Charmless B decay measurements at Belle II

Sagar Hazra
(On behalf of the Belle II collaboration)

Tata Institute of Fundamental Research

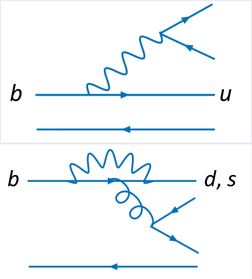
November 24, 2021 @CKM 2021

Flavor physics and charmless B decays

Flavor physics: fundamental to test SM and its extensions

Charmless B decays:

- Hadronic decays not mediated by $b \to c$
- Cabibbo-suppressed $b \to u$ trees and $b \to d, s$ penguins
  $\to$ Highly sensitive to non-SM loops
  $\to$ Probe non-SM dynamics in all three CKM angles



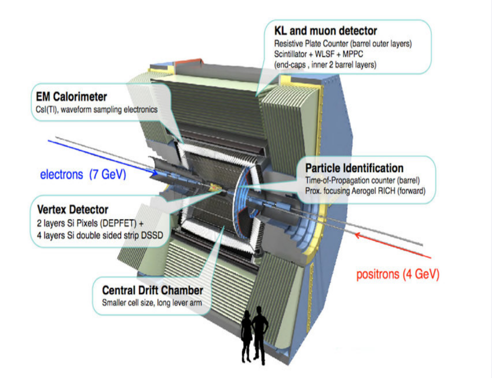
Exp. challenges: low $\mathscr{B}(10^{-5})$, $e^+e^- \to q\bar{q}$ - background dominated

Belle II charmless B program

- Test SM using isospin sum rules
- Investigate localized CP asymmetries in Dalitz plot
- Improve precision on $\alpha/\phi_2 = arg[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}]$ angle

SuperKEKB and Belle II Detector

- Asymmetric collider: e^- to $7\ \mathrm{GeV}$ and e^+ to $4\ \mathrm{GeV}$
  $\rightarrow$ clean experimental environment
- World record peak luminosity: $3.1 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- New tracking system and improved vertexing
- Improved particle identification
- Better time resolution at calorimeter



Goal:

- Collect more than $50\ \mathrm{ab}^{-1}$ data ($5 \times 10^{10} B\bar{B}$ pairs)
- 700 $B\bar{B}$ pairs/second

Currently:

- $216\ \mathrm{fb}^{-1}$ data are collected. Today: results on $\approx 63\mathrm{fb}^{-1}$

Analysis overview

Selection

- baseline selection cut optimised on simulation followed by optimisation of continumm suppression cut and particle identification cut

Efficiencies and corrections

- efficiencies from simulation, validated on data

Signal extraction

- develop fit model from simulation, adjusted on control mode
- determine selection efficiencies for $\mathscr{B}$ calculation

Sytematic uncertainties

- toy studies and control mode analyses

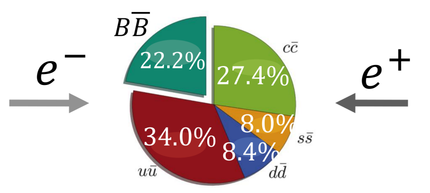
Validation & unblinding

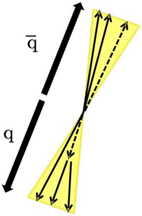
- validate the full analysis on control on data
- apply full analysis to data

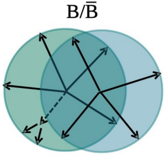
Challenges

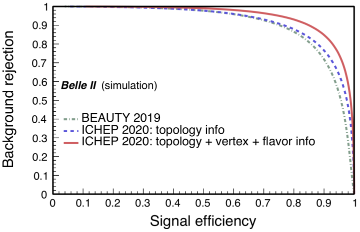
Suppress $10^5\times$ larger $q\bar{q}$ (continuum) background

- Combine 40 kinematic, decay-time and topological variables in multivariate techniques
- $q\bar{q}$ background rejection: $\approx 99\%$



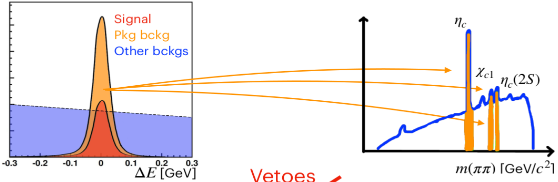




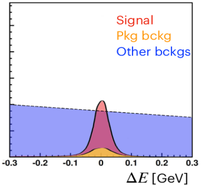


Peaking backgrounds

- B background events that peak in the signal region
- Either veto from the sample or have a separate fit component
  $\rightarrow$ eg: contributions of $B^+ \rightarrow D(\rightarrow K^+\pi^-)\pi^+$ decay can be suppressed by excluding $m(K^+\pi^-)$ in $1.84 - 1.89\,\mathrm{GeV}$



Vetoes

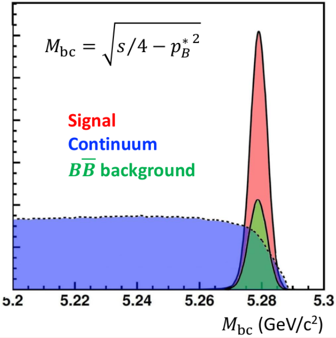


Account for survivors adding fit component from simulation.

Fit variables

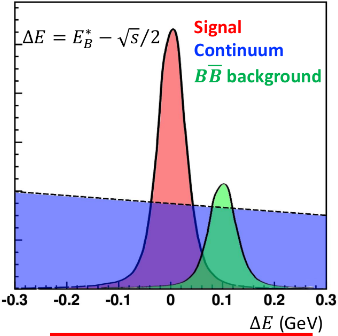
- Perform $M_{bc} \times \Delta E$ fit to extract signal yields
- Offset in ΔE is due to the wrong mass hypothesis associated with a track

Beam-constrainted mass ($M_{\rm bc}$)



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

Energy difference (ΔE)



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

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

- Isospin sum-rule relation for $B \to K\pi$ provides a stringent SM test

$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)} = 0$$

(Phys.Lett. B627 (2005) 82-8)

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

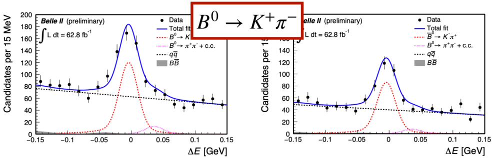
$A_{CP}(B^0 \to K^+\pi^-) = -0.16 \pm 0.05(stat) \pm 0.01(syst)$

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

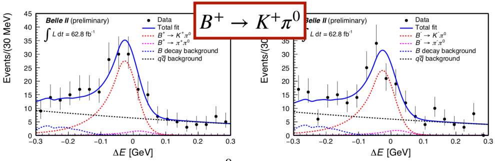
$A_{CP}(B^+ \to K^0\pi^+) = -0.01 \pm 0.08(stat) \pm 0.05(syst)$

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

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



Probes tracking.



Probes π^0 reconstruction.

https://arxiv.org/abs/2105.04111

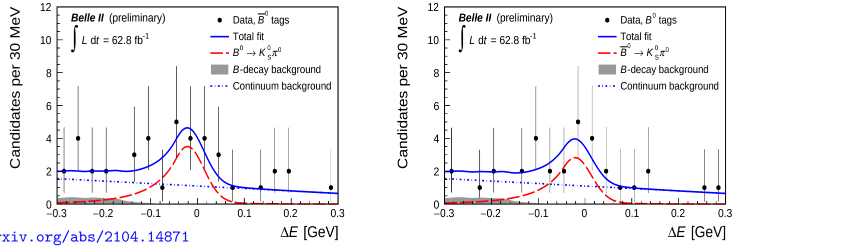
Belle II: the only experiment that accesses all channels

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

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

- $\mathscr{B}$: challenging as it requires K_S^0 and π^0 reconstruction
- A_{CP} : requires flavor tagging: fit of $\Delta E - M_{bc}$ -flavor of the B-meson (q)
- $P_{sig}(q) = \frac{1}{2}.(1 + q.(1 - 2w_r).(1 - 2.\chi_d).A_{K^0\pi^0})$, where q : flavor of the B meson, w_r : wrong-tag fraction and χ_d : B^0 mixing parameter (https://arxiv.org/pdf/2110.00790.pdf)

$B^0 \to K_S^0\pi^0$ $\qquad\qquad$ $\bar{B}^0 \to K_S^0\pi^0$



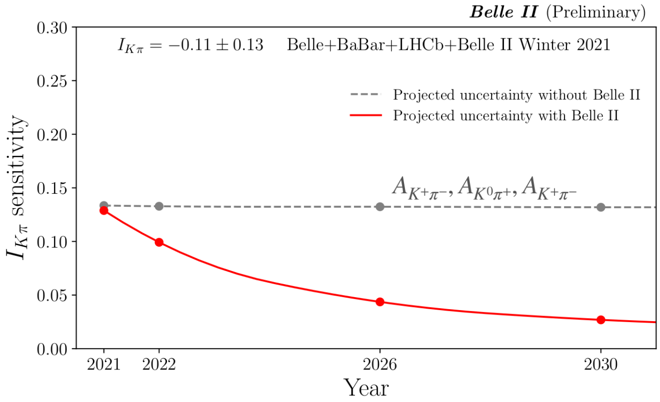
https://arxiv.org/abs/2104.14871

$$N(B^0 \to K^0\pi^0) = 45^{+9}_{-8} \quad \mathscr{B}(B^0 \to K^0\pi^0) = [8.5^{+1.7}_{-1.6}(stat) \pm 1.2(syst)] \times 10^{-6}$$

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

Isospin sum rule- uncertainty projection

- Extrapolate the uncertainty on $I_{K\pi}$ into next decade
- Future projections with Belle II and LHCb expected luminosities
- Only limiting factor due to $A_{K^0\pi^0}$ precision

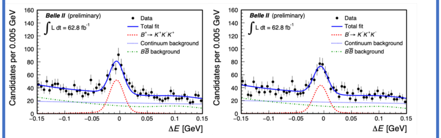


Belle II is the key player

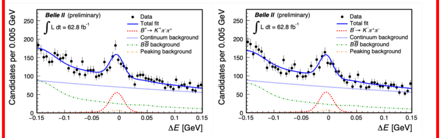
CPV in multibody decays

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

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



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

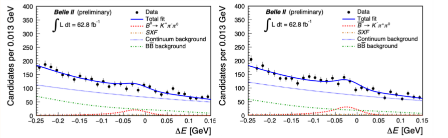


https://arxiv.org/abs/2109.10807

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

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

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



First reconstruction in Belle II data!

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

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

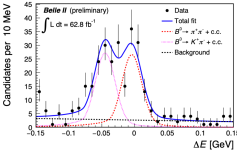
$\mathscr{B}(B^0 \to K^+\pi^-\pi^0) = [38.1 \pm 3.5(stat) \pm 3.9(syst)] \times 10^{-6}$

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

Determination of $\alpha/\phi_2 : B \to \pi^+\pi^-, \pi^+\pi^0$

- $\alpha/\phi_2 = arg[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}]$ as complementary test
- Unique Belle II capability to study all the $B \to \pi\pi$, $\rho\rho$ decays to determine the CKM angle α

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

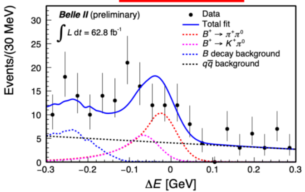


Benchmarks PID and ΔE resolution.

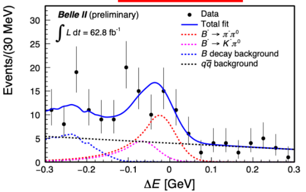
$\mathscr{B}(B^0 \to \pi^+\pi^-) = [5.8 \pm 0.7(\text{stat}) \pm 0.3(\text{syst})] \times 10^{-6}$

https://arxiv.org/abs/2106.03766

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



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

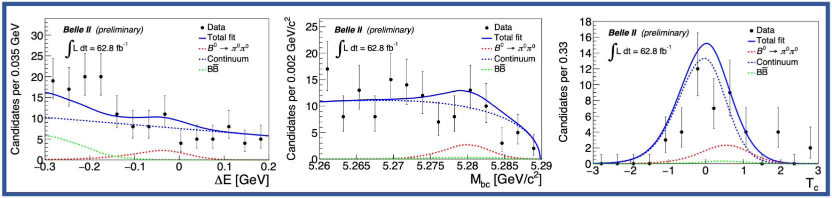


Probes π^0 reconstruction and PID separation. arXiv:2105.04111

$\mathscr{B}(B^+ \to \pi^+\pi^0) = [5.5^{+1.0}_{-0.9}(stat) \pm 0.7(syst)] \times 10^{-6}$ $A_{CP}(B^+ \to \pi^+\pi^0) = -0.04 \pm 0.17(stat) \pm 0.06(syst)$

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

- Very challenging mode:
  $\to$ two π^0's in final state
  $\to$ very low branching fraction (10^{-6})
- π^0 optimisation:combine 20 ECL variables to suppress background photons
- 3D-fit in $\Delta E, M_{bc}$ and transformed continuum suppression variable T_c



https://arxiv.org/pdf/2107.02373.pdf

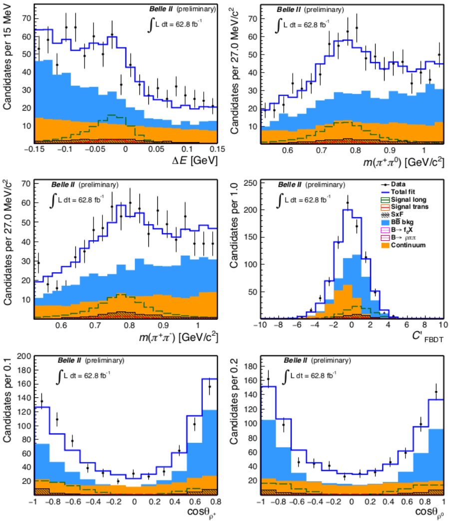
$N(B^0 \to \pi^0\pi^0) = 14^{+6.8}_{-5.6}$ $\quad \mathscr{B}(B^0 \to \pi^0\pi^0) = [0.98^{+0.48}_{-0.39}(stat) \pm 0.27(syst)] \times 10^{-6}$

Unique capability of Belle II of reaching this state.

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

Challenges:

- Pion-only final state and broad ρ peak
  $\to$ large background
- Spin-0 $\to$ spin-1 + spin-1
  $\to$ 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



https://arxiv.org/abs/2109.11456

$N = 104 \pm 16$

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

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

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

Summary

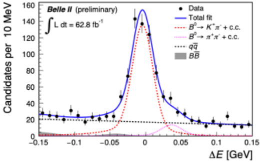
- Charmless B physics plays an important role in sharpening flavor picture.
- Belle II is preparing for a leading role in isospin sum rules, local CPVs, and α .
- First/improved measurements of charmless decays in 63 fb^{-1} of early data.
- First Belle II measurement of $K^0\pi^0$ completes the ingredients 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.

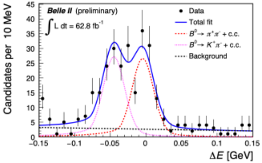
Thank You

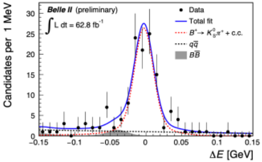
- Following slides are taken from Sebastiano Raiz's talk at PHENO2021

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

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





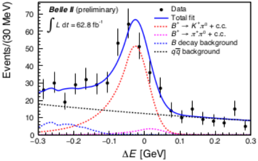


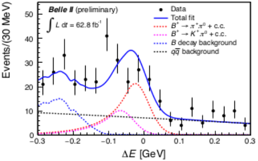
Probe of tracking and PID performances.

Benchmark of K^0_S reconstruction

N($B^0 \to K^+\pi^-$): $568\ ^{+29}_{-28}$ | N($B^0 \to \pi^+\pi^-$): $115\ ^{+14}_{-13}$ | N($B^+ \to K^0_S\pi^+$): $103\ ^{+11}_{-10}$

$\mathcal{B}\ [10^{-6}]$: 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)



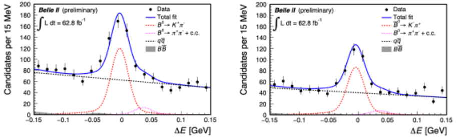


Challenge of π^0 reconstruction performances, require good PID.

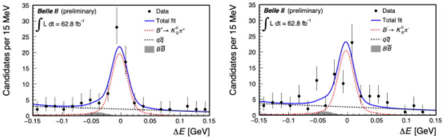
N($B^+ \to K^+\pi^0$): $211\ ^{+18.8}_{-18}$ | N($B^+ \to \pi^+\pi^0$): $83.9\ ^{+14.7}_{-13.9}$

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

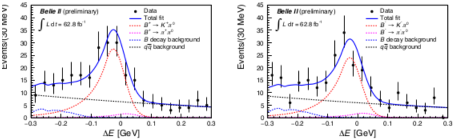
CP asymmetries in two-body decays



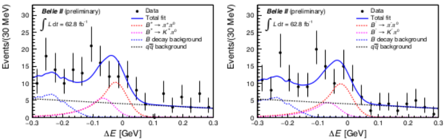
$A_{CP}(B^0 \to K^+\pi^-) = -0.16 \pm 0.05(\text{stat}) \pm 0.01(\text{syst})$



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

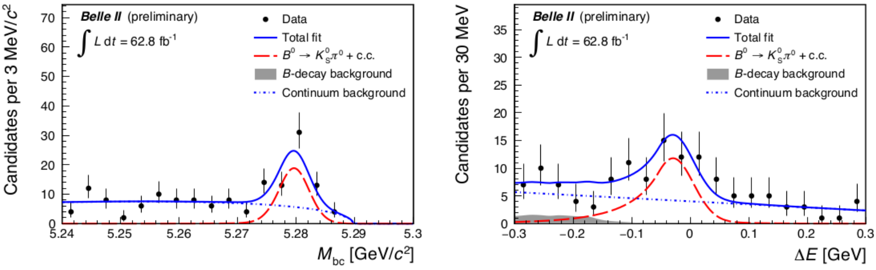


$A_{CP}(B^+ \to K^+\pi^0) = -0.09 \pm 0.09(\text{stat}) \pm 0.03(\text{syst})$



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

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

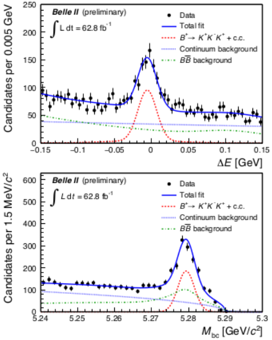


N$(B^0 \to K_S^0\pi^0)$: $45\ ^{+9}_{-8}$

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

Multibody: branching fractions

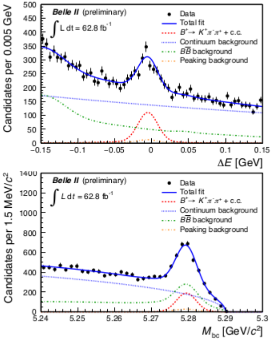
$B^+ \to K^+K^-K^+$



N_{Sig}: 690 ± 30

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

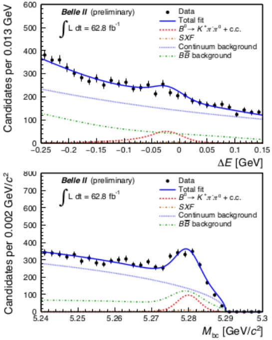
$B^+ \to K^+\pi^-\pi^+$



N_{Sig}: 843 ± 42

67.0 ± 3.3(stat) $\pm$ 2.3(syst)

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



N_{Sig}: 380 ± 35

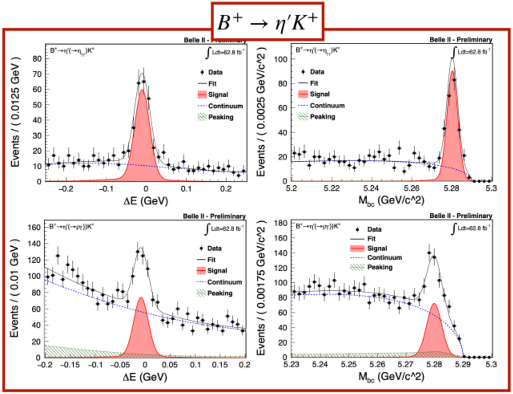
38.1 ± 3.5(stat) $\pm$ 3.9(syst)

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	$\mathcal{B}$ $(\times 10^6)$	
$B^\pm \to \eta' K$	$63.4\ ^{+3.4}_{-3.3}(\text{stat}) \pm 3.2(\text{syst})$	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.

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