TDCPV and charmless B decays at Belle II

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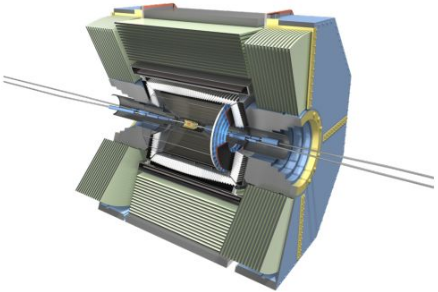
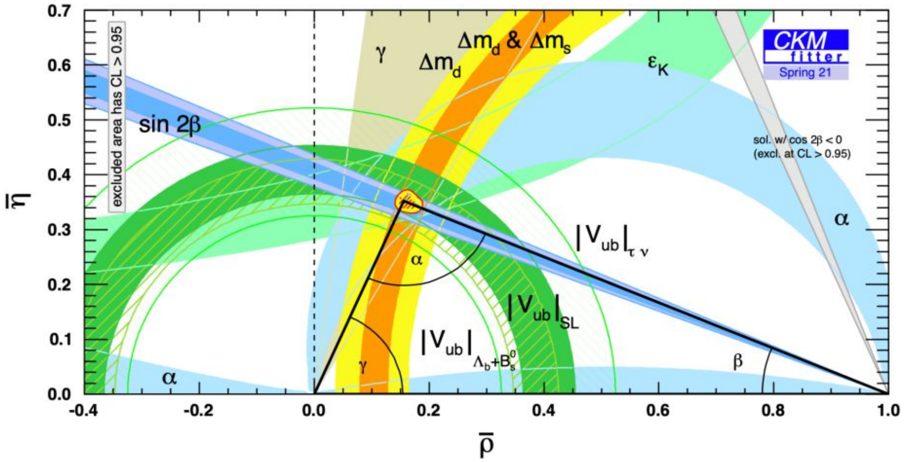
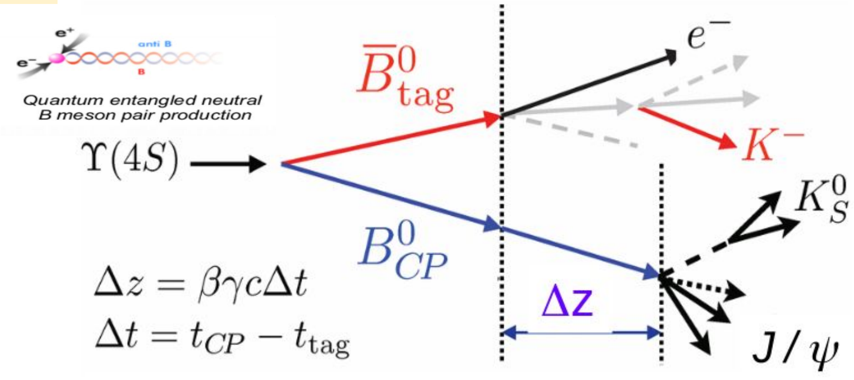
Motivation

- Belle II experiment at SuperKEKB
  - Collected so far **428/fb**: today will show results based on **~190/fb**
- Can access to many modes unique to B factories
  - In particular modes with neutral, π^0, K_L, η('), …
  - Constrained kinematics and low background environment wrt LHC
- Will improve existing precision measurement on CKM Unitarity Triangles
  - As well search for new physics
- In this talk:
  - Time Dependent measurement
    - B^0 lifetime and mixing
    - ϕ_1/□
    - $B \to K_S K_S K_S$ / $K_S \pi^0$
  - Charmless B decay
    - $K\pi$ puzzle: $B \to K^+ \pi^0$
    - ϕ_2/α: $B \to \pi^0 \pi^0$, ρρ





TDCPV analysis



<Δz> ~ 130 μm at Belle II

Flagship measurement of the B Factories, still very important at Belle II;

$$\mathcal{A}_f(\Delta t) = \frac{\Gamma(\bar{B}^0(\Delta t) \to f) - \Gamma(B^0(\Delta t) \to f)}{\Gamma(\bar{B}^0(\Delta t) \to f) + \Gamma(B^0(\Delta t) \to f)} = S_f \sin(\Delta m_B \Delta t) + \mathcal{A}_f \cos(\Delta m_B \Delta t)$$

$\mathcal{S}_{CP} = \sin(2\phi_i^{eff})$
mixing induced CPV
$|B^0\rangle \to |f_{CP}\rangle$, $|B^0\rangle \to |\bar{B}^0\rangle \to |f_{CP}\rangle$

$\mathcal{A}_{CP} = -\mathcal{C}_{CP}$
Direct CPV
$|B\rangle \to |f\rangle \neq |\bar{B}\rangle \to |\bar{f}\rangle$

- **B**$_{CP}$ fully reconstructed CP eigenstate
- **B**$_{tag}$ vertex and flavour information
- Complex analysis, many key elements:
  - high signal efficiency
  - excellent vertex resolution **Δz** [More on Tadeas' talk later today]
  - high flavour tagging efficiency [Eur. Phys. J 82, 283 (2022)]
  - background modelling

B^0 lifetime and mixing frequency

- Key step toward time dependent CPV analysis
  - Develop and validate Δt resolution function
  - Hard to compete with LHCb
- Signal side: $B^0 \to D^{(*)-} h^+$ ($h=\pi$,K)
- Tag side: assign flavour via Flavour Tagger

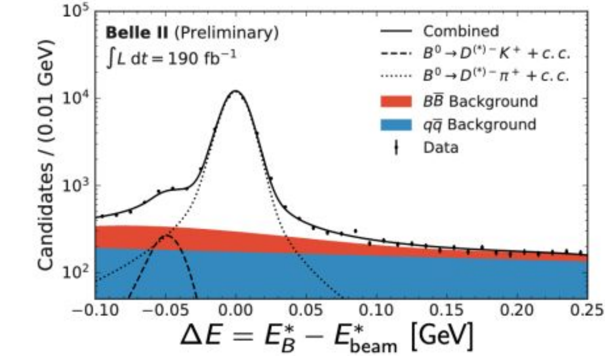
$$\mathcal{A}(\Delta t) = \frac{N_{B\bar{B}} - N_{BB,\bar{B}\bar{B}}}{N_{B\bar{B}} + N_{BB,\bar{B}\bar{B}}} = cos(\Delta m_d \Delta t)(1-2w) \otimes R(\Delta t)$$

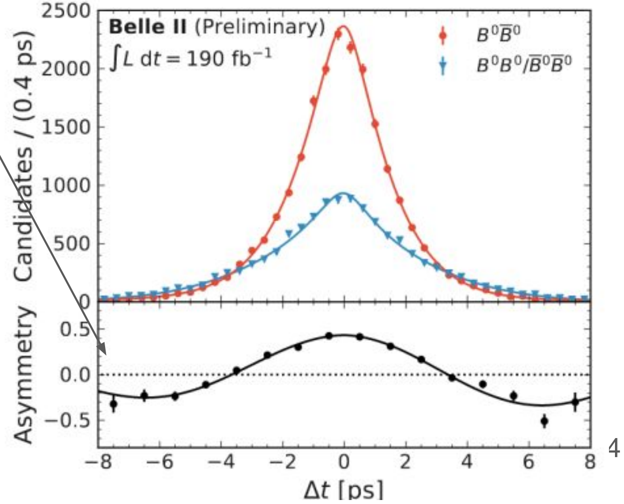
- Fit:
  - ΔE and continuum suppression BDT output
  - Use sWeight to get background subtracted Δt distribution
  - Fit τ_B and Δm_d

$$\tau_{B^0} = 1.499 \pm 0.013\,(\text{stat}) \pm 0.008\,(\text{syst})\ \text{ps},$$
$$\Delta m_d = 0.516 \pm 0.008\,(\text{stat}) \pm 0.005\,(\text{syst})\ \text{ps}^{-1}$$

- Better syst than Belle/BaBar

Signal yield: 33317 ± 203





Good agreement with WA

$\sin(2\phi_1/\square)$ from $B \to J/\psi\ K_S$

- Golden channel, almost background free
  - Full TDCPV analysis
  - Using only K_s for the time being
    - K_L and other $c\bar{c}$ to be added
- Using resolution function developed for lifetime and mixing analysis
  - parameters from $B^0 \to D^{(*)-}h^+$ modes
- Results:

$$S_{CP} = 0.720 \pm 0.062(\text{stat}) \pm 0.016(\text{syst})$$

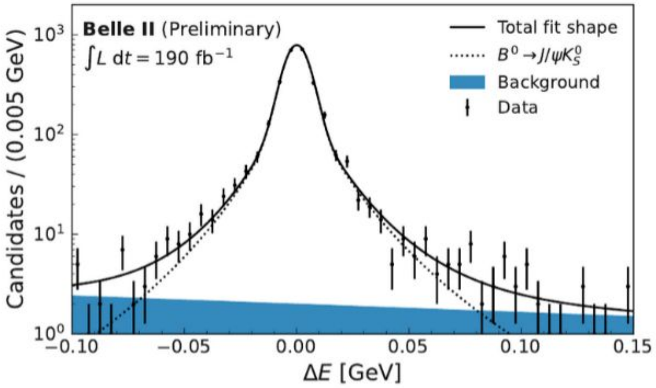
$$A_{CP} = 0.094 \pm 0.044(\text{stat})\,^{+0.042}_{-0.017}(\text{syst})$$

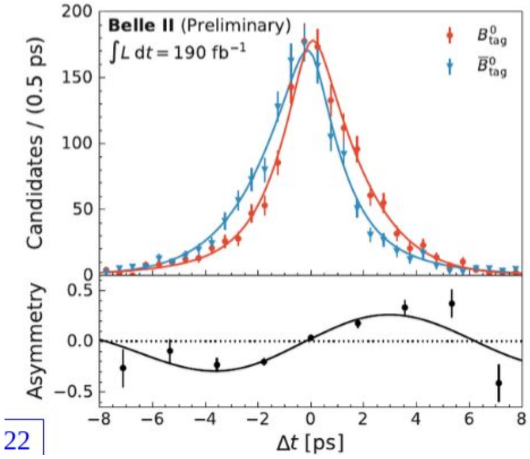
World average (K_S mode only):

$S_{CP} = 0.695 \pm 0.019$

$A_{CP} = 0.000 \pm 0.020$

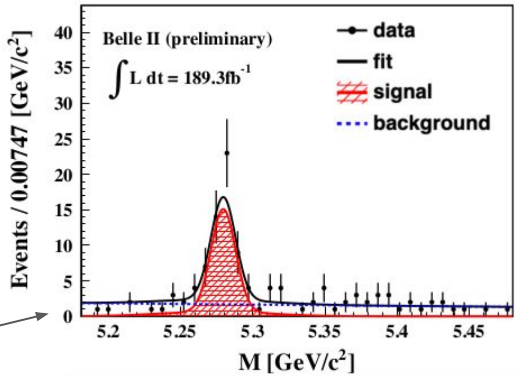
- Still limited by statistics
  - Main syst S_{CP} from size of control samples
  - For A_{CP} from tag-side interference and charge asym





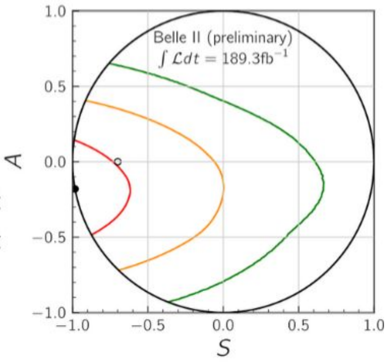
Time dependent B → $K_S K_S K_S$

- b→s decay mediated by penguin loop, potentially sensitive to new physics
  - Very clean theoretically
- Experimentally challenging: no prompt tracks, but only reconstructed $K_S \rightarrow \pi^+\pi^-$ extrapolated back;
  - For TD analysis, using only candidates with enough hits on silicon VTX detector;
- Signal from 3-dimensional fit: M_{bc}, M_{KsKsKs}, $BDT_{Cont.Supp.}$

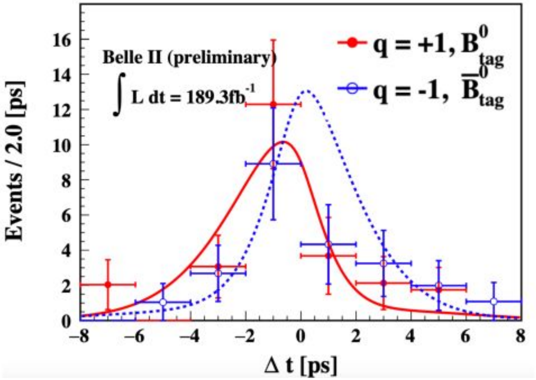


- Results:

$$\mathcal{S} = -1.86\ ^{+0.91}_{-0.46}\ \text{(stat)} \pm 0.09\ \text{(syst}$$
$$\mathcal{A} = -0.22\ ^{+0.30}_{-0.27}\ \text{(stat)} \pm 0.04\ \text{(syst}$$



68.37%
95.45%
99.73%
Conf regions
In physical space



Time dependent $B \to K_S \pi^0$

arXiv:2206.07453

- Key ingredient of "$K\pi$" puzzle
  - Large unexpected isospin violation in $B \to K\pi$

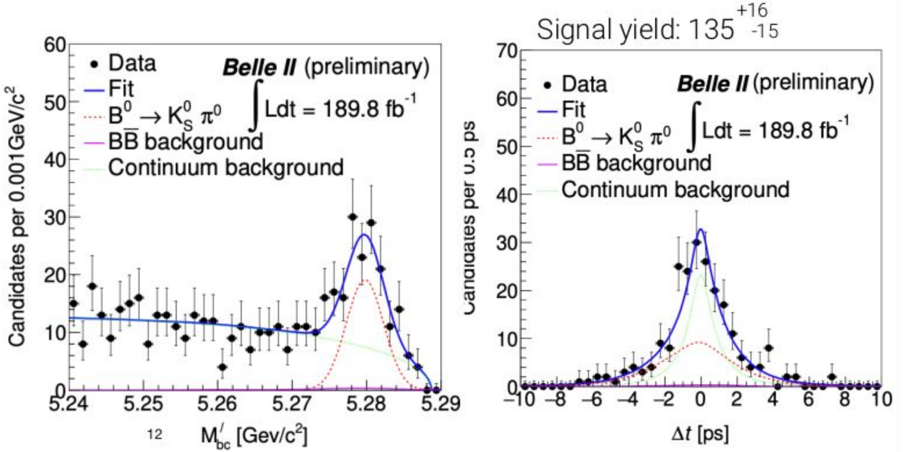
$$I_{K\pi} = A^{CP}_{K^+\pi^-} + A^{CP}_{K^0\pi^+}\frac{\mathcal{B}_{K^0\pi^+}}{\mathcal{B}_{K^+\pi^-}}\frac{\tau_{B^0}}{\tau_{B^+}} - 2A^{CP}_{K^+\pi^0}\frac{\mathcal{B}_{K^+\pi^0}}{\mathcal{B}_{K^+\pi^-}}\frac{\tau_{B^0}}{\tau_{B^+}} - 2A^{CP}_{K^0\pi^0}\frac{\mathcal{B}_{K^0\pi^0}}{\mathcal{B}_{K^+\pi^-}}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

  - Uncertainty dominated by $A_{CP}(K_S\pi^0)$: accessible only to Belle II
- Key challenge is signal decay vertex, from $K_S \to \pi^+\pi^-$ and IP constraint
  - Control channel $B \to J/\psi\, K_S$, with J/ψ not used for vertexing
- 4D fit: M_{bc}, ΔE, Δt, $BDT_{Cont.Supp.}$
- Results:

$A_{CP} = -0.41\,^{+0.30}_{+0.32}$ (stat.) $\pm$ 0.09 (syst.)

$\mathcal{B} = (11.0 \pm 1.2\ (stat.) \pm 1.0\ (syst.)) \times 10^{-6}$

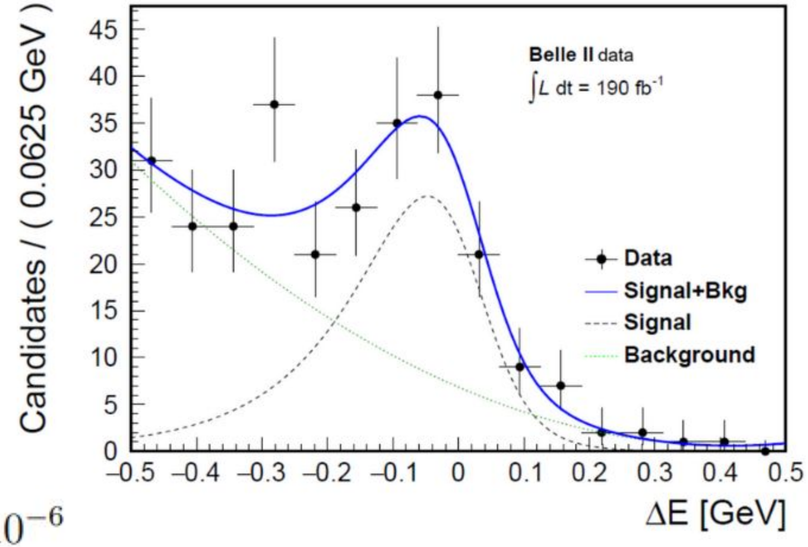
- $B^0 \to K^+\pi^-$, $B^+ \to K_S^0\pi^+$ arXiv:2106.03766
- $B^+ \to K^+\pi^0$ (later)



$B \to K_S \pi^0 \gamma$

arxiv:2206.08280

- $B^0 \to K_S \pi^0 \gamma$ is expected to have small/none mixing induced CPV in SM
  - $b \to s\gamma_R$ is helicity suppressed (m_s/m_b) wrt $b \to s\gamma_L$
  - $B^0 \to s\gamma_L$ vs $B^0 \to \bar{B}^0 \to s\gamma_R$
- First measurement of BR
- Signal selection:
  - $1.4 < E(\gamma) < 4.0$ GeV
  - $M(K_S\pi^0) < 1.1$ GeV/c^2
    - Dominated by $K^{0*}(892)$
- Fit ΔE to extract signal
- Results:
  - Yield: 121± 29 events

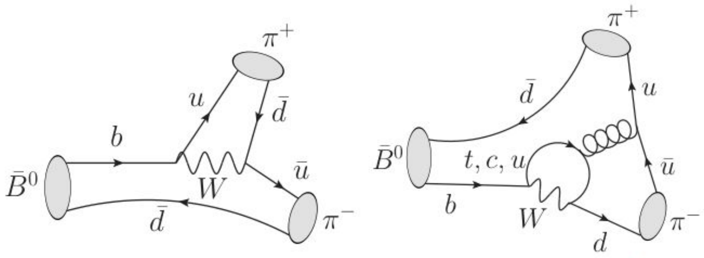


$$\mathcal{B}\left(B^0 \to K^0_S \pi^0 \gamma\right) = (7.3 \pm 1.8\,(\text{stat}) \pm 1.0\,(\text{syst})) \times 10^{-6}$$

Full TDCPV analysis to follow

Measurement of ϕ_2/α

Two amplitudes of comparable size with different weak phase:



Penguin in $B^0 \to \pi^+\pi^-, \pi^0\pi^0$, but not in $B^\pm \to \pi^\pm\pi^0$

$$\phi_2 = (\widehat{\bar{A}^{+0}, A^{+0}}),\ \phi_2^{eff} = (\widehat{\bar{A}^{+-}, A^{+-}})$$

Isospin analysis[Gronau-London PRL, 64 3381 (1990)]: constraints B^0 and $B^\pm$ amplitudes:

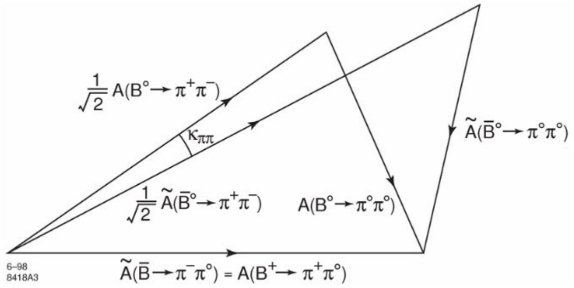
$$A^{+0} = A^{+-}/\sqrt{2} + A^{00}$$

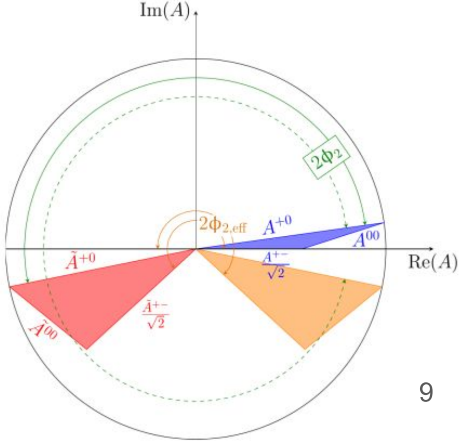
$$\bar{A}^{+0} = \bar{A}^{+-}/\sqrt{2} + \bar{A}^{00}$$

$$|A^{+0}| = |\bar{A}^{+0}|$$

Similar for $B \to \rho\rho$

- Need all branching fractions;
- Direct CP asymmetries: C^{+-}, C^{00};
- TD CP asymmetries: S^{+-}, S^{00};
  - S^{00} reduces folding ambiguities
- Belle II will be able to measure all these observables
  - Final sensitivity ~1°



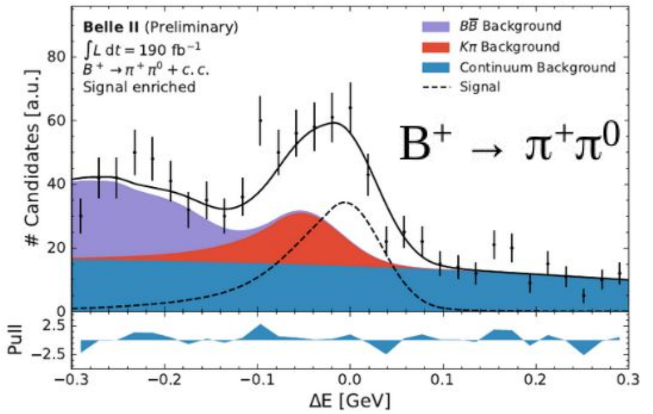


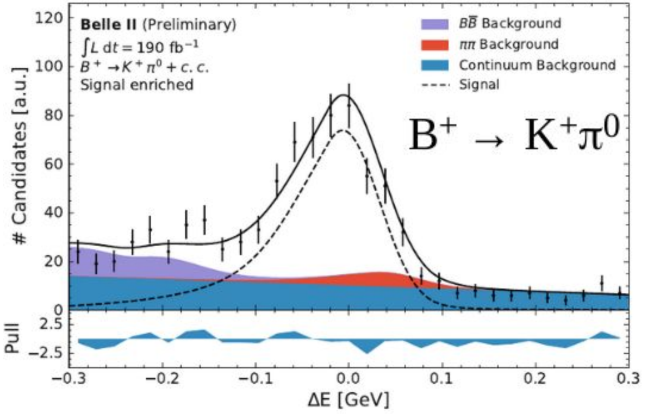
$B^+ \to \pi^+\pi^0$ / $K^+\pi^0$

- $B^+ \to K^+\pi^0$ enters in "$K\pi$" puzzle
- Using common selection for both channels
  - Enhance pion and kaon final state
  - Background from continuum $q\bar{q}$ reduced with MVA
- B and A^{CP} from 3D fit on M_{bc}, ΔE, $BDT_{Cont.Supp.}$
  - Simultaneous fit to both samples
  - $D^+ \to K_s\pi^+$ and $D^0 \to K^-\pi^+$ for detector asymmetries
- Results:

$$\mathcal{B}(\pi^+\pi^0) = (6.1 \pm 0.5 \pm 0.5) \times 10^{-6}$$
$$\mathcal{B}(K^+\pi^0) = (14.3 \pm 0.7 \pm 0.8) \times 10^{-6}$$
$$\mathcal{A}^{CP}(\pi^+\pi^0) = -0.09 \pm 0.09 \pm 0.02$$
$$\mathcal{A}^{CP}(K^+\pi^0) = 0.01 \pm 0.05 \pm 0.01$$

WA: $\mathcal{A}^{CP}_{K^+\pi^0} = 0.030 \pm 0.013$, $\mathcal{A}^{CP}_{\pi^+\pi^0} = 0.03 \pm 0.04$





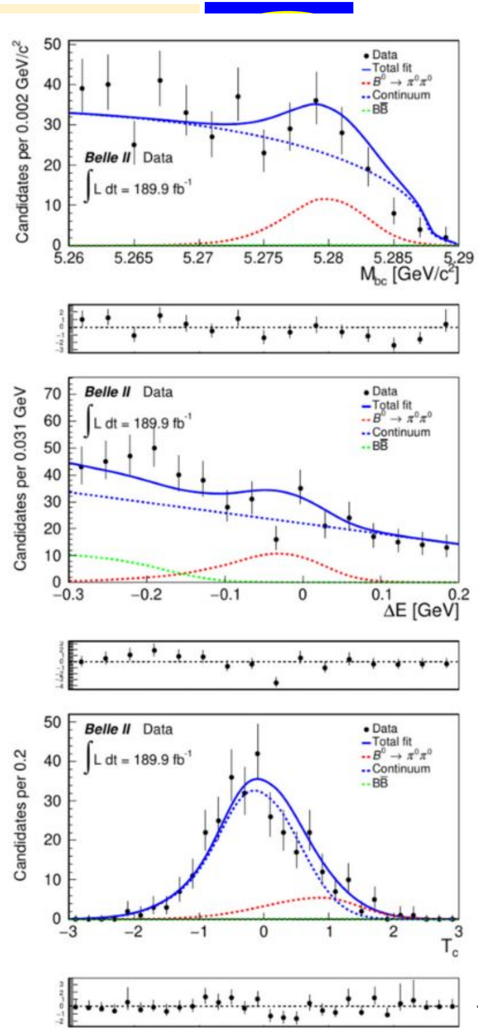
$B^0 \rightarrow \pi^0\pi^0$

- Most challenging $\pi\pi$ mode, very hard for LHCb
- Fake photons background reduced with multivariate algorithm for $\pi^0 \rightarrow \gamma\gamma$ purity
- Control channel: $B^0 \rightarrow D^0(K^+\pi^-\pi^0)\,\pi^0$
- Using Flavour Tagger to get direct CP asymmetry
- Results:
  - N Yield: 93 ± 18 (7.5 σ significance)

$$\mathcal{A}^{CP} = 0.14 \pm 0.46\ (\text{stat}) \pm 0.07\ (\text{syst})$$
$$\mathcal{B} = (1.27 \pm 0.25\ (\text{stat}) \pm 0.17\ (\text{syst})) \cdot 10^{-6}$$

WA: $\mathcal{A}^{CP} = 0.33 \pm 0.22, \mathcal{B} = (1.59 \pm 0.26) \cdot 10^{-6}$

- Competitive with Belle with ⅓ of dataset

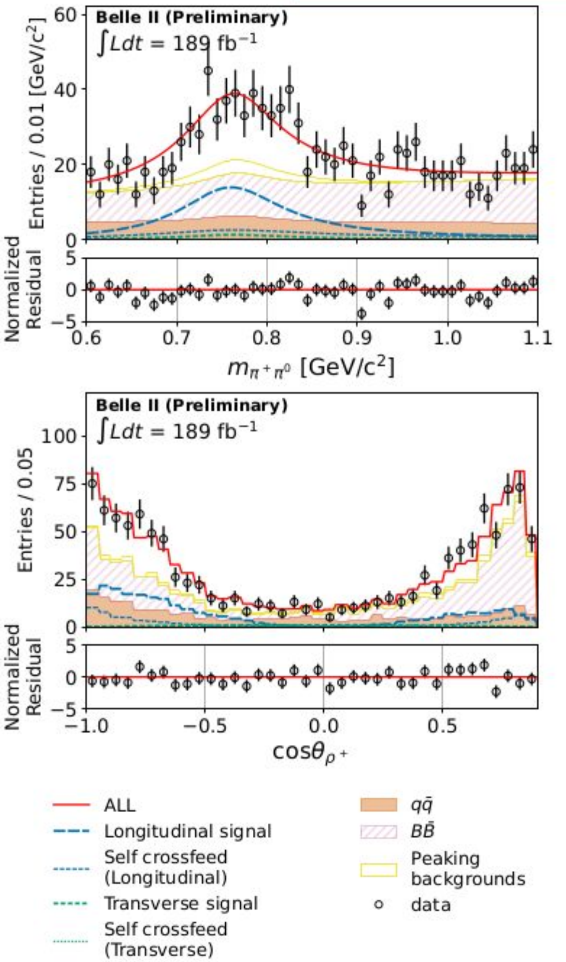


$B^0 \to \rho^+\rho^-$

- Broad resonances of vector mesons, π^0 in final state
- CP analysis requires measurement of longitudinal polarization
- Angular analysis using helicity angles of ρ's
- Fit 6D: ΔE, 2*M($\pi\pi$), 2*helicity angles, $BDT_{cont.supp.}$
- Results:
  - $N(\text{long.}) = 235^{+24}_{-23}$, $N(\text{trans.}) = 21^{+19}_{-17}$

$$\mathcal{B} = (2.67 \pm 0.28 \ (\text{stat}) \pm 0.28 \ (\text{syst})) \cdot 10^{-5}$$
$$f_L = 0.956 \pm 0.035 \ (\text{stat}) \pm 0.033 \ (\text{syst})$$

WA: $\mathcal{B} = (2.77 \pm 0.19) \cdot 10^{-5}$



$B^+ \rightarrow \rho^+\rho^0$

arXiv:2206.12362

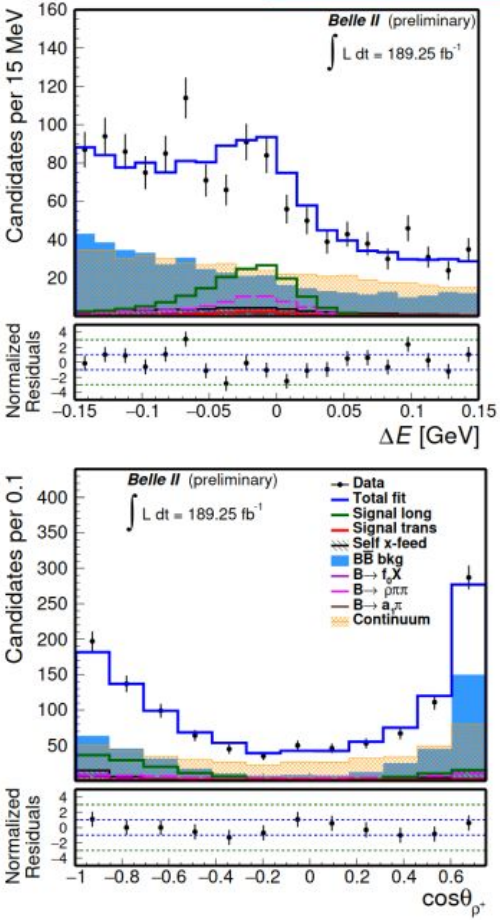
- Similar to $B^0 \rightarrow \rho^+\rho^-$
- 6D fit: ΔE, BDT, 2*M($\pi\pi$), 2*helicity angles
  - Template fit w/ correlation
- Results:
  - N(sig) = 345 ± 31

$$\mathcal{A}^{CP} = -0.069 \pm 0.068 \text{ (stat)} \pm 0.060 \text{ (syst)}$$

$$\mathcal{B} = (23.2^{+2.2}_{-2.1} \text{ (stat)} \pm 2.7 \text{ (syst)}) \cdot 10^{-6}$$

$$f_L = 0.943^{+0.035}_{-0.033} \text{ (stat)} \pm 0.027 \text{ (syst)}$$

WA: $\mathcal{A}^{CP} = -0.05 \pm 0.05, \mathcal{B} = (24.0 \pm 1.9) \cdot 10^{-6}$



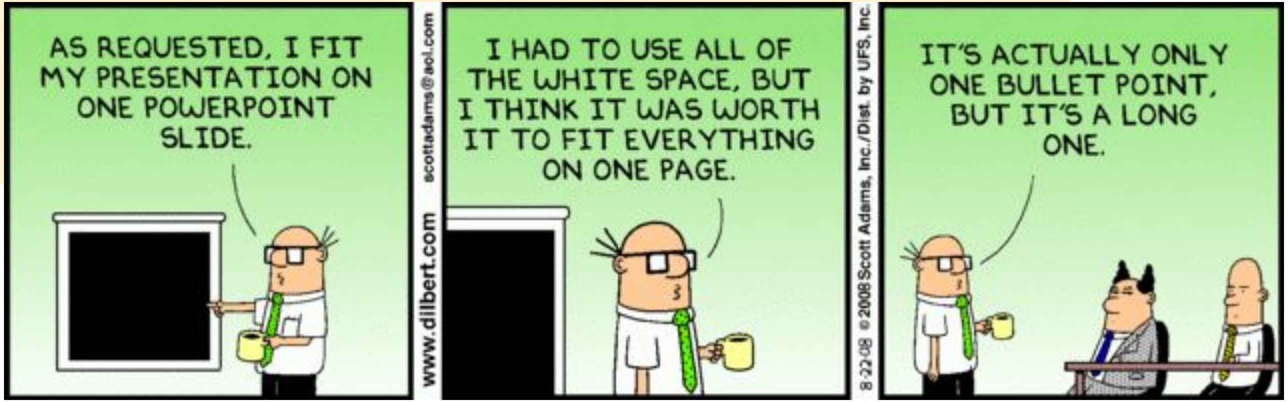
Summary

- Several TDCPV and charmless analysis using a dataset of ~190/fb collected at Belle II presented:
- Complex analyses with many inputs:
  - tracking, neutral reconstruction, Ks, vertexing, Δt resolution modelling, flavour tagging, complex fit, etc
- Belle II has now a dataset comparable to that of BaBar
- We will soon produce physics results impacting world averages.

Belle II talk at IPA2022

- A.Schwartz
  - B factory achievements, early Belle II results and outlook — Earlier today
- J. Dingfelder
  - Status and prospects for flavour anomalies at Belle II — Earlier today
- SL
  - This talk
- T.Bilka
  - Early charm physics results from Belle II and prospects — Later today
- A.Boschetti
  - Status and prospects for quarkonium at Belle II — Later today
- S.Banerjee (Belle)
  - Tau physics results at Belle — Thursday
- A.Martini
  - Tau physics programme at Belle II — Thursday
- L.Corona
  - Dark sector searches at Belle II and other e+e- colliders — Friday

Backup

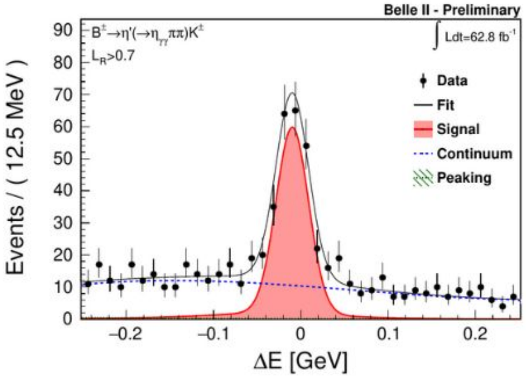

AS REQUESTED, I FIT MY PRESENTATION ON ONE POWERPOINT SLIDE.
scottadams@aol.com
www.dilbert.com
I HAD TO USE ALL OF THE WHITE SPACE, BUT I THINK IT WAS WORTH IT TO FIT EVERYTHING ON ONE PAGE.
8-22-08 © 2008 Scott Adams, Inc./Dist. by UFS, Inc.
IT'S ACTUALLY ONLY ONE BULLET POINT, BUT IT'S A LONG ONE.

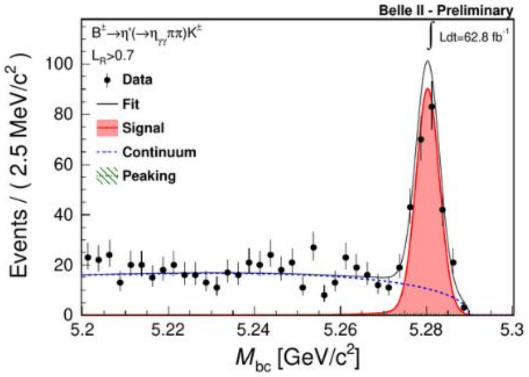
B factory variables

Two key variables discriminate against background for fully reconstructed (hadronic) final states:

$$\Delta E = E_B^* - \frac{\sqrt{s}}{2}$$

$$M_{bc} = \sqrt{\frac{s}{4} - p_B^{*2}}$$





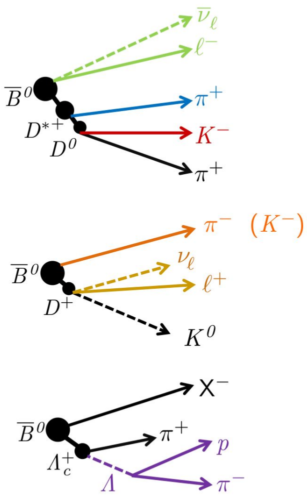
For many final states, the dominant source of background is the ‘$q\bar{q}$ continuum’, which is suppressed based on the different topology with respect to $B\bar{B}$ events:

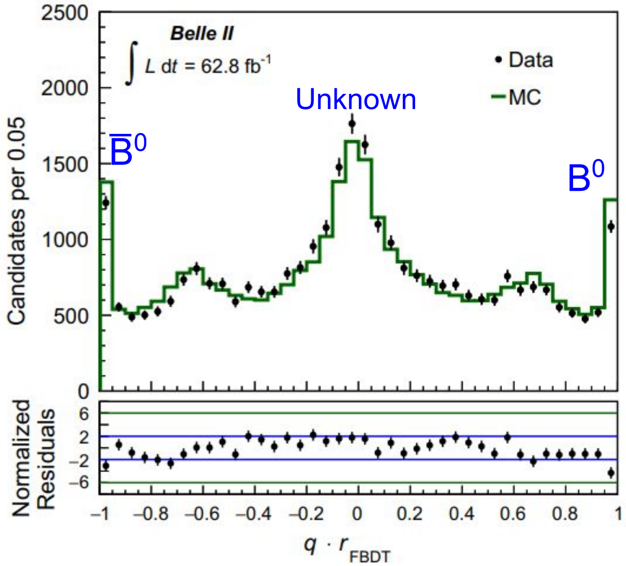
Flavour Tagger

Eur. Phys. J. C 82, 283(2022)

- Used to determine the quark-flavour of B_{tag}
- Many different final states considered, combined with two layers of MVA discriminators.
  - Developed also a **D**eep **N**eural **N**etwork with similar performance

Categories	Targets
Electron	e^-
Intermediate Electron	e^+
Muon	μ^-
Intermediate Muon	μ^+
KinLepton	e^-
Intermediate KinLepton	ℓ^+
Kaon	K^-
KaonPion	K^-, π^+
SlowPion	π^+
FastHadron	π^-, K^-
MaximumP	ℓ^-, π^-
FSC	ℓ^-, π^+
Lambda	Λ
Total= 13	





Performance measured on data using B0->D(*)-h+ decays

- Effective efficiency:

$$\varepsilon_{eff} = \Sigma_i \varepsilon_i (1 - 2w_i)^2$$
$$= (30.0 \pm 1.2 \pm 0.4)\%$$

sin2ϕ1 validation on B+

Exercise and validate procedure on $B^+ \to J/\psi K^+$ decays

1- $B^+ \to D^0 \pi^+$ events from lifetime and mixing measurement used as calibration

2- ΔE distribution of signal events fitted and background subtracted

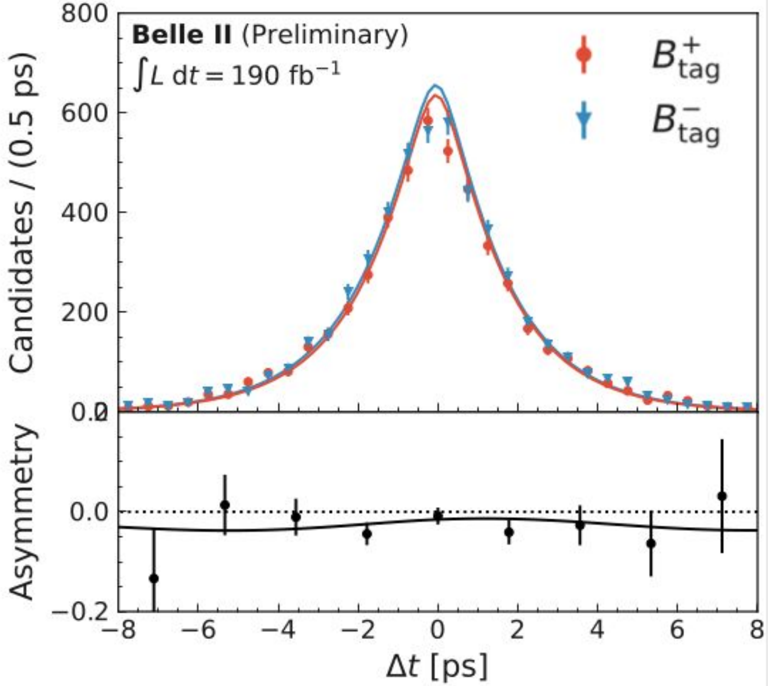
3- time-dependent fit on signal events performed with all flavor tagger and resolution function parameters fixed from step 1

Cross-checks with $B^+ \to J/\psi K^+$. Calibration done with $B^+ \to D^0 \pi^+$:

$S^{B+}_{CP} = 0.016 \pm 0.029$
$A^{B+}_{CP} = 0.021 \pm 0.021$

Null asymmetries as expected - the analysis is ready

Signal yield: 10028 ± 105



Lifetime and mixing systematics

TABLE I. Systematic uncertainties.

Source	τ_{B^0} [ps]	Δm_d [ps$^{-1}\hbar/c^2$]
Fixed Response-Function Parameters	0.006	0.003
Detector Alignment	0.003	0.002
Multiple-Candidate Inclusion	0.002	0.001
Interaction-Region Precision	0.002	0.001
C-Distribution Modeling	—	0.001
Analysis Bias	0.000	0.001
$\sigma_{\Delta t}$-Distribution Modeling	0.001	0.001
Total Systematic Uncertainty	0.008	0.005
Statistical Uncertainty	0.013	0.008

sin2ϕ1 results systematics

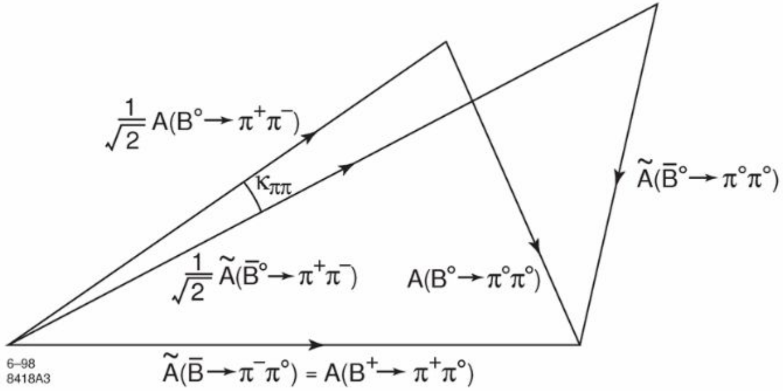
Source	$\sigma(S_{CP})$	$\sigma(A_{CP})$
Statistical	0.0622	0.0439
$B^0 \to D^{(*)-}\pi^+$ sample size	0.0111	0.0093
Analysis bias	0.0080	0.0020
Signal charge asymmetry	0.0027	0.0126
$w_6^+ = 0$ limit	0.0014	0.0001
Resolution function parametrization	0.0039	0.0008
τ_{B^0}, Δm_d	0.0007	0.0002
Alignment	0.0020	0.0042
Beam spot	0.0024	0.0020
Momentum scale	0.0005	0.0013
$\sigma_{\Delta t}$ binning	0.0050	0.0051
Multiple candidates	0.0005	0.0008
Tag-side interference	0.0020	$^{+0.0380}_{-0.000}$
Total systematic	0.0159	$^{+0.0418}_{-0.0173}$

Measurement of ϕ_2/α

- The measurement of ϕ_2 from B → ππ (or B → ρρ) final states comes from an isospin analysis:

The following equalities hold:

$$\frac{1}{\sqrt{2}}A^{+-} + A^{00} = A^{+0}$$
$$\frac{1}{\sqrt{2}}\tilde{A}^{+-} + \tilde{A}^{00} = \tilde{A}^{+0}$$
$$A^{+0} = \tilde{A}^{+0}$$



M. Gronau and D. London, PRL 65 (1990), 3381

- Observables (for e.g. B → ππ):
  - branching fractions of: $B^0 \to \pi^+\pi^0, \pi^+\pi^-, \pi^0\pi^0$;
  - direct (time-independent) CP asymmetries: C^{+-}, C^{00};
  - time-dependent CP asymmetries: S^{+-}, S^{00}.
- Belle II will be able to measure all these observables;
- We expect to push the sensitivity to α to ~1º.

$B \to K_S \pi^0$ systematics

Source	$\delta\mathcal{B}$ (%)	$\delta\mathcal{A}_{CP}$
Tracking efficiency	0.6	–
K_S^0 reconstruction efficiency	4.2	–
π^0 reconstruction efficiency	7.5	–
Continuum suppression efficiency	1.6	–
Number of $B\overline{B}$ pairs	3.2	–
Flavor tagging	–	0.040
Resolution function	–	0.050
External inputs	0.4	0.021
$B\overline{B}$ background asymmetry	–	0.002
Signal modelling	1.0	0.015
Background modelling	0.9	0.004
Possible fit bias	2.0	0.010
Tag-side interference	–	0.038
Total	9.6	0.086

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

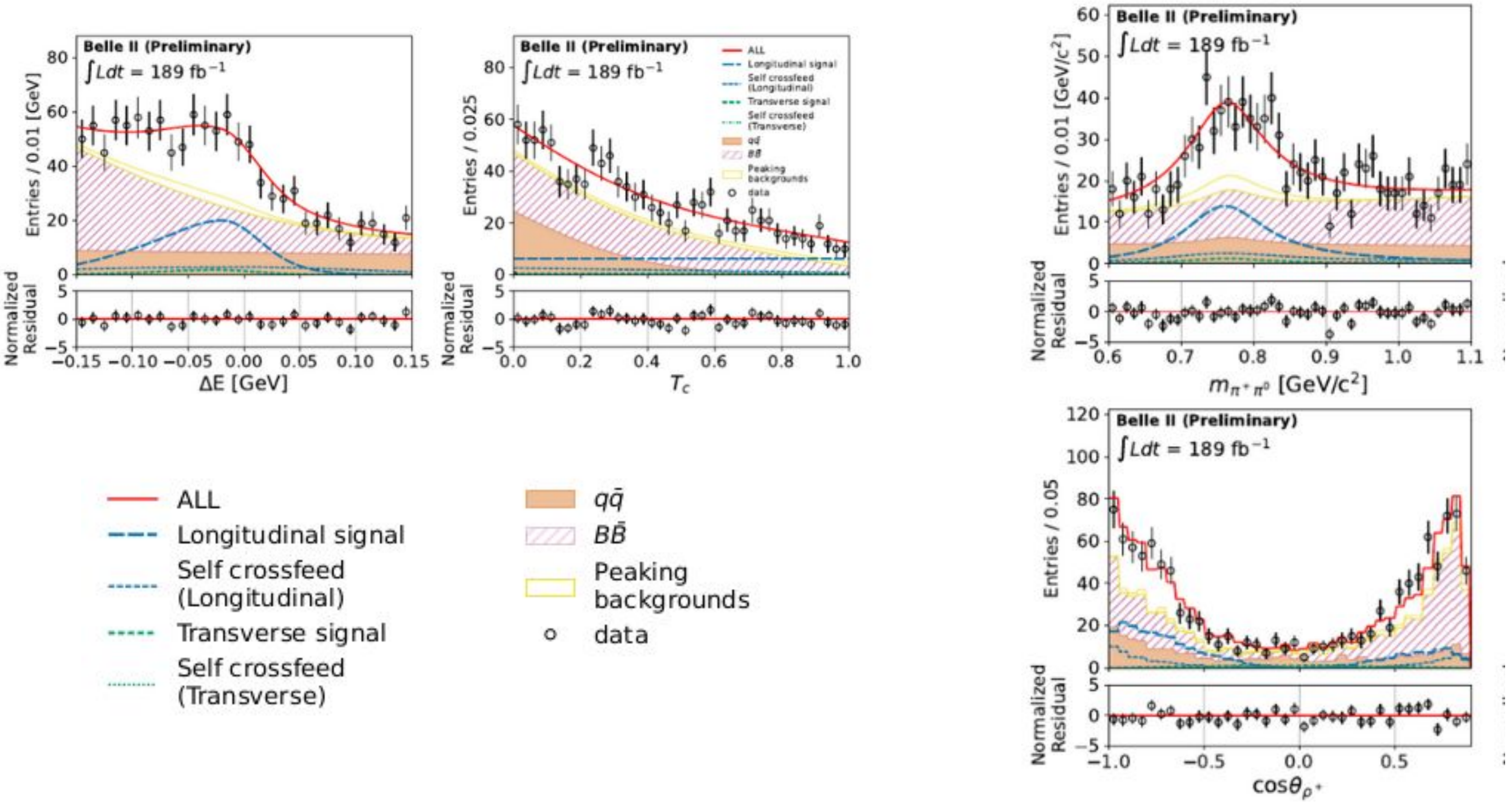
TABLE II. Summary of the fractional uncertainties on the branching ratios.

Source	$B^+ \to K^+\pi^0$ [%]	$B^+ \to \pi^+\pi^0$ [%]
Tracking	0.30	0.30
B counting	1.5	1.5
$R(B^+B^-)$	1.2	1.2
π^0 efficiency	4.4	4.4
CS efficiency	0.9	1.1
Particle identification	0.2	0.5
Multiple candidates	0.01	0.9
Continuum BDT shift and scale (K^+ π^0)	0.5	0.08
Continuum BDT shift and scale (π^+ π^0)	0.1	1.6
ΔE shift and scale	2.0	6.3
$M_{\rm bc}$ shift and scale	1.1	2.3
Signal BDT shift and scale (K^+ π^0)	0.4	0.1
Signal BDT shift and scale (π^+ π^0)	0.02	0.8
$B\overline{B}$ Shape	0.4	0.2
Total systematic uncertainty	5.5	8.6
Statistical uncertainty	4.8	8.7

TABLE III. Summary of the absolute uncertainties on the *CP* asymmetries.

Source	$B^+ \to K^+\pi^0$	$B^+ \to \pi^+\pi^0$
Continuum BDT shift and scale (K^+ π^0)	0.0002	0.0006
Continuum BDT shift and scale (π^+ π^0)	0.0010	0.0092
ΔE shift and scale	0.0014	0.0038
$M_{\rm bc}$ shift and scale	0.0008	0.0023
Signal BDT shift and scale (K^+ π^0)	0.0002	< 0.0001
Signal BDT shift and scale (π^+ π^0)	0.0002	0.0005
$B\overline{B}$ Shape	0.0000	0.0001
Instrumental asymmetry	0.010	0.010
Fit bias	-	0.0118
Total systematic uncertainty	0.0102	0.0185
Statistical uncertainty	0.0470	0.0851

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


Belle II (Preliminary)
∫Ldt = 189 fb⁻¹
Entries / 0.01 [GeV]
Normalized Residual
ΔE [GeV]
Entries / 0.025
T_c
Entries / 0.01 [GeV/c²]
$m_{\pi^+\pi^0}$ [GeV/c²]
Entries / 0.05
$\cos\theta_{\rho^+}$
ALL
Longitudinal signal
Self crossfeed (Longitudinal)
Transverse signal
Self crossfeed (Transverse)
$q\bar{q}$
$B\bar{B}$
Peaking backgrounds
data

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

Table 3: Summary of the systematic uncertainties

source	$\mathcal{B}$ [%]	f_L [%]
Tracking	0.6	-
Photon and π^0 selection	7.7	-
PID	0.8	-
Continuum suppression	2.1	-
$N_{B\bar{B}}$	1.5	-
Single candidate selection	2.2	0.9
Signal model	2.4	2.0
Self cross-feed model	$^{+2.7}_{-0.9}$	< 0.1
Continuum model	1.3	0.7
$B\bar{B}$ model	2.0	2.2
Peaking background model	0.4	0.7
$\cos\theta_{\rho^\pm}$ mismodeling	4.4	0.3
Fit bias	0.9	1.0
Simulation sample size	1.0	0.2
Total	$^{+10.6}_{-10.3}$	± 3.4

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

TABLE II. Summary of the (fractional) systematic uncertainties of the branching-fraction and longitudinal-polarization-fraction measurements.

Source	$\mathcal{B}$	f_L	$\mathcal{A}_{CP}$
Tracking	0.9%	n/a	n/a
π^0 efficiency	5.7%	n/a	n/a
PID and continuum-supp. eff.	1.2%	n/a	n/a
$N_{B^+B^-}$	3.1%	n/a	n/a
Instrumental asymmetry correction	n/a	n/a	0.005
Single candidate selection	2.2%	1.1%	0.037
Signal model	0.10%	0.02%	0.002
Continuum bkg. model	0.04 %	1.2%	0.003
$B\overline{B}$ bkg. model	0.05%	0.08%	0.002
Fit biases	4.4%	1.1%	0.010
Data-simulation mismodeling	8.0%	2.1%	0.002
Peaking background *CP* asymmetries	0.3%	0.1%	0.046
Total	11.5%	2.9%	0.060