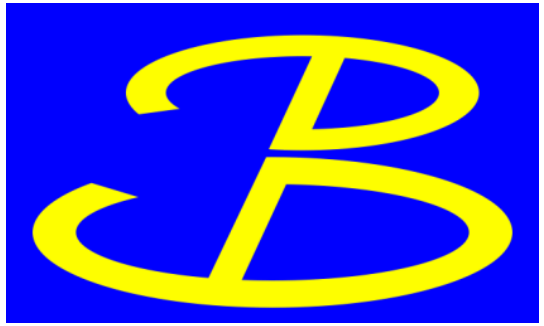
CP violation with heavy quarks at Belle and Belle II

Jim Libby (IIT Madras) on behalf of Belle (II) Collaborations

14th September 2021

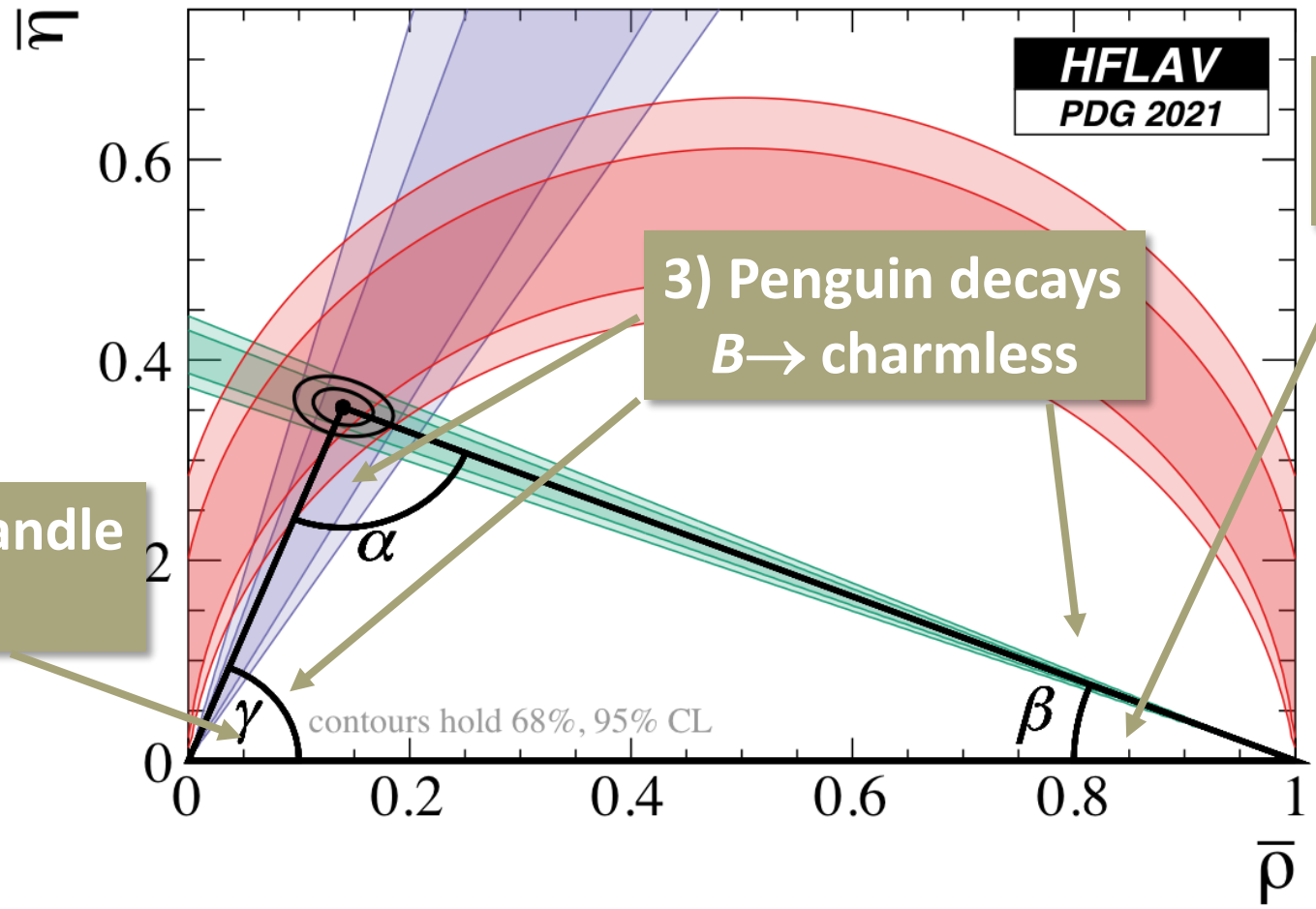
Heavy Quark Leptons 2021

University of Warwick and online



Introduction and outline

Standard model *CP* violation (CPV) well tested: Belle, BaBar and LHCb



1) Golden modes and time-dependent CPV

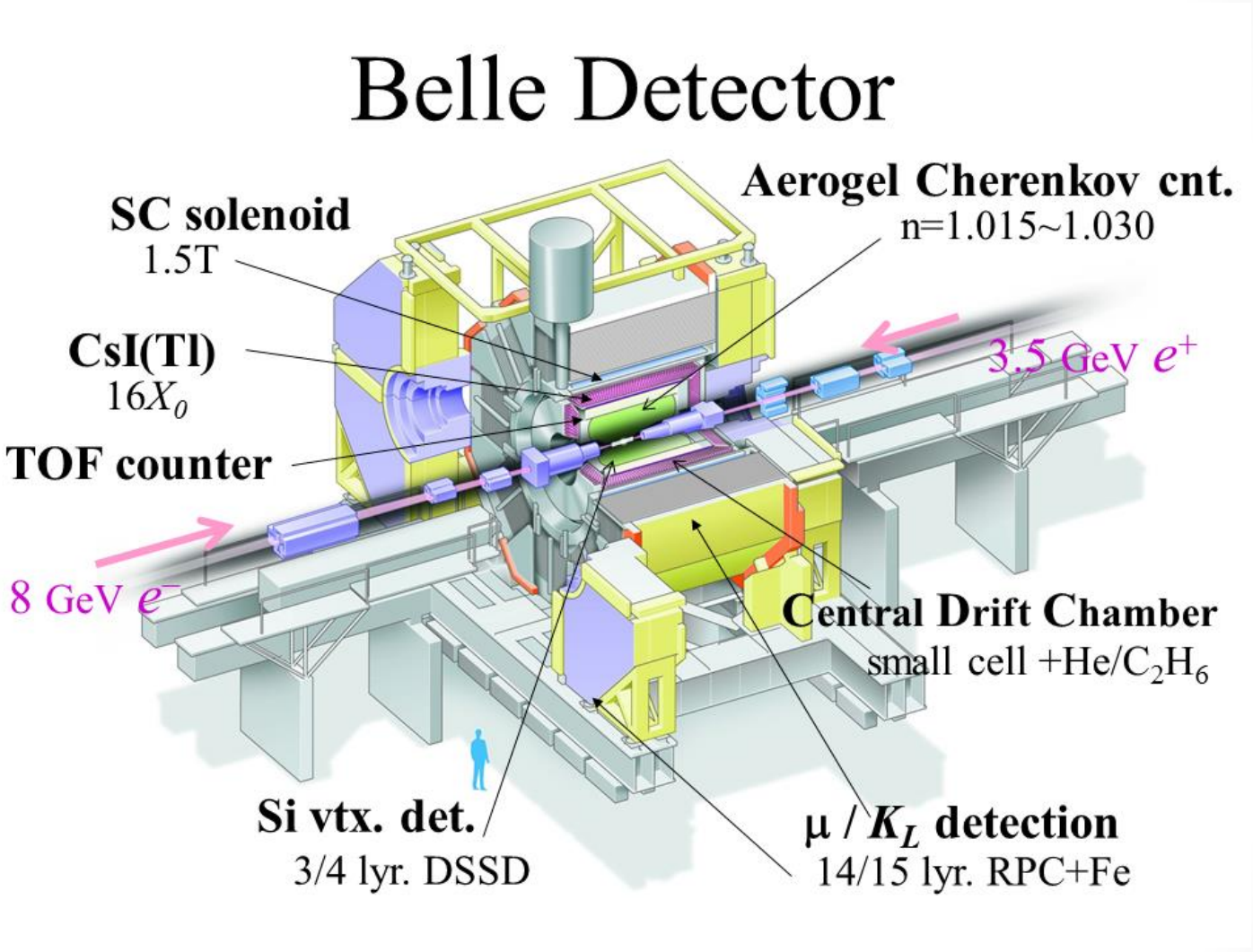
3) Penguin decays $B \to$ charmless

2) Standard candle $B \to Dh$

But of course there is room for further improvement and overconstraint

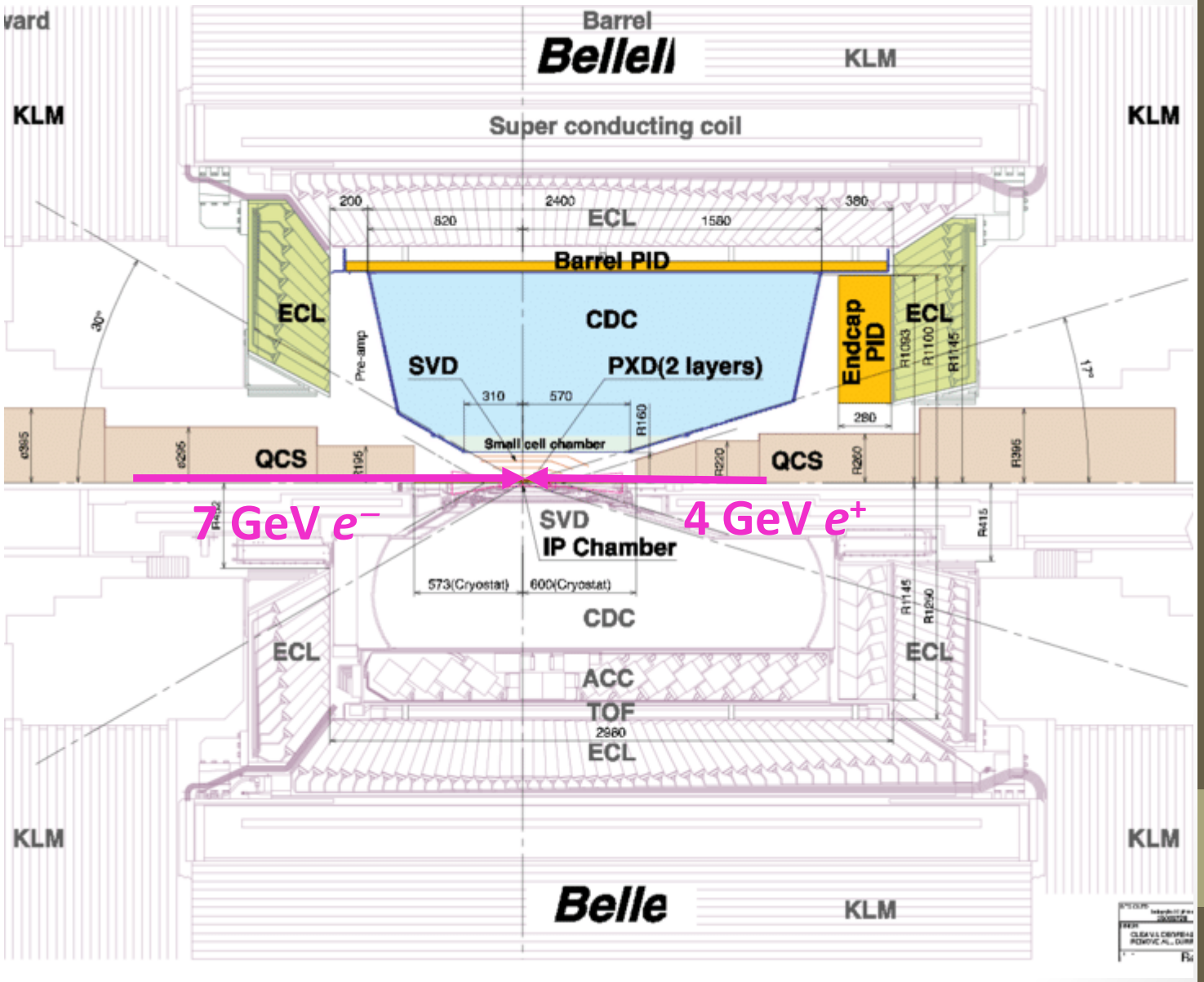
Belle

- $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$
- Asymmetric energy to allow time-dependent measurements
- Coherent production
- Low multiplicity
- Kinematic constraints from the initial state
- KEKB/Belle (1999-2010)
  - ~1 ab^{-1} with ~70% at $\Upsilon(4S)$



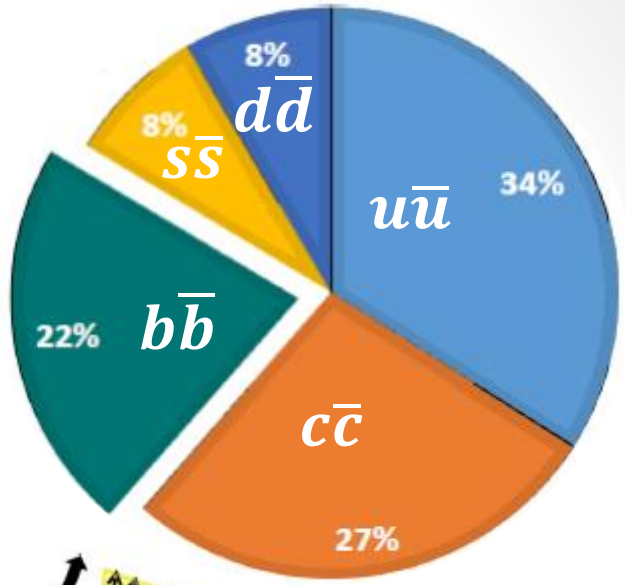
Belle and Belle II

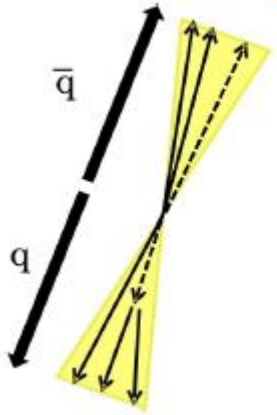
- $e^+e^- \to \Upsilon(4S) \to B\bar{B}$
- Asymmetric energy to allow time-dependent measurements
- Coherent production
- Low multiplicity
- Kinematic constraints from the initial state
- KEKB/Belle (1999-2010)
  - ~1 ab^{-1} with ~70% at $\Upsilon(4S)$
- SuperKEKB/Belle II (2018+)
  - Target 30 × (50 ×) instantaneous (integrated) luminosity
  - Upgraded detector
  - 213 fb^{-1} recorded up to July 2021 but results presented for a subset

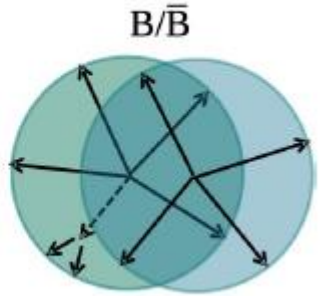


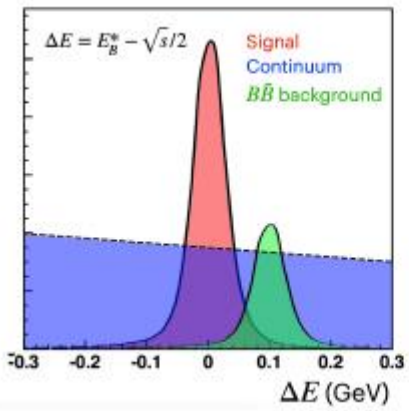
General e^+e^- considerations

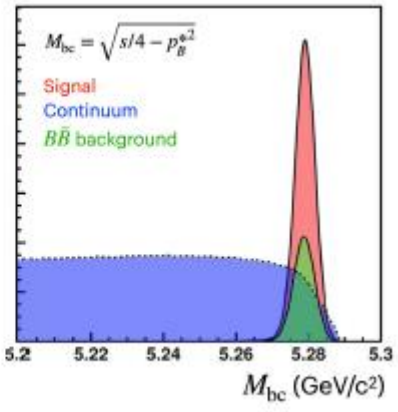
- Not just *B* mesons
  - $e^+e^- \to q\bar{q}$ continuum
    - charm physics (see backup)
    - significant background for *B* decays with small BF or high multiplicity final state
- Continuum suppression in many analyses
  - event shape
  - vertexing and
  - flavour tag
- Constrained kinematics
  - Exploit the known $\sqrt{s}$: ΔE and M_{bc}





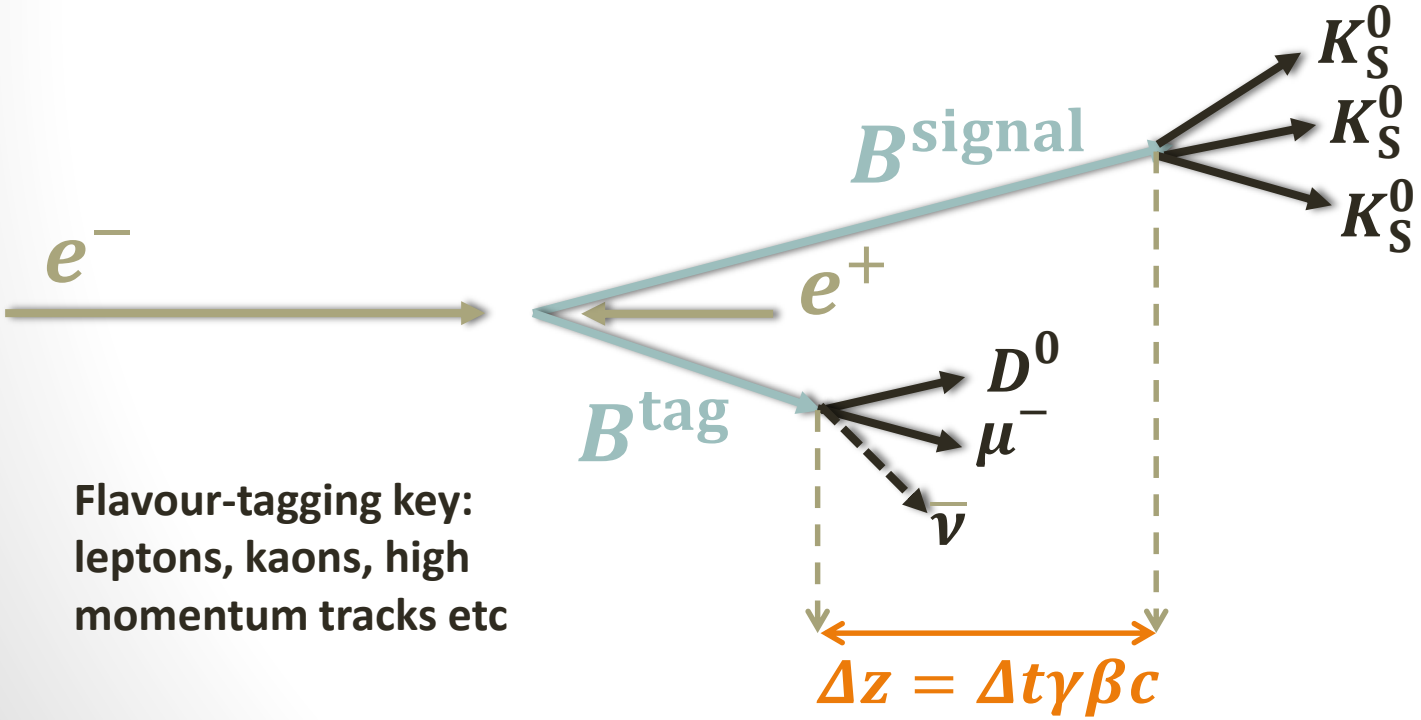






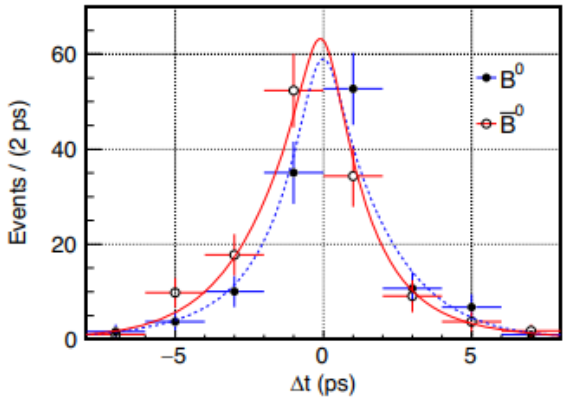
1) Time-dependent CPV

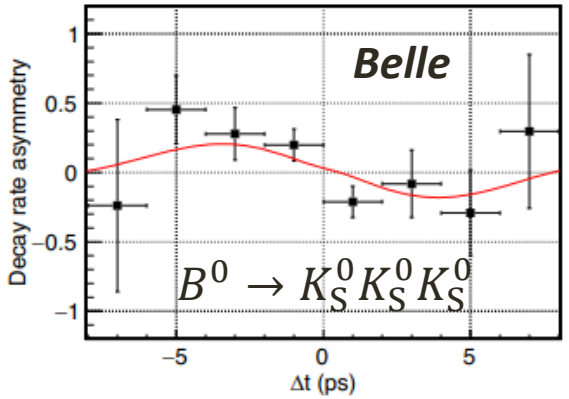
- *Raison d'etre* for BaBar and Belle:
  - CPV due to interference between mixing and decay in $B^0 \to J/\psi K_S^0$
  - Precision measurement of sin 2β (or sin $2\phi_1$)
  - Nobel Prize 2008 for Kobayashi and Maskawa



Flavour-tagging key: leptons, kaons, high momentum tracks etc

PRD **103**, 032003 (2021)





1) $B^0 \to K^0_S K^0_S K^0_S$

- Pure penguin
  - seek new weak phases in the loop
- Signal extraction from 711 fb^{-1} of Belle data
  - ΔE, $M_{\rm bc}$ and continuum suppression variable
- Vertex using $K^0_S \to \pi^+\pi^-$ where pions have hits in the SVD and IP constraints
- Fit to asymmetry as a function of Δt

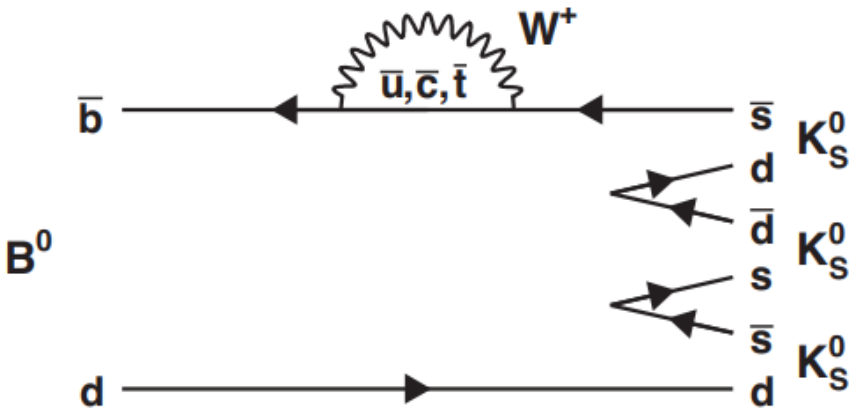
$$A_{CP} = S\sin\left(\Delta m_d \Delta t\right) + A\cos\left(\Delta m_d \Delta t\right)$$

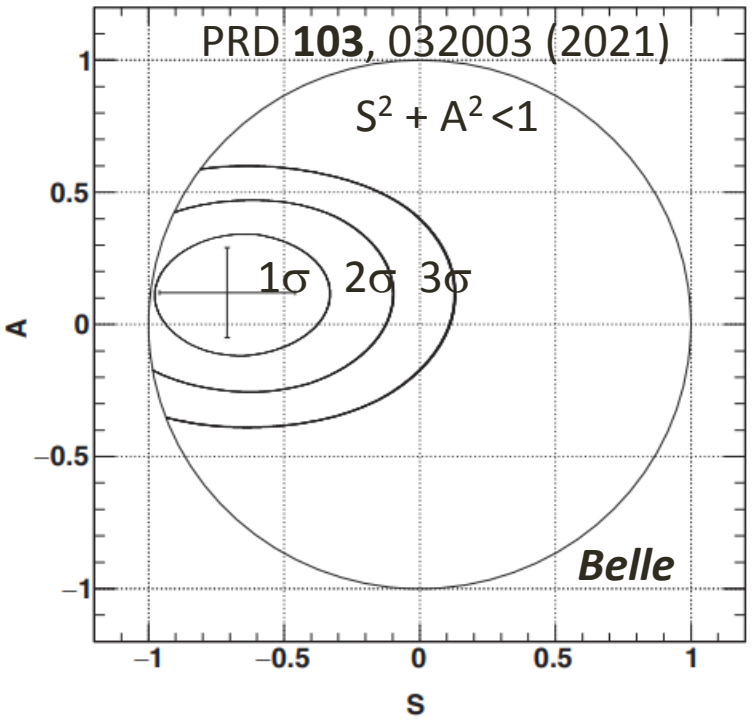
$$S_{SM} = -\sin 2\phi_1 \approx -0.7$$

$$A_{SM} = 0$$

$$S = -0.71 \pm 0.23\,(\text{stat}) \pm 0.05\,(\text{syst})$$

$$A = 0.12 \pm 0.16\,(\text{stat}) \pm 0.05\,(\text{syst})$$



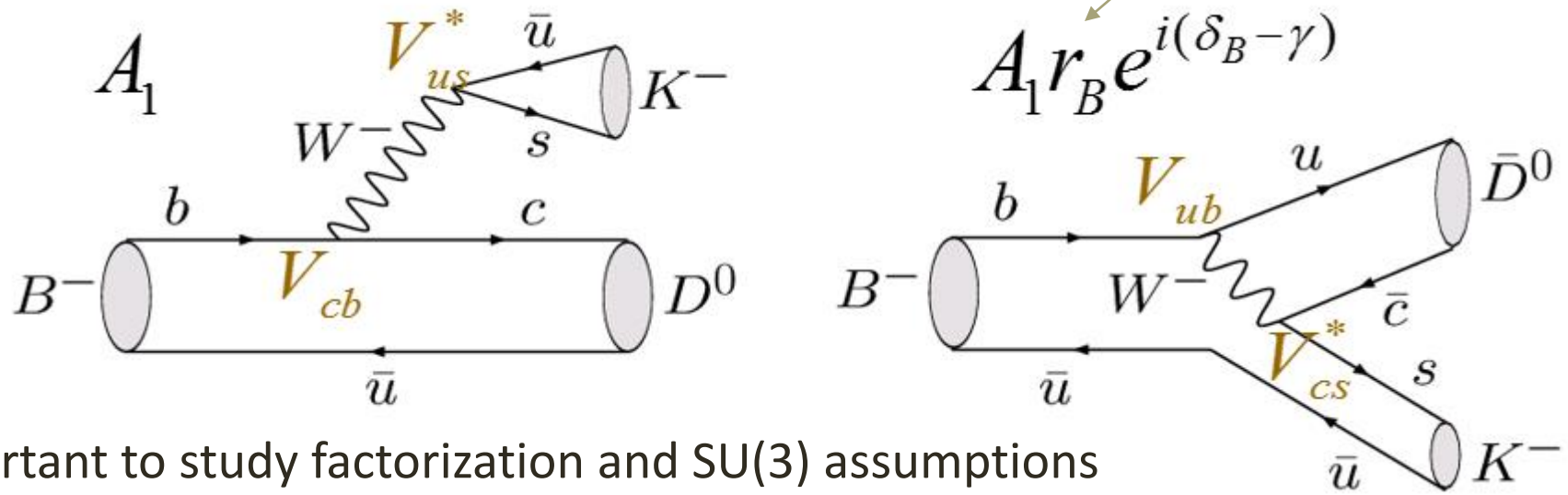


First steps with Belle II: flavour tagger and golden mode (see backup)

2) Tree decay: $B \to Dh$ ($h = \pi/K$)

- Related to determination of γ (see A. Gilman's talk)

colour and CKM suppression



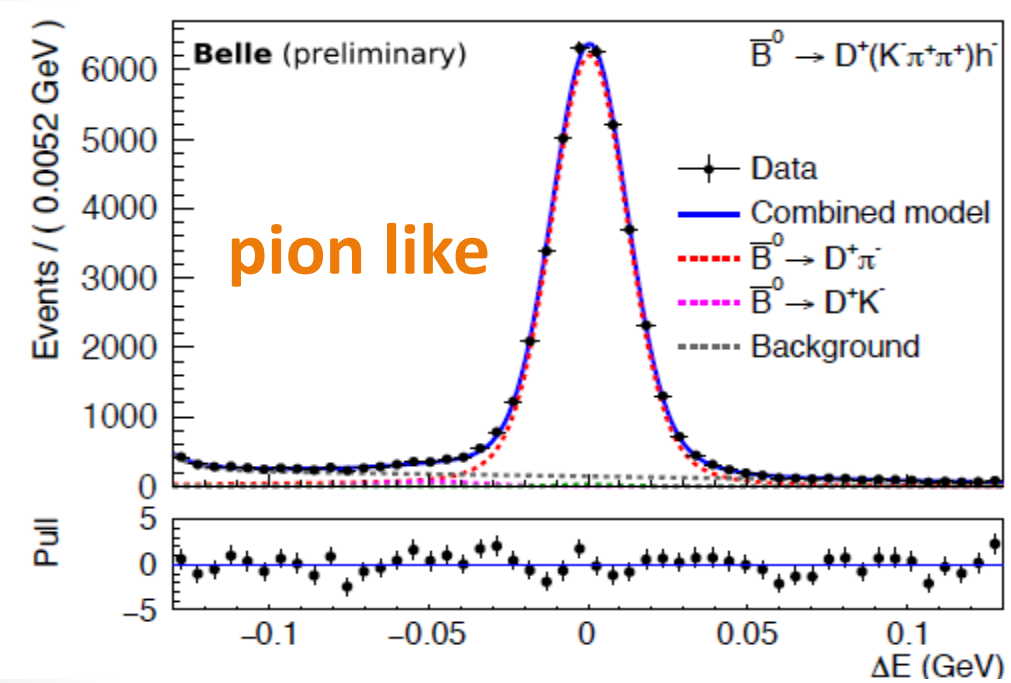
- Important to study factorization and SU(3) assumptions
- New Belle result on

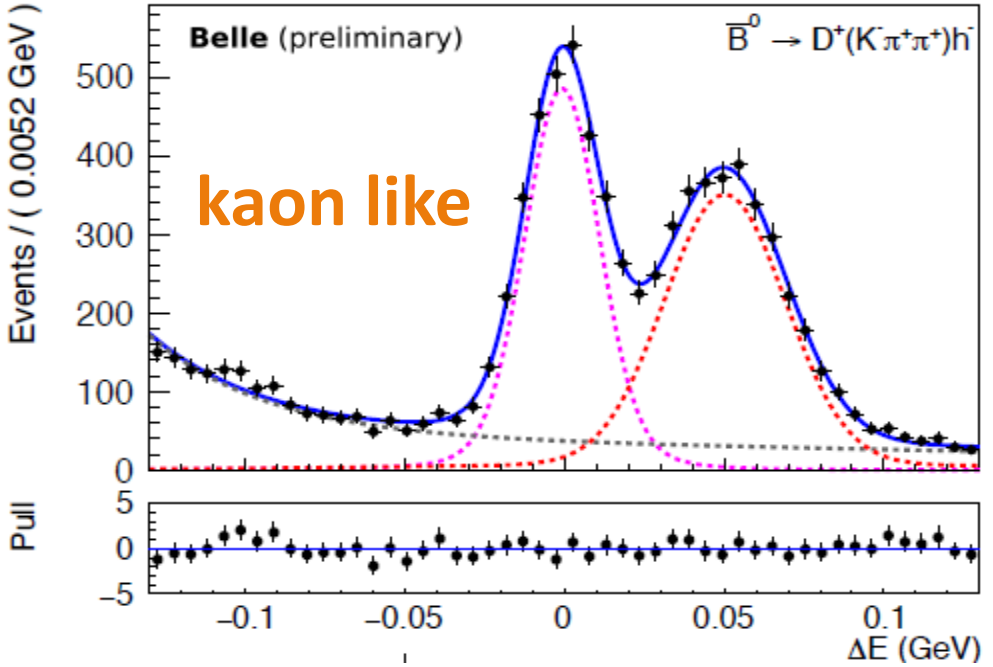
$$R^D \equiv \frac{\mathcal{B}(\bar{B}^0 \to D^+ K^-)}{\mathcal{B}(\bar{B}^0 \to D^+ \pi^-)} \simeq \tan^2\theta_C \left(\frac{f_K}{f_\pi}\right)^2 = 0.077 \pm 0.002$$

NNLO prediction
JHEP **2016**, 112 (2016)

2) Preliminary $B^0 \to D^-(K^+\pi^-\pi^-)h^+$

- Simultaneous fit to sample separated by particle ID of the h
- R^D, total $B \to D\pi$ yield (for BF($B \to D\pi$)) and mis-ID rate all from data





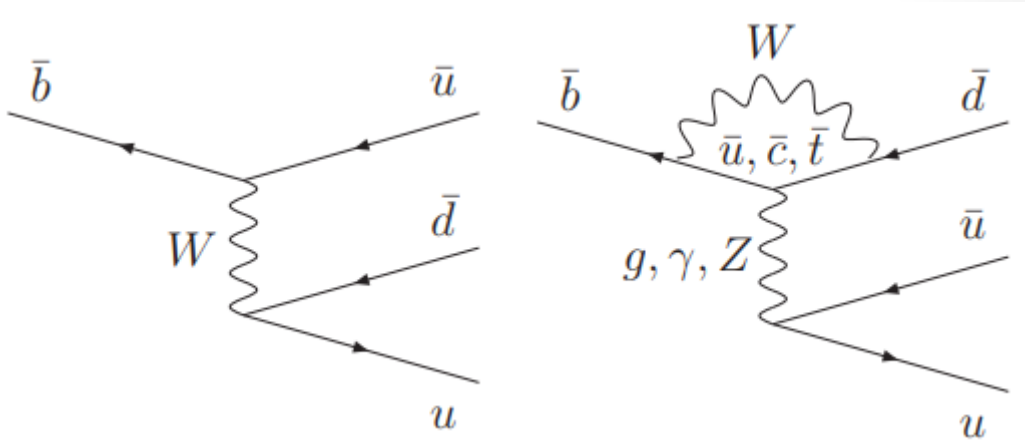
$$R^D \equiv \frac{\mathcal{B}(\bar{B}^0 \to D^+K^-)}{\mathcal{B}(\bar{B}^0 \to D^+\pi^-)} = (8.20 \pm 0.20(\text{stat}) \pm 0.20(\text{syst})) \times 10^{-2}$$

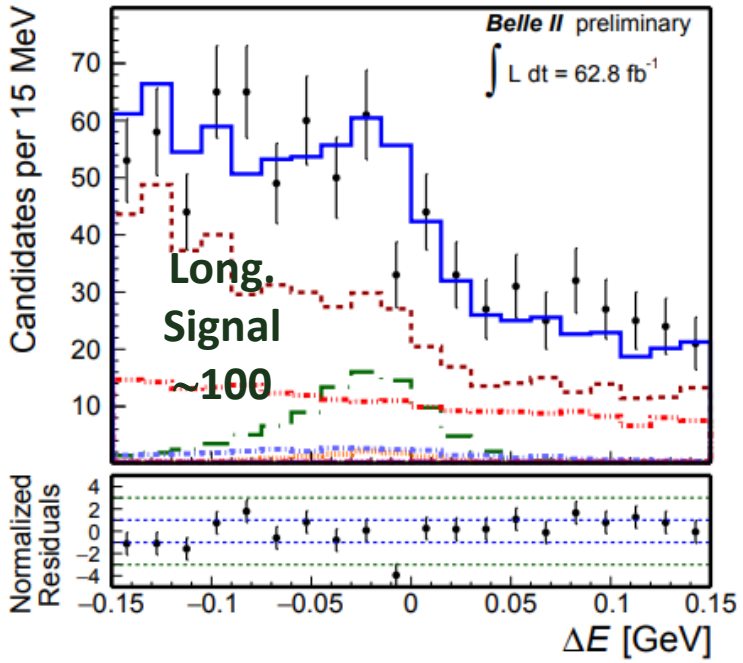
Agrees with NNLO and LHCb [JHEP 2013, 1 (2013)]
Similar precision to LHCb

Similar studies at Belle II (arxiv:2104.03628)
with a 63 fb^{-1} sample
More modes including $B^+ \to D(K_S\pi^-\pi^-)h^+$
- **the first step toward a γ**

3) Charmless *B* decay

- Mediated through suppressed $b \to u$ transition and/or FCNC loop $b \to d$ and $b \to s$
  - access to all angles of the unitarity triangle
  - loop sensitivity to new physics
- QCD influence on the relative size and strong phases of amplitudes makes theoretical relation to weak phases difficult
  - SU(3) and isospin relations can help
- **Example:** Isospin combination of $B \to \rho\rho$ measurements allows determination of α
  - PRL **65**, 3381 (1990)
- 63 fb^{-1} of Belle II data with 6D fit signal extraction
  - FBDT continuum suppression, ΔE, $2 \times m_{\pi\pi}$ and $2 \times$ helicity angle





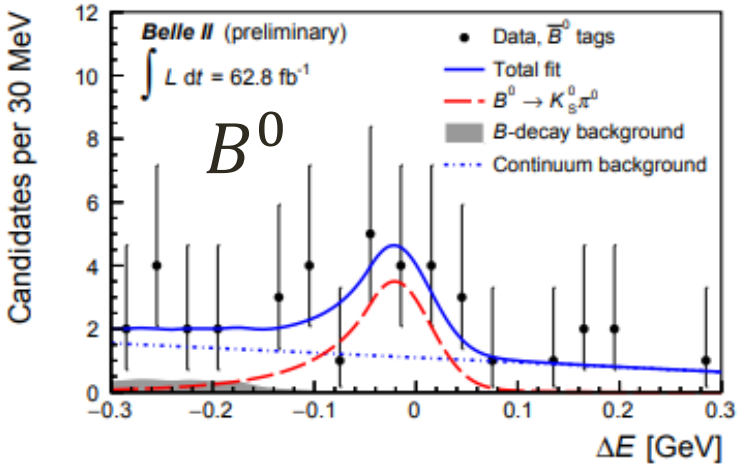
BF = $(20.6 \pm 3.2 \pm 4.0) \times 10^{-6}$
(data driven π^0 systematic dominates)
$f_L = 0.936 \pm 0.045 \pm 0.021$

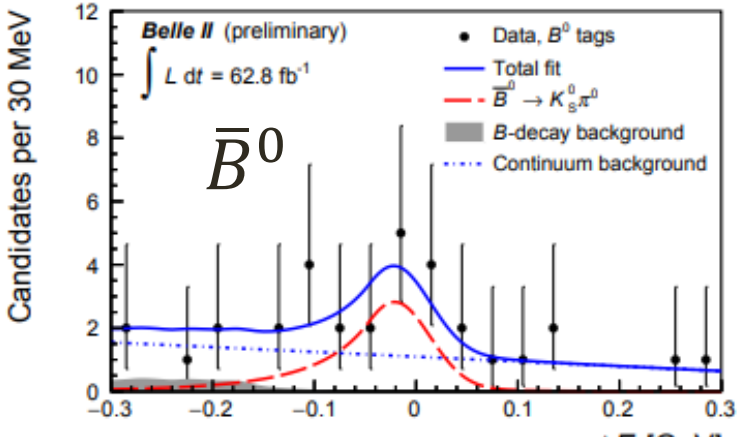
3) A_{CP} in $B^0 \to K_S \pi^0$

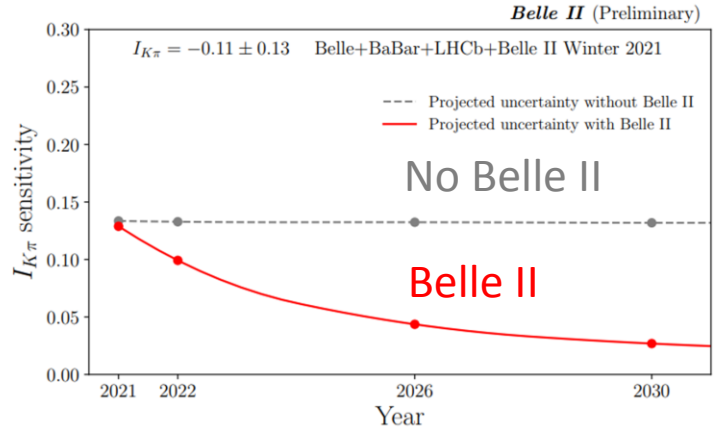
- $K\pi$ puzzle: differences in A_{CP} between isospin related $B \to K\pi$ decays
- Isospin sum-rule null test [PLB 627, 82 (2005)]

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

- 63 fb^{-1} of Belle II data – time-integrated measurement with 2D fit to ΔE and M_{bc}
  - BF = $(8.5 \pm 1.7 \pm 1.2) \times 10^{-6}$
  - A_{CP}= $0.40 \pm 0.45 \pm 0.04$
  - arXiv:2104.14871
- **Key to future improvements in $I_{K\pi}$**

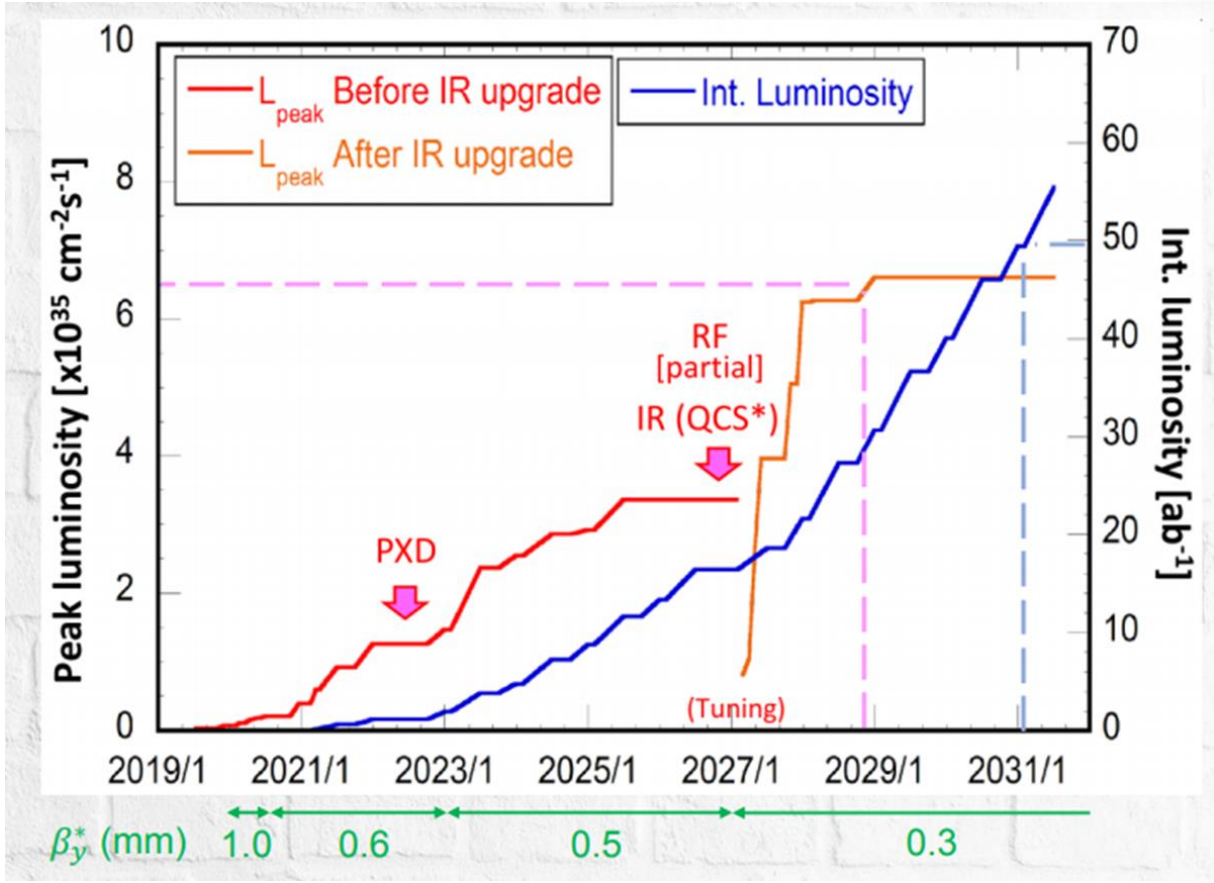






Belle (II) outlook

- Belle will continue to exploit its unique data set for further measurements related to CPV
- Belle II is beginning its journey to supersede it
  - $3.1 \times 10^{34}\,\mathrm{cm^{-2}s^{-1}}$ world record (June 2021)
  - Accumulating ~400 $\mathrm{fb^{-1}}$ by next summer
- To look out for at next HQL
  - combined measurements of Belle + Belle II data sets



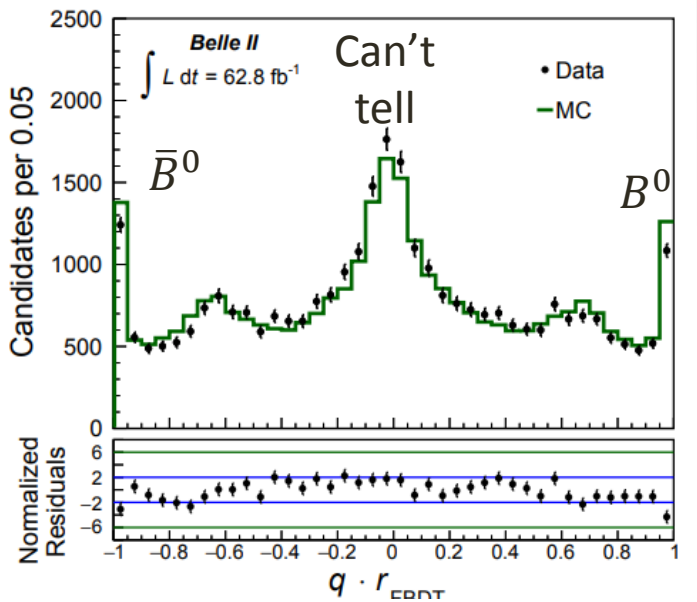
Much more on Belle (II): Casarosa, Kaliyar, Bauer, Bennett, Cao, Hayasaka and Dong

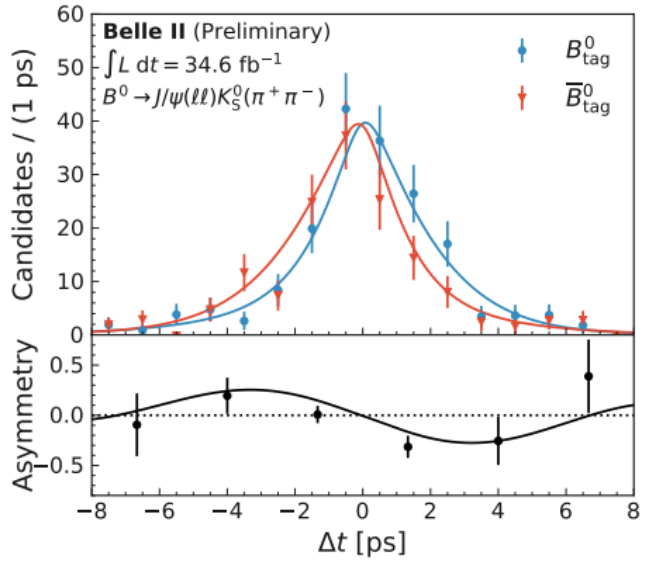
BACKUP

1) TDCPV – first steps at Belle II

- Flavour-tagger development
  - two multivariate techniques
    - category-based BDT or
    - deep-learning neural net on the tag side
  - similar performance to each other and to Belle
    - effective tagging efficiency ~30%
  - room for improvement:
    - lepton ID and impact parameter
- First TDCPV measurement
  - BELLE2-NOTE-PL-2020-011
  - 35 fb^{-1} of data
  - reconstruct $B^0 \to J/\psi(l^+l^-)K_S^0(\pi^+\pi^-)$
  - **sin 2ϕ_1= 0.55 ± 0.21 ± 0.04**
  - **PDG sin 2ϕ_1=0.699 ± 0.017**

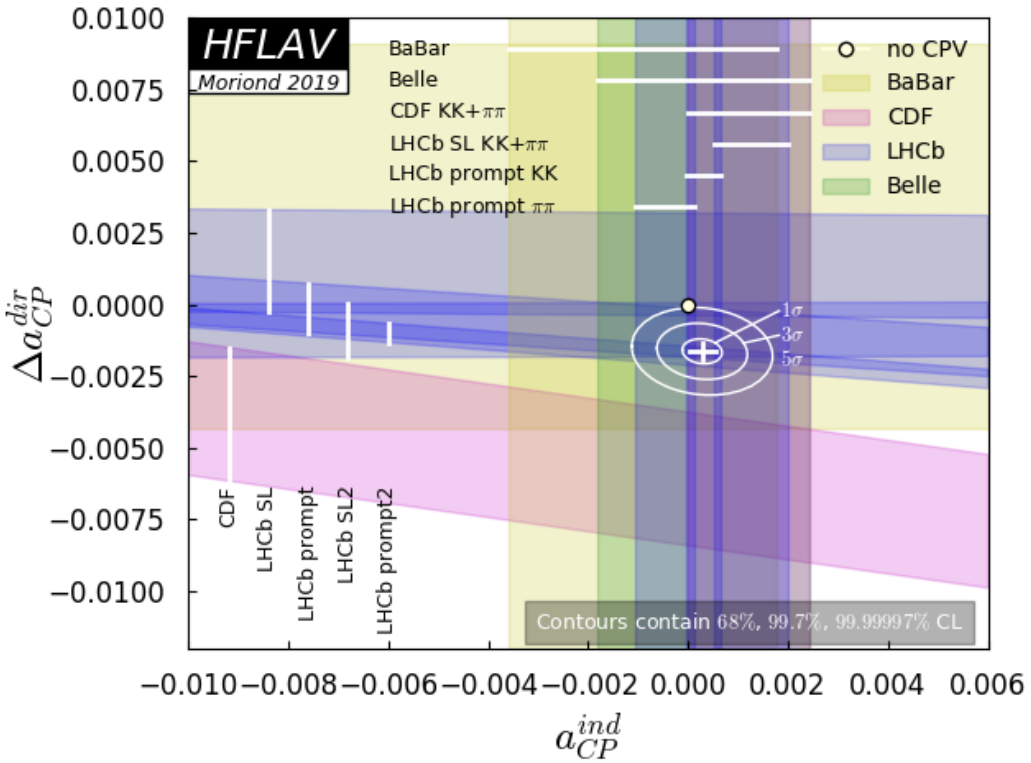
To appear this week





4) CPV in *D* decay

- CPV in charm is highly supressed in SM
- Discovery of direct CPV in $D^0 \to K^+K^-/\pi^+\pi^-$ by LHCb at 10^{-3} level
  - PRL **122**, 211803 (2019)
- To understand if there is any new physics the long range QCD effects must be controlled
  - Various SU(3) and isospin tests suggested to disentangle these effects
- Singly Cabbibo supressed (SCS) decays with neutrals important for these tests
  - Complementary role to LHCb



New measurements from Belle of
$D^0 \to \phi\eta, K^+K^-\eta, \pi^+\pi^-\eta$ (SCS)
[Not shown today
PRD 103, 112005 (2021)
$D_s^+ \to K^+\eta, K^+\pi^0$ (SCS)
$D_s^+ \to \pi^+\eta$ (CF)
$D_s^+ \to \pi^+\pi^0$ (weak annihilation)]

4) $D^0 \to \phi\eta, K^+K^-\eta, \pi^+\pi^-\eta$

arXiv:2106.04286
accepted by JHEP

- 980 fb^{-1} of Belle data
- $D^{*+} \to D^0\pi^+$ slow-pion tag and background suppression

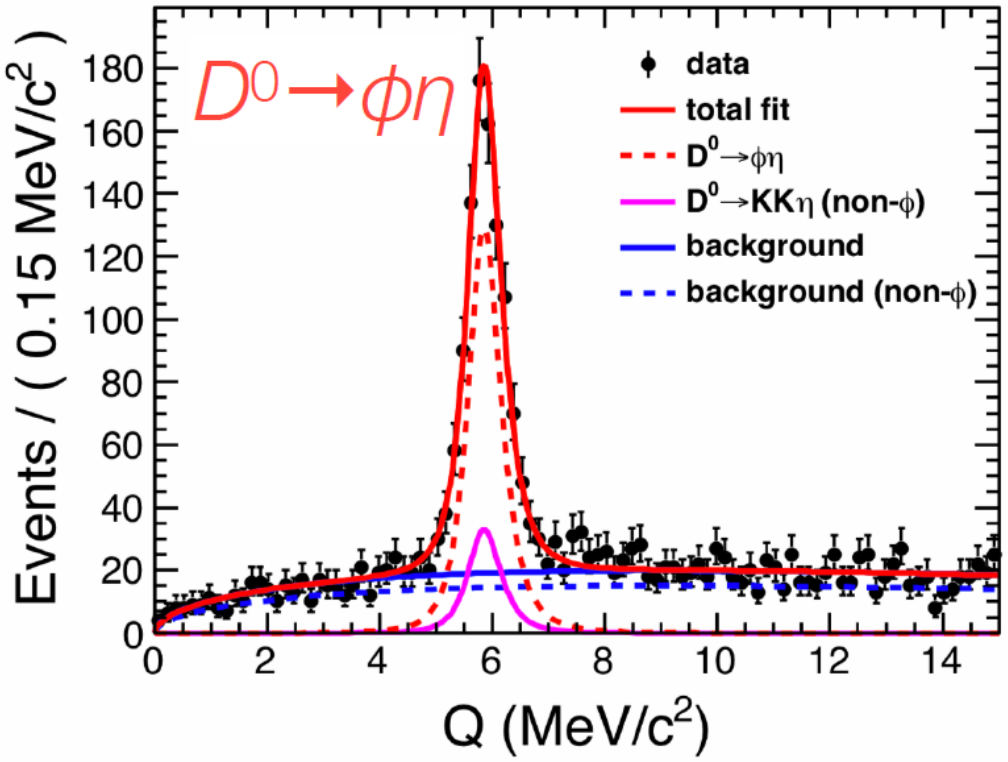
$$Q = M(\phi\eta\pi^+) - M(\phi\eta) - m_{\pi\,\mathrm{PDG}}$$

- The raw asymmetry has three contributions

$$A_{\mathrm{raw}} = A_{CP} + A_{\gamma-Z} + A_{\mathrm{slow}\,\pi}$$

Corrected by measuring as function of D* polar angle

Corrected with charge-dependent control sample



$$A_{CP}(D^0 \to \pi^+\pi^-\eta) = [0.9 \pm 1.2\,(\mathrm{stat}) \pm 0.4\,(\mathrm{syst})]\%\,,$$
$$A_{CP}(D^0 \to K^+K^-\eta) = [-1.4 \pm 3.3\,(\mathrm{stat}) \pm 1.0\,(\mathrm{syst})]\%$$
$$A_{CP}(D^0 \to \phi\eta) = [-1.9 \pm 4.4\,(\mathrm{stat}) \pm 0.6\,(\mathrm{syst})]\%$$