CKM and CPV: Experimental Overview

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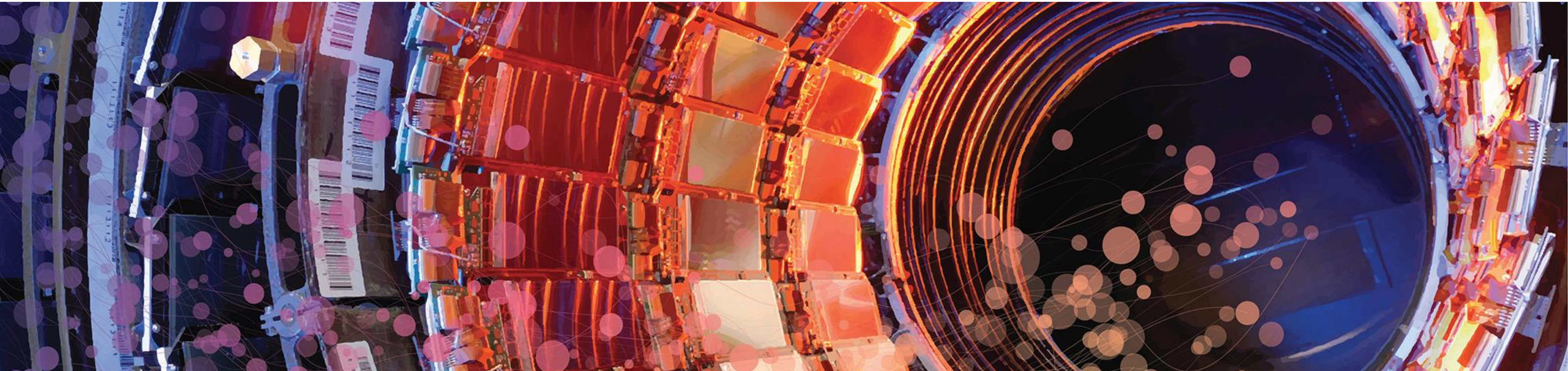

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  - V_{xy} from (semi)-leptonic decays
- CPV
  - CPV phase ϕ_s in B_s mixing
  - Time dependent analyses
- News from Belle II
- Summary

Disclaimer:
There is an enormous variety of interesting topics on CKM/CPV.
Given the time constraint, only selected subjects are summarized.

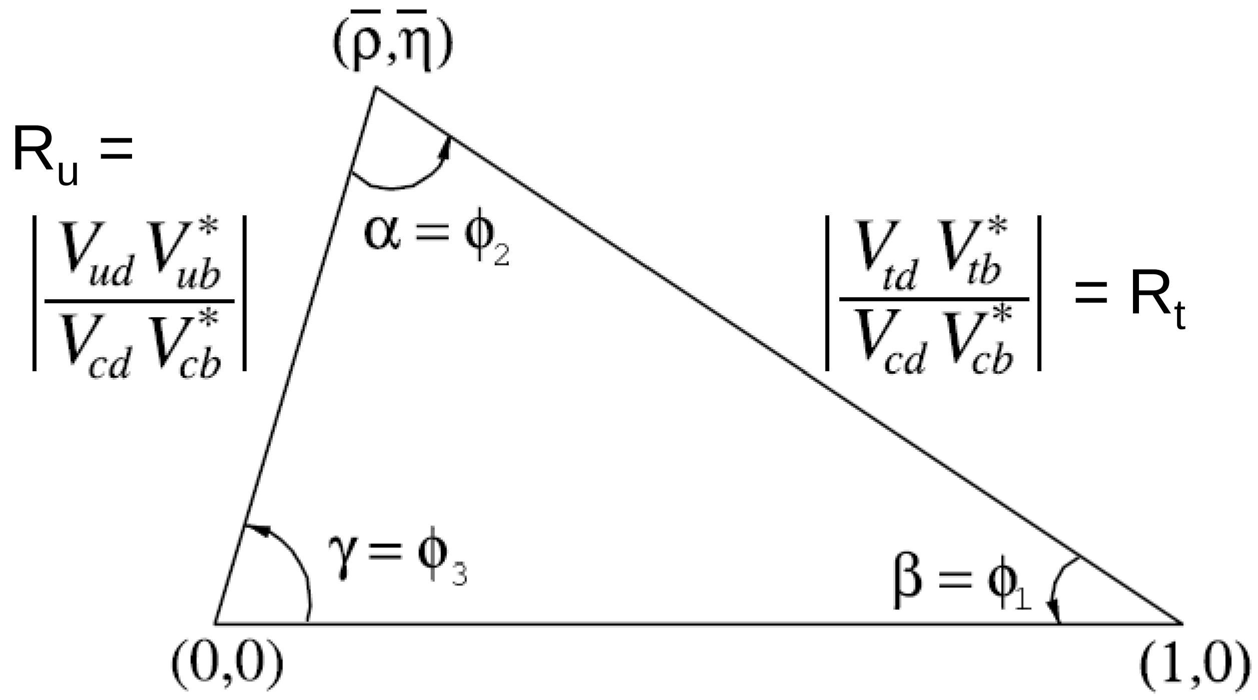


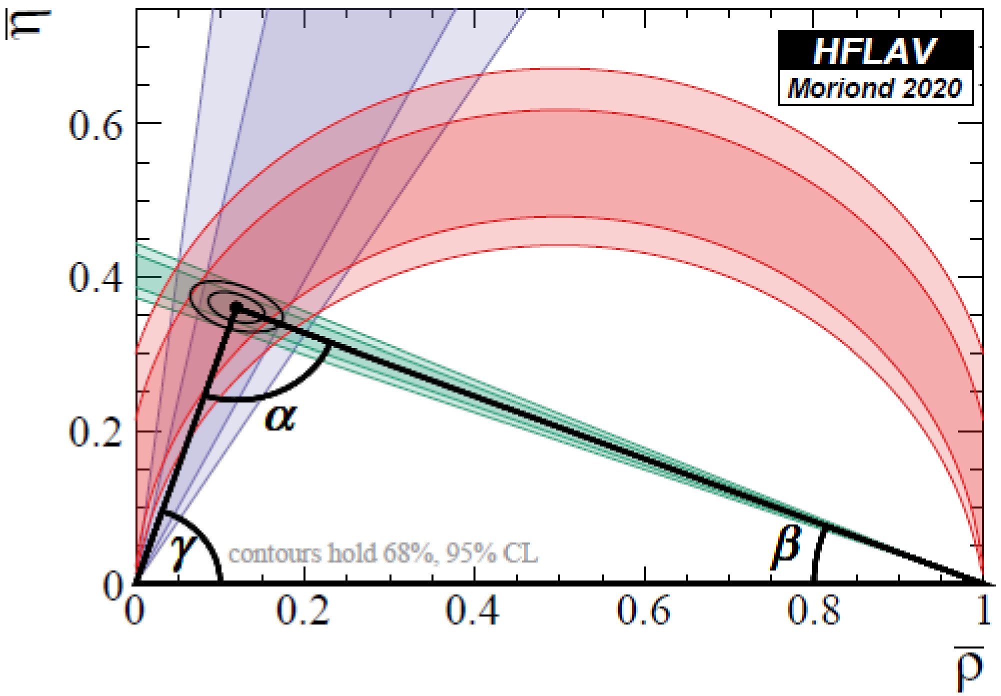
Figure 12.1: Sketch of the unitarity triangle.

CKM

Prog. Theor. Exp. Phys. 2020 083C01 (2020)
aka PDG 2020

Current Status of CKM Angles

$$\alpha = 84.9^{+5.1}_{-4.5}, \quad \beta = 22.2 \pm 0.7, \quad \gamma = 72.1^{+4.1}_{-4.5} \quad \text{deg}$$



Prog. Theor. Exp. Phys. 2020 083C01 (2020)

- The measurement on γ has been improved nicely with LHCb data. However,
  - Direct measurement at tree level:

    $$\gamma = 72.1^{+4.1}_{-4.5} \quad \text{deg}$$

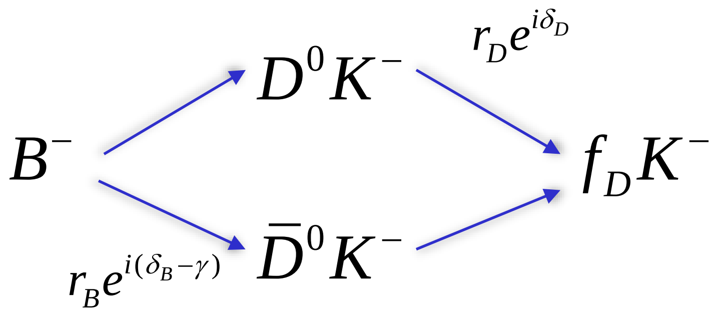
  - Indirect calculation at loop level:

    $$\gamma = 65.66^{+0.9}_{-2.65} \quad \text{deg}$$

    (CKMFitter 2019 summer)
  - There is a 2 σ tension between the values, which could be an indication for New Physics.

The CKM Angle γ

$$\gamma = \phi_3 = \arg\left(\frac{-V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$



- γ can be measured with a very small theoretical error.
  - Calculable at the tree level as an interference between "b to u" and "b to c".

    $\delta\gamma / \gamma \approx O(10^{-7})$ Brod & Zupan, JHEP01, 051 (2014).

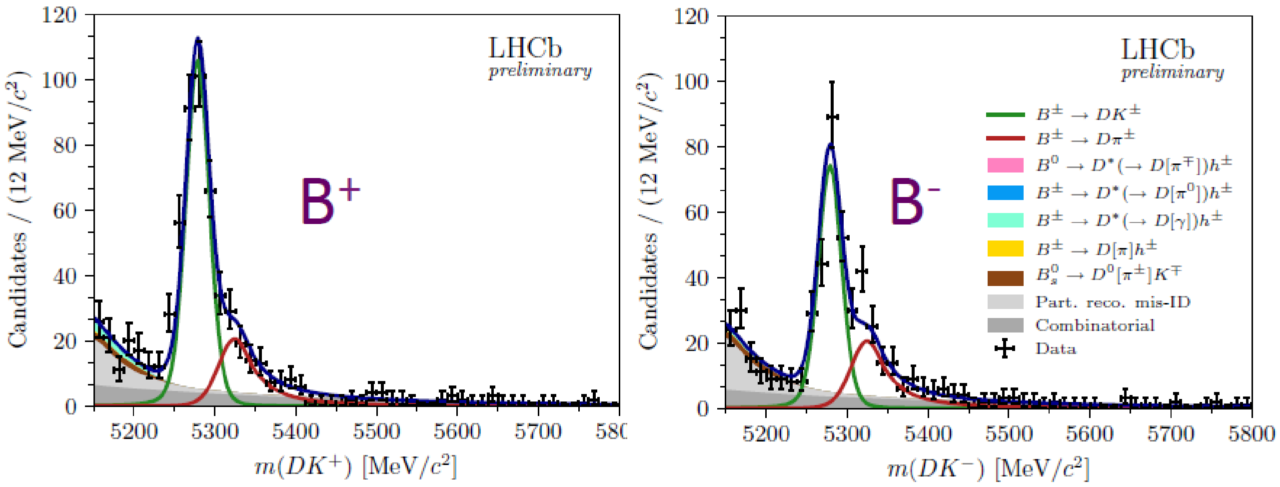
- Experimentally, not so simple:
  - Uses hadronic B decay channels with small branching fractions; sizable LHCb data sets incredibly useful.
  - Modes involving neutrals need Belle (II) data.
  - Analyses need inputs from other beauty and charm experiments (CLEO-c, BES III)
  - Strategy: Measure γ from many D decay channels and combine them.

Testing $B \to Dh'$ with $D \to K_S^0 hh$, $h = K, \pi$

- LHCb is studying various $B \to Dh'$ combinations with full Run 1 and Run 2 data.
- An example: BPGGSZ (D to 3 body final states) analysis on $D \to K_S^0\pi^+\pi^-$ and $D \to K_S^0 K^+K^-$.
  - B^+ and B^- yields are compared for each Dalitz mass bin of *D*, resulting in asymmetry.

preliminary

Dalitz mass bin #4



Preliminary LHCb $\gamma = (69 \pm 5)$ deg

with uncertainty ~ 5(stat) ~1(sys) ~1(ext) deg

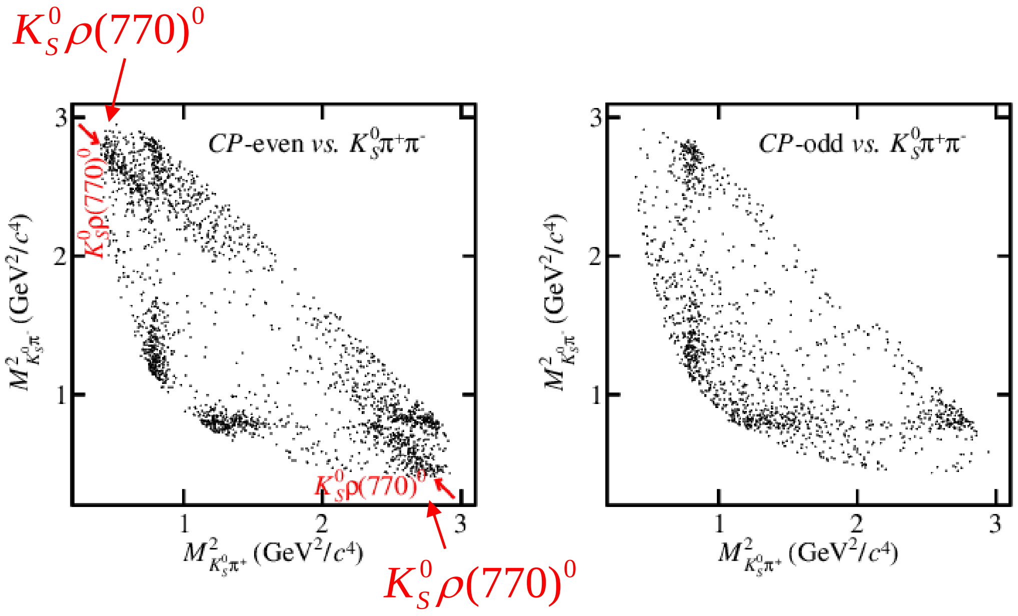
- CPV is observed clearly in $B \to DK$.
- This preliminary result is the most precise single measurement on γ.
  (Talk Malde, July 30th)
- The last uncertainty is from δ_D (next slide)

Previous LHCb: $\gamma = (80^{+10}_{-9})$ deg

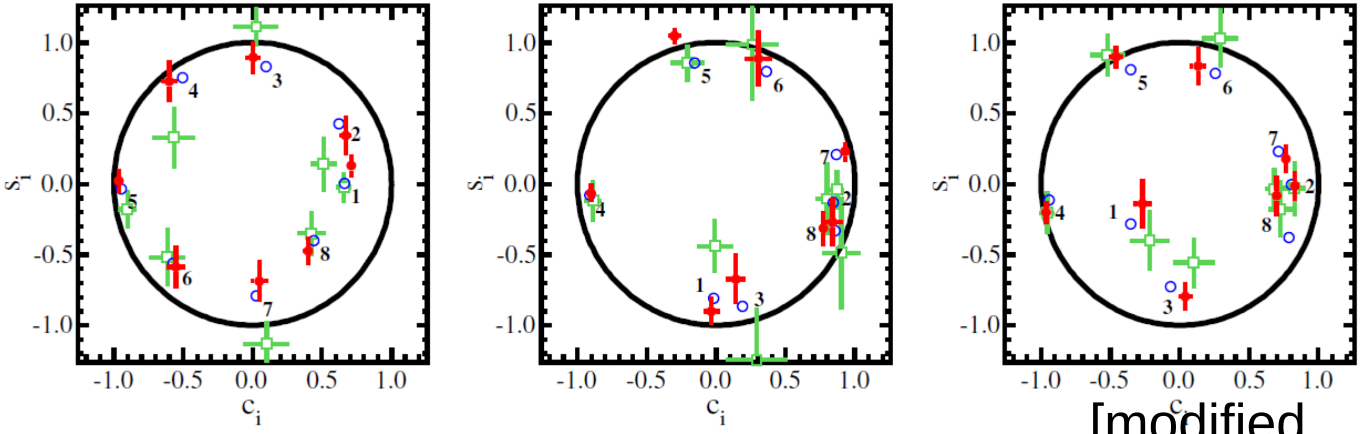
with uncertainty ~9(stat) ~3(sys) ~4(ext) deg

Measurement of Strong Phase δ_D

- Charm factories (CLEO-c, BES III) running at ψ (3770) create C- odd $D\bar{D}$ pairs (Quantum correlation).
  - If tag side $\bar{D}$ is CP odd, then signal side D is CP even. And vice versa.
- BES III conducted Dalitz analysis of $\boldsymbol{D \rightarrow K^0_{S,L}\pi^+\pi^-}$ and measured δ_D. Phys. Rev. Lett. 124, 241802 (2020), Phys. Rev. D 101, 112002 (2020).
  - The associated uncertainty on γ is reduced from ~3 to ~1 deg. (Talk Lin, July 28th)



Red: BES III, Blue: expected values, Green: CLEO-c

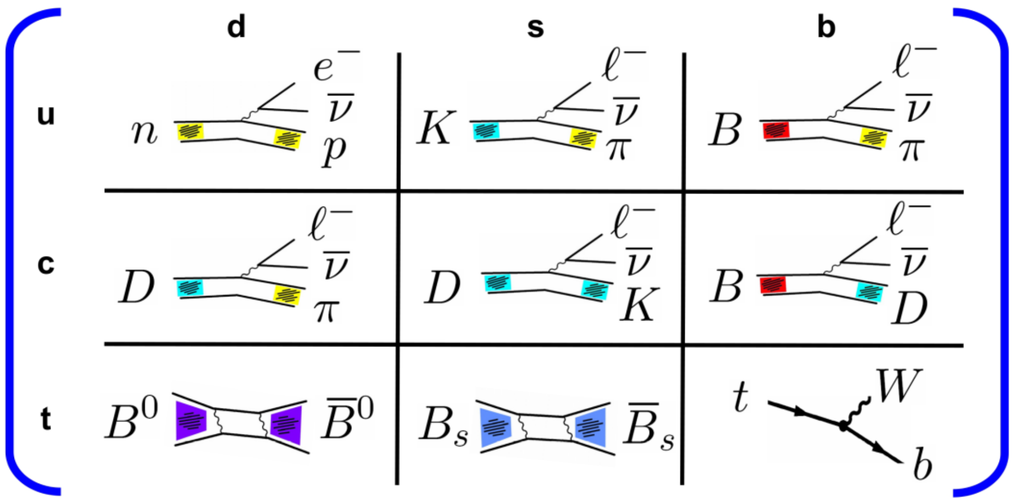


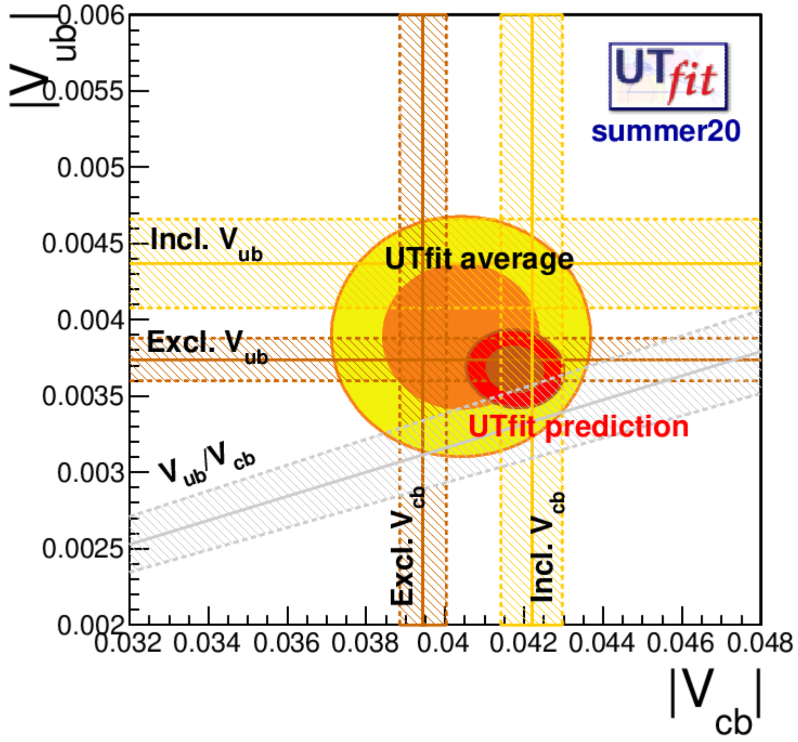
[equal Δ δ_D] [optimal] [modified optimal]

Expected values by PRD 98,110212(2018)

(Semi)-Leptonic Decays

V =





(Talk Bona, July 29th)

- Semi-leptonic decay rates are described as

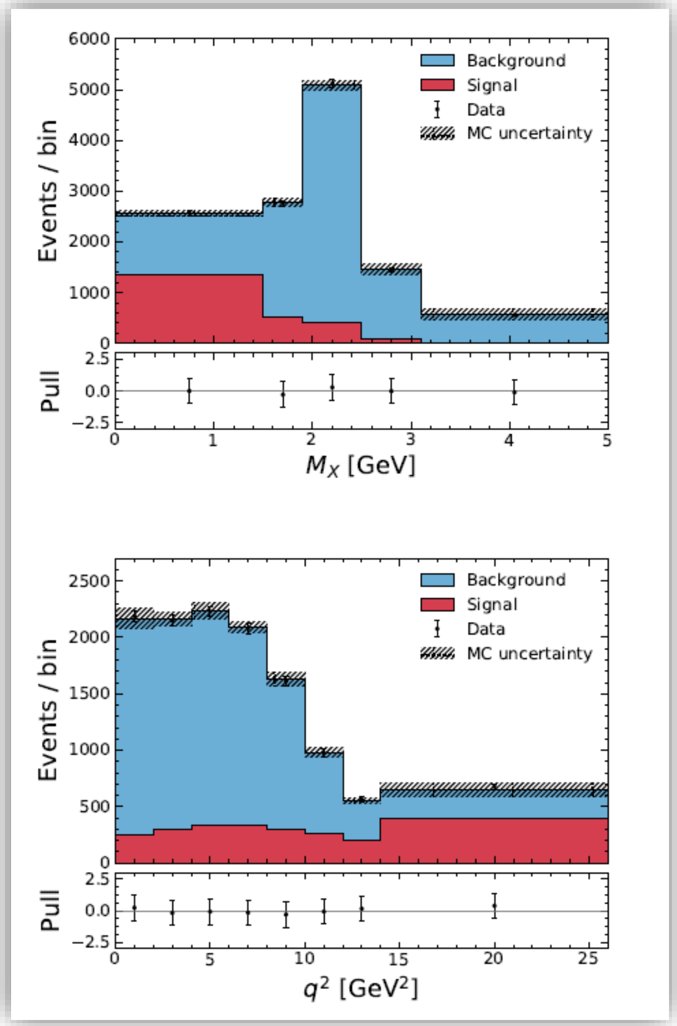
$$\frac{d\Gamma(B \to h_x l\nu)}{dq^2 d\Omega} \propto |V_{xb}|^2 \times FF_{B\to h_x}(q^2, \Omega)$$

- The measurement of h_x final states gives additional kinematic information, such as angles.
- Form factors, which represent hadronic interactions, need inputs from LQCD, light cone, etc.

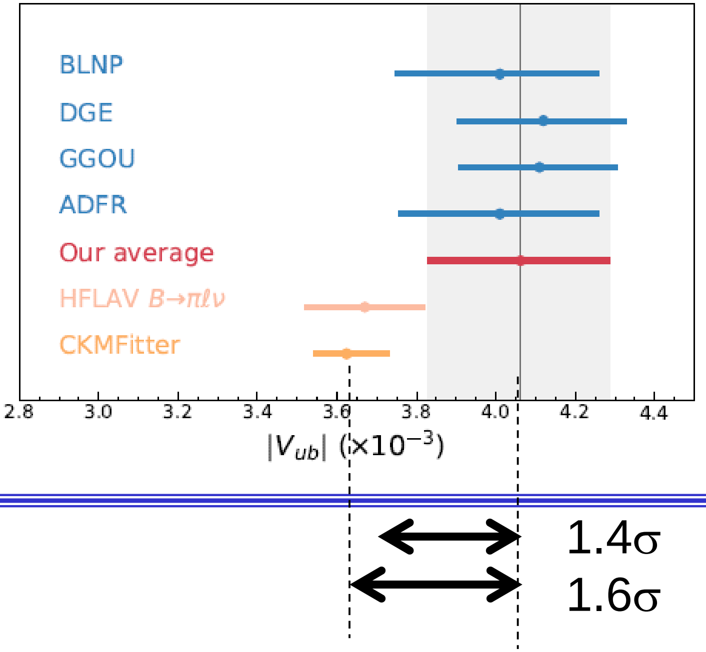
- Historically, V_{xb} measurements using exclusive and inclusive approaches did not agree very well, leading to speculations regarding new physics from e.g. right-handed currents.

V_{ub}: Inclusive Measurement

preliminary



- Cabibbo favored $\boldsymbol{B \to X_c l \nu}$ is a major background to CKM suppressed $\boldsymbol{B \to X_u l \nu}$.
- Lepton energy endpoint and/or low M_X regions give clear info on $\boldsymbol{B \to X_u l \nu}$.
- The new Belle analysis used neural network for hadronic tagging of the other B. Machine learning (BDT) is used to suppress backgrounds such as $\boldsymbol{X_c l \nu}$.



From the 2-d fit on q^2 and M_x with $E_l > 1.0$ GeV, Belle obtained a preliminary result of

$|V_{ub}| = (4.06 \pm 0.09 \pm 0.16 \pm 0.15) \times 10^{-3}$.

(last uncertainty theoretical)

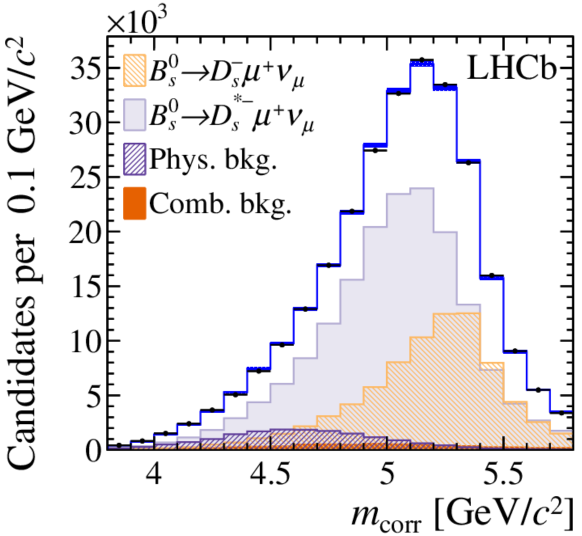
(Talk Cao, July 30th)

V_{cb}: Exclusive Measurement

- $B \rightarrow D^{(*)} l\nu$ is studied extensively to obtain exclusive V_{cb}.
- Fit variable ω + Full angular analysis strategy is used.

$$\omega = \frac{m_B^2 + m_D^2 - q^2}{2m_B m_D}, \quad z = \frac{\sqrt{\omega+1} - \sqrt{2}}{\sqrt{\omega+1} + \sqrt{2}}$$

- Note that uncertainty in form factors and *F*(1) should be considered.



	V_{cb} BGL fit (10^{-3})	V_{cb} CLN fit (10^{-3})	Reference
Belle (B^0)	$38.3 \pm 0.2 \pm 0.7 \pm 0.6$ (ext)	$38.4 \pm 0.2 \pm 0.6 \pm 0.6$ (ext)	Phys. Rev. D 100, 052007 (2019)
BABAR (B^0)	38.36 ± 0.90	38.40 ± 0.84	Phys. Rev. Lett. 123, 091801 (2019) (Talk Simonetto, July 29th)
LHCb (B_s)	$42.3 \pm 0.8 \pm 0.9 \pm 1.2$ (ext)	$41.4 \pm 0.6 \pm 0.9 \pm 1.2$ (ext)	Phys. Rev. D 101, 072004 (2020) (Talk Ferrari, July 29th)
PDG2020	39.5 ± 0.9		Mannel and Urquijo, PDG 2020

FF by 1) Boyd Grinstein Lebed, 2) Caprini Lellouch Neubert.

tan θ_C and Isospin: Old Issue but New Result

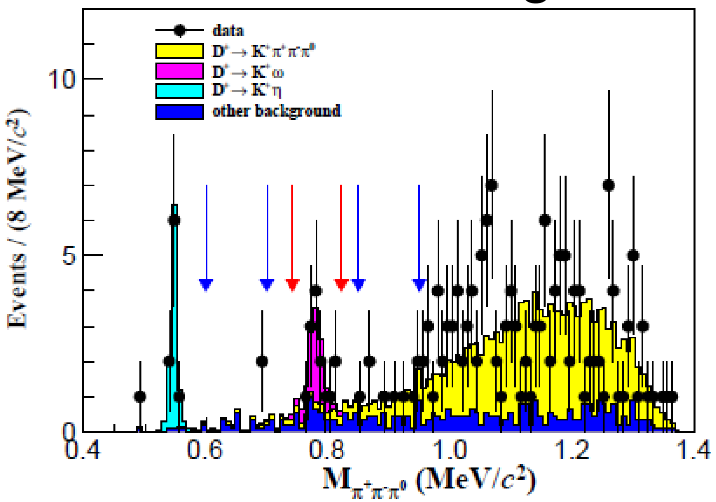
- BES III measured DCS BF $D^+ \to K^+\pi^+\pi^-\pi^0$ by reconstructing double tag events. arXiv:2007.07674. This world first measurement provides the ratio of DCS/CF BRs, which is related to tan θ_C as,

$$\frac{B(D \to K^+\pi^+\pi^-\pi^0)}{B(D \to K^-\pi^+\pi^-\pi^0)} = (1.81 \pm 0.15)\% = (6.28 \pm 0.52)\tan^4\theta_C$$

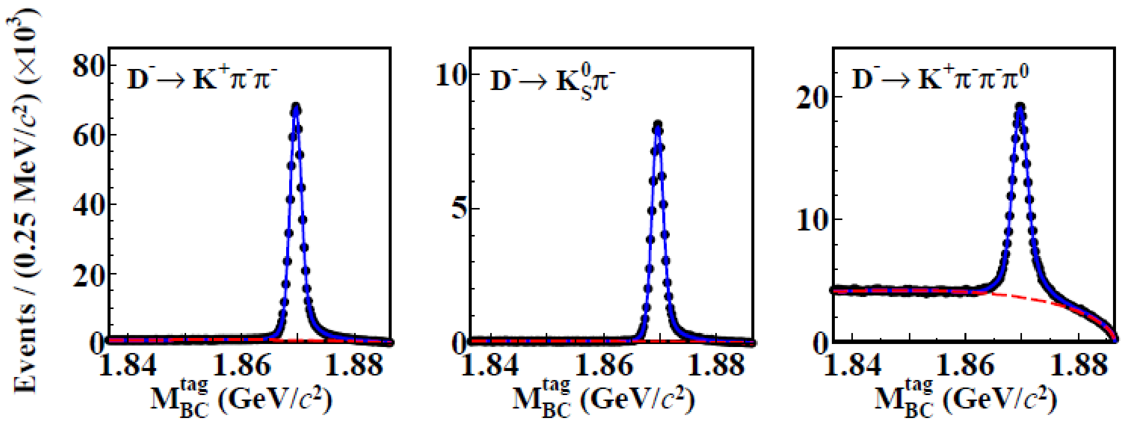
  – This value is much larger compared to the other DCS/CF ratios. There may be a large isospin violation between $D^+ \to K^+\pi^+\pi^-\pi^0$ and $D^0 \to K^+\pi^-\pi^-\pi^+$.

- There was no clear evidence of CPV in the charge asymmetry measurement.

signal



The other D



(Talk Zheng, July 28th)

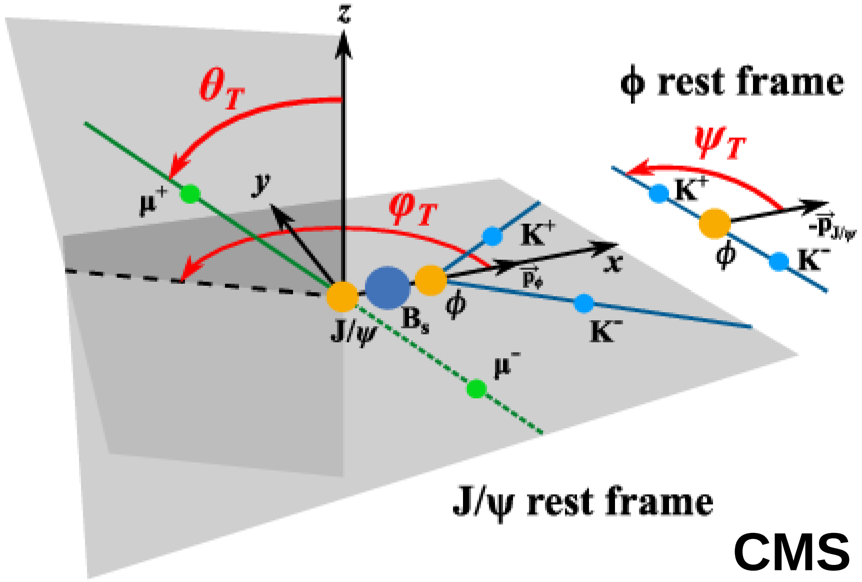
CPV

CPV phase ϕ_s in B_s mixing

- ϕ_s is a CPV phase, which is a weak phase difference between the B_s - $\bar{B}_s$ mixing and the direct decay of B_s into a common final state.
- The golden mixing decay $B_s \rightarrow J/\psi\ \phi$, ($\phi \rightarrow K^+K^-$) is well known, less complicated environment to measure the phase. (No direct CPV. Only one weak phase.)
- At the tree level, SM predicts

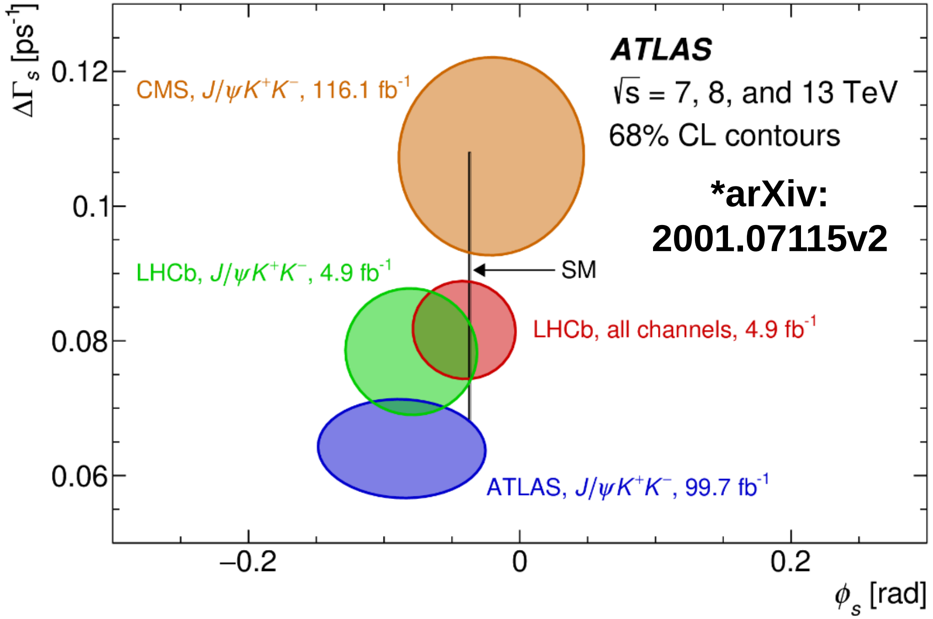
$$\phi_s \approx -2\beta_s = -2\arg\left(\frac{-V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

- At LHC experiments, the flavor of B_s is determined by Opposite Side Tagging (muon, electron, jet-charge) or Same Side Tagging (Kaon, LHCb only).

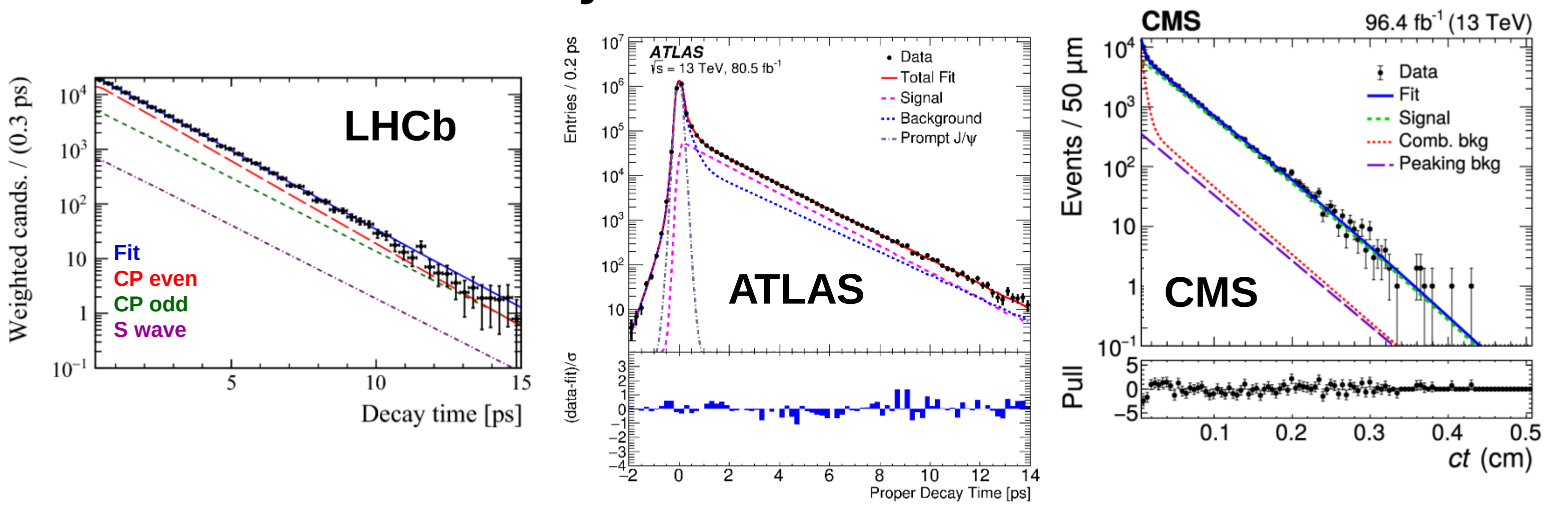


CMS

Measurements of ϕ_s and $\Delta\Gamma_s$ at LHC



Decay time distributions

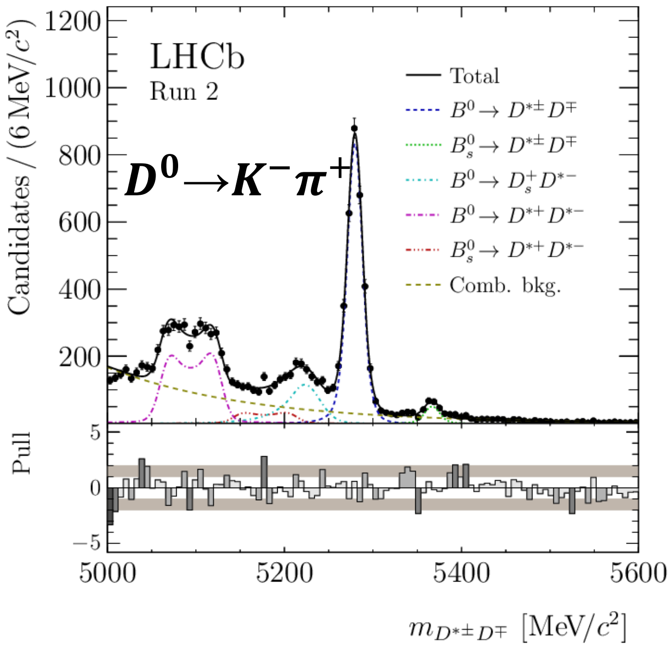


	ϕ_s (mrad)	$\Delta\Gamma_s$ (ps^{-1})	Reference	Sample (fb^{-1})
LHCb (K^+K^-)	–81 ± 32	0.0777 ± 0.0062	Erratum: Eur. Phys. J. C **80**, 601 (2020) (Talk Li, July 30th)	4.9
LHCb (all)	–42 ± 25	0.0813 ± 0.0048		
ATLAS	–87 ± 41	0.0641 ± 0.0049	arXiv: 2001.07115v2 (Talk, Jakoubek July 29th)	99.7
CMS	–21 ± 45	0.1073 ± 0.0097	arXiv: 2007.02434 (Talk, Lusiani July 29th + Poster, Alibordi July 29th)	116.1
SM	$-36.96^{+0.72}_{-0.84}$	0.087 ± 0.0021	CKMFitter 2019 summer	

Note*: LHCb Numbers from Eur. Phys. J. C 79, 706 (2019)

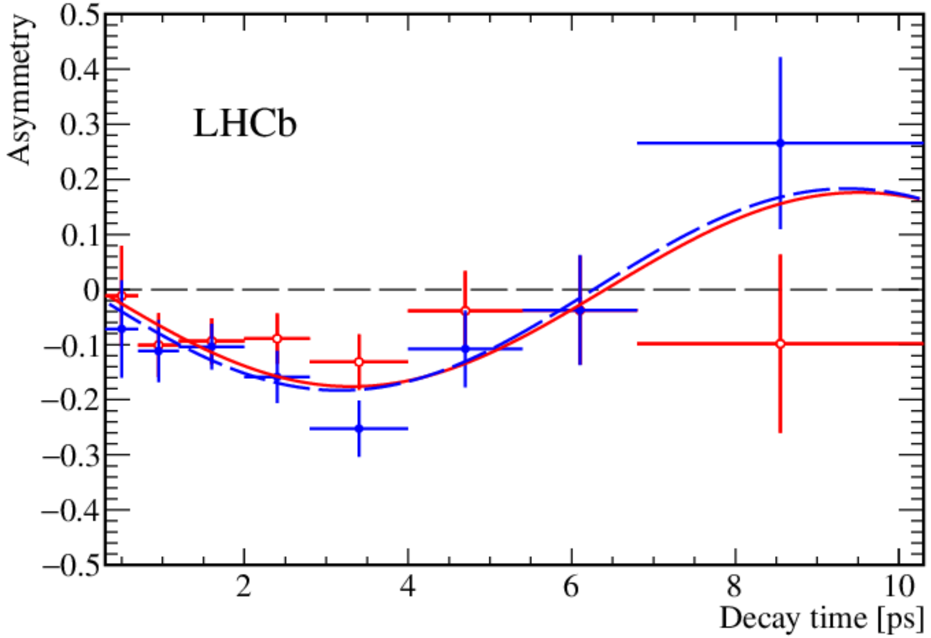
Time Dependent CPV in $B \to D^{*\pm}D^{\mp}$

- In the $B \to D^{*\pm}D^{\mp}$ decays, in addition to the CKM angle 2β, New Physics contributions may appear.
  - Recent LHCb results, JHEP 03, 147 (2020), are comparable to the previous Belle/Babar numbers, and are the most precise up to date.
  - Used modes are $D^{*+} \to D^0\pi^+$ ($D^0 \to K^-\pi^+\pi^+\pi^-$, $D^0 \to K^-\pi^+$) and $D^- \to K^+\pi^-\pi^-$.



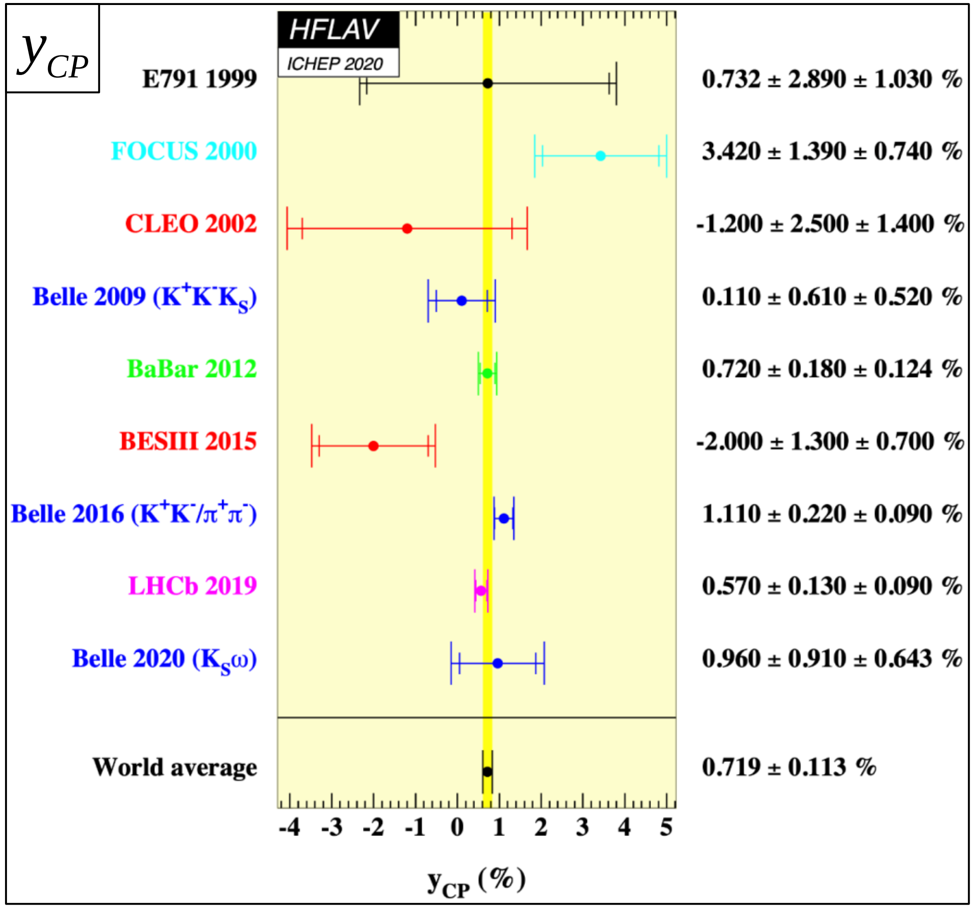
S_{D^*D}	$-0.861 \pm 0.077 \pm 0.019$
ΔS_{D^*D}	$0.019 \pm 0.075 \pm 0.012$
C_{D^*D}	$-0.059 \pm 0.092 \pm 0.020$
ΔC_{D^*D}	$-0.031 \pm 0.092 \pm 0.016$
A_{D^*D}	$0.008 \pm 0.014 \pm 0.006$

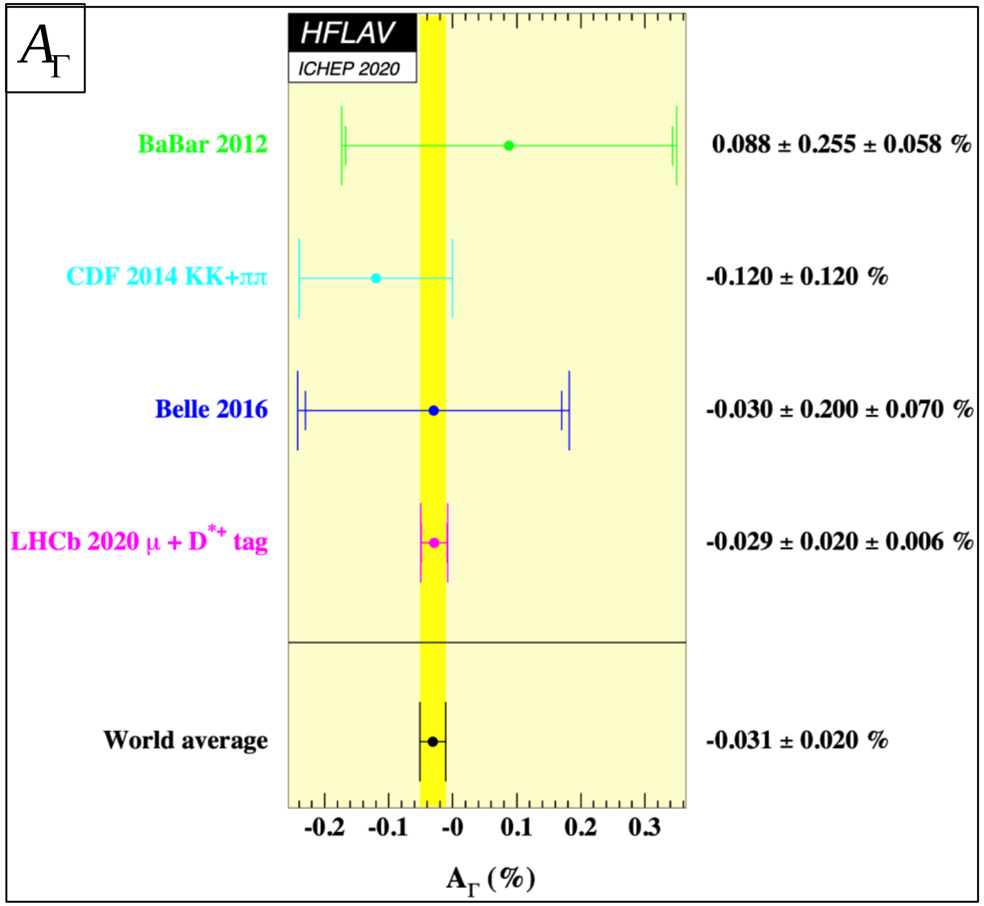
(Talk Gersabeck, July 29th)



Update of Charm mixing/CPV: ICHEP 2020

- HFLAV updated the charm sector as https://hflav.web.cern.ch/content/charm-physics



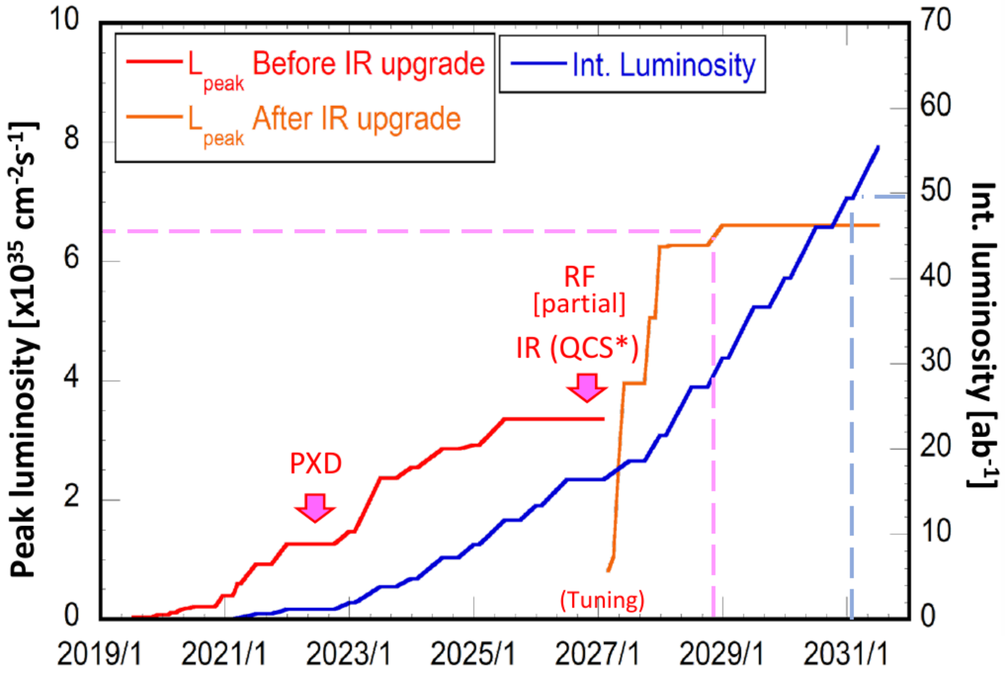


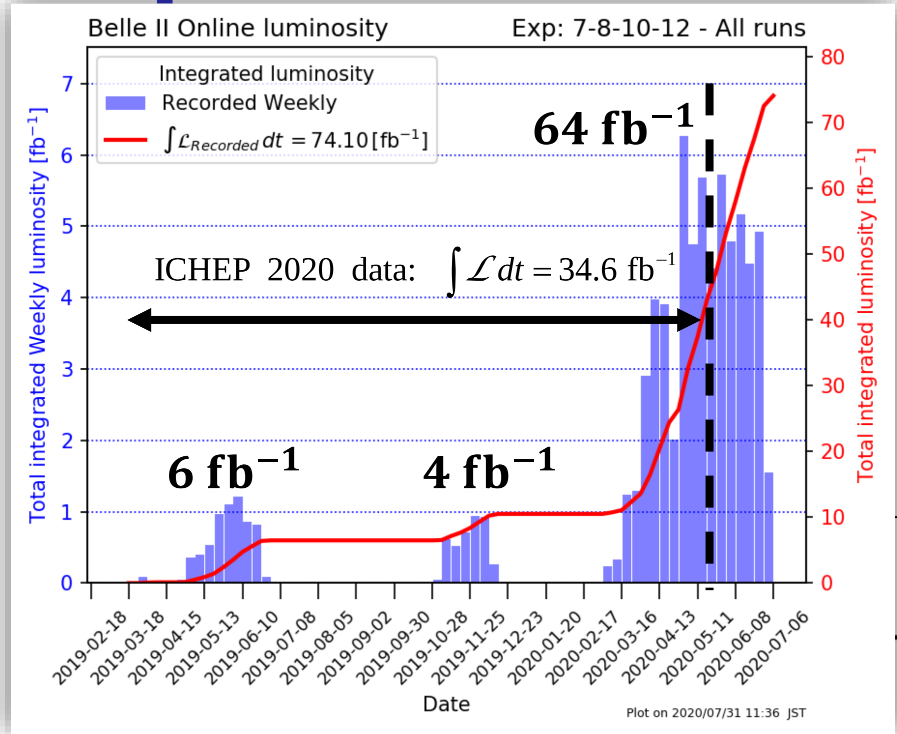
LHCb $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$ Phys. Rev. D 101, 012005 (2020) (Talk Tuci, July 30th)

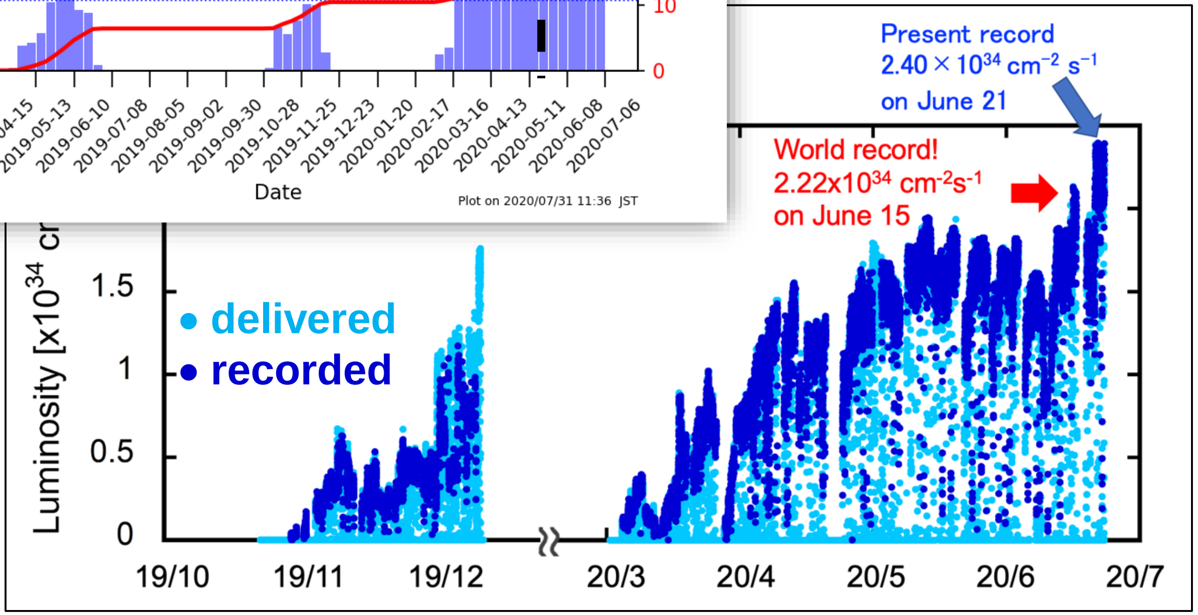
Belle $D^+ \to K_S^0\,\omega$ arXiv:1912.10912 (Talk Li, July 28th)

NEWS FROM BELLE II

Belle II Luminosity: Proposed Plan and Status

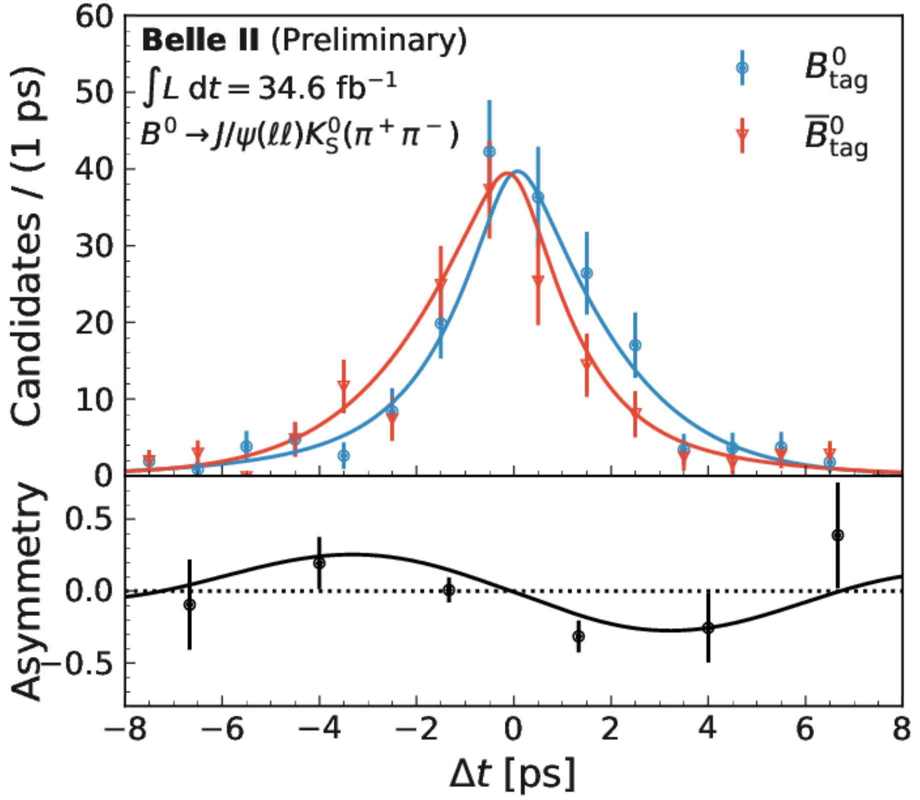






- In general, 8 months running per year.
- 2021-2022: PXD exchange.
- 2026: Partial RF-power upgrade. IR upgrade.
- β_y^* ~ 0.5 mm before 2026. 0.3 mm after 2026.

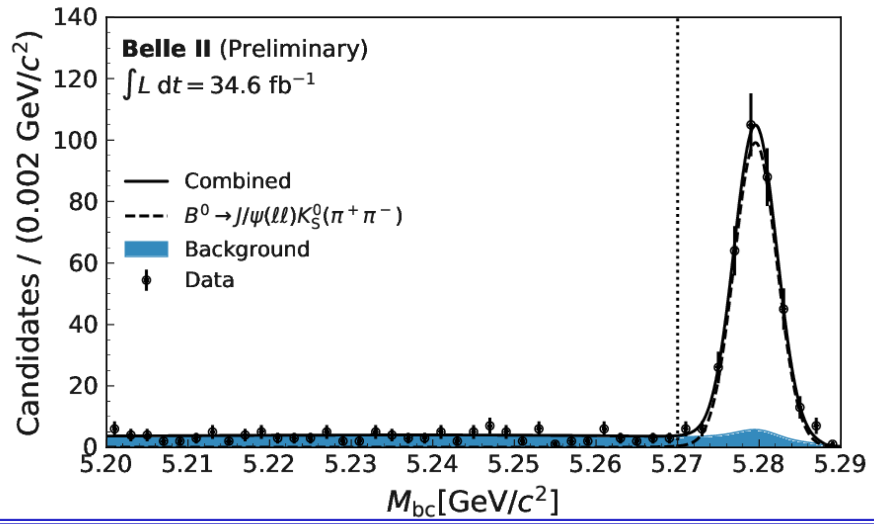
Time Dependent CPV and Mixing



$\text{Belle II:}\ S_f \approx \sin 2\phi_1 = 0.55 \pm 0.21 \pm 0.04.$

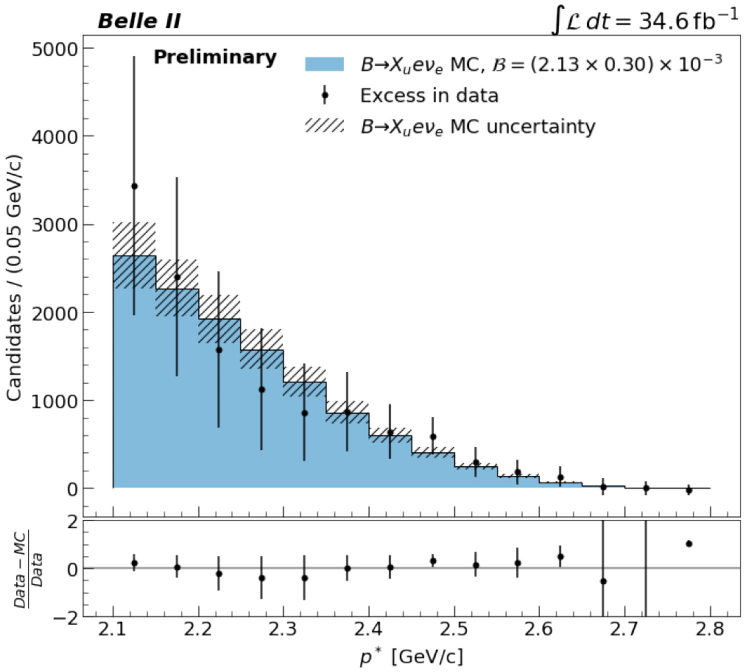
$\text{W. A.:}\ S_f \approx 0.691 \pm 0.017.$

- The golden channel $B^0 \to J/\psi(ll)K_S^0(\pi^+\pi^-)$ is studied and the time dependent CPV parameter $\sin 2\phi_1$ is extracted.
- CPV is assumed only from the B^0 mixing ($A_{CP} = 0$).
- The wrong sign tag ratio $w = (20.9 \pm 2.1)\%$ is obtained from the $B^0 \to D^-(K^+\pi^-\pi^-)\pi^+$ sample where $\Delta m_d = (0.531 \pm 0.046 \pm 0.013)\ \mathrm{ps}^{-1}$.

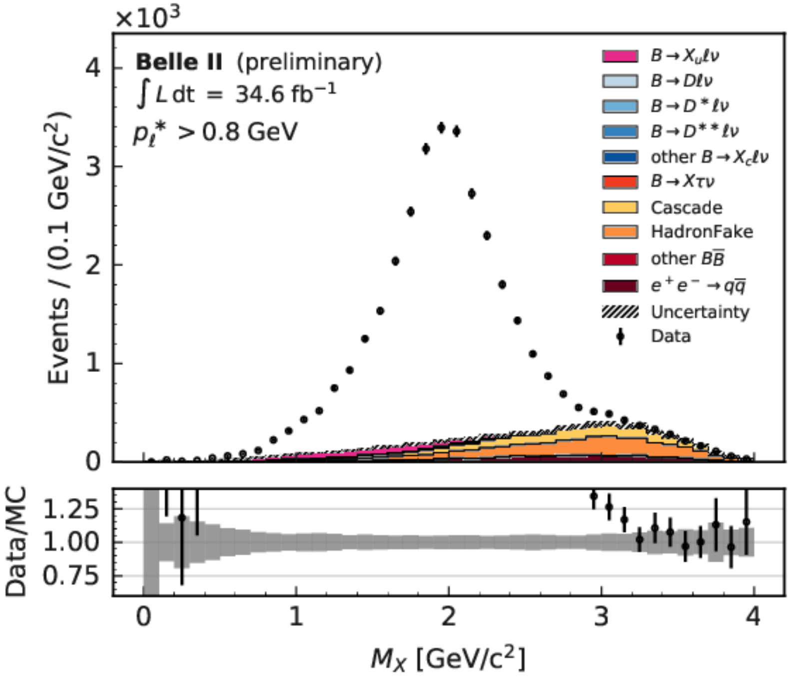


Toward V_{cb} and V_{ub}: Semi-Leptonic Decays

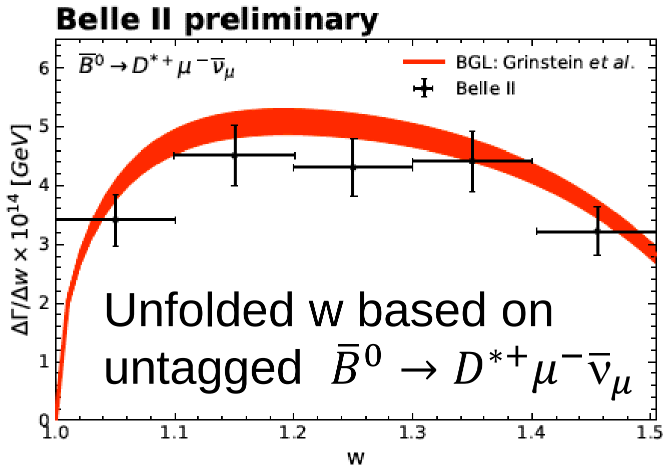
(Talk Cheaib, July 29th & poster Granderath, July 29th)



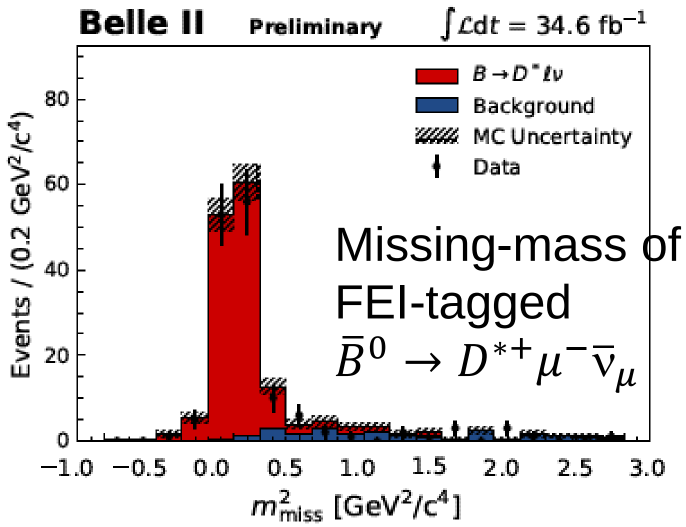
Untagged $B \to X_u e \nu_e$ at the endpoint region of electron momentum



Hadronic mass moment M_x of FEI-tagged $B \to X_c l \nu$



Unfolded w based on untagged $\bar{B}^0 \to D^{*+} \mu^- \bar{\nu}_\mu$



Missing-mass of FEI-tagged $\bar{B}^0 \to D^{*+} \mu^- \bar{\nu}_\mu$

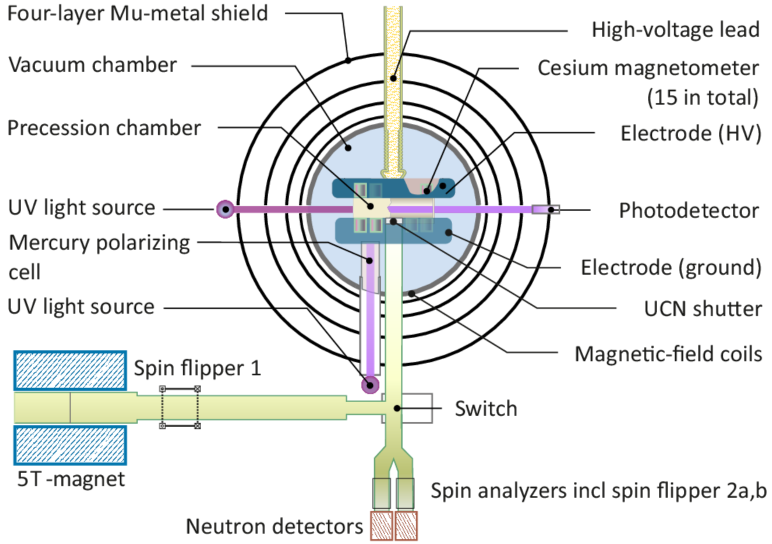
FEI: Full event interpretation algorithm for hadronic tagging
(Talk Sutcliffe, July 30th)

Summary

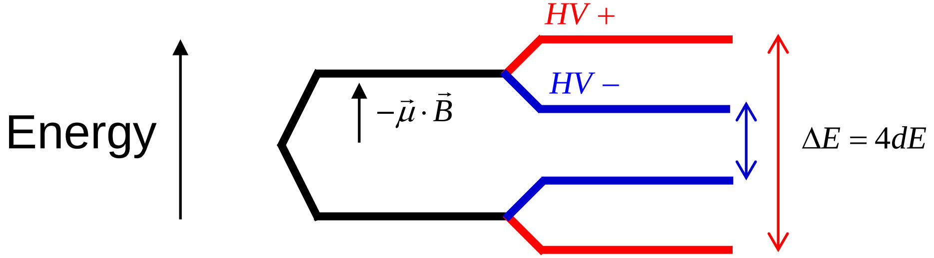
- Measurement on γ slowly enters the precision area.
  - Inputs from charm/beauty experiments are needed.
- The CKM elements are being updated relentlessly.
  - (semi)-leptonic decay modes are leading the efforts.
- Belle II started generating comparable physics results.
- The CKM/CPV is a great handle to look for new physics.

EXTRA

nEDM: neutron Electric Dipole Moment



$$H = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E} \quad \Rightarrow \text{ Larmor precession}$$



(Ayres @ FPCP 2020)

- A new measurement at Paul Scherrer Institute (Phys. Rev. Lett. **124**, 081803)
- Classically, EDM represents an asymmetric charge distribution inside a particle.
- Non-zero EDM in neutron implies T violation. Under CPT conservation, it also means CPV.
- Ramsey's method was used to extract frequency of ultracold neutrons in B and E fields.

$$d_n = (0.0 \pm 1.1 \pm 0.2)\times 10^{-26}\, e.\text{cm}$$

$$\Rightarrow |d_n| < 1.8\times 10^{-26}\, e.\text{cm} \;\; (90\% \;\text{C.L.})$$

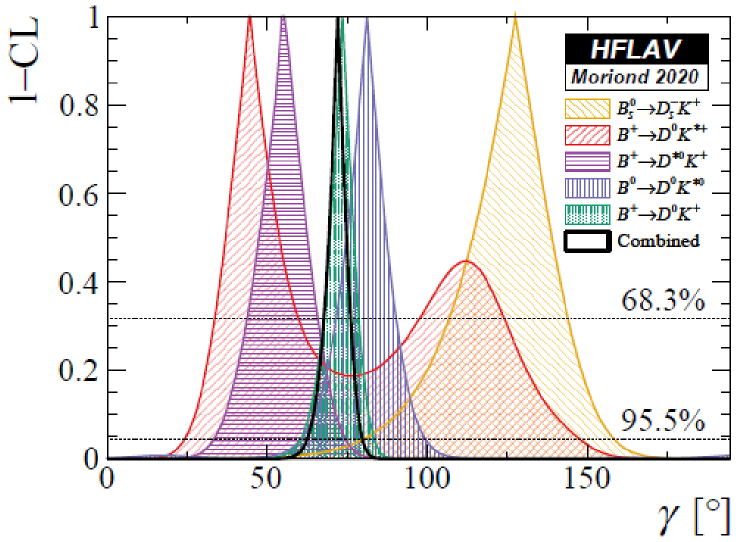
- Previously, Phys. Rev. **29**, 092003 (2015)

$$d_n = (-0.2 \pm 1.5 \pm 1.0)\times 10^{-26}\, e.\text{cm}$$

$$\Rightarrow |d_n| < 3\times 10^{-26}\, e.\text{cm} \;\; (90\% \;\text{C.L.})$$

Final D Category for Measurement of γ

- GLW: CP eigenstate D decays
  - $D \to KK,\ D \to \pi\pi.$ Phys. Lett. B 253, 483 (1991), Phys. Lett. B 265, 172 (1991)
- ADS: CF or DCS D decays
  - $D \to K\pi.$ Phys. Rev. Lett. 78, 3257 (1997), Phys. Rev. D63, 036005 (2001)
- BPGGSZ: D to 3 body final states
  - $D \to K_S^0\pi\pi.$ Phys. Rev. D68, 054018 (2003)
- TD (time dependent): Interference between mixing and decay
- Dalitz: 3-body B decays with a neutral D
  - $B \to \overline{D}^0 K\pi.$ Phys. Rev. D79, 051301 (2009)

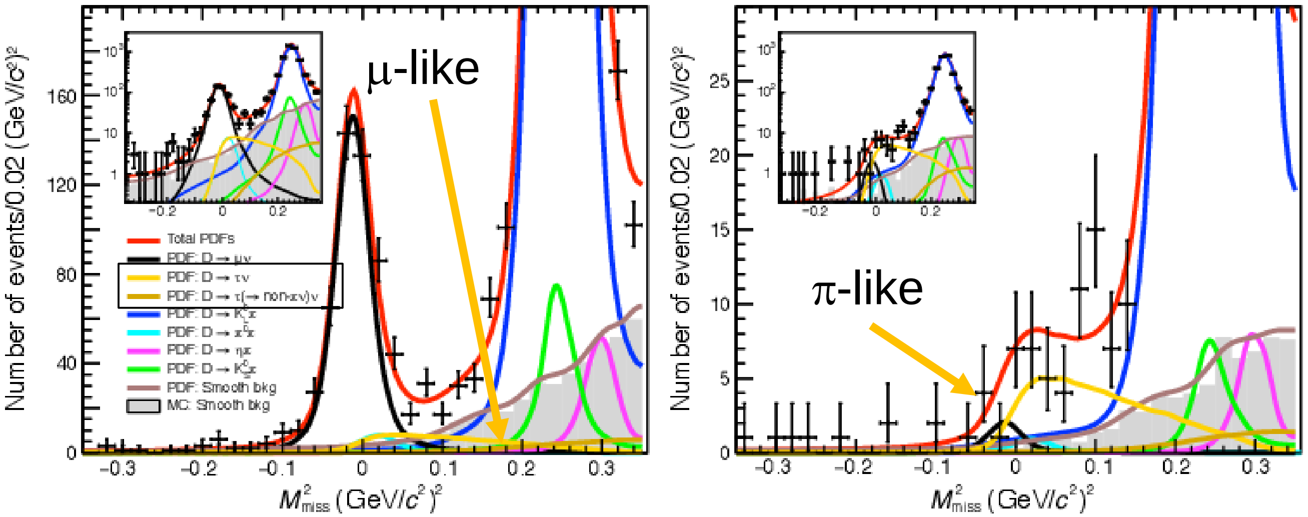


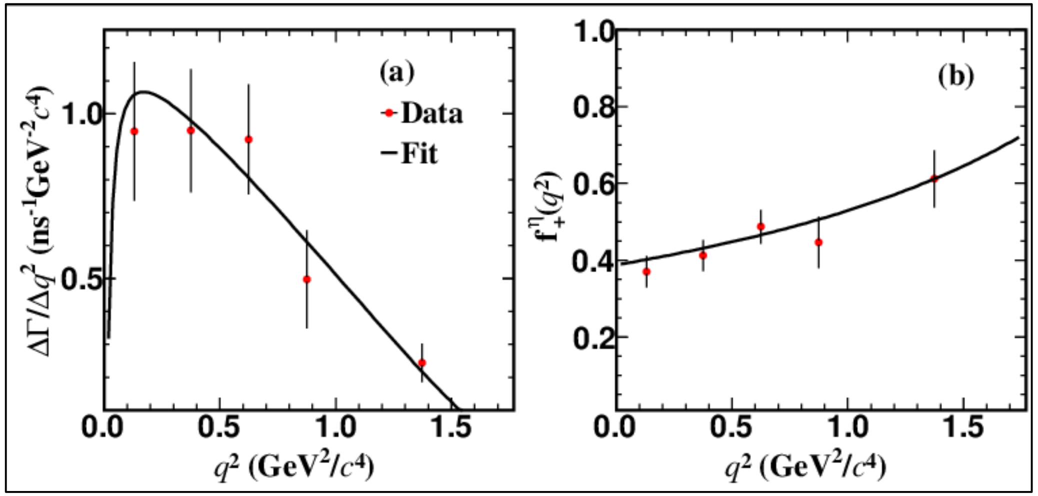
Prog. Theor. Exp. Phys. 2020 083C01 (2020)

Other (Semi)-Leptonic Decays

Observation of $D^+ \to \tau^+ \nu_\tau$ by BES III.
Phys. Rev. Lett. **123**, 211802

First measurement of BF $D^+ \to \eta \mu^+ \nu_\mu$ by BES III.
Phys. Rev. Lett. **124**, 231801





- Note that the signal is represented by yellow curves.
- With LQCD inputs on f_{D+} (ETM 2015, Fermilab + MILC 2018),
  $|V_{cd}| = 0.237 \pm 0.024 \pm 0.012 \pm 0.001$ (theory)

- Fit to $f_+^{\eta}(0)|V_{cd}| = 0.087 \pm 0.008 \pm 0.002$.
- Ivanov et al. (2019) review on $f_+^{\eta}(0)$ gives $|V_{cd}| = 0.242 \pm 0.022 \pm 0.006 \pm 0.033$ (theory)
- Note) PDG 2020 $|V_{cd}| = 0.221 \pm 0.004$

(Talk Qu, July 28th)