Recent results on hadronic *B* decays at Belle and Belle II

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On behalf of Belle and Belle II collaboration

58th Rencontres de Moriond 2024

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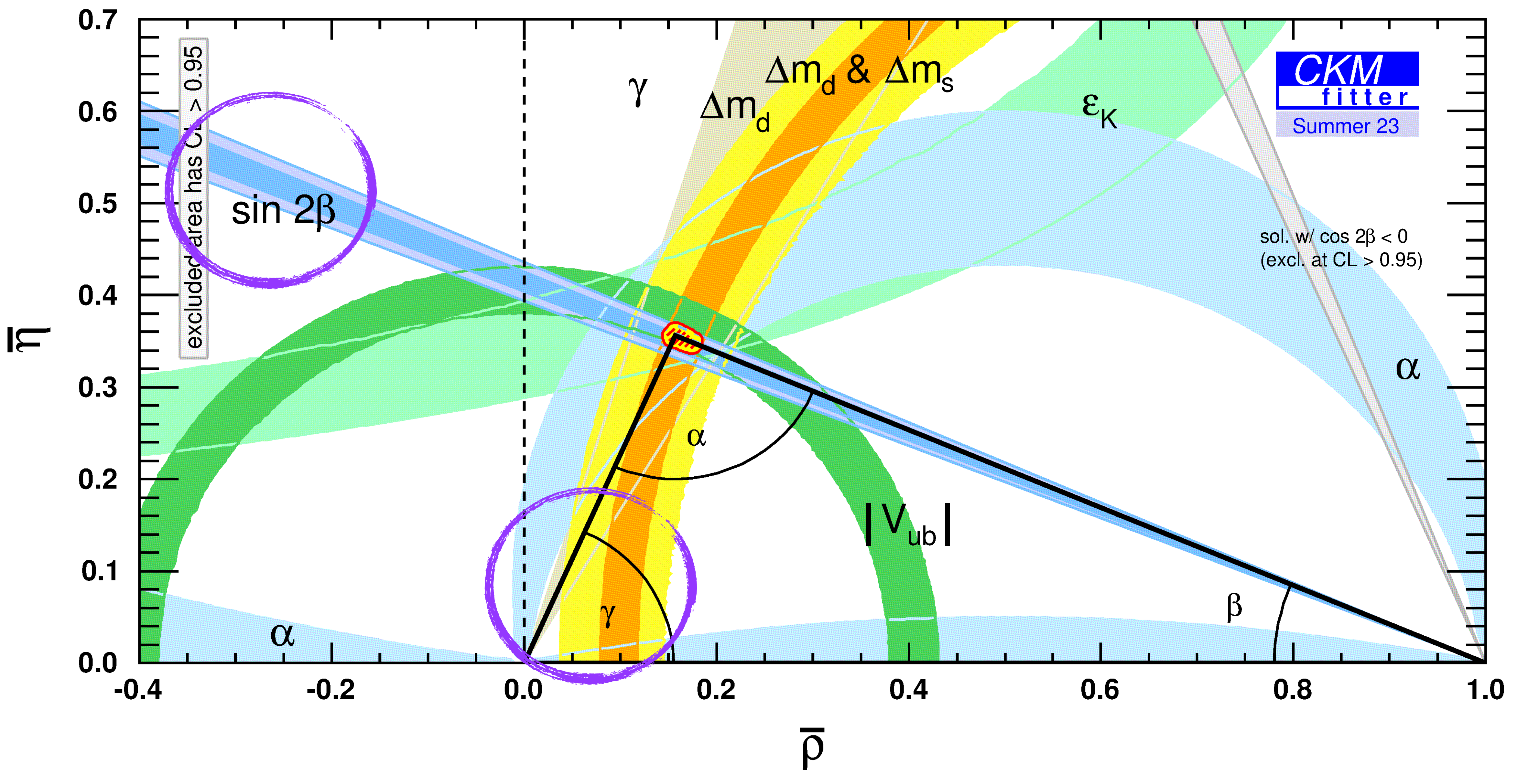
Outline and motivation

Goal: probe indirectly the SM via weak interactions of quarks

Exploit our available dataset, 387 M (Belle II) + 772 M (Belle) $B\bar{B}$ pairs, to accomplish competitive and world-best results

Today's focus is on improvement of our knowledge on B decays and measurement of CPV parameters via CKM angles ϕ_1 and ϕ_3:

- $B^+ \to D^0\rho^+$
- $B \to D^{(*)}K^-K_{(s)}^{(*)0}$
- First Belle + Belle II combination of all ϕ_3 measurements
- Measurement of $\sin 2\phi_1$: $B^0 \to \eta' K_S^0$
- CPV in $B^0 \to K_S^0\pi^0\gamma$ decays



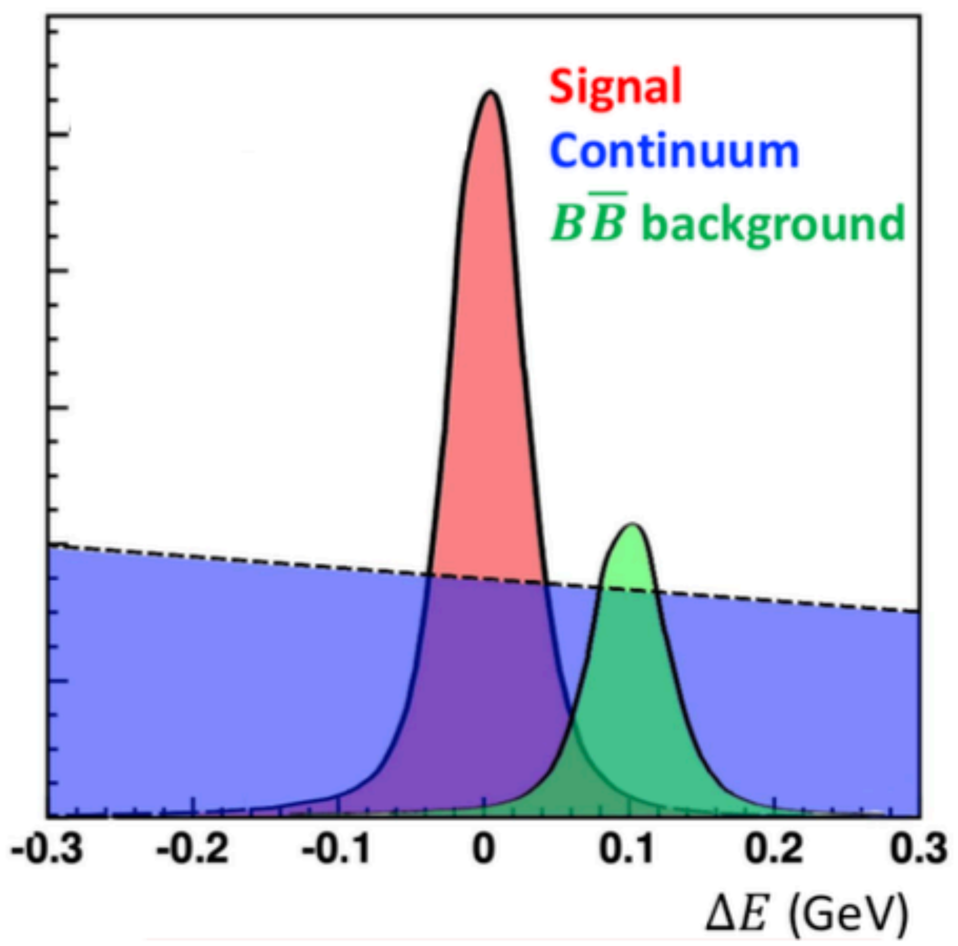
All results are new since last Moriond

B-factory basics

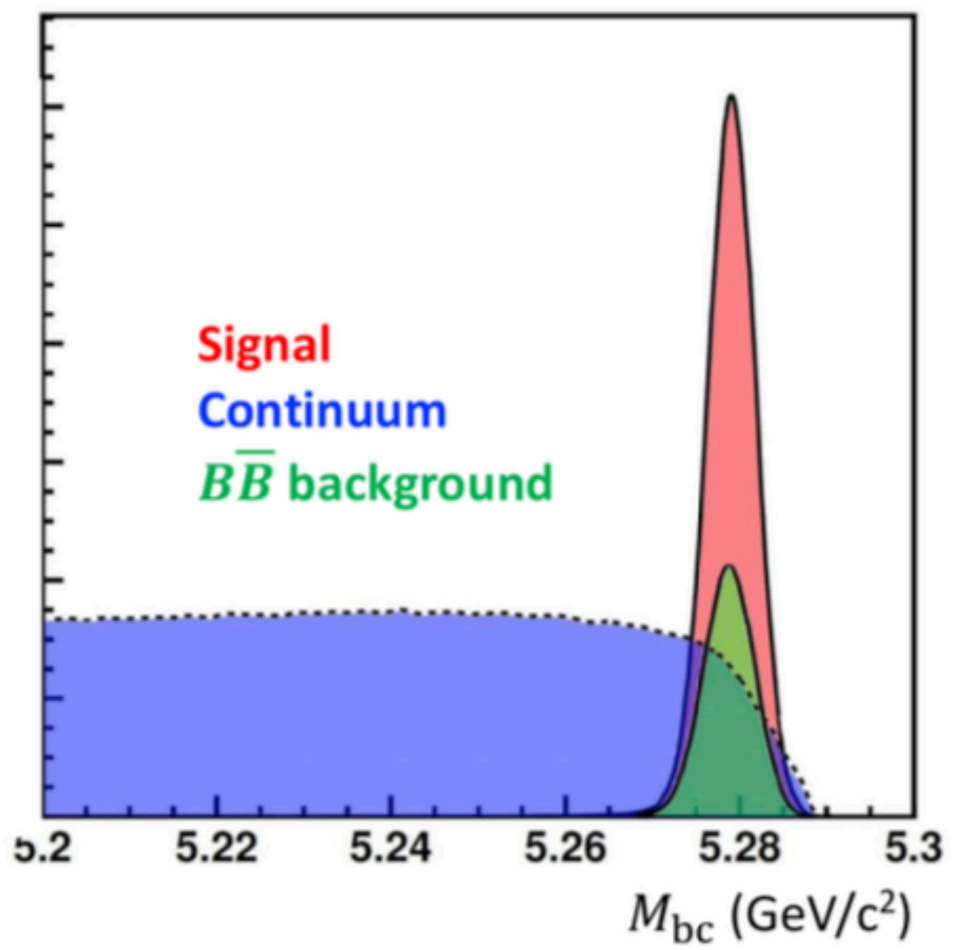
SuperKEKB collides 7 GeV-e^- on 4 GeV-e^+ in a submillimeter region: smaller beamspot

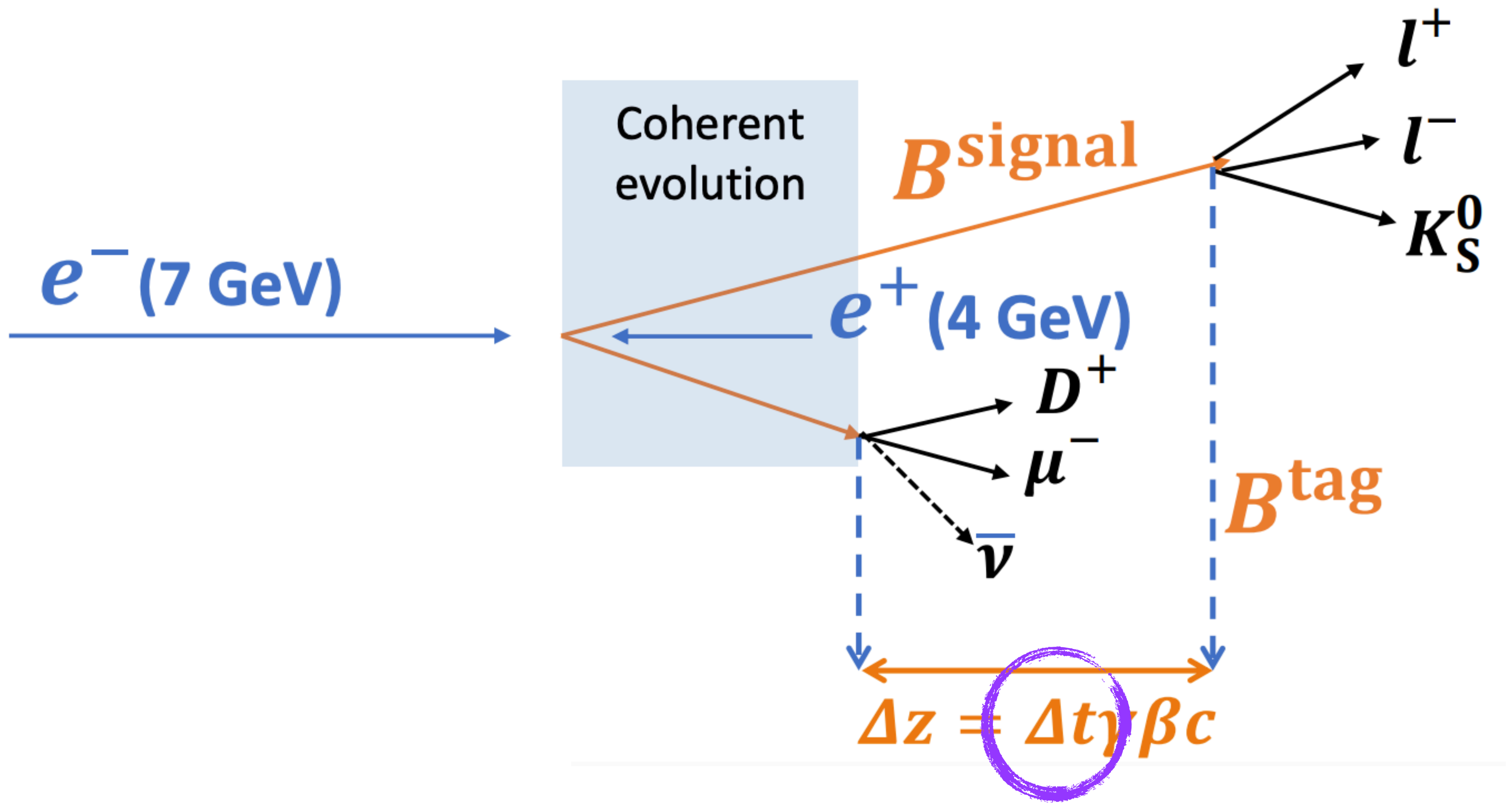
- B production threshold from point-like colliding particles, $e^+e^- \to \Upsilon(4S) \to B\bar{B}$: **kinematics well constrained**
- Hermetic detector: **full event reconstruction**
- **Asymmetric** collider $\Longrightarrow$ boost of centre-of-mass: measurement of decay time for time-dependent CPV, arising from interference between decays of mixed and unmixed neutral B mesons
- Good **vertexing** performance ($\sigma = 15\ \mu$m)
- Good **flavour tagging** performance ($\epsilon = 37\,\%$) : *see YSF talk by Petros Stavroulakis*

Difference between expected and observed B energy



Invariant B mass with energy replaced by beam energy



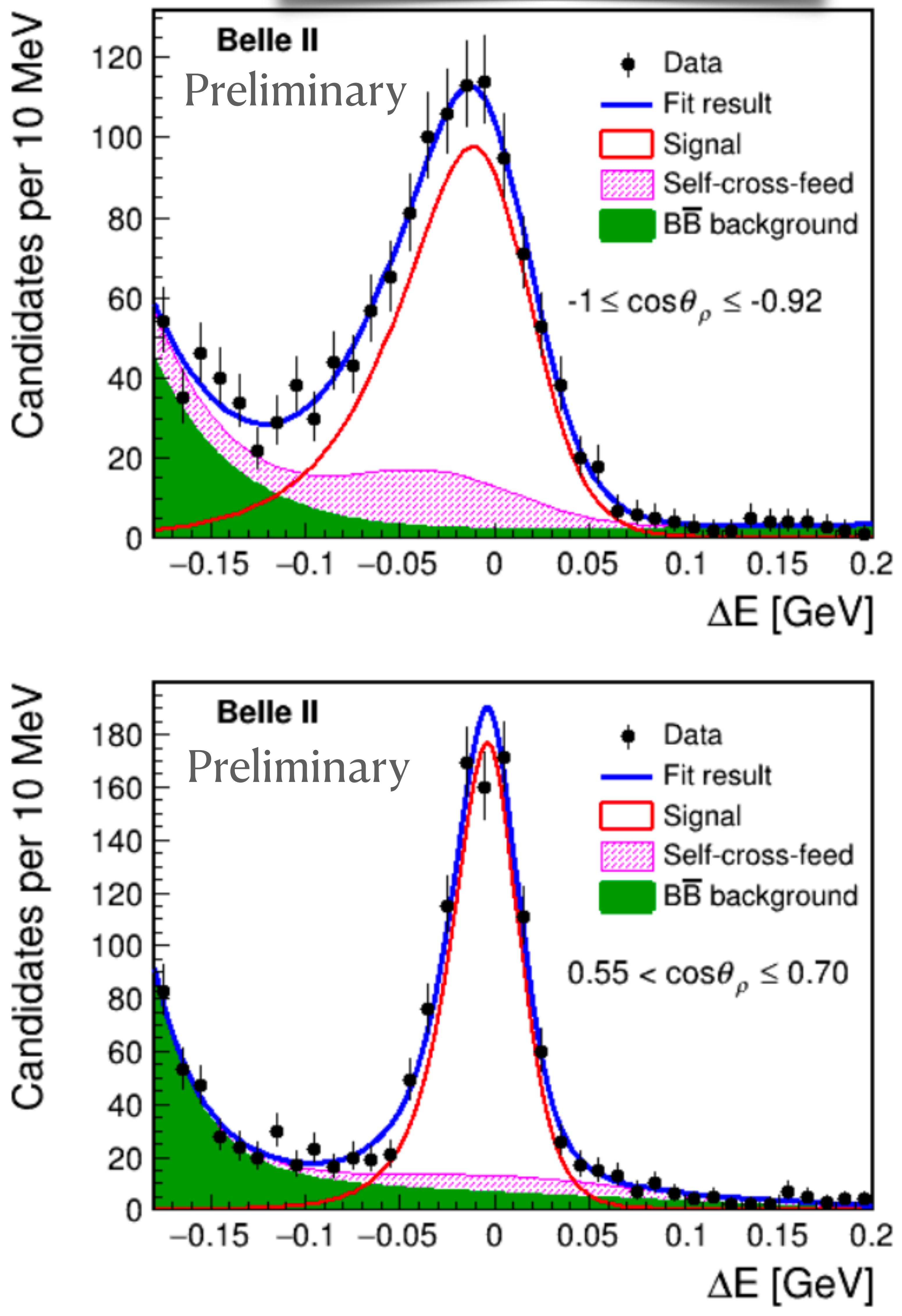


Improved B and D decay knowledge

Branching fraction of $B^+ \to D^0\rho(770)^+$

Run 1 Belle II dataset

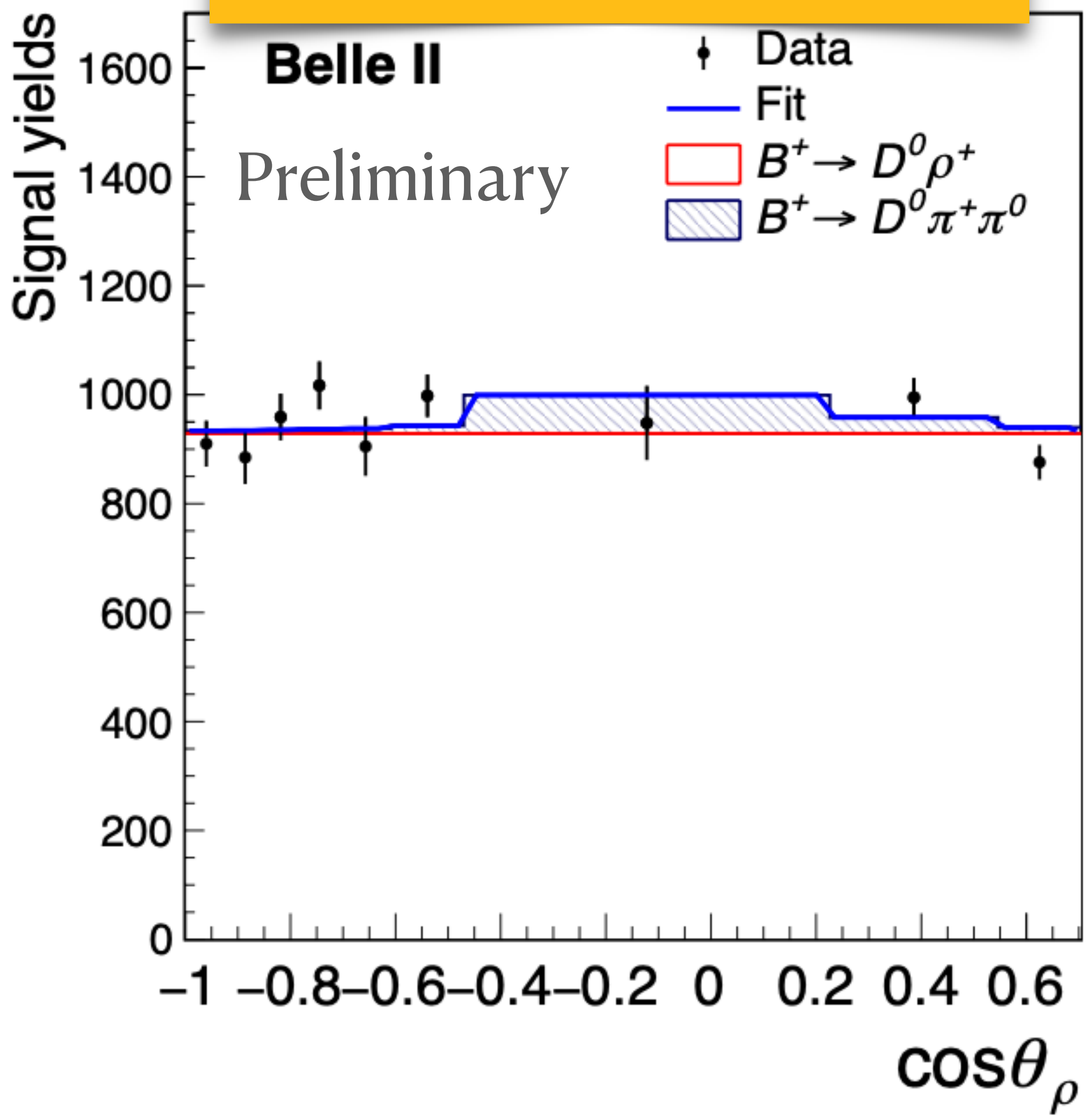
- $B^+ \to D^0\rho^+$: test heavy-quark limit and factorisation models [*Nucl. Phys. B 591, 313 (2000)*]
- WA BF: $(1.35 \pm 0.18)\%$; driven by old CLEO measurement [*CLEO, PRD 50, 43 (1994)*]
  - Very large (14 %) uncertainty
- Signal extracted from fit to ΔE
- **Challenge: separate $B \to D^0\rho(\to \pi^+\pi^0)$ and non-resonant $B \to D^0\pi^+\pi^0$ component**
  - Fit performed in bins of helicity angle ($\cos\theta_\rho$)



Branching fraction of $B^+ \to D^0\rho(770)^+$

Run 1 Belle II dataset

- Template fit to $\cos\theta_\rho$ distribution
  - Non-uniform binning: flat $\cos\theta_\rho$ distribution for $B \to D\rho$
  - $< 2\,\%$ contribution of $B \to D^0\pi^+\pi^0$ s-wave component

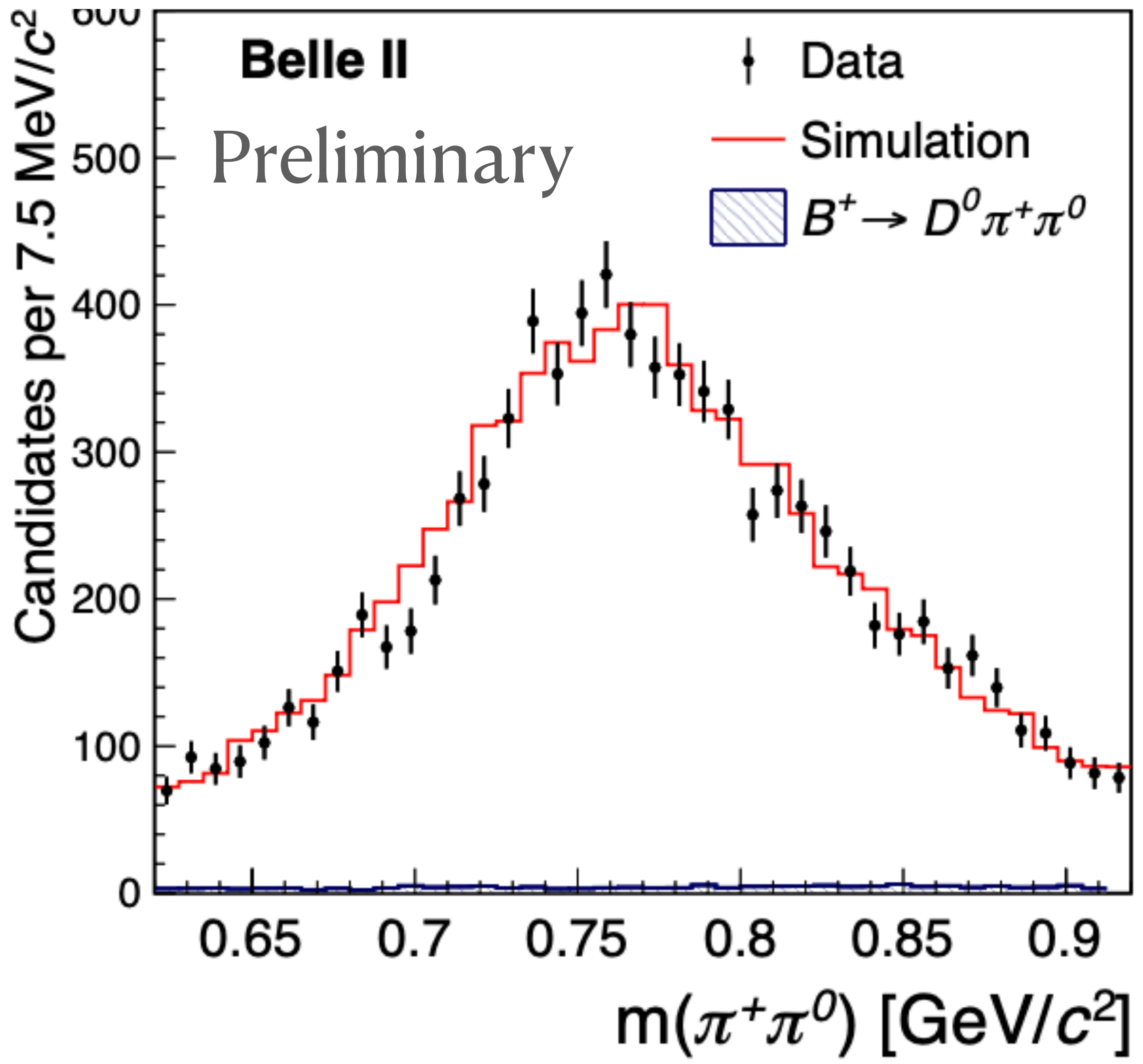


$$\mathscr{B}(B^+ \to D^0\rho^+) = (0.939 \pm 0.021 \pm 0.050)\,\%$$

World best result with more than $2\times$ improvement in precision

Factorisation test has been performed: in agreement with the prediction and improves the precision (backup)

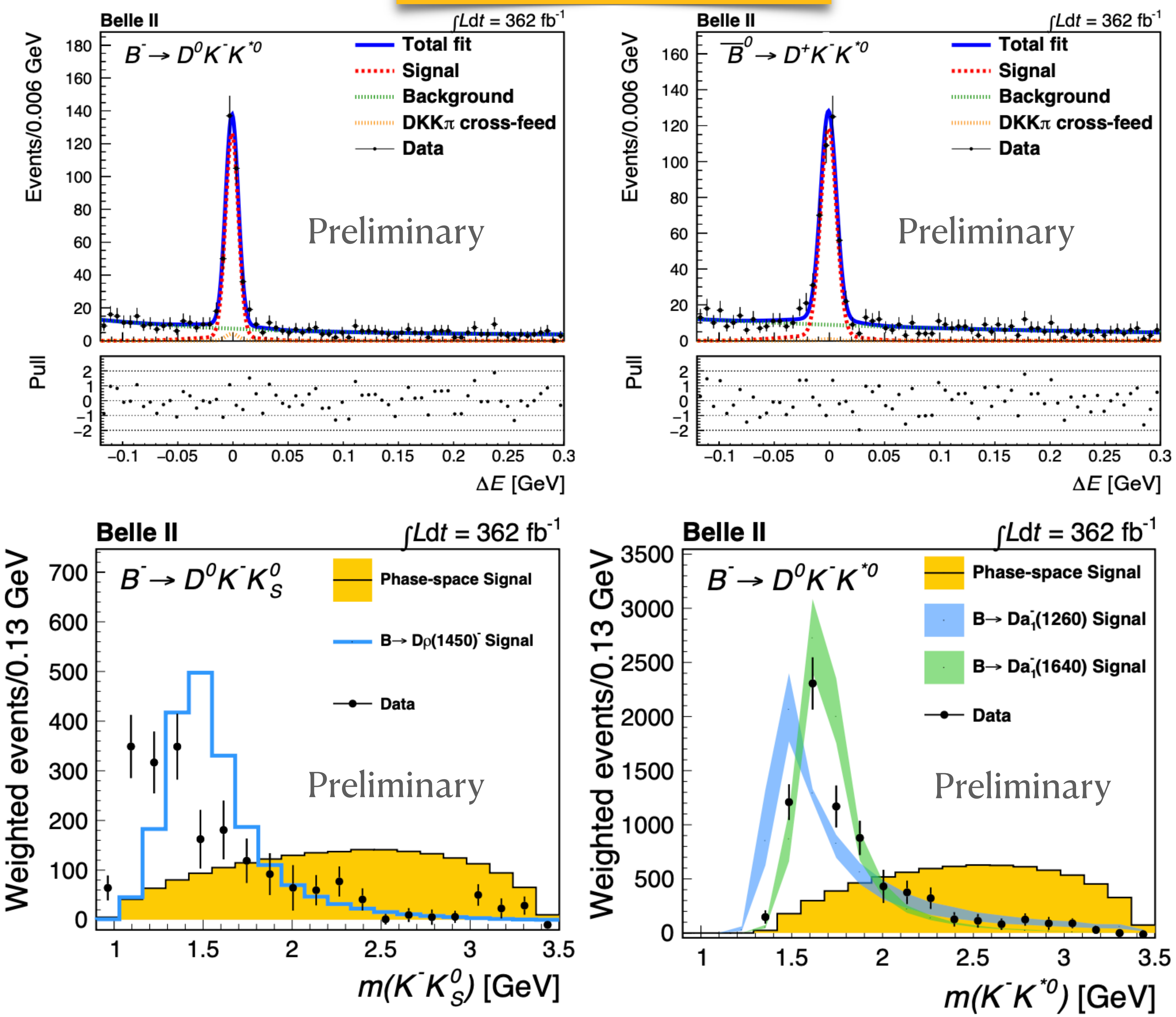
Systematically limited by π^0-efficiency knowledge



$B \to D^{(*)}K^-K^{(*)0}_{(s)}$ and $B \to D^{(*)}D_s^-$ decays

Run 1 Belle II dataset

- $B \to DKK$: largely unexplored sector
  - few % of B branching fraction expected
  - only 0.28 % measured *[PLB 542, 171-182 (2002)]*
- Signal extracted from fit to ΔE
- **Challenge: bkg from non-resonant $B \to DK^-K^+\pi$ in K^* modes**
- Efficiency correction applied in the plane $[m(D^{(*)}K^{0(*)}_{(S)}), m(K^-)K^{0(*)}_{(S)}]$
- Extraction of bkg-subtracted and efficiency-corrected **invariant mass** and **helicity angles:** dominant $J^P = 1^{-/+}$ transitions



($\rho' = 1^-$ resonances) ($a_1 = 1^+$ resonances)

$B \to D^{(*)} K^- K^{(*)0}_{(s)}$ and $B \to D^{(*)} D_s^-$ decays

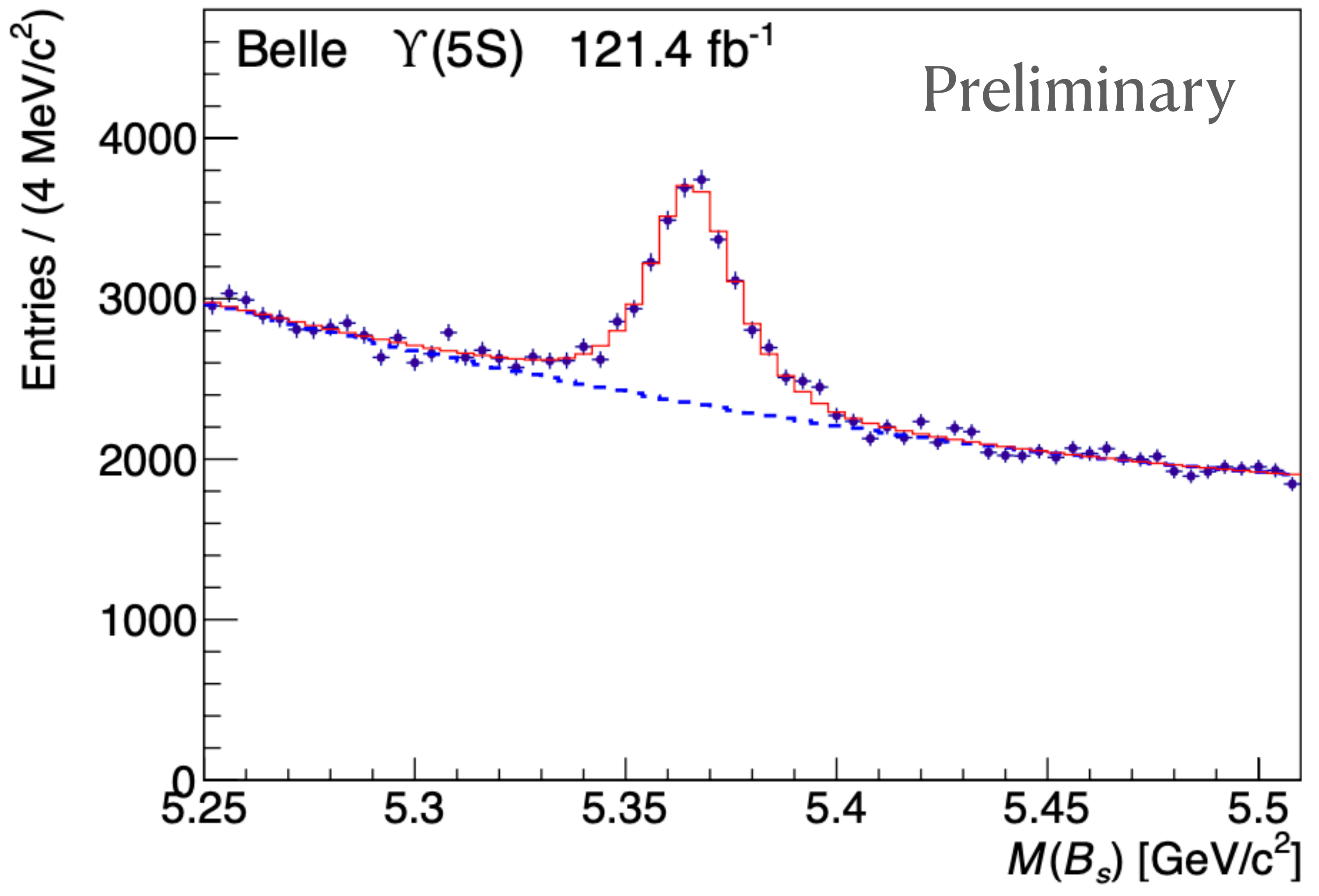
Run 1 Belle II dataset

Channel	Yield (K_S^0 / K^{*0})	Average ε (K_S^0 / K^{*0})	$\mathcal{B}$ $[10^{-4}]$	
$B^- \to D^0 K^- K_S^0$	209 ± 17	0.098	$1.82 \pm 0.16 \pm 0.08$	3 × higher precision
$\bar{B}^0 \to D^+ K^- K_S^0$	105 ± 14	0.048	$0.82 \pm 0.12 \pm 0.05$	First observation
$B^- \to D^{*0} K^- K_S^0$	51 ± 9	0.044	$1.47 \pm 0.27 \pm 0.10$	First observation
$\bar{B}^0 \to D^{*+} K^- K_S^0$	36 ± 7	0.046	$0.91 \pm 0.19 \pm 0.05$	First observation
$B^- \to D^0 K^- K^{*0}$	325 ± 19	0.043	$7.19 \pm 0.45 \pm 0.33$	3 × higher precision
$\bar{B}^0 \to D^+ K^- K^{*0}$	385 ± 22	0.021	$7.56 \pm 0.45 \pm 0.38$	3 × higher precision
$B^- \to D^{*0} K^- K^{*0}$	160 ± 15	0.019	$11.93 \pm 1.14 \pm 0.93$	3 × higher precision
$\bar{B}^0 \to D^{*+} K^- K^{*0}$	193 ± 14	0.020	$13.12 \pm 1.21 \pm 0.71$	3 × higher precision
$B^- \to D^0 D_s^-$	144 ± 12 / 153 ± 13	0.04 / 0.09	$95 \pm 6 \pm 5$	World's best
$\bar{B}^0 \to D^+ D_s^-$	145 ± 12 / 159 ± 13	0.02 / 0.05	$89 \pm 5 \pm 5$	World's best
$B^- \to D^{*0} D_s^-$	30 ± 6 / 29 ± 7	0.02 / 0.04	$65 \pm 10 \pm 6$	World's best
$\bar{B}^0 \to D^{*+} D_s^-$	43 ± 7 / 37 ± 7	0.02 / 0.04	$83 \pm 10 \pm 6$	World's best

First observation of 3 new channels with improved precision for many

$B_s^0 \to D/\bar{D}X$ inclusive decays

- B_s^0 production fraction in $\Upsilon(5S)$ decays (f_s) important for accuracy in absolute B_s^0 BF
  - Dominated by the uncertainty of inclusive $B_s^0 \to D_s^{\pm}X$ BF
- B_s^0 candidates are selected in events where the other B_s^0 candidate is reconstructed from fully hadronic final state
- Signal extraction: fit to $M(B_s)$ and $M(D)$



Decay	N_{B_s-D}	$\mathcal{B}_D$, %	$\varepsilon_D^{\rm ROE}$, %	$\mathcal{B}(B_s^0 \to D/\bar{D}X)$, %
$B_s^0 \to D_s^{\pm}X$				
$\phi\pi^+$	76 ± 11	5.37 ± 0.10	17.6 ± 0.8	$75.2 \pm 11.4 \pm 5.3$
$\bar{K}^{*0}K^+$	56 ± 12	5.37 ± 0.10	18.0 ± 0.8	$54.5 \pm 11.9 \pm 5.3$
$K_S^0K^+$	49 ± 9	1.450 ± 0.035	35.1 ± 1.7	$89.3 \pm 16.7 \pm 6.7$
$B_s^0 \to D^0/\bar{D}^0X$	51 ± 15	3.947 ± 0.030	73.8 ± 6.6	$20.2 \pm 5.7 \pm 2.1$
$B_s^0 \to D^{\pm}X$	25 ± 11	9.31 ± 0.16	52.8 ± 6.5	$8.5 \pm 3.7 \pm 1.1$

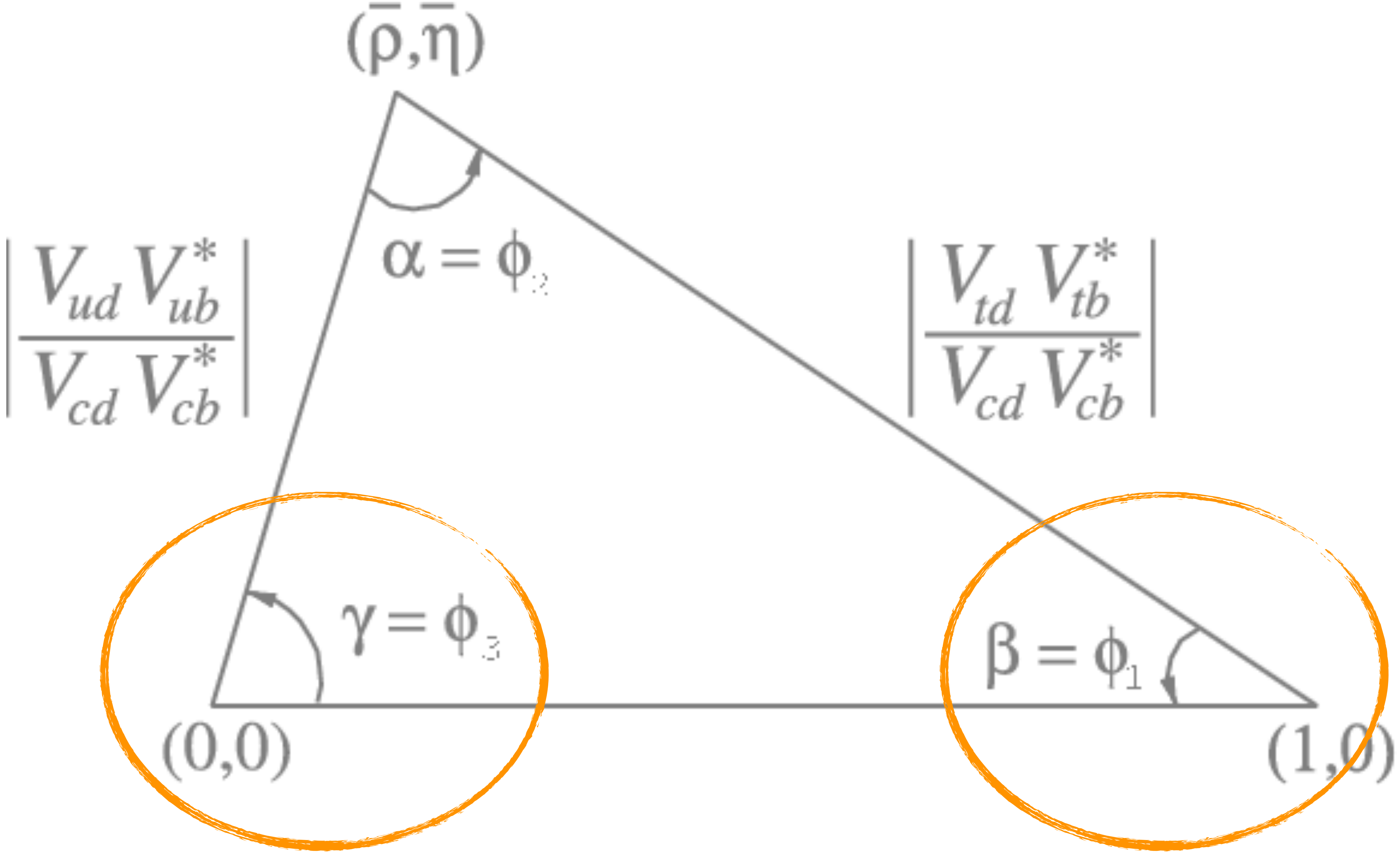
- Compatible with previous Belle results
- $B_s^0 \to D^{\pm}X$ measured for the first time

Uncertainty on B_S^0 production fraction improved compared to Belle

$$f_s = (21.3^{+1.7}_{-1.6})\ \%$$

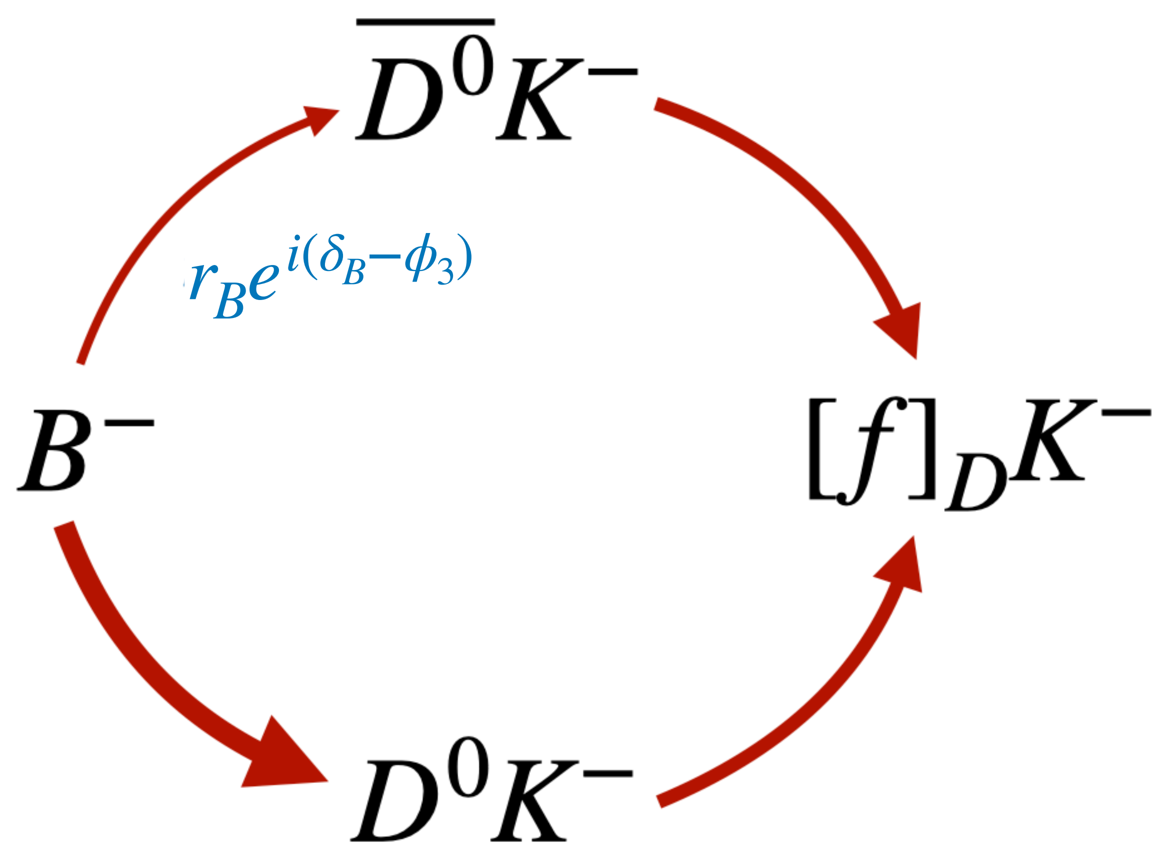
[JHEP 08, 131 (2023)]

CPV via CKM

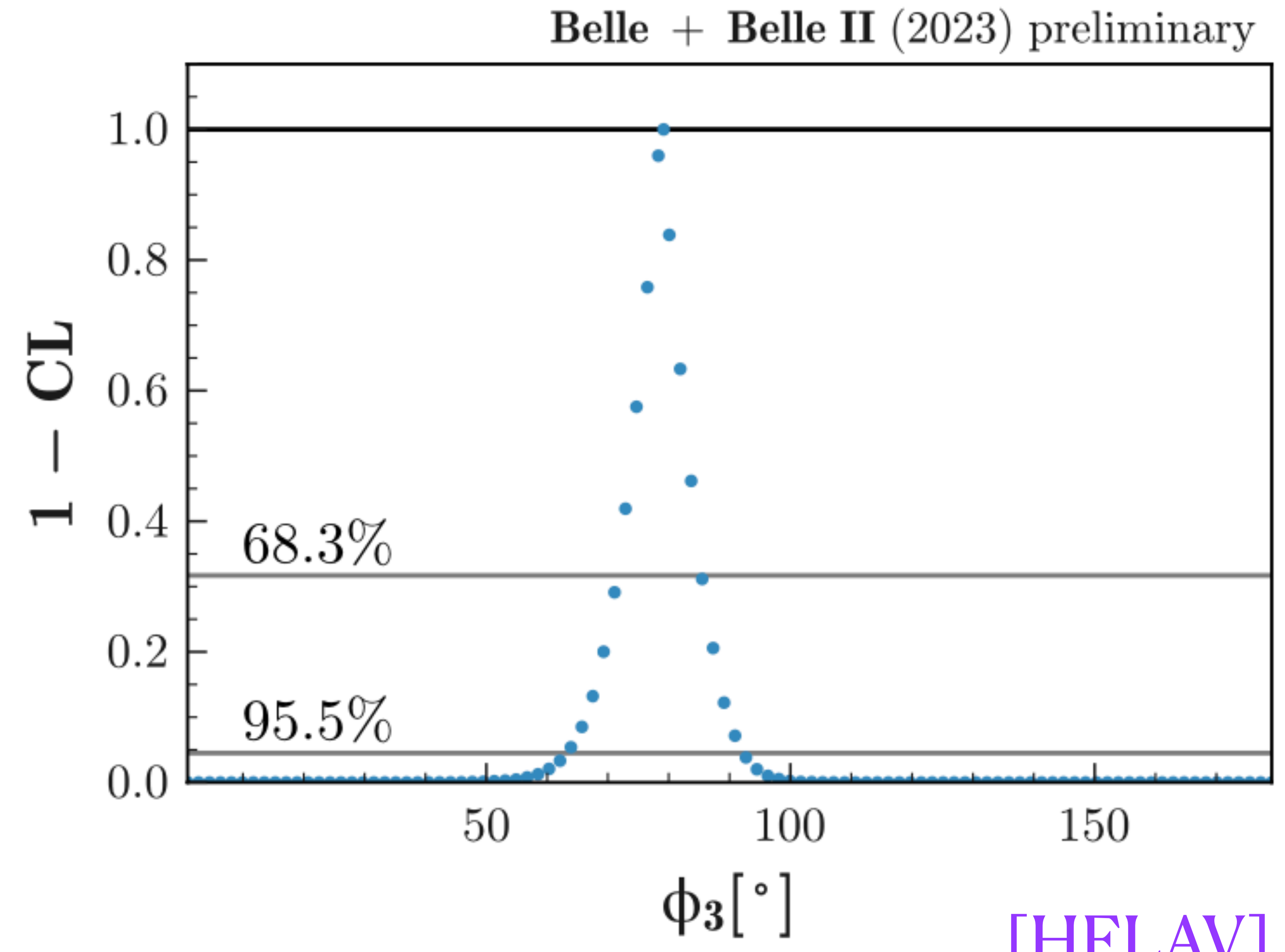

$(\bar{\rho},\bar{\eta})$
$\alpha = \phi_2$
$\left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right|$
$\left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right|$
$\gamma = \phi_3$
$\beta = \phi_1$
(0,0)
(1,0)

ϕ_3/γ: Belle + Belle II combination

- SM benchmark — very reliably predicted (10^{-7} relative)
- Tree level decays — no (large) BSM
- First combination of all Belle and Belle II ϕ_3-measurements
- **Total 60 input observables and 16 auxiliary *D*-decay inputs**



B decay	*D* decay	Method	Data set (Belle + Belle II) [fb^{-1}]	
$B^+\to Dh^+$	$D\to K^0_Sh^-h^+$	BPGGSZ	711 + 128	[JHEP 02 063 (2022)]
$B^+\to Dh^+$	$D\to K^0_S\pi^-\pi^+\pi^0$	BPGGSZ	711 + 0	[JHEP 10 178 (2019)]
$B^+\to Dh^+$	$D\to K^0_S\pi^0, K^-K^+$	GLW	711 + 189	[arxiv:2308.05048]
$B^+\to Dh^+$	$D\to K^+\pi^-, K^+\pi^-\pi^0$	ADS	711 + 0	[PRL 106 231803 (2011)]
$B^+\to Dh^+$	$D\to K^0_SK^-\pi^+$	GLS	711 + 362	[JHEP 09 (2023) 146]
$B^+\to D^*K^+$	$D\to K^0_S\pi^-\pi^+$	BPGGSZ	605 + 0	[PRD 81 112002 (2010)]
$B^+\to D^*K^+$	$D\to K^0_S\pi^0, K^0_S\phi, K^0_S\omega, K^-K^+, \pi^-\pi^+$	GLW	210+0	[PRD 73 051106 (2006)]



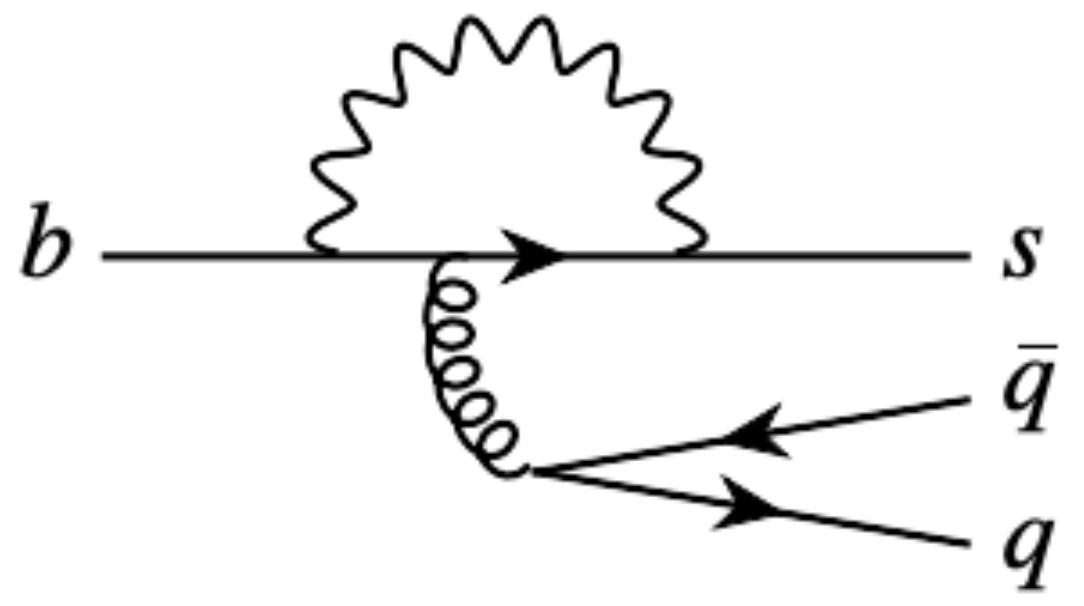
$$\phi_3(^\circ) = 78.6^{+7.2}_{-7.3}$$

[HFLAV]

$$\phi_3^{WA}(^\circ) = 66.2^{+3.4}_{-3.6}$$

$\phi_1^{\text{eff}}/\beta^{\text{eff}}$ from suppressed penguins

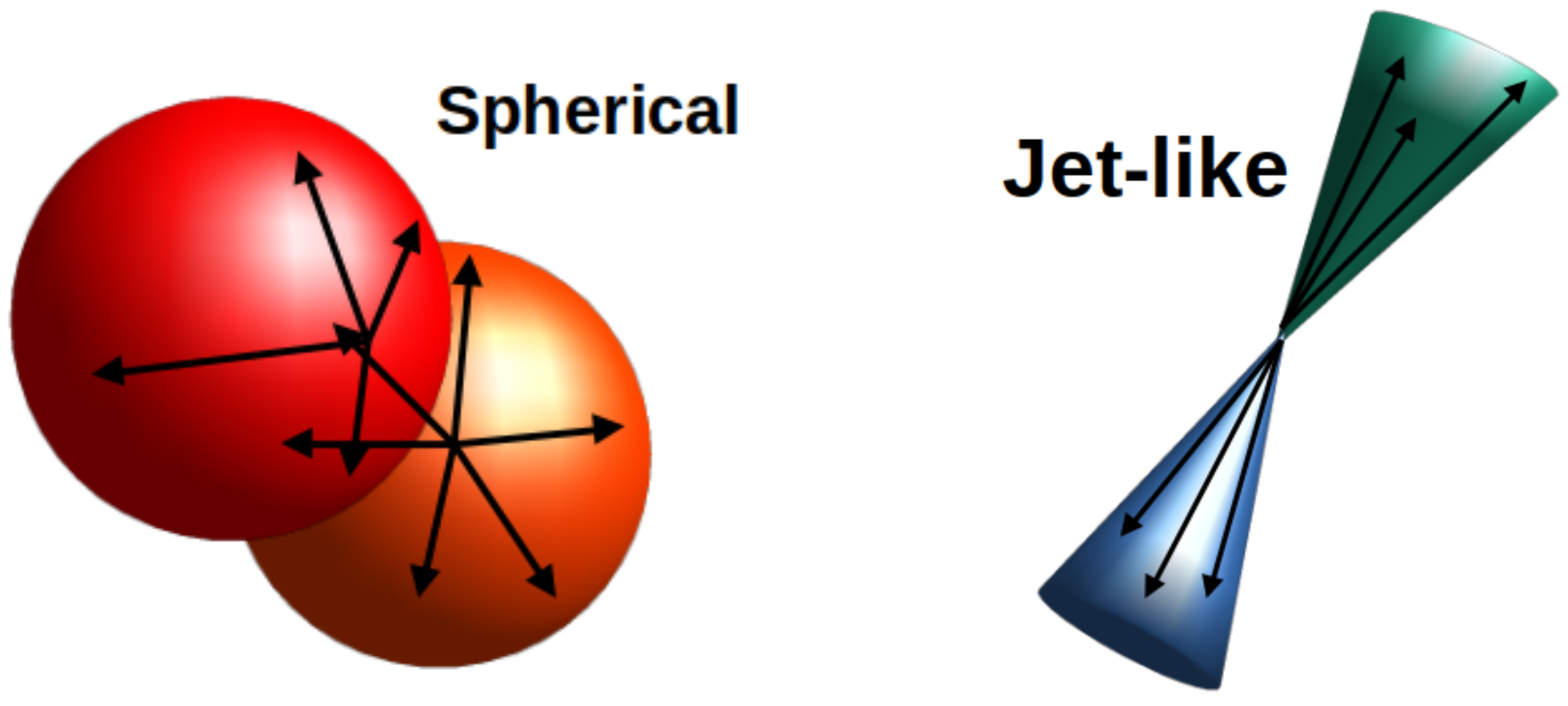
- Gluonic penguin modes suppressed in SM, BR: $10^{-5} - 10^{-6}$
- BSM sensitive if any deviation from reference channel observed
- Reliable theory prediction ($< 1\ \%$) *[PLB 620, 143 (2005)]*



$$\mathcal{A}_{CP}(\Delta t) = \frac{\Gamma(\bar{B}^0 \to f_{CP}) - \Gamma(B^0 \to f_{CP})}{\Gamma(\bar{B}^0 \to f_{CP}) + \Gamma(B^0 \to f_{CP})}(\Delta t) = S \sin(\Delta m \Delta t) - C \cos(\Delta m \Delta t)$$

$C \simeq 0,\ S \simeq \sin 2\phi_1$ in SM

- **Experimentally challenging:**
  - Fully hadronic final state with neutrals: unique to Belle II
  - Large background from continuum production: exploit event-topology to boost classification via machine learning



$e^+e^- \to \Upsilon(4S) \to B\bar{B}$ $\quad$ $e^+e^- \to q\bar{q}$

Gluonic penguin: $B^0 \to \eta' K_S^0$

[arXiv:2402:03713]

Run 1 Belle II dataset

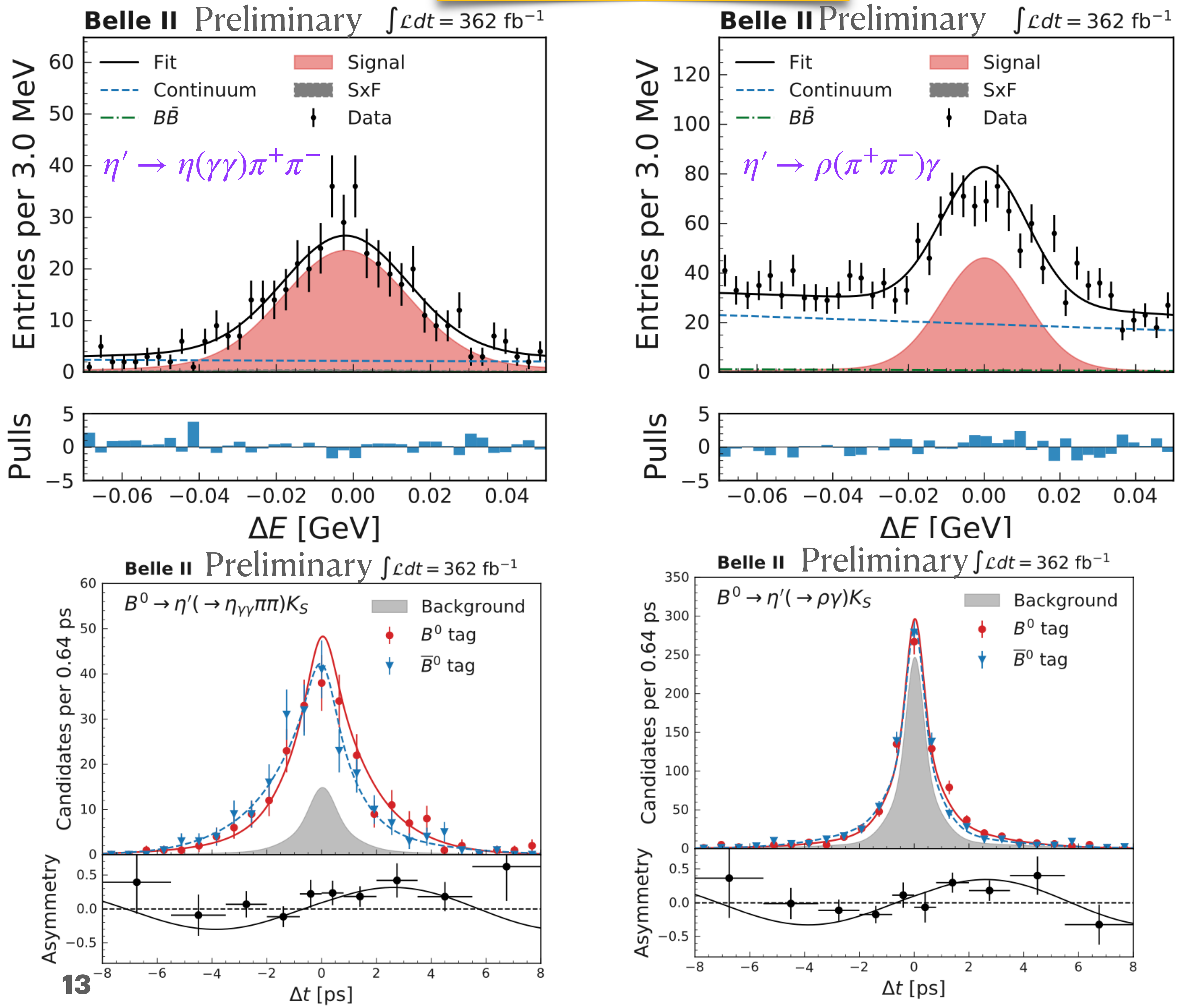
Signal extraction via fit to ΔE, M_{bc} and continuum suppression output

- Bkg Δt shape from sideband
- Bkg asymmetry included in the fit
- Validation on control sample $B^+ \to \eta' K^+$

$$S = 0.67 \pm 0.10 \pm 0.04$$
$$C = -0.19 \pm 0.08 \pm 0.03$$

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

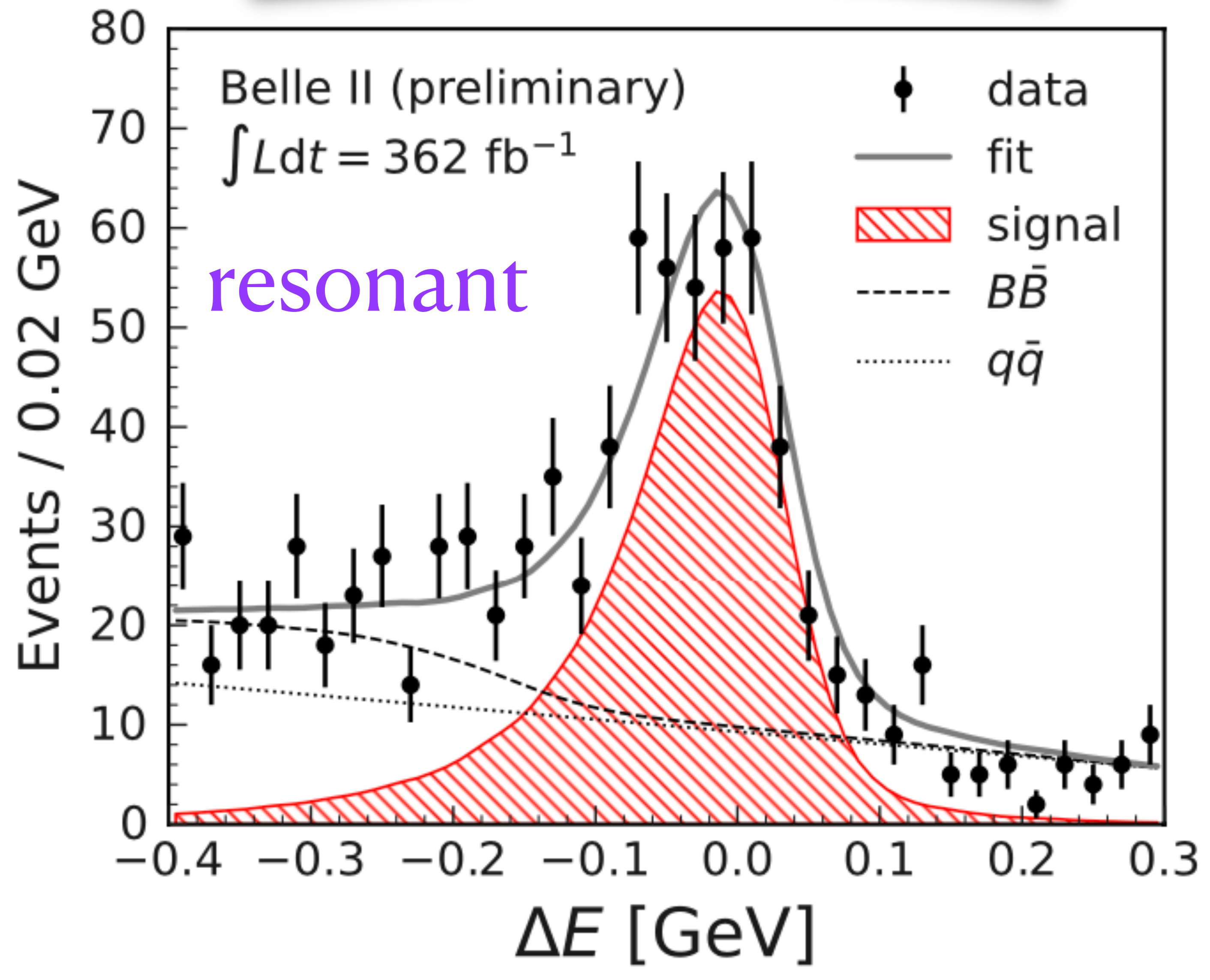
Precision comparable with Belle/BaBar in spite of smaller sample



Radiative penguin: $B^0 \to K_S^0 \pi^0 \gamma$ *paper in progress*

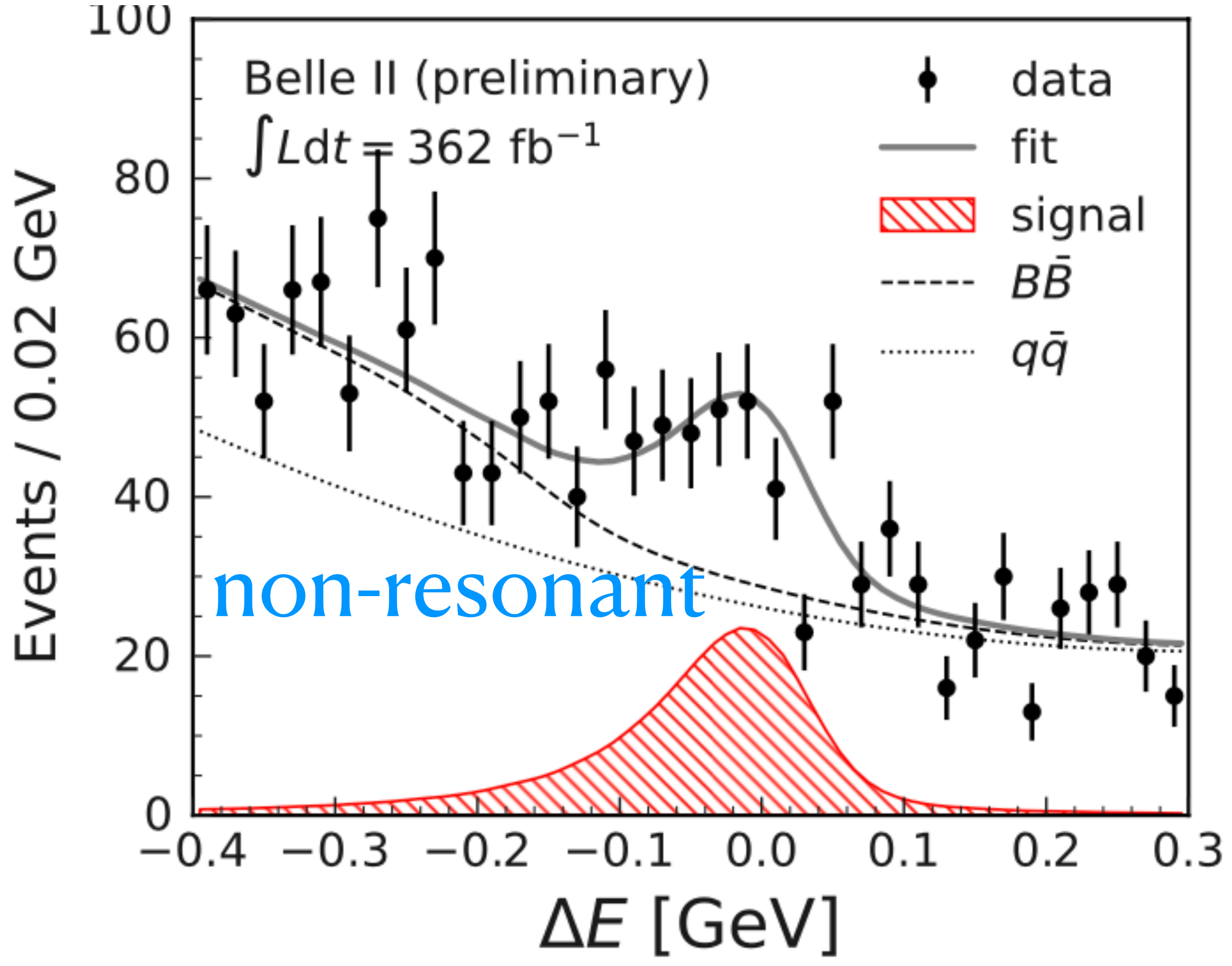
Run 1 Belle II dataset

- In SM, photons from B^0 ($\bar{B}^0$) decays are predominantly right-handed (left-handed) as weak interaction is chiral in nature
  - Limited interference between mixed and unmixed B decays: $S \simeq 0$ in SM
  - Flipping of photon polarisation suppressed by m_s/m_b
  - Large CPV suggests right-handed non-SM contribution



- **Main challenge: B^0 vertex without prompt tracks**
  - Use $K_S^0 \to \pi^+\pi^-$ information + beamspot constraint
- Channels: $K^{*0}(892)\gamma$ (resonant) , and $K_S^0\pi^0\gamma$ (non-resonant)

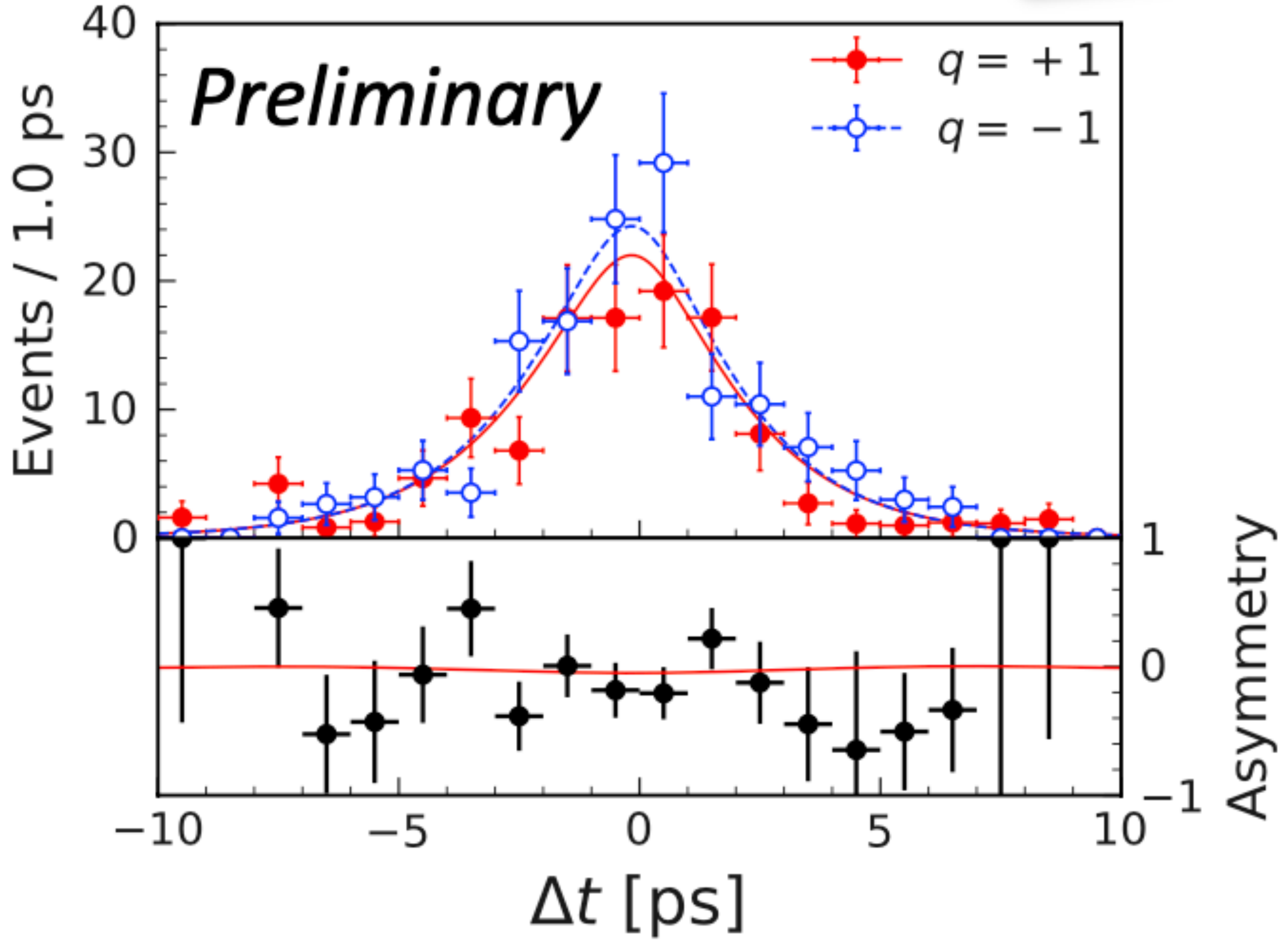
  $m(K\pi) \in$ [0.8,1] [0.6,0.8] ∪ [1.0,1.8]
- Signal extraction: fit to (ΔE, M_{bc}) followed by fit to Δt



Radiative penguin: $B^0 \to K_S^0 \pi^0 \gamma$

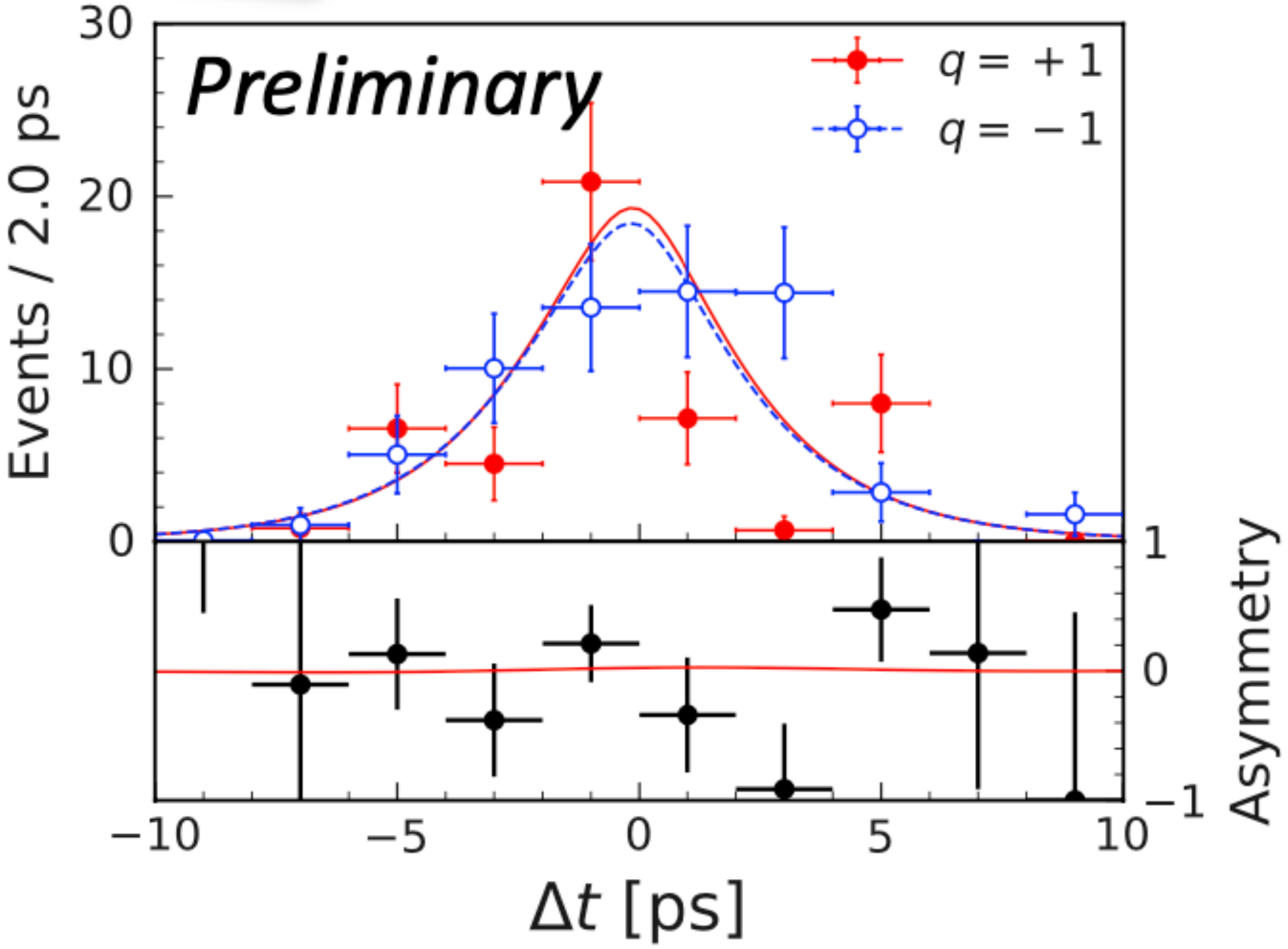
Run 1 Belle II dataset

resonant



$$S = 0.00^{+0.27+0.03}_{-0.26-0.04}$$
$$C = 0.10 \pm 0.13 \pm 0.03$$

non-resonant



$$S = 0.04^{+0.45}_{-0.44} \pm 0.10$$
$$C = -0.06 \pm 0.25 \pm 0.07$$

HFLAV: $S = -0.16 \pm 0.22,\ C = -0.07 \pm 0.12$ $S = -0.15 \pm 0.20,\ C = -0.07 \pm 0.12$

World's best result in spite of smaller sample: attributed to better bkg suppression, vertexing and K_S^0 acceptance

Summary

Fully exploiting Run 1 Belle II dataset with its unique capabilities along with Belle dataset

- Improve B decay knowledge ($B^+ \to D^0\rho^+$ and B_s^0 production fraction) and observe new decay channels ($B \to D^{(*)}K^-K_{(s)}^{(*)0}$, $B_s^0 \to D^\pm X$ and more in backup)
- Refine our ϕ_3-measurement strategies by combining Belle and Belle II measurements
- CPV parameters from gluonic ($B^0 \to \eta' K_S^0$) and radiative penguins ($B^0 \to K_S^0\pi^0\gamma$) produces unique and competitive results

Unique and competitive and results with smaller dataset.
Run 2 started, more luminosity is coming!

Thank you!

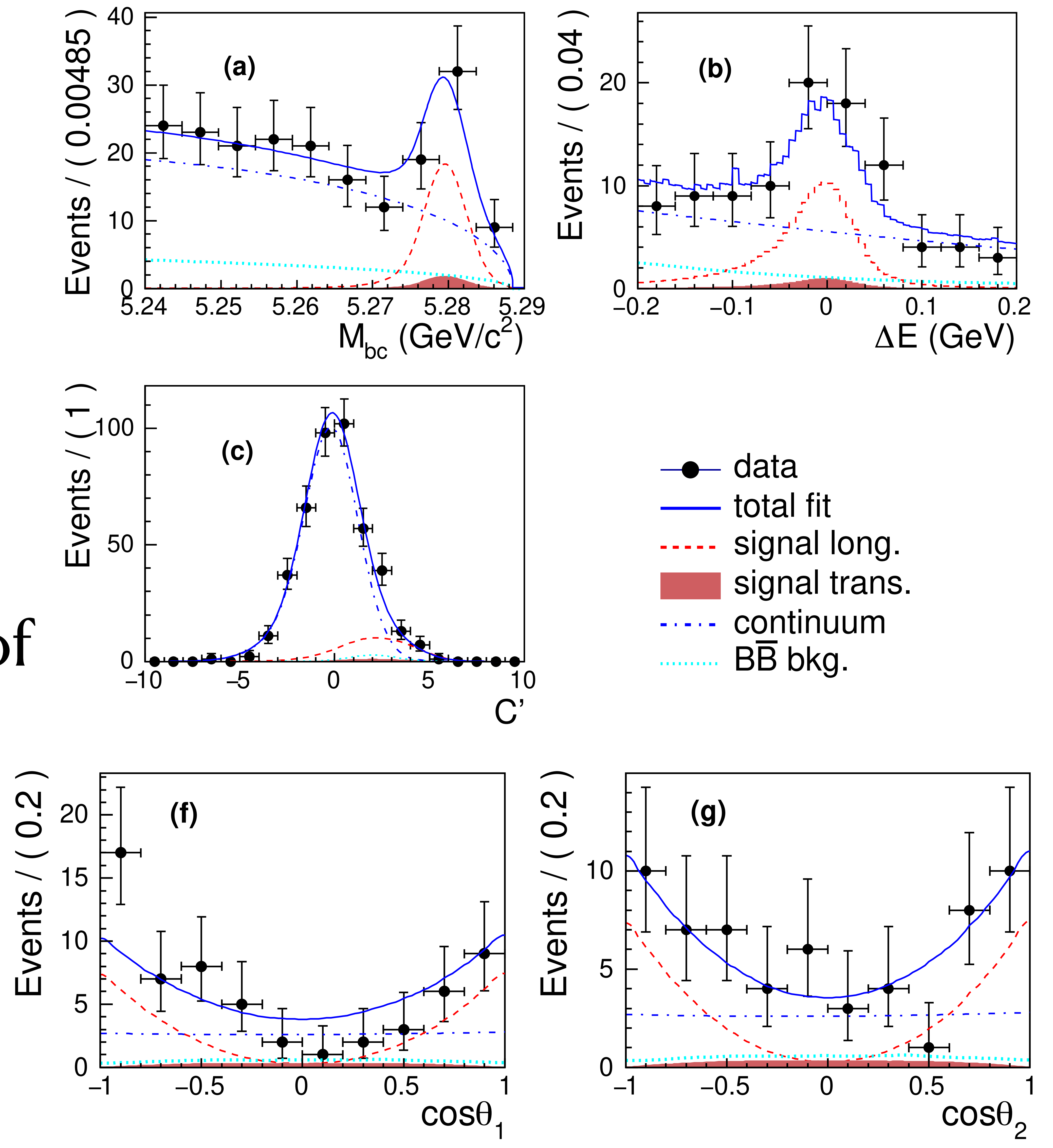
Questions?

$B^0 \to \omega\omega$

[arXiv:2401:04646]

- Rare and never observed decay
- Polarisation (f_L) and direct-CPV parameter A_{CP} useful for $B \to VV$ decays
- BF, f_L and A_{CP} extraction in full Belle dataset
- Bkg suppressed using event-topology information
- Signal extraction from fit to: ΔE, M_{bc}, continuum suppression output, ω invariant masses and cosine of helicity angles of both the ω's

$$\mathcal{B} = (1.53 \pm 0.29 \pm 0.17) \times 10^{-6}$$
$$f_L = 0.87 \pm 0.13 \pm 0.13$$
$$A_{CP} = -0.44 \pm 0.43 \pm 0.11\,,$$



First observation of the decay (7.9σ), no significant A_{CP}

$B^+ \to D^0\rho$: HQL and factorisation test

Isospin symmetry relates amplitudes of $B^{(+,0)} \to D^{(+,0)}\rho^{(+,0)}$

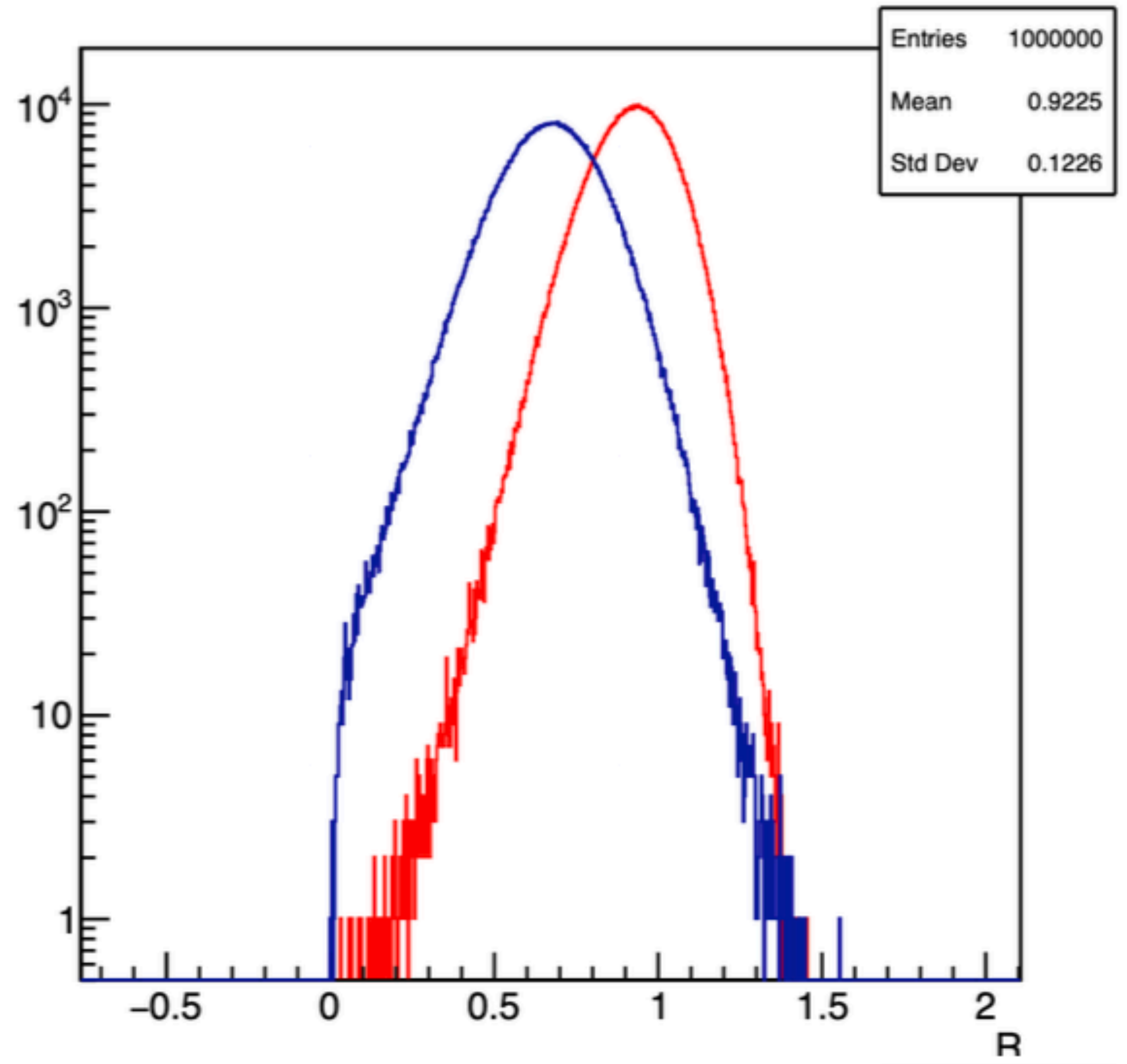
$$R = \left(\frac{3}{2} \frac{\tau_+}{\tau_0} \frac{\mathcal{B}(D^0\rho^0) + \mathcal{B}(D^+\rho^-)}{\mathcal{B}(D^0\rho^-)} - \frac{1}{2} \right)^{\frac{1}{2}}$$

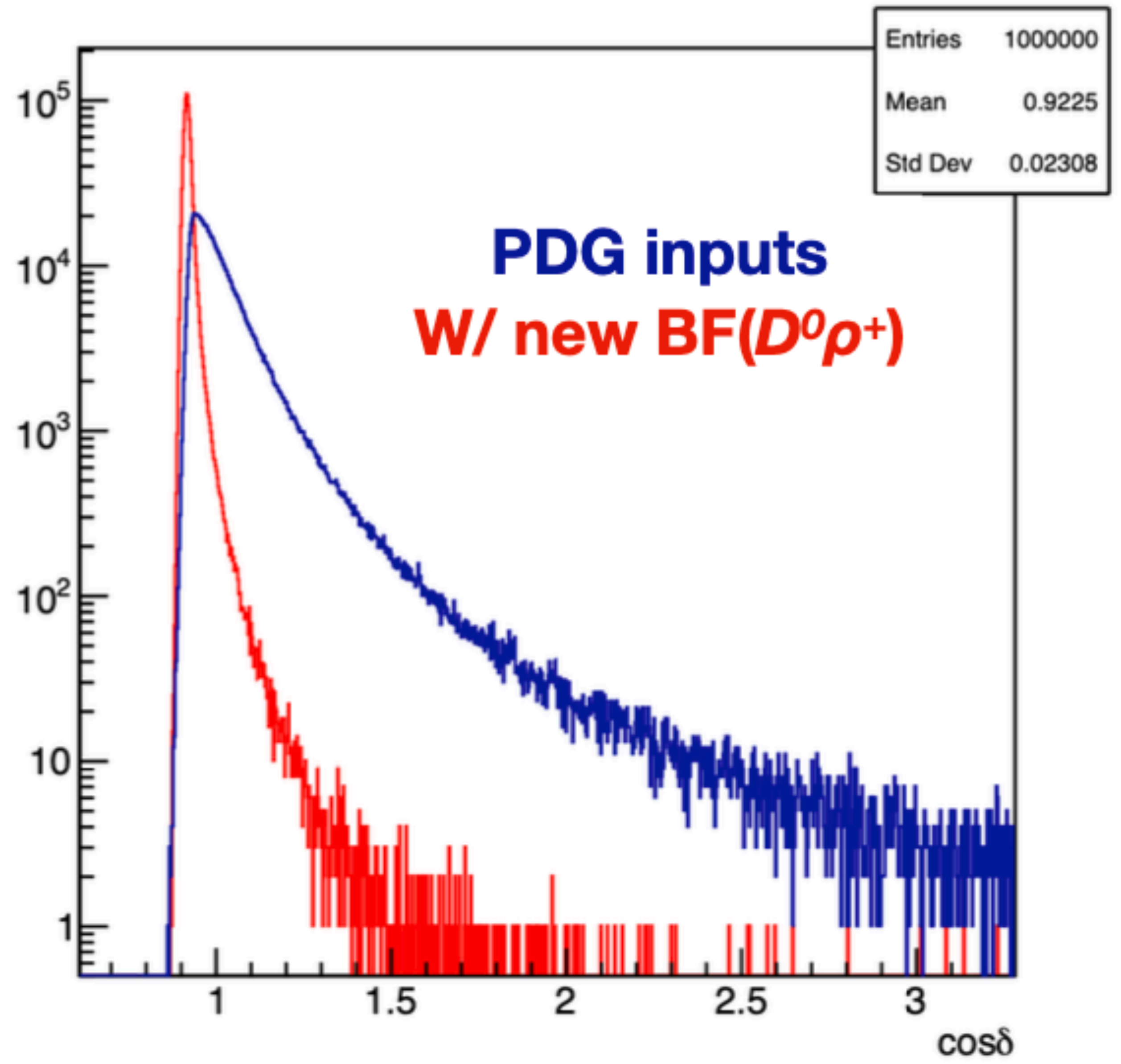
$$\cos\delta = \frac{1}{2R}\left(\frac{3}{2} \frac{\tau_+}{\tau_0} \frac{\mathcal{B}(D^0\rho^0) - 2\mathcal{B}(D^+\rho^-)}{\mathcal{B}(D^0\rho^-)} + \frac{1}{2} \right)$$

LHCb measured BF($D^0\rho^0$) [arxiv:1505.01710] and reported R and δ in agreement with HQL and factorization models (R~1, δ~0)

Improve significantly with our measurement

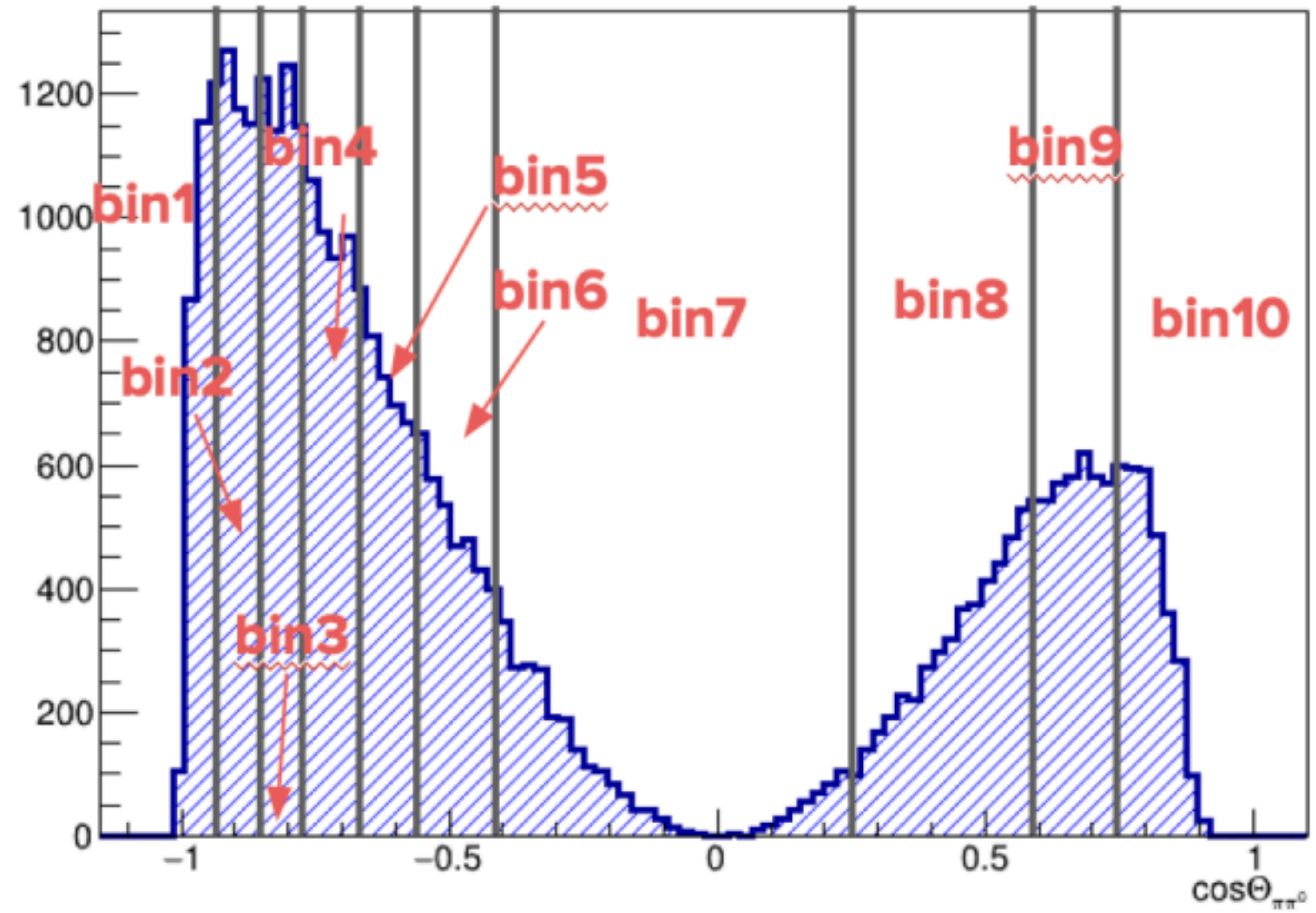
	R	cosδ
LHCb	0.69 ± 0.15	$0.984^{+0.113}_{-0.048}$
W/ new BF($D^0\rho^+$)	$0.93^{+0.11}_{-0.12}$	$0.919^{+0.012}_{-0.009}$



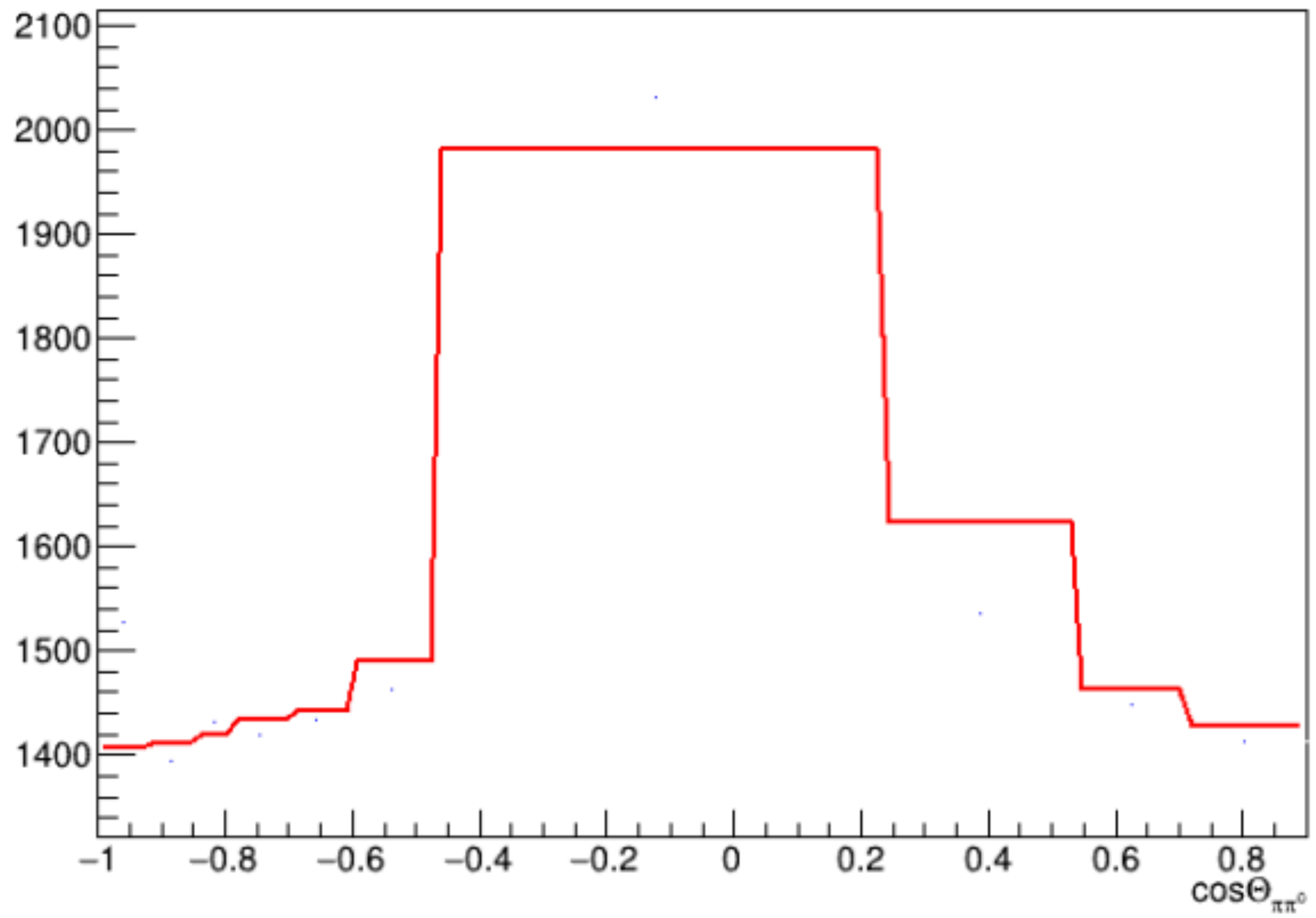


$B^+ \to D^0\rho$

$\cos\theta_\rho$ distribution



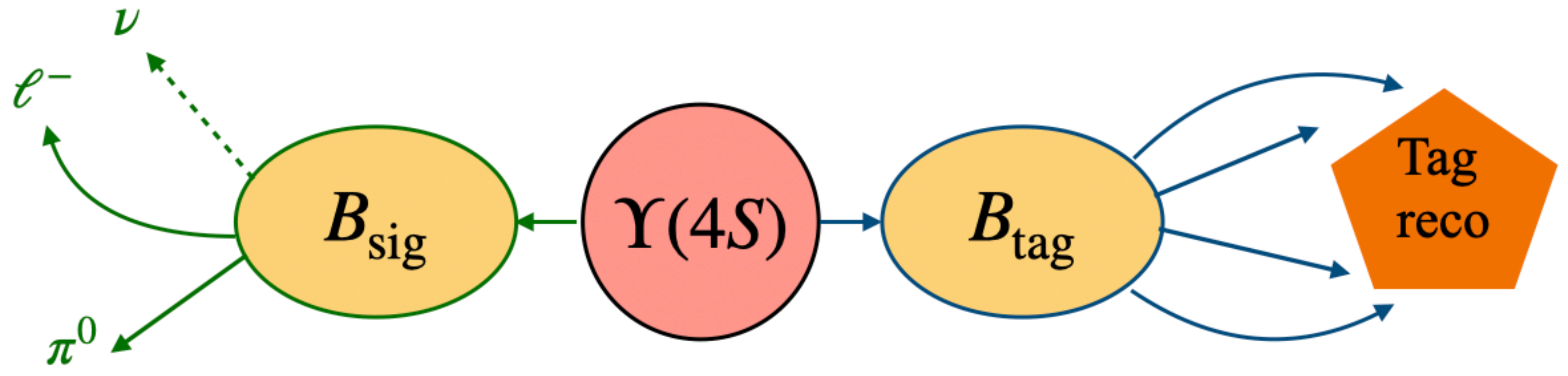
$B^+ \to D^0\rho^+$



$B^+ \to D^0\pi^+\pi^0$

B-tagging at Belle II

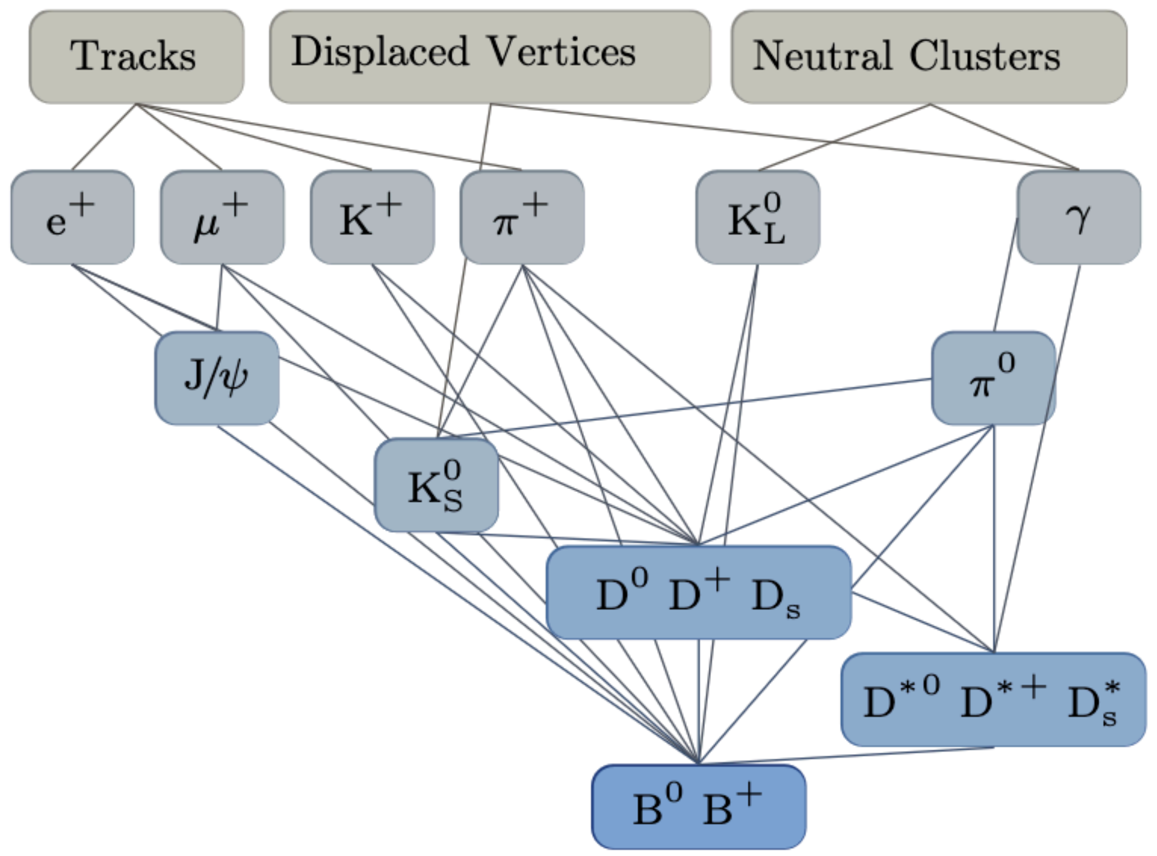
A large part of our physics program (**Missing energy analyses**) relies on B-tagging



Step 1: reconstruction of the partner B (B_{tag}) using well-known channels

Step 2: use beam constraint and infer the information on the second B (B_{sig}): **flavour, charge and kinematic constraints**

- **Full Event Interpretation (FEI)**
- MVA based B-tagging algorithm
- Hierarchical approach to reconstruct $\mathcal{O}(10^4)$ decay chains

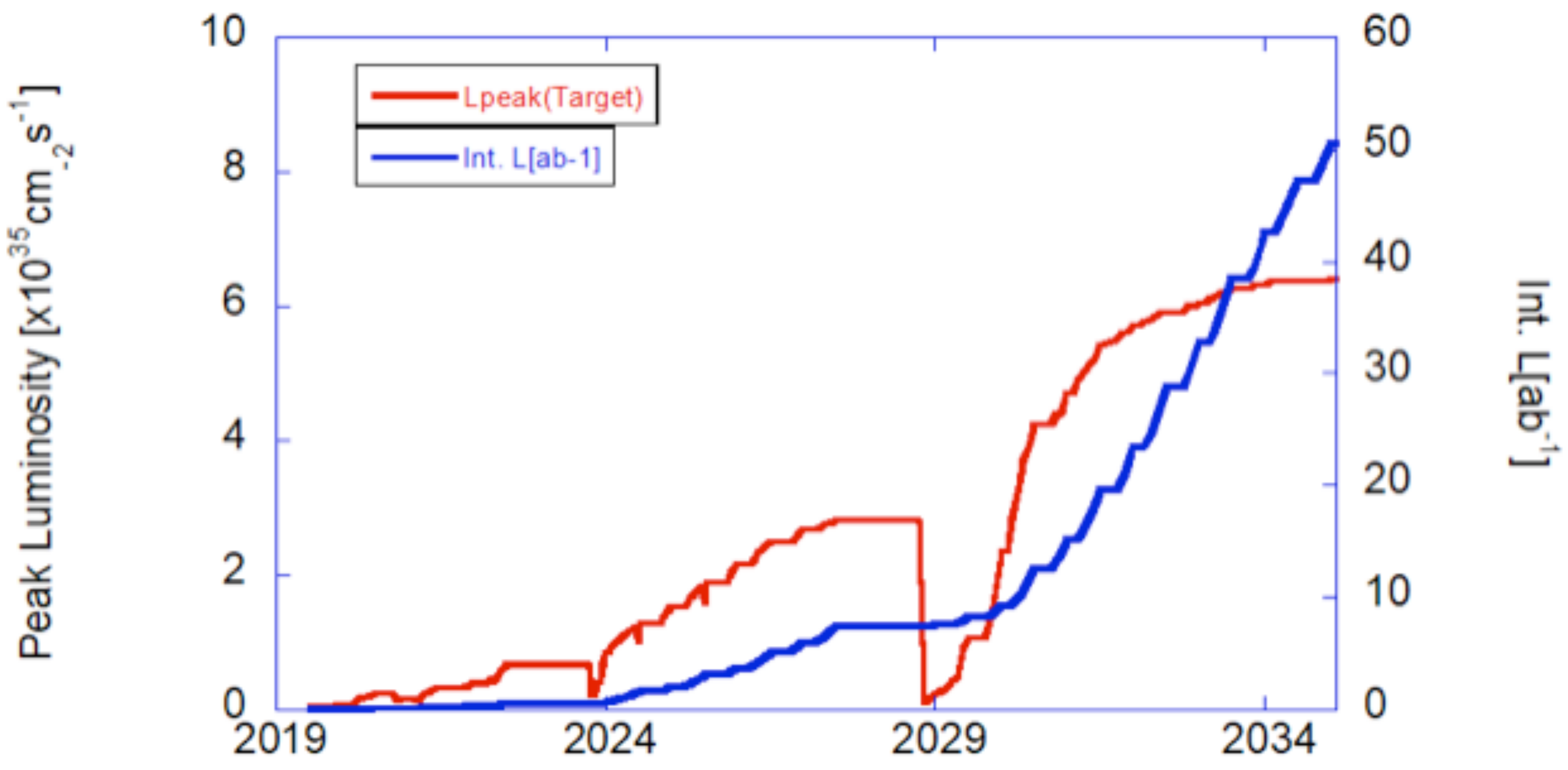


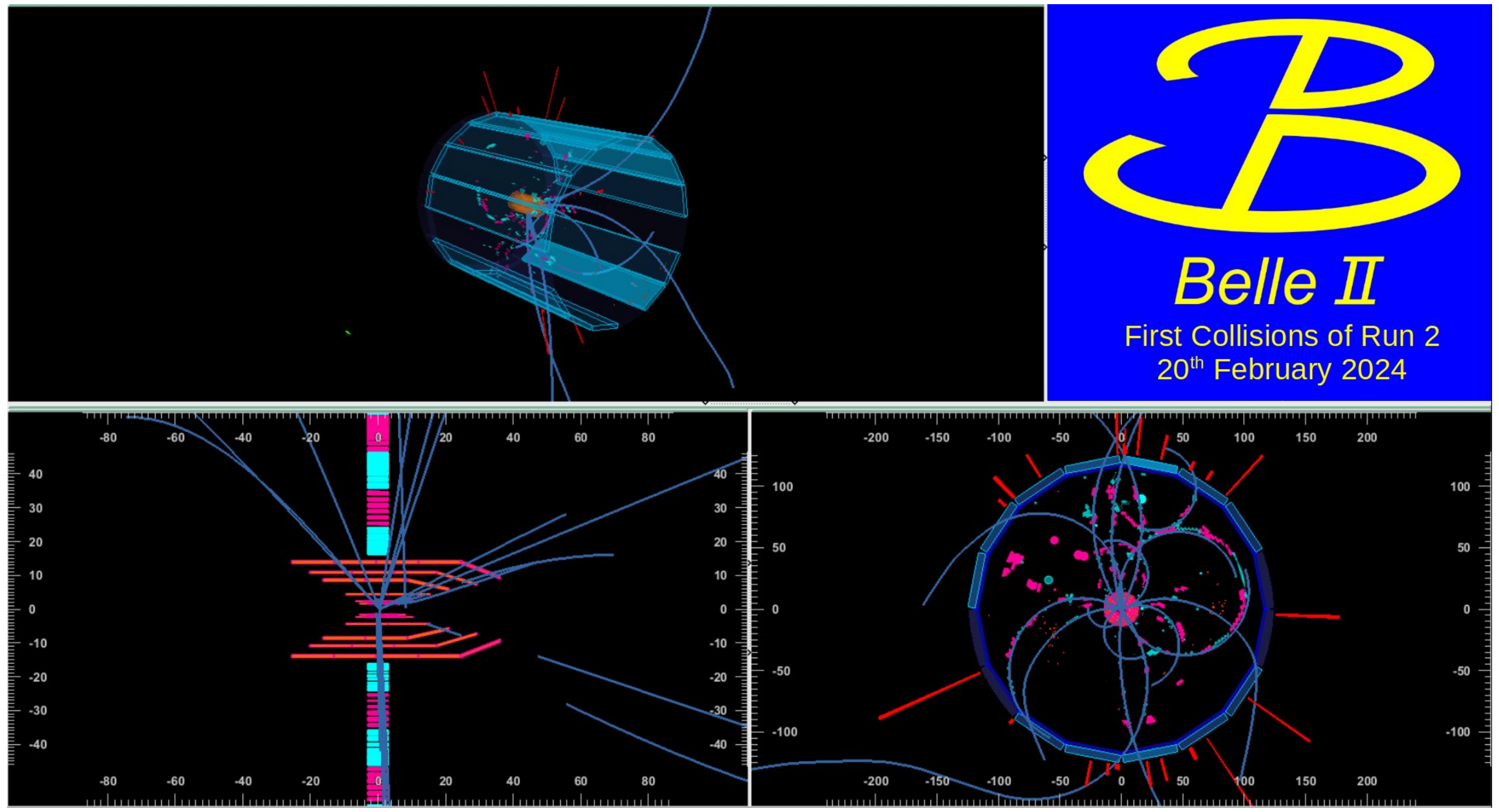
[T. Keck et al, Comput. Soft Big Sci 3, 6 (2019)]

Improved B and D decay knowledge helps to improve the simulation, hence improve B-tagging

Belle II & SuperKEKB status

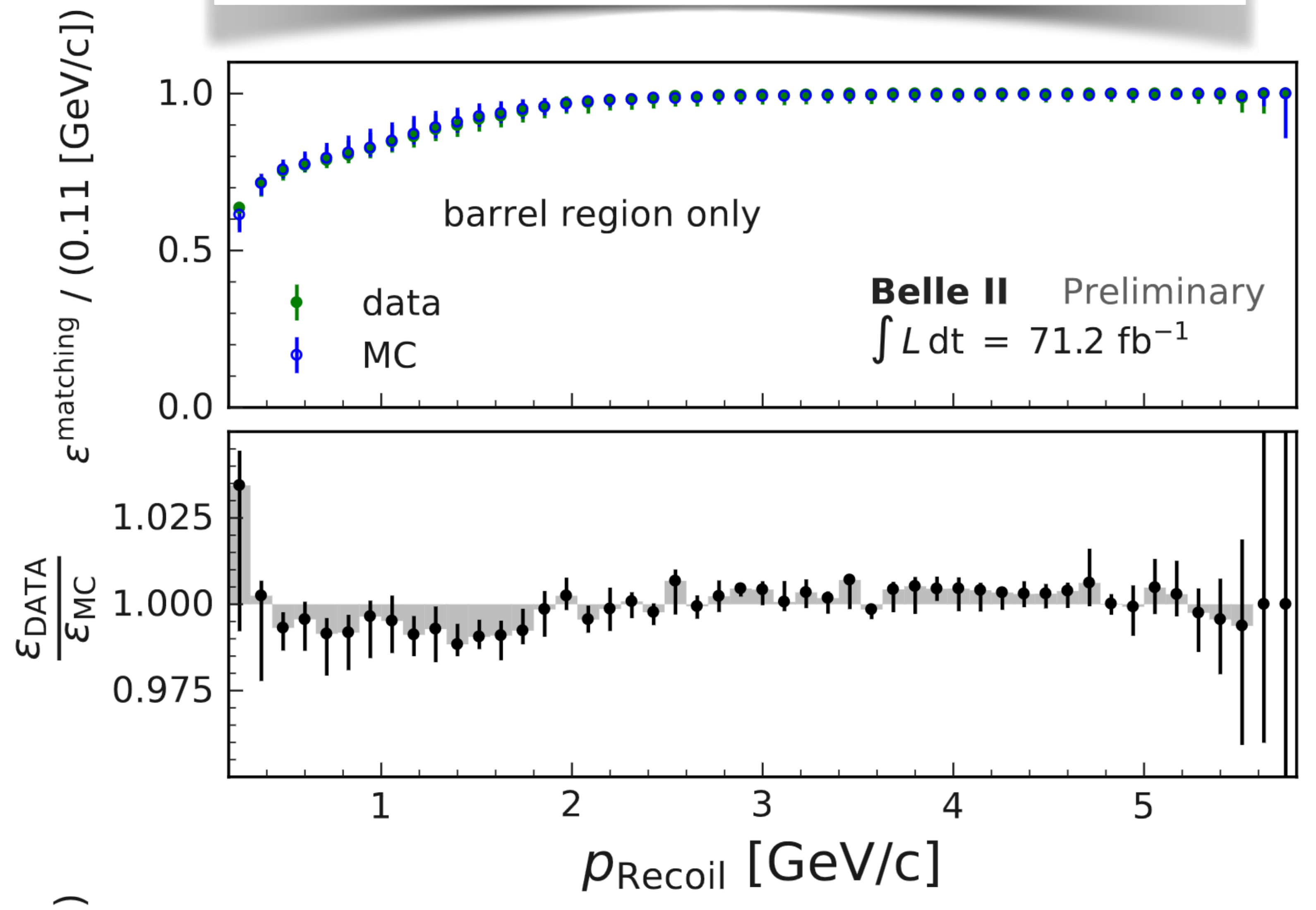
- Thanks to the dedication of people based at KEK, we could keep taking data even during the worst of the pandemic
- Record instantaneous luminosity (of any collider): $4.71 \times 10^{34}\ cm^{-2}\ s^{-1}$
- **Recorded in total (Run I) ~424 fb^{-1}**
- Long shutdown 1 (07/2022 — 01/2024) for major upgrades
  - **New two-layer pixel detector**
- **Run 2: data taking resumed in February 2024**

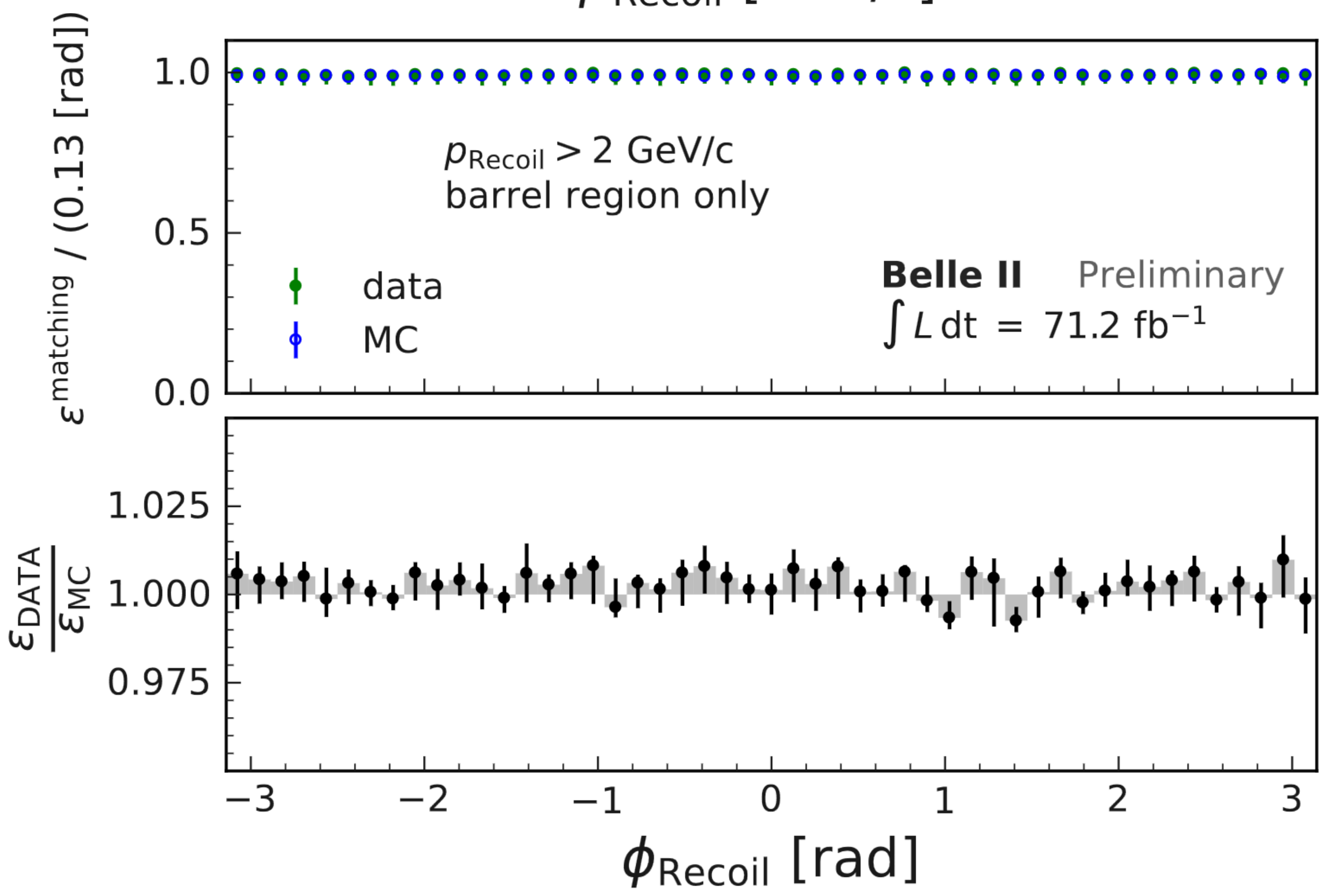




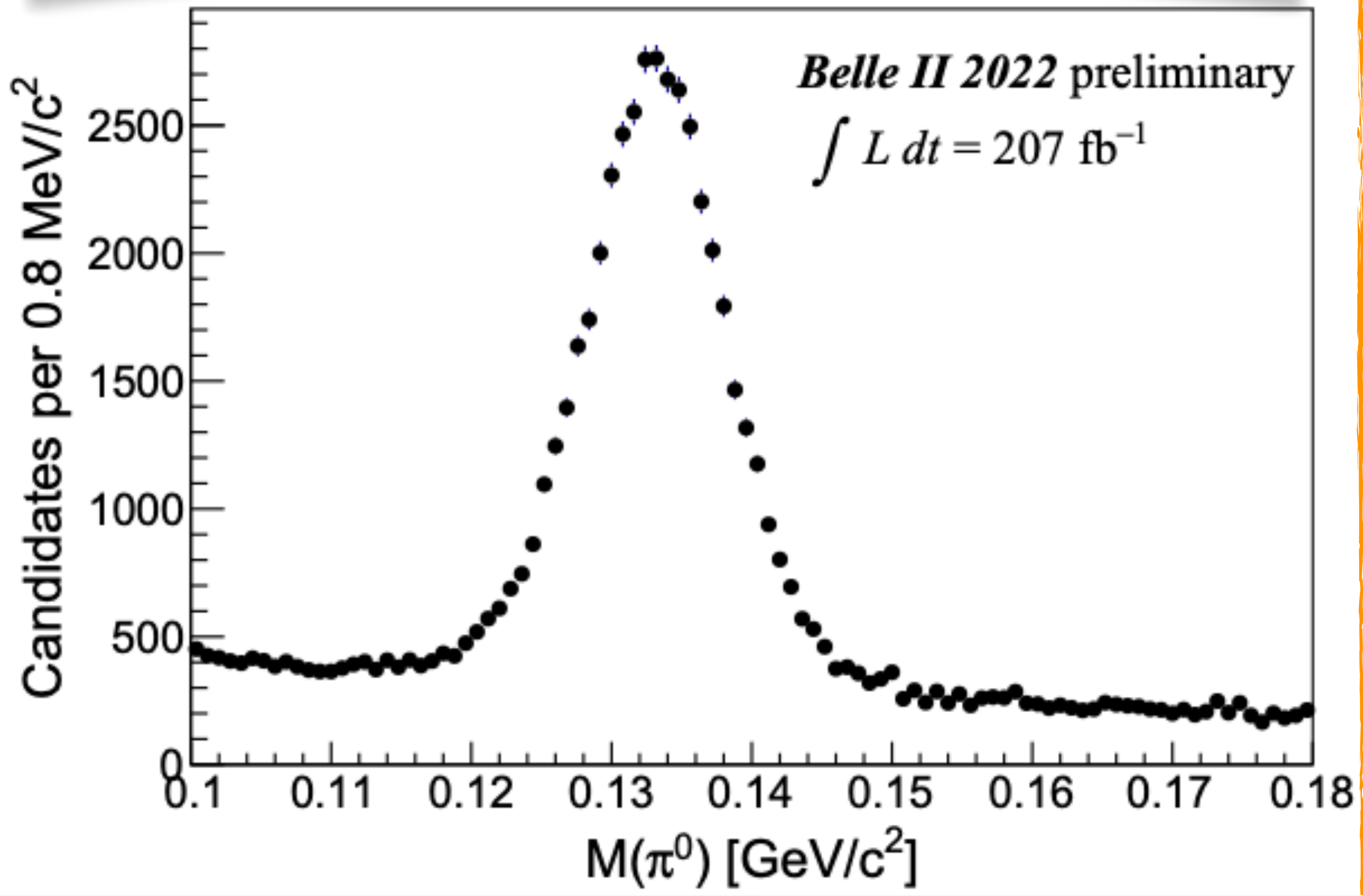
Performance

High photon efficiency

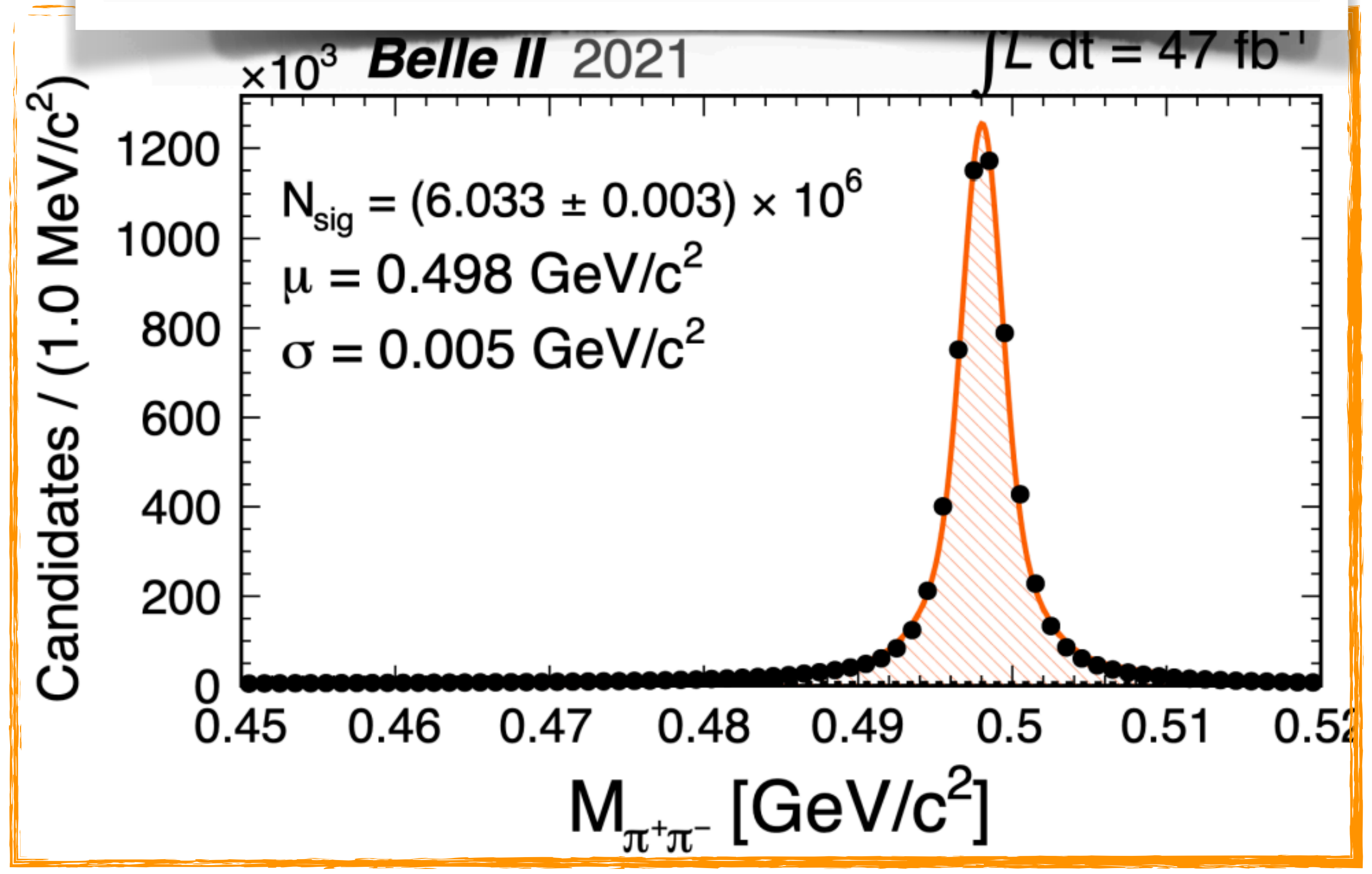




Good π^0 reconstruction

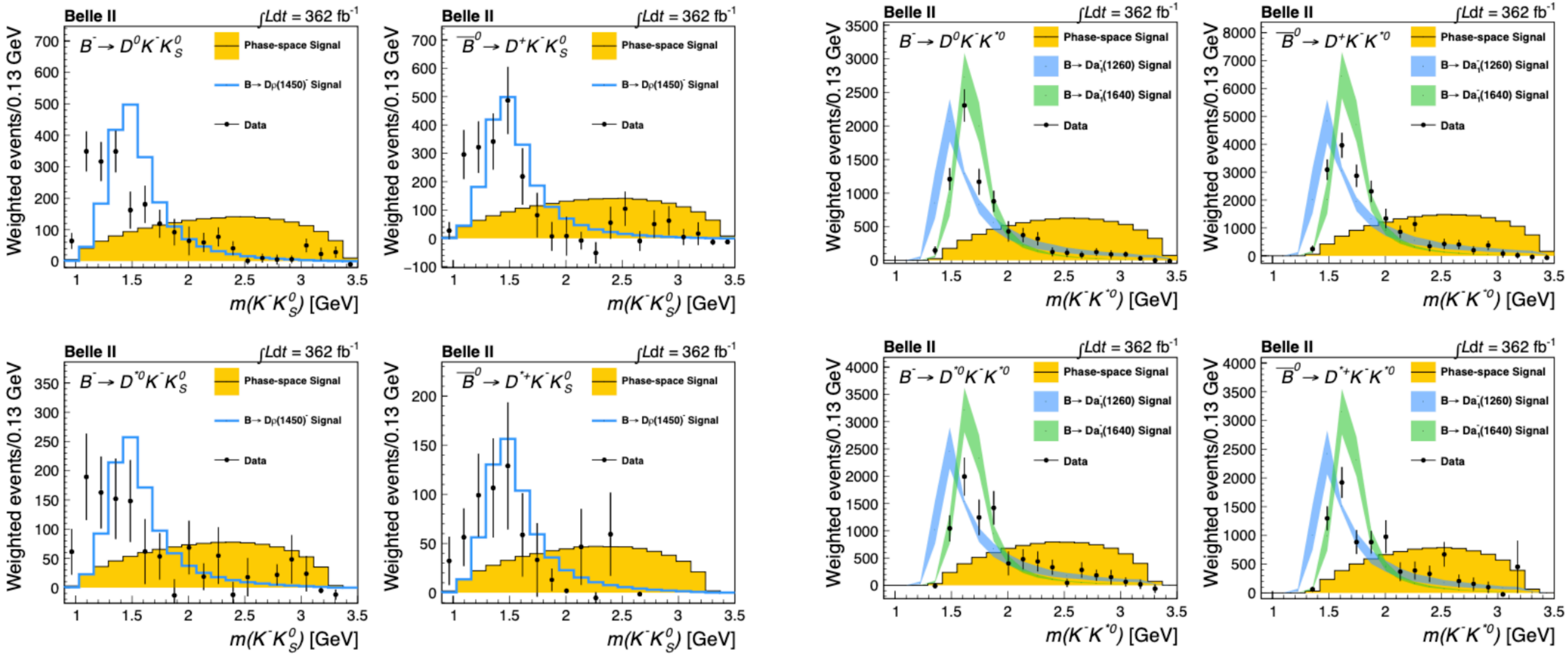


Excellent K_S^0 reconstruction



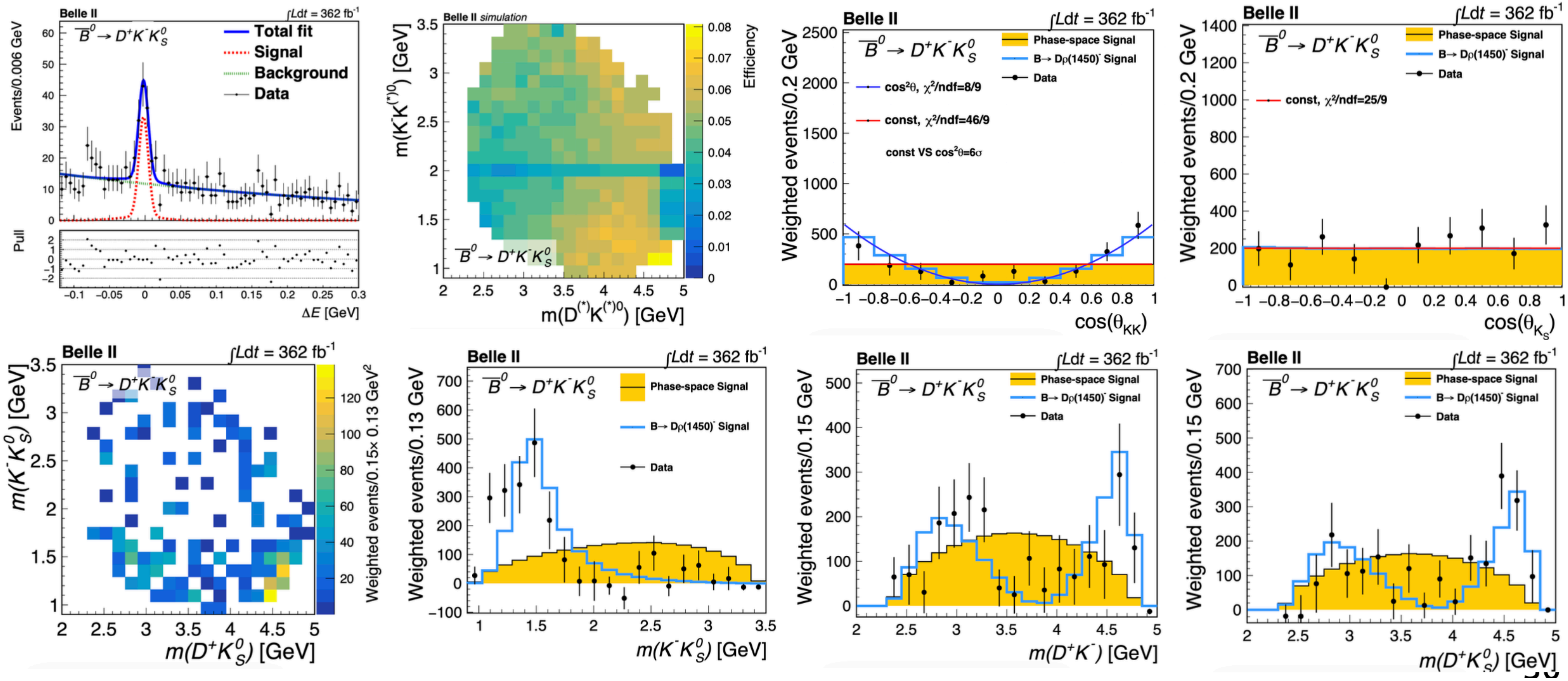
$B \to D^{(*)}K^-K^{(*)0}_{(s)}$ and $B \to D^{(*)}D_s^-$ decays

bkg-subtracted and efficiency corrected $m(K^-K)$ distributions

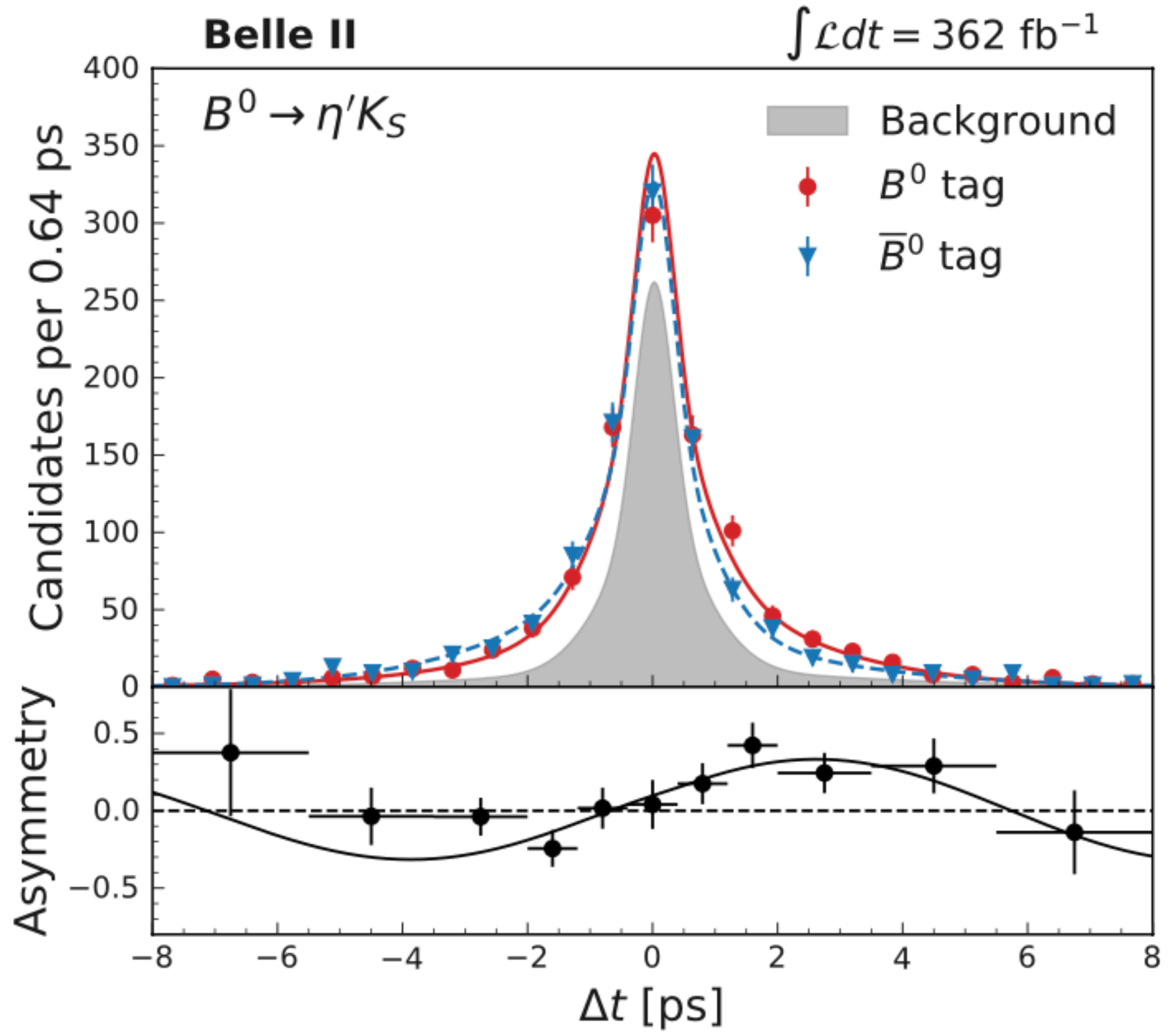


$B \to D^{(*)}K^-K^{(*)0}_{(S)}$ and $B \to D^{(*)}D_s^-$ decays

Example of all the derived results for a single channel ($\bar{B}^0 \to D^+K^-K^0_S$)



$B^0 \to \eta' K_S^0$: extra info



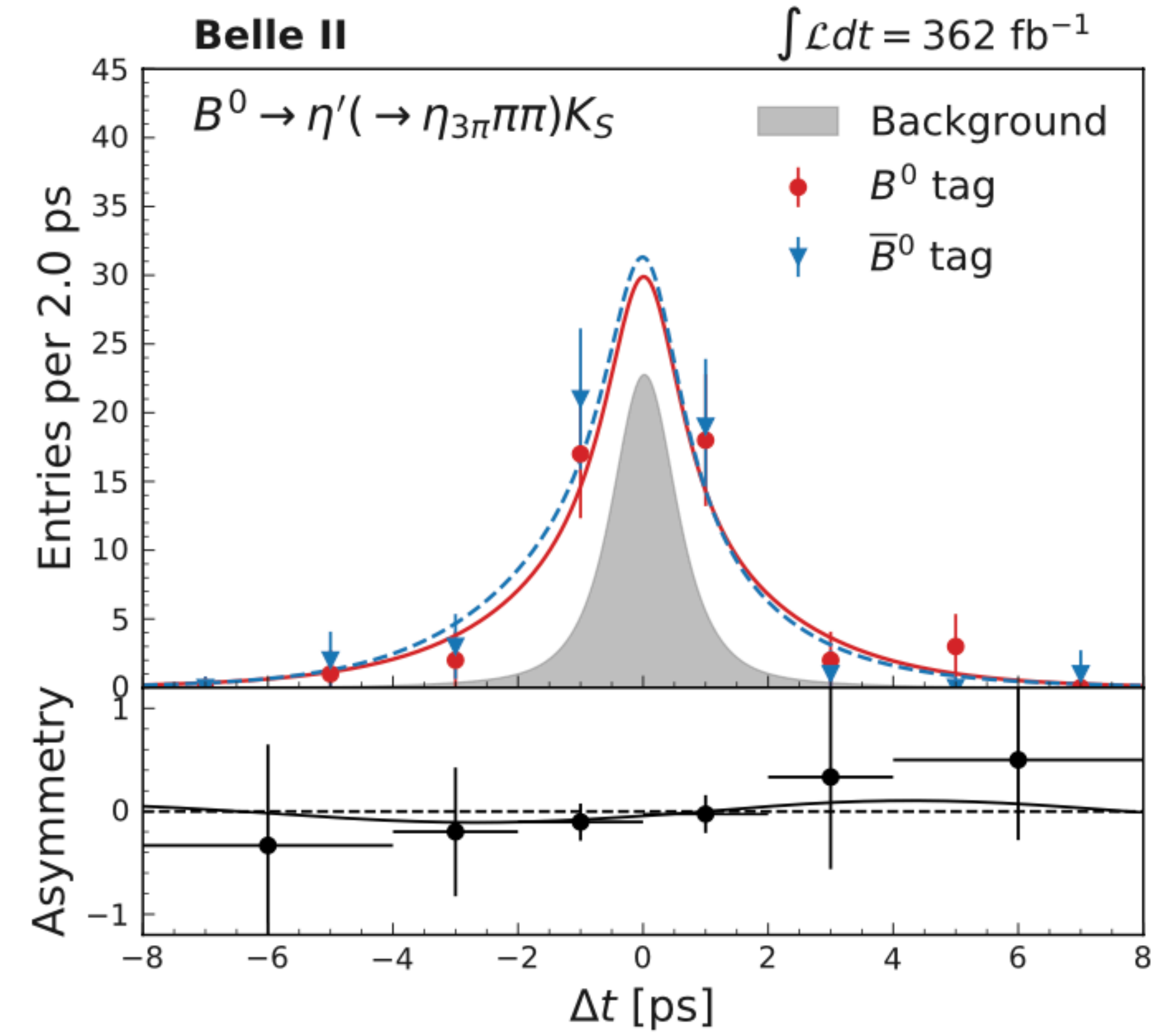
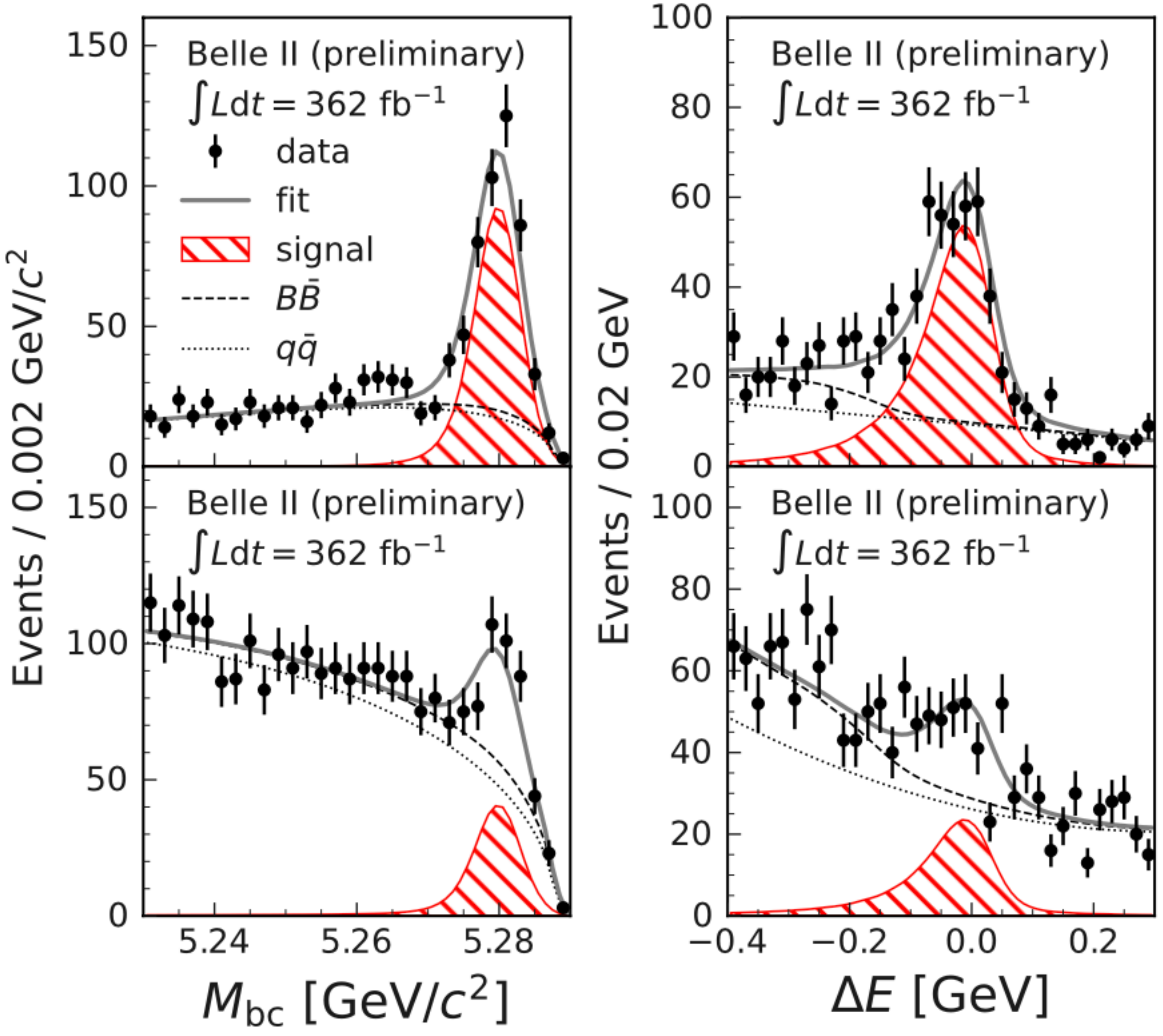


Table II: Summary of systematic uncertainties for $C_{\eta' K_S^0}$ and $S_{\eta' K_S^0}$.

Source	$C_{\eta' K_S^0}$	$S_{\eta' K_S^0}$
Signal and continuum yields	< 0.001	0.002
SxF and $B\overline{B}$ yields	< 0.001	0.006
$C_{\rm BDT}$ mismodeling	0.004	0.010
Signal and background modeling	0.020	0.014
Observable correlations	0.008	0.001
Δt resolution fixed parameters	0.005	0.009
Δt resolution model	0.004	0.019
Flavor tagging	0.007	0.004
τ_{B^0} and Δm_d	< 0.001	0.002
Fit bias	0.003	0.002
Tracker misalignment	0.004	0.006
Momentum scale	0.001	0.001
Beam spot	0.002	0.002
B-meson motion in the $\Upsilon(4S)$ frame	< 0.001	0.017
Tag-side interference	0.005	0.011
$B\overline{B}$ background asymmetry	0.008	0.006
Candidate selection	0.007	0.009
Total	0.027	0.037

$B^0 \to K_S^0\pi^0\gamma$: extra info



Top plots: $B^0 \to K^{*0}\gamma,\ 0.8\,\mathrm{GeV} < m(K_S^0\pi^0) < 1\,\mathrm{GeV}$

Bottom plots: $B^0 \to$ non-$K^{*0}\gamma$, excluding above mass region

Table II: Summary of systematic uncertainties.

	$K^{*0}\gamma$		$K_S^0\pi^0\gamma$	
Source	S	C	S	C
E and p scales	±0.017	±0.015	±0.083	±0.047
Vertex measurement	±0.021	±0.009	±0.023	±0.036
Flavor tagging	±0.005	$^{+0.012}_{-0.009}$	±0.008	$^{+0.013}_{-0.009}$
Event-by-event fractions	±0.003	$^{+0.004}_{-0.003}$	±0.032	±0.013
Resolution functions	±0.014	±0.009	±0.032	±0.013
Physics parameters	< 0.001	< 0.001	±0.003	< 0.001
$B\bar{B}$ asymmetries	$^{+0.010}_{-0.021}$	±0.022	$^{+0.023}_{-0.015}$	$^{+0.032}_{-0.033}$
Tag-side interference	< 0.001	-0.002	$+0.001$	$+0.001$
Total	$^{+0.033}_{-0.037}$	$^{+0.032}_{-0.031}$	$^{+0.100}_{-0.098}$	$^{+0.071}_{-0.070}$

Sample	Signal yield	$B\bar{B}$ bkg yield	S/N
$B^0 \to K_S^0\pi^0\gamma$ in MR1	385 ± 24	20 ± 8	2.36
$B^0 \to K_S^0\pi^0\gamma$ in non-MR1	171 ± 23	69 ± 19	0.34
$B^+ \to K_S^0\pi^+\gamma$	843 ± 34	55 ± 10	2.68

ϕ_3/γ: Belle + Belle II combination

Parameters	$\phi_3(^\circ)$	r_B^{DK}	$\delta_B^{DK}(^\circ)$	$r_B^{D\pi}$	$\delta_B^{D\pi}(^\circ)$	$r_B^{D^*K}$	$\delta_B^{D^*K}(^\circ)$
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]