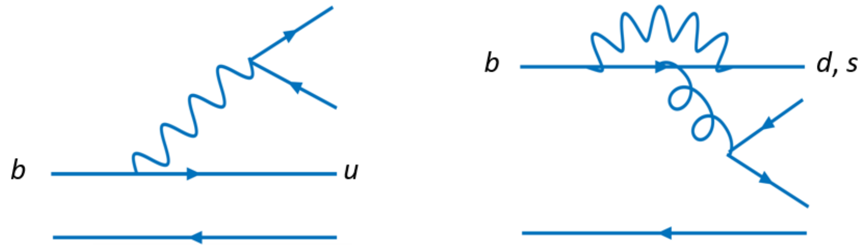
Charmless B decays in Belle II
FPCP 2021

June, 10, 2021

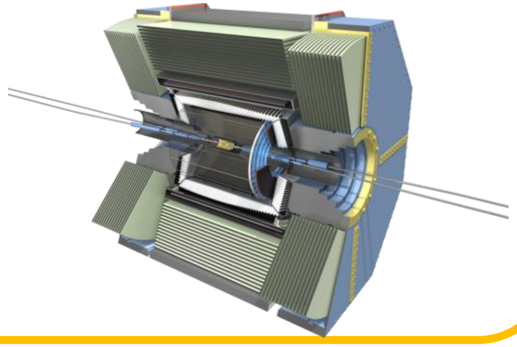
Ching-Hua Li
National Taiwan University
(on behalf of the Belle II Collaboration)

Outline

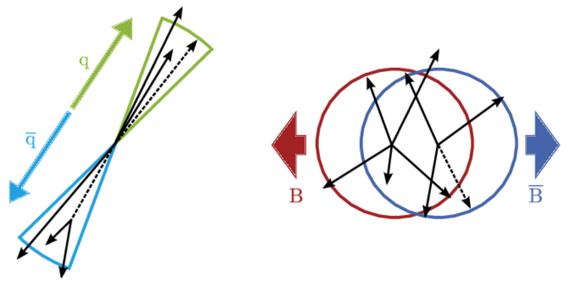
1 Physics of charmless B decays



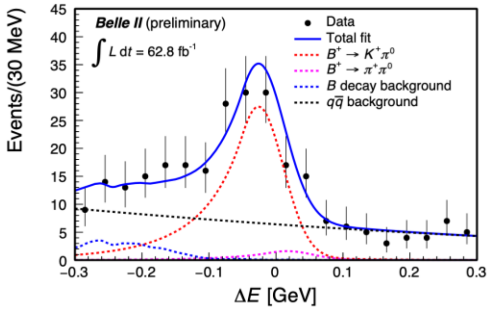
2 Belle II Detector



3 Analysis Challenges



4 Results



5 Summary

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.

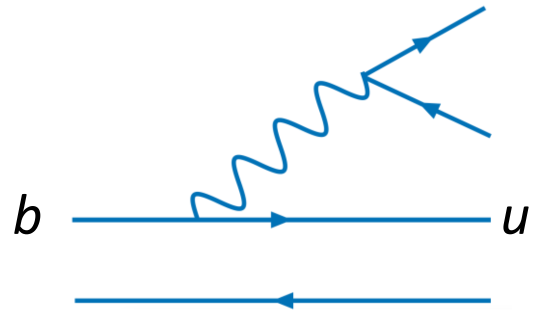
Charmless B decays :

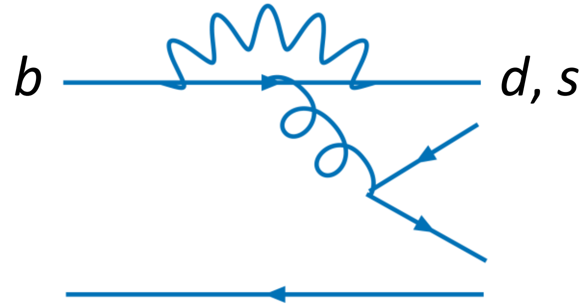
Hadronic decays not mediated by b → c. ⇒ low BF (10^{-5}).

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

→ Highly sensitive to non-SM loops

→ Probe non-SM dynamics in all three CKM angles





Belle II charmless B program

- Test SM using isospin sum rules $(I_{K\pi})$: $B \to K\pi$
- Investigate localized CP asymmetries in Dalitz plot :

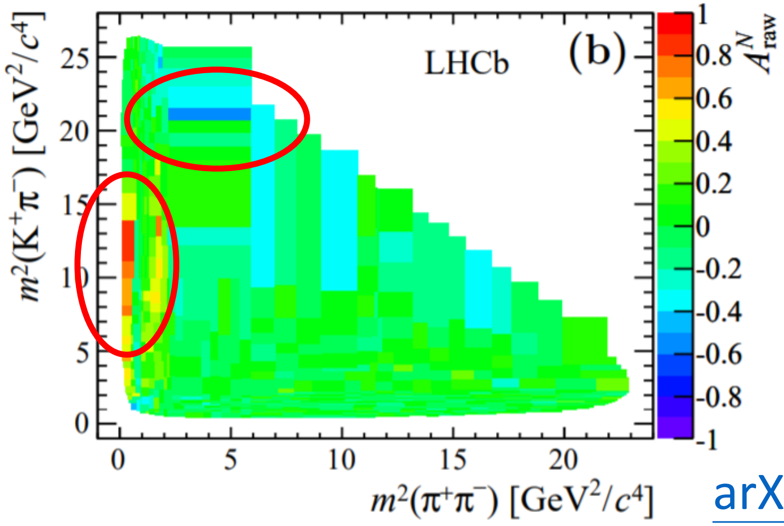
$B \to hhh$

- Improve precision on angle α/ϕ_2 : $B \to \pi\pi, \rho\rho$

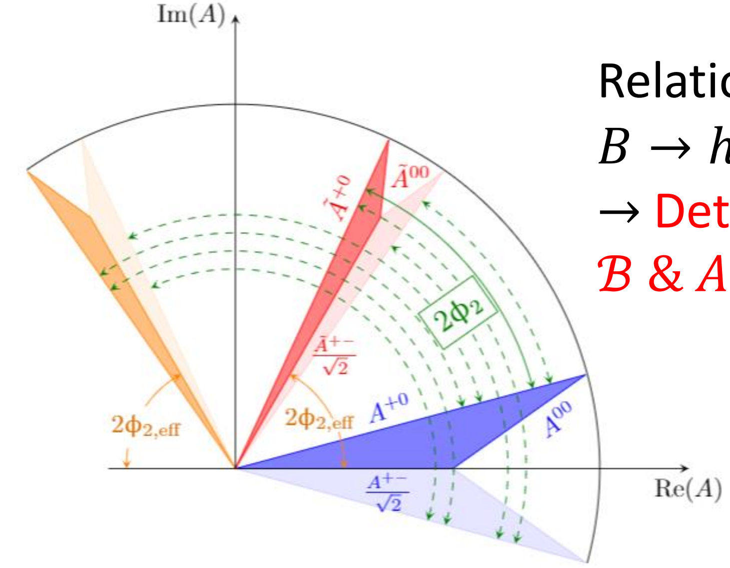
$B^+ \to K^+\pi^0$ $B^0 \to K^+\pi^-$

$I_{K\pi}$

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



arXiv:1408.5373



Relationships between α/ϕ_2 and $B \to h^i h^j$ decay amplitudes
→ Determine α/ϕ_2 by $\mathcal{B}$ & A_{CP} of $B \to \pi\pi, \rho\rho$

Unique Belle II capability to study all the decays !

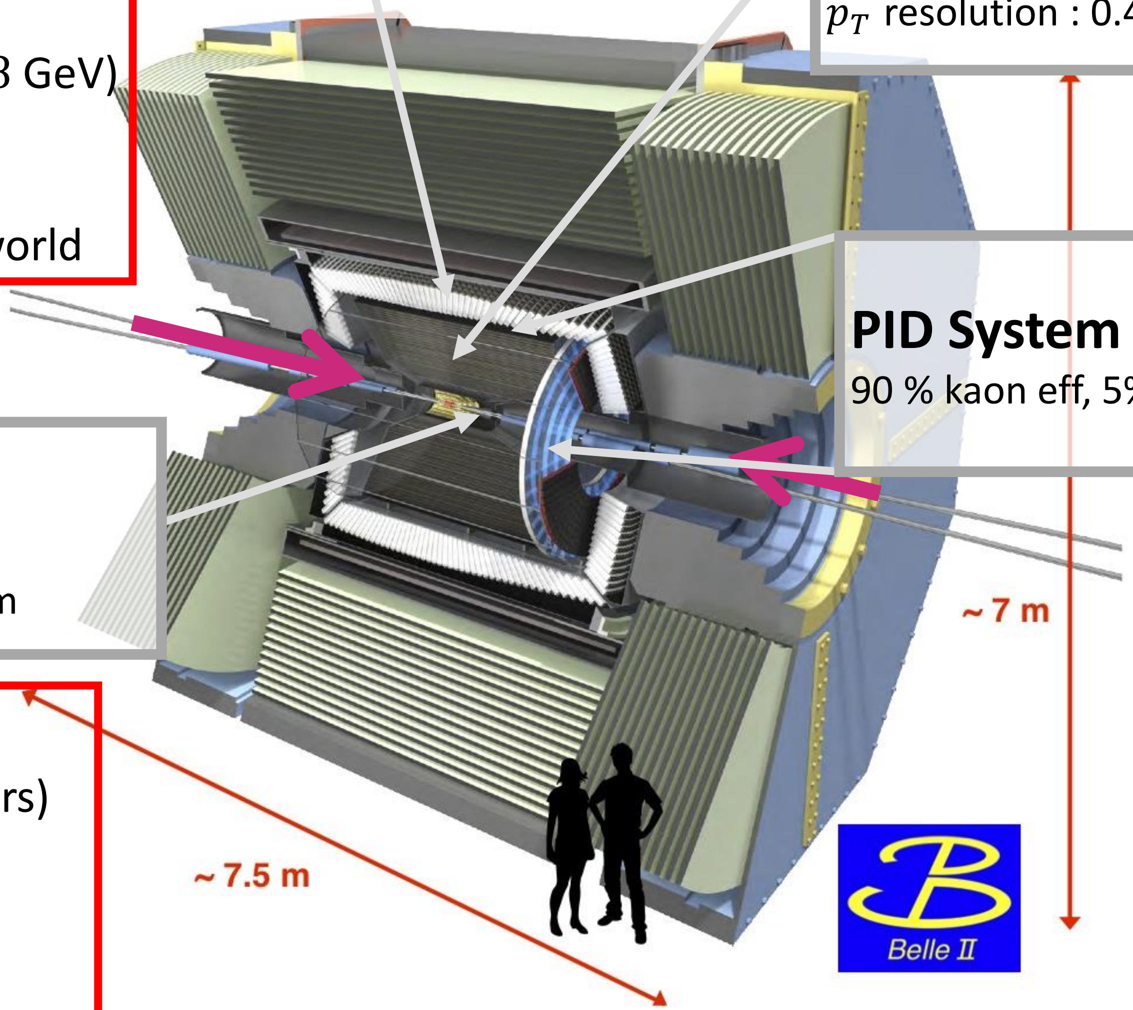
Detector

Electromagnetic Calorimeter
π^0 reconstruction
Energy resolution : 1.6 - 4%

Central Drift Chamber
Track efficiency ~ 99%
dE/dx resolution : 5%
p_T resolution : 0.4 %

Features :
- Energy-asymmetric $e^+ e^-$ collider ($\sqrt{s} = 10.58$ GeV)

⇒ low background environment for analysis
- Advantage in $B \to h^0$, invisible analysis
- Highest luminosity (2.8 X 10^{34} cm^{-2} s^{-1}) in the world



PID System
90 % kaon eff, 5% pion fake rate

Vertex Detector
High K_s^0 efficiency
Vertex resolution : 15 μm

Target :
- Collect more than 50 ab^{-1} data (5 X 10^{10} $B\overline{B}$ pairs)
- 700 $B\overline{B}$ pairs/second

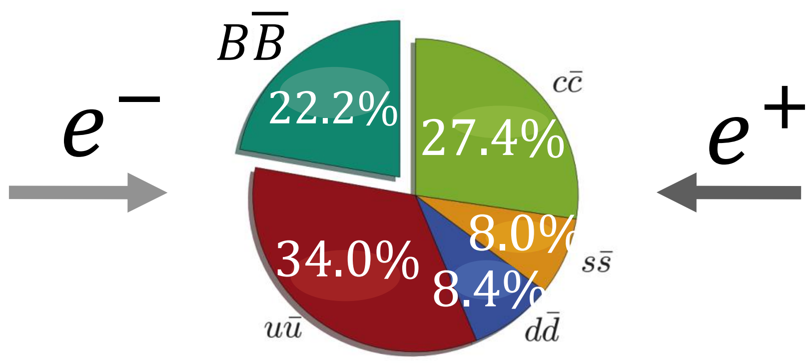
Currently :
- 140 fb^{-1} data are collected (1.4 X 10^8 $B\overline{B}$ pairs)
- ~30 $B\overline{B}$ pairs/second

Detail covered by Minakshi Nayak

Analysis Challenges

Background suppression

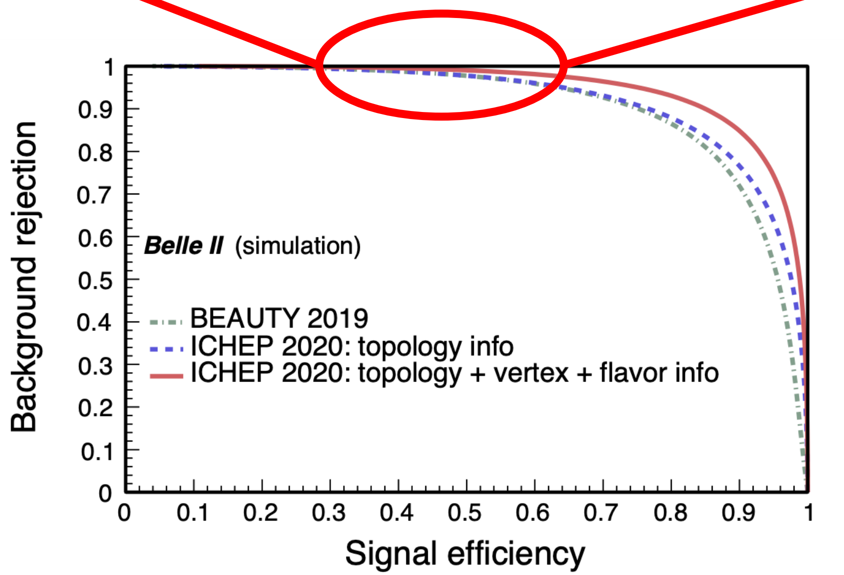
Most of background come from $\underline{e^+e^- \to q\bar{q}}$ process
$(c\bar{c}, d\bar{d}, s\bar{s}, u\bar{u})$

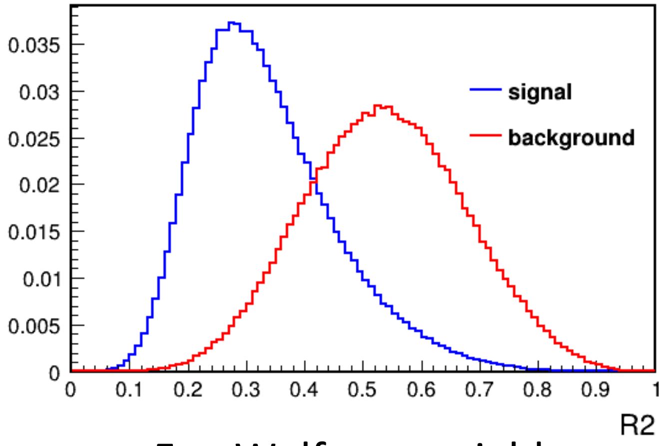


In charmless B decay :
1 signal event in every $\mathcal{O}(10^5)$ events

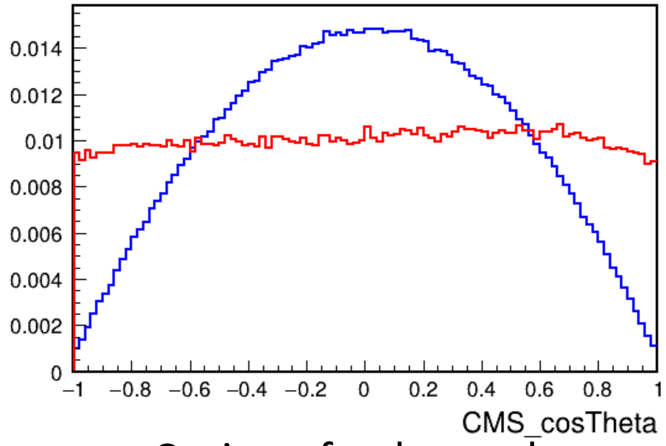
$q\bar{q}$ (continuum) bckg suppression :
Combine 40 kinematic, decay-time and topological variables in multivariate techniques.

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





Fox-Wolfram variable

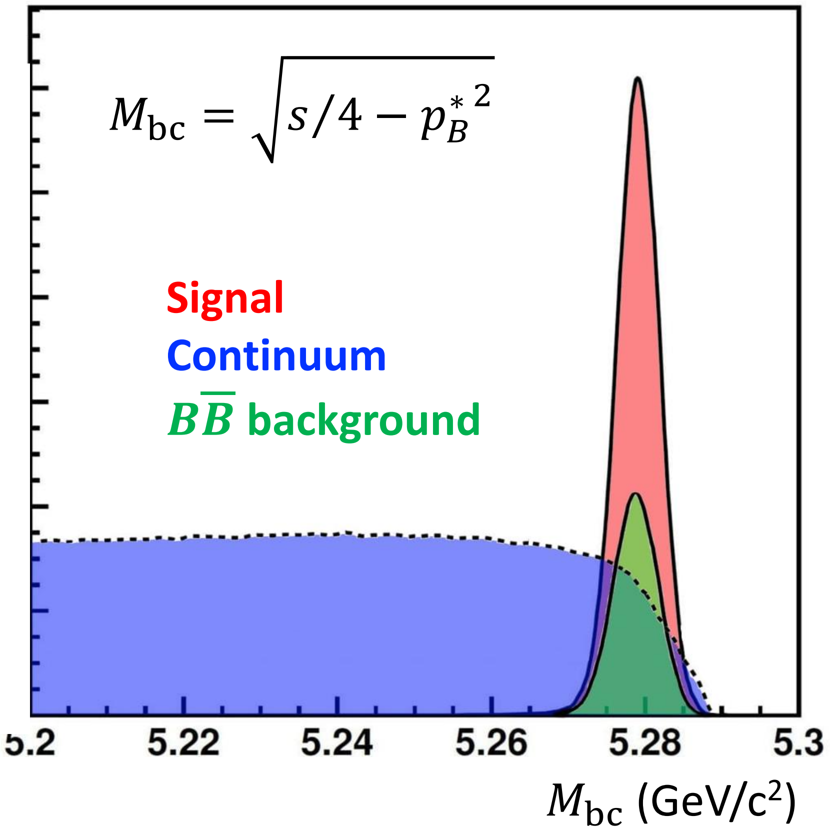


Cosine of polar angle

Signal extraction

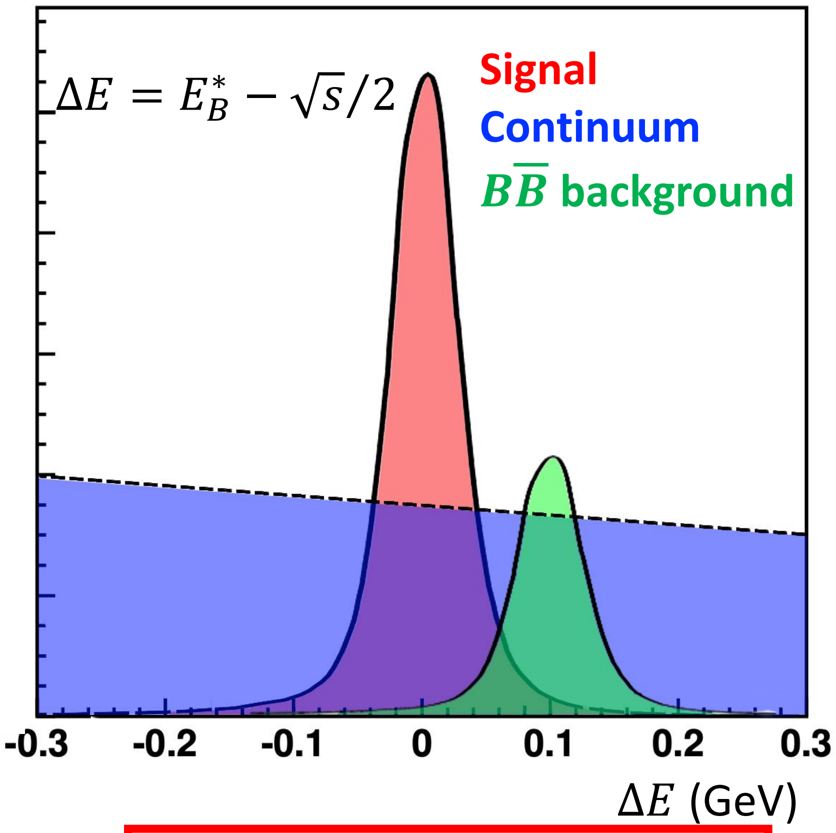
Perform $M_{\mathrm{bc}} \times \Delta E$ fit to extract signal yields

Beam-constrainted mass (M_{bc})



Separate $B\bar{B}$ events from $q\bar{q}$ background

Energy difference (ΔE)



Separate signal events from $B\bar{B}$, $q\bar{q}$ background

Most recent results (62.8 fb^{-1})

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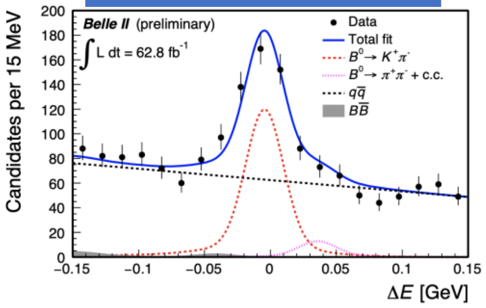
Isospin sum rule : $B \to K^+\pi^-, K^+\pi^0, K^0\pi^+$

Sensitive test for non-SM physics

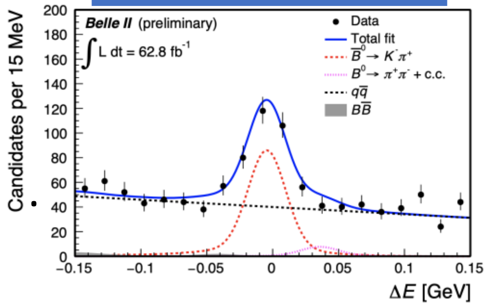
$$I_{K\pi} = A_{CP}^{K^+\pi^-} + A_{CP}^{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2A_{CP}^{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2A_{CP}^{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}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

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

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

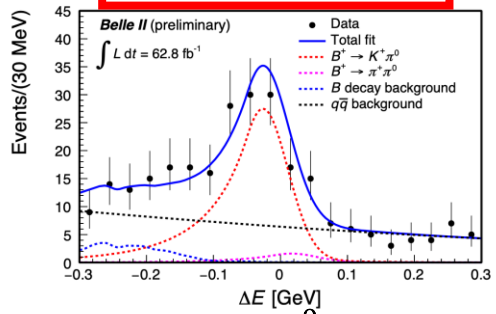


$\bar{B}^0 \to K^-\pi^+$

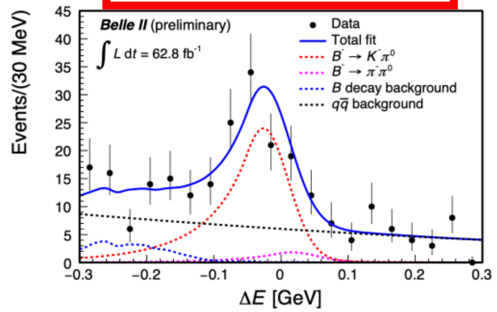


Probes tracking & PID separation

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

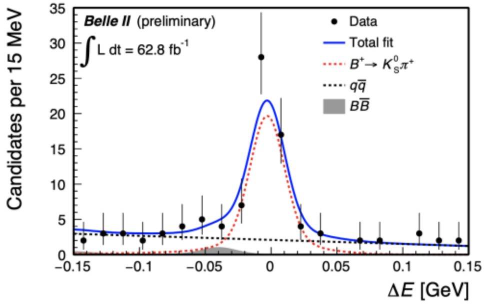


$B^- \to K^-\pi^0$

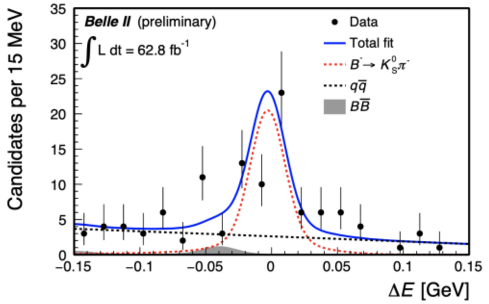


Probes π^0 reconstruction & PID separation

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



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



K_S^0 reconstruction

$\mathcal{B}(B^0 \to K^+\pi^-) = [18.0 \pm 0.9(stat) \pm 0.9(syst)] \times 10^{-6}$
$A_{CP}(B^0 \to K^+\pi^-) = -0.16 \pm 0.05(stat) \pm 0.01(syst)$

arXiv:2106.03766

$\mathcal{B}(B^+ \to K^+\pi^0) = [11.9^{+1.1}_{-1.0}(stat) \pm 1.6(syst)] \times 10^{-6}$
$A_{CP}(B^+ \to K^+\pi^0) = -0.09 \pm 0.09(stat) \pm 0.03(syst)$

arXiv:2105.04111

$\mathcal{B}(B^+ \to K^0\pi^+) = [21.4^{+2.3}_{-2.2}(stat) \pm 1.6(syst)] \times 10^{-6}$
$A_{CP}(B^+ \to K^0\pi^+) = -0.01 \pm 0.08(stat) \pm 0.05(syst)$

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

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Belle II: unique access to this channel !

major limitation in $I_{K\pi}$ determination

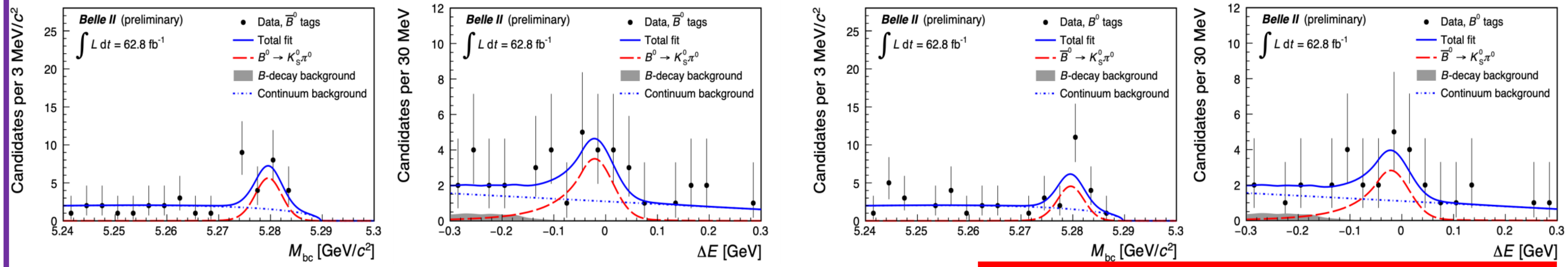
$$I_{K\pi} = A_{\rm CP}^{K^+\pi^-} + A_{\rm CP}^{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2A_{\rm CP}^{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2A_{\rm CP}^{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}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

$$P_{\rm sig}(q) = \frac{1}{2}(1 + q\cdot(1-2w_r)\cdot(1-2\chi_d)\cdot A_{CP}(K^0\pi^0))$$

q : flavor of the B meson
w_r : wrong-tag fraction
χ_d : B^0 mixing parameter

Flavor-tagging technique in Belle II arXiv:2008.02707

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



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

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

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

Fit of ΔE-M_{bc}-q, simultaneously in 7 ranges of w_r (output from flavor tagger).

arXiv:2104.14871

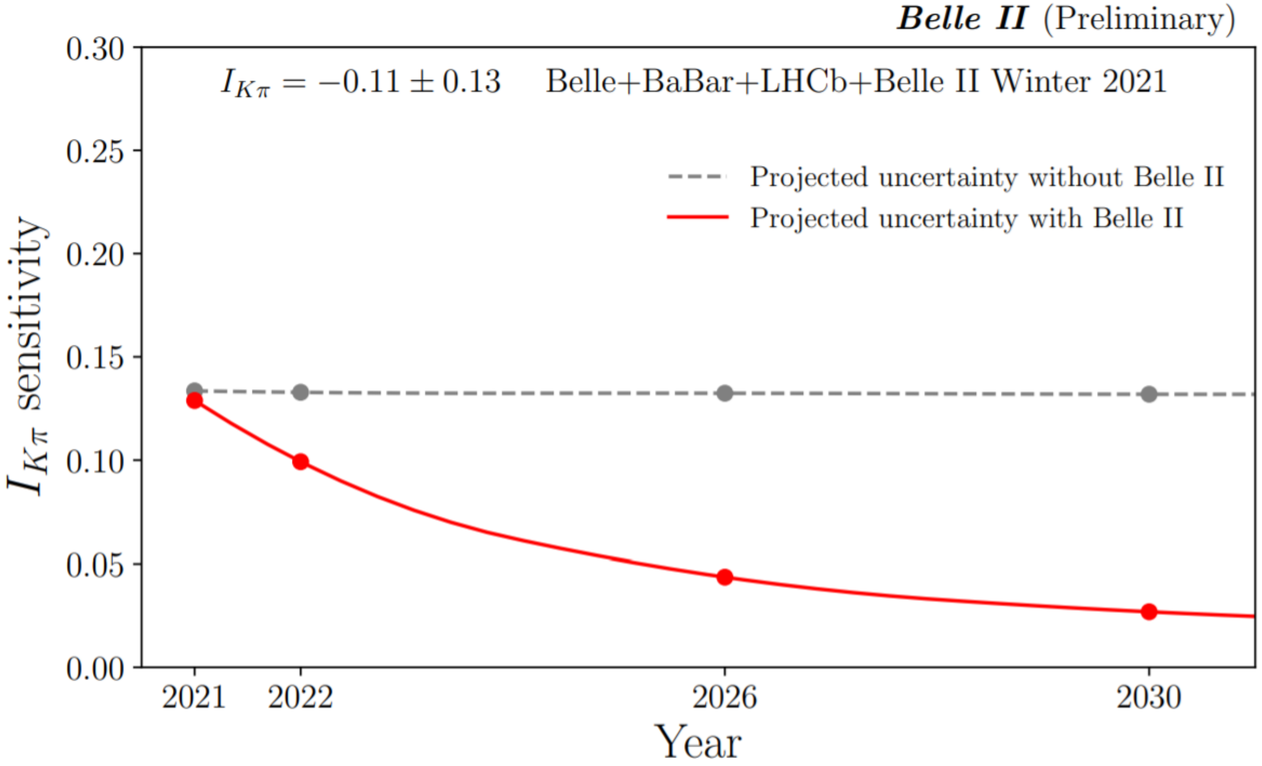
First measurement in Belle II data!

Isospin sum rule – projected uncertainty

Procedure

- $K^0\pi^0$: Dominant uncertainty from $A_{CP}(K^0\pi^0)$. Calculate $\sigma_{I_{K\pi}}$ with Belle II results
- $K^+\pi^-$,$K^+\pi^0$, and $K^0\pi^+$: Take world best measurements, and investigate

future projections with Belle II and LHCb expected luminosities.



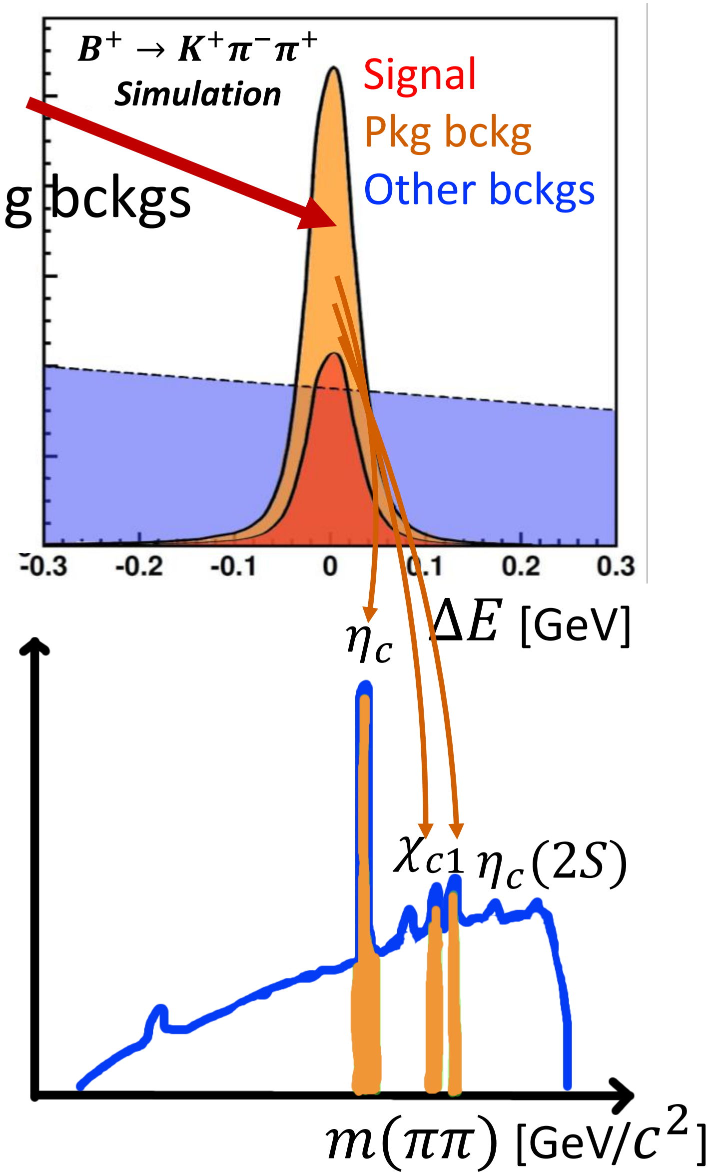
arXiv:2104.14871

The projected uncertainty on $I_{K\pi}$

Fundamental role of Belle II in improvement of precision !

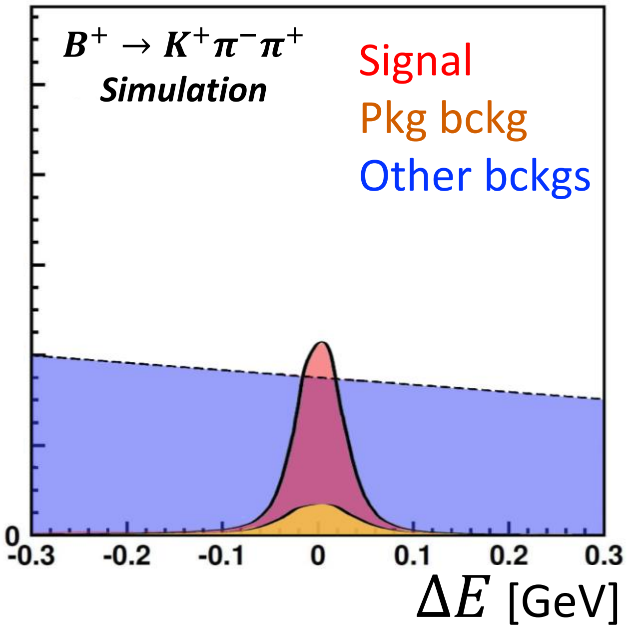
$B \to hhh$: charm resonance veto

Many peaking bckgs



Vetoes

(Studied in simulation)

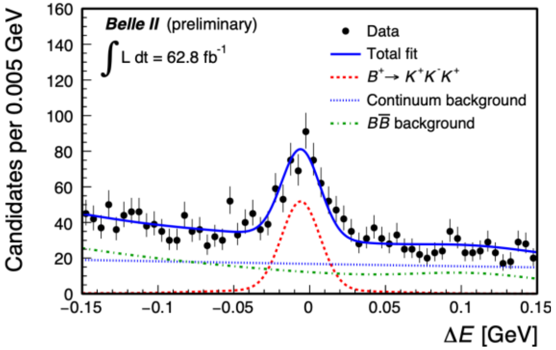


Account for survivors adding fit component from simulation.

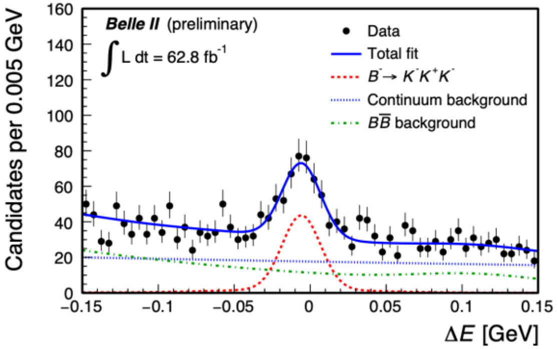
$B \to hhh$: results

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

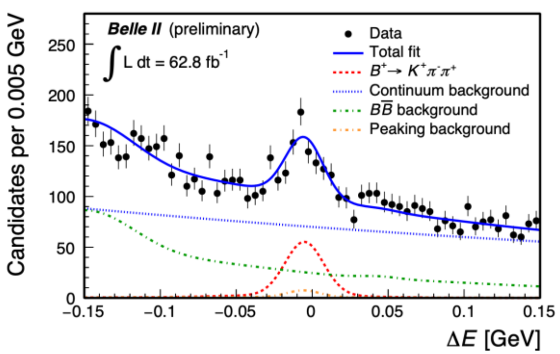
$B^+ \to K^+K^-K^+$



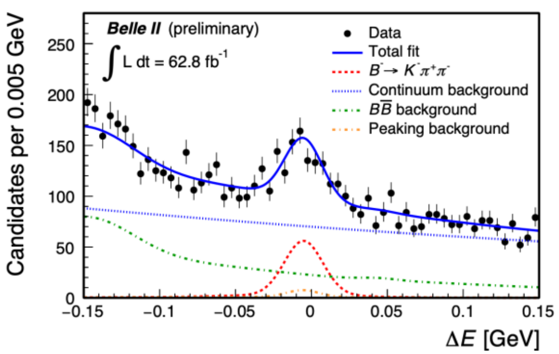
$B^- \to K^-K^+K^-$



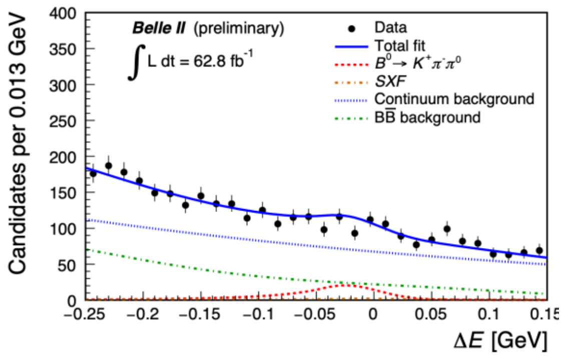
$B^+ \to K^+\pi^-\pi^+$



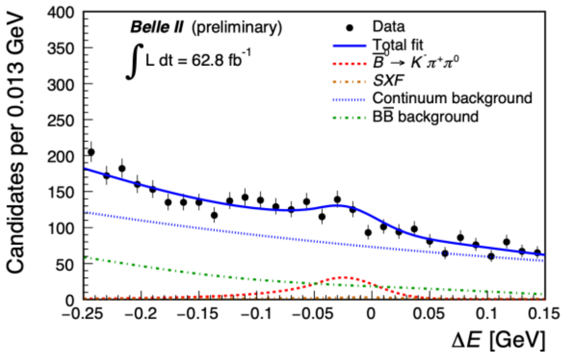
$B^- \to K^-\pi^+\pi^-$



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



$\bar{B}^0 \to K^-\pi^+\pi^0$



First reconstruction in Belle II data!

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

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

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

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

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

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

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

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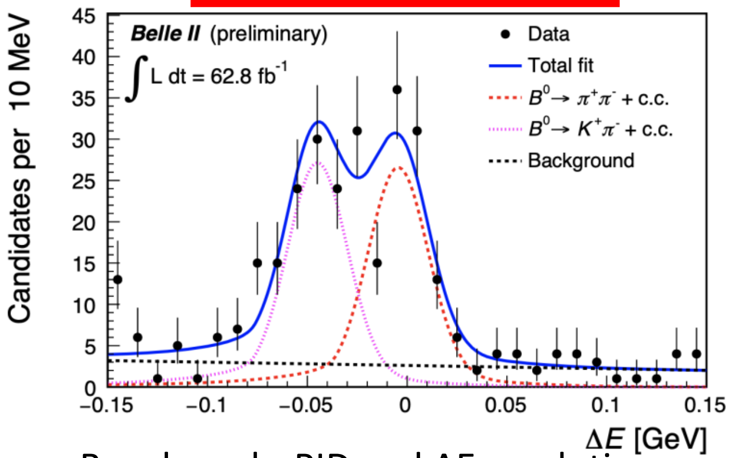
$B^0 \rightarrow \pi^+\pi^- + c.c.$



Benchmarks PID and ΔE resolution.

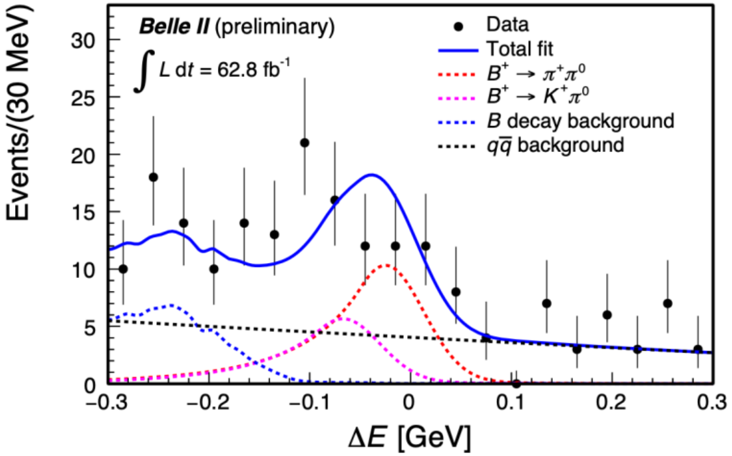
arXiv:2106.03766

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

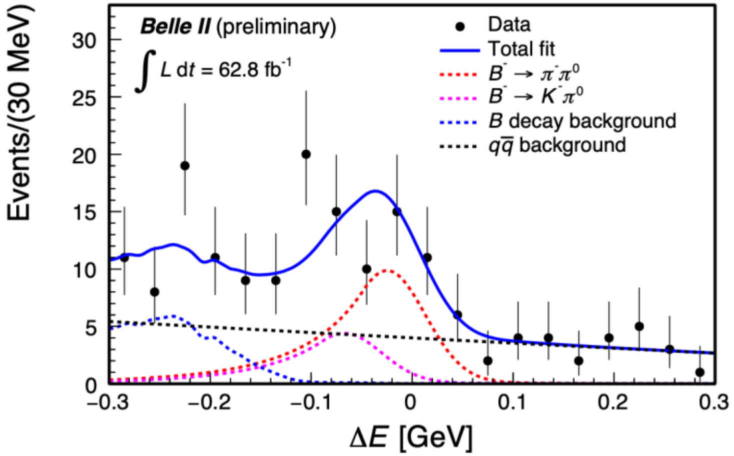
$$\mathcal{B}(B^+ \rightarrow \pi^+\pi^0) = [5.5^{+1.0}_{-0.9}(stat) \pm 0.7(syst)] \times 10^{-6}$$

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

$B^+ \rightarrow \pi^+\pi^0$



$B^- \rightarrow \pi^-\pi^0$



Probes π^0 reconstruction and PID separation.

arXiv:2105.04111

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

Unique to Belle II

Challenges :

- Low $\mathcal{B}$ (10^{-6}) and large bckg level
- Two π^0's in final state

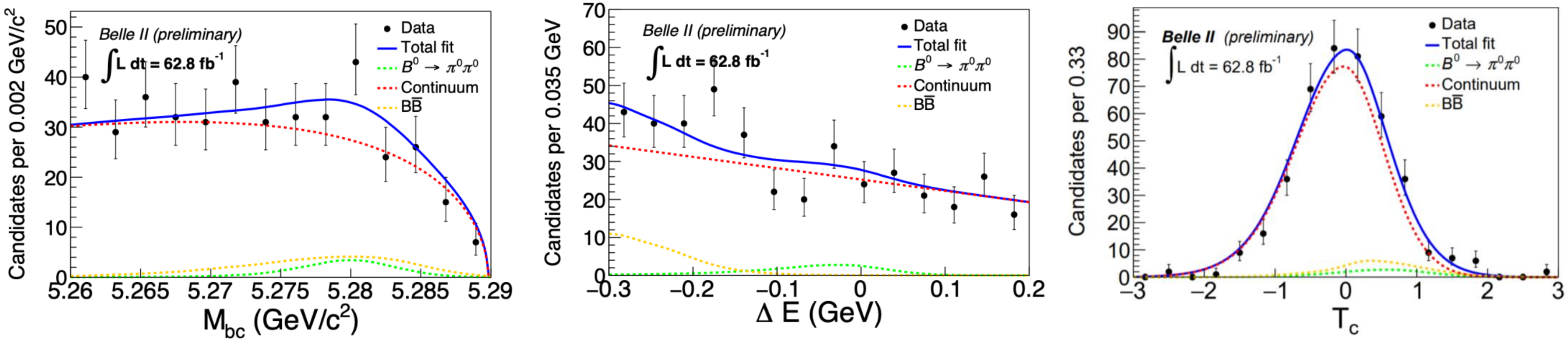
→ major limitation in α/ϕ_2 determination

Analysis :

- Remove fake γ in multivariate techniques
- Validate with $B \to \overline{D^0}[K^+\pi^-\pi^0]\pi^0$ channel
- $M_{bc} \times \Delta E \times T_c$ fit to extract signal

$$T_c \equiv log\frac{cs - cs_{min}}{1 - cs}$$

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



First reconstruction in Belle II data!

$N(B^0 \to \pi^0\pi^0) = 14^{+6.8}_{-5.6}$ with **3.4 σ**

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

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

Unique Belle II capability to determine α/ϕ_2 using $B \to \rho\rho$ decays

Challenges:

- Pion-only final state and broad ρ peak
  $\Rightarrow$ large bckg
- Spin-0 → spin-1 + spin-1 ⇒ angular analysis.

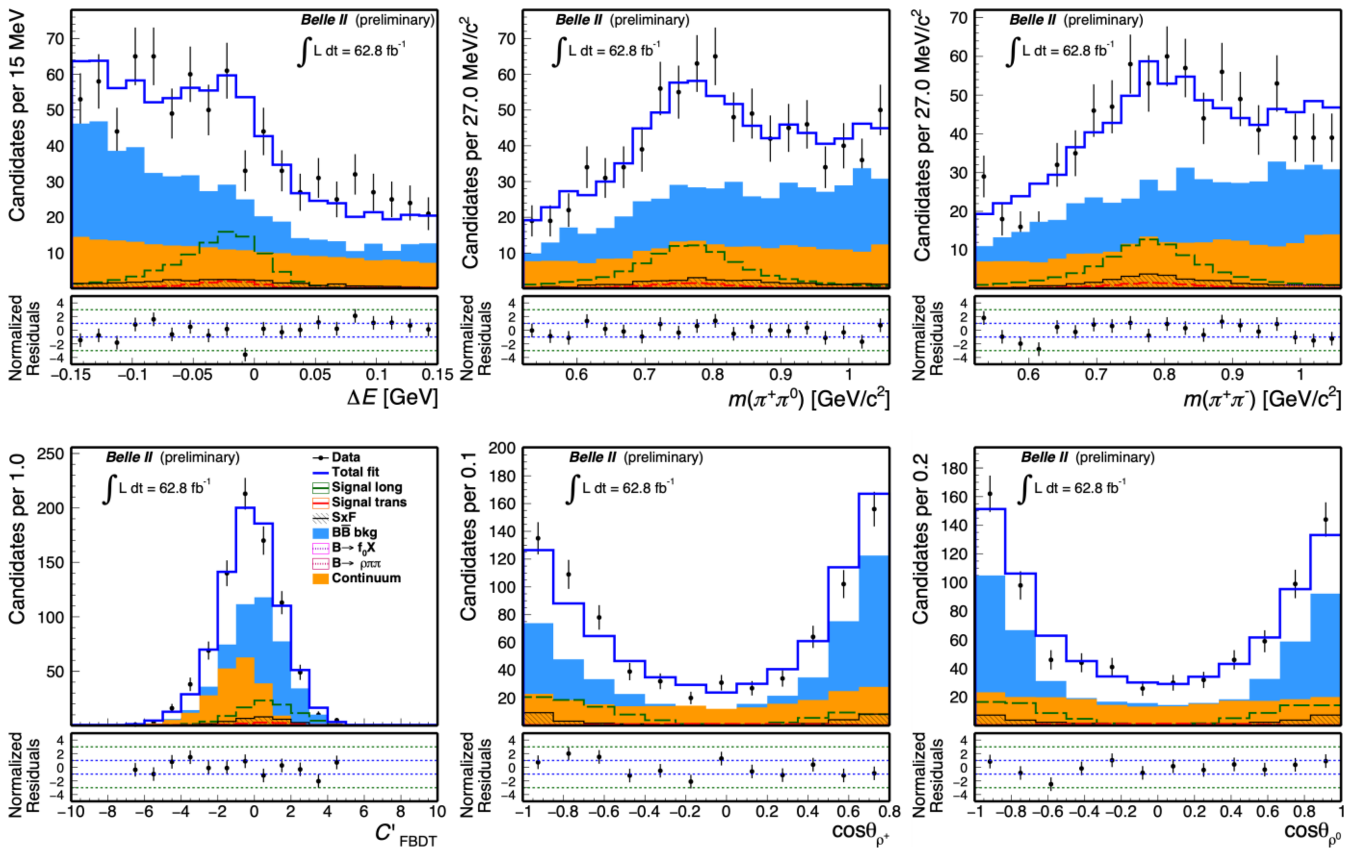
6D fit including ΔE, T_c , and ρ masses to extract signal, and helicity angles to measure fraction f_L of decays with longitudinal polarization.

$\mathrm{N} = 104 \pm 16$

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

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

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



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 : α/ϕ_2, local CPVs, isospin sum rules.

First/improved measurements of charmless decays in 62.8 fb^{-1} of early data.

First Belle II measurement of $B \to K\pi$ decays completes the ingredients for the isospin sum rule; $B \to \rho^+\rho^0$ analysis surpasses early Belle's.

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

Backup

Determination of $A_{CP}(B^0 \to K^0\pi^0)$: r-bins

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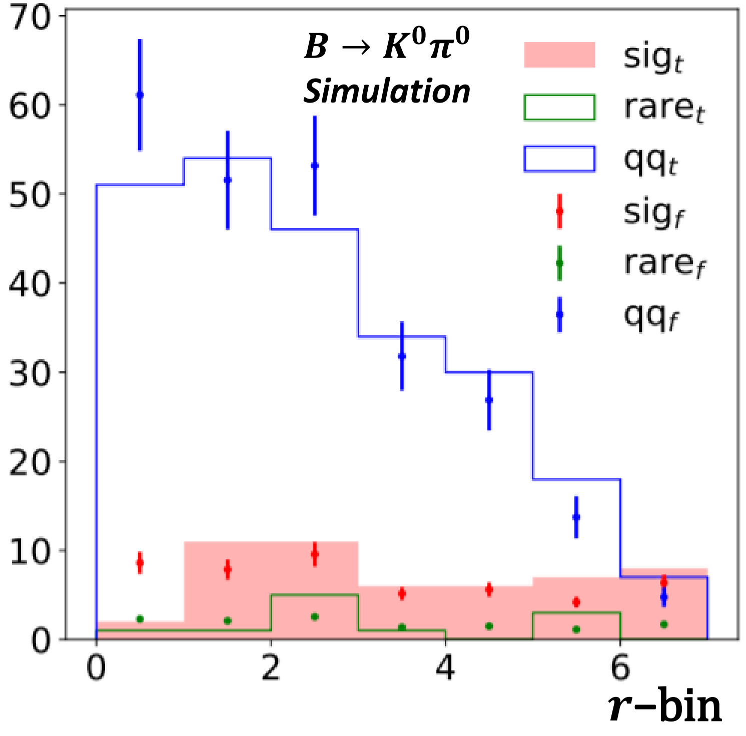
$$P_{\rm sig}(q) = \frac{1}{2}(1 + q \cdot (1 - 2w_r) \cdot (1 - 2\chi_d) \cdot A_{CP}(K^0\pi^0))$$

q : flavor of the B meson
w_r : wrong-tag fraction
χ_d : B^0 mixing parameter

→ Flavor-tagging technique in Belle II arXiv:2008.02707



Fit 7 r-bins simultaneously to get time-integrated A_{CP}

w_r in each r-bins, studied by $B^0 \to D^{(*)-}h^+$ data

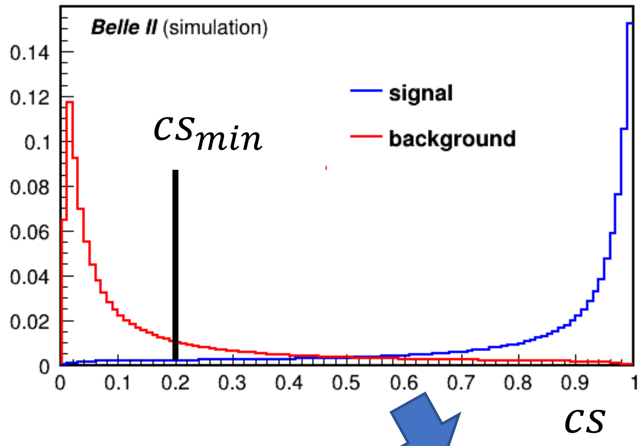
r-bin	r interval	w_r
0	0.000 - 0.100	$0.4920 \pm 0.0400 \pm 0.0090$
1	0.100 - 0.250	$0.4470 \pm 0.0430 \pm 0.0046$
2	0.250 - 0.500	$0.2870 \pm 0.0360 \pm 0.0014$
3	0.500 - 0.625	$0.1620 \pm 0.0480 \pm 0.0240$
4	0.625 - 0.750	$0.1600 \pm 0.0490 \pm 0.0400$
5	0.750 - 0.875	$0.1040 \pm 0.0530 \pm 0.0080$
6	0.875 - 1.000	$-0.0020 \pm 0.0310 \pm 0.0012$

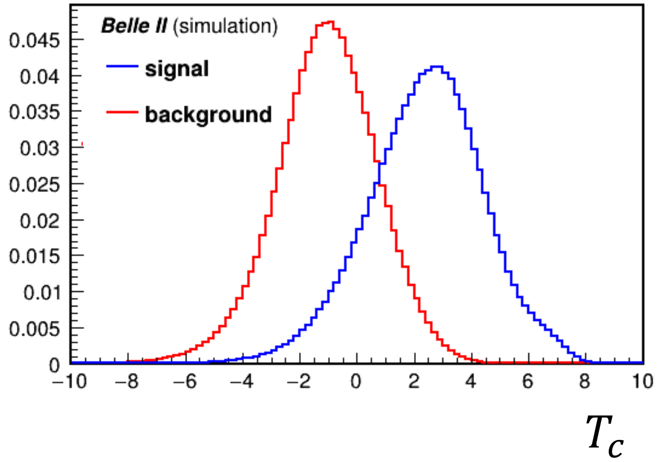
*$r \equiv 1 - 2w_r$
($r = 0$: can't decide the q ; $= 1$: certain the q)

T_c & $\cos\theta_H$

$T_c \equiv log\frac{cs - cs_{min}}{1 - cs}$

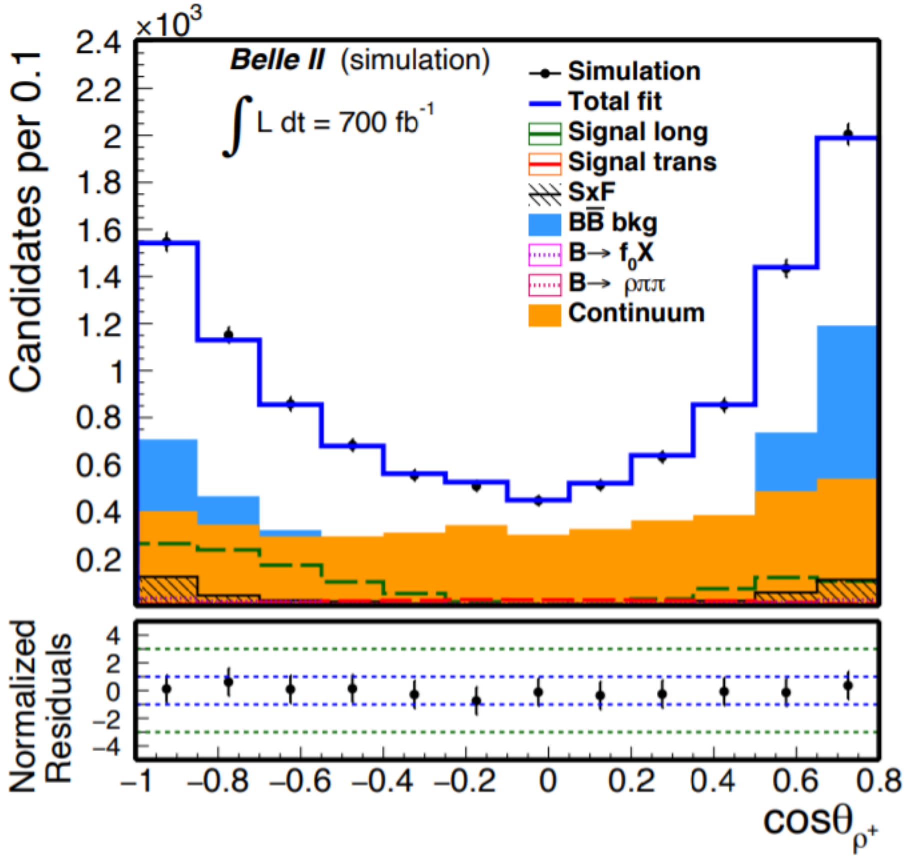
$*$ cs : continuum suppression output





$\cos\theta_H$:

cos the angle between the momentum of π^+ and the flight direction of the ρ in B rest frame



$\cos\theta_H$ of ρ^+ in $B \to \rho^+\rho^0$ simulation