First B →DK results at Belle II

11th International Workshop on the CKM Unitarity Triangle
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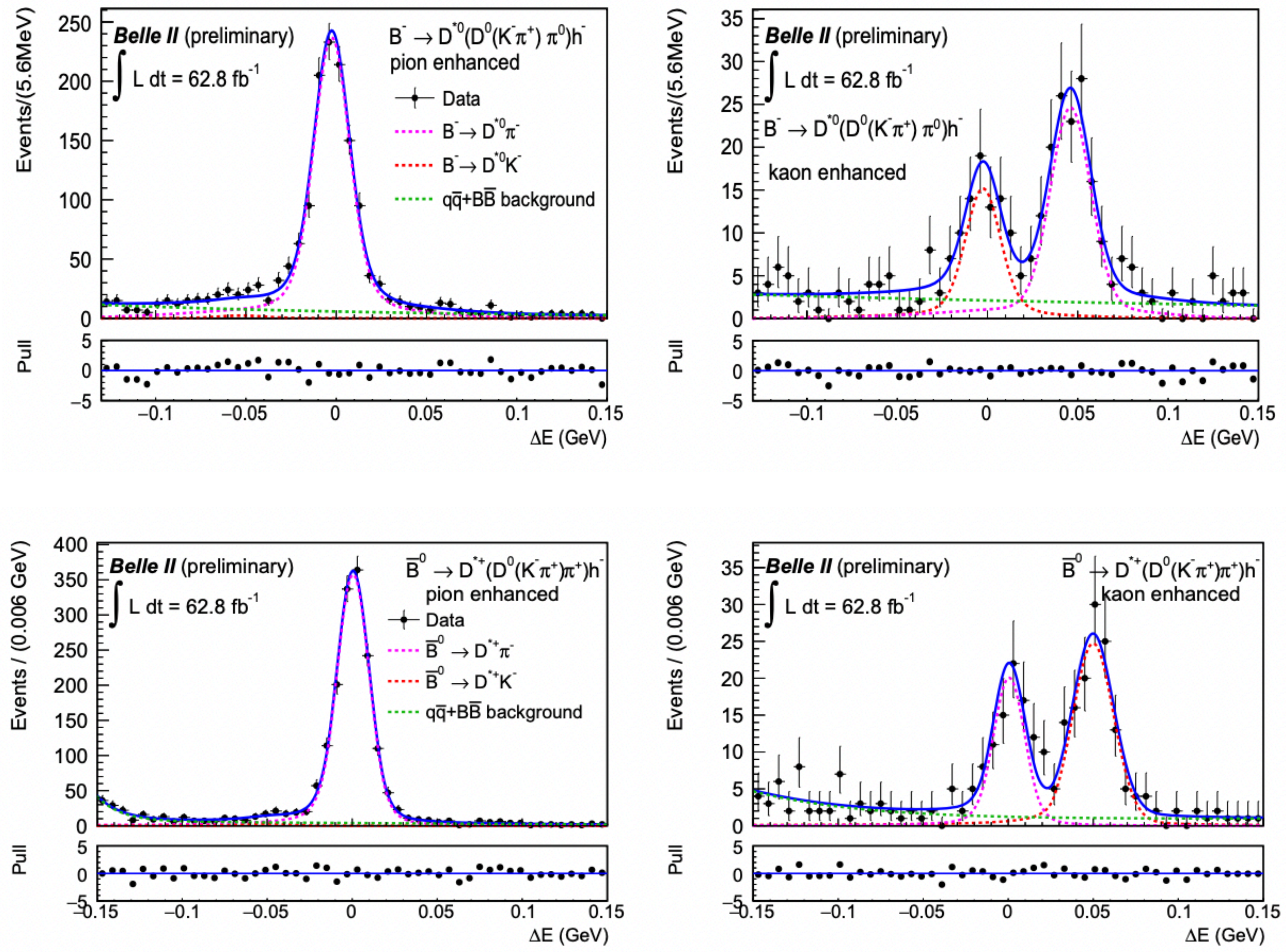
(On behalf of the Belle II collaboration)

22 Nov, 2021

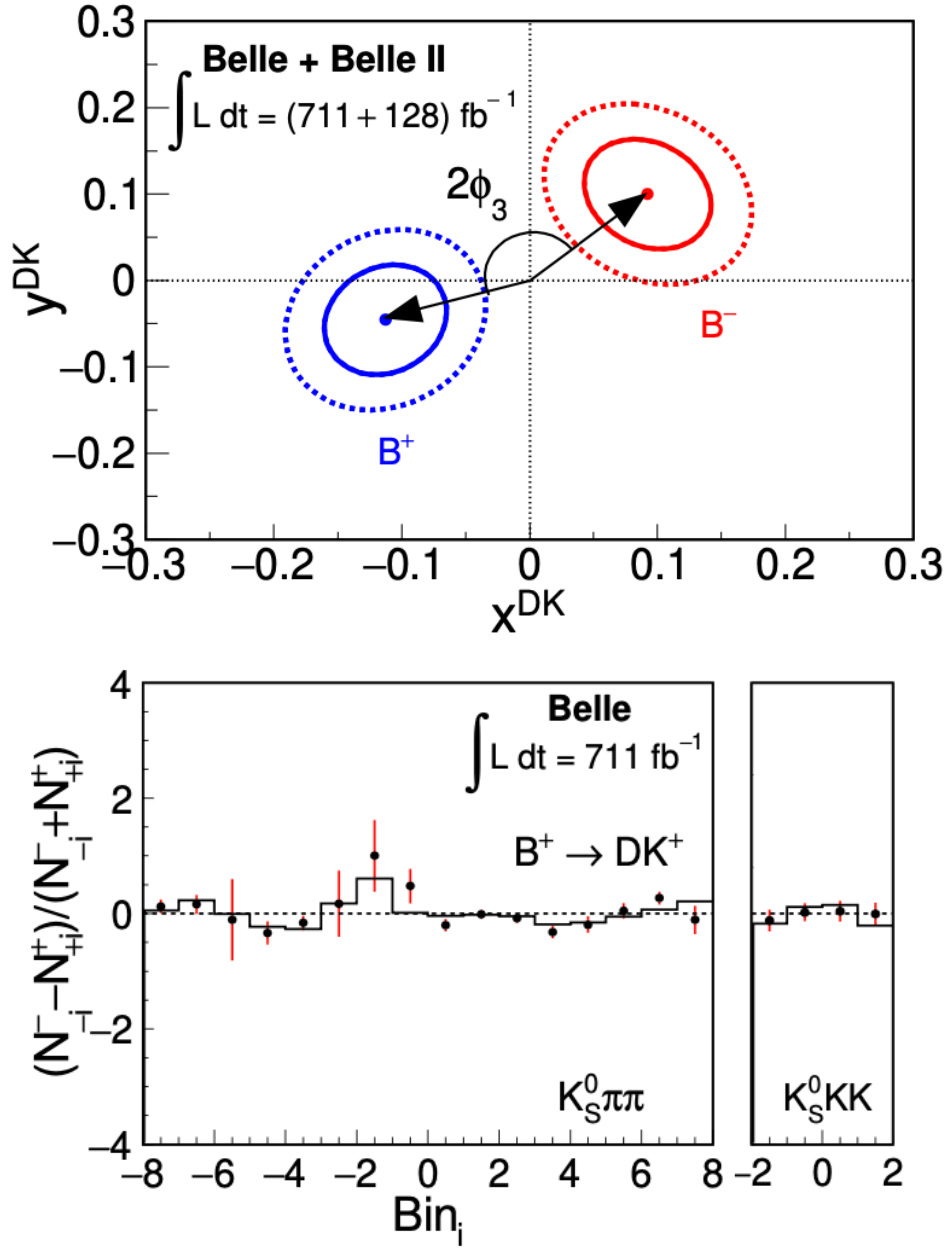
Outline

- CKM angle ϕ_3 from B → DK decays
- Belle II detector and status
- Results from B → D$^{(*)}$h decays at Belle II arXiv: 2104.03628



Outline

- CKM angle ϕ_3 from B → DK decays
- Belle II detector and status
- Results from B → $D^{(*)}h$ decays at Belle II arXiv:2104.03628
- Measurement of ϕ_3 from combined Belle + Belle II analysis arXiv:2110.12125
- Future prospects
- Summary



CKM angles - current status

World average (HFLAV)

[hflav.web.cern.ch]

$$\beta(^\circ) = \phi_1 = 22.2 \pm 0.7$$

$$\alpha(^\circ) = \phi_2 = 85.2^{+4.8}_{-4.3}$$

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

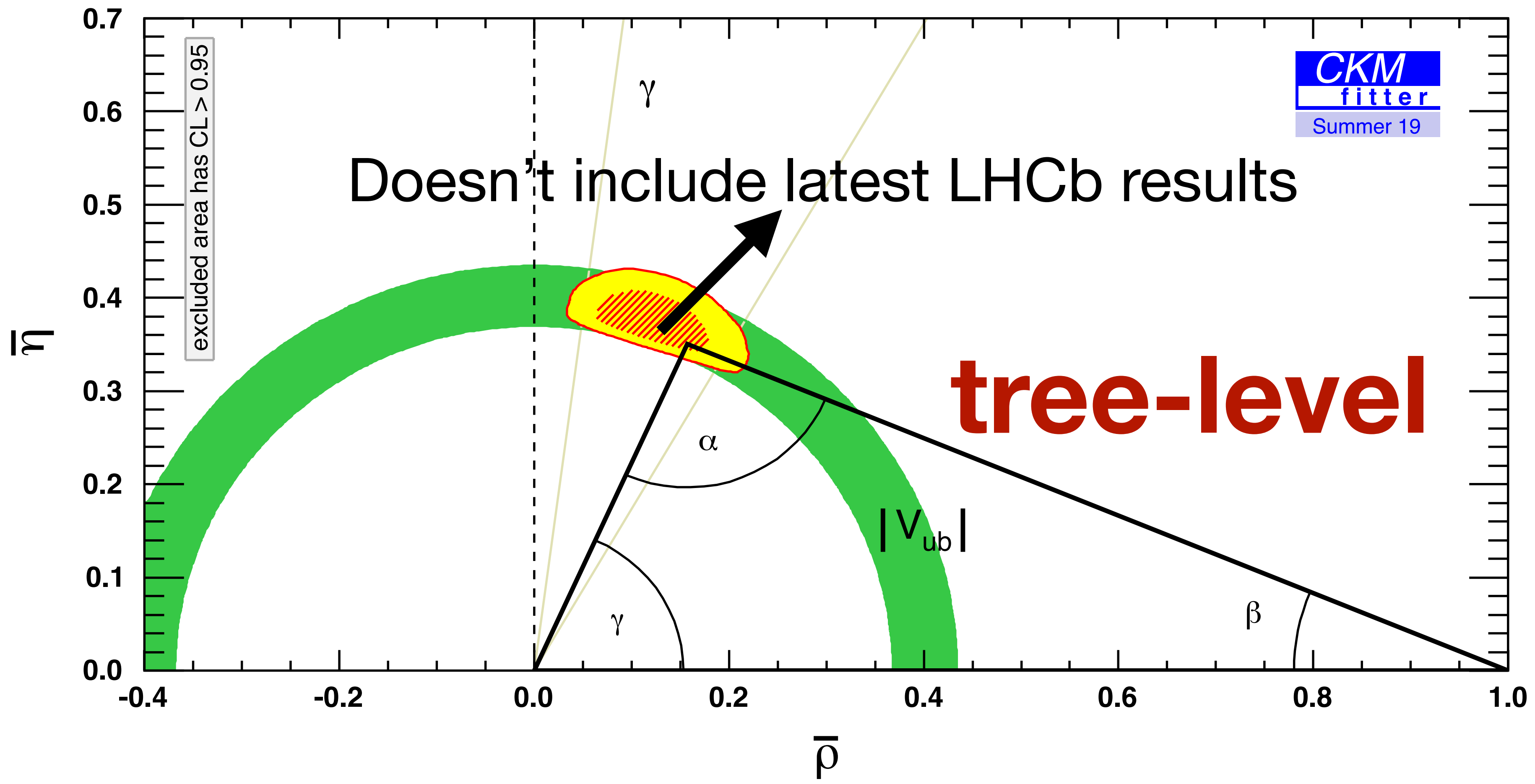
Global fit (CKM fitter)

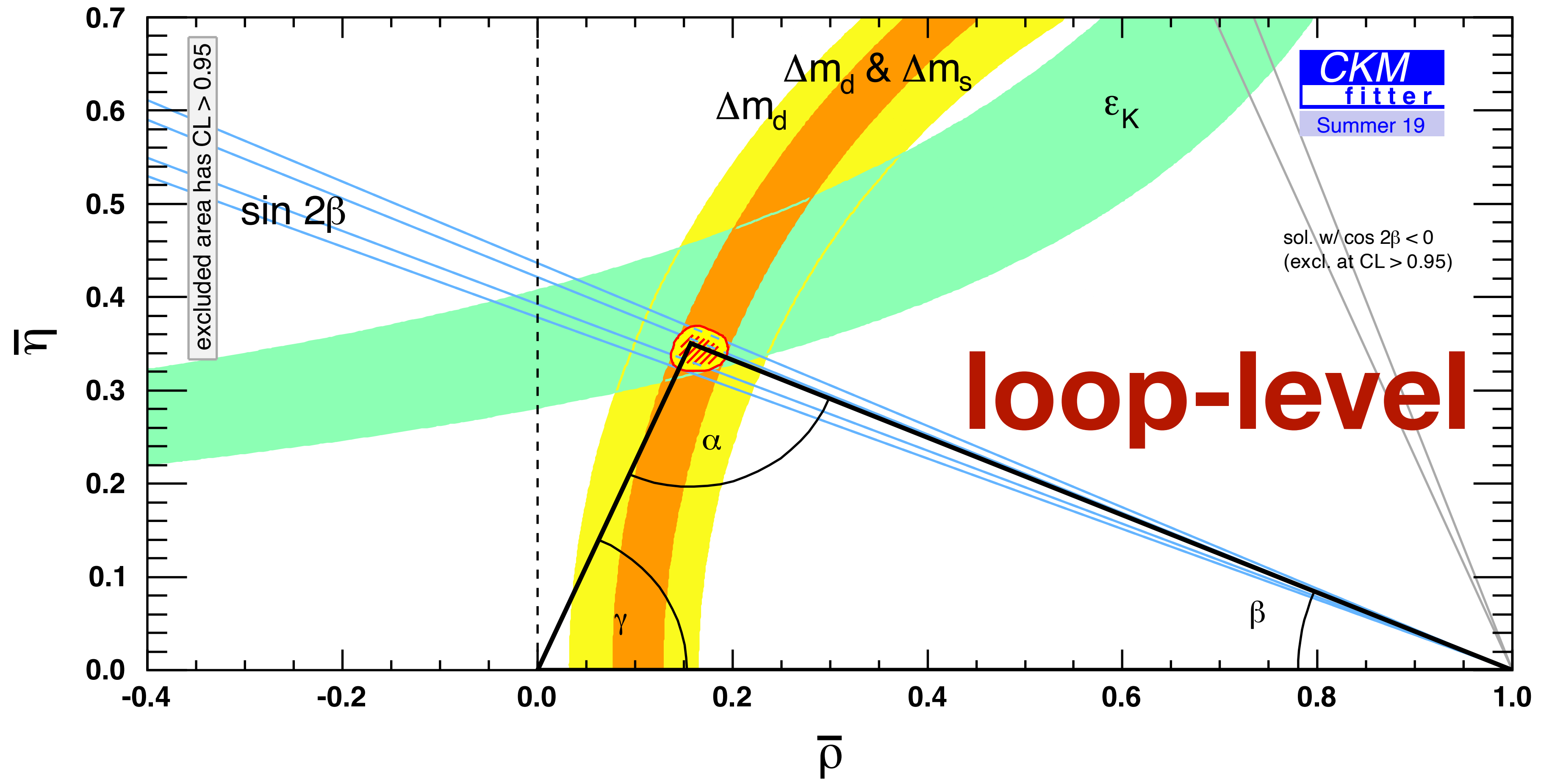
[http://ckmfitter.in2p3.fr]

$$\beta(^\circ) = \phi_1 = 23.7^{+1.3}_{-1.2}$$

$$\alpha(^\circ) = \phi_2 = 91.8^{+2.7}_{-1.0}$$

$$\gamma(^\circ) = \phi_3 = 65.6^{+0.9}_{-2.6}$$

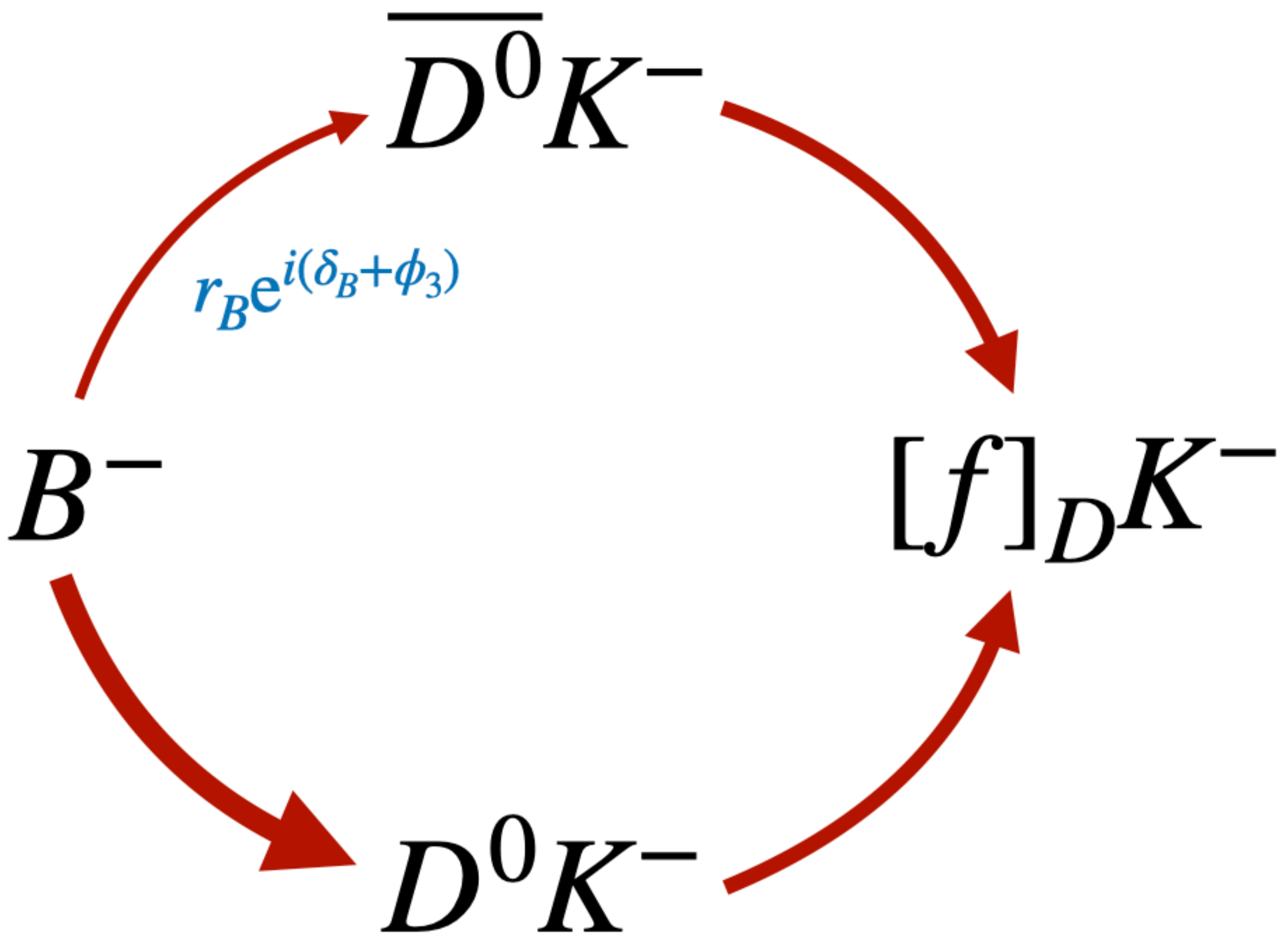




NP sensitivity arises from comparison of results from tree- and loop-dominated processes

ϕ3 measurements from B →DK decays

ϕ3 is the phase between $b\to u$ and $b\to c$ quark transitions: $B \to DK$

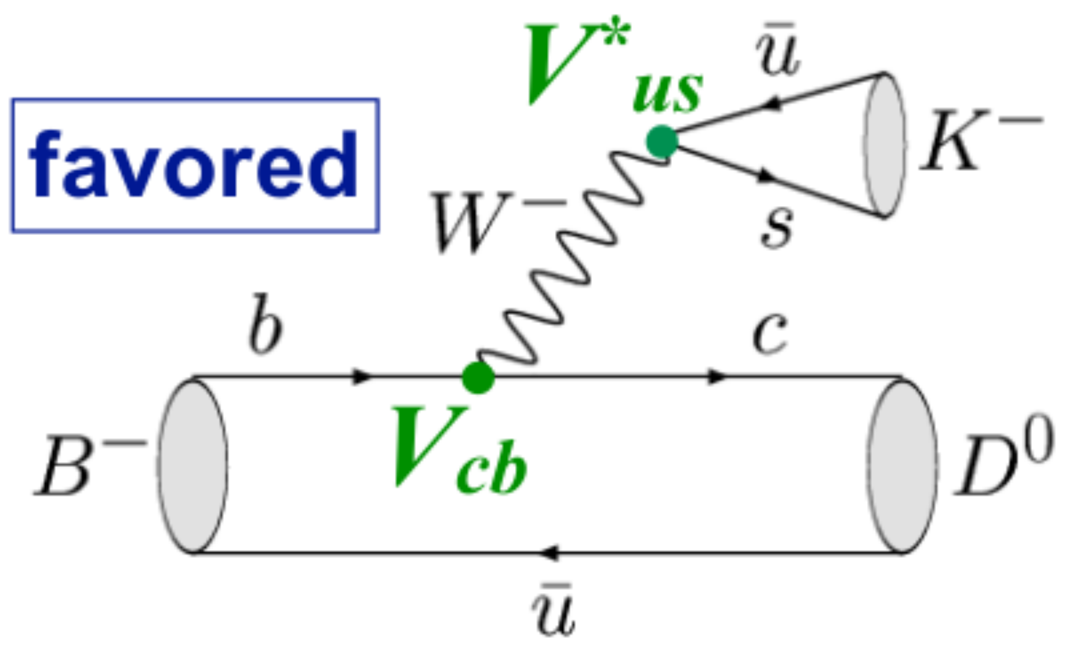


$$\frac{\mathcal{A}^{\text{suppr.}}(B^- \to \overline{D^0}K^-)}{\mathcal{A}^{\text{favor.}}(B^- \to D^0K^-)} = r_B e^{i(\delta_B+\phi_3)}$$

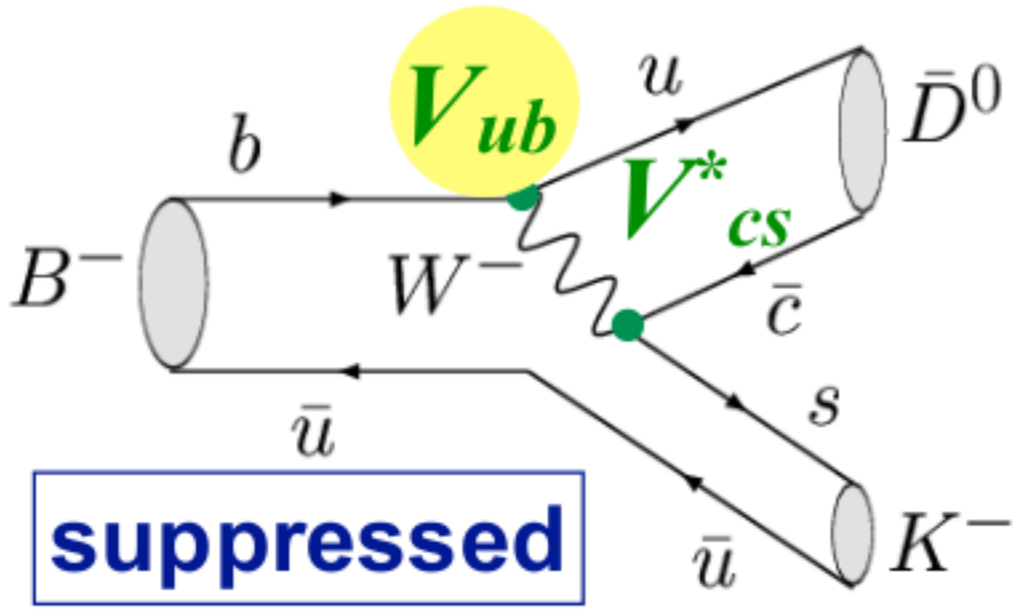
Results are limited by the sample size because of the small branching fraction of the decays involved

- Common final states allow the interference between the two paths
- Interference gives access to the phase
- The level of interference, and its exact interpretation, depend on the physics of *B* and *D* decays

$B^- \to D^0 K^-$



$B^- \to \overline{D^0} K^-$



ϕ3 measurements from B →DK decays

GLW *Phys. Lett. B* **253**, *483*

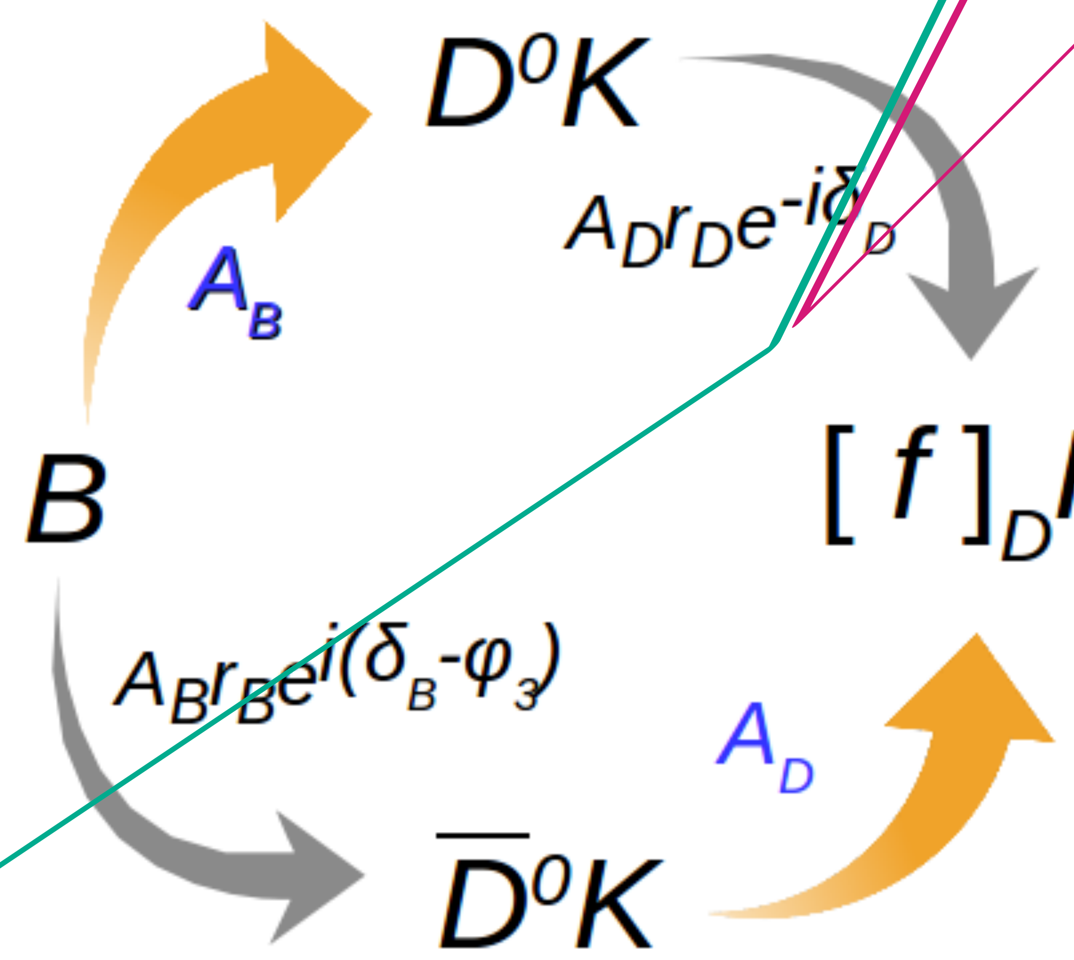
- CP eigenstates such as $K^+K^-, \pi^+\pi^-$ (CP-even) or $K^0_S\pi^0, K^0_S\eta$ (CP-odd)
- Four observables: $R^{\pm}_{CP}, A^{\pm}_{CP}$
- No external charm factory inputs are required

$$R^{\pm}_{CP} = \frac{\mathscr{B}(B^- \to D_{CP\pm}K^-) + \mathscr{B}(B^+ \to D_{CP\pm}K^+)}{\mathscr{B}(B^- \to D^0K^-) + \mathscr{B}(B^+ \to \bar{D}^0K^+)}$$
$$= 1 + r_B^2 \pm 2r_B\cos(\delta_B)\cos(\phi_3)$$

$$A^{\pm}_{CP} = \frac{\mathscr{B}(B^- \to D_{CP\pm}K^-) - \mathscr{B}(B^+ \to D_{CP\pm}K^+)}{\mathscr{B}(B^- \to D_{CP\pm}K^-) + \mathscr{B}(B^+ \to D_{CP\pm}K^+)}$$
$$= \pm 2r_B\sin(\delta_B)\sin(\phi_3)/R^{\pm}_{CP}$$

ADS *Phys. Rev. Lett.* **78**, *3257*

- *D* from a favoured amplitude decays to a doubly-Cabibbo-suppressed state
- Two observables: R_{ADS}, A_{ADS}
- External inputs: r_D, δ_D



BPGGSZ *Phys. Rev. D* **68**, *054018*

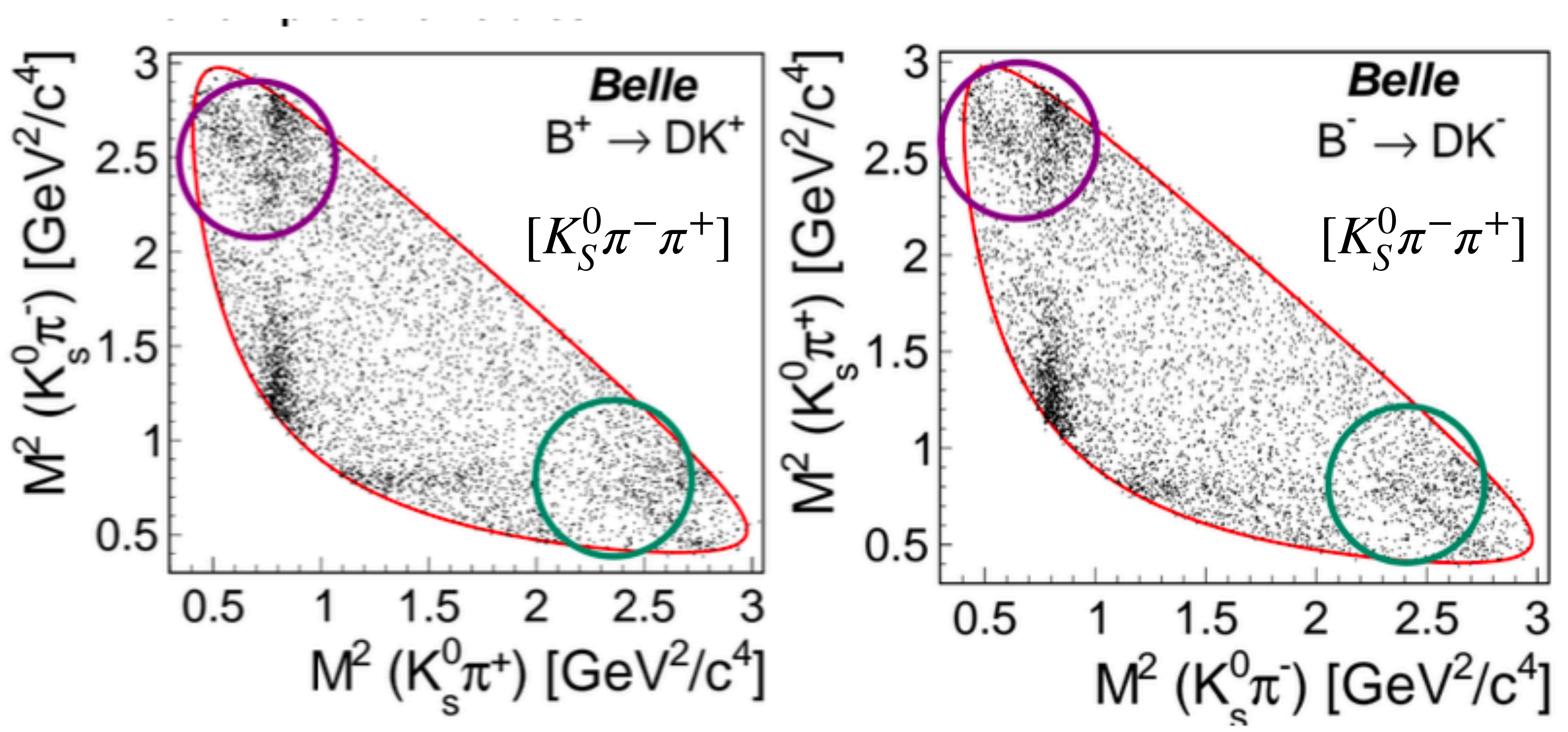
- Self-conjugate multi body final states : $K^0_S\pi\pi, K^0_SKK, K^0_S\pi\pi\pi^0$
- Sensitivity to ϕ3 by comparing *D* Dalitz plot distributions of B^+ and B^-
- Fit D Dalitz plot with full Amplitude model

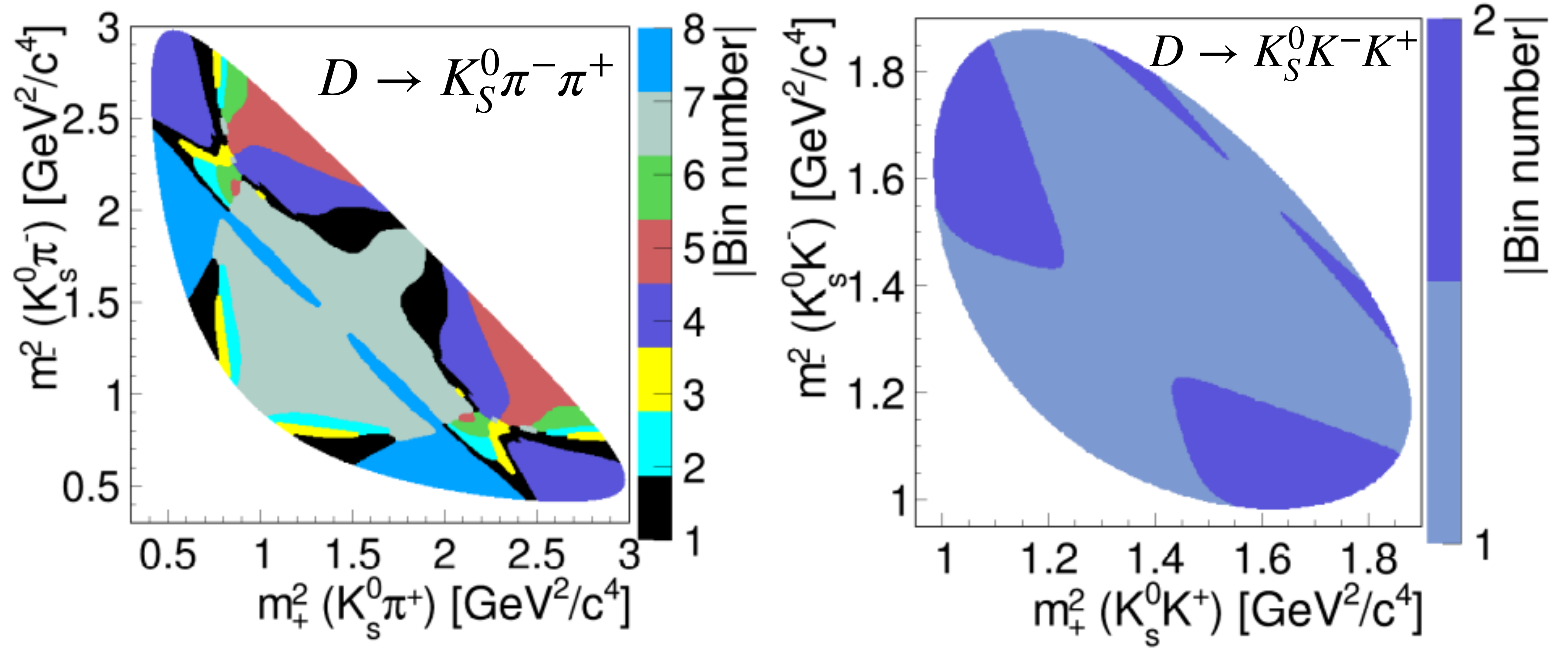
$$A_{B^+} = \bar{A}(m^2_-, m^2_+) + r_Be^{i(\delta_B-\phi_3)}A(m^2_-, m^2_+)$$

$m^2_{\pm}$ = squared invariant mass of $K^0_Sh^{\pm}$: *D* Dalitz plot variable

BPGGSZ: Model-independent approach

- In presence of *CP* violation, differences between B^+ and B^- distributions are expected
- The magnitude and position of the difference is driven by r_B, δ_B, ϕ_3 and the physics of the *D* decays
- Model-dependent uncertainty is avoided through *D* Dalitz plot binning
- Binning schemes are chosen to provide maximum sensitivity
- Observed yields in each bin can be related to physics parameters of interest and *D* decay information





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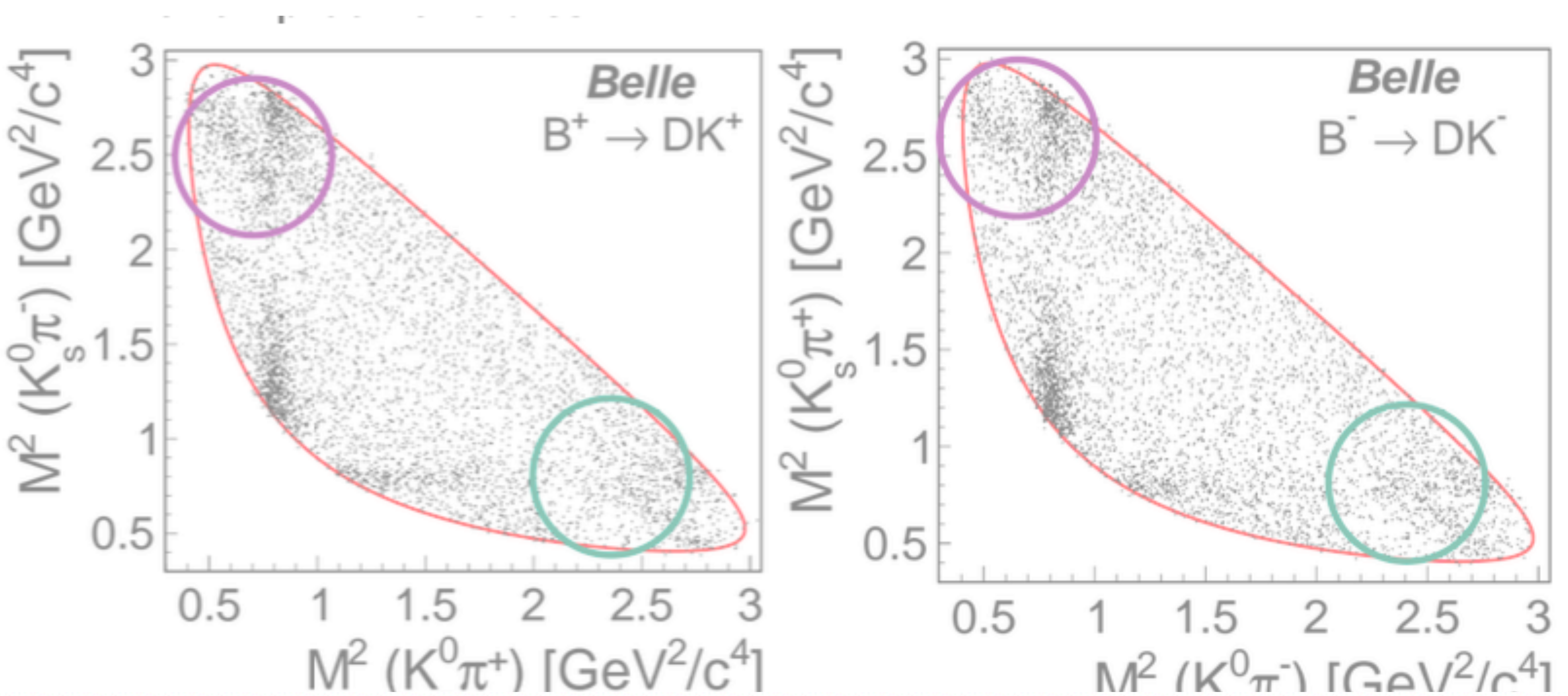


$$N_i^{\pm} = h_{B^\pm}\left[F_i + r_B^2\overline{F}_i + 2\sqrt{F_i\overline{F}_i}(c_i x_\pm + s_i y_\pm)\right].$$

$h_{B^\pm}$: Normalization constant.

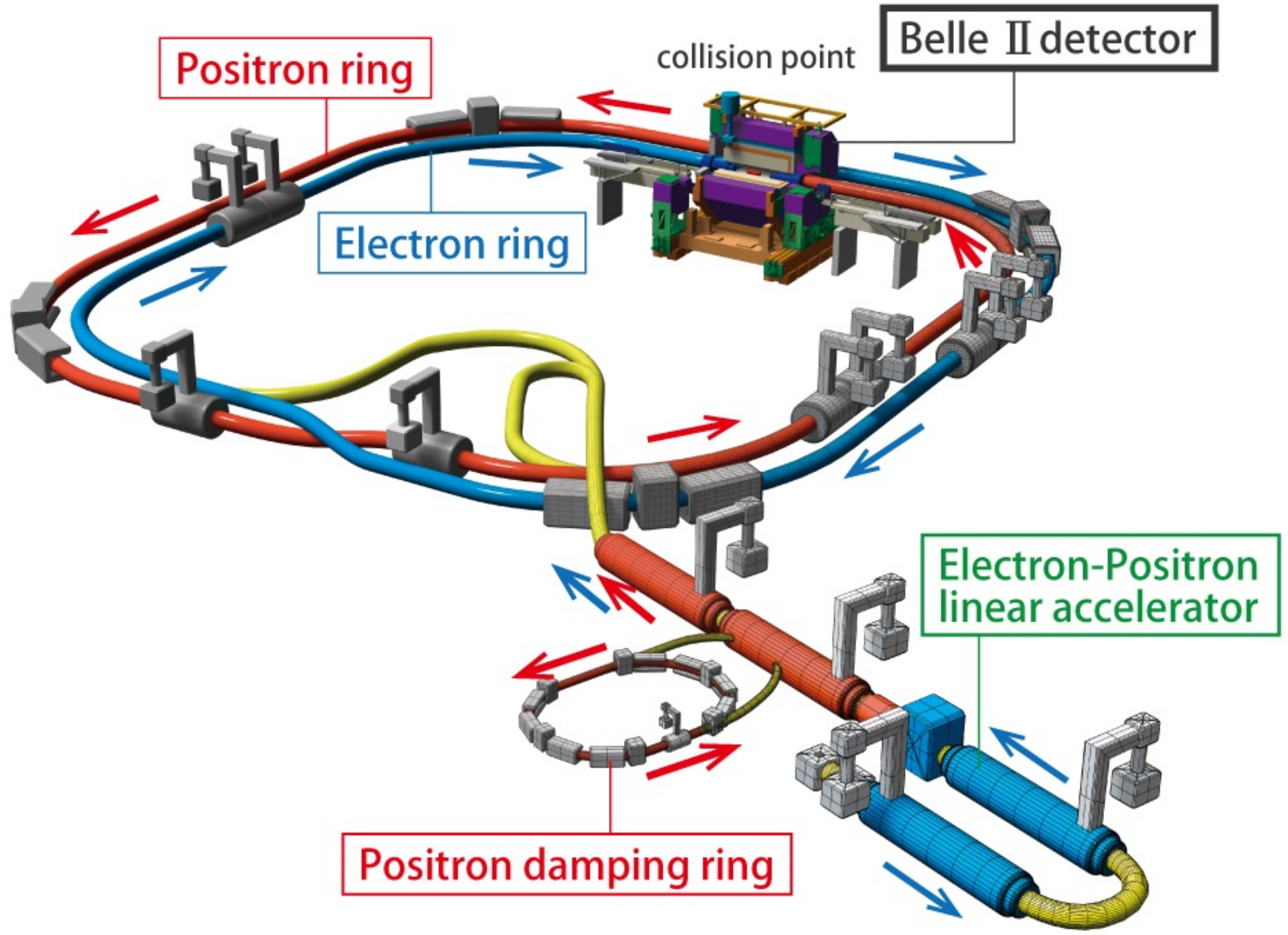
Physics parameters of interest: $(x_\pm, y_\pm) = r_B(\cos(\phi_3 + \delta_B), \sin(\phi_3 + \delta_B))$

Amplitude-averaged strong phase difference between $\overline{D^0}$ and D^0 over i^{th} bin and are obtained from external charm factories like *CLEO* and *BESIII*.

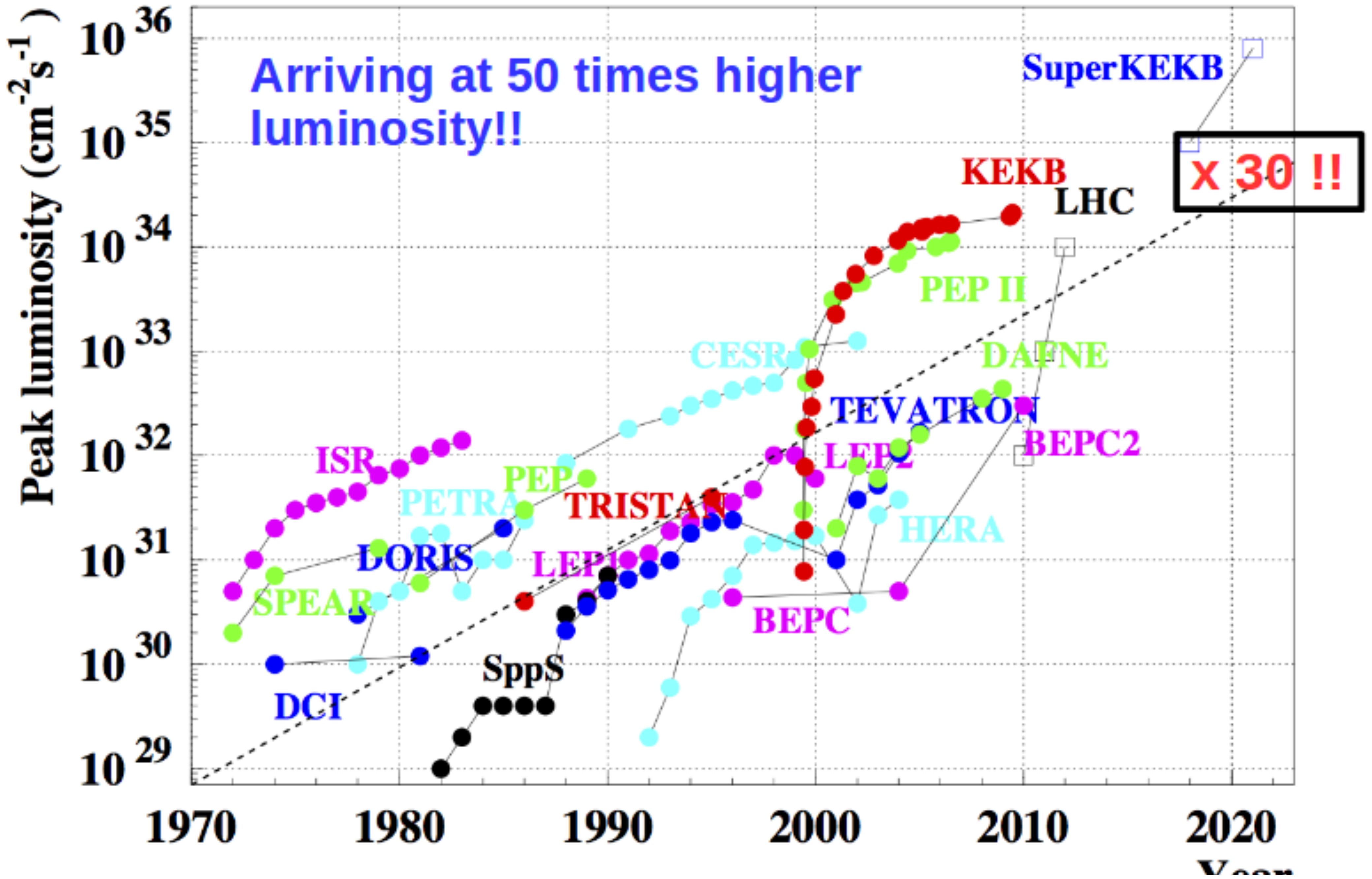
Fraction of pure D^0 decay to bin i taking into account the reconstruction and selection efficiency.

SuperKEKB accelerator

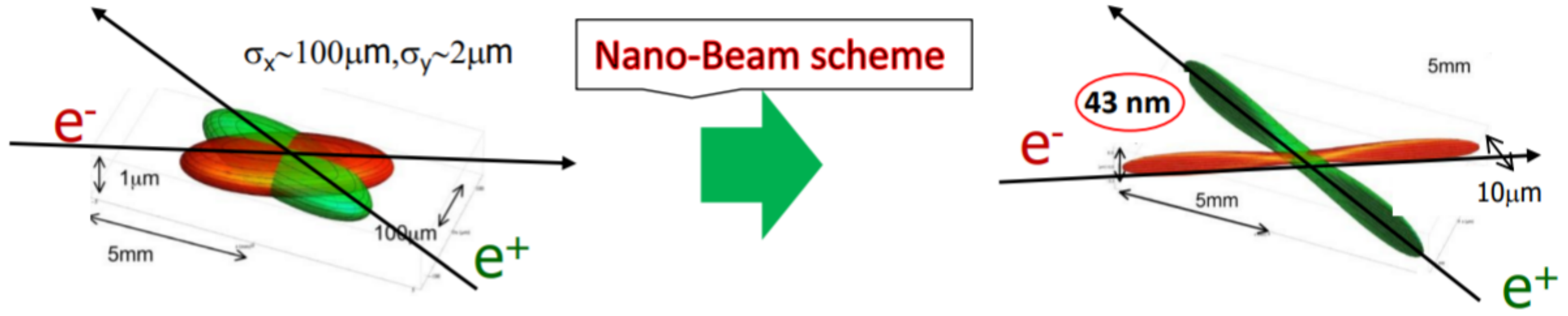
Asymmetric energy e^+e^- collider at KEK: 7 GeV e^- and 4 GeV e^+



A 30 fold increase in instantaneous luminosity over Belle, $\mathscr{L} = 6 \times 10^{35} cm^{-2} s^{-1}$

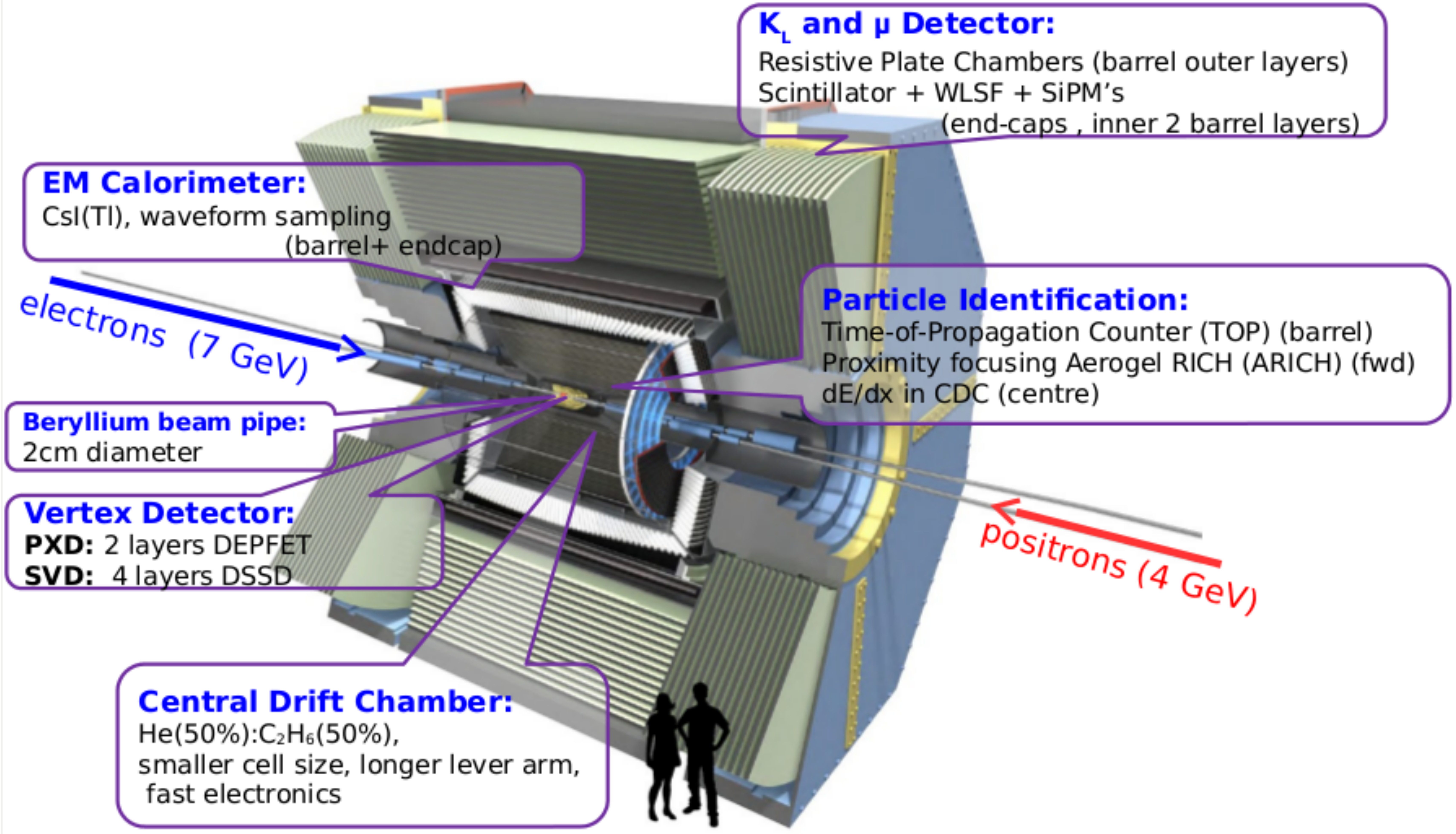


20 times smaller beam spot and 1.5 times increase in beam current ➡️ 30 x luminosity

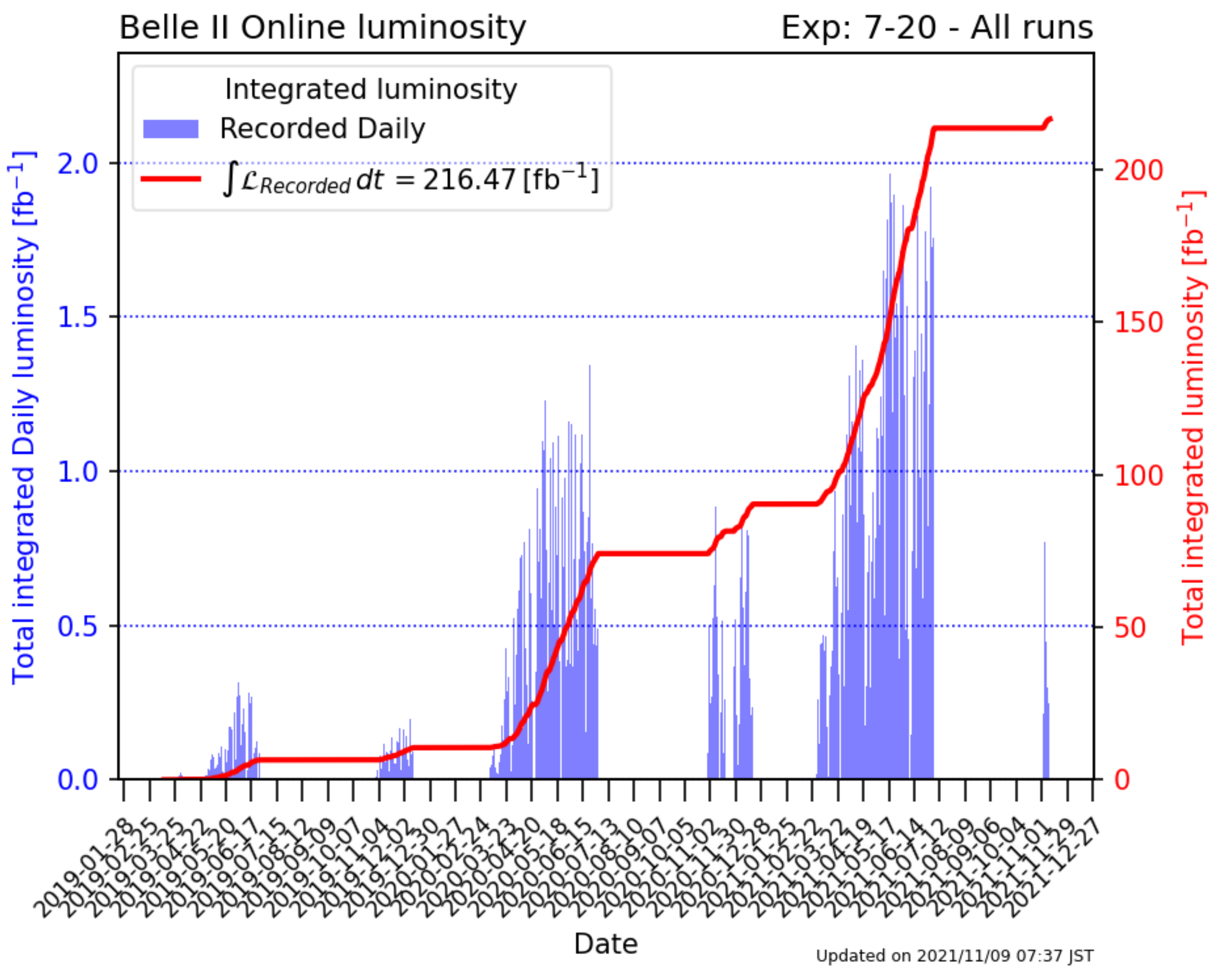


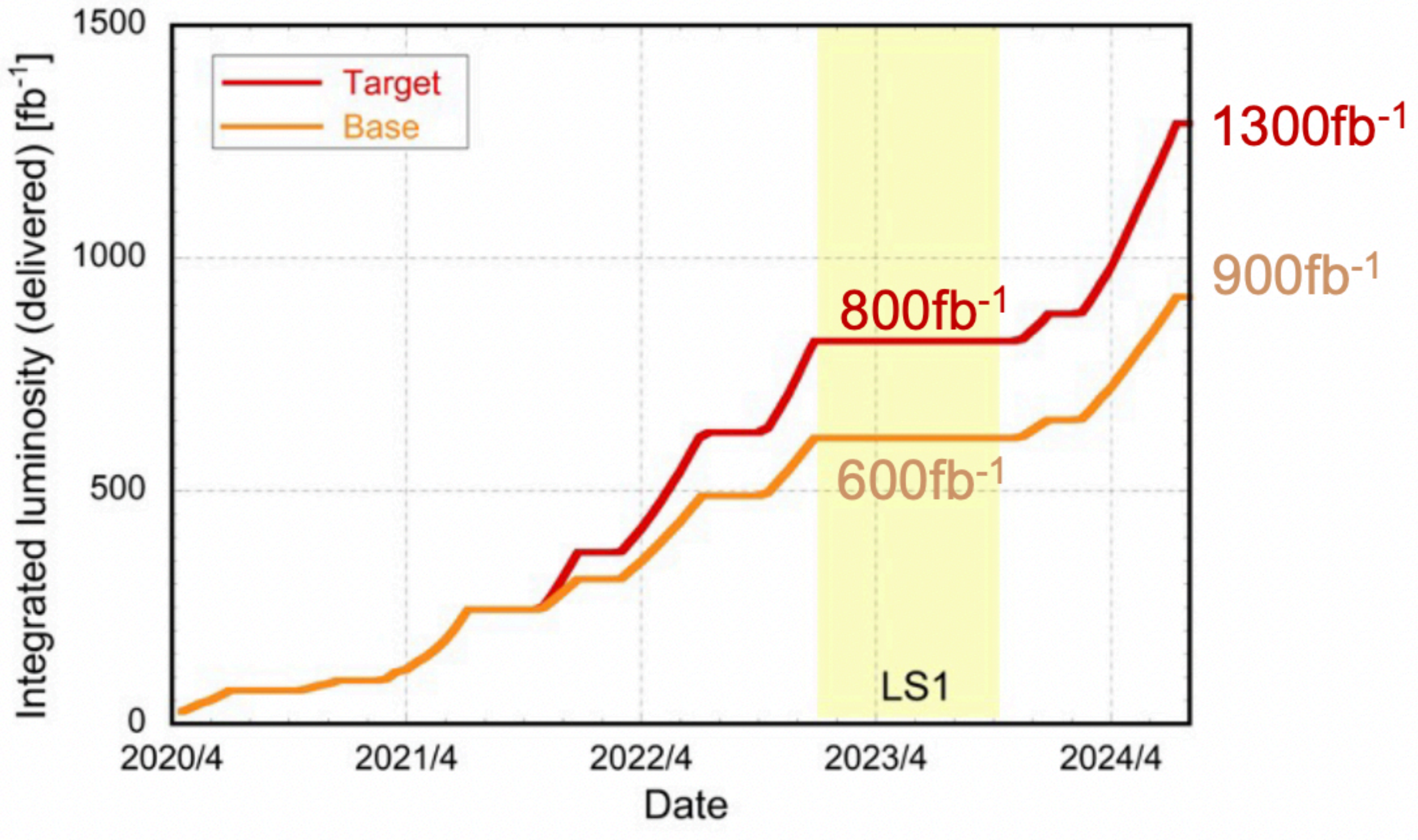
Belle II detector and status

- Higher beam background
- Higher trigger rate
- New tracking system and improved vertexing capability
- New particle identification systems
- Better time resolution at calorimeter



Belle II detector and status





- Next goal is to accumulate Belle equivalent data set before the long shut-down scheduled in Jan 2023 (may vary because of the difficulties due to the COVID-19 restrictions)

- 50 ab^{-1} of data sample will be collected as soon as possible

Measurement of $R^{0(*)}$

$$R^{0(*)} = \frac{\Gamma_{D^{(*)}K}}{\Gamma_{D^{(*)}\pi}}$$

Already discussed in Seema's talk

Ratio of B.F of $B \to D^{(*)}K$ to B.F of $B \to D^{(*)}\pi$ decays

- Important observable related to *B* to hadronic decays
- It can test theoretical predictions related to factorisation and *SU*(3) symmetry breaking in QCD

Phys. Rev. D **83**, *014017 (2011)*
Phys. Rev. D **82**, *034038 (2010)*

Decay modes

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

- $B \to D^{(*)}\pi$ modes are important control channels for time-dependent *CPV* analyses and charmless *B* decays.
- $B^- \to D^{(*)0}K^-$ are sensitive to angle ϕ_3

Results from B → D(*)h decays

$$N^{D\pi}_{\text{pion enhanced}} = (1-\kappa)N^{D\pi}_{\text{tot}}$$

$$N^{\text{DK}}_{\text{pion enhanced}} = (1-\epsilon)R^0 N^{D\pi}_{\text{tot}}$$

$$N^{DK}_{\text{kaon enhanced}} = \epsilon R^0 N^{D\pi}_{\text{tot}}$$

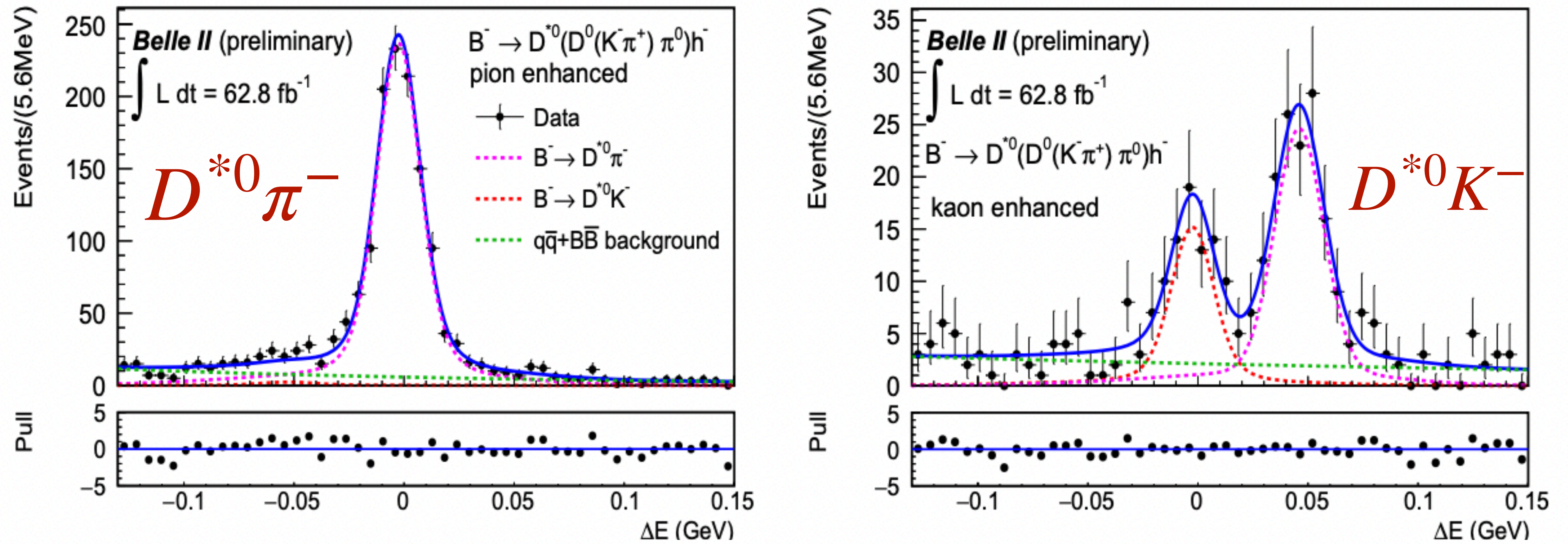
$$N^{D\pi}_{\text{kaon enhanced}} = \kappa N^{D\pi}_{\text{tot}}$$

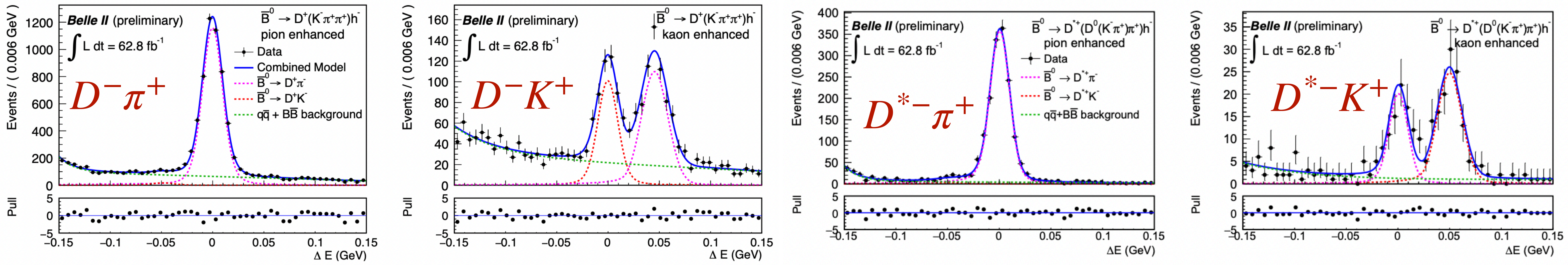
$\epsilon = \text{kaonID efficiency}$

$\kappa = \text{pion fake} - \text{rate}$

$\kappa, R^0, N^{D\pi}_{tot}$ are directly extracted from simultaneous fit of $B \to Dh$

- Common selection to all the final states
- Common signal extraction strategy
- PID selection prompt *h*: pion-enhanced and kaon-enhanced





Results from B → $D^{(*)}h$ decays

R^0 (10^{-2}) results

	$D^0(K\pi)h$	$D^0(K_S^0\pi\pi)h$	$D^-(K\pi\pi)h$
Belle II (62.7 fb^{-1})	$\mathbf{7.66 \pm 0.55\ ^{+0.11}_{-0.08}}$	$\mathbf{6.32 \pm 0.81^{+0.09}_{-0.11}}$	$\mathbf{9.22 \pm 0.58^{+0.11}_{-0.09}}$
LHCb (5 (1) fb^{-1})	$7.77 \pm 0.04 \pm 0.07$	$7.77 \pm 0.04 \pm 0.07$	$8.22 \pm 0.11 \pm 0.25$

	$D^{*0}h$	$D^{*-}h$
Belle II (62.7 fb^{-1})	$\mathbf{6.80 \pm 1.01 \pm 0.07}$	$\mathbf{5.99 \pm 0.82\ ^{+0.17}_{-0.08}}$
LHCb (5 (1) fb^{-1})	$7.93 \pm 0.11 \pm 0.56$	$7.76 \pm 0.34 \pm 0.26$

In agreement with the W.A value within 2σ!

$B^{\pm} \to D(K_S^0 h^- h^+)K^{\pm}$ decays at Belle and Belle II

Selections are similar to previous Belle analysis

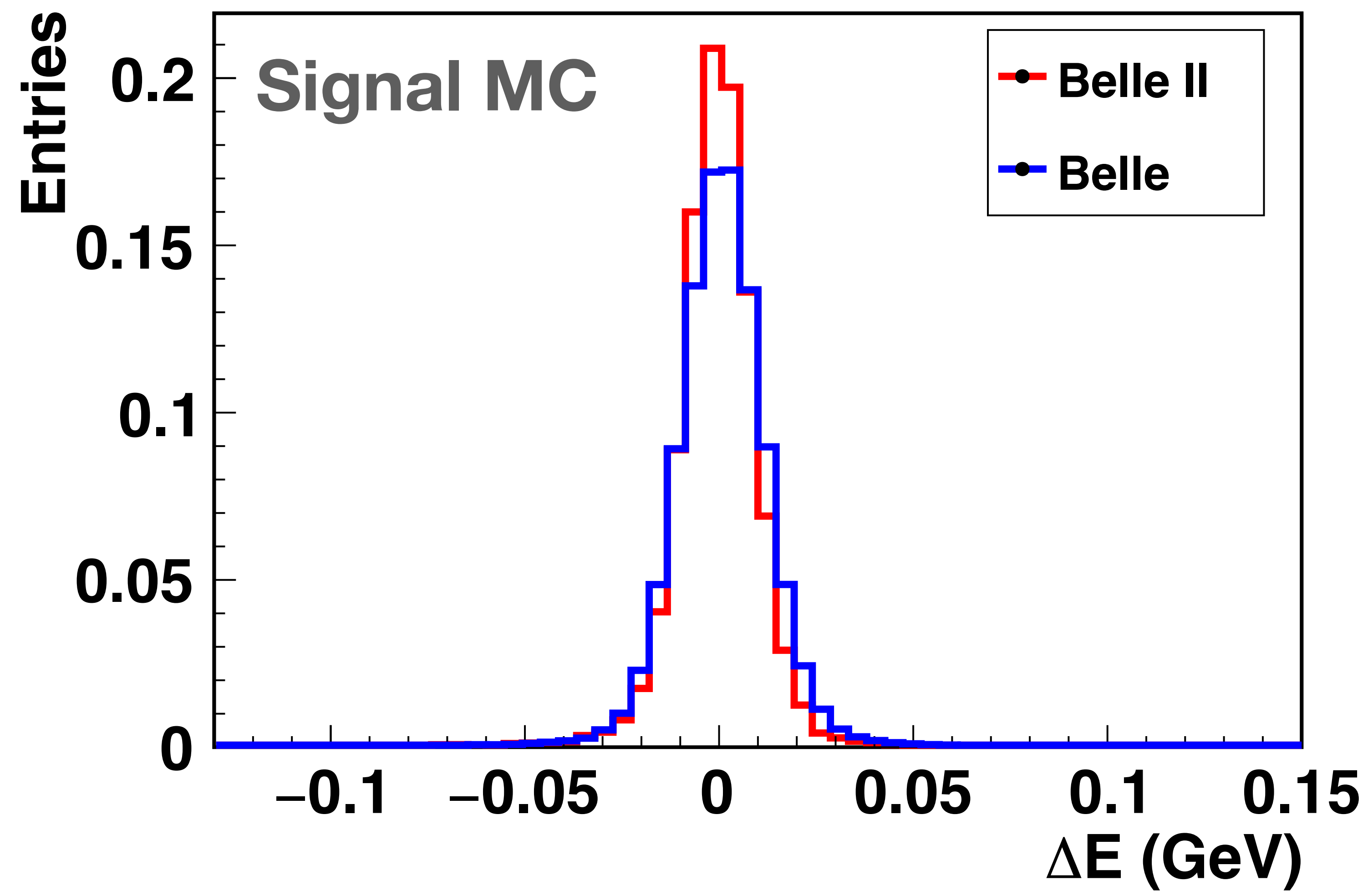
PRD 85, 112014 (2012)

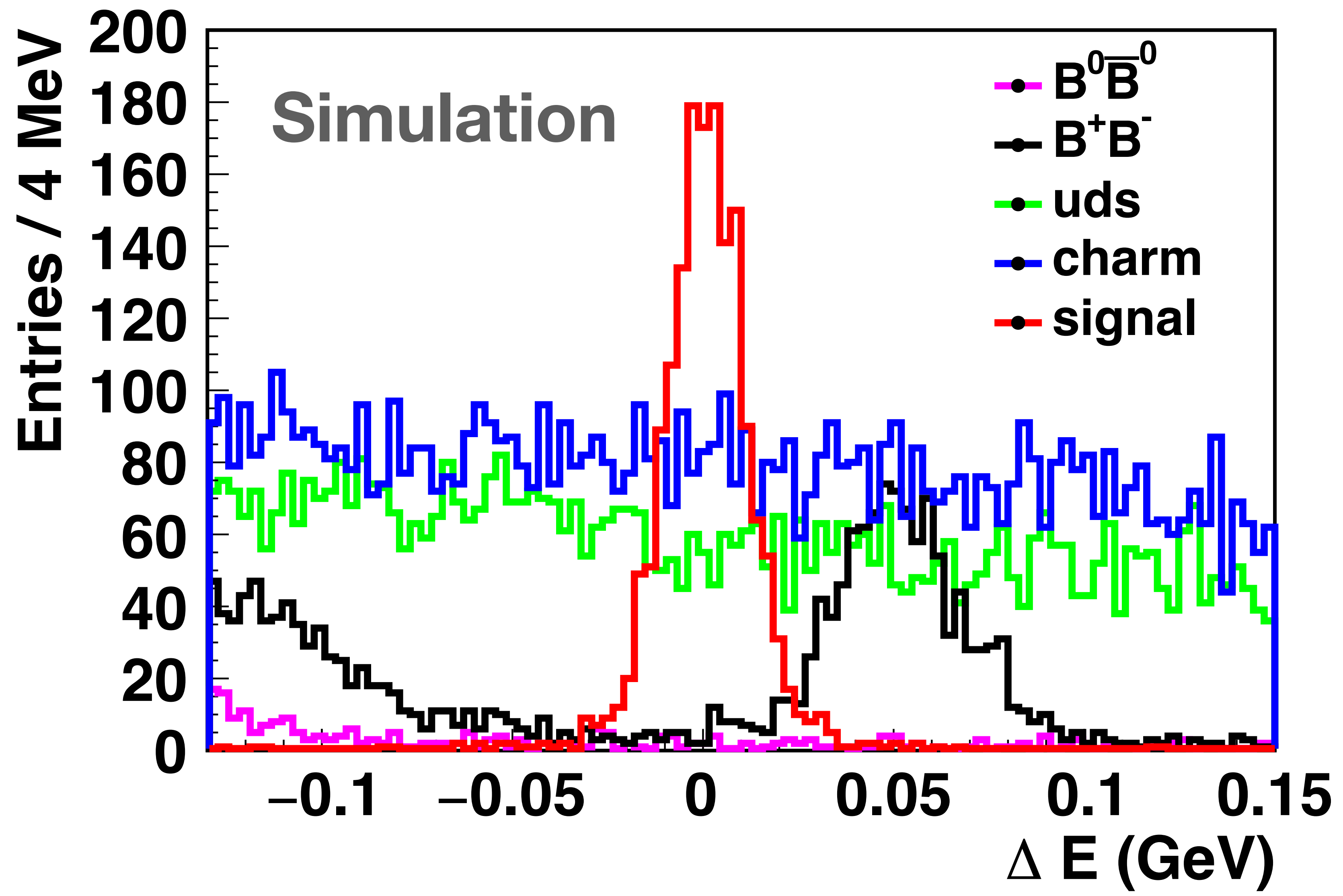
- Track quality criteria
- K/π separation using PID info
- $|M_i - M_{\text{PDG}}| < 3\sigma; i = D, K_S^0$
- $M_{\text{bc}} > 5.27\ \text{GeV}/c^2$
- $-0.13 < \Delta E < 0.18\ \text{GeV}$

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

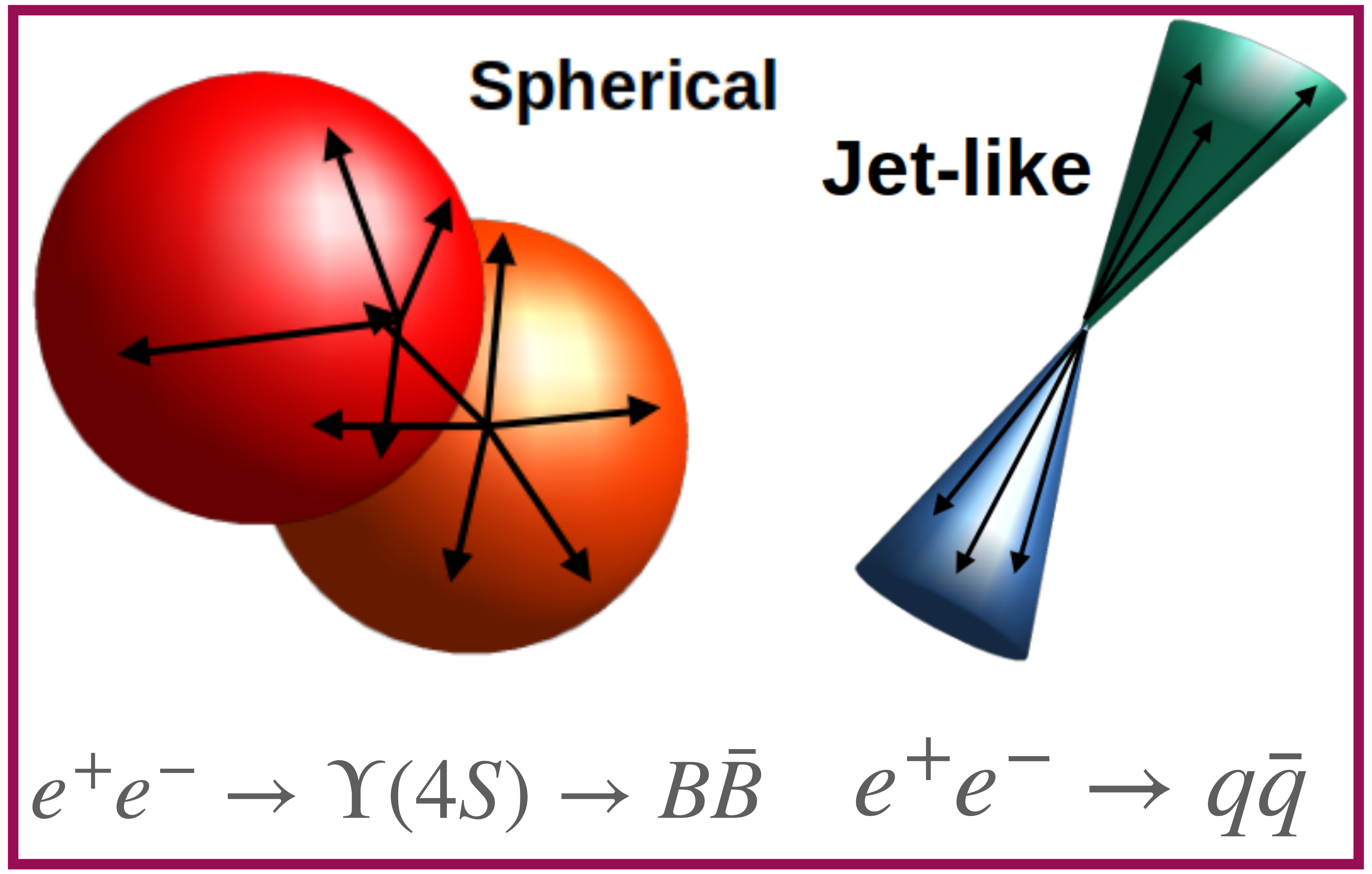
Improvements

1. Multivariate K_S^0 selection (9% increase in signal yield)
2. Improved background rejection tool
3. New signal extraction strategy
4. New strong-phase inputs from BESIII (reduces systematics)
5. Additional statistics from $K_S^0 KK$ final state and Belle II (more 30% increase in signal yield)

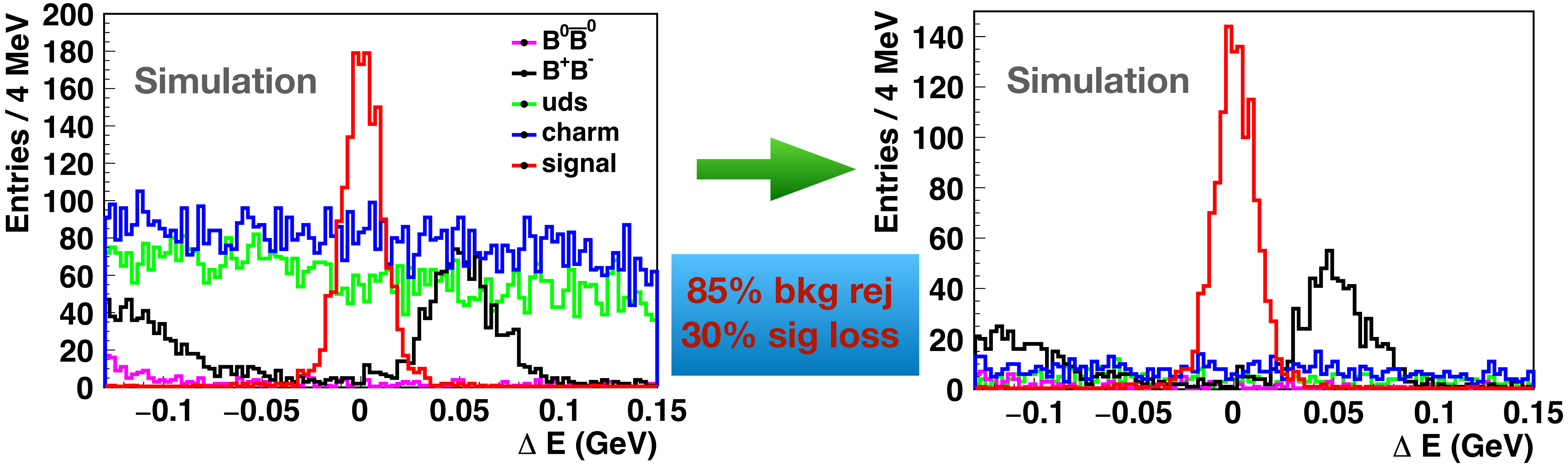




Background suppression



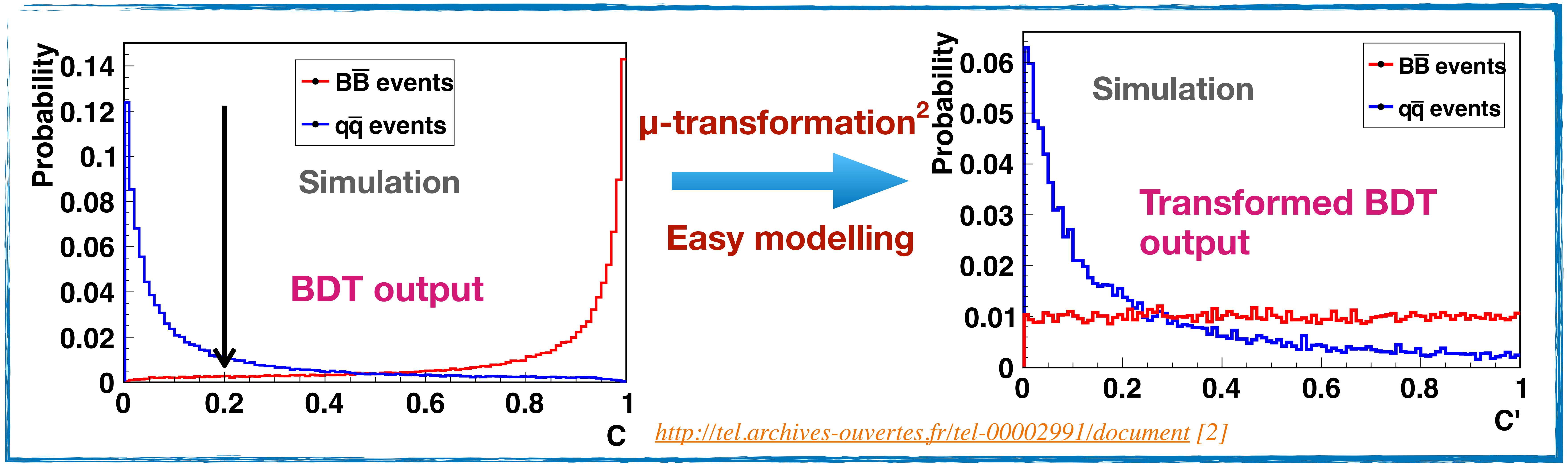
Dominant background from $e^+e^- \to q\bar{q}$ processes



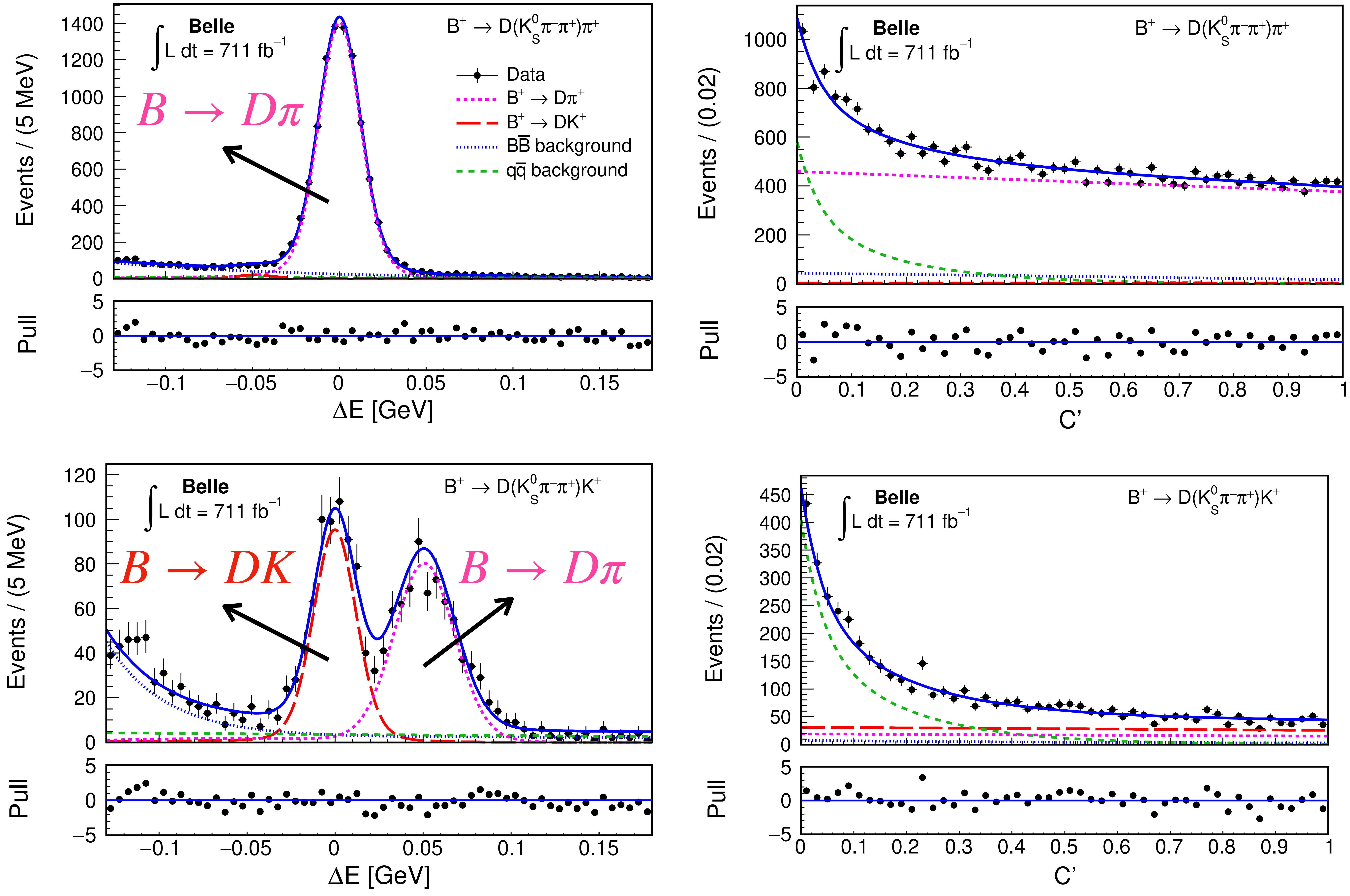
Inputs to boosted-decision-tree (BDT)

⬇️

- Event shape variables
- Angular variables
- Vertex variables
- Flavour tag variables



Signal extraction: Belle data



- 2D $(\Delta E, C')$ simultaneous fit of $B \to D\pi$ and $B \to DK$
- $K-\pi$ misidentification rate is directly extracted from data

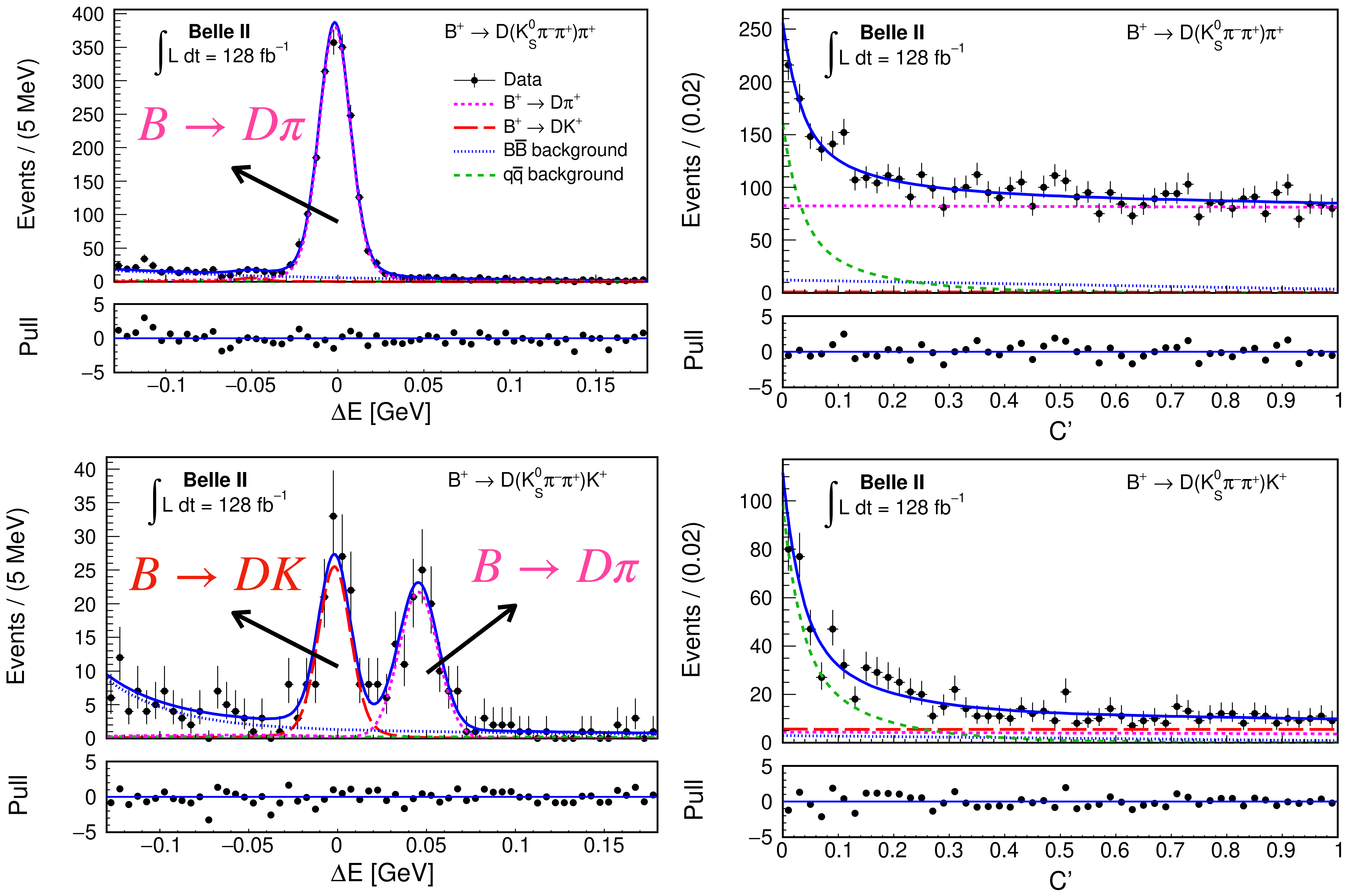
N$_{signal}$: Belle

$K_S^0\pi\pi = 1467 \pm 53$

$K_S^0KK = 194 \pm 17$

40% increase in signal yield as compared to previous best result of Belle

Signal extraction: Belle II data



- 2D $(\Delta E, C')$ simultaneous fit of $B \to D\pi$ and $B \to DK$
- $K - \pi$ misidentification rate is directly extracted from data

N_{signal}: Belle II

$K_S^0\pi\pi = 280 \pm 21$

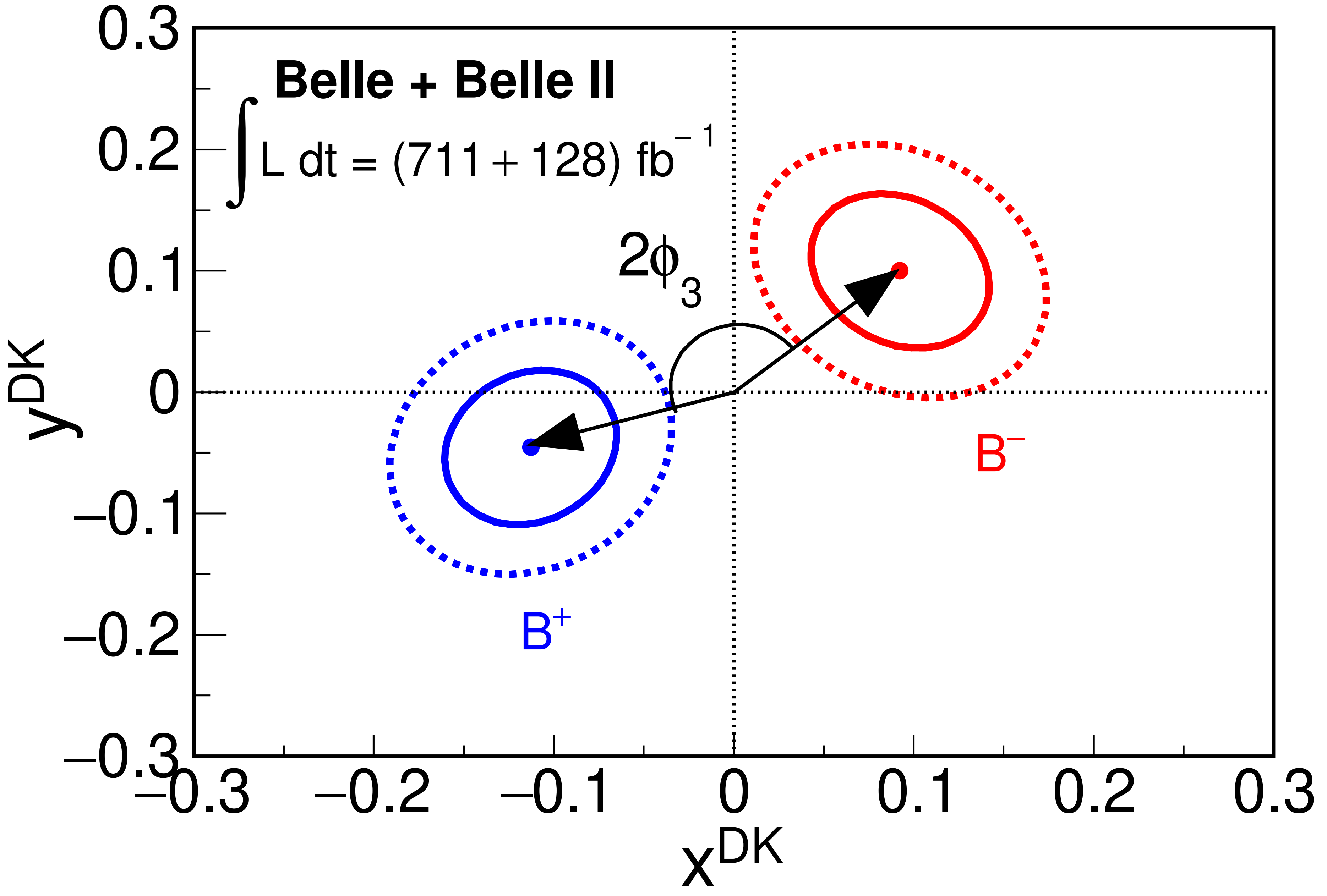
$K_S^0KK = 34 \pm 7$

Additional 17%

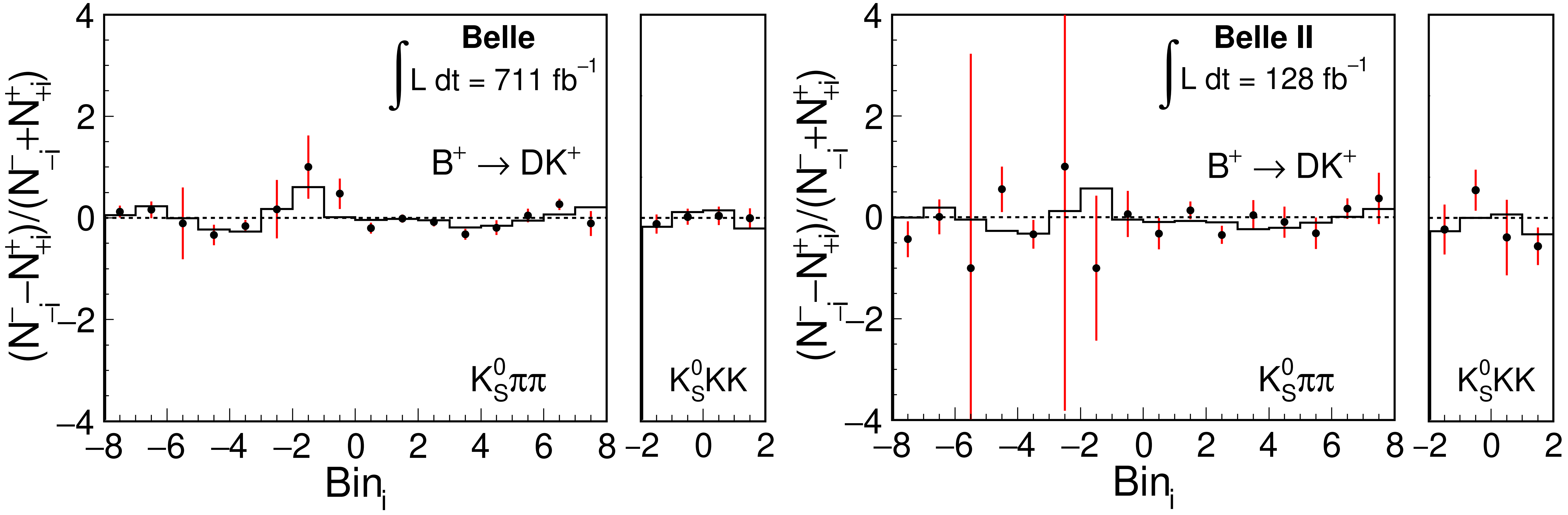
Extraction of *CPV* parameters

- Simultaneous fit is performed in each Dalitz plot bin to extract CP observables: $x_\pm$ and $y_\pm$
- F_i parameters are obtained from $B \to Dh$ data in the fit itself ➡️ reduce systematic uncertainty and reliance on simulation

[LHCb collaboration: JHEP 02 (2021) 169]



Asymmetry as a function of bin yields



$$x_+^{DK} = -0.113 \pm 0.032$$
$$y_+^{DK} = -0.046 \pm 0.042$$
$$x_-^{DK} = 0.092 \pm 0.033$$
$$y_-^{DK} = 0.100 \pm 0.042$$

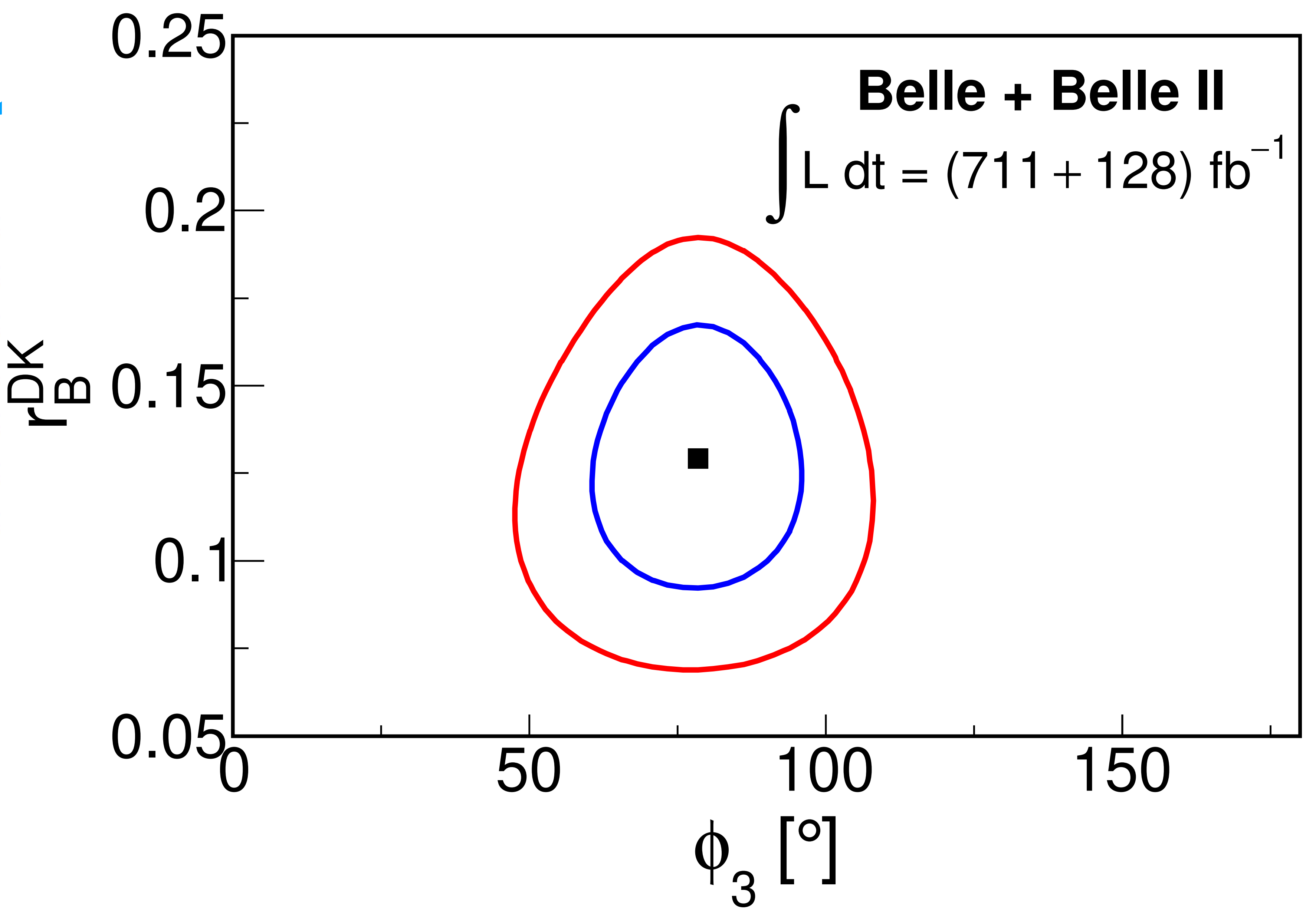
Results

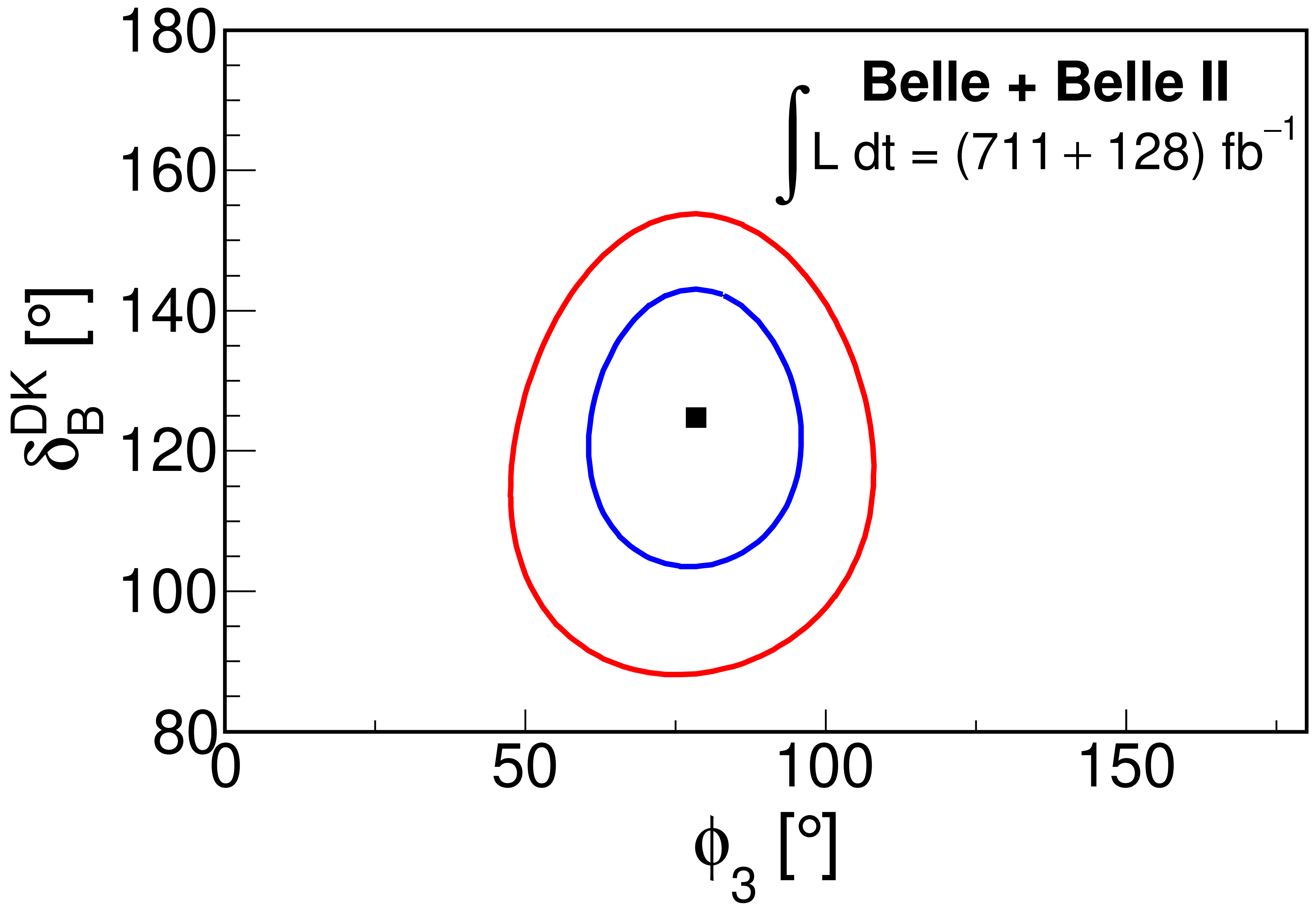
$\delta_B(°)$	124.8 ± 12.9 (stat.) ± 0.5 (syst.) ± 1.7 (ext. input)
r_B^{DK}	0.129 ± 0.024 (stat.) ± 0.001 (syst.) ± 0.002 (ext. input)
$\phi_3(°)$	78.4 ± 11.4 (stat.) ± 0.5 (syst.) ± 1.0 (ext. input)

Belle previous results: *PRD **85**, 112014 (2012)*

$$\phi_3(°) = 77.3^{+15.1}_{-14.9} \pm 4.1 \pm 4.3$$

- This result is most precise to date from the *B*-factory experiments
- New inputs from BESIII on strong-phase has significant impact on systematic uncertainty
  *Phys. Rev. D **101** (2020) 112002*
  *Phys. Rev. D **102** (2020) 052008*
- Use of $B \to Dh$ decay mode to incorporate efficiency effects reduces the experimental systematic uncertainty

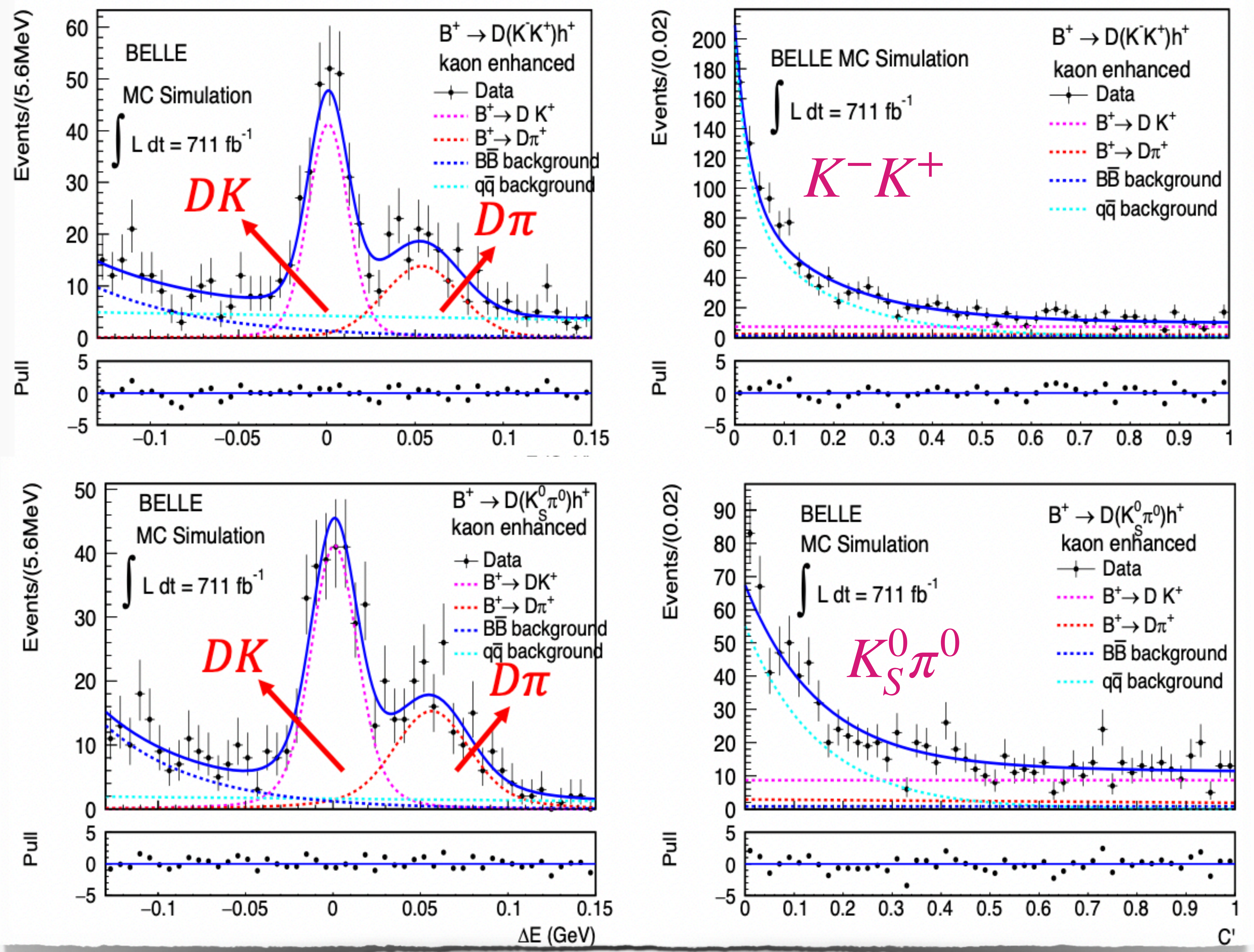


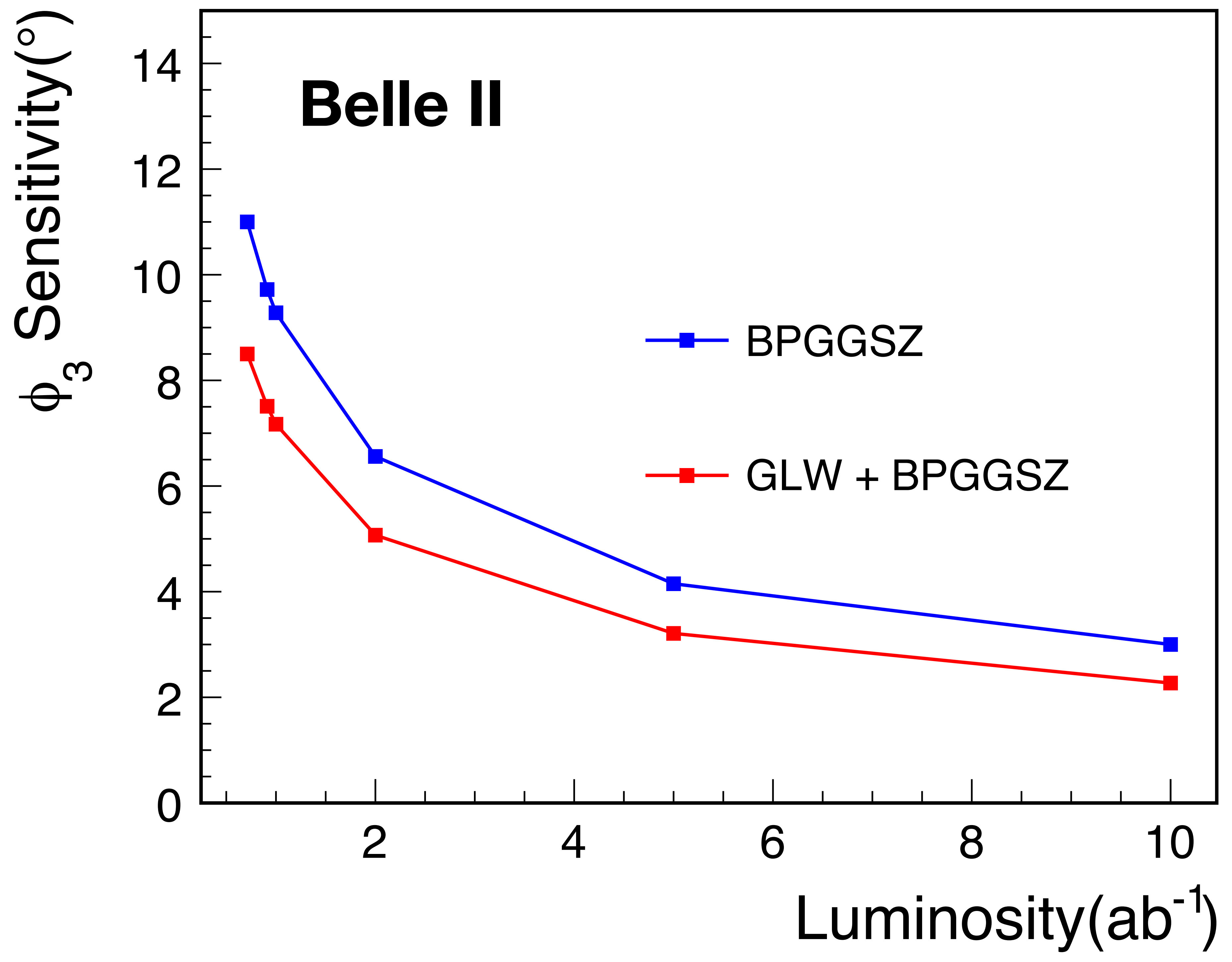


Future prospects

Ongoing sensitivity studies with $D_{CP\pm}$ final states:

Belle + Belle II: *previously performed with 275 fb^{-1} Belle data set*



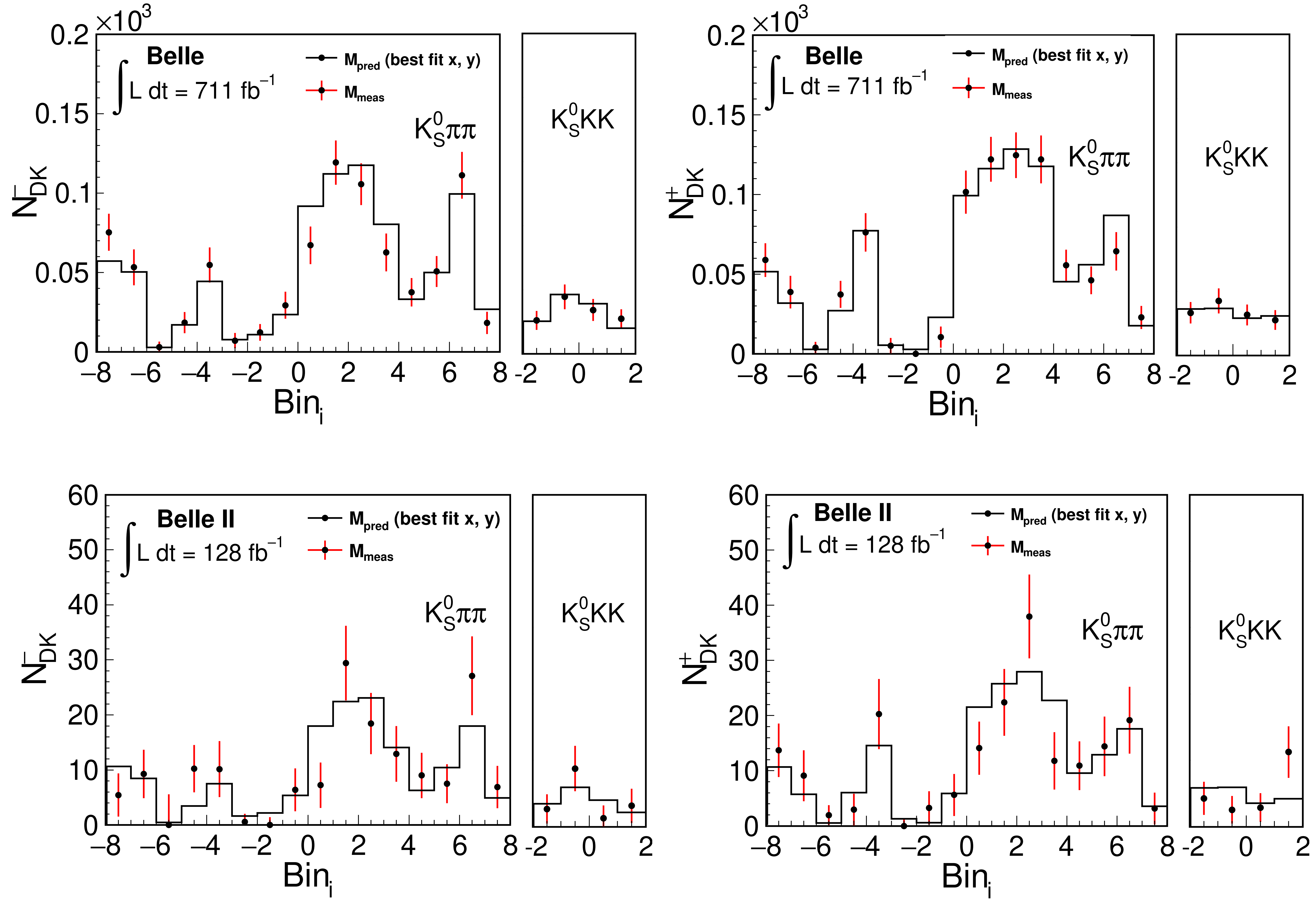


- Expected uncertainty with 10 ab^{-1} data set is < 3°
- Many other multi-body final states and $K_S^0 hh$ from inclusive $D^{*0(+)}$ are ongoing

Summary

- **The analysis of the first Belle and Belle II combined model-independent measurement of the CKM angle ϕ_3 have been presented.**
- The uncertainty on ϕ_3 has been reduced from 15° to 11° along with the systematic uncertainty and uncertainty due to strong-phase.
- This is the most precise result so far from *B*-factories.
- The results from measurements of ratio of B.F of $B \to DK$ to $B \to D\pi$ from various final states is consistent with the world average value.
- **Future analyses with Belle II data will provide an uncertainty of 3° or so with 10 ab^{-1} of data set.**

Backup



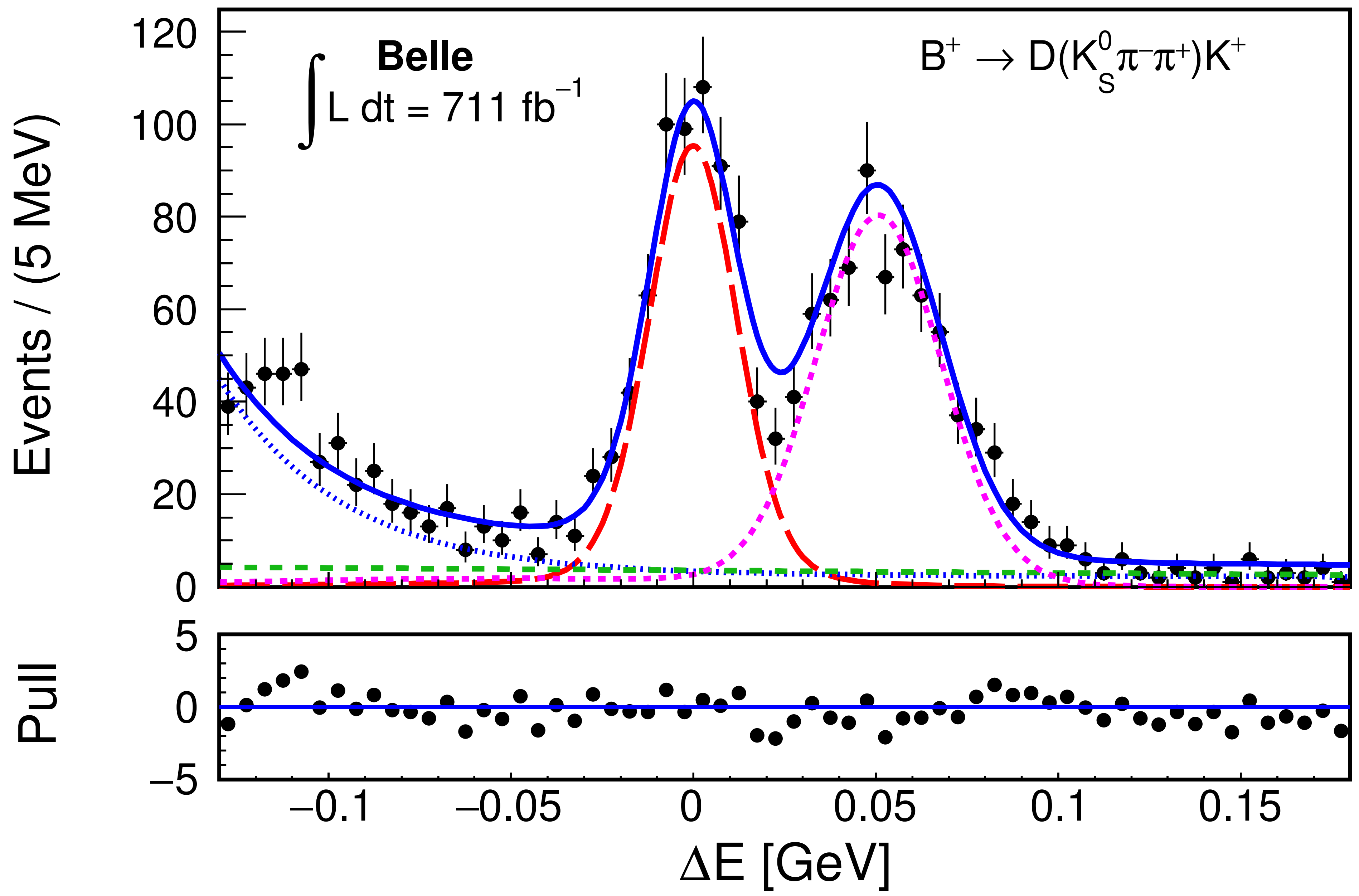
Belle
$\int L\,dt = 711\ fb^{-1}$
M_{pred} (best fit x, y)
M_{meas}
$K^0_S\pi\pi$
K^0_SKK
N^-_{DK}
N^+_{DK}
$\times10^3$
Belle II
$\int L\,dt = 128\ fb^{-1}$
Bin_i

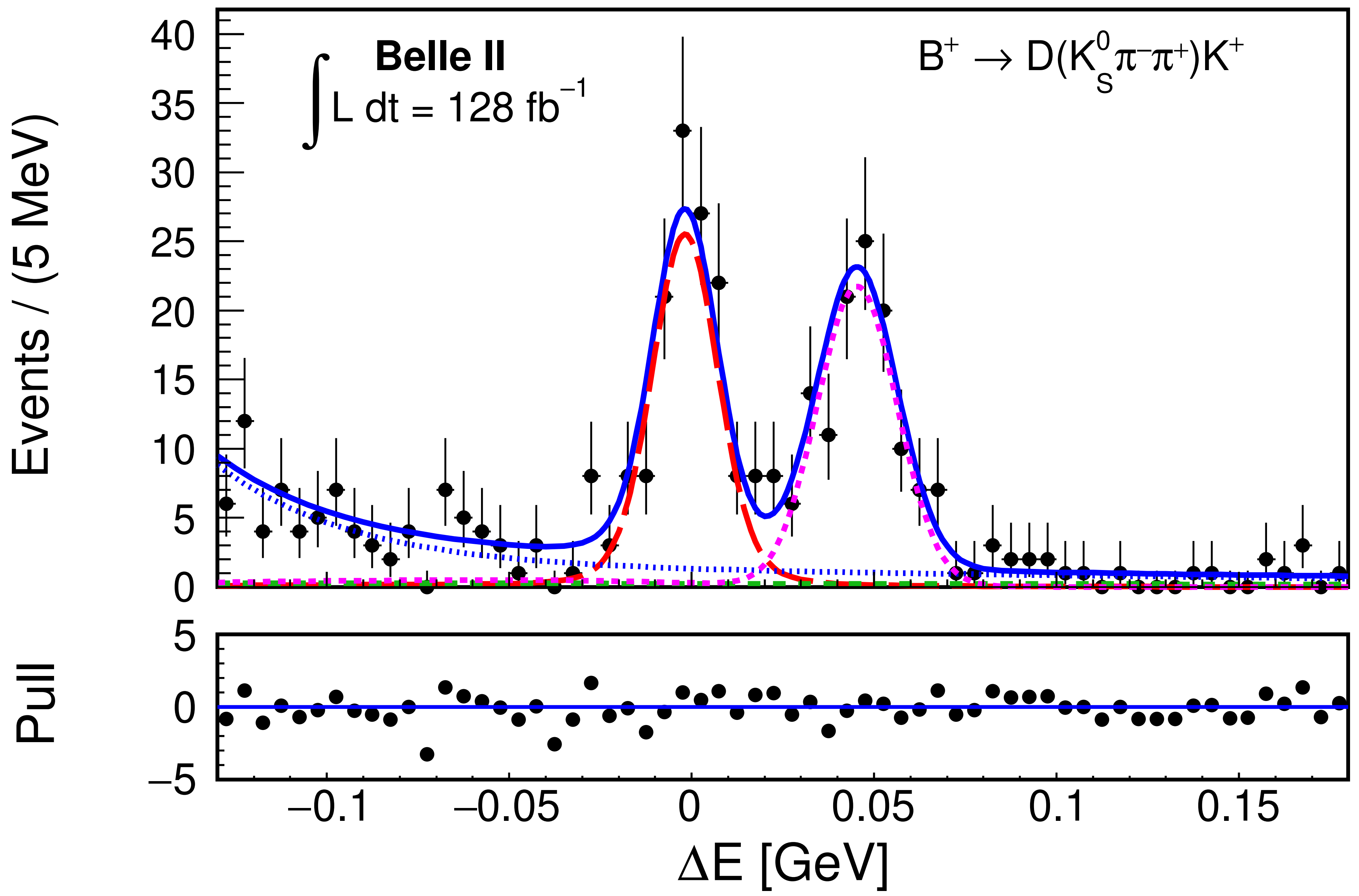
Systematics

All values are quoted $\times 10^{-2}$.

Source	$\sigma_{x_+^{DK}}$	$\sigma_{y_+^{DK}}$	$\sigma_{x_-^{DK}}$	$\sigma_{y_-^{DK}}$	$\sigma_{x_\xi^{D\pi}}$	$\sigma_{y_\xi^{D\pi}}$
Fit bias	0.16	0.04	0.05	0.14	0.49	0.08
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 bkg	0.03	0.05	0.03	0.04	0.02	0.10
Total	0.18	0.10	0.13	0.22	0.51	0.18
Input c_i, s_i	0.22	0.55	0.23	0.67	0.73	0.82
Statistical	3.15	4.20	3.27	4.20	4.75	5.44

Data resolution





20% improvement in resolution at Belle II.