Belle II

Physics Program

(B factory flavour physics)

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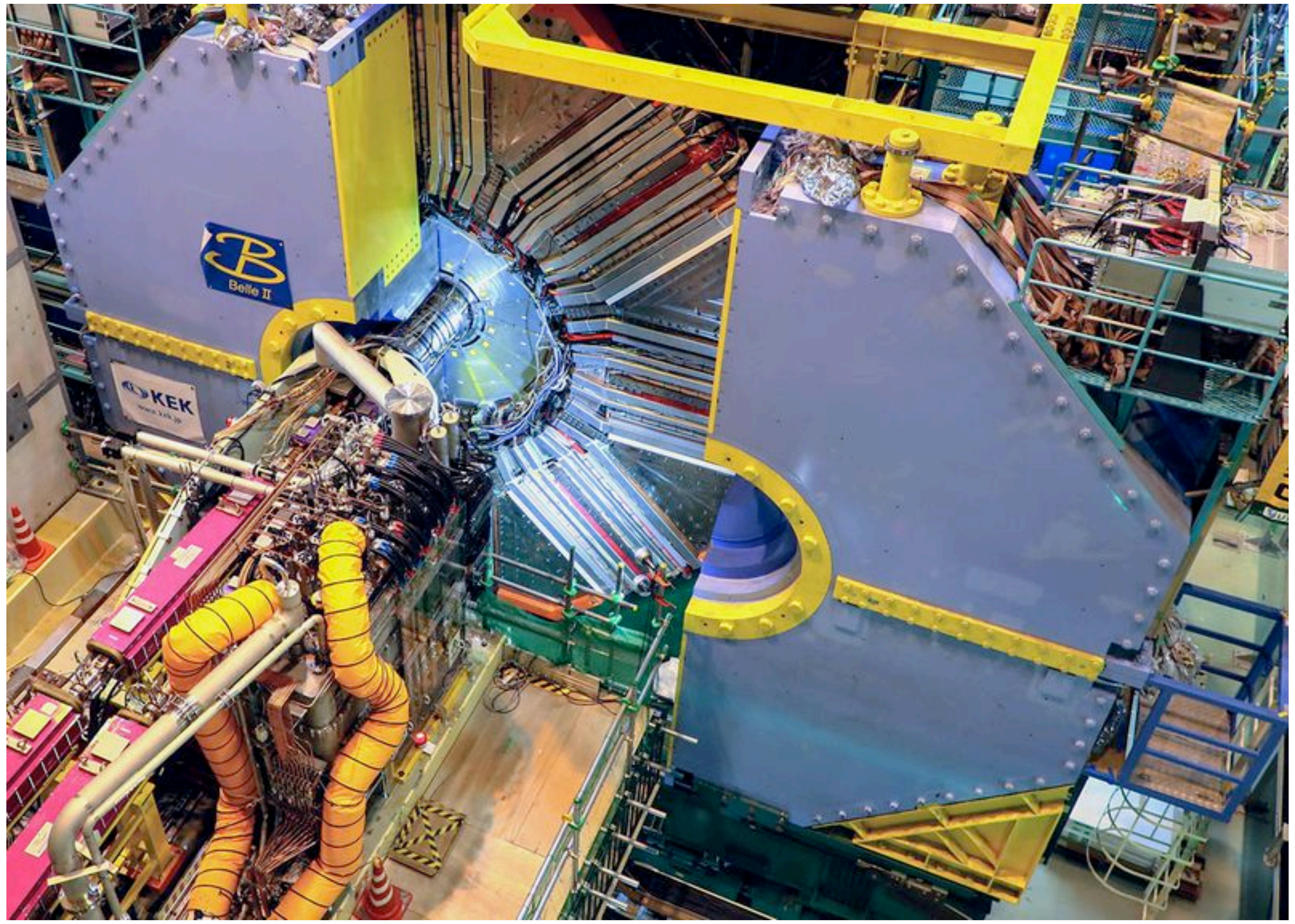
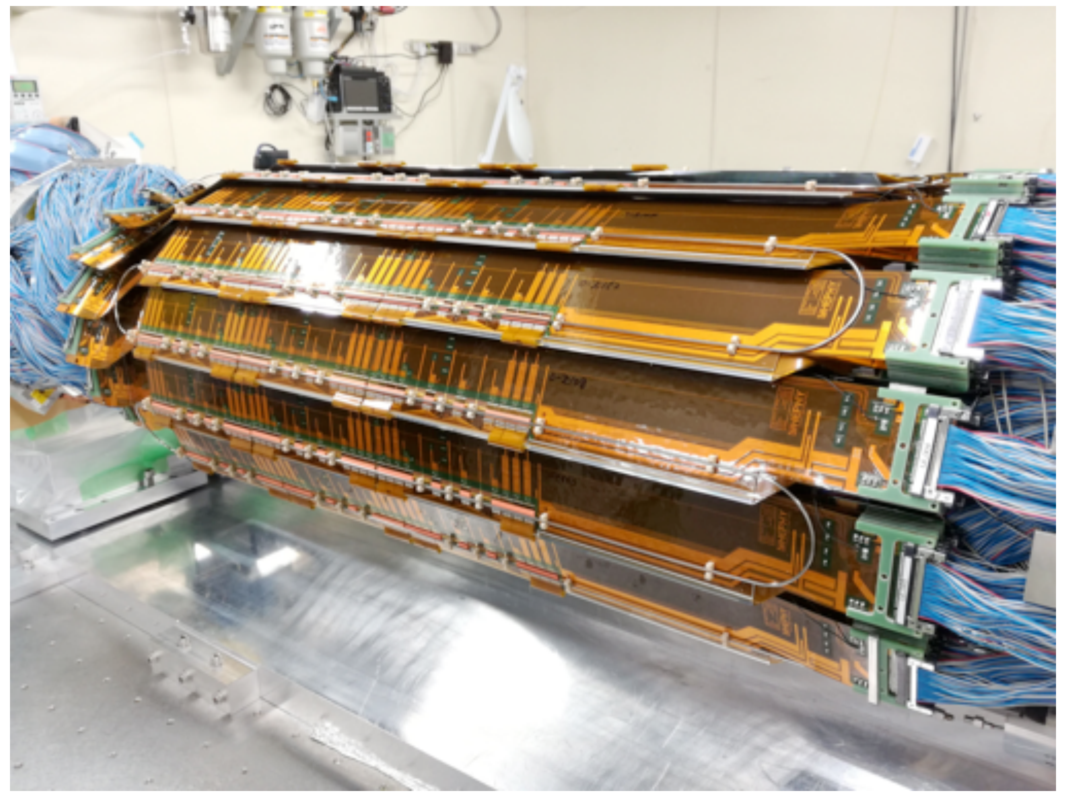
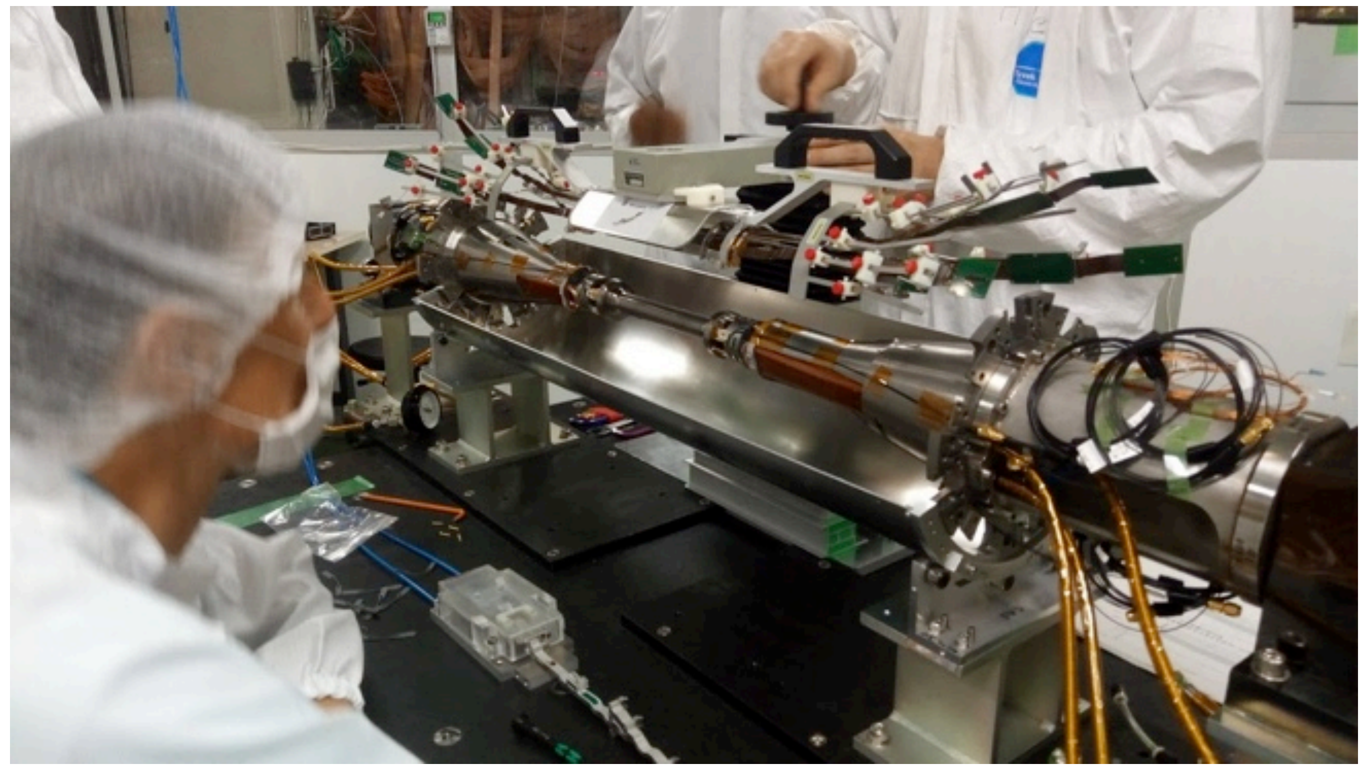
The University of Melbourne



The superconducting final focus is partially visible here (before closing the endcap).





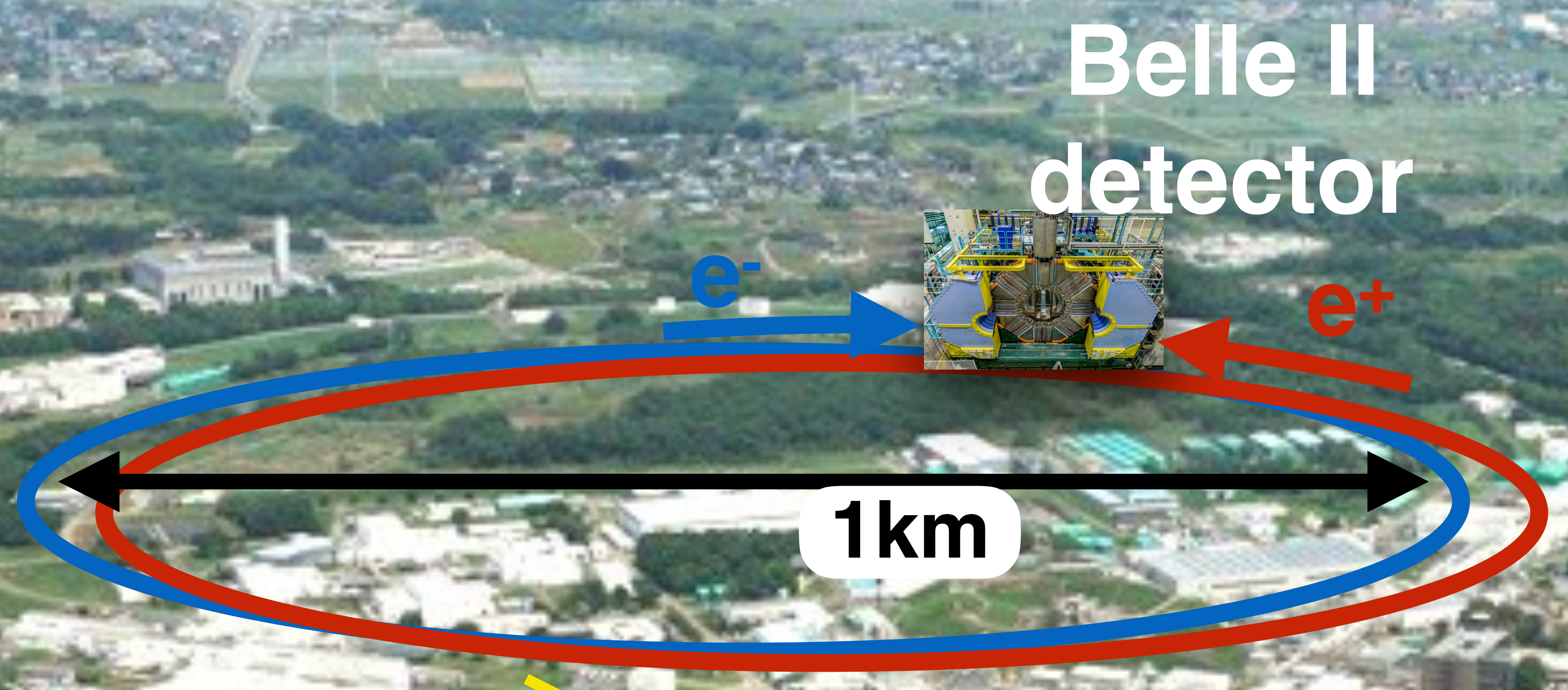
Completion of the 2nd SVD half shell; 1st PXD half-shell at KEK

Belle II

THE UNIVERSITY OF MELBOURNE

Belle II @ Super-KEKB

Intensity frontier B-factory experiment, Successor to Belle @KEKB (1999-2010)

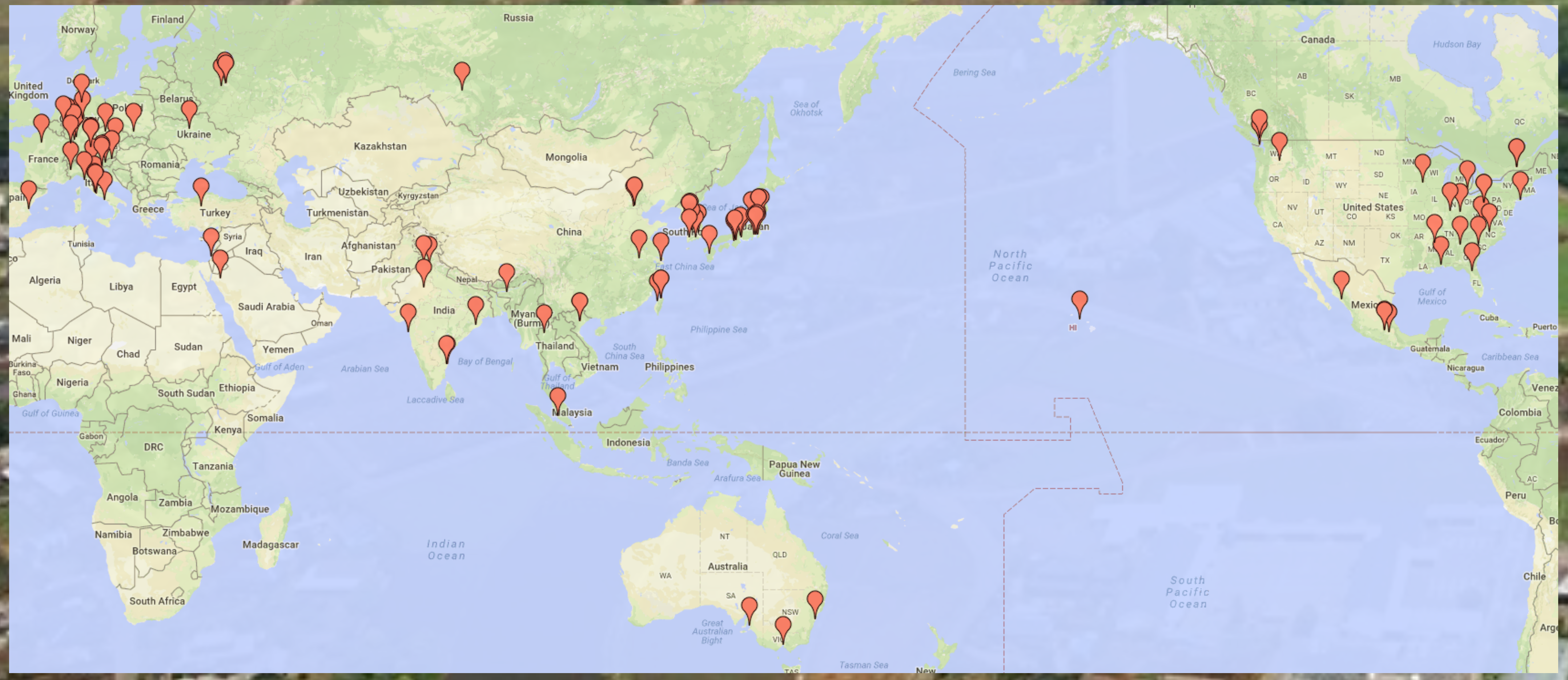


7 GeV e^-, 4 GeV e^+

E_{CM} $\Upsilon(4S) = 10.58$ GeV + scans

$\Upsilon(4S) \rightarrow B$ anti-B

B + Charm + τ factory



Belle II now has grown to ~800 researchers (267 grad students) from 25 countries

Heavy flavour data sets from colliders

- **SuperKEKB is the first new collider since the LHC.**
- **Unique strengths in CKM metrology, rare and missing energy decays.**

Expt.	∫ *L* dt	σ(bb)	σ(cc)	Operation
Babar	530 fb^{-1}	1.1 nb	1.6 nb	1999-2008
Belle	1040 fb^{-1}	1.1 nb	1.6 nb	1999-2010
Belle II	**0.5 fb^{-1} (50 ab^{-1})**	**1.1 nb**	**1.6 nb**	**2018-**
BESIII	~16 fb^{-1}	-	6 nb (3770 MeV)	2008-
LHCb	1 + 2 + >5 fb^{-1}	250-500 μb	1200-2400 μb	2009-

Observables	Expected the. accuracy		Expected exp. uncertainty	Facility (2025)
UT angles & sides				
ϕ_1 [°]	***	**CKM**	0.4	Belle II
ϕ_2 [°]	**		1.0	Belle II
ϕ_3 [°]	***		1.0	LHCb/Belle II
$\|V_{cb}\|$ incl.	***		1%	Belle II
$\|V_{cb}\|$ excl.	***		1.5%	Belle II
$\|V_{ub}\|$ incl.	**		3%	Belle II
$\|V_{ub}\|$ excl.	**		2%	Belle II/LHCb
CPV				
$S(B \to \phi K^0)$	***	**CPV**	0.02	Belle II
$S(B \to \eta' K^0)$	***		0.01	Belle II
$\mathcal{A}(B \to K^0\pi^0)[10^{-2}]$	***		4	Belle II
$\mathcal{A}(B \to K^+\pi^-)$ $[10^{-2}]$	***		0.20	LHCb/Belle II
(Semi-)leptonic				
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	**SL**	3%	Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**		7%	Belle II
$R(B \to D\tau\nu)$	***		3%	Belle II
$R(B \to D^*\tau\nu)$	***		2%	Belle II/LHCb
Radiative & EW Penguins				
$\mathcal{B}(B \to X_s\gamma)$	**	**EWP**	4%	Belle II
$A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	***		0.005	Belle II
$S(B \to K_S^0\pi^0\gamma)$	***		0.03	Belle II
$S(B \to \rho\gamma)$	**		0.07	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	**		0.3	Belle II
$\mathcal{B}(B \to K^*\nu\overline{\nu})$ $[10^{-6}]$	***		15%	Belle II
$\mathcal{B}(B \to K\nu\overline{\nu})$ $[10^{-6}]$	***		20%	Belle II
$R(B \to K^*\ell\ell)$	***		0.03	Belle II/LHCb
Charm				
$\mathcal{B}(D_s \to \mu\nu)$	***	**D**	0.9%	Belle II
$\mathcal{B}(D_s \to \tau\nu)$	***		2%	Belle II
$A_{CP}(D^0 \to K_S^0\pi^0)$ $[10^{-2}]$	**		0.03	Belle II
$\|q/p\|(D^0 \to K_S^0\pi^+\pi^-)$	***		0.03	Belle II
$\phi(D^0 \to K_S^0\pi^+\pi^-)$ [°]	***		4	Belle II
Tau				
$\tau \to \mu\gamma$ $[10^{-10}]$	***	**τ**	< 50	Belle II
$\tau \to e\gamma$ $[10^{-10}]$	***		< 100	Belle II
$\tau \to \mu\mu\mu$ $[10^{-10}]$	***		< 3	Belle II/LHCb

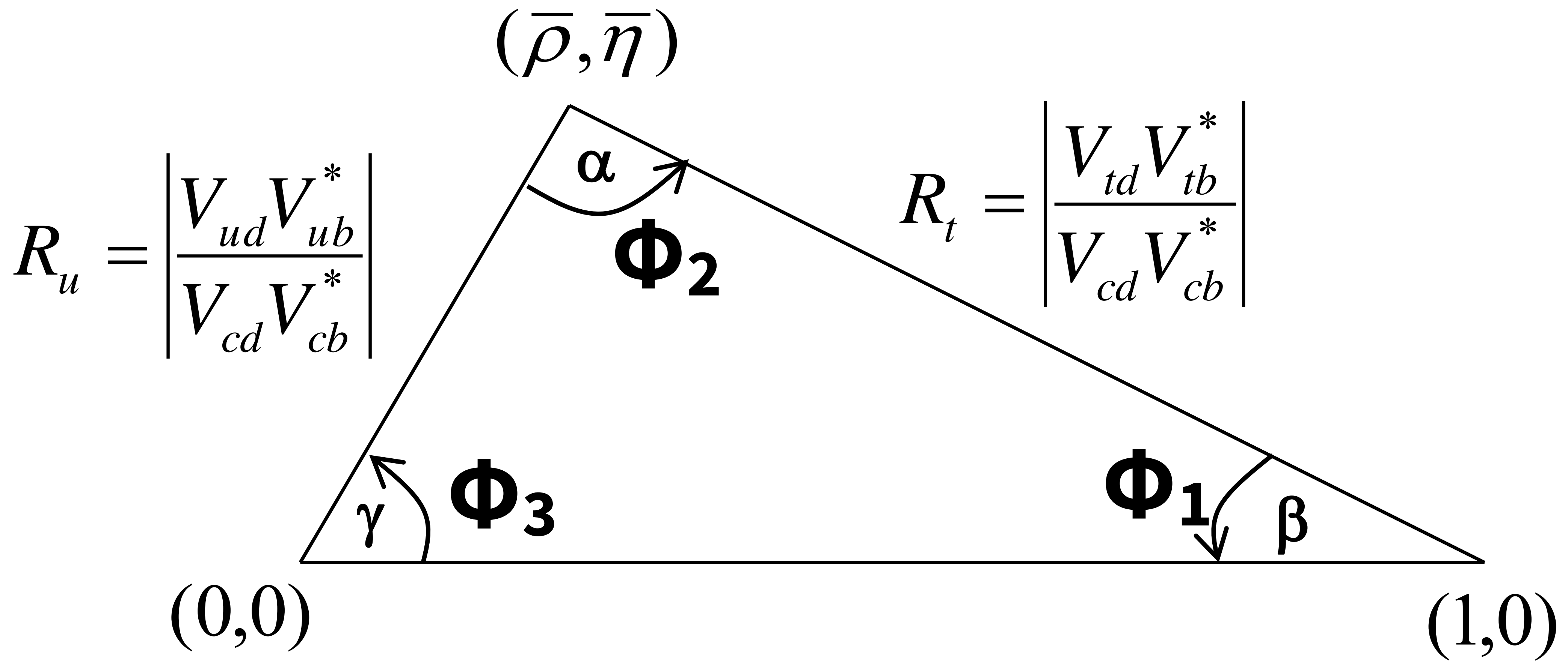
CKM and CPV SM Metrology: Belle II core program

- The SM describes the mixing of quarks of different generations through the weak force.

$$V_{\mathrm{CKM}} \propto \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|\, e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|\, e^{-i\beta} & -|V_{ts}|\, e^{-i\beta_s} & |V_{tb}| \end{pmatrix}$$

3 Generations, 1 Phase: single source of CPV in the SM.

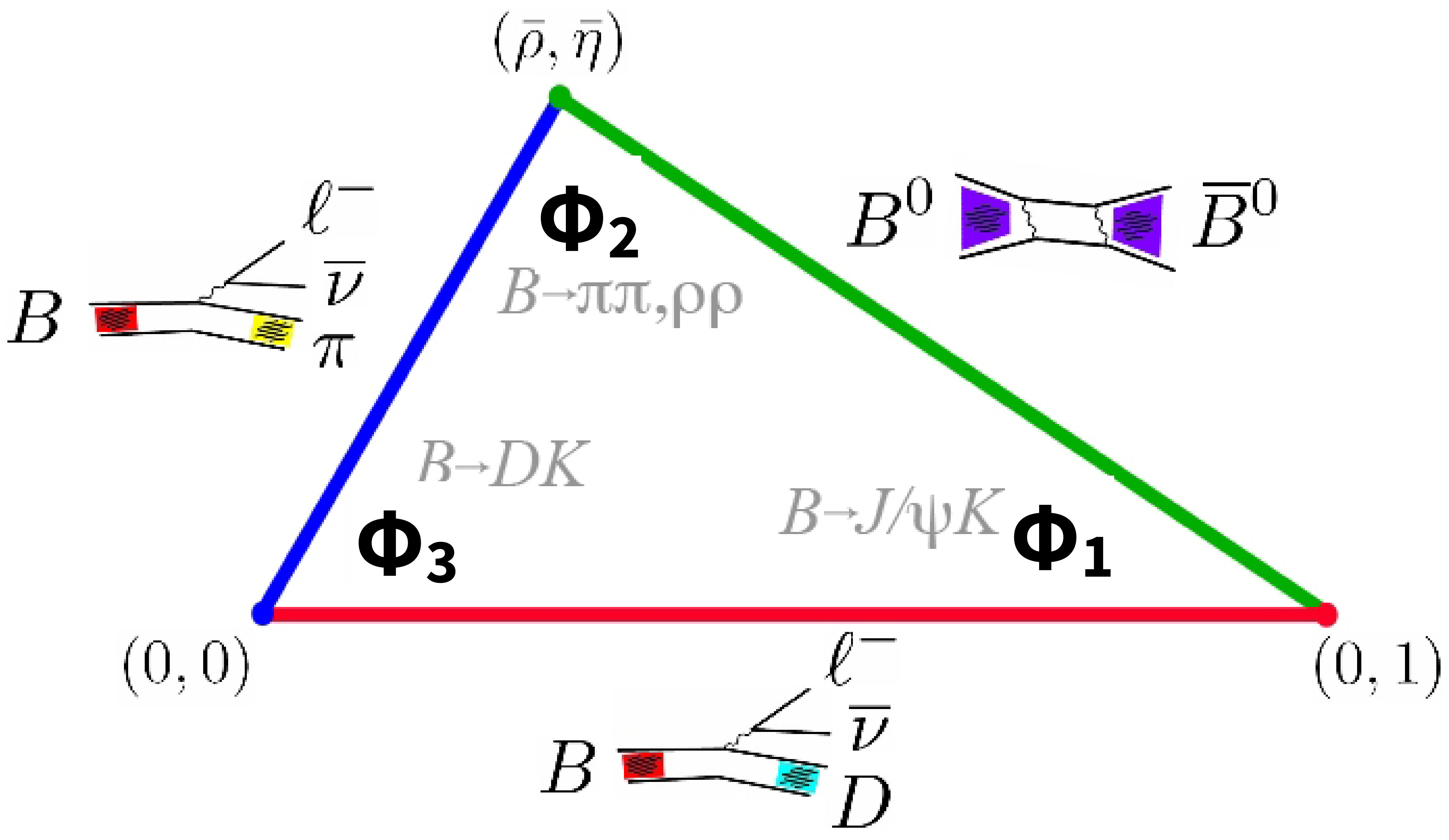
Wolfenstein parameterisation: Phase invariant, conserving CKM matrix unitarity at any order in λ.



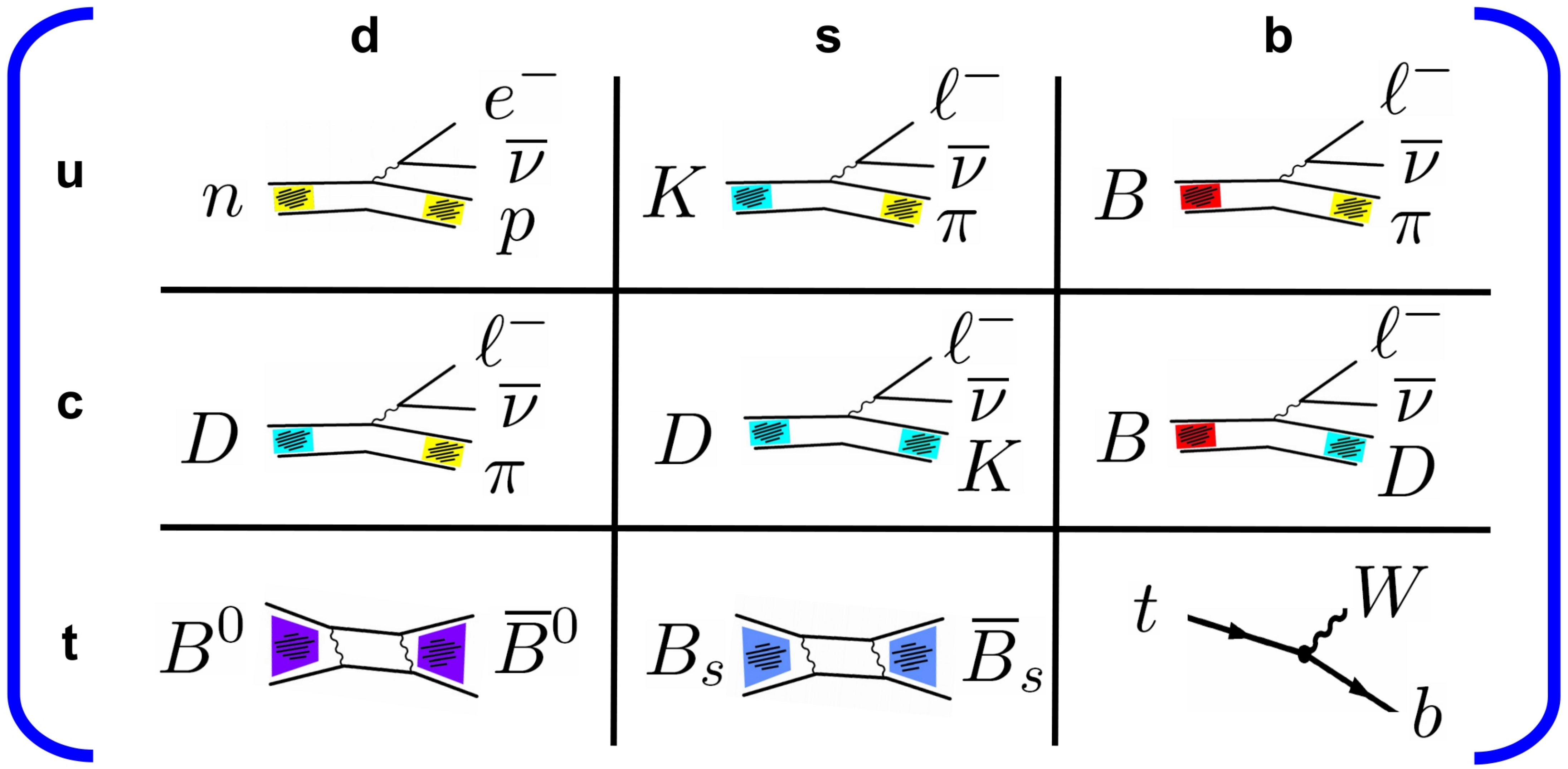
$$\lambda^2 \equiv \frac{|V_{us}|^2}{|V_{ud}|^2 + |V_{us}|^2} \qquad A^2\lambda^4 \equiv \frac{|V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2} \qquad \bar{\rho} + i\bar{\eta} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

CKM and CPV SM Metrology: Belle II core program

- How do we measure the CKM parameters?



$V =$



$B\to\pi\pi,\ \rho\rho$	α / Φ_2	$B\to D^* l\nu$ / $b\to c\,l\nu$	$\lvert V_{cb}\rvert$ via Form factor / OPE
$B\to D^{(*)} K^{(*)}$	γ / Φ_3	$B\to\pi l\nu$ / $b\to u\,l\nu$	$\lvert V_{ub}\rvert$ via Form factor / OPE
$B\to J/\psi K_S$	β / Φ_1	$M\to l\nu\,(\gamma)$	$\lvert V_{UD}\rvert$ via Decay constant f_M
$B_s\to J/\psi\,\Phi$	β_s	Δm_d, Δm_s	$\lvert V_{tb} V_{t\{d,s\}}\rvert$ via Bag factor B_B

WA HFLAV & CKMfitter 2018

$\sin2\Phi_1 = 0.70 \pm 0.02$

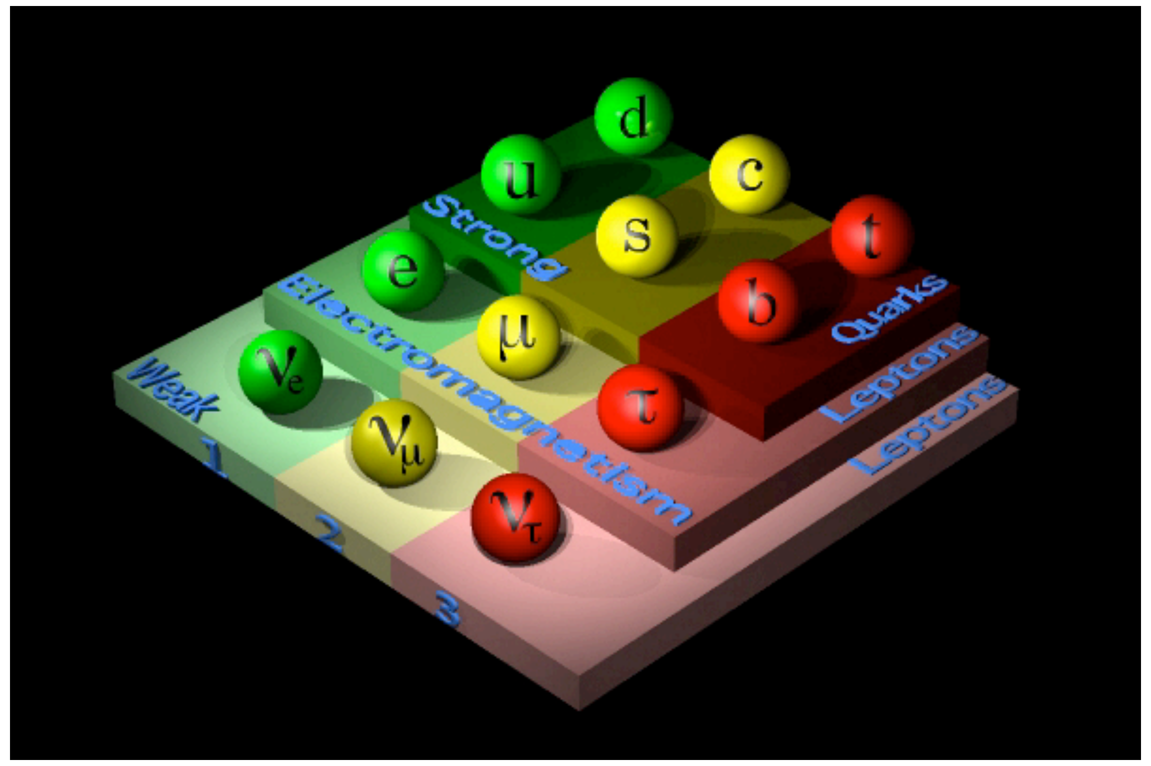
$\Phi_2 = (84.9\,^{+5.1}_{-4.5})°$

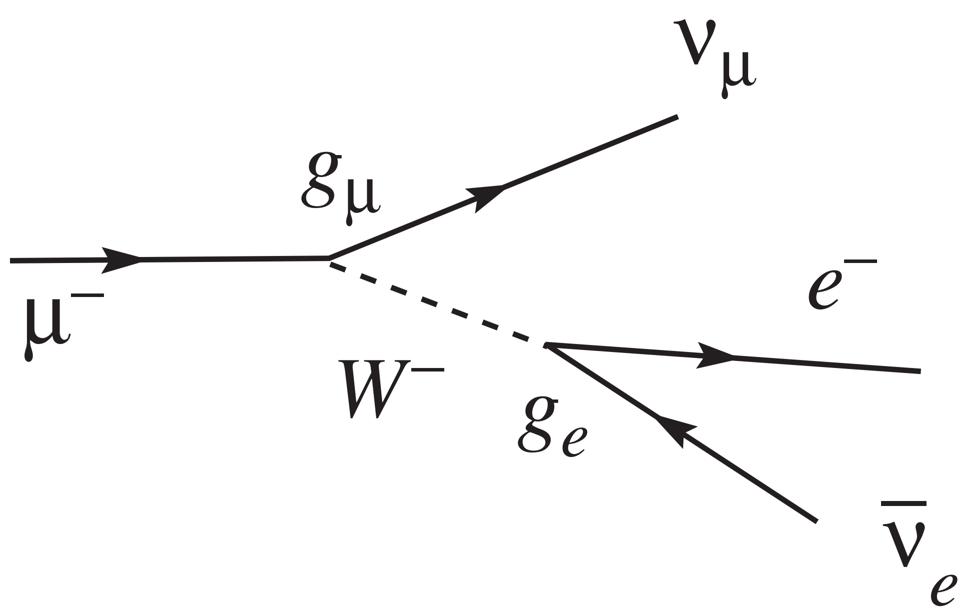
$\Phi_3 = (73.5^{+4.2}_{-5.1})°$

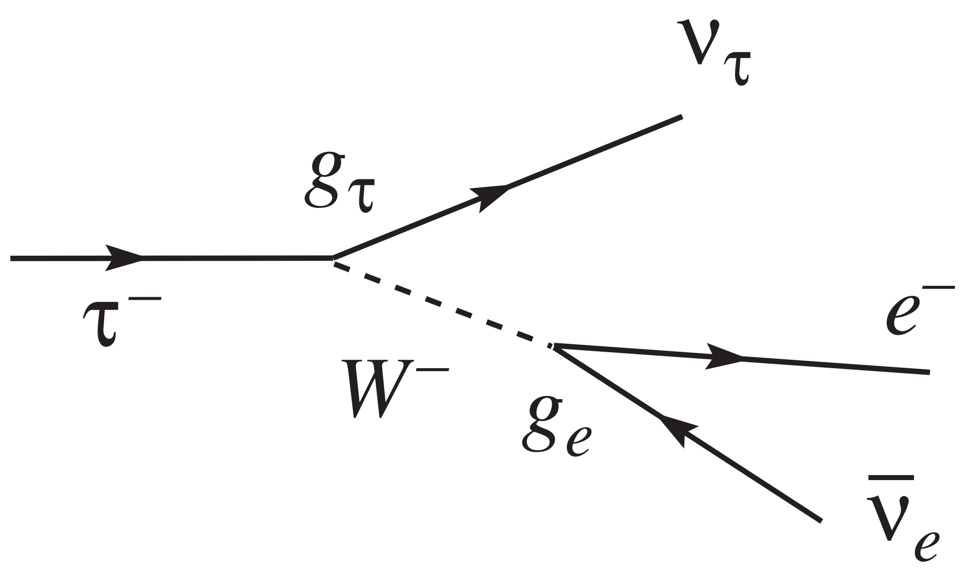
$|V_{ub}| = (3.98 \pm 0.08 \pm 0.22)\ 10^{-3}$

$|V_{cb}| = (41.8 \pm 0.4 \pm 0.6) \times 10^{-3}$

Lepton flavour universality



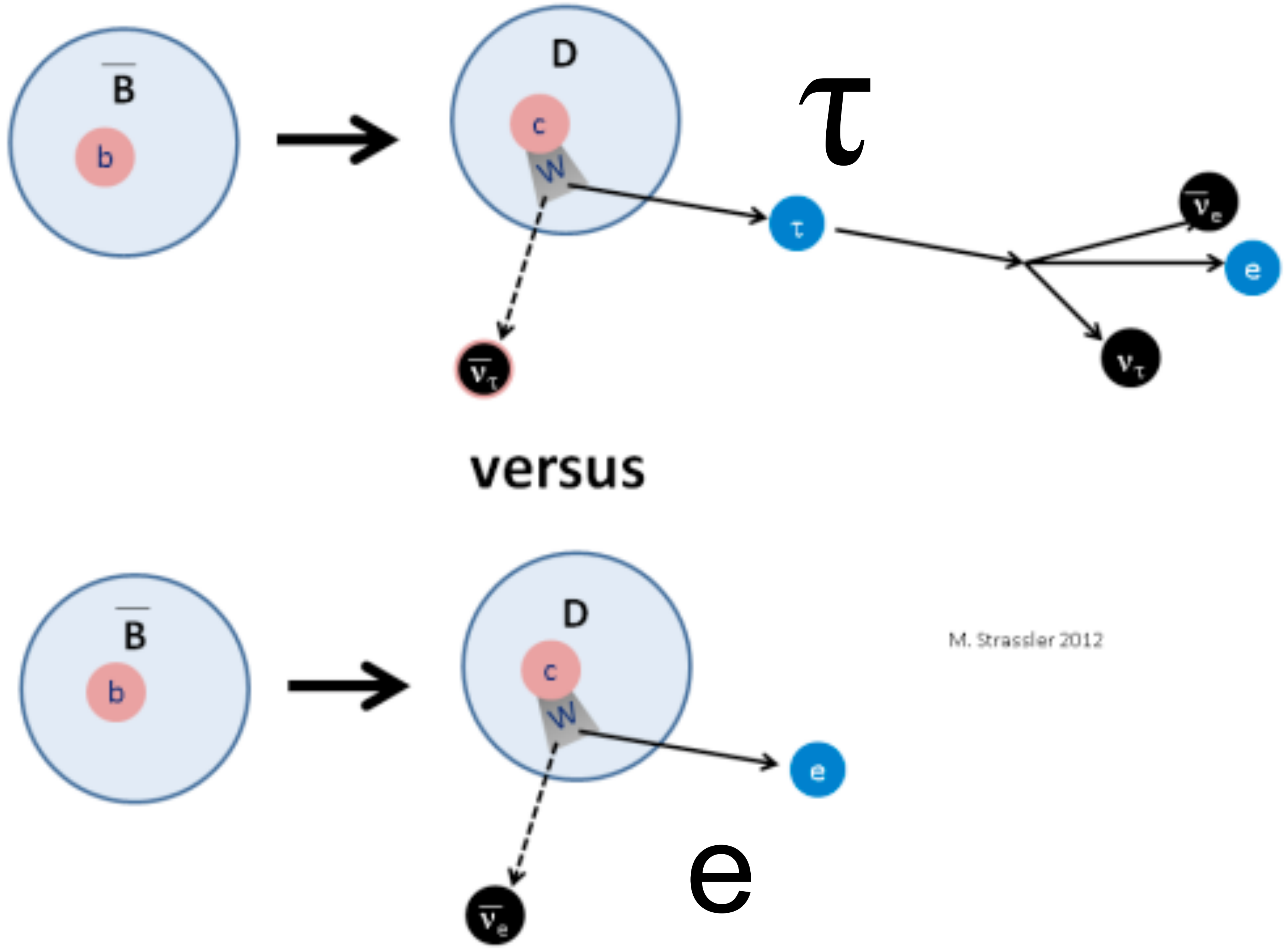




$$\frac{g_\mu^2}{g_\tau^2} = \frac{1}{\tau_\mu} \frac{\tau_\tau}{BR(\tau^- \to e^- \bar{\nu}_e \nu_\tau)} \frac{m_\tau^5}{m_\mu^5} \frac{\rho_\tau}{\rho_\mu}$$

$$\frac{g_\tau}{g_\mu} = 1.0000 \pm 0.0014$$

Experimentally good for leptonic decays to an accuracy much better than 1%.



Now can access the 3rd generation of leptons and couple to quarks!

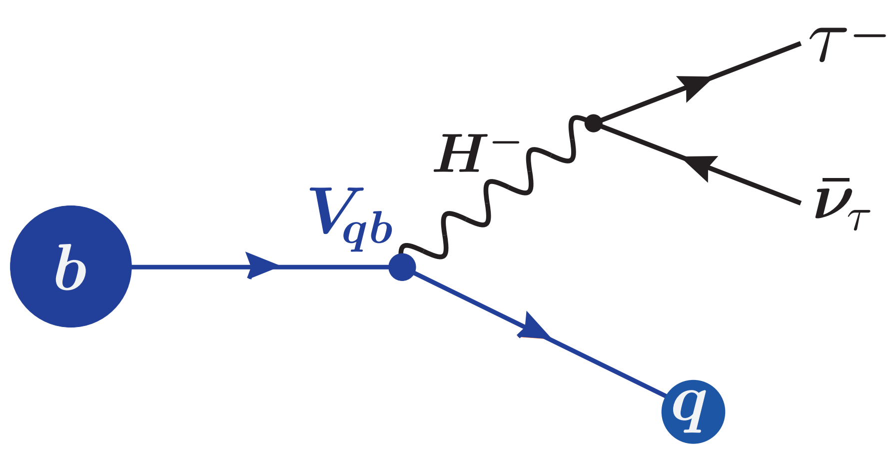
The only SM differences are are due to masses - easy* to calculate!

Any further difference would imply non-SM interaction.

R(D) and R(D*) Tree anomalies

2018 summer

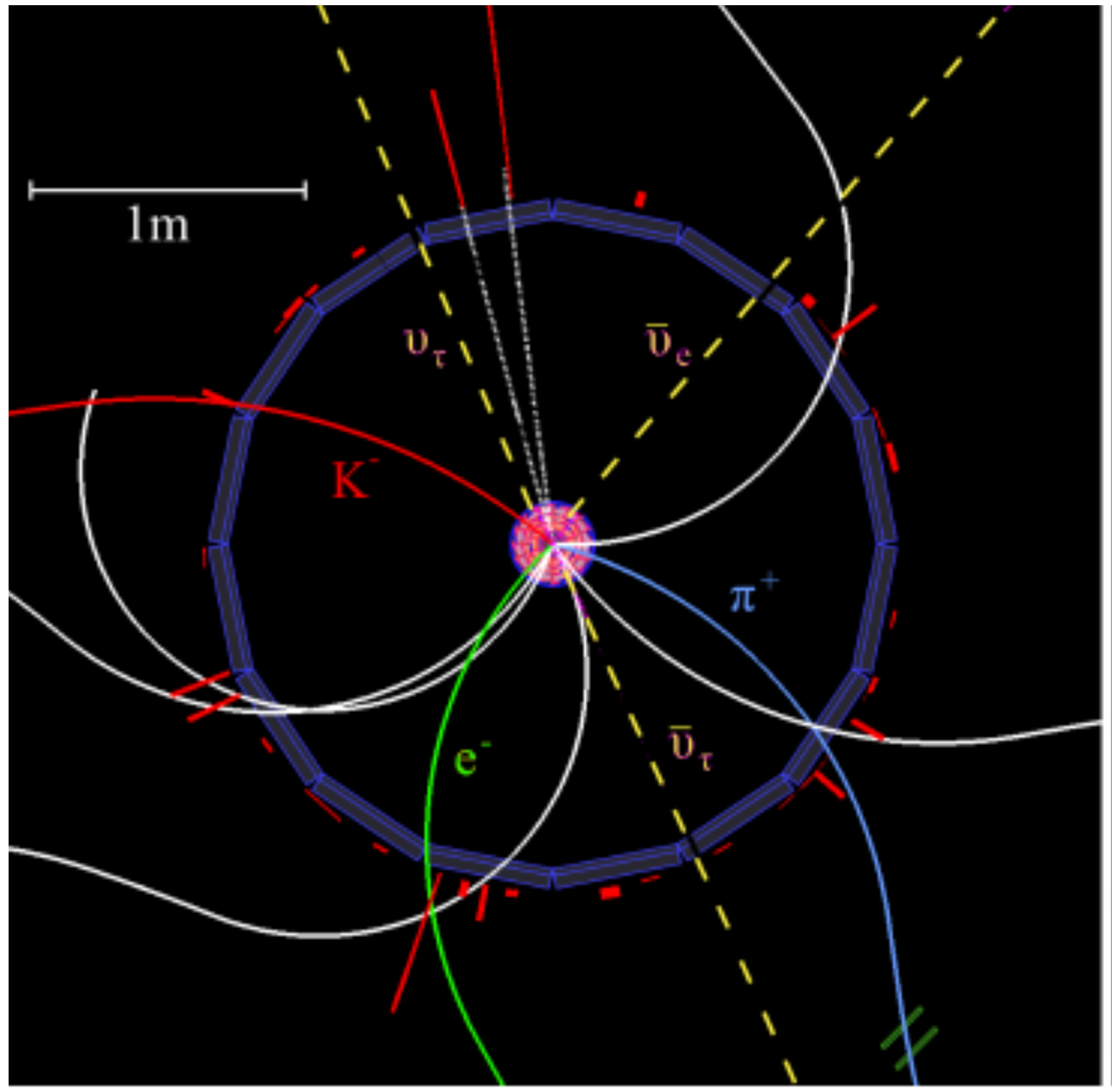
World Average is (still) 4σ from the SM



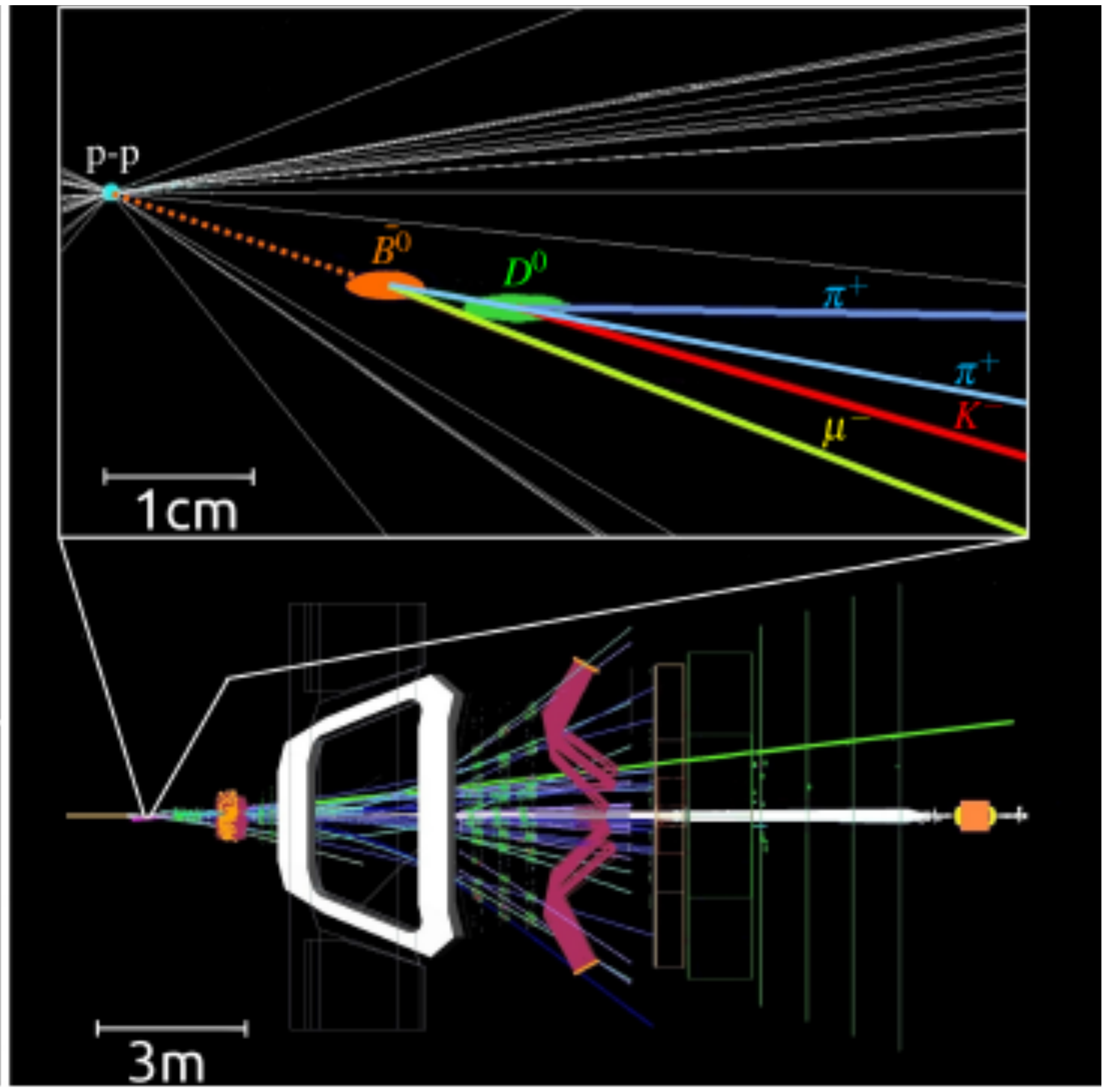
$$R = \frac{\mathcal{B}(b \to q\,\tau\,\bar{\nu}_\tau)}{\mathcal{B}(b \to q\,\ell\,\bar{\nu}_\ell)}$$

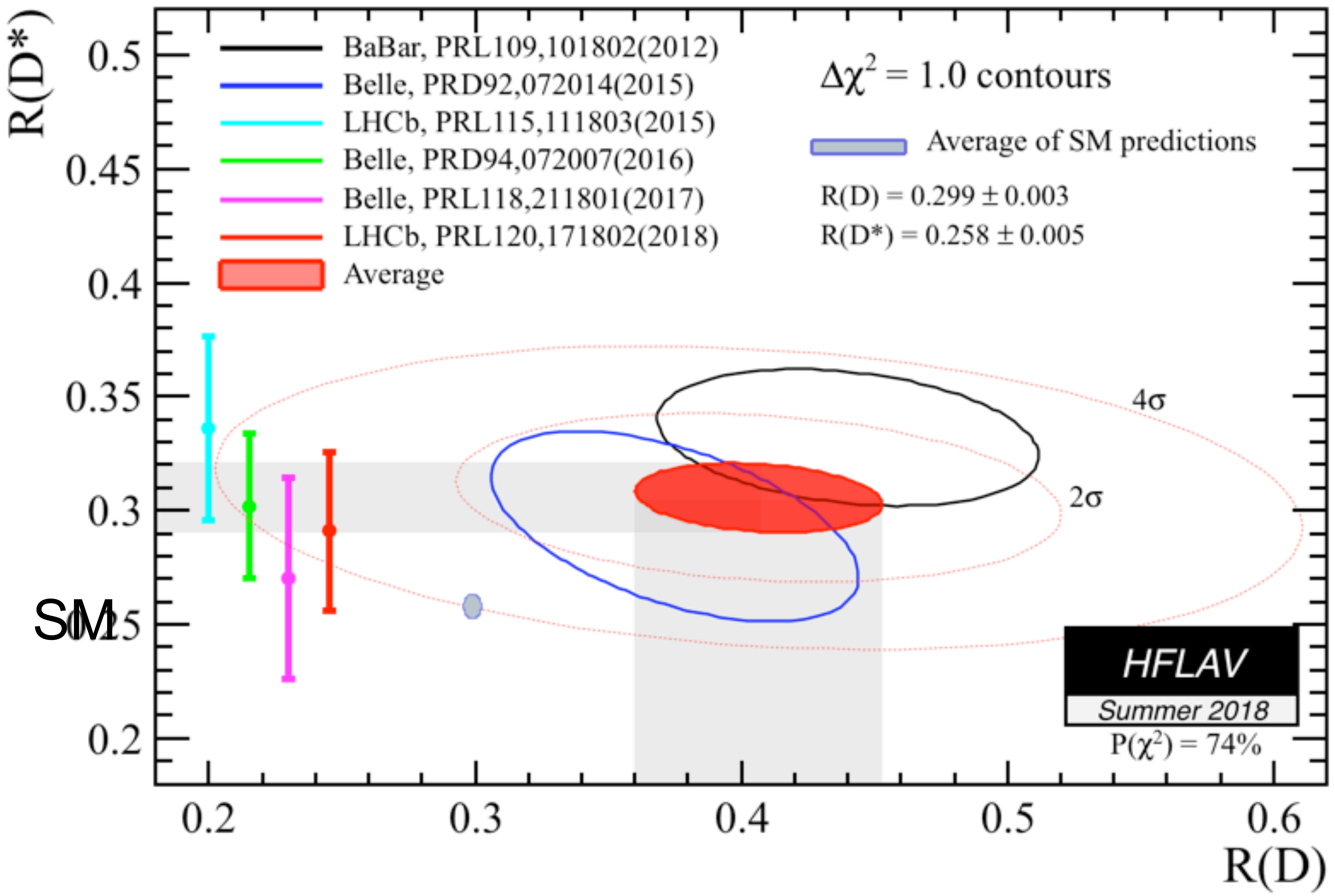
$\ell = e, \mu$

Belle



LHCb





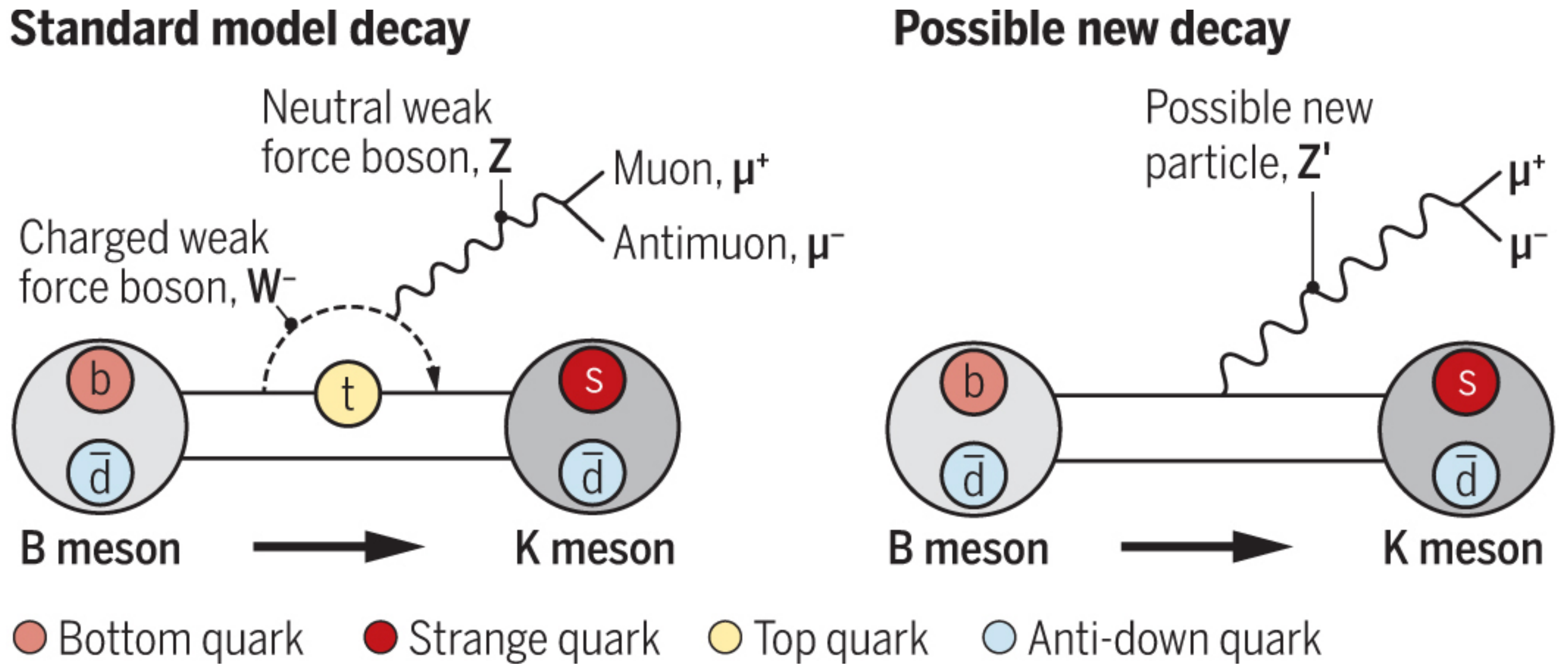
A similar ratio was measured in e Vs. μ at ICHEP 2018 at 3% precision (agreed with SM).

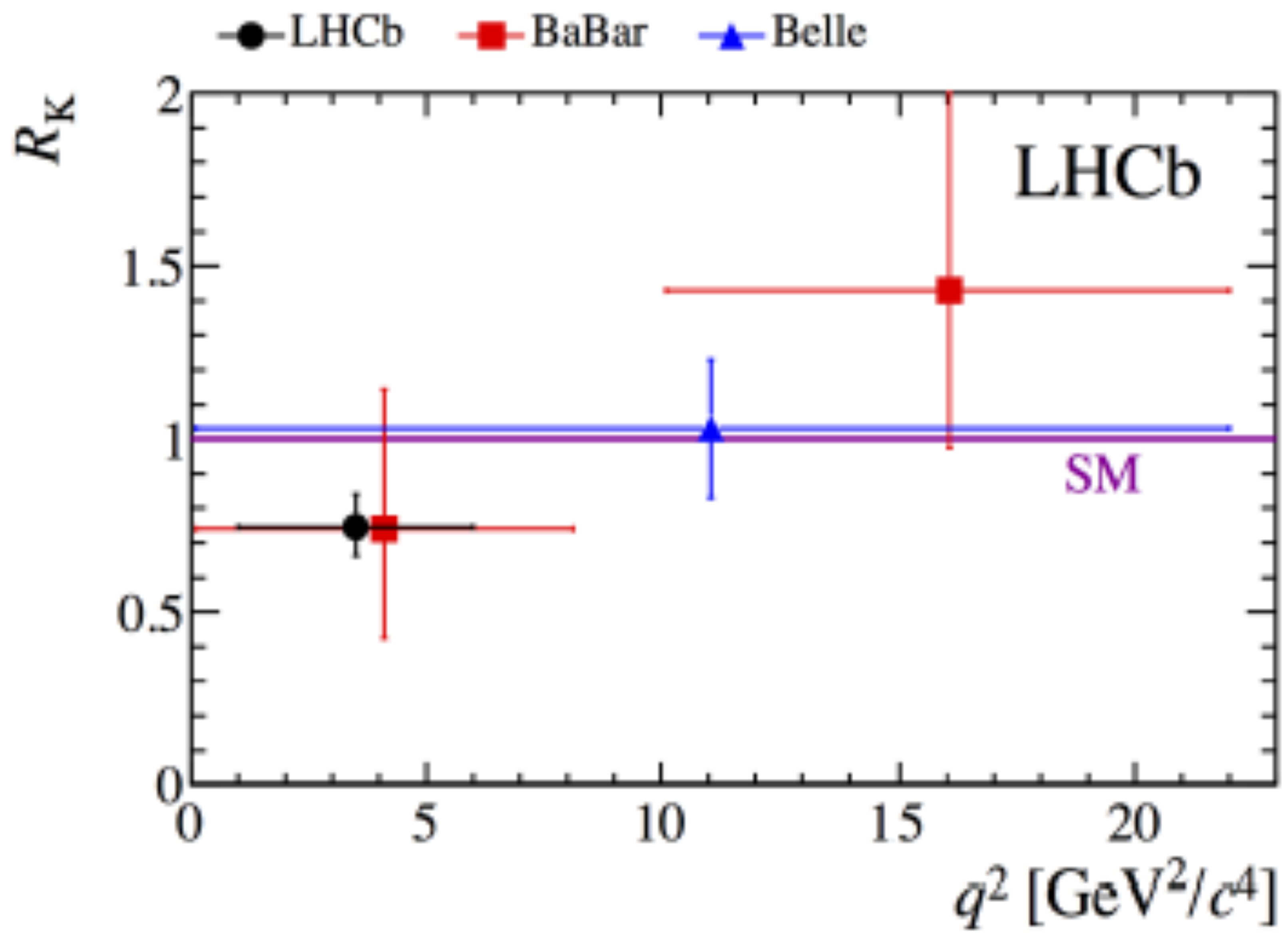
R(K) and R(K*) Loop anomalies

$$R_{K^{(*)}}(q^2) = \frac{BF(B \to K^{(*)}\mu^+\mu^-)}{BF(B \to K^{(*)}e^+e^-)}$$

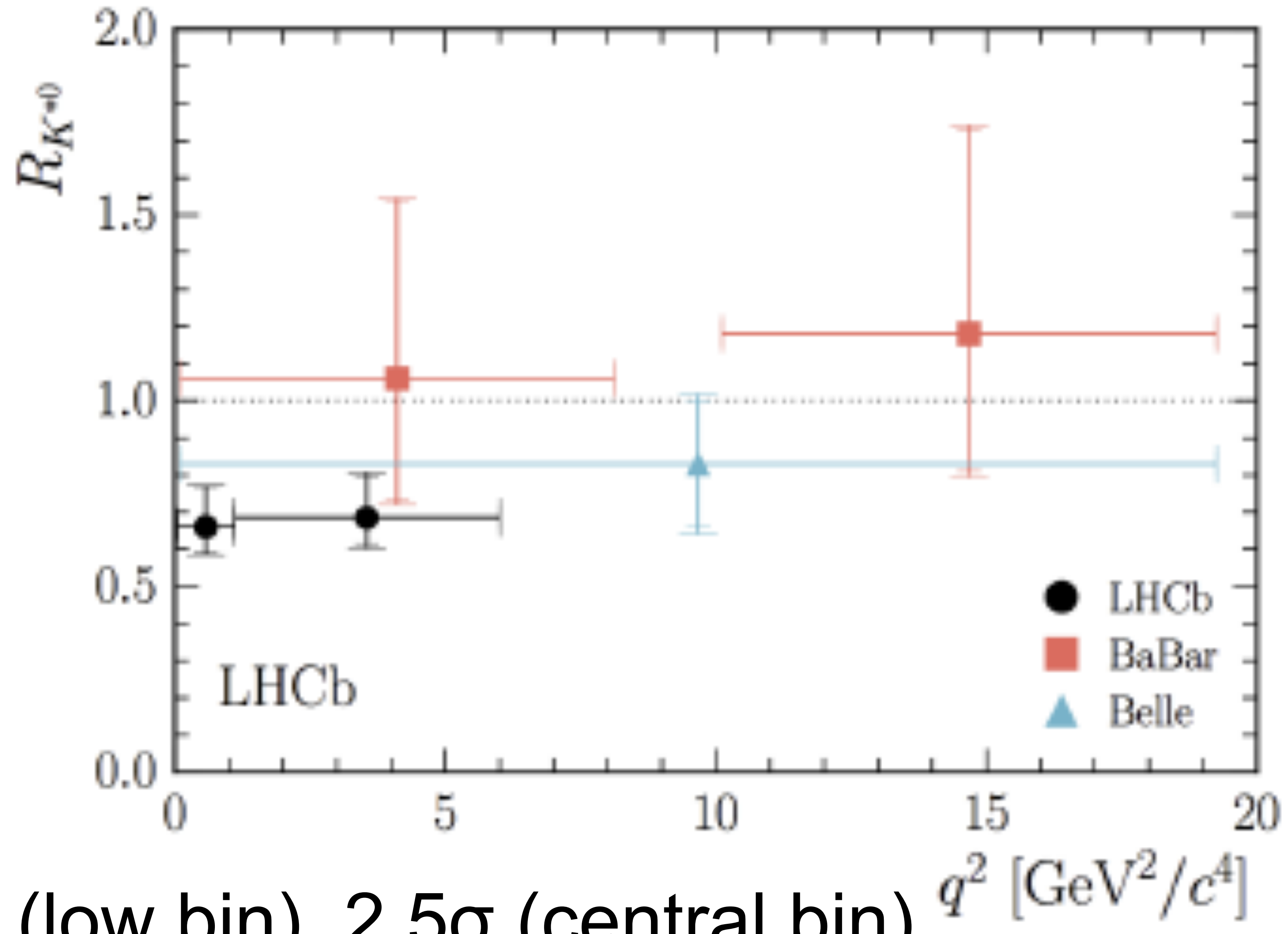
For experts: $q^2 = M^2(l^+l^-)$

Angular correlations in B→ K l l also show deviations from the SM.*





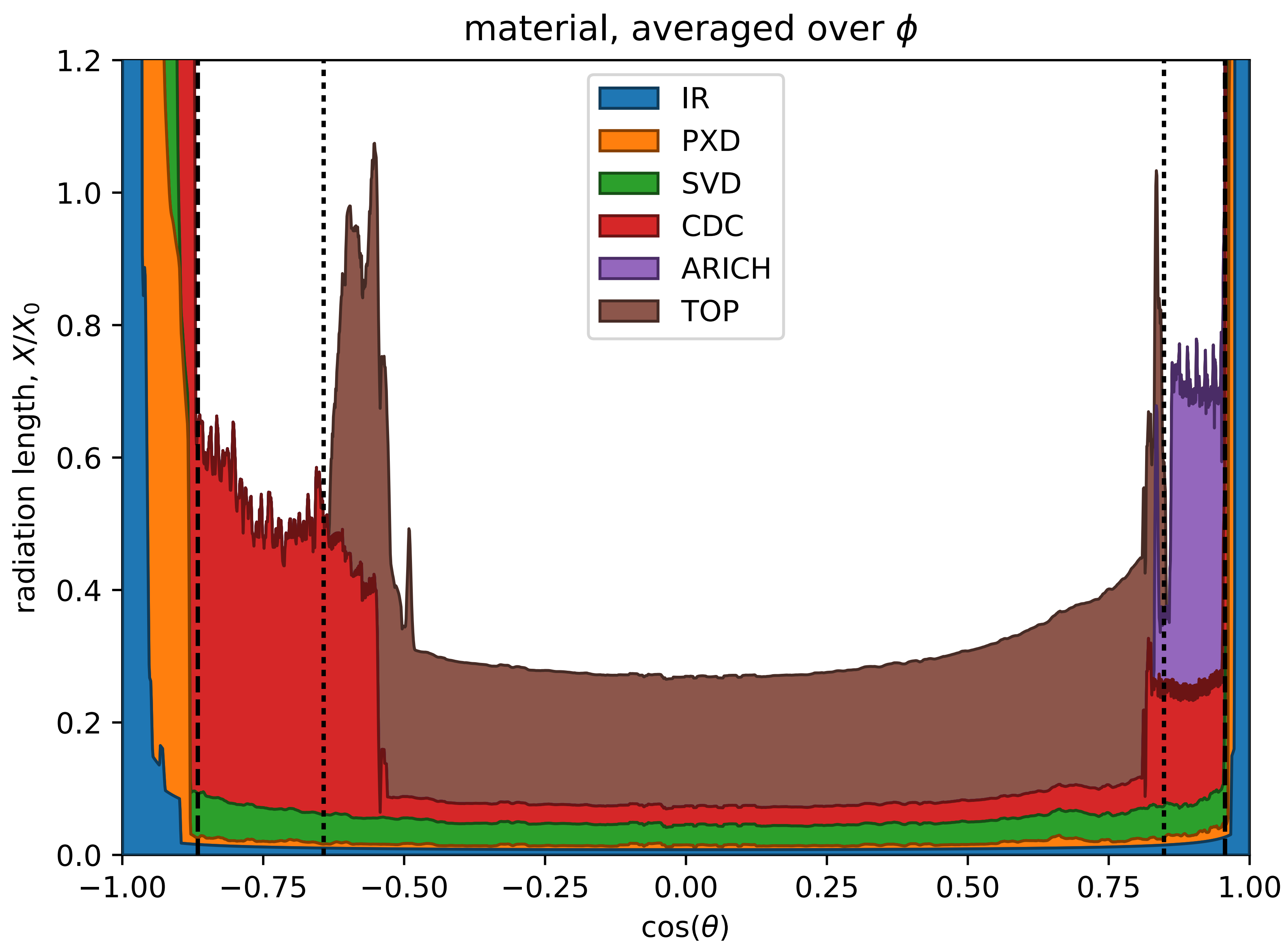
R_K is ~2.6σ from the SM

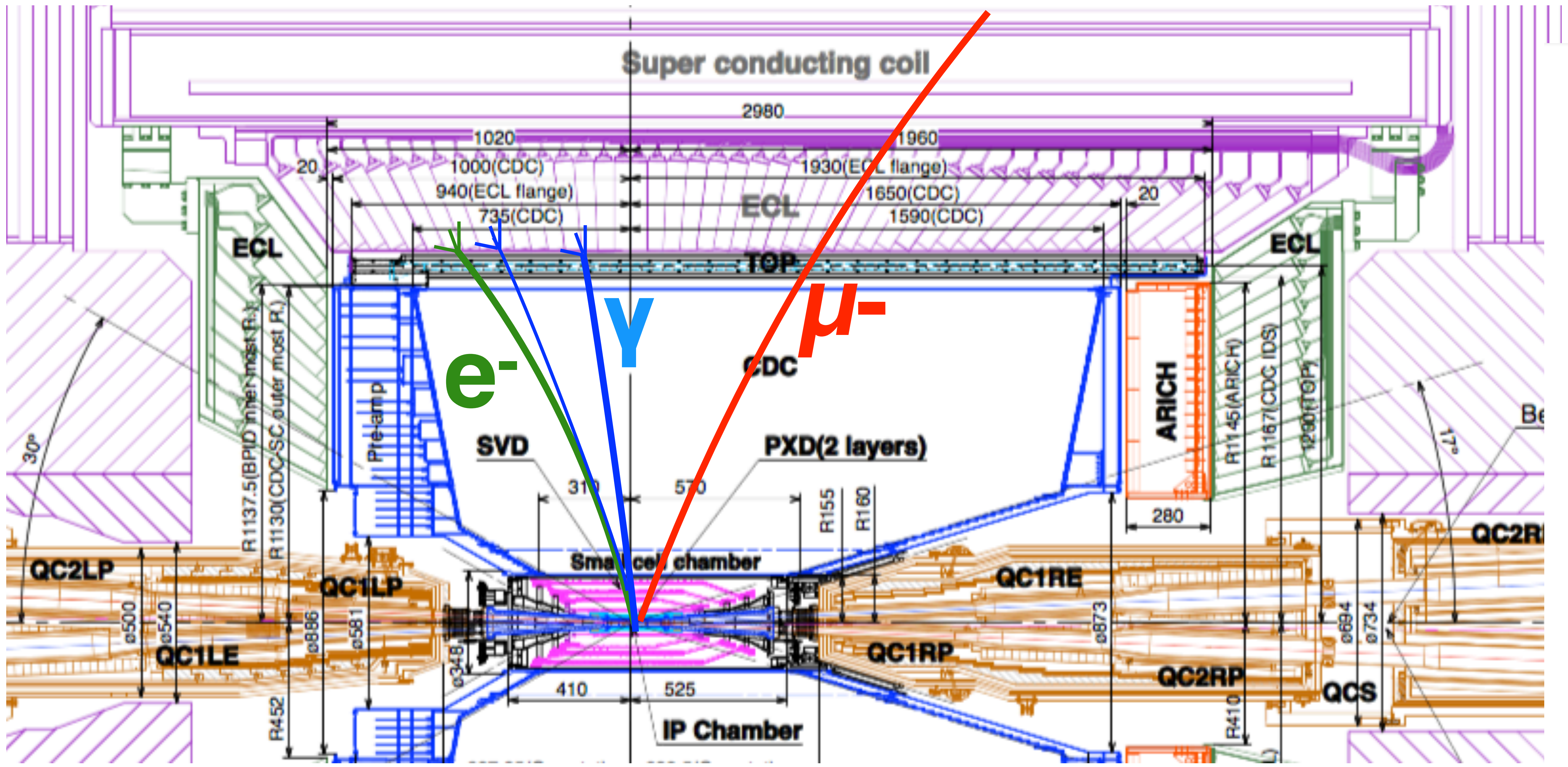


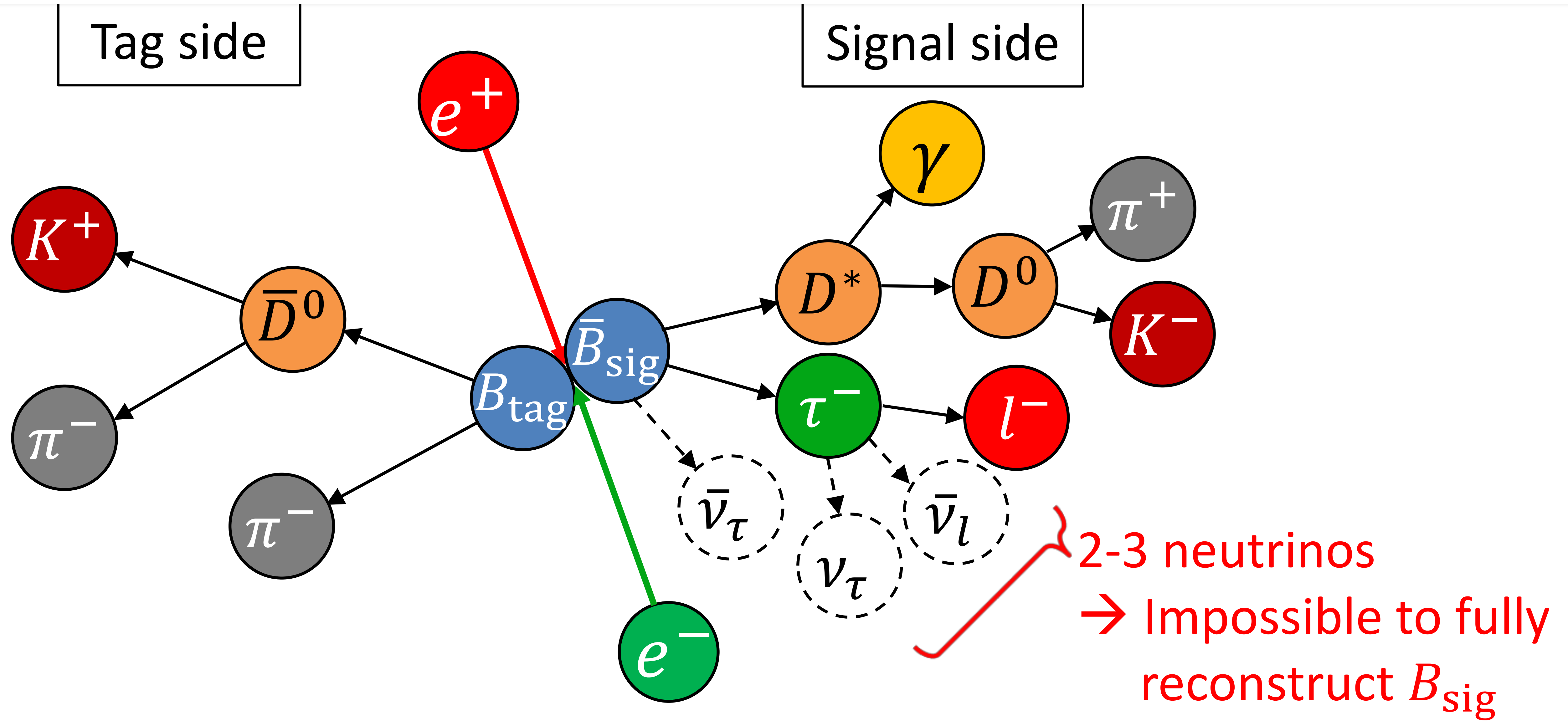
R_{K^*} ~2.1σ (low bin), 2.5σ (central bin)

Lepton reconstruction non-universality

- **Muons**: Little to **no radiation** (heavy), **Stable** within particle detectors, no strong interactions
- **Electrons** are light: Final state radiation, Bremsstrahlung in material is likely.
- **Taus** lifetime is 10^{-12} s: background mimics signal where daughters are lost e.g. K_L, π^0.

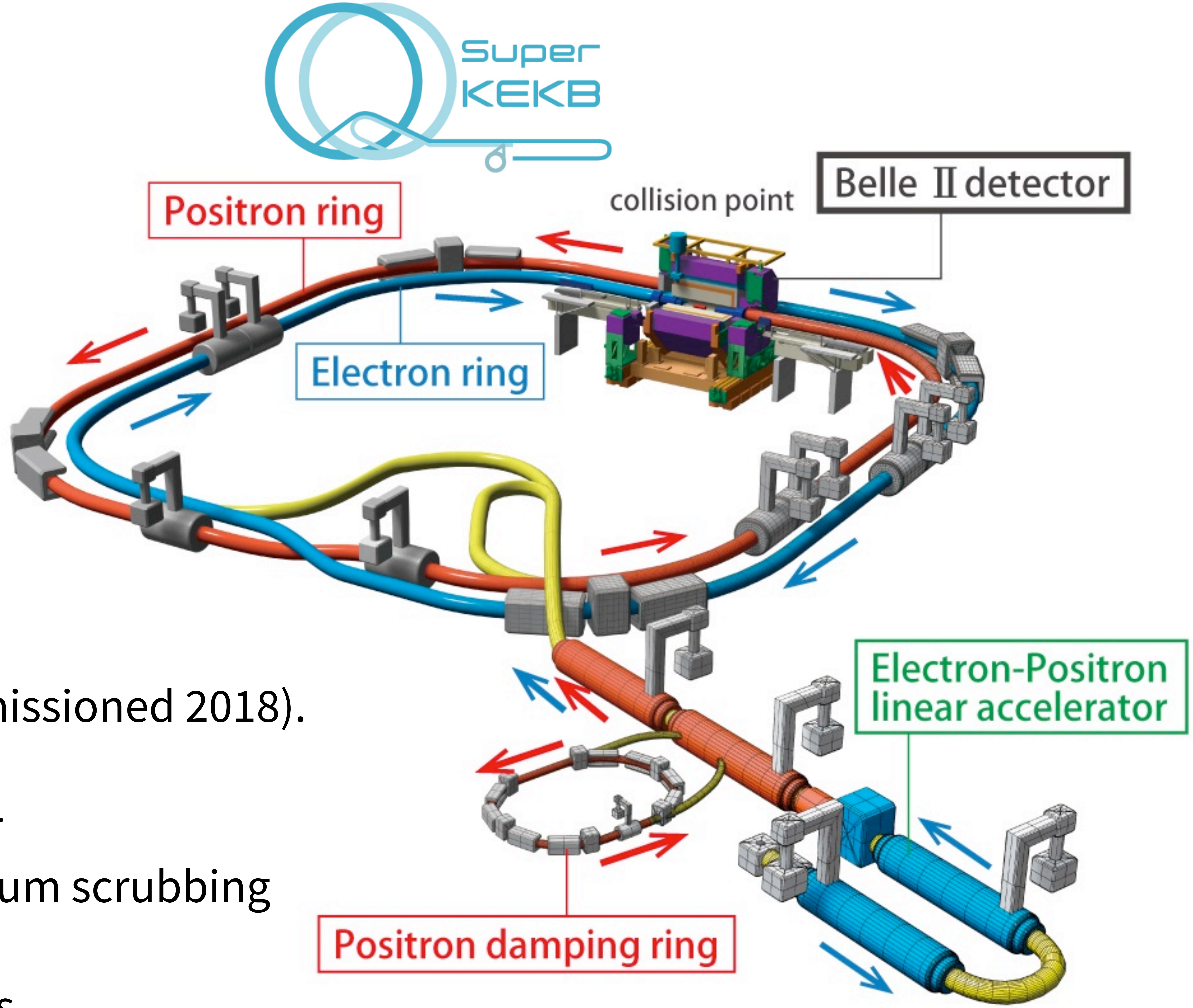






SuperKEKB

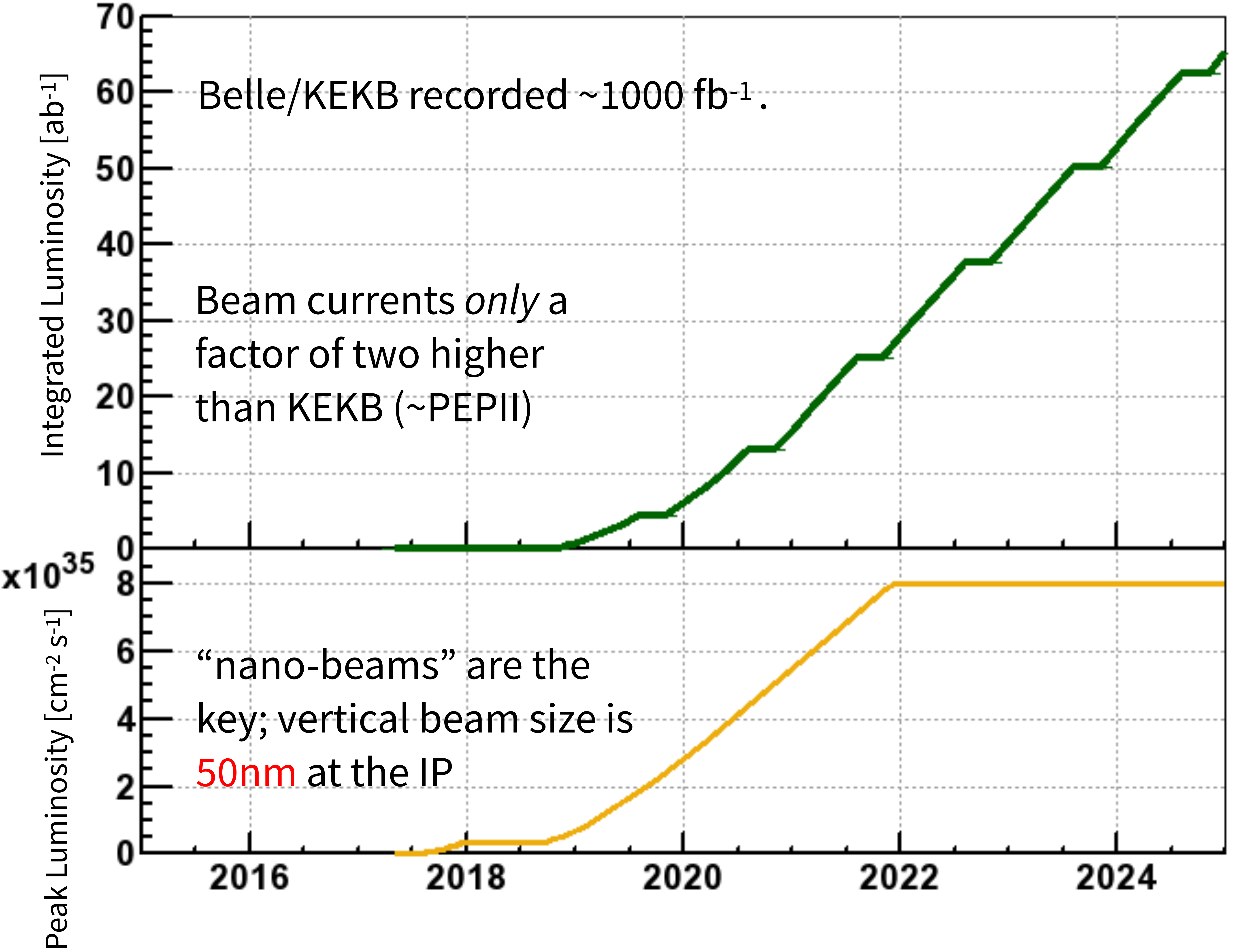
QCS(R) before connecting to Belle II

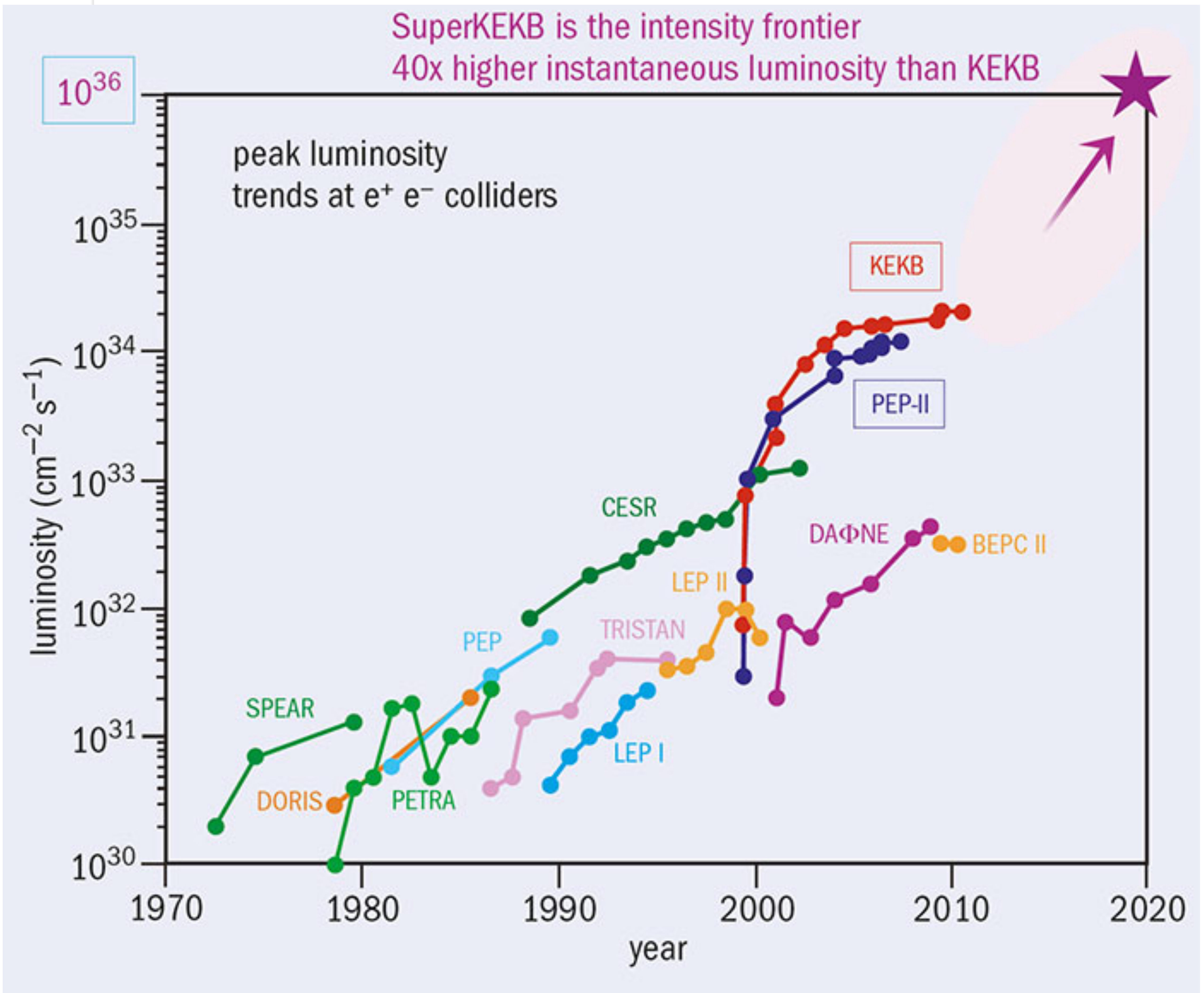


1) Brand-new positron damping ring (commissioned 2018).

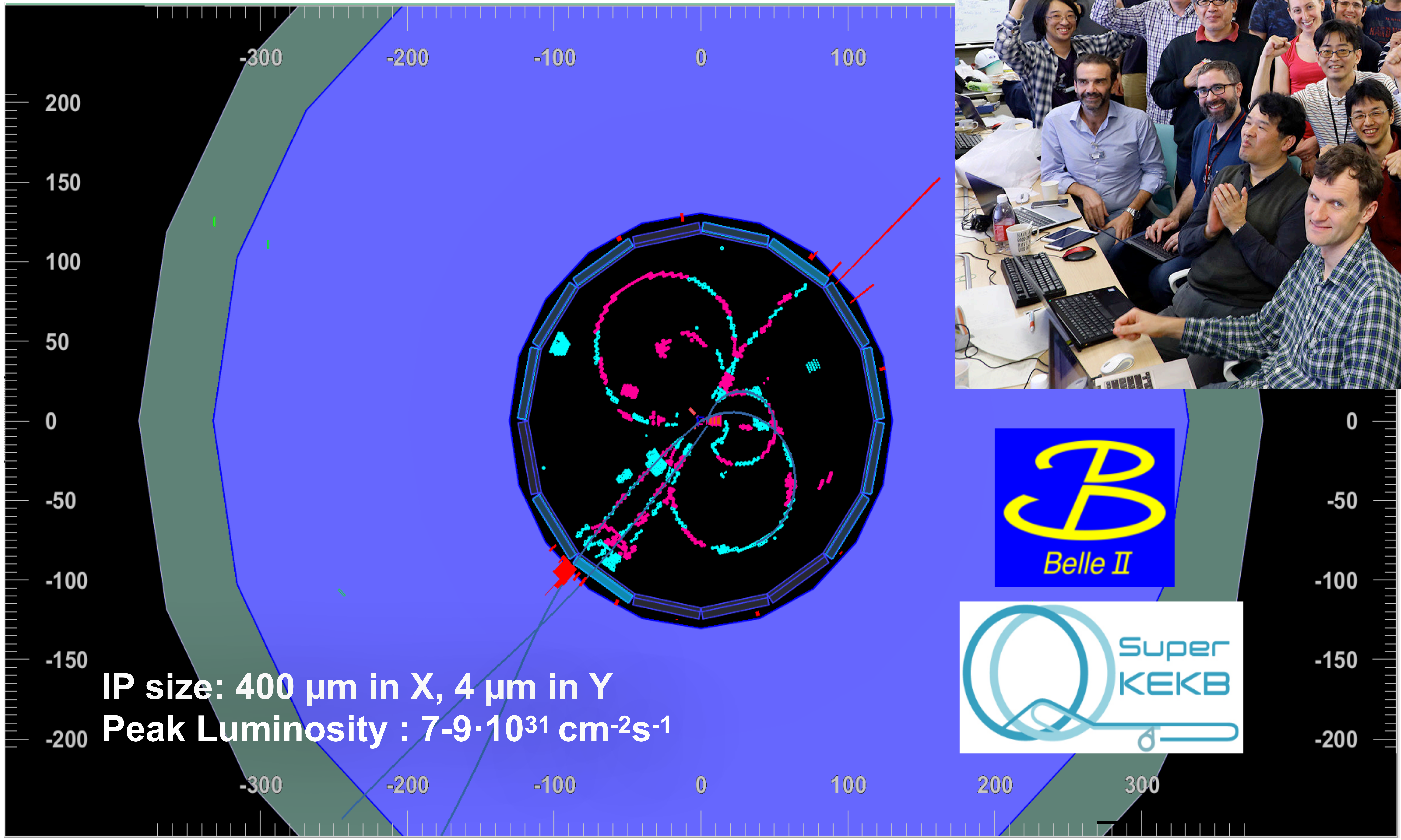
2) New 3 km positron ring vacuum chamber (commissioned in 2016). Optics and vacuum scrubbing in 2018.
3) New complex superconducting final focus (commissioned 2018).

SuperKEKB/Belle II Luminosity Profile





First collisions (April 26)

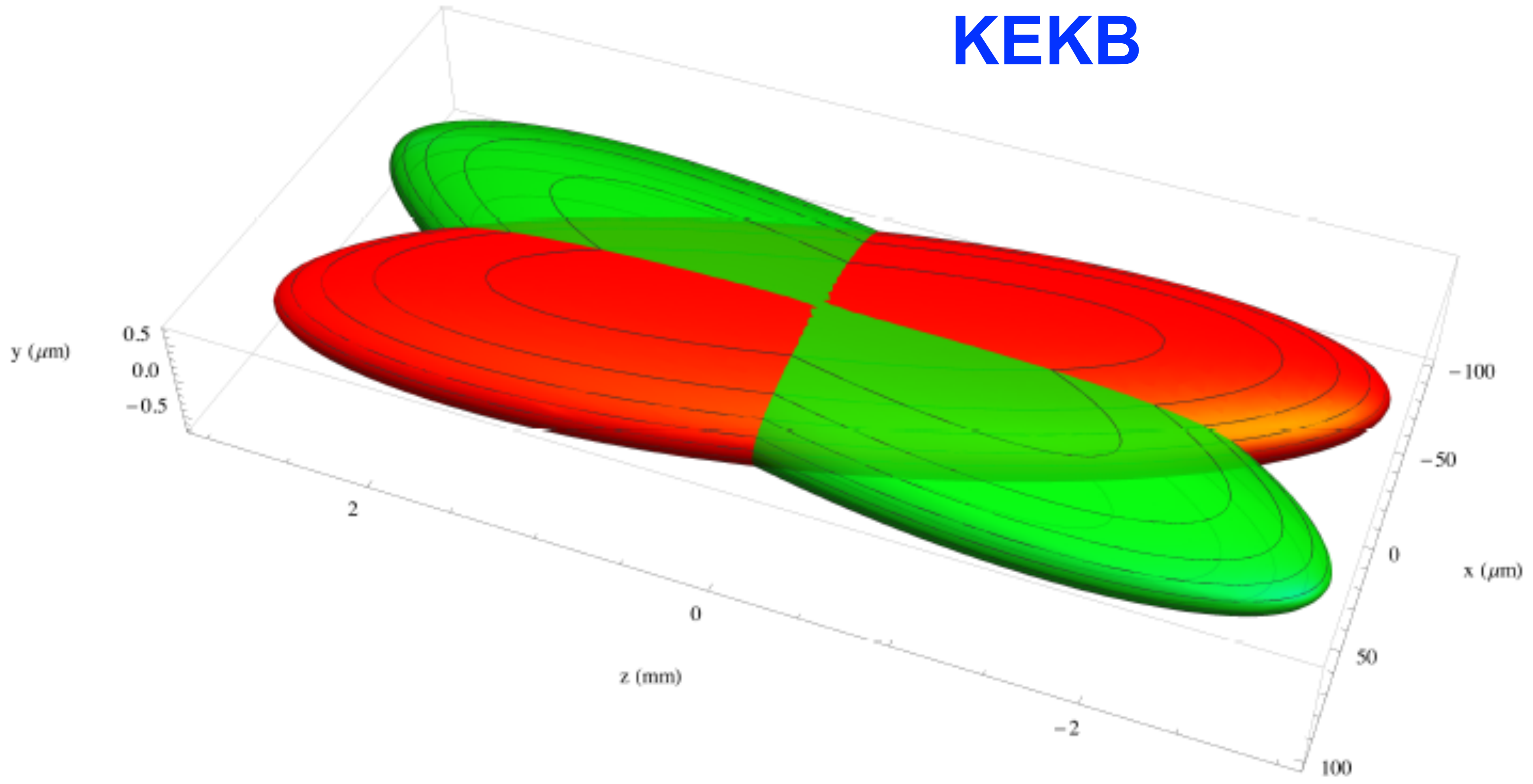


SuperKEKB/Belle II joins DORIS/ARGUS, CESR/CLEO, and PEP-II/BaBar and KEKB/Belle.

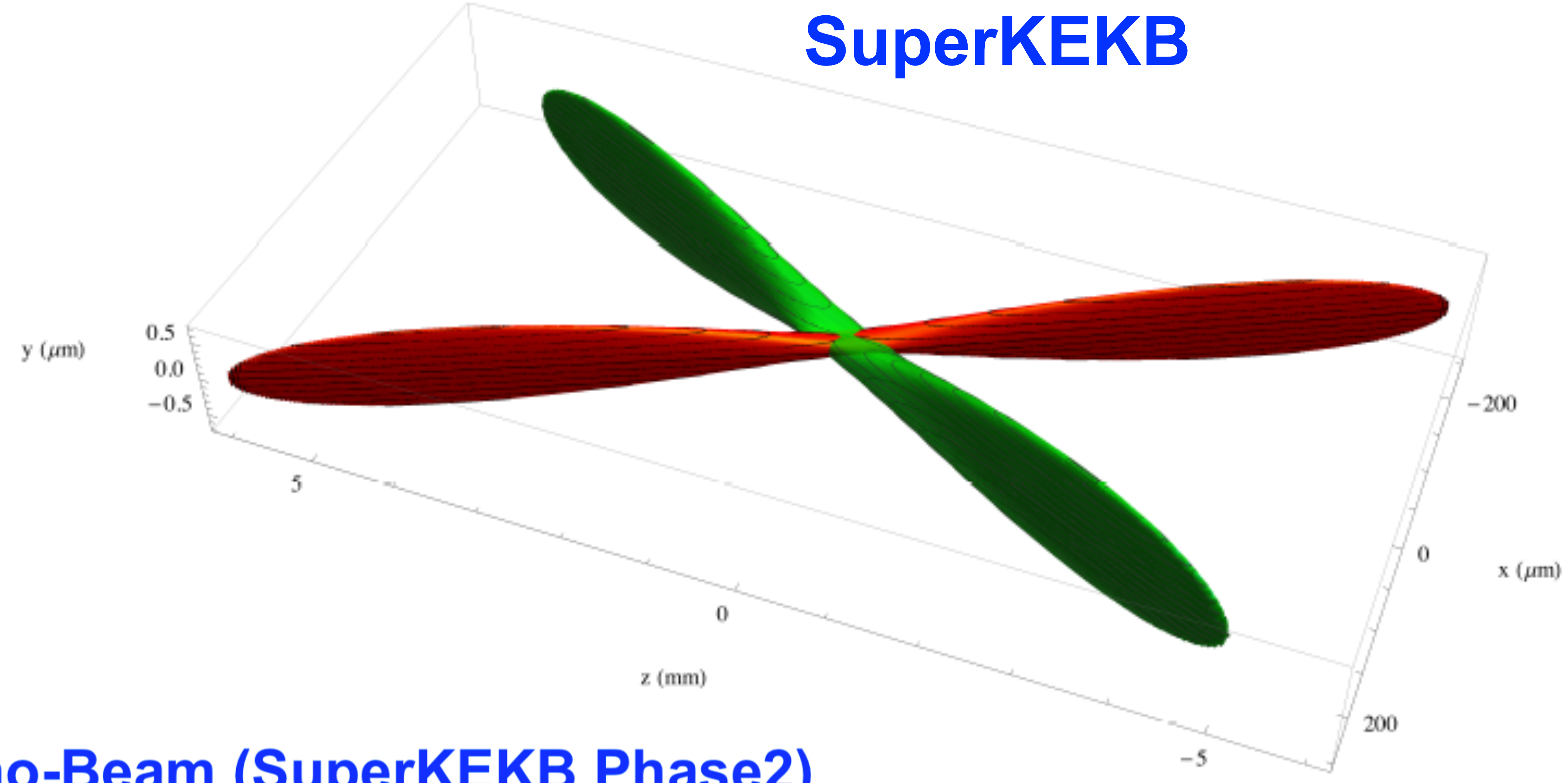
Probably $e^+e^- \to \gamma^* \to q\bar{q}$

Large crossing angle nano-beams

KEKB

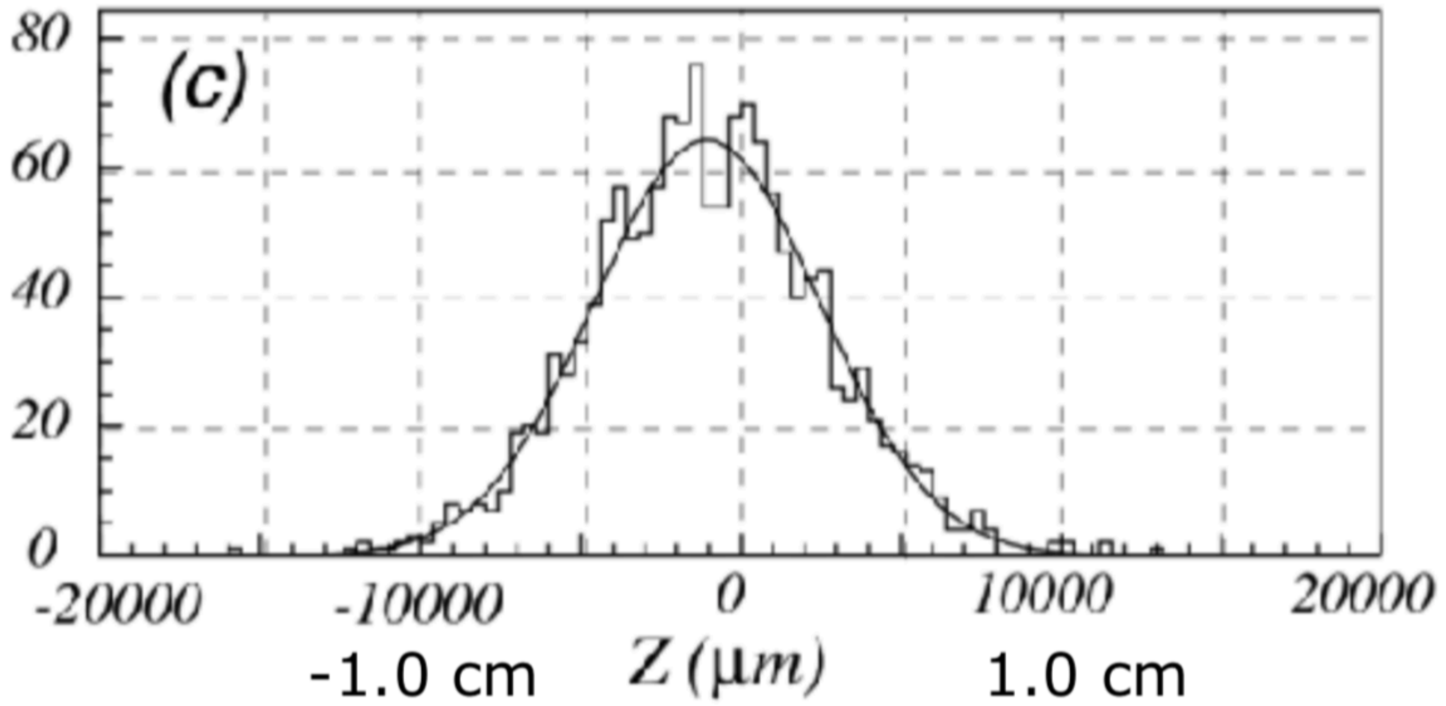


SuperKEKB



Ordinary collision (KEKB)

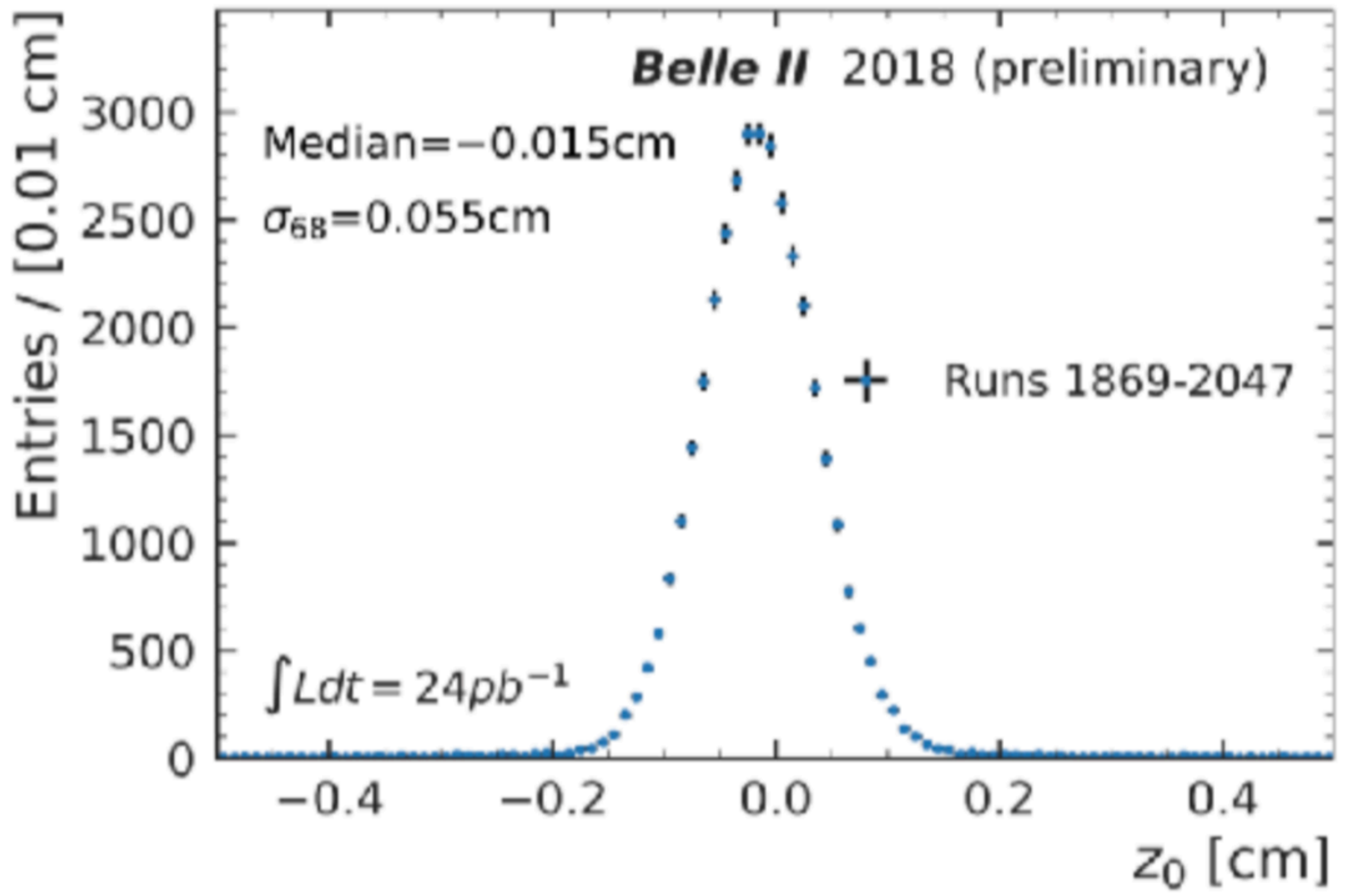
Belle case 1999 data



σ = 4.5 mm

Nano-Beam (SuperKEKB Phase2)

Z vertex distribution



σ = 550 μm

As expected, the effective bunch length is *reduced* from ~5 mm (KEKB) to 0.5 mm (SuperKEKB)

We measure this in 2-track events in Belle II data with one wedge of the silicon detector.

Luminosity in 2018

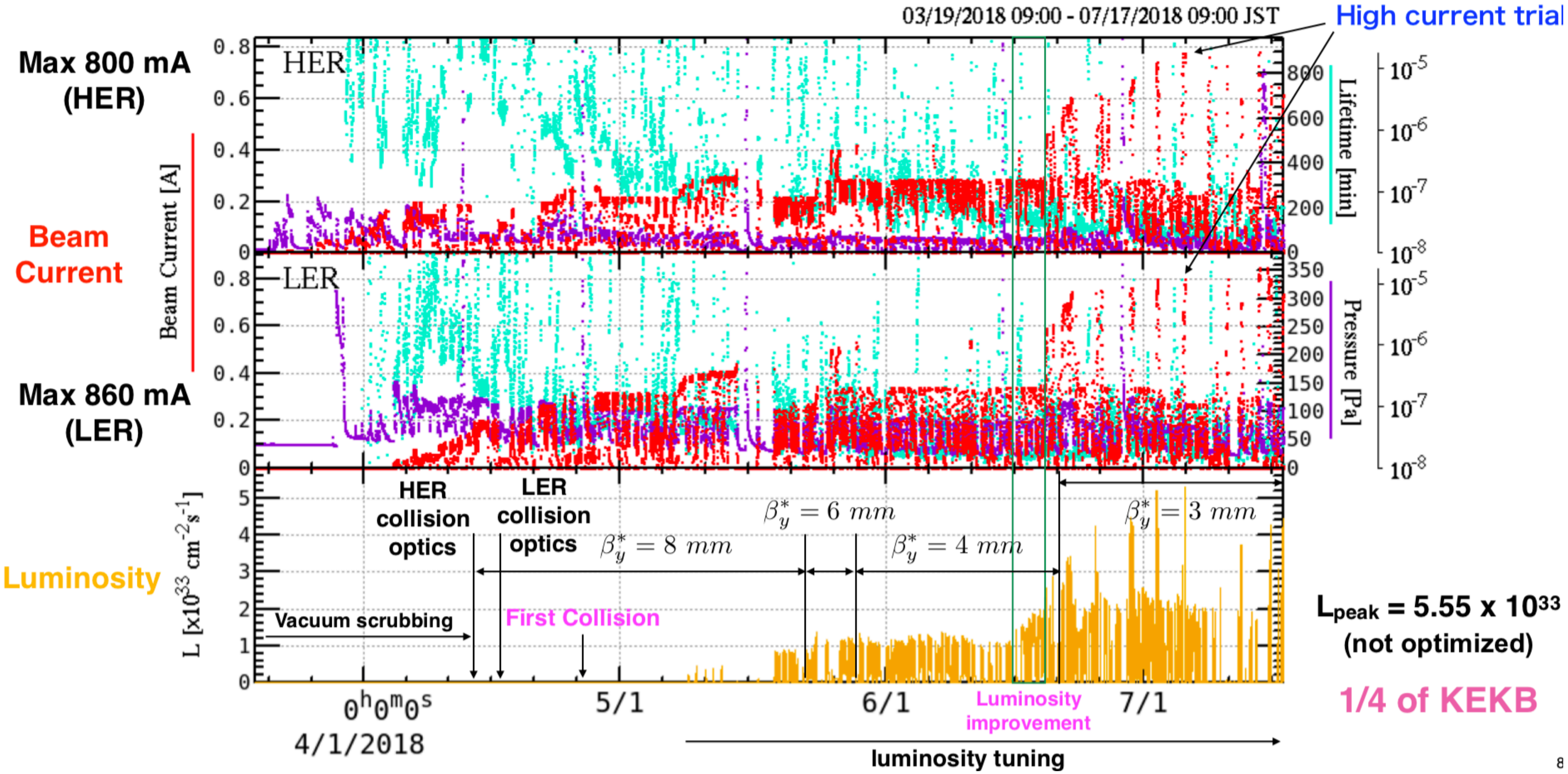
Phase 2 run, April-July 2018

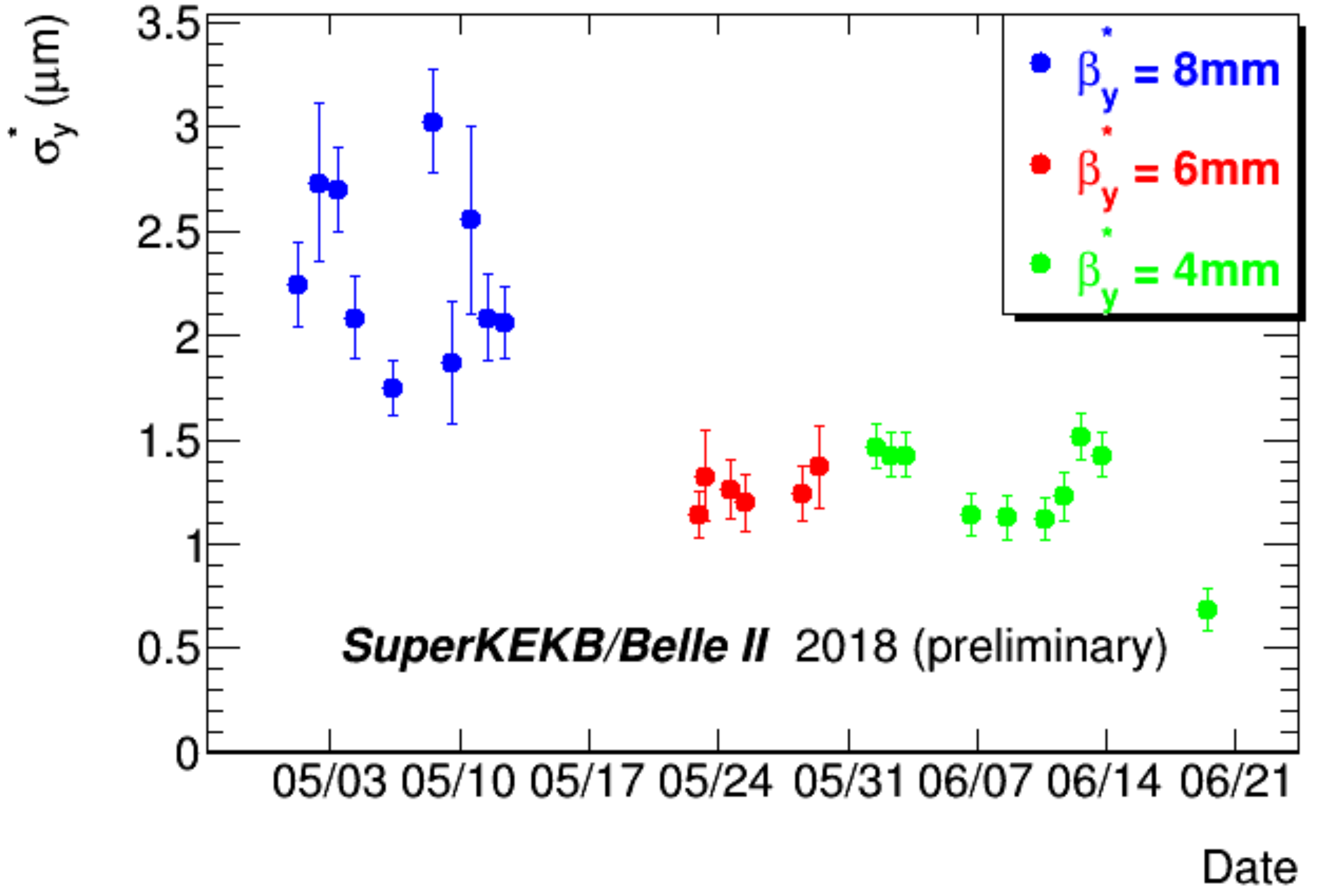
PEP-II design luminosity 3 x 10^{33}

L_{peak} = 5.5 x 10^{33}/cm²/s

Integrated luminosity ~ 500/pb

Measured with ee→ ee(γ), γγ, μμ(γ)

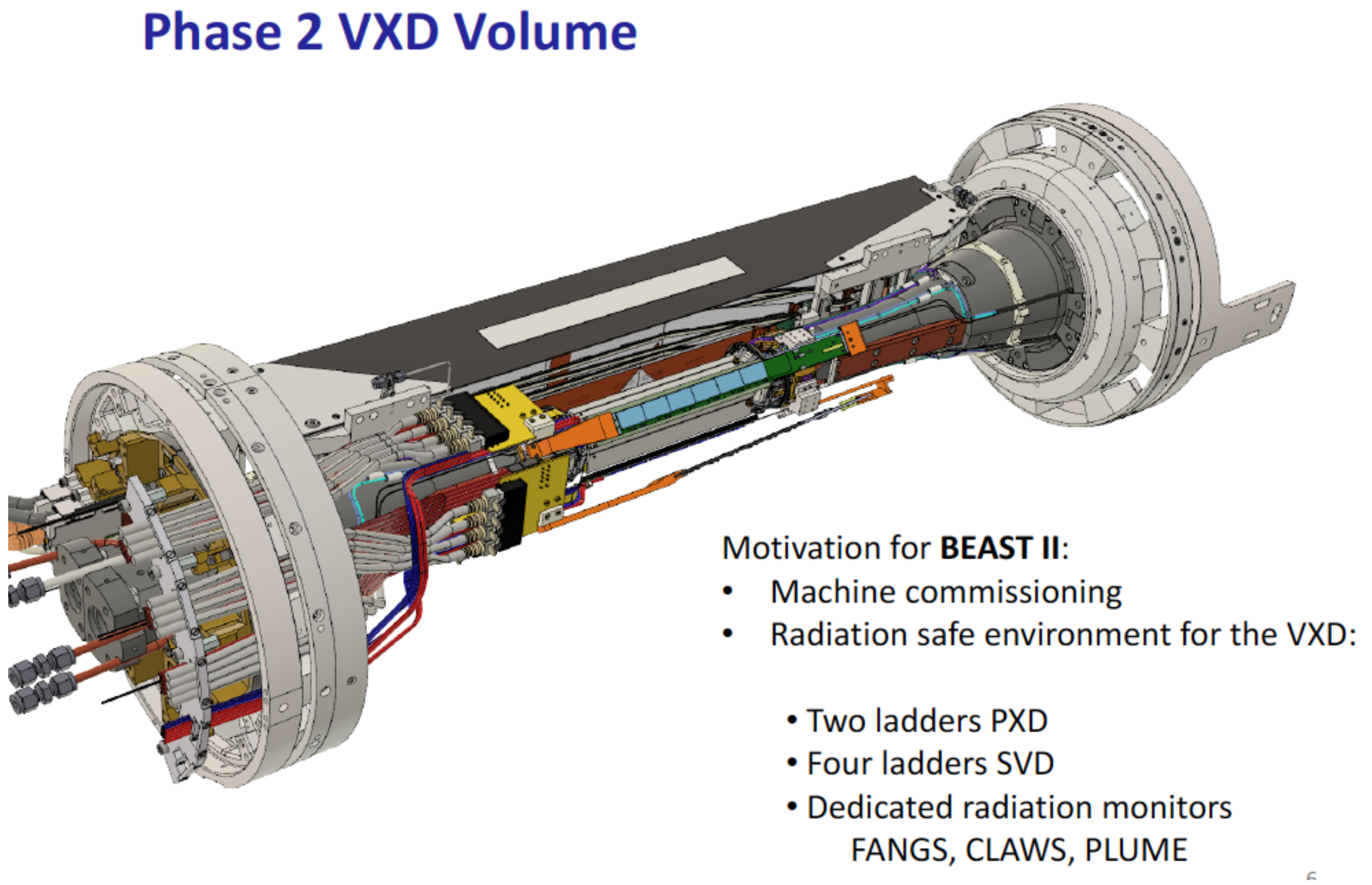


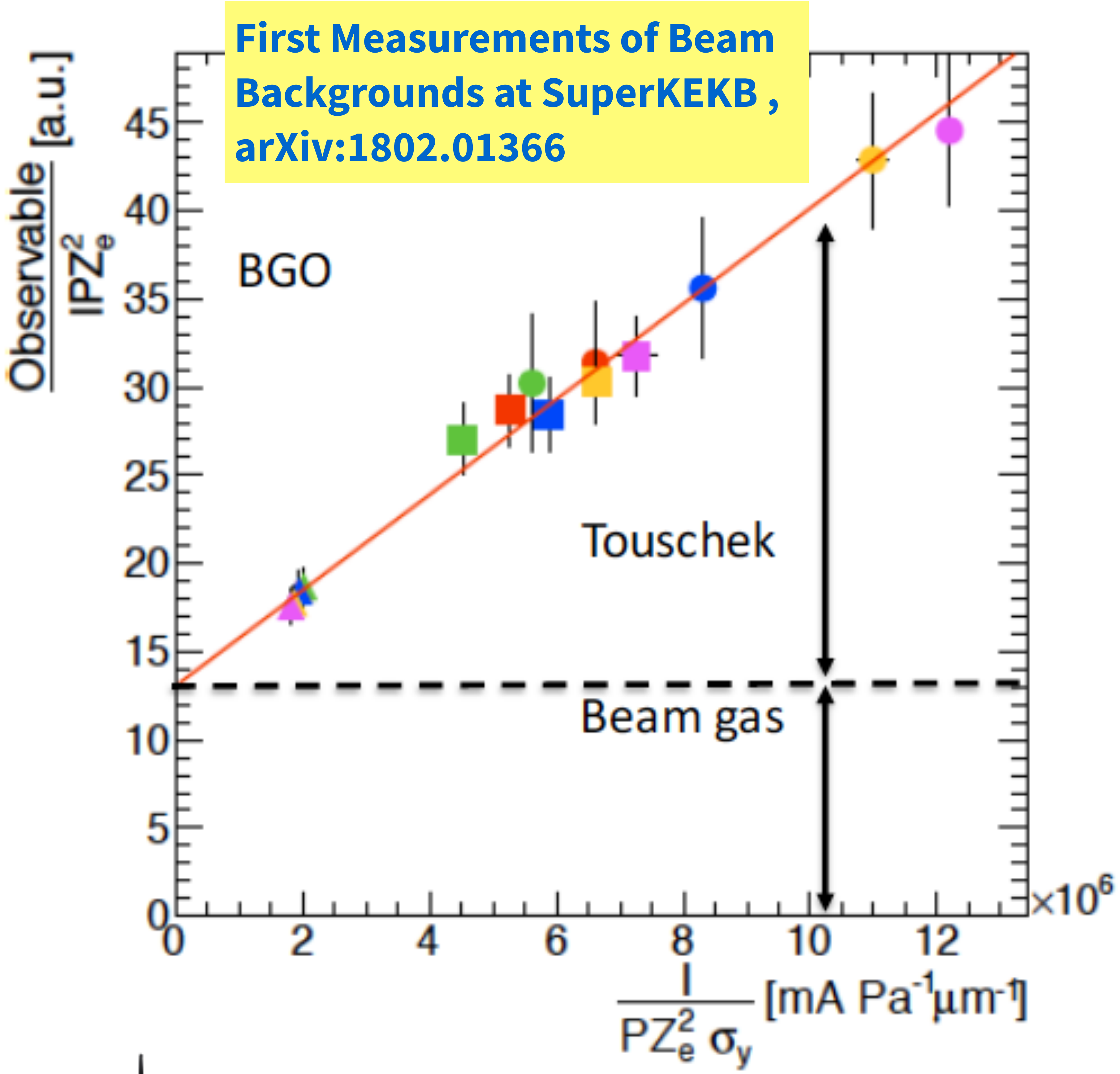


(final goal is O(50nm)).

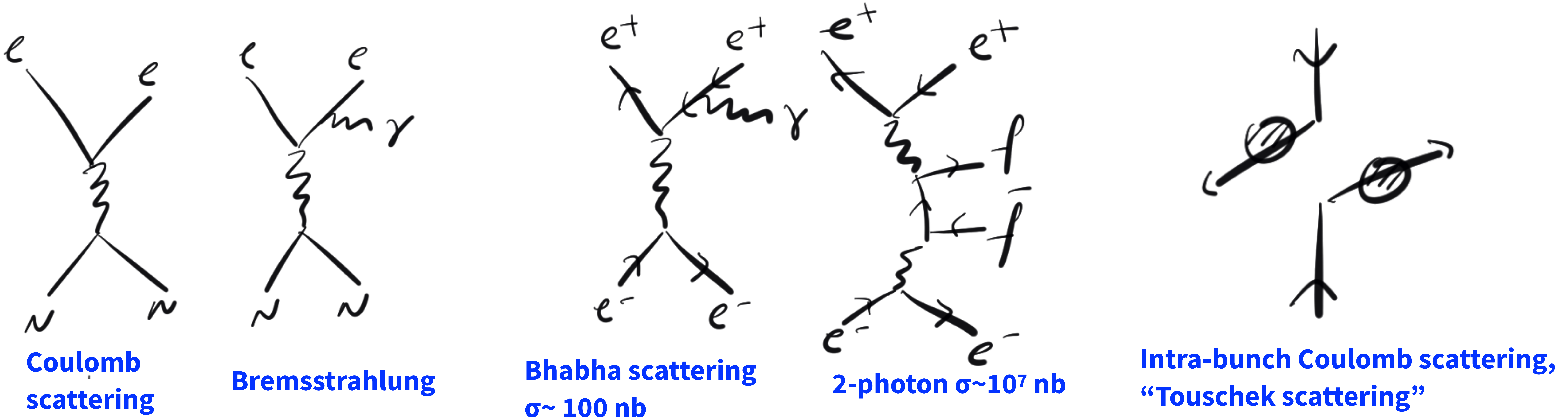
Beam background / Commissioning

Phase 1 2016: Simple background commissioning detector (diodes, diamonds TPCs, crystals…). No final focus. Only single beam studies.



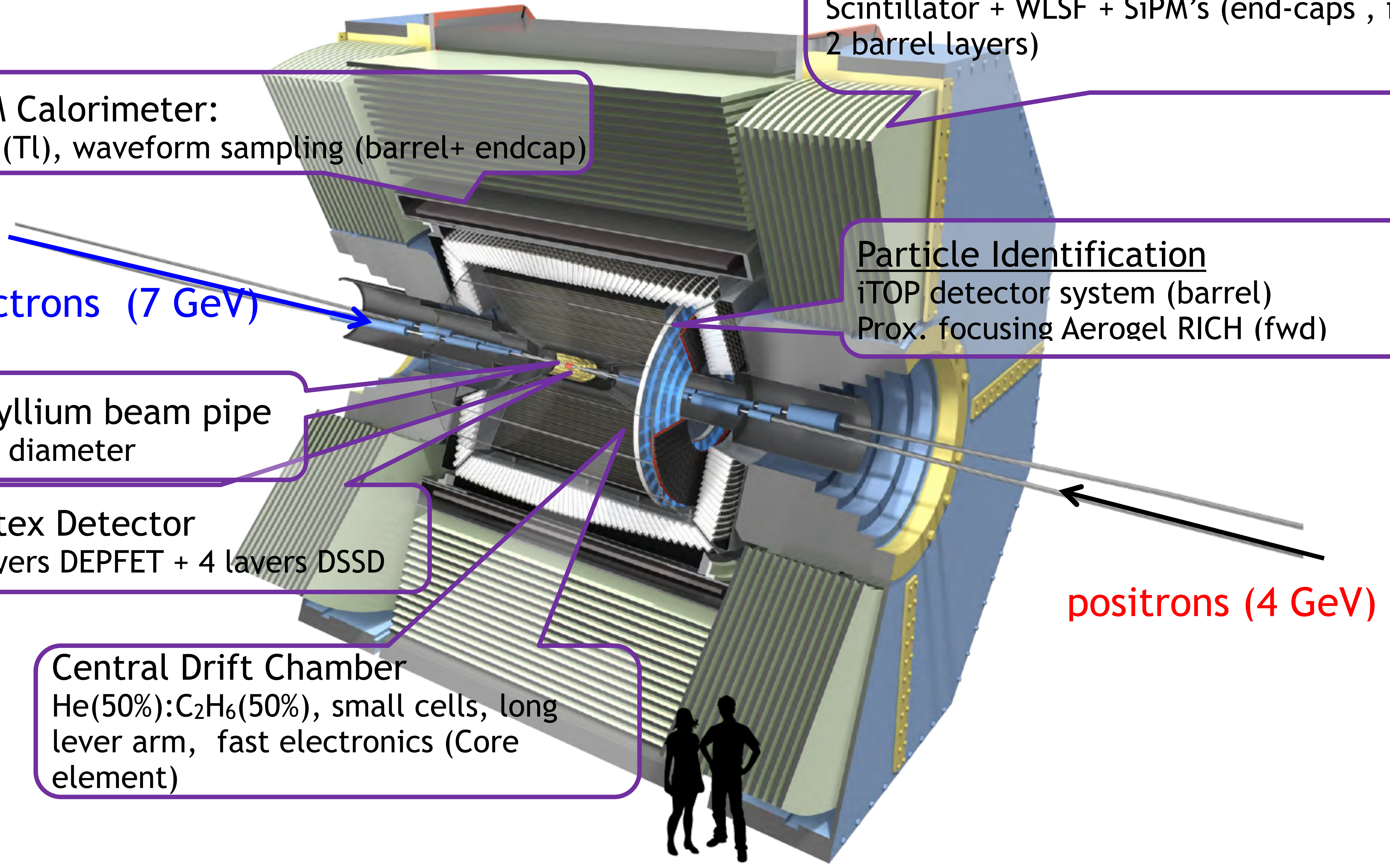


Phase 2 2018: Full Belle II outer detector. Full superconducting final focus. *Collisions ! Result: Safe to install silicon detectors!*



+ Synchrotron, beam gas …

Belle II Detector



K-Long and muon detector:
Resistive Plate Chambers (barrel outer layers)
Scintillator + WLSF + SiPM's (end-caps , inner 2 barrel layers)

EM Calorimeter:
CsI(Tl), waveform sampling (barrel+ endcap)

electrons (7 GeV)

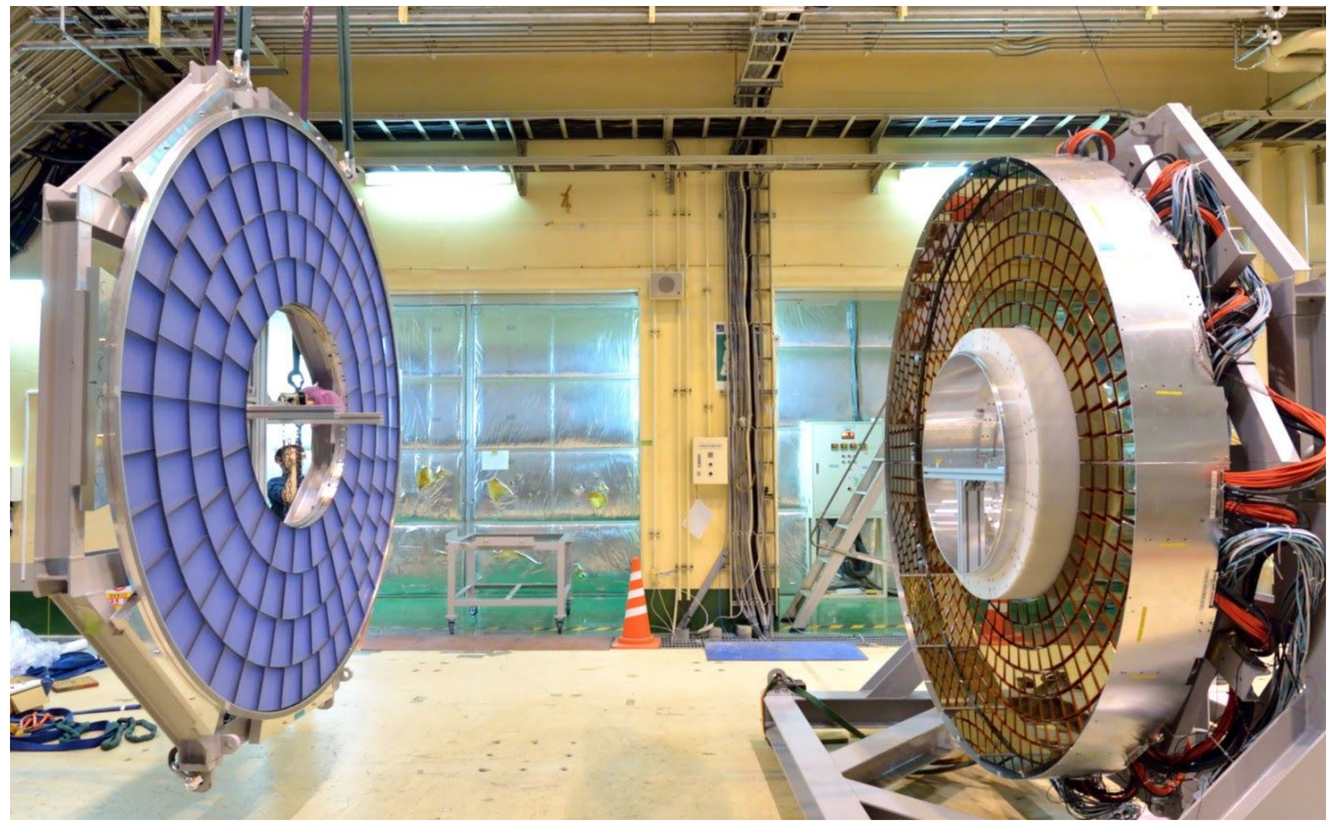
Particle Identification
iTOP detector system (barrel)
Prox. focusing Aerogel RICH (fwd)

Beryllium beam pipe
2cm diameter

Vertex Detector
2 layers DEPFET + 4 layers DSSD

positrons (4 GeV)

Central Drift Chamber
He(50%):C_2H_6(50%), small cells, long lever arm, fast electronics (Core element)



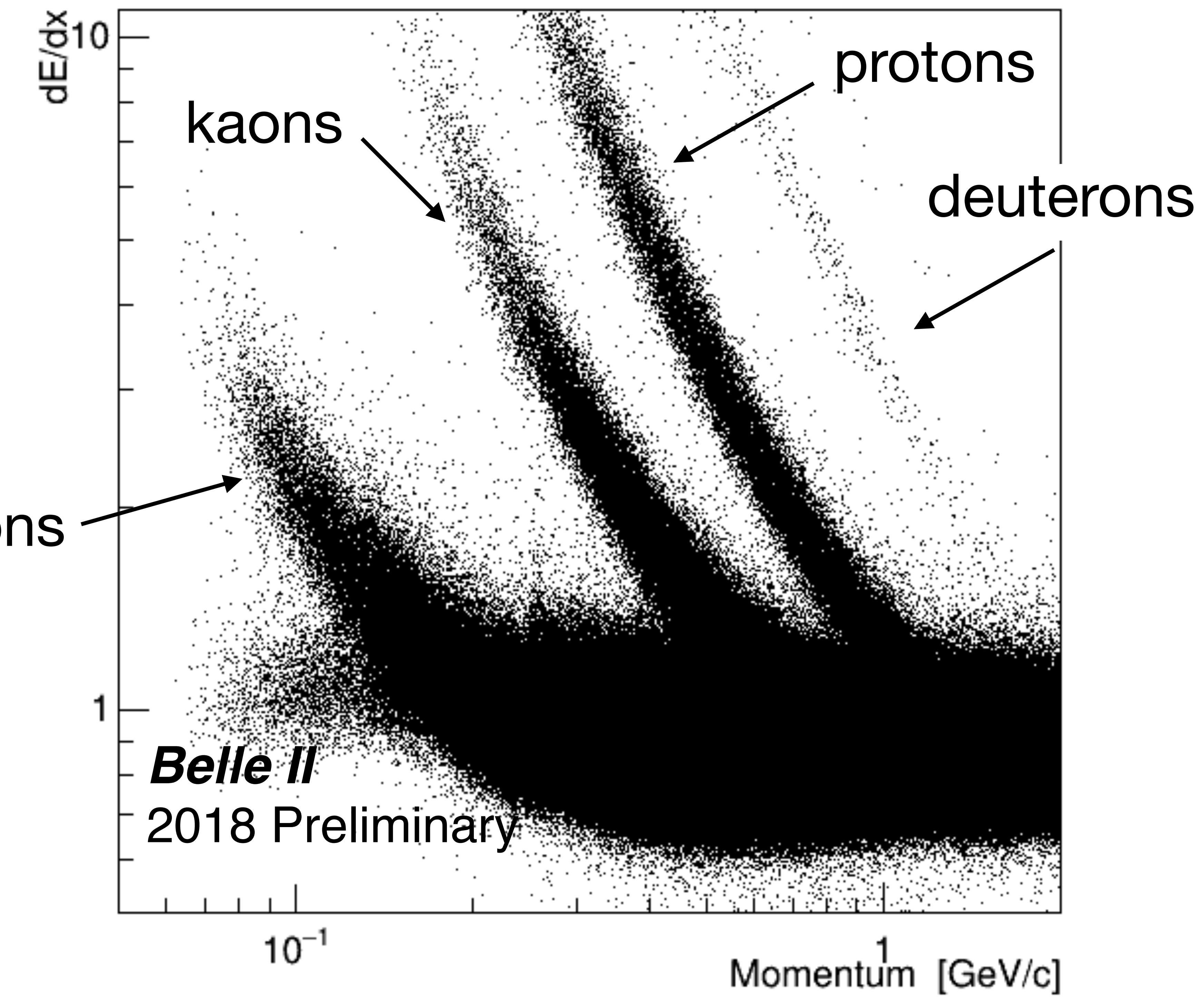
Particle identification in 2018

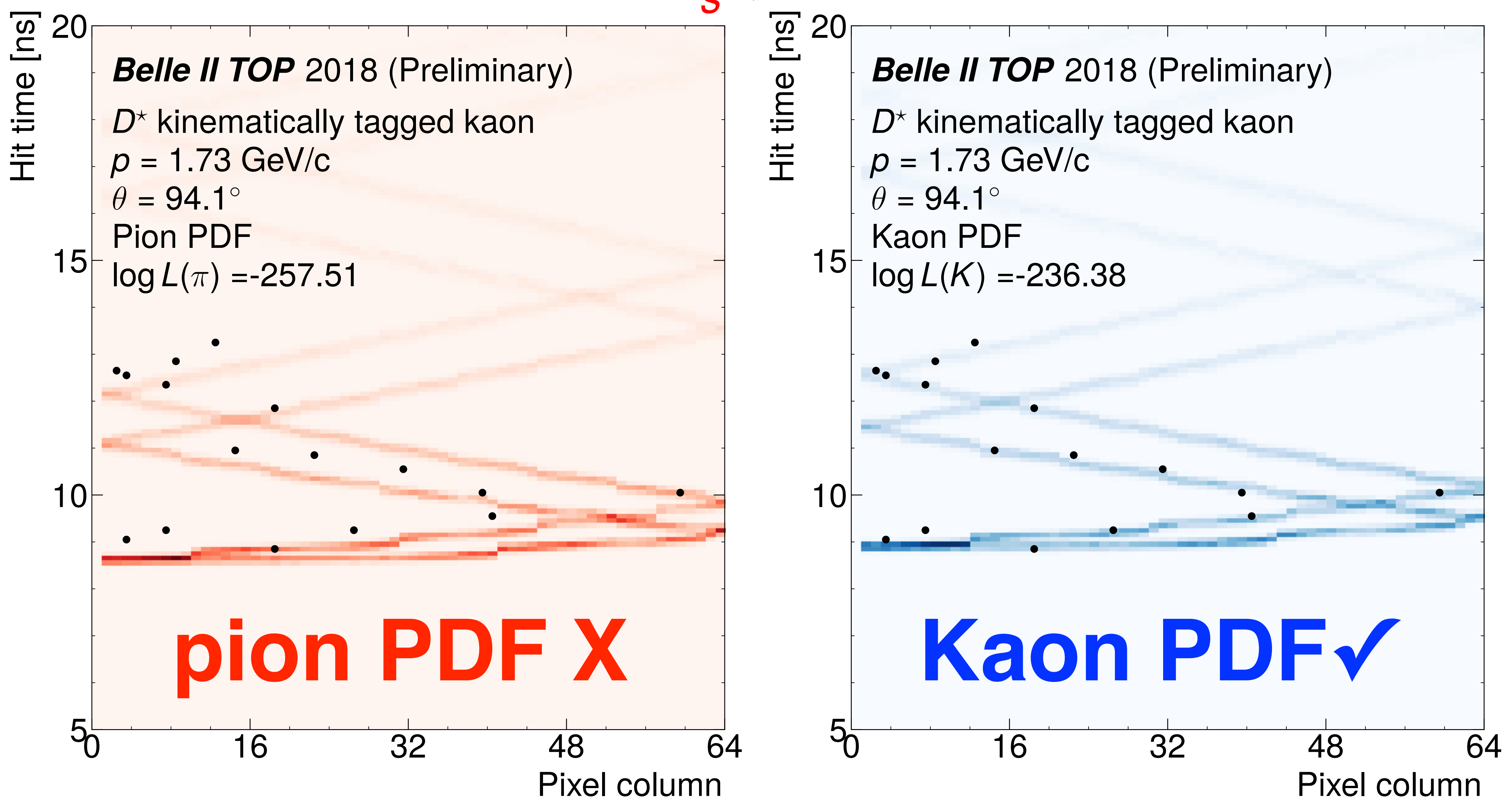
- Central Drift Chamber dE/dx & Time of propagation Cherenkov patterns - 2018 data

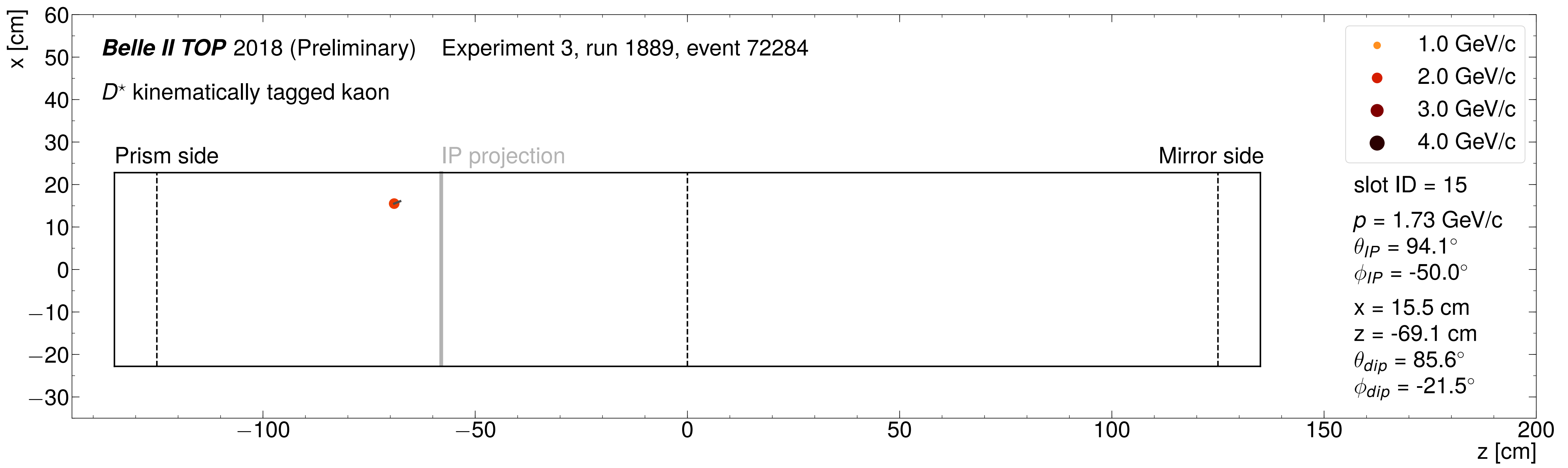
Kinematically identified kaon from D^{*+} in TOP; x vs t pattern (mapping of Cherenkov ring)

$$D^{*+} \to D^0\pi_s^+;\ D^0 \to K^-\pi^+$$

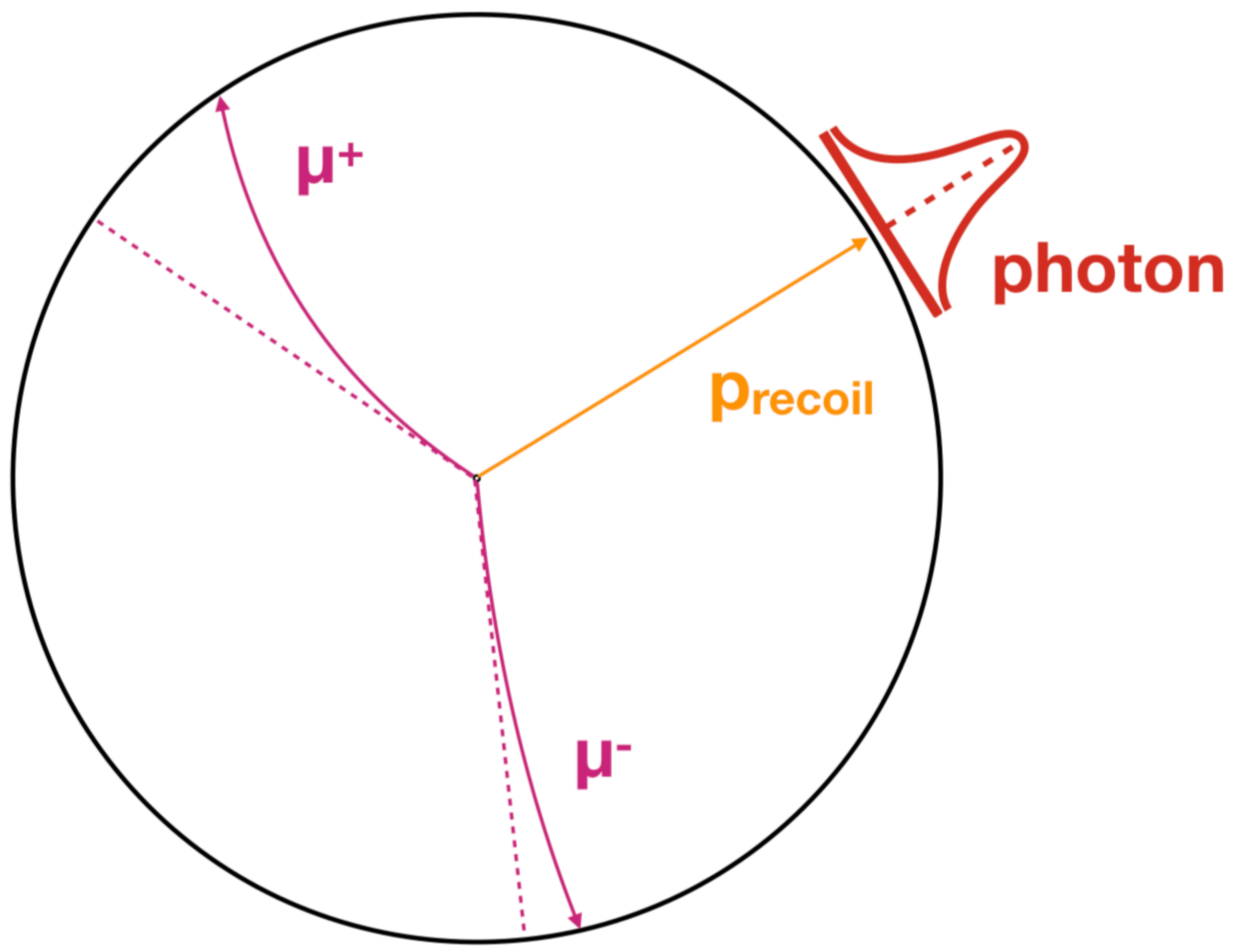
CDC dE/dx

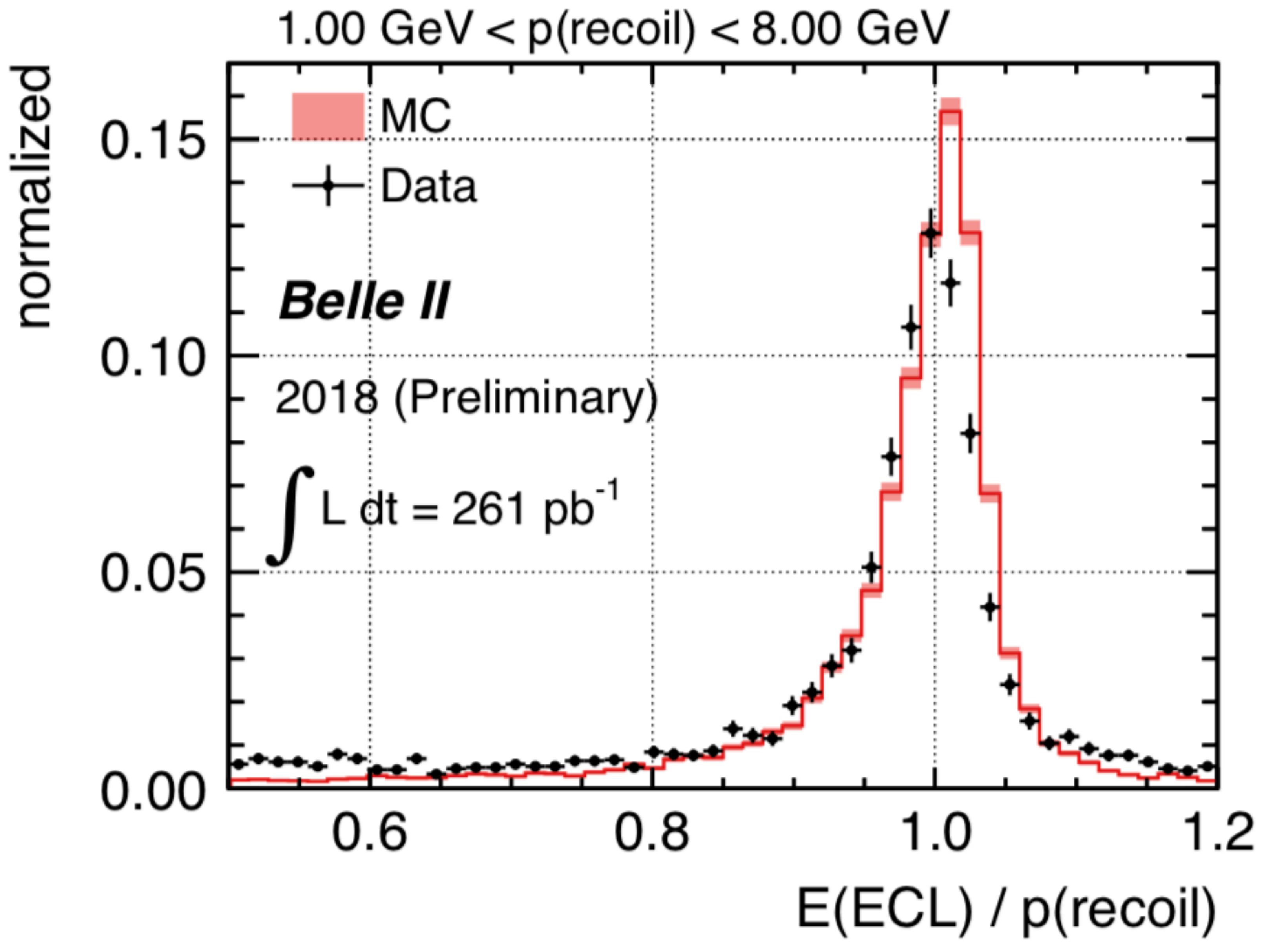




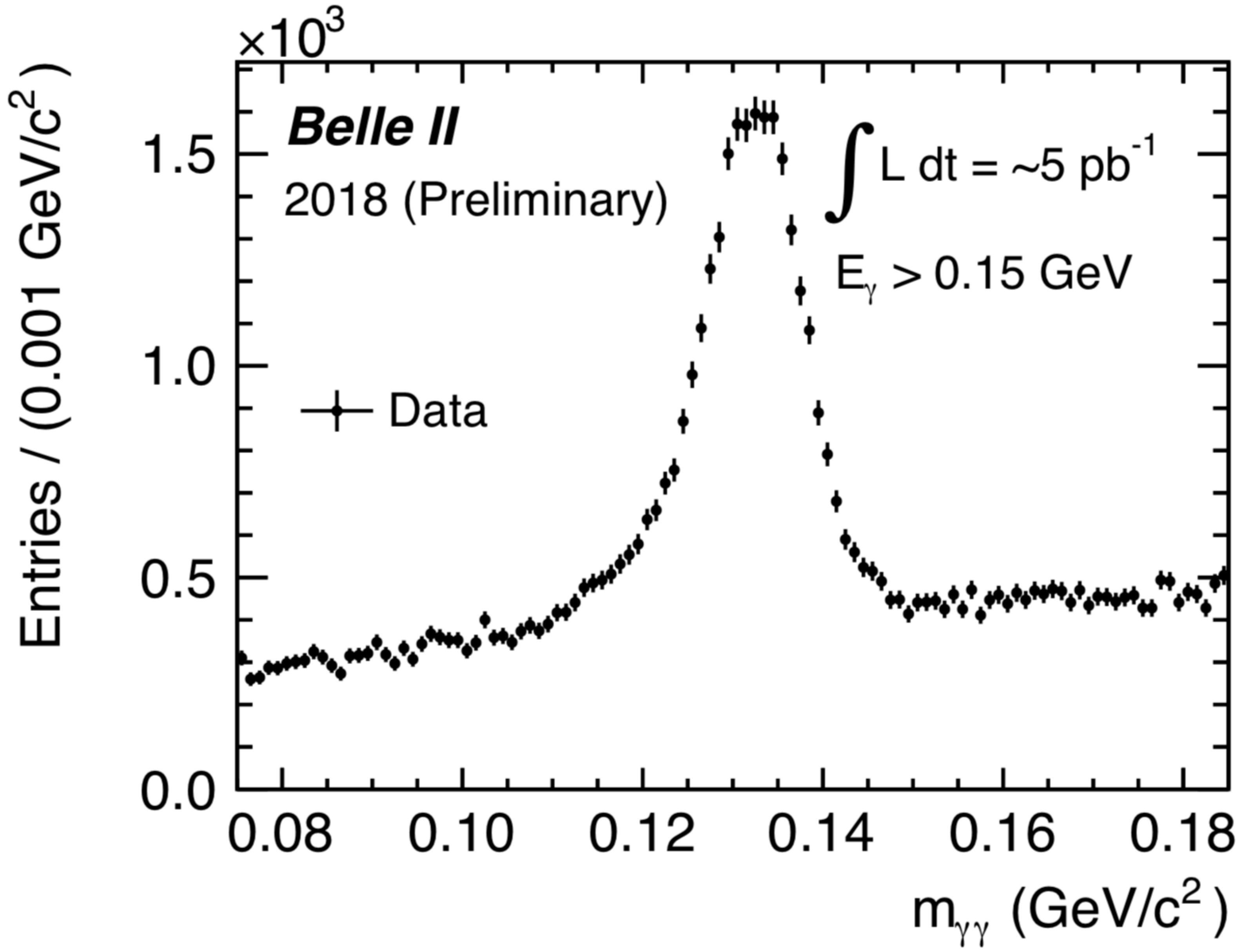


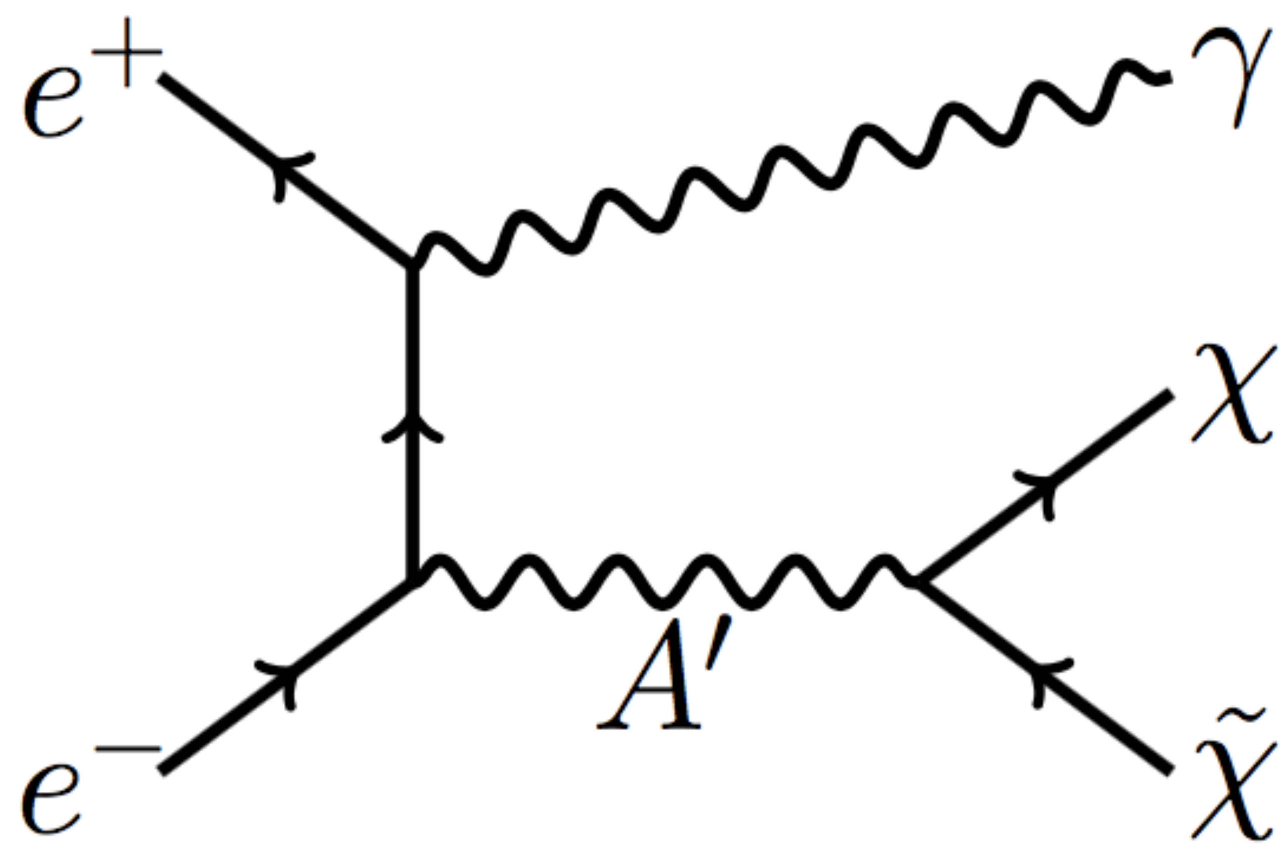
Nice examples of signal involving photons

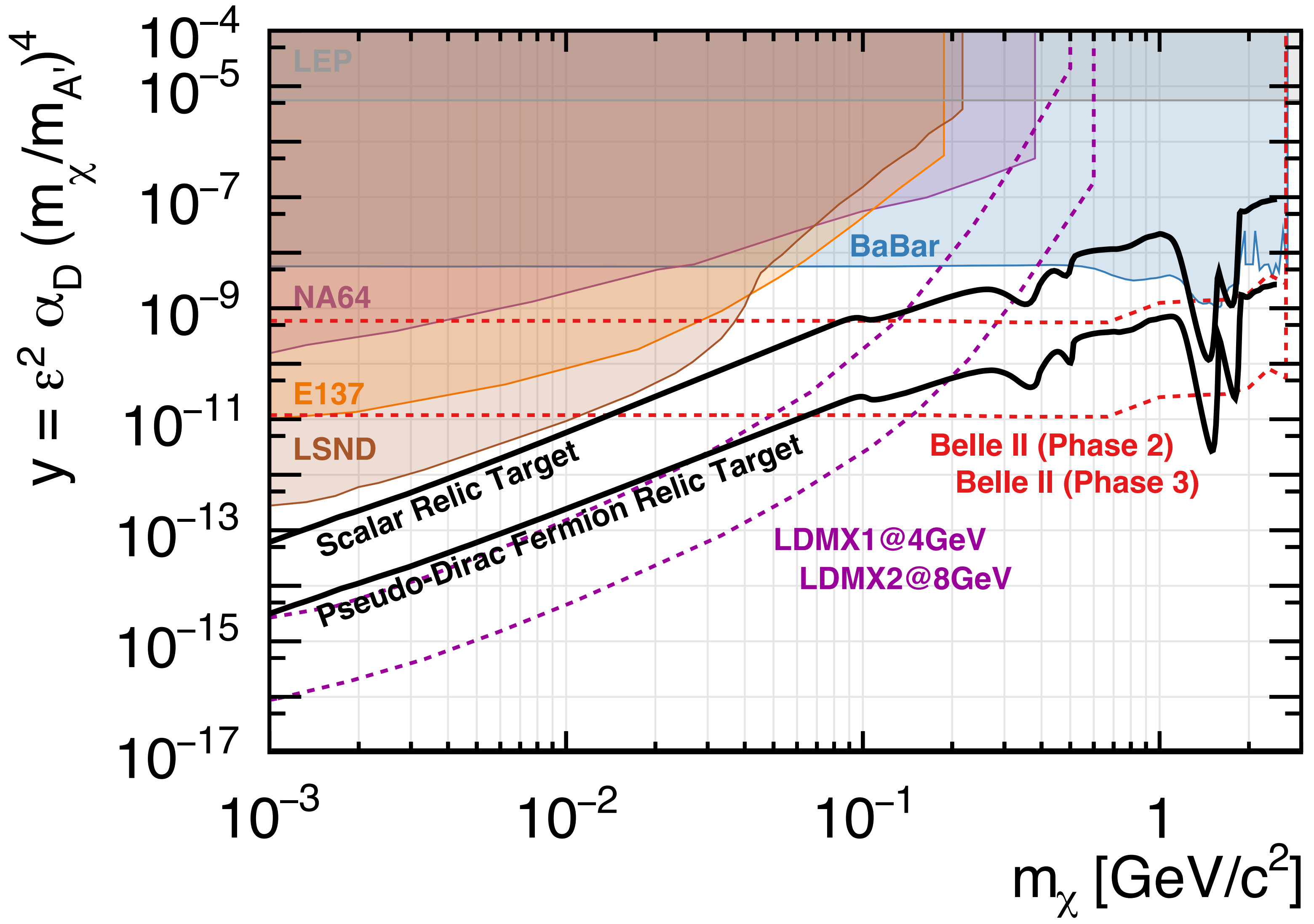




Single Photon Lines







Ready for the dark sector !

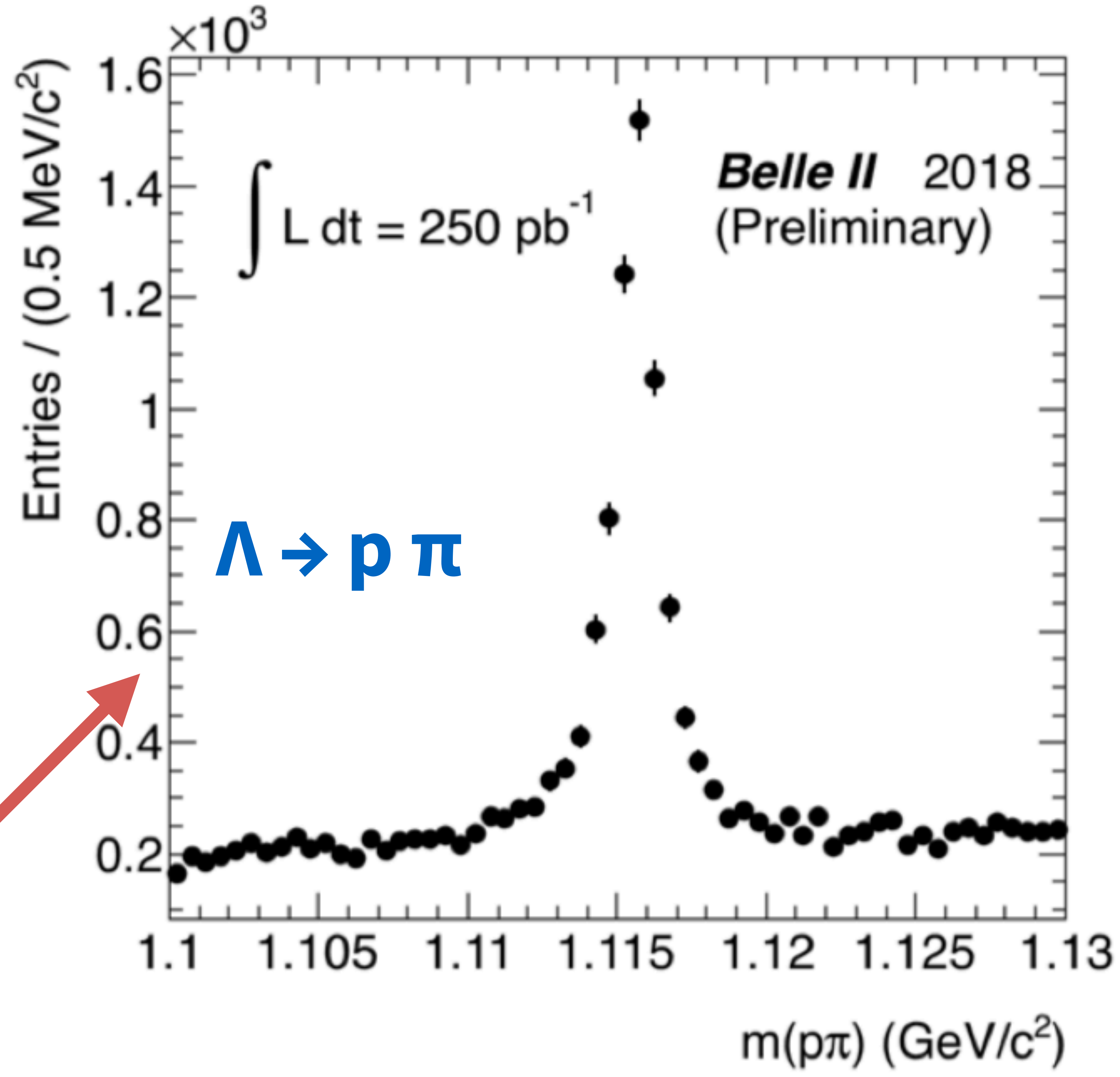
$e^+e^- \rightarrow \gamma X$

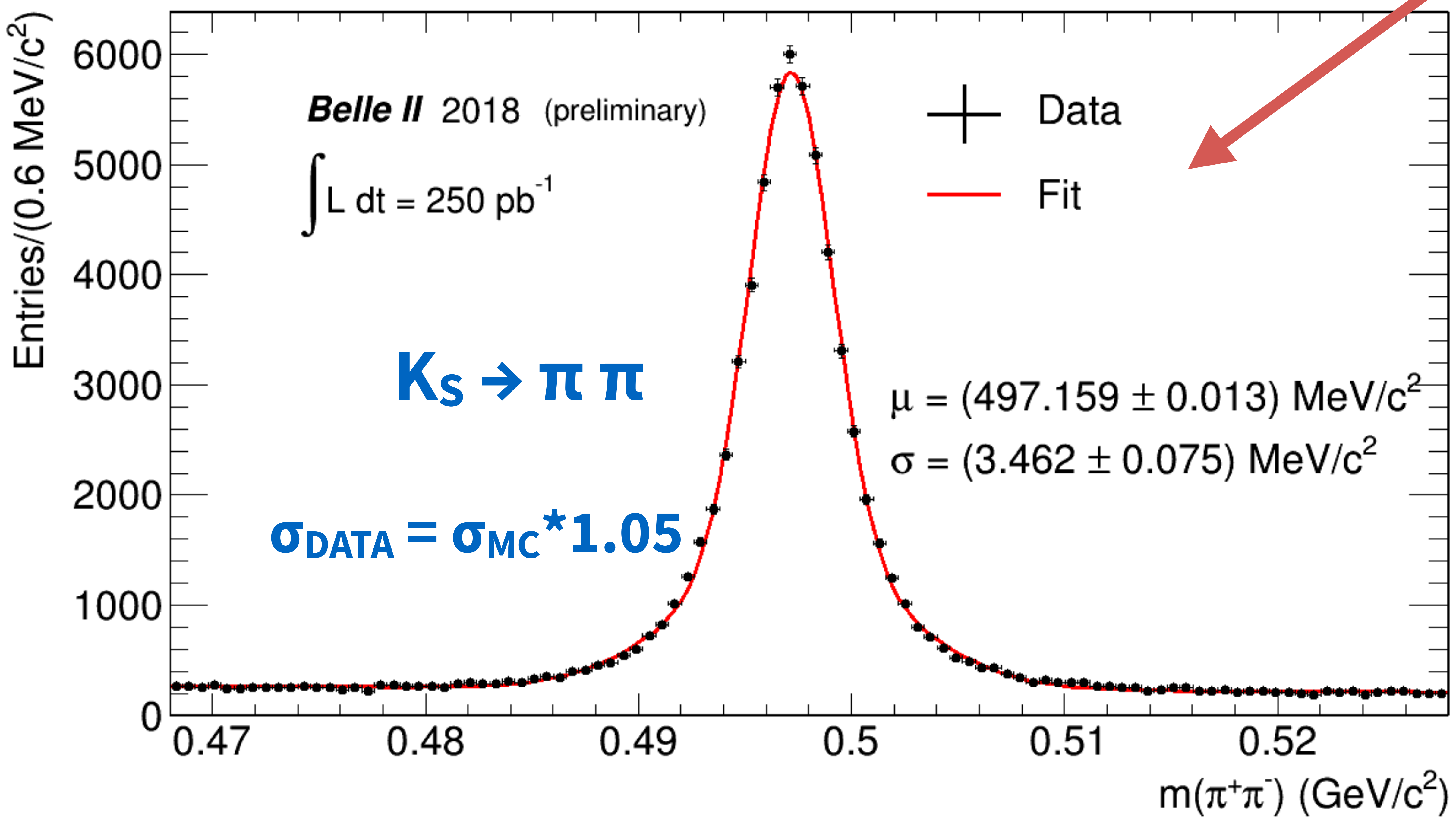
$e^+e^- \rightarrow \gamma$ ALP ($\rightarrow\gamma\gamma$)

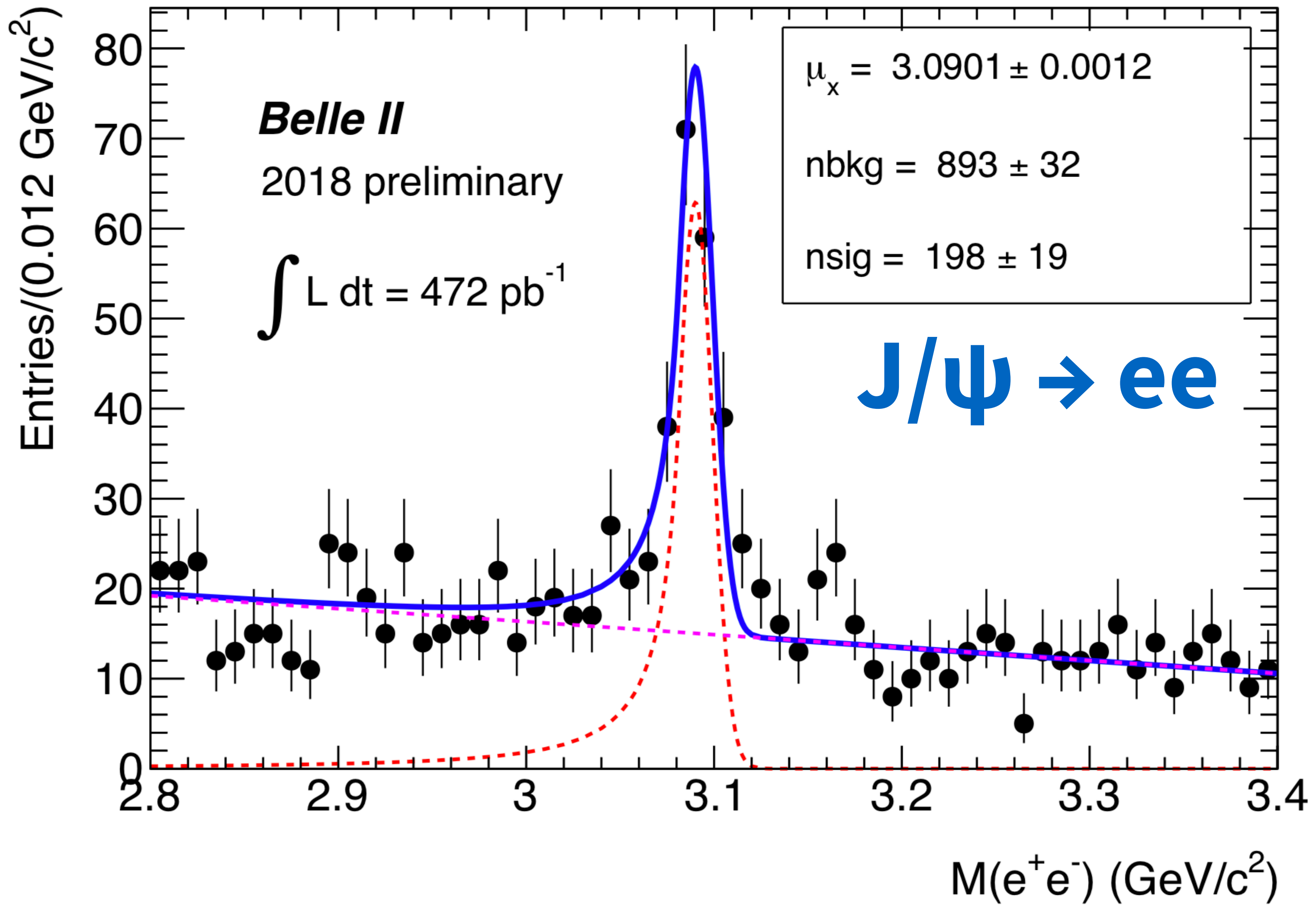
Signal involving charged tracks

- Most subsystems work well.
- Within days / first calibration, neutrals and track resolution good to better than 5%.
    - Calibrated as well as Belle already!

V⁰ particles



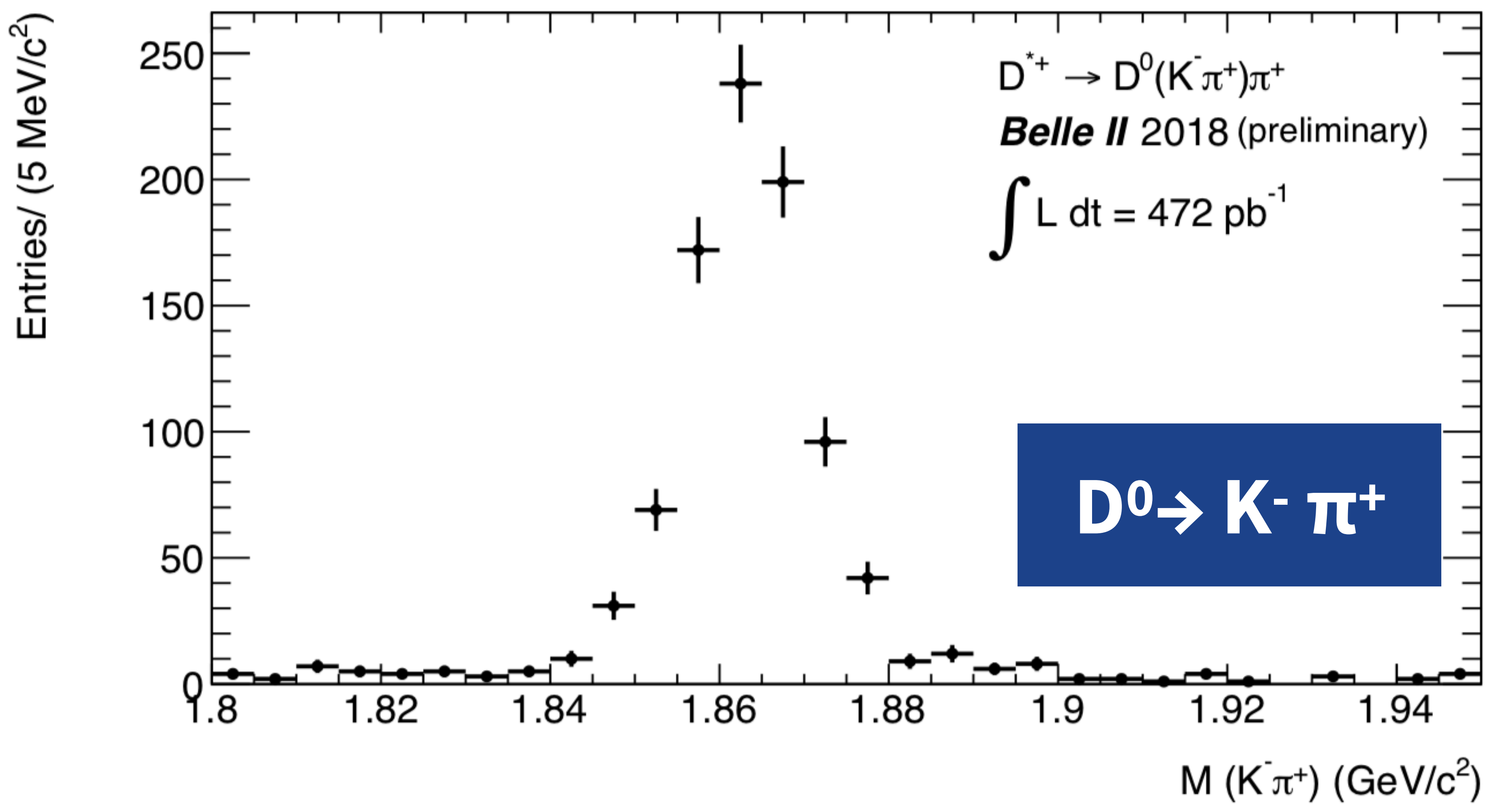


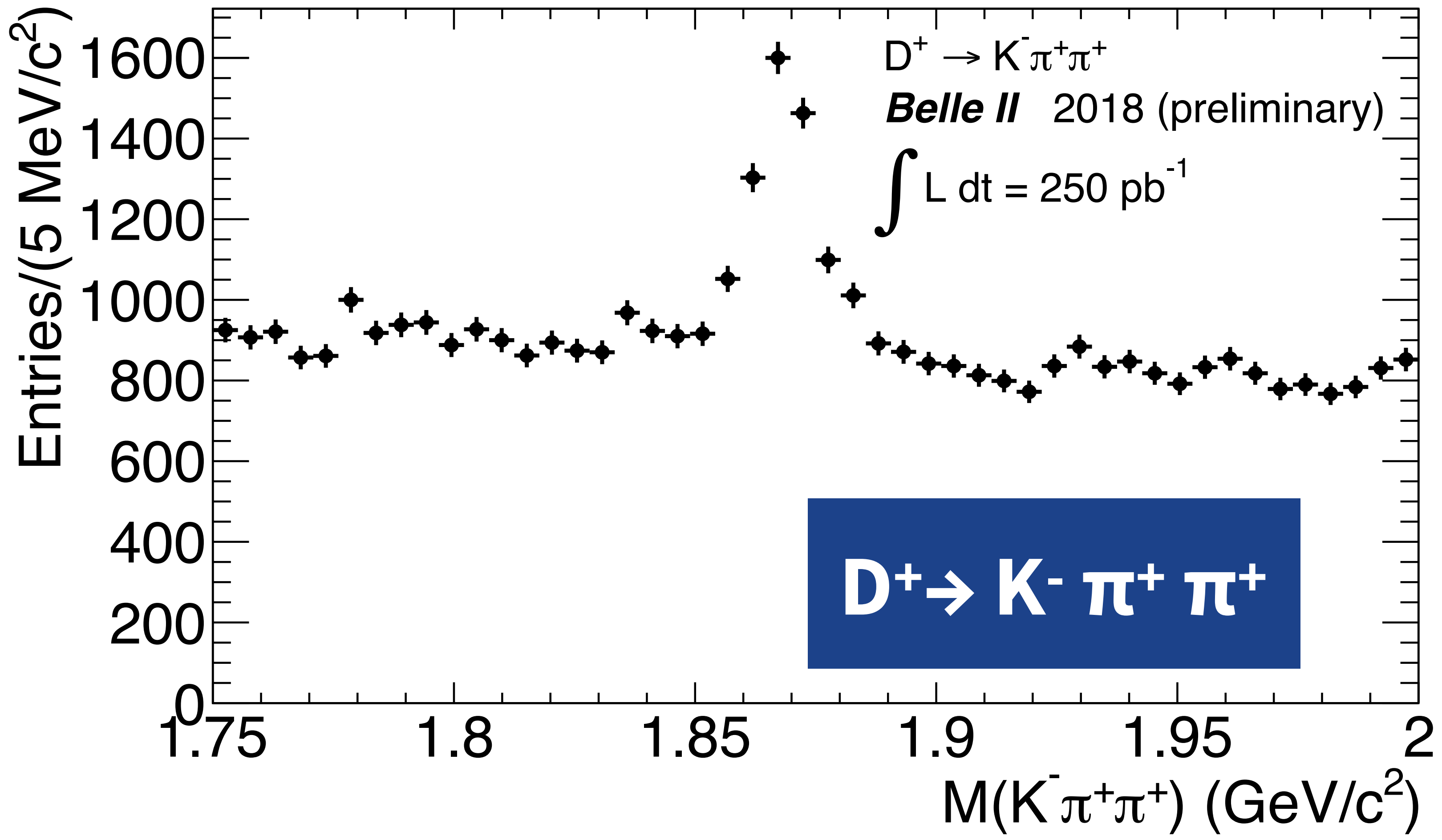


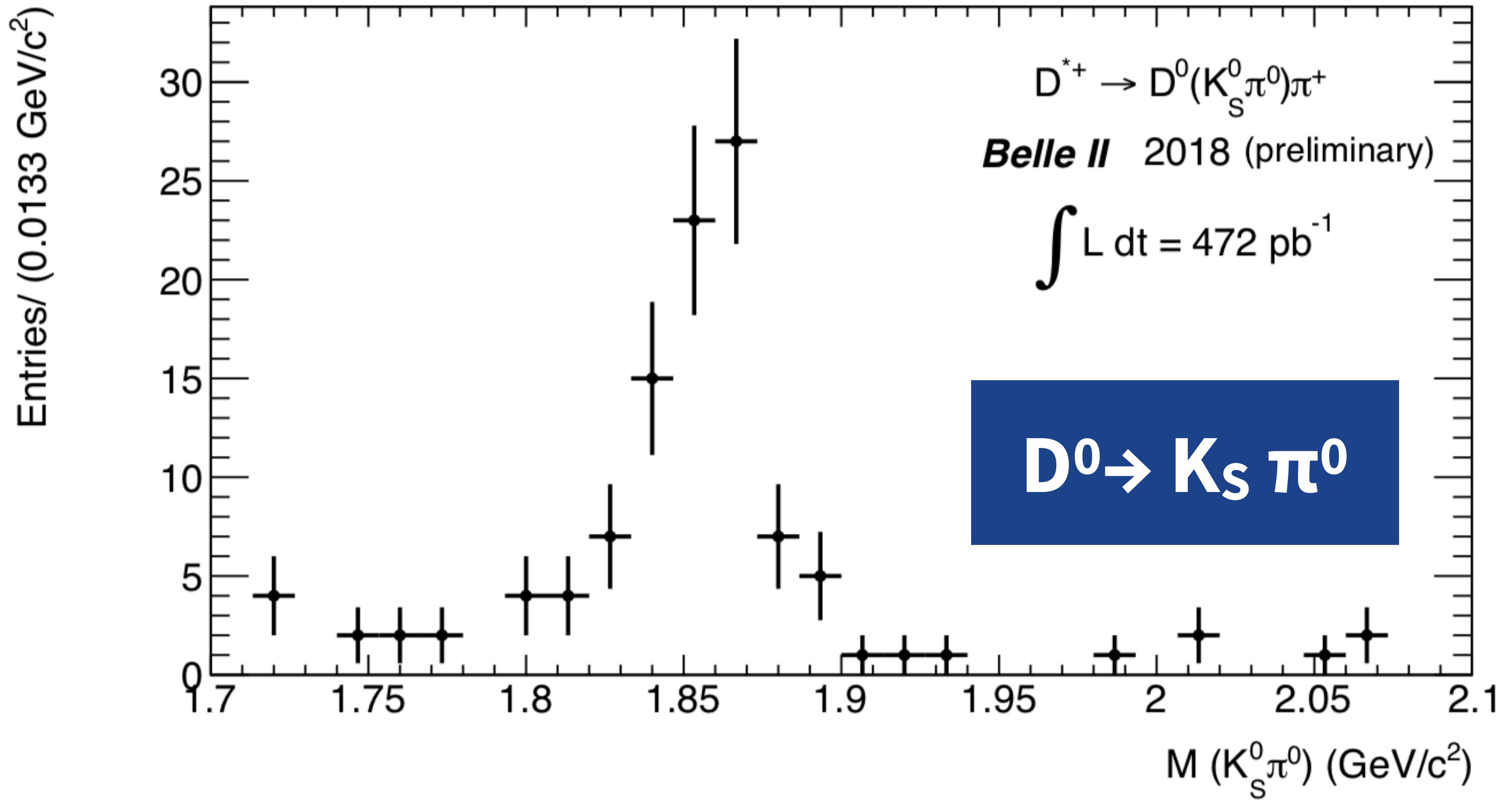
Charm "rediscovery"

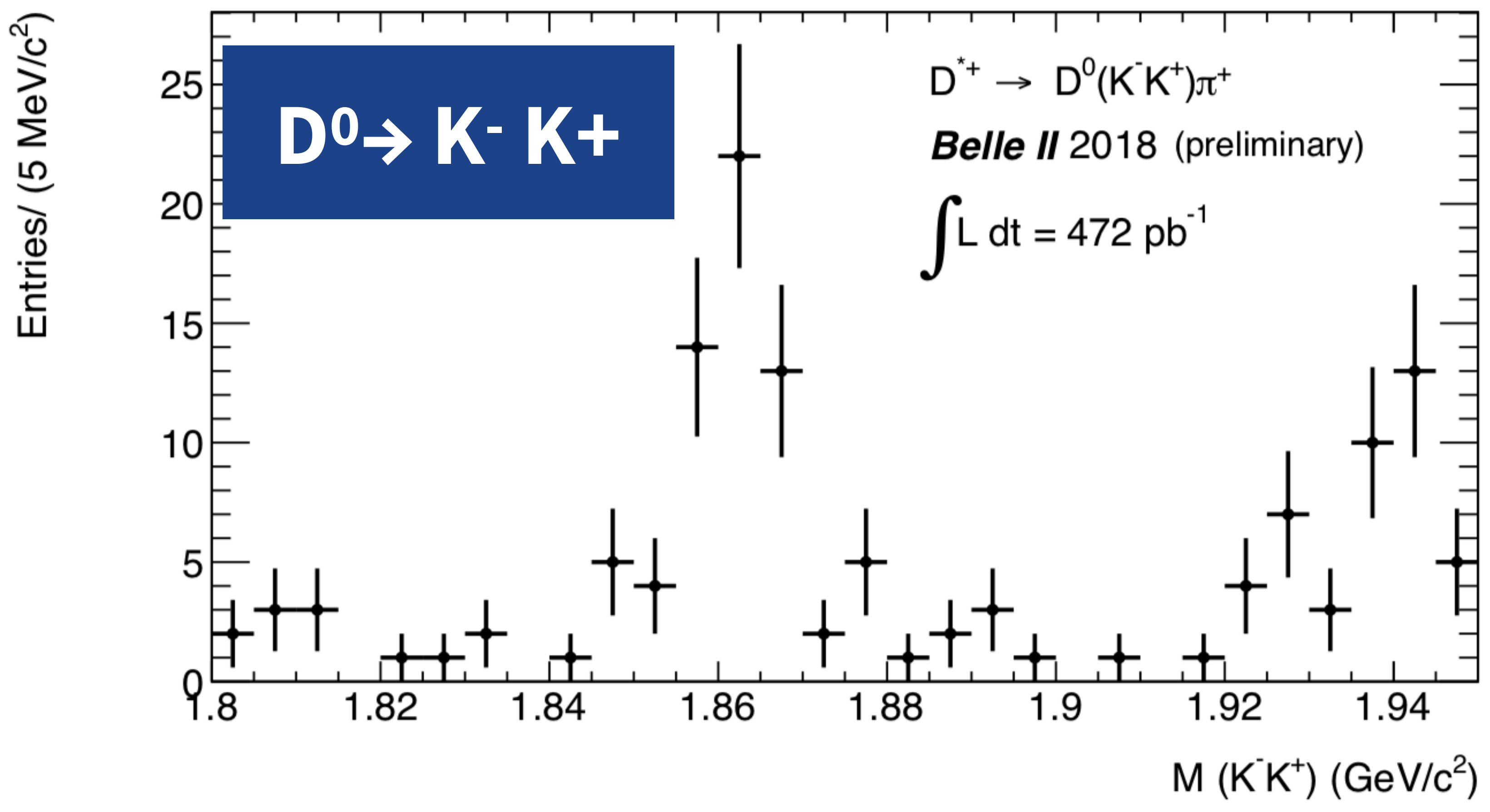
e+e- → c anti-c

- Open charm, D^0, D^+, D_s^+, D^{*+}, D^{*0} and Charmonium J/ψ. Found the difficult to see $D^0 \to K_S \pi^0$.





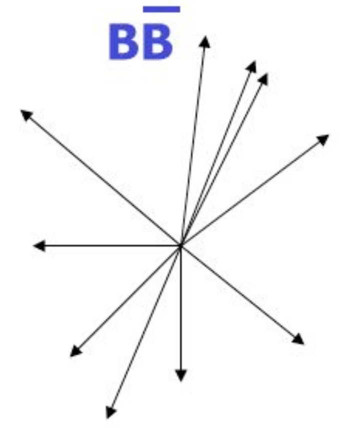


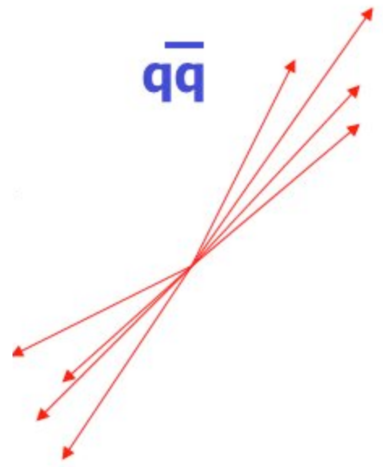


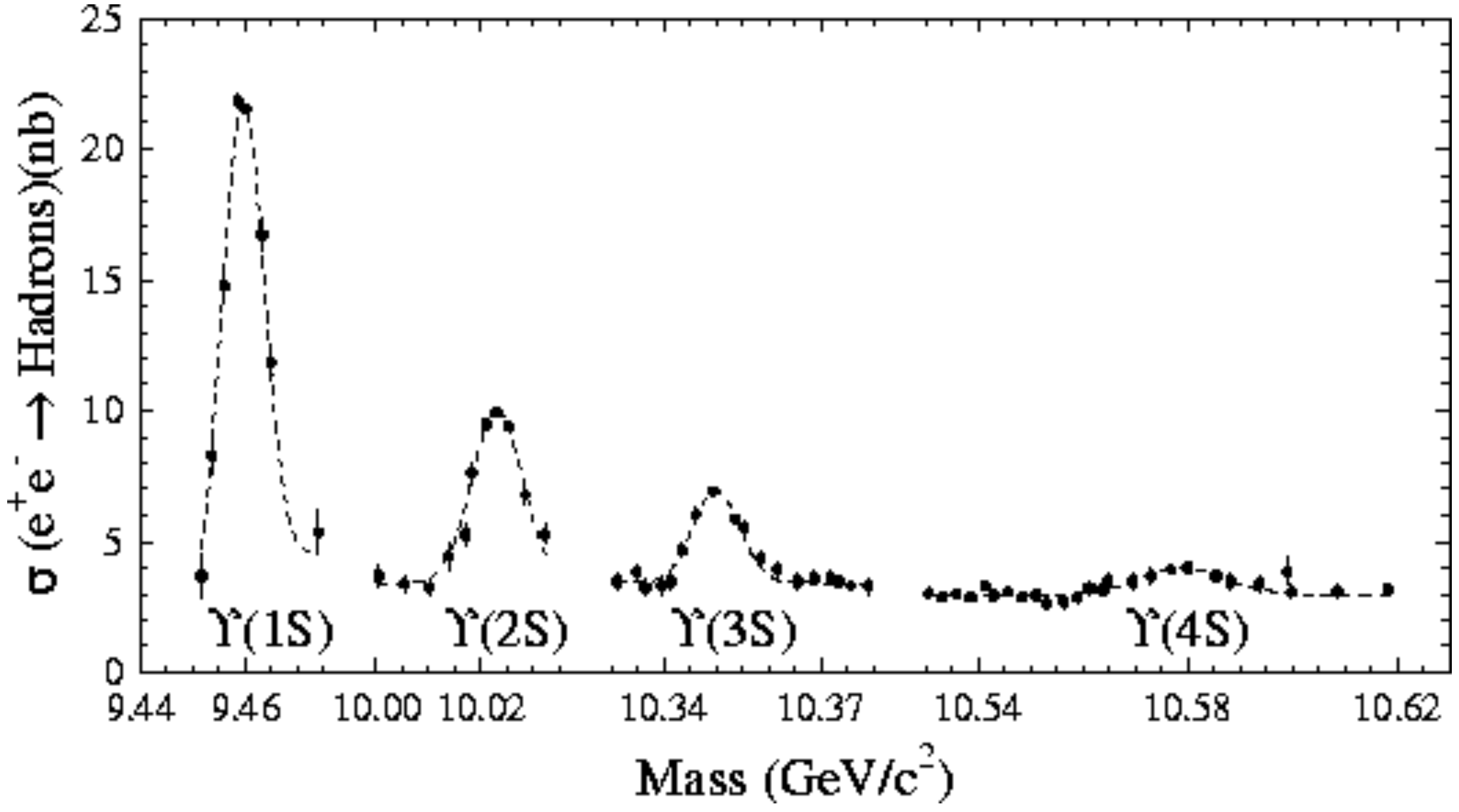
- Clearly illustrates the capabilities of Belle II and the potential for charm physics and the building blocks of B mesons.
- CP Eigenstate $D^0 \to K_S \pi^0$ impossible to see at LHCb!

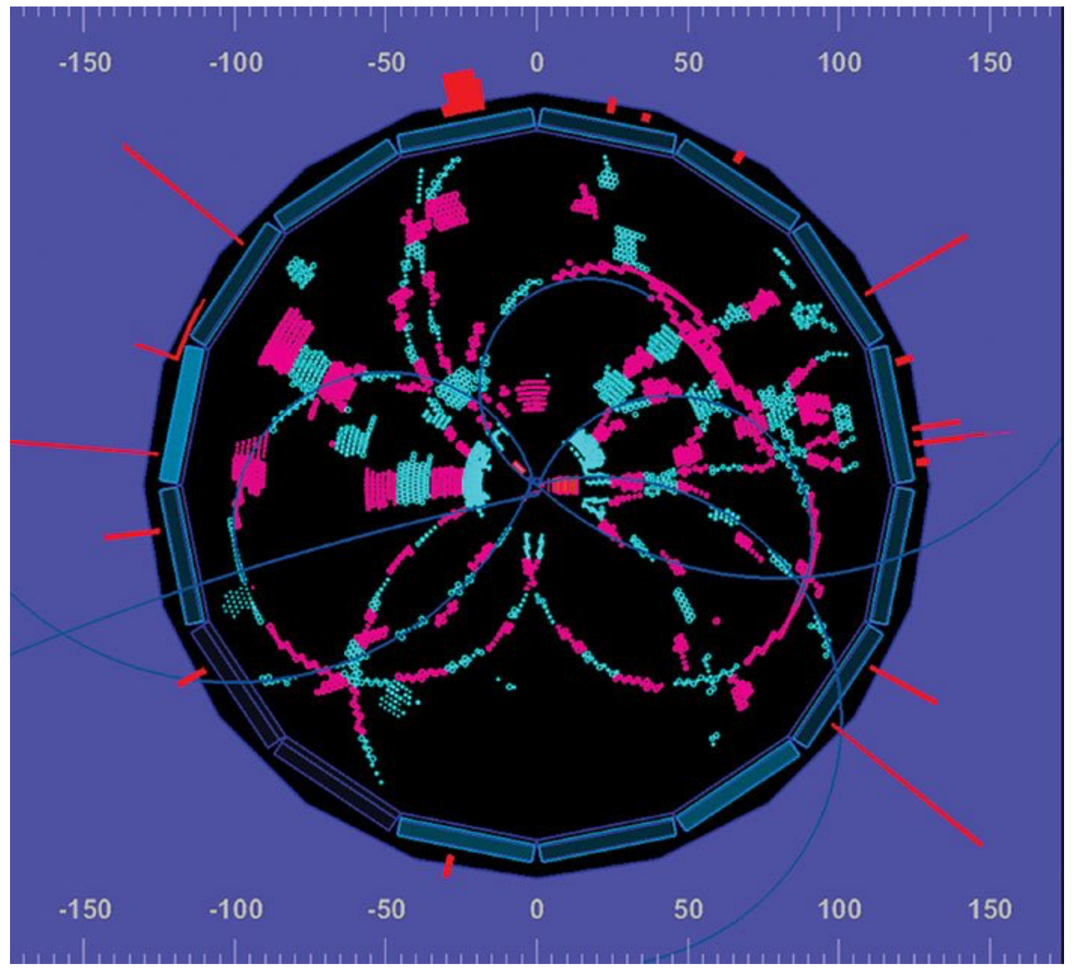
B production

B pairs produced at rest in the CM with no extra particles

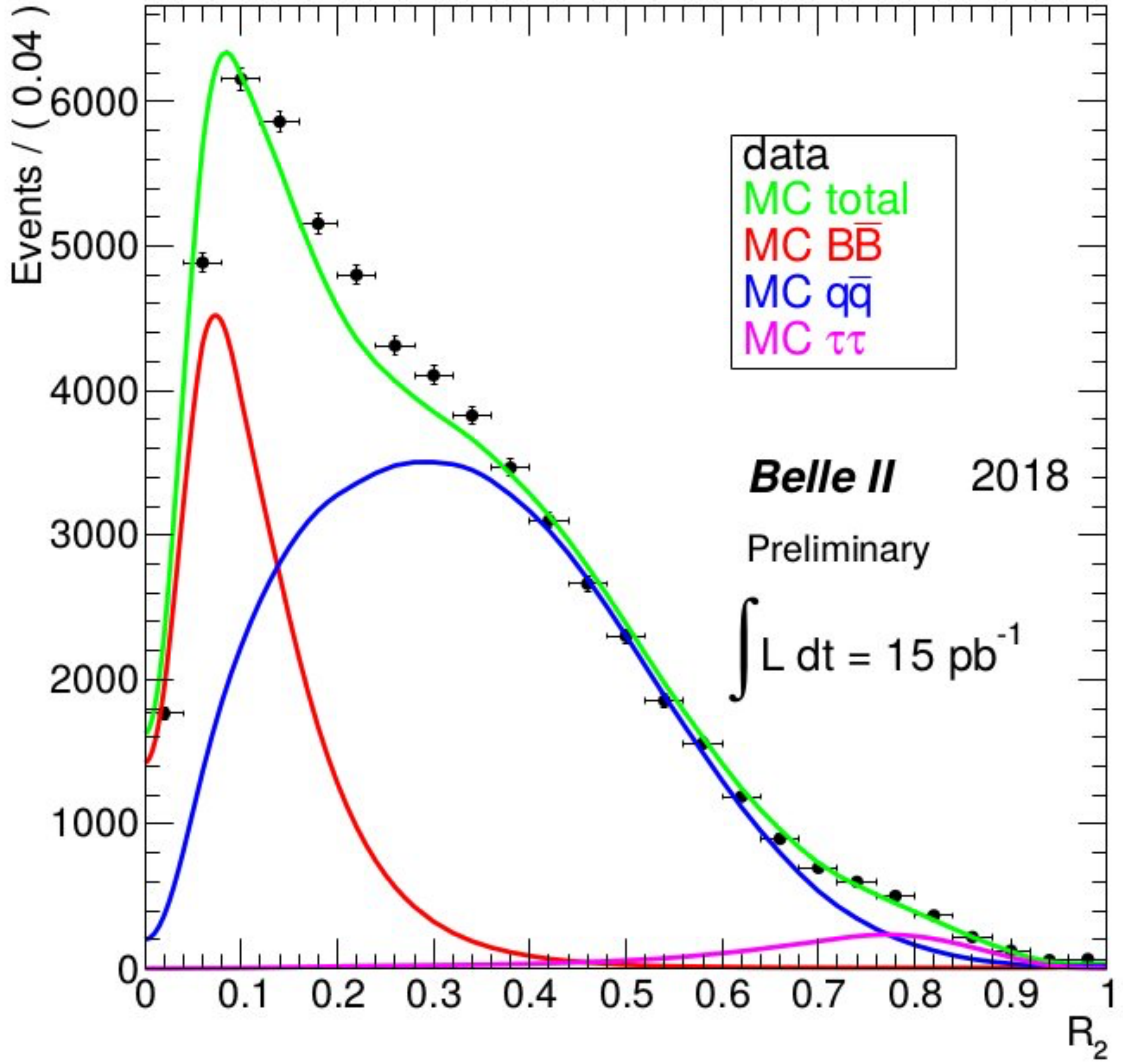








Probably a Y(4S) event



- We are on the Y(4S) resonance and recording B anti-B pairs with ~99% efficiency.
- *Not so obvious: When we change accelerator optics, we remain on Y(4S).*

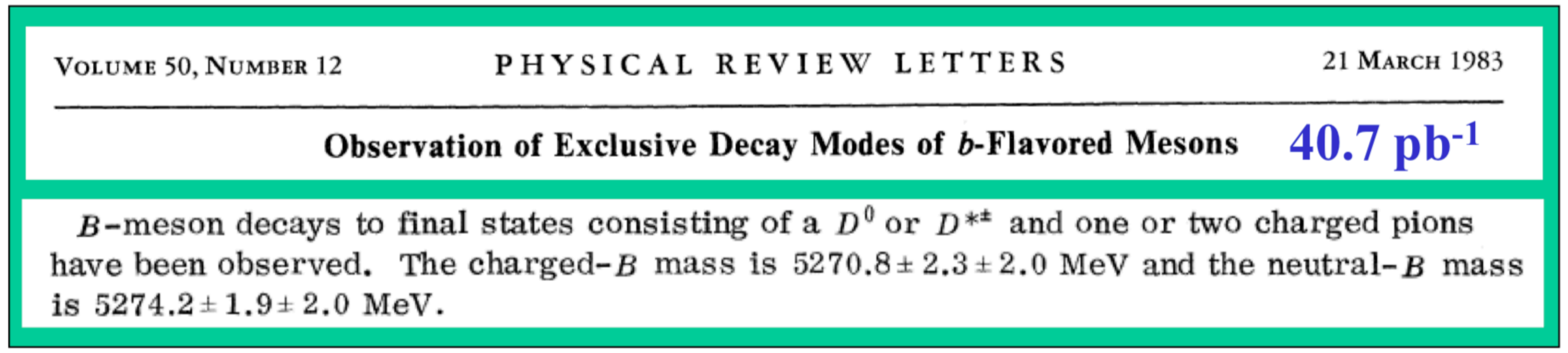
Event Topology (fits to R_2) tells us we are seeing B's

$R_2 = H_2/H_0$

$$H_l = \sum_{i,j} \frac{|\mathbf{p}_i||\mathbf{p}_j|}{E_{\mathrm{vis}}^2} P_l(\cos\theta_{ij}) \, ,$$

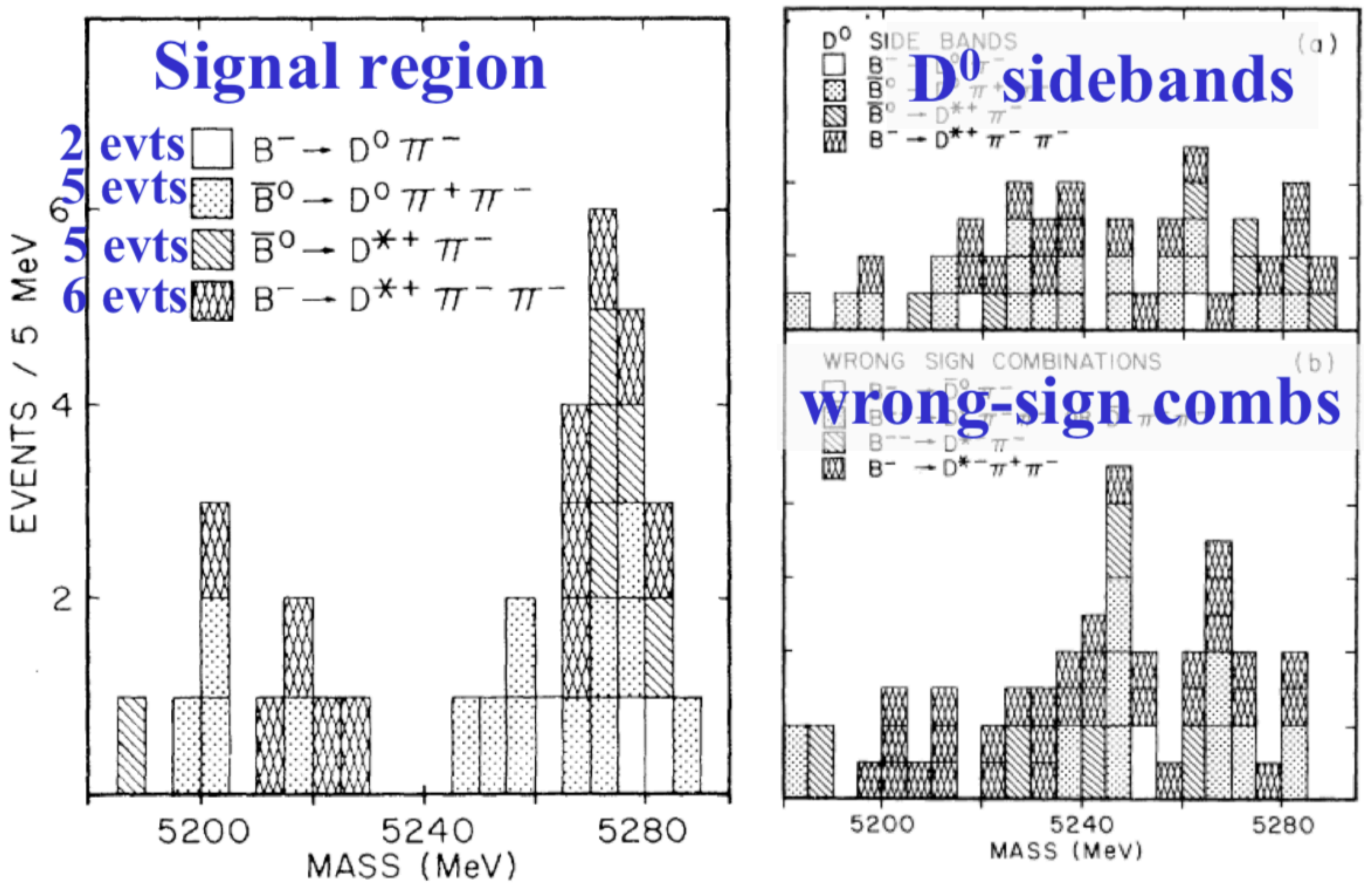
Beauty “Rediscovery” (cut-based analysis)

- Recreating CLEO & ARGUS
  - > 200 B candidates in hadronic modes (470/pb)
  - ~14 $B \to D^* e \nu$ found (250/pb)


VOLUME 50, NUMBER 12 PHYSICAL REVIEW LETTERS 21 MARCH 1983

Observation of Exclusive Decay Modes of b-Flavored Mesons 40.7 pb^{-1}

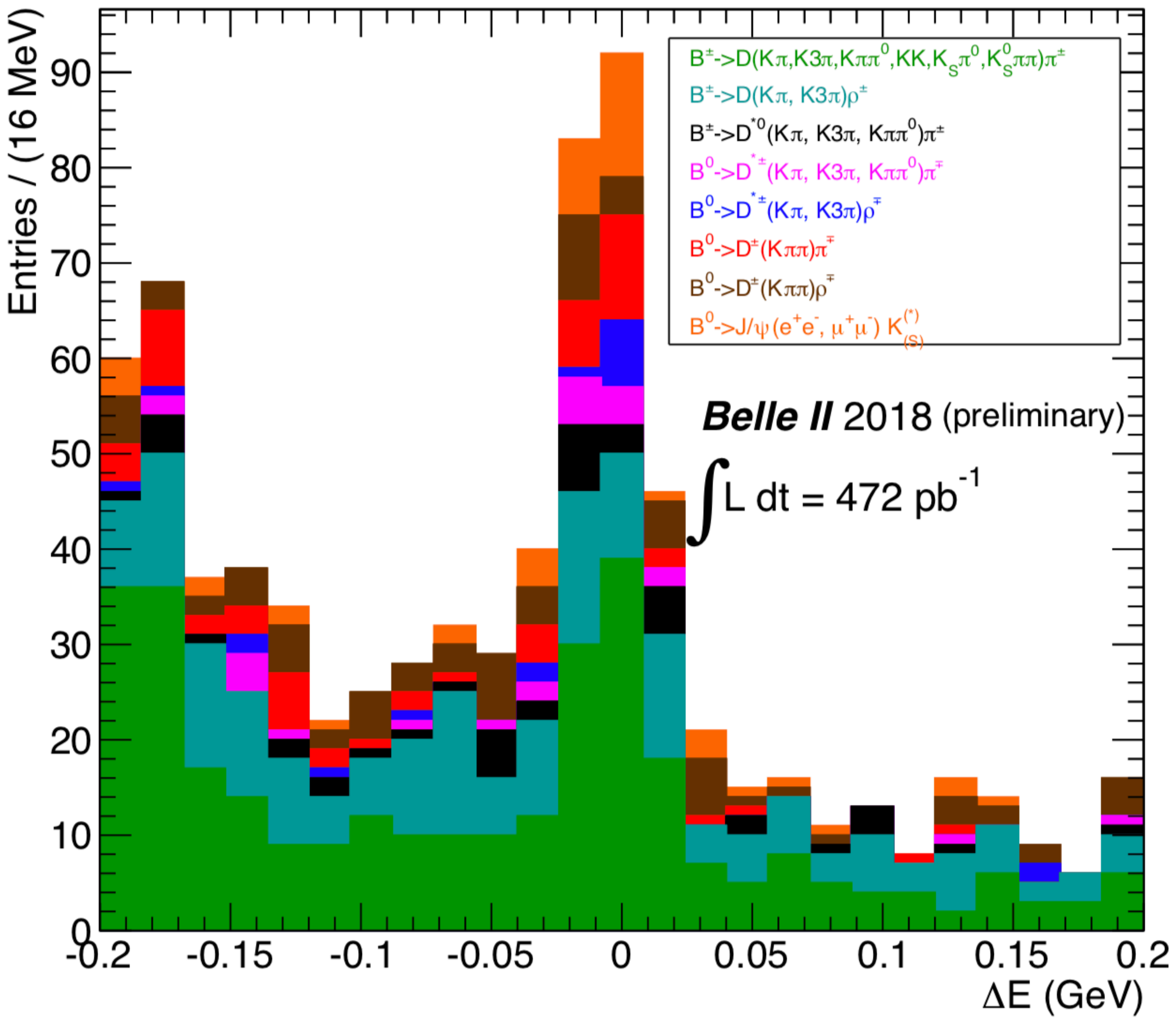
B-meson decays to final states consisting of a D^0 or $D^{*\pm}$ and one or two charged pions have been observed. The charged-B mass is 5270.8 ± 2.3 ± 2.0 MeV and the neutral-B mass is 5274.2 ± 1.9 ± 2.0 MeV.

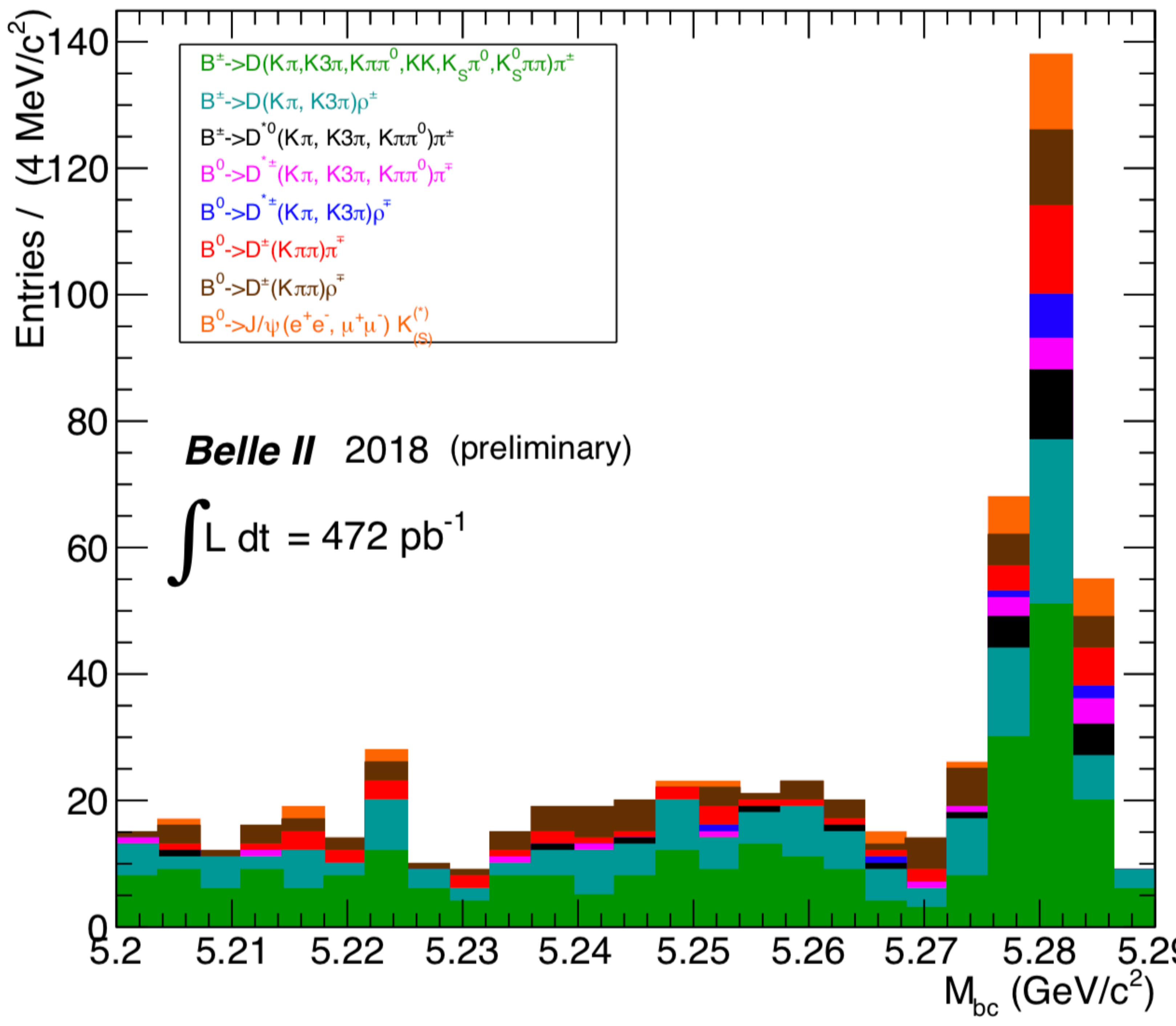


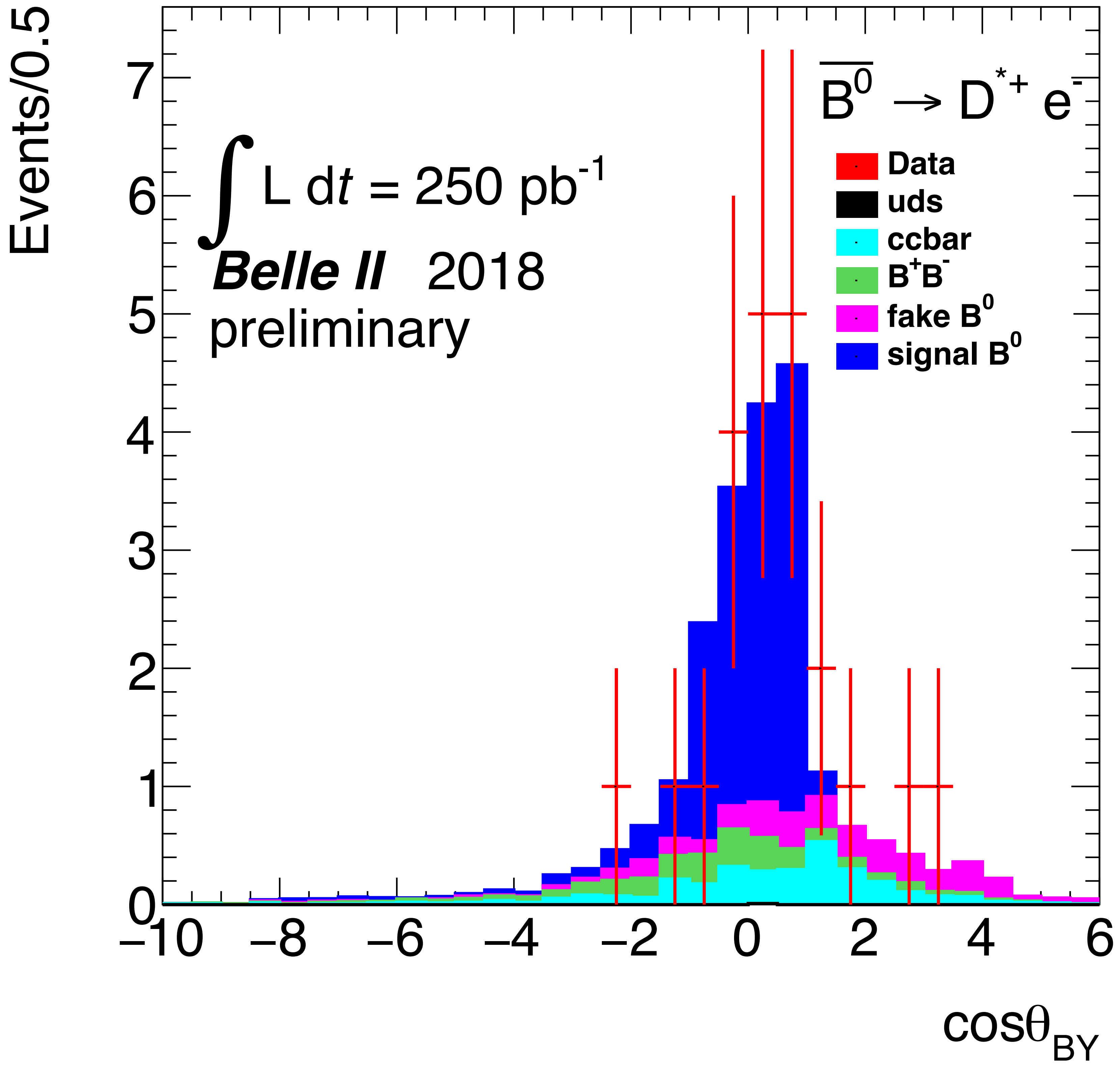
$$\Delta E = E_{cm}/2 - E_{recon}$$

$$M_{bc} = \sqrt{(E_{cm}/2)^2 - p^2_{recon}}$$

$B \to D^* e \nu$







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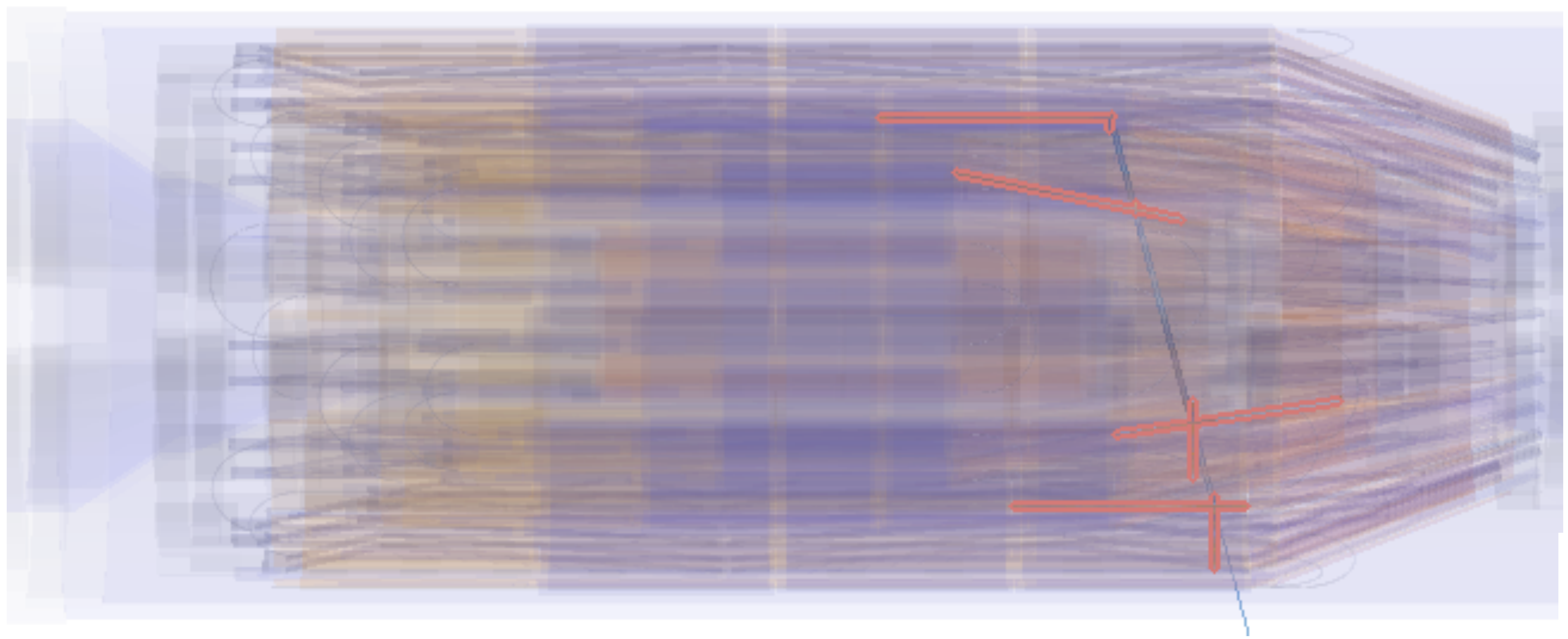
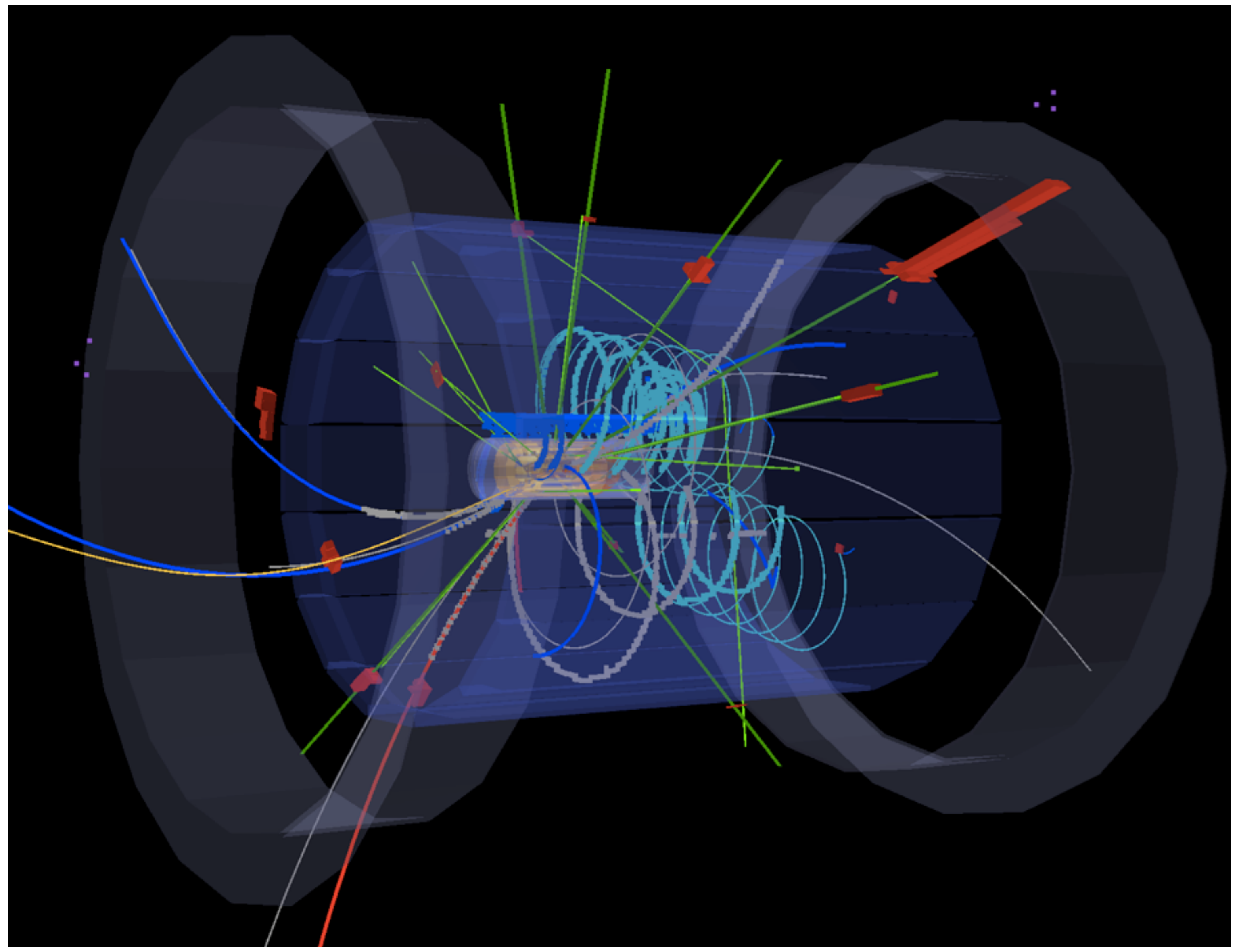
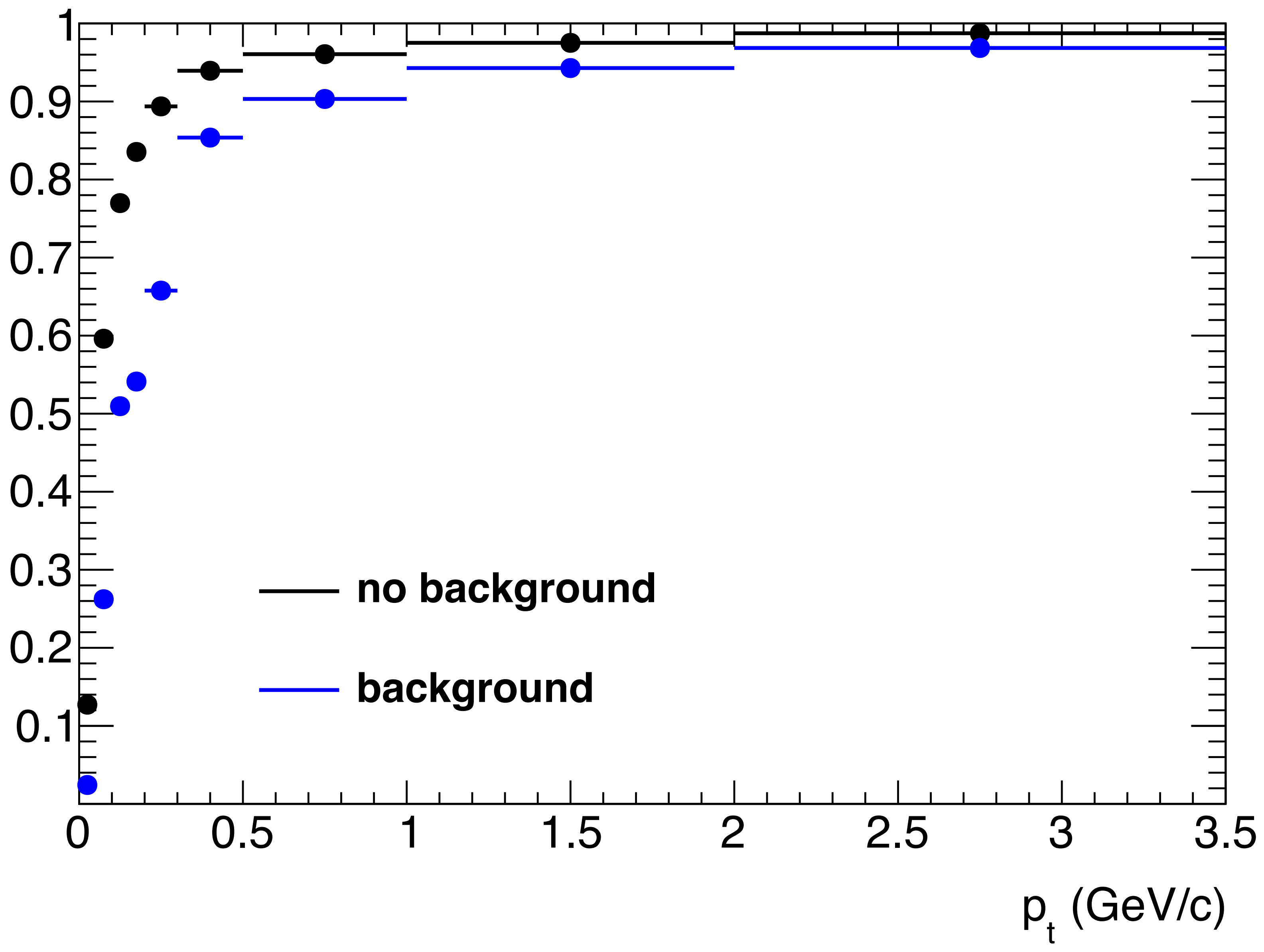
First Cosmic Ray Muon in the full SVD at KEK, August 2018



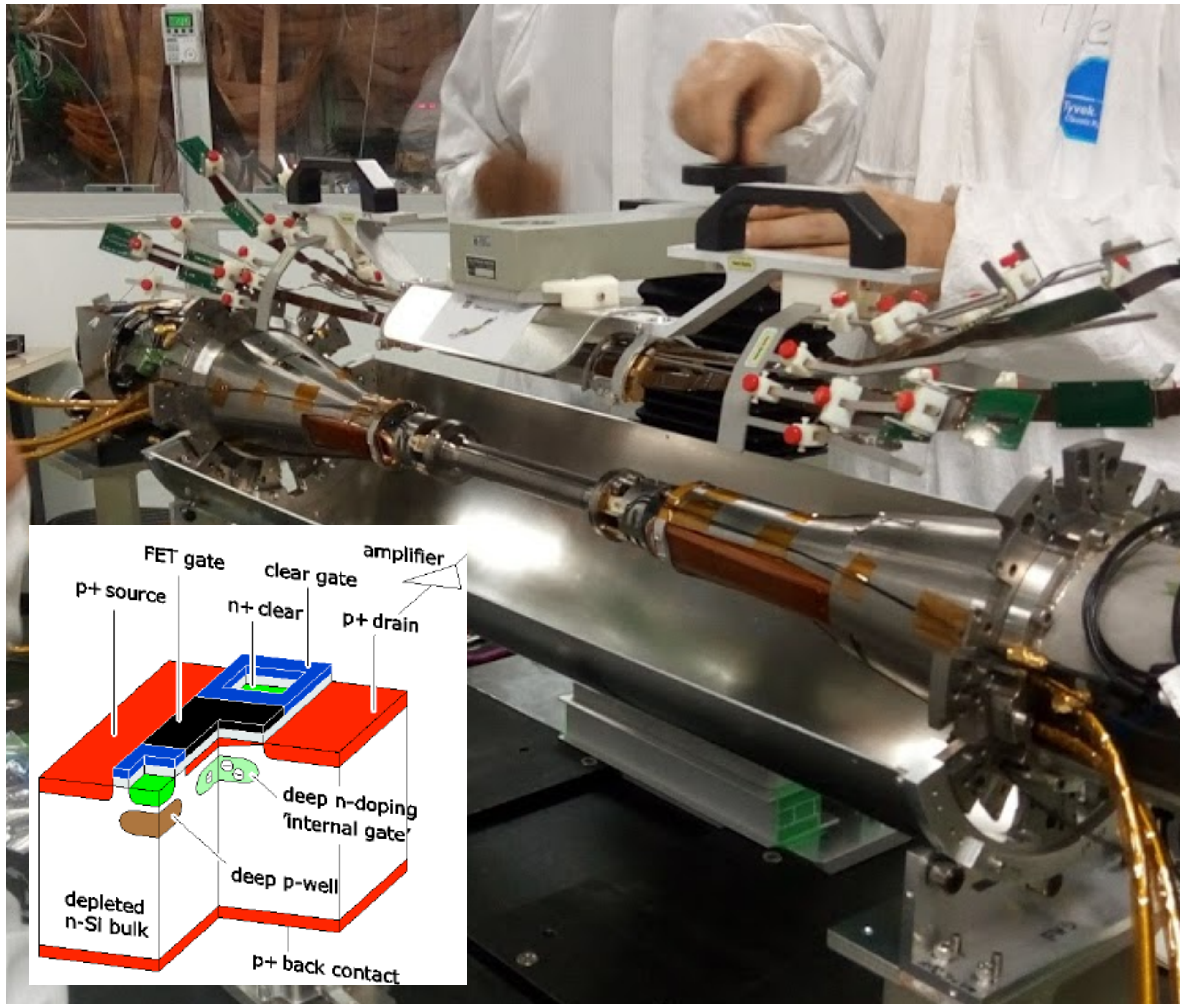


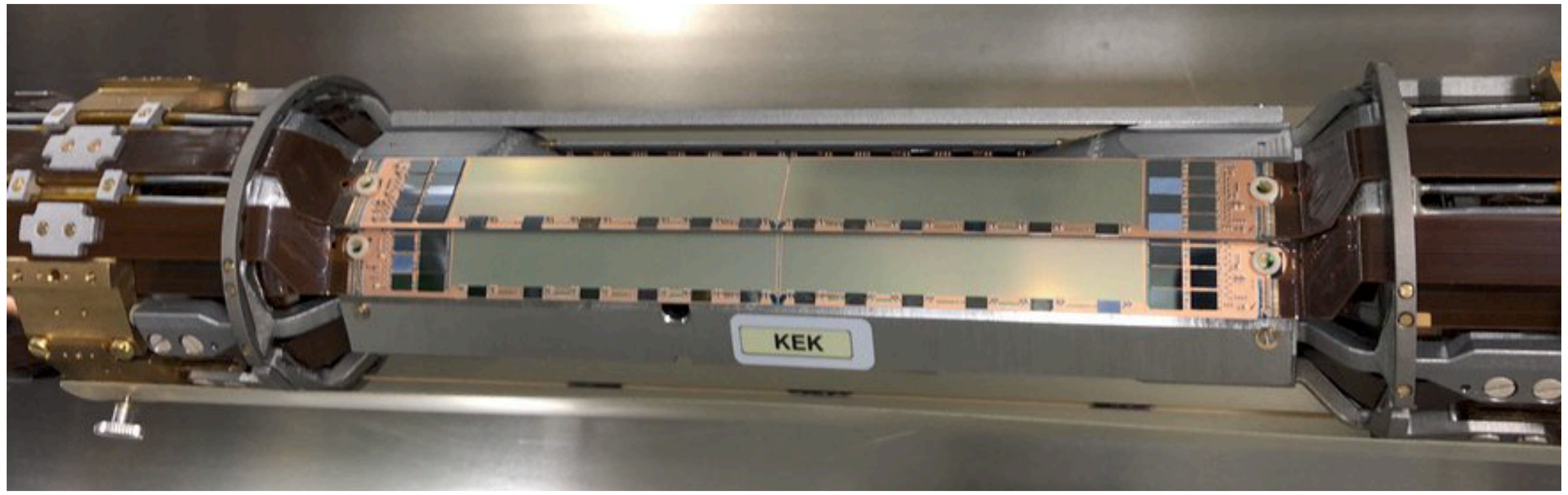


SVD is on-track for mid-October integration with the PXD and installation in time for the Phase 3 run in late Feb 2019.

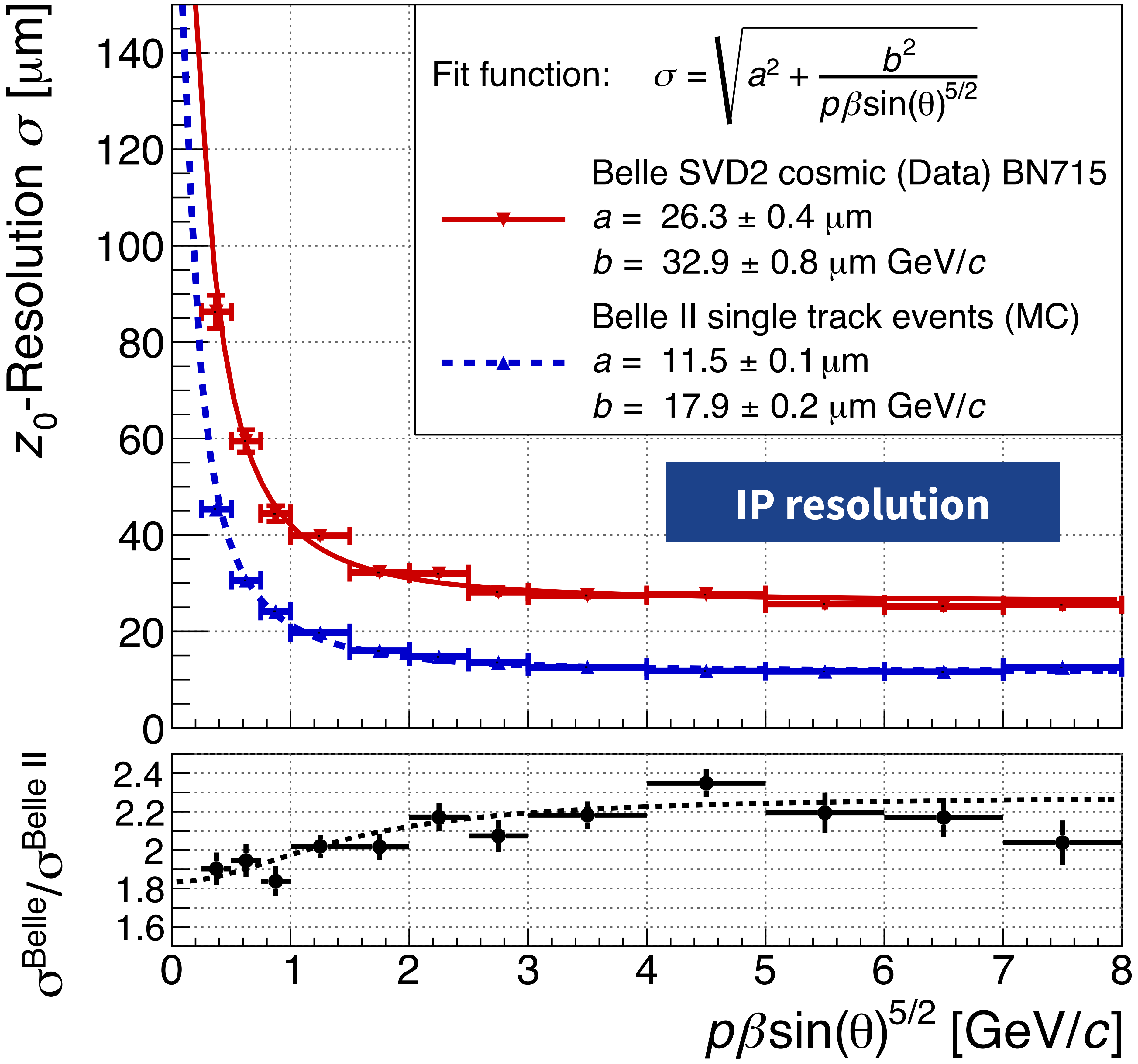
- Novel silicon—dedicated tracking. Good for D* efficiencies <$p_{\pi\text{-slow}}$> ~ 100 MeV.

Pixel detector ready





PXD mounted onto SuperKEKB beam pipe at KEK. The full VXD (PXD+SVD) should be completed within weeks.



- Impact parameters: σ_{d0} Belle II < 0.5 x σ_{d0} Belle, Mass: σ_M Belle II ~ 0.7 x σ_M Belle

Belle (II) Reconstruction

- Belle (II) analyses use semileptonic and hadronic “tagging”.

- Based on M_{miss}^2 and calorimeter extra energy $E_{ECL/extra}$

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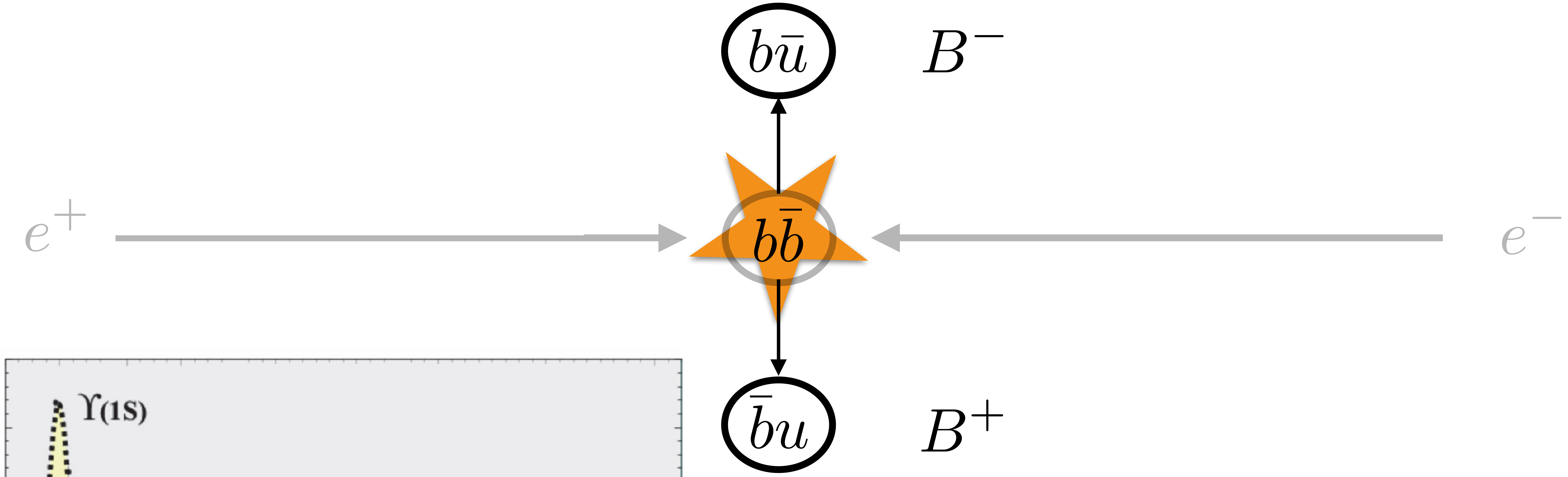

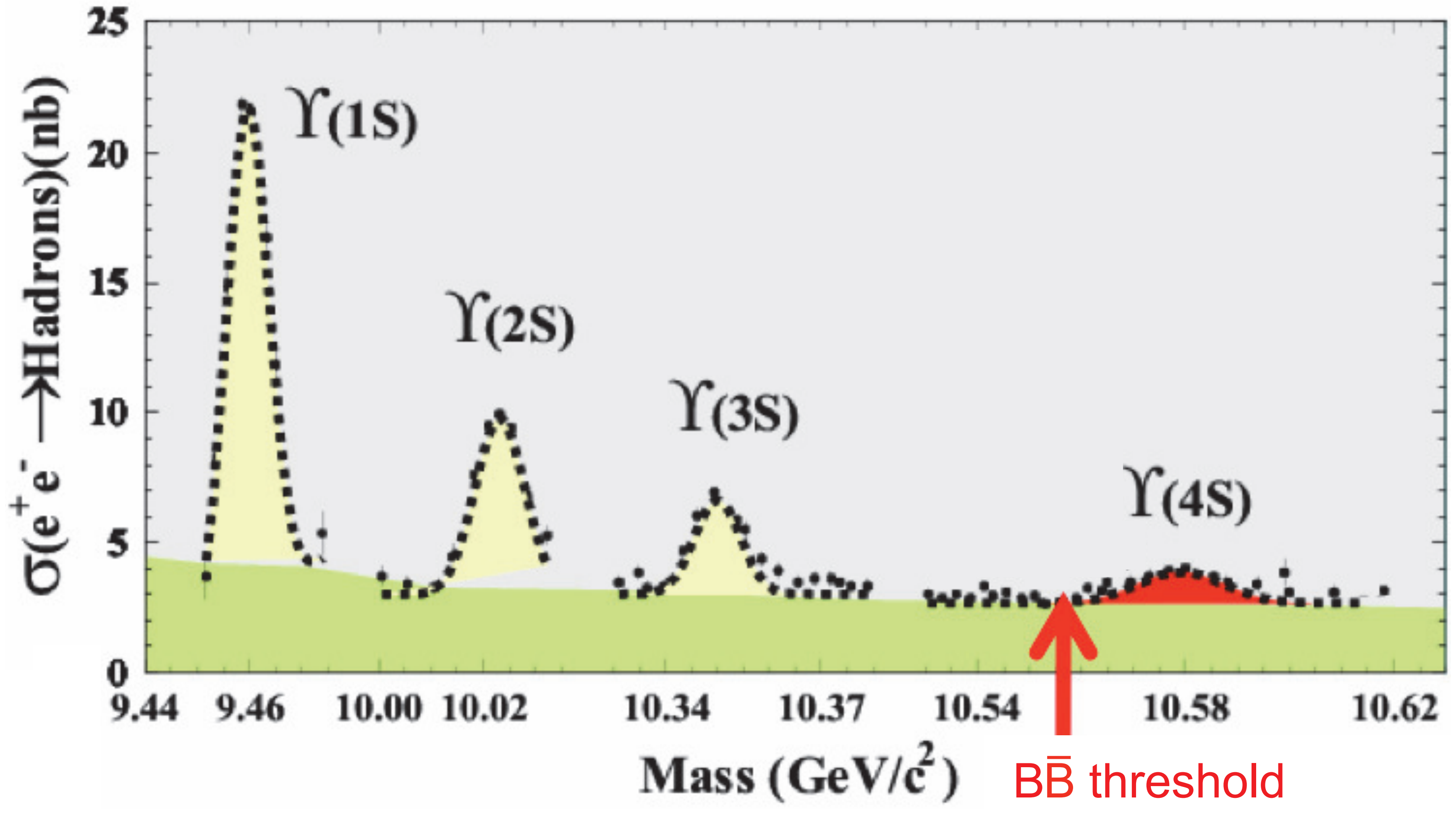

$\Upsilon(1S) = \langle b\bar{b} \rangle$

$\Upsilon(4S) = \langle b\bar{b} \rangle$

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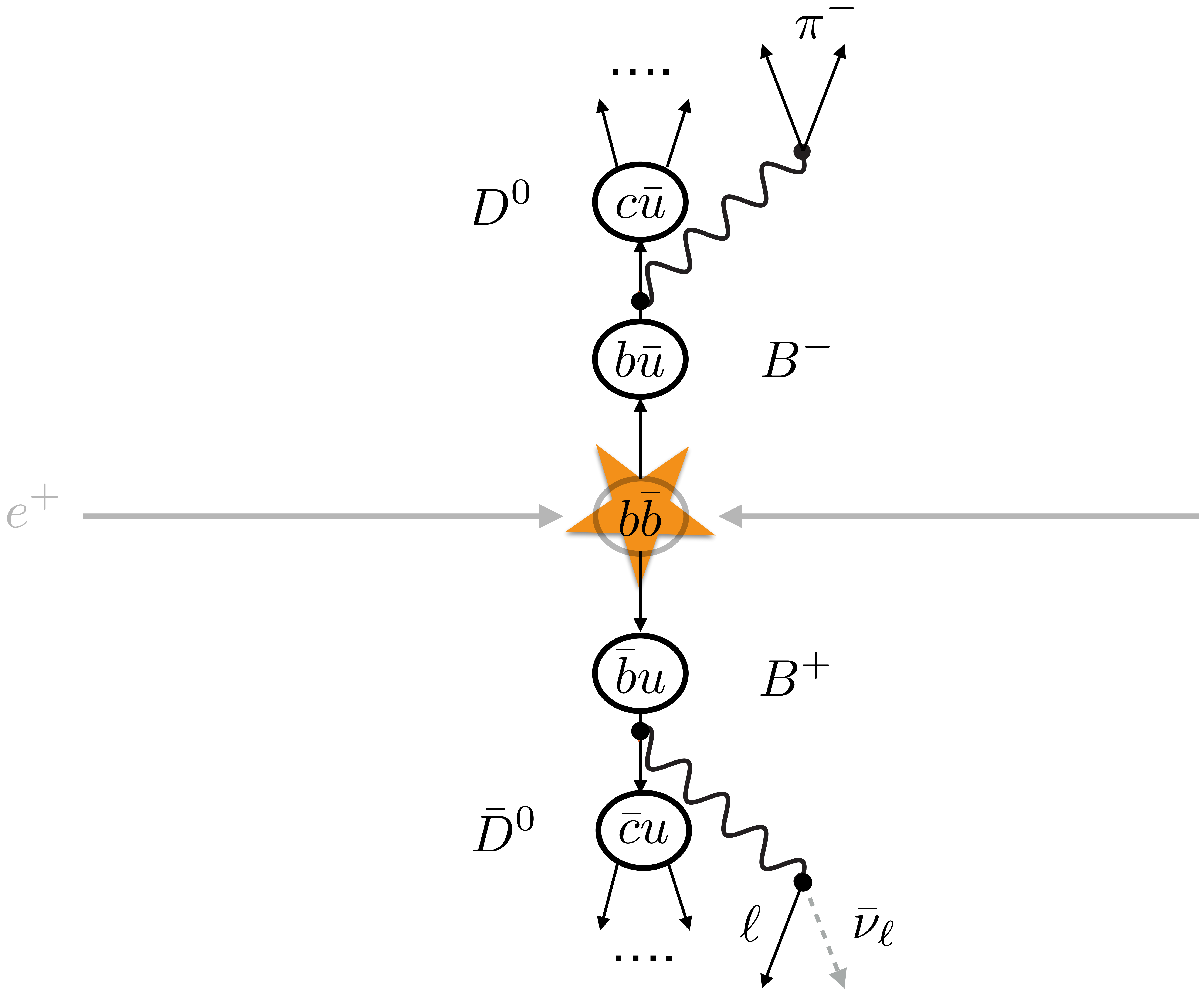

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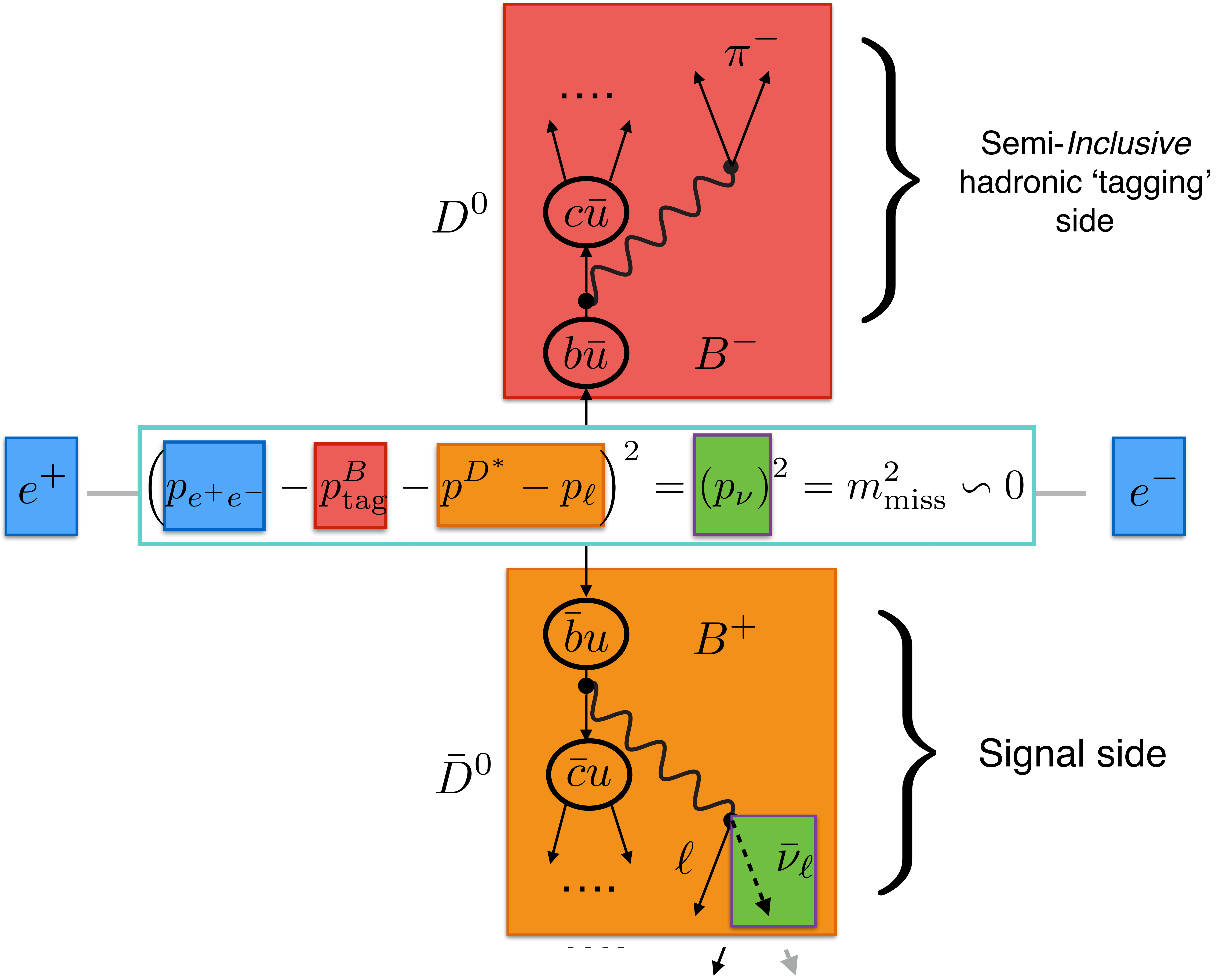
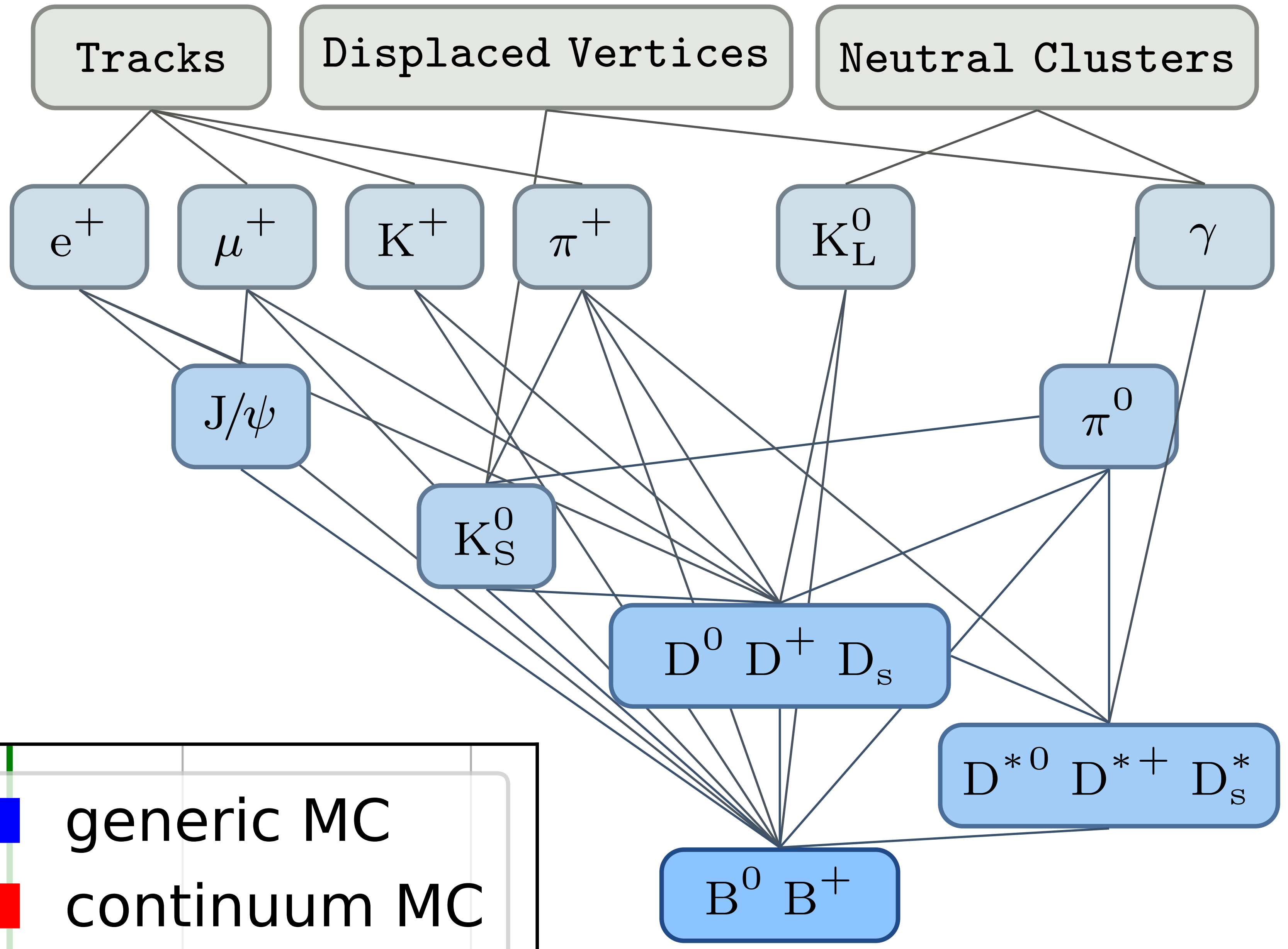
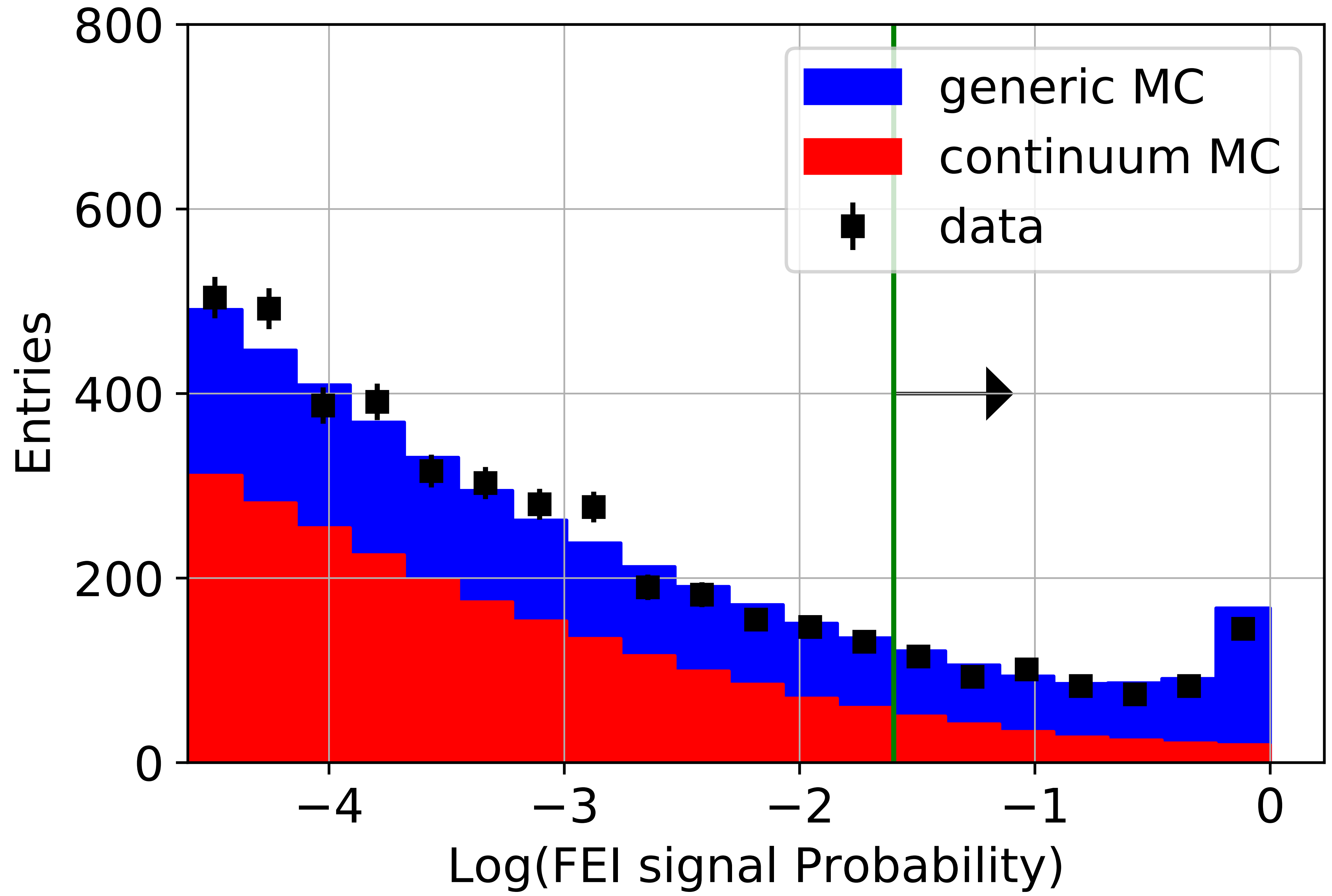


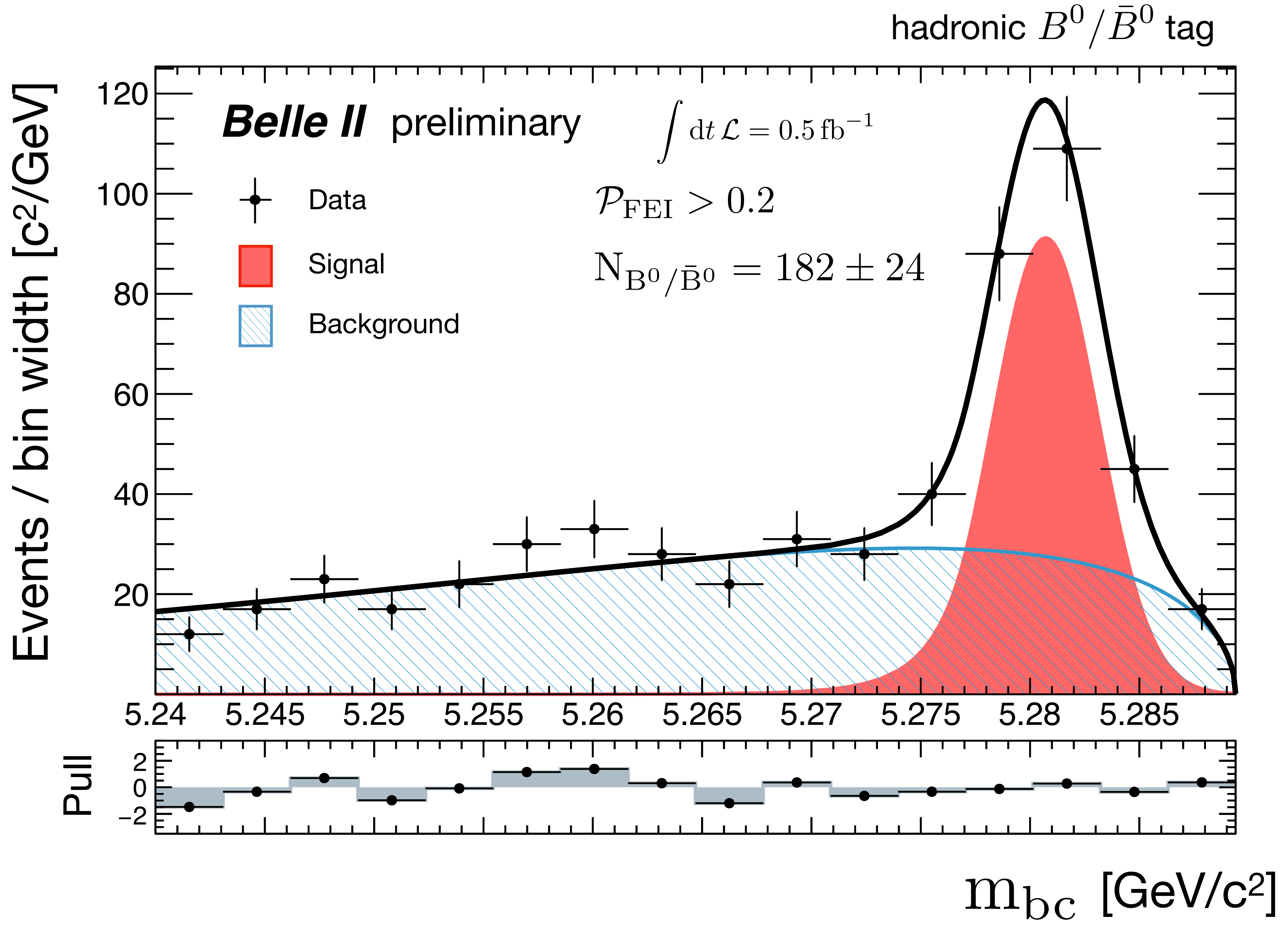
$$\left(p_{e^+e^-} - p^B_{\rm tag} - p^{D^*} - p_\ell\right)^2 = (p_\nu)^2 = m^2_{\rm miss} \backsim 0$$

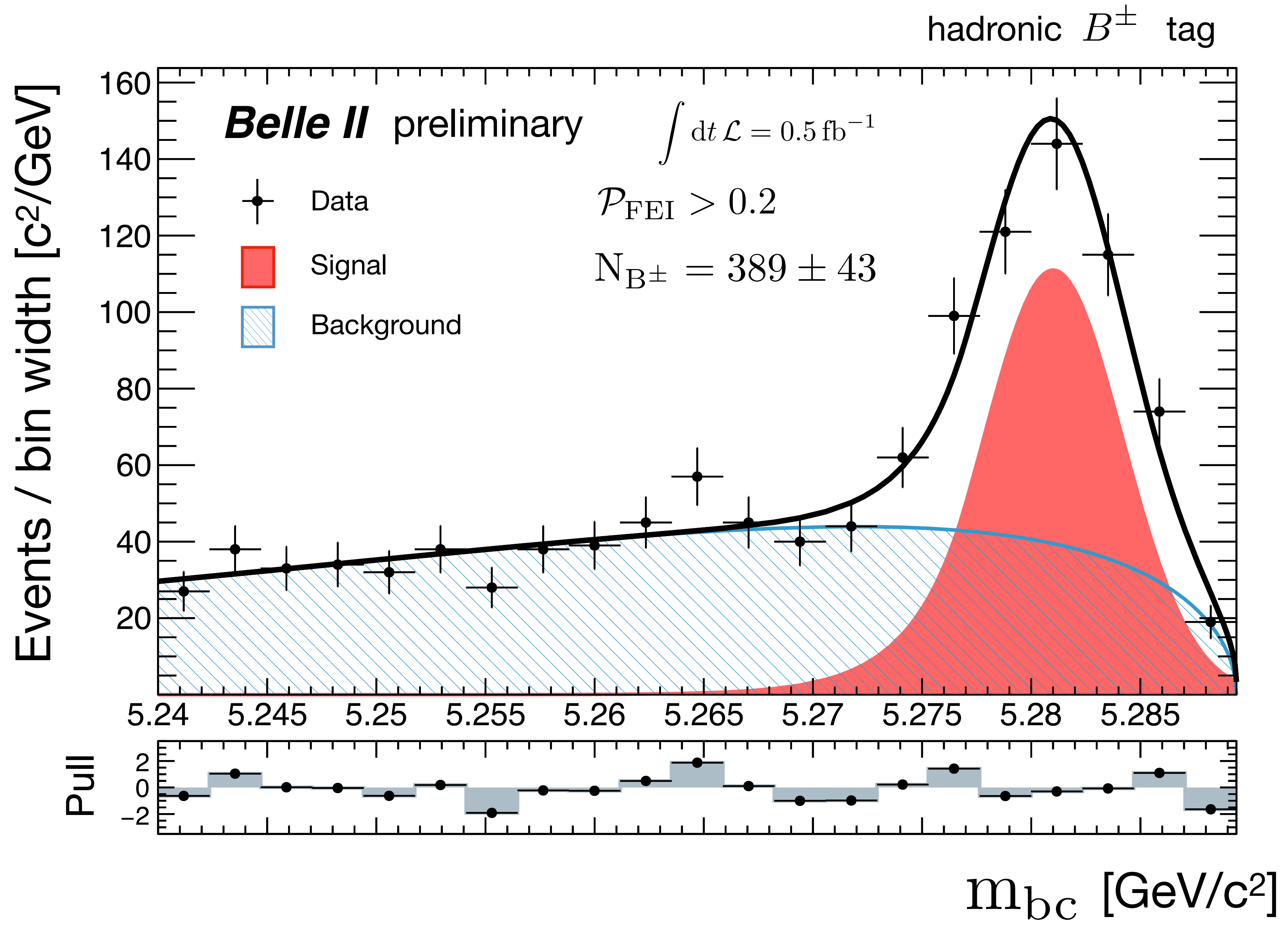
B-full reconstruction in 2018

- Recursive reconstruction algorithm (FEI): **> 5000 B decay modes**!
- Boosted decision tree classifier.









B → D* τ⁻ ν Measurements

- Belle: Semileptonic tag, 772M B anti-B pairs
  - B0 → D*⁻ τ+ ν : 231±23(stat) events
    B0 → D*⁻ l+ ν: 2800±57(stat.) events.
- R(D*) = 0.302±0.030±0.011

Belle PRD 94, 072007 (2016)

Belle PRL 118, 211801 (2017)
Belle arXiv:1709.00129

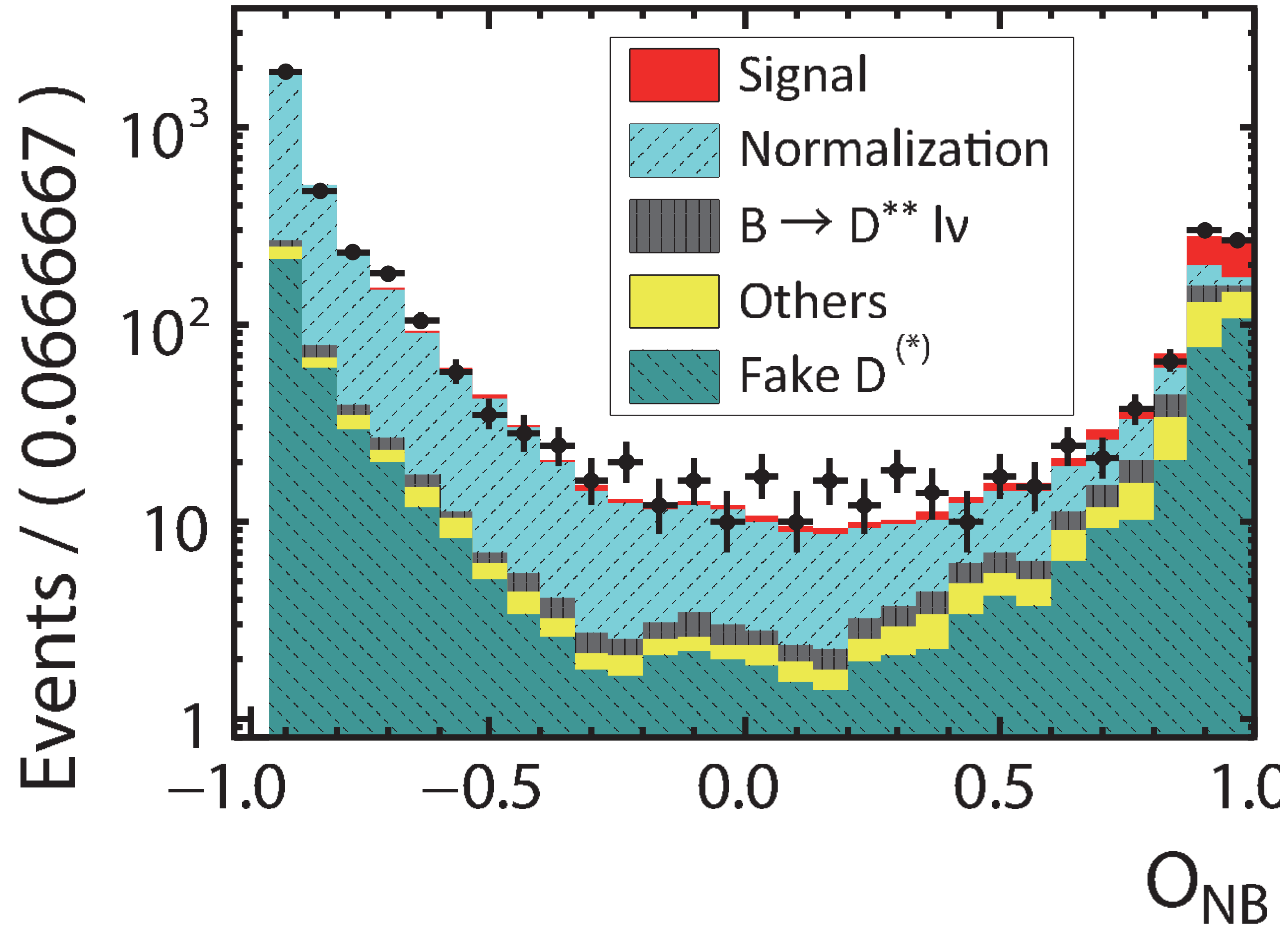
LHCb arXiv:1711.02505

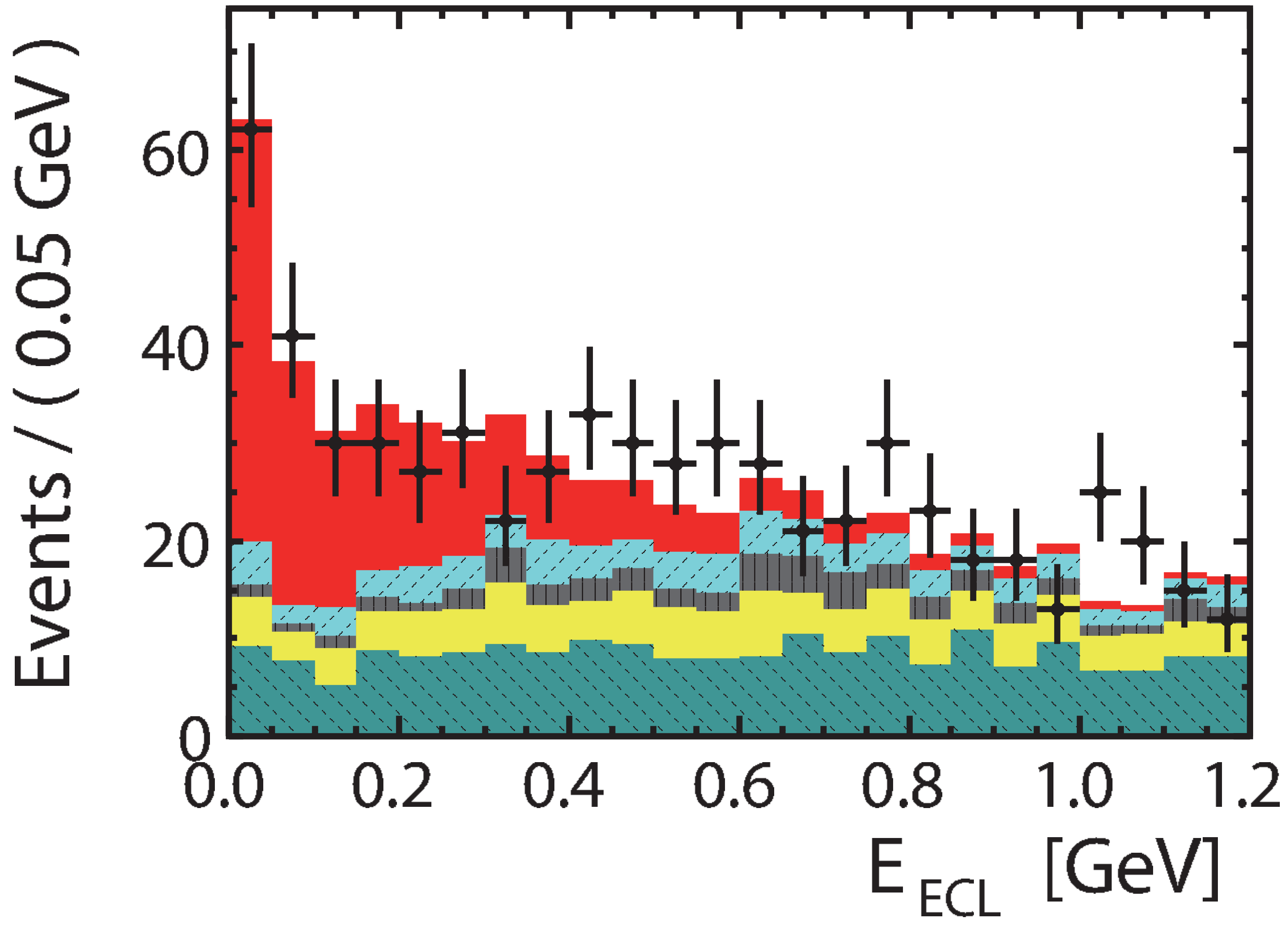
LHCb arXiv:1711.05623

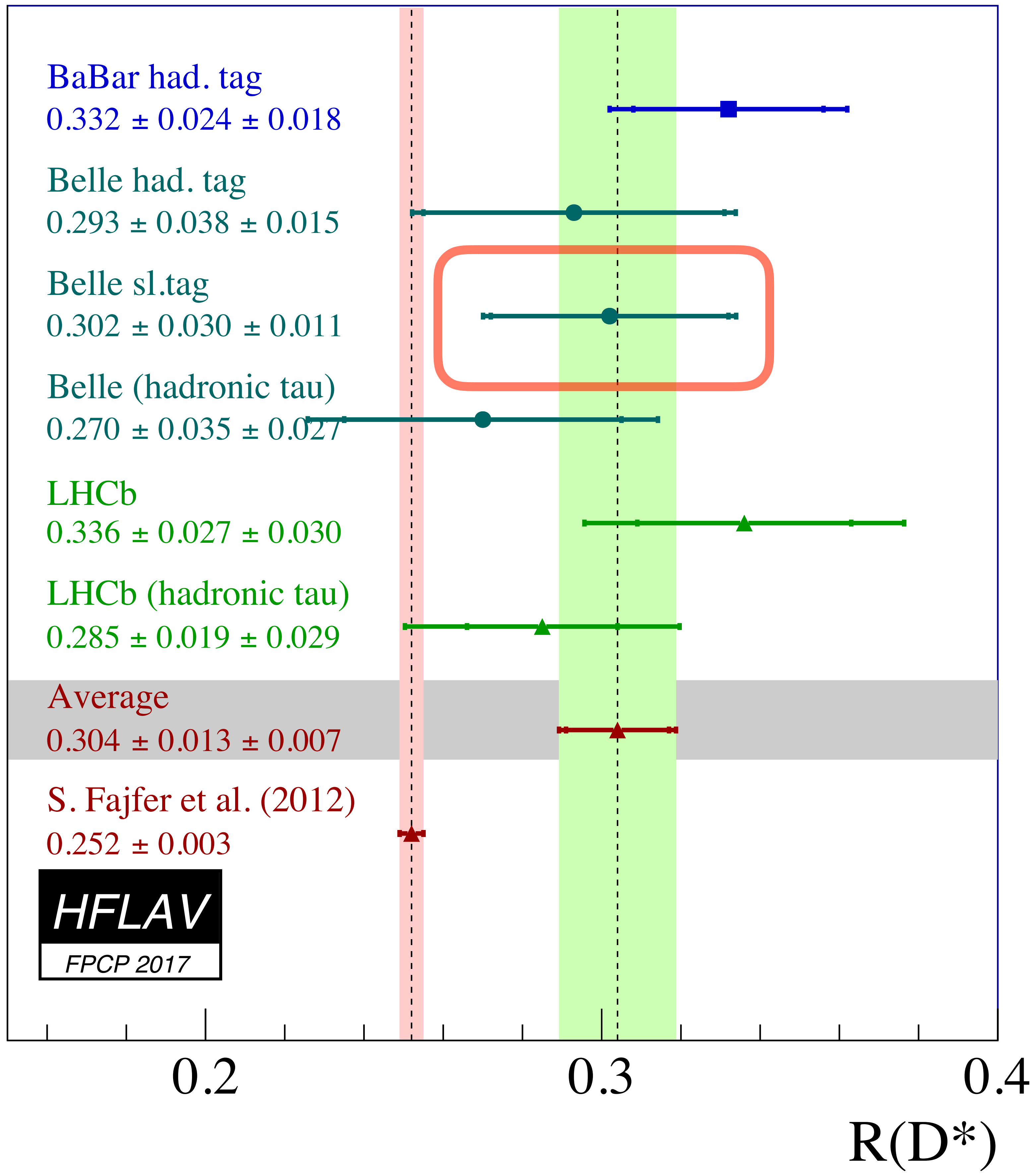
$\cos\theta^{sig}_{B-D^*l}$

M^2_{miss}

Total energy of $B_{tag} + B_{sig}$



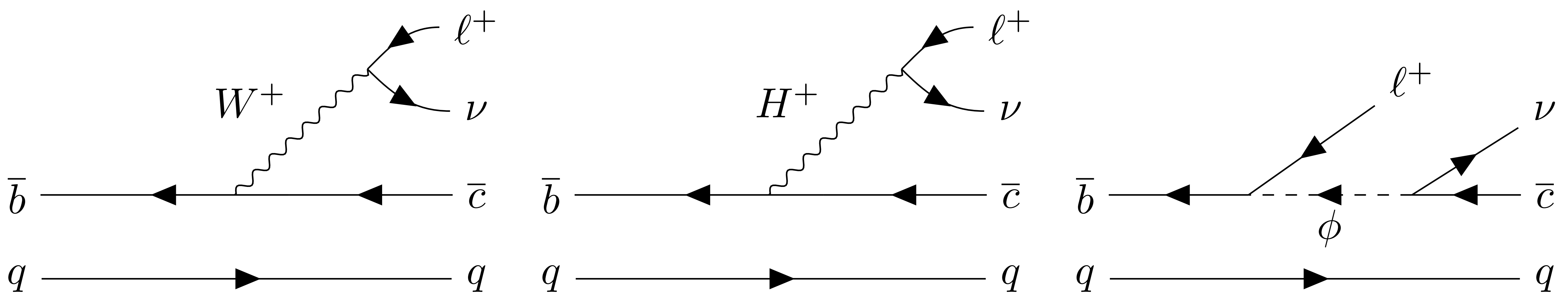


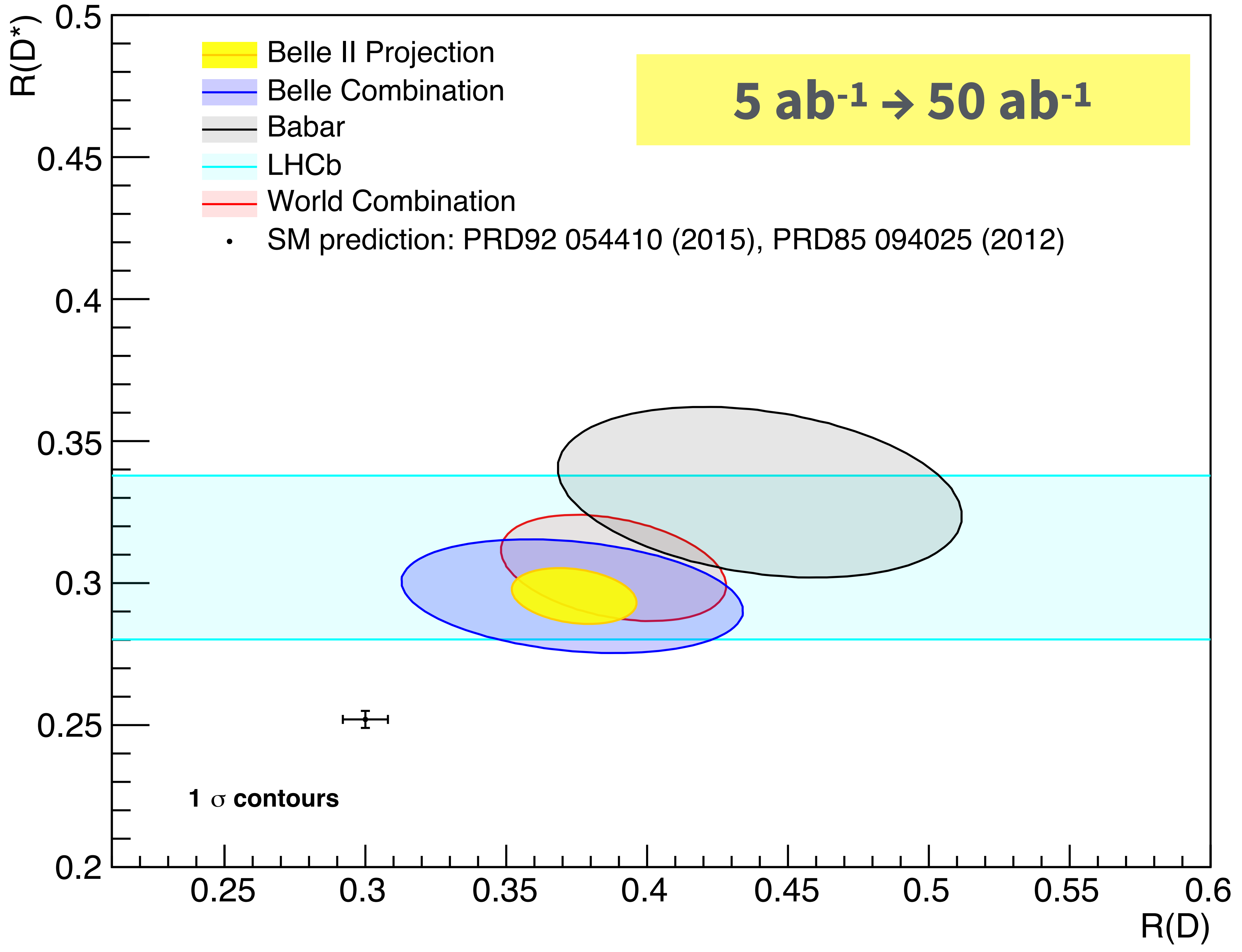


B→D(*) τ ν

Belle II Physics Book

- Belle II should confirm/deny anomaly with 5 ab^{-1}
- **Determine the type of mediator by analysis of kinematic spectra with 50 ab^{-1}**





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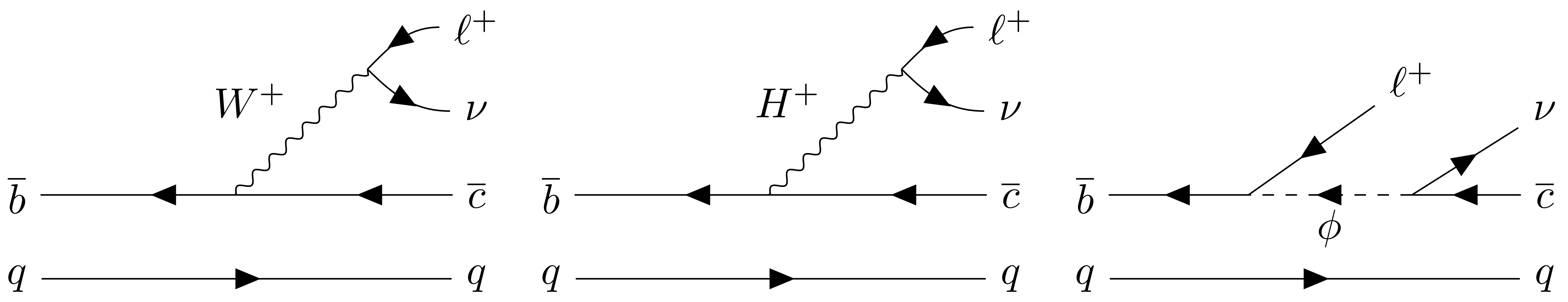

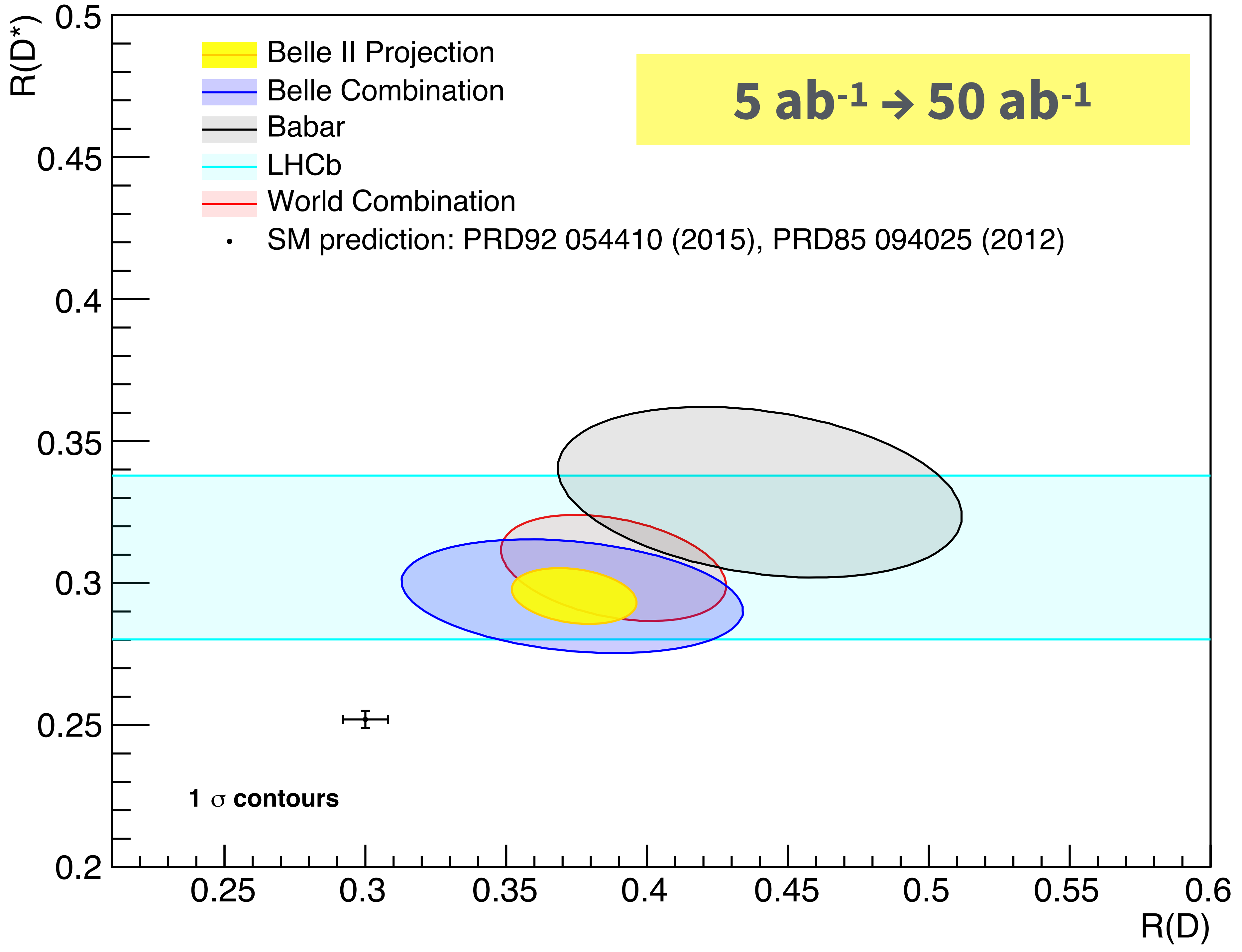

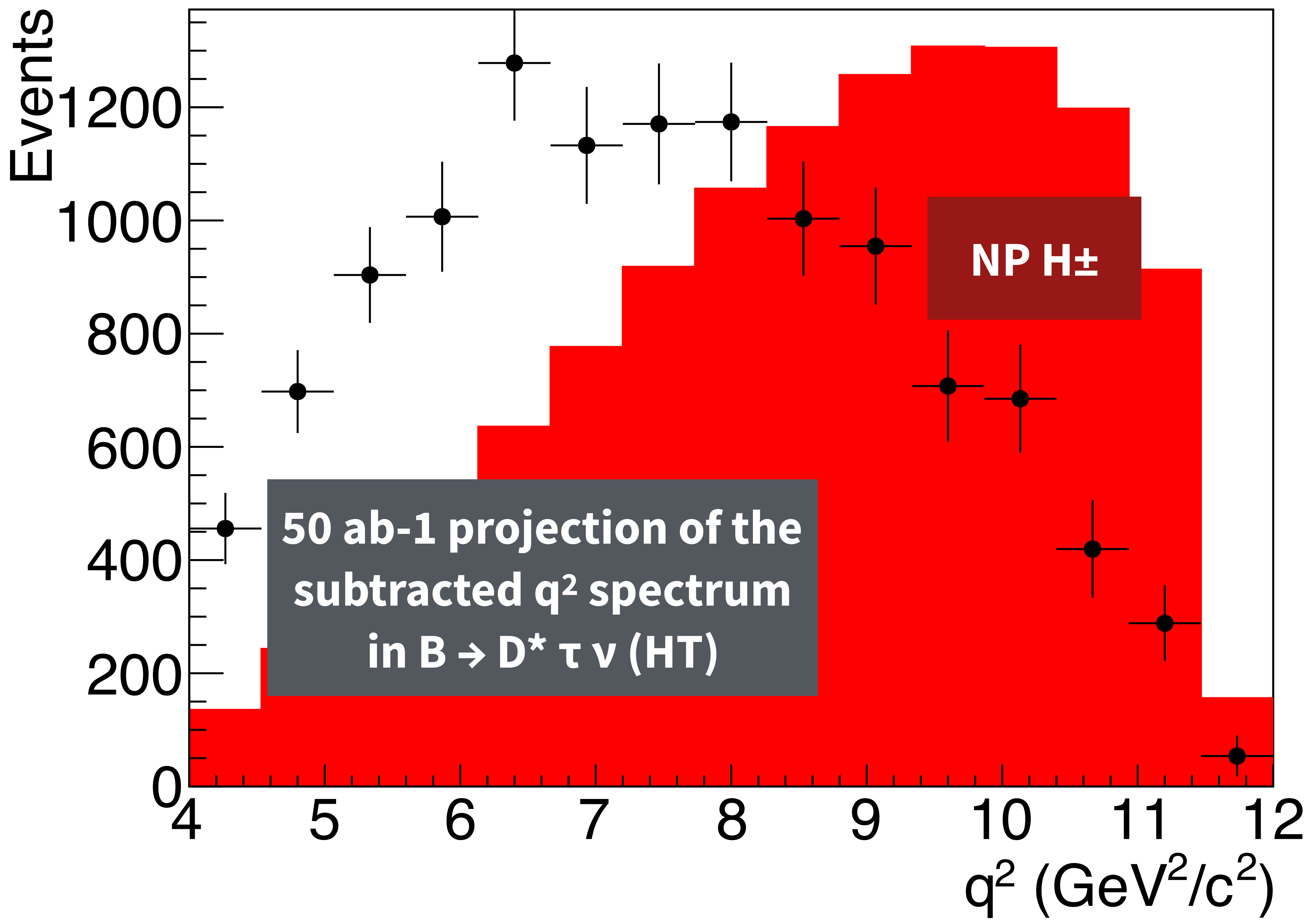

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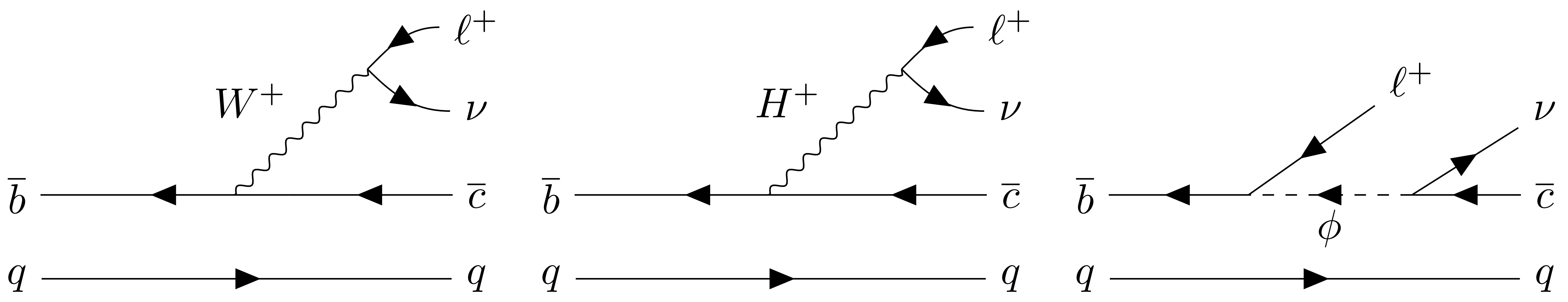

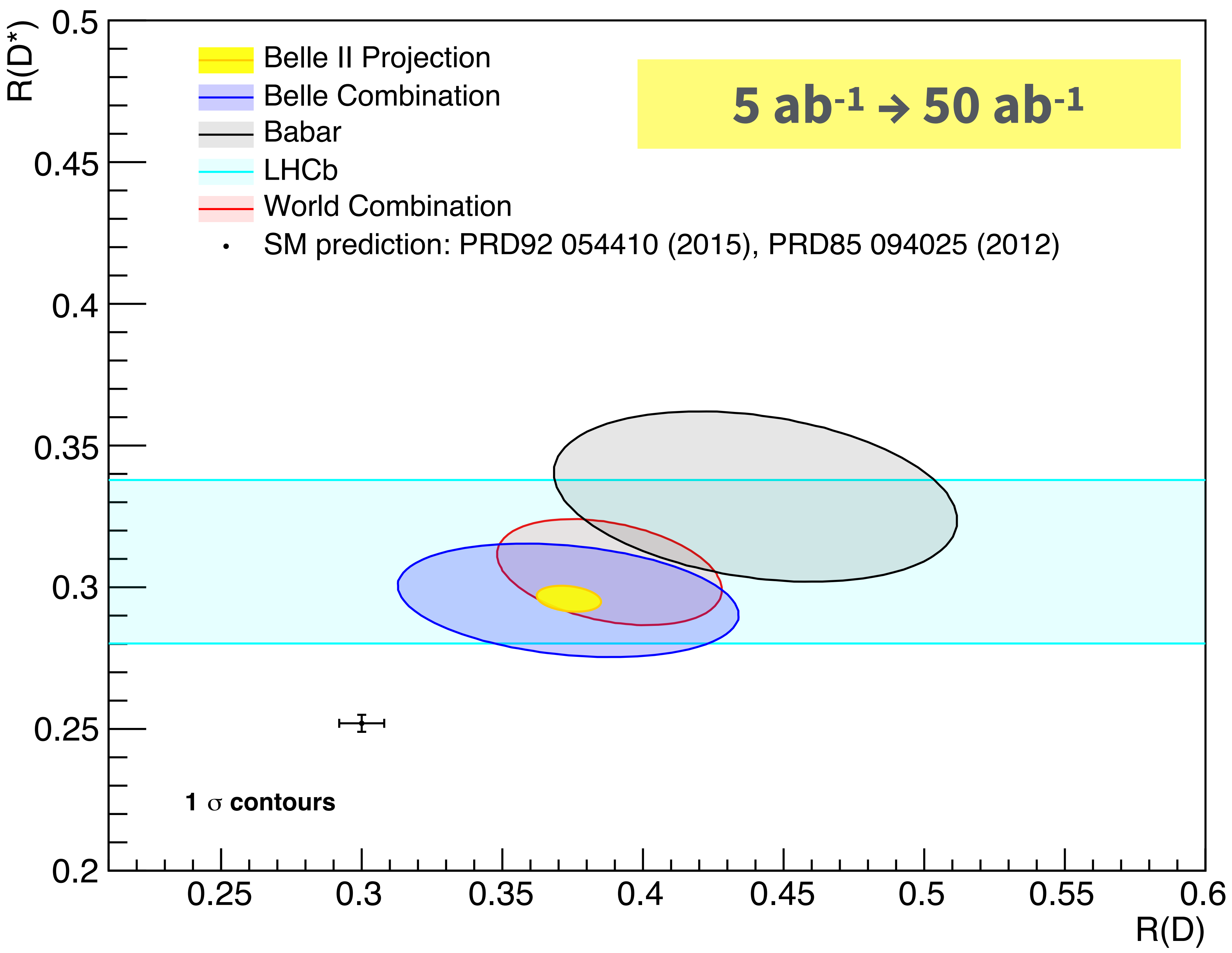

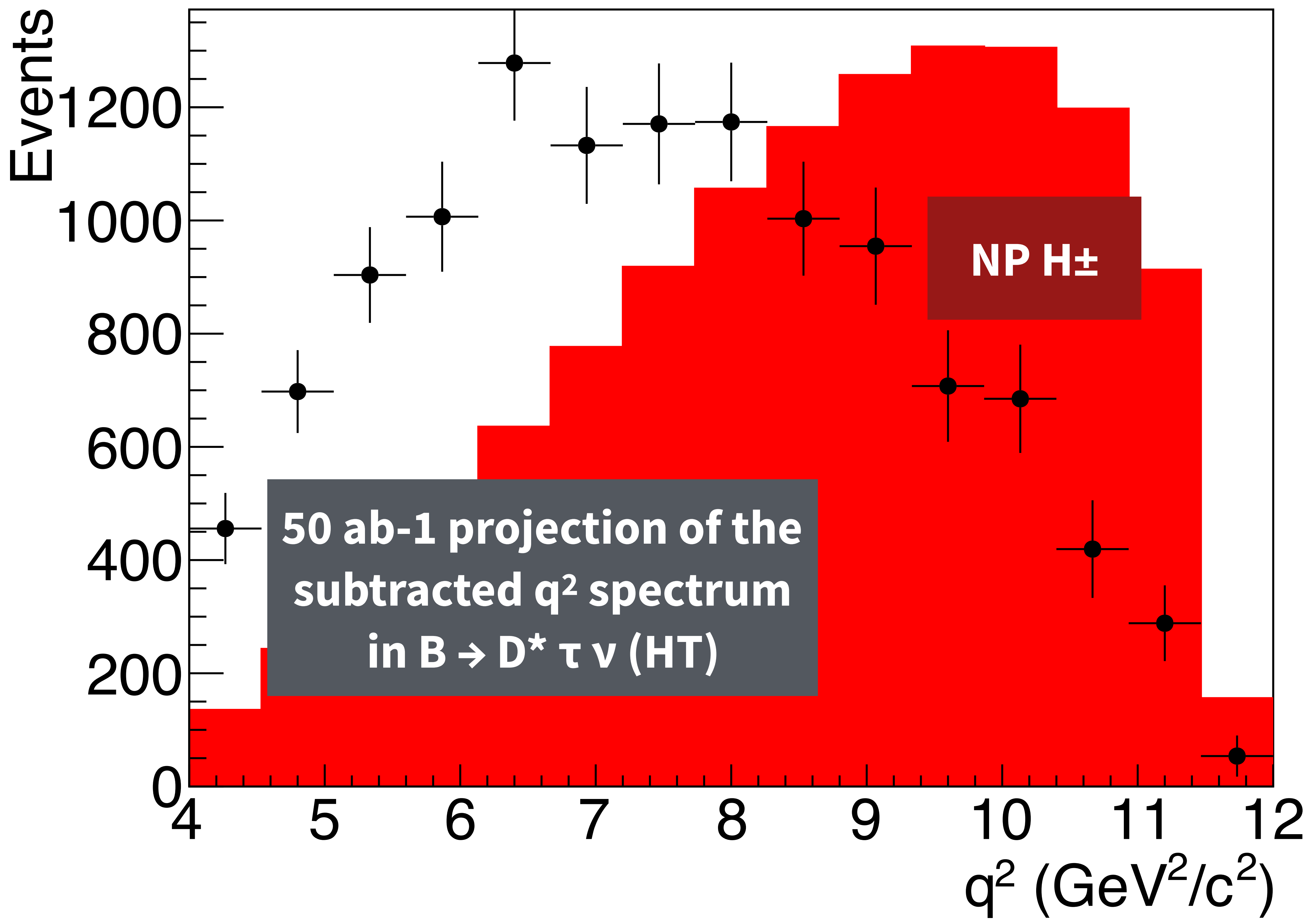

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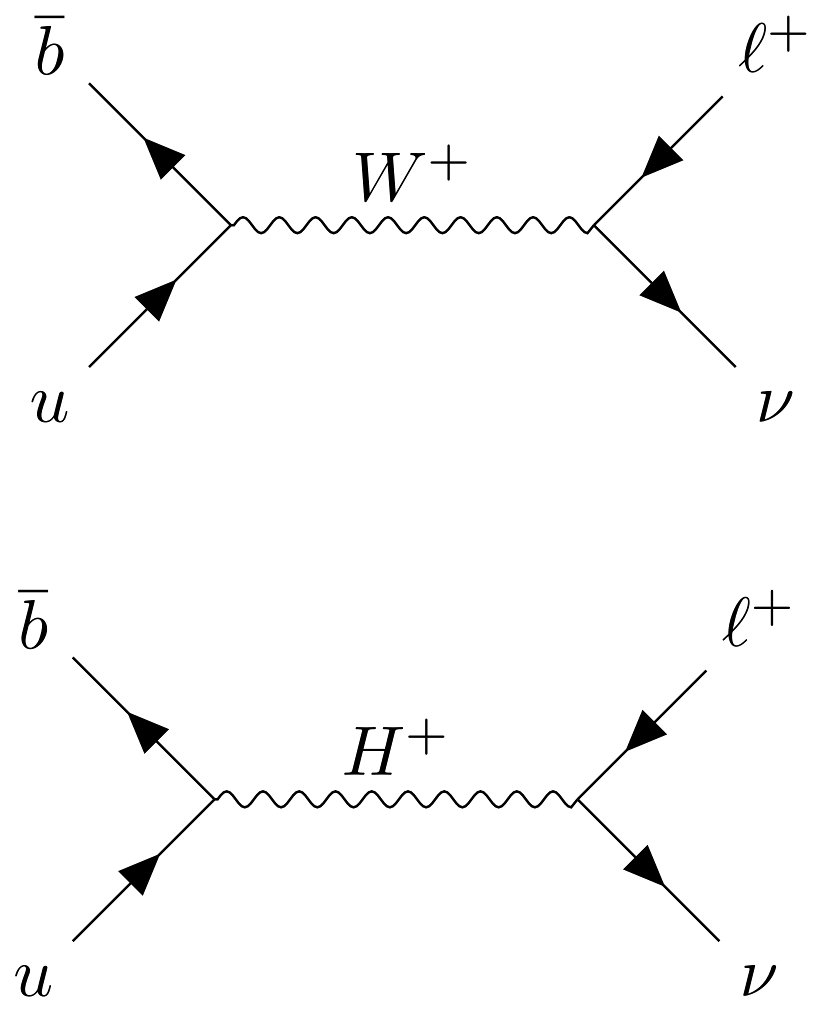
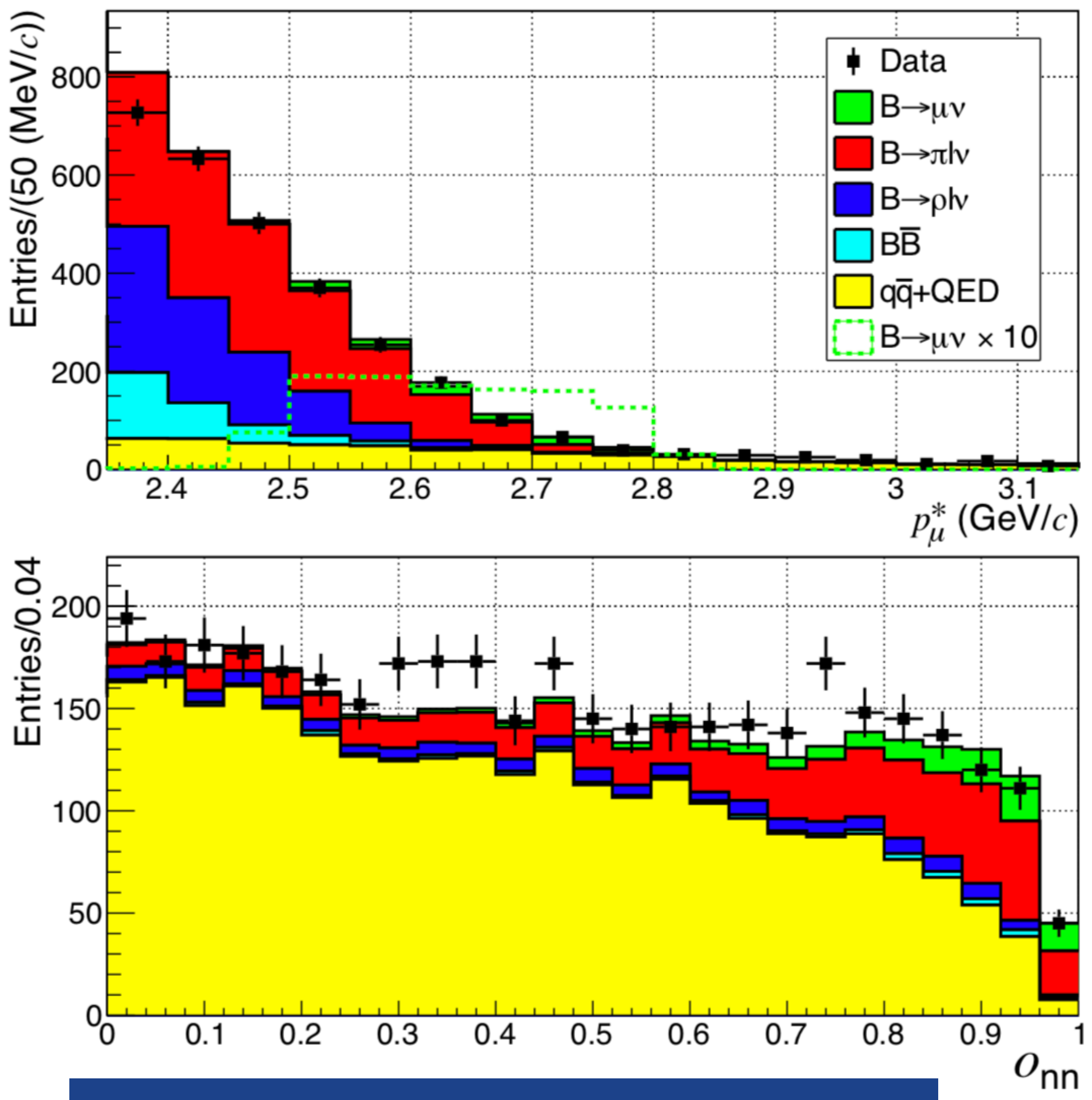
$|V_{ub}|$ and B→lν

- $|V_{ub}|$ only measured to about 10% accuracy → 1% at Belle II.
- 5 σ discoveries of B→ τ ν and B→ μ ν expected with < 5 ab^{-1}.

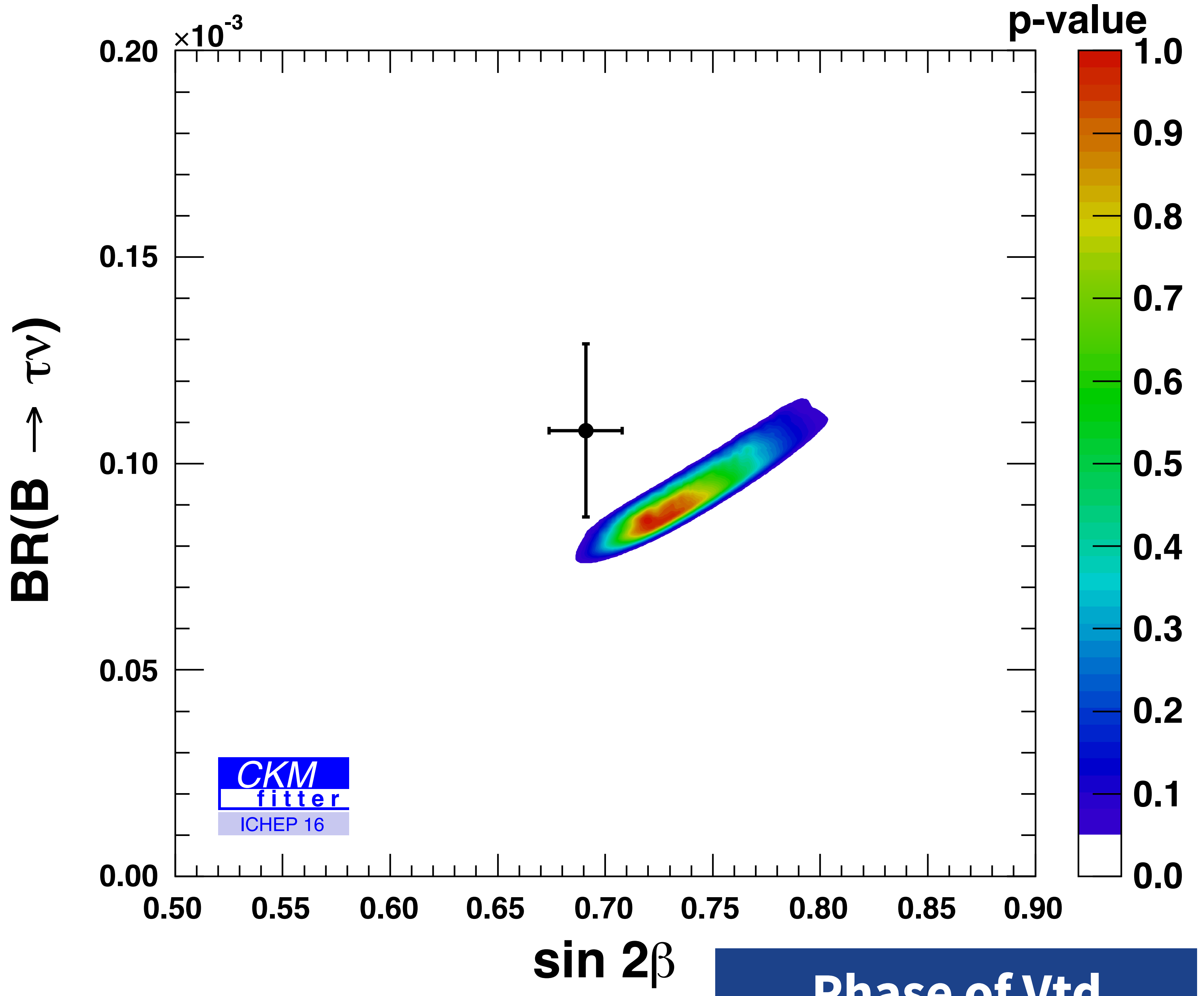


E. Kou, PU et al. arXiv: 1808.10567

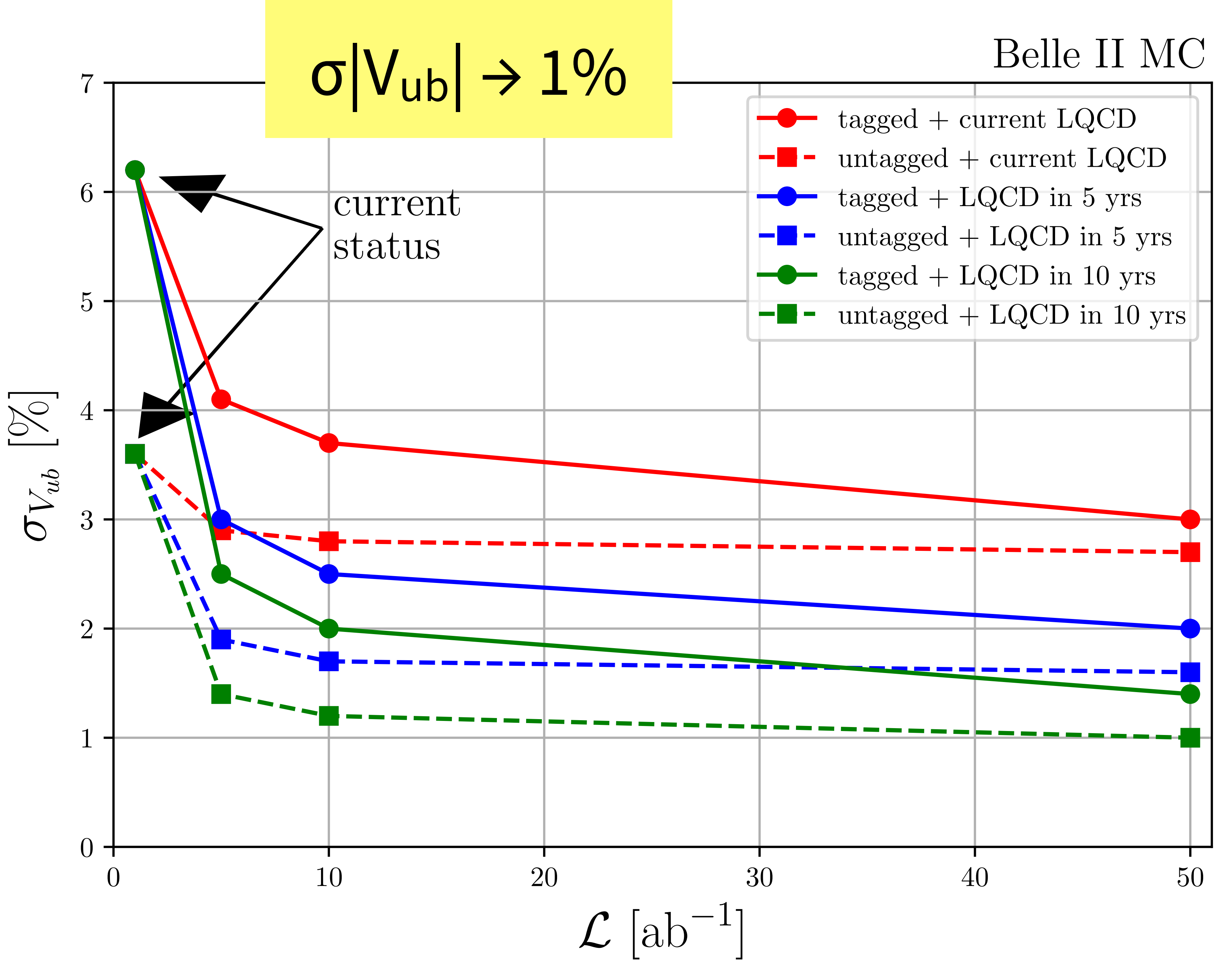
L [ab^{-1}]		σ $|V_{ub}|$ [%]
50	B→ π l ν	1.2
	B→ τ ν	1.5 - 2
	B→ μ ν	5



Belle arXiv: 1712.04123
$B(B\to \mu \nu)=(6.5\pm2.2\pm1.6)10^{-7}$



Phase of Vtd



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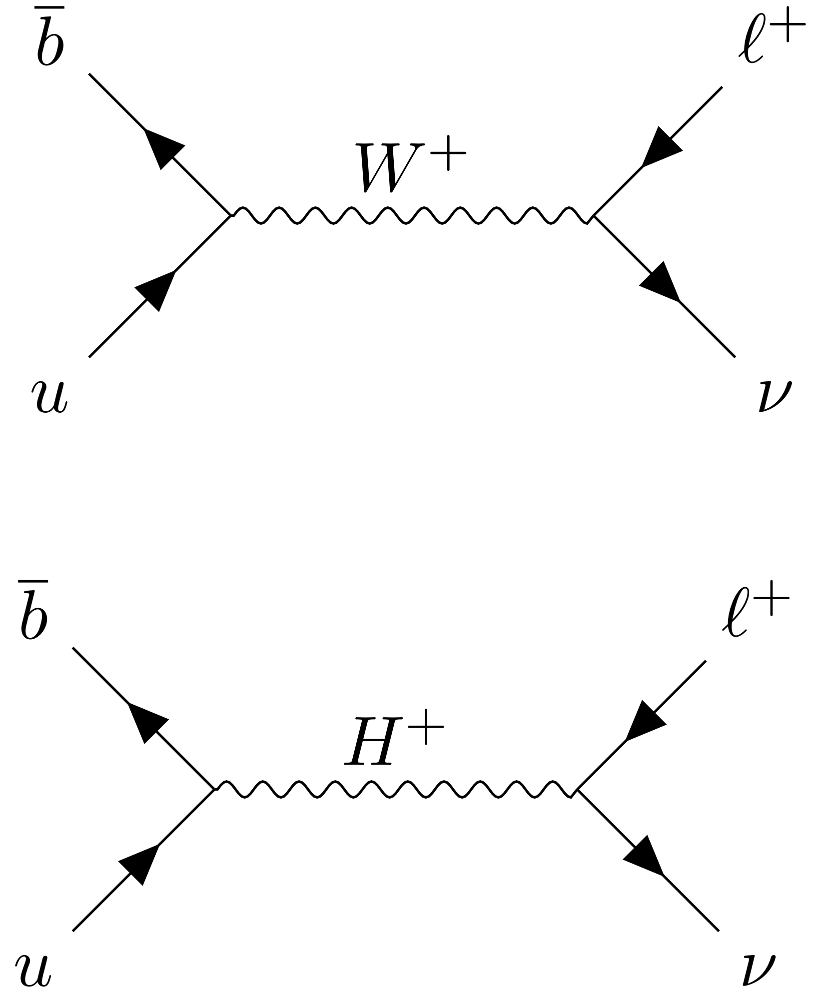

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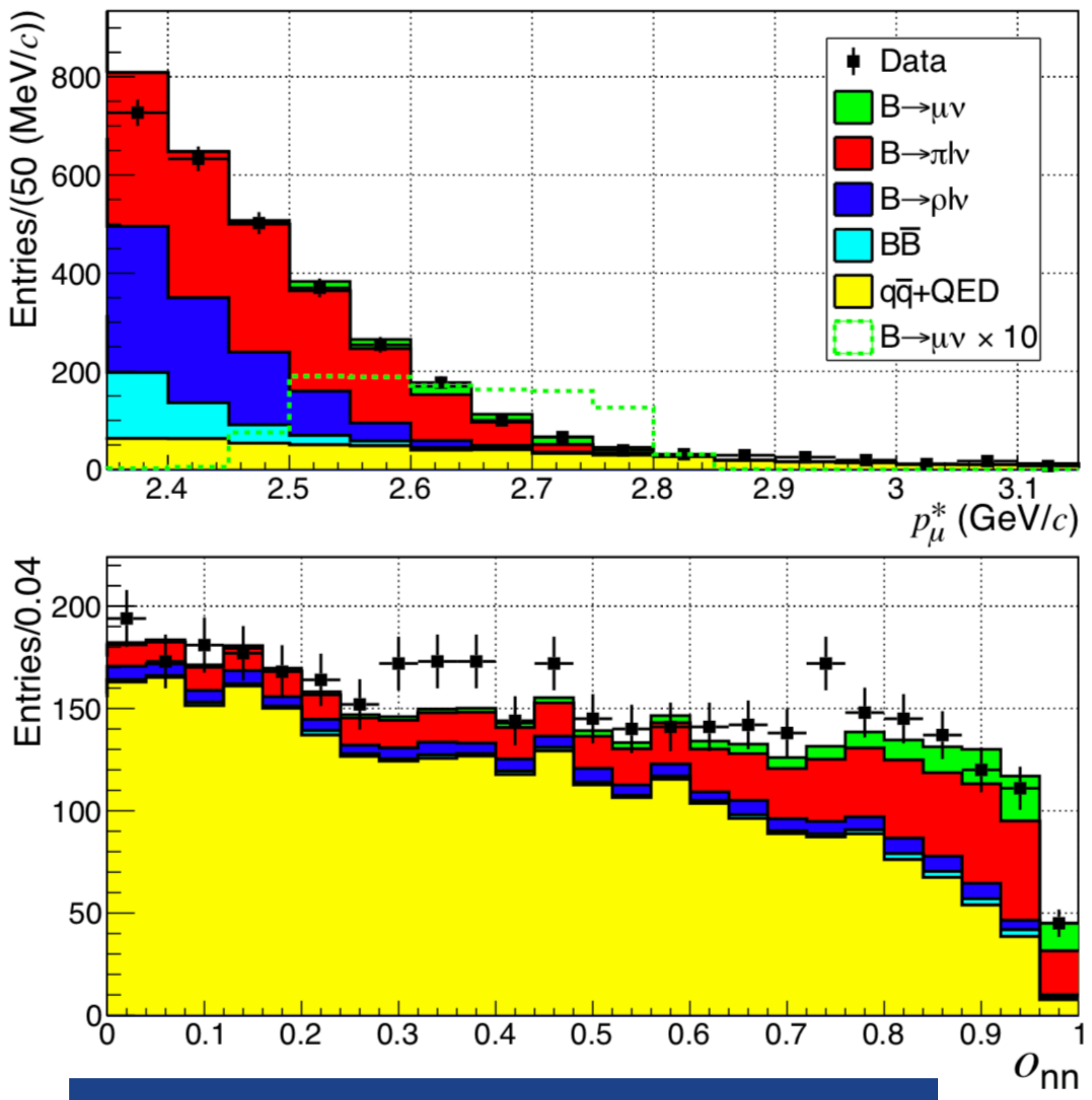

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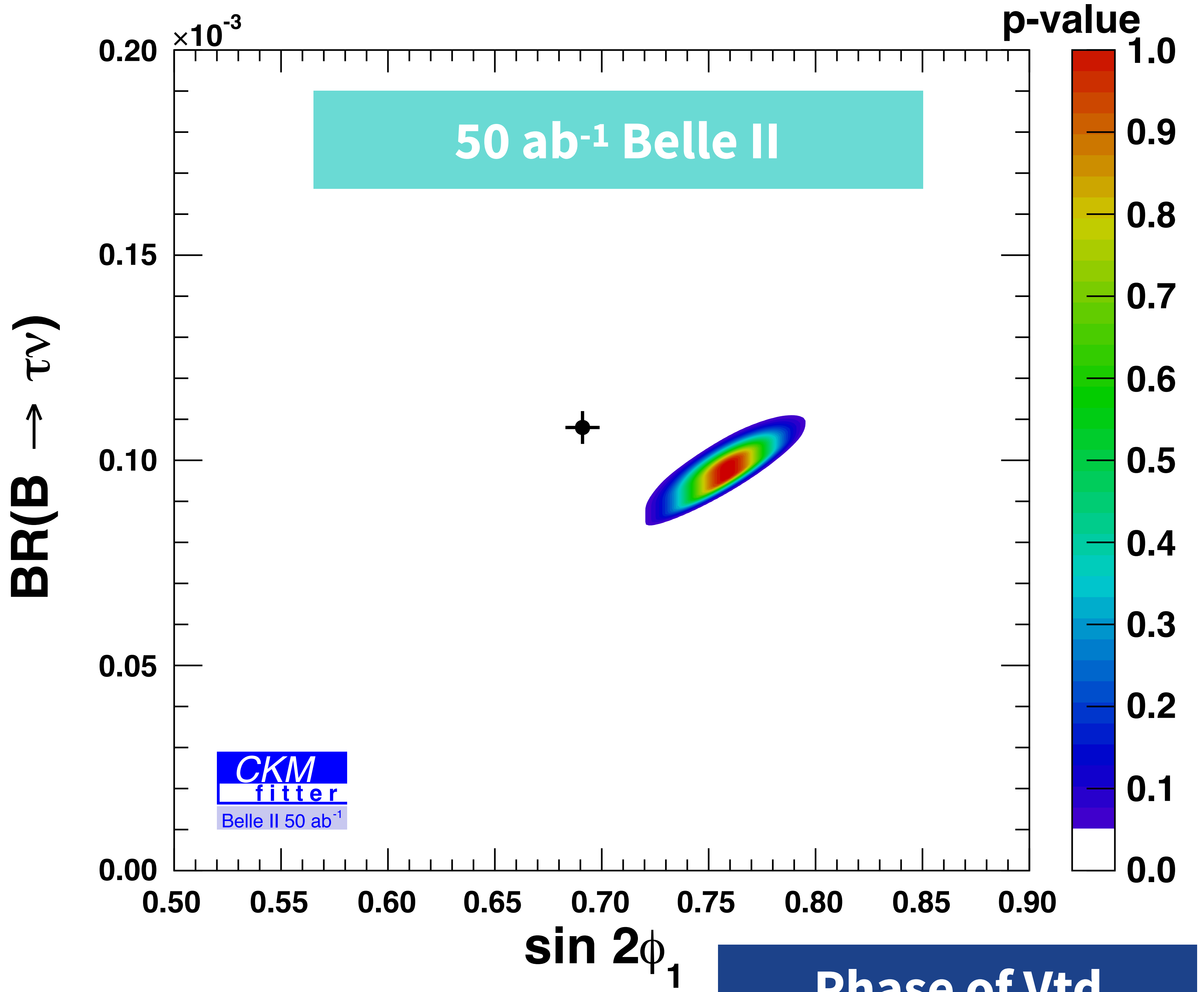
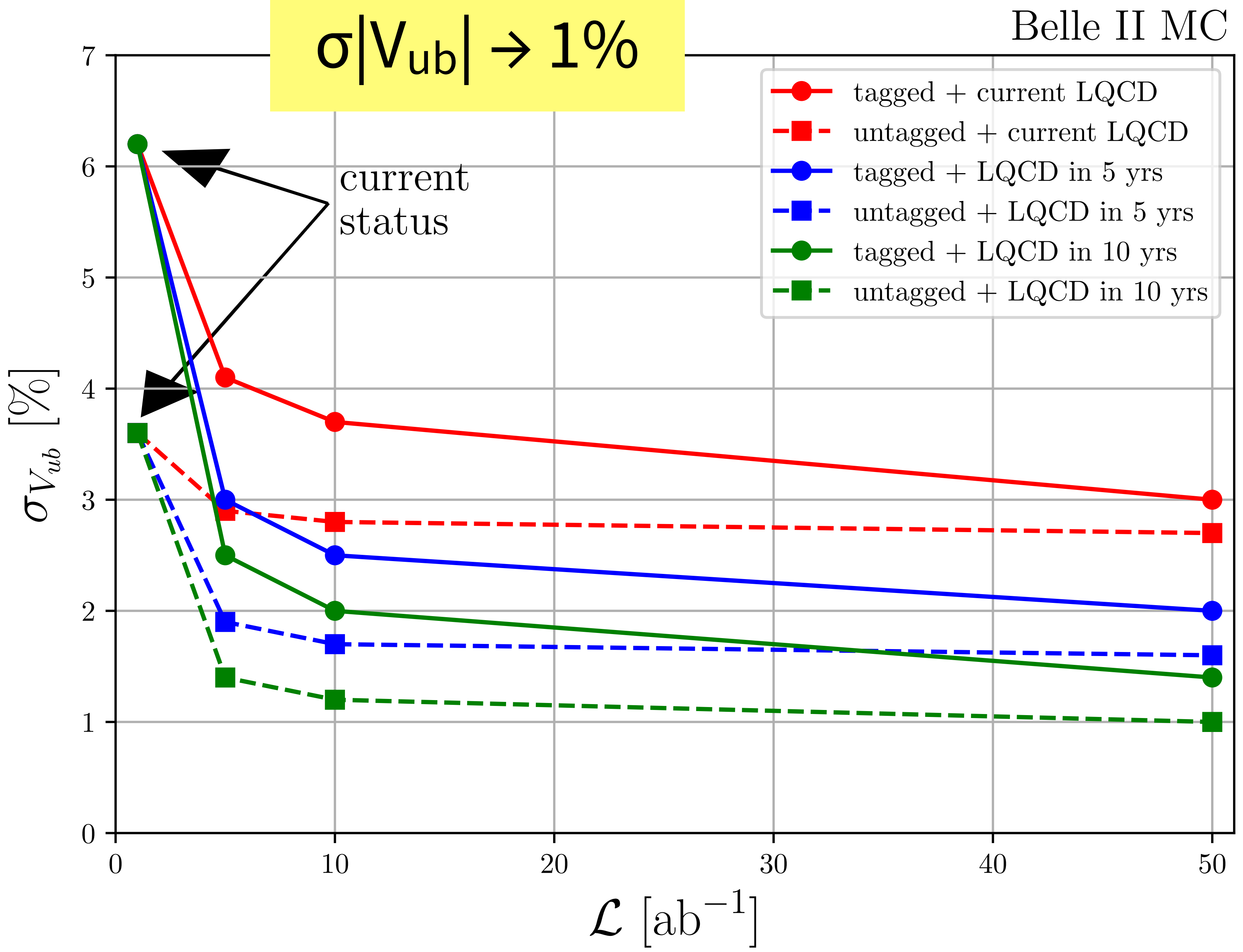
B(B→ μ ν)=(6.5±2.2±1.6)10^{-7}



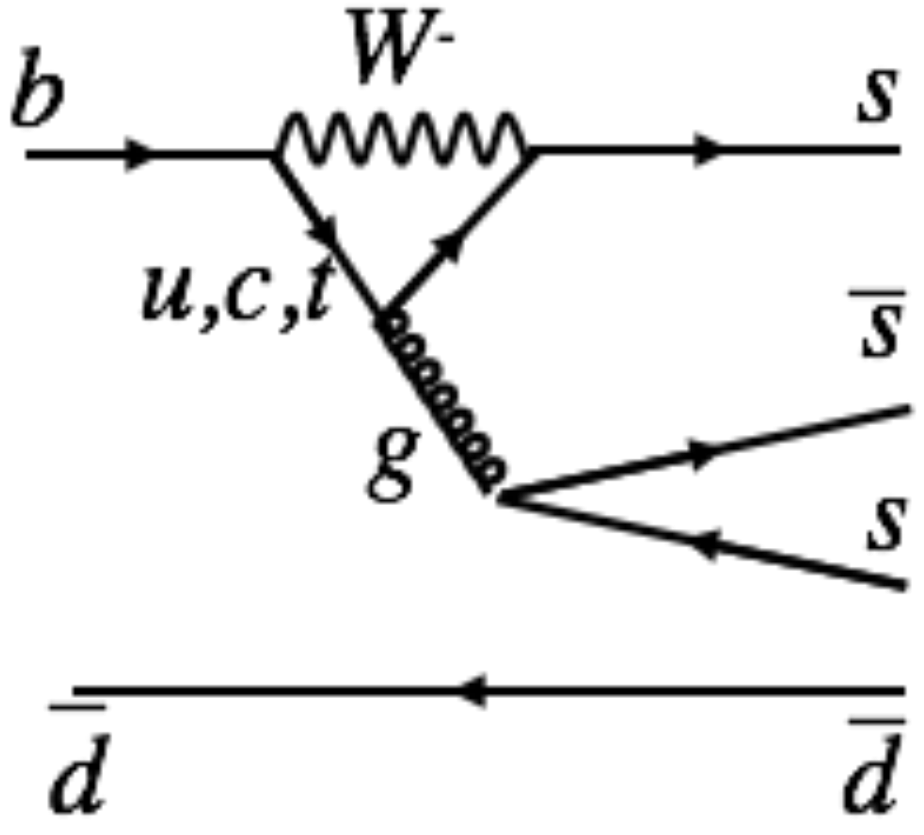
Phase of Vtd

σ|V_{ub}| → 1%

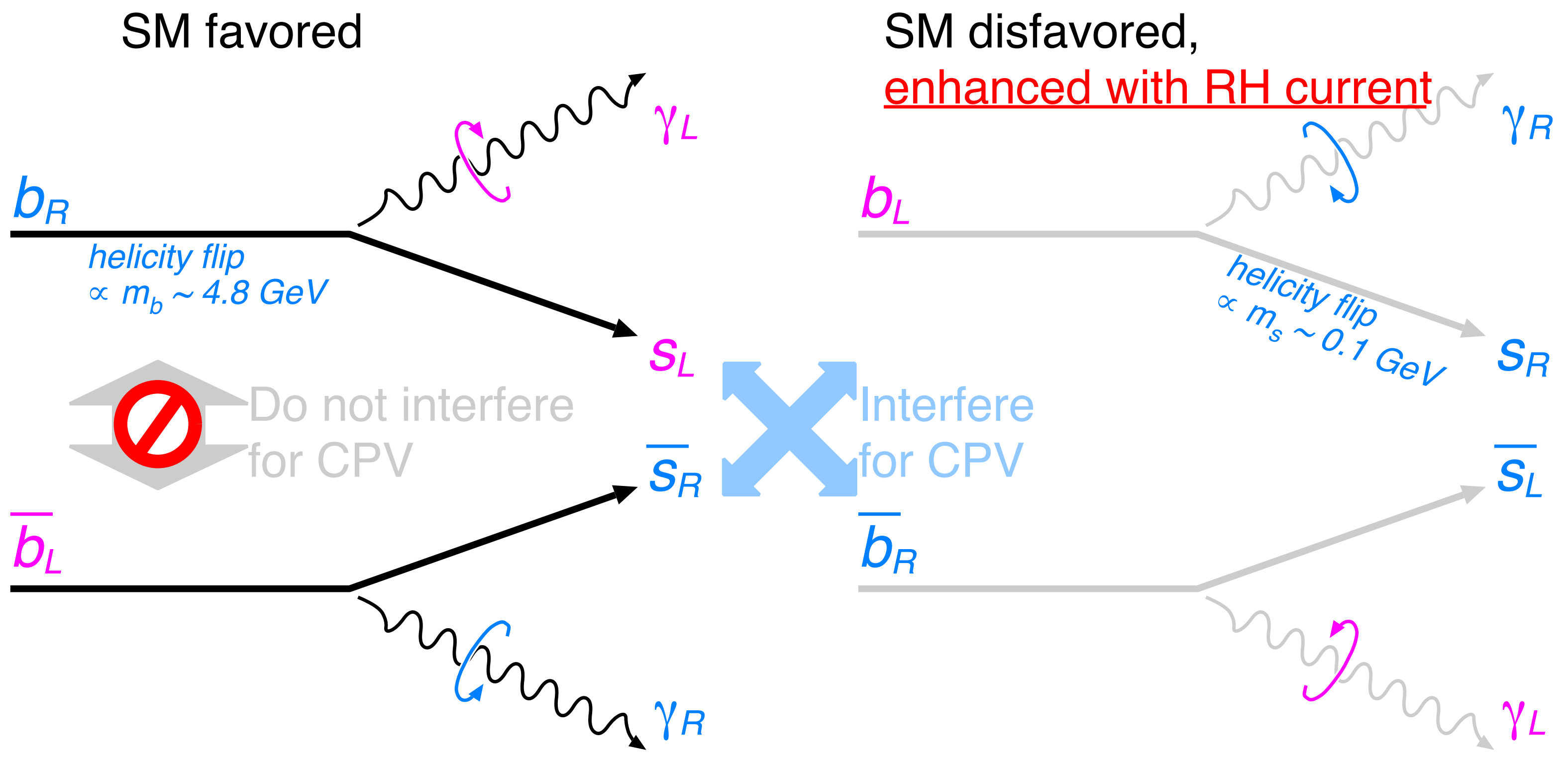


CP Violation

- **Φ_1 @ 0.7%, Φ_2 <1°, Φ_3~1°**
- Search for new phases in b→s gluon and EW penguins
- TDCP Violation flavour tagging at Belle II ~ 35%

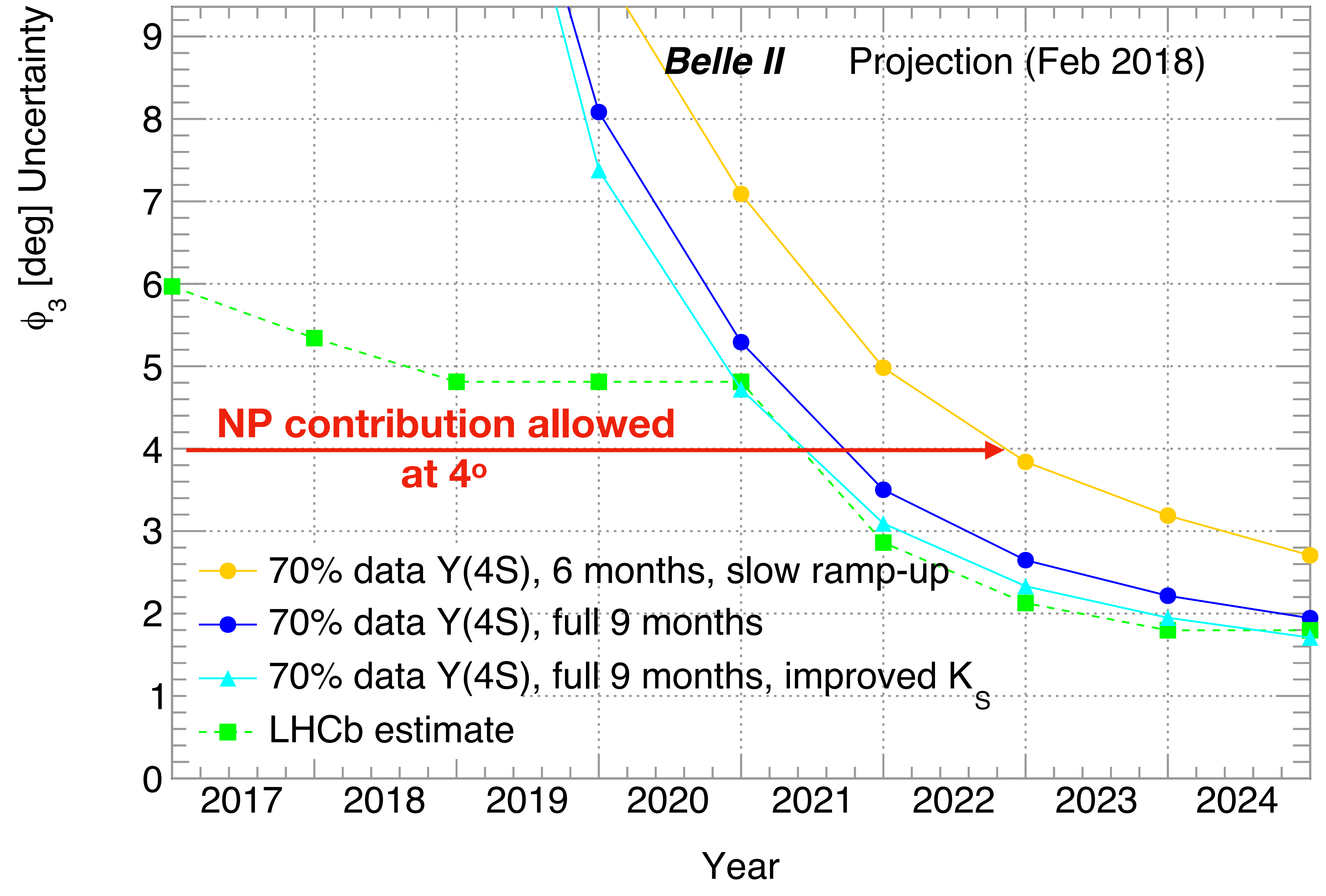


- *Gluonic Penguin (NP sensitive)*

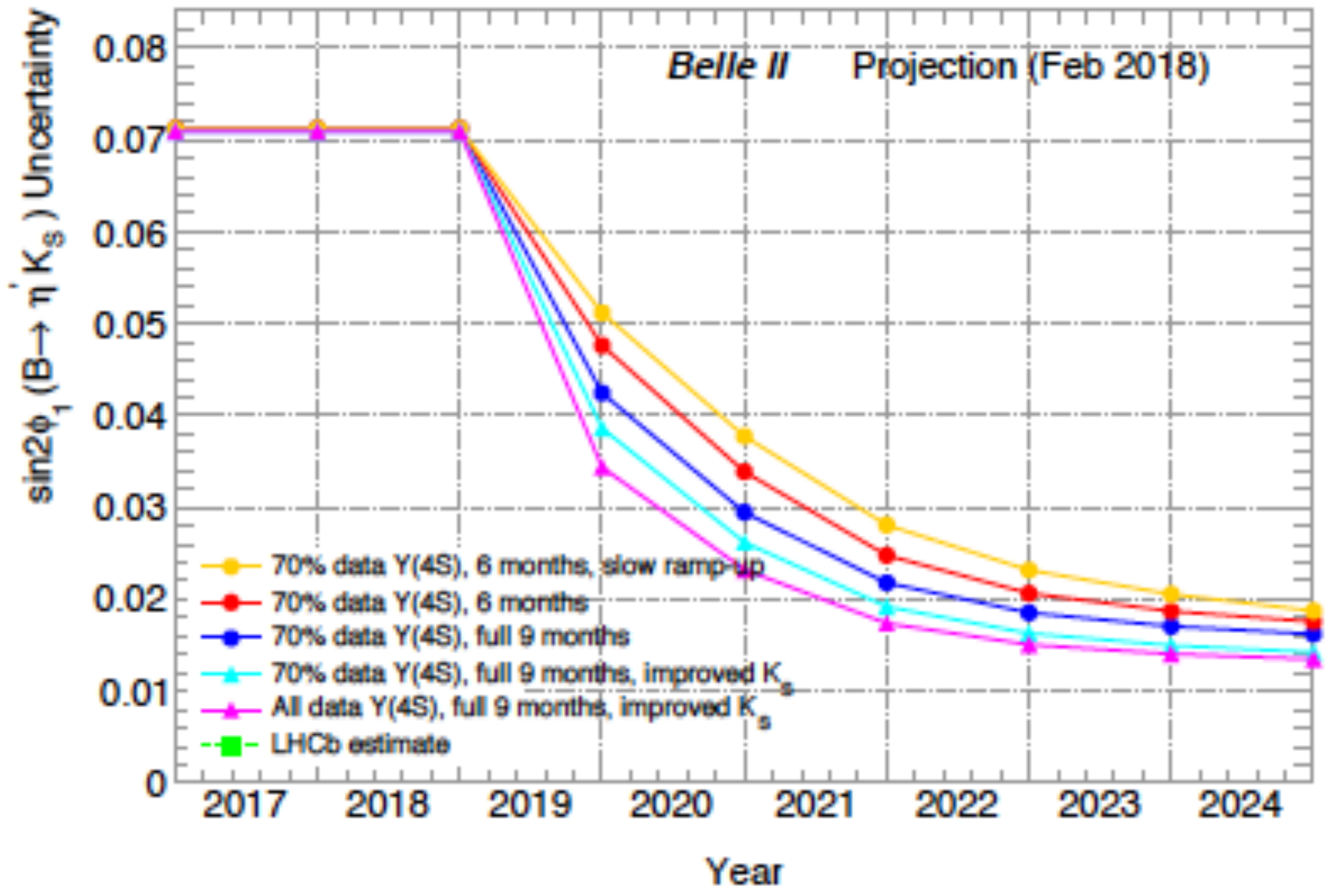


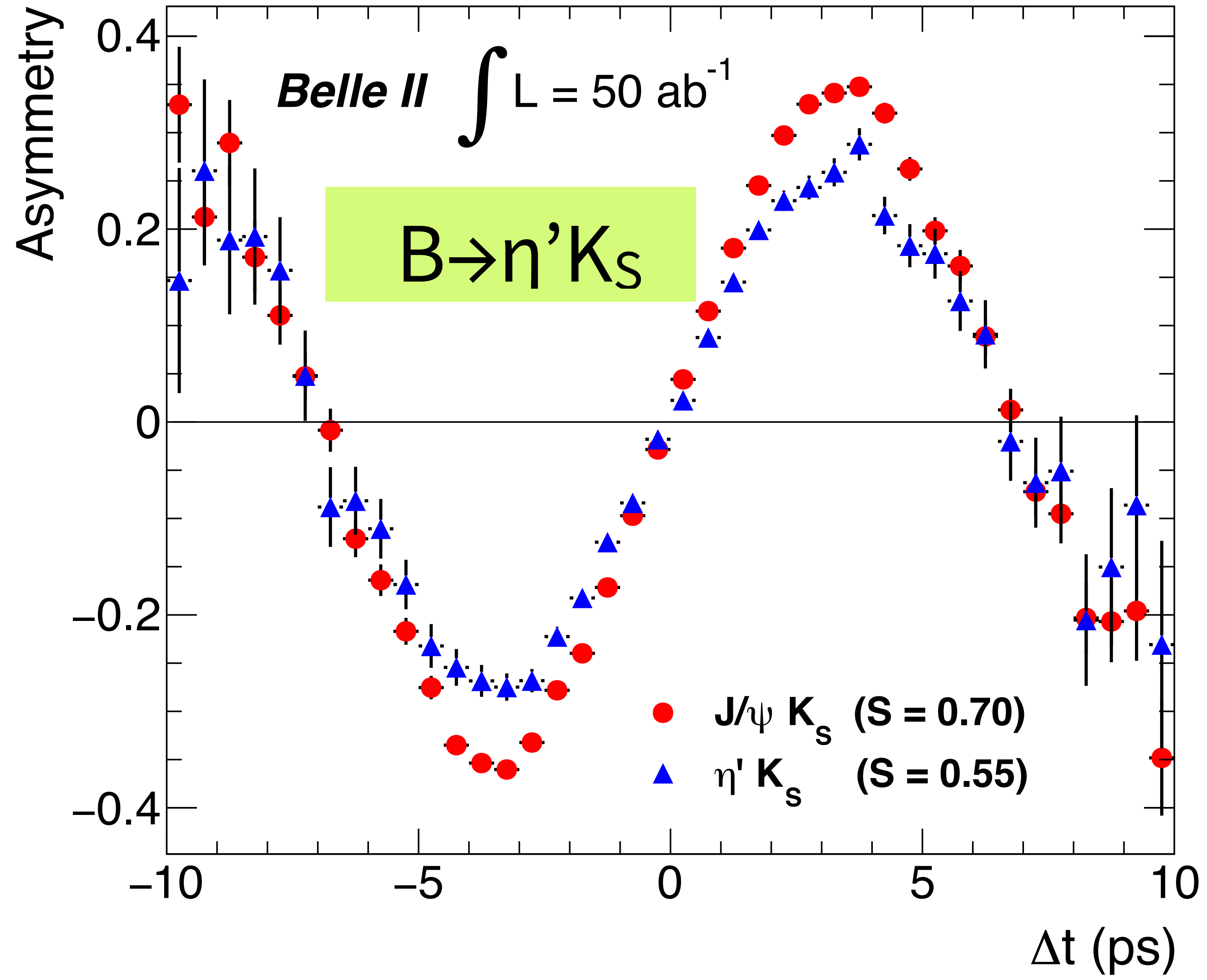
- *EW Radiative Penguin (NP sensitive)*

(phase of V_{ub}) - B→$D^{(*)}K^{(*)}$



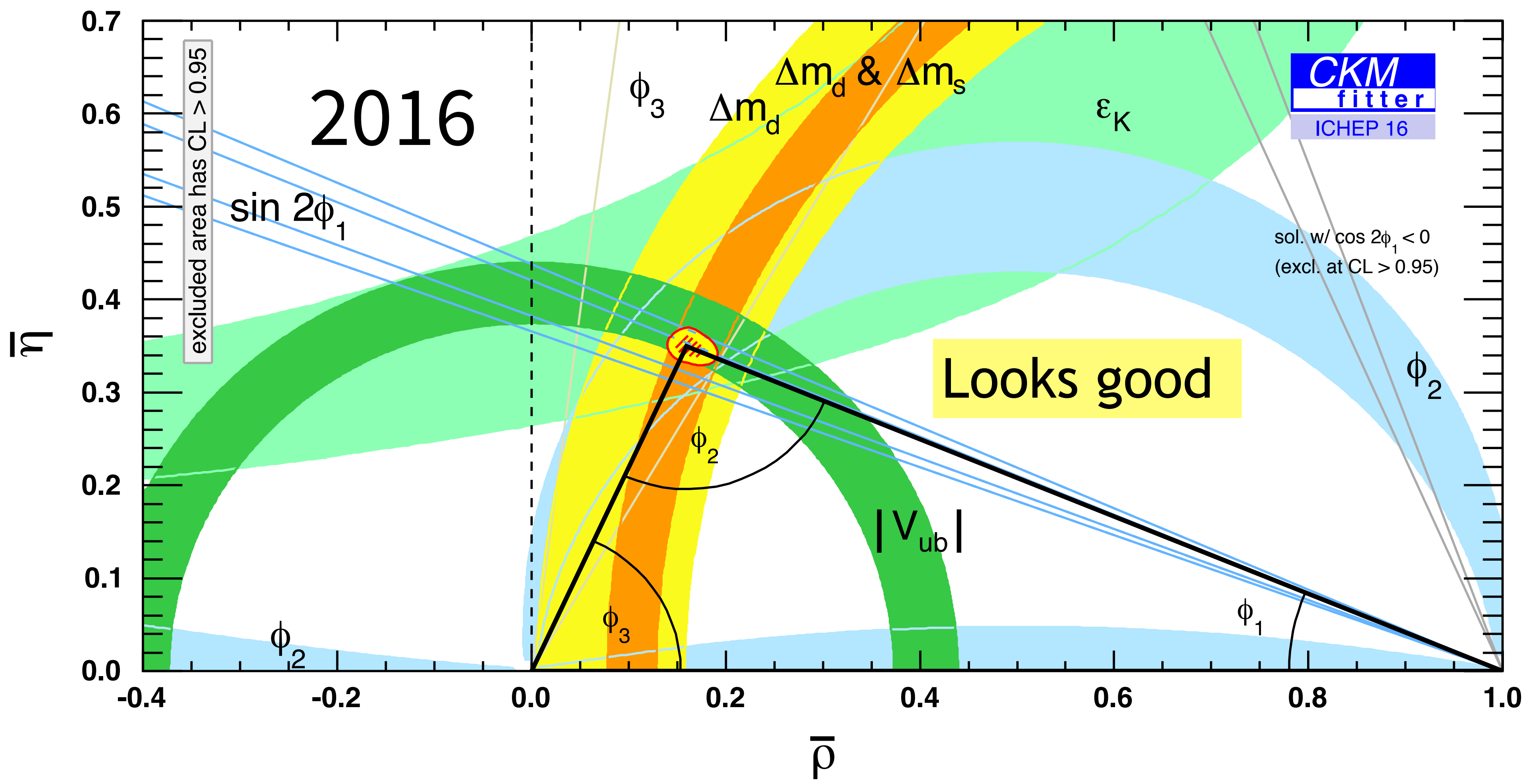
(phase of V_{ub}) - B→$D^{(*)}K^{(*)}$





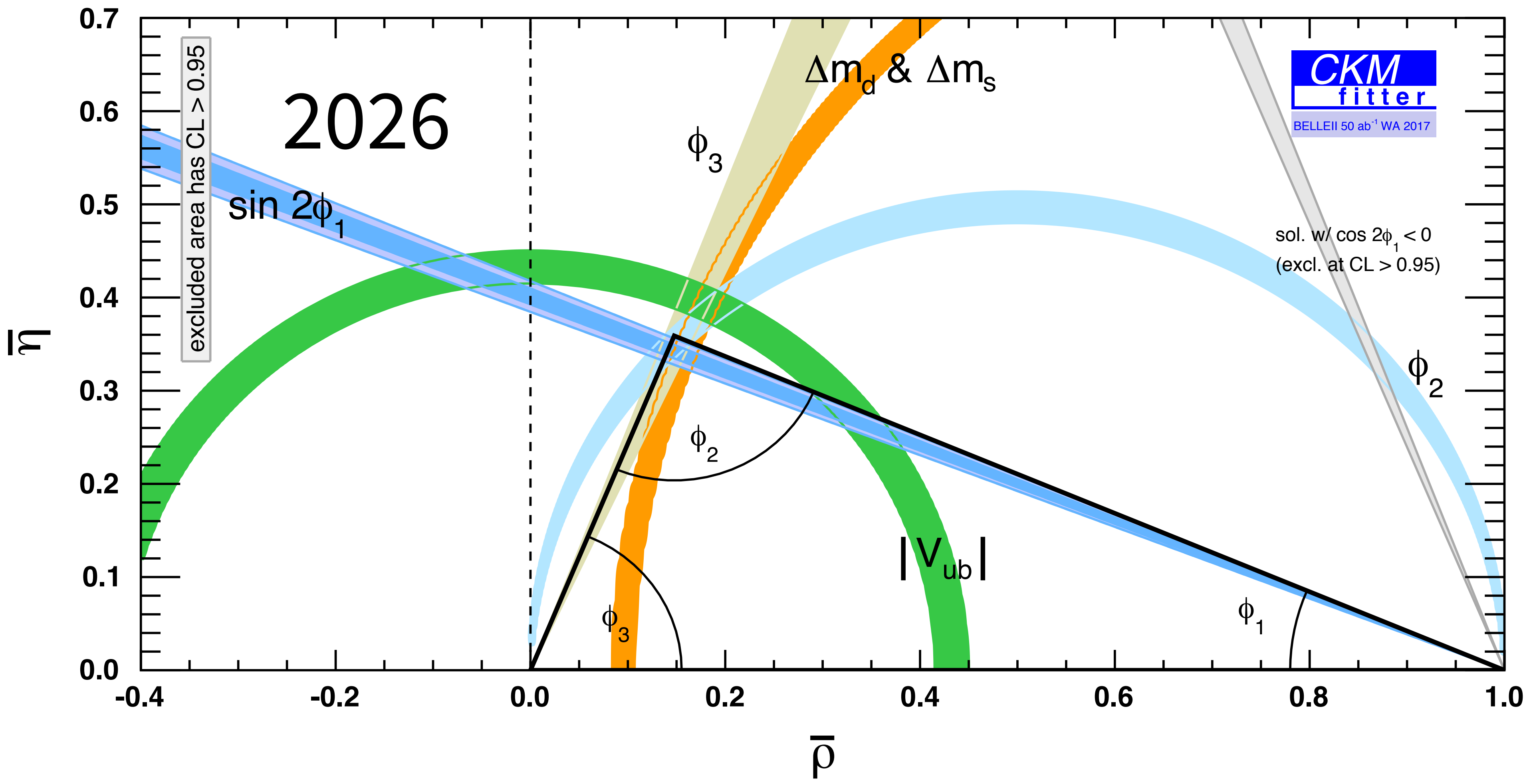
CKM Global Fit Projection: Belle II

E. Kou, PU et al. arXiv: 1808.10567



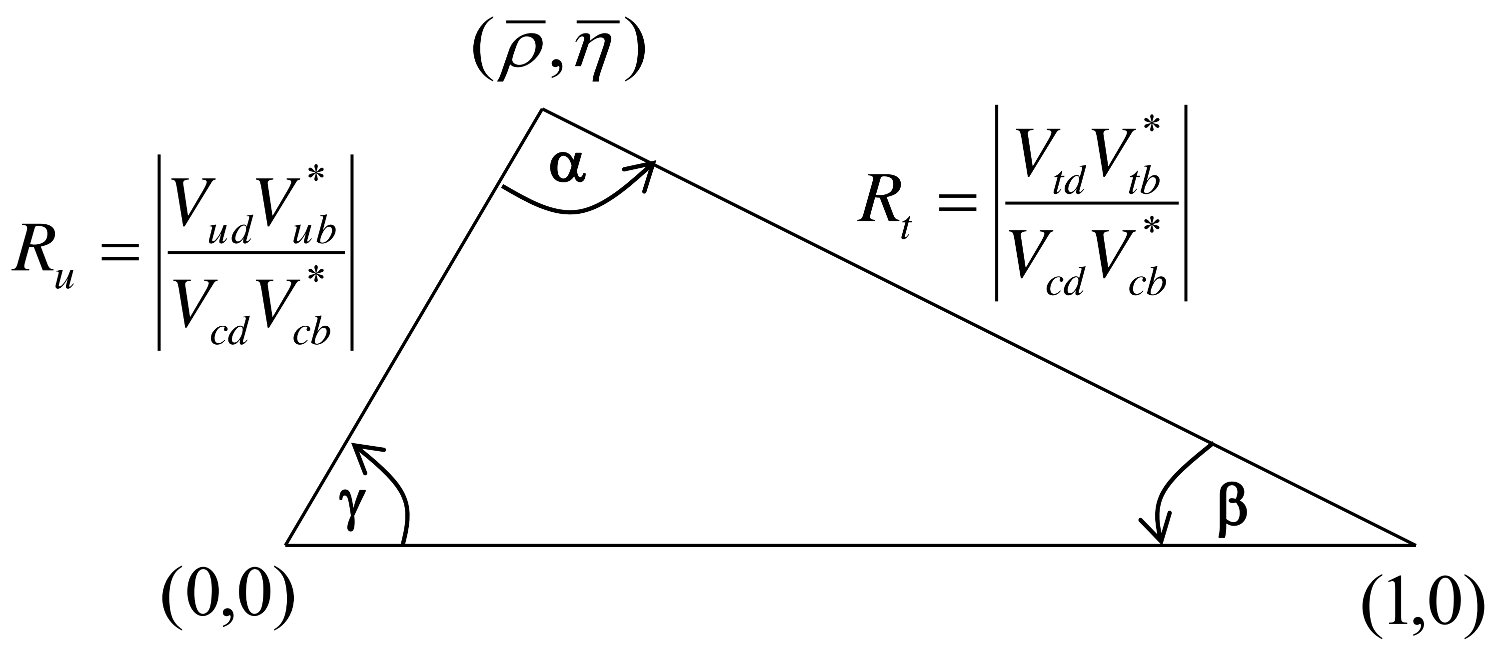
Φ_3 ~ 1-1.5° at LHCb & Belle II

$|V_{ub}|$ ~ 1.2% Belle II

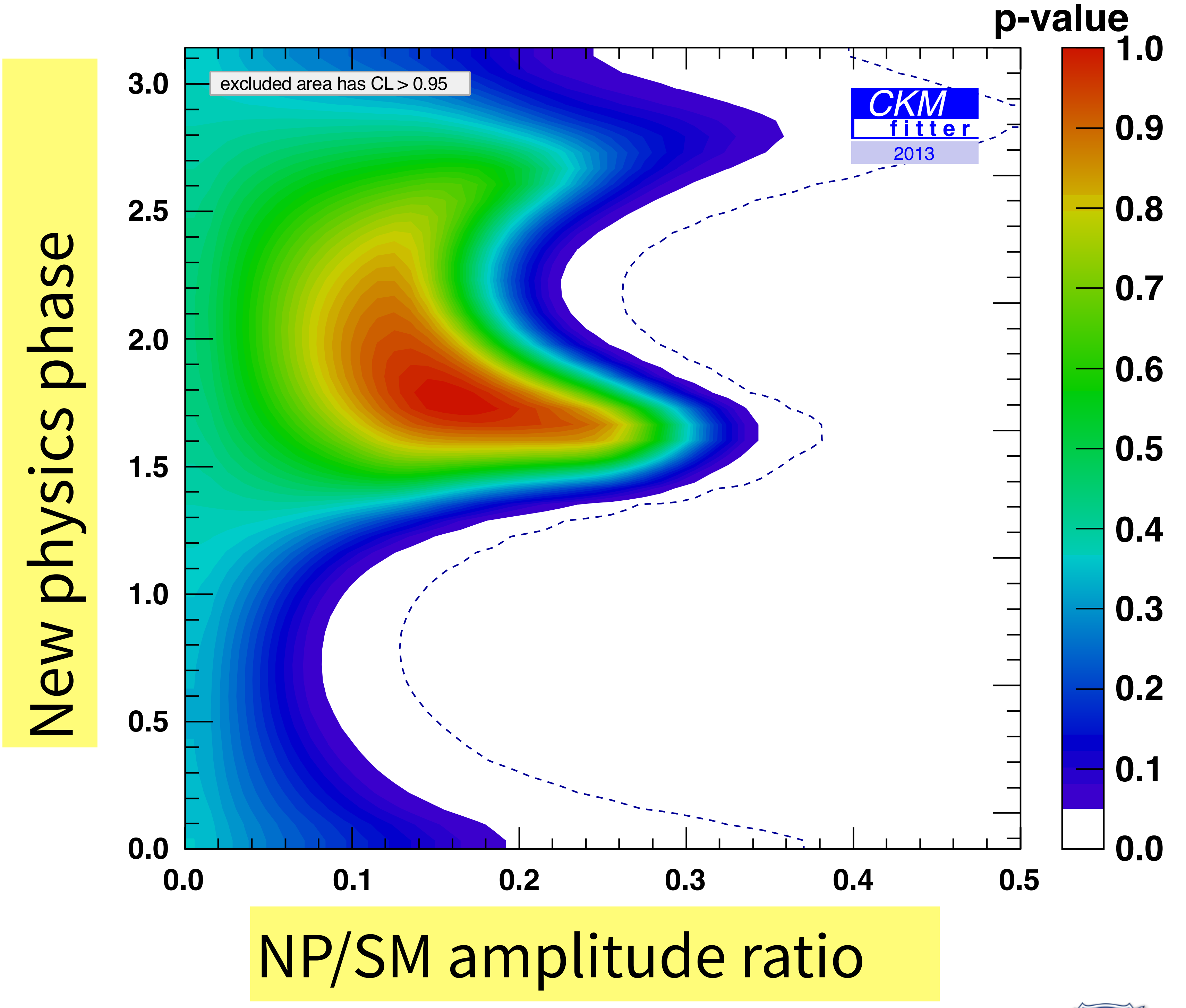


Great progress on φ_3 or γ (first from B factories and now in the last four years from LHCb). *These measure the phase of V_{ub}*

$$V_{\rm CKM} \propto \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|\, e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|\, e^{-i\beta} & -|V_{ts}|\, e^{-i\beta_s} & |V_{tb}| \end{pmatrix}$$

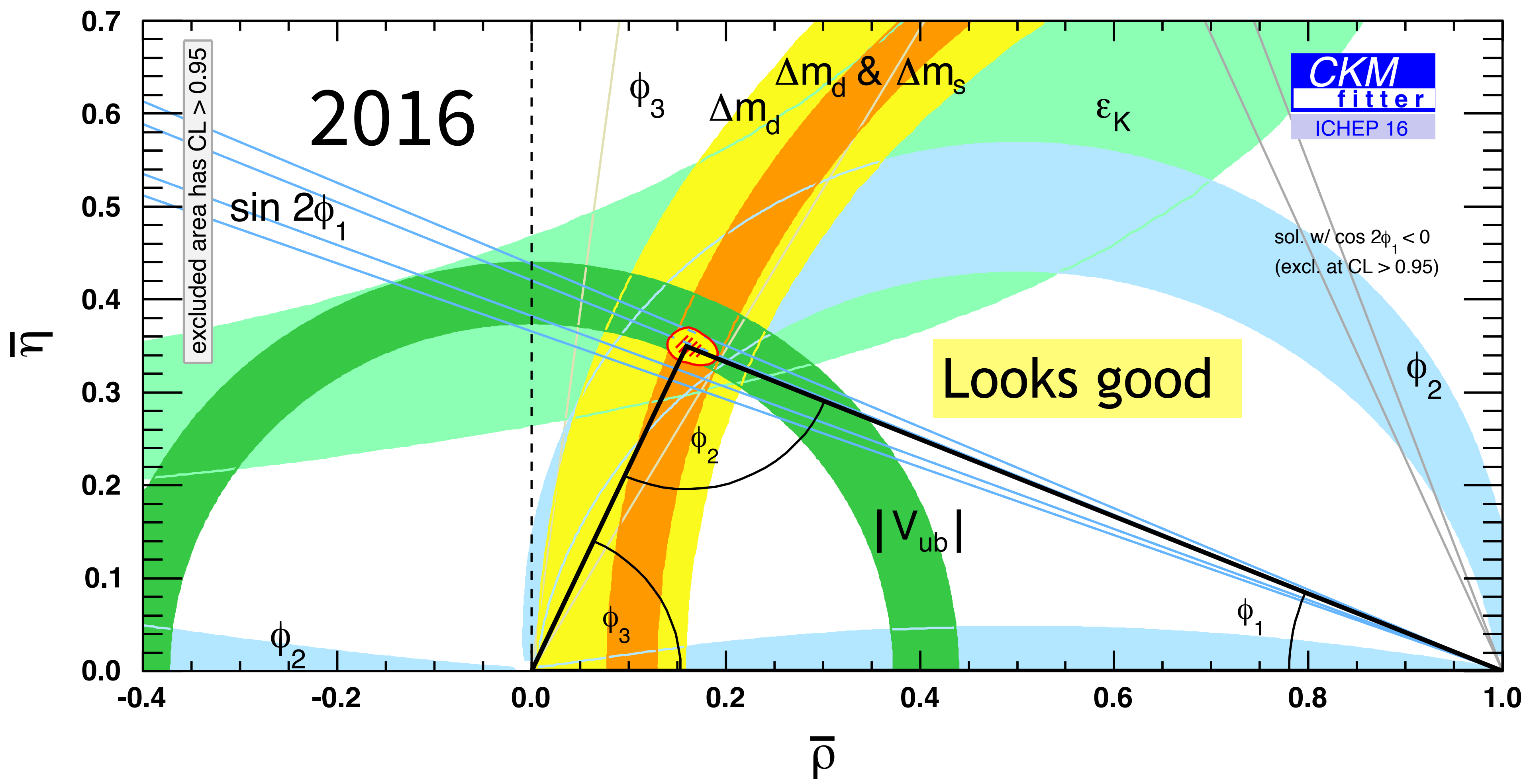


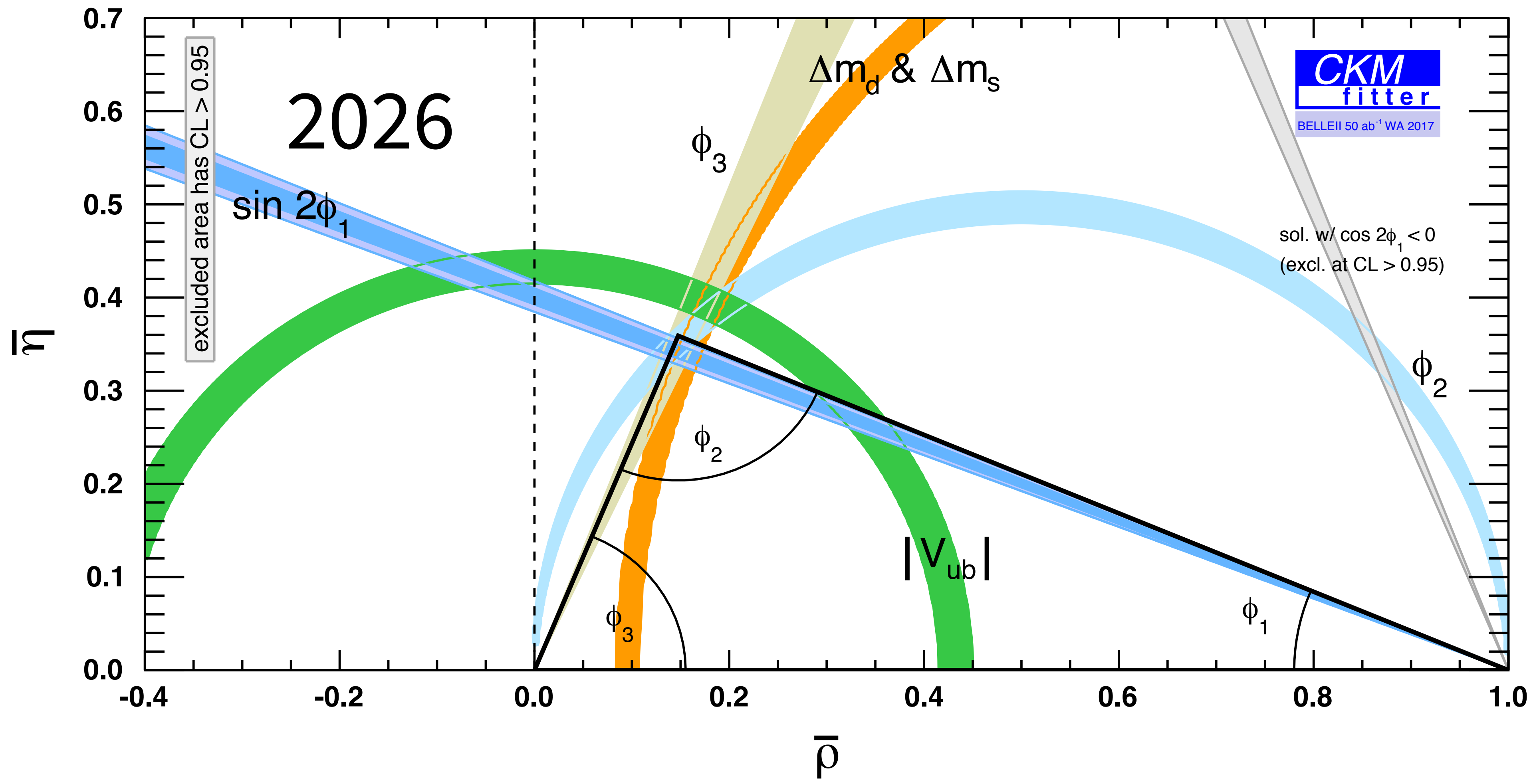
But a 10-20% NP amplitude in B_d mixing is perfectly compatible with all current data.



CKM Global Fit Projection: Belle II

E. Kou, PU et al. arXiv: 1808.10567



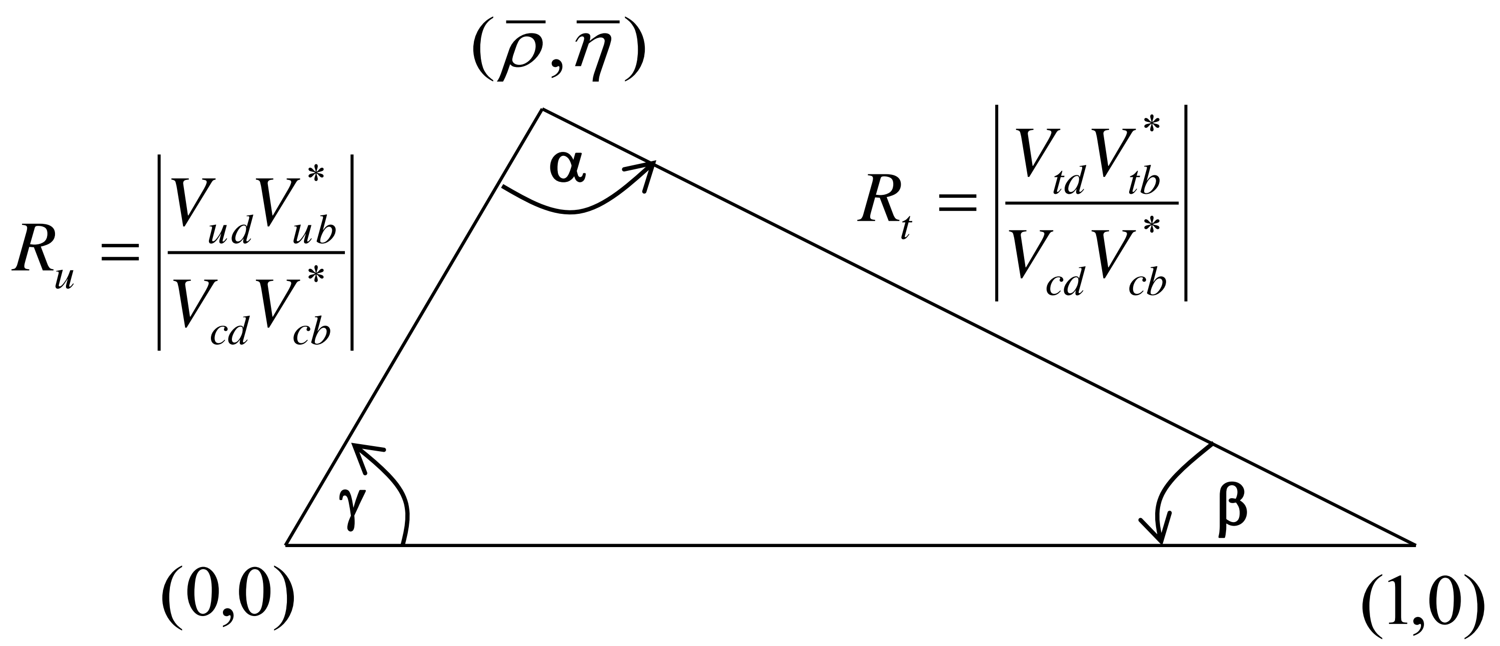


Φ_3 ~ 1-1.5º at LHCb & Belle II

$|V_{ub}|$ ~ 1.2% Belle II

Great progress on φ_3 or γ (first from B factories and now in the last four years from LHCb). *These measure the phase of V_{ub}*

$$V_{\mathrm{CKM}} \propto \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|\, e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|\, e^{-i\beta} & -|V_{ts}|\, e^{-i\beta_s} & |V_{tb}| \end{pmatrix}$$



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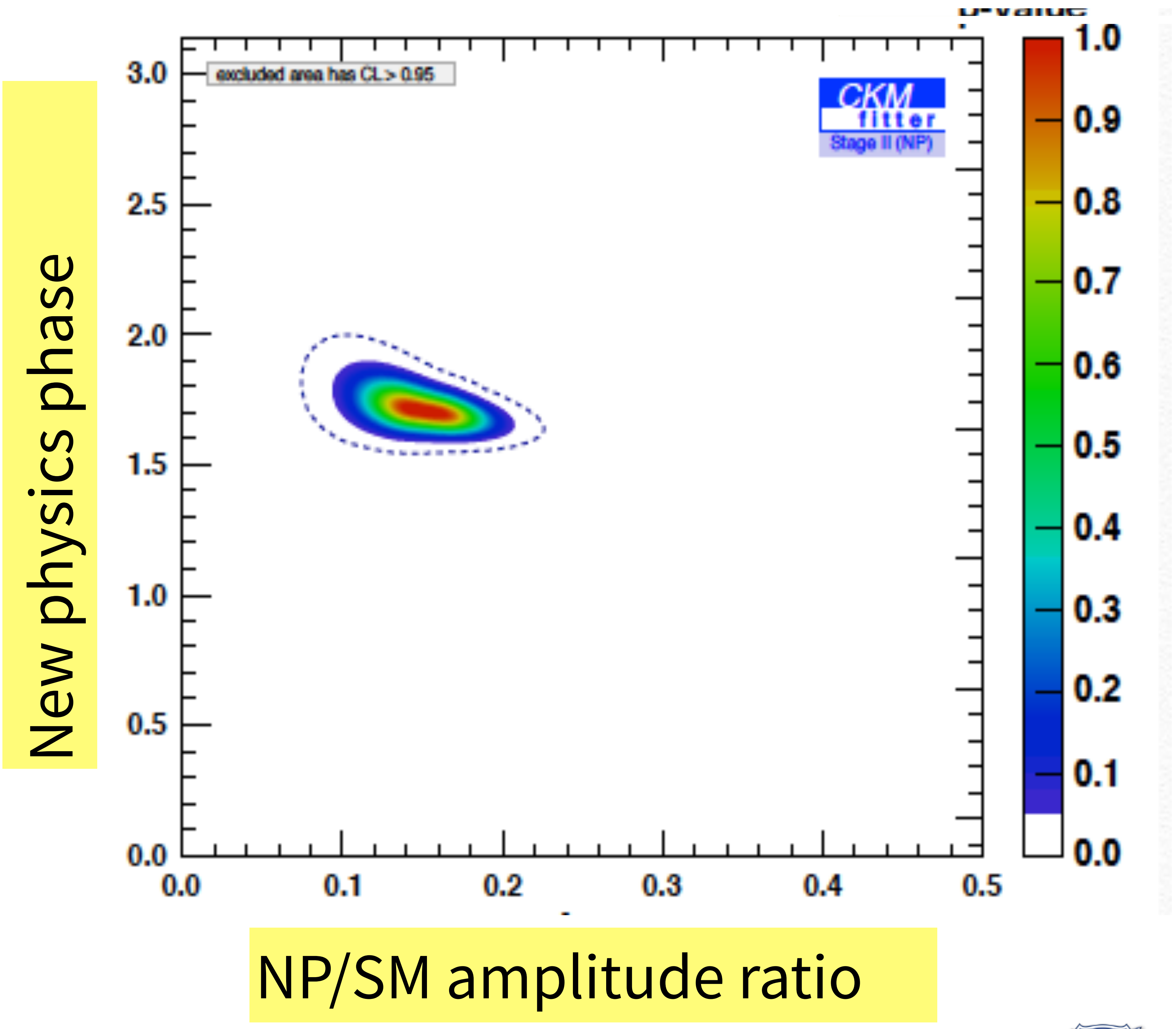


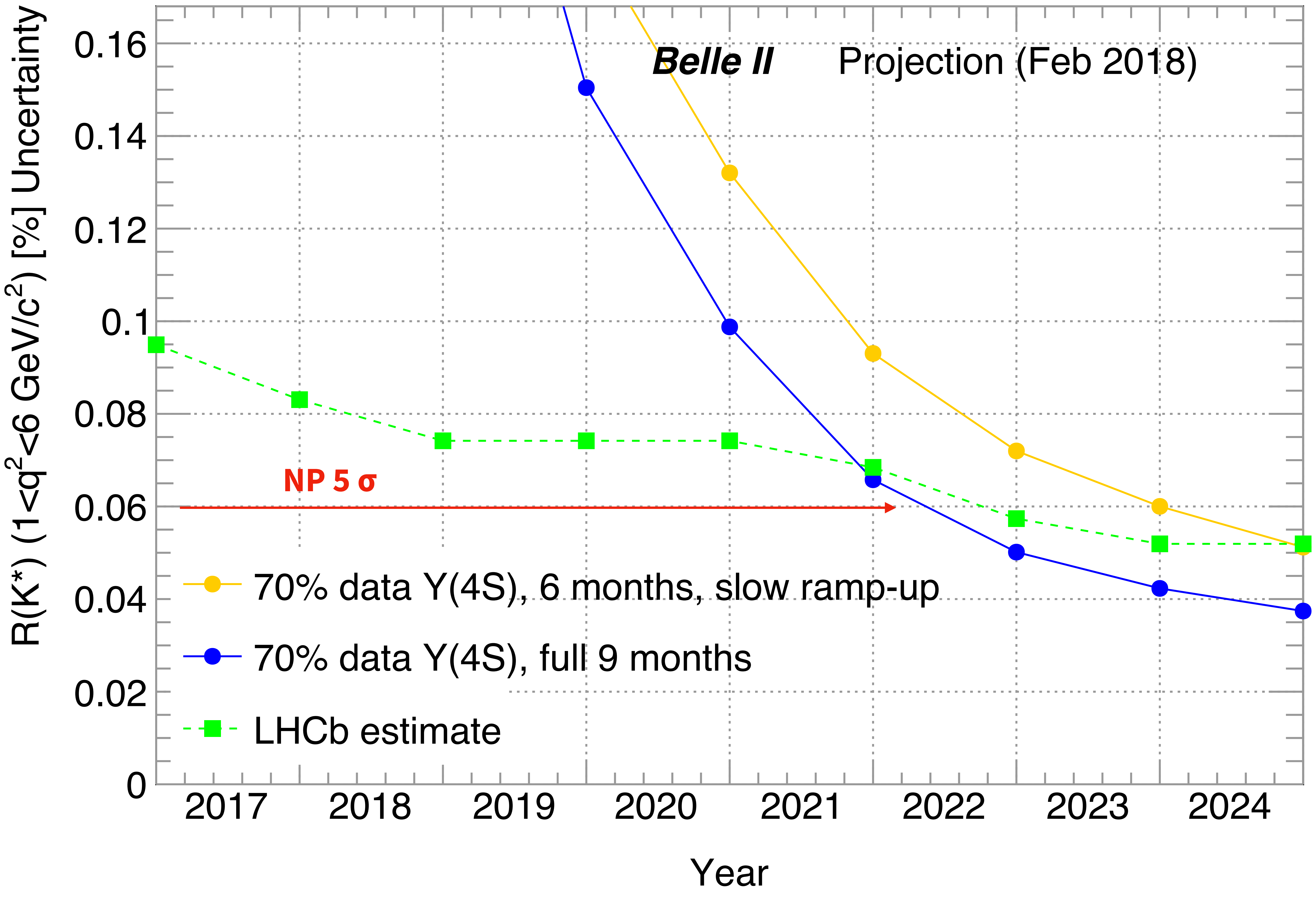
The RACE for R(K*) NP discovery

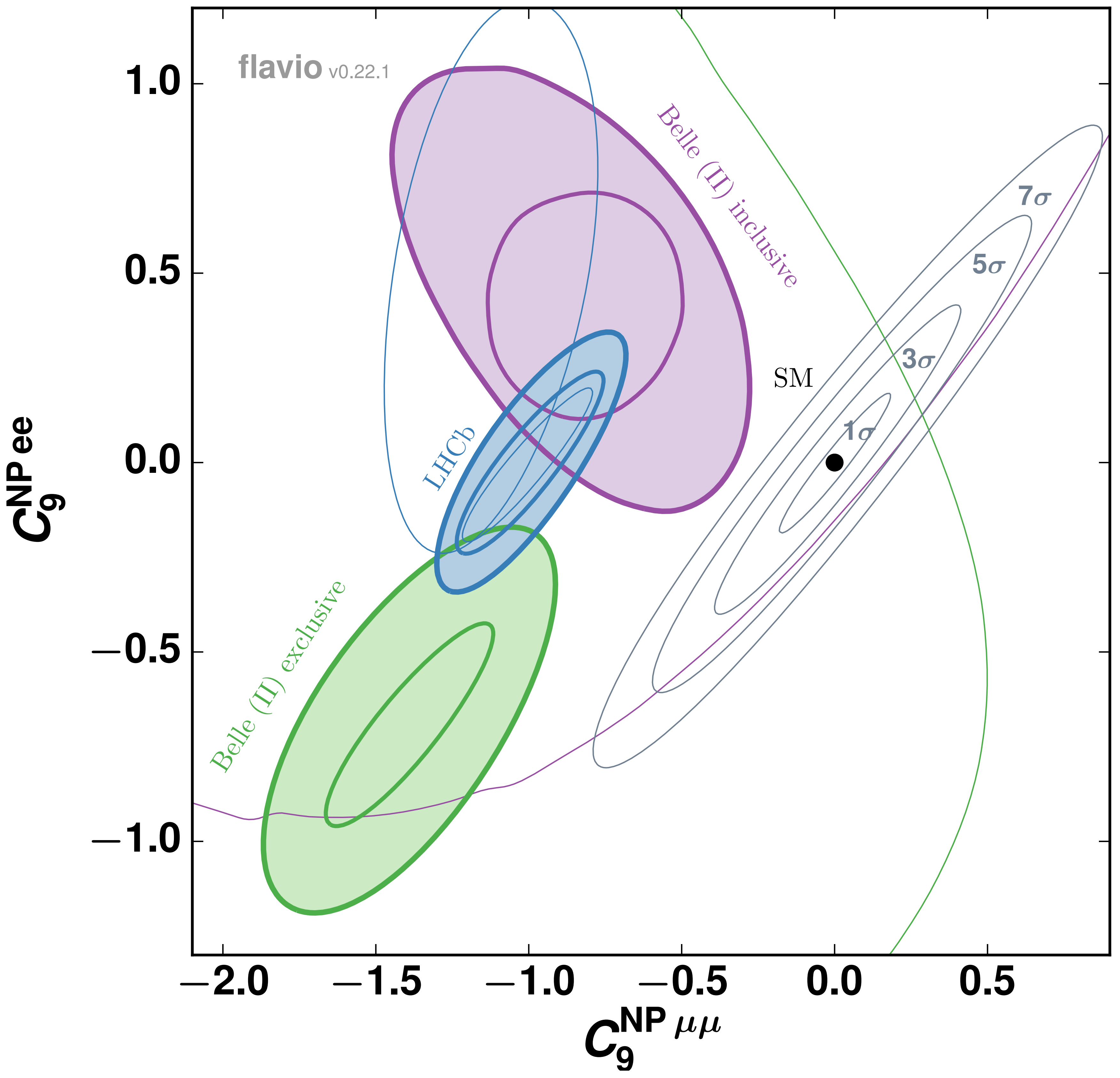
Belle PRL. 118 (2017) no.11, 111801
E. Kou, PU et al. arXiv: 1808.10567

Belle II can do both <u>inclusive</u> and exclusive.
Equally strong capabilities for electrons and muons (LHCb not as good for e)

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

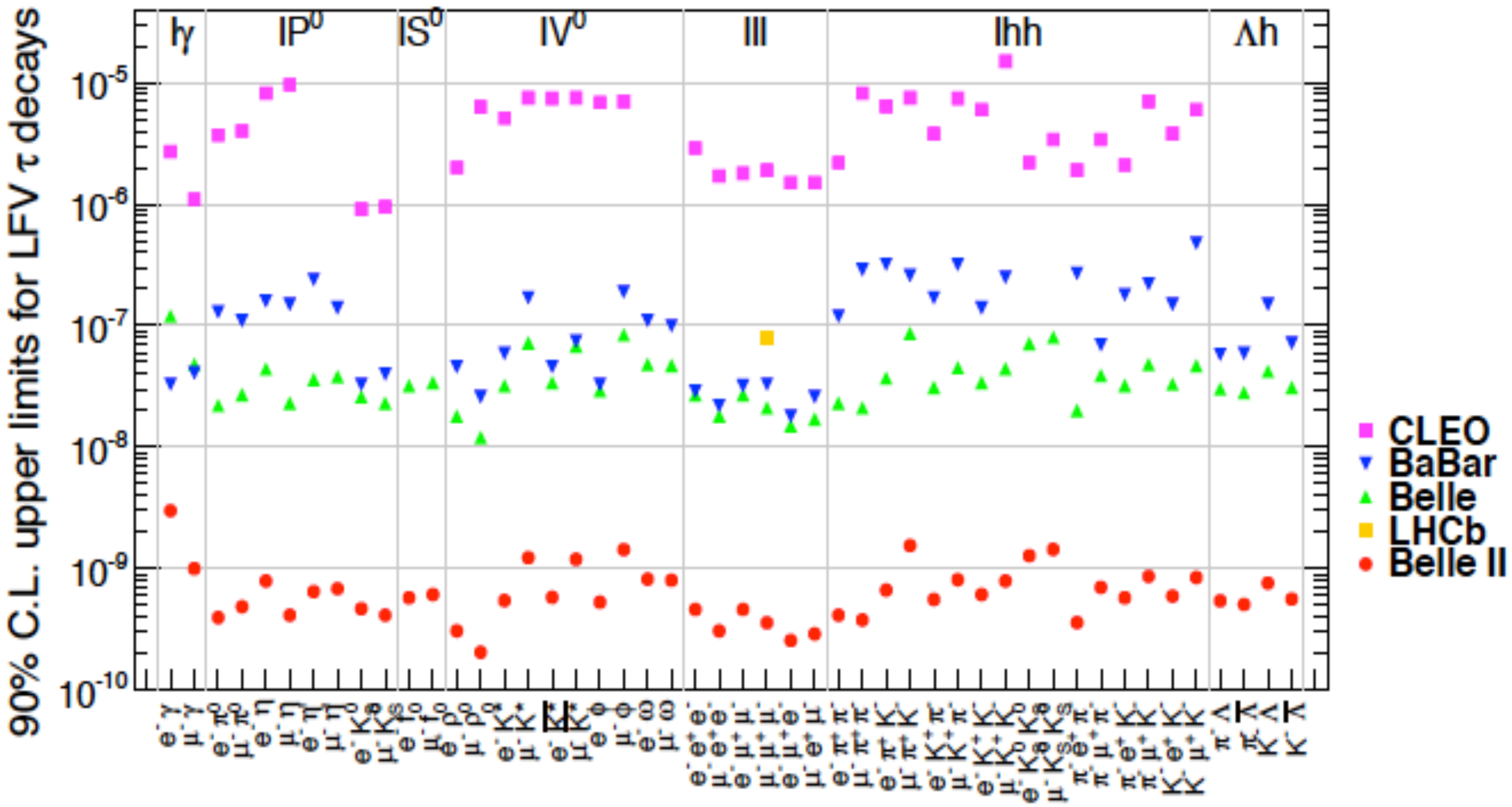
$$O_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,,$$
$$O_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,,$$





b→sμμ Vs b→see
Belle II 50 ab^{-1} Vs LHCb 50 fb^{-1}

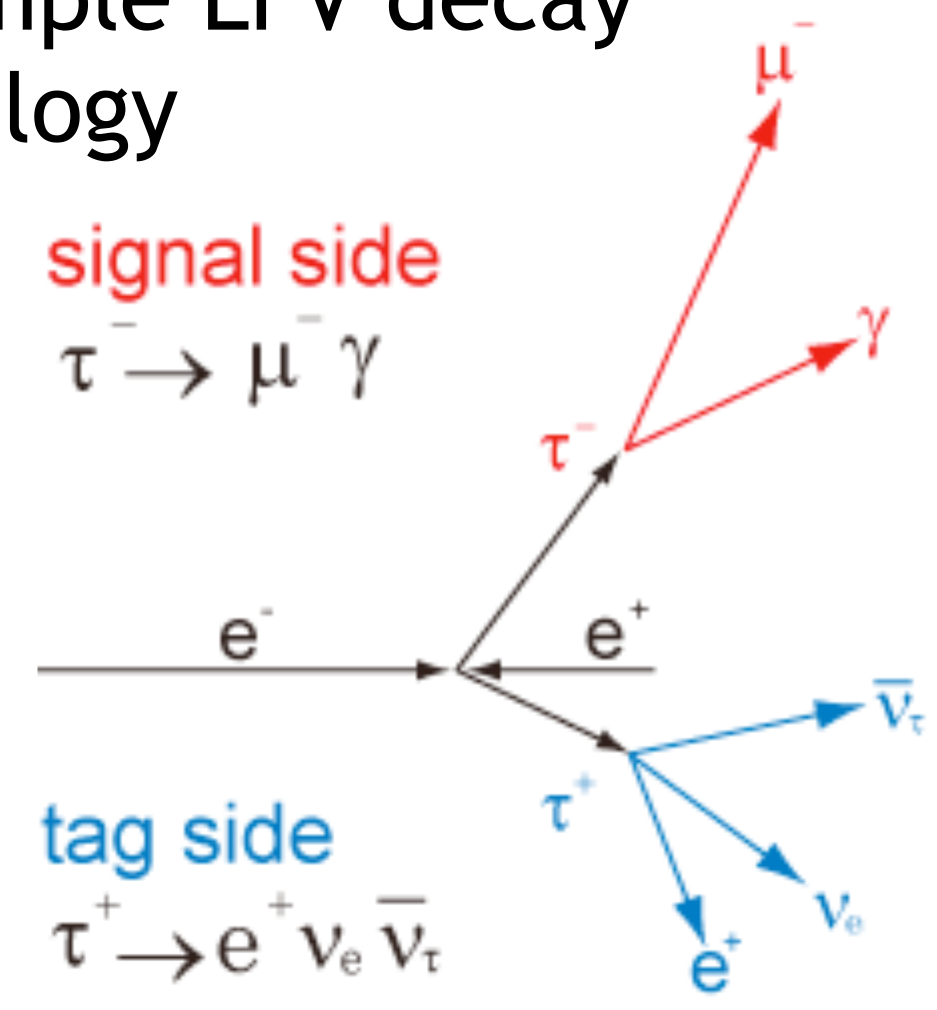
τ Lepton Flavour Violation



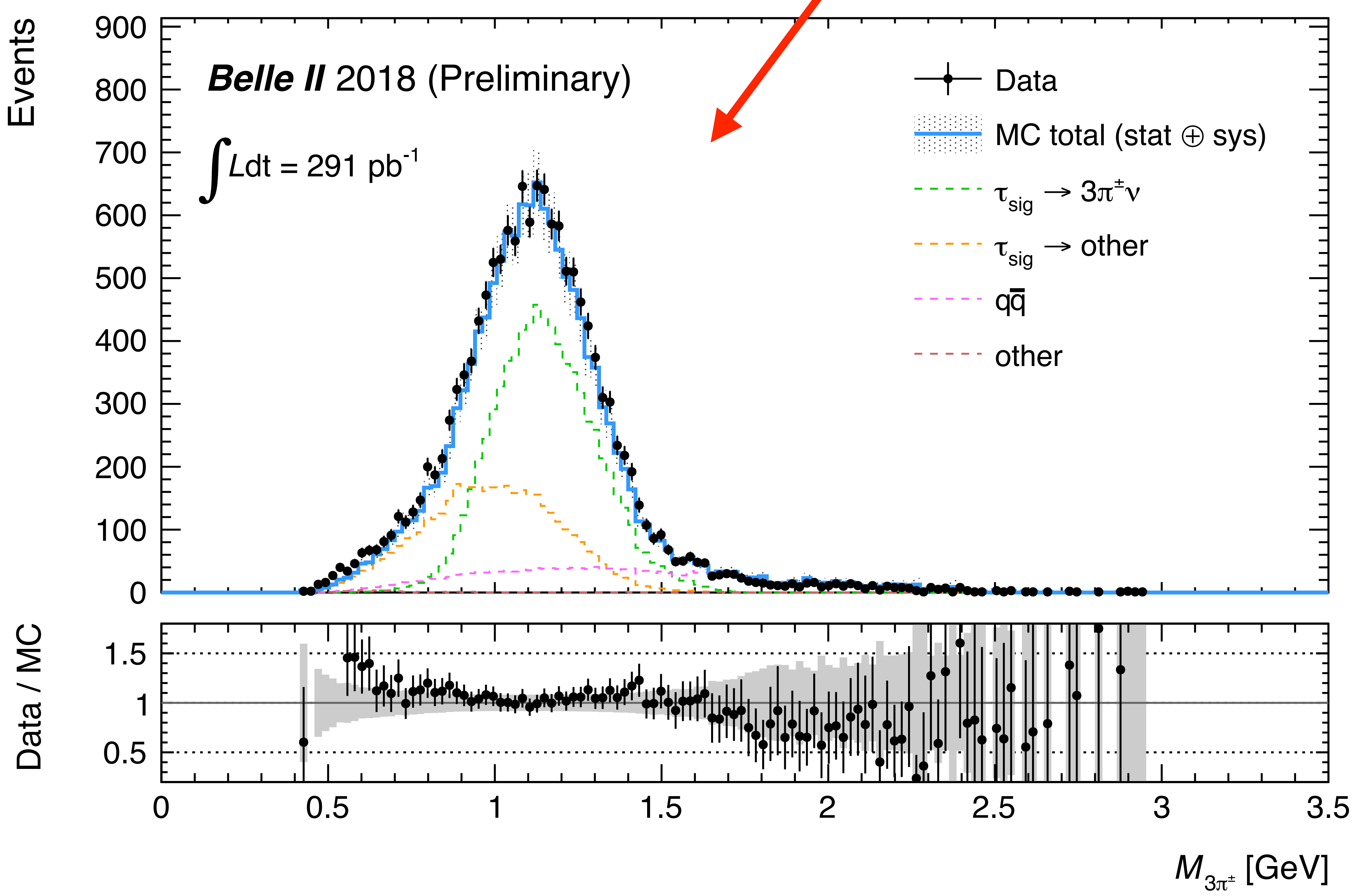
Note vertical log-scale (50 ab^{-1} assumed for Belle II; 3 fb^{-1} result for LHCb

<u>Belle II will push many limits below 10^{-9}</u>; LHCb, CMS and ATLAS have very *limited* capabilities.

Example LFV decay topology

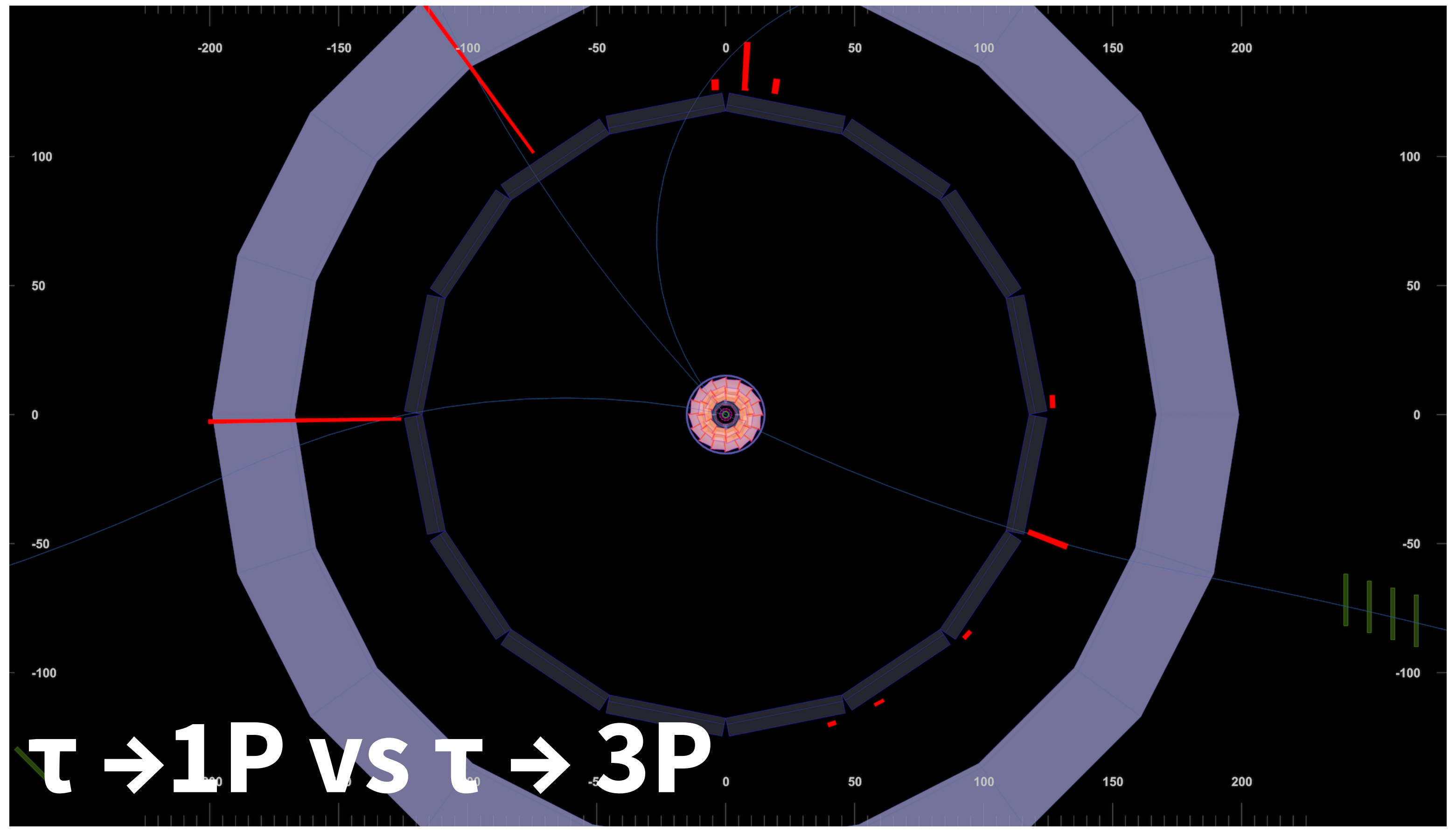


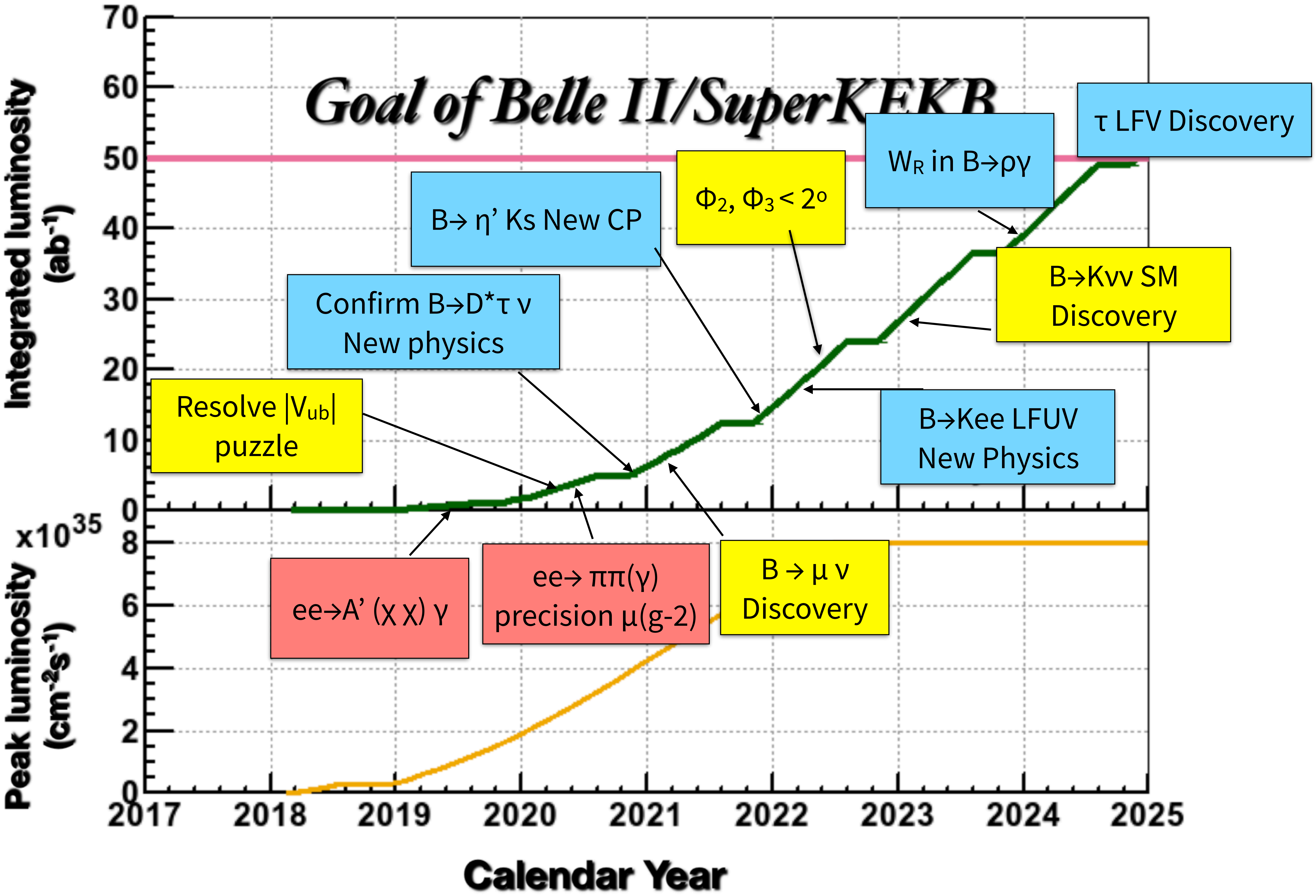
- ~7500 τ→1-Prong, vs τ→3-Prong
- CDC track triggered.
- τ-mass



Roadmap

- Our most powerful tests will continue to be statistics limited, clean theoretically and systematically.





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Summary

- Belle II will explore New Physics on the Luminosity or Intensity Frontier.
- Belle II / SuperKEKB came online in 2018 - rediscovered heavy flavour : charm, beauty and τ.
- We are ready to start a long physics run in the Super Factory mode (Phase 3). This requires *high-efficiency* data-taking by Belle II and *extensive running* by Super KEK-B, soon to be the world's highest luminosity accelerator.
- There is competition and complementarity with LHCb and BES III.

E. Kou, PU (Editors) et al., arXiv: 1808.10567 (688p), Submitted to PTEP

KEK Preprint 2018-27
BELLE2-PAPER-2018-001
FERMILAB-PUB-18-398-T
JLAB-THY-18-2780
INT-PUB-18-047

The Belle II Physics Book

E. Kou[73,¶,†], P. Urquijo[141,§,†], W. Altmannshofer[131,¶], F. Beaujean[77,¶], G. Bell[118,¶], M. Beneke[110,¶], I. I. Bigi[144,¶], F. Bishara[146,16,¶], M. Blanke[48,49,¶], C. Bobeth[109,110,¶], M. Bona[148,¶], N. Brambilla[110,¶], V. M. Braun[42,¶], J. Brod[108,131,¶], A. J. Buras[111,¶], H. Y. Cheng[43,¶], C. W. Chiang[90,¶], G. Colangelo[124,¶], H. Czyz[152,29,¶], A. Datta[142,¶], F. De Fazio[51,¶], T. Deppisch[49,¶], M. J. Dolan[141,¶], S. Fajfer[105,137,¶], T. Feldmann[118,¶], S. Godfrey[7,¶], M. Gronau[60,¶], Y. Grossman[15,¶], F. K. Guo[40,130,¶], U. Haisch[146,11,¶], C. Hanhart[21,¶], S. Hashimoto[30,26,¶], S. Hirose[87,¶], J. Hisano[87,88,¶], L. Hofer[123,¶], M. Hoferichter[164,¶], W. S. Hou[90,¶], T. Huber[118,¶], S. Jaeger[155,¶], S. Jahn[81,¶], M. Jamin[122,¶], J. Jones[101,¶], M. Jung[109,¶], A. L. Kagan[131,¶], F. Kahlhoefer[1,¶], J. F. Kamenik[105,137,¶], T. Kaneko[30,26,¶], Y. Kiyo[62,¶], A. Kokulu[110,136,¶], N. Kosnik[105,137,¶], A. S. Kronfeld[20,¶], Z. Ligeti[19,¶], H. Logan[7,¶], C. D. Lu[40,¶], V. Lubicz[149,¶], F. Mahmoudi[138,¶], K. Maltman[169,120,¶], M. Misiak[162,¶], S. Mishima[30,¶], K. Moats[7,¶], B. Moussallam[72,¶], A. Nefediev[38,86,75,¶], U. Nierste[49,¶], D. Nomura[30,¶], N. Offen[42,¶], S. L. Olsen[129,¶], E. Passemar[36,114,¶], A. Paul[56¶], G. Paz[166,¶], A. A. Petrov[166,¶], A. Pich[161,¶], A. D. Polosa[56,¶], J. Pradler[39,¶], S. Prelovsek[105,137,42,¶], M. Procura[119,¶], G. Ricciardi[52,¶], D. J. Robinson[128,19,¶], P. Roig[9,¶], S. Schacht[58,¶], K. Schmidt-Hoberg[16,¶], J. Schwichtenberg[49,¶], S. R. Sharpe[163,¶], J. Shigemitsu[113,¶], N. Shimizu[158,¶], Y. Shimizu[67,¶], L. Silvestrini[56,¶], S. Simula[57,¶], C. Smith[74,¶], P. Stoffer[127,¶], D. Straub[109,¶], F. J. Tackmann[16,¶], M. Tanaka[96,¶], A. Tayduganov[108,¶], G. Tetlalmatzi-Xolocotzi[93,¶], T. Teubner[136,¶], A. Vairo[110,¶], D. van Dyk[110,¶], J. Virto[80,110,¶], Z. Was[91,¶], R. Watanabe[143,¶], I. Watson [151,¶], J. Zupan[131,¶], R. Zwicky[132,¶], F. Abudinén[81,§], I. Adachi[30,26,§], K. Adamczyk[91,§], P. Ahlburg[125,§], H. Aihara[158,§], A. Aloisio[52,§], L. Andricek[82,§], N. Anh Ky[44,§], M. Arndt[125,§], D. M. Asner[5,§], H. Atmacan[154,§], T. Aushev[85,§], V. Aushev[106,§], R. Ayad[157,§], T. Aziz[107,§], S. Baehr[47,§], S. Bahinipati[32,§], P. Bambade[73,§], Y. Ban[100,§], M. Barrett[166,§], J. Baudot[46,§], P. Behera[35,§], K. Belous[37,§], M. Bender[76,§], J. Bennett[8,§], M. Berger[39,§], E. Bernieri[57,§], F. U. Bernlochner[47,§], M. Bessner[134,§], D. Besson[86,§], S. Bettarini[55,§], V. Bhardwaj[31,§], B. Bhuyan[33,§], T. Bilka[10,§], S. Bilmis[84,§], S. Bilokin[46,§], G. Bonvicini[166,§], A. Bozek[91,§], M. Bračko[140,105,§], P. Branchini[57,§], N. Braun[47,§], R. A. Briere[8,§], T. E. Browder[134,§], L. Burmistrov[73,§], S. Bussino[57,§], L. Cao[47,§], G. Caria[142,§], G. Casarosa[55,§], C. Cecchi[54,§], D. Červenkov[10,§], M.-C. Chang[22,§], P. Chang[90,§], R. Cheaib[142,§], V. Chekelian[81,§], Y. Chen[150,§], B. G. Cheon[28,§], K. Chilikin[75,§], K. Cho[68,§], J. Choi[14,§], S.-K. Choi[27,§], S. Choudhury[34,§], D. Cinabro[166,§], L. M. Cremaldi[142,§], D. Cuesta[46,§], S. Cunliffe[16,§], N. Dash[32,§], E. de la Cruz Burelo[80,§], G. De Nardo[52,§], M. De Nuccio[16,§], G. De Pietro[57,§], A. De Yta Hernandez[80,§], B. Deschamps[125,§], M. Destefanis[58,§], S. Dey[112,§], F. Di Capua[52,§], S. Di Carlo[73,§], J. Dingfelder[125,§], Z. Doležal[10,§],

Backup

New physics DNA

- What new physics could it be?
- Matter antimatter asymmetry
  → New sources of CP Violation
- Quark and Lepton flavour & mass hierarchy
  →extended gauge sector coupling to third generation **(H±, W’, Z’)**
  →restored L-R symmetry
- **Finite neutrino masses**
  → LFV and LFUV.
- 19 free parameters
  → GUTs, **leptoquarks**

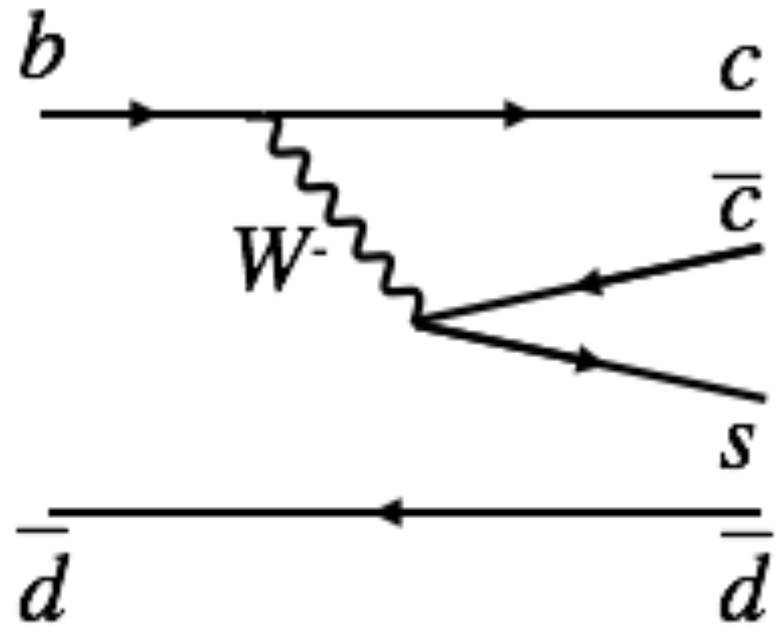
- τ LFV is an excellent example.

Observables	Experimental Sensitivity	Multi-Higgs Models (§17.2)	generic SUSY	MFV (§17.3)	Z' models (§17.6.1)	gauged flavour (§17.6.2)	3-3-1 (§17.6.3)	left-right (§17.6.4)	leptoquarks (§18.2.1)	compositeness (§17.7)	dark sector (§16.1)
τ tree decays:											
$\mathcal{B}(\tau \to K\nu)/\mathcal{B}(\tau \to \pi\nu)$	⋆⋆⋆	⋆⋆	×	×	×	×	×	⋆	⋆⋆⋆	□	⋆⋆
$\mathcal{B}(\tau \to K^*\nu)/\mathcal{B}(\tau \to \rho\nu)$	⋆⋆⋆	×	×	×	×	×	×	⋆	⋆⋆⋆	□	⋆⋆
$\tau \to \mu$ decays:											
$\tau \to \mu\gamma$	⋆⋆⋆	⋆	⋆⋆⋆	⋆	⋆	⋆	⋆	×	⋆	⋆⋆⋆	□
$\tau \to \mu\pi^0$	⋆⋆⋆	⋆	⋆⋆	×	⋆⋆⋆	×	⋆⋆⋆	×	⋆⋆⋆	□	□
$\tau \to \mu K_S$	⋆⋆⋆	⋆	⋆	×	⋆	×	⋆	×	⋆⋆⋆	□	□
$\tau \to \mu\rho^0$	⋆⋆⋆	×	⋆⋆	×	⋆⋆⋆	×	⋆⋆⋆	×	⋆⋆⋆	□	□
$\tau \to \mu K^{0*}$	⋆⋆⋆	×	⋆	×	⋆	×	⋆	×	⋆⋆⋆	□	□
$\tau^- \to \mu^-\ell^-\ell^+$	⋆⋆	⋆⋆	⋆	×	⋆⋆⋆	⋆⋆⋆	⋆⋆⋆	×	⋆	⋆⋆⋆	□
$\tau^- \to \mu^-\mu^-e^+$	⋆⋆	⋆	×	×	⋆	⋆⋆⋆	⋆	×	×	⋆⋆⋆	□

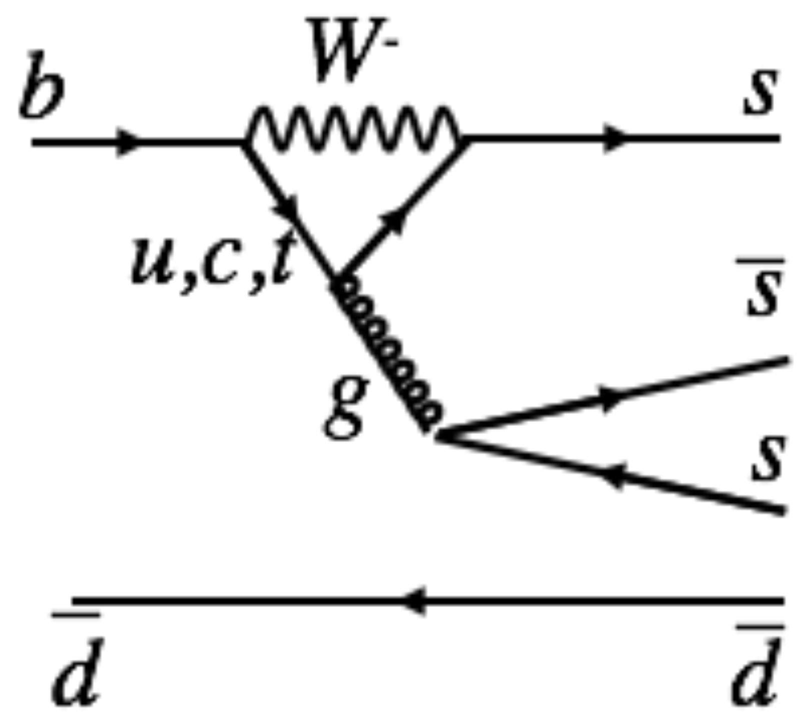
CP Violation

Process	Observable	Theory	Sys. limit (Discovery) [ab^{-1}]	vs LHCb	vs Belle	Anomaly	NP
$B \to J/\psi K_S$	ϕ_1	⋆⋆⋆	5-10	⋆⋆	⋆⋆	⋆	⋆
$B \to \phi K_S$	ϕ_1	⋆⋆	>50	⋆⋆	⋆⋆⋆	⋆	⋆⋆⋆
$B \to \eta' K_S$	ϕ_1	⋆⋆	>50	⋆⋆	⋆⋆⋆	⋆	⋆⋆⋆
$B \to J/\psi \pi^0$	ϕ_1	⋆⋆⋆	>50	⋆	⋆⋆⋆	—	—
$B \to \rho^\pm \rho^0$	ϕ_2	⋆⋆⋆	—	⋆	⋆⋆⋆	⋆	⋆
$B \to \pi^0 \pi^0$	ϕ_2	⋆⋆	>50	⋆⋆⋆	⋆⋆⋆	⋆⋆	⋆⋆
$B \to \pi^0 K_S$	S_{CP}	⋆⋆	>50	⋆⋆⋆	⋆⋆⋆	⋆⋆	⋆⋆

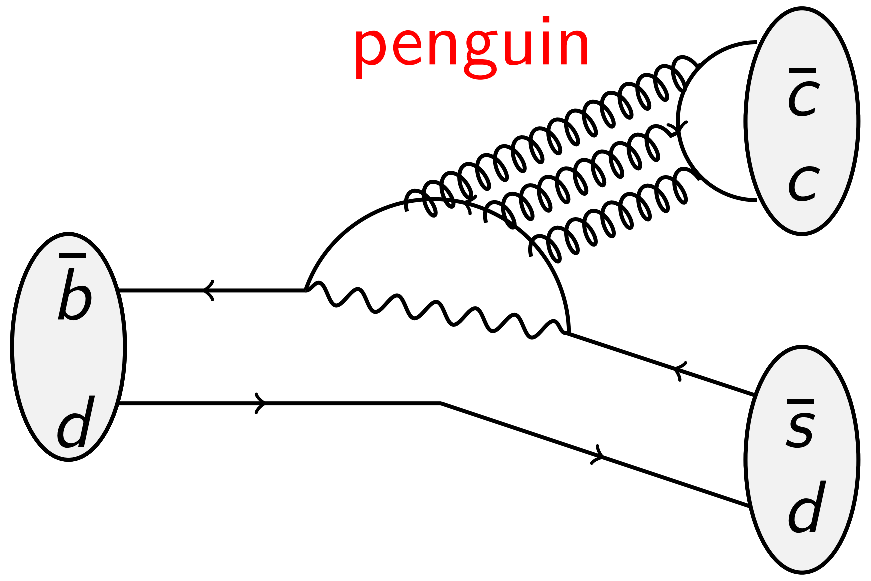
- Tree



- Gluonic Penguin (NP sensitive)



- Constrains penguin pollution (theory precision)

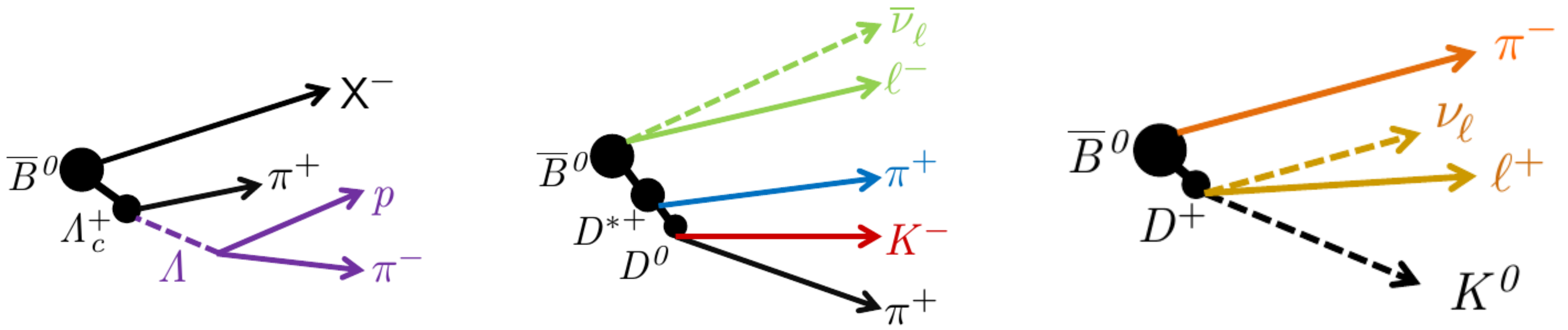


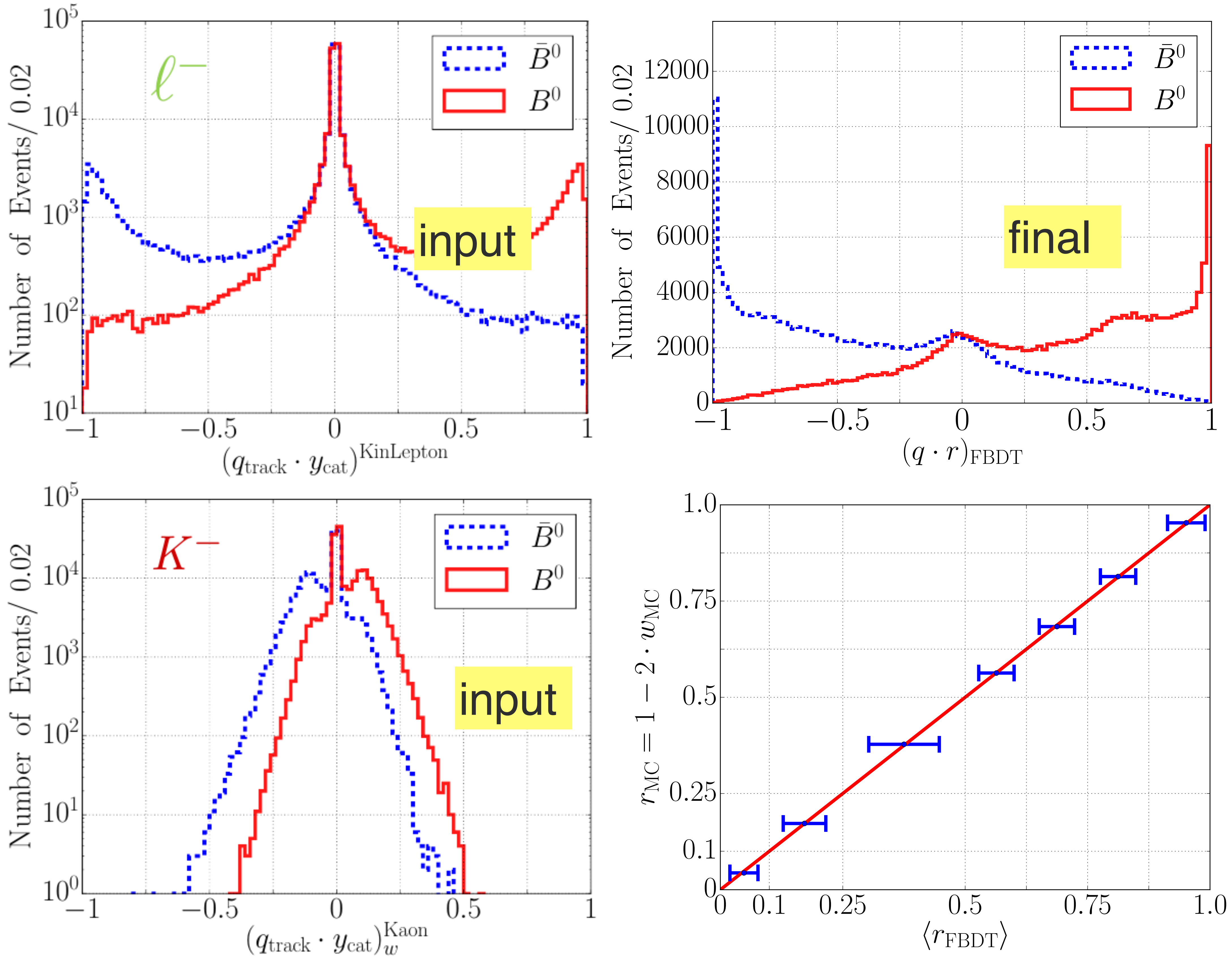
Flavour Tagging

- Categories based on different signatures

Categories	$\varepsilon_{\text{eff}}(\%)$	$\Delta\varepsilon_{\text{eff}}(\%)$
Electron	5.26	−0.05
IntermediateElectron	1.06	−0.02
Muon	5.55	−0.02
IntermediateMuon	0.17	−0.01
KinLepton	10.86	−0.07
IntermediateKinLepton	0.98	−0.04
Kaon	21.83	−1.72
KaonPion	15.12	−0.87
SlowPion	7.96	−0.23
FSC	13.11	−0.33
MaximumPstar	13.24	0.39
FastPion	2.58	−0.06
Lambda	1.98	0.36

- Belle II: 35% (varies with release)
  - few% less w/ beam bkg
- Belle (this algo): 32%
- Belle (old algo):29%





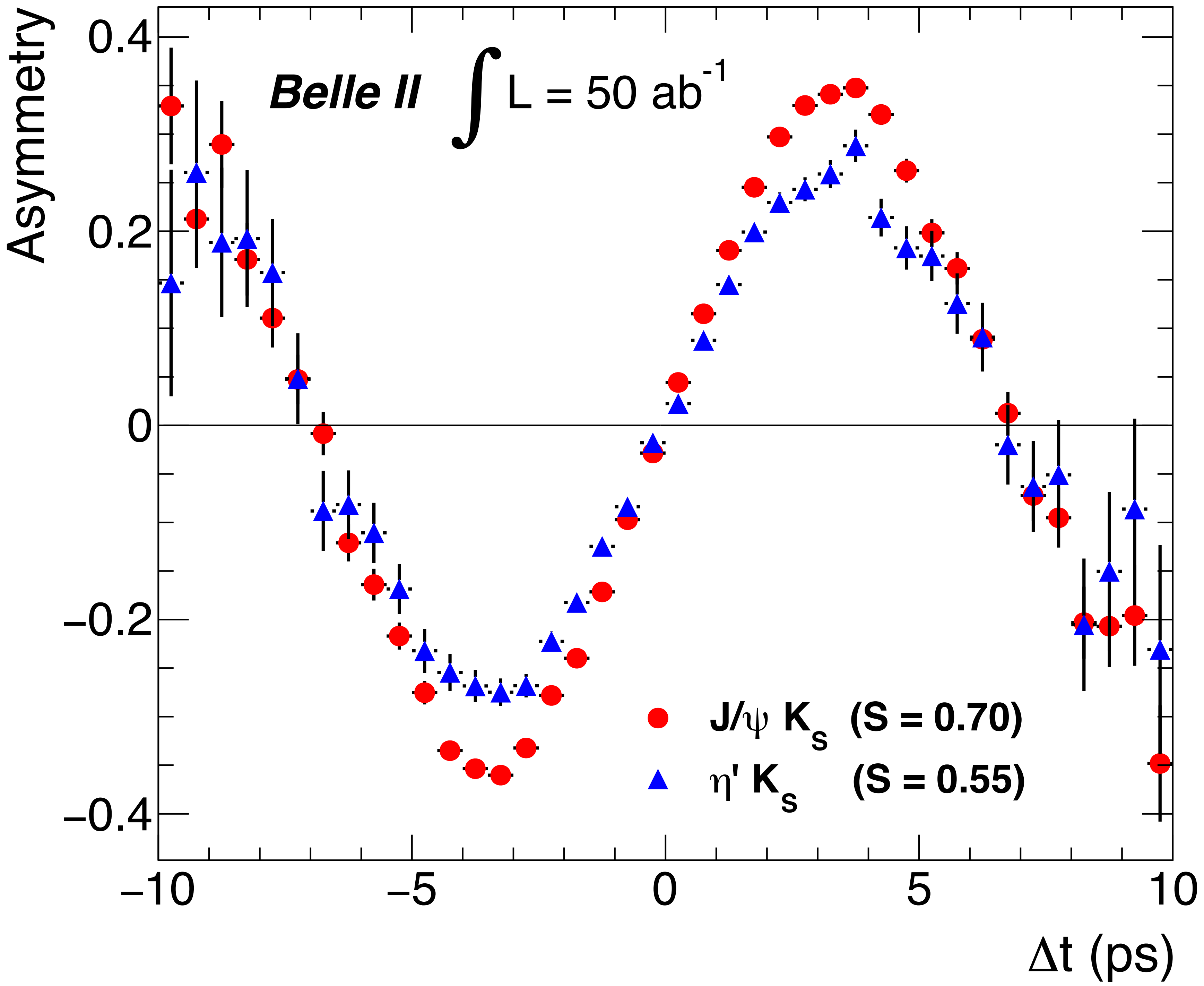
Time dependent CP Violation with Penguins

Channel	$\int \mathcal{L}$	Event yield	$\sigma(S)$	$\sigma(S)_{2017}$	$\sigma(A)$	$\sigma(A)_{2017}$
$J/\psi K^0$	50 ab^{-1}	$1.4 \cdot 10^6$	0.0052	0.022	0.0050	0.021
ϕK^0	5 ab^{-1}	5590	0.048	0.12	0.035	0.14
$\eta' K^0$	5 ab^{-1}	27200	0.027	0.06	0.020	0.04
ωK_S^0	5 ab^{-1}	1670	0.08	0.21	0.06	0.14
$K_S \pi^0 \gamma$	5 ab^{-1}	1400	0.10	0.20	0.07	0.12
$K_S \pi^0$	5 ab^{-1}	5699	0.09	0.17	0.06	0.10

Mode	QCDF [27]	QCDF (scan) [27]	$SU(3)$	Data
$\pi^0 K_S$	$0.07^{+0.05}_{-0.04}$	$[0.02, 0.15]$	$[-0.11, 0.12]$ [41]	$-0.11^{+0.17}_{-0.17}$
$\rho^0 K_S$	$-0.08^{+0.08}_{-0.12}$	$[-0.29, 0.02]$		$-0.14^{+0.18}_{-0.21}$
$\eta' K_S$	$0.01^{+0.01}_{-0.01}$	$[0.00, 0.03]$	$(0 \pm 0.36) \times 2\cos(\phi_1)\sin\gamma$ [42]	-0.05 ± 0.06
ηK_S	$0.10^{+0.11}_{-0.07}$	$[-1.67, 0.27]$		—
ϕK_S	$0.02^{+0.01}_{-0.01}$	$[0.01, 0.05]$	$(0 \pm 0.25) \times 2\cos(\phi_1)\sin\gamma$ [42]	$0.06^{+0.11}_{-0.13}$
ωK_S	$0.13^{+0.08}_{-0.08}$	$[0.01, 0.21]$		$0.03^{+0.21}_{-0.21}$

Error on $\sin(2\beta)$ from $B \to J/\psi K_s$	tot.
LHCb 22/fb	**0.014**
Belle II 50/ab	**0.007**

Time dependent CP Asymmetry



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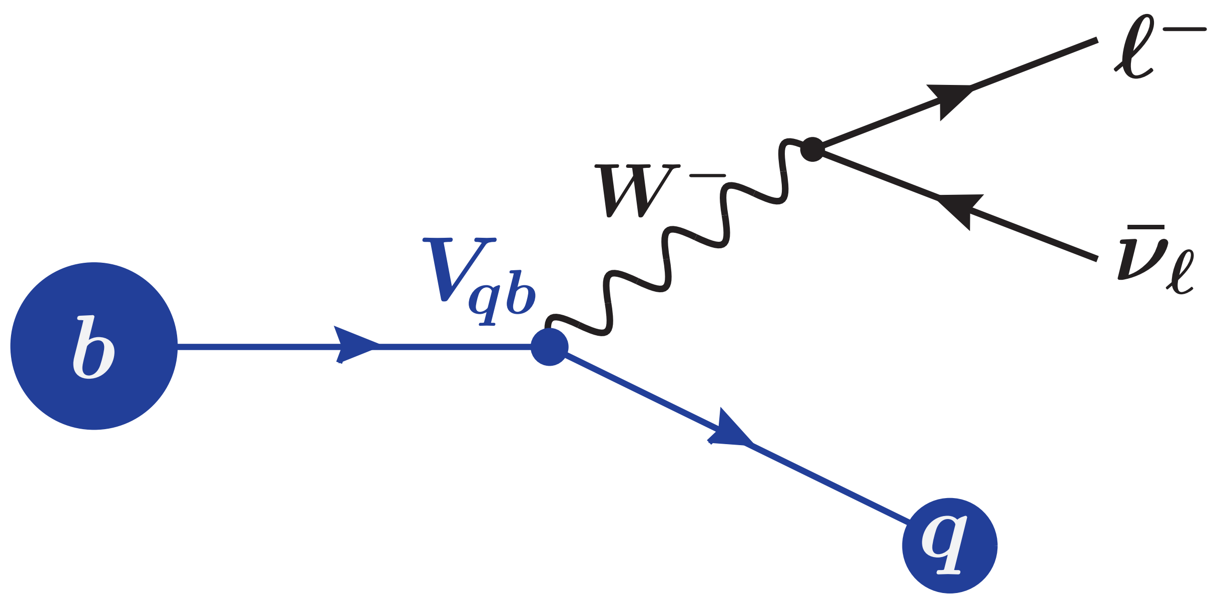
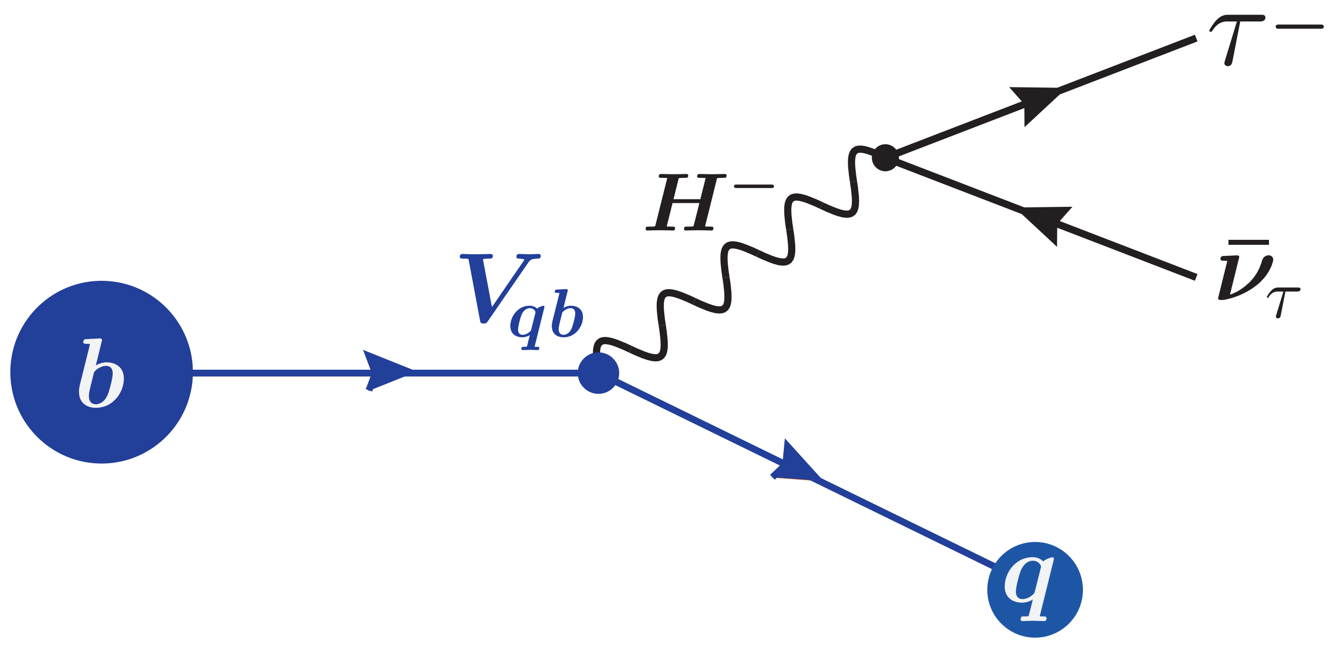
Leptonic and Semileptonic Decay

- 3-ways to measure $|V_{CKM}|$ with leptonic and semileptonic decays



- **Leptonic**: decay constant from LQCD

$$\Gamma(B \to \ell_1 \ell_2) = \frac{M_B}{4\pi} |G|^2 f_B^2 \zeta_{12} \frac{\lambda_{12}^{1/2}}{M_B^2} \qquad G = \frac{G_F}{\sqrt{2}} V_{ub}, \quad (m_{\nu_\ell} \to 0)$$



- **Exclusive semileptonic**: form factor parameterisation with normalisation from LQCD or Light Cone Sum Rules

$$\frac{d\Gamma}{dq^2} = C_q |\eta_{\rm EW}|^2 \frac{G_F^2 |V_{qb}|^2}{(2\pi)^3} \frac{\lambda^{1/2}}{4M_B^3} \frac{\lambda_{12}^{1/2}}{q^2} \left\{ q^2 \beta_{12} \left[|H_+|^2 + |H_-|^2 + |H_0|^2 \right] + \zeta_{12} |H_s|^2 \right\}$$

- **Inclusive semileptonic**: Heavy quark symmetry if you measure the full rate, described by heavy quark expansion

$$\Gamma(B \to X_c \ell \nu) = \frac{G_{\rm F}^2 m_b^5}{192\pi^3} |V_{cb}|^2 [[1 + {\rm A_{ew}}] {\rm A_{nonpert}} {\rm A_{pert}}]$$

$$\lambda_{12} = (M_B^2 - m_1^2 - m_2^2)^2 - 4m_1^2 m_2^2,$$

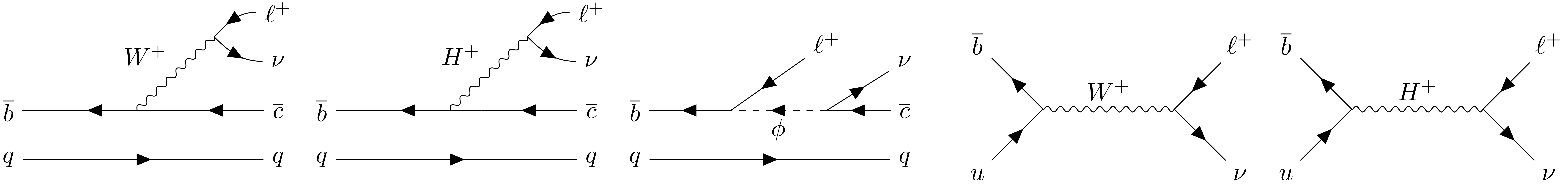
$$\zeta_{12} = m_1^2 + m_2^2 - \frac{(m_1^2 - m_2^2)^2}{M_B^2},$$

$$\beta_{12} = 1 - \frac{m_1^2 + m_2^2}{q^2} - \frac{\lambda_{12}}{q^{2\,2}}$$

Golden modes for Belle II

Process	Observable	Theory	Sys. limit (Discovery) [ab^{-1}]	vs LHCb	vs Belle	Anomaly	NP
$B \to \pi \ell \nu_l$	$\lvert V_{ub} \rvert$	$\star\star\star$	10-20	$\star\star\star$	$\star\star\star$	$\star\star$	$\star$
$B \to X_u \ell \nu_\ell$	$\lvert V_{ub} \rvert$	$\star\star$	2-10	$\star\star\star$	$\star\star$	$\star\star\star$	$\star$
$B \to \tau \nu$	$Br.$	$\star\star\star$	$>$50 (2)	$\star\star\star$	$\star\star\star$	$\star$	$\star\star\star$
$B \to \mu \nu$	$Br.$	$\star\star\star$	$>$50 (5)	$\star\star\star$	$\star\star\star$	$\star$	$\star\star\star$
$B \to D^{(*)} \ell \nu_\ell$	$\lvert V_{cb} \rvert$	$\star\star\star$	1-10	$\star\star\star$	$\star\star$	$\star\star$	$\star$
$B \to X_c \ell \nu_\ell$	$\lvert V_{cb} \rvert$	$\star\star\star$	1-5	$\star\star\star$	$\star\star$	$\star\star$	$\star\star$
$B \to D^{(*)} \tau \nu_\tau$	$R(D^{(*)})$	$\star\star\star$	5-10	$\star\star$	$\star\star\star$	$\star\star\star$	$\star\star\star$
$B \to D^{(*)} \tau \nu_\tau$	P_τ	$\star\star\star$	15-20	$\star\star\star$	$\star\star\star$	$\star\star$	$\star\star\star$
$B \to D^{**} \ell \nu_\ell$	$Br.$	$\star$	-	$\star\star$	$\star\star\star$	$\star\star$	-

Least well constrained CKM element



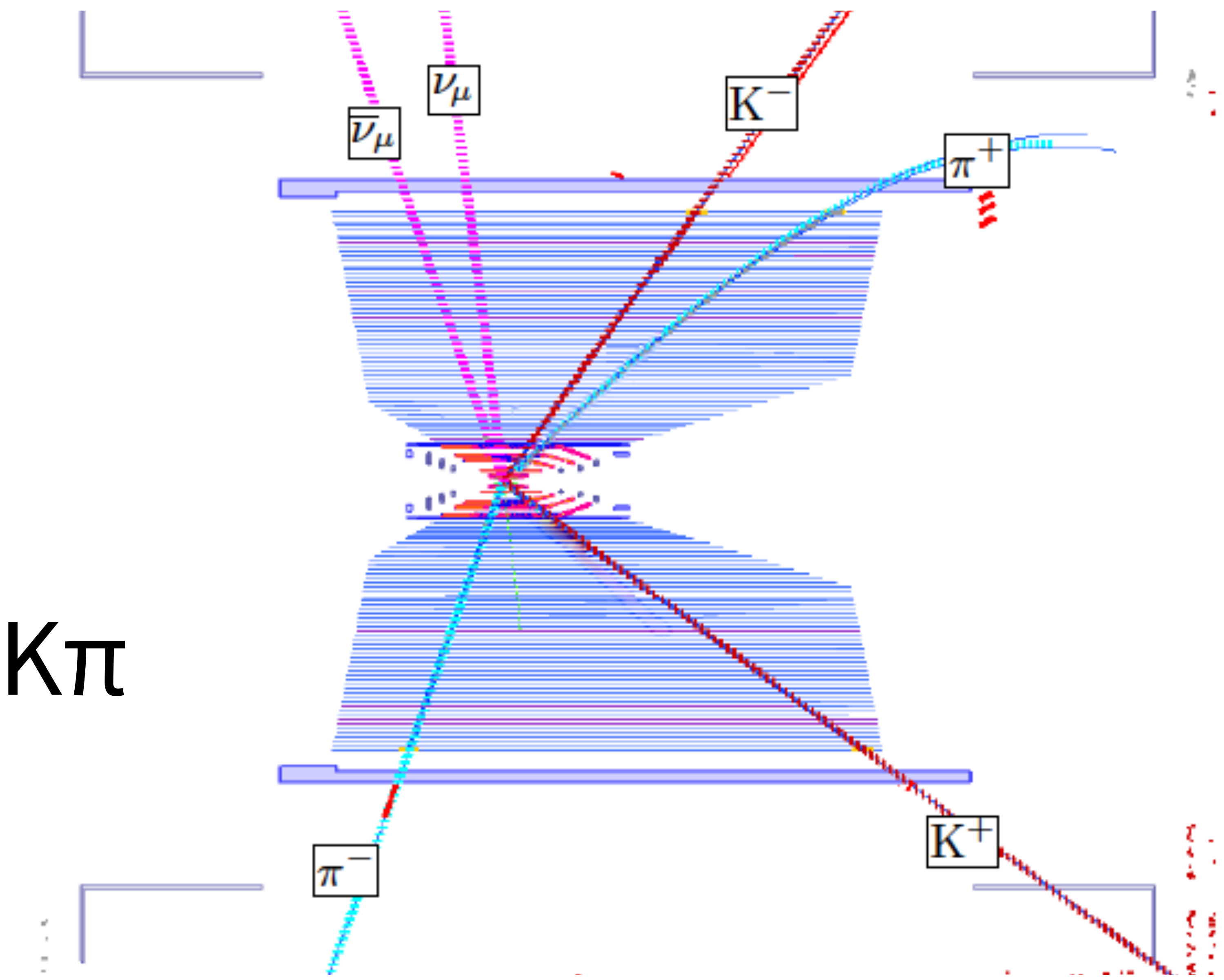
B→ $K^{(*)}$ ν ν

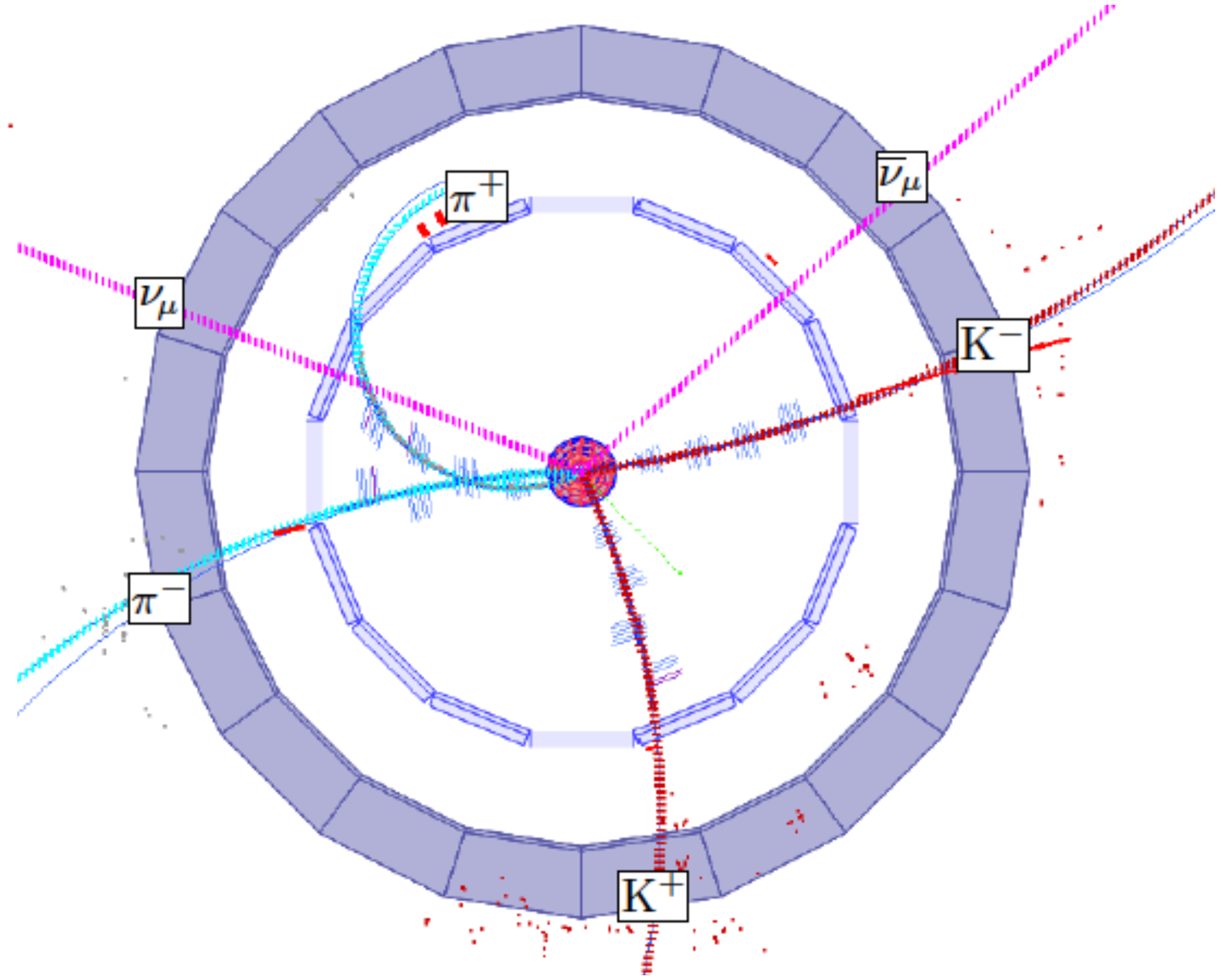
Signal:

B→ K ν ν

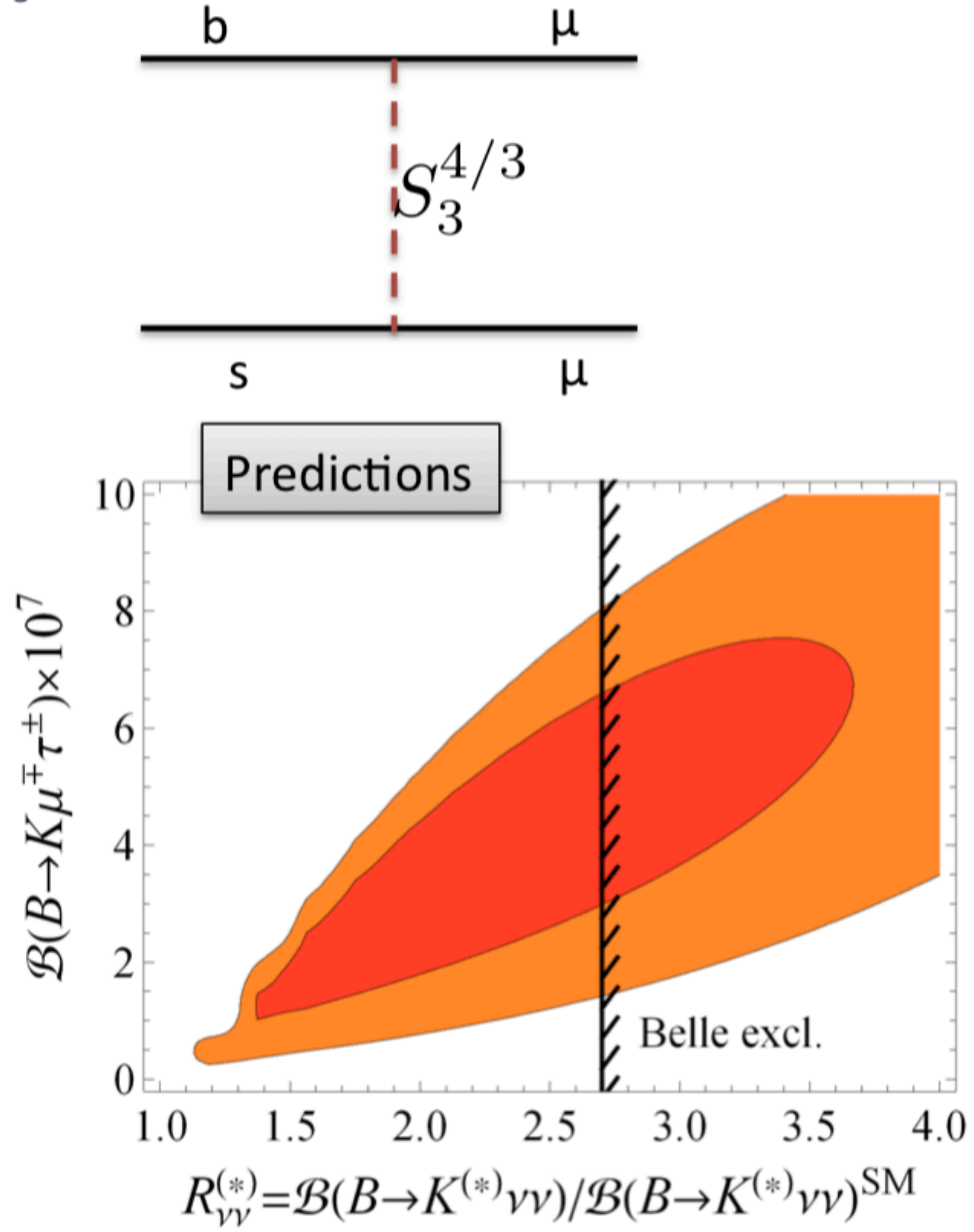
Tag mode:

B→ Dπ; D→ Kπ





$R_{K(*)}$ explained by V-A contributions of S_3 =(3,3,1/3)



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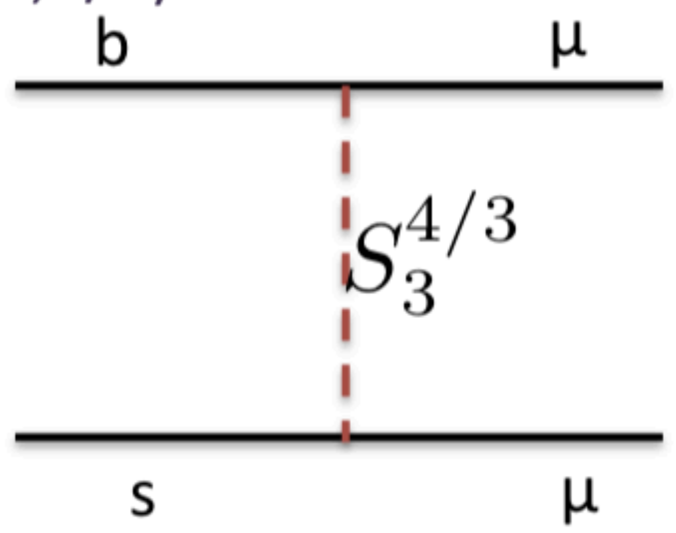
B→ $K^{(*)}$ ν ν

Rate of b→s ν ν is a pure Z penguin (C_9), and only accessed at *Belle II*

Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$B(B^+ \to K^+ \nu\bar{\nu})$	$< 450\%$	38%	12%
$B(B^0 \to K^{*0} \nu\bar{\nu})$	$< 180\%$	35%	11%
$F_L(B^0 \to K^{*0} \nu\bar{\nu})$	–	–	0.11
$B(B^0 \to \nu\bar{\nu}) \times 10^6$	< 14	< 5.0	< 1.5
$B(B^+ \to K^+ \tau^+ \tau^-) \times 10^5$	< 32	< 6.5	< 2.0
$B(B^0 \to \tau^+ \tau^-) \times 10^5$	< 140	< 30	< 9.6

$R_{K(*)}$ explained by V-A contributions of S_3 =(3,3,1/3)

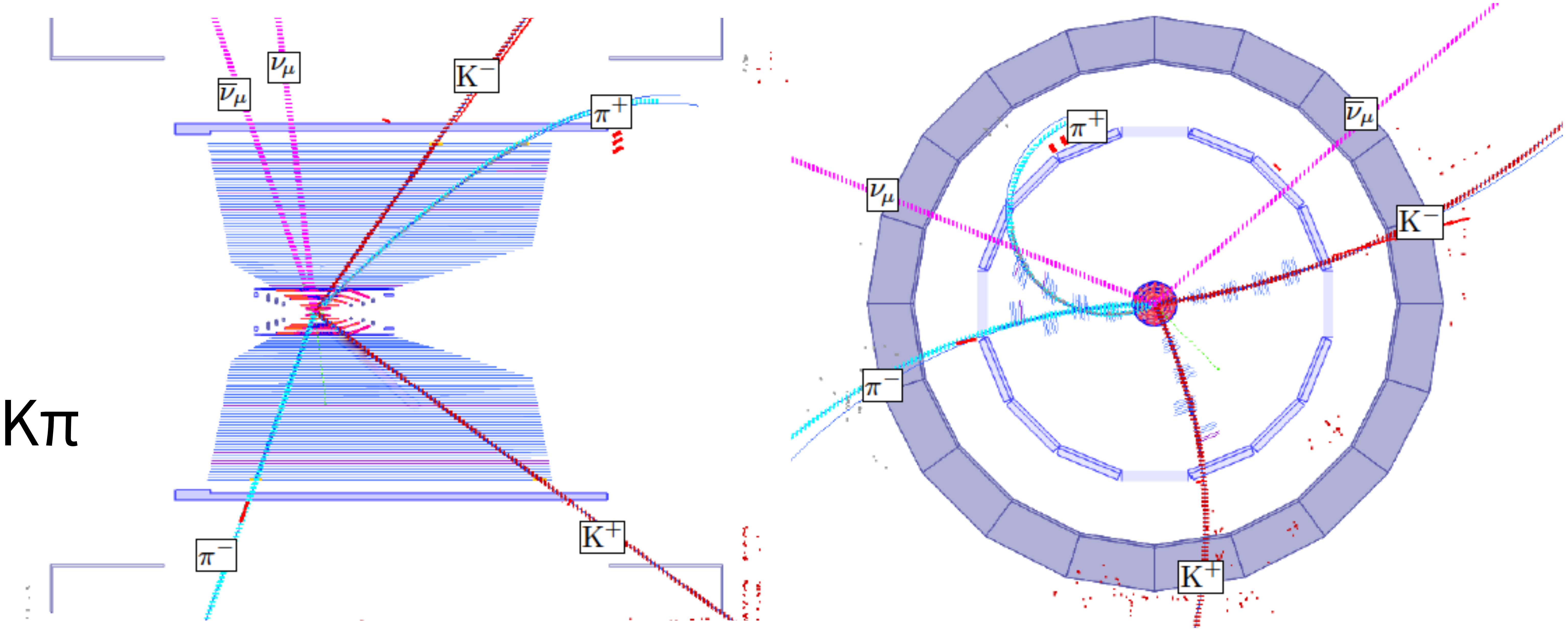


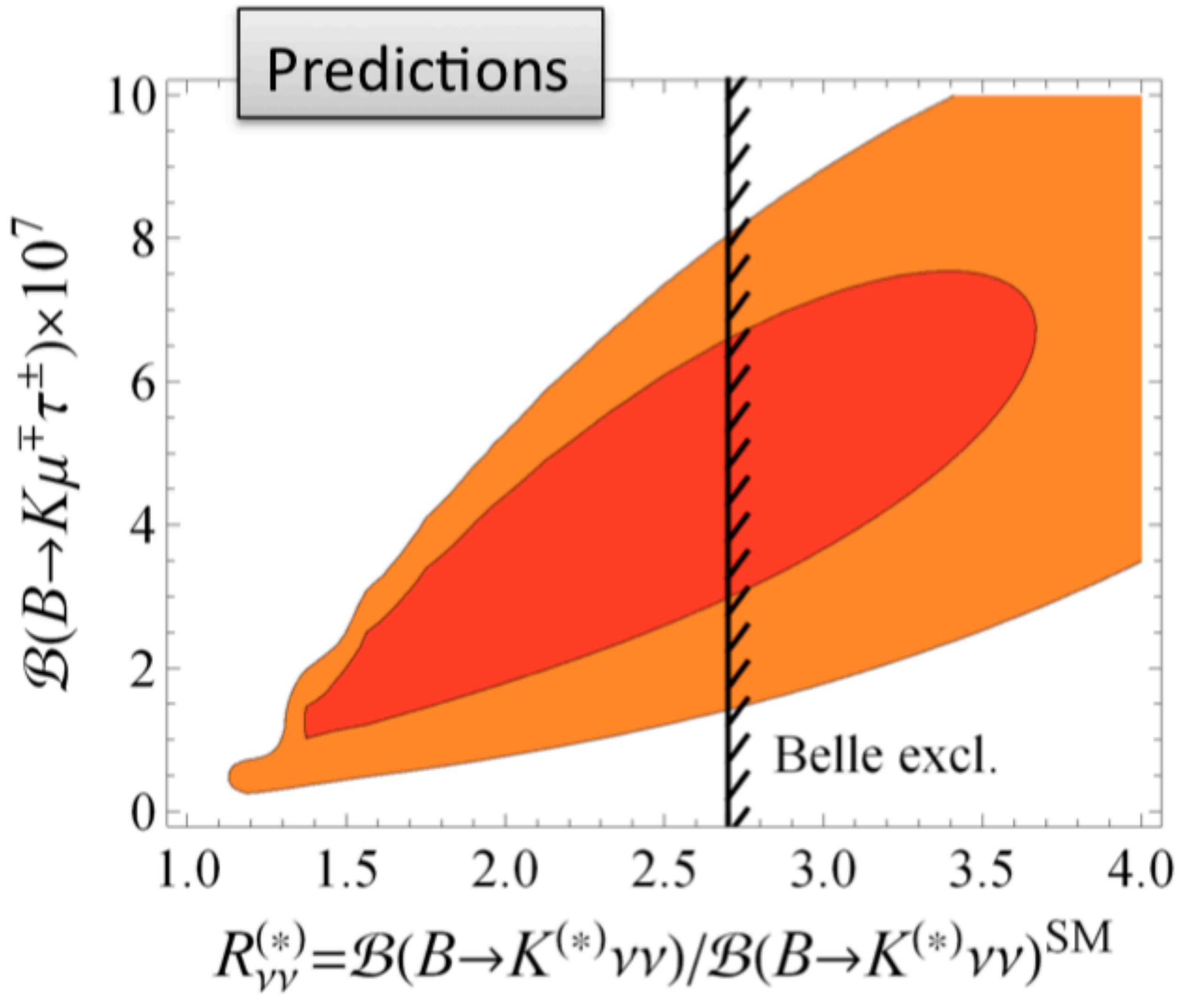
Signal:

B→ K ν ν

Tag mode:

B→ Dπ; D→ Kπ





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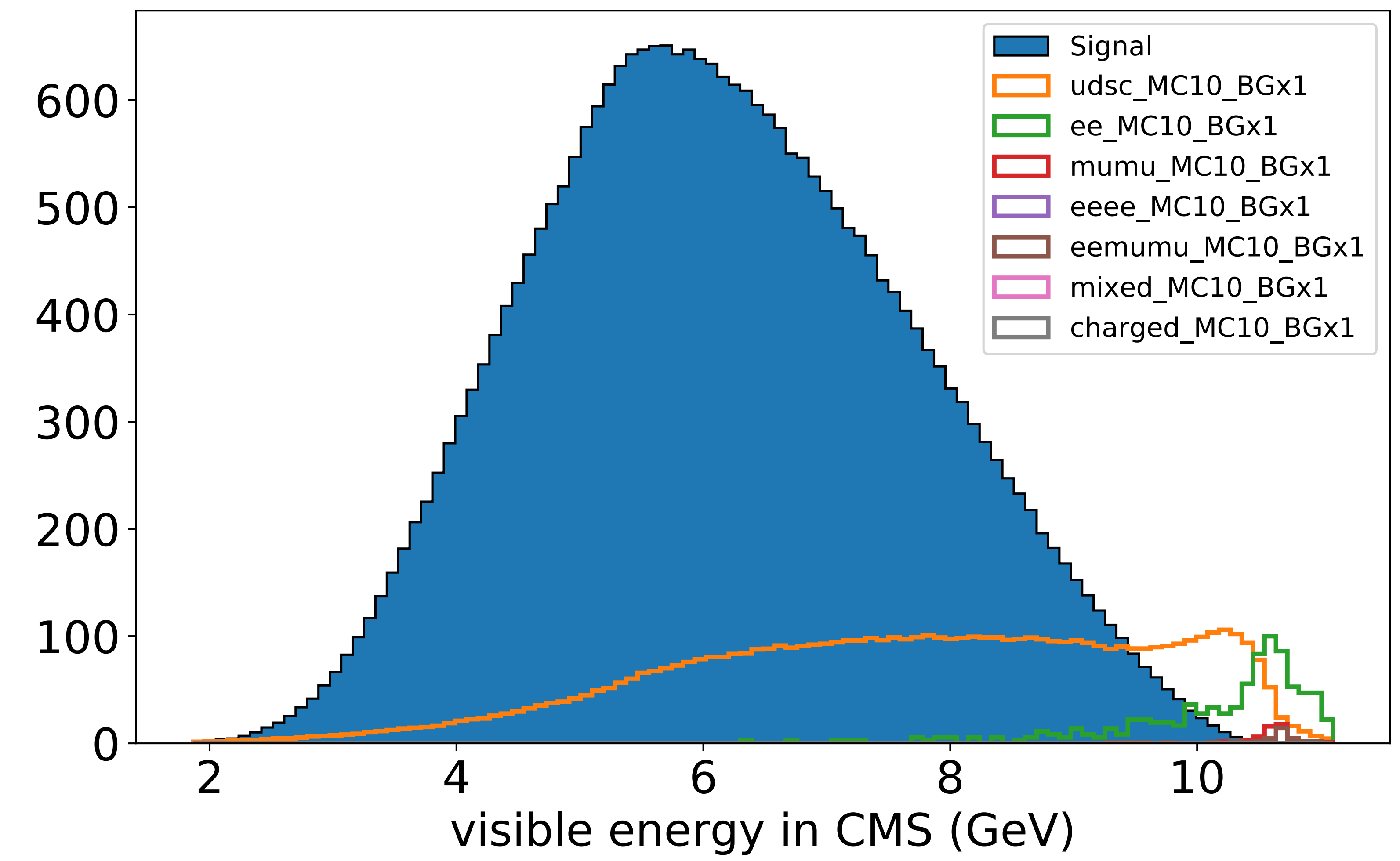
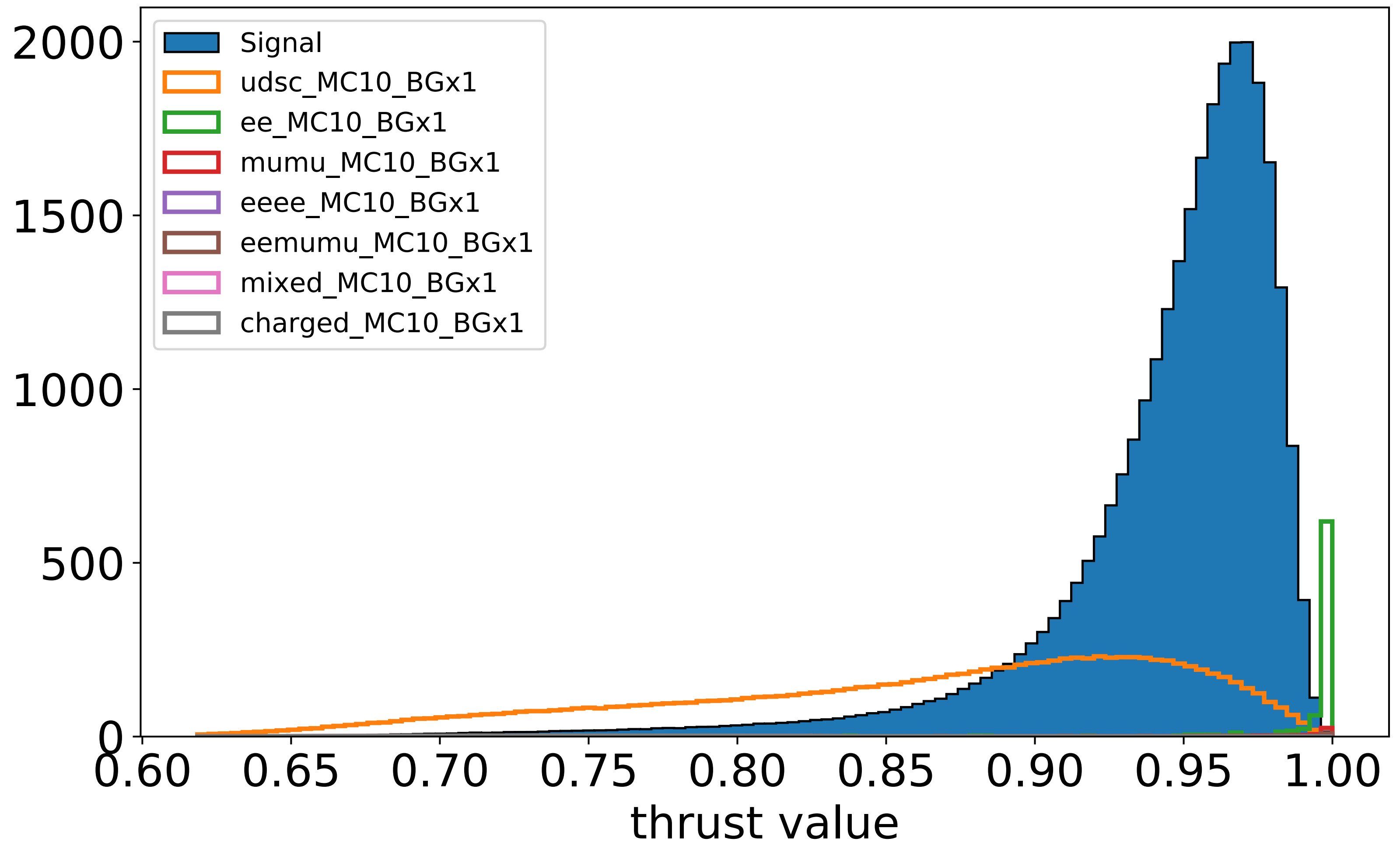
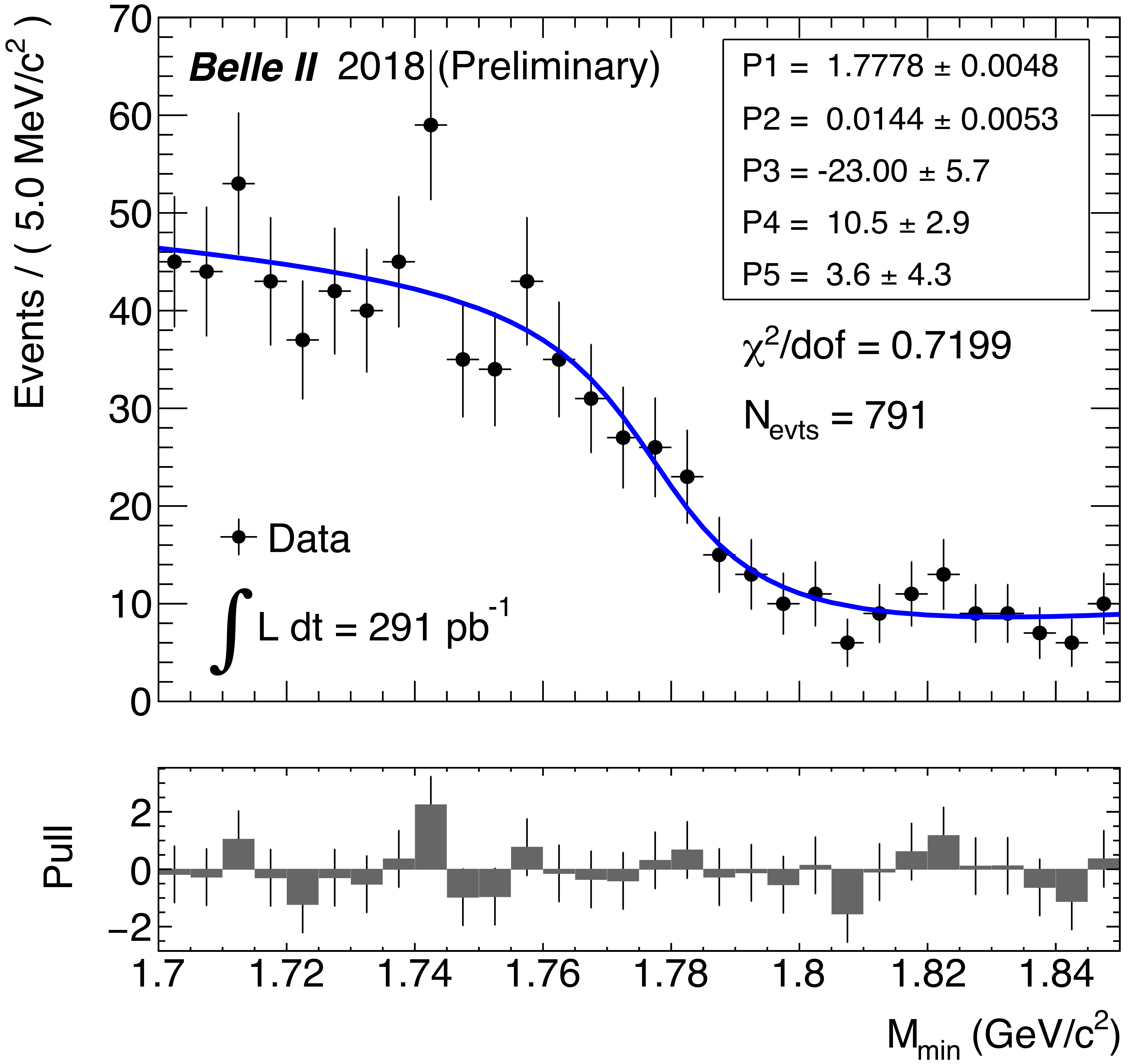
τ Candidates at Belle II



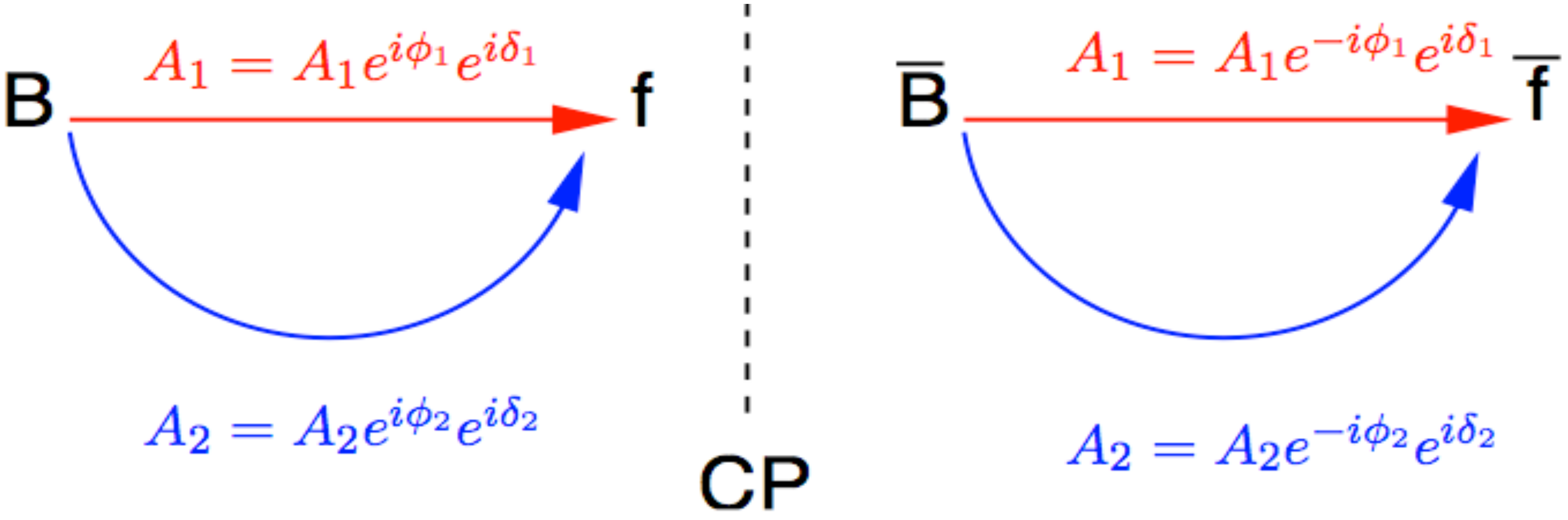


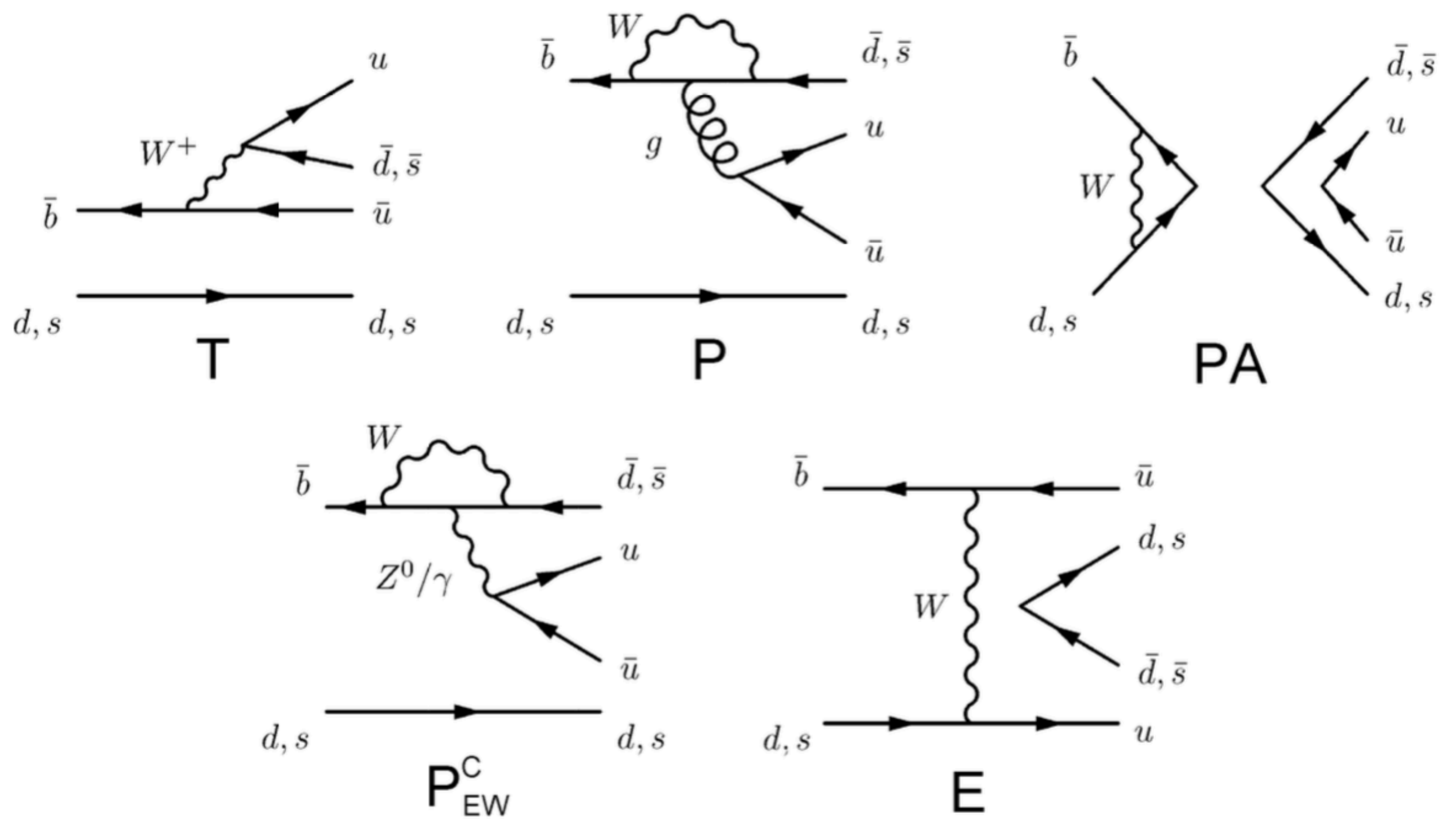
$$M_{min} = \sqrt{M_{3\pi}^2 + 2(E_{beam} - E_{3\pi})(E_{3\pi} - P_{3\pi})}$$



Direct CP Violation

Φ_1 relies on $\Delta F=2$ (mixing+decay), but we can also use $\Delta F=1$ (direct) as a precise probe





$$\text{CPV: } |A_f|^2 \neq |\bar{A}_{\bar{f}}|^2 \Rightarrow \Delta\phi \text{ and } \Delta\delta \neq 0$$

For CPV A_1 and A_2 need to have **different weak phases Φ** and different **CP invariant (e.g. strong) phases δ.**

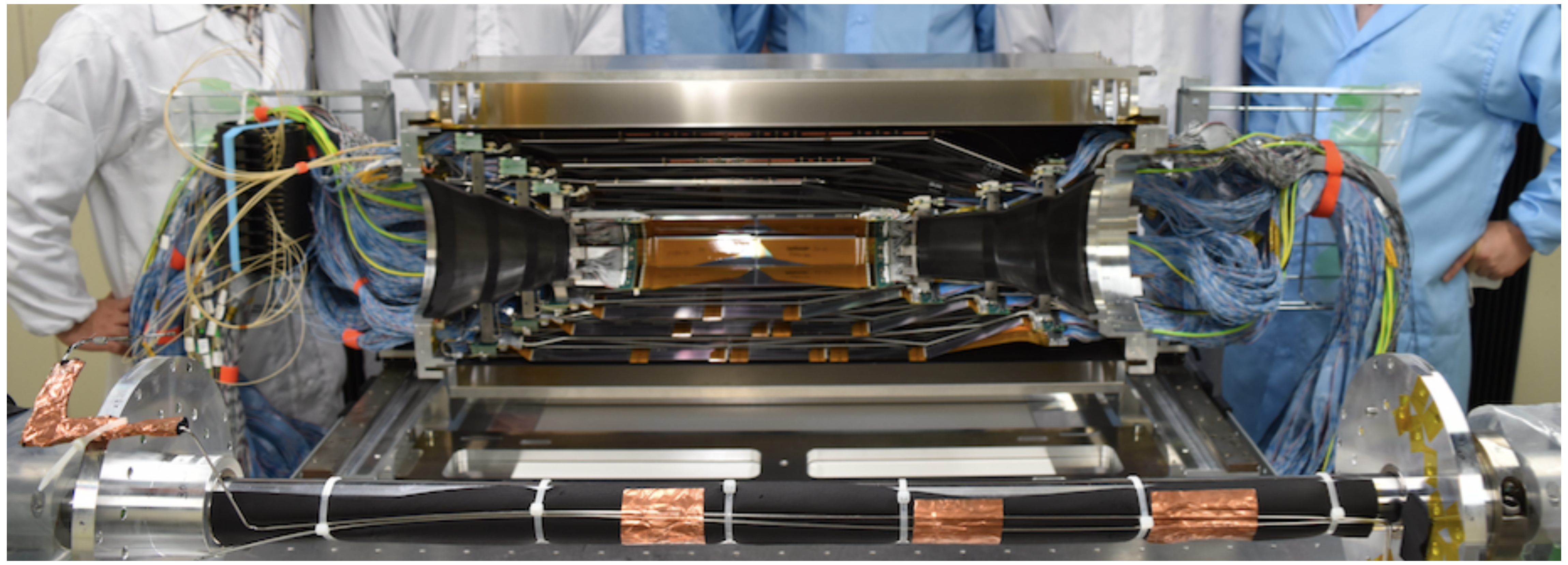
To measure Φ you need to know δ, and ratio of amplitudes -

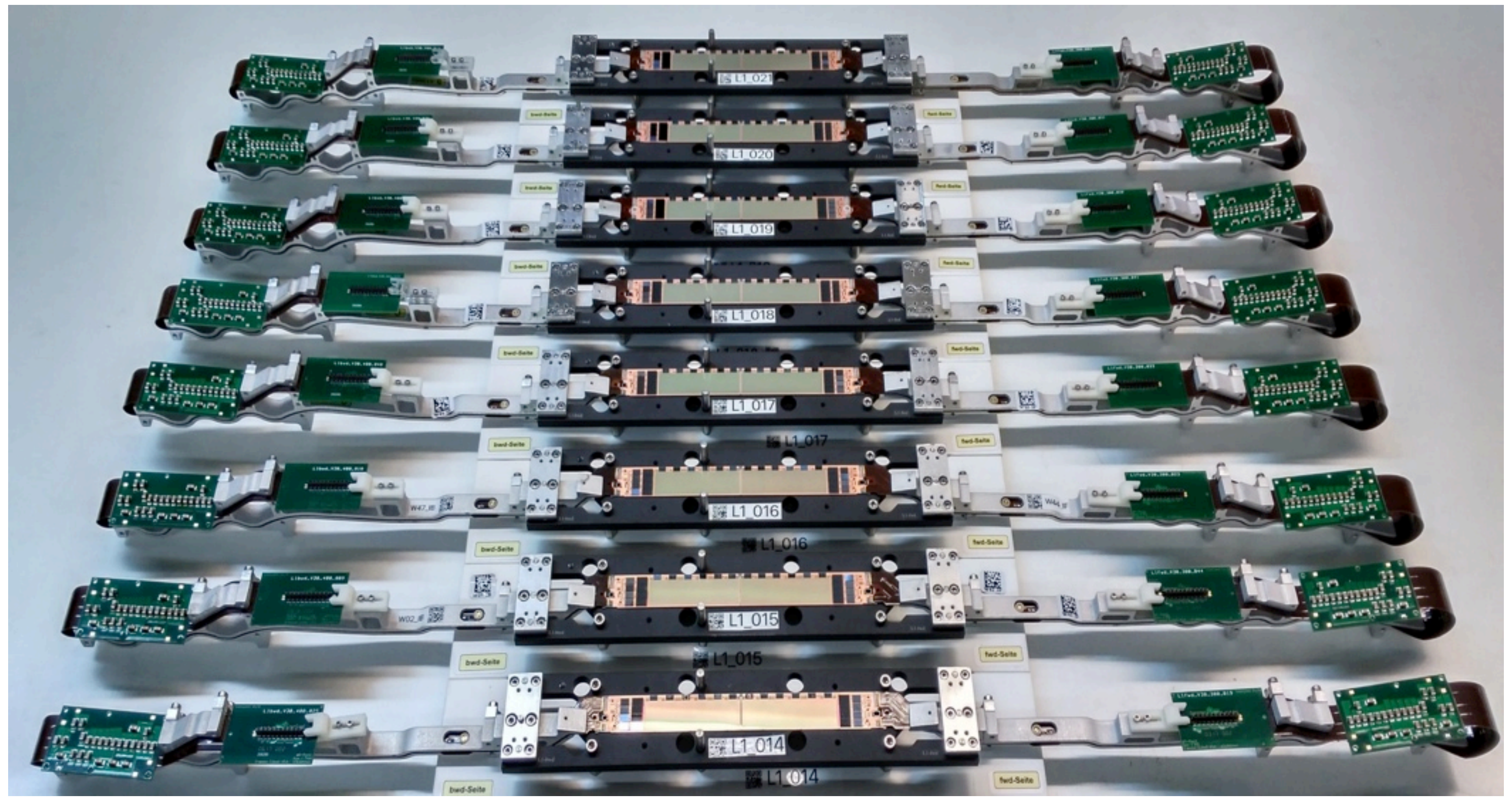
e.g. in γ/Φ_3 measurements the relative strength of V_{ub} and V_{cb} processes and colour suppression.

Towards Phase 3 and the Physics Run

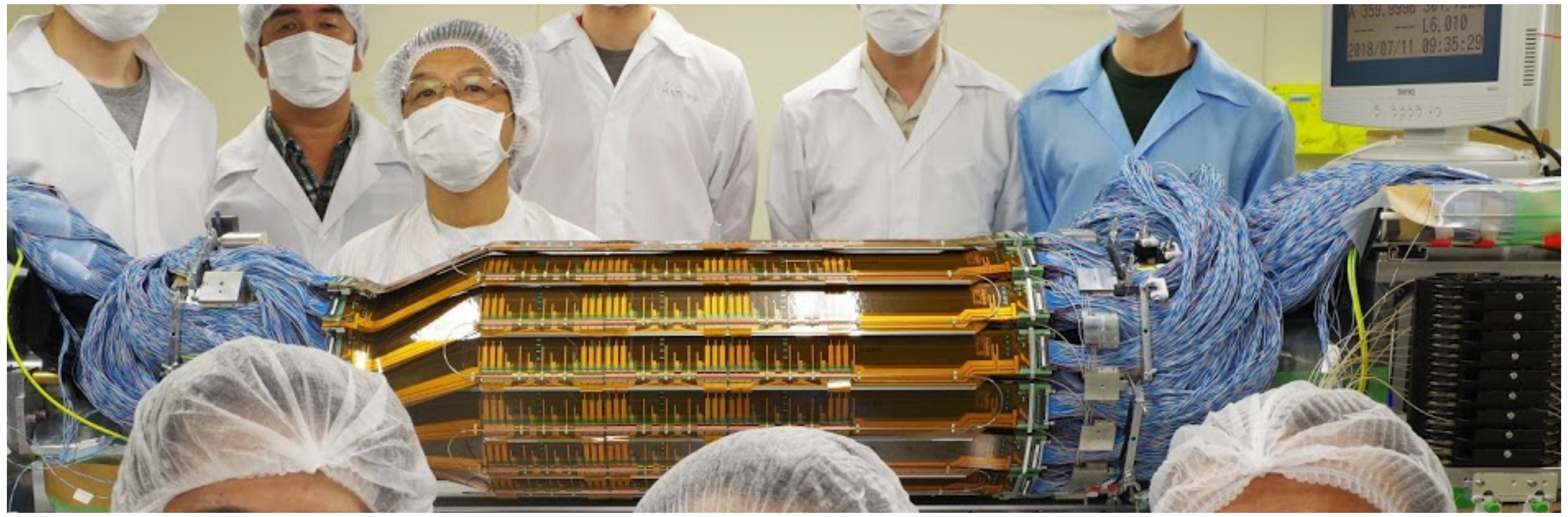
The VXD will be installed in Phase 3.
Restart Belle II data taking in late February 2019.

SVD +x half-shell, Jan 2018 KEK

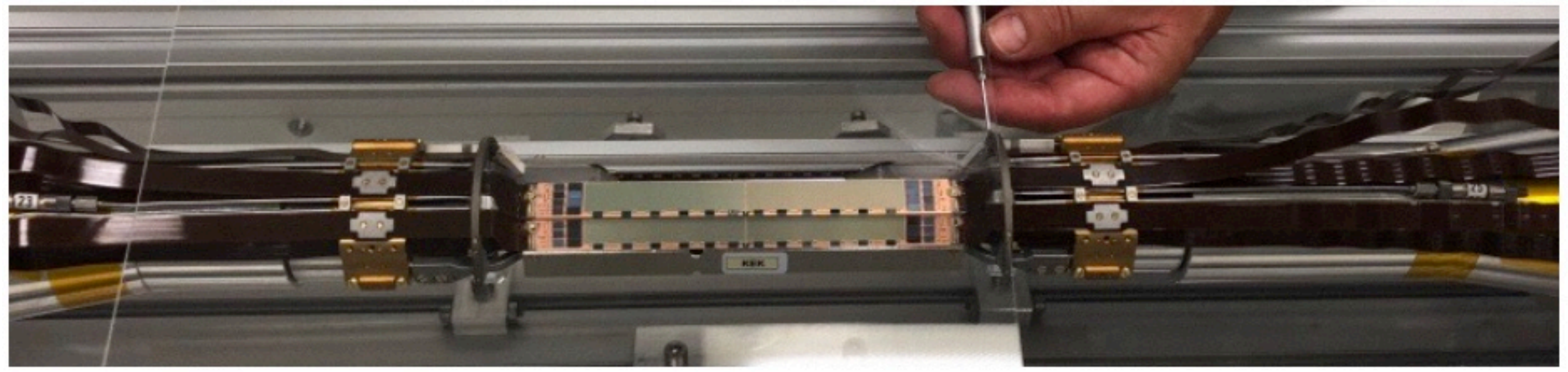




SVD -x half-shell, July 2018, KEK



PXD layer 1 ladders, Feb 2018



First PXD half-shell being tested at DESY, July 2018