CP violation in B mesons

Daniele Manuzzi on behalf of the LHCb collaboration,
with results from Belle and Belle II collaborations

May 23/27, 2022, FPCP 2022

Today

- Introduction

- Recent results by LHCb, Belle and Belle II
    - Measurements of CKM phase $\gamma \equiv \phi_3$
    - Update on $B \to K\pi$ puzzle
    - $\not{C}\not{P}$ in B decays to charmless resonances and multi-body final states

- Some prospects

Generalities

- The matter-antimatter asymmetry of the universe requires $\cancel{CP}$ sources not predicted by the Standard Model
- $\cancel{CP}$ manifests due to interference of quantum processes

Where do we observe $\cancel{CP}$ phenomena?

✓ Observed
✓✓ Several observations
✗ Not observed (yet)
⊖ Not expected

$\cancel{CP}$ category	Hadronic system										
	K^0	$K^\pm$	Λ	D^0	$D^\pm$	$D_s^\pm$	Λ_c^+	B^0	$B^\pm$	B_s^0	Λ_b^0
decay	✓	✗	✗	✓	✗	✗	✗	✓✓	✓✓	✓	✗
mixing	✓✓	⊖	⊖	✗	⊖	⊖	⊖	✗	⊖	✗	⊖
decay/mixing interf.	✓	⊖	⊖	✗	⊖	⊖	⊖	✓✓	⊖	✓	⊖

a lot of work already done, and still to do

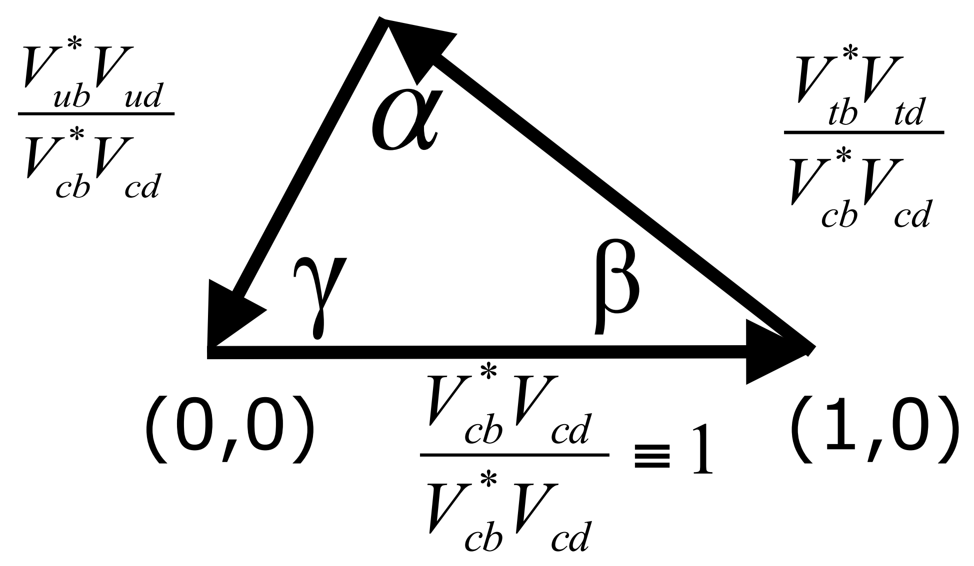
→ **Several SM consistency checks are available!**

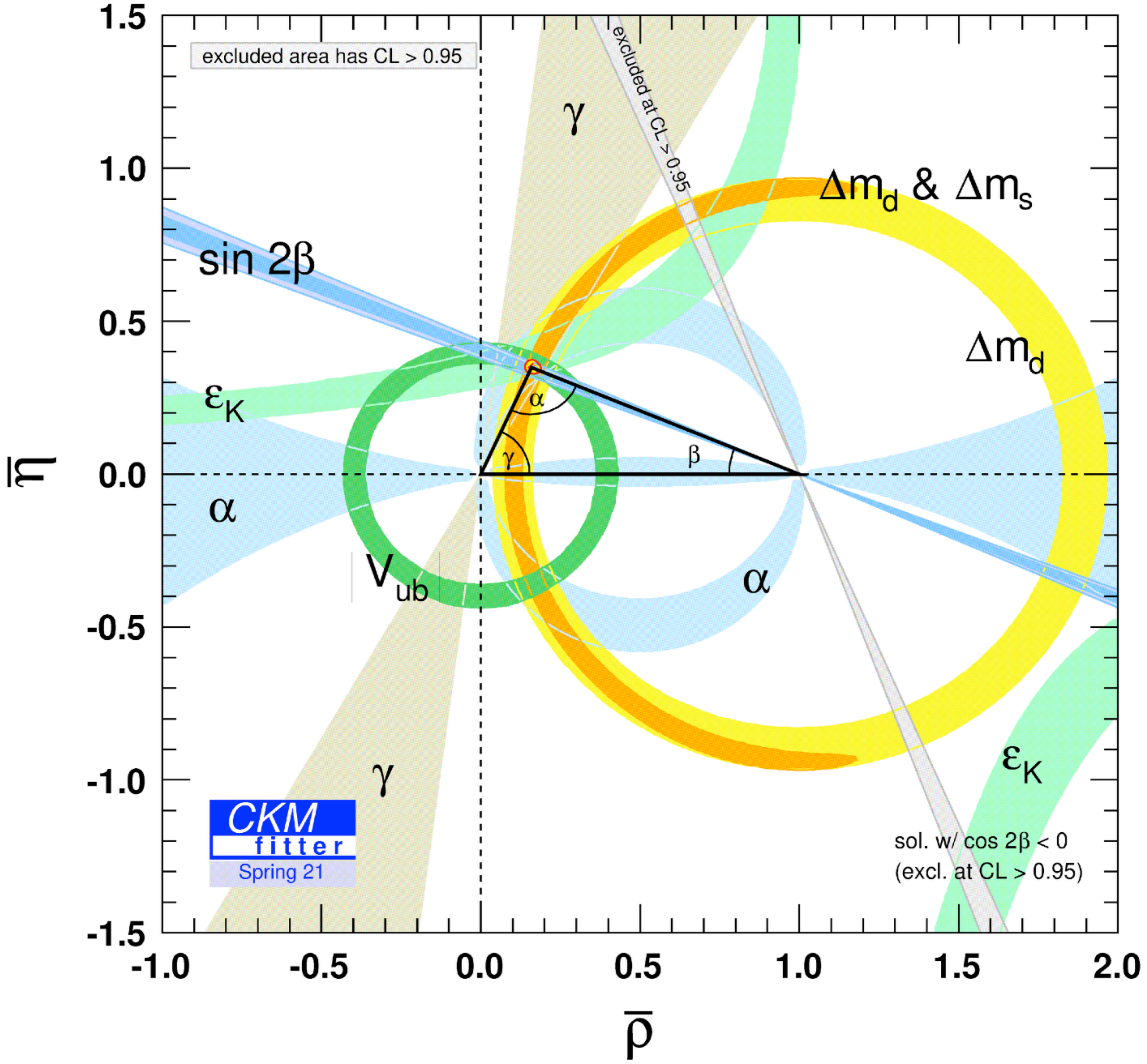
Testing the SM with $\cancel{CP}$: the UT

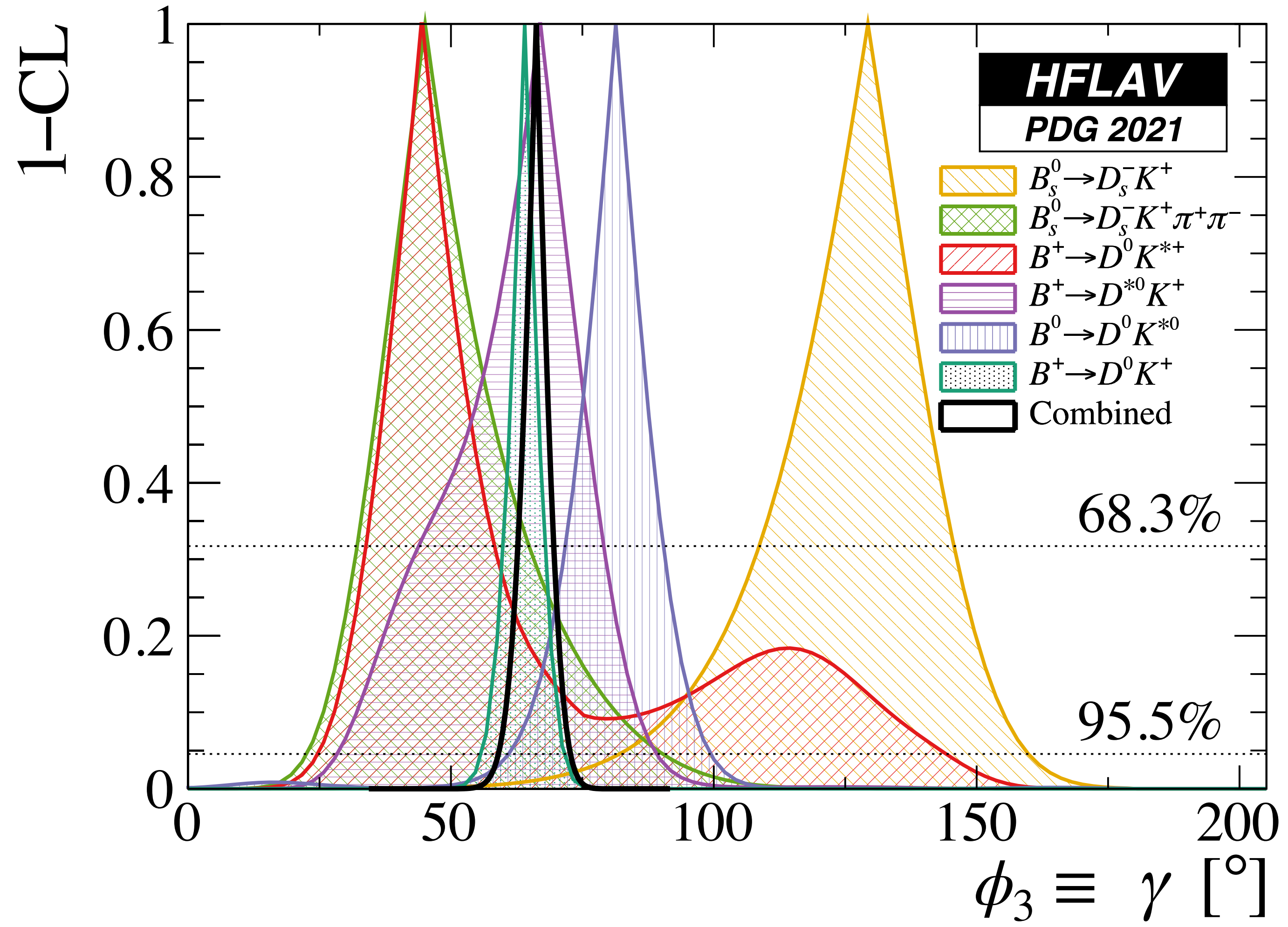
- The SM encodes the $\cancel{CP}$ phenomena with a single complex phase in the CKM matrix
- The CKM matrix is unitary

$$V^{+}V = \begin{pmatrix} V^*_{ud} & V^*_{cd} & V^*_{td} \\ V^*_{us} & V^*_{cs} & V^*_{ts} \\ V^*_{ub} & V^*_{cb} & V^*_{tb} \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\boxed{V^*_{ub}V_{ud} + V^*_{cb}V_{cd} + V^*_{tb}V_{td} = 0}$$







Updates to the Unitary Triangle global fits tomorrow!

talk by M. Valli from the UTFit collaboration

The UT angle γ

- Measured in tree-level decays sensitive to **interference** between the favoured $b \to cW$ and the suppressed $b \to uW$ decay amplitudes

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

- Golden mode: $B^\pm \to DK^\pm$
- Several **time-independent** modes
  - $B^\pm \to D^{(*)}h^{(*)}$ with D mixture of D^0 and $\overline{D}^0$ decaying to same f_D
- **Time-dependent** (mixing/decay interf.)
  - $B^0 \to D^\mp\pi^\pm$
  - $B_s^0 \to D_s^\mp K^\pm$

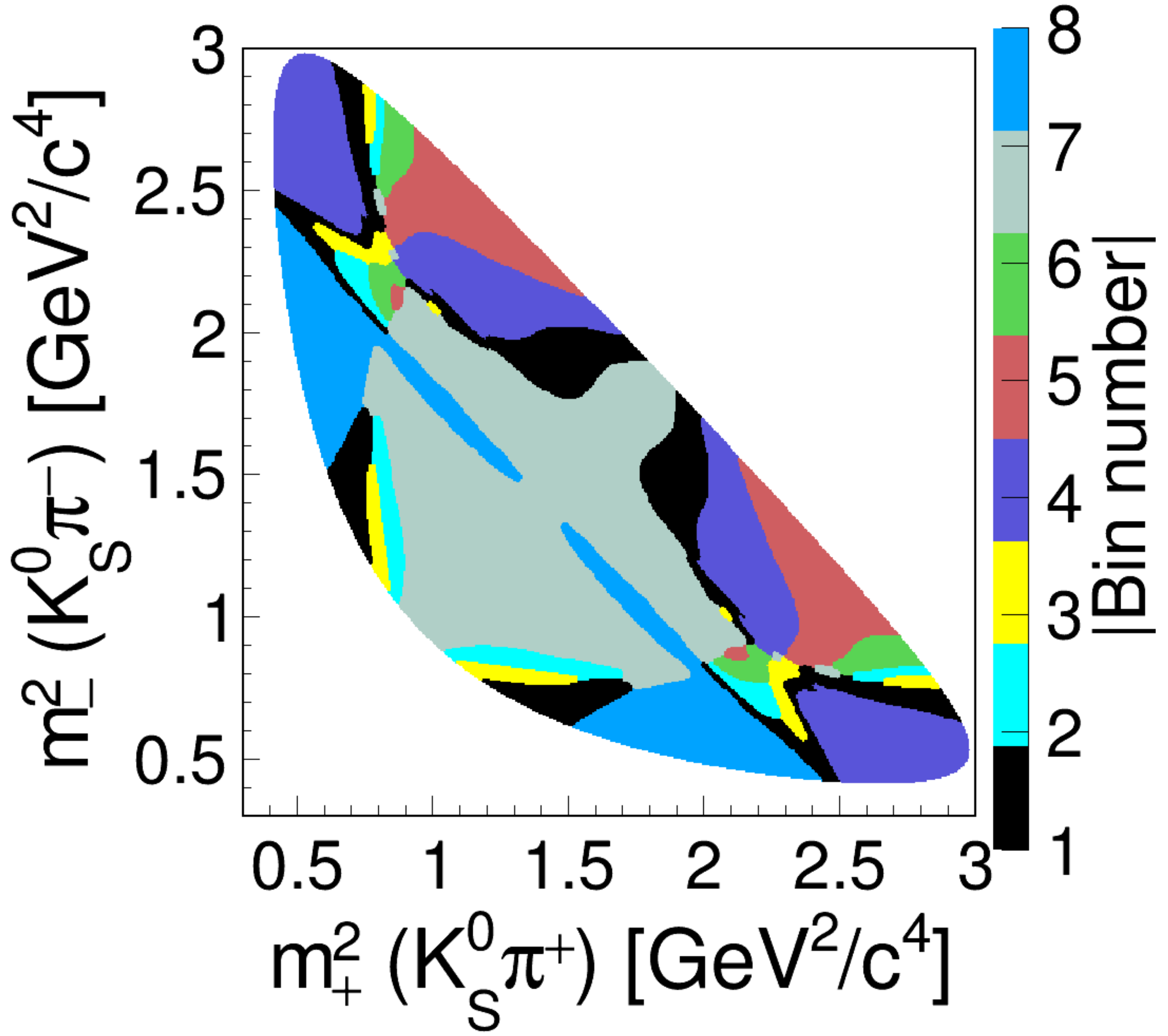
$$\begin{tikzcd}
 & \overline{D}^0K^- \arrow[dr, bend left] & \\
B^- \arrow[ur, bend left, "r_Be^{i(\delta_B-\gamma)}"] \arrow[dr, bend right] & & f_DK^- \\
 & D^0K^- \arrow[ur, bend right, "r_De^{i\delta_D}"'] &
\end{tikzcd}$$

$$\frac{\mathscr{A}^{\text{suppr.}}(B^- \to \overline{D}^0K^-)}{\mathscr{A}^{\text{favor.}}(B^- \to D^0K^-)} = r_Be^{i(\delta_B-\gamma)}$$

γ using $B^{\pm} \to Dh^{+}$ ($D \to K_s^0 h^+ h^-$) by Belle + Belle II

JHEP 02, 063 (2022)

- $h \in \{\pi, K\}$
- **Joint** data sample:
  - $711\ \mathrm{fb}^{-1}$ from Belle
  - $128\ \mathrm{fb}^{-1}$ from Belle II
- **Improvements** wrt previous Belle
  - K_s^0 selection, bkg. suppression, sig. determination, more stat. from $D^0 \to K_s^0 K^+ K^-$



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

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

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

F_i: fraction of D decays to i-th bin

- **Model independent**: analysis performed in Dalitz bins, using (new) inputs from CLEO and BESIII

PRD 82 (2010) 112006 PRD 101 (2020) 112002 PRD 102 (2020) 052008

γ using $B^{\pm} \to Dh^{+}$ ($D \to K_s^0 h^+ h^-$) by Belle + Belle II

JHEP 02, 063 (2022)

JHEP 02, 063 (2022)

$$\boxed{\gamma \equiv \phi_3 = (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^{\circ}\,,}$$

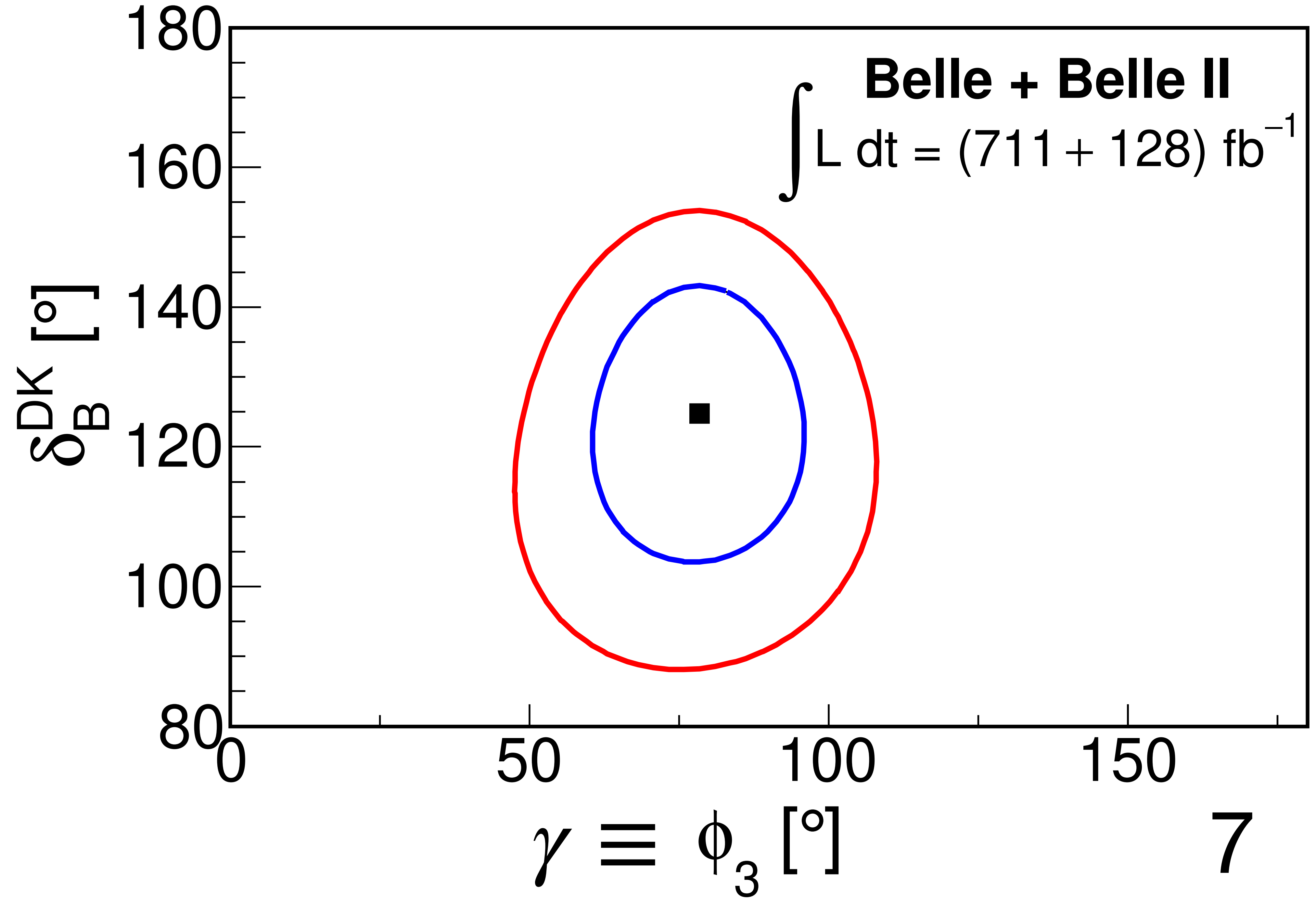
$$r_B^{DK} = 0.129 \pm 0.024 \pm 0.001 \pm 0.002,$$

$$\delta_B^{DK} = (124.8 \pm 12.9 \pm 0.5 \pm 1.7)^{\circ}\,,$$

$$r_B^{D\pi} = 0.017 \pm 0.006 \pm 0.001 \pm 0.001,$$

$$\delta_B^{D\pi} = (341.0 \pm 17.0 \pm 1.2 \pm 2.6)^{\circ}\,.$$

Most precise determination from B factories
(first Belle+Bellle2)

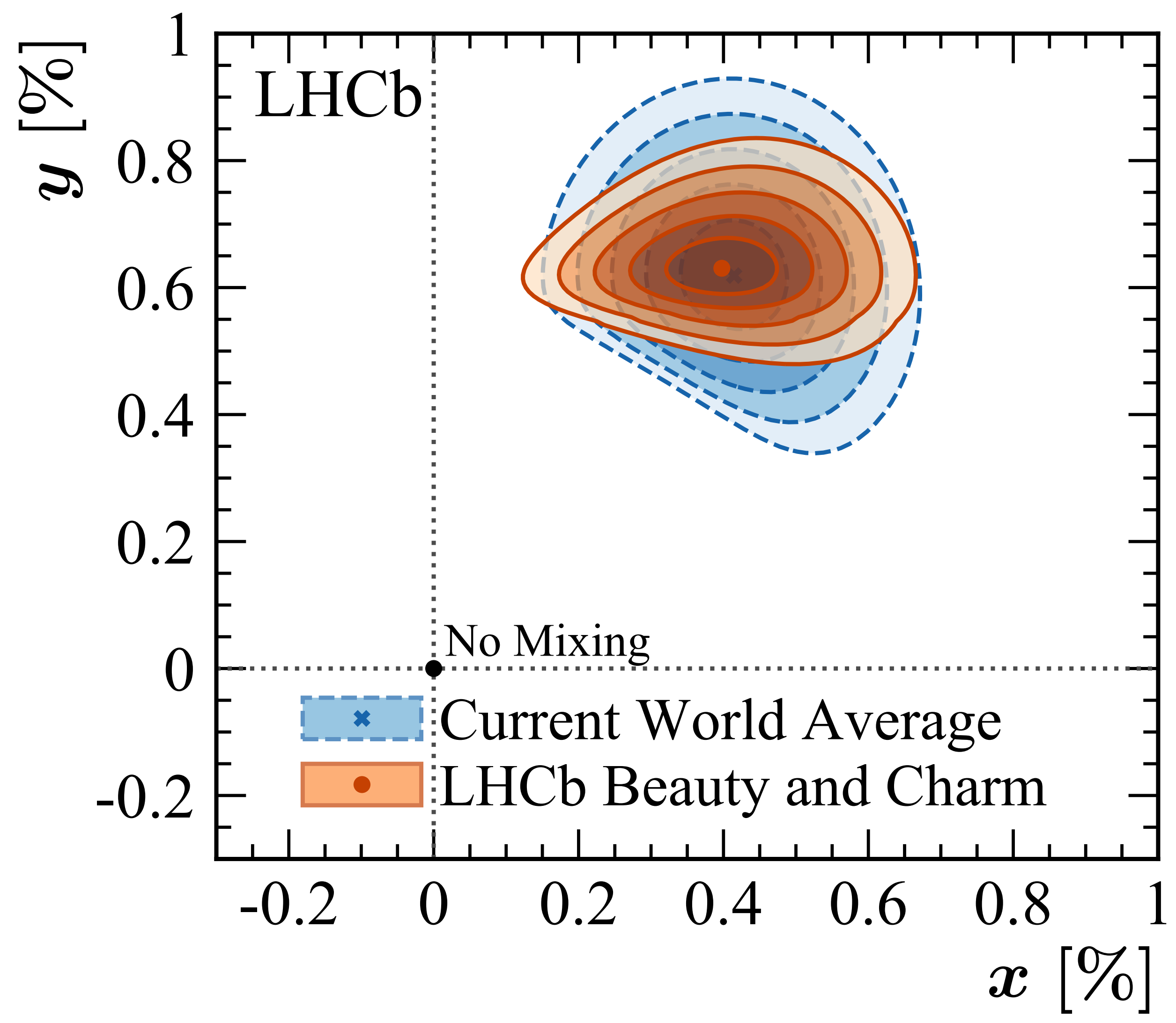


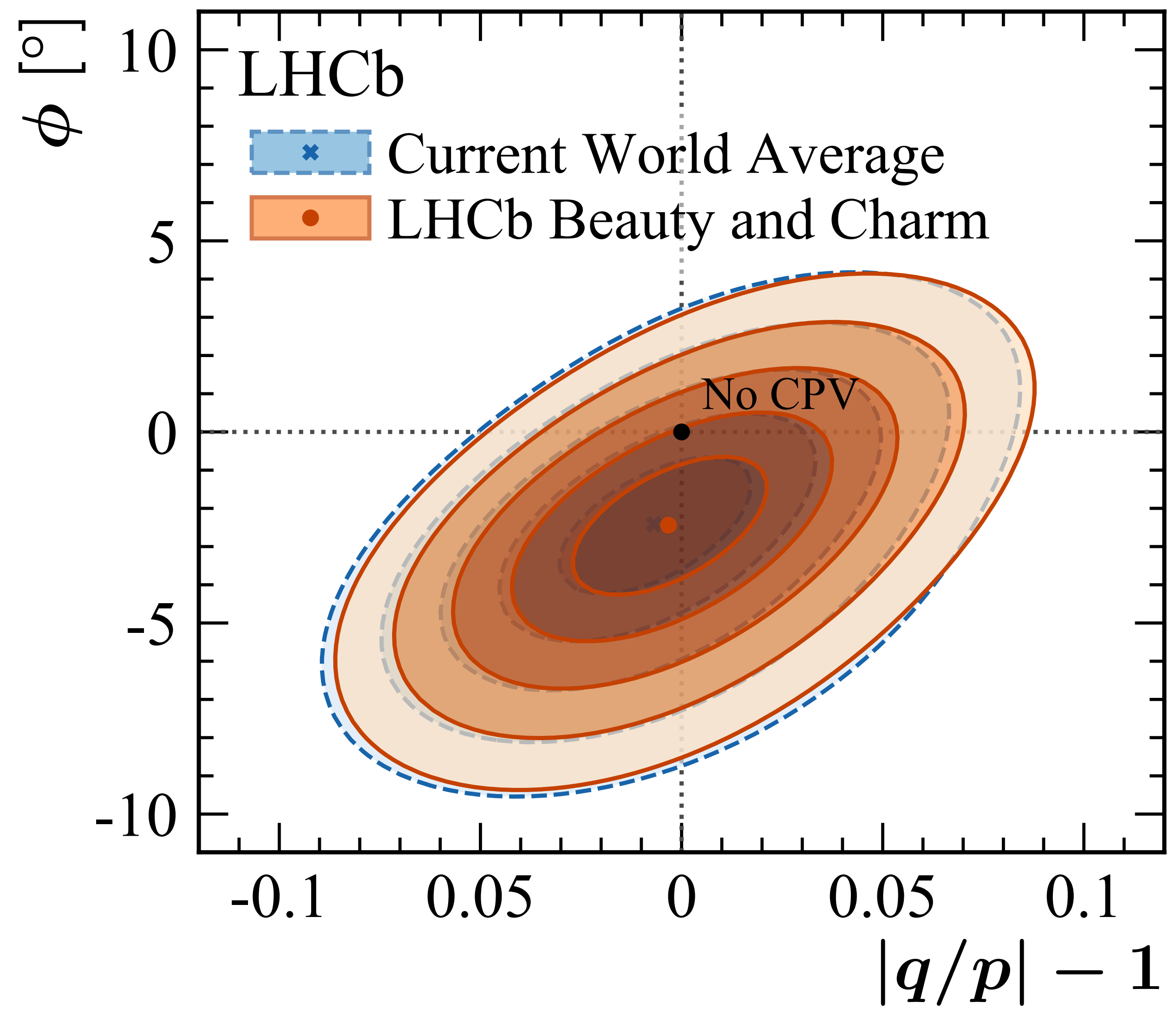
- Improvement wrt previous Belle equivalent to doubling statistics
- Latest inputs from BESIII highly reduced systematics

LHCb combination of UT angle γ

JHEP 12 (2021) 141

- New: combination of results from **beauty** and **charm** sectors
  - Correlation between y_D and $\delta_D^{K\pi}$ in $D^0 \to K^\pm\pi^\mp$
  - D mixing affects $B^\pm \to D\pi^\pm$
- Frequentist approach
  - 151 observables, 52 unknowns
  - External constraints: see backup





$$\gamma = (65.4^{+3.8}_{-4.2})^\circ$$

$$x_D = \Delta m/\Gamma = (4.00^{+0.52}_{-0.53}) \times 10^{-3}$$

$$y_D = \Delta\Gamma/\Gamma = (6.30^{+0.33}_{-0.30}) \times 10^{-3}$$

$$|q/p| = 0.997 \pm 0.016$$

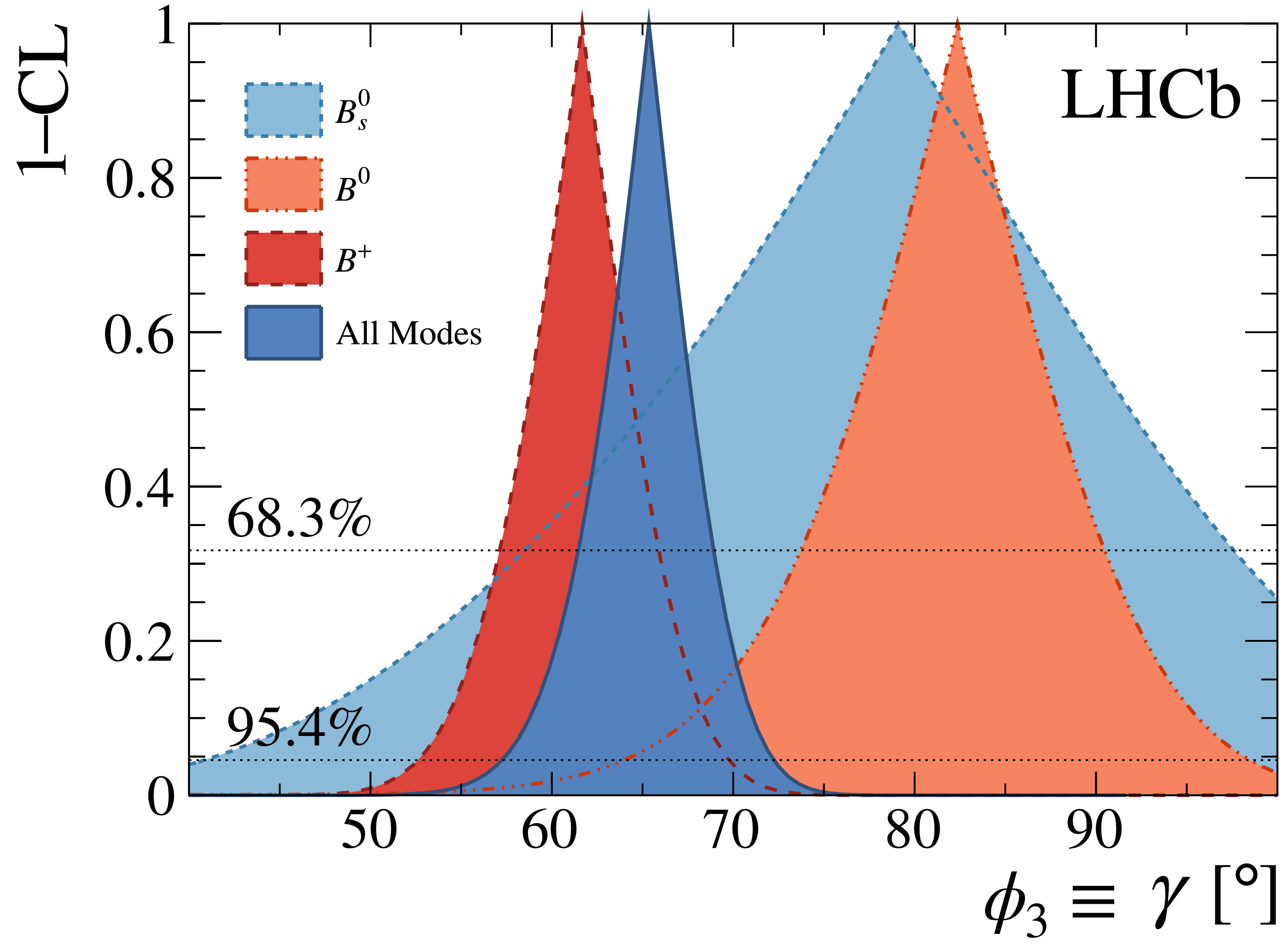
$$\phi = -2.4 \pm 1.2$$

factor 2 improvement wrt previous W.A.

MOST PRECISE DETERMINATION BY A SINGLE EXPERIMENT

agreement with *indirect* global CKM fitters

Stat. dominated



~ 2σ tension between B^+ and B^0 results

γ using $B^{\pm} \to Dh^{\pm}\,(D \to h^{+}h'^{\pm}\pi^{0})$ by LHCb

arXiv:2112.10617
submitted to JHEP

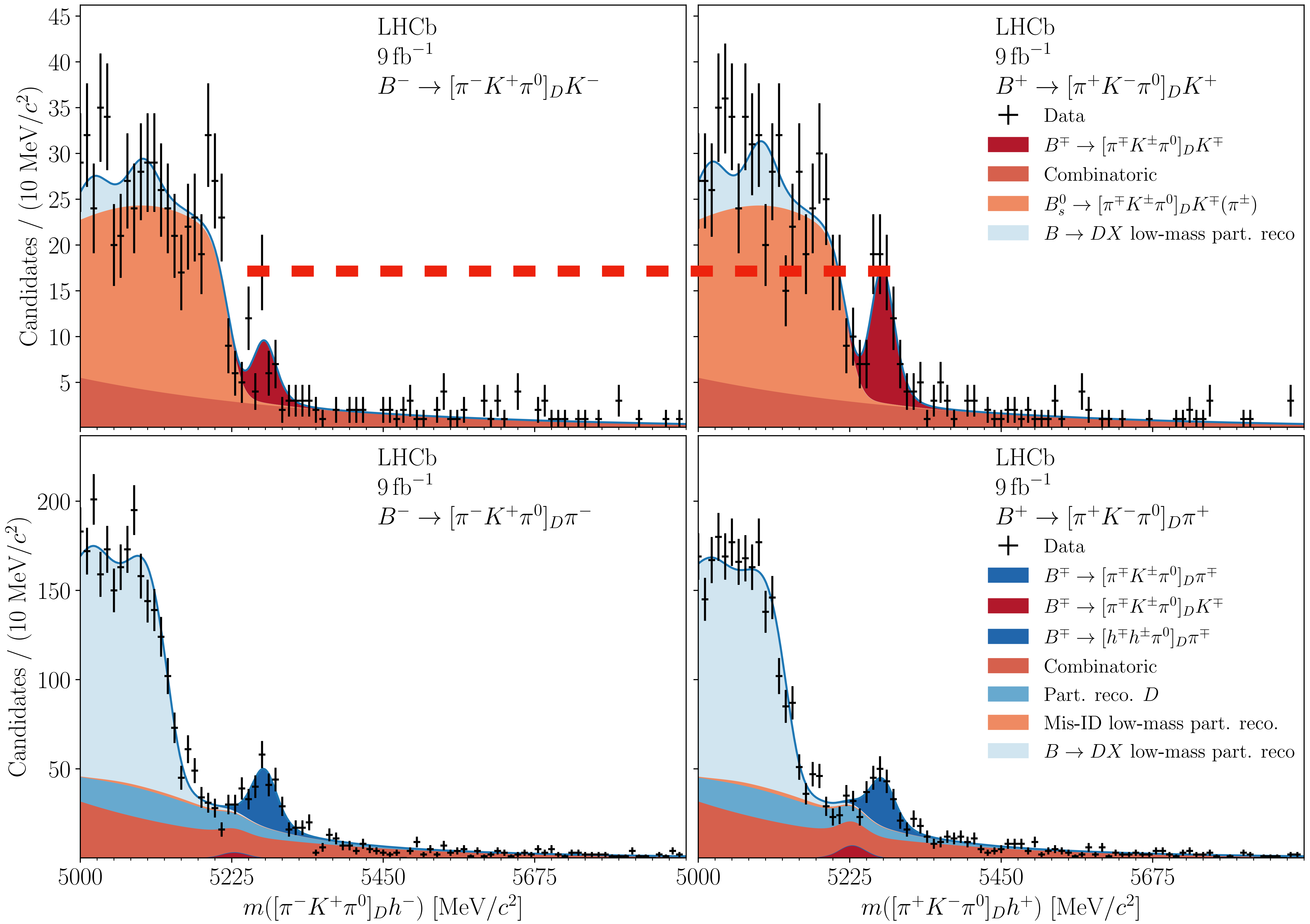
- Study 8 final states

Mode $(h^{-} = \{\pi^{-}, K^{-}\})$	Analysis type
$B^{-} \to [K^{-}\pi^{+}\pi^{0}]_{D}h^{-}$	quasi-ADS (fav.)
$B^{-} \to [\pi^{-}K^{+}\pi^{0}]_{D}h^{-}$	quasi-ADS (sup.)
$B^{-} \to [K^{-}K^{+}\pi^{0}]_{D}h^{-}$	quasi-GLW
$B^{-} \to [\pi^{-}\pi^{+}\pi^{0}]_{D}h^{-}$	quasi-GLW

- Discovery of $B^{-} \to [\pi^{-}K^{+}\pi^{0}]_{D}K^{-}$ (7.8σ !)

- Simultaneous invariant-mass fit to 16 sub-samples

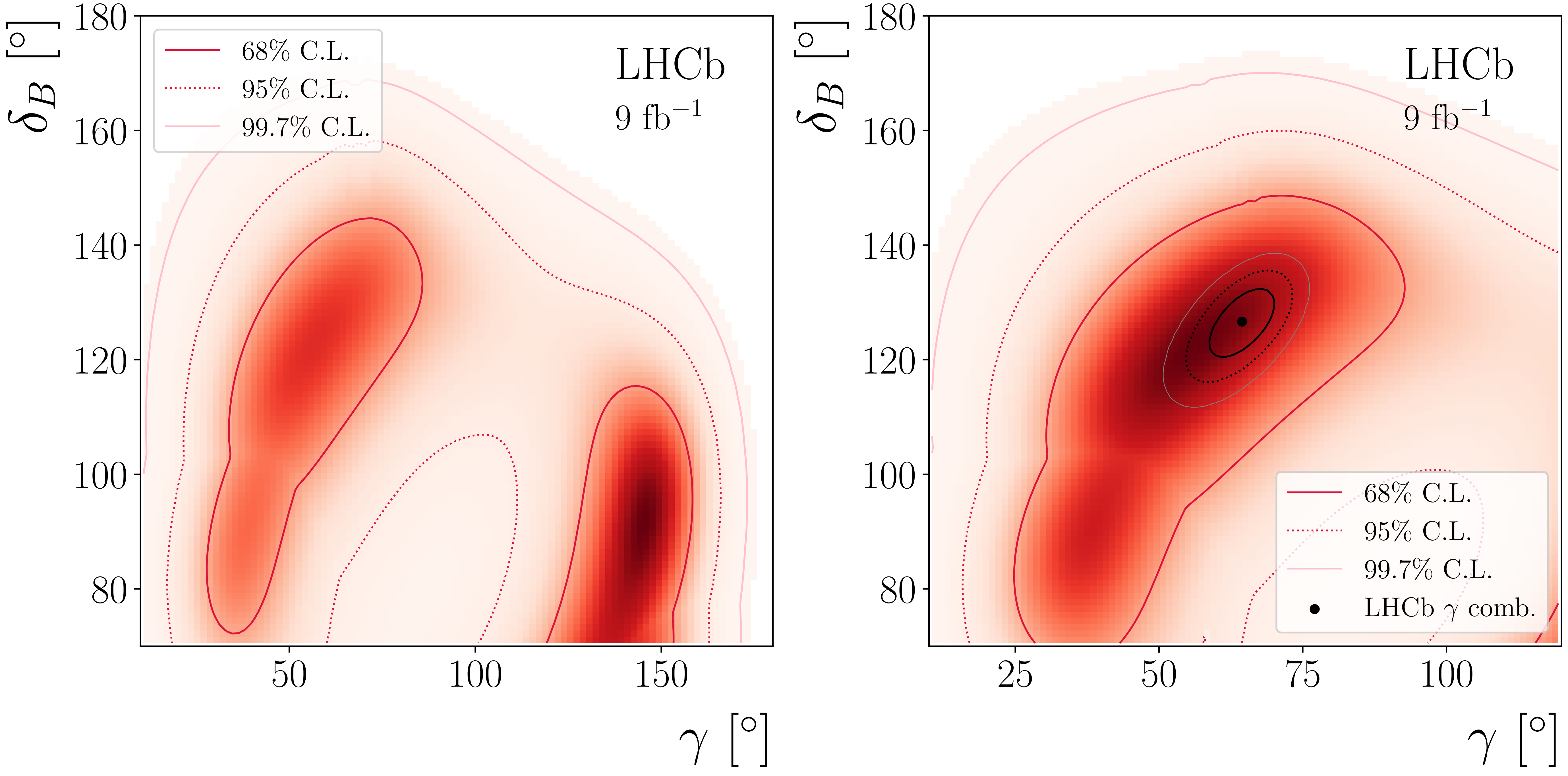
Dataset: full Run1+Run2 ($9\ \mathrm{fb}^{-1}$)



γ using $B^{\pm} \to Dh^{\pm}$ $(D \to h^{+}h'^{\pm}\pi^{0})$ by LHCb

arXiv:2112.10617
submitted to JHEP

- Fit performed to 11 $\cancel{CP}$ observables (ratios $R_h^{\pm}$ / asym. $A_h^{hh'\pi^0}$) with world best precision
- Interpret in terms of γ, r_B, δ_B
- Global minimum $\gamma = (145^{+9}_{-39})^{\circ}$
- Second solution consistent with LHCb γ combination



Results:

$$\delta_B = (122^{+19}_{-23})^{\circ}$$

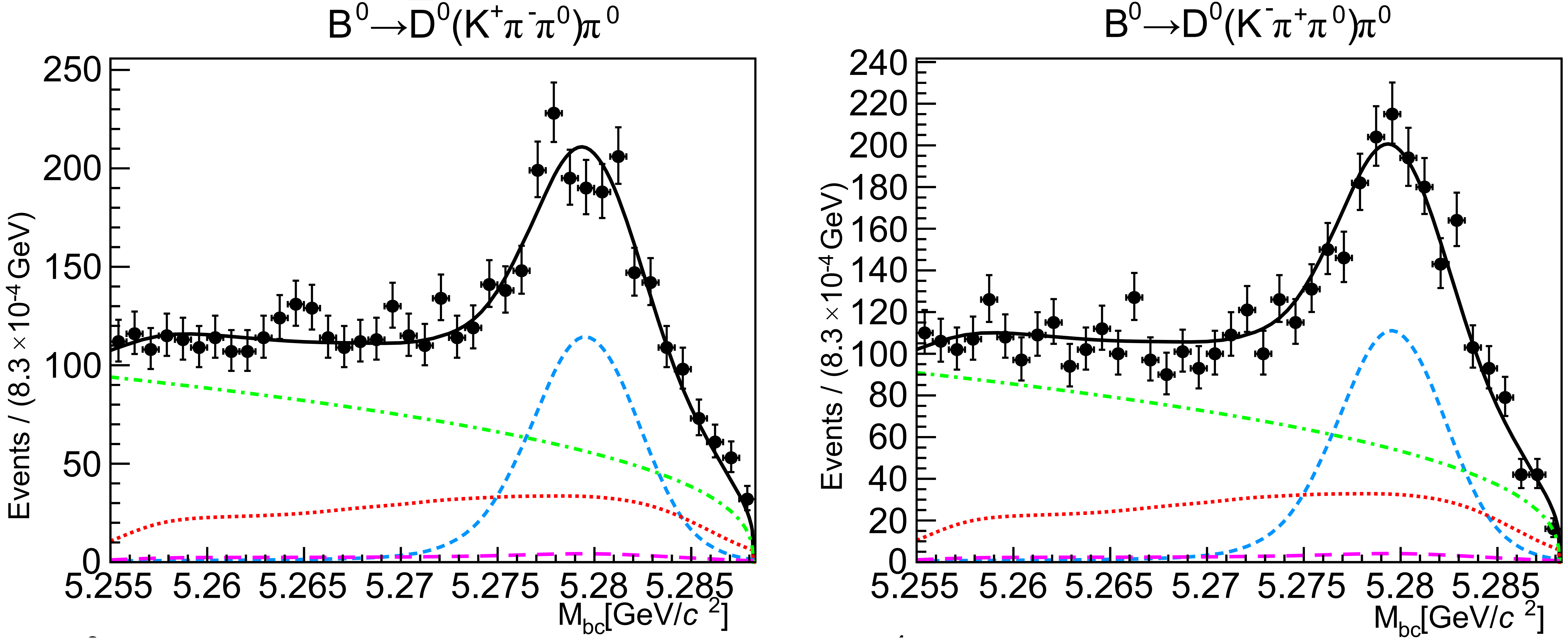
$$r_B = (9.3^{+1.0}_{-0.9})^{\circ}$$

$$\gamma = (56^{+24}_{-19})^{\circ}$$

BR and $\cancel{CP}$ in $B \to \overline{D}^0\pi$ decays

PRD 105, 072007 (2022)

- $\overline{D}^0 \to K^+\pi^-, K^+\pi^-\pi^0$
- **Motivations**:
  - The measured $\mathbf{BR}(B^0 \to \overline{D}^0\pi^0)$ is $\times 4$ theory predictions PhysRevD.82.074007
  - Large $\cancel{CP}$ would be hint of new physics
  - Control mode for rare charmless B decays
- **Full Belle** data sample $(711\ \mathrm{fb}^{-1})$
- Fit to M_{bc}, ΔE, BDT output variable
- B-flavour tagged by K charge
  - corrections to $\mathbf{BF}$
  - negligible for A_{CP}
- Analysis applied also to $B^+ \to \overline{D}^0\pi^+$



Results:

$$\mathcal{A}_{CP}(B^0 \to \bar{D}^0\pi^0) = (0.42 \pm 2.05 \pm 1.22)\%$$

$$\mathcal{B}(B^0 \to \bar{D}^0\pi^0) = [2.70 \pm 0.06\ \pm 0.10\ ] \times 10^{-4}$$

$$\mathcal{A}_{CP}(B^+ \to \bar{D}^0\pi^+) = (0.19 \pm 0.36 \pm 0.57)\%$$

$$\mathcal{B}(B^+ \to \bar{D}^0\pi^+) = (4.53 \pm 0.02 \pm 0.15) \times 10^{-3}$$

1^{st} **determination**

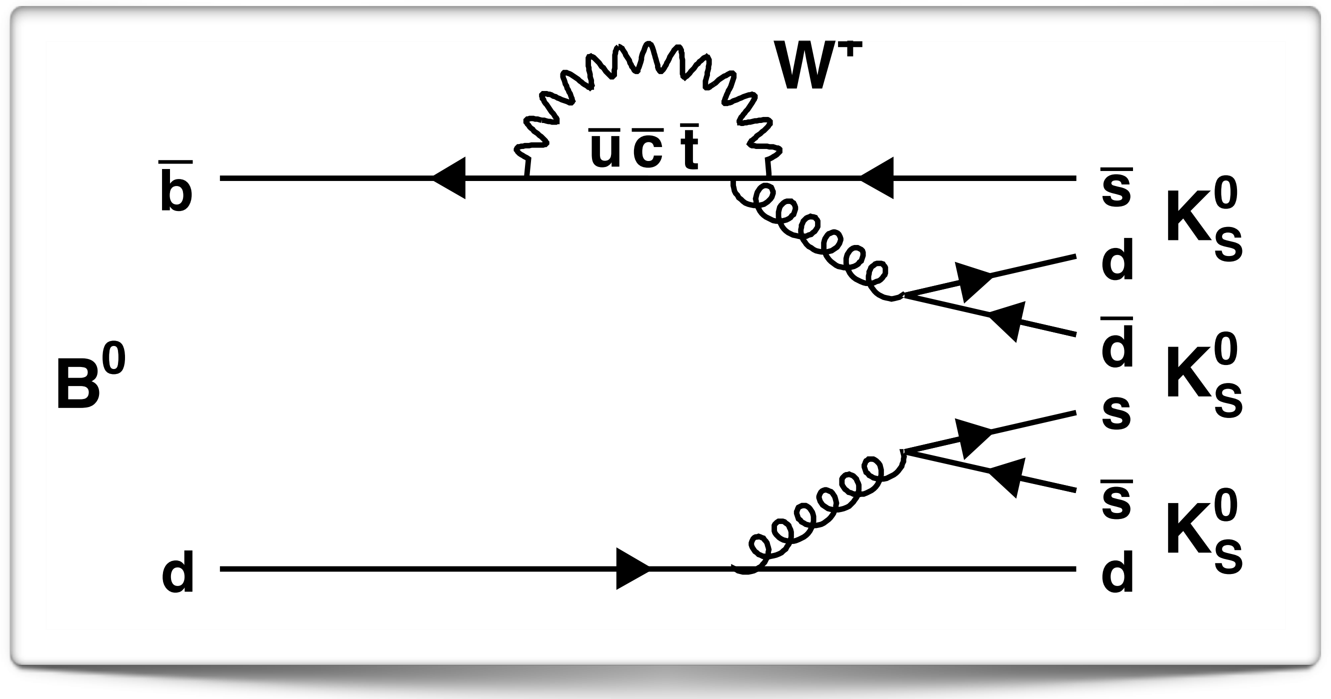
Most precise measurements to date

All results agree with previous measurements

Time dependent $\cancel{CP}$ in $B \to K_S K_S K_S$ by Belle

PRD103,032003

- Penguin topology



- The SM predicts:
  $S = -\sin(2\beta)$ and $A = 0$

- **Full Belle** dataset (711 fb^{-1})
  - Selection with NN (dominant bkg: $e^+e^- \to q\bar{q}$)
  - Veto for charmed resonances

- Fit strategy:
  1) fit to M_{bc}, ΔE, NN output variable, to get sig. and bkg yields
  2) fit to Δt for time dependent $\cancel{CP}$ parameters

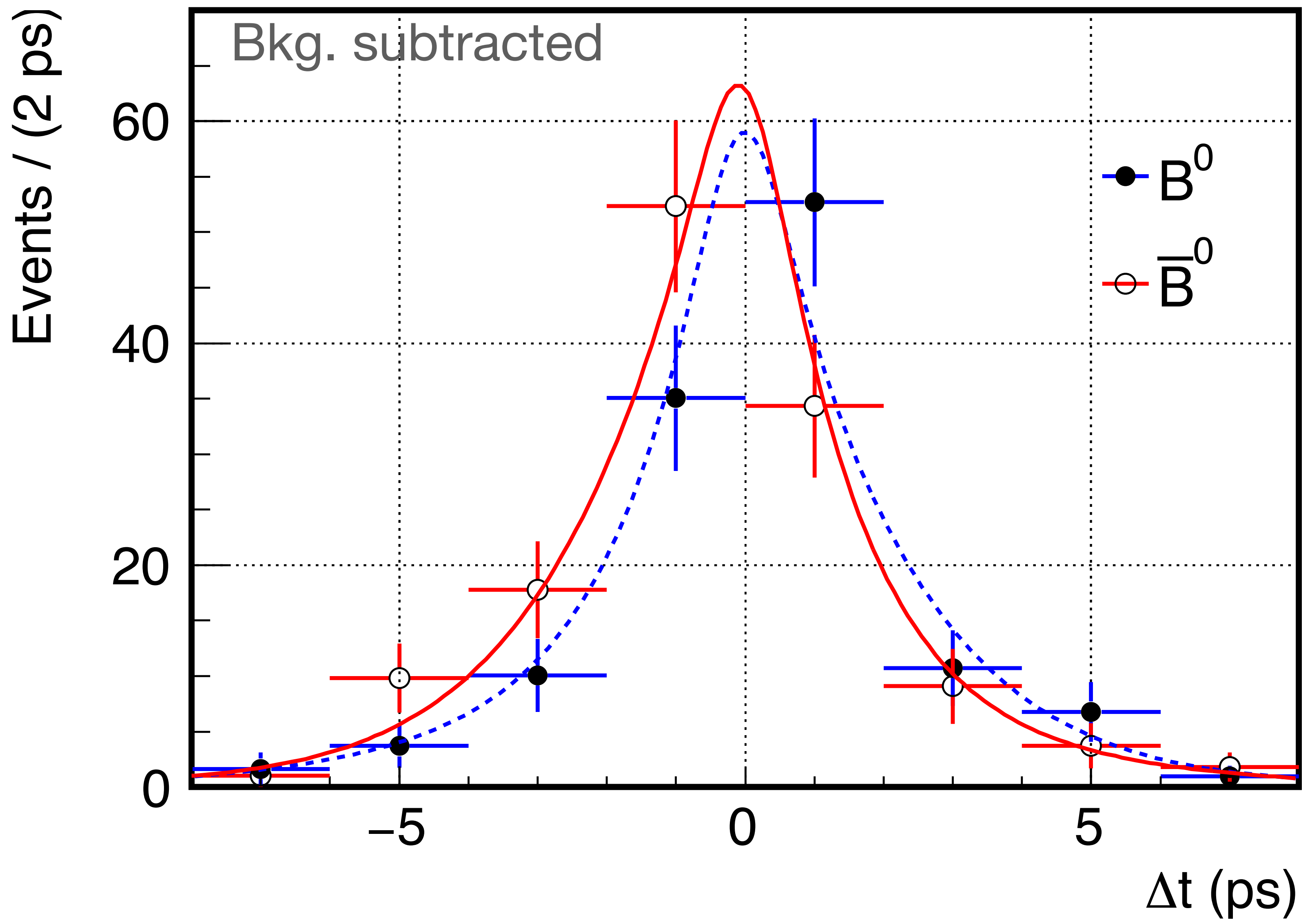
Results:

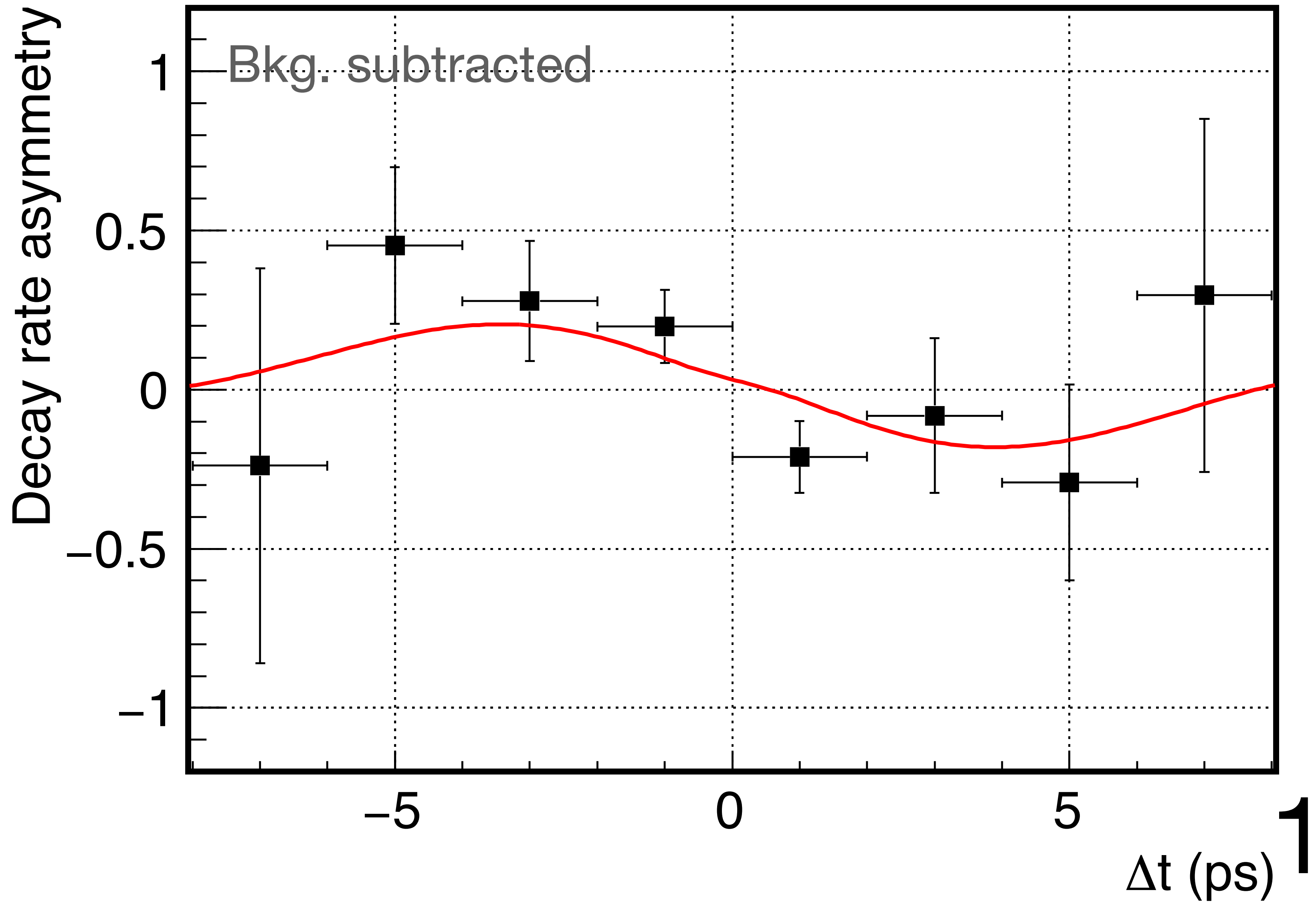
$$\begin{aligned} \mathcal{S} &= -0.71 \pm 0.23(\mathrm{stat}) \pm 0.05(\mathrm{syst}), \\ \mathcal{A} &= 0.12 \pm 0.16(\mathrm{stat}) \pm 0.05(\mathrm{syst}). \end{aligned}$$

better than W.A

2.5σ **evidence of** $\cancel{CP}$

All results agree with previous measurements and SM prediction





The long-standing $B \to K\pi$ puzzle:

- Isospin relations → $A_{CP}(\underline{B^+ \to K^+}\pi^0) - A_{CP}(B^0 \to \underline{K^+\pi^-}) = 0$
- The experimental state of the art is:

$$\underline{A_{CP}(B^+ \to K^+\pi^0)} - \underline{A_{CP}(B^0 \to K^+\pi^-)} = (11.5 \pm 1.4)\,\%$$

nonzero
at 8σ

Recently measured by LHCb
[PRL126(2021)9, 091802]

Recently measured by LHCb
[JHEP 2021, 75 (2021)]

- Is it due to strong phases and amplitudes or is new physics emerging from the loops?

any deviation from this
would be a sign of new physics

- **Full** $B \to K\pi$ puzzle sum rule [PLB627(2005)82]:

$$A_{CP}(\underline{B^0 \to K^+}\pi^-) + A_{CP}(\underline{B^+ \to K^0}\pi^+)\frac{\mathbf{B}(B^+ \to K^0\pi^+)}{\mathbf{B}(B^0 \to K^+\pi^-)}\frac{\tau^0}{\tau^+} = A_{CP}(\underline{B^+ \to K^+}\pi^0)\frac{2\mathbf{B}(B^+ \to K^+\pi^0)}{\mathbf{B}(B^0 \to K^+\pi^-)}\frac{\tau^0}{\tau^+} + A_{CP}(\underline{B^0 \to K^0\pi^0})\frac{2\mathbf{B}(B^0 \to K^0\pi^0)}{\mathbf{B}(B^0 \to K^+\pi^-)}\frac{\tau^0}{\tau^+}$$

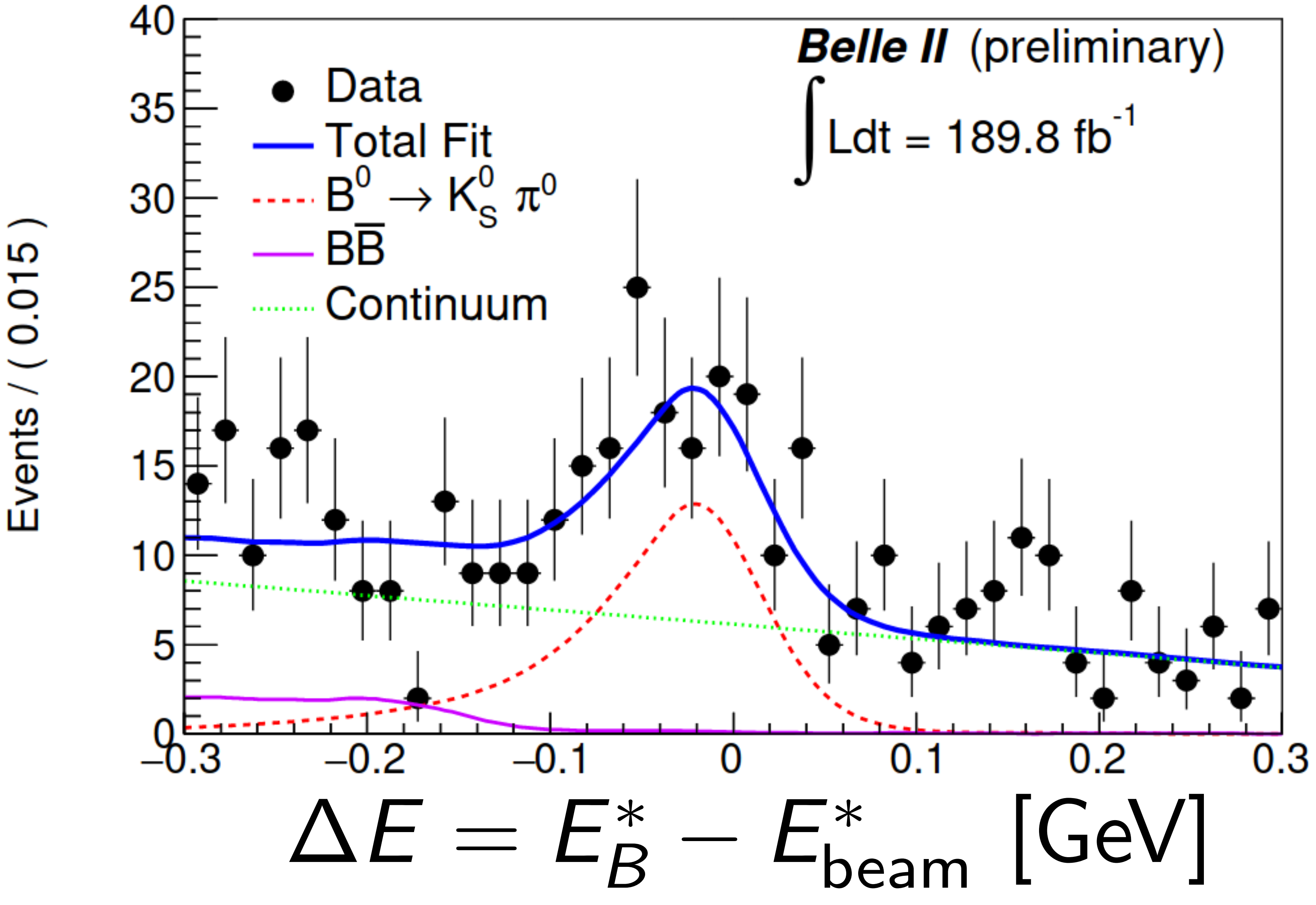
**INPUT WITH
HIGHER UNCERTAINTY!**

$\cancel{CP}$ in $B^0 \to K_S^0\pi^0$ decays by Belle II

Firstly showed at Moriond EW 2022, preliminary

- Perform a 4D fit to ΔE, M_{bc}, Δt, and continuum-suppression output
- $B^0 \to J/\psi(\mu^+\mu^-)K_S^0$ used as a control sample. Measured lifetime and ACP consistent with know values.
- Wrong-tag fraction measured from mixing measurements using $B^0 \to D^{(*)}h$ decays
- Limited sample size: constrain S_{CP} using previous measurements to maximise precision in A_{CP}

talk by Chunhui Chen this morning



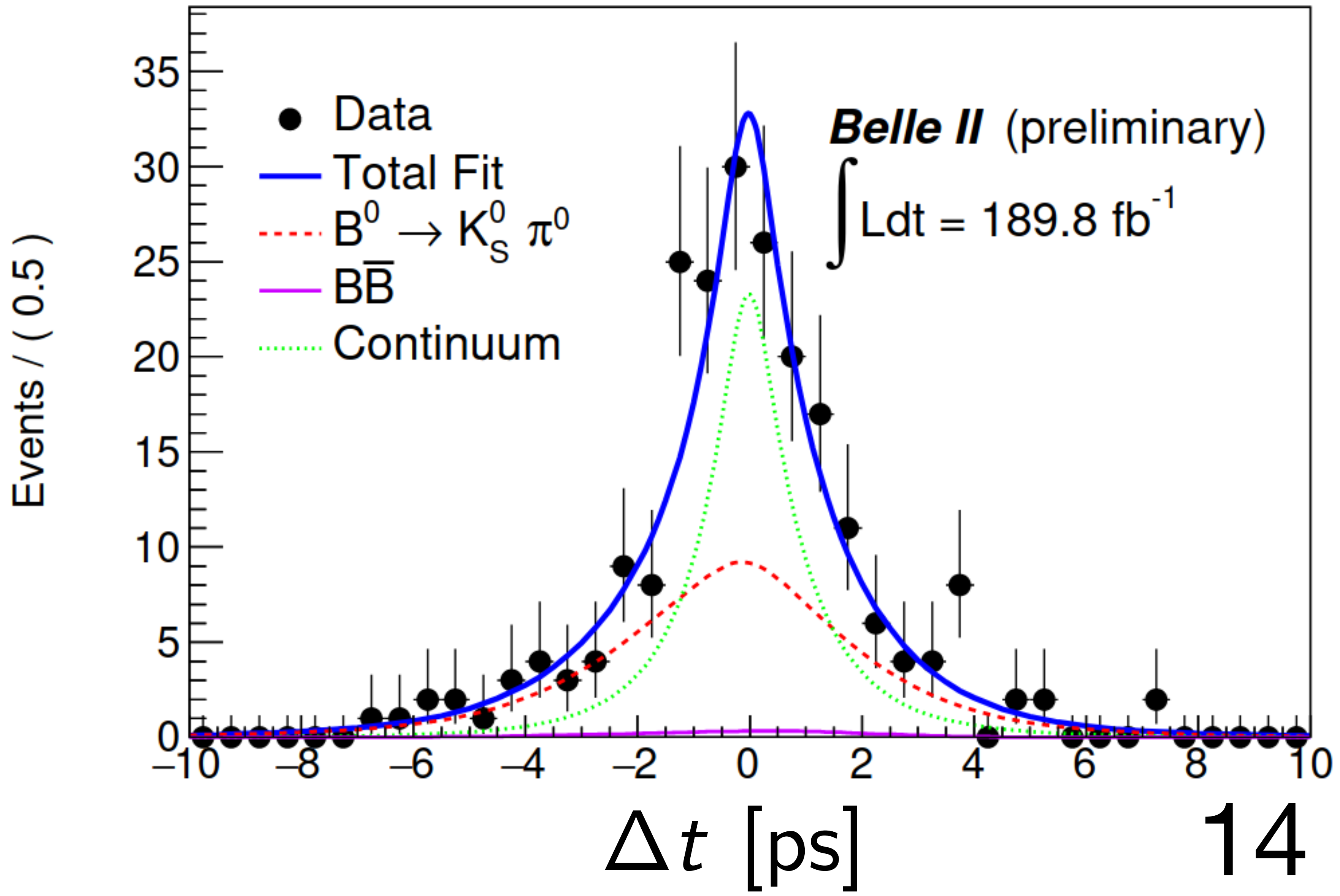
Results:

$$A_{CP}(B^0 \to K_S^0\pi^0) = -0.41^{+0.32}_{-0.30}\,(\text{stat.}) \pm 0.09\,(\text{syst.})$$

$$\mathbf{B}(B^0 \to K_S^0\pi^0) = (11.0 \pm 1.2\,(\text{stat.}) \pm 1.0\,(\text{syst.})) \times 10^{-6}$$

World average: $A_{CP}(B^0 \to K_S^0\pi^0) = 0.00 \pm 0.13$

- Results establish Belle II capabilities.
- Expect to obtain 0.03 precision on the isospin sum-rule with 50/ab



Direct $\cancel{CP}$ in $B^{\pm} \to h^{\pm}h^{+}h^{-}$ by LHCb

LHCb-PAPER-2021-049
LHCb-PAPER-2021-050
Preliminary

- Prequels:
  - Evidence of global direct CPV and high localised CP asymmetries across the Dalitz plot in charmless 3-body B decay [PRD90(2014)112004]
  - Amplitude analysis of $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$: large $\cancel{CP}$ related to S- and P-wave interference [PRL124(2020)031801, PRD101(2020)012006]
  - Amplitude analysis of $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$: $\cancel{CP}$ connected to $\pi\pi \leftrightarrow KK$ rescattering [PRL123 (2019) 231802] [Prog. Part. Nucl. Phys. 114 (2020) 103808]

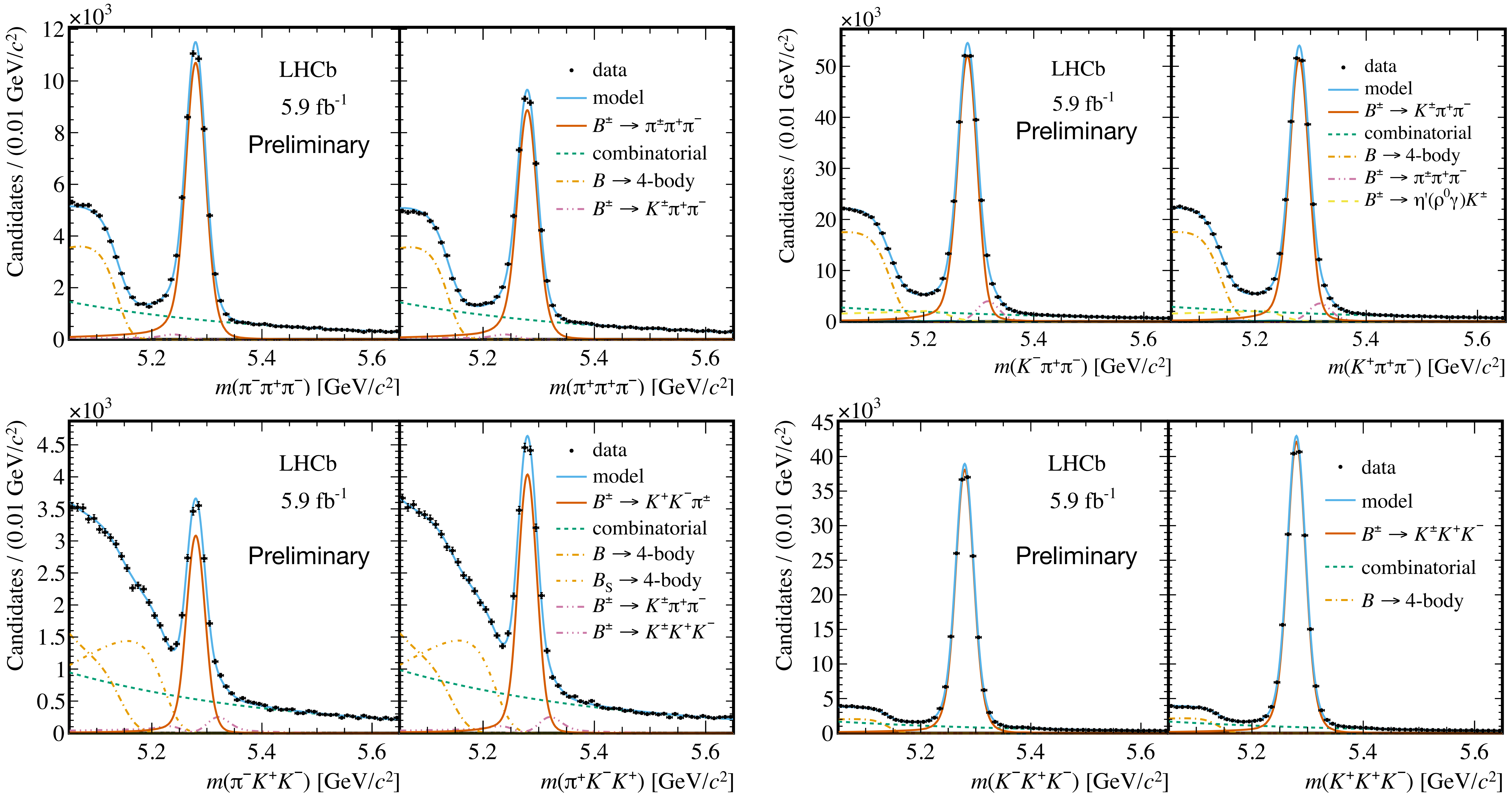
- Analysis using **Run2** data $(5.9\ \mathrm{fb}^{-1})$
  - Measurement of $\cancel{CP}$ in the decay for $\left\{\begin{array}{ll} B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-} & B^{\pm} \to K^{\pm}\pi^{+}\pi^{-} \\ B^{\pm} \to \pi^{\pm}K^{+}K^{-} & B^{\pm} \to K^{\pm}K^{+}K^{-} \end{array}\right.$
    - **phase-space integrated**
    - depending on the **regions of the phase space**
  - Measurement of CP asymmetry in $B \to PV$ decays

Global $\cancel{CP}$ in $B^\pm \to h^\pm h^+ h^-$

LHCb-PAPER-2021-049
Preliminary

- Simultaneous invariant mass fit to B^+/B^- to extract raw asymmetries

- Raw asymmetries corrected for
  - detector efficiency effects
    (simulation & data-driven tech.)
  - production asymmetries
    $A_\mathrm{P} = A^{\mathrm{ACC}}_{raw}(B^\pm \to J/\psi K^\pm) - A_{CP}(B^\pm \to J/\psi K^\pm)$
    ↑ meas. (LHCb data) ↑ ext. (PDG)



Results:

$$A_{CP}(B^\pm \to K^\pm\pi^+\pi^-) = +0.011 \pm 0.002 \pm 0.003 \pm 0.003$$
(2.4σ)

$$A_{CP}(B^\pm \to K^\pm K^+ K^-) = -0.037 \pm 0.002 \pm 0.002 \pm 0.003$$
1^{st} obs. (8.5σ)

$$A_{CP}(B^\pm \to \pi^\pm\pi^+\pi^-) = +0.080 \pm 0.004 \pm 0.003 \pm 0.003$$
1^{st} obs. (14σ)

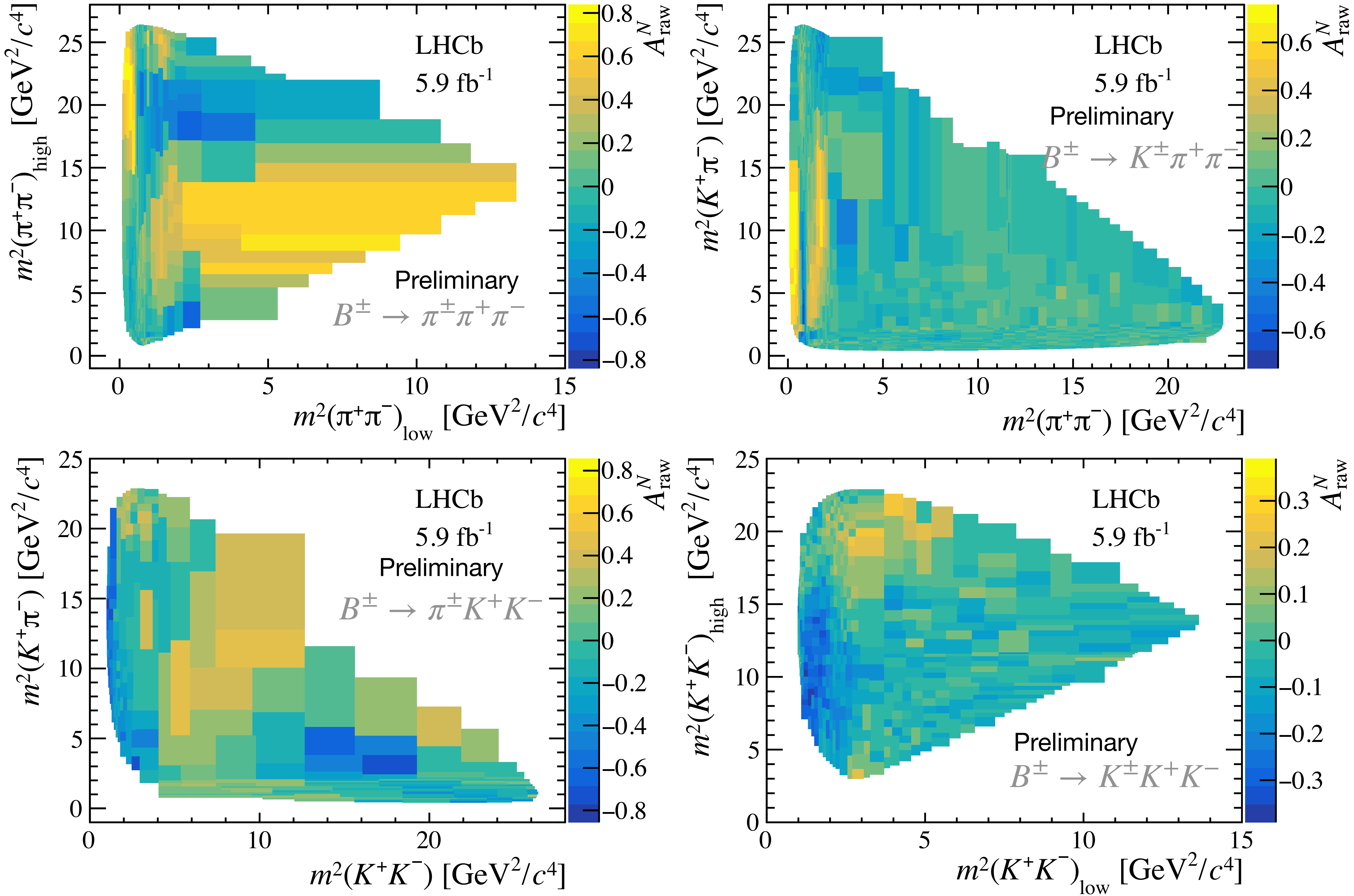
$$A_{CP}(B^\pm \to \pi^\pm K^+ K^-) = -0.114 \pm 0.007 \pm 0.003 \pm 0.003$$
1^{st} obs. (14σ)

↑ stat. ↑ syst. ↑ ext.

CP asymmetry: phase space

LHCb-PAPER-2021-049
Preliminary

- Measurement of A_{CP} in bins of the phase space, using an adaptive binning and taking into account acceptance correction



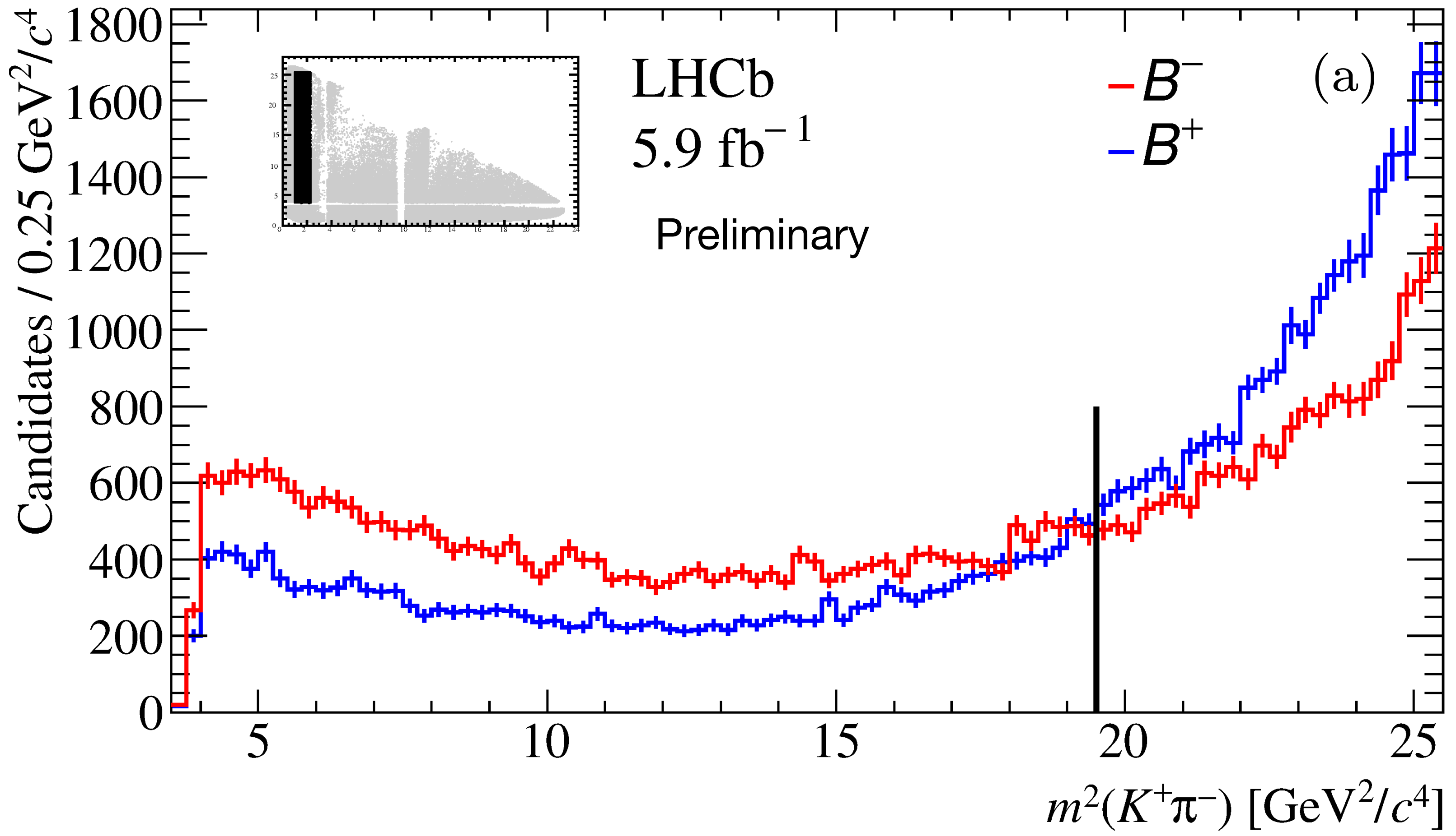
Rich pattern of high localised asymmetries!

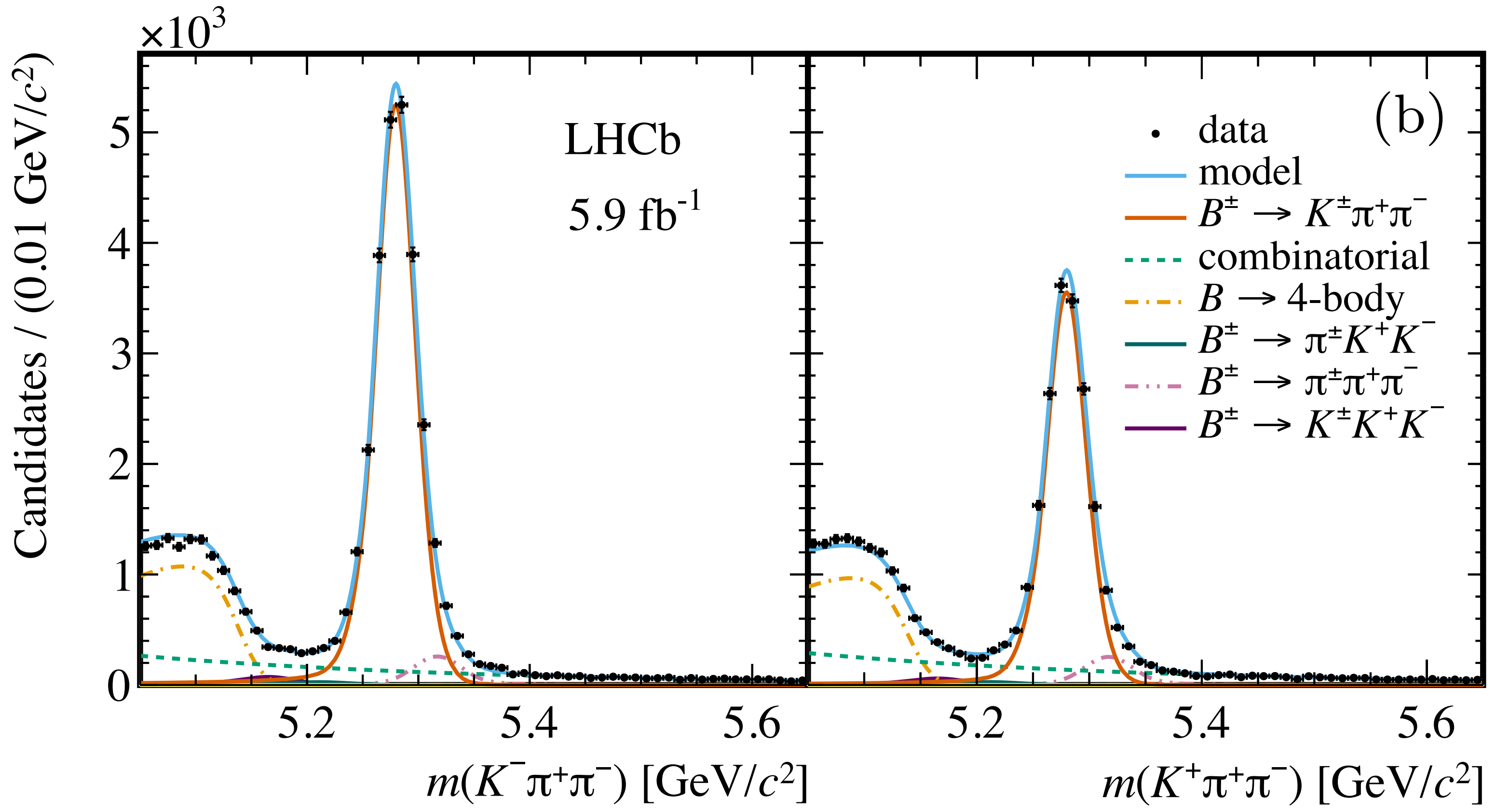
CP asymmetry: phase space

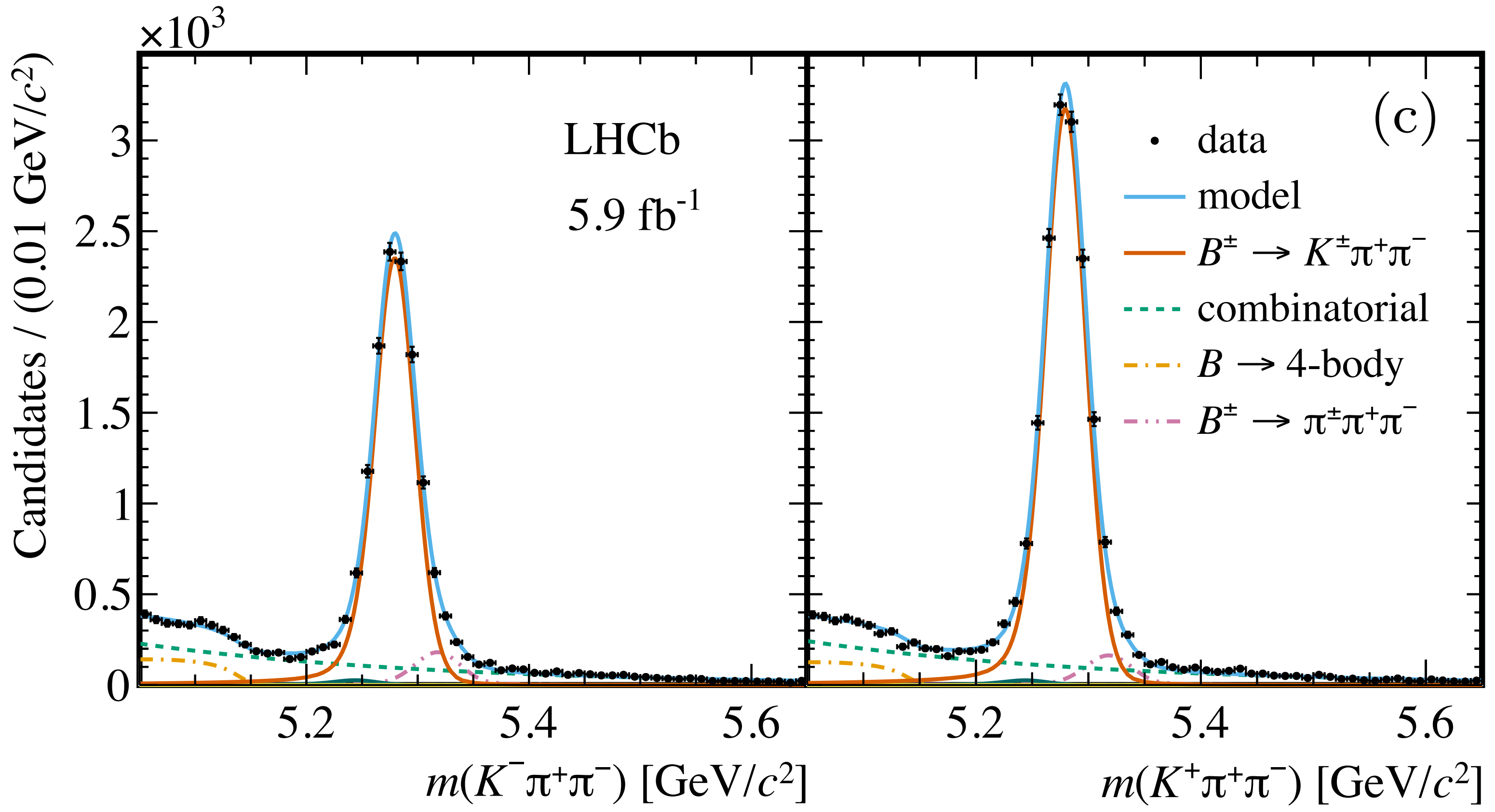
LHCb-PAPER-2021-049
Preliminary

- Significant $\cancel{CP}$ in the $\pi\pi \leftrightarrow KK$ rescattering region $\longrightarrow$ $m^2 \in [1, 2.25]\ \mathrm{GeV}^2/\mathrm{c}^4$ seen in all four channels

$$B^\pm \to K^\pm\pi^+\pi^-$$







$\cancel{CP}$ in $B \to PV$

- Few measurements $B \to PV$ decays in the literature and huge theoretical interest
- Large phase space available: different interfering resonant intermediate amplitudes

- Simplified method to extract A_{CP}
  - Valid for low-mass resonant amplitudes

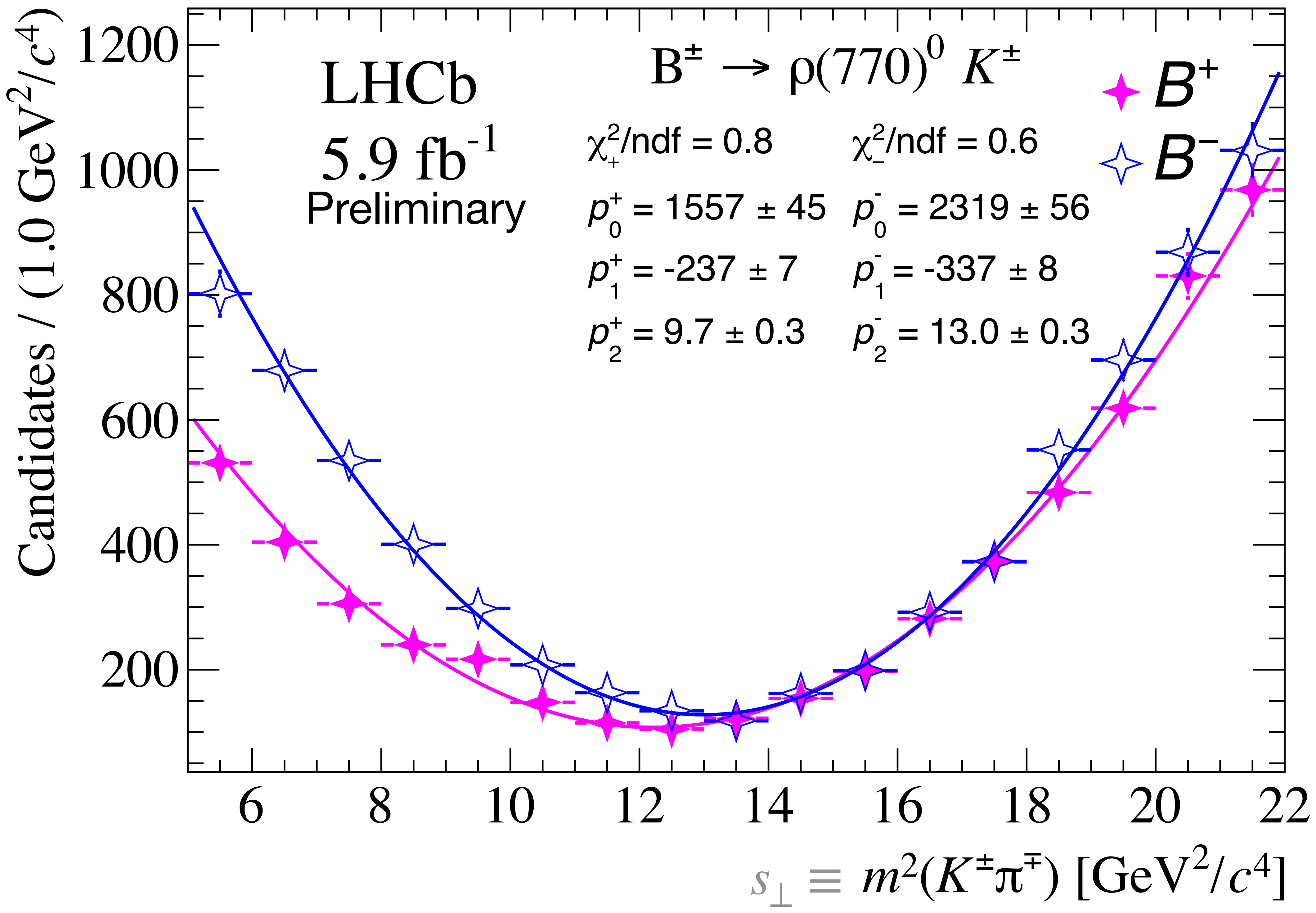
[PRD94(2016)054028]

$B \to R(\to h_1^- h_2^+)h_3^+$

$$|\mathcal{M}_\pm|^2 = p_0^\pm + p_1^\pm \cos\theta(s_\perp, m_v^2) + p_2^\pm \cos^2\theta(s_\perp, m_v^2)$$

where $s_\perp \equiv m^2(h_1^- h_3^+)$ and $\theta \equiv$ helicity angle

$$A_{CP}^V = \frac{p_2^- - p_2^+}{p_2^- - p_2^+}$$



Decay channel	$A_{CP} \pm \sigma_{\text{stat}} \pm \sigma_{\text{syst}}$
$B^\pm \to (\rho(770)^0 \to \pi^+\pi^-)\pi^\pm$	$-0.004 \pm 0.017 \pm 0.009$
$B^\pm \to (\rho(770)^0 \to \pi^+\pi^-)K^\pm$	$+0.150 \pm 0.019 \pm 0.011$
$B^\pm \to (\overset{(-)}{K}{}^*(892)^0 \to K^\pm\pi^\mp)\pi^\pm$	$-0.015 \pm 0.021 \pm 0.012$
$B^\pm \to (\overset{(-)}{K}{}^*(892)^0 \to K^\pm\pi^\mp)K^\pm$	$+0.007 \pm 0.054 \pm 0.032$
$B^\pm \to (\phi(1020) \to K^+K^-)K^\pm$	$+0.004 \pm 0.010 \pm 0.007$

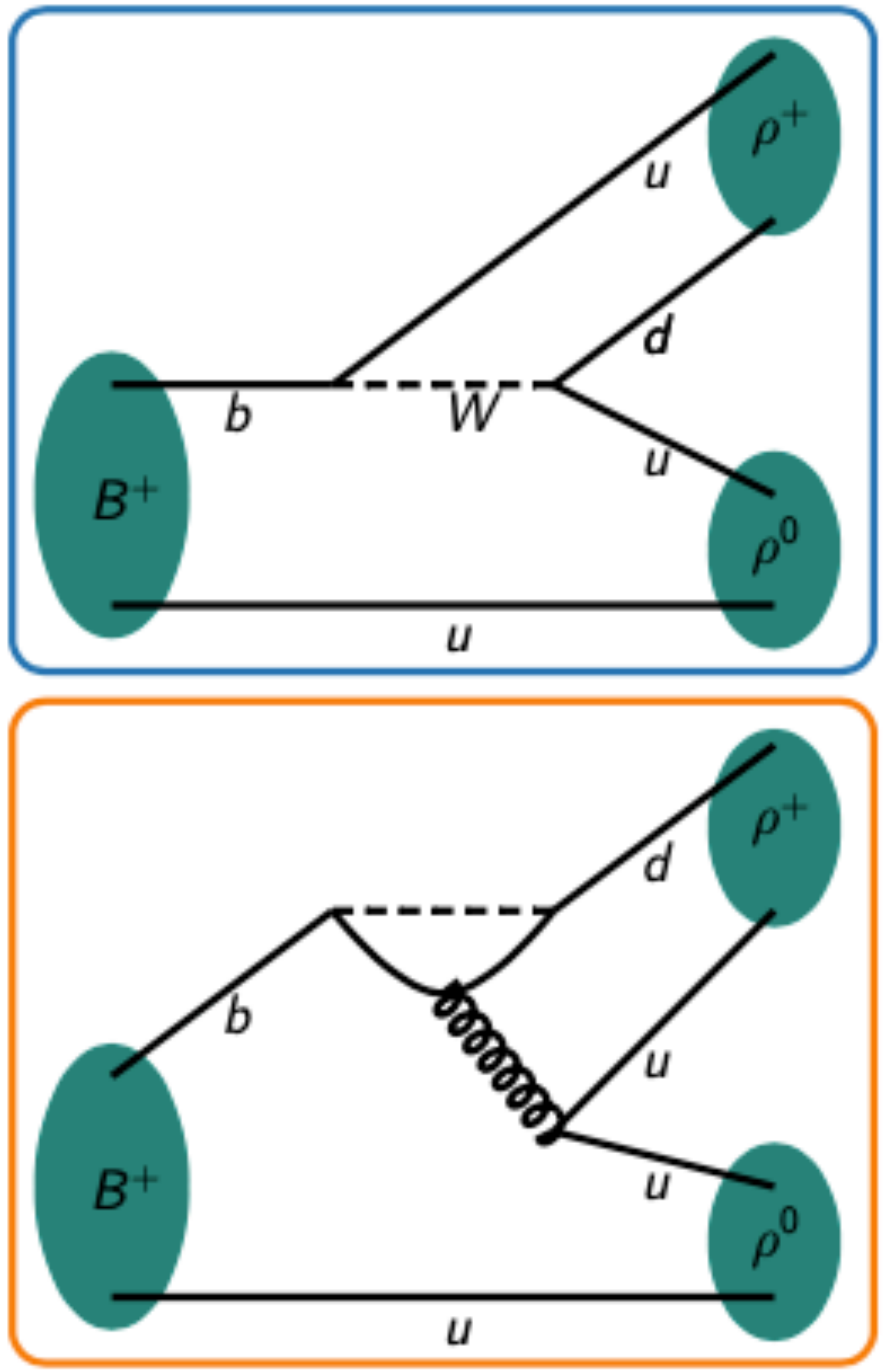
First observation!
6.8σ

$\cancel{CP}$ in $B^{\pm} \to \rho^{\pm}\rho^{0}$ decays by Belle II

Firstly showed at Moriond EW 2022 , preliminary

- **Motivation**: CKM angle α measurable through combination of:
  $B^0 \to \rho^0\rho^0, B^0 \to \rho^+\rho^-, B^+ \to \rho^+\rho^0$
  $\hookrightarrow \pi^+\pi^-$
  $\hookrightarrow \pi^+\pi^0$

- To do that, measure direct $\cancel{CP}$ in decays where ρ^+ and ρ^0 are longitudinally polarised, need:
  - Longitudinal polarisation fraction (f_L)
    → measure $\pi^{\pm}$ helicity angles
  - Asymmetry in rate $B^+ \to \rho^+\rho^0$ vs. $B^- \to \rho^-\rho^0$



↑

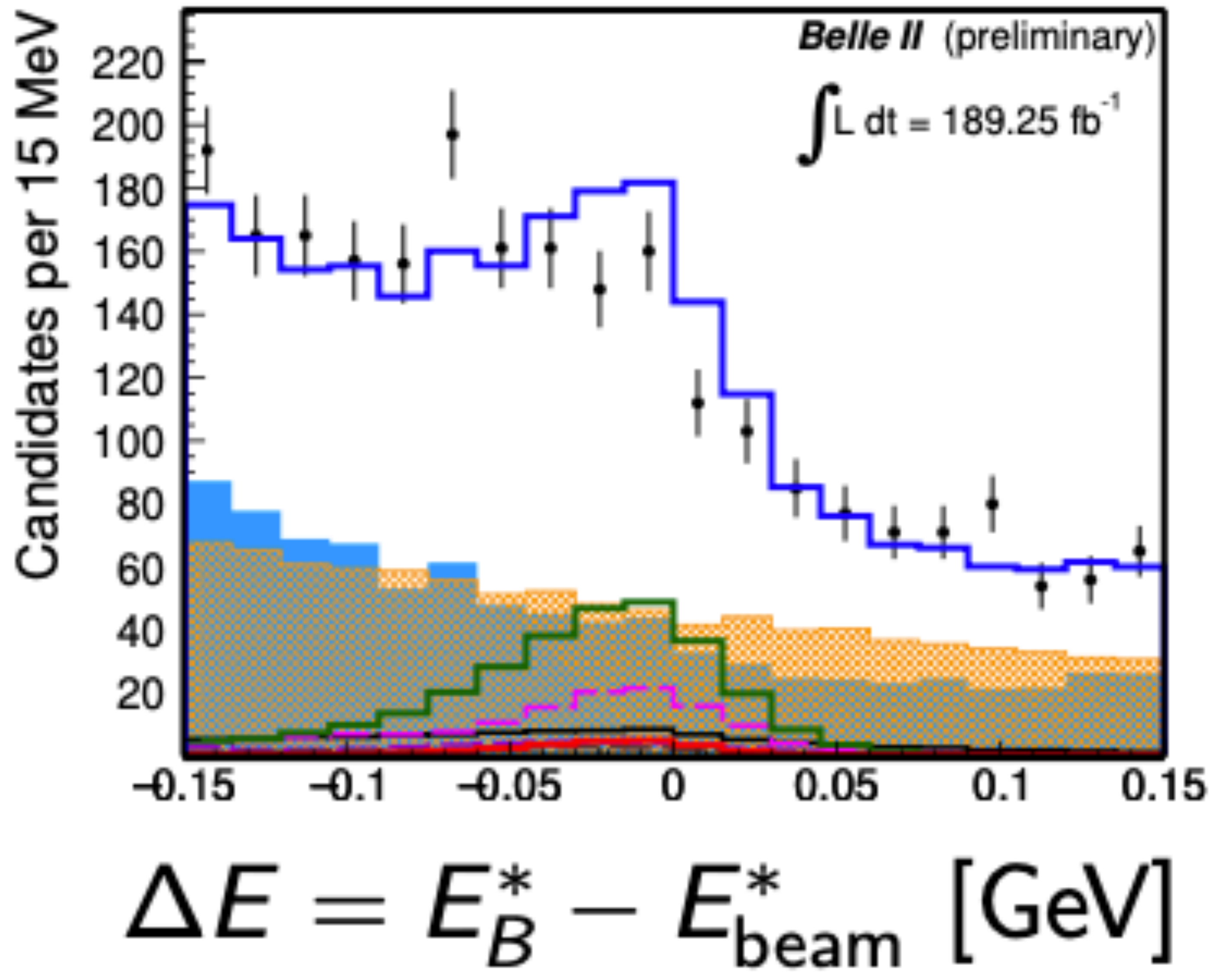
$\cancel{CP}$ due to interference between tree and penguin

$\not{C}\not{P}$ in $B^{\pm} \to \rho^{\pm}\rho^{0}$ decays by Belle II

Firstly showed at Moriond EW 2022 , preliminary

- Large bkg. from: $e^+e^- \to u\bar{u}, d\bar{d}, c\bar{c}, s\bar{s}$
    - Reduced with MVA
- 6D templates fit taking considering correlations in
    - Templates from MC, calibrated using control channels
- Instrumental asymmetry measured with $D^+ \to K_s^0\pi^+$
    - $A_{\rm det} = (0.4 \pm 0.5)\,\%$

talk by Chunhui Chen this morning



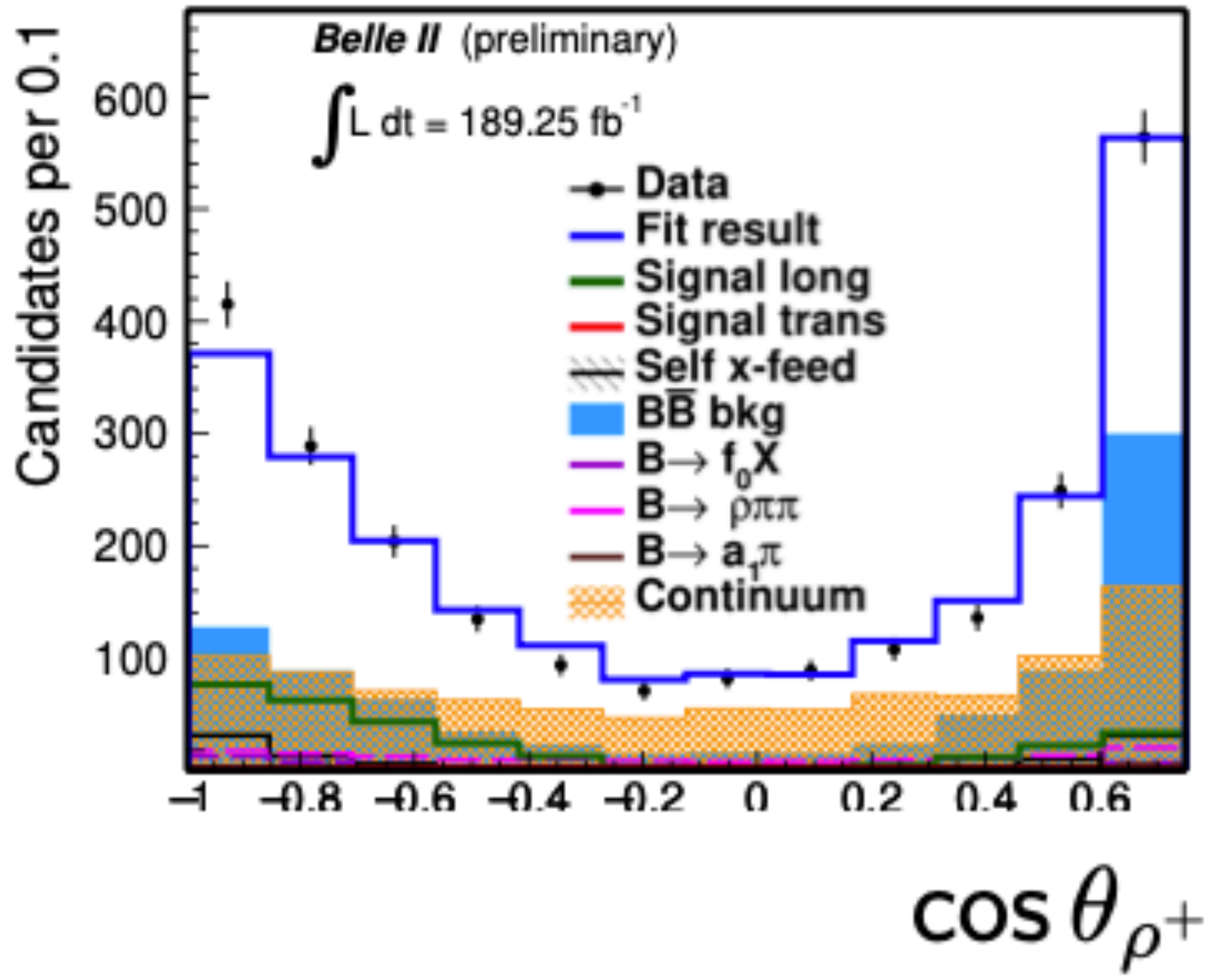
Result compatible with previous measurements:

$$A_{CP}(B^+ \to \rho^+\rho^0) = -0.069 \pm 0.068\,(\text{stat}) \pm 0.060\,(\text{syst.})$$

$$\mathbf{B}(B^+ \to \rho^+\rho^0) = (23.2^{+2.2}_{2.1}\,(\text{stat.}) \pm 2.7\,(\text{syst.})) \times 10^{-6}$$

$$f_L = 0.943^{+0.035}_{-0.033}\,(\text{stat.}) \pm 0.027\,(\text{syst.})$$

World average: $A_{CP}(B^+ \to \rho^+\rho^0) = -0.05 \pm 0.05$



- Belle II performance superior to Belle.
- Systematic uncertainties mainly data-driven, expect to be reduced with more data.

$\cancel{CP}$ search in $B^0 \to p\bar{p}K^+\pi^-$ decays

arXiv:2205.08973

- Promising process to observe for the first time $\cancel{CP}$ in B decays to final states with half-spin particles [Eur.Phys.J. C (2020) 80:565]

- Search for P and CP violation using **triple-product asymmetries**
  - $\hat{T}$-odd observables: $C_{\hat{T}} = \vec{p}_{K^+} \cdot (\vec{p}_{\pi^-} \times \vec{p}_p) \quad \bar{C}_{\hat{T}} = \vec{p}_{K^-} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\bar{p}})$
  - Asymmetries: $A_{\hat{T}} = \dfrac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)}, \quad \bar{A}_{\hat{T}} = \dfrac{\bar{N}(-\bar{C}_{\hat{T}} > 0) - \bar{N}(-\bar{C}_{\hat{T}} < 0)}{\bar{N}(-\bar{C}_{\hat{T}} > 0) + \bar{N}(-\bar{C}_{\hat{T}} < 0)}$
  - P and CP observables: $\boxed{a_P^{\hat{T}\text{-odd}} = \frac{1}{2}(A_{\hat{T}} + \bar{A}_{\hat{T}}) \qquad a_{CP}^{\hat{T}\text{-odd}} = \frac{1}{2}(A_{\hat{T}} - \bar{A}_{\hat{T}})}$

→ Sensitive to interference of P-even and P-odd amplitudes and have different sensitivity to strong phases

→ Not sensitive to reconstruction efficiency and b-hadron production asymmetries

$\cancel{CP}$ search in $B^0 \to p\bar{p}K^+\pi^-$ decays

arXiv:2205.08973

- Measurements:
  - **integrated** over the full phase space

$$a_P^{\hat{T}\text{-odd}} = (1.49 \pm 0.85 \pm 0.08)\%$$
$$a_{CP}^{\hat{T}\text{-odd}} = (0.51 \pm 0.85 \pm 0.08)\%.$$

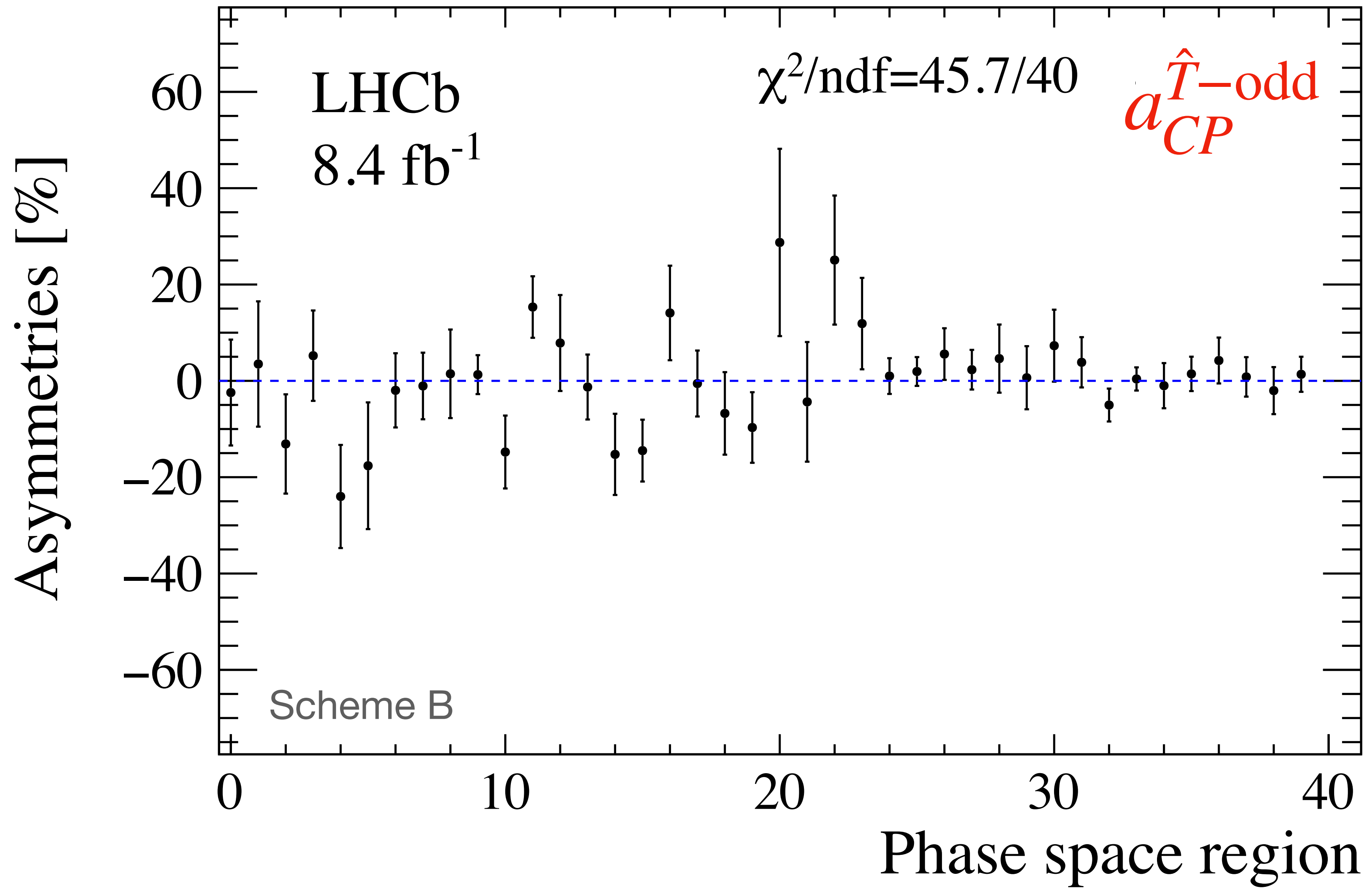
NO evidence of P or CP violation

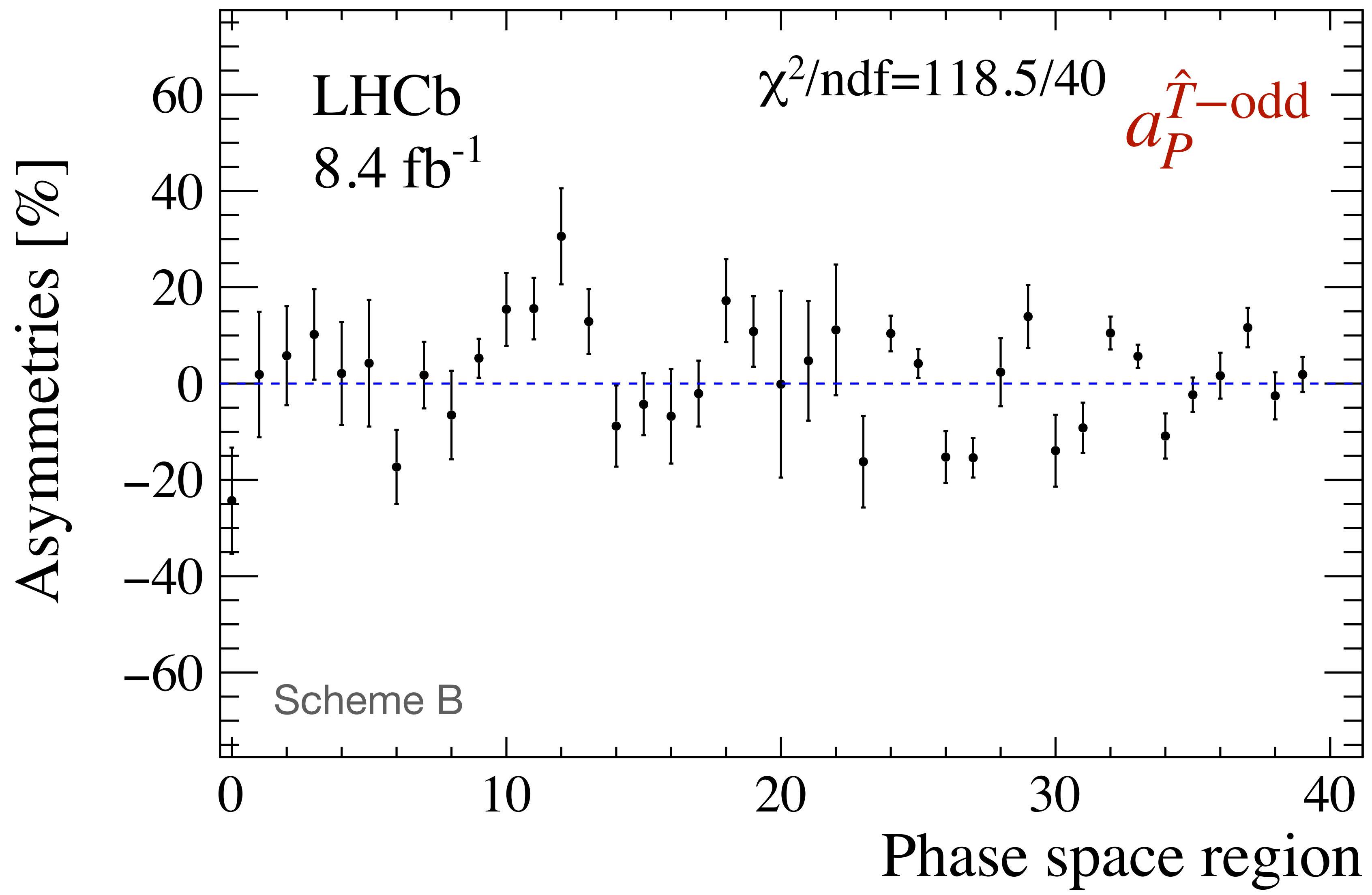
  - **bins** of the phase space enhance sensitivity

CP conservation at 1σ

P violation at 6σ

- Improvements are expected for Run3
  - Higher Luminosity and trigger eff.





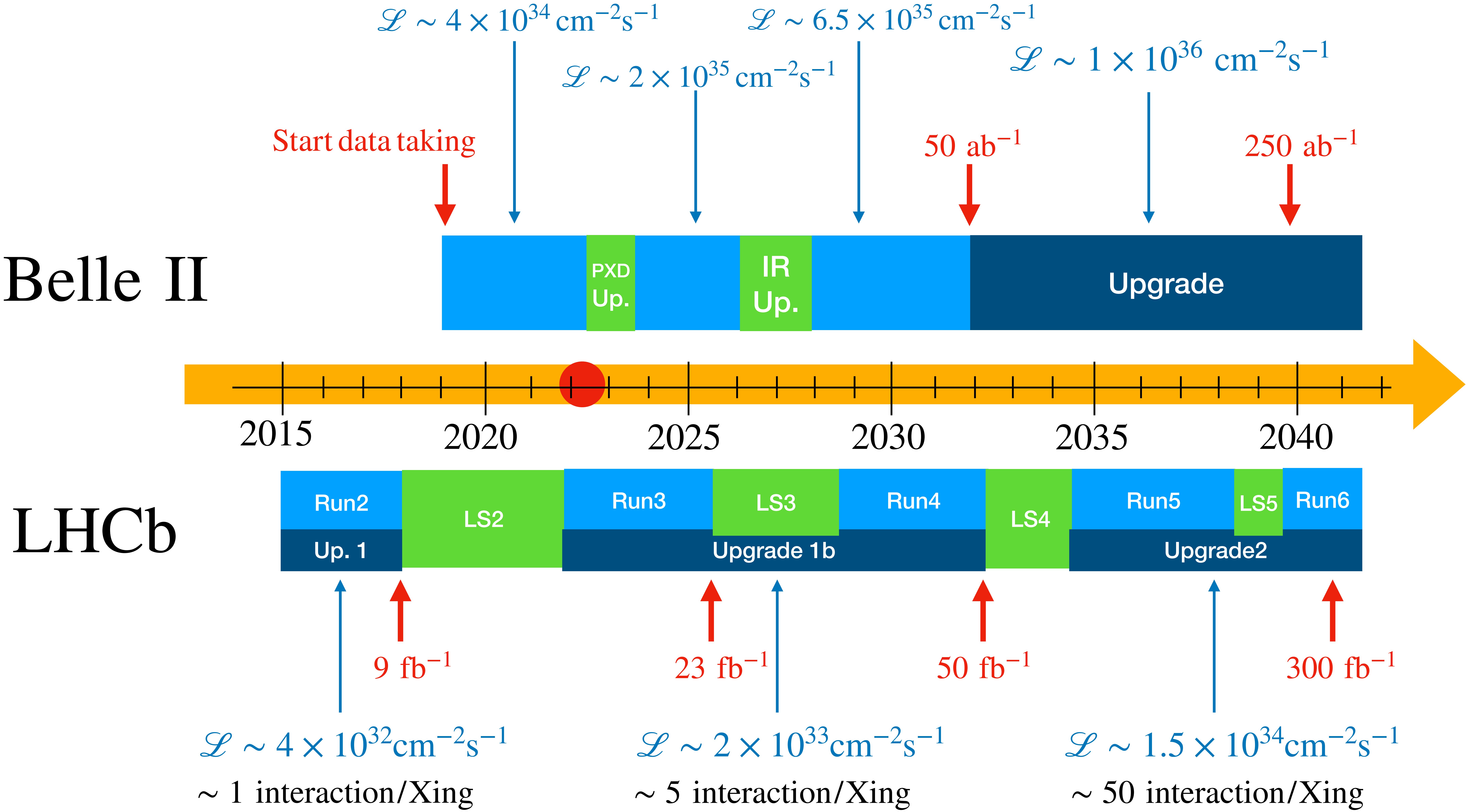
Scheme B: some region edges in the $m(K\pi)$ variable corresponds to the resonance mass pole where the strong phase changes its sign

Some Prospects

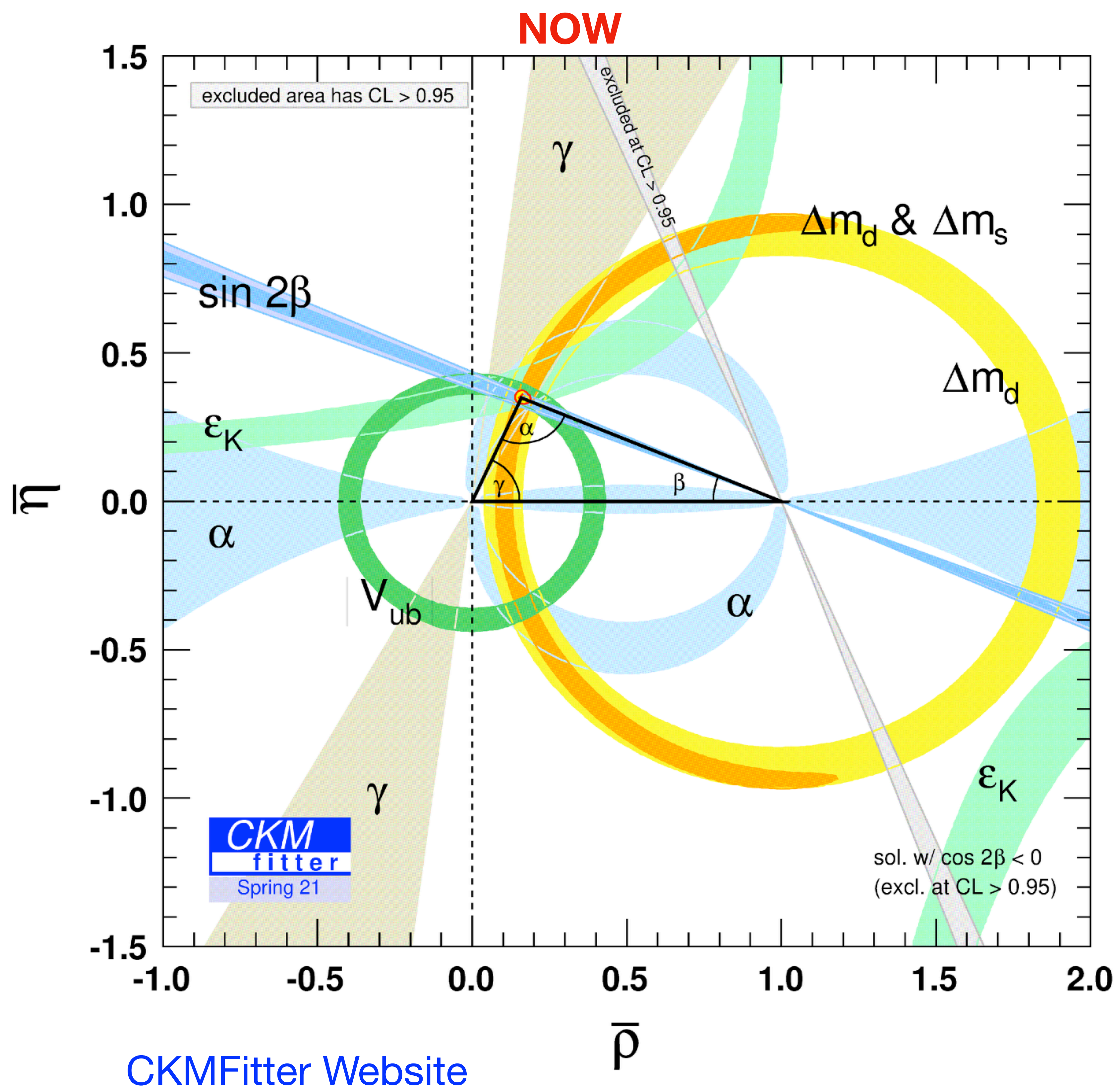
The plan

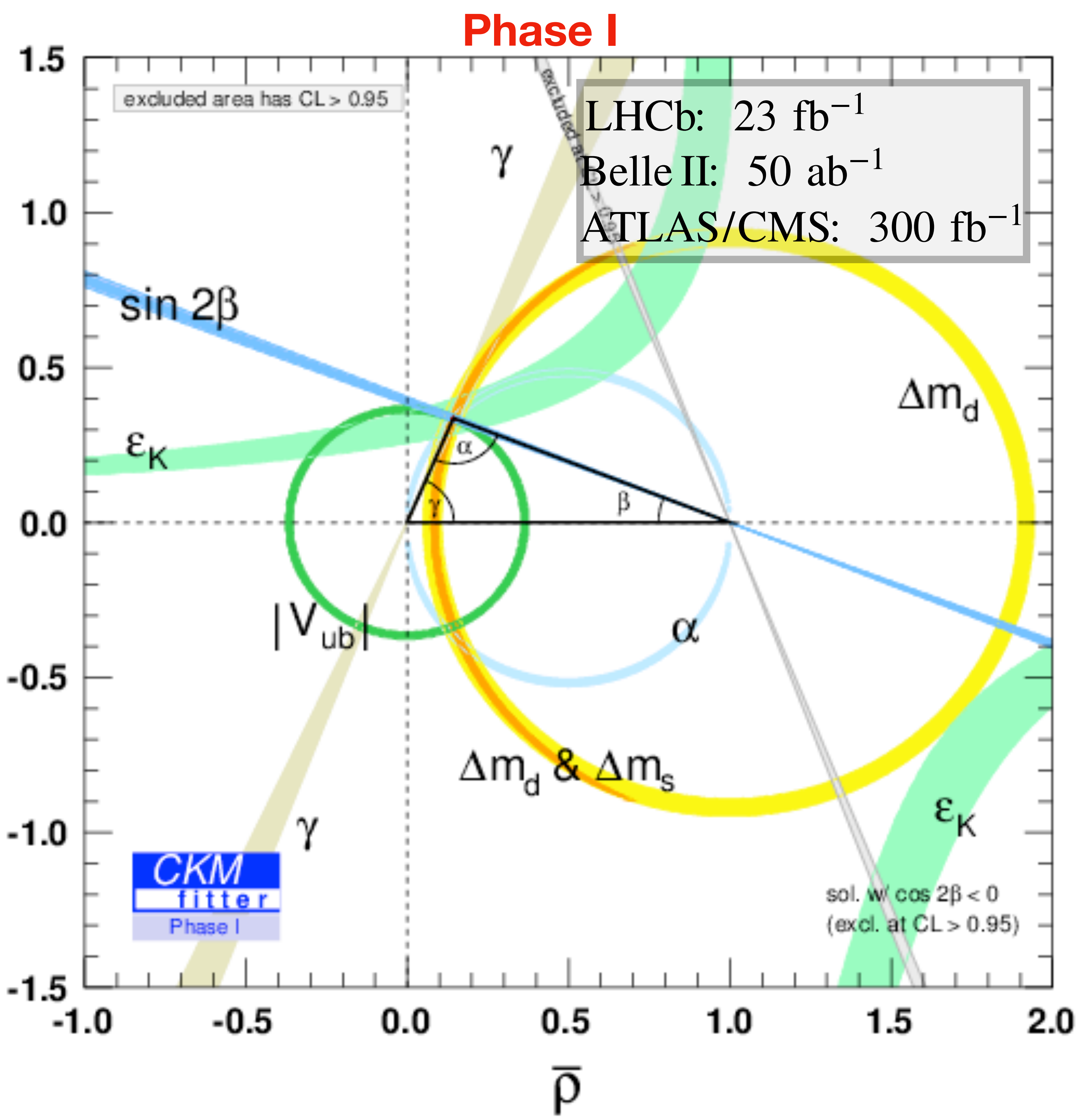
arXiv:2203.11349v1

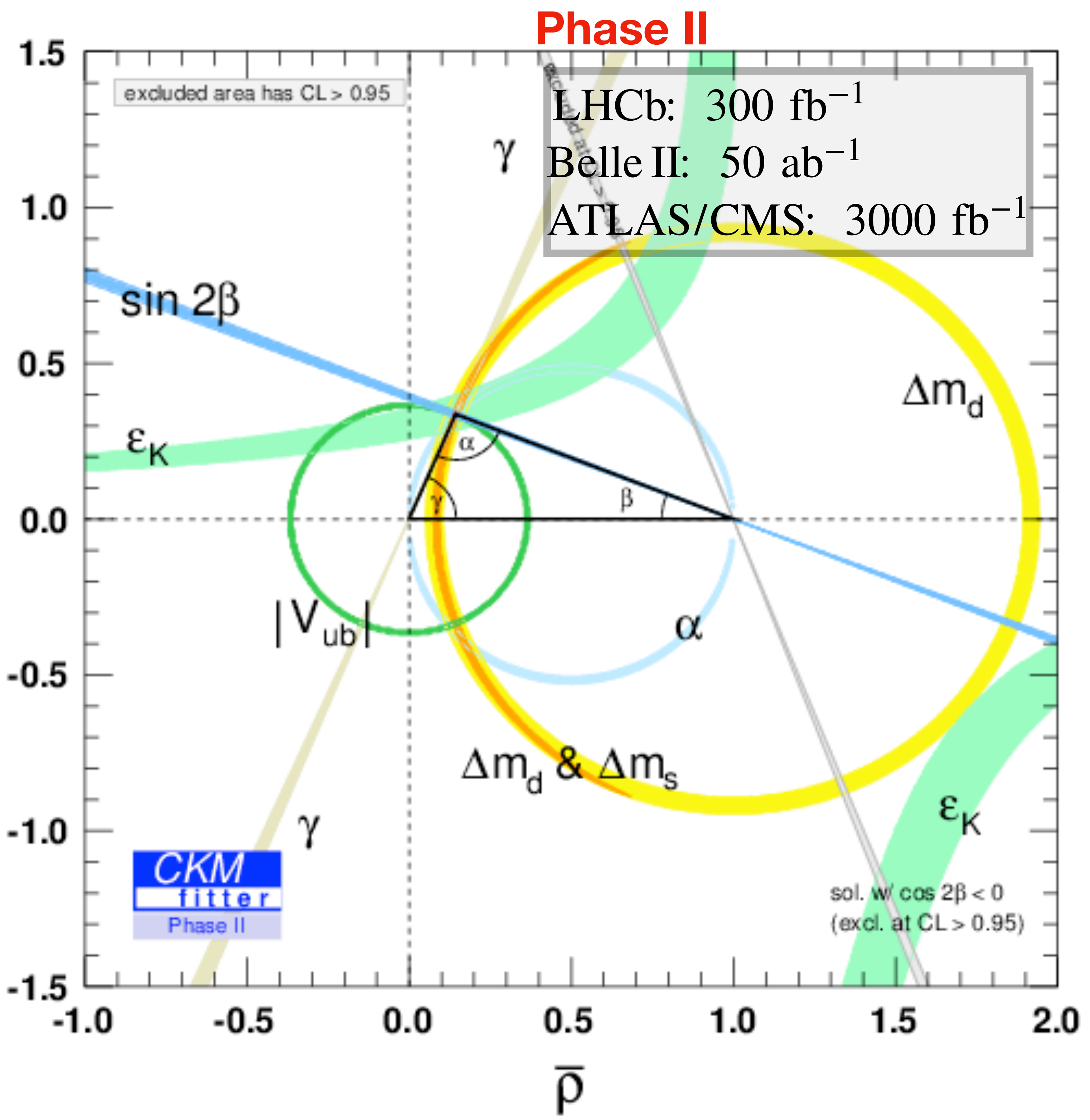
LHCC-2021-012



Future potential for the UT


NOW


Phase I


Phase II

CKMFitter Website

Assumptions:
- current central values
- improvements on lattice

EXPECTED UNCERTAINTIES

Observable	LHCb 50 fb^{-1}	Belle II 50 ab^{-1}	LHCb 300 fb^{-1} + Belle II 250 ab^{-1}
$\alpha \equiv \phi_2$		0.6°	0.3°
$\sin 2\beta \equiv \sin 2\phi_1$	0.006	0.005	< 0.002
$\gamma \equiv \phi_3$	1.5°	1.5°	$< 0.35°$

Belle II Physics Program White Paper

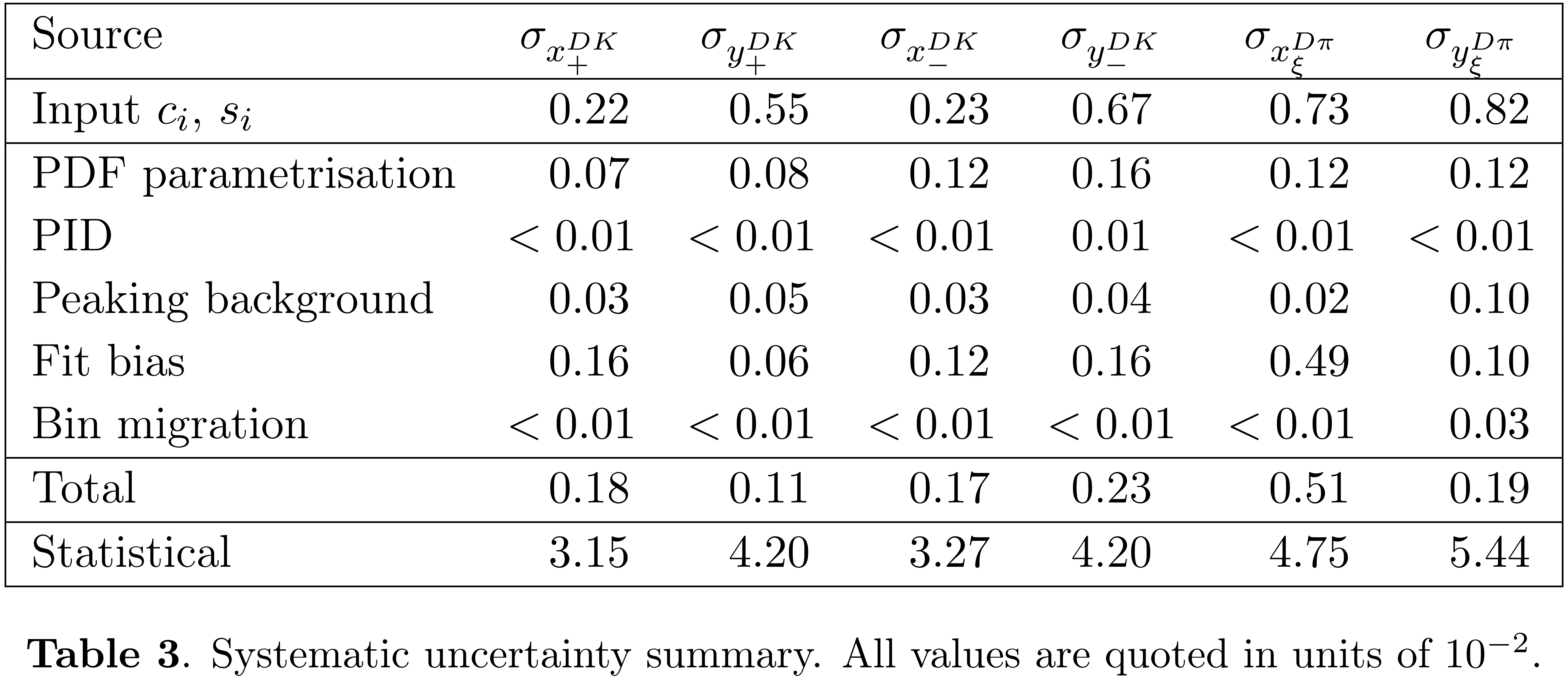
Belle II Detector Upgrade Program

Physics Case for LHCb Upgrade II

Backup

γ using $B^{\pm} \to Dh^{+}$ ($D \to K_s^0 h^+ h^-$) by Belle + Belle II

JHEP 02, 063 (2022)

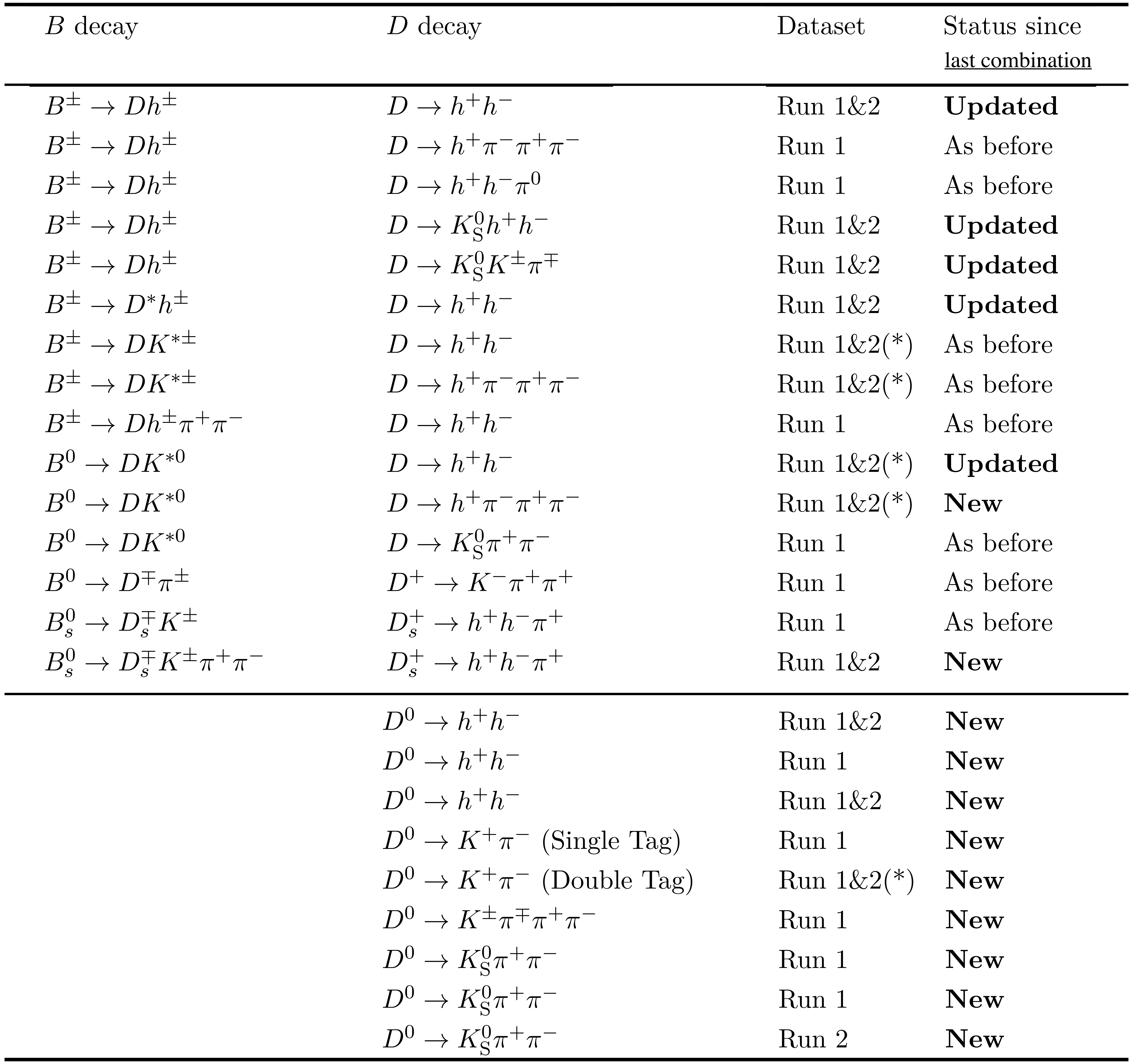


Source	$\sigma_{x_+^{DK}}$	$\sigma_{y_+^{DK}}$	$\sigma_{x_-^{DK}}$	$\sigma_{y_-^{DK}}$	$\sigma_{x_\xi^{D\pi}}$	$\sigma_{y_\xi^{D\pi}}$
Input c_i, s_i	0.22	0.55	0.23	0.67	0.73	0.82
PDF parametrisation	0.07	0.08	0.12	0.16	0.12	0.12
PID	< 0.01	< 0.01	< 0.01	0.01	< 0.01	< 0.01
Peaking background	0.03	0.05	0.03	0.04	0.02	0.10
Fit bias	0.16	0.06	0.12	0.16	0.49	0.10
Bin migration	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.03
Total	0.18	0.11	0.17	0.23	0.51	0.19
Statistical	3.15	4.20	3.27	4.20	4.75	5.44

Table 3. Systematic uncertainty summary. All values are quoted in units of 10^{-2}.

LHCb combination of UT angle γ

JHEP 12 (2021) 141

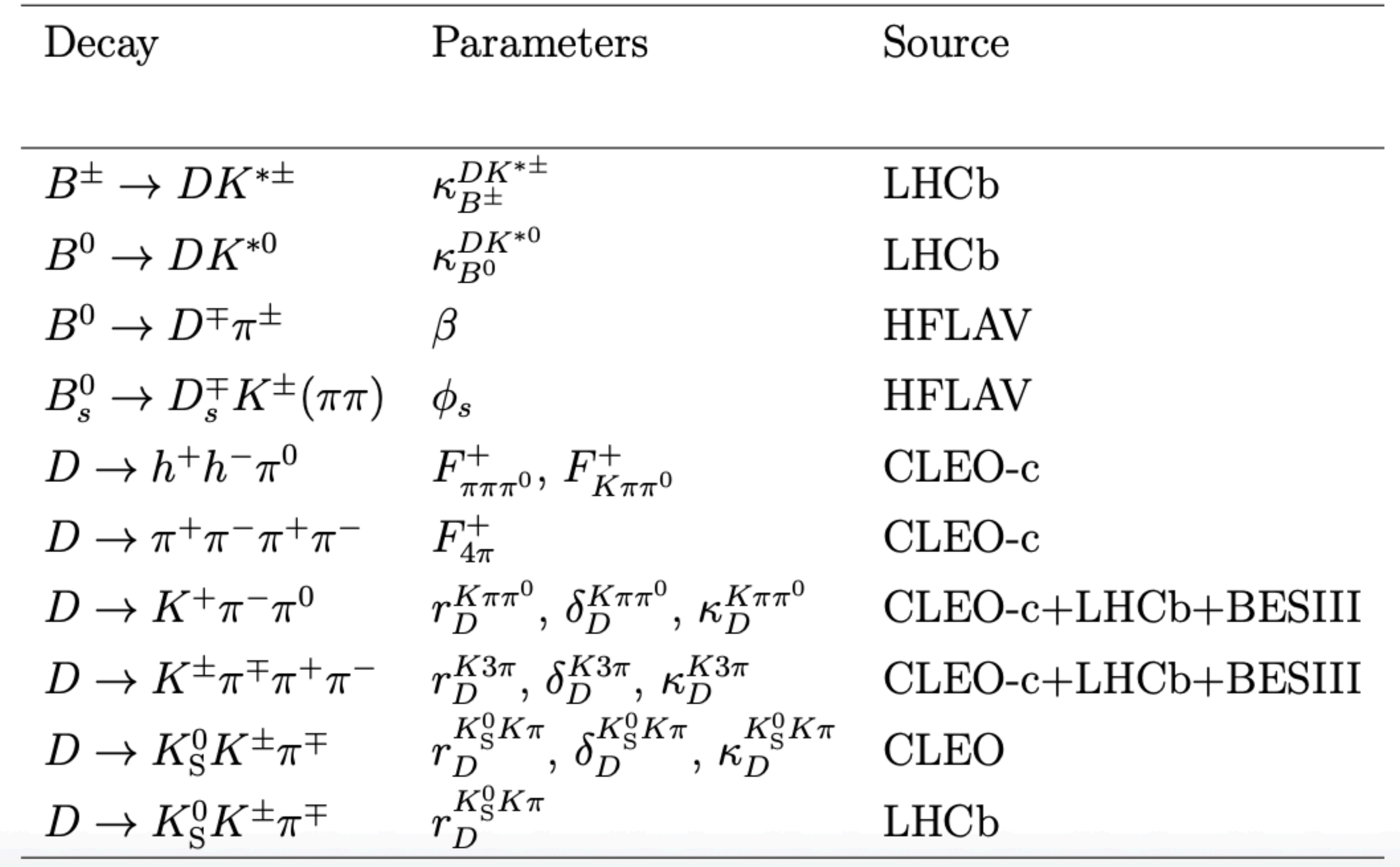


B decay	D decay	Dataset	Status since last combination
$B^{\pm} \to Dh^{\pm}$	$D \to h^+h^-$	Run 1&2	**Updated**
$B^{\pm} \to Dh^{\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	Run 1	As before
$B^{\pm} \to Dh^{\pm}$	$D \to h^+h^-\pi^0$	Run 1	As before
$B^{\pm} \to Dh^{\pm}$	$D \to K^0_S h^+h^-$	Run 1&2	**Updated**
$B^{\pm} \to Dh^{\pm}$	$D \to K^0_S K^{\pm}\pi^{\mp}$	Run 1&2	**Updated**
$B^{\pm} \to D^*h^{\pm}$	$D \to h^+h^-$	Run 1&2	**Updated**
$B^{\pm} \to DK^{*\pm}$	$D \to h^+h^-$	Run 1&2(*)	As before
$B^{\pm} \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	Run 1&2(*)	As before
$B^{\pm} \to Dh^{\pm}\pi^+\pi^-$	$D \to h^+h^-$	Run 1	As before
$B^0 \to DK^{*0}$	$D \to h^+h^-$	Run 1&2(*)	**Updated**
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	Run 1&2(*)	**New**
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	Run 1	As before
$B^0 \to D^{\mp}\pi^{\pm}$	$D^+ \to K^-\pi^+\pi^+$	Run 1	As before
$B^0_s \to D_s^{\mp}K^{\pm}$	$D_s^+ \to h^+h^-\pi^+$	Run 1	As before
$B^0_s \to D_s^{\mp}K^{\pm}\pi^+\pi^-$	$D_s^+ \to h^+h^-\pi^+$	Run 1&2	**New**
	$D^0 \to h^+h^-$	Run 1&2	**New**
	$D^0 \to h^+h^-$	Run 1	**New**
	$D^0 \to h^+h^-$	Run 1&2	**New**
	$D^0 \to K^+\pi^-$ (Single Tag)	Run 1	**New**
	$D^0 \to K^+\pi^-$ (Double Tag)	Run 1&2(*)	**New**
	$D^0 \to K^{\pm}\pi^{\mp}\pi^+\pi^-$	Run 1	**New**
	$D^0 \to K^0_S\pi^+\pi^-$	Run 1	**New**
	$D^0 \to K^0_S\pi^+\pi^-$	Run 1	**New**
	$D^0 \to K^0_S\pi^+\pi^-$	Run 2	**New**

γ combination: auxiliary inputs

JHEP 12 (2021) 141

- External inputs to the combination



Decay	Parameters	Source
$B^{\pm} \to DK^{*\pm}$	$\kappa_{B^{\pm}}^{DK^{*\pm}}$	LHCb
$B^{0} \to DK^{*0}$	$\kappa_{B^{0}}^{DK^{*0}}$	LHCb
$B^{0} \to D^{\mp}\pi^{\pm}$	β	HFLAV
$B_s^{0} \to D_s^{\mp}K^{\pm}(\pi\pi)$	ϕ_s	HFLAV
$D \to h^{+}h^{-}\pi^{0}$	$F_{\pi\pi\pi^0}^{+}$, $F_{K\pi\pi^0}^{+}$	CLEO-c
$D \to \pi^{+}\pi^{-}\pi^{+}\pi^{-}$	$F_{4\pi}^{+}$	CLEO-c
$D \to K^{+}\pi^{-}\pi^{0}$	$r_D^{K\pi\pi^0}$, $\delta_D^{K\pi\pi^0}$, $\kappa_D^{K\pi\pi^0}$	CLEO-c+LHCb+BESIII
$D \to K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$	$r_D^{K3\pi}$, $\delta_D^{K3\pi}$, $\kappa_D^{K3\pi}$	CLEO-c+LHCb+BESIII
$D \to K_{\rm S}^{0}K^{\pm}\pi^{\mp}$	$r_D^{K_{\rm S}^0 K\pi}$, $\delta_D^{K_{\rm S}^0 K\pi}$, $\kappa_D^{K_{\rm S}^0 K\pi}$	CLEO
$D \to K_{\rm S}^{0}K^{\pm}\pi^{\mp}$	$r_D^{K_{\rm S}^0 K\pi}$	LHCb

γ using $B^\pm \to Dh^\pm$ $(D \to h^+h'^\pm\pi^0)$ by LHCb

arXiv:2112.10617

submitted to JHEP

$$R_K^{\mp} \equiv \frac{\Gamma(B^\mp \to [\pi^\mp K^\pm \pi^0]_D K^\mp)}{\Gamma(B^\mp \to [K^\mp \pi^\pm \pi^0]_D K^\mp)},$$

$$R_\pi^{\mp} \equiv \frac{\Gamma(B^\mp \to [\pi^\mp K^\pm \pi^0]_D \pi^\mp)}{\Gamma(B^\mp \to [K^\mp \pi^\pm \pi^0]_D \pi^\mp)}.$$

$$A_K^{hh\pi^0} = \frac{\Gamma(B^- \to [hh\pi^0]_D K^-) - \Gamma(B^+ \to [hh\pi^0]_D K^+)}{\Gamma(B^- \to [hh\pi^0]_D K^-) + \Gamma(B^+ \to [hh\pi^0]_D K^+)},$$

$$A_\pi^{hh\pi^0} = \frac{\Gamma(B^- \to [hh\pi^0]_D \pi^-) - \Gamma(B^+ \to [hh\pi^0]_D \pi^+)}{\Gamma(B^- \to [hh\pi^0]_D \pi^-) + \Gamma(B^+ \to [hh\pi^0]_D \pi^+)}$$

$$R^{KK\pi^0} = R_{K/\pi}^{KK\pi^0} / R_{K/\pi}^{K\pi\pi^0}, \qquad R^{\pi\pi\pi^0} = R_{K/\pi}^{\pi\pi\pi^0} / R_{K/\pi}^{K\pi\pi^0},$$

$$R_{K/\pi}^{hh\pi^0} = \frac{\Gamma(B^- \to [hh\pi^0]_D K^-) + \Gamma(B^+ \to [hh\pi^0]_D K^+)}{\Gamma(B^- \to [hh\pi^0]_D \pi^-) + \Gamma(B^+ \to [hh\pi^0]_D \pi^+)}$$

$$A_K^{K\pi\pi^0} = \frac{\Gamma(B^- \to [K^-\pi^+\pi^0]_D K^-) - \Gamma(B^+ \to [K^+\pi^-\pi^0]_D K^+)}{\Gamma(B^- \to [K^-\pi^+\pi^0]_D K^-) + \Gamma(B^+ \to [K^+\pi^-\pi^0]_D K^+)}.$$

$$R_{\mathrm{ADS}(h)} = \frac{\Gamma(B^- \to [\pi^- K^+ \pi^0]_D h^-) + \Gamma(B^- \to [\pi^- K^+ \pi^0]_D h^-)}{\Gamma(B^- \to [K^- \pi^+ \pi^0]_D h^-) + \Gamma(B^- \to [K^- \pi^+ \pi^0]_D h^-)}$$

$$A_{\mathrm{ADS}(h)} = \frac{\Gamma(B^- \to [\pi^- K^+ \pi^0]_D h^-) - \Gamma(B^- \to [\pi^- K^+ \pi^0]_D h^-)}{\Gamma(B^- \to [\pi^- K^+ \pi^0]_D h^-) + \Gamma(B^- \to [\pi^- K^+ \pi^0]_D h^-)}.$$

The results for the observables, as determined by the fit, are

$$\begin{array}{rcrcrcl}
R^{KK\pi^0} & = & 1.021 & \pm & 0.079 & \pm & 0.005 \\
R^{\pi\pi\pi^0} & = & 0.902 & \pm & 0.041 & \pm & 0.004 \\
A_K^{K\pi\pi^0} & = & -0.024 & \pm & 0.013 & \pm & 0.002 \\
A_K^{KK\pi^0} & = & 0.067 & \pm & 0.073 & \pm & 0.003 \\
A_K^{\pi\pi\pi^0} & = & 0.109 & \pm & 0.043 & \pm & 0.003 \\
A_\pi^{KK\pi^0} & = & -0.001 & \pm & 0.019 & \pm & 0.002 \\
A_\pi^{\pi\pi\pi^0} & = & 0.001 & \pm & 0.010 & \pm & 0.002 \\
R_K^+ & = & 0.0179 & \pm & 0.0024 & \pm & 0.0003 \\
R_K^- & = & 0.0085 & \pm & 0.0020 & \pm & 0.0004 \\
R_\pi^+ & = & 0.00188 & \pm & 0.00027 & \pm & 0.00005 \\
R_\pi^- & = & 0.00227 & \pm & 0.00028 & \pm & 0.00004,
\end{array}$$

where the first uncertainties are statistical and the second are systematic. The four $R_h^\pm$ observables can be used to calculate

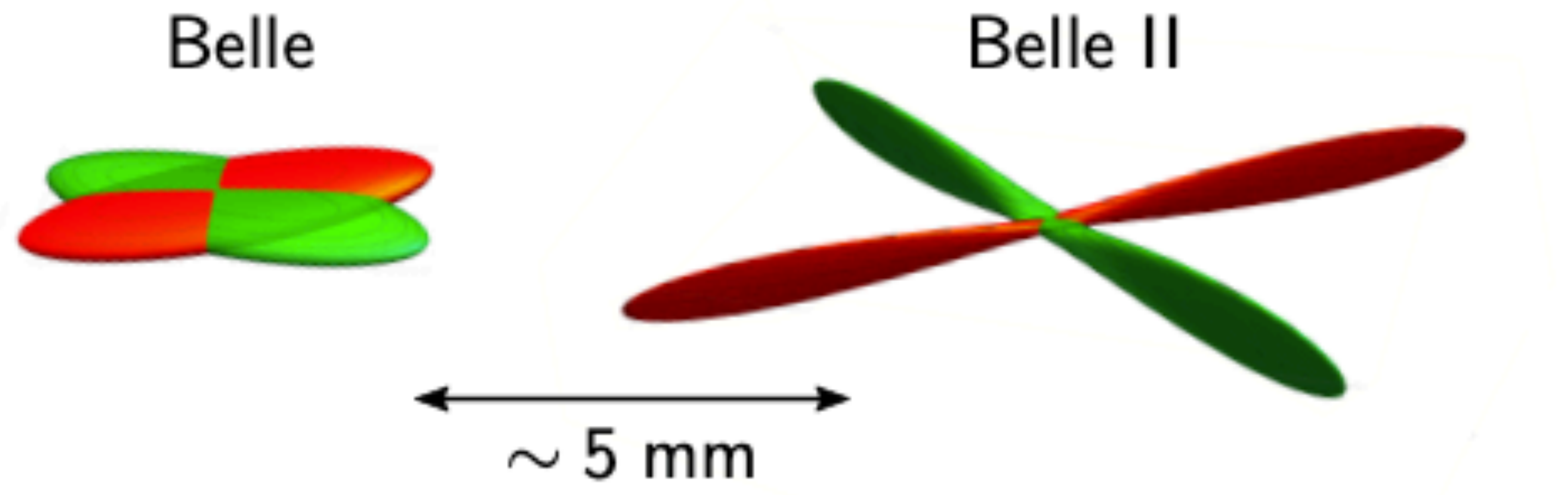
$$\begin{array}{rcrcrcl}
R_{\mathrm{ADS}(K)} & = & 0.0127 & \pm & 0.0016 & \pm & 0.0002 \\
A_{\mathrm{ADS}(K)} & = & -0.38 & \pm & 0.12 & \pm & 0.02 \\
R_{\mathrm{ADS}(\pi)} & = & 0.00207 & \pm & 0.00020 & \pm & 0.00003 \\
A_{\mathrm{ADS}(\pi)} & = & 0.069 & \pm & 0.094 & \pm & 0.016,
\end{array}$$

The results for the ADS observables are more precise than those obtained by previous experiments and are compatible with them.

Belle II and SuperKEKB

SuperKEKB e^+e^- collider achieves higher instant luminosity using so-called nano beam scheme.

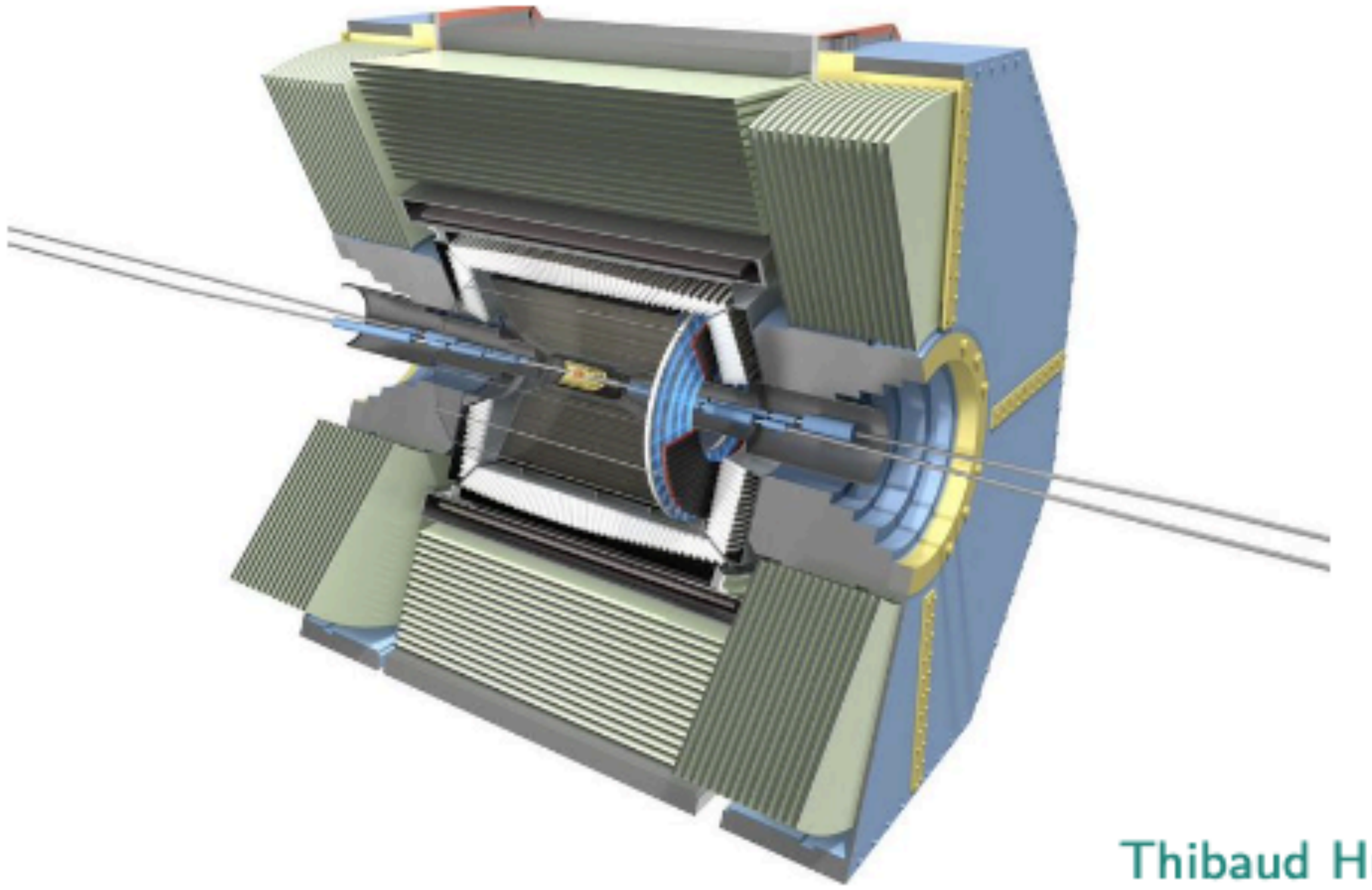
- Goal: $L = 6 \times 10^{35}\ \mathrm{cm}^{-2}s^{-1}$ (30× Belle)
- Achieved: $3.8 \times 10^{34}\ \mathrm{cm}^{-2}s^{-1}$ World record!



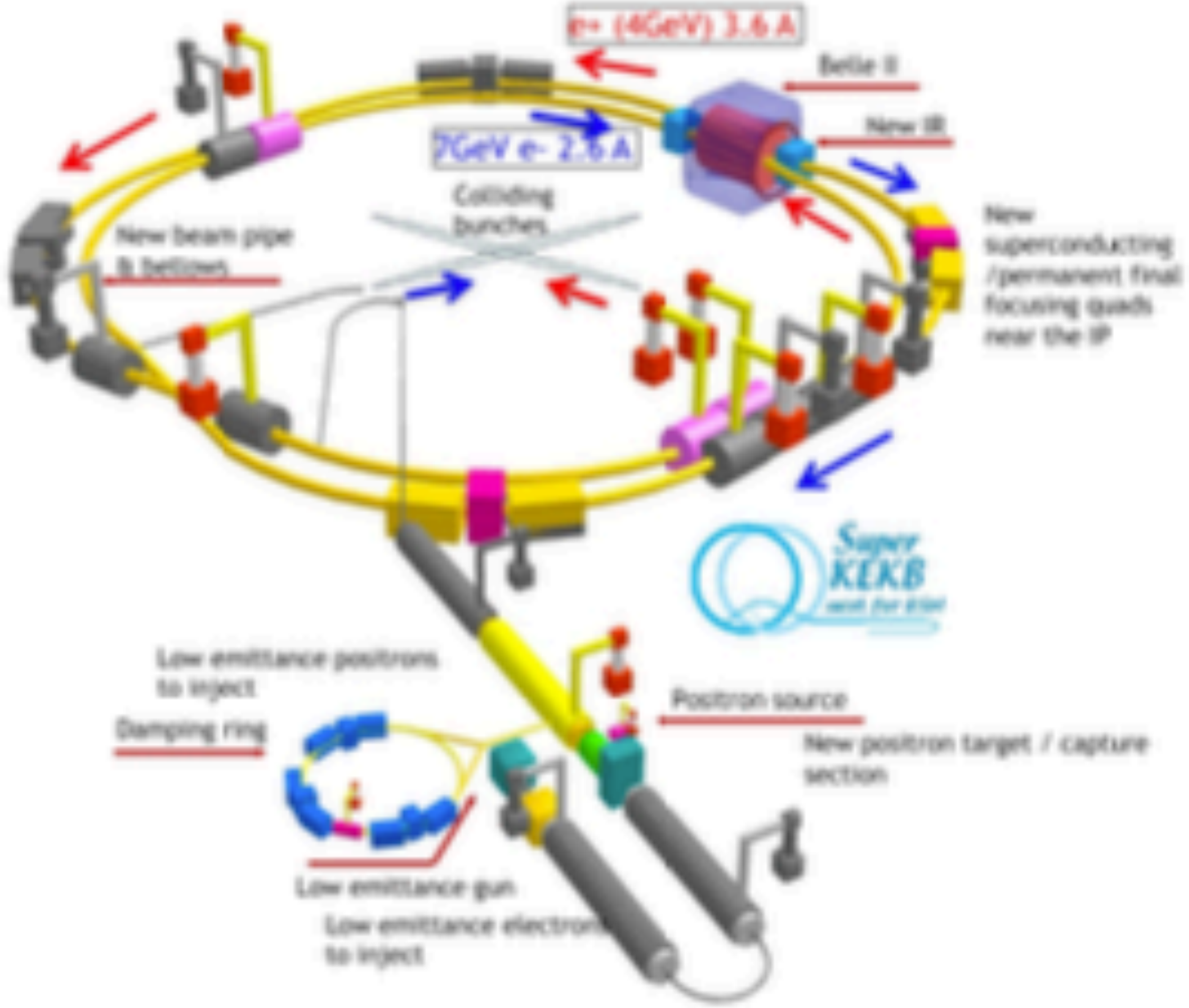
Belle II: all sub-detectors underwent a major upgrade from Belle, improving performance in spite of higher beam background, *e.g.*:

⇒ Enhanced K/π separation

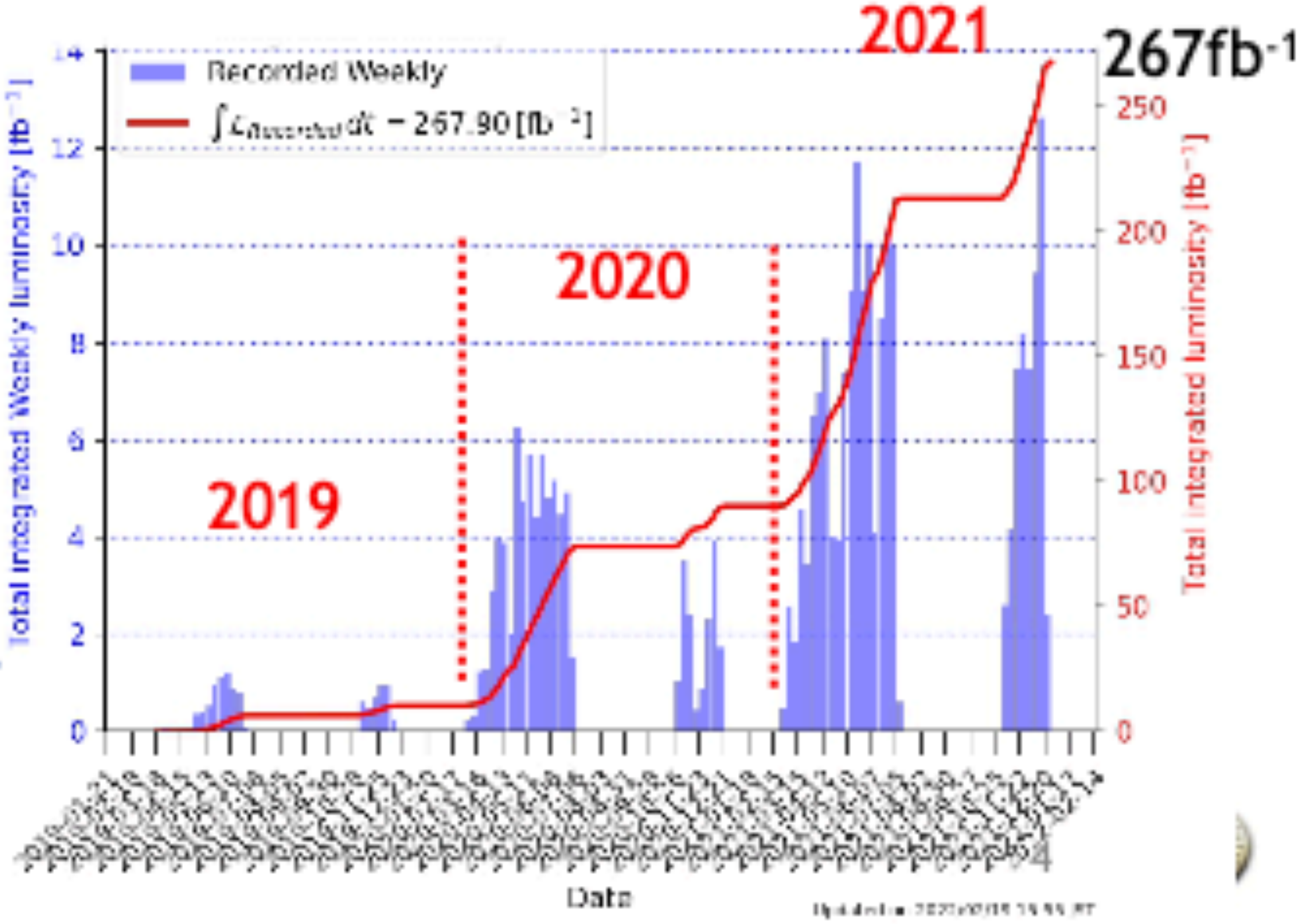
⇒ Improved vertex resolution (more later...)



The SKB/Belle II program

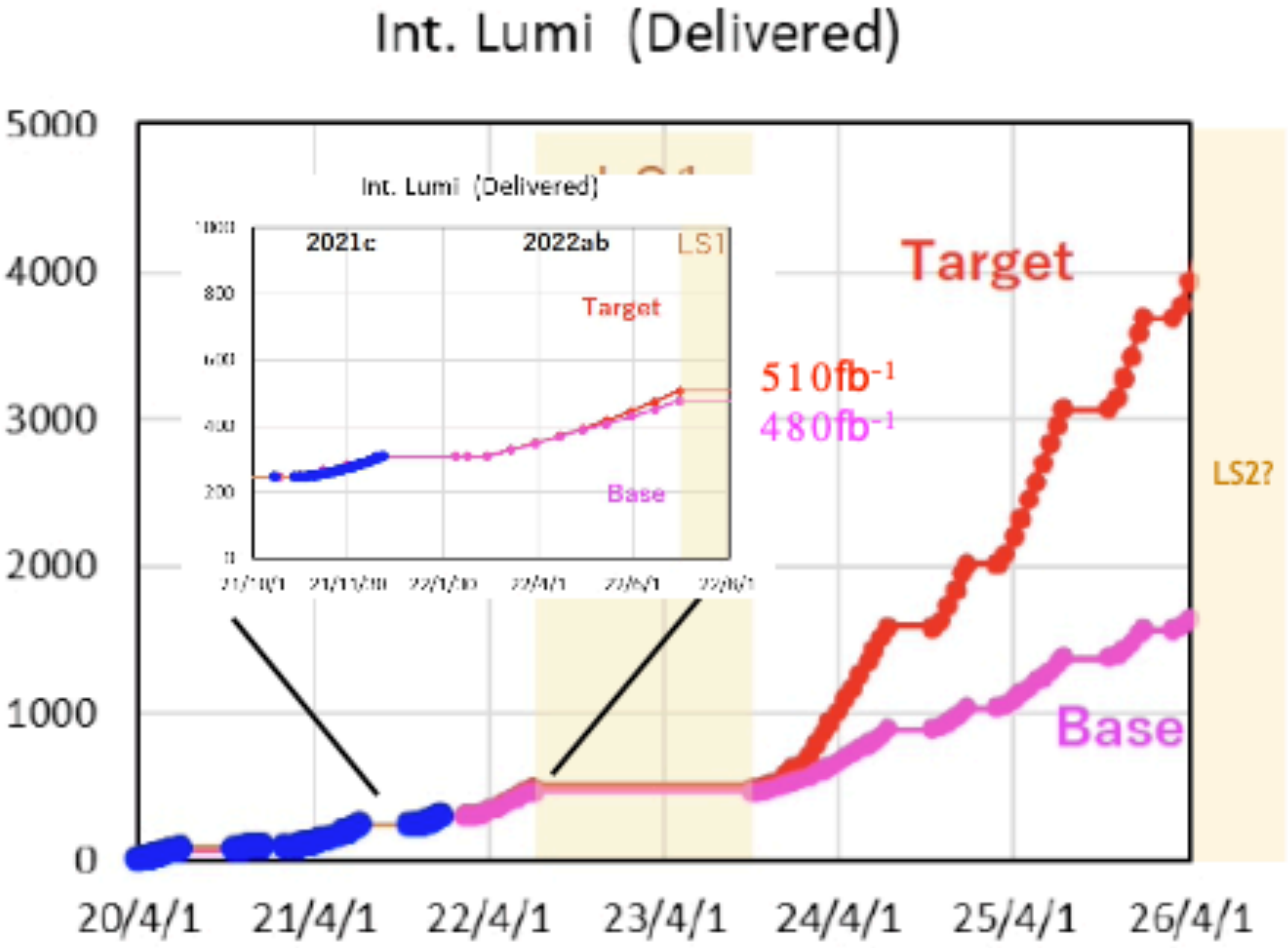


- Phase 1(2016): no detector, no collision, test the rings
- Phase 2 (2018): first collisions with complete accelerator
  - Incomplete detector: Vertex detector replaced by dedicated background detector (Beast 2)
- Phase 3 (2019-): luminosity run with complete detector
  - Pixel Detector (PXD): layer 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 × 10^{34}cm^{-2}s^{-1}.
- Path to reach 2 × 10^{35}cm^{-2}s^{-1} identified.
- Still large factors to reach the target peak luminosity of 6.5 × 10^{35}cm^{-2}s^{-1}.



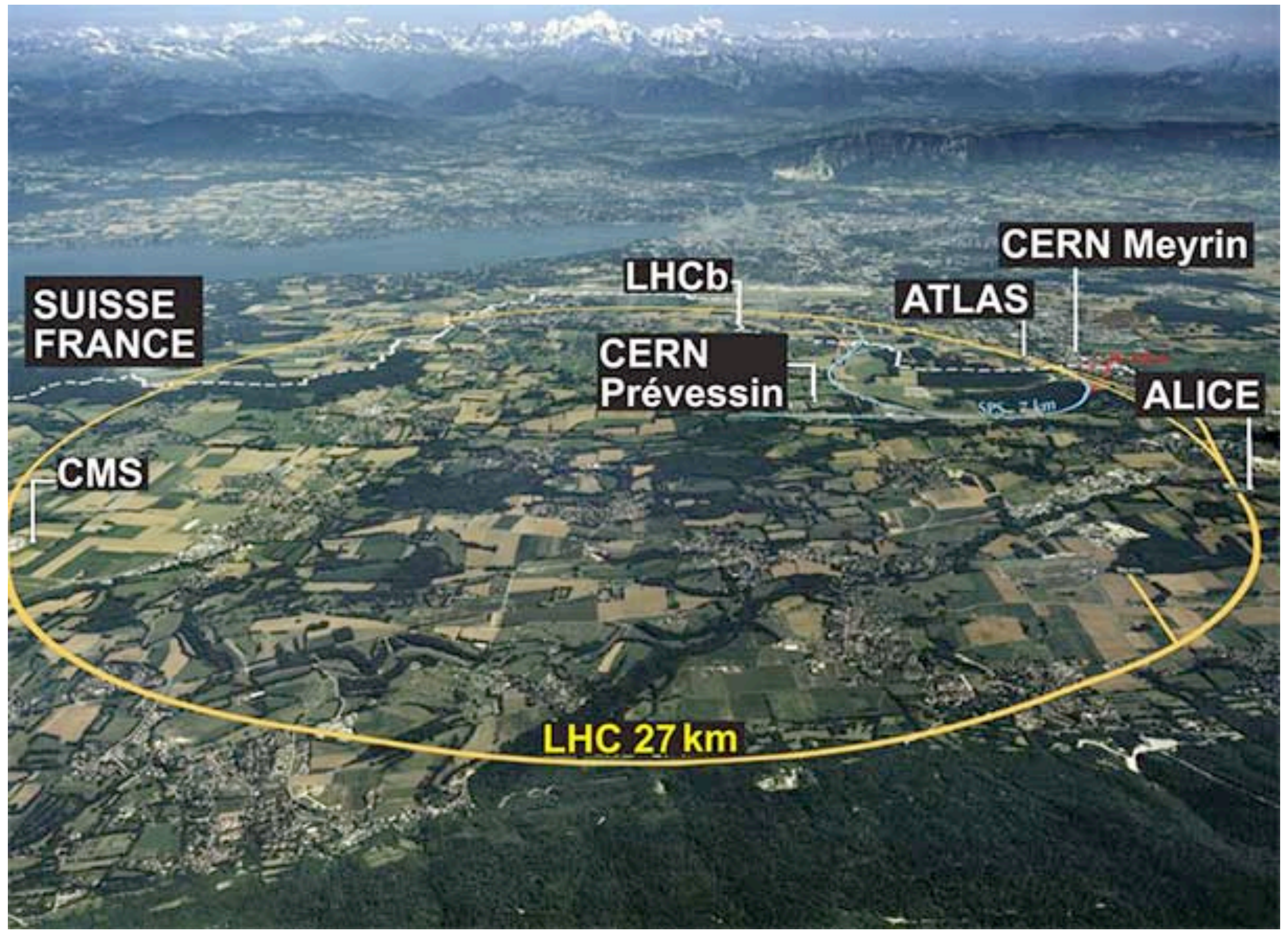
Short term luminosity projections

- Base scenario: conservative extrapolation of SKB parameters from 2021
- Target scenario: extrapolation including possible improvement during LS1
- LS1 starts in summer 2022 for 15 months to replace VXD. There will be other maintenance/improvement work on machine and detector.
- We resume machine operation from fall 2023.
- An International Taskforce (aiming to conclude in summer 2022) is discussing additional improvements.

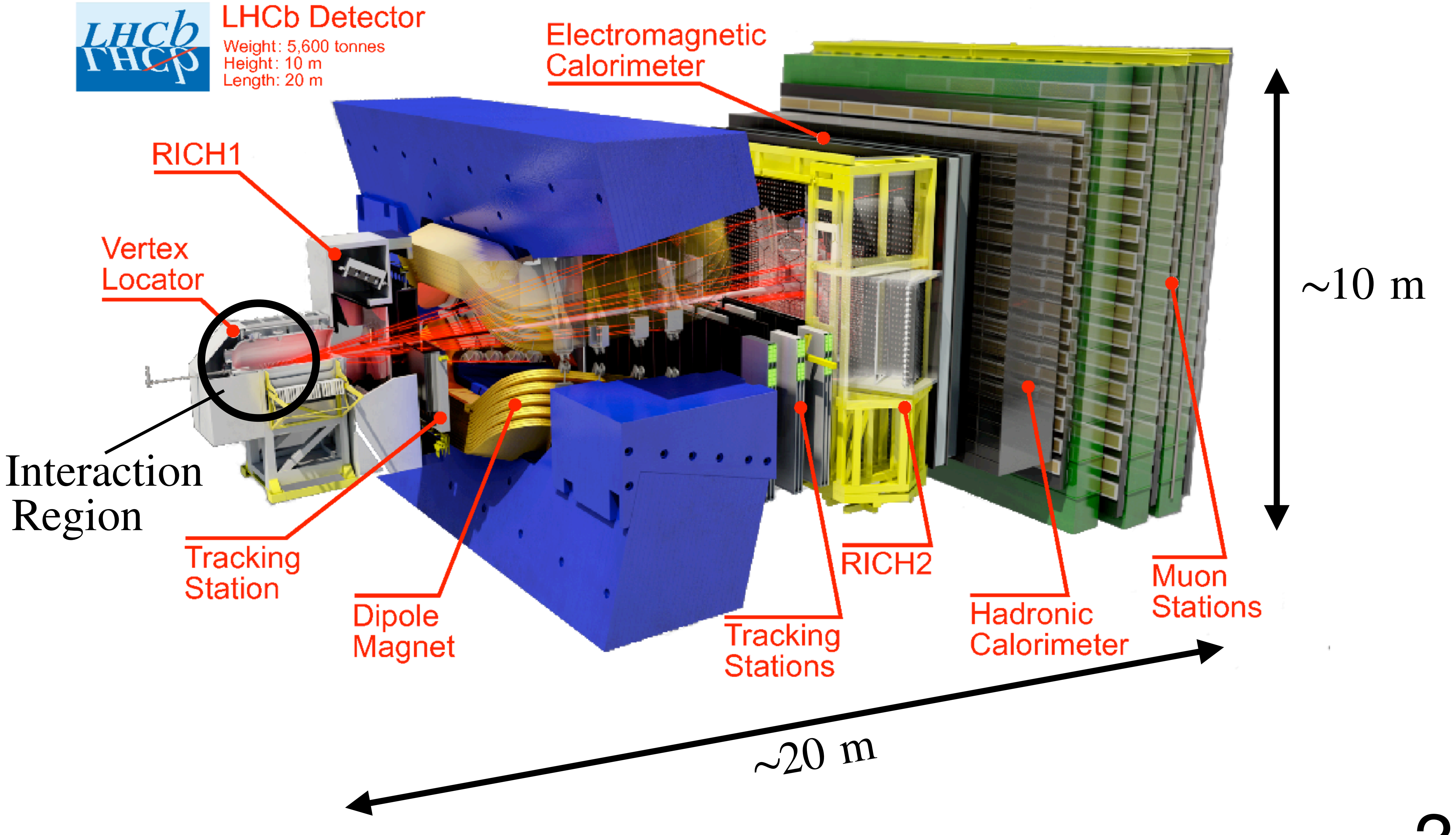


The LHCb experiment

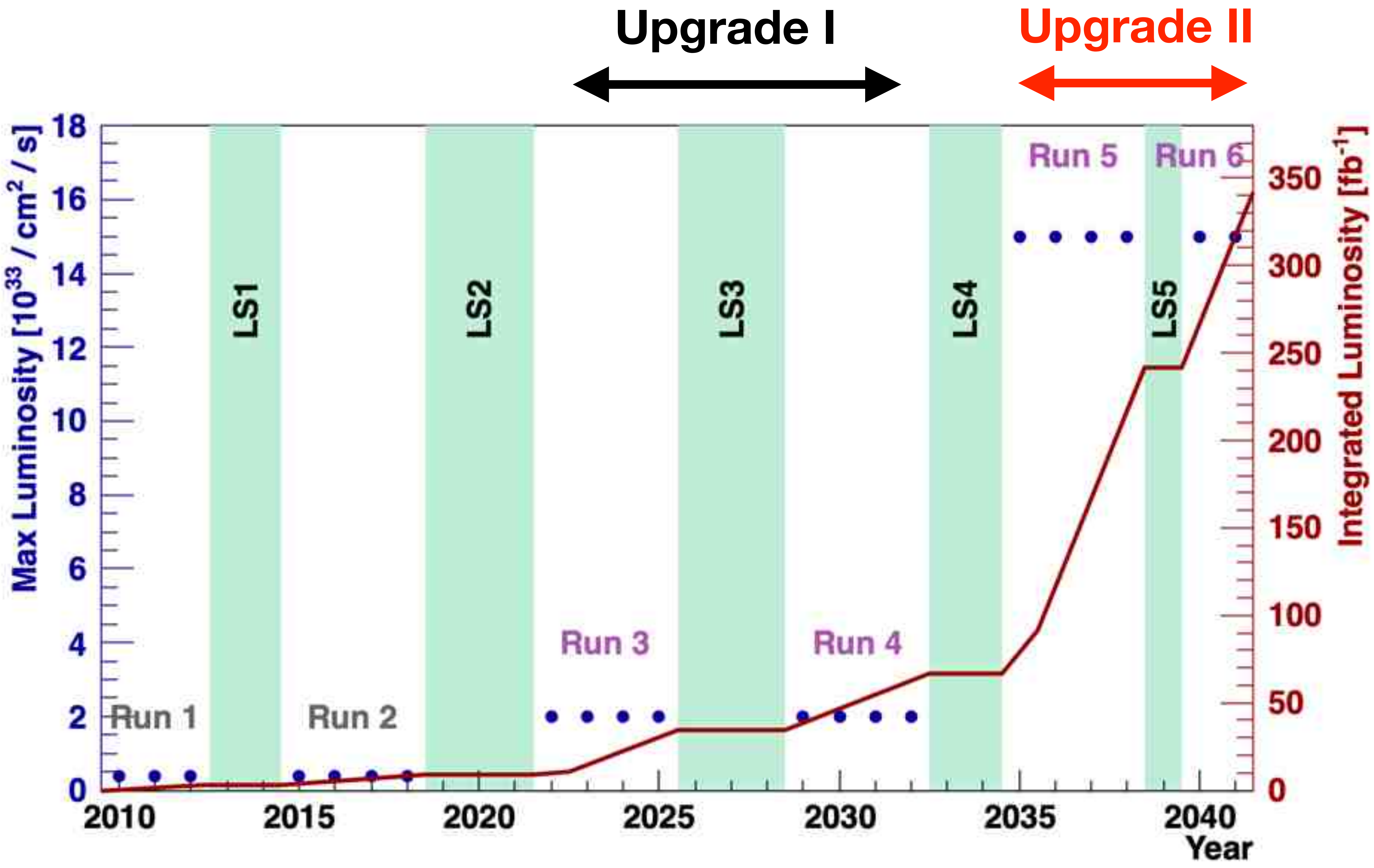
- LHCb is a forward spectrometer, operating at LHC ($\sqrt{s} = 13$ TeV)
  - High geometrical efficiency in collecting $b\bar{b}$ and $c\bar{c}$ quark pairs
  - Excellent time resolution, momentum resolution, PID performances



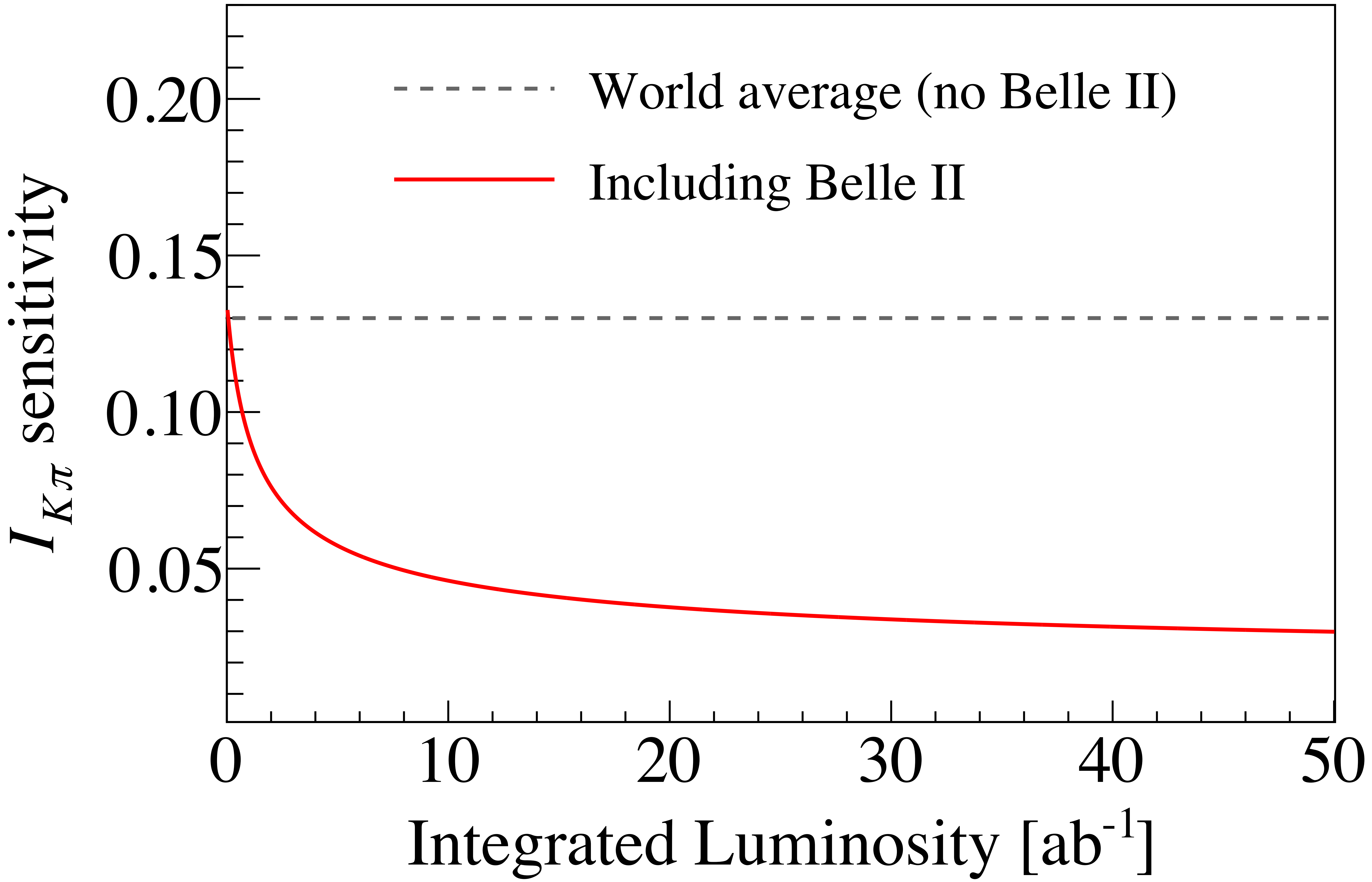
[JINST 3 S08005]
[Int. J. Mod. Phys. A 30 (2015)1530022]



Expected luminosity collection by LHCb



Prospects on isospin sum rule



Prospects on on UT angle γ by LHCb

LHCb upgrade II physics case

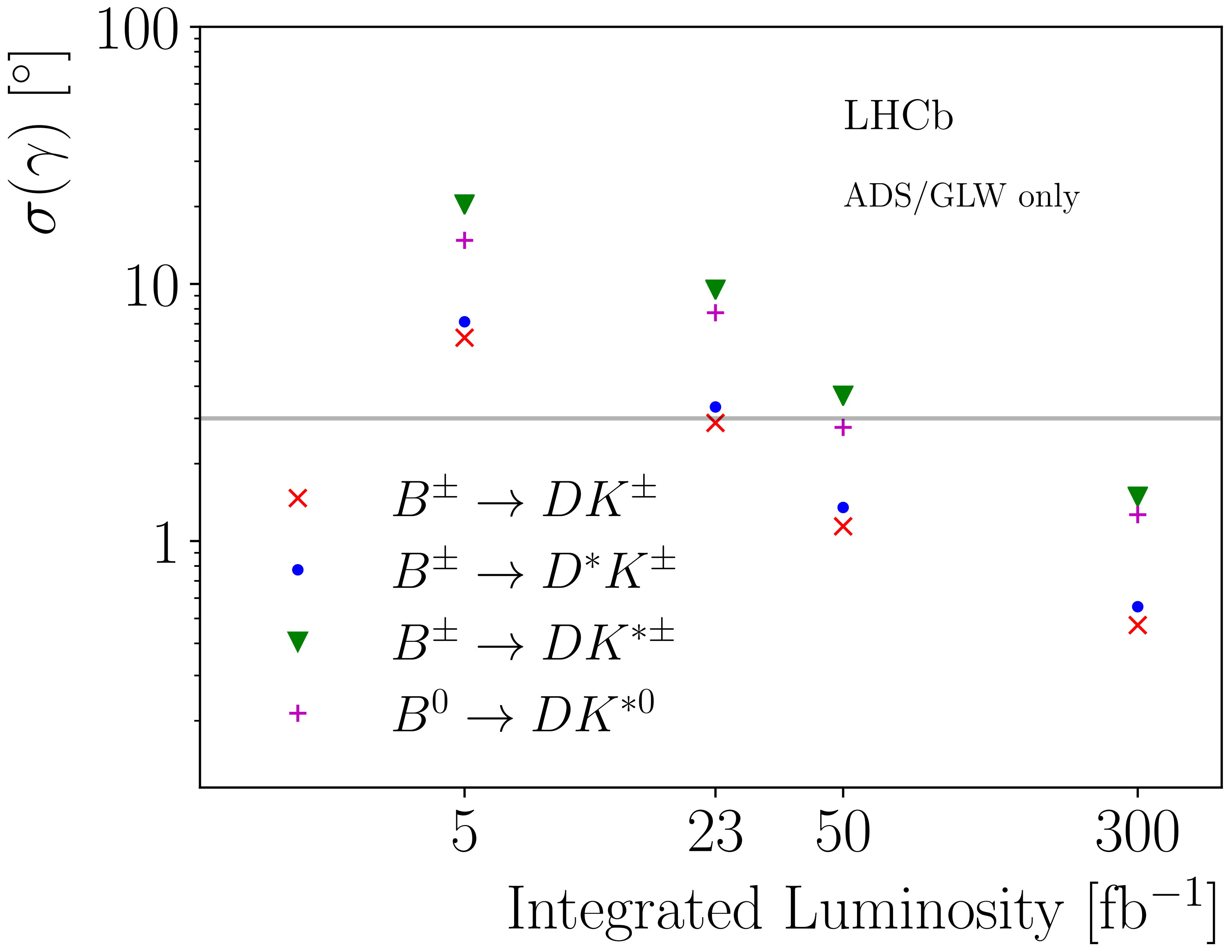


Figure 4.1: Extrapolation of γ sensitivity from the ADS/GLW analyses where disfavoured ambiguities are ignored. The expected Belle II γ precision at an integrated luminosity of 50 ab^{-1} is shown by the horizontal grey lines.

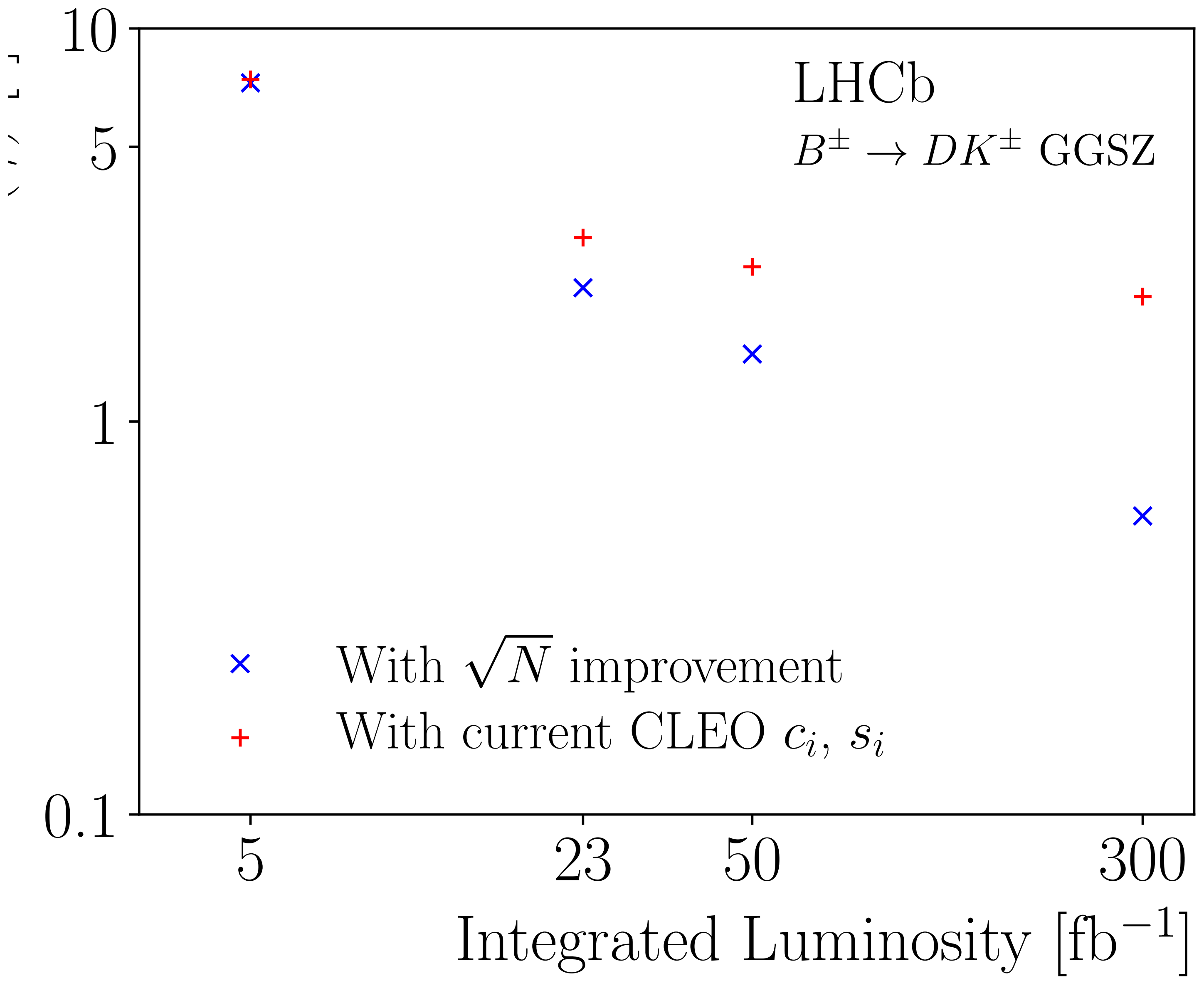


Figure 4.3: Expected evolution of γ sensitivity with the GGSZ method with (red crosses) current CLEO inputs and with (blue ×-marks) $\sqrt{N}$ improvements on their uncertainty.

CP asymmetry in semileptonic B decays

Table 5.1: Current theoretical and experimental determinations of the semileptonic asymmetries $a^d_{\rm sl}$ and $a^s_{\rm sl}$.

Sample ($\mathcal{L}$)	$\delta a^s_{\rm sl}[10^{-4}]$	$\delta a^d_{\rm sl}[10^{-4}]$
Run 1 (3 $\rm fb^{-1}$) [210, 211]	33	36
Run 1-3 (23 $\rm fb^{-1}$)	10	8
Run 1-3 (50 $\rm fb^{-1}$)	7	5
Run 1-5 (300 $\rm fb^{-1}$)	3	2
Current theory [34, 200]	0.03	0.6

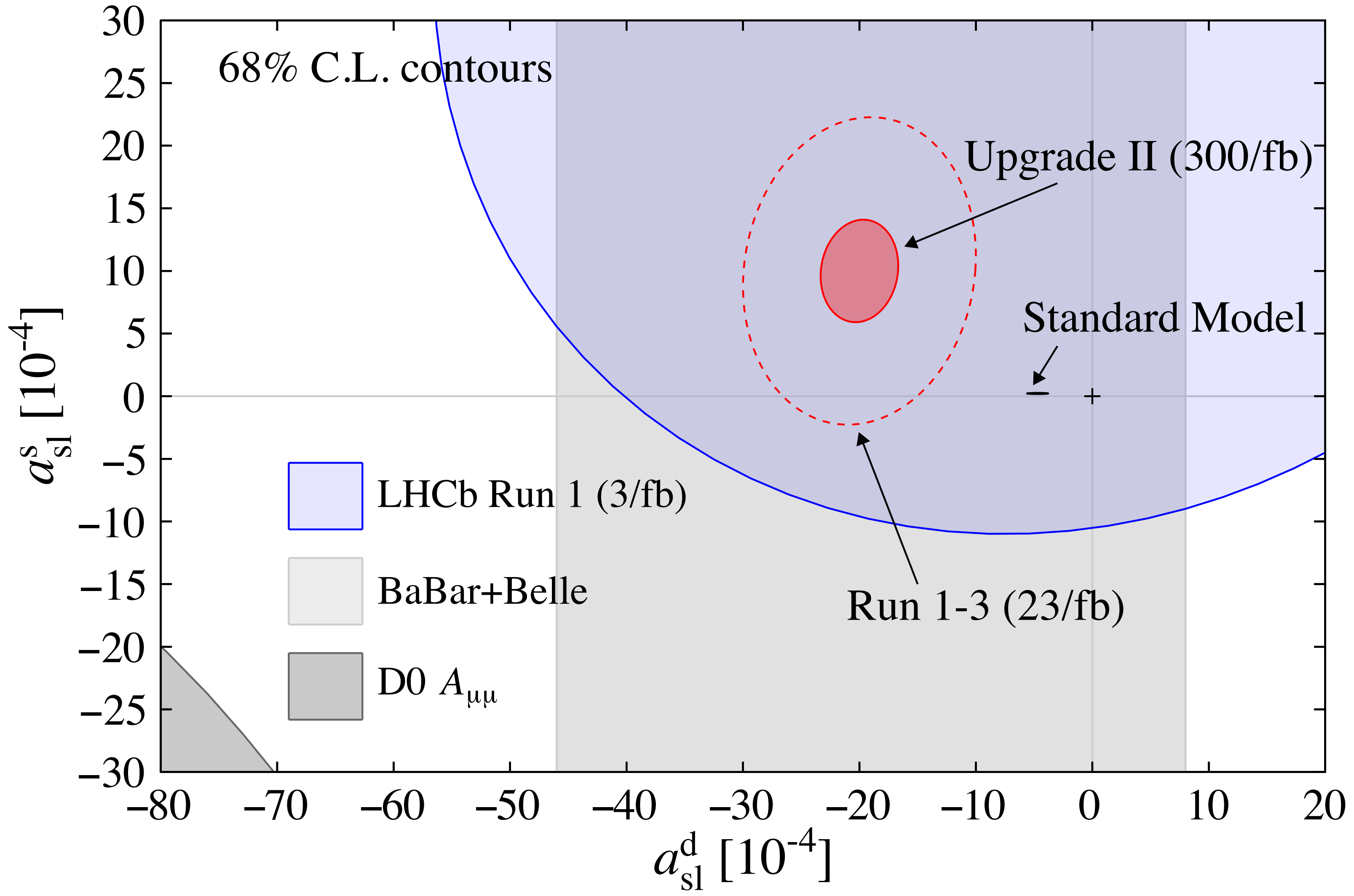


Figure 5.2: Current and future landscape for the semileptonic asymmetries. The grey vertical band indicates the current B-Factory average for $a^d_{\rm sl}$ [25]. The blue ellipse represents the current LHCb Run 1 measurements [210, 211]. The red ellipse, which is arbitrarily centred, delineates the Upgrade II projected precision. The black ellipse shows the SM prediction, the uncertainty of which is barely visible with these axes.