Charmless *B* decays at Belle II

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

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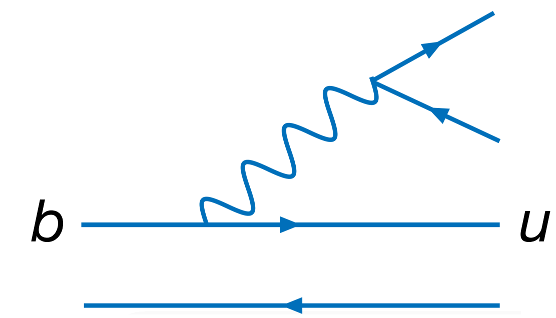
Flavor physics and charmless B decays

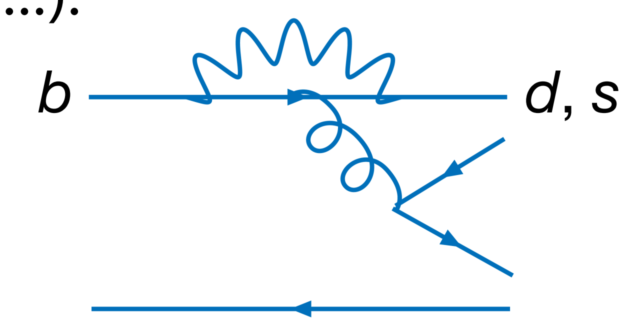
Standard Model: $\mathcal{O}(1000)$ predictions from eV to TeV with only 20 parameters, but still incomplete (dark matter, matter-antimatter asymmetry, ...)

Flavor physics: fundamental to test SM and its extensions.



Charmless hadronic *B* decays: decays not mediated by $b \to c$.

Cabibbo-suppressed $\boldsymbol{b \to u}$ trees and $\boldsymbol{b \to d, s}$ penguins ($B \to K\pi, B \to \rho\rho$...).



→ Highly sensitive to non-SM loops.

→ Probe non-SM dynamics in all three CKM angles.

Pheno challenges: predictions limited by complicated calculations of non-perturbative QCD.

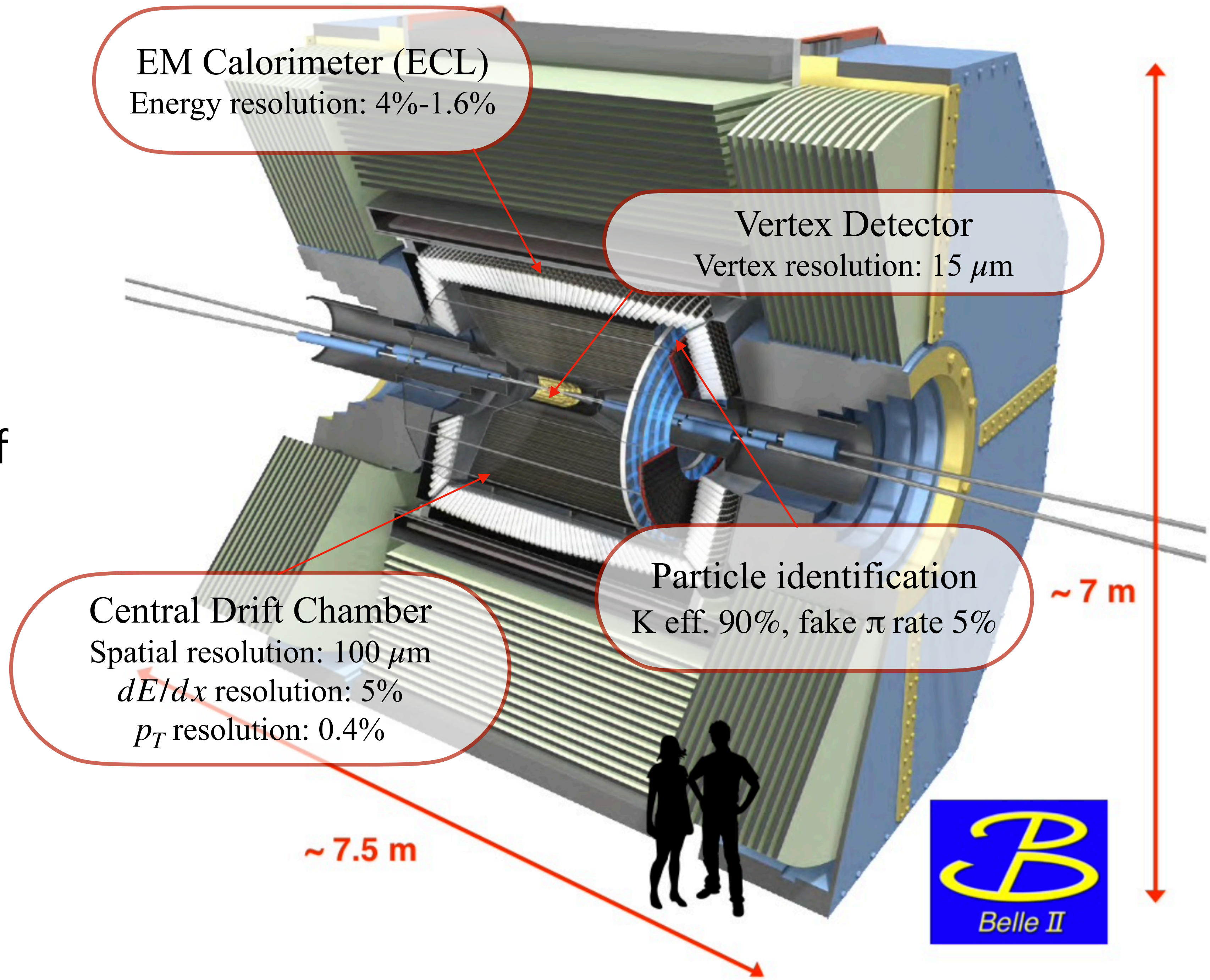
Exp. challenges: rare, *BF*~O(10^{-5}), signal-like bckg from $e^+e^- \to q\bar{q}$ continuum.

Belle II charmless B program

- Test SM using isospin sum rules;
- Investigate localized CP asymmetries in Dalitz plot of three-body decays;
- Improve precision on $\alpha/\phi_2 = arg\left[-V_{td}V^*_{tb}/V_{ud}V^*_{ub}\right]$ angle.

The Belle II detector

- SuperKEKB: 7-on-4 e^+e^- collider at 10.58 GeV;
- Aim at 700 $B\bar{B}$ pairs/second in low-bkg environment;
- 140 fb^{-1} (140x10^6 $B\bar{B}$ pairs) of data collected;
- World record peak luminosity: 2.8x10^{34} cm^{-2} s^{-1}
- Unique reach on final states with multiple neutrinos and π^0/photons.



Key role in charmless decays: unified and consistent approach to all final states.

Today: results on 65 fb^{-1}.

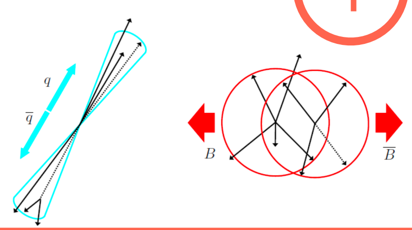
In-depth validation of detector early operation and analysis tools.

Analysis overview

Goal: blind measurements of branching fractions, *CP* asymmetries and polarizations.

Selection (1)

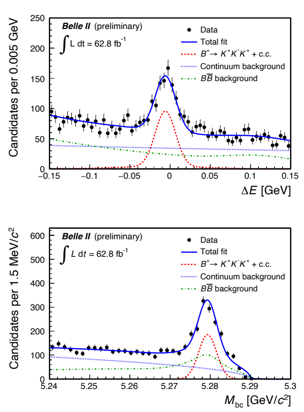
Continuum suppression, optimize on simulation and data.



Efficiencies and corrections (2)

Efficiencies from simulation, validated on data. Instrumental asymmetries from data.

Signal extraction (3)



$$\Delta E = E_B^* - E_{\text{beam}}^*, \; M_{\text{bc}} = \sqrt{E_{\text{beam}}^{*\,2} - p_B^{*2}}$$

Models from simulation, adjusted on control modes. Use flavour tagging in $B^0 \to$ neutrals modes (2008.02707).

Combine yields, efficiencies and instrumental asymmetries to extract final results. (4)

Systematic uncertainties (5)

Toy studies or control modes in data.

Validation (6)

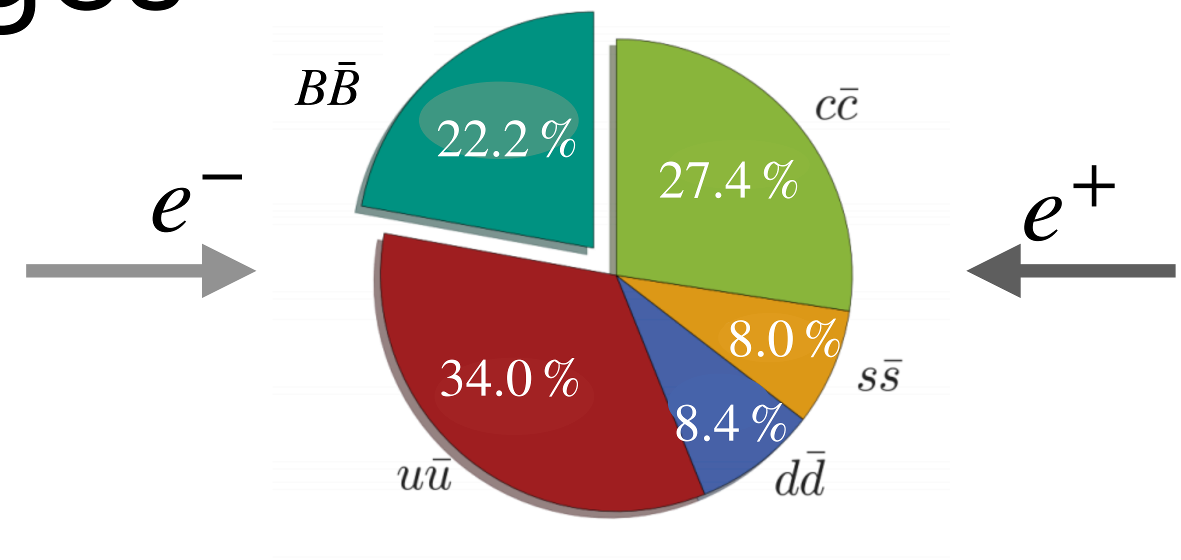
Validation of the full analysis on more abundant control modes on signal data.

Unblinding (7)

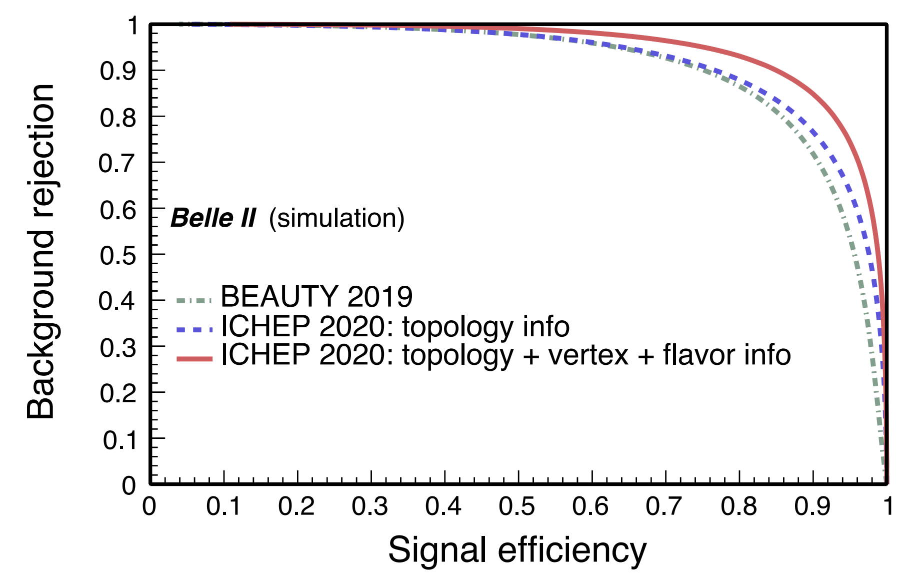
Apply full analysis to data.

All results compatible with known values within ~6% to ~25% precision, dominated by statistical component.

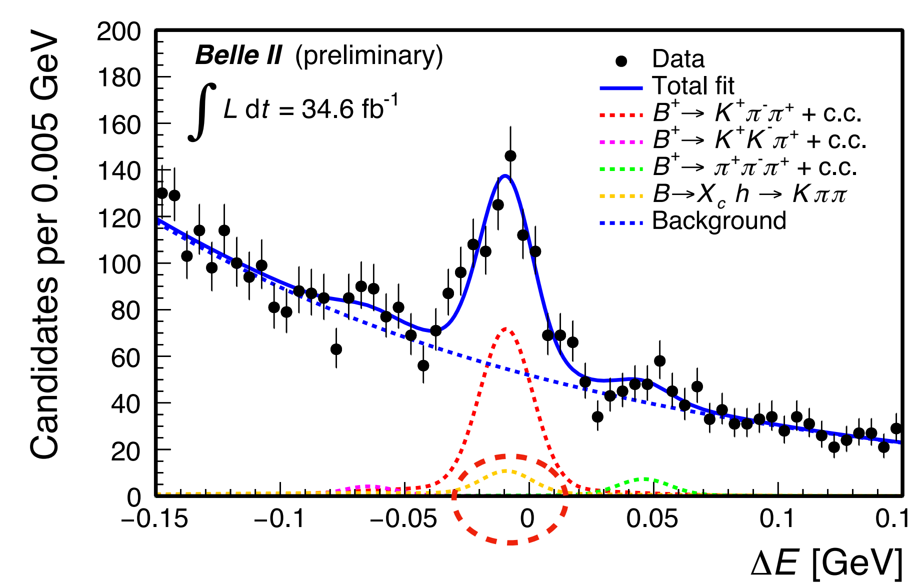
Challenges



Suppress 10^5 larger background, mainly $e^+e^- \to q\bar{q}$ (continuum): combine 40 kinematic, decay-time and topological variables in multivariate techniques.
$q\bar{q}$ background rejection: ~99 %



Peaking backgrounds: in multibody decays, study vetoes from simulation to exclude them and add fit components to account for survivors.

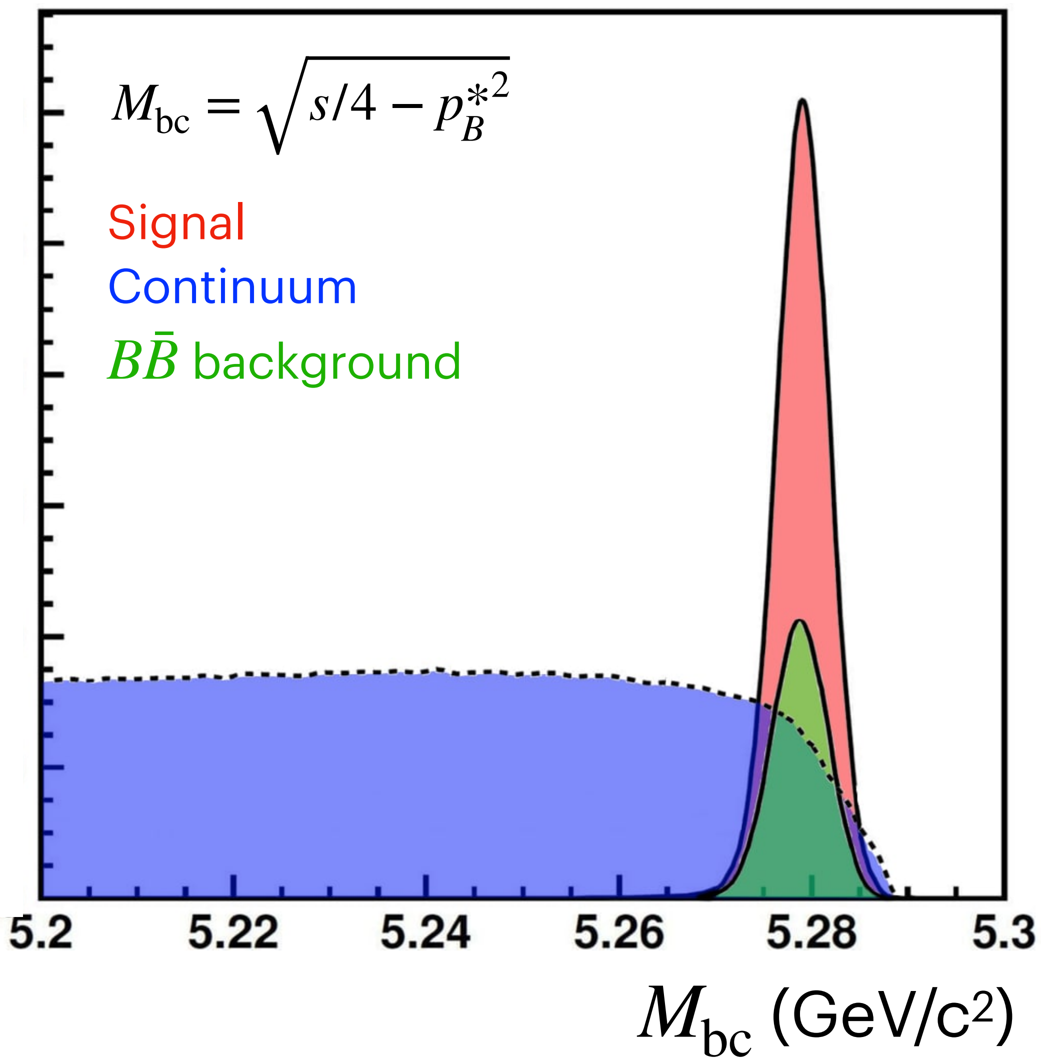


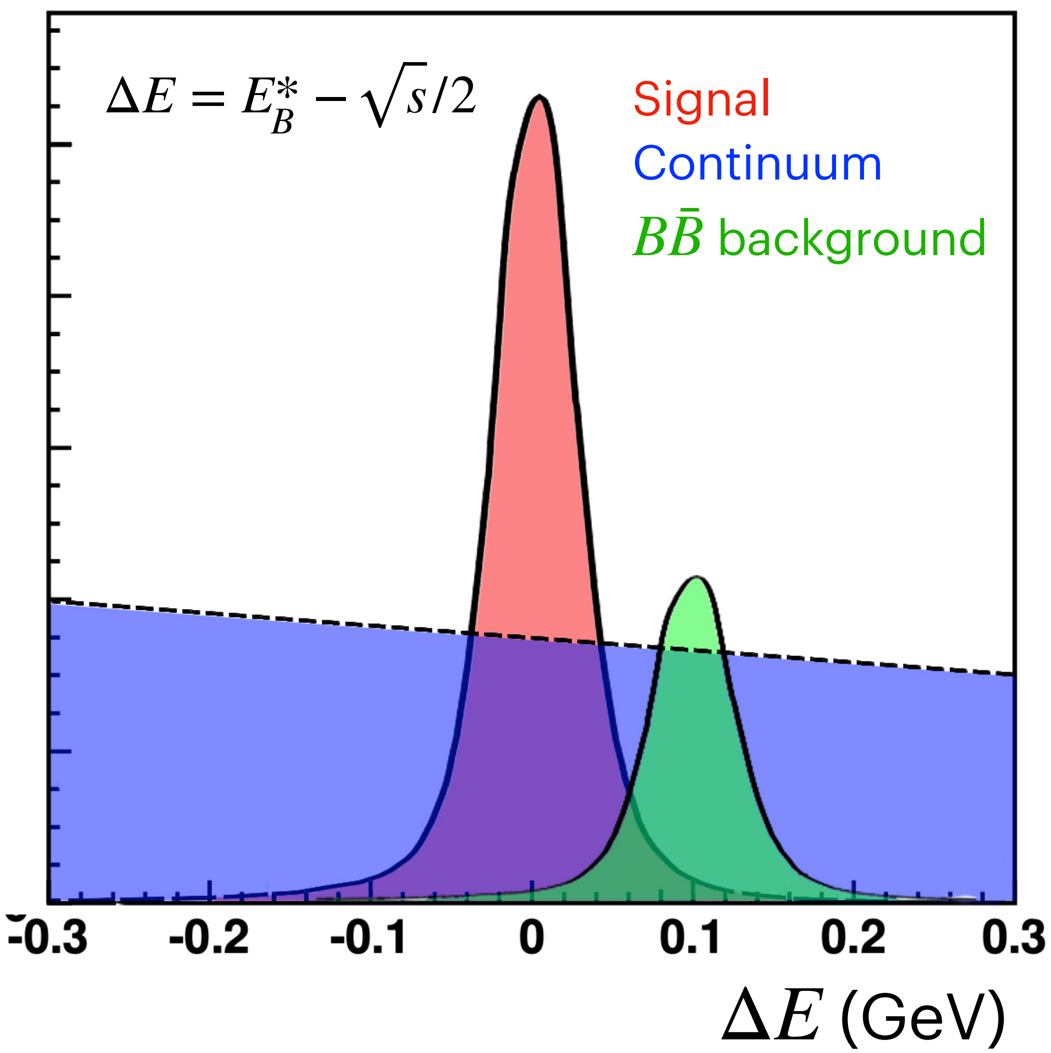
Fit variables

Extract signal by fitting simultaneously ΔE and $M_{\rm bc}$.

B invariant mass with reconstructed B energy replaced by half of the CMS energy.

Difference between the reconstructed B energy and half of the CMS energy.





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

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

Isospin sum rule

Stringent null test of SM, sensitive to presence of non-SM dynamics.

Inconsistency between current measurements: "$K\pi$ puzzle". [Gronau (Phys. Lett. B 627 (2005) no.1, 82-88)](#)

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

Belle II: unique access to $K^0\pi^0$ (major limitation in $I_{K\pi}$ determination).

$$\mathscr{B}(B^0 \to K^+\pi^-) = [18.0 \pm 0.9(\text{stat}) \pm 0.9(\text{syst})] \times 10^{-6}$$

$$A_{CP}(B^0 \to K^+\pi^-) = -0.16 \pm 0.05(\text{stat}) \pm 0.01(\text{syst})$$

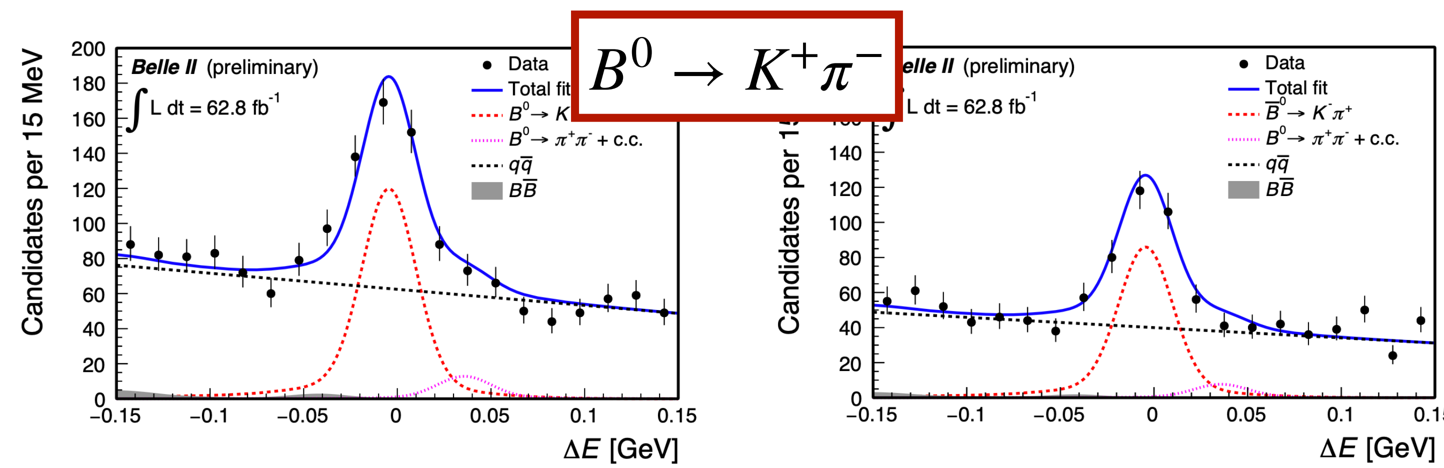
$$\mathscr{B}(B^+ \to K^0\pi^+) = [21.4^{+2.3}_{-2.2}(\text{stat}) \pm 1.6(\text{syst})] \times 10^{-6}$$

$$A_{CP}(B^+ \to K^0\pi^+) = -0.01 \pm 0.08(\text{stat}) \pm 0.05(\text{syst})$$

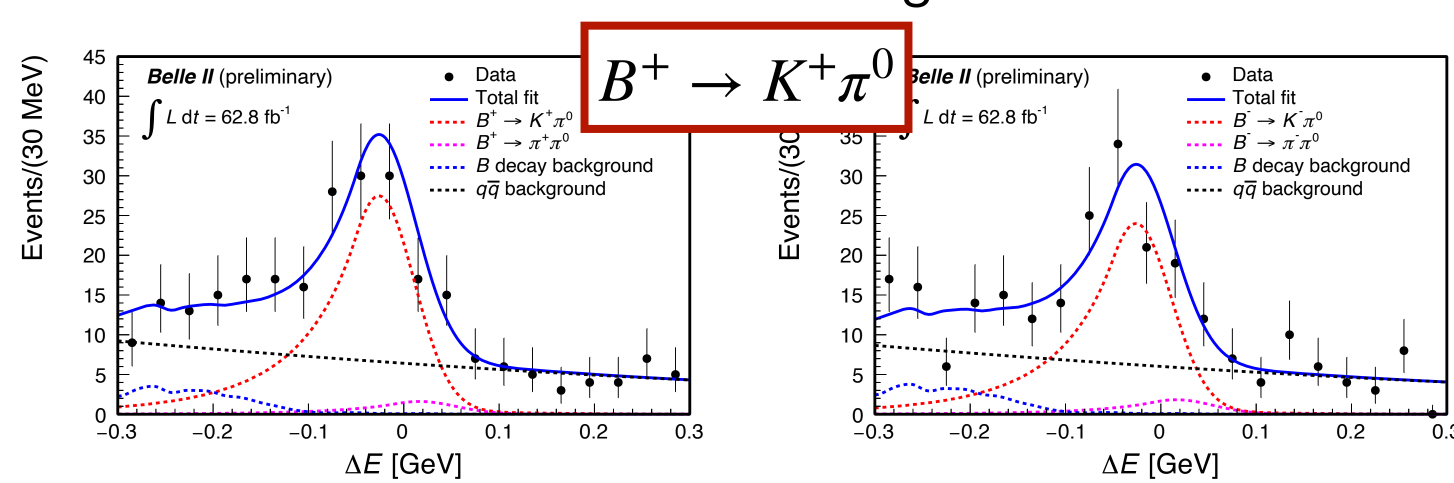
$$\mathscr{B}(B^+ \to K^+\pi^0) = [11.9^{+1.1}_{-1.0}(\text{stat}) \pm 1.6(\text{syst})] \times 10^{-6}$$

$$A_{CP}(B^+ \to K^+\pi^0) = -0.09 \pm 0.09(\text{stat}) \pm 0.03(\text{syst})$$

https://arxiv.org/abs/2105.04111



Probes tracking.



Probes π^0 reconstruction.

Belle II: the only experiment that accesses all channels

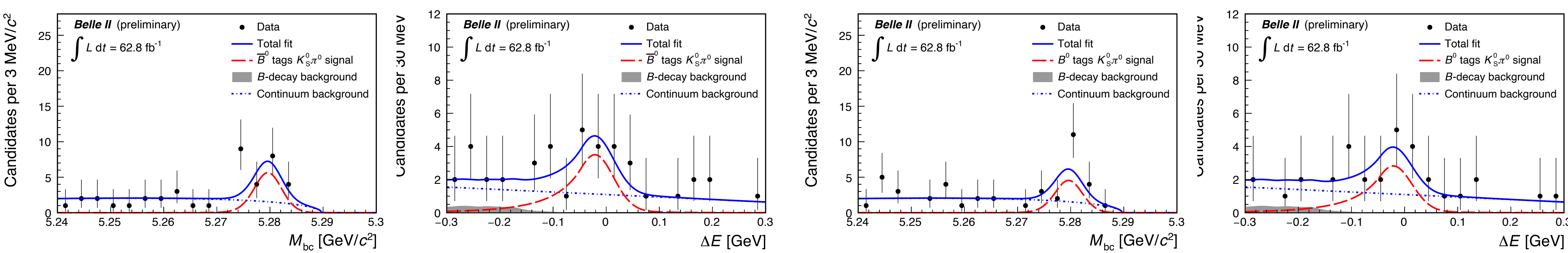
Isospin sum rule: $K^0\pi^0$

$\mathscr{B}$: challenging as it requires K_S^0 and π^0 reconstruction.

$\mathscr{A}_{CP}$: requires flavor tagging (Chiara's talk). Fit of ΔE-M_{bc}-flavor of the B meson (q), simultaneously in 7 ranges of wrong-tag fraction (output from flavor tagger).

$$P_{\text{sig}}(q) = \frac{1}{2}\left(1 + q \cdot (1 - 2w_r) \cdot (1 - 2\chi_d) \cdot \mathscr{A}_{\text{CP}}(K^0\pi^0)\right)$$

$\overline{B}^0$ tags | B^0 tags



N($B^0 \to K_S^0\pi^0$): 45 $^{+9}_{-8}$

$\mathscr{B}(B^0 \to K^0\pi^0) = [8.5^{+1.7}_{-1.6}(\text{stat}) \pm 1.2(\text{syst})] \times 10^{-6}$

$A_{CP}(B^0 \to K^0\pi^0) = -0.40^{+0.46}_{-0.44}(\text{stat}) \pm 0.04(\text{syst})$

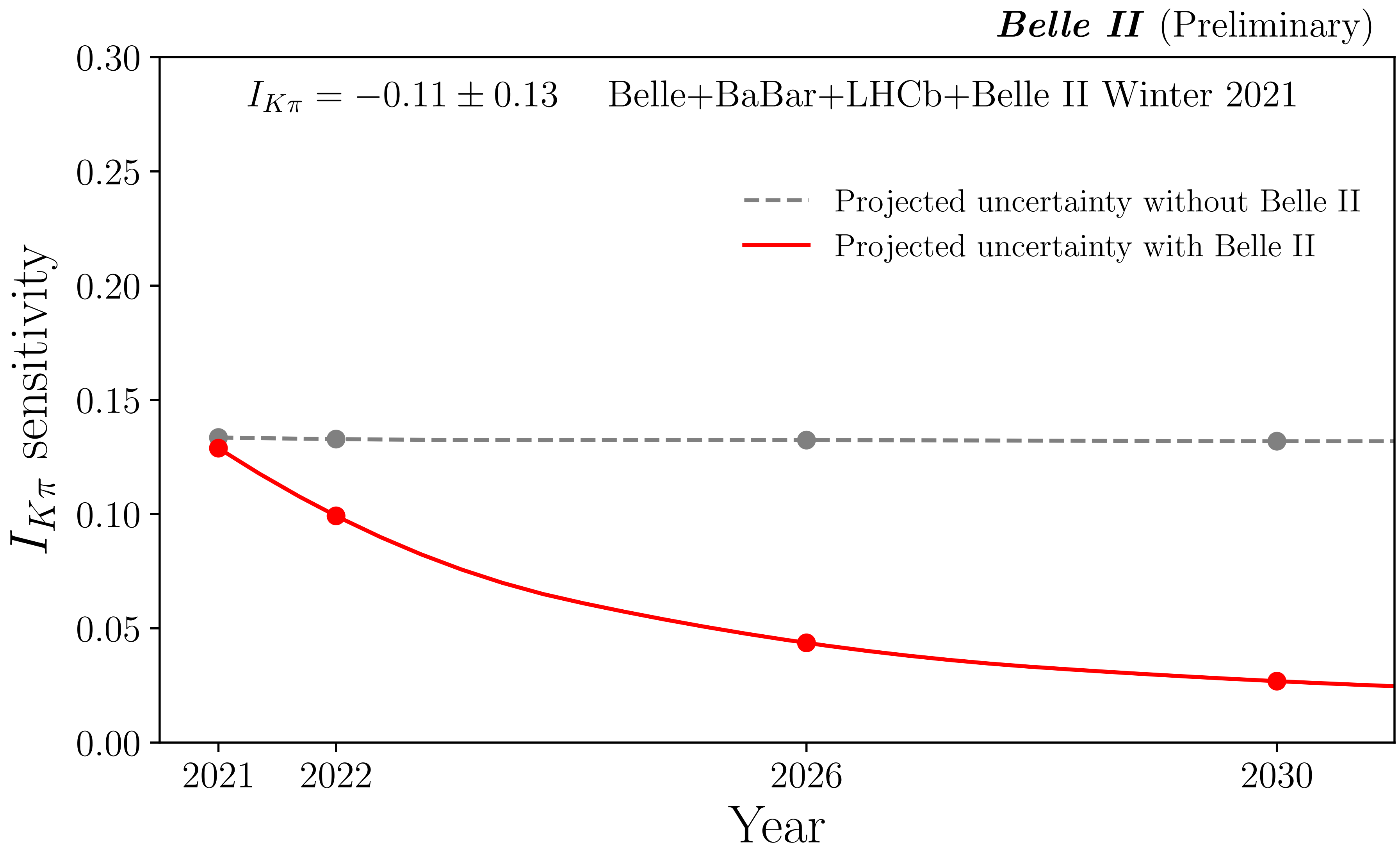
https://arxiv.org/abs/2104.14871

First measurement in Belle II data!

Isospin sum rule

Extrapolate the uncertainty on $I_{K\pi}$ (capability of measuring a deviation from its SM value).

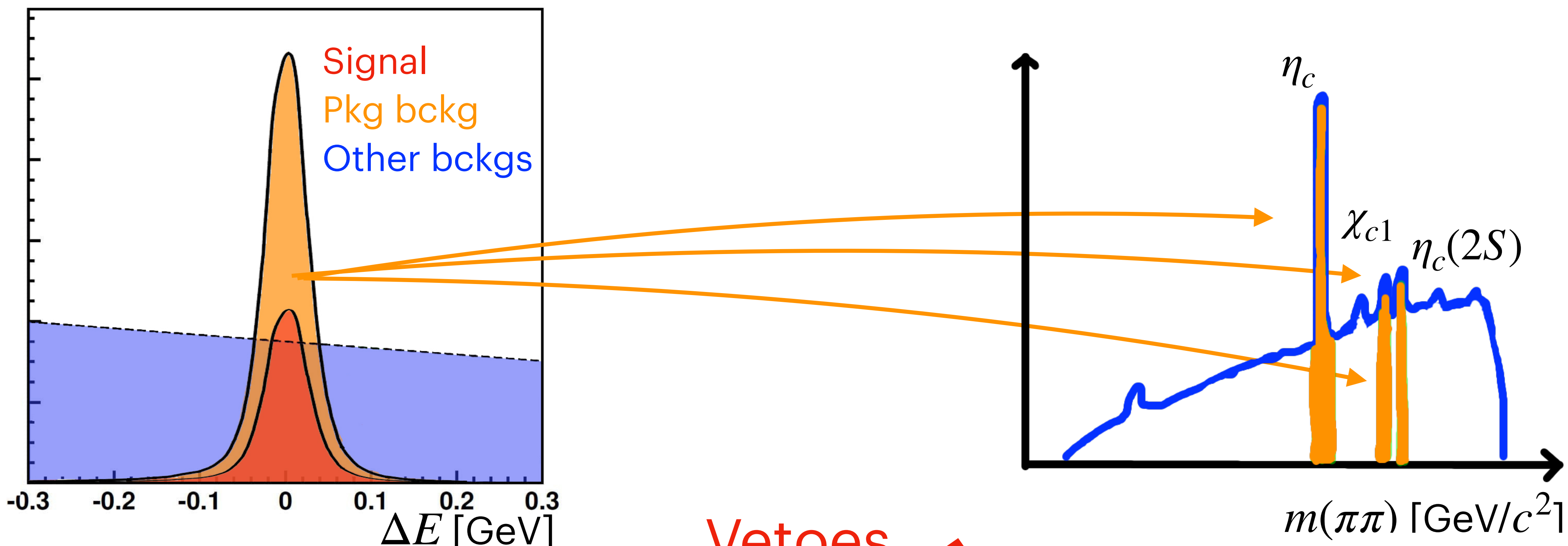
Dominant uncertainty coming from $\mathscr{A}_{K^0\pi^0}$ (from Belle II). Investigate future projections with Belle II and LHCb expected luminosities.



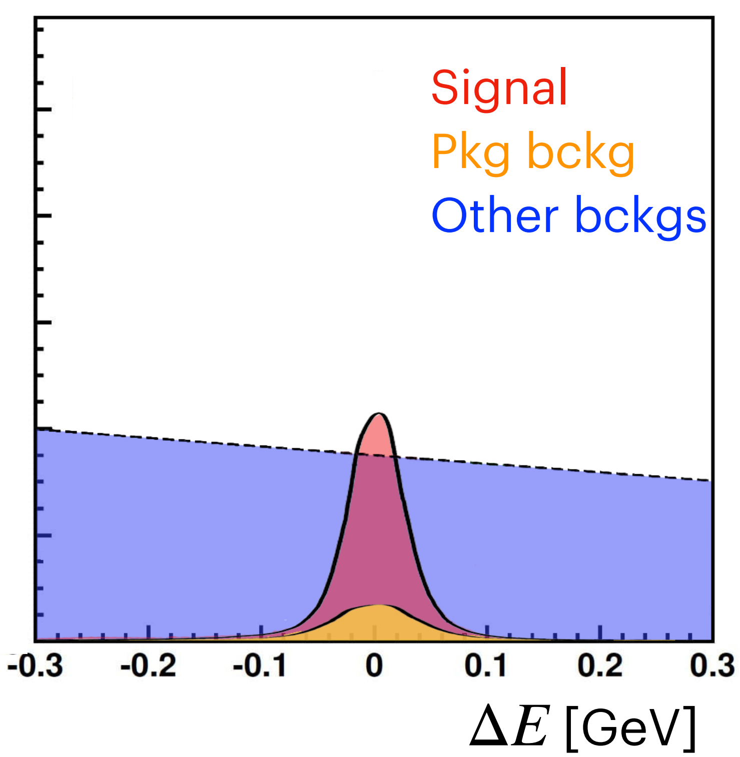
Fundamental role of Belle II in improvement of precision.

Multibody decays

Rich Dalitz structure → many peaking backgrounds: use simulation to veto charm resonances in 2-particle invariant masses.



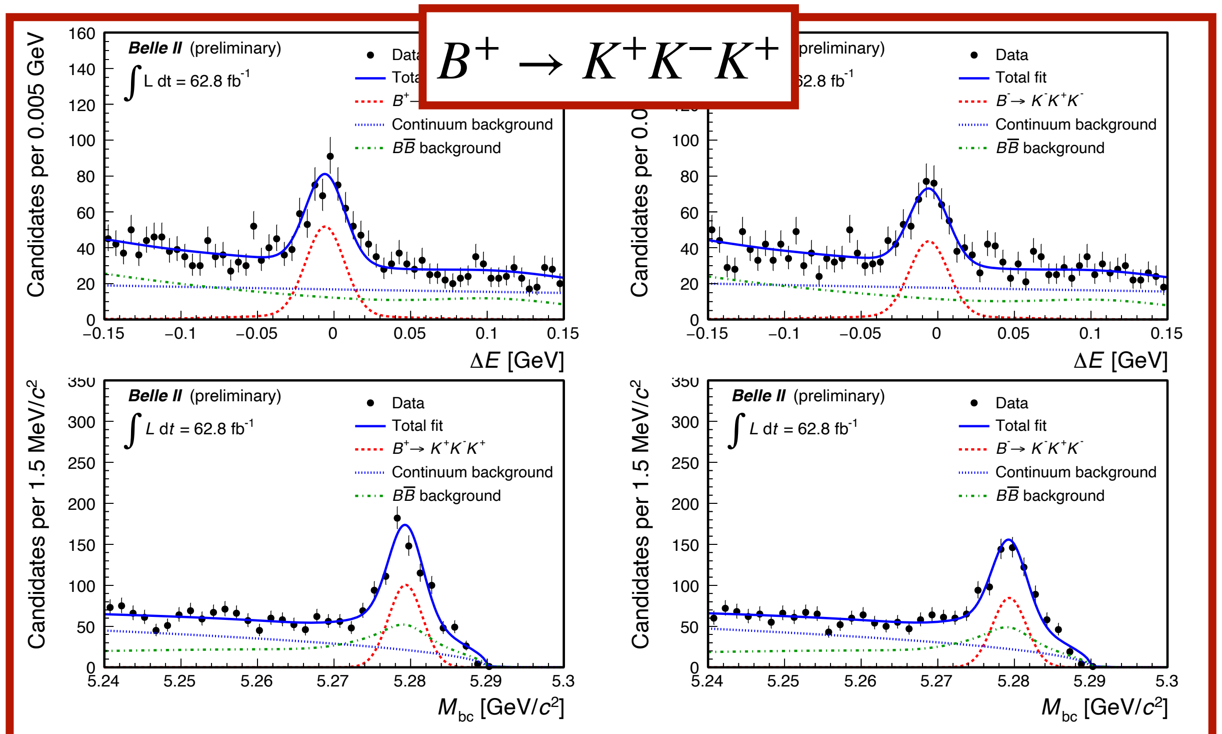
Vetoes

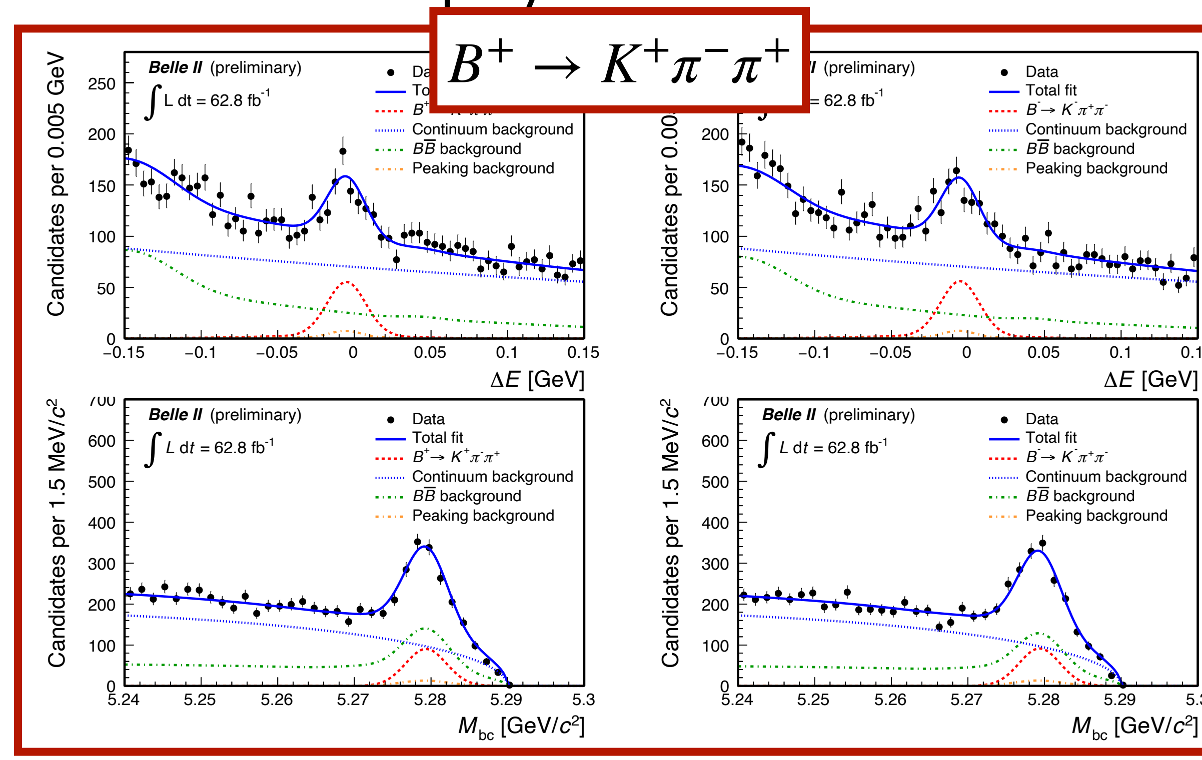


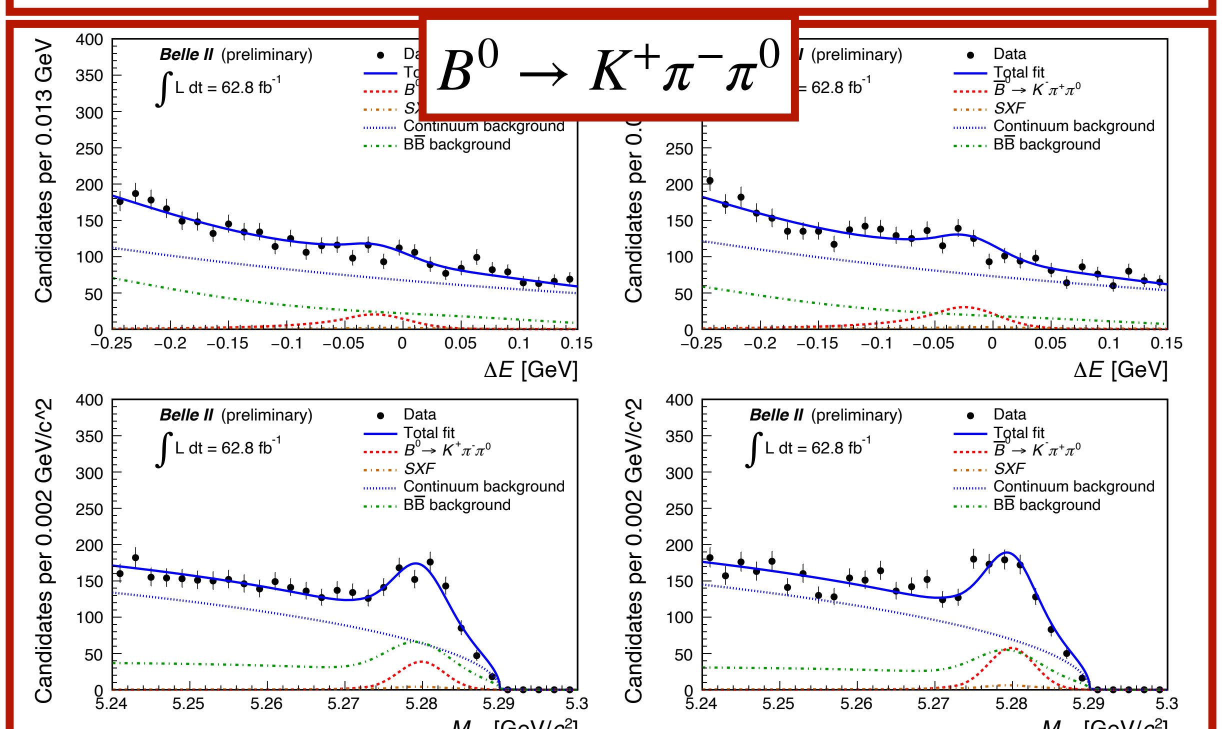
Account for survivors adding fit component from simulation.

CPV in multibody decays

First step towards search of local CPV in Dalitz plots: investigates relative contributions of tree and penguins, and probes non-SM physics.







First reconstruction in Belle II data!

$$\mathscr{B}(B^+ \to K^+K^-K^+) = [35.8 \pm 1.6(\text{stat}) \pm 1.4(\text{syst})] \times 10^{-6}$$

$$A_{CP}(B^+ \to K^+K^-K^+) = -0.103 \pm 0.042(\text{stat}) \pm 0.020(\text{syst})$$

$$\mathscr{B}(B^+ \to K^+\pi^-\pi^+) = [67.0 \pm 3.3(\text{stat}) \pm 2.3(\text{syst})] \times 10^{-6}$$

$$A_{CP}(B^+ \to K^+\pi^-\pi^+) = -0.010 \pm 0.050(\text{stat}) \pm 0.021(\text{syst})$$

$$\mathscr{B}(B^0 \to K^+\pi^-\pi^0) = [38.1 \pm 3.5(\text{stat}) \pm 3.9(\text{syst})] \times 10^{-6}$$

$$A_{CP}(B^0 \to K^+\pi^-\pi^0) = 0.207 \pm 0.088(\text{stat}) \pm 0.011(\text{syst})$$

Belle II accesses consistently all channels

Determination of α/ϕ_2

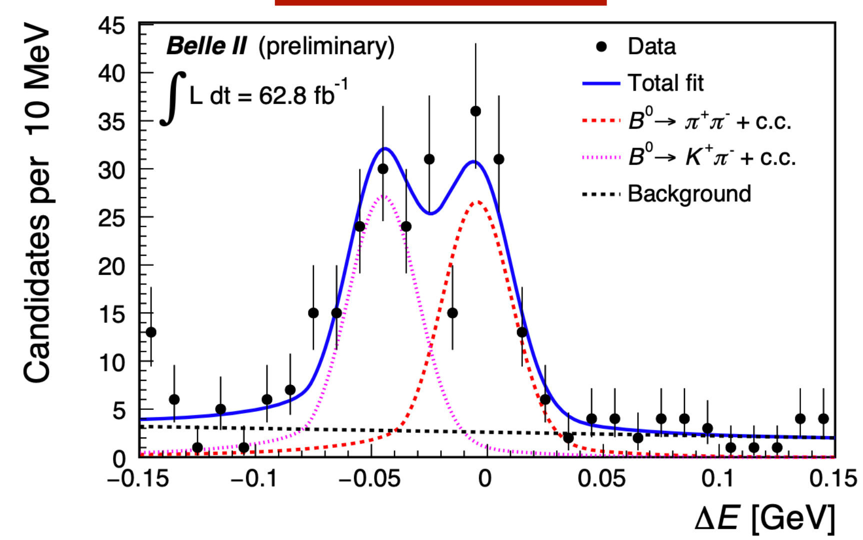
Unique Belle II capability to study all the $B \to \pi\pi$, $\rho\rho$ decays to determine the CKM angle

$$\alpha = arg\left[-V_{td}V_{tb}^{*}/V_{ud}V_{ub}^{*}\right].$$

Comparing α from penguins or trees offers non-SM sensitivity.

Currently known with 6% uncertainty.

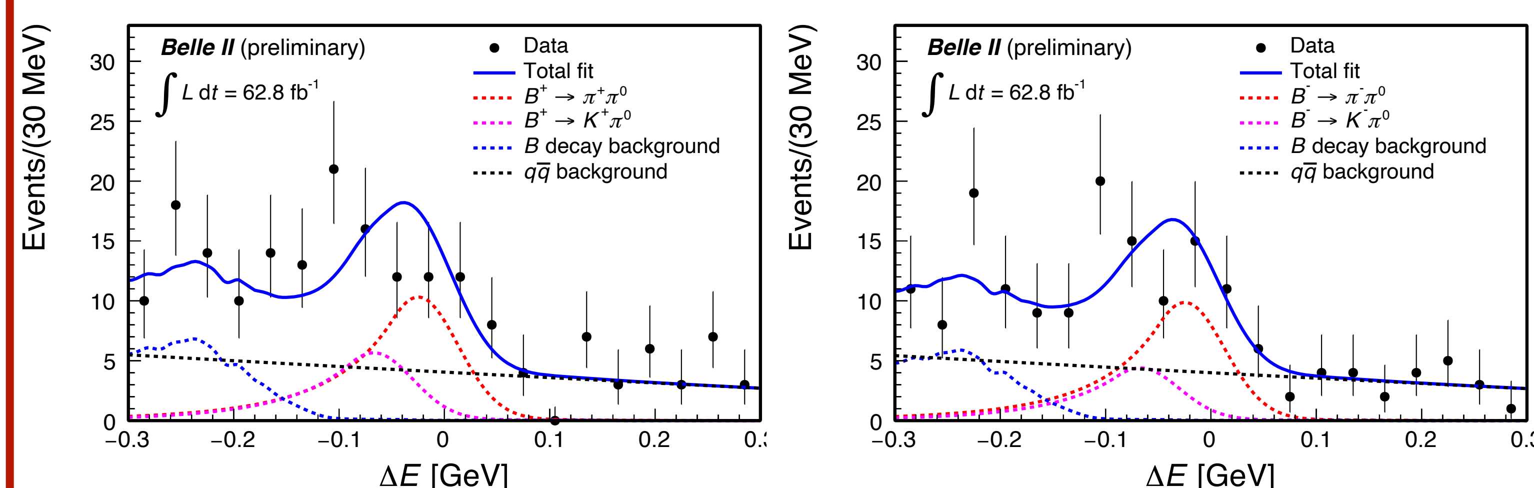
$B^0 \to \pi^+\pi^-$



Benchmarks PID and ΔE resolution.

$\mathscr{B}(B^0 \to \pi^+\pi^-) = [5.8 \pm 0.7(\text{stat}) \pm 0.3(\text{syst})] \times 10^{-6}$

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



Probes π^0 reconstruction and PID.

$\mathscr{B}(B^+ \to \pi^+\pi^0) = [5.5^{+1.0}_{-0.9}(\text{stat}) \pm 0.7(\text{syst})] \times 10^{-6}$

$A_{CP}(B^+ \to \pi^+\pi^0) = -0.04 \pm 0.17(\text{stat}) \pm 0.06(\text{syst})$

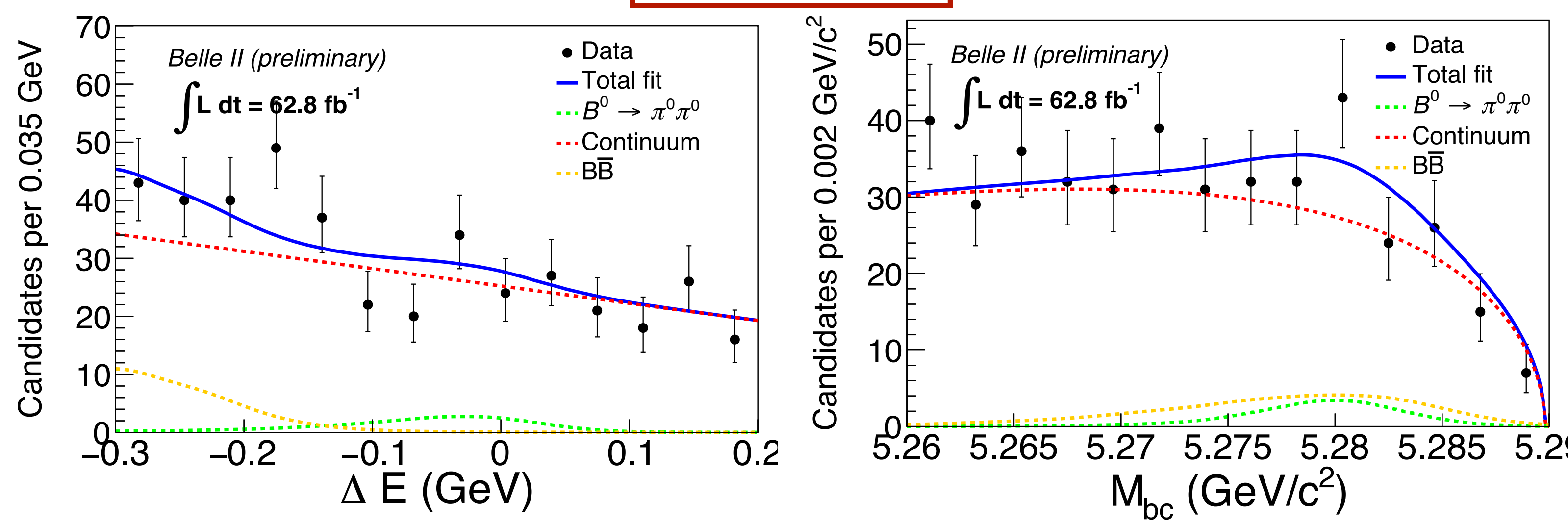
Determination of α/ϕ_2: $B^0 \to \pi^0\pi^0$

Very challenging as there are only two π^0's in final state.

π^0 optimisation: combine 20 ECL variables to suppress bckg photons.

Use $B^0 \to D^0(K^-\pi^+\pi^0)\pi^0$ control channel to determine data/simulation mismodelings.

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



First reconstruction in Belle II data!

N($B^0 \to \pi^0\pi^0$): $14\,^{+6.8}_{-5.6}$

$\mathscr{B}(B^0 \to \pi^0\pi^0) = [1.09^{+0.50}_{-0.41}(\text{stat}) \pm 0.27(\text{syst})] \times 10^{-6}$

Unique capability of Belle II of reaching this state. Surpass early Belle's performance.

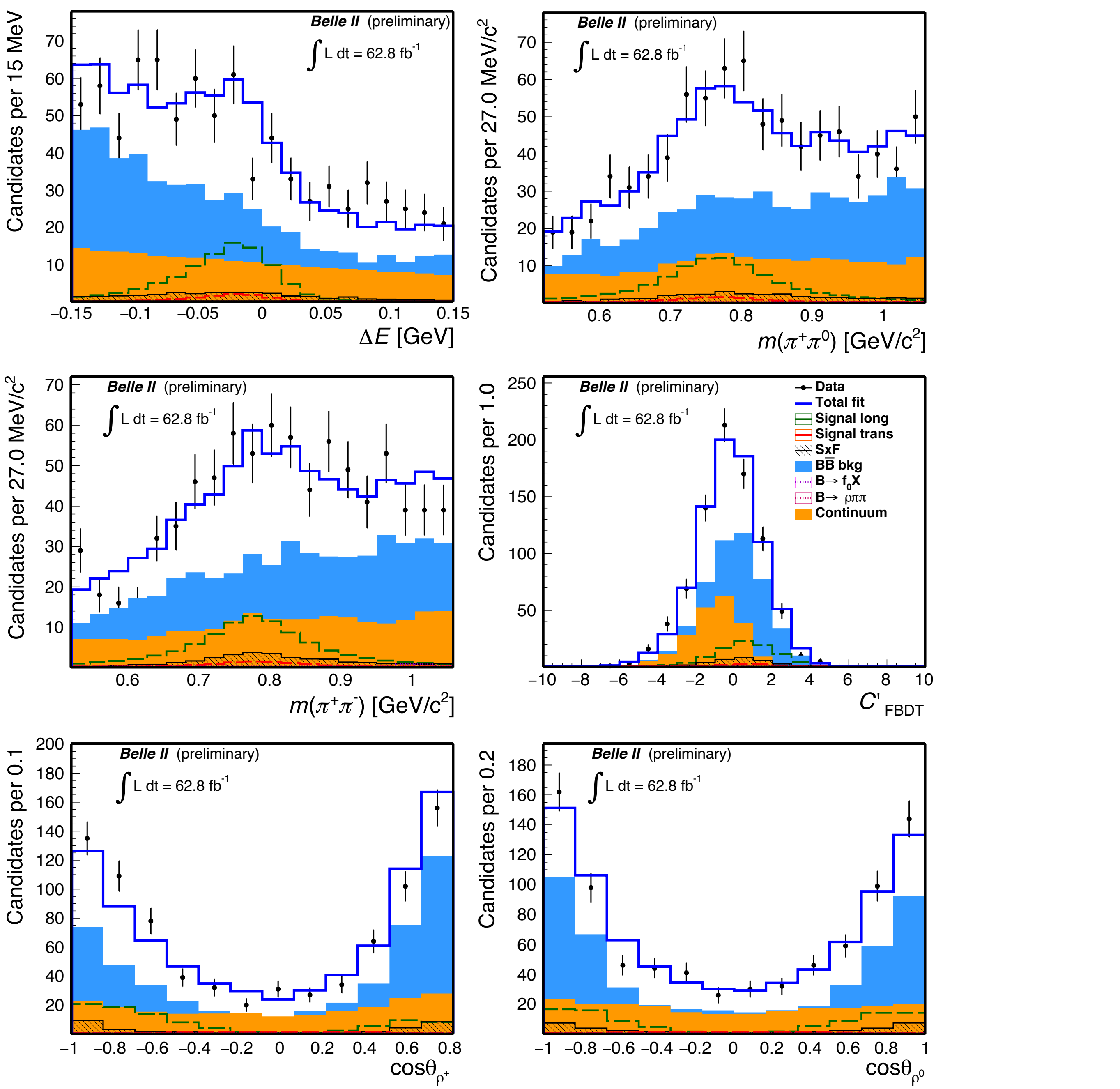
$B^+ \to \rho^+\rho^0$ results

Unique Belle II capability to determine $\alpha/\phi_2 = arg\left[-V_{td}V^*_{tb}/V_{ud}V^*_{ub}\right]$ using $B \to \rho\rho$ decays

Challenges:

- pion-only final state and broad ρ peak
  ⇒ large bckg
- Spin-0 → spin1 + spin-1
  ⇒ angular analysis.

6D fit to extract signal and to measure fraction f_L of decays with longitudinal polarization.



$N = 104 \pm 16$

$\mathscr{B} = [20.6 \pm 3.2(\text{stat}) \pm 4.0(\text{syst})] \times 10^{-6}$

$f_L = 0.936^{+0.049}_{-0.041}(\text{stat}) \pm 0.021(\text{syst})$

20% better precision than Belle on 78 fb^{-1} (PRL 91, 221801 (2003)).

First reconstruction in Belle II data! Surpass early Belle's performance.

Summary

Charmless *B* physics plays an important role in sharpening flavor picture.

Belle II preparing for a leading role in isospin sum rules, local CPVs, and α.

First/improved measurements of charmless decays in 63 fb^{-1} of early data.

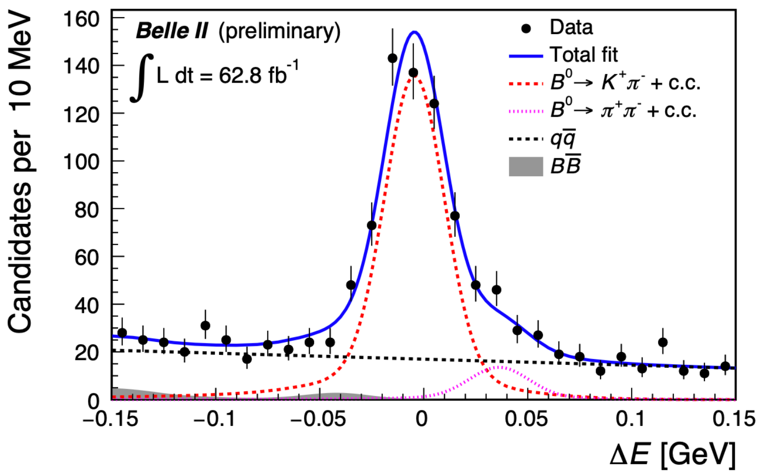
First Belle II measurement of $\mathscr{A}_{K^0\pi^0}$ completes the ingredients for the isospin sum rule; $\rho\rho$ and $\pi\pi$ analysis surpass early Belle's.

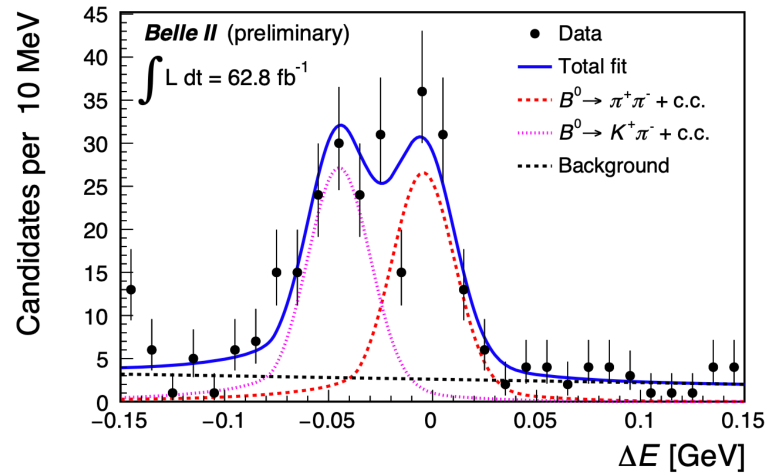
All results agree with known values within uncertainties dominated by small sample size. Performance comparable/better than at Belle demonstrates advanced understanding of detector/analysis tools.

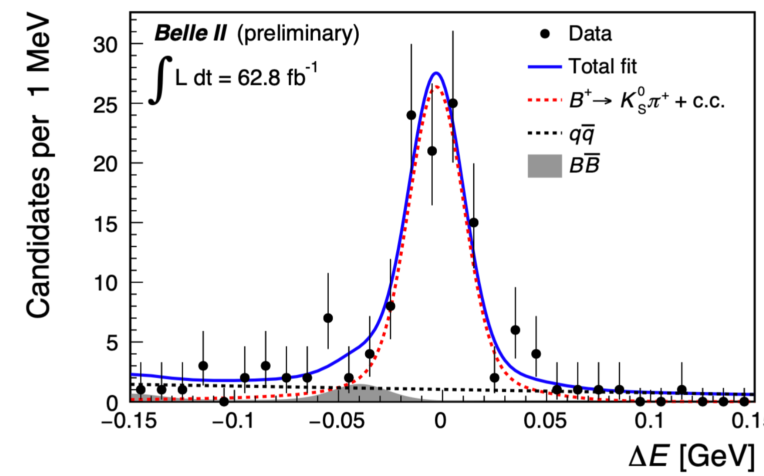
Backup

Two-body: $B^{+,0} \to h^+\pi^-, h^+\pi^0, K_S^0\pi^+$

Unique Belle II capability to study all the $B \to K\pi$ decays to investigate isospin sum-rules.







Probe of tracking and PID performances.

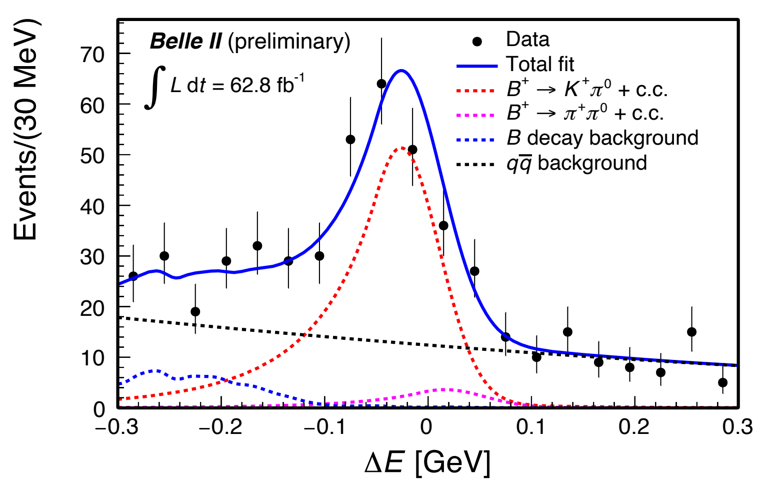
Benchmark of K_S^0 reconstruction.

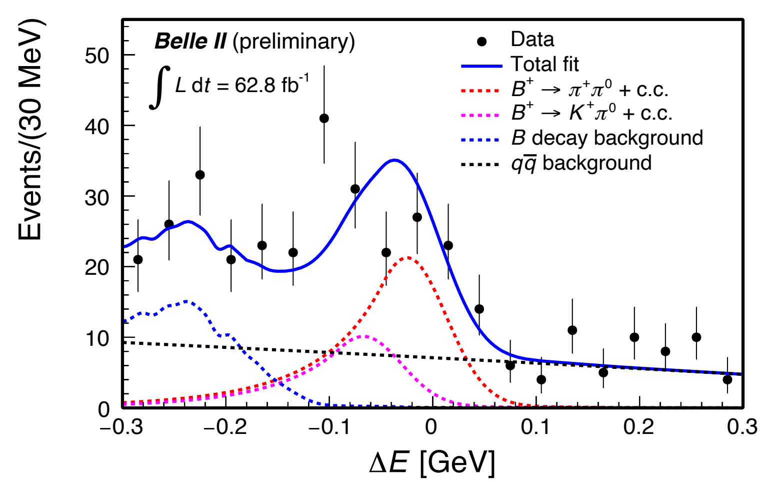
N($B^0 \to K^+\pi^-$): $568\ ^{+29}_{-28}$

N($B^0 \to \pi^+\pi^-$): $115\ ^{+14}_{-13}$

N($B^+ \to K_S^0\pi^+$): $103\ ^{+11}_{-10}$

$\mathcal{B}\ [10^{-6}]$: 18.0 ± 0.9(stat) $\pm\ 0.9$(syst) | 5.8 ± 0.7(stat) $\pm\ 0.3$(syst) | $21.4^{+2.3}_{-2.2}$(stat) $\pm\ 1.6$(syst)





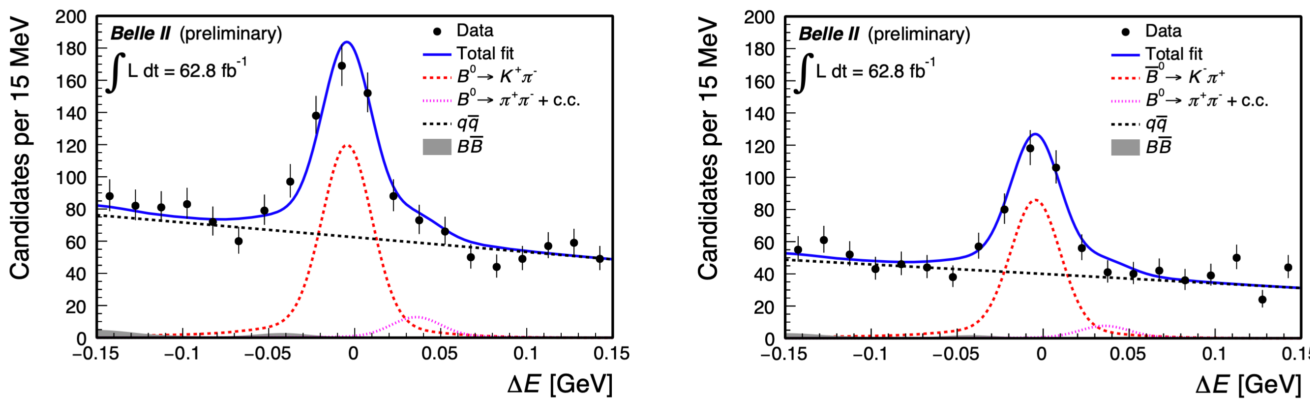
Challenge of π^0 reconstruction performances, require good PID.

N($B^+ \to K^+\pi^0$): $211\ ^{+18.8}_{-18}$

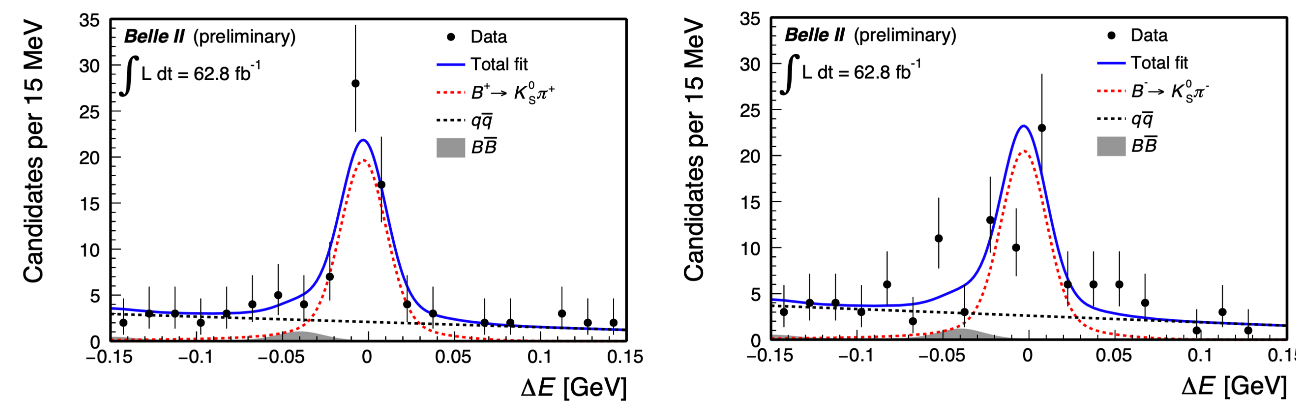
N($B^+ \to \pi^+\pi^0$): $83.9\ ^{+14.7}_{-13.9}$

$\mathcal{B}\ [10^{-6}]$: $11.9^{+1.1}_{-1.0}$(stat) $\pm\ 1.6$(syst) | $5.5^{+1.0}_{-0.9}$(stat) $\pm\ 0.7$(syst)

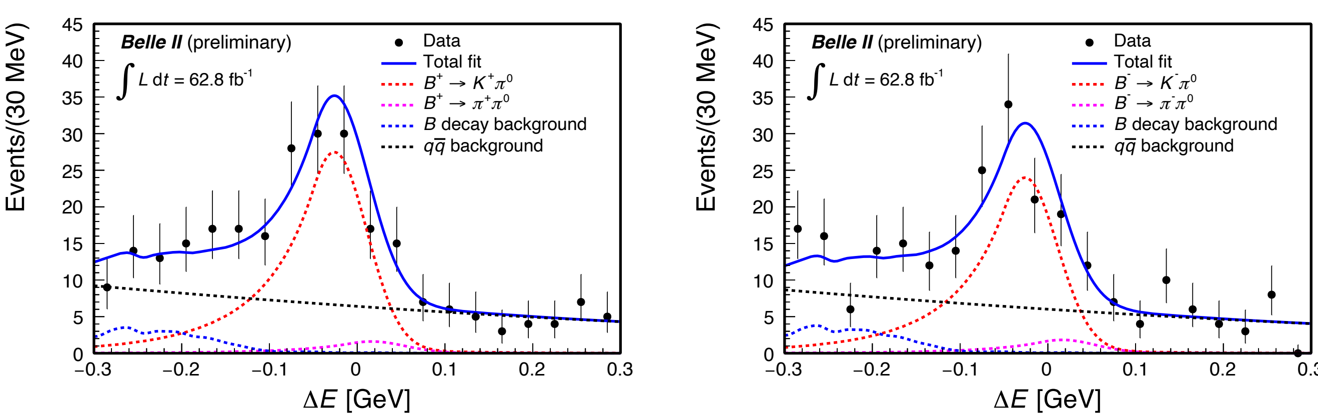
CP asymmetries in two-body decays



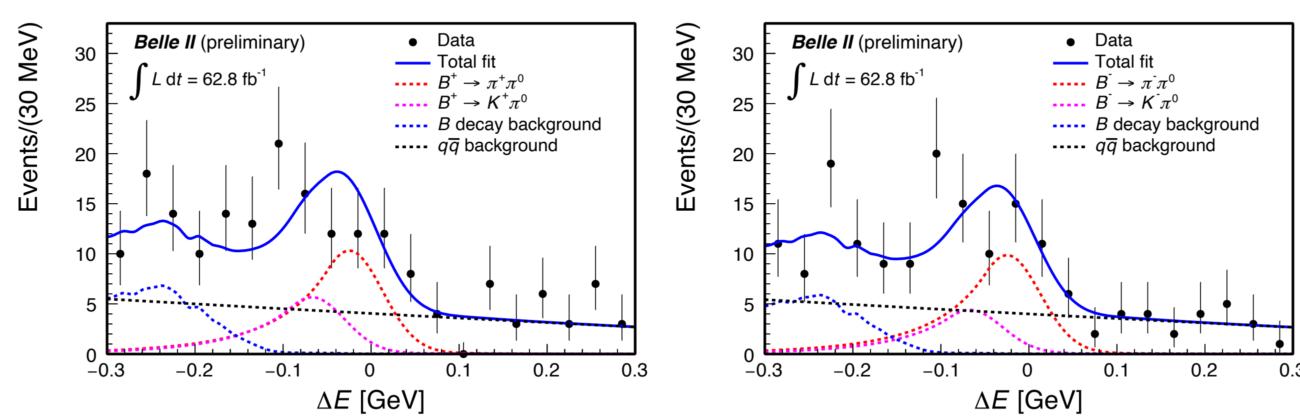
$A_{CP}(B^0 \to K^+\pi^-) = -0.16 \pm 0.05(\text{stat}) \pm 0.01(\text{syst})$



$A_{CP}(B^+ \to K^0\pi^+) = -0.01 \pm 0.08(\text{stat}) \pm 0.05(\text{syst})$

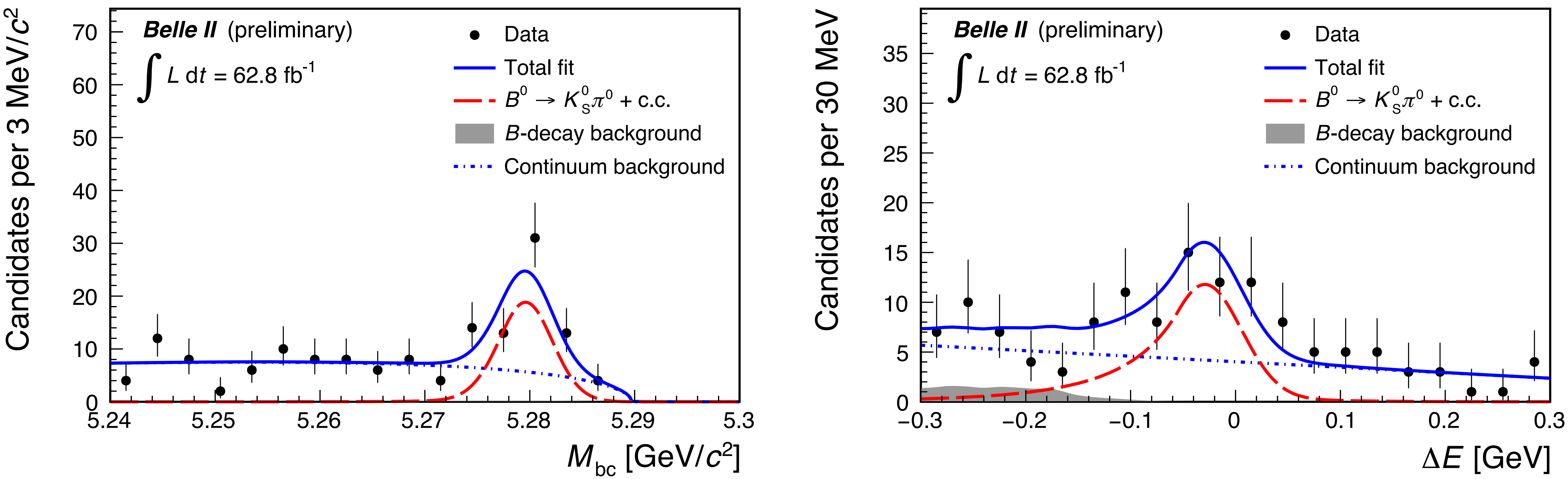


$A_{CP}(B^+ \to K^+\pi^0) = -0.09 \pm 0.09(\text{stat}) \pm 0.03(\text{syst})$



$A_{CP}(B^+ \to \pi^+\pi^0) = -0.04 \pm 0.17(\text{stat}) \pm 0.06(\text{syst})$

$B^0 \to K^0\pi^0$: branching fraction

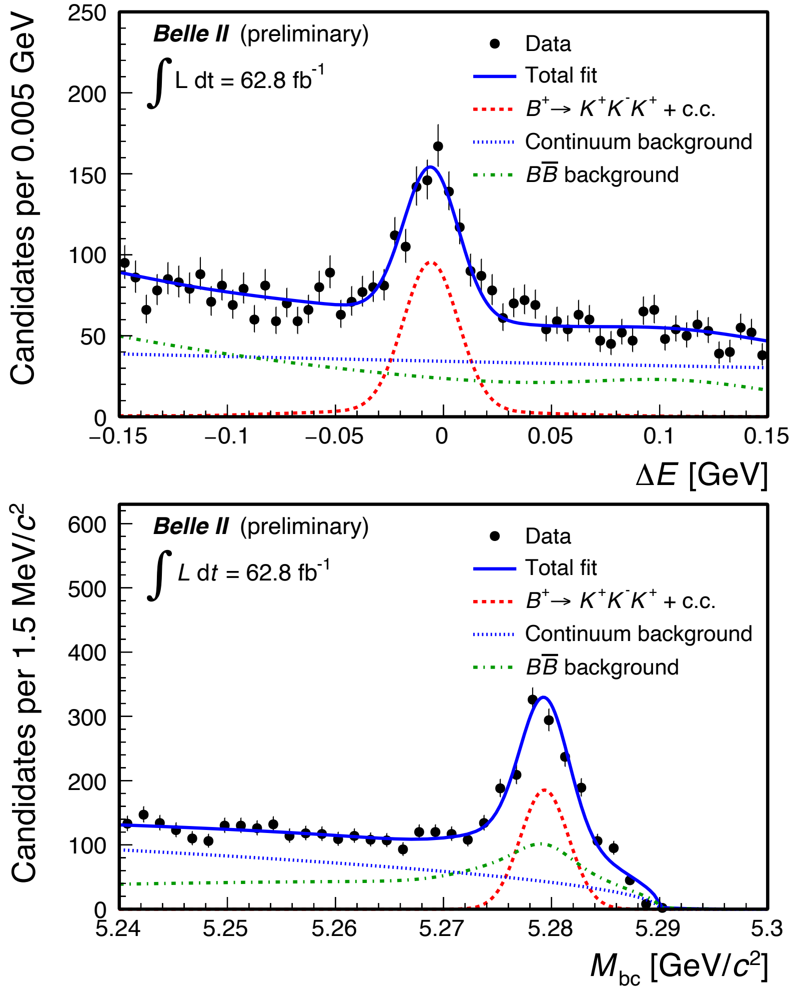


N($B^0 \to K^0_S\pi^0$): 45 $^{+9}_{-8}$

$\mathscr{B}(B^0 \to K^0\pi^0) = [8.5^{+1.7}_{-1.6}(\text{stat}) \pm 1.2(\text{syst})] \times 10^{-6}$

Multibody: branching fractions

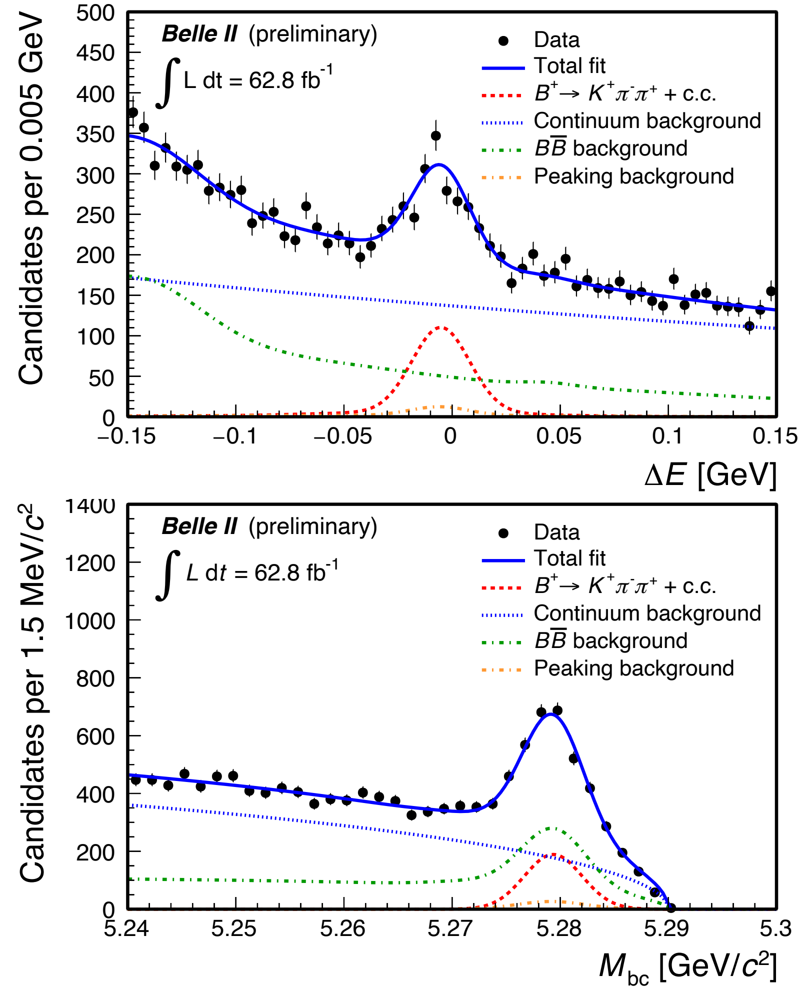
$B^+ \to K^+K^-K^+$



N_{Sig}: 690 ± 30

$\mathscr{B}\ [10^{-6}]$: 35.8 ± 1.6(stat) ± 1.4(syst)

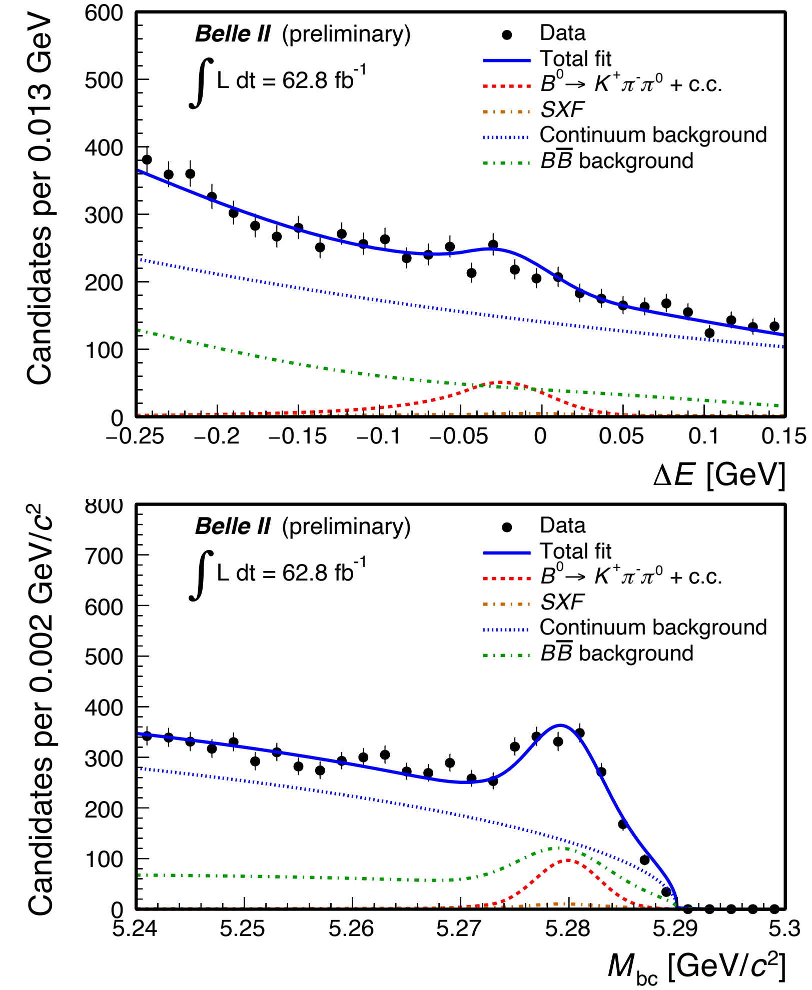
$B^+ \to K^+\pi^-\pi^+$



N_{Sig}: 843 ± 42

67.0 ± 3.3(stat) ± 2.3(syst)

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



N_{Sig}: 380 ± 35

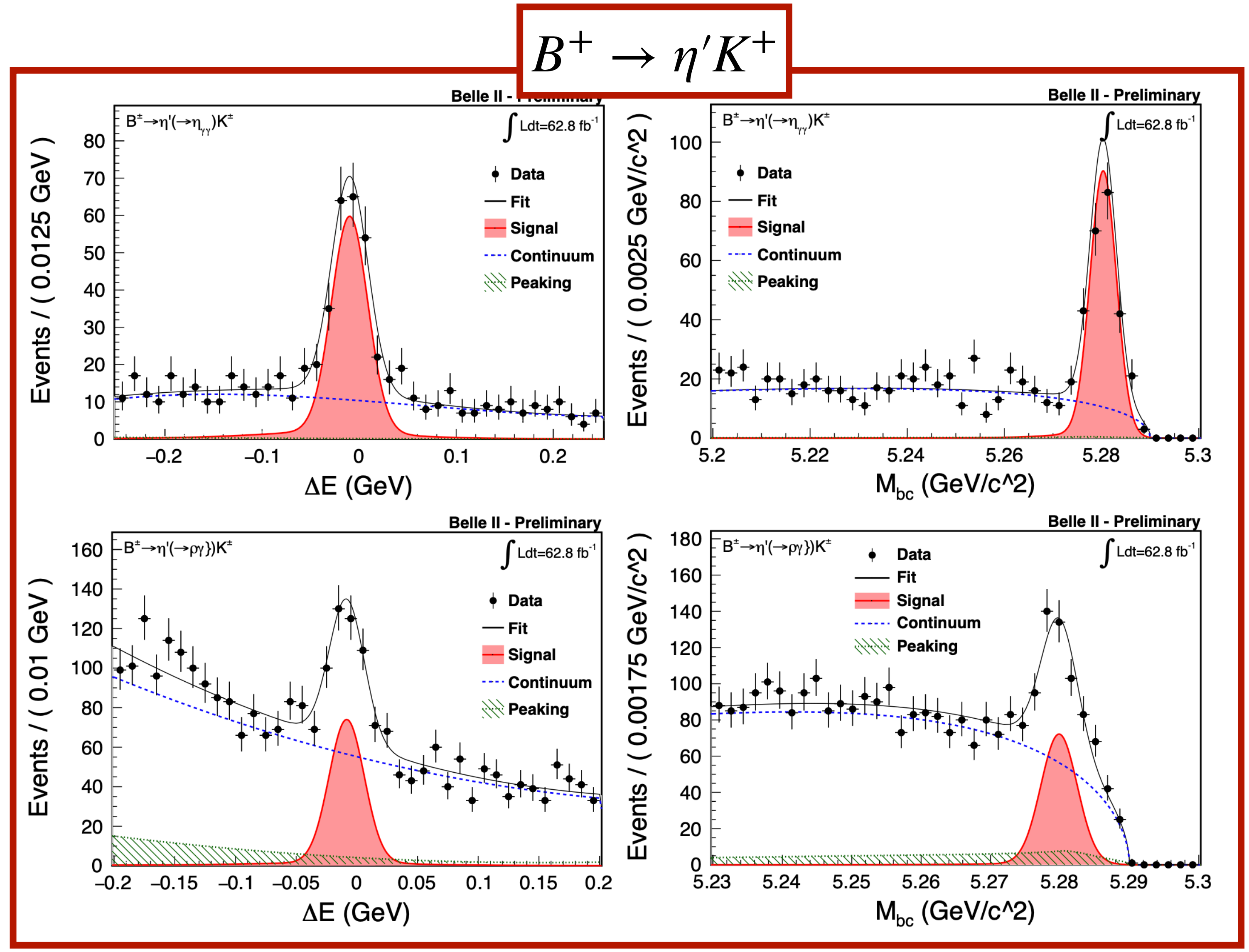
38.1 ± 3.5(stat) ± 3.9(syst)

First reconstruction in Belle II data!

$B \to \eta' K$ results

Measure *BF* of $B^+ \to \eta' K^+$ and $B^0 \to \eta' K^0_S$, where $\eta' \to \eta(\to \gamma\gamma)\pi^+\pi^-$ or $\eta' \to \rho(\to \pi^+\pi^-)\gamma$.

Challenge: pion/photon-only final state
⇒ large bckg



	This analisis	World average
Channel	B $(\times 10^6)$	
$B^\pm \to \eta' K$	$63.4\ ^{+3.4}_{-3.3}(\text{stat}) \pm 3.2(\text{syst})$	70.6 ± 2.5
$B^0 \to \eta' K^0$	$60.4\ ^{+3.3}_{-3.4}(\text{stat}) \pm 2.9(\text{syst})$	66 ± 4

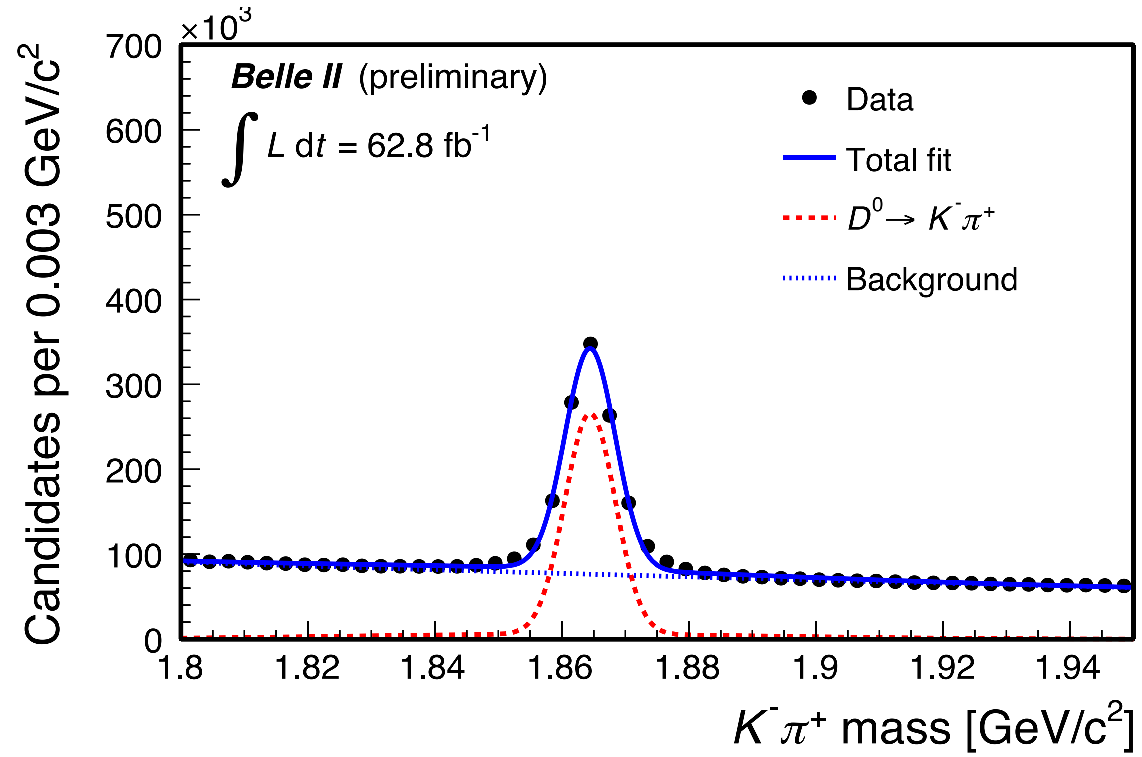
Instrumental asymmetries

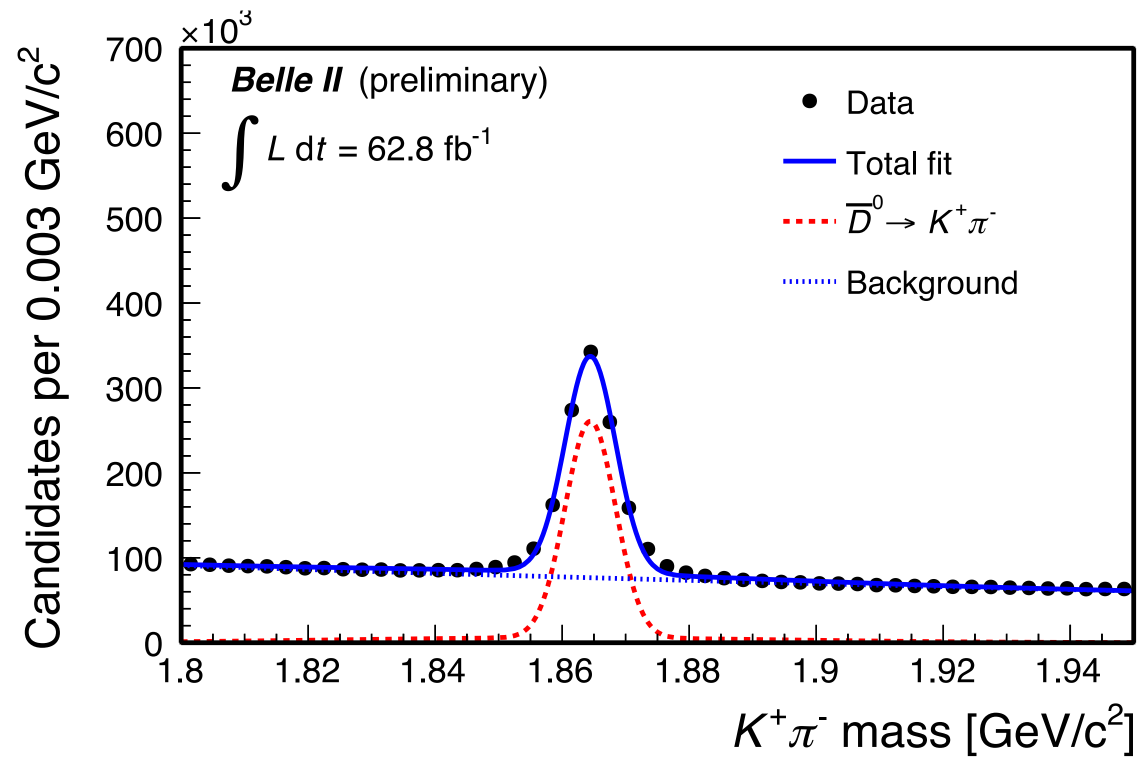
Observed charge-dependent signal yields depend on CP violation but also on charge-dependent instrumental reconstruction asymmetries (K_+/K_- ecc) that need be corrected for CP violation measurements

$$\mathscr{A} = \mathscr{A}_{CP} + \mathscr{A}_{det}$$

Tree-dominated hadronic D decays $D^+ \to K_S \pi^+$ and $D^0 \to K^-\pi^+$ restricted to charmless-like kinematics to determine instrumental asymmetries on data. CPV in charm tree decays assumed inexistent or irrelevant.

$\mathcal{A}_{\rm det}(K^+\pi^-)$	-0.010 ± 0.001
$\mathcal{A}_{\rm det}(K^0_S\pi^+)$	$+0.026 \pm 0.019$
$\mathcal{A}_{\rm det}(K^+)$	$+0.017 \pm 0.019$
$\mathcal{A}_{\rm det}(\pi^+)$	$+0.026 \pm 0.019$





Efficiencies validation

Validate the efficiencies by applying the same selection on data and simulation for abundant and signal-rich control channels.

Here, as example the π^0 reconstruction efficiency.

$$\varepsilon(\pi^0) = \frac{\text{Yield}(B^0 \to D^{*-}[\to \overline{D^0}[\to K^+\pi^-\pi^0]\pi^-]\pi^+)}{\text{Yield}(B^0 \to D^{*-}[\to \overline{D^0}[\to K^+\pi^-]\pi^-]\pi^+)} \cdot \frac{\mathcal{B}(\overline{D^0} \to K^+\pi^-)}{\mathcal{B}(\overline{D^0} \to K^+\pi^-\pi^0) \cdot \mathcal{B}(\pi^0 \to \gamma\gamma)}$$

Similar strategy adopted for continuum suppression and PID selections.

Data/MC efficiency ratios generally compatible with one within $O(10)\%$ uncertainties, which propagate as systematics.