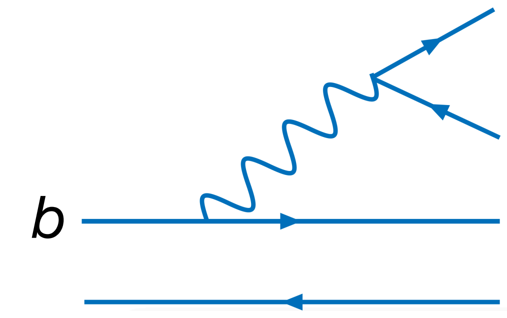
Recent Belle II results on hadronic B decays

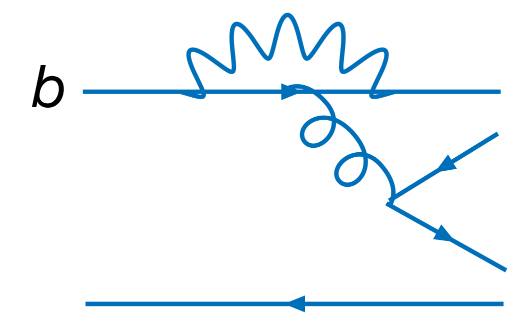
Sebastiano Raiz (University and INFN Trieste)
on behalf of the Belle II collaboration

FPCP2023 - Parallel session
May 30, 2023

Hadronic B decays

b **→** ***c*, *u*** trees and ***b*** **→** ***d*, *s*** penguins.





Probe SM dynamics in all three CKM angles

- γ with theoretically clean modes $B \to DK$,
- α with $B \to \rho\rho$, $B \to \rho\pi$, $B \to \pi\pi$ isospin analyses,
- β with $B^0 \to J/\psi K^0_S$, $B^0 \to \eta' K^0_S$, $B^0 \to \phi K^0_S$

and by testing isospin sum rules, chiral structure, ...

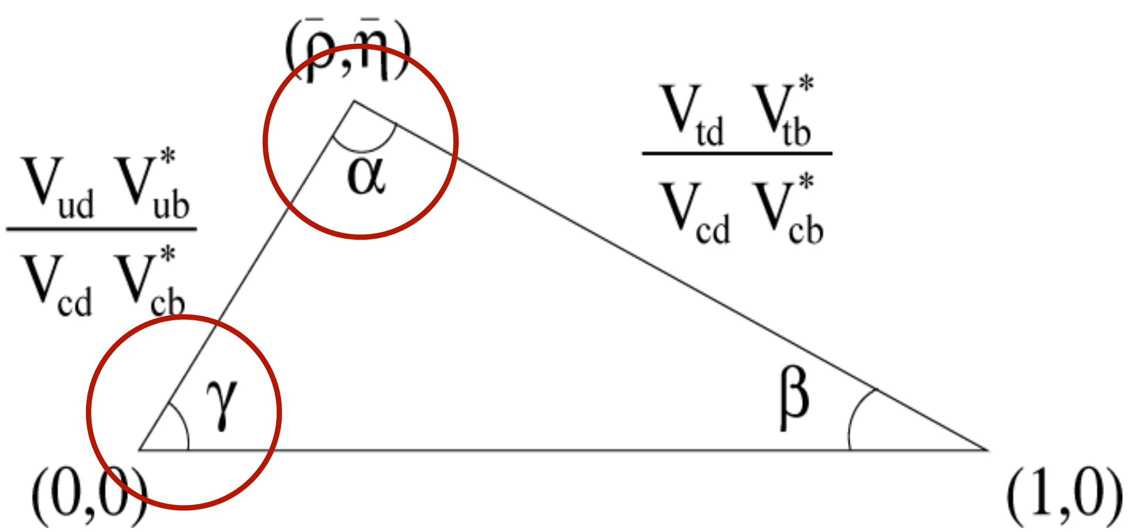
Today:

γ determination using two different methods,

$B \to \rho\rho$ and $B \to \pi\pi$ towards α,

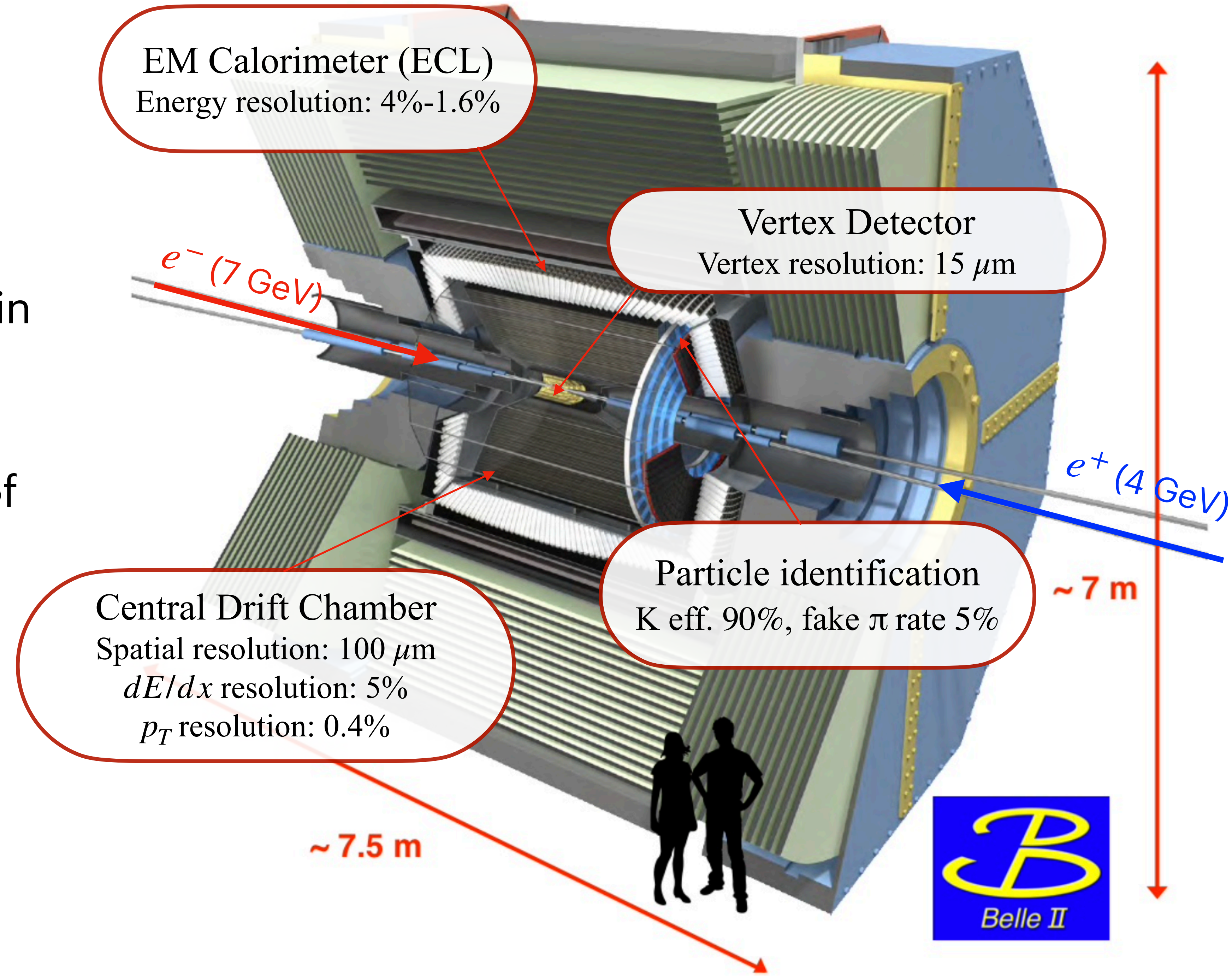
$K\pi$ isospin sum rule,

observation of new $B \to D^{(*)} K^- K^0_S$ decays.



The Belle II detector

- SuperKEKB: 7-on-4 GeV e^-e^+ collider at 10.58 GeV;
- Aim at 700 $B\bar{B}$ pairs/second in low-bkg environment;
- 424 fb^{-1} (400 x10^6 $B\bar{B}$ pairs) of data collected;
- Record peak luminosity: 4.7x10^{34} cm^{-2} s^{-1}



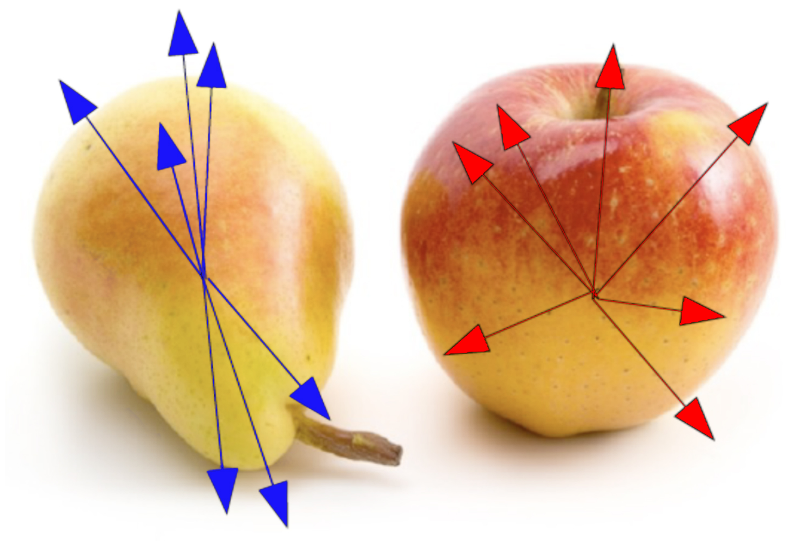
Unique reach on final states with multiple neutrinos and π^0/photons.

Analysis workflow

~1/5 of hadronic events from e^+e^- are $B\bar{B}$.

Typical B hadronic event: 10 tracks/clusters — easy to trigger on unbiasing variables (e.g. number of tracks) — isotropically distributed in space.

Main backgrounds: $e^+e^- \to q\bar{q}$ (collimated jets, very different event shape), other misidentified B events.



Reconstruction

- combine final state particles (K, π, ...) in kinematic fits to form the B decay

Selection

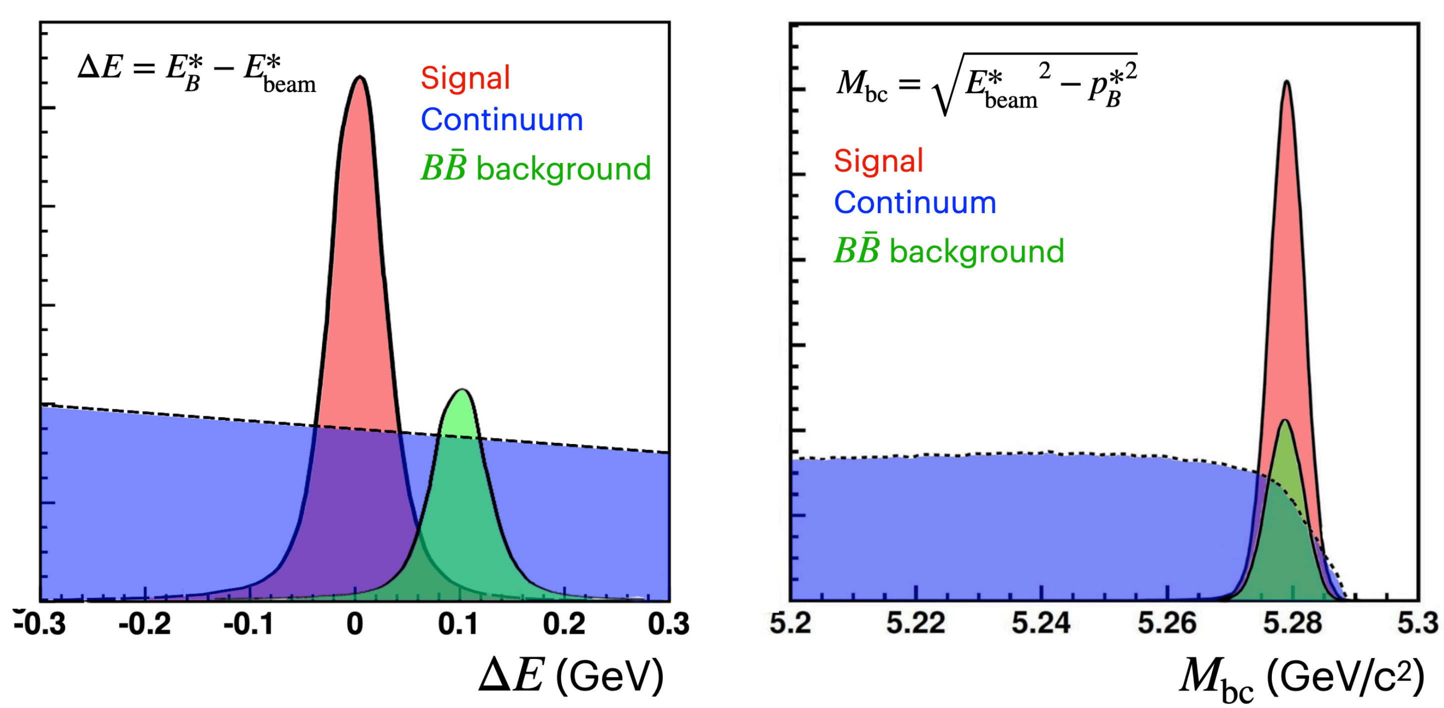
- optimize event-shape multivariate classifier (CS) and particle ID criteria

Fit

- extract models from simulation (calibrate on data), fit in to data and evaluate physics quantities

Systematic uncertainties

- with control modes and simulations



Separate signal from $q\bar{q}$ and misidentified B's.

Separate B-events from $q\bar{q}$.

Measurement of γ

γ from $B \to DK$ decays

γ: phase between $b \to u$ and $b \to c$ transitions. Accessible via tree-level decays: no direct new physics $\to$ strong constraints on SM.

Current WA dominated by LHCb:

$$\gamma[^\circ] = 65.9 \, ^{+\,3.3}_{-\,3.5}$$ HFLAV

Various approaches — different D final states:

- Self-congjugate final states $D \to K^0_S h^+ h^-$

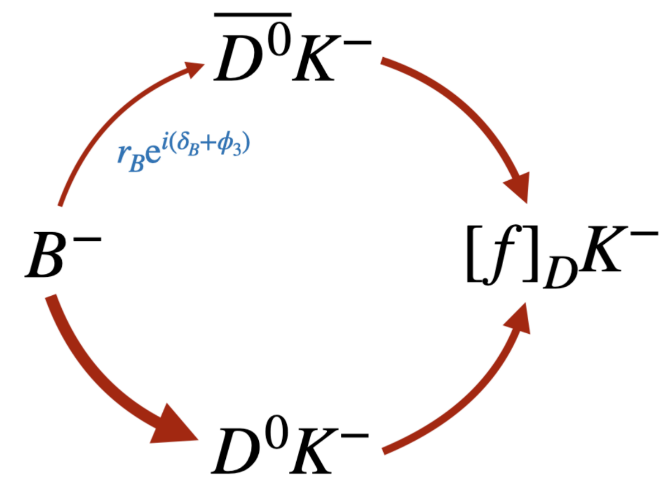
Belle + Belle II $\gamma = (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ$

https://link.springer.com/article/10.1007/JHEP02(2022)063

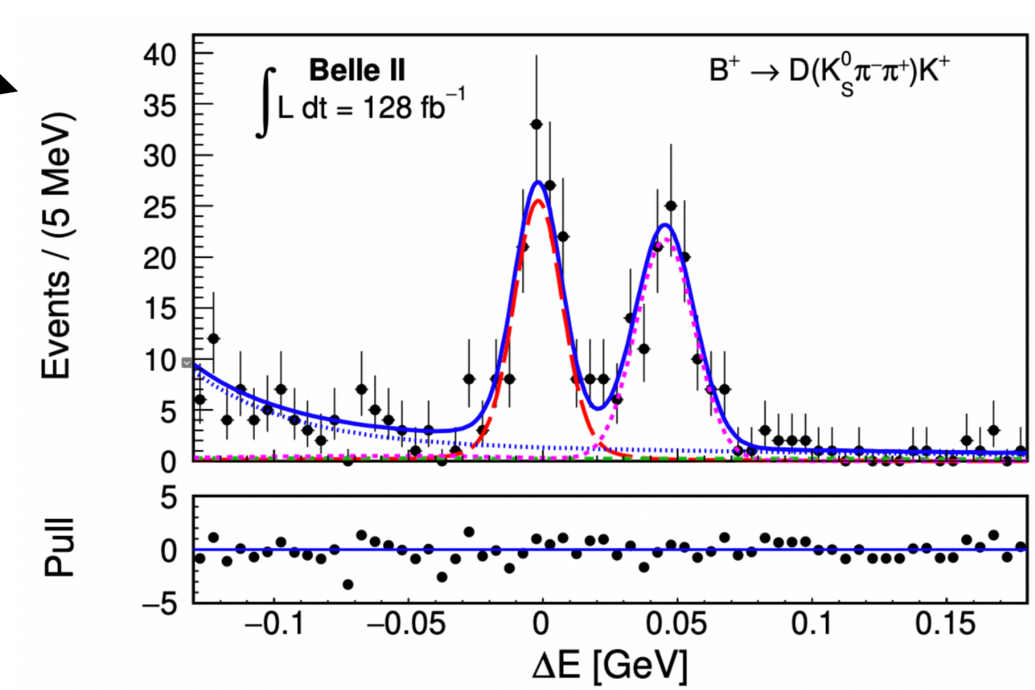
- Cabibbo-suppressed decays $D \to K^0_S K^\pm \pi^\mp$

-CP eigenstates $D \to K^+K^-, K^0_S\pi^0$

Interference between two decays to same final state gives access to phase:



$$\frac{\mathscr{A}^{\text{suppr.}}\left(B^- \to \overline{D}^0 K^-\right)}{\mathscr{A}^{\text{favor.}}\left(B^- \to D^0 K^-\right)} = r_{\text{B}} e^{i(\delta_{\text{B}}+\gamma)}$$



γ using Cabibbo-suppressed decays

362 fb^{-1} Belle II
+ 711 fb^{-1} Belle

$B^{\pm} \rightarrow DK^{\pm}, D\pi^{\pm} \quad (D \rightarrow K^0_S K^{\pm} \pi^{\mp})$

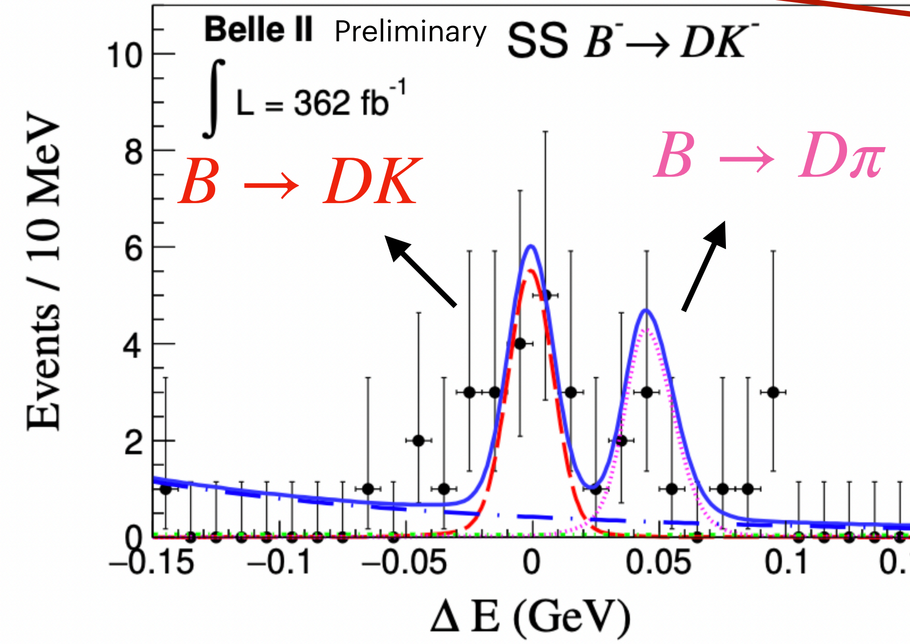
SS: same-sign, *OS*: opposite sign.

2D fit ($\Delta E, CS'$) of 8 categories:

$(+,-) \times (SS, OS) \times (DK, D\pi)$ in full D phase space

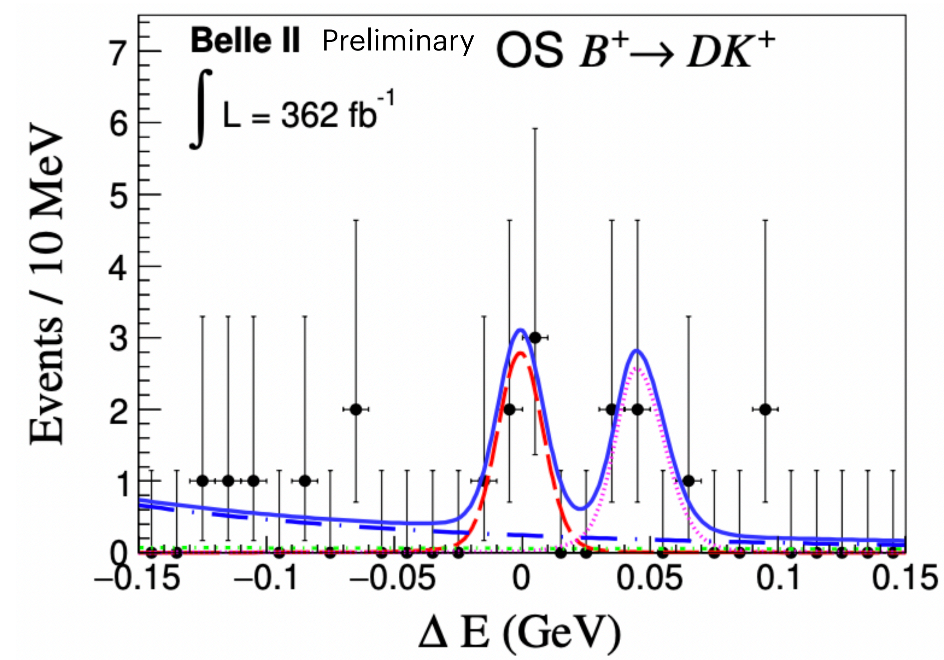
and in interference-enhanced $D \rightarrow K^* K$ region.

Combination of $\mathscr{R}$ and $\mathscr{A}$ constraints γ.



Full D phase space

$$\mathscr{A}^{DK}_{SS} = -0.089 \pm 0.091 \pm 0.011$$
$$\mathscr{A}^{DK}_{OS} = +0.109 \pm 0.133 \pm 0.013$$
$$\mathscr{A}^{D\pi}_{SS} = +0.018 \pm 0.026 \pm 0.009$$
$$\mathscr{A}^{D\pi}_{OS} = -0.028 \pm 0.031 \pm 0.009$$
$$\mathscr{R}^{DK/D\pi}_{SS} = 0.122 \pm 0.012 \pm 0.004$$
$$\mathscr{R}^{DK/D\pi}_{OS} = 0.093 \pm 0.013 \pm 0.003$$
$$\mathscr{R}^{D\pi}_{SS/OS} = 1.428 \pm 0.057 \pm 0.002$$



Results consistent with LHCb, but not competitive.

Contribute to constrain γ in combination with other measurements.

γ using CP eigenstates

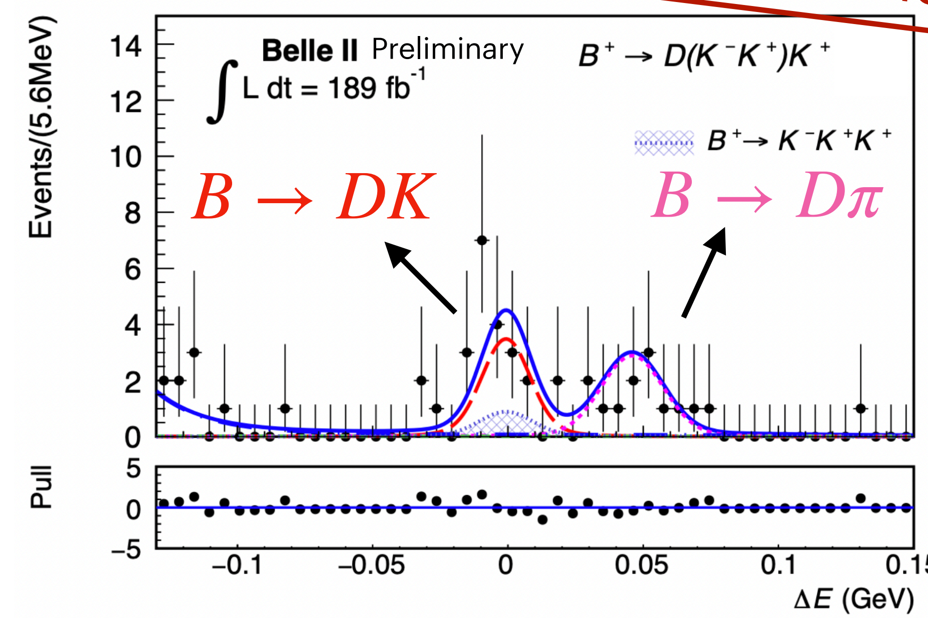
189 fb^{-1} Belle II
+ 711 fb^{-1} Belle

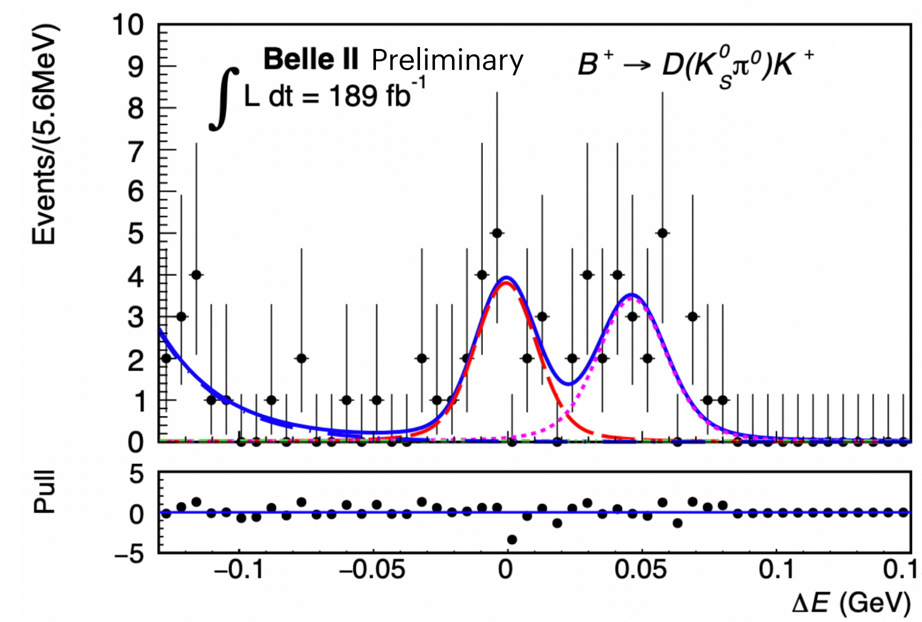
$B^{\pm} \rightarrow D_{CP\pm}$, $D \rightarrow K^+K^-$ (CP even) $D \rightarrow K^0_S\pi^0$ (CP odd)

Only accessible to Belle/Belle II

2D fit ($\Delta E, CS'$) of 6 categories:
$(DK, D\pi) \times (K^+K^-, K^0_S\pi^0, K^+\pi^-)$

Combination of $\mathscr{R}$ and $\mathscr{A}$ gives access to γ.





$$\mathscr{R}_{CP+} = 1.164 \pm 0.081 \pm 0.036$$
$$\mathscr{R}_{CP-} = 1.151 \pm 0.074 \pm 0.019$$
$$\mathscr{A}_{CP+} = +0.125 \pm 0.058 \pm 0.014$$
$$\mathscr{A}_{CP-} = -0.167 \pm 0.057 \pm 0.006$$

Evidence for difference in $\mathscr{A}_{CP\pm}$.

Results consistent with BaBar and LHCb, but not competitive.
Contribute to constrain γ in combination with other measurements.

Towards CKM angle α

Towards CKM angle α

$\alpha = arg\left[-V_{td}V_{tb}^{*}/V_{ud}V_{ub}^{*}\right]$ less precisely known angle, may limit the global testing power of CKM fits.

$$\alpha[^\circ] = 85.2 \,^{+\,4.8}_{-\,4.3}$$

HFLAV

Determined using $B \to \rho\rho$ and $B \to \pi\pi$ isospin analyses: combine information from BF and A_{CP} to reduce impact of hadronic uncertainties — non-perturbative QCD.

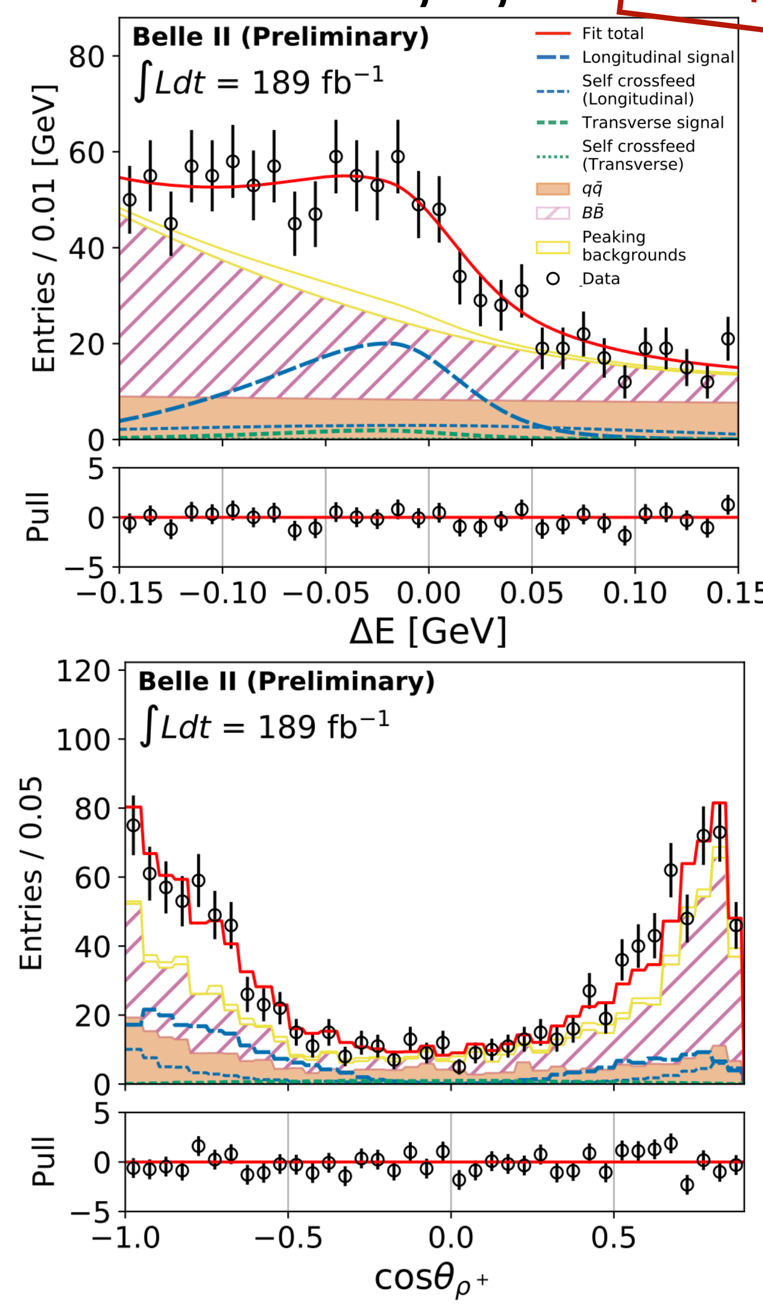
Unique Belle II capability to study in consistent way all $B \to \rho\rho$ and $B \to \pi\pi$ channels.

$B \to \rho\rho$ measurements require angular analysis:

- Winter 2022 $B^+ \to \rho^+\rho^0$ result: arxiv.org/abs/2206.12362;
- result for $B^0 \to \rho^+\rho^-$.

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

189 fb^{-1}

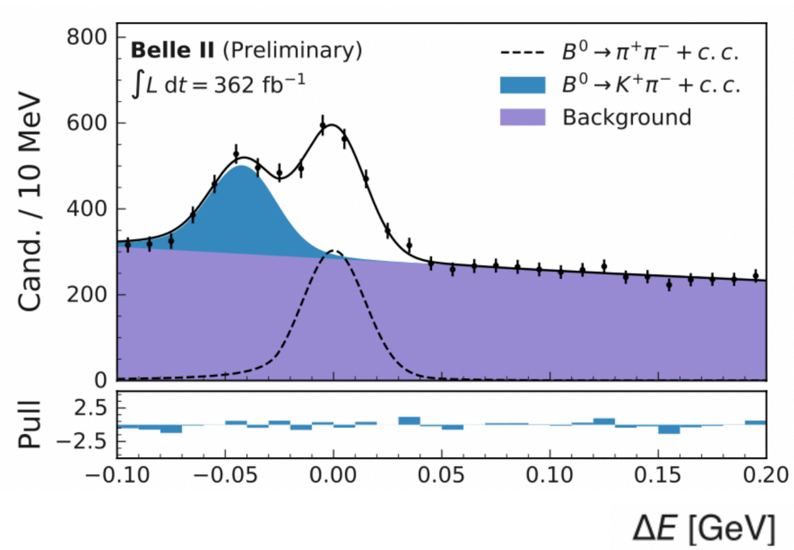


$$\mathscr{B} = (26.7 \pm 2.8 \pm 2.8) \times 10^{-6}$$
$$f_L = 0.956 \pm 0.035 \pm 0.033$$

arxiv.org/abs/2208.03554

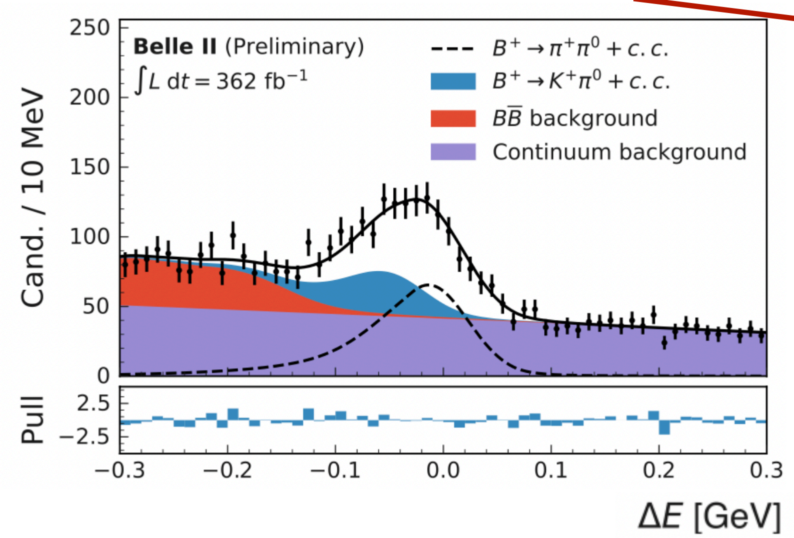
$B \to \pi\pi$ results

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



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

362 fb^{-1}

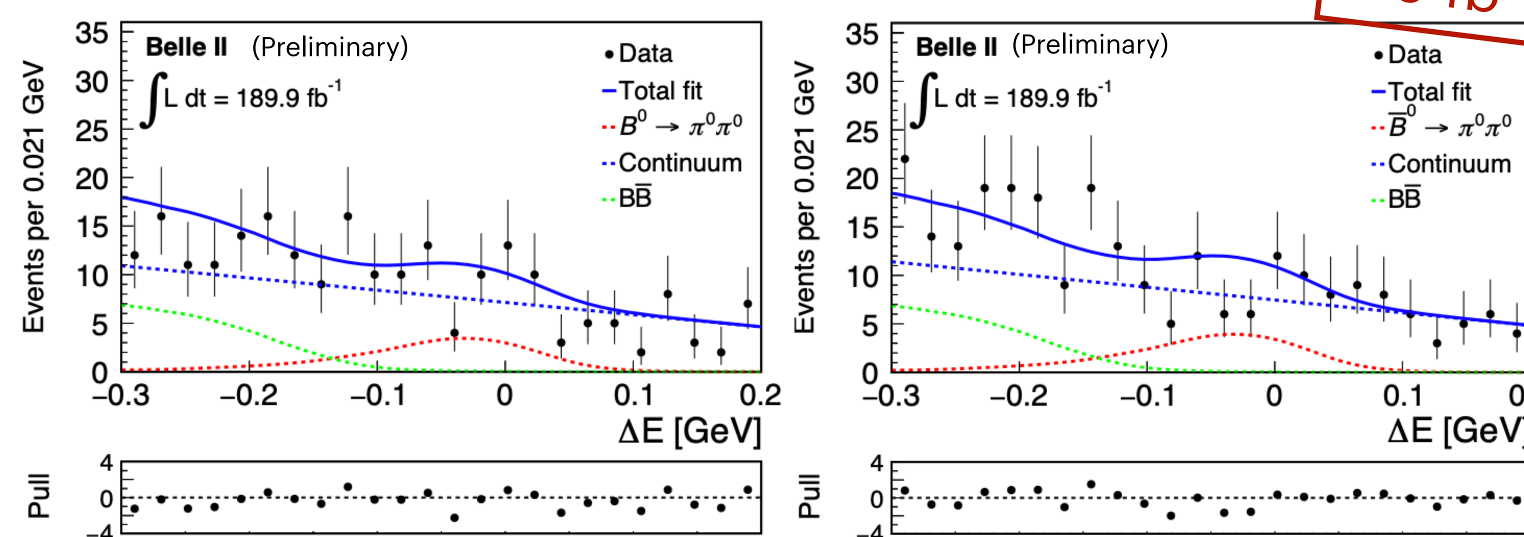


$$\mathscr{B}(\pi^+\pi^-) = (5.83 \pm 0.22 \pm 0.17) \times 10^{-6}$$
$$\mathscr{B}(\pi^+\pi^0) = (5.10 \pm 0.29 \pm 0.32) \times 10^{-6}$$
$$\mathscr{A}(\pi^+\pi^0) = -0.081 \pm 0.54 \pm 0.008$$

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

189 fb^{-1}

First $B^0 \to \pi^0\pi^0$ measurement at Belle II:
- rare, small *BF* (10^{-6}),
- only photons in the final state — dominated by signal-like background,
- large theoretical uncertainties.



arxiv.org/abs/2303.08354

Achieved Belle *BF* precision using only 1/3 of data.

$$\mathscr{B}(\pi^0\pi^0) = (1.38 \pm 0.27 \pm 0.22) \times 10^{-6}$$
$$\mathscr{A}(\pi^0\pi^0) = 0.14 \pm 0.46 \pm 0.07$$

Preliminary Belle II results on par with best performance from Belle/Babar.

Isospin sum rule

Isospin sum rule

Stringent null test of SM, sensitive to presence of non-SM dynamics. Inconsistency between current measurements: "$K\pi$ puzzle" (anomalously enhanced amplitudes or new physics):

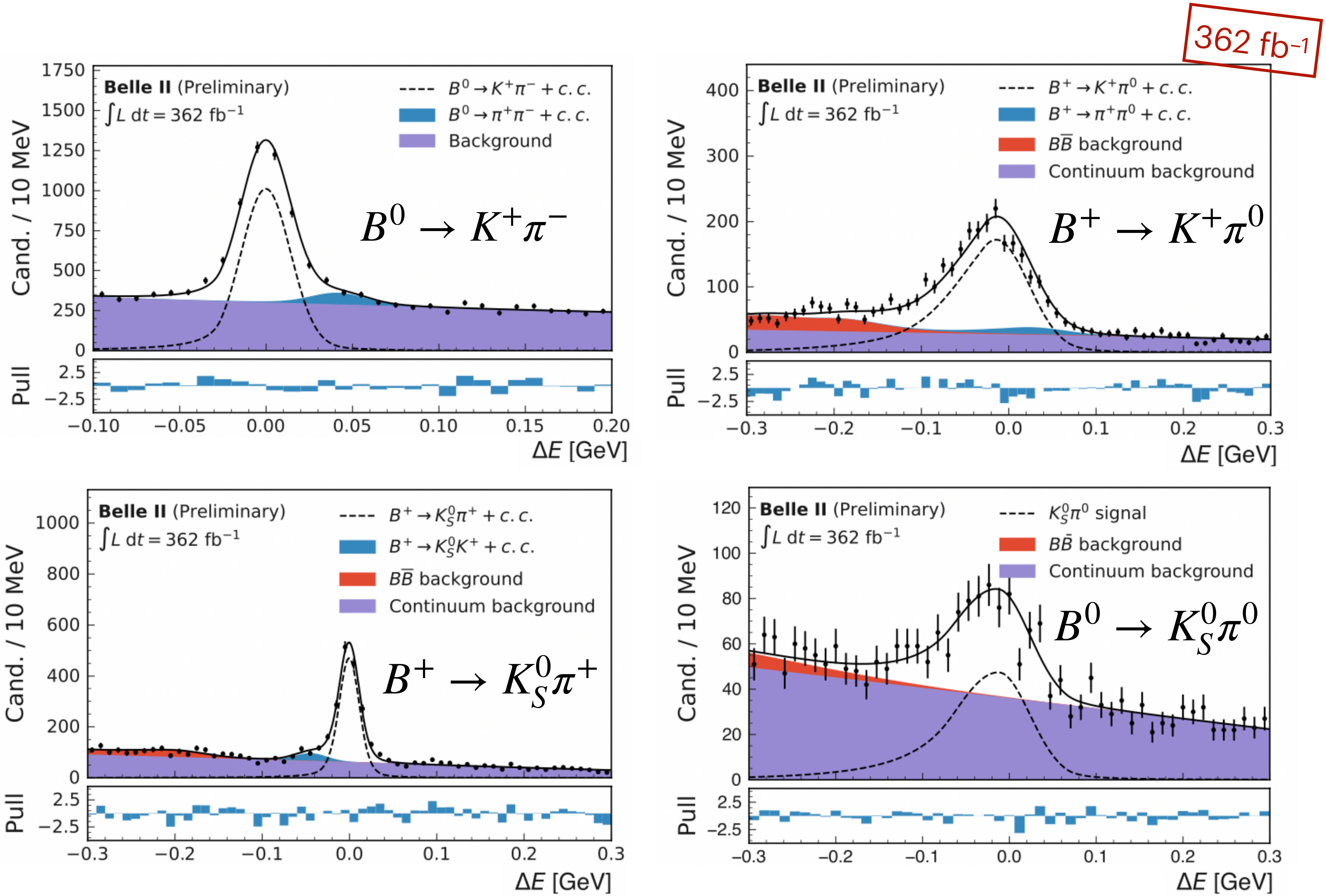
$$I_{K\pi} = \mathscr{A}_{\rm CP}^{K^+\pi^-} + \mathscr{A}_{\rm CP}^{K^0\pi^+}\frac{\mathscr{B}(K^0\pi^+)}{\mathscr{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathscr{A}_{\rm CP}^{K^+\pi^0}\frac{\mathscr{B}(K^+\pi^0)}{\mathscr{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathscr{A}_{\rm CP}^{K^0\pi^0}\frac{\mathscr{B}(K^0\pi^0)}{\mathscr{B}(K^+\pi^-)}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

Gronau (Phys. Lett. B 627 (2005) no.1, 82-88)

Belle II: measure all final states, with unique access to $B^0 \to K^0\pi^0$ (major limitation in $I_{K\pi}$).

Similar strategy for all the modes:
- common selection for final-state particles,
- continuum suppression,
- 2D fit (ΔE, CS') for branching fractions and time-integrated $\mathscr{A}_{CP}$.

Isospin sum rule results



Isospin sum rule results

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

$\mathcal{B}(K^+\pi^-) = (20.67 \pm 0.37 \pm 0.62) \times 10^{-6}$
$\mathcal{A}_{CP}(K^+\pi^-) = -0.072 \pm 0.019 \pm 0.007$

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

$\mathcal{B}(K^+\pi^0) = (13.93 \pm 0.38 \pm 0.84) \times 10^{-6}$
$\mathcal{A}_{CP}(K^+\pi^0) = +0.013 \pm 0.027 \pm 0.005$

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

$\mathcal{B}(K^0_S\pi^+) = (24.40 \pm 0.71 \pm 0.86) \times 10^{-6}$
$\mathcal{A}_{CP}(K^0_S\pi^+) = +0.046 \pm 0.029 \pm 0.007$

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

$\mathcal{B}(K^0_S\pi^0) = (10.16 \pm 0.65 \pm 0.67) \times 10^{-6}$
$\mathcal{A}_{CP}(K^0_S\pi^0) = -0.006 \pm 0.15 \pm 0.05$

$\mathcal{B}$ and $\mathcal{A}_{CP}$ agree and are competitive with world's best, $\mathcal{B}$ systematically limited.

$B^0 \to K^0_S\pi^0$ result combined with time-dependent analysis (arxiv.org/abs/2206.07453), obtaining world's best:

$$A_{CP}(K^0_S\pi^0) = -0.10 \pm 0.12 \pm 0.05$$

More detail in talk by Jake Bennett

$I_{K\pi} = -0.03 \pm 0.13 \pm 0.05$ (world average 0.13 ± 0.11)

$\Rightarrow$ Competitive precision to world's best already with this data size.

$B \to D^{(*)} K^- K_S^0$ decays

$B \to D^{(*)} K^- K_S^0$ decays

$362\ \text{fb}^{-1}$

$B \to D^{(*)} KK$ makes up a few % of hadronic decay, but only a small fraction is known.

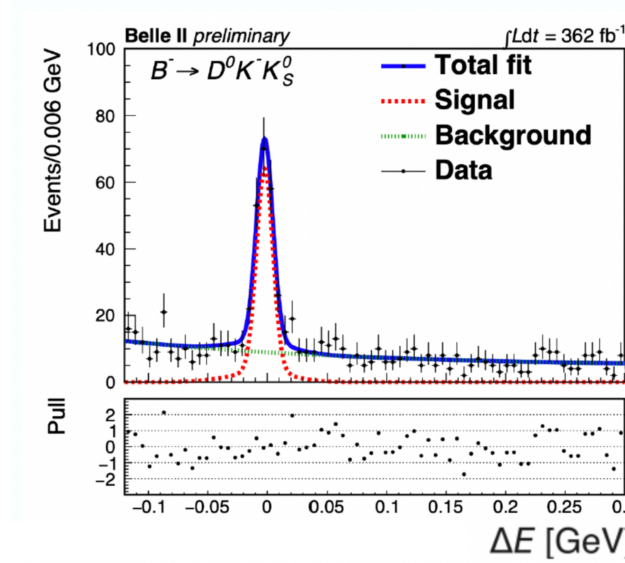
Improve simulation and tagging techniques: need to know well *BF*'s and possible intermediate states.

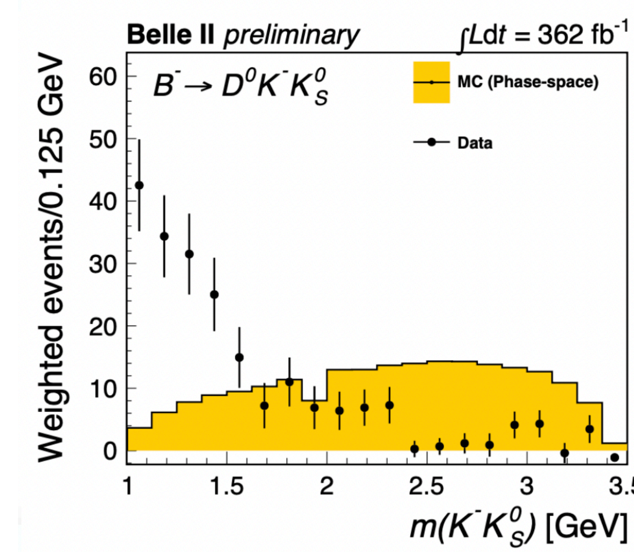
Fit ΔE, subtract background, and look at $m(K^- K_S^0)$ and Dalitz distributions.

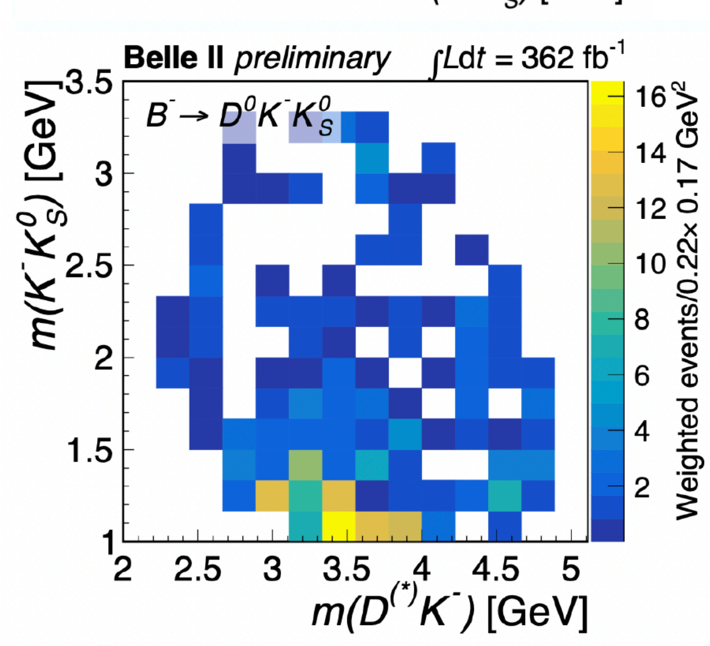
Structures observed in low mass region.

$$\mathscr{B}(B^- \to D^0 K^- K_S^0) = (1.89 \pm 0.16 \pm 0.10) \times 10^{-4}$$
$$\mathscr{B}(\bar{B}^0 \to D^+ K^- K_S^0) = (0.85 \pm 0.11 \pm 0.05) \times 10^{-4}$$
$$\mathscr{B}(B^- \to D^{*0} K^- K_S^0) = (1.57 \pm 0.27 \pm 0.12) \times 10^{-4}$$
$$\mathscr{B}(\bar{B}^0 \to D^{*+} K^- K_S^0) = (0.96 \pm 0.18 \pm 0.06) \times 10^{-4}$$

First observation of three new decay channels.







arxiv.org/abs/2305.01321

Summary

Hadronic decays important element in Belle II *B* physics program. First analyses using the full data sample (362 fb^{-1}).

- $B \to DK$ decay measurements, with D decaying in Cabibbo-suppressed or CP eigenstates final states contribute in Belle + Belle II combined γ program.

- Measurements of $B \to \pi\pi$ and $B \to \rho\rho$ contribute in Belle II program for angle α.

- $B^0 \to K_S^0\pi^0$ asymmetry achieves world's best precision, competitive $I_{K\pi}$ sensitivity.

- Three new decay channels observed in $B \to DKK$, with structures observed in $m(K^-K_S^0)$ and Dalitz distributions.

Backup

γ using GLS method

Parameters physics meanings

- 2 $\mathcal{A}_{CP}$ for DK $(D\pi)$:

$$\mathcal{A}_{SS}^{DK} \equiv \frac{N_{\bar{S}S}^{-} - N_{SS}^{+}}{N_{\bar{S}S}^{-} + N_{SS}^{+}}$$

$$\mathcal{A}_{OS}^{DK} \equiv \frac{N_{\bar{O}S}^{-} - N_{\bar{O}S}^{+}}{N_{\bar{O}S}^{-} + N_{\bar{O}S}^{+}}$$

Physics meanings →

$$\mathcal{A}_{SS}^{DK} = \frac{2r_B r_D \kappa \sin(\delta_B - \delta_D)\sin\phi_3}{1 + r_B^2 r_D^2 + 2r_B r_D \kappa cos(\delta_B - \delta_D)\cos\phi_3}$$

$$\mathcal{A}_{SS}^{DK} = \frac{2r_B r_D \kappa \sin(\delta_B + \delta_D)\sin\phi_3}{1 + r_B^2 + r_D^2 + 2r_B r_D \kappa cos(\delta_B + \delta_D)\cos\phi_3}$$

- 3 ratios:

$$\mathcal{R}_{SS}^{DK/D\pi} \equiv \frac{N_{\bar{S}S}^{-} + N_{SS}^{+}}{N_{\bar{S}S}^{\prime -} + N_{SS}^{\prime +}}$$

$$\mathcal{R}_{OS}^{DK/D\pi} \equiv \frac{N_{\bar{O}S}^{-} + N_{\bar{O}S}^{+}}{N_{\bar{O}S}^{\prime -} + N_{\bar{O}S}^{\prime +}}$$

$$\mathcal{R}_{SS/OS}^{D\pi} \equiv \frac{N_{\bar{S}S}^{\prime -} + N_{SS}^{\prime +}}{N_{\bar{O}S}^{\prime -} + N_{\bar{O}S}^{\prime +}}$$

Physics meanings →

$$\mathcal{R}_{SS}^{DK/D\pi} = R\frac{1 + r_B^2 r_D^2 + 2r_B r_D \kappa \cos(\delta_B - \delta_D)\cos\phi_3}{1 + r_B^{\prime 2} r_D^2 + 2r_B^{\prime} r_D \kappa \cos(\delta_B^{\prime} - \delta_D)\cos\phi_3}$$

$$\mathcal{R}_{OS}^{DK/D\pi} = R\frac{r_B^2 + r_D^2 + 2r_B r_D \kappa \cos(\delta_B + \delta_D)\cos\phi_3}{r_B^{\prime 2} + r_D^2 + 2r_B^{\prime} r_D \kappa \cos(\delta_B^{\prime} + \delta_D)\cos\phi_3}$$

$$\mathcal{R}_{SS}^{DK/D\pi} = \frac{1 + r_B^{\prime 2} r_D^2 + 2r_B^{\prime} r_D \kappa \cos(\delta_B^{\prime} - \delta_D)\cos\phi_3}{r_B^{\prime 2} + r_D^2 + 2r_B^{\prime} r_D \kappa \cos(\delta_B^{\prime} + \delta_D)\cos\phi_3}$$

γ using GLS method

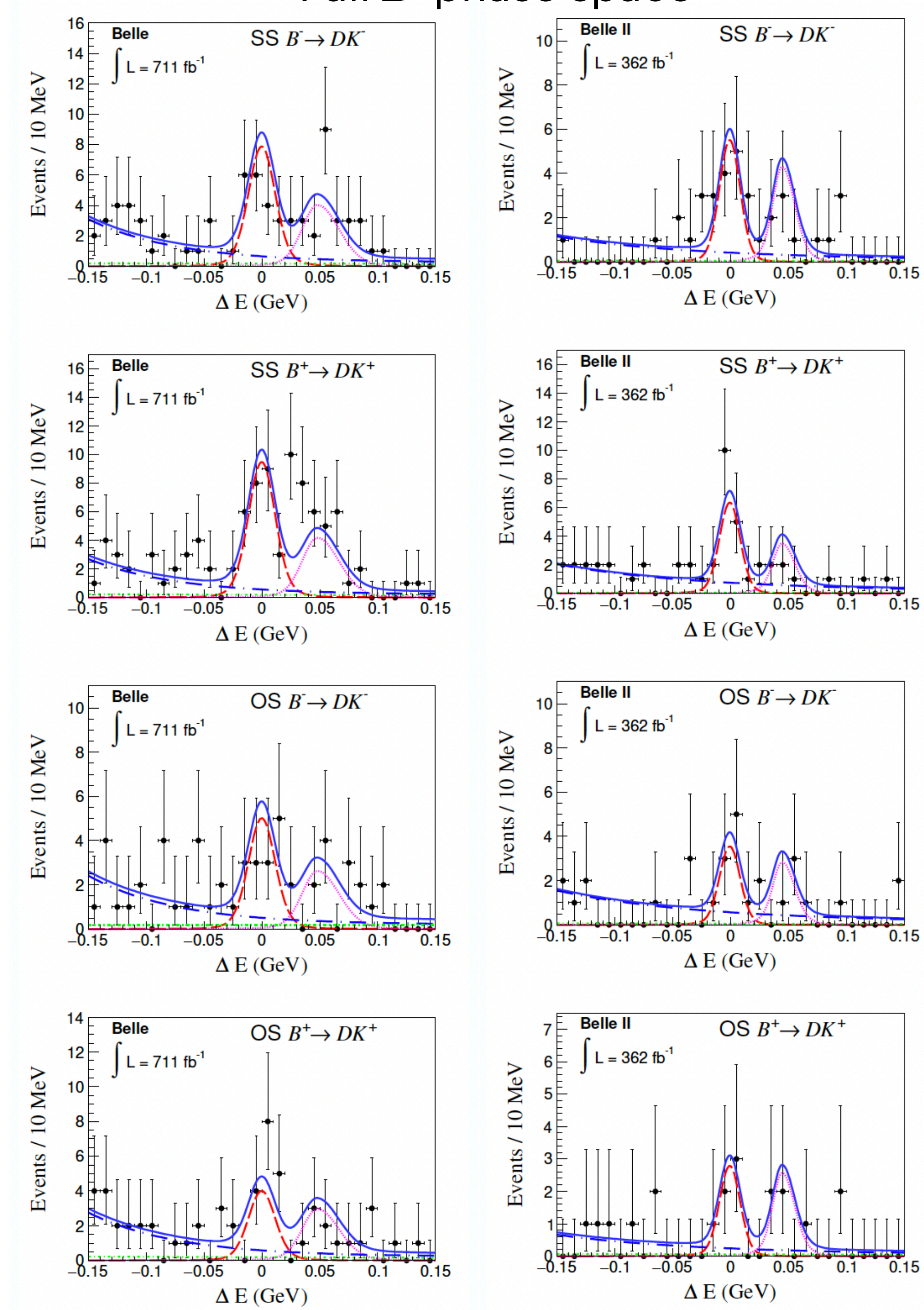
Full D phase space

$$\mathscr{A}_{SS}^{DK} = -0.089 \pm 0.091 \pm 0.011$$
$$\mathscr{A}_{OS}^{DK} = +0.109 \pm 0.133 \pm 0.013$$
$$\mathscr{A}_{SS}^{D\pi} = +0.018 \pm 0.026 \pm 0.009$$
$$\mathscr{A}_{OS}^{D\pi} = -0.028 \pm 0.031 \pm 0.009$$
$$\mathscr{R}_{SS}^{DK/D\pi} = 0.122 \pm 0.012 \pm 0.004$$
$$\mathscr{R}_{OS}^{DK/D\pi} = 0.093 \pm 0.013 \pm 0.003$$
$$\mathscr{R}_{SS/OS}^{D\pi} = 1.428 \pm 0.057 \pm 0.002$$

K^* region

$$\mathscr{A}_{SS}^{DK} = +0.055 \pm 0.119 \pm 0.020$$
$$\mathscr{A}_{OS}^{DK} = +0.231 \pm 0.184 \pm 0.014$$
$$\mathscr{A}_{SS}^{D\pi} = +0.046 \pm 0.029 \pm 0.016$$
$$\mathscr{A}_{OS}^{D\pi} = +0.009 \pm 0.046 \pm 0.009$$
$$\mathscr{R}_{SS}^{DK/D\pi} = 0.093 \pm 0.012 \pm 0.005$$
$$\mathscr{R}_{OS}^{DK/D\pi} = 0.103 \pm 0.020 \pm 0.006$$
$$\mathscr{R}_{SS/OS}^{D\pi} = 2.412 \pm 0.132 \pm 0.019$$

Full D phase space



γ using GLS method

Systematic uncertainties (absolute)

	A_{SS}^{DK}	A_{OS}^{DK}	$A_{SS}^{D\pi}$	$A_{OS}^{D\pi}$	$R_{SS}^{DK/D\pi}$	$R_{OS}^{DK/D\pi}$	$R_{SS/OS}^{D\pi}$
				Full D phase space			
$\epsilon_{K^\pm}, \epsilon_{\pi^\pm}$	0.38	0.56	0.19	0.14	0.05	0.06	0.09
δ	—	0.03	—	—	0.04	0.03	0.02
Model	0.62	0.78	0.02	0.02	0.30	0.22	0.07
$\epsilon_{K_S^0 K^- \pi^+}/\epsilon_{K_S^0 K^+ \pi^-}$	0.82	0.83	0.82	0.83	0.01	0.01	0.02
Total syst. unc.	1.1	1.3	0.9	0.9	0.4	0.3	0.2
Stat. unc.	9.1	13.3	2.6	3.1	1.2	1.3	5.7
				$K^*(892)^\pm$ region			
$\epsilon_{K^\pm}, \epsilon_{\pi^\pm}$	0.37	0.61	0.17	0.15	0.03	0.08	0.13
δ	0.02	0.02	0.01	0.01	0.03	0.04	0.04
Model	1.04	0.97	0.20	0.03	0.46	0.49	0.61
$\epsilon_{K_S^0 K^- \pi^+}/\epsilon_{K_S^0 K^+ \pi^-}$	1.6	0.8	1.6	0.8	0.1	0.1	1.7
Total syst. unc.	2.0	1.4	1.6	0.9	0.5	0.6	1.9
Stat. unc.	11.9	18.4	2.9	4.6	1.2	2.0	13.2

γ using GLW method

Physics meanings

$$\mathscr{A}_{CP\pm} = \frac{\Gamma(B^- \to D_{CP\pm}K^-) - \Gamma(B^+ \to D_{CP\pm}K^+)}{\Gamma(B^- \to D_{CP\pm}K^-) + \Gamma(B^+ \to D_{CP\pm}K^+)} = \pm \frac{r_B \sin \delta_B sin\phi_2}{1 + r_B^2 \pm 2r_B \cos delta_B \cos \phi_3},$$

$$\mathscr{R}_{CP\pm} = \frac{\mathscr{B}(B^- \to D_{CP\pm}K^-) + \mathscr{B}(B^+ \to D_{CP\pm}K^+)}{\mathscr{B}(B^- \to D_{flav}K^-) + \mathscr{B}(B^+ \to D_{flav}K^+)} \approx \frac{R_{CP\pm}}{R_{flav}}, \text{ with}$$

$$R_X \equiv \frac{\mathscr{B}(B^- \to D_X K^-) + \mathscr{B}^+ \to D_X K^+)}{\mathscr{B}(B^- \to D_X \pi^-) + \mathscr{B}^+ \to D_X \pi^+)}.$$

$$\Rightarrow \begin{cases} \mathscr{R}_{CP\pm} = 1 + r_B^2 \pm 2 \cos \delta_B \cos \phi_3 \\ \mathscr{A}_{CP\pm} = \pm 2r_B \sin \phi_3 / \mathscr{R}_{CP\pm} \end{cases}, \text{ assuming } CP \text{ conservation in } B^\pm \to D\pi^\pm$$

- Channels:
  - Signal: $B \to D(\to KK, K_S^0\pi^0)K$
  - R_{flav} control channel: $B \to D(\to K\pi)K$
  - R_X control channel: $B \to D\pi$

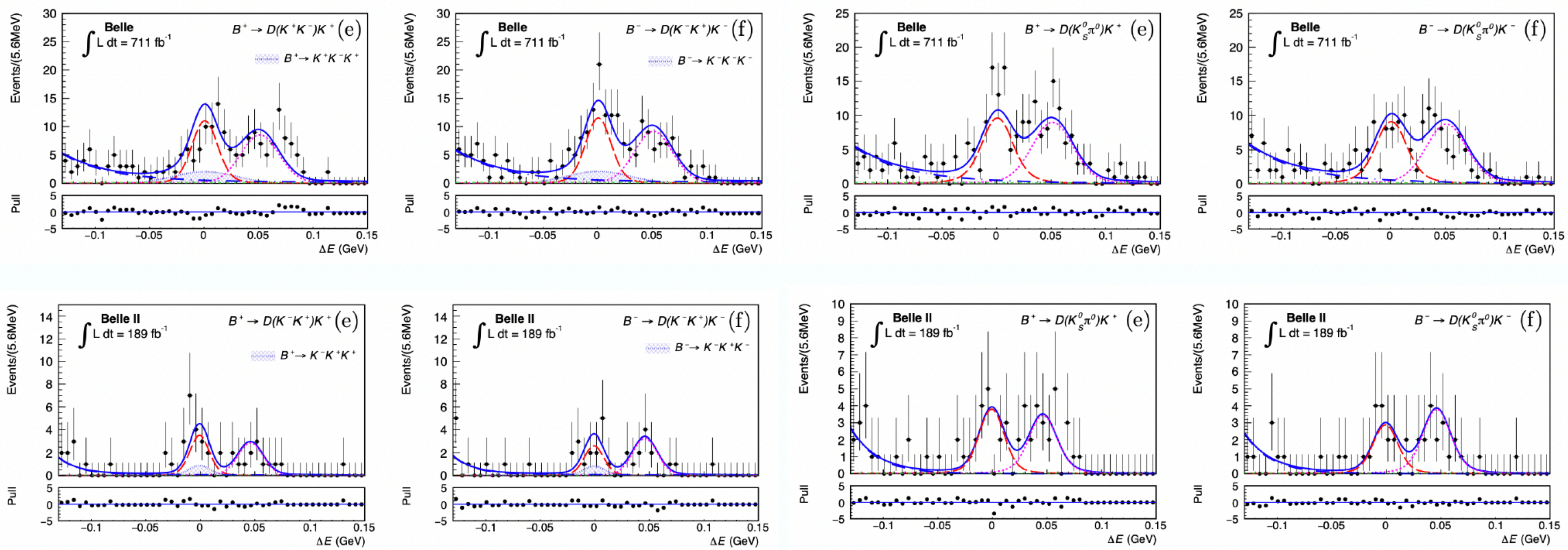
γ using GLW method

Results

	68.3% CL	95.4% CL
	[8.5, 16.5]	[5.0, 22.0]
ϕ_3 (°)	[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]

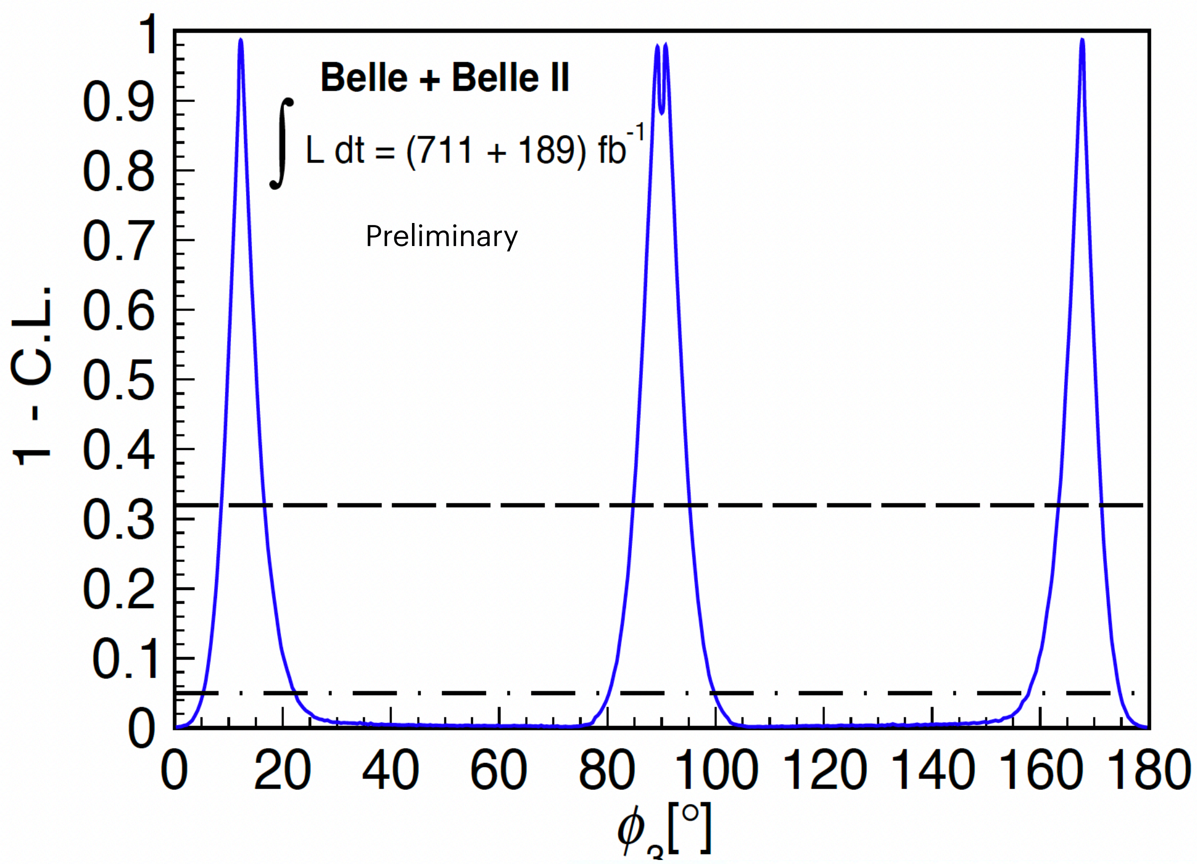
Yields

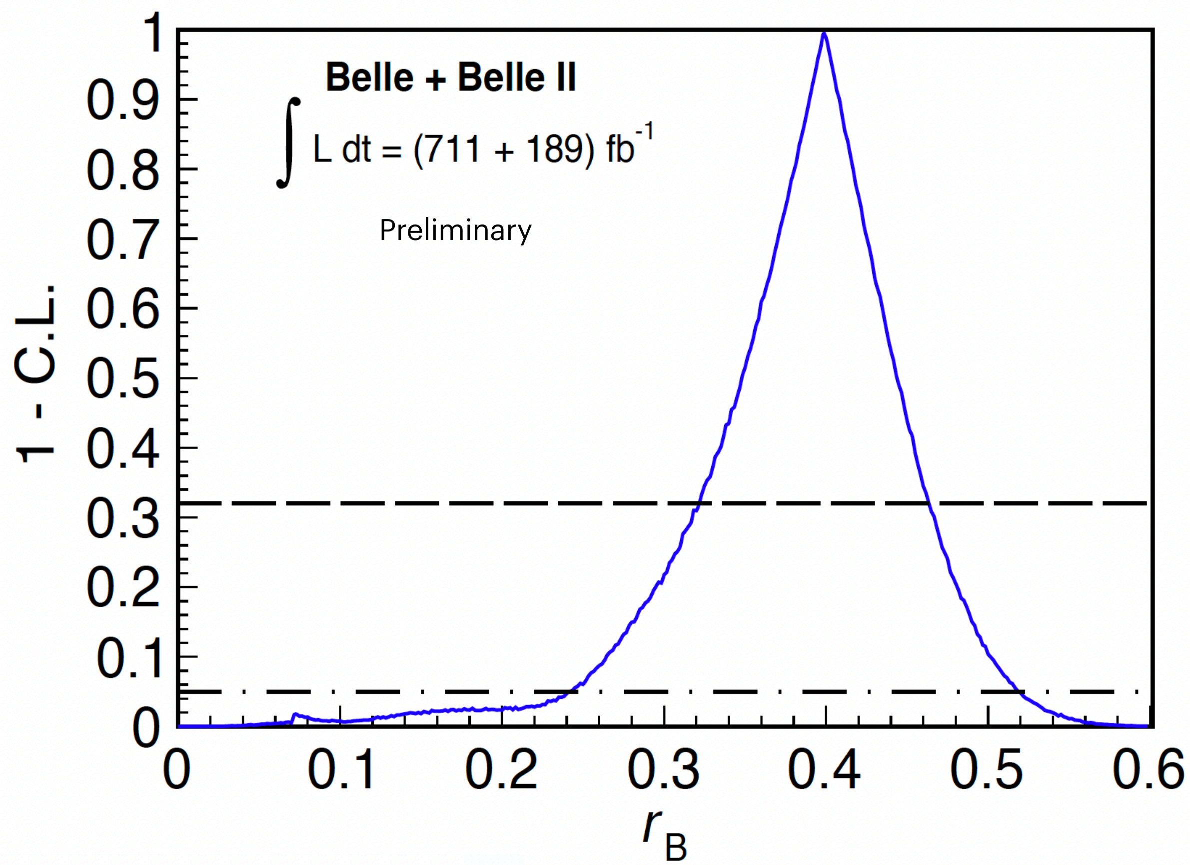
D_X mode		$N(B \to D_X K)$	$N(B \to D_X \pi)$
$D \to K^{\pm}\pi^{\mp}$	Belle	4238(94)	59 481(267)
	Belle II	1084(44)	14 229(126)
$D \to K^+K^-$	Belle	476(36)	5559(85)
	Belle II	107(15)	1336(40)
$D \to K_S^0\pi^0$	Belle	541(42)	6484(95)
	Belle II	145(16)	1763(46)



γ using GLW method

γ estimation





	68.3% CL	95.4% CL
	[8.5, 16.5]	[5.0, 22.0]
ϕ_3 (°)	[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]

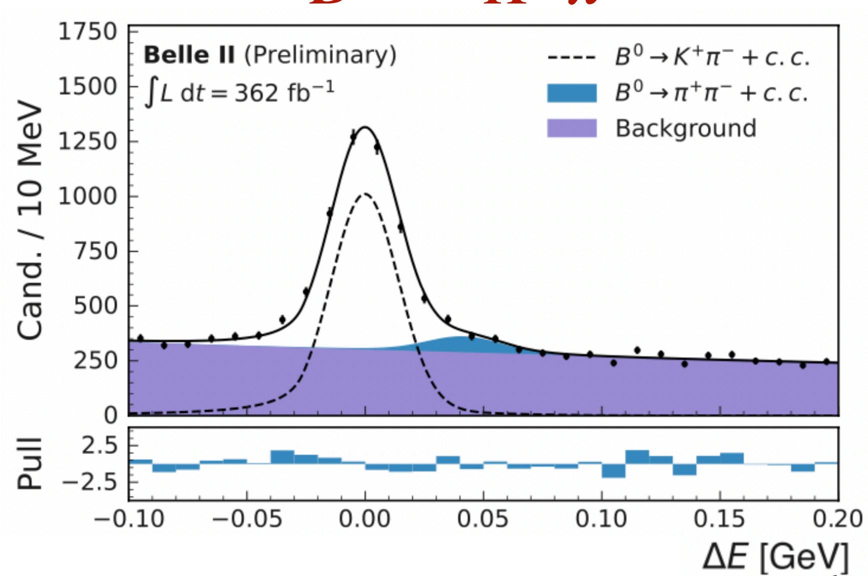
γ using GLW method

Systematic uncertainties (absolute)

	$\mathcal{R}_{CP+}$	$\mathcal{R}_{CP-}$	$\mathcal{A}_{CP+}$	$\mathcal{A}_{CP-}$
PDF parameters	0.012	0.014	0.002	0.002
PID parameters	0.009	0.010	0.003	0.005
peaking background yields	0.033	0.002	0.013	—
Efficiency ratio	0.001	0.001	<0.001	<0.001
commonality of ΔE modes	-0.005	-0.006	<0.001	<0.001
Total systematic uncertainty	0.036	0.019	0.014	0.006
Statistical uncertainty	0.081	0.074	0.058	0.057

Isospin sum rule

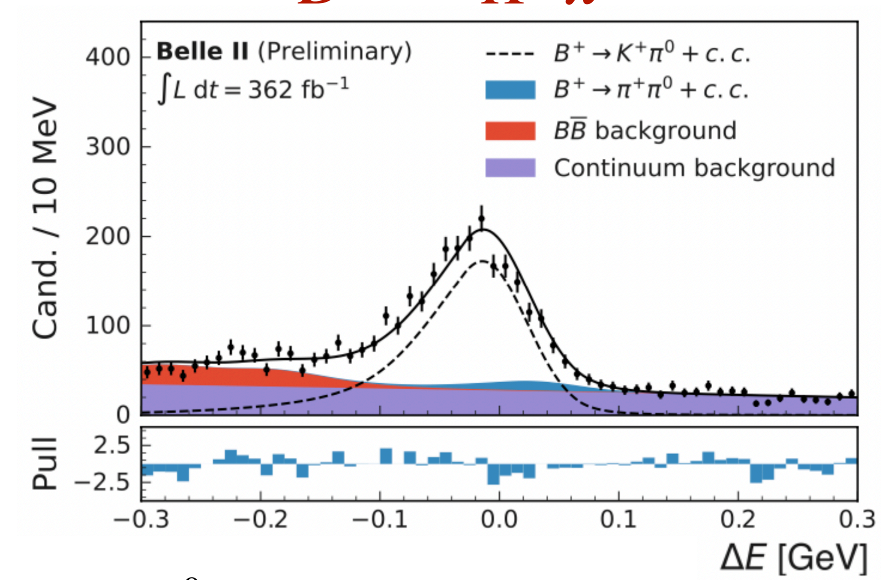
$B^0 \to K^+\pi^-$



$\mathcal{B} = (20.67 \pm 0.37 \pm 0.62) \times 10^{-6}$

$\mathcal{A}_{CP} = -0.072 \pm 0.019 \pm 0.007$

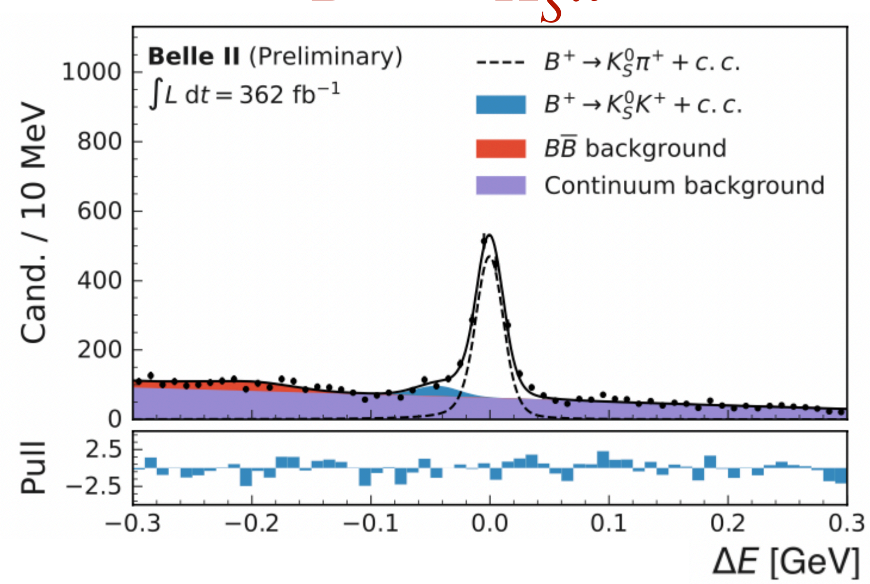
$B^+ \to K^+\pi^0$



$\mathcal{B}(K^+\pi^0) = (14.21 \pm 0.38 \pm 0.85) \times 10^{-6}$

$\mathcal{A}_{CP}(K^+\pi^0) = +0.013 \pm 0.027 \pm 0.005$

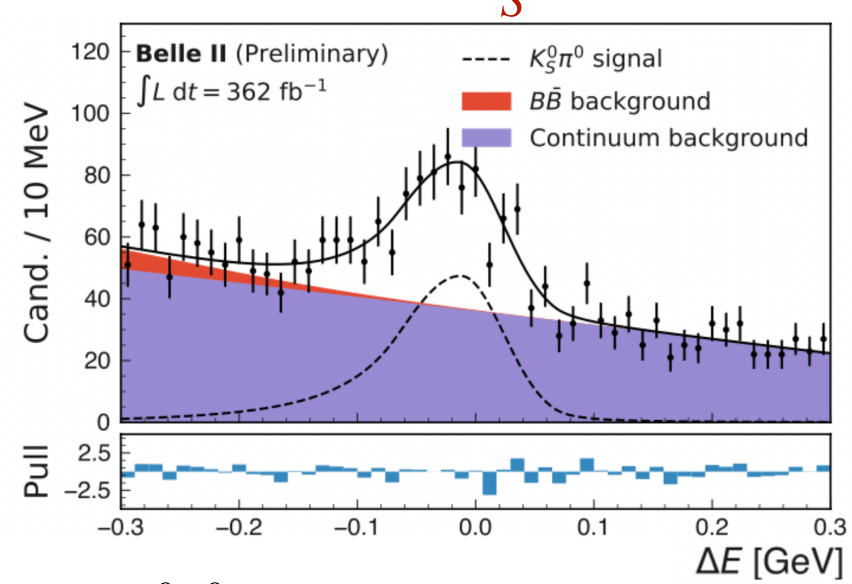
$B^+ \to K^0_S\pi^+$



$\mathcal{B}(K^0_S\pi^+) = (24.40 \pm 0.71 \pm 0.86) \times 10^{-6}$

$\mathcal{A}_{CP}(K^0_S\pi^+) = +0.046 \pm 0.029 \pm 0.007$

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



$\mathcal{B}(K^0_S\pi^0) = (10.16 \pm 0.65 \pm 0.67) \times 10^{-6}$

$\mathcal{A}_{CP}(K^0_S\pi^0) = -0.006 \pm 0.15 \pm 0.05$

Isospin sum rule

Systematic uncertainties

TABLE II. Summary of the relative systematic uncertainties (%) on the branching ratios.

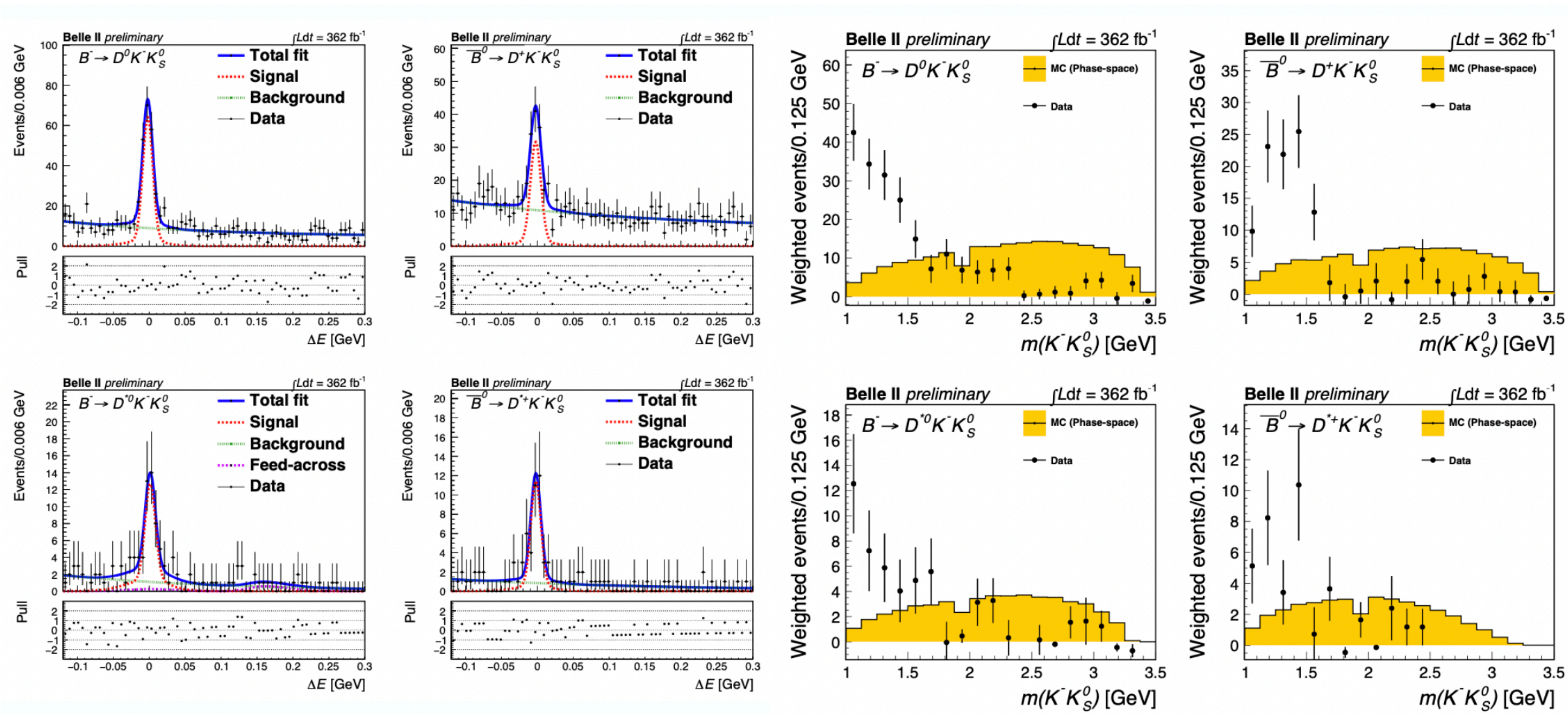
Source	$B^0 \to K^+\pi^-$	$B^0 \to \pi^+\pi^-$	$B^+ \to K^+\pi^0$	$B^+ \to \pi^+\pi^0$	$B^+ \to K^0_S\pi^+$	$B^0 \to K^0_S\pi^0$
Tracking	0.5	0.5	0.2	0.2	0.7	0.5
$N_{B\bar{B}}$	1.5	1.5	1.5	1.5	1.5	1.5
$f^{+-/00}$	2.5	2.5	2.4	2.4	2.4	2.5
π^0 efficiency	-	-	5.0	5.0	-	5.0
K^0_S efficiency	-	-	-	-	2.0	2.0
CS efficiency	0.2	0.2	0.7	0.7	0.5	1.7
PID correction	0.1	0.1	0.1	0.2	-	-
ΔE shift and scale	0.1	0.2	1.2	2.0	0.3	1.7
$K\pi$ signal model	0.1	0.2	0.1	<0.1	<0.1	0.1
$\pi\pi$ signal model	<0.1	0.1	<0.1	<0.1	-	-
$K\pi$ CF model	<0.1	0.1	<0.1	0.1	-	-
$\pi\pi$ CF model	0.1	0.2	<0.1	0.1	-	-
$K^0_S K^+$ model	-	-	-	-	0.1	-
$B\bar{B}$ model	-	-	0.3	0.5	<0.1	0.3
Multiple candidates	<0.1	<0.1	1.0	0.3	0.1	0.3
Total	3.0	3.0	6.0	6.2	3.6	6.6

TABLE III. Summary of the absolute systematic uncertainties on the *CP* asymmetries.

Source	$B^+ \to K^+\pi^-$	$B^+ \to K^+\pi^0$	$B^+ \to \pi^+\pi^0$	$B^+ \to K^0_S\pi^+$	$B^0 \to K^0_S\pi^0$
ΔE shift and scale	<0.001	0.001	0.002	0.001	0.003
$K^0_S K^+$ model	-	-	-	0.001	-
$B\bar{B}$ background asymmetry	-	-	-	-	0.046
$q\bar{q}$ background asymmetry	-	-	-	-	0.024
Fitting bias	-	-	0.007	0.006	-
Instrumental asymmetry	0.007	0.005	0.004	0.004	-
Total	0.007	0.005	0.008	0.007	0.052

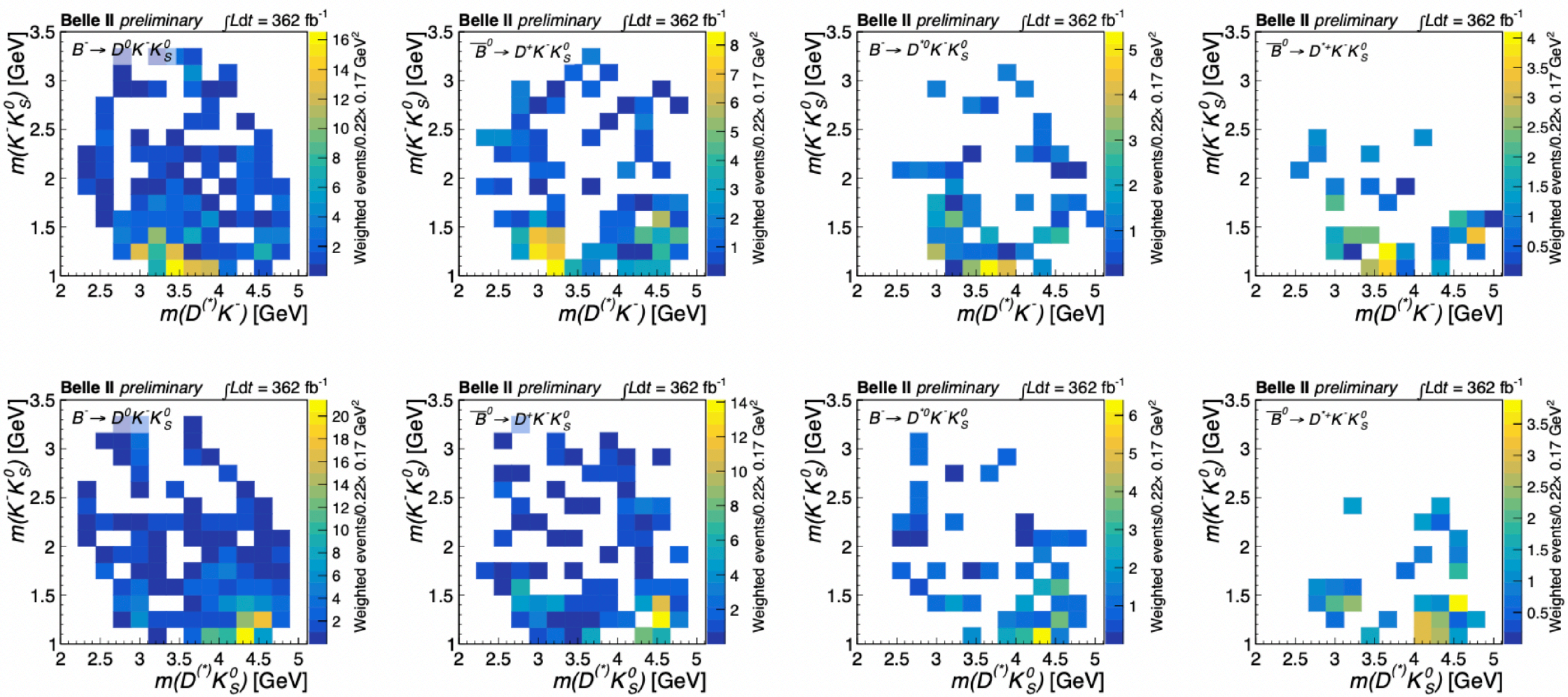
$B \to D^{(*)}K^-K_S^0$ decays

ΔE fit and $m(K^-K_S^0)$ distributions



$B \to D^{(*)}K^-K_S^0$ decays

Dalitz distributions



$B \to D^{(*)} K^- K_S^0$ decays

Systematic uncertainties (relative)

Source	$B^- \to D^0 K^- K_S^0$	$\overline{B}^0 \to D^+ K^- K_S^0$	$B^- \to D^{*0} K^- K_S^0$	$\overline{B}^0 \to D^{*+} K^- K_S^0$
Eff. - MC sample size	0.6	0.9	1.0	0.8
Eff. - tracking	0.7	1.0	0.7	1.0
Eff. - π^+ from D^{*+}	-	-	-	2.7
Eff. - K_S^0	3.4	3.4	3.4	3.3
Eff. - PID	1.3	1.4	0.5	0.6
Eff. - π^0	-	-	5.1	-
Signal model	1.9	3.3	2.7	3.1
Bkg model	1.1	0.8	0.1	0.1
Self-cross-feed	-	-	2.7	-
D^{*0} peaking bkg	-	-	0.9	-
$N_{B\overline{B}}$, $f_{+-,00}$	2.7	2.8	2.7	2.8
Intermediate $\mathcal{B}$s	0.7	1.7	1.6	1.1
Total systematic	5.2	6.1	7.6	6.2
Statistical	8.3	13.5	17.1	19.0