Hadronic *B* decays at Belle II

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on behalf of the Belle II collaboration

BEACH2022
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Hadronic B decays

Charmed decays: Cabibbo-favoured ***b*→*c*** tree transitions ($B \to D(*)K$, $B \to D(*)\pi$...).

Charmless decays: Cabibbo-suppressed ***b* → *u*** trees and ***b* → *d*, *s*** penguins ($B \to K\pi$, $B \to \rho\rho$...).

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 $B^0 \to J/\psi K^0_S$, $B^0 \to \eta' K^0_S$, $B^0 \to \phi K^0_S$

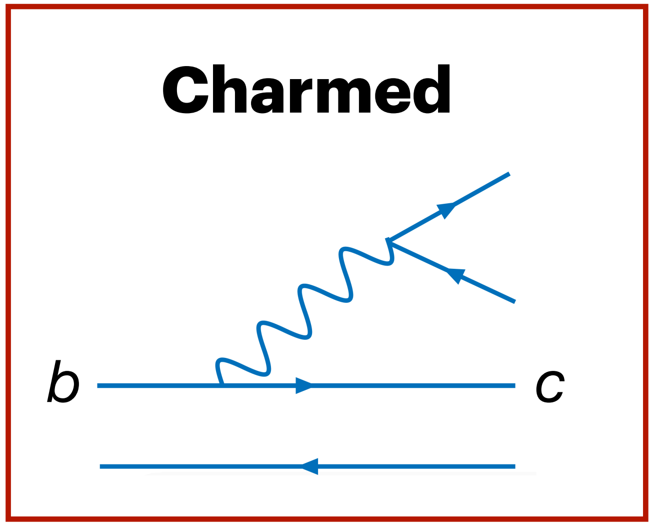
and by testing isospin sum rules, chiral structure, ...

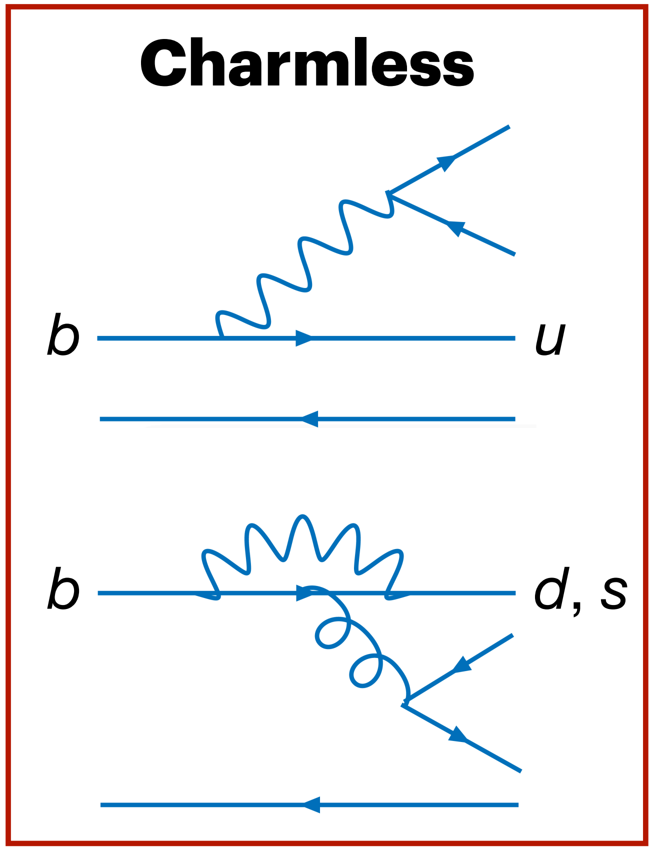
Charmed: competitive on channels with neutrals (e.g. $B \to D(K^0_S\pi^0)h$)
$\to$ challenging reconstruction. Key control channels for other analyses.

Charmless: highly sensitive to new physics but

pheno challenges: predictions limited by complicated calculations of non-perturbative QCD,

exp. challenges: rare, *BF*~O(10^{-5}), same final states of the dominant background ("continuum" $e^+e^- \to q\bar{q}$ at Belle II).

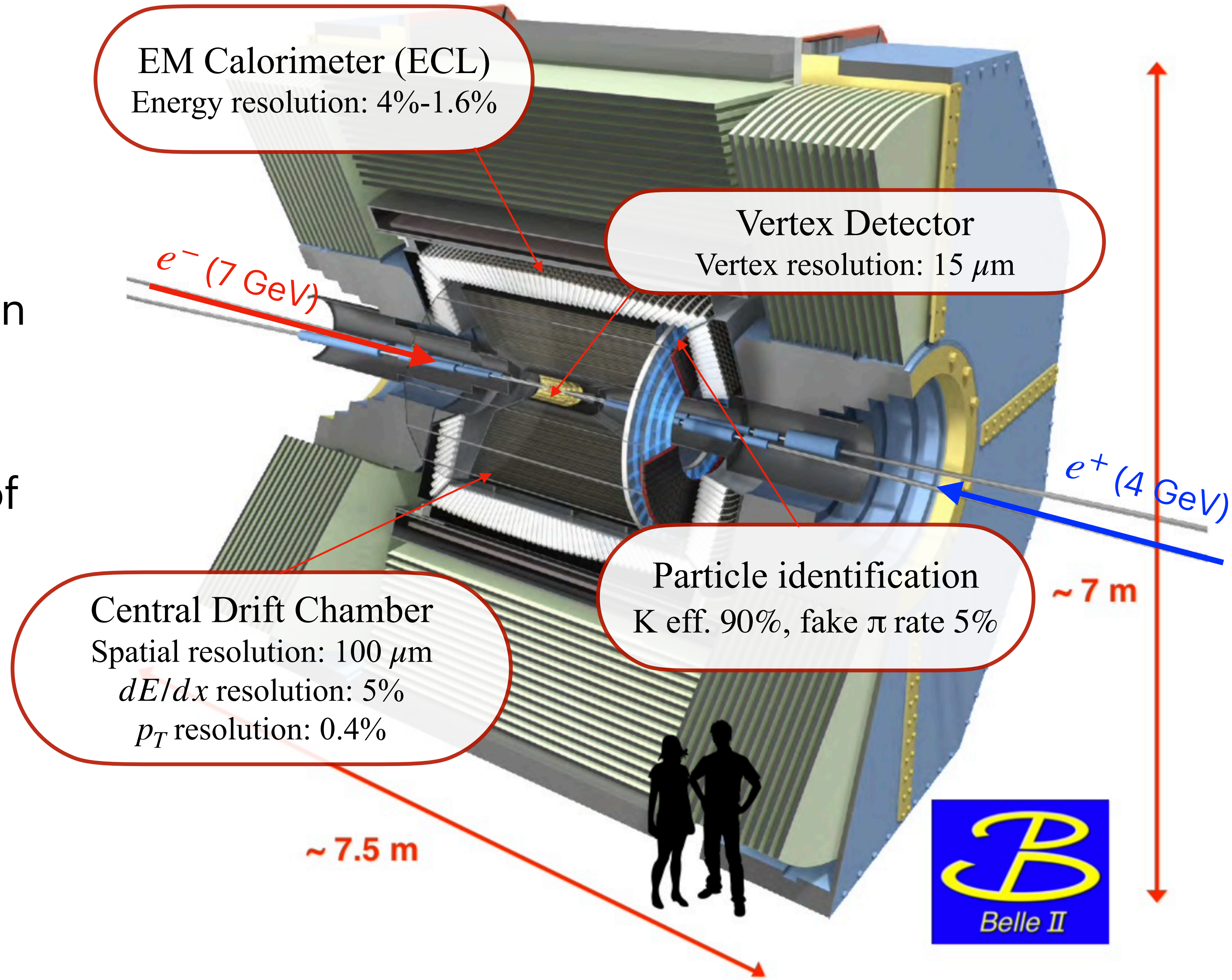




Today: γ direct determination, $B^+ \to \rho^+\rho^0$ towards α, time-dependent measurements.

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;
- 400 fb^{-1} (440 x10^6 $B\bar{B}$ pairs) of data collected;
- Record peak luminosity: 4.1x10^{34} cm^{-2} s^{-1}



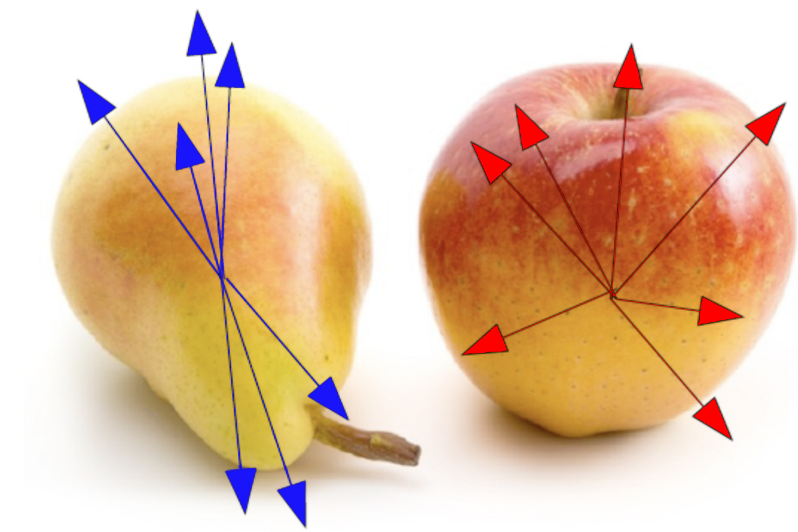
Main Belle II strength: unique reach on final states with multiple neutrinos and π^0/photons.

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.



$q\bar{q}$ events $B\bar{B}$ events

Reconstruction

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

Selection

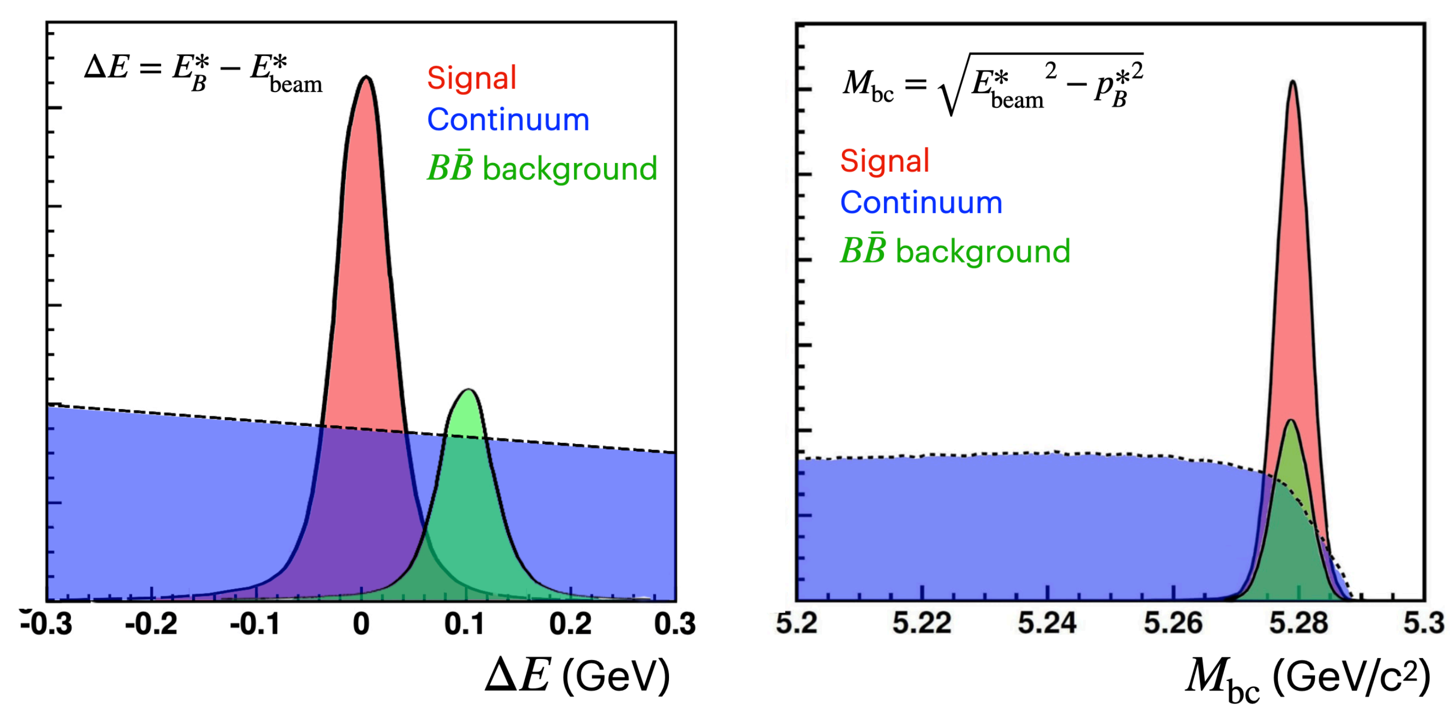
- optimize event-shape multivariate classifier (CS) and particle ID criteria

Fit

- extract models from simulation (calibrate on data), fit in to data and calculate 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

Use $D \to K^0_S h^+ h^-$ decays and model-independent method: divide Dalitz plot in bins (less information, but no amplitude-model systematics):

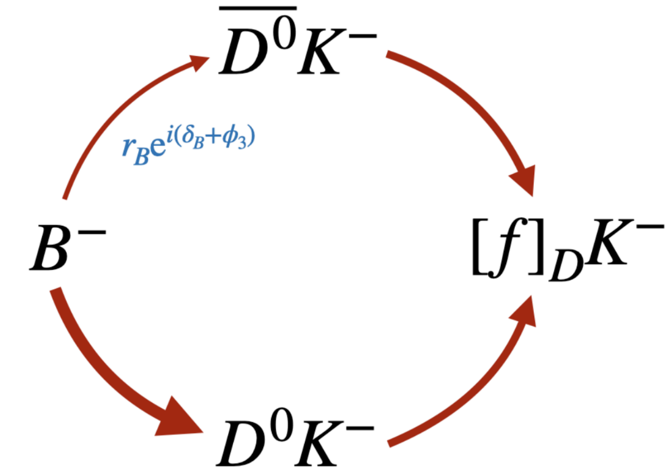
$$\mathrm{N}_i^{\pm} = \mathrm{h}_{\mathrm{B}}^{\pm}\left[\mathrm{F}_i + \mathrm{r_B}^2\overline{\mathrm{F}}_i + 2\sqrt{\mathrm{F}_i\overline{\mathrm{F}}_i}(\mathrm{c}_i x_\pm + \mathrm{s}_i y_\pm)\right]$$

$$(x_\pm,\ y_\pm) = r_{\mathrm{B}}\left(\cos(\gamma + \delta_{\mathrm{B}}),\ \sin(\gamma + \delta_{\mathrm{B}})\right)$$

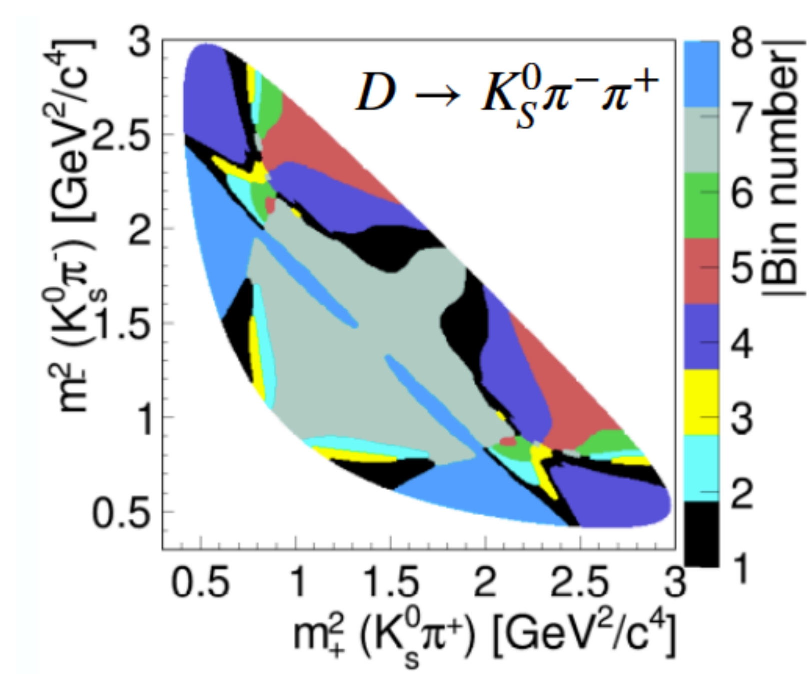
c_i, s_i: D^0-$\overline{D}^0$ strong phase differences (inputs from BES III/CLEO)

F_i: fraction of D decays to i-th bin

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



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



Results limited by sample size (small branching fractions).

Signal yield determination

128 fb⁻¹ Belle II + 711 fb⁻¹ Belle.

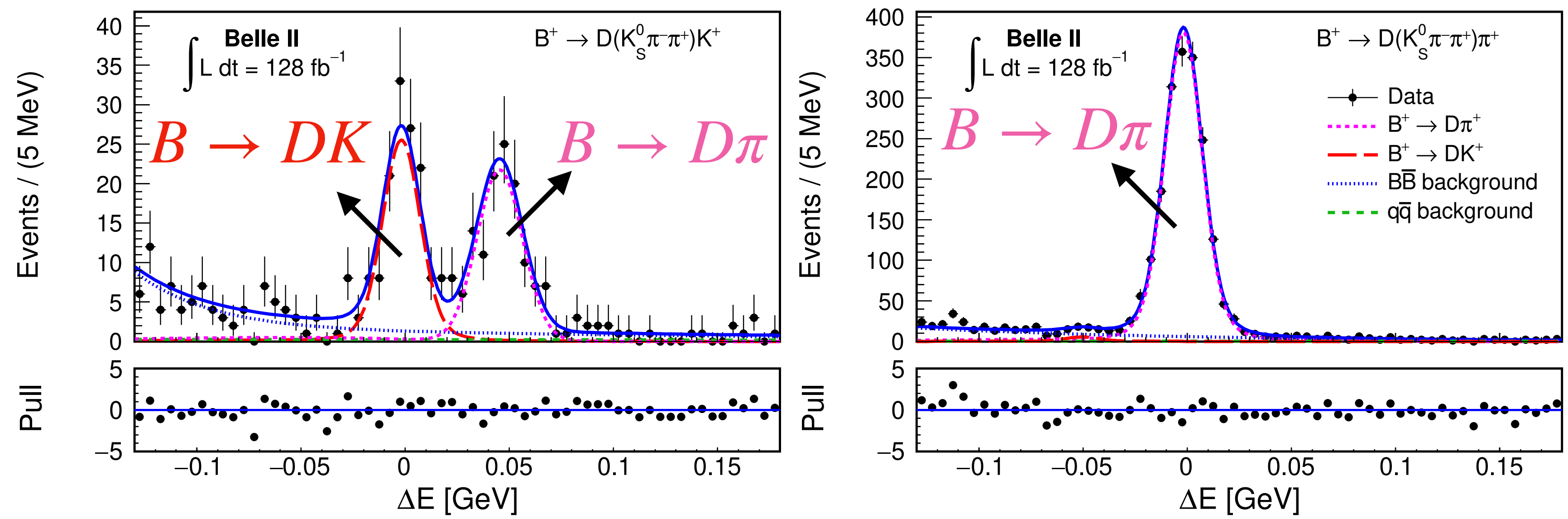
Improvements wrt previous Belle:
- K_S^0 selection
- background suppression
- signal determination
- include $D^0 \to K_S^0 KK$
- new inputs from BESIII

Simultaneous fit of $B \to DK$ and $B \to D\pi$: K/π misID rate is extracted from data.

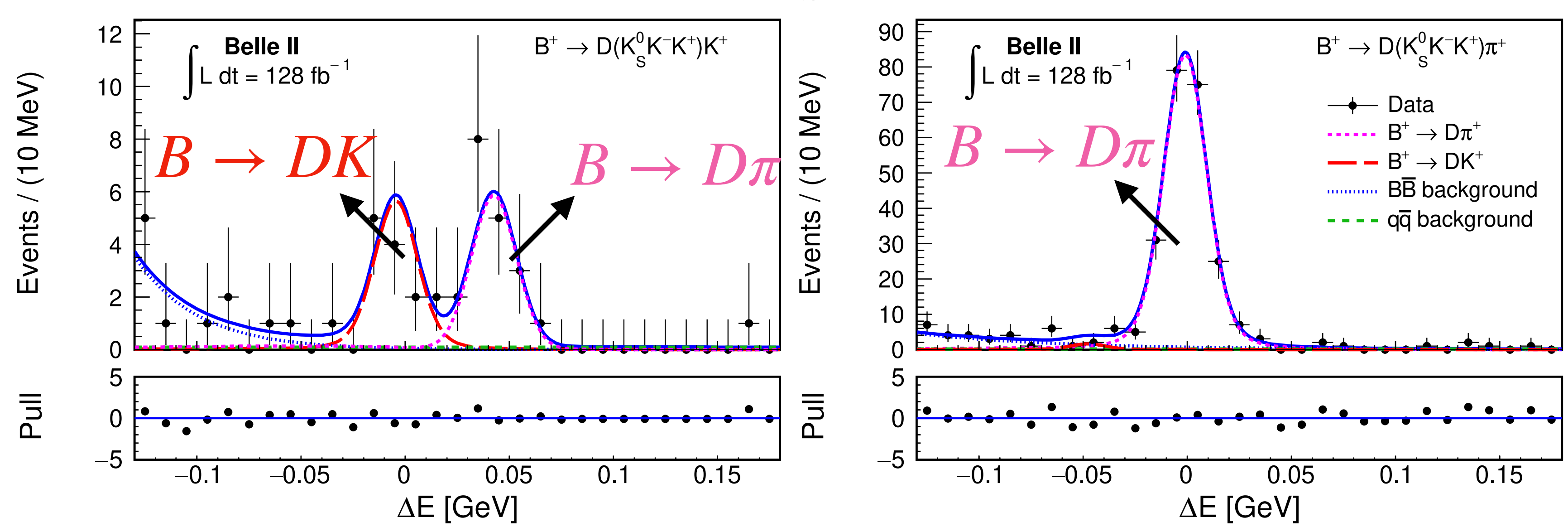
Signal yields

Belle:	Belle II :
$K_S^0\pi\pi$: 1467 ± 53	$K_S^0\pi\pi$: 280 ± 21
K_S^0KK: 194 ± 17	K_S^0KK: 34 ± 7

$$D^0 \to K_S^0\pi^+\pi^-$$



$$D^0 \to K_S^0 K^+ K^-$$



Determination of CPV parameters

Simultaneous fit in Dalitz bins to extract CP observables $(x_\pm,\ y_\pm)$. MisID fixed from previous fit.

Extract F_i directly in data to cancel associated systematics and reduce reliance on simulation.

$$\delta_\mathrm{B}[^\circ] = 124.8 \pm 12.9\ (\mathrm{stat})\ \pm 0.5\ (\mathrm{syst})\ \pm 1.7\ (\mathrm{ext})$$

$$\mathrm{r}_\mathrm{B}^\mathrm{DK} = 0.129 \pm 0.024\ (\mathrm{stat})\ \pm 0.001\ (\mathrm{syst})\ \pm 0.002\ (\mathrm{ext})$$

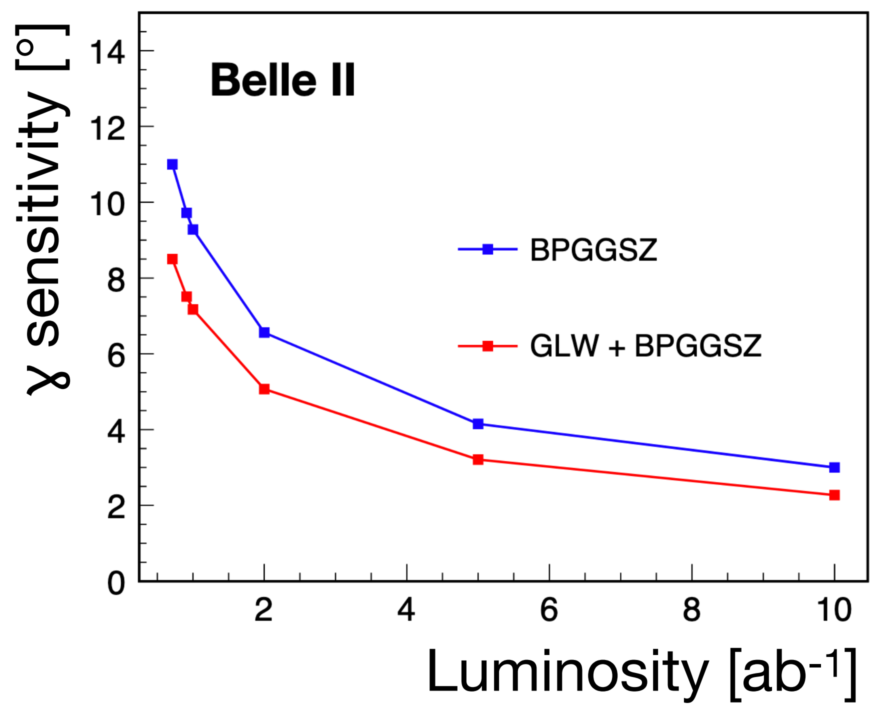
$$\gamma[^\circ] = 78.4 \pm 11.4\ (\mathrm{stat})\ \pm 0.5\ (\mathrm{syst})\ \pm 1.0\ (\mathrm{ext})$$

JHEP 02, 063 (2022)

Still not competitive with LHCb, but most precise result from a *B*-factory.

Latest inputs on strong-phase from BESIII highly reduce systematics.

Expect < 3° uncertainty with 10 ab^{-1}, including also more D final states.
Uncertainty dominated by the data sample size.



Towards CKM angle α

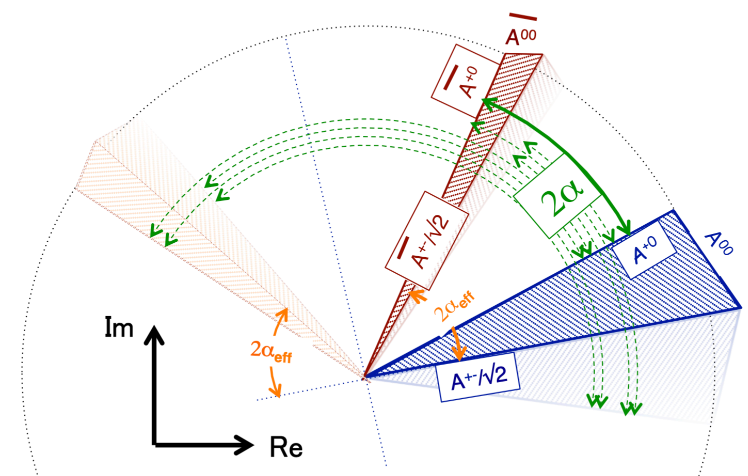
α and $B^+ \to \rho^+\rho^0$ analysis

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

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

HFLAV

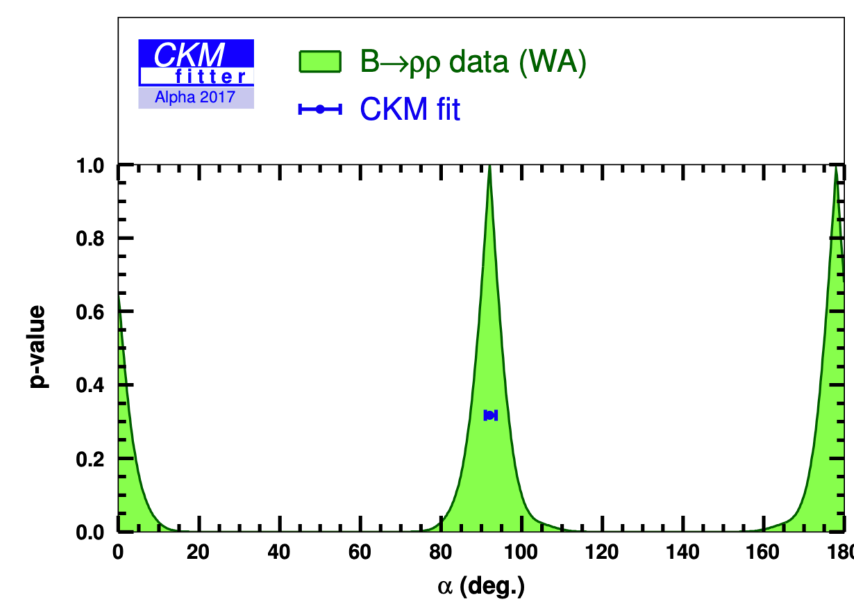
Determined using $B \to \rho\rho$, $B \to \rho\pi$, and $B \to \pi\pi$ isospin analyses (to reduce impact of hadronic uncertainties — non-perturbative QCD).



$$A^{+0} = A^{+-}/\sqrt{2} + A^{00}$$

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

Current best $B^+ \to \rho^+\rho^0$ measurement is from BaBar (424fb^{-1}).



Goal: measure $B^+ \to \rho^+\rho^0$ branching fraction, A_{CP}, and fraction of longitudinal polarised decays f_L.

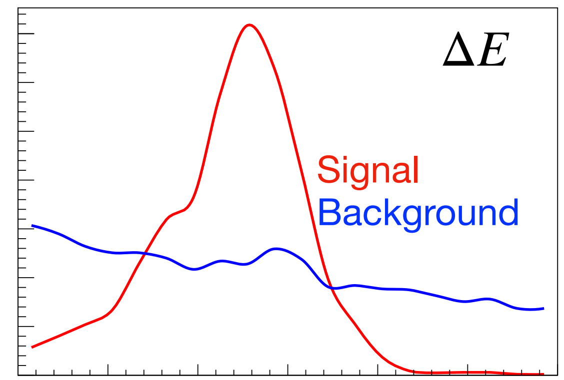
$B^+ \to \rho^+\rho^0$ challenges

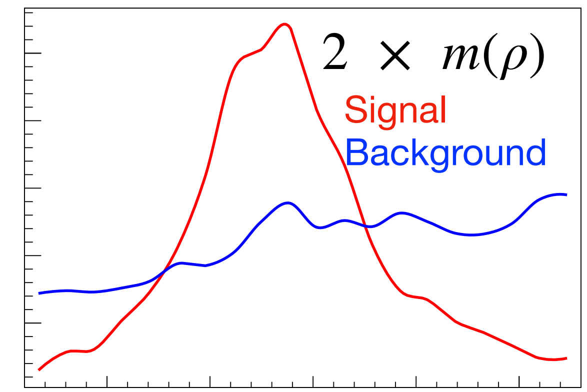
Pion-only final state $(\pi^+\pi^0)(\pi^+\pi^-)$ and broad ρ peak $\rightarrow$ large background.

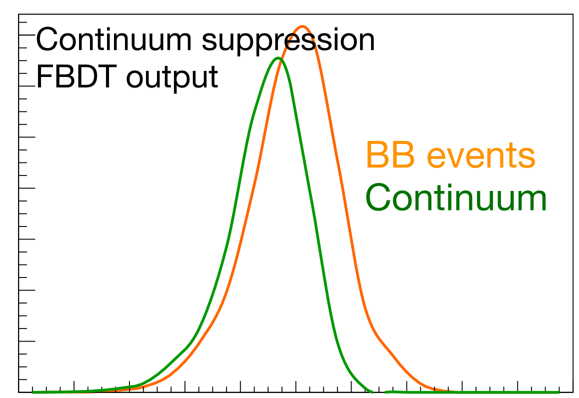
Intermediate ρ states have spin = 1 $\rightarrow$ need to fit also angular distributions to determine fraction of longitudinal polarization.

6D fit with multidimensional shapes to take correlations into account.

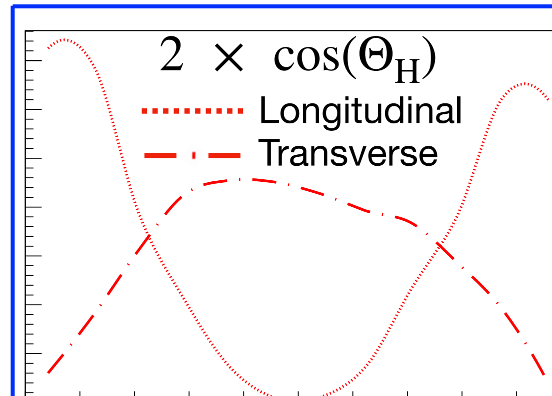
Shapes calibrated using BtoCharm control mode.







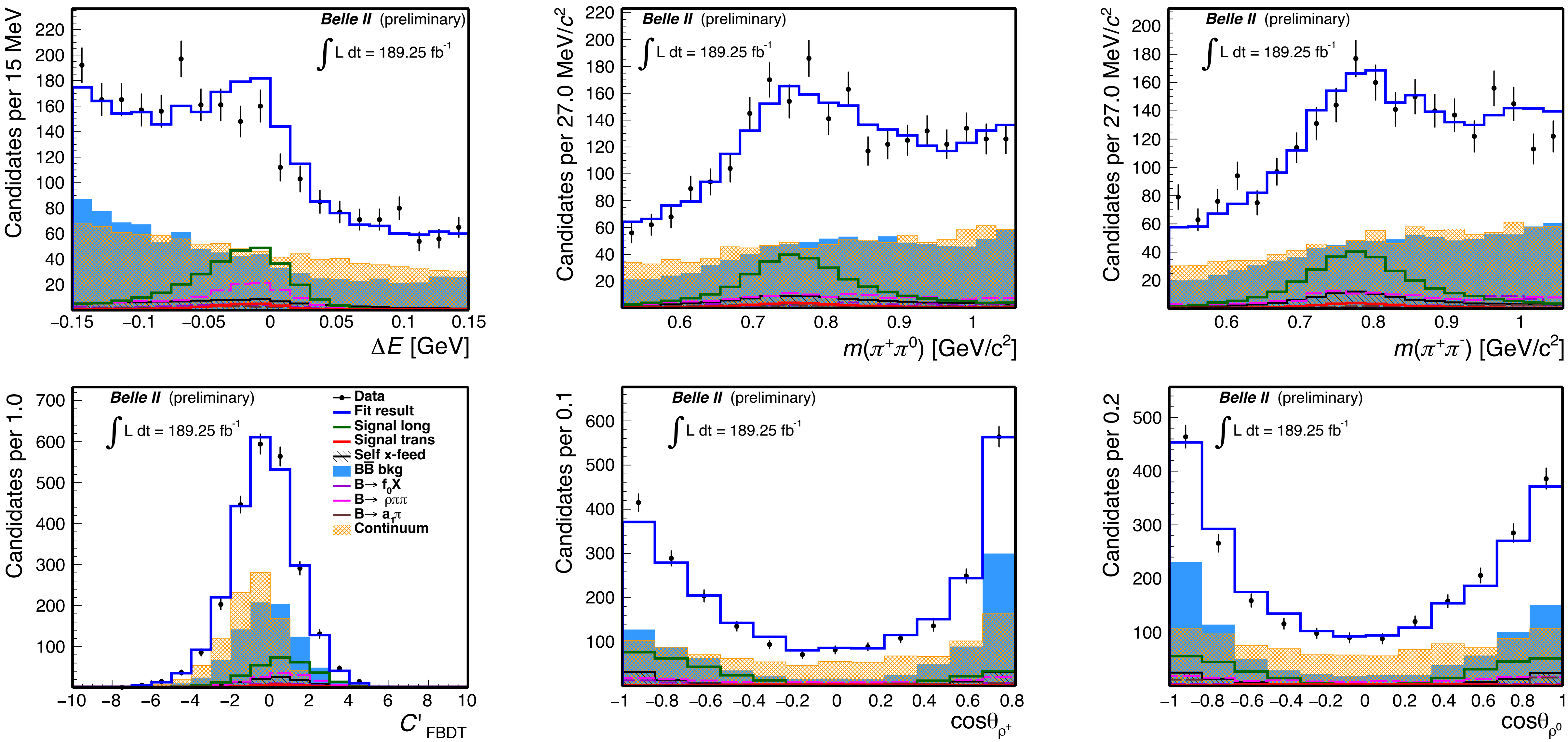
Separate signal from backgrounds



Distinguish the two signal polarizations

A_{CP} is corrected for instrumental asymmetries (use $D^+ \to K_S^0\pi^+$).

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



$\mathscr{B} = [23.2^{+2.2}_{-2.1}(\mathrm{stat}) \pm 2.7(\mathrm{syst})] \times 10^{-6}$

$A_{\mathrm{CP}} = -0.069 \pm 0.068(\mathrm{stat}) \pm 0.060(\mathrm{syst})$

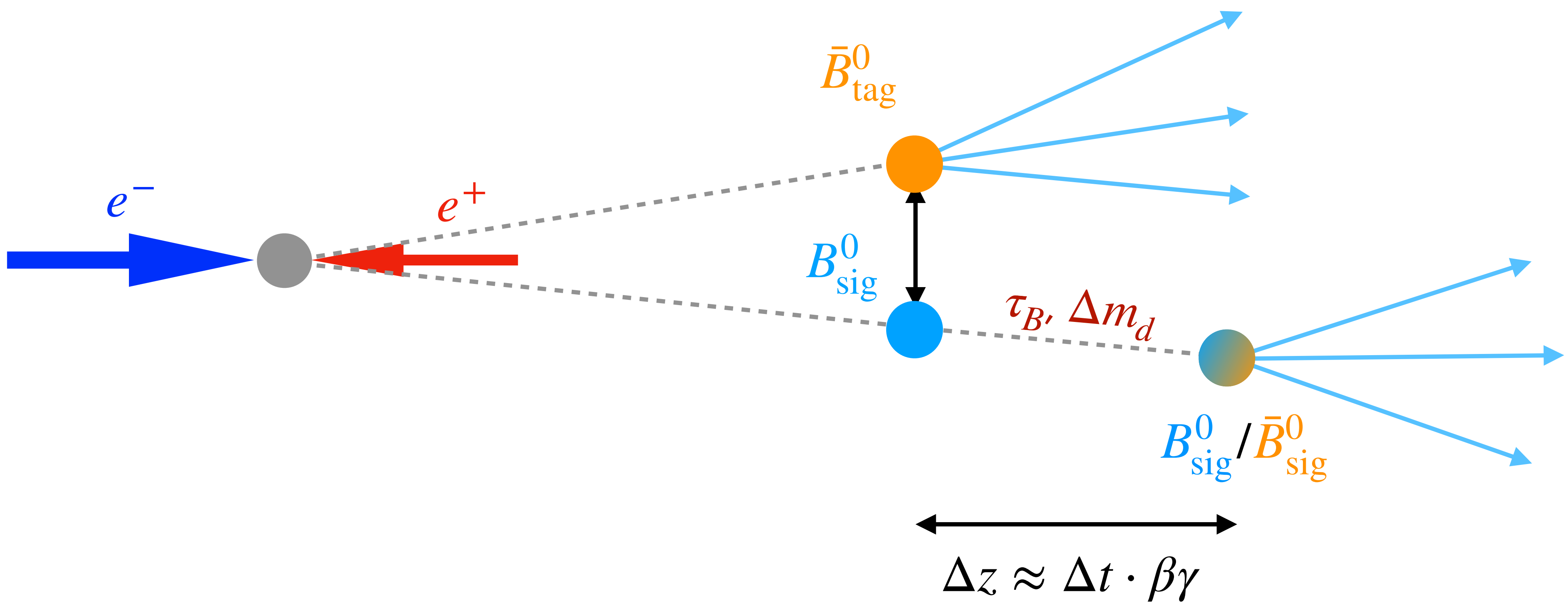
$\mathrm{f_L} = 0.943^{+0.035}_{-0.033}(\mathrm{stat}) \pm 0.027(\mathrm{syst})$

First $A_{\mathrm{CP}}(B^+ \to \rho^+\rho^0)$ measurement in Belle II data.

B^0 lifetime and $B^0 - \bar{B}^0$ mixing

Analyses of time evolution

Lifetime (τ_B) and oscillation frequency (Δm_d) measurement: fundamental validation for time-dependent CP-violation analyses.



Must-have elements:

- good vertex resolution
- high tagging efficiency (flavour-tagger)

Belle II

$$\varepsilon_{\text{tag}} = (30.0 \pm 1.3)\,\%$$

Eur. Phys. J. C **82,** 283 (2022)

B^0 lifetime and $B^0 - \bar{B}^0$ mixing

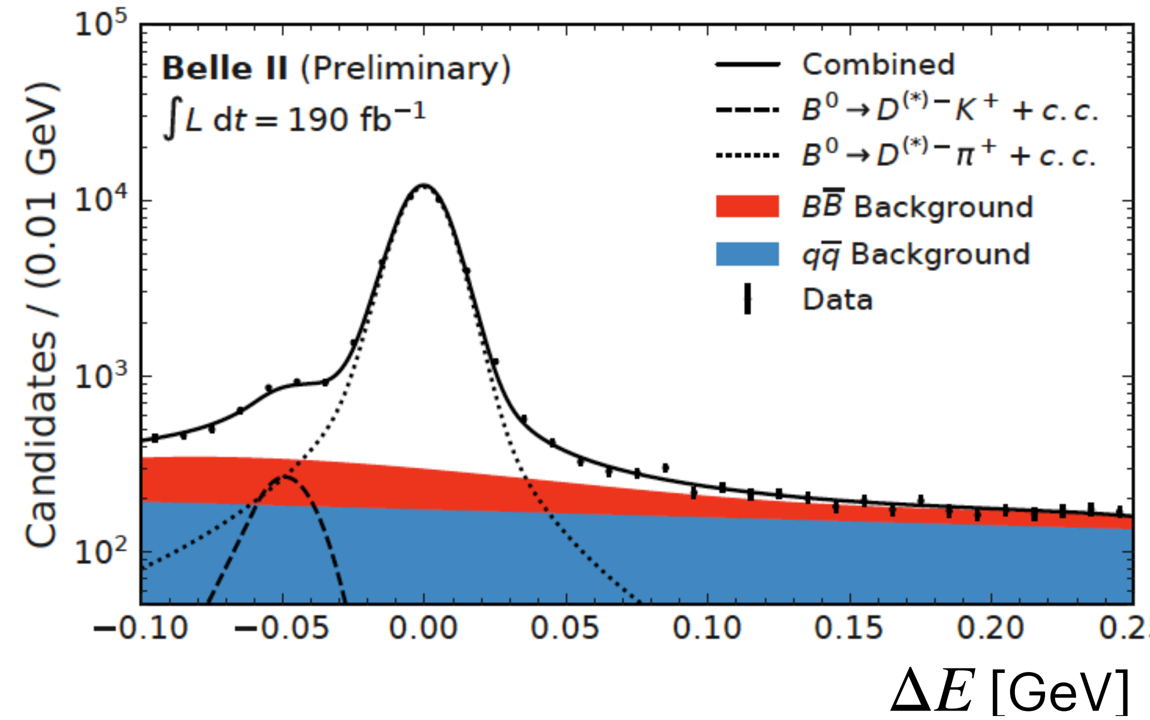
Use $B^0 \to D^{(*)-}\pi^+/K^+$ modes
(~40k total events).

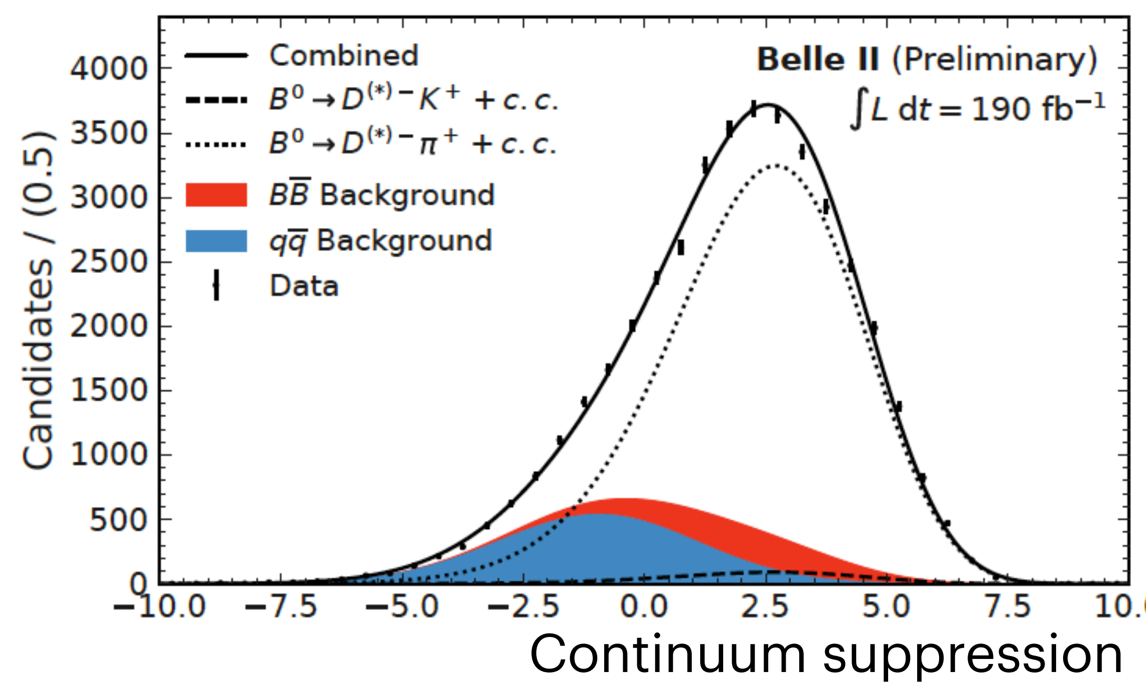
Strategy:

- 2D fit to ΔE and CS;
- subtract background (sWeights) to obtain background-free signal sample;
- fit background-subtracted Δt distribution.

Main challenge:

- complicated likelihood taking into account wrong-tag fraction, finite vertex resolution.

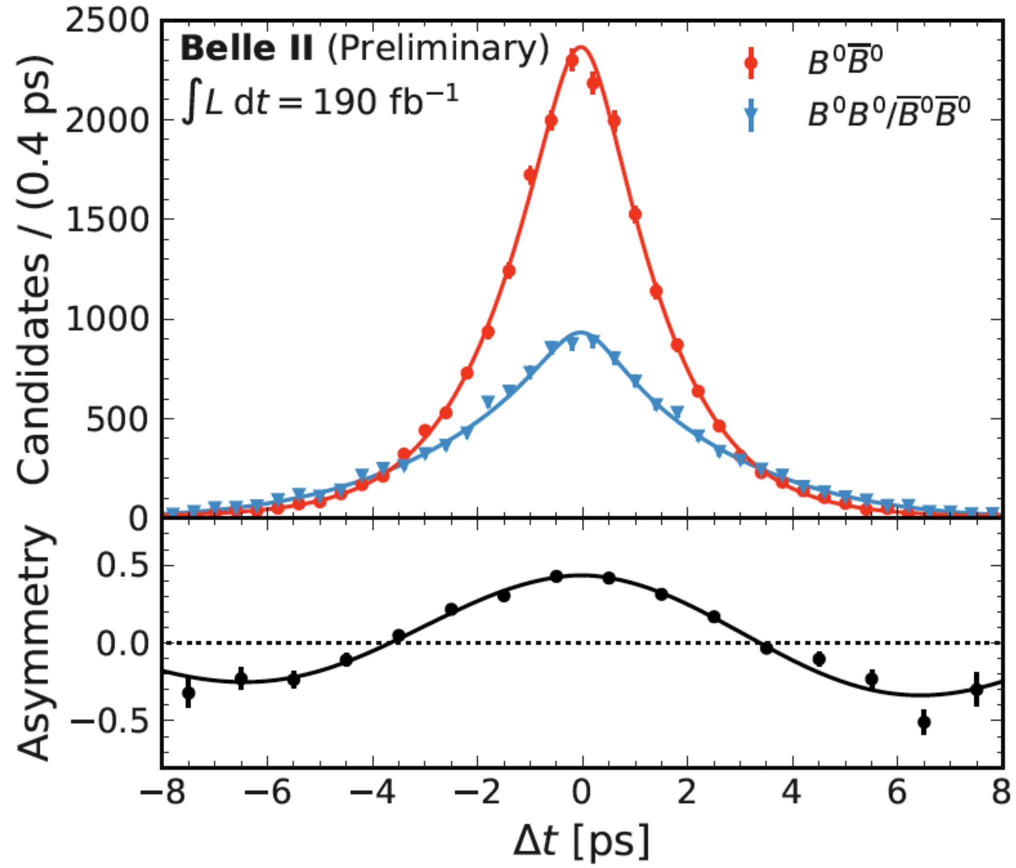




Lifetime and mixing results

$$\tau_{B^0} = 1.499 \pm 0.013(\text{stat}) \pm 0.008(\text{syst})\ \text{ps}$$

$$\Delta m_d = 0.516 \pm 0.008(\text{stat}) \pm 0.005(\text{syst})\ \text{ps}^{-1}$$



Not yet competitive with global best results, but systematic uncertainties already on par with best Belle/Babar results.

Milestone in Belle II program: we are fully ready for time-dependent analyses (e.g. sin2ß).

Next step: improve precision by using also $B^0 \to D^{*-} l^+ \nu$ modes.

Time evolution of $B^0 \to K_S^0 \pi^0$

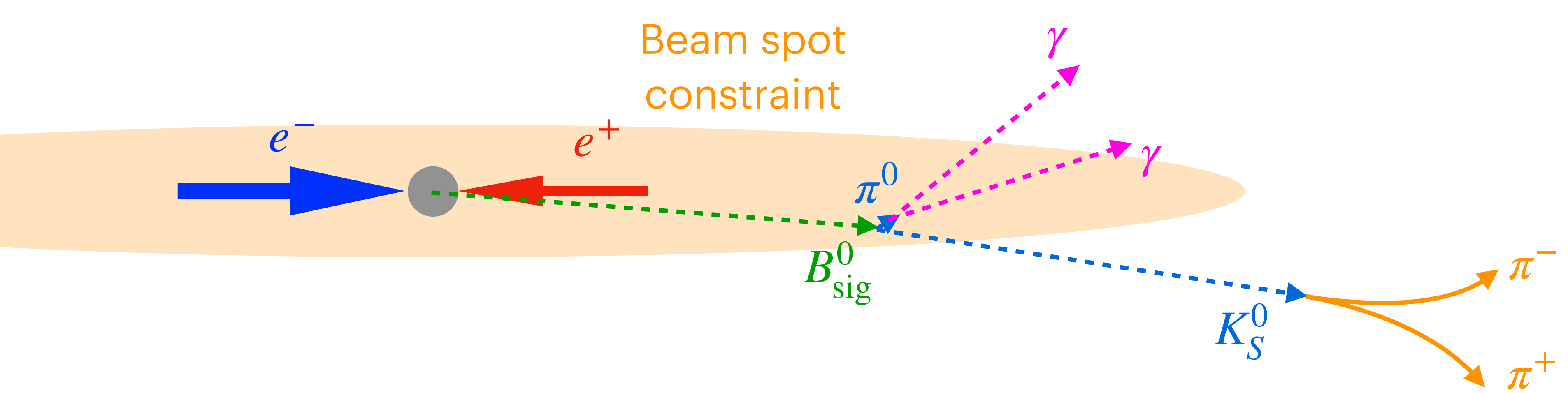
Isospin sum rule and $B^0 \to K_S^0 \pi^0$

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):

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

$$I_{K\pi} = A_{\mathrm{CP}}^{K^+\pi^-} + A_{\mathrm{CP}}^{K^0\pi^+} \frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)} \frac{\tau_{B^0}}{\tau_{B^+}} - 2A_{\mathrm{CP}}^{K^+\pi^0} \frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)} \frac{\tau_{B^0}}{\tau_{B^+}} - 2A_{\mathrm{CP}}^{K^0\pi^0} \frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)} \approx 0$$

Belle II: unique access to $B^0 \to K^0\pi^0$ (major limitation in $I_{K\pi}$). Need time-dependent A_{CP}.



Challenges:

Requires K_S^0 and π^0 reconstruction.

Vertexing with K_S^0 decay products only.

Strategy:

Perform 4D fit (ΔE, M_{bc}, Δt, and CS).

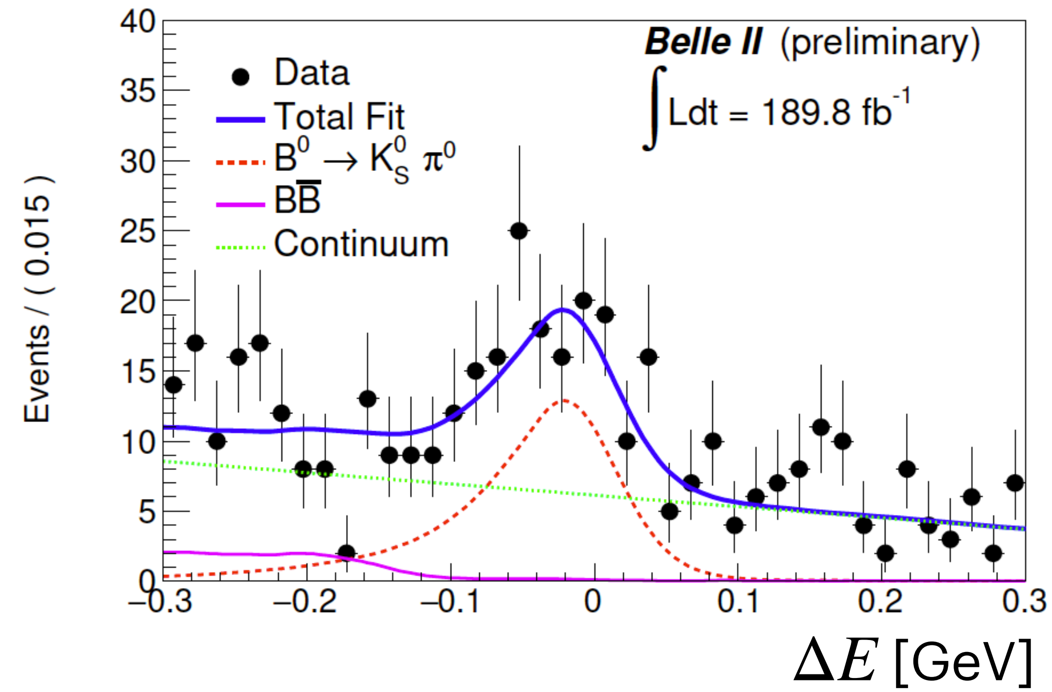
Use $B^0 \to J/\psi K_S^0$ to calibrate Δt shapes.

Constrain $\tau_{B_{\mathrm{sig}}}$, Δm_d, and S_{CP} from WA.

$B^0 \to K_S^0 \pi^0$ results

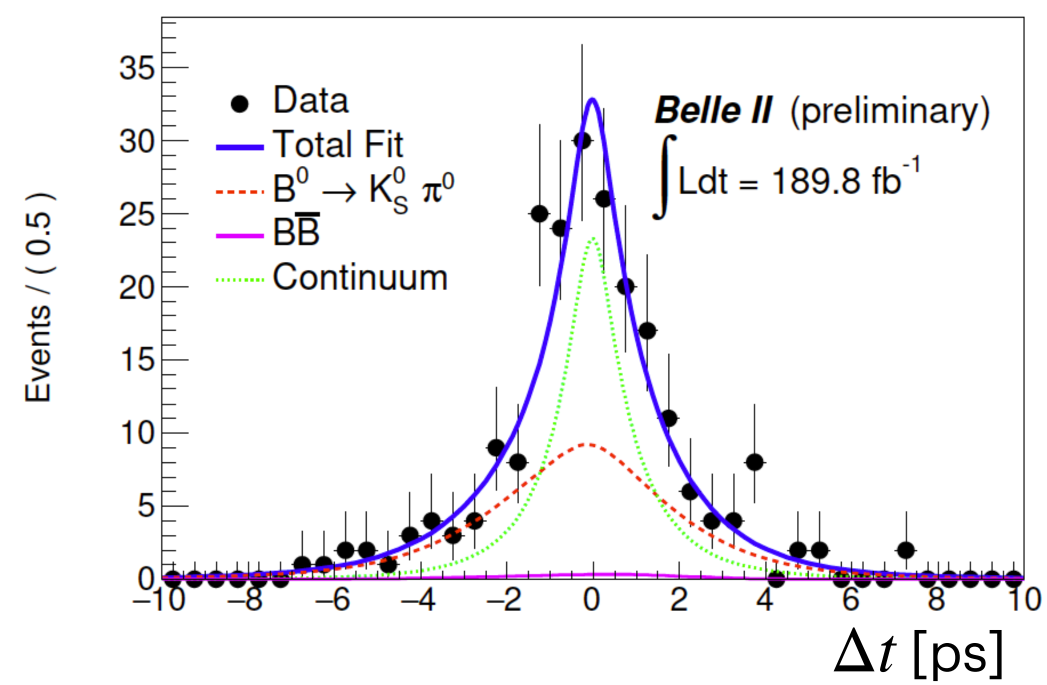
$$\mathcal{B}(B^0 \to K^0\pi^0) = [11.0 \pm 1.2(\text{stat}) \pm 1.0(\text{syst})] \times 10^{-6}$$

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

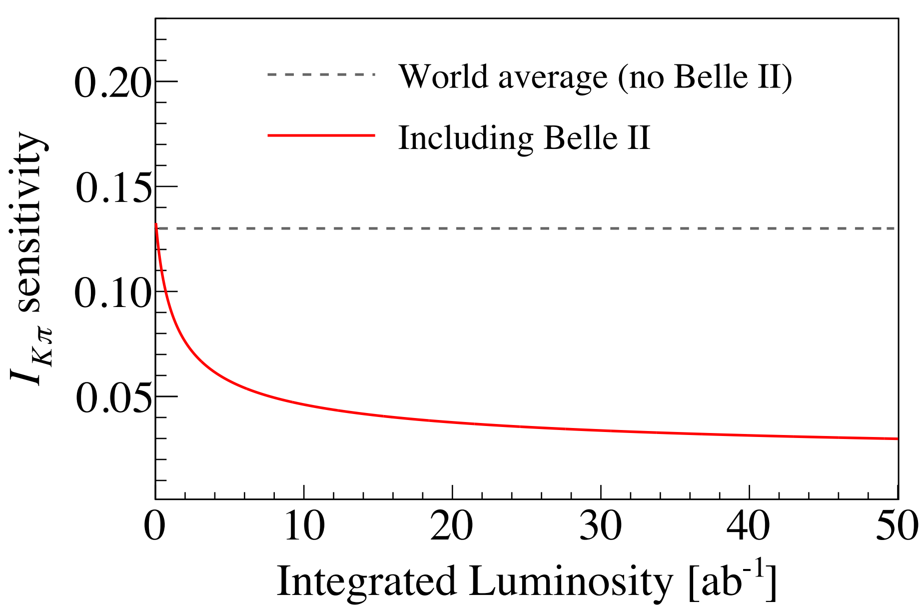


Extrapolate uncertainty on $I_{K\pi}$ (capability of measuring a deviation from its SM value) using also LHCb prospects:

dominant uncertainty coming from $A_{K^0\pi^0}$.



N($B^0 \to K_S^0\pi^0$): $135\ ^{+16}_{-15}$



Fundamental role of Belle II in improvement of precision.

Summary

Hadronic decays important element in Belle II *B* physics program.

- Most precise CKM γ determination from *B*-factories (combine Belle and Belle II data to be impactful with early data).

- Angular *CP*-violation analysis with $B^+ \to \rho^+\rho^0$: key element in $B \to \rho\rho$ analysis.

- Precision lifetime and B^0 oscillation frequency measurement, important validation for time-dependent analyses.

- Time-dependent $B^0 \to K_S^0\pi^0$: unique to Belle II (multiple neutrals).

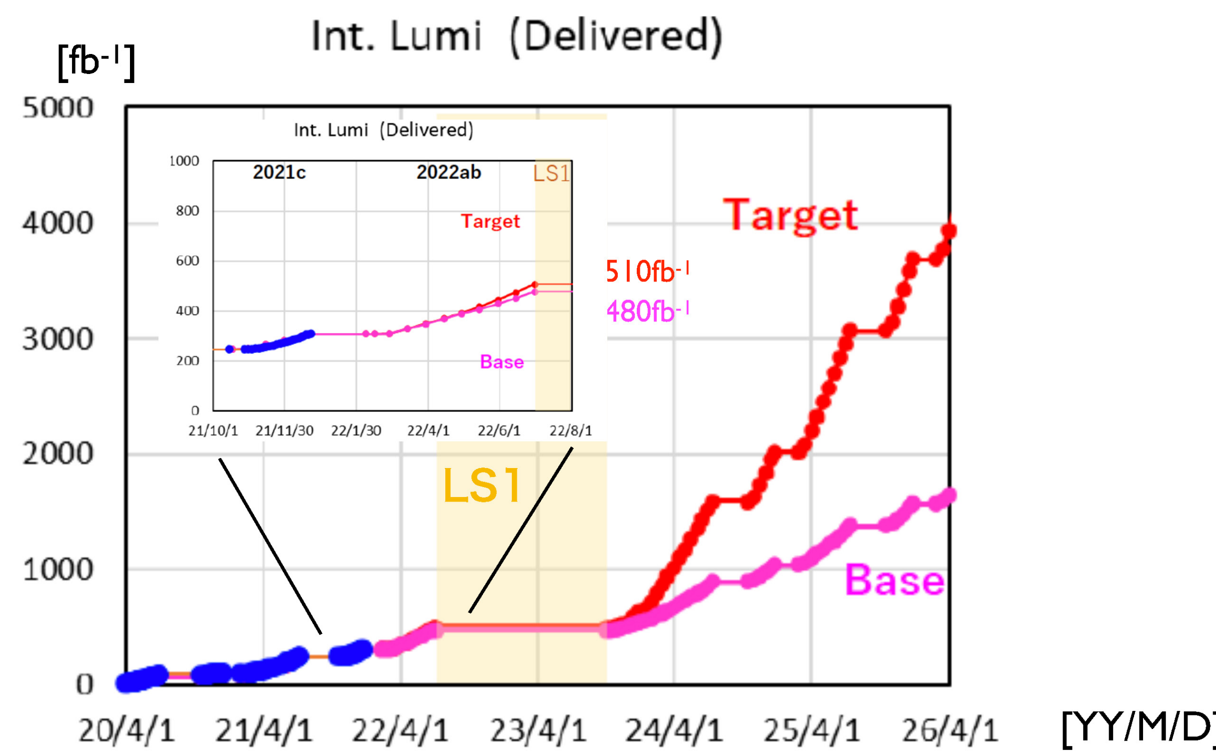
Competitive physics results even with initial data sets

Backup

Projections of integrated luminosity delivered by SuperKEKB to Belle II

Target scenario: extrapolation from 2021 run including expected improvements.

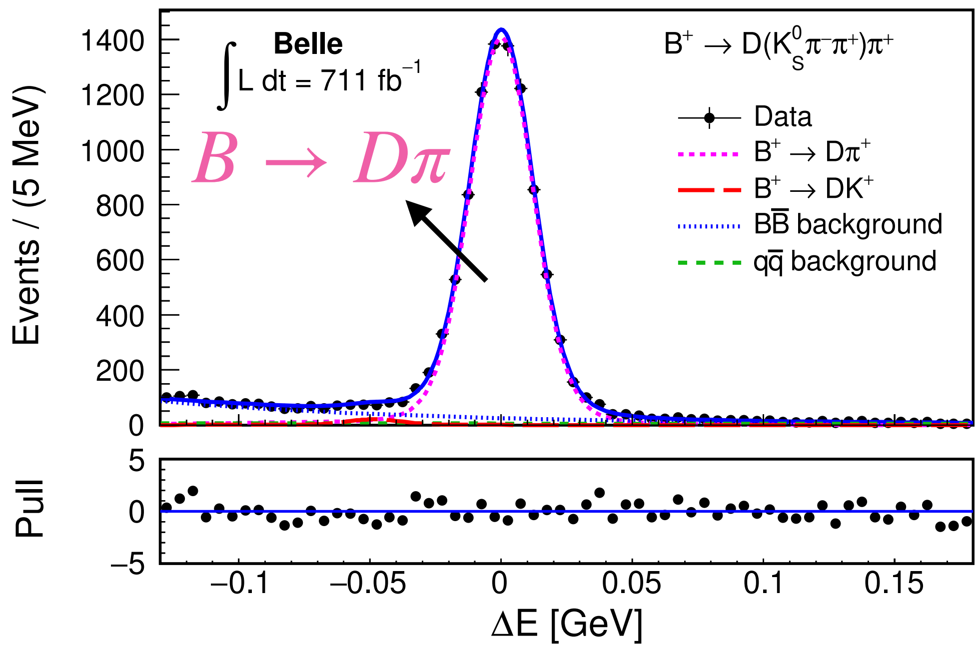
Base scenario: conservative extrapolation of SuperKEKB parameters from 2021 run.

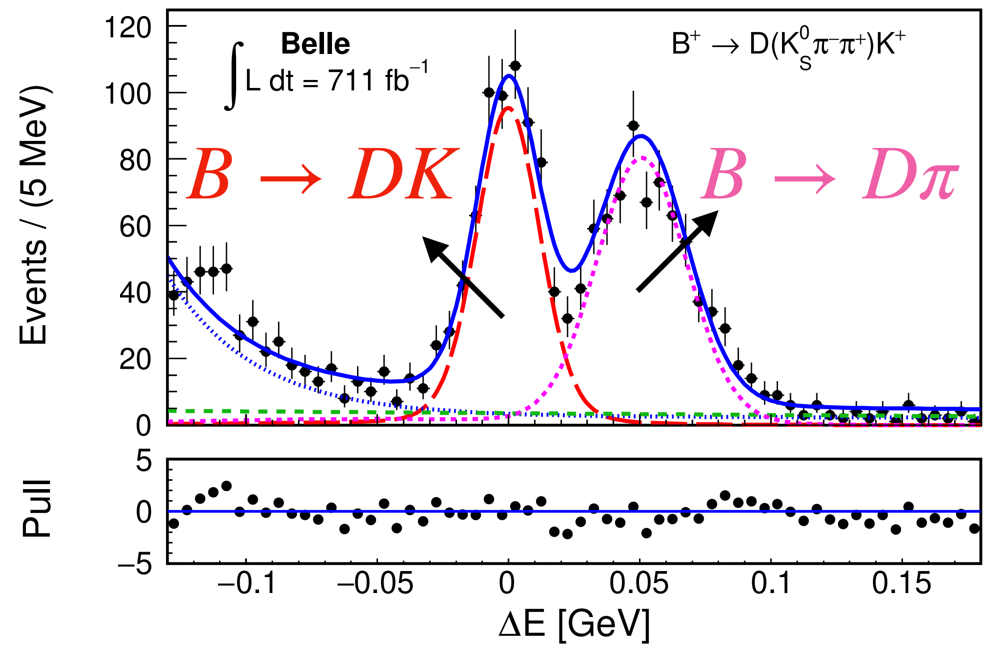


- We start long shutdown I (LS I) from summer 2022 for 15 months to replace VXD. There will be other maintenance/improvements works of machine and detector.
- We resume physics running from Fall 2023.
- A SuperKEKB International Taskforce (aiming to conclude in summer 2022) is discussing additional improvements.
- An LS2 for machine improvements could happen on the time frame of 2026-2027.

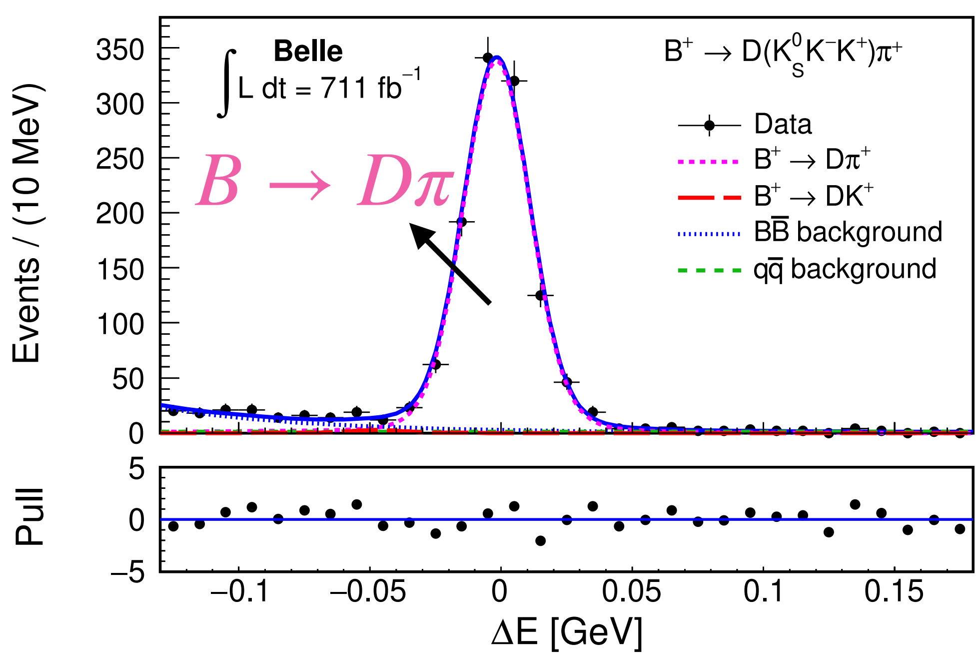
Fit of Belle data

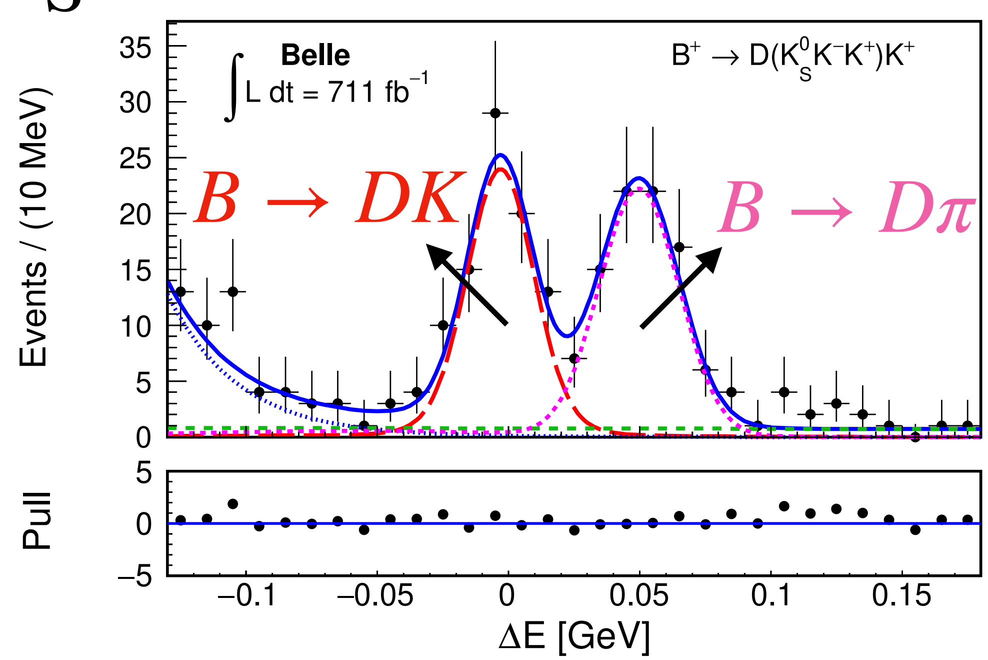
$D^0 \to K_S^0 \pi^+ \pi^-$





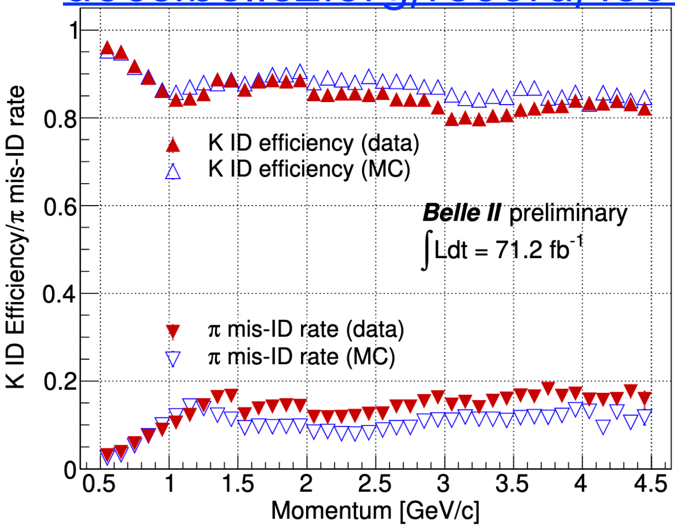
$D^0 \to K_S^0 K^+ K^-$





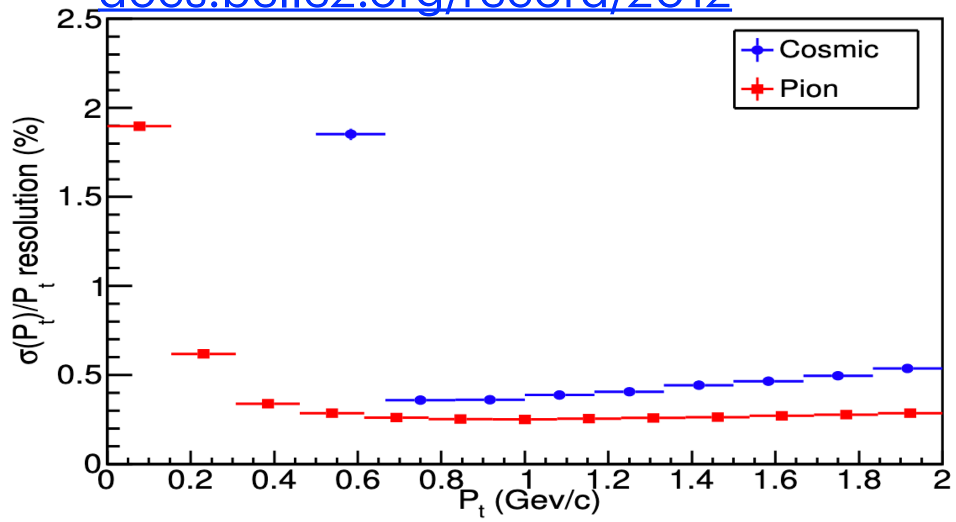
Performance overview

docs.belle2.org/record/1558



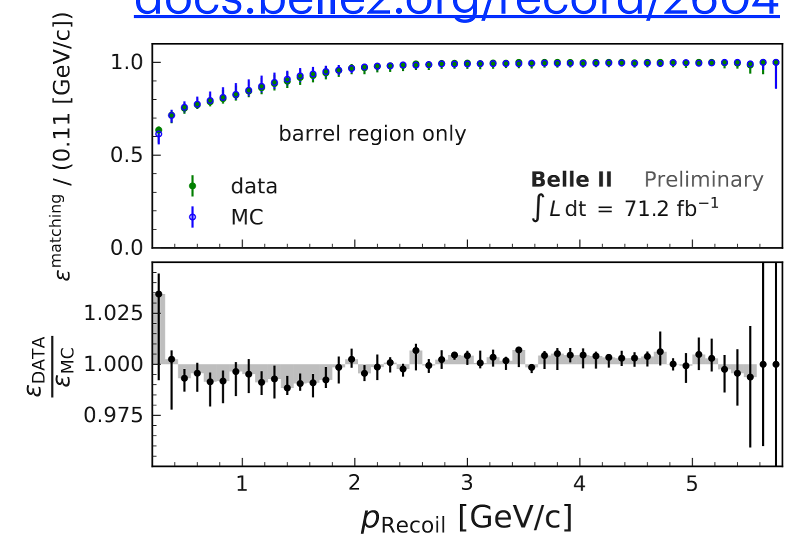
Strong charged particle identification.

docs.belle2.org/record/2012



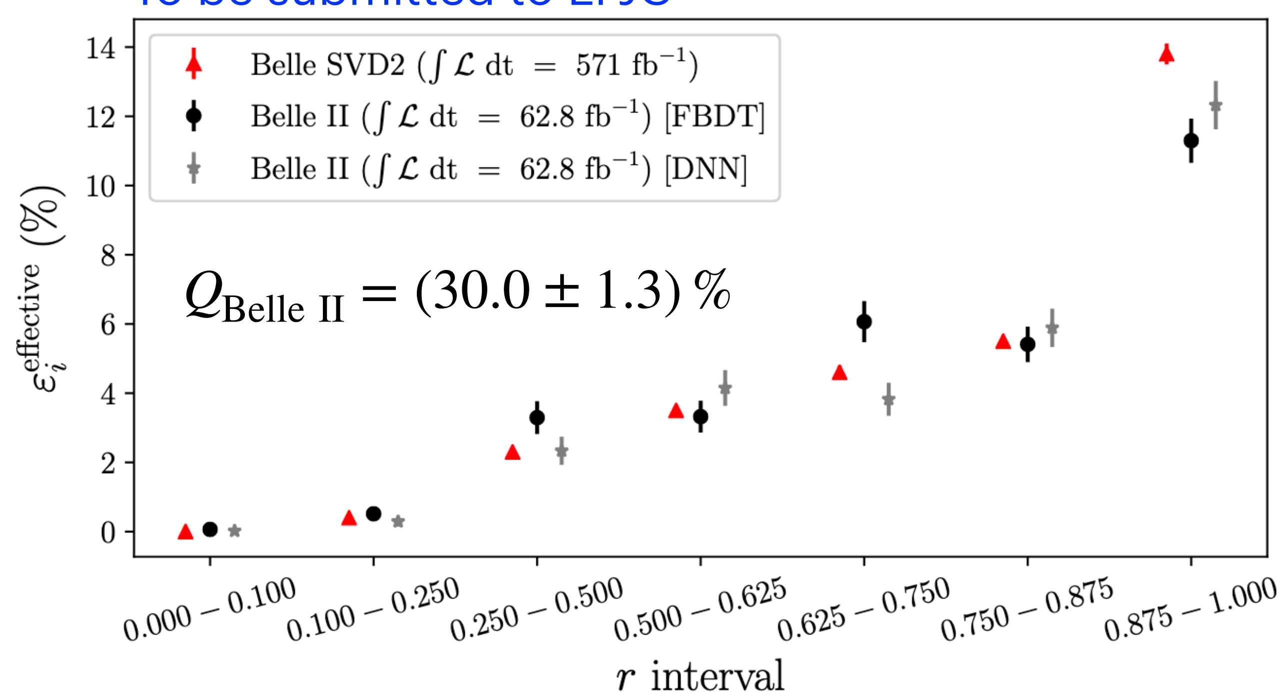
Good momentum resolution.

docs.belle2.org/record/2604



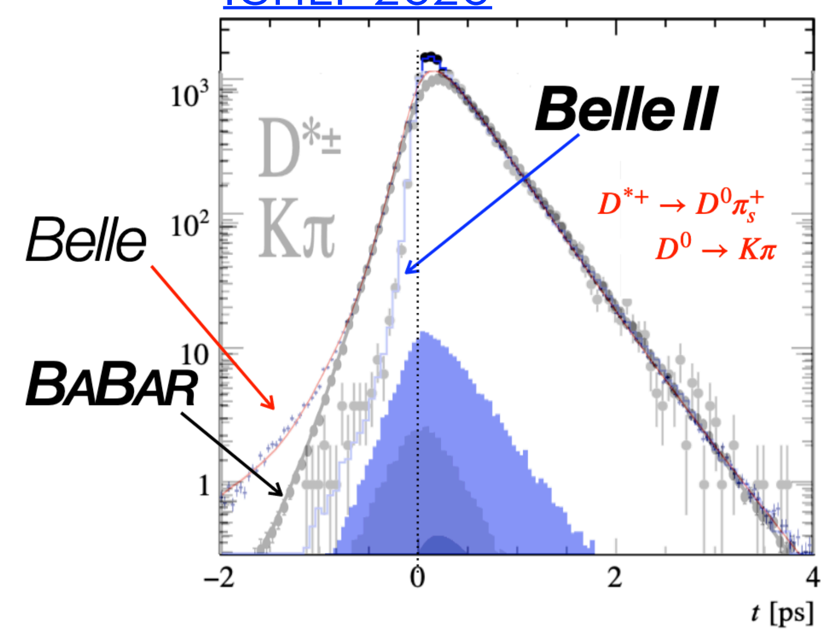
High ɣ efficiency.

To be submitted to EPJC



Flavor tagging efficiency comparable to Belle.

ICHEP 2020



Greatly improved time resolution compared to previous *B*-factories.