B CKM physics

Jake Bennett
University of Mississippi
Physics in Collisions 2023

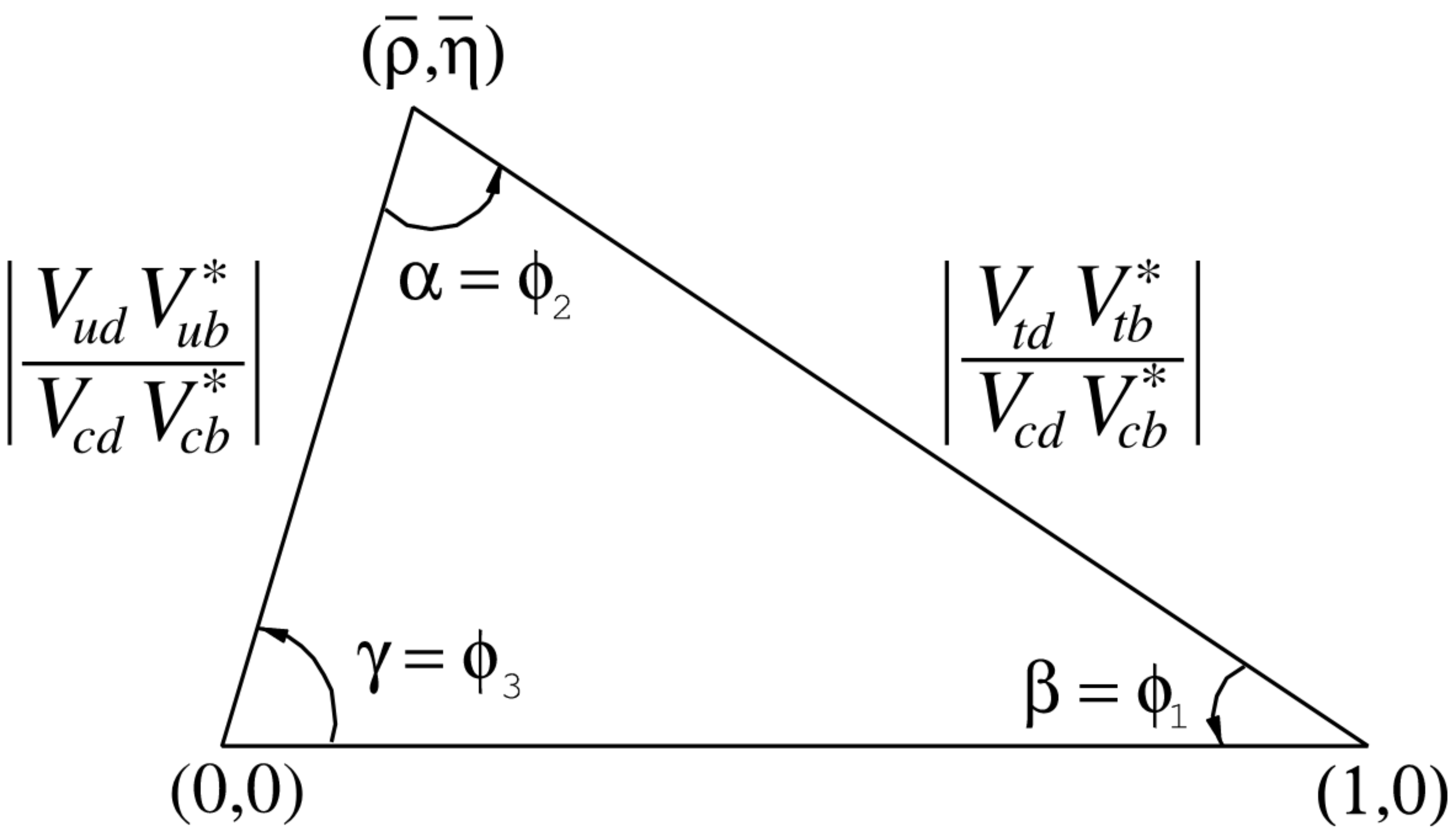
CP violation and the CKM matrix

Quark mixing via charged-current interactions

N. Cabibbo M. Kobayashi T. Maskawa

- Kobayashi and Maskawa predict three generations of quarks
  - Three mixing angles and one CP violating phase
  - Unitarity condition represented as triangles, e.g.

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



Interaction eigenstates Mass eigenstates

$$\begin{pmatrix} d_W \\ s_W \\ b_W \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d_m \\ s_m \\ b_m \end{pmatrix}$$

- Common CKM parameterization: Wolfenstein
  - Exploit hierarchy of matrix elements

$$V_{\rm CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

scaled apex parameters

CKM parameters

and where to find them

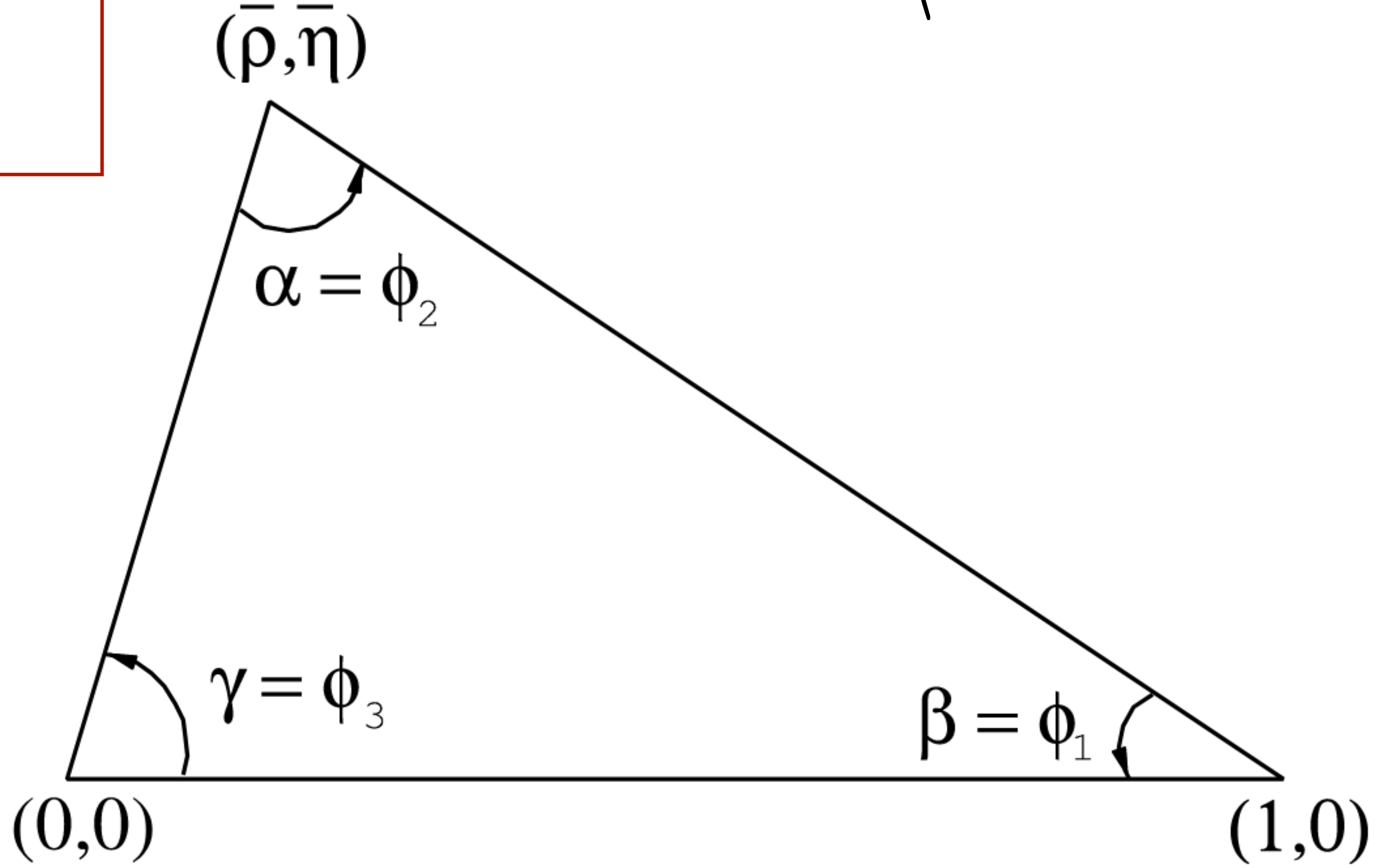
Angles

$$\alpha = \phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

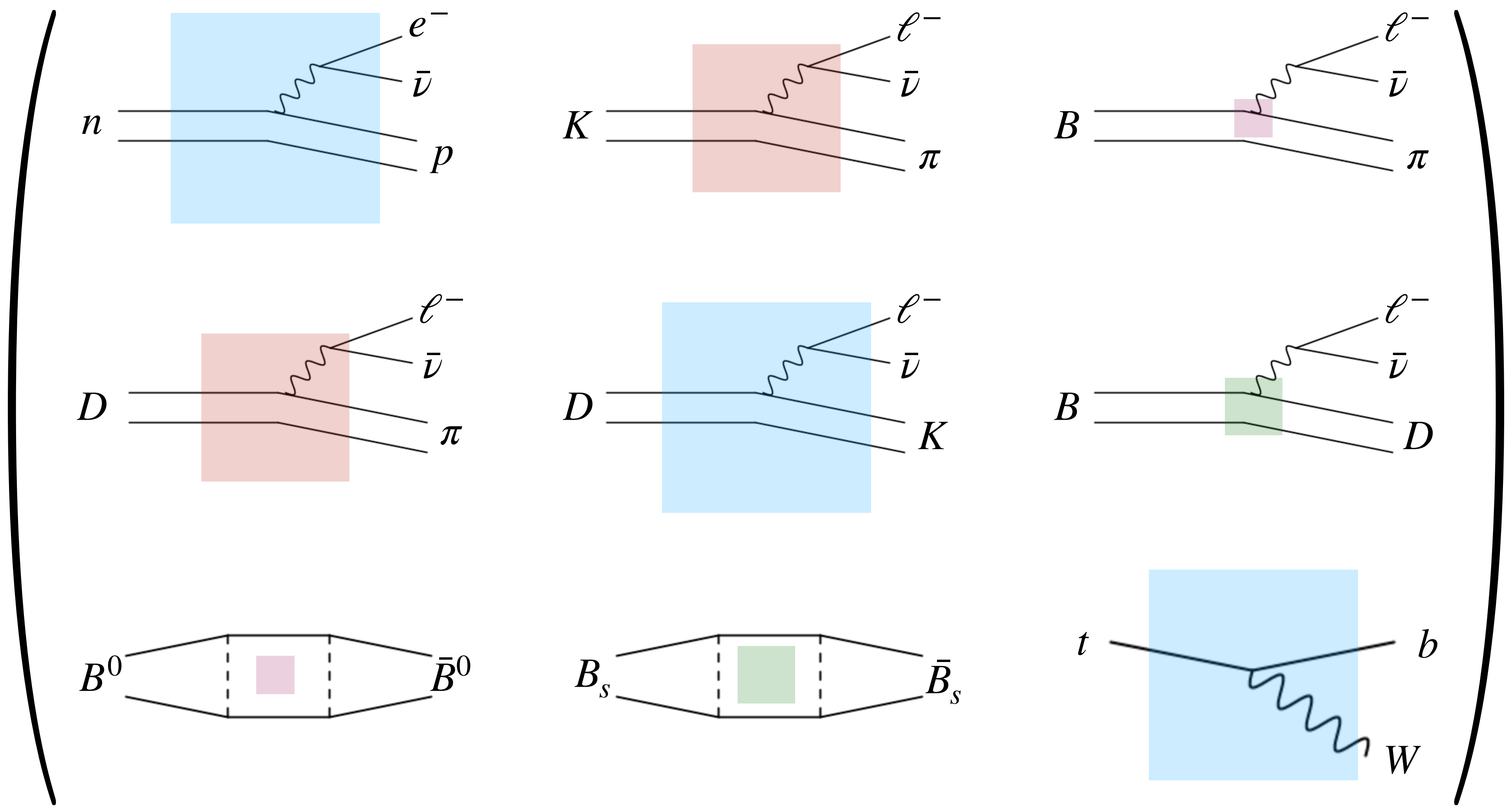
$$B \to \pi^+\pi^-, \pi^+\pi^0, \pi^0\pi^0$$
$$B \to \rho^+\rho^-, \rho^+\rho^0, \rho^0\rho^0$$
$$B^0 \to \rho\pi$$
$$B^0 \to a_1(\rho\pi)^+\pi^-$$

$$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

$$B^- \to D_{CP}^{(*)}K^{(*)-}$$
$$B^0 \to D_{CP}K^{*0}$$
$$B^- \to D^{(*)}(K_S h^+ h^-)K^{(*)-}$$
$$B^- \to D(K_S K^+\pi^-)K^-$$



Matrix elements



$$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

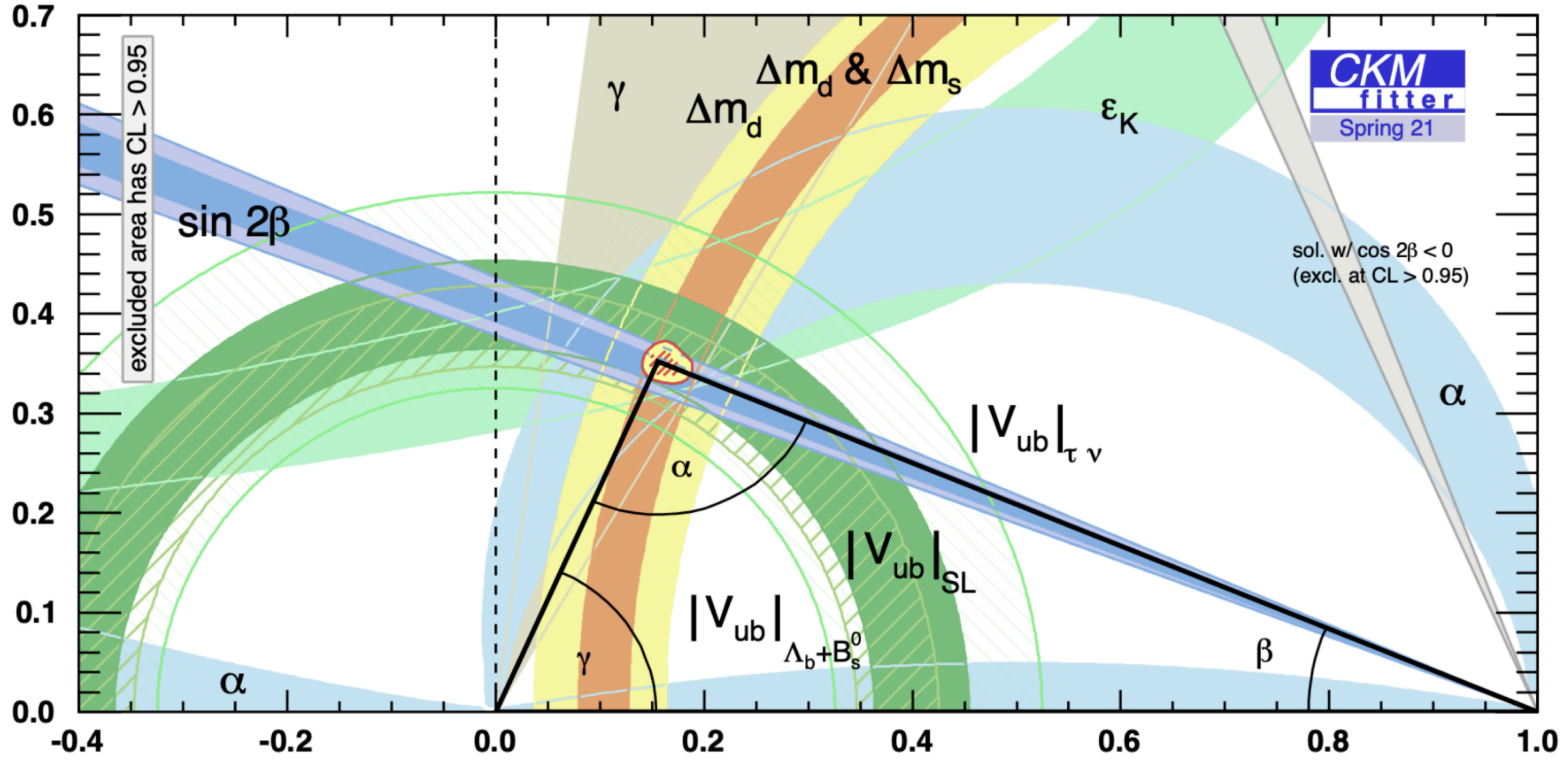
$$B^0 \to (c\bar c)K_S, (c\bar c)K_L$$
$$B^0 \to D_{CP}^{(*)}h^0$$
$$B^0 \to (\phi/\eta'/\pi^0/f^0)K^0$$
$$B^0 \to (K_S K_S/\rho^0/\omega)K_S$$

*Potential for new physics

CKM parameters

and where to find them

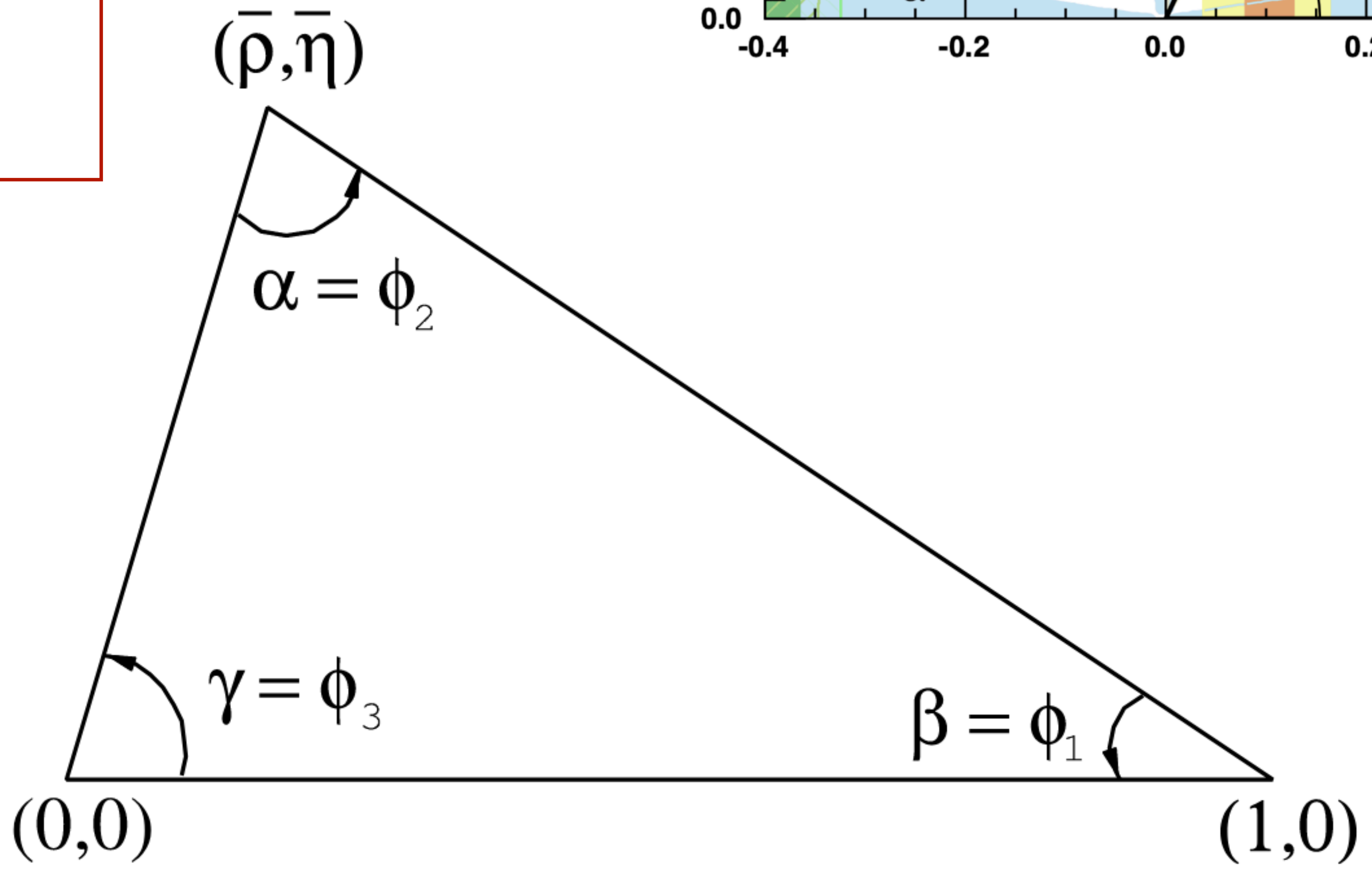
Current state-of-the-art



Angles

$$\alpha = \phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$B \to \pi^+\pi^-, \pi^+\pi^0, \pi^0\pi^0$$
$$B \to \rho^+\rho^-, \rho^+\rho^0, \rho^0\rho^0$$
$$B^0 \to \rho\pi$$
$$B^0 \to a_1(\rho\pi)^+\pi^-$$



$$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

$$B^- \to D_{CP}^{(*)}K^{(*)-}$$
$$B^0 \to D_{CP}K^{*0}$$
$$B^- \to D^{(*)}(K_S h^+h^-)K^{(*)-}$$
$$B^- \to D(K_S K^+\pi^-)K^-$$

$$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

$$B^0 \to (c\bar{c})K_S, (c\bar{c})K_L$$
$$B^0 \to D_{CP}^{(*)}h^0$$
$$B^0 \to (\phi/\eta'/\pi^0/f^0)K^0$$
$$B^0 \to (K_S K_S/\rho^0/\omega)K_S$$

*Potential for new physics

CKM parameters

and where to find them

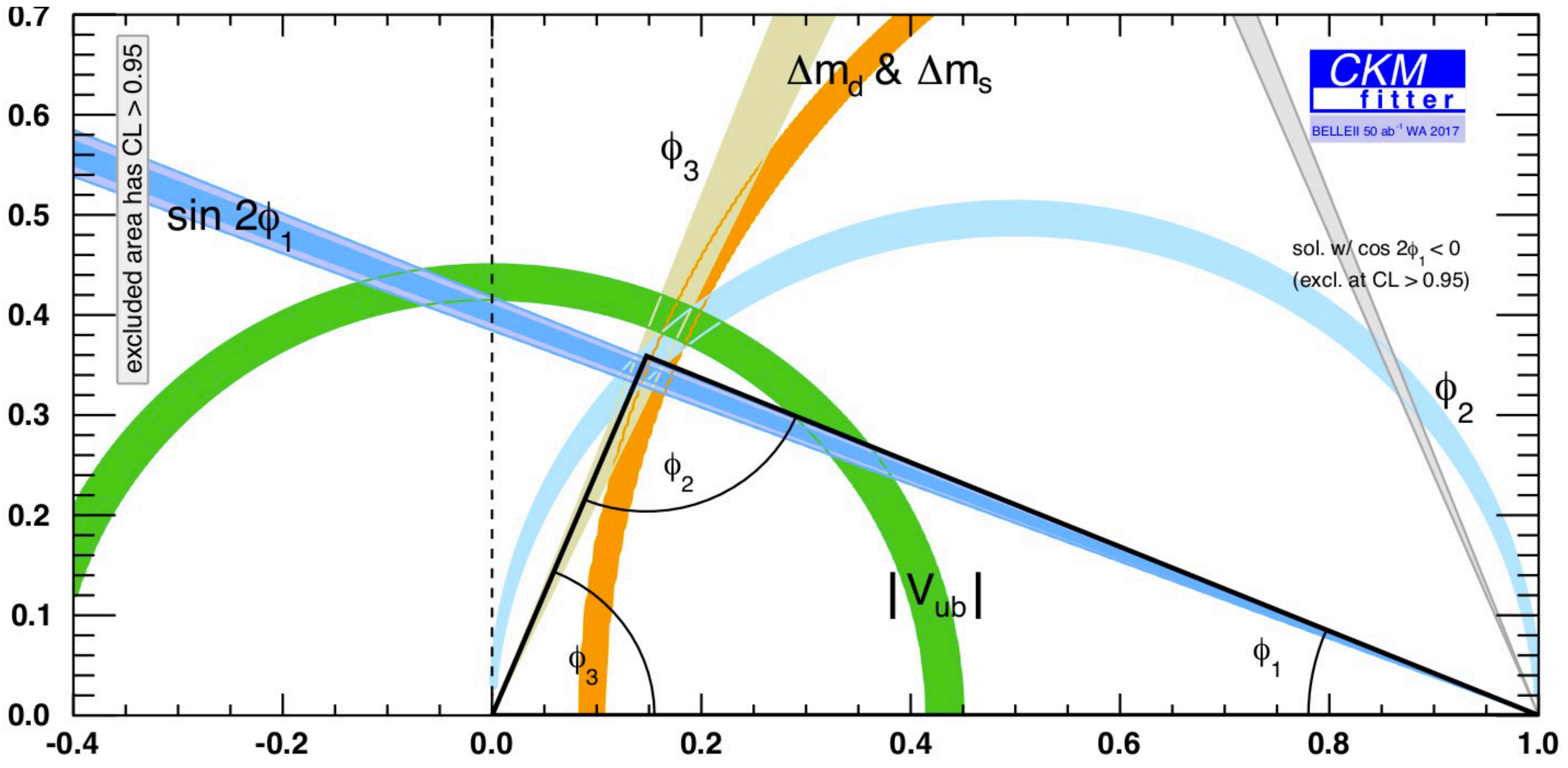
Angles $\alpha = \phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$

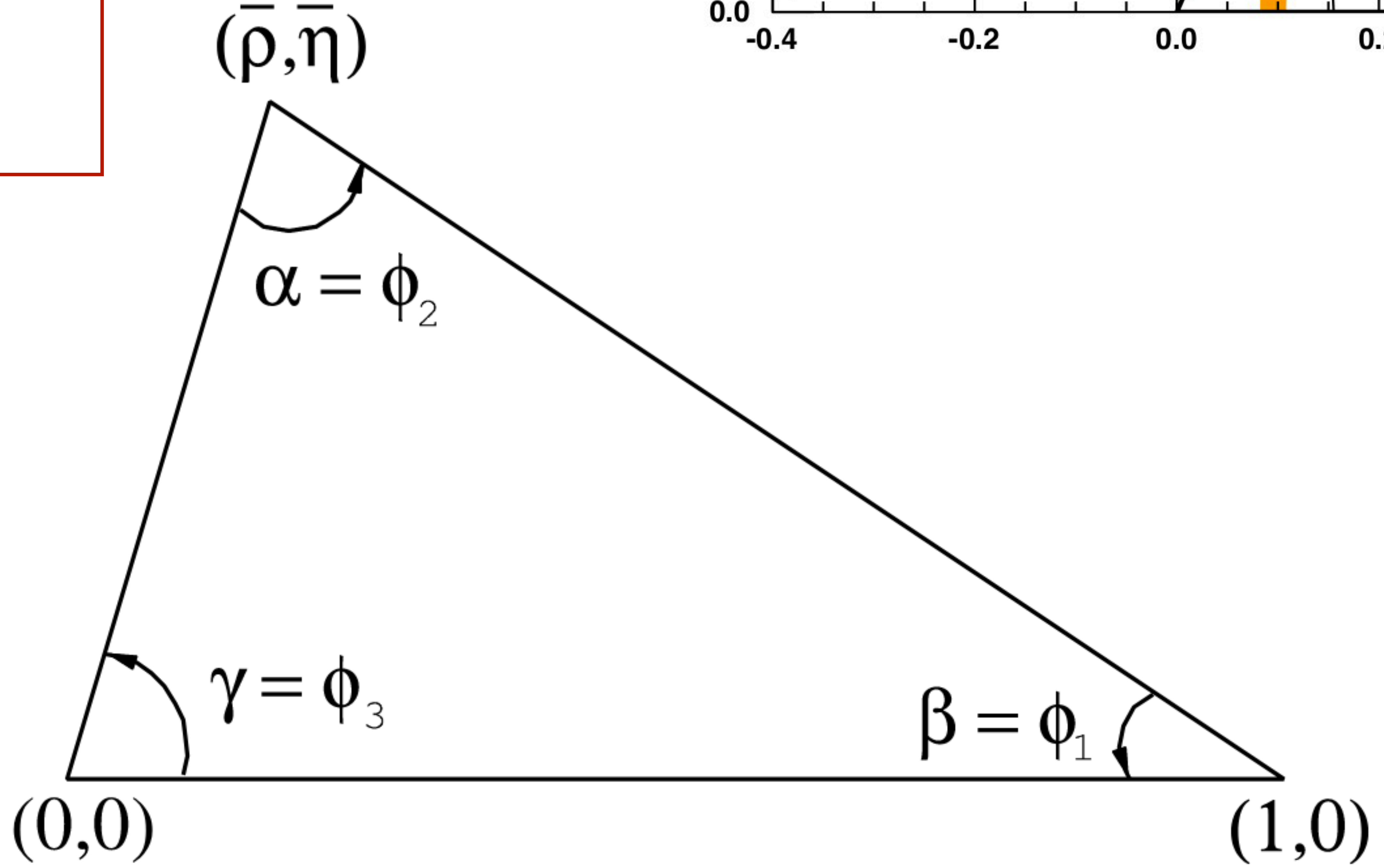
$$B \to \pi^+\pi^-, \pi^+\pi^0, \pi^0\pi^0$$
$$B \to \rho^+\rho^-, \rho^+\rho^0, \rho^0\rho^0$$
$$B^0 \to \rho\pi$$
$$B^0 \to a_1(\rho\pi)^+\pi^-$$

$$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

$$B^- \to D_{CP}^{(*)}K^{(*)-}$$
$$B^0 \to D_{CP}K^{*0}$$
$$B^- \to D^{(*)}(K_S h^+h^-)K^{(*)-}$$
$$B^- \to D(K_S K^+\pi^-)K^-$$

Possible view with the full Belle II dataset





$$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

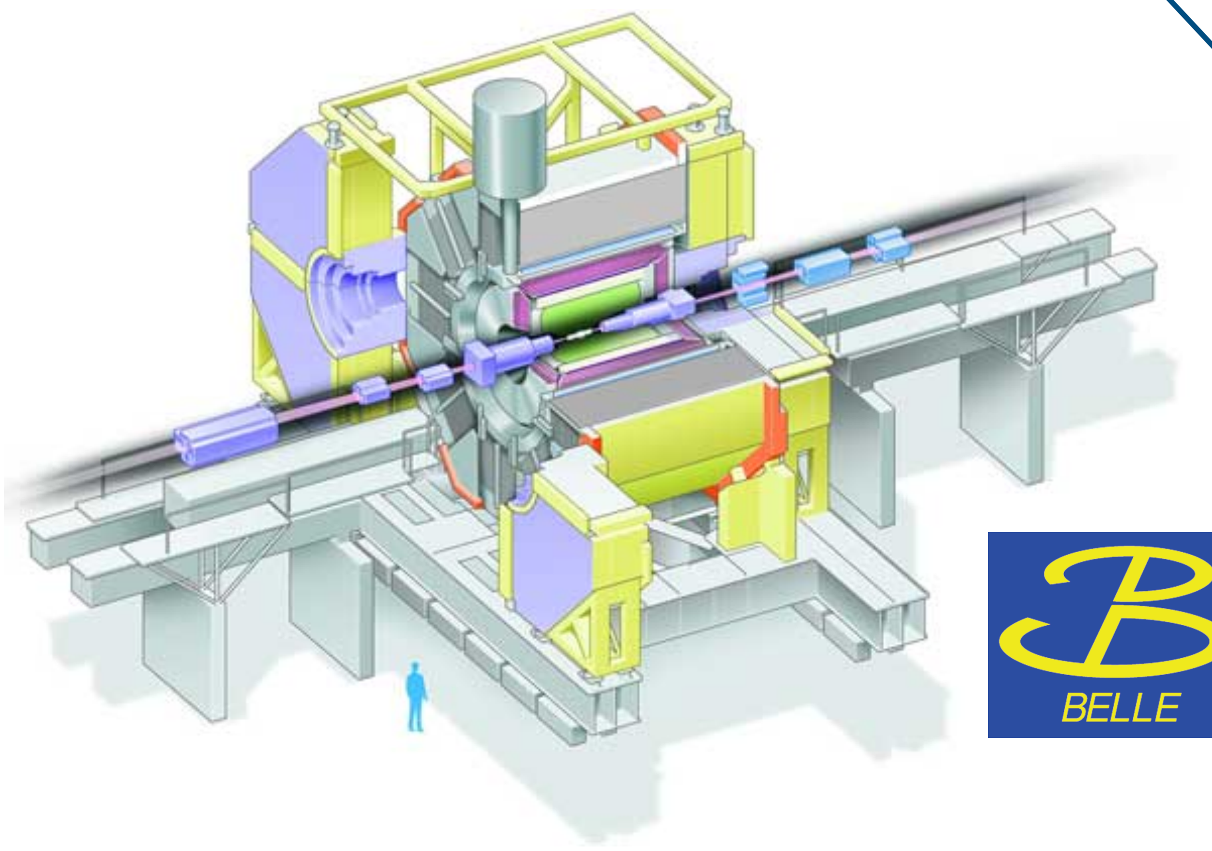
$$B^0 \to (c\bar c)K_S, (c\bar c)K_L$$
$$B^0 \to D_{CP}^{(*)}h^0$$
$$B^0 \to (\phi/\eta'/\pi^0/f^0)K^0$$
$$B^0 \to (K_S K_S/\rho^0/\omega)K_S$$

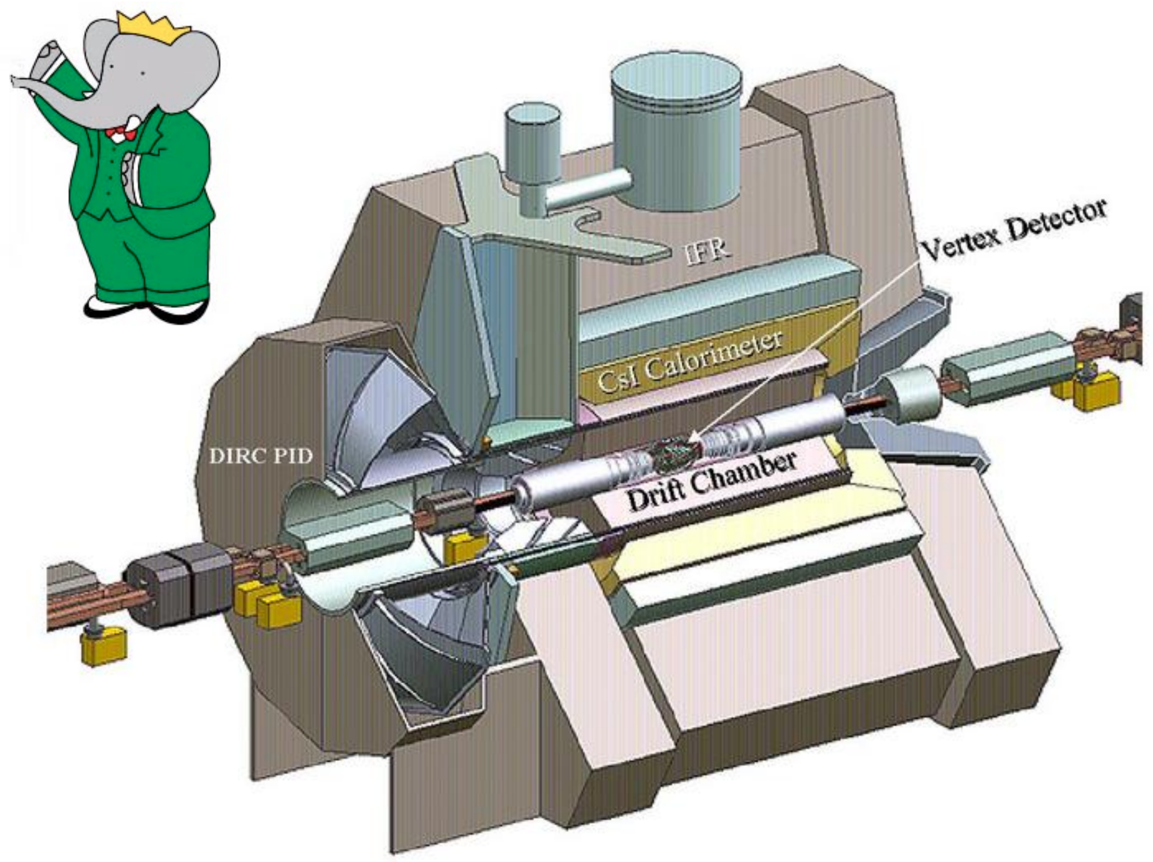
*Potential for new physics

Heavy flavor experiments

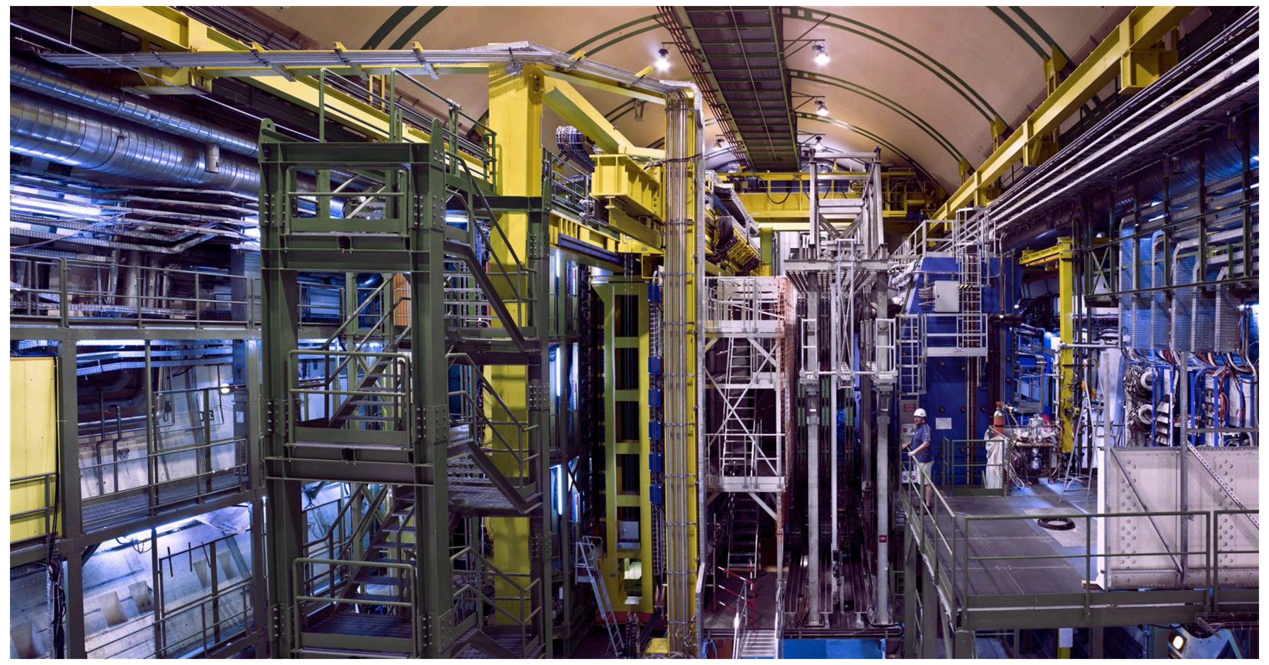
the primary players

The “B-factories”

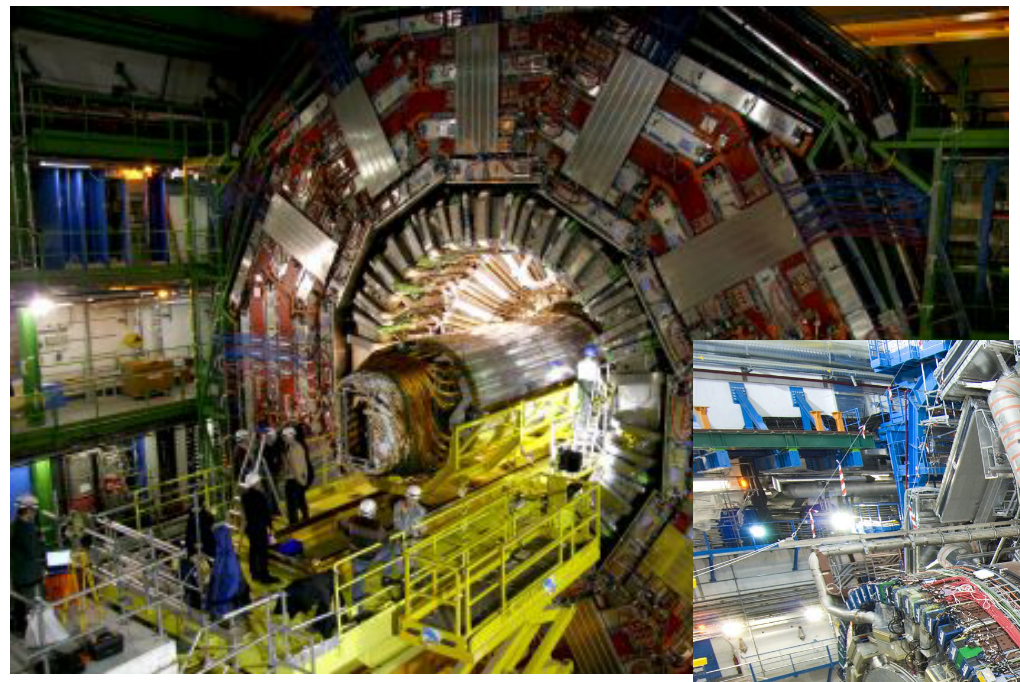


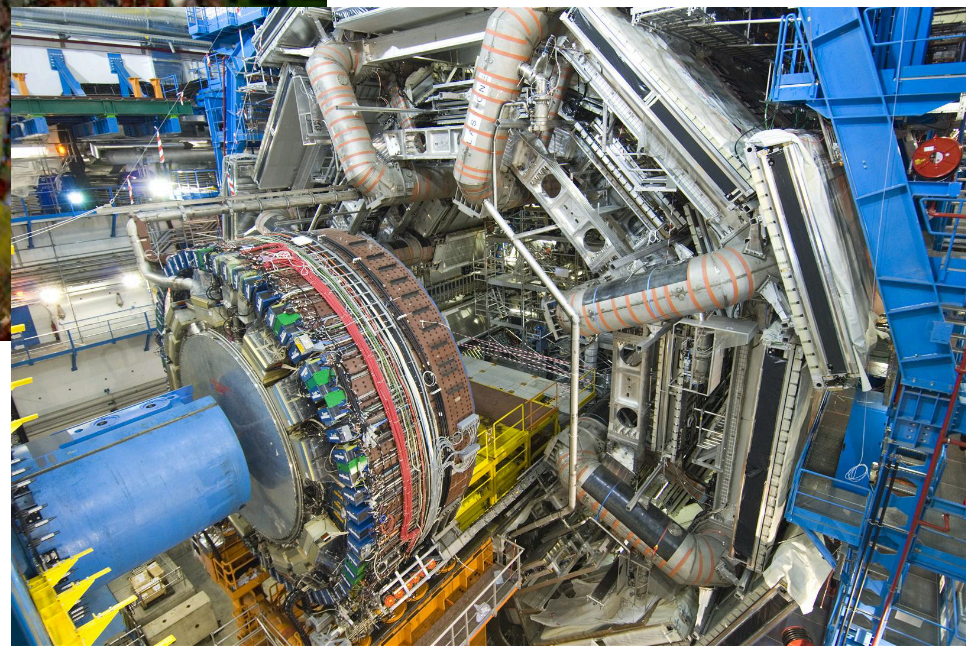


hadron machines



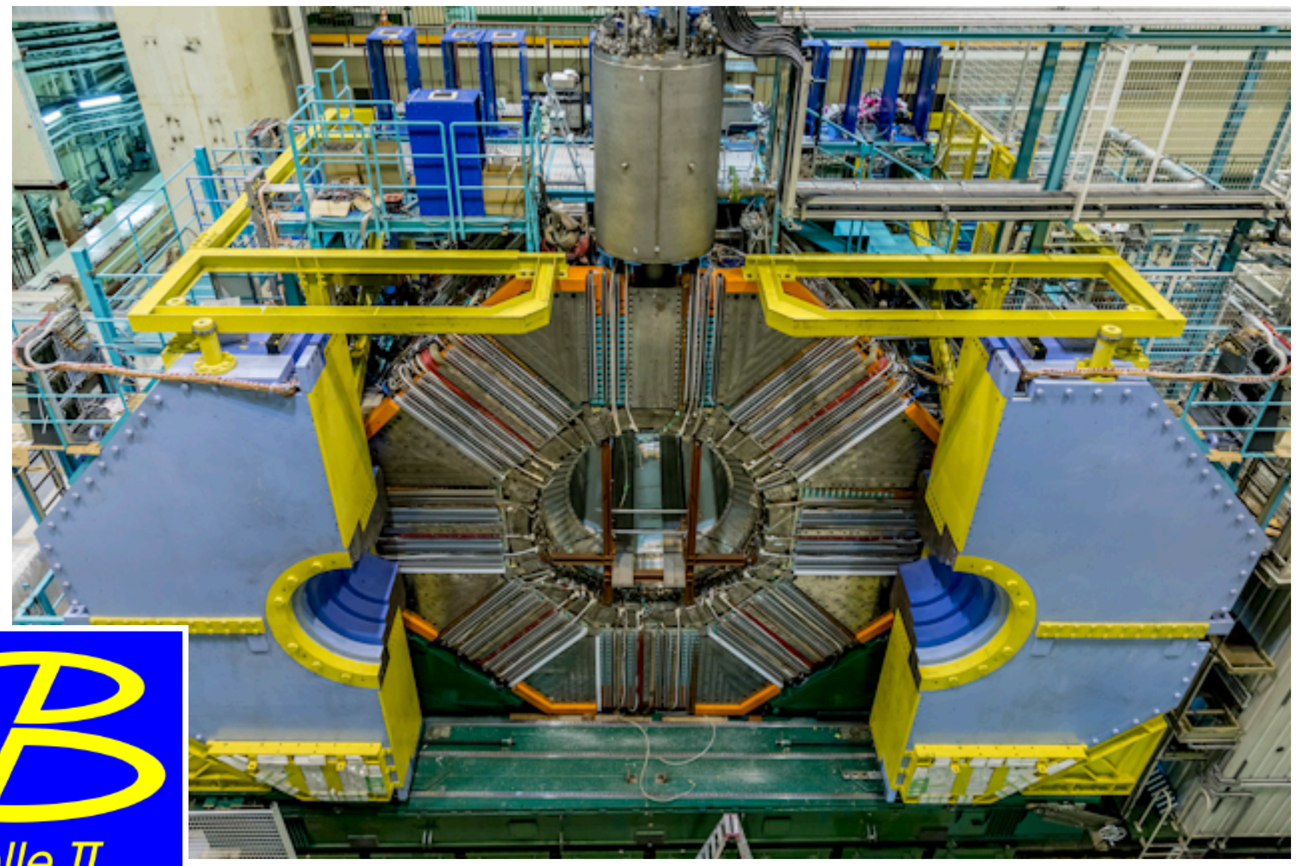
LHCb (beauty/charm at LHC)



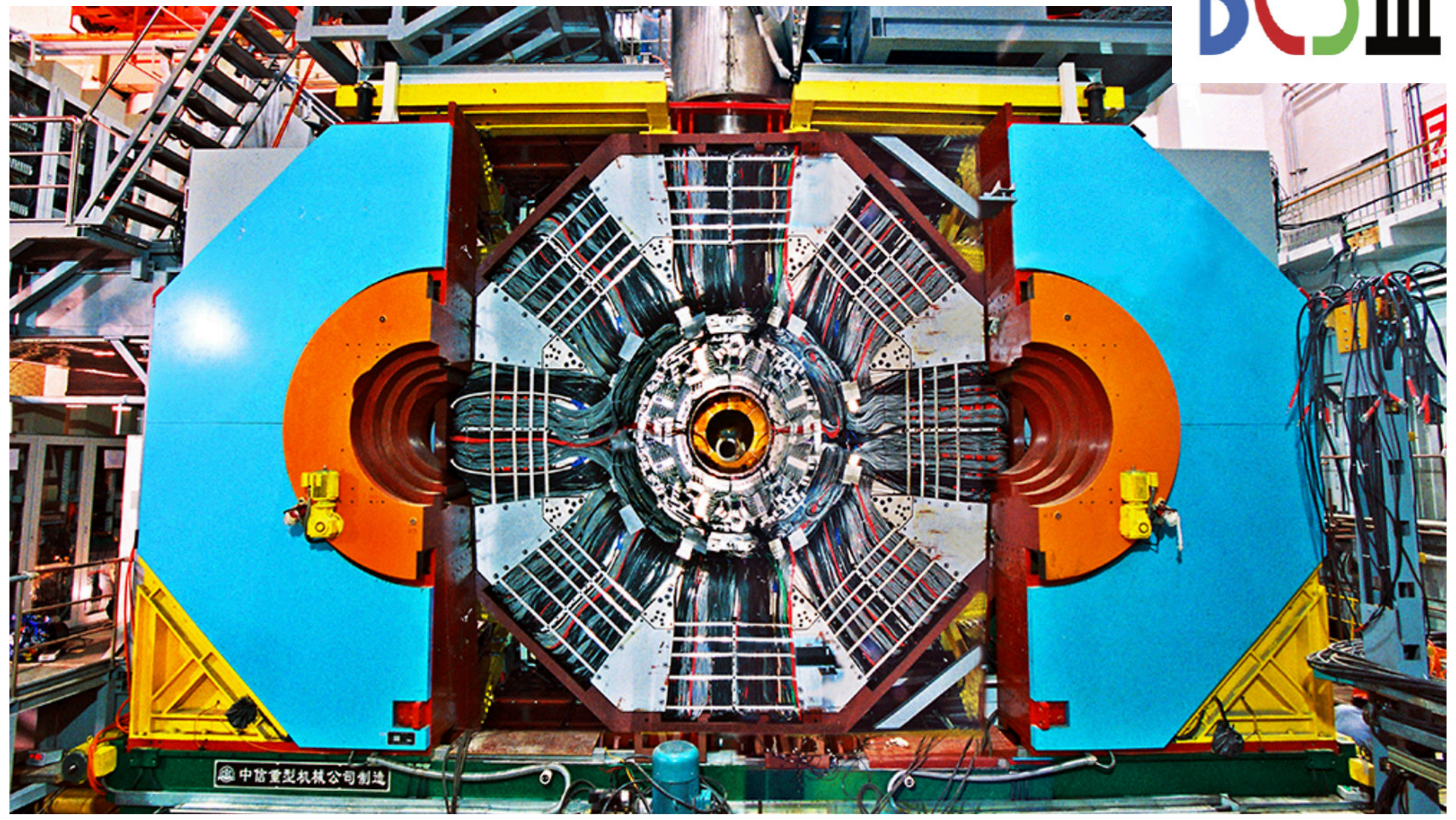


CMS and ATLAS (general purpose at LHC)

Belle II: the “super B-factory”



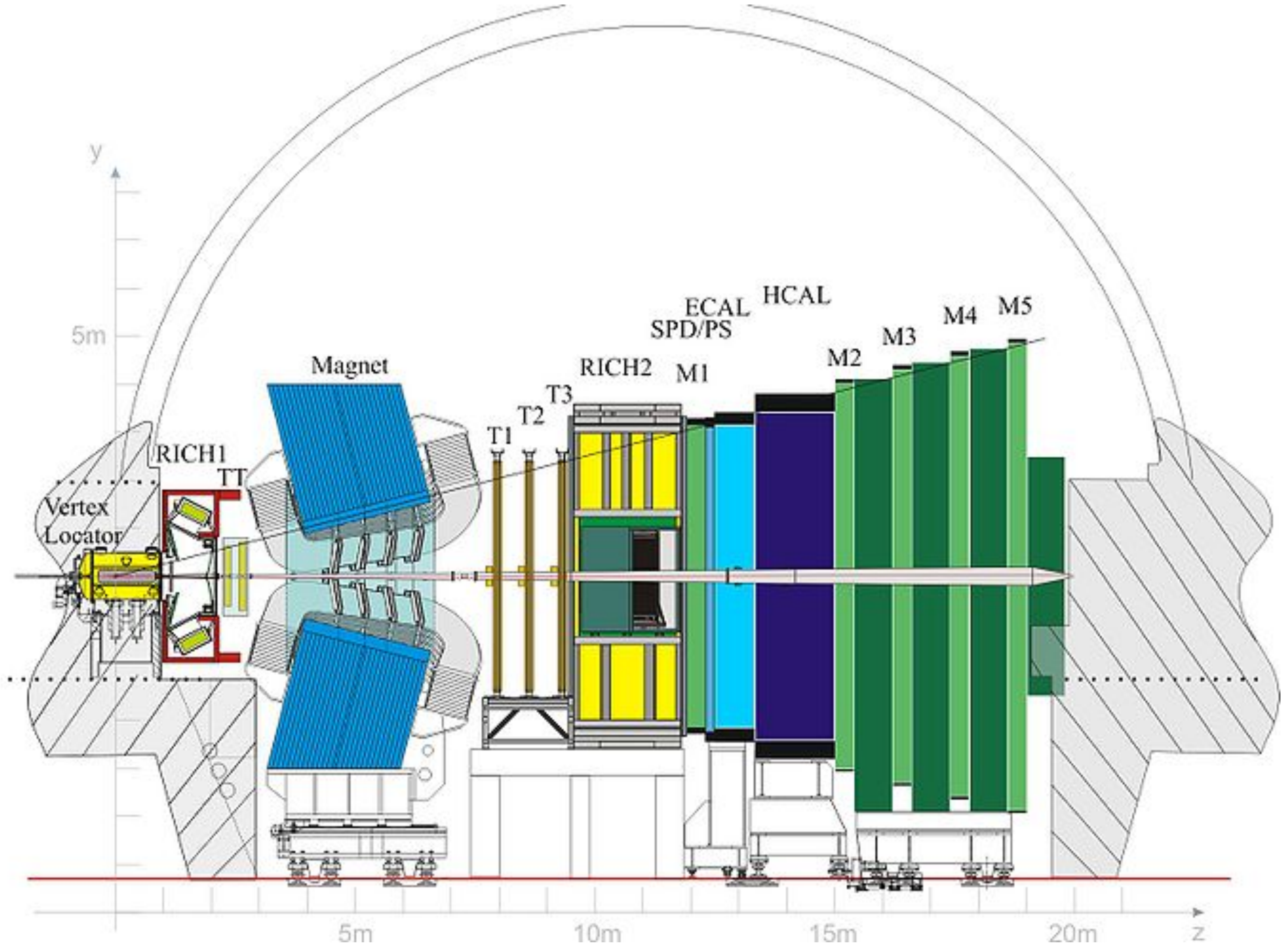
BESIII (“charm factory”)



e^+e^- machines

Belle II and LHCb

The next generation of B physics experiments

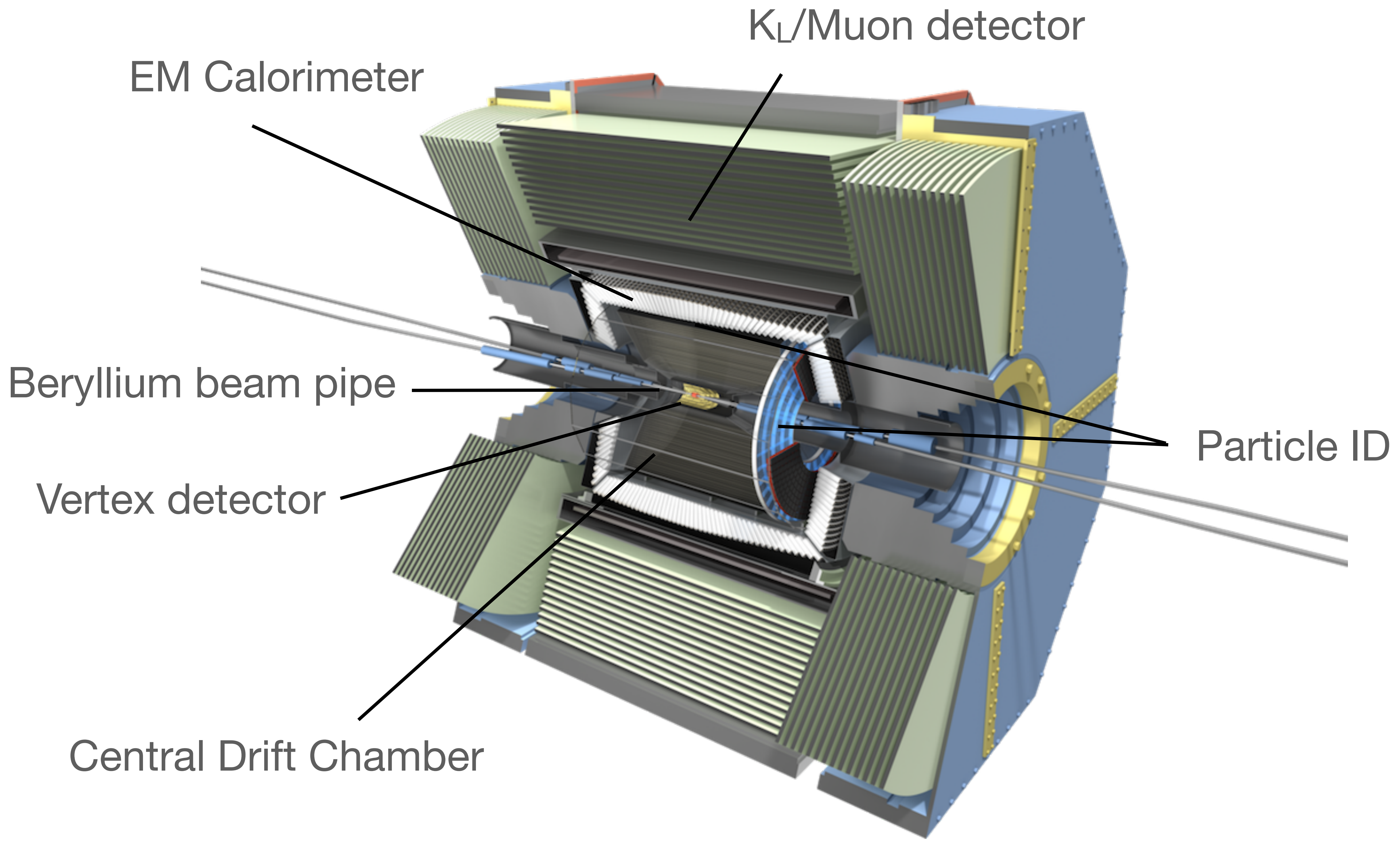


LHCb (proton collisions)

- General purpose LHC experiment covering the forward region
- Large cross section for $b\bar{b}$ production
- Precise tracking, excellent particle ID, decay time resolution
- Access to heavy b hadrons

Belle II (e^+e^- collisions)

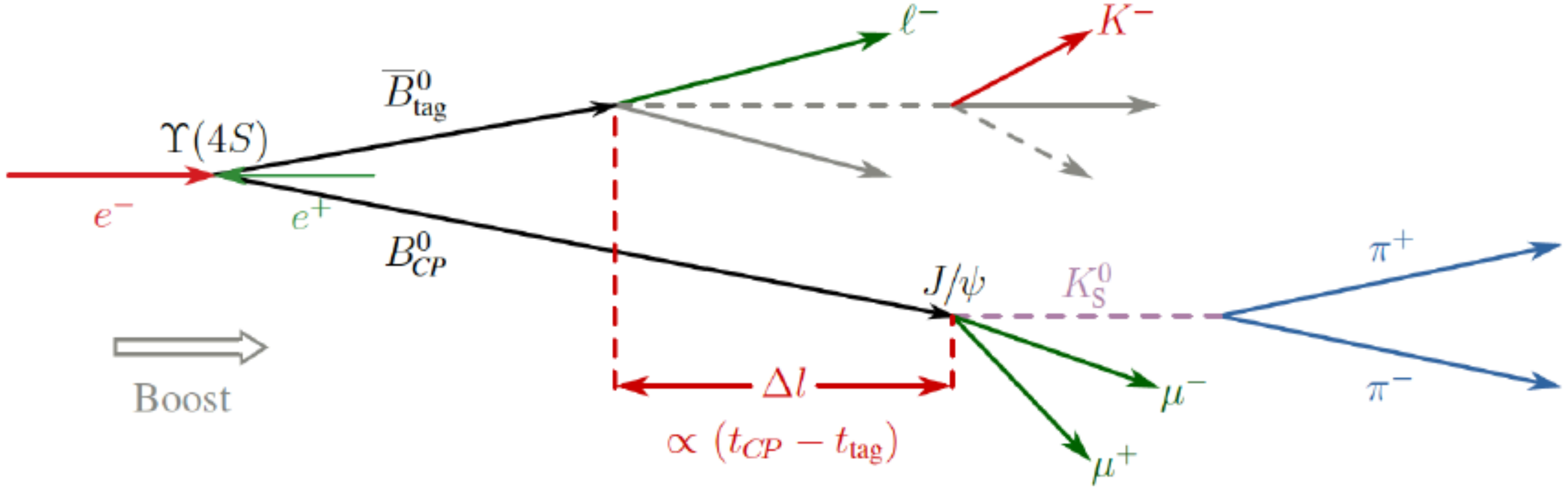
- High luminosity from SuperKEKB accelerator at $\Upsilon(4S)$ (lower $b\bar{b}$ cross section)
- Hermetic detector in low background environment, high reconstruction efficiency
- Well known initial state, efficient neutrals reconstruction
- High flavor tagging efficiency



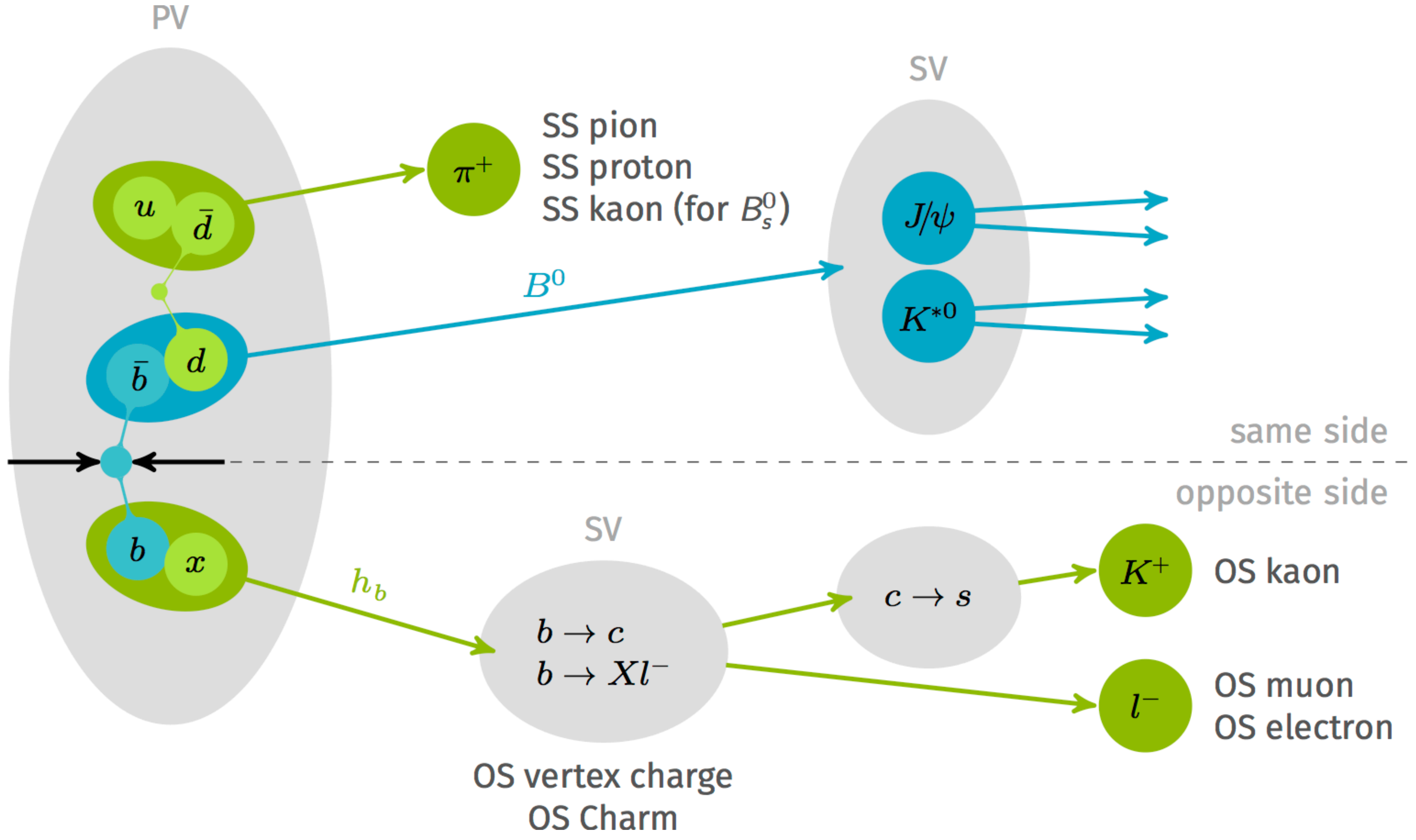
Flavor tagging

Technique to identify the flavor of a particle

- At threshold: take into account quantum correlation and identify characteristic particles
  - "Tag" the flavor of one of the particles
  - Also identifies the flavor of the partner, useful for time-dependent CPV measurements
  - **Very high efficiency** (~37% at Belle II, ~30% at Belle)

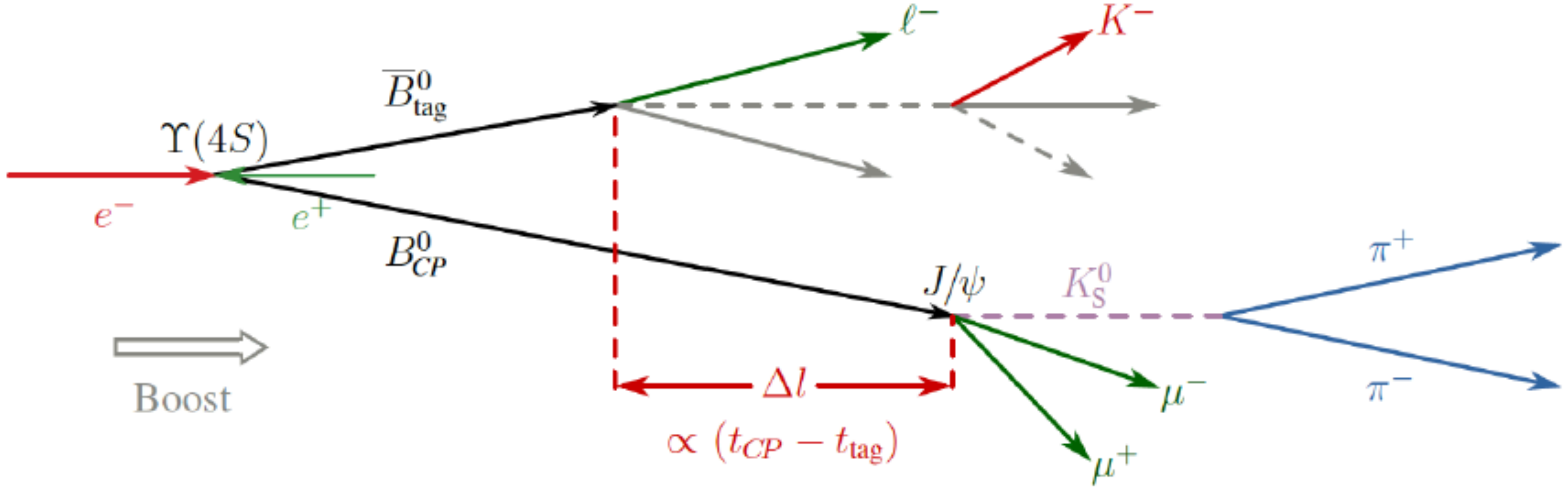


- At LHC: identify flavor at production
  - Same side taggers: use particles produced in fragmentation of signal B^0, B^0_s
  - Opposite side taggers: use the decay products of non-signal B^0, B^0_s
  - Efficiency ~3-5% at LHCb



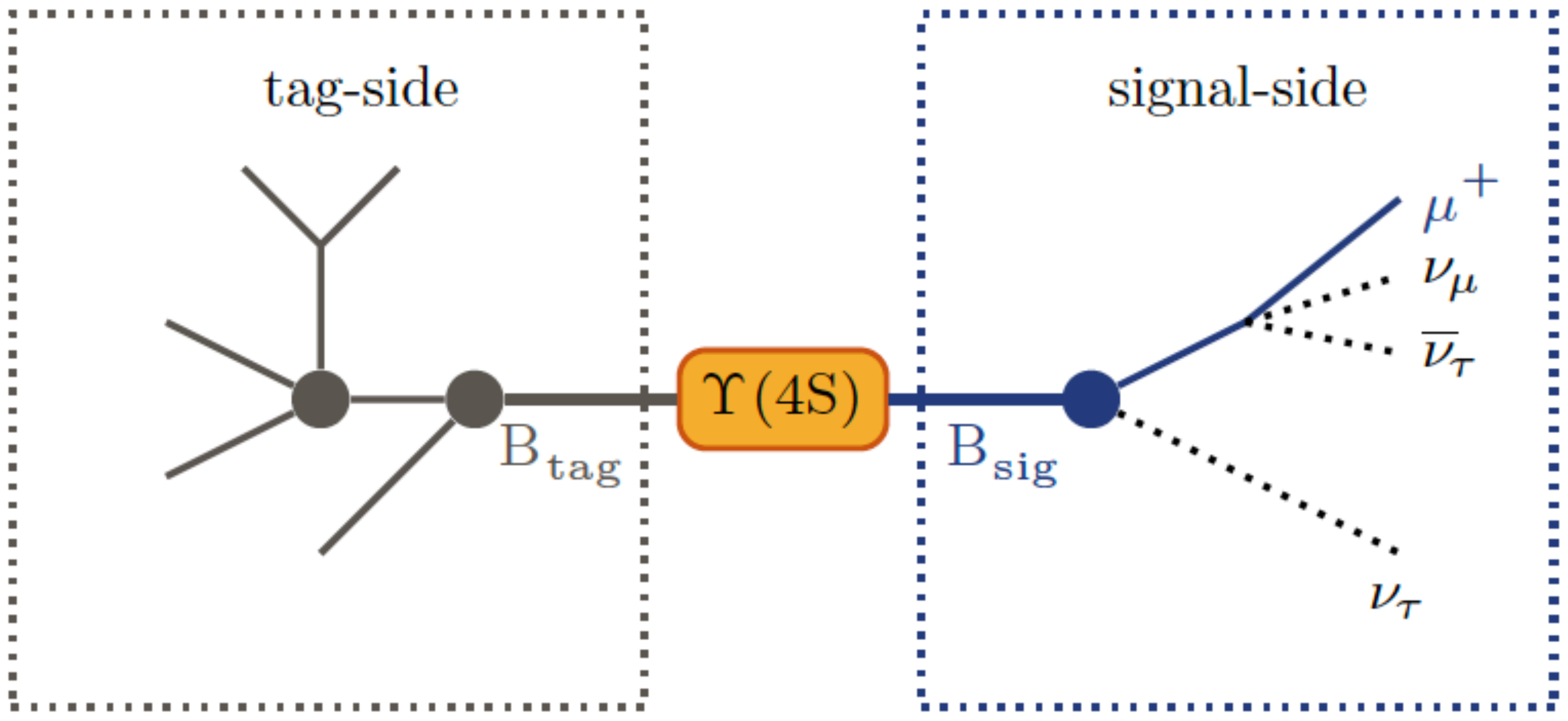
Flavor tagging

Technique to identify the flavor of a particle



- At threshold: take into account quantum correlation and identify characteristic particles
  - “Tag” the flavor of one of the particles
  - Also identifies the flavor of the partner, useful for time-dependent CPV measurements
  - **Very high efficiency** (~37% at Belle II, ~30% at Belle)

Powerful technique for missing energy, missing mass analyses: Full Reconstruction (full event interpretation)



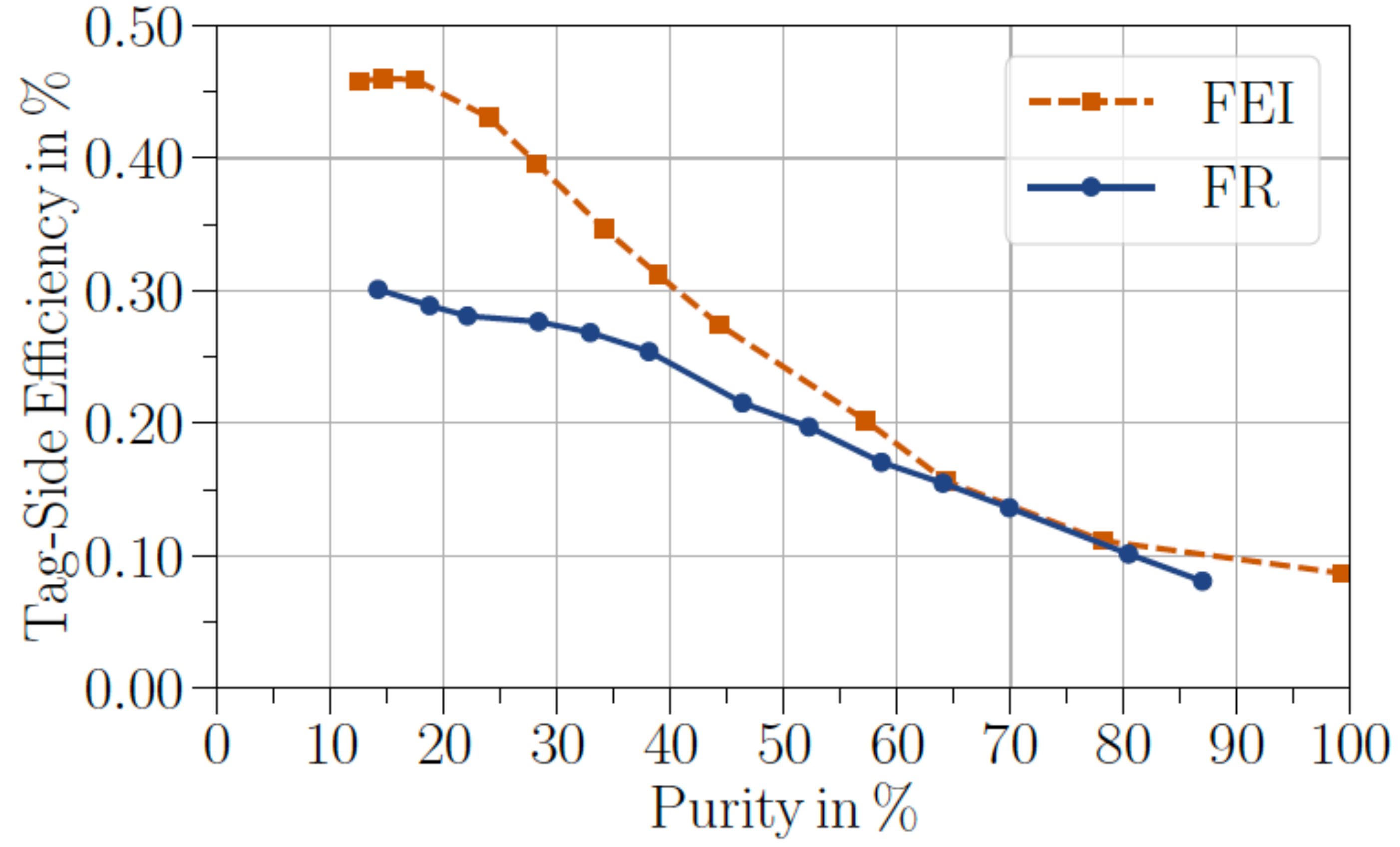
B-factories, Belle II, BESIII

<u>Signal side</u>:

$B \to X\ell\nu$ - Precise meas. of $|V_{ub}|$

$B \to \tau\nu$ - Search for NP

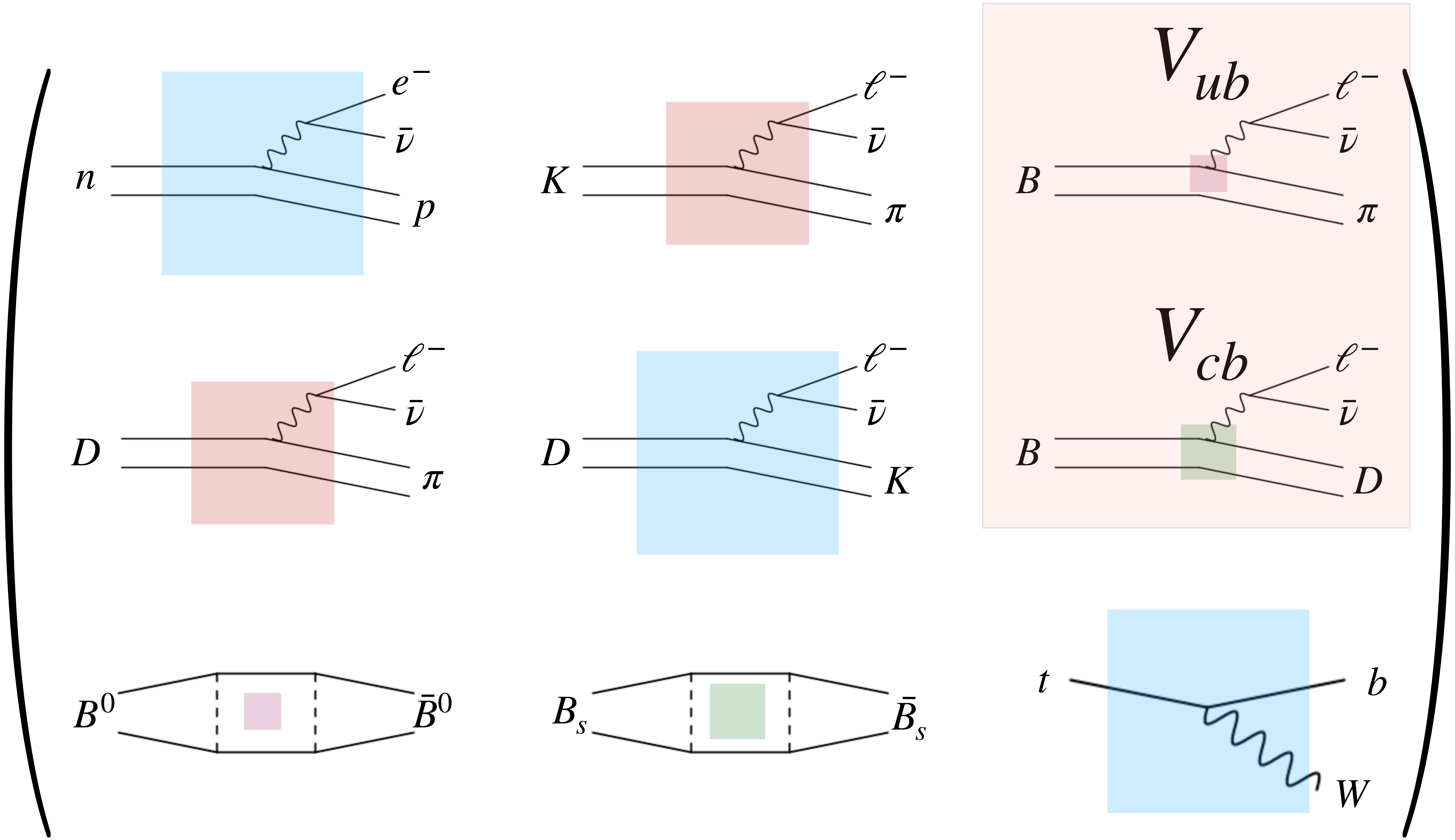
$B \to K\nu\bar{\nu}$ - Search for NP



*Apologies if I left out your favorite results

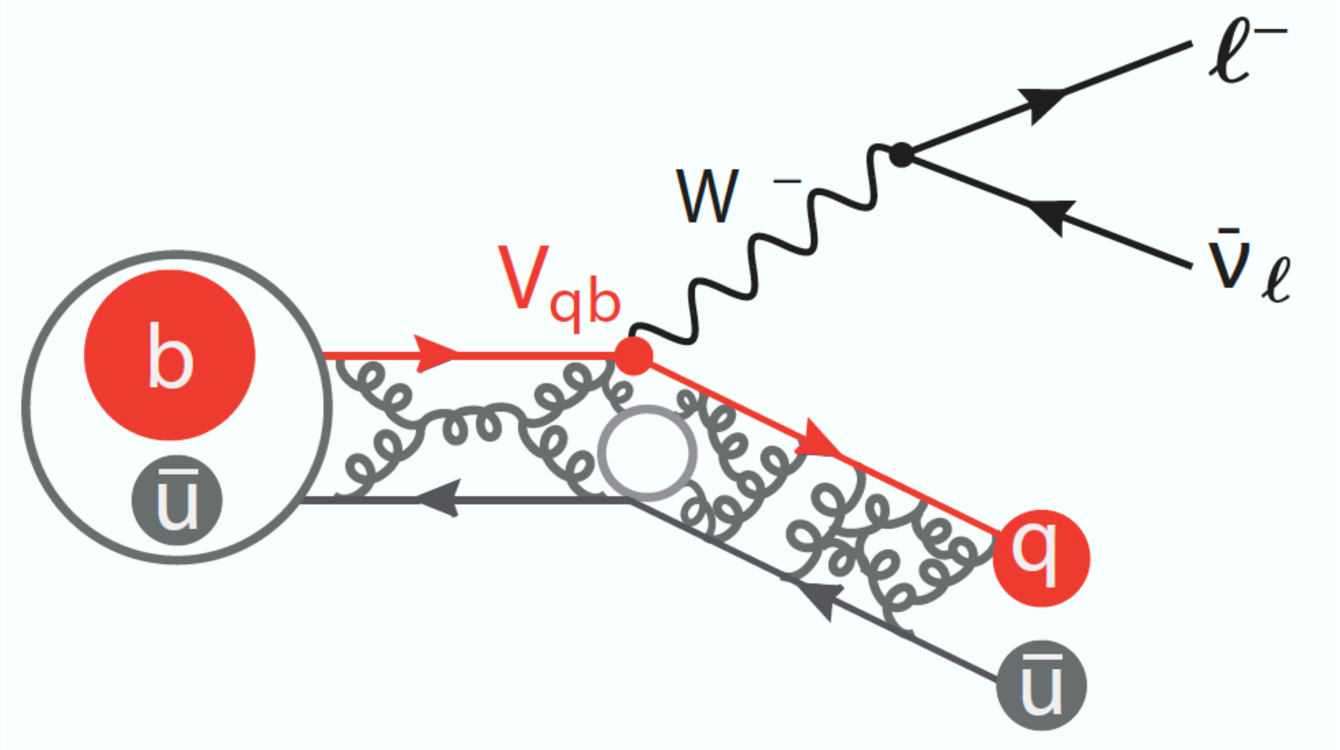
Measuring CKM matrix elements in B decays

Not an exhaustive accounting



Measuring V_{ub} and V_{cb}

Status and methods



- Decay rate depends on product of CKM element and hadronic form factor
  - Global fit for CKM element, extract form factors (test theory predictions)
  - Theory prediction for form factor, extract CKM elements

Exclusive V_{ub}

$$B \to (\pi, \rho, \omega)\ \ell \bar{\nu}_\ell$$

$$B_s \to K \mu \bar{\nu}_\mu$$

Exclusive V_{cb}

$$B_{(s)} \to D^{(*)}_{(s)} \ell \bar{\nu}_\ell$$

$$\mathrm{BR} \propto |V_{qb}|^2 f^2$$

Inclusive V_{ub}

$$B \to X_u \ell \bar{\nu}_\ell$$

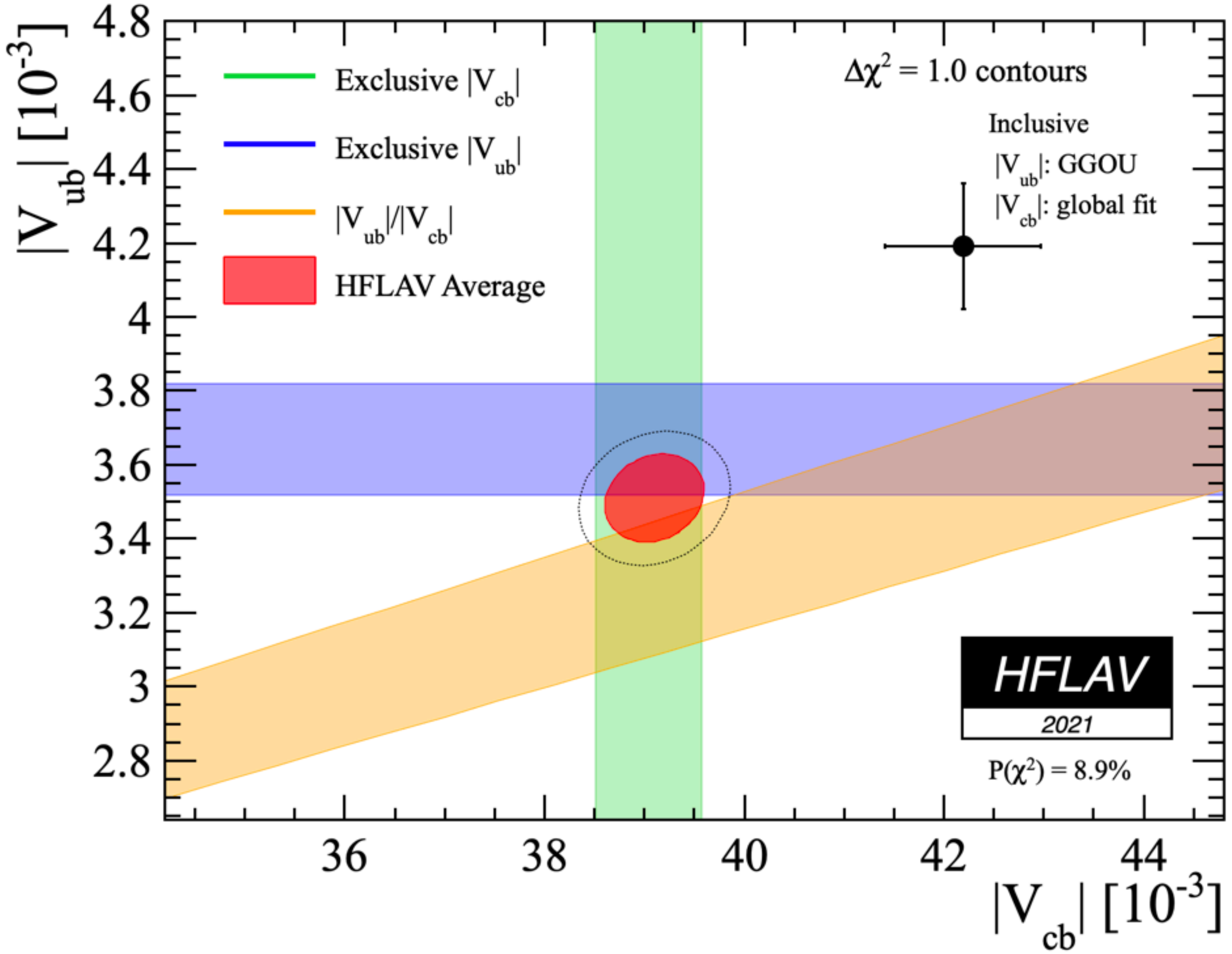
Inclusive V_{cb}

$$B \to X_c \ell \bar{\nu}_\ell$$

Operator Product Expansion

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

Significant tension between inclusive and exclusive determinations



Exclusive V_{ub} from $B \to \pi \ell \nu$

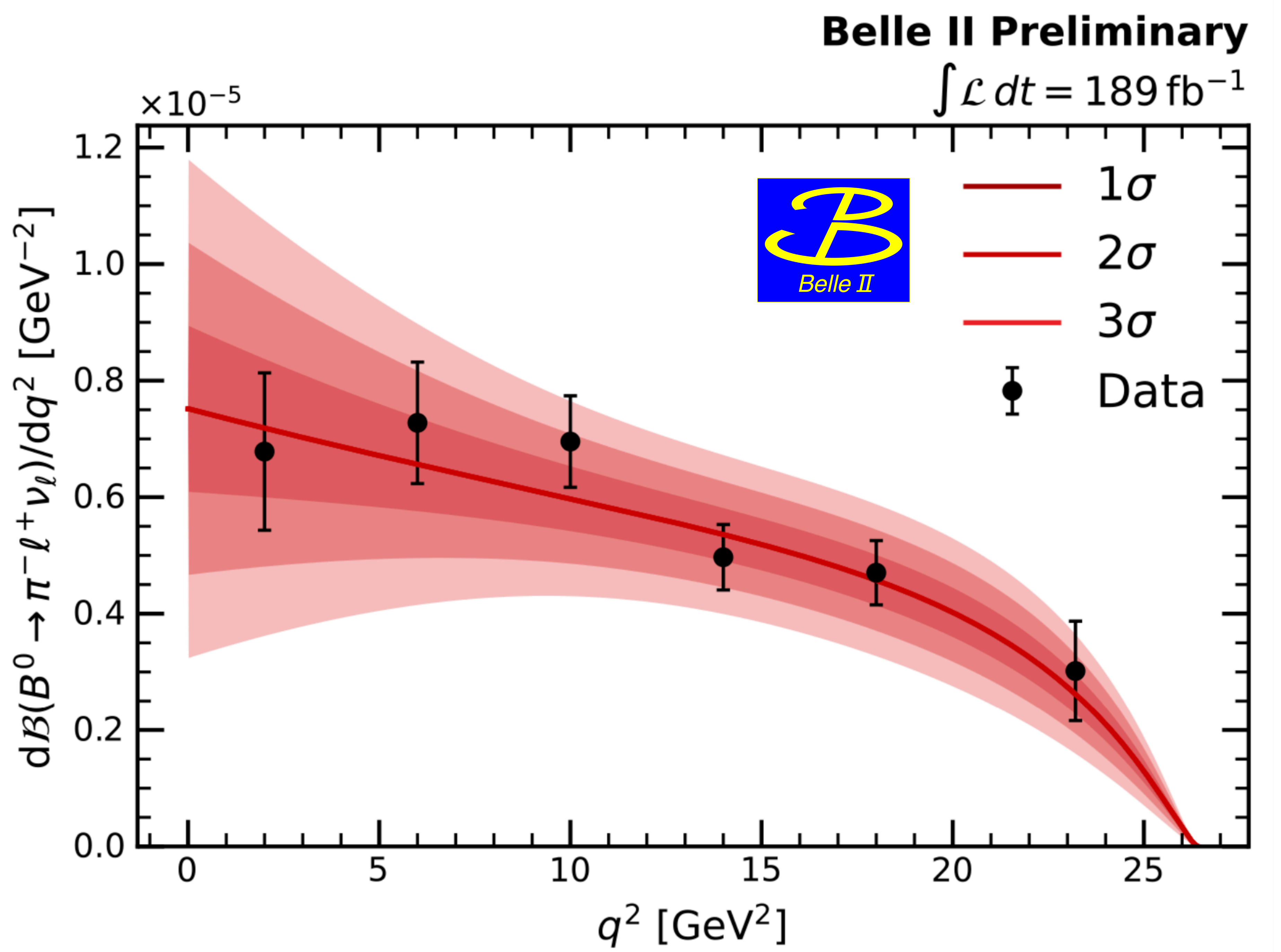
Preliminary result from Belle II

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

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

- Extract yield in 6 bins of q^2 by fitting to

$$M_{bc} = \sqrt{E_{\text{beam}}^{*2} - |\vec{p}_B^{\,*}|^2} \text{ and } \Delta E = E_B^* - E_{\text{beam}}^*$$



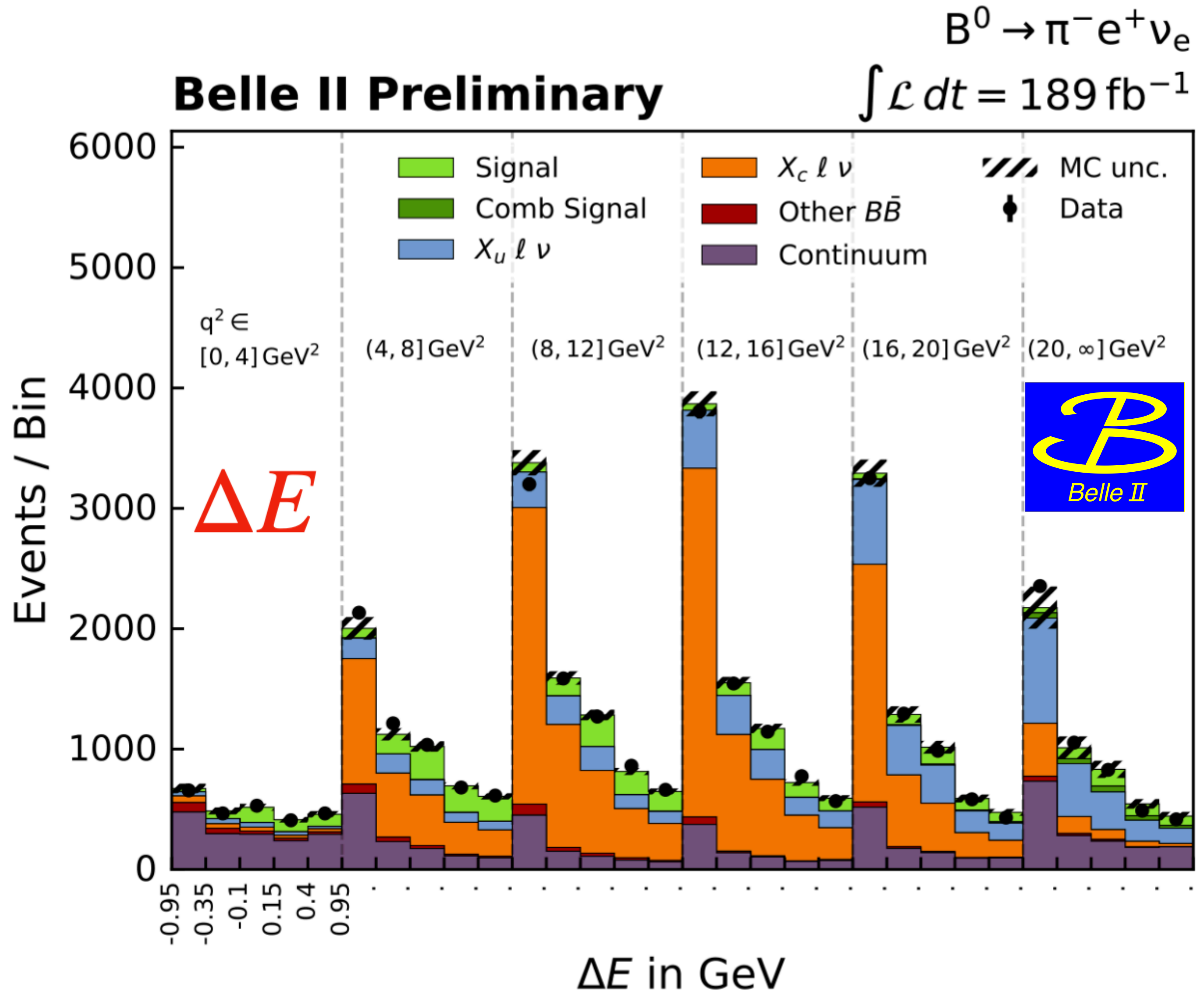
$$|V_{ub}| = (3.55 \pm 0.12 \pm 0.13 \pm 0.17) \times 10^{-3}$$

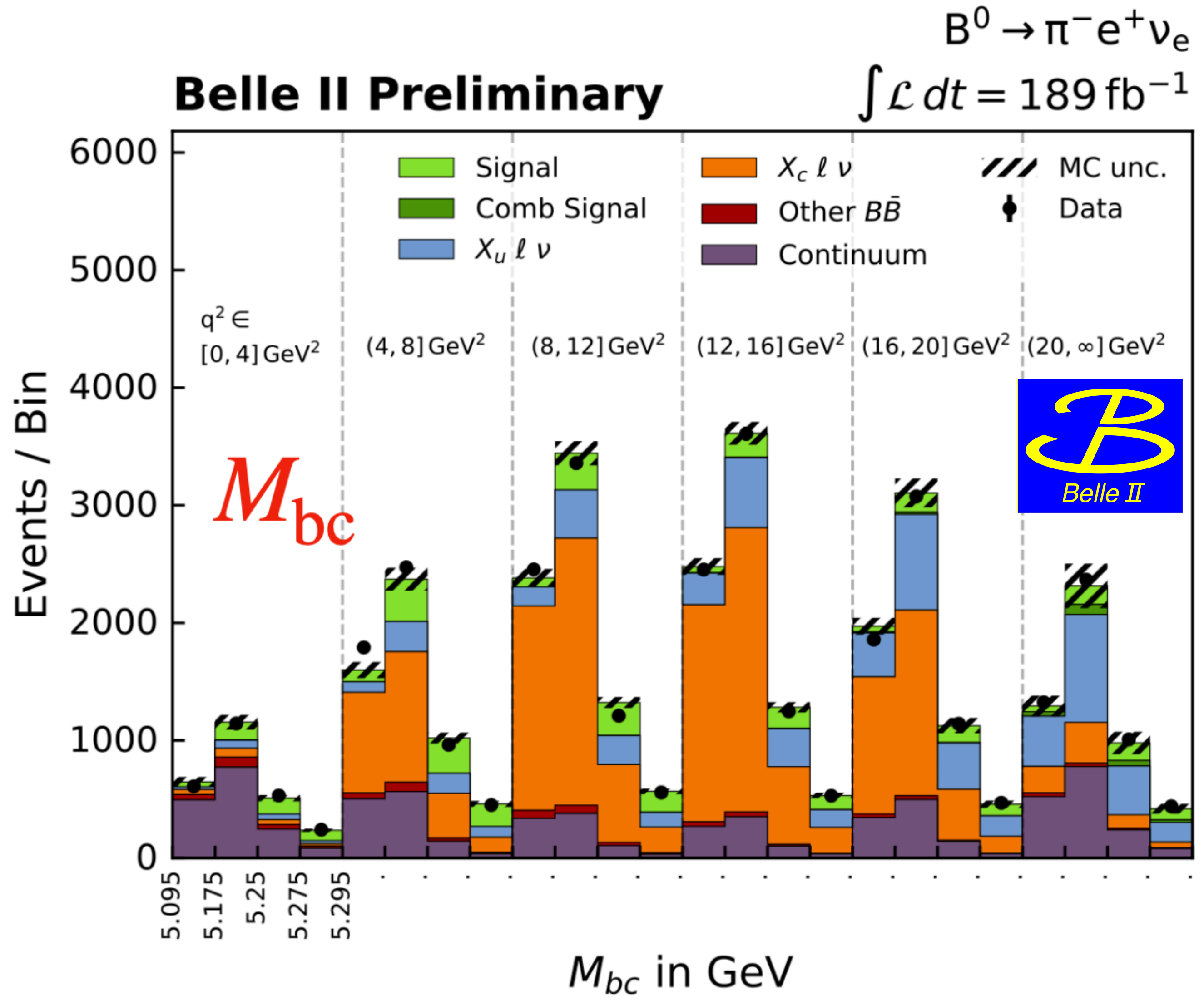
With LQCD input from FNAL/MILC [PRD 92 014024]

Consistent with world average exclusive value

$$|V_{ub}^{\text{excl.}}| = (3.51 \pm 0.12) \times 10^{-3}$$

$$|V_{ub}^{\text{incl.}}| = (4.19 \pm 0.16) \times 10^{-3}$$





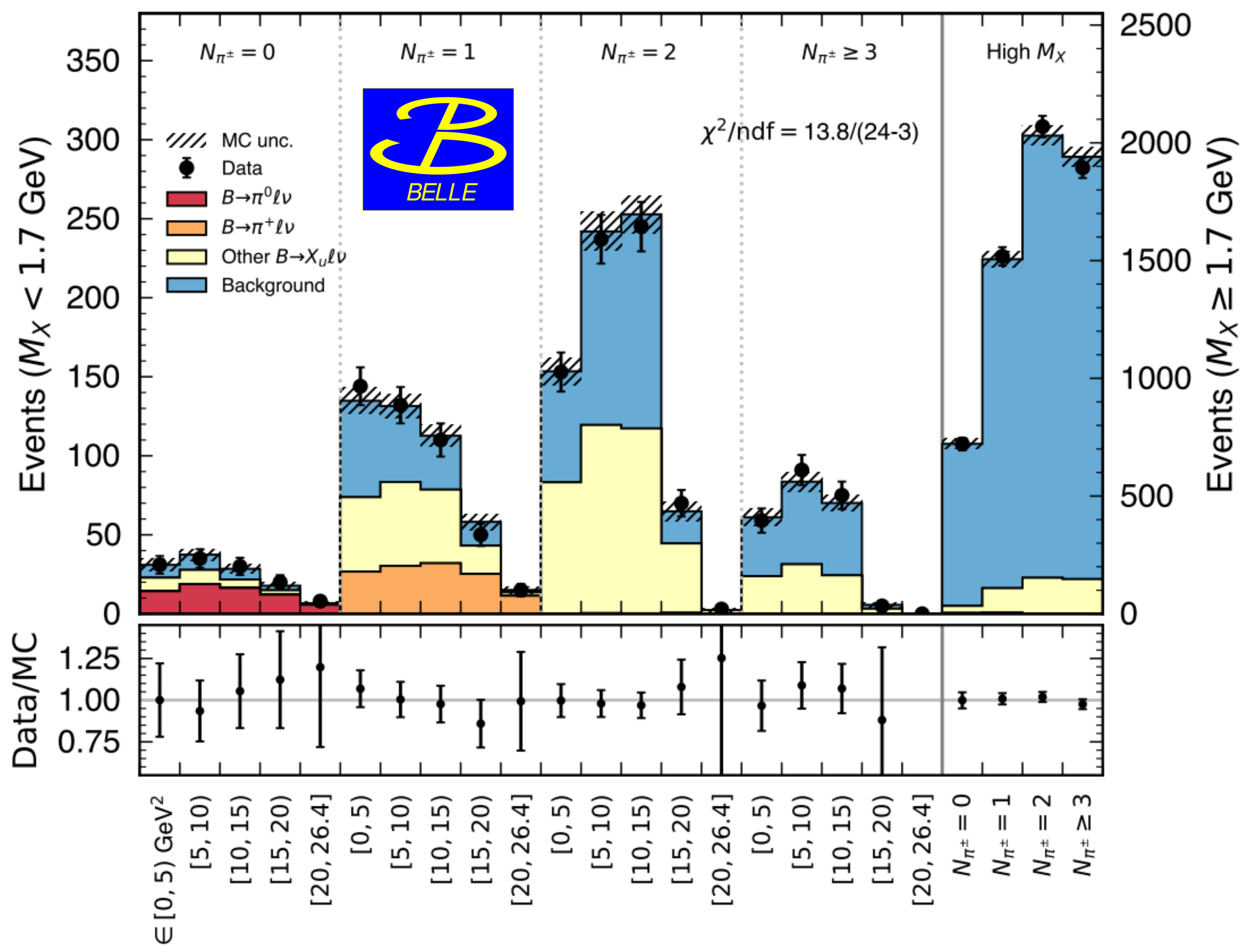
First simultaneous inclusive/exclusive V_{ub} determination in a signal analysis

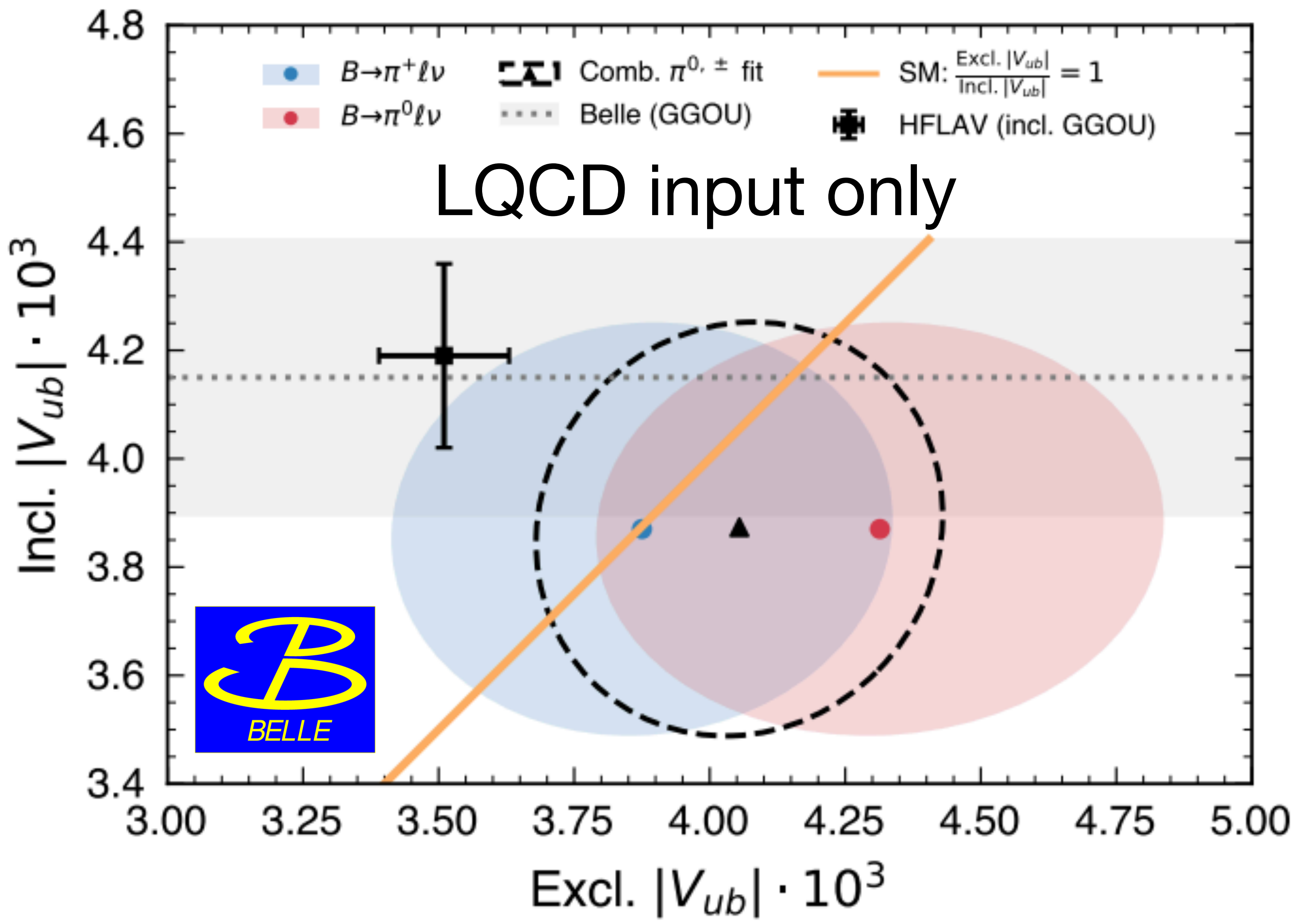
Gain insights on inclusive-exclusive puzzle with combined analysis

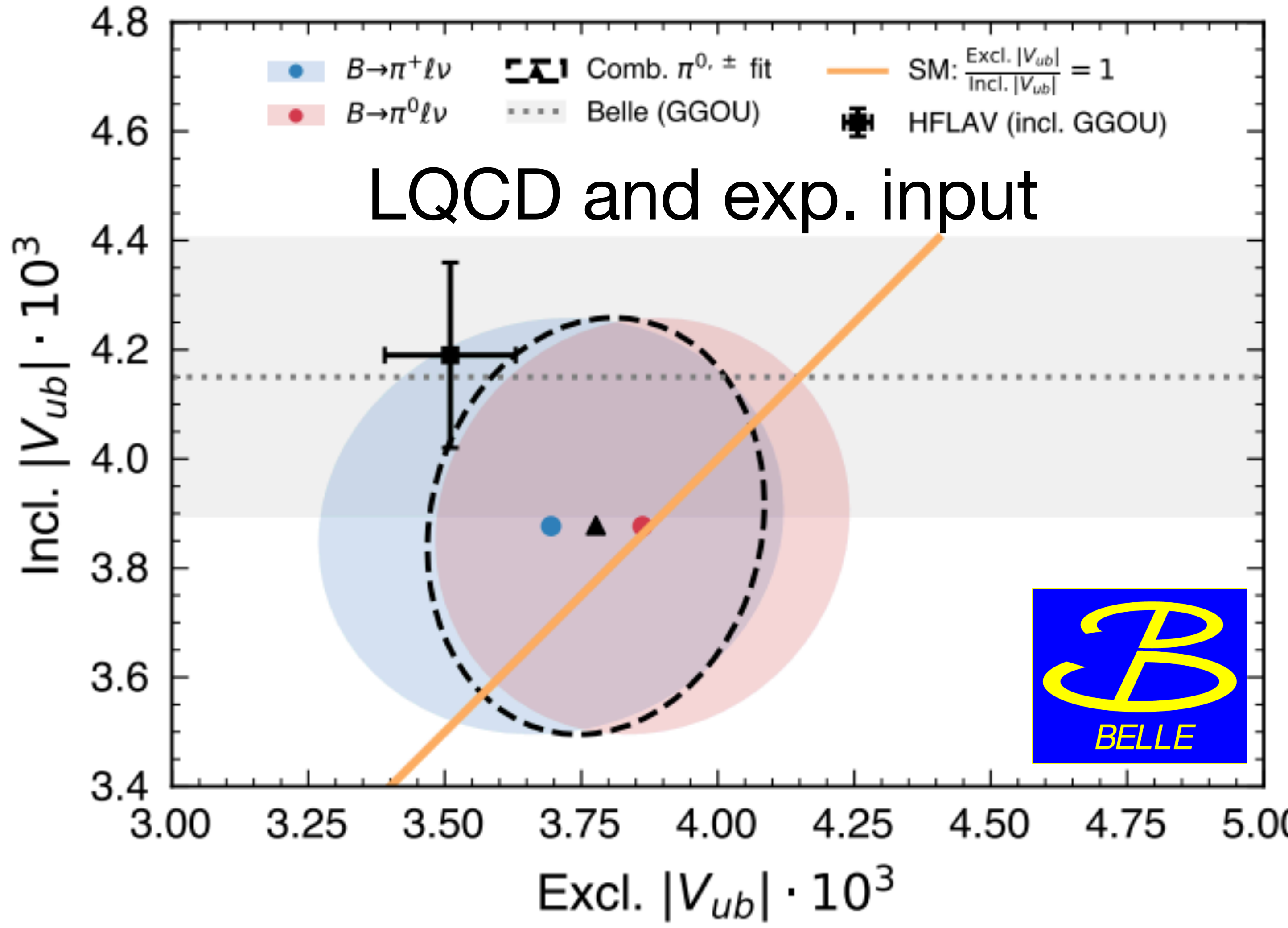
- Extract signal for exclusive $B \to \pi \ell \bar{\nu}$ from inclusive $B \to X_u \ell \bar{\nu}$ in bins of $N_{\pi^\pm}$ and q^2 (between B and X_u)

$$\mathcal{B}(B \to \pi^0 \ell \nu) + \mathcal{B}(B \to \pi^+ \ell \nu) + \mathcal{B}(B \to X_u^{\text{other}} \ell \nu) = \mathcal{B}(B \to X_u \ell \nu)$$

$$|V_{ub}^{\text{excl.}}| = \sqrt{\frac{\mathcal{B}(B \to \pi \ell \nu)}{\tau_B \Gamma_{FF}}} \qquad |V_{ub}^{\text{incl.}}| = \sqrt{\frac{\mathcal{B}(B \to X_u \ell \nu)}{\tau_B \Gamma_{GGOU}}}$$







arXiv:2303.17309

With LQCD and experimental constraints

$$\left|V_{ub}^{\text{excl.}}\right| = (3.78 \pm 0.23 \pm 0.16 \pm 0.14) \times 10^{-3}$$

$$\left|V_{ub}^{\text{incl.}}\right| = (3.88 \pm 0.20 \pm 0.31 \pm 0.09) \times 10^{-3}$$

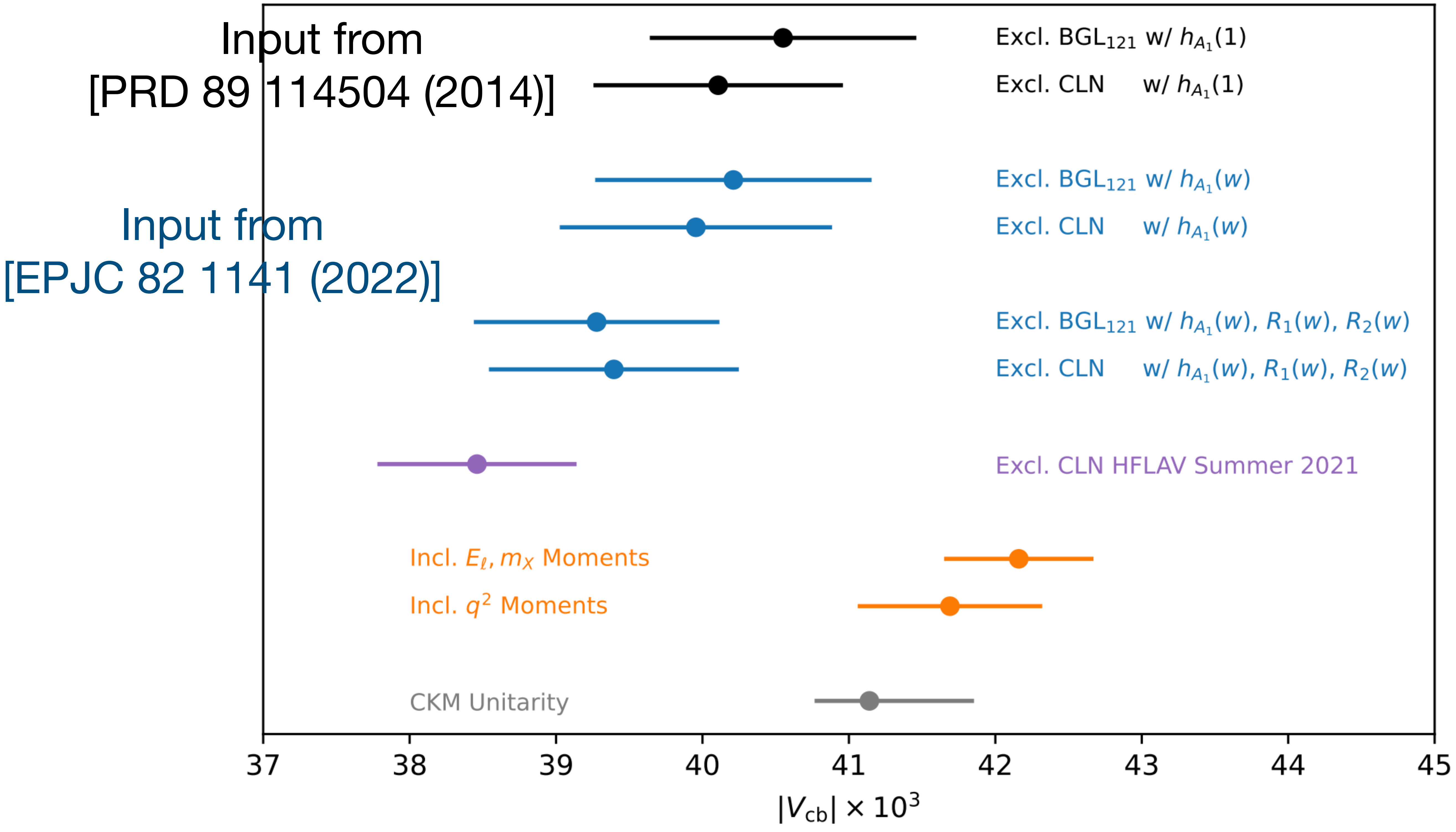
$$\left|V_{ub}^{\text{excl.}}\right| / \left|V_{ub}^{\text{incl.}}\right| = 0.97 \pm 0.12$$

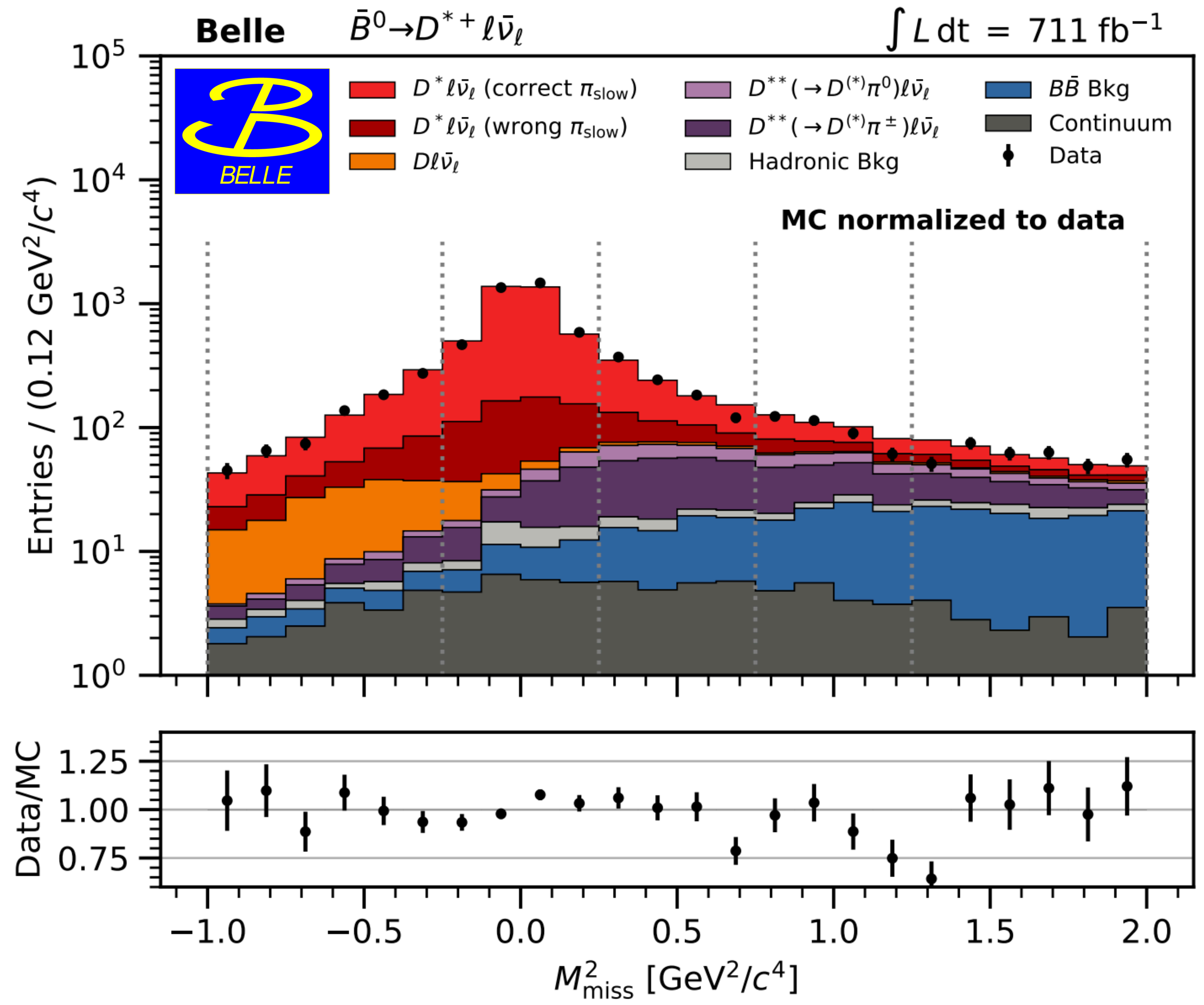
Compatible with world-average within 1.2σ

Exclusive V_{cb} from $B \to D^*\ell^+\nu_\ell$ differential distributions

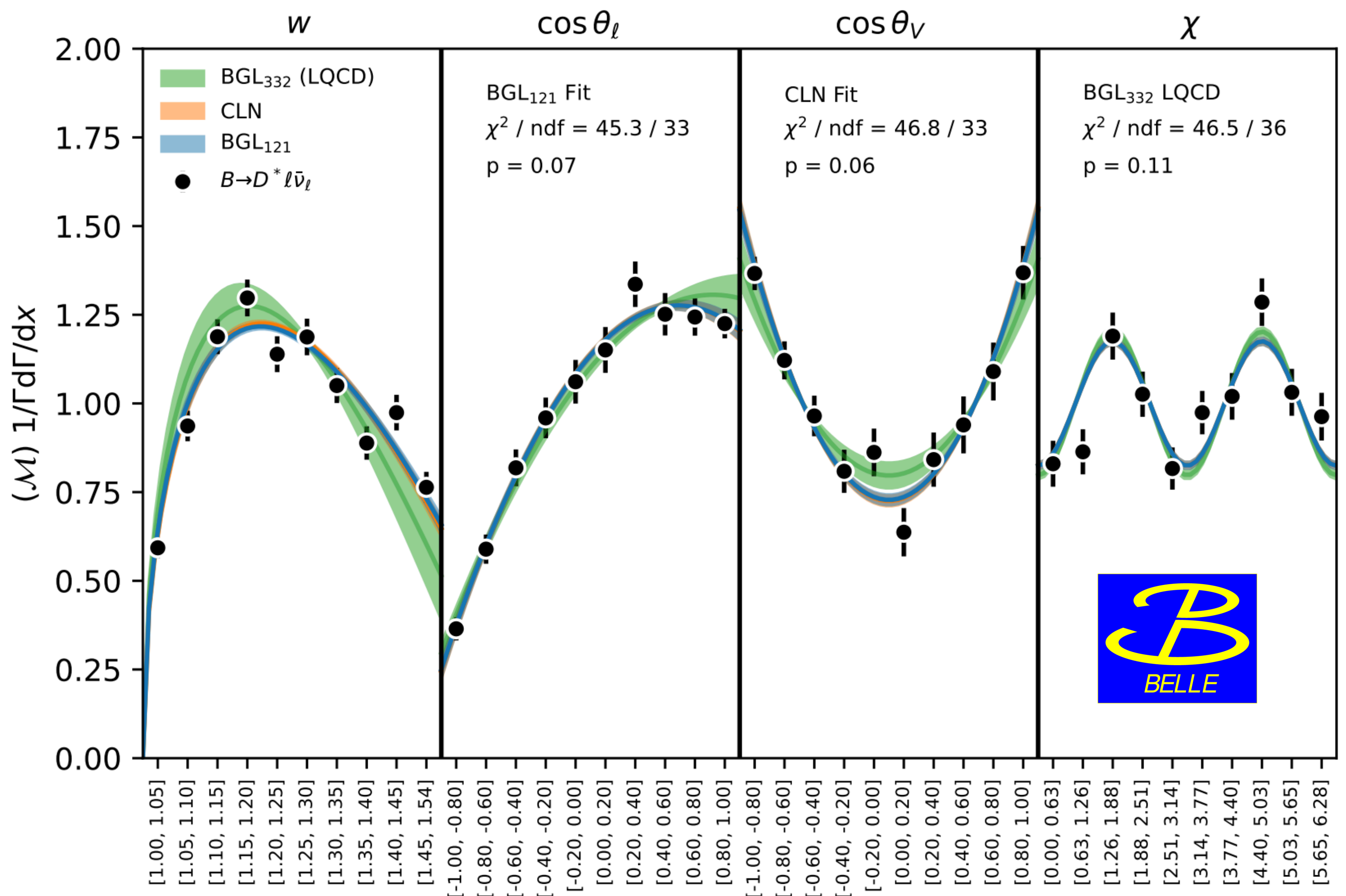
Latest and greatest from Belle

- One B meson is fully reconstructed in a hadronic mode (tag side)
- Reconstruct D^* and combine with a charged lepton to identify $B \to D^*\ell\nu$ (signal side)
- Normalization is not measured, $\mathscr{B}$ taken from HFLAV





PRD 108 (2023) 1



Angular coefficients of $B \to D^* \ell^+ \nu_\ell$

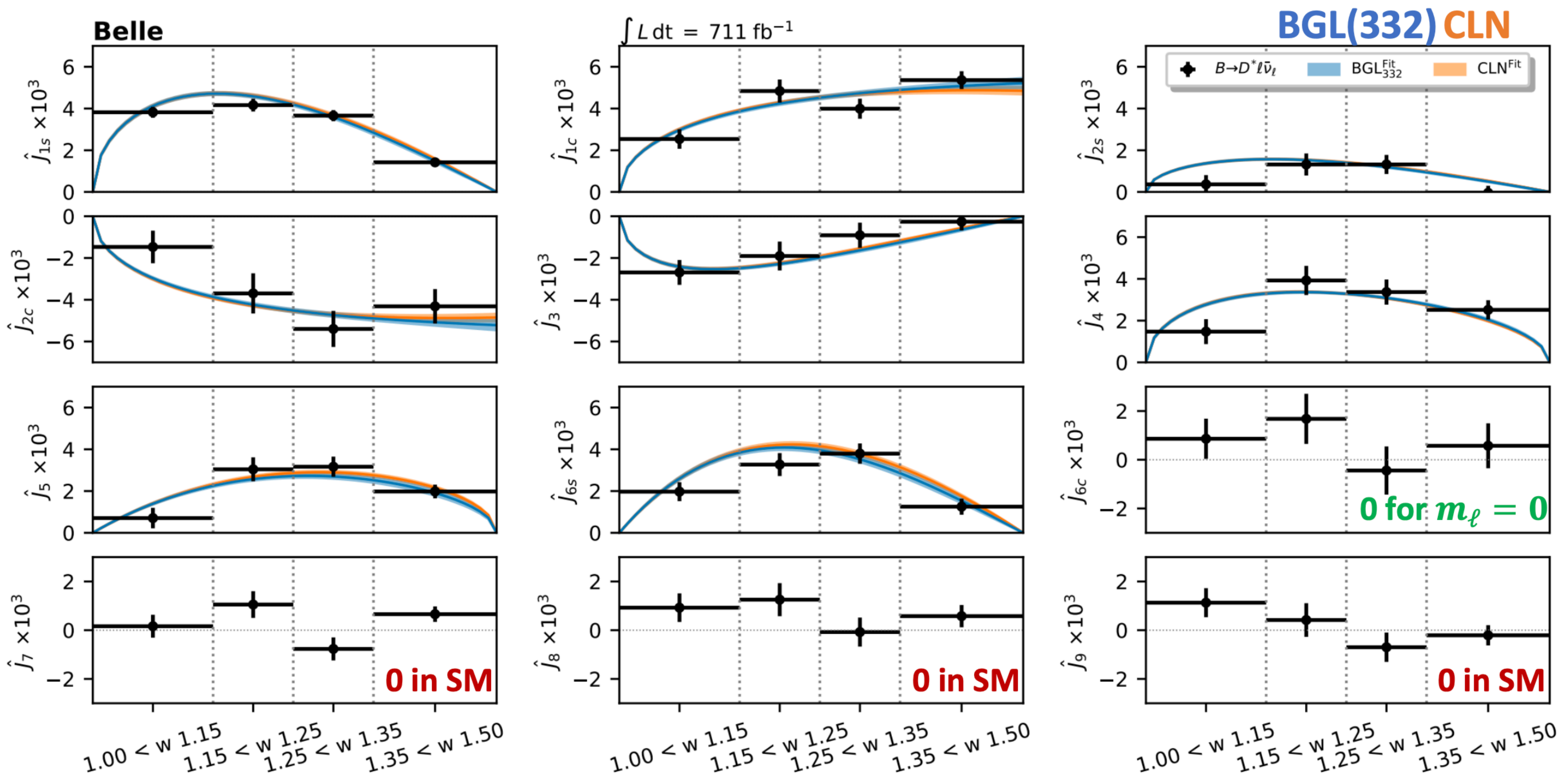
New preliminary results from Belle

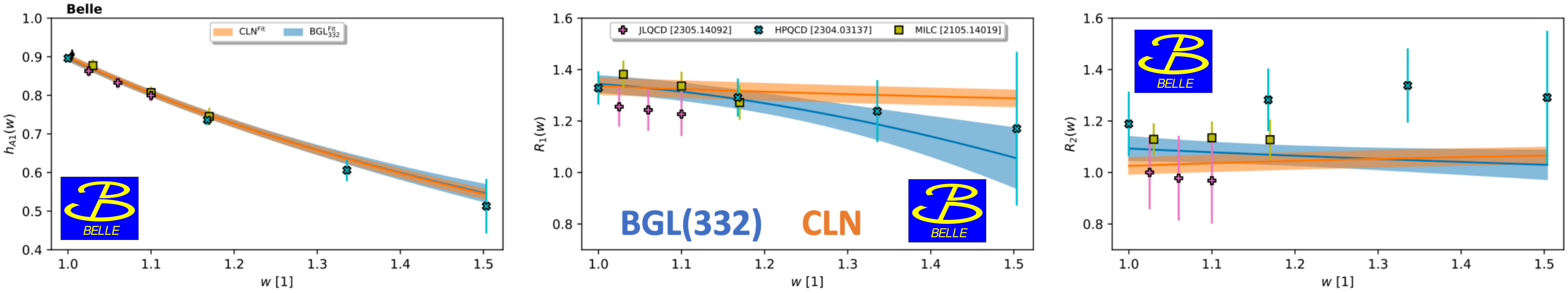
- Same dataset, fit 12 angular coefficients $J_i = J_i(w)$ in 4 bins of w
- In total 144 $M^2_{\rm miss}$ fits per mode, 576 in total

Phys.Rev.D 90 (2014) 9, 094003

$$\bar{J}_i = \frac{1}{N_i} \sum_{j=1}^{8} \sum_{k,l=1}^{4} \eta^{\chi}_{i,j}\, \eta^{\theta_\ell}_{i,k}\, \eta^{\theta_V}_{i,l} \left[\chi^{(j)} \otimes \chi^{(k)} \otimes \chi^{(l)} \right]$$

Normalization   Weights   Unfolded Yields





$|V_{cb}|^{\rm BGL} = (41.0 \pm 0.7) \times 10^{-3}$

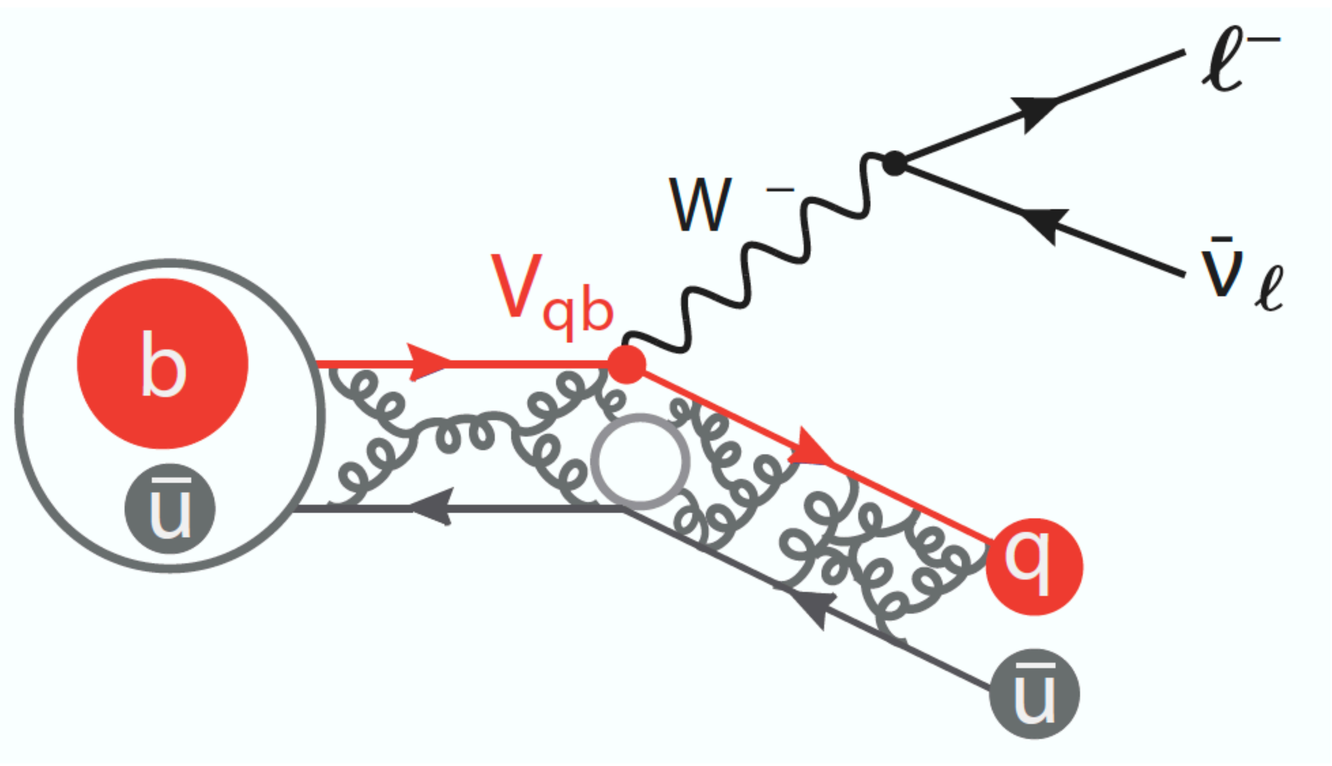
$|V_{cb}|^{\rm CLN} = (40.9 \pm 0.7) \times 10^{-3}$

Combined fit with non-zero recoil lattice data (FNAL/MILC, HPQCD, JLQCD)

Average $\mathcal{F}(1)$ or new LQCD results: $\mathcal{F}(1) = 0.895 \pm 0.007$

$|V_{cb}|$ from inclusive $B \to X_c \ell \nu$ decays

Precision measurement using OPE



Operator Product Expansion

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

- **Traditional approach**: Use hadronic mass moments, lepton energy moments, etc. to determine non-perturbative matrix elements of OPE and extract $|V_{cb}|$
  - Allows model-independent extraction of HQE parameters up to $\mathcal{O}(1/m_b^3)$
  - Extraction of higher order terms complicated by proliferation of hadronic parameters - rely on modeling

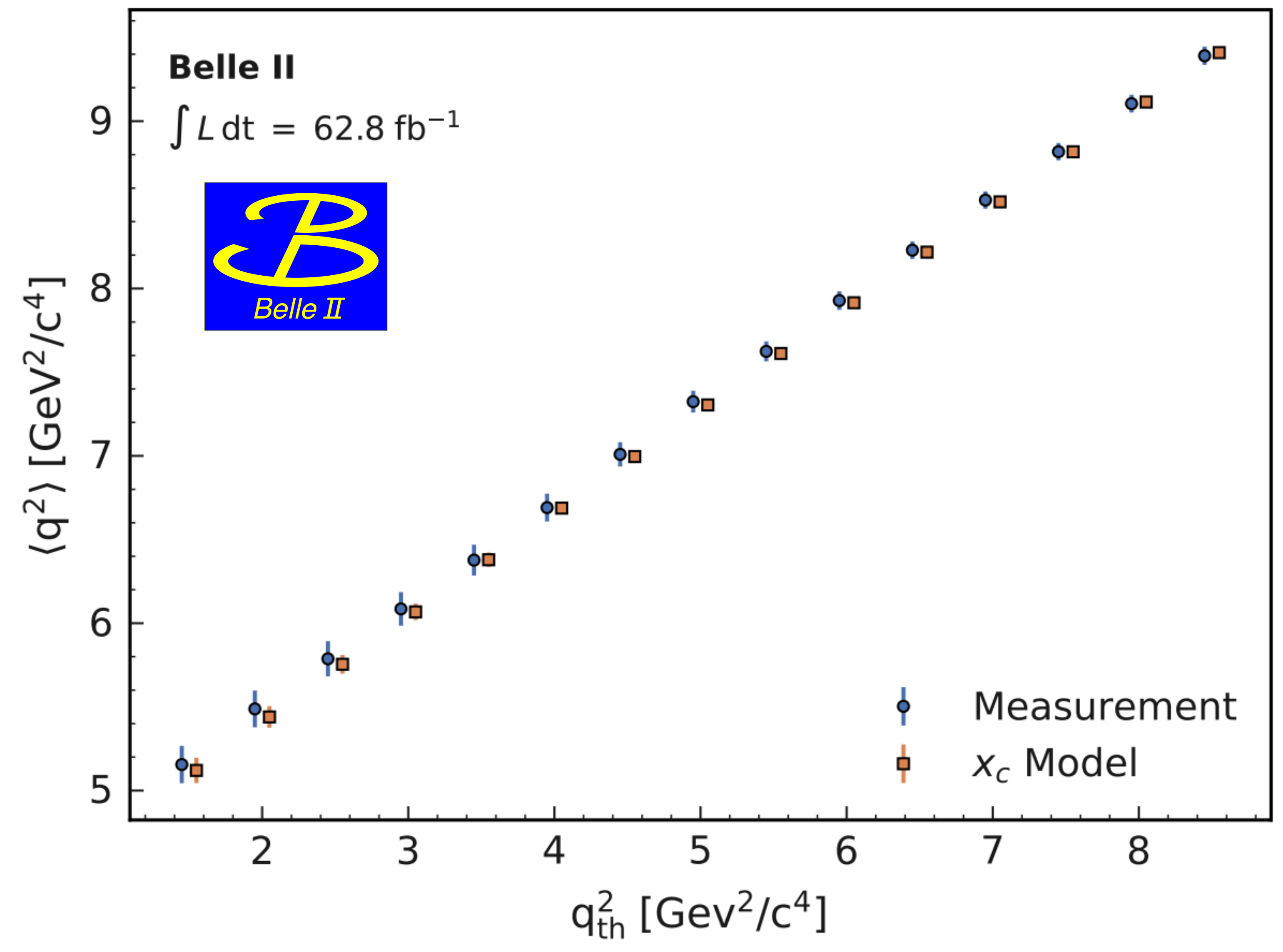
- **Alternative approach** [JHEP 02 (2019) 177] (M. Fael, T. Mannel, K. Vos): exploit relations between HQE parameters due to *reparameterization invariance* to reduce the number of independent parameters
  - Not true for every observable (e.g. not for $\langle M_X \rangle$), but holds for $\langle q^2 \rangle$
  - At $1/m_b^4$ the number of matrix elements reduces from 13 to 8

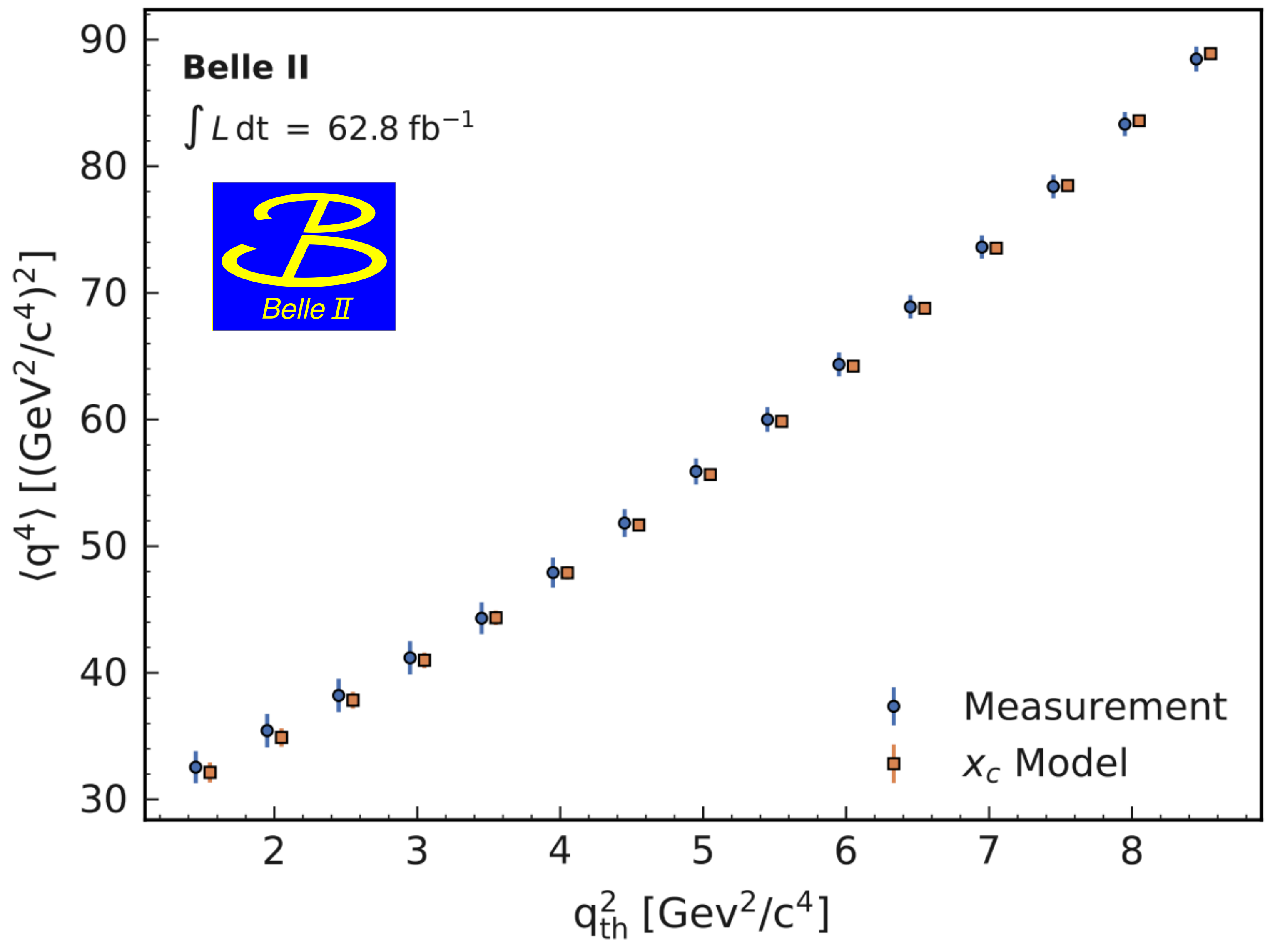
$$q^2 = (p_{sig} - p_{X_c})^2$$

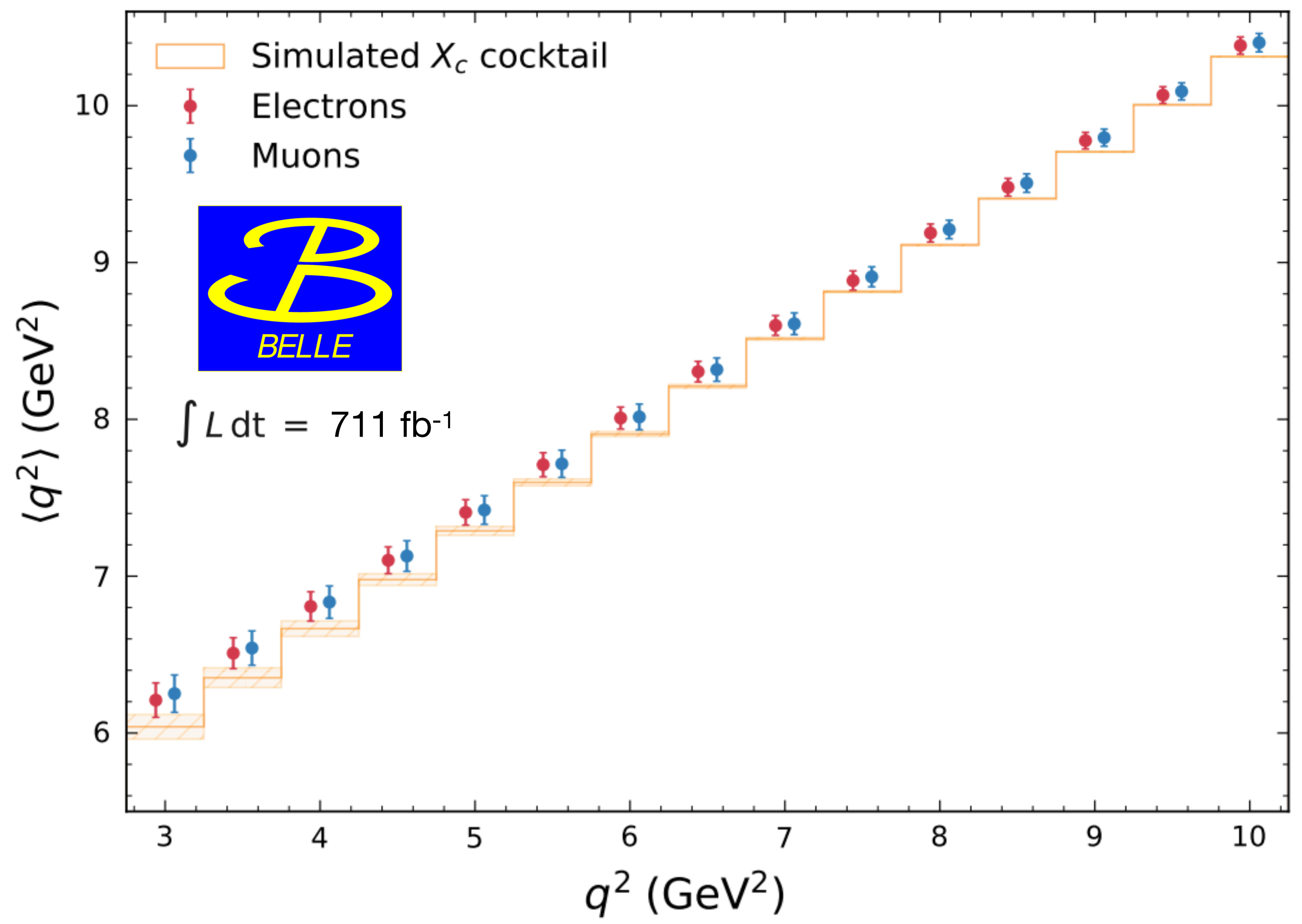
q^2 moments from $B \to X_c \ell \nu$ decays

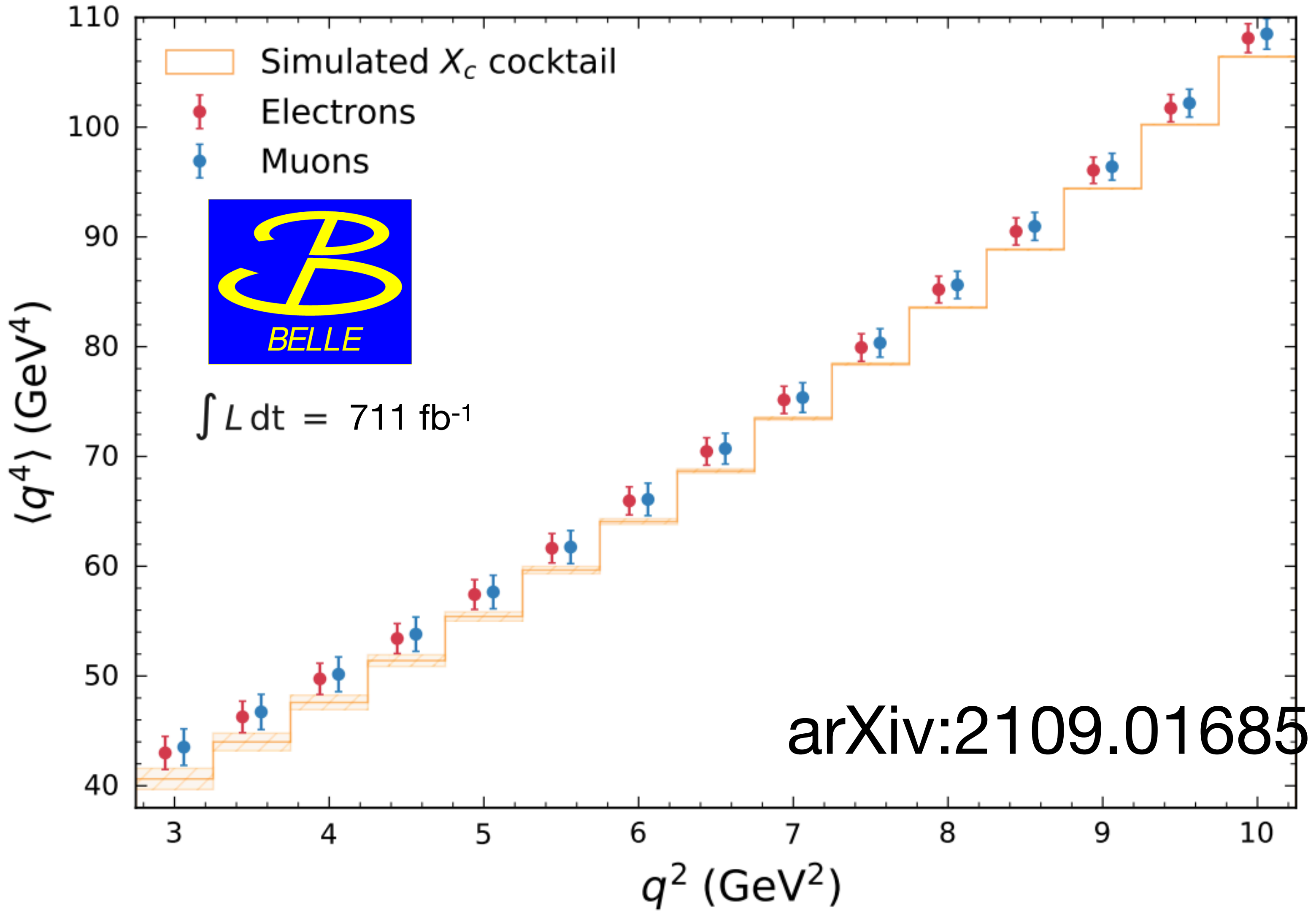
Crucial experimental input for $|V_{cb}|$, HQE parameters

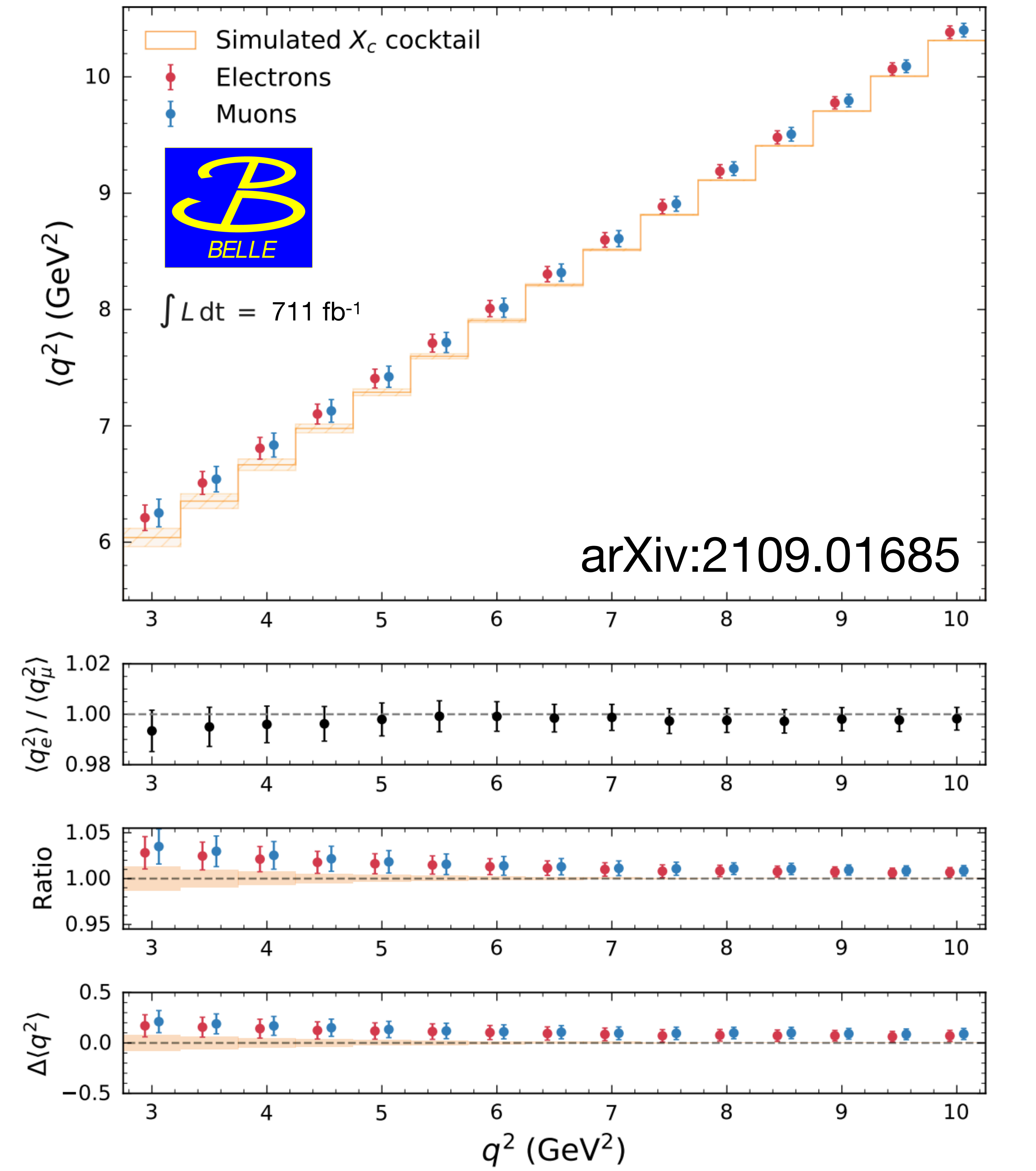
arXiv:2205.06372











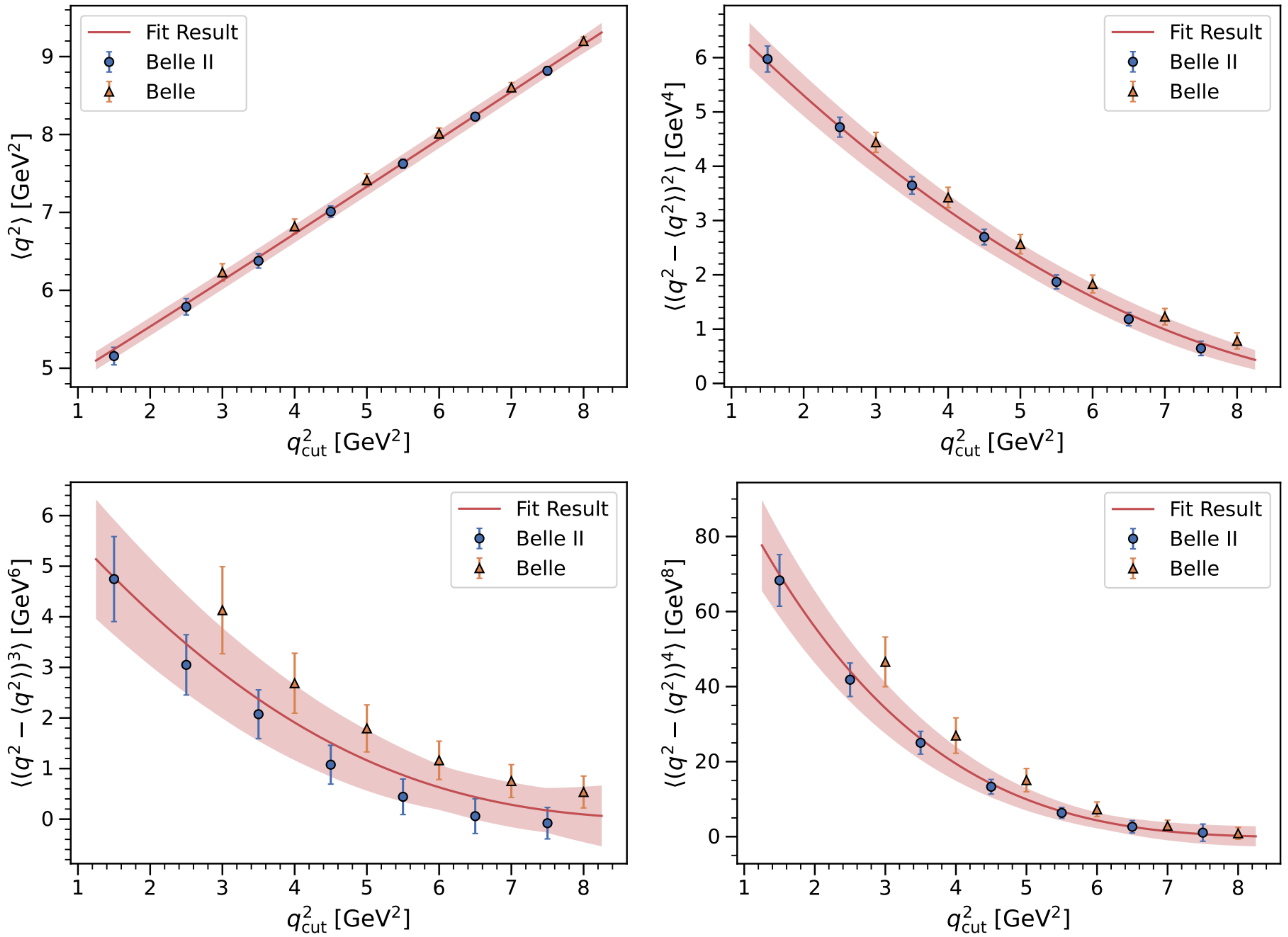
Belle II already reaches similar precision to Belle and can reach lower q^2 threshold

First extraction of inclusive $|V_{cb}|$ from q^2 moments

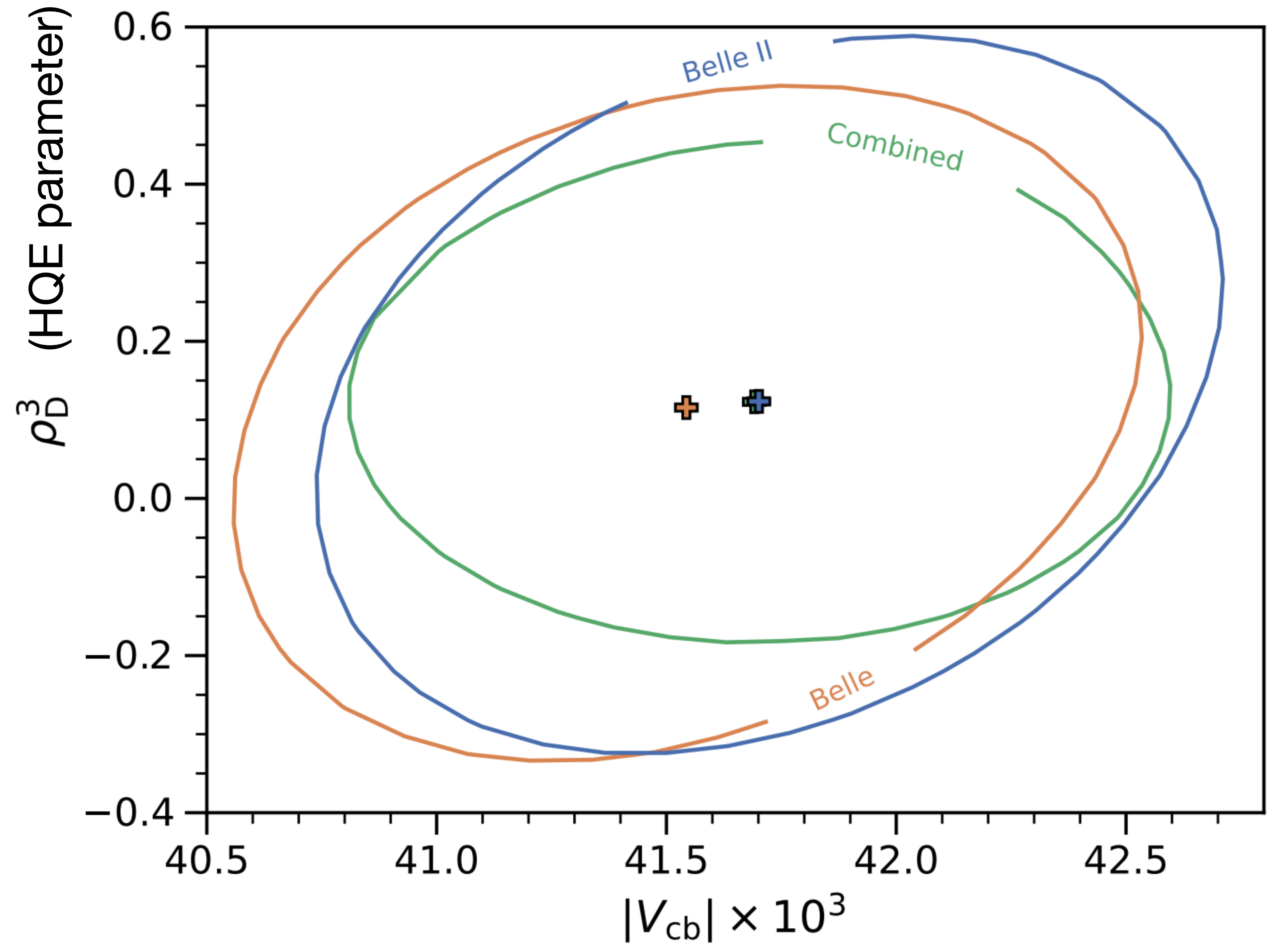
Important, independent cross-check on inclusive measurements

- Good agreement with the most precise previous measurement, $|V_{cb}| = 42.16(51) \times 10^{-3}$ [hep-ph/2107.00604]
- Provides strong evidence that inclusive $|V_{cb}|$ can be reliably obtained using the HQE
  - Uncertainties well under control

hep-ph/2205.10274



	$\lvert V_{cb}\rvert \times 10^3$	m_b^{kin}	$\overline{m}_c$	μ_G^2	μ_π^2	ρ_D^3	r_G^4	$r_E^4 \times 10$	ρ_{cut}	ρ_{mom}
Value	41.69	4.56	1.09	0.37	0.43	0.12	-0.21	0.02	0.05	0.09
Uncertainty	0.59	0.02	0.01	0.07	0.24	0.20	0.69	0.34	$^{+0.03}_{-0.01}$	$^{+0.10}_{-0.10}$



CKM metrology with semileptonic B_s decays at LHCb

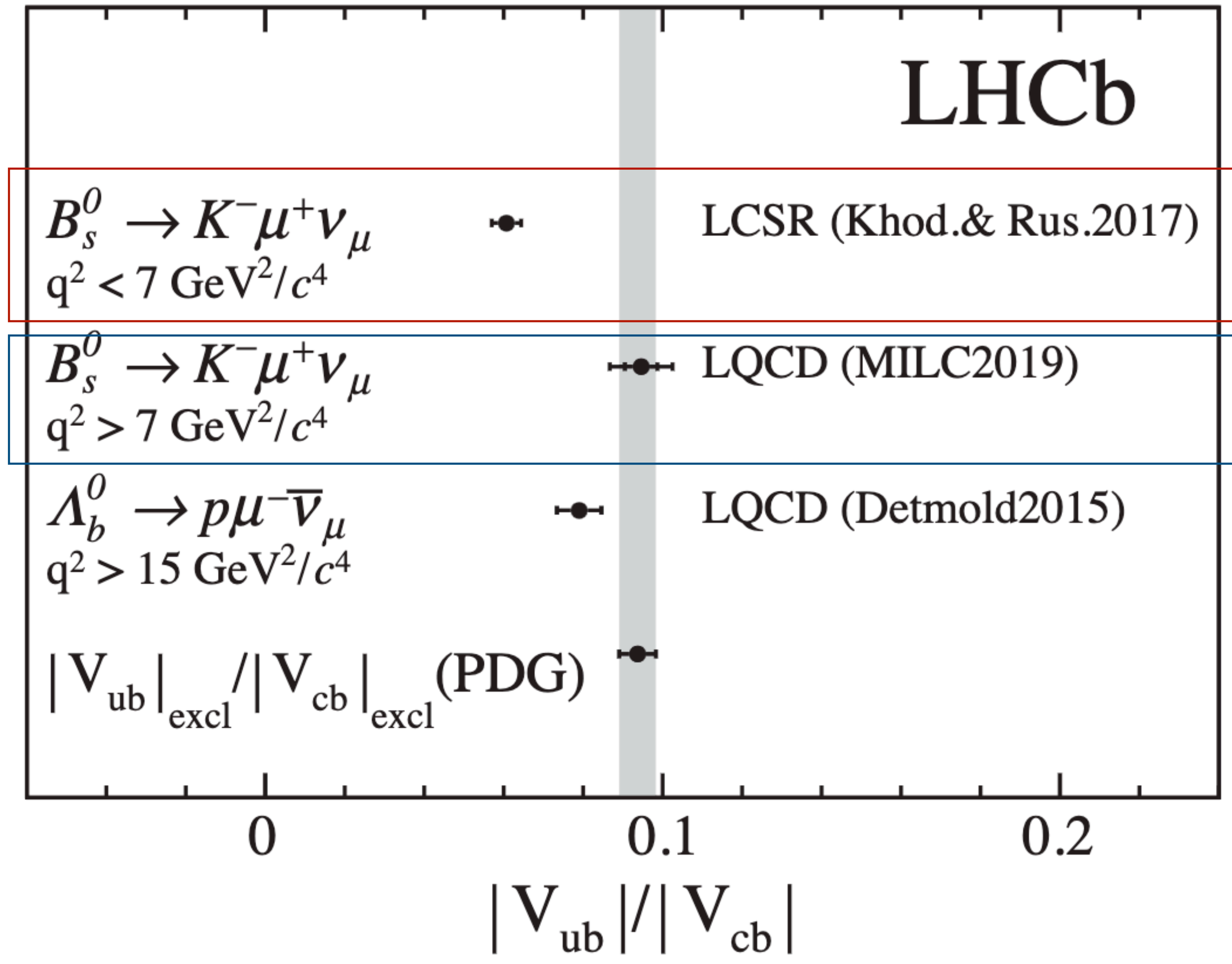
$|V_{ub}|/|V_{cb}|$ with heavy B mesons

$$\frac{|V_{ub}|^2}{|V_{cb}|^2} \times \frac{FF_K}{FF_{D_s}} = \frac{\mathscr{B}(B_s^0 \to K^-\mu^+\nu_\mu)}{\mathscr{B}(B_s^0 \to D_s^-\mu^+\nu_\mu)} = \frac{N_K}{N_{D_s}}\frac{\epsilon_{D_s}}{\epsilon_K} \times \mathscr{B}(D_s^+ \to K^+K^-\pi^+)$$

Simulation

Theory input — Experiment — Fit — External input

PRL 126, 081804 (2021)



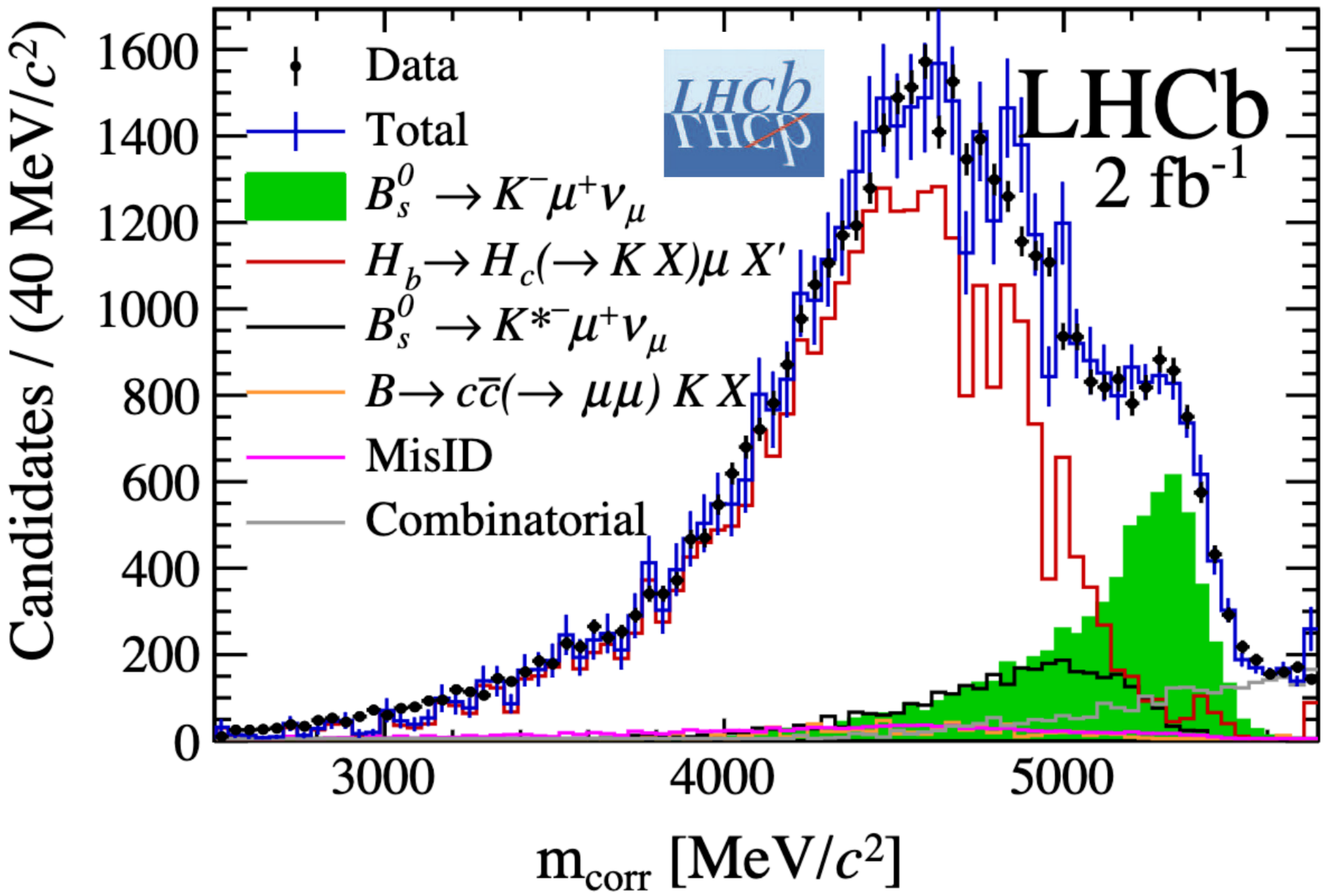
Low q^2

FF from LCSR [JHEP 112 (2017)]

FF from LQCD [PRD 100 034501]

High q^2

$B_s^0 \to K^-\mu^+\nu_\mu$ low q^2

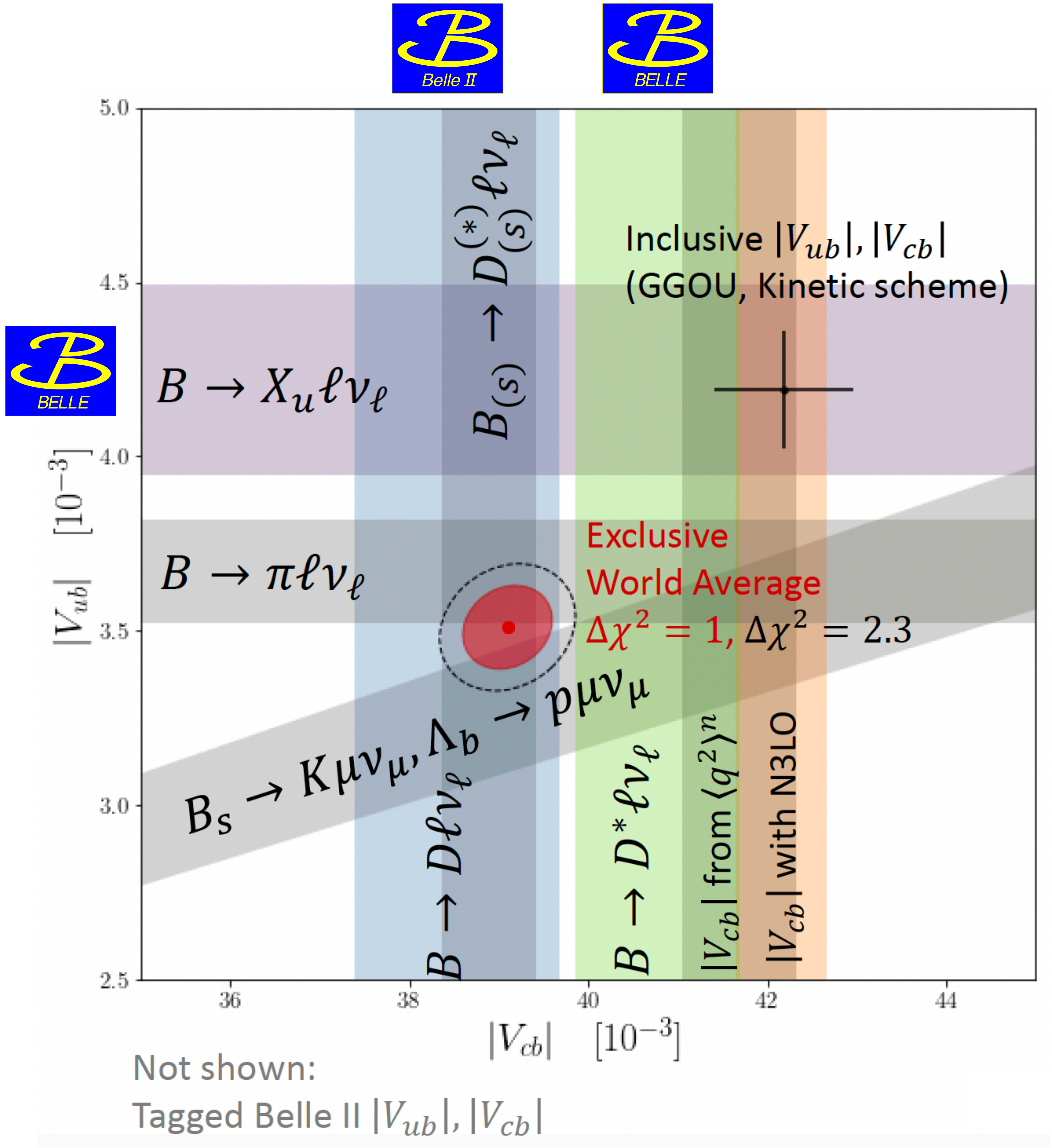


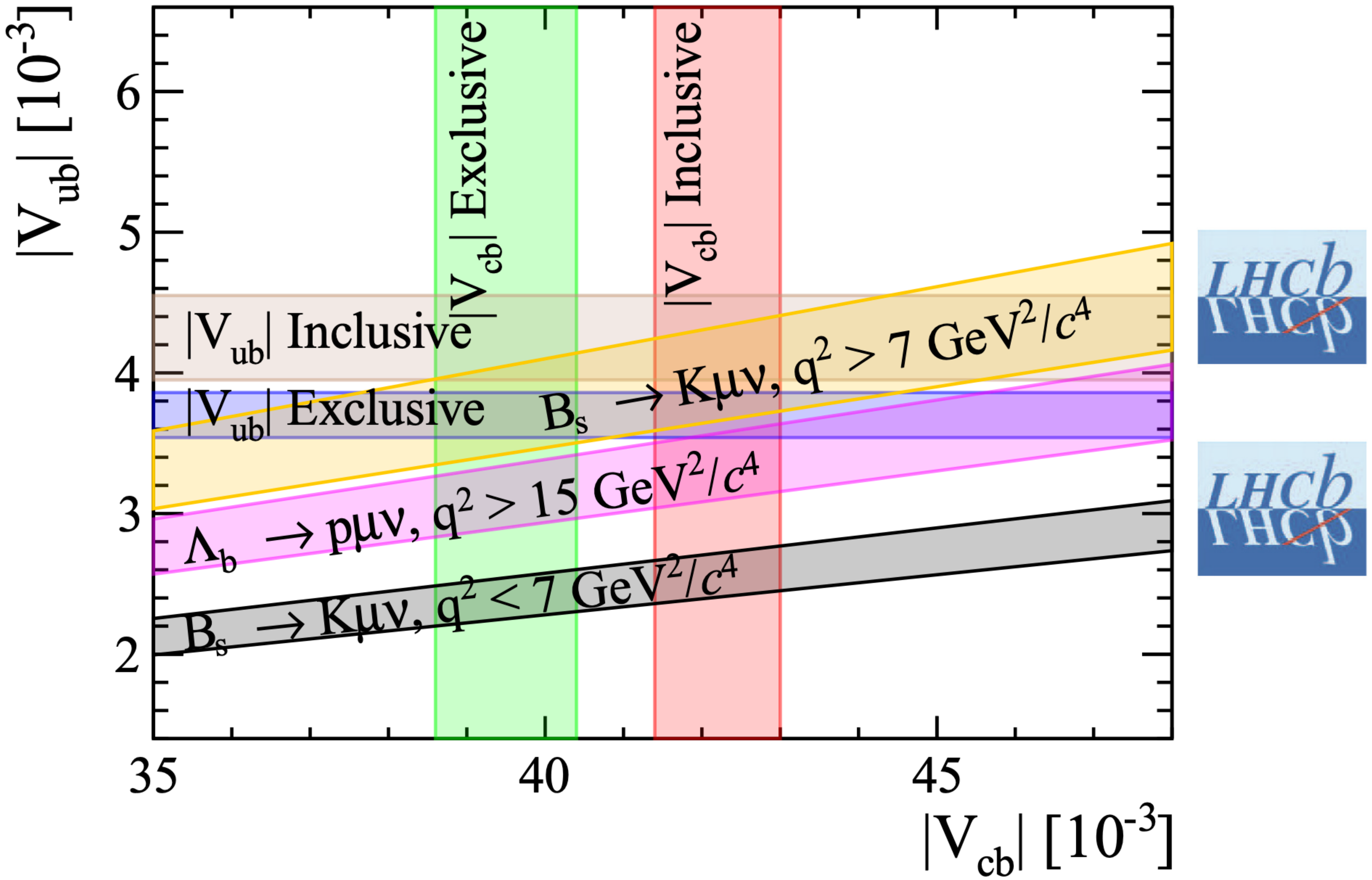
$$|V_{ub}|/|V_{cb}|_{low} = 0.0607 \pm 0.0015(\text{stat}) \pm 0.0013(\text{syst}) \pm 0.0008(\text{D}_s) \pm 0.0030(\text{FF})$$

$$|V_{ub}|/|V_{cb}|_{high} = 0.0946 \pm 0.0030(\text{stat}) \pm^{+0.0024}_{-0.0025}(\text{syst}) \pm 0.0013(\text{D}_s) \pm 0.0068(\text{FF})$$

Progress

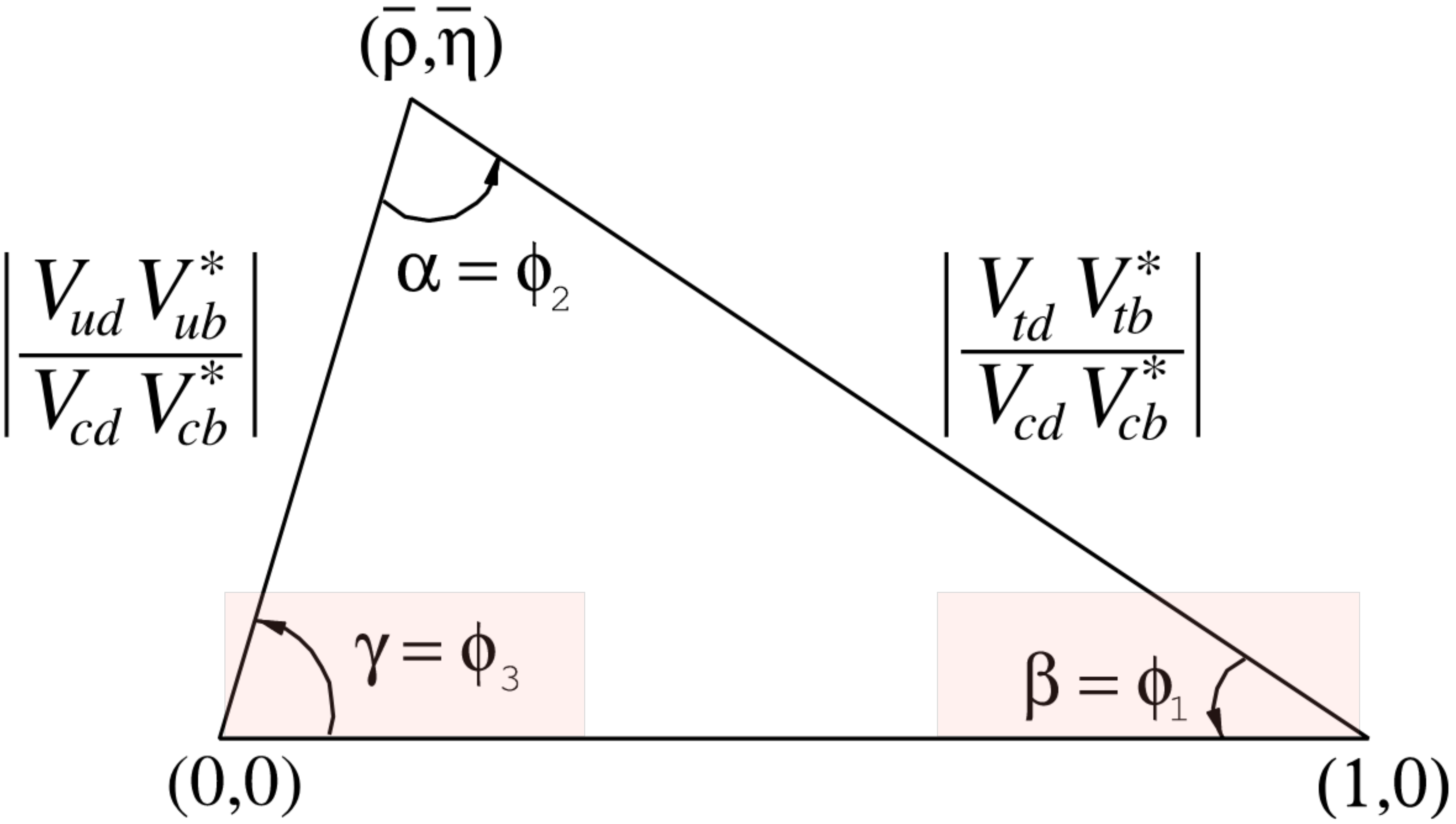
V_{ub}, V_{cb} inclusive and exclusive measurements with heavy B mesons





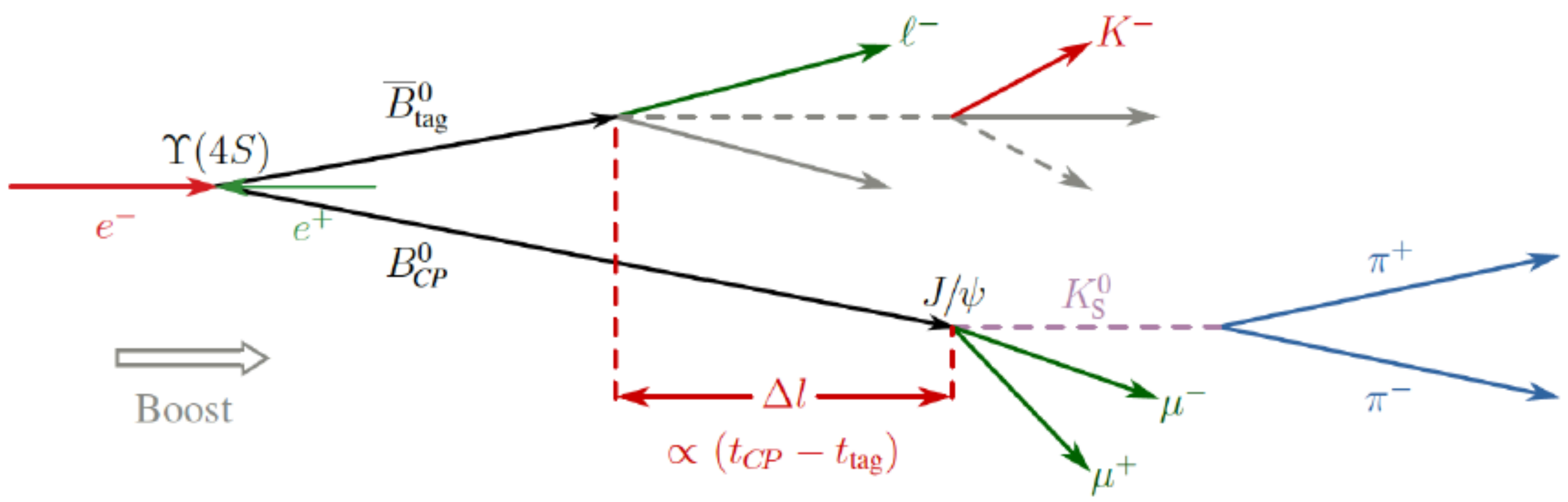
Measuring the Unitary Triangle angles in B decays

Not an exhaustive accounting



Time dependent CP Violation and β/ϕ_1

Bread-and-butter B-factory physics



- CPV measurements in B⁰ decays useful to extract CKM angles
- Time dependent CP asymmetry of neutral B decays:

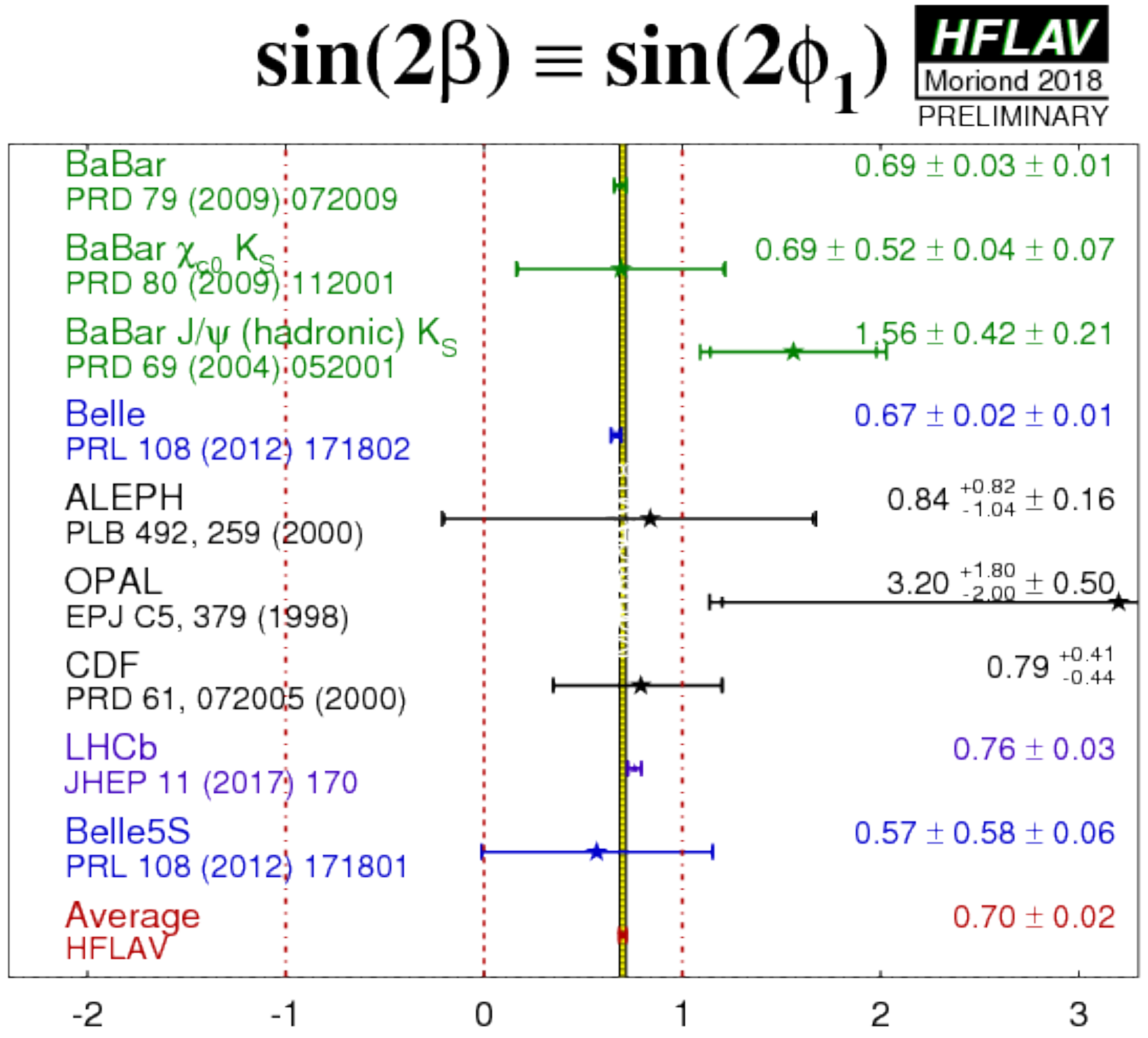
$$\mathcal{A}_f = \frac{\Gamma(\overline{B}^0(t) \to f) - \Gamma(B^0(t) \to f)}{\Gamma(\overline{B}^0(t) \to f) + \Gamma(B^0(t) \to f)} = S_f \sin(\Delta m_d t) - C_f \cos(\Delta m_d t)$$

Mass difference between physical B meson eigenstates ("$B^0 - \bar{B}^0$ oscillation frequency")

$$S_f = \frac{2\,\mathrm{Im}\lambda_f}{1 + |\lambda_f|^2}, \qquad C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}, \qquad \lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

- Non-zero cosine arises from interference between decay amplitudes with different weak and strong phases (direct CP violation) or from $B^0 - \bar{B}^0$ mixing
  - Negligible for SM under $b \to c\bar{c}s$ transitions
- If f is a CP eigenstate and amplitudes with one CKM phase dominate,

$$S_f = \sin(\arg\lambda_f) = \eta_f \sin 2\phi_1$$

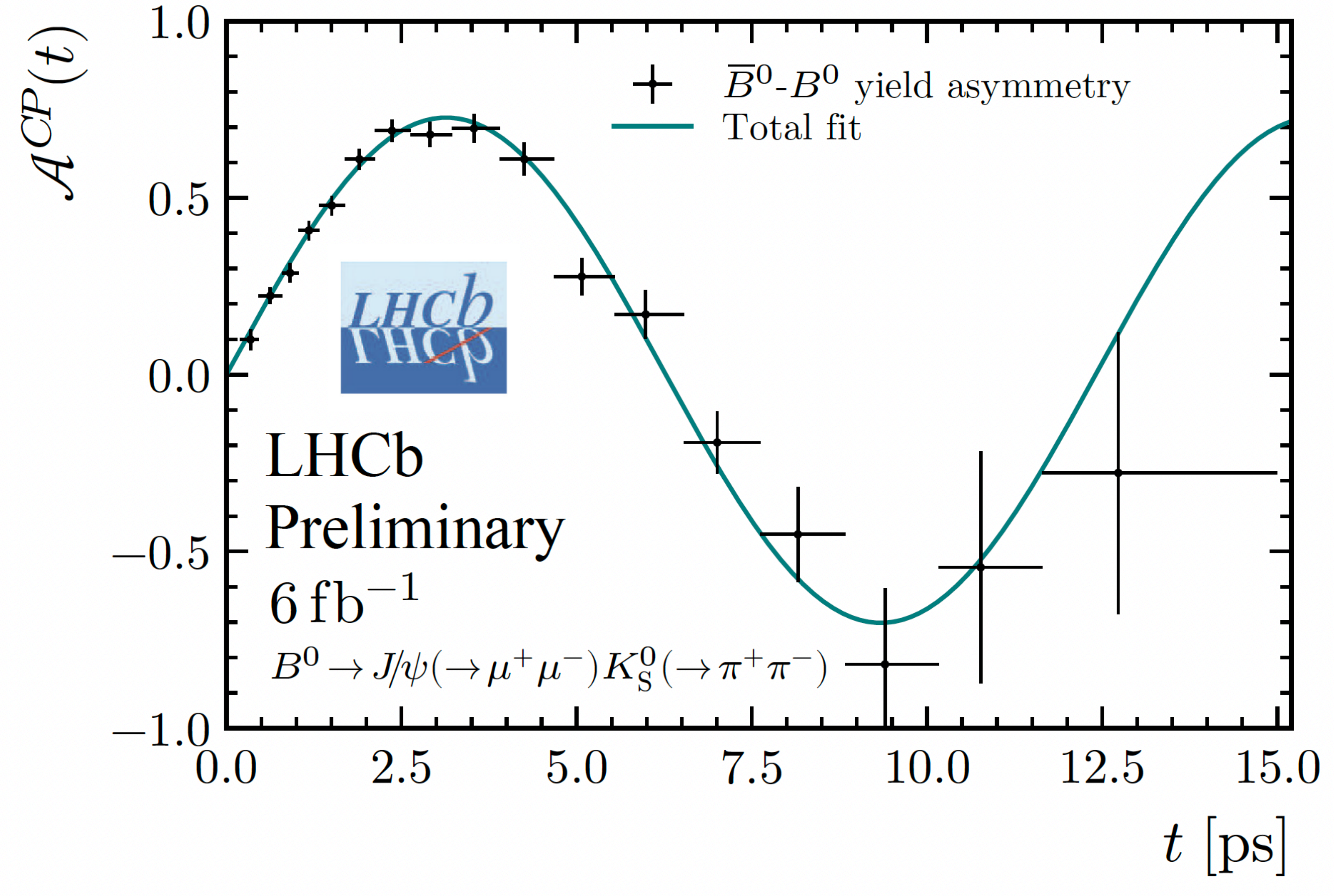


Measurement of $\sin 2\phi_1$

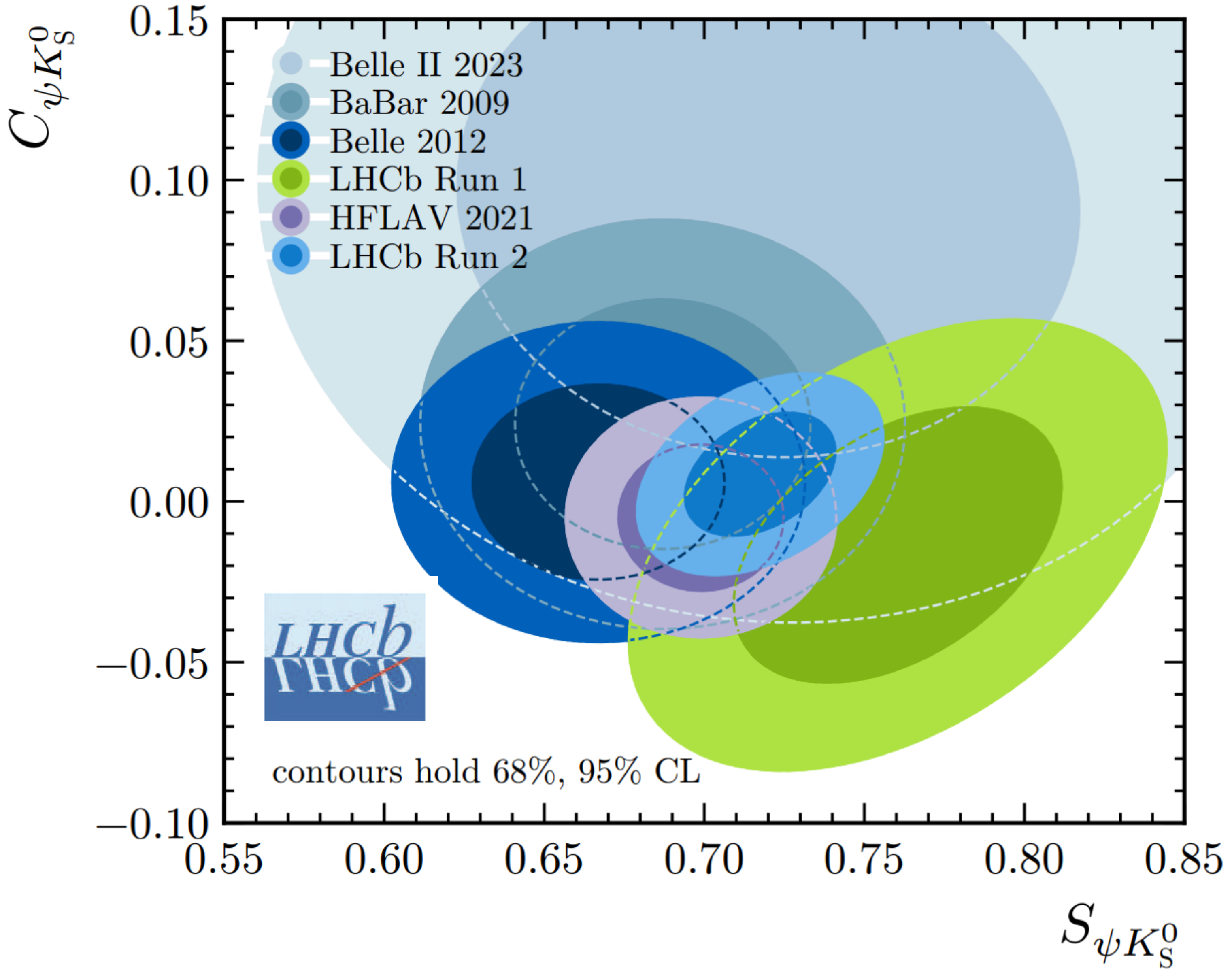
Bread-and-butter B-factory physics

LHCb: $B^0 \to J/\psi(\to \mu^+\mu^-, e^+e^-)\ K_S^0$
$B^0 \to \psi(2S)(\to \mu^+\mu^-)\ K_S^0$

LHCb-PAPER-2023-013



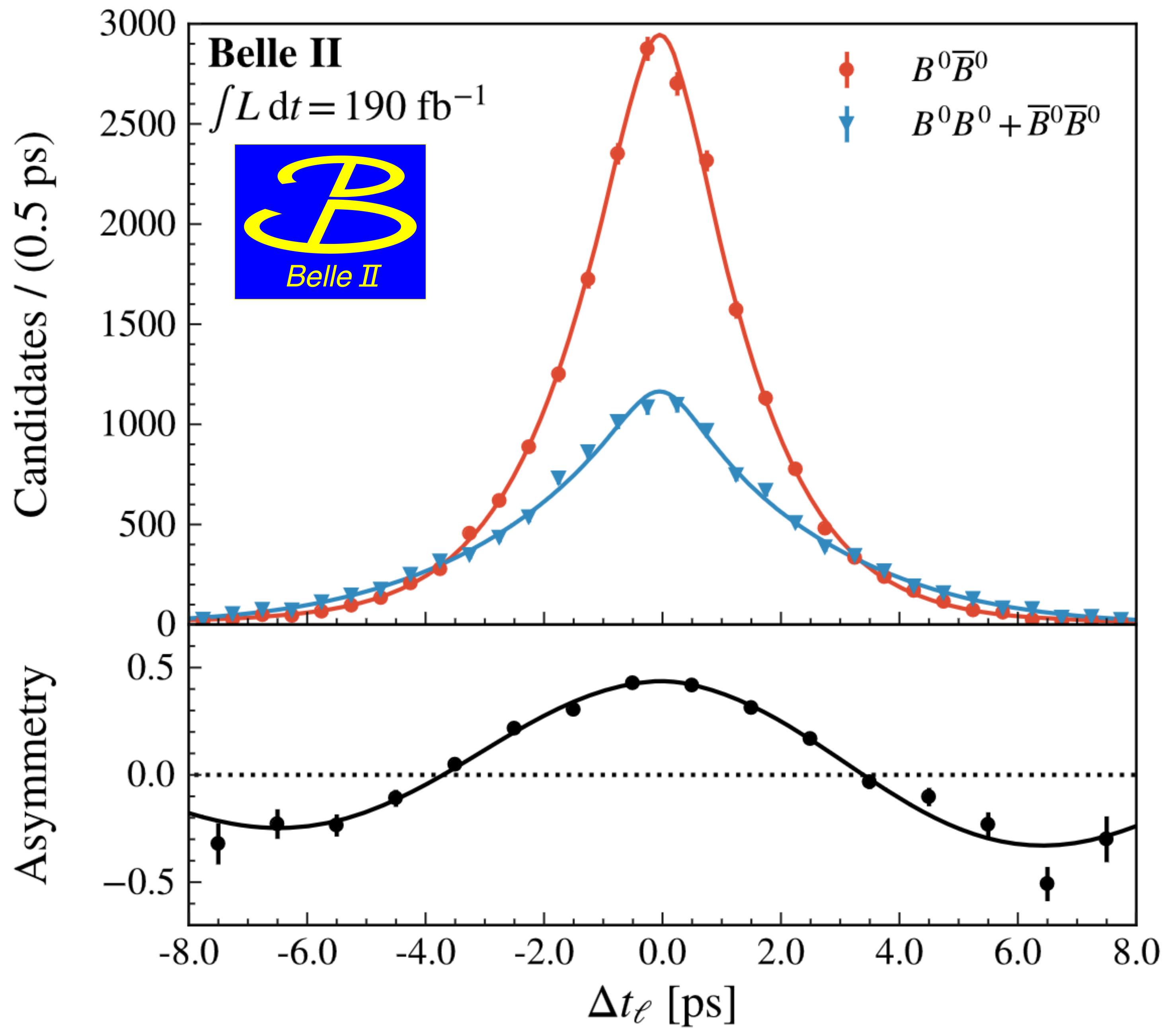
Combined results
(without latest Belle II measurements)



- Most precise measurement in a single mode to date (still statistics limited)

$$S_{\psi K_S^0} = 0.717 \pm 0.013 \pm 0.008 \qquad C_{\psi K_S^0} = 0.008 \pm 0.012 \pm 0.003$$

Belle II: $B^0 \to J/\psi K_S^0$

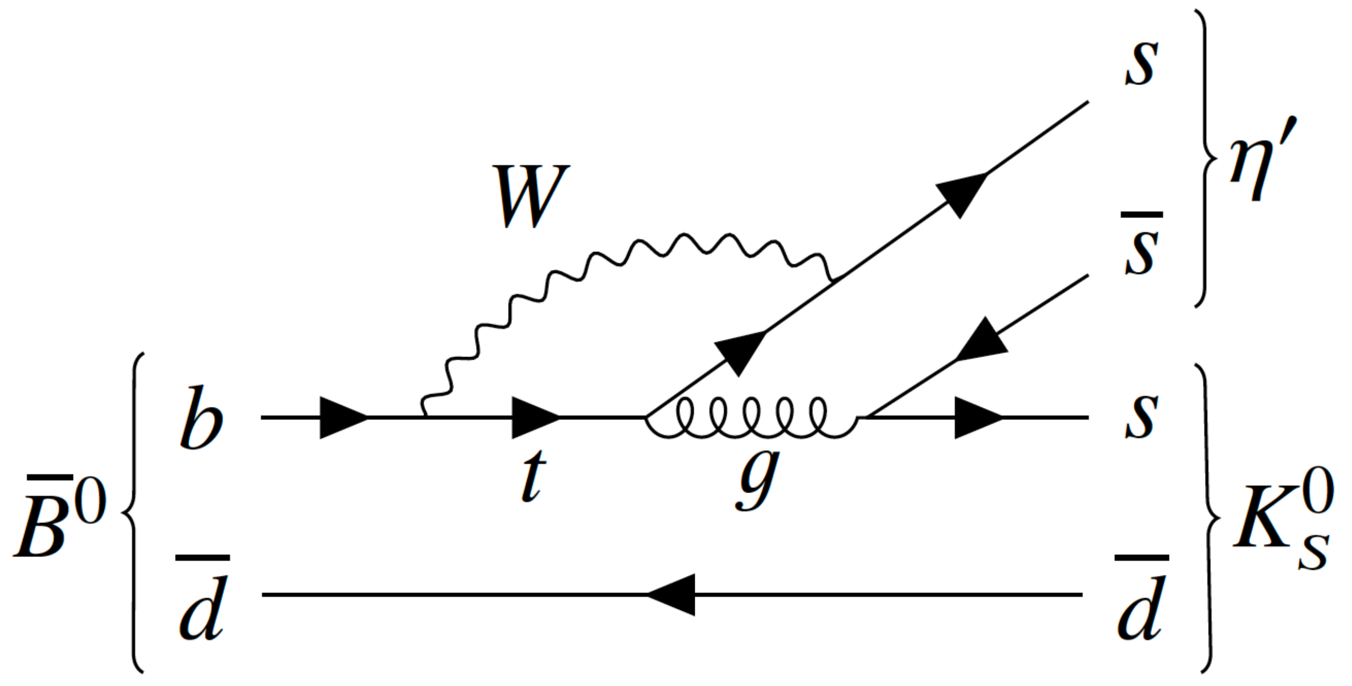


$$S = 0.724 \pm 0.035 \pm 0.014$$
$$C = 0.035 \pm 0.026 \pm 0.012$$

Measurement of $\sin 2\phi_1^{\rm eff}$ at Belle II

Potential to expose New Physics

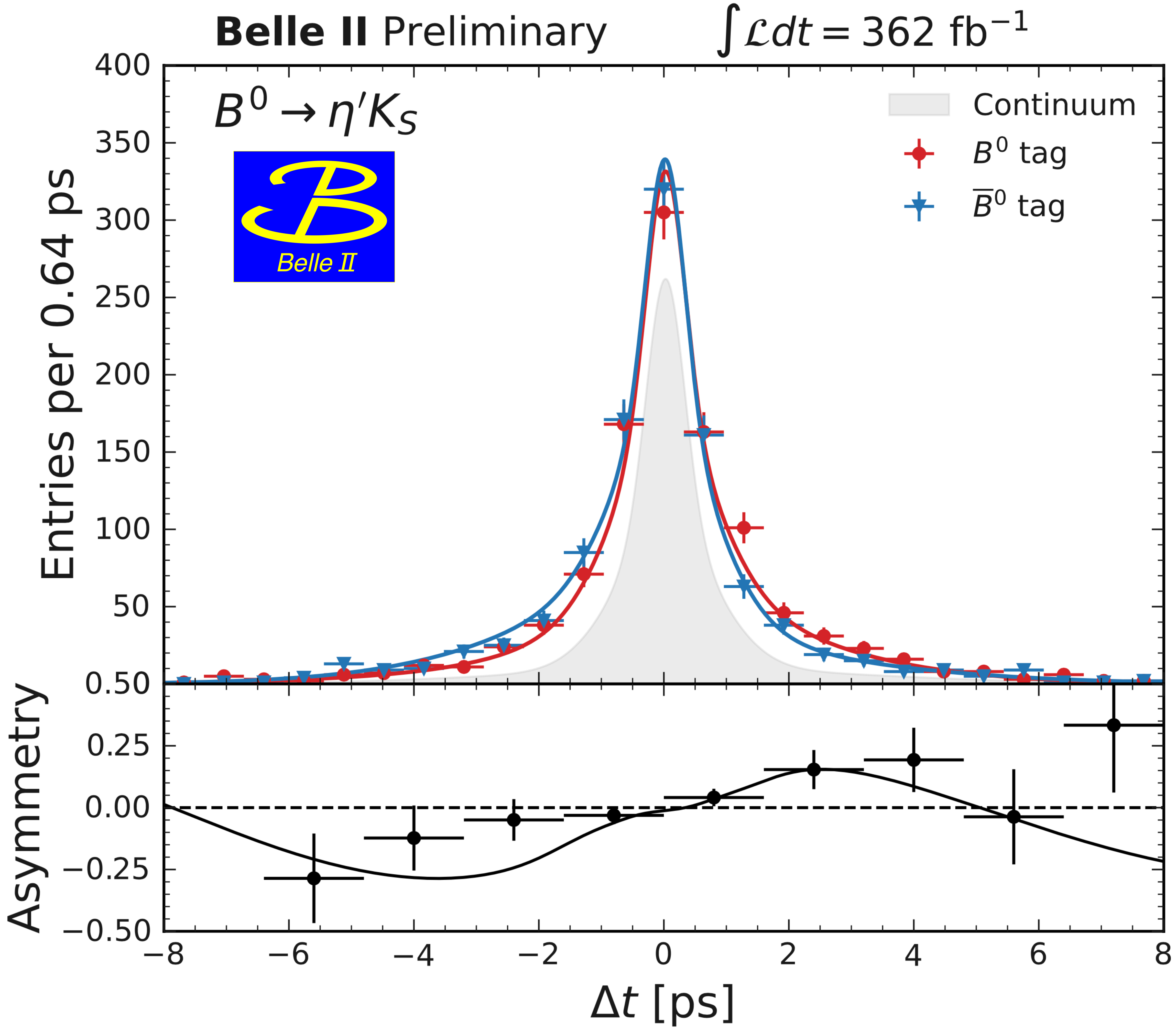
- Loop-suppressed $b \to sq\bar{q}$ transition
- Relatively high rate relative to other gluonic penguins
- Deviation from $\sin 2\phi_1$ would suggest BSM physics



$$S = 0.67 \pm 0.10 \pm 0.04$$

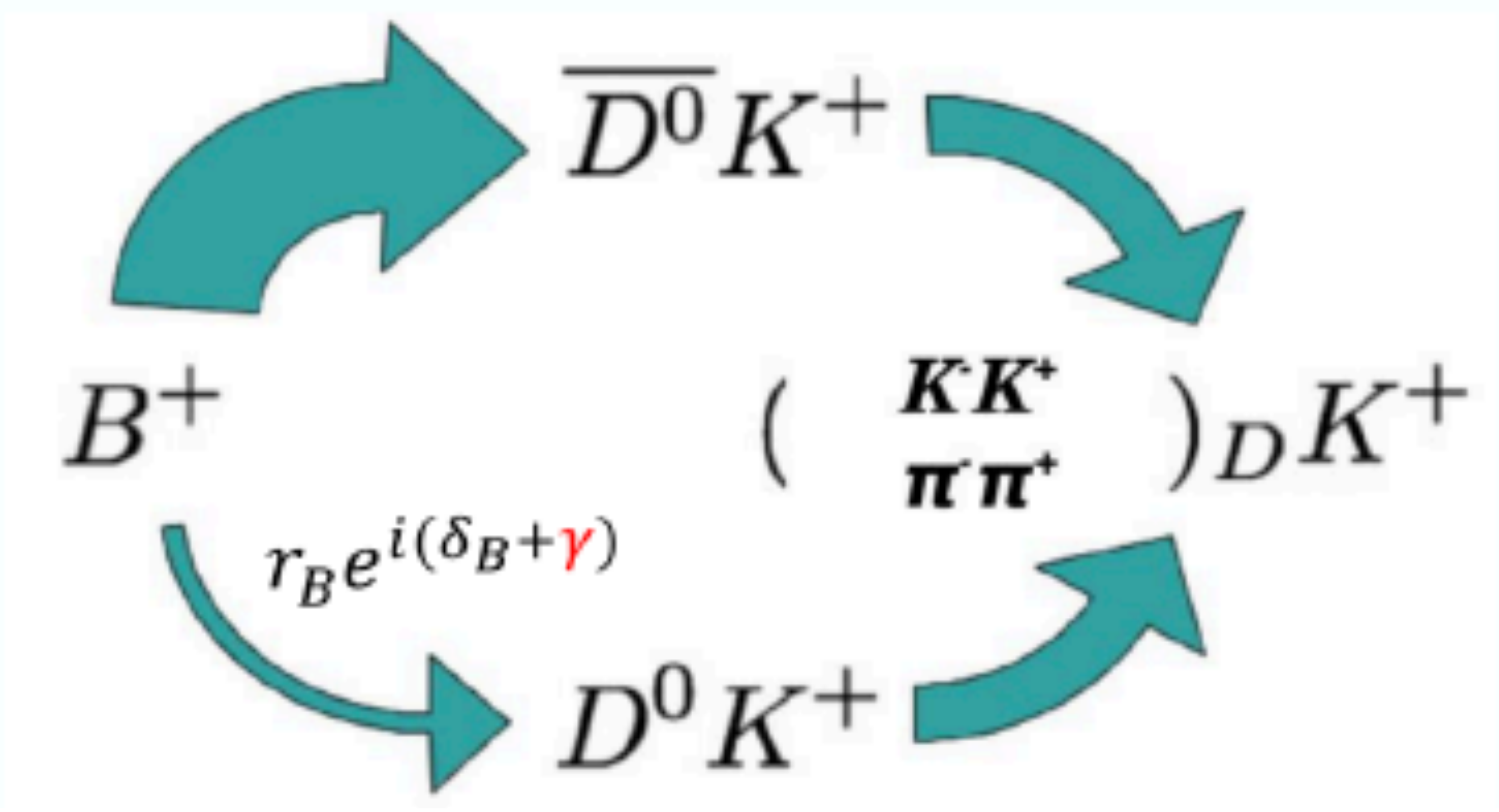
$$C = -0.19 \pm 0.08 \pm 0.03$$

HFLAV: $S = 0.63 \pm 0.06$, $C = -0.05 \pm 0.04$



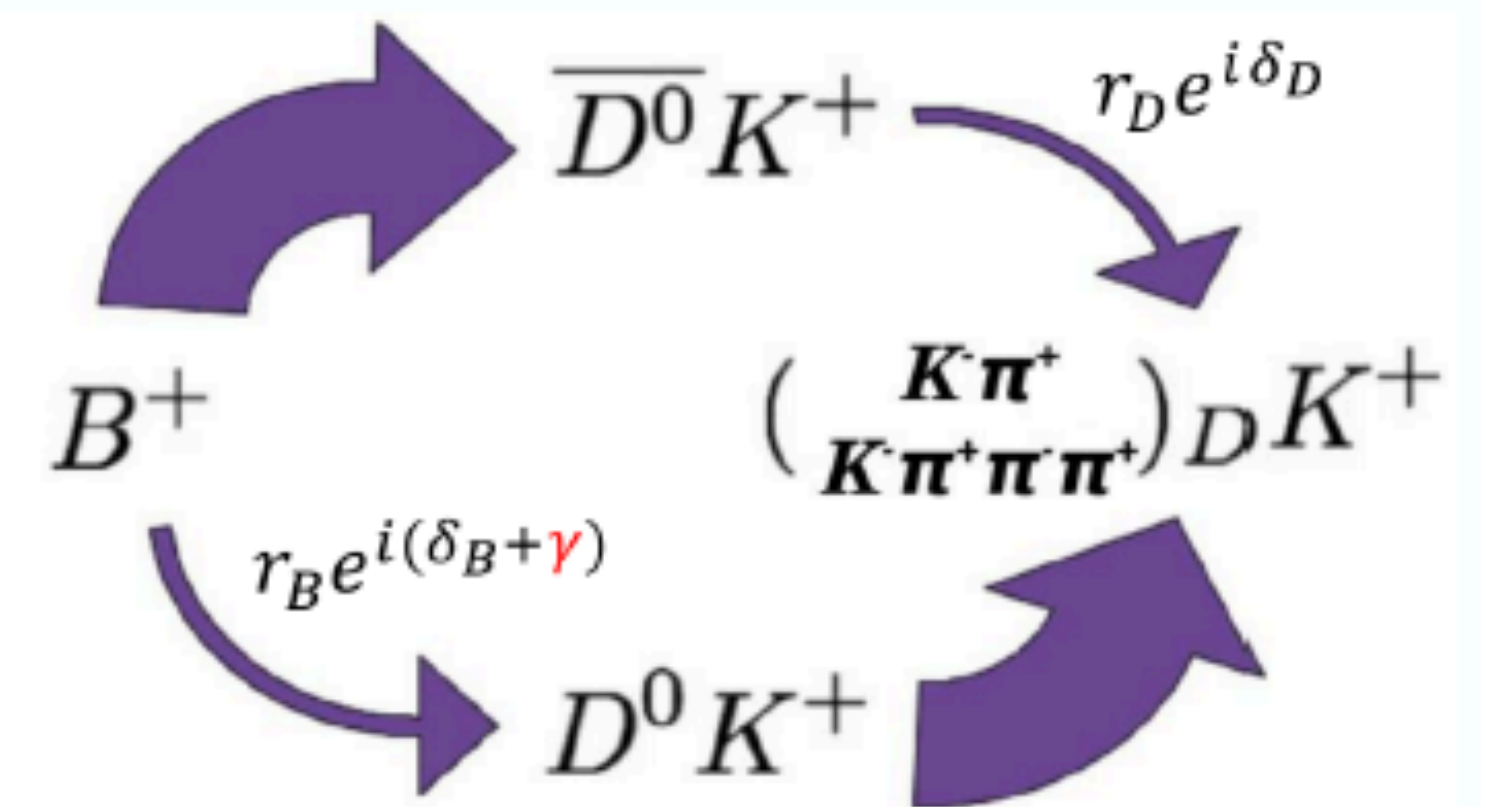
γ/ϕ_3

GLW



Final states are CP eigenstates.
Interference is O(10%)

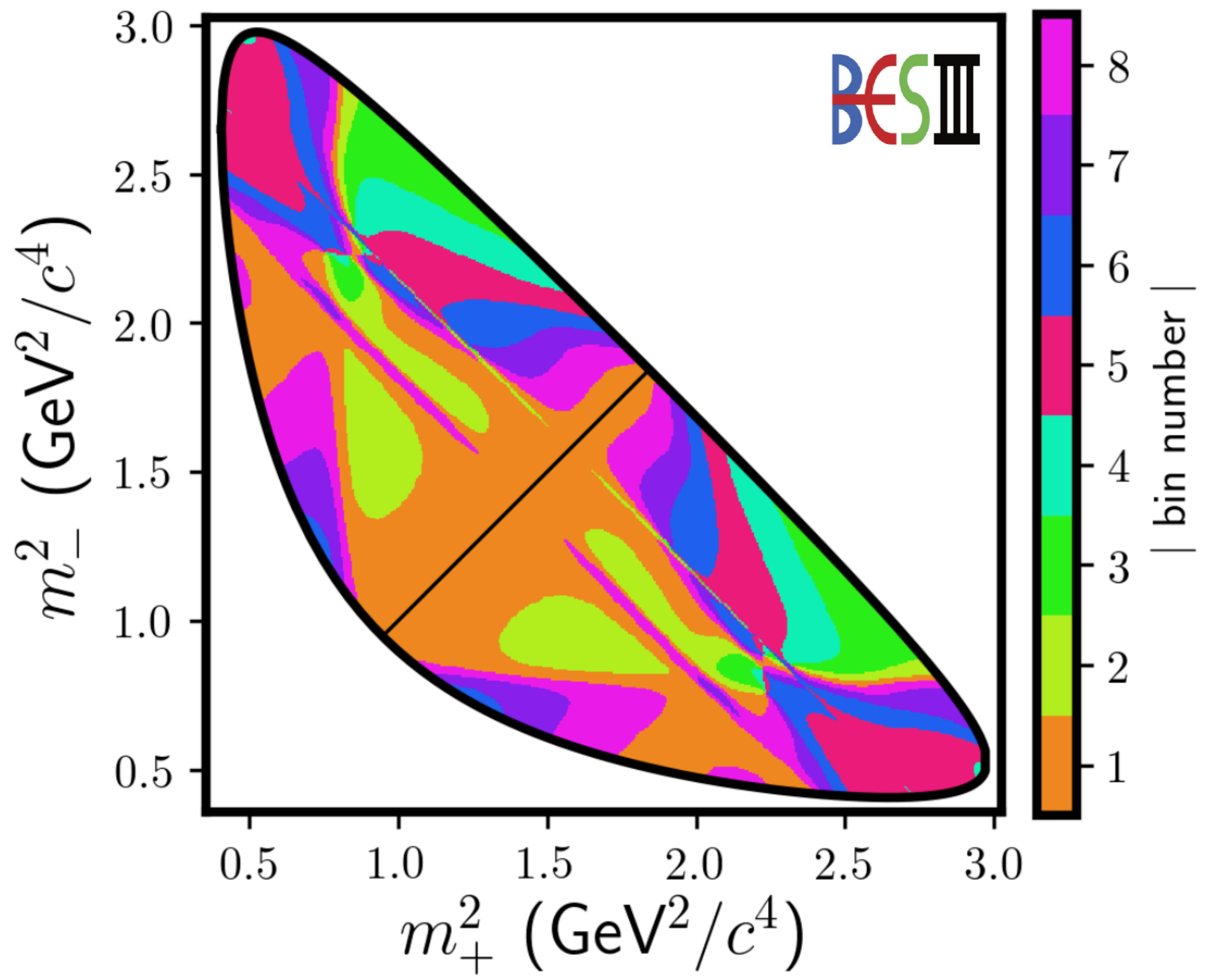
ADS



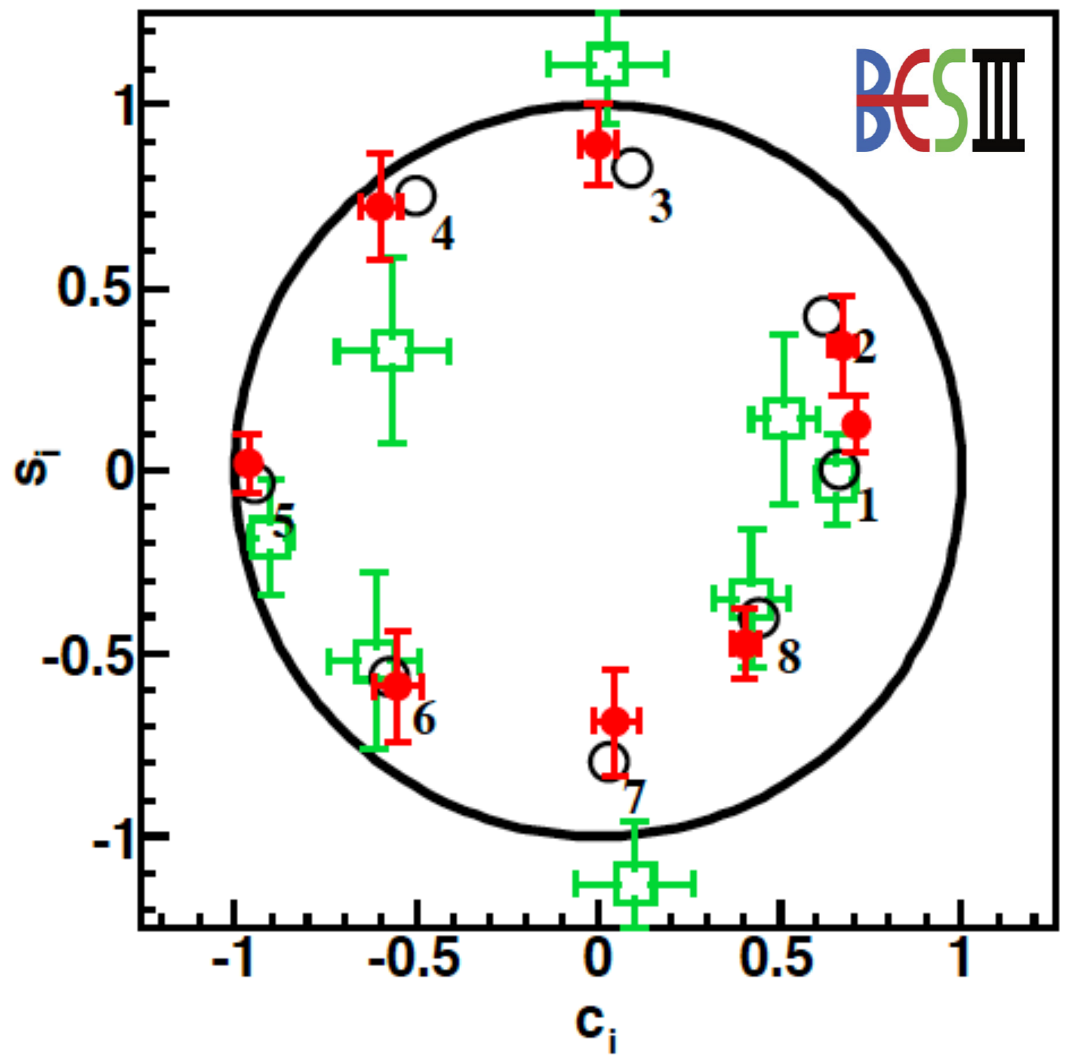
Final states are flavor modes ($K\pi$, $K3\pi$),
CF and DCSD decays. Interference is large

BPGGSZ

- Final states are three body, self-conjugate modes, eg. K_SKK, $K_S\pi\pi$, $\pi^+\pi^-\pi^0$
- Binning regions of Dalitz plot where δ_D is similar
- Model independent, there is no incorrect binning
- Optimization for binning for increased sensitivity
- Important input from BESIII on measurements of strong-phase differences (overcome systematics)



JHEP 05 (2021) 164



PRL 124, 241802 (2020)

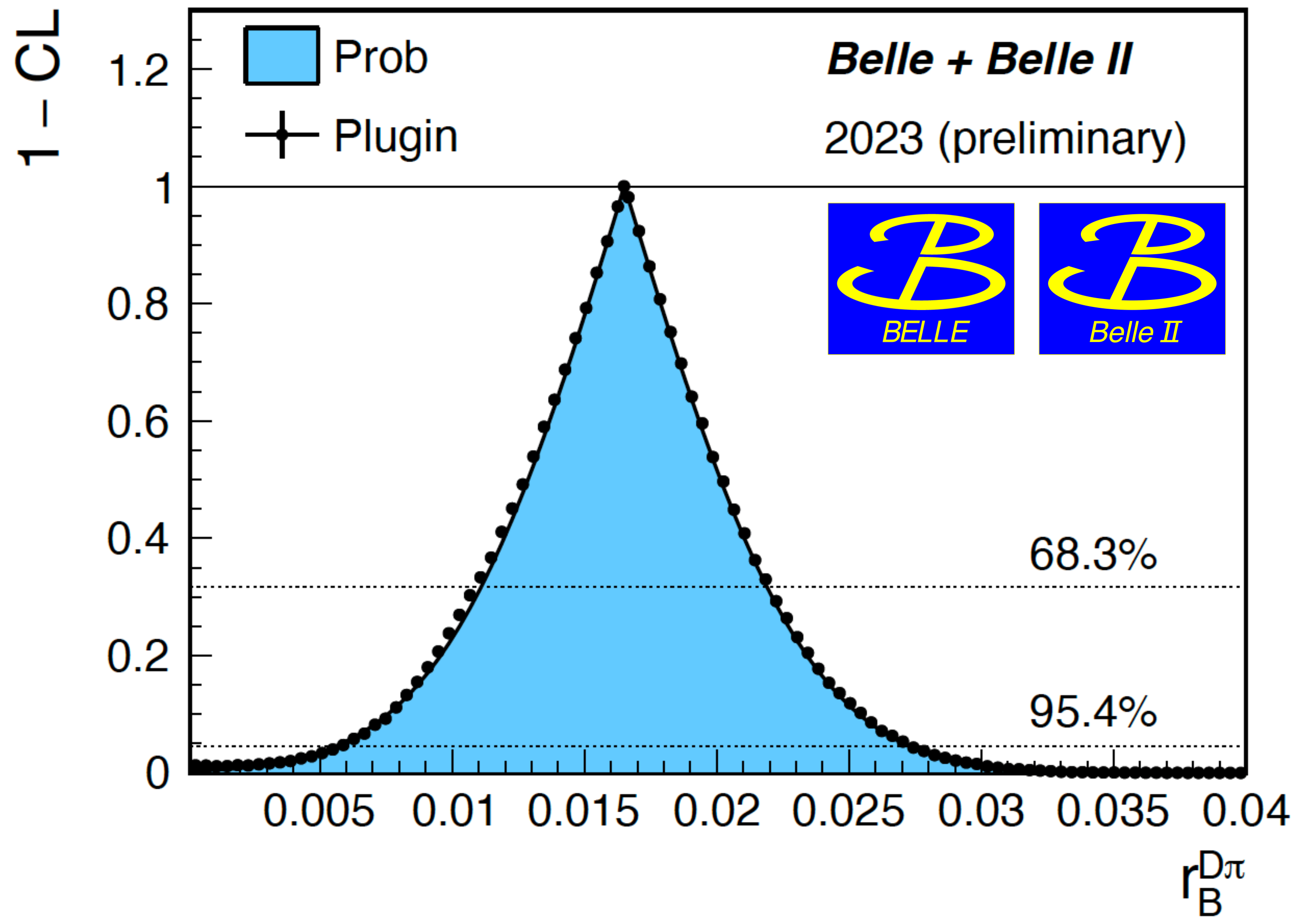
Combined measurement of ϕ_3 with Belle and Belle II data

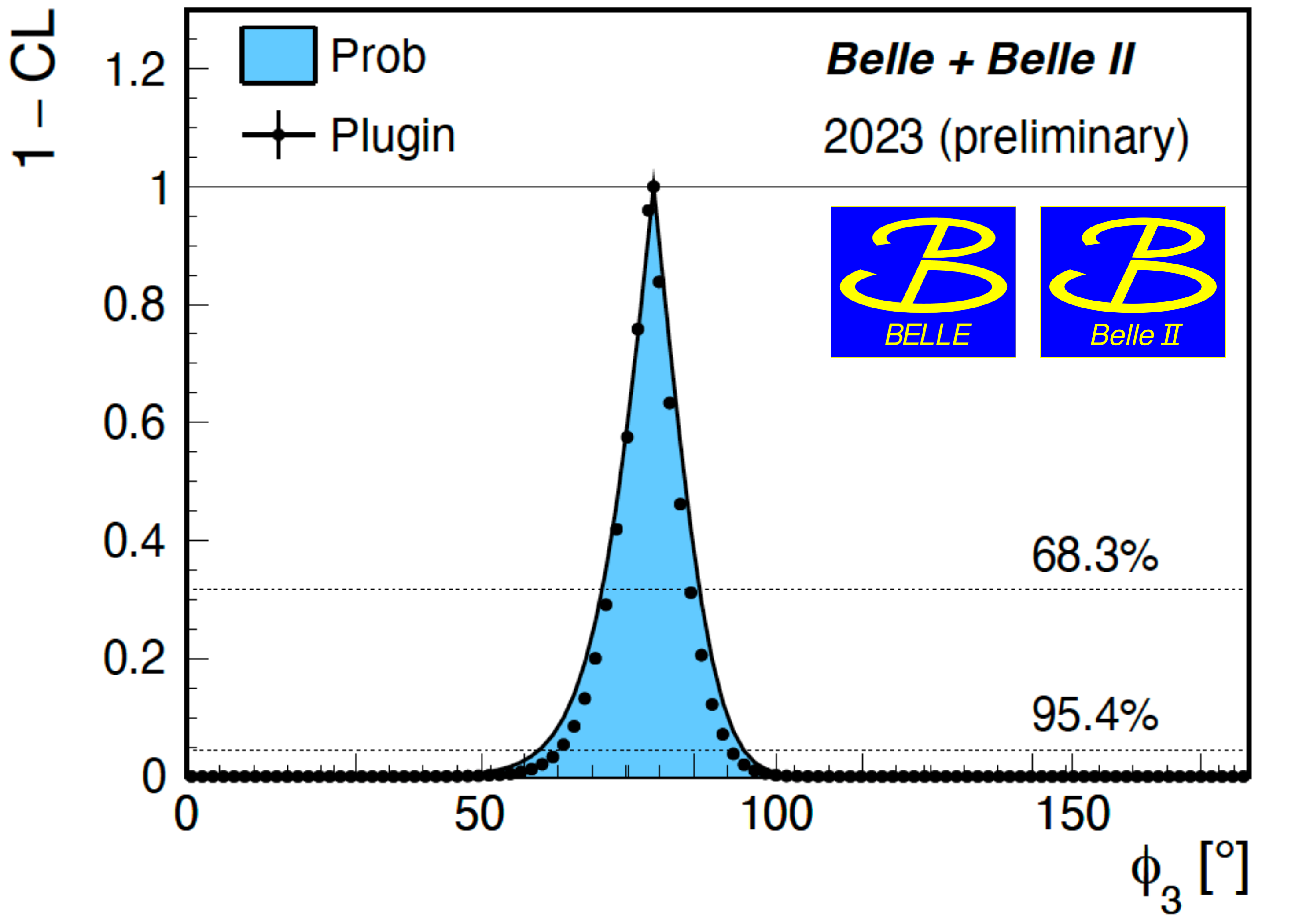
First Belle and Belle II combination

- Four different methods using 17 different final states
- Inputs on D decays dynamics from other experiments
  - r_D (amplitude ratio), δ_D (strong-phase difference), κ_D (coherence factor), etc.

B decay	D decay	Method	Data set (Belle + Belle II) [fb^{-1}]	
$B^+ \to Dh^+$	$D \to K_S^0 h^- h^+$	BPGGSZ	$711 + 128$	[JHEP 02 063 (2022)]
$B^+ \to Dh^+$	$D \to K_S^0 \pi^- \pi^+ \pi^0$	BPGGSZ	$711 + 0$	[JHEP 10 178 (2019)]
$B^+ \to Dh^+$	$D \to K_S^0 \pi^0, K^- K^+$	GLW	$711 + 189$	[arxiv:2308.05048]
$B^+ \to Dh^+$	$D \to K^+ \pi^-, K^+ \pi^- \pi^0$	ADS	$711 + 0$	[PRL 106 231803 (2011)]
$B^+ \to Dh^+$	$D \to K_S^0 K^- \pi^+$	GLS	$711 + 362$	[arxiv:2306.02940]
$B^+ \to D^* K^+$	$D \to K_S^0 \pi^- \pi^+$	BPGGSZ	$605 + 0$	[PRD 81 112002 (2010)]
$B^+ \to D^* K^+$	$D \to K_S^0 \pi^0, K_S^0 \phi, K_S^0 \omega, K^- K^+, \pi^- \pi^+$	GLW	210+0	[PRD 73 051106 (2006)]

Parameters	$\phi_3(^\circ)$	r_B^{DK}	$\delta_B^{DK}(^\circ)$	$r_B^{D\pi}$	$\delta_B^{D\pi}(^\circ)$	$r_B^{D^*K}$	$\delta_B^{D^*K}(^\circ)$
PLUGIN method							
Best fit value	78.6	0.117	138.4	0.0165	347.0	0.234	341
68.3% interval	[71.4, 85.4]	[0.105, 0.130]	[129.1, 146.5]	[0.0109, 0.0220]	[337.4, 355.7]	[0.165, 0.303]	[327,355]
95.5% interval	[63, 92]	[0.092, 0.141]	[118, 154]	[0.006, 0.027]	[322, 366]	[0.10, 0.37]	[307, 369]





$\phi_3 = (78.6 \pm 7.3)^\circ$, consistent with WA, $\phi_3 = (66.2^{+3.2}_{-3.6})^\circ$, within 2σ

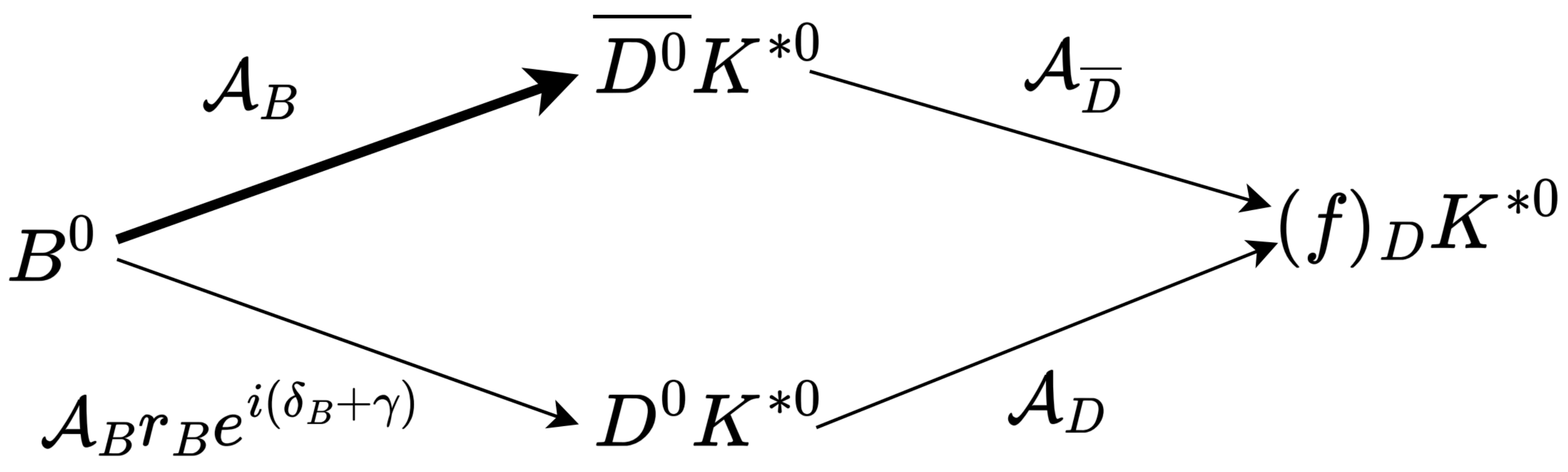
New results of γ measurements at LHCb

ADS and GLW-like decays

LHCb-CONF-2023-003

GLW: decays to CP-eigenstates(*)

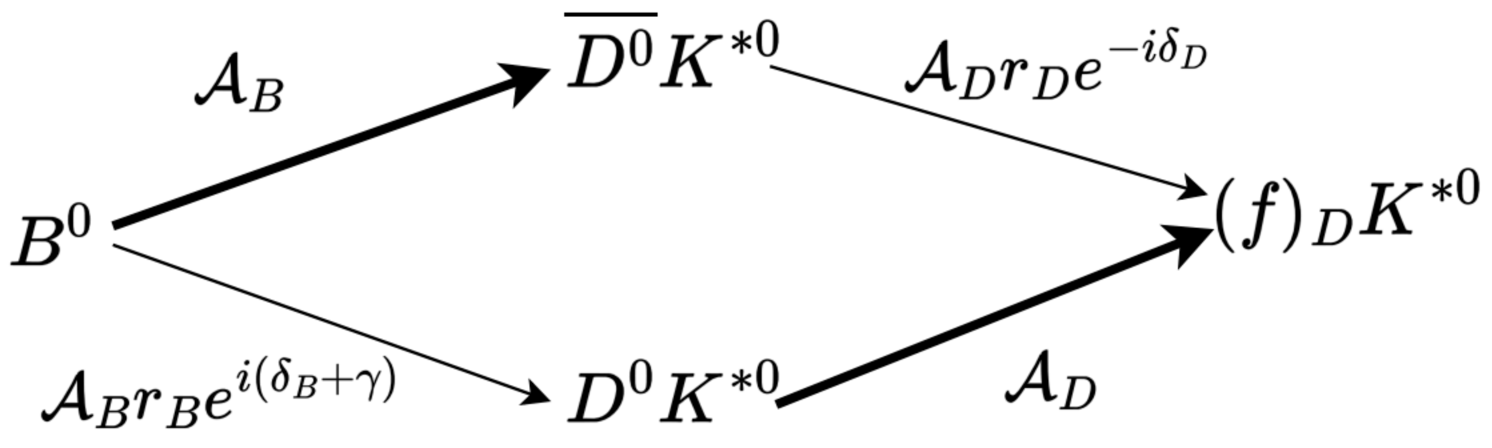
$D \to K^+K^-$, $D \to \pi^+\pi^-$, $D \to \pi^+\pi^-\pi^+\pi^-$



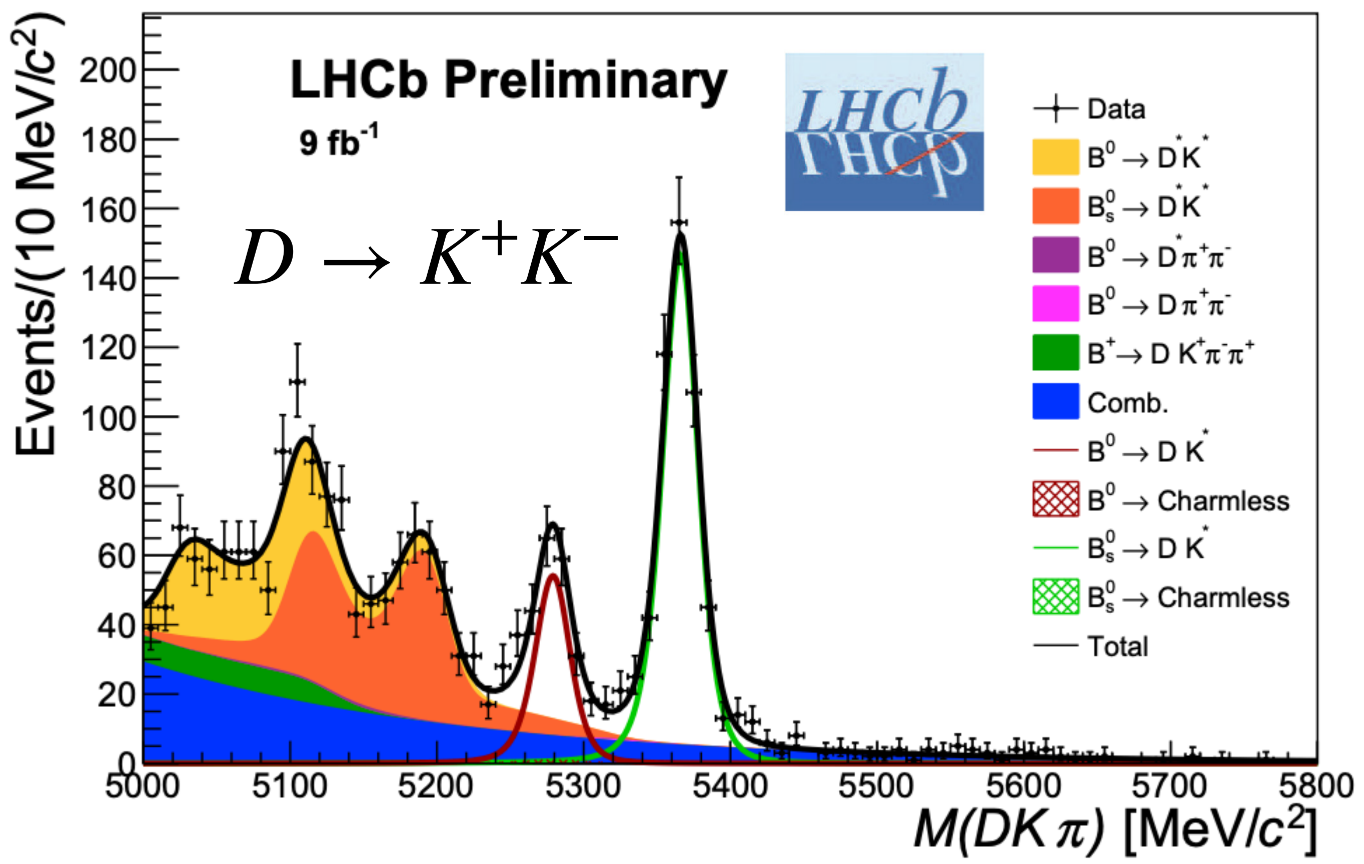
Interference (sensitivity to $\gamma \propto r_B \approx 25\,\%$)

ADS: doubly-Cabibbo suppressed decays

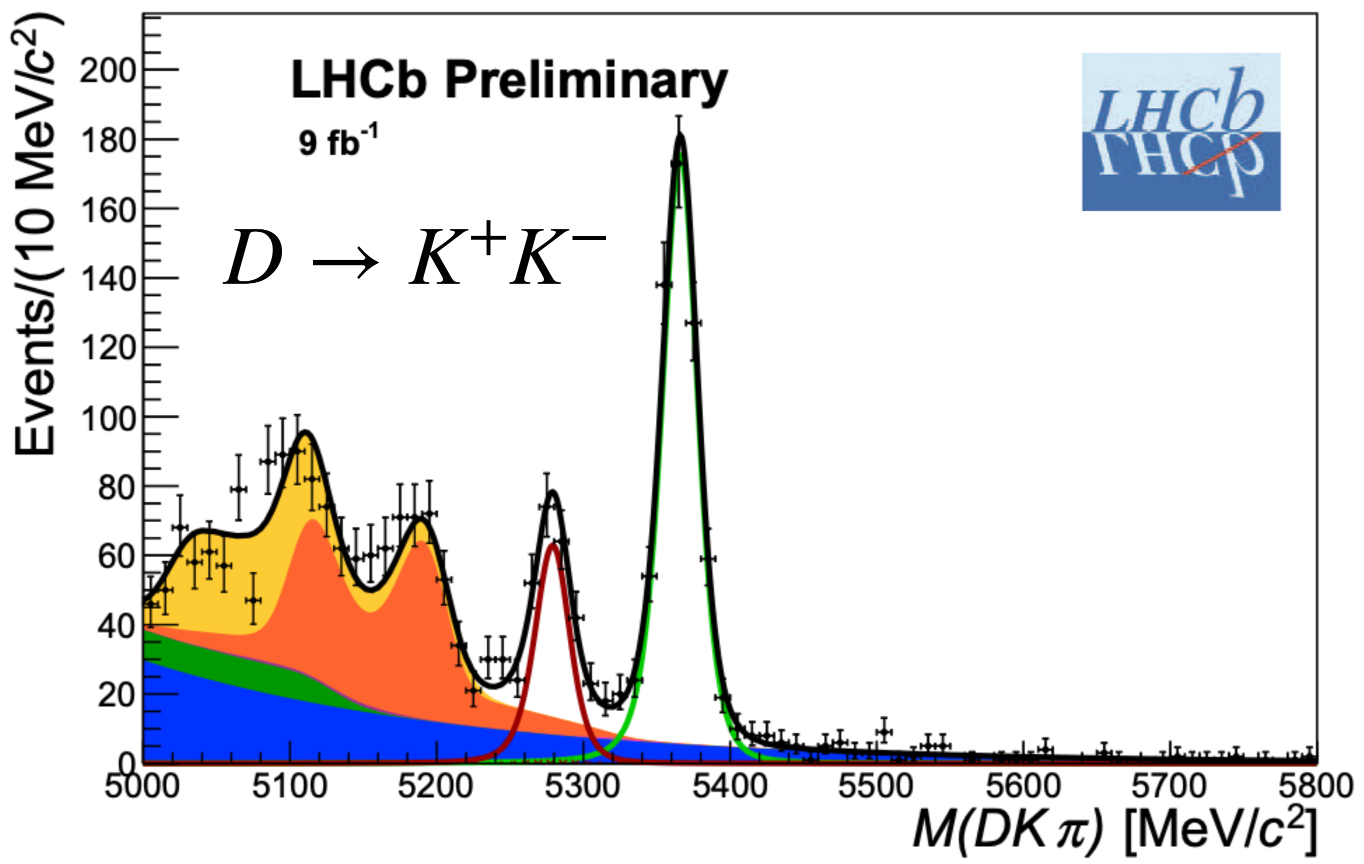
$D \to K^+\pi^-$, $D \to \pi^+K^-\pi^+\pi^-$



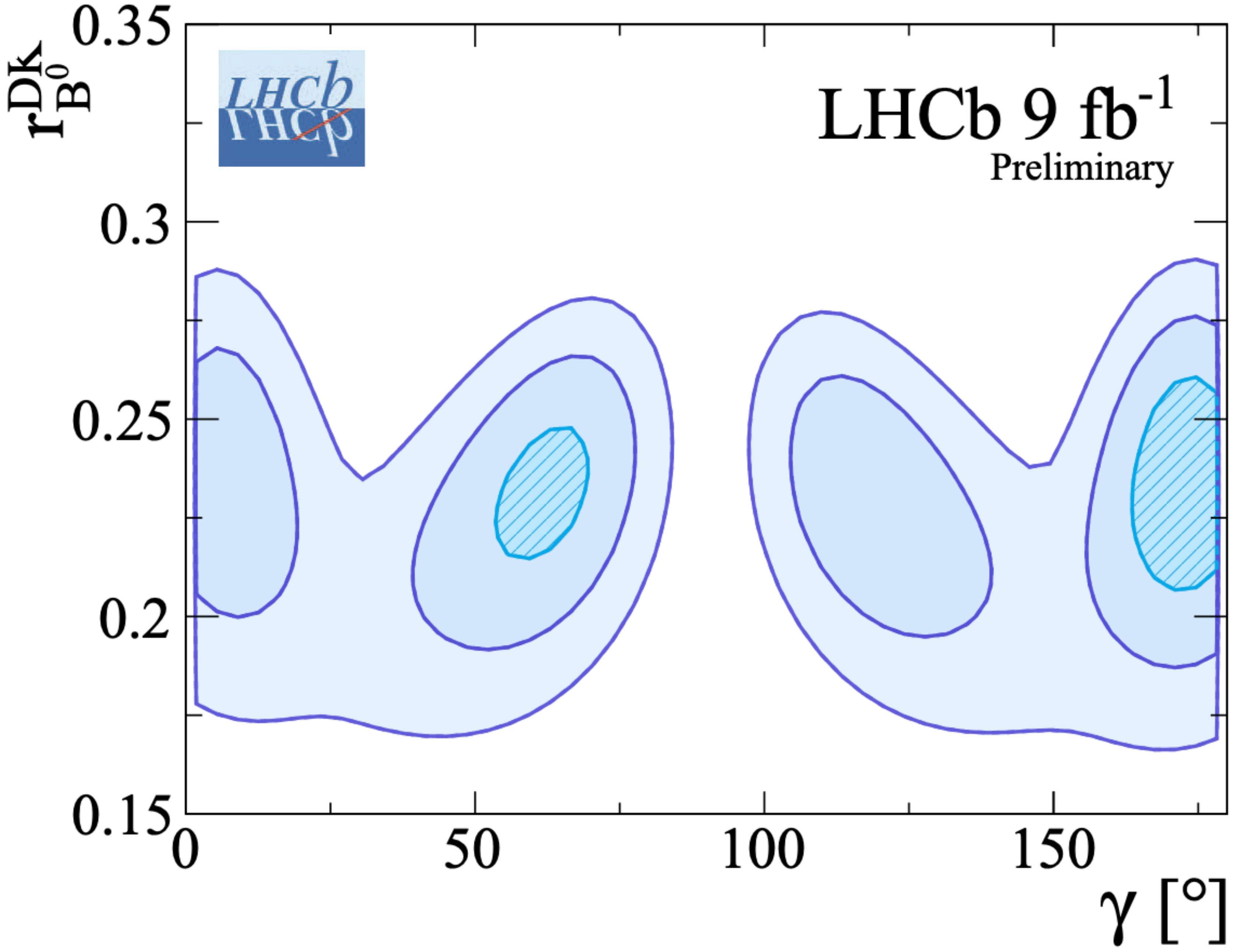
Maximal interference (similarly sized amplitudes)



$\overline{B^0}$



B^0



Four-fold degeneracy:

$(\gamma, \delta_B) \to (\delta_B, \gamma)$ or $(\pi - \gamma, \pi - \delta_B)$

preferred solution: $\gamma = 172 \pm 6°$

alternate solution: $\gamma = 62 \pm 8°$

Results from

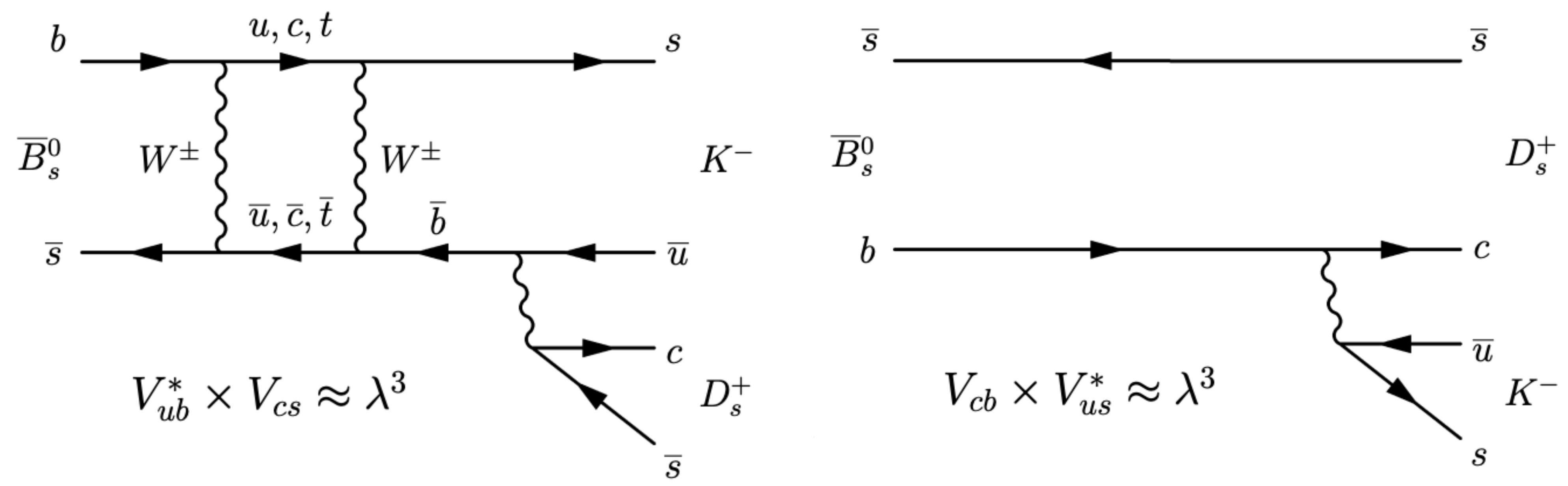
$B^0 \to [D^0 \to K_S^0 h^+h^-]K^{*0}$

will break the degeneracy

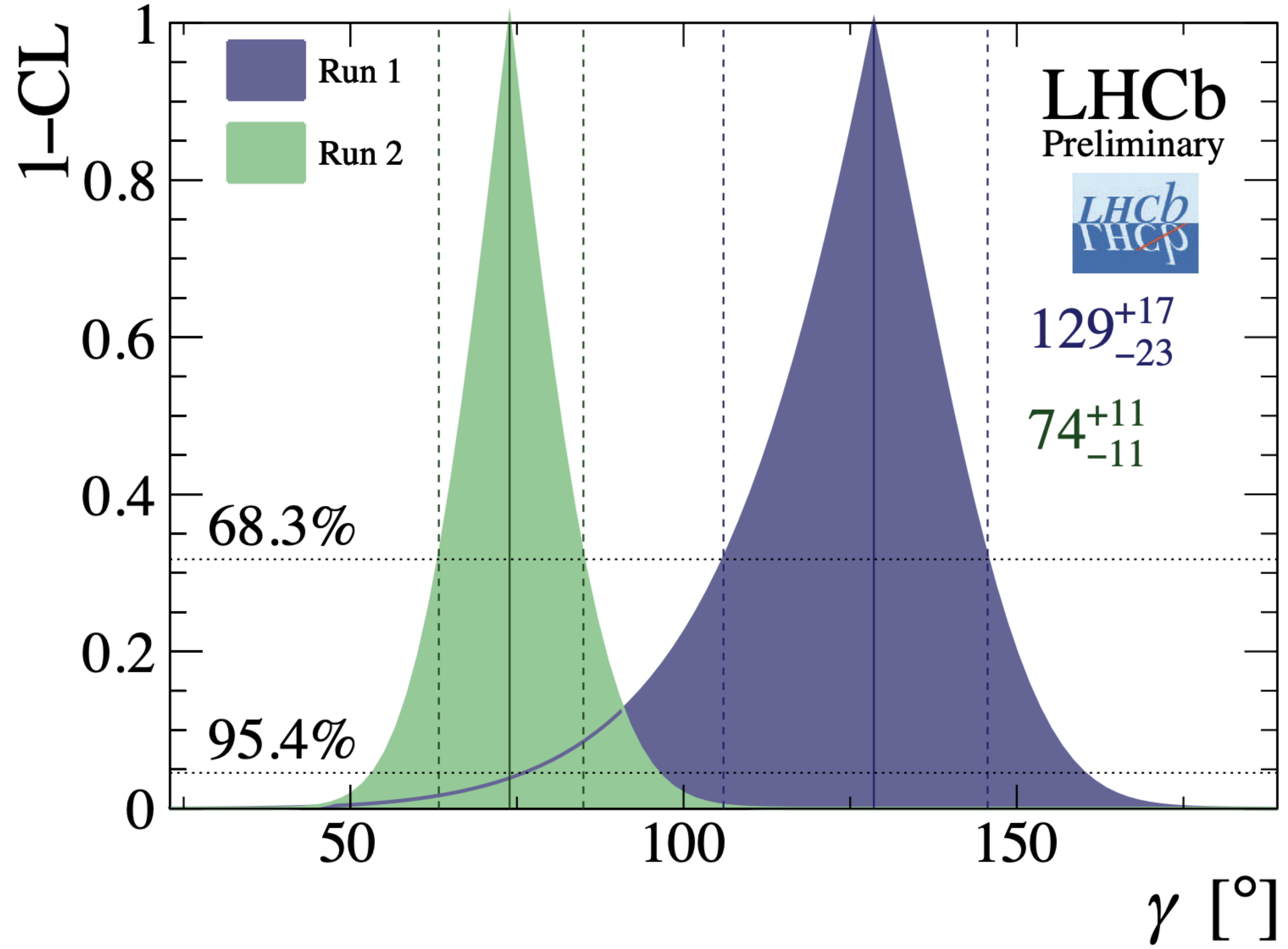
LHCb-CONF-2023-004

Time-dependent measurement of γ at LHCb

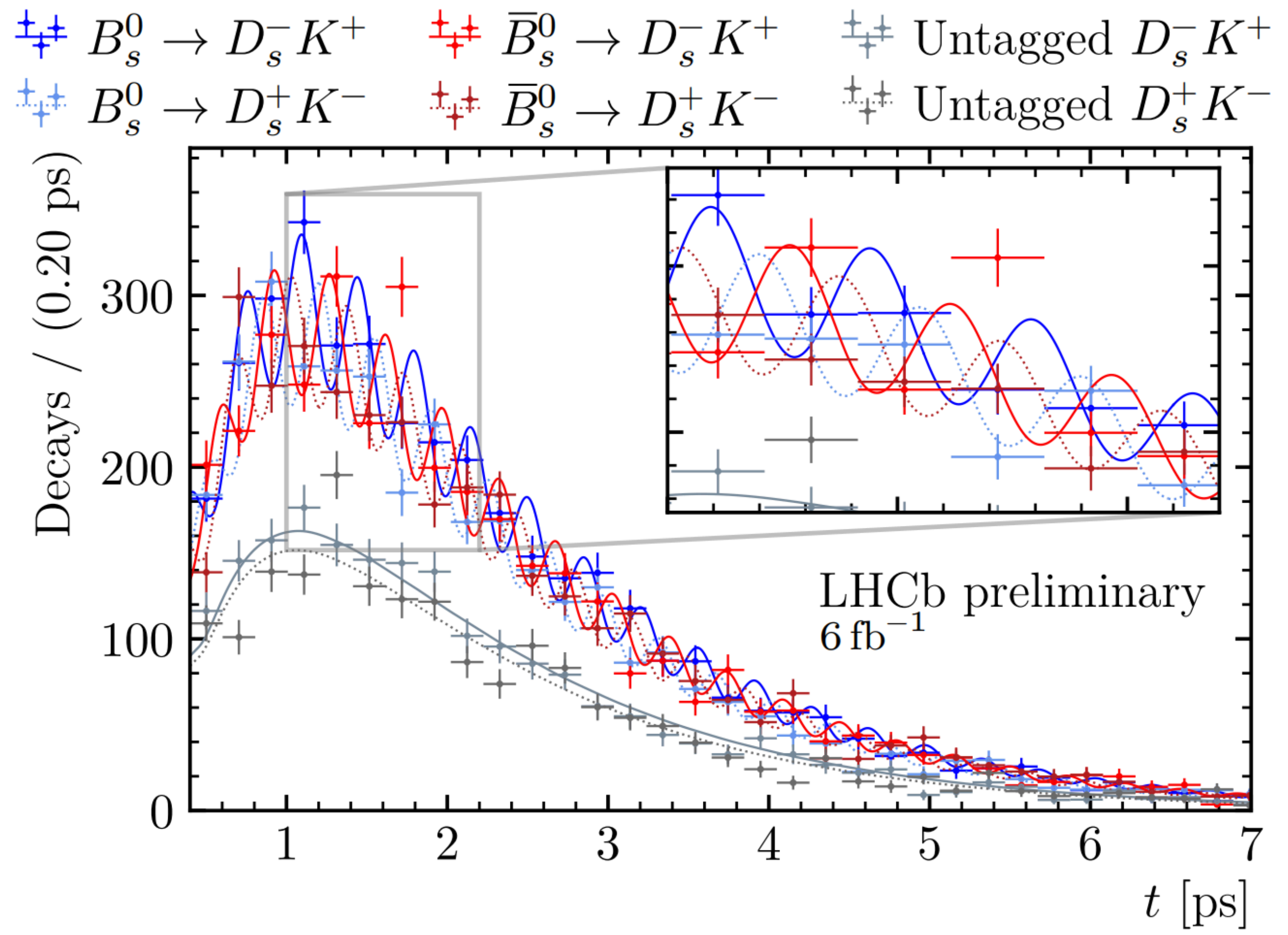
Good sensitivity in B_s decays, large interference

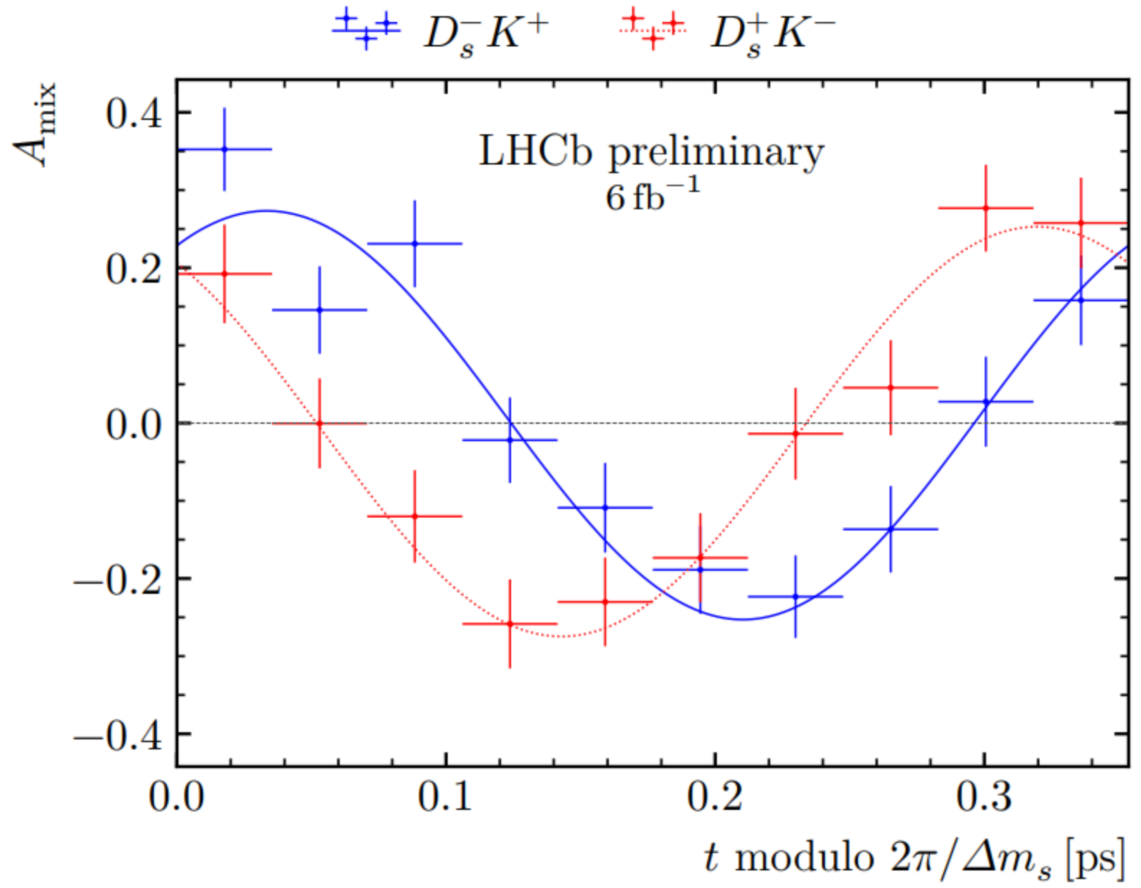


Relative phase: $\gamma - 2\beta_s$



External inputs:
Γ_s and $\Delta\Gamma_s$,
detection asymmetry





Significant CP violation in interference

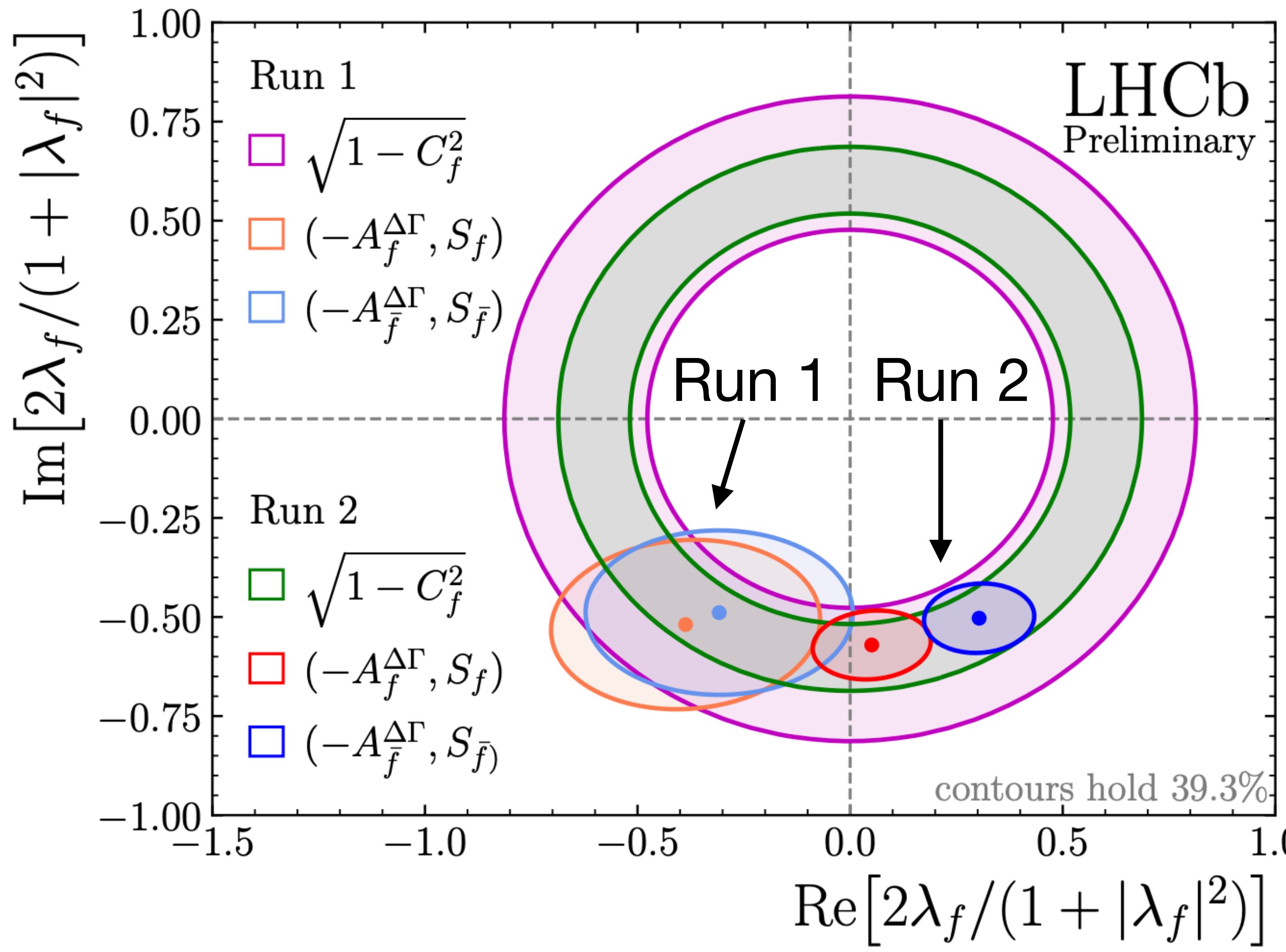
$S_f \neq -S_{\bar{f}}$ at 8.8σ

External input:

$-2\beta_s = \phi_s = (-0.031 \pm 0.018)$ rad

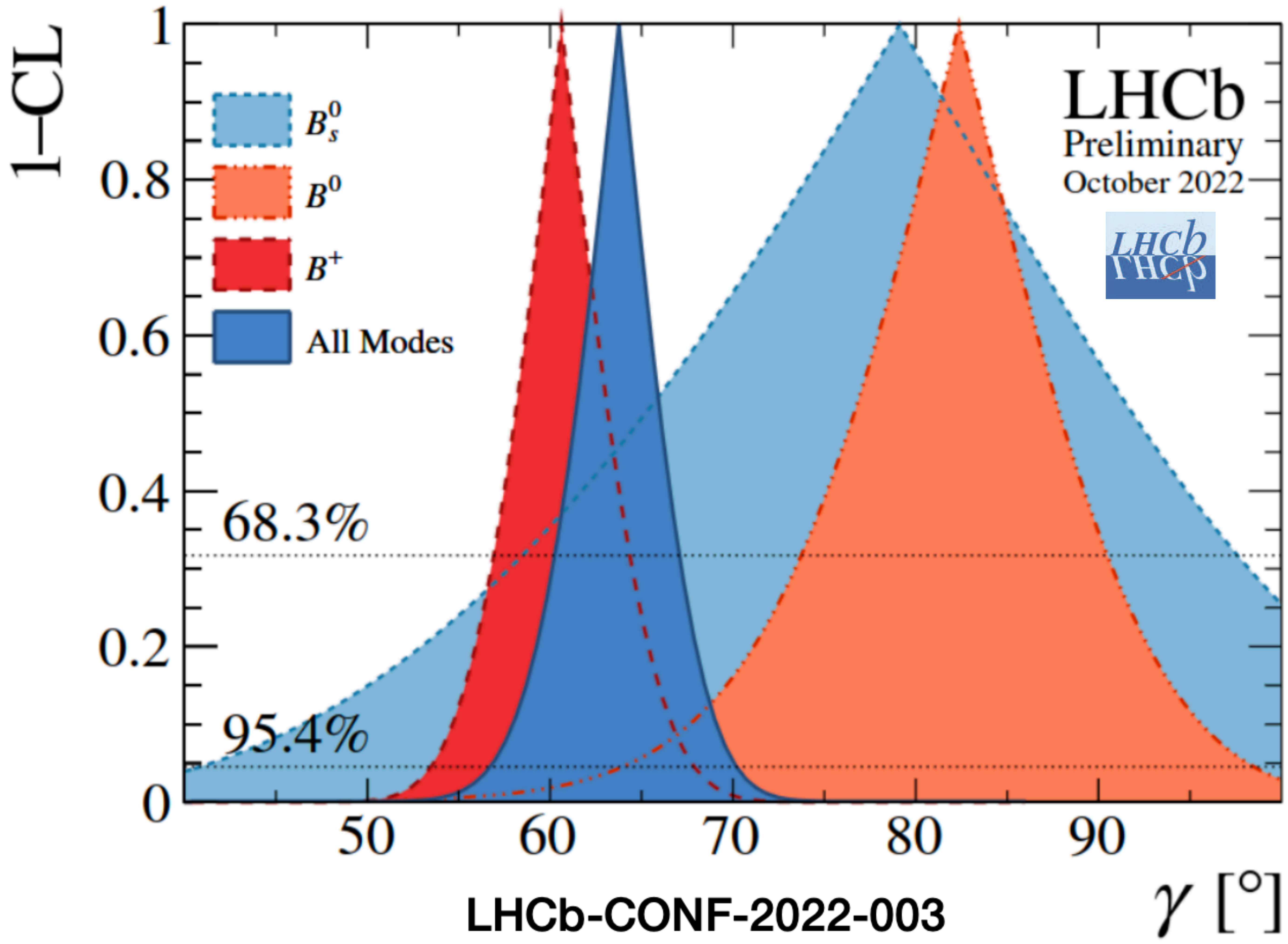
Compatibility at 1.3σ

Combination in preparation



LHCb combination

$$\gamma = (63.8^{+3.5}_{-3.7})^\circ$$



LHCb-CONF-2022-003

HFLAV: $\gamma_{\text{direct}} = (66.2^{+3.4}_{-3.6})^\circ$

Indirect combinations:

$\gamma = (65.6^{+0.9}_{-2.7})^\circ$ or [CKMFit]

$\gamma = (65.8 \pm 2.2)^\circ$ [UTFit]

Measurement of ϕ_s at the LHC

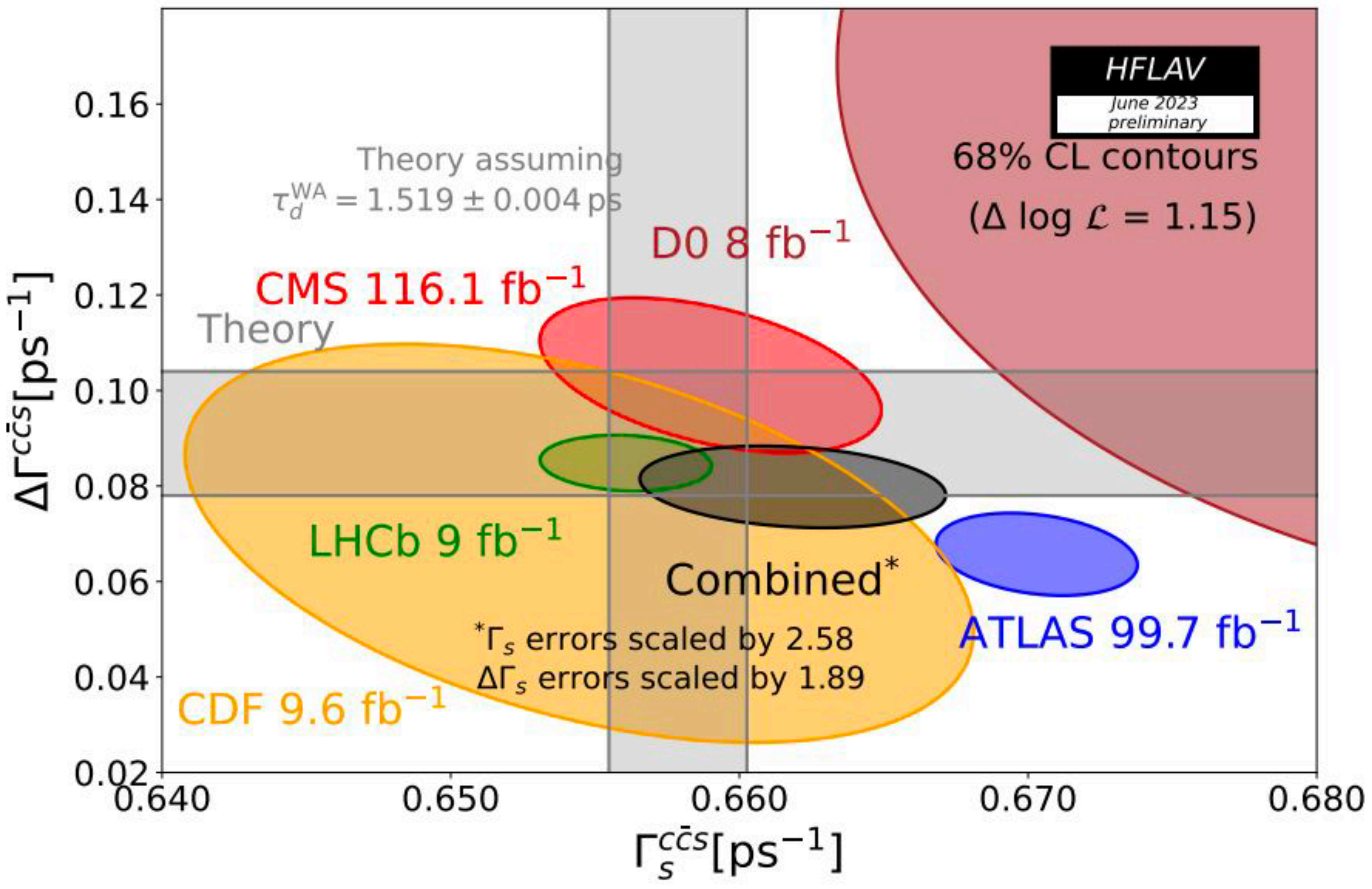
Another weak phase

$$\phi_s^{SM} \equiv -2\beta_s = -2arg(\frac{-V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*})$$

- Weak phase ϕ_s precisely predicted by the SM
- New physics can change the value of ϕ_s by up to ~100% [RMP 88 (2016) 045002]

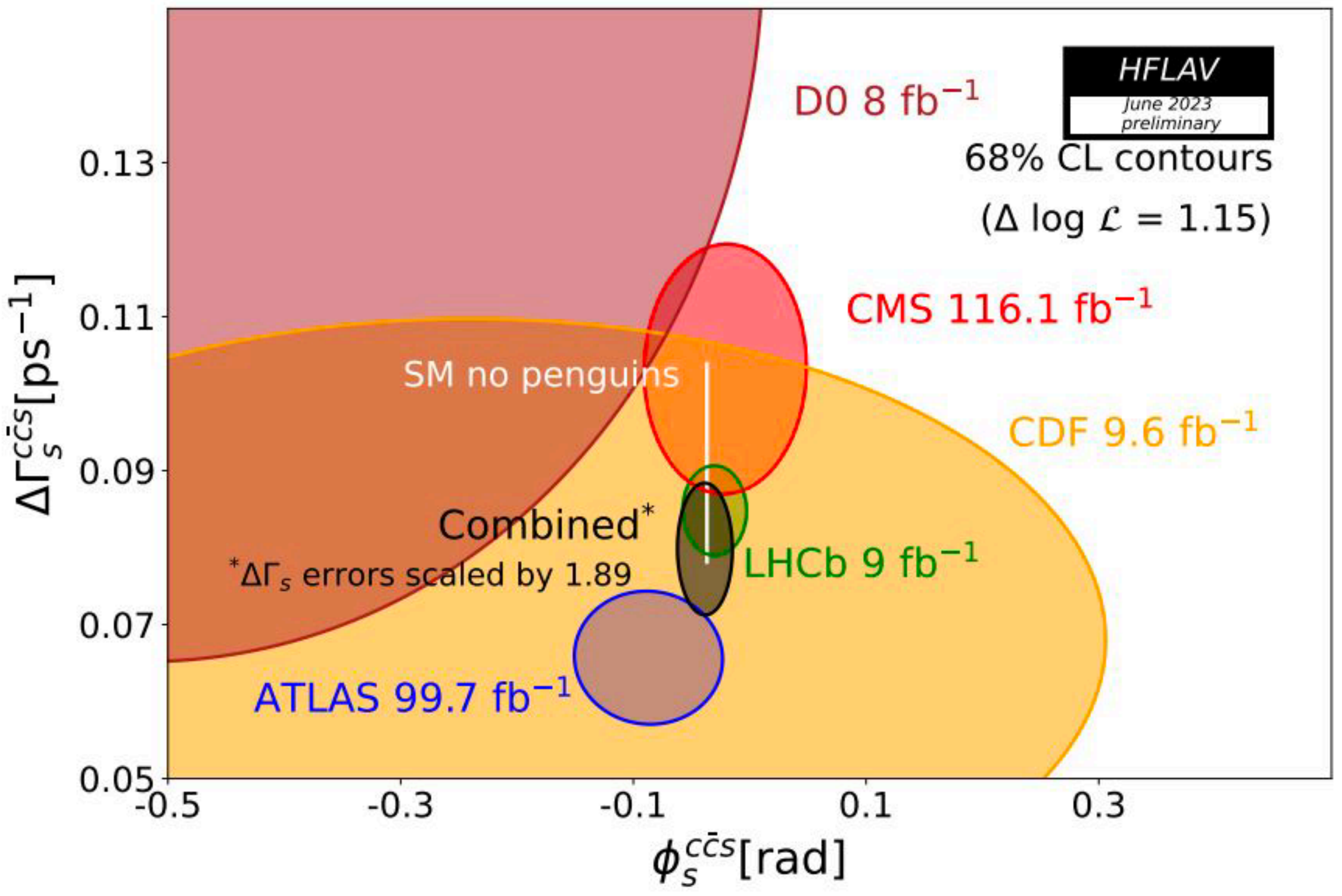
Global fits to experimental data assuming CKM paradigm:

$$\phi_s = -0.0368^{+0.0009}_{-0.0006} \text{ rad}$$



LHCb in $B_s^0 \to J/\psi h^+h^-$, $B_s^0 \to \psi K^+K^-$, $B_s^0 \to D_s^+D_s^-$

$$\phi_s = -0.031 \pm 0.018 \text{ rad}$$



Combined result from CDF, D0, ATLAS, CMS, LHCb [HFLAV]

Summary and prospects

- Many exciting new experimental measurements with high statistics datasets
- Precision improving as datasets grow
- Novel techniques leveraging differential measurements and full angular dependence
- Significant work ongoing on theory side as well!

Adapted from arXiv:2208.05403

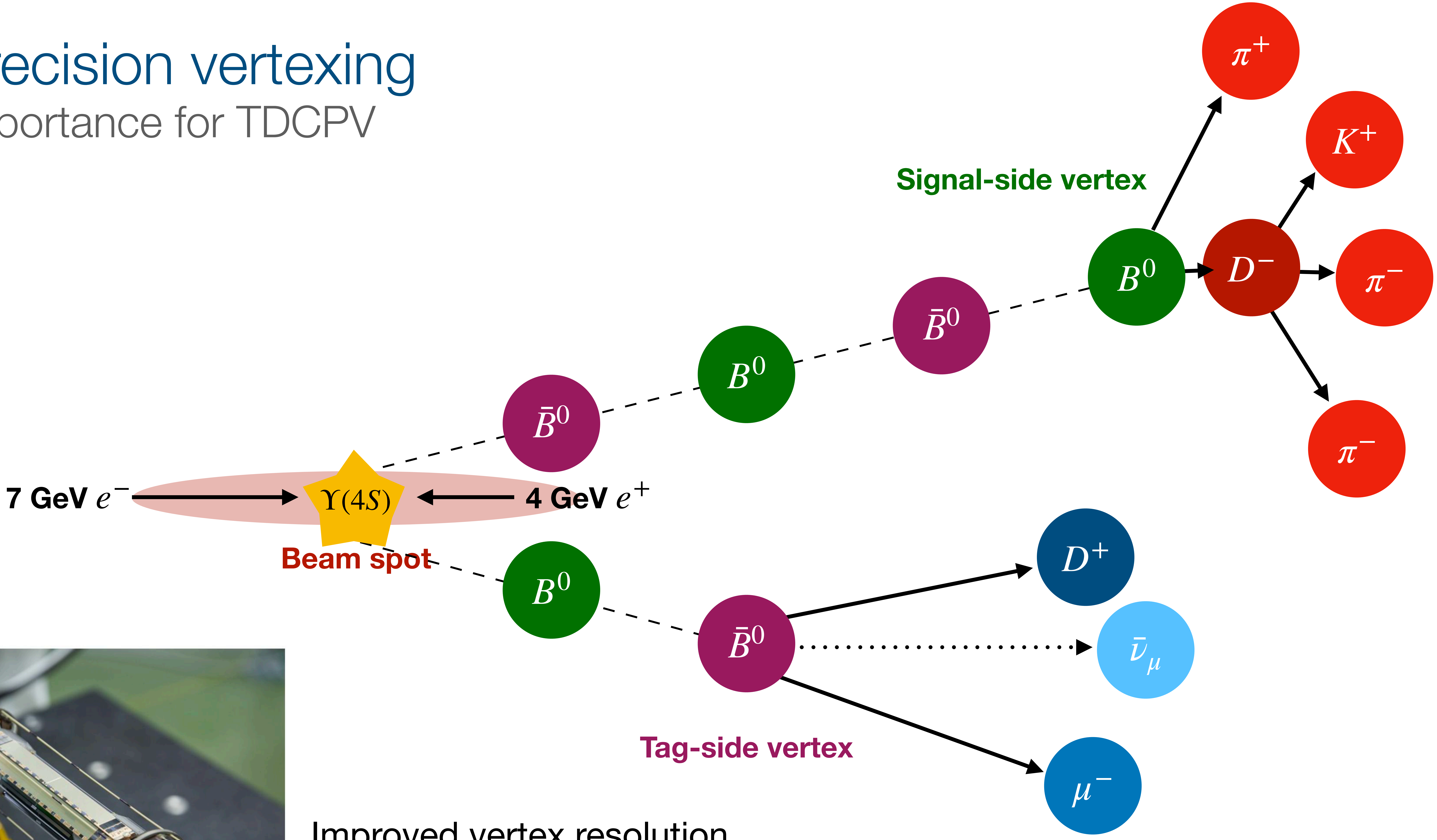
Observable	Current best	Belle II $50\,\mathrm{ab}^{-1}$	Belle II $250\,\mathrm{ab}^{-1}$	LHCb $50\,\mathrm{fb}^{-1}$	LHCb $300\,\mathrm{fb}^{-1}$	ATLAS $3\,\mathrm{ab}^{-1}$	CMS $3\,\mathrm{ab}^{-1}$	BESIII $20\,\mathrm{fb}^{-1}$ $(*)$	STCF $1\,\mathrm{ab}^{-1}$ $(*)$
CKM tests and *CP* violation									
α	5° [60]	0.6°	0.3°						
$\sin 2\beta(B^0 \to J/\psi K^0_S)$	0.029 [61]	0.005	0.002	0.006	0.003				
γ	4° [62]	1.5°	0.8°	1°	0.35°			0.4° (†)	$< 0.1^\circ$ (†)
$\phi_s(B^0_s \to J/\psi\,\phi)$	32 mrad [63]			10 mrad	4 mrad	4–9 mrad	5–6 mrad		
$\|V_{ub}\|(B^0 \to \pi^-\ell^+\nu)$	5% [64, 65]	2%	$< 1\%$	na	na				
$\|V_{ub}\|/\|V_{cb}\|(\Lambda^0_b \to p\mu^-\overline{\nu})$	6% [66]			2%	1%				
$f_{D^+}\|V_{cd}\|(D^+ \to \mu^+\nu)$	2.6% [67]	1.4%	na					1.0%	0.15%
$S_{CP}(B^0 \to \eta' K^0_S)$	0.08 [68, 69]	0.015	0.007	na	na				
$A_{CP}(B^0 \to K^0_S\pi^0)$	0.15 [68, 70]	0.025	0.018	na	na				
$A_{CP}(D^+ \to \pi^+\pi^0)$	11×10^{-3} [71]	1.7×10^{-3}	na	na	na			na	na
$\Delta x(D^0 \to K^0_S\pi^+\pi^-)$	18×10^{-5} [72]	na	na	4.1×10^{-5}	1.6×10^{-5}				
$A_\Gamma(D^0 \to K^+K^-, \pi^+\pi^-)$	11×10^{-5} [73]	na	na	3.2×10^{-5}	1.2×10^{-5}				

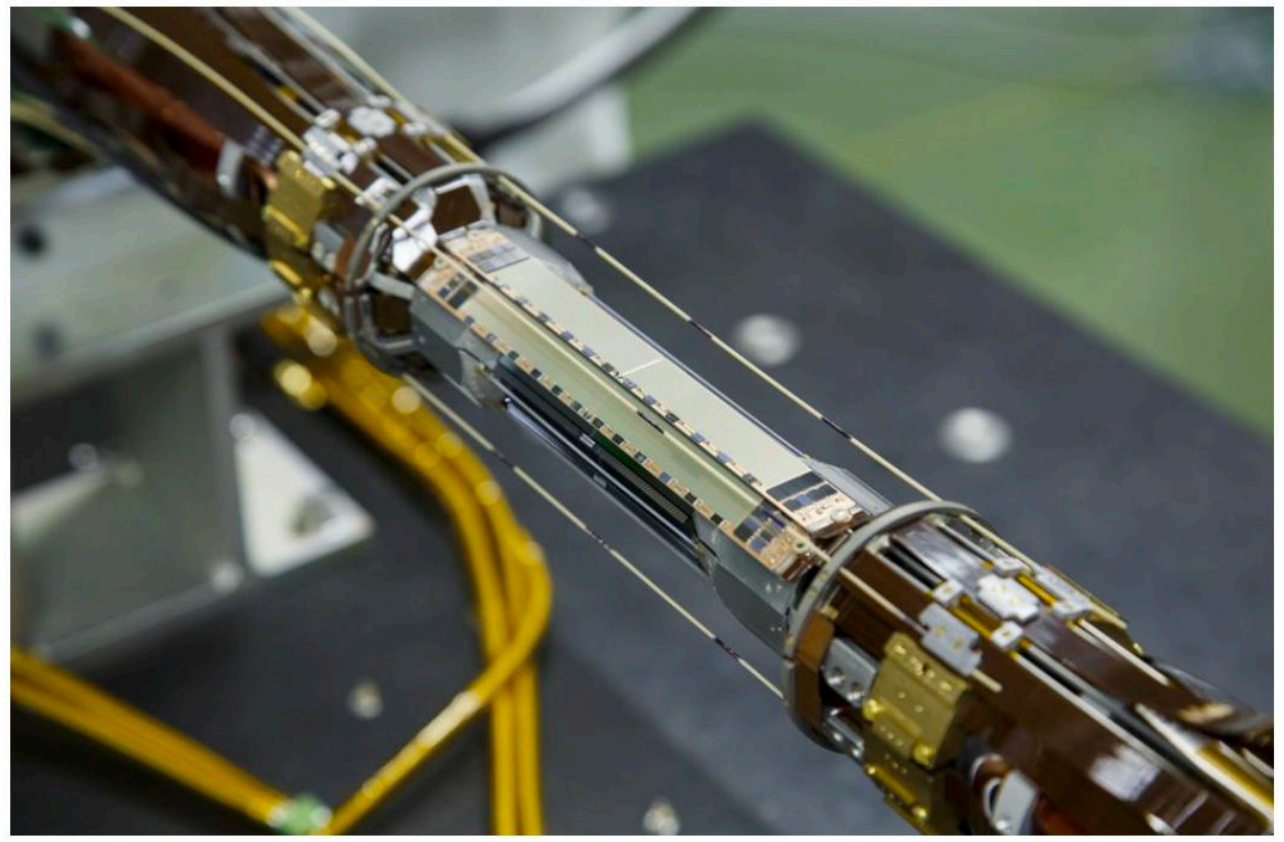
61: PRL 108 (2012) 171802
62: JHEP 12 (2021) 141
63: EPJC 79 (2019) 706
64: PRD 83 (2011) 032007
65: PRD 83 (2011) 071101
66: Nature Phys 11 (2015) 743
67: PRD 89 (2014) 051104
68: PRD 79 (2009) 052003
69: JHEP 10 (2014) 165
70: PRD 81 (2010) 011101
71: JHEP 06 (2021) 019
72: PRL 127 (2021) 111801

Extra slides

High-precision vertexing

and its importance for TDCPV



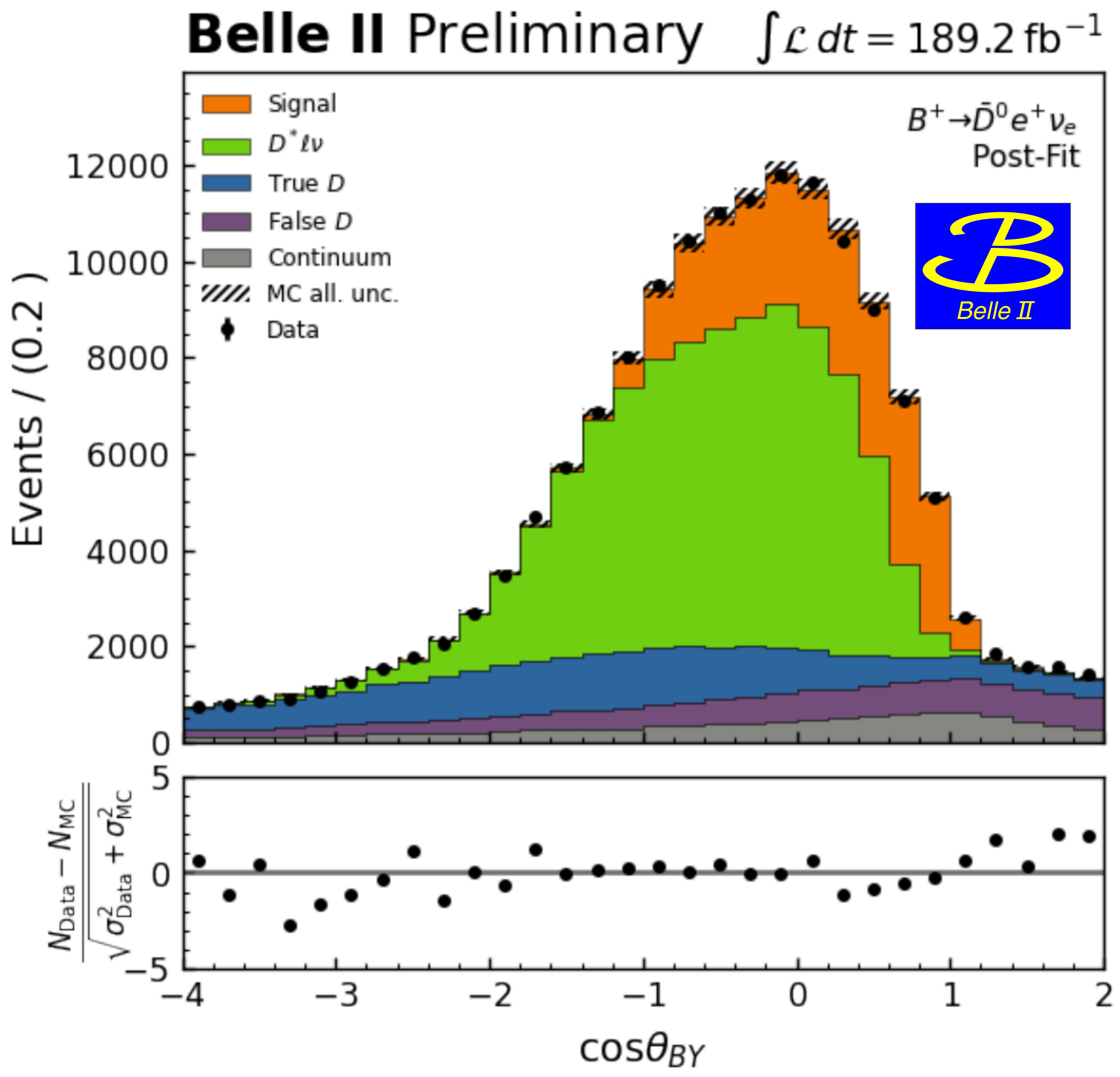


Improved vertex resolution
due to pixel detector
(despite lower boost)

$|V_{cb}|$ from exclusive $B \to D\ell^+\nu_\ell$ untagged (189/fb) at Belle II

New result from Belle II

- Signal extraction in $\cos\theta_{BY} = \dfrac{2E_B^* E_Y^* - m_B^2 - m_Y^2}{2|p_B^*||p_Y^*|}$
- Yield extracted in bins of w by fitting the $\cos\theta_{BY}$ distributions

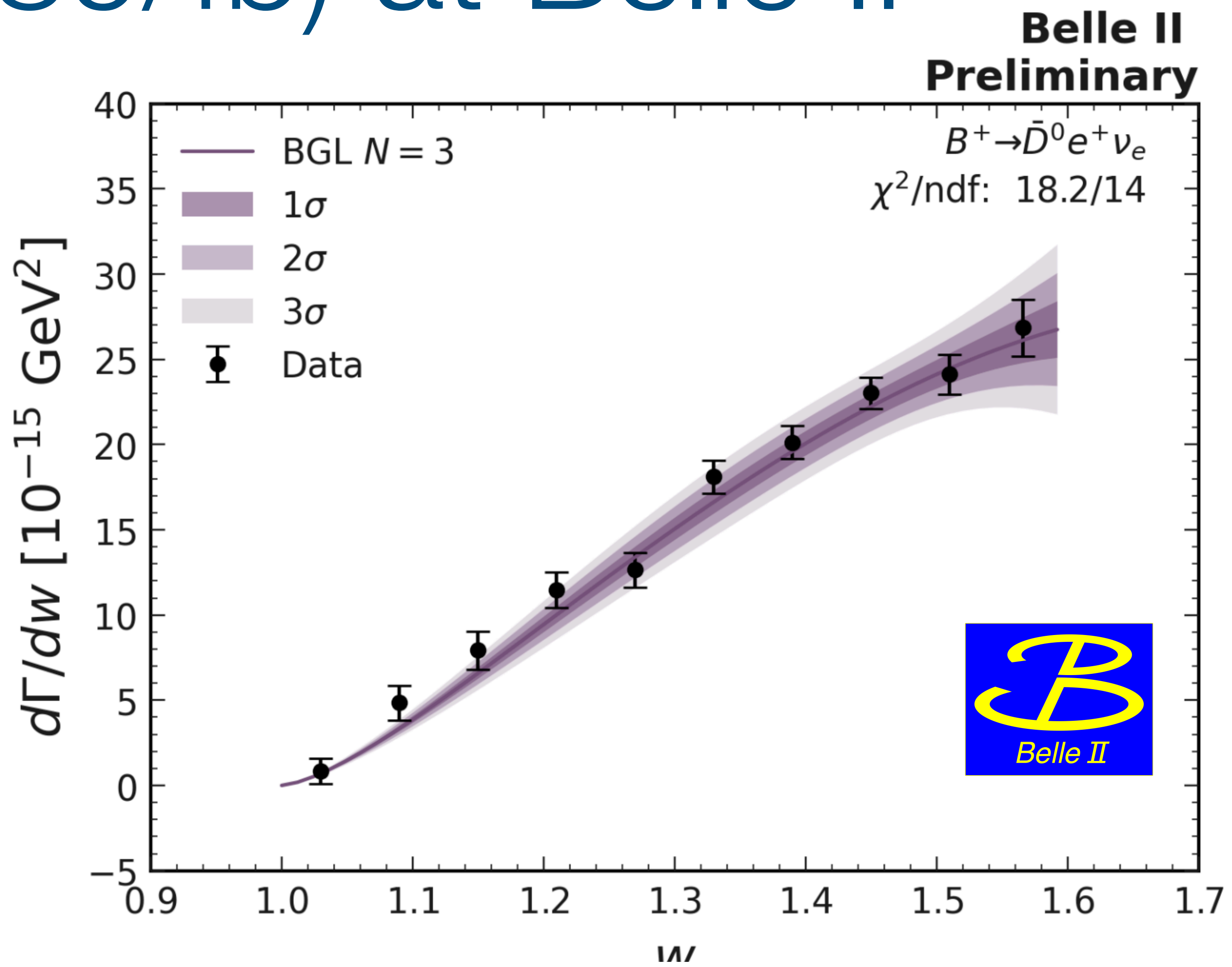


[NPB 196 83]

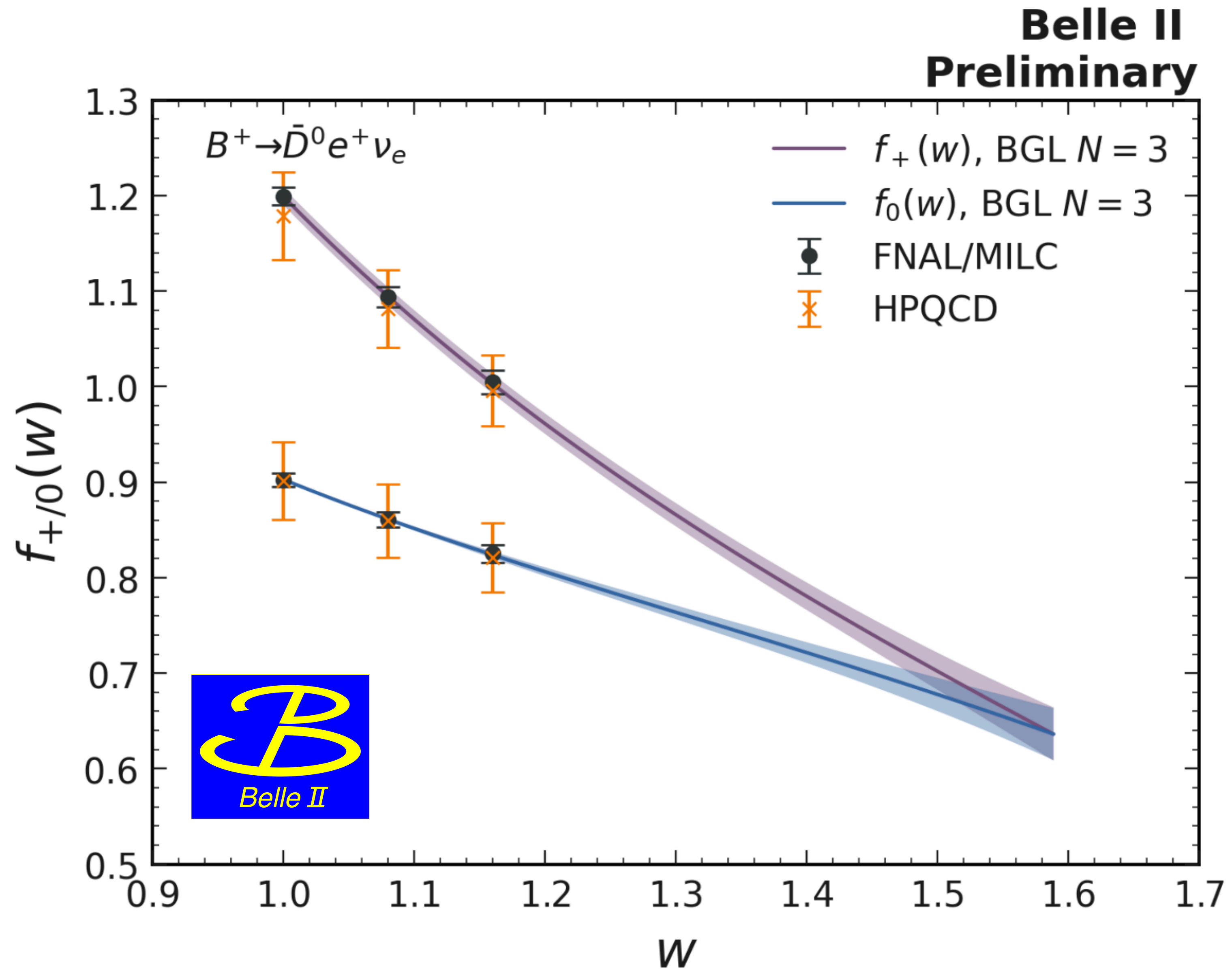
Small EW correction (1.0066 ± 0.0050)

$$\eta_{\mathrm{EW}}|V_{cb}| = (38.53 \pm 1.15) \times 10^{-3}$$

Weighted average over B^0, B^+ and e, μ
(four decays)



arXiv:2210.13143



Determine $|V_{cb}|$ with fit using lattice QCD data for FF

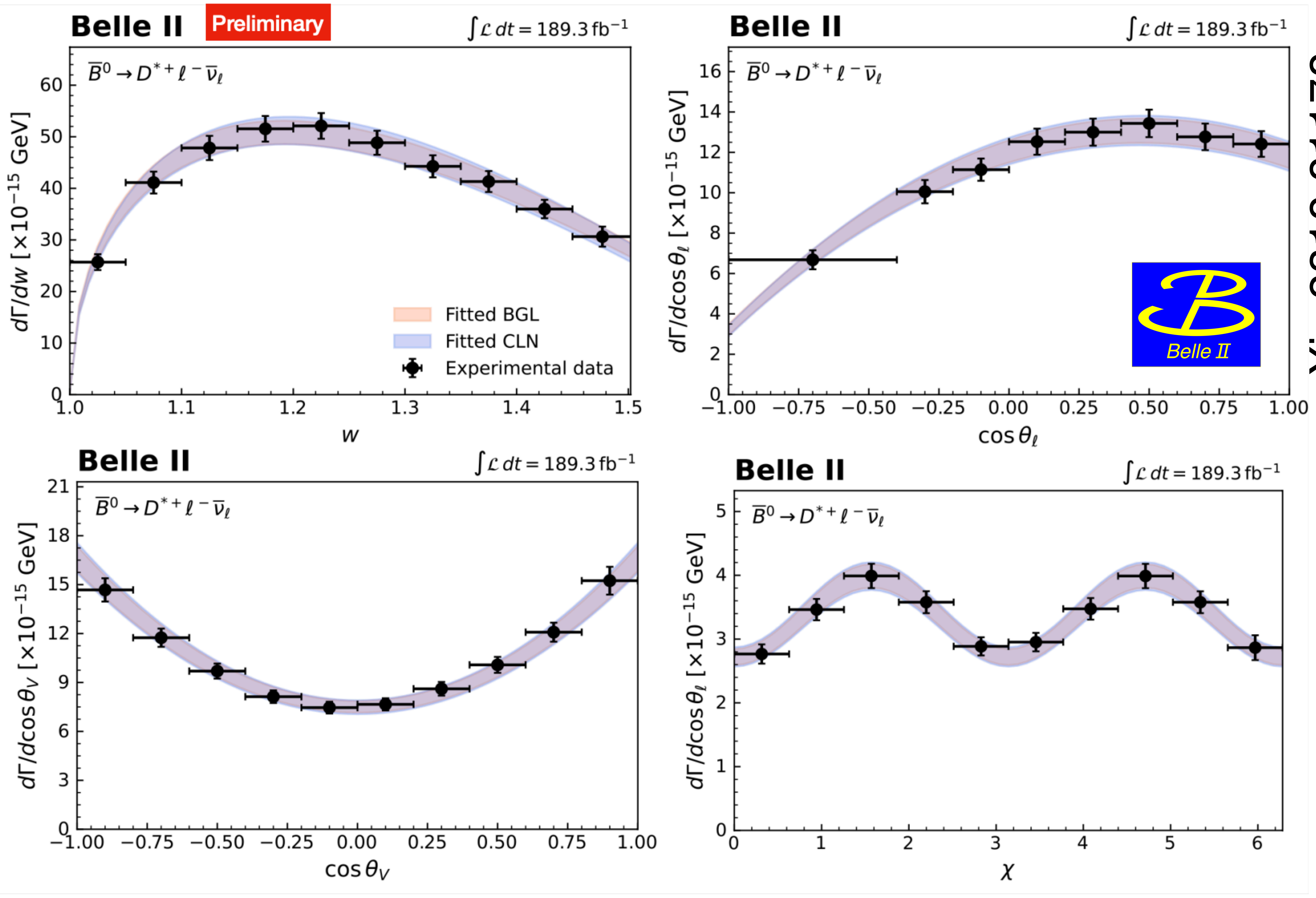
$|V_{cb}|$ from exclusive $B \to D^{*-}\ell^{+}\nu_{\ell}$ untagged (189/fb) at Belle II

New result from Belle II

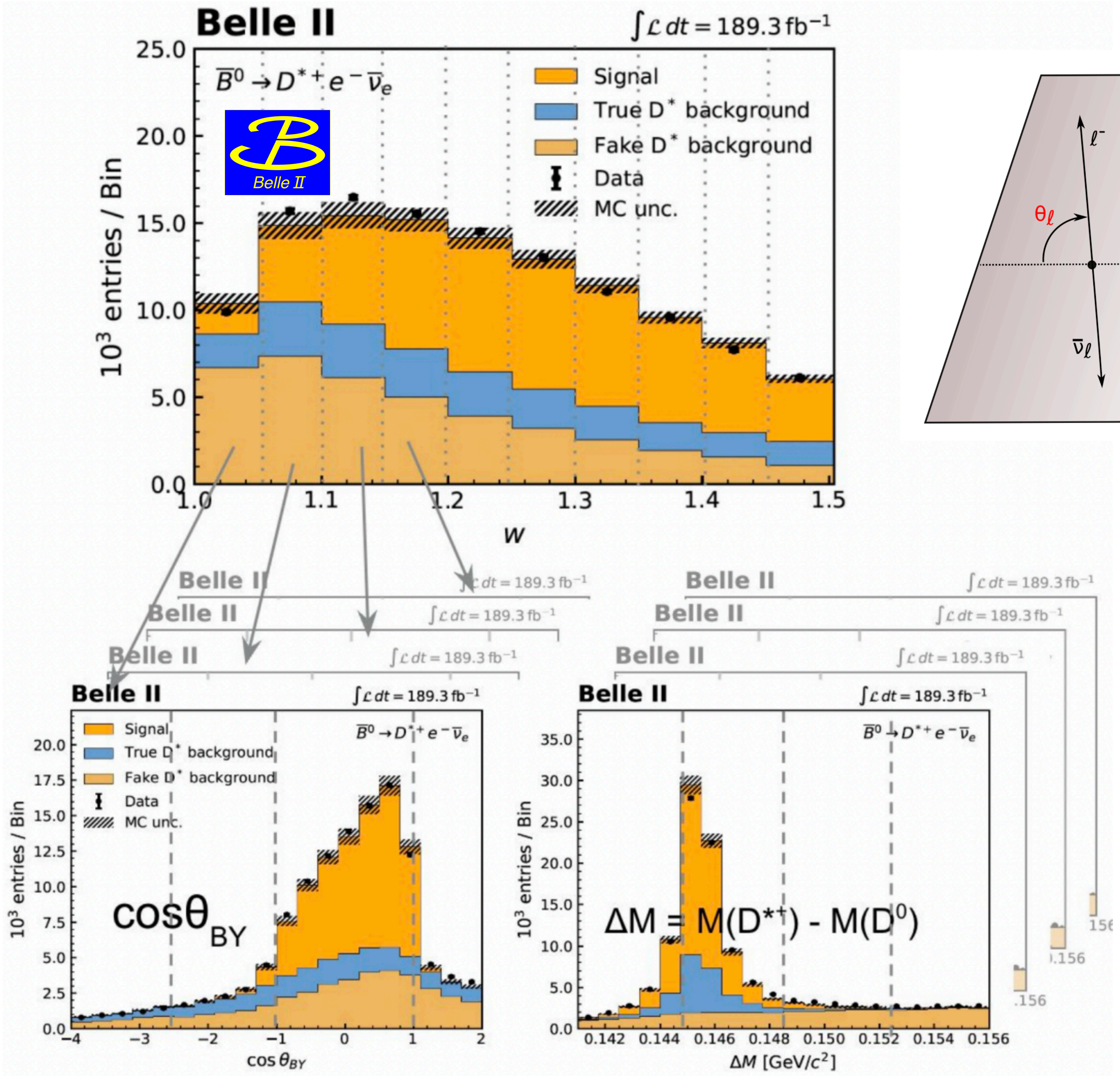
$$w = v_B \cdot v_{D^*}$$

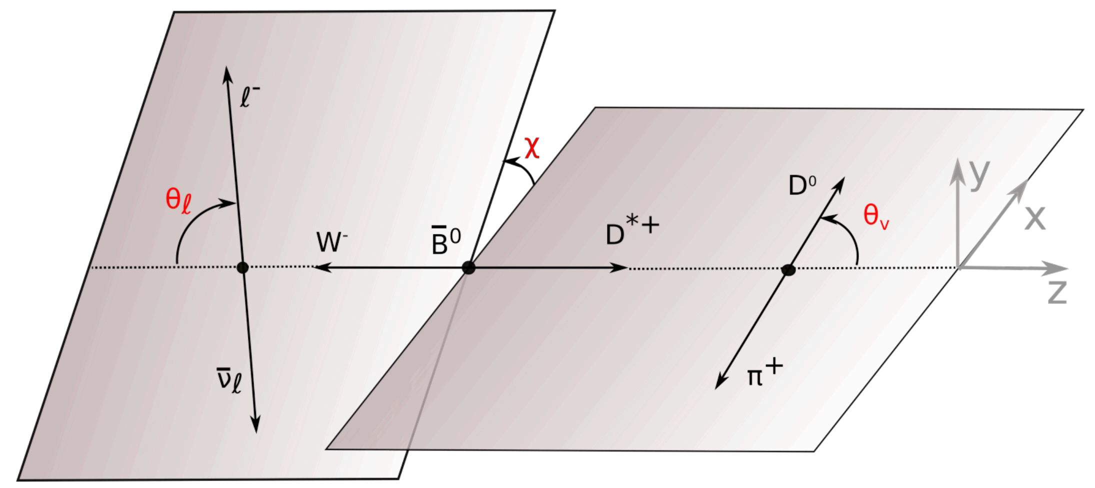
$$\frac{d^4\Gamma}{dw\, d\cos\theta_\ell\, d\cos\theta_V\, d\chi} \propto |V_{cb}|^2 F^2(w, \cos\theta_\ell, \cos\theta_V, \chi)$$

Form factors parameterize the non-perturbative physics



arXiv:2310.01170





$$|V_{cb}|_{\mathrm{BGL}} = (40.57 \pm 0.31 \pm 0.95 \pm 0.58) \times 10^{-3}$$

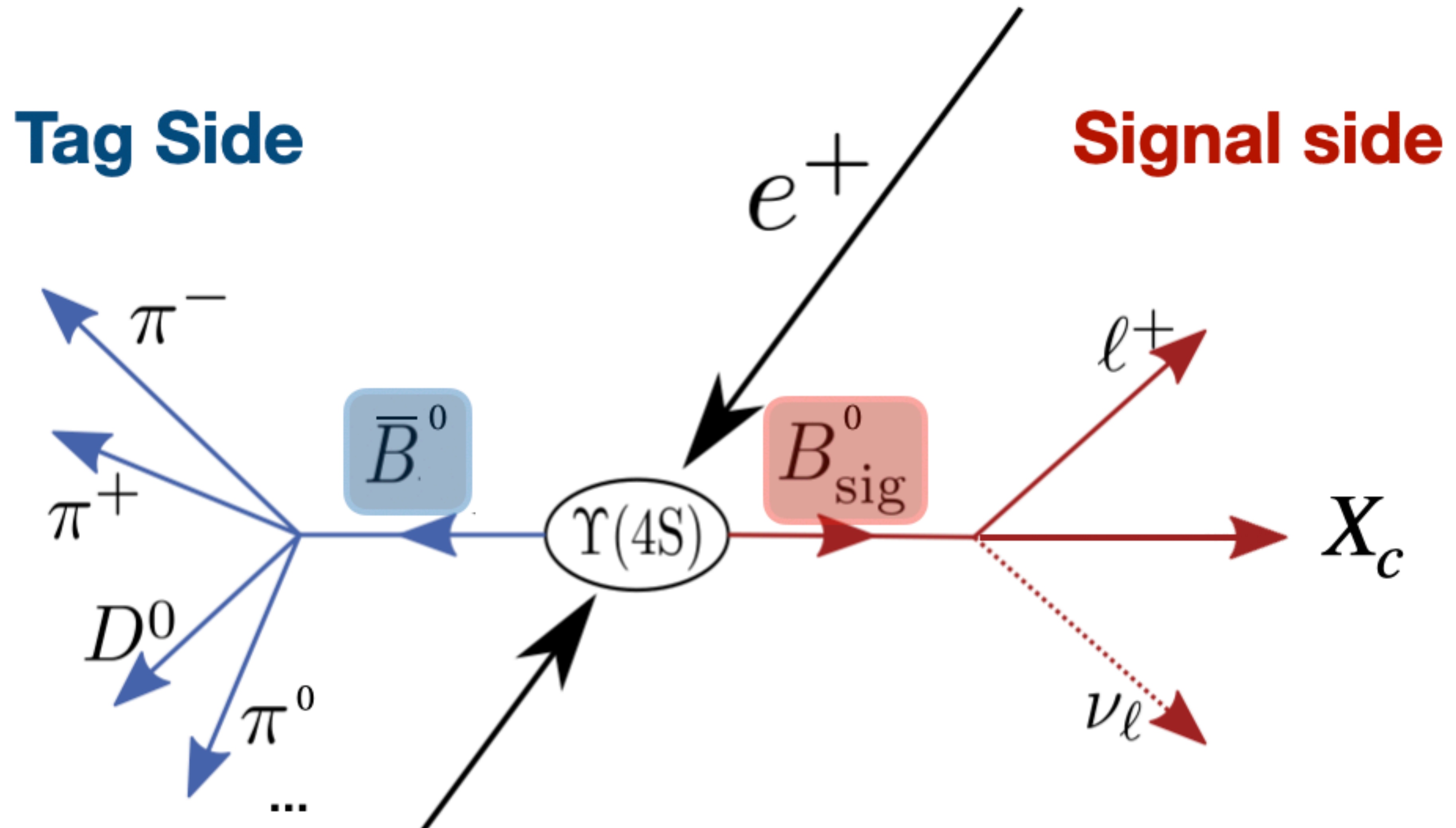
$$|V_{cb}|_{\mathrm{CLN}} = (40.13 \pm 0.27 \pm 0.93 \pm 0.58) \times 10^{-3}$$

In good agreement with WA and recent Belle measurement: PRD 108, 012002 (2023)

q^2 moments from $B \to X_c \ell \nu$ decays

Crucial experimental input for $|V_{cb}|$, HQE parameters

Improved Hadronic Tagging technique using Belle II algorithm (approximately twice better efficiency than Belle)



$$p_{\rm sig} = p_{e^+e^-} - p_{\rm tag}$$

$$q^2 = (p_{sig} - p_{X_c})^2 \qquad M_X = \sqrt{(p_{X_c})_\mu (p_{X_c})^\mu}$$

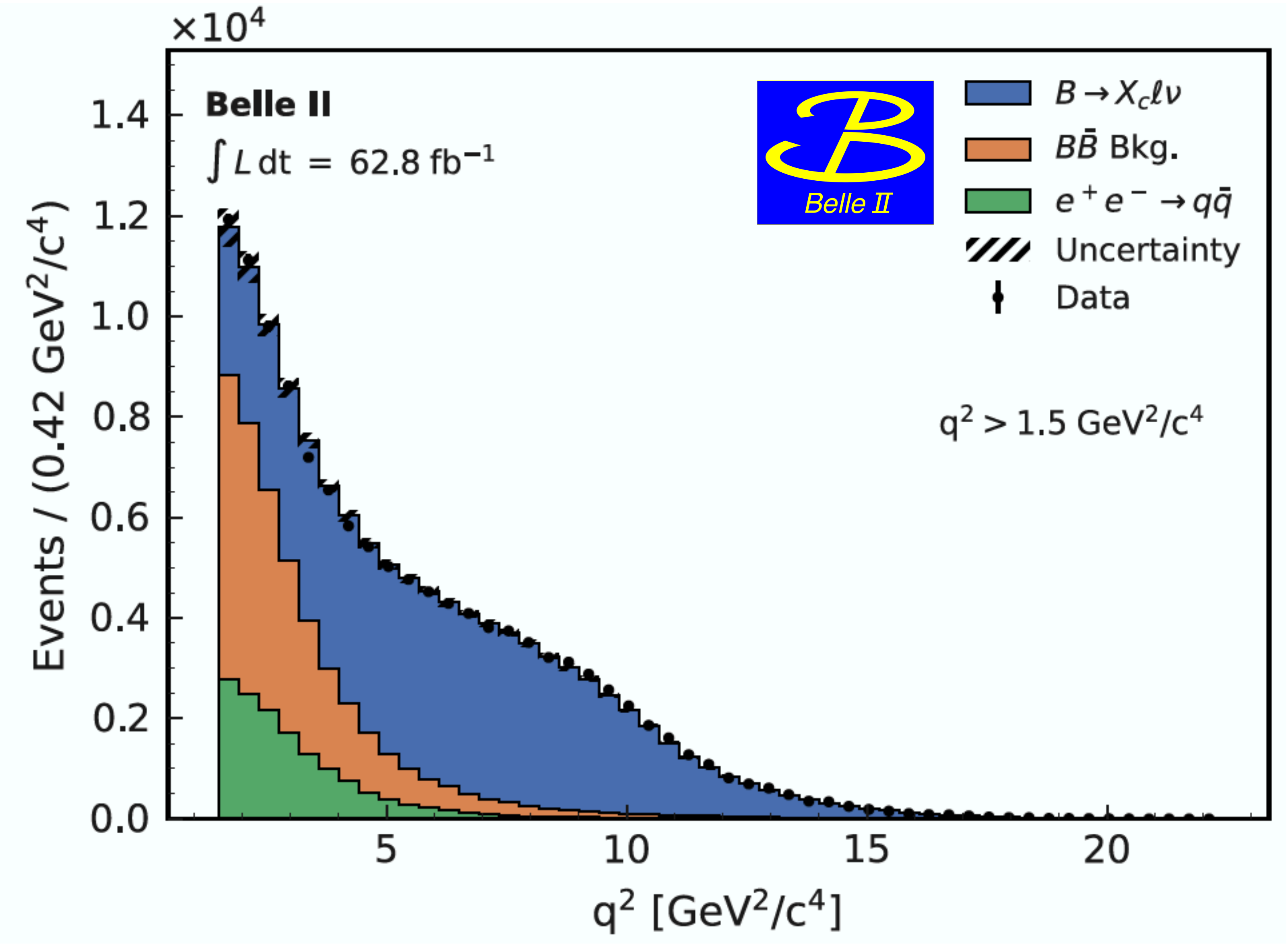
Acceptance corrected

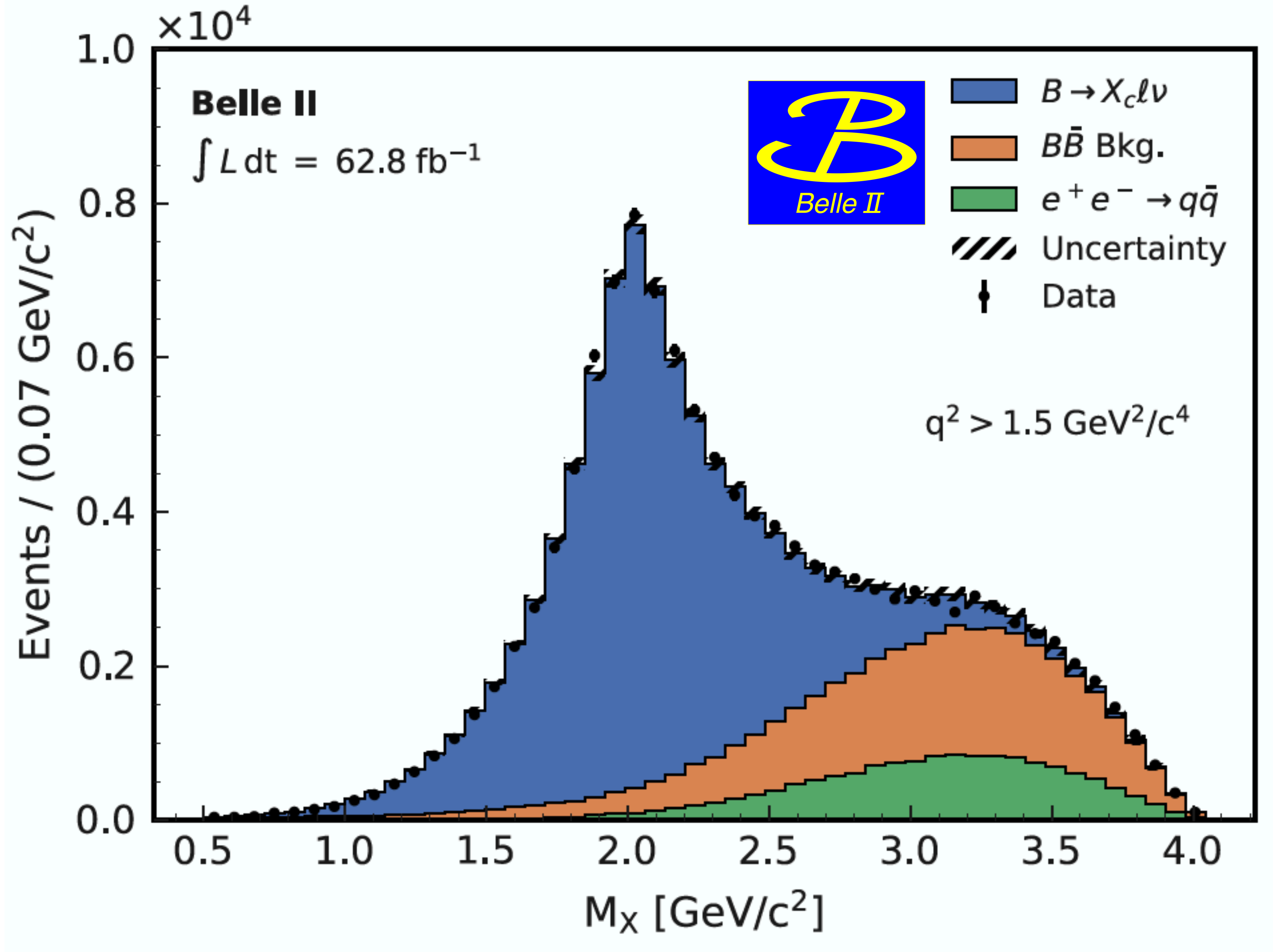
Calibration factors

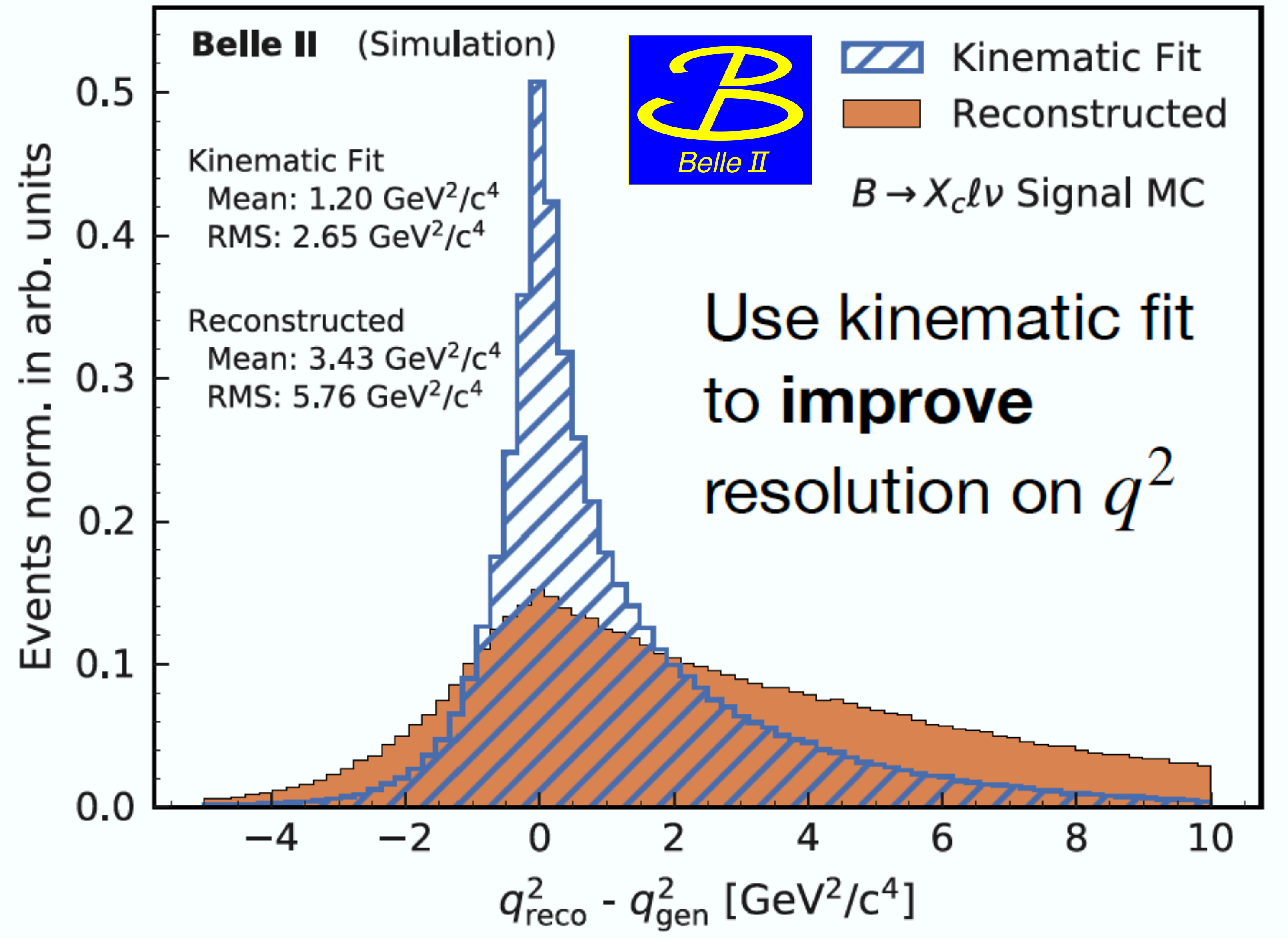
$$\langle q^{2n} \rangle = \frac{\sum_i^{N_{\rm data}} w(q_i^2) \times q^{2n}_{{\rm calib},i}}{\sum_j^{N_{\rm data}} w(q_j^2)} \times \mathcal{C}_{\rm calib} \times \mathcal{C}_{\rm gen}$$

Event-wise signal probability

arXiv:2205.06372



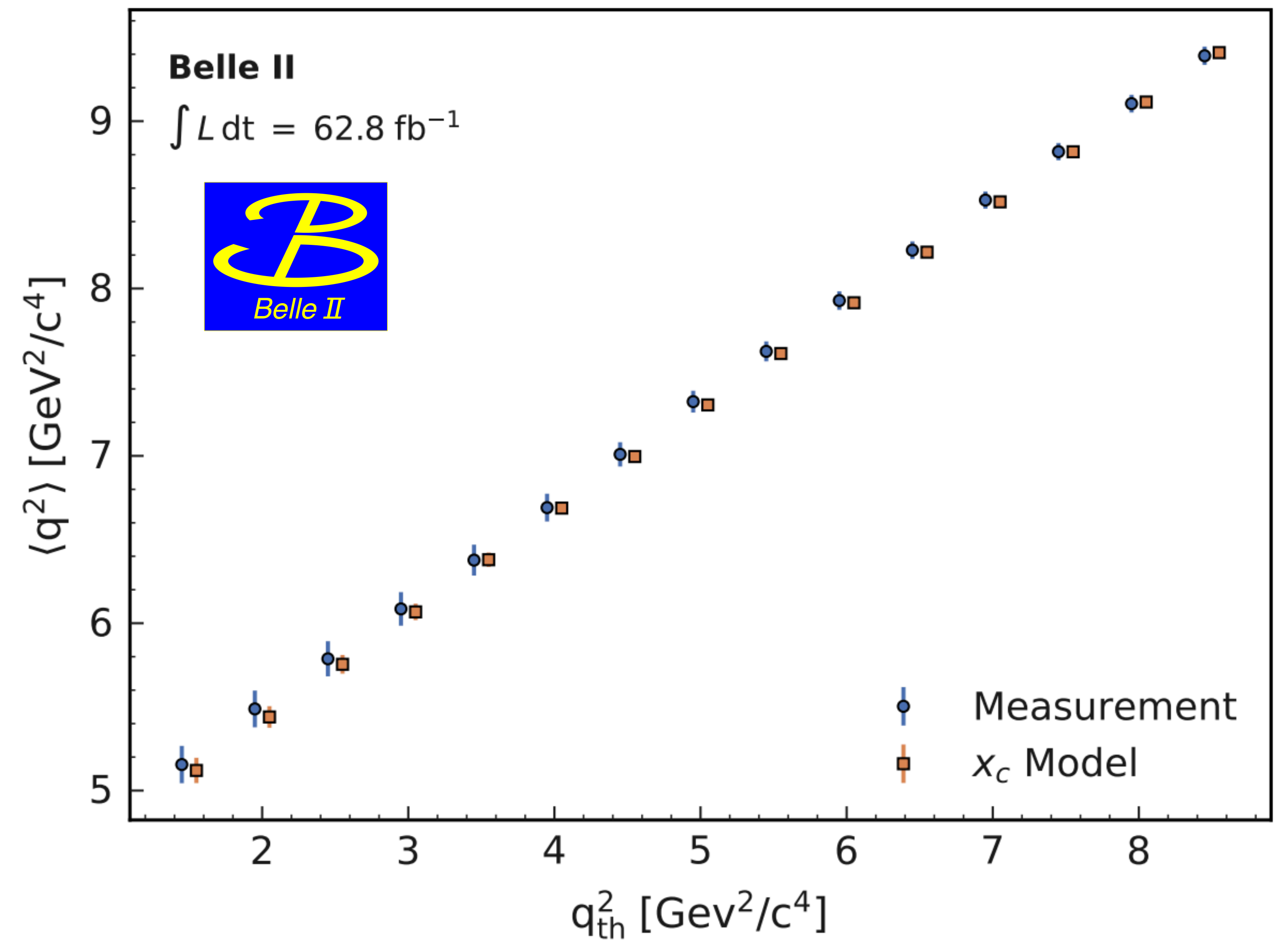


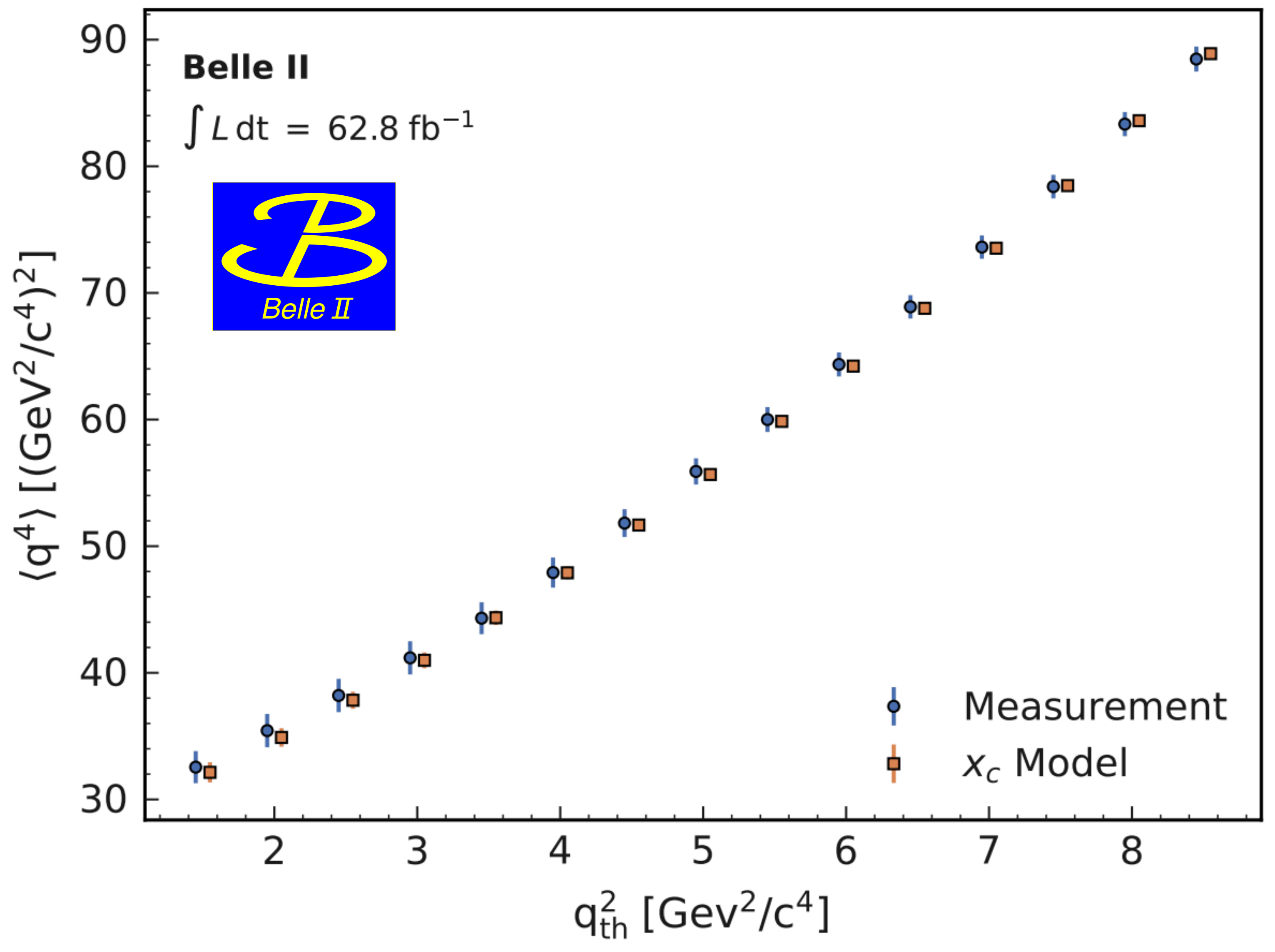


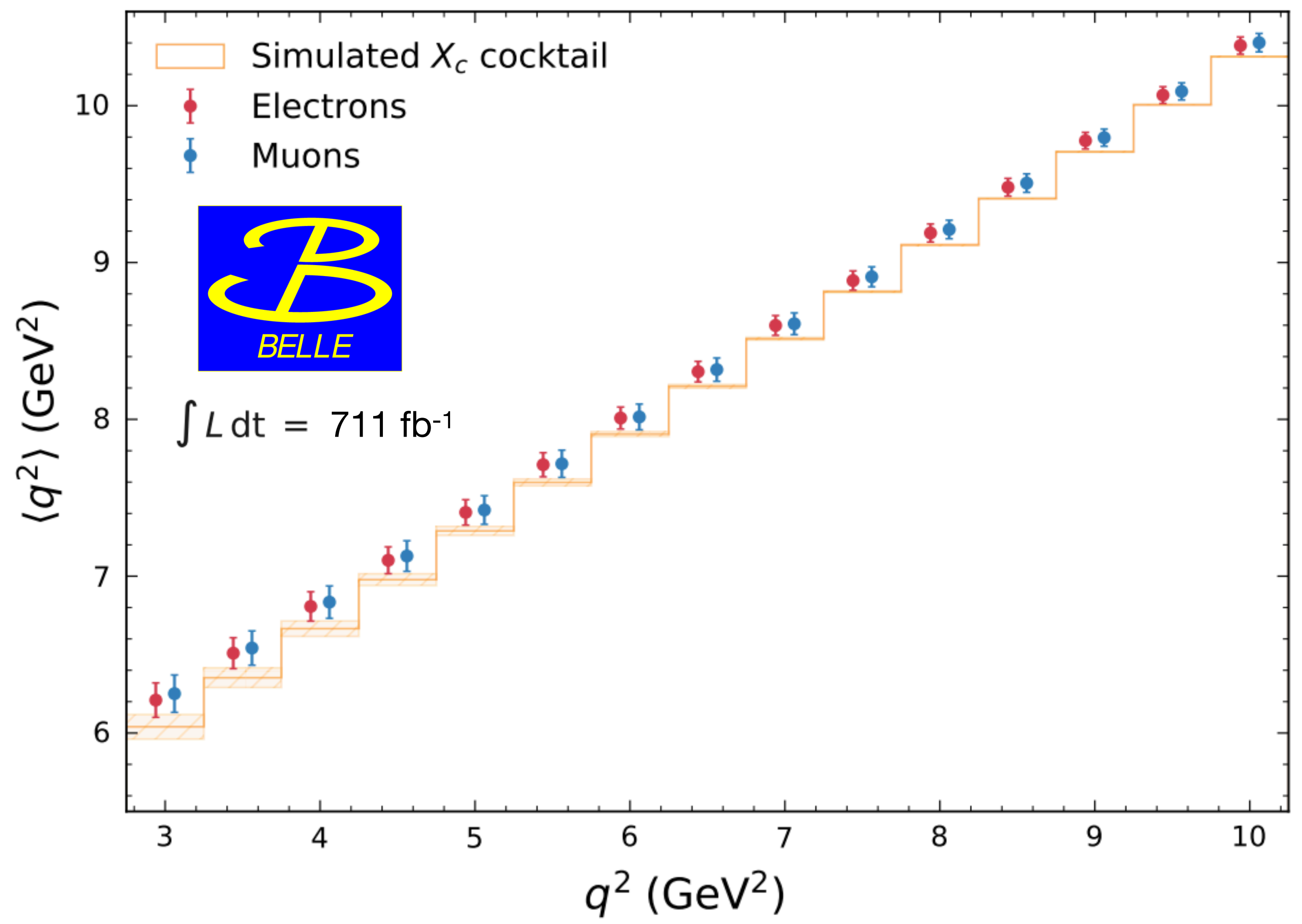
q^2 moments from $B \to X_c \ell \nu$ decays

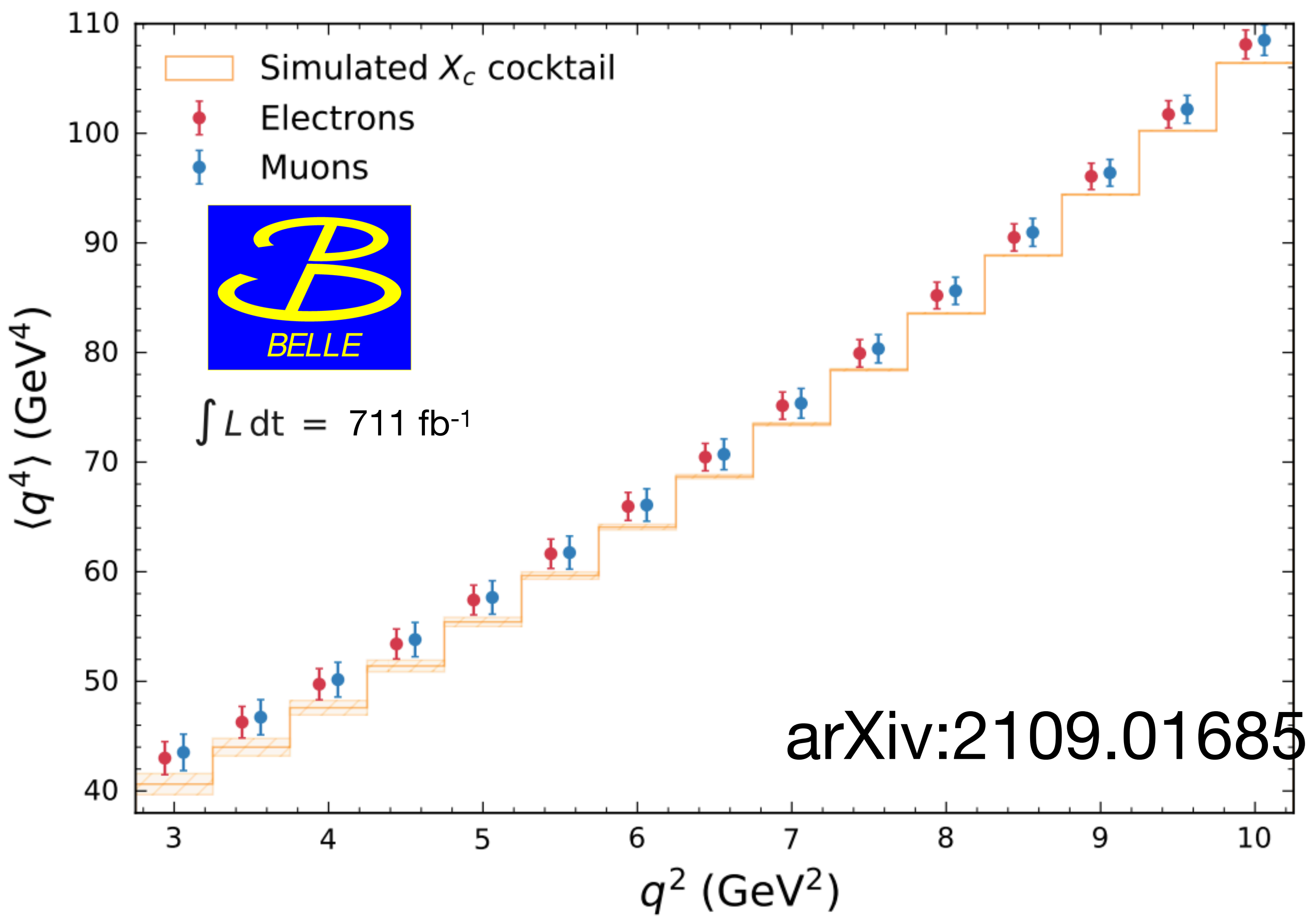
Crucial experimental input for $|V_{cb}|$, HQE parameters

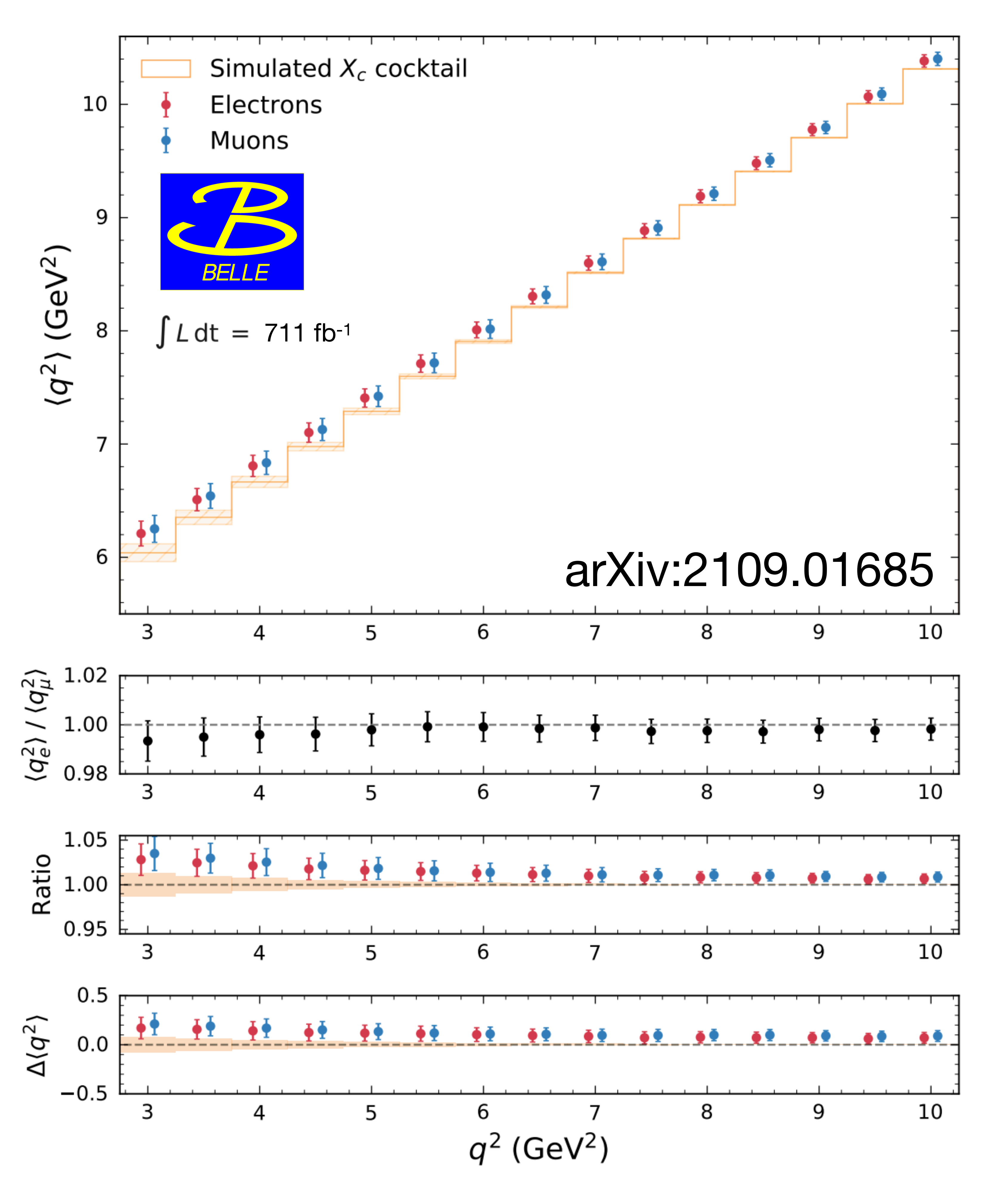
arXiv:2205.06372







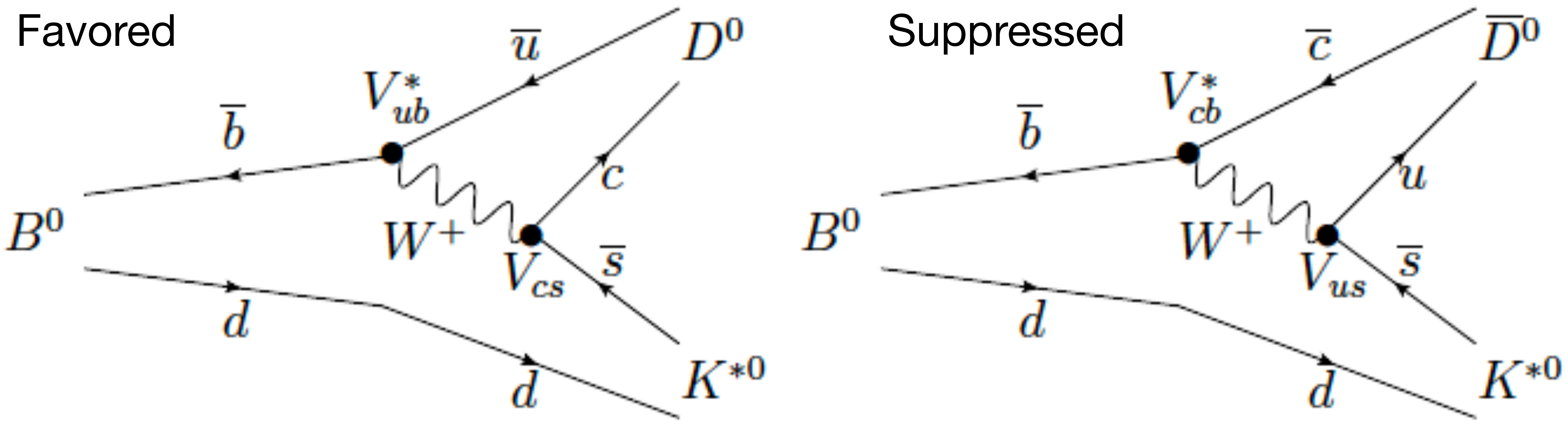




Belle II already reaches similar precision to Belle and can reach lower q^2 threshold

Measuring γ/ϕ_3

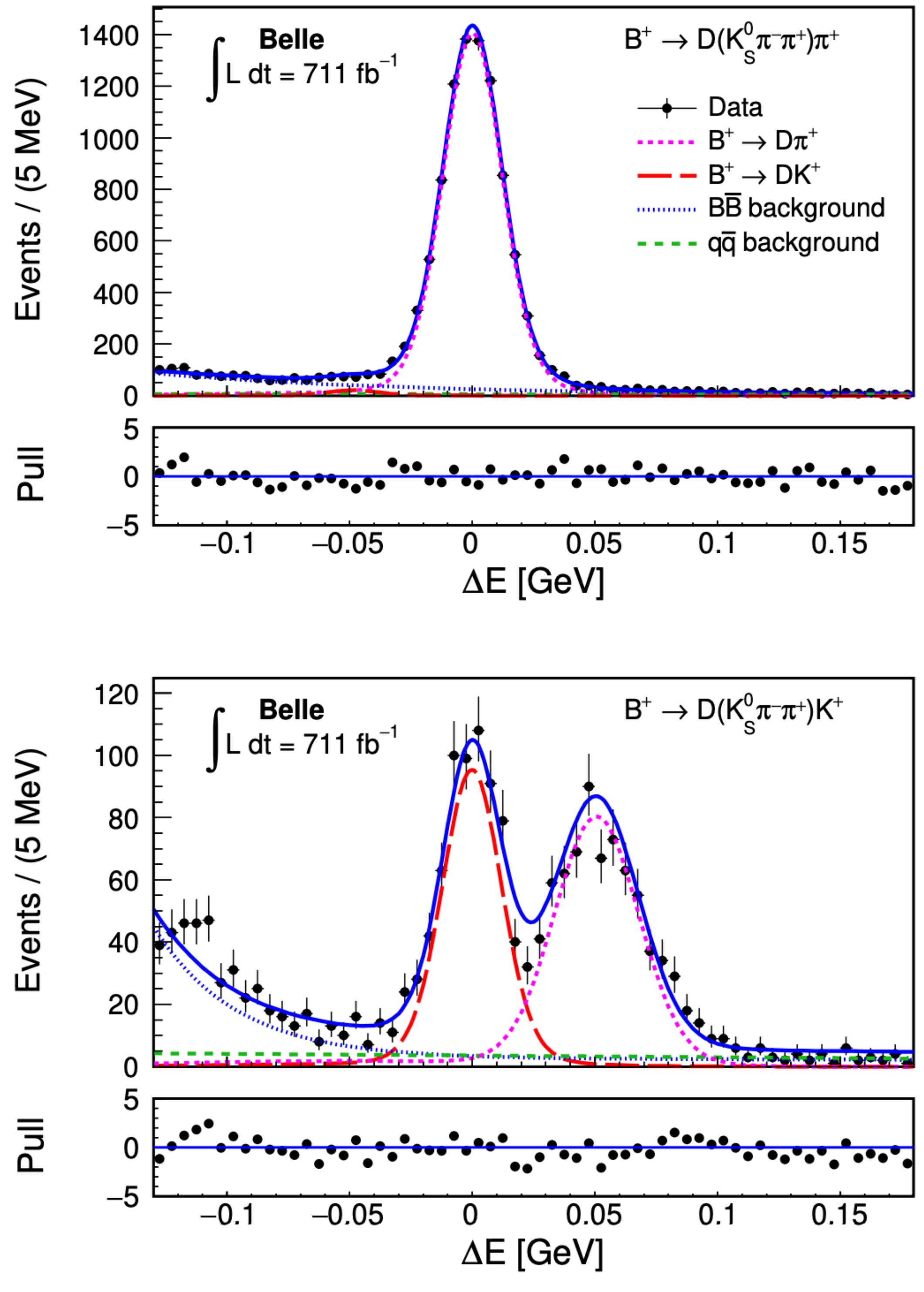
- Angle γ does not depend on CKM elements containing a top quark
  - Can be measured in tree-level B decays (weak phase between $b \to c$ and $b \to u$ transitions)
  - Unlikely to be affected by BSM physics
  - Negligible theoretical uncertainty in SM → benchmark for other determinations involving loop diagrams

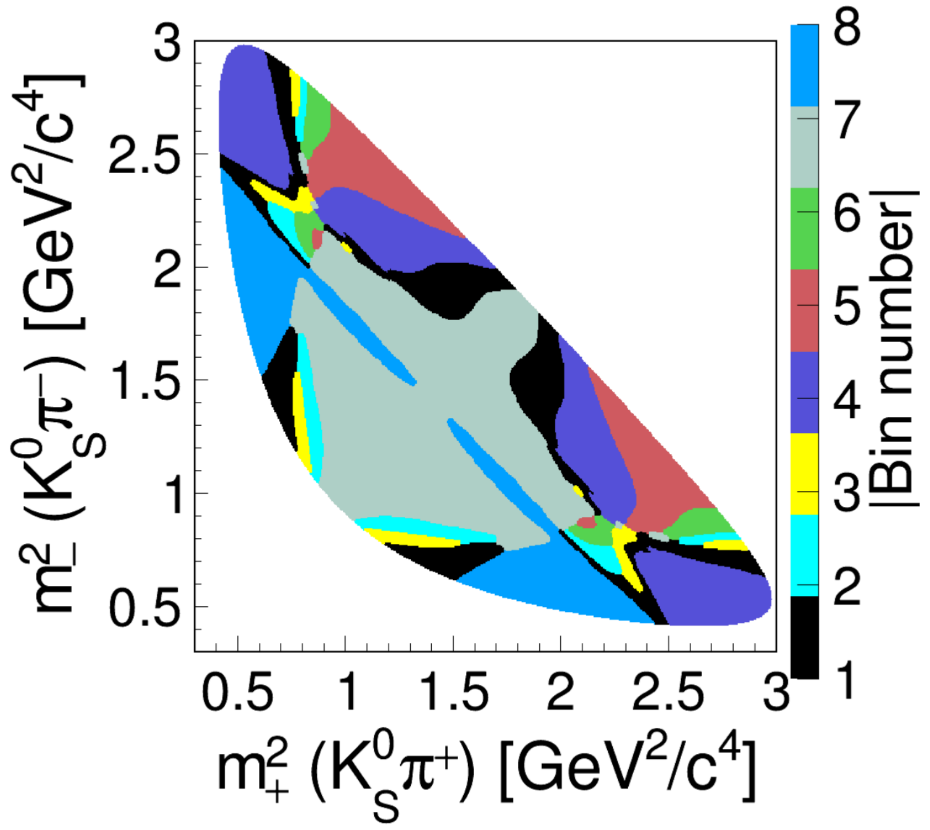


$B^- \to D\pi^-$ has the same dependence on the relative weak phase, γ, but different relative strong phase, δ_B, with $V_{us} \to V_{ud}$, $V_{cs} \to V_{cd}$

$$r_B e^{i(\delta_B \pm \gamma)} = \frac{A_{\text{sup}}}{A_{\text{fav}}}$$

γ measurement in $B^+ \to D(K^0_S h^+ h^-) h^+$ with Belle and Belle II data

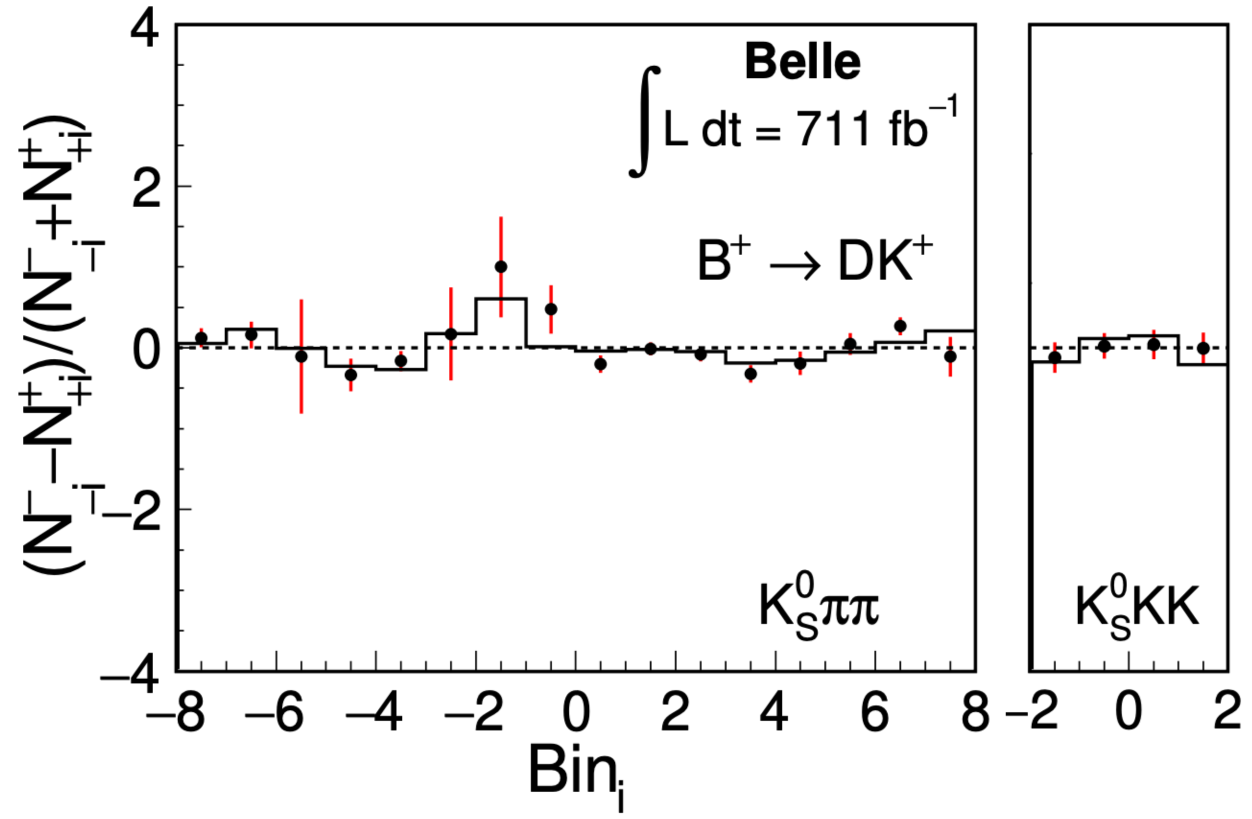


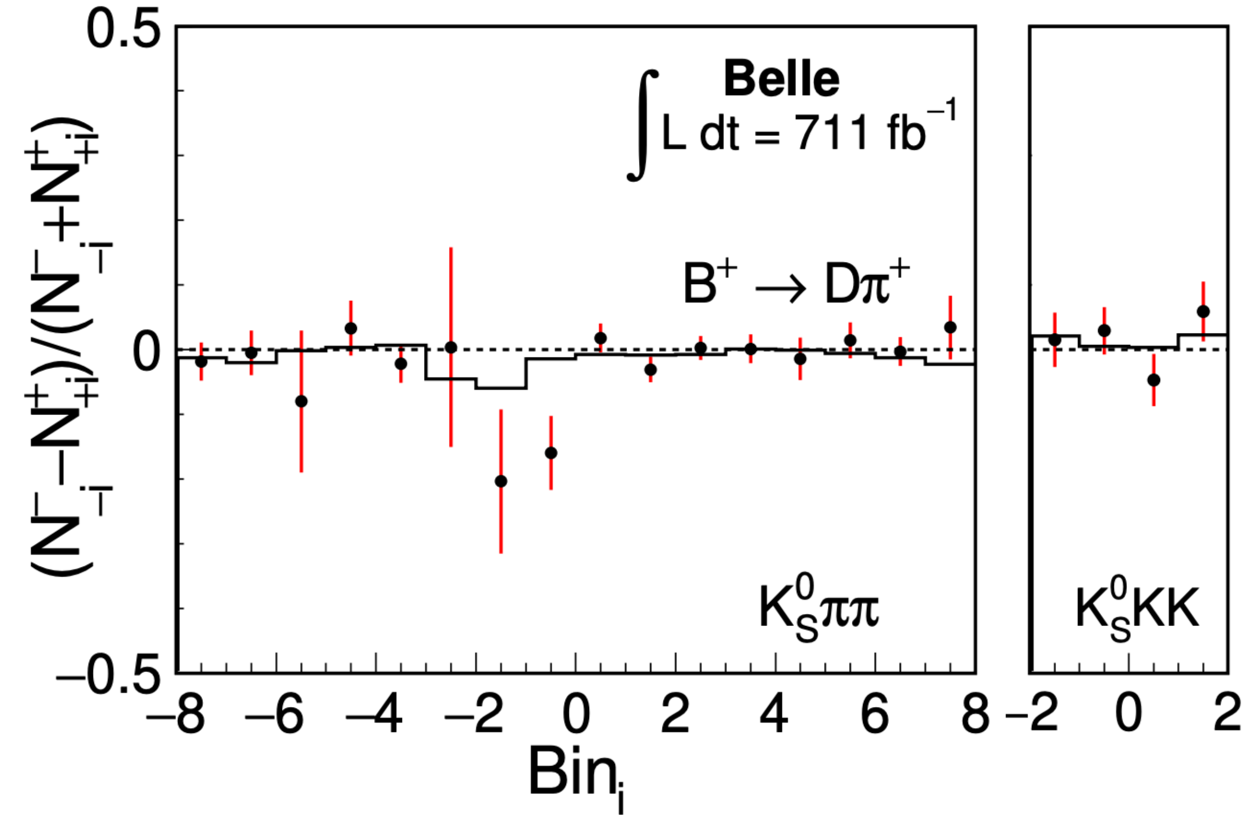


Determine bin-by-bin asymmetries

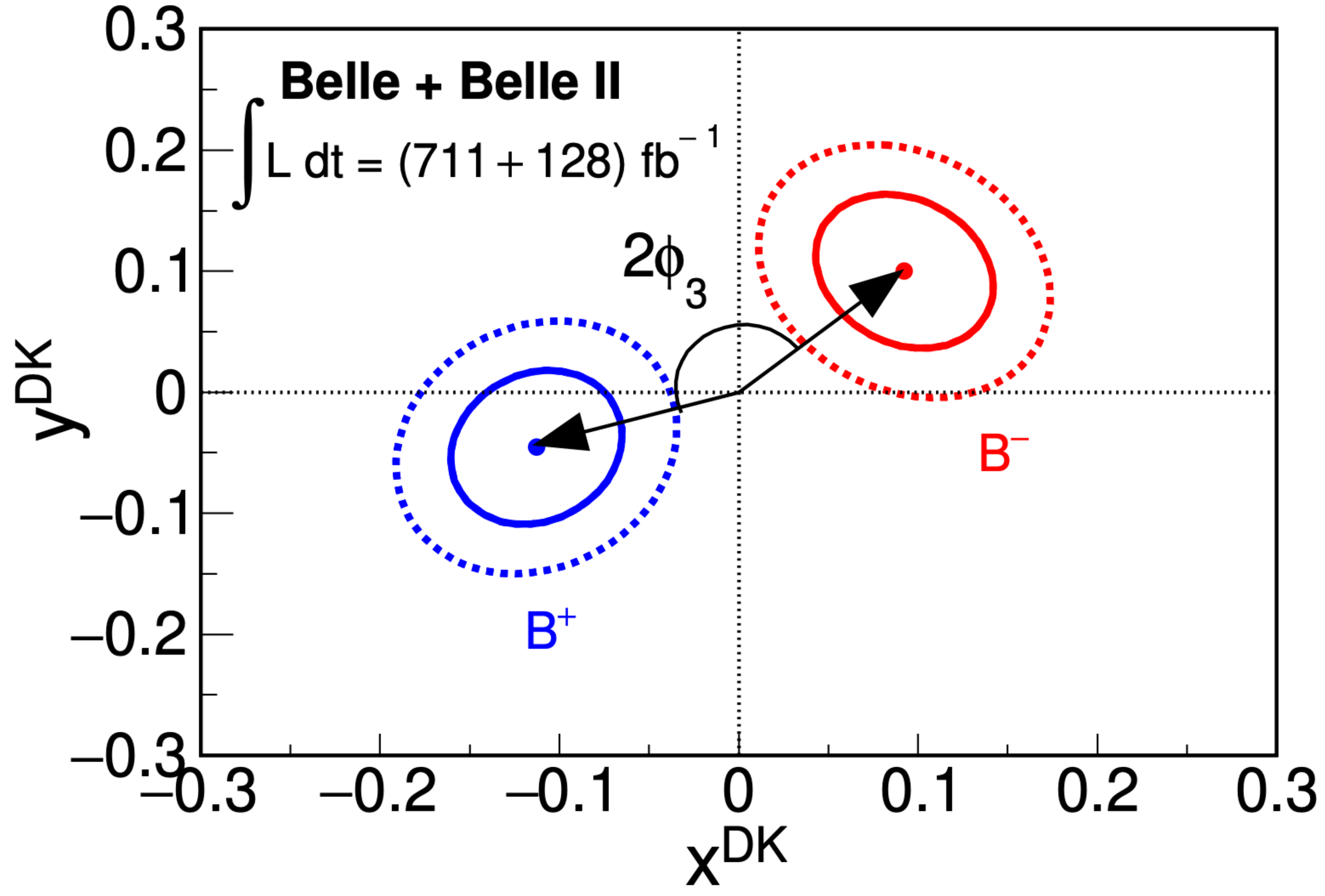
$(N_-^{-i} - N_+^{+i})/(N_-^{-i} + N_+^{+i})$

in each Dalitz plot bin i





$$x_\pm^{DK} = r_B^{DK}\cos(\delta_B^{DK} \pm \phi_3)$$
$$y_\pm^{DK} = r_B^{DK}\sin(\delta_B^{DK} \pm \phi_3)$$



$$\phi_3 = (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ\,,$$
$$r_B^{DK} = 0.129 \pm 0.024 \pm 0.001 \pm 0.002,$$
$$\delta_B^{DK} = (124.8 \pm 12.9 \pm 0.5 \pm 1.7)^\circ\,,$$
$$r_B^{D\pi} = 0.017 \pm 0.006 \pm 0.001 \pm 0.001,$$
$$\delta_B^{D\pi} = (341.0 \pm 17.0 \pm 1.2 \pm 2.6)^\circ\,.$$

Measurement of $B^\pm \to D_{CP\pm} K^\pm$ with Belle and Belle II data

- Simultaneous fit to $B^\pm \to D K^\pm$ and $B^\pm \to D\pi^\pm$ with D decays to CP eigenstates

$$\mathcal{R}_{CP\pm} \equiv \frac{\mathcal{B}(B^- \to D_{CP\pm}K^-) + \mathcal{B}(B^+ \to D_{CP\pm}K^+)}{(\mathcal{B}(B^- \to D_{\text{flav}}K^-) + \mathcal{B}(B^+ \to \overline{D}_{\text{flav}}K^+))/2}$$

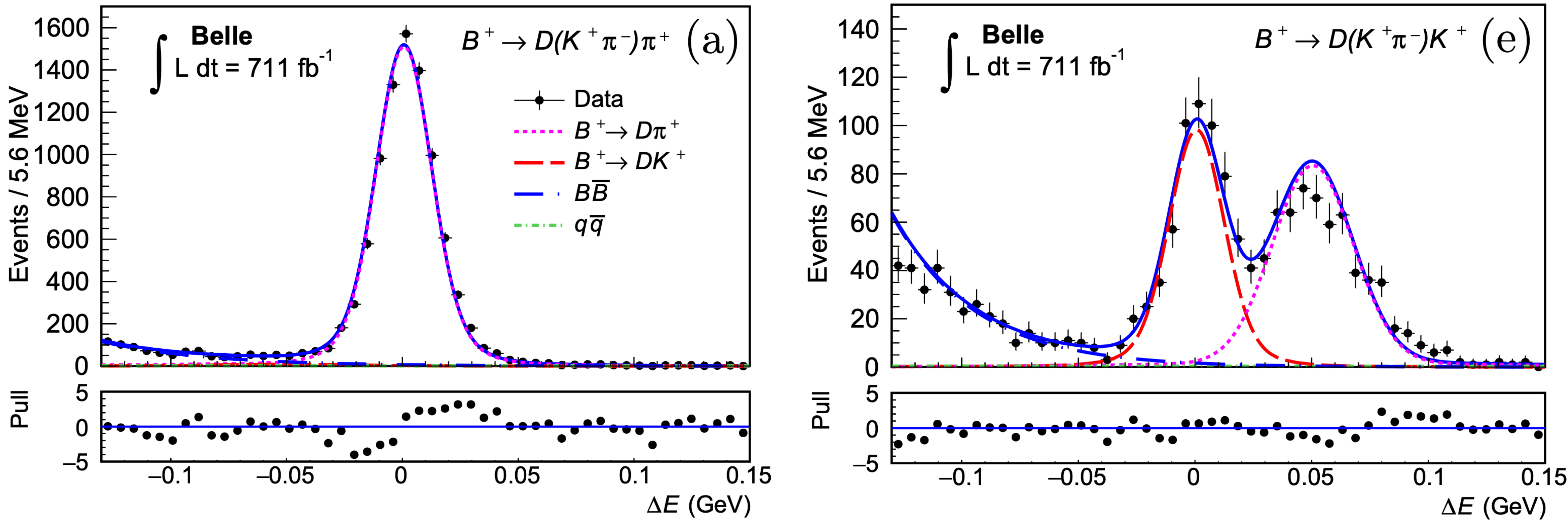
$$\mathcal{A}_{CP\pm} \equiv \frac{\mathcal{B}(B^- \to D_{CP\pm}K^-) - \mathcal{B}(B^+ \to D_{CP\pm}K^+)}{\mathcal{B}(B^- \to D_{CP\pm}K^-) + \mathcal{B}(B^+ \to D_{CP\pm}K^+)}$$

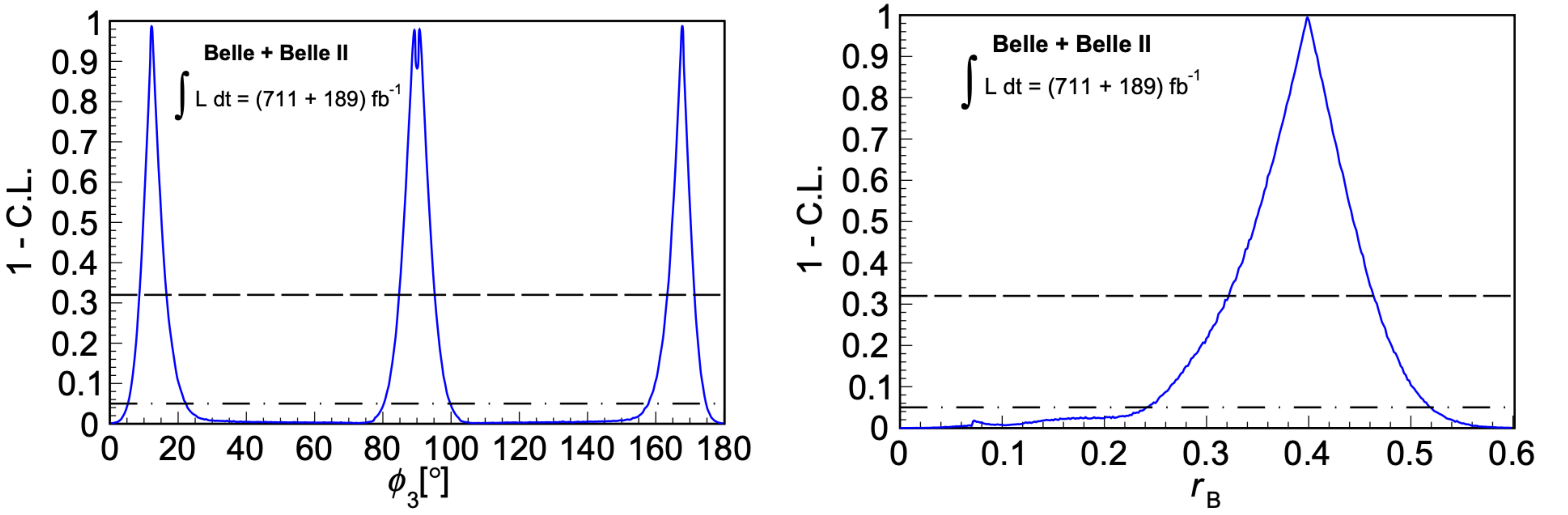
$$\mathcal{R}_{CP\pm} \approx \frac{R_{CP\pm}}{R_{\text{flav}}}$$

$$\mathcal{R}_{CP\pm} = 1 + r_B^2 \pm 2r_B \cos\delta_B \cos\phi_3$$

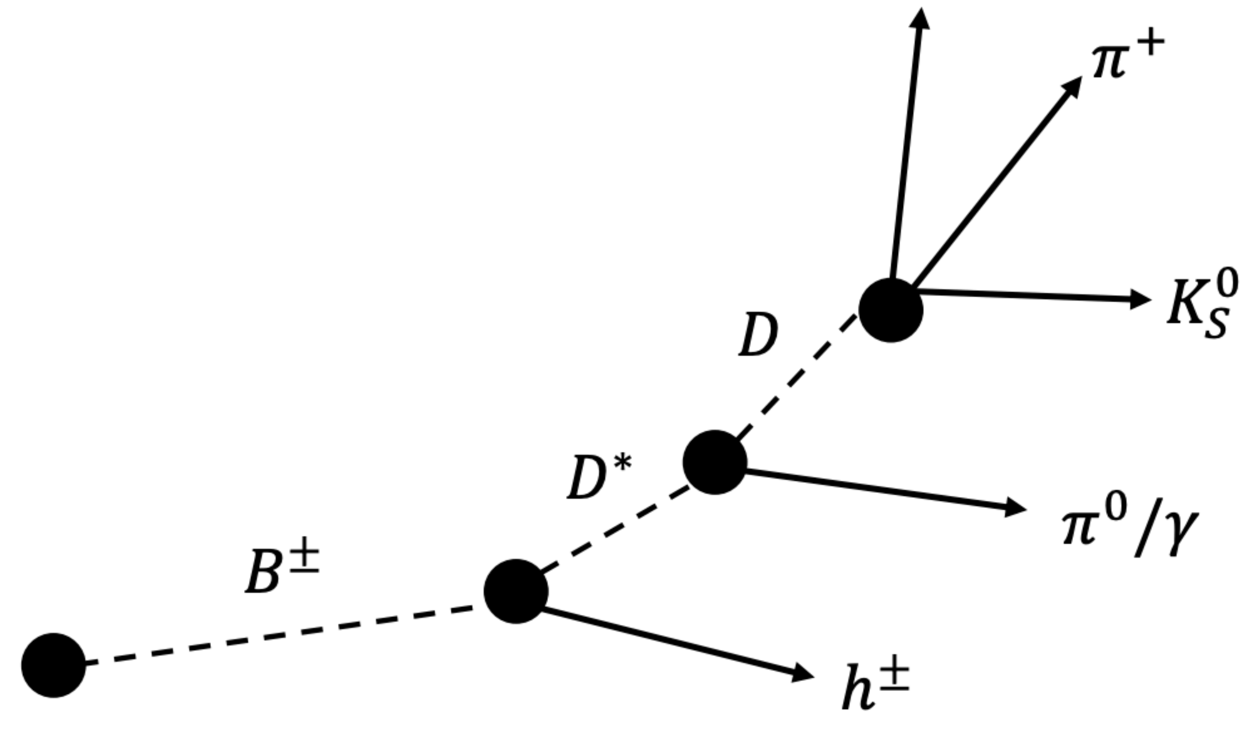
$$\mathcal{A}_{CP\pm} = \pm 2r_B \sin\delta_B \sin\phi_3 \,/\, \mathcal{R}_{CP\pm}$$

	68.3% CL	95.4% CL
ϕ_3 (°)	[8.5, 16.5]	[5.0, 22.0]
	[84.5, 95.5]	[80.0, 100.0]
	[163.3, 171.5]	[157.5, 175.0]
r_B	[0.321, 0.465]	[0.241, 0.522]





Measuring γ using $B^{\pm} \to D^{*}K^{\pm}$ decays at LHCb

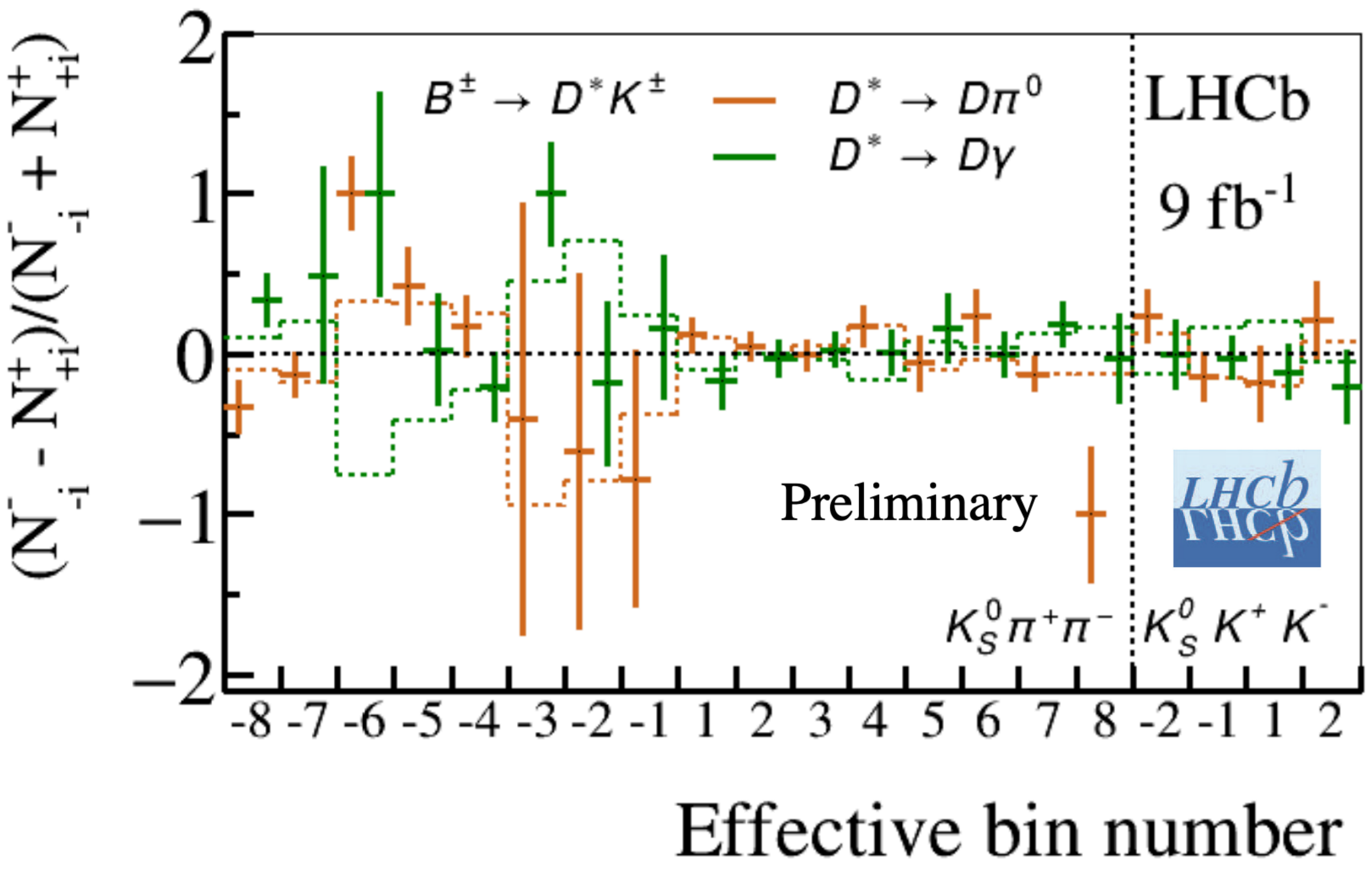


Can reconstruct neutral (π^0, γ)

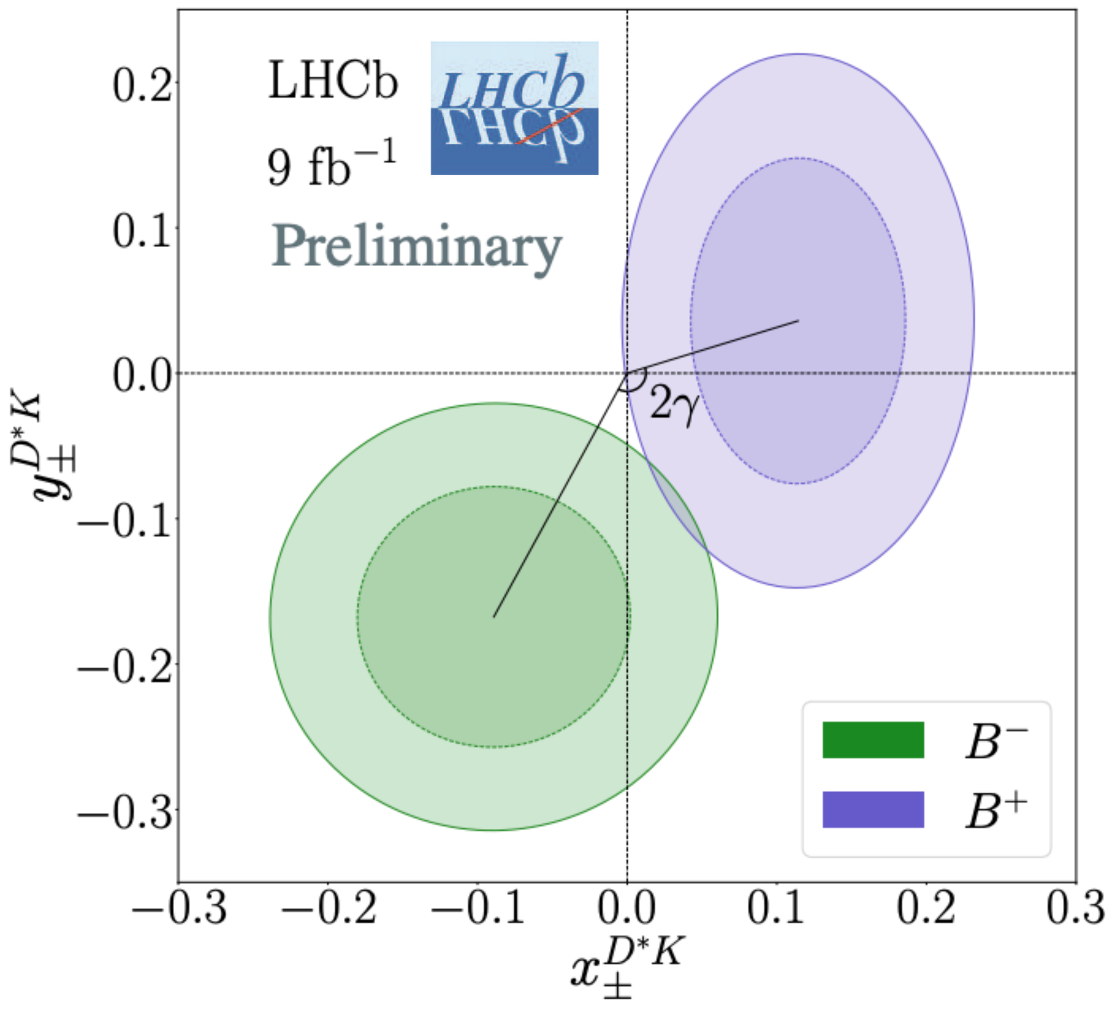
or not

$CP(\pi^0) = -1$ & $CP(\gamma) = 1$

Introduces phase shift of $\pi \to \mathcal{A}(\pi^0) = -\mathcal{A}(\gamma)$



Fully reconstructed

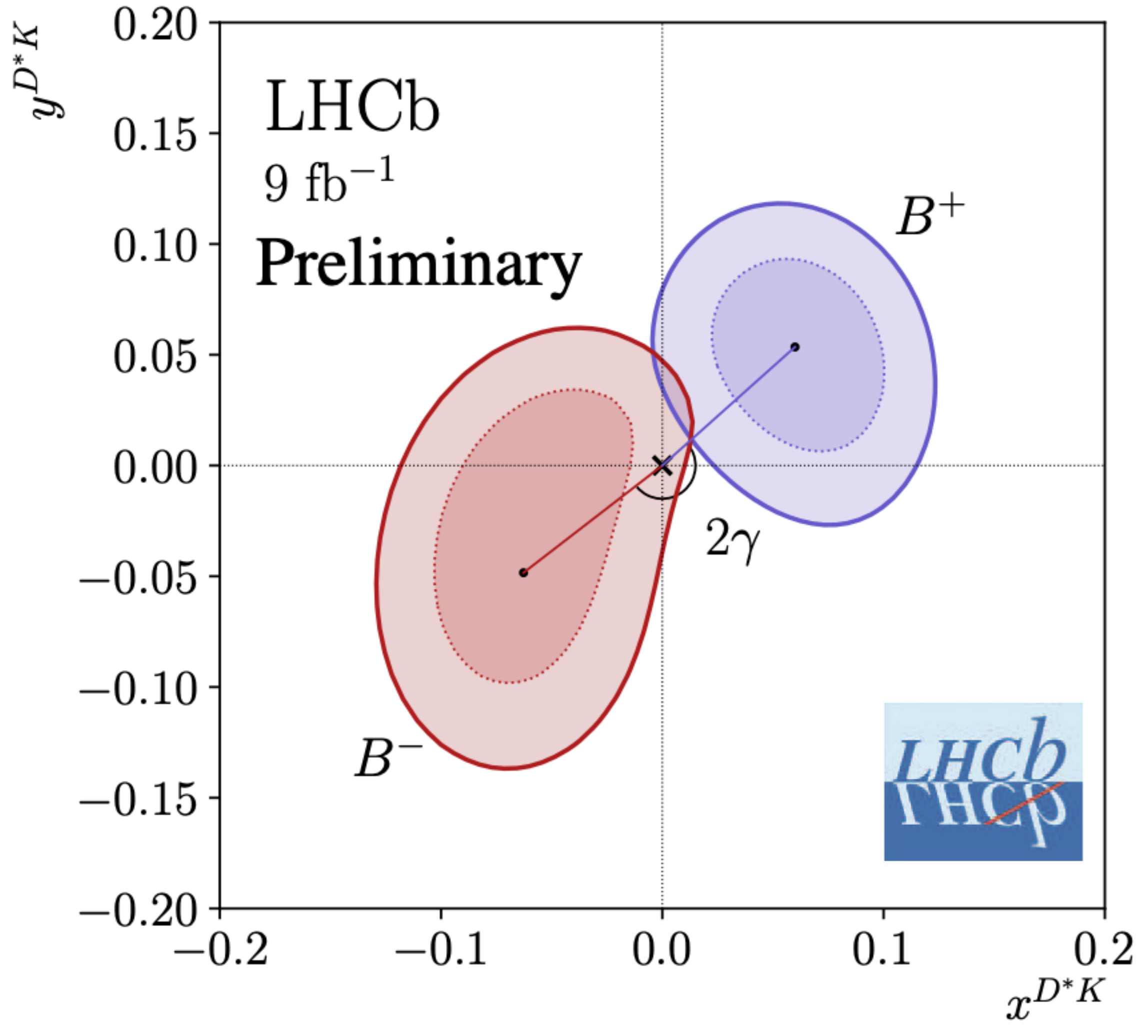


$$\gamma = (69^{+13}_{-14})^{\circ}$$

$$r_B^{D^*K} = 0.15 \pm 0.03$$

$$\delta_B^{D^*K} = (311 \pm 15)^{\circ}$$

Partially reconstructed



$$\gamma = (92^{+21}_{-17})^{\circ}$$

$$r_B^{D^*K} = 0.080^{+0.022}_{-0.023}$$

$$\delta_B^{D^*K} = \left(310^{+15}_{-20}\right)^{\circ}$$

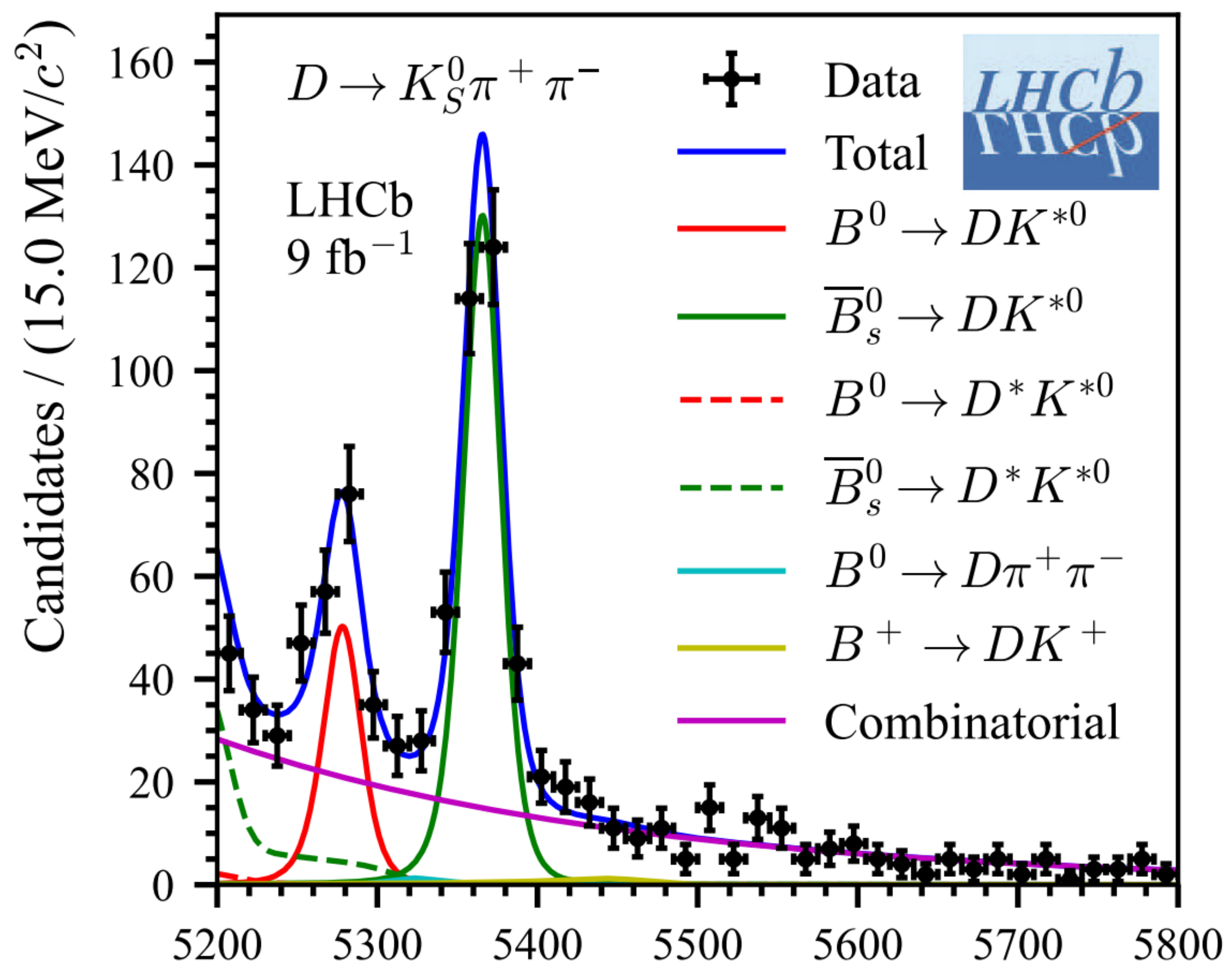
Direct measurements of γ with multibody D-decays at LHCb

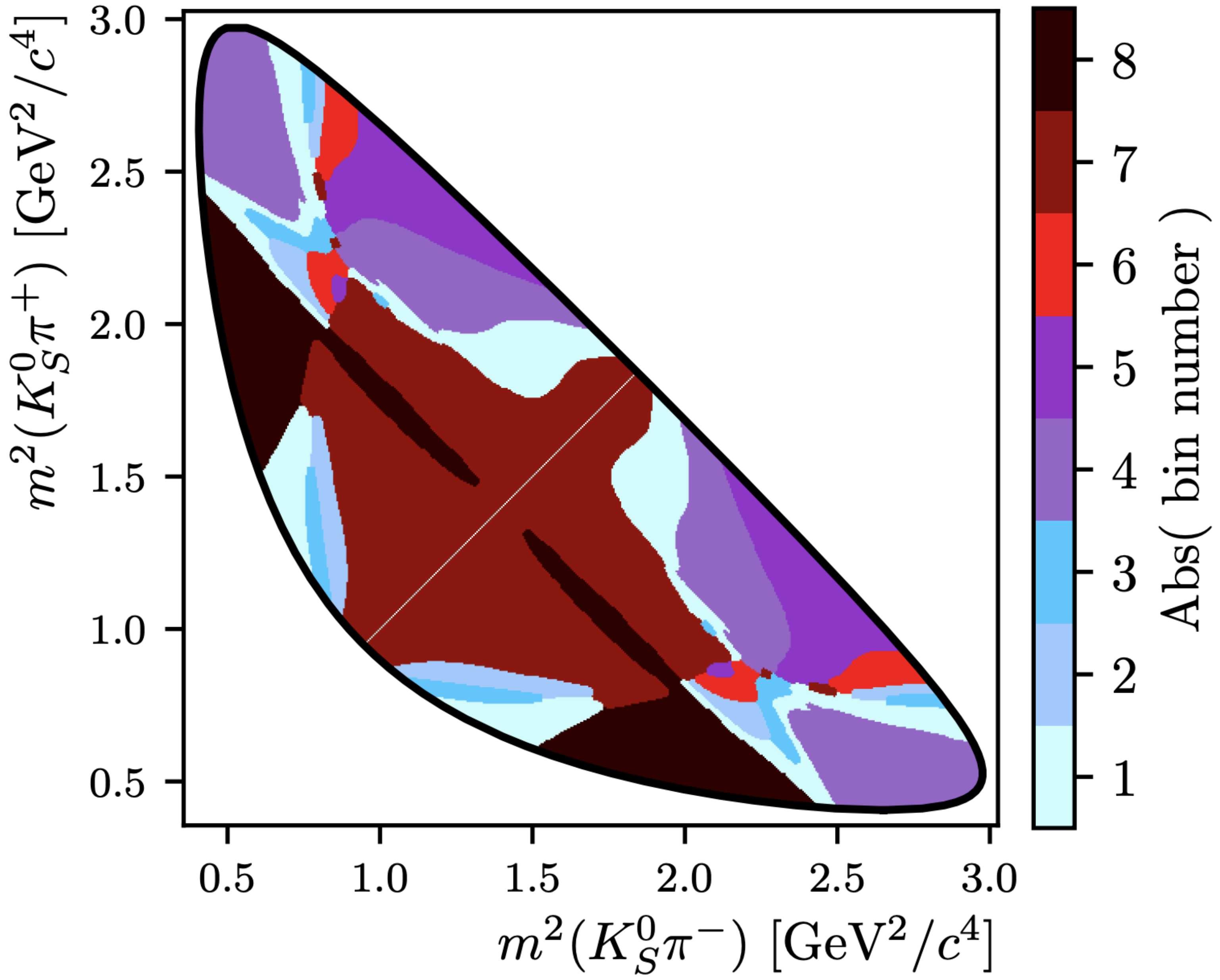
Breaks degeneracy in ADS and GLW-like decays

arxiv:2309.05514

- Intermediate resonances introduce phase-space dependence on the D-decay amplitudes
- Self-conjugate $D \to K_S^0 h^+ h^-$ modes described by Dalitz plots
- Measurement requires D-decay strong-phase information as input

$$|A(B^-)|^2(\boldsymbol{x}) \propto 1 + r_B^2 + 2 r_B r_D(\boldsymbol{x}) \cos(\delta_B - \gamma + \delta_D(\boldsymbol{x}))$$





Binning schemes chosen to optimize sensitivity to γ (isolate regions with similar δ_D)

Branching fractions lower than in $B^\pm \to DK^\pm$, but interference is larger ($r_{B^0} \approx 3 r_{B^\pm}$)

$$\gamma = (49^{+23}_{-18})^\circ$$