CPV at e^+/e^- colliders

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

Stefano Lacaprara
for the Belle II collaboration
INFN Padova

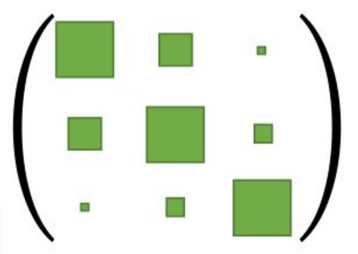
CPV in Standard Model: CKM matrix

- 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)

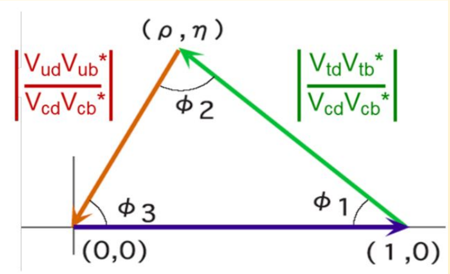

Dirac Medal 2010


Nobel Prize 2008

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

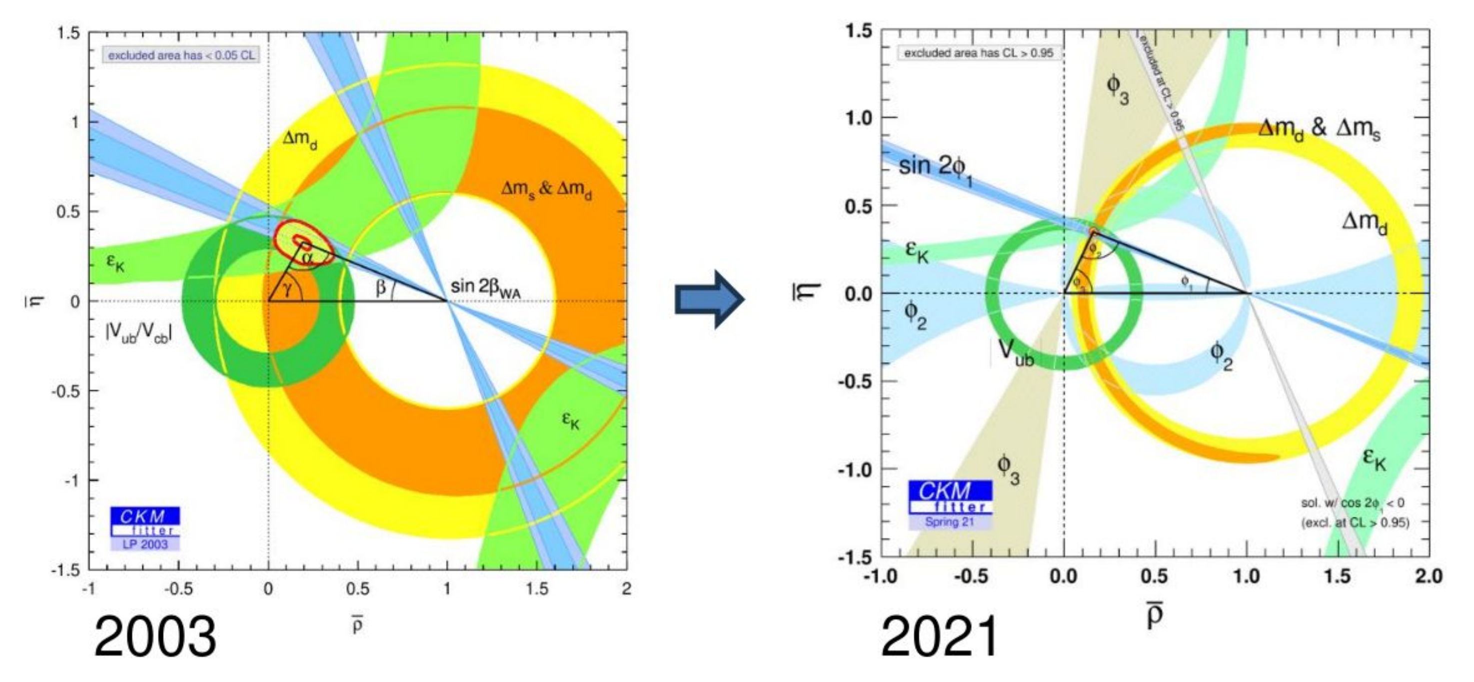


- From CKM unitarity: $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$
  - Triangle in complex plane
  - Three angles
  - Other triangles exists



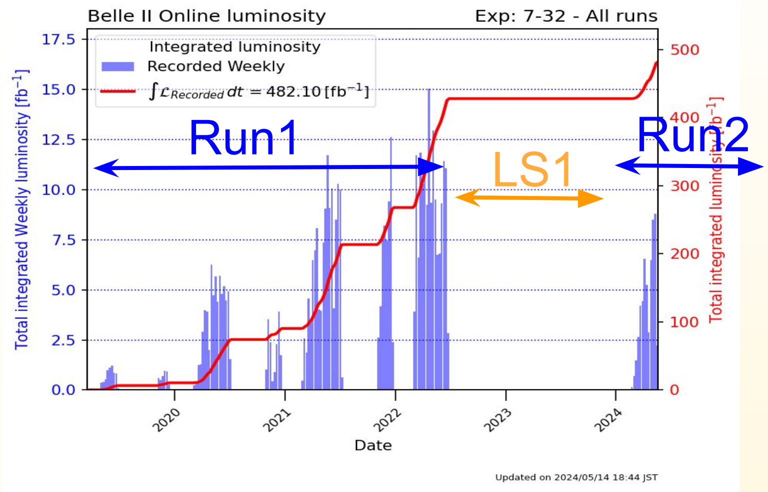
$$\phi_1 = \beta$$
$$\phi_2 = \alpha$$
$$\phi_3 = \gamma$$

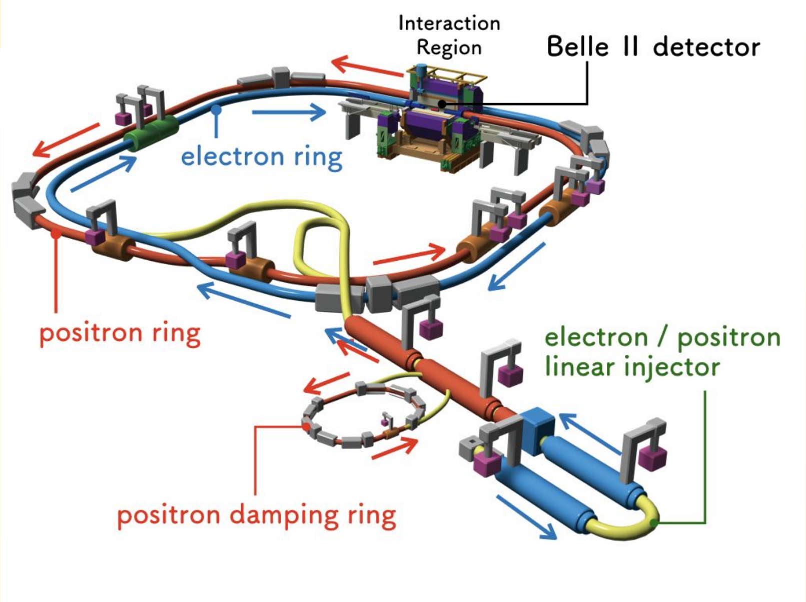
CPV and Unitarity Triangle



- Precise test of SM by overconstraint Unitarity Triangle
- Search for New Physics effects, especially in loop mediated diagrams

SuperKEKB and Belle II





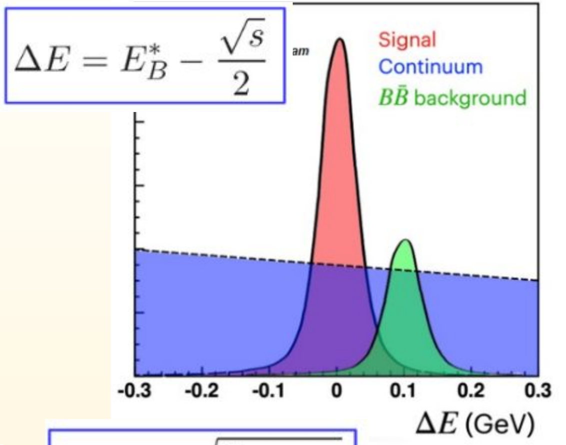
- e^+/e^- (4/7 GeV) at KEK
- Run 1 operation 2019-2022
  - **424/fb collected - 362/fb at Υ(4S)**
- Long Shutdown 1 (LS1) until end of 2023
  - For accelerator and detector upgrades
- Run 2 operation form Jan 2024

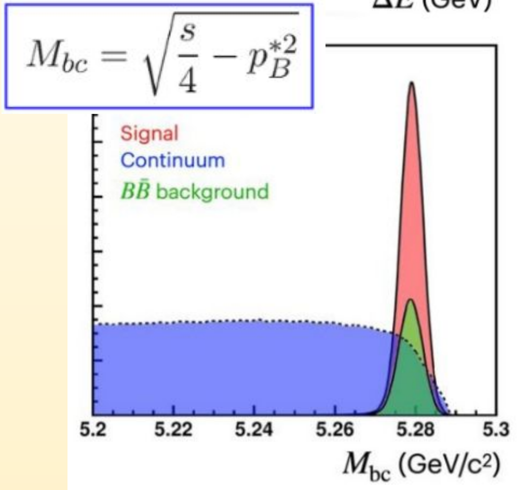
Luminosity record 4.7×10^{34} cm^{-2}s^{-1}

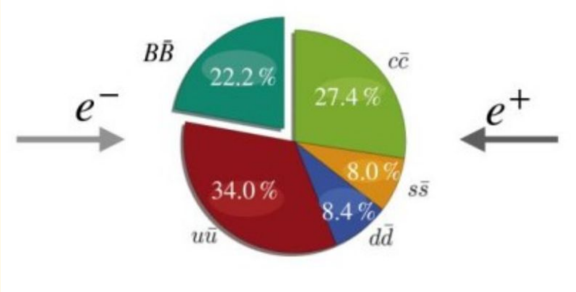
- 2x KEKB
- Goal 6×10^{35} cm^{-2}s^{-1}

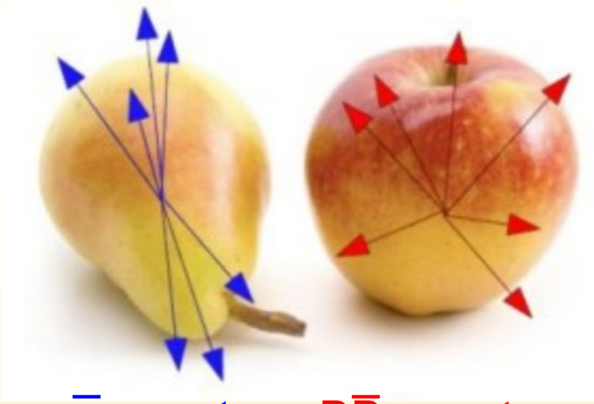
B-Factories variables

- 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



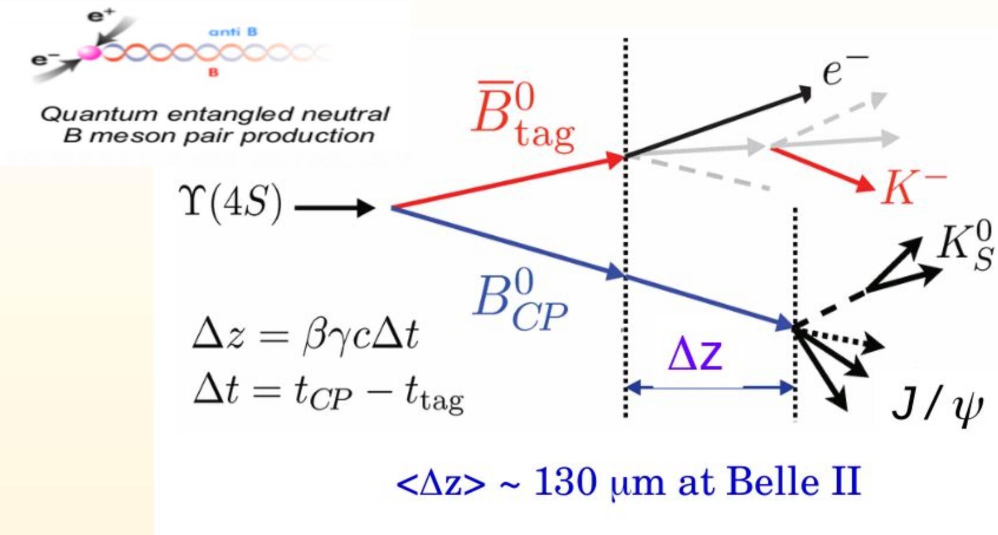






$q\bar{q}$ events $B\bar{B}$ events

TDCPV analysis



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

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

$\mathcal{S}_{CP} = \sin(2\phi_i^{eff})$

mixing induced CPV

$|B^0\rangle \to |f_{CP}\rangle$, $|B^0\rangle \to |\overline{B}^0\rangle \to |f_{CP}\rangle$

$\mathcal{A}_{CP} = -\mathcal{C}_{CP}$

Direct CPV

$|B\rangle \to |f\rangle \neq |\bar{B}\rangle \to |\bar{f}\rangle$

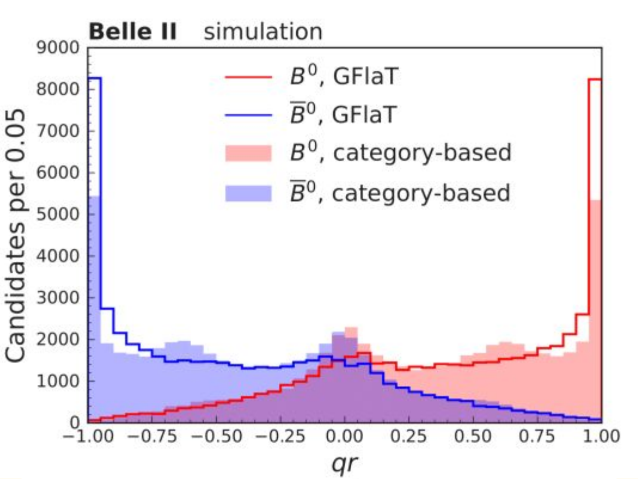
- **B_{CP}** fully reconstructed CP eigenstate
- **B_{tag}** vertex and flavour information
- Complex analysis, many key elements:
  - high signal efficiency
  - excellent vertex resolution σ_z~26/50μm (signal/tag side)
  - high flavour tagging efficiency ***ε* = 37%**

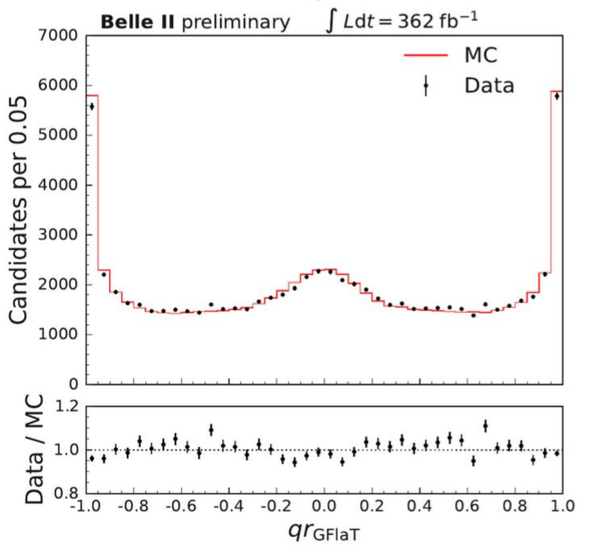
B flavour tagging: GFlaT

arXiv:2402.17260

- 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 on self-tagging $B^0 \rightarrow D^{(*)-}\pi^+$ 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**) %





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

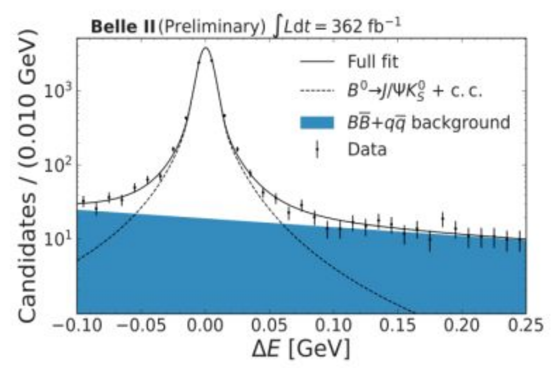
arXiv:2402.17260

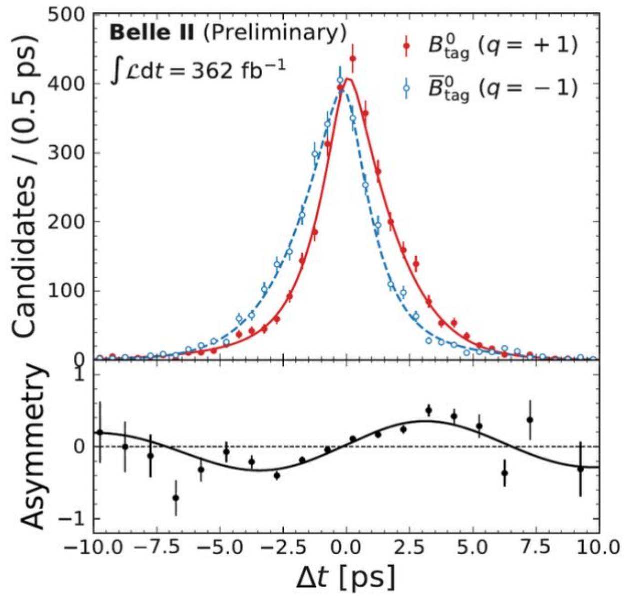
- Golden channel, almost background free
- Updated results using improved GFlaT flavour tagger
- Fit ΔE distribution to subtract background
- Fit background-subtracted Δt distribution to extract CPV parameters

$S = \ \ 0.724 \pm 0.035 \pm 0.014$
$C = -\,0.035 \pm 0.026 \pm 0.013$

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

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

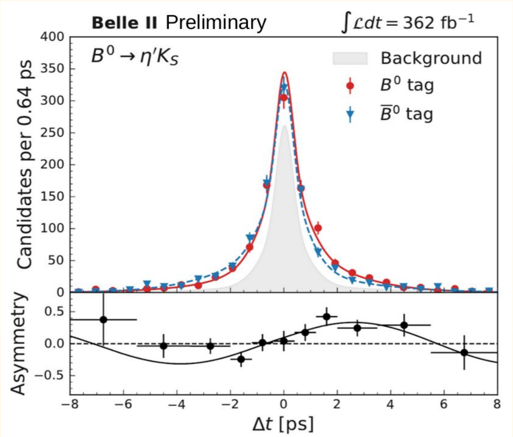




TDCPV in Charmless B decay

arXiv:2402.03713

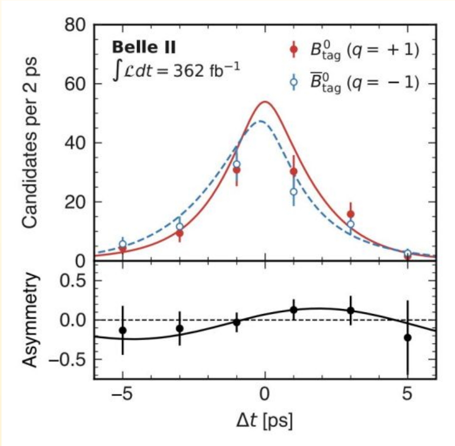
- $B \rightarrow \eta' K_S$
- 2 sub-channels:
  - $\eta' \rightarrow \eta(\rightarrow\gamma\gamma)\pi^+\pi^-$, $\eta' \rightarrow \rho\gamma$
  - ~800 signal events



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

arXiv:2307.02802

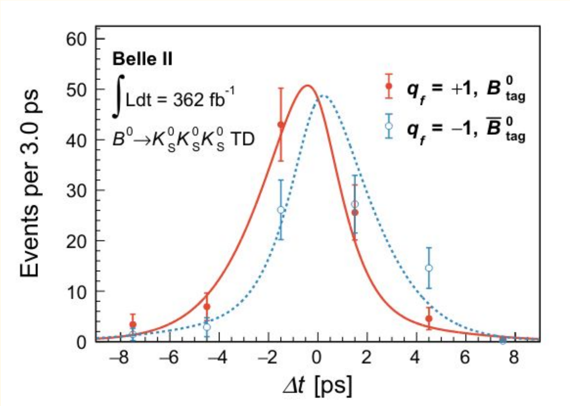
- $B \rightarrow \varphi K_S$
- challenge : non resonant background with opposite-CP
  - ~160 signal events



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

arXiv:2403.02590

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



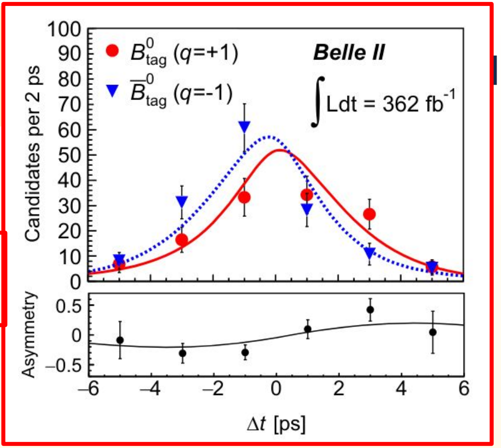
S = -1.37 $^{+0.35}_{-0.45}$ ± 0.03
C = - 0.07 ± 0.20 ± 0.05

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 **$B^0 \to K_S \pi^0$**
  - Signal yield: 415^{+26}_{-25} events
- Key ingredient in Isospin Sum Rule

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



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

(within ~1%)

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

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

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

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

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

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

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

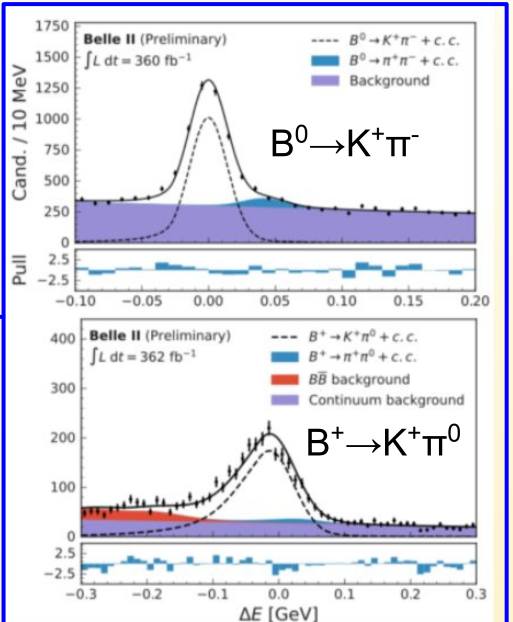
$B^0 \to K^0_S\pi^0$

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

world's best

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

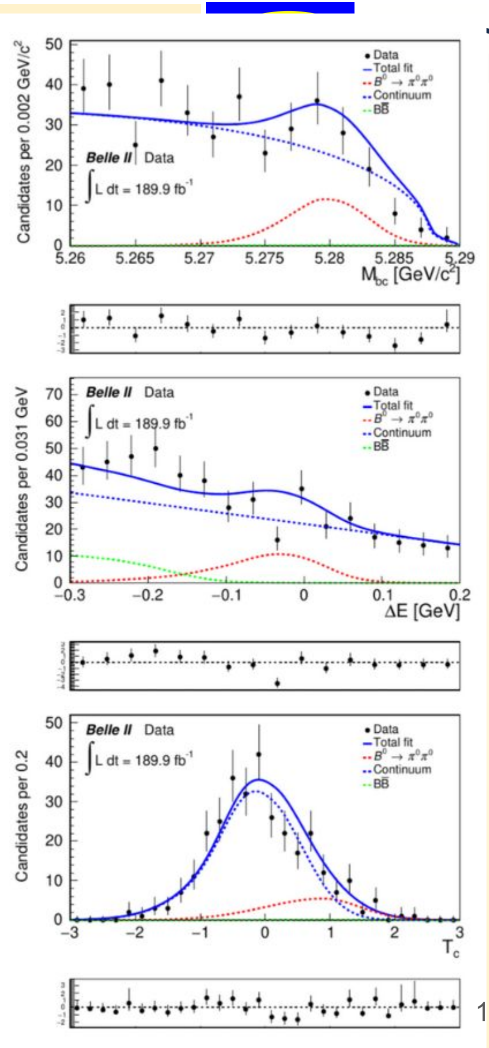
precision on par with W/A!
→ 5% uncertainty achievable @ 10 ab^{-1}



Toward ϕ_2/α: $B^0 \to \pi^0\pi^0$

[PRD107 (2023) 112009]

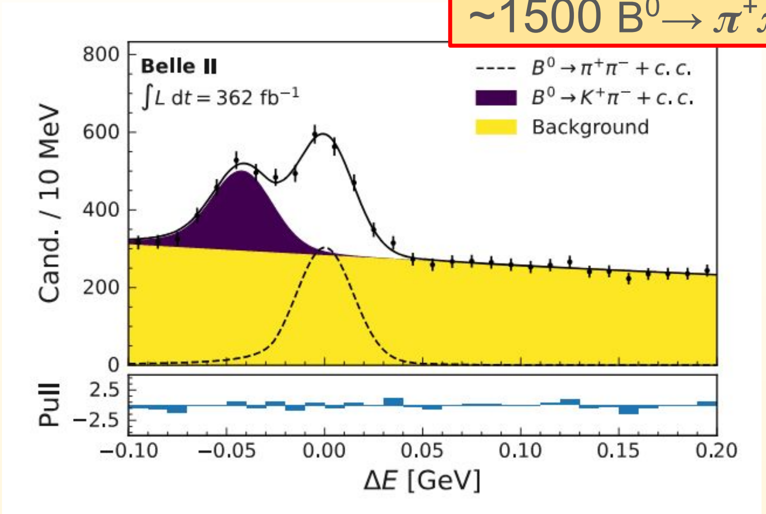
- ϕ_2/α from isospin analysis of $B \to \pi\pi/\rho\rho$ modes
  - BelleII will measure all modes
- $B^0 \to \pi^0\pi^0$ most challenging mode, very hard for LHCb
- Fake photons background reduced with multivariate algorithm for $\pi^0 \to \gamma\gamma$ purity
  - Control channel: $B^0 \to D^0(K^+\pi^-\pi^0)\,\pi^0$
- Using Flavour Tagger to get direct CP asymmetry
- Results:
  - N Yield: 93 ± 18
  - $$\mathcal{B} = (1.38 \pm 0.27 \pm 0.22)\times 10^{-6}$$
    $$A_{CP} = 0.14 \pm 0.46 \pm 0.07$$
- Competitive with Belle with ⅓ of dataset



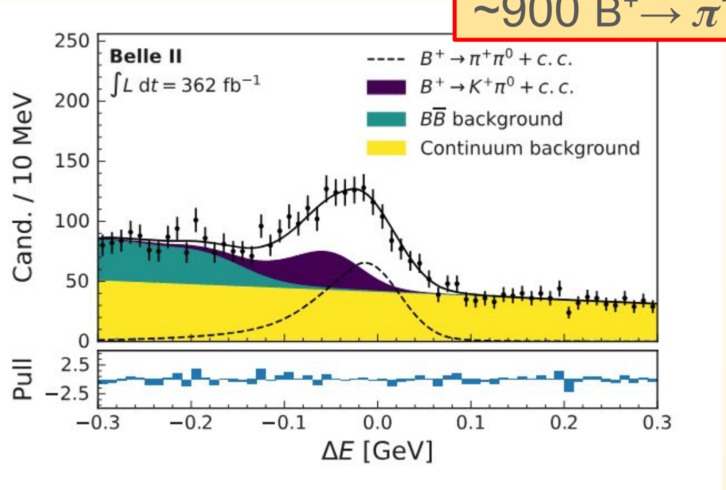
Toward ϕ_2/α: $B \to \pi\pi$

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

$\mathcal{B}(\pi^+\pi^0) = (5.10 \pm 0.29 \pm 0.32)\times 10^{-6}$
$A_{CP}(\pi^+\pi^0) = -0.081 \pm 0.54 \pm 0.008$

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

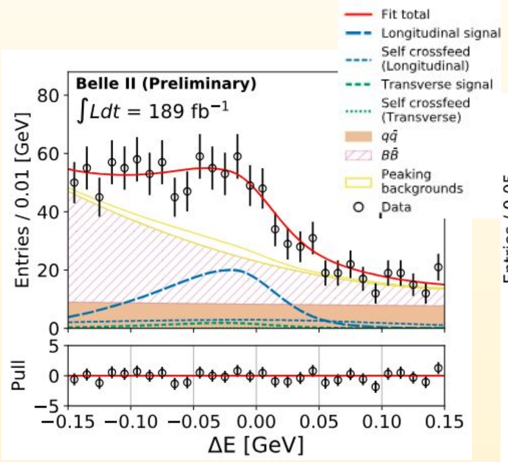
Toward ϕ_2/α: $B \rightarrow \rho\rho$

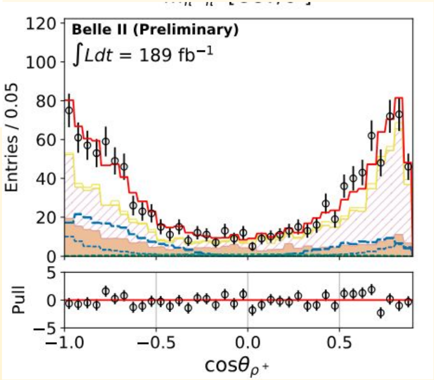
[arxiv:2208.03554](https://arxiv.org/abs/2208.03554)
[arxiv:2206.12362](https://arxiv.org/abs/2206.12362)

Belle II INFN

- 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

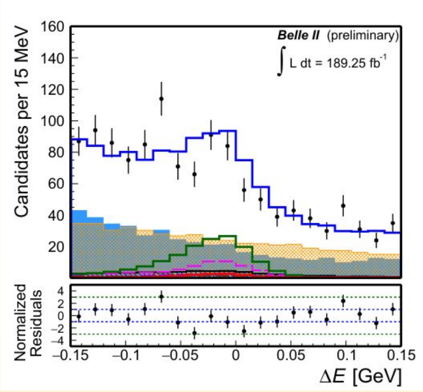
$B^0 \rightarrow \rho^+\rho^-$

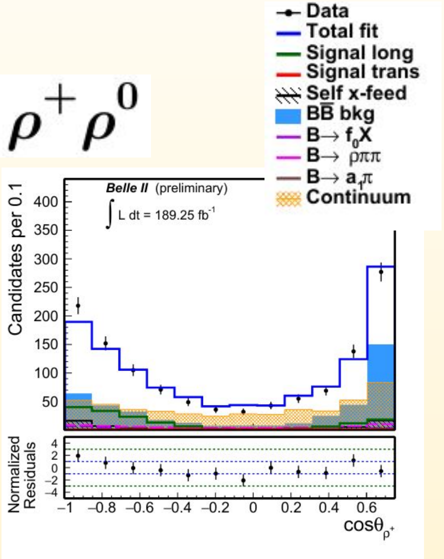




$$\mathcal{B}(B^0 \rightarrow \rho^+\rho^-) = [2.67 \pm 0.28\,(\text{stat}) \pm 0.28\,(\text{syst})] \times 10^{-5},$$
$$f_L = 0.956 \pm 0.035\,(\text{stat}) \pm 0.033\,(\text{syst}),$$

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

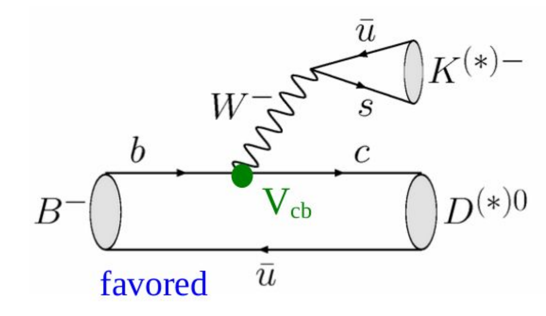


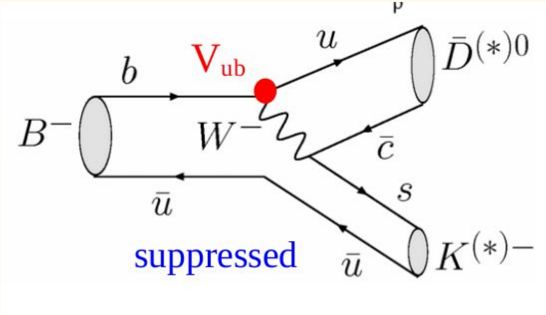


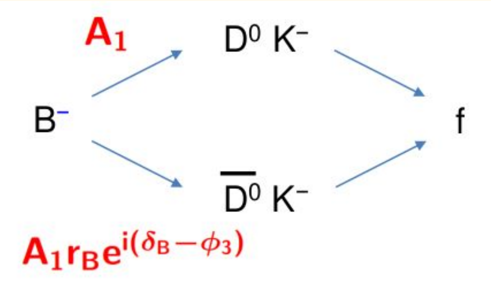
$$\mathcal{B}(B^+ \rightarrow \rho^+\rho^0) = [23.2^{+\,2.2}_{-\,2.1}(\text{stat}) \pm 2.7(\text{syst})] \times 10^{-6},$$
$$f_L = 0.943^{+\,0.035}_{-\,0.033}(\text{stat}) \pm 0.027(\text{syst}),$$
$$\mathcal{A}_{CP} = -0.069 \pm 0.068(\text{stat}) \pm 0.060(\text{syst}).$$

Results on γ/φ_3

- γ/φ_3 from interference of tree level amplitudes:
  - Fundamental input of CKM UT fit
- Phi3 can be measured using interference B→DK and B→DK (or DK*, Dpi)







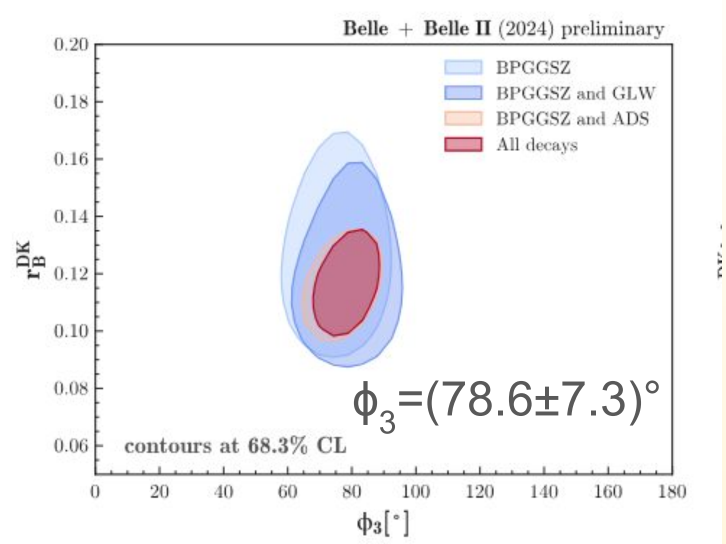
$B^- \to D^0K^- \approx V_{cb}V^*_{us}$
A_1

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

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

Belle/BelleII combined results on γ/ϕ_3 arXiv:2308.05048

- 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, 63 (2022)
    - Different amplitude and strong phase in different region of Dalitz plot.
  - GLS $D^0 \to K_S K\pi$ arXiv:2306.02940 [hep-ex]
- D-decay strong phase from CLEO-c & BESIII
  - Need improvement by BESIII for more



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

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

Few ab-1 needed for a meaningful comparison

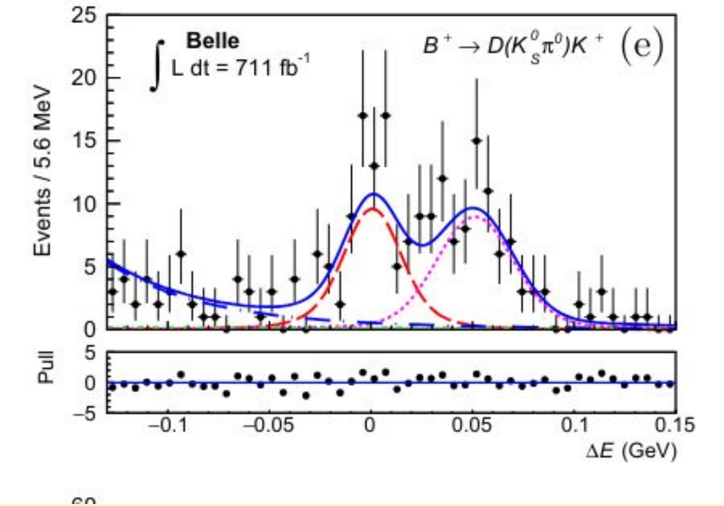
- Likelihood with 60 input observables
  - and 16 auxiliary inputs (D-decay)
- r_B with little high-fluctuation
  - Worse precisione with WA value

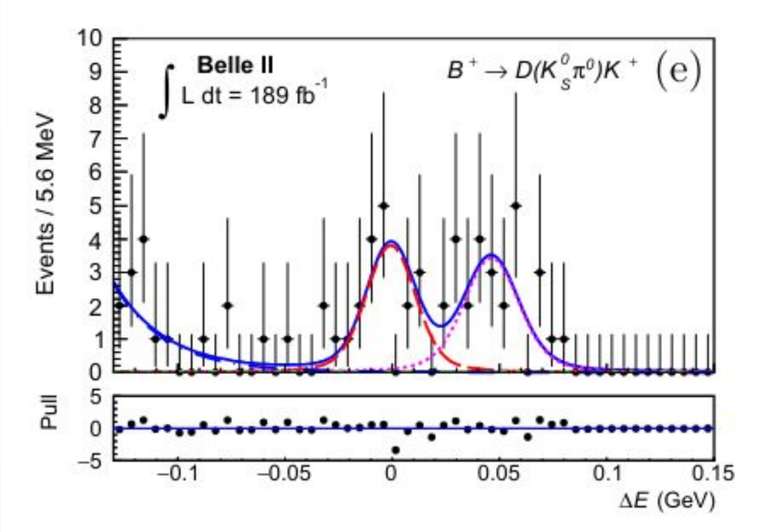
Belle + Belle II Combined

arXiv:2308.05048

- Example:
  - CP-odd $K_s$pi0: only in Belle(II)
  - $B^{\pm} \rightarrow D_{CP} K^{\pm}$ with $D_{CP} \rightarrow K^+ K^-$, $K_S{}^0$ (GLW)
  - Combined Belle and BelleII analysis

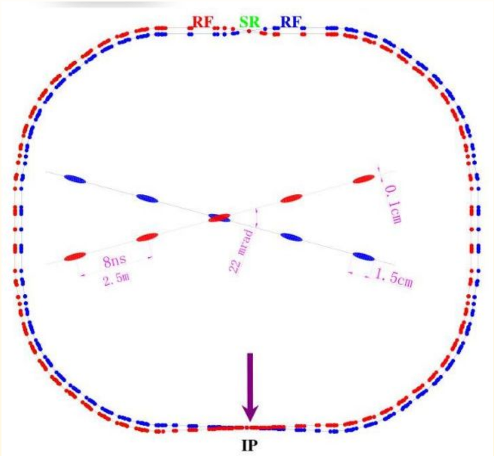
B decay	D decay	Method	Data set (Belle + Belle II)[fb^{-1}]
$B^+ \to Dh^+$	$D \to K_S^0\pi^0, K^-K^+$	GLW	$711 + 189$
$B^+ \to Dh^+$	$D \to K^+\pi^-, K^+\pi^-\pi^0$	ADS	$711 + 0$
$B^+ \to Dh^+$	$D \to K_S^0 K^-\pi^+$	GLS	$711 + 362$
$B^+ \to Dh^+$	$D \to K_S^0 h^- h^+$	BPGGSZ (m.i.)	$711 + 128$
$B^+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





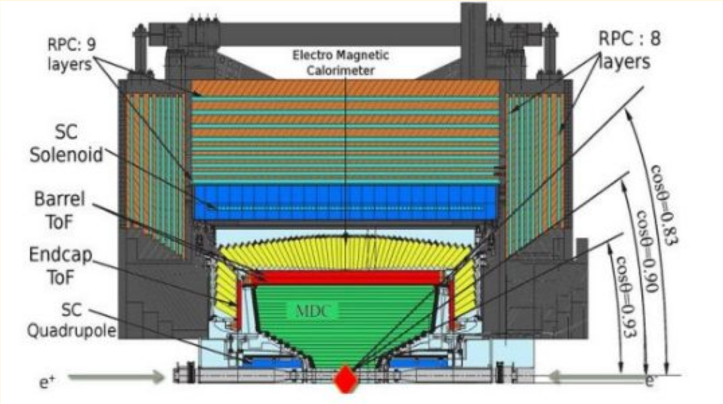
BESIII @ Beijing Electron-Positron Collider (BEPC-II)

- CM Energies: [2-4.95] GeV: **τ**-charm region
  - Luminosity: ~10^{33} $cm^{-2}s^{-1}$
- Collected 10 billion of J/ψ and 3 billion of ψ(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)



CPV in Hyperon decay

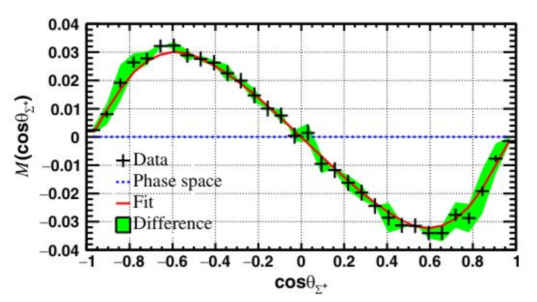
PRL.131.191802 (2023)

- 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** $A_{CP} = \frac{\alpha_+ + \bar{\alpha}_-}{\alpha_+ - \bar{\alpha}_-}$ **⇒ CP violation**

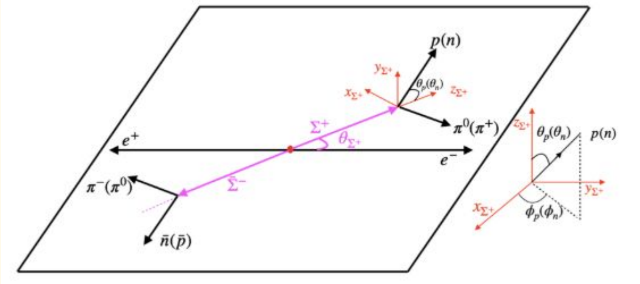
$$\frac{dN}{d\Omega} = \frac{1}{4\pi}(1 + \alpha \mathbf{P}_{\Sigma^+} \cdot \hat{\mathbf{p}})$$

- Selected events with $J/\psi \to$ **Σ+ 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 result with neutron in the final state

Moment of polarization



Non flat ⇒ polarization observed

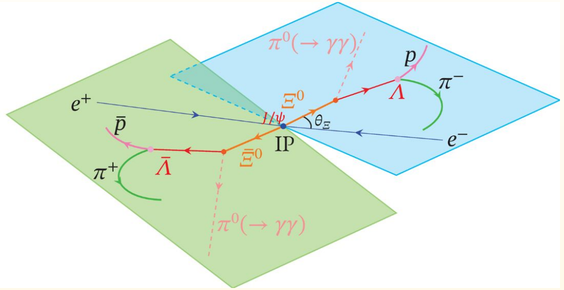


$Acp = 0.080 \pm 0.052 \pm 0.028$

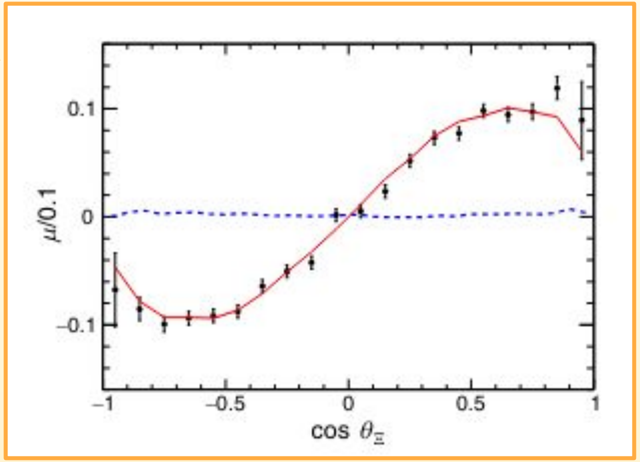
$e^+e^-\to J/\psi\to$ Ξ^0anti-Ξ^0, $\Xi^0\to\Lambda(\to p\pi^-)\pi^0$ +cc

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

PhysRevD.108.L031106 (2023)



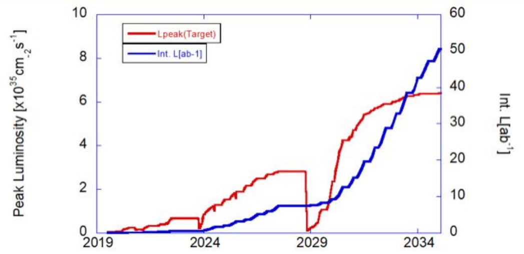
- Results:
  - Ξ^- polarization observed (first time)
  - Independent measurement of Λ decay parameters
  - First measurement of weak phase difference in Ξ decay
  - Three independent CP test



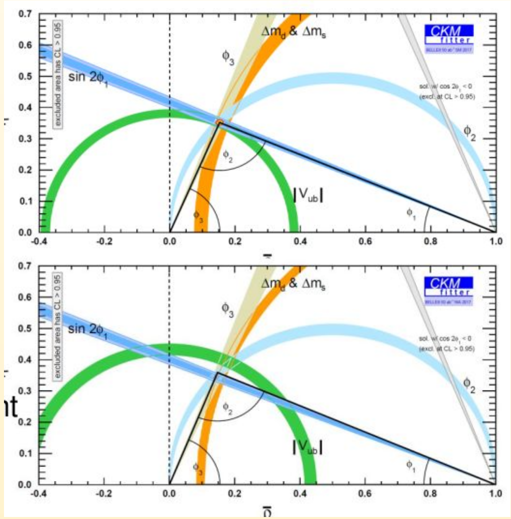
Parameter	This work	Previous result
A^{Ξ}_{CP}	$(-5.4\pm6.5\pm3.1)\times10^{-3}$	$(-0.7\pm8.5)\times10^{-2}$ [49]
$\Delta\phi^{\Xi}_{CP}$(rad)	$(-0.1\pm6.9\pm0.9)\times10^{-3}$	$(-7.9\pm8.3)\times10^{-2}$ [49]
A^{Λ}_{CP}	$(6.9\pm5.8\pm1.8)\times10^{-3}$	$(-2.5\pm4.8)\times10^{-3}$ [20]

Perspective

- **Belle II goal: L=6x10^{35}cm^{-2}s^{-1} ; L$_{int}$50/ab**

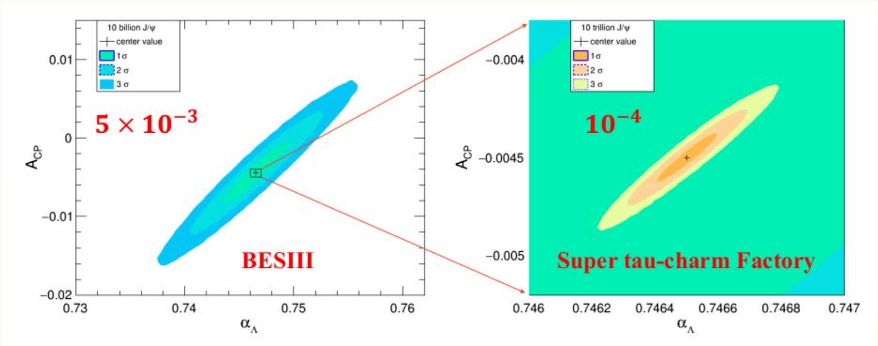


[PTEP (2019) 123C01]



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

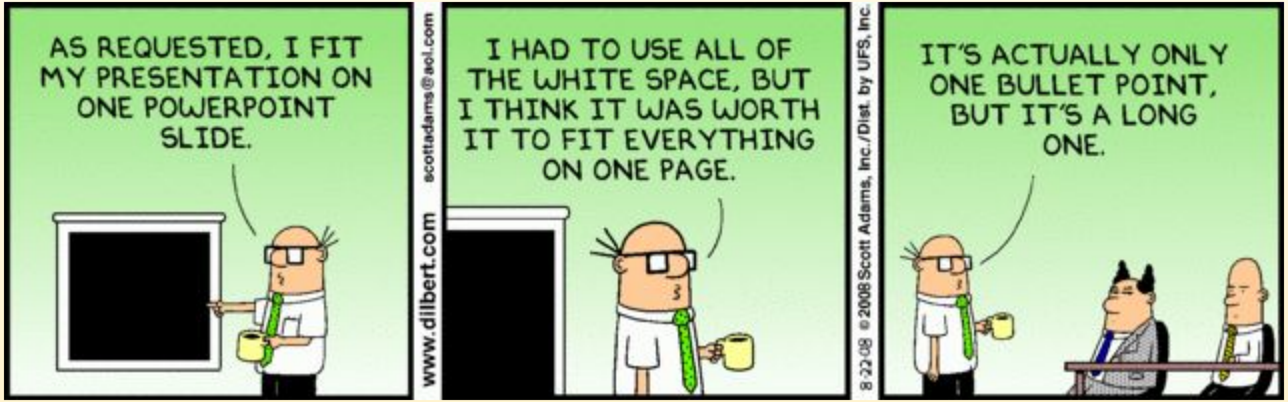
- **BESIII and Super Tau-Charm Facility**
  - today 10^{10} J/ψ
  - At super J/ψ factory **10^{12} J/ψ per year**
    - L~10^{35}
    - polarized beam (phase II)
- CPV sensitivity in hyperon's decay
  - **10^{-4} - 10^{-5}**
  - challenging SM predictions



Summary

- CPV studies is 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 significant better performance compared to Belle
- Hyperon polarization at J/ψ, $\psi(2S)$ decays at BESIII
  - new way to study CPV

Backup


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

$\sin(2\phi_1/\beta)$ 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 $B \to J/\psi\pi^0$

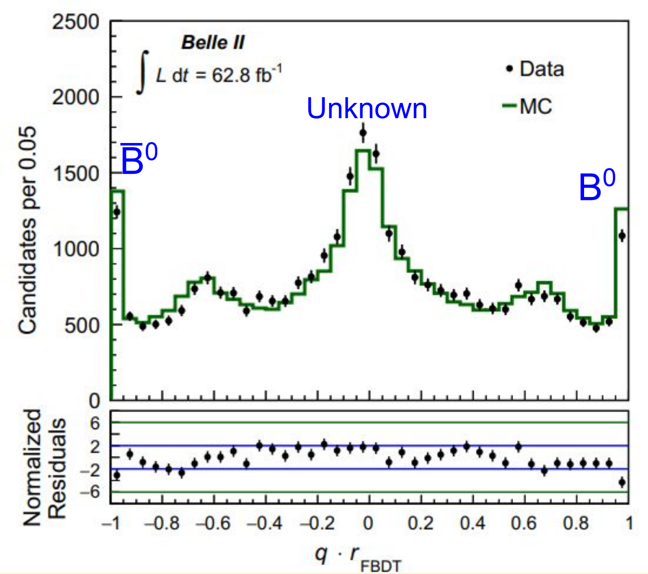
Belle II Physics Book

	No improvement	Vertex improvement	Leptonic categories
$S_{c\bar{c}s}$ (50 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 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

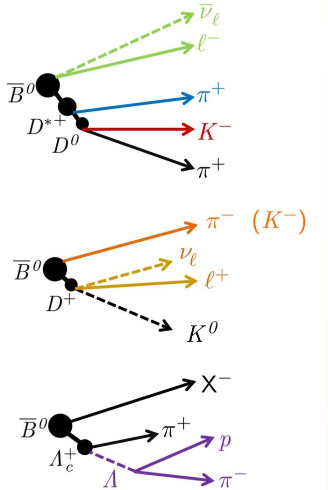
Flavour Tagger

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:

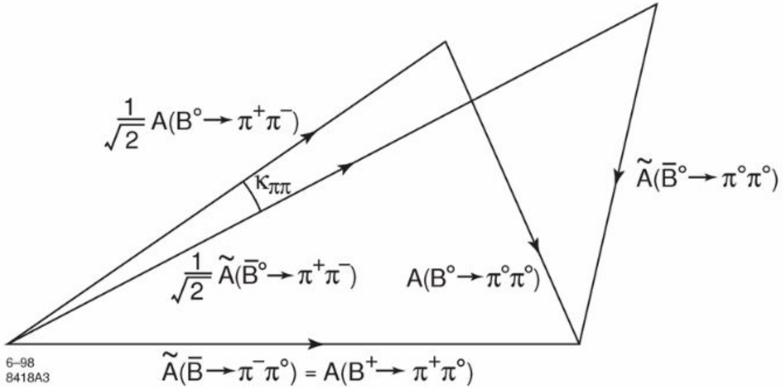
$$\varepsilon_{eff} = \Sigma_i \varepsilon_i (1-2w_i)^2$$
$$= (30.0 \pm 1.2 \pm 0.4)\%$$

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:

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



- 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}.

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

- Belle II will be able to measure all these observables;
- We expect to push the sensitivity to α to ~1º.

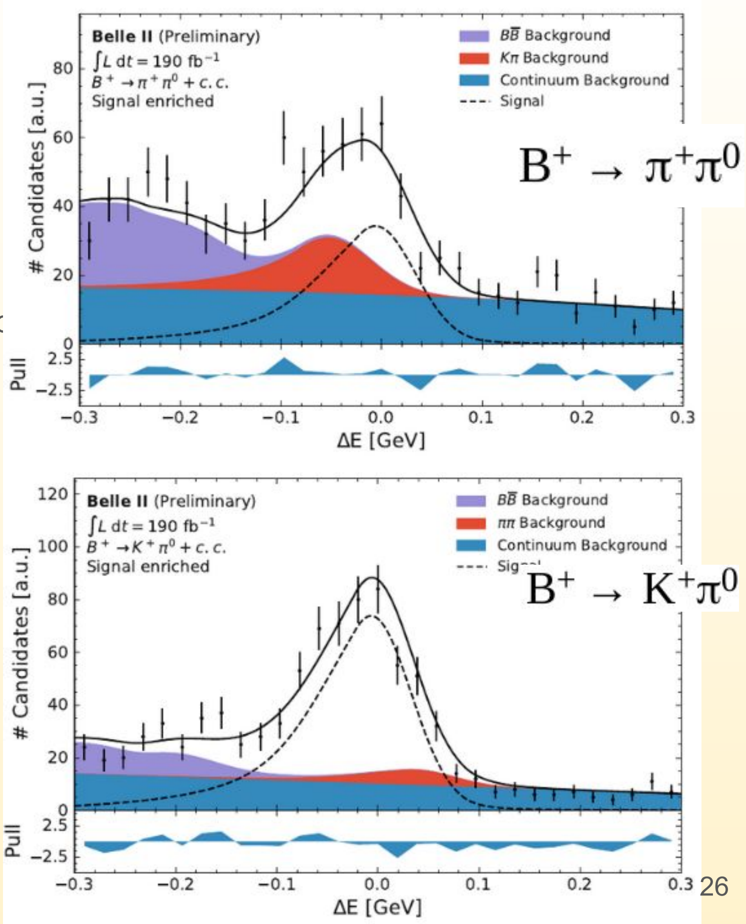
$B^+ \to K^+\pi^0$ / $\pi^+\pi^0$

J. Skorupa @ ICHEP 2022

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

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

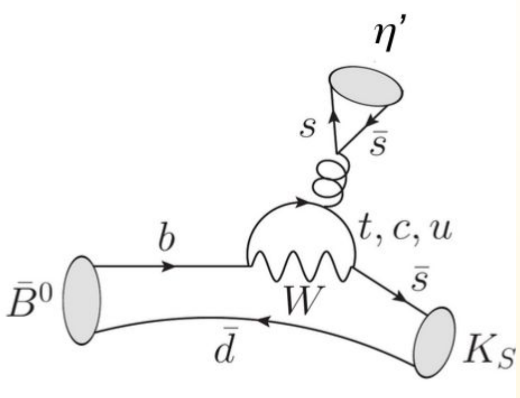
WA: $\mathcal{A}^{CP}_{K^+\pi^0} = 0.030 \pm 0.013$, $\mathcal{A}^{CP}_{\pi^+\pi^0} = 0.03 \pm 0.04$



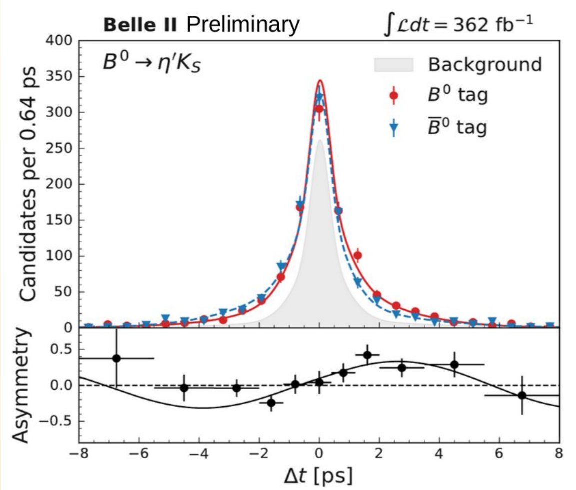
Time dependent B → η'K$_S$

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:
  - $\eta' \to \eta(\to\gamma\gamma)\pi^+\pi^-$, $\eta' \to \rho\gamma$
- Found ~800 signal in total, performed time dependent fit in De, Mbc, ContSupp and DeltaT variables



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



- In agreement with WA and B0 → J/y KS result

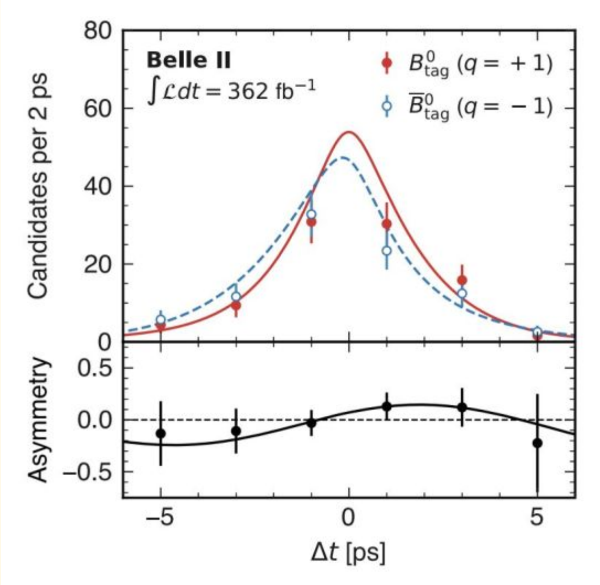
Time dependent $B \to \varphi' K_S$

arXiv:2307.02802

- Two tracks from φ, clean signature
- Major challenge : non resonant background with opposite-CP
- Found ~800 signal in total, performed time dependent fit in De, Mbc, ContSupp and DeltaT variables

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

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

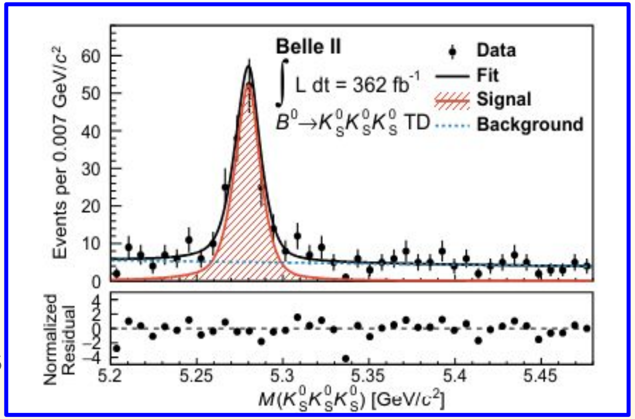


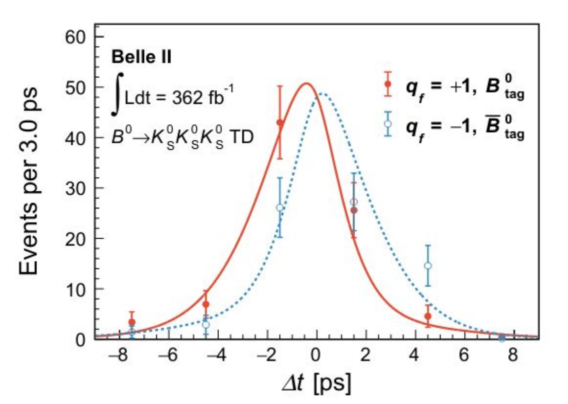
Time dependent $B \to K_S K_S K_S$

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

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





Isospin Sum Rule

arxiv:2310.06381

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

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%)

→ experimentally consistent with 0 at 10% level, limited by $K_S^0\pi^0$ mode

→ **Belle II in unique position to measure all observables at single experiment**

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

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

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

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

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

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

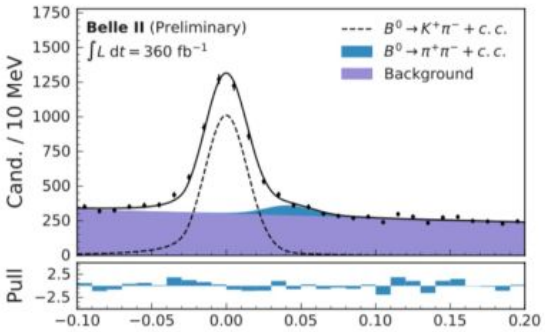
$B^0 \to K_S^0\pi^0$

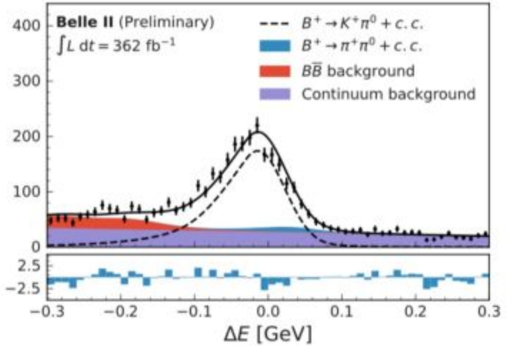
$\mathcal{B} = (10.50 \pm 0.62 \pm 0.67) \times 10^{-6}$
$A_{CP} = -0.01 \pm 0.12 \pm 0.05$

world's best

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

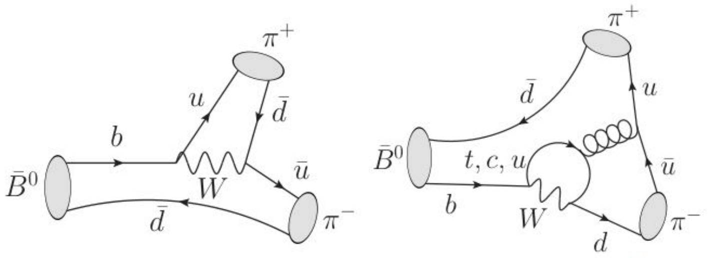
precision on par with W/A!
→ 5% uncertainty achievable @ 10 ab^{-1}





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

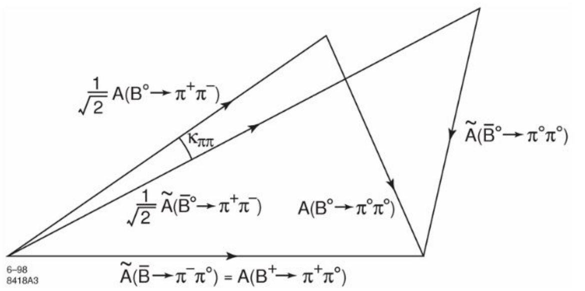
$$\phi_2 = (\widehat{\bar{A}^{+0}, A^{+0}}),\ \phi_2^{eff} = (\widehat{\bar{A}^{+-}, A^{+-}})$$

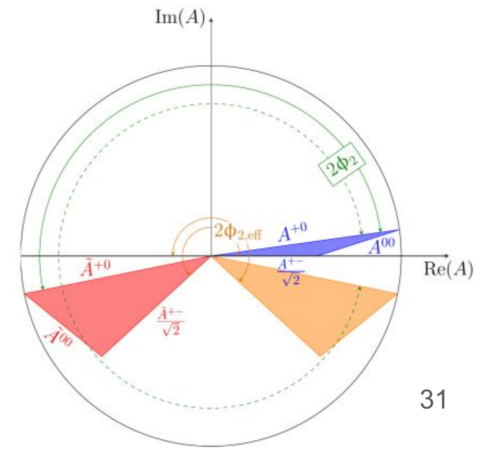
Isospin analysis[Gronau-London PRL, 64 3381 (1990)]: constraints B^0 and B$^\pm$ amplitudes:

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

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^o





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

EPS-HEP 2023

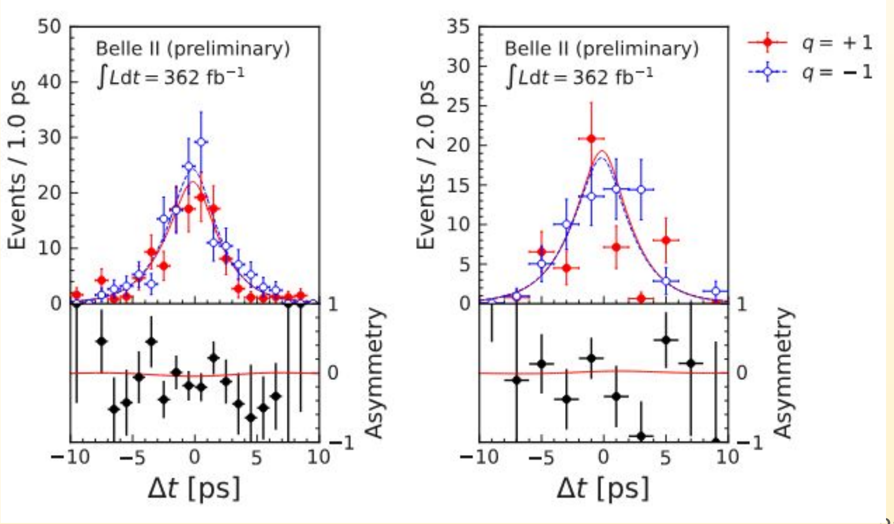
- $B^0 \to K_S \pi^0 \gamma$ is expected to have small/none mixing induced CPV in SM
  - $b \to s\gamma_R$ is helicity suppressed (m_s/m_b) wrt $b \to s\gamma_L$
  - $B^0 \to s\gamma_L$ vs $B^0 \to \bar{B}^0 \to s\gamma_R$
- Vertex from $K_S \to \pi^+\pi^-$ and IP constraint
- Measured separately for exclusive: $K^{*0}(\to K^S \pi^0)\gamma$

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

- and inclusive decay $K^S \pi^0 \gamma$

$$S = 0.04\ ^{+0.45}_{-0.44} \pm 0.10$$
$$C = -0.0.6 \pm 0.25 \pm 0.07$$

Most precise result so far



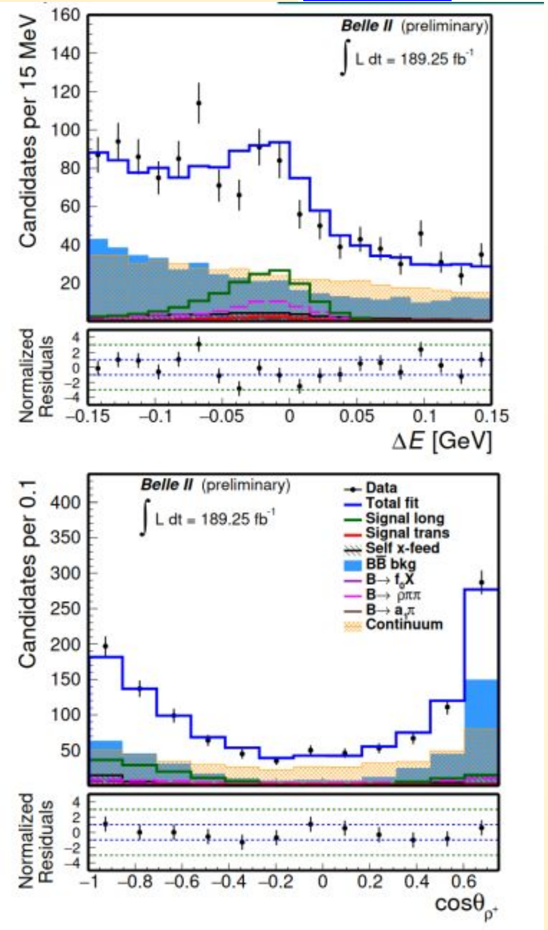
Toward ϕ_2/α: $B^+ \to \rho^+\rho^0$

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

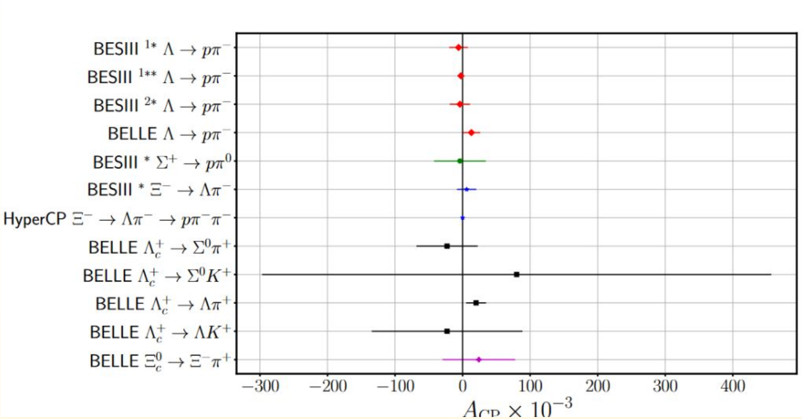
$$\mathcal{A}^{CP} = -0.069 \pm 0.068 \text{ (stat)} \pm 0.060 \text{ (syst)}$$
$$\mathcal{B} = (23.2^{+2.2}_{-2.1} \text{ (stat)} \pm 2.7 \text{ (syst)}) \cdot 10^{-6}$$
$$f_L = 0.943^{+0.035}_{-0.033} \text{ (stat)} \pm 0.027 \text{ (syst)}$$

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



Hyperon at Super Tau-Charm Facility (STCF)

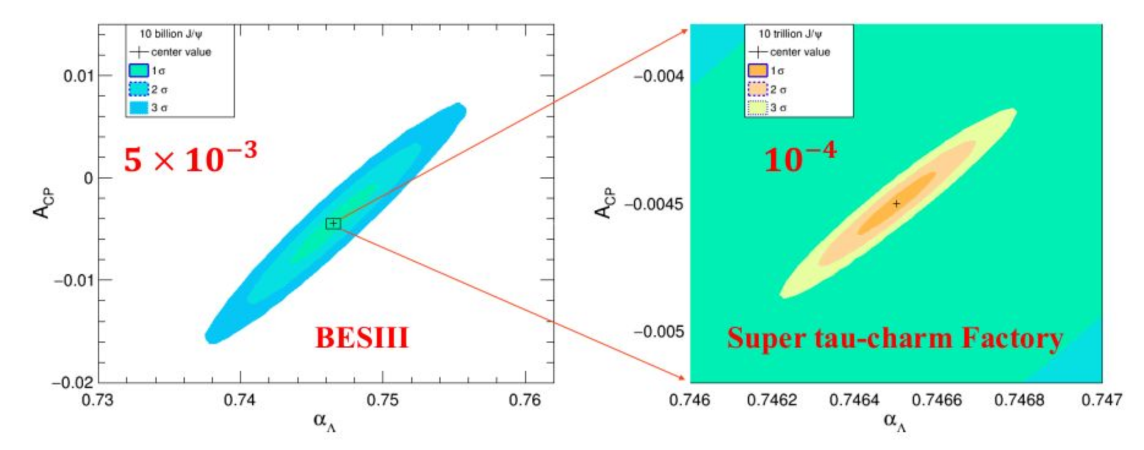
- Many (null) results so far
  - BESIII and Belle
- BESIII: today
  - 10 billion J/ψ
- At super J/ψ factory
  - 10^{12} J/ψ per year
- CPV sensitivity in hyperon's decay
  - **10^{-4} - 10^{-5}**
  - challenging SM predictions



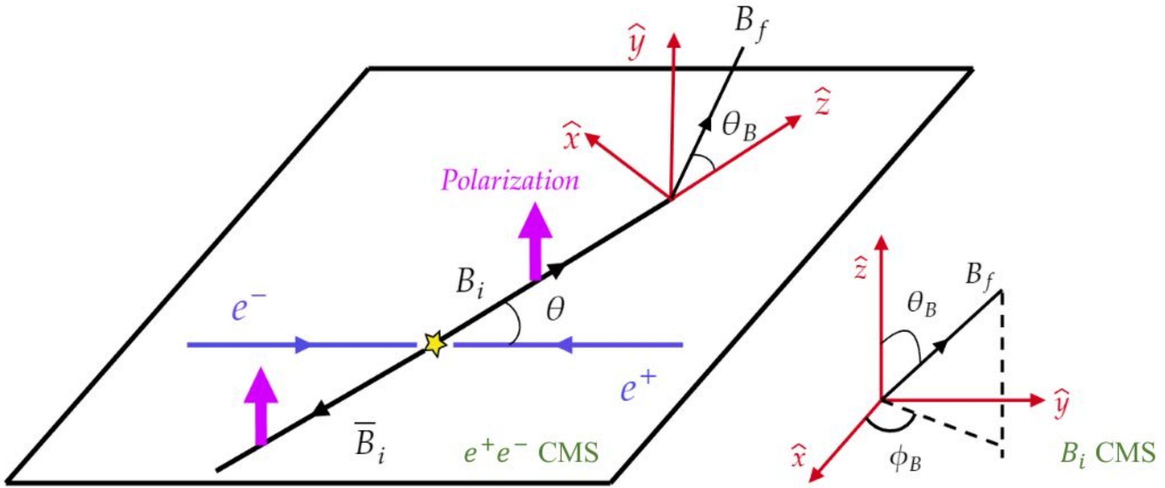
BESIII:
Nature Phys. **15**, p 631-634 (2019)
Phys. Rev. Lett. 125, 052004 (2020)
Nature 606, 64-69 (2022)
Phys. Rev. Lett. 129, 131801 (2022)
Phys. Rev. D 108, L031106 (2023)

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

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



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 ⇒ transverse polarized hyperon (if $\Delta\Phi \neq 0$):