CPV at e^+/e^- colliders

FPCP2024, Chulalongkorn University, Bangkok Thailand 30/05/2024

Stefano Lacaprara
for the Belle II collaboration
INFN Padova

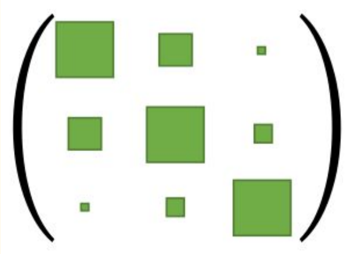
CPV in Standard Model: CKM matrix

Dirac Medal 2010

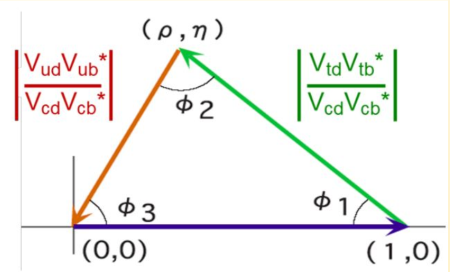
Nobel Prize 2008

- CPV: a key for matter-antimatter asymmetry in the universe
  - In SM, only source is complex phase in CKM matrix
  - (and possible similar phase in PMNS matrix)

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

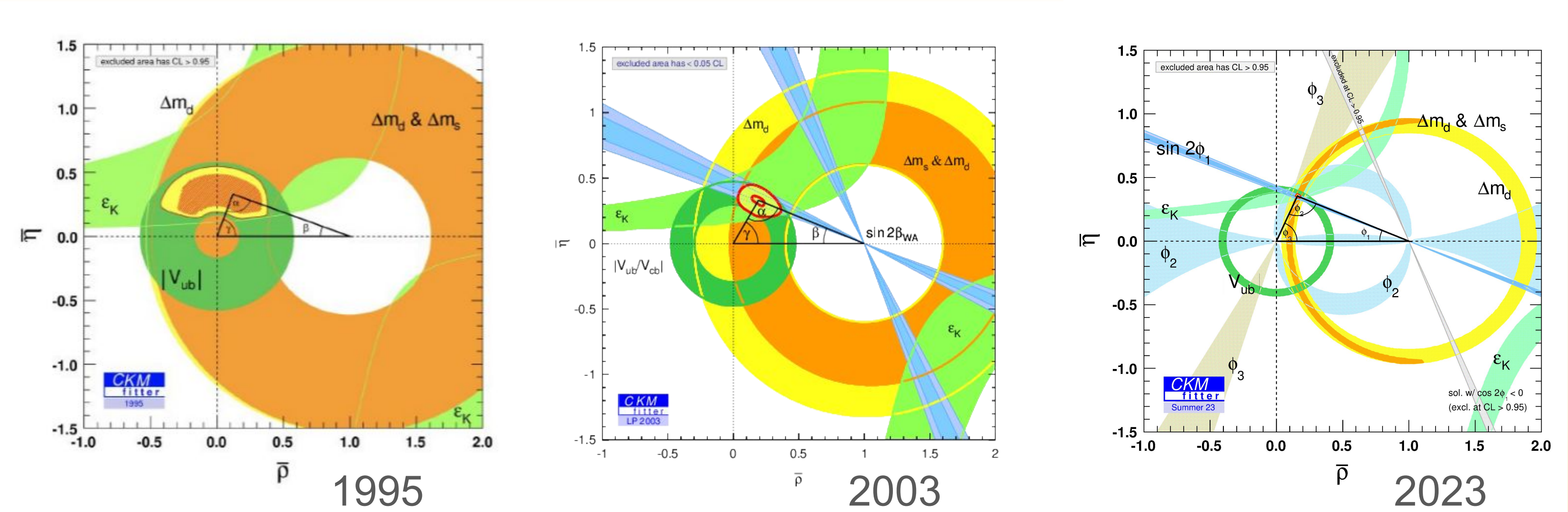


- From CKM unitarity: $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$
  - Triangle in complex plane
  - Three angles
  - Other triangles exist



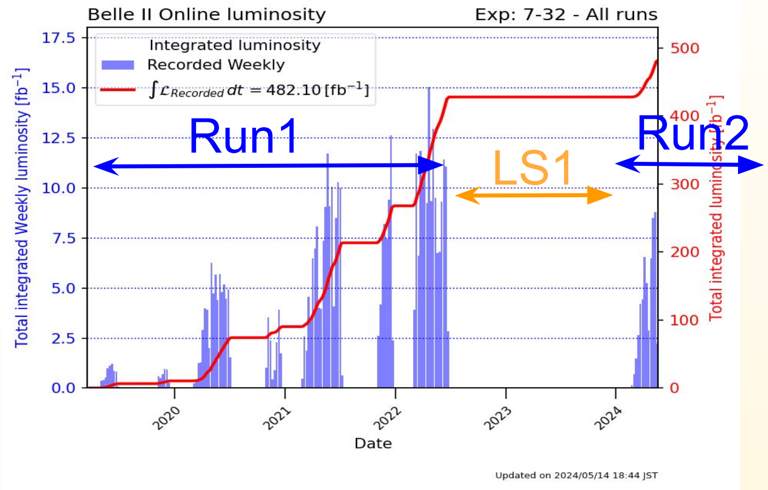
$\phi_1 = \beta$
$\phi_2 = \alpha$
$\phi_3 = \gamma$

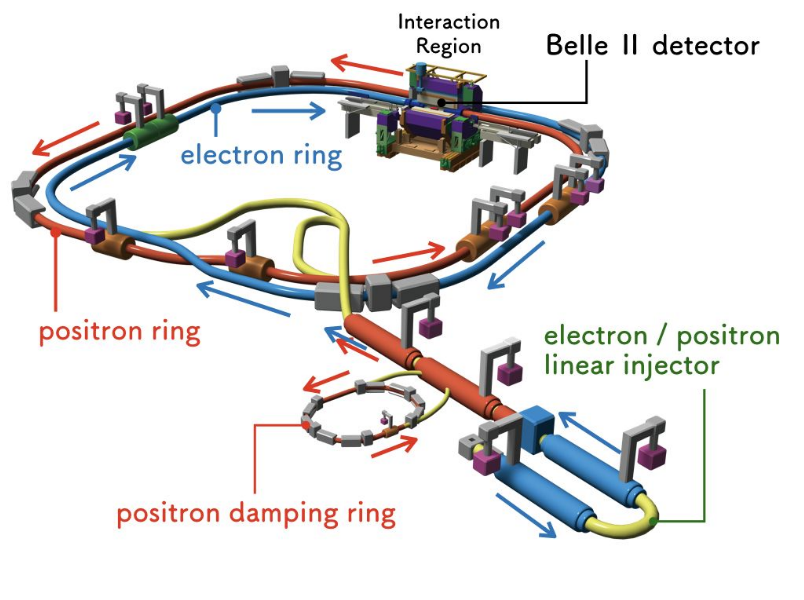
CPV and Unitarity Triangle



- Precise test of SM by over constraining Unitarity Triangle
- Search for New Physics effects, especially in loop mediated diagrams
- **At e^+/e^- collider:**
  - clean environment, full reconstruction, access to modes with neutrals in the final states

SuperKEKB and Belle II





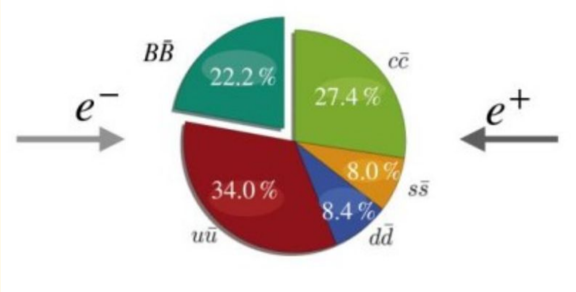
- e^+/e^- (4/7 GeV) at KEK
  - Around ϒ(4S) resonance
- Run 1 operation 2019-2022
  - **424 fb^{-1} collected - 362 fb^{-1} at ϒ(4S)**
- Long Shutdown 1 (LS1) until end of 2023
  - For accelerator and detector upgrades
- Run 2 operation from Jan 2024

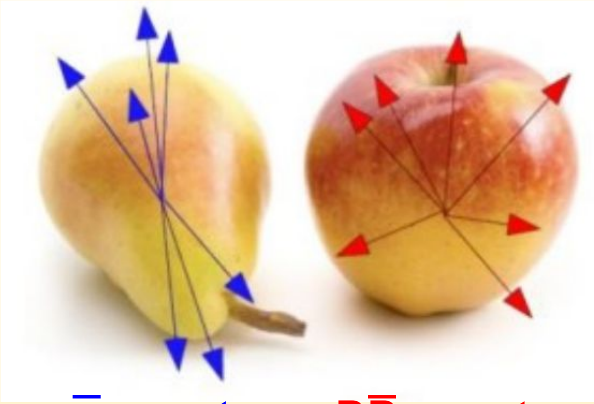
Luminosity record $4.7 \times 10^{34}\ cm^{-2}s^{-1}$

- 2x KEKB
- Goal to collect multi ab^{-1} of data

B-Factory variables

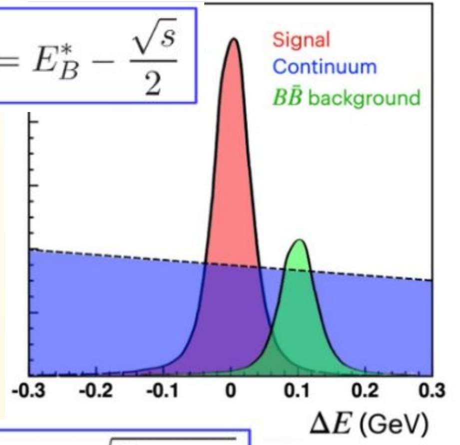
- Two key variables to discriminate fully reconstructed (hadronic) signal from background
  - Background from continuum (qq-bar) and from BB
- Discrimination against continuum (qq-bar) background using event-shape variables via a multivariate classifier



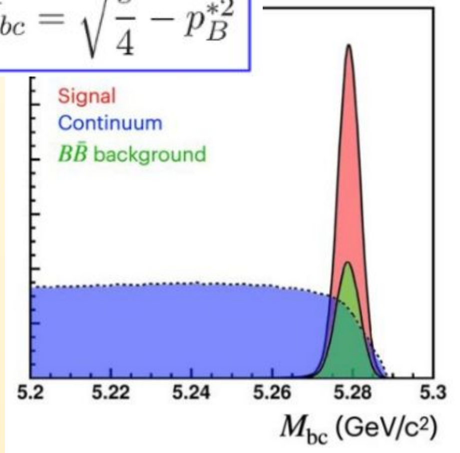


$q\bar{q}$ events $B\bar{B}$ events

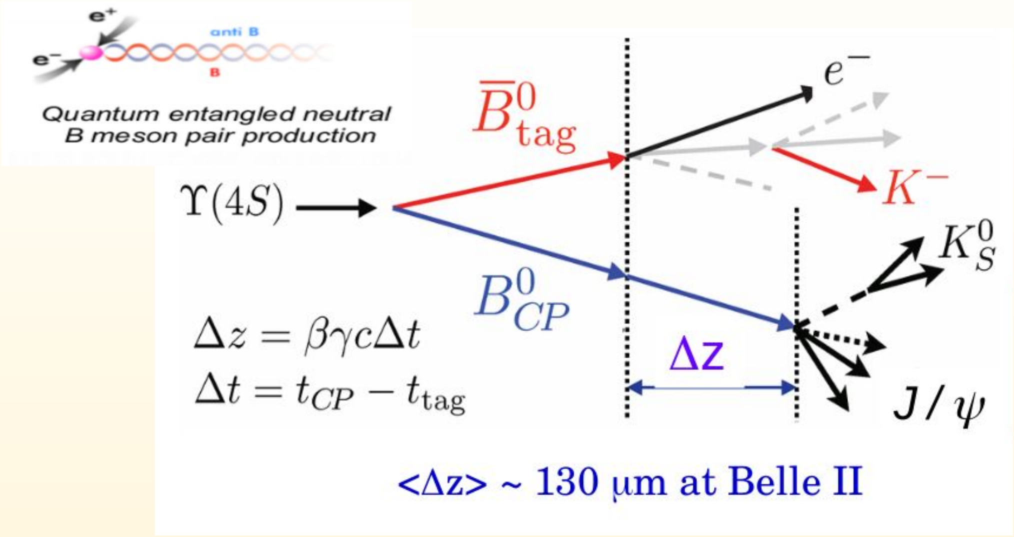
$$\Delta E = E_B^* - \frac{\sqrt{s}}{2}$$



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



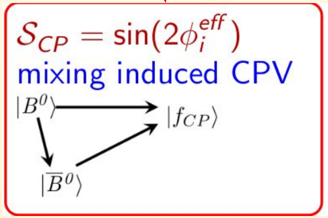
Time-Dependent (TD) CPV analysis

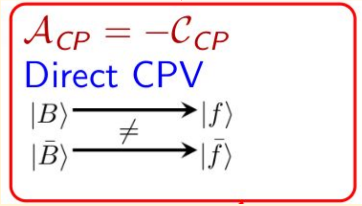


Flagship measurement at B factories
Still very important at Belle II

$$\mathcal{A}_{CP}(\Delta t) = \frac{\Gamma(B_{tag=B^0}(\Delta t) \to f_{CP}) - \Gamma(B_{tag=\bar{B}^0}(\Delta t) \to f_{CP})}{\Gamma(B_{tag=B^0}(\Delta t) \to f_{CP}) + \Gamma(B_{tag=\bar{B}^0}(\Delta t) \to f_{CP})} = $$

$$= S \cdot \sin(\Delta m_d \Delta t) - C \cdot \cos(\Delta m_d \Delta t)$$





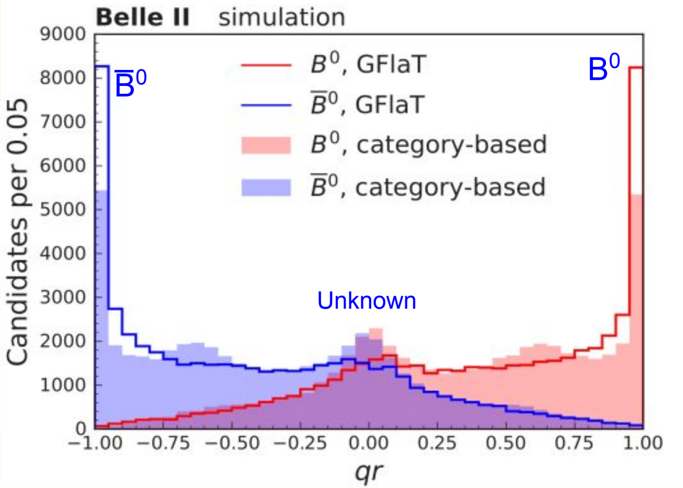
- **B_{CP}** fully reconstructed CP eigenstate
- **B_{tag}** vertex and flavour information
- Complex analysis, many key elements:
  - high signal efficiency
  - excellent vertex resolution σ_z~26/50μm (signal/tag side)
  - high flavour-tagging efficiency **ε = 37%**

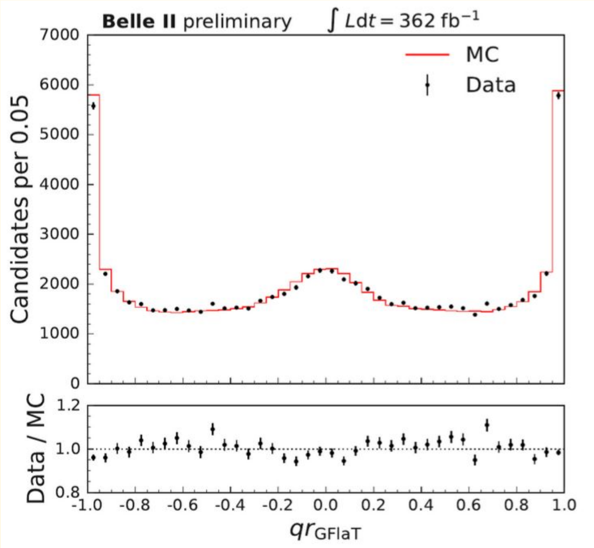
B flavour tagging: GFlaT

arXiv:2402.17260
Accepted by PRD

- CPV analysis in Belle II used a category-based (CB) algorithm [Eur. Phys. J 82, 283 (2022)]
- A more advanced algorithm GFlaT, based on graph convolutional neural network (GNN), was developed
  - Using 25 variables for each track from the B_{tag} decay
- Performance evaluated on data using self-tagging $B^0 \to D^{(*)-}\pi^+$ decays
- Significant improvement in performance
  - **+18%** (relative)

ε_{tag}(CB) = (31.7 ± 0.5 ± 0.4) %
ε_{tag}(GFlaT) = (**37.4 ± 0.4 ± 0.3**) %

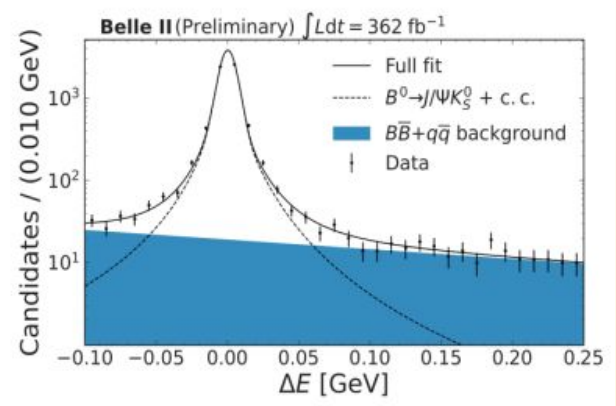




sin(2ϕ_1/β) from $B \to J/\psi K_S$

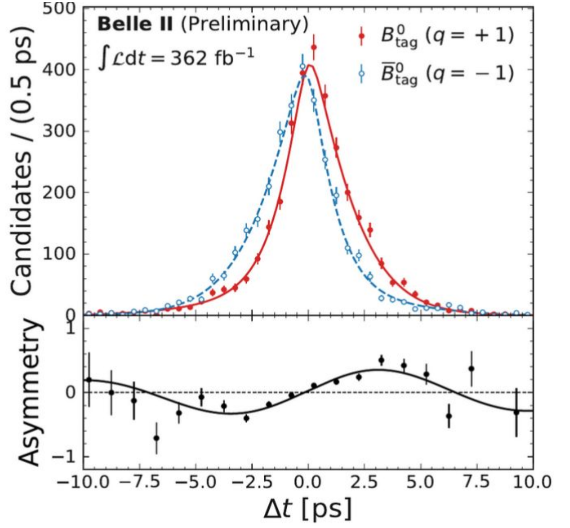
arXiv:2402.17260
Accepted by PRD

- Golden channel, almost background free
- Updated results using improved GFlaT flavour tagger
- Fit ΔE distribution to subtract background
- Fit background-subtracted Δt distribution to extract CPV parameters



S = 0.724 ± 0.035 ± 0.014
C = - 0.035 ± 0.026 ± 0.013

World average (K_S mode only):
S_{CP} = 0.695 ± 0.019
A_{CP} = 0.000 ± 0.020



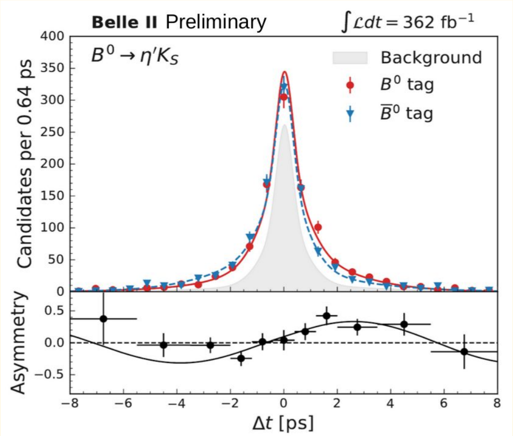
- Statistical uncertainties **8%** smaller than with category-based Flavour Tagger

TDCPV in Charmless B decay

See also S.Raiz talk on Tue

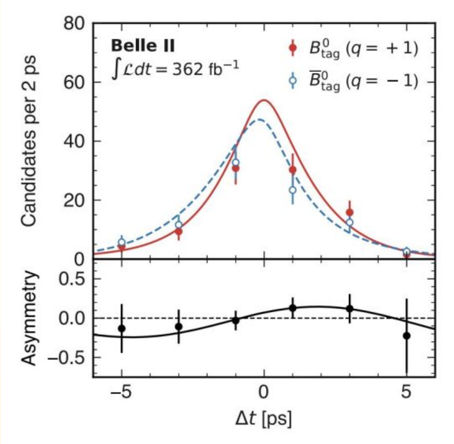
Belle II INFN

- $B \to \eta' K_S$ arXiv:2402.03713
  - $\eta' \to \eta(\to\gamma\gamma)\pi^+\pi^-$
  - $\eta' \to \rho\gamma$
- High $\mathcal{B}$, theoretically clean
  - ~800 signal events



S = 0.67 ± 0.10 ± 0.04
C = - 0.19 ± 0.08 ± 0.03

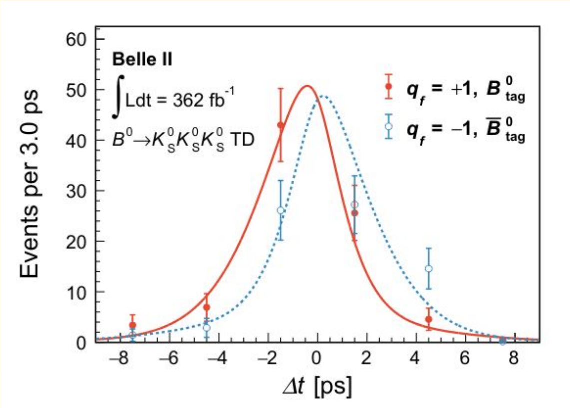
- $B \to \phi K_S$ PRD 108, 072012 (2023)
- Challenge: non resonant background with opposite-CP
  - ~160 signal events



$S = 0.54 \pm 0.26\ ^{+0.06}_{-0.08}$
C = - 0.31 ± 0.20 ± 0.05

arXiv:2403.02590
Accepted by PRD

- $B \to K_S K_S K_S$
- Challenge: no prompt tracks from B vertex
  - Use $K_S \to \pi^+\pi^-$ extrapolated to IP
  - ~160 signal events



$S = -1.37\ ^{+0.35}_{-0.45} \pm 0.03$
C = - 0.07 ± 0.20 ± 0.05

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

EPS-HEP 2023
Paper in preparation

- $B^0 \to K_S \pi^0 \gamma$ 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 $B^0 \to \bar{B}^0 \to s\gamma_R$
- Vertex from $K_S \to \pi^+\pi^-$ and IP constraint
- Measured separately for resonant $K^{*0}(\to K_S\pi^0)\gamma$

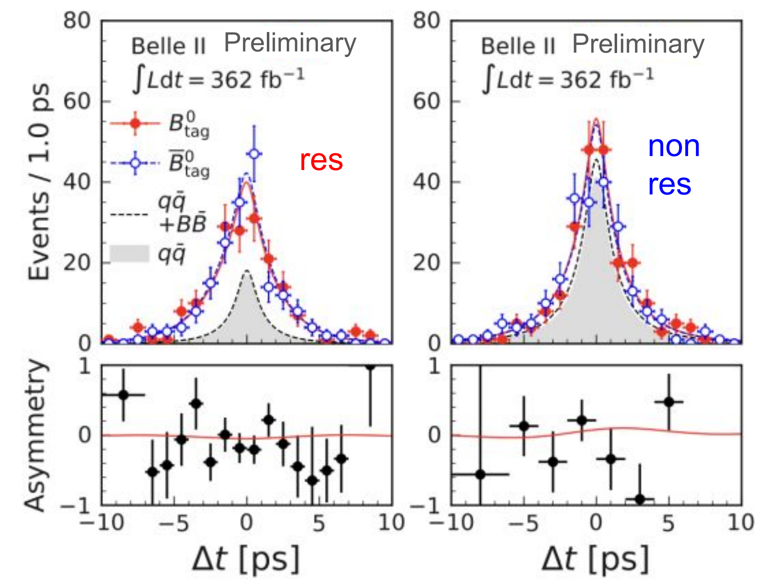
See also S.Raiz talk on Tue

$$S = 0.00\ ^{+0.27}_{-0.26}\ ^{+0.03}_{-0.04}$$
$$C = 0.10 \pm 0.13 \pm 0.03$$

- and inclusive (non resonant) decay $K_S\pi^0\gamma$

$$S = 0.04\ ^{+0.45}_{-0.44} \pm 0.10$$
$$C = -0.06 \pm 0.25 \pm 0.07$$

Most precise result so far

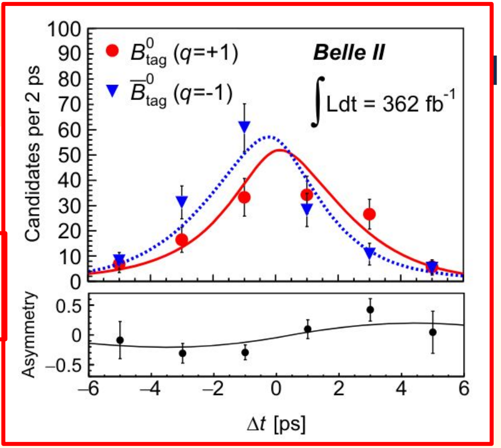


CPV in $B^0 \to K^0_S \pi^0$

PRL 131, 111803 (2023)
PRD 109, 012001 (2024)

- First Belle II measurement of TDCPV in $\mathbf{B^0 \to K_S \pi^0}$
  - Signal yield: 415^{+26}_{-25} events
- Key ingredient in Isospin Sum Rule

$$S = 0.75^{+0.20}_{-0.23} \pm 0.04,$$
$$C = -0.04^{+0.14}_{-0.15} \pm 0.05$$



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

$$I_{K\pi} = \mathcal{A}_{CP}^{K^+\pi^-} + \mathcal{A}_{CP}^{K^0\pi^+} \frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)} \frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{CP}^{K^+\pi^0} \frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)} \frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{CP}^{K^0\pi^0} \frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)} \approx 0$$ (within ~1%)

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

$\mathcal{B}(K^+\pi^-) = (20.67 \pm 0.37 \pm 0.62) \times 10^{-6}$
$\mathcal{A}_{CP}(K^+\pi^-) = -0.072 \pm 0.019 \pm 0.007$

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

$\mathcal{B}(K^+\pi^0) = (13.93 \pm 0.38 \pm 0.84) \times 10^{-6}$
$\mathcal{A}_{CP}(K^+\pi^0) = +0.013 \pm 0.027 \pm 0.005$

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

$\mathcal{B}(K^0_S\pi^+) = (24.40 \pm 0.71 \pm 0.86) \times 10^{-6}$
$\mathcal{A}_{CP}(K^0_S\pi^+) = +0.046 \pm 0.029 \pm 0.007$

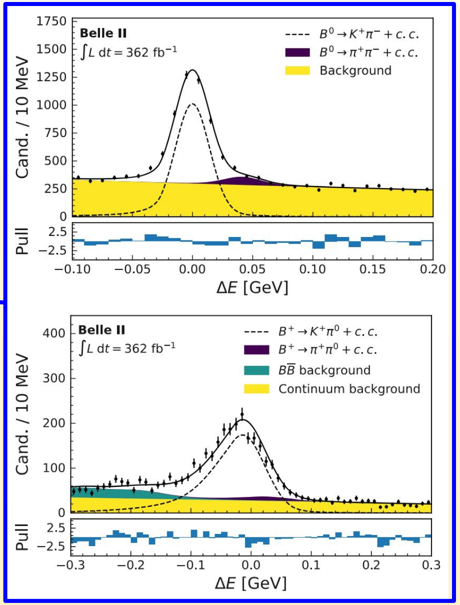
$B^0 \to K^0_S\pi^0$

$\mathcal{B} = (10.50 \pm 0.62 \pm 0.67) \times 10^{-6}$
$A_{CP} = -0.01 \pm 0.12 \pm 0.05$

world's best

$\Rightarrow$ $I_{K\pi} = -0.03 \pm 0.13 \pm 0.05$
(world average 0.13 ± 0.11)

precision on par with W/A!
→ 5% uncertainty achievable @ 10 ab^{-1}



Toward ϕ_2/α: $B^0 \to \pi^0\pi^0$

New for FPCP 2024

See also S.Raiz talk on Tue

Previous results
[PRD107 (2023) 112009]

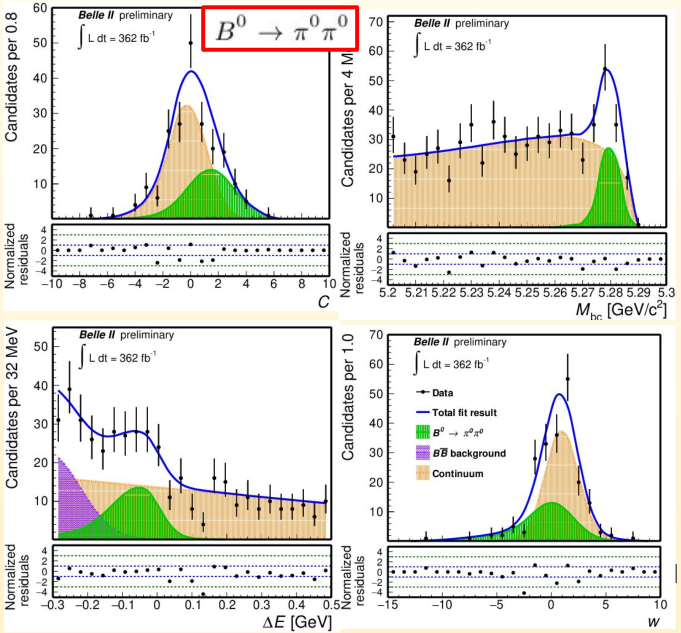
- Update on $\mathcal{B}$ and A_{CP} using full Run1 statistics:
- Improved selections, new flavour tagger (GFlaT), reduction of systematics
  - Background dominated by continuum, then $B\bar{B}$ ($B^+ \to \rho^+(\to \pi^+\pi^0)\pi^0$, $B^0 \to K^0_S(\to \pi^0\pi^0)\pi^0$)
  - Photons selected with BDT, continuum suppression trained on off-resonance data
  - 4D fit including M_{BC}, ΔE, cont.suppression, w (wrong tag probability - unbinned)
  - Validated on $B^+ \to K^+\pi^0$ / $B^0 \to \bar{D}^0(K^+\pi^-\pi^0)\pi^0$

$$\mathcal{B} = (1.26 \pm 0.20 \pm 0.11) \times 10^{-6}$$
$$A_{CP} = 0.06 \pm 0.30 \pm 0.06$$

- Compatible with known values
- World-best B determination.
- A_{CP} on par with world best

$\mathcal{B} = (1.59 \pm 0.26) \times 10^{-6}$
$A_{CP} = 0.30 \pm 0.20$ WA

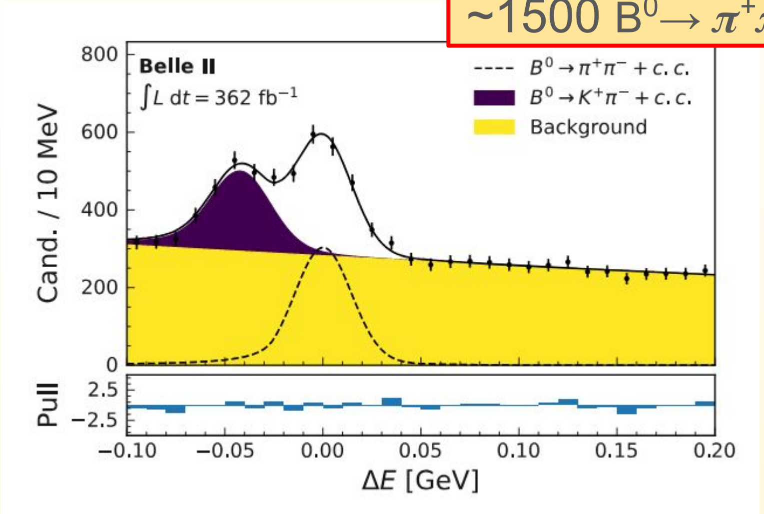
Signal enhanced region



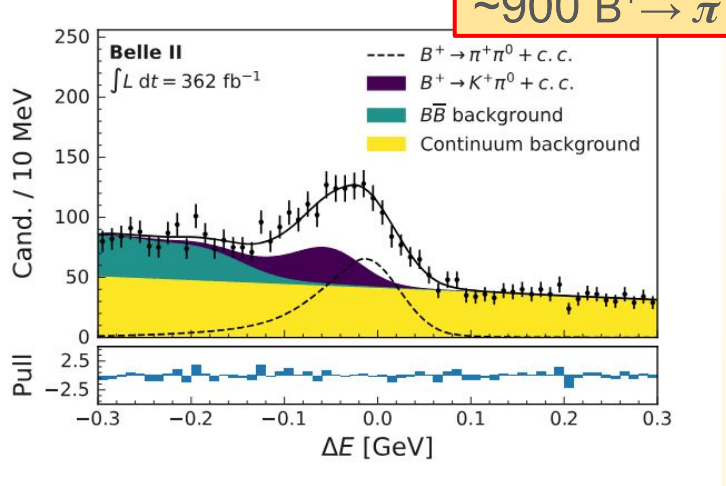
Toward ϕ_2/α: $B \to \pi\pi$

PRD 109, 012001 (2024)

~1500 $B^0 \to \pi^+\pi^-$



~900 $B^+ \to \pi^+\pi^0$



$\mathcal{B}(B^0 \to \pi^+\pi^-) = (5.83 \pm 0.22 \pm 0.17) \times 10^{-6}$

world's best

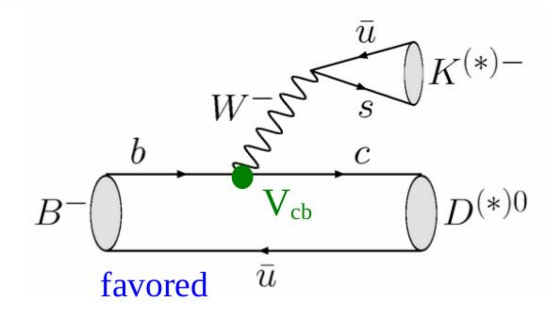
$\mathcal{B}(\pi^+\pi^0) = (5.10 \pm 0.29 \pm 0.32) \times 10^{-6}$

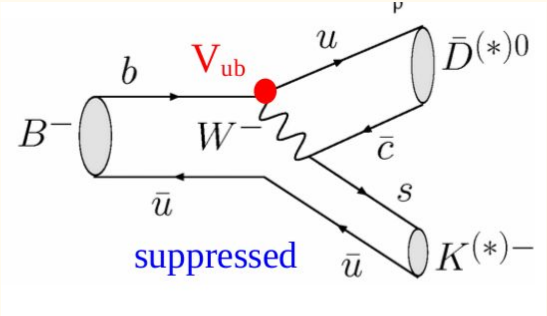
$A_{CP}(\pi^+\pi^0) = -0.081 \pm 0.054 \pm 0.008$

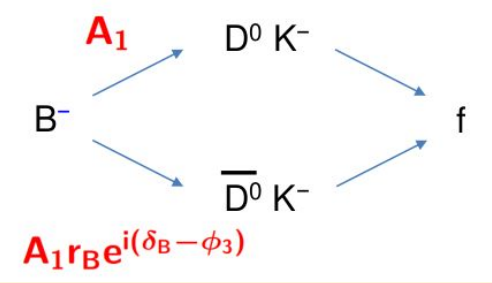
- Compatible and competitive with WA
- Modes with π^0 limited by π^0 systematics: will be reduced with more data

Results on γ/φ_3

- γ/φ_3 from interference of tree level amplitudes:
  - Fundamental input of CKM UT fit
- φ_3 can be measured using interference $B \to DK$ and $B \to \bar{D}K$ (or D^*K^*, $D\pi$)







$B^- \to D^0K^- \approx V_{cb}V^*_{us}$
A_1

$B^- \to \bar{D}^0K^- \approx V_{ub}V^*_{cs}$
$A_1 r_B e^{i(\delta_B - \phi_3)}$

- Amplitude ratio r_B and strong phase δ_B are mode-dependent

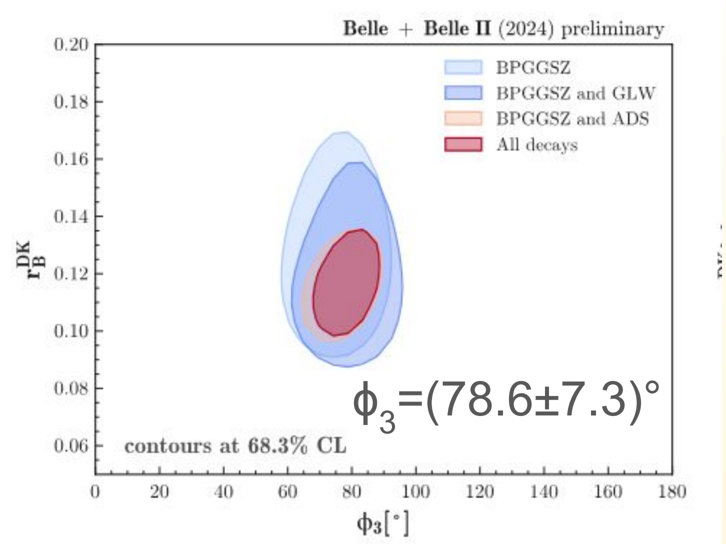
Belle/BelleII combined results on γ/ϕ_3

arXiv [2404.12817]

- Several methods used
  - GLW $B^\pm \to D^0_{CP} K^\pm$ arXiv:2308.05048 [hep-ex]
    - Use CP eigenstate of D meson
  - ADS PRL 78 (1997) 3257
    - Enhancement of CP violation by using doubly Cabibbo suppressed decays.
  - BPGGSZ $D^0 \to K_S h^+ h^-$ JHEP 2022(2022), 63
    - Different amplitude and strong phase in different region of Dalitz plot.
  - GLS $D^0 \to K_S K\pi$ JHEP 09(2023)146
- D-decay strong phase from CLEO-c & BESIII
  - Need improvement by BESIII

LHCb: $\phi_3=(63.8\pm3.6)^\circ$ LHCb-CONF-2022-003

Few ab^{-1} needed for a meaningful comparison



$\phi_3=(78.6\pm7.3)^\circ$

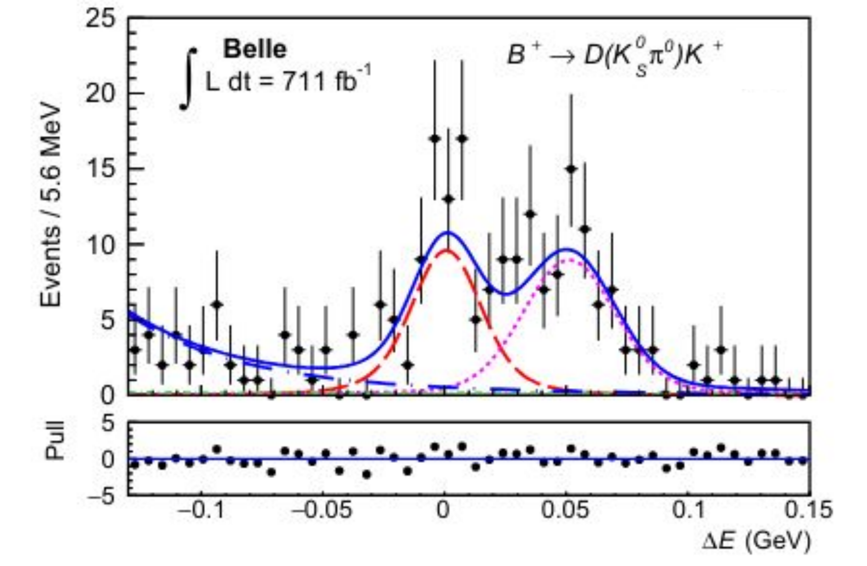
- Likelihood with 60 input observables
  - including 15 auxiliary inputs (D-decay)
  - 16 free parameters
- $r_B(\delta_B)$ with little high-fluctuation
  - Worse precision with WA values

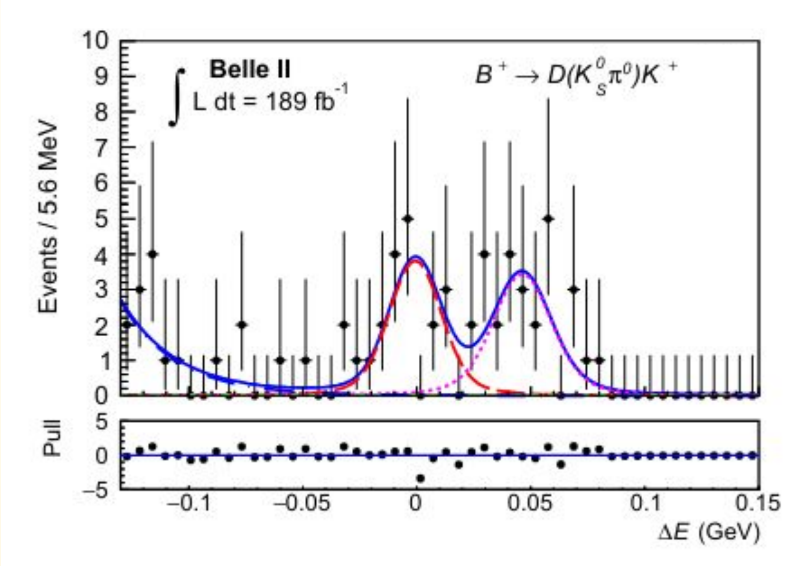
Belle + Belle II Combined γ/φ_3

arXiv:2308.05048

- Example:
  - $B^{\pm} \to D_{CP} K^{\pm}$ (GLW)
  - CP-odd $D_{CP} \to K_S \pi^0$: only in Belle(II)
  - Combined Belle and BelleII analysis

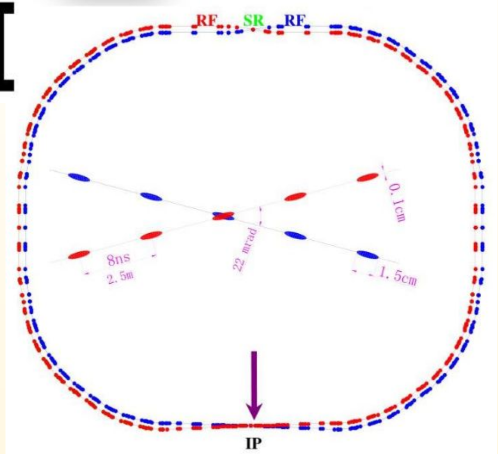
B decay	D decay	Method	Data set (Belle + Belle II)[fb^{-1}]
$B^+ \to Dh^+$	$D \to K_S^0\pi^0, K^-K^+$	GLW	$711 + 189$
$B^+ \to Dh^+$	$D \to K^+\pi^-, K^+\pi^-\pi^0$	ADS	$711 + 0$
$B^+ \to Dh^+$	$D \to K_S^0 K^-\pi^+$	GLS	$711 + 362$
$B^+ \to Dh^+$	$D \to K_S^0 h^- h^+$	BPGGSZ (m.i.)	$711 + 128$
$B^+ \to Dh^+$	$D \to K_S^0\pi^-\pi^+\pi^0$	BPGGSZ (m.i.)	$711 + 0$
$B^+ \to D^*K^+$	$D^* \to D\pi^0, D \to K_S^0\pi^0, K_S^0\phi, K_S^0\omega, K^-K^+, \pi^-\pi^+$	GLW	210+0
$B^+ \to D^*K^+$	$D^* \to D\pi^0, D\gamma, D \to K_S^0\pi^-\pi^+$	BPGGSZ (m.d.)	$605 + 0$





BESIII @ Beijing Electron-Positron Collider (BEPC-II)

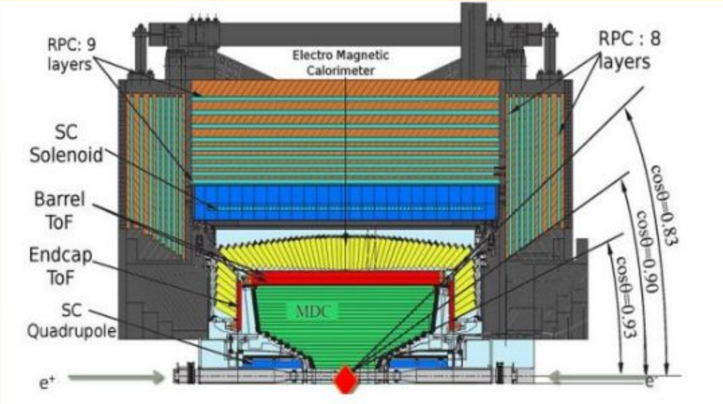
- CM Energies: [2-4.95] GeV: τ-charm region
  - Luminosity: ~10^{33} cm^{-2}s^{-1}
- Collected 10 billion J/ψ and 3 billion $\psi(2S)$
  - Possible to study CPV on **hyperons**
  - ~10^7 entangled hyperon pairs



Decay	$\mathcal{B}$ (10^{-5})	Events at BESIII
$J/\psi \to \Lambda\bar{\Lambda}$	189 ± 9	18.9×10^6
$J/\psi \to \Sigma^+\bar{\Sigma}^-$	150 ± 24	15.0×10^6
$J/\psi \to \Xi\bar{\Xi}$	97 ± 8	9.7×10^6
$\psi(2S) \to \Sigma\bar{\Sigma}$	23.2 ± 1.2	116×10^3
$\psi(2S) \to \Omega\bar{\Omega}$	5.66 ± 0.30	28×10^3

Front. Phys. 12(5), 121301 (2017)

More on BESIII and BEBC-II on Luyan Tao talk on Monday



CPV in Hyperon decay

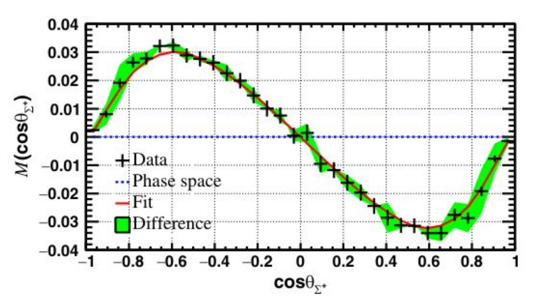
PRL.131.191802 (2023)

- Polarized and entangled pair of hyperons from J/ψ decays
- Decay asymmetry parameters **α** from S-wave (parity conserving) and P-wave (parity violating) amplitudes. $\bar{\alpha}$ for anti-hyperons
  - **α** is CP-odd
  - **Non zero** $\mathcal{A}_{CP} = \frac{\alpha_+ + \bar{\alpha}_-}{\alpha_+ - \bar{\alpha}_-}$ **⇒ CP violation**

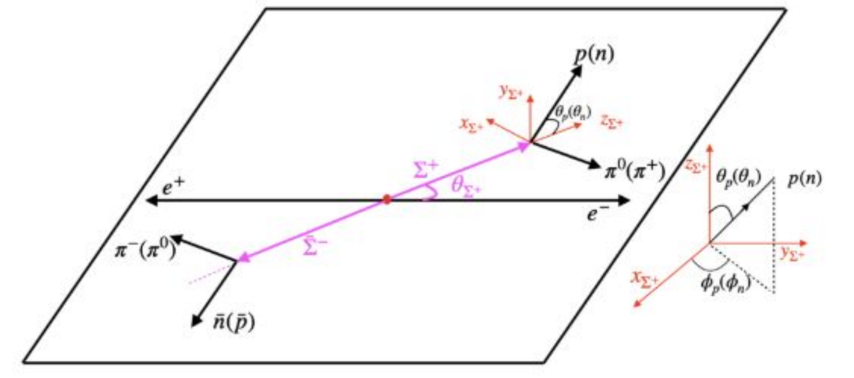
$$\frac{dN}{d\Omega} = \frac{1}{4\pi}(1 + \alpha \mathbf{P}_{\Sigma^+} \cdot \hat{\mathbf{n}})$$

- Events: $J/\psi \to \Sigma^+$ anti-Σ^-, $\Sigma^+ \to n\pi^+$, anti-$\Sigma^- \to \bar{p}\pi^0$ or c.c.
  - 10 billion $J/\psi \to \Sigma^+$ anti-Σ^-
  - Complex angular analysis: 5 observables
  - First CPV result with neutron in the final state

Moment of polarization



Non flat ⇒ polarization observed

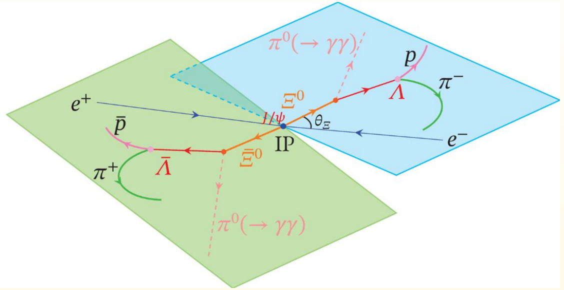


$A_{CP} = 0.080 \pm 0.052 \pm 0.028$

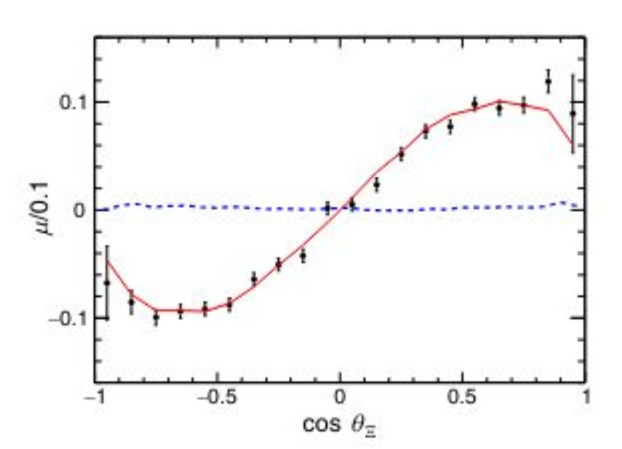
$e^+e^-\to J/\psi\to$ Ξ^{0}anti-Ξ^0, Ξ$^0\to\Lambda(\to p\pi^-)\pi^0$ +cc

- Even more complex angular analysis (9 helicity angles)
- 8 free parameters (plus other in daughter's decay)
  - 10 billion J/ψ events:
  - 320k signal events with little background

PhysRevD.108.L031106 (2023)



- Results:
  - Ξ$^-$ polarization observed (first time)
  - Independent measurement of Λ decay parameters
  - First measurement of weak phase difference in Ξ decay
  - Three independent CP test

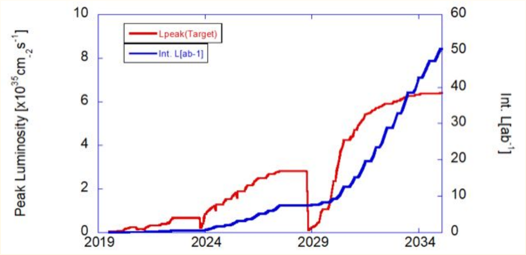


Parameter	This work	Previous result
A_{CP}^{Ξ}	$(-5.4\pm6.5\pm3.1)\times10^{-3}$	$(-0.7\pm8.5)\times10^{-2}$ [49]
$\Delta\phi_{CP}^{\Xi}$(rad)	$(-0.1\pm6.9\pm0.9)\times10^{-3}$	$(-7.9\pm8.3)\times10^{-2}$ [49]
A_{CP}^{Λ}	$(6.9\pm5.8\pm1.8)\times10^{-3}$	$(-2.5\pm4.8)\times10^{-3}$ [20]

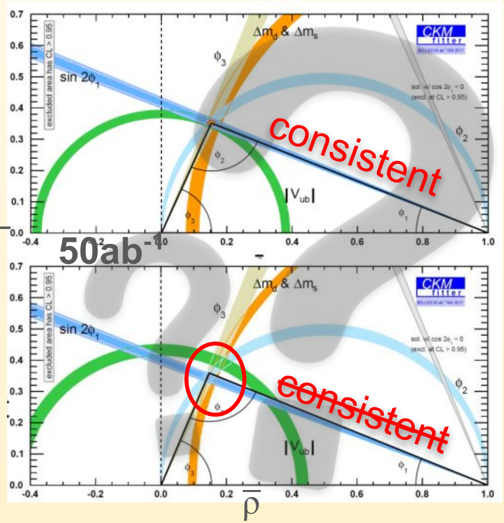
Similar results for $e^+e^-\to J/\psi\to$ Ξ$^+$Ξ$^-\to\Lambda(\to p\pi^-)\pi^-\ \bar{\Lambda}(\to\bar{n}\pi^0)\pi^+$
PhysRevLett.132.101801

Perspective

- **Belle II goal: $L = 6\times10^{35} cm^{-2}s^{-1}$; $L_{int} \sim 50 ab^{-1}$**

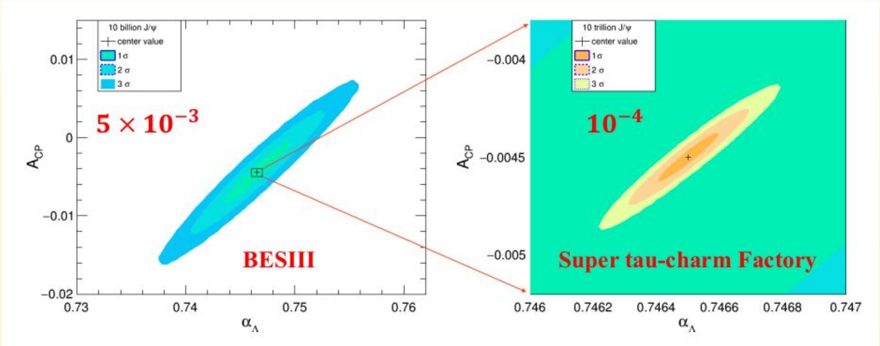


[PTEP (2019) 123C01]



- Together with LHCb will further constrain UT
- Unique measurements in many modes
- UT consistent with SM or not?

- **BESIII and Super Tau-Charm Facility**
  - today 10^{10} J/ψ
  - At super J/ψ factory **10^{12} J/ψ per year**
    - $L \sim 10^{35} cm^{-2}s^{-1}$
    - polarized beam (phase II)
- CPV sensitivity in hyperon's decay
  - **10^{-4} - 10^{-5}**
  - challenging SM predictions

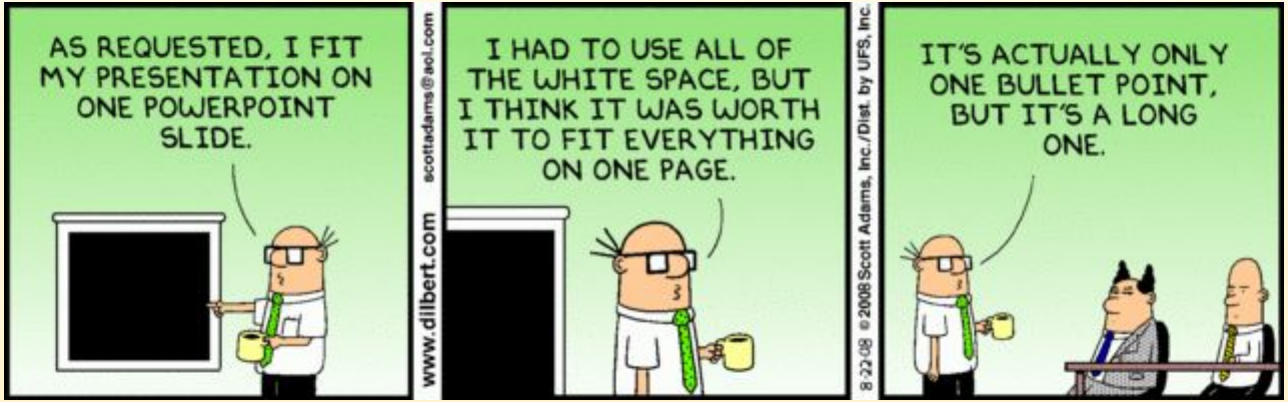


More on STCF on Qipeng Hu talk later today

Summary

- CPV studies are a key ingredient of e^+/e^- colliders
- Large CPV program in B physics at Belle II
  - Precise measurement of Unitary Triangles
  - Search for new physics
  - Results on Run1 show significantly better performance compared to Belle
- Hyperon polarization in J/ψ, $\psi(2S)$ decays at BESIII
  - new way to study CPV

Backup

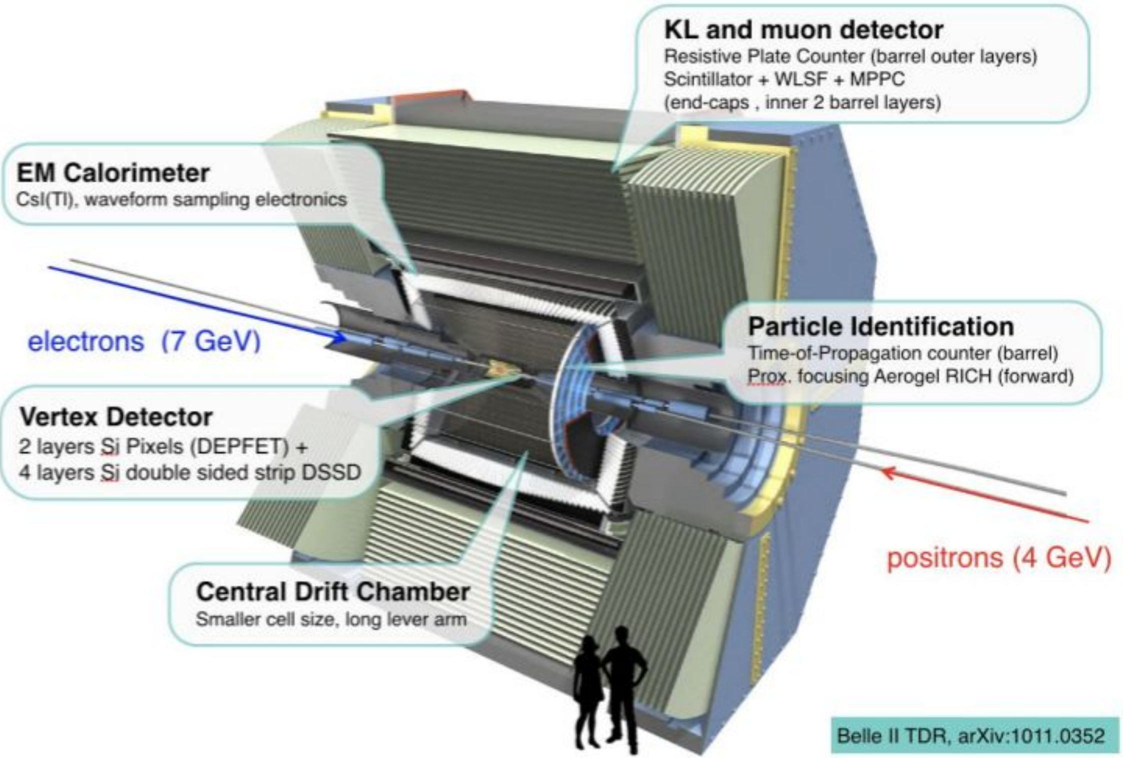


AS REQUESTED, I FIT MY PRESENTATION ON ONE POWERPOINT SLIDE.
www.dilbert.com scottadams@aol.com
I HAD TO USE ALL OF THE WHITE SPACE, BUT I THINK IT WAS WORTH IT TO FIT EVERYTHING ON ONE PAGE.
8-22-08 ©2008 Scott Adams, Inc./Dist. by UFS, Inc.
IT'S ACTUALLY ONLY ONE BULLET POINT, BUT IT'S A LONG ONE.

Belle and Belle II

- Asymmetric e^+-e^- colliders- B factories, also charm and τ factories
- Belle Belle II: e^+ (3.5 GeV) e^- (8 GeV) e$^+$ (4 GeV) e$^-$(7 GeV)
- Improved vertex resolution allows lower boost
- 424 fb^{-1} (362 fb^{-1} at Y(4S)) collected at Belle II so far; Goal: 50 ab^{-1}

Luminosity Frontier experiment



$\sin(2\phi_1/\beta)$ future

- Expected to be dominated by systematics with 50/ab
- Mostly from alignment of vertex detector and tag-side interference
- Penguin pollution will need to be constrained from $B \to J/\psi\pi^0$

Belle II Physics Book

	No improvement	Vertex improvement	Leptonic categories
$S_{c\bar{c}s}$ $(50\ \text{ab}^{-1})$ time dependent CP parameter			
stat.	0.0027	0.0027	0.0048
syst. reducible	0.0026	0.0026	0.0026
syst. irreducible	0.0070	0.0036	0.0035
$A_{c\bar{c}s}$ $(50\ \text{ab}^{-1})$ direct CP asymmetry			
stat.	0.0019	0.0019	0.0033
syst. reducible	0.0014	0.0014	0.0014
syst. irreducible	0.0106	0.0087	0.0035

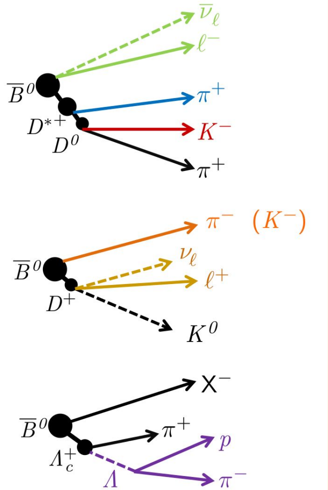
https://doi.org/10.1093/ptep/ptz106

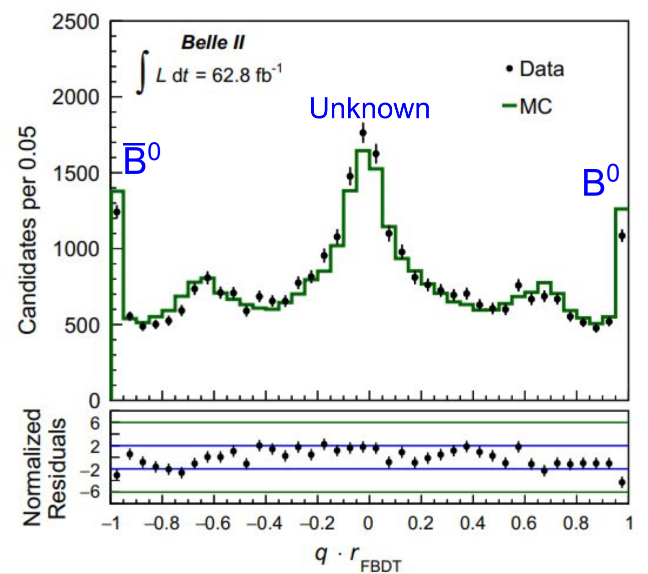
Flavour Tagger

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 $B^0 \to D^{(*)-}h^+$ decays

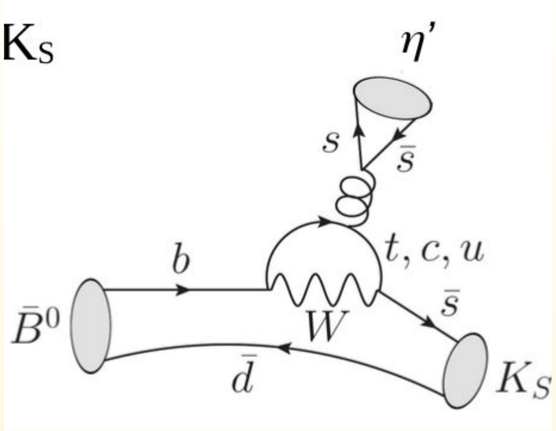
- Effective efficiency:

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

Time dependent $B \to \eta' K_S$

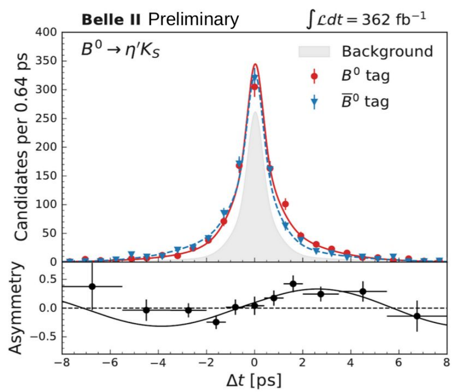
arXiv:2402.03713

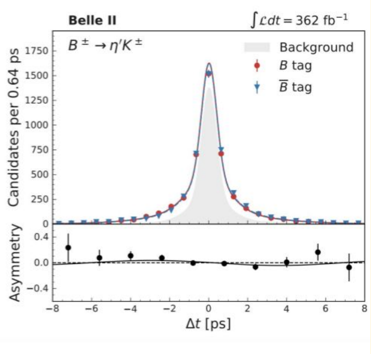
- Mediated by loop diagram, CPV expected to be the same as in $B^0 \to J/\psi\ K_S$ (tree)
- Deviation would be indication of new physics in the loop
- Reconstruct in 2 sub-channels:
  - $\eta' \to \eta(\to\gamma\gamma)\pi^+\pi^-$, $\eta' \to \rho\gamma$ (and $\eta' \to \eta(\to\pi^+\pi^-\pi^0)\pi^+\pi^-$)
- Found ~800 signal in total, performed time dependent fit in ΔE, M_{BC}, ContSupp and ΔT variables



Channel	Signal yield	$C_{\eta' K_S^0}$	$S_{\eta' K_S^0}$
$\eta' \to \eta_{\gamma\gamma}\pi^+\pi^-$	358 ± 20	-0.10 ± 0.13	0.69 ± 0.14
$\eta' \to \rho\gamma$	471 ± 29	-0.24 ± 0.10	0.65 ± 0.13
$\eta' \to \eta_{3\pi}\pi^+\pi^-$	55 ± 8	0.11 ± 0.32	0.25 ± 0.50
Sim. fit	829 ± 35	-0.19 ± 0.08	0.67 ± 0.10

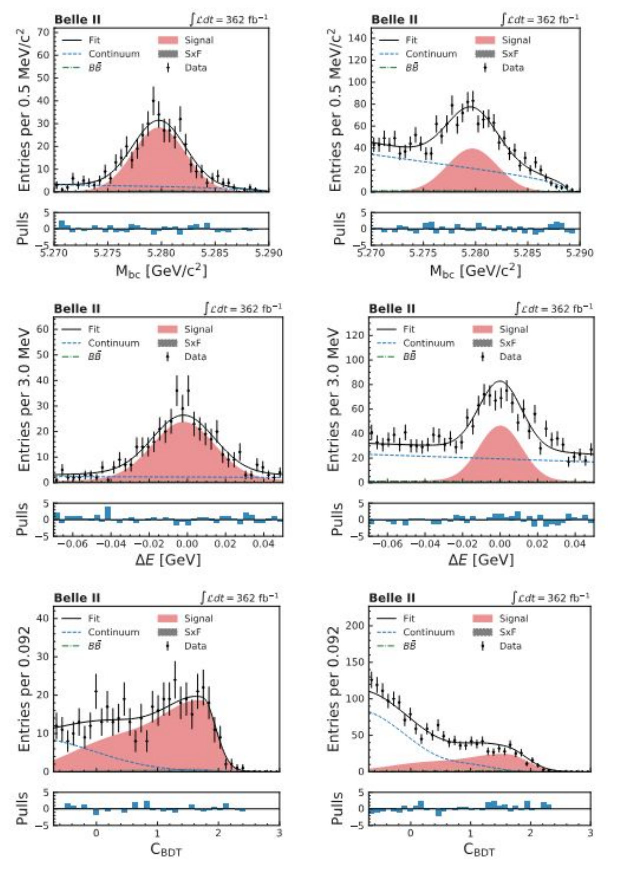
- In agreement with WA and $B^0 \to J/\psi\ K_S$ result

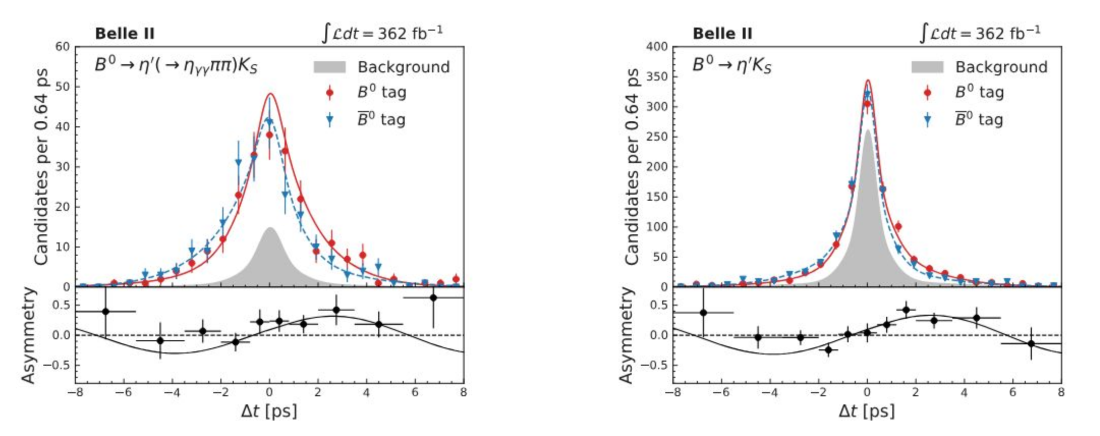


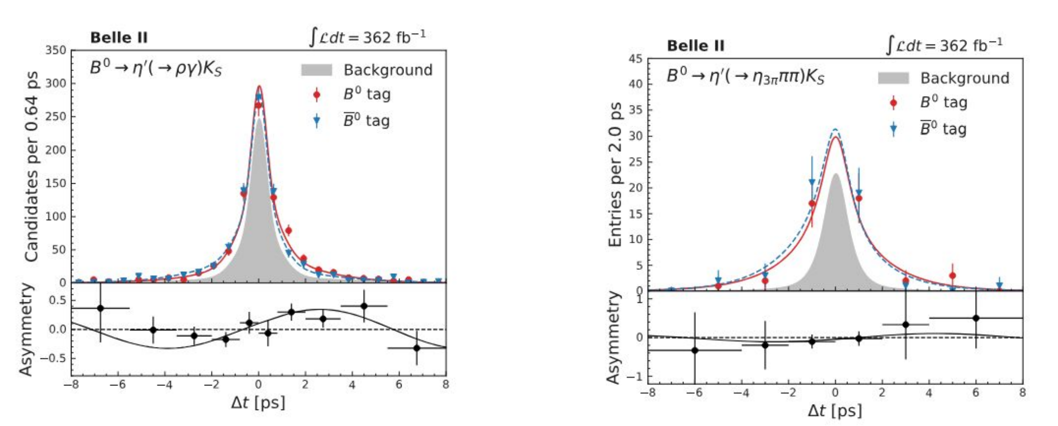


Time dependent $B \to \eta' K_S$

arXiv:2402.03713





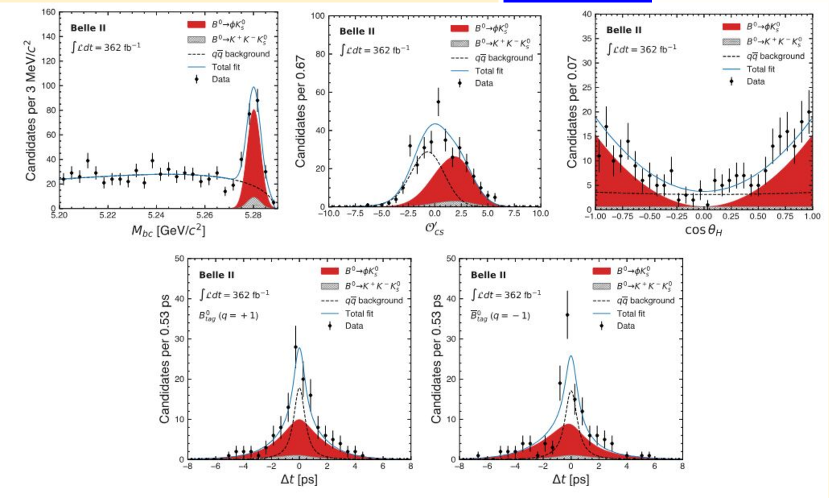


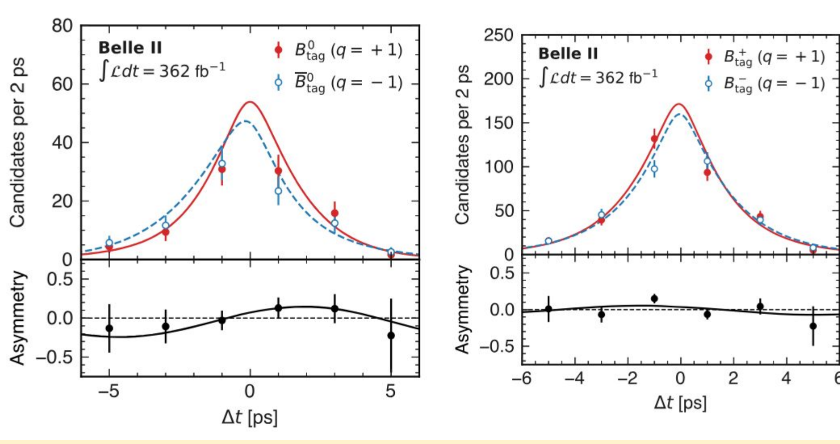
Time dependent $B \to \varphi' K_S$

arXiv:2307.02802

- Two tracks from φ, clean signature
- Major challenge : non resonant background with opposite-CP
- Helicity for longitudinal polarization
- Found ~160 signal in total, performed time dependent fit in ΔE, M_{BC}, ContSupp and ΔT variables

$S = \quad 0.54 \pm 0.26 \; {}^{+0.06}_{-0.08}$
$C = -0.31 \pm 0.20 \pm 0.05$





- Results competitive with best measurements
  - HFLAV $C_{CP} = 0.01 \pm 0.14$, $S_{CP} = 0.74^{+0.11}_{-0.13}$

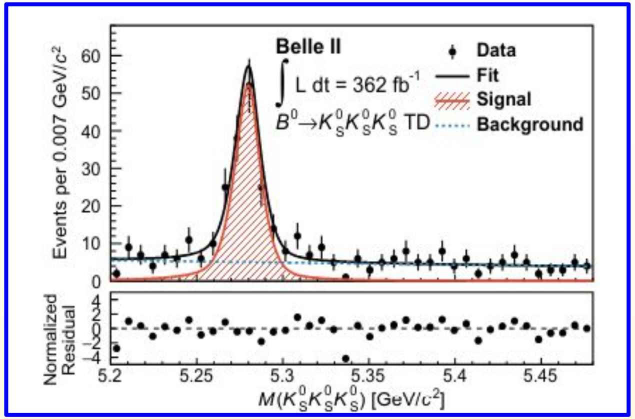
Time dependent $B \to K_S K_S K_S$

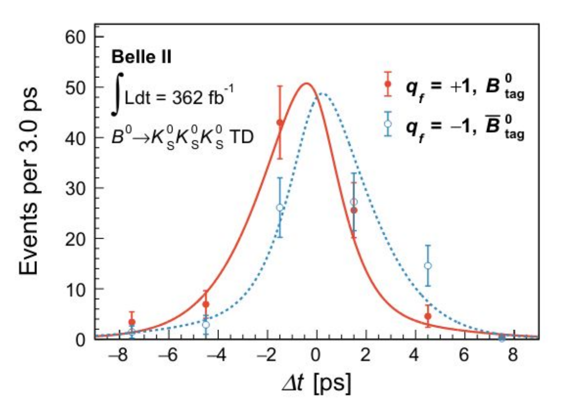
arXiv:2403.02590

- b→s decay mediated by penguin loop, potentially sensitive to new physics
  - Very reliable theoretically
- B vertex challenging: no *prompt* tracks from B, but only reconstructed $K_S \to \pi^+ \pi^-$ extrapolated back;
  - For TD analysis (S_{CP}), using only candidates with enough hits on inner silicon vertex detector;
- Signal from 3-dimensional fit: M_{BC}, M_{KsKsKs}, $BDT_{Cont.Supp.}$
- Signal yield = 158 ± 14 events

$S = -1.37 \; ^{+0.35}_{-0.45} \pm 0.03$

$C = -0.07 \pm 0.20 \pm 0.05$



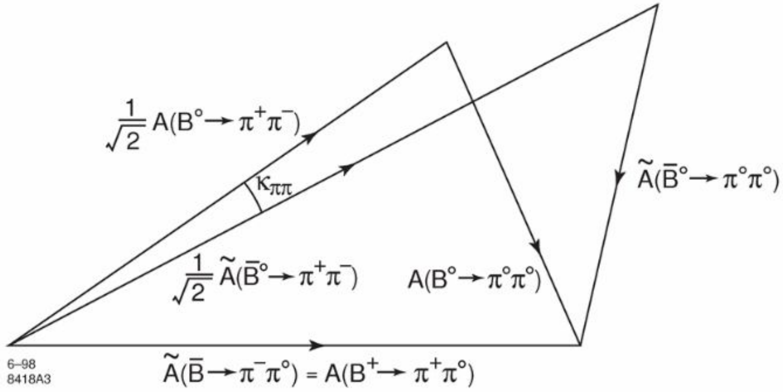


Measurement of ϕ_2/α

- The measurement of ϕ_2 from $B \to \pi\pi$ (or $B \to \rho\rho$) final states comes from an isospin analysis:

The following equalities hold:

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

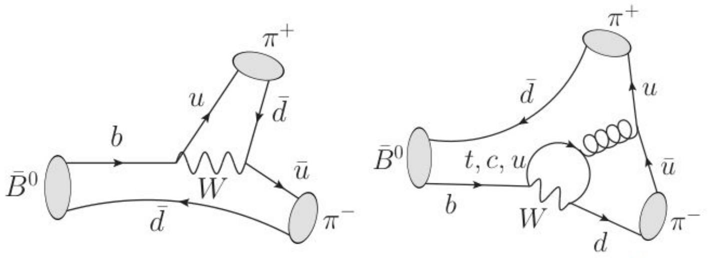


M. Gronau and D. London, PRL 65 (1990), 3381

- Observables (for e.g. $B \to \pi\pi$):
  - 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 ~1°.

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

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

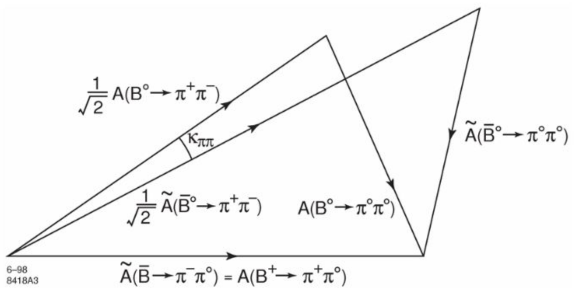
Isospin analysis[Gronau-London PRL, 64 3381 (1990)]: constraints B^0 and $B^\pm$ amplitudes:

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

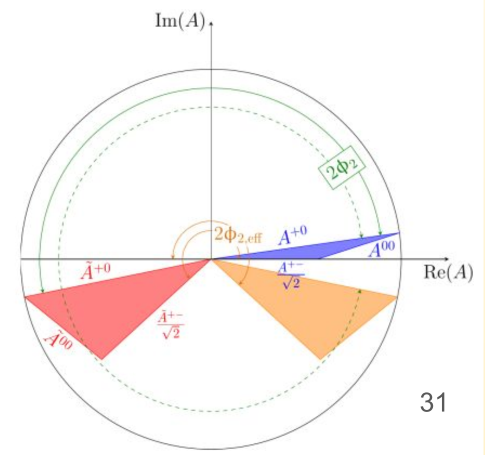
$$\bar{A}^{+0} = \bar{A}^{+-}/\sqrt{2} + \bar{A}^{00}$$

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

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°



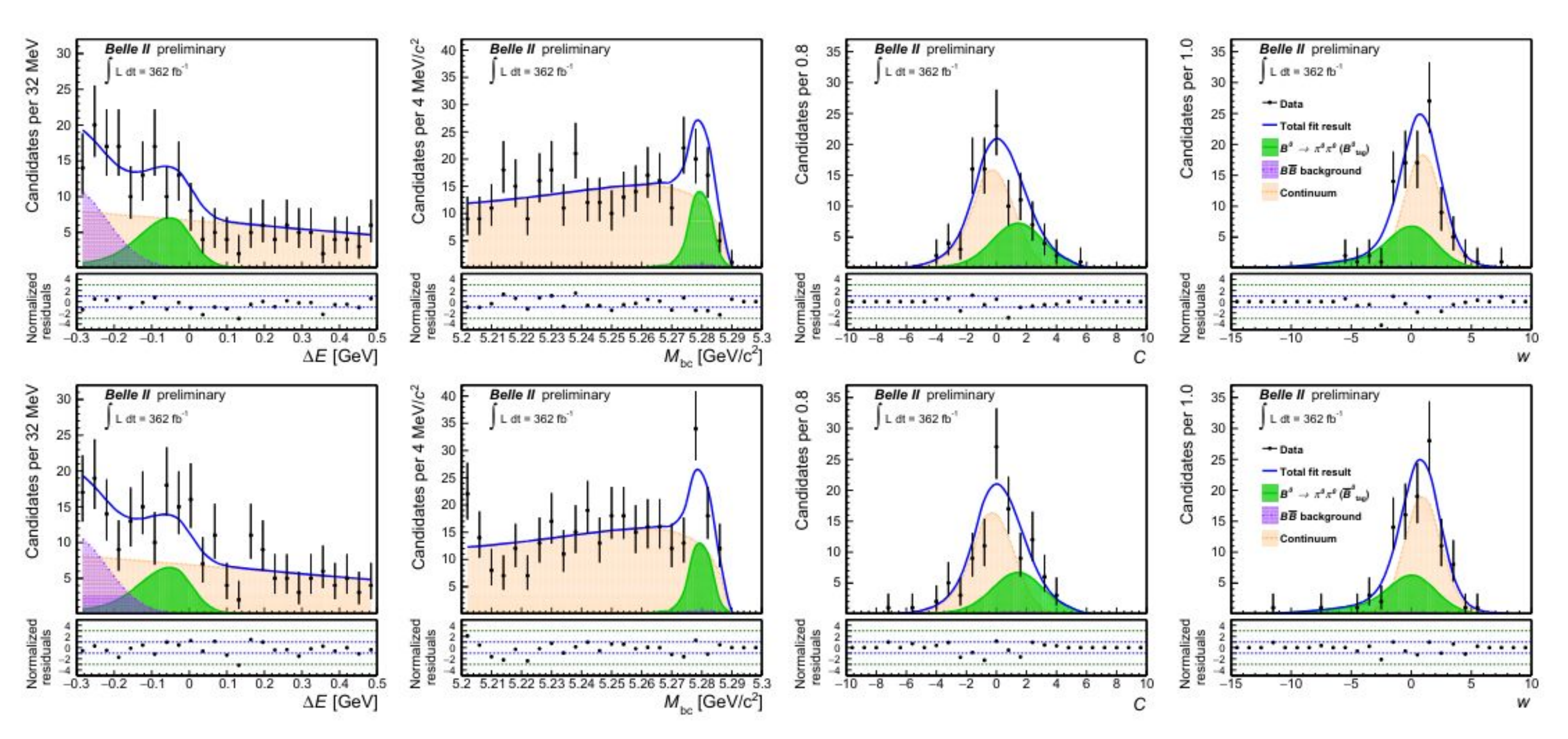
Toward ϕ_2/α: $B^0 \to \pi^0\pi^0$

New for FCPC 2024

Previous results
[PRD107 (2023) 112009]

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

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



Signal enhanced region

Toward ϕ_2/α: $B^0 \to \pi^0\pi^0$

New for FCPC 2024

Previous results
[PRD107 (2023) 112009]

Source	$\mathcal{B}$	$\mathcal{A}_{CP}$
π^0 efficiency	8.6 %	n/a
$\Upsilon(4S)$ branching fractions $(1 + f^{+-}/f^{00})$	2.5 %	n/a
Continuum-suppression efficiency	1.9 %	n/a
$B\overline{B}$-background model	1.7 %	0.034
Sample size $N_{B\bar{B}}$	1.5 %	n/a
Signal model	1.2 %	0.021
Continuum-background model	0.9 %	0.025
Wrong-tag probability calibration	n/a	0.008
Total systematic uncertainty	9.6 %	0.048
Statistical uncertainty	15.9 %	0.303

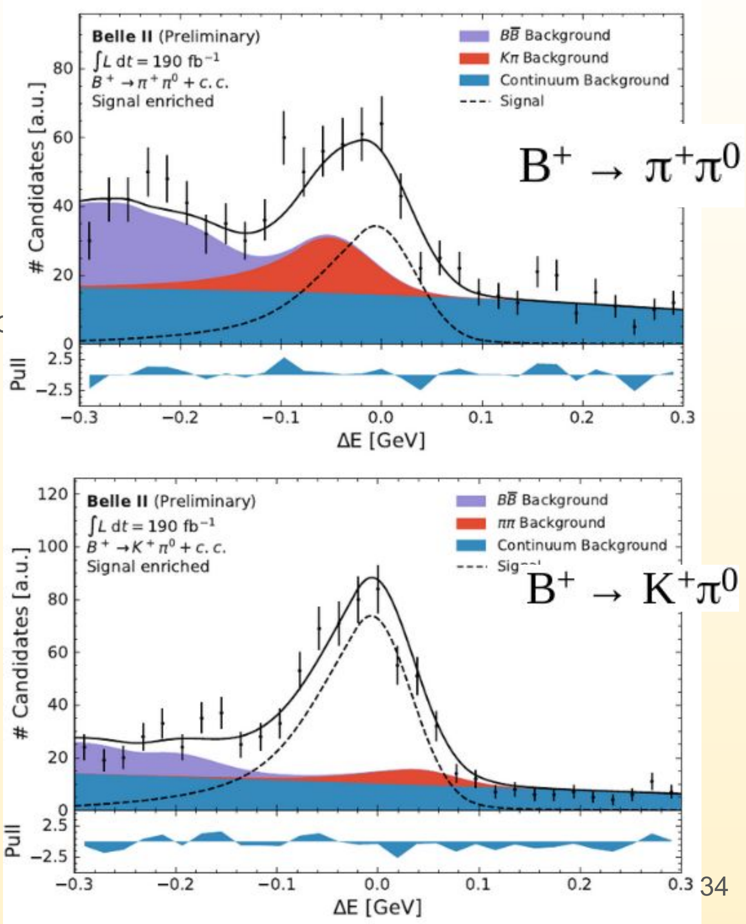
TABLE I. Fractional systematic uncertainties on the branching fraction and absolute systematic uncertainties on the *CP* asymmetry. Total systematic uncertainties, resulting from their sums in quadrature, are also given, and compared with statistical uncertainties.

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

- $B^+ \to K^+\pi^0$ enters in "Kπ" puzzle
- Using common selection for both channels
  - Enhance pion and kaon final state
  - Background from continuum $q\bar{q}$ reduced with MVA
- BR 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: $\mathcal{A}^{CP}_{K^+\pi^0} = 0.030 \pm 0.013$, $\mathcal{A}^{CP}_{\pi^+\pi^0} = 0.03 \pm 0.04$

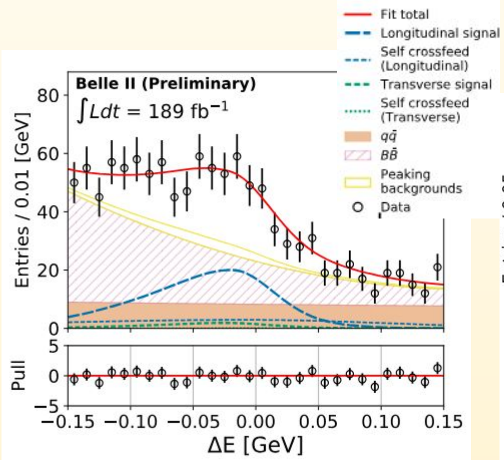


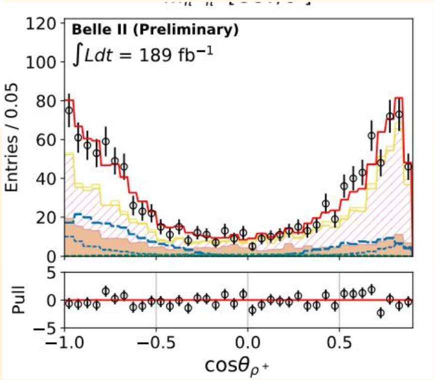
Toward ϕ_2/α: B→ ρρ

arxiv:2208.03554
arxiv:2206.12362

- Broad resonances of vector mesons, π^0 in final state
  - multiple non-negligible peaking background contributions
- CP analysis requires measurement of longitudinal polarization:
  - angular analysis using helicity angles of ρ's

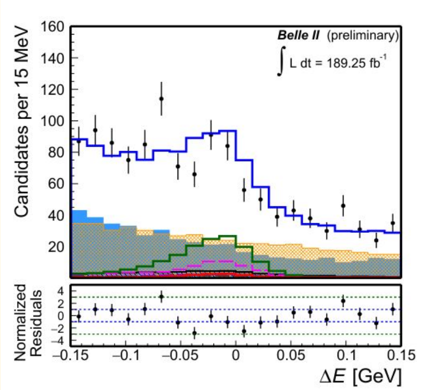
$B^0 \to \rho^+\rho^-$

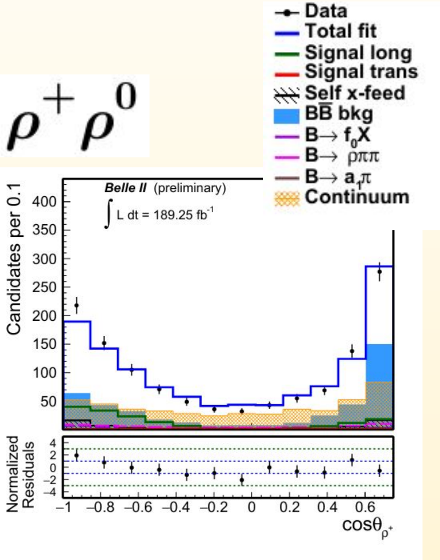




$$\mathcal{B}(B^0 \to \rho^+\rho^-) = [2.67 \pm 0.28\,(\text{stat}) \pm 0.28\,(\text{syst})] \times 10^{-5},$$
$$f_L = 0.956 \pm 0.035\,(\text{stat}) \pm 0.033\,(\text{syst}),$$

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





$$\mathcal{B}(B^+ \to \rho^+\rho^0) = [23.2^{+\,2.2}_{-\,2.1}(\text{stat}) \pm 2.7(\text{syst})] \times 10^{-6},$$
$$f_L = 0.943^{+\,0.035}_{-\,0.033}(\text{stat}) \pm 0.027(\text{syst}),$$
$$\mathcal{A}_{CP} = -0.069 \pm 0.068(\text{stat}) \pm 0.060(\text{syst}).$$

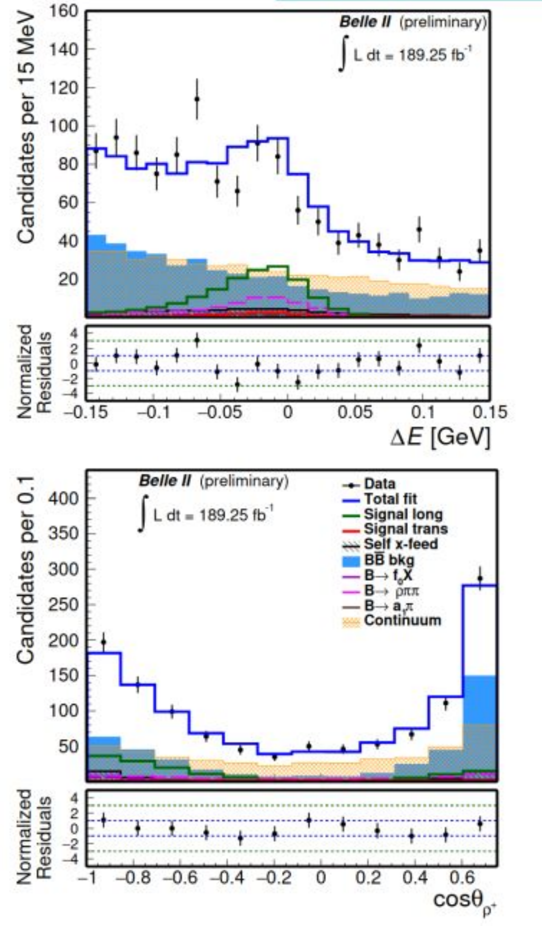
Toward ϕ_2/α: $B^+ \to \rho^+\rho^0$

arXiv:2206.12362

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

$$\mathcal{A}^{CP} = -0.069 \pm 0.068 \text{ (stat)} \pm 0.060 \text{ (syst)}$$
$$\mathcal{B} = (23.2^{+2.2}_{-2.1} \text{ (stat)} \pm 2.7 \text{ (syst)}) \cdot 10^{-6}$$
$$f_L = 0.943^{+0.035}_{-0.033} \text{ (stat)} \pm 0.027 \text{ (syst)}$$

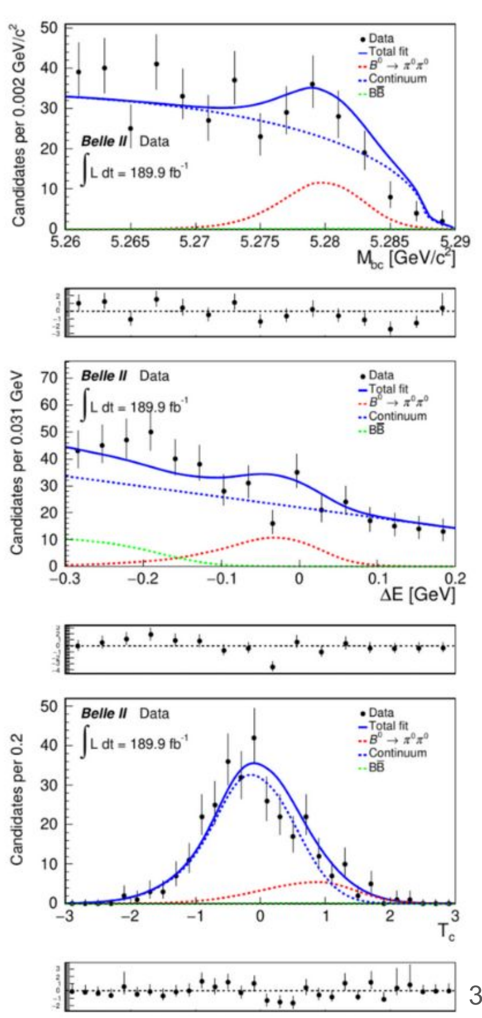
$$\text{WA: } \mathcal{A}^{CP} = -0.05 \pm 0.05,\ \mathcal{B} = (24.0 \pm 1.9) \cdot 10^{-6}$$



Toward ϕ_2/α: $B^0 \rightarrow \pi^0\pi^0$

[PRD107 (2023) 112009]
Superseded result

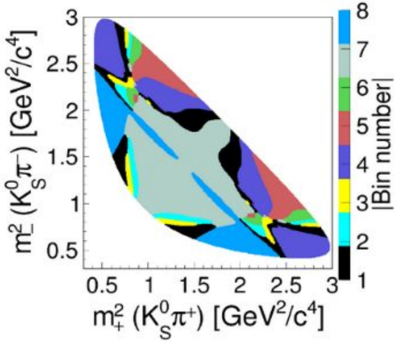
- ϕ_2/α from isospin analysis of $B \rightarrow \pi\pi/\rho\rho$ modes
  - BelleII will measure all modes
- $B^0 \rightarrow \pi^0\pi^0$ most challenging mode, very hard for LHCb
- Fake photons background reduced with multivariate algorithm for $\pi^0 \rightarrow \gamma\gamma$ purity
  - Control channel: $B^0 \rightarrow D^0(K^+\pi^-\pi^0)\,\pi^0$
- Using Flavour Tagger to get direct CP asymmetry
- Results:
  - N Yield: 93 ± 18
  - $\mathcal{B} = (1.38 \pm 0.27 \pm 0.22)\times10^{-6}$
    $A_{CP} = 0.14 \pm 0.46 \pm 0.07$
- Competitive with Belle with ⅓ of dataset

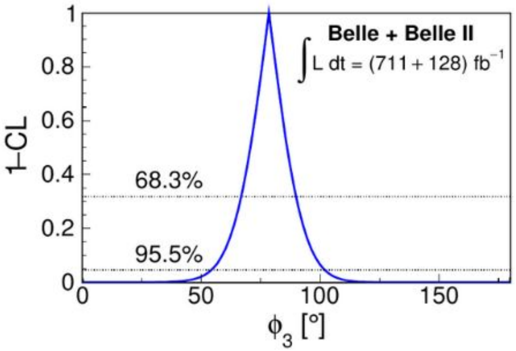


Belle/BelleII combined results on γ/ϕ_3

- Best sensitivity from the BPGGSZ method, exploiting the interference in the $D^0 \to K_S \pi^+ \pi^-$ Dalitz plot:

J. High Energ. Phys. 2022, 63 (2022)





$$\phi_3 = (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ\,,$$
$$r_B^{DK} = 0.129 \pm 0.024 \pm 0.001 \pm 0.002,$$
$$\delta_B^{DK} = (124.8 \pm 12.9 \pm 0.5 \pm 1.7)^\circ\,,$$
$$r_B^{D\pi} = 0.017 \pm 0.006 \pm 0.001 \pm 0.001,$$
$$\delta_B^{D\pi} = (341.0 \pm 17.0 \pm 1.2 \pm 2.6)^\circ\,.$$

- GLW method [Phys.Lett.B 253 (1991) 483-488, Phys.Lett.B 265 (1991) 172-176]: consider decays of the D^0 to odd (-) and even (+) CP eigenstates and measure the observables:

$$\mathcal{A}_{CP\pm} \equiv \frac{\mathcal{B}(B^- \to D_{CP\pm}K^-) - \mathcal{B}(B^+ \to D_{CP\pm}K^+)}{\mathcal{B}(B^- \to D_{CP\pm}K^-) + \mathcal{B}(B^+ \to D_{CP\pm}K^+)} \qquad \mathcal{R}_{CP\pm} \equiv \frac{\mathcal{B}(B^- \to D_{CP\pm}K^-) + \mathcal{B}(B^+ \to D_{CP\pm}K^+)}{\mathcal{B}(B^- \to D_{\text{flav}}K^-) + \mathcal{B}(B^+ \to D_{\text{flav}}K^+)}$$

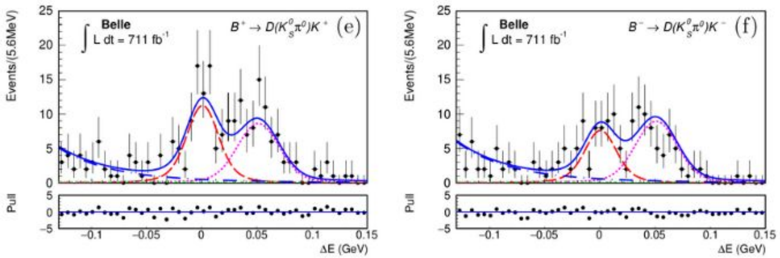
which are related to ϕ_3:

$$\mathcal{R}_{CP\pm} = 1 + r_B^2 \pm 2 r_B \cos\delta_B \cos\phi_3$$
$$\mathcal{A}_{CP\pm} = \pm 2 r_B \sin\delta_B \sin\phi_3 \,/\, \mathcal{R}_{CP\pm}$$

Belle/BelleII combined results on γ/ϕ_3

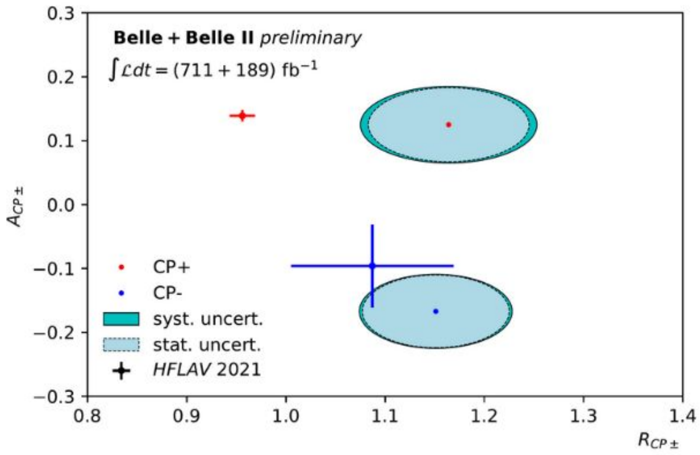
- Considering $D^0 \to K^+K^-$ as CP+, $D^0 \to K_S\pi^0$ as CP-, and $D^0 \to K^-\pi^+$ as flavor specific final state, we measure (on the Belle + Belle II data set):

$$\mathcal{R}_{CP+} = 1.164 \pm 0.081 \pm 0.036,$$
$$\mathcal{R}_{CP-} = 1.151 \pm 0.074 \pm 0.019,$$
$$\mathcal{A}_{CP+} = (+12.5 \pm 5.8 \pm 1.4)\%,$$
$$\mathcal{A}_{CP-} = (-16.7 \pm 5.7 \pm 0.6)\%.$$



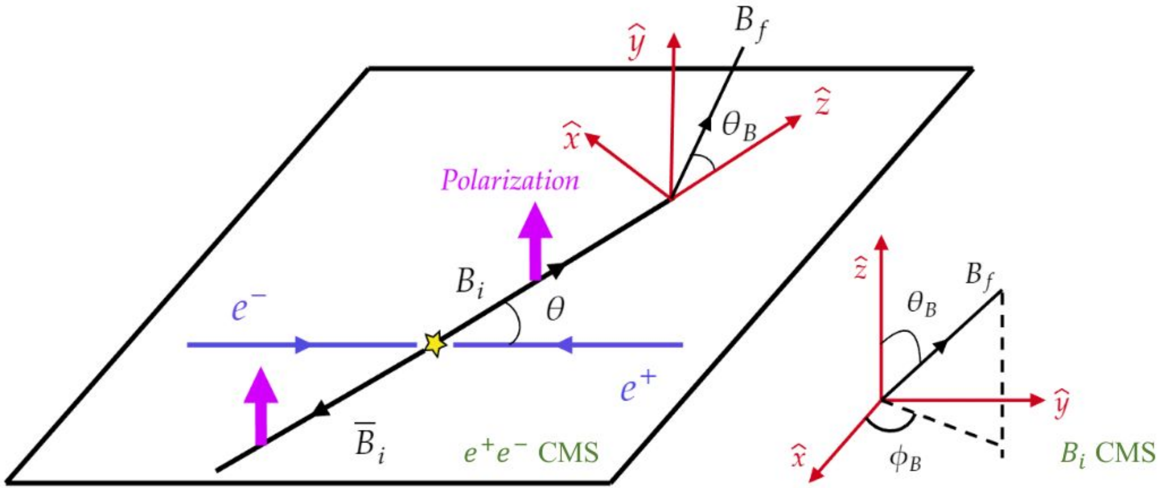
- The A_{CP}'s differ from each other at ~3.5σ;
- This translates into constraints on ϕ_3:

	68.3% CL	95.4% CL
ϕ_3 (°)	[8.7, 20.5] [83.8, 96.1] [163.4, 173.1]	[4.7, 175.8]
r_B	[0.282, 0.489]	[0.069, 0.560]



arXiv:2308.05048 [hep-ex]

Polarized hyperon pairs in e^+e^- collisions



Polarization:

$$P_y(\cos\theta) = \frac{\sqrt{1-\alpha_\psi^2}\cos\theta\sin\theta}{1+\alpha_\psi\cos^2\theta}\sin(\Delta\Phi)$$

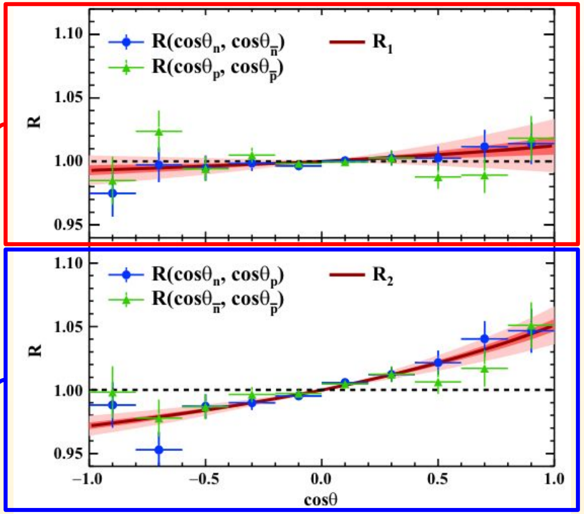
- Angular distribution of $\frac{d\Gamma}{d\Omega} \propto 1 + \alpha_\psi \cos^2\theta,\ \alpha_\psi \in [-1.0, 1.0]$
- Unpolarized e^+e^- beams $\Rightarrow$ transverse polarized hyperon (if $\Delta\Phi \neq 0$):

$e^+e^- \to J/\psi \to \Xi^+\Xi^- \to \Lambda(\to p\pi^-)\pi^-\ \bar{\Lambda}(\to \bar{n}\pi^0)\pi^+$ + cc

- CPV in hyperons might arise from interference of S and P-wave
  - 10 billion J/ψ events: (144+123)k signal events (91% purity)
  - 9 helicity angles, 8 global parameters
- Several decay properties of Ξ^- and Λ are determined:

PhysRevLett.132.101801

Parameters	This work	Previous result
$\alpha_{J/\psi}$	$0.611 \pm 0.007^{+0.013}_{-0.007}$	$0.586 \pm 0.012 \pm 0.010$ [18]
$\Delta\Phi_{J/\psi}$ (rad)	$1.30 \pm 0.03^{+0.02}_{-0.03}$	$1.213 \pm 0.046 \pm 0.016$ [18]
α_Ξ	$-0.367 \pm 0.004^{+0.003}_{-0.004}$	$-0.376 \pm 0.007 \pm 0.003$ [18]
ϕ_Ξ (rad)	$-0.016 \pm 0.012^{+0.004}_{-0.008}$	$0.011 \pm 0.019 \pm 0.009$ [18]
$\bar{\alpha}_\Xi$	$0.374 \pm 0.004^{+0.003}_{-0.004}$	$0.371 \pm 0.007 \pm 0.002$ [18]
$\bar{\phi}_\Xi$ (rad)	$0.010 \pm 0.012^{+0.003}_{-0.013}$	$-0.021 \pm 0.019 \pm 0.007$ [18]
$\alpha_{\Lambda-}$	$0.764 \pm 0.008^{+0.005}_{-0.006}$	$0.7519 \pm 0.0036 \pm 0.0024$ [37]
$\alpha_{\Lambda+}$	$-0.774 \pm 0.009^{+0.005}_{-0.005}$	$-0.7559 \pm 0.0036 \pm 0.0030$ [37]
$\alpha_{\Lambda 0}$	$0.670 \pm 0.009^{+0.009}_{-0.008}$	0.75 ± 0.05 [29]
$\bar{\alpha}_{\Lambda 0}$	$-0.668 \pm 0.008^{+0.006}_{-0.008}$	$-0.692 \pm 0.016 \pm 0.006$ [17]
$\delta_P - \delta_S$ (rad)	$0.033 \pm 0.020^{+0.008}_{-0.012}$	$-0.040 \pm 0.033 \pm 0.017$ [18]
$\xi_P - \xi_S$ (rad)	$0.007 \pm 0.020^{+0.018}_{-0.005}$	$0.012 \pm 0.034 \pm 0.008$ [18]
A^Ξ_{CP}	$-0.009 \pm 0.008^{+0.007}_{-0.002}$	$0.006 \pm 0.013 \pm 0.006$ [18]
$\Delta\phi^\Xi_{CP}$ (rad)	$-0.003 \pm 0.008^{+0.003}_{-0.007}$	$-0.005 \pm 0.014 \pm 0.003$ [18]
A^-_{CP}	$-0.007 \pm 0.008^{+0.002}_{-0.003}$	$-0.0025 \pm 0.0046 \pm 0.0012$ [37]
A^0_{CP}	$0.001 \pm 0.009^{+0.005}_{-0.007}$	...
A^Λ_{CP}	$-0.004 \pm 0.007^{+0.003}_{-0.004}$	...
$\alpha_{\Lambda 0}/\alpha_{\Lambda -}$	$0.877 \pm 0.015^{+0.014}_{-0.010}$	1.01 ± 0.07 [29]
$\bar{\alpha}_{\Lambda 0}/\alpha_{\Lambda +}$	$0.863 \pm 0.014^{+0.012}_{-0.008}$	$0.913 \pm 0.028 \pm 0.012$ [17]

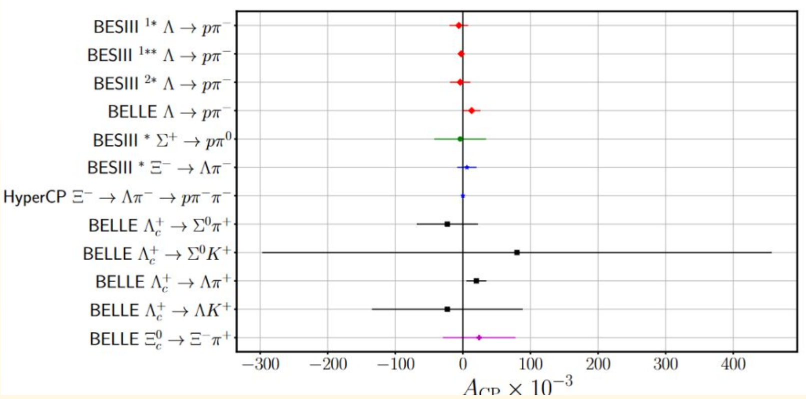


No CPV at $<10^{-2}$ precision level
- SM predictions $\sim 10^{-4}$-10^{-5}

$\Delta I = 3/2$ transition in Λ decay

Hyperon at Super Tau-Charm Facility (STCF)

- Many (null) results so far
  - BESIII and Belle
- BESIII: today
  - 10 billion J/ψ
- At super J/ψ factory
  - 10^{12} J/ψ per year
- CPV sensitivity in hyperon's decay
  - **10^{-4} - 10^{-5}**
  - challenging SM predictions



BESIII:
Nature Phys. **15**, p 631-634 (2019)
Phys. Rev. Lett. 125, 052004 (2020)
Nature 606, 64-69 (2022)
Phys. Rev. Lett. 129, 131801 (2022)
Phys. Rev. D 108, L031106 (2023)

Belle:
Sci. Bull. 68, 583-592 (2023)

HyperCP:
Phys. Rev. Lett. 93, 262001, 2004.