# Measurements of charmless *B* decays at Belle II

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on behalf of the Belle II collaboration

La Thuile 2021 — Les Rencontres de Physique de la Vallée d’Aoste
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# Charmless *B* decays


Hadronic *B* decays not mediated by $b \to c$.
Cabibbo-suppressed $\boldsymbol{b \to u}$ trees and $\boldsymbol{b \to d, s}$ 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.

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

Exp. challenges: $O(10^{-5})$ branching fractions, same final states of the dominant background ($e^+e^- \to q\bar{q}$ at Belle II).

**Belle II goals**

- Test SM using isospin sum rules;
- Investigate localized CP asymmetries in Dalitz plot of three-body decays;
- Improve precision on $\phi_2/\alpha$ angle.

**Today**: results on 35 fb$^{-1}$ and 63 fb$^{-1}$ (new for La Thuile).

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

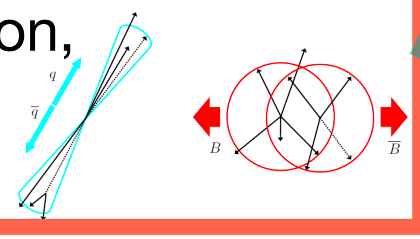
See details on the detector on today's talk by E. Torassa

# Analysis overview

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

**Selection**

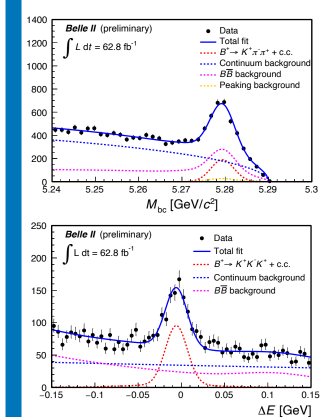
Continuum suppression, optimize on simulation and data.



**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.

**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 on signal data.

**Unblinding**

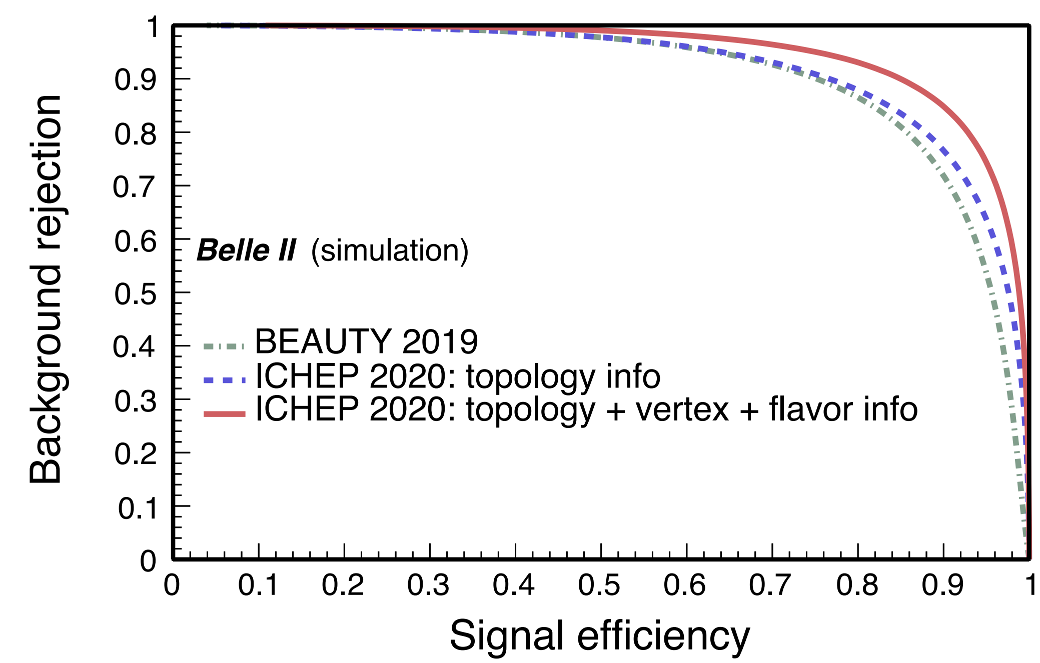
Apply full analysis to data.

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

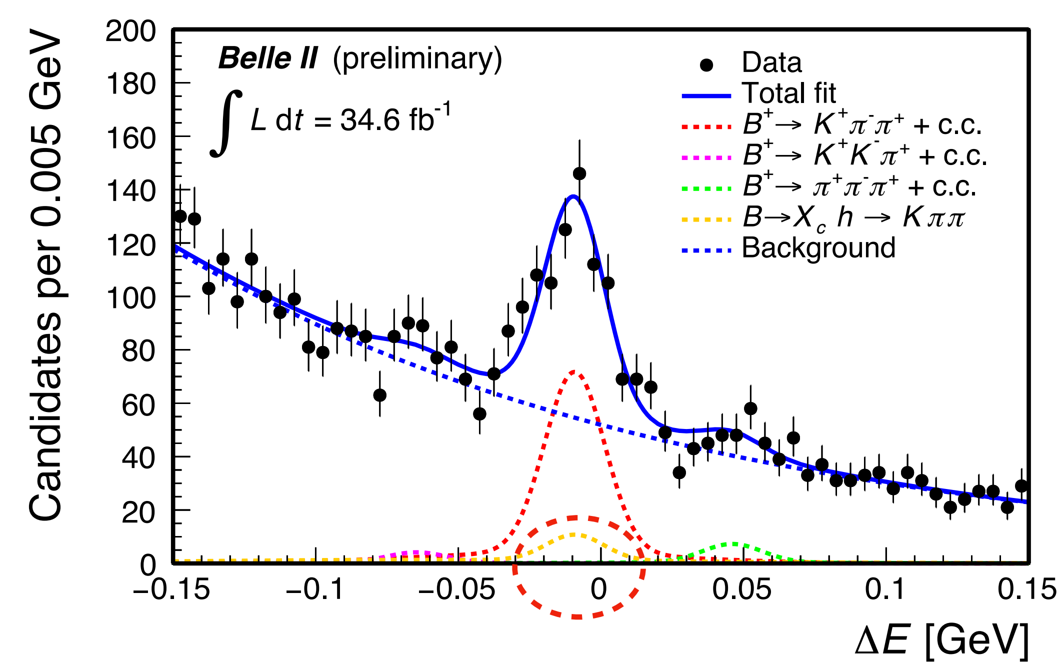
# Challenges

**Continuum suppression**: exploit topological differences, combine 30+ kinematic, decay-time and topological variables in multivariate techniques.

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




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




**Multidimensional fits**: fit simultaneously more variables to improve fit precision.

# Results

# Isospin sum rule: $K^+\pi^-$, $K^+\pi^0$, $K^0\pi^+$

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

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

Unique Belle II capability to study consistently all the $B \to K\pi$ decays.

$\mathcal{B}(B^0 \to K^+\pi^-) = [35.8 \pm 1.6(\text{stat}) \pm 1.4(\text{syst})] \times 10^{-6}$

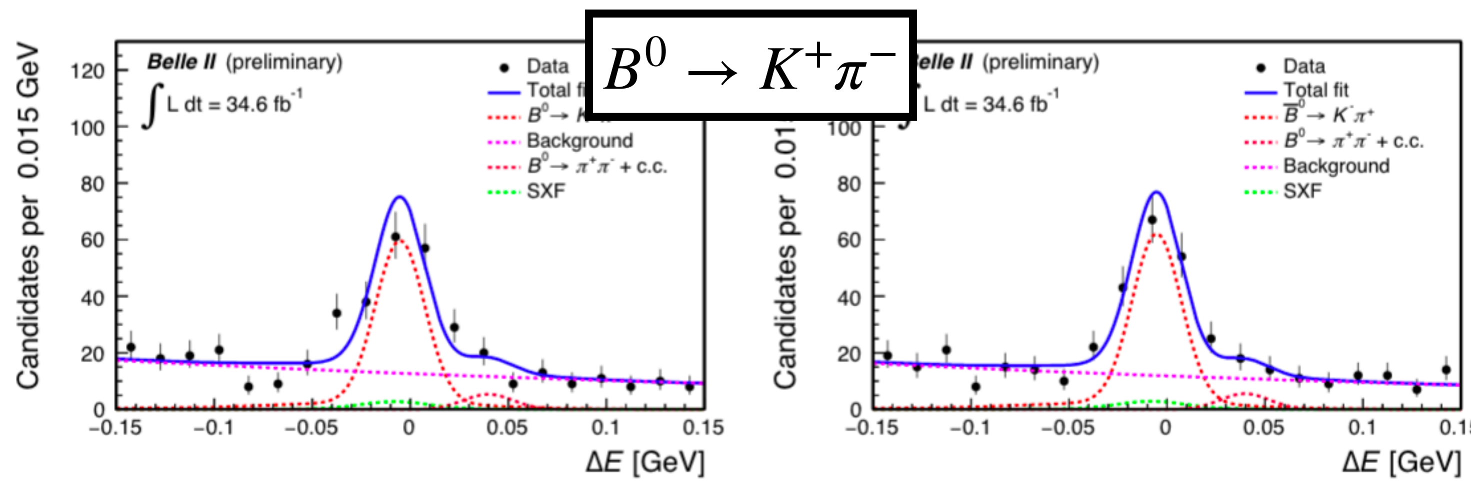
$A_{CP}(B^0 \to K^+\pi^-) = 0.030 \pm 0.064(\text{stat}) \pm 0.008(\text{syst})$

$\mathcal{B}(B^+ \to K^0\pi^+) = [21.8^{+3.3}_{-3.0}(\text{stat}) \pm 2.9(\text{syst})] \times 10^{-6}$

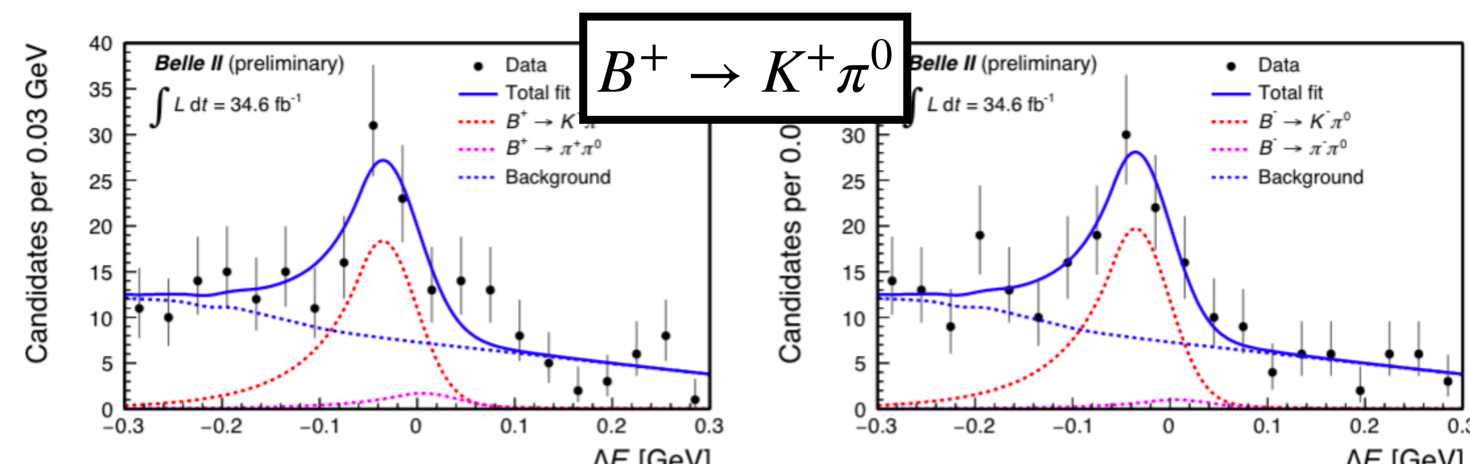
$A_{CP}(B^+ \to K^0\pi^+) = -0.072^{+0.109}_{-0.114}(\text{stat}) \pm 0.024(\text{syst})$

$\mathcal{B}(B^+ \to K^+\pi^0) = [12.7^{+2.2}_{-2.1}(\text{stat}) \pm 1.1(\text{syst})] \times 10^{-6}$

$A_{CP}(B^+ \to K^+\pi^0) = 0.052^{+0.121}_{-0.119}(\text{stat}) \pm 0.022(\text{syst})$




Probes tracking.




Probes $\pi^0$ reconstruction.

https://arxiv.org/pdf/2009.09452.pdf (34.6 fb$^{-1}$)

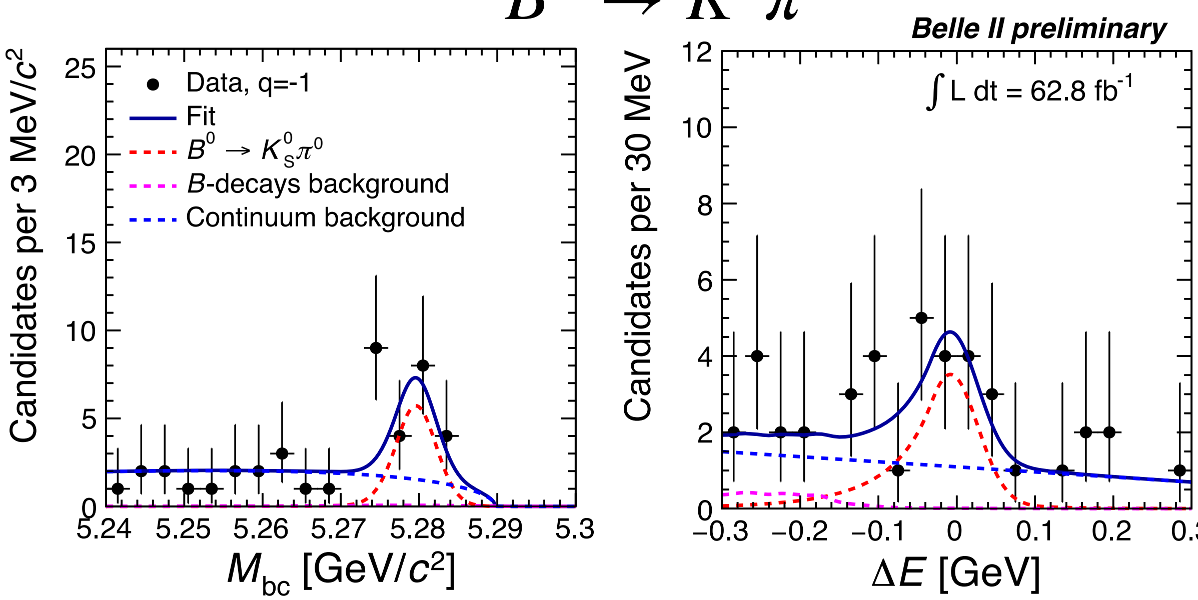
# Isospin sum rule: $K^0\pi^0$

62.8 fb$^{-1}$: new for La Thuile

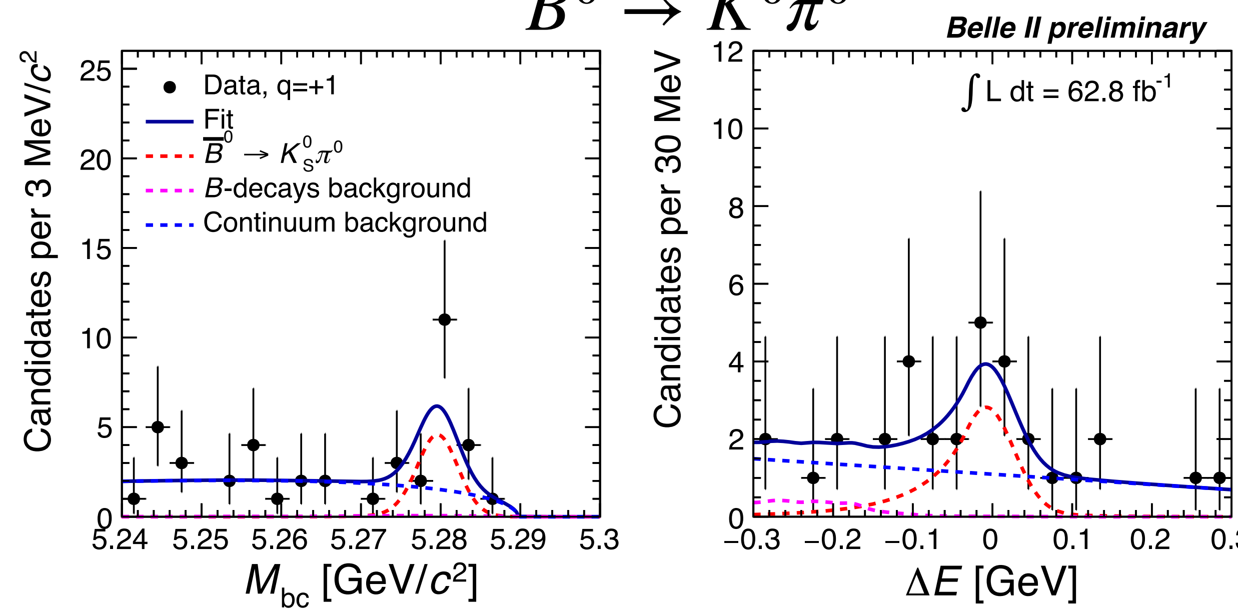
BF: challenging as it requires $K_S^0$ and $\pi^0$ reconstruction.
A$_{CP}$: requires also flavor tagging. Fit of ΔE-M$_{bc}$-flavor of the $B$ meson (q), simultaneously in 7 ranges of wrong-tag fraction (output from flavor tagger).

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

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




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




N($B^0 \to K_S^0\pi^0$): $46\ ^{+9}_{-8}$

**First measurement in Belle II data!**

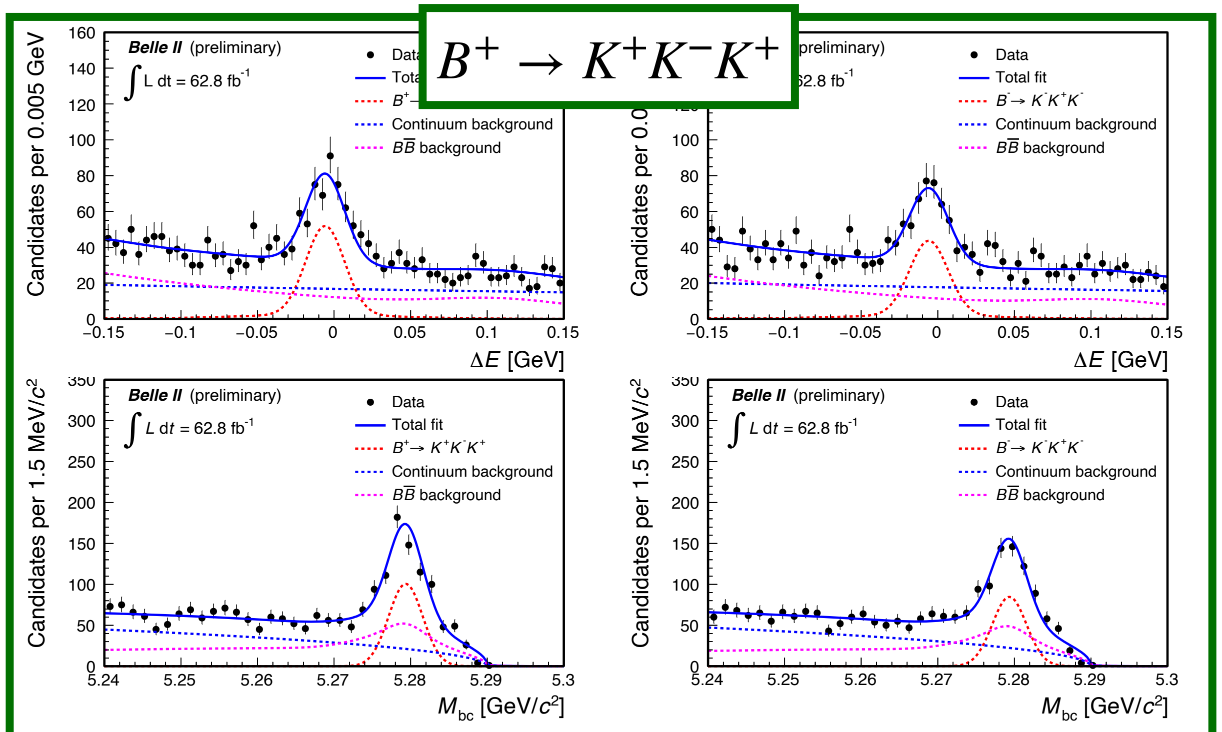
$\mathscr{B}(B^0 \to K^0\pi^0) = [8.6^{+1.7}_{-1.6}(\text{stat}) \pm 0.5(\text{syst})] \times 10^{-6}$

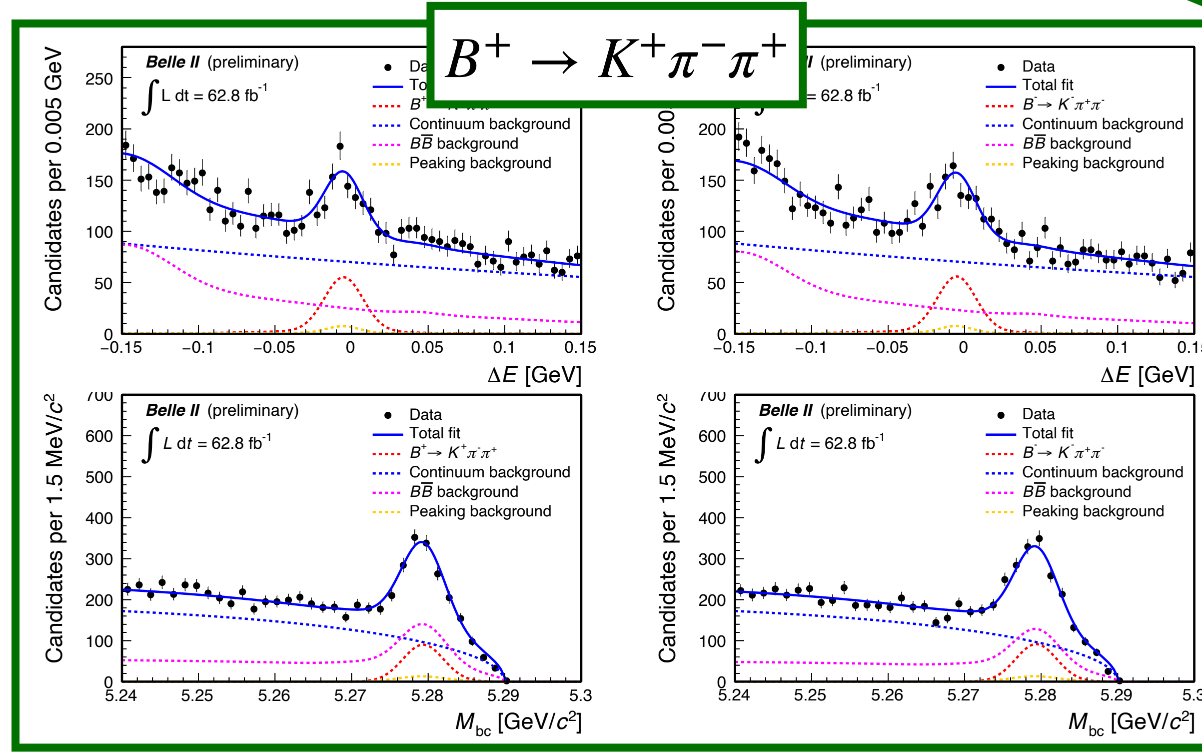
$A_{CP}(B^0 \to K^0\pi^0) = -0.41^{+0.46}_{-0.44}(\text{stat}) \pm 0.04(\text{syst})$

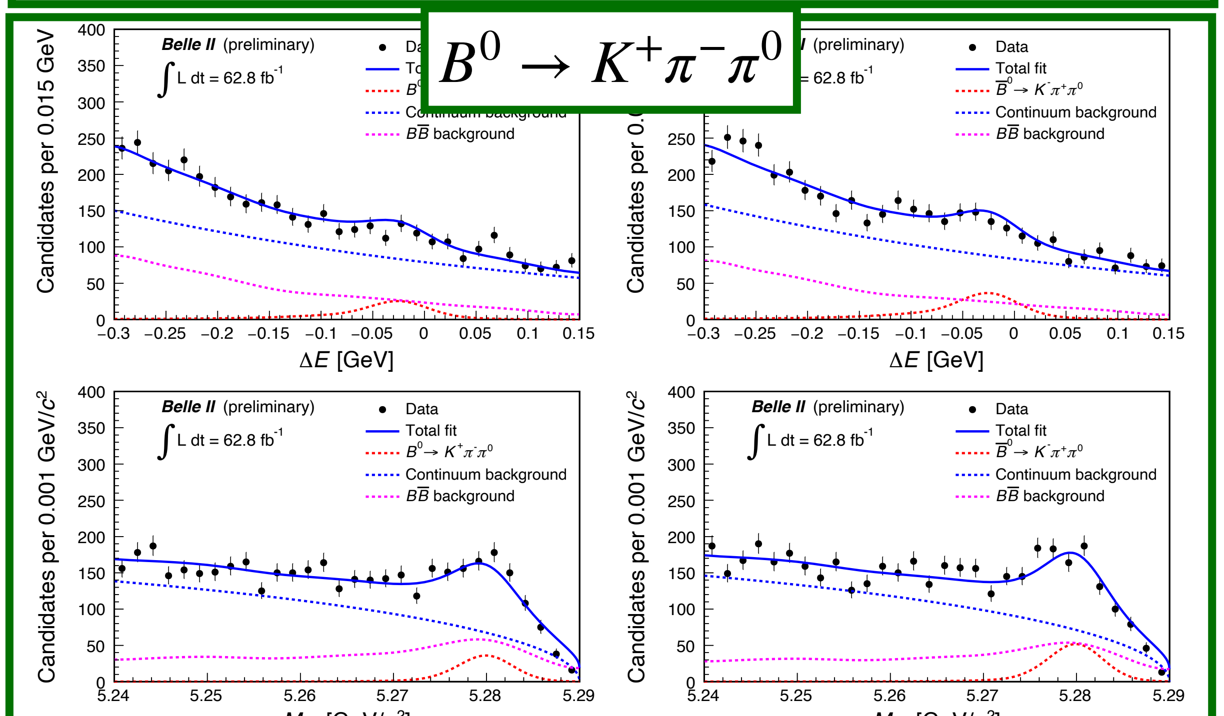
# CPV in multibody decays

62.8 fb$^{-1}$: new for La Thuile

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!**

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

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

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

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

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

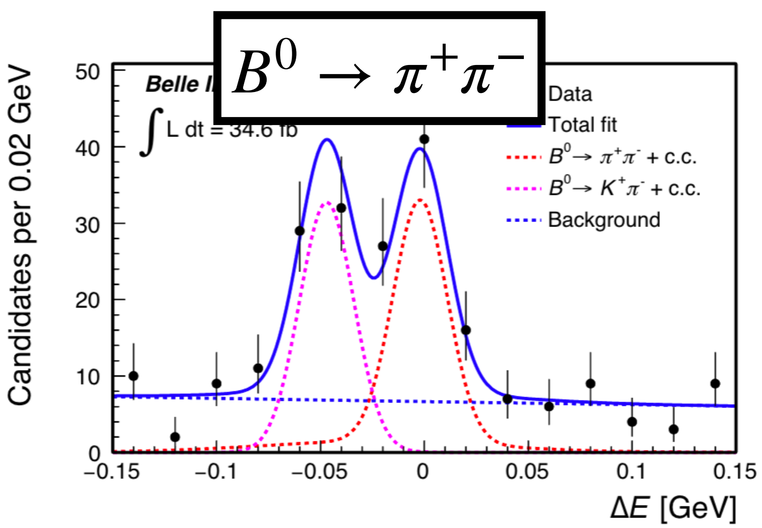
$$\mathscr{B}(B^0 \to K^+\pi^-\pi^0) = [41.7 \pm 3.7(\text{stat}) \pm 1.8(\text{syst})] \times 10^{-6}$$

$$A_{CP}(B^0 \to K^+\pi^-\pi^0) = 0.190 \pm 0.085(\text{stat}) \pm 0.005(\text{syst})$$

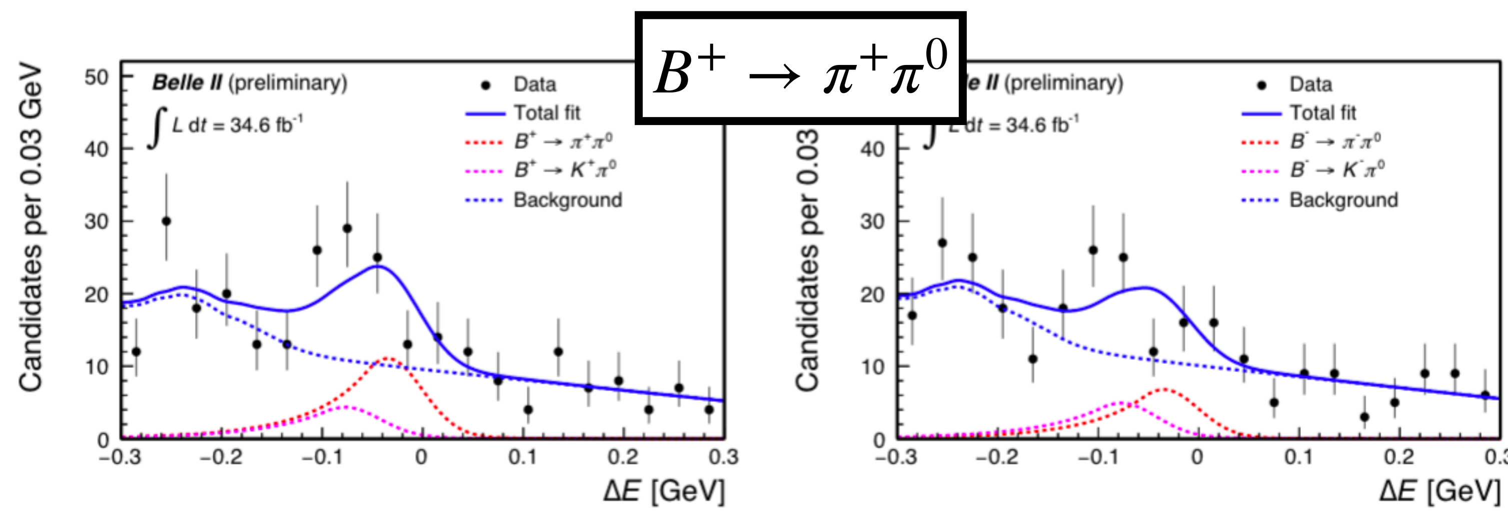
# Determination of $\alpha/\phi_2$

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 $\alpha$ from penguins or trees offers non-SM sensitivity.

Currently known with 6% uncertainty.




Benchmarks PID.




Probes $\pi^0$ reconstruction and PID.

$$\mathscr{B}(B^0 \to \pi^+\pi^-) = [5.6^{+1.0}_{-0.9}(\text{stat}) \pm 0.3(\text{syst})] \times 10^{-6}$$

$$\mathscr{B}(B^+ \to \pi^+\pi^0) = [5.7 \pm 2.3(\text{stat}) \pm 0.5(\text{syst})] \times 10^{-6}$$

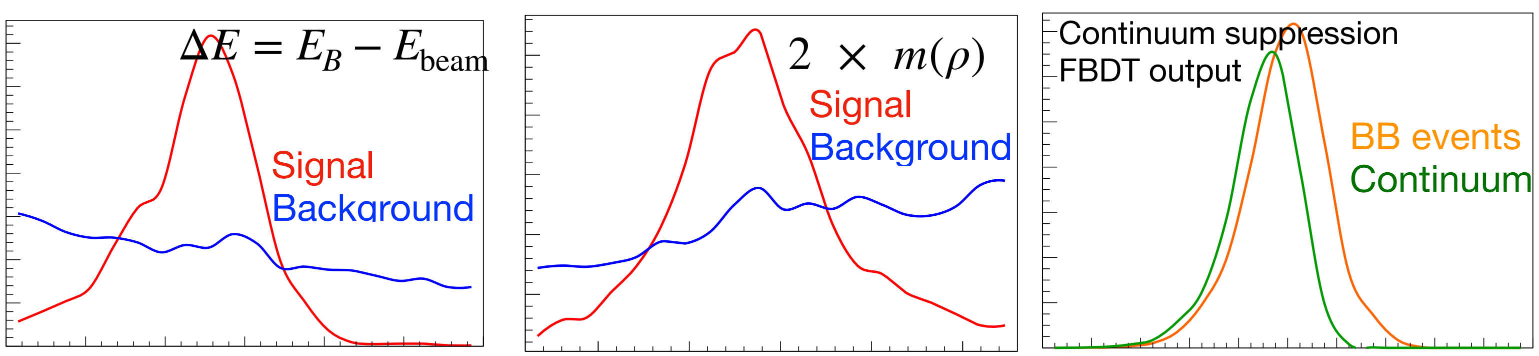
$$A_{CP}(B^+ \to \pi^+\pi^0) = -0.268^{+0.249}_{-0.322}(\text{stat}) \pm 0.123(\text{syst})$$

https://arxiv.org/pdf/2009.09452.pdf (34.6 $\mathrm{fb}^{-1}$)

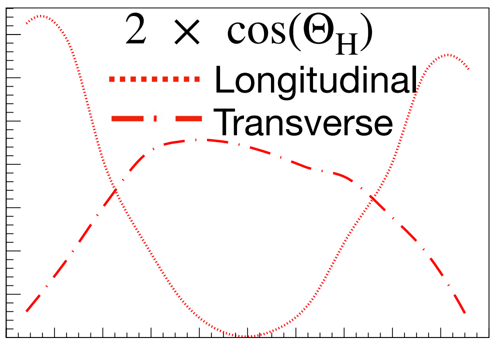
# Determination of $\alpha/\phi_2$: $B^+ \to \rho^+\rho^0$

$B \to \rho\rho$: the most promising probe of $\alpha$. Current best result from BaBar on 424 fb$^{-1}$ (PRL 102, 141802 (2009)): $\mathscr{B} = [23.7 \pm 2.0] \times 10^{-6}$, $f_L = 0.950 \pm 0.016$

Reconstruct the final state $(\pi^+\pi^0)(\pi^+\pi^-)$ → challenge of $\pi^0$.
Intermediate $\rho$ states have spin = 1 → need to fit also angular distributions to determine fraction of longitudinal polarization.
Broad mass peak of $\rho$ meson → accepts lots of background, need to fit.
⇒ 6D fit including $\rho$ masses and helicity angles.



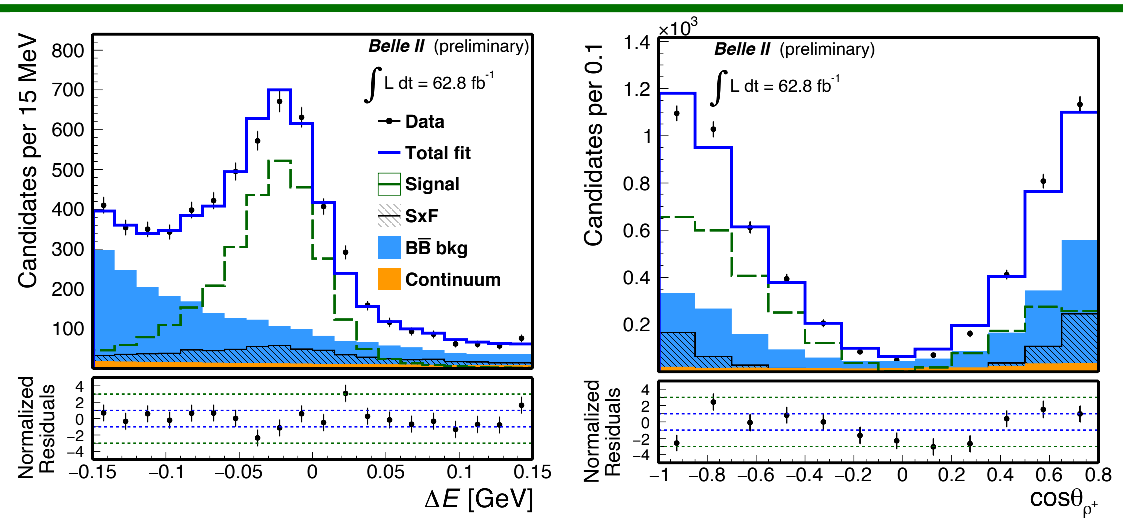

Separate signal from backgrounds.




Distinguish the two signal polarizations.

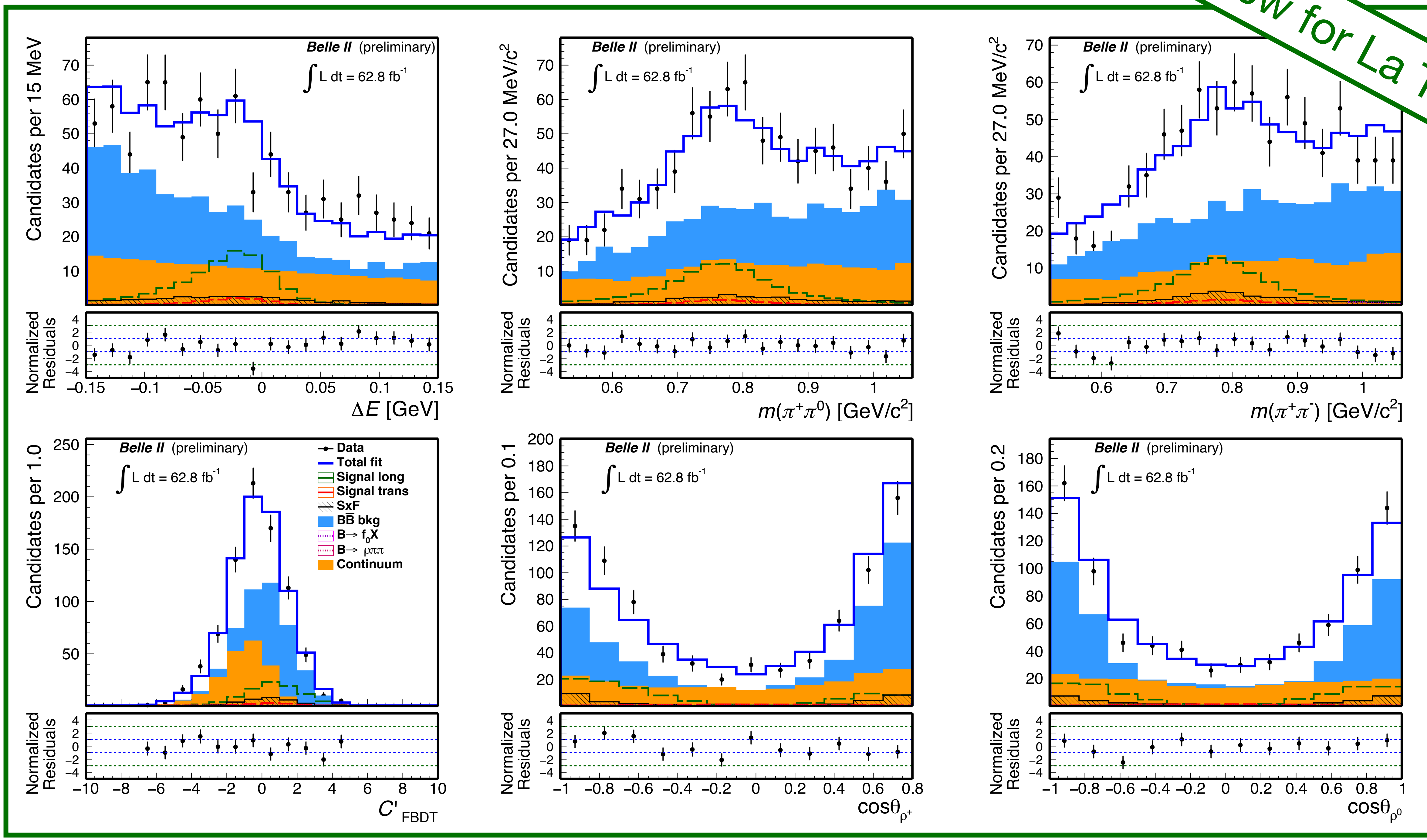
Full angular analysis validated on $B^+ \to \overline{D^0}(\to K^+\pi^-)\rho^+(\to \pi^+\pi^0)$ in data.

$$N_{sig} = 2877 \pm 79$$



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

62.8 fb-1: new for La Thuile




**First reconstruction in Belle II data!**

$\mathscr{B} = [20.6 \pm 3.2(\text{stat}) \pm 3.1(\text{syst})] \times 10^{-6}$

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

N: $104 \pm 17$

Belle on 78 fb$^{-1}$ (PRL 91, 221801 (2003)):

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

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

N: $59 \pm 13$

# Summary

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

Belle II preparing for a leading role in: $\alpha$, local CPVs, isospin sum rules.

First/improved measurements of charmless decays in 35-63 $fb^{-1}$ of early data.

New for La Thuile: first Belle II measurement of $A_{CP}(K^0\pi^0)$ completes the ingredients for the isospin sum rule; ρρ analysis surpasses early Belle's.
First Belle II measurement of $B^0 \rightarrow K^+\pi^-\pi^0$

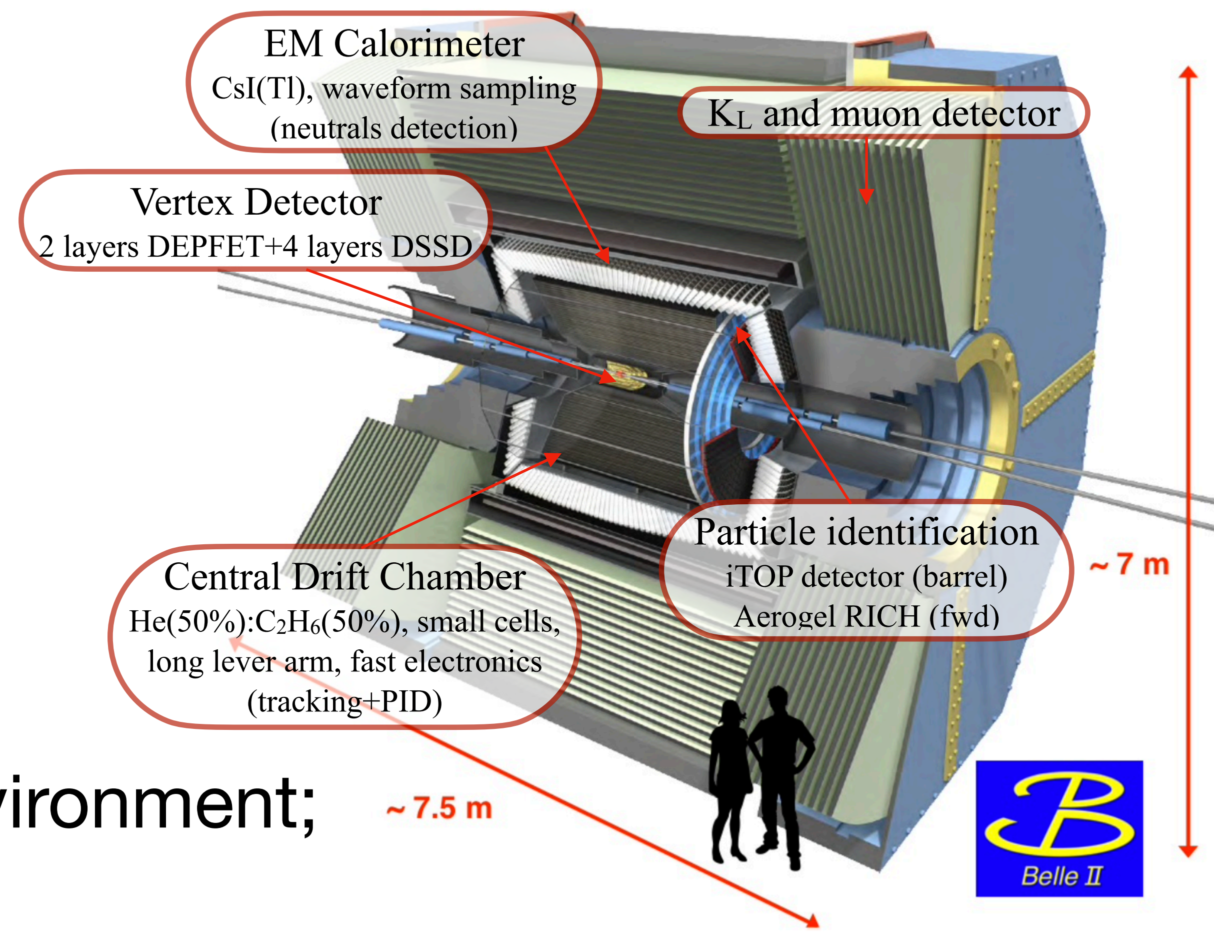
All results agree with known values within uncertainties dominated by small sample size. Performance comparable/better than at Belle demonstrates advanced understanding of detector/analysis tools.

# backup

# Charmless physics at Belle II

## Goals

- Improve precision on $\phi_2/\alpha$ angle;
- Test SM using isospin sum rules;
- Investigate localized CP asymmetries in three-body *B* decays;
- Study time-dependent CP violations.



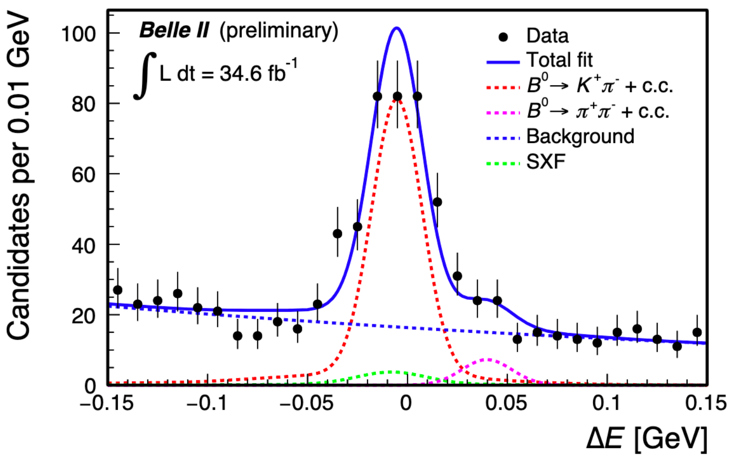

## Belle II

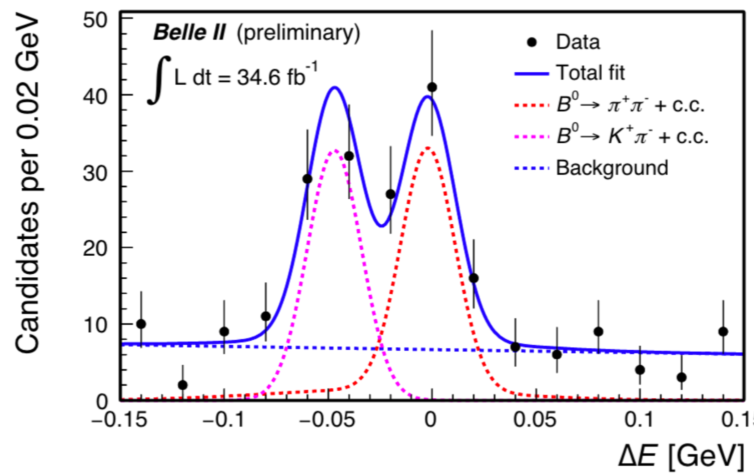
- ~900 BB pairs/second in low-bkg environment;
- xxx $fb^{-1}$ of data collected;
- World record peak luminosity in June 2020: 2.4x$10^{34}$ $cm^{-2}$ $s^{-1}$
- Complementary to LHCb (final states with neutrals and V0s).

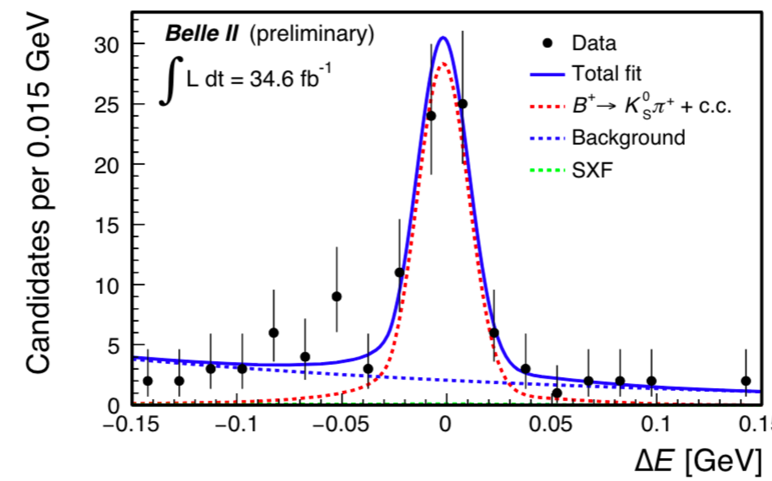
**Today:** measurements of branching fractions, CP asymmetries and polarizations for various charmless B decays using 35 or 62 $fb^{-1}$

# 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($B^0 \to K^+\pi^-$): $289\ ^{+22}_{-21}$

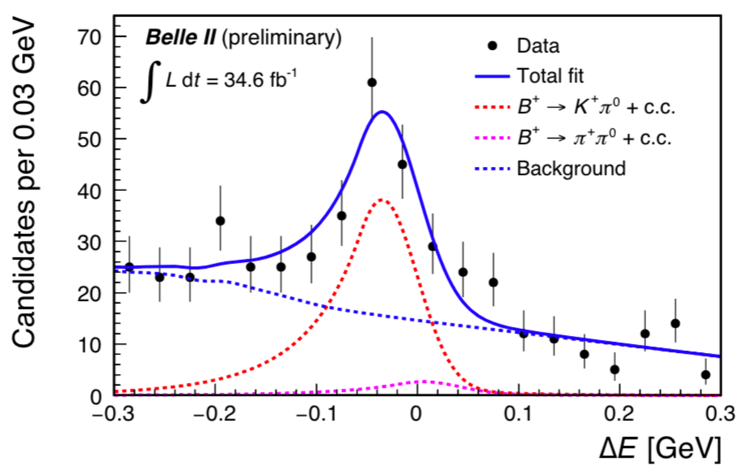
N($B^0 \to \pi^+\pi^-$) $62\ ^{+10}_{-11}$

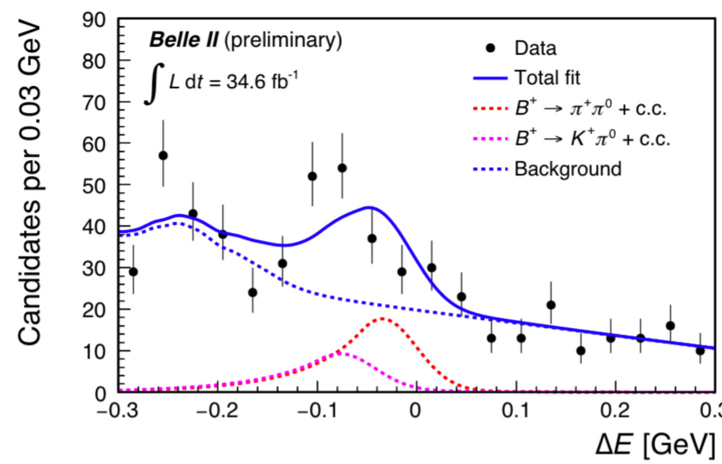
N($B^+ \to K_S^0\pi^+$): $65\ ^{+10}_{-\ 9}$

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

$5.6^{+1.0}_{-0.9}$(stat) $\pm\ 0.3$(syst)

$21.8^{+3.3}_{-3.0}$(stat) $\pm\ 2.9$(syst)




Challenge of $\pi^0$ reconstruction performances, require good PID.

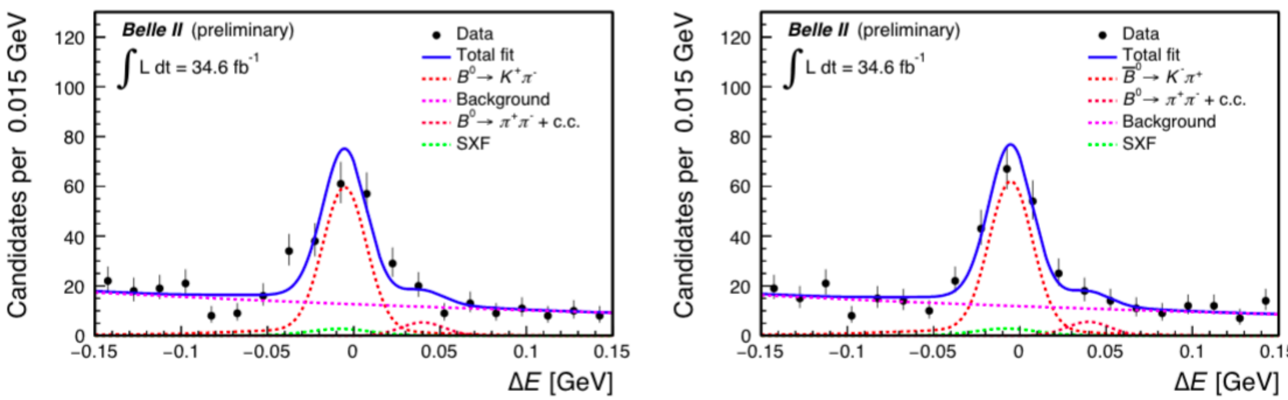
N($B^+ \to K^+\pi^0$): $289\ ^{+22}_{-21}$

N($B^+ \to \pi^+\pi^0$): $62\ ^{+10}_{-11}$

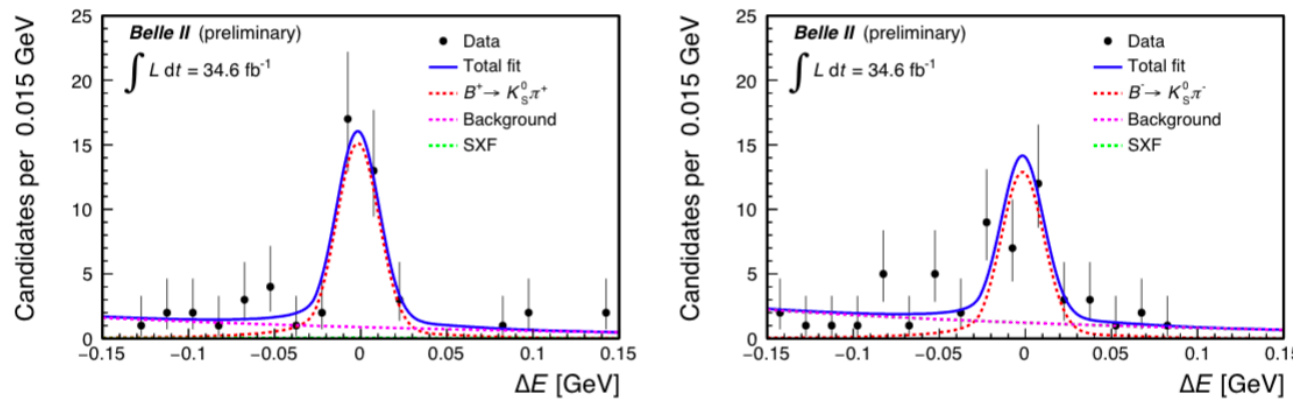
$\mathscr{B}\ [10^{-6}]$ : $12.7^{+2.2}_{-2.1}$(stat) $\pm\ 1.1$(syst)

$5.7 \pm 2.3$(stat) $\pm\ 0.5$(syst)

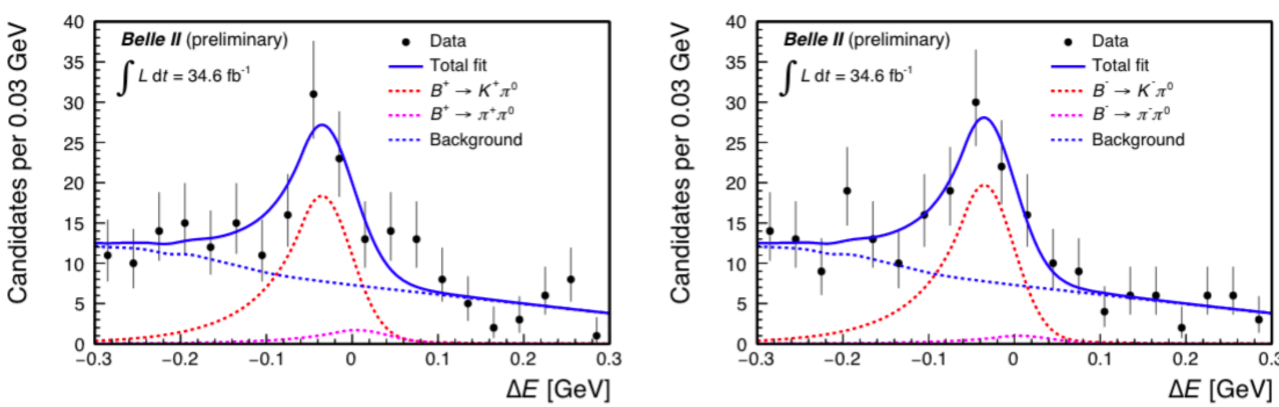
# CP asymmetries in two-body decays



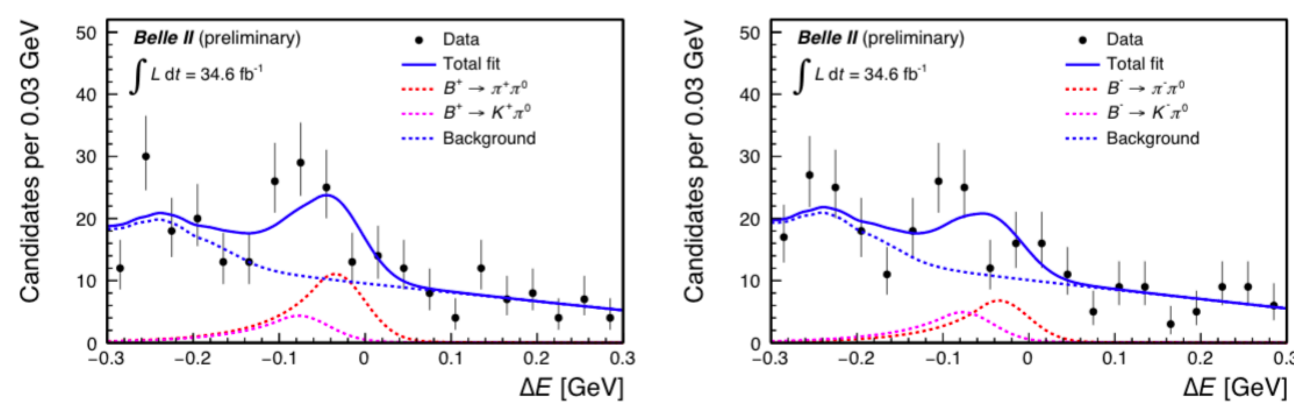

$A_{CP}(B^0 \to K^+\pi^-) = 0.030 \pm 0.064(\text{stat}) \pm 0.008(\text{syst})$




$A_{CP}(B^+ \to K^0\pi^+) = -0.072^{+0.109}_{-0.114}(\text{stat}) \pm 0.024(\text{syst})$



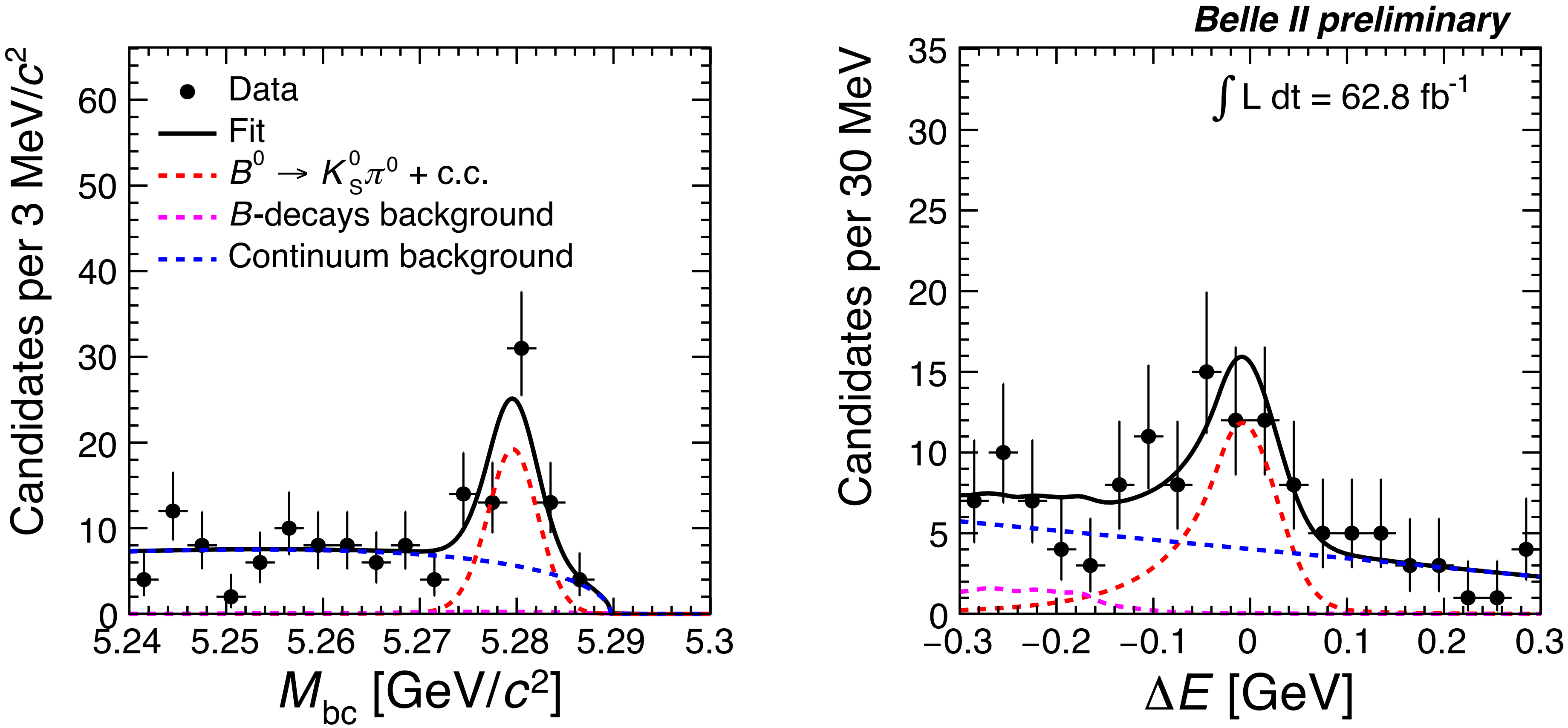

$A_{CP}(B^+ \to K^+\pi^0) = 0.052^{+0.121}_{-0.119}(\text{stat}) \pm 0.022(\text{syst})$




$A_{CP}(B^+ \to \pi^+\pi^0) = -0.268^{+0.249}_{-0.322}(\text{stat}) \pm 0.123(\text{syst})$

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

62.8 fb$^{-1}$: new for La Thuile



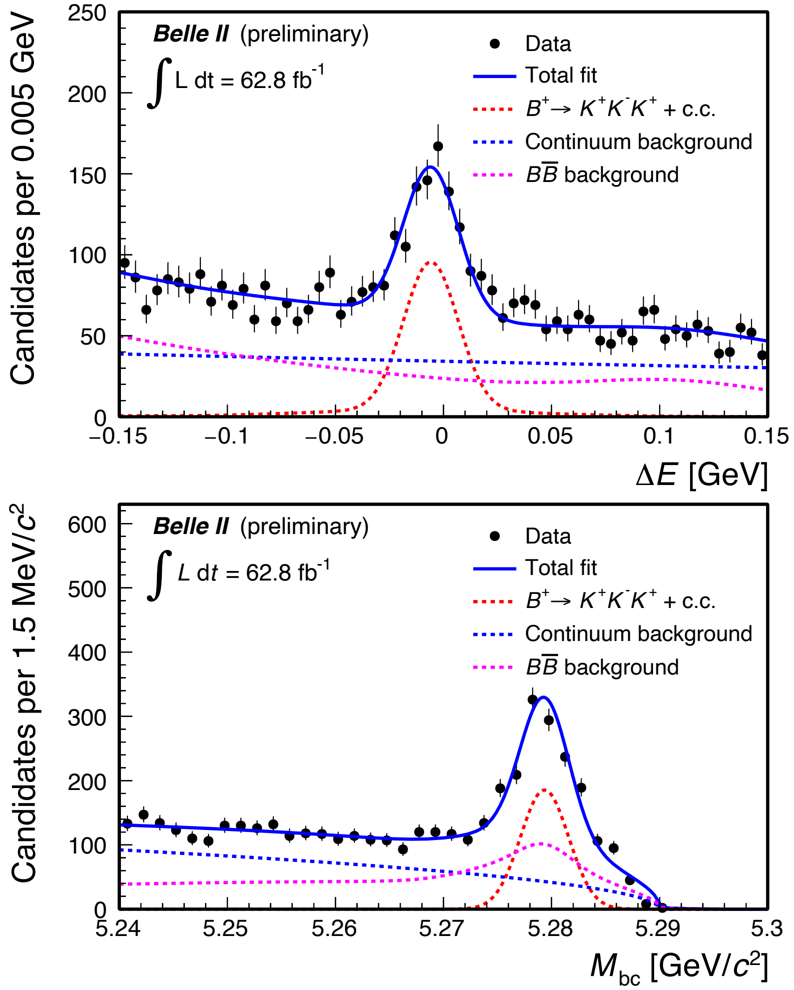

N($B^0 \to K^0_S\pi^0$): $46\ ^{+9}_{-8}$

$\mathscr{B}(B^0 \to K^0\pi^0) = [8.6^{+1.7}_{-1.6}(\text{stat}) \pm 0.5(\text{syst})] \times 10^{-6}$

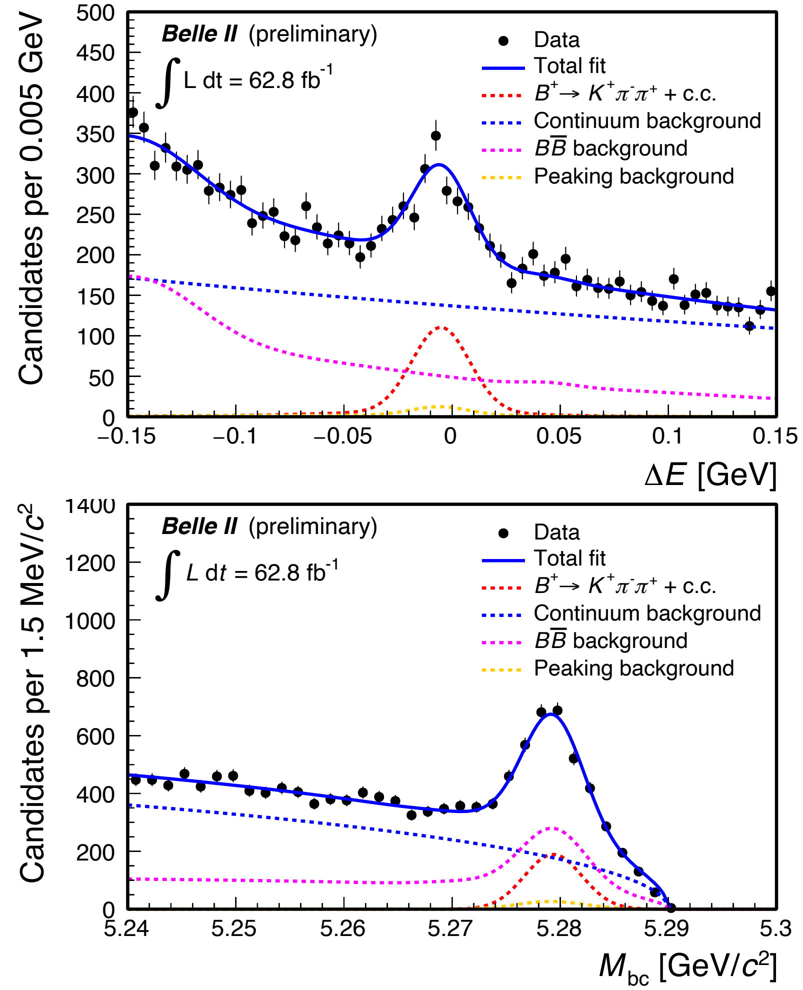
# Multibody: branching fractions

62.8 fb$^{-1}$: new for La Thuile

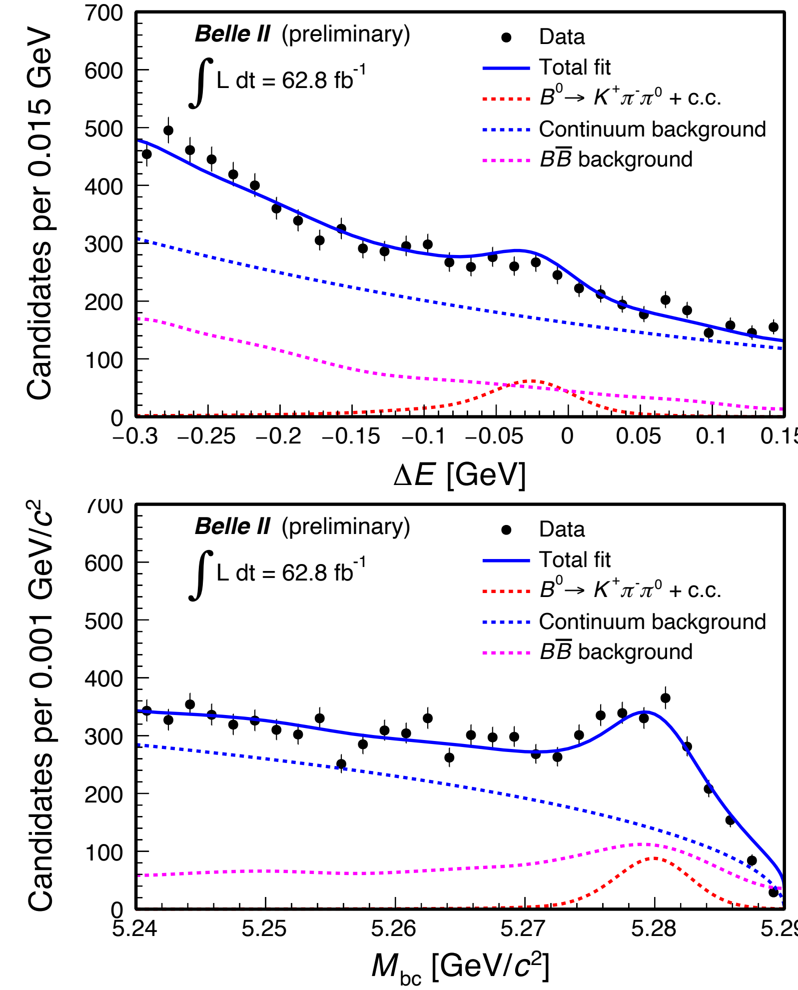
$B^+ \to K^+K^-K^+$




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




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




$N_{Sig}$: 690 ± 30

$N_{Sig}$: 843 ± 42

$N_{Sig}$: 415 ± 37

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

67.0 ± 3.3(stat) ± 2.3(syst)

41.7 ± 3.7(stat) ± 1.8(syst)

**First reconstruction in Belle II data!**

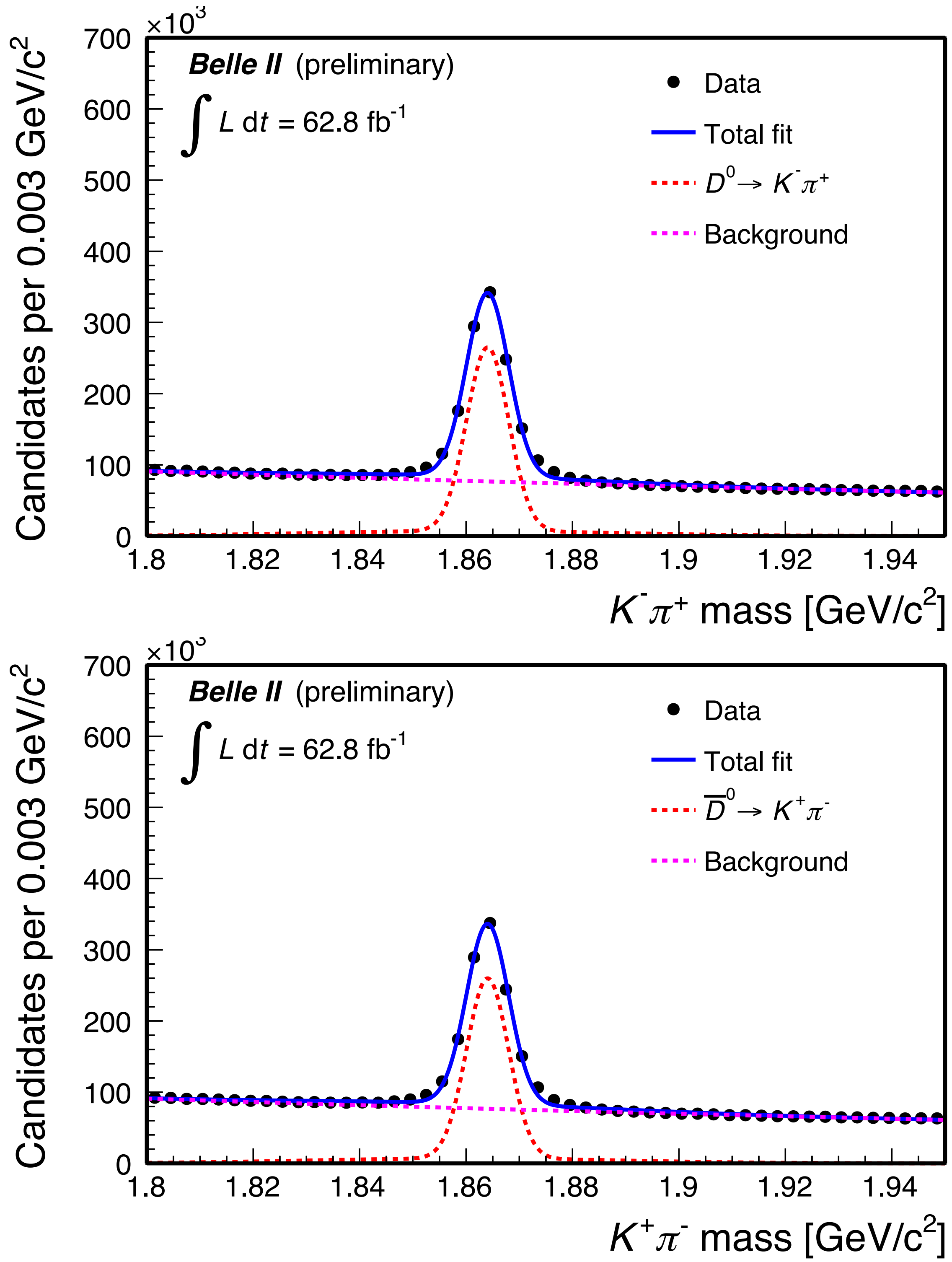
# Instrumental asymmetries

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 $D^+ \rightarrow K_S \pi^+$ 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.

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



# 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 $\pi^0$ 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.