Quirks in Quark Flavour Physics, June 14-17, 2022, Zadar (Croatia)

Recent Belle II results related to anomalies in semileptonic and hadronic B decays

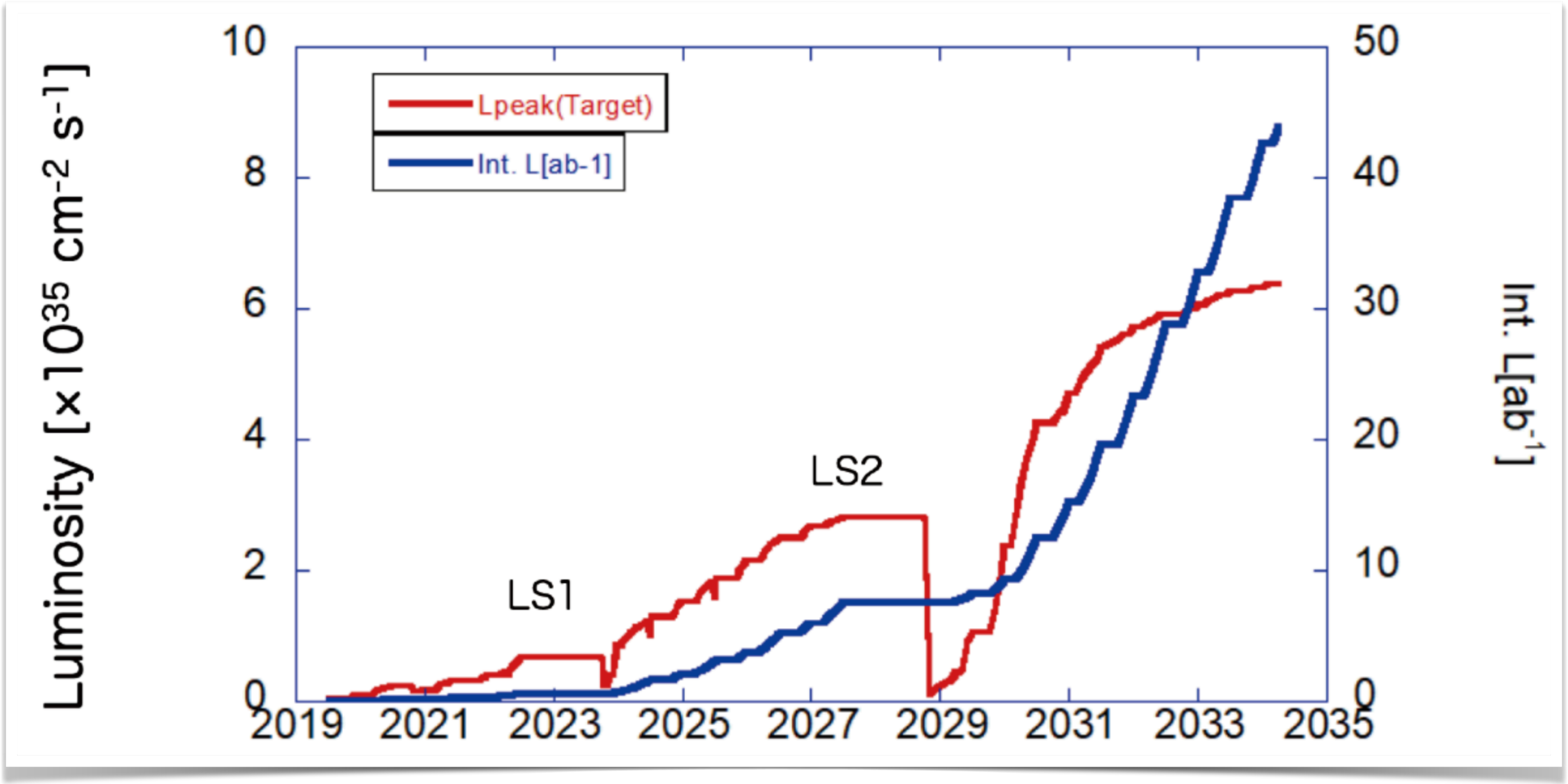
Christoph Schwanda
for the Belle II collaboration

Belle II luminosity

- The experiment is collecting date since 2019 and will reach an integrated luminosity of about **450/fb** by end of June 2022

- After the ongoing run, the experiment enters long shutdown 1 (LS1) until autumn 2023

- The ultimate goal of Belle II by >2030 is an integrated luminosity of **50/ab**

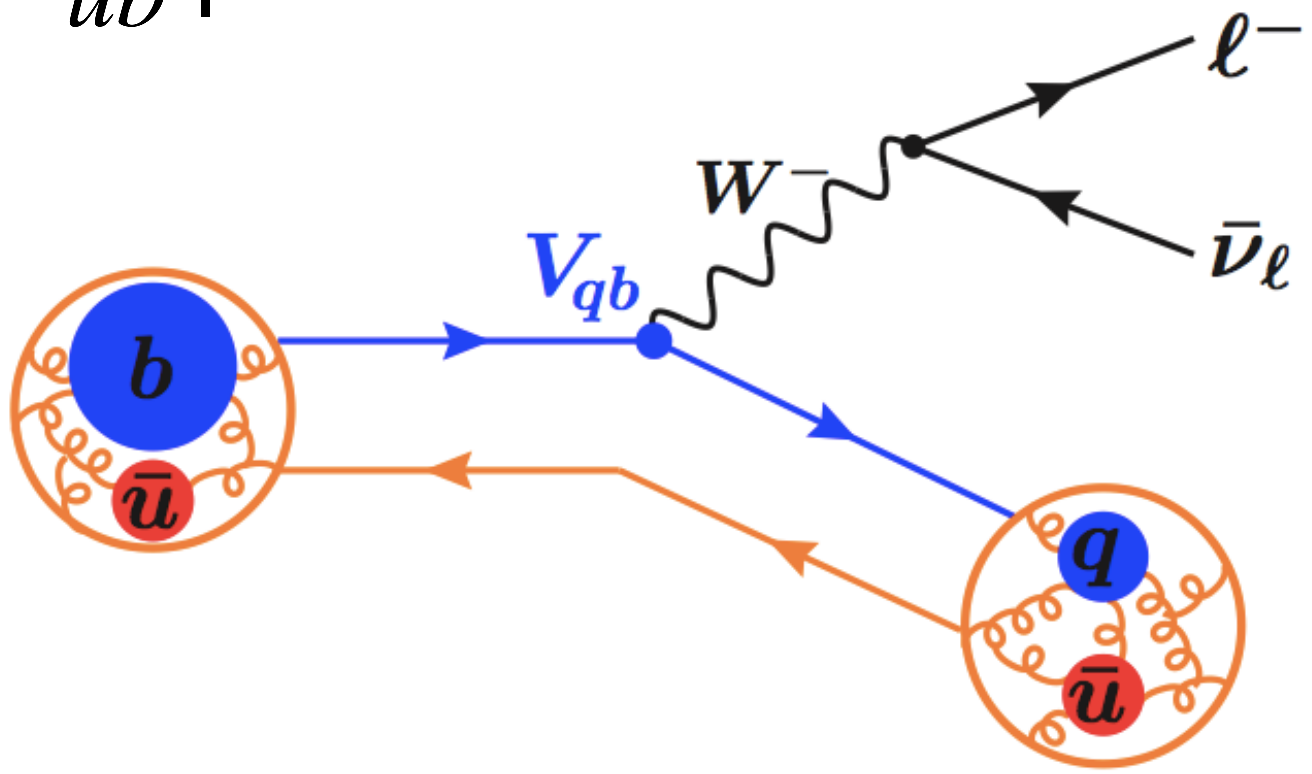


Semileptonic B decays

Semileptonic B decays

Determination of the CKM elements $|V_{cb}|$ and $|V_{ub}|$

- SL B decays are studied to determine the CKM elements $|V_{cb}|$ and $|V_{ub}|$
  - $|V_{xb}|$ are limiting the global constraining power of UT fits
  - Important inputs in predictions of SM rates for ultrarare decays such as $B_s \to \mu\nu$ and $K \to \pi\nu\nu$
- The determinations can be
  - *Exclusive* — from a single final state
  - *Inclusive* — sensitive to all SL final states

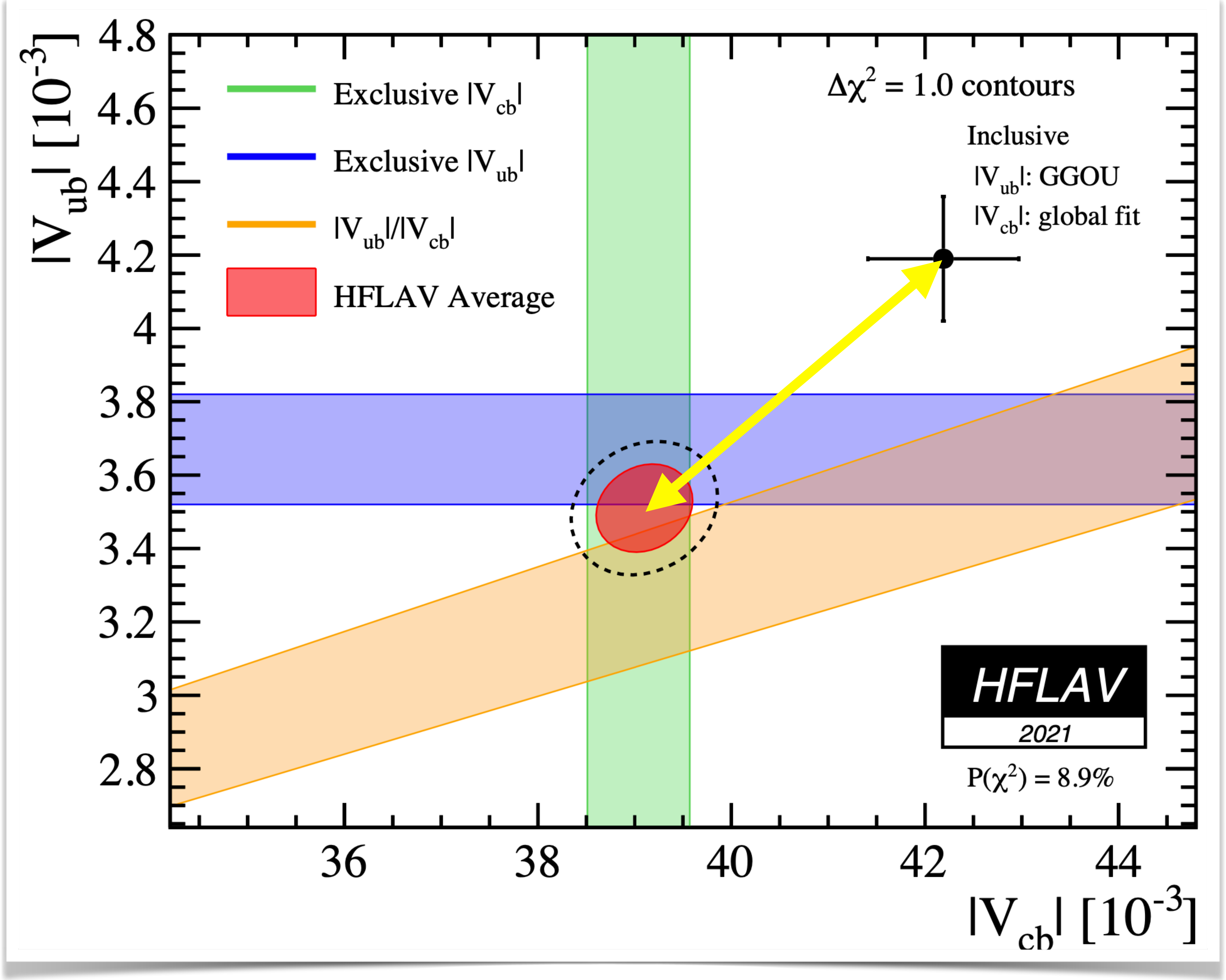


$$d\Gamma \propto G_F^2 |V_{qb}|^2 \left| L_\mu \langle X | \bar{q} \gamma_\mu P_L b | B \rangle \right|^2$$

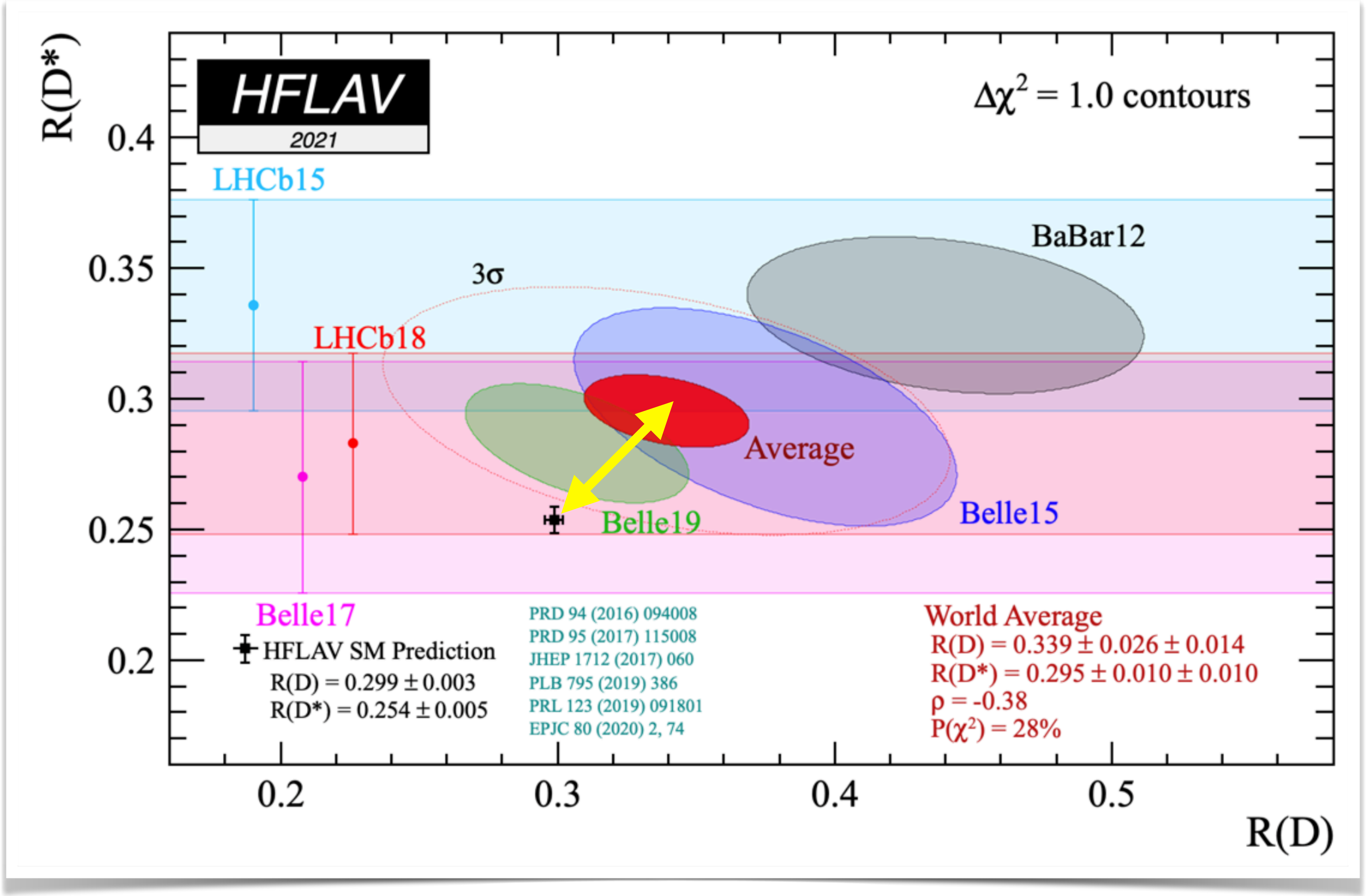
	Experiment	Theory
Exclusive $\lvert V_{cb} \rvert$	$B \to D l\nu$, $D^* l\nu$ (low backgrounds)	Lattice QCD, light cone sum rules
Inclusive $\lvert V_{cb} \rvert$	$B \to X l\nu$ (higher background)	Operator product expansion

Semileptonic B decays

Anomalies



~3σ difference between *inclusive* and *exclusive* $|V_{xb}|$

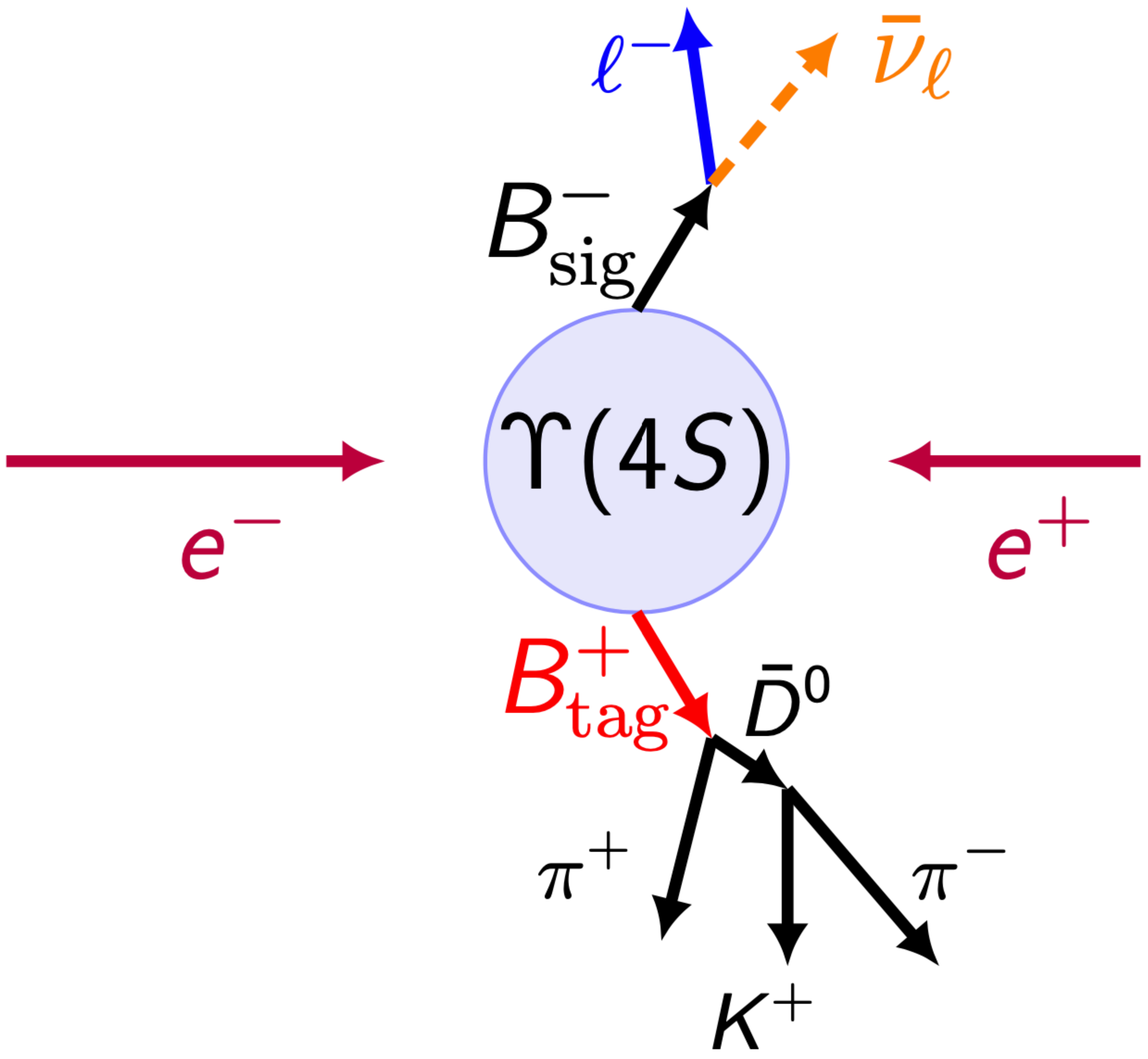


~3σ excess in semitauonic B decays

Untagged vs. Tagged

Untagged:
only $B_{\rm sig}$ is reconstructed

high signal yield (+)
high backgrounds (-)
poor neutrino reconstruction (-)

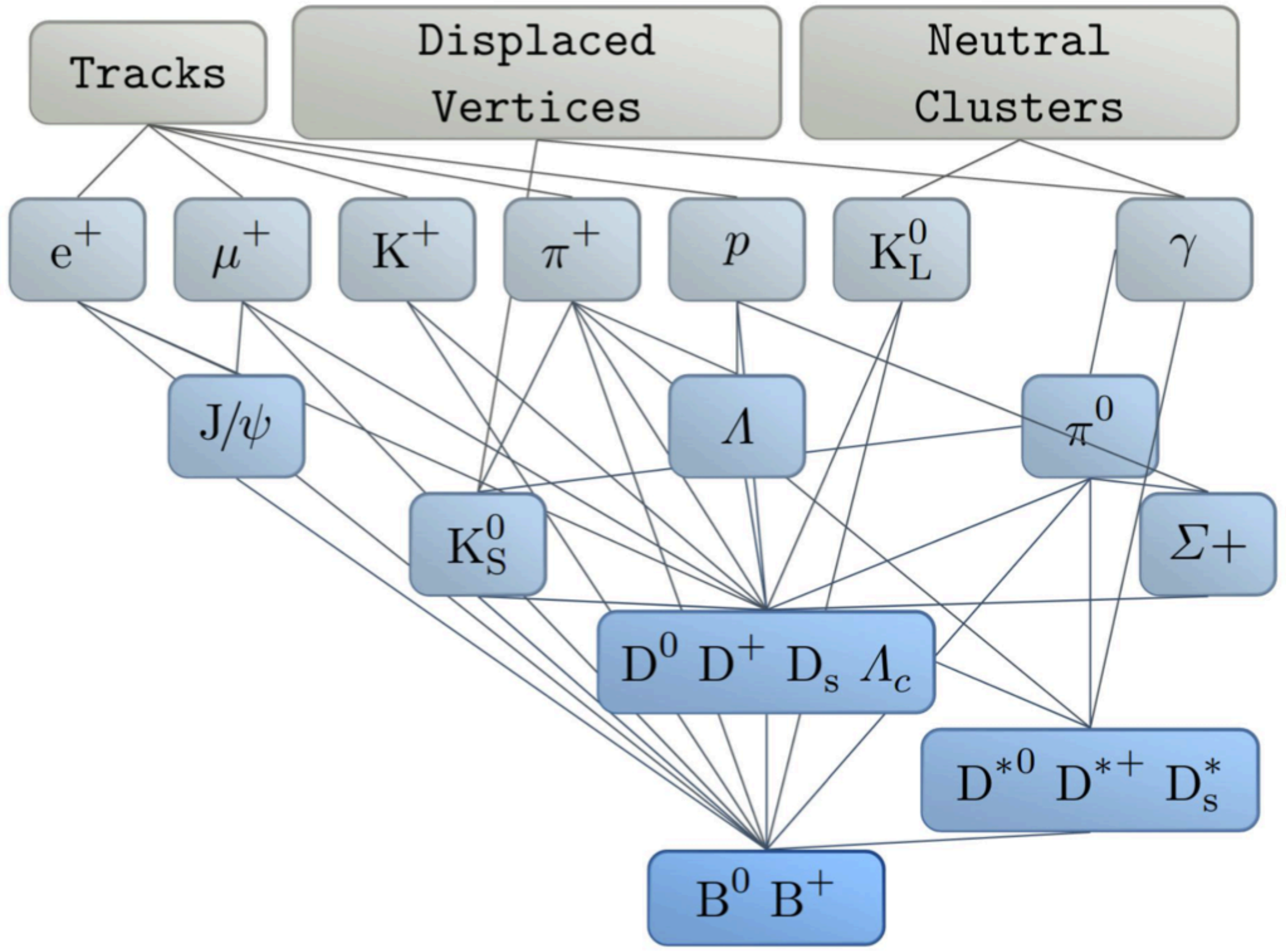


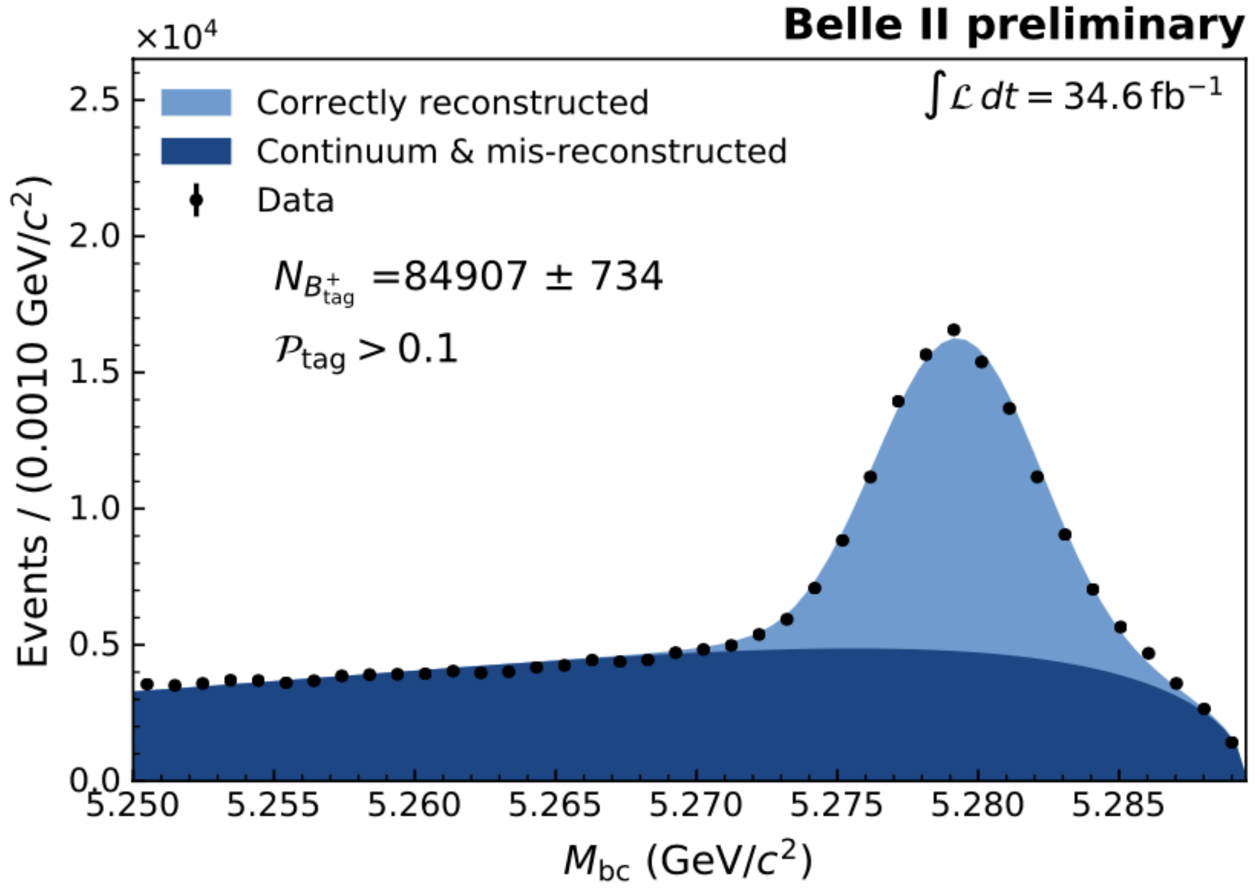
Tagged:
$B_{\rm sig}$ and $B_{\rm tag}$ are reconstructed

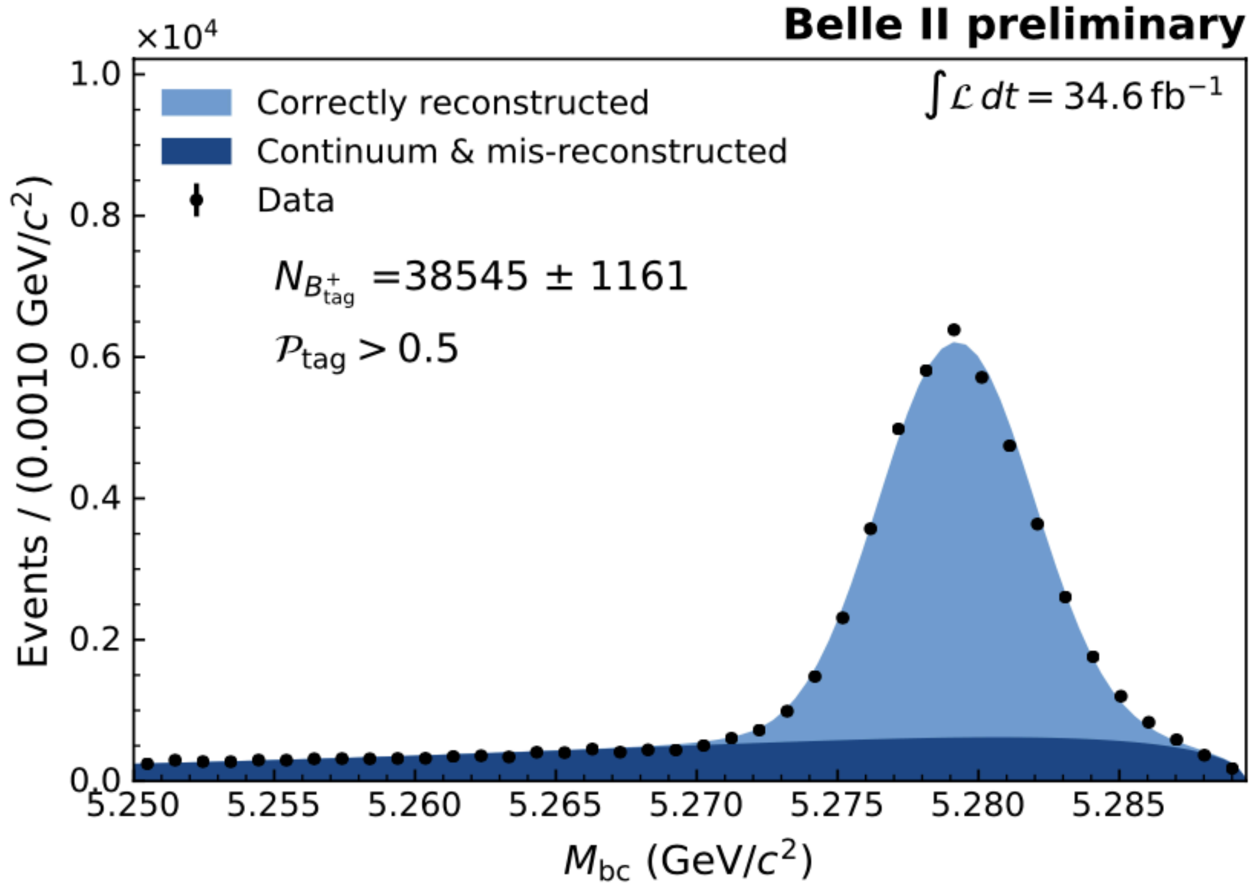
signal yield $O(10^3)$ lower (-)
low backgrounds (+)
good neutrino reconstruction (+)
tag calibration (-)

Hadronic tagging at Belle II

Comput Softw Big Sci (2019) 3: 6.







$$M_{bc} = \sqrt{E^2_{beam}/4 - (p^{\rm cm}_{B_{\rm tag}})^2} > 5.27\ \mathrm{GeV}/c^2$$

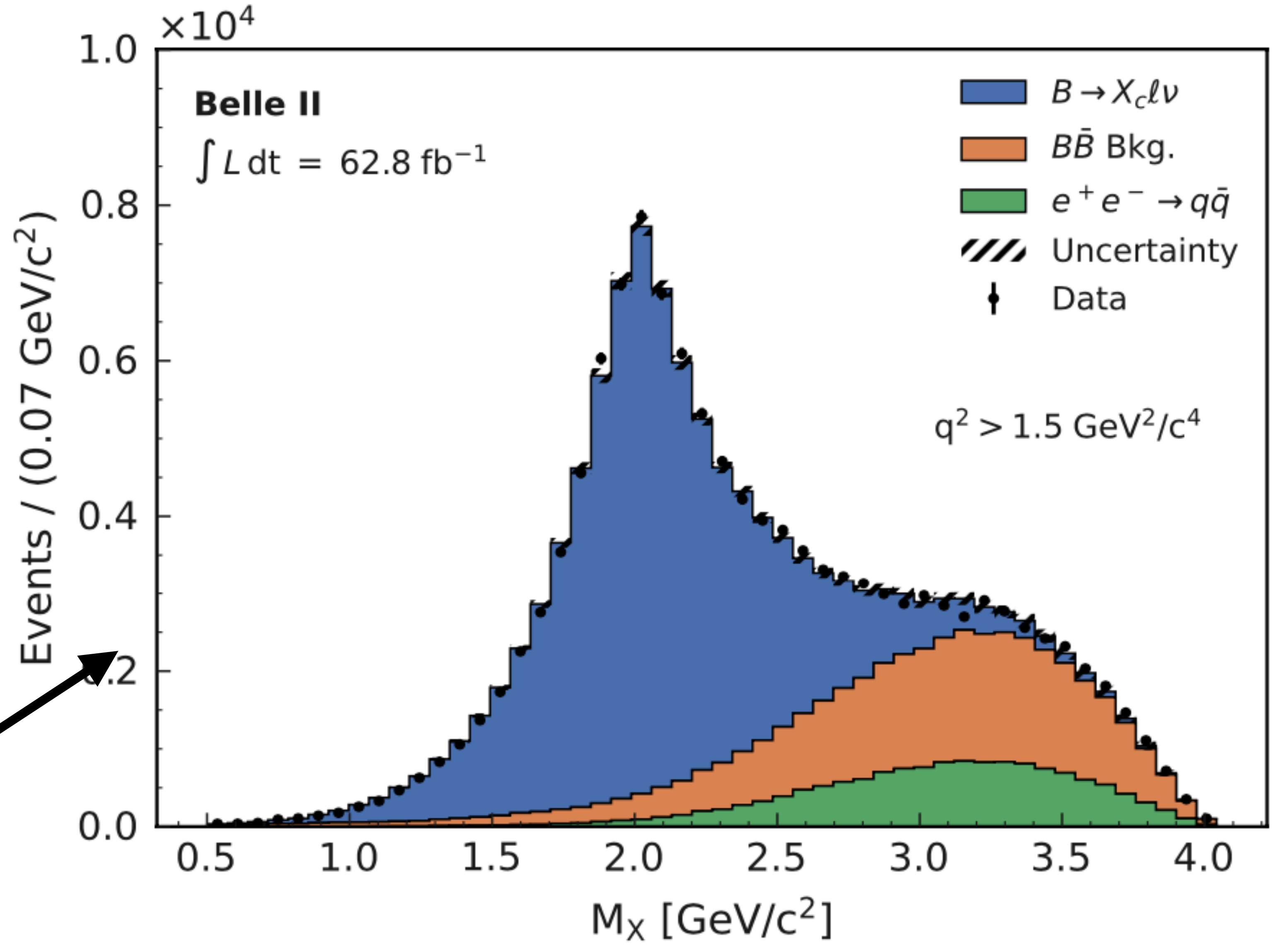
- The hadronic FEI employs over 200 boosted decision trees to reconstruct 10000 B decay chains
  - $\epsilon_{B^+} \approx 0.5\ \%$, $\epsilon_{B^0} \approx 0.3\ \%$ at low purity (about 50% increase with respect to the Belle tag)

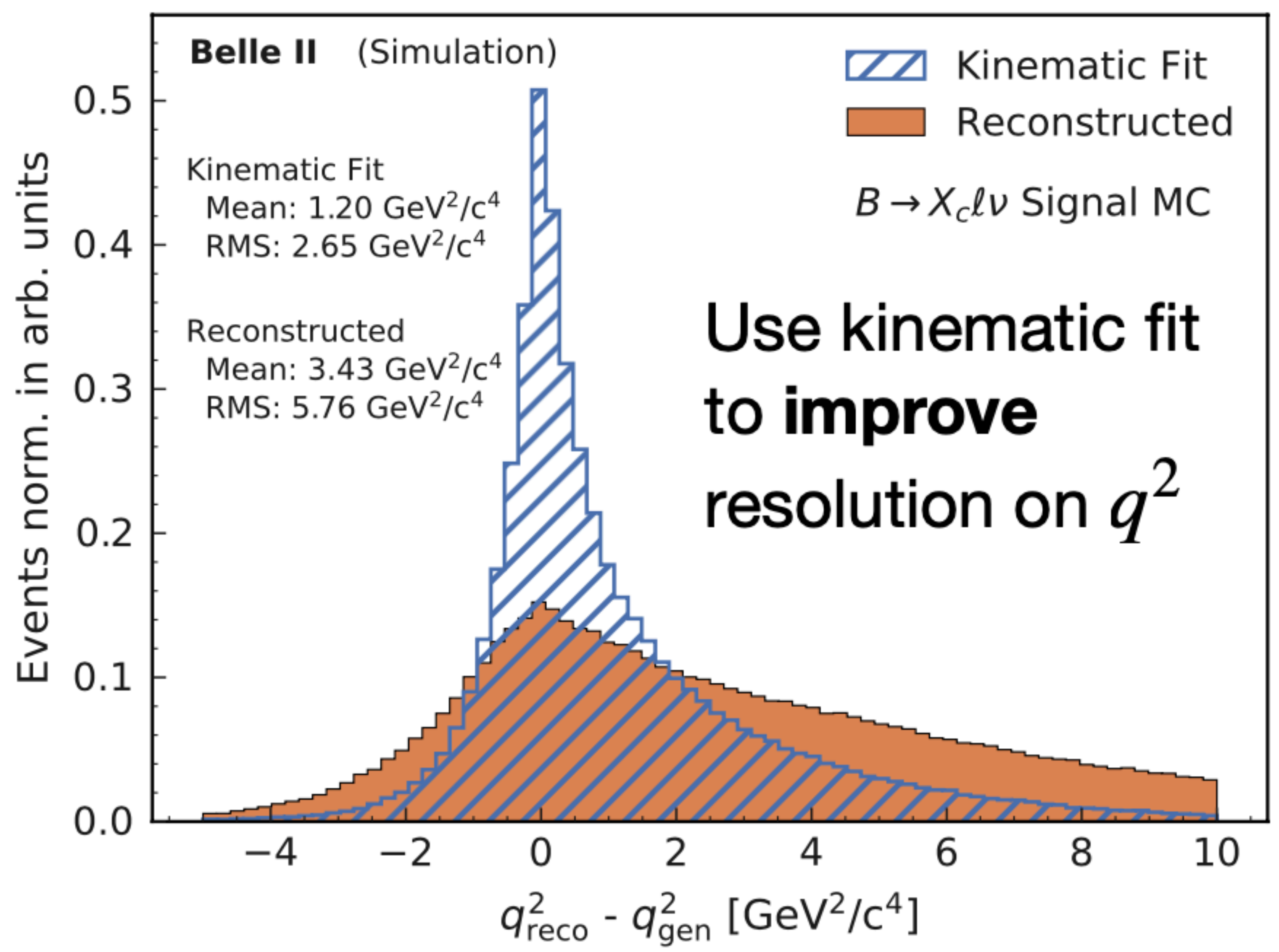
$q^2 = (p_\ell + p_\nu)^2$

q^2 moments in $B \to X_c \ell \nu$

[arXiv:2205.06372] submitted to PRD

- Motivated by JHEP 02 (2019) 177 [arXiv:1812.07472]
- Semileptonic B decays are reconstructed in 62.8/fb of hadronic tagged Belle II events
- Signal weight w as a function of q^2 determined from fitting the hadronic mass M_X
- q^2 spectra are calculated as event-wise average
- Leading systematics: background, moment calibration





$$\langle q^{2m} \rangle = \frac{C_{\mathrm{cal}} \cdot C_{\mathrm{acc}}}{\sum_i^{\mathrm{events}} w(q_i^2)} \times \sum_i^{\mathrm{events}} w(q_i^2) \cdot q^{2m}_{\mathrm{cal}\,i}$$

q^2 moments in $B \to X_c \ell \nu$

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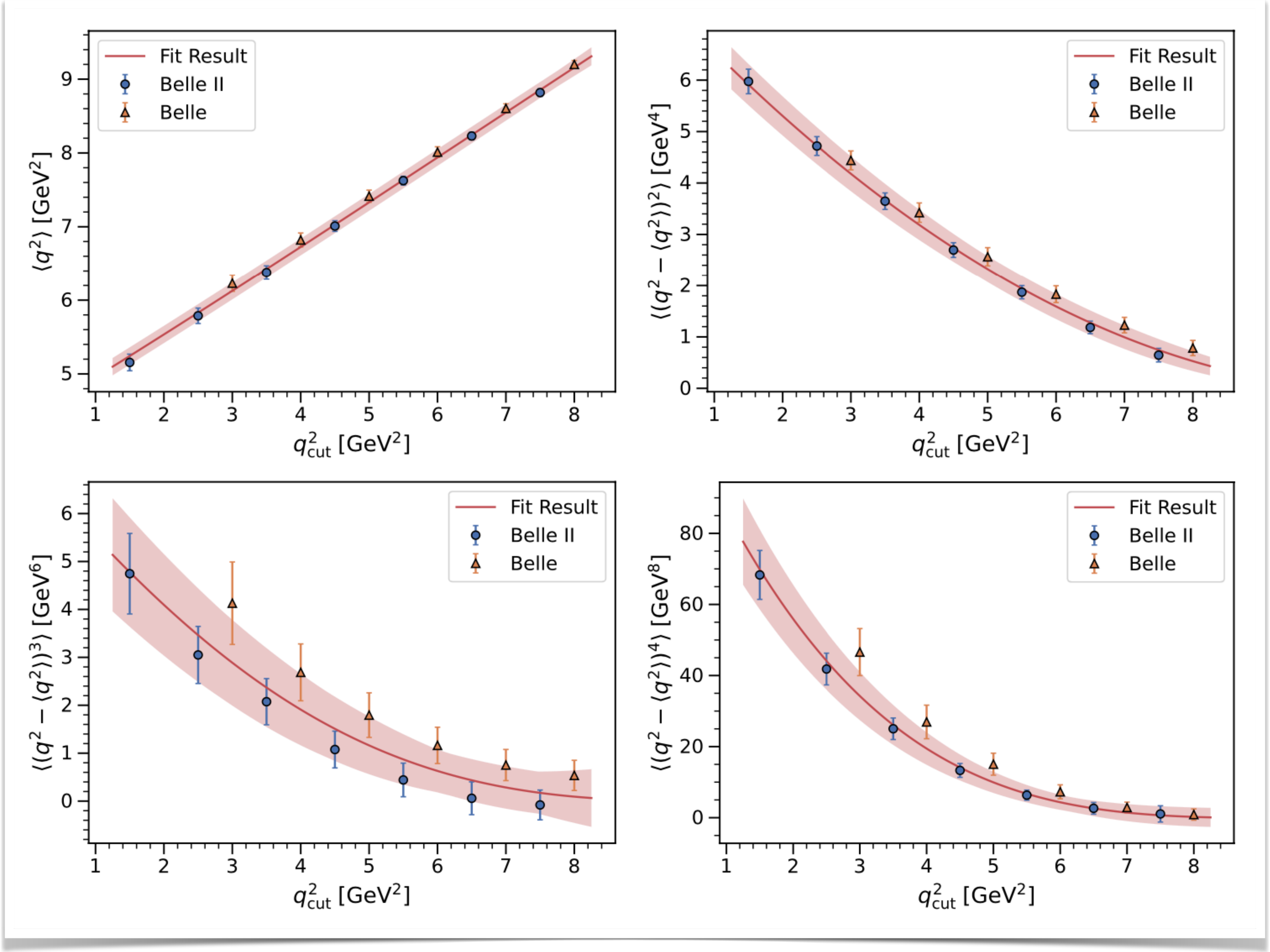

- Belle II q^2 moments compared to Belle q^2 moments PRD 104, 112011 (2021) [arXiv:2109.01685]
- And fit by Bernlochner et al. [arXiv:2205.10274]
- This fit gives $|V_{cb}| = (41.69 \pm 0.63) \cdot 10^{-3}$

$B^0 \to D^{*-}\ell^+\nu$ tagged and $|V_{cb}|$

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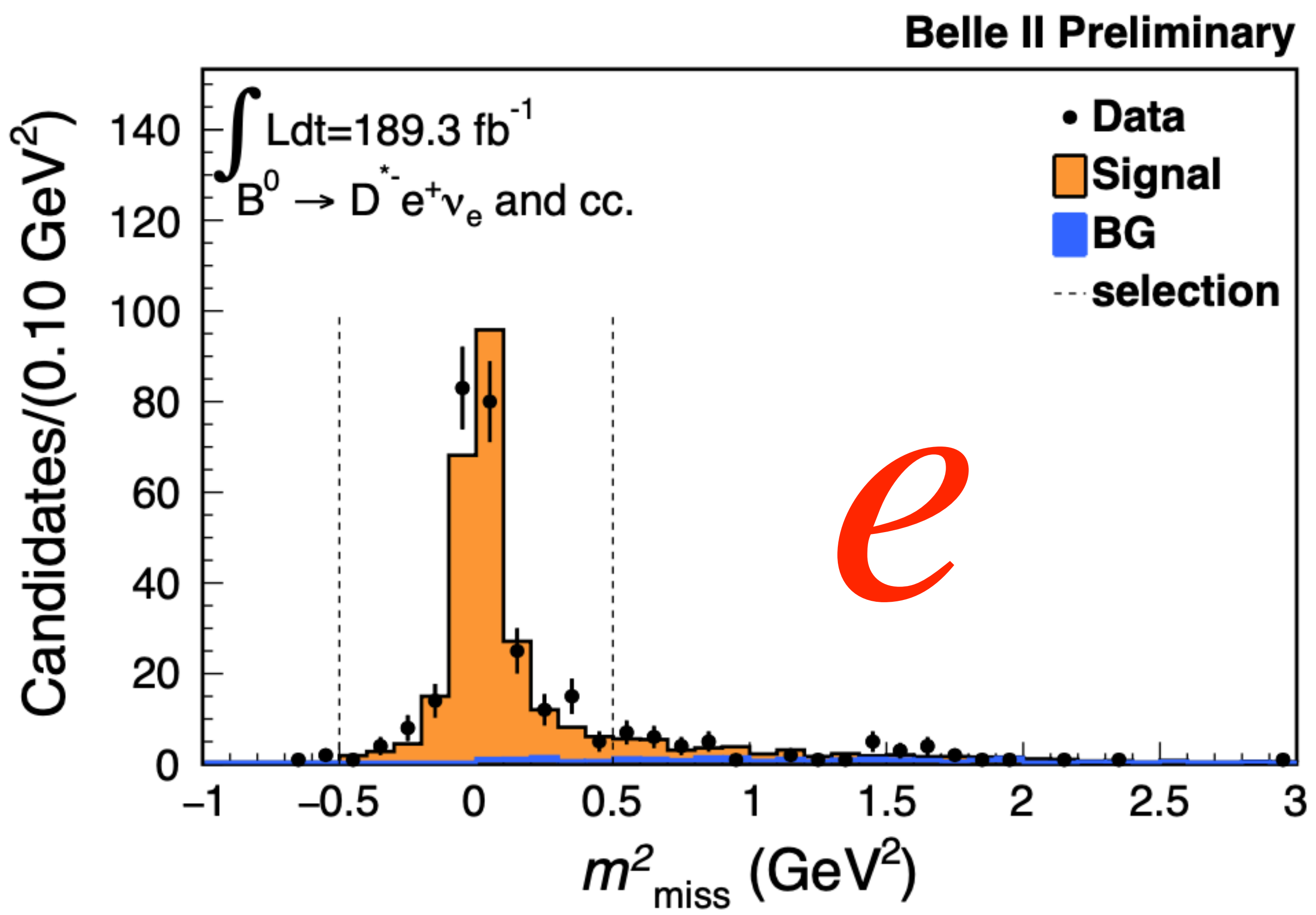
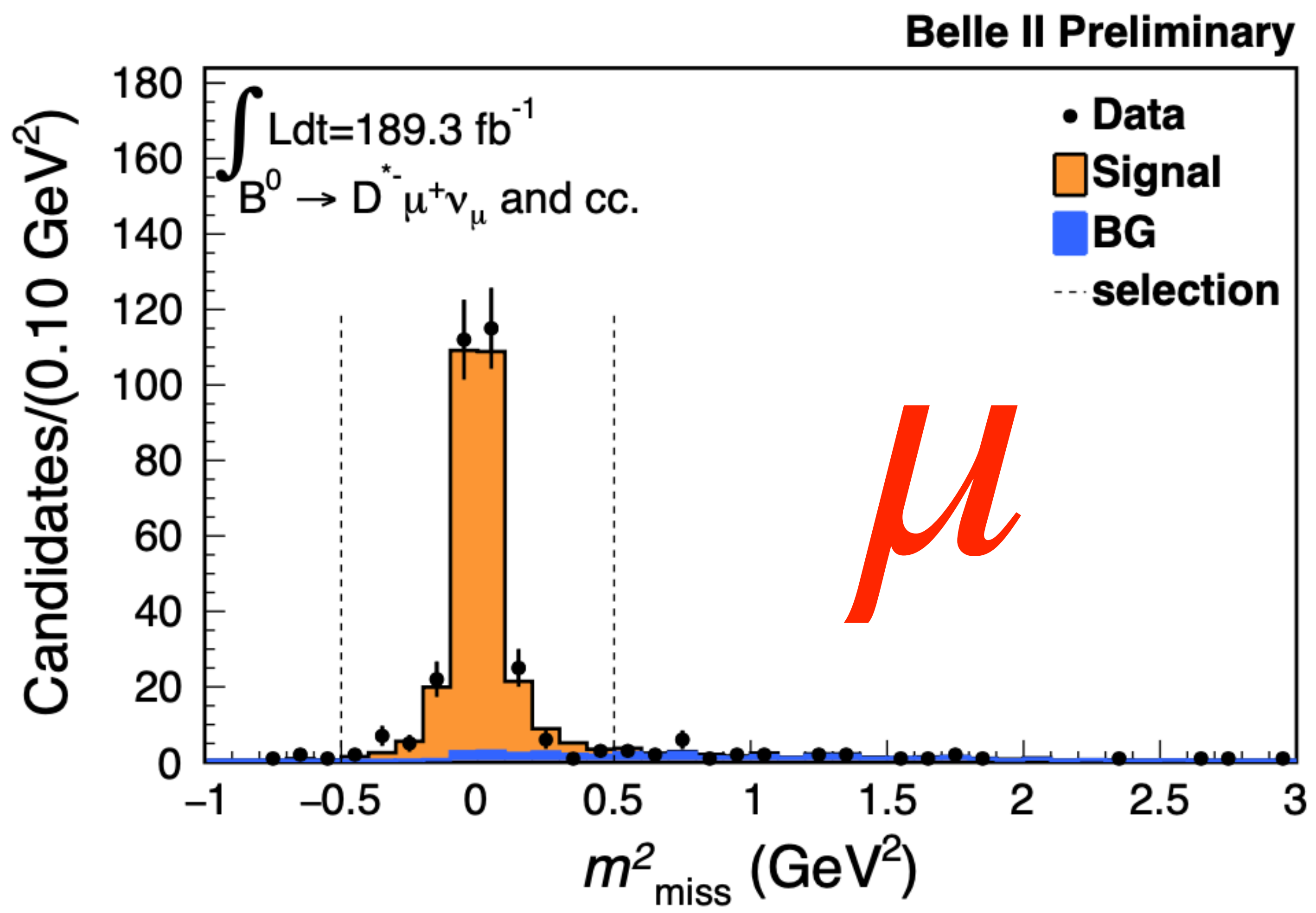
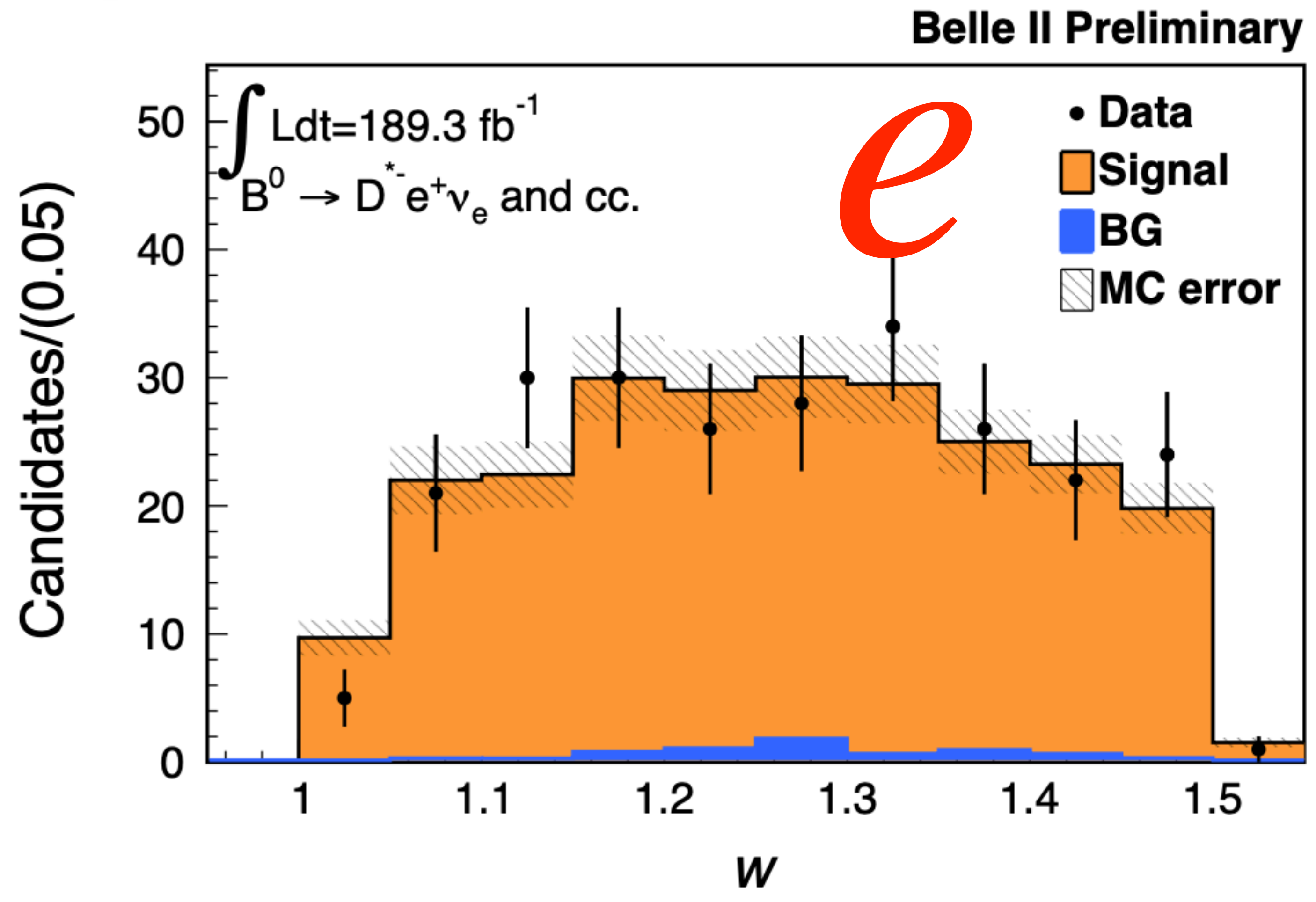
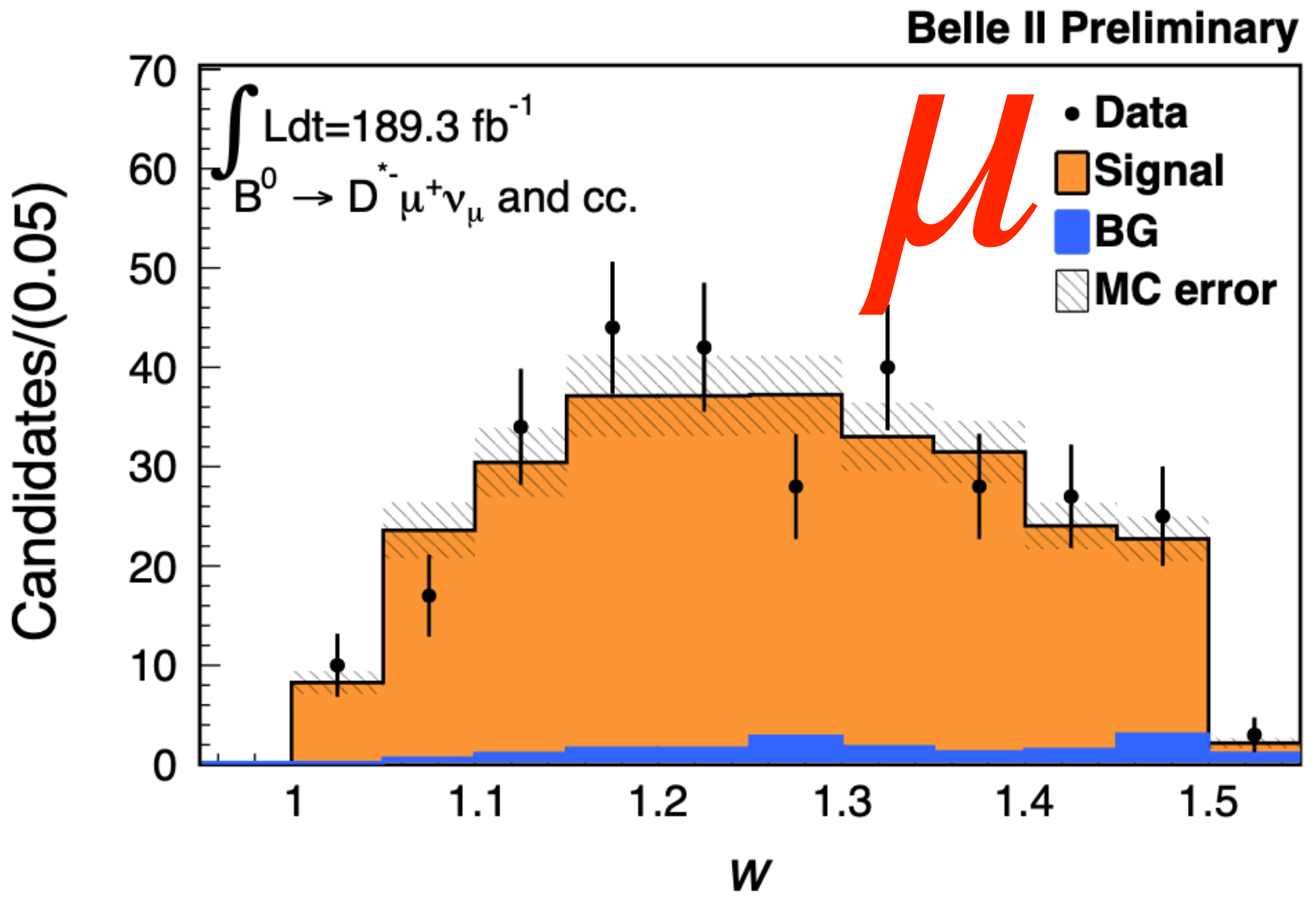
- 189.3/fb of hadronic tagged Belle II events
- Reconstruct $D^{*+} \to D^0(K^-\pi^+)\pi^+$ and identify ℓ (e or μ)
- Fit missing mass squared $m^2_{\rm miss} = (p_{\Upsilon(4S)} - p_{B_{\rm tag}} - p_{D^*} - p_\ell)^2$ in bins of $w = v_B \cdot v_{D^*}$ to extract w spectrum





$$\mathcal{B}\left(B^0 \to D^{*-}\ell^+\nu_\ell\right) = (5.27 \pm 0.22\,(\text{stat.}) \pm 0.38\,(\text{syst.}))\,\%$$





$B^0 \to D^{*-}\ell^+\nu$ tagged and $|V_{cb}|$

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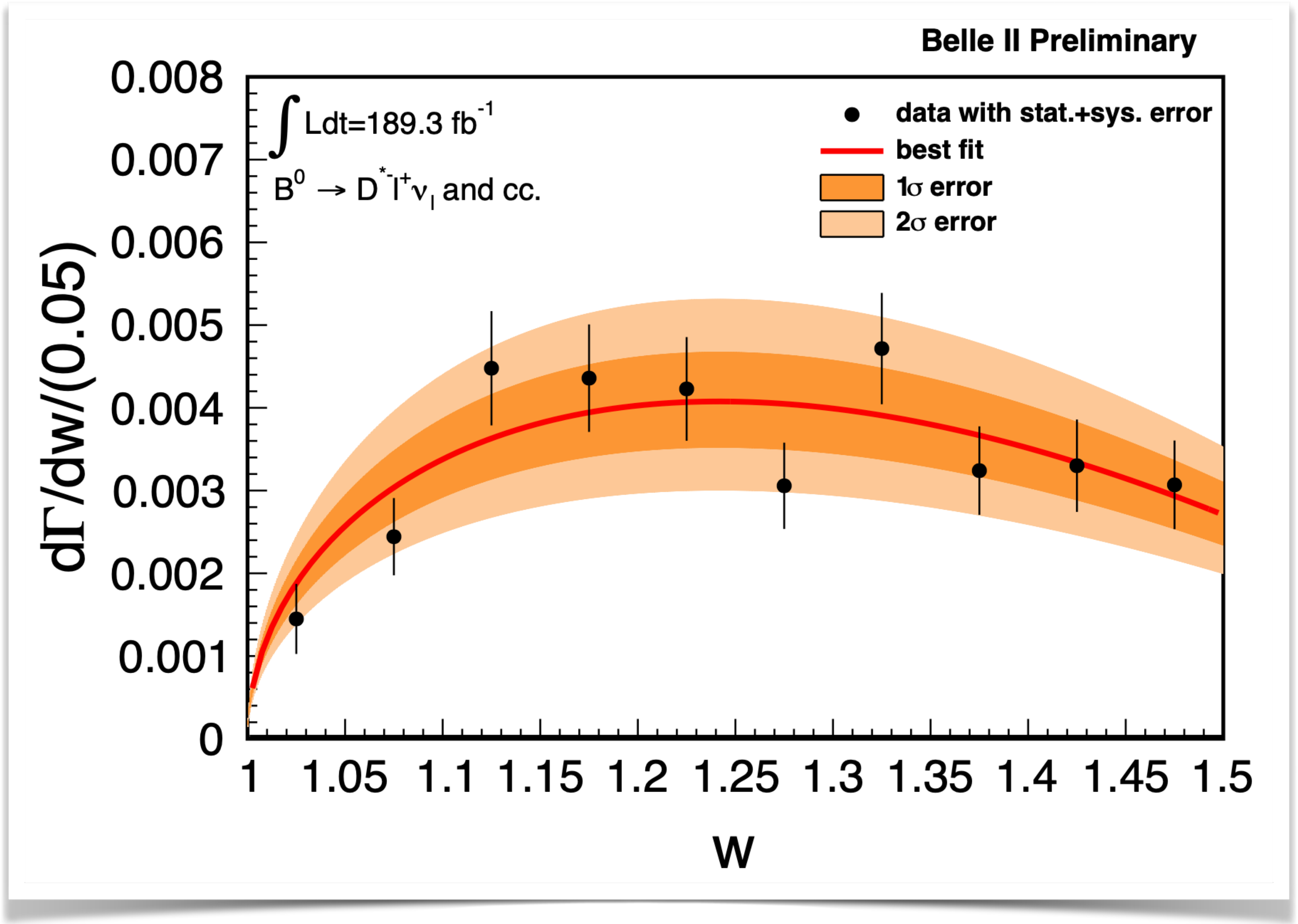
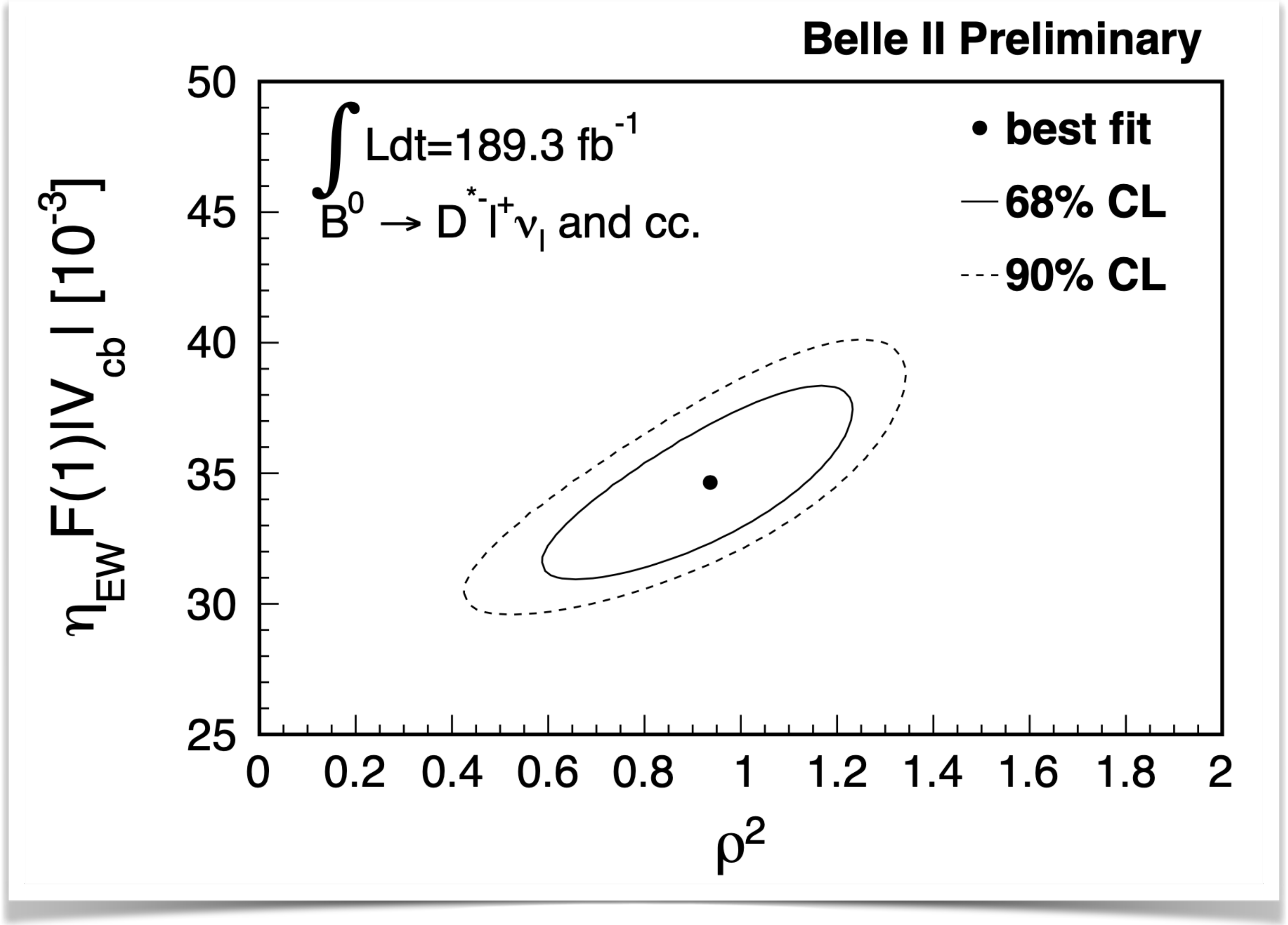
In the CLN parameterisation [NPB530, 153 (1998)]
$\mathscr{F}(w)$ depends on $\mathscr{F}(1)$, ρ^2, $R_1(1)$ and $R_2(1)$

- Fit of the w spectrum

$$\frac{d\Gamma}{dw} = \frac{G_F^2 m_{D^*}^3}{48\pi^3}(m_B - m_{D^*})^2\sqrt{w^2-1}\,\chi(w)\mathcal{F}^2(w)|V_{cb}|^2$$





$$\eta_{\mathrm{EW}}\mathscr{F}(1)\,|V_{cb}| = (34.6 \pm 2.5)\cdot 10^{-3}$$
$$\rho^2 = 0.94 \pm 0.21$$

- Largest systematics: tag calibration, slow pion tracking

$B \to \pi \ell \nu$

The golden mode for $|V_{ub}|$ exclusive

- Differential rate in terms of $q^2 = (p_\ell + p_\nu)^2$

$$\frac{d\Gamma(B^0 \to \pi^- \ell^+ \nu)}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{ub}|^2 |p_\pi|^3 |f_+(q^2)|^2$$

- BCL extraction of $|V_{ub}|$ [Phys.Rev.D79:013008,2009; Erratum-ibid.D82:099902,2010]
    - Measure the differential rate in bins of q^2
    - Theory calculates $f_+(q^2)$ at values of q^2
    - Combined fit to the BCL expansion to determine $|V_{ub}|$ and b_k (z is a map of q^2)

$$f_+(q^2) = \frac{1}{1 - q^2/m_{B*}^2} \sum_{k=0}^{K-1} b_k \left[z^k - (-1)^{k-K} \frac{k}{K} z^K \right]$$

$B \to \pi e \nu$ tagged and $|V_{ub}|$

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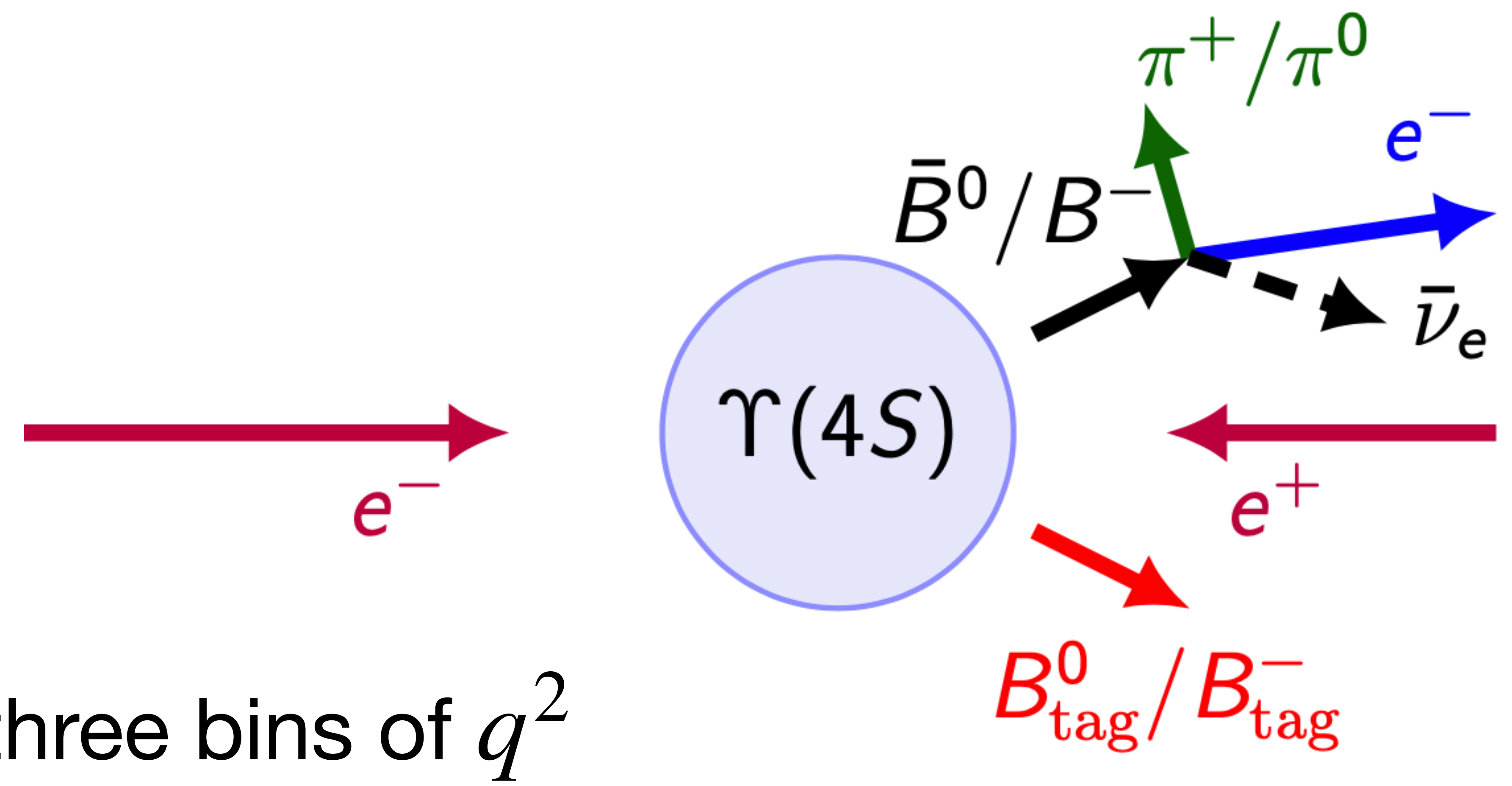
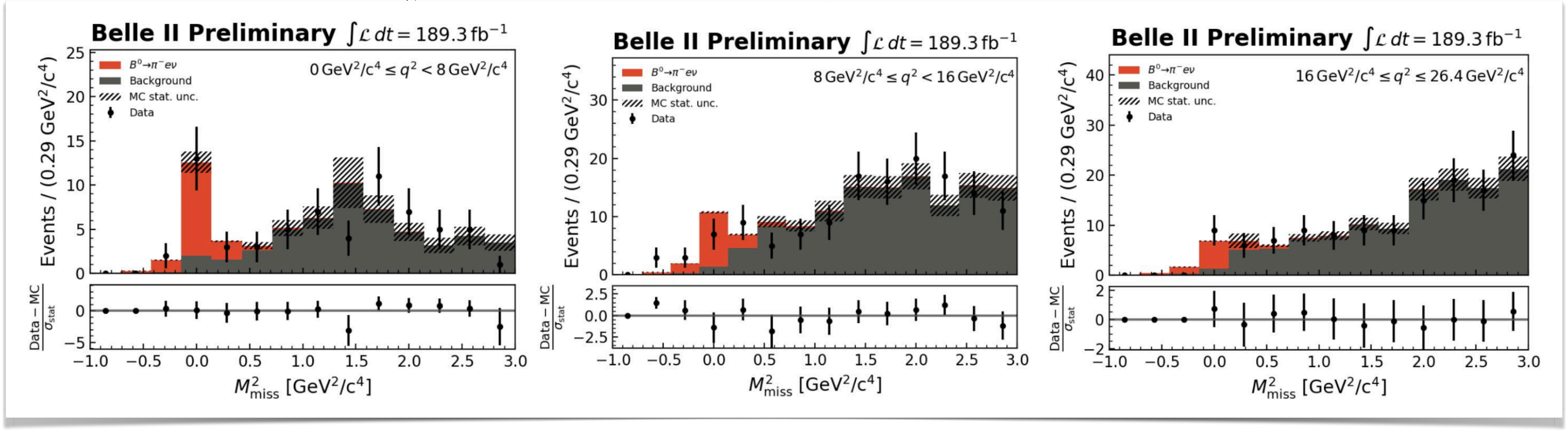
- 189.3/fb of Belle II, tag side is reconstructed by hadronic FEI
- $\pi^- e^+$ and $\pi^0 e^+$ are reconstructed on the signal side
- Signal yield is extracted from the missing mass distribution in three bins of q^2
  - $M^2_{\text{miss}} = (p_{\Upsilon(4S)} - p_{B_{\text{tag}}} - p_\pi - p_e)^2$





$B \to \pi e \nu$ tagged and $|V_{ub}|$

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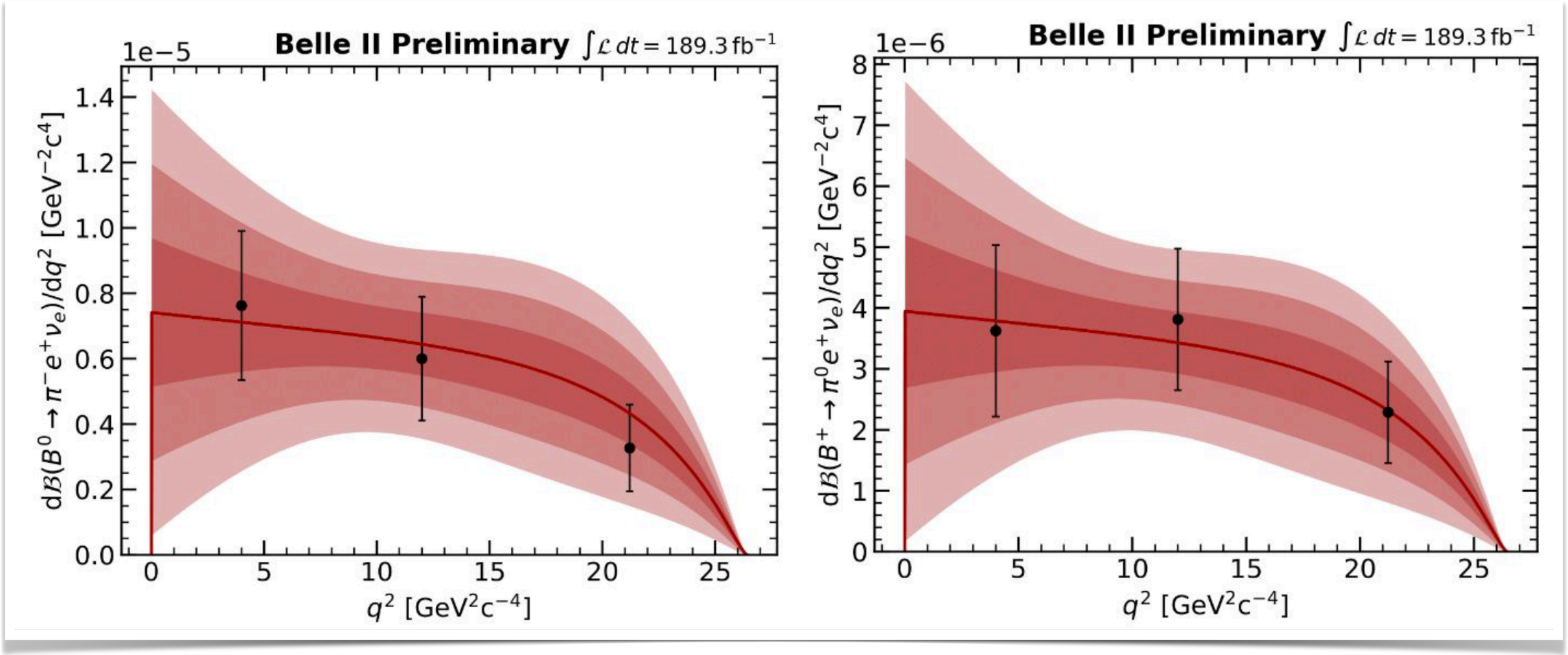
- BCL fit with the FNAL-MILC form factor [Phys. Rev. D 92, 014024 (2015)]



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

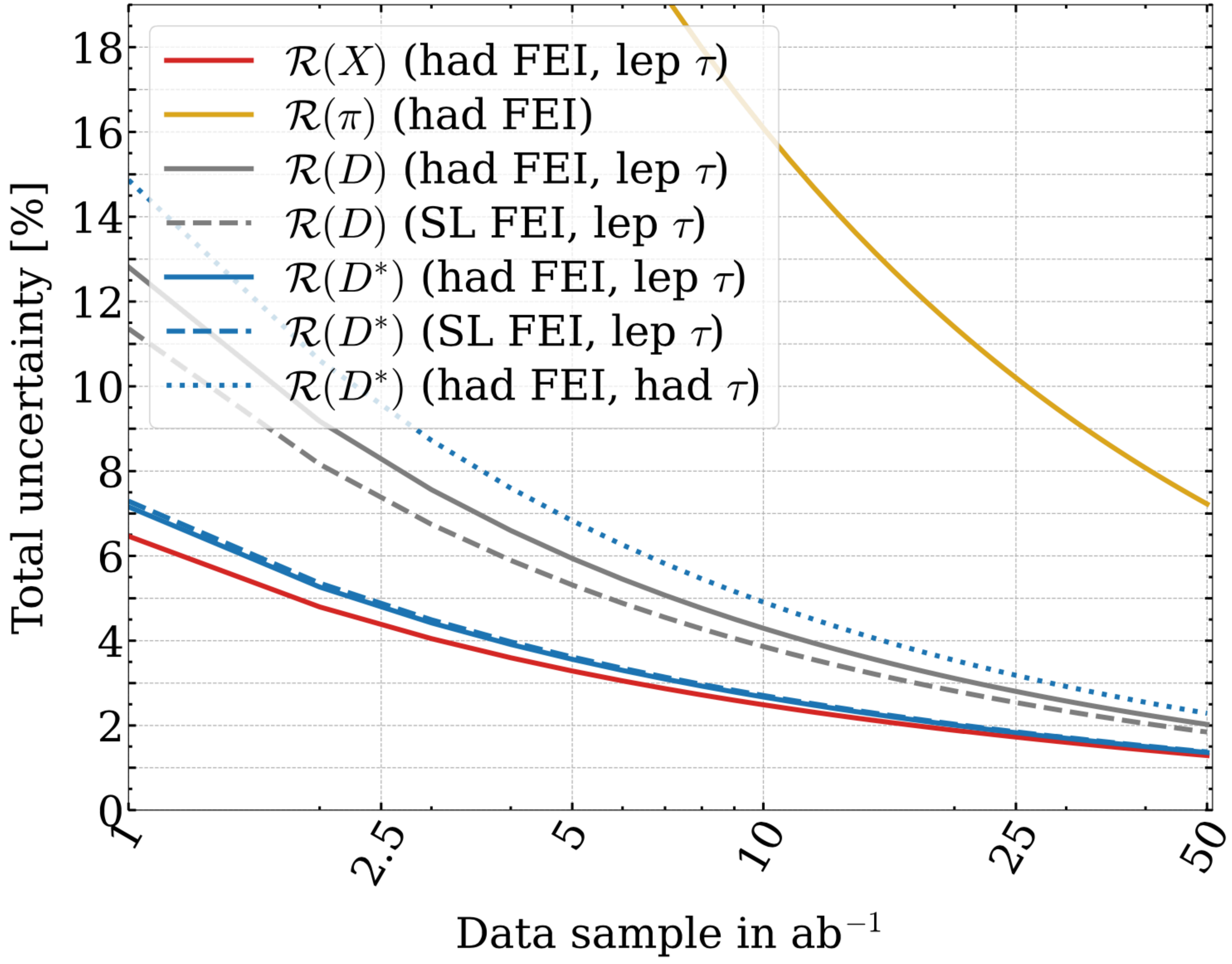
- Largest systematics: tag calibration

Semitauonic B decays

Belle II prospects

$$R(D, D^*, X) = \frac{\mathscr{B}(B \to D, D^*, X\tau\nu)}{\mathscr{B}(B \to D, D^*, X\ell\nu)}$$

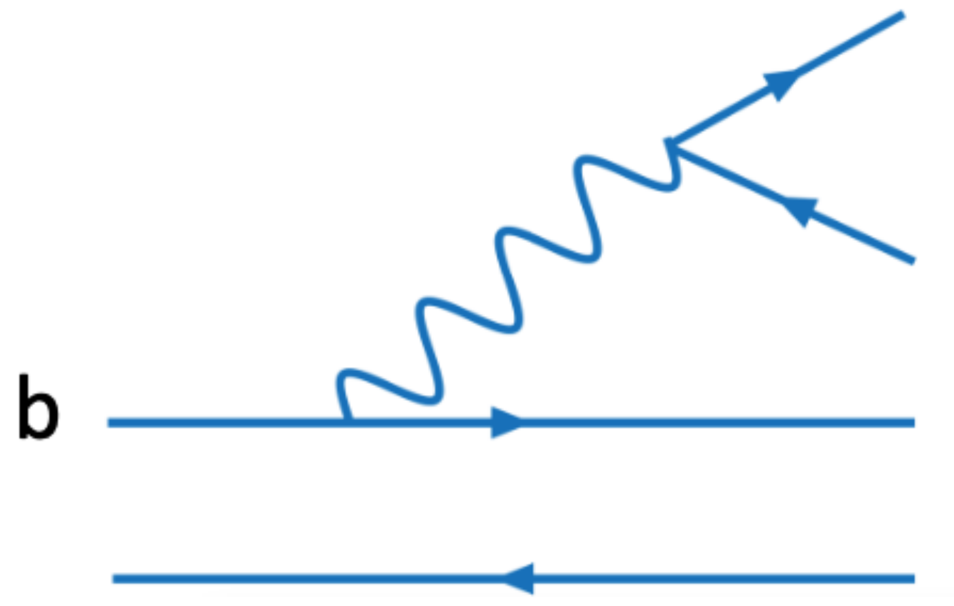
with ℓ a light lepton



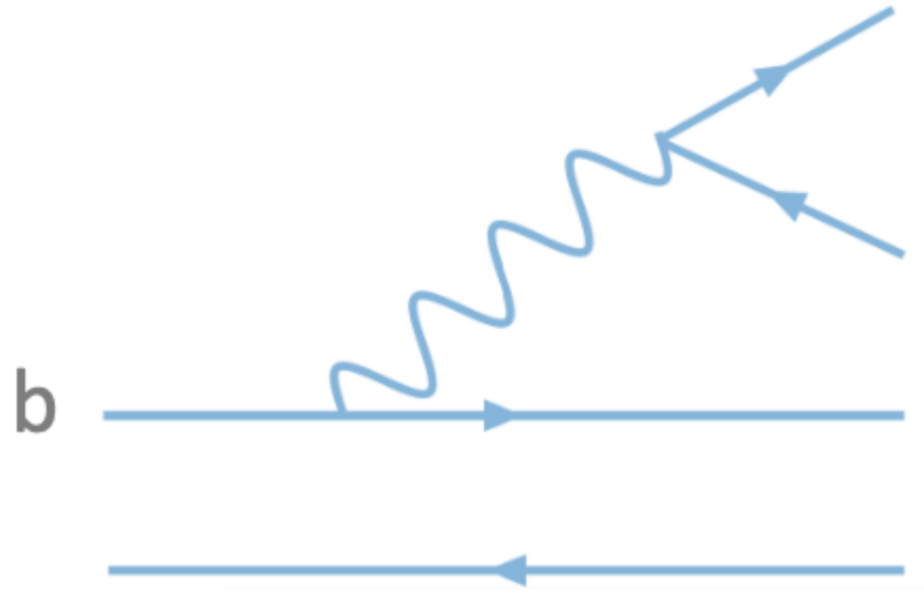
From:
Snowmass white paper "Belle II physics reach and plans for the next decade and beyond"
https://www.slac.stanford.edu/~mpeskin/Snowmass2021/BelleIIPhysicsforSnowmass.pdf

Hadronic B decays

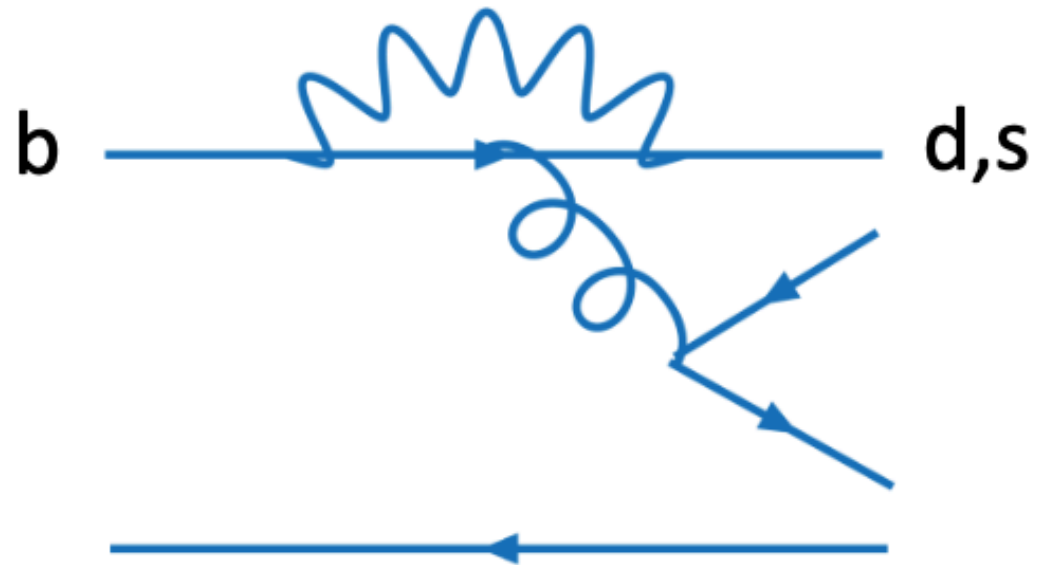
Hadronic B decays — motivation



- Charmed decays $B \to D^{(*)}h$
  - Mediated through Cabibbo-favoured $b \to c$ tree transition
  - Test of QCD predictions
  - $B \to D^{(*)}K$ are theoretically clean modes to measure the CKM angle ϕ_3/γ
    - New Belle II measurement of ϕ_3/γ with 11° precision: JHEP 02, 063 (2022) [arXiv:2110.12125]



- Charmless decays $B \to hh(h)$
  - Cabibbo-suppressed $b \to u$ tree or $b \to s, d$ loop transitions
  - Sensitive to non-SM loop contributions



- Observables: (ratios of) branching fractions, CP asymmetries

$B^0 \to K^0\pi^0$
[arXiv:2104.14871]

- $K\pi$ puzzle: unexpected large difference in direct CP-violating asymmetries ($\mathscr{A}$) between $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$

- Isospin sum rule

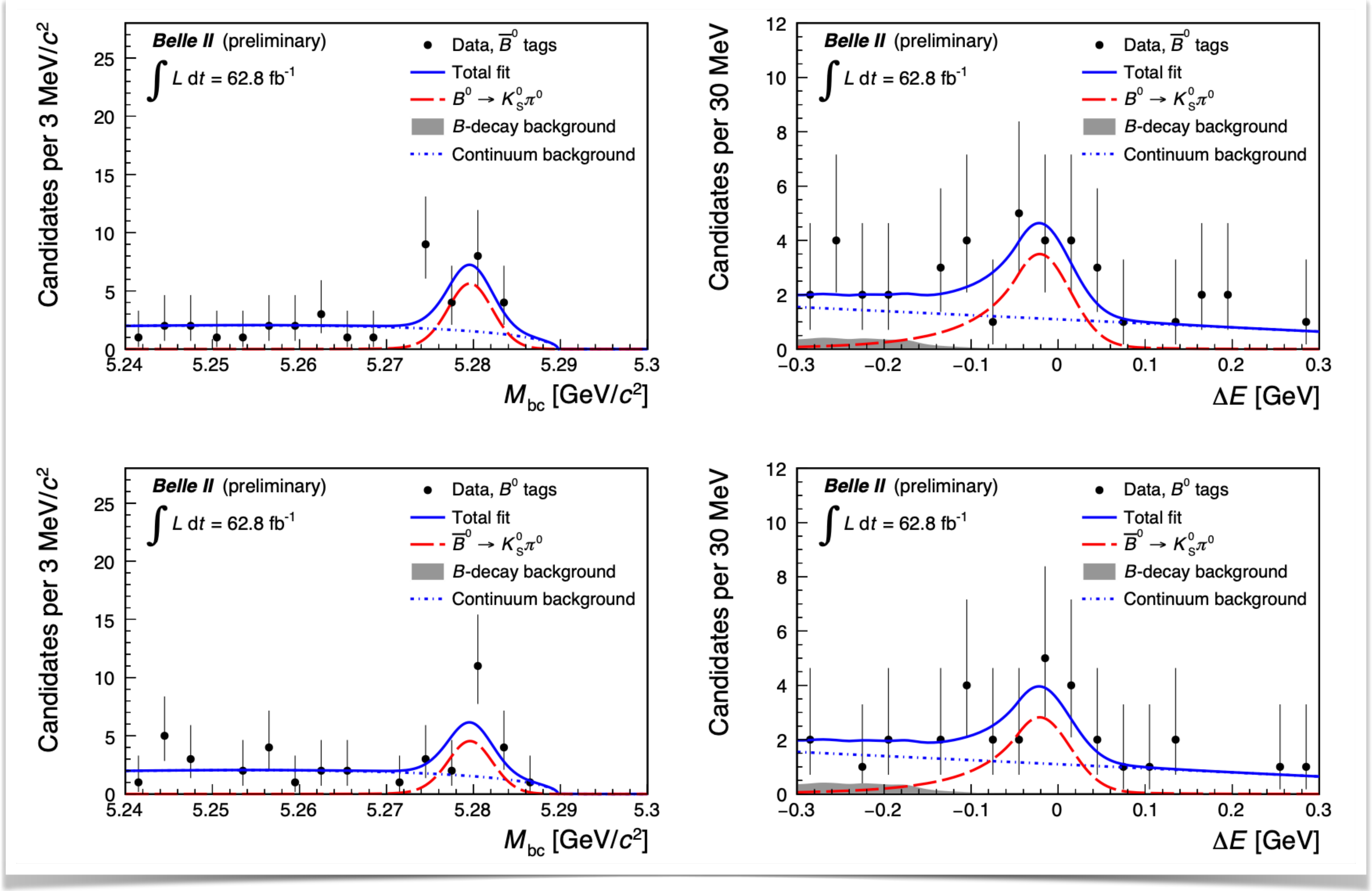
$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

- Null test: SM predicts $I_{K\pi} = 0$ in the limit of isospin symmetry and no electroweak penguin contribution [PLB 627 (2005) 82]

- Belle II can study all relevant final states

$B^0 \to K^0\pi^0$

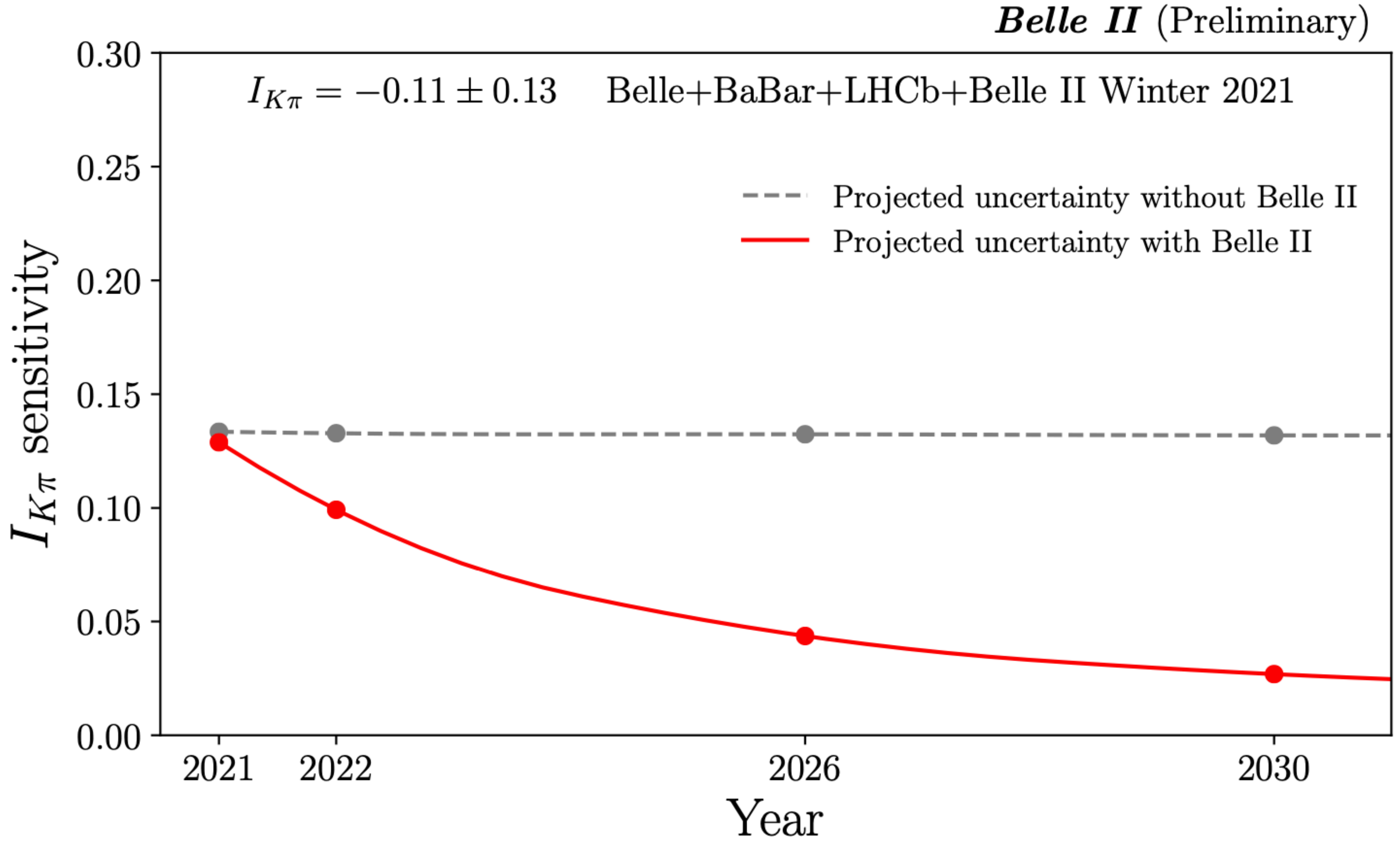
[arXiv:2104.14871]



- Yield: 45^{+9}_{-8} candidates in 62.8/fb of Belle II data
- Challenge: Measurement of $\mathscr{A}_{K^0\pi^0}$ must rely on rest of the event flavour tagging

$$\mathcal{A}_{K^0\pi^0} = -0.40^{+0.46}_{-0.44}(\text{stat}) \pm 0.04(\text{syst}), \text{ and}$$

$$\mathcal{B}(B^0 \to K^0\pi^0) = [8.5^{+1.7}_{-1.6}(\text{stat}) \pm 1.2(\text{syst})] \times 10^{-6}$$



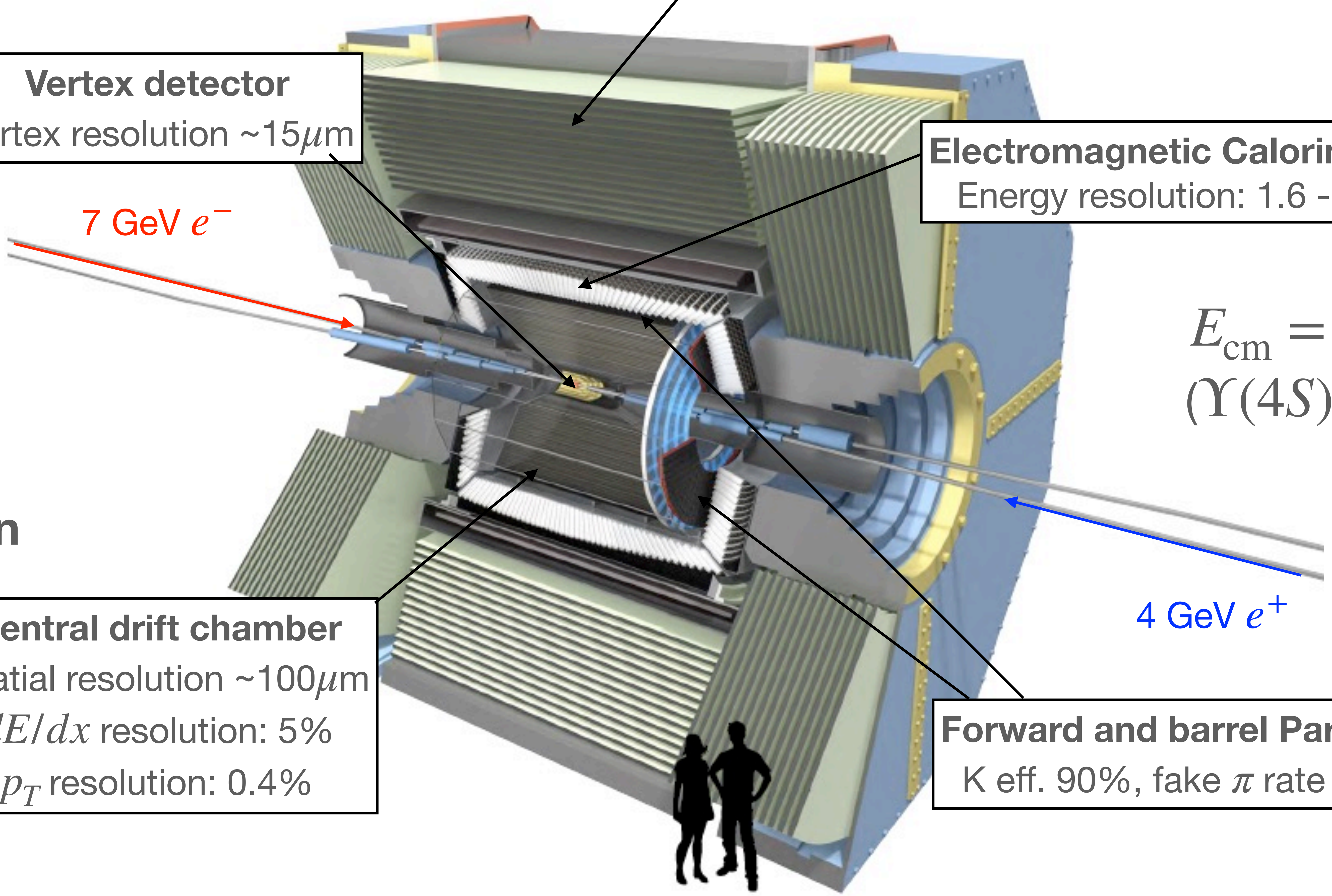
Summary

- *Belle II is starting to shed light on anomalies in B flavour physics*
- V_{cb}/V_{ub} *inclusive/exclusive anomaly*
  - Belle II measurement of q^2 moments in $B \to X_c \ell \nu$
    [arXiv:2205.06372] submitted to PRD
  - Preliminary tagged measurements of $B^0 \to D^{*-}\ell^+\nu$ and $B \to \pi e \nu$,
    first Belle II determinations of $|V_{cb}|$ and $|V_{ub}|$
- $K\pi$ *puzzle*
  - First search for $\mathscr{A}_{CP}$ in $B^0 \to K^0\pi^0$
- *We are looking forward to what we can do on more data!*

Backup

The Belle II detector

KEK
Tsukuba, Japan



$E_{\rm cm} = 10.58$ GeV
($\Upsilon(4S)$ resonance)

$B \to \pi e \nu$ tagged at Belle II
Winter 2021

q^2 bin	Signal efficiency	Unfolded signal yield	$\Delta\mathcal{B}$
		$B^0 \to \pi^- e^+ \nu_e$	
$0\ \mathrm{GeV}^2 \leq q^2 < 8\ \mathrm{GeV}^2$	$(0.189 \pm 0.002)\%$	15.5 ± 4.6	$(0.61 \pm 0.18(\mathrm{stat}) \pm 0.03(\mathrm{syst})) \times 10^{-4}$
$8\ \mathrm{GeV}^2 \leq q^2 < 16\ \mathrm{GeV}^2$	$(0.239 \pm 0.003)\%$	15.3 ± 4.8	$(0.48 \pm 0.15(\mathrm{stat}) \pm 0.02(\mathrm{syst})) \times 10^{-4}$
$16\ \mathrm{GeV}^2 \leq q^2 \leq 26.4\ \mathrm{GeV}^2$	$(0.229 \pm 0.003)\%$	10.3 ± 4.2	$(0.34 \pm 0.14(\mathrm{stat}) \pm 0.02(\mathrm{syst})) \times 10^{-4}$
Sum	–	41.1 ± 7.8	$(1.43 \pm 0.27(\mathrm{stat}) \pm 0.07(\mathrm{syst})) \times 10^{-4}$
Fit over full q^2 range	$(0.217 \pm 0.002)\%$	42.0 ± 7.9	$(1.45 \pm 0.27(\mathrm{stat}) \pm 0.07(\mathrm{syst})) \times 10^{-4}$

q^2 bin	Signal efficiency	Unfolded signal yield	$\Delta\mathcal{B}$
		$B^+ \to \pi^0 e^+ \nu_e$	
$0\ \mathrm{GeV}^2 \leq q^2 < 8\ \mathrm{GeV}^2$	$(0.329 \pm 0.004)\%$	12.9 ± 4.7	$(2.90 \pm 1.12(\mathrm{stat}) \pm 0.19(\mathrm{syst})) \times 10^{-5}$
$8\ \mathrm{GeV}^2 \leq q^2 < 16\ \mathrm{GeV}^2$	$(0.439 \pm 0.005)\%$	18.1 ± 5.1	$(3.05 \pm 0.91(\mathrm{stat}) \pm 0.20(\mathrm{syst})) \times 10^{-5}$
$16\ \mathrm{GeV}^2 \leq q^2 \leq 26.4\ \mathrm{GeV}^2$	$(0.451 \pm 0.006)\%$	14.5 ± 4.9	$(2.38 \pm 0.85(\mathrm{stat}) \pm 0.16(\mathrm{syst})) \times 10^{-5}$
Sum	–	45.5 ± 8.5	$(8.33 \pm 1.67(\mathrm{stat}) \pm 0.55(\mathrm{syst})) \times 10^{-5}$
Fit over full q^2 range	$(0.402 \pm 0.003)\%$	43.9 ± 8.3	$(8.06 \pm 1.62(\mathrm{stat}) \pm 0.53(\mathrm{syst})) \times 10^{-5}$

- Yields in q^2 bins are corrected by bin-by-bin unfolding

$B \to \pi e \nu$ tagged at Belle II

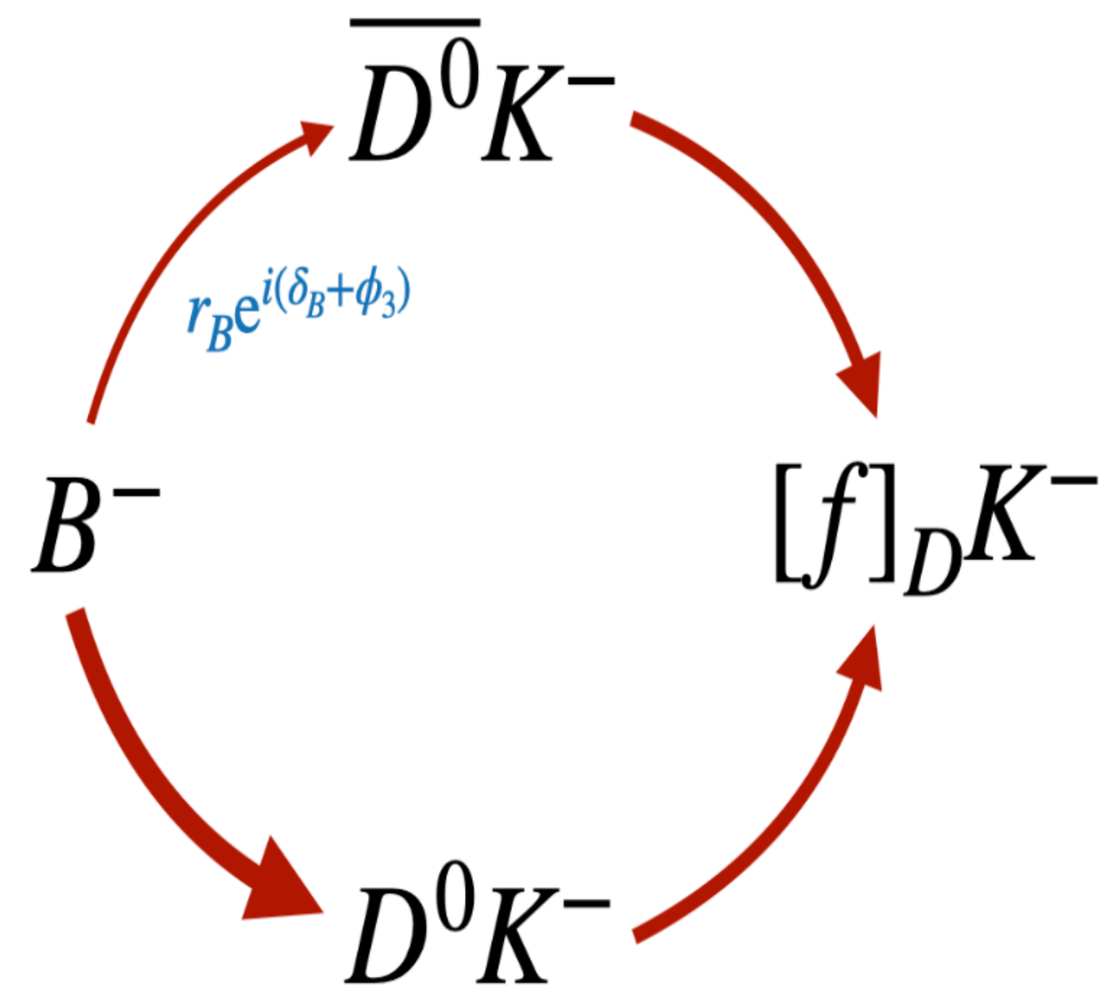
Winter 2021

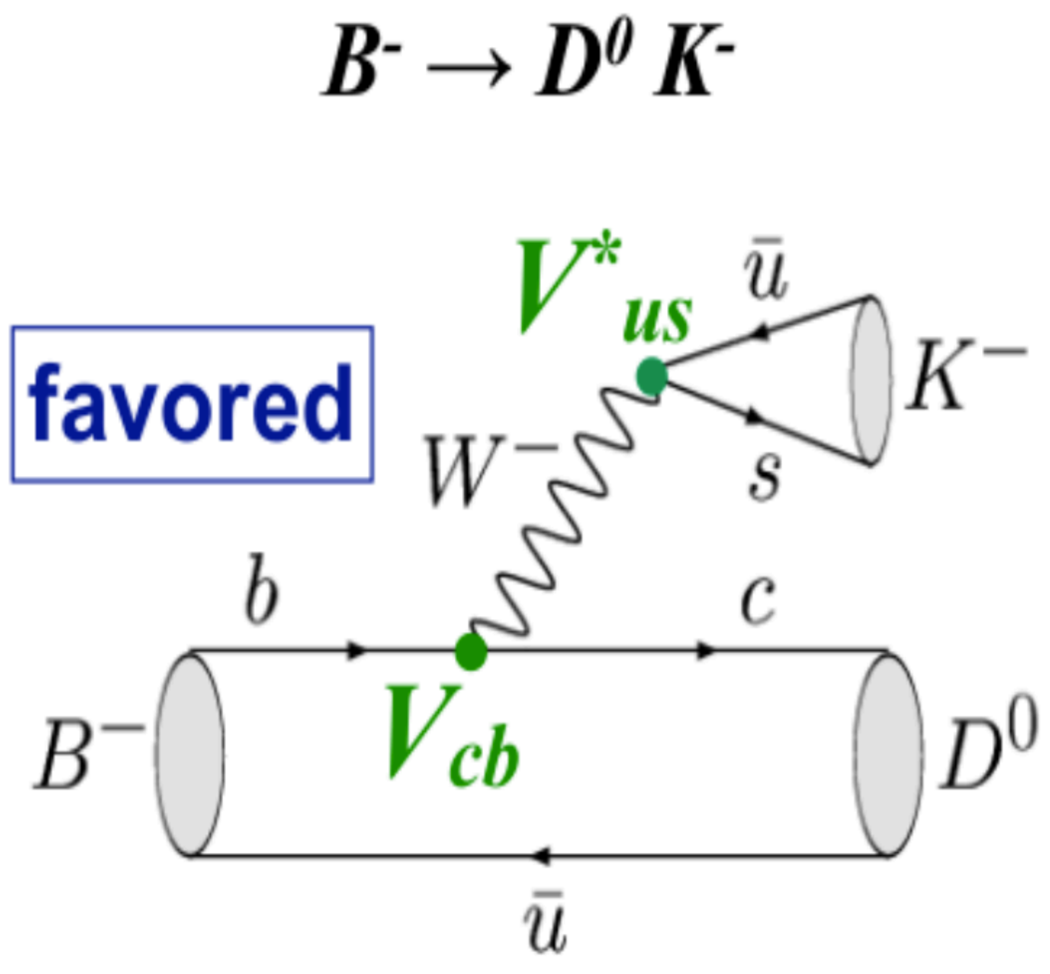
Source	% of $\mathcal{B}(B^0 \to \pi^- e^+ \nu_e)$			% of $\mathcal{B}(B^+ \to \pi^0 e^+ \nu_e)$		
q^2 bin index	1	2	3	1	2	3
$N_{B\bar{B}}$	2.9					
f_{+0}	1.2					
FEI calibration	3.2			3.1		
Tracking	0.6			0.3		
π^0 efficiency	–			4.8		
Signal efficiency ϵ	1.3	1.2	1.4	1.3	1.2	1.3
Electron ID	1.0	0.4	0.4	1.0	0.5	0.5
Pion ID	0.4	0.4	0.4	–		
Total	4.8	4.7	4.8	6.7	6.7	6.7

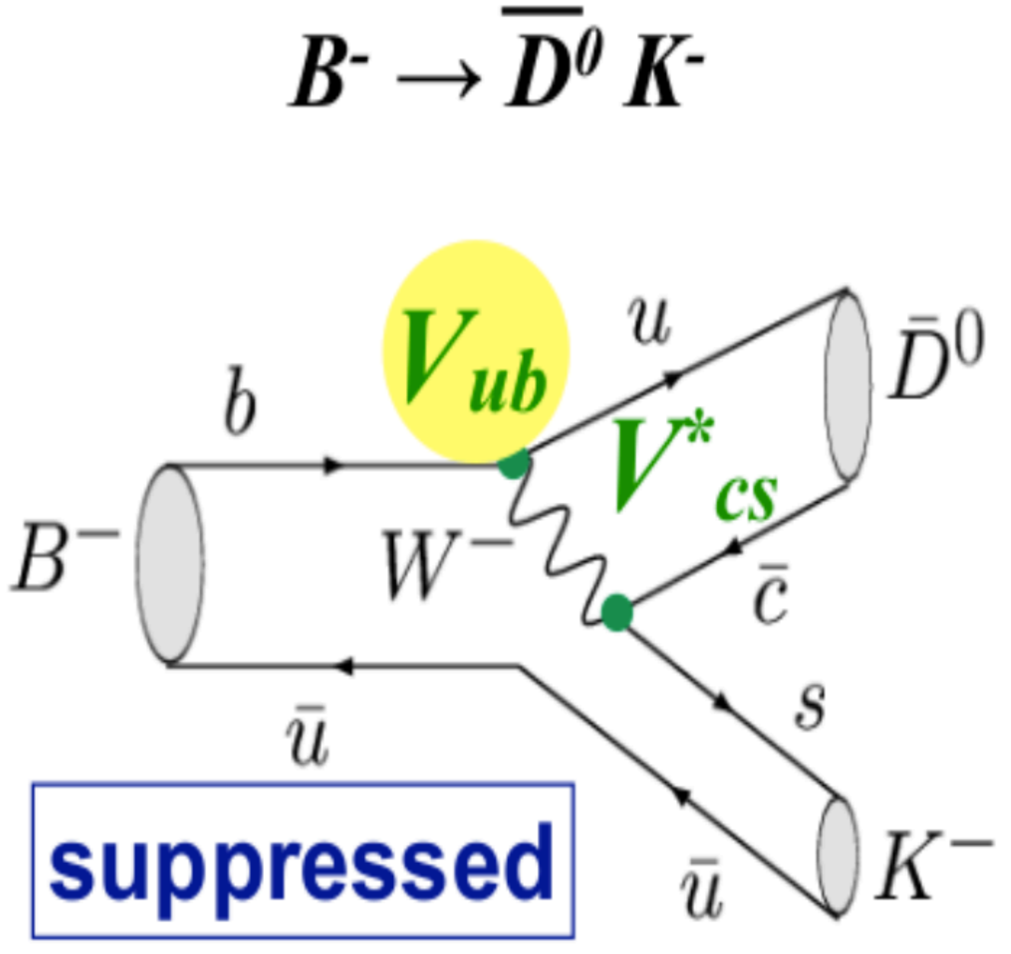
CKM angle ϕ_3/γ

BPGGSZ method (binned model-independent) [Phys.Rev.D68, 054018]

- ϕ_3/γ is the phase between $b \to u$ and $b \to c$ transitions
- The interference between these two diagrams gives access to the amplitude ratio, which contains ϕ_3/γ





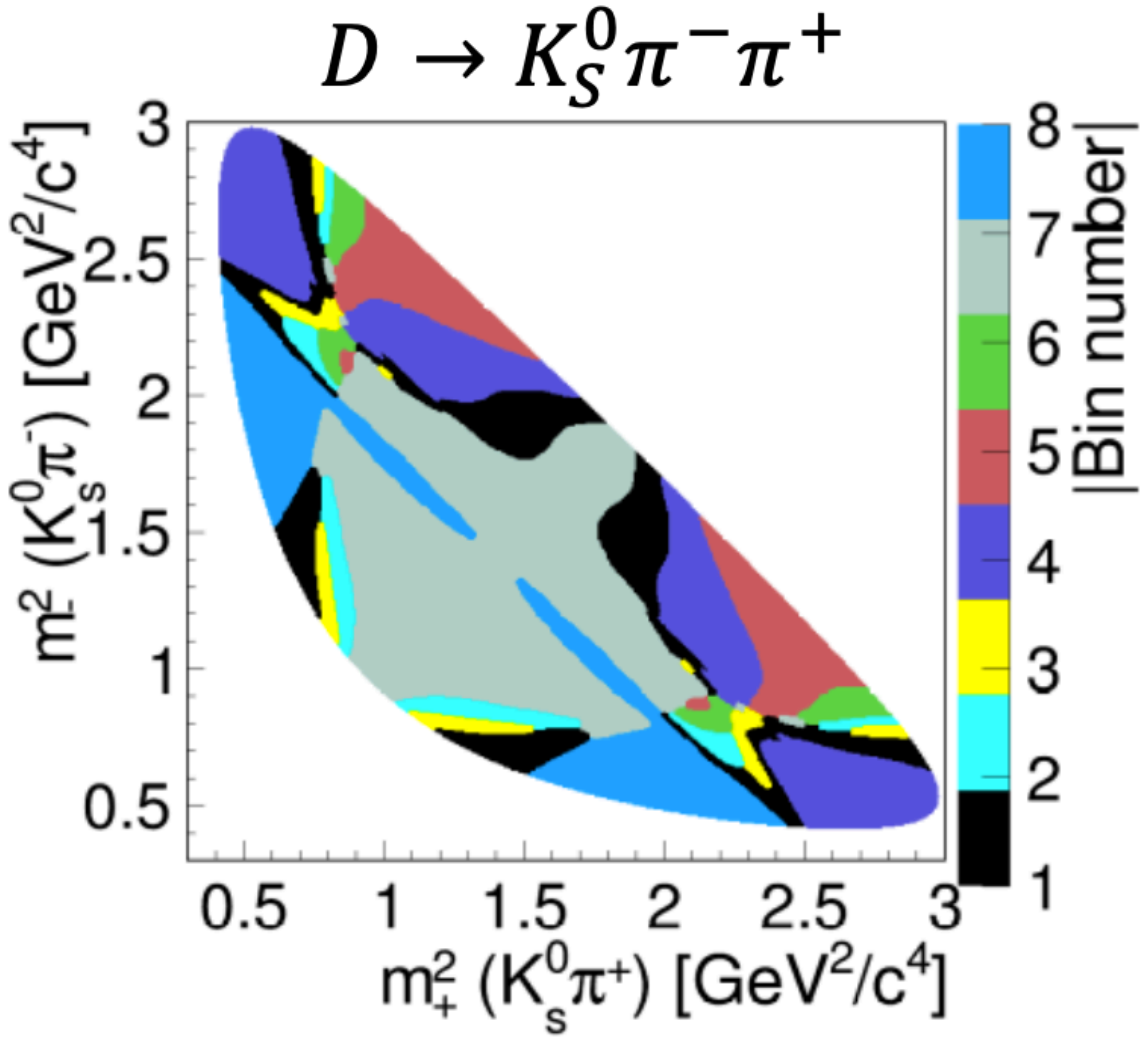


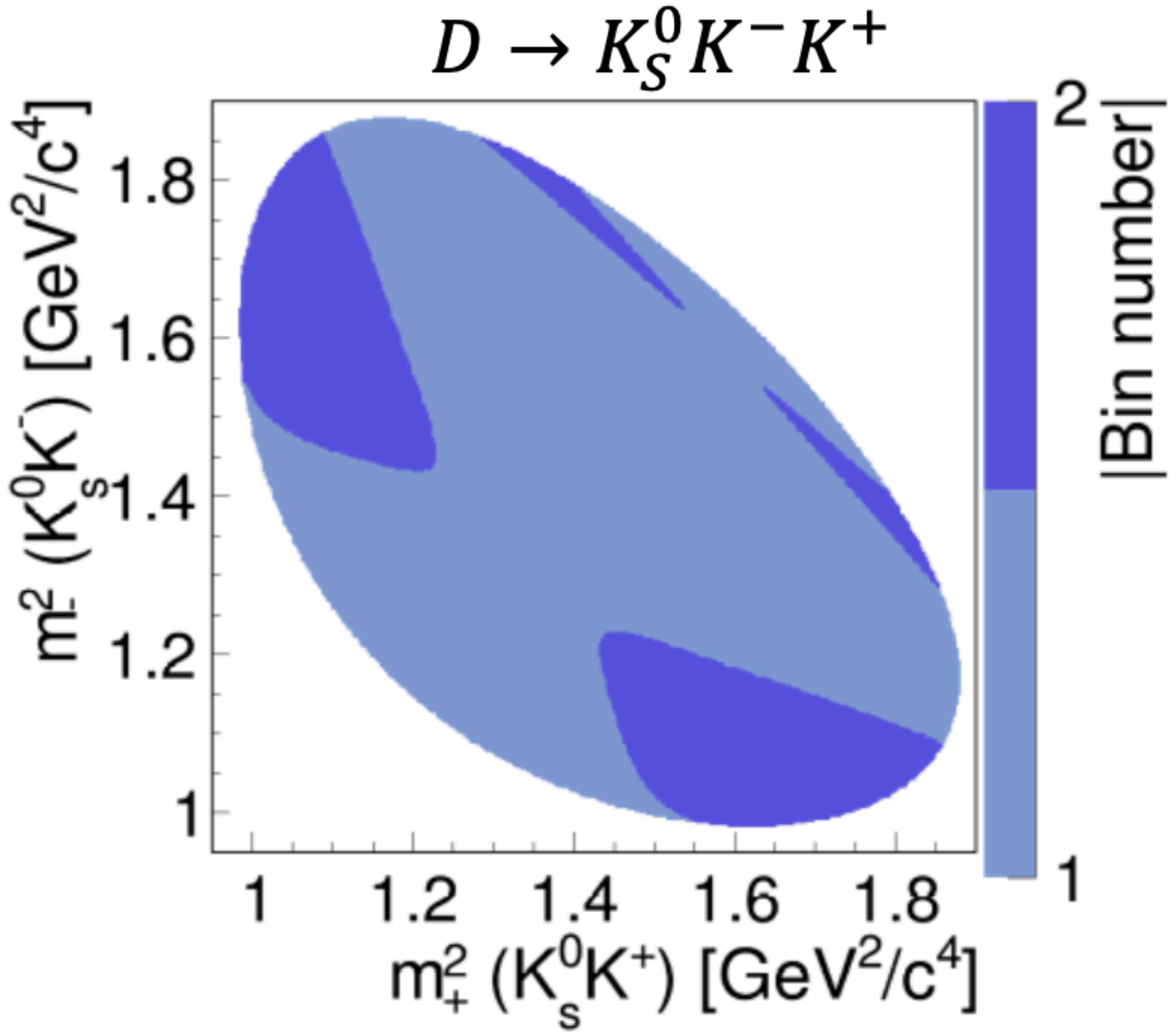
$$\frac{\mathcal{A}^{\text{suppr.}}(B^- \to \overline{D^0}K^-)}{\mathcal{A}^{\text{favor.}}(B^- \to D^0 K^-)} = r_B e^{i(\delta_B+\phi_3)}$$

CKM angle ϕ_3/γ

BPGGSZ method (binned model-independent) [Phys.Rev.D68, 054018]

- To observe interference, we need to reconstruct D^0 in a self-conjugate mode
- To avoid model dependence, the strong phase difference between the D^0 and $\bar{D}^0$ decays is measured by CLEO/BES III





$$(x_\pm,\ y_\pm) = r_B \left(\cos(\gamma + \delta_B),\ \sin(\gamma + \delta_B)\right)$$

c_i, s_i: D^0-$\bar{D}^0$ strong phase differences (inputs from BES III/CLEO)

F_i: fraction of D decays to i-th bin

$$N_i^\pm = h_{B^\pm} \left[F_i + r_B^2 \bar{F}_i + 2\sqrt{F_i \bar{F}_i}(c_i x_\pm + s_i y_\pm) \right]$$

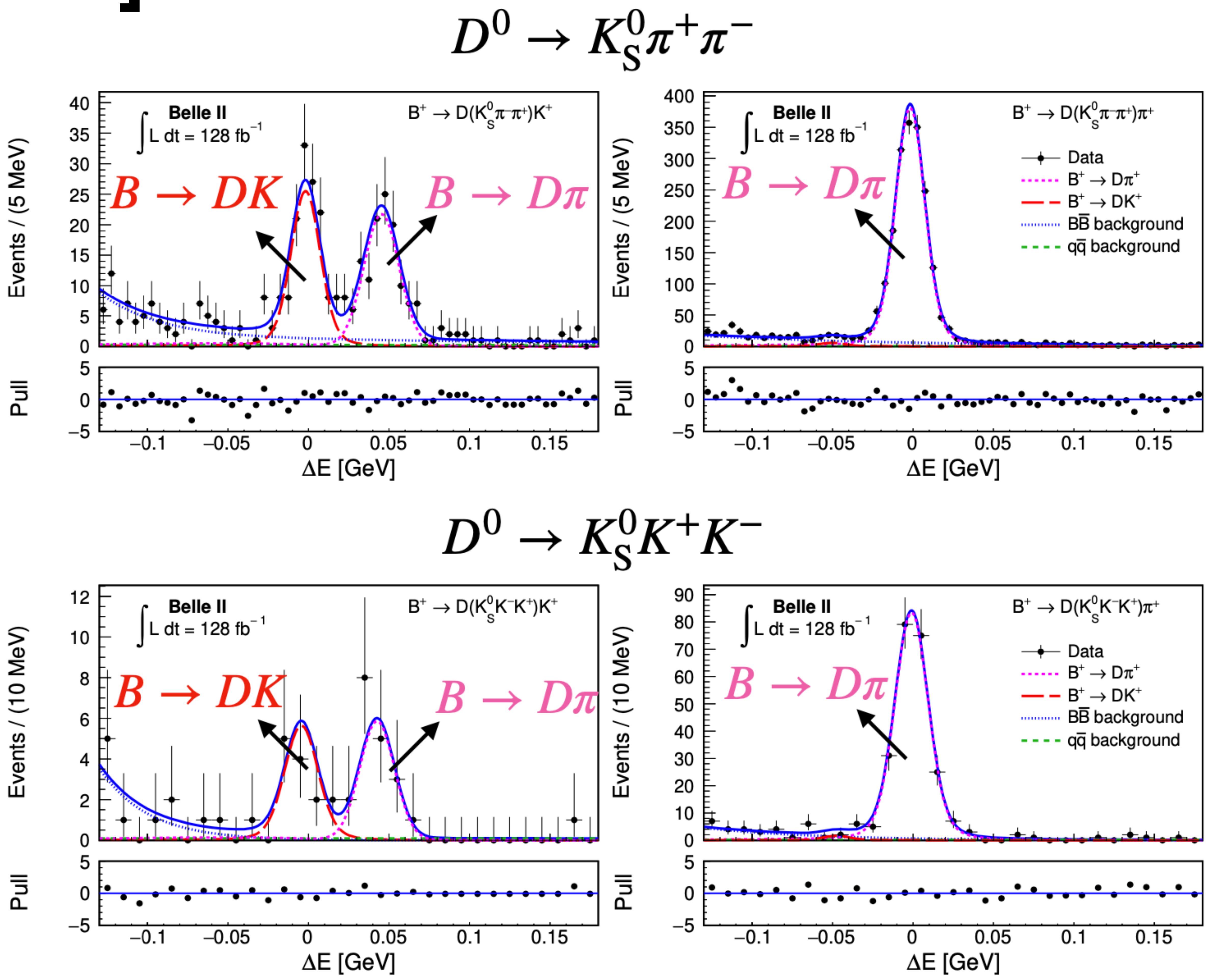
Belle+Belle II measurement of $B \to DK$

JHEP 02, 063 (2022) [arXiv:2110.12125]

- 711/fb of Belle and 128/fb of Belle II data
- Using both $D^0 \to K_S^0\pi^+\pi^-$ and $D^0 \to K_S^0K^+K^-$
- Yields extracted in simultaneous fit to $B \to DK$ and $B \to D\pi$ (misID rate determined from data)

Signal yields:

Belle:	Belle II :
$K_S^0\pi\pi$: 1467 ± 53	$K_S^0\pi\pi$: 280 ± 21
K_S^0KK: 194 ± 17	K_S^0KK: 34 ± 7



Belle+Belle II measurement of $B \to DK$

JHEP 02, 063 (2022) [arXiv:2110.12125]

- Simultaneous fit in Dalitz bins to extract CP observables $(x_{\pm}, y_{\pm})$ which contain r_B, δ_B and ϕ_3/γ
- Extract F_i directly from data to reduce systematics
- Best result from B factories but still not competitive with LHCb (~3 degrees uncertainty)

$$\delta_B[^\circ] = 124.8 \pm 12.9\ (\text{stat})\ \ \pm 0.5\ (\text{syst})\ \ \pm 1.7\ (\text{ext})$$

$$r_B^{DK} = 0.129 \pm 0.024\ (\text{stat})\ \ \pm 0.001\ (\text{syst})\ \ \pm 0.002\ (\text{ext})$$

$$\gamma[^\circ] = 78.4 \pm 11.4\ (\text{stat})\ \ \pm 0.5\ (\text{syst})\ \ \pm 1.0\ (\text{ext})$$