub}\|$ exclusive (untagged)					
605 fb^{-1}	1.4	(2.1, 0.8)	2.7	7.0	7.5
5 ab^{-1}	1.0	(0.8, 0.8)	1.2	1.7	2.1
50 ab^{-1}	0.3	(0.3, 0.8)	0.9	0.9	1.3
$\|V_{ub}\|$ inclusive					
605 fb^{-1} (old B tag)	4.5	(3.7, 1.6)	6.0	2.5–4.5	6.5–7.5
5 ab^{-1}	1.1	(1.3, 1.6)	2.3	2.5–4.5	3.4–5.1
50 ab^{-1}	0.4	(0.4, 1.6)	1.7	2.5–4.5	3.0–4.8
$\|V_{ub}\|$ $B \to \tau\nu$ (had. tagged)					
711 fb^{-1}	18.0	(7.1, 2.2)	19.5	2.5	19.6
5 ab^{-1}	6.5	(2.7, 2.2)	7.3	1.5	7.5
50 ab^{-1}	2.1	(0.8, 2.2)	3.1	1.0	3.2
$\|V_{ub}\|$ $B \to \tau\nu$ (SL tagged)					
711 fb^{-1}	11.3	(10.4, 1.9)	15.4	2.5	15.6
5 ab^{-1}	4.2	(4.4, 1.9)	6.1	1.5	6.3
50 ab^{-1}	1.3	(2.3, 1.9)	2.6	1.0	2.8

$|V_{ub}|$ uncertainty @ Belle II

exclusive ~1.5%

inclusive ~ 4%

leptonic ~ 3%

Radiative Leptonic: $B^+ \to \ell^+ \nu_\ell \gamma$

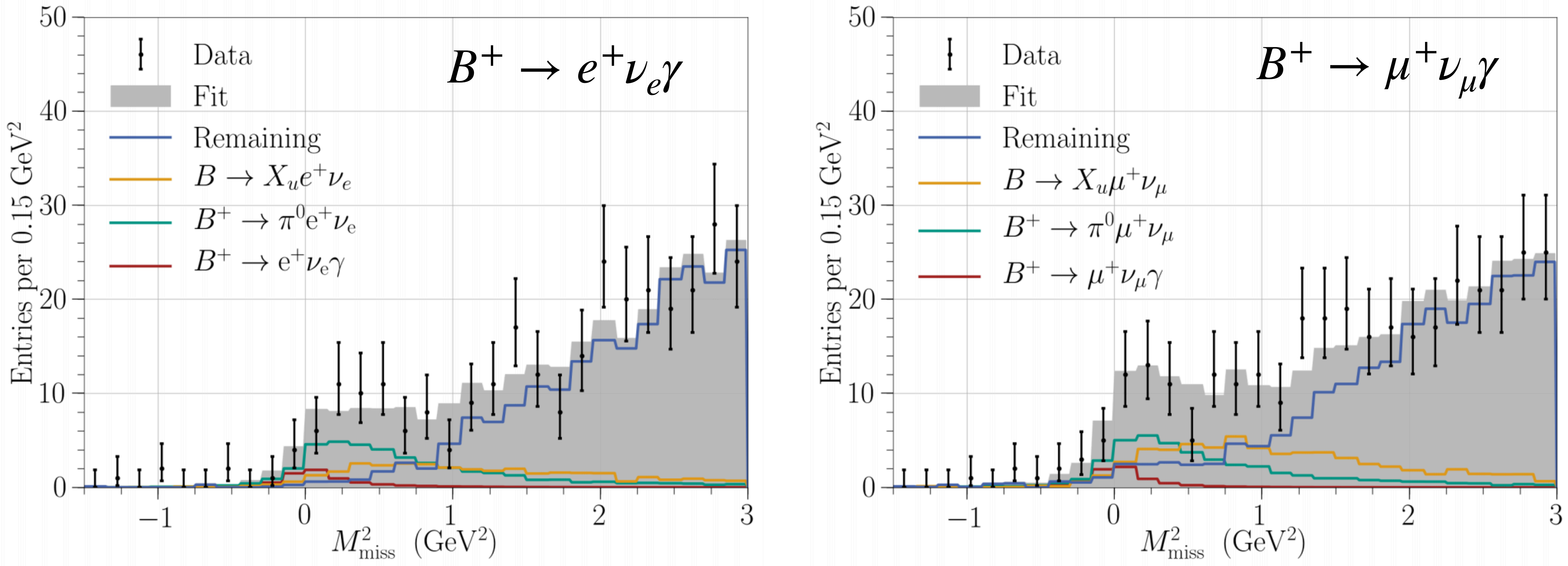
- Belle full data set 711fb^{-1} with new tagging algorithm (FEI)
- Photon energy selection above 1 GeV
- Measured upper limit of ΔB and the first inverse moment λ_B

$$\frac{d\Gamma(B^+ \to \ell^+\nu_\ell\gamma)}{dE_\gamma} = \frac{\alpha_{em} G_F^2 |V_{ub}|^2}{6\pi^2} m_B E_\gamma^3 \left(1 - \frac{2E_\gamma}{m_B}\right) \times \left(\left|F_V\right|^2 + \left|F_A + \frac{e_\ell f_B}{E_\gamma}\right|^2 \right)$$

$$\Delta\mathcal{B}(B^+ \to \ell^+\nu_\ell\gamma) = \tau_B \int_{\text{Selection}} dE_\gamma \frac{d\Gamma}{dE_\gamma}$$

ℓ	$\Delta\mathcal{B}(B^+ \to \ell^+\nu_\ell\gamma)$ limit (10^{-6})		
	BaBar 2009	Belle 2015	Belle 2018
e	-	< 6.1	< 4.3
μ	-	< 3.4	< 3.4
e, μ	< 14	< 3.5	< 3.0

PRD 98, 112016 (2018)



Expected signal yields assuming $\Delta\mathcal{B}(B^+ \to \ell^+\nu_\ell\gamma) = 5.0 \times 10^{-6}$

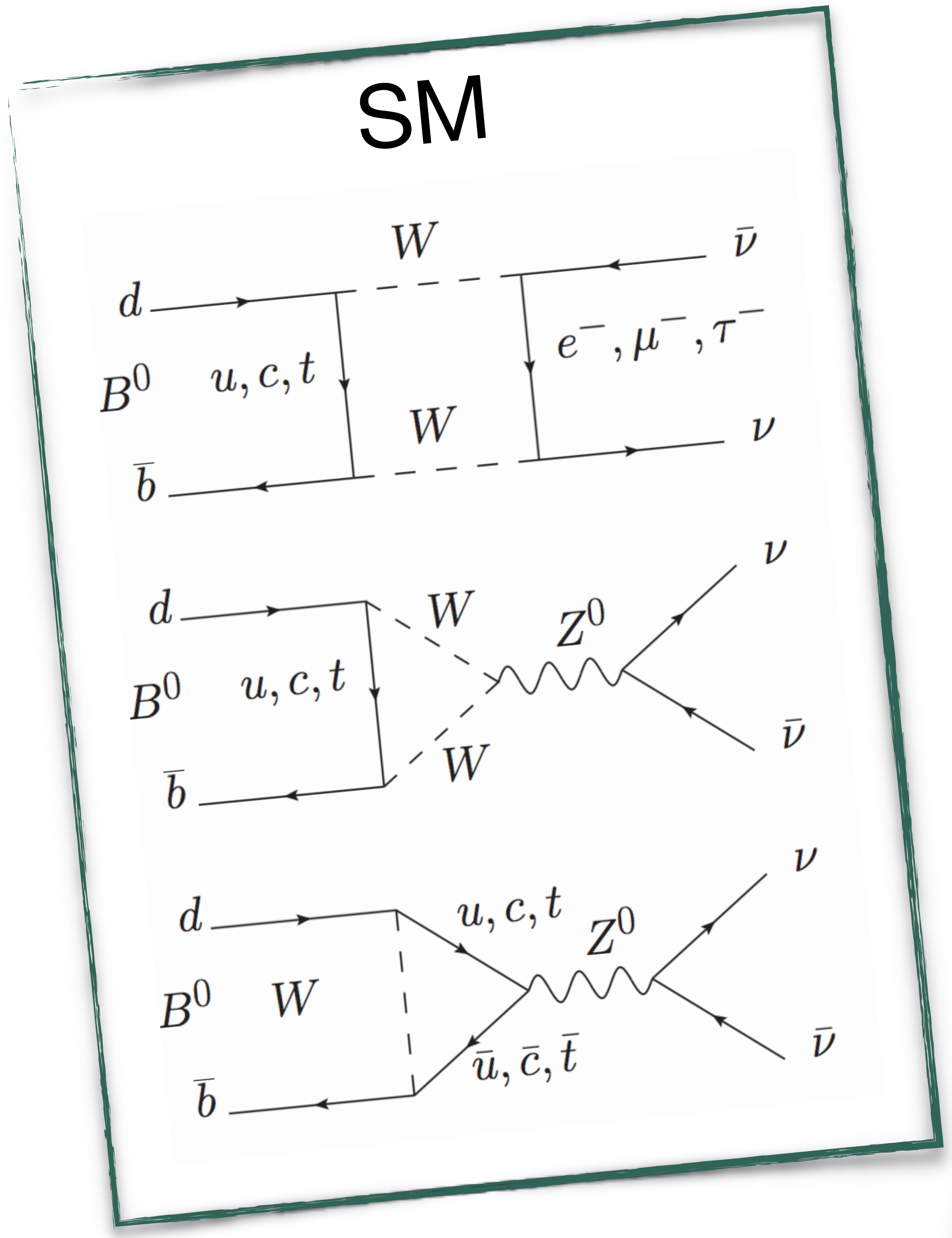
	$B^+ \to e^+\nu_e\gamma$	$B^+ \to \mu^+\nu_\mu\gamma$	Combined
N_{New}	24.8	25.7	50.5
$N_{Published}$	8.0	8.7	16.5

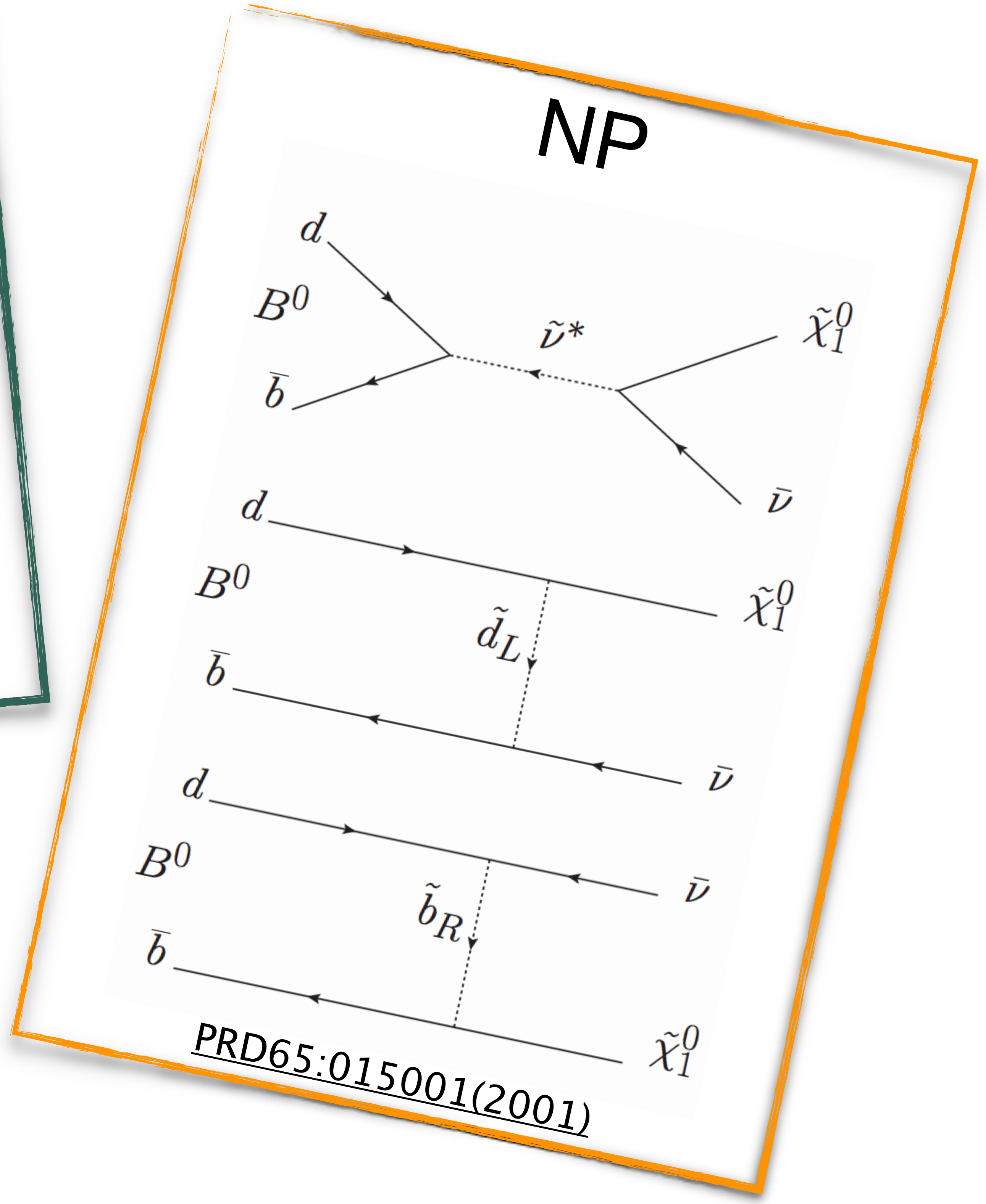
Expected statistical error

Belle New analysis	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
+1.48	+0.56	+0.18
-1.39	-0.53	-0.17

MC test:
FEI brings ×3 yields!

B→invisibles





- Adventured by BaBar 2012 and Belle 2012

Mode	Upper limit @ 90% C.L.	Experiment
$B^0 \to \nu\nu$	2.4×10^{-5}	BaBar PRD 86, 051105(R) (2012)
$B^0 \to \nu\nu\gamma$	1.7×10^{-5}	
$B^0 \to \nu\nu$	1.3×10^{-4}	Belle PRD 86, 032002 (2012)

- Opportunity for Belle II
  - Much improved tagging algorithm
  - Combining hadronic and semileptonic tagging for a higher statistics
  - Hadronic B_s tagging efficiency seen 2 times higher than for B^0
  - Possible search for missing every signals as non-standard invisible states $B \to X_{dark}$

Observables	Belle $0.71\,\text{ab}^{-1}$ $(0.12\,\text{ab}^{-1})$	Belle II $5\,\text{ab}^{-1}$	Belle II $50\,\text{ab}^{-1}$
$\text{Br}(B^0 \to \nu\bar{\nu}) \times 10^6$	< 14	< 5.0	< 1.5
$\text{Br}(B_s \to \nu\bar{\nu}) \times 10^5$	< 9.7	< 1.1	–

Golden Channels @ Belle II

Flavor Milestone

Process	Observable	Theory	Sys. limit (Discovery) [ab-1]	vs LHCb	vs Belle	Anomaly	New Physics
$B \to \pi l \nu$	$\|V_{ub}\|$	★★★	10-20	★★★	★★★	★★	★
$B \to X_u l \nu$	$\|V_{ub}\|$	★★	2-10	★★★	★★	★★★	★
$B \to \tau \nu$	$\mathcal{B}$	★★★	>50 (2)	★★★	★★★	★	★★★
$B \to \mu \nu$	$\mathcal{B}$	★★★	>50 (5)	★★★	★★★	★	★★★
$B \to D^{(*)} l \nu$	$\|V_{cb}\|$	★★★	1-10	★★★	★★	★★	★
$B \to X_c l \nu$	$\|V_{cb}\|$	★★★	1-5	★★★	★★	★★	★★
$B \to D^{(*)} \tau \nu$	$R(D^{(*)})$	★★★	5-10	★★	★★★	★★★	★★★
$B \to D^{(*)} \tau \nu$	P_τ	★★★	15-20	★★★	★★★	★★	★★★
$B \to D^{**} l \nu$	$\mathcal{B}$	★	-	★★	★★★	★★	-
$B \to l \nu \gamma$	λ_B	★★	-	★★★	★★★	★	★★
$B \to K^{(*)} \nu \nu$	$\mathcal{B},\ F_L$	★★★	>50	★★★	★★★	★	★★

Summary

- Belle II has successfully finished commissioning run and ready for taking physics data
- Improved tagging algorithm increases reconstruction efficiency significantly
- Promising performance of missing energy channels proved by MC studies
- Issues seen in form factor parameterisation need to be understood
- Deviation between inclusive and exclusive measurements still exist
- Upcoming Belle II data will help to resolve these questions…

Thank you

Back up

$\bar{B}^0 \to \pi^+ l^- \nu$ @ Belle

Source	Error (Limit) [%] Tagged [%]	Untagged
Tracking efficiency	0.4	2.0
Pion identification	–	1.3
Lepton identification	1.0	2.4
Kaon veto	0.9	–
Continuum description	1.0	1.8
Tag calibration and $N_{B\bar{B}}$	4.5 (2.0)	2.0 (1.0)
$X_u \ell \nu$ cross-feed	0.9	0.5 (0.5)
$X_c \ell \nu$ background	–	0.2 (0.2)
Form factor shapes	1.1	1.0 (1.0)
Form factor background	–	0.4 (0.4)
Total	5.0	4.5
(reducible, irreducible)	(4.6, 2.0)	(4.2, 1.6)

$B \to X_u l \nu$ @ Belle

Source	Error on $\mathcal{B}$ (irreducible limit)
$\mathcal{B}(D^{(*)}\ell\nu)$	1.2 (0.6)
Form factors $(D^{(*)}\ell\nu)$	1.2 (0.6)
Form factors & $\mathcal{B}(D^{(**)}\ell\nu)$	0.2
$B \to X_u \ell\nu(\text{SF})$	3.6 (1.8)
$B \to X_u \ell\nu(g \to s\bar{s})$	1.5
$\mathcal{B}(B \to \pi/\rho/\omega\ell\nu)$	2.3
$\mathcal{B}(B \to \eta^{(\prime)}\ell\nu)$	3.2
$\mathcal{B}(B \to X_u\ell\nu)$ unmeasured/fragmentation	2.9 (1.5)
Continuum & Combinatorial	1.8
Secondaries, Fakes & Fit	1.0
PID& Reconstruction	3.1
BDT/Normalisation	3.1 (2.0)
Total	8.1
(Total reducible)	7.4
(Total irreducible)	3.2