THE UNIVERSITY OF MELBOURNE

Belle II

ICTS INTERNATIONAL CENTRE *for* THEORETICAL SCIENCES

TATA INSTITUTE OF FUNDAMENTAL RESEARCH

Belle II and Beyond

Phillip Urquijo
The University of Melbourne

FUTURE FLAVOURS: PROSPECTS FOR BEAUTY, CHARM AND TAU PHYSICS (ONLINE)

May 2022

Flavour Programs at e^+e^- near Υ(4S)

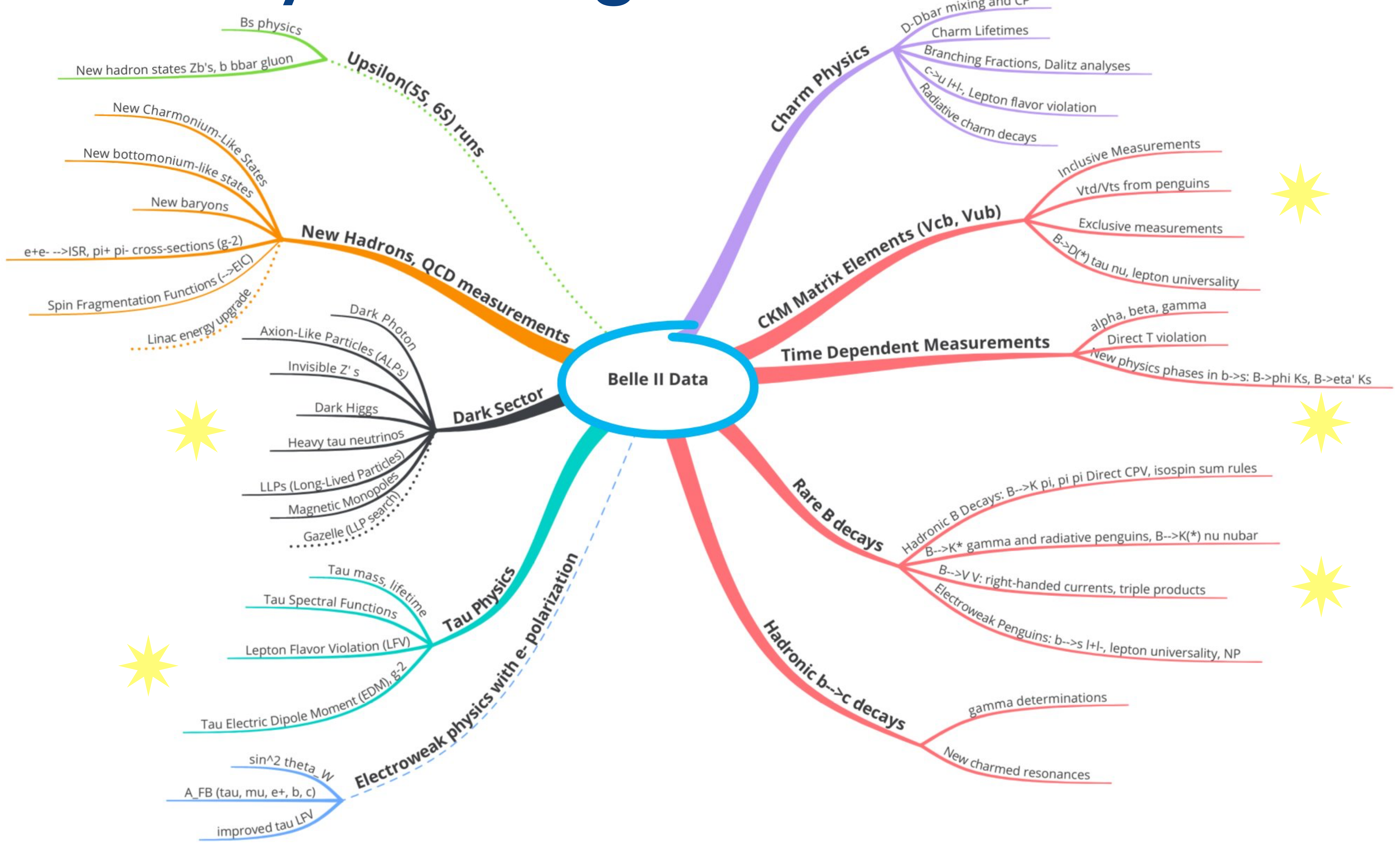
- **Are there new CP-violating phases in the quark sector? (Why is the Universe missing all its antimatter?).**
  - *Quark mixing in B decays, searches for new sources of CP violation, CKM precision metrology.*
  - *Need to disentangle strong phases.*

- **Does nature have multiple Higgs bosons? (Why is there a mass hierarchy in fermions)**
  - *Semileptonic and Leptonic B decays, lepton flavour universality violation.*
  - *Good "detection universality" (e.g. leptons) to tackle anomalies.*

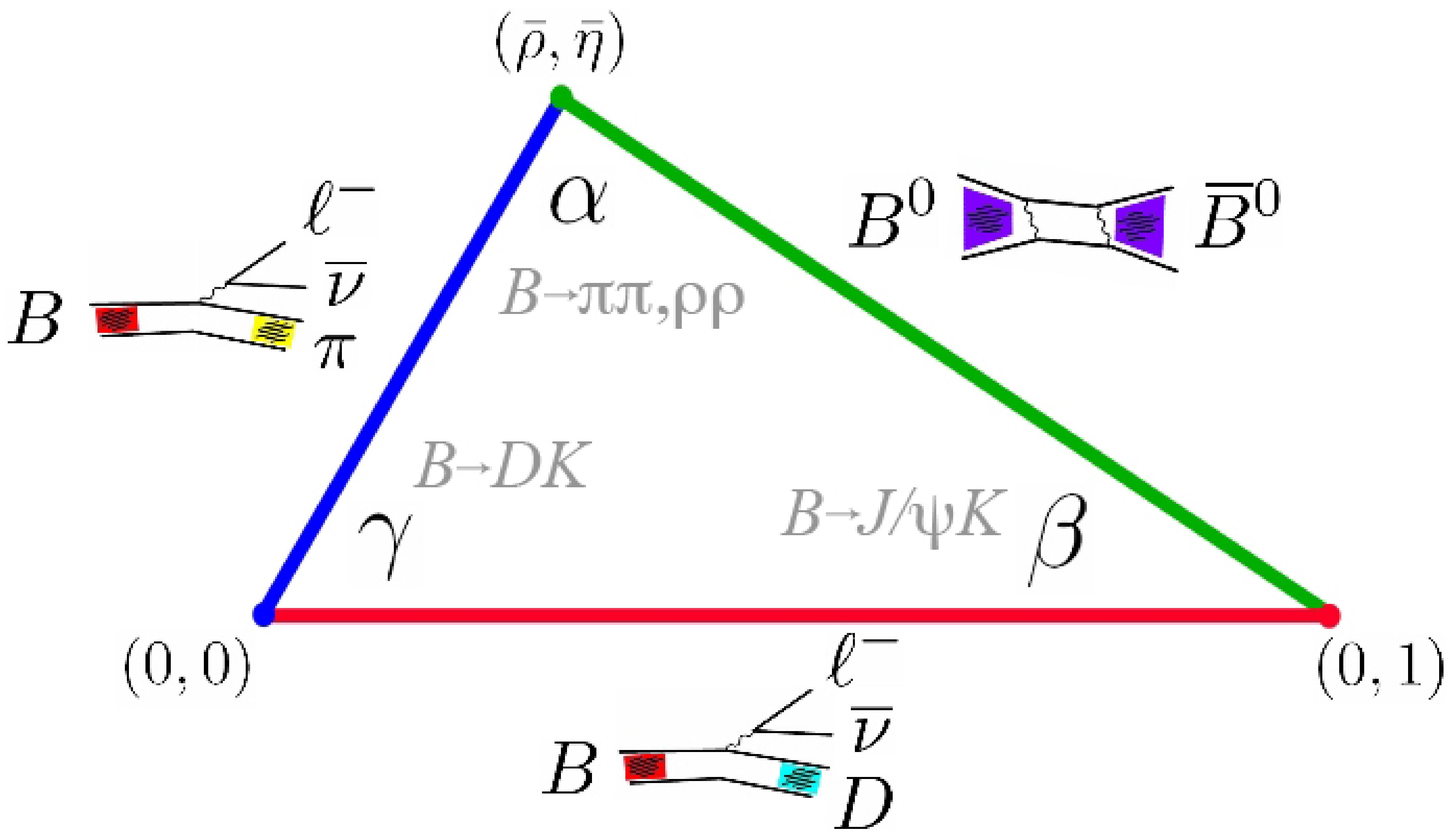
- **Does nature have a L–R symmetry?**
  - *Radiative and Semileptonic rare B decays.*

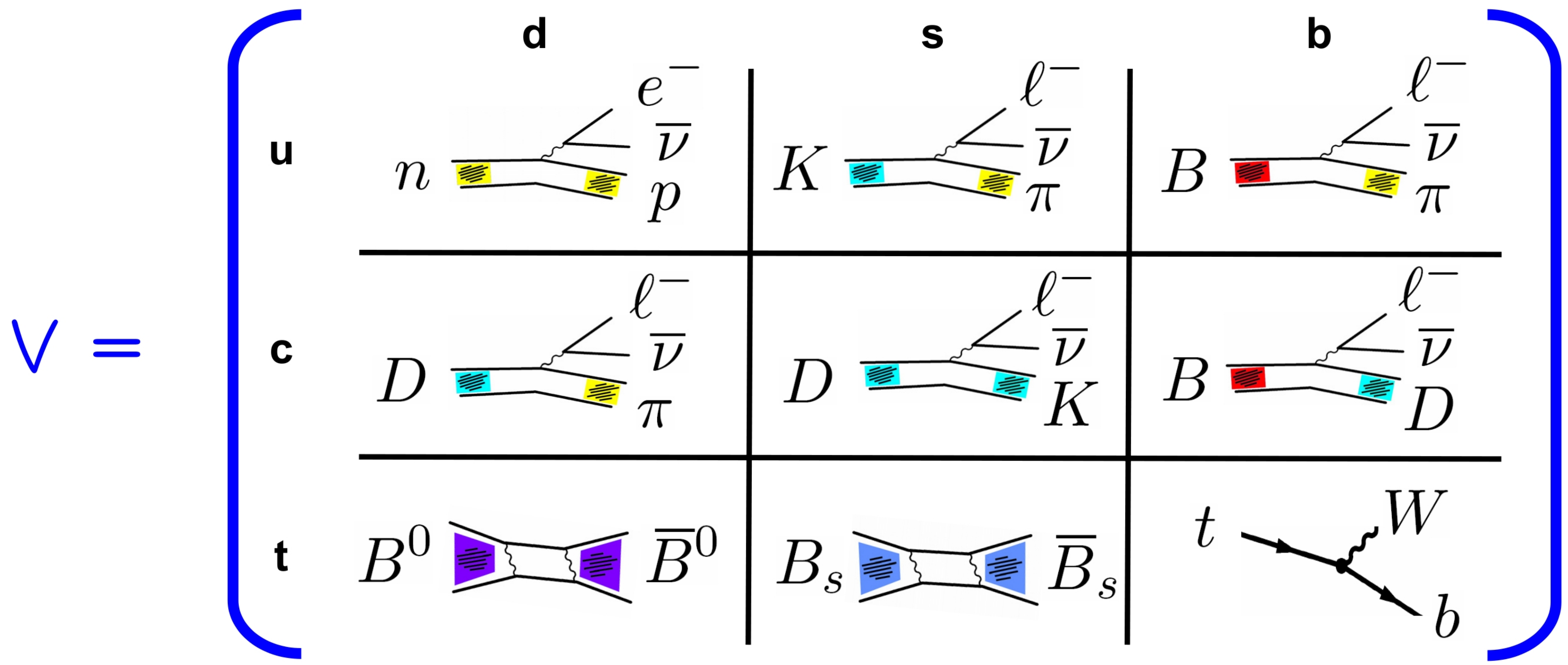
- **Is there a dark sector of particle physics at the same mass scale as ordinary matter?**
  - *Dark photons, axion like particles, and dark matter, via flavour transitions.*

Belle II Physics Program



CKM and CPV SM Metrology





$B \to \pi\pi, \rho\rho$	**Φ_2**	*$B \to D\, l\, \nu$ / $b \to c\, l\, \nu$*	$\|V_{cb}\|$ via Form factor / OPE
$B \to D^{(*)} K^{(*)}$	**Φ_3**	*$B \to \pi\, l\, \nu$ / $b \to u\, l\, \nu$*	$\|V_{ub}\|$ via Form factor / OPE
$B \to J/\psi K_S$	**Φ_1**	*$M \to l\, \nu\, (\gamma)$*	$\|V_{UD}\|$ via Decay constant f_M
$B_s \to J/\psi \Phi$	**β_s**	*ε_K*	**(ρ, η)** via B_K
$K \to \pi\, \nu$ anti-ν	**ρ, η**	*Δm_d, Δm_s*	$\|V_{tb} V_{t\{d,s\}}\|$ via Bag factor B_B
		$B_{(s)} \to \mu^+ \mu^-$	$\|V_{t\{d,s\}}\|$ via Decay constant f_B

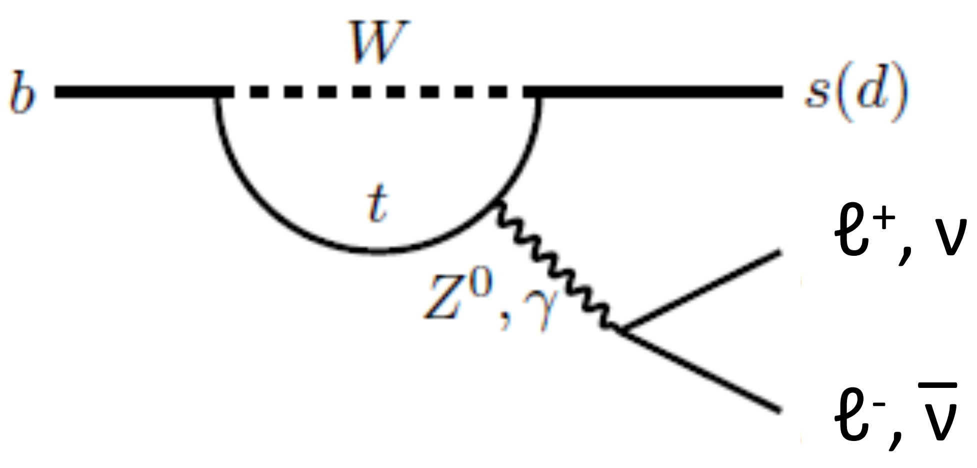
Observables with very different properties

Tree: e.g., $|V_{ub}|/|V_{cb}|$, Φ_3
Loop: e.g., Δm_d, Δm_s, ε_K, $\sin(2\Phi_1)$
CP-conserving: e.g., $|V_{ub}|$, Δm_d, Δm_s
CP-violating: e.g., γ, ε_K, $\sin(2\Phi_1)$

Exp. uncs.: e.g., α, $\sin(2\Phi_1)$, Φ_3
Syst. uncs.: e.g., $|V_{ub}|$, $|V_{cb}|$, ε_K, Δm_d, Δm_s

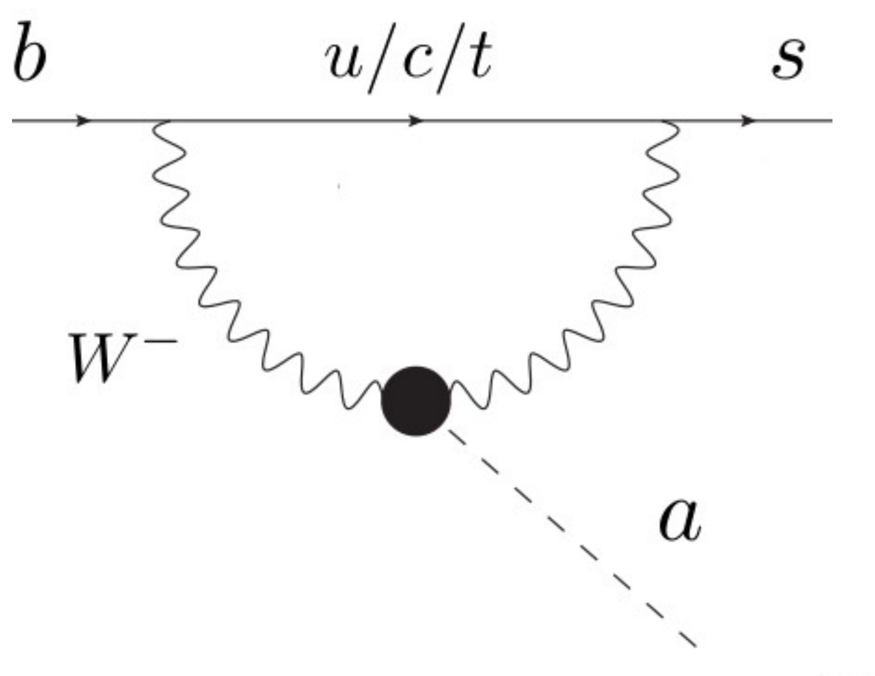
Missing particle and (semi-)leptonic signatures

Flavour changing neutral currents



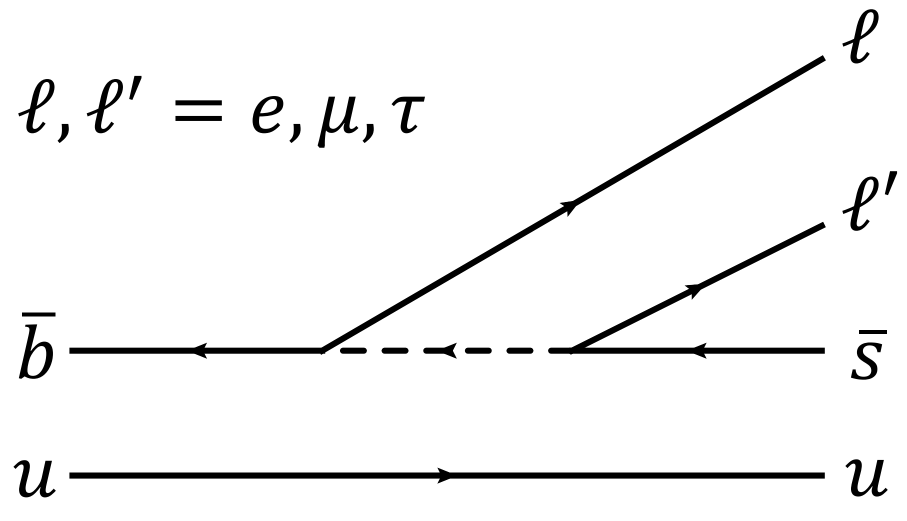
- $B \rightarrow X_s\, l^+ l^-$
- Loop in SM
- Rare at BR < ~10^{-6}

New particle searches



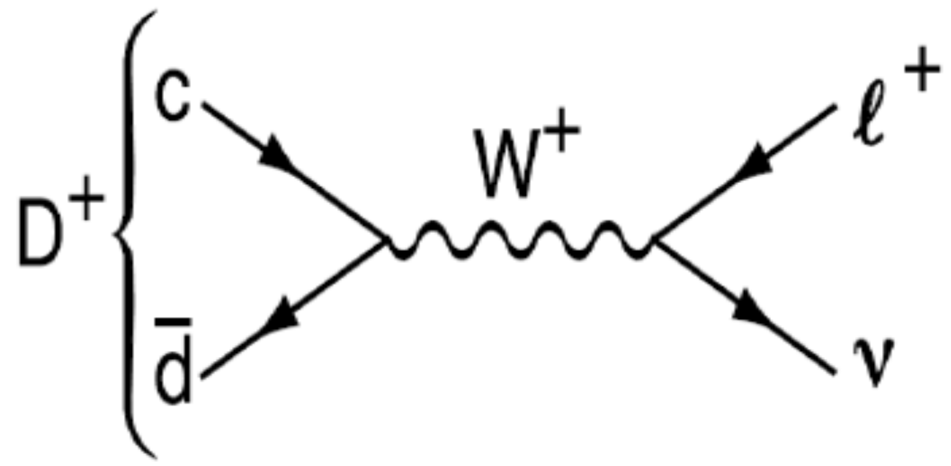
- ALPs (Pseudoscalars)
- Higgs-like (Scalars)
- Dark photons (Vector)

Forbidden decays



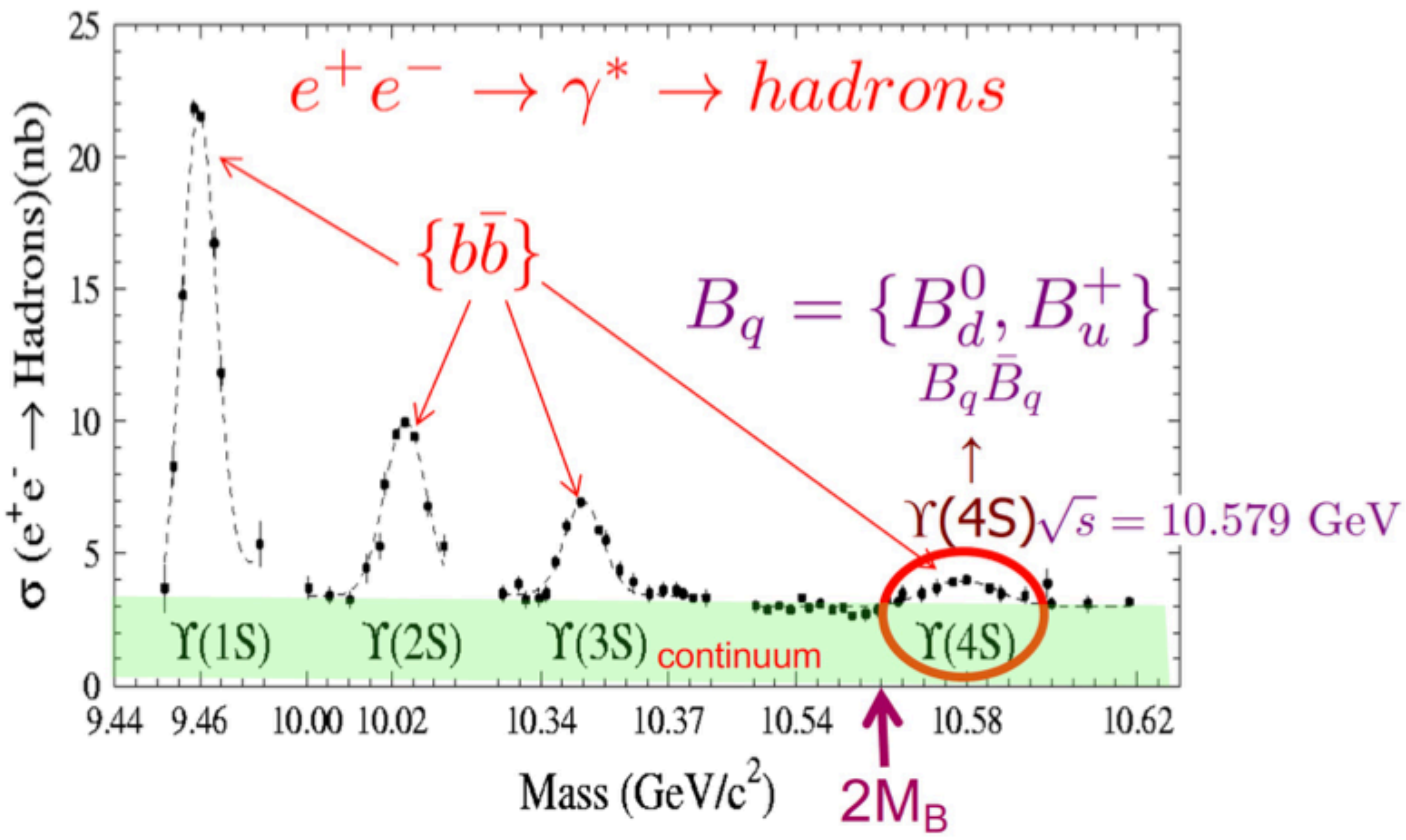
- Lepton flavour violating
- Lepton number violating
- Forbidden or very highly suppressed

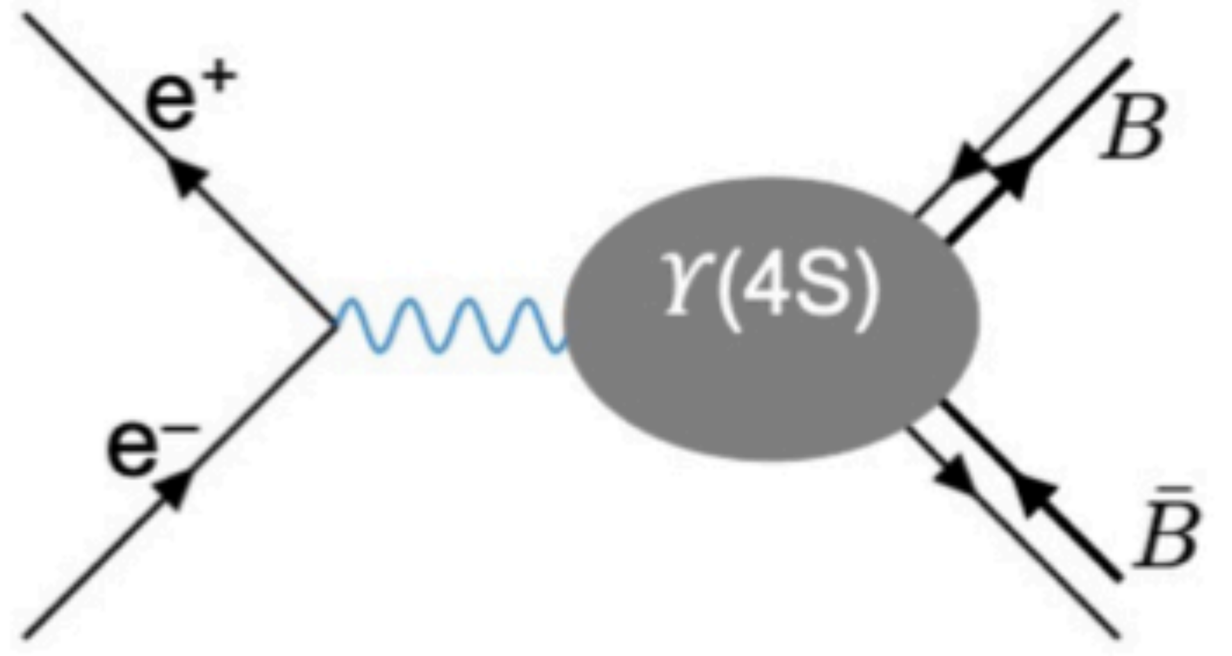
Tests of lepton flavour universality



- Semileptonic or leptonic
- BR ratios with τ/μ, τ/e, μ/e
- Tree or loop

Collision Environment





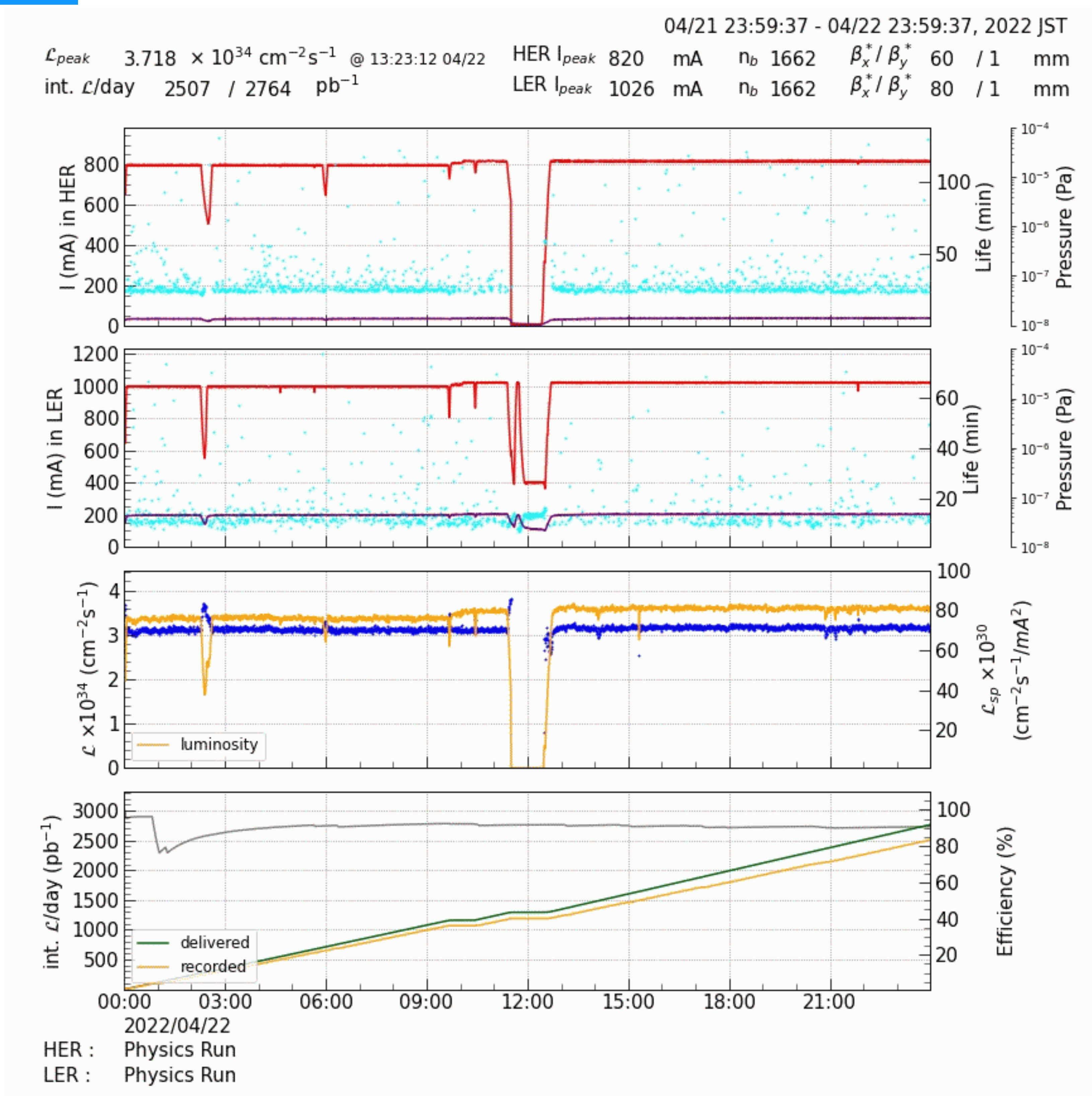
- e^+e^- annihilation at a centre-of-mass $\sqrt{s}$ near the $\Upsilon(4S)$ resonance ⇒ the production of coherent B-meson (B^0 or B^+) pairs.
- Data recorded below the peak ("off-resonance") used to the model the $e^+e^- \to q\bar{q}$ continuum background.
- Hermetic detector enables the capture of almost all detectable particles; great for reconstruction of neutrals (γ, π^0, K_L^0)
- Average particle (charged and neutral) multiplicity from the collision: 15 – 20.

SuperKEKB Record Breaking Luminosity

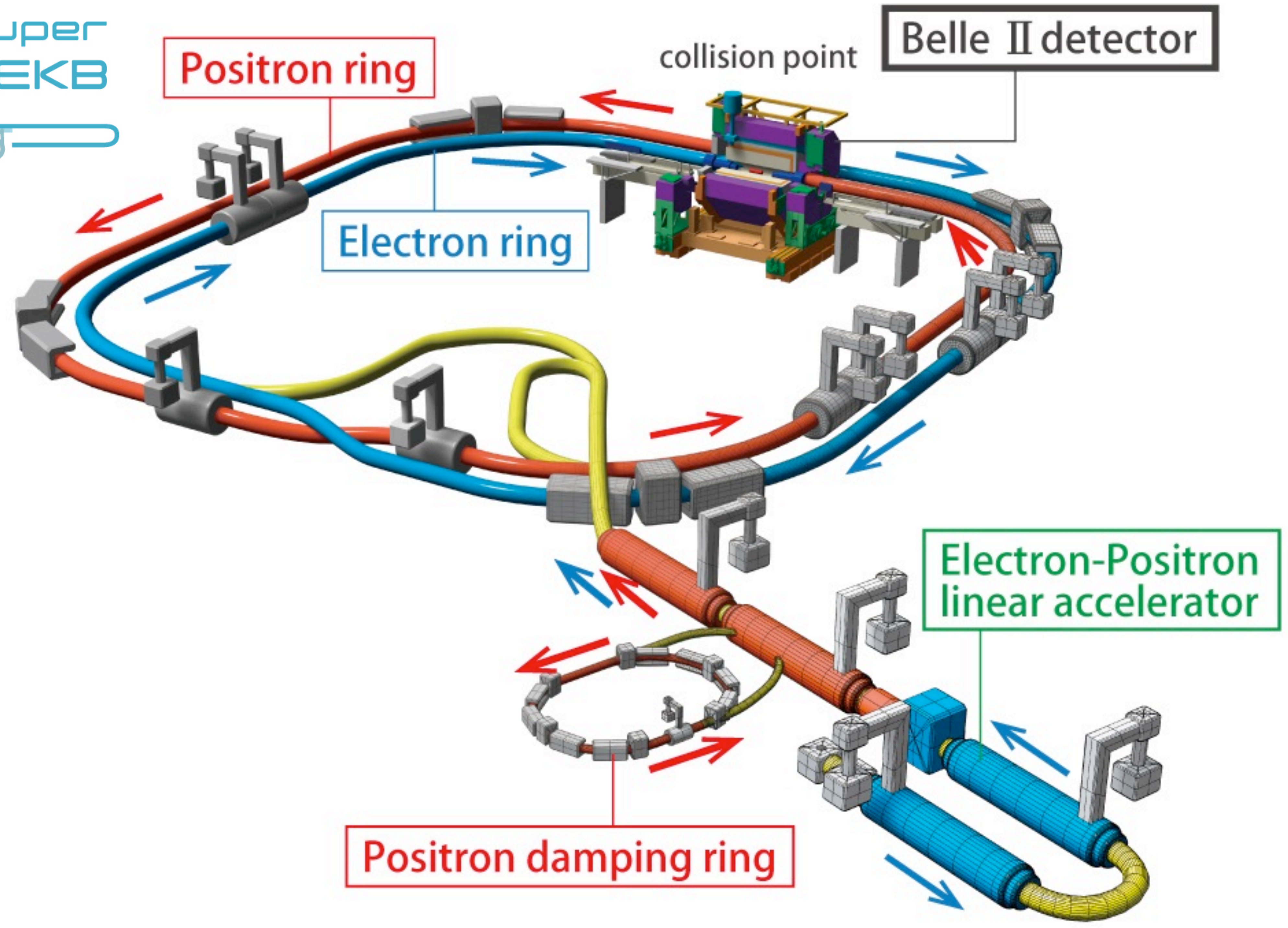
$$L = \frac{\gamma_{\pm}}{2er_e}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_{\pm}\zeta_{\pm y}}{\beta_y^*}\frac{R_L}{R_y}$$

	KEKB	SuperKEKB	Achievements
β^*_y(mm)	5.9/5.9	0.3/0.27	**1/1**
I_{beam}(A)	1.19/1.65	2.6/3.6	**0.8/1.0 ****
L($cm^{-2}s^{-1}$)	2.11×10^{34}	80×10^{34}	**3.7×10^{34}**

SuperKEKB, 21/4/2022

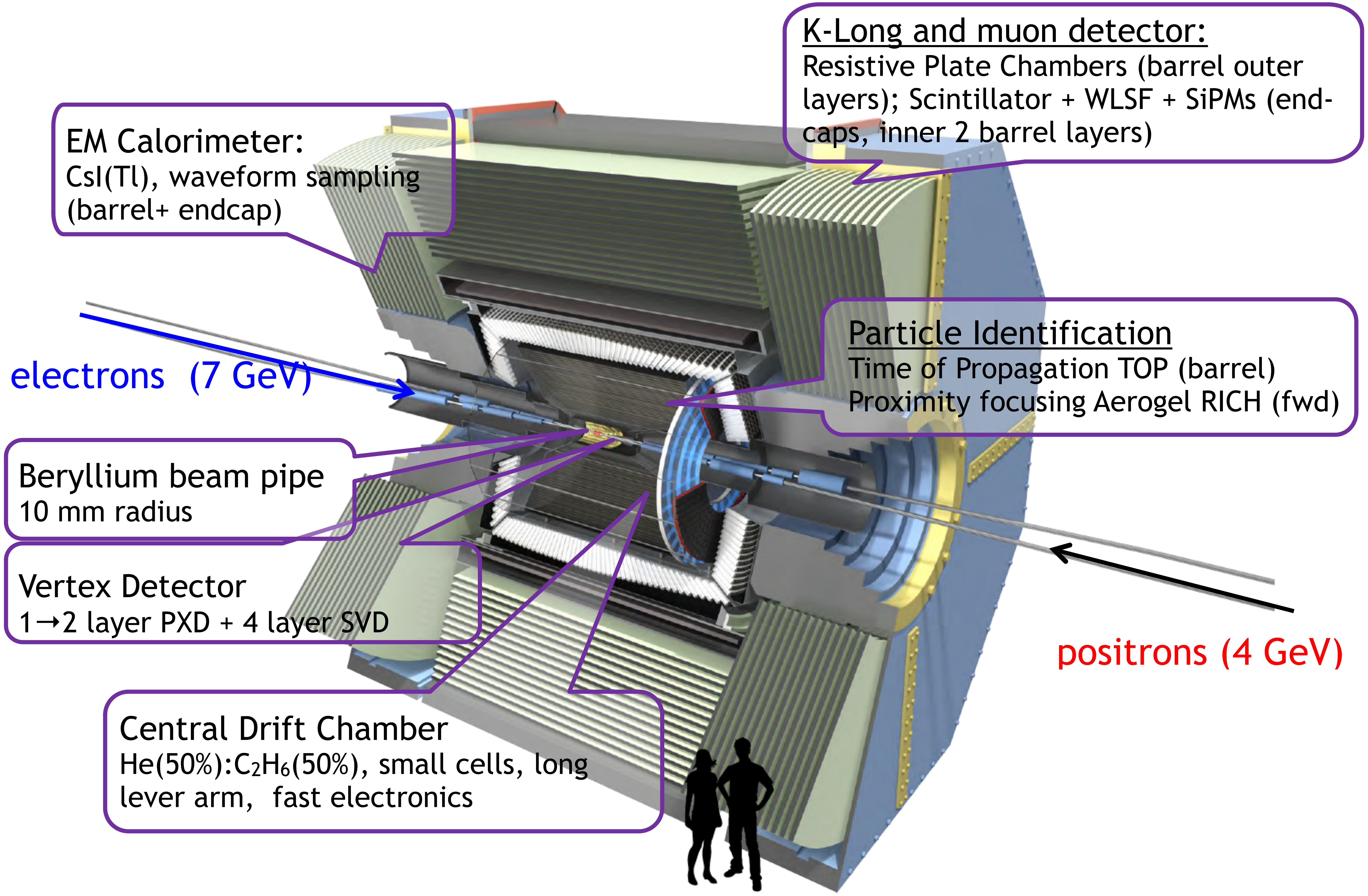


SuperKEKB



20× smaller beam spot (σ_y=50 nm) but *generally higher beam background*

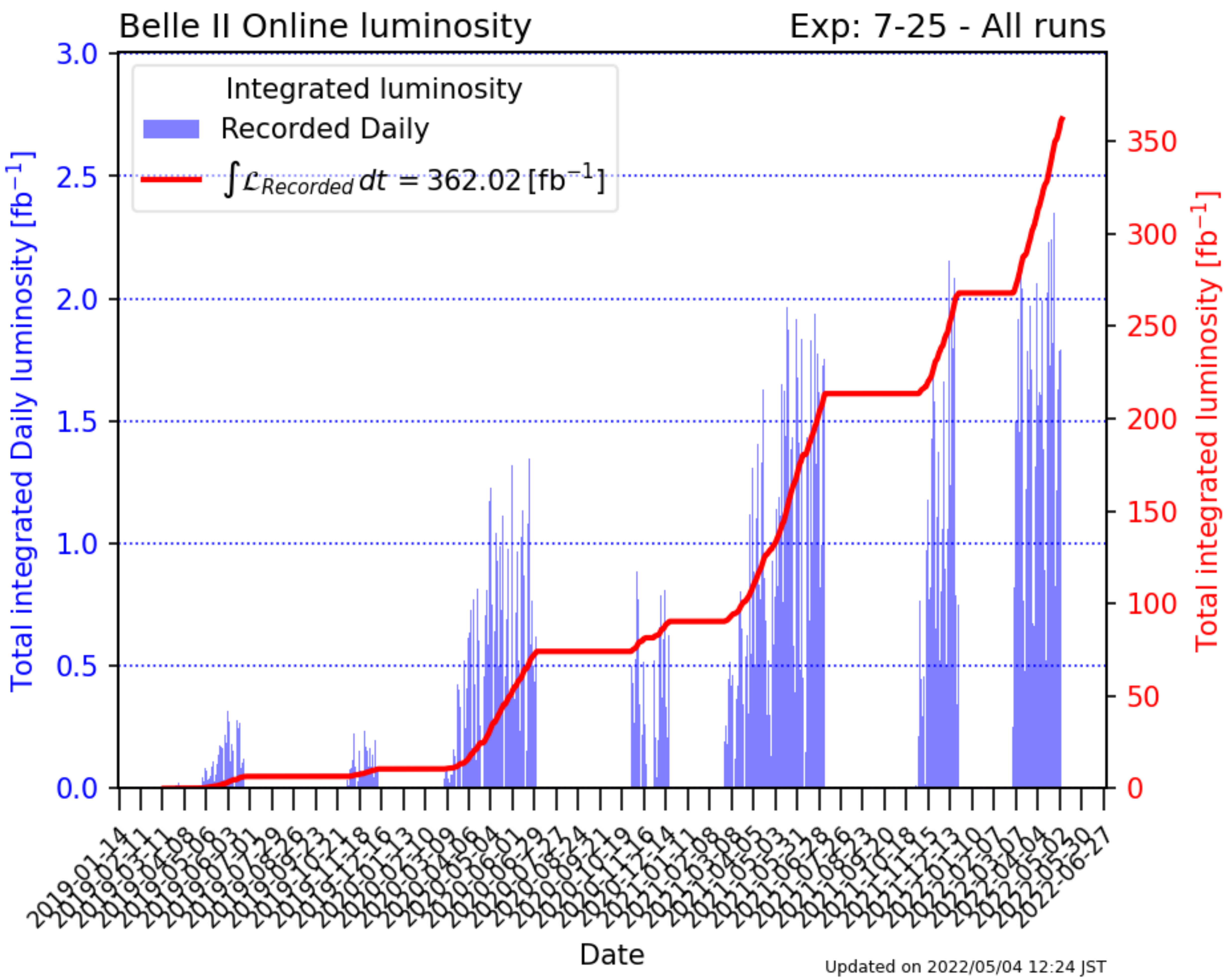
The Belle II experiment

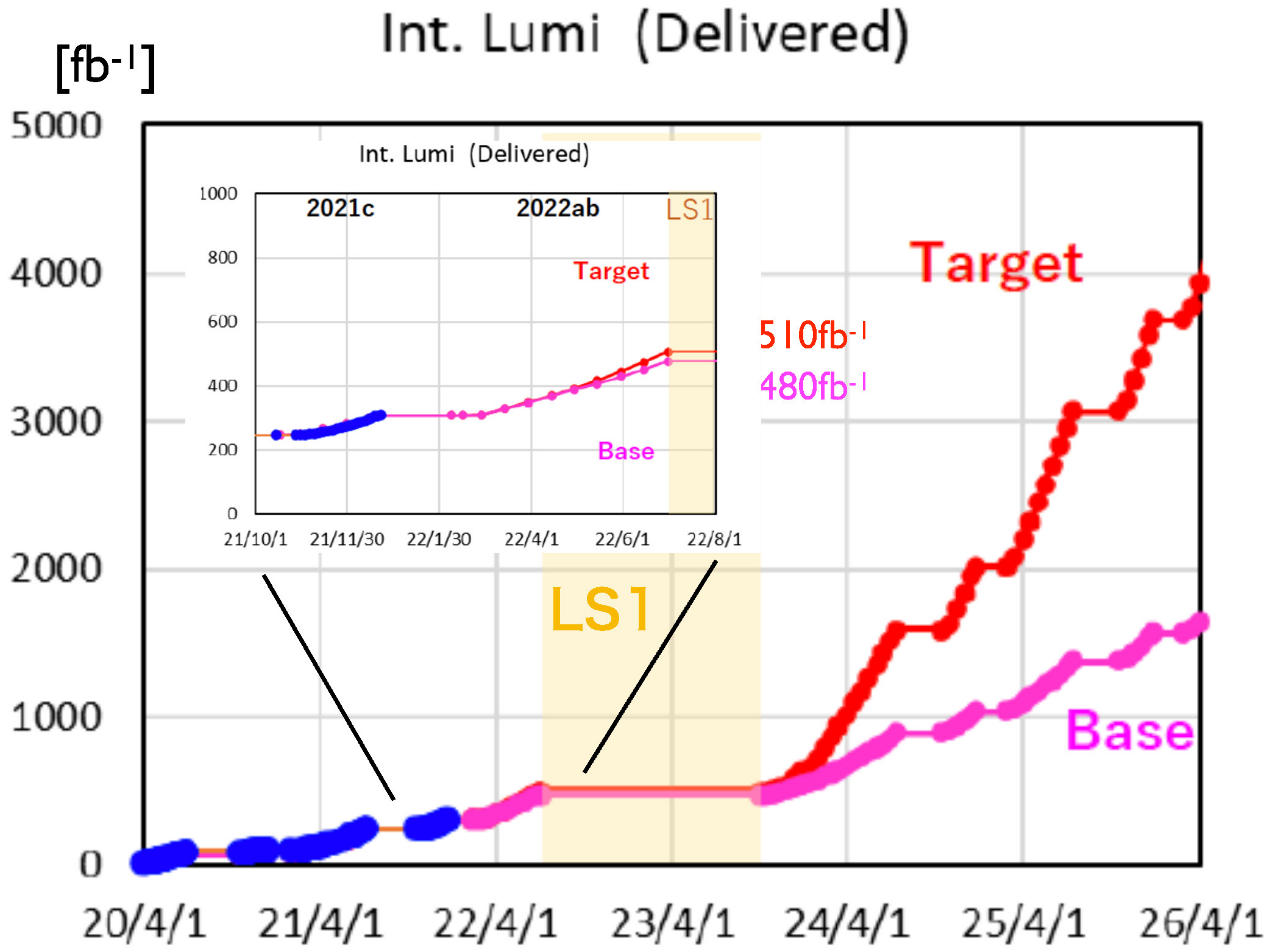


(Anticipated) SuperKEKB/Belle II Luminosity Profile

Starting to achieve Super B-factory performance levels.
Int(L dt)/day =2.4 fb^{-1}/day (May 18, 2020)
Int(L dt)/week = 15 fb^{-1}/week

B factory reference values:
KEKB (1.48 fb^{-1}/day); PEP-II (0.911 fb^{-1}/day);
KEKB (8 fb^{-1} /week); PEP-II (5 fb^{-1}/week);

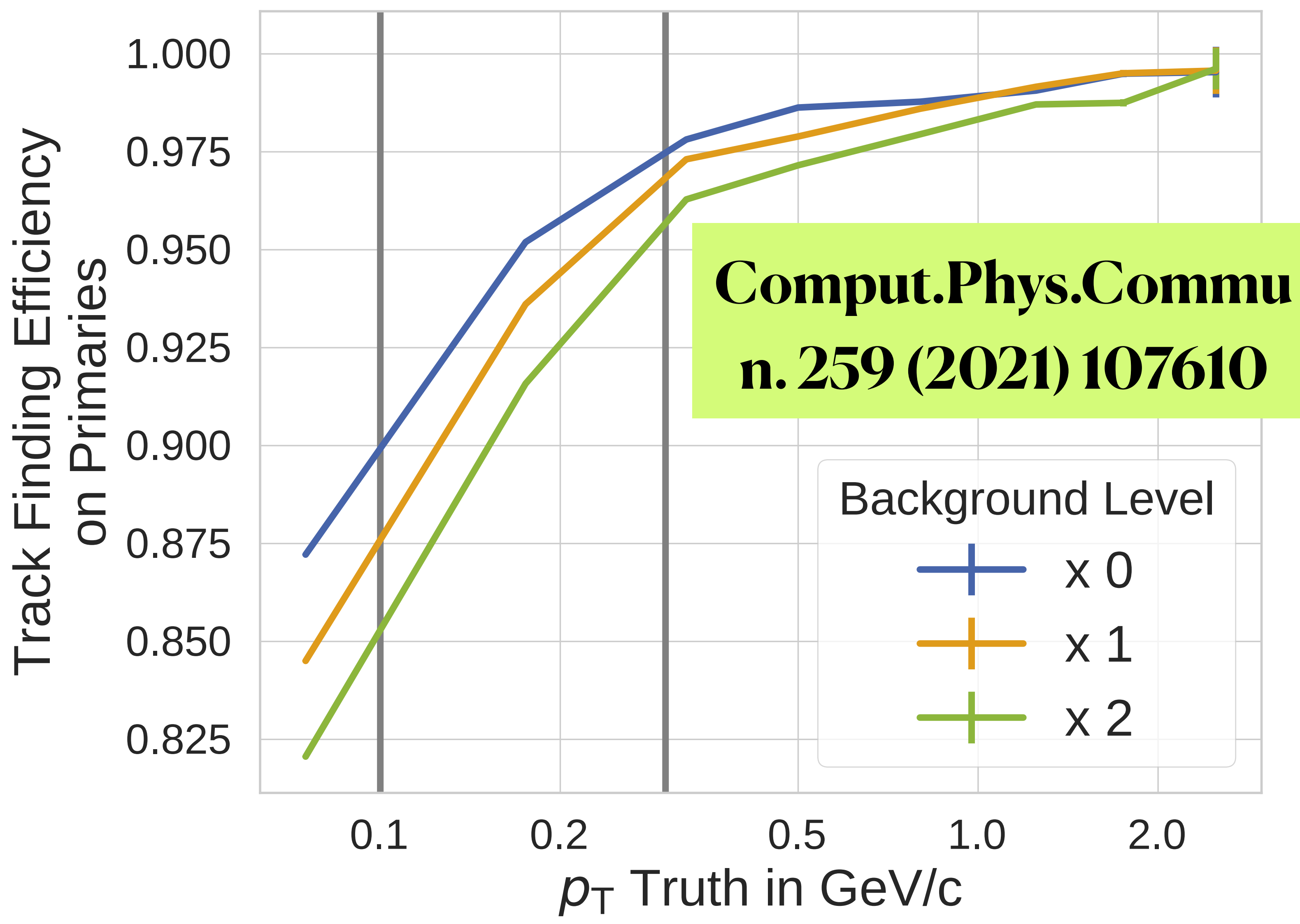




Neutrals and vetos

- Fundamentals of missing energy B decay studies at Belle II.
  - Photon efficiencies and identification.
  - K_L - veto (ECL- pulse shape discrimination, KLM).
  - Track counting based veto (absolutely crucial).

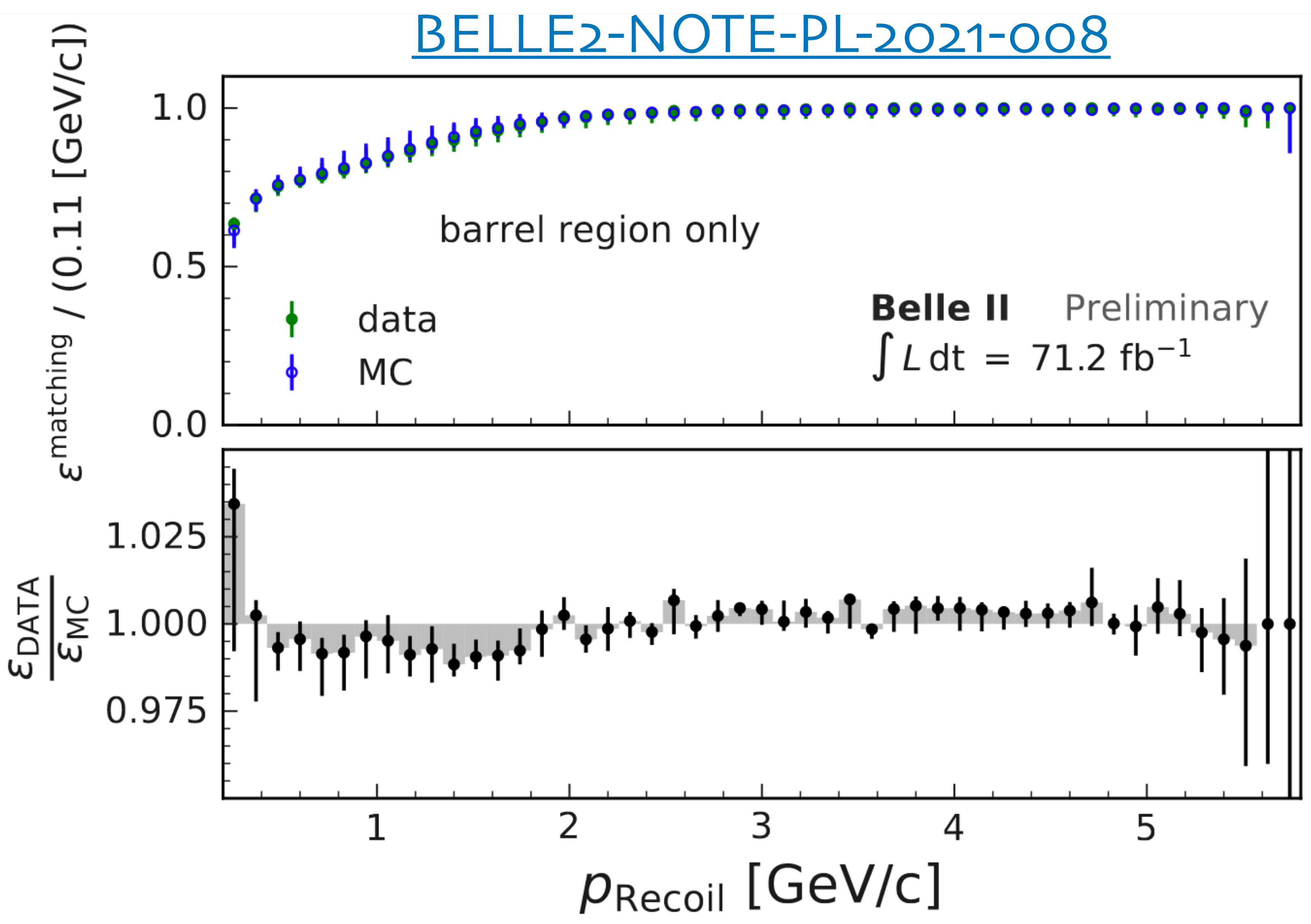
Belle II Track Counting

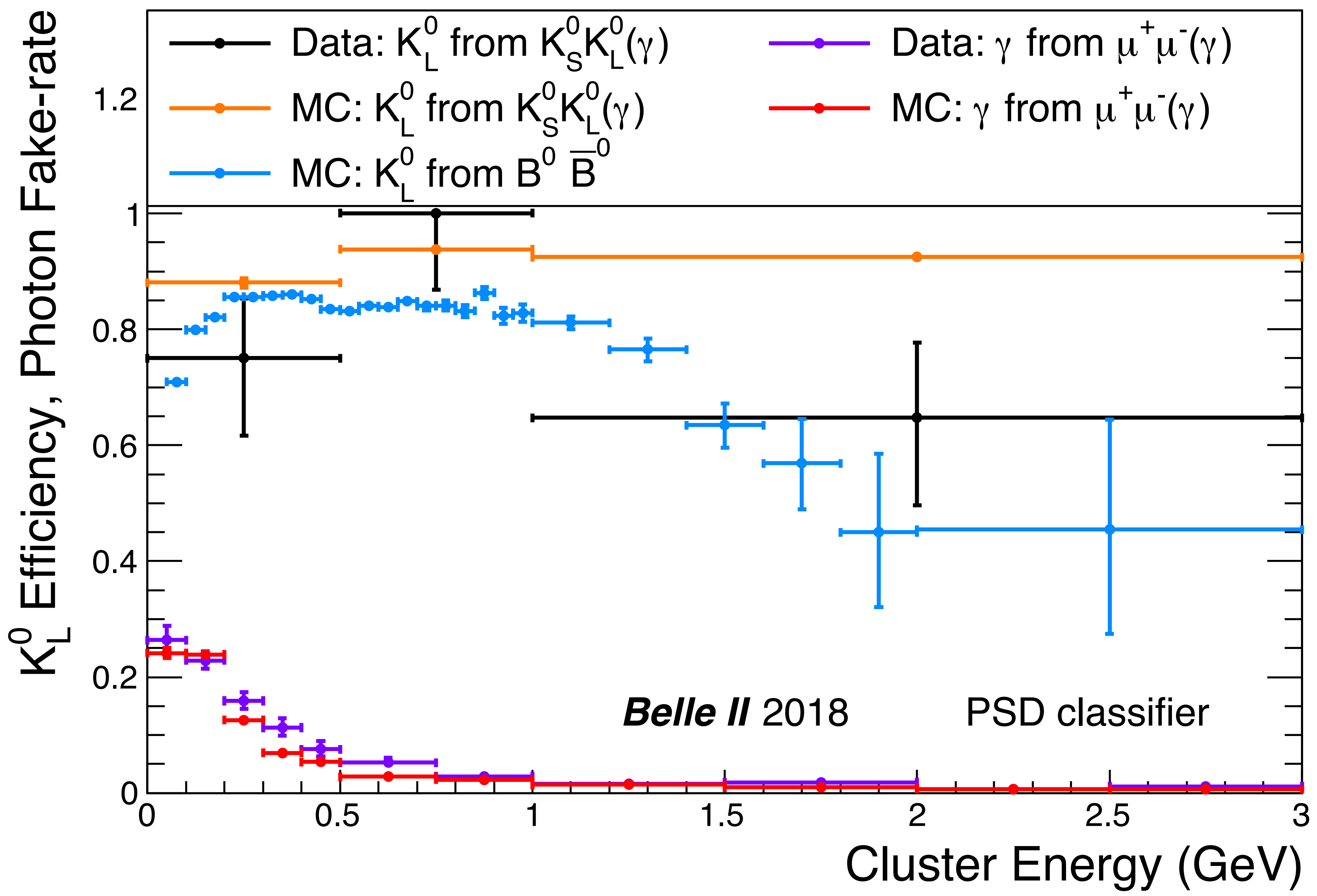


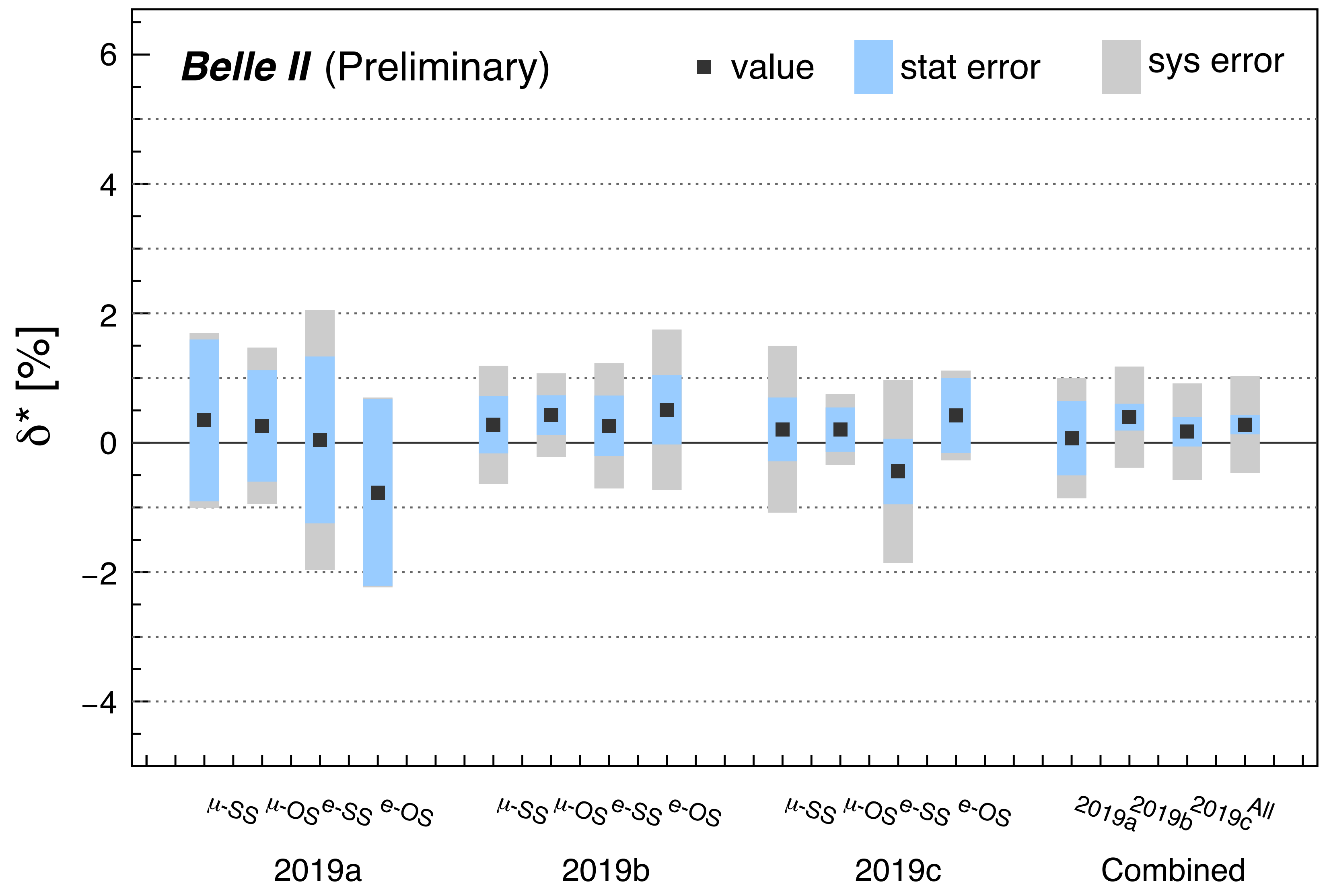
Comput.Phys.Commun. 259 (2021) 107610

ECL PSD K_L/γ -ID (New to Belle II)
NIM A 982 (2020) 164562

BELLE2-NOTE-PL-2021-008



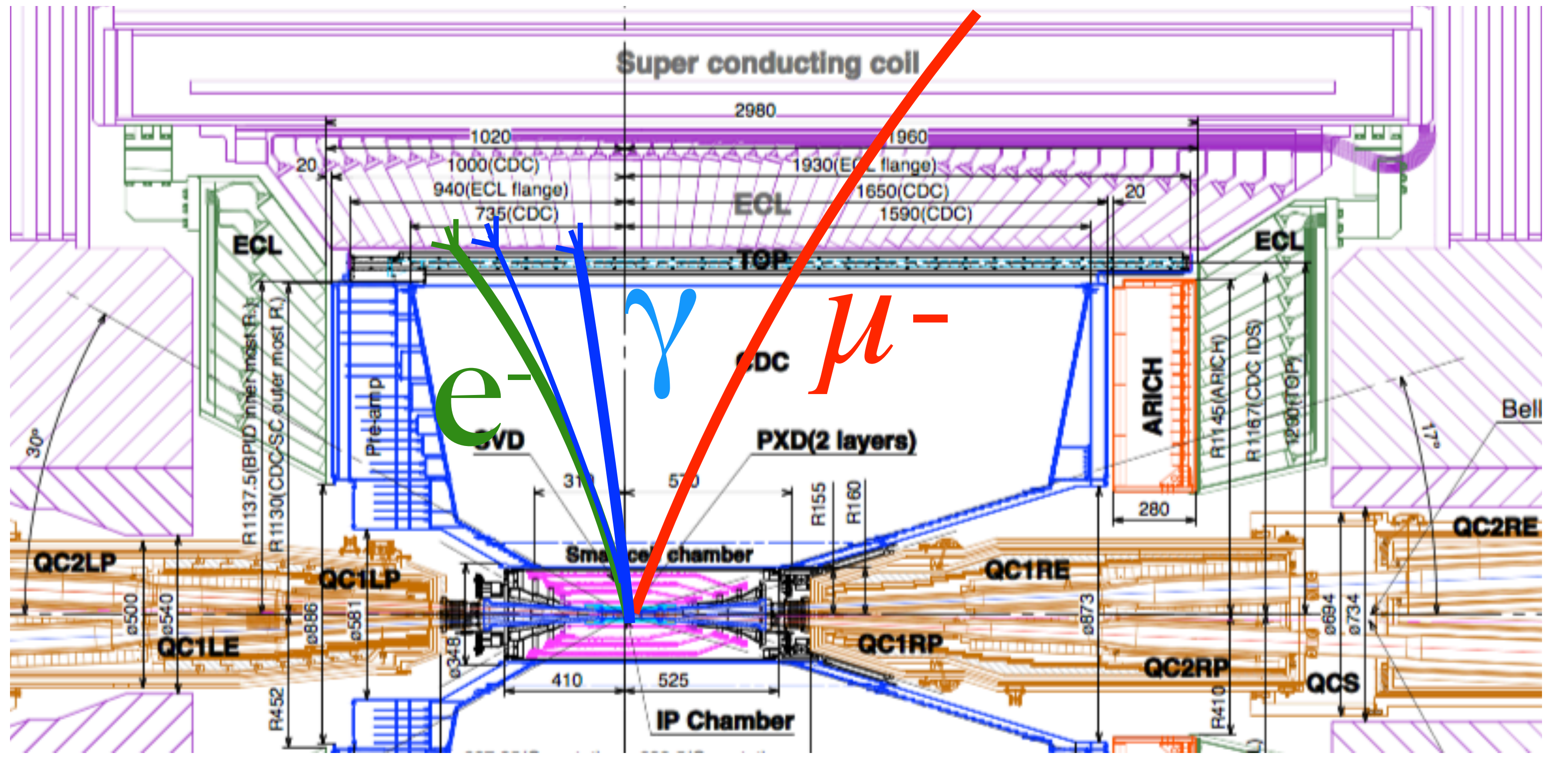




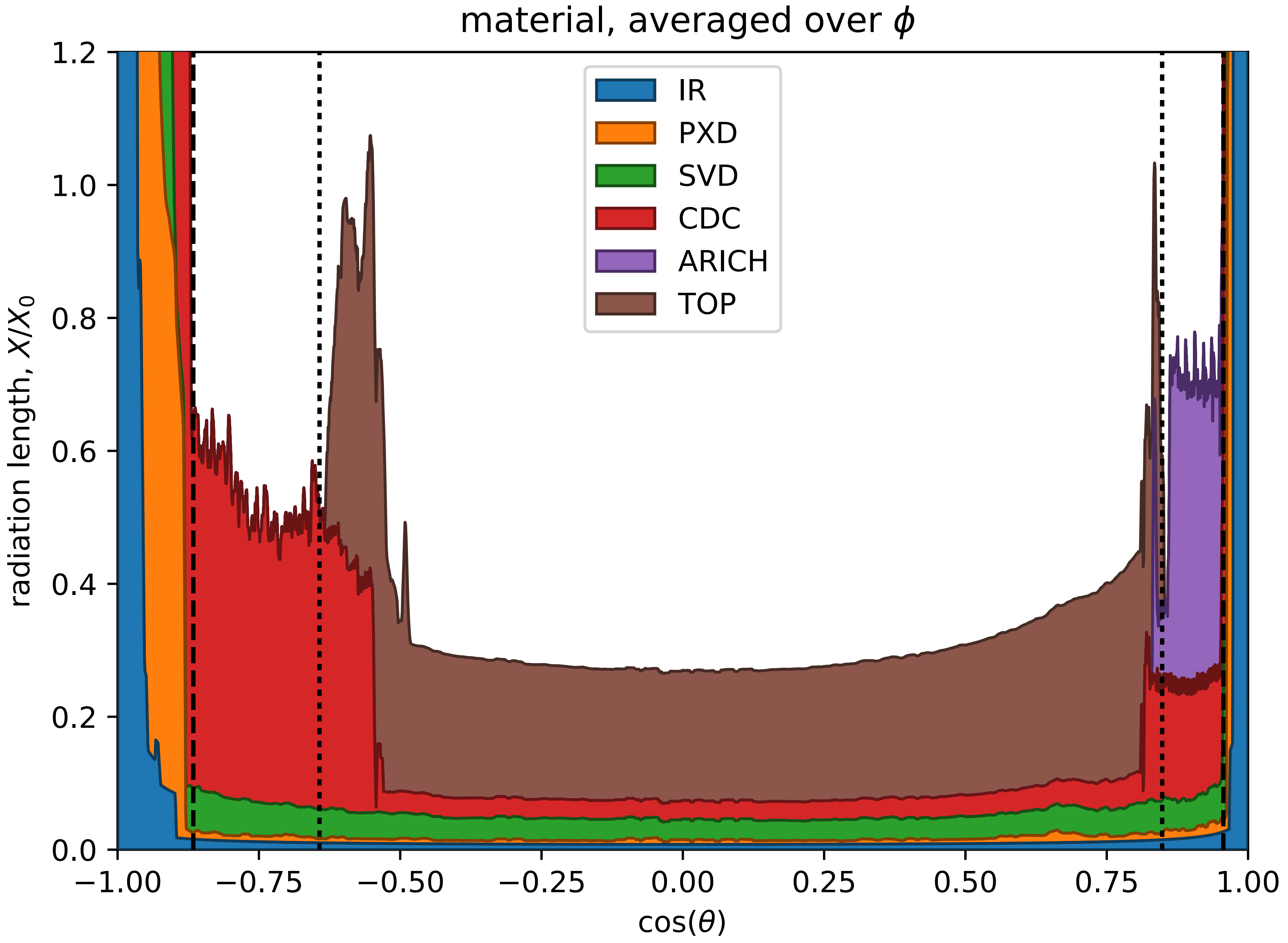
δ^* = Calibrated Data-MC discrepancy for tracking efficiency

Lepton reconstruction

- Good universality in efficiency, and in resolution after bremsstrahlung corrections.

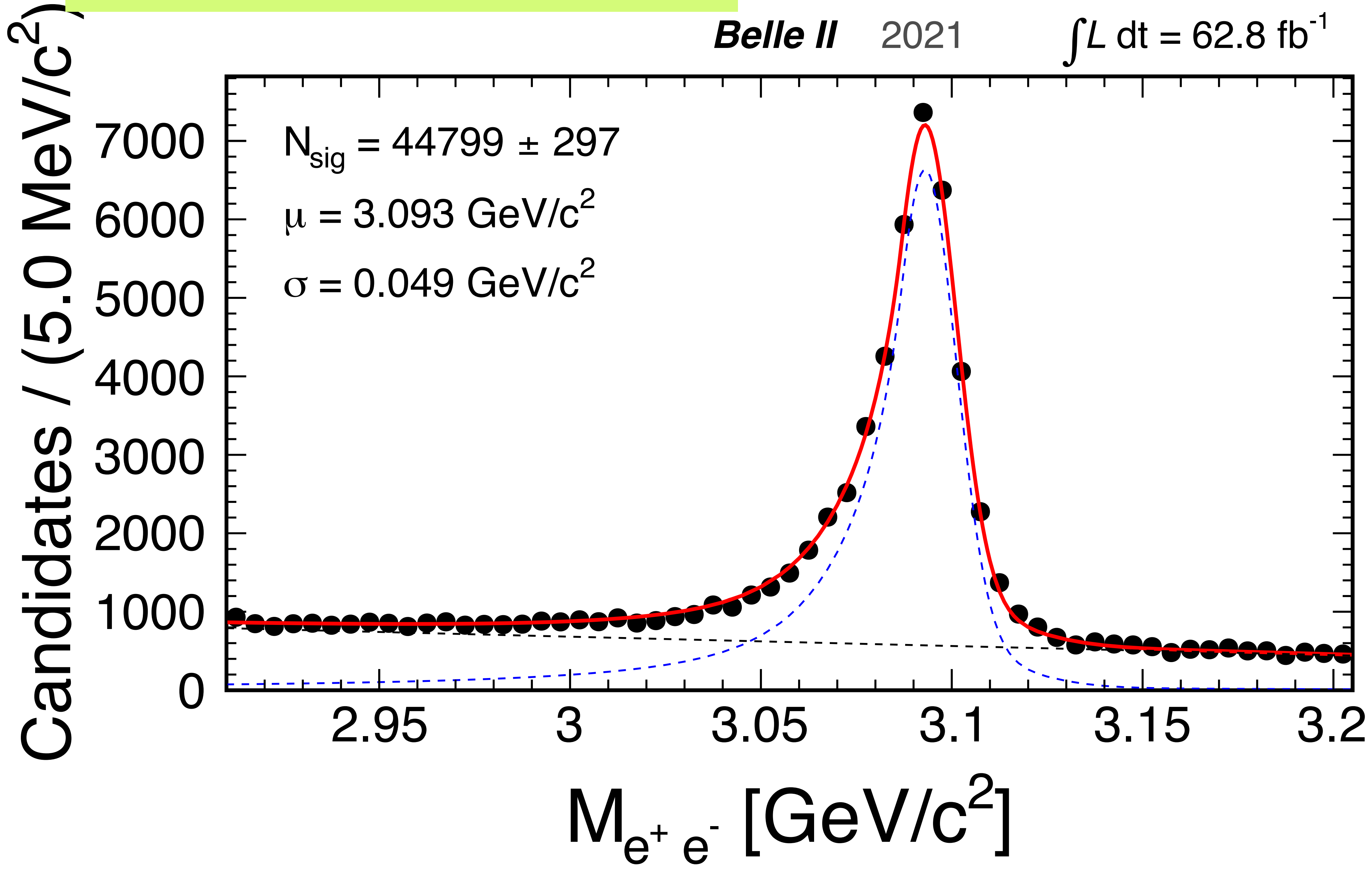


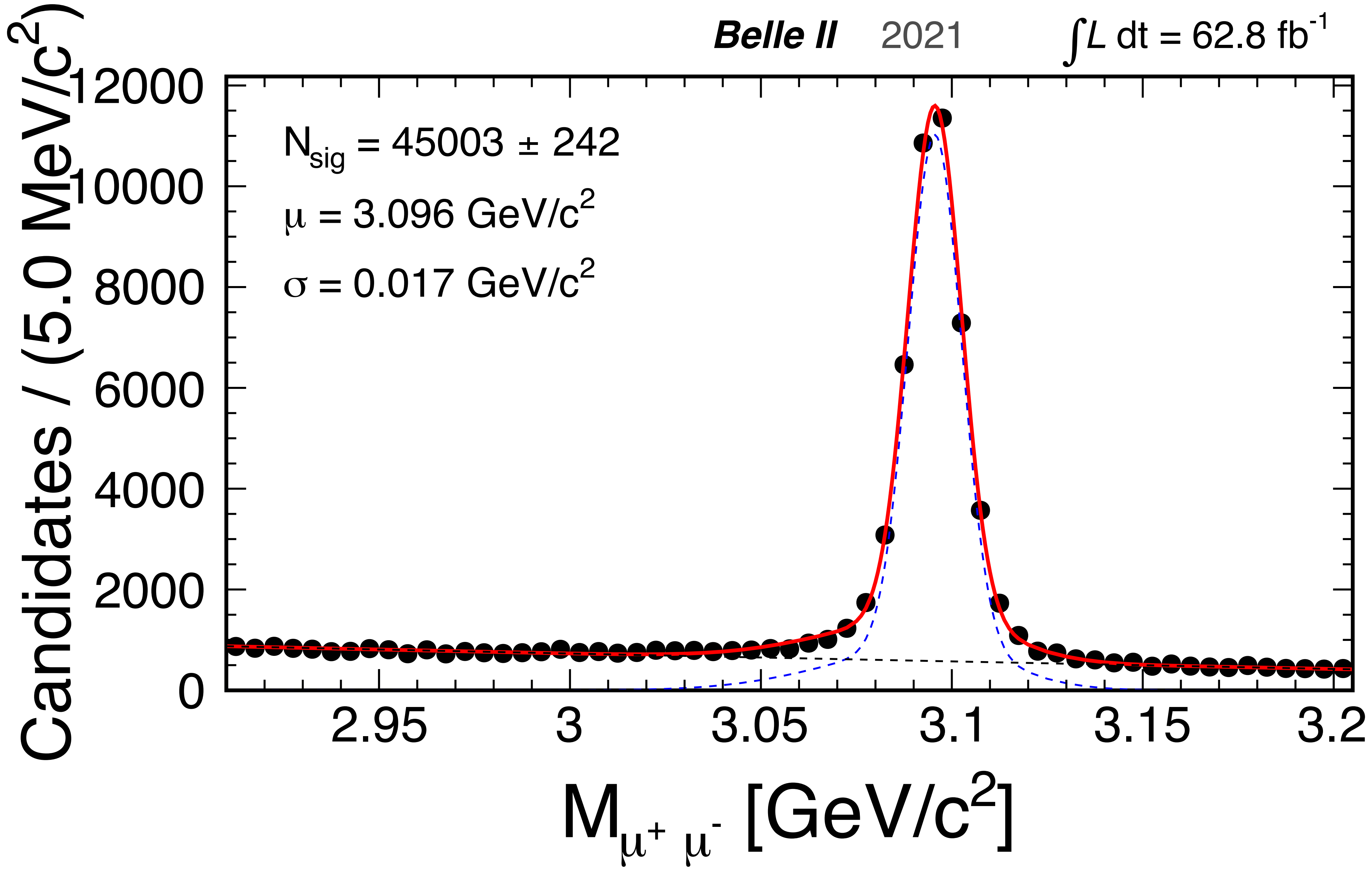
e: FSR, bremsstrahlung in material (less material in tracking volume than LHC detectors). Corrected at track level and/or calorimeter level.



Belle II 2022

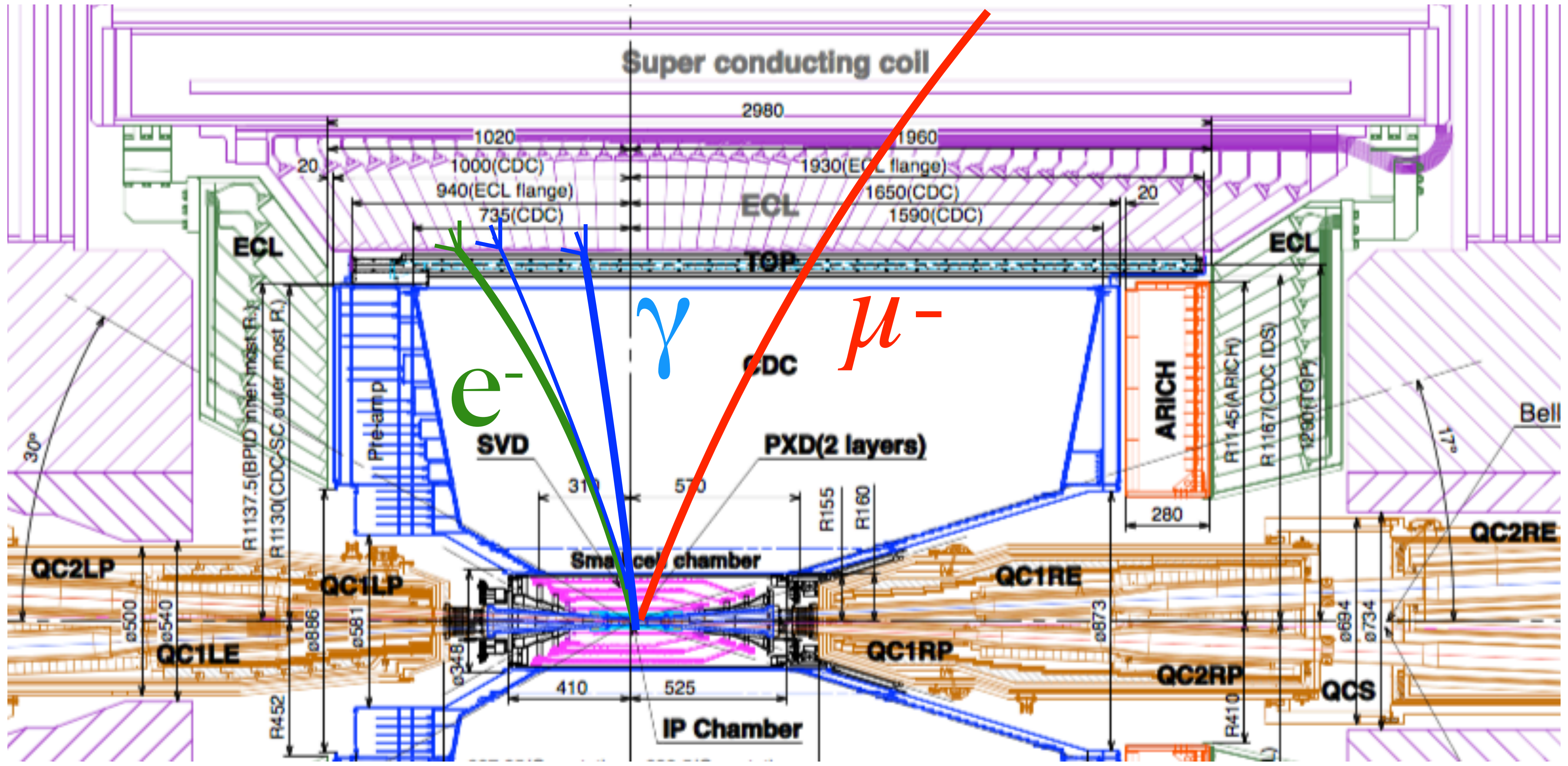
BELLE2-NOTE-PL-2020-027



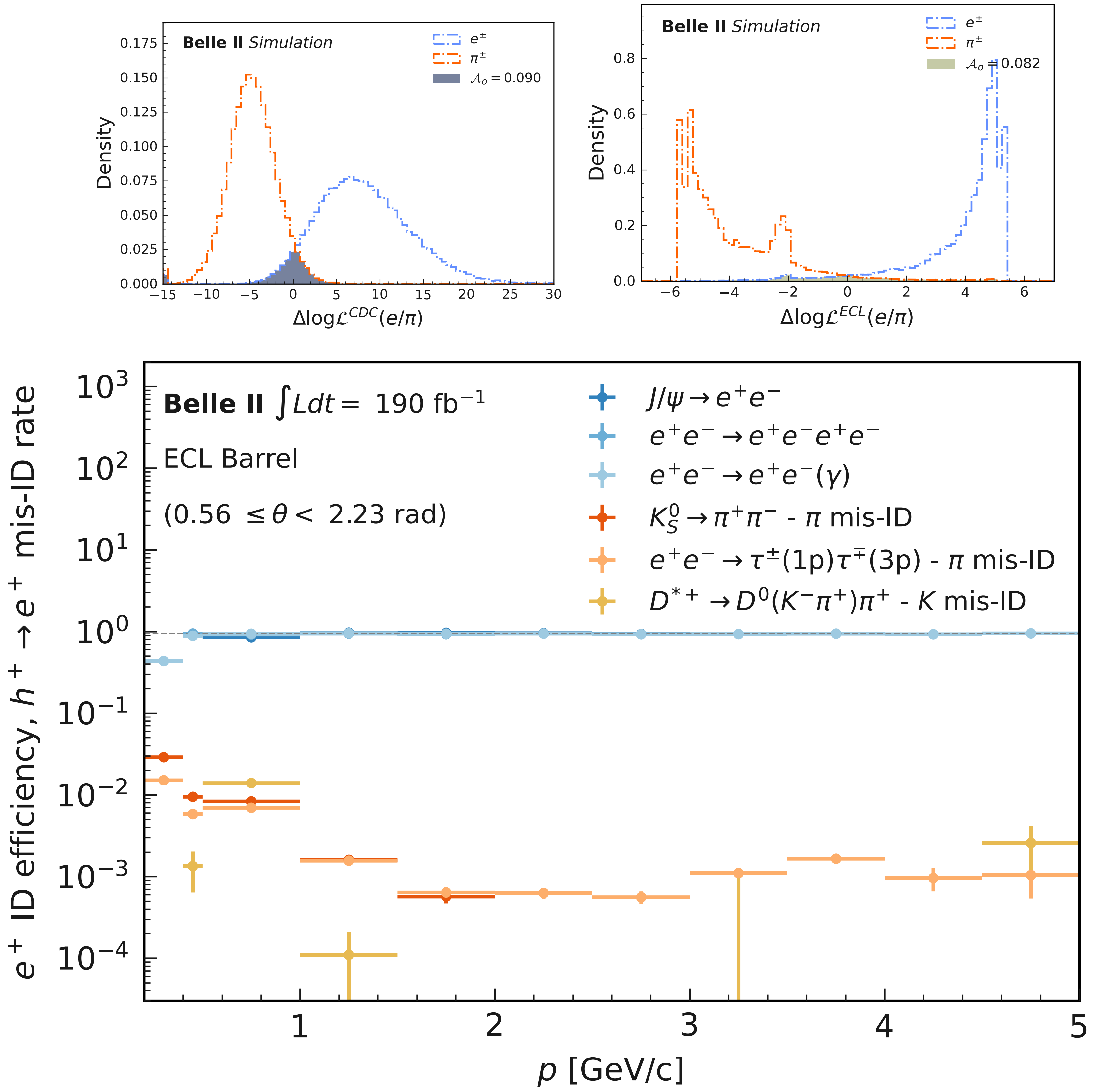


Lepton identification

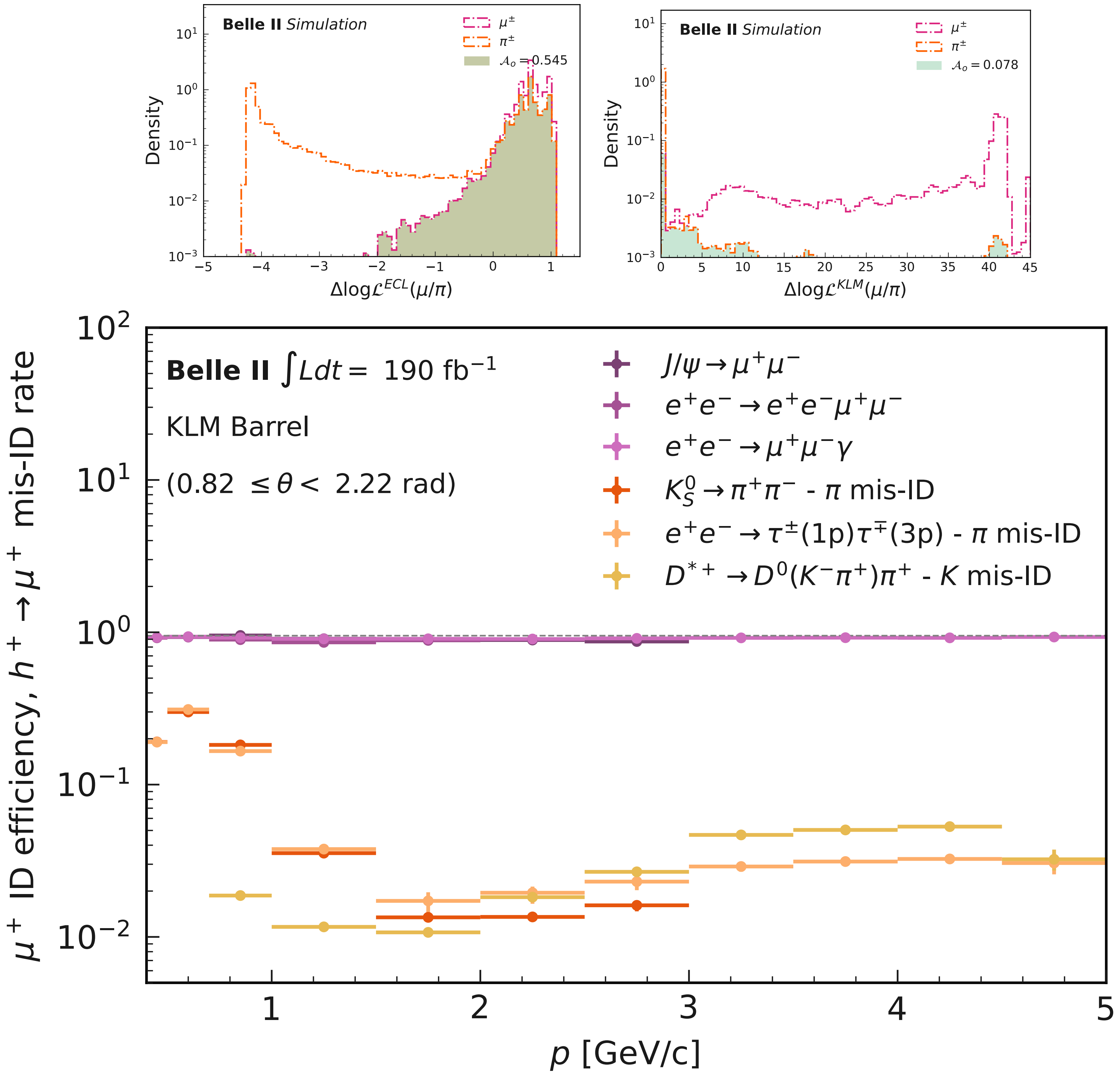
- Electrons strongly rely on ECL shower shapes, E/p, dE/dx (CDC).
- Muons rely on KLM (above ~700 MeV/c), and ECL (lower momenta).
- The τ problem: B→ τ→l have <p>~500 MeV/c.
  - Use of ML methods for e & μ ID in use, optimised for low p (big improvements with ECL shower shape BDT).



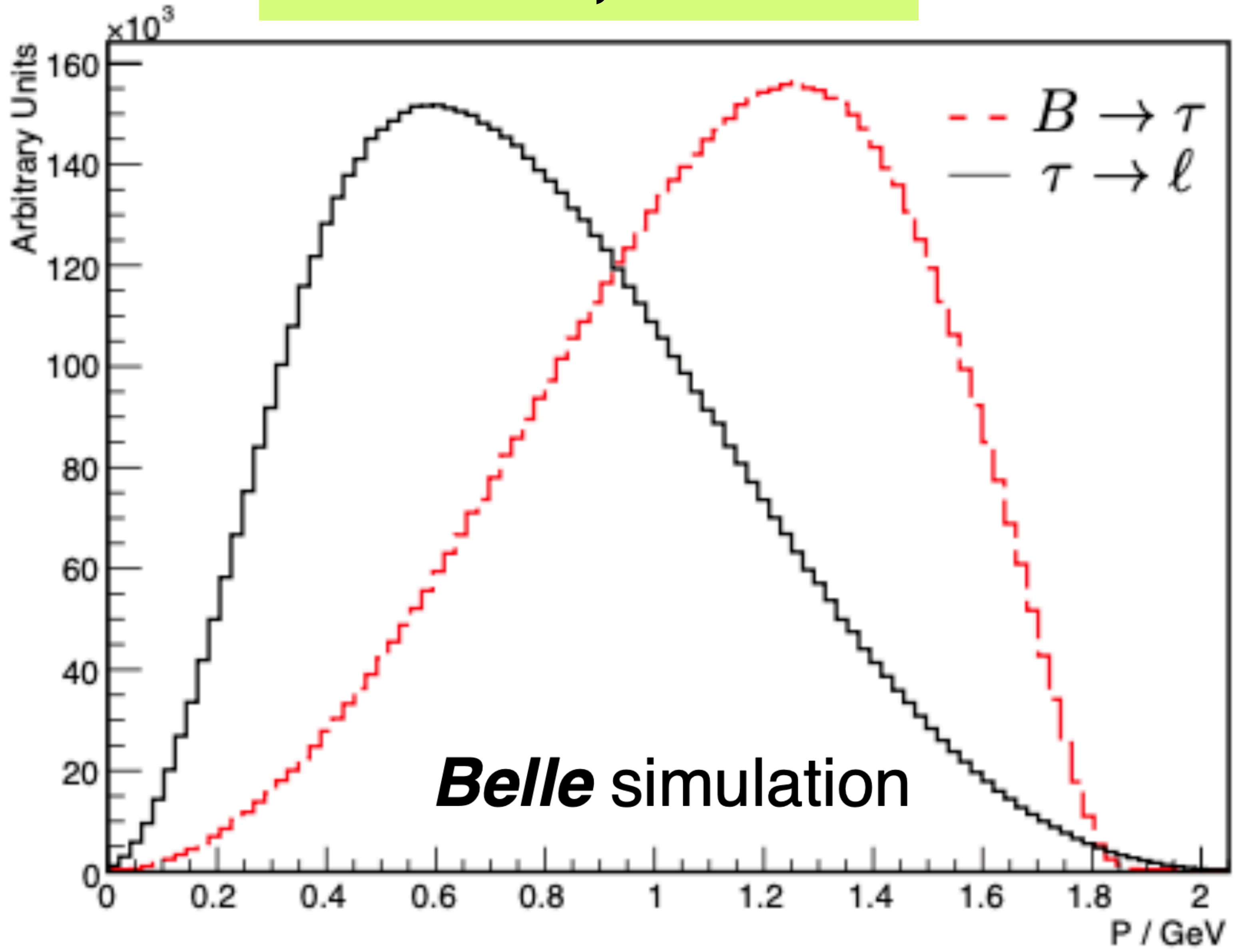
Electron ID



Muon ID



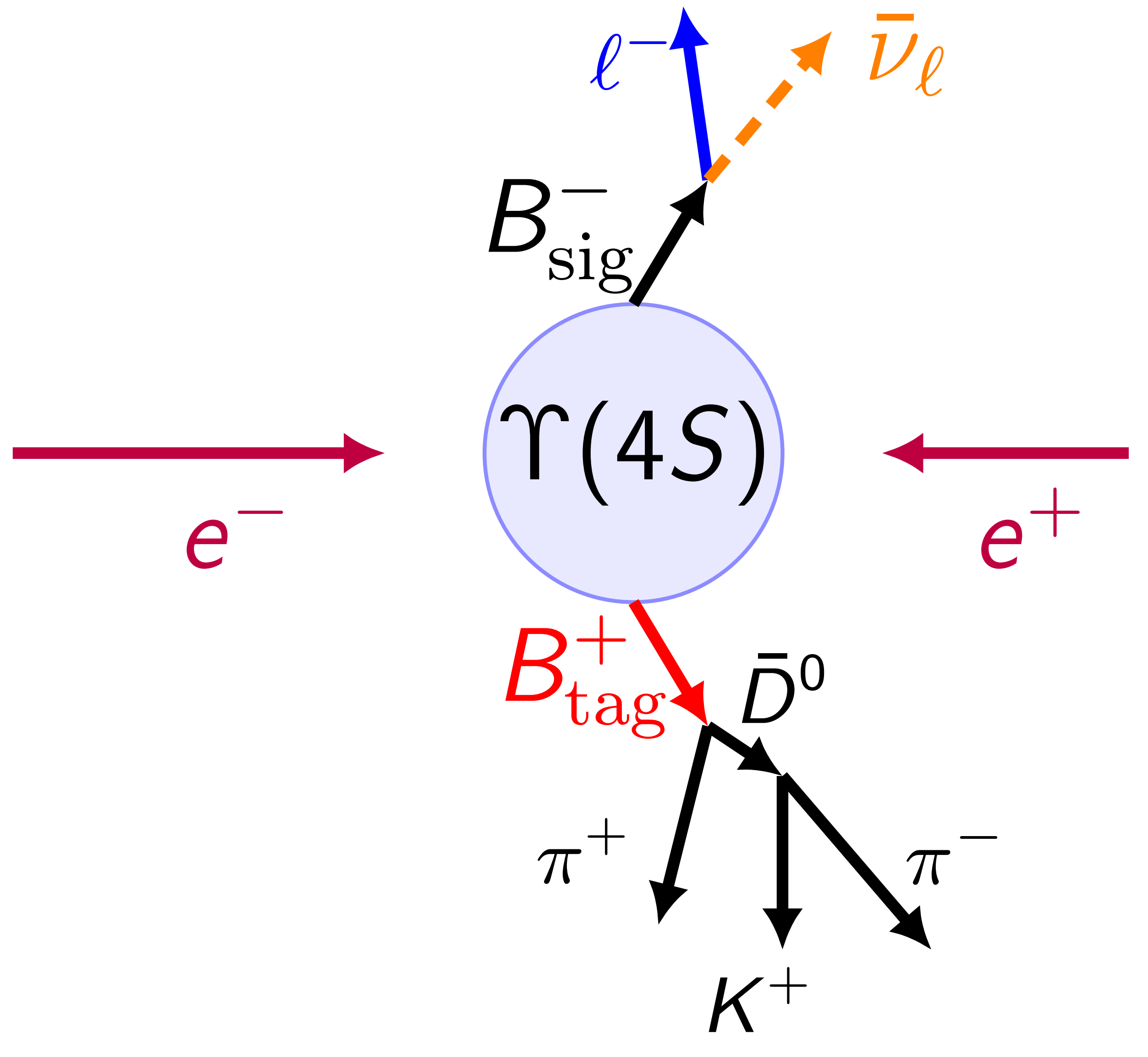
B→ τ→l decay kinematics



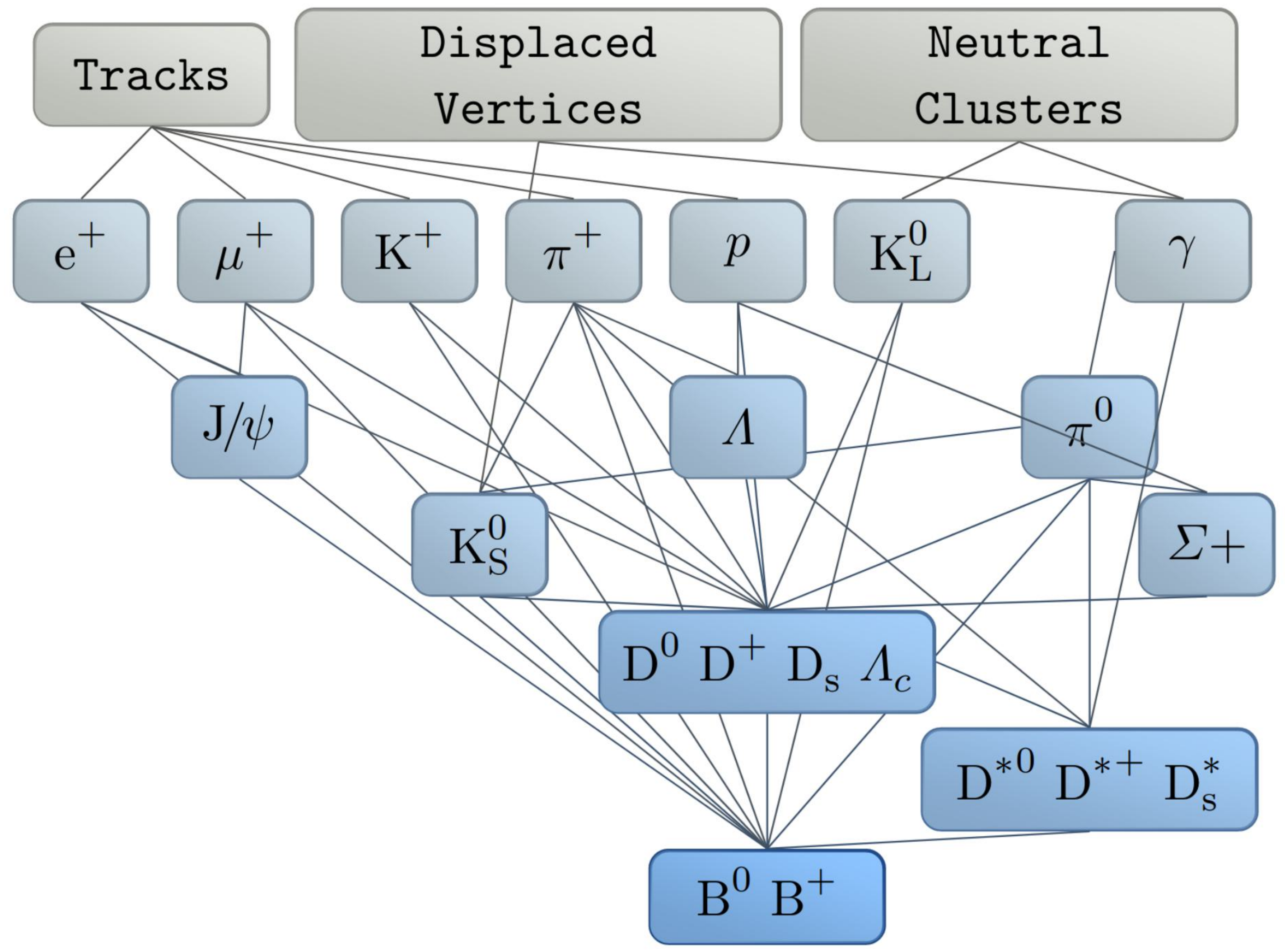
Belle II 2022

Key Analysis Steps

- Exploit the clean e^+e^- environment and well-defined kinematics (beam energy known to a few MeV precision) to reconstruct signal-side B candidates.
  - $M_{\rm bc} \equiv \sqrt{E_{\rm beam}^2 - \vec{p}_B^{\,*2}}, \qquad \Delta E \equiv E^*_{\rm beam} - E^*_B$
- Mitigate continuum background using the difference in event topology (spherical $B\bar{B}$ vs. jetlike $q\bar{q}$) and decay properties (exponential $B\bar{B}$ decay vs. prompt $q\bar{q}$).
- If the signal B candidate has ≥ 1 invisible decay product, utilise properties of the recoiling ('tag') B candidate.
- For CP eigenstates use the *tag* candidate to determine flavour.

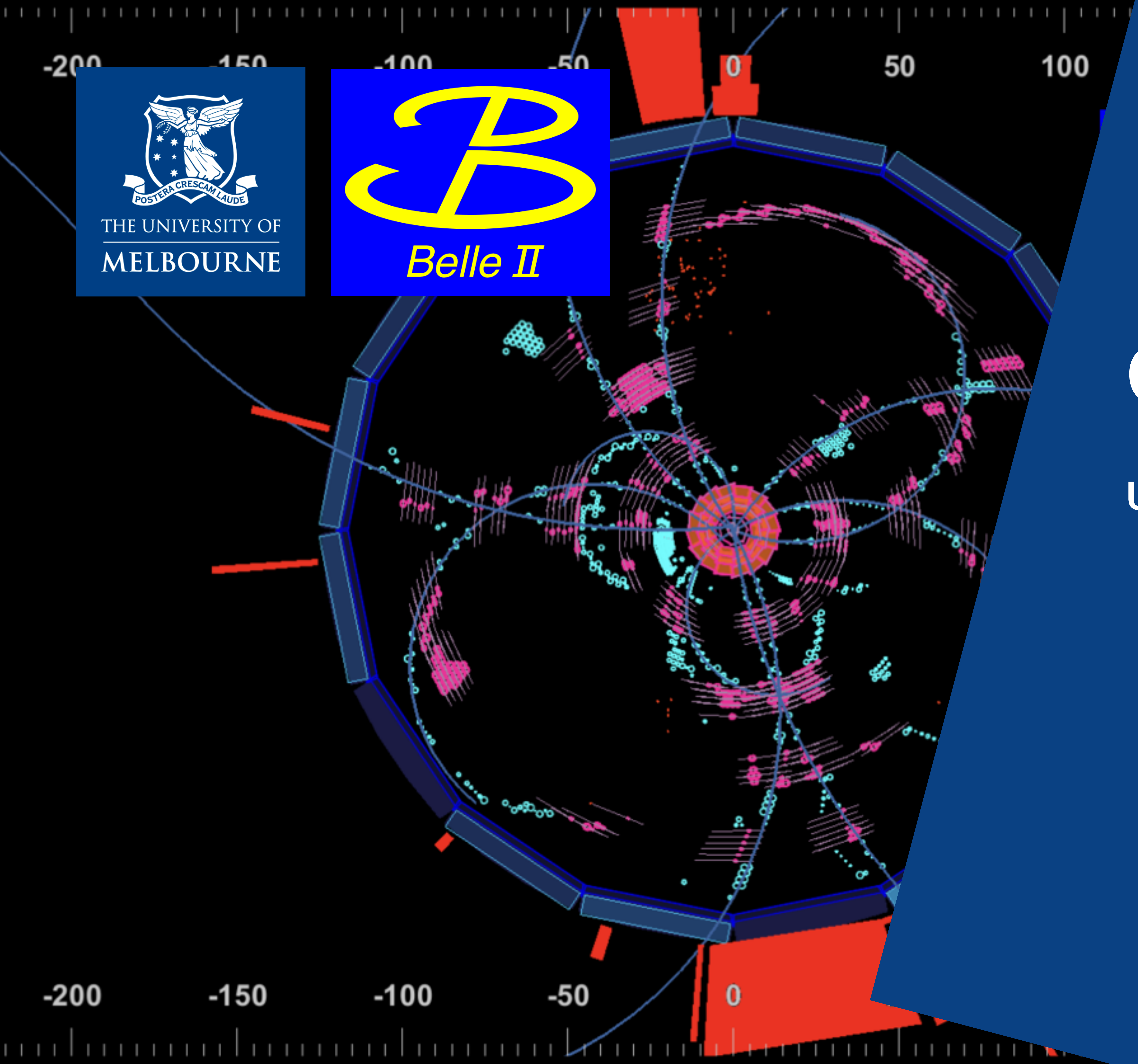


Comput Softw Big Sci (2019) 3: 6.



Summary vs Belle (Approximate values only)

		<Systematics>		Performance/Notes	
		Belle	Belle II	Belle	Belle II
Tracking	Fast	0.35%	0.70%		
	Slow	1.3%	4%		
Lepton ID	eID (1-1.5 GeV/c barrel)	1-1.5% (0.3% J/ψ)	1-2% (0.5% J/ψ)	90%(eff) 0.06% (fake)	90%(eff) 0.06% (fake)
	μID (1-1.5 GeV/c barrel)	1-1.5% (0.3% J/ψ)	1-2% (0.5% J/ψ)	90%(eff) 12% (fake)	90%(eff) 1.9% (fake)
Hadron ID	KID	0.8%	<0.9%		
	πID	0.8%	<0.9%		
Photons & π^0	γ Eff	2%	<1%	Belle approach takes Δ not mea. error	
	π^0 Eff	2%	<4%		
Counting	nBB	1.4%	2.6% (1.1%)		



THE UNIVERSITY OF MELBOURNE

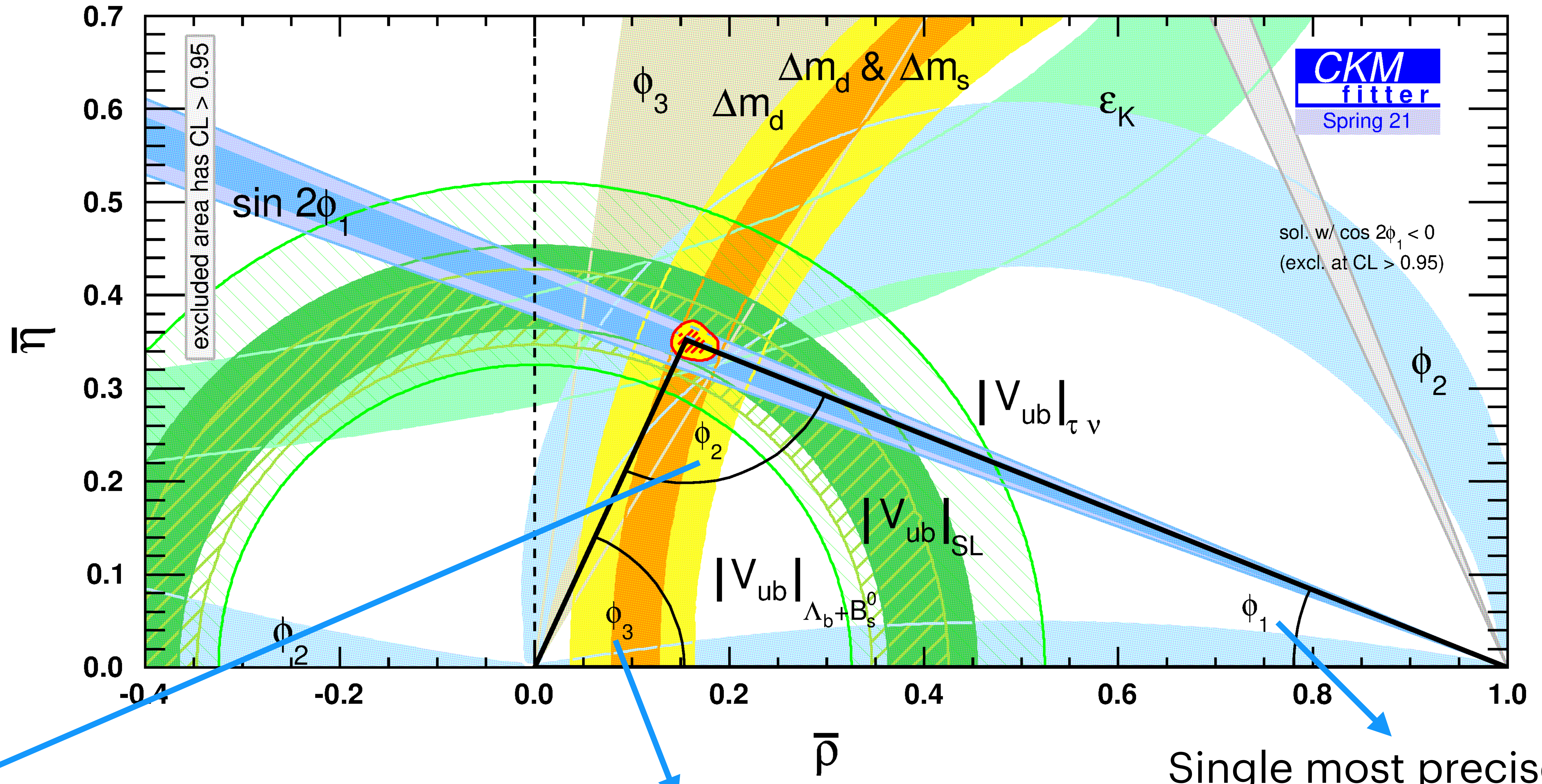
Belle II

CP Violation

UT angles, NP

UT angle current precision

5-10% precision on individual constraints. Lots of room for new physics!!



Combination of $B \to \pi\pi, \pi\pi\pi, \rho\rho$ from Belle and BaBar $\phi_2 = (85.2^{+4.8}_{-4.3})^\circ$

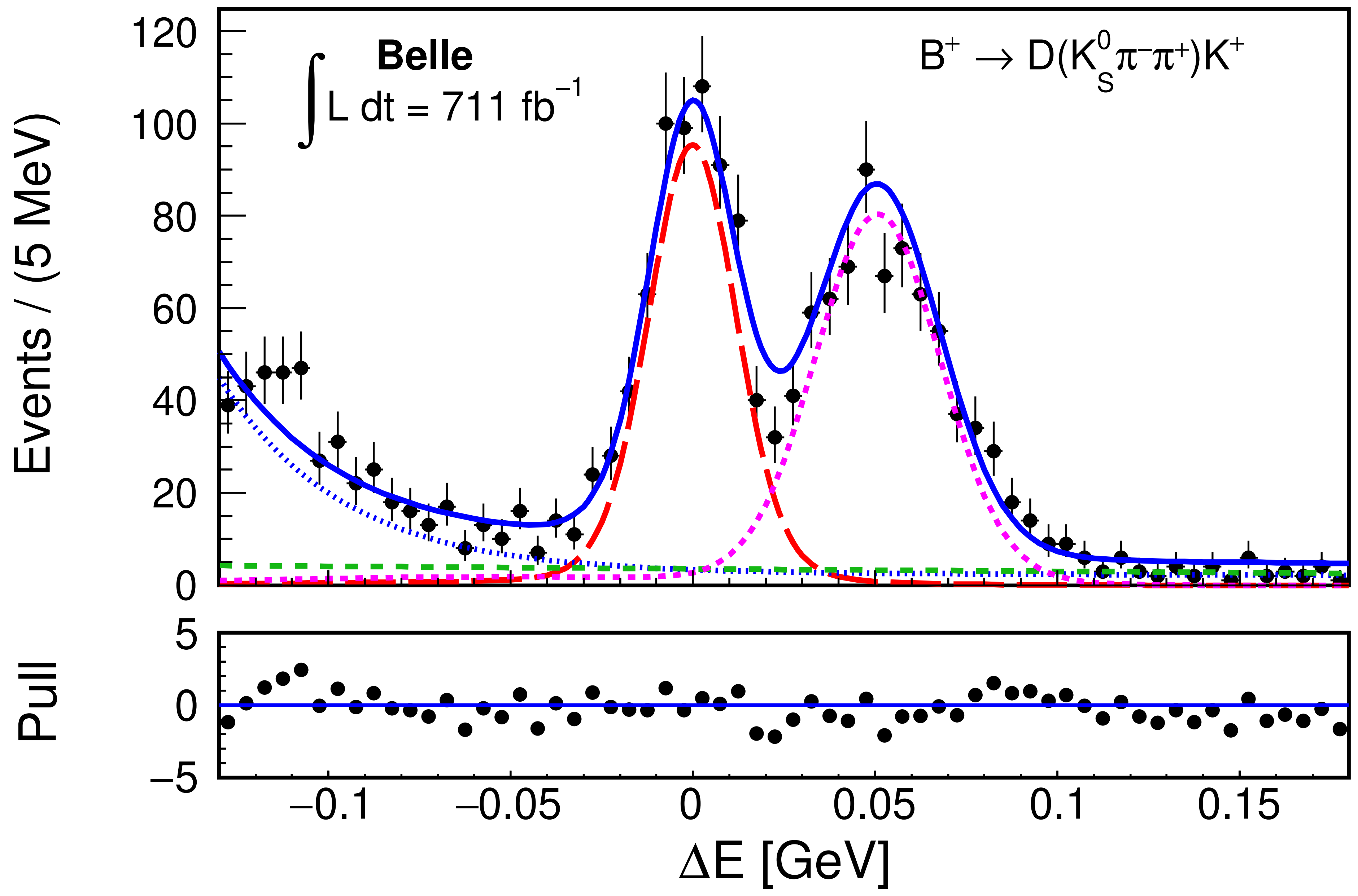
Single most precise value from LHCb $\phi_3 = (65.4^{+3.8}_{-4.2})^\circ$

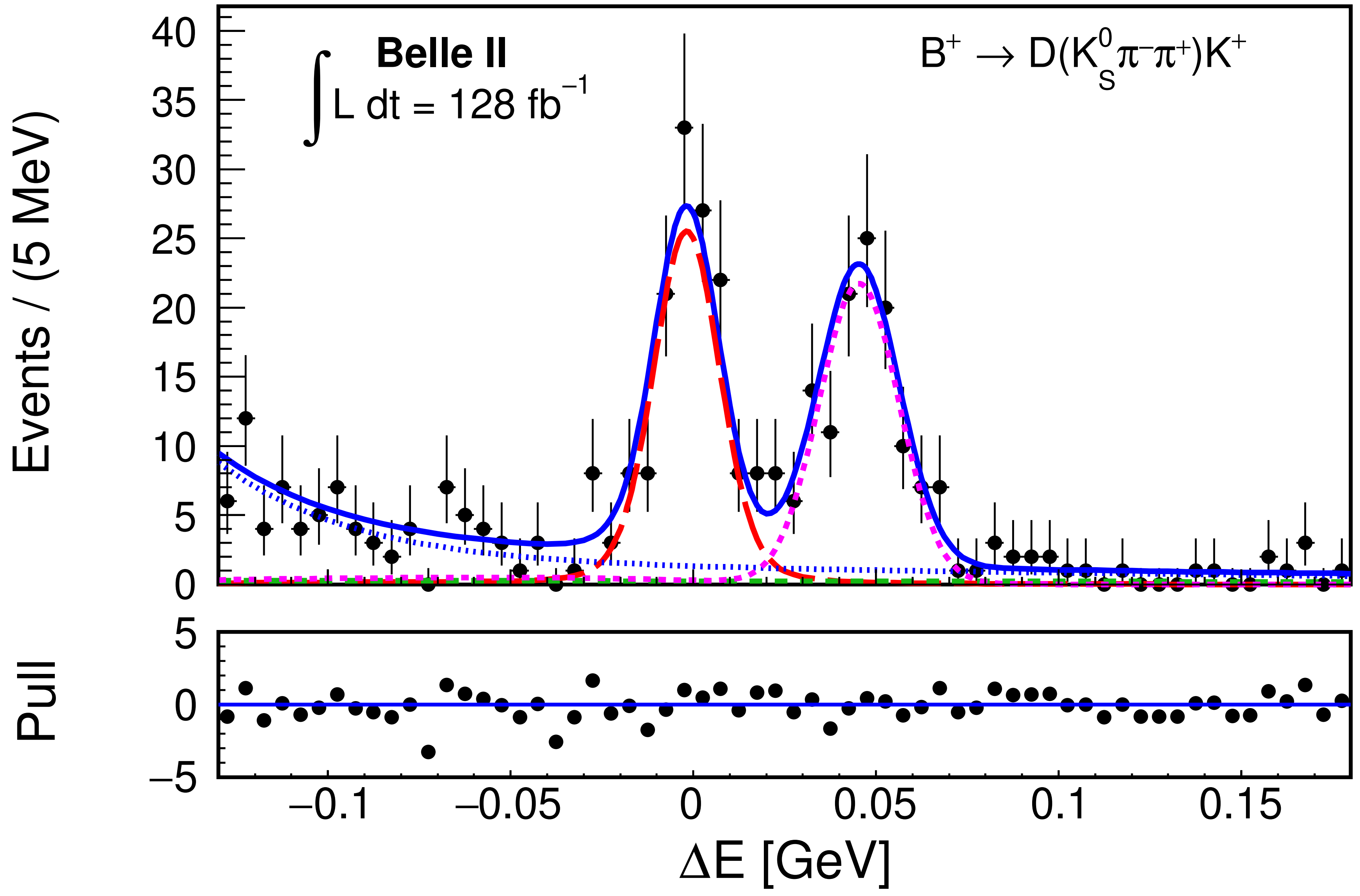
Single most precise value from Belle $\sin(\phi_1) = (0.667 \pm 0.023 \pm 0.012)$ $\phi_1 = (22.14^{+0.69}_{-0.67})^\circ$

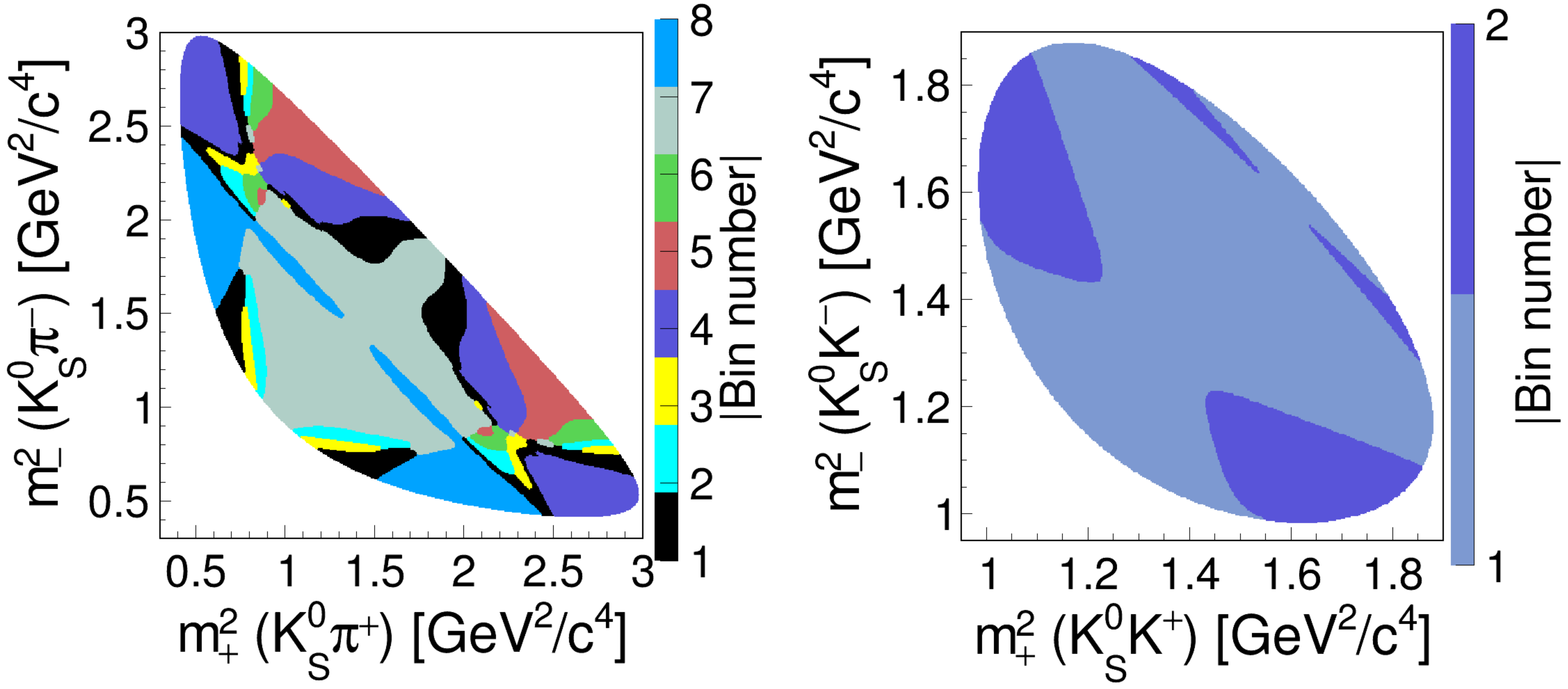
Φ_3 with Belle + Belle II

- First measurement combining Belle and Belle II data.
- Model independent Dalitz analysis of $B^+ \to D(K_S^0 h^+ h^-)h^+, (h = K, \pi)$. Simultaneous fit of two channels.
- $\phi_3 = (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ$ is statistics limited. Expect LHCb-like precision with 10 ab^{-1} in this channel but others will be added.

Belle + Belle II JHEP 02 (2022) 063







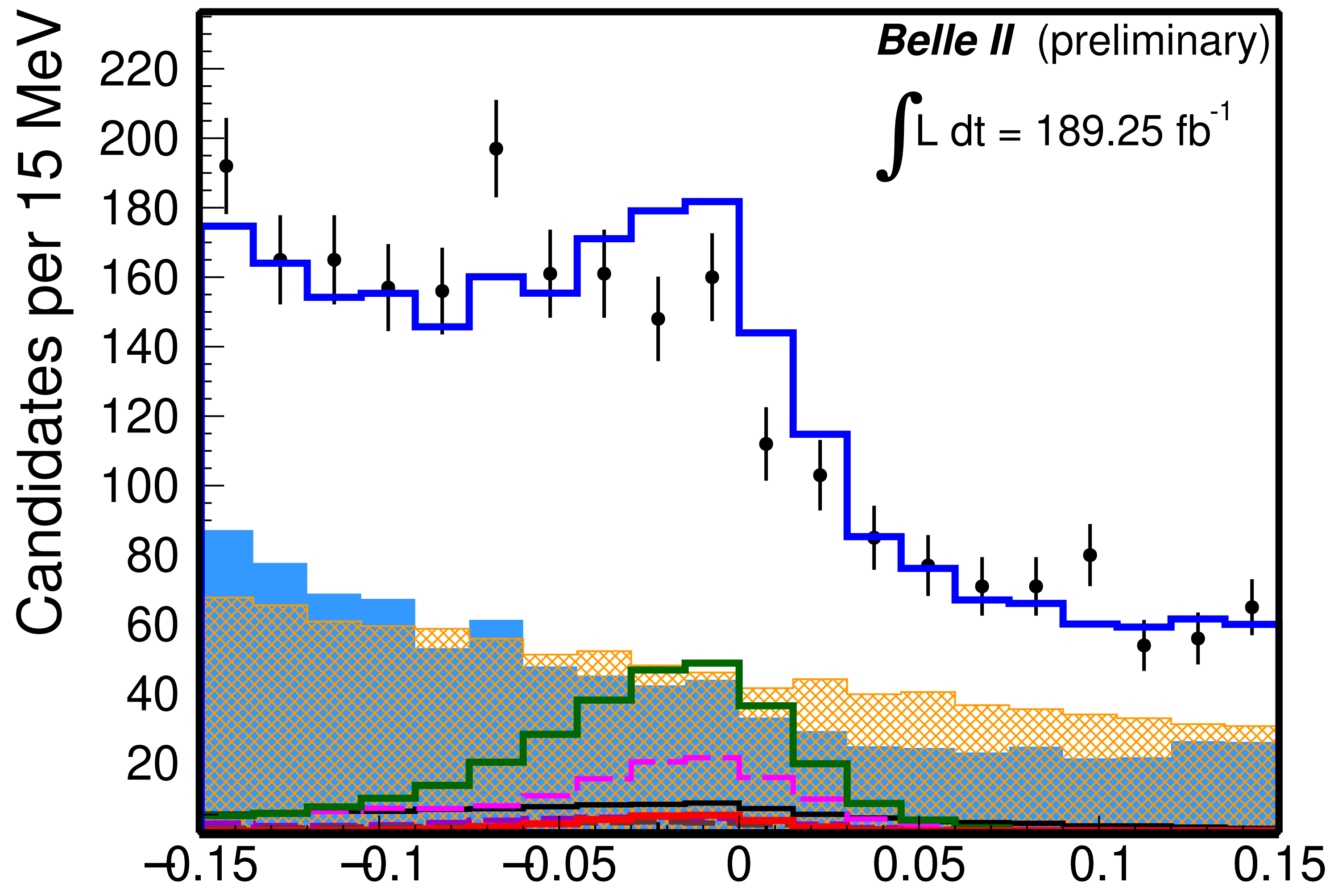
Towards Φ_2

Belle II Preliminary

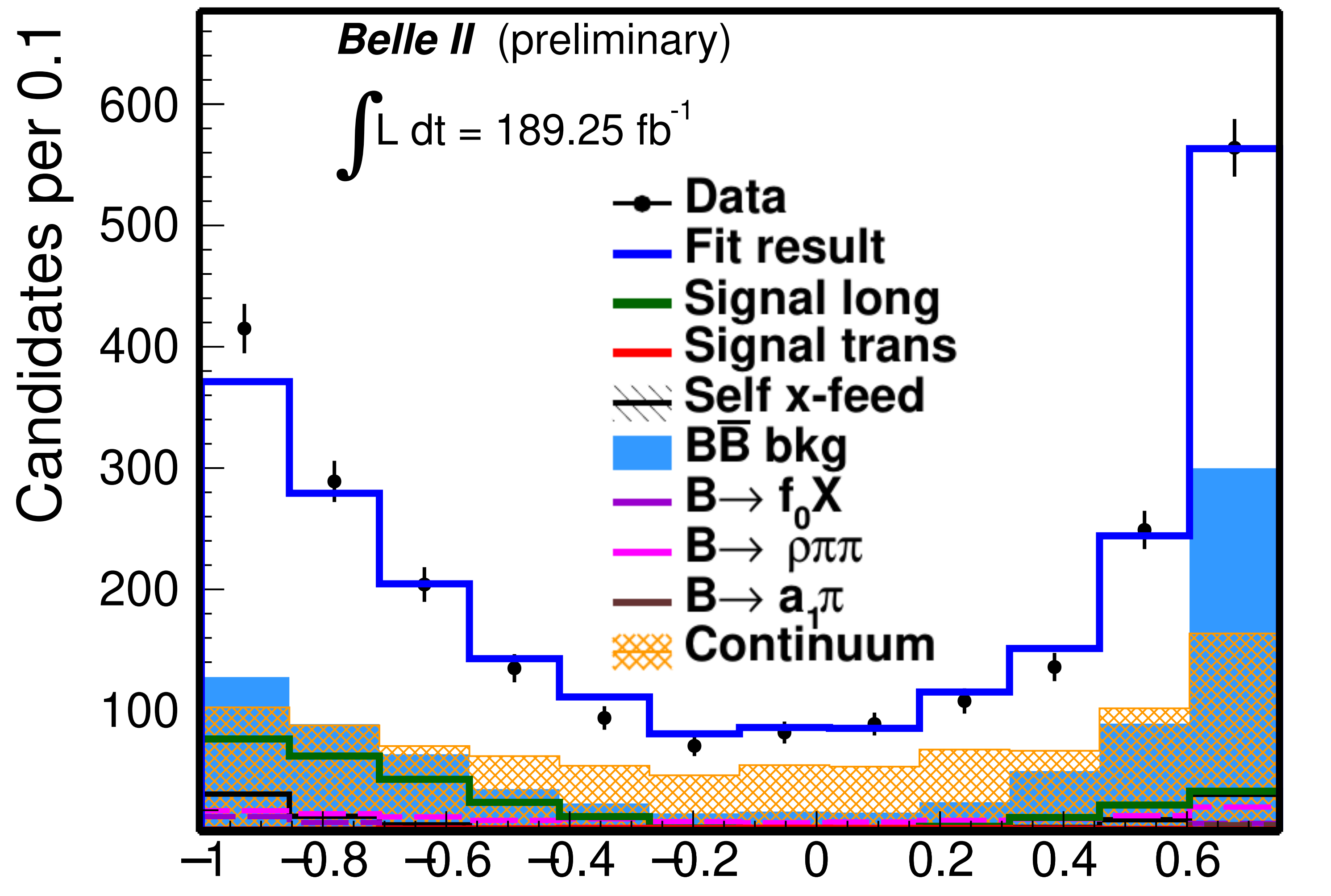
- Can extract α using info from three isospin- related decays $B \to \rho^+\rho^0$, $\rho^0\rho^0$, $\rho^+\rho^-$.
  - Belle II has unique access to all.
- Measure direct CP asymmetry in $B \to \rho^+\rho^0$ where both ρ^+ and ρ^0 are longitudinally polarised.

$$A_{CP} = -0.069 \pm 0.068\,(\text{stat.}) \pm 0.060\,(\text{syst.})$$
$$\mathcal{B}(B^+ \to \rho^+\rho^0) = (23.2^{+2.2}_{-2.1}\,(\text{stat.}) \pm 2.7\,(\text{syst.})) \times 10^{-6}$$
$$f_L = 0.943^{+0.035}_{-0.033}\,(\text{stat.}) \pm 0.027\,(\text{syst.})$$

World average: $A_{CP} = -0.05 \pm 0.05$



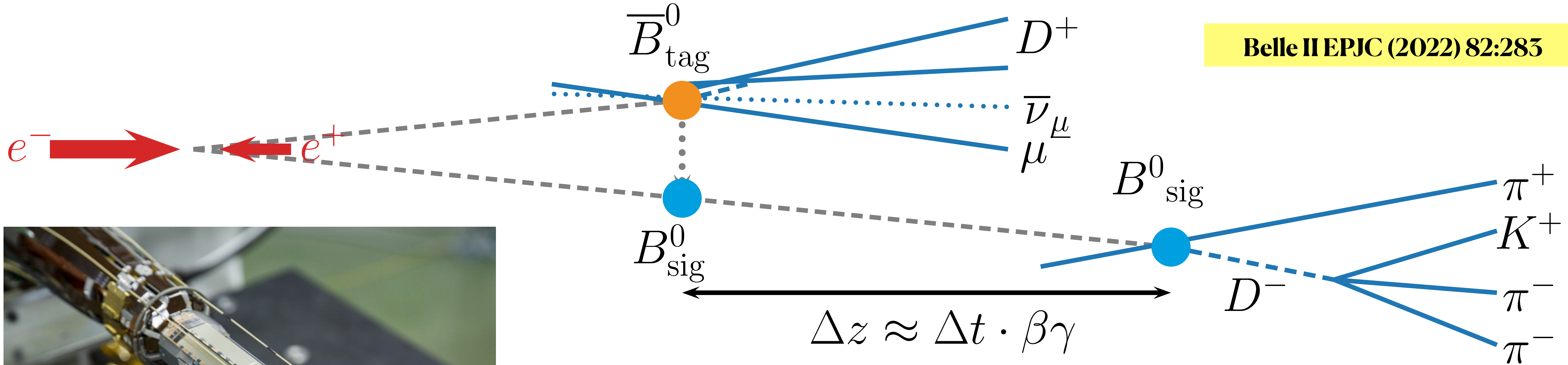
$\Delta E = E^*_B - E^*_{\text{beam}}$ [GeV]

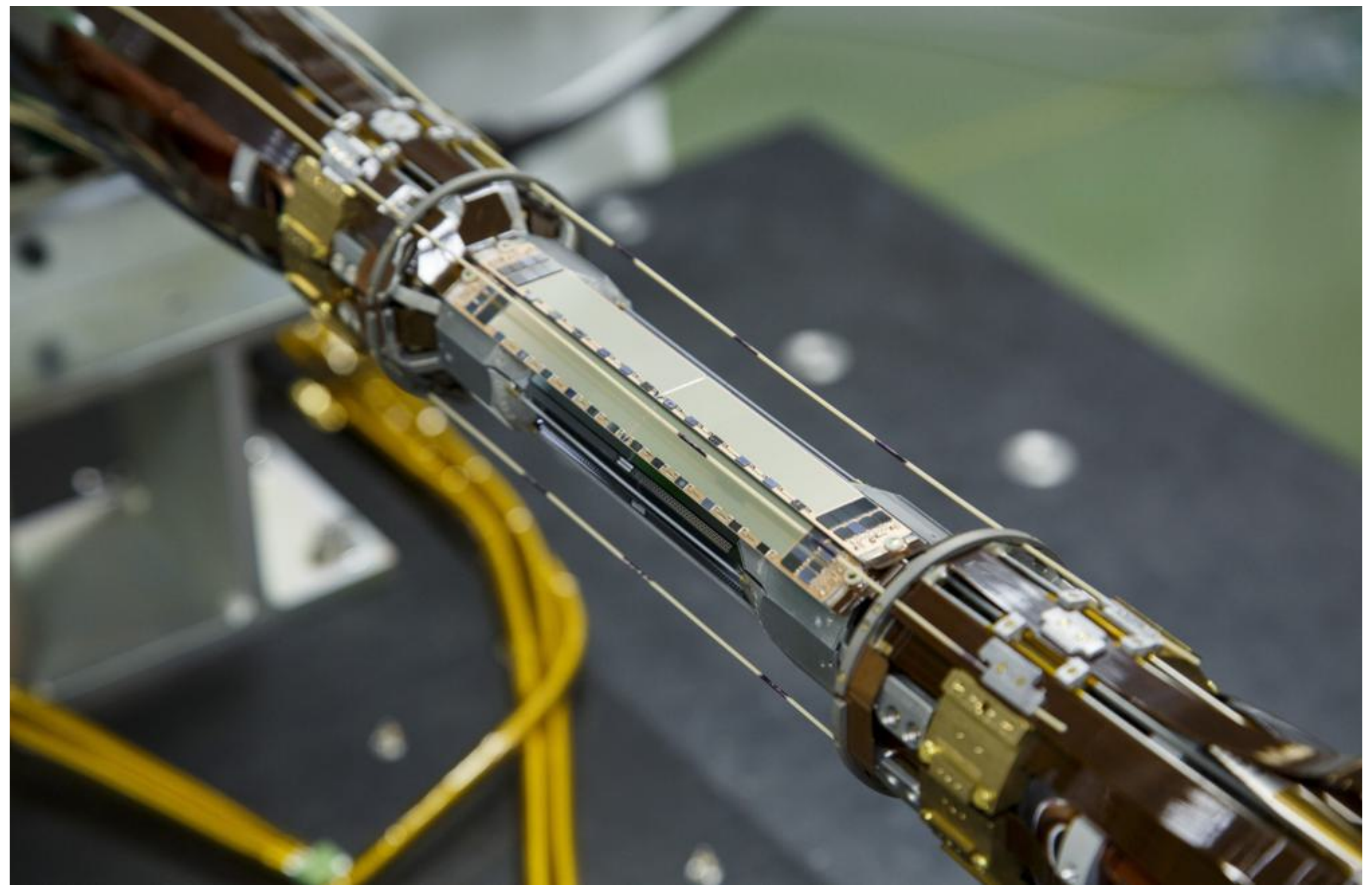


$\cos\theta_{\rho^+}$

Towards Φ_1 Time Dependent Analysis

Belle II EPJC (2022) 82:283





Belle II $\epsilon_{\rm tag} = (30.0 \pm 1.3)\,\%$

Belle $\epsilon_{\rm tag} = (30.1 \pm 0.4)\,\%$

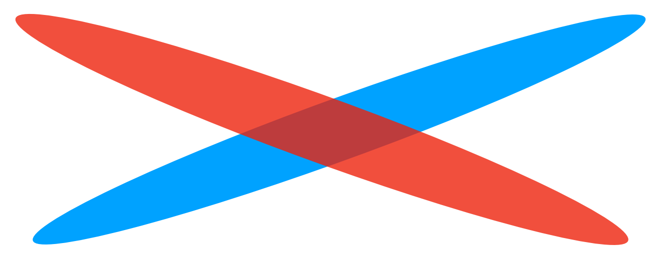
- Crucial inputs: a) vertex (IP) resolution, b) tagging efficiency.
- Modified beam-energies with reduced boost with respect to Belle $\beta\gamma = 0.43 \rightarrow 0.29 \Rightarrow \Delta z \approx 200 \rightarrow 130\ \mu$m
  - Recover the precision on Δt ($\approx \Delta z/\beta\gamma c$) with 1st layer of the vertex detector closer to beam-pipe

Nano-beams and the vertex detector

Effective bunch length *reduced x 1/10*

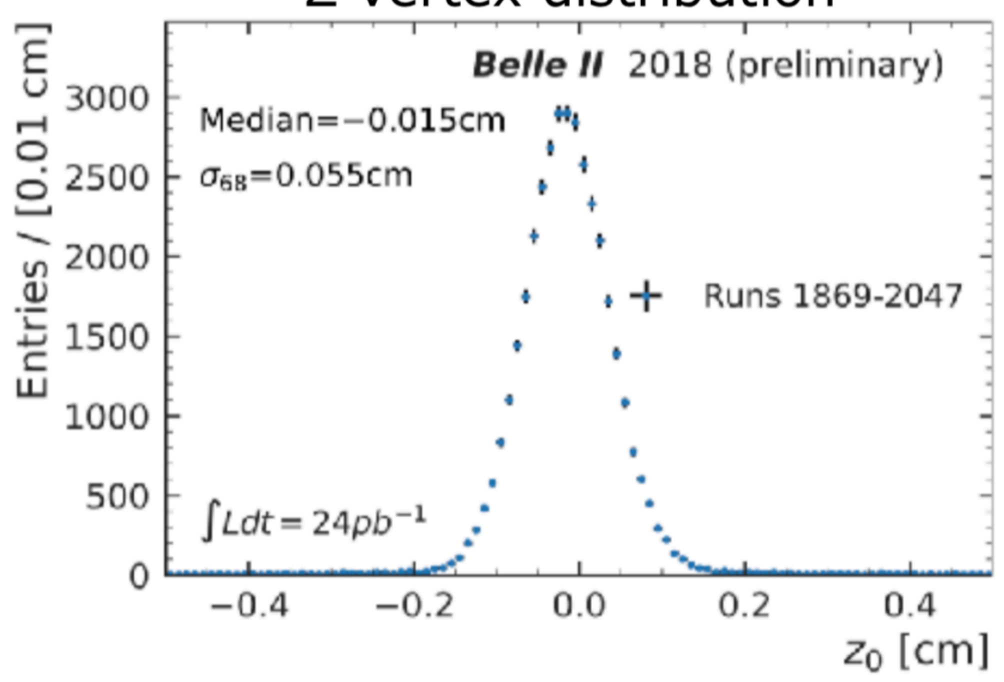
And vertex resolution 2x better than Belle

SuperKEKB

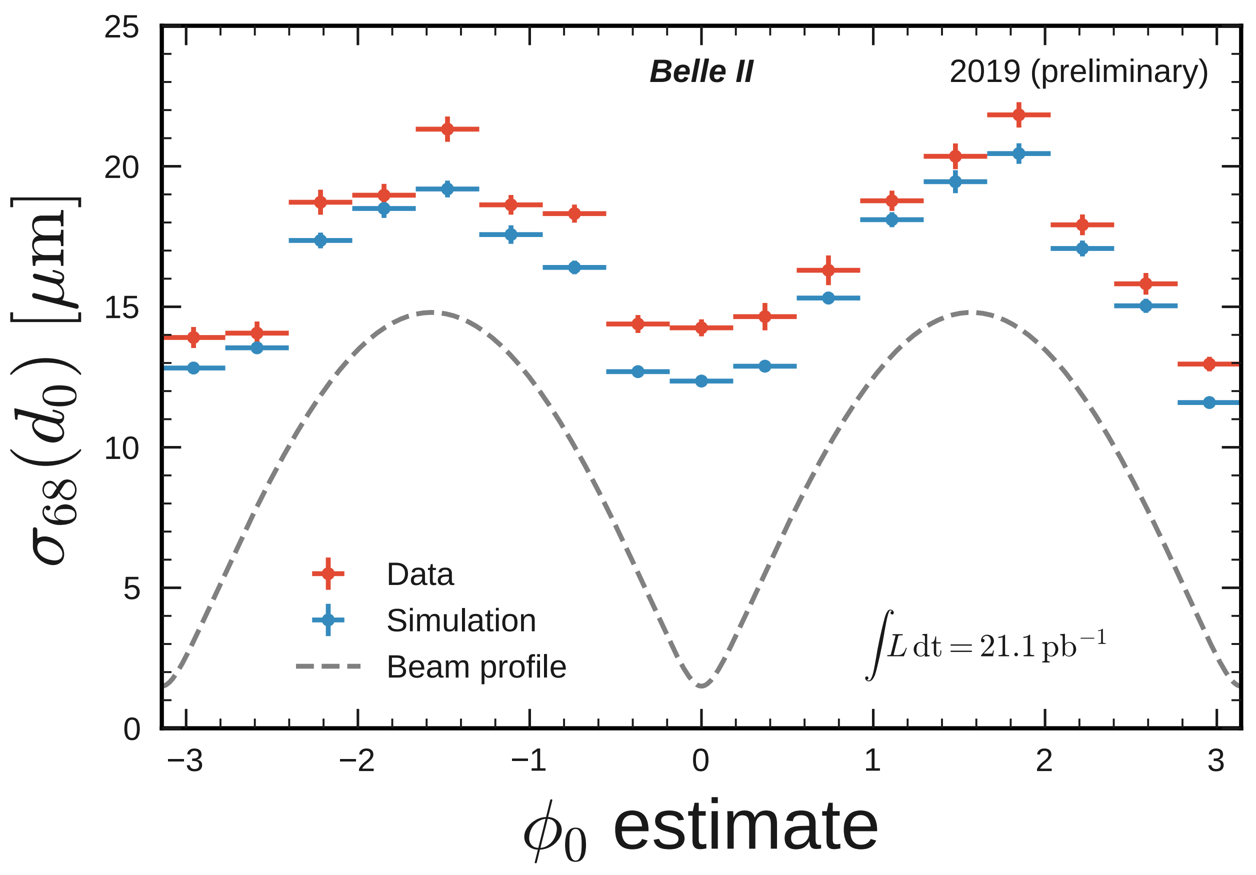


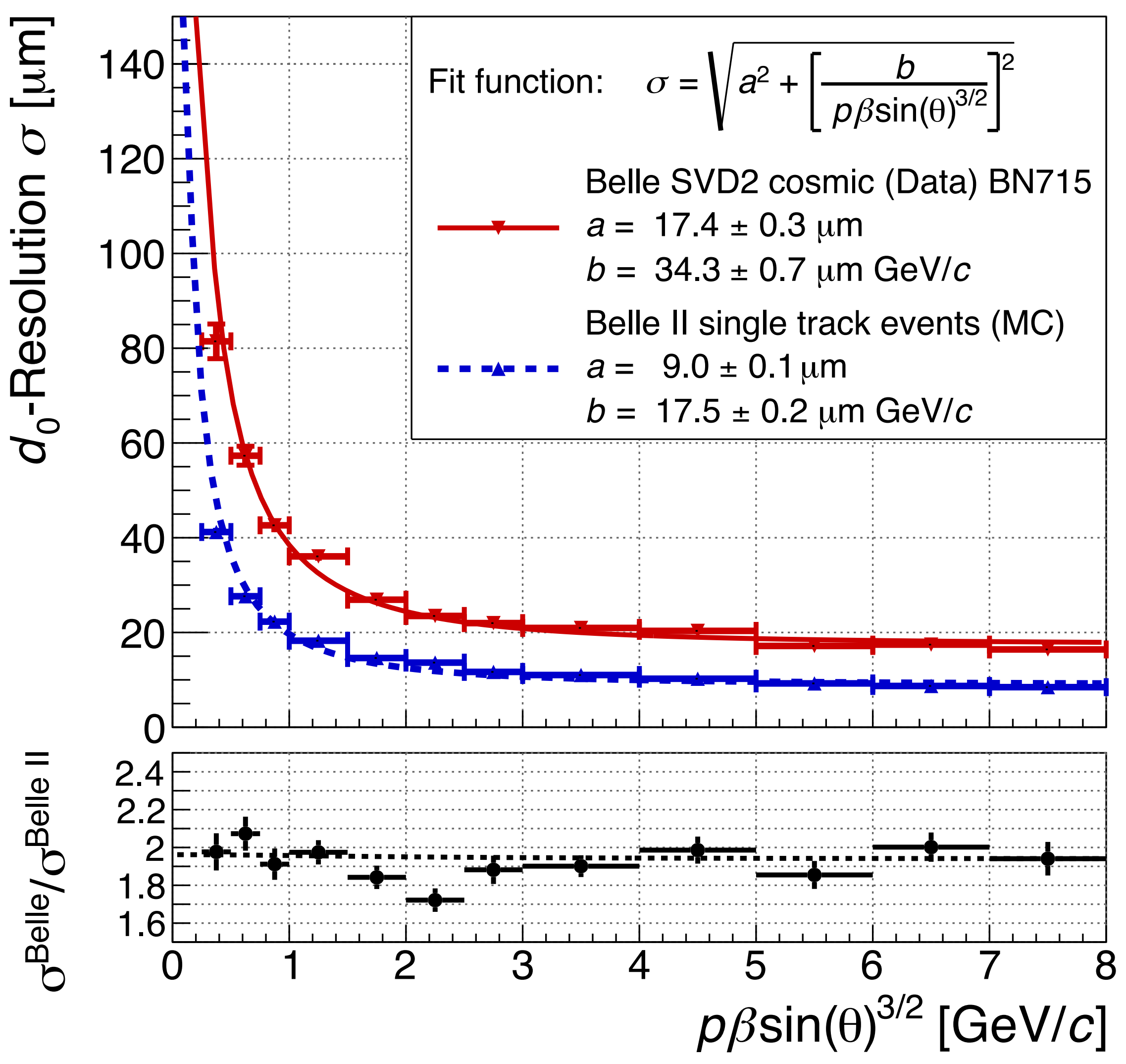
The vertex distribution is constrained in the nano-beam scheme.

Nano-Beam (SuperKEKB Phase2)

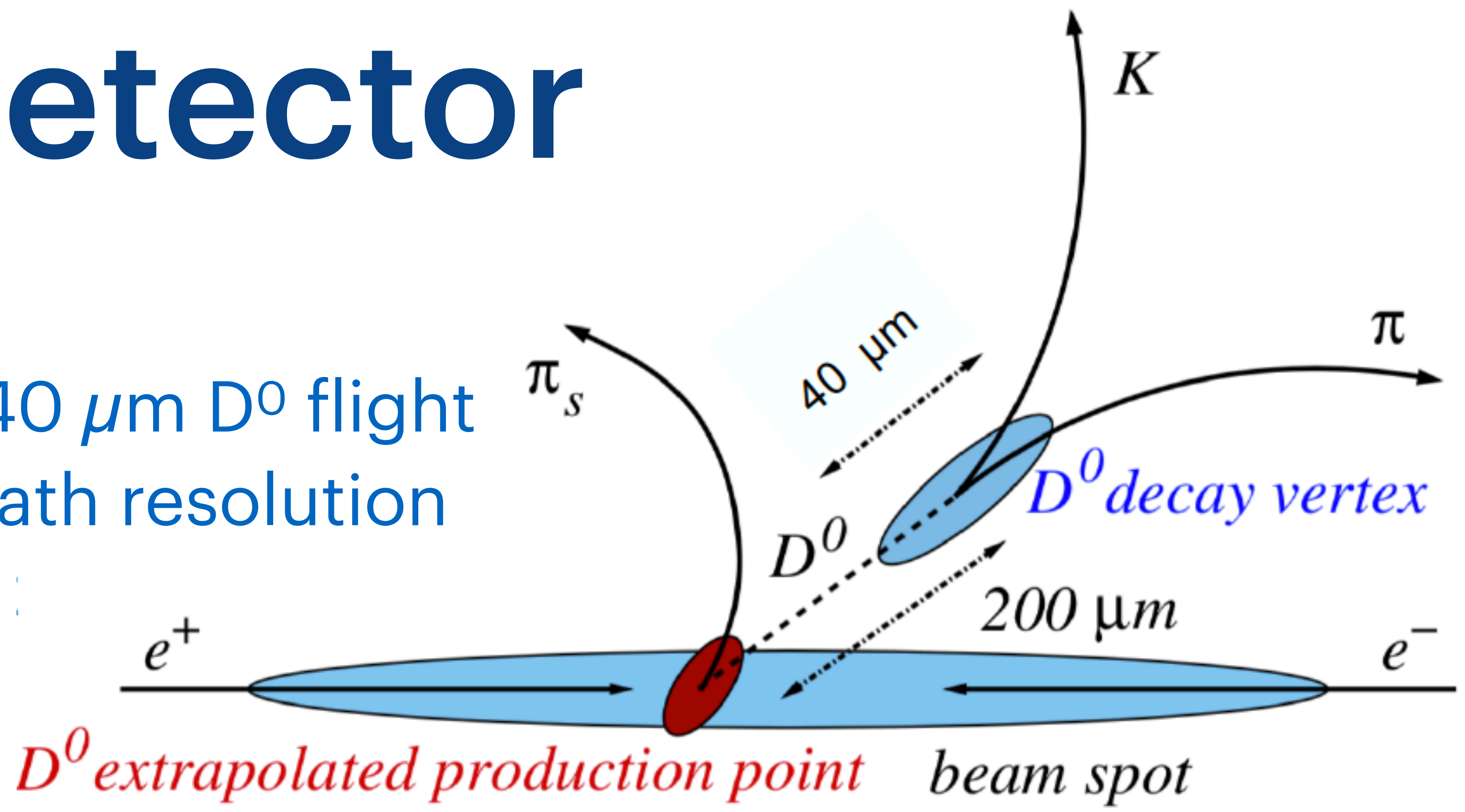


σ = 550 μm



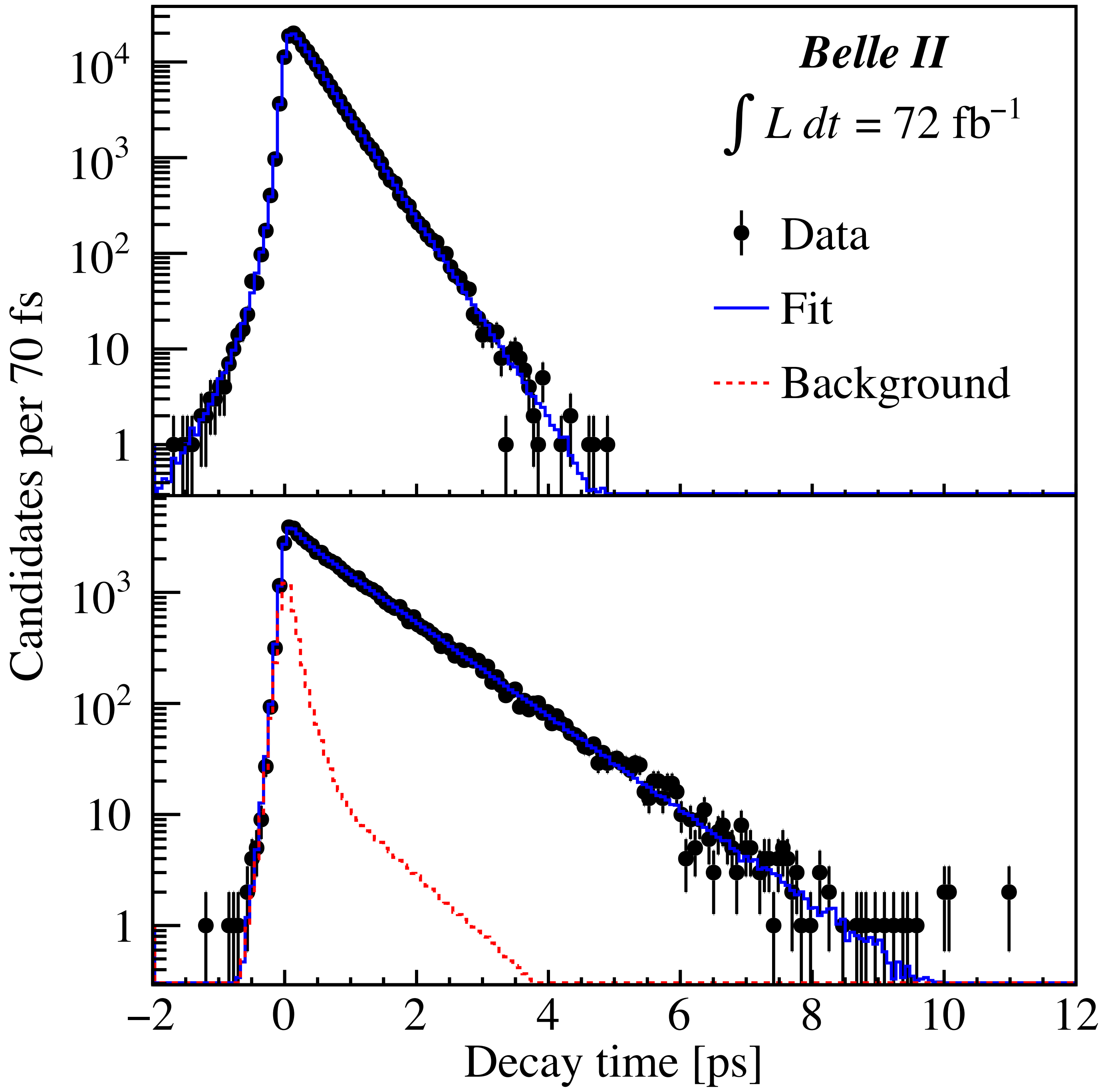


~ 40 μm D^0 flight path resolution



Belle II Phys.Rev.Lett. 127 (2021) 21, 211801

$$\tau(D^0) = 410.5 \pm 1.1\,(\text{stat}) \pm 0.8\,(\text{syst})\ \text{fs}$$
$$\tau(D^+) = 1030.4 \pm 4.7\,(\text{stat}) \pm 3.1\,(\text{syst})\ \text{fs}$$



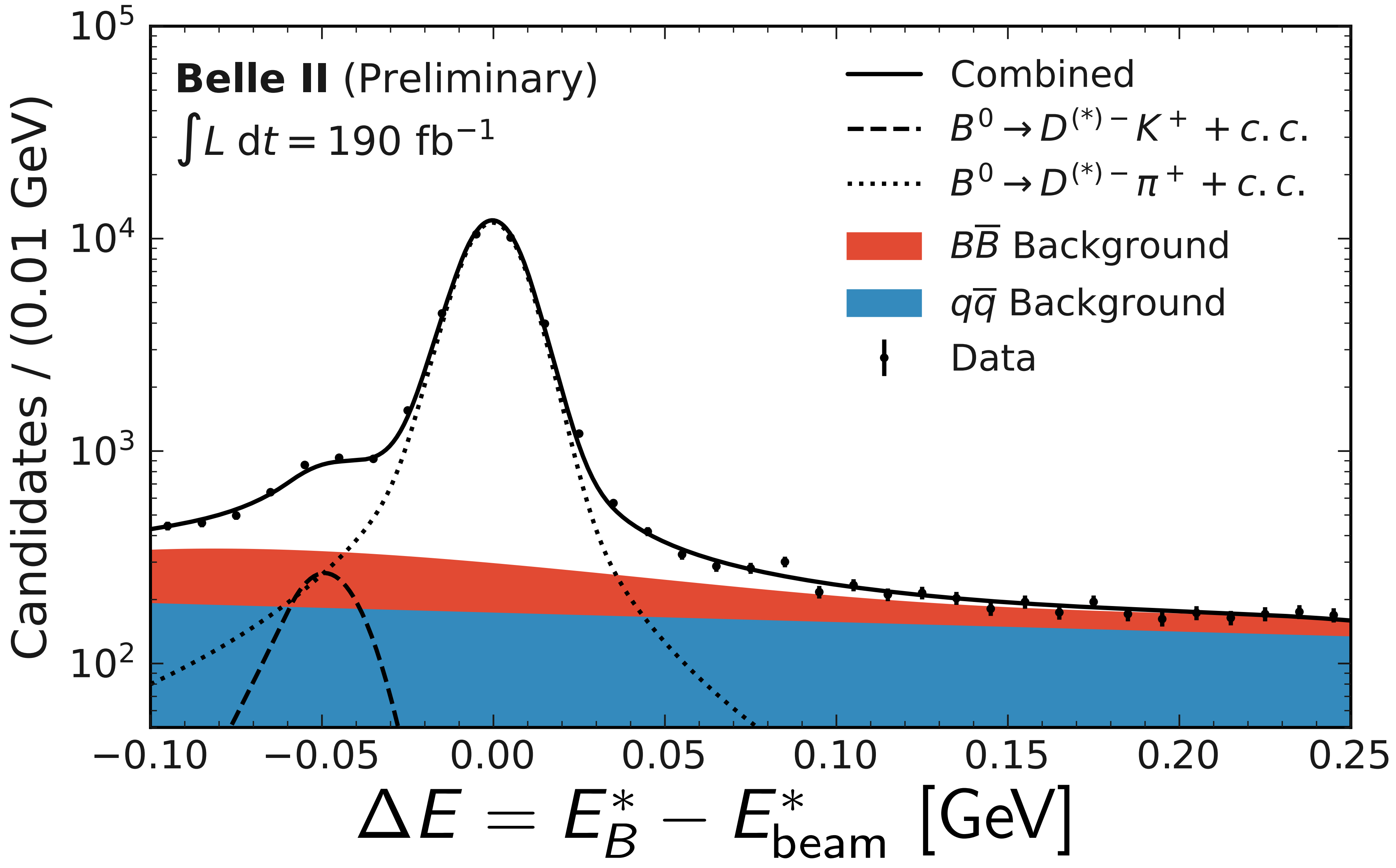
Mixing and lifetimes

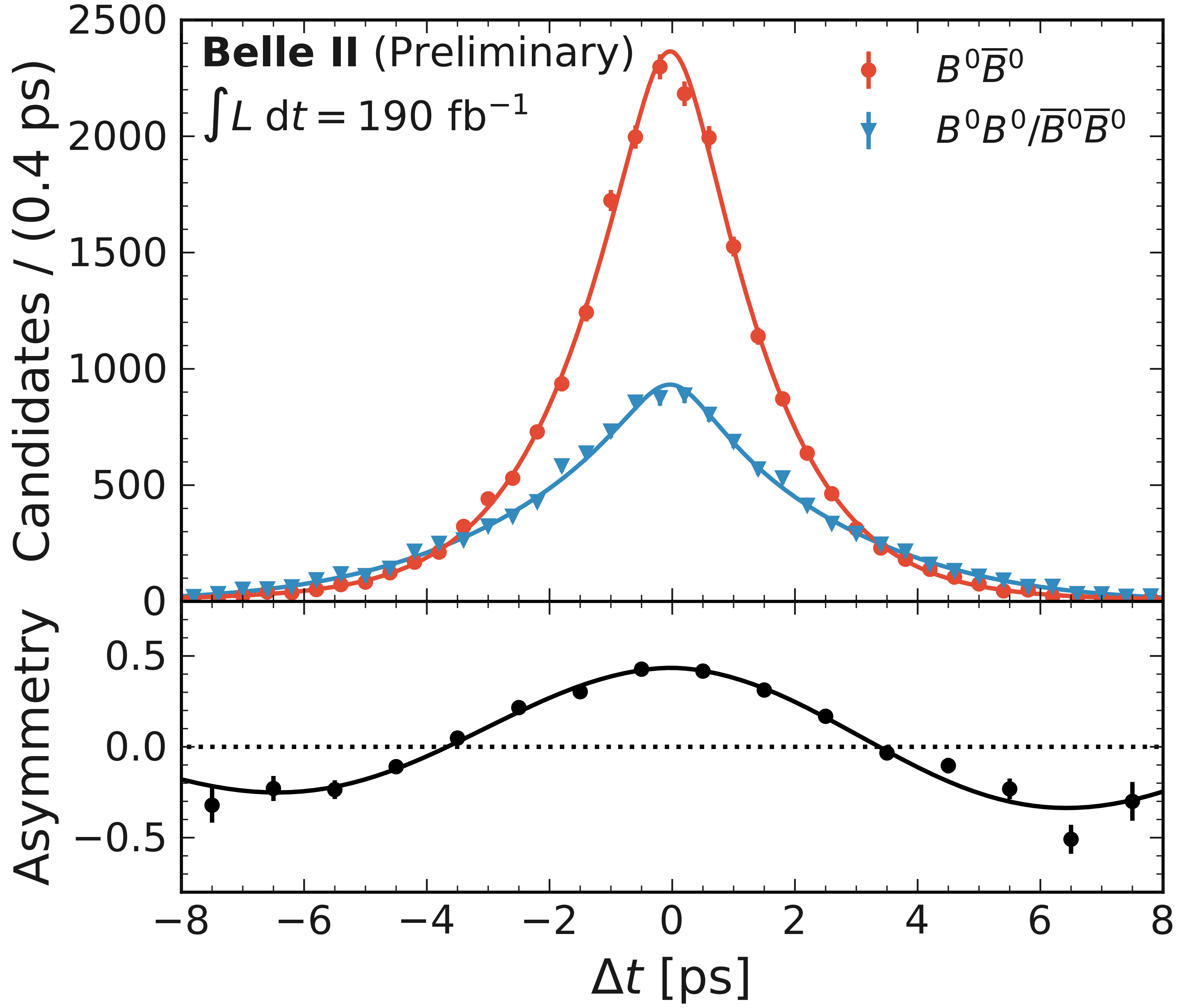
Belle II Preliminary

- Use about 40k decays reconstructed from hadronic $B \to D^{(*)}h^+$, $(h = K, \pi)$ channels.
- Compatible with WA. Slightly worse stat error than Belle as $B \to D^{(*)}\ell\nu$ not used here.
  - Better alignment and background systematics.
  - Prepared to tackle Φ_1.

$$\text{mix}(t) = \frac{N(B^0 \to B^0) - N(B^0 \to \overline{B}^0)}{N(B^0 \to B^0) + N(B^0 \to \overline{B}^0)}(t) = \cos(\Delta m_d t)$$

$$\tau_{B^0} = 1.499 \pm 0.013\,(\text{stat.}) \pm 0.008\,(\text{syst.})\ \text{ps},$$
$$\Delta m_d = 0.516 \pm 0.008\,(\text{stat.}) \pm 0.005\,(\text{syst.})\ \text{ps}^{-1}.$$





Time dependent measurement of $B \to K_S \pi^0$

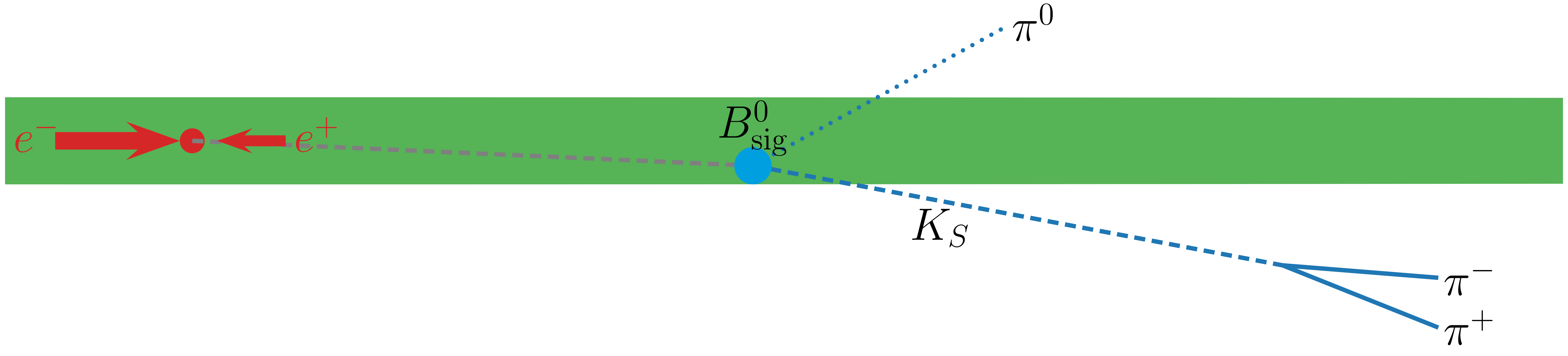
- Aim: Time-dependent study to measure the branching fraction and direct CP asymmetry for $B \to K_S^0 \pi^0$ decays.

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}[1 + q\{\mathcal{A}_{CP}\cos(\Delta m_d \Delta t) + \mathcal{S}_{CP}\sin(\Delta m_d \Delta t)\}]$$

- The isospin sum-rule is a precise null test, but depends crucially on precision in this channel.

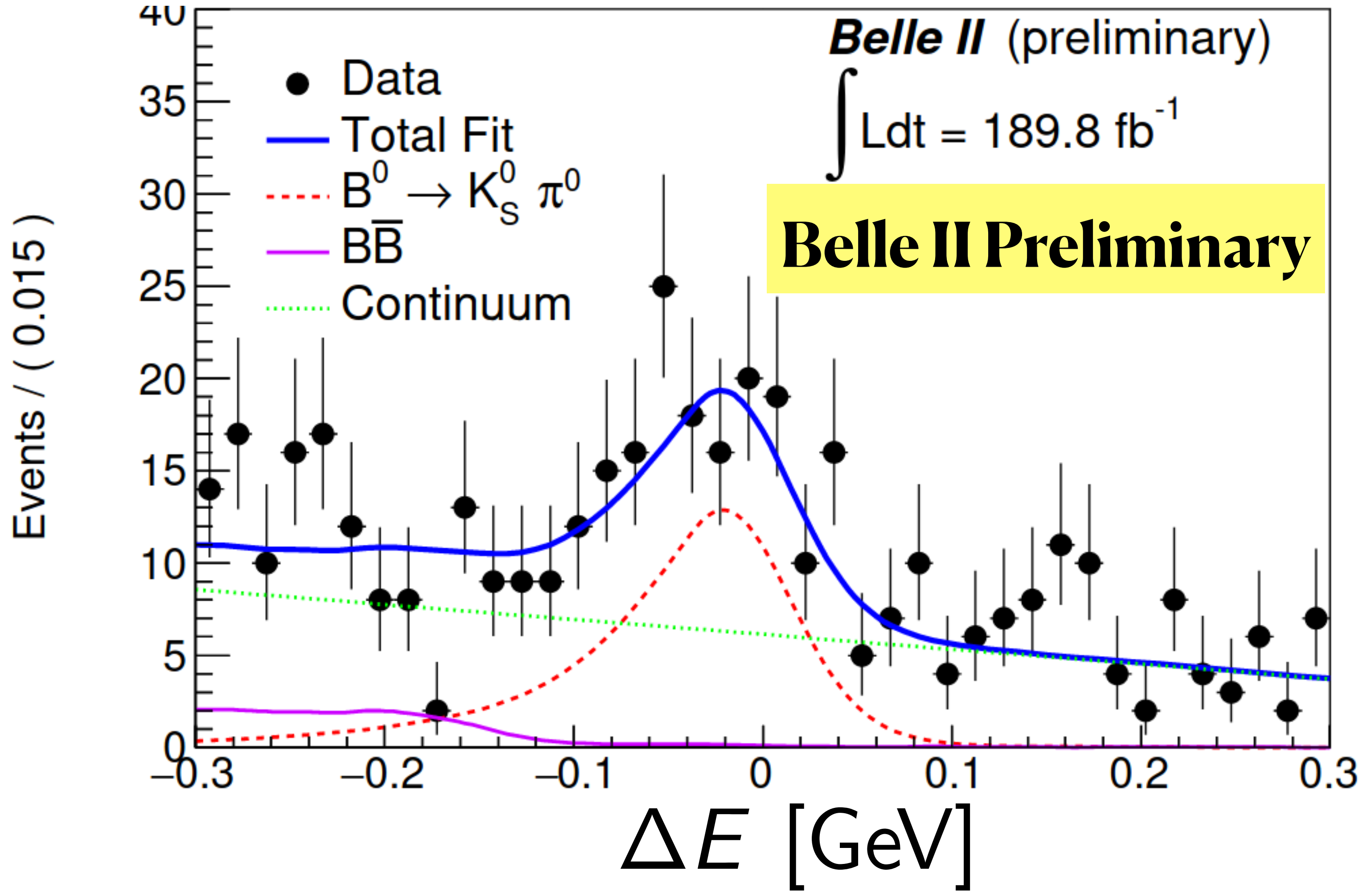
$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)} = 0$$

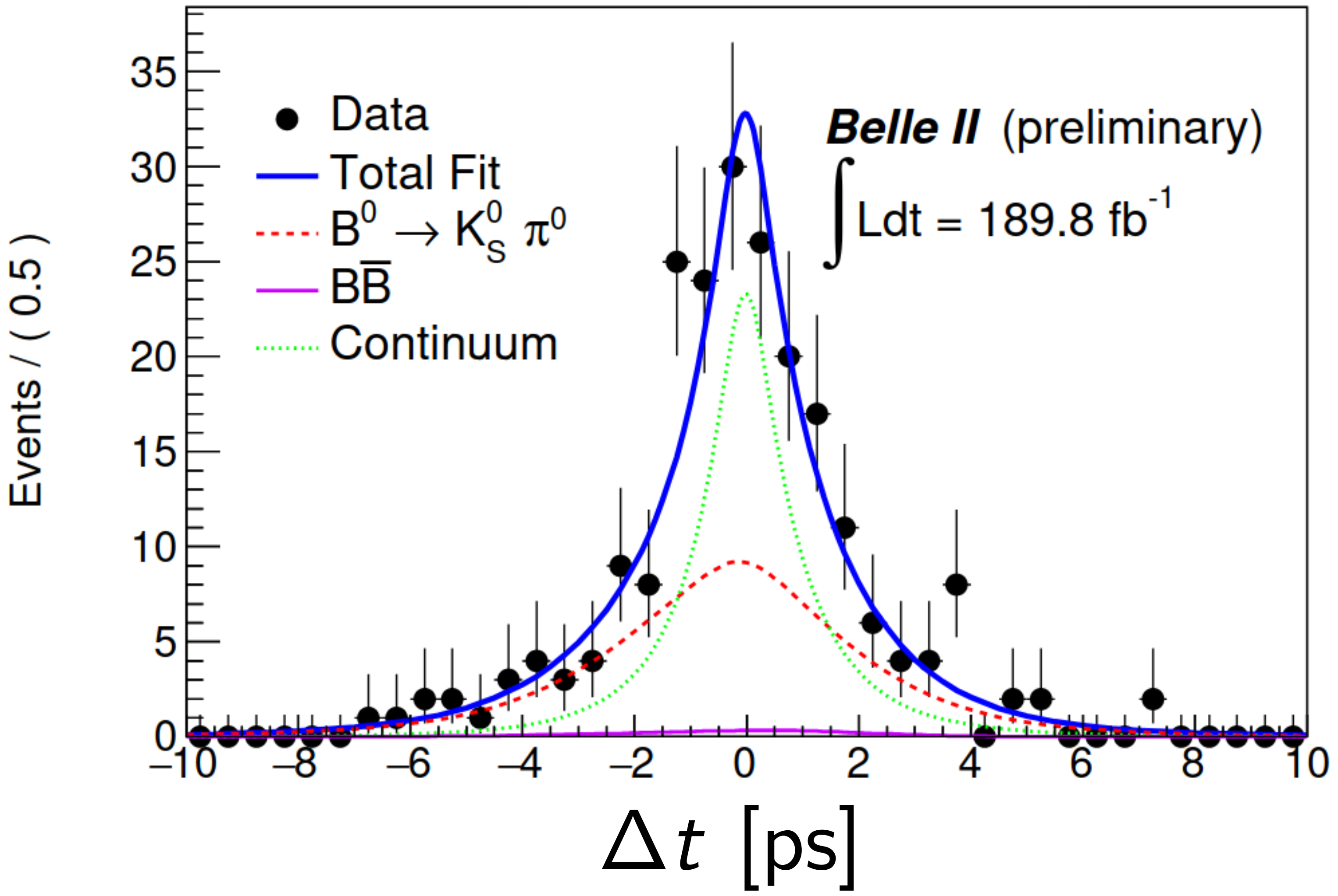
- Time dependent study very challenging with neutrals.



$$A_{CP} = -0.41^{+0.30}_{-0.32}\,(\text{stat.}) \pm 0.09\,(\text{syst.})$$

$$\mathcal{B} = (11.0 \pm 1.2\,(\text{stat.}) \pm 1.0\,(\text{syst.})) \times 10^{-6}$$

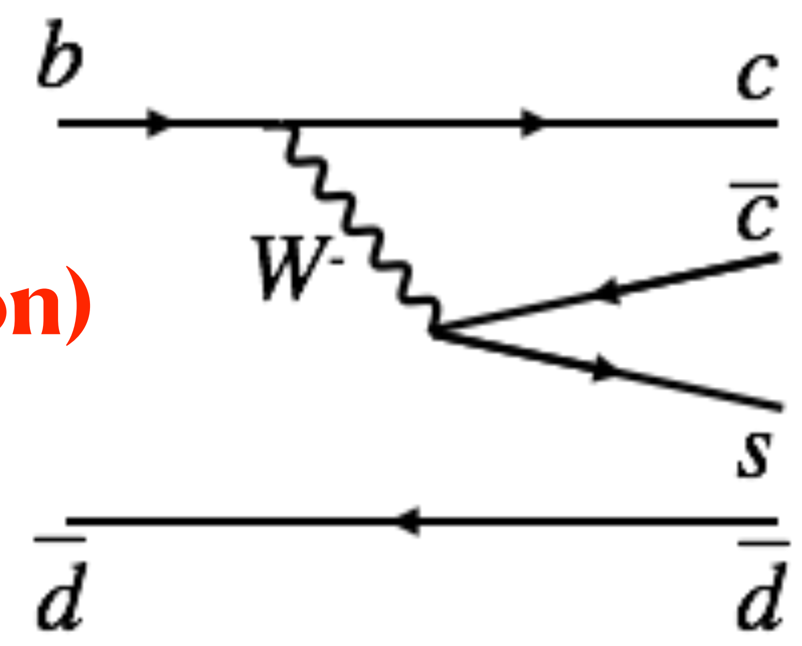




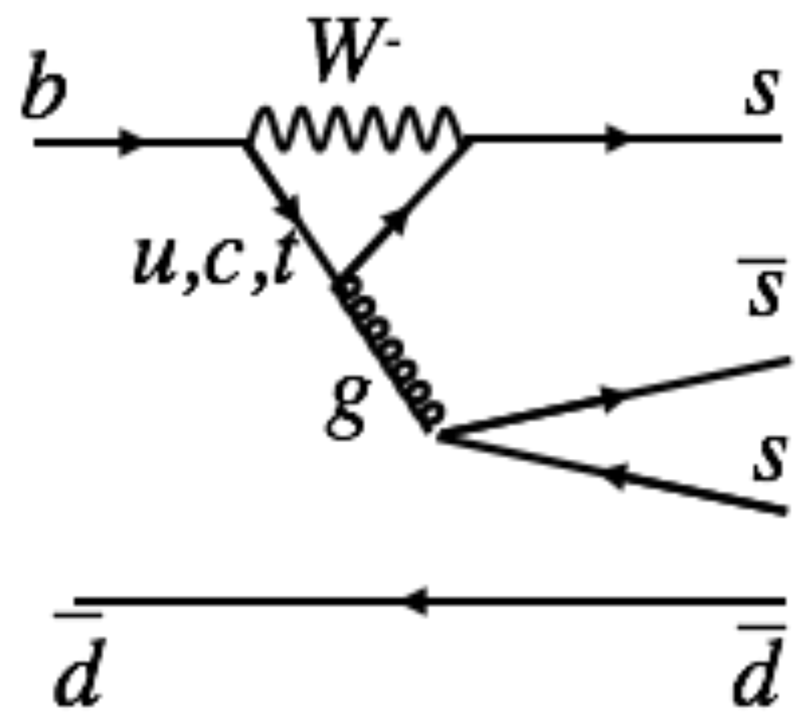
Time dependent CP Violation Future

- Φ_1 & New physics TDCPV in b → qqs transitions (q = u,d,s) are major targets
- Δt resolution ~0.77 ps (30% to a factor 2 better than Belle);

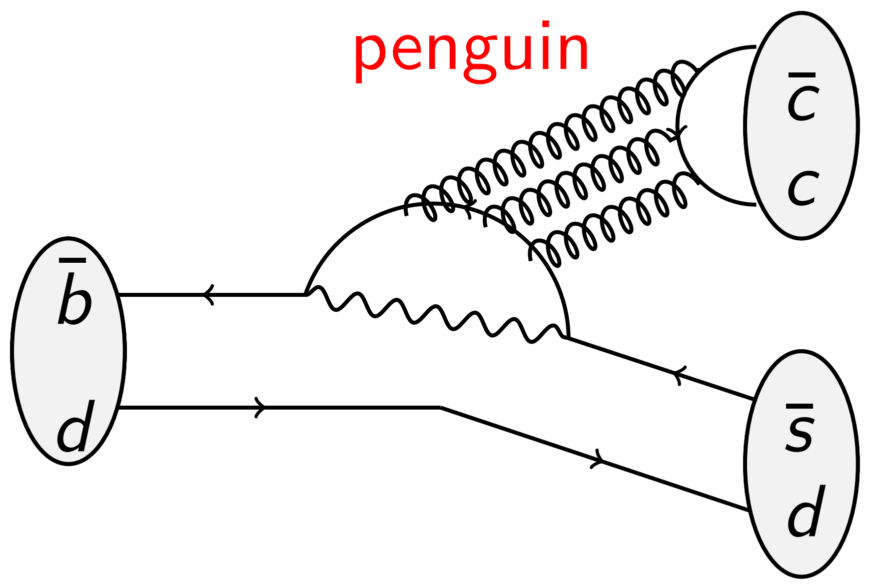
Tree (SM precision)



Gluonic Penguin (NP sensitive)



Constrains penguin pollution



	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
ϕK^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
ωK_S^0	0.21	0.14	0.08	0.06	0.024	0.020
$K_S^0 \pi^0 \gamma$	0.20	0.12	0.10	0.07	0.031	0.021
$K_S^0 \pi^0$	0.17	0.10	0.09	0.06	0.028	0.018

PTEP 2019 (2019) 12, 123C01

SM

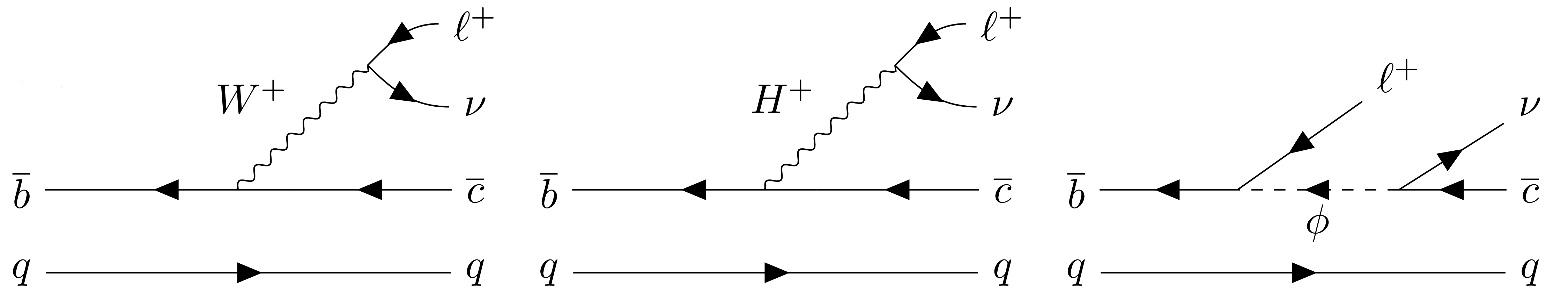
NP

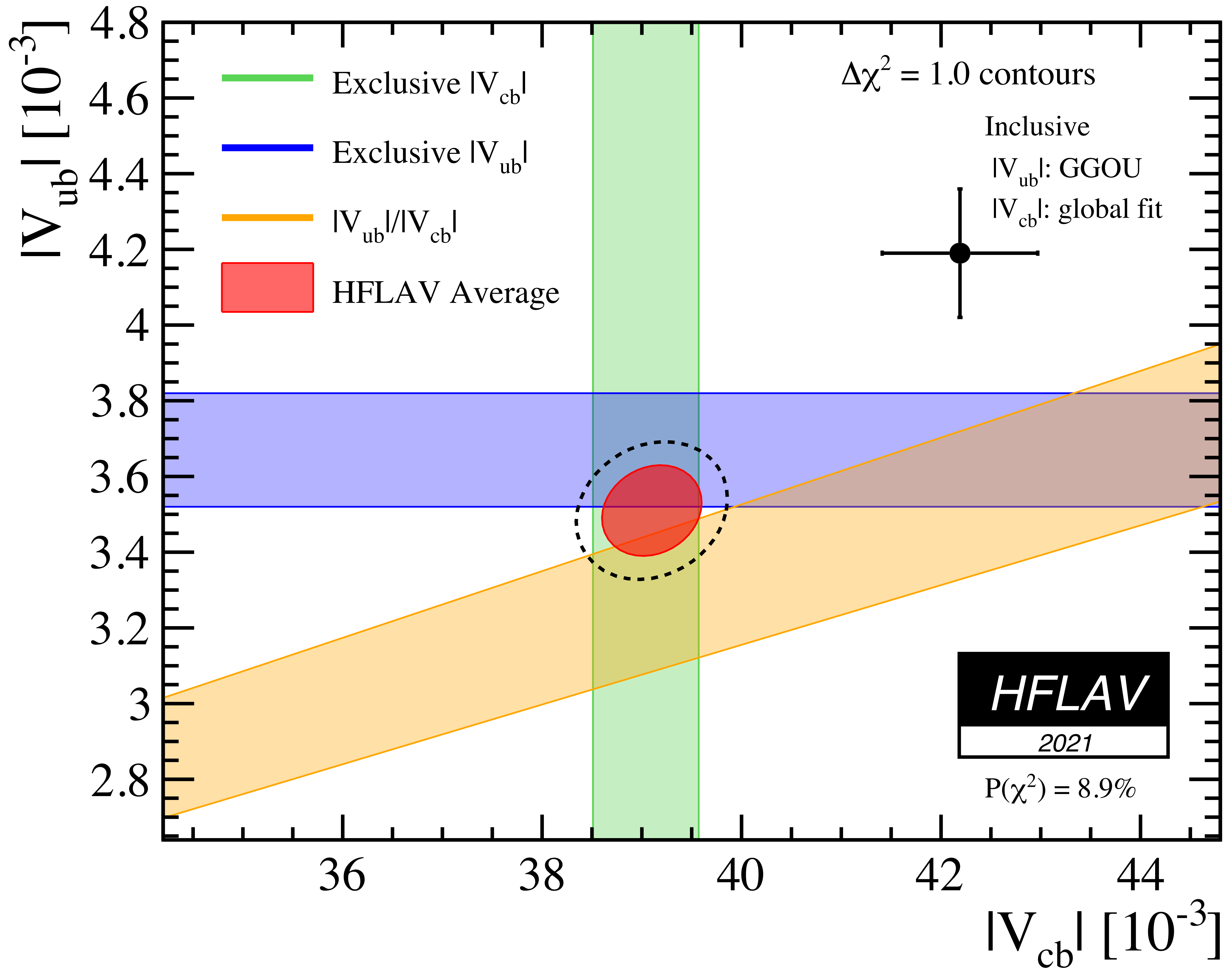
Expect Belle II to dominate all these channels

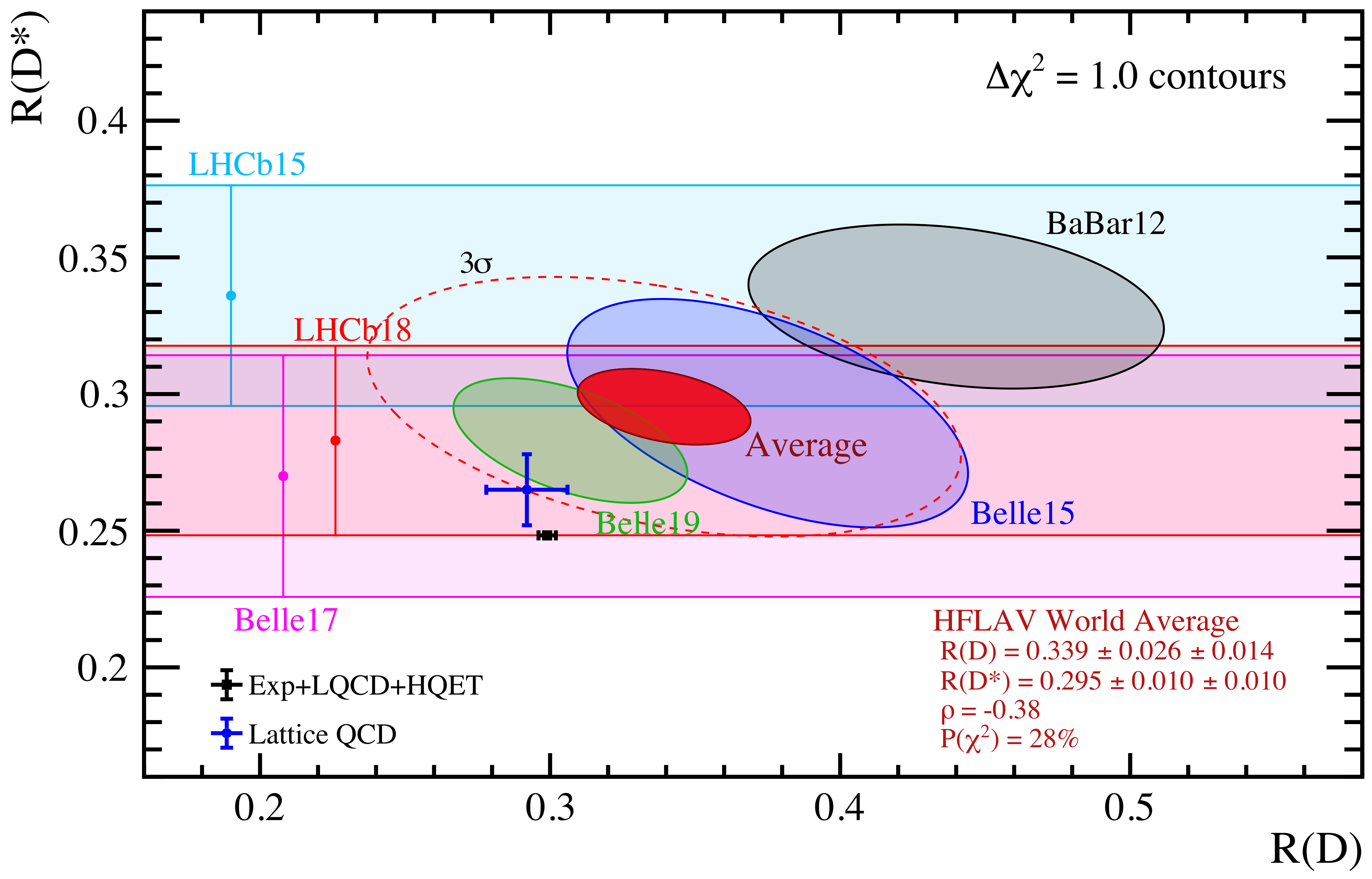
Leptonic and semileptonic Tree Decays

$|V_{ub}|$, Leptonic, LFUV

Semileptonic B decays







- Discrepancy between exclusive and inclusive.
- Persistent, but diminishing LFUV results.

Flavour physics anomalies

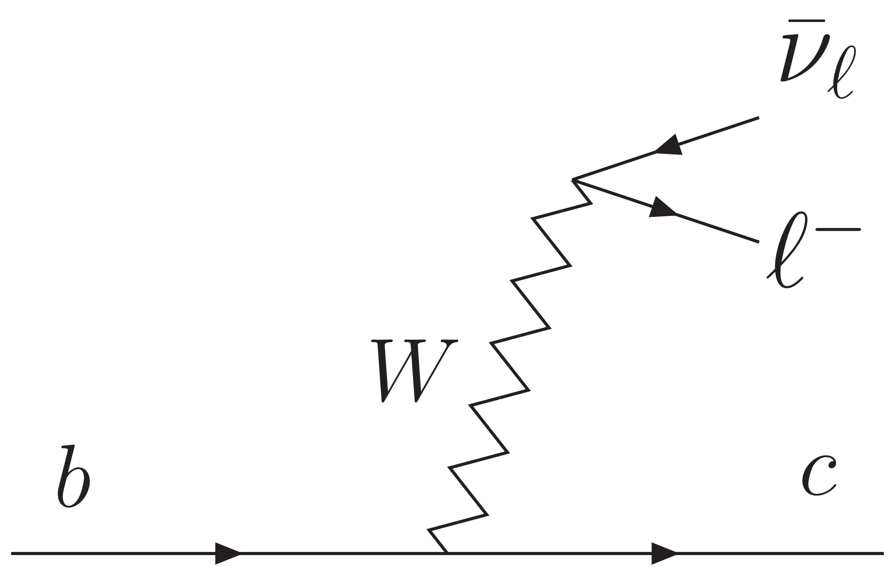
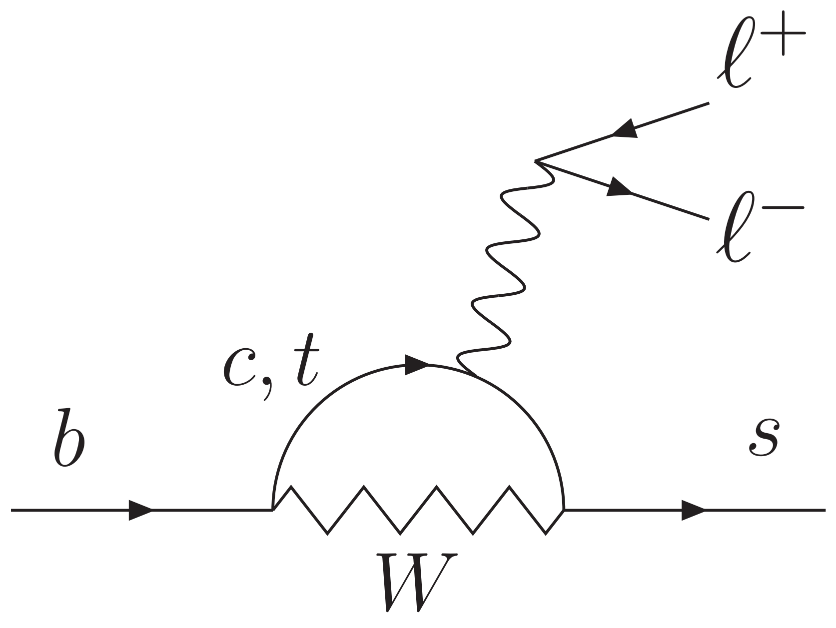
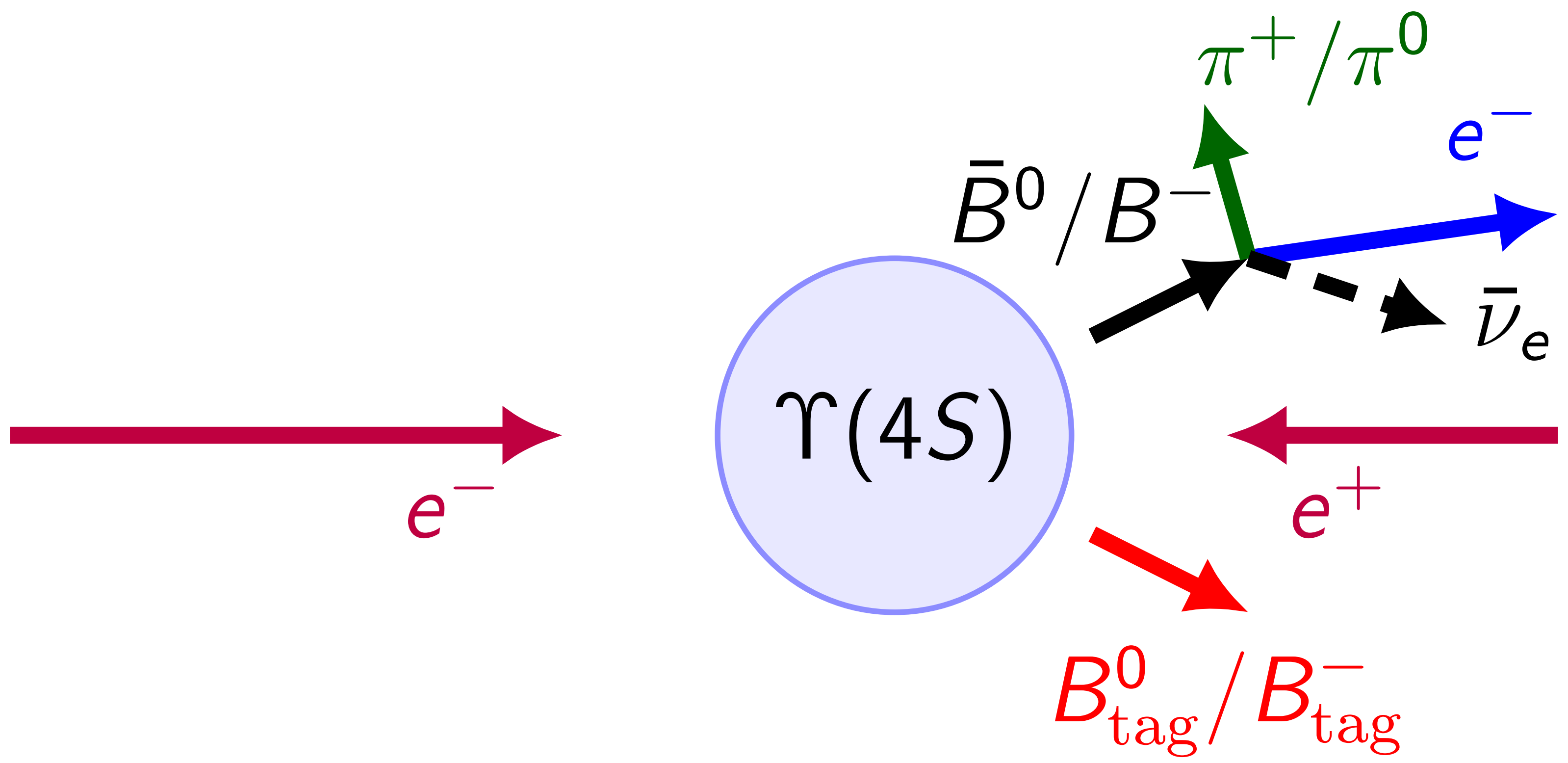
	$b \to c\ell\bar{\nu}_\ell$	$b \to s\ell^+\ell^-$
		
SM	tree (charged) $(V - A)$	loop (neutral)
Spin 0	$\overline{B} \to D\ell\bar{\nu}_\ell$	$B \to K\ell\ell$
Spin 1	$\overline{B} \to D^*\ell\bar{\nu}_\ell$	$B \to K^*\ell\ell$, $B_s \to \phi\ell\ell$
Observables	BR, Polarisation	$d\Gamma/dq^2$ + Angular obs
with	$\ell = \tau, \mu, e$	$\ell = \mu, e$
Tensions	$R_{D(*)} = \frac{Br(B \to D(*)\tau\nu)}{Br(B \to D(*)\ell\bar{\nu}_\ell)}$ $\lvert V_{cb}\rvert$ & $\lvert V_{ub}\rvert$ inclusive-exclusive tension	$R_K = \frac{Br(B \to K\mu\mu)}{Br(B \to Kee)}$ $Br\ (K, K^*, \phi + \mu\mu)$ angular obs (e.g., P_5')

Table from S. Descotes-Genon

Measuring the CKM matrix element $|V_{ub}|$



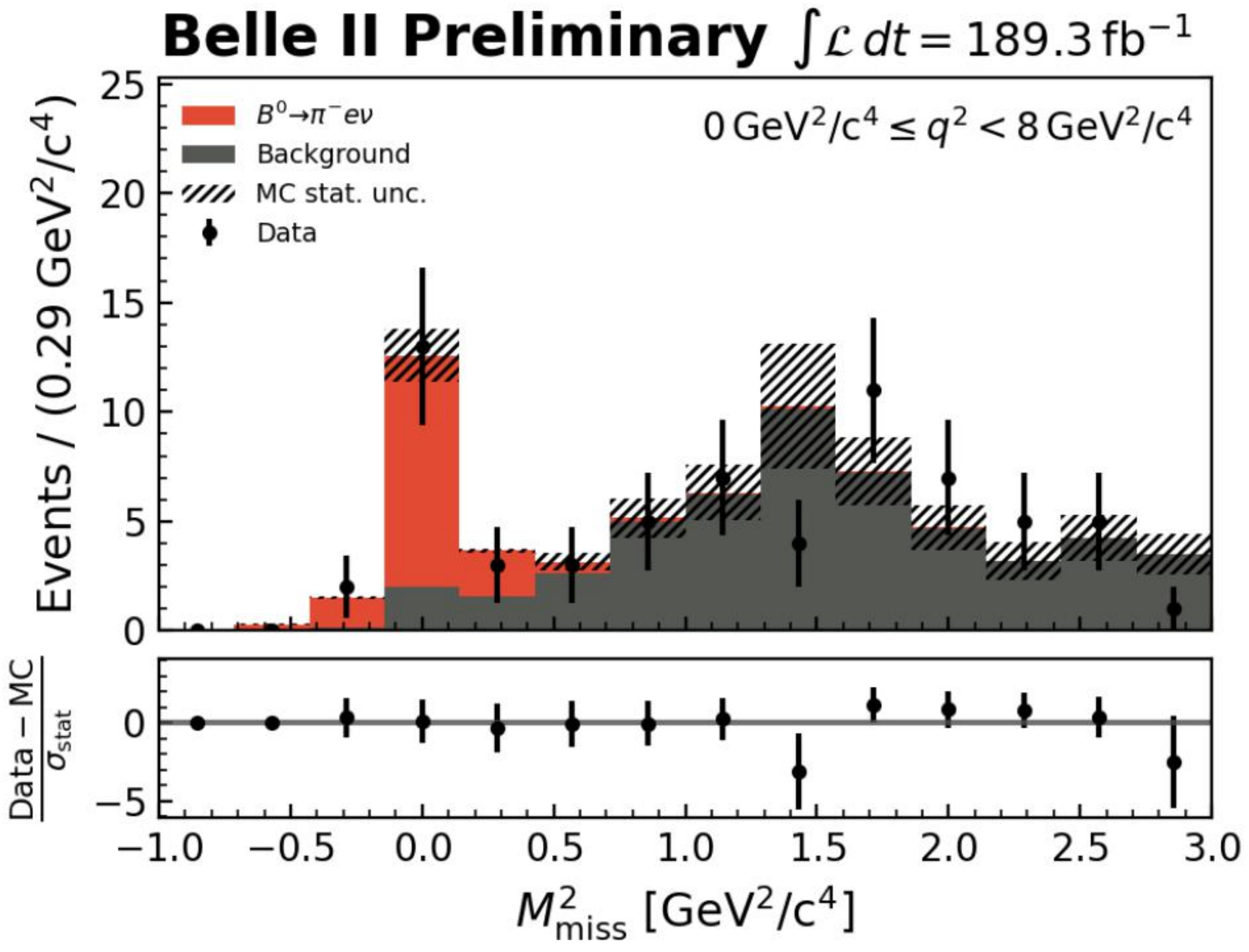
- Reconstruct $B \to \pi e \bar{\nu}_e$.

Belle II Preliminary

- Perform likelihood fit to missing mass squared in bins of q^2.

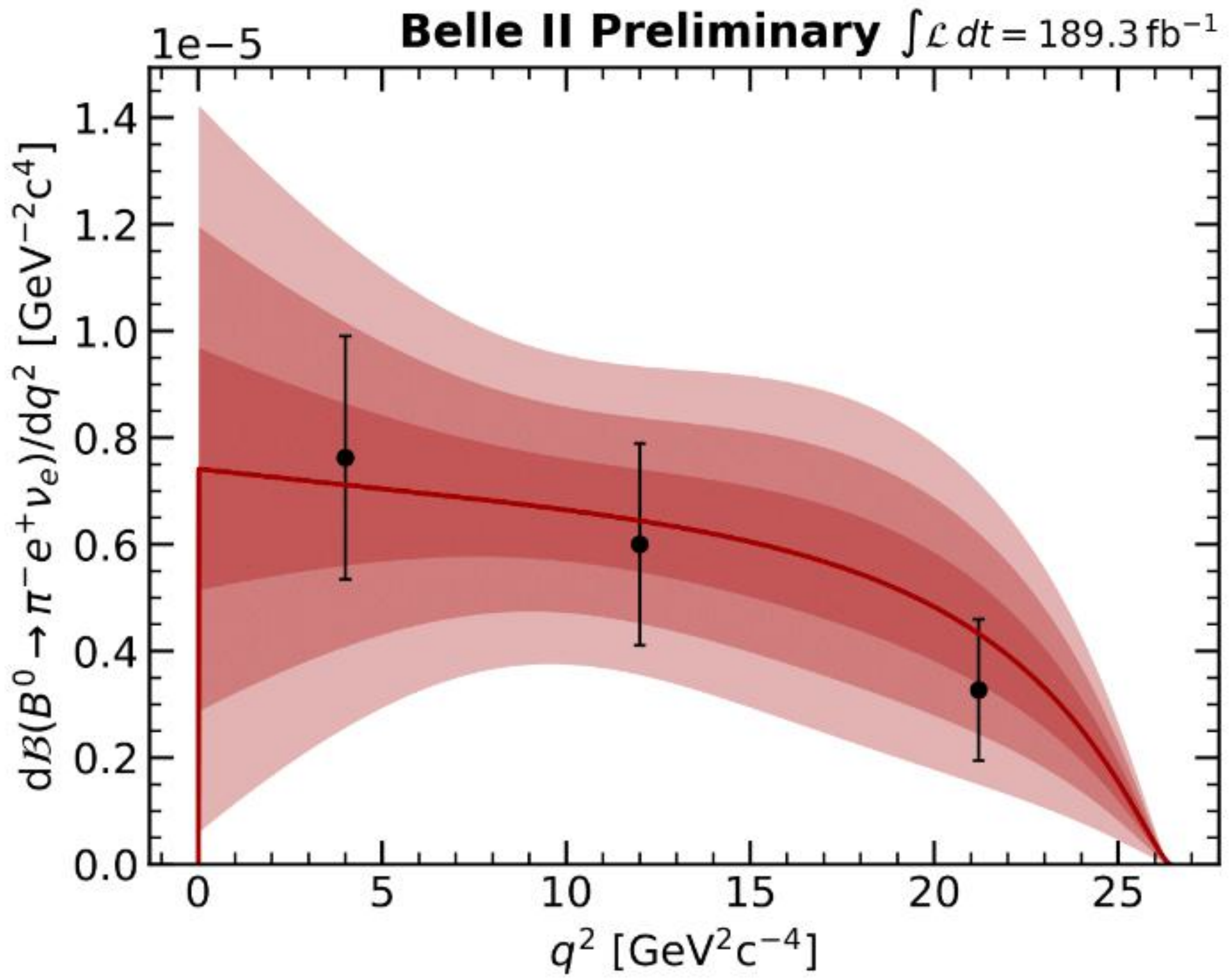
$$q^2 = m^2_{\ell\nu} = (p_{e^+e^-} - p_{B_{\text{tag}}} - p_\pi)^2$$

$$\frac{d\mathcal{B}}{dq^2}(B \to \pi\ell\nu) \propto |V_{ub}|^2 f_+^2(q^2)$$



$$M^2_{\text{miss}} = (p_{e^+e^-} - p_{B_{\text{tag}}} - p_e - p_\pi)^2$$

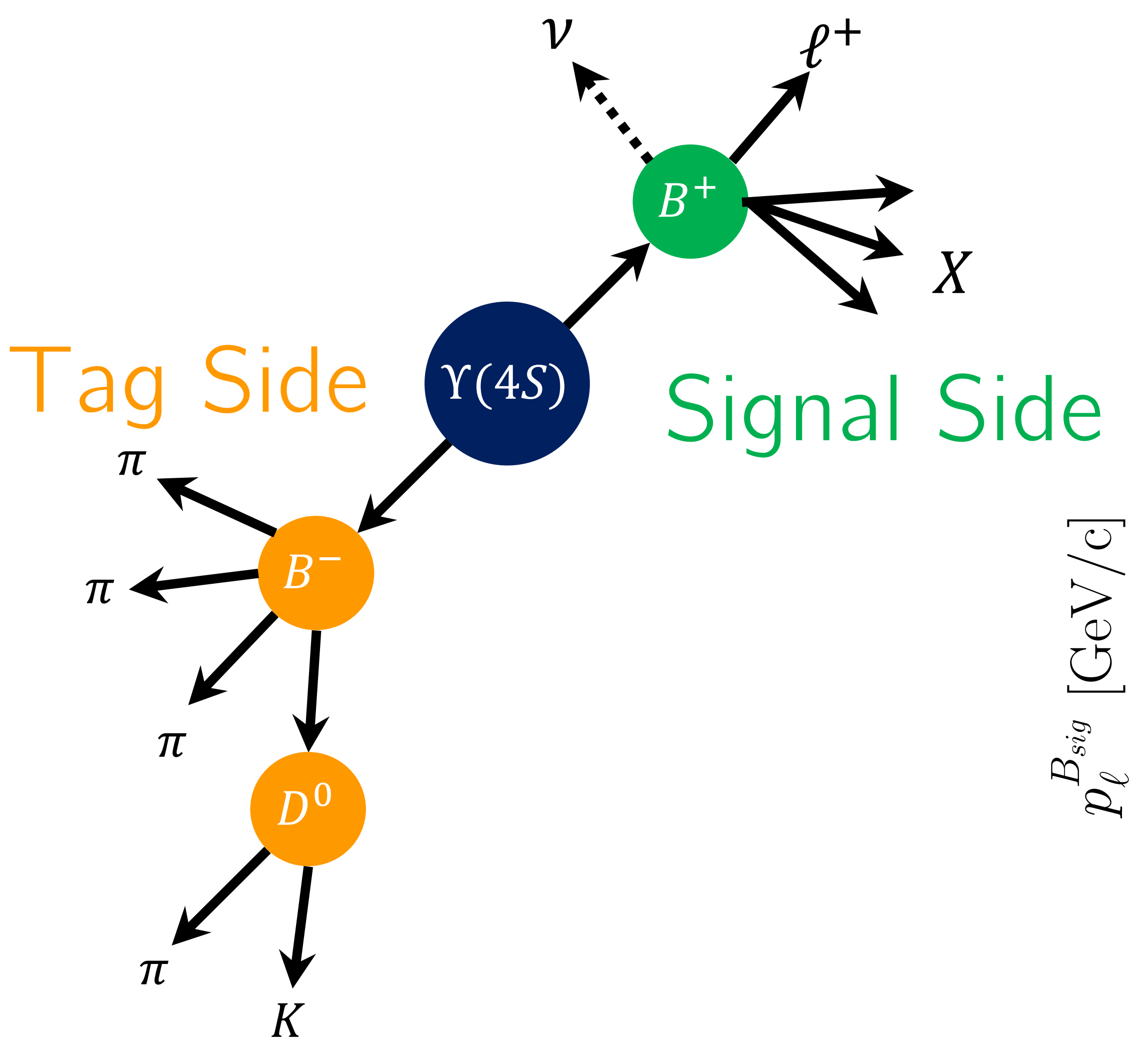
- Second fit performed to $d\Gamma/dq^2 \propto f_+^2(q^2)\,|V_{ub}|^2$ from data and LQCD (FNAL-MILC) with BCL (z-expansion) parameterisation.



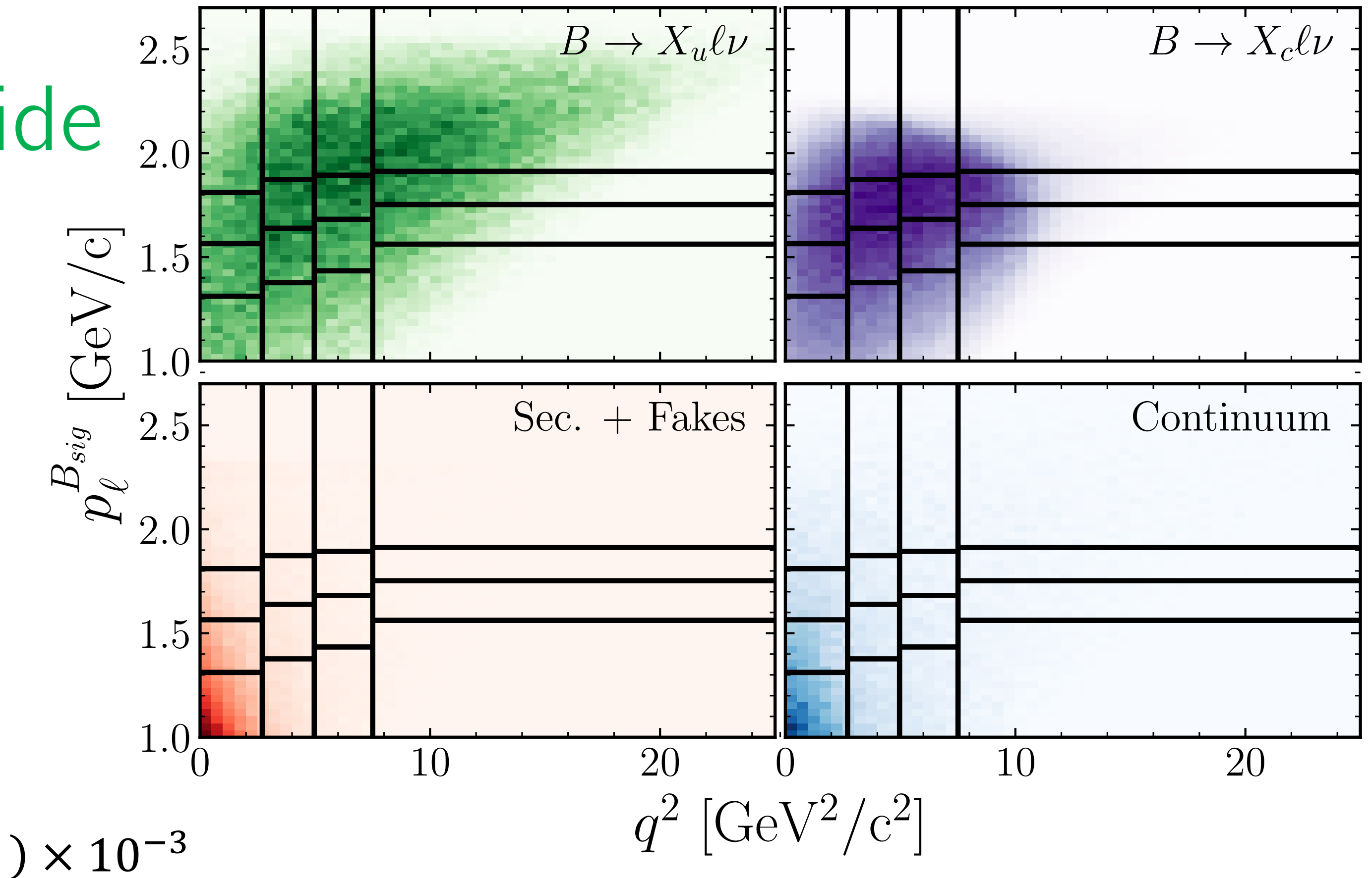
Decay mode	Fitted $\lvert V_{ub}\rvert$
$B^0 \to \pi^- e^+ \nu_e$	$(3.71 \pm 0.55)\ \times 10^{-3}$
$B^+ \to \pi^0 e^+ \nu_e$	$(4.21 \pm 0.63)\ \times 10^{-3}$
Combined fit	$(3.88 \pm 0.45)\ \times 10^{-3}$

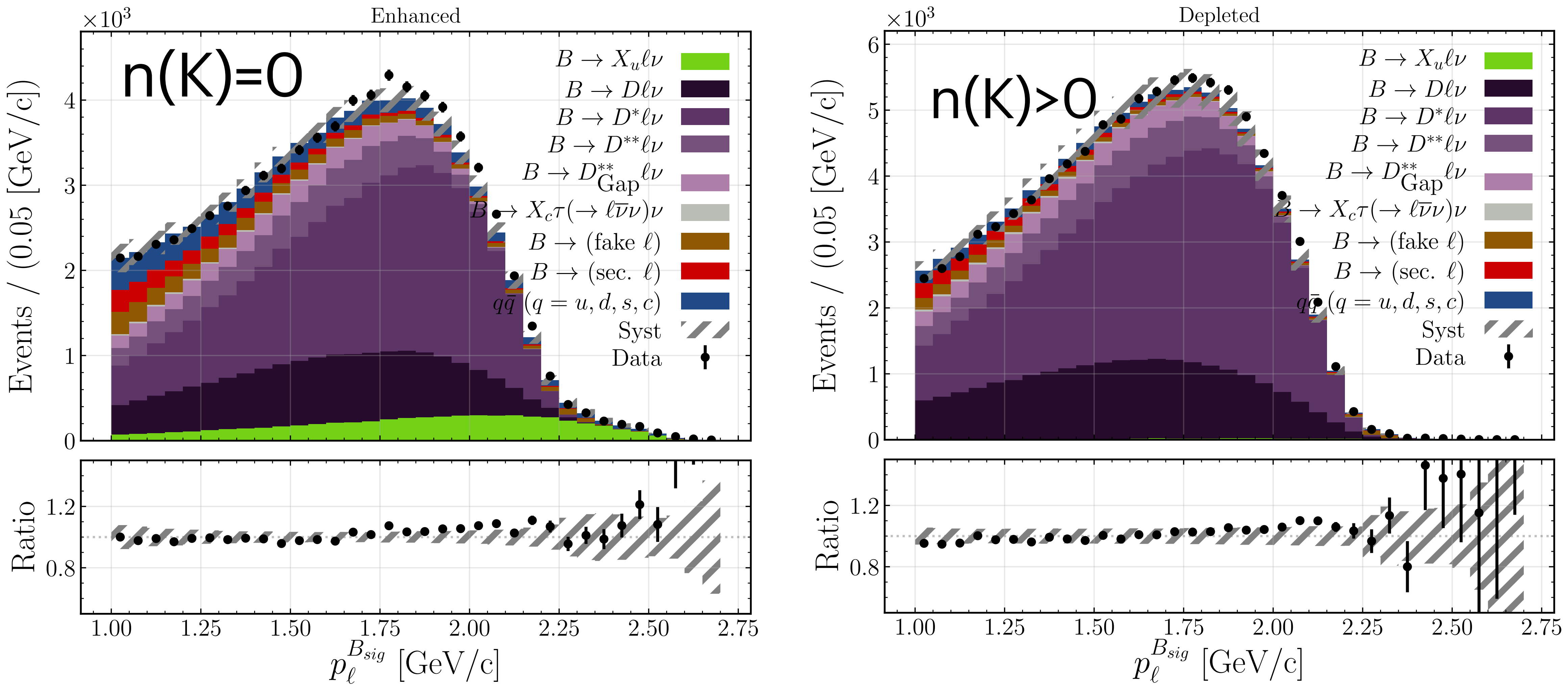
Inclusive $|V_{ub}|/|V_{cb}|$

- Belle analysis with Belle II software and B-tag framework.
  - Ratio measured to cancel systematics.
- Require very M^2_{miss} to be small, and Kaon veto.
- Background $B \to X_c \ell \nu$ model corrected using veto sample.



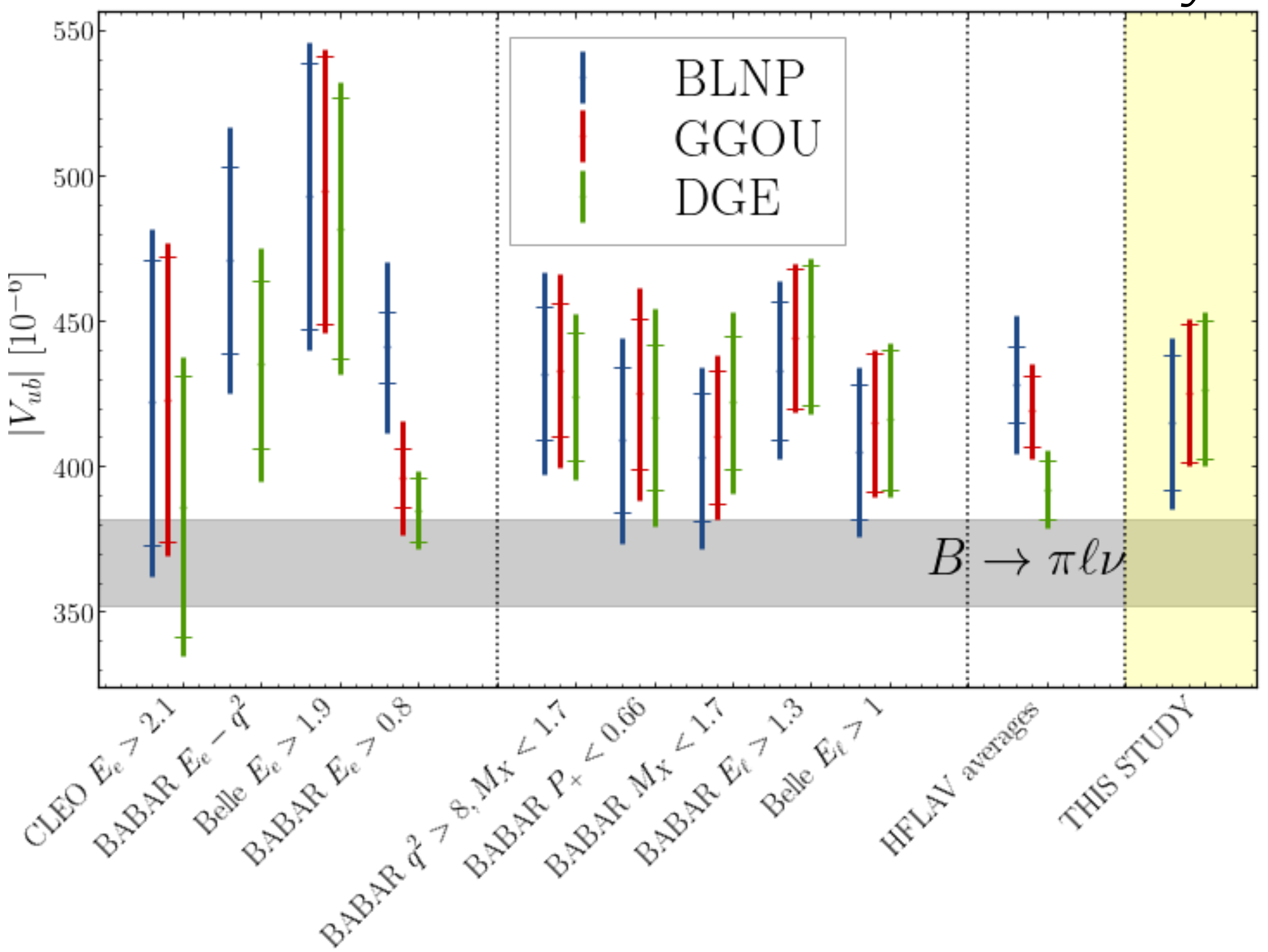
Belle arXiv:2102.00020
Belle Preliminary





$|V_{ub}|^{GGOU} = (4.25 \pm 0.18 \pm 0.16\ ^{+0.09}_{-0.09}) \times 10^{-3}$
$|V_{ub}|^{BLNP} = (4.15\ \pm 0.17 \pm 0.15\ ^{+0.18}_{-0.20}) \times 10^{-3}$
$|V_{ub}|^{DGE} = (4.26\ \pm 0.18 \pm 0.16\ ^{+0.11}_{-0.13}) \times 10^{-3}$

Belle *Preliminary*



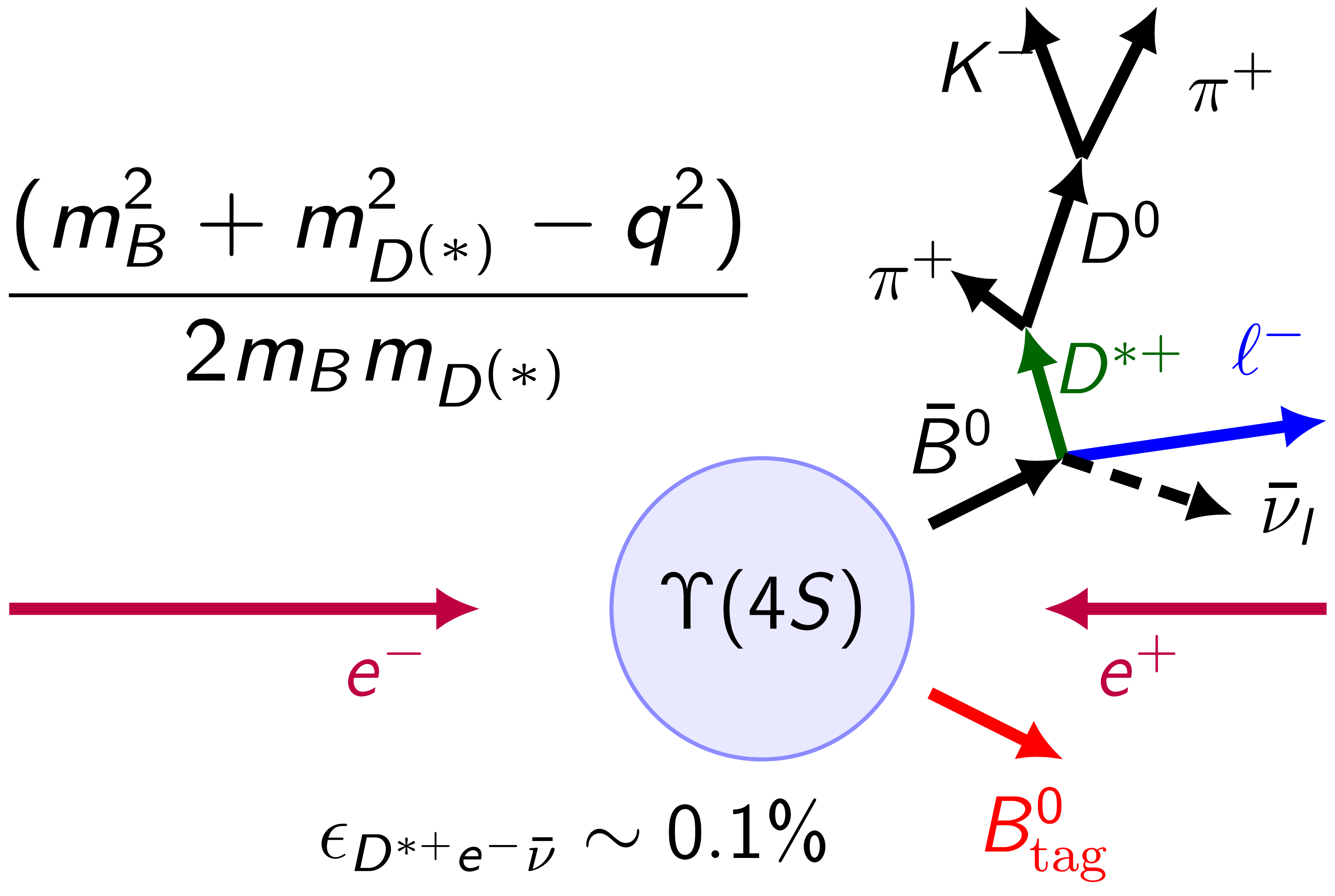
- Fit performed to q² and lepton momentum to determine $\mathcal{B}(B \to X_u \ell \nu)/\mathcal{B}(B \to X_c \ell \nu)$.
  - Lowest systematic error of any measurement - excellent technique for large Belle II data sets.

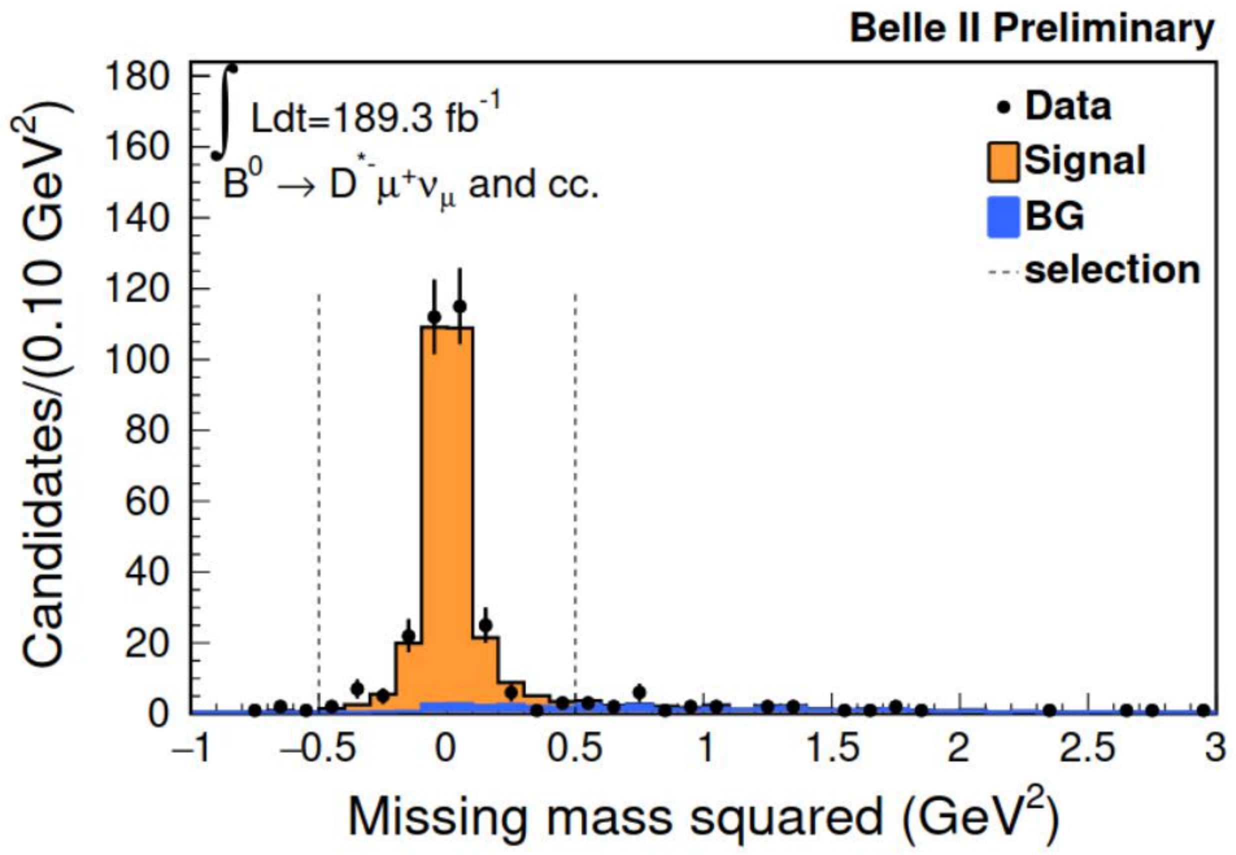
Measuring the CKM matrix element $|V_{cb}|$

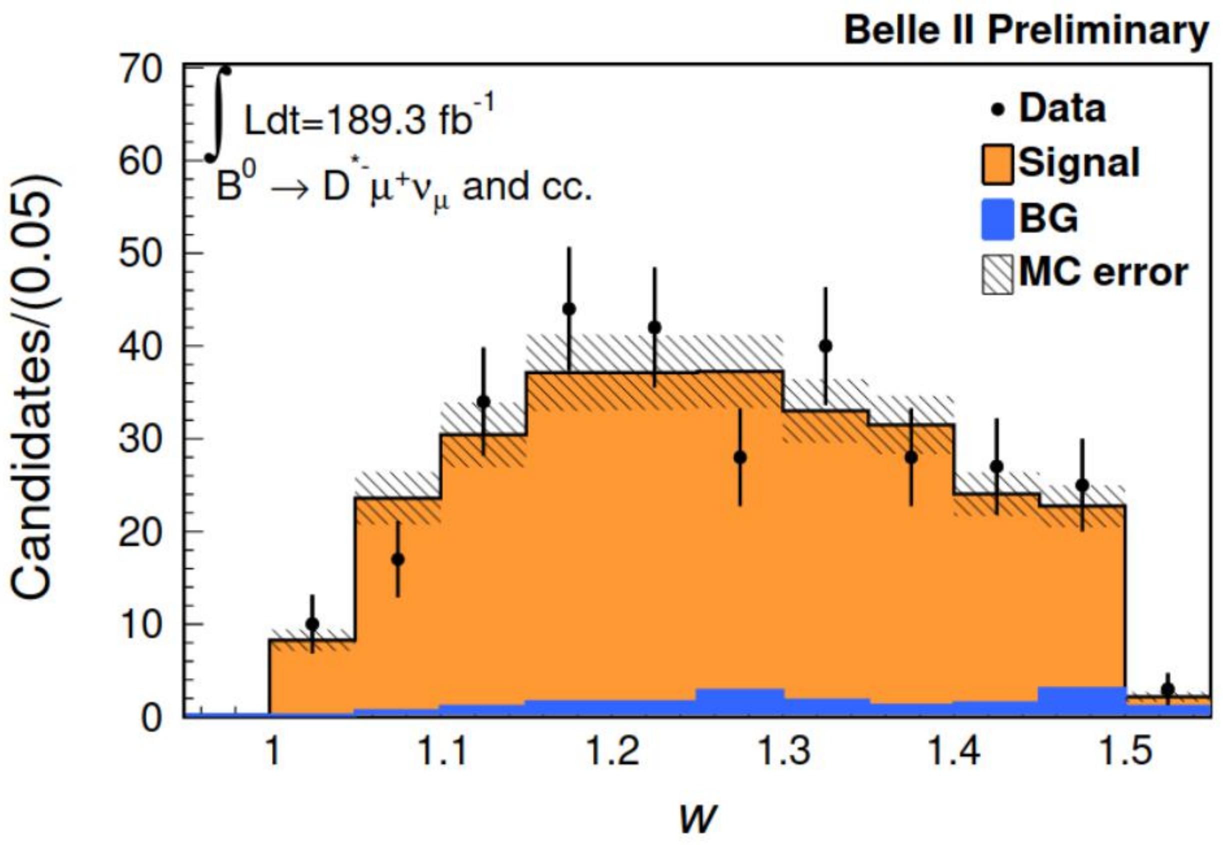
- Reconstruct decay chain $B^0 \to D^{*-}[\bar{D}^0(\to K^+\pi^-)\pi_s^-]\ell^+\nu_\ell$.
  - Candidate selection based on M^2_{miss}, $m(D) - m(D^*)$, $m(D)$.
  - Key challenge: detection of π_s from the D^*.

Belle II Preliminary

$$w = \frac{(m_B^2 + m_{D^{(*)}}^2 - q^2)}{2 m_B m_{D^{(*)}}}$$



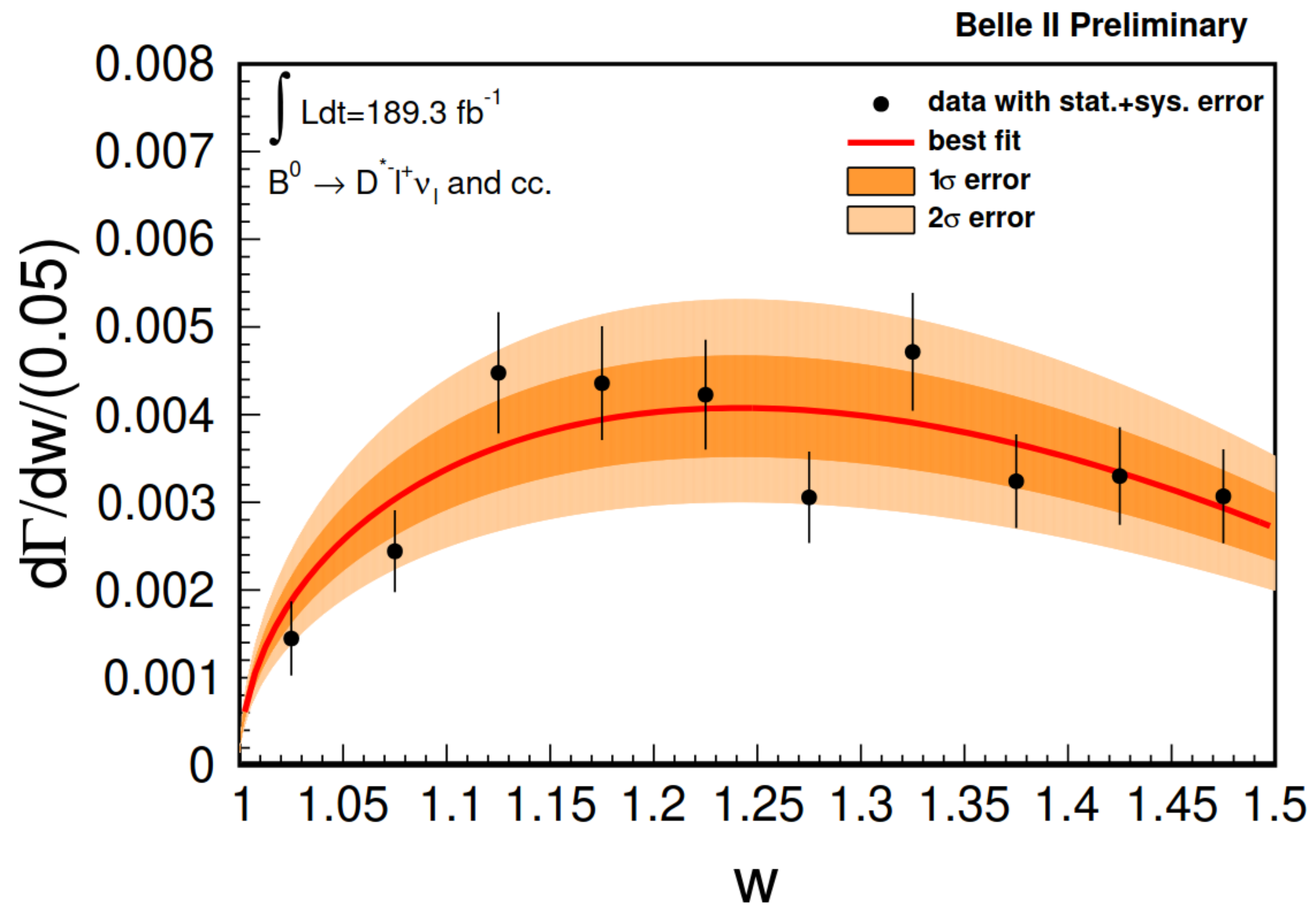


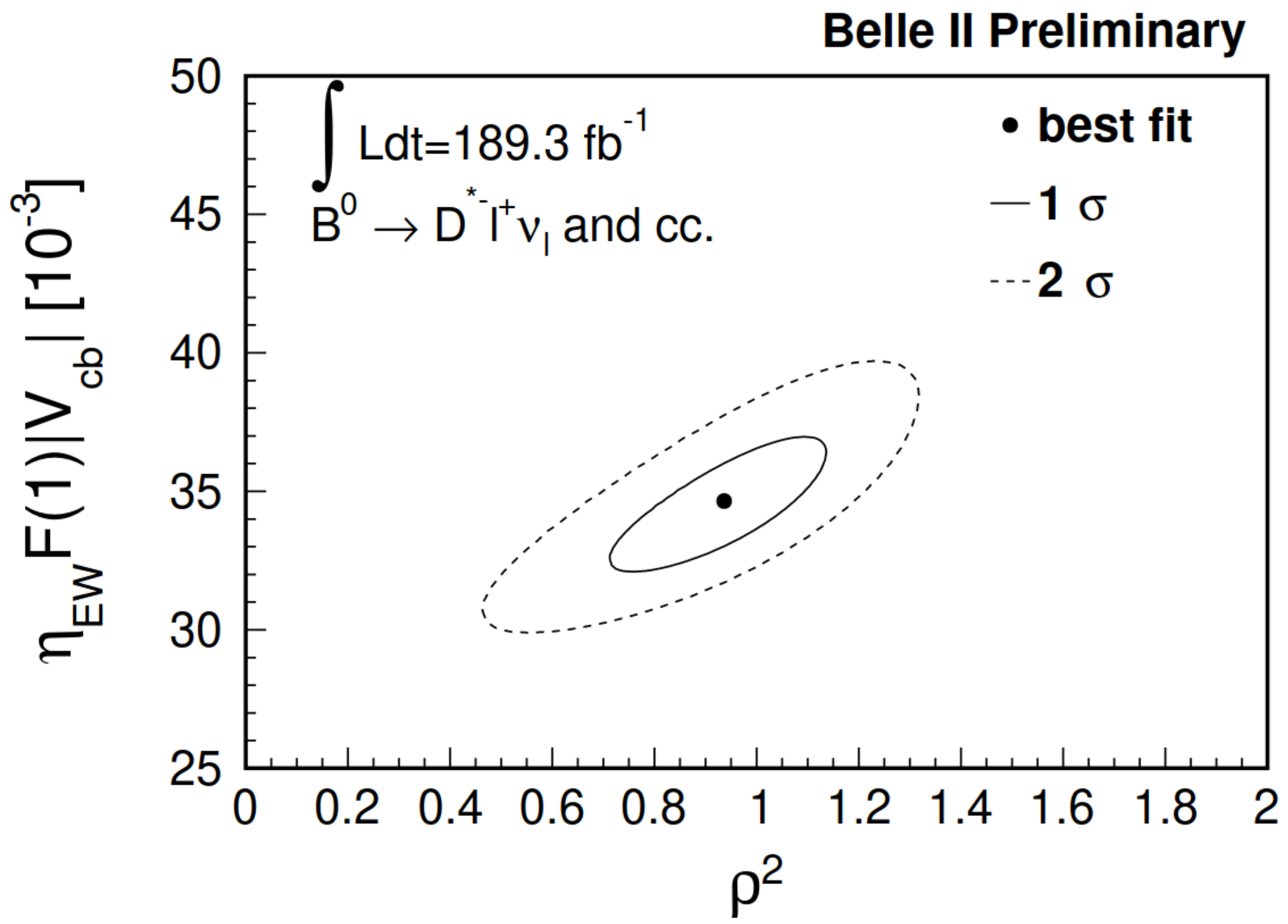


- Fit $d\Gamma/dw \propto \mathcal{F}^2(w)\,|V_{cb}|^2\eta^2_{\text{EW}}$ using CLN parameterisation with $R_1(1)$ and $R_2(1)$ constrained to HFLAV averages (BGL can be done as well).

$$\eta_{\text{EW}}F(1)|V_{cb}| = (34.6 \pm 2.5) \times 10^{-3}$$

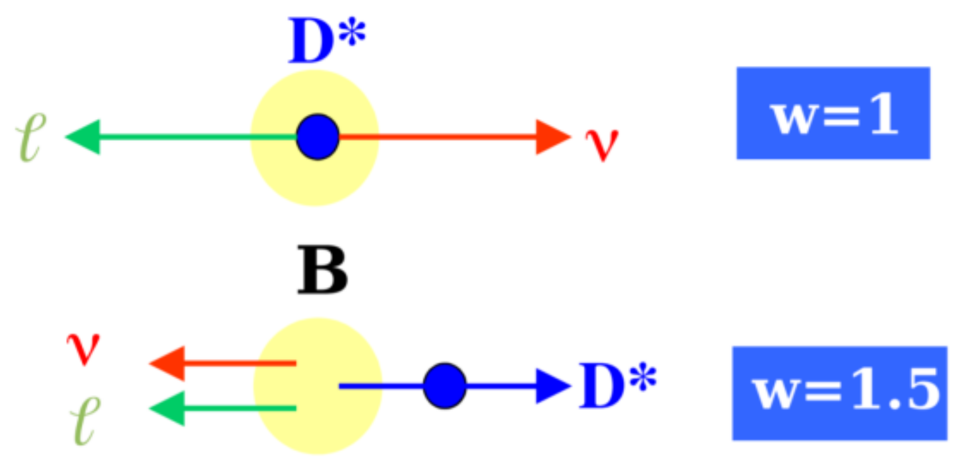
$$\boxed{|V_{cb}| = (37.9 \pm 2.7) \times 10^{-3}}$$





New LQCD inputs to exclusive $|V_{cb}|$

- Belle 2019 untagged study measured full decay differentials.
- Fit to BGL with non-zero lattice QCD inputs - new in 2021.
  - Helicity amplitudes defined in terms of power series.
  - The difference to inclusive remains!

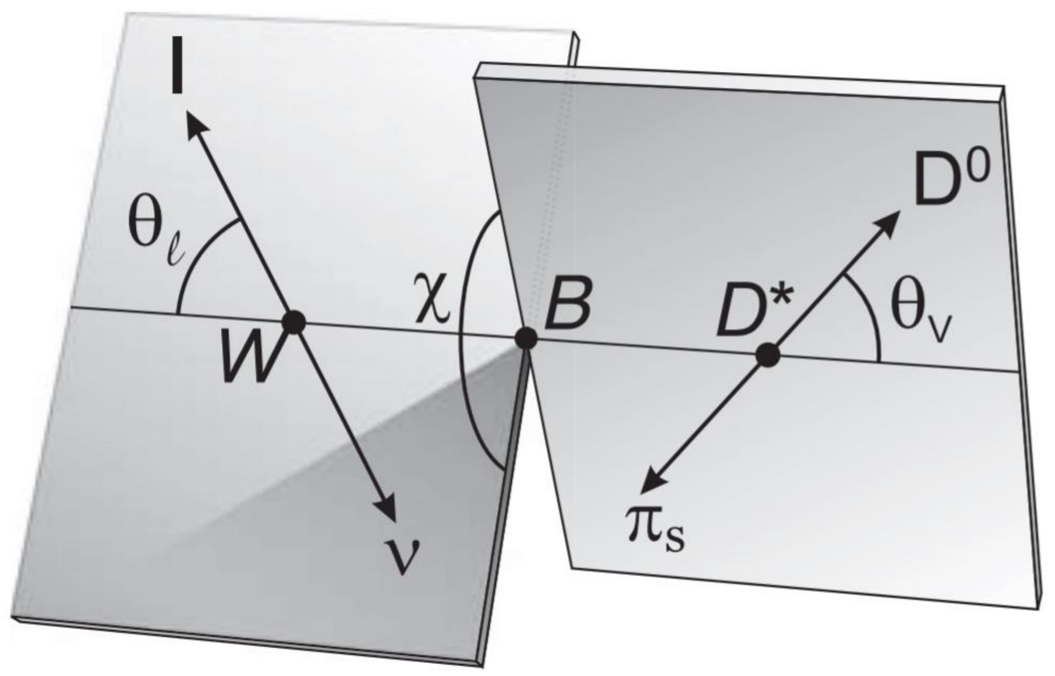


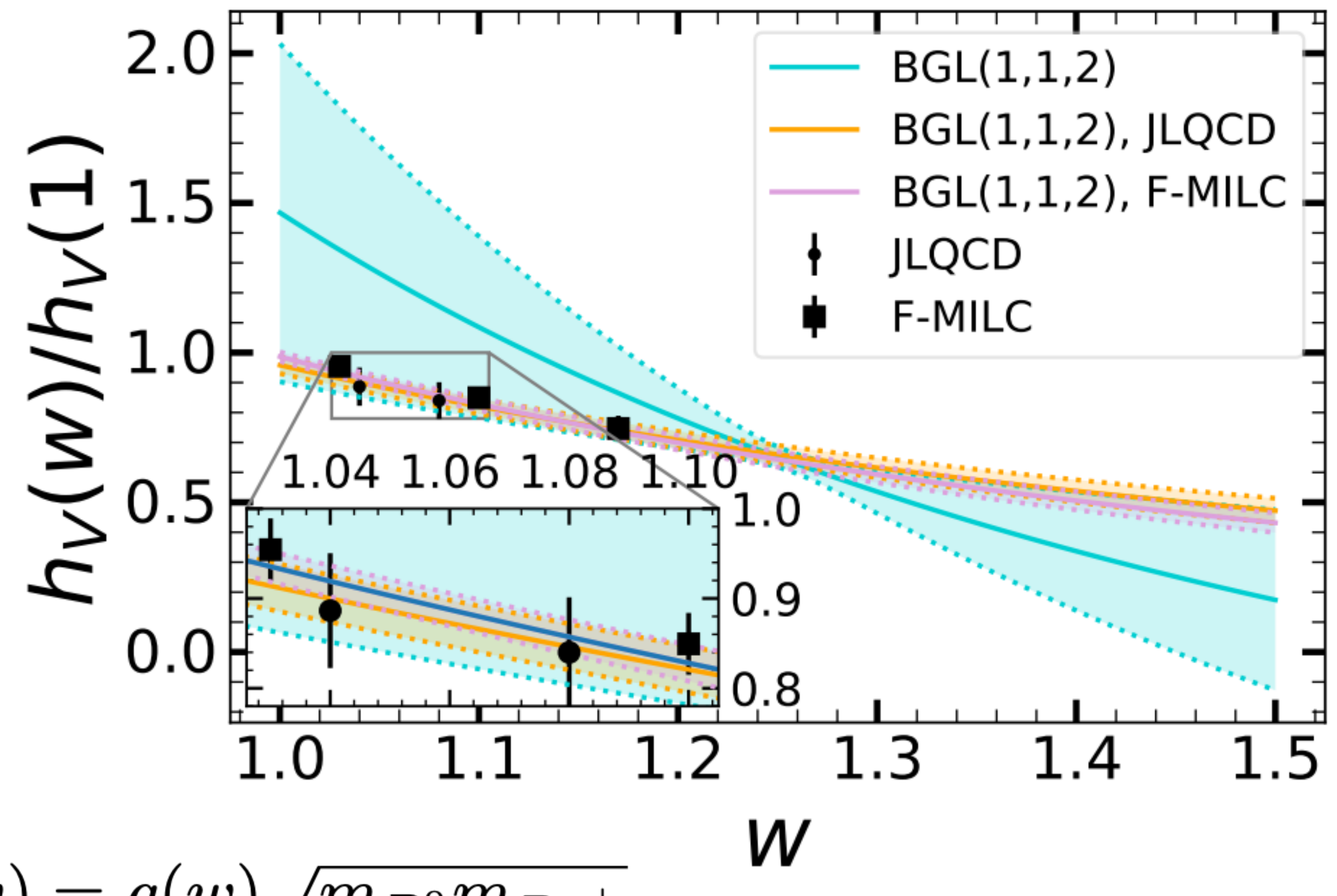
E. Waheed et al. (Belle 2019) Phys Rev D. 100.052007
D. Ferlewicz, E. Waheed, PU (2021) Phys Rev D.103.073005

$$\frac{d\Gamma(B^0 \to D^{*-}\ell^+\nu_\ell)}{dw\, d\cos\theta_\ell\, d\cos\theta_V\, d\chi} = \frac{\eta_{\rm EW}^2 3 m_{B^0} m_{D^{*\pm}}^2}{4(4\pi)^4} G_F^2 |V_{cb}|^2 \sqrt{w^2-1}(1-2wr+r^2)$$
$$\{(1-\cos\theta_\ell)^2 \sin^2\theta_V H_+^2 + (1+\cos\theta_\ell)^2 \sin^2\theta_V H_-^2$$
$$+4\sin^2\theta_\ell \cos^2\theta_V H_0^2 - 2\sin^2\theta_\ell \sin^2\theta_V \cos 2\chi H_+ H_-$$
$$-4\sin\theta_\ell(1-\cos\theta_\ell)\sin\theta_V\cos\theta_V\cos\chi H_+ H_0$$
$$+4\sin\theta_\ell(1+\cos\theta_\ell)\sin\theta_V\cos\theta_V\cos\chi H_- H_0\},$$

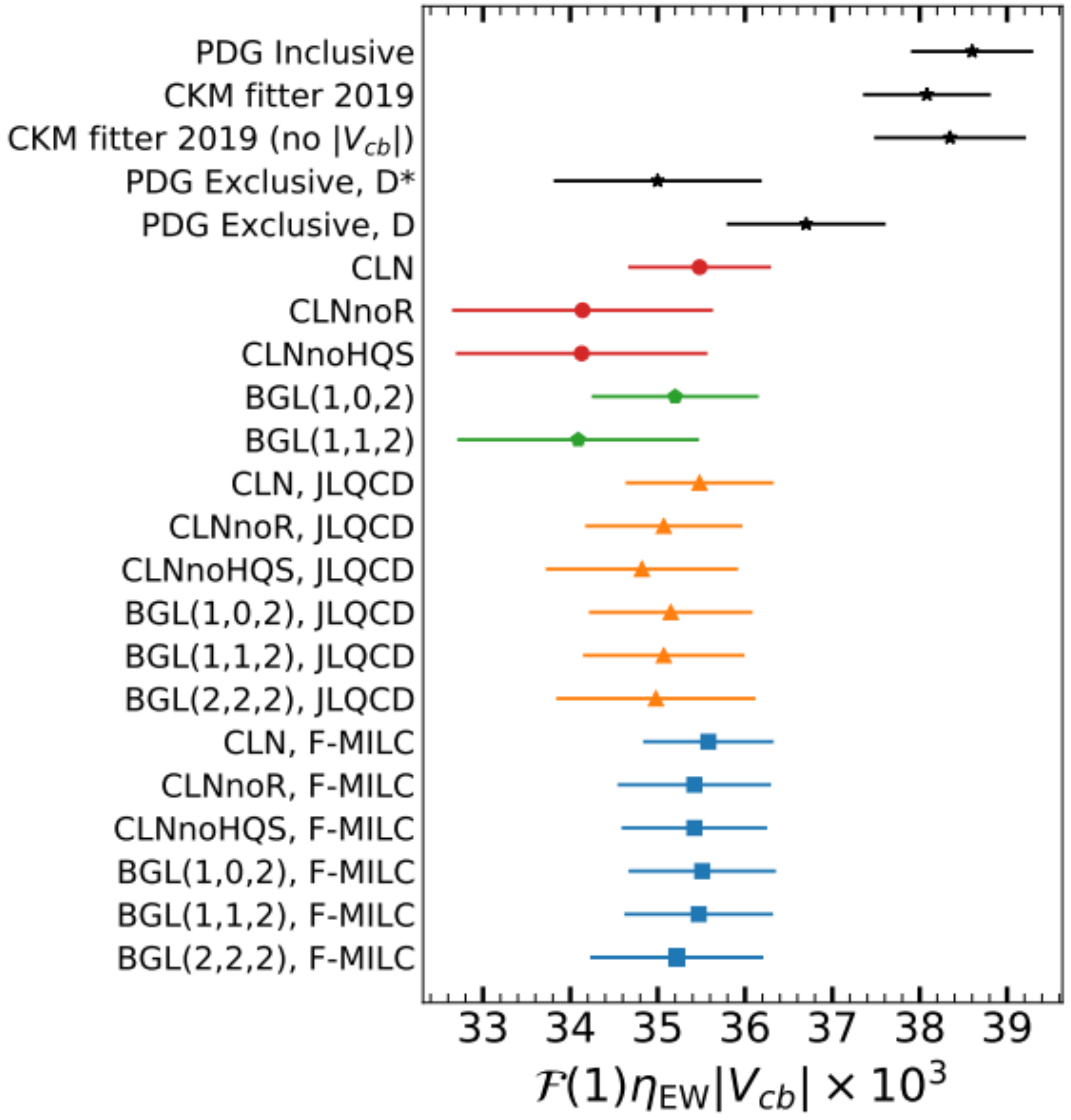
$$H_0(w) = \mathcal{F}_1(w)/\sqrt{q^2},$$
$$H_\pm(w) = f(w) \mp m_{B^0} m_{D^{*\pm}} \sqrt{w^2-1}\, g(w),$$

$$f(z) = \frac{1}{P_{1+}(z)\phi_f(z)} \sum_{n=0}^{\infty} a_n^f z^n ,$$
$$\mathcal{F}_1(z) = \frac{1}{P_{1+}(z)\phi_{\mathcal{F}_1}(z)} \sum_{n=0}^{\infty} a_n^{\mathcal{F}_1} z^n ,$$
$$g(z) = \frac{1}{P_{1-}(z)\phi_g(z)} \sum_{n=0}^{\infty} a_n^g z^n ,$$





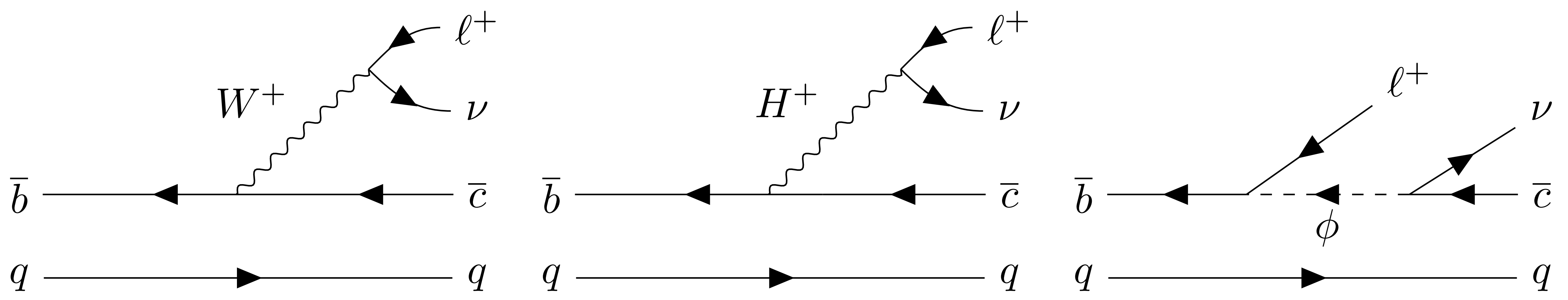
$$h_V(w) = g(w)\sqrt{m_{B^0} m_{D^{*\pm}}}$$



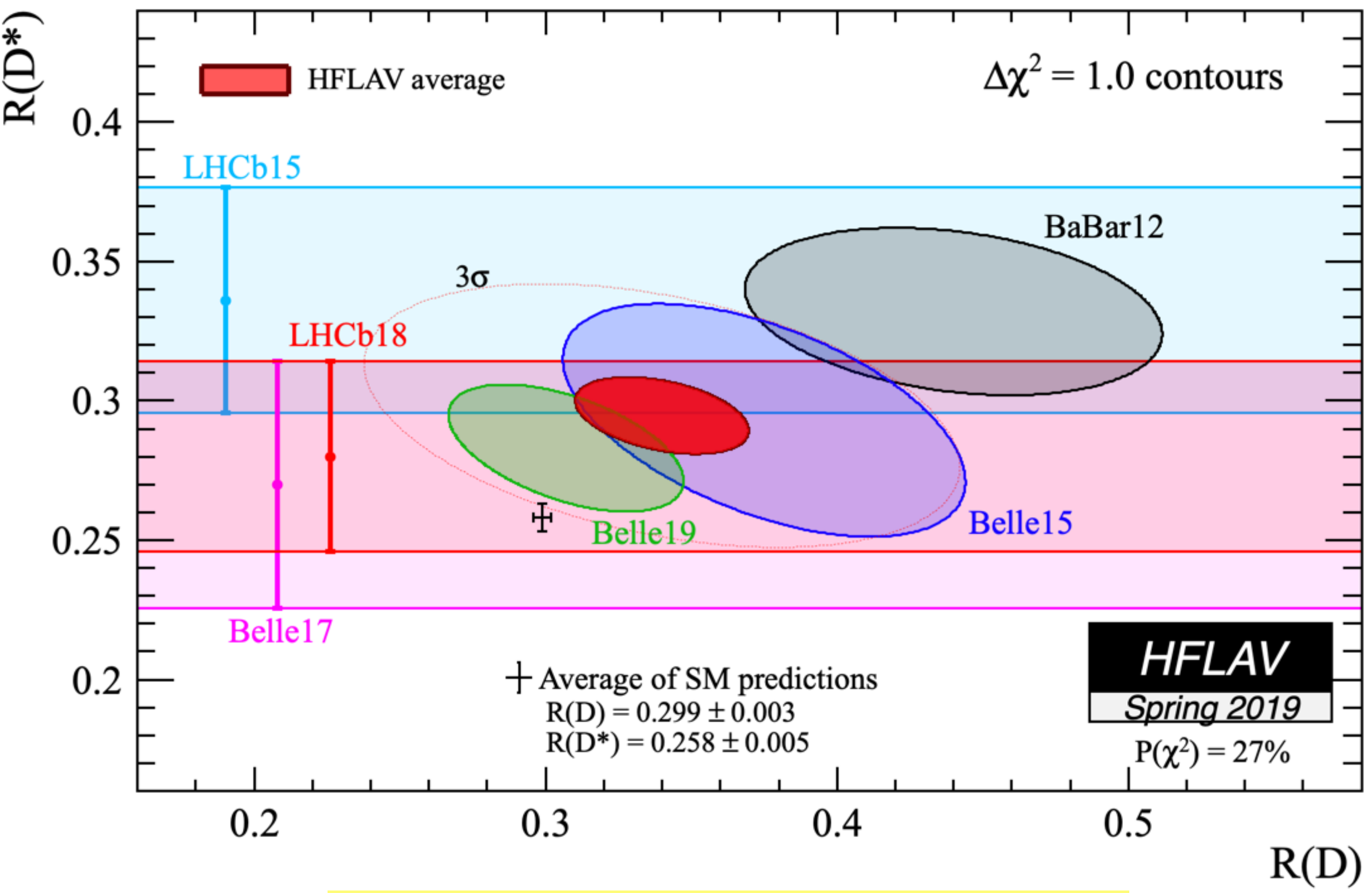
Belle II 2022

What about LFUV?

- Belle II needs to improve R(D) - also more sensitive to $H^{\pm}$-like scalar.
- Beyond R(D) and R(D*) - kinematics, polarisation and other observables.

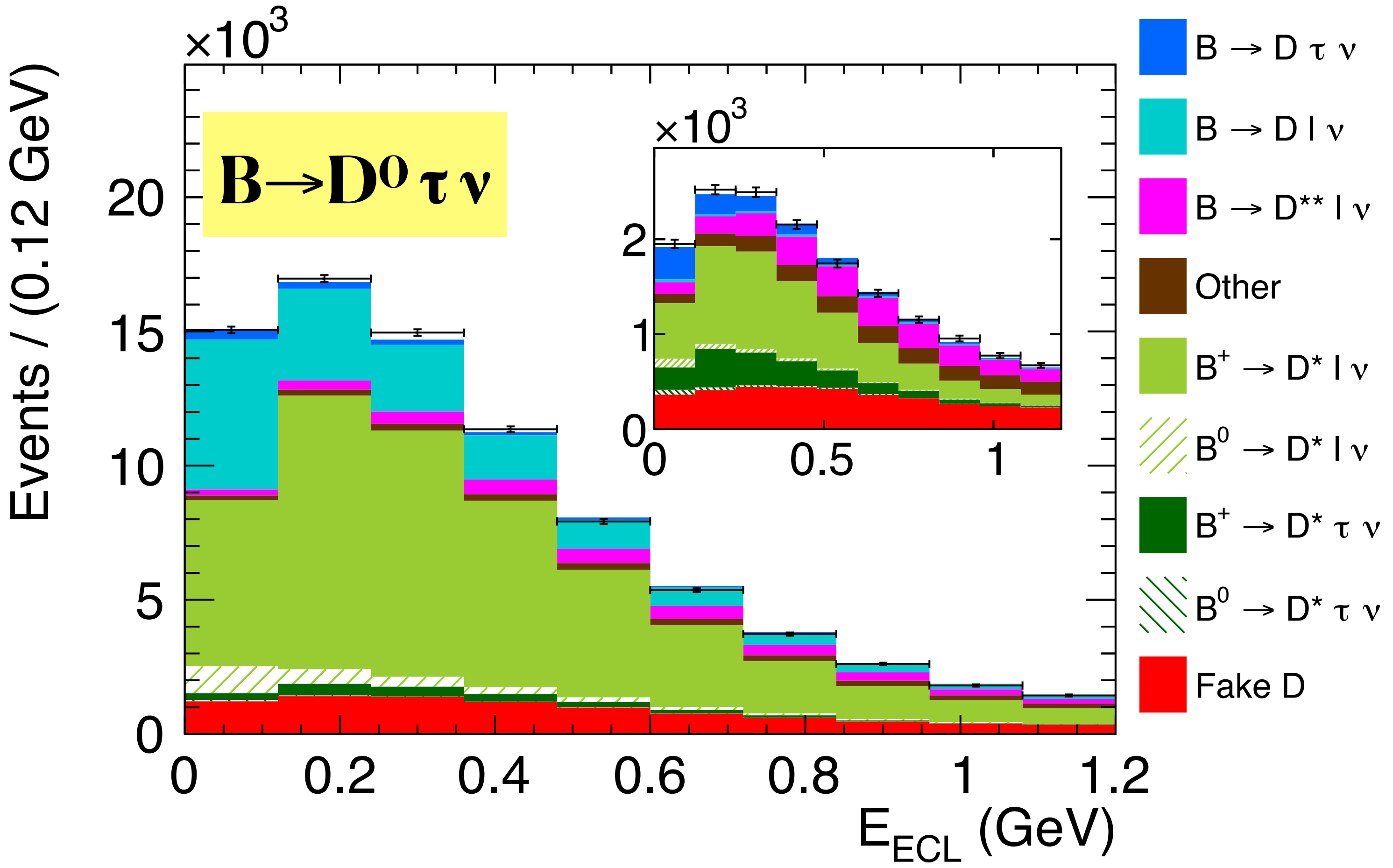


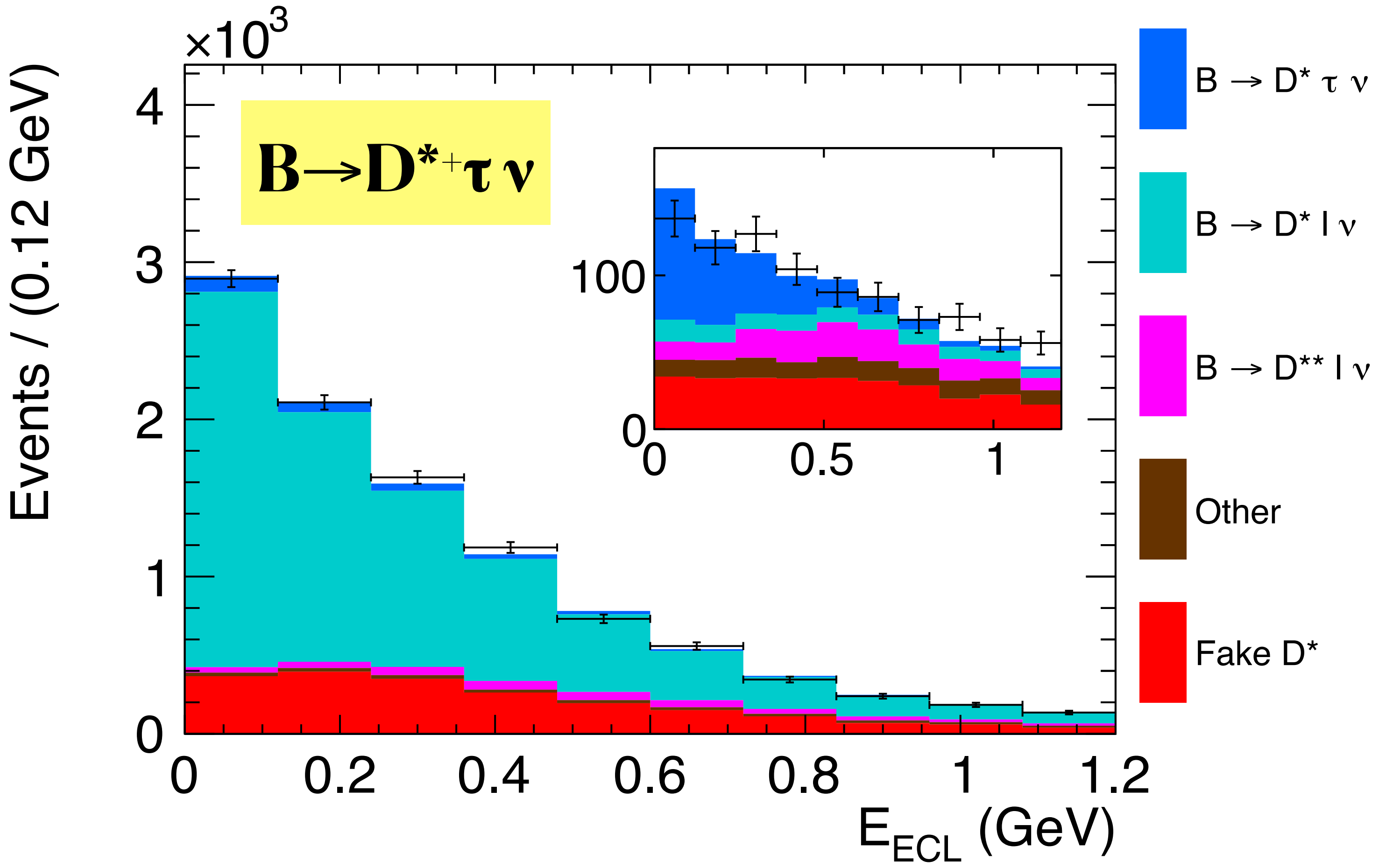
	5 ab^{-1}	50 ab^{-1}
R_D	$(\pm 6.0 \pm 3.9)\%$	$(\pm 2.0 \pm 2.5)\%$
R_{D^*}	$(\pm 3.0 \pm 2.5)\%$	$(\pm 1.0 \pm 2.0)\%$
$P_\tau(D^*)$	$\pm 0.18 \pm 0.08$	$\pm 0.06 \pm 0.04$



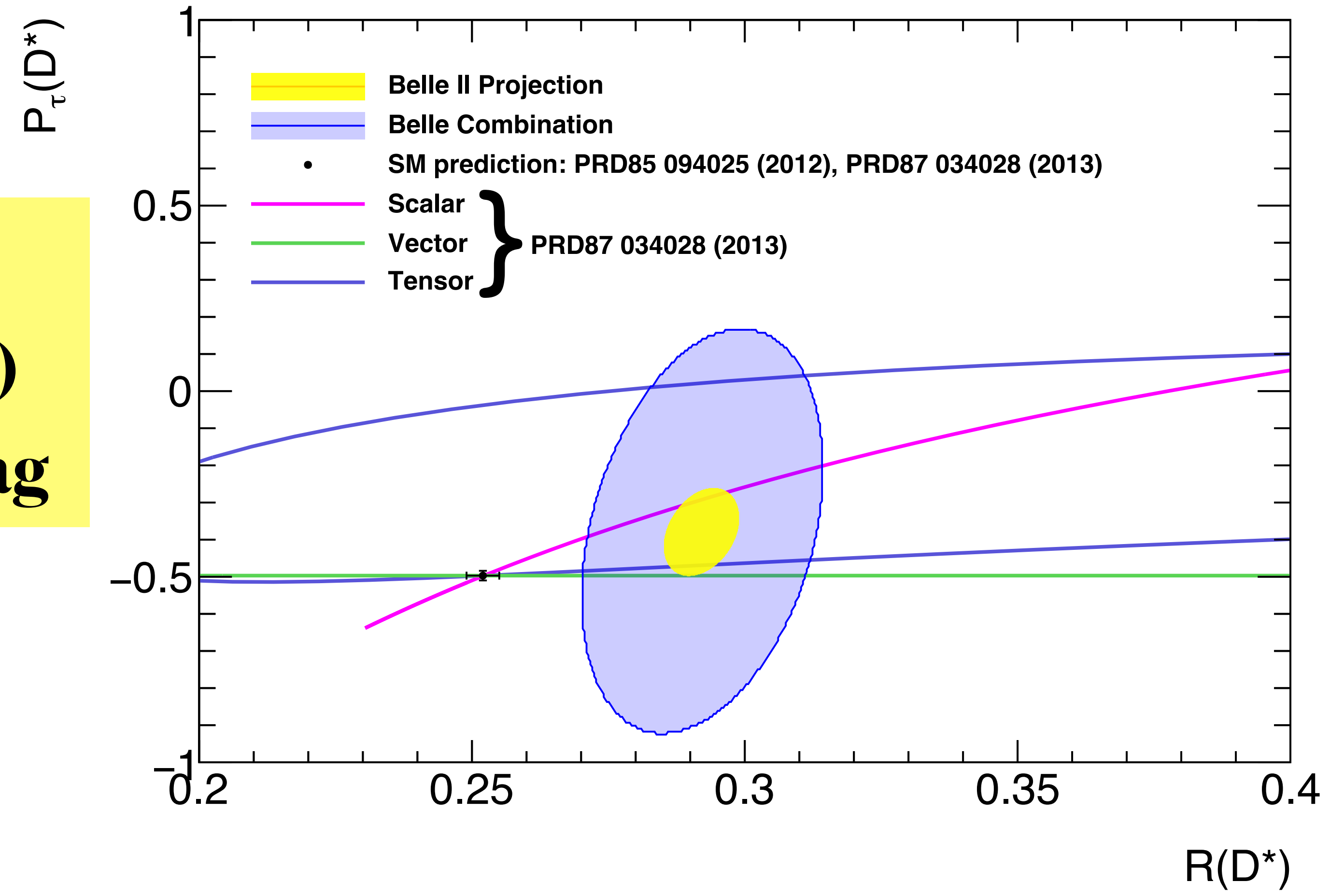
Belle PRL 124, 161803 (2020)
R(D), R(D*) SL tag

$$\mathscr{R}(D) = 0.307 \pm 0.037 \pm 0.016 \quad (13\%)$$
$$\mathscr{R}(D^*) = 0.283 \pm 0.018 \pm 0.014 \quad (8\%)$$

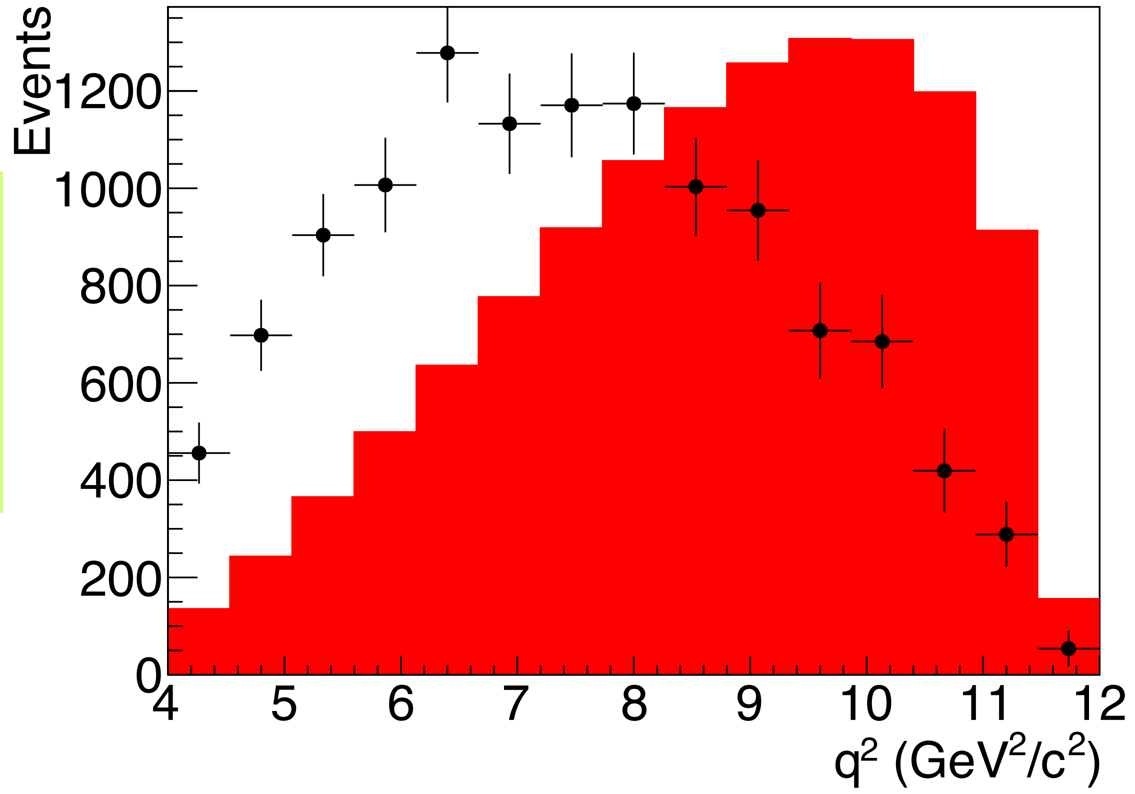


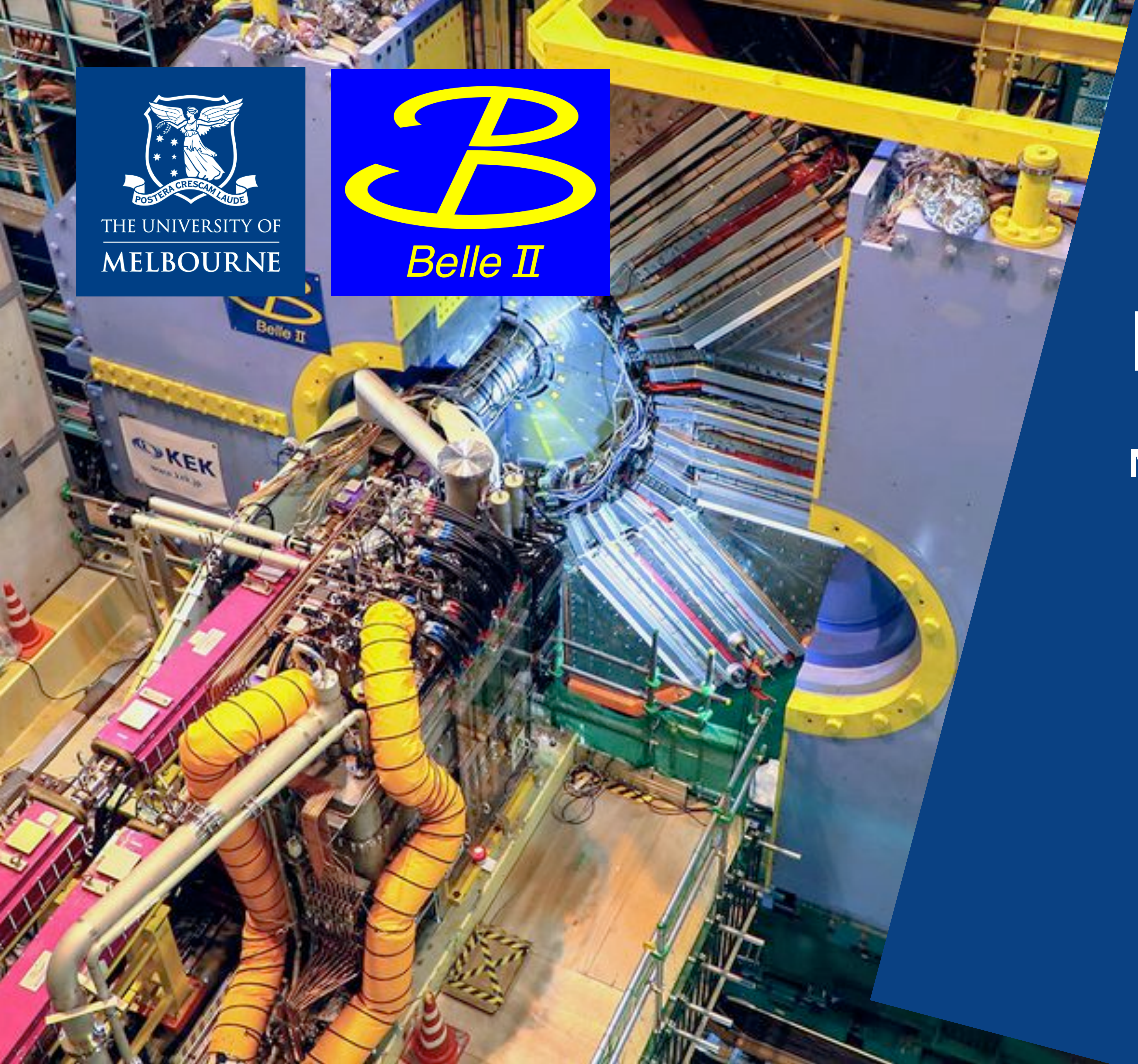


Belle PRD97, 012004 (2018)
R(D*), P_L Had tag



Belle II 50 ab⁻¹, SM (data) vs 2HDM (Hist)



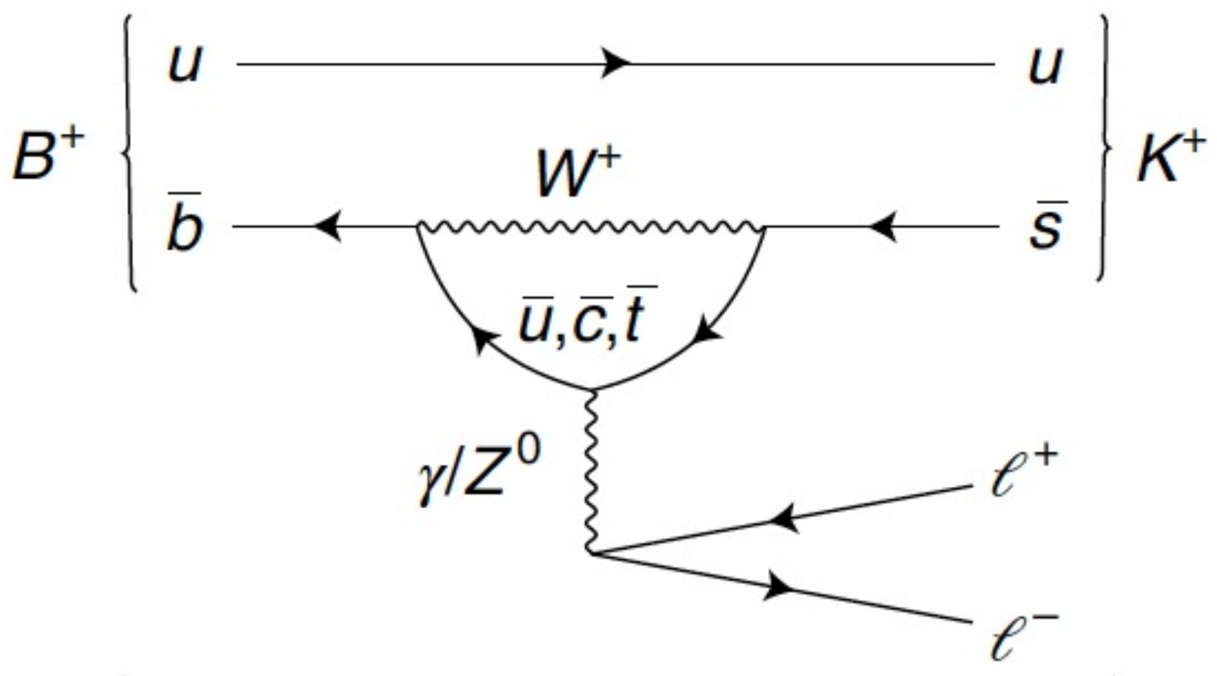


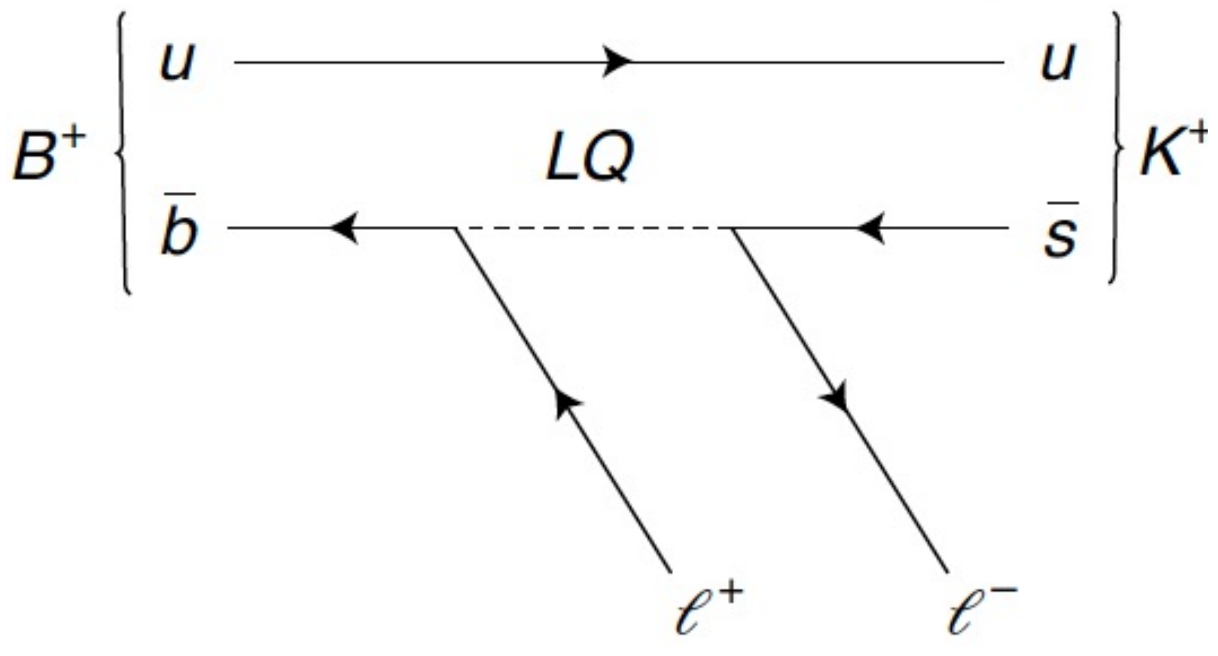
Loop Decays

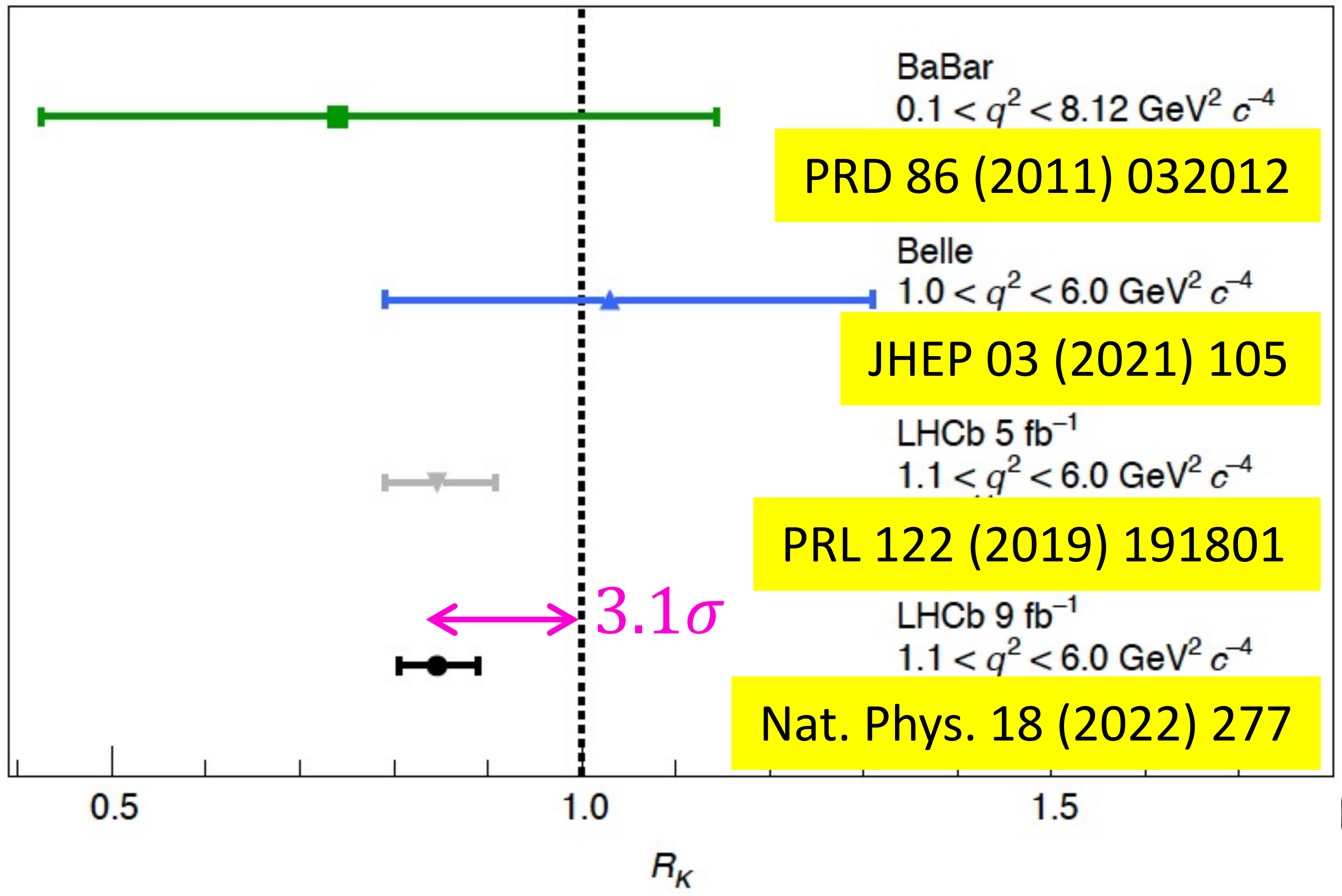
Missing energy, dilepton

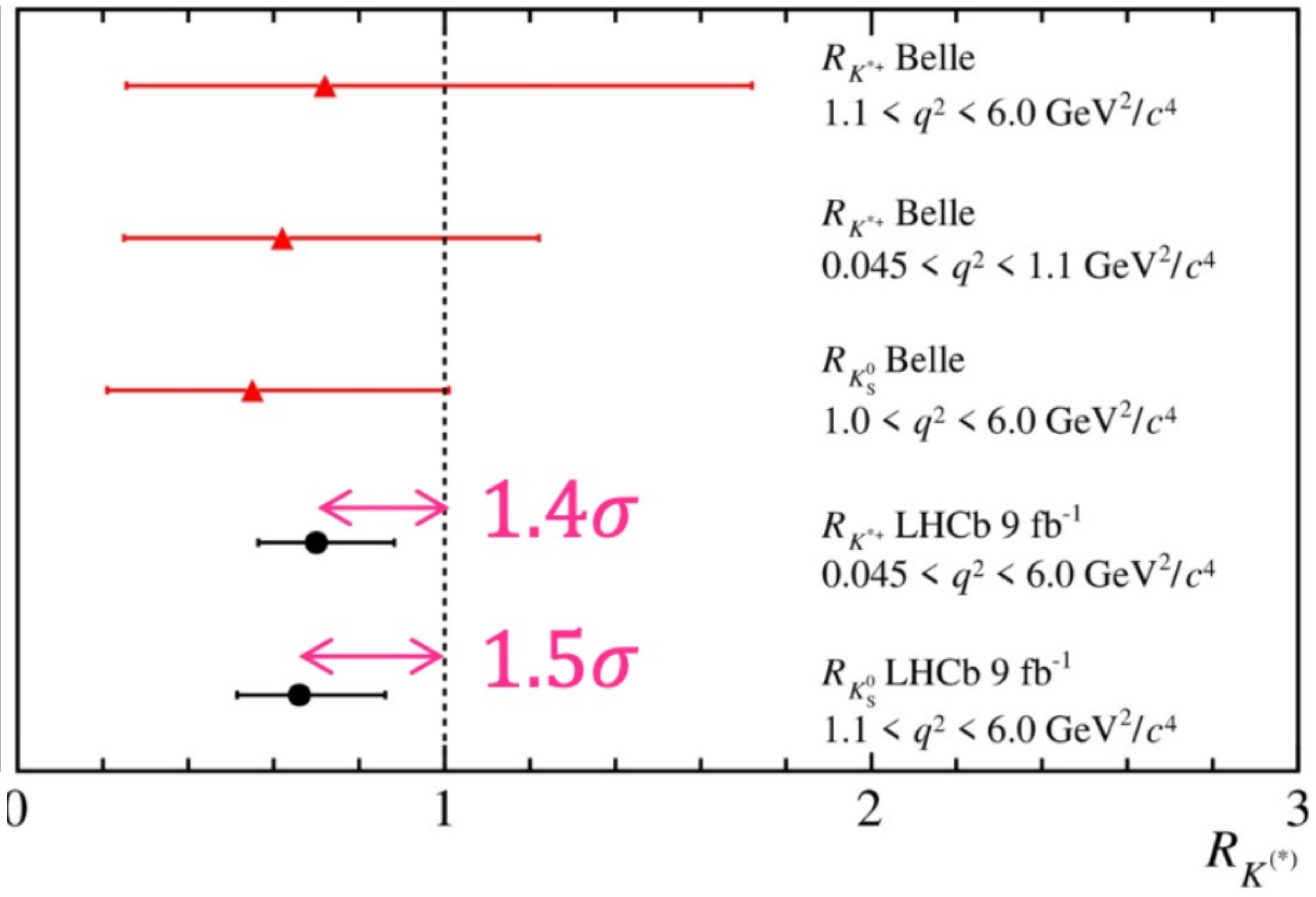
The light lepton anomaly

- If one keeps mass terms aside, the SM does not distinguish between leptons of different flavour
- $R(K^{(*)}) = \dfrac{\mathscr{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathscr{B}(B \to K^{(*)}e^+e^-)}$ is expected to be 1 with corrections for phase space differences.
- LHCb finds evidence for lepton flavour universality violation.







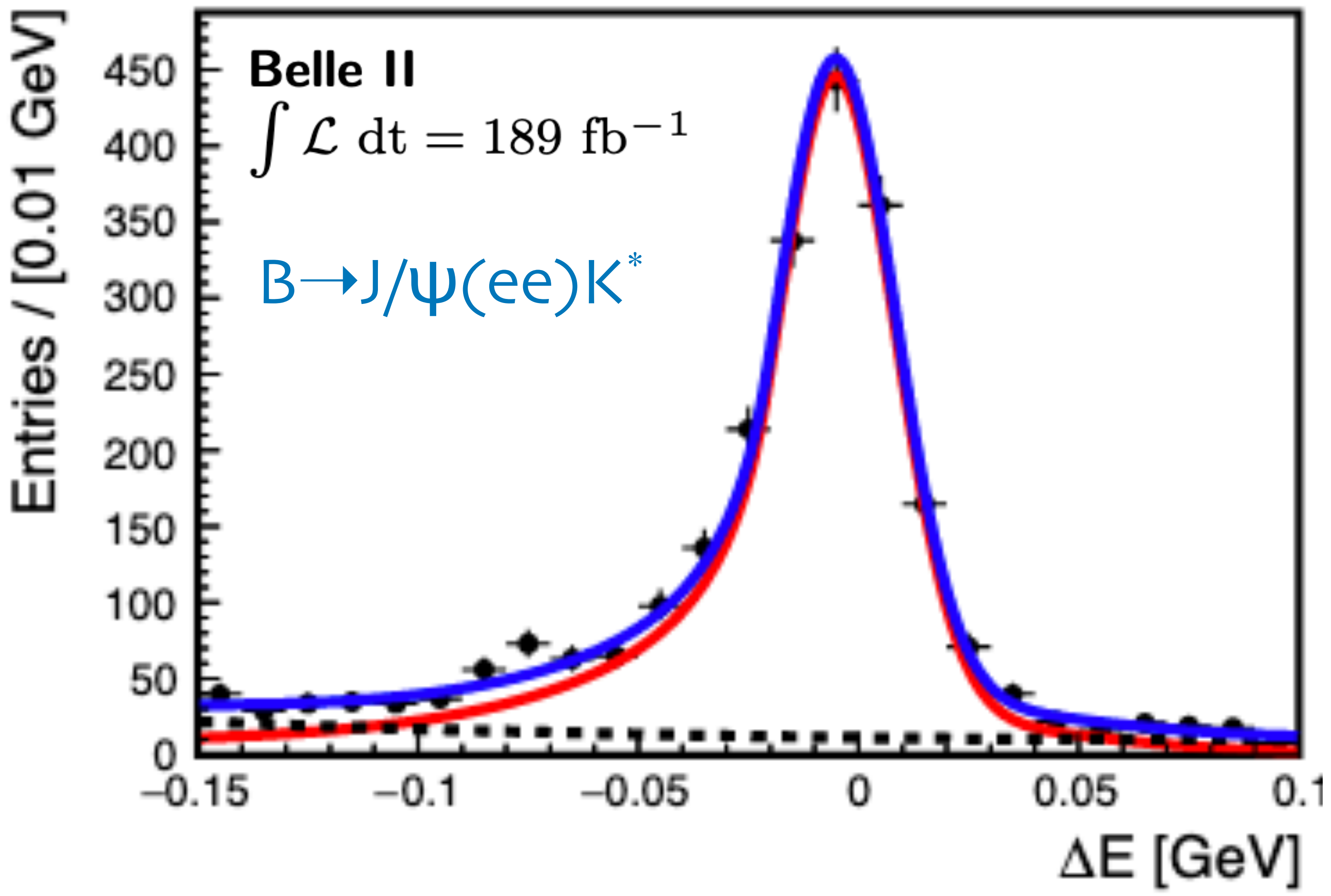


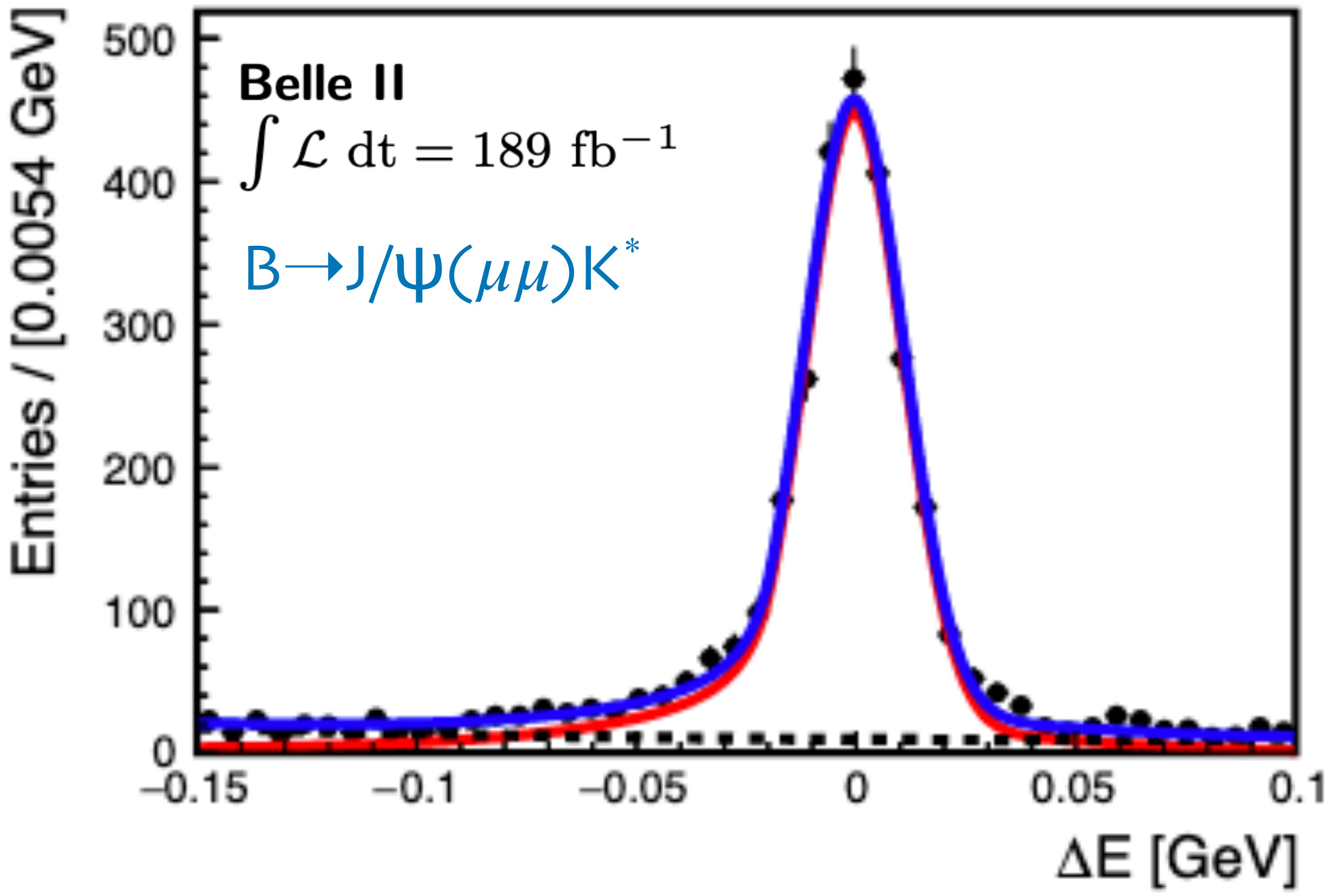
$B \to K^* J/\psi(\ell^+\ell^-)$ & early measurements

- $B \to K^* J/\psi(\ell^+\ell^-)$ used as a control mode - also a background. Bremsstrahlung recovered in electron channels.
- Belle (II) has similar sensitivity both for electron and muon modes. Also seen in $B \to K\ell\ell$ at Belle.

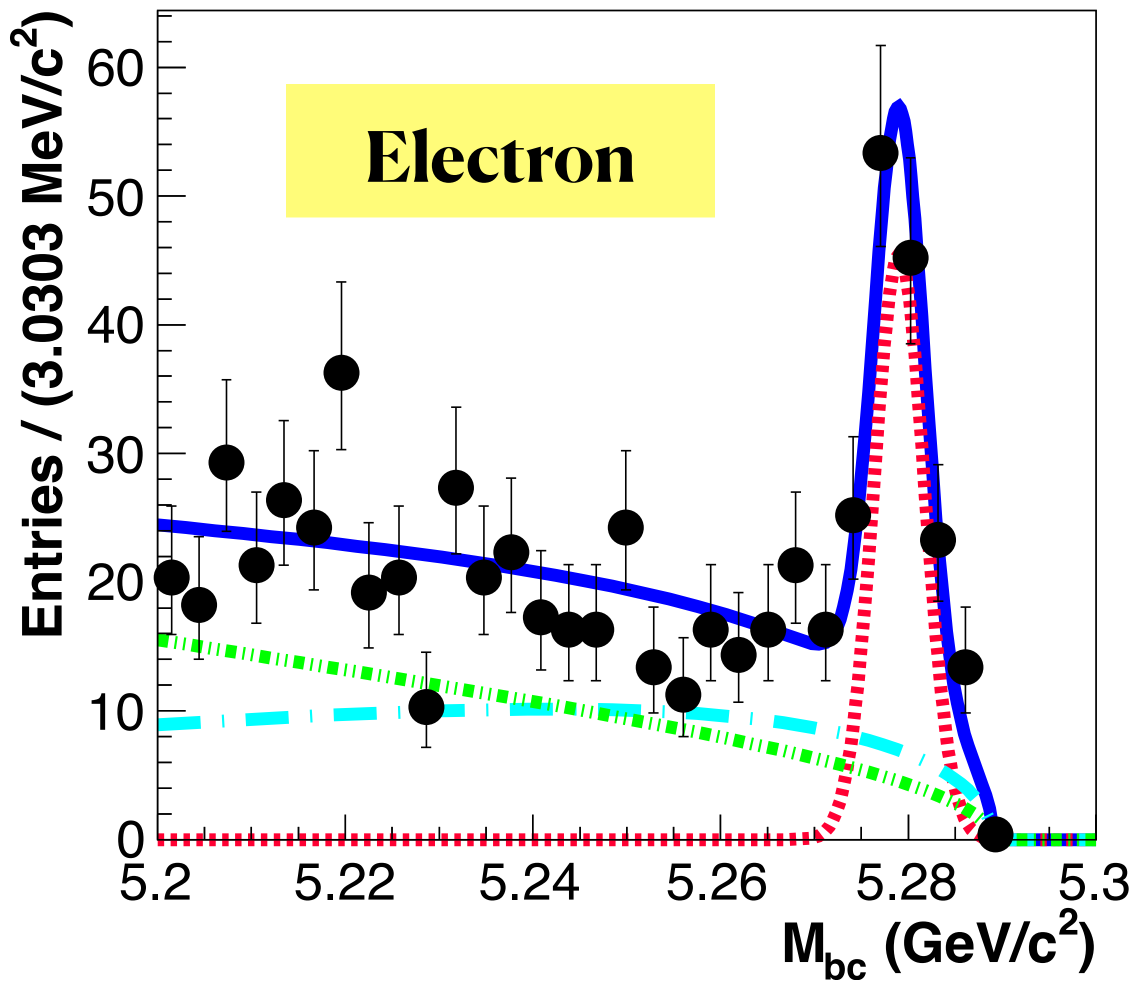
$M_{bc} \equiv \sqrt{E^2_{beam} - \vec{p}^{\,*2}_B}, \qquad \Delta E \equiv E^*_{beam} - E^*_B$

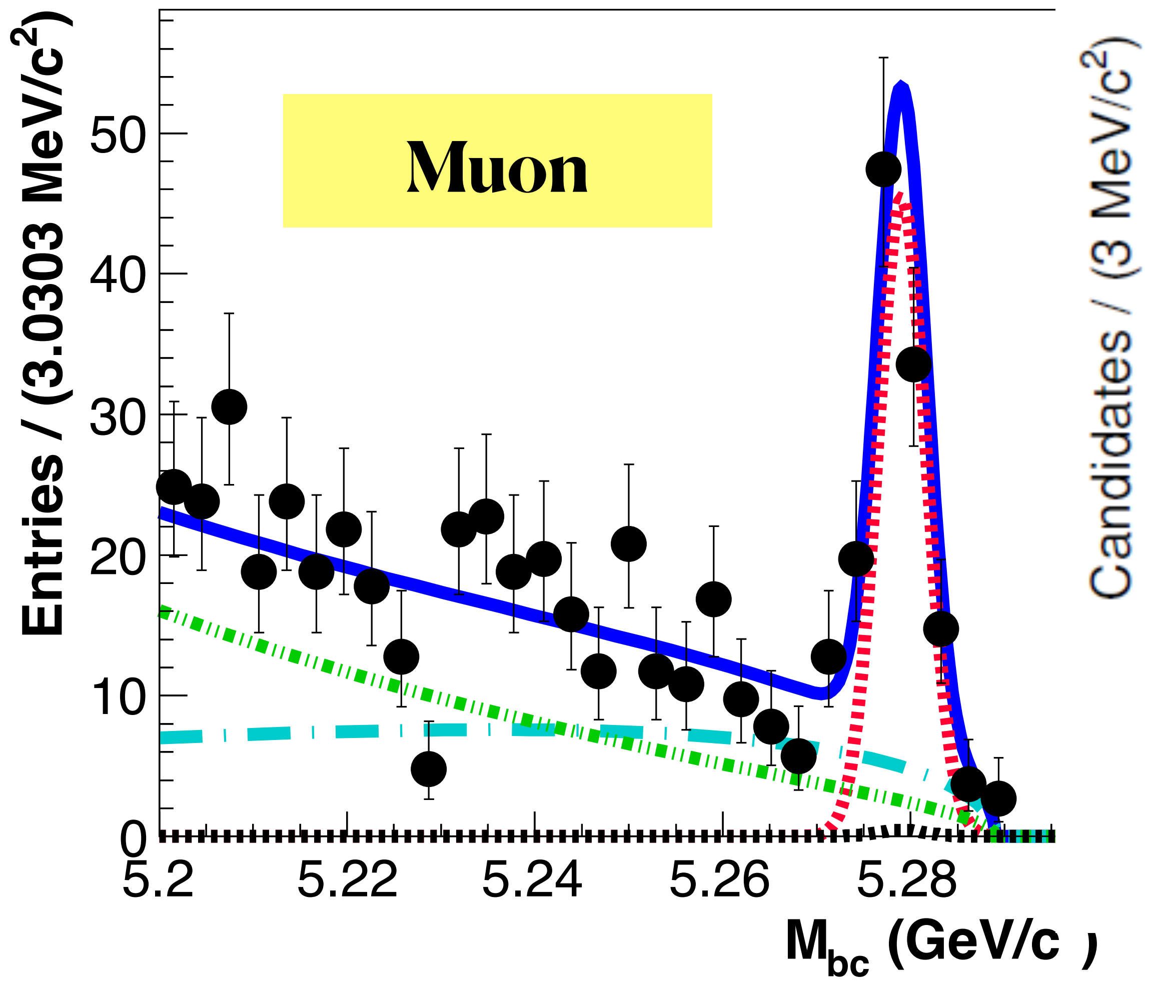
Belle II Preliminary



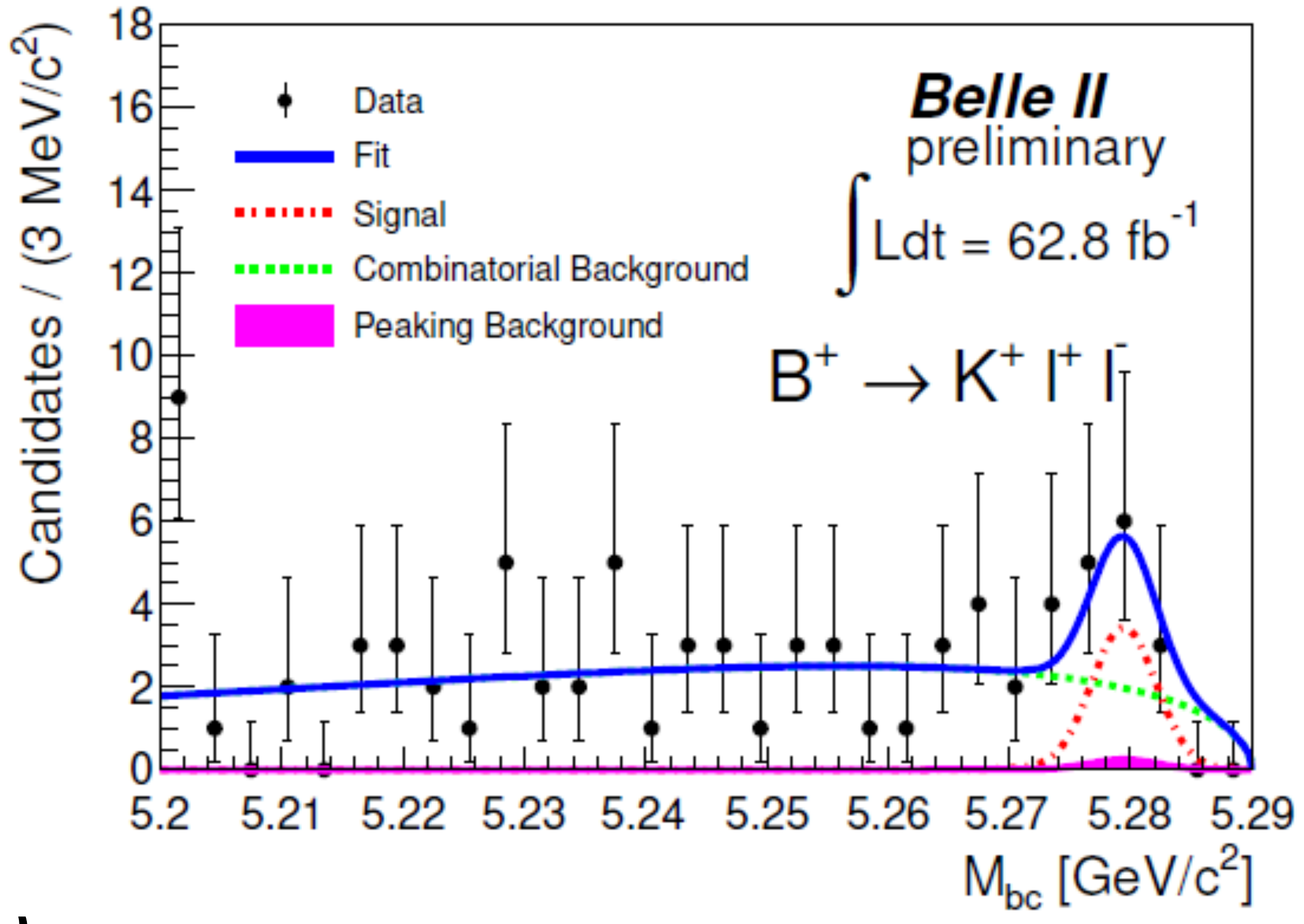


Belle JHEP 2103, 105 (2021) $B \to K\ell\ell$
Belle Phys. Rev. Lett. 126, 161801 (2021)





Belle II Preliminary $B \to K\ell\ell$

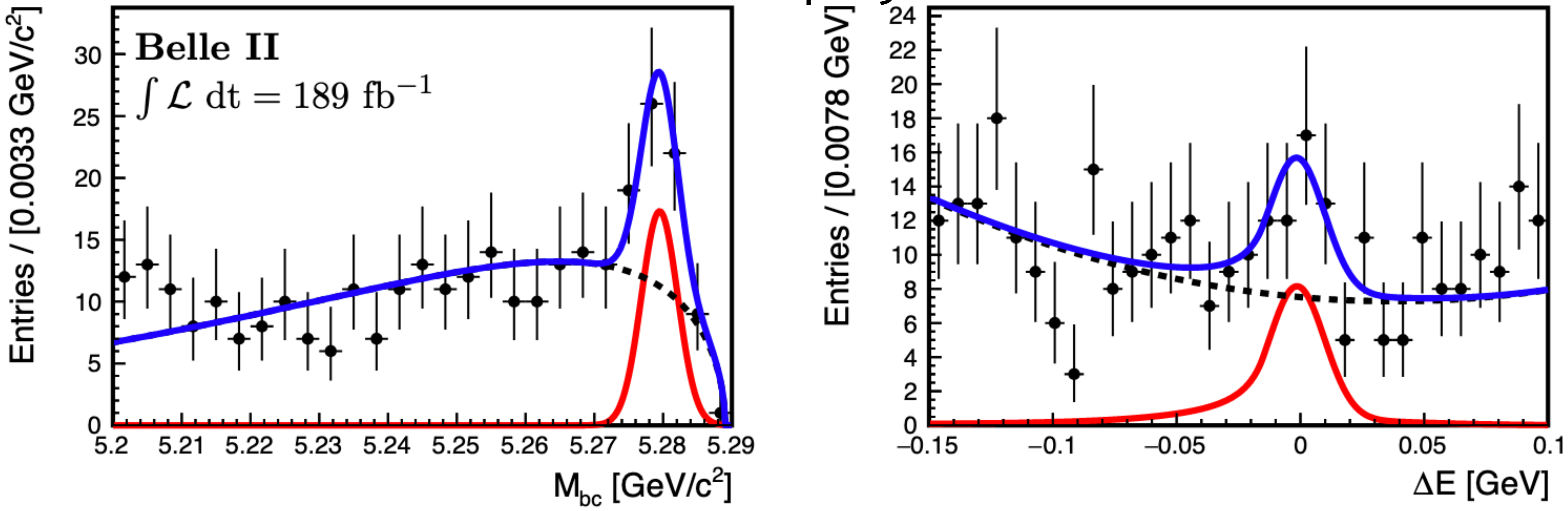


$B \to K^{*}\ell^{+}\ell^{-}$

- Signal extraction from 2D fit to M_{bc} and ΔE.
- Uncertainty in electron channel only 2.5 times that of PDG average.
- Expected to be competitive with 1 ab^{-1}.

$B \to K^{*}\ell\ell$ fit projections

Belle II Preliminary



$$\mathcal{B}(B \to K^{*}\mu\mu) = (1.19 \pm 0.31 \pm^{+0.08}_{-0.07}) \times 10^{-6},$$
$$\mathcal{B}(B \to K^{*}ee) = (1.42 \pm 0.48 \pm 0.09) \times 10^{-6},$$
$$\mathcal{B}(B \to K^{*}\ell\ell) = (1.25 \pm 0.30 \pm^{+0.08}_{-0.07}) \times 10^{-6},$$

PDG averages

$(1.06 \pm 0.09) \times 10^{-6}$

$(1.19 \pm 0.20) \times 10^{-6}$

$(1.05 \pm 0.10) \times 10^{-6}$

- Belle II can
  a) provide essential independent checks of $R(K^{*})$ anomalies with a few ab^{-1} data,
  b) measure $R(X_s)$ for inclusive B decays ,
  c) provide independent measurements of absolute branching fractions for e and μ modes .

Where are we going?

- Need to wait till 2026 to have 5 ab^{-1} of data that would allow us to probe LFU to $\mathcal{O}$(10%).
- … But we will have many channels to probe.

Belle Σ Exclusive: Phys. Rev. D 93, 032008 (2016)

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

PTEP 2019 (2019) 12, 123C01 (Belle II Physics Book)

Exclusive projections

Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
R_K ([1.0, 6.0] GeV^2)	28%	11%	3.6%
R_K (> 14.4 GeV^2)	30%	12%	3.6%
R_{K^*} ([1.0, 6.0] GeV^2)	26%	10%	3.2%
R_{K^*} (> 14.4 GeV^2)	24%	9.2%	2.8%
R_{X_s} ([1.0, 6.0] GeV^2)	32%	12%	4.0%
R_{X_s} (> 14.4 GeV^2)	28%	11%	3.4%

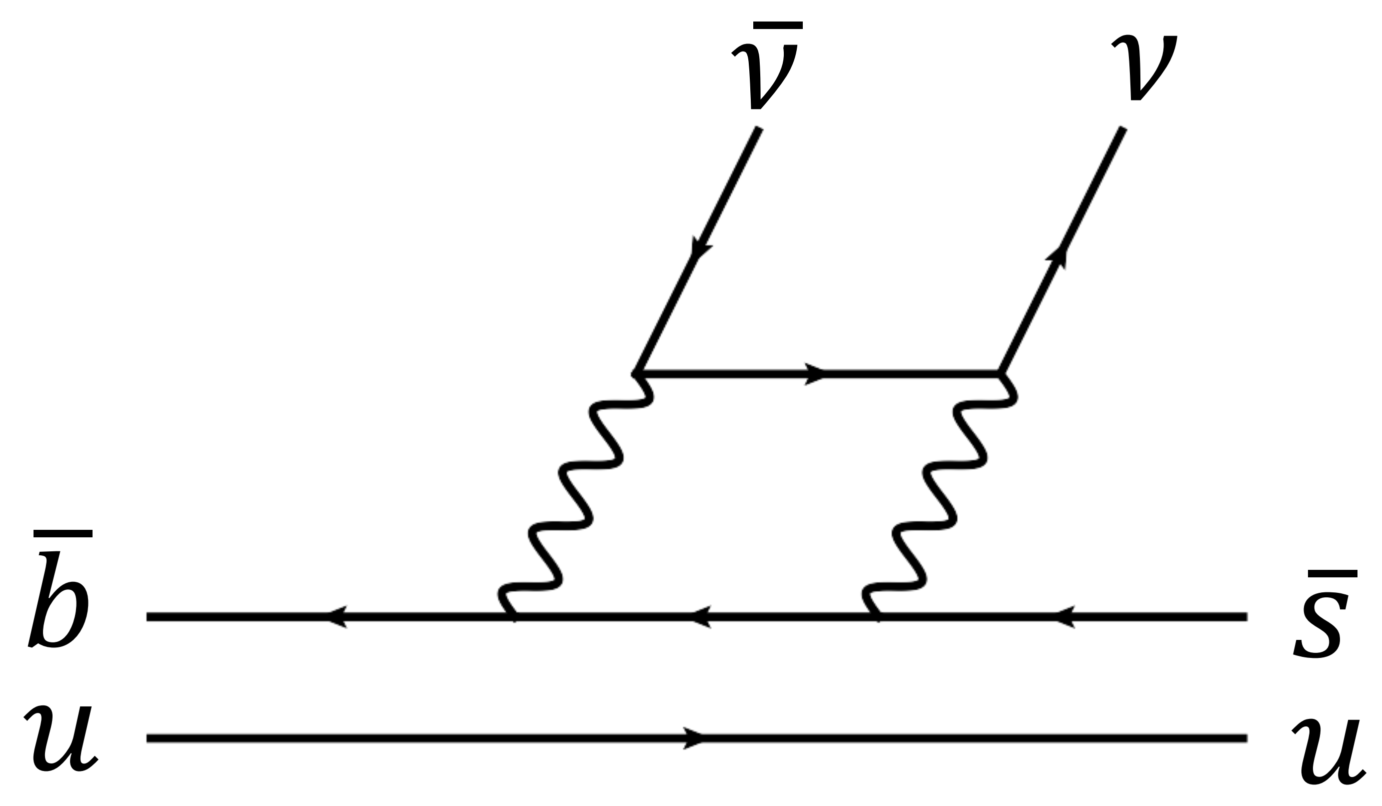
Inclusive projections

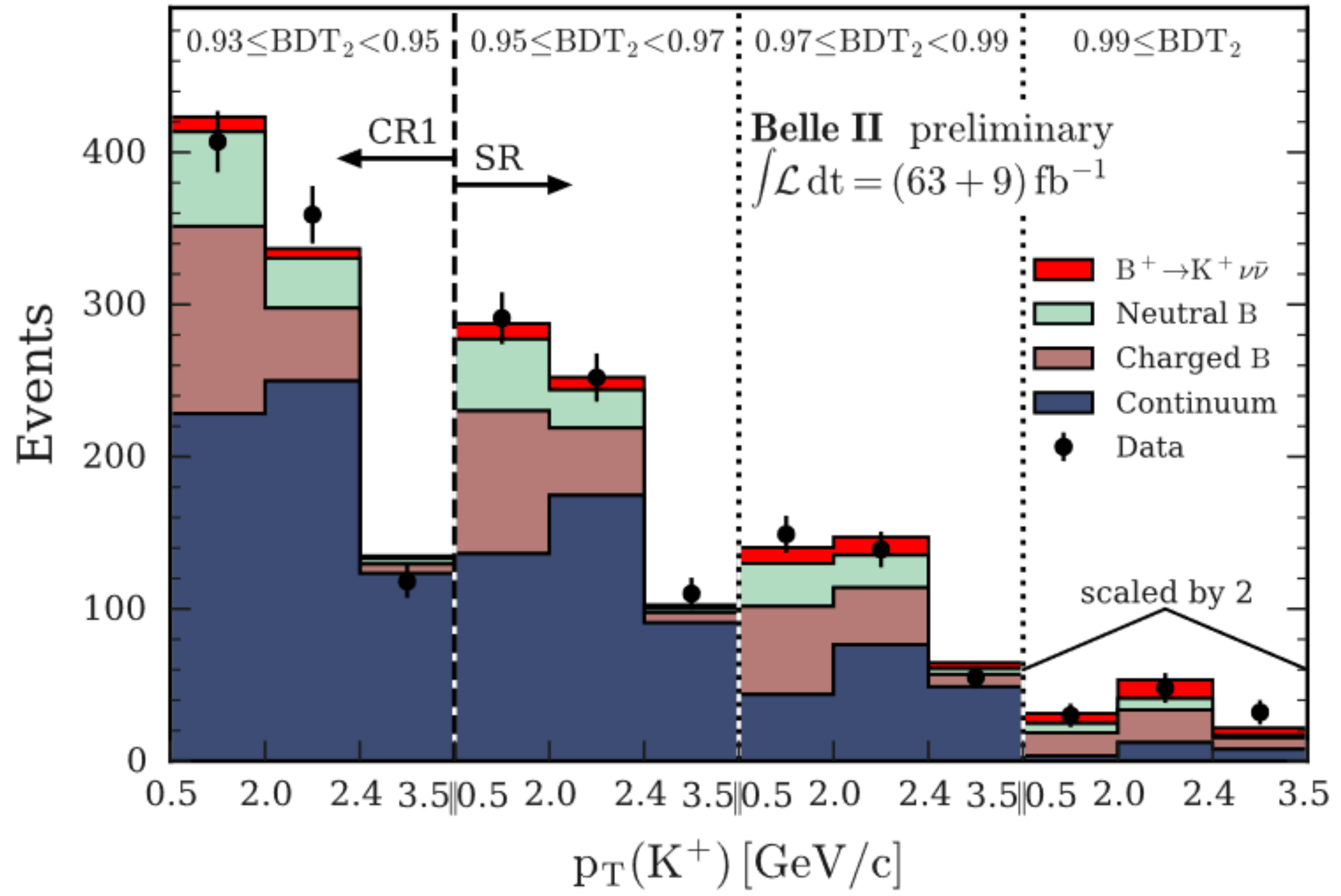
Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathrm{Br}(B \to X_s\ell^+\ell^-)$ ([1.0, 3.5] GeV^2)	29%	13%	6.6%
$\mathrm{Br}(B \to X_s\ell^+\ell^-)$ ([3.5, 6.0] GeV^2)	24%	11%	6.4%
$\mathrm{Br}(B \to X_s\ell^+\ell^-)$ (>14.4 GeV^2)	23%	10%	4.7%
$A_{\mathrm{CP}}(B \to X_s\ell^+\ell^-)$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

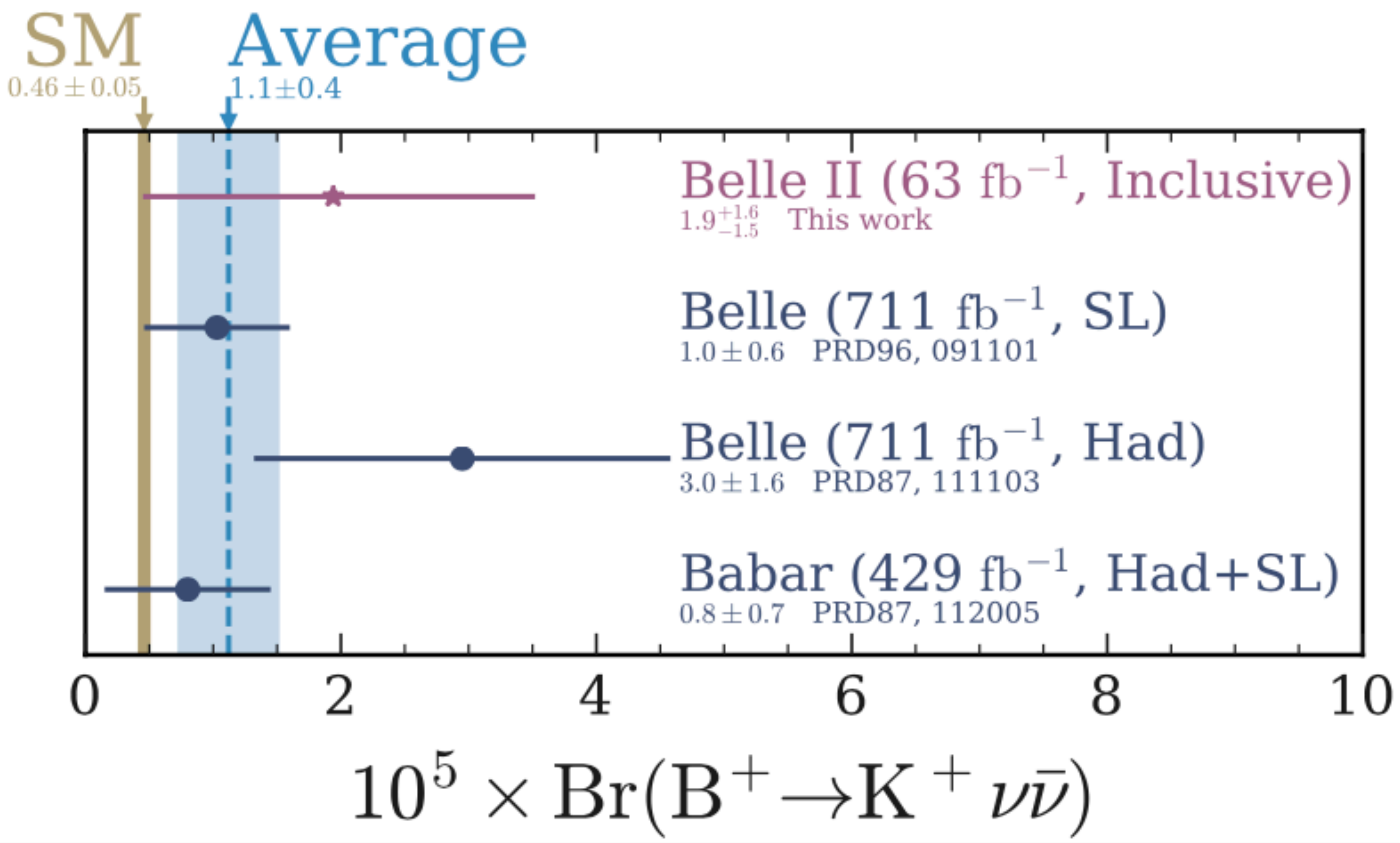
$B \to K\nu\bar{\nu}$

Belle II Phys.Rev.Lett. 127 (2021) 18, 181802

- This suppressed FCNC decay offers a complementary probe of NP scenarios proposed to explain flavour anomalies.
  - Novel inclusive approach on 63 fb^{-1} of Belle II data
  - Use ML approach (2 BDTs in cascade) based on kinematics, event shape and vertex variables to suppress background
  - Signal efficiency ~4.3% - very sensitive!







Beyond Belle II

Why, Future Landscape, Upgrade program

What can we learn with A LOT more data?

- **New observables and channels opened up with larger data sets. e.g.**
  - Helicity or Cabibbo suppressed: $B\to\pi\,\tau\,\nu$, $\mu\,\nu$
  - CPV in $b\to s$ EW and radiative transitions: $B\to K_S\,\pi^0\,\{\gamma, l^+l^-\}$

- **Forbidden processes**
  - Feeble (dark sector) interactions in missing energy decays
  - Lepton flavour violation

- **Classes of channels with very low measurement systematic uncertainties**
  - LFUV, Tree level hadronic decays (Φ_3)

- **Better precision = sensitivity to larger energy scale or smaller couplings**
  - Advances in LQCD will evolve simultaneously

Belle II Projections & LHCb Comparison

Belle II
Higher sensitivity to decays with photons and neutrinos (e.g. $B \to K\nu\nu$, $\mu\nu$), inclusive decays, time dependent CPV in B_d, τ physics.

LHCb
Higher production rates for ultra rare B, D, & K decays, access to all b-hadron flavours (e.g. Λ_b), high boost for fast B_s oscillations.

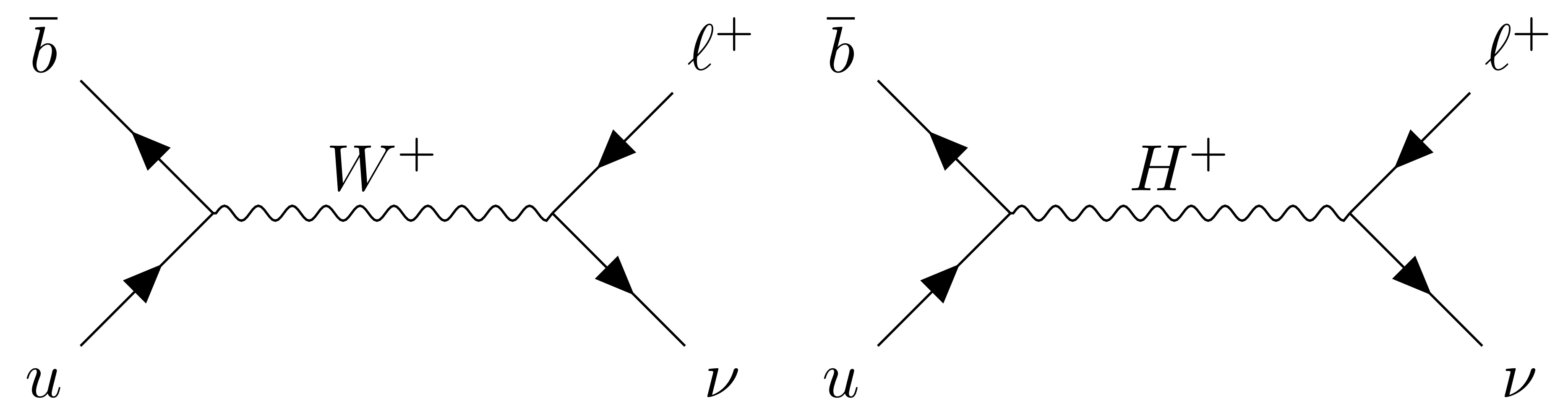
Overlap in various key areas to verify discoveries.

Upgrades
Most key channels will be stats. limited (not theory or syst.).

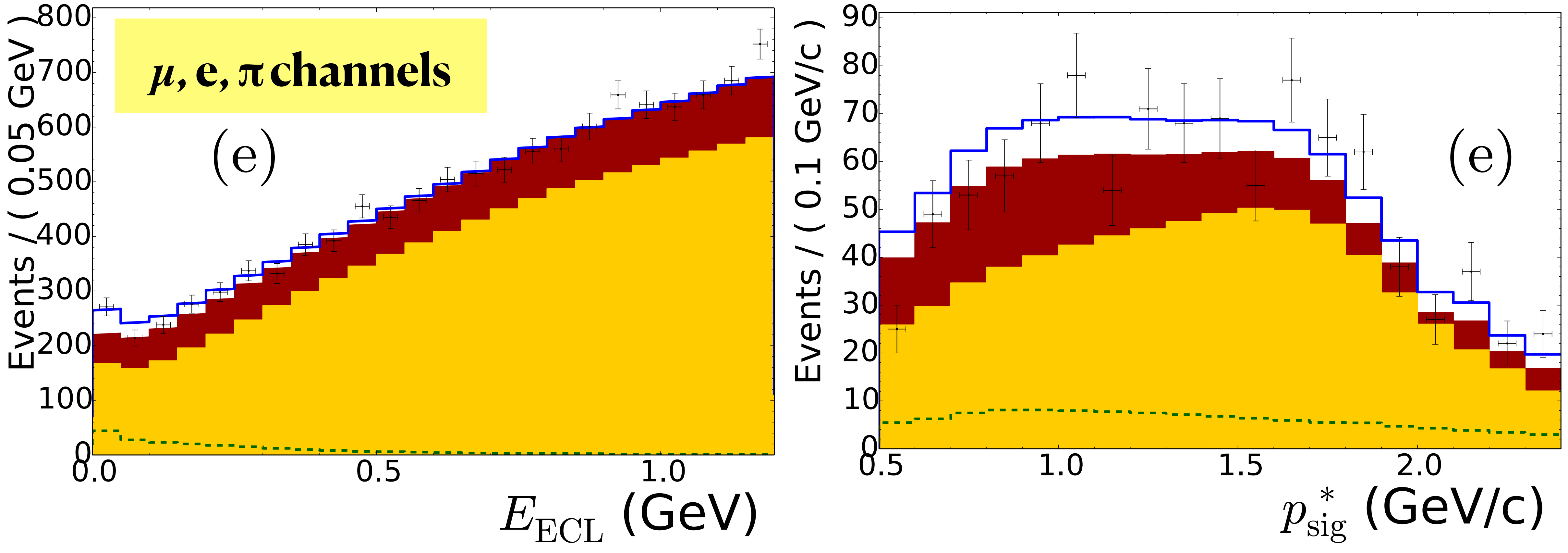
Observable	2022 Belle(II), BaBar	2022 LHCb	Belle-II 5 ab^{-1}	Belle-II 50 ab^{-1}	LHCb 50 fb^{-1}	Belle-II 250 ab^{-1}	LHCb 300 fb^{-1}
$\sin 2\beta/\phi_1$	0.03	0.04	0.012	0.005	0.011	0.002	0.003
γ/ϕ_3	11°	4°	4.7°	1.5°	1°	0.8°	0.35°
α/ϕ_2	4°	–	2°	0.6°	–	0.3°	–
$\|V_{ub}\|/\|V_{cb}\|$	4.5%	6%	2%	1%	2%	< 1%	1%
$S_{CP}(B \to \eta' K_S^0)$	0.08	–	0.03	0.015	–	0.007	–
$A_{CP}(B \to \pi^0 K_S^0)$	0.15	–	0.07	0.04	–	0.018	–
$S_{CP}(B \to K^{*0}\gamma)$	0.32	–	0.11	0.035	–	0.015	–
$R(B \to K^*\ell^+\ell^-)^\dagger$	0.26	0.12	0.09	0.03	0.022	0.01	0.009
$R(B \to D^*\tau\nu)$	0.018	0.026	0.009	0.0045	0.0072	<0.003	<0.003
$R(B \to D\tau\nu)$	0.034	–	0.016	0.008	–	<0.003	–
$\mathcal{B}(B \to \tau\nu)$	24%	–	9%	4%	–	2%	–
$\mathcal{B}(B \to K^*\nu\bar{\nu})$	–	–	25%	9%	–	4%	–
$\mathcal{B}(\tau \to e\gamma)$ UL	42×10^{-9}	–	22×10^{-9}	6.9×10^{-9}	–	3.1×10^{-9}	–
$\mathcal{B}(\tau \to \mu\mu\mu)$ UL	21×10^{-9}	46×10^{-9}	3.6×10^{-9}	0.36×10^{-9}	1.1×10^{-9}	0.07×10^{-9}	5×10^{-9}

Table 1: Projected precision of selected flavour physics measurements at Belle II and LHCb.(The † symbol denotes the measurement in the $1 < q^2 < 6$ GeV/c^2 bin.)

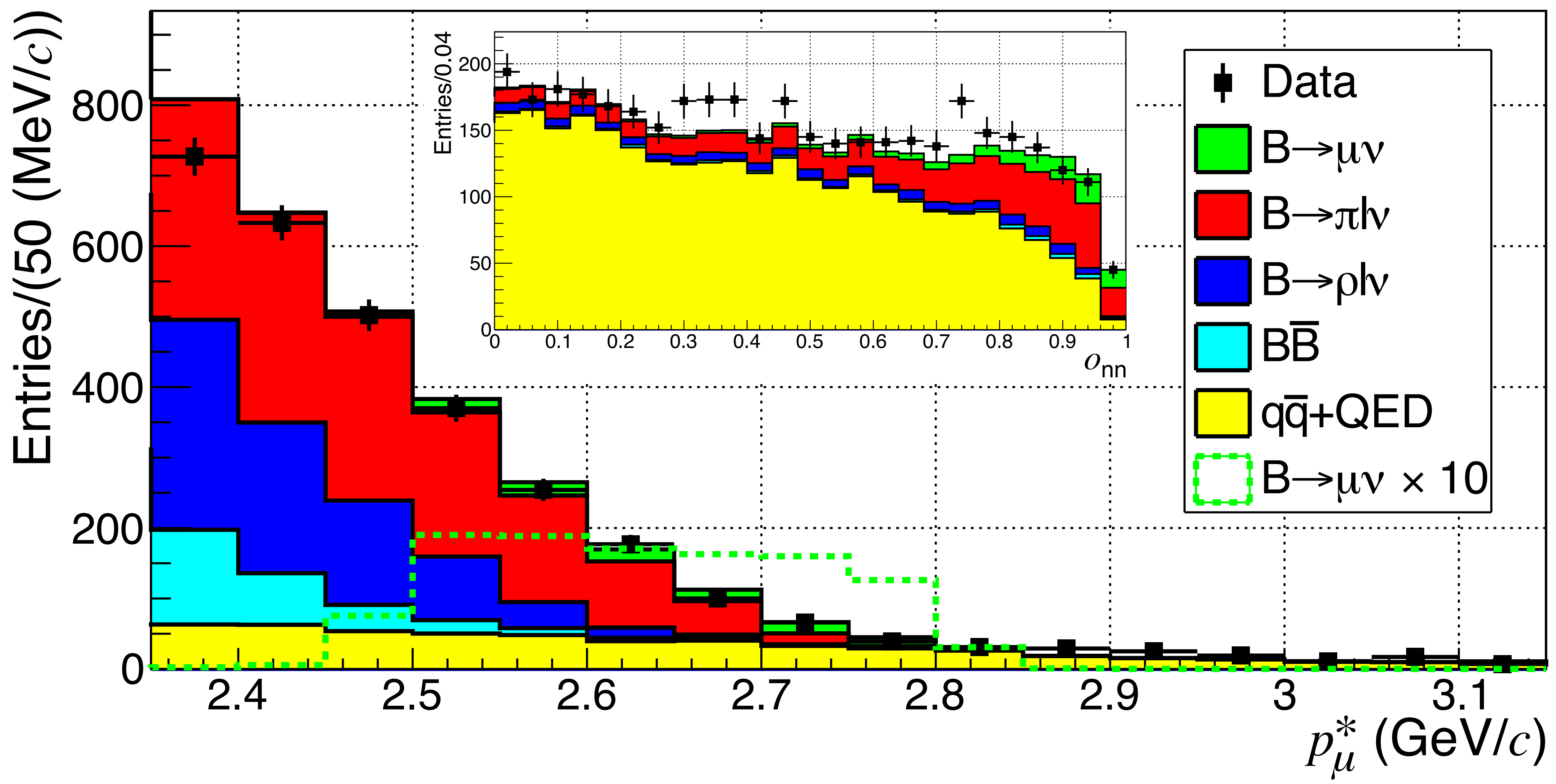
Leptonic $B \to \tau\nu, \mu\nu$



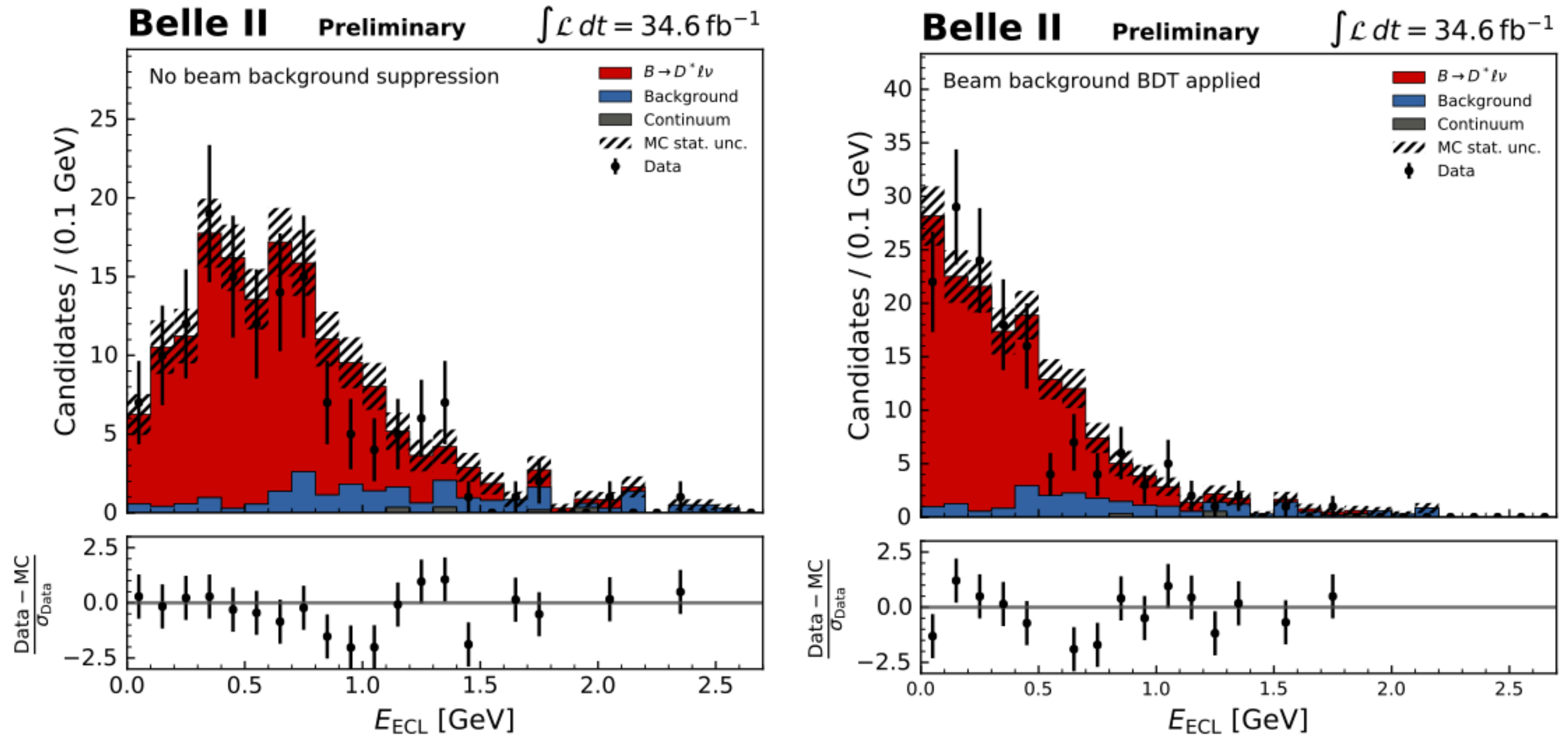
Belle, PRD 92, 051102 (2015) SL tagged B→ τ ν



Belle, Phys. Rev. Lett. 121, 031801 (2018) untagged B→ μ ν



Belle II, B→D* l ν, arXiv: 2008.10299
BDT ECL neutral energy classifier (left before, right after)



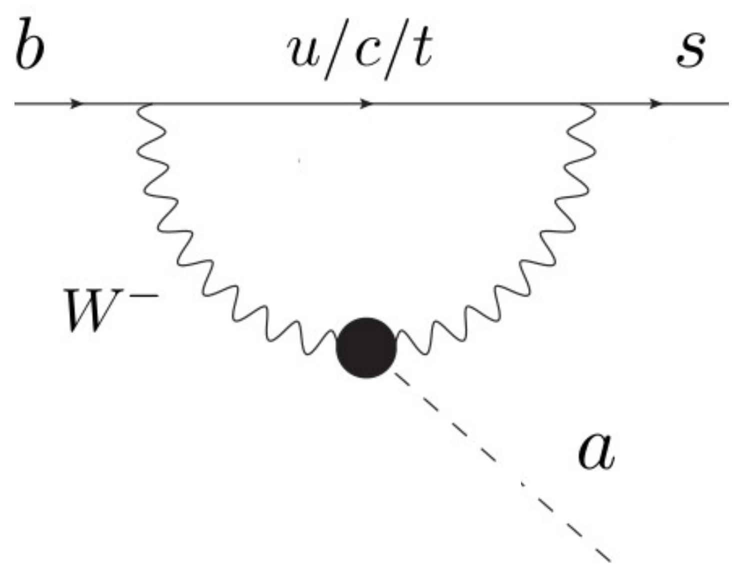
- f_B is known very well - precise extraction of V_{ub}.

Observables	Belle	Belle II	
		5 ab^{-1}	50 ab^{-1}
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	$91 \cdot (1 \pm 24\%)$	9%	4%
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	< 1.7	20%	7%

- **Leptonic** decays will *soon* reach <10% precision on $|V_{ub}|$.

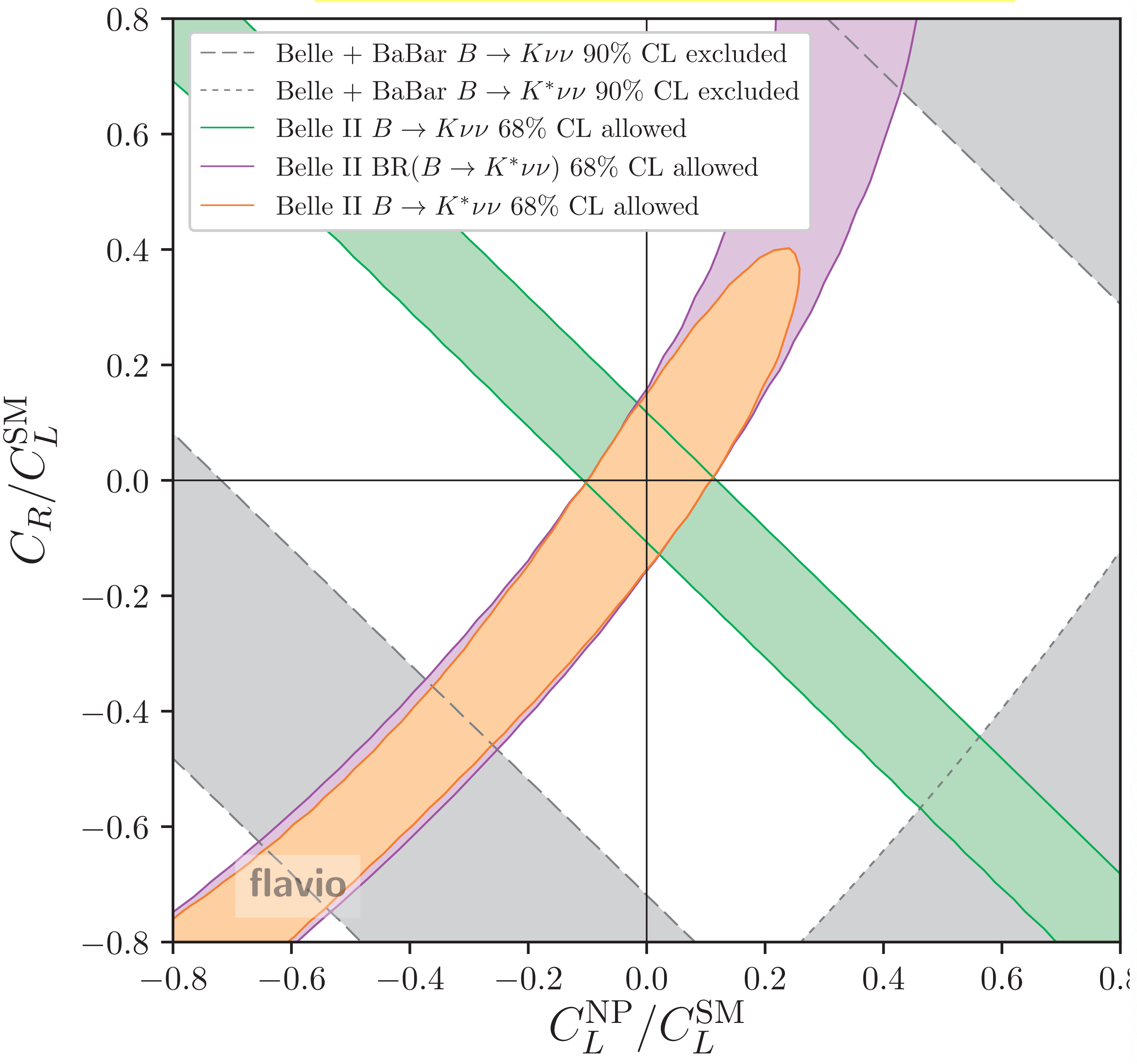
B→ K/K*/π/ρ … + invisible or long-lived

- $B \to K^{(*)}\nu\nu$ studies: We may have significant signal of SM with 2-5 ab^{-1}.
- B→X + ALPs, Dark Photons, **Higgs like scalars**. B→ X + (invisible, γγ, l^+l^-, h^+h^- etc.).

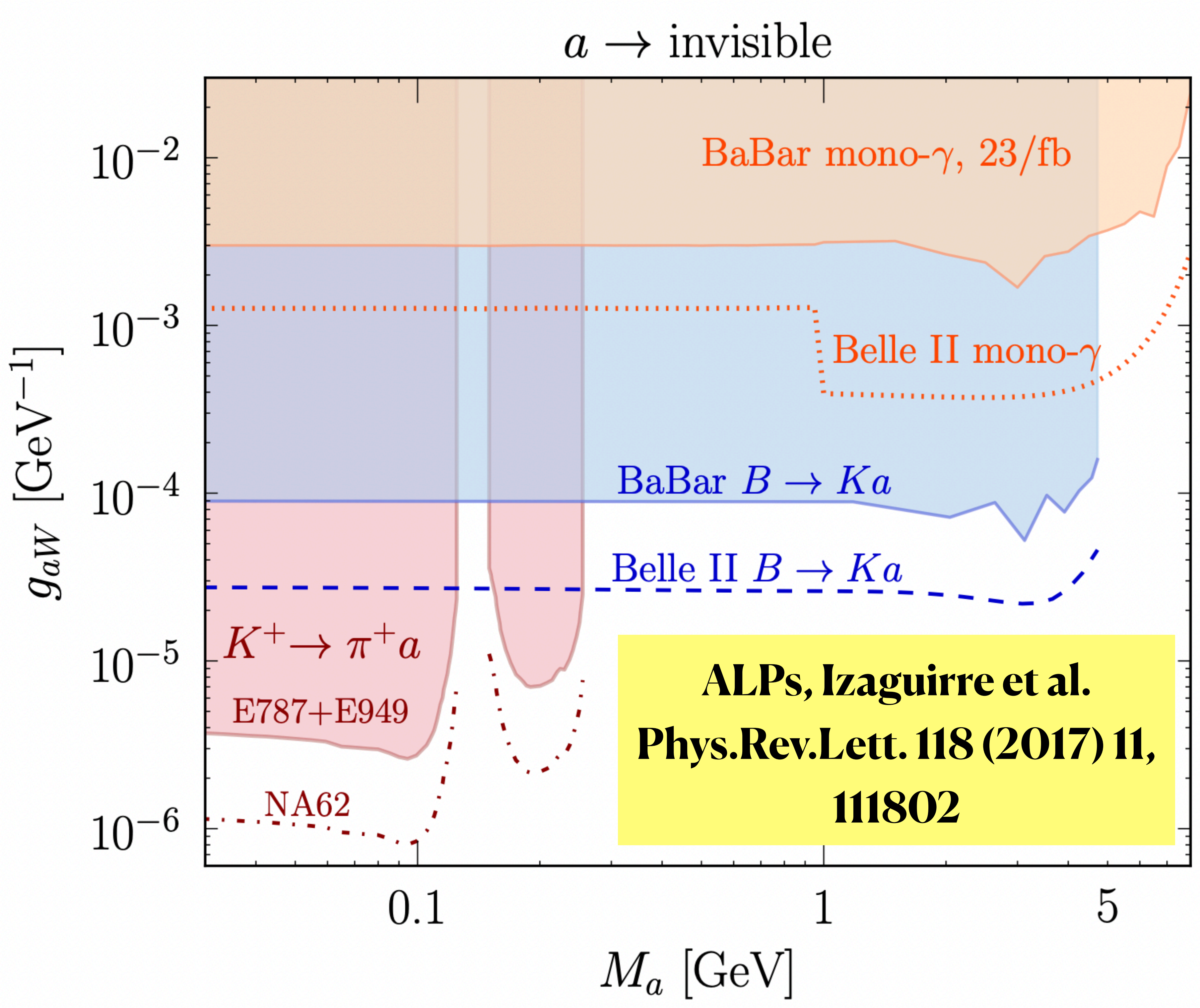


Observables	Belle 0.71 ab^{-1} (0.12 ab^{-1})	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$Br(B^+ \to K^+\nu\bar{\nu})$	$< 450\%$	30%	11%
$Br(B^0 \to K^{*0}\nu\bar{\nu})$	$< 180\%$	26%	9.6%
$Br(B^+ \to K^{*+}\nu\bar{\nu})$	$< 420\%$	25%	9.3%
$F_L(B^0 \to K^{*0}\nu\bar{\nu})$	—	—	0.079
$F_L(B^+ \to K^{*+}\nu\bar{\nu})$	—	—	0.077
$Br(B^0 \to \nu\bar{\nu}) \times 10^6$	< 14	< 5.0	< 1.5
$Br(B_s \to \nu\bar{\nu}) \times 10^5$	< 9.7	< 1.1	—

PTEP 2019 (2019) 12, 123C01

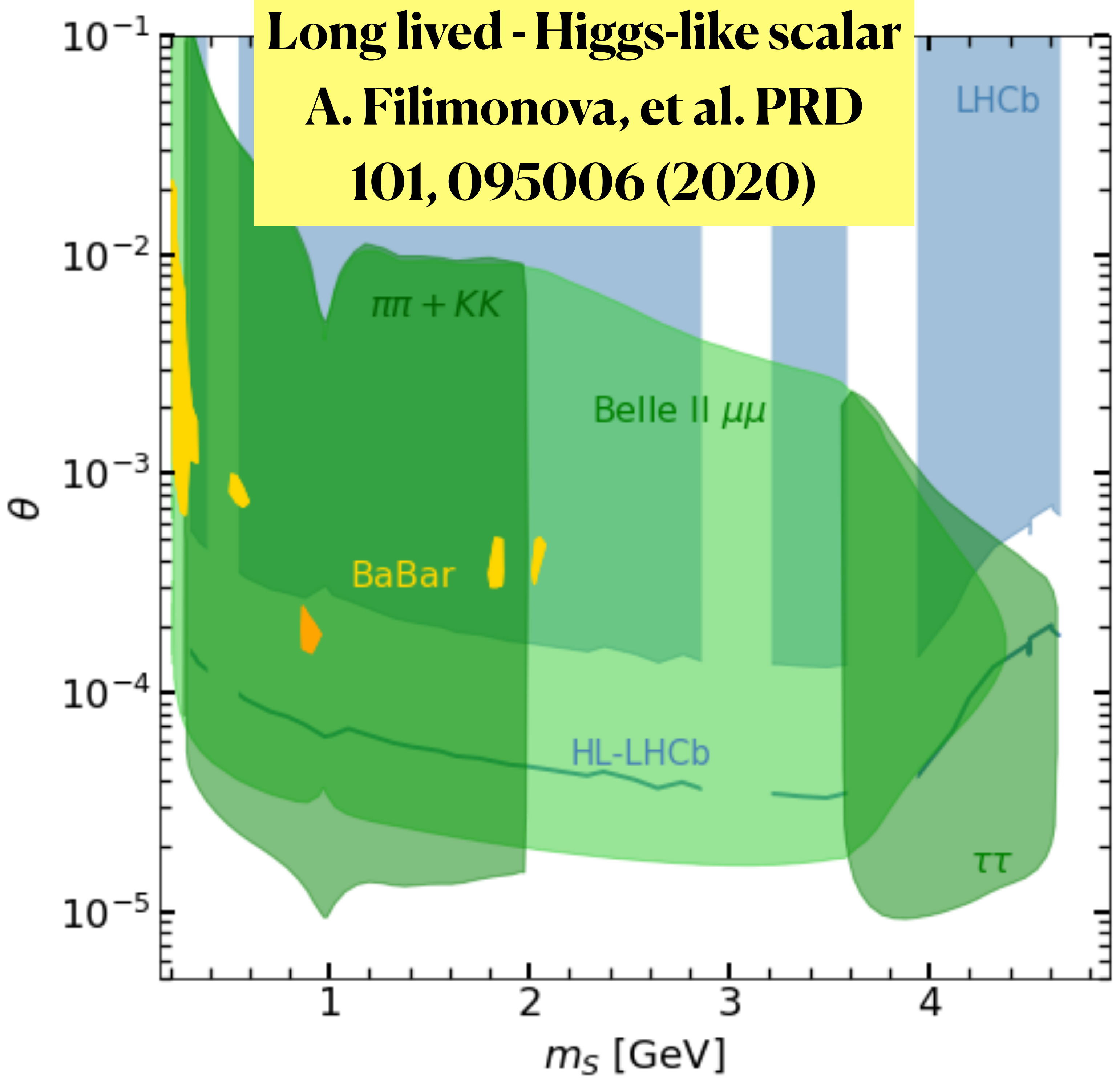


Belle II 2022



ALPs, Izaguirre et al. Phys.Rev.Lett. 118 (2017) 11, 111802

Long lived - Higgs-like scalar A. Filimonova, et al. PRD 101, 095006 (2020)



SuperKEKB / Belle II Program

- **Phase 1(2016): no detector, no collision, test rings**
- **Phase 2 (2018): first collisions complete accelerator**
  - Incomplete detector: Vertex detector replaced by background detector
- **Phase 3 (2019-): luminosity run with complete detector**
  - Pixel Detector (PXD): layer 1 + only 2 ladders in layer 2
  - Full 4-layers strip detector (SVD)
  - First physics paper appeared in January 2020

- *New and difficult accelerator. Additional operational complexity during the pandemic.*
  - Record peak luminosity $3.81 \times 10^{34} cm^{-2}s^{-1}$.
  - Path to reach 2×10^{35} $cm^{-2}s^{-1}$ identified.
  - Still large factors to reach 6.5×10^{35} $cm^{-2}s^{-1}$.

1.Consolidate the machine

Four steps: *Intermediate luminosity* (1-2 x 10^{35} /cm^2/sec, 5ab^{-1});

High Luminosity (6.5 x 10^{35}/cm^2/sec, 50 ab^{-1}) a detector upgrade

Polarisation Upgrade, Advanced R&D

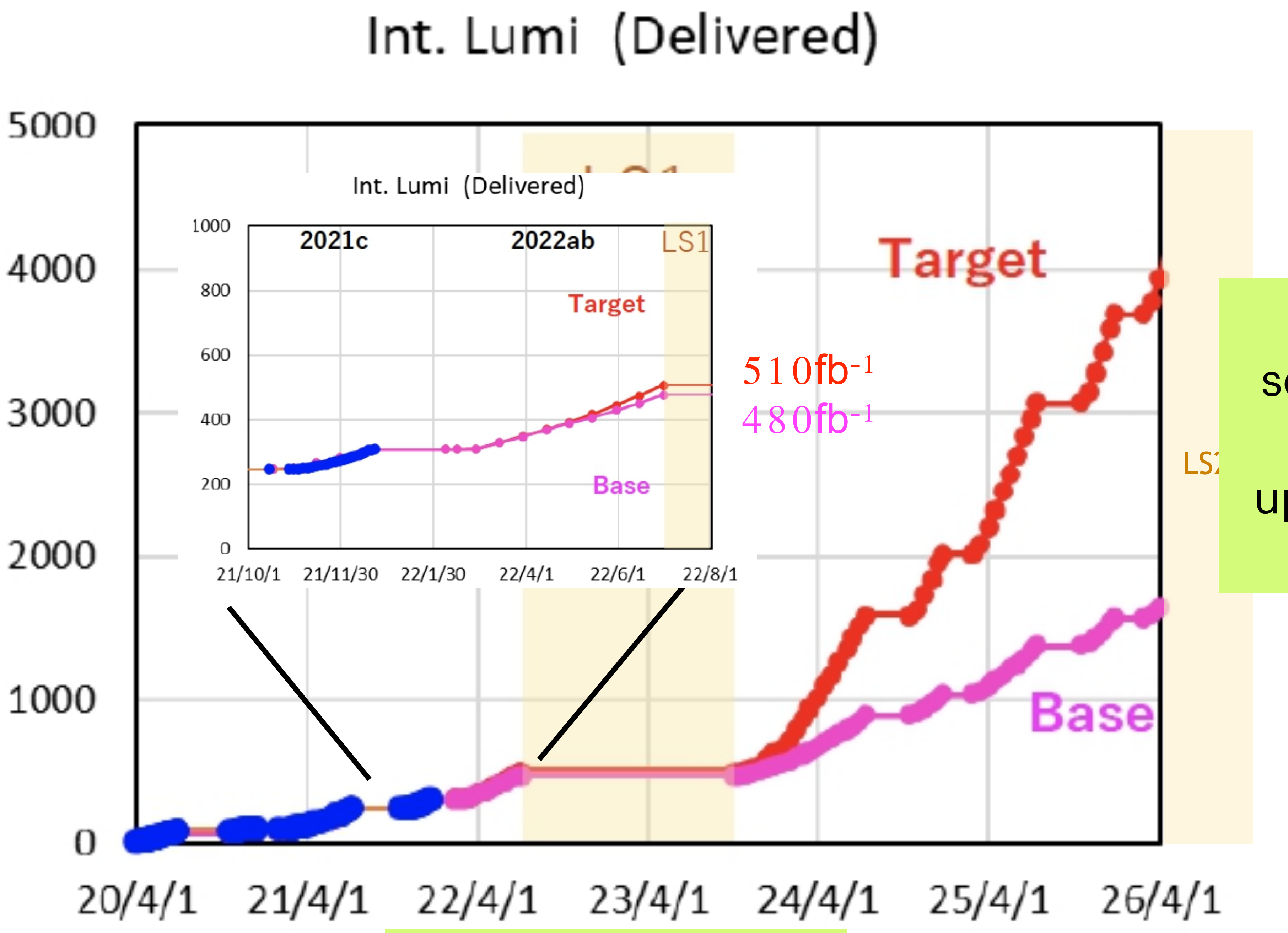
Ultra high luminosity (4 x 10^{36}/cm^2/sec, 250 ab^{-1}), R&D Project

2.Consolidate and complete the detector **(LS1)**

PXD completion in LS1, TOP detector PMT replacements

3.Improve the detector **(LS2)**

Upgrade programs for LS2 and for Ultra high luminosity



LS2 2026 Possible second shutdown for high luminosity upgrades (SuperKEKB and Belle II)

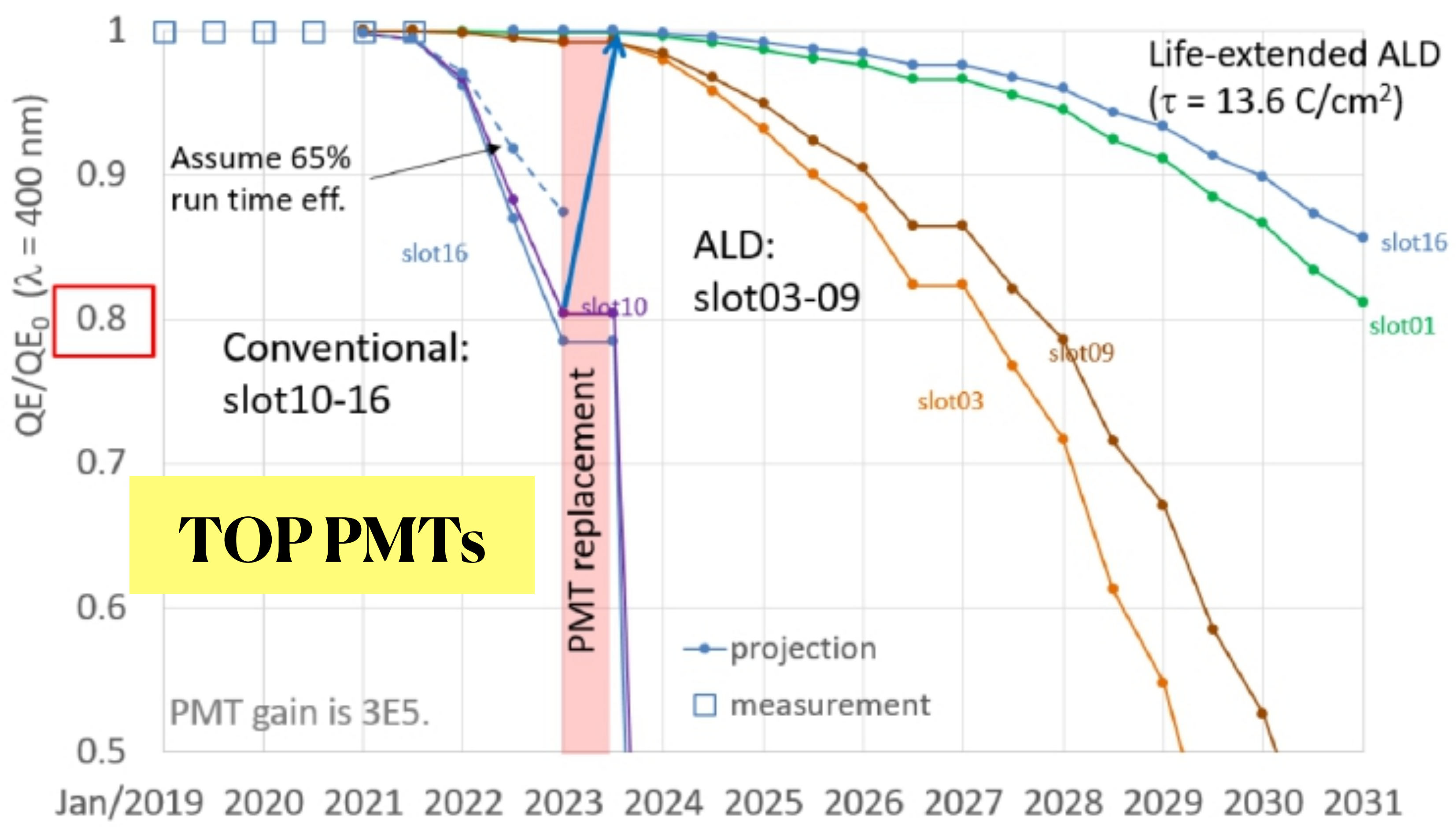
LS1 PXD completion and CDC electronics

Motivation for Belle II upgrades

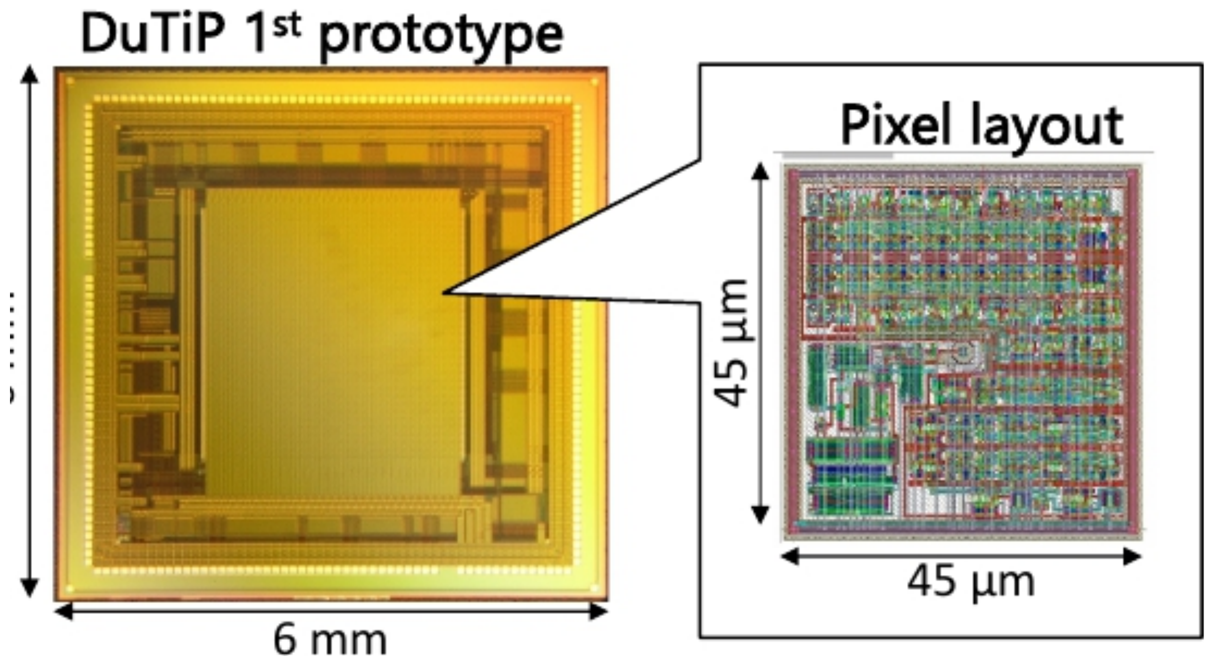
Belle II arXiv:2203.11349 Snowmass white paper on Belle II upgrade

- Improve detector robustness against backgrounds
  - Provide larger safety factors for running at higher luminosity
- Increase longer term subdetector radiation resistance
- Develop the technology to cope with different future paths, e.g. IR redesign for target luminosity
- Improve physics performance: get more physics per ab^{-1}.

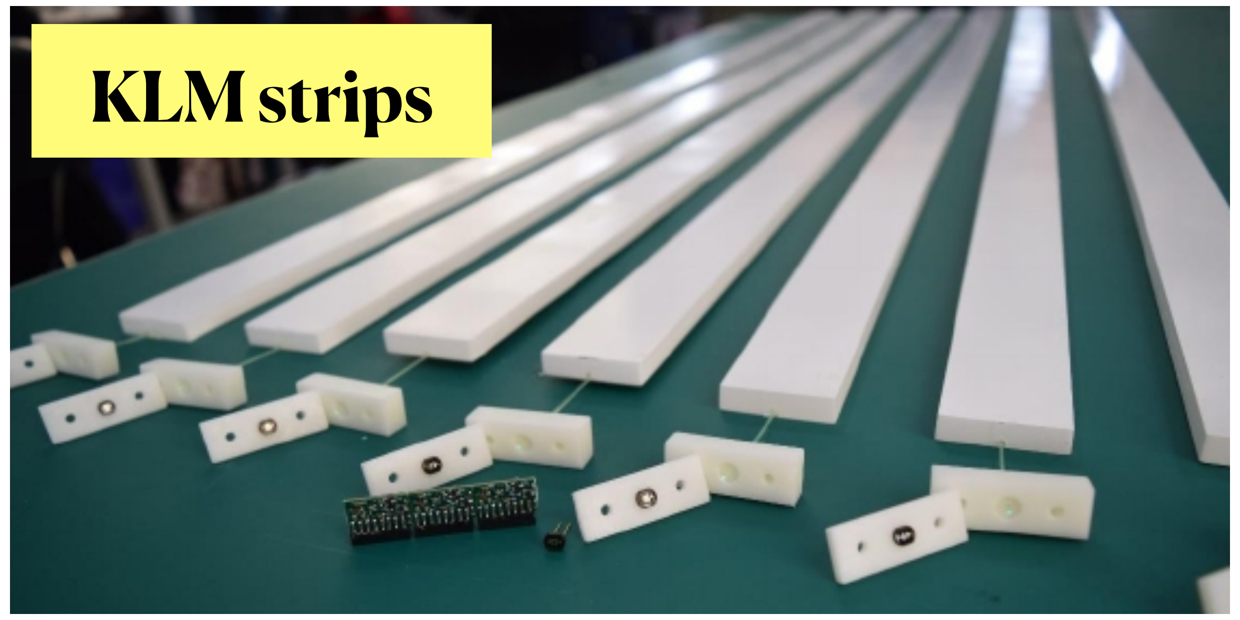
TOP PMTs



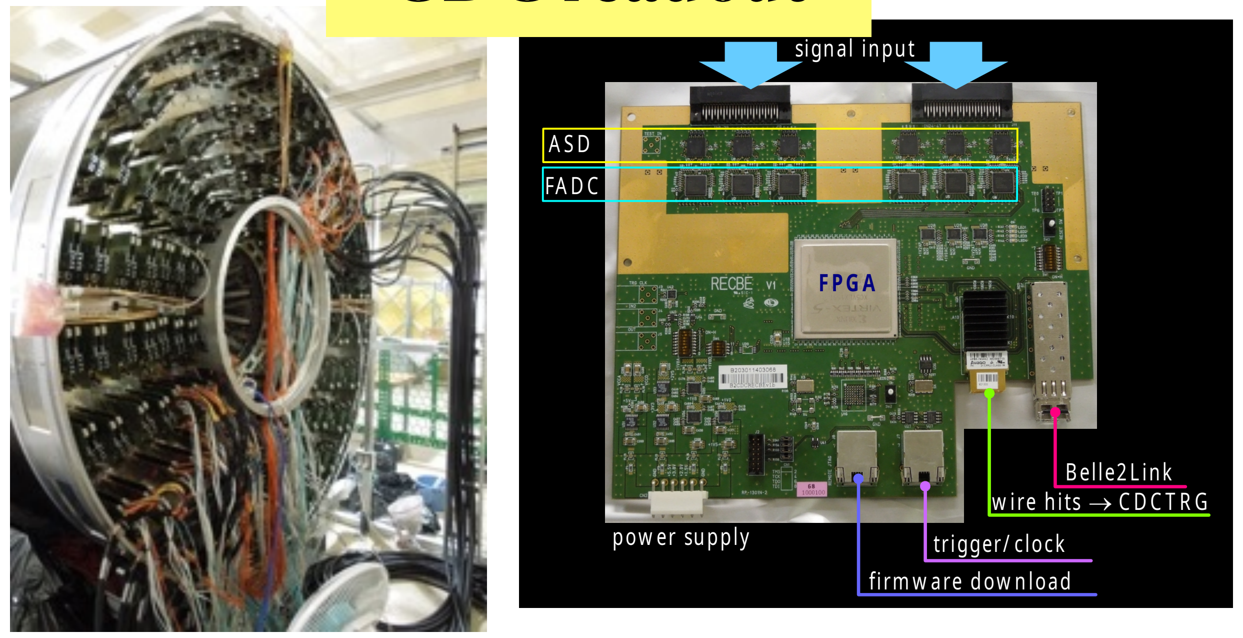
Pixel detector technologies



KLM strips



CDC readout

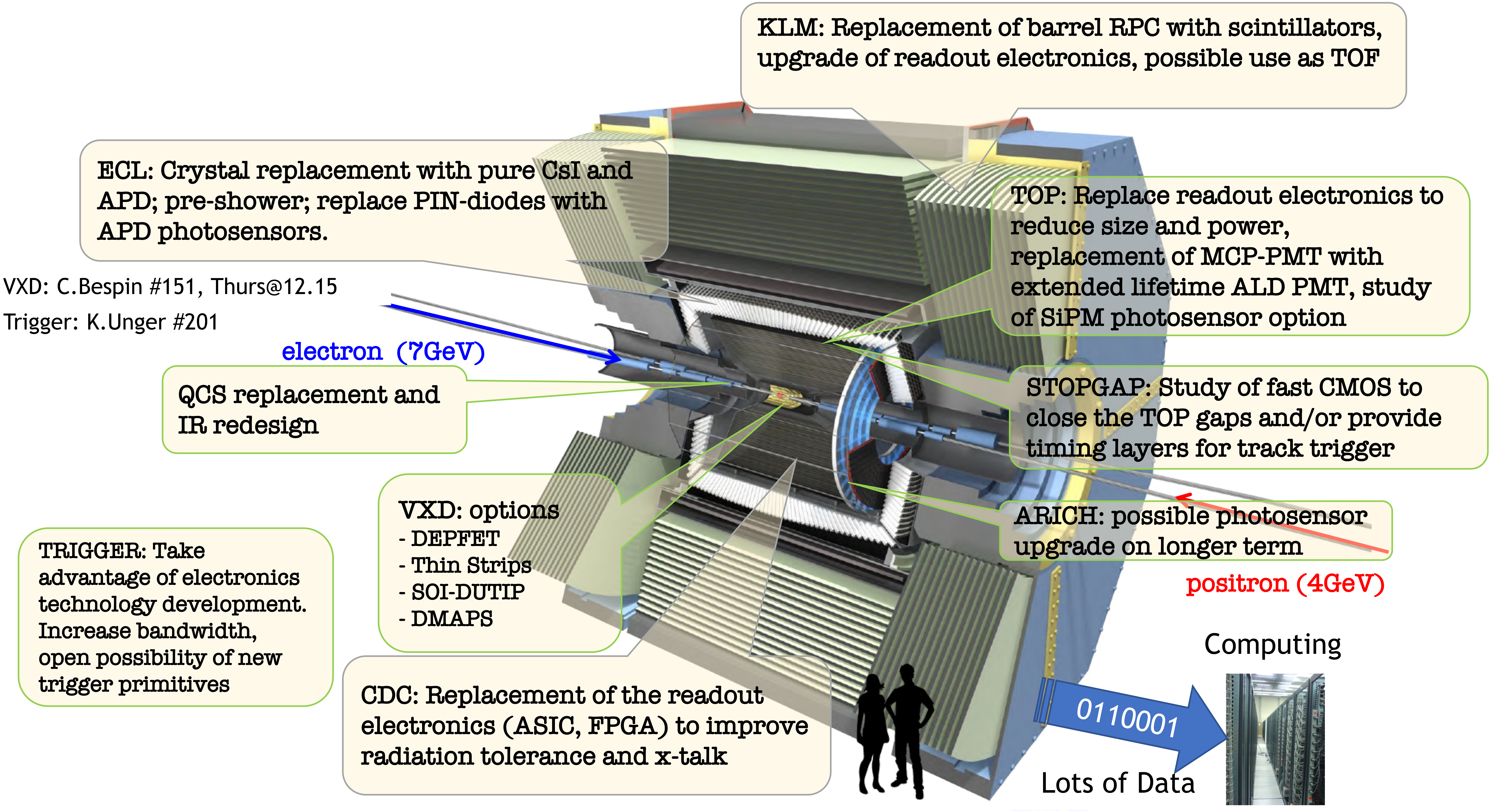


Upgrade overview

Belle II arXiv:2203.11349 Snowmass white paper on Belle II upgrade

VXD: C.Bespin #151, Thurs@12.15

Trigger: K.Unger #201



Upgrade time scale

Belle II arXiv:2203.11349 Snowmass white paper on Belle II upgrade

EOI	Upgrade ideas scope and technology	Time scale
DEPFETs	Adiabatically improved replacement of existing PXD system	LS2
DMAPS	Fully pixelated Depleted CMOS tracker, replacing the current VXD. Evolution from ALICE ITS developed for ATLAS ITK.	LS2
SOI-DUTIP	Fully pixelated system replacing the current VXD based on Dual Timer Pixel concept on SOI	LS2
Thin Strips	Thin and fine-pitch double-sided silicon strip detector system replacing the current SVD and potentially the inner part of the CDC	LS2
CDC	Replacement of the readout electronics (ASIC, FPGA) to improve radiation tolerance and x-talk	< LS2
TOP	Replace readout electronics to reduce size and power, replacement of MCP-PMT with extended lifetime ALD PMT, study of SiPM photosensor option	LS2 and later
ECL	Crystal replacement with pure CsI and APD; pre-shower; replace PIN-diodes with APD photosensors.	> LS2
KLM	Replacement of barrel RPC with scintillators, upgrade of readout electronics, possible use as TOF	LS2 and later
Trigger	Take advantage of electronics technology development. Increase bandwidth, open possibility of new trigger primitives	< LS2 and later
STOPGAP	Study of fast CMOS to close the TOP gaps and/or provide timing layers for track trigger	> LS2
TPC	TPC option under study for longer term upgrade	> LS2

Upgrade Impact

Belle II arXiv:2203.11349 Snowmass white paper on Belle II upgrade

- Identifying crucial performance challenges impacting physics reach.

Topic	VXD	CDC	PID	ECL	KLM
Low momentum track finding	✓	✓			
Track p, M resolution		✓			
IP/Vertex resolution	✓				
Hadron ID		✓	✓		
K_L^0 ID				✓	✓
Lepton ID		✓		✓	✓
π^0, γ				✓	
Trigger	✓	✓			

Table 3: Key performance requirements vs subdetector upgrades.

Topic	VXD	CDC (incl. Trigger)	PID	PID Ω	ECL	KLM
$\mathcal{B}(B \to \tau\nu, B \to K^{(*)}\nu\bar{\nu})$	✓			✓	✓	✓
$\mathcal{B}(B \to X_u \ell\nu)$	✓		✓	✓		✓
R, Polarisation$(B \to D^{(*)}\tau\nu)$	✓				✓	
FEI	✓	✓		✓		
$S_{\rm CP}, C_{\rm CP}(B \to \pi^0\pi^0, K_S^0\pi^0)$	✓	✓			✓	
$S_{\rm CP}, C_{\rm CP}(B \to \rho\gamma)$		✓	✓		✓	
$S_{\rm CP}, C_{\rm CP}(B \to J/\psi K_S^0, \eta' K_S^0)$	✓	✓				
Flavour tagger	✓		✓			
τ LFV		✓			✓	
Dark sector searches		✓			✓	✓

Table 4: Selected key physics channels and high-level analysis algorithms with the sub-detector upgrades that would make substantial impacts to measurement reach. The symbol Ω refers to solid angle coverage of the particle identification systems.

- The transition to a construction project is needed soon
  - SKB International Task Force should reach conclusion by summer 2022
  - The preparation of an Upgrades Conceptual Design Report should start afterwards, ready in 2023

Summary

- 360 fb^{-1} of data collected - now in a competitive realm for flavour measurements!
  - Performance generally better than Belle on lepton ID, neutral/extra calorimeter energy, K_L-ID, tracking at low momenta and *B* full-reconstruction (etc.).

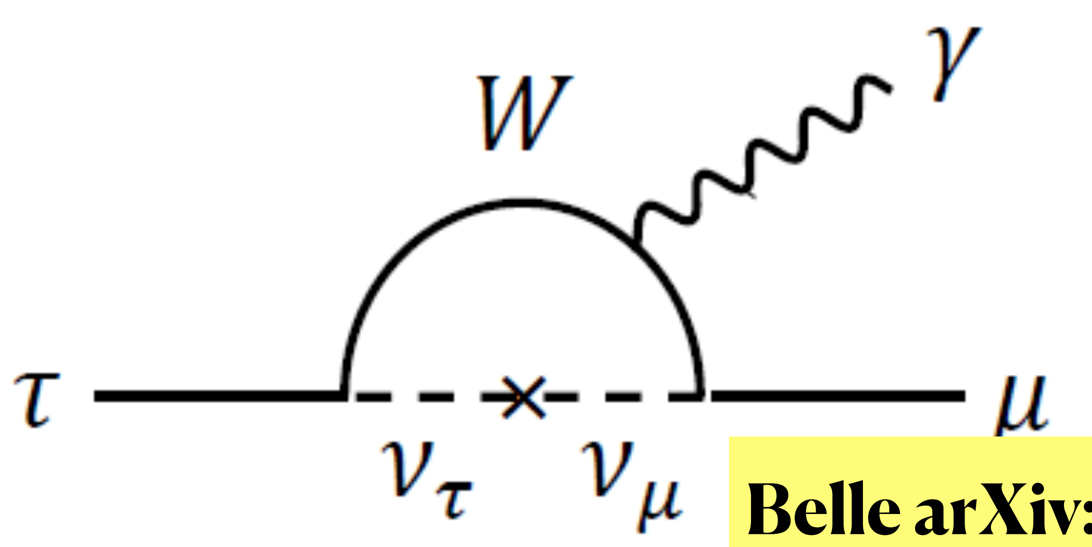
- Focused on some of the recent analyses from Belle II (and some from Belle with Belle II software) that are mostly sensitive to new physics
  - See Belle II publication page for much more.

- **Reaching for 50 ab^{-1} and beyond is still a big challenge, with an ongoing upgrade program to support the ambition.**
  - Most flavour observables will continue to improve uninhibited by systematic or theoretical uncertainties.

Additional slides

τ LFUV & LFV

- New phenomena coupling to τs can be probed directly via ee→ττ.
- Good near term prospects for exotic searches, e.g. τ→l α (invisible), and τ decay LFUV (need to push Lepton ID systematics).

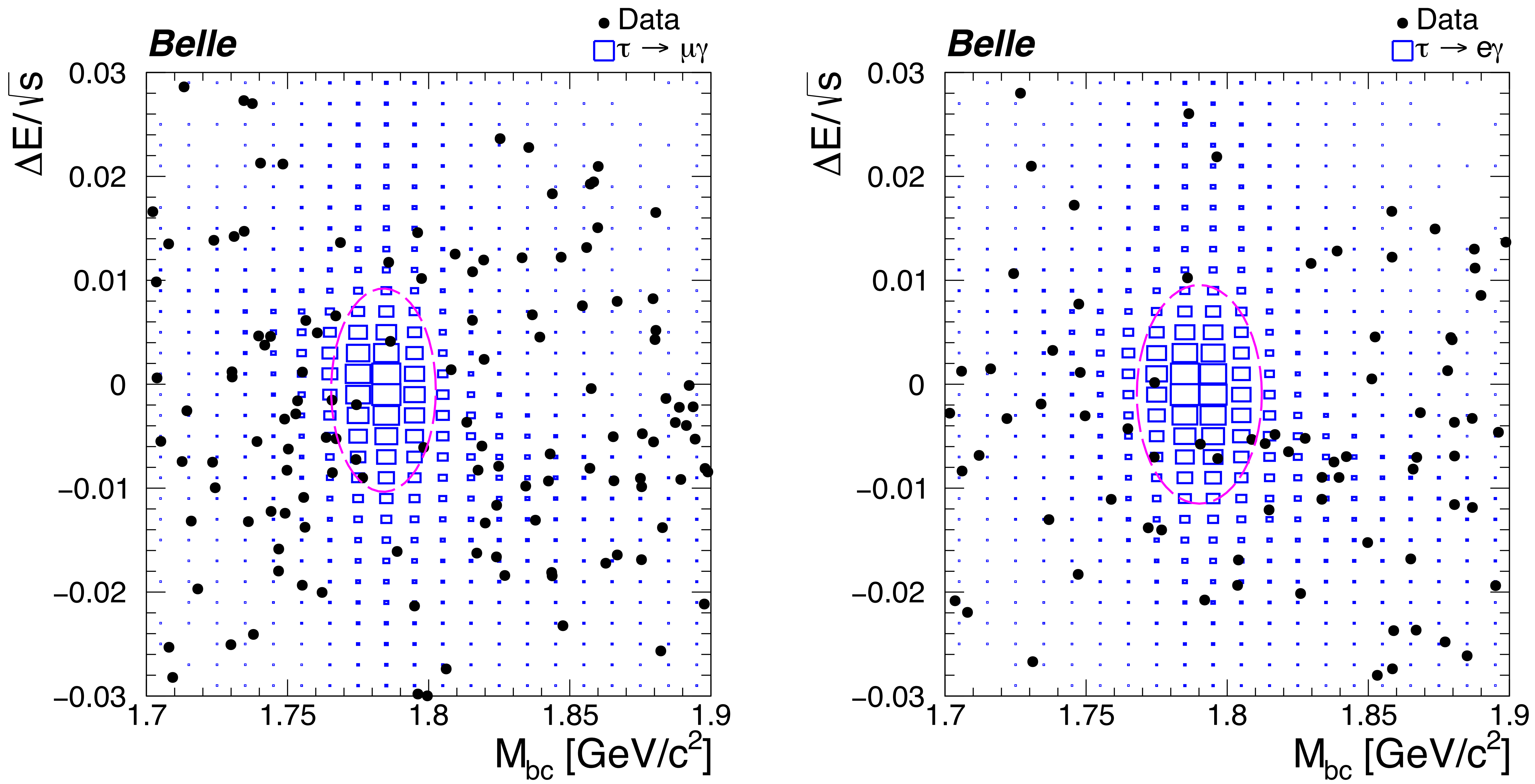


Belle arXiv:2103.12994

$$\mathcal{B}(\tau^\pm \to \mu^\pm\gamma) < \frac{\tilde{s}_{90}}{2\epsilon N_{\tau\tau}} = 4.2 \times 10^{-8},$$

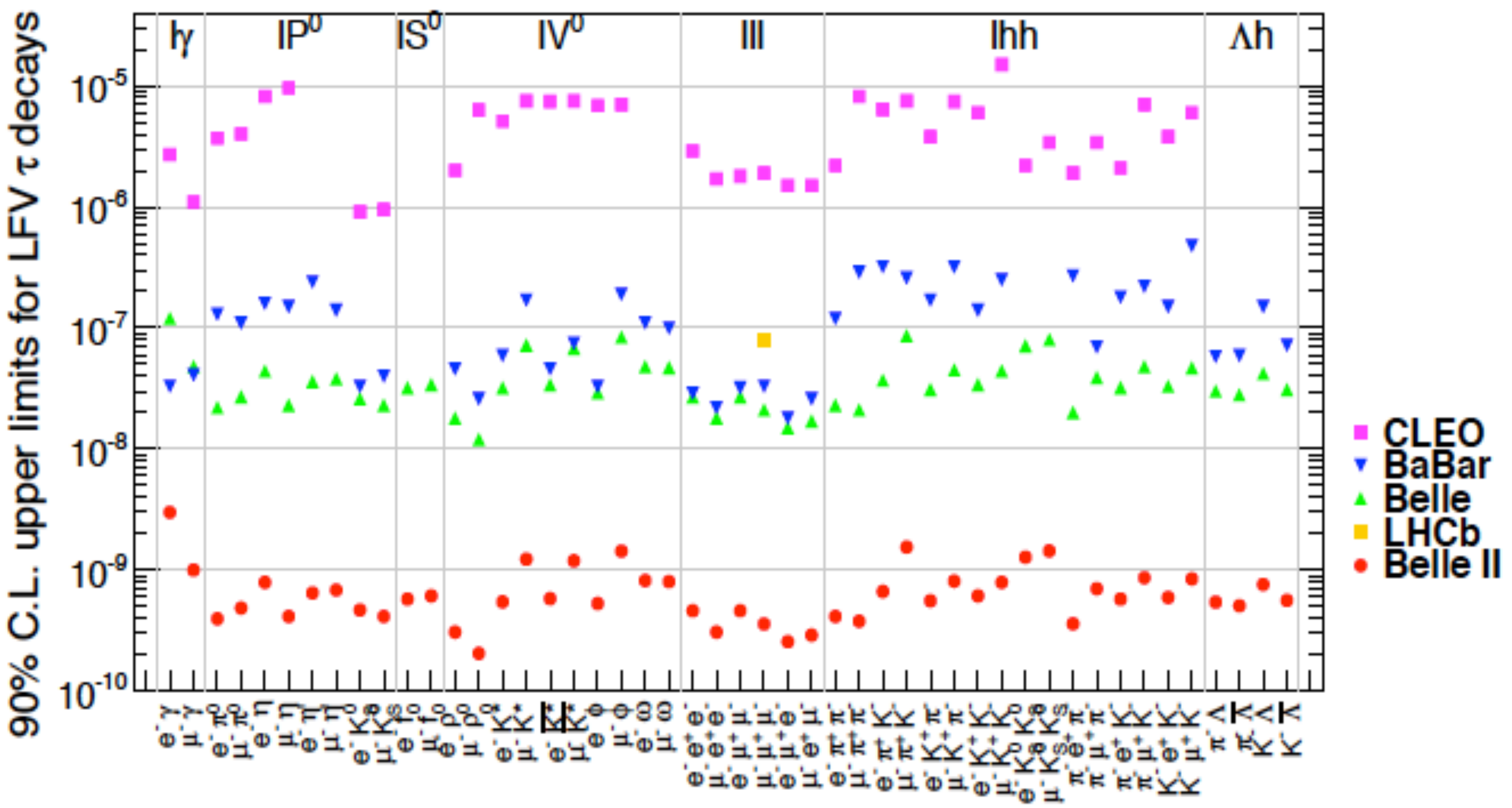
$$\mathcal{B}(\tau^\pm \to e^\pm\gamma) < \frac{\tilde{s}_{90}}{2\epsilon N_{\tau\tau}} = 5.6 \times 10^{-8},$$

Belle JHEP 10 (2021) 19



(a) $\tau^\pm \to \mu^\pm\gamma$ (b) $\tau^\pm \to e^\pm\gamma$

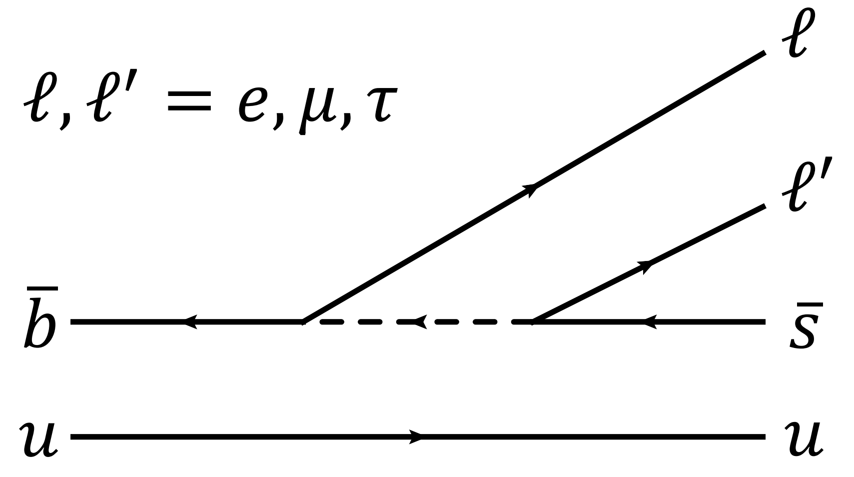
PTEP 2019 (2019) 12, 123C01



$B \to \tau\ell,\ B \to X_s\tau\tau$

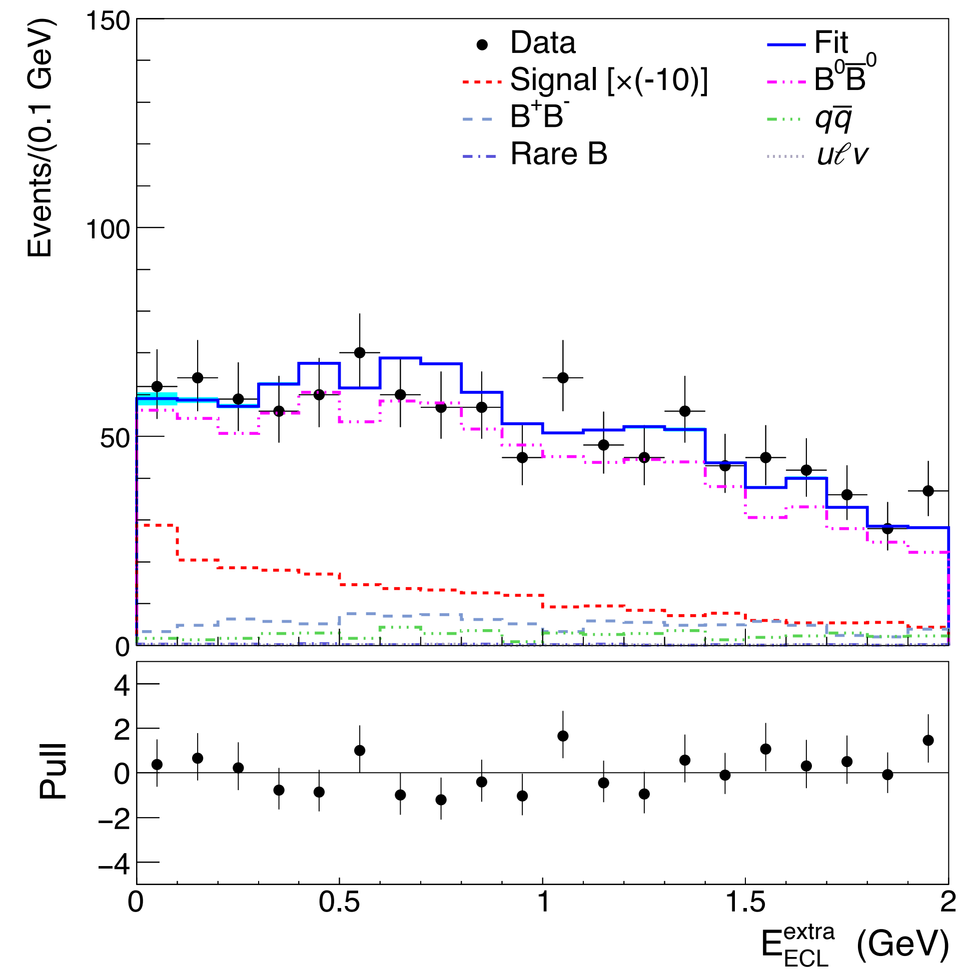
- LFV channels, use tagging to infer recoil mass near m_τ.
- LF conserving channels with τ probably out of reach of SM, but good for NP sensitivity.
- Results from Belle II on the way.

$$\mathrm{Br}(B^+ \to K^{*+}\tau^+\tau^-)_{\mathrm{SM}} = (0.99 \pm 0.12)\cdot 10^{-7},$$
$$\mathrm{Br}(B^0 \to K^{*0}\tau^+\tau^-)_{\mathrm{SM}} = (0.91 \pm 0.11)\cdot 10^{-7},$$



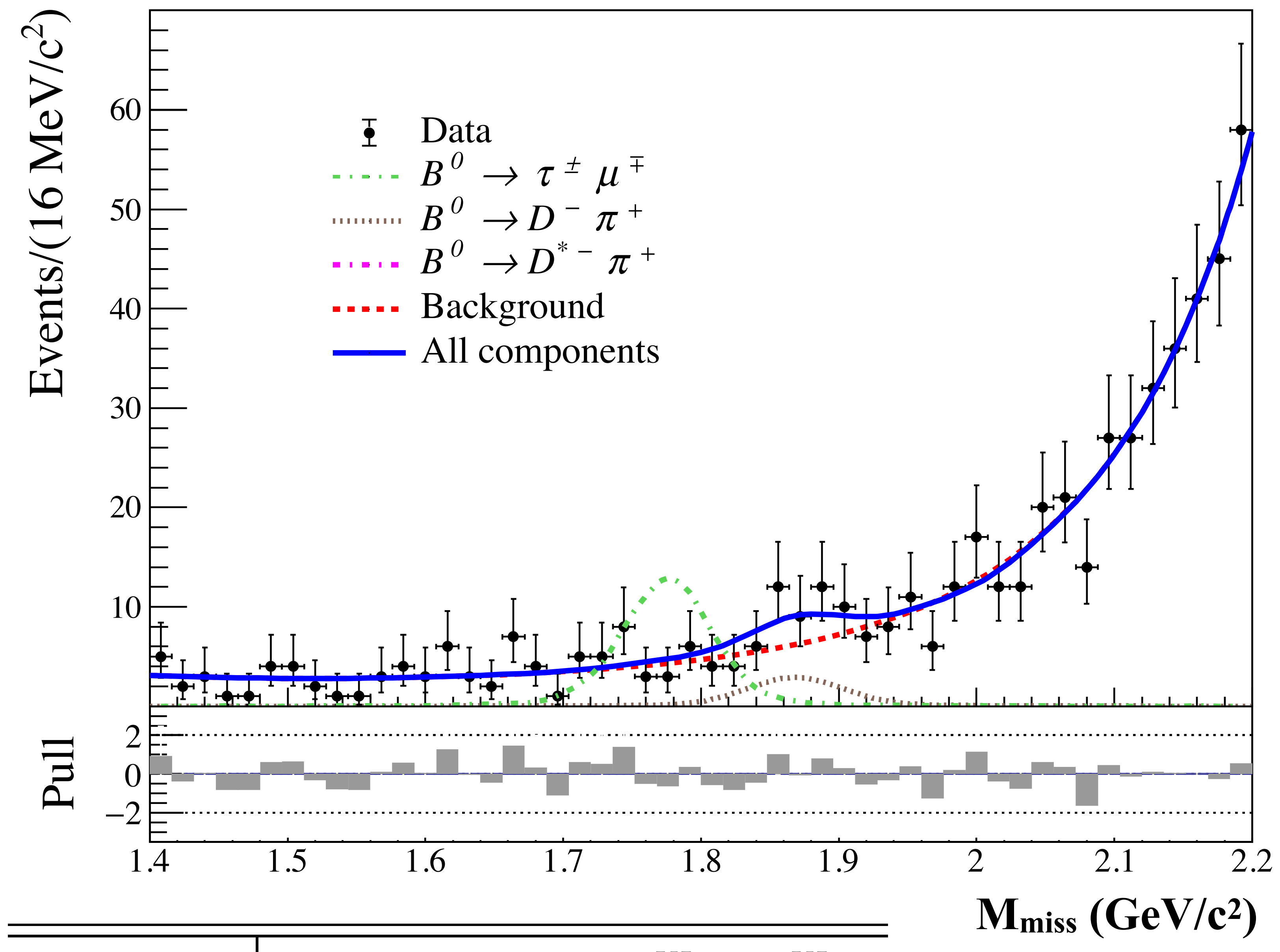
Belle arXiv: 2110.03871

Signal Mode	$M_{K^{*0}\pi^-}$ (GeV/c^2)	M^2_{miss} (GeV^2/c^4)
$K^{*0}e^+e^-$	> 1.4	> 3.2
$K^{*0}e^\mp\mu^\pm$	> 1.4	> 1.6
$K^{*0}\mu^+\mu^-$	> 1.6	> 1.6
$K^{*0}\pi^\mp e^\pm$	> 1.4	> 2.0
$K^{*0}\pi^\mp\mu^\pm$	> 1.4	> 2.0
$K^{*0}\pi^+\pi^-$	> 1.5	< 9



$$\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-) < 2.0 \times 10^{-3} \text{ at } 90\% \text{ confidence level}$$

Belle *Phys.Rev.D* 104 (2021) 9, L091105



Mode	ε $(\times 10^{-4})$	N_{sig}	$N^{\mathrm{UL}}_{\mathrm{sig}}$	$\mathcal{B}^{\mathrm{UL}}$ $(\times 10^{-5})$
$B^0 \to \tau^\pm\mu^\mp$	11.0	$1.8^{+8.2}_{-7.6}$	12.4	1.5
$B^0 \to \tau^\pm e^\mp$	9.8	$0.3^{+8.8}_{-8.2}$	11.6	1.6

Observables	Belle 0.71 ab^{-1} (0.12 ab^{-1})	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathrm{Br}(B^+ \to K^+\tau^+\tau^-)\cdot 10^5$	< 32	< 6.5	< 2.0
$\mathrm{Br}(B^0 \to \tau^+\tau^-)\cdot 10^5$	< 140	< 30	< 9.6
$\mathrm{Br}(B^0_s \to \tau^+\tau^-)\cdot 10^4$	< 70	< 8.1	—
$\mathrm{Br}(B^+ \to K^+\tau^\pm e^\mp)\cdot 10^6$	—	—	< 2.1
$\mathrm{Br}(B^+ \to K^+\tau^\pm\mu^\mp)\cdot 10^6$	—	—	< 3.3
$\mathrm{Br}(B^0 \to \tau^\pm e^\mp)\cdot 10^6$	<16	—	< 1.6
$\mathrm{Br}(B^0 \to \tau^\pm\mu^\mp)\cdot 10^6$	<15	—	< 1.3

Belle II 2022