CPV in B decays: results at Belle and prospects at Belle 2

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on behalf of the Belle and Belle II Collaborations

Brookhaven Forum 2019
Particle Physics and Cosmology in the 2020's
25-27 Sep. 2019

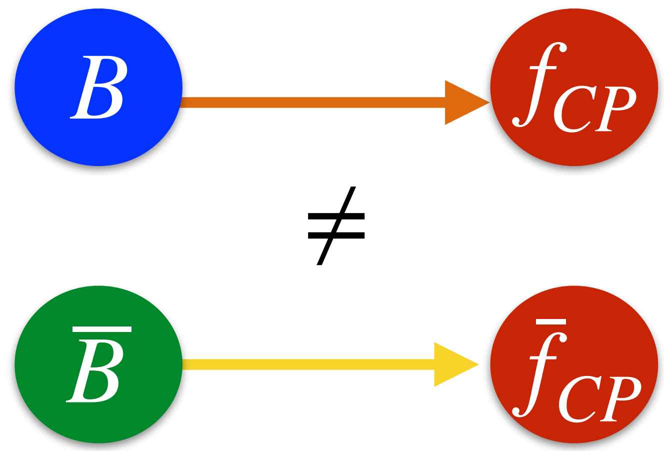
Outline

- Introduction of CP violation
- Overview of Belle experiment
- Recent Belle results
  - $B^0 \to J/\psi\pi^0$
  - $B^0 \to \overline{D}^0\pi^0$ and $B^+ \to \overline{D}^0\pi^+$
- Overview of Belle2 experiment
- Latest results from Belle2
- Some prospects of CPV at Belle2
- Summary

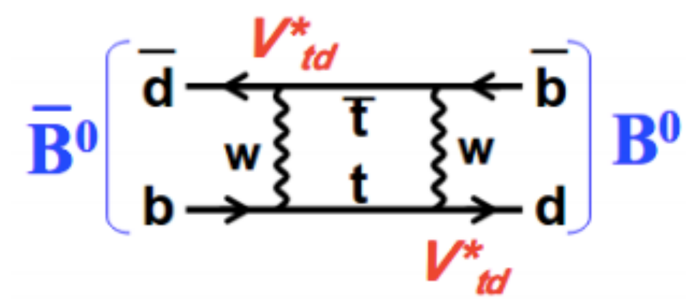
CP Violation

- **Direct CP violation**
  CP violation in the decay

$$\mathcal{A}_{CP} \equiv \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} = \frac{N_{\bar{B}} - N_B}{N_{\bar{B}} + N_B}$$



- CP violation in mixing
  difference in the probabilities between
  $P(B^0 \to \overline{B}^0) \neq P(\overline{B}^0 \to B^0)$

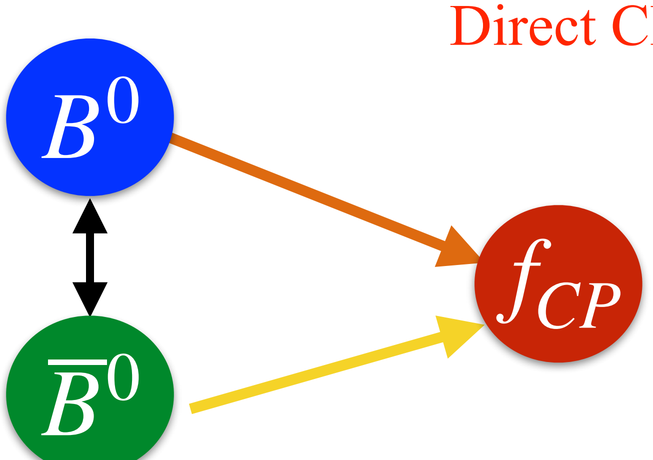


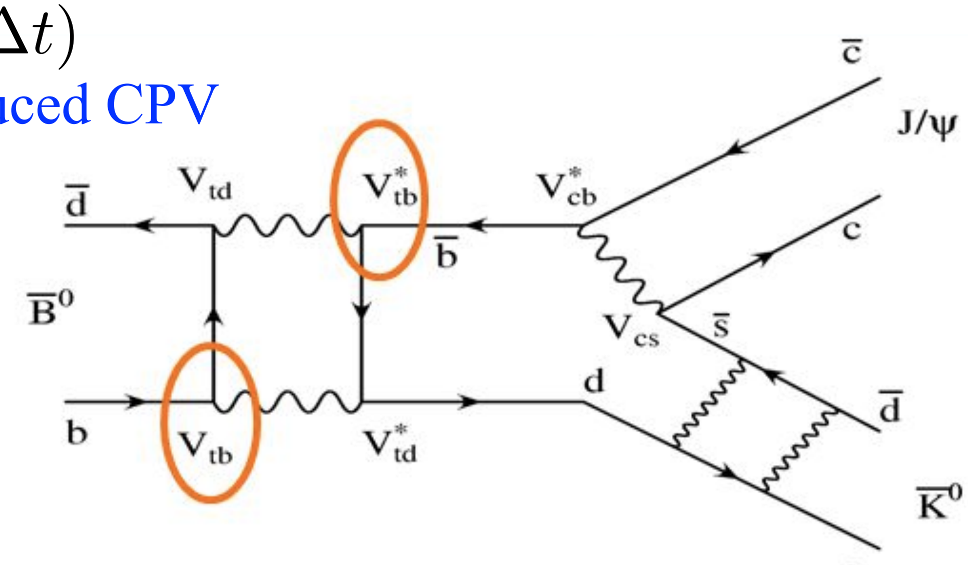
- CP violation from interference between mixing/decay

$$A_{f_{CP}}(\Delta t) \equiv \frac{\Gamma[\overline{B}(\Delta t)] - \Gamma[B(\Delta t)]}{\Gamma[\overline{B}(\Delta t)] + \Gamma[B(\Delta t)]}$$

$$= A\cos(\Delta m \Delta t) + S\sin(\Delta m \Delta t)$$

Direct CPV — Mixing-induced CPV





CPV in the SM

- CKM matrix describes the couplings between quarks of different generations via weak interaction

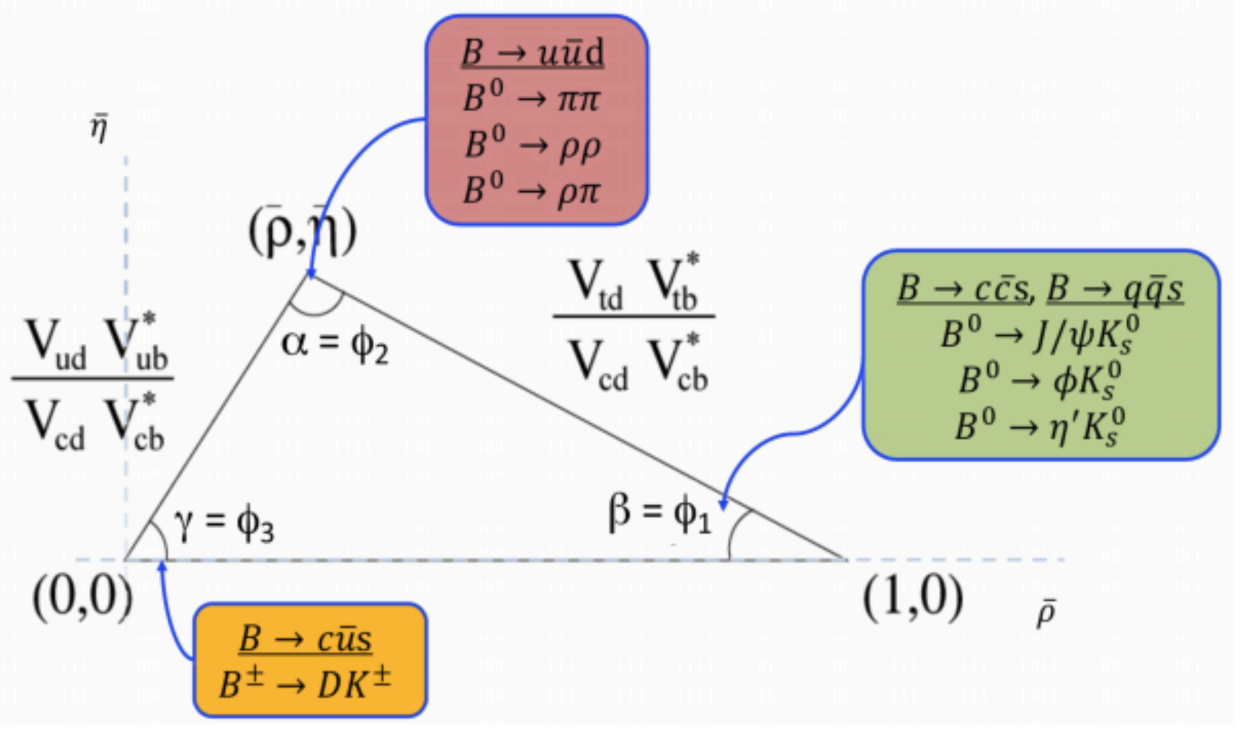
CKM Matrix **Wolfenstein representation**

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

CPV is due to a complex phase in the quark mixing matrix

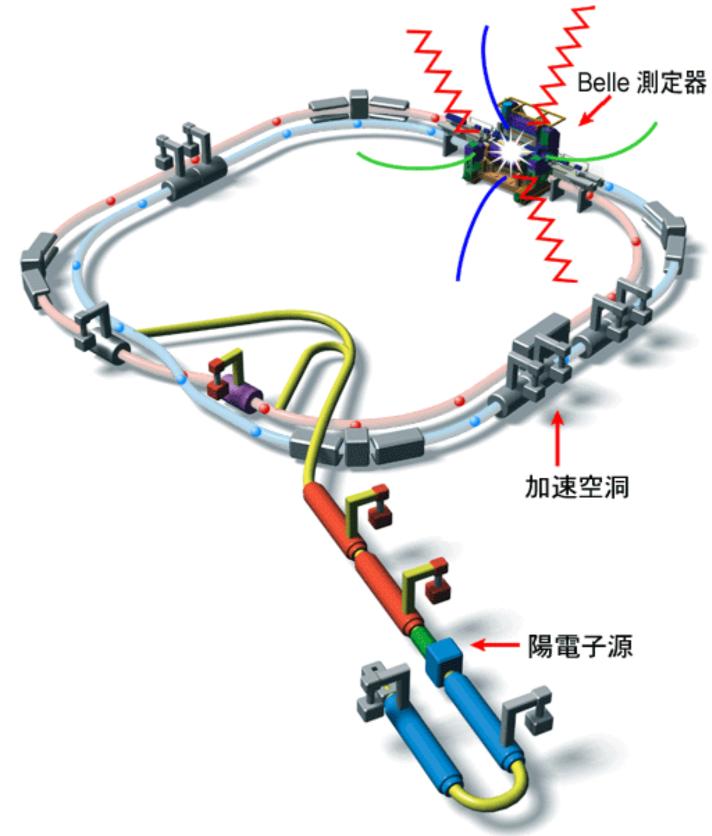
Unitary requires

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

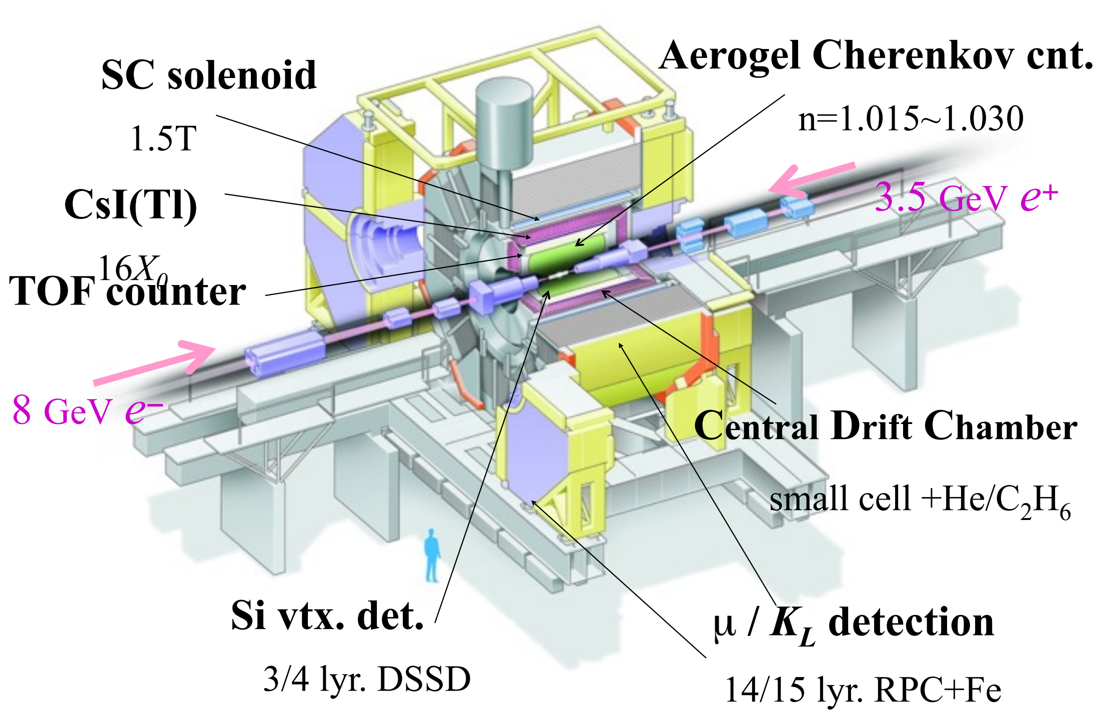


Belle Experiment

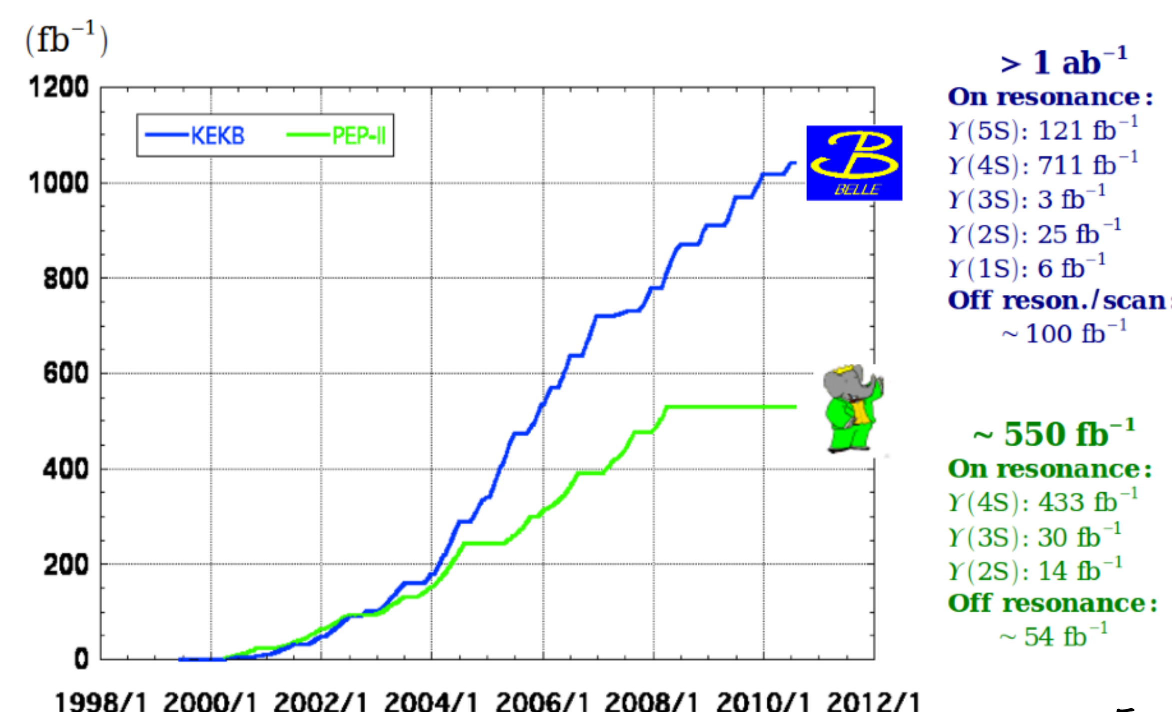
- Asymmetric energy e^+e^- collider at KEK
- LER(e^+): 3.5 GeV
  HER(e^-): 8.0 GeV
  with crossing angle ±11 mrad
- The CM energy was set to be Υ(4S) resonance to produce B meson pairs.
- 711 fb^{-1} Υ(4S) were collected at Belle
  All results presented here are based on the full Belle data set.



Belle Detector



Integrated luminosity of B factories



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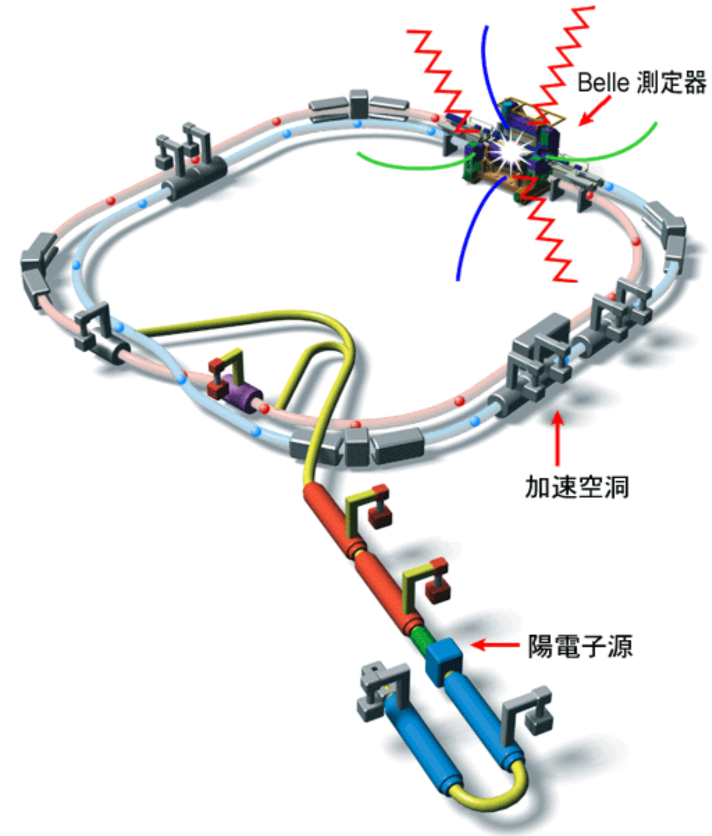

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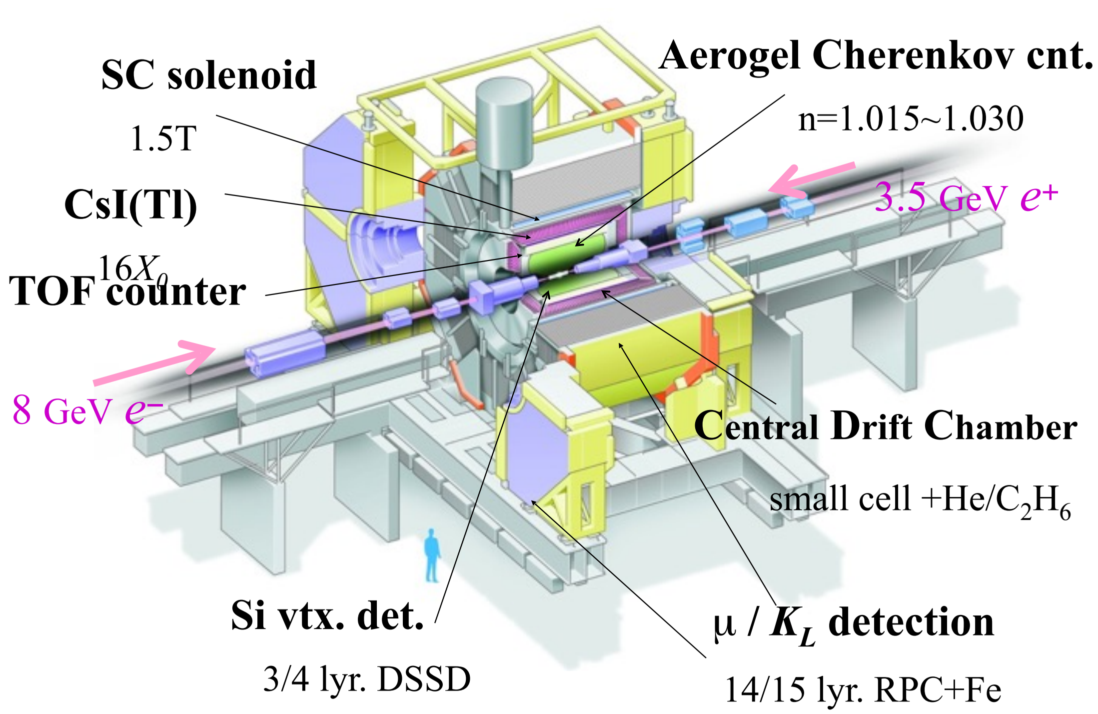

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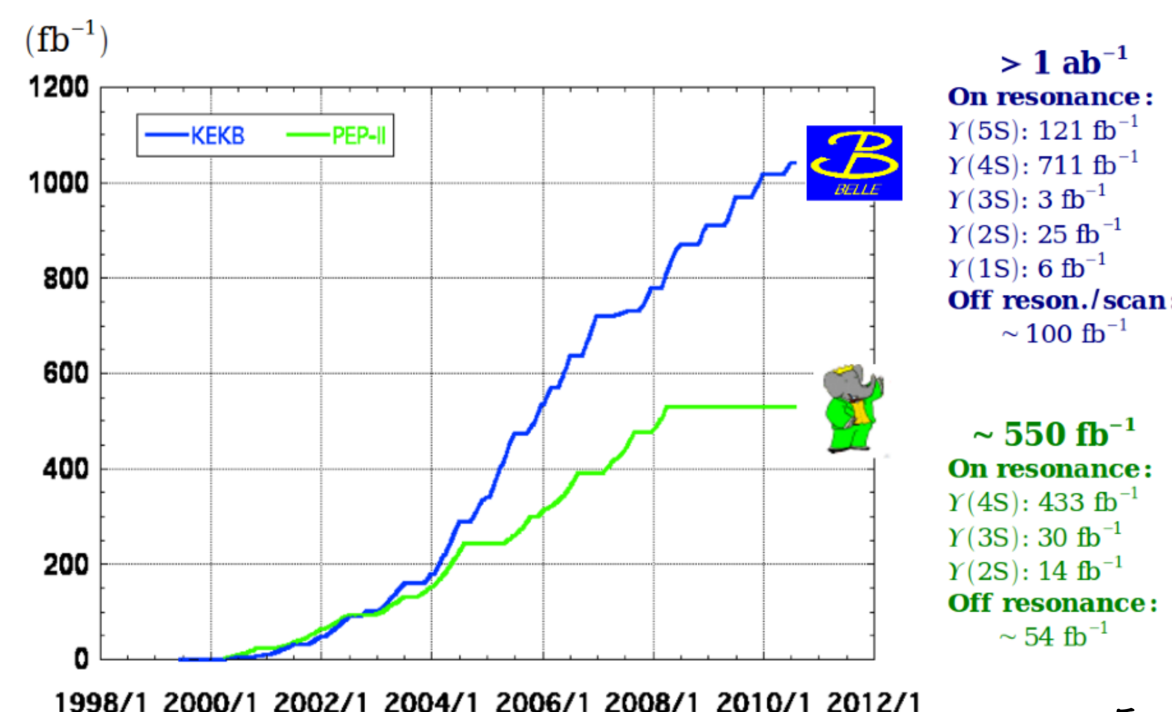
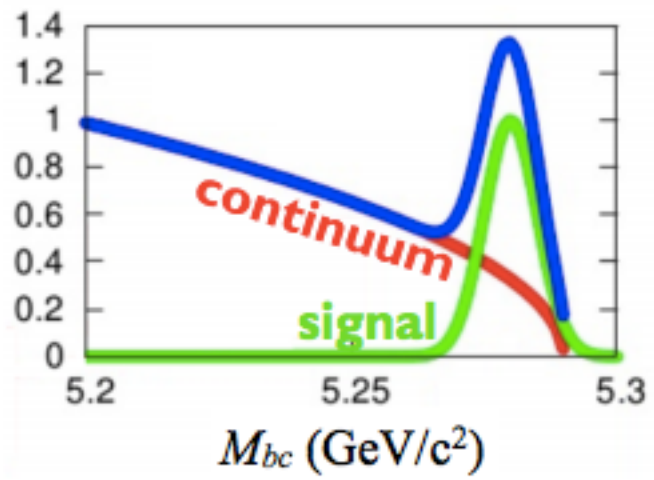
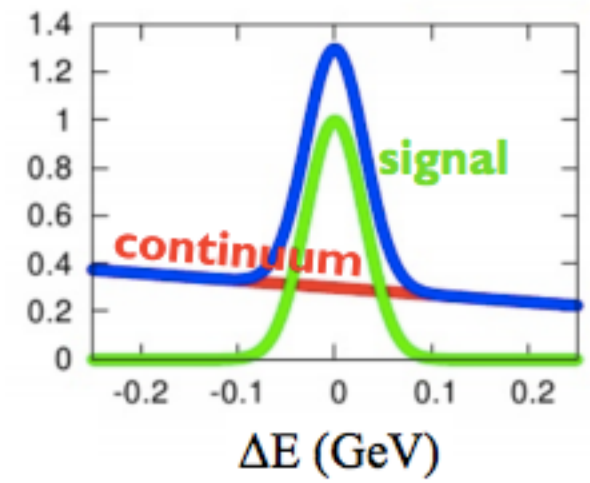


Analysis technique

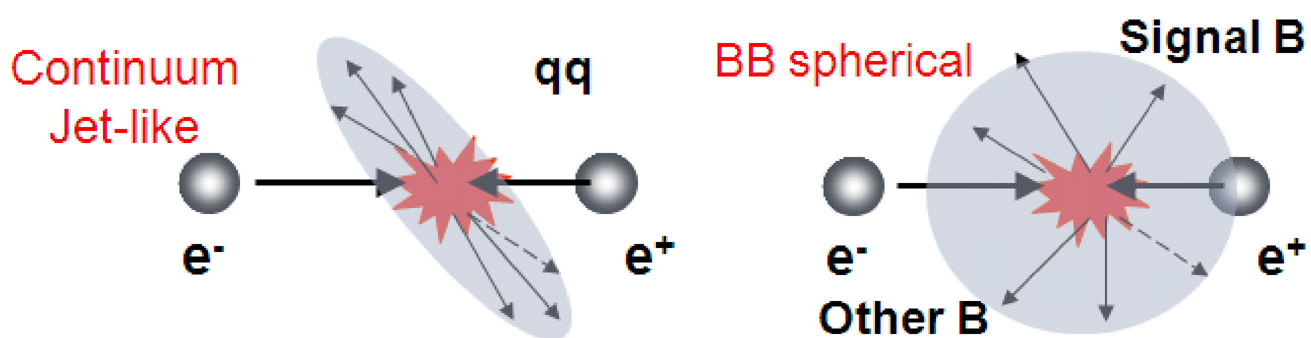
- Kinematic variables are used to identify B decays:

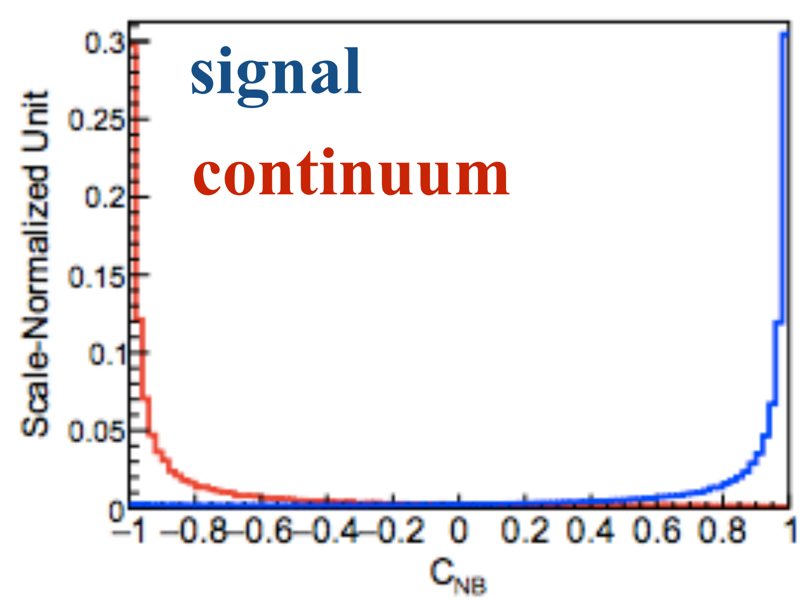
$$M_{bc} = \sqrt{E_{beam}^{*2} - p_B^{*2}} \qquad \Delta E = E_B^* - E_{beam}^*$$





- Continuum suppression:
  Variables describing the event topology are combined in a multivariate analysis (Fisher Discriminant or Neural Network).





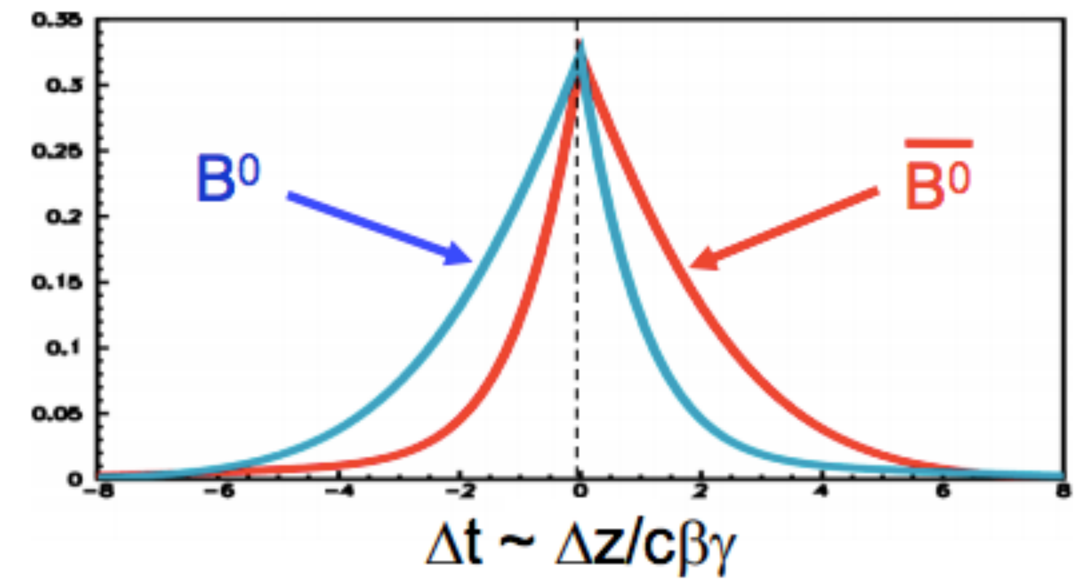
- The information can be used to extract signals.

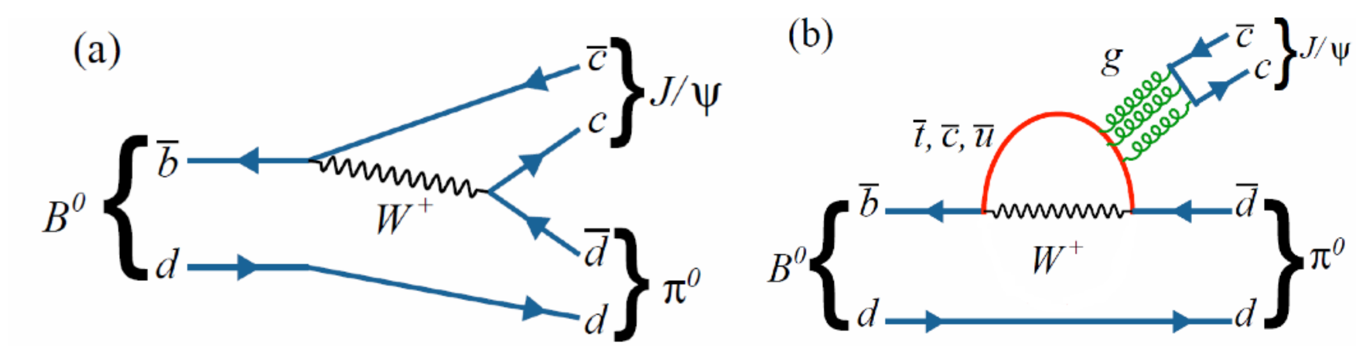
TCPV in $B^0 \to J/\psi\pi^0$

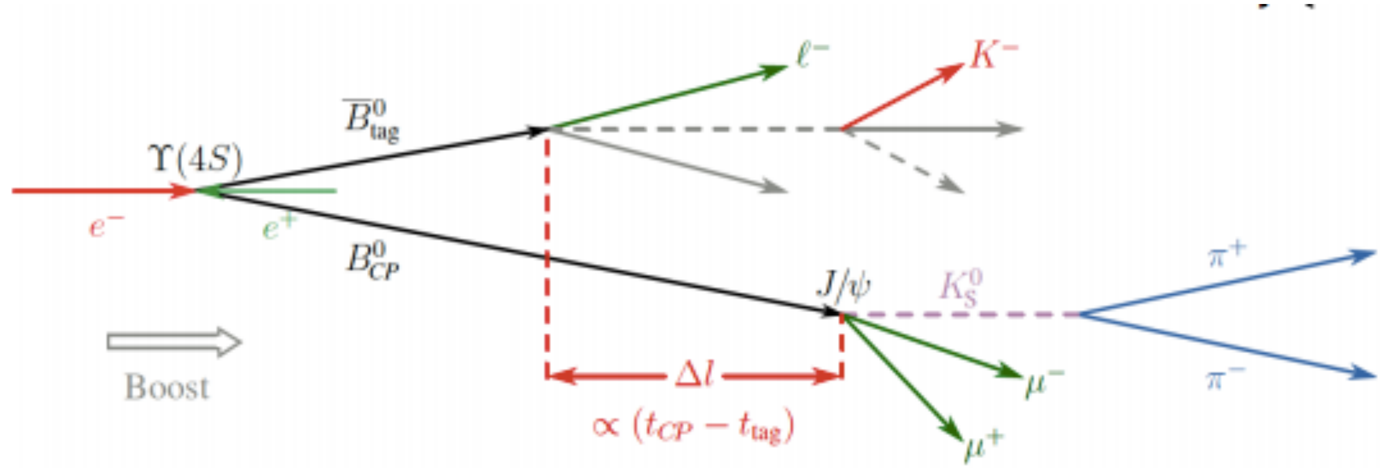
PRD98 112008 (2018)

- CP violation appears as a decay time difference.
- Tag-side determines its flavour, and is used to reconstruct the B_{tag} vertex. (ε_{eff}~30%)
- Sensitive to the CP violating angle ϕ_1
- In the absence of the penguin amplitude, the direct CP asymmetry A = 0 and the mixing-induced CP asymmetry S = -sin(2ϕ_1)
- $\sin(2\phi_1) = 0.699 \pm 0.017$ from b→ccq **(HFLAV)**
- Compare the results with one in $B^0 \to J/\psi K_S$ to understand the contribution from penguin diagram.

Measure decay position instead of time







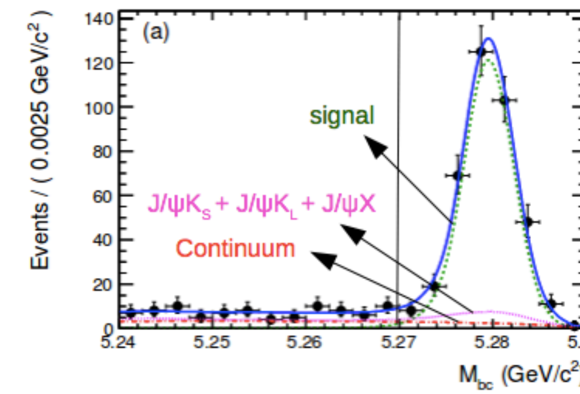
Measurement of $B^0 \rightarrow J/\psi\pi^0$

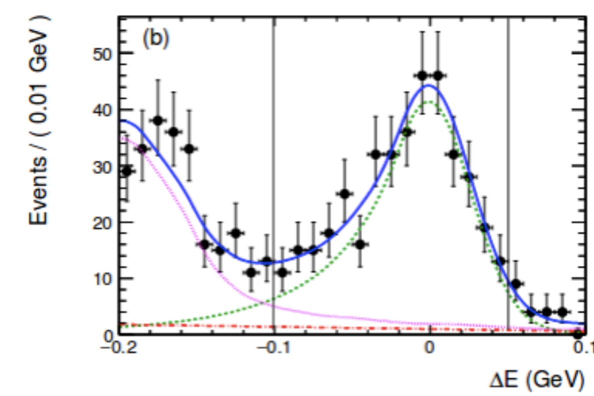
PRD98 112008 (2018)

$$Br(B^0 \rightarrow J/\psi\pi^0) = \frac{N_{Sig}}{\epsilon_{sig} \times N_{B\overline{B}} \times Br(J/\psi) \times Br(\pi^0)}$$

$$= (1.62 \pm 0.11 \pm 0.06) \times 10^{-5}$$

- Consistent with the world average $(1.76 \pm 0.16) \times 10^{-5}$
  most precise measurement to-date



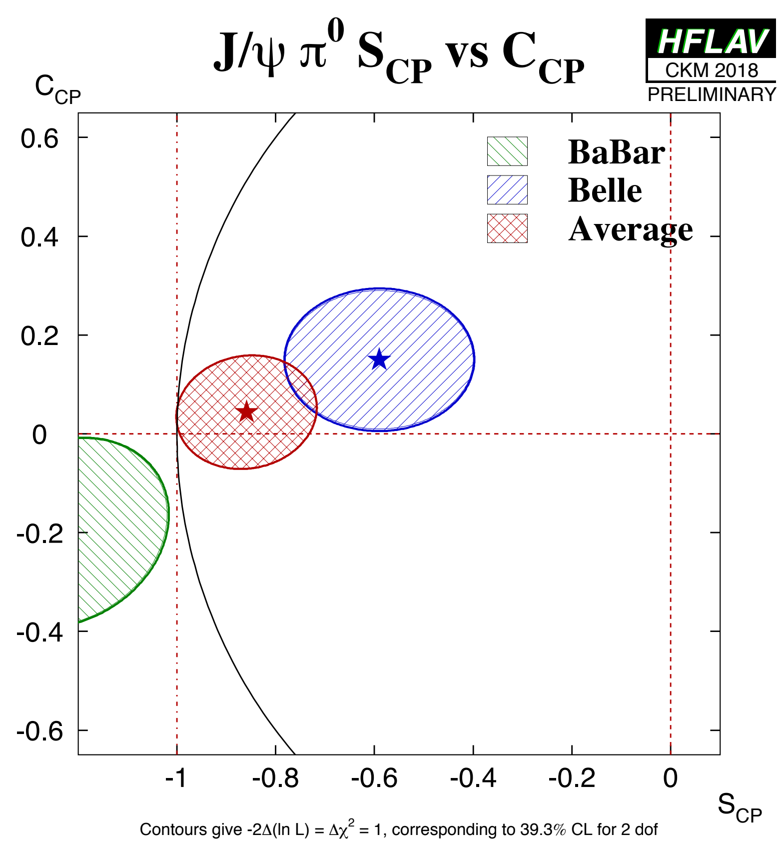


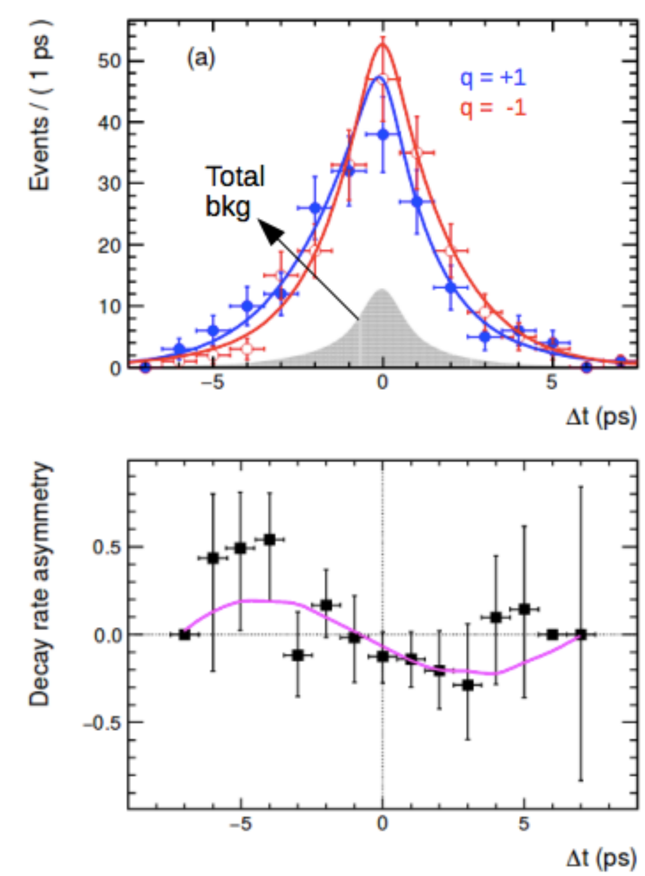
- Extract from a fit to (Δt)

$$\mathcal{S} = -0.59 \pm 0.19 \pm 0.03$$

$$\mathcal{A} = -0.15 \pm 0.14^{+0.04}_{-0.03}$$

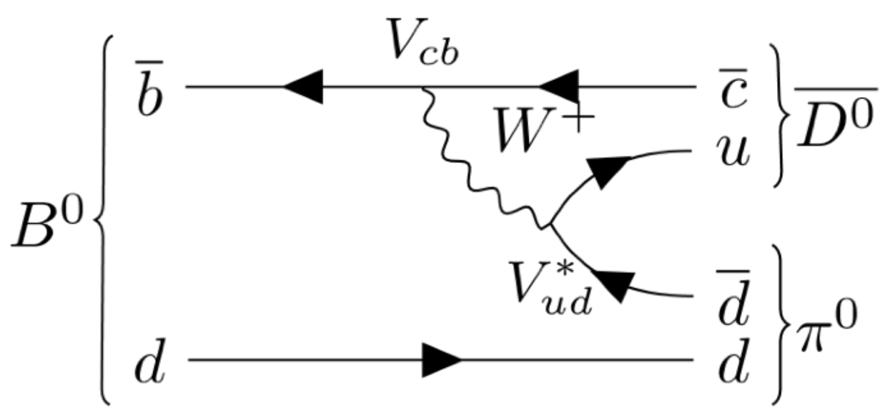
- Consistent with results from $B^0 \rightarrow J/\psi K_S$
- 3.2σ(*) away from BaBar measurement

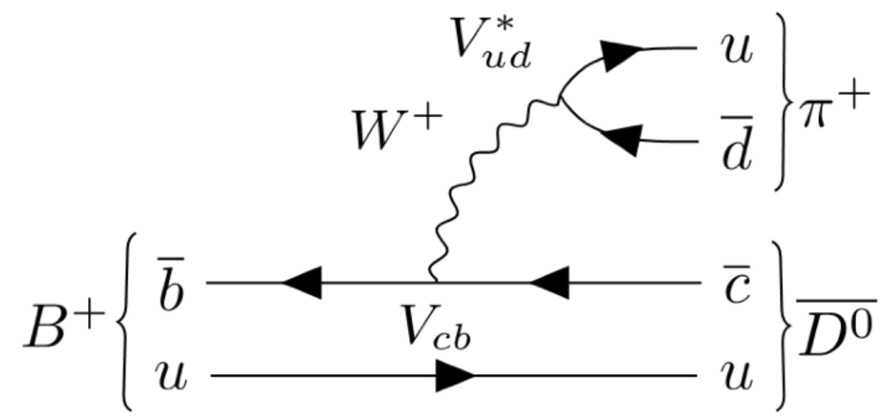




$B^0 \to \overline{D}^0\pi^0$ And $B^+ \to \overline{D}^0\pi^+$

Preliminary

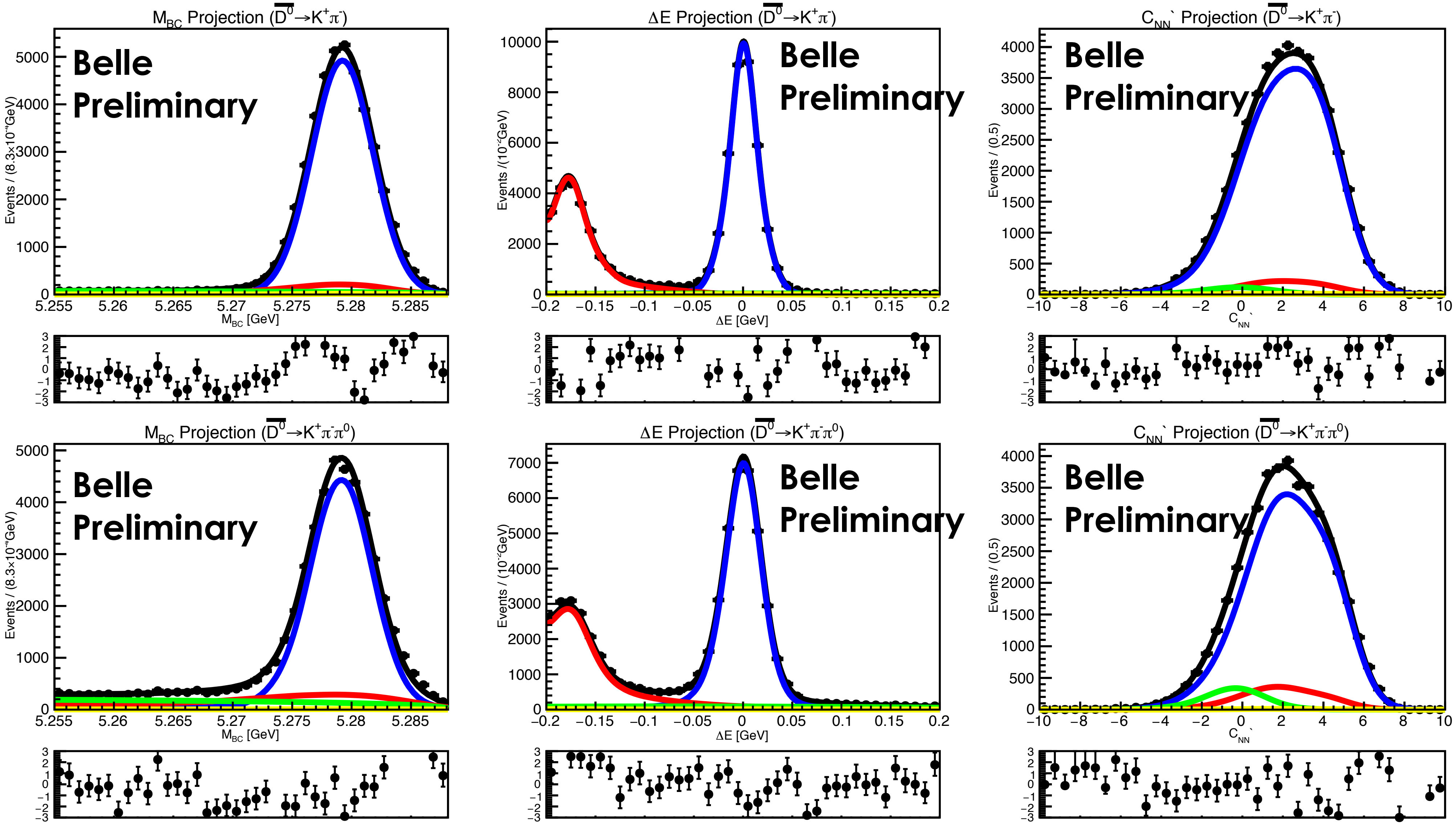




- $b \to c\bar{u}d$ decay, no penguin contribution ⇒ large A_{CP} could hint at BSM physics
    - Time-dependent measurement $C(B^0 \to \overline{D}^{(*)}h^0) = (-2 \pm 8)\,\%$
      Time independent measurement allows higher precision.
- $B^0 \to \overline{D}^0\pi^0$ with notable large non-factorizable components
    - branching fraction >> "naive" factorisation predictions
    - Constraints for models of final state interactions
- Both commonly used control mode in experiments, allow for high-precision validations of techniques.
    - **Important for Belle II precision frontier.**
- Previous experimental results:

	dataset	$\mathcal{B}$	$\mathcal{A}_{CP}(\%)$
$B^0 \to \overline{D}^0\pi^0$ (Belle)	152×10^6	$(2.25 \pm 0.14 \pm 0.35) \times 10^{-4}$	-
$B^0 \to \overline{D}^0\pi^0$ (BaBar)	454×10^6	$(2.69 \pm 0.09 \pm 0.13) \times 10^{-4}$	-
$B^+ \to \overline{D}^0\pi^+$ (Belle)	$772 \times 10^6/275 \times 10^6$	$(4.34 \pm 0.10 \pm 0.23) \times 10^{-3}$	-0.8 ± 0.8
$B^+ \to \overline{D}^0\pi^+$ (BaBar)	454×10^6	$(4.90 \pm 0.07 \pm 0.22) \times 10^{-3}$	-
$B^+ \to \overline{D}^0\pi^+$ (LHCb)	$1 fb^{-1}$	-	$-0.6 \pm 0.5 \pm 1.0$

$B^+ \to \overline{D}^0\pi^+$ Result



- 3D unbinned ML fit to M_{bc}, ΔE, and C'_{NN}. Simultaneous fit to four datasets divided by Kaon charge

$$C'_{NN} = \log \frac{C_{NN} - C_{NN}^{min}}{C_{NN}^{max} - C_{NN}}$$

all
signal
BB
continuum
Rare B

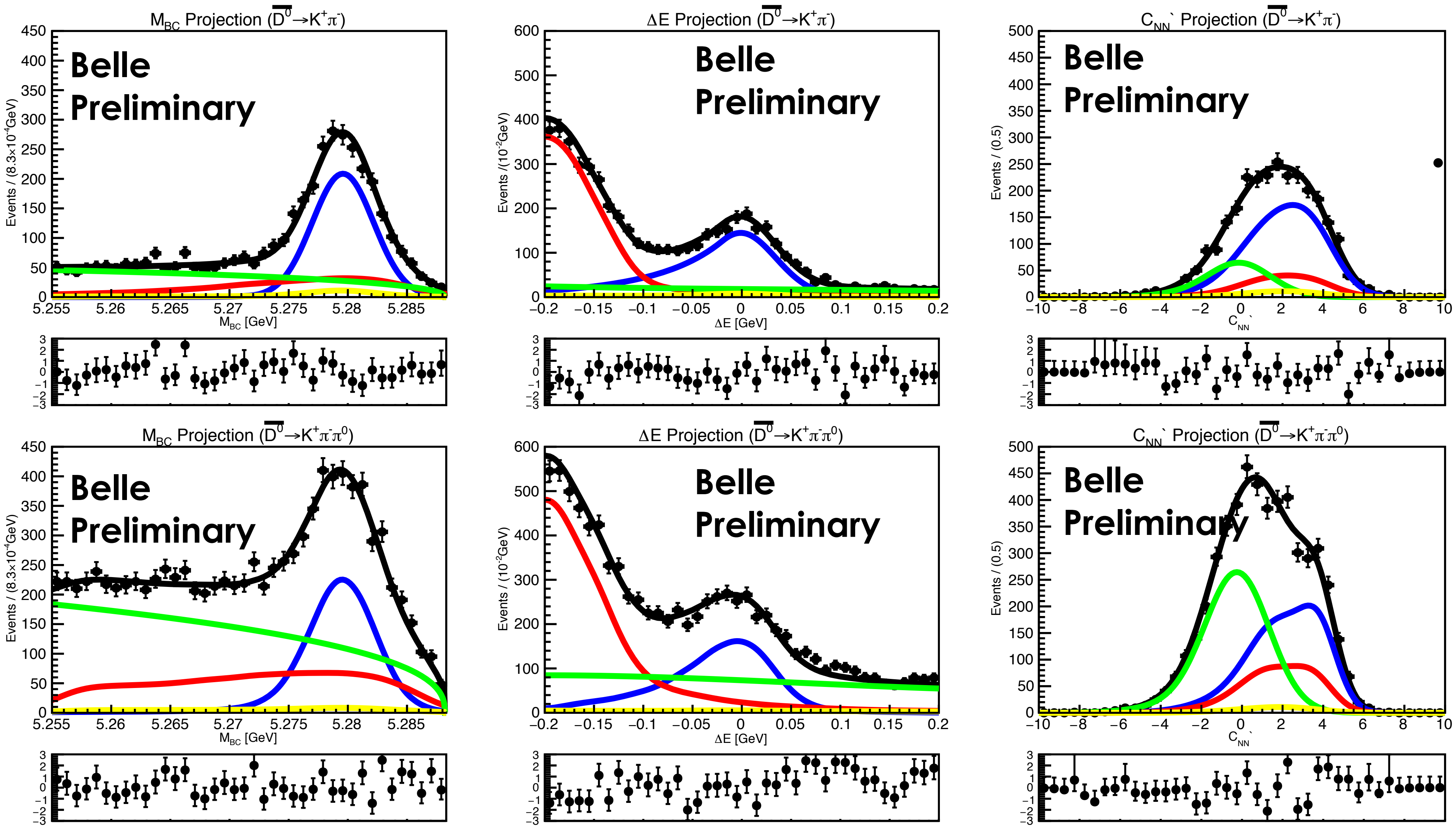
$$Br(B^+ \to \overline{D}^0\pi^+) = (4.53 \pm 0.02 \pm 0.14) \times 10^{-3}$$

$$A_{CP} = (0.19 \pm 0.36 \pm 0.57)\ \%$$

Highest precision measurement for this decay

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

- 3D unbinned ML fit to M_{bc}, ΔE, and C'_{NN}.
- Simultaneous fit to four datasets divided by Kaon charge



all
signal
BB
continuum
Rare B

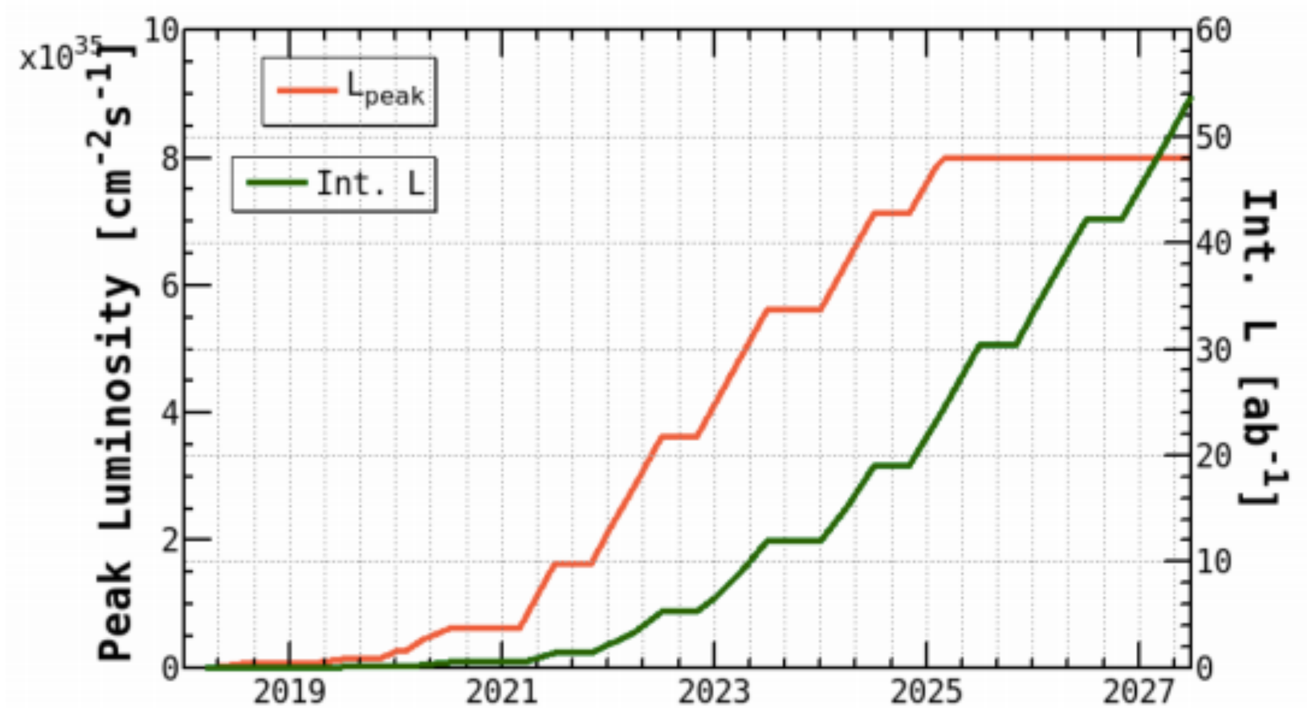
$$Br(B^0 \to \overline{D}^0\pi^0) = (2.68 \pm 0.06 \pm 0.09) \times 10^{-4}$$

$$A_{CP} = (0.10 \pm 2.05 \pm 1.22)\ \%$$

First measurement in this channel

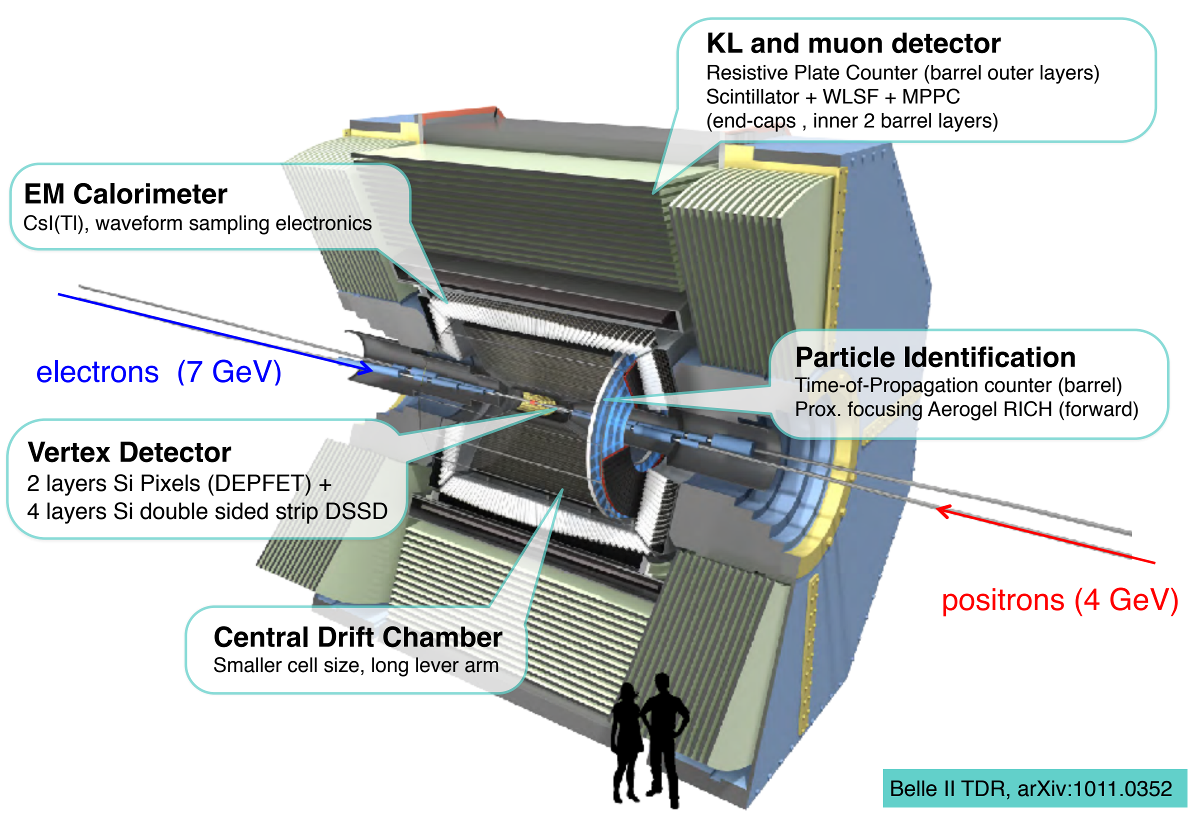
Highest precision measurement for this decay

SuperKEKB and Belle II



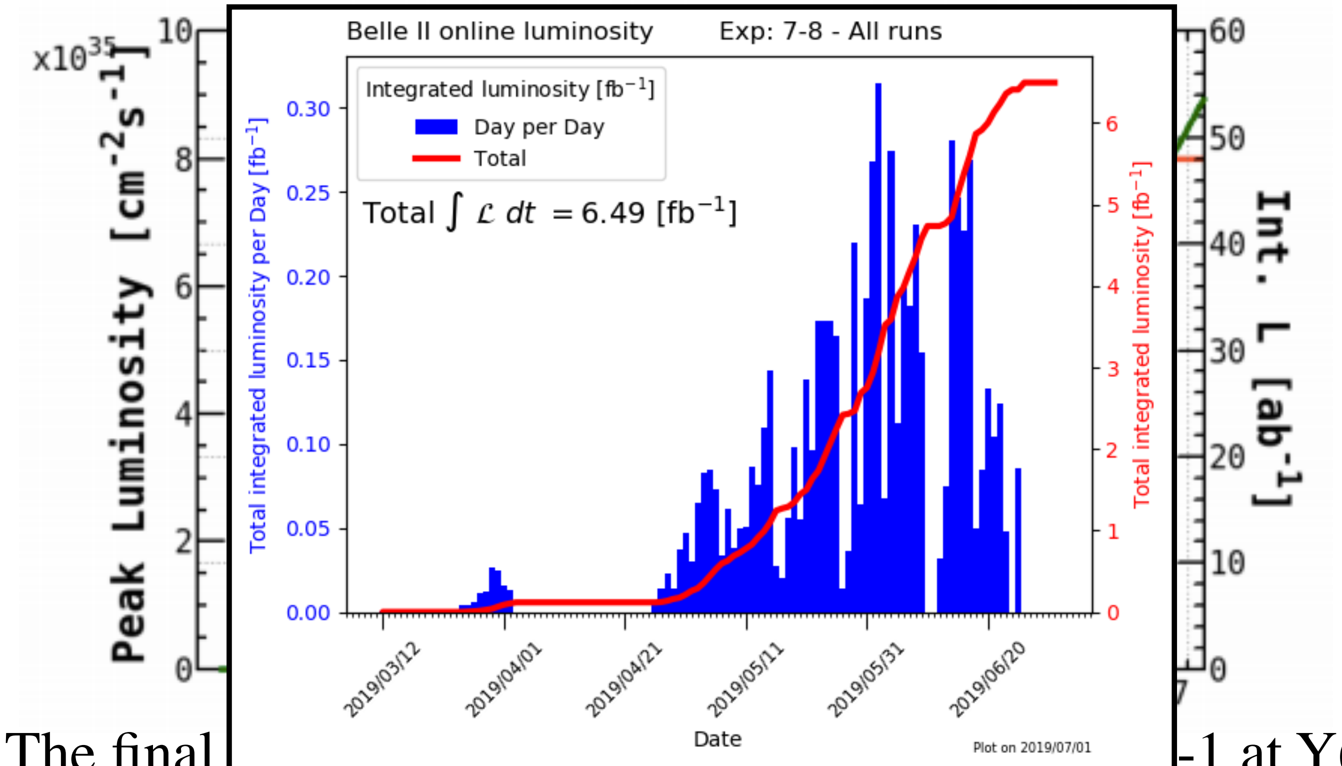
- 40 times larger peak luminosity than at KEKB
- Data taking started.
- Achieved luminosity of 1.2×10^{34} $cm^{-2}s^{-1}$
- Accumulated 6.5 fb^{-1} data by this summer. (results shown today are from a subset of the data)

The final goal is an integrated luminosity of 50 ab-1 at Υ(4S)



- Use frame of the Belle detector and ECL
- **New vertex detector VXD (PXD + SVD)**
- Improved particle identification for K/p/π separation
- Improved CDC tracking - smaller cells and larger coverage
- Improved KLM for μ and K-long detection
- New electronics for ECL

SuperKEKB and Belle II



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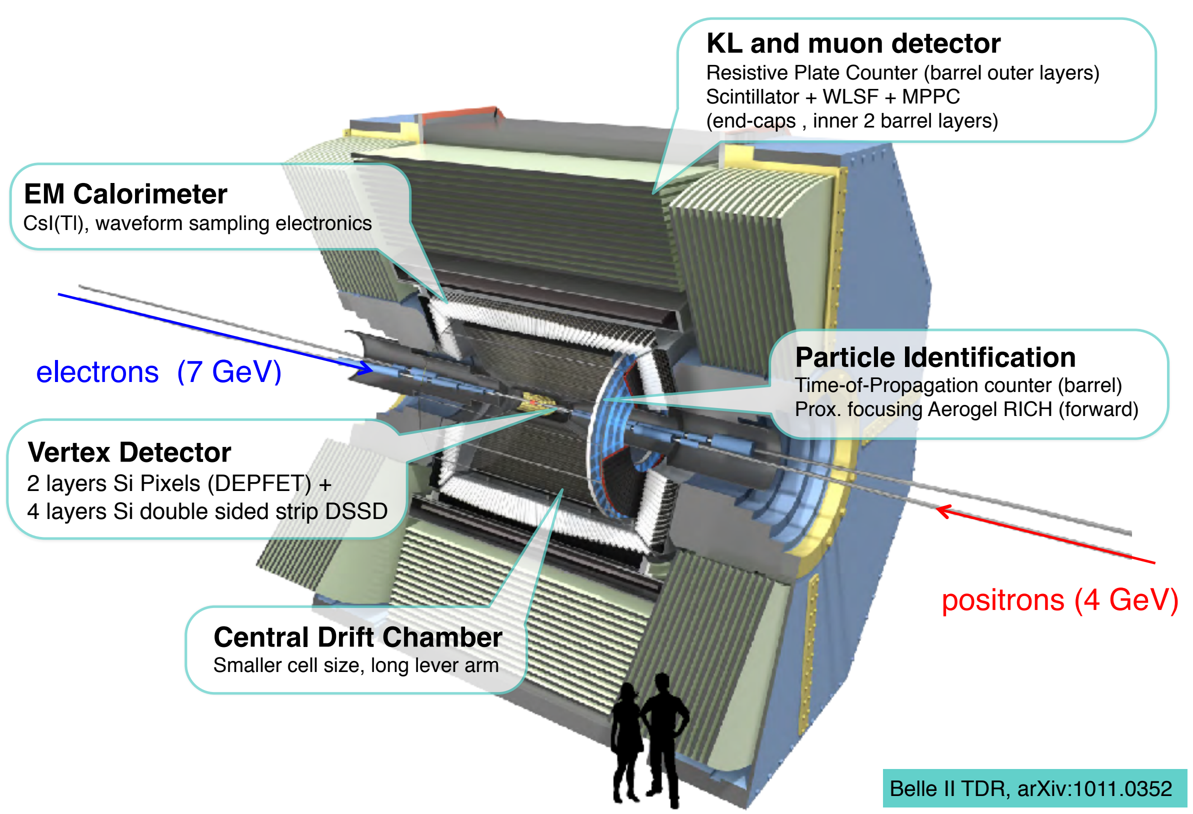
The final [illegible] -1 at Y(4S)



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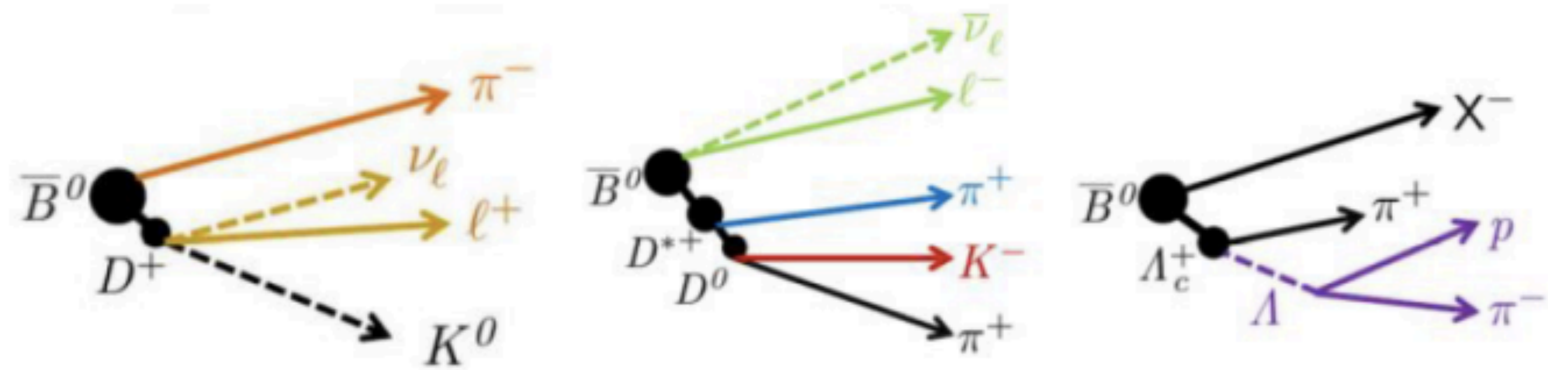
Flavour tagging at Belle II

- Flavour tagging method improved with
  - improved vertex resolution
  - algorithm includes more modes
  - better particle identification reduced wrongly tagged rate
- Effective efficiency of flavour tagging is **37.2%.** (~30% at Belle)
- More precise measurement for time-dep. analyses.



Categories	Targets for $\overline{B}^0$
Electron	e^-
Intermediate Electron	e^+
Muon	μ^-
Intermediate Muon	μ^+
Kinetic Lepton	l^-
Intermediate Kinetic Lepton	l^+
Kaon	K^-
Kaon-Pion	K^-, π^+
Slow Pion	π^+
Maximum P*	l^-, π^-
Fast-Slow-Correlated (FSC)	l^-, π^+
Fast Hadron	π^-, K^-
Lambda	Λ

Underlying decay modes

$\overline{B}^0 \to D^{*+}\ \overline{\nu}_\ell\ \ell^-$
$\quad \hookrightarrow D^0\ \pi^+$
$\quad\quad \hookrightarrow X\ K^-$

$\overline{B}^0 \to D^+\ \pi^-\ (K^-)$
$\quad \hookrightarrow K^0\ \nu_\ell\ \ell^+$

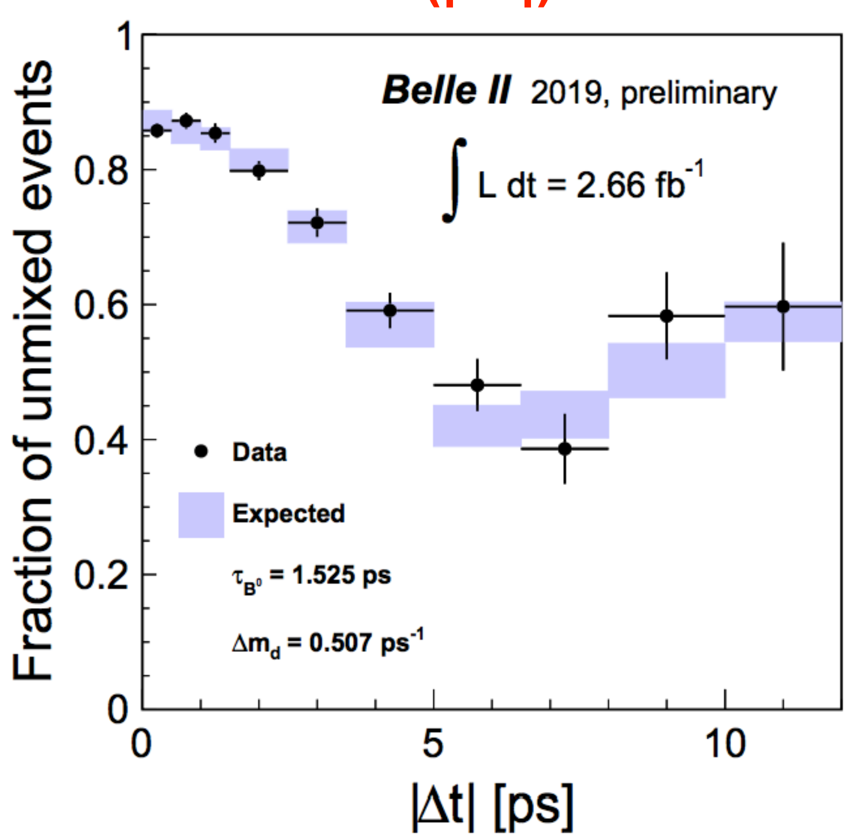
$\overline{B}^0 \to \Lambda_c^+\ \ X^-$
$\quad \hookrightarrow \Lambda\ \ \pi^+$
$\quad\quad \hookrightarrow p\ \pi^-$

B2TiP book [10.1093/ptep/ptz106]

B mixing in Belle II

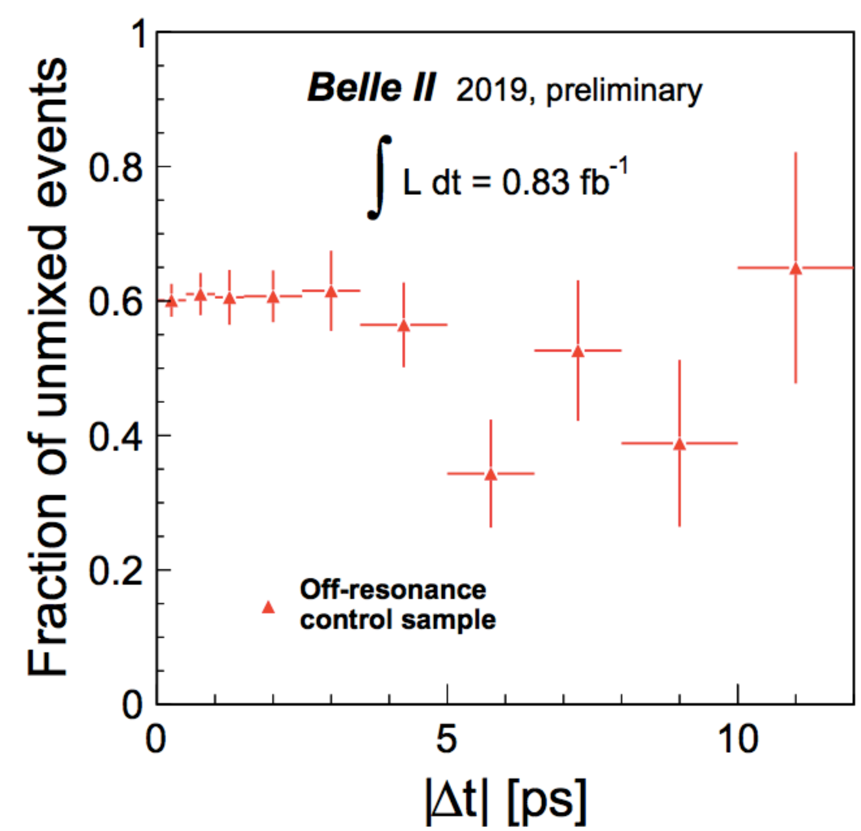
- Mixed-unmixed yield asymmetry as a function of Δt using semileptonic B decays $B^0 \to D^{*+}\ell\nu, \quad \ell = e, \mu$
  - Dilepton tagging, only reconstruct a lepton (l_{tag}) on the tag side.
  - Vertex from l_{tag}
  - Unmixed: opposite sign leptons   Mixed: same-sign leptons
  - Good agreement between data and expectations.
  - Sufficient to observe the pattern of BB oscillations.

A(|Δt|)



Evidence of mixing

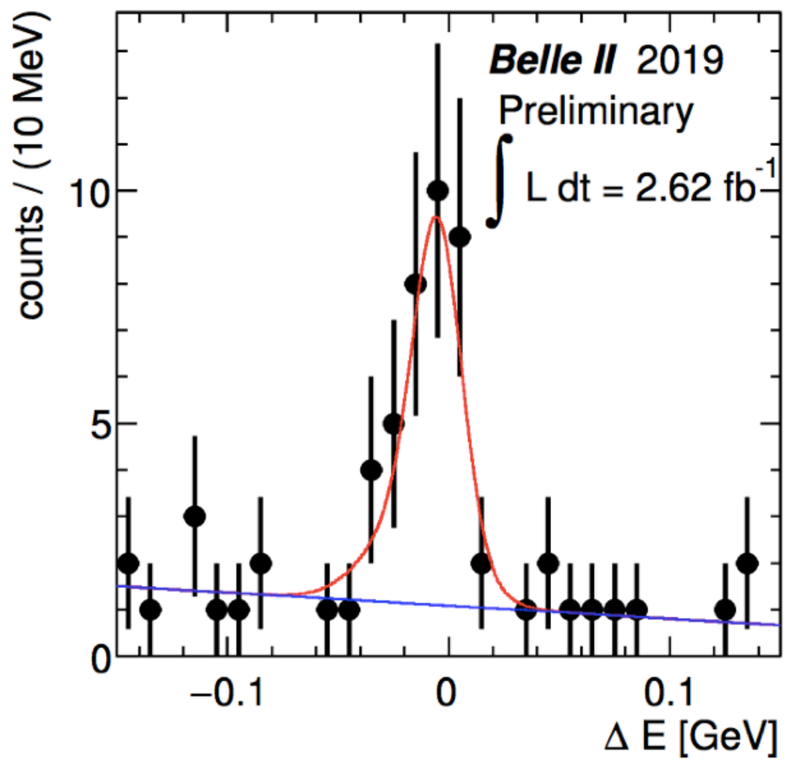
A(|Δt|) - off-res data

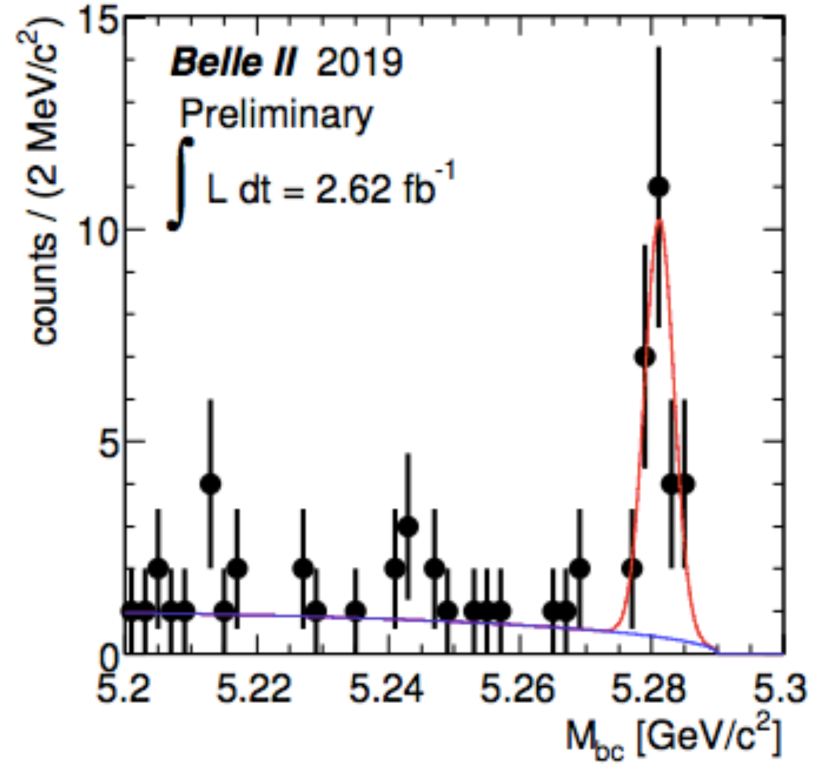


Flat behavior with statistical uncer.

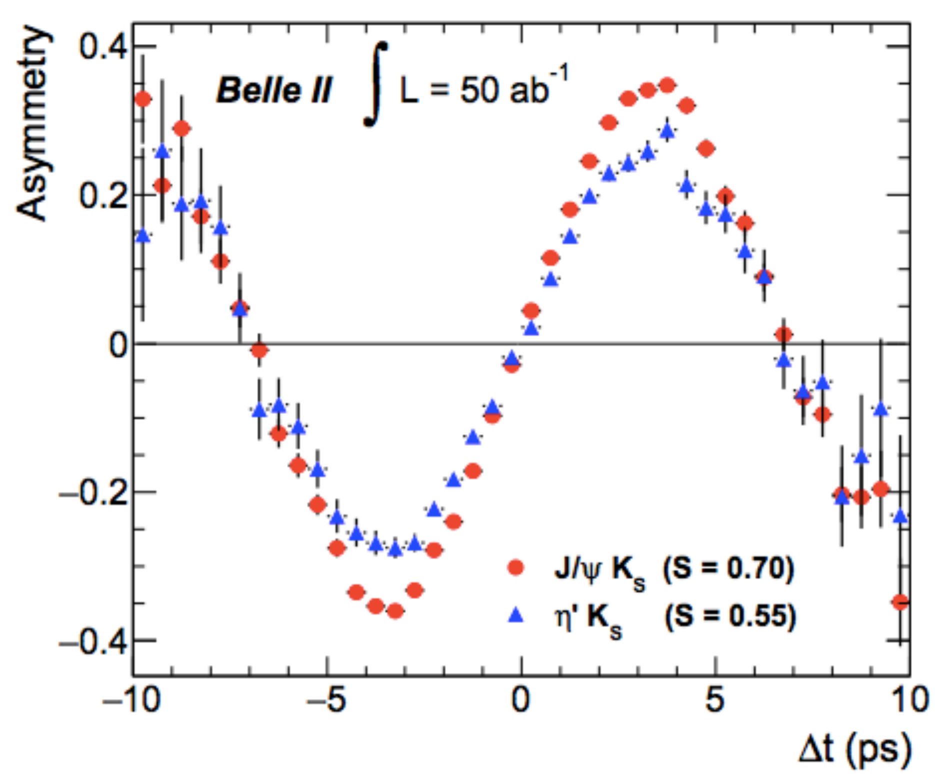
Prospects for ϕ_1

- Golden mode for $\sin(2\phi_1)$ measurement
- Theoretically and exp. precise
- $A = 0$, $S = \sin(2\phi_1)$
- Expected total uncertainty $\delta\phi_1 \lesssim 0.1°$@50ab^{-1}
- Re-discovery of $B^0 \to J/\psi K_S$ N = 26.9 ± 5.2 at Belle II





- Projection of CPV @50ab^{-1}

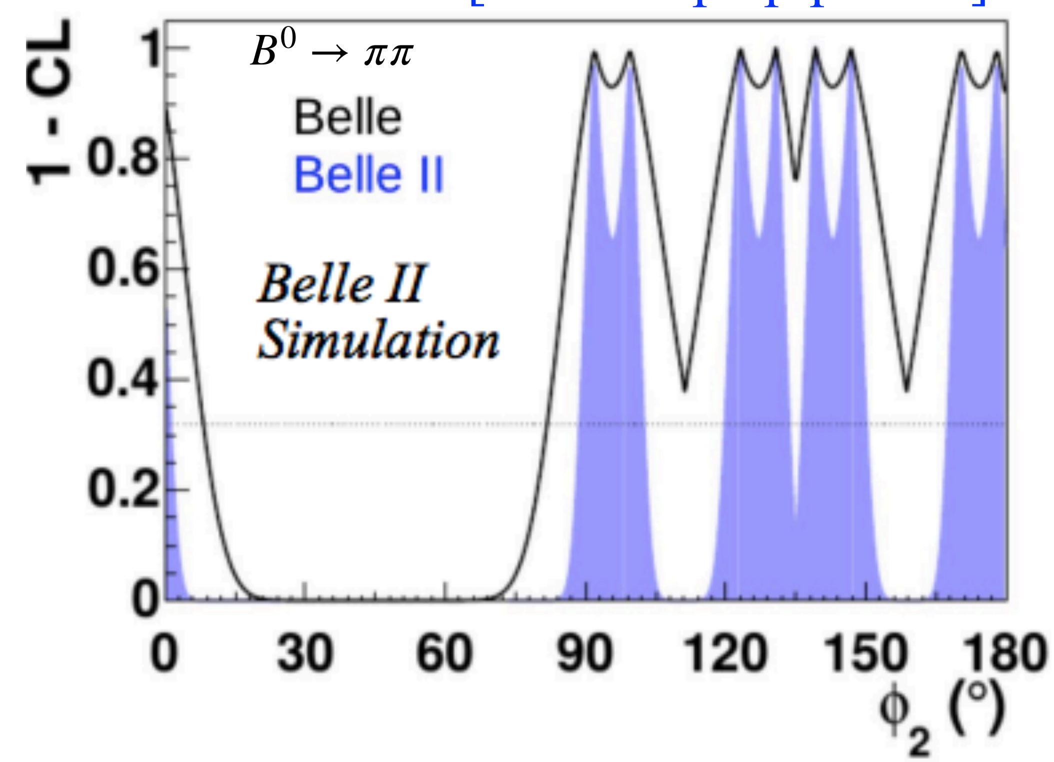


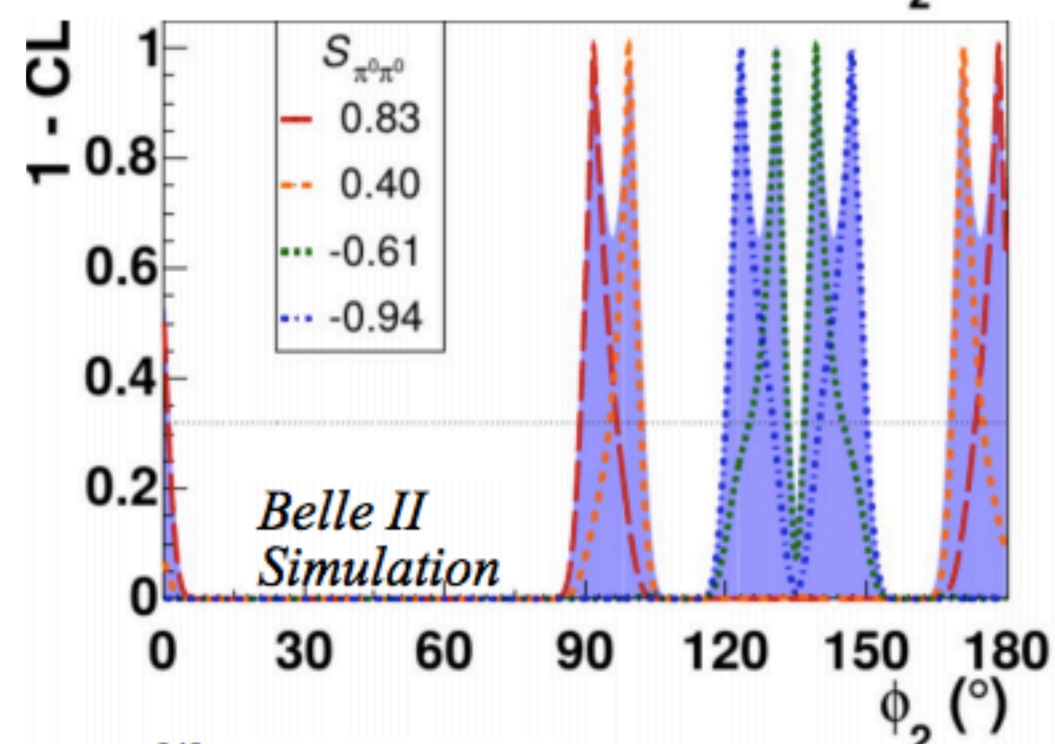
B2TiP book [10.1093/ptep/ptz106]

Prospects for ϕ_2

B2TiP book [10.1093/ptep/ptz106]

- $\sin(2\phi_2)$ can be measured from $B \to \pi\pi/\rho\rho$ decays.
- $S_{\pi^0\pi^0}$ has never been measured
  - Decay vertex only from π^0 Dalitz decay ($\pi^0 \to \gamma ee$) or photon conversion($\pi^0 \to \gamma\gamma(e^+e^-)$).
- $B^0 \to \pi\pi/\rho\rho$ should reach $\sigma(\phi_2) \approx 0.6°$@50 ab^{-1} Reduce ambiguity for ϕ_2, breaking the degeneracy with $B^0 \to \pi\pi$.





	Value	Belle @ 0.8 ab^{-1}	Belle2 @ 50 ab^{-1}
$\mathcal{B}_{\pi^+\pi^-}$ [10^{-6}]	5.04	$\pm 0.21 \pm 0.18$ [2]	$\pm 0.03 \pm 0.08$
$\mathcal{B}_{\pi^0\pi^0}$ [10^{-6}]	1.31	$\pm 0.19 \pm 0.18$ [1]	$\pm 0.04 \pm 0.04$
$\mathcal{B}_{\pi^+\pi^0}$ [10^{-6}]	5.86	$\pm 0.26 \pm 0.38$ [2]	$\pm 0.03 \pm 0.09$
$C_{\pi^+\pi^-}$	-0.33	$\pm 0.06 \pm 0.03$ [3]	$\pm 0.01 \pm 0.03$
$S_{\pi^+\pi^-}$	-0.64	$\pm 0.08 \pm 0.03$ [3]	$\pm 0.01 \pm 0.01$
$C_{\pi^0\pi^0}$	-0.14	$\pm 0.36 \pm 0.12$ [1]	$\pm 0.03 \pm 0.01$
$S_{\pi^0\pi^0}$	—	—	$\pm 0.29 \pm 0.03$

[1]: PRD 96(3) 032007
[2]: PRD 87(3) 031103
[3]: PRD 88(9) 092003

Summary

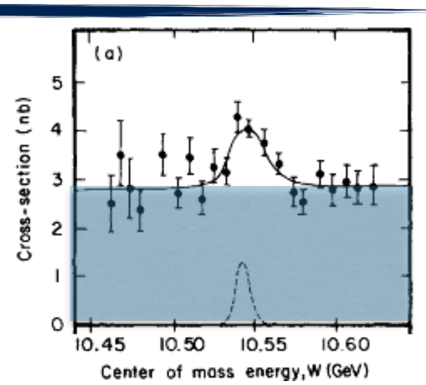
- Flavour physics at high luminosity B-factory offers good probe for testing SM and looking for NP
- Branching fractions and A_{CP} of $B \rightarrow D^0 \pi$ is measured.
  A_{CP} is consistent with the SM prediction.

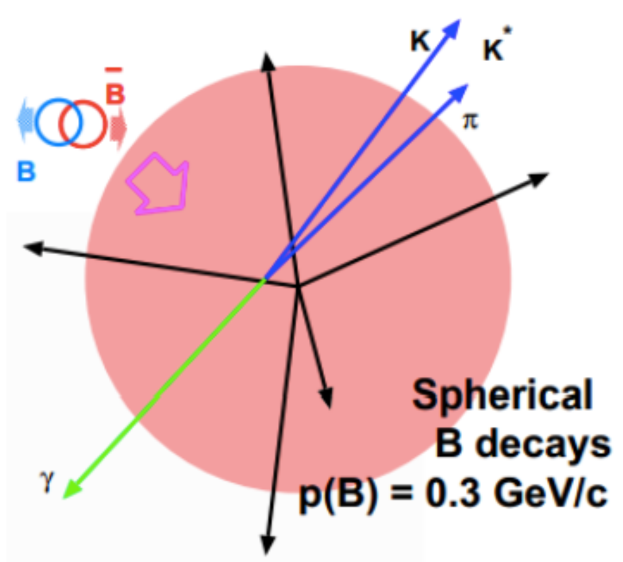
- Belle II physics run started
- More precise measurements will be provided by Belle II in the coming years!

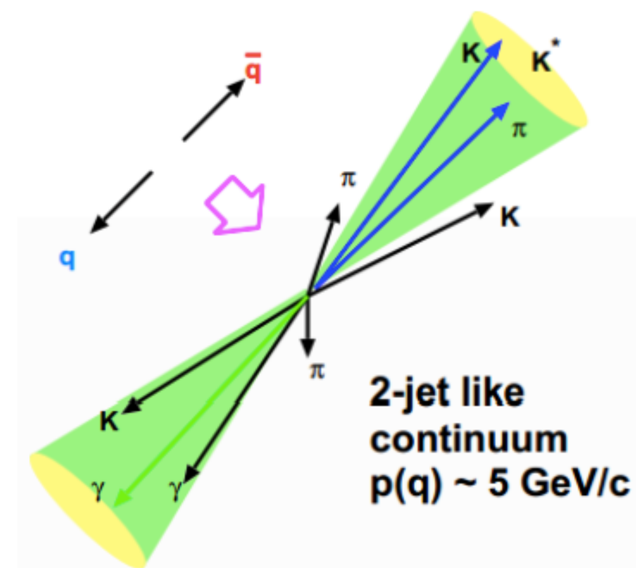
Backup

Continuum Suppression

- Continuum background $e^+e^- \to q\bar{q}(u,d,s,c)$
  - Dominant background
  - Different event topology from signal







- Using modified Fox-Wolfram moments expand events in terms of Legendre polynomials

$$H_l = \sum_{i,j=1}^{N} \frac{|\vec{p_i}|\,|\vec{p_j}|}{s} P_l\left(\cos\Omega_{ij}\right)$$

$$i, j = \text{particles}$$

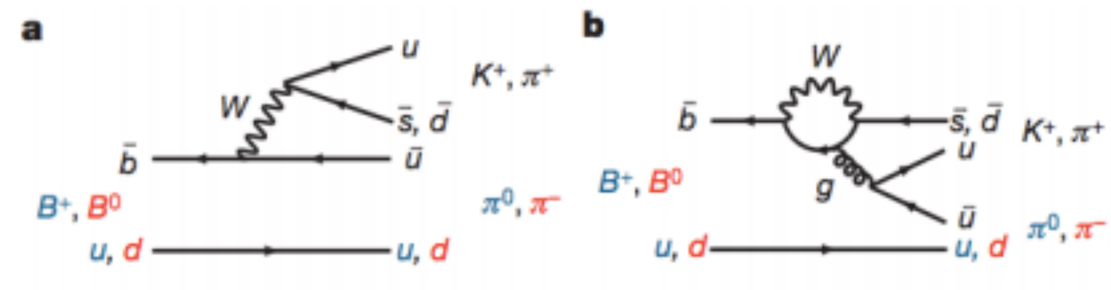
- Information combining with other shape variables are used to suppress the continuum background.

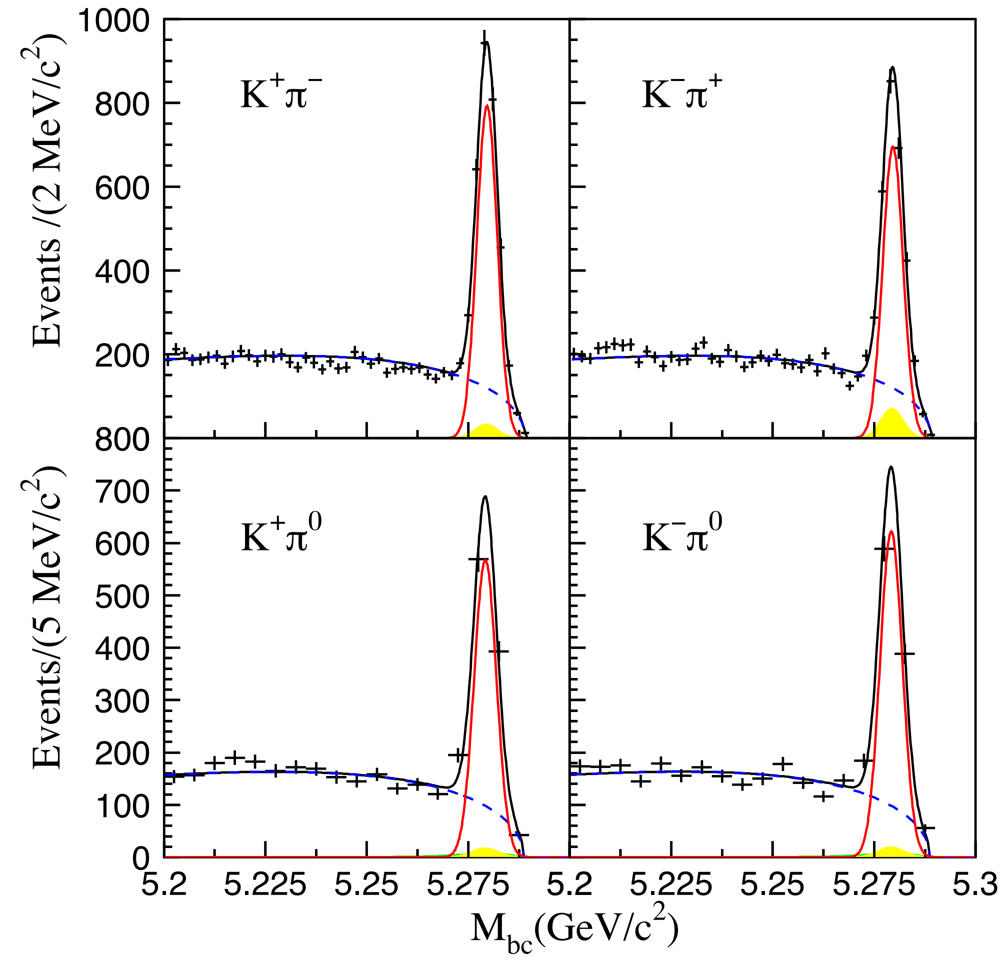
$B \to K\pi$ at Belle II

- Measurements of DCPV in $B^+ \to K^+\pi^0$ found to be different than the same quantity in $B^0 \to K^+\pi^-$

$$\mathcal{A}_{K^+\pi^0} - \mathcal{A}_{K^+\pi^-} = 0.112 \pm 0.027 \pm 0.007 \ (4\sigma)$$

- Combine with other measurements and with the larger Belle II dataset, strong interaction effects can be controlled and the validity of the SM can be tested in a model-independent way.
- Isospin sum rule can be presented as a band in the $\mathcal{A}_{K^0\pi^0}$ vs. $\mathcal{A}_{K^+\pi^0}$ plane.





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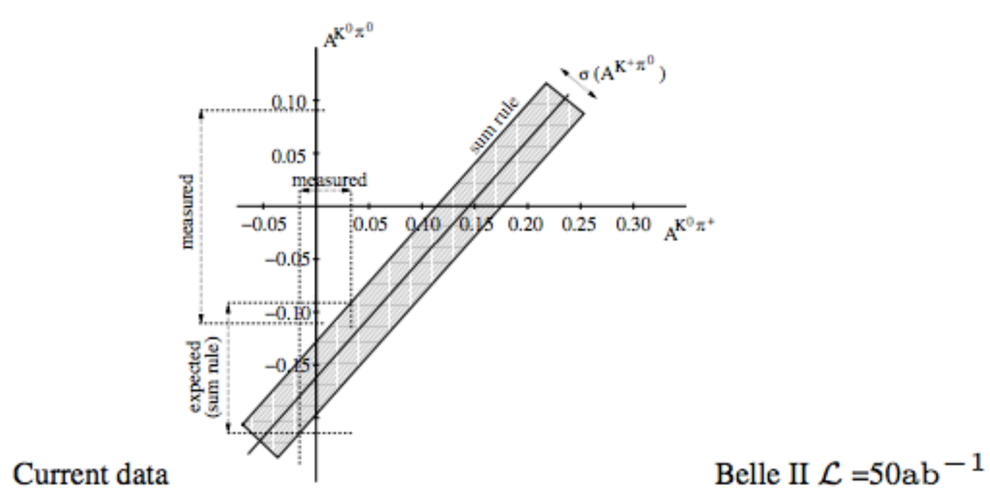
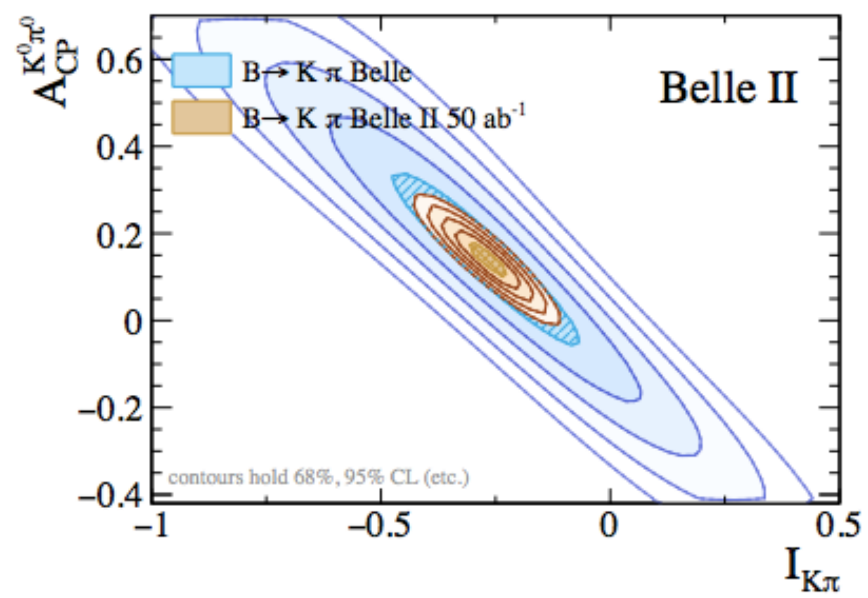


Most demanding measurement is $K^0\pi^0$ final state. With Belle II, the uncertainty on A_{CP} from time-dep. analyses is expected to reach ~**4%** ⇒ **sufficient for NP studies**

$B \to K\pi$ at Belle II

- A 2D[$A_{K\pi}$, $I_{K\pi}$] scan for different Belle II scenarios.
  - Asymmetry of K^0/ $\bar{K}^0$ interactions in material ($\sigma_{ired} \approx 0.2\%$)
    Phys. Rev. D 84, 111501 (2011)
    - Assume that the errors are not correlated.
  - Additionally the systematic uncertainties are conservatively provided and they are still smaller than the statistical errors.



Projections for the $B \to K\pi$ isospin sum rule parameter, $I_{K\pi}$, at the Belle measured central value.

Scenario	$\mathcal{A}_{K^0\pi^0}$ Value	Stat.	(Red., Irred.)	$I_{K\pi}$
Belle	0.14	0.13	(0.06, 0.02)	-0.27 ± 0.14
Belle + $B \to K^0\pi^0$ at Belle II 5 ab^{-1}		0.05	(0.02, 0.02)	-0.27 ± 0.07
Belle II 50 ab^{-1}		0.01	(0.01, 0.02)	-0.27 ± 0.03