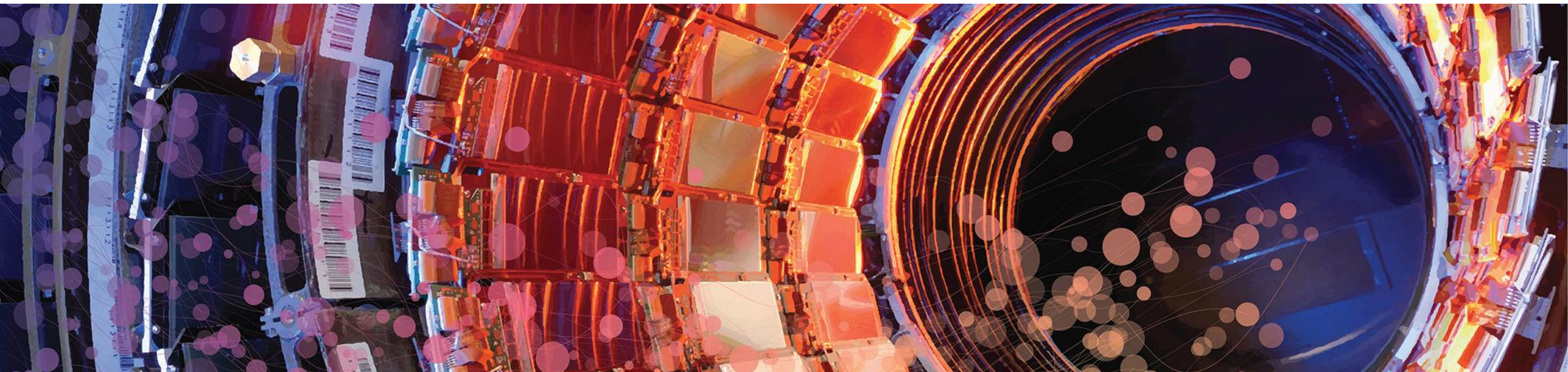


CKM and CPV: Experimental Overview

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ICHEP 2020 (Virtual Conference / Prague, Czech Republic)



Contents

- CKM
 - Status of CKM angle γ
 - 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.

CKM

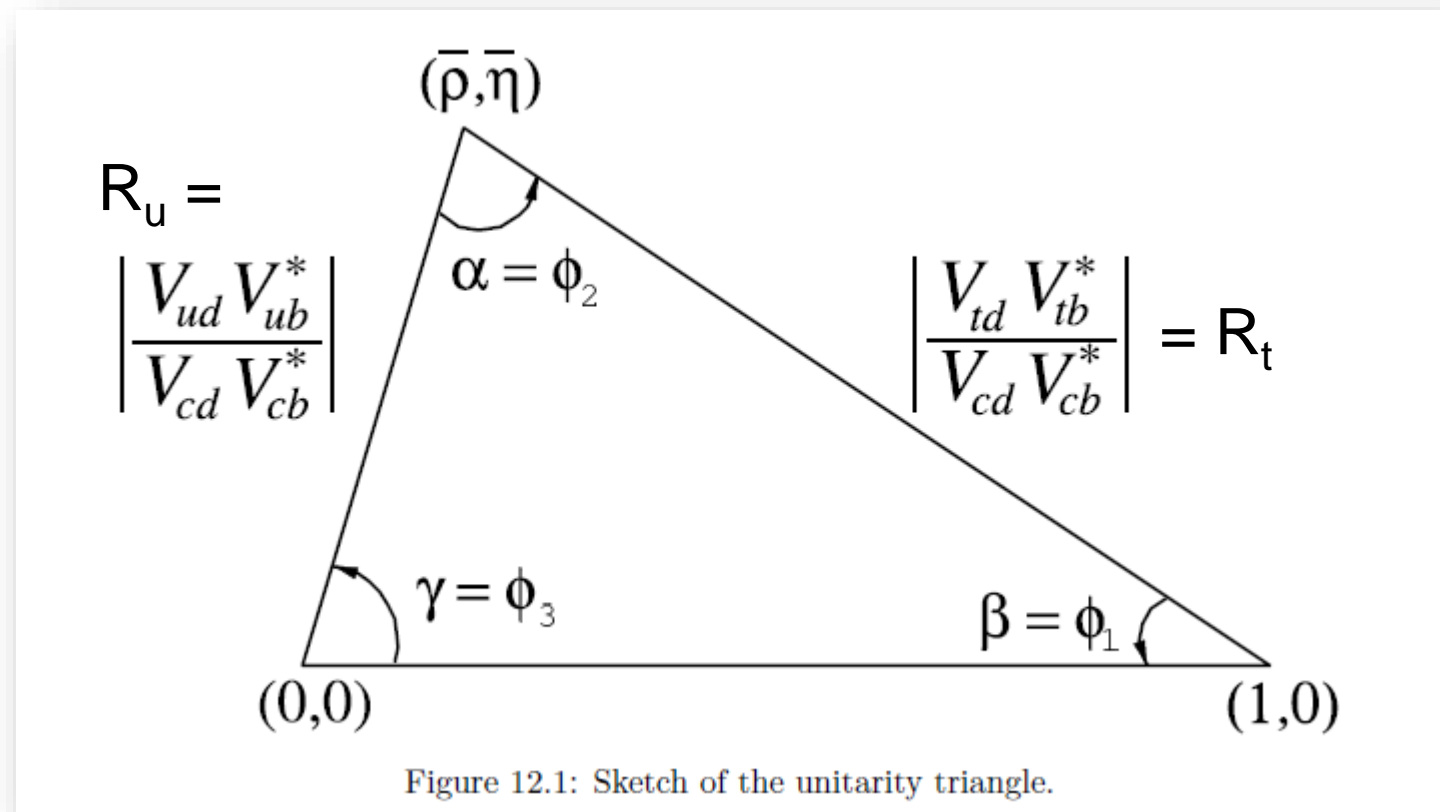
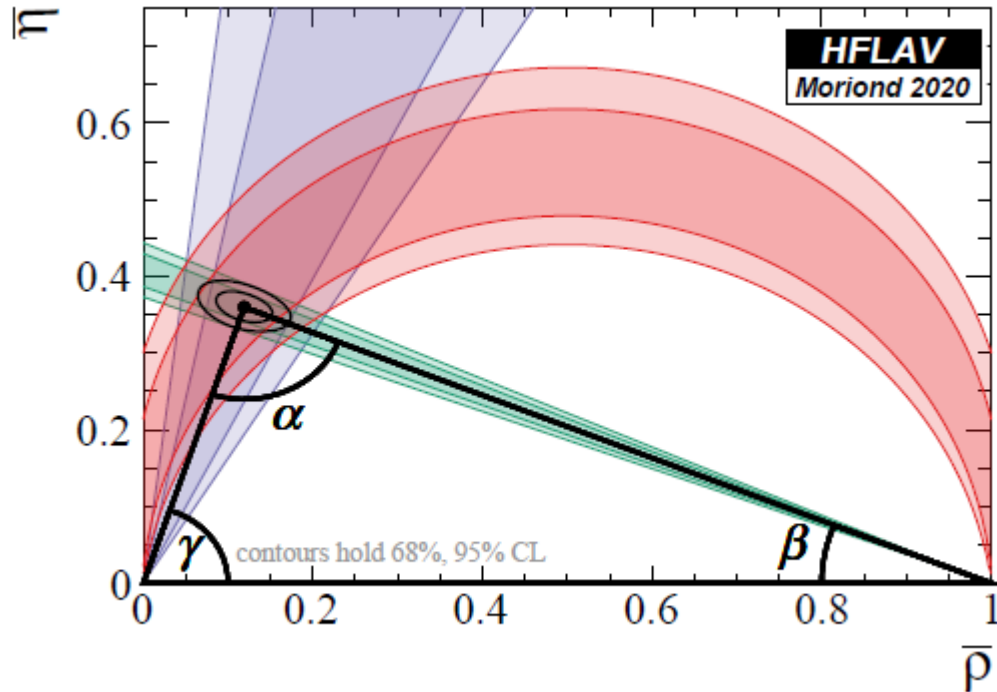


Figure 12.1: Sketch of the unitarity triangle.

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

Current Status of CKM Angles

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



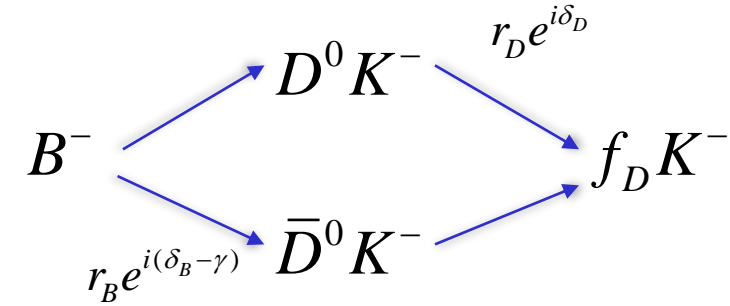
Prog. Theor. Exp. Phys. 2020 083C01
(2020)

- The measurement on γ has been improved nicely with LHCb data. However,
 - Direct measurement at tree level:
$$\gamma = 72.1_{-4.5}^{+4.1} \text{ deg}$$
 - Indirect calculation at loop level:
$$\gamma = 65.66_{-2.65}^{+0.9} \text{ deg}$$

(CKMFitter 2019 summer)
 - There is a 2σ 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”.

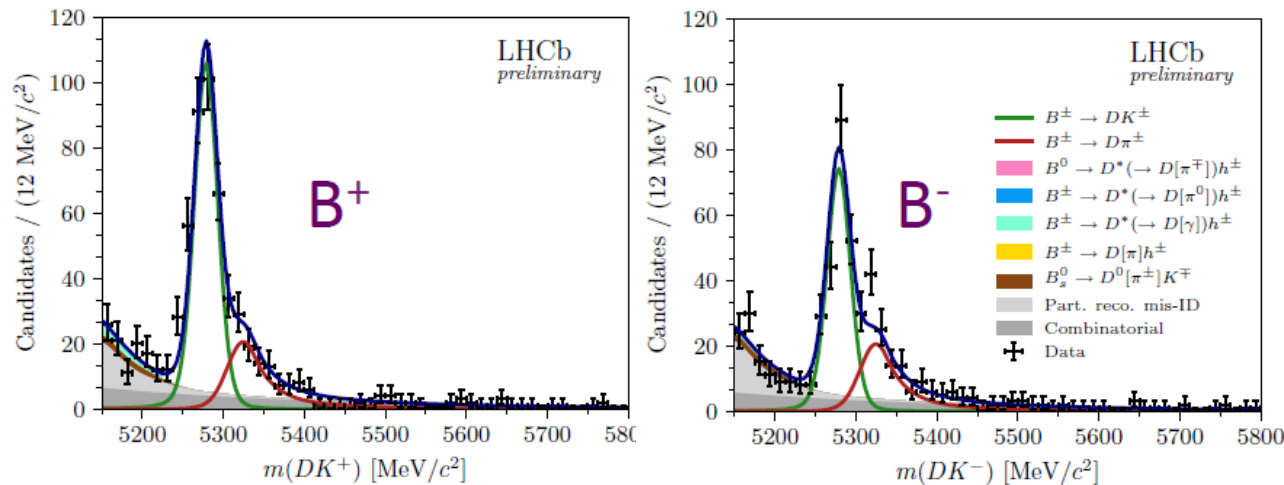
$$\delta\gamma / \gamma \approx O(10^{-7}) \text{ Brod \& Zupan, JHEP01, 051 (2014).}$$

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

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

Dalitz mass bin #4



<https://cds.cern.ch/record/2725936>

Preliminary LHCb $\gamma = (69 \pm 5)$ deg
with uncertainty $\sim 5(\text{stat}) \sim 1(\text{sys}) \sim 1(\text{ext})$ deg

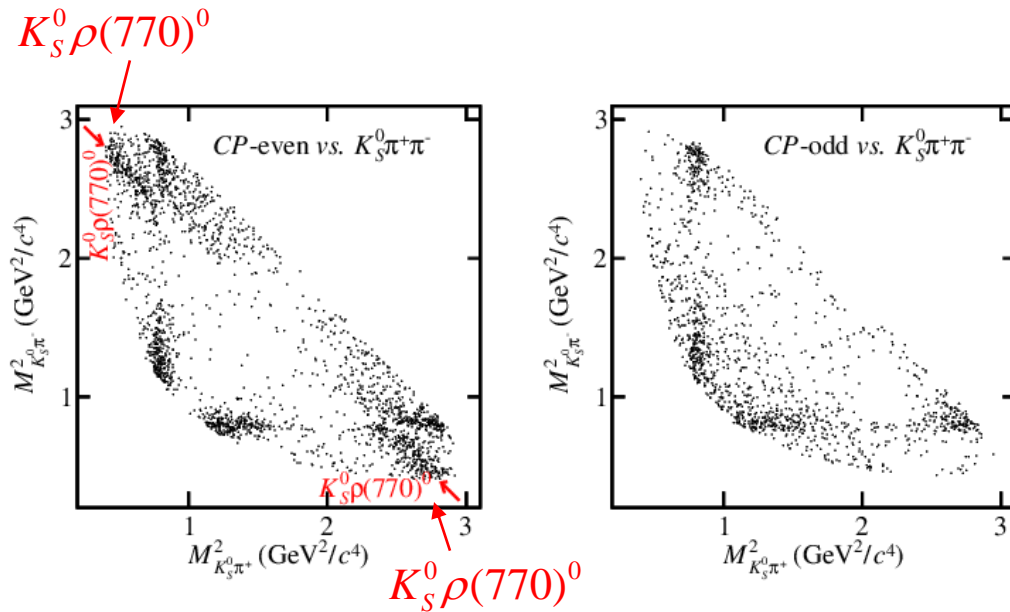
- CPV is observed clearly in $B \rightarrow DK$.
- This preliminary result is the most precise single measurement on γ .
(Talk Malde, July 30th)
- The last uncertainty is from δ_D (next slide)

Previous LHCb: $\gamma = (80_{-9}^{+10})$ deg
with uncertainty $\sim 9(\text{stat}) \sim 3(\text{sys}) \sim 4(\text{ext})$ deg

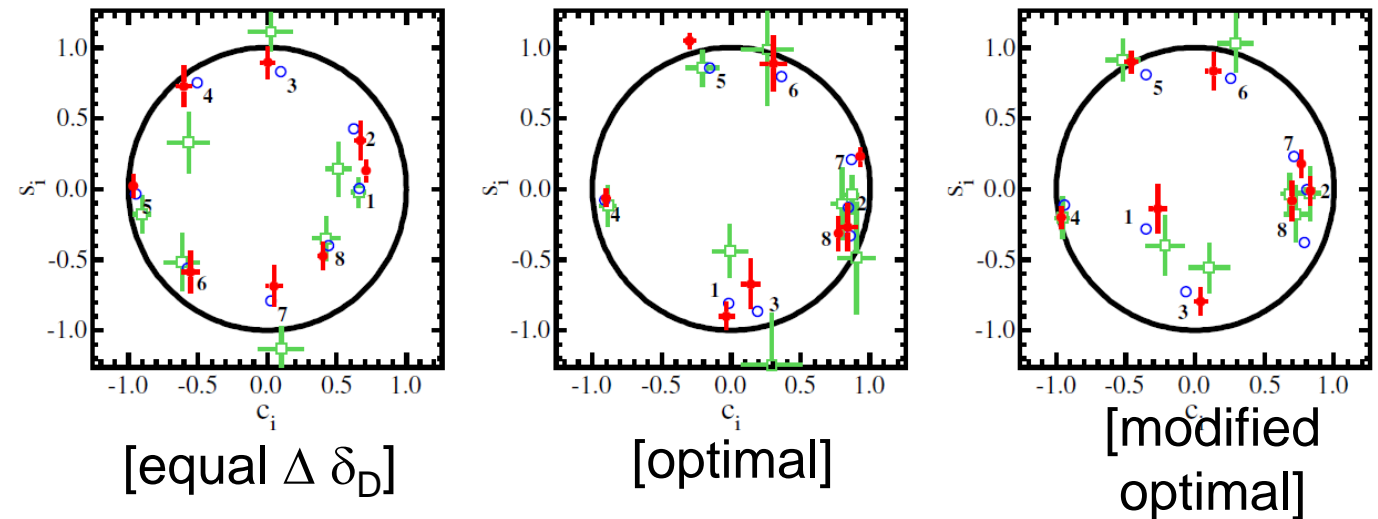
preliminary

Measurement of Strong Phase δ_D

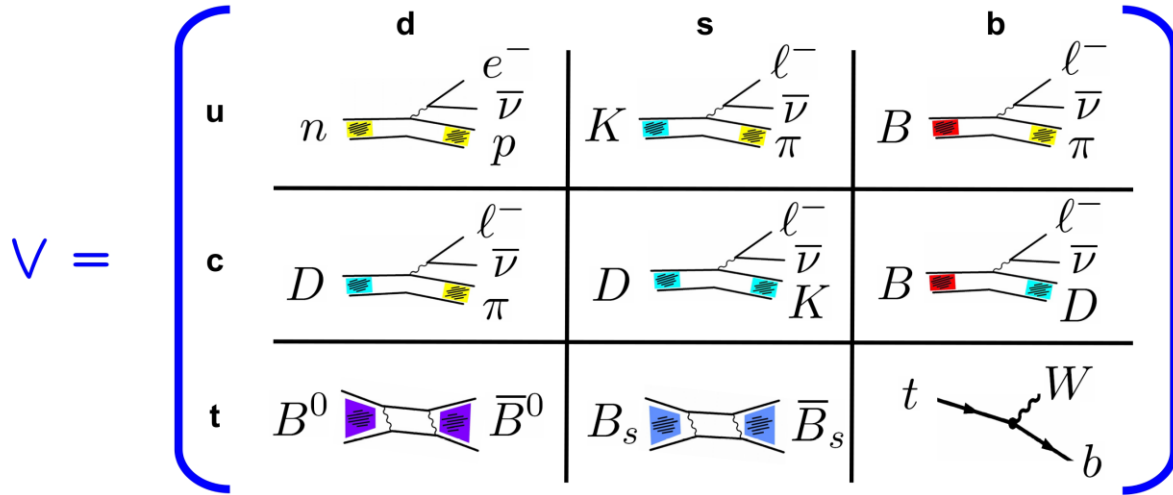
- Charm factories (CLEO-c, BES III) running at ψ (3770) create C- odd $D\bar{D}$ pairs (Quantum correlation).
 - If tag side \bar{D} is CP odd, then signal side D is CP even. And vice versa.
- BES III conducted Dalitz analysis of $D \rightarrow K_{S,L}^0 \pi^+ \pi^-$ and measured δ_D . Phys. Rev. Lett. 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



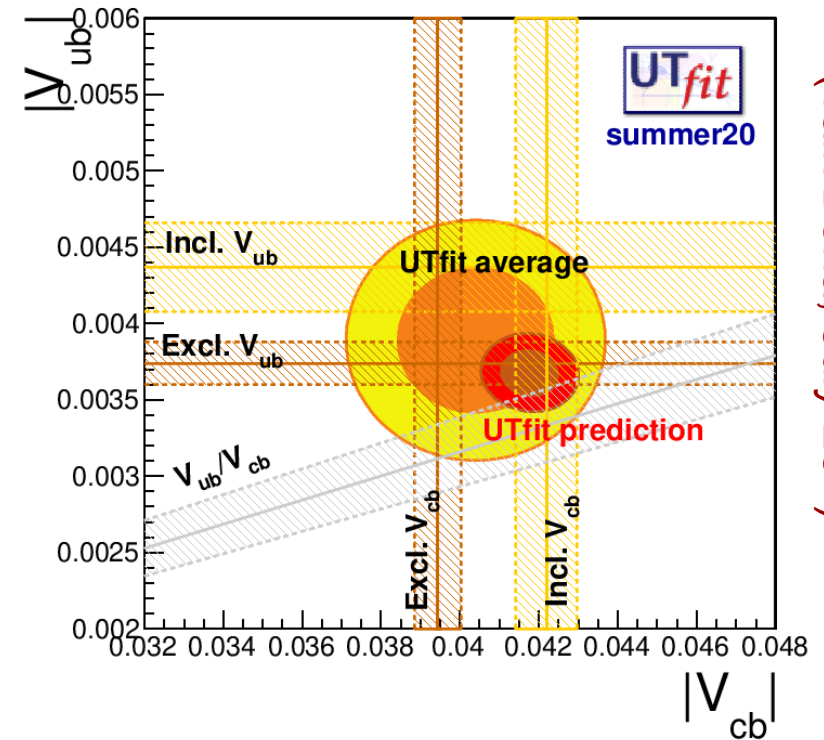
(Semi)-Leptonic Decays



- Semi-leptonic decay rates are described as

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

- 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.

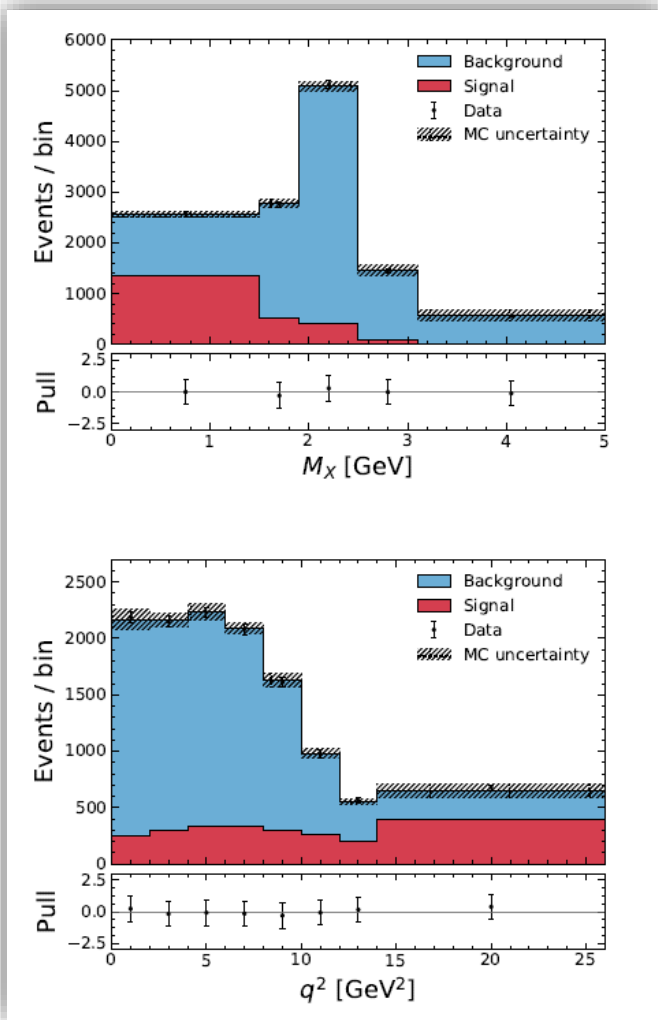


(Talk Bona, July 29th)

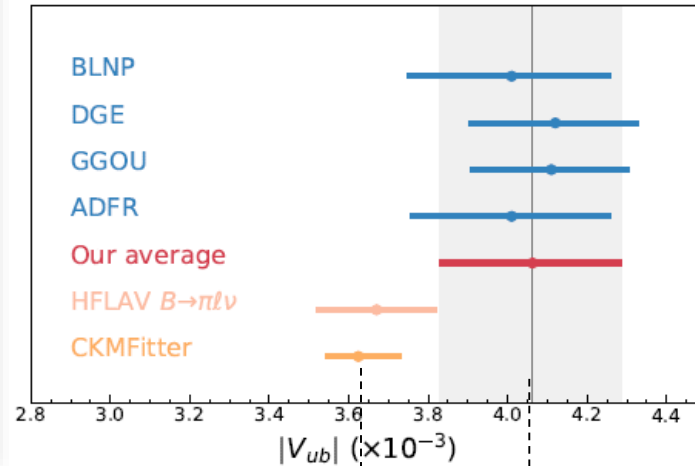
- Historically, V_{xb} measurements using **exclusive** and **inclusive** approaches did not agree very well, leading to speculations regarding new physics from e.g. right-handed currents.

V_{ub} : Inclusive Measurement

preliminary



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



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

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

(Talk Cao, July 30th)

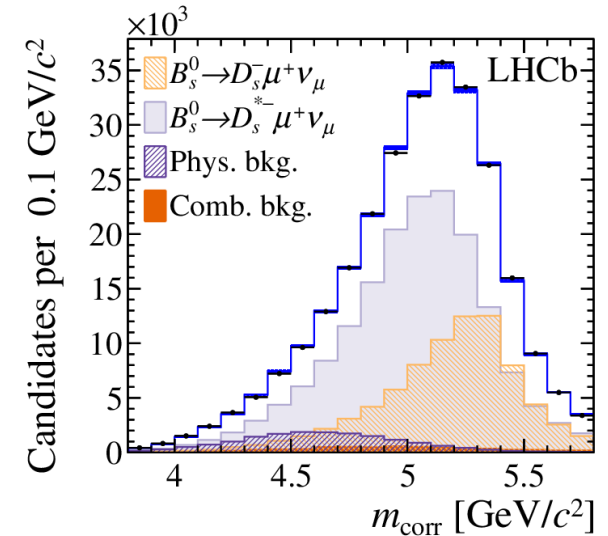
\longleftrightarrow 1.4 σ
 \longleftrightarrow 1.6 σ

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.



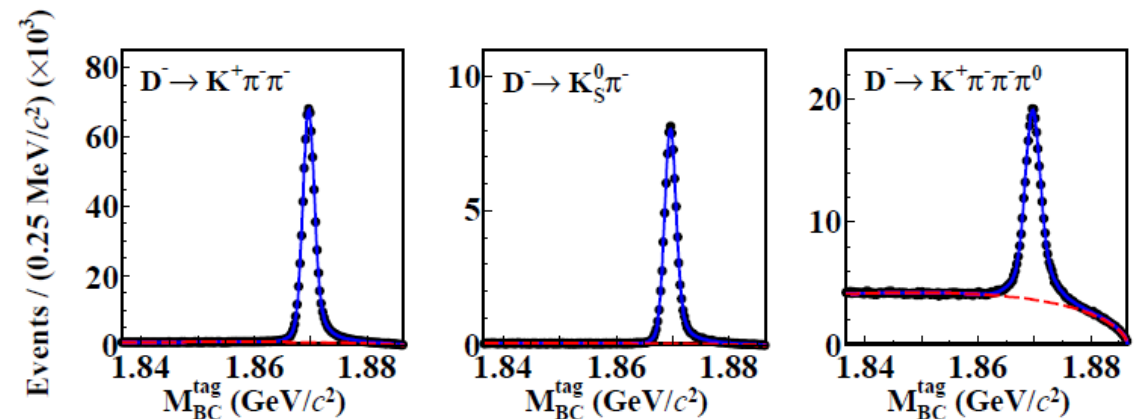
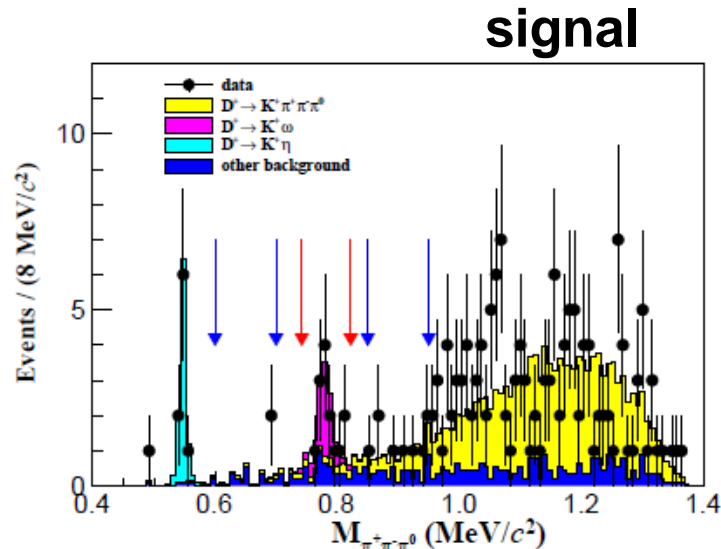
	V_{cb} BGL fit (10^{-3})	V_{cb} CLN fit (10^{-3})	Reference
Belle (B^0)	$38.3 \pm 0.2 \pm 0.7 \pm 0.6$ (ext)	$38.4 \pm 0.2 \pm 0.6 \pm 0.6$ (ext)	Phys. Rev. D 100, 052007 (2019)
BABAR (B^0)	38.36 ± 0.90	38.40 ± 0.84	Phys. Rev. Lett. 123, 091801 (2019) (Talk Simonetto, July 29 th)
LHCb (B_s)	$42.3 \pm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

$\tan \theta_c$ and Isospin: Old Issue but New Result

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

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

- This value is much larger compared to the other DCS/CF ratios. There may be a large isospin violation between $D^+ \rightarrow K^+ \pi^+ \pi^- \pi^0$ and $D^0 \rightarrow K^+ \pi^- \pi^- \pi^+$.
- There was no clear evidence of CPV in the charge asymmetry measurement.



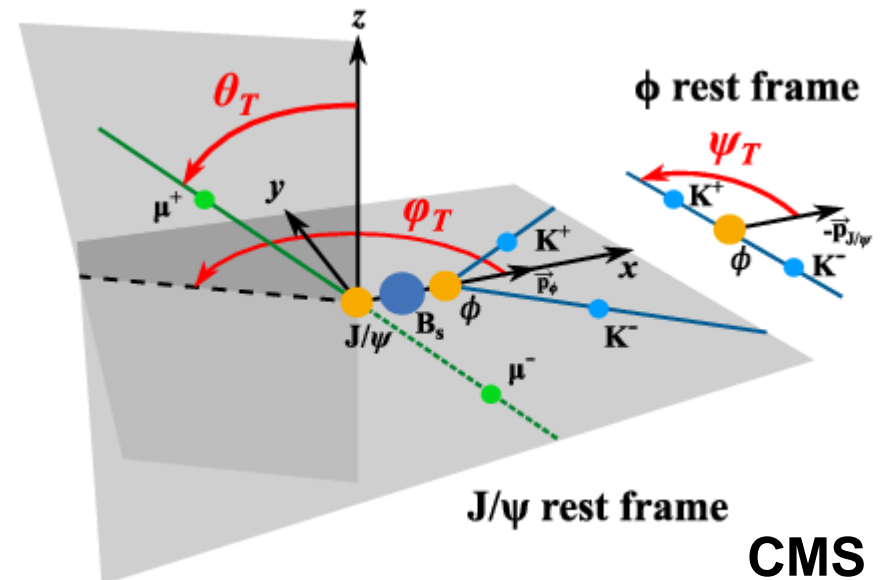
CPV

CPV phase ϕ_s in B_s mixing

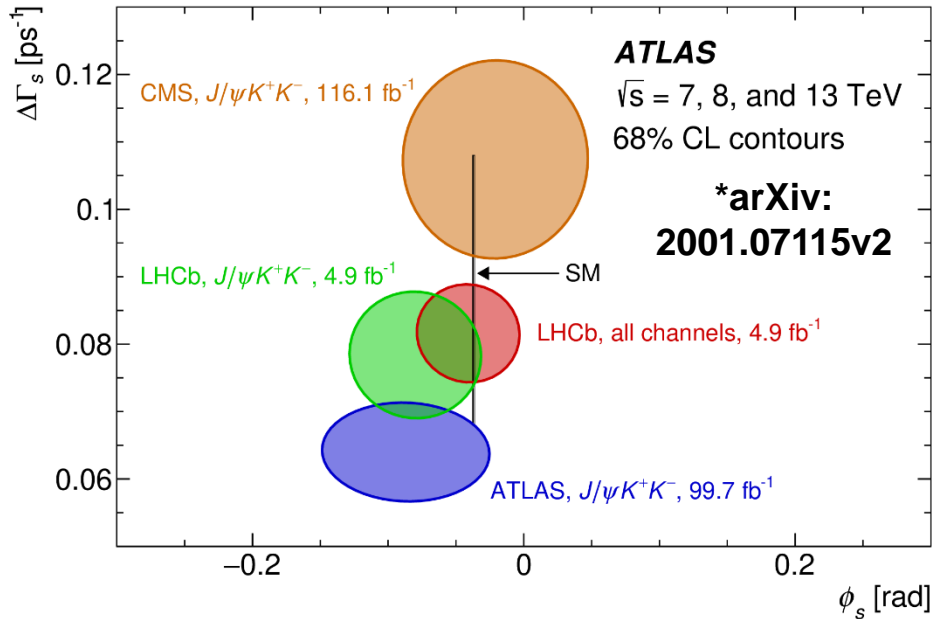
- ϕ_s is a CPV phase, which is a weak phase difference between the $B_s - \bar{B}_s$ mixing and the direct decay of B_s into a common final state.
- The golden mixing decay $B_s \rightarrow J/\psi \phi$, ($\phi \rightarrow K^+ K^-$) is well known, less complicated environment to measure the phase. (No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

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

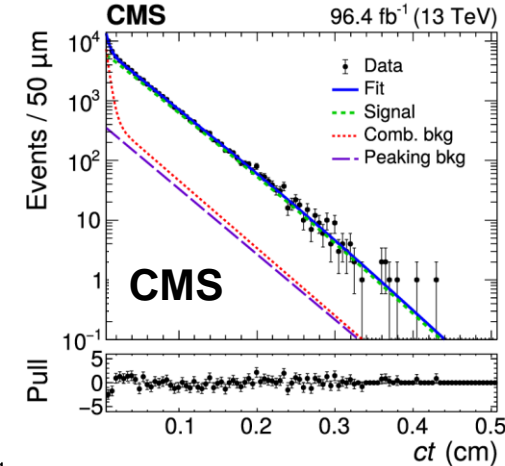
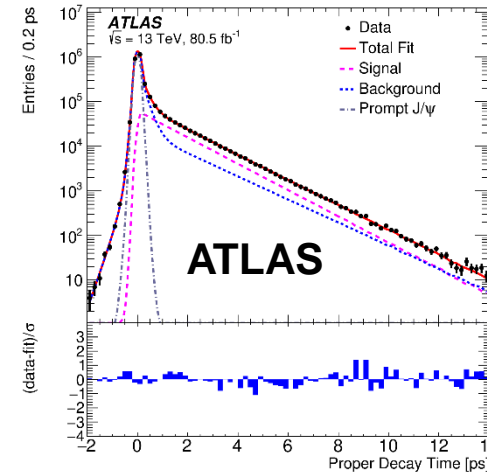
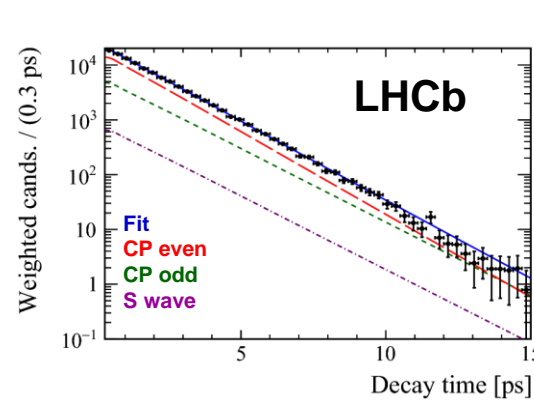
- At LHC experiments, the flavor of B_s is determined by Opposite Side Tagging (muon, electron, jet-charge) or Same Side Tagging (Kaon, LHCb only).



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



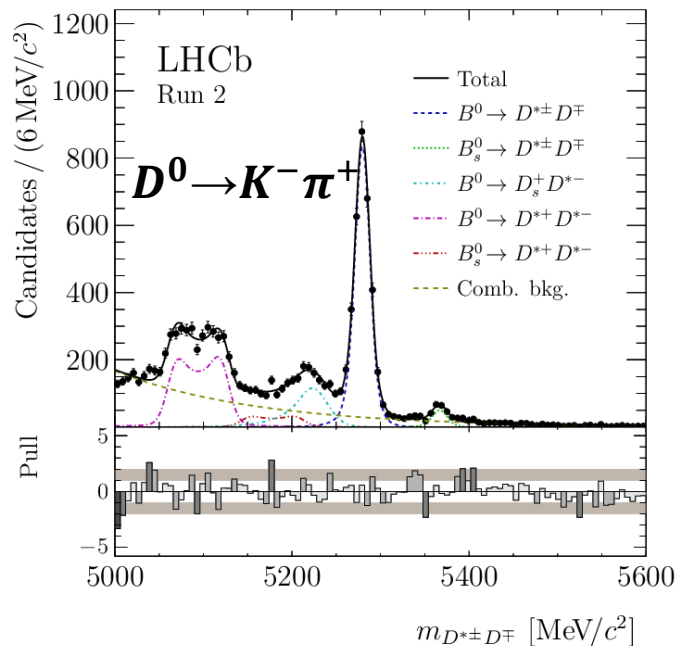
Decay time distributions



	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 30 th)	4.9
LHCb (all)	-42 ± 25	0.0813 ± 0.0048		
ATLAS	-87 ± 41	0.0641 ± 0.0049	arXiv: 2001.07115v2 (Talk, Jakoubek July 29 th)	99.7
CMS	-21 ± 45	0.1073 ± 0.0097	arXiv: 2007.02434 (Talk, Lusiani July 29 th + Poster, Alibordi July 29 th)	116.1
SM	$-36.96^{+0.72}_{-0.84}$	0.087 ± 0.0021	CKMFitter 2019 summer	

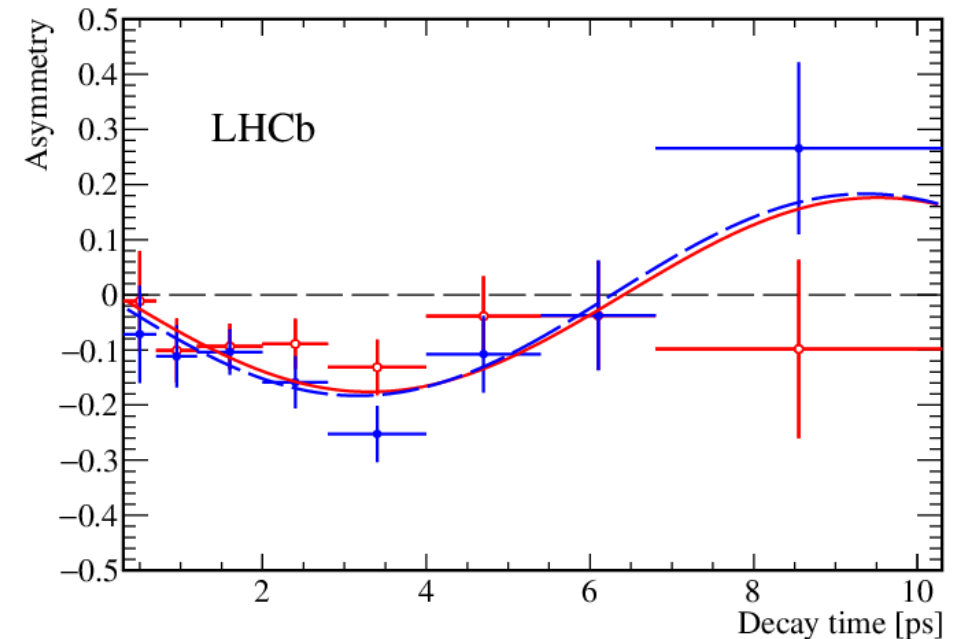
Time Dependent CPV in $B \rightarrow D^{*\pm} D^{\mp}$

- In the $B \rightarrow D^{*\pm} D^{\mp}$ 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 $D^{*+} \rightarrow D^0 \pi^+$ ($D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$, $D^0 \rightarrow K^- \pi^+$) and $D^- \rightarrow K^+ \pi^- \pi^-$.



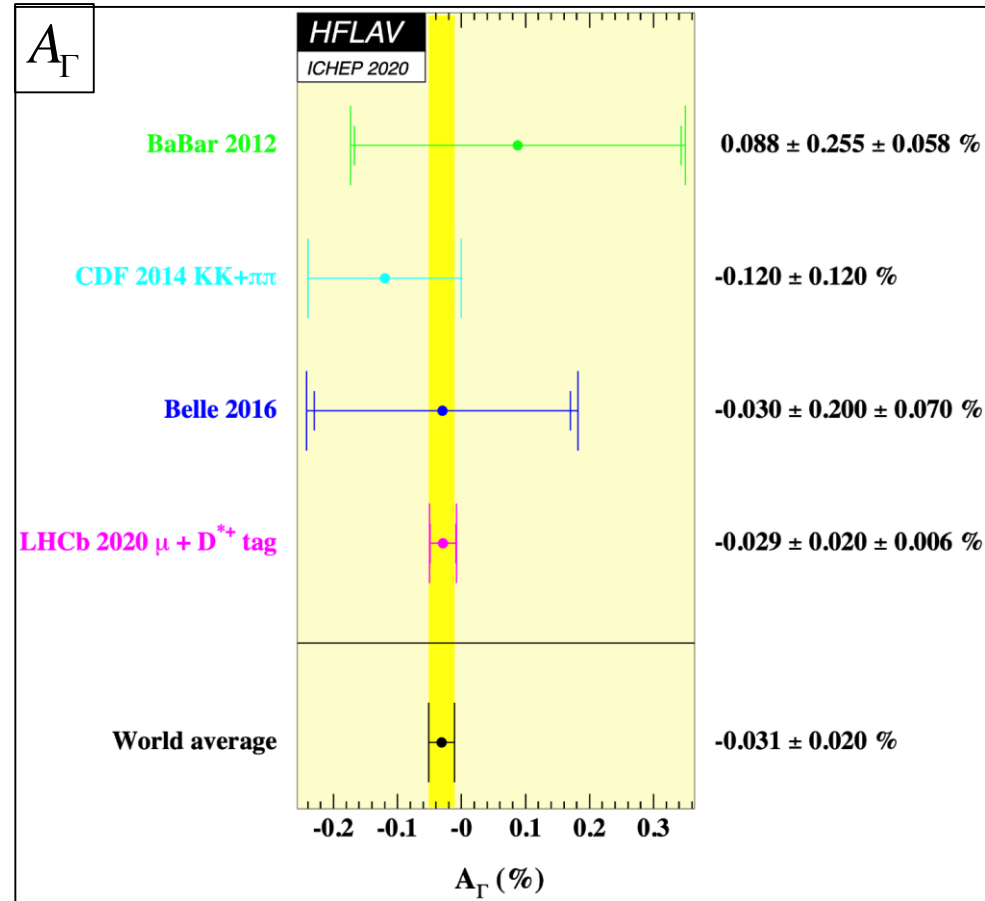
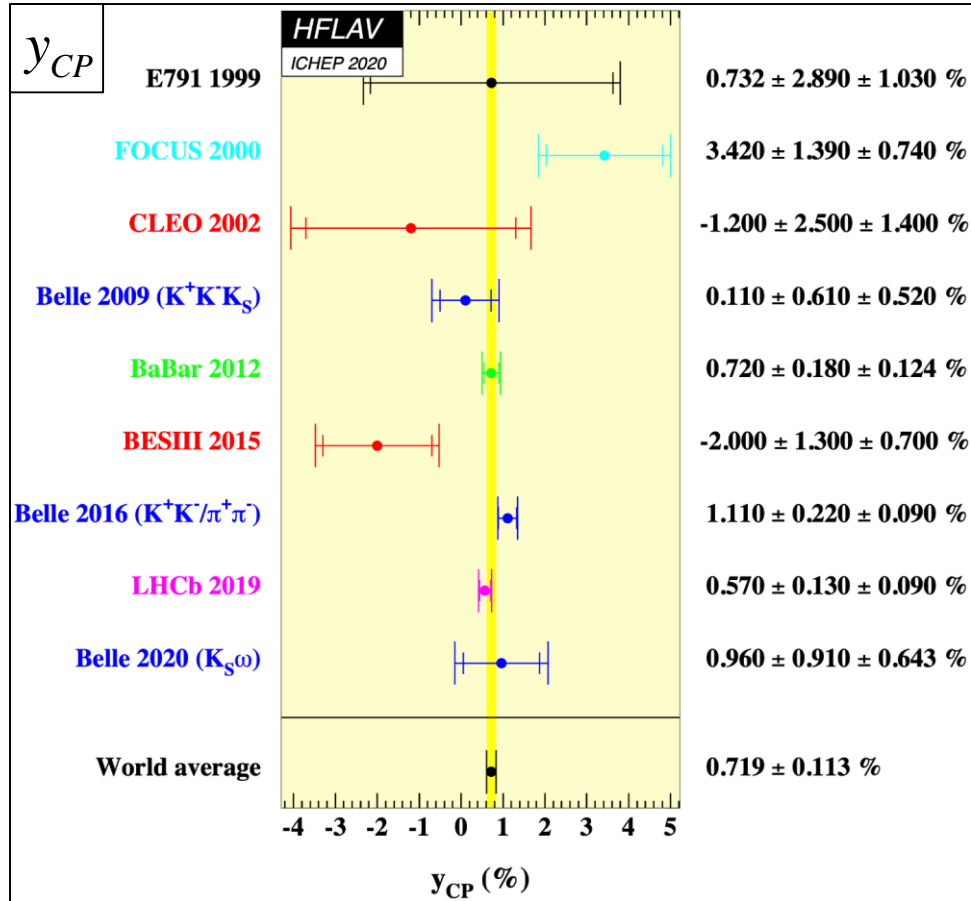
S_{D^*D}	$-0.861 \pm 0.077 \pm 0.019$
ΔS_{D^*D}	$0.019 \pm 0.075 \pm 0.012$
C_{D^*D}	$-0.059 \pm 0.092 \pm 0.020$
ΔC_{D^*D}	$-0.031 \pm 0.092 \pm 0.016$
A_{D^*D}	$0.008 \pm 0.014 \pm 0.006$

(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>

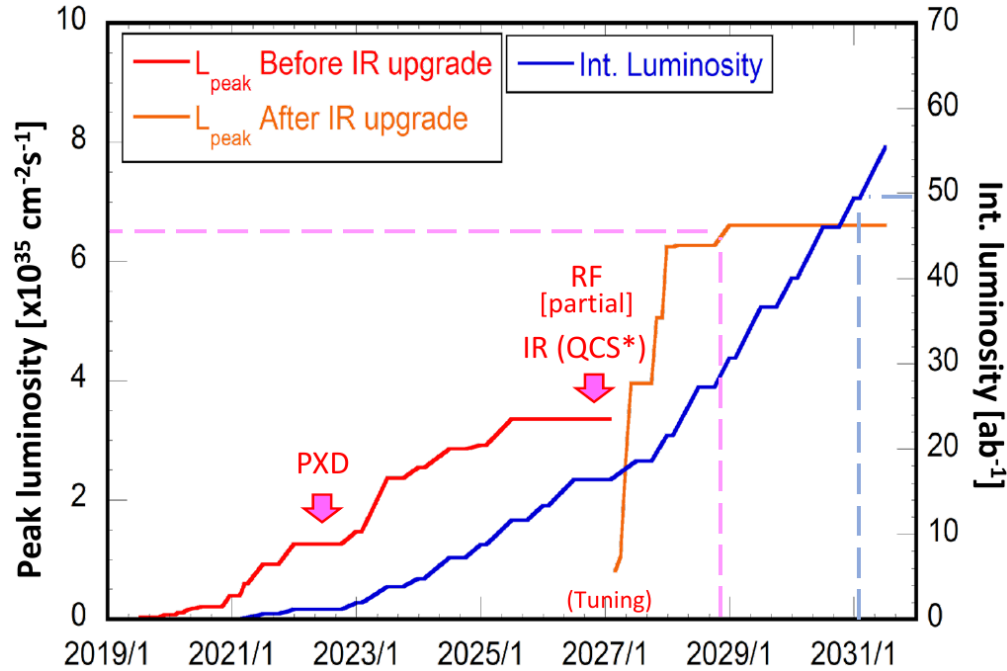


LHCb $D^0 \rightarrow K^+K^-$, $D^0 \rightarrow \pi^+\pi^-$ Phys. Rev. D 101, 012005 (2020) (Talk Tuci, July 30th)

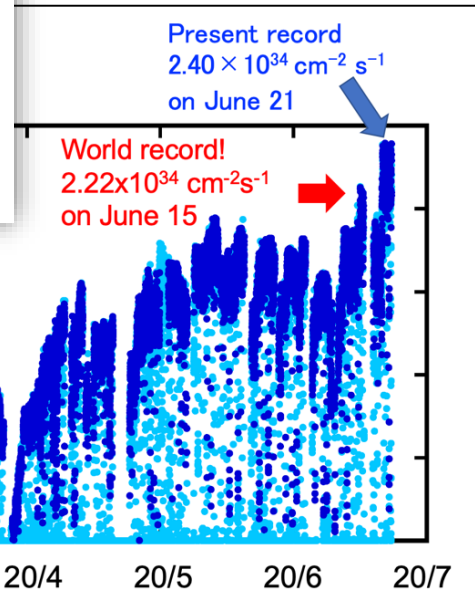
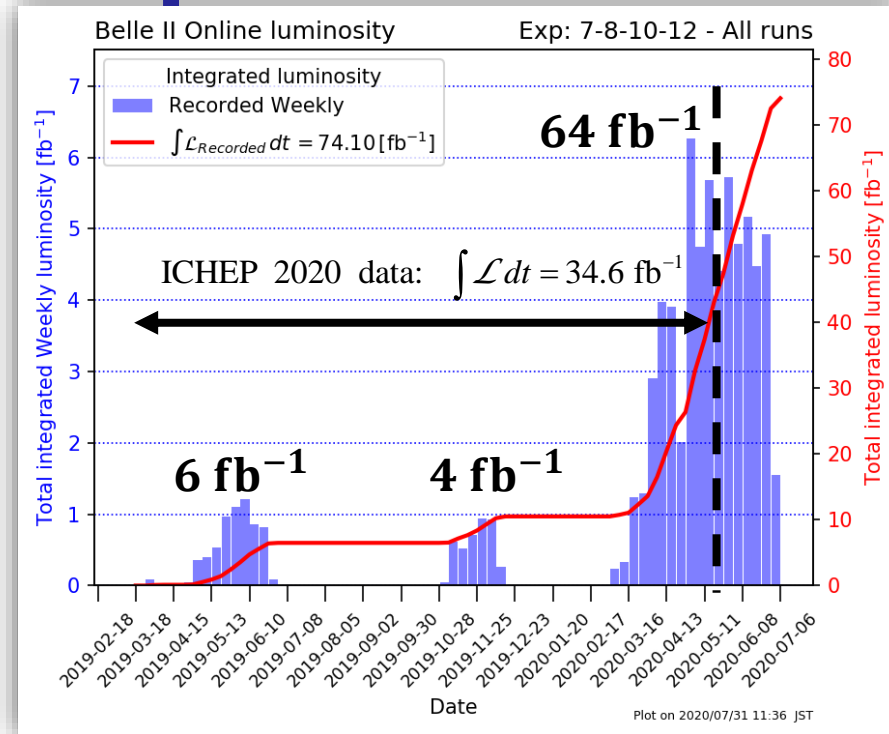
Belle $D^+ \rightarrow K_S^0\omega$ arXiv:1912.10912 (Talk Li, July 28th)

NEWS FROM BELLE II

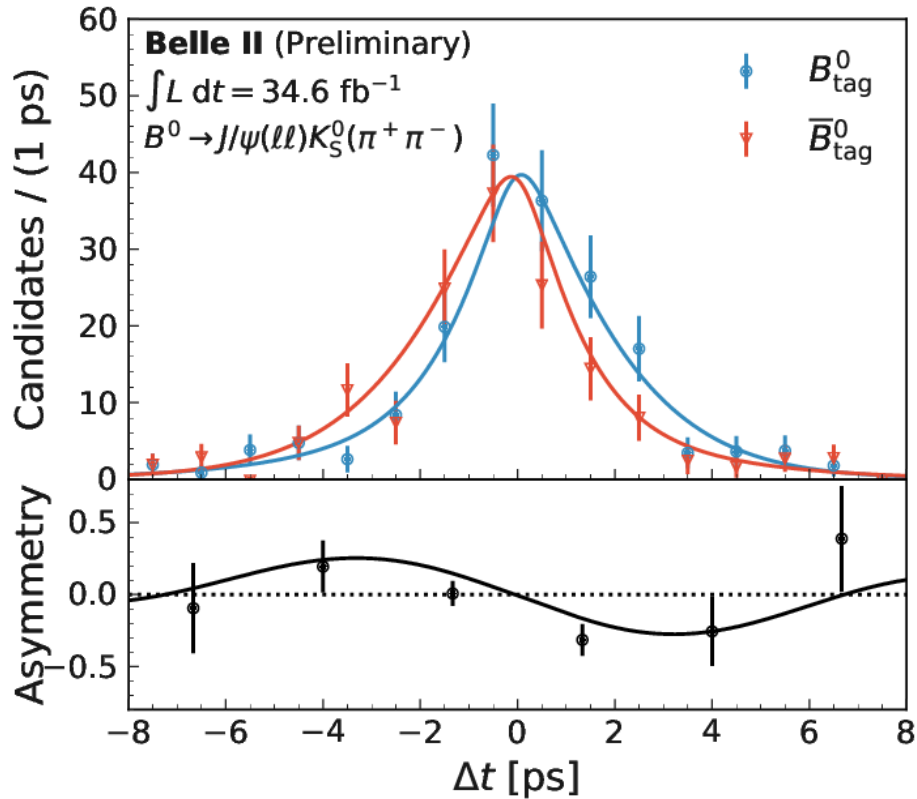
Belle II Luminosity: Proposed Plan and Status



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



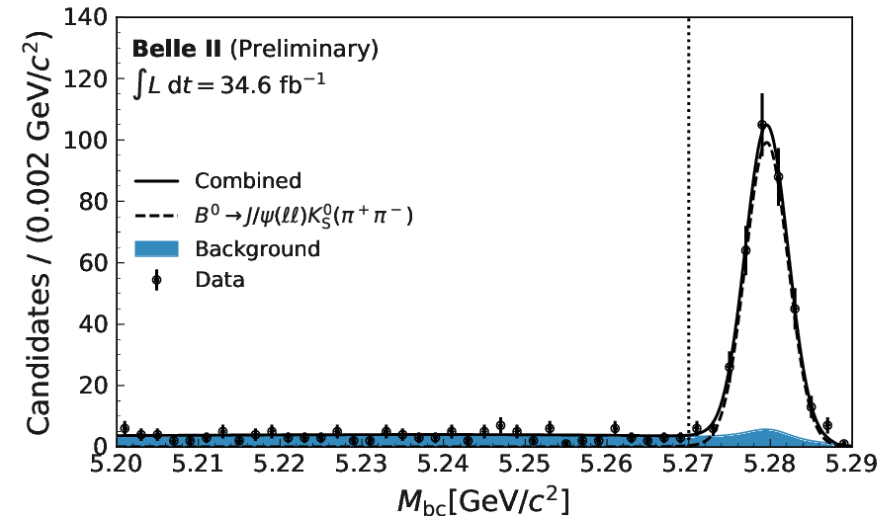
Time Dependent CPV and Mixing



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

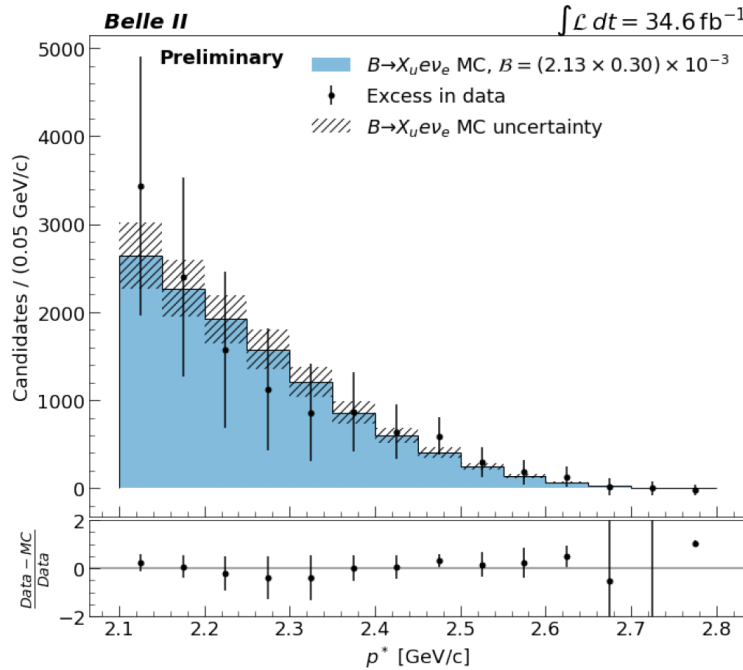
W. A.: $S_f \approx 0.691 \pm 0.017$.

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

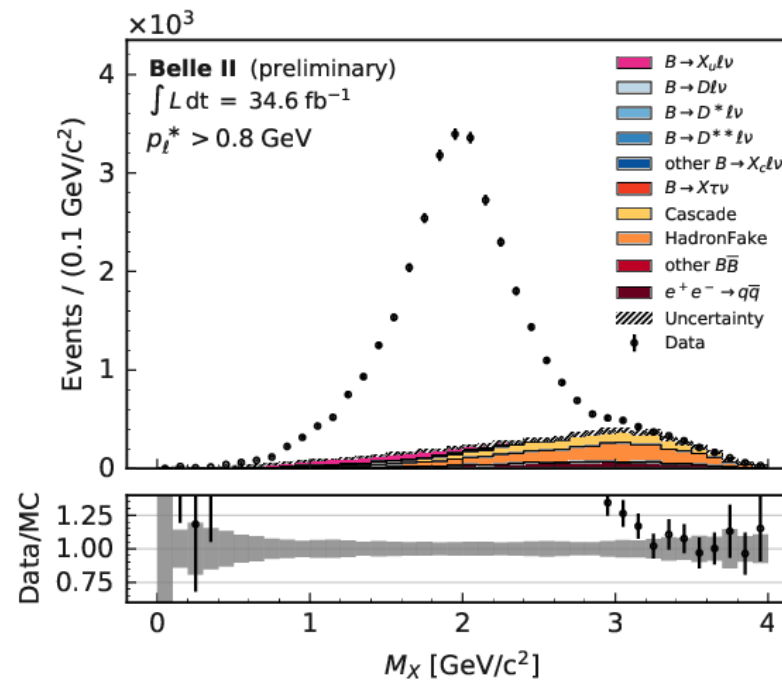


Toward V_{cb} and V_{ub} : Semi-Leptonic Decays

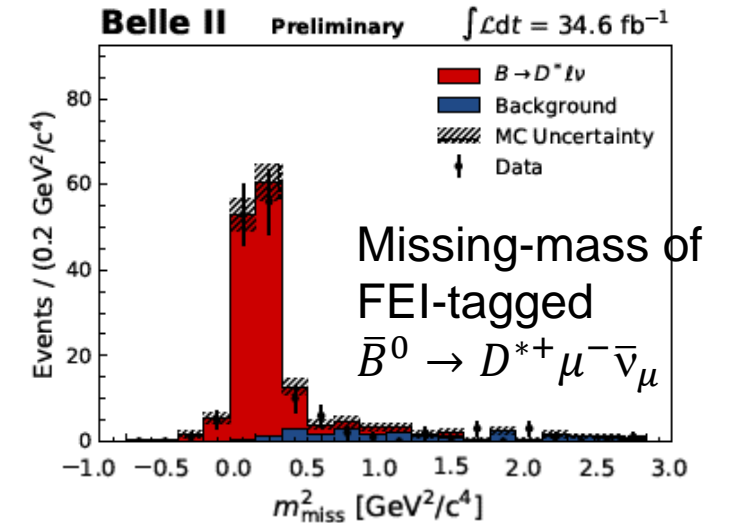
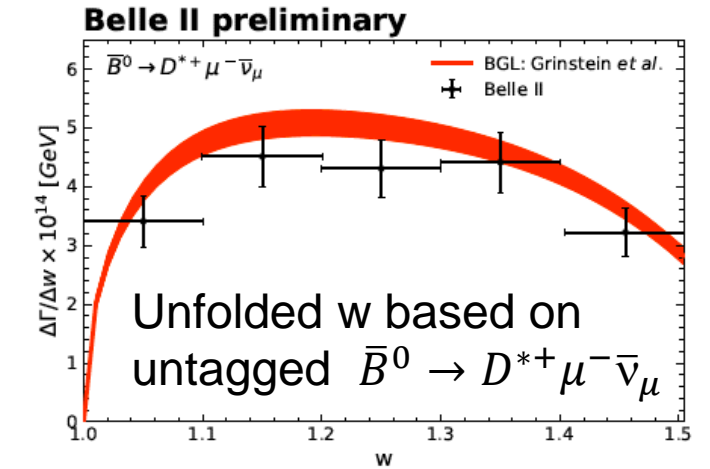
(Talk Cheaib, July 29th & poster Granderath, July 29th)



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



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



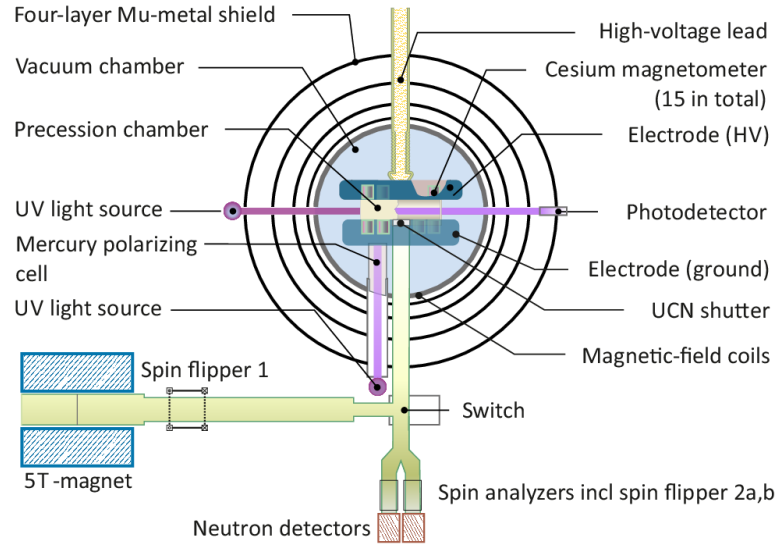
Summary

- 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.

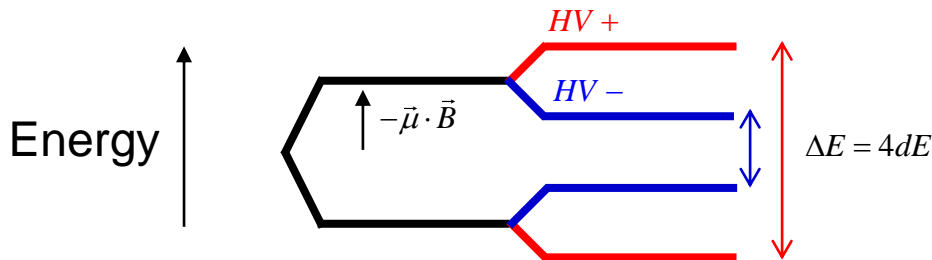


EXTRA

nEDM: neutron Electric Dipole Moment



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



(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.

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

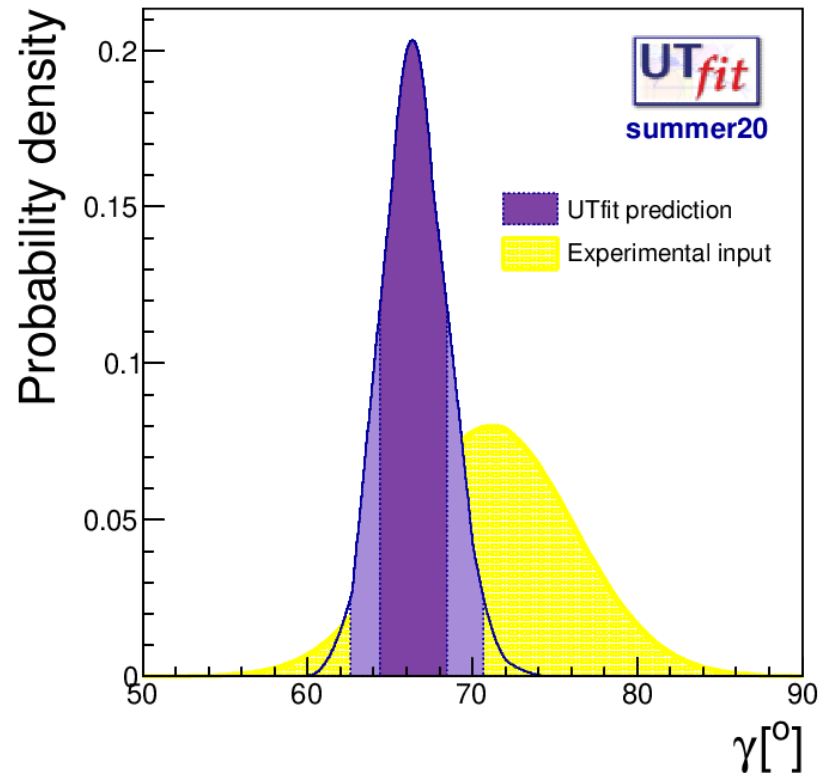
$$\Rightarrow |d_n| < 1.8 \times 10^{-26} e.cm \text{ (90\% C.L.)}$$

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

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

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

UTfit Update of γ : ICHEP 2020



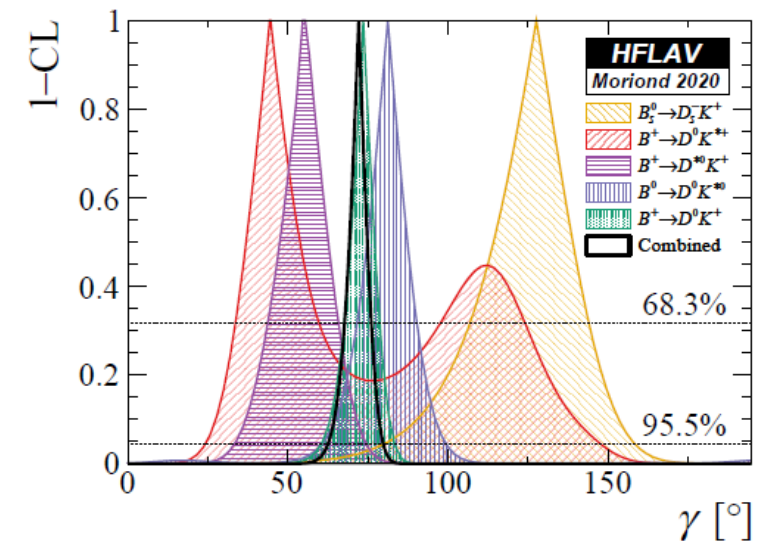
- Plot courtesy: Marcella Bona

Input: HFLAV $\gamma(\text{exp}) = (71.1 \pm 5.0)$ deg

Output: UTfit prediction $\gamma = (66.4 \pm 2.0)$ deg

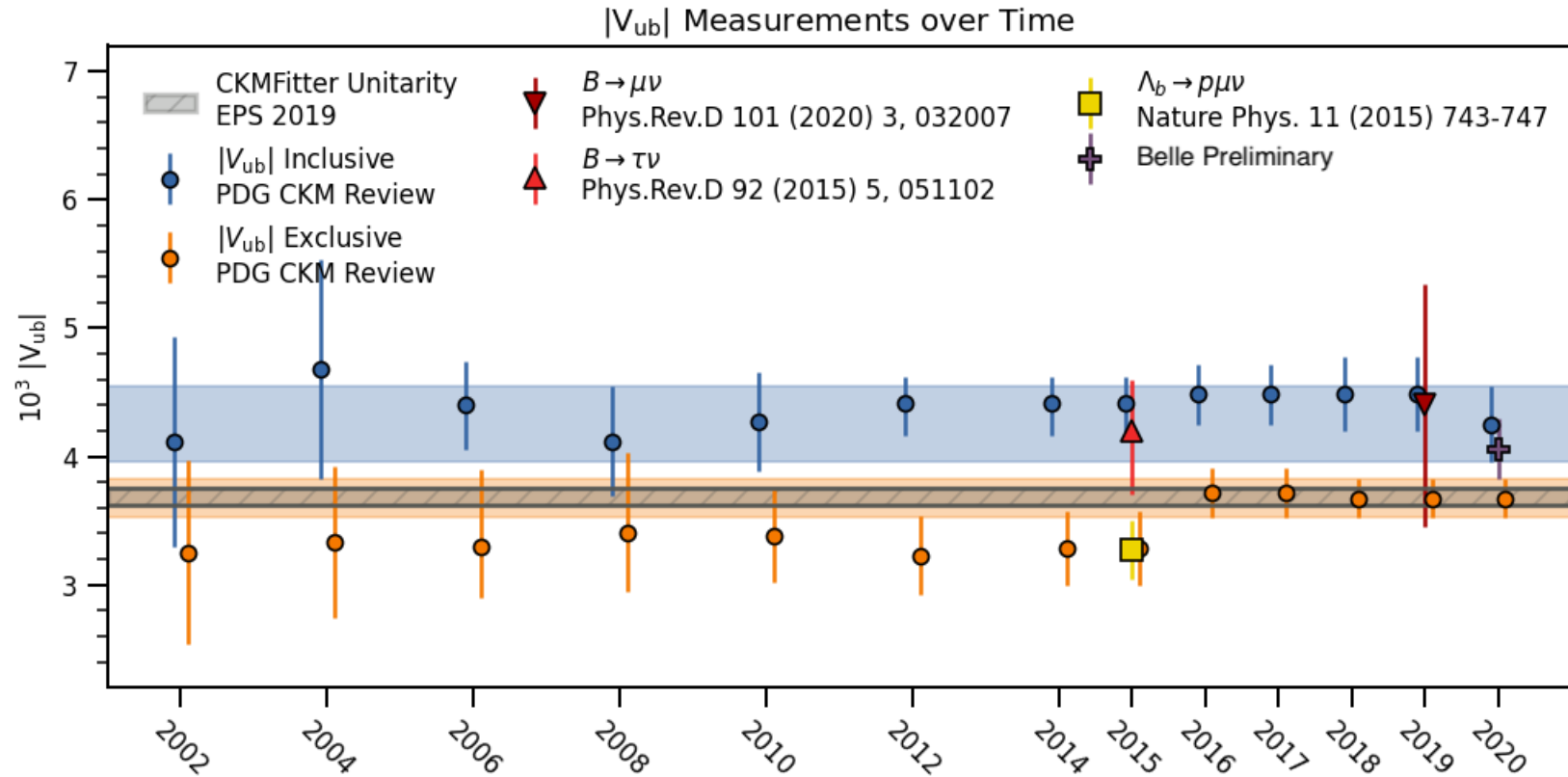
Final D Category for Measurement of γ

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



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

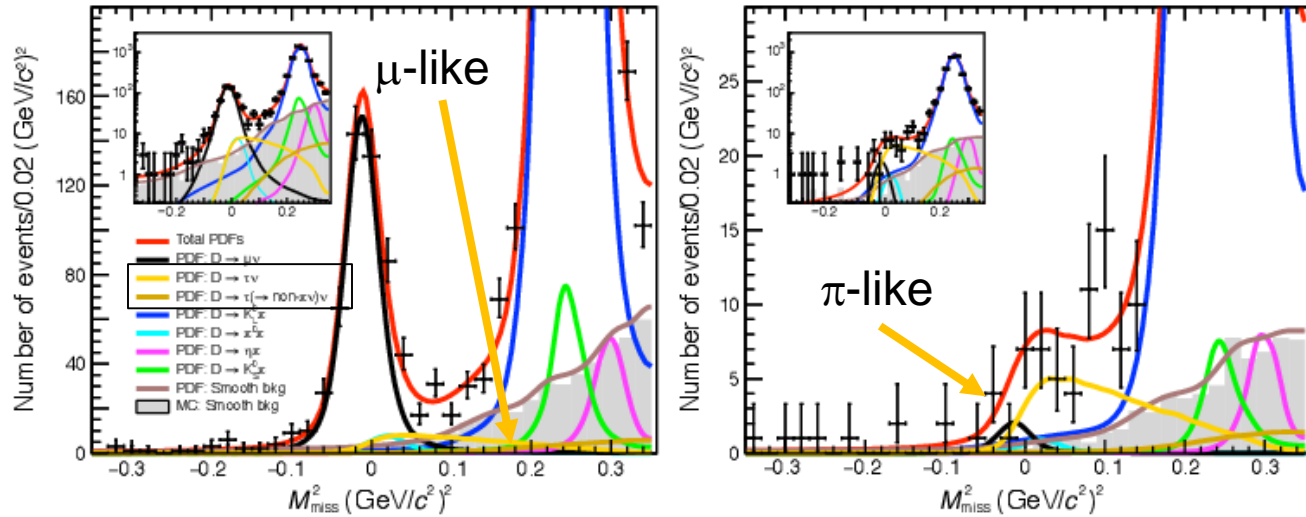
History of V_{ub} Measurements



- Plot courtesy: Belle
- Also <https://hflav-eos.web.cern.ch/hflav-eos/semi/summer16/html/InclusiveVub/inclXuInu.html>

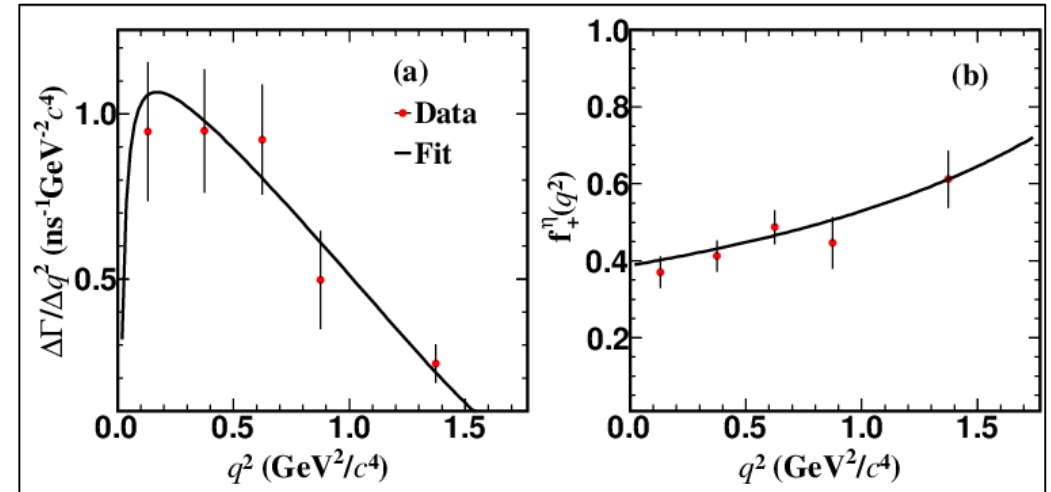
Other (Semi)-Leptonic Decays

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



- 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)

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



- 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 $|V_{cd}| = 0.221 \pm 0.004$