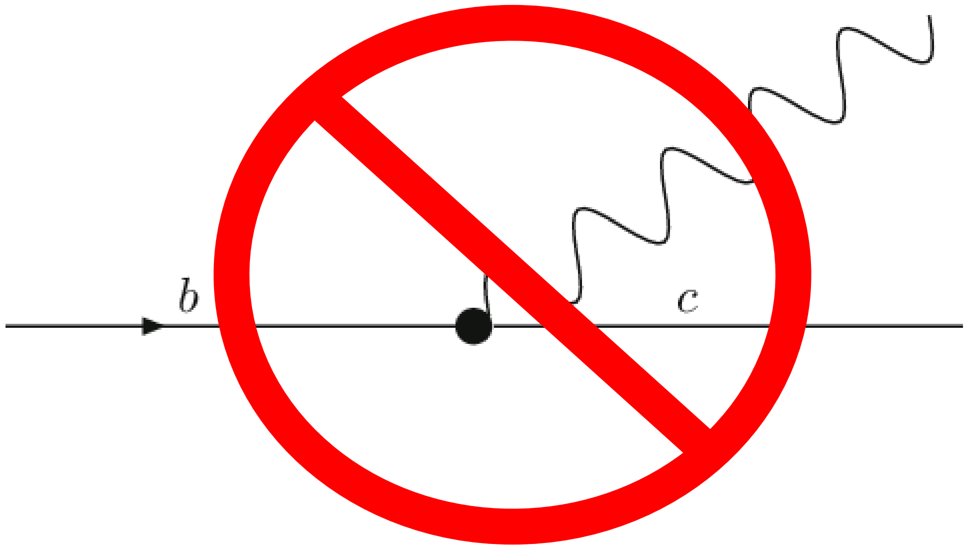
Measurements of charmless *B* decays at Belle II



May 18, 2021

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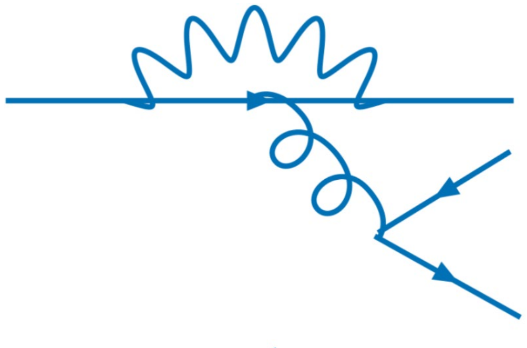
on behalf of the Belle II collaboration

Charmless B decay

Hadronic *B* decays not mediated by *b*→*c*.
Cabibbo-suppressed ***b*** → ***u*** trees and ***b*** → ***d*, *s*** penguins.

- ☐ Highly sensitive to non-SM loops.
- ☐ Probe non-SM dynamics in all the three CKM angles.

Account for ~15% of experimental flavor physics papers.



b → *d*, *s*

Pheno challenges: predictions limited by complicated calculation of hadronic matrix elements.

Exp. challenges: O(10^{-5} -10^{-6}) branching fractions means highly limited by statistics, same final states of the dominant background ("continuum" $e^+e^- \rightarrow q\overline{q}$ at Belle II)

Belle II goals

- ⊙ Improve precision on ϕ_2/α angle
- ⊙ Test SM using isospin sum rules
- ⊙ Investigate localized CP asymmetries in Dalitz plot of three-body decays

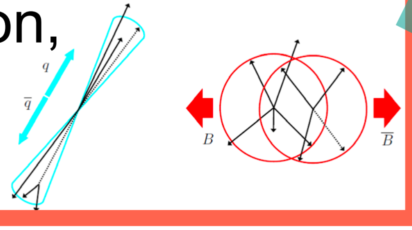
Today: charmless B decay results on 62.8 fb^{-1}

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

Analysis Overview

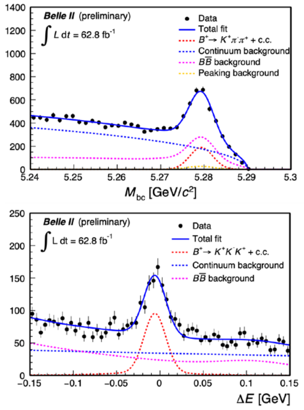
Goal: blind measurements of branching fractions, CP asymmetries and polarizations. for various charmless B decays using 62.8 fb^{-1}

Selection
Continuum suppression, optimize on simulation and data.



Efficiencies and corrections

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



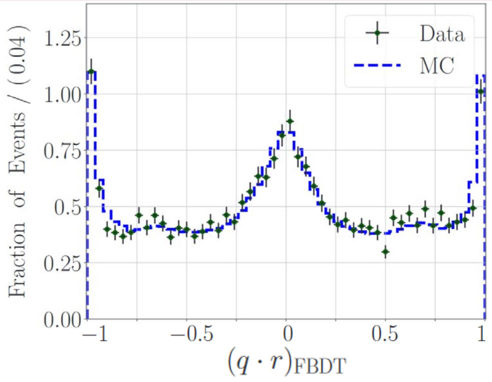
Signal extraction

$$\Delta E = E_B^* - E_{\text{beam}}^*$$

$$M_{\text{bc}} = \sqrt{{E_{\text{beam}}^*}^2 - {p_B^*}^2}$$

Models from simulation, adjusted on control modes.

Flavor Tagger
Multivariate methods determines flavor of the not reconstruct B^0



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

Systematic uncertainties
Toy studies or control modes in data.

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

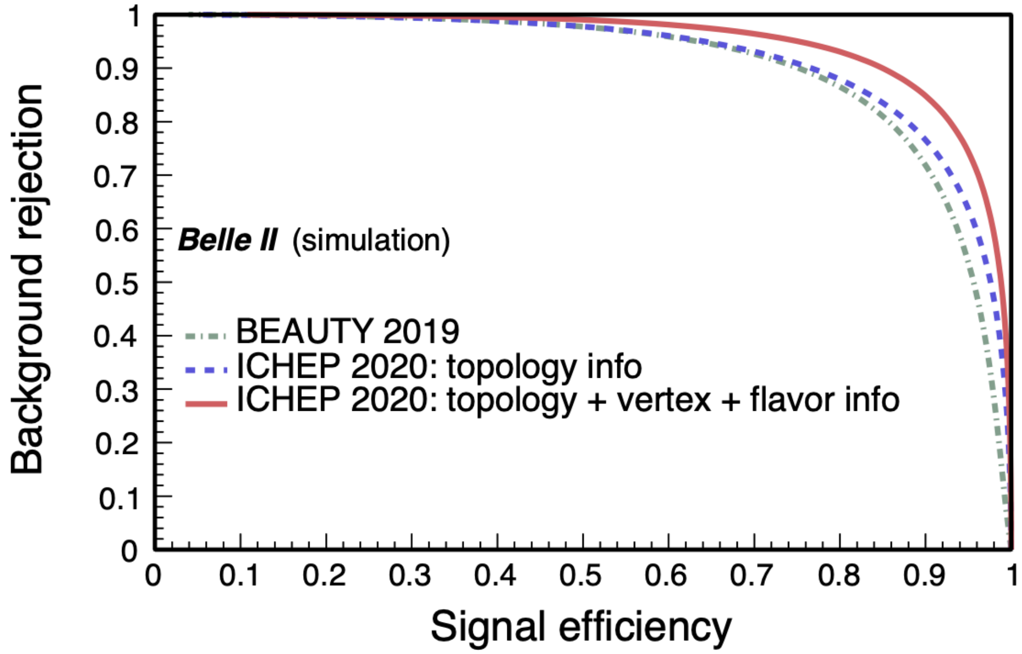
Unblinding
Apply full analysis to data.

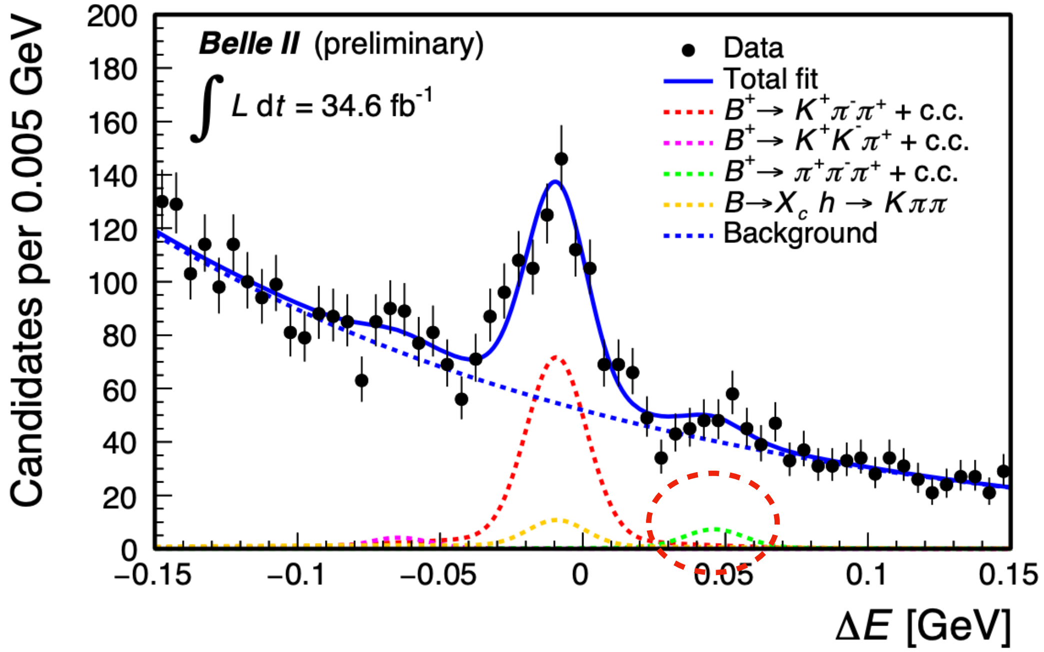
Challenges

Continuum suppression: exploit topological differences, combine 30+ kinematic, decay-time and topological variables in multivariate techniques. E.g. $B^0 \rightarrow \pi^0\pi^0$: 0.62 signal/fb^{-1} and 245 continuum/fb^{-1}

$q\overline{q}$ background rejection: ~99 %

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





Results

$K\pi$ isospin sum-rule

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

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

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

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

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

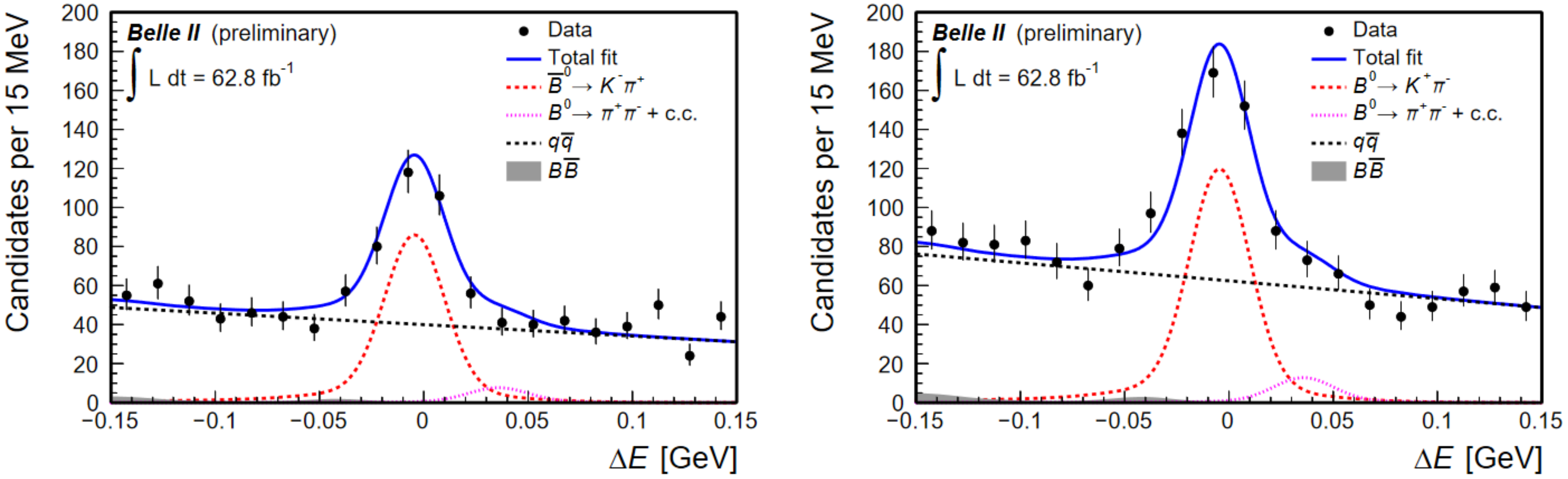
$$A_{CP}(B^+ \to K^0\pi^+) = -0.01 \pm 0.08(stat) \pm 0.05(syst)$$

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

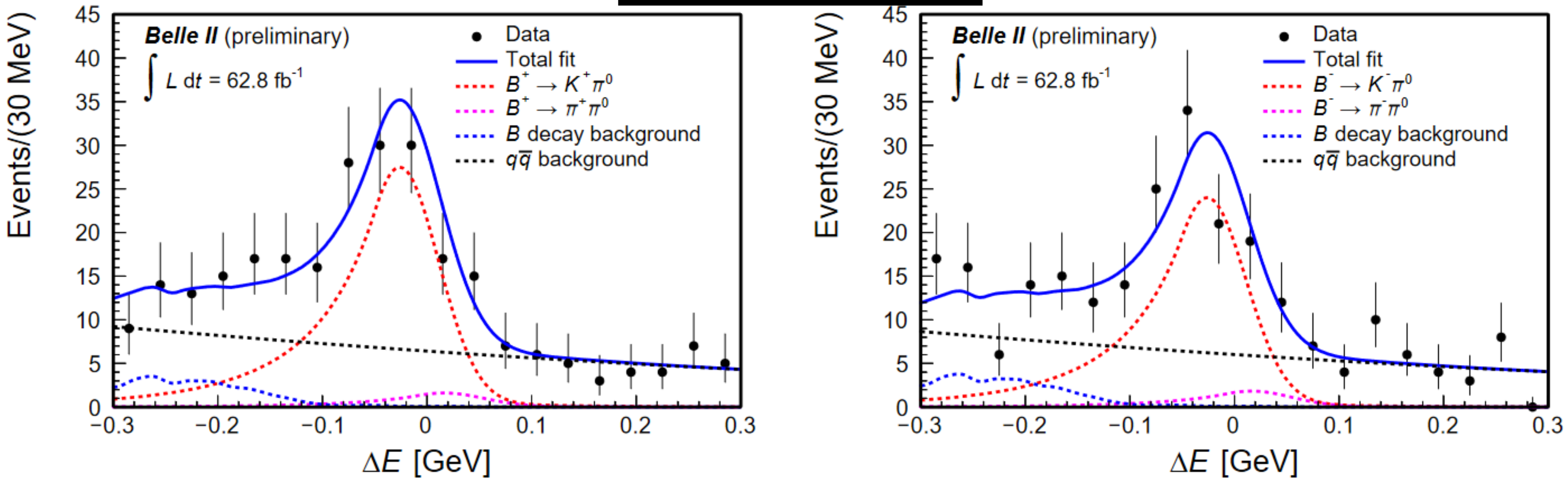
$$A_{CP}(B^+ \to K^+\pi^0) = -0.09 \pm 0.09(stat) \pm 0.03(syst)$$

Belle II is the only experiment capable to analysing all modes in a consistent way

Probes tracking. $\boxed{B^0 \to K^+\pi^-}$



Probes π^0 reconstruction. $\boxed{B^+ \to K^+\pi^0}$



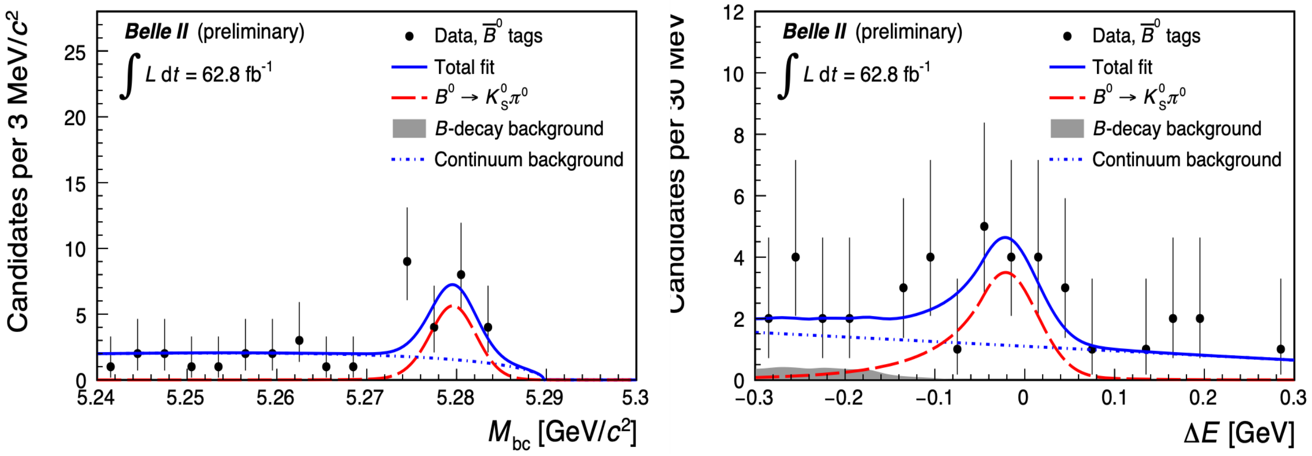
https://arxiv.org/abs/hep-ph/0508047

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

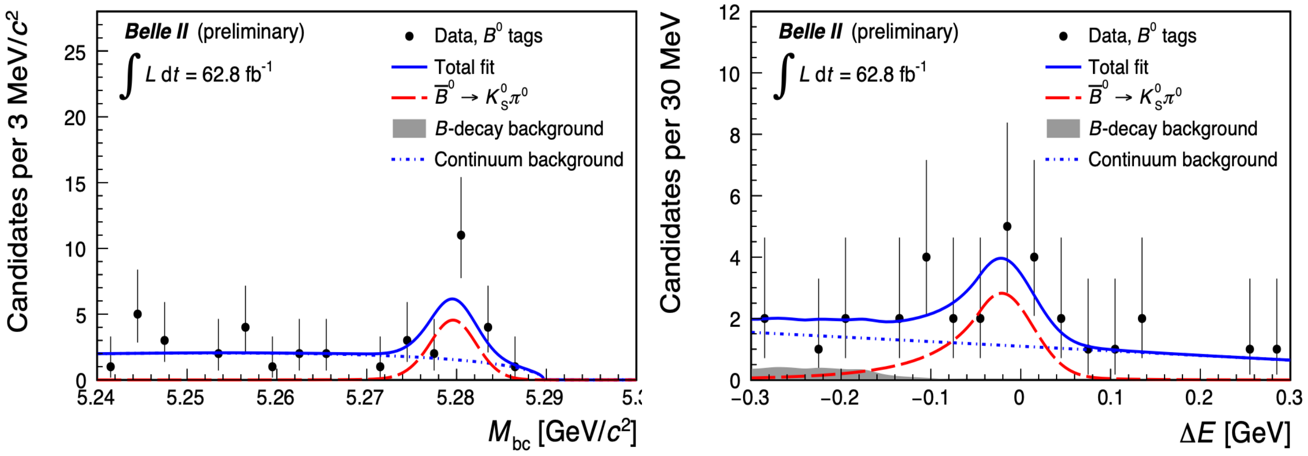
BF: challenging as it requires K_S^0 and π^0 reconstruction.
ACP: requires also flavor tagging. Fit of ΔE-Mbc of the *B* meson (q), simultaneously in 7 ranges of wrong-tag fraction (output from flavor tagger).

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

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



$\overline{B^0} \to \overline{K}^0\pi^0$



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

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

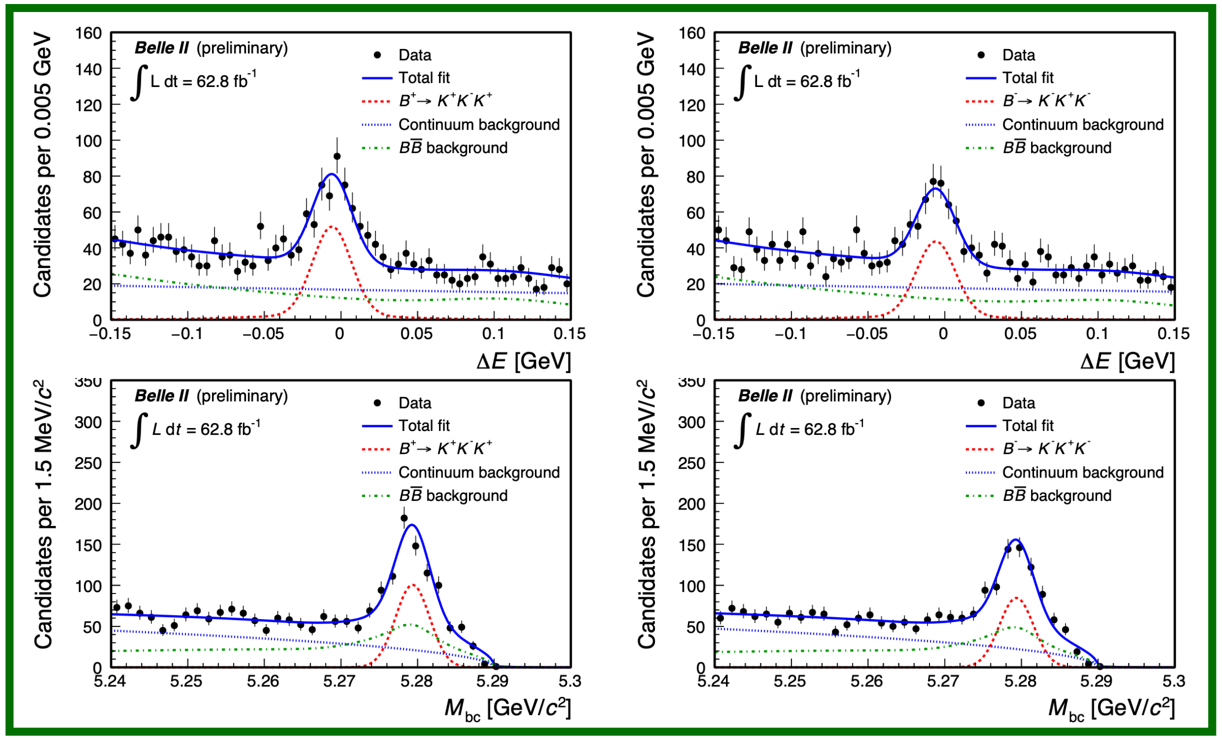
$A_{CP}(B^0 \to K^0\pi^0) = -0.40^{+0.46}_{-0.44}(stat) \pm 0.04(syst)$

First measurement in Belle II data!

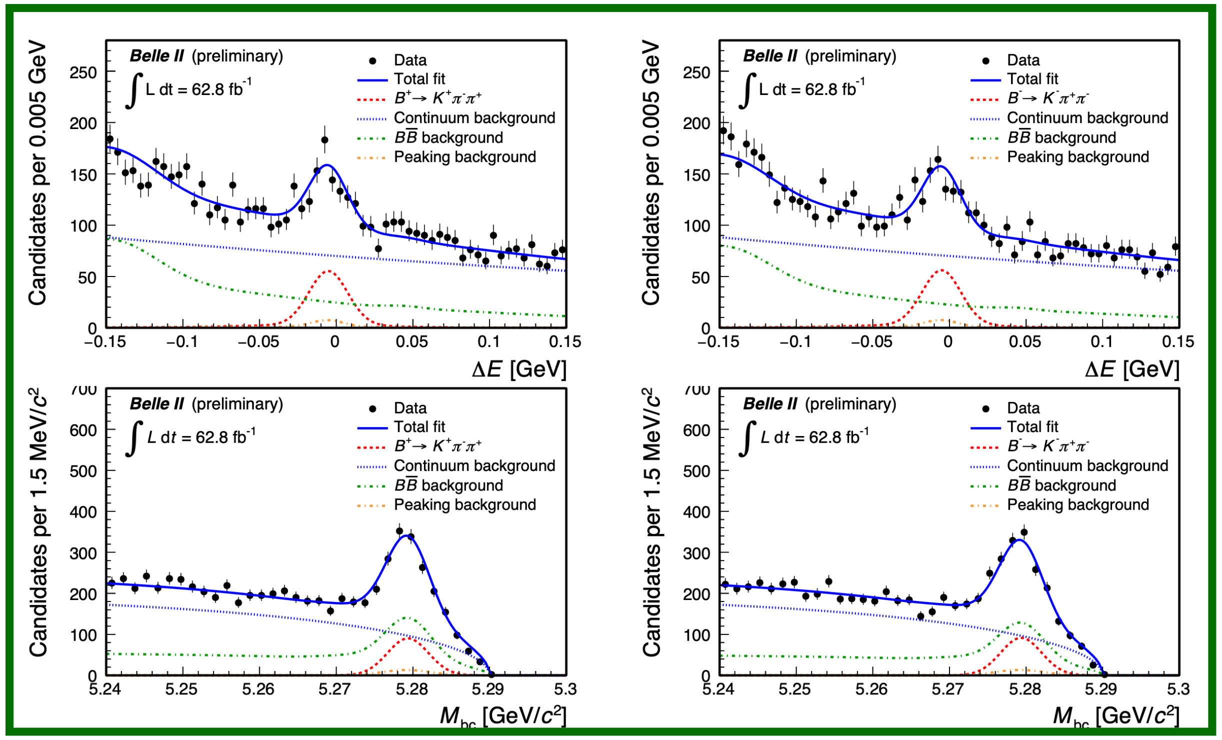
CPV in multibody

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

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



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



Rich Dalitz structure poses the additional challenge of many peaking backgrounds.

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

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

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

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

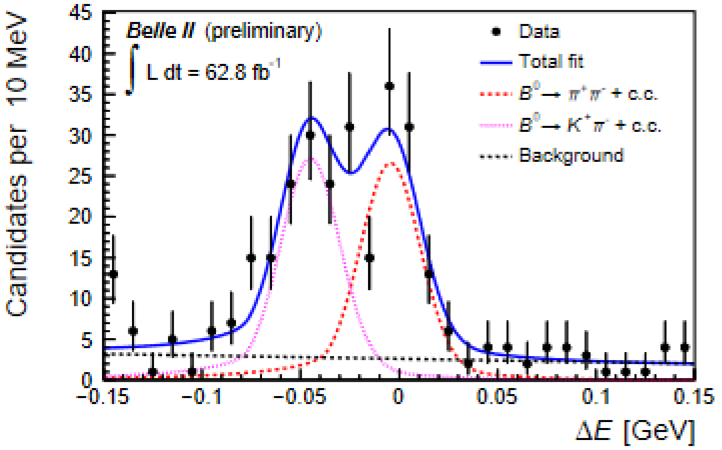
https://arxiv.org/abs/hep-ph/0608243

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 $\alpha = arg[-V_{td}V^*_{tb}/V_{ud}V^*_{ub}]$, known to 6% precision

Isospin relation can be used to disentangle penguins and trees contribution to determine α
Requires all BF and CP violation parameters for $B \to \pi\pi$

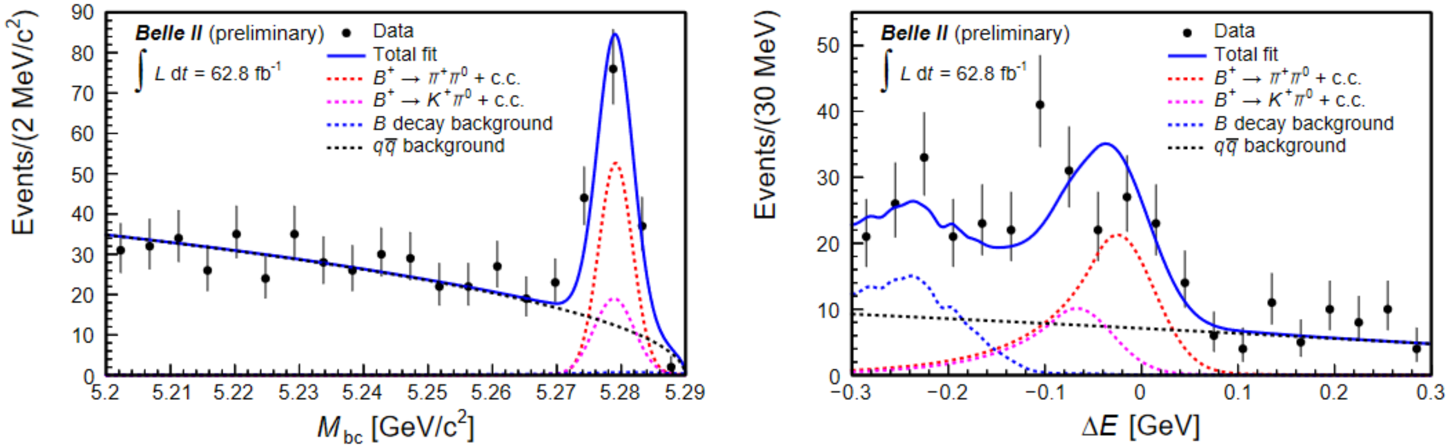
$\boxed{B^0 \to \pi^+\pi^-}$



Benchmarks PID and ΔE resolution.

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

$\boxed{B^+ \to \pi^+\pi^0}$



Probes π^0 reconstruction and PID.

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

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

https://doi.org/10.1103/PhysRevLett.65.3381

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

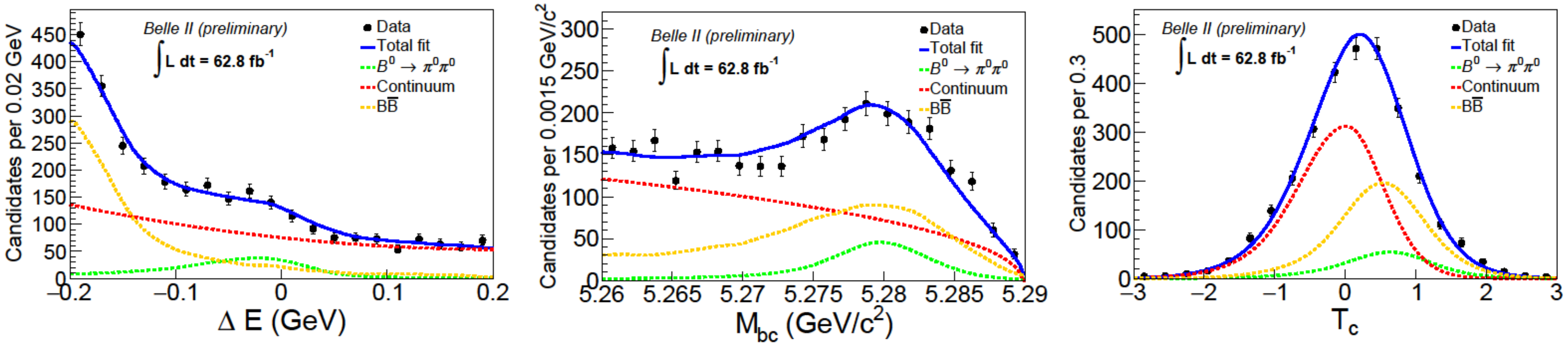
Challenging with two π^0: high continuum, low BF (1.26×10^{-6}), higher beam background relative to Belle, lowest signal-to-background ratio in current Belle II charmless studies

$B^0 \rightarrow \pi^0\pi^0$ has the largest branching fraction and A_{CP} uncertainties of all three $B \rightarrow \pi\pi$ modes, i.e. 16% on BF for $B^0 \rightarrow \pi^0\pi^0$ vs 4% for $B^0 \rightarrow \pi^+\pi^-$ and is currently posing the greatest limitation to the determination of α from $\mathrm{B} \rightarrow \pi\pi$

Belle II is currently the only experiment that can improve the current world average

Analysis validated on $B^0 \rightarrow D^0(\rightarrow K^+\pi^-\pi^0)\,\pi^0$ in data.

$N_{\text{sig}} = 295 \pm 31$

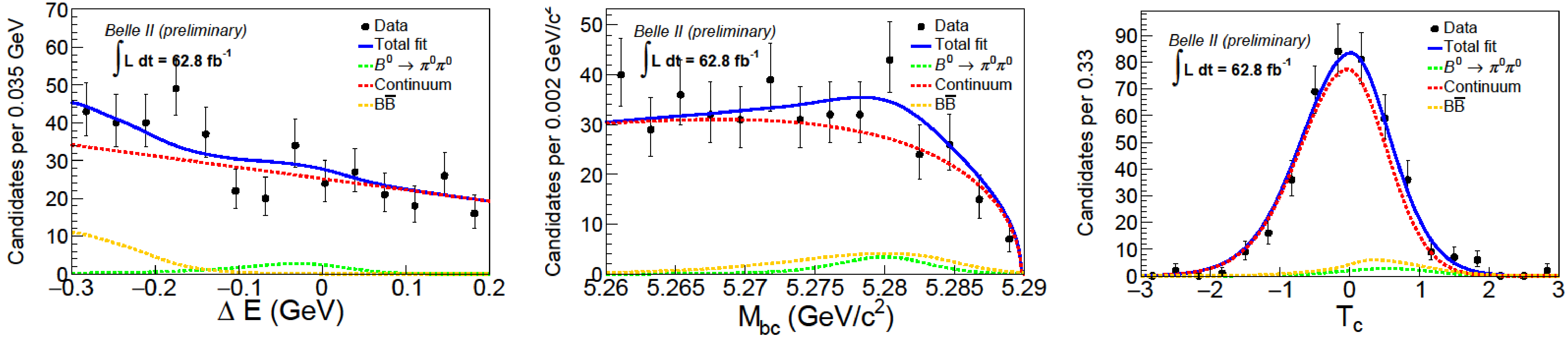


Determination of α/ϕ_2: $B^0 \rightarrow \pi^0\pi^0$

Fit to ΔE, M_{bc} and the continuum suppression output T_c simultaneously in 8 ranges of flavour tagger output (q.r)

Candidates with higher flavour tagger output are more likely to be genuine $B^0 \rightarrow \pi^0\pi^0$

$\boxed{B^0 \rightarrow \pi^0\pi^0}$



$$\mathcal{B}(B^0 \rightarrow \pi^0\pi^0) = [0.98^{+0.48}_{-0.39}(stat) \pm 0.27(syst)] \times 10^{-6}$$

First reconstruction in Belle II data!
Evidence (3.4 σ) at 62.8 fb^{-1} a performance comparable with Belle with 140 fb^{-1}

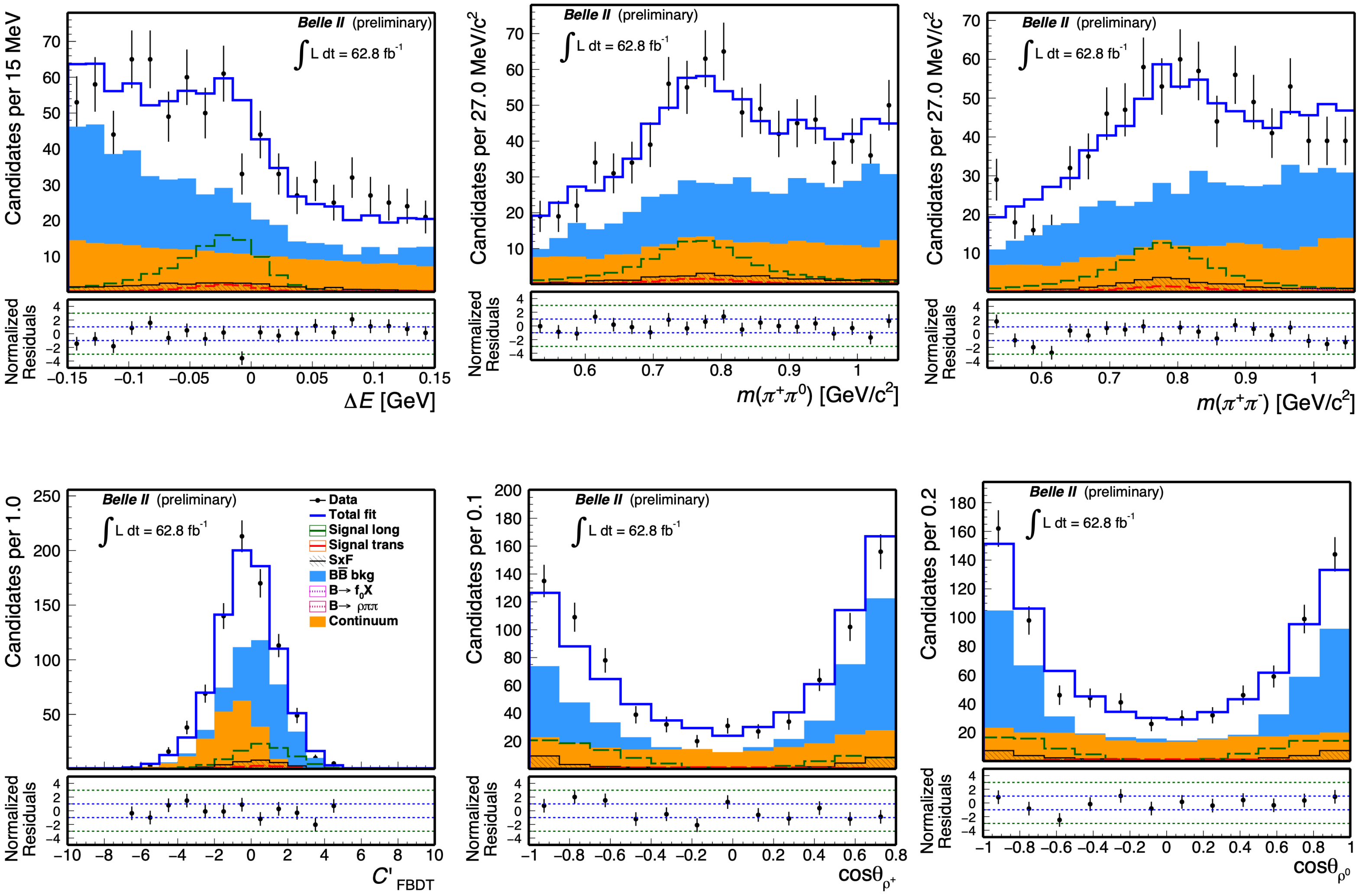
$B^+ \to \rho^+\rho^0$ results

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

Challenges:

- pion-only $(\pi^+\pi^0)(\pi^+\pi^-)$ final state and broad ρ peak ⇒ large bckg
- Spin-0 → spin1 + spin-1 ⇒ angular analysis.

6D fit including ΔE, CS, and ρ masses to extract signal, and helicity angles to measure fraction f_L of decays with longitudinal polarization.



$N = 104 \pm 16$

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

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

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

$N = 59 \pm 13$

$\mathcal{B} = [31.7 \pm 7.1(stat)^{+3.8}_{-6.7}(syst)] \times 10^{-6}$

$f_L = 0.948 \pm 0.106(stat) \pm 0.021(syst)$

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

Summary

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

Era of precision physics! Belle II will play a leading role in: α/ϕ_2, local CPVs, isospin sum rules.

First/improved measurements of charmless decays in 62.8 fb^{-1} of early data compatible with known values within ~6% to ~25% precision, dominated by small sample size

First Belle II measurement of $A_{CP}(K^0\pi^0)$ completes the ingredients for the isospin sum rule; ρρ and ππ analysis surpasses early Belle's.

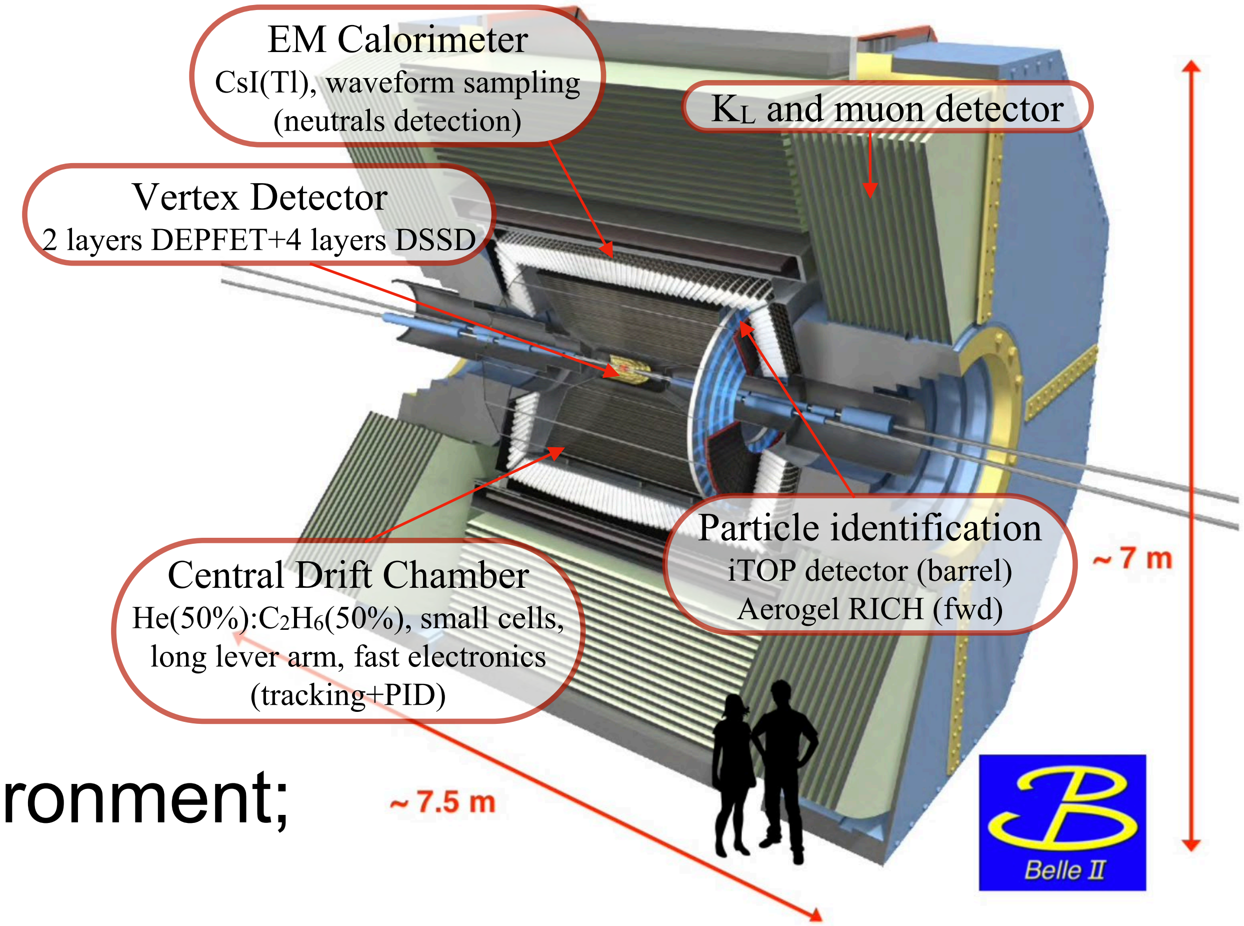
Performance comparable/better than at Belle demonstrates advanced understanding of detector/analysis tools.

Backup

Charmless physics at Belle II

Goals

- Improve precision on ϕ_2/α angle;
- Test SM using isospin sum rules;
- Investigate localized CP asymmetries in three-body B decays;
- Study time-dependent CP violations.

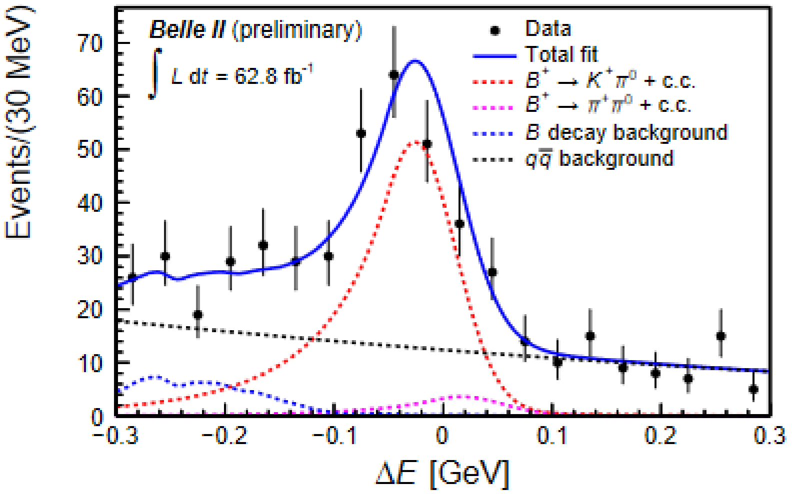


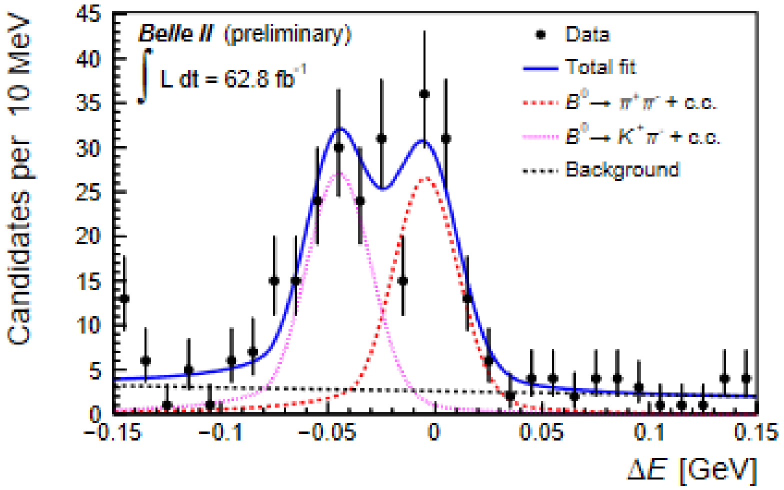
Belle II

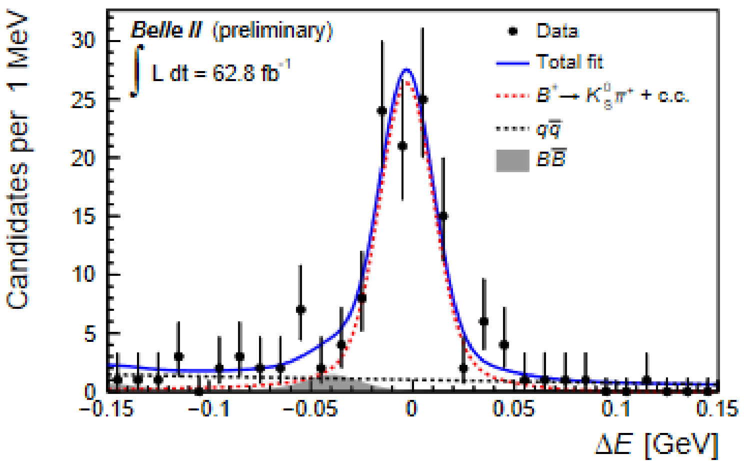
- ~700 BB pairs/second in low-bkg environment;
- 140 fb^{-1} of data collected;
- World record peak luminosity in June 2020: 2.4x10^{34} cm^{-2} s^{-1}
- Complementary to LHCb (final states with neutrals and V0s).

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.







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}

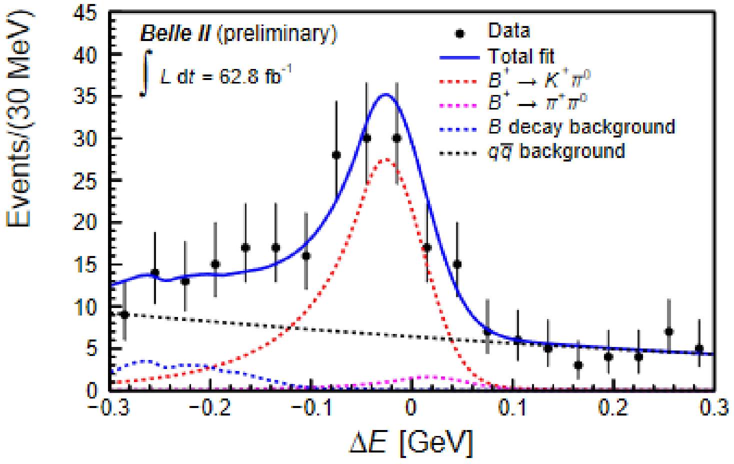
$\mathcal{B}[10^{-6}]$: $18.0 \pm 0.9(stat) \pm 0.9(syst)$

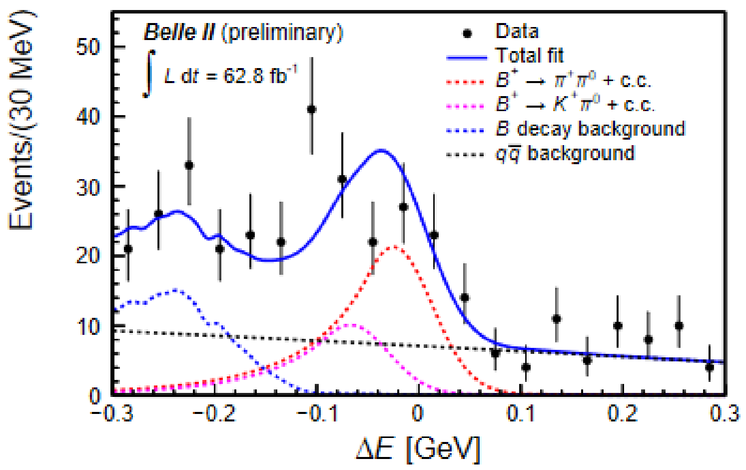
$5.8 \pm 0.7(stat) \pm 0.3(syst)$

$21.4^{+2.3}_{-2.2}(stat) \pm 1.6(syst)$

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

Probe of tracking and PID performances.





Benchmark of K_S^0 reconstruction.

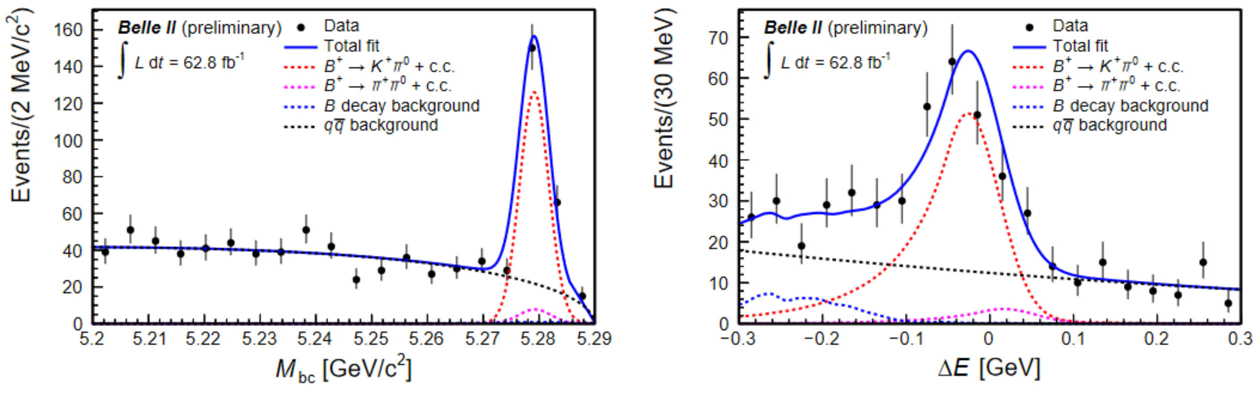
N($B^+ \to K^+\pi^0$): 211^{+18}_{-18}

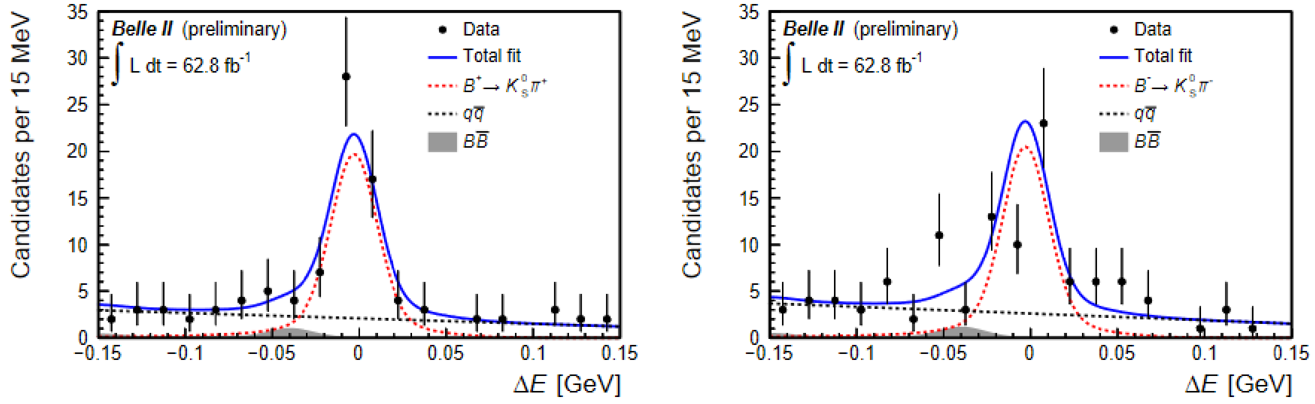
N($B^+ \to \pi^+\pi^0$): $83.9^{+14.7}_{-13.9}$

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

$5.5^{+1.0}_{-0.9}(stat) \pm 0.7(syst)$

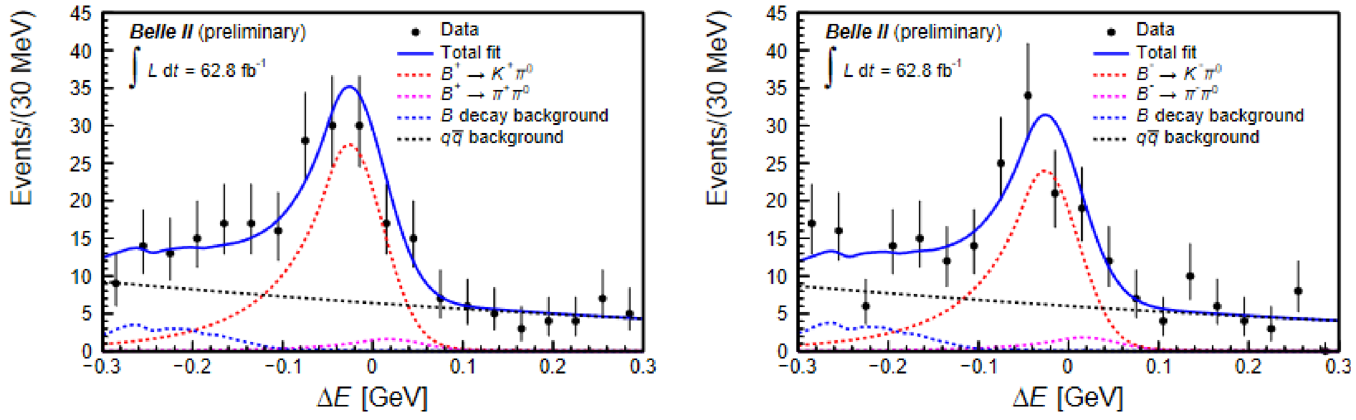
CP asymmetries in two-body decays

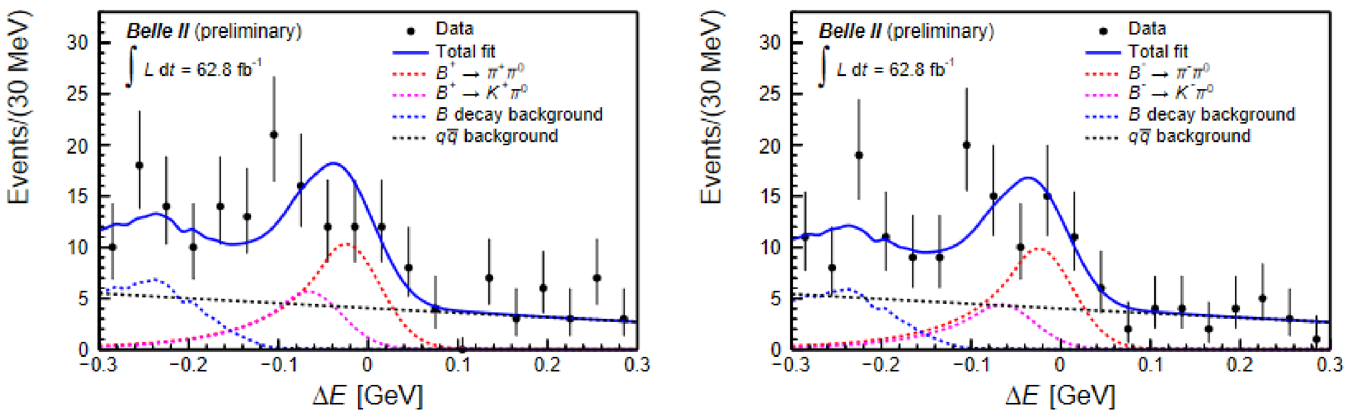




$A_{CP}(B^0 \to K^+\pi^-) = -0.16 \pm 0.05(stat) \pm 0.01(syst)$

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

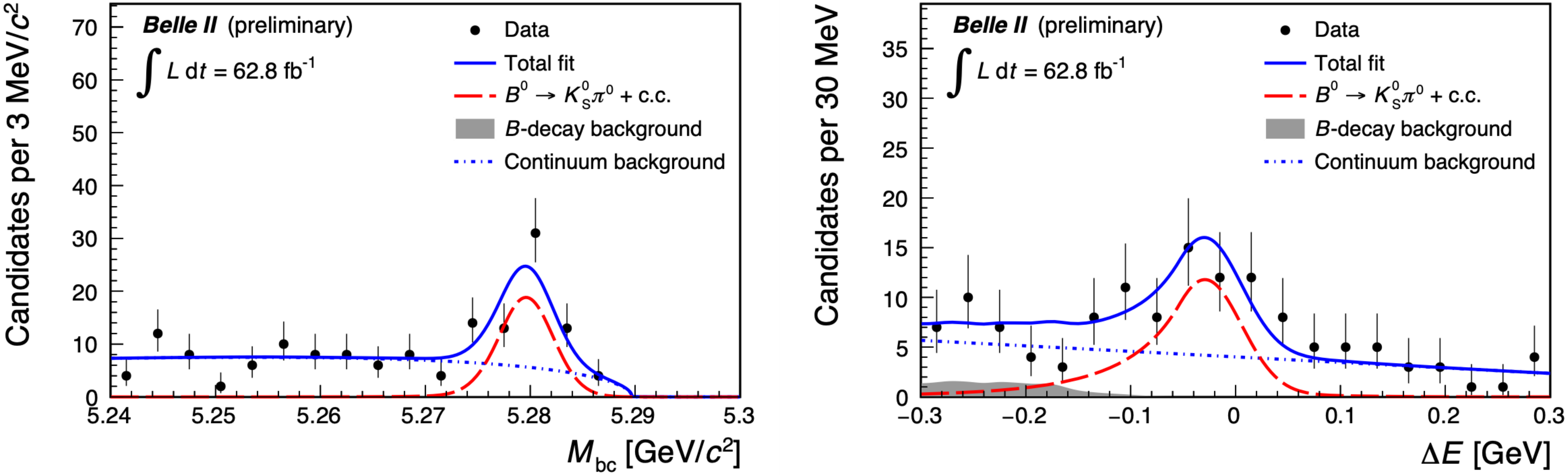




$A_{CP}(B^+ \to K^+\pi^0)$
$= -0.09 \pm 0.09(stat) \pm 0.022(syst)$

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

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

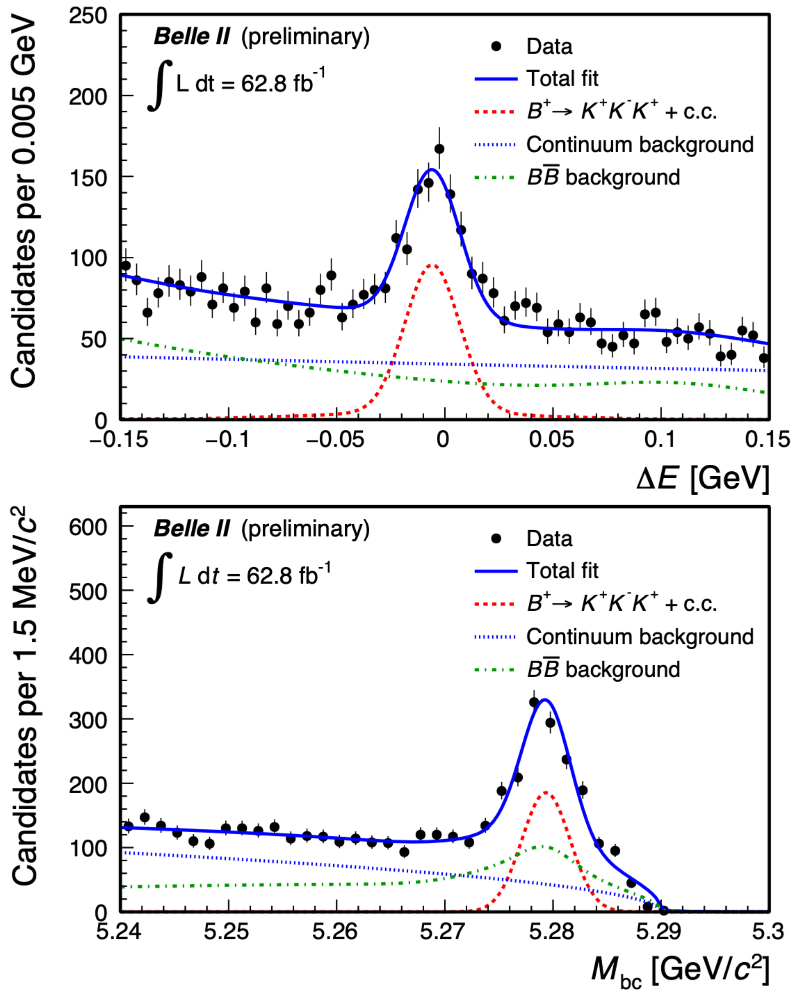


$$N(B^0 \to K_S^0\pi^0):\ 45^{+9}_{-8}$$

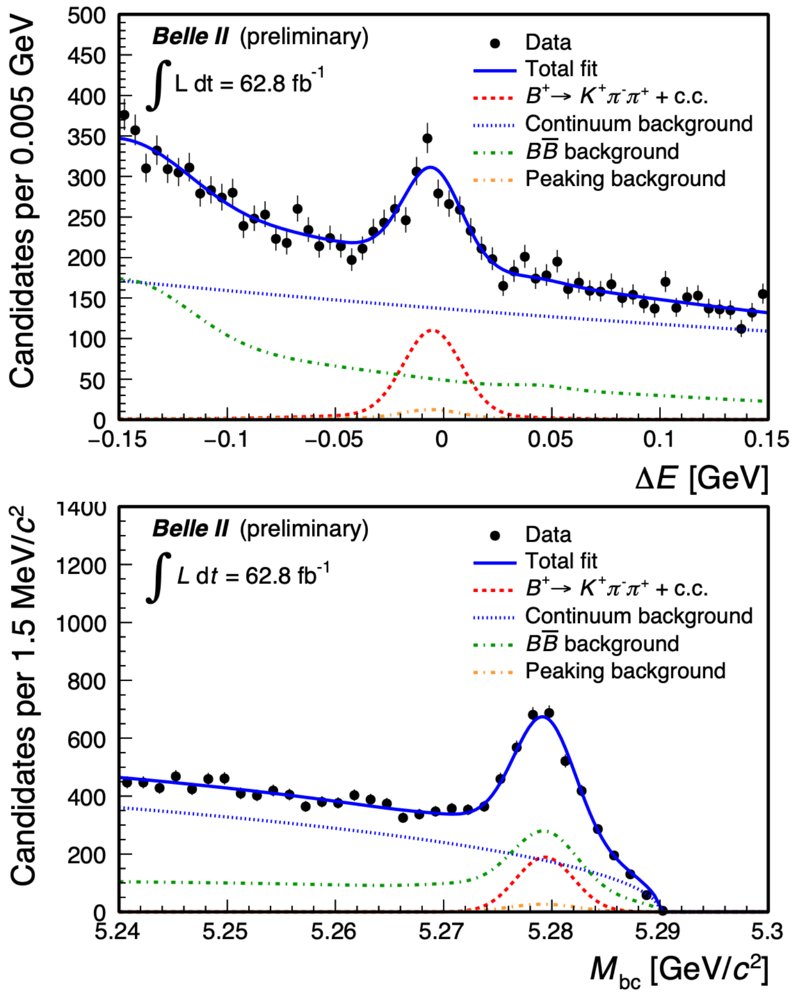
$$\mathcal{B}(B^0 \to K^0\pi^0) = [8.5^{+1.7}_{-1.6}(stat) \pm 1.2(syst)] \times 10^{-6}$$

Multibody: branching fractions

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



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



N$_{\text{Sig}}$: 690 ± 30 N$_{\text{Sig}}$: 843 ± 42

$\mathcal{B}[10^{-6}]$: $35.8 \pm 1.6(stat) \pm 1.4(syst)$ $67.0 \pm 3.3(stat) \pm 2.3(syst)$

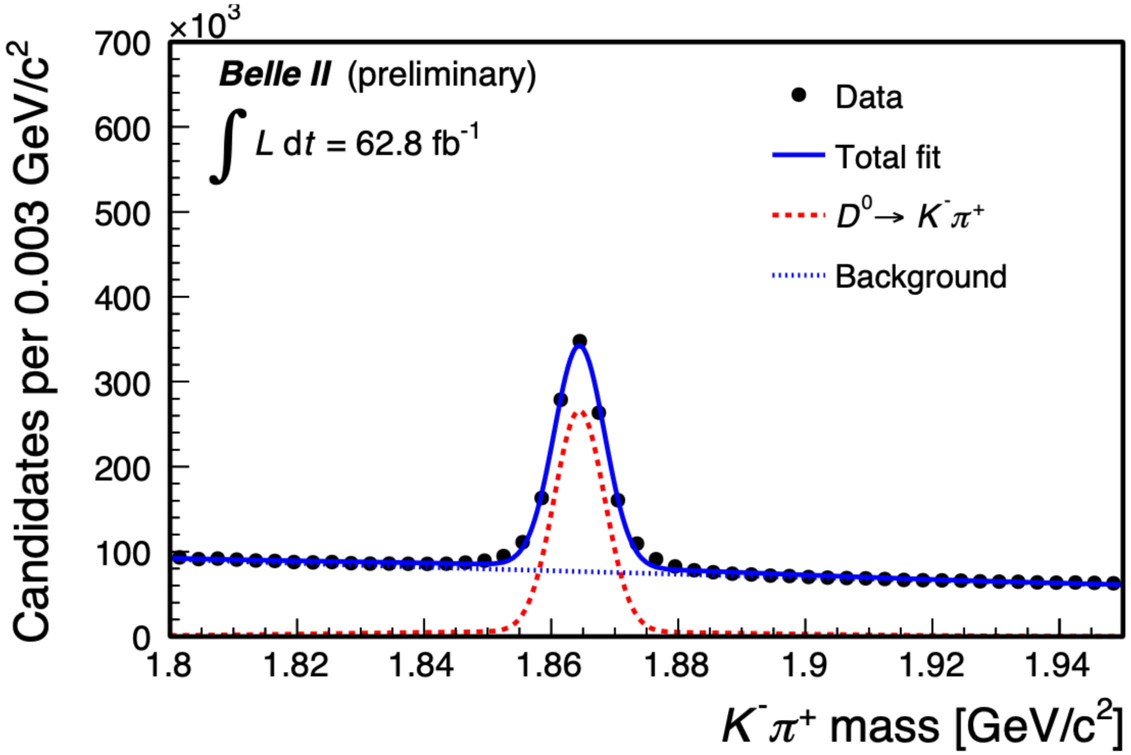
Instrumental asymmetries

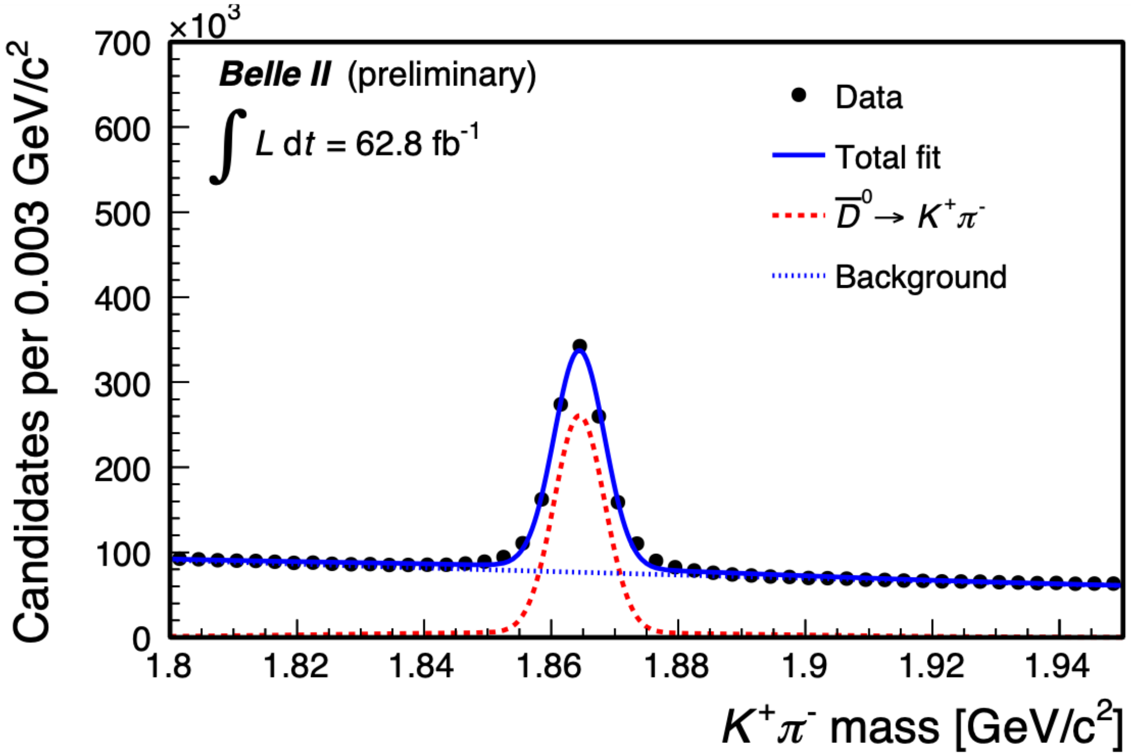
Observed charge-dependent signal yields depend on CP violation but also on charge-dependent instrumental reconstruction asymmetries (K_+/K_- ecc) that need be corrected for CP violation measurements

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

Tree-dominated hadronic D decays $D^+ \rightarrow K_S \pi^+$ and $D^0 \rightarrow K^- \pi^+$ 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.

Results generally compatible within $O(1)$% uncertainties, which propagate as systematics.