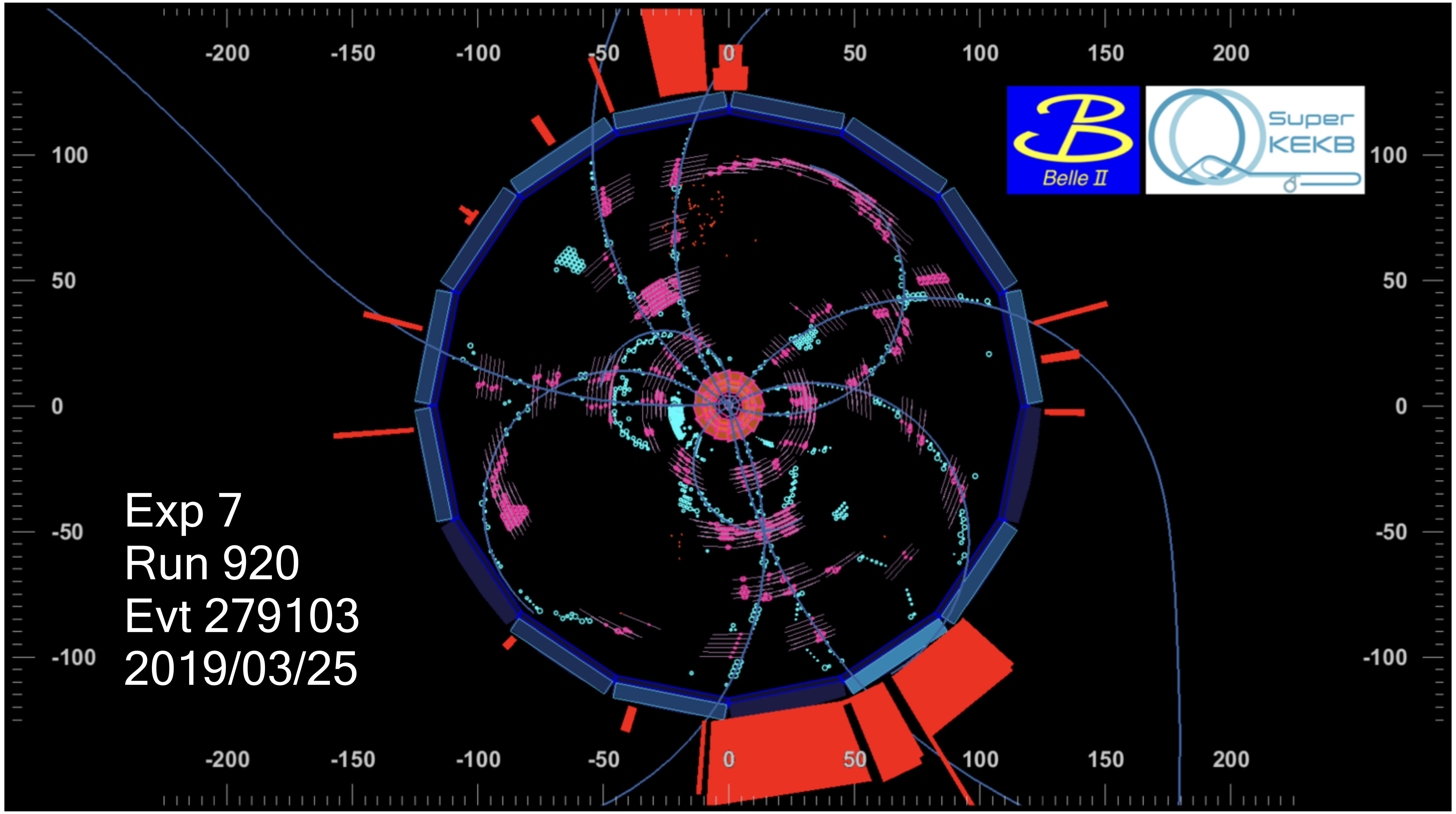



# Belle II status and plans

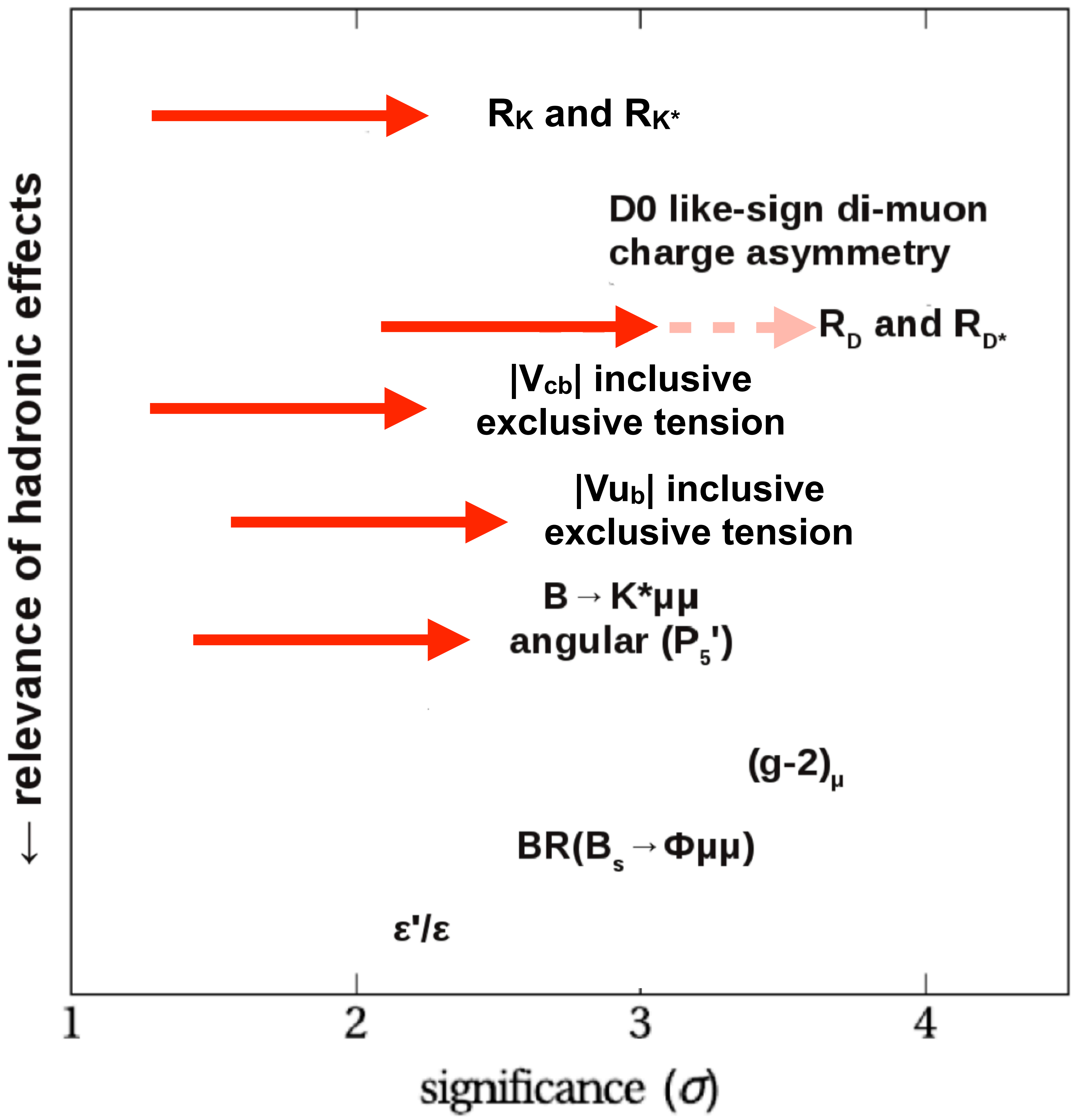
**Phillip Urquijo**
**The University of Melbourne**

Towards the Ultimate Precision in Flavour Physics
Durham, April 2019

# Belle II Flavour Program

- Belle II plans to collect 50 $ab^{-1}$ of collisions near Υ(4S)
  - a (Super) B-factory (~1.1 x $10^9$ BB pairs per $ab^{-1}$)
    a (Super) charm factory (~1.3 x $10^9$ cc pairs per $ab^{-1}$)
    a (Super) τ factory (~0.9 x $10^9$ ττ pairs per $ab^{-1}$)
- *Flavour program at Belle II*
  - CKM precision metrology.
  - Flavour BSM analyses with good "detection universality" (e.g. leptons).
  - Dark, missing energy: hidden portals, axiflavons etc.
- Important, unexplained hierarchy among 10 of 19 params of SM $m_\nu=0$
  - Mass (6 params, small ratios of scales)
  - CP violation (4 params, strong hierarchy between generations)
- With phenomenological consequences for quark flavour dynamics

"Zoltan plot"



# CKM and CPV SM Metrology: Belle II core program

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

| | | | |
|---|---|---|---|
| $B \to \pi\pi, \rho\rho$ | $\alpha / \Phi_2$ | $B \to D^* l \nu / b \to c l \nu$ | $\lvert V_{cb}\rvert$ via Form factor / OPE |
| $B \to D^{(*)} K^{(*)}$ | $\gamma / \Phi_3$ | $B \to \pi l \nu / b \to u l \nu$ | $\lvert V_{ub}\rvert$ via Form factor / OPE |
| $B \to J/\psi K_s$ | $\beta / \Phi_1$ | $M \to l \nu (\gamma)$ | $\lvert V_{UD}\rvert$ via Decay constant $f_M$ |
| $B_s \to J/\psi \Phi$ | $\beta_s$ | $\Delta m_d, \Delta m_s$ | $\lvert V_{tb} V_{t\{d,s\}}\rvert$ via Bag factor $B_B$ |

- Precision improvements require improved uncertainties and resolved tensions, e.g. $|V_{ub}|$ inc.-excl.

**WA HFLAV & CKMfitter 2018**

$\sin 2\Phi_1 = 0.70 \pm 0.02$

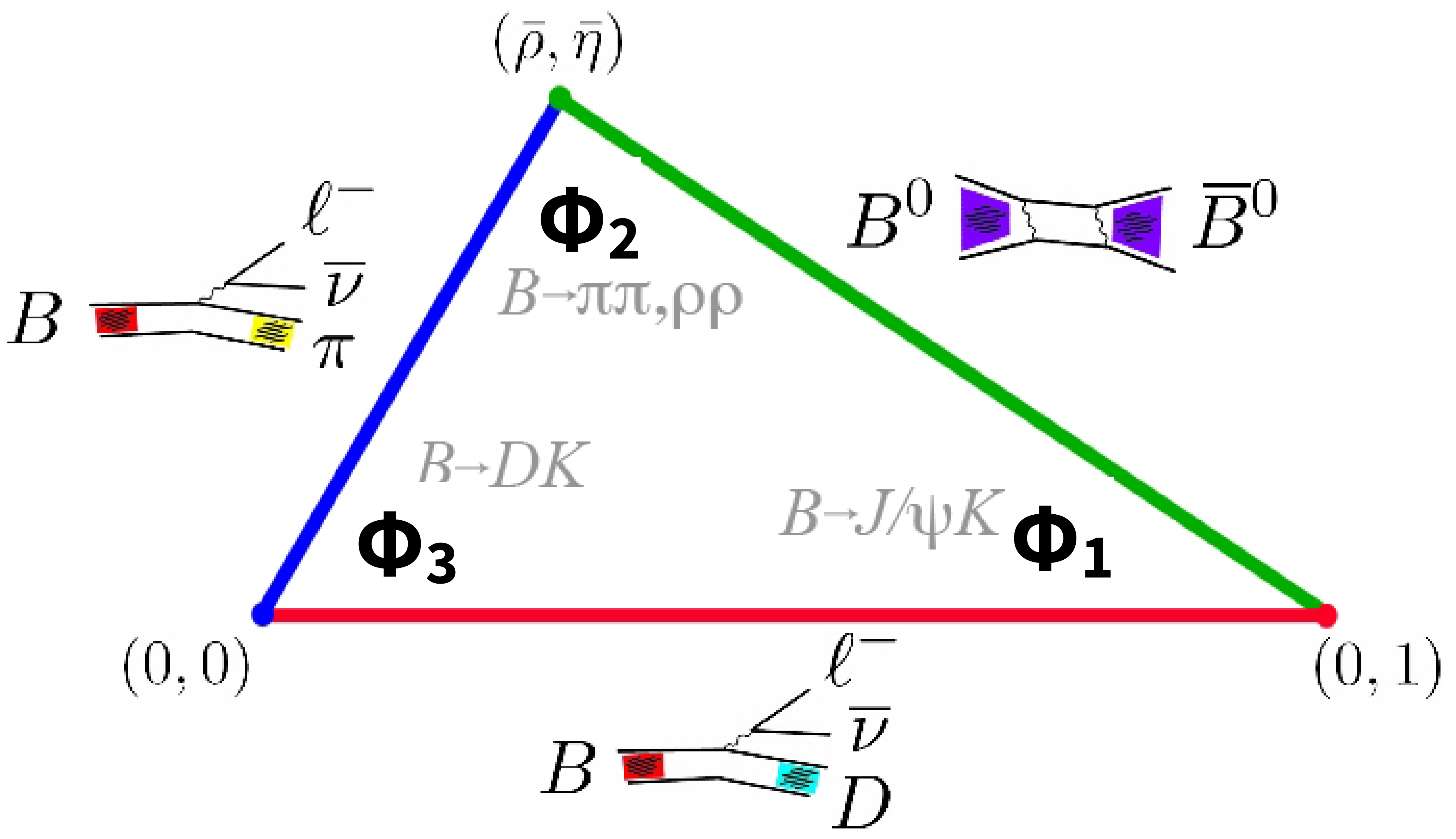
$\Phi_2 = (84.9^{+5.1}_{-4.5})^\circ$

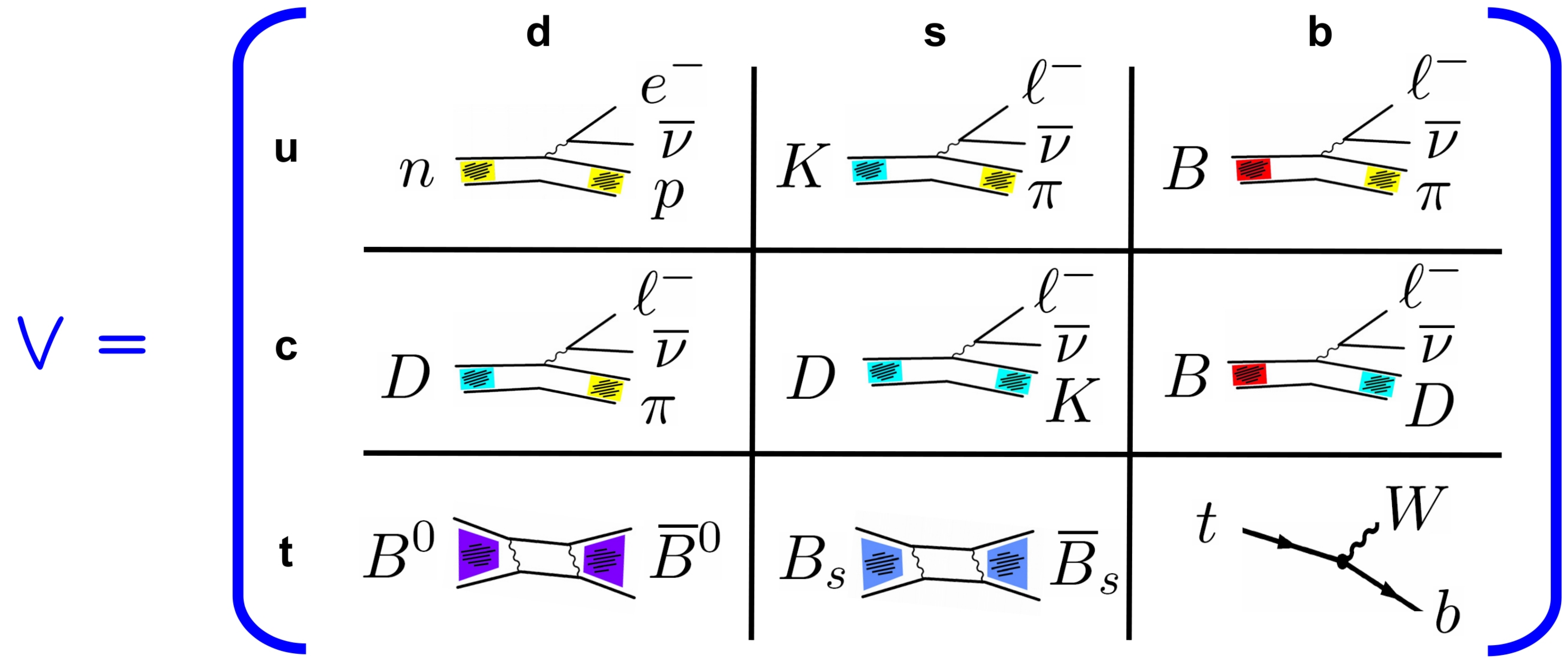
$\Phi_3 = (73.5^{+4.2}_{-5.1})^\circ$

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

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

# CKM and CPV SM Metrology: Belle II core program




| | | | |
|---|---|---|---|
| $B\to\pi\pi,\rho\rho$ | $\alpha/\Phi_2$ | $B\to D^* l\nu / b\to c l\nu$ | $\lvert V_{cb}\rvert$ via Form factor / OPE |
| $B\to D^{(*)}K^{(*)}$ | $\gamma/\Phi_3$ | $B\to\pi l\nu / b\to u l\nu$ | $\lvert V_{ub}\rvert$ via Form factor / OPE |
| $B\to J/\psi K_s$ | $\beta/\Phi_1$ | $M\to l\nu(\gamma)$ | $\lvert V_{UD}\rvert$ via Decay constant $f_M$ |
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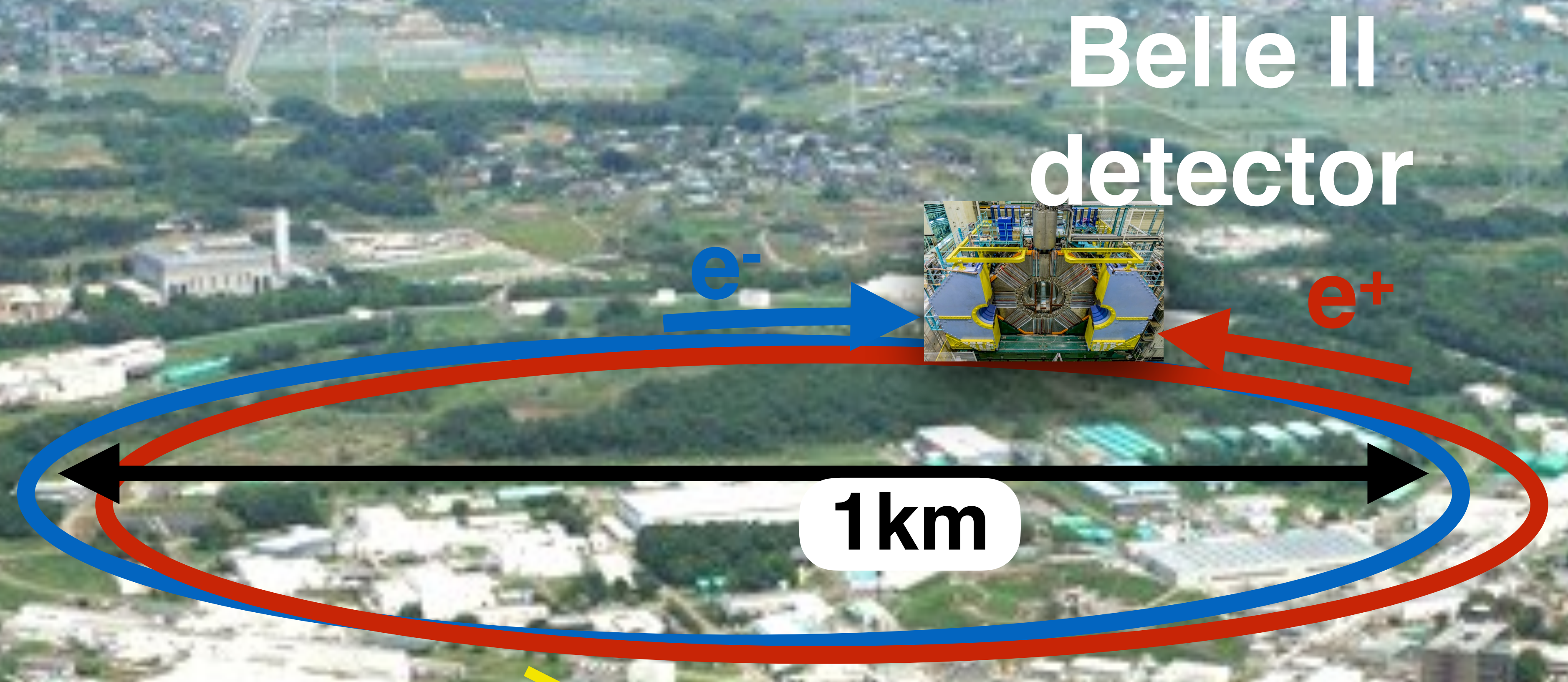
# Belle II @ Super-KEKB

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



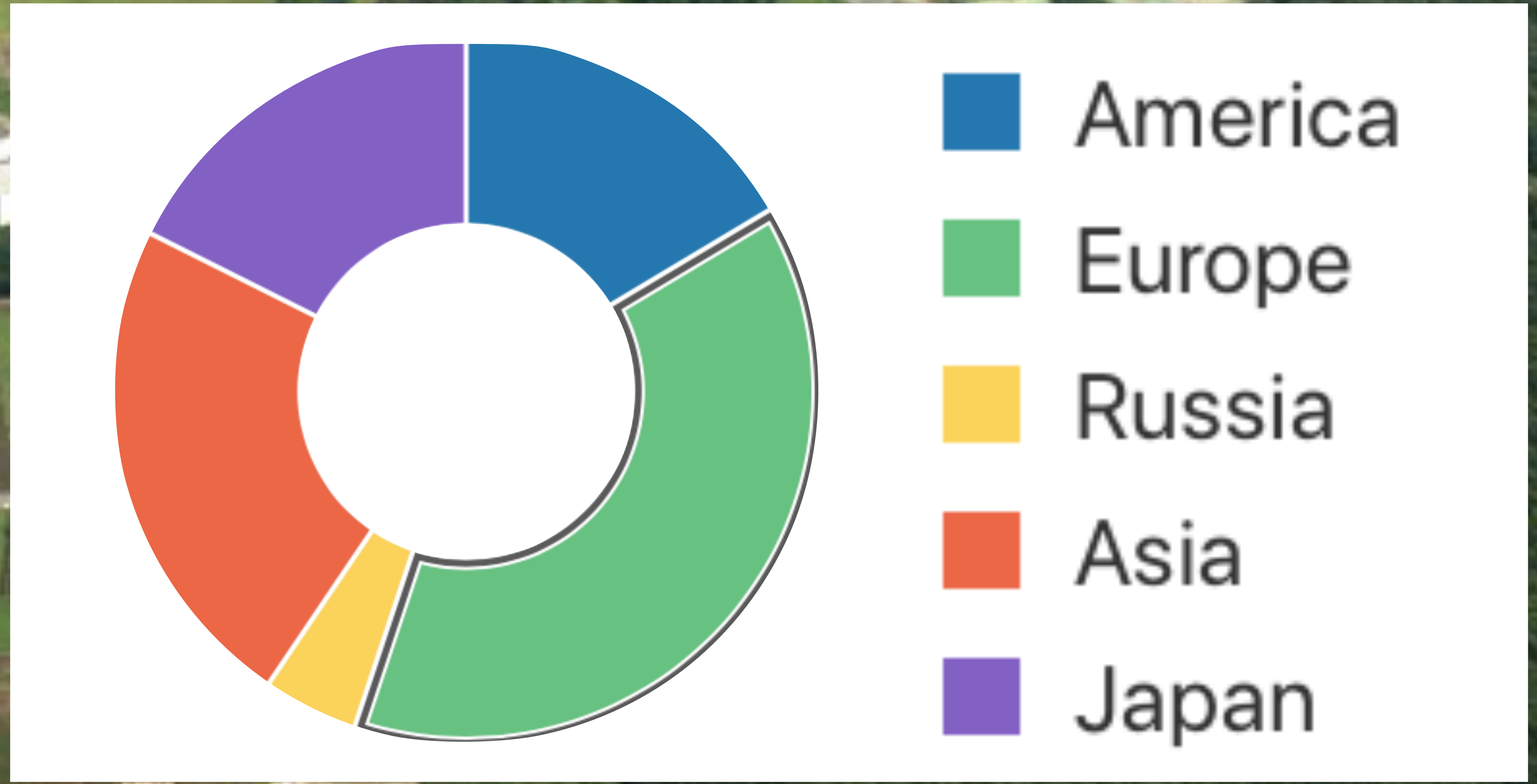

$7$ GeV $e^-$, $4$ GeV $e^+$

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

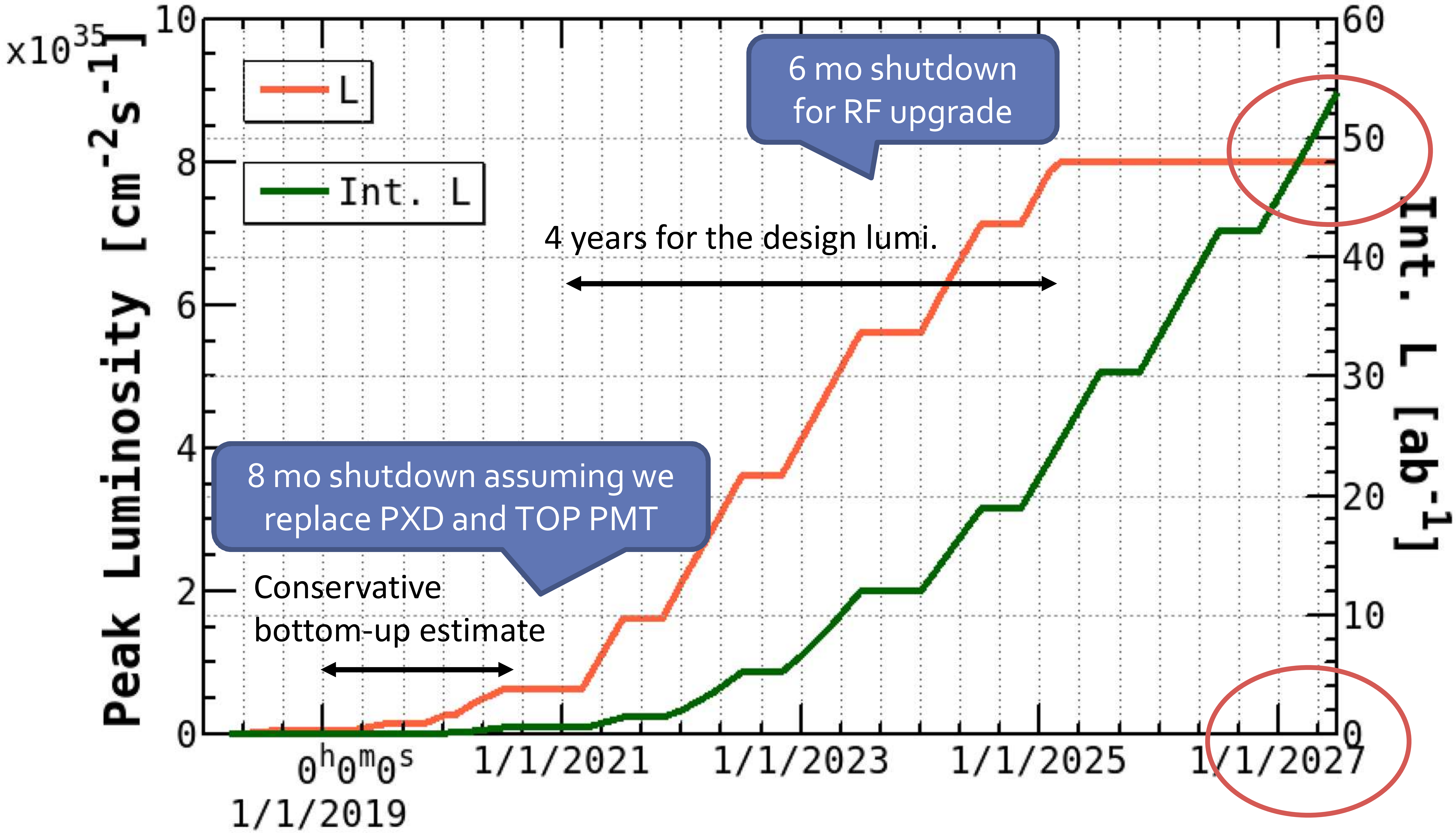
$\Upsilon(4S) \rightarrow B$ anti-$B$

B + Charm + $\tau$ factory

~900 researchers
(306 grad students)
from 25 countries.

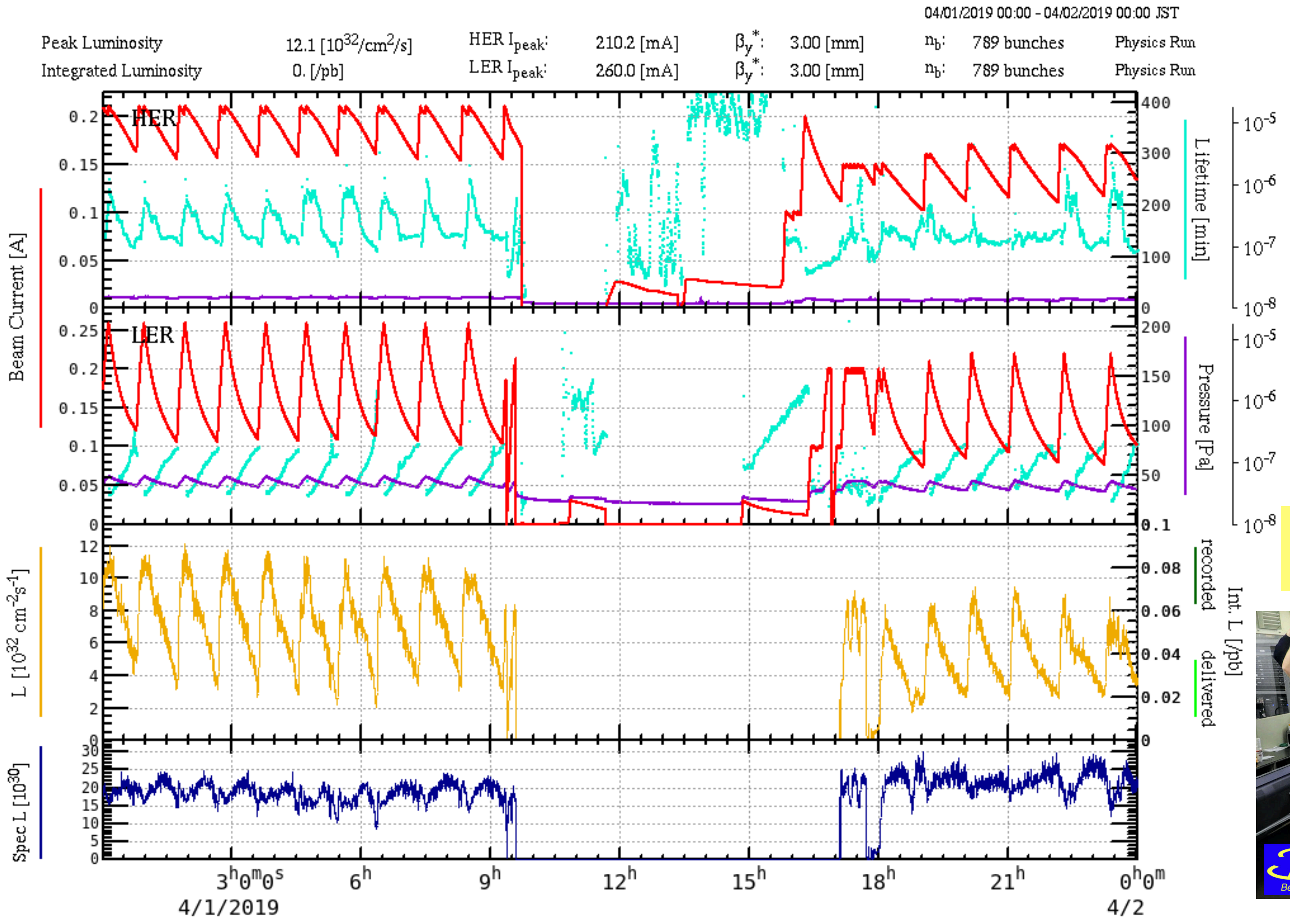


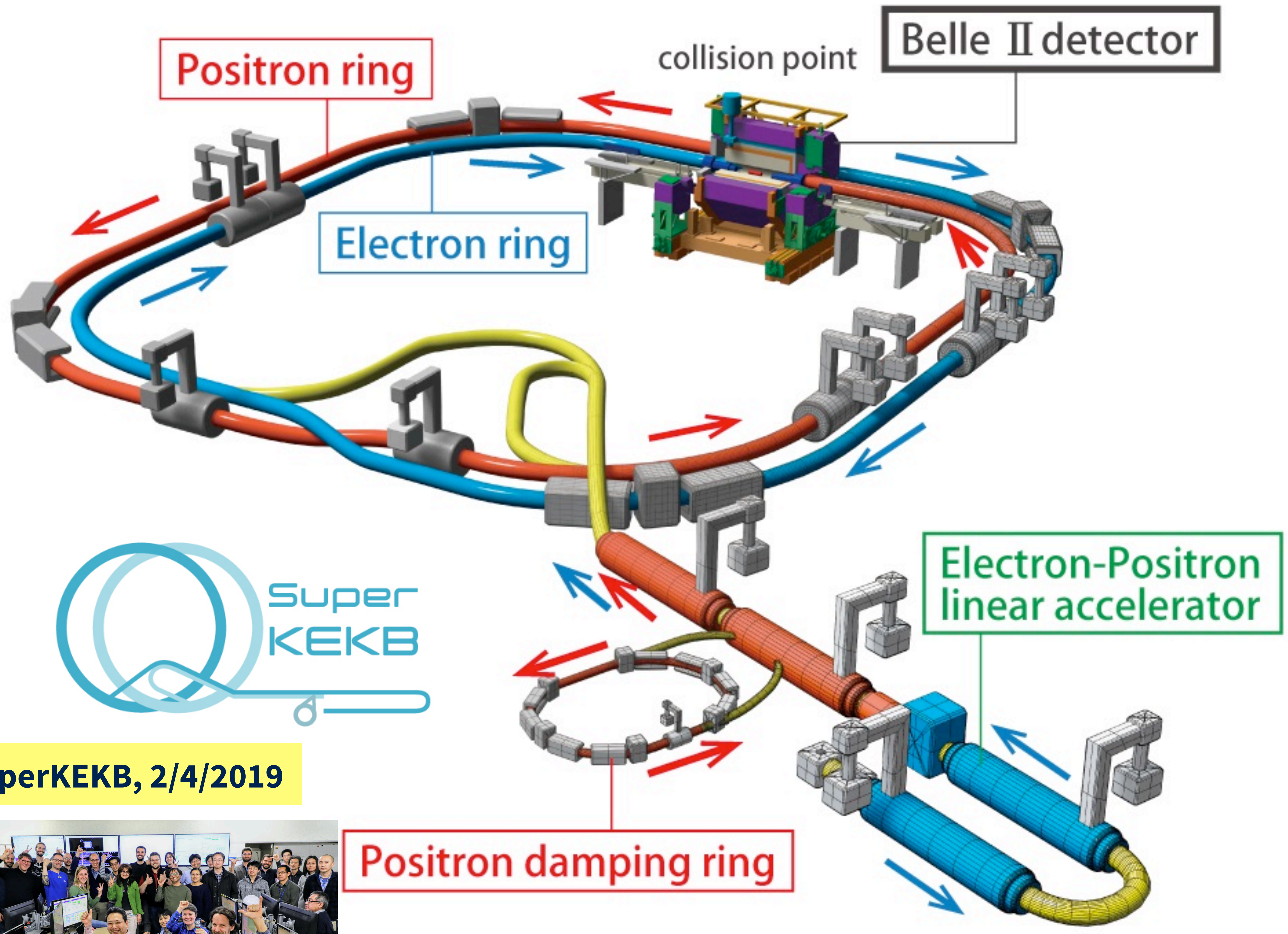
# Expected (Integrated) Luminosity



# SuperKEKB - March 25 2019 “Phase 3” Begins

1) New $e^+$ damping ring (commissioned 2018).
2) New 3 km $e^+$ ring vacuum chamber (commissioned in 2016). Optics and vacuum scrubbing in 2018.
3) New superconducting final focus (commissioned 2018).

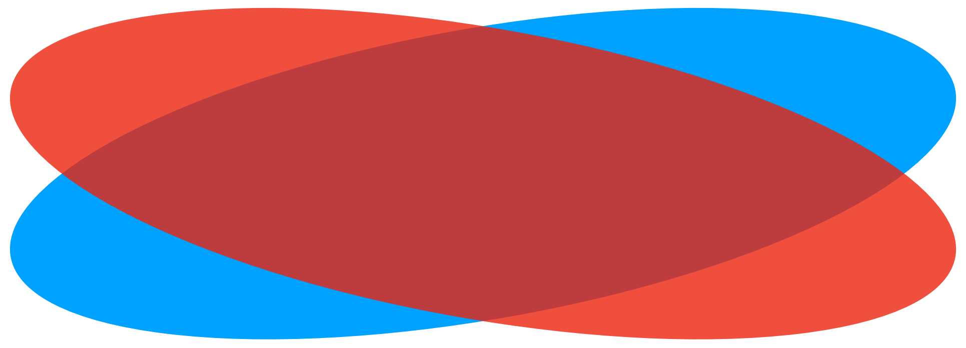


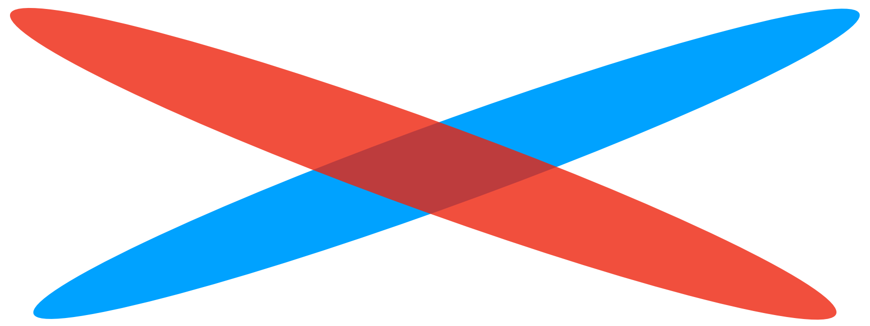

SuperKEKB, 2/4/2019

# Large crossing angle nano-beams

**KEKB**



**SuperKEKB**



**The vertex distribution is constrained in the nano-beam scheme.**

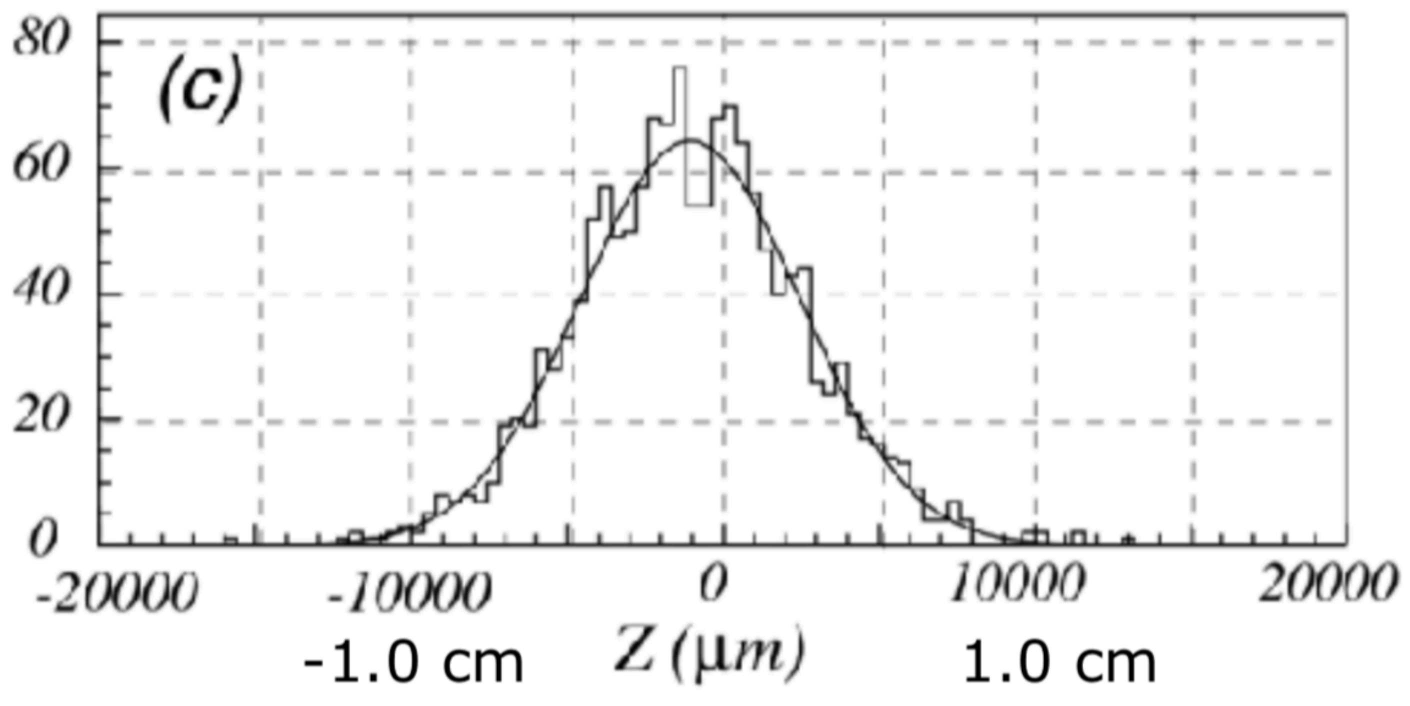
Effective bunch length *reduced x 1/10*

*Measured in 2-track events in Belle II data with one wedge of the silicon detector.*

*Tiny beam size is a useful constraint for TDCPV analyses.*

**Ordinary collision (KEKB)**

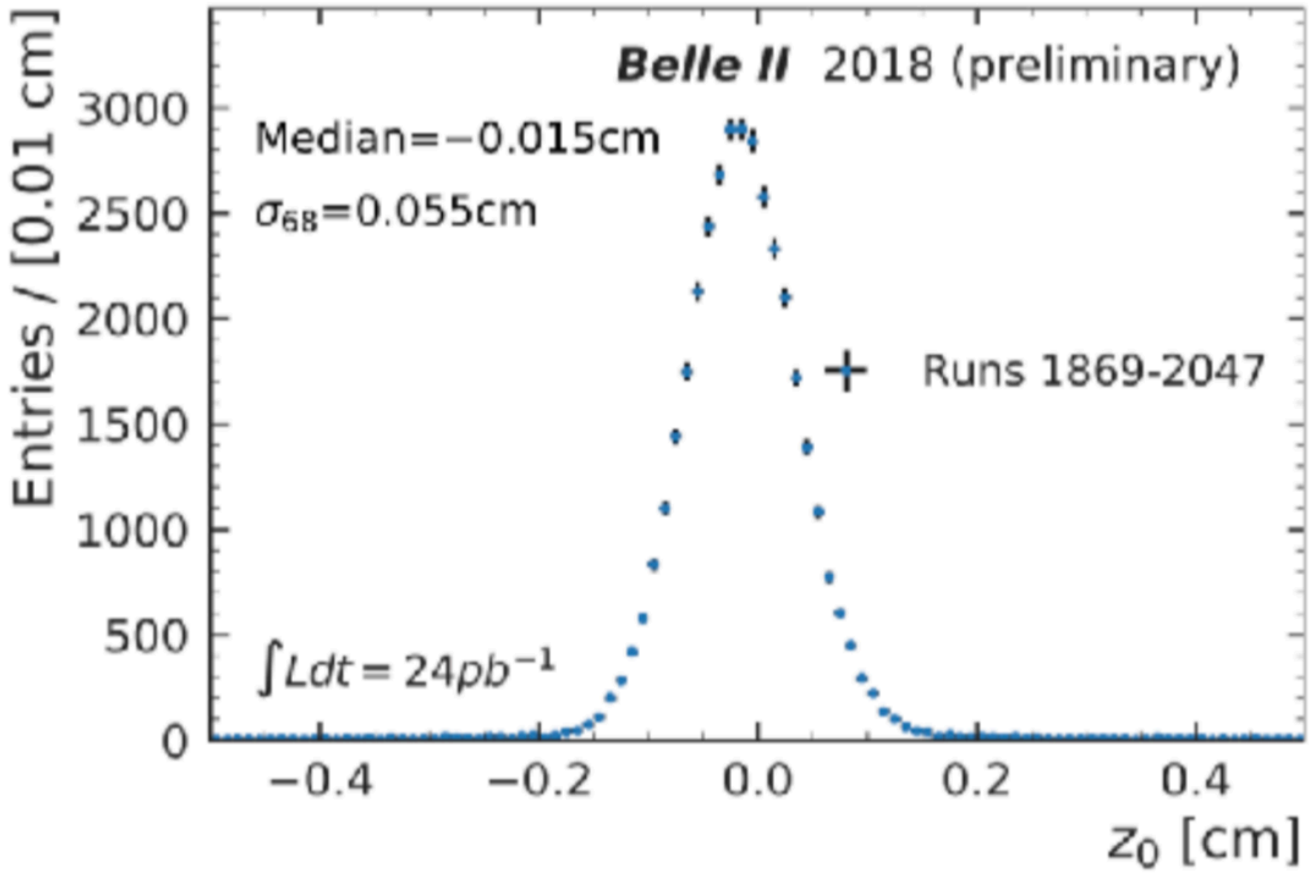
Belle case 1999 data



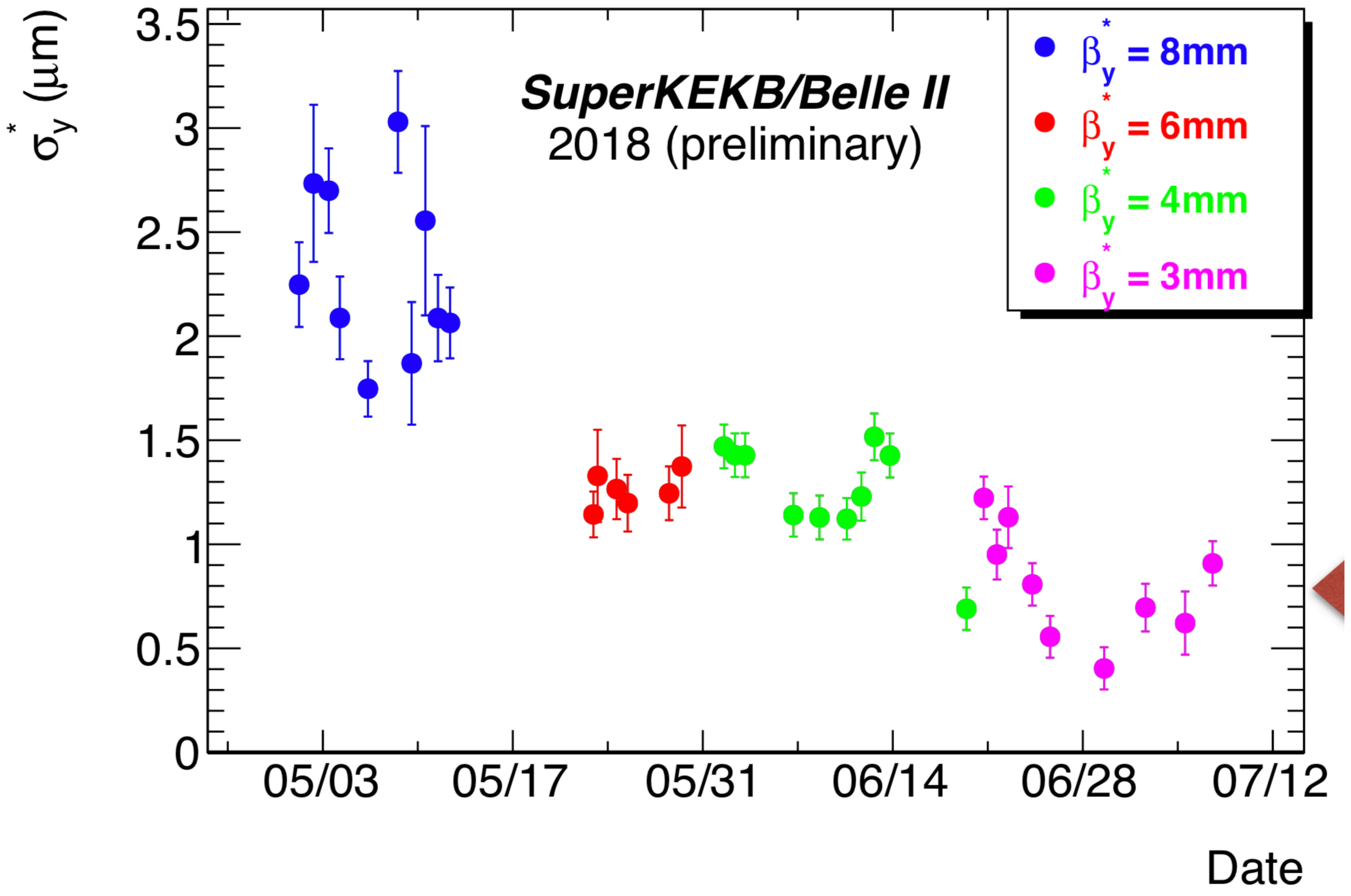

**σ = 4.5 mm**

**Nano-Beam (SuperKEKB Phase2)**

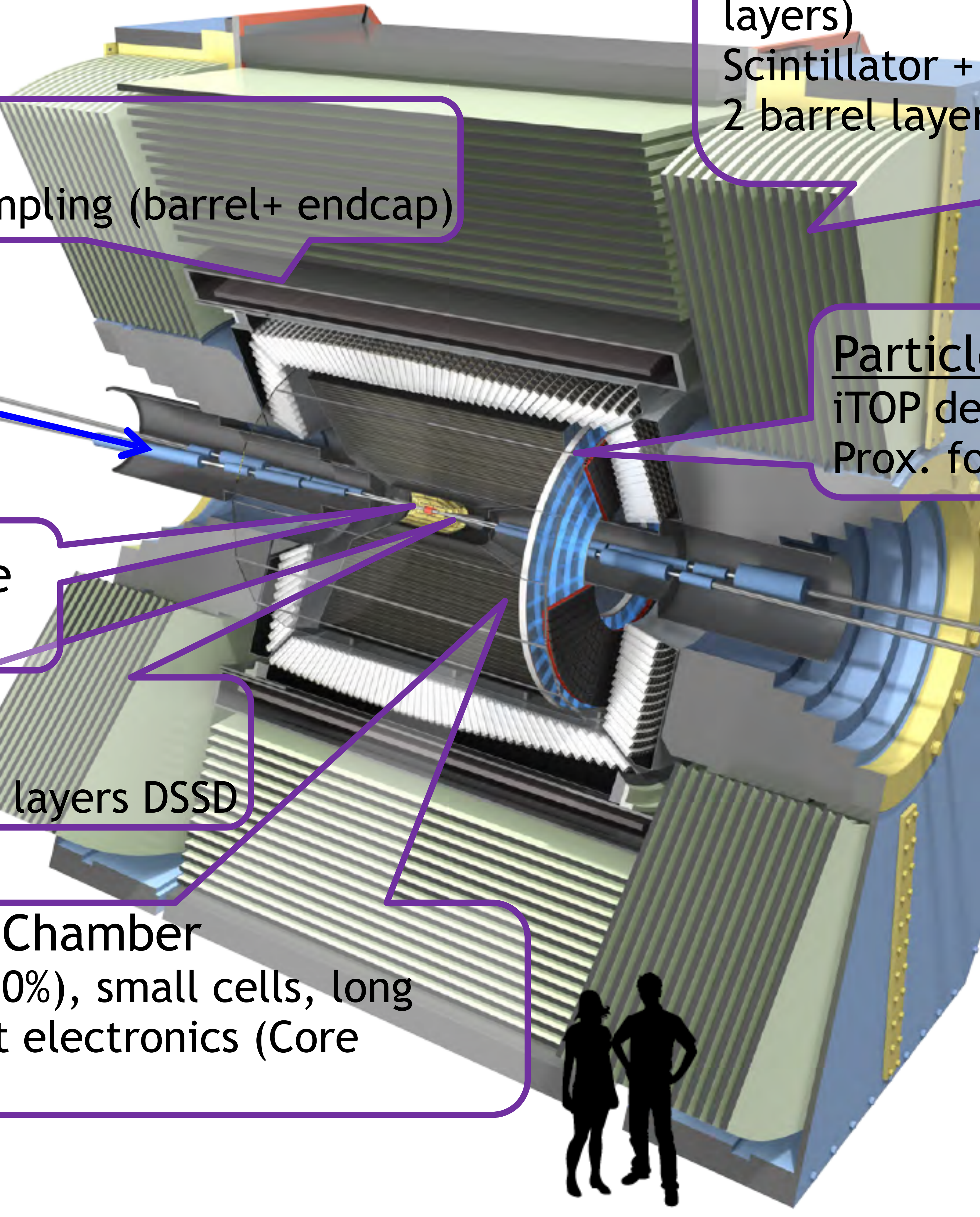
Z vertex distribution




**σ = 550 μm**



# Belle II Detector, 2019 commissioning of new VXD



**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)

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

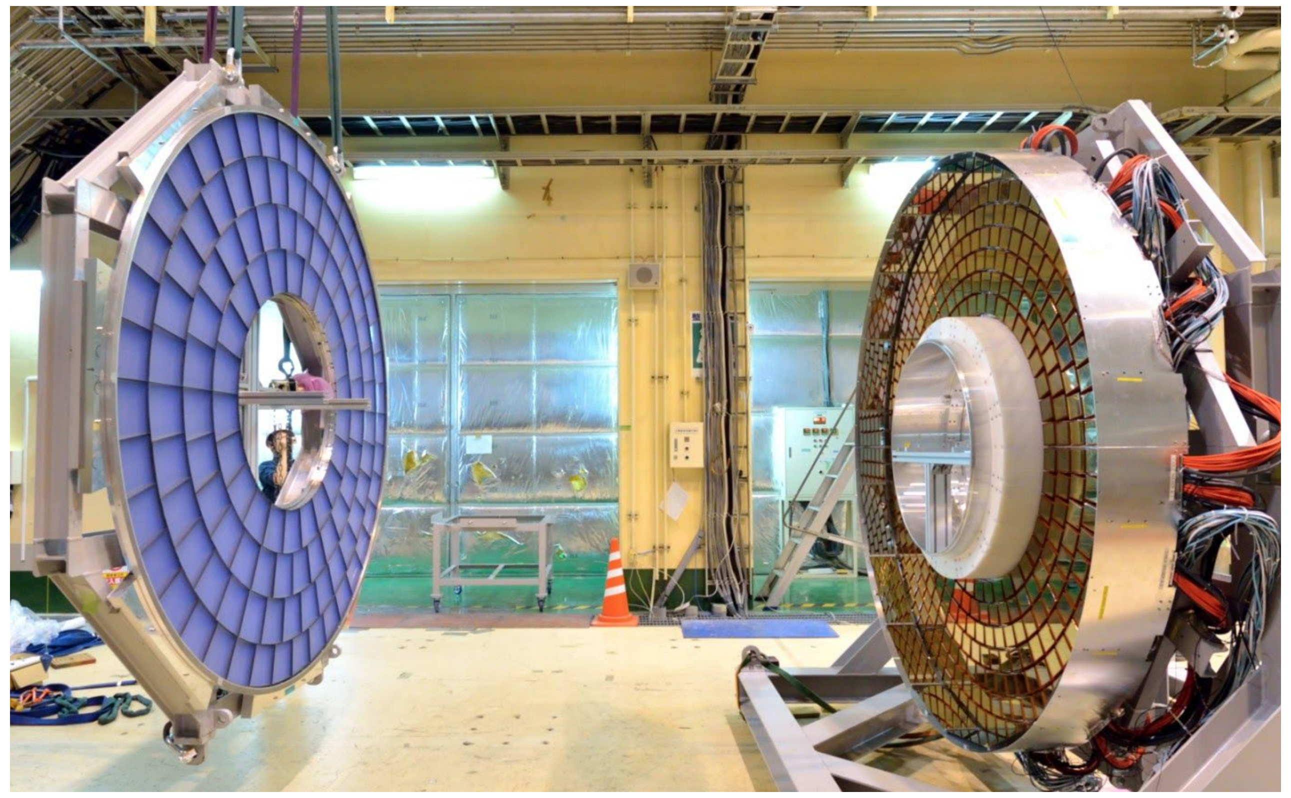
electrons (7 GeV)

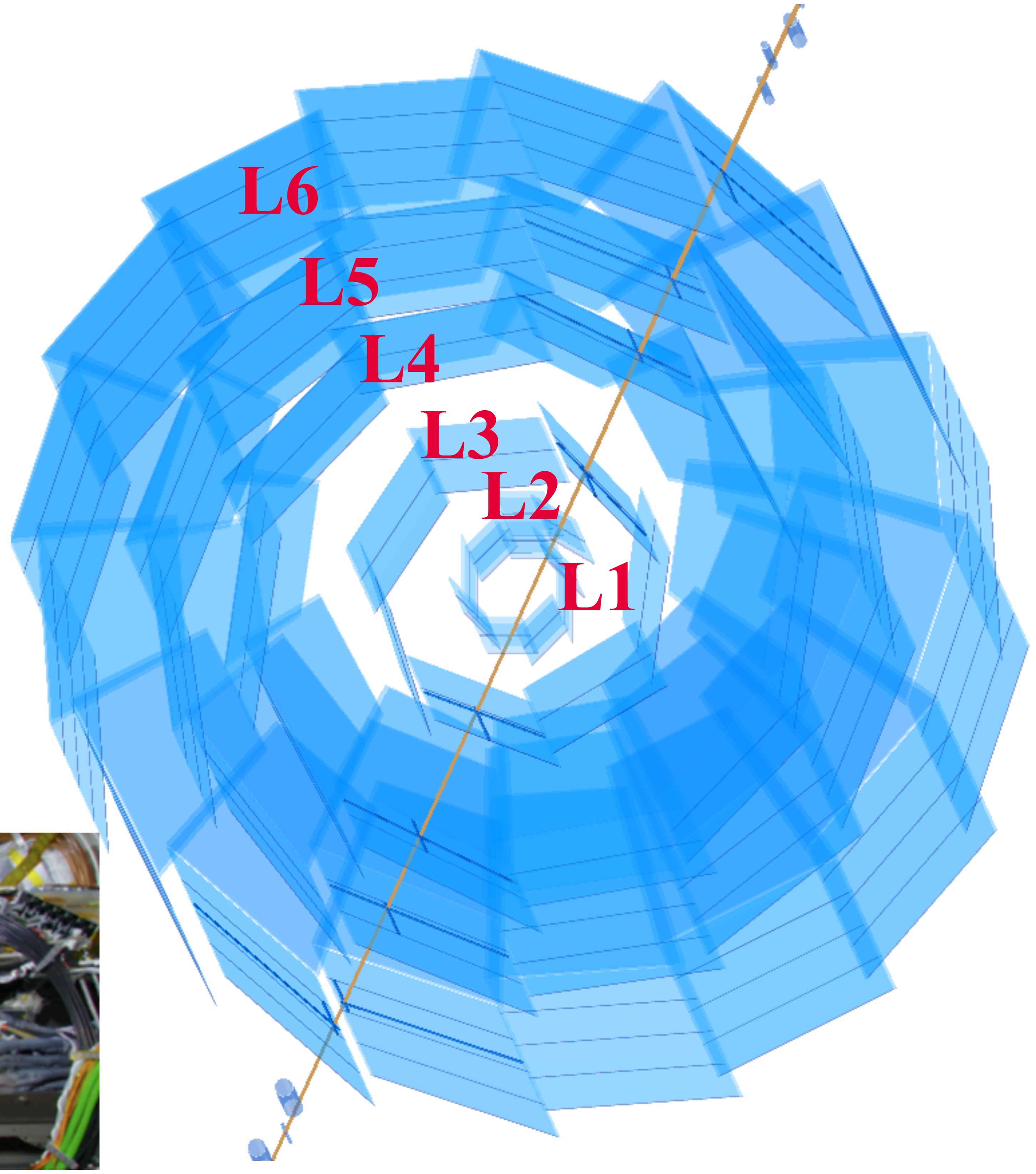
**Beryllium beam pipe**
2cm diameter

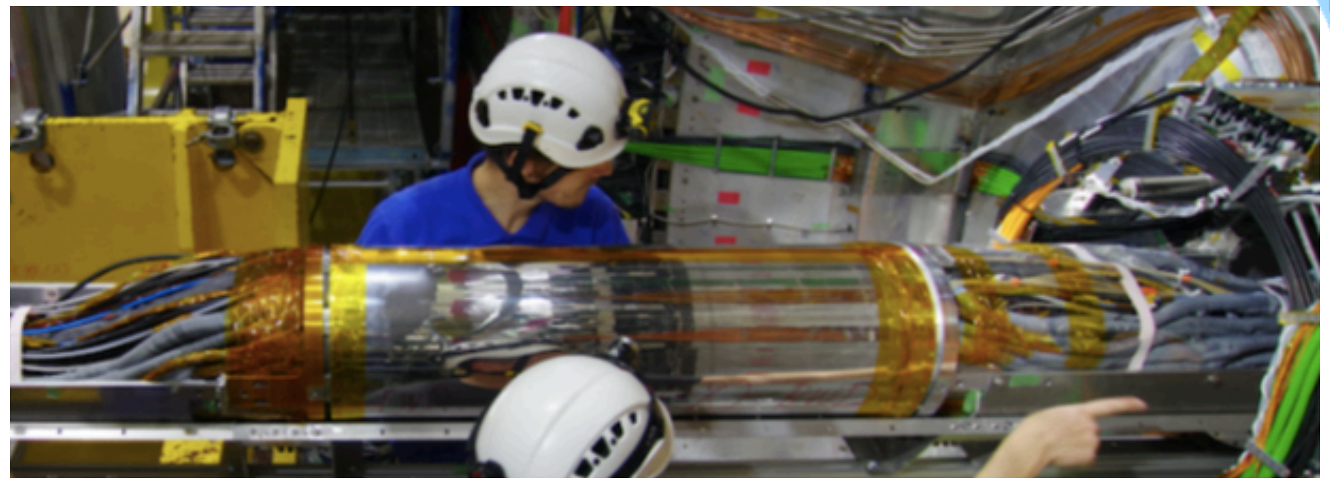
**Vertex Detector**
1→2 layers DEPFET + 4 layers DSSD

positrons (4 GeV)

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

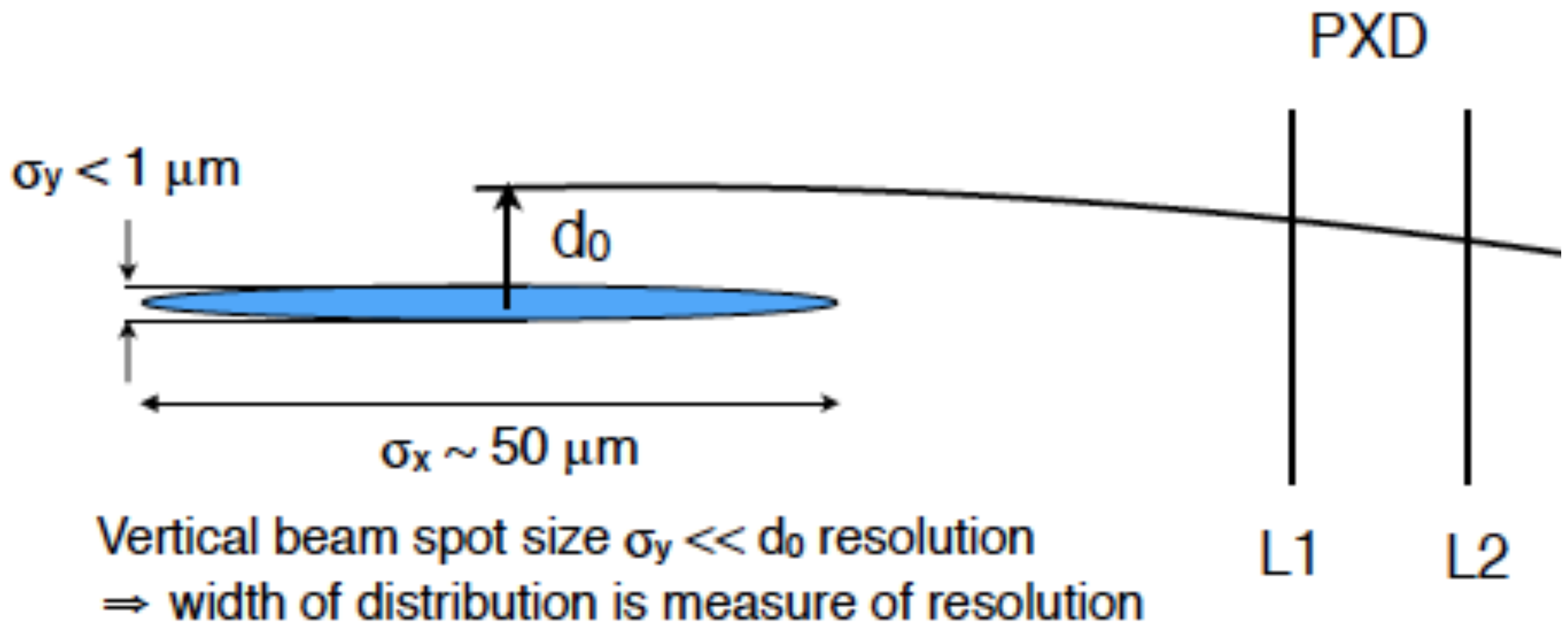




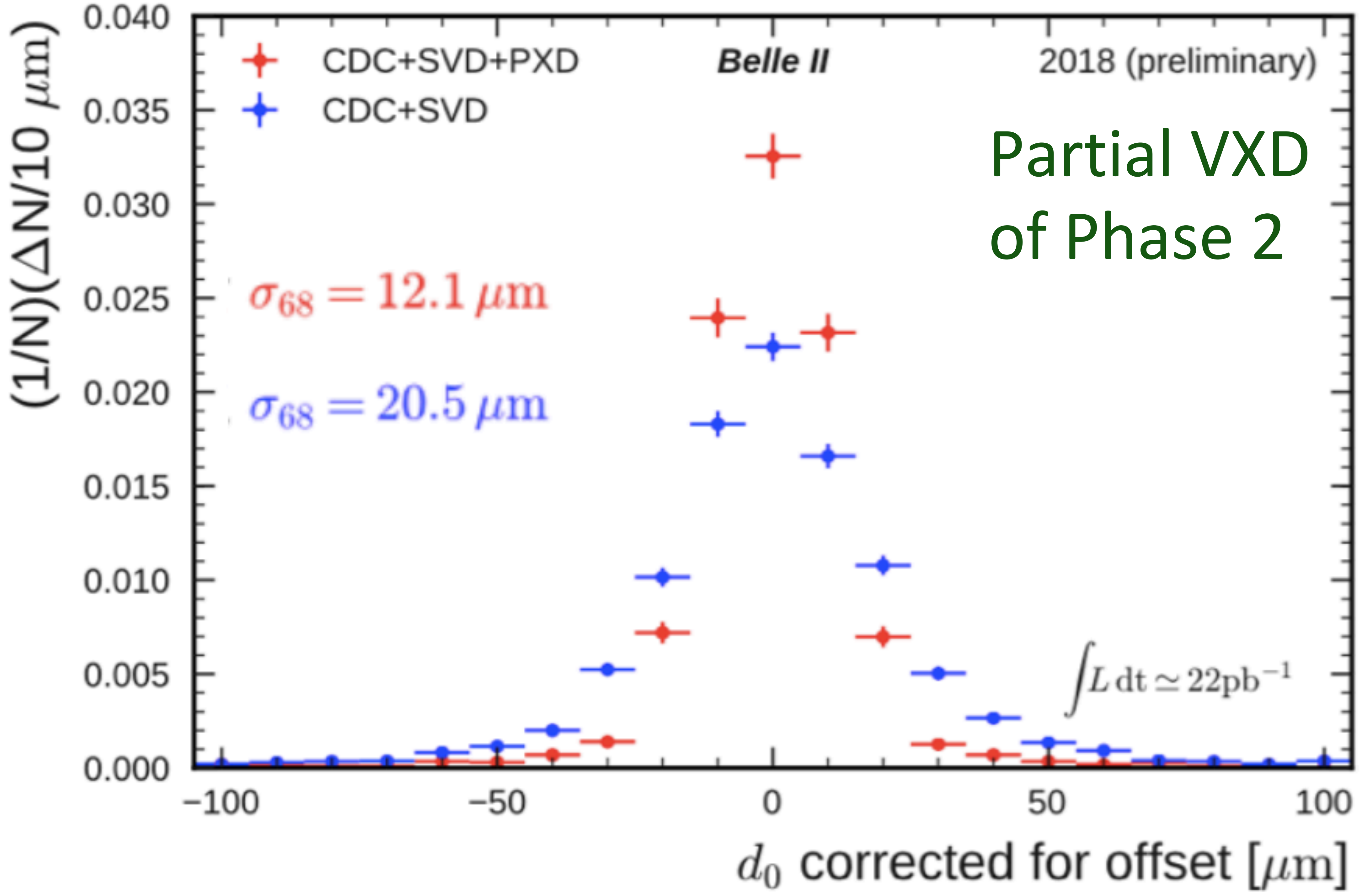
# VXD measured and expected performance

- PXD: L1+1/6 of L2 (rest will be added in 2020)
- VXD (tracking) already working in phase 3.

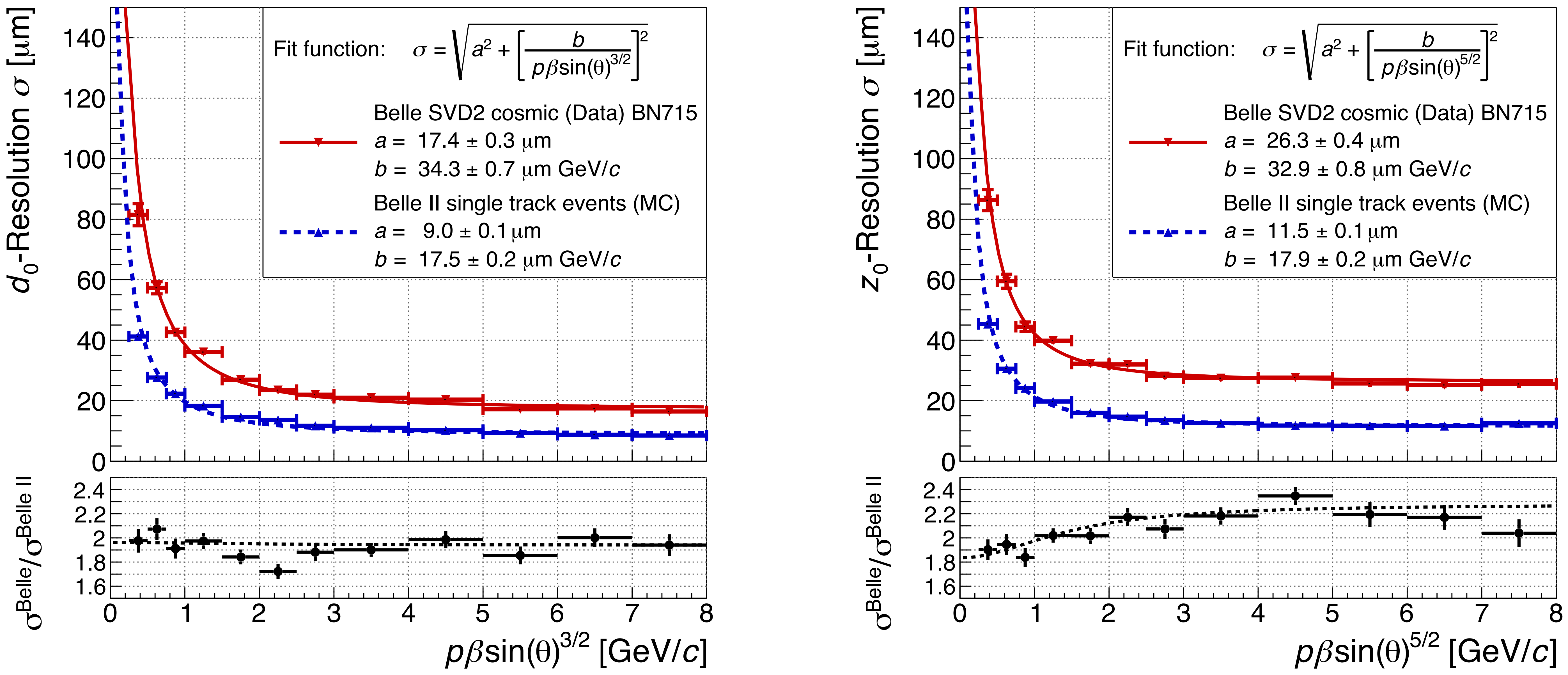



Transverse impact parameter resolution of 12 µm (vs 10 µm expected) thanks to PXD, about 2x better than Belle.

**Phase 2**




**Belle II MC Vs Belle**



# 2018 Standard Candles, ee→γγ, ee(γ), ττ (γ)

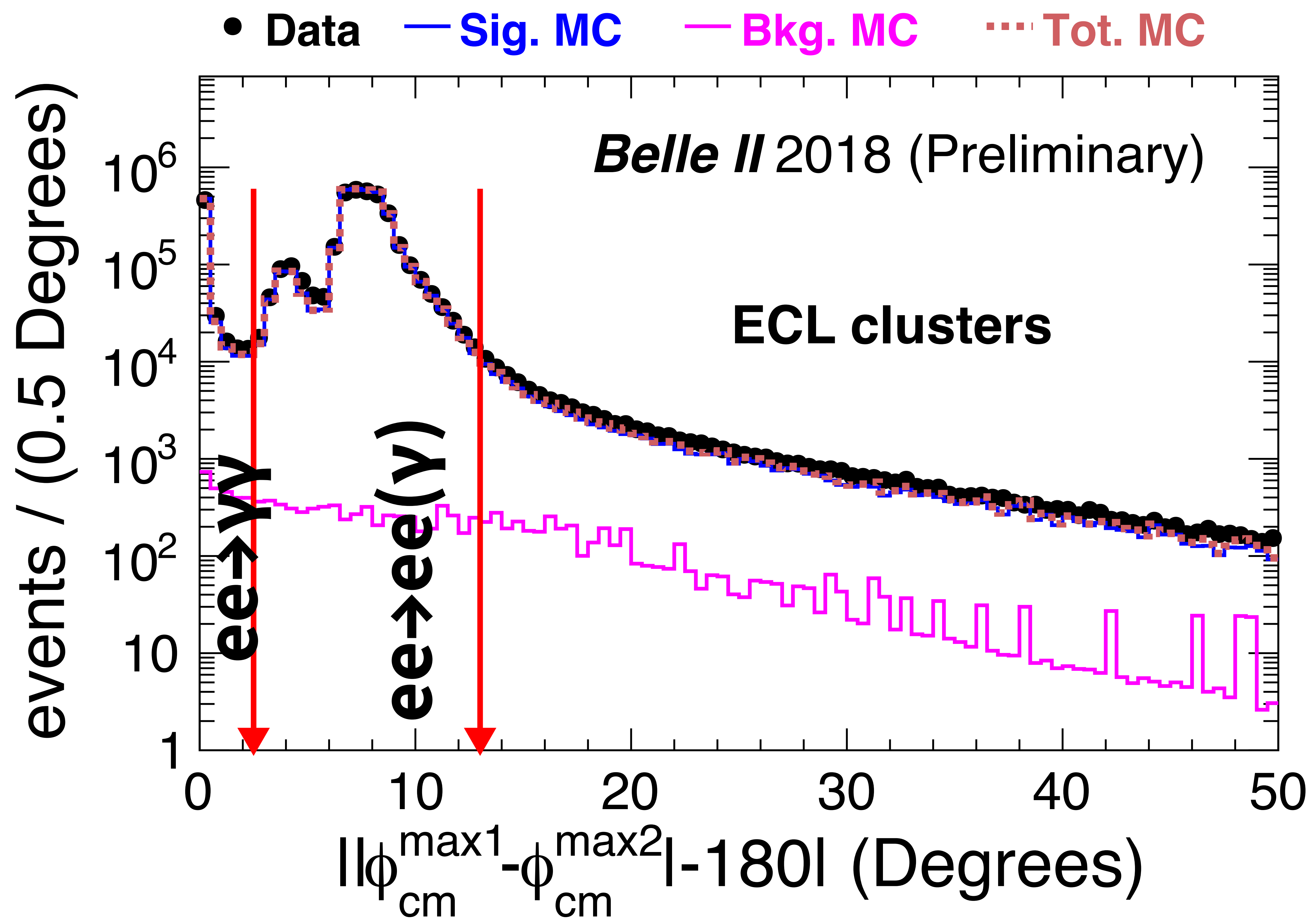
*Phase 2 run, April-July 2018*

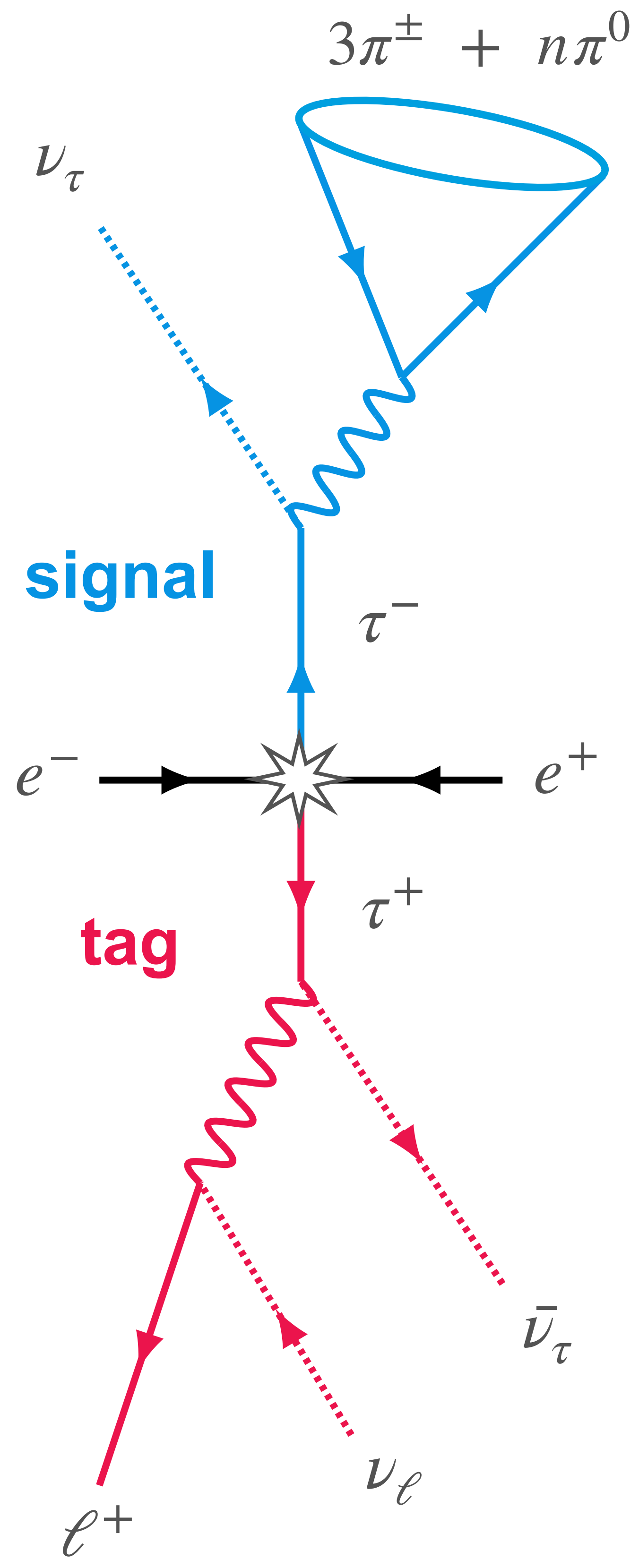
**$L_{peak}$ = 5.5 x $10^{33}/cm^2/s$**

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

**Integrated luminosity ~ 500/pb**

Measured with ee→ ee(γ), γγ

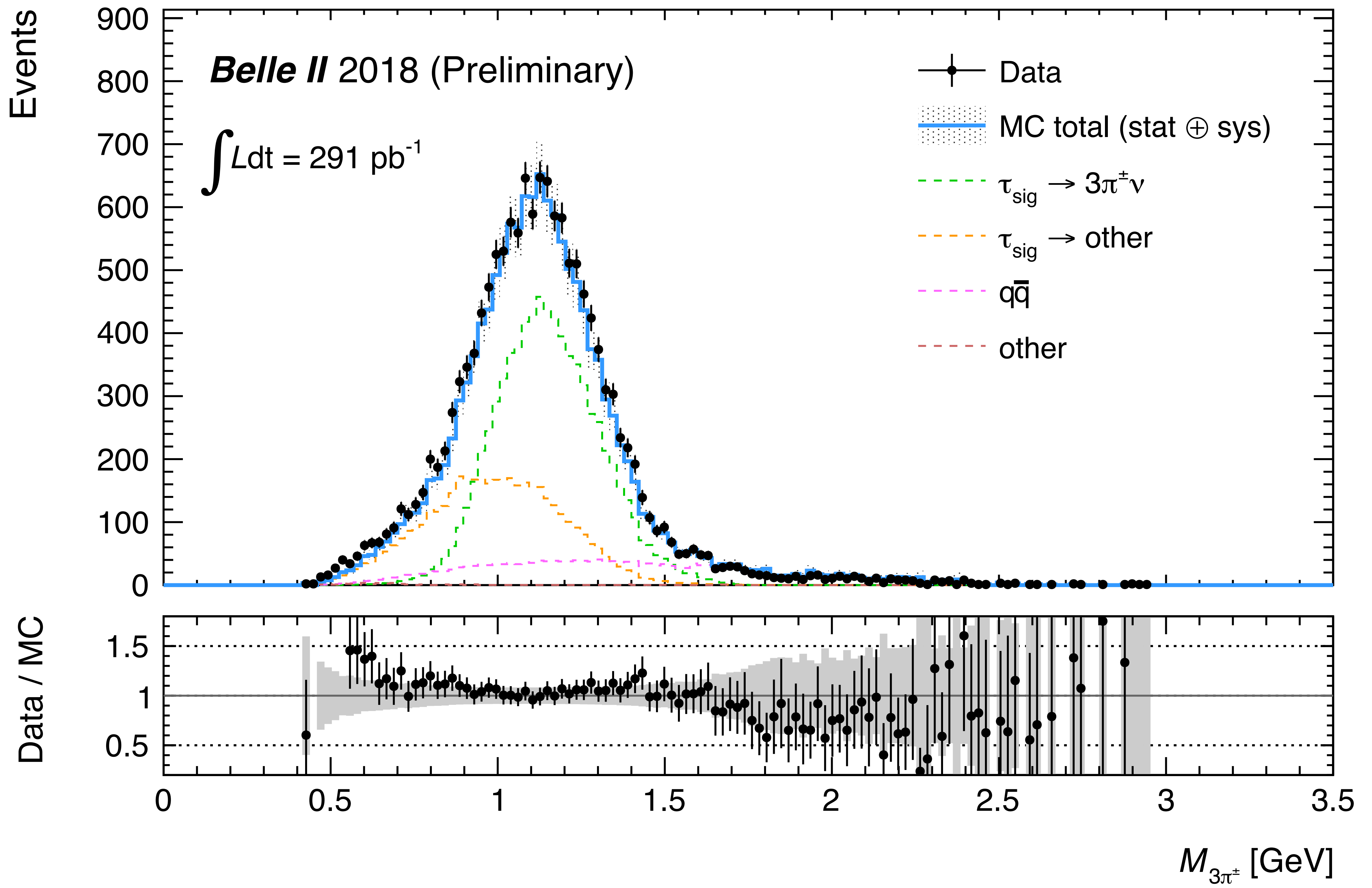



**ee→ττ(γ)**

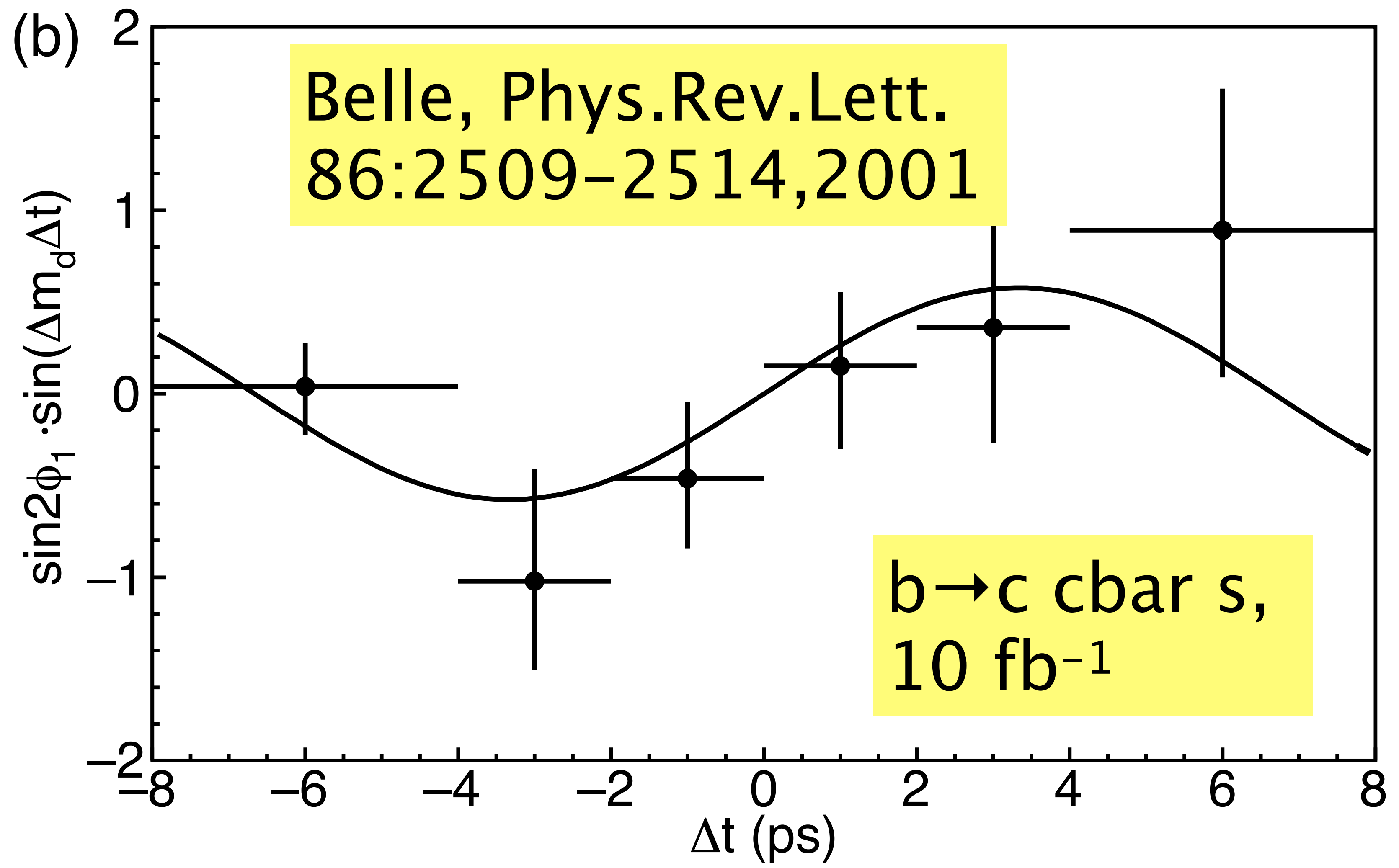
Used for early trigger & track efficiency measurements

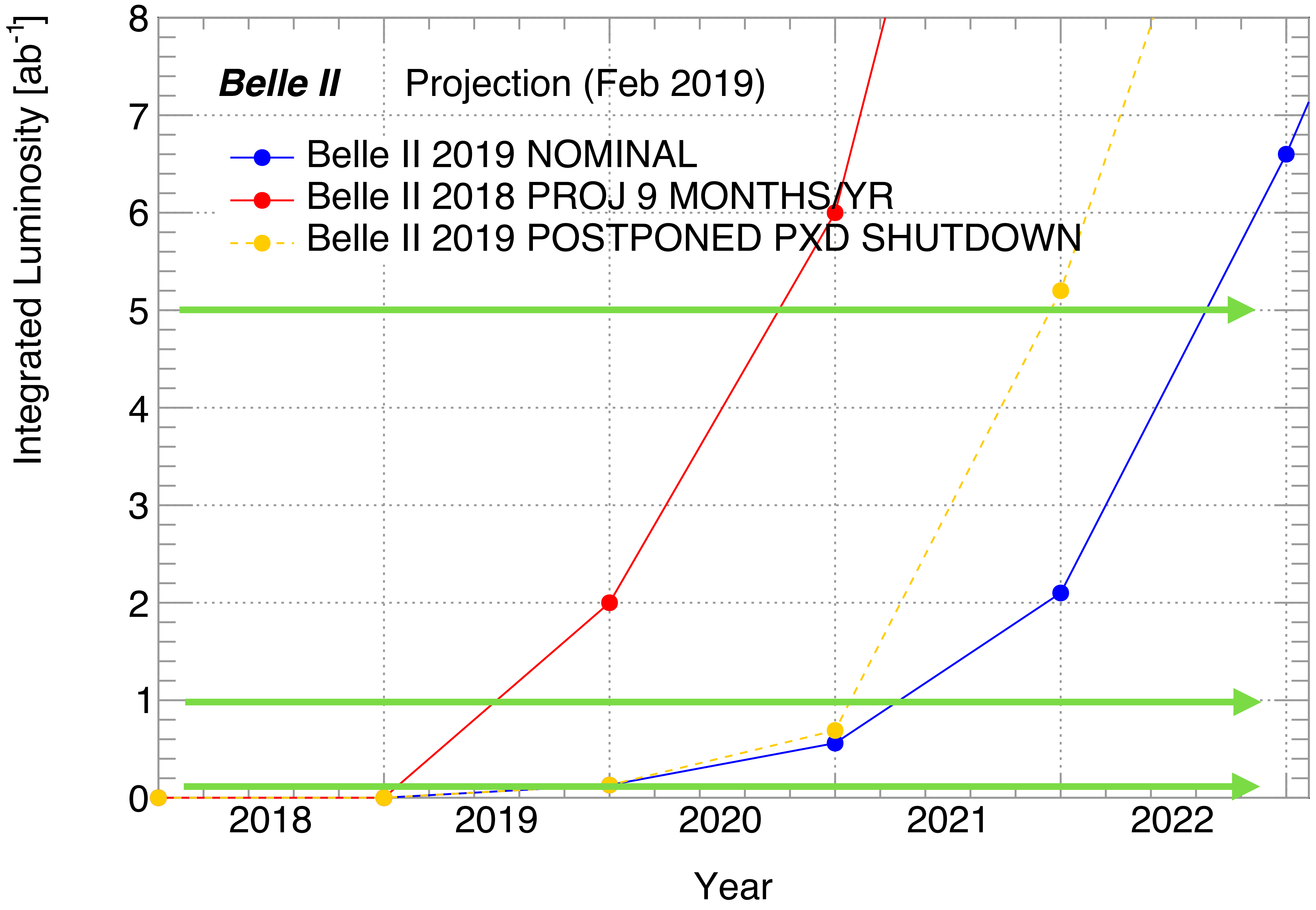
*exclusive* decay: $\tau_{signal} \to 3\pi^\pm \nu_\tau$



# 2019 & Early Phase 3

- First 2019 target is (up to) order(10) $fb^{-1}$ measurements,
  → 100 $fb^{-1}$ by Dec
  - Publication prospects for dark sector searches.
    - Performance studies **(particularly VXD)** with heavy flavour channels; Rediscovery of TDCPV,lifetime measurement precision.
- Most new heavy flavour publications likely to start with 2020 data set




2021-2022 B2TiP Milestone
arXiv: 1808.10567 / PTEP (99 citations)

2021: > 1 $ab^{-1}$ (Belle)

2020: > 500 $fb^{-1}$ (Babar)

2019: 10-50 $fb^{-1}$ (July) 100 $fb^{-1}$ (Dec)

# Example Milestones (B-physics oriented)

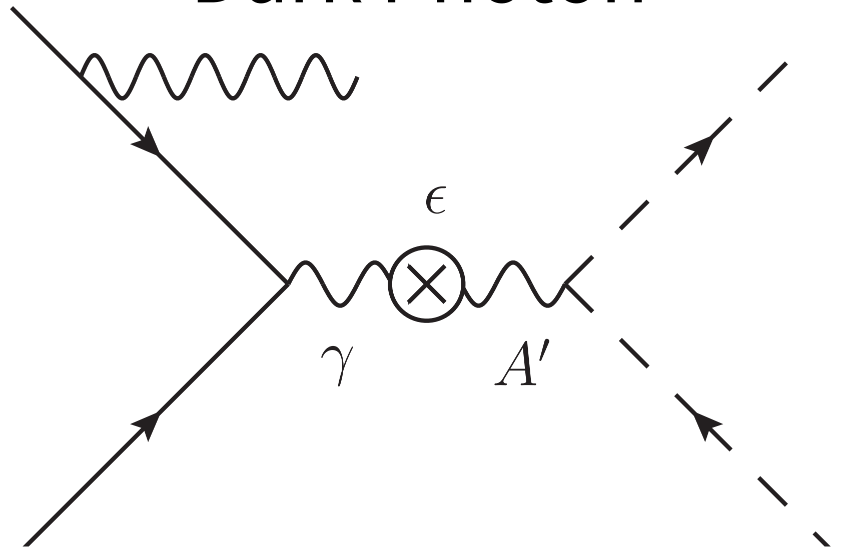
- Modes highlighted as golden in the B2TiP (Belle II Physics) book (non exhaustive).
- Expect ongoing publication output from >500 fb-1 on heavy flavour - precision milestone points are shown.

| [$ab^{-1}$] | Group | Channel | Current precision (Belle) | Precision |
|---|---|---|---|---|
| 0.05 | LOWM | ee→ A’ γ, A’→ invisible | - | Unique |
| | LOWM | ee→ a’ γ, a’ → γ γ | - | Unique |
| | LOWM | ee→ Z’ μμ, Z’→ invisible | - | Unique |
| | LOWM | ee→ MM | - | Unique |
| 2 | SL | R(B→$D^*$τν) | 0.02 | 0.012 |
| | SL | R(B→Dτν) | 0.07 (0.04) | 0.035 (0.024) |
| | SL | $\|V_{ub}\|$ (B→π l ν) +LQCD improvements | 5% | 2.5% |
| | TDCPV | $S_{CP}$(B→ J/ψ $K_S$) | 0.023 | 0.012 |
| 6 | SL | Br(B→τν) | 21% | 9% |
| | SL | Br(B →μν) | 2 σ | > 5 σ |
| | SL | Br(B → Xu l ν) inclusive dΓ/dMx for $\|V_{ub}\|$ | 9% | 4% |
| | EWP | R(K) e.g. $1<q^2<6$ GeV/$c^2$ | 28% | 11% |
| | EWP | R(K*) e.g. $1<q^2<6$ GeV/$c^2$ | 26% | 10% |
| | EWP | P(5’) in B→ K*l+l- e.g. $4<q^2<6$ GeV/$c^2$ | 0.34 | 0.12 |
| | TDCPV | $S_{CP}$(B→η’ KS) | 0.08 | 0.03 |
| | TDCPV | $S_{CP}$(B→$K^*$ γ) | 0.32 | 0.12 |
| | HAD | Φ3 (B→DK) | 15 deg | 5 deg |
| 15 | EWP | Br(B→$X_s$ $l^+l^-$), e.g. $3.5<q^2<6$ GeV/$c^2$ | 24% | 8% |
| | TDCPV | $S_{CP}$(B→ργ) | 60 | 10 |
| | TDCPV | $S_{CP}$(B→J/ψ $\pi^0$) | 0.22 | 0.10 |
| | HAD | $A_{CP}$(B→$K_S$ $\pi^0$) | 0.15 | 0.05 |
| 20+ | EWP | Br(B→K ν ν) | ~100% | 11% |
| | EWP | Br(B→$K^*$ ν ν) | ~100% | 10% |
| | EWP | Br($B_s$→ γ γ) | < $8.7\ 10^{-6}$ | $0.3\ 10^{-6}$ |
| | TDCPV | $S_{CP}$(B→$\pi^0\pi^0$) | - | 0.06 |

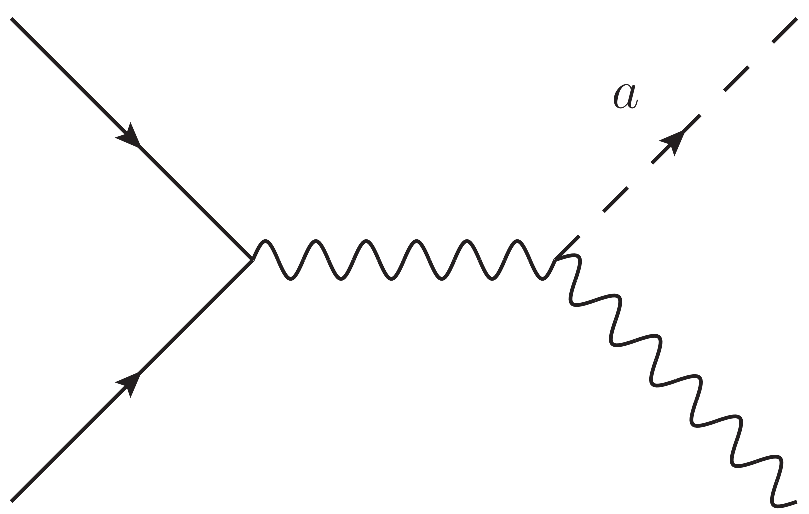
# Dark Sector, rates & trigger

- **Vector portal** $\epsilon F_Y^{\mu\nu} F'_{\mu\nu}$ (dark photon $A'$), $\sum_l \theta g' \bar{l} \gamma^\mu Z'_\mu l$ (dark $Z'$)
- **Axion portal** $\frac{G_{agg}}{4} a G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{G_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}$ (axion, alps)
- **Scalar portal** $\lambda H^2 S^2 + \mu H^2 S$ (dark Higgs)

Dark Photon



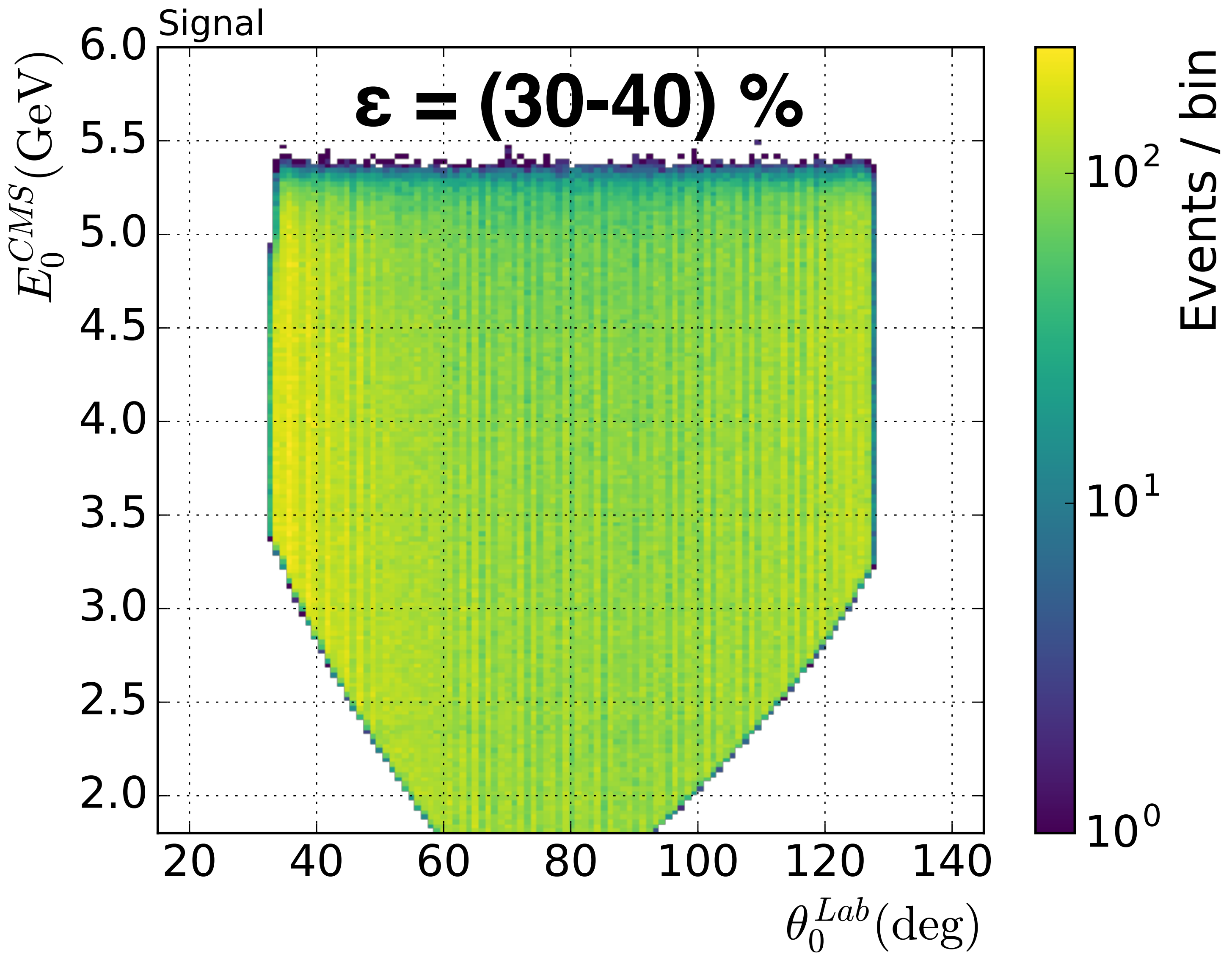

Axion-like particle

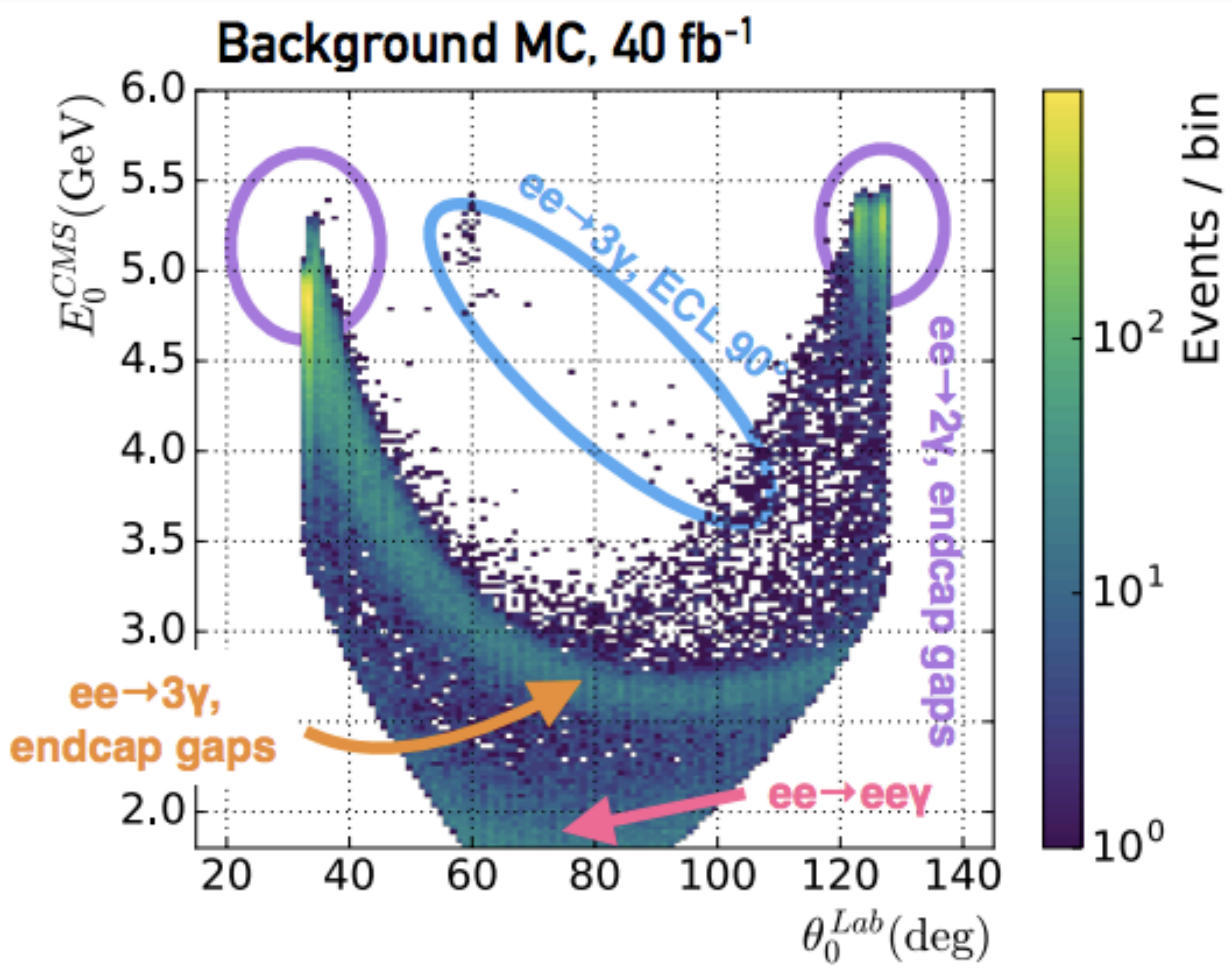



- **Trigger: $O$(10 nb) acceptance** / suppress QED events, B & D > 99% efficiency

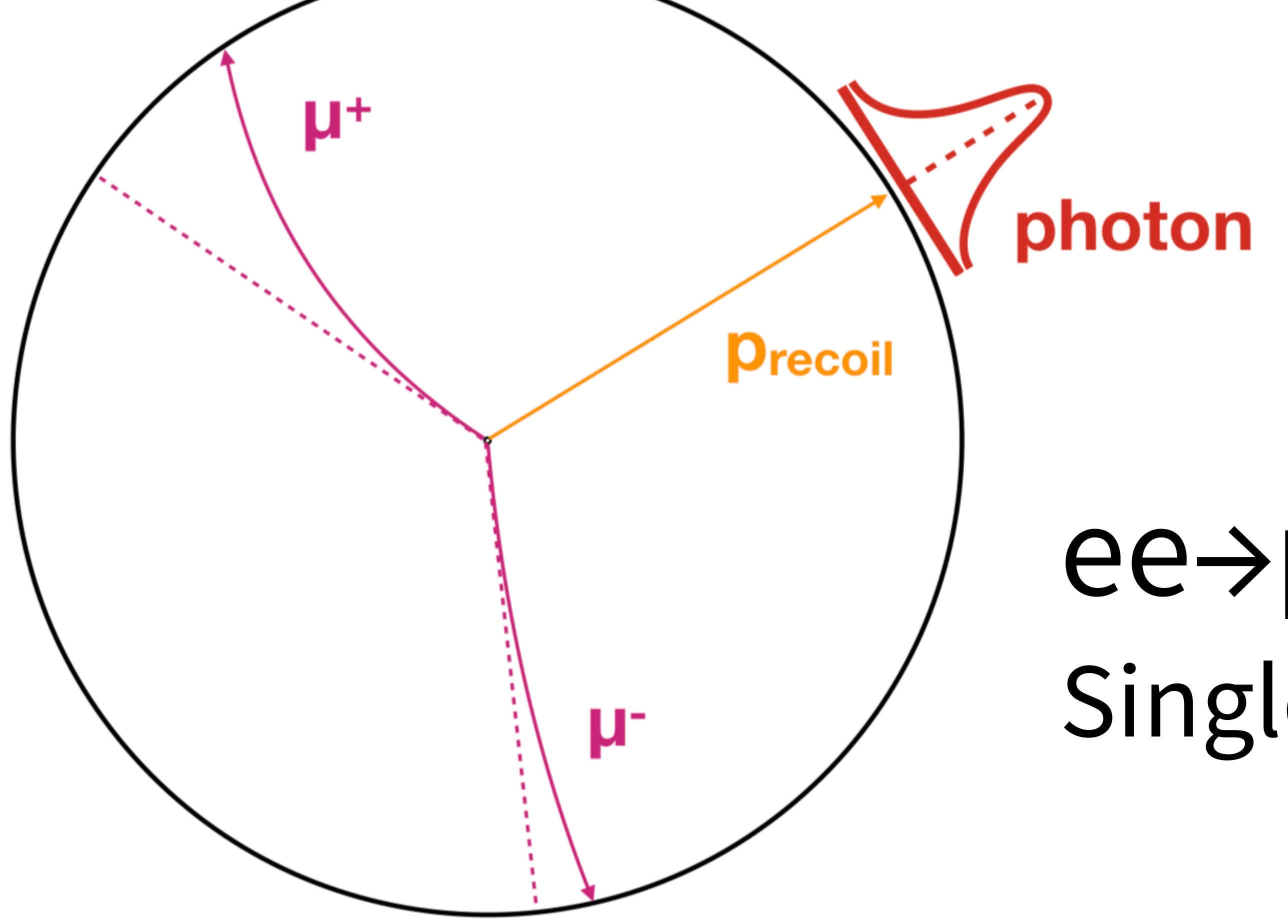
| Physics process | Cross section [nb] | Cuts |
|---|---|---|
| $\Upsilon(4S)$ | $1.05 \pm 0.10$ | - |
| $u\bar{u}(\gamma)$ | 1.61 | - |
| $d\bar{d}(\gamma)$ | 0.40 | - |
| $s\bar{s}(\gamma)$ | 0.38 | - |
| $c\bar{c}(\gamma)$ | 1.30 | - |
| $e^+e^-(\gamma)$ | $300 \pm 3$ (MC stat.) | $10° < \theta^*_{e's} < 170°$, $E^*_{e's} > 0.15$ GeV |
| $e^+e^-(\gamma)$ | 74.4 | $e$'s ($p$ >0.5GeV) in ECL |
| $\gamma\gamma(\gamma)$ | $4.99 \pm 0.05$ (MC stat.) | $10° < \theta^*_{\gamma's} < 170°$, $E^*_{\gamma's} > 0.15$ GeV |
| $\gamma\gamma(\gamma)$ | 3.30 | $\gamma$'s ($p$ >0.5GeV) in ECL |
| $\mu^+\mu^-(\gamma)$ | 1.148 | - |
| $\mu^+\mu^-(\gamma)$ | 0.831 | $\mu$'s ($p$ >0.5GeV) in CDC |
| $\mu^+\mu^-\gamma(\gamma)$ | 0.242 | $\mu$'s ($p$ >0.5GeV) in CDC, $\geq 1$ $\gamma$ ($E_\gamma$ >0.5GeV) in ECL |
| $\tau^+\tau^-(\gamma)$ | 0.919 | - |
| $\nu\bar{\nu}(\gamma)$ | $0.25 \times 10^{-3}$ | - |
| $e^+e^-e^+e^-$ | $39.7 \pm 0.1$ (MC stat.) | $W_{\ell\ell} > 0.5$GeV |
| $e^+e^-\mu^+\mu^-$ | $18.9 \pm 0.1$ (MC stat.) | $W_{\ell\ell} > 0.5$GeV |

*Single photon signature from dark photon.*



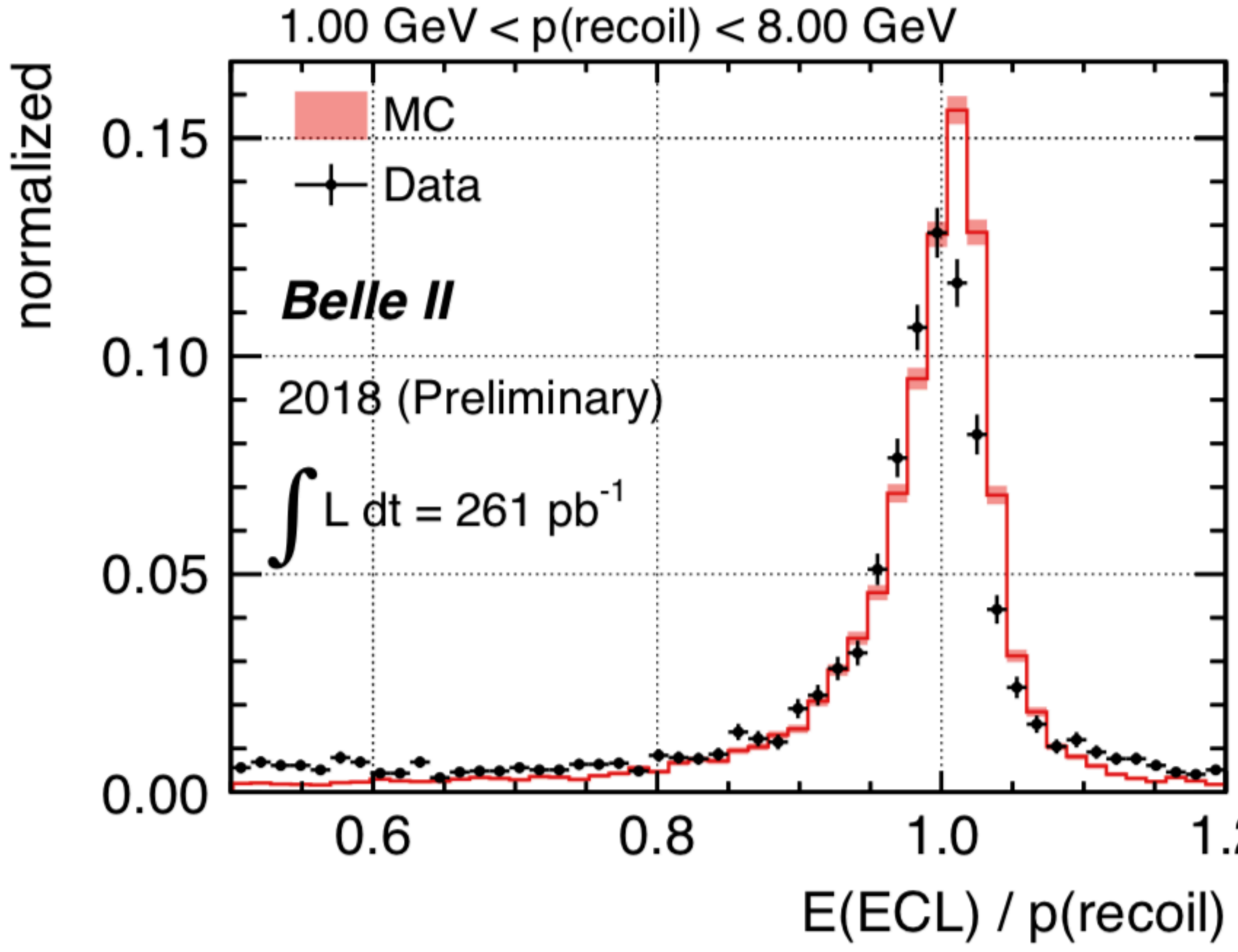



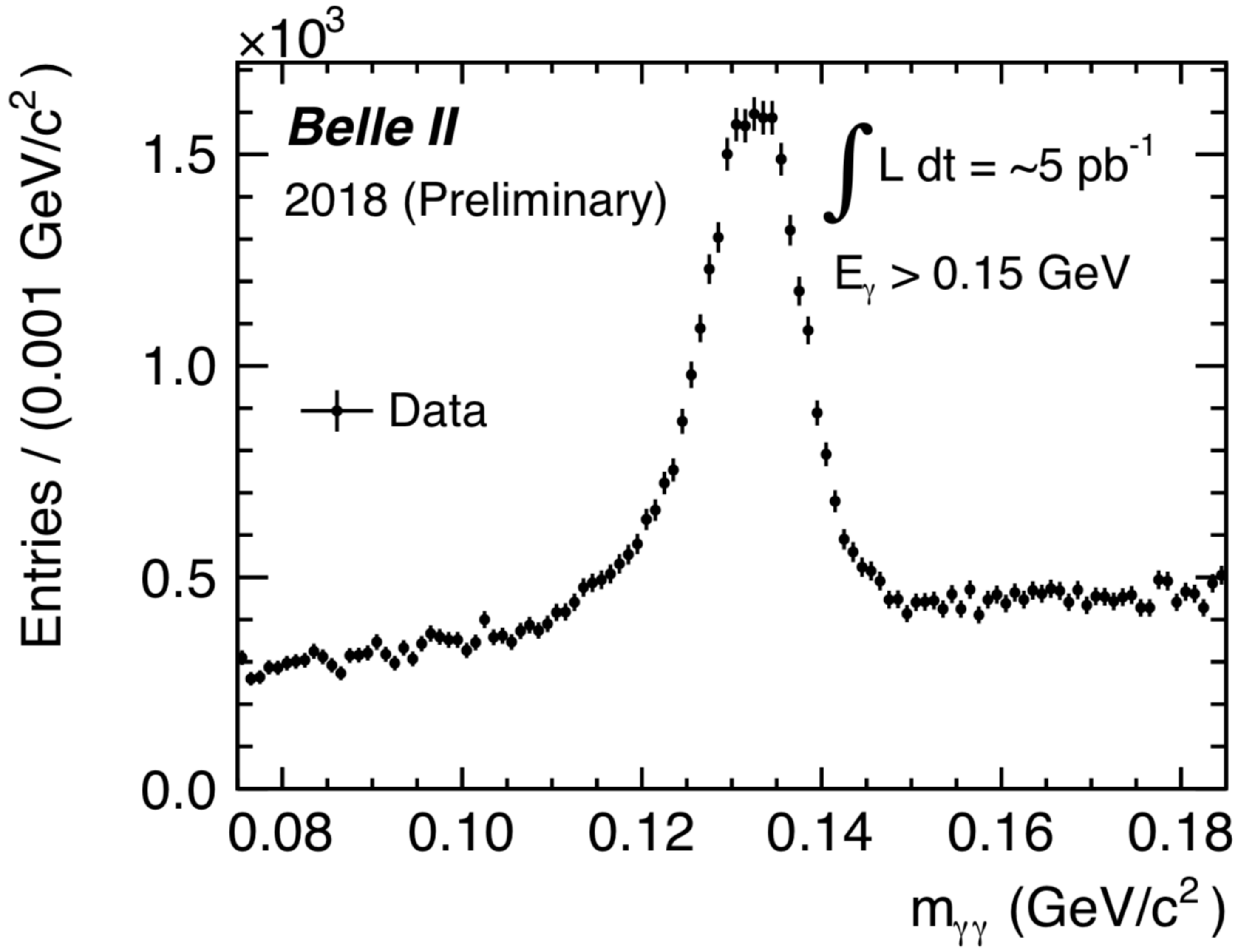
# Dark Sector, expected sensitivity




ee→μμγ

Single Photon Lines




**Ready for the dark sector early 2019**

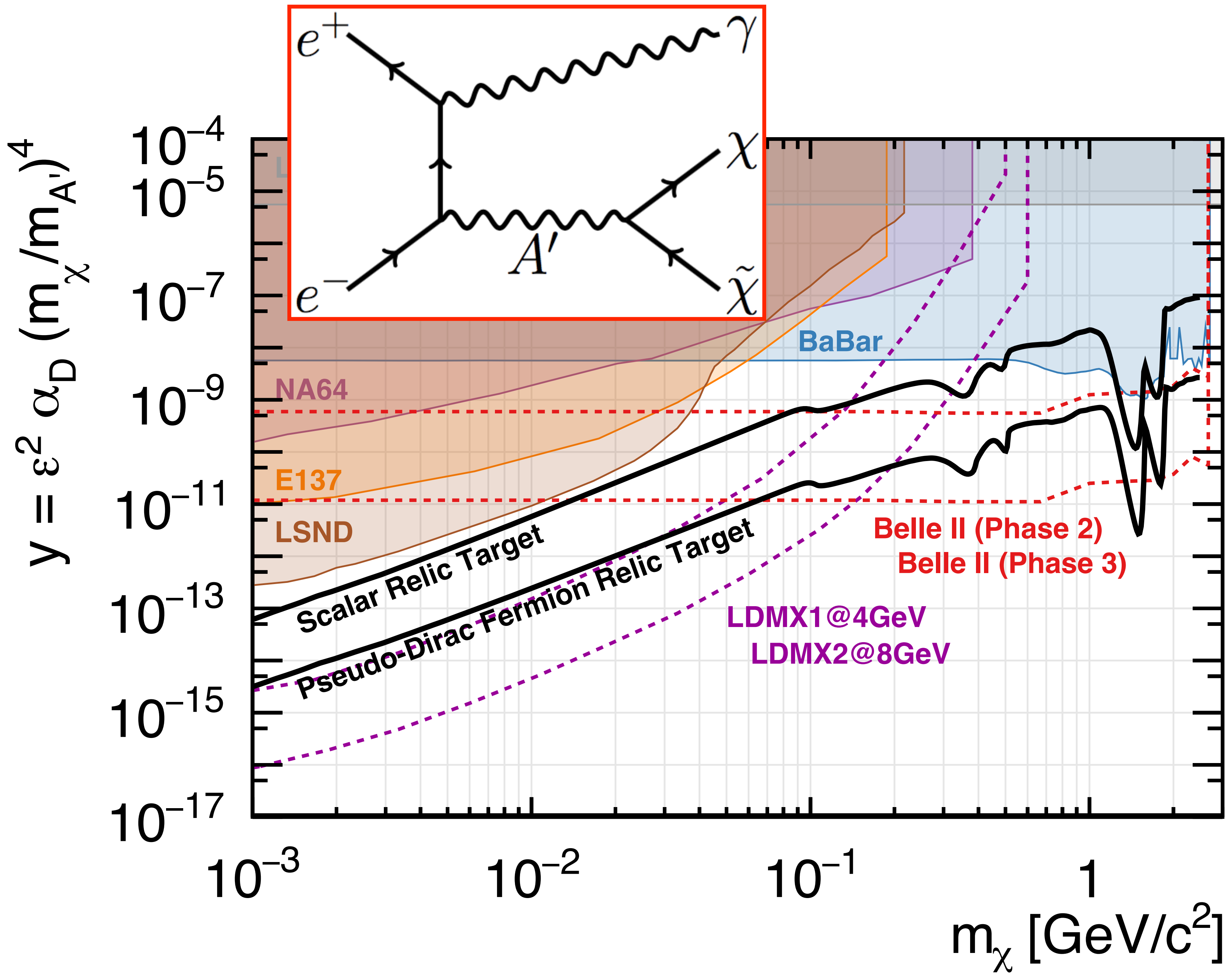
$e^+e^- \to \gamma X$

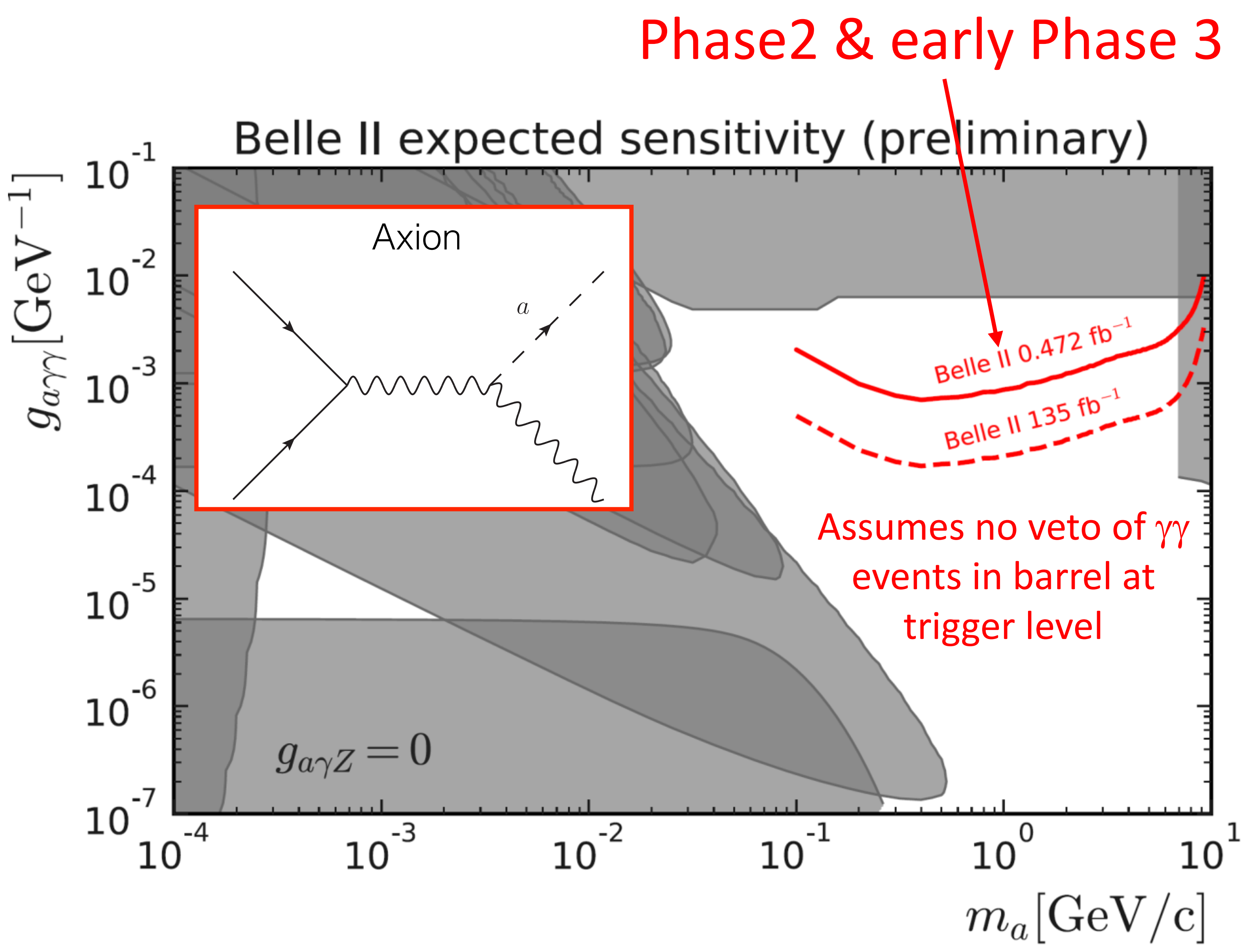
$e^+e^- \to \gamma$ ALP ($\to\gamma\gamma$)

$e^+e^- \to \gamma A'$ (dark photon)

Dark Z', Magn. Monopoles

**Can also access through flavour transitions.**





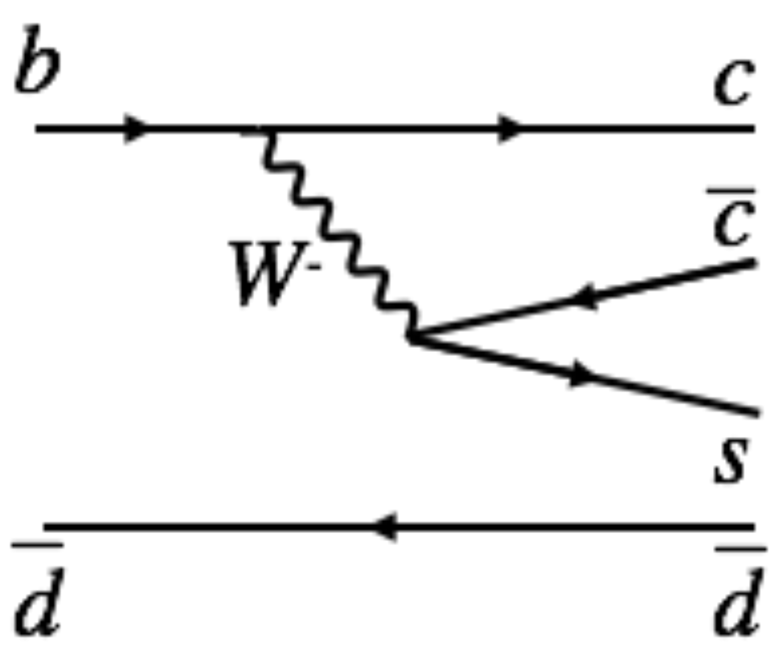

THE UNIVERSITY OF MELBOURNE

# Time dependent CP Violation / Overview

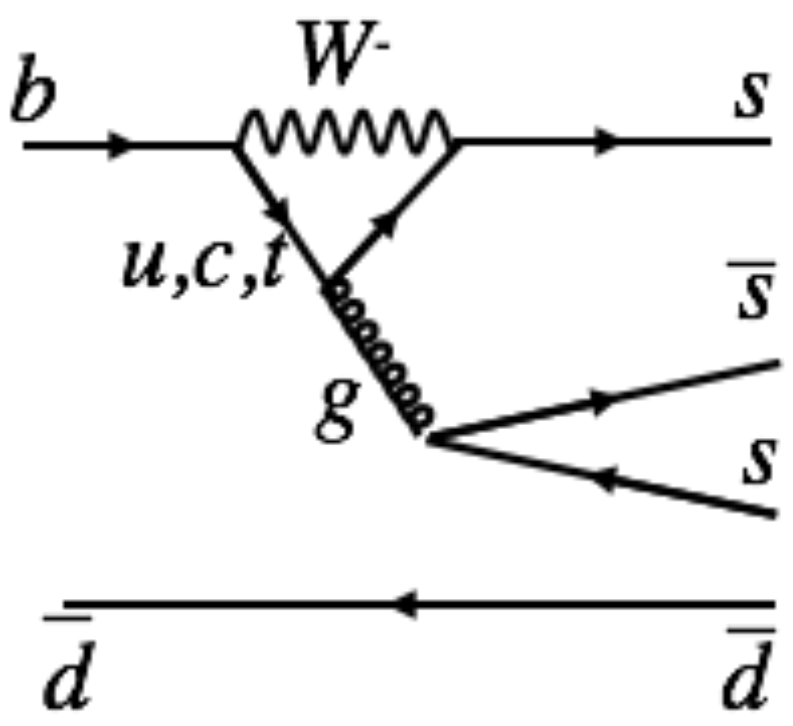
Improving on $\sin 2\Phi_1$ will be a challenge:

- for **experiments**: soon the measurement will be systematics limited: need to control them;
- for **theory**: so far neglected the contributions from suppressed amplitudes carrying a different phase.

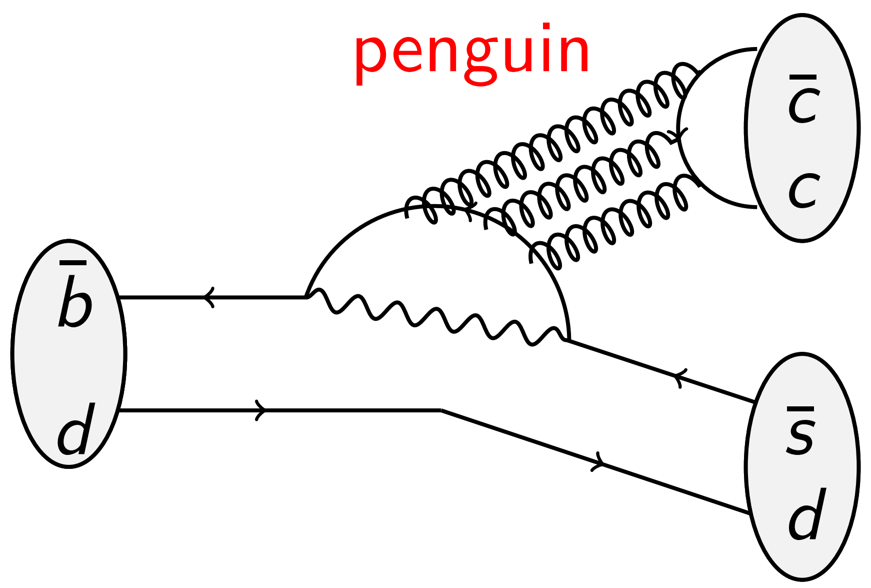
TD CP violation measurements of $b \to qqs$ transitions (q = u, d, s) are a major target




- Tree



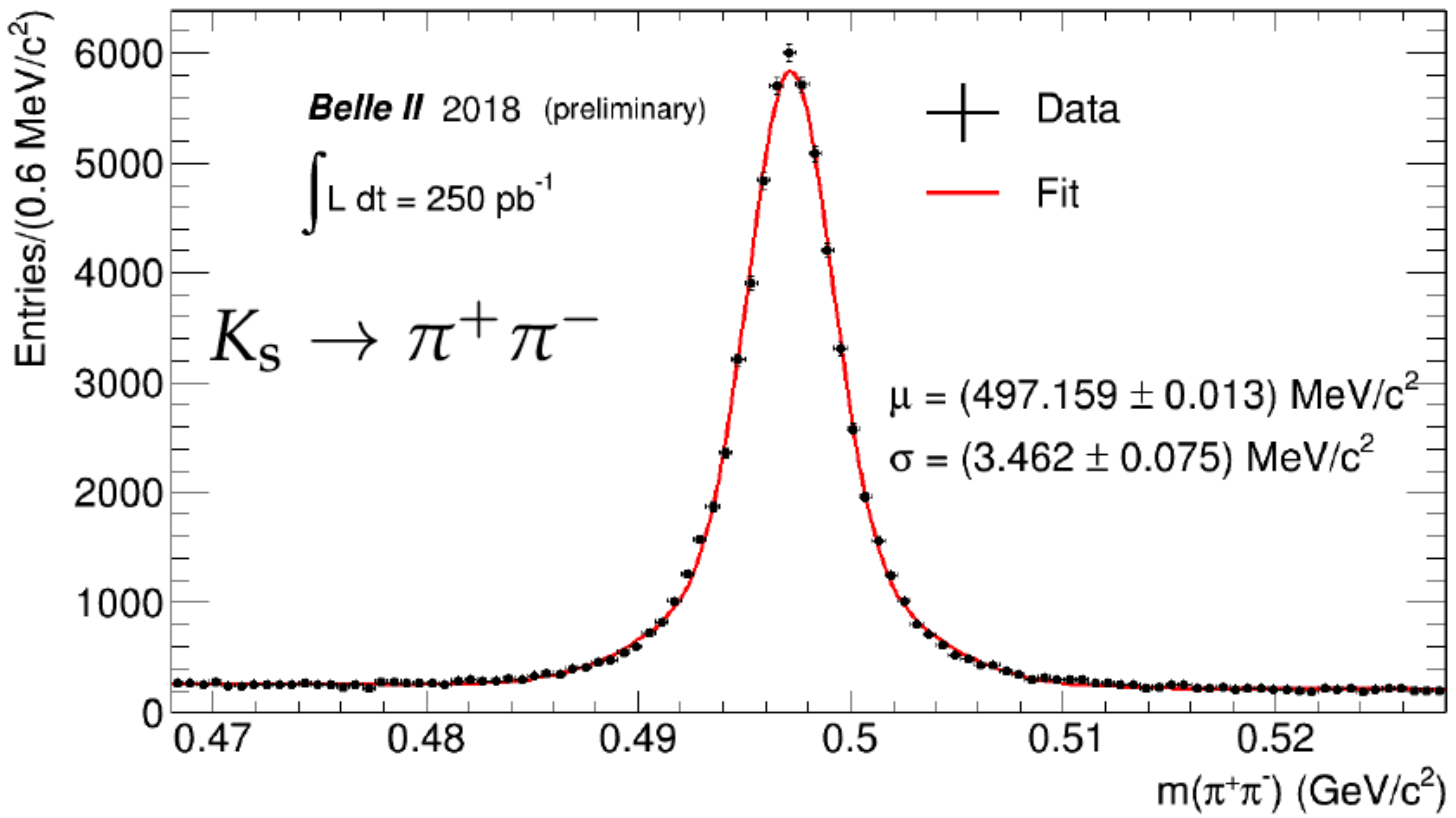

- Gluonic Penguin (NP sensitive)




- Constrains penguin pollution

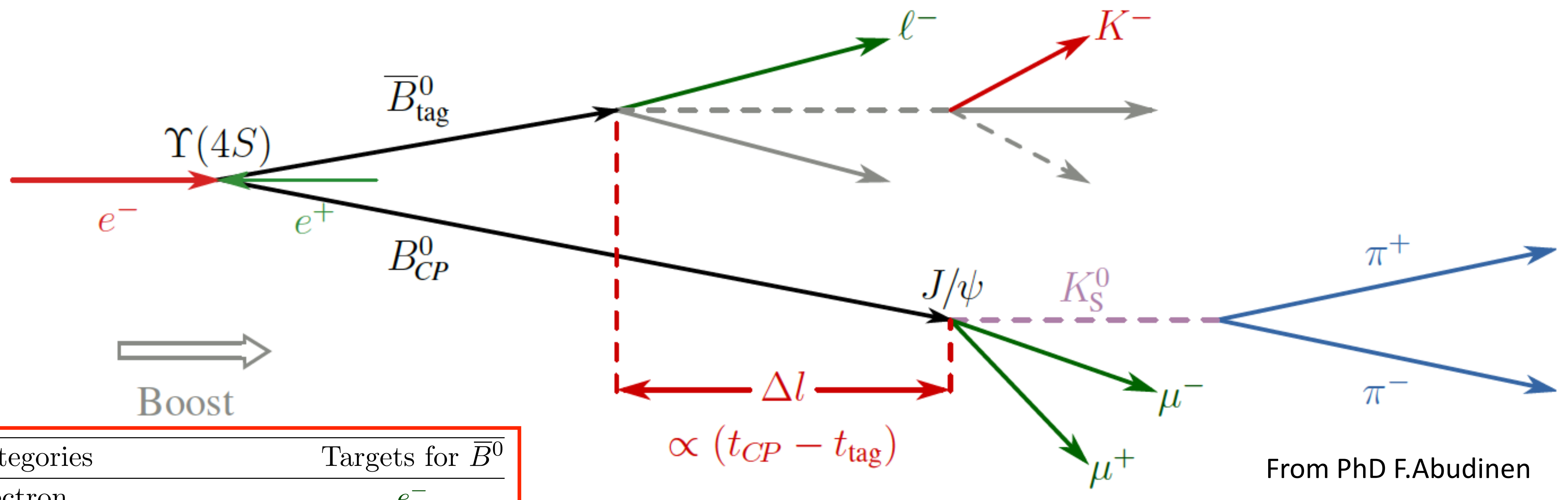
**arXiv: 1808.10567**

| | WA (2017) | | $5\ \mathrm{ab}^{-1}$ | | $50\ \mathrm{ab}^{-1}$ | |
|---|---|---|---|---|---|---|
| Channel | $\sigma(S)$ | $\sigma(A)$ | $\sigma(S)$ | $\sigma(A)$ | $\sigma(S)$ | $\sigma(A)$ |
| $J/\psi K^0$ | 0.022 | 0.021 | 0.012 | 0.011 | 0.0052 | 0.0090 |
| $\phi K^0$ | 0.12 | 0.14 | 0.048 | 0.035 | 0.020 | 0.011 |
| $\eta' K^0$ | 0.06 | 0.04 | 0.032 | 0.020 | 0.015 | 0.008 |
| $\omega K^0_S$ | 0.21 | 0.14 | 0.08 | 0.06 | 0.024 | 0.020 |
| $K^0_S \pi^0 \gamma$ | 0.20 | 0.12 | 0.10 | 0.07 | 0.031 | 0.021 |
| $K^0_S \pi^0$ | 0.17 | 0.10 | 0.09 | 0.06 | 0.028 | 0.018 |



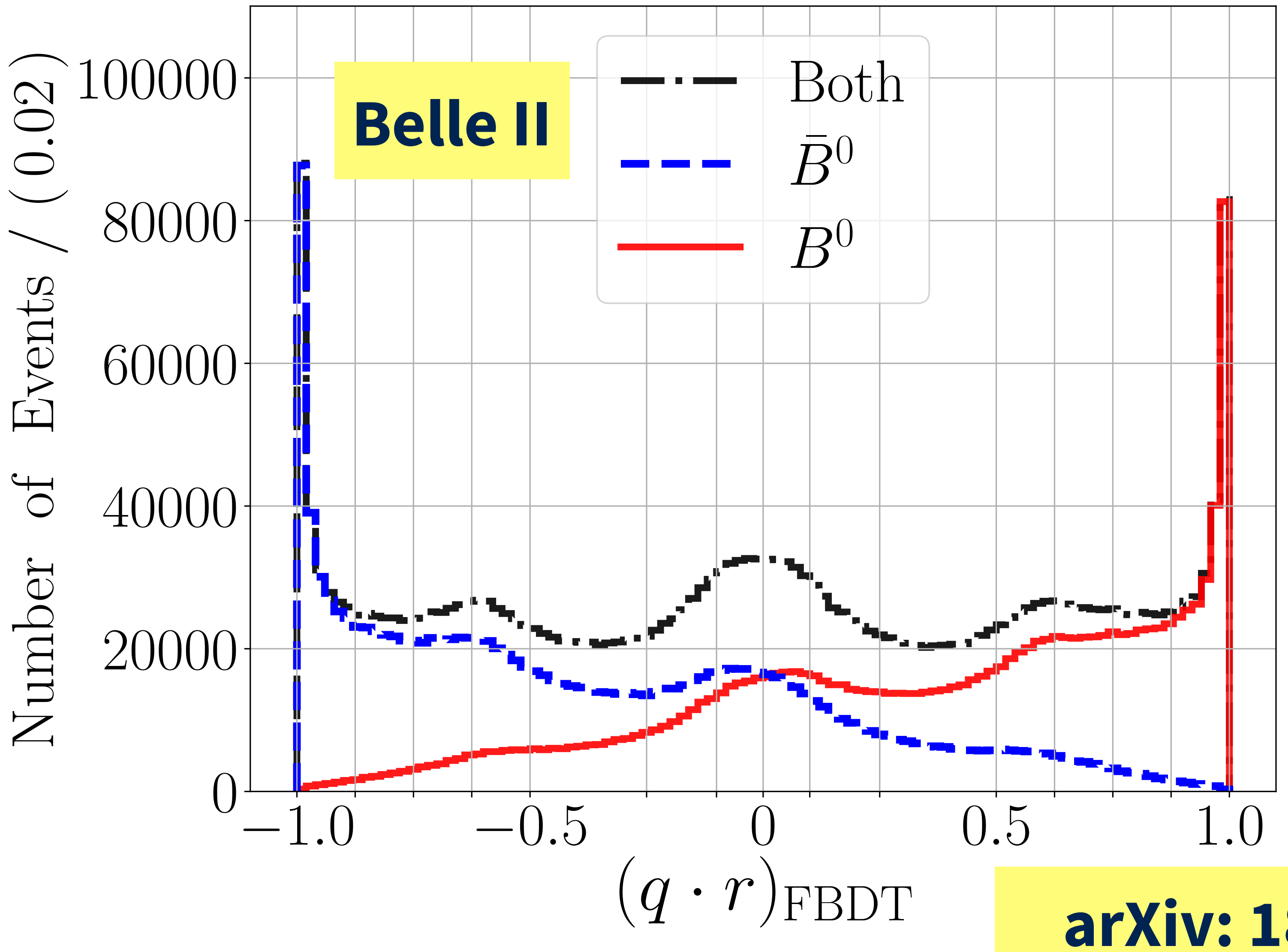
# Time dependent CP Violation / Performance

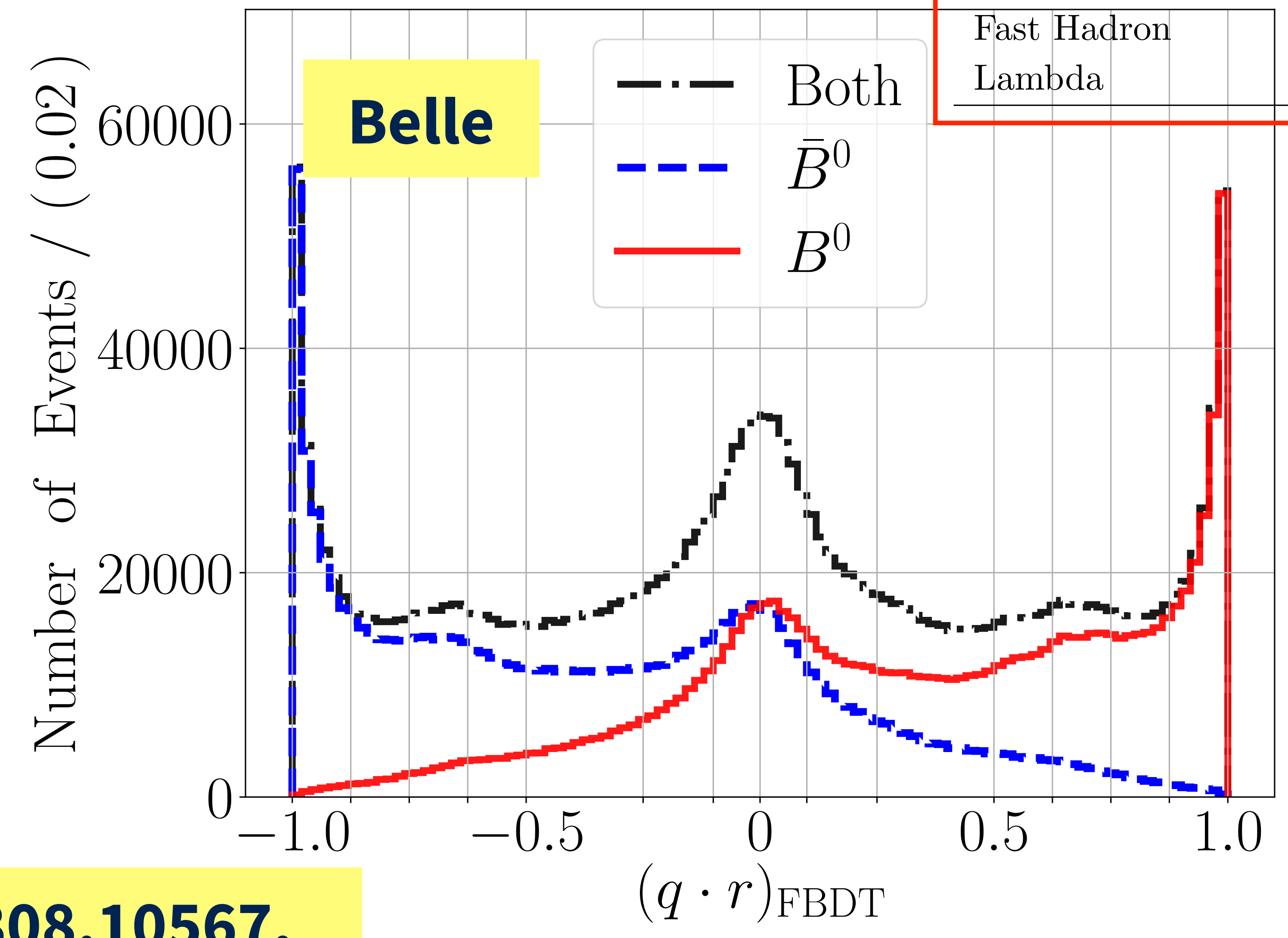
- Δt resolution ~0.77 ps
  (30% to a factor 2 better compared to Belle);
  - **PXD + nano-beam spot in Belle II.**
  - **Optimised fitters** for neutrals,
    +30% $K_S$ accept.
- Effective flavour tagging efficiency ~**36%**
  (F-BDT, MC estimate, was **30%** at Belle)



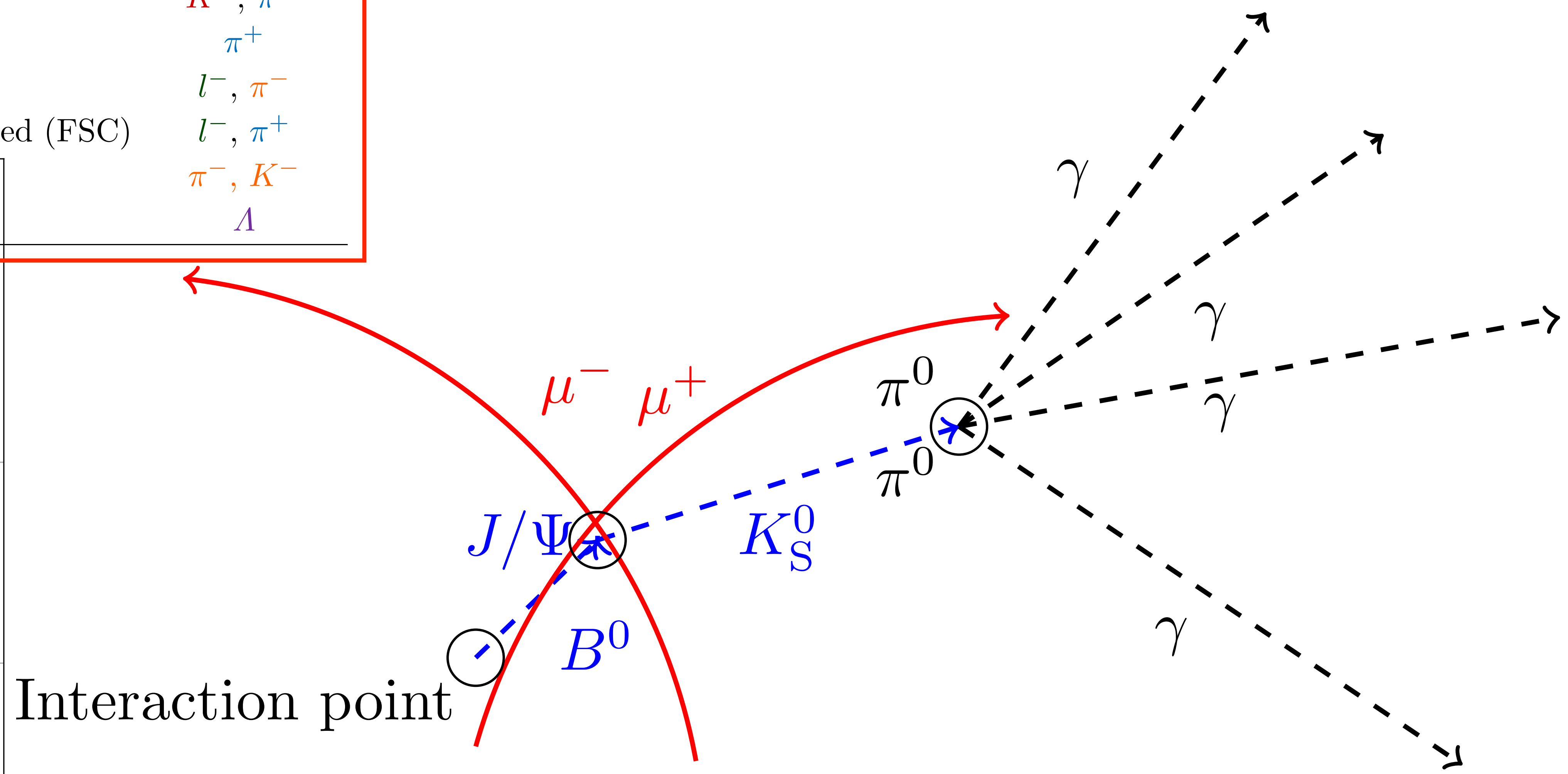

From PhD F.Abudinen

| Categories | Targets for $\bar{B}^0$ |
|---|---|
| Electron | $e^-$ |
| Intermediate Electron | $e^+$ |
| Muon | $\mu^-$ |
| Intermediate Muon | $\mu^+$ |
| Kinetic Lepton | $l^-$ |
| Intermediate Kinetic Lepton | $l^+$ |
| Kaon | $K^-$ |
| Kaon-Pion | $K^-, \pi^+$ |
| Slow Pion | $\pi^+$ |
| Maximum P* | $l^-, \pi^-$ |
| Fast-Slow-Correlated (FSC) | $l^-, \pi^+$ |
| Fast Hadron | $\pi^-, K^-$ |
| Lambda | $\Lambda$ |



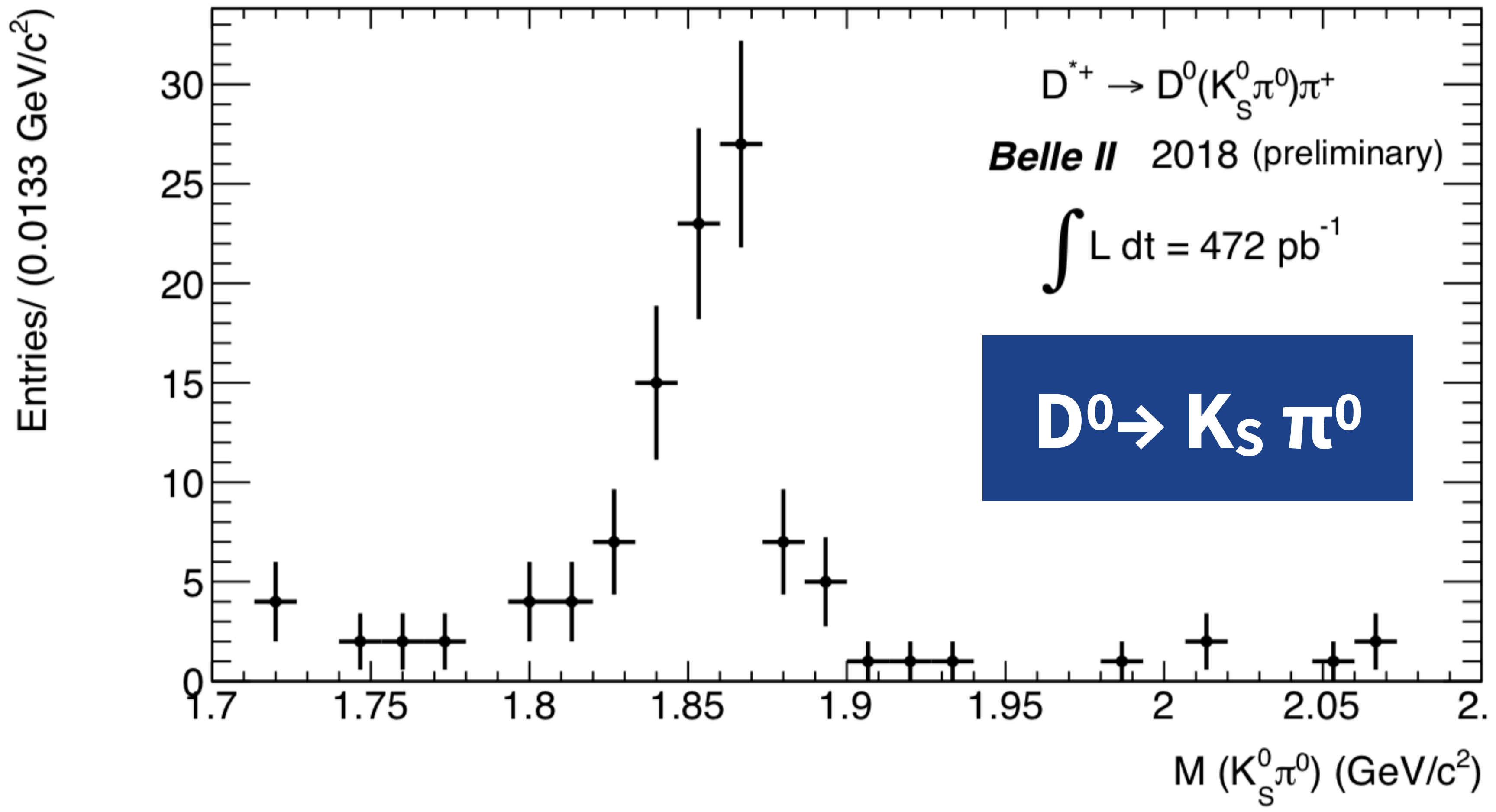

**arXiv: 1808.10567, accepted to PTEP**

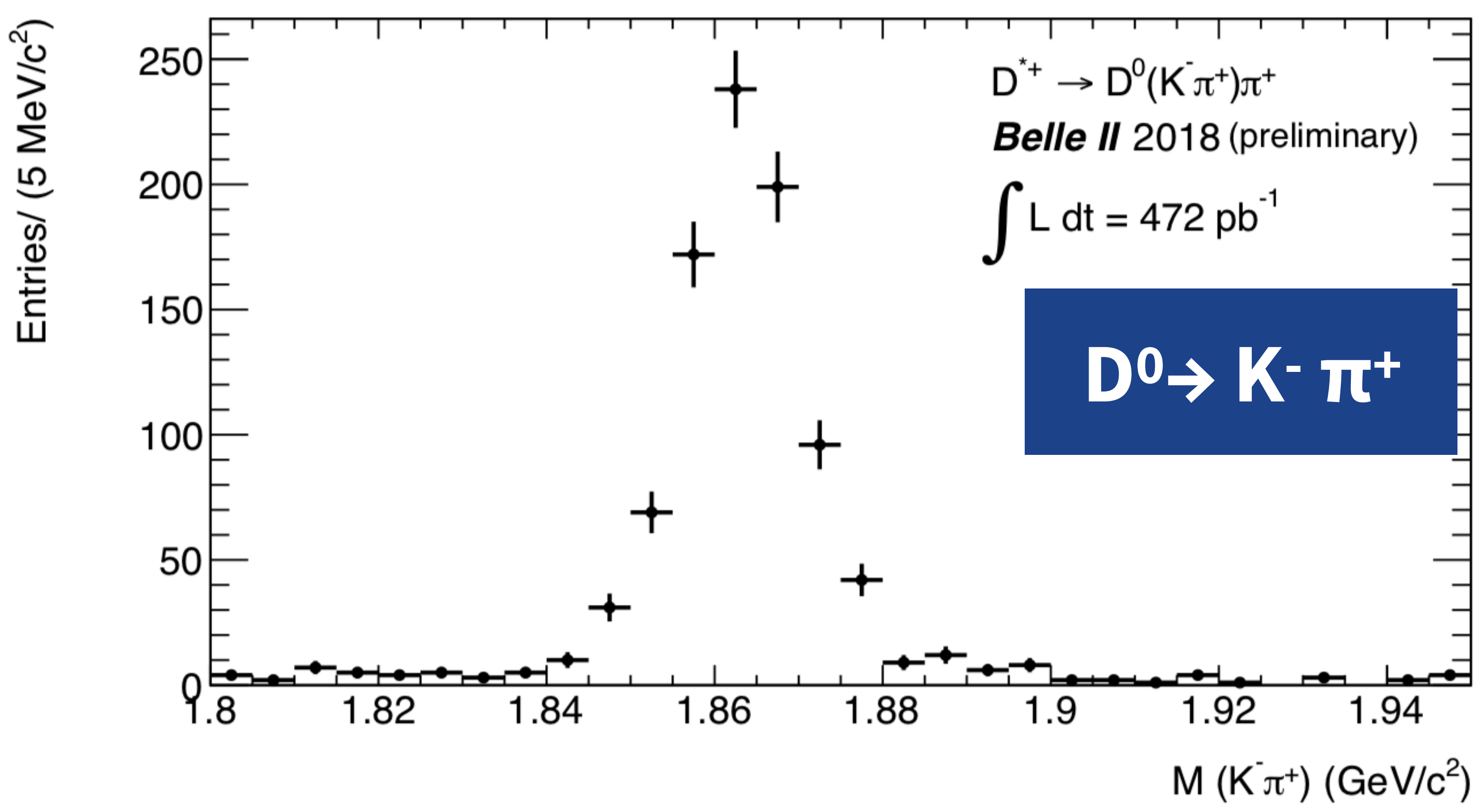



**J-F Krohn, PU (Belle II), submitted to NIMA, arXiv:1901.11198**

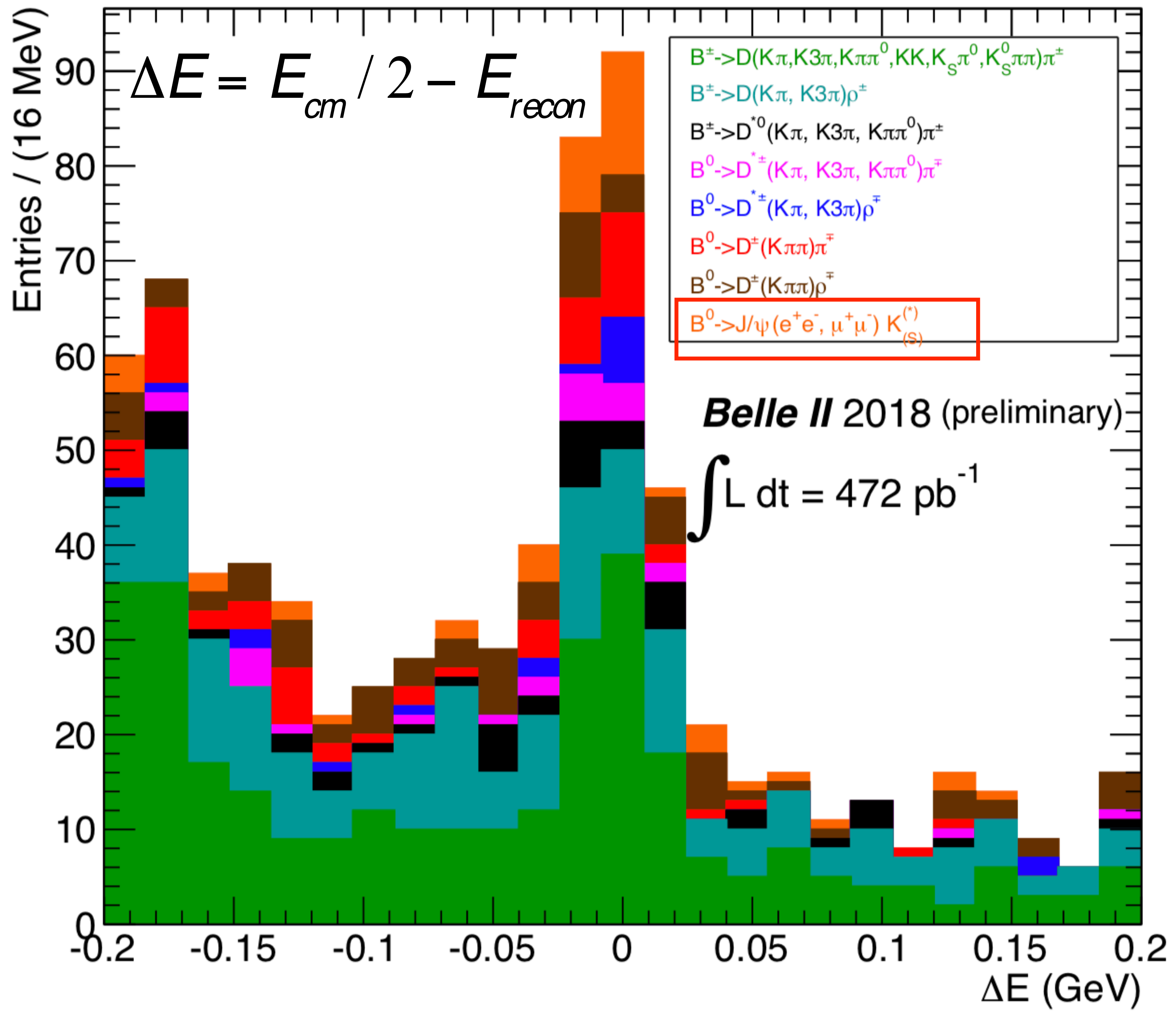
# Hadronic D and B reconstruction in phase 2

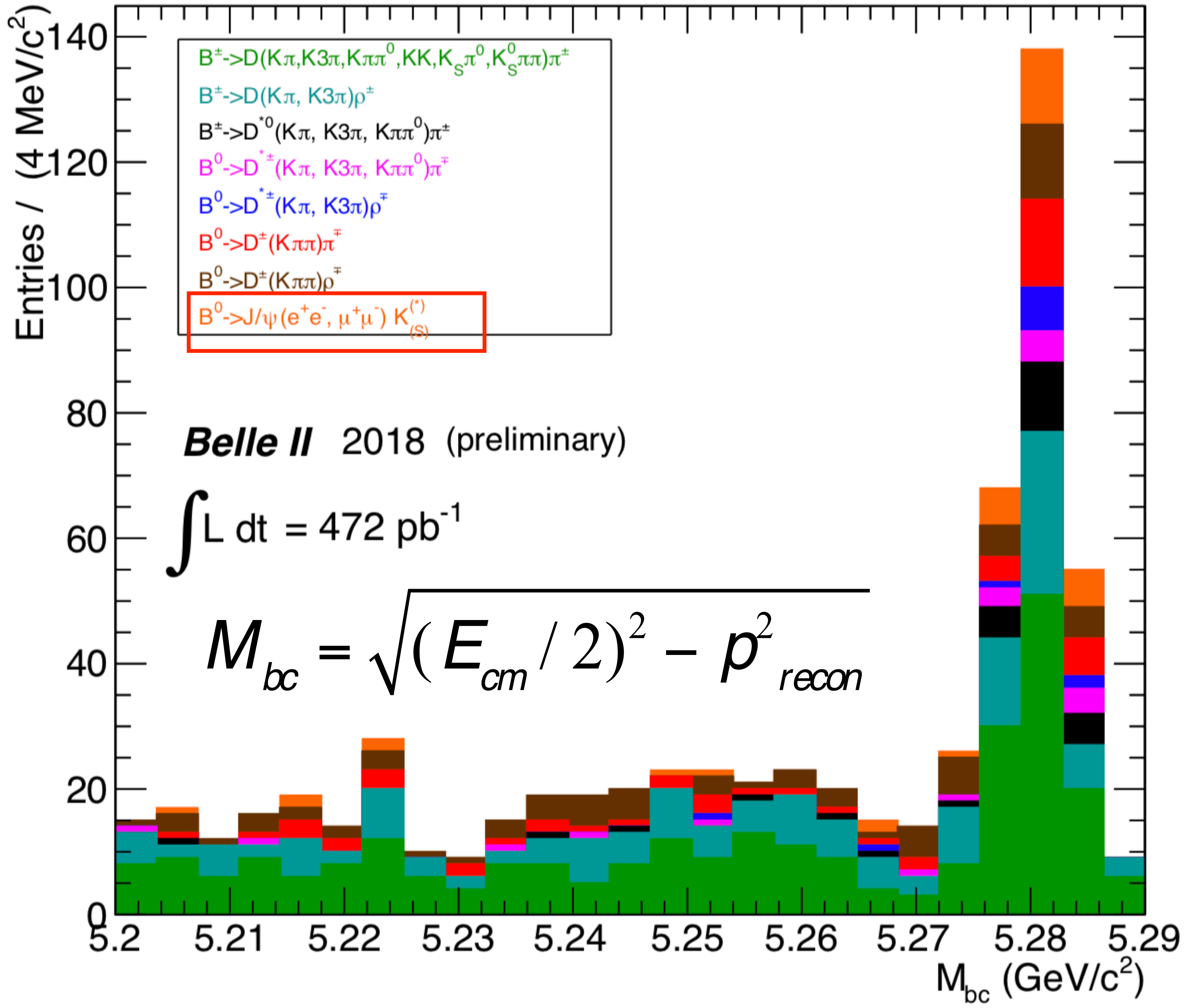
- Illustrates capabilities of Belle II and potential for c and b physics.
- CP Eigenstate $D^0 \to K_S \pi^0$ difficult at LHCb!




- Recreating CLEO & ARGUS
  - > 200 B candidates in hadronic modes (470/pb)



# Hadronic D and B reconstruction in phase 2

- Illustrates capabilities of Belle II and potential for c and b physics.
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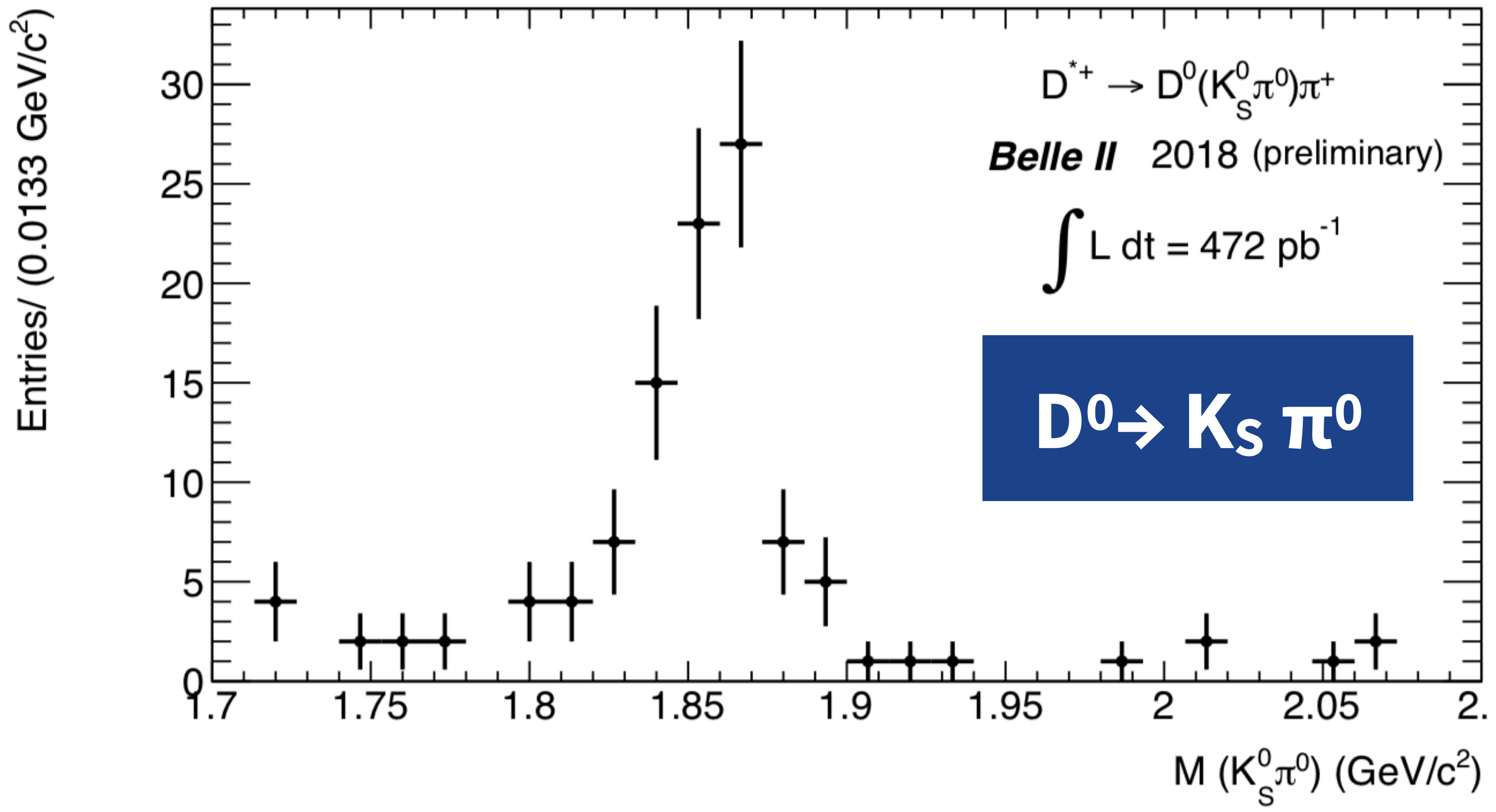
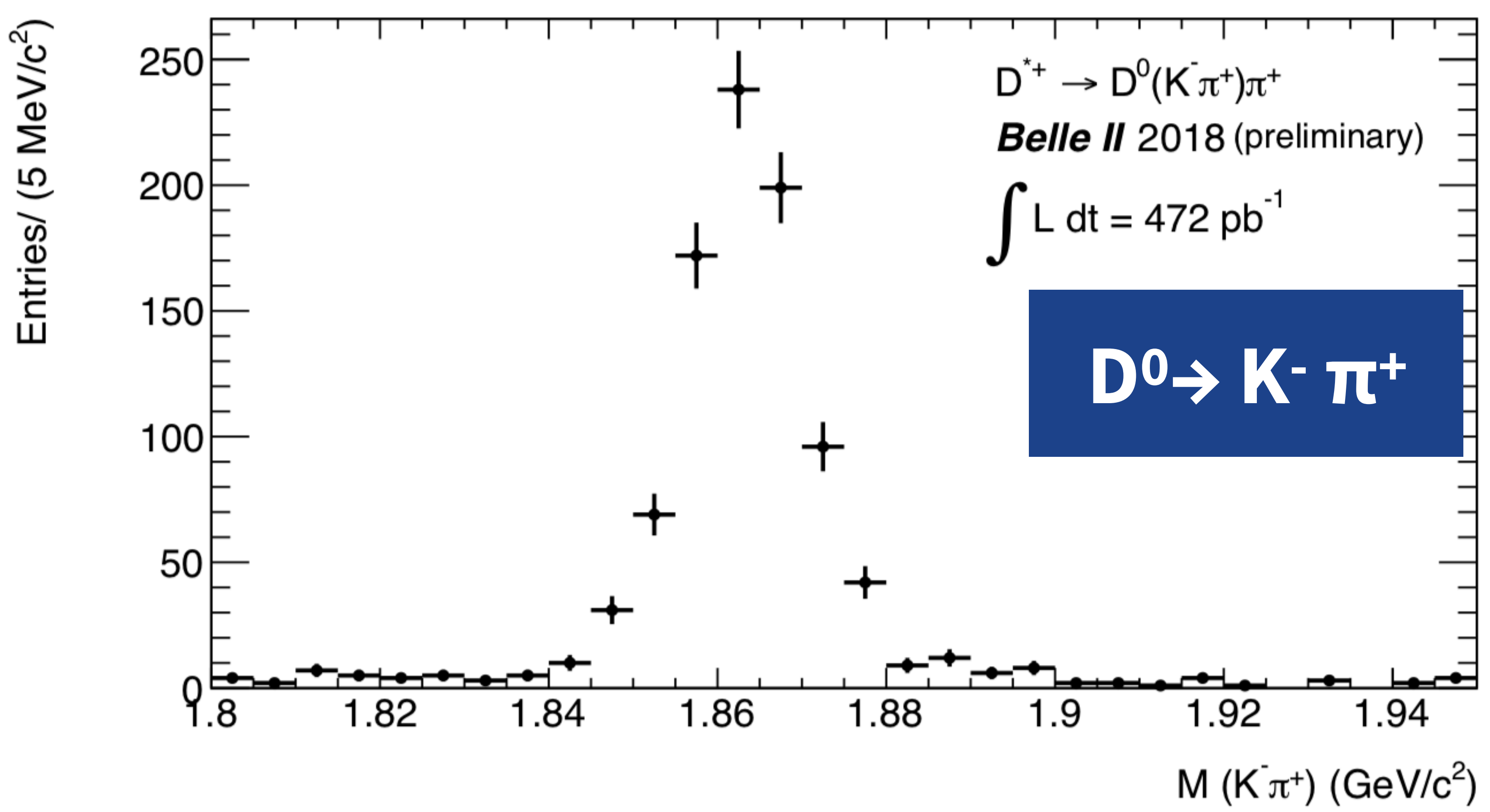
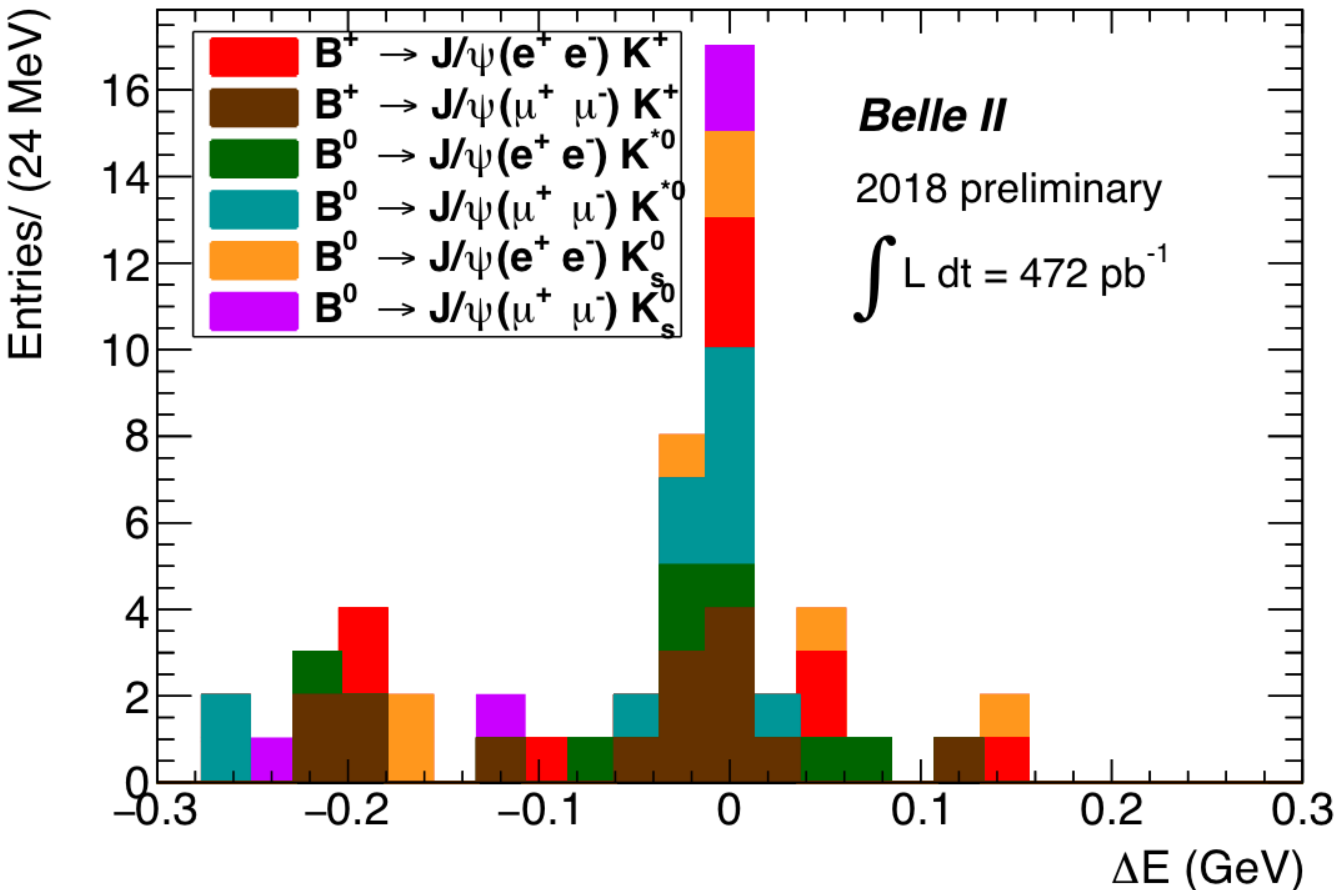
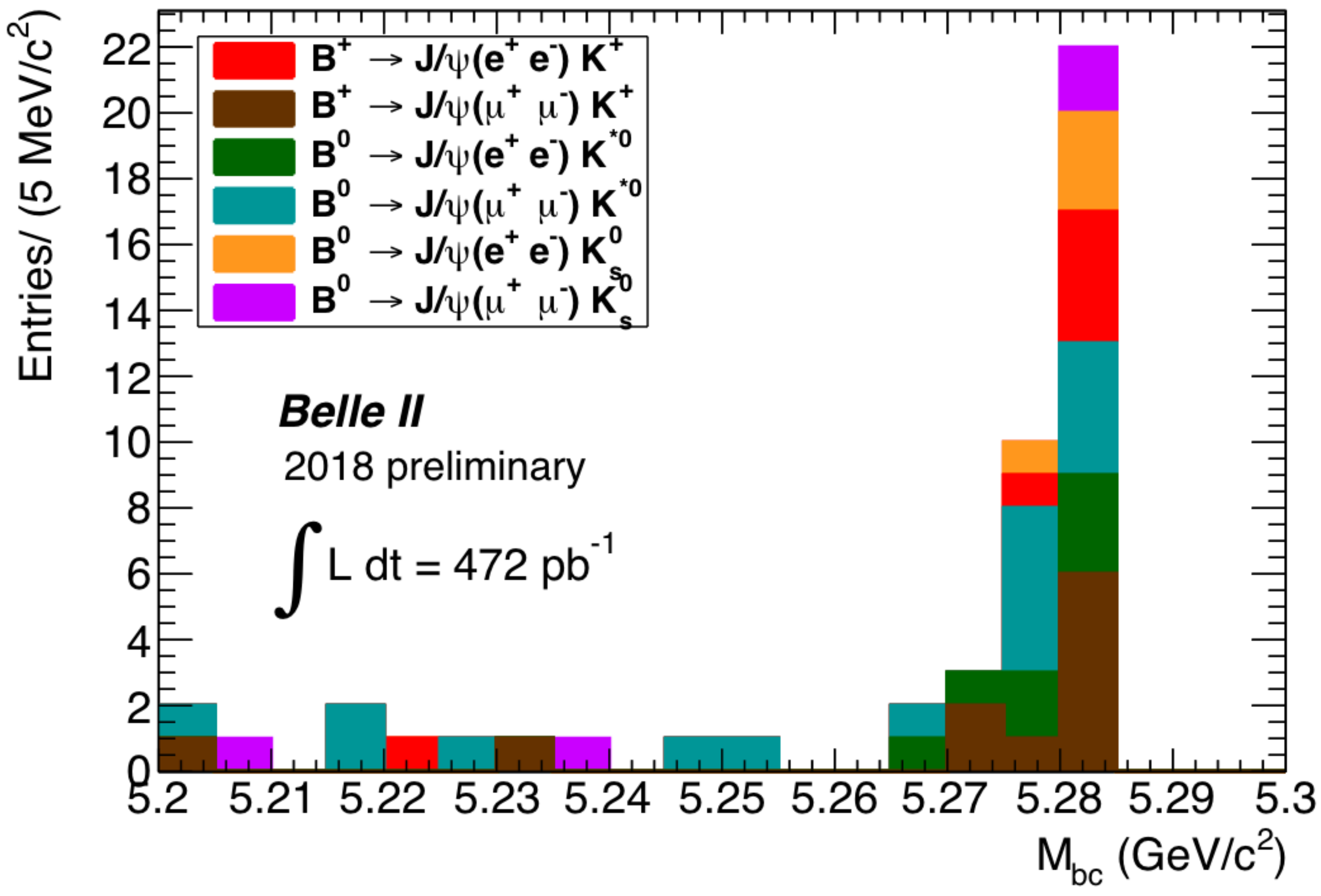


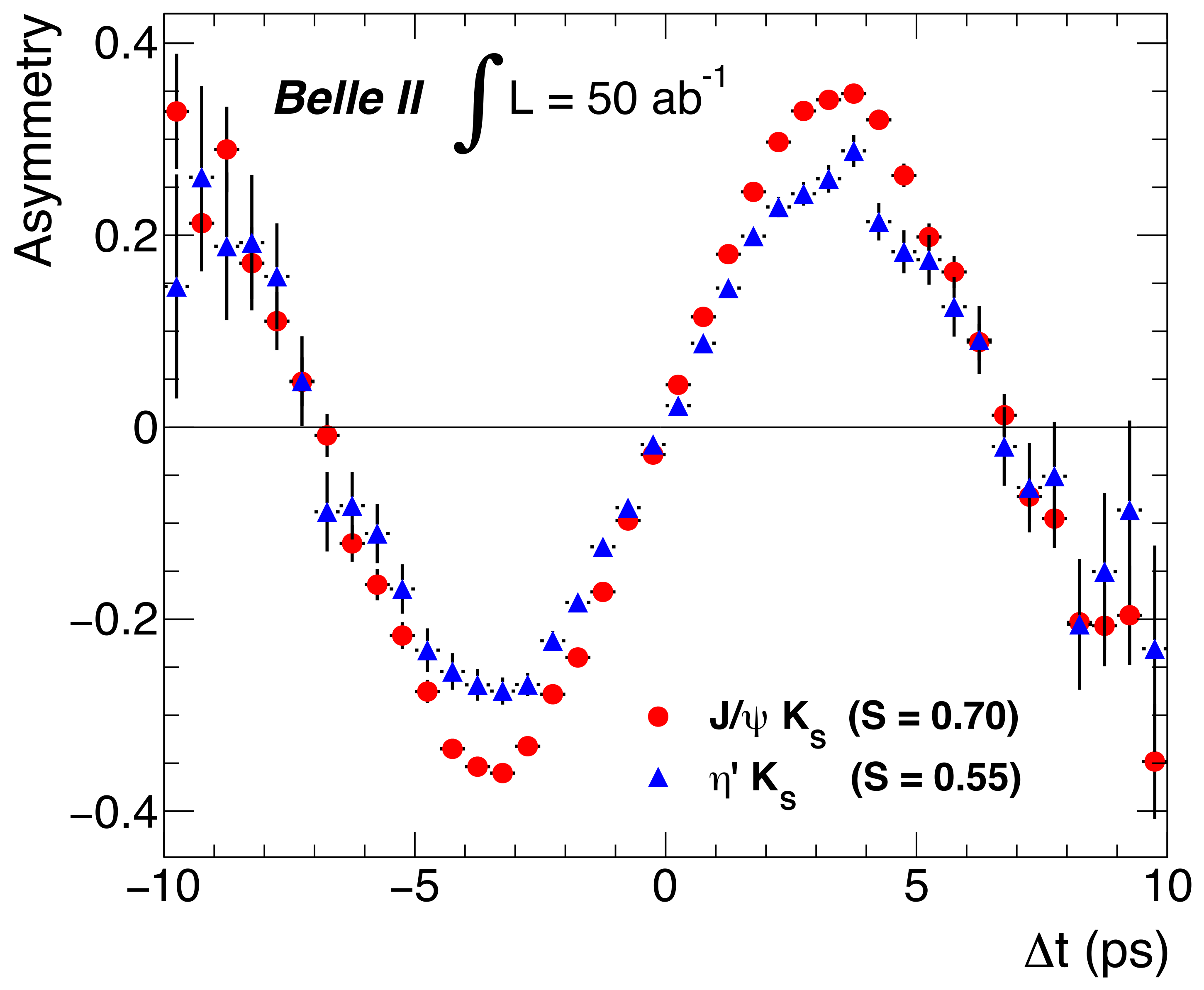

- Recreating CLEO & ARGUS
  - > 200 B candidates in hadronic modes (470/pb)



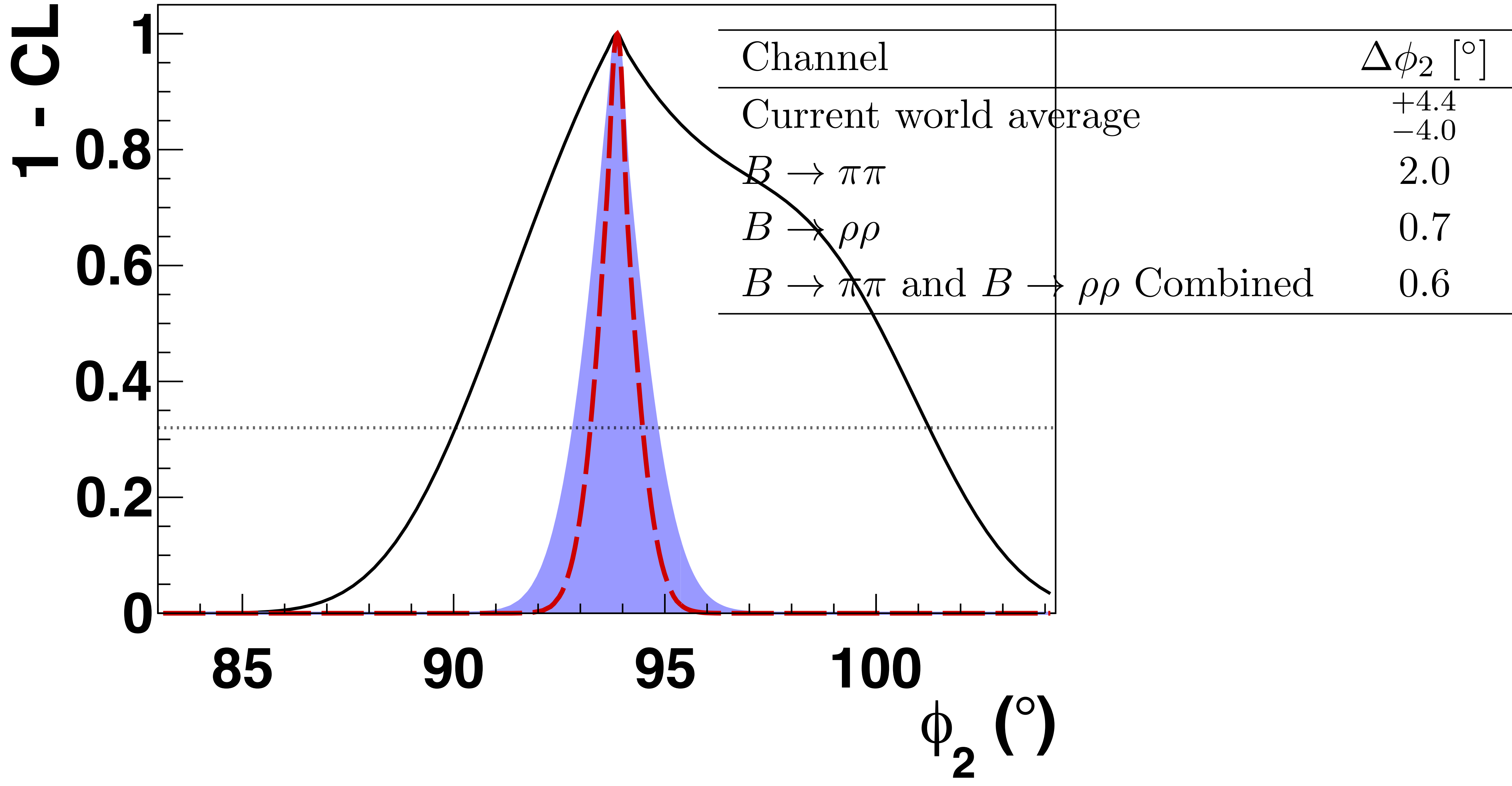
# Time dependent CP Violation / UT targets

- sin2Φ1 from B → cc $K^0$ with the full dataset will be dominated by systematic uncertainties.
  - Balance stat-power with good vertex fitted events.
- All others are stat limited through to 50 $ab^{-1}$
- $Φ_3$ covered by K. Trabelsi




**arXiv: 1808.10567**

| | Current | 50 $ab^{-1}$ projection |
|---|---|---|
| $\phi_1$: | | |
| Experimental: | 0.7° | 0.2° |
| Theoretical - QCDF & pQCD | 0.1° | 0.1° |
| Theoretical - SU(3) | 1.7° | 0.8° |
| $\phi_2$: | | |
| Experimental: | 4.2° | 0.6° |
| Theoretical: | 1.2° | $< 1.0°$ |

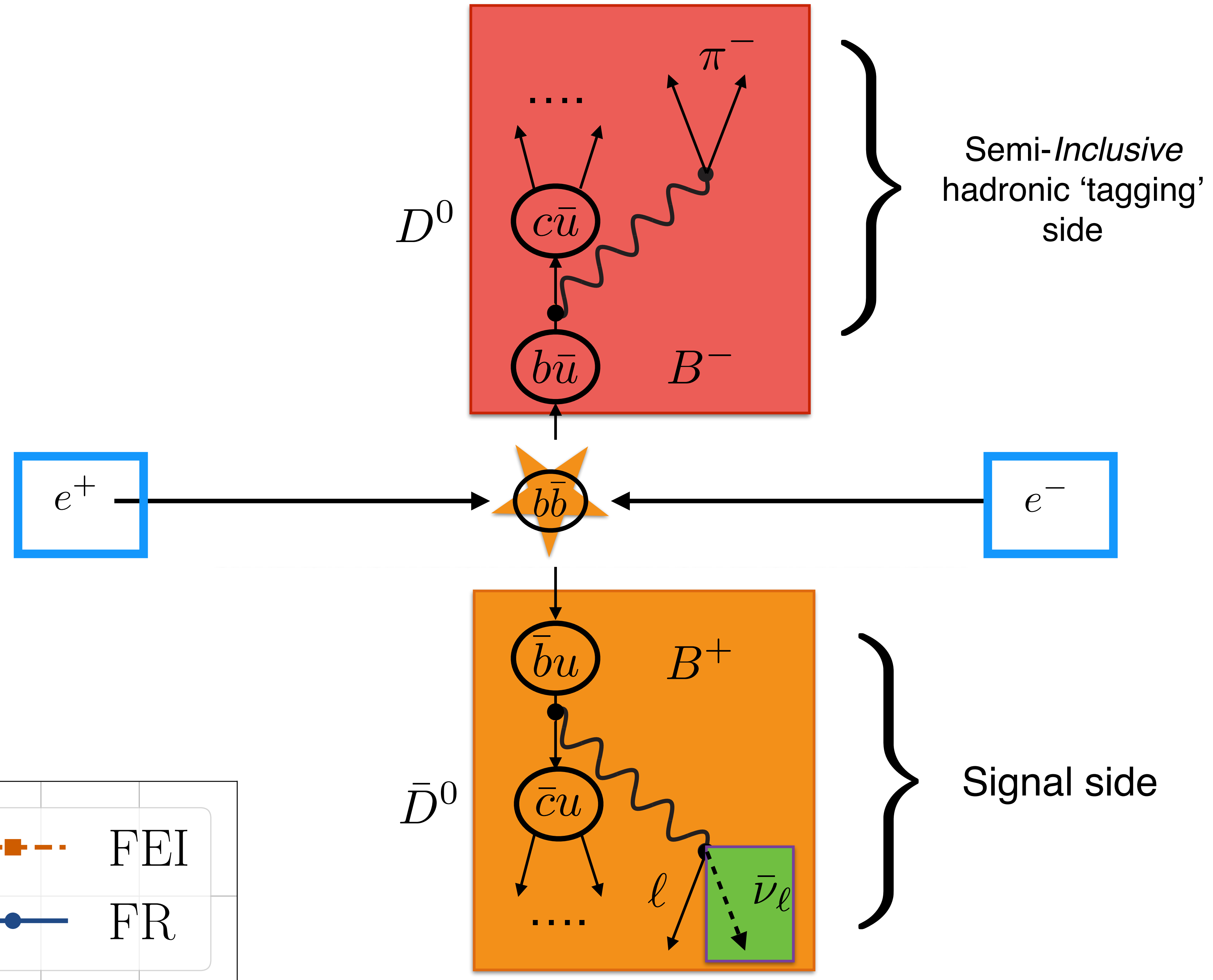


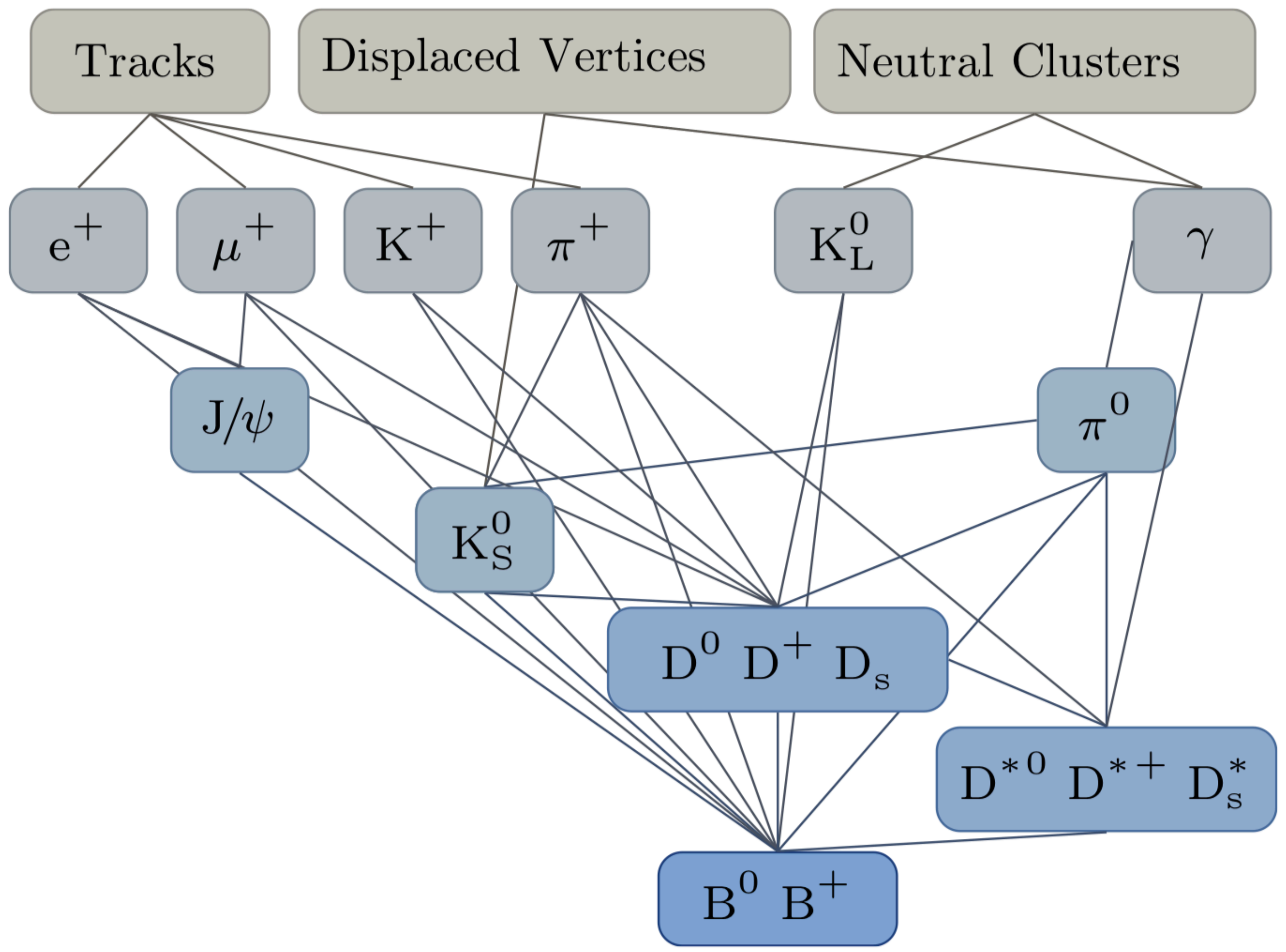
# Semileptonic and leptonic B decays / Techniques

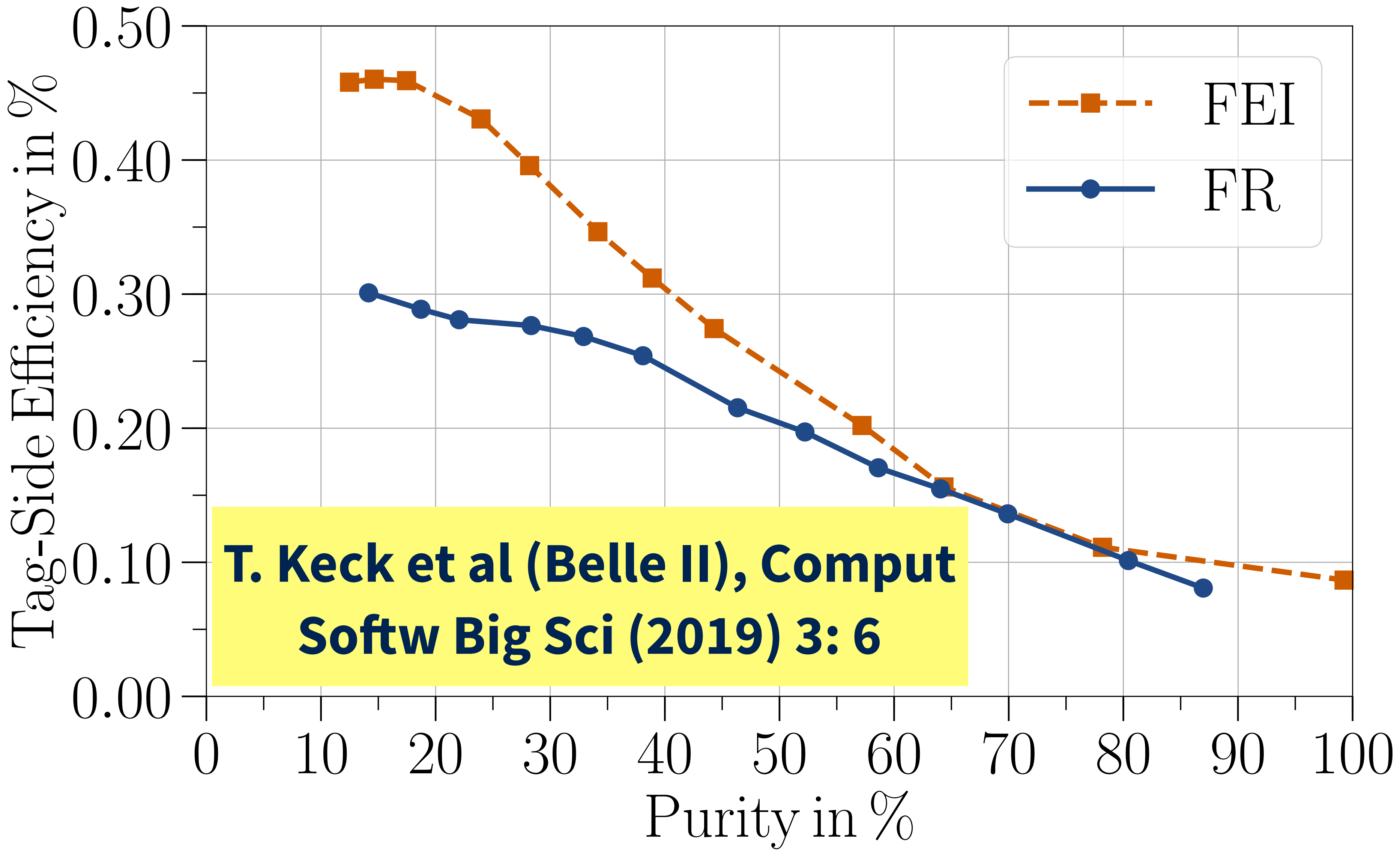
- Belle (II) analyses use **semileptonic** and **hadronic** “tagging” for flavour, charge, kinematics.

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

- Signal fits based on $M_{miss}^2$, $\cos\theta_{D^*\text{-}l}$, calorimeter extra energy $E_{ECL/extra}$




**T. Keck et al (Belle II), Comput Softw Big Sci (2019) 3: 6**

*Ongoing iterations on algorithms to improve efficiency - driven by more computationally efficient ways to add more hadronic modes.*

# Belle B → D$^{(*)}$ τ$^-$ ν analysis / Converted Belle→Belle II Data

- Semileptonic tag / FEI BDT, B→D τ ν and B→D* τ ν *Simultaneously*
- 2D fit to 3-var. XG-boost BDT classifier and extra energy in EM calo.

**Belle PRD 94, 072007 (2016)**

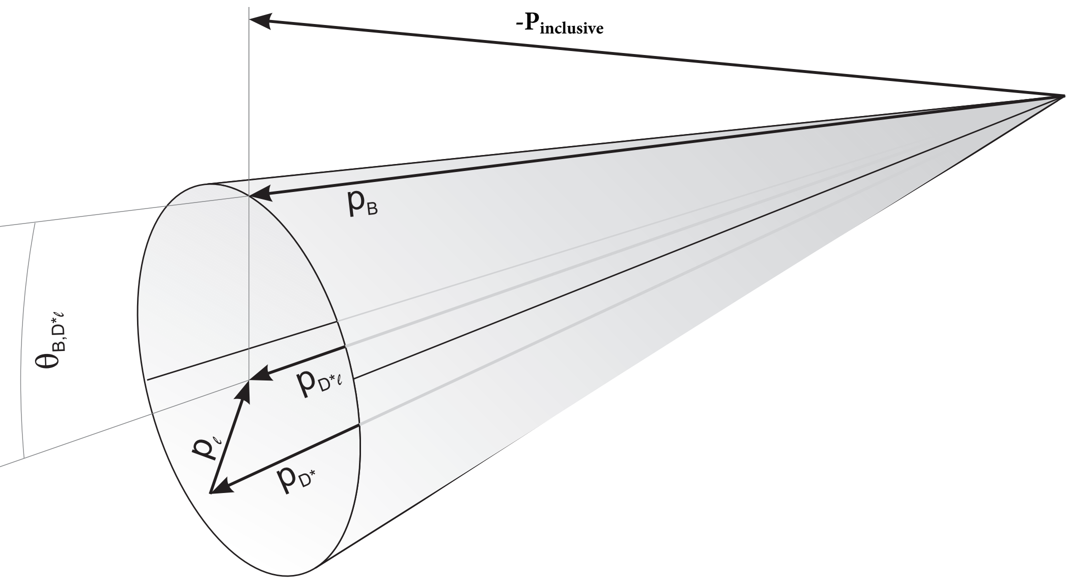
**Belle PRL 118, 211801 (2017)**
**Belle arXiv:1709.00129**

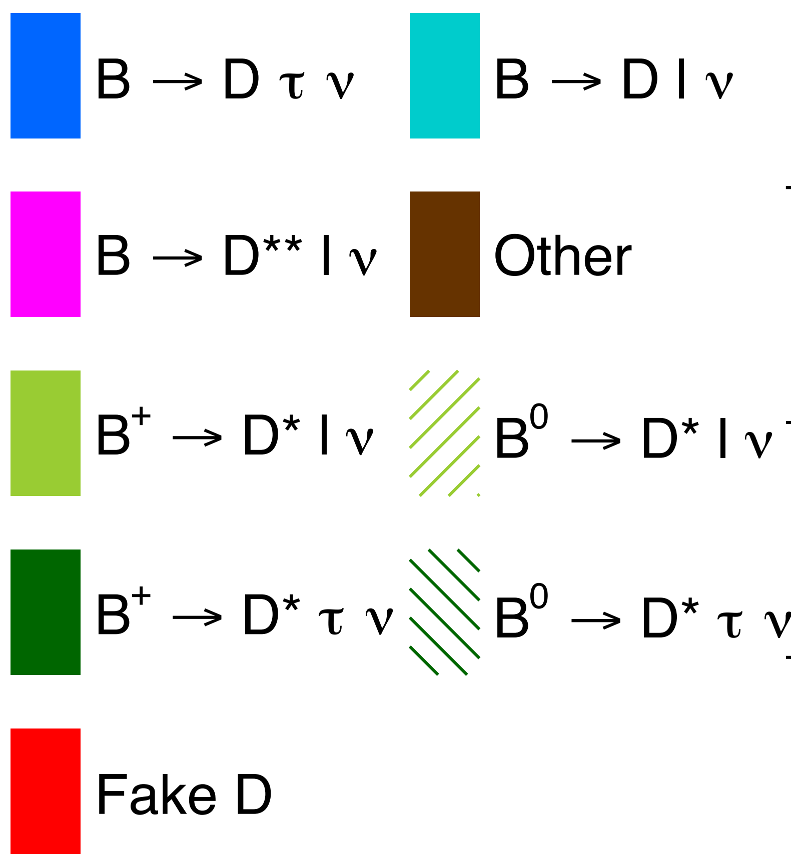
**$M^2_{miss}$**
**$E_{vis}$**
**$\cos\theta_{B-D^*l}$**

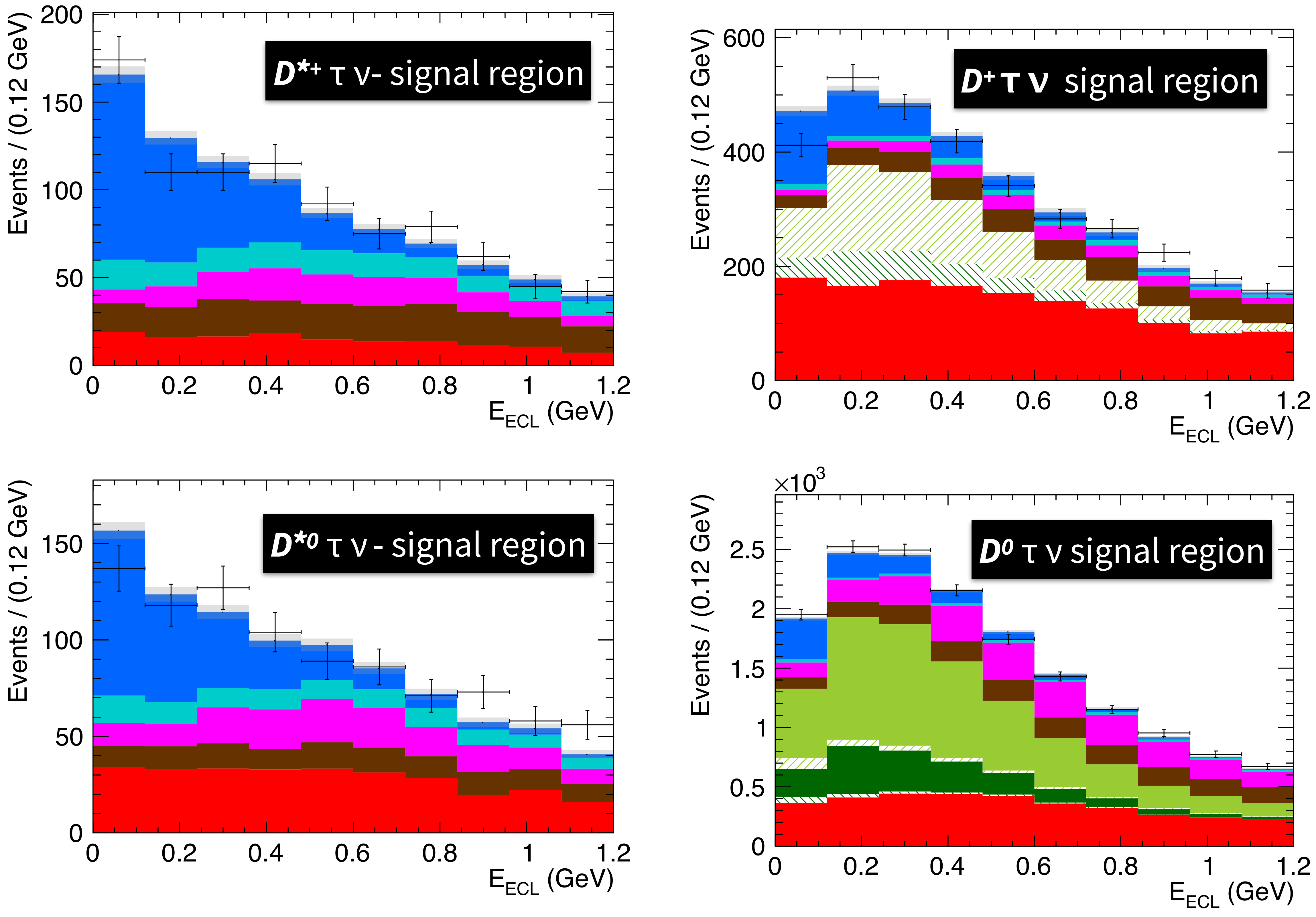
**Belle Preliminary 2019**

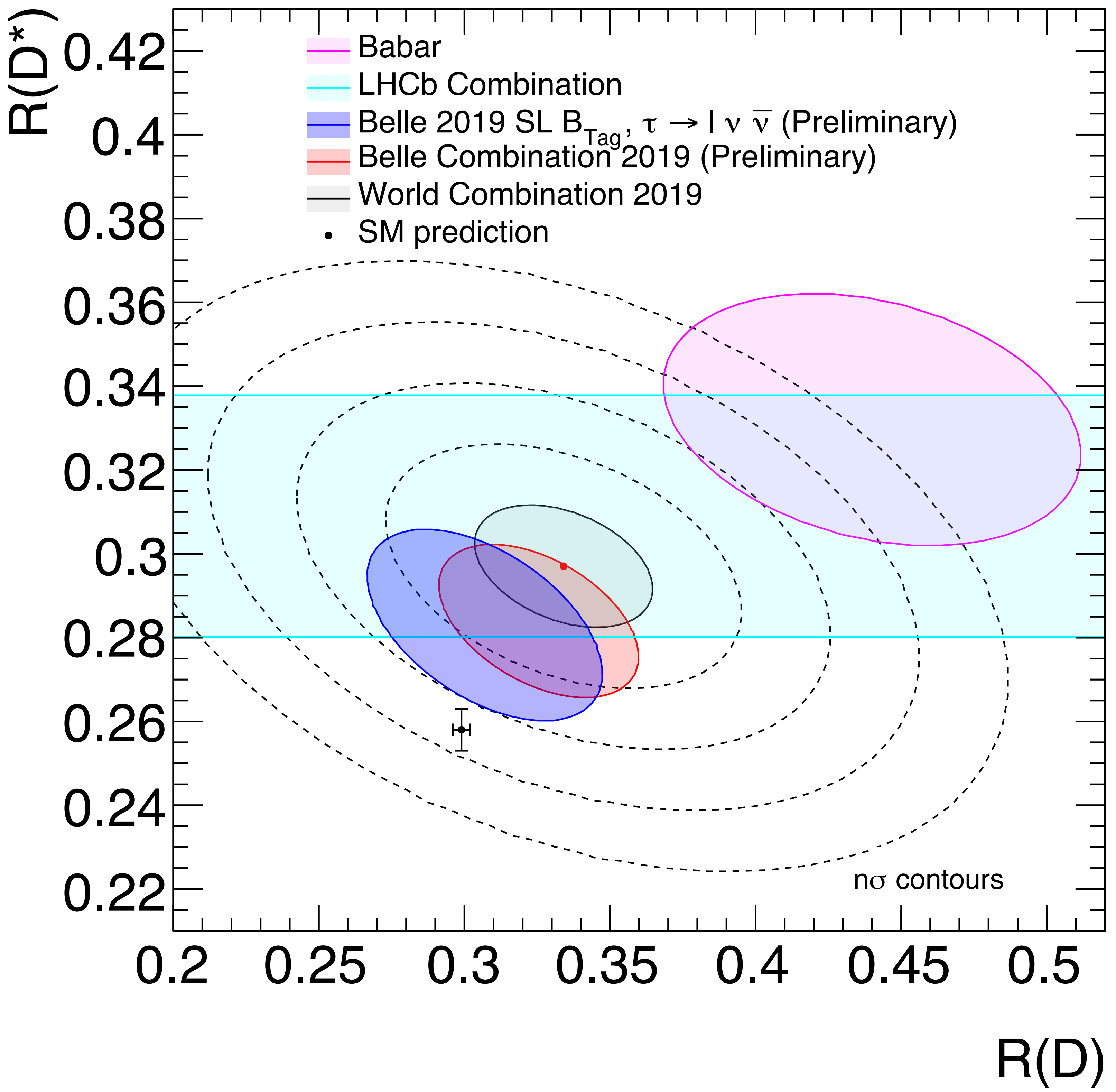
$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014,$$

**Measurement of the $D^{*-}$ polarization in the decay B→D* τ ν, arXiV: 1903.03102**



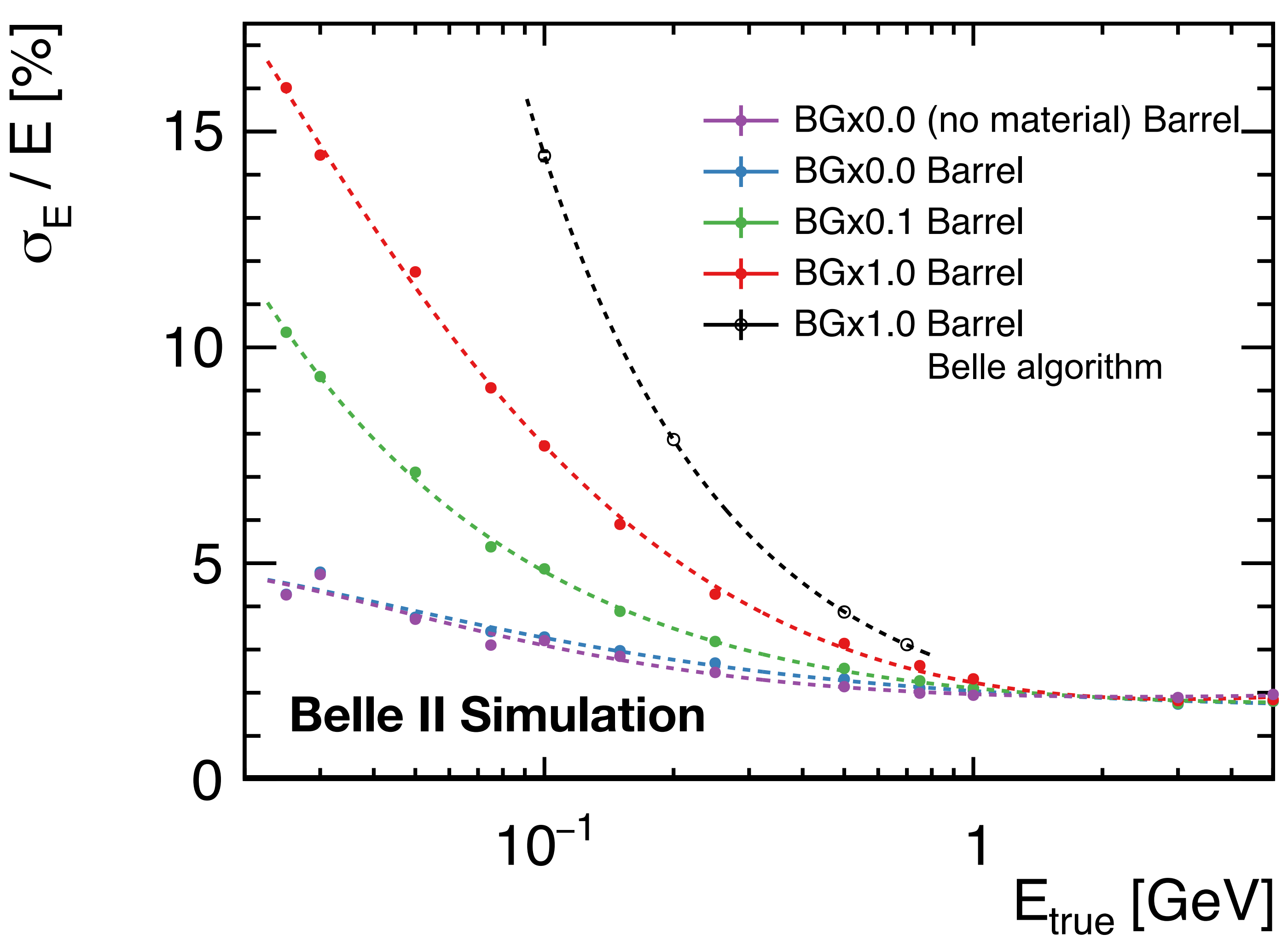



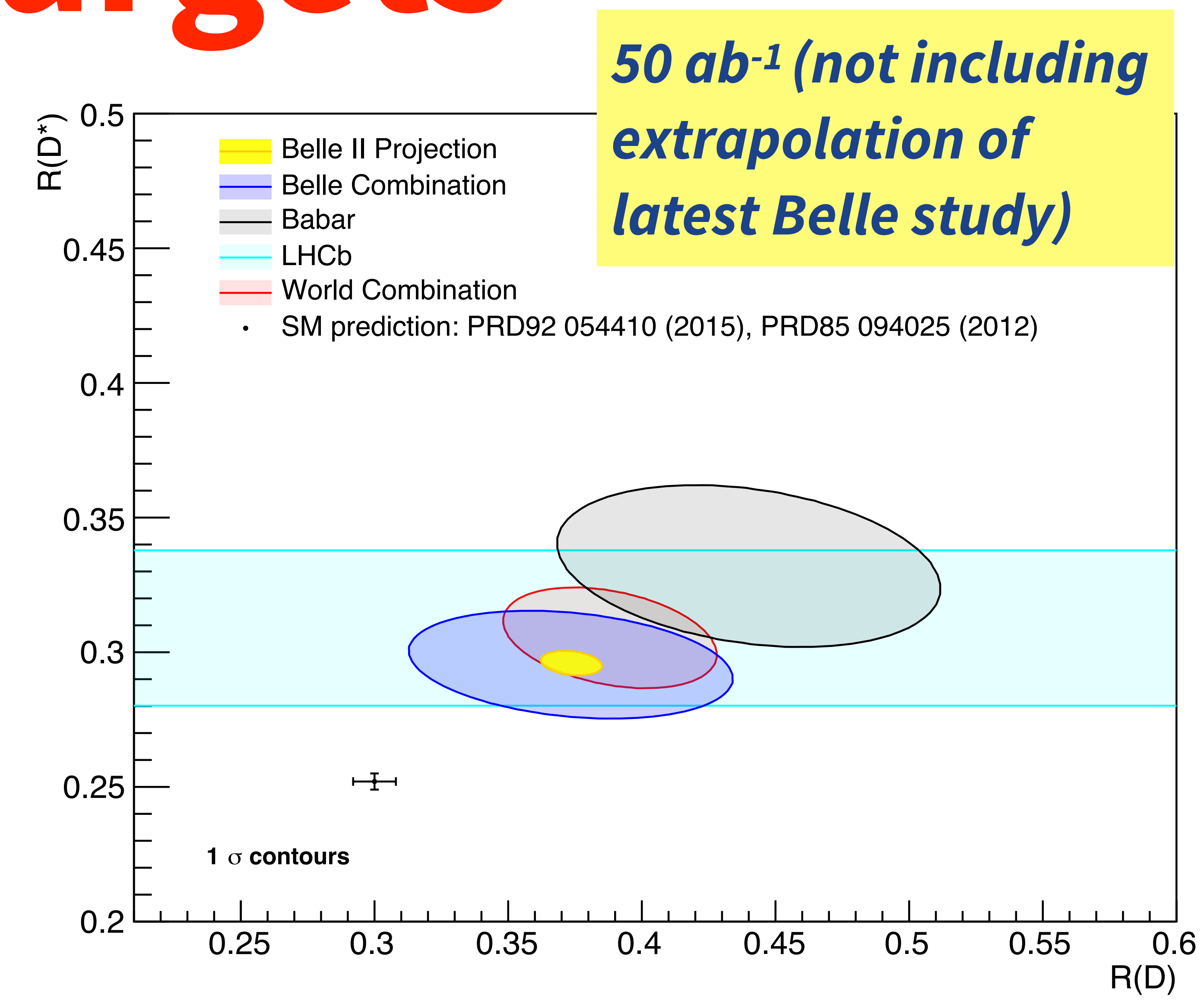



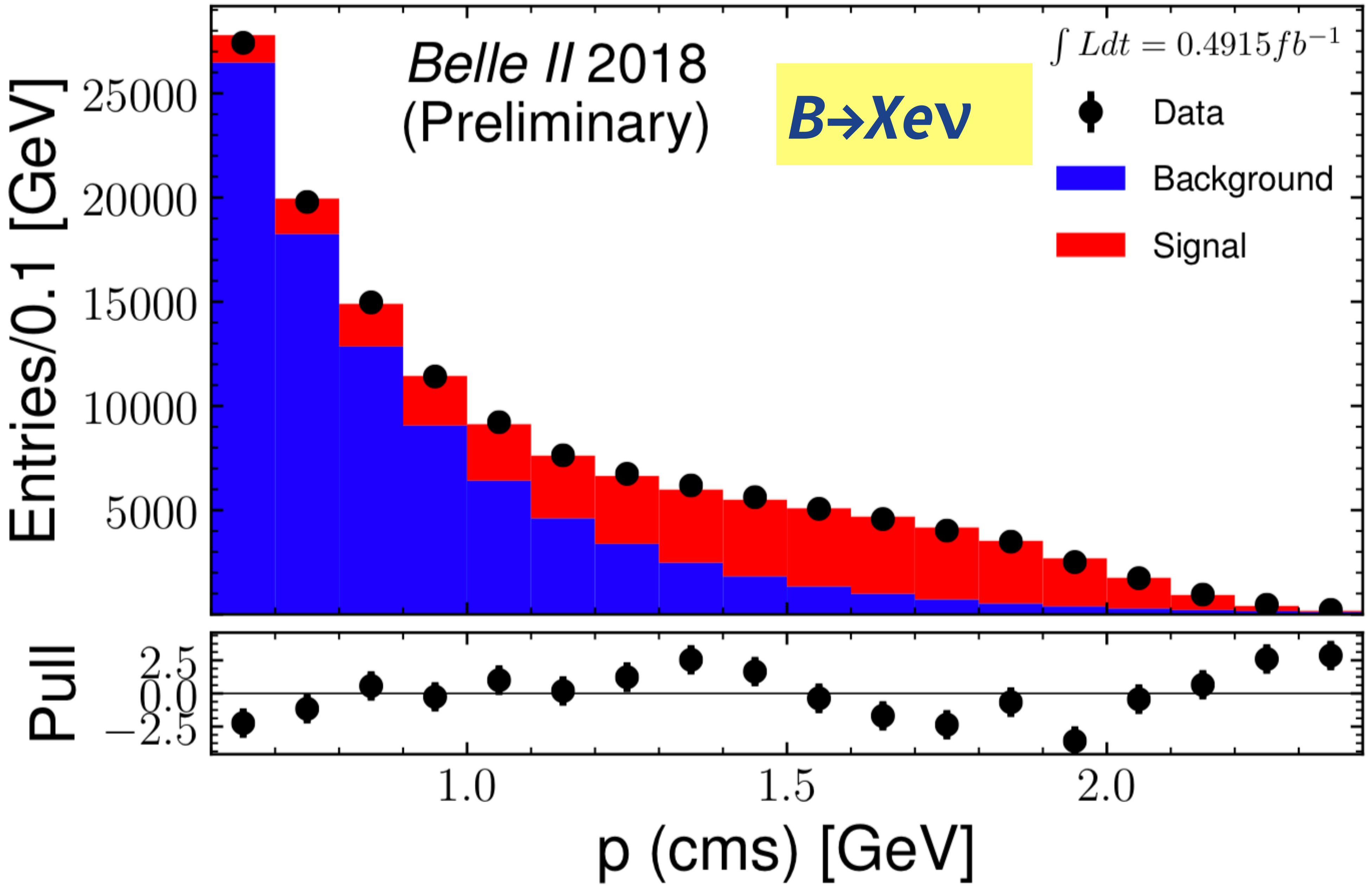
# Semileptonic and leptonic B decays / Targets

- History of anomalies - key to identify bias.
  - $K_L$ reconstruction, beam background mitigation for $\Sigma E_{ECL}$, $B \to D^{**} l \nu$ background, tag calibration.
- $|V_{xb}|$ covered by W. Sutcliffe



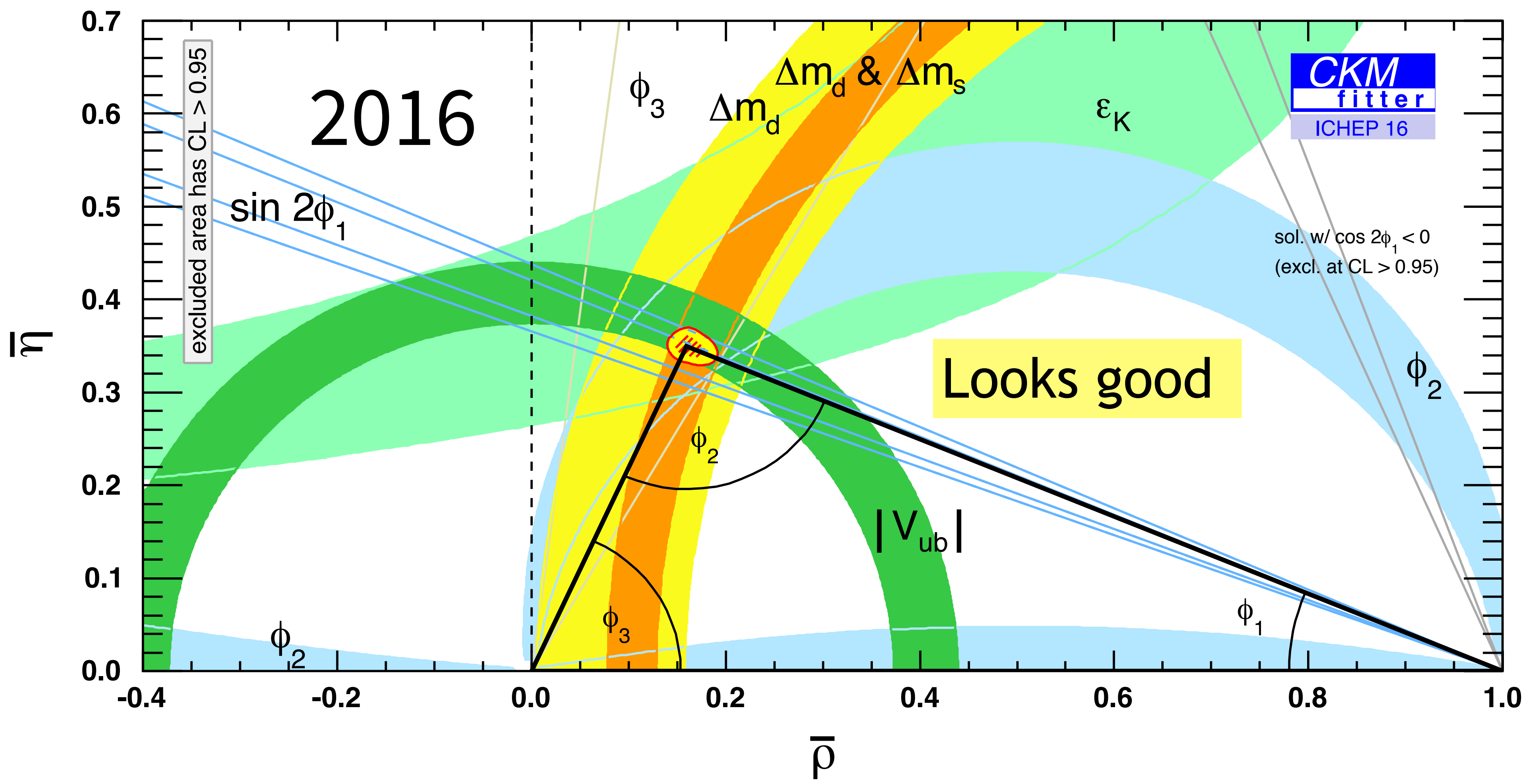




| Observables | Belle (2017) | Belle II 5 $ab^{-1}$ | Belle II 50 $ab^{-1}$ |
|---|---|---|---|
| $\lvert V_{cb}\rvert$ incl. | $42.2 \cdot 10^{-3} \cdot (1 \pm 1.8\%)$ | 1.2% | — |
| $\lvert V_{cb}\rvert$ excl. | $39.0 \cdot 10^{-3} \cdot (1 \pm 3.0\%_{\text{ex.}} \pm 1.4\%_{\text{th.}})$ | 1.8% | 1.4% |
| $\lvert V_{ub}\rvert$ incl. | $4.47 \cdot 10^{-3} \cdot (1 \pm 6.0\%_{\text{ex.}} \pm 2.5\%_{\text{th.}})$ | 3.4% | 3.0% |
| $\lvert V_{ub}\rvert$ excl. (WA) | $3.65 \cdot 10^{-3} \cdot (1 \pm 2.5\%_{\text{ex.}} \pm 3.0\%_{\text{th.}})$ | 2.4% | 1.2% |
| $\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$ | $91 \cdot (1 \pm 24\%)$ | 9% | 4% |
| $\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$ | $< 1.7$ | 20% | 7% |
| $R(B \to D\tau\nu)$ (Had. tag) | $0.374 \cdot (1 \pm 16.5\%)$ | 6% | 3% |
| $R(B \to D^*\tau\nu)$ (Had. tag) | $0.296 \cdot (1 \pm 7.4\%)$ | 3% | 2% |



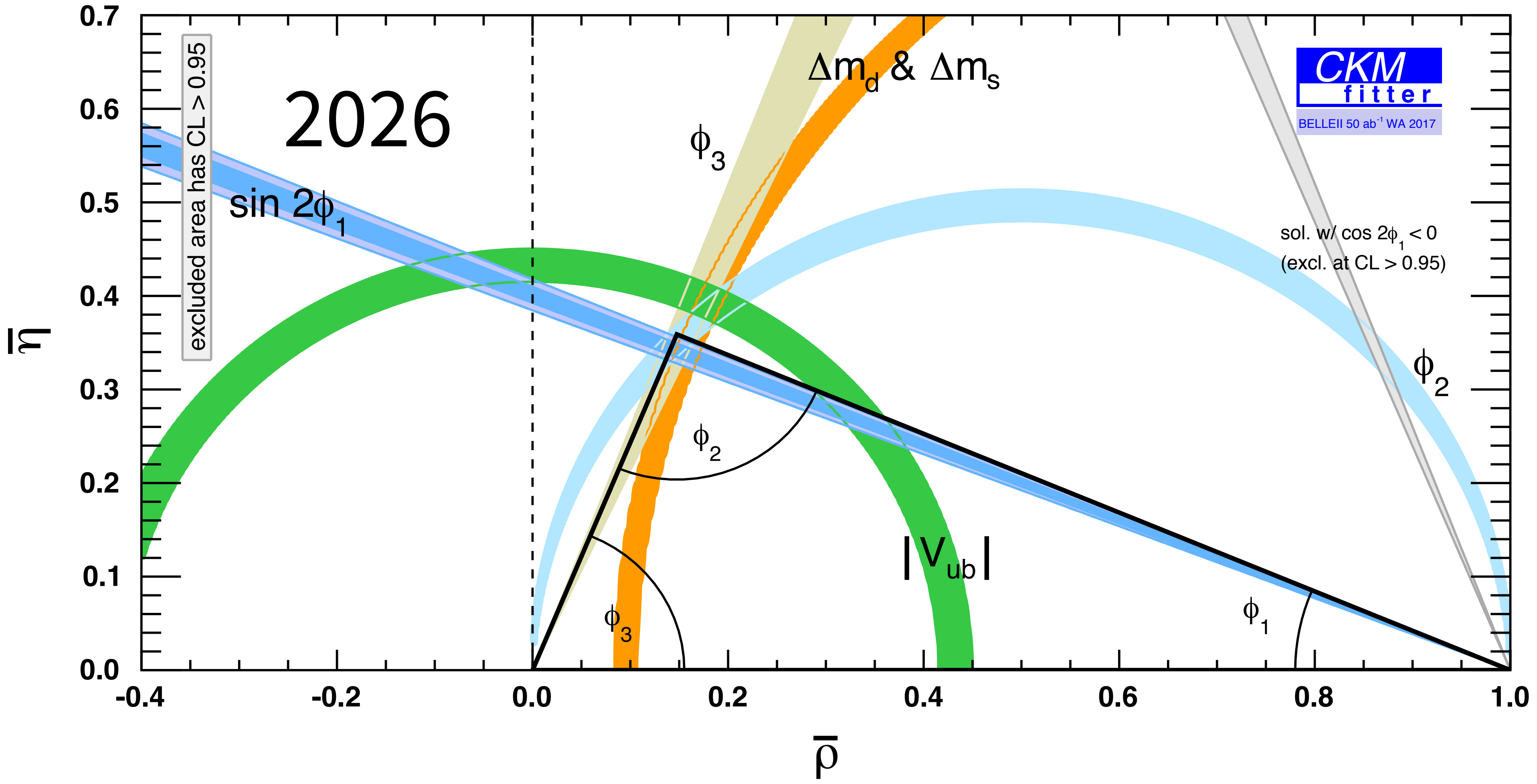
# CKM Global Fit Projection: Belle II

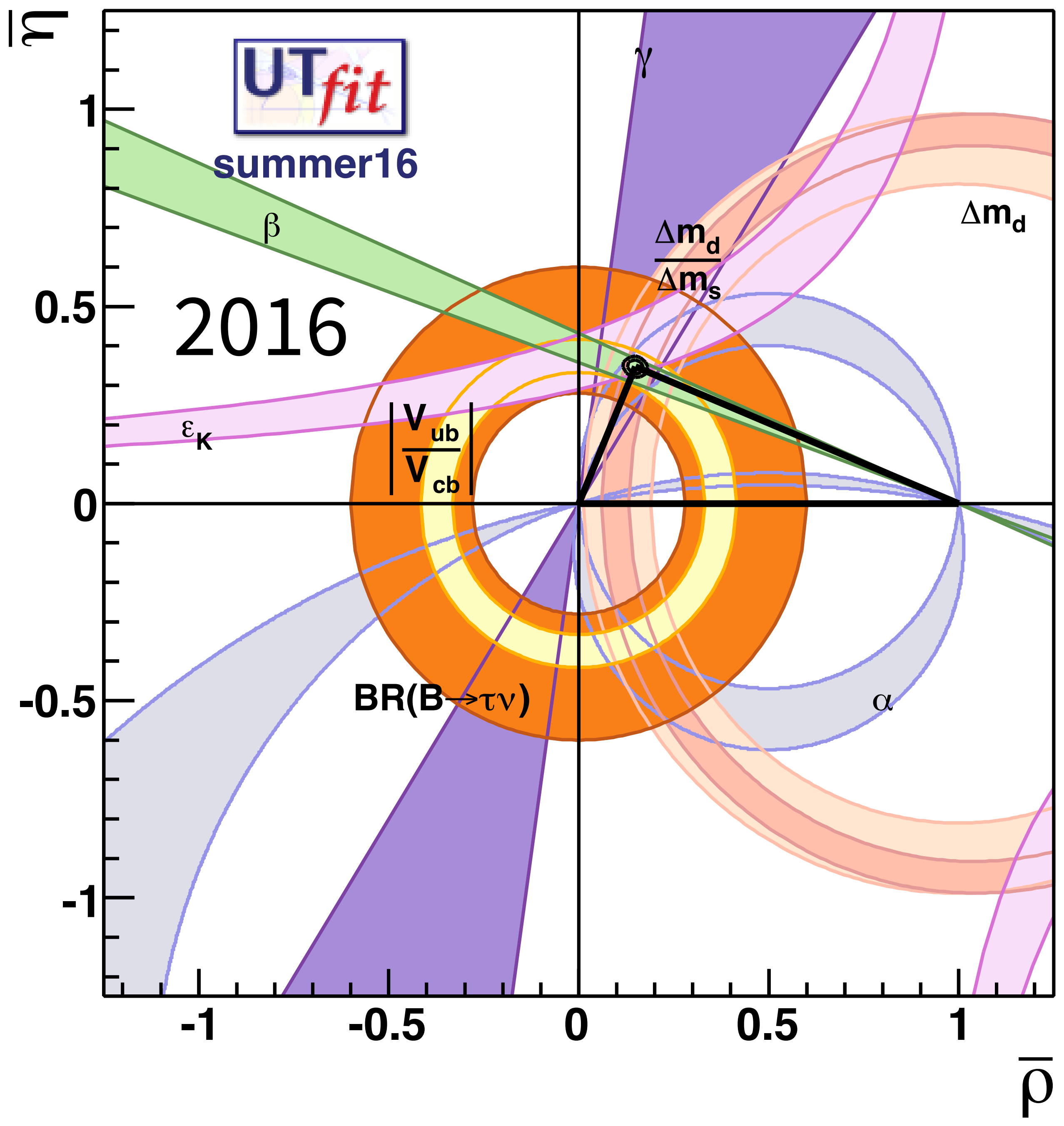
E. Kou, PU et al. arXiv: 1808.10567

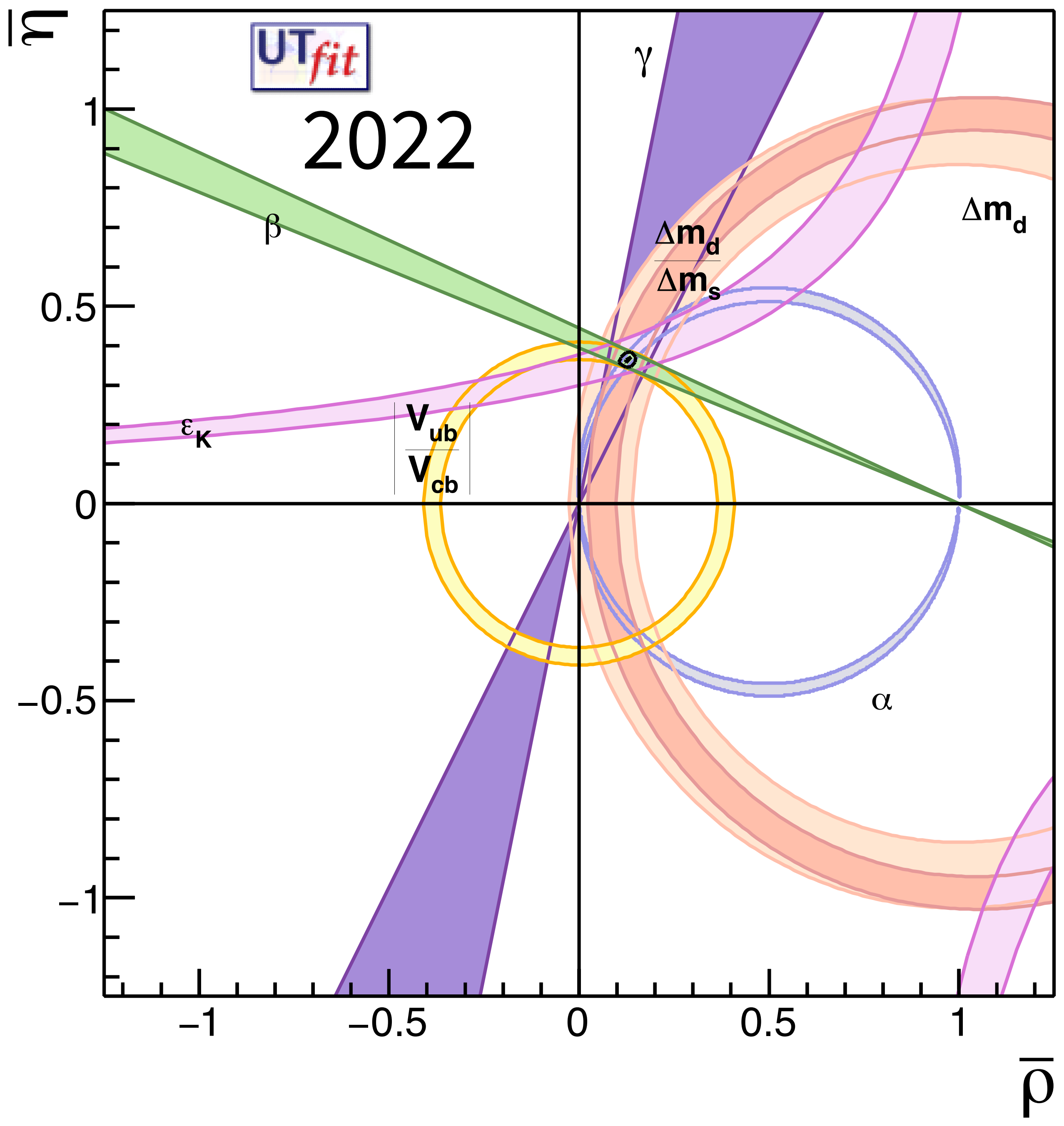


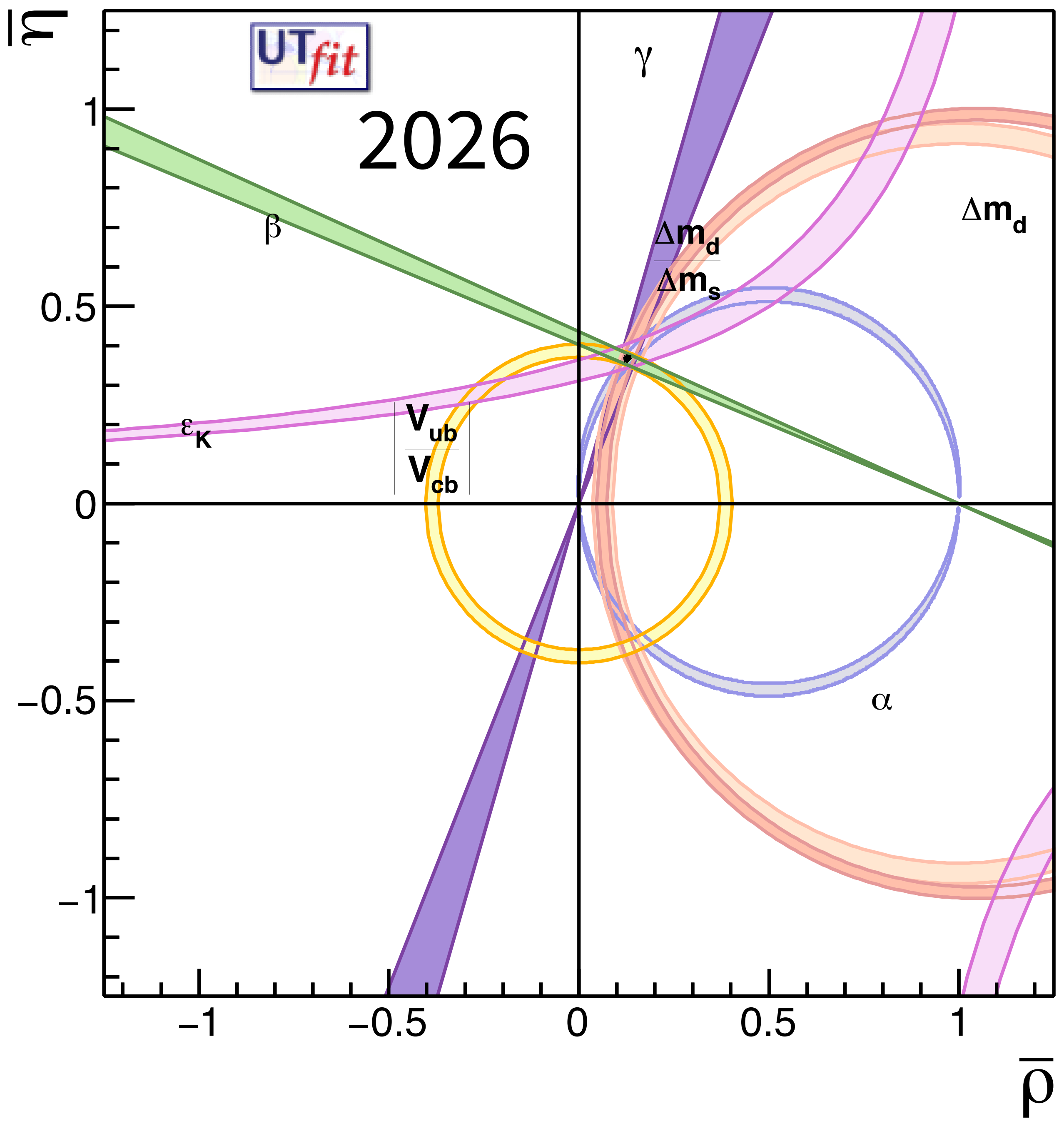

$\Phi_3$ ~ 1-1.5° at LHCb & Belle II

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



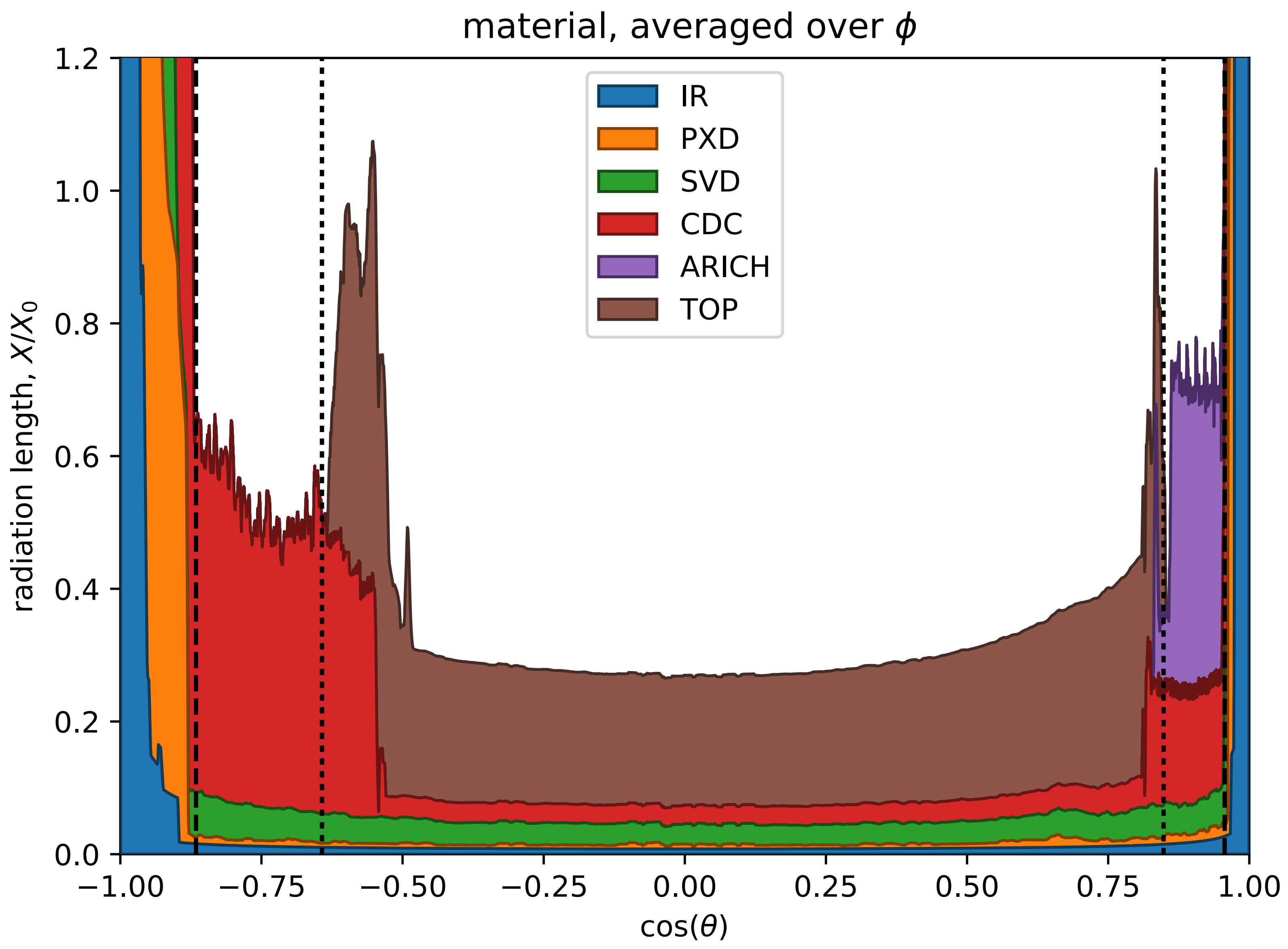



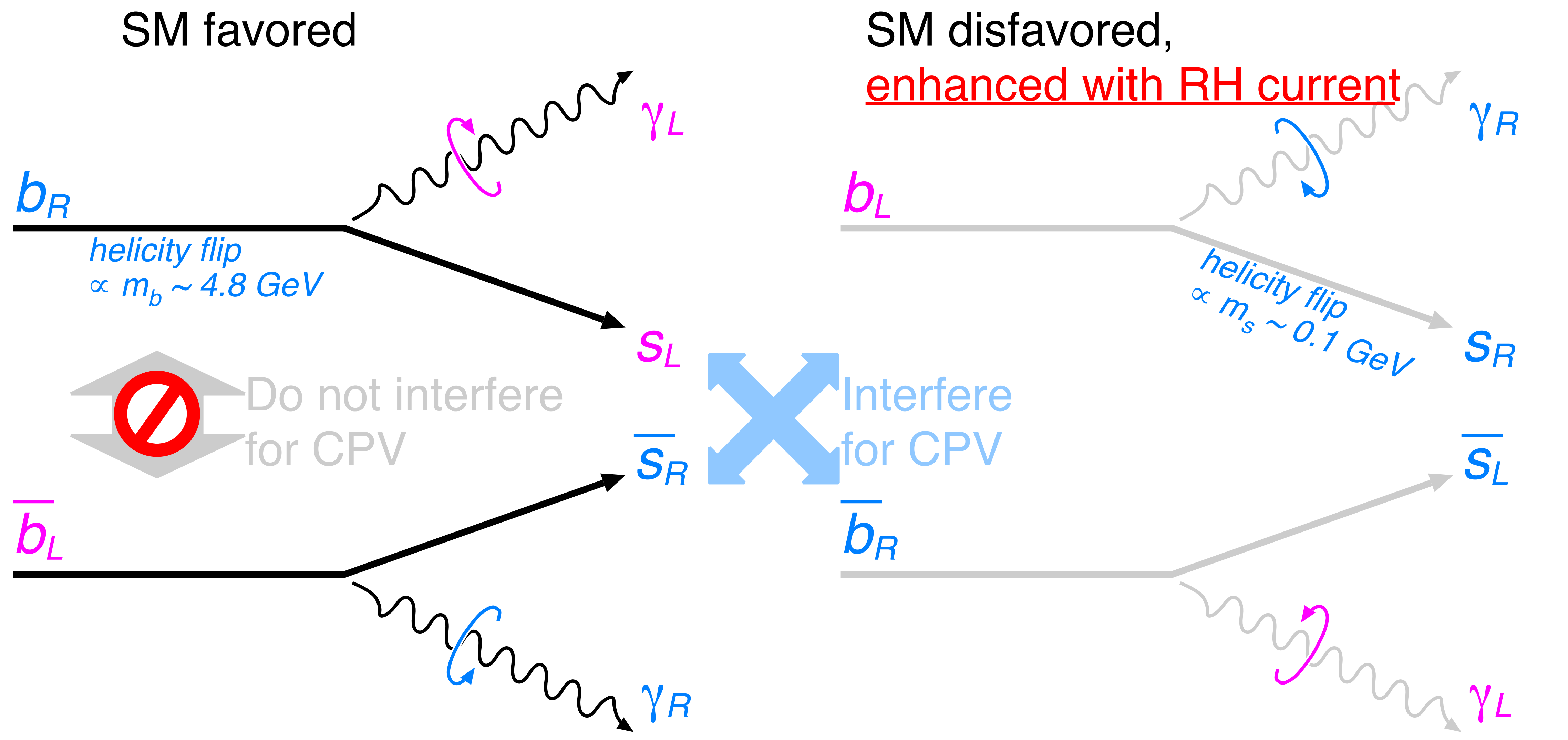



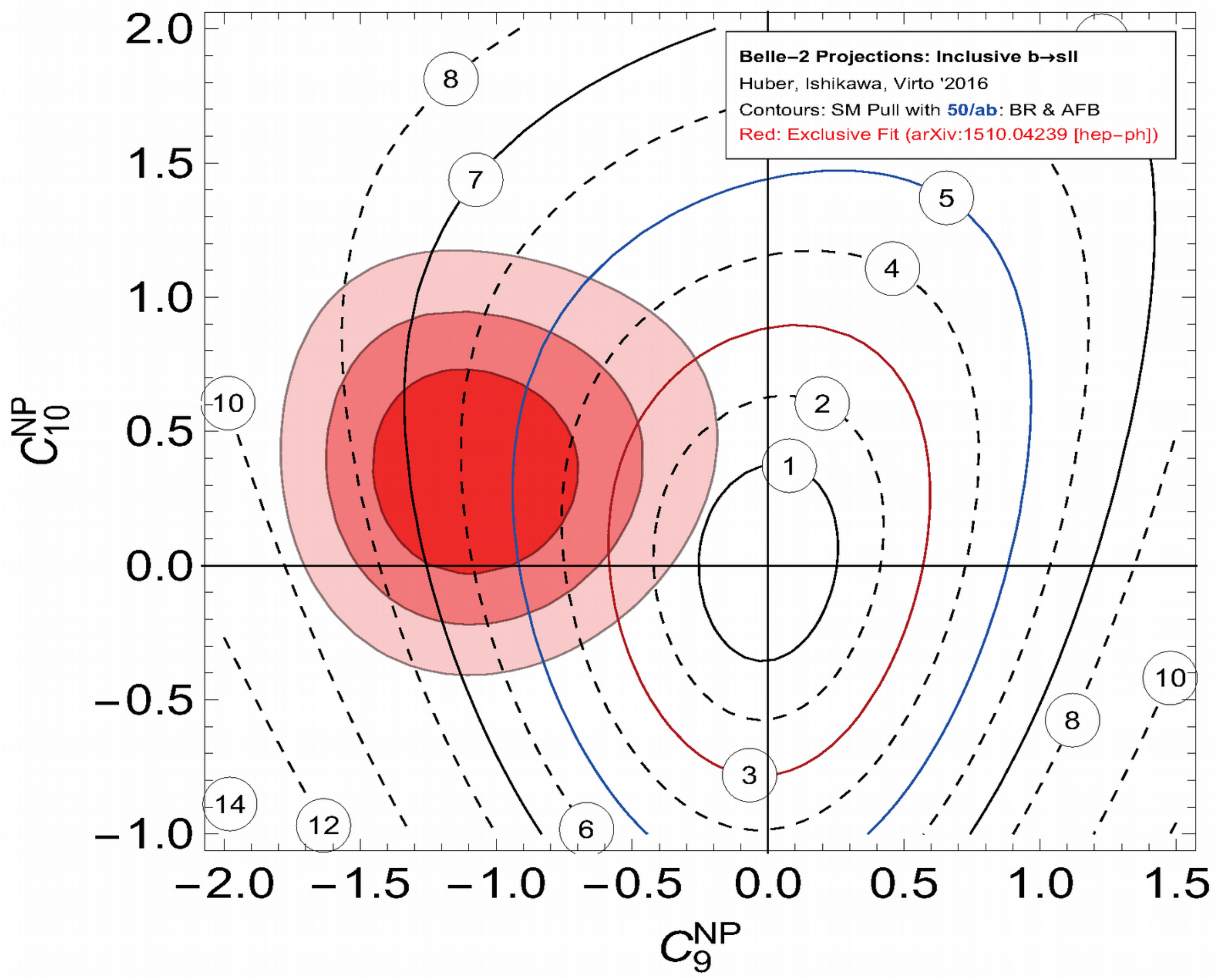



# Radiative and EW penguin B decays / Overview

- Several tensions at the 2-3 σ level: Statistics limited at Belle II.
- Belle II dominant measurements
  - TD CPV in radiative $B_d \rightarrow \rho\gamma$, $K^*\gamma$
  - Inclusive spectra in $B \rightarrow X l^+ l^-$ (initially sum over exclusives with $M_{X_s} < 1.8$ GeV, eventually: explore fully inclusive recoil).
  - Electron (low $X/X_0$) & τ channels
  - SM level (5 σ)in $B \rightarrow X\nu\nu$



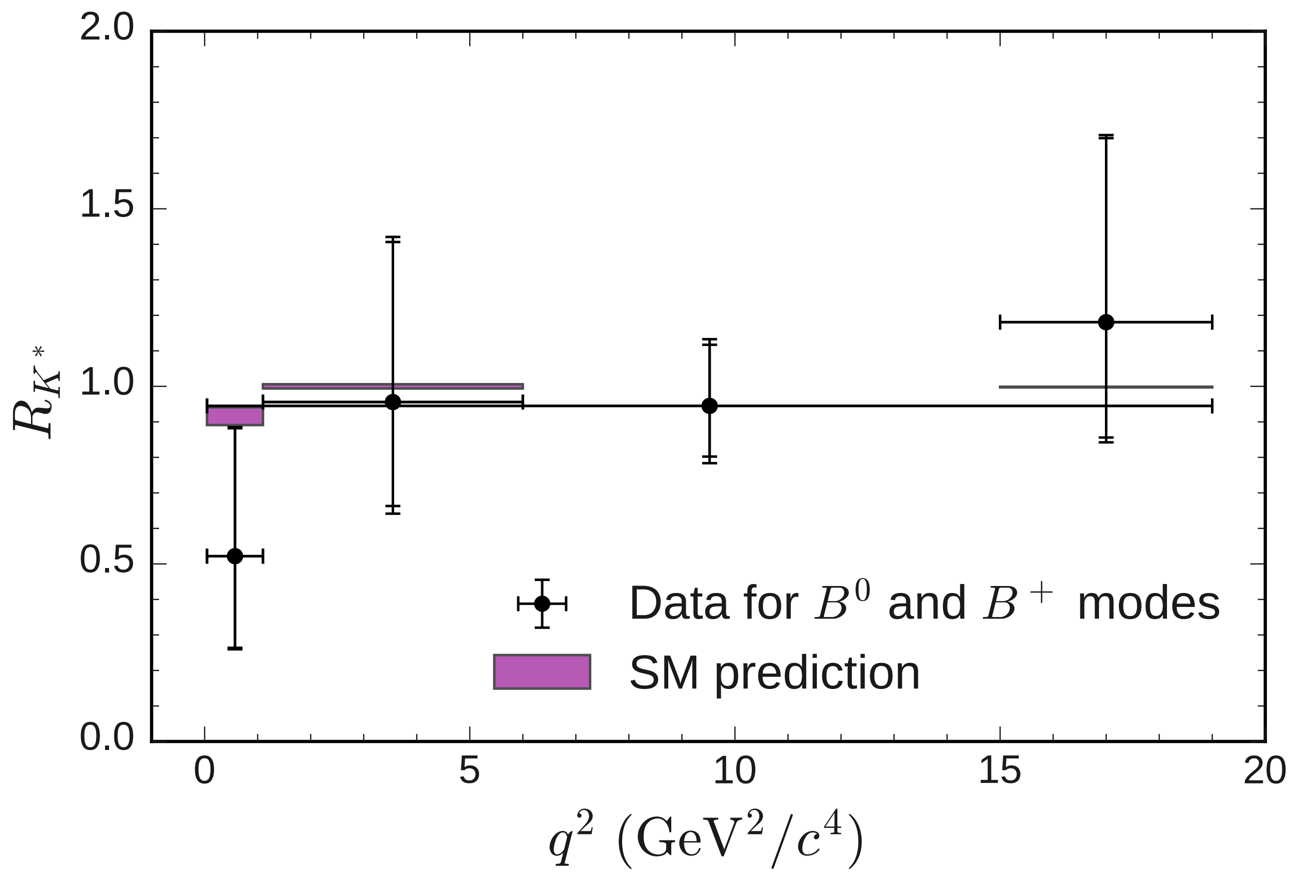



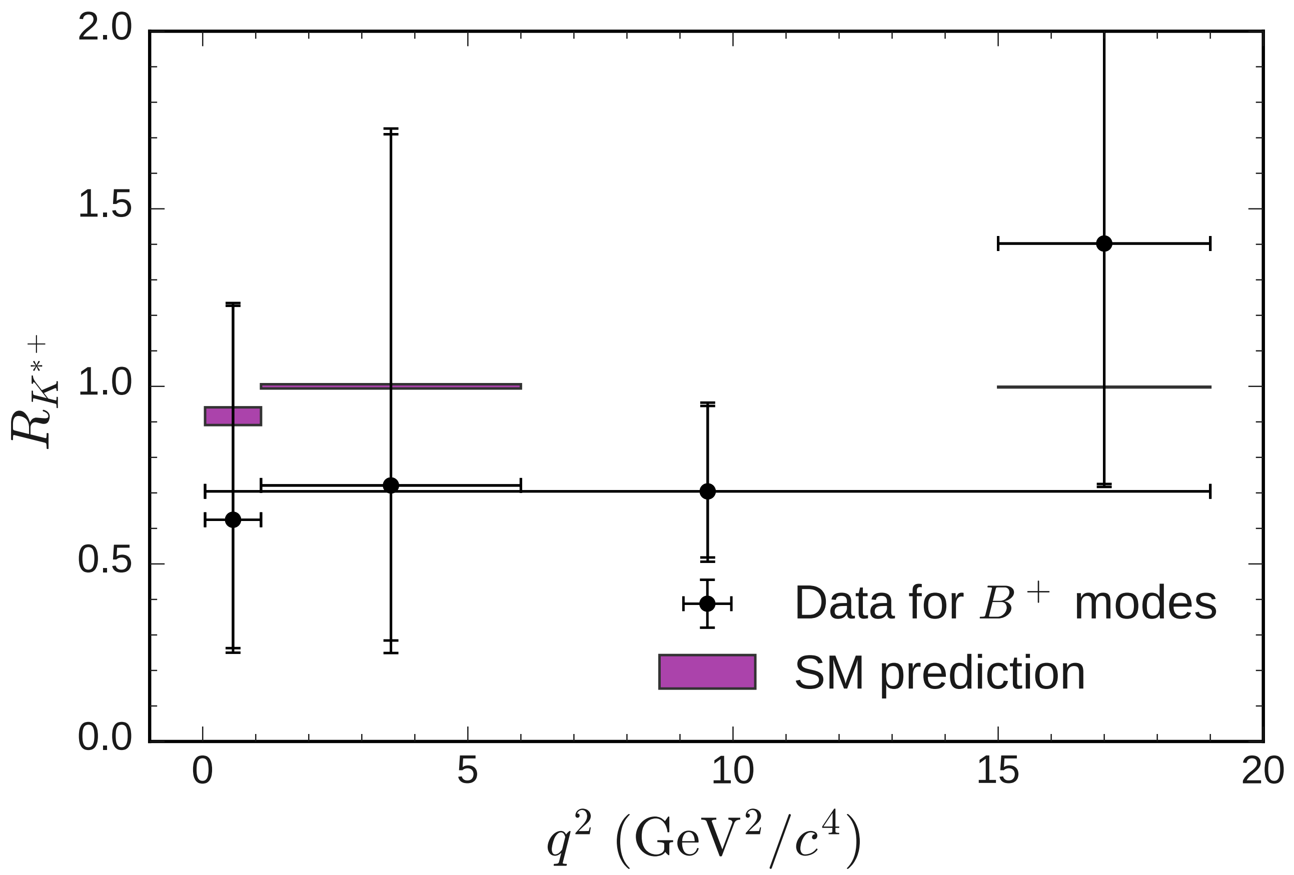
# Radiative and EW penguin B decays / Belle $R_{K^*}$

**Belle Preliminary 2019**

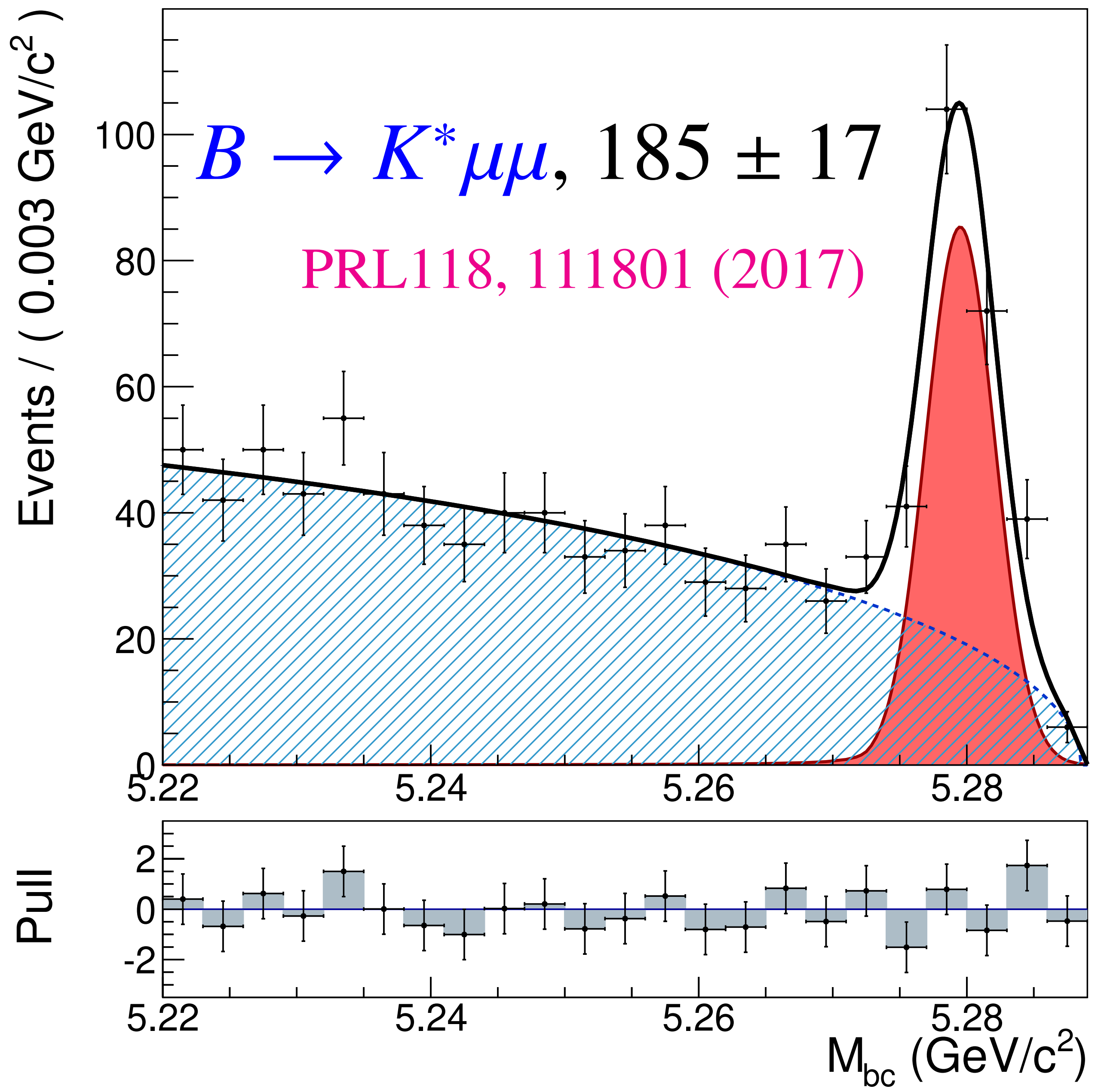
| $q^2$ in $\mathrm{GeV}^2/c^4$ | All modes | $B^0$ modes | $B^+$ modes |
|---|---|---|---|
| $[0.045, 1.1]$ | $0.52^{+0.36}_{-0.26} \pm 0.05$ | $0.46^{+0.55}_{-0.27} \pm 0.07$ | $0.62^{+0.60}_{-0.36} \pm 0.10$ |
| $[1.1, 6]$ | $0.96^{+0.45}_{-0.29} \pm 0.11$ | $1.06^{+0.63}_{-0.38} \pm 0.13$ | $0.72^{+0.99}_{-0.44} \pm 0.18$ |
| $[0.1, 8]$ | $0.90^{+0.27}_{-0.21} \pm 0.10$ | $0.86^{+0.33}_{-0.24} \pm 0.08$ | $0.96^{+0.56}_{-0.35} \pm 0.14$ |
| $[15, 19]$ | $1.18^{+0.52}_{-0.32} \pm 0.10$ | $1.12^{+0.61}_{-0.36} \pm 0.10$ | $1.40^{+1.99}_{-0.68} \pm 0.11$ |
| $[0.045, ]$ | $0.94^{+0.17}_{-0.14} \pm 0.08$ | $1.12^{+0.27}_{-0.21} \pm 0.09$ | $0.70^{+0.24}_{-0.19} \pm 0.07$ |

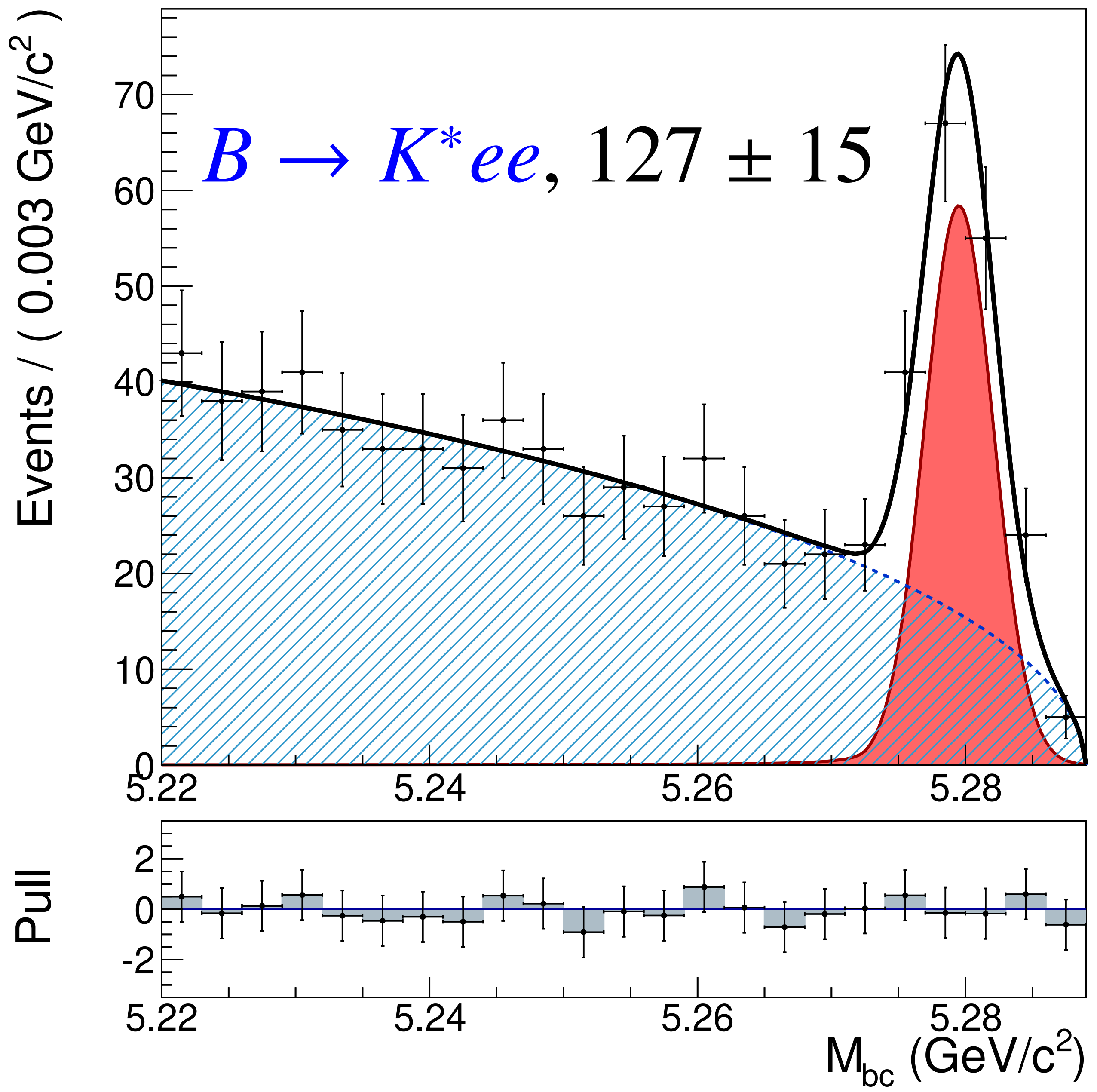


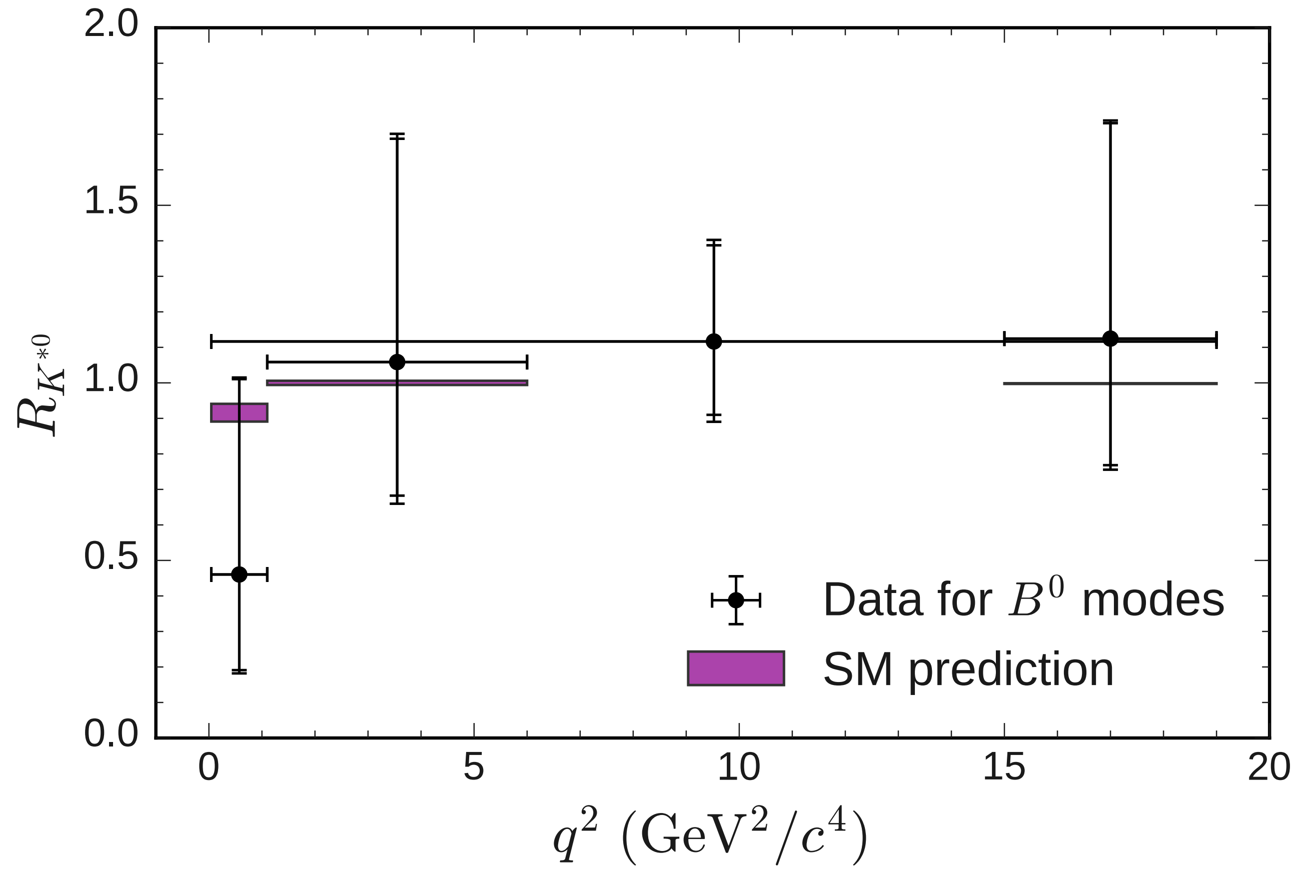
(a)



(b)



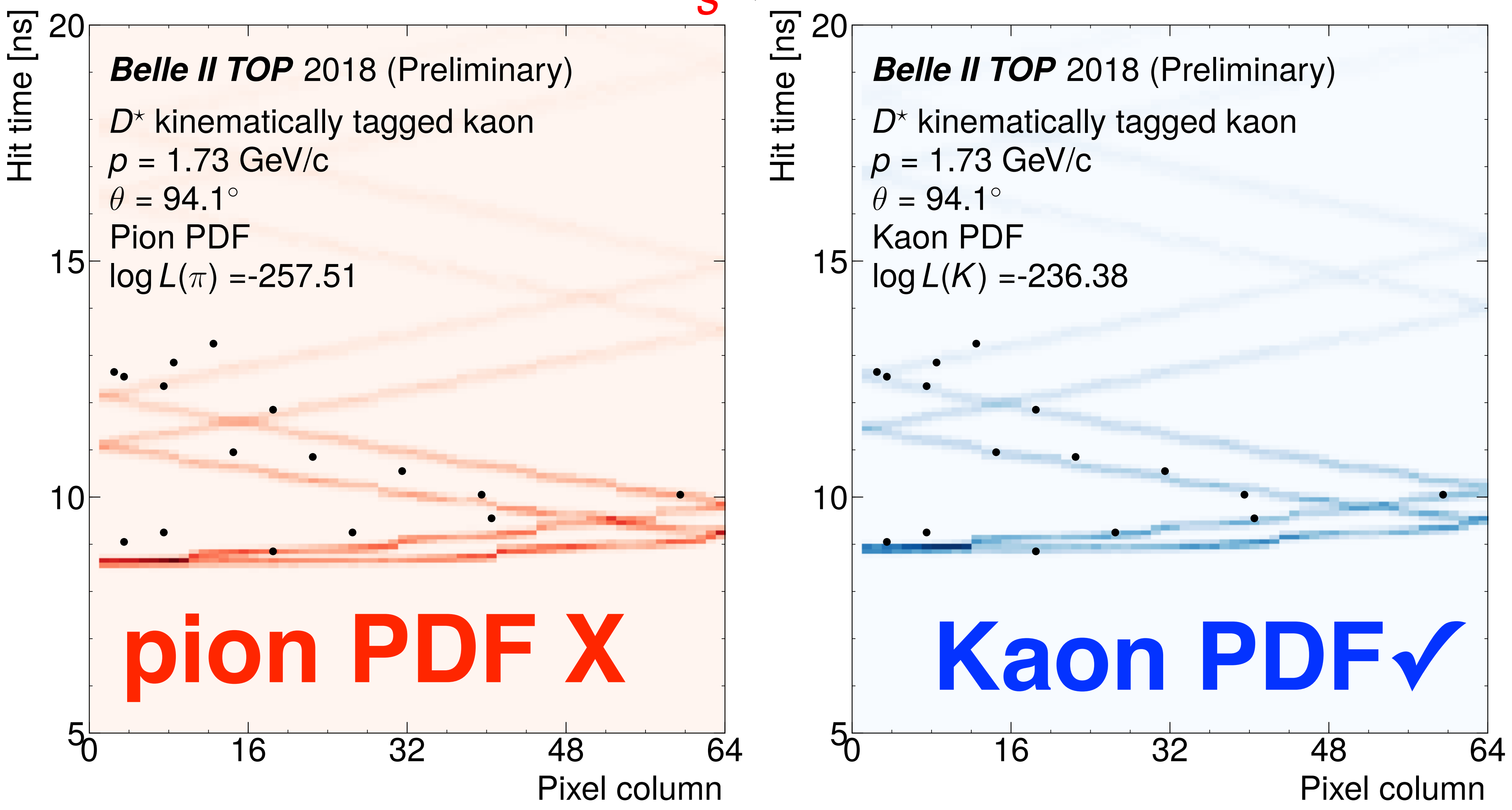
# Radiative and EW penguin B decays / Performance

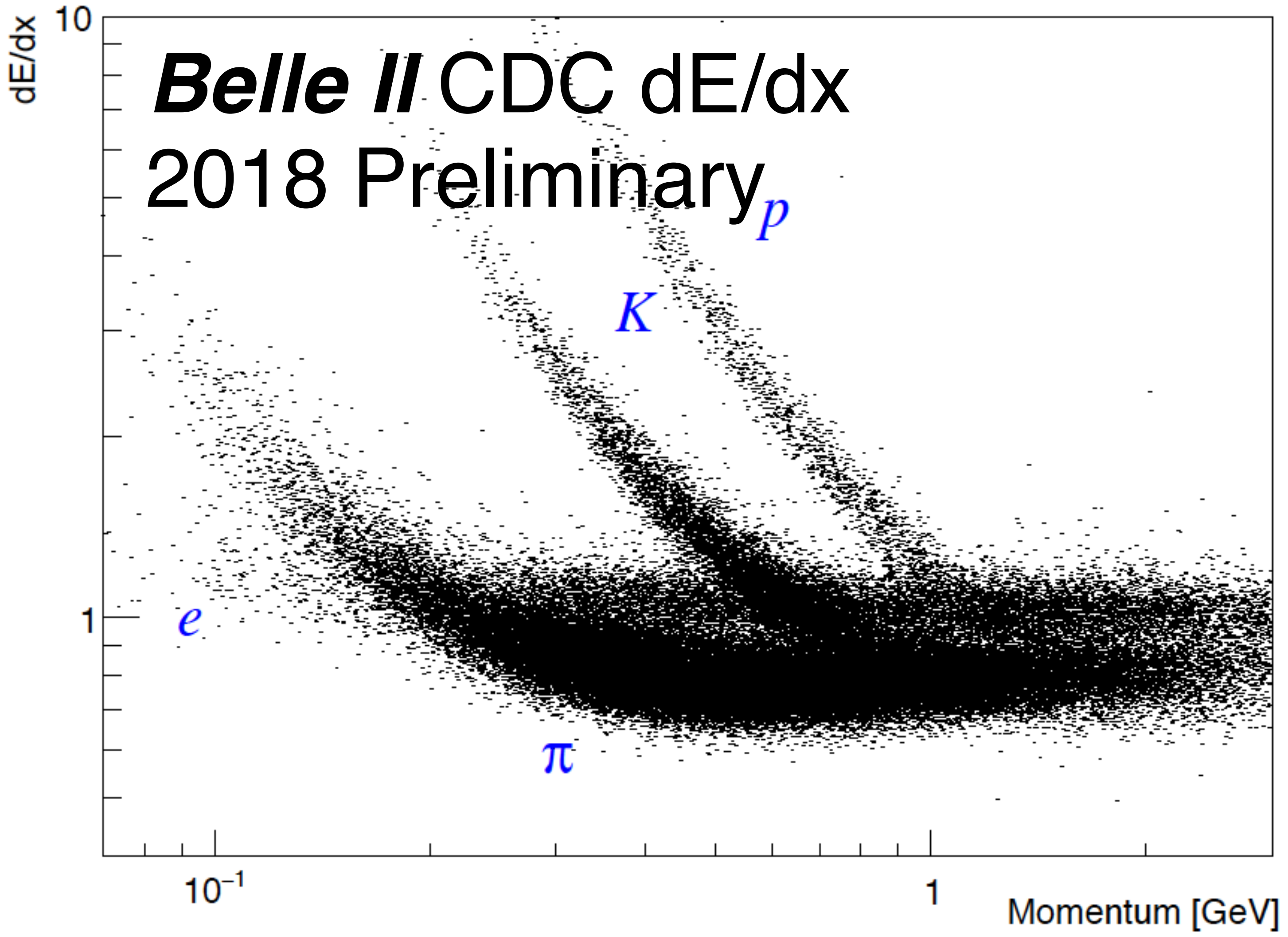
- **b→d γ transitions** are a key opportunity, requiring better K/π Particle ID performance than Belle.

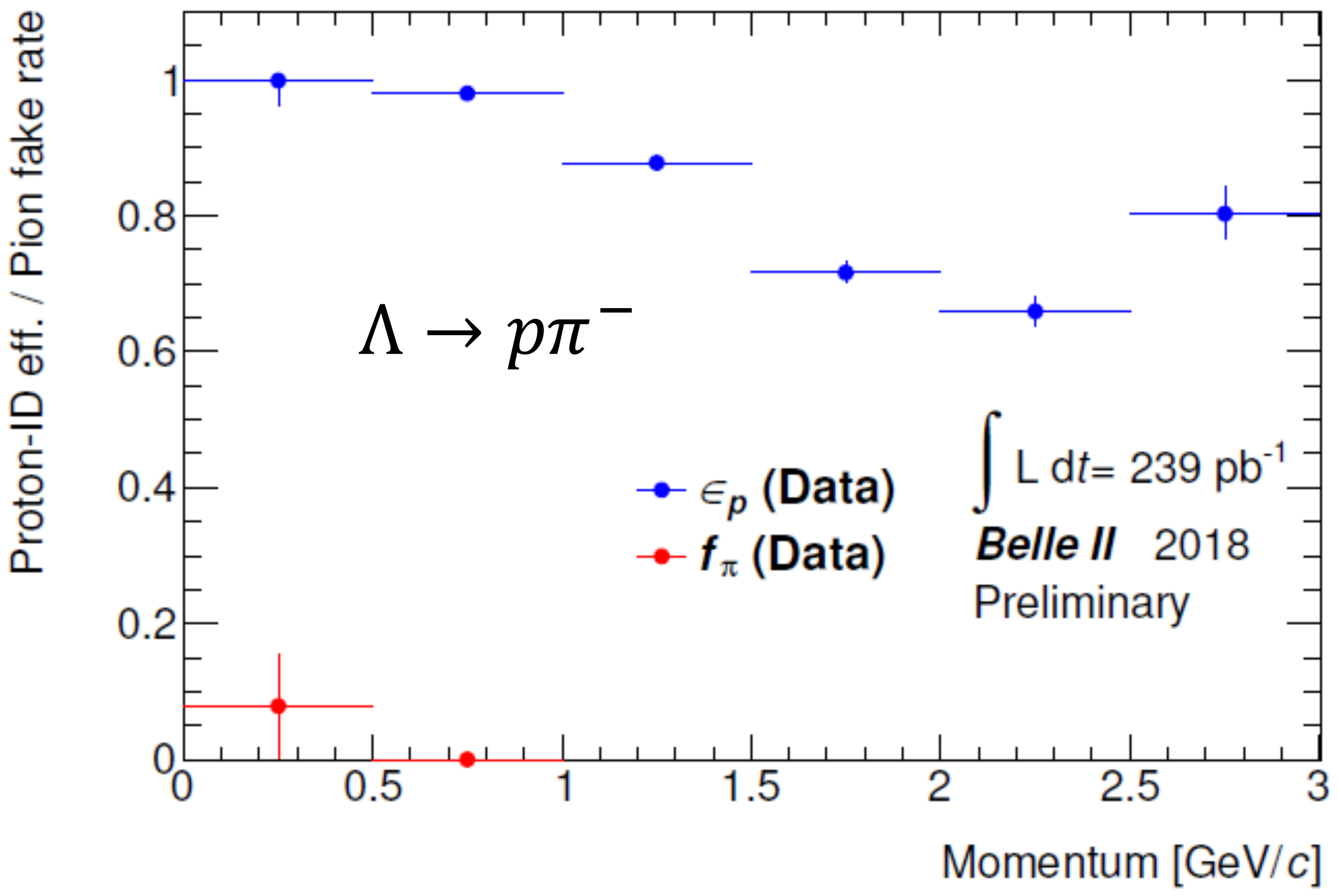
Central Drift Chamber dE/dx & Time of propagation Cherenkov patterns - 2018 data

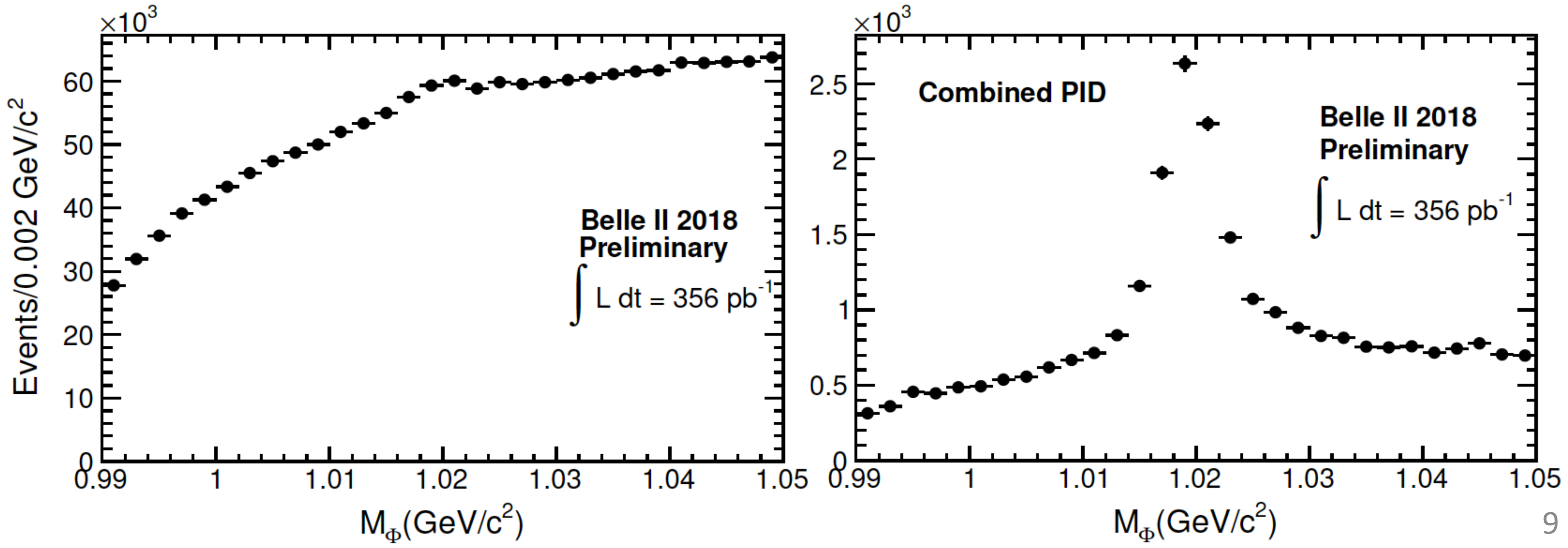
Kinematically identified kaon from $D^{*+}$ in TOP; x vs t pattern (mapping of Cherenkov ring)

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



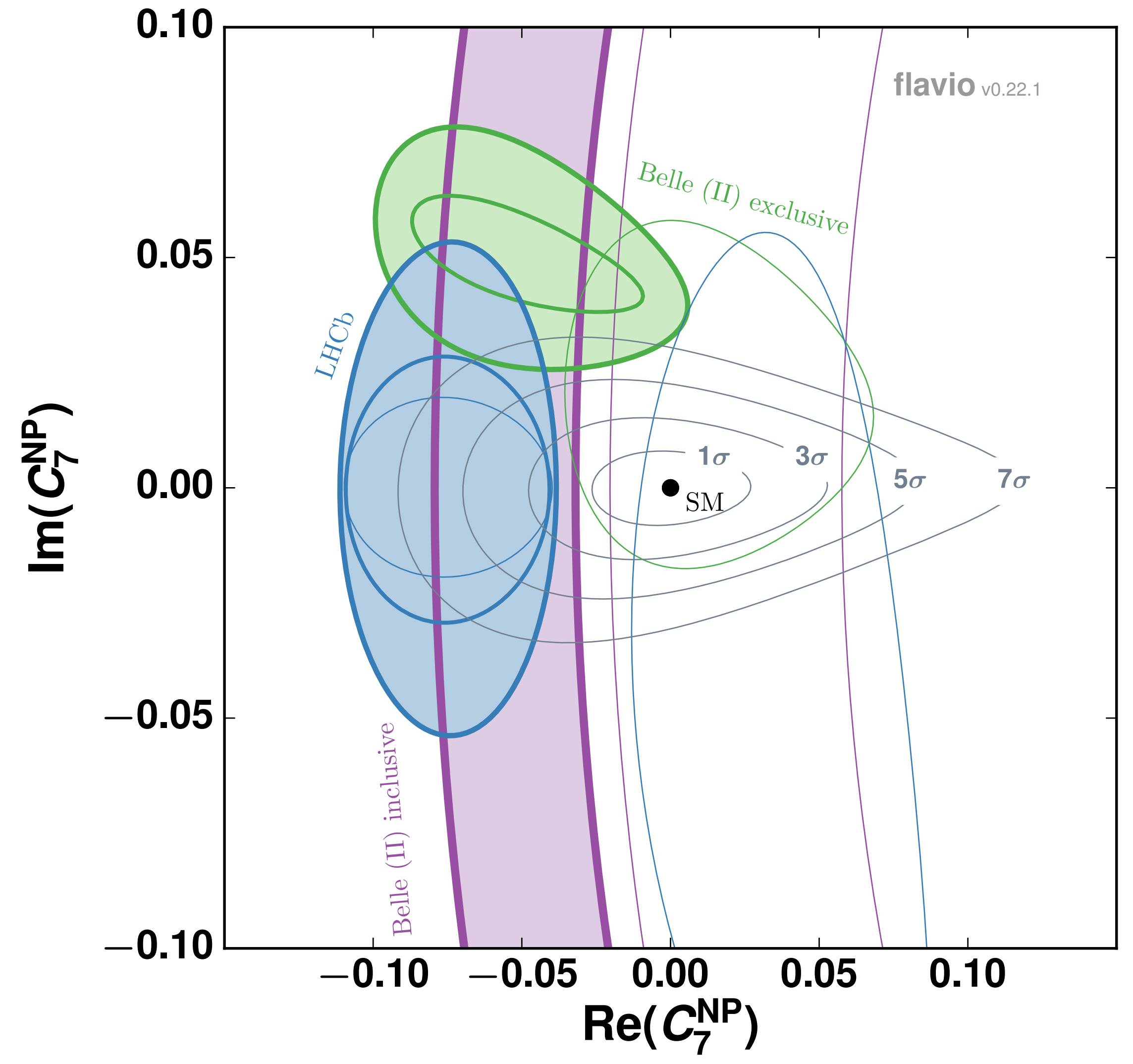



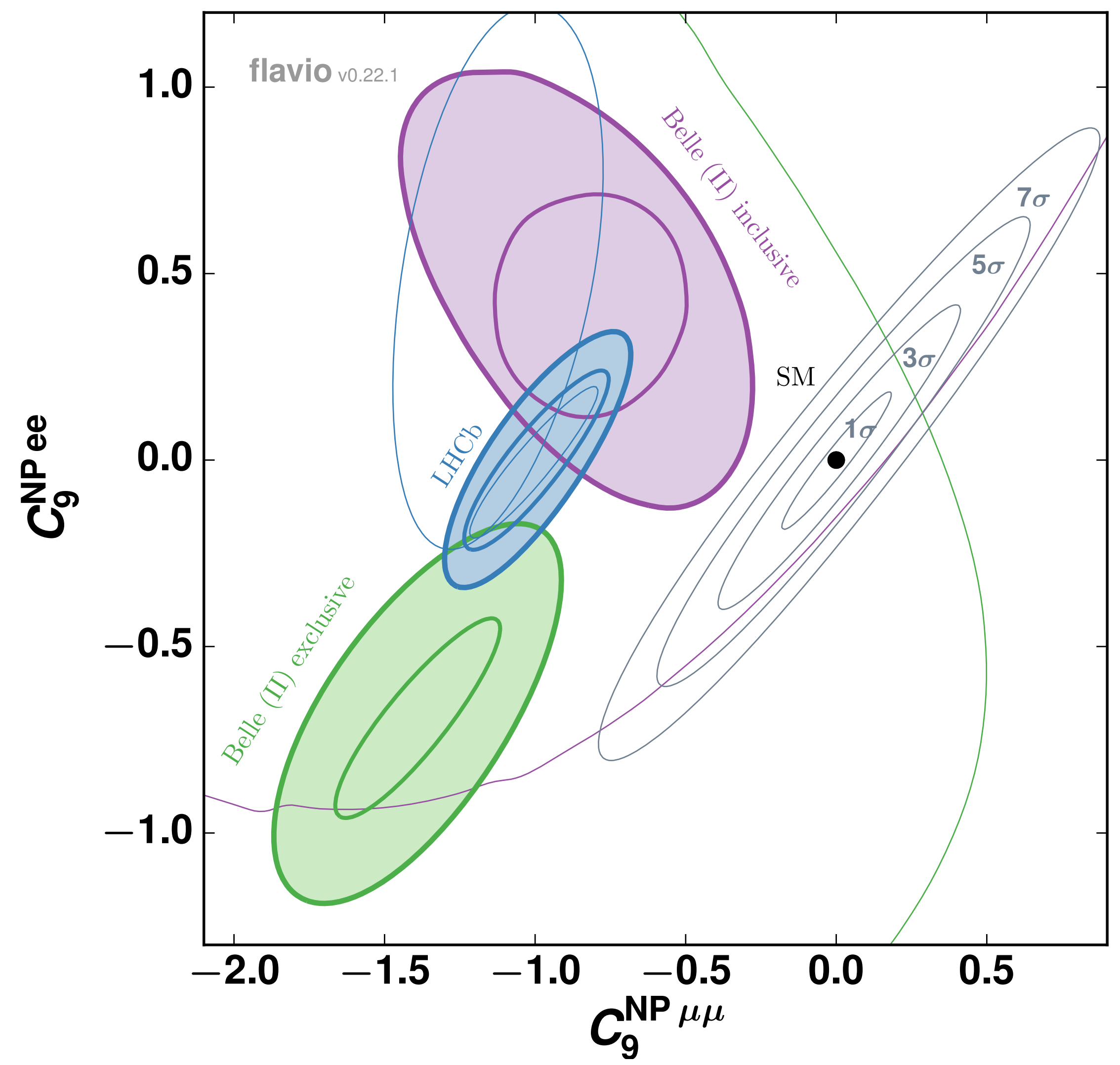
# Radiative and EW penguin B decays / Targets

- Except for $B \to X_{s+d}\,\gamma$, all channels are highly statistics limited.
  - Expect systematics to be subdominant beyond 50 $ab^{-1}$
  - Key to understand beam **background induced efficiency loss and $E_{ECL}$ degradation** in $B \to K\nu\nu$ and to be unprejudiced to NP, i.e. ALPs/axiflavons

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

| Observables | Belle (2017) | Belle II 5 $ab^{-1}$ | Belle II 50 $ab^{-1}$ |
|---|---|---|---|
| $\mathcal{B}(B \to K^{*+}\nu\overline{\nu})$ | $< 40 \times 10^{-6}$ | 25% | 9% |
| $\mathcal{B}(B \to K^{+}\nu\overline{\nu})$ | $< 19 \times 10^{-6}$ | 30% | 11% |
| $A_{CP}(B \to X_{s+d}\gamma)$ $[10^{-2}]$ | $2.2 \pm 4.0 \pm 0.8$ | 1.5 | 0.5 |
| $S(B \to K_S^0\pi^0\gamma)$ | $-0.10 \pm 0.31 \pm 0.07$ | 0.11 | 0.035 |
| $S(B \to \rho\gamma)$ | $-0.83 \pm 0.65 \pm 0.18$ | 0.23 | 0.07 |
| $A_{FB}(B \to X_s\ell^+\ell^-)$ $(1 < q^2 < 3.5\ \mathrm{GeV}^2/c^4)$ | 26% | 10% | 3% |
| $Br(B \to K^+\mu^+\mu^-)/Br(B \to K^+e^+e^-)$ $(1 < q^2 < 6\ \mathrm{GeV}^2/c^4)$ | 28% | 11% | 4% |
| $Br(B \to K^{*+}(892)\mu^+\mu^-)/Br(B \to K^{*+}(892)e^+e^-)$ $(1 < q^2 < 6\ \mathrm{GeV}^2/c^4)$ | 24% | 9% | 3% |
| $\mathcal{B}(B_s \to \gamma\gamma)$ | $< 8.7 \times 10^{-6}$ | 23% | – |
| $\mathcal{B}(B_s \to \tau\tau)$ $[10^{-3}]$ | – | $< 0.8$ | – |



# Belle II Physics Ultimate Precision, 50 $ab^{-1}$

- The full physics data taking program has just commenced!
- Beam background remediation the current (April 2019) focus.

**E. Kou, PU et al. Belle II Physics book, arXiv: 1808.10567 (Accepted to PTEP)**

| Observables | Expected the. accuracy | | Expected exp. uncertainty | Facility (2025) |
|---|---|---|---|---|
| UT angles & sides | | | | |
| $\phi_1$ [°] | *** | CKM | 0.4 | Belle II |
| $\phi_2$ [°] | ** | | 1.0 | Belle II |
| $\phi_3$ [°] | *** | | 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 |

- Charm covered by M Staric

| | | | | |
|---|---|---|---|---|
| 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 |

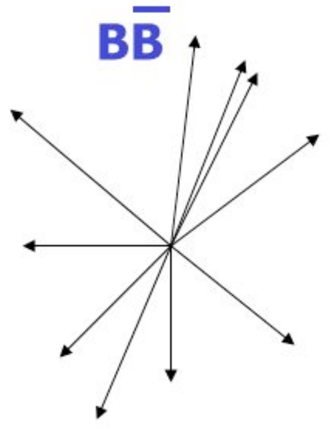
# Upgrade 50 $ab^{-1}$ → 250 $ab^{-1}$ (Belle III?)

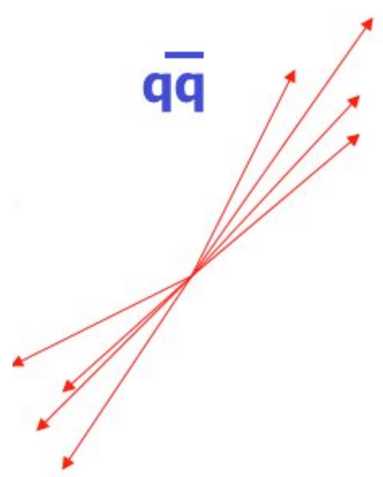
- **Flavour physics has the potential to continue exploring new physics territory provided large enough samples are available.**
- Machine (SuperKEKB) upgrades are possible.
  - No concrete plan yet, just initial discussions.
  - Consider factor 5 increase in luminosity (peak and integrated).
  - Also considering possibility of polarisation.
- Exploring upgrade possibilities for Belle II.
  - Commencing studies to understand detector limits and mitigation measures
- Open upgrade effort (not just Belle II members).
  - Also open to new ideas from theory for new flavour measurements.

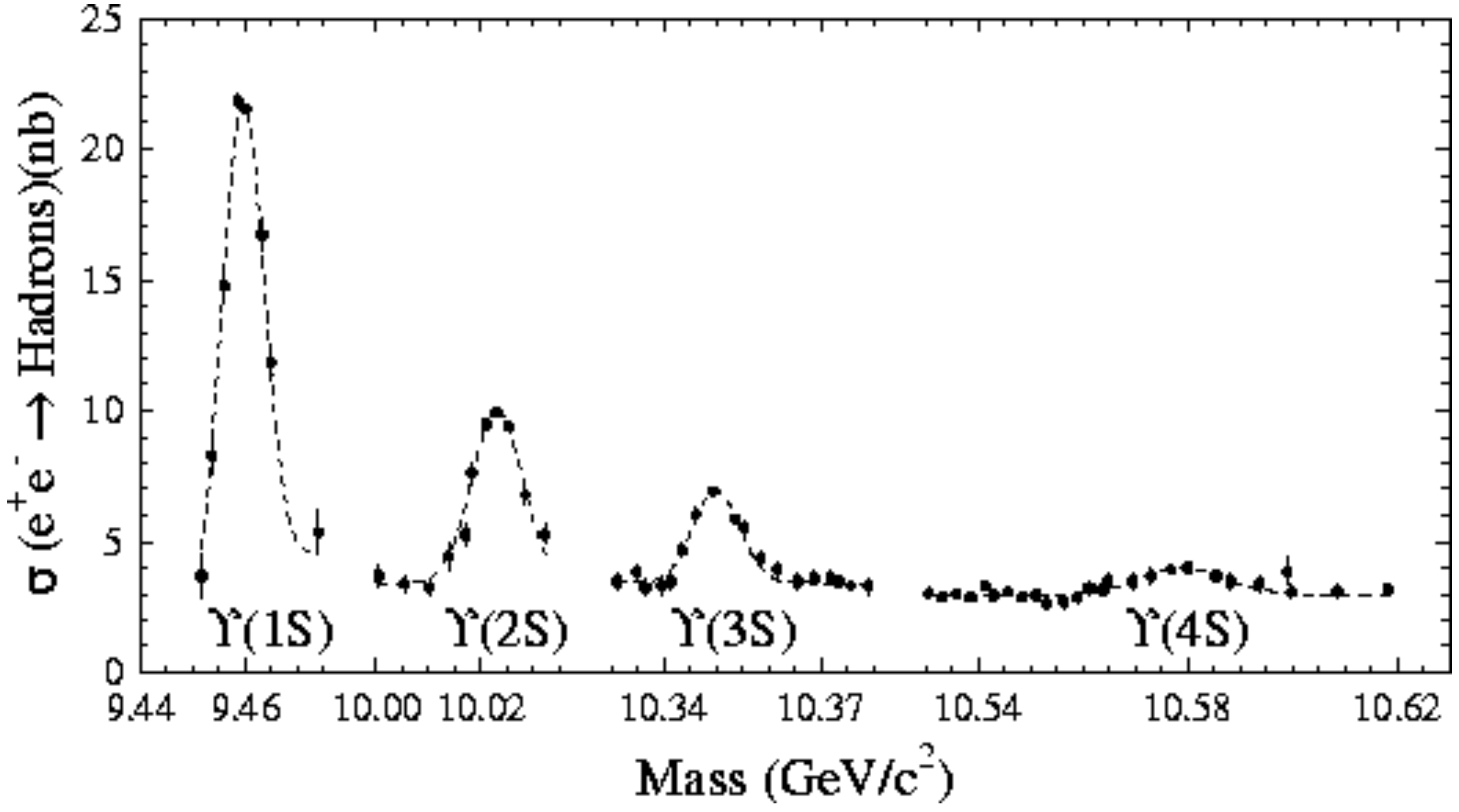
# Backup

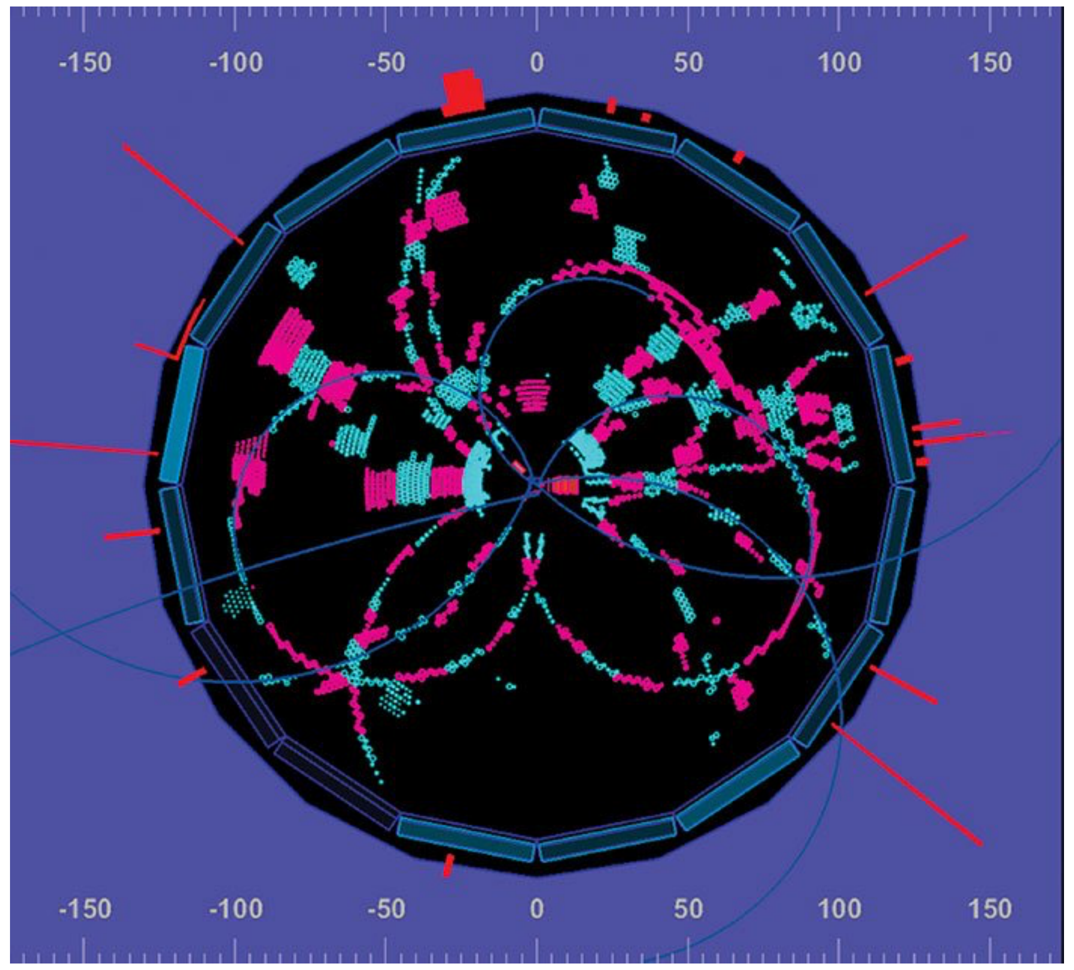
# B production

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

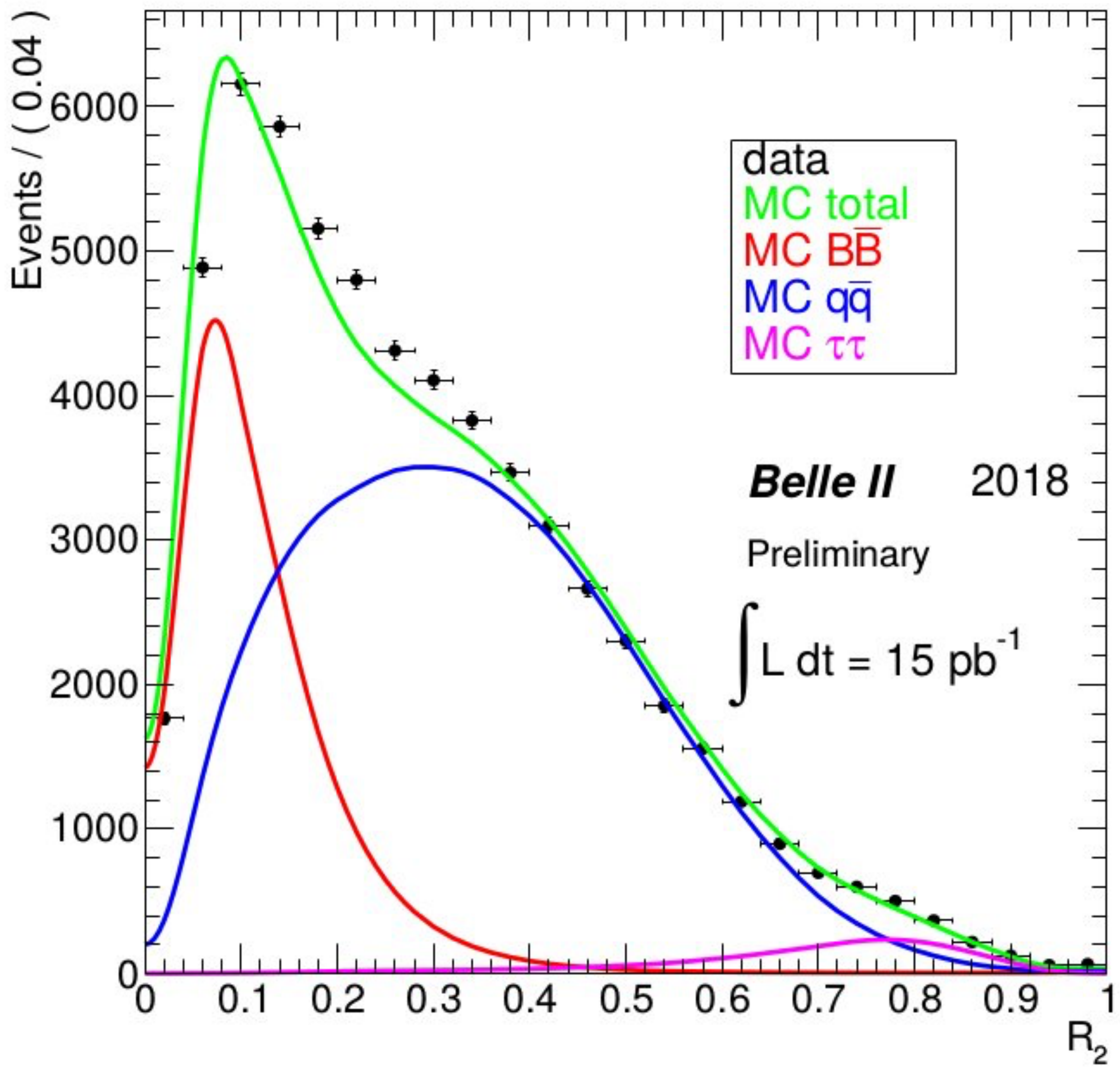



Probably a Y(4S) event




- 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*

$R_2 = H_2/H_0$

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



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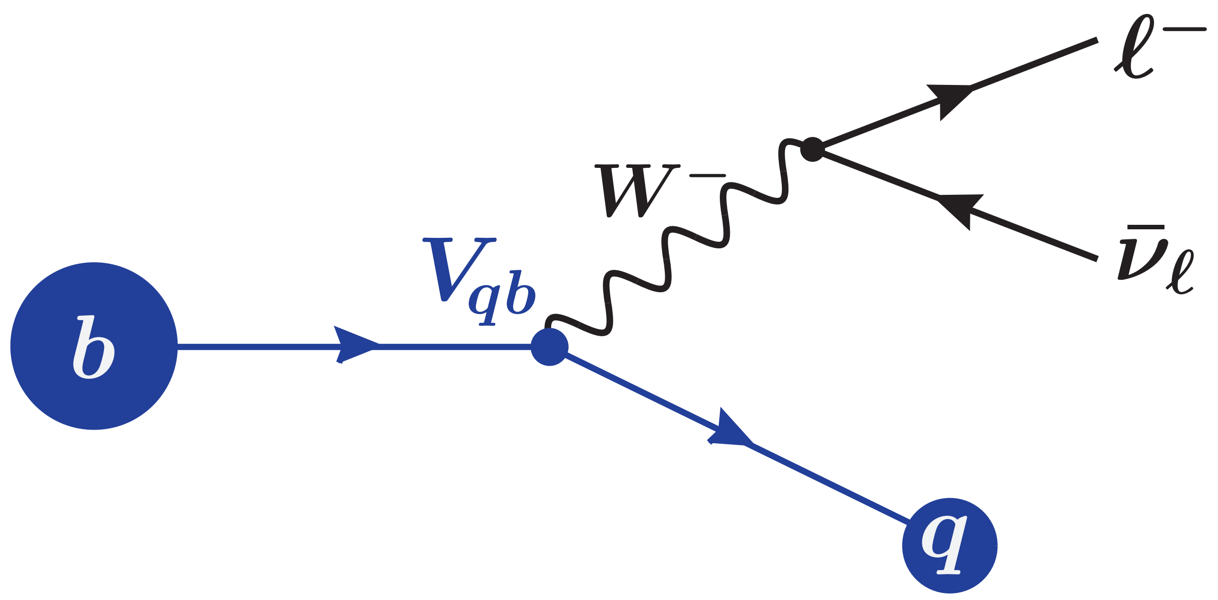
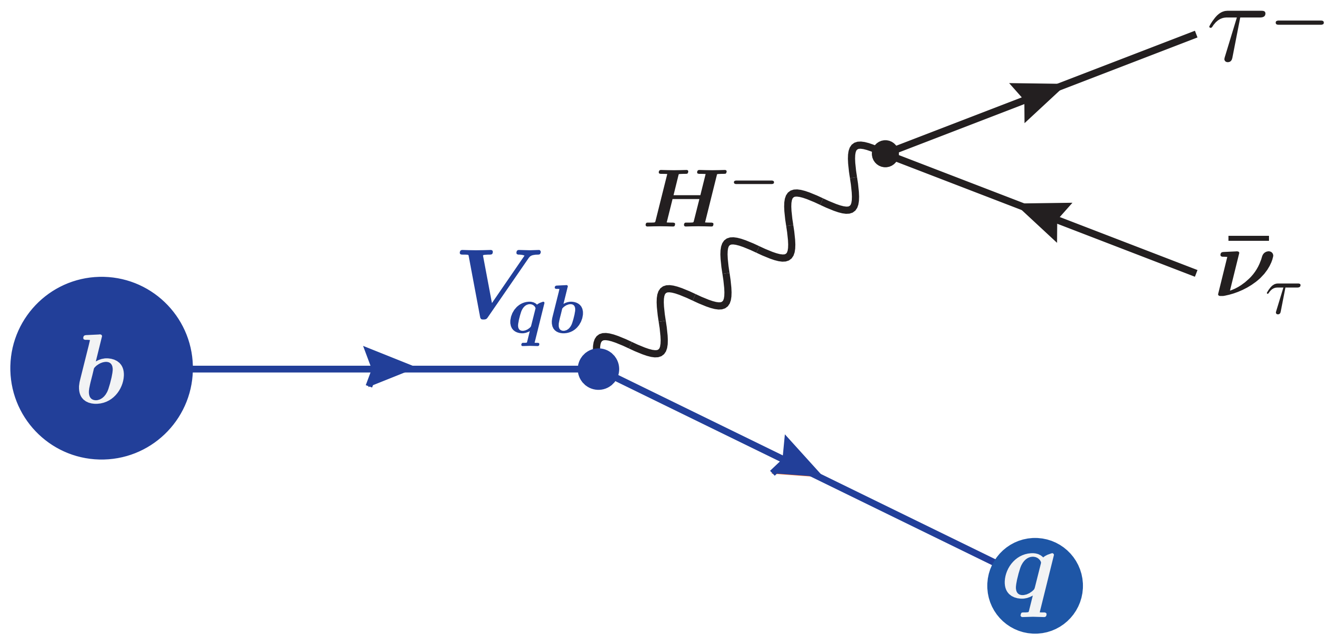
# Leptonic and Semileptonic Decay

- 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

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

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

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

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

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

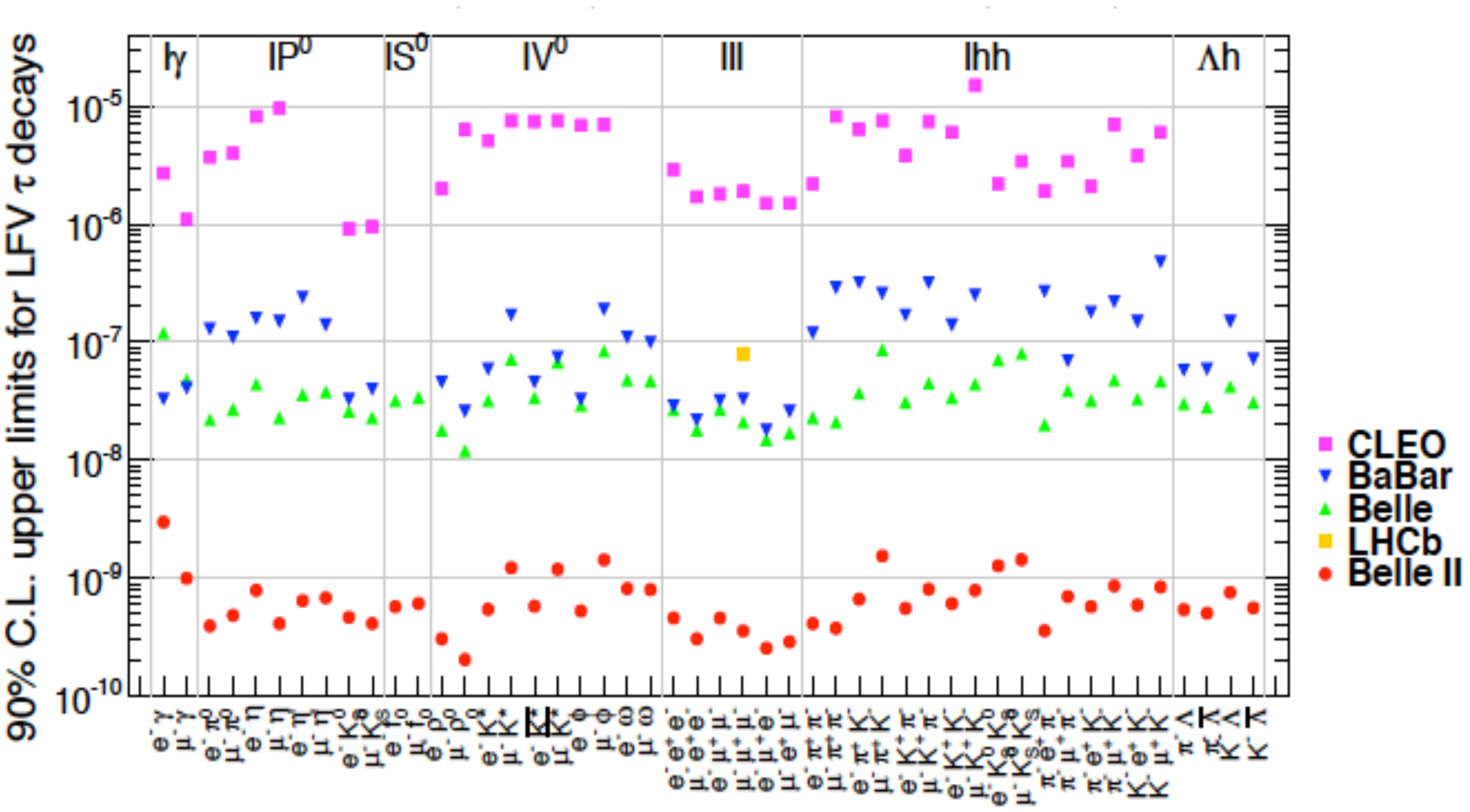
$$\beta_{12} = 1 - \frac{m_1^2 + m_2^2}{q^2} - \frac{\lambda_{12}}{q^2}$$

# Golden modes for Belle II

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

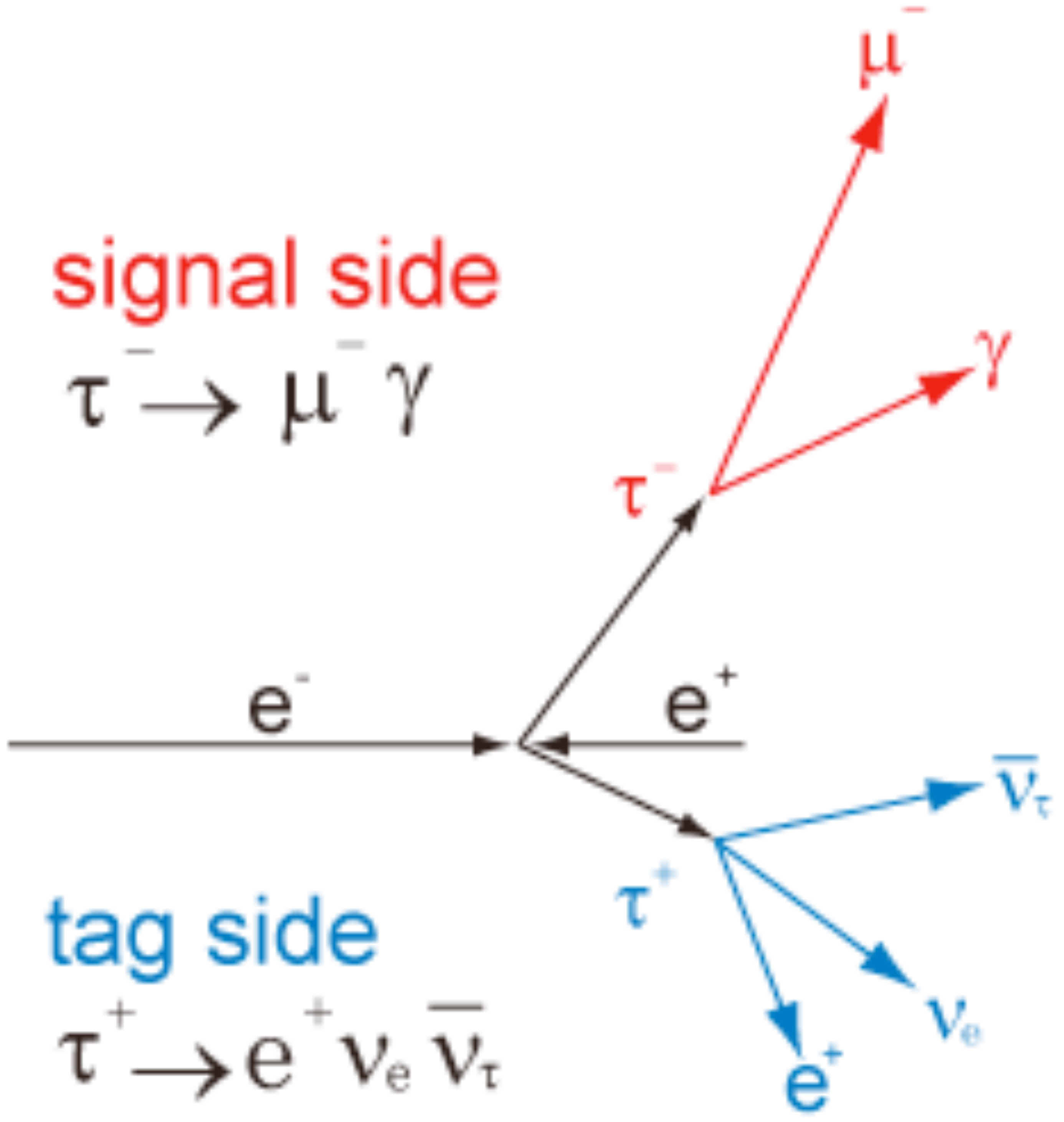
Least well constrained CKM element

# τ Lepton Flavour Violation



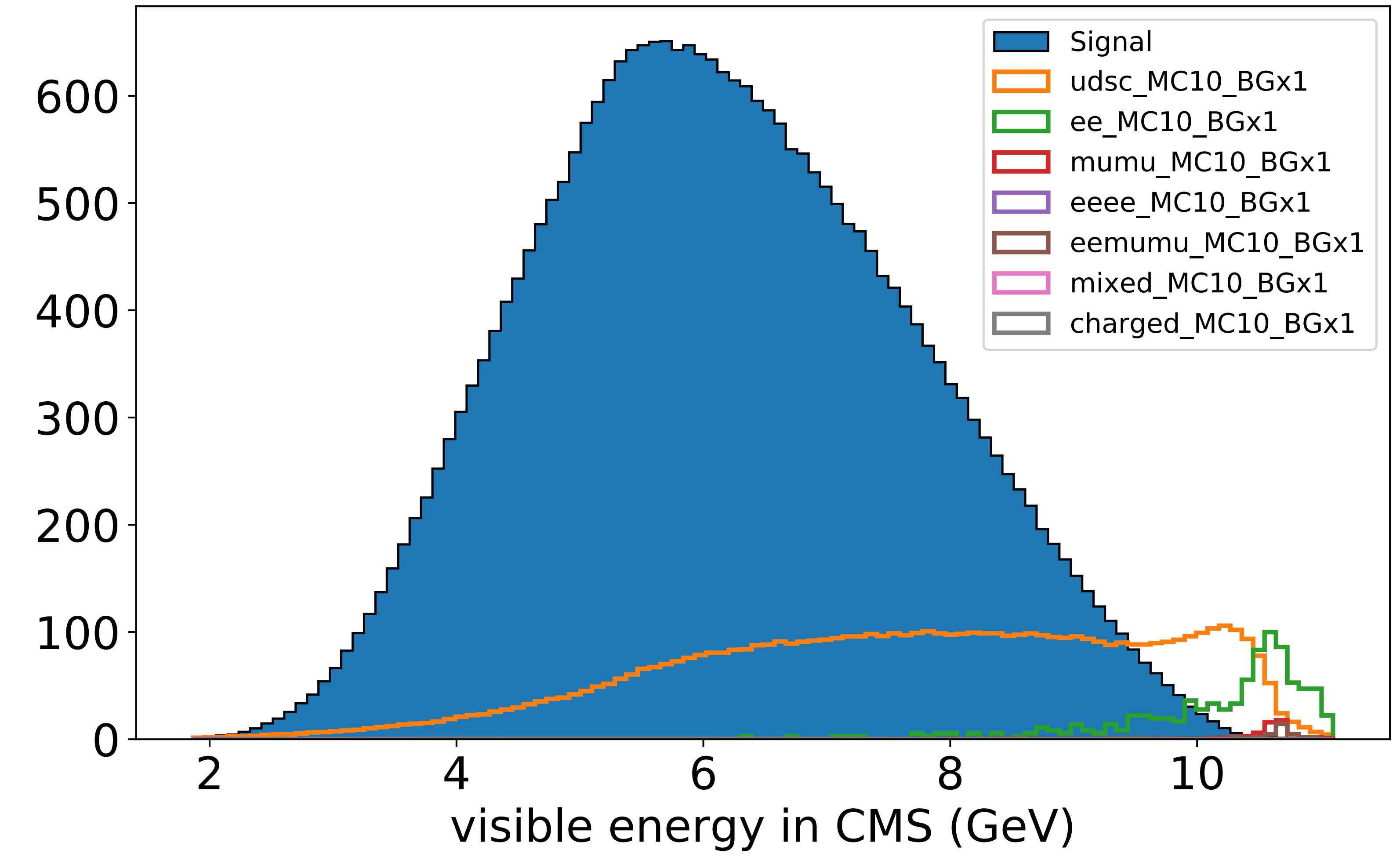

Note vertical log-scale (50 ab$^{-1}$ assumed for Belle II; 3 fb$^{-1}$ result for LHCb

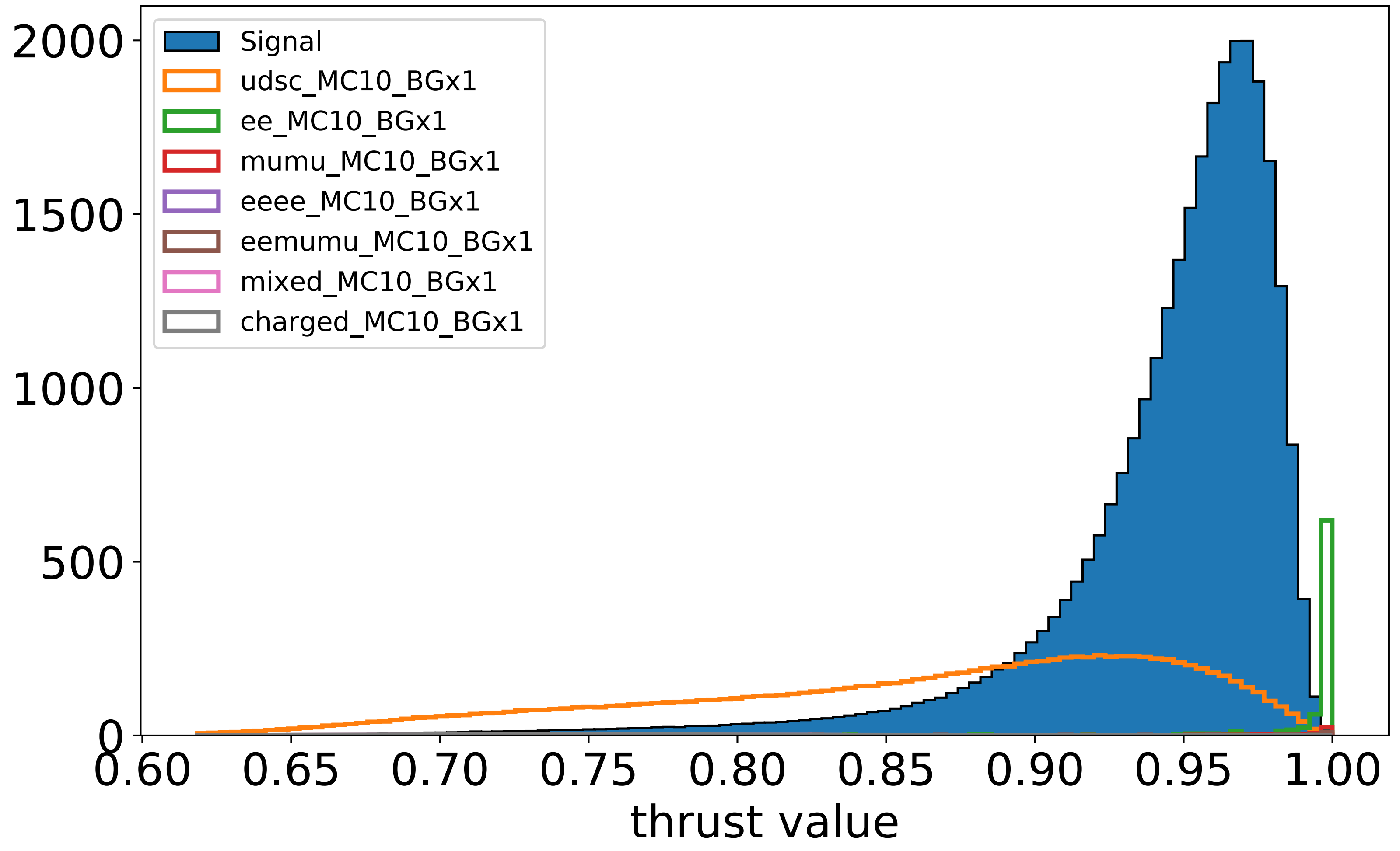
Example of the decay topology



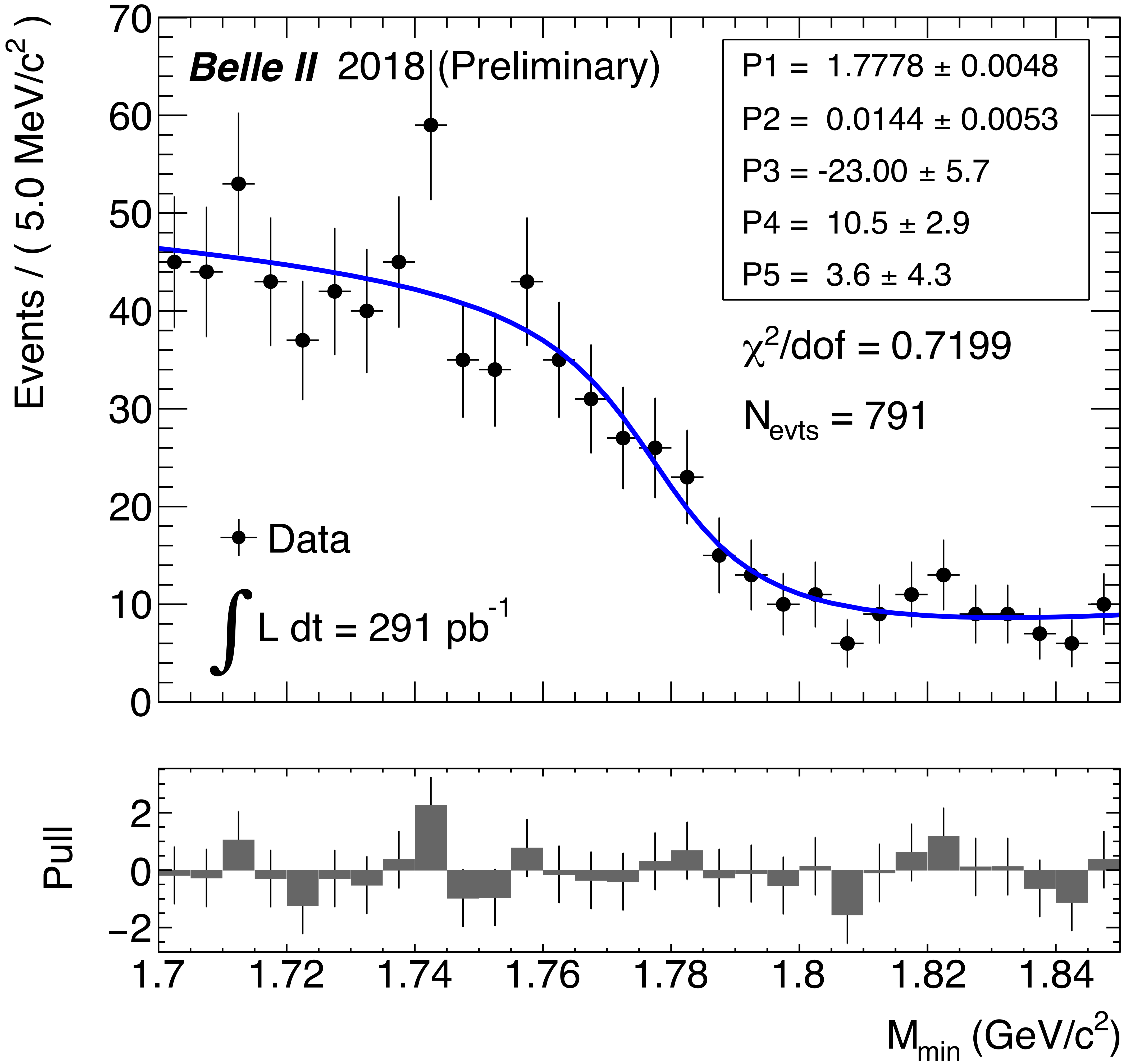

*__Belle II will push many limits below 10$^{-9}$__*

# τ Candidates at Belle II




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



# 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) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $\tau$ tree decays: | | | | | | | | | | | |
| $\mathcal{B}(\tau \to K\nu)/\mathcal{B}(\tau \to \pi\nu)$ | $\star\star\star$ | $\star\star$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\star$ | $\star\star\star$ | $\square$ | $\star\star$ |
| $\mathcal{B}(\tau \to K^*\nu)/\mathcal{B}(\tau \to \rho\nu)$ | $\star\star\star$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\star$ | $\star\star\star$ | $\square$ | $\star\star$ |
| $\tau \to \mu$ decays: | | | | | | | | | | | |
| $\tau \to \mu\gamma$ | $\star\star\star$ | $\star$ | $\star\star\star$ | $\star$ | $\star$ | $\star$ | $\star$ | $\times$ | $\star$ | $\star\star\star$ | $\square$ |
| $\tau \to \mu\pi^0$ | $\star\star\star$ | $\star$ | $\star\star$ | $\times$ | $\star\star\star$ | $\times$ | $\star\star\star$ | $\times$ | $\star\star\star$ | $\square$ | $\square$ |
| $\tau \to \mu K_S$ | $\star\star\star$ | $\star$ | $\star$ | $\times$ | $\star$ | $\times$ | $\star$ | $\times$ | $\star\star\star$ | $\square$ | $\square$ |
| $\tau \to \mu\rho^0$ | $\star\star\star$ | $\times$ | $\star\star$ | $\times$ | $\star\star\star$ | $\times$ | $\star\star\star$ | $\times$ | $\star\star\star$ | $\square$ | $\square$ |
| $\tau \to \mu K^{0*}$ | $\star\star\star$ | $\times$ | $\star$ | $\times$ | $\star$ | $\times$ | $\star$ | $\times$ | $\star\star\star$ | $\square$ | $\square$ |
| $\tau^- \to \mu^-\ell^-\ell^+$ | $\star\star$ | $\star\star$ | $\star$ | $\times$ | $\star\star\star$ | $\star\star\star$ | $\star\star\star$ | $\times$ | $\star$ | $\star\star\star$ | $\square$ |
| $\tau^- \to \mu^-\mu^-e^+$ | $\star\star$ | $\star$ | $\times$ | $\times$ | $\star$ | $\star\star\star$ | $\star$ | $\times$ | $\times$ | $\star\star\star$ | $\square$ |