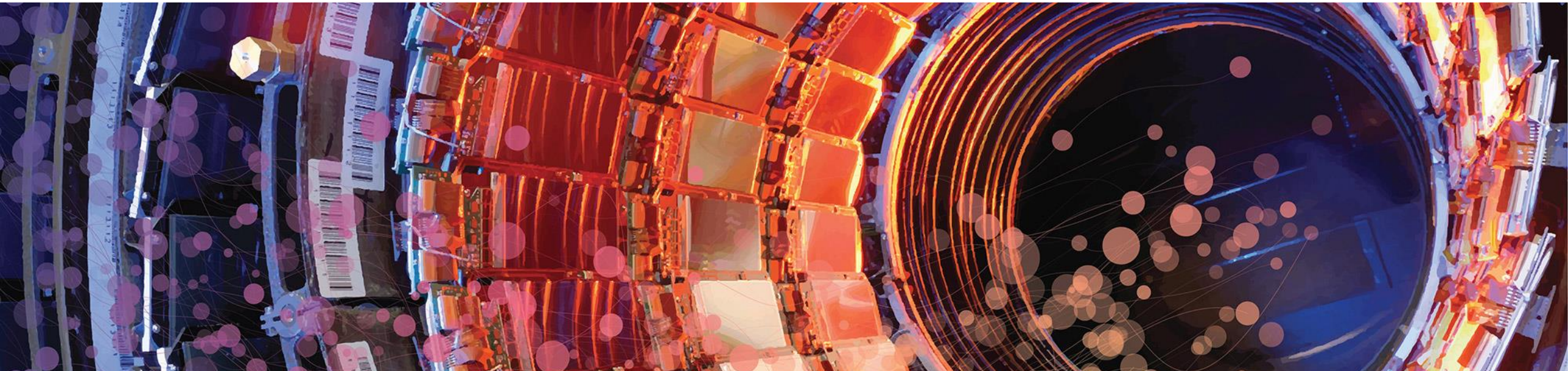


# CKM and CPV: Experimental Overview

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  - Time dependent analyses
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- Summary

**Disclaimer:**

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

# CKM

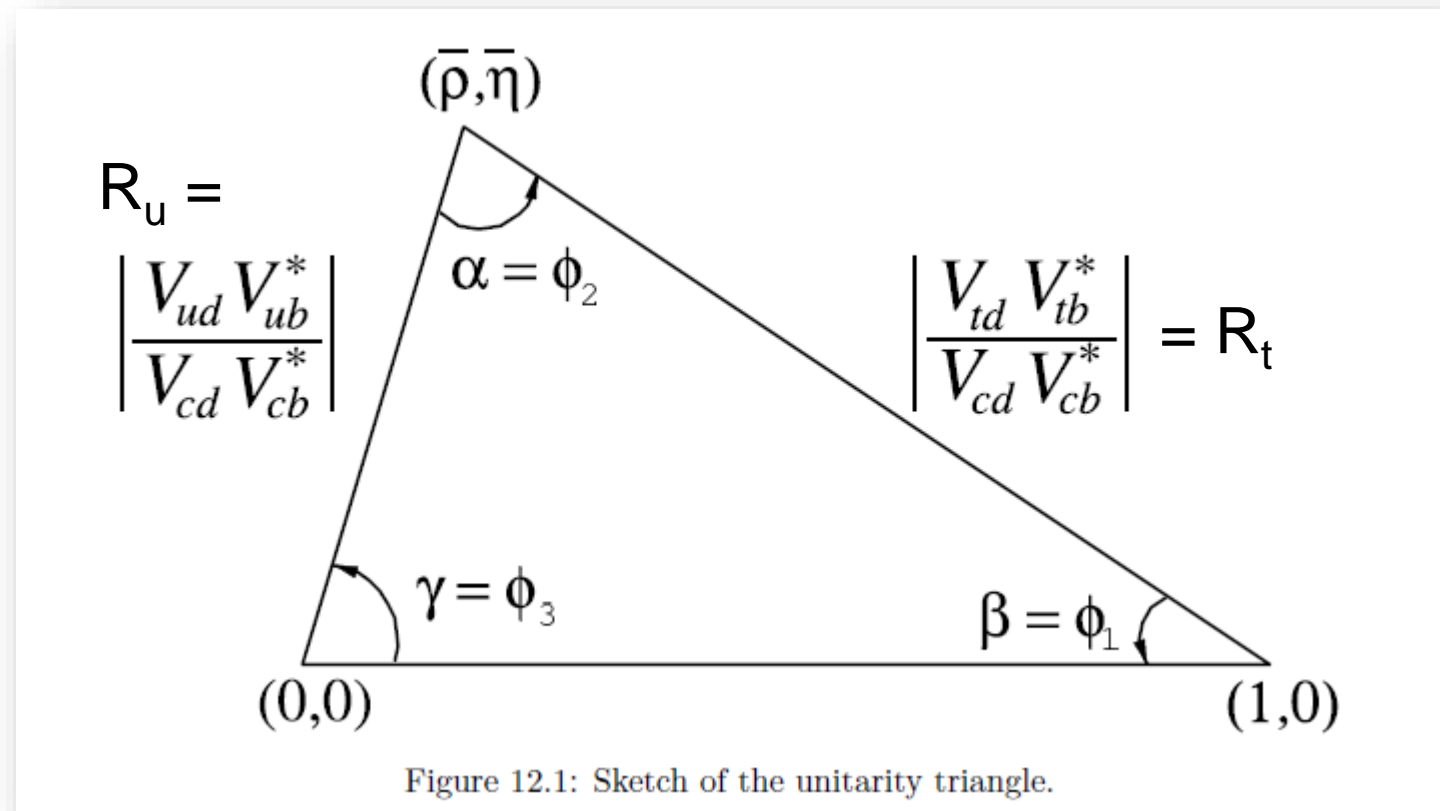
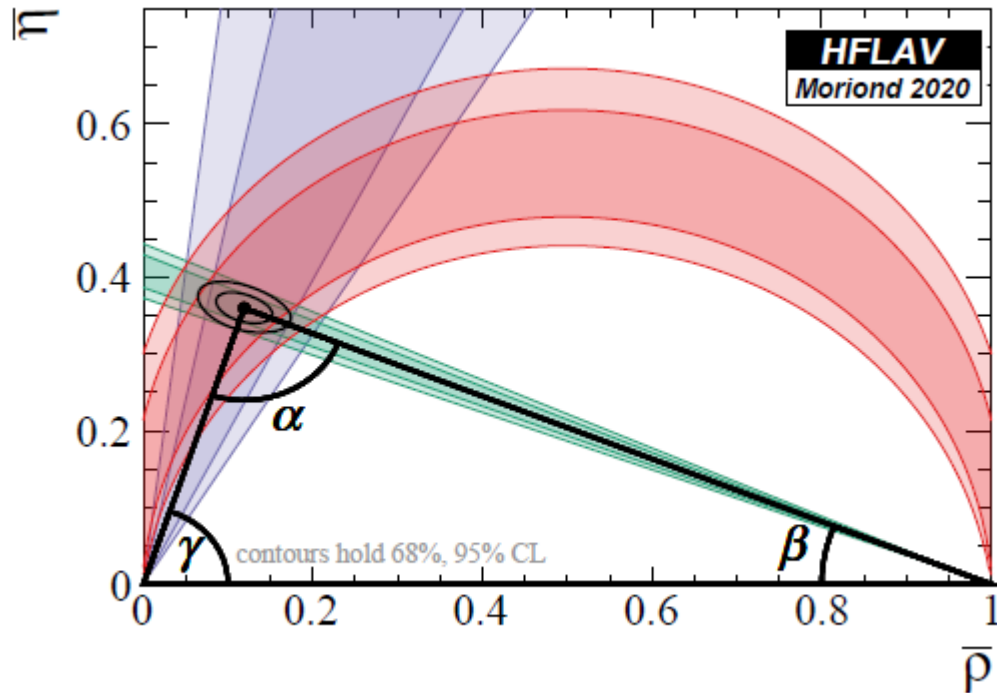


Figure 12.1: Sketch of the unitarity triangle.

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

# Current Status of CKM Angles

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

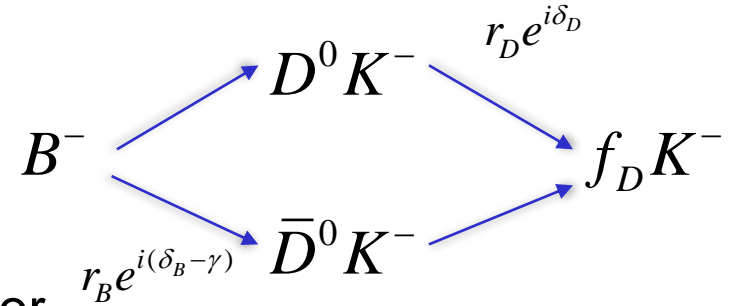


Prog. Theor. Exp. Phys. 2020 083C01  
(2020)

- The measurement on  $\gamma$  has been improved nicely with LHCb data. However,
  - Direct measurement at tree level:
$$\gamma = 72.1_{-5.7}^{+5.4} \text{ deg}$$
  - Indirect calculation at loop level:
$$\gamma = 65.66_{-2.65}^{+0.9} \text{ deg}$$(CKMFitter 2019 summer)
- There is a  $2\sigma$  tension between the values, which could be an indication for New Physics.

# The CKM Angle $\gamma$

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



- $\gamma$  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).

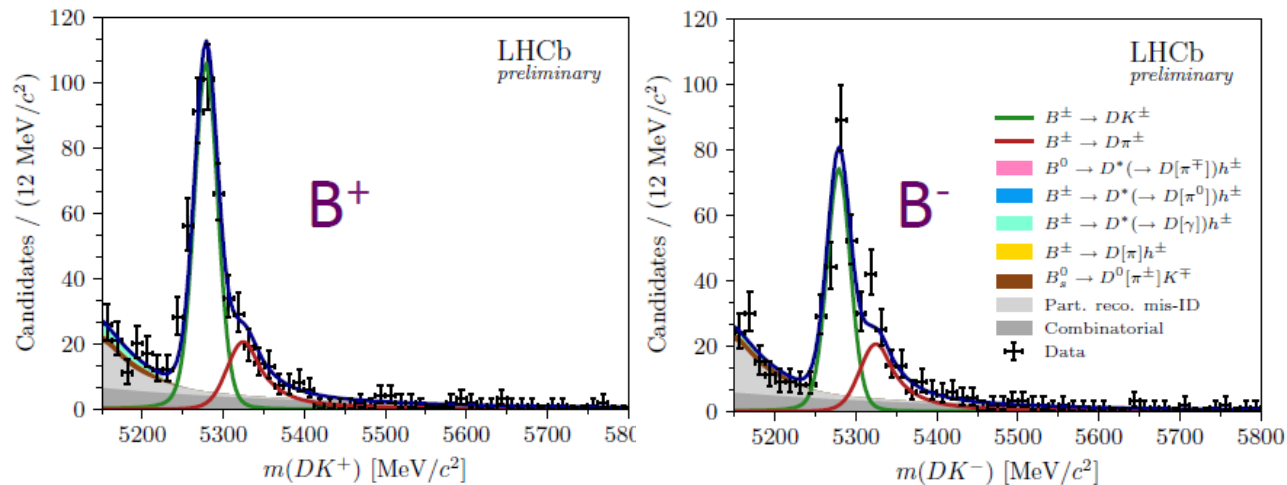
- Experimentally, not so simple:
  - Uses hadronic B decay channels with small branching fractions; sizable LHCb data sets incredibly useful.
  - Modes involving neutrals need Belle (II) data.
  - Analyses need inputs from other beauty and charm experiments (CLEO-c, BES III)
  - Strategy: Measure  $\gamma$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

preliminary

Dalitz mass bin #4



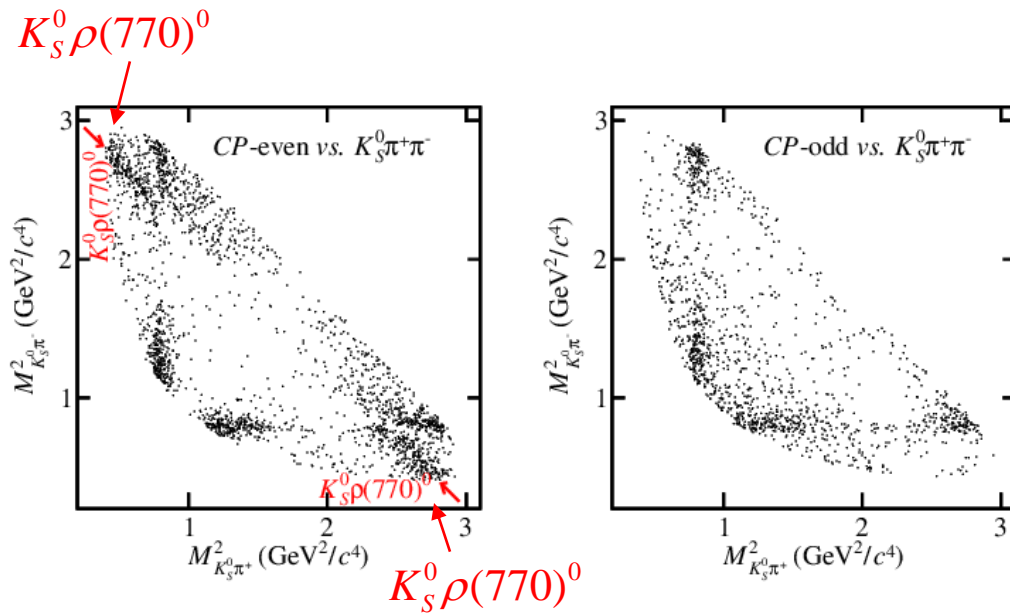
Preliminary LHCb

$$\gamma = (69 \pm 5 \pm 1 \pm 1) \text{ deg}$$

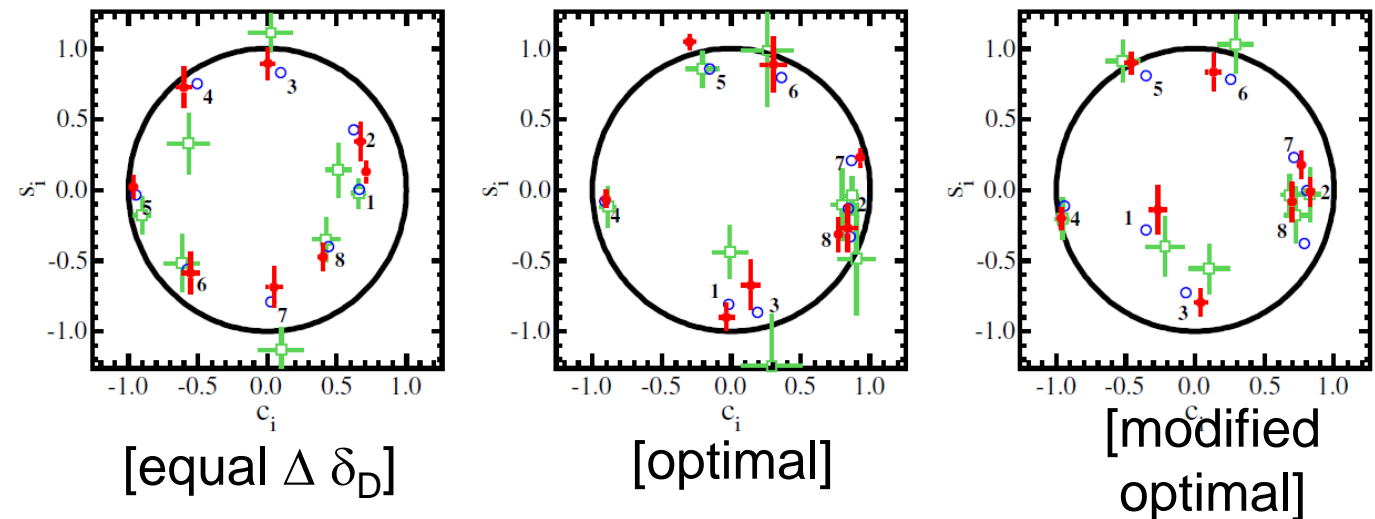
- CPV is observed clearly in  $B \rightarrow DK$ .
- This preliminary result is the most precise single measurement on  $\gamma$ .  
(Talk Malde, July 30<sup>th</sup>)
- The last uncertainty is from  $\delta_D$  (next slide)

# Measurement of Strong Phase $\delta_D$

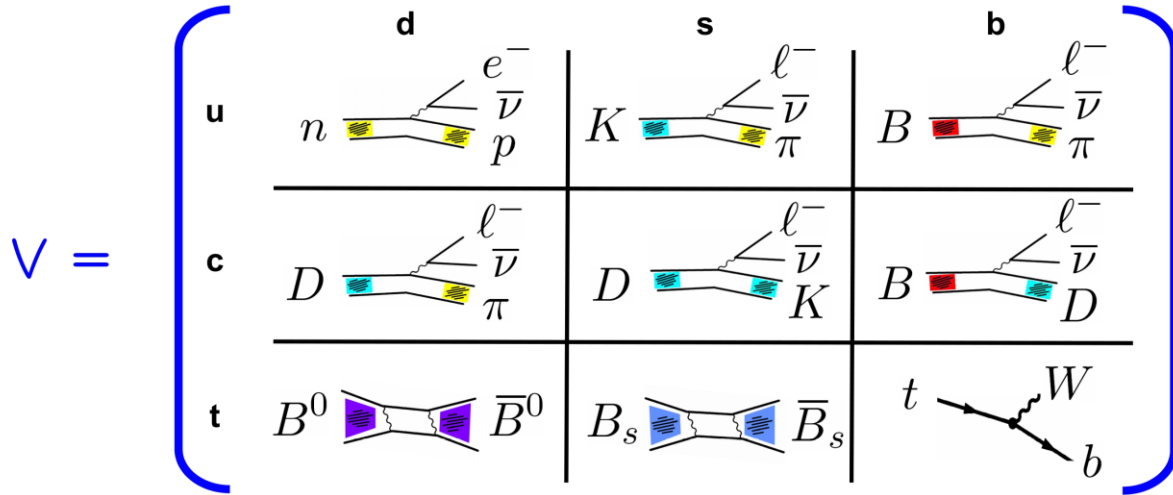
- Charm factories (CLEO-c, BES III) running at  $\psi$  (3770) create C- odd  $D\bar{D}$  pairs (Quantum correlation).
  - If tag side  $\bar{D}$  is CP odd, then signal side  $D$  is CP even. And vice versa.
- BES III conducted Dalitz analysis of  $D \rightarrow K_{S,L}^0 \pi^+ \pi^-$  and measured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



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



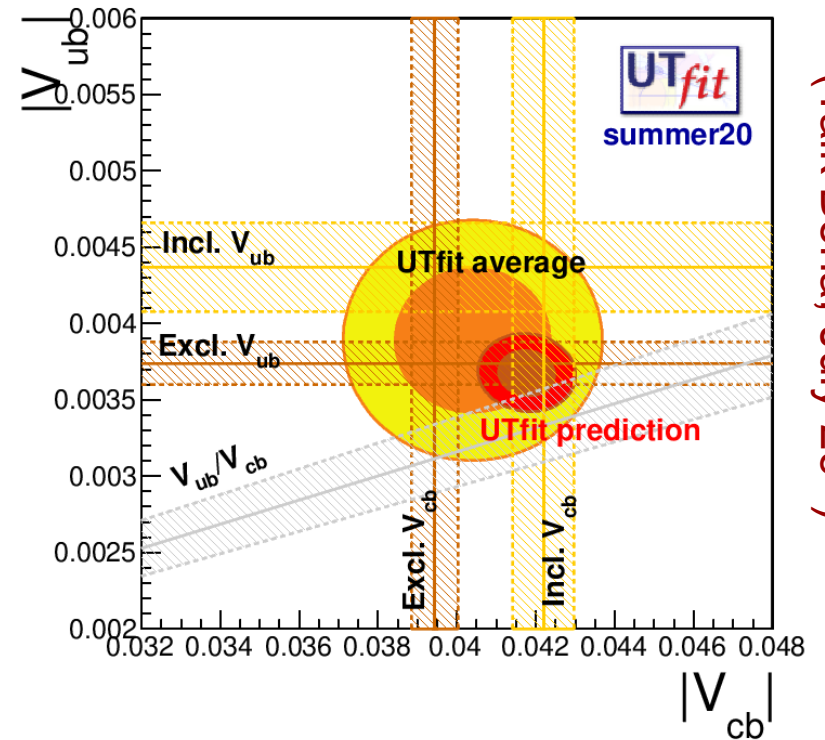
# (Semi)-Leptonic Decays



- 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.



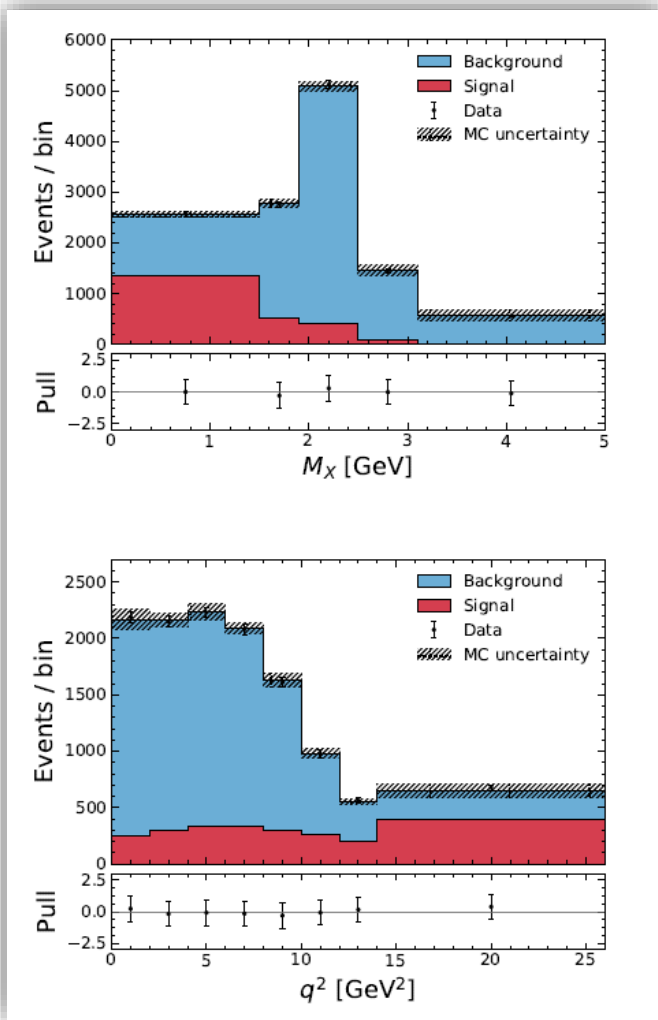
(Talk Bona, July 29<sup>th</sup>)

- 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.

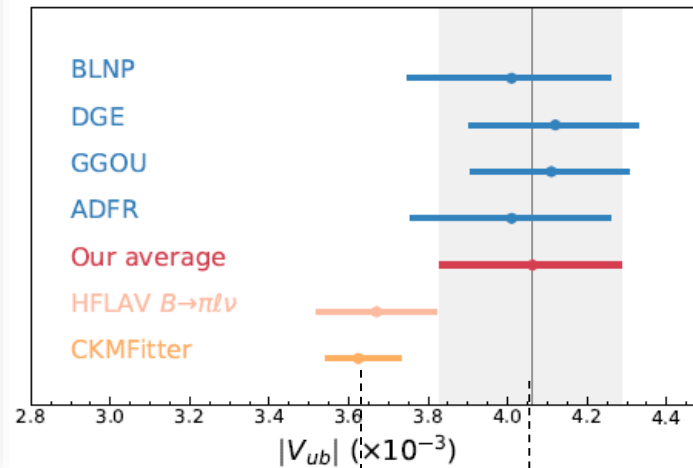


# $V_{ub}$ : Inclusive Measurement

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

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

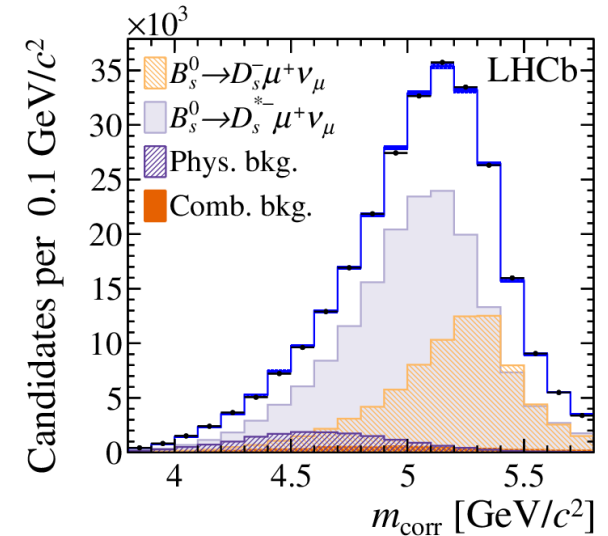
(Talk Cao, July 30<sup>th</sup>)

# $V_{cb}$ : Exclusive Measurement

- $B \rightarrow D^{(*)} l \nu$  is studied extensively to obtain exclusive  $V_{cb}$ .
- Fit variable  $\omega$  + 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.



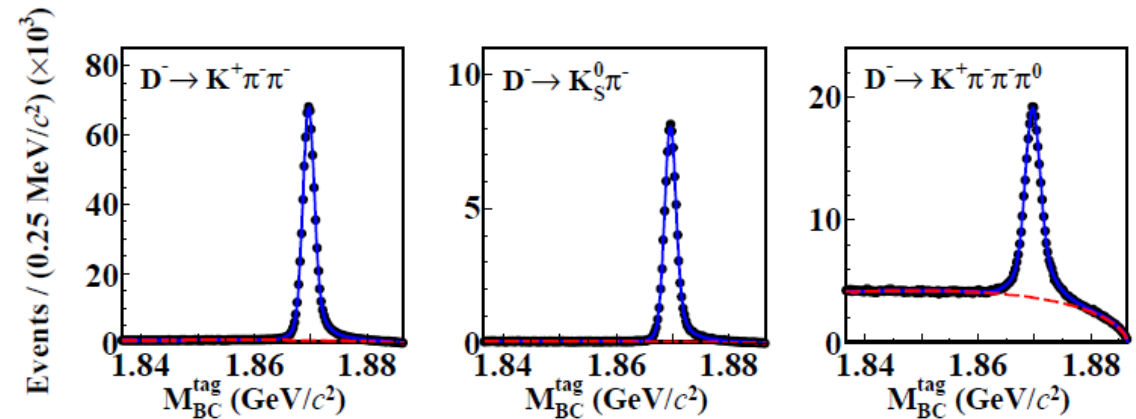
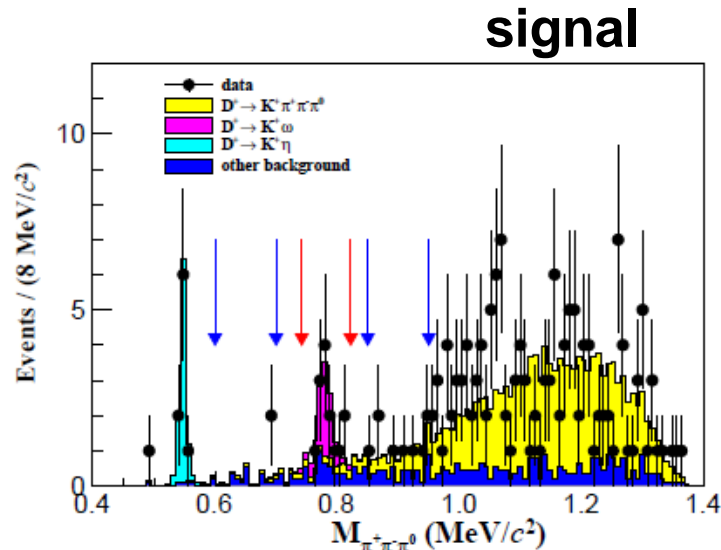
	$V_{cb}$ BGL fit ( $10^{-3}$ )	$V_{cb}$ CLN fit ( $10^{-3}$ )	Reference
Belle ( $B^0$ )	$38.3 \pm 0.2 \pm 0.7 \pm 0.6$ (ext)	$38.4 \pm 0.2 \pm 0.6 \pm 0.6$ (ext)	Phys. Rev. D 100, 052007 (2019)
BABAR ( $B^0$ )	$38.36 \pm 0.90$	$38.40 \pm 0.84$	Phys. Rev. Lett. 123, 091801 (2019) (Talk Simonetto, July 29 <sup>th</sup> )
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 <sup>th</sup> )
PDG2020	$39.5 \pm 0.9$		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 evidence of CPV in the charge asymmetry.



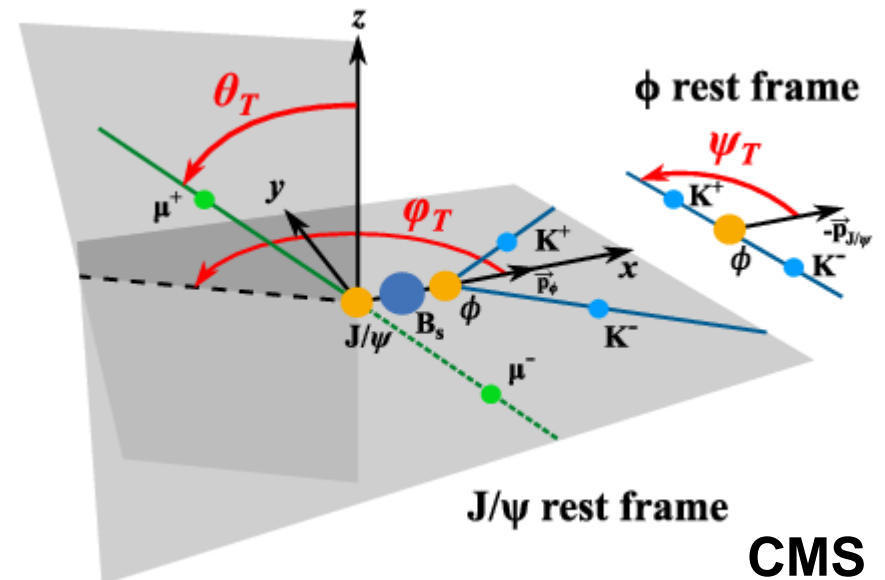
# CPV

# CPV phase $\phi_s$ in $B_s$ mixing

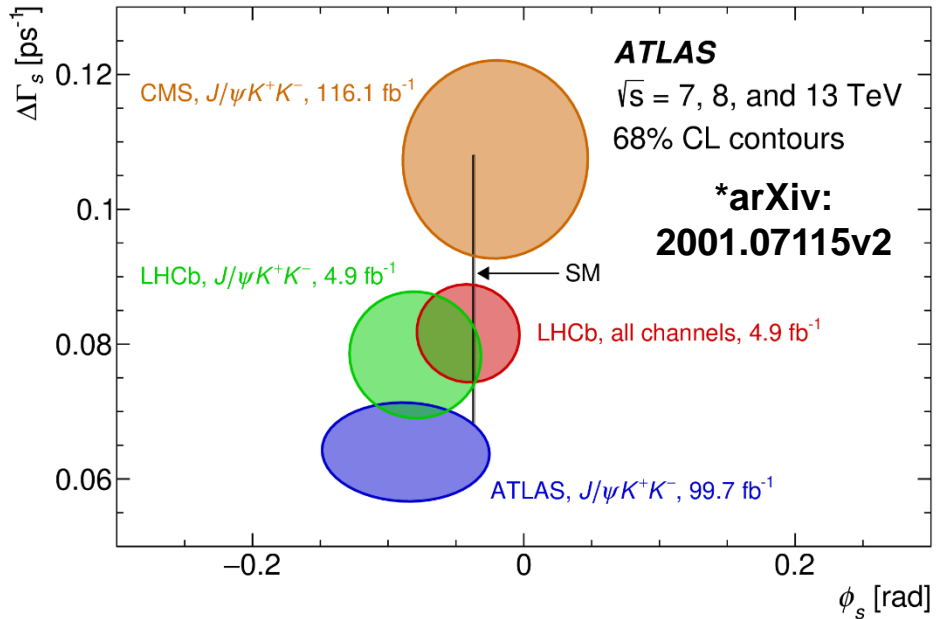
- $\phi_s$  is a CPV phase, which is a weak phase difference between the  $B_s - \bar{B}_s$  mixing and the direct decay of  $B_s$  into a common final state.
- The golden mixing decay  $B_s \rightarrow J/\psi \phi$ , ( $\phi \rightarrow K^+ K^-$ ) is well known, less complicated environment to measure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

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

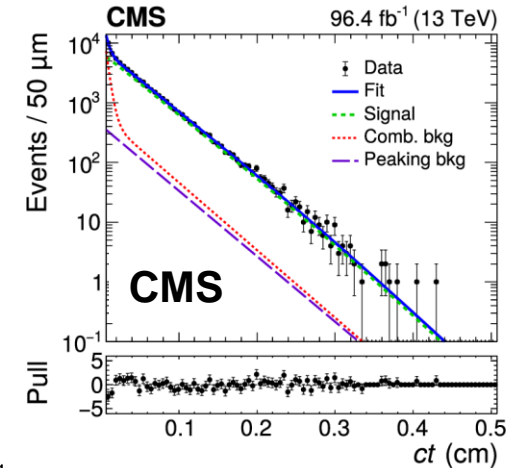
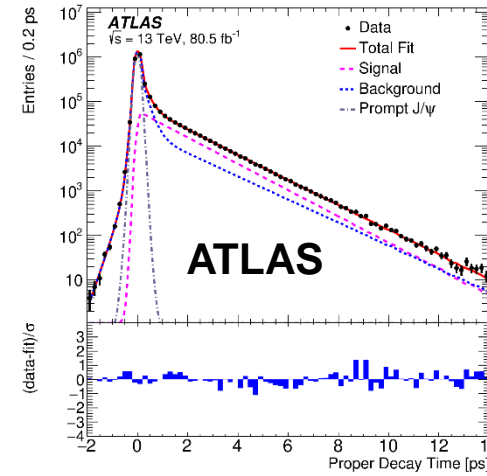
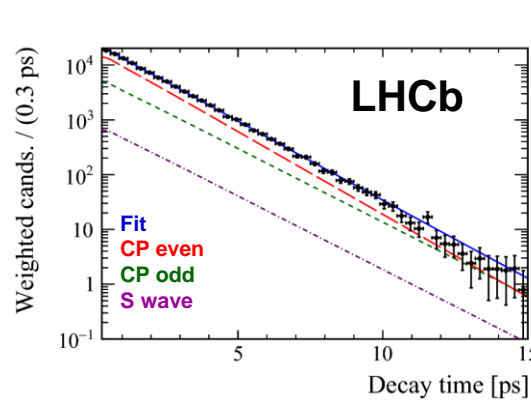
- At LHC experiments, the flavor of  $B_s$  is determined by Opposite Side Tagging (muon, electron, jet-charge) or Same Side Tagging (Kaon, LHCb only).



# Measurements of $\phi_s$ and $\Delta\Gamma_s$ at LHC



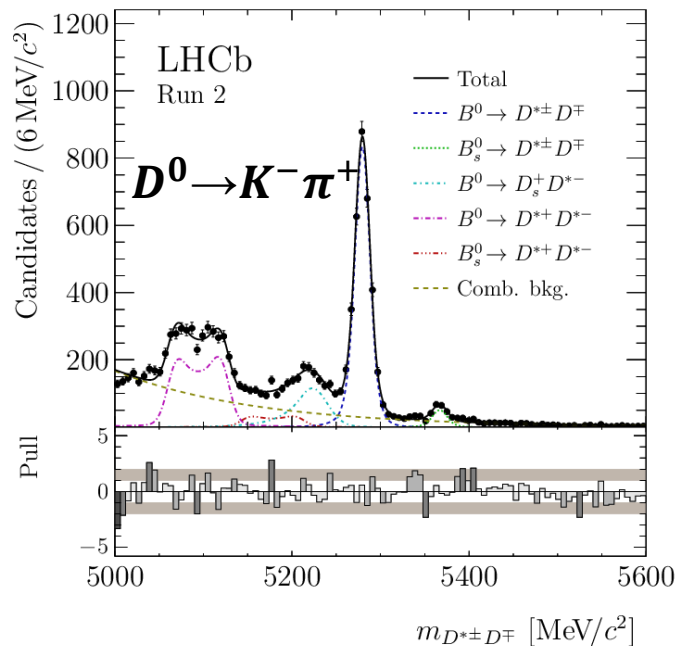
## Decay time distributions



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

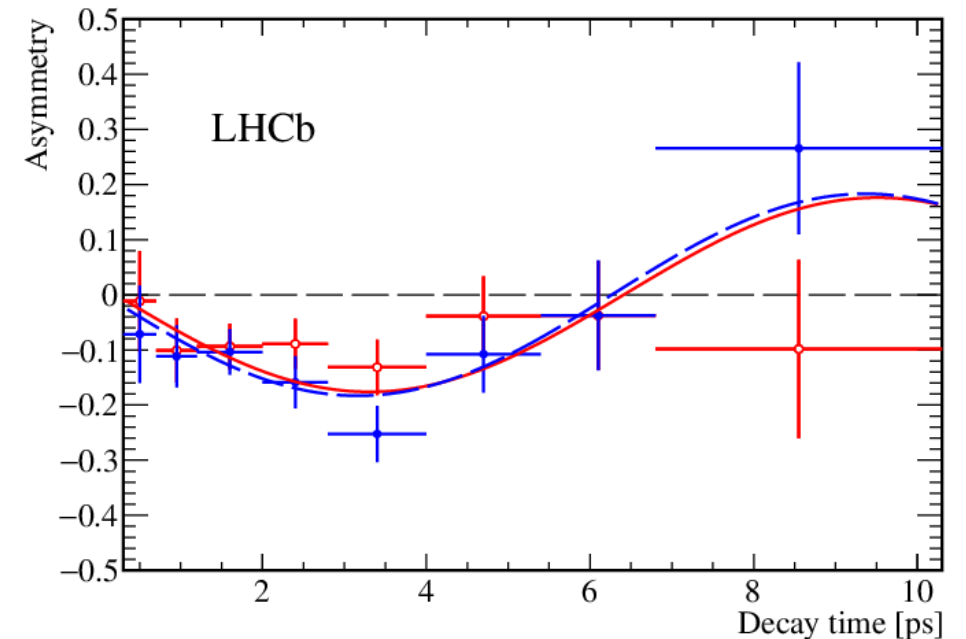
# Time Dependent CPV in $B \rightarrow D^{*\pm} D^{\mp}$

- In the  $B \rightarrow D^{*\pm} D^{\mp}$  decays, in addition to the CKM angle  $2\beta$ , 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  $D^- \rightarrow K^+ \pi^- \pi^-$ .



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

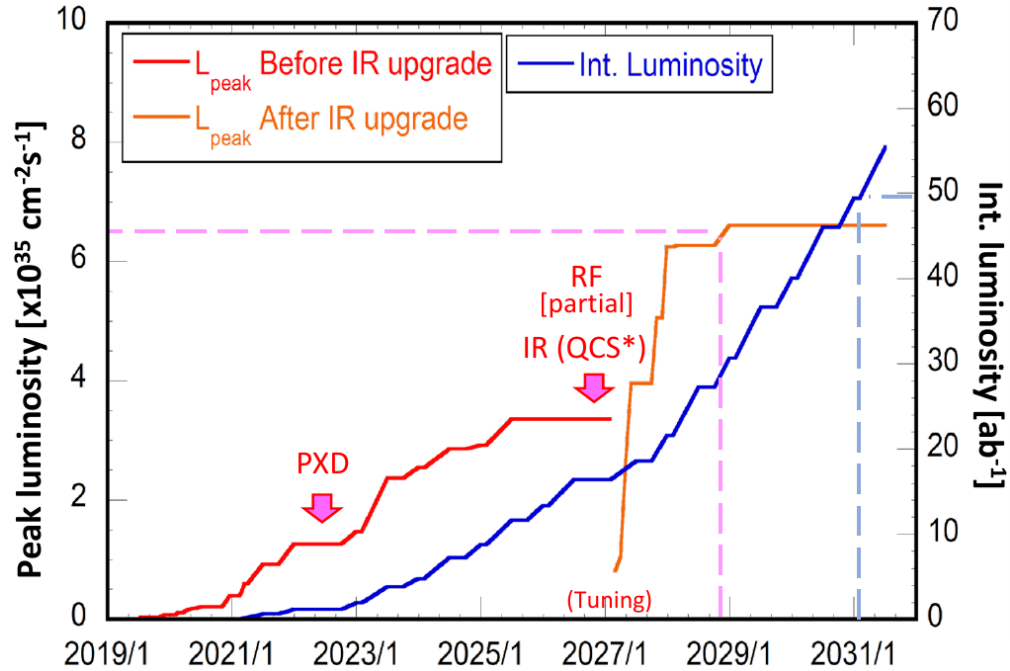
(Talk Gersabeck, July 29<sup>th</sup>)



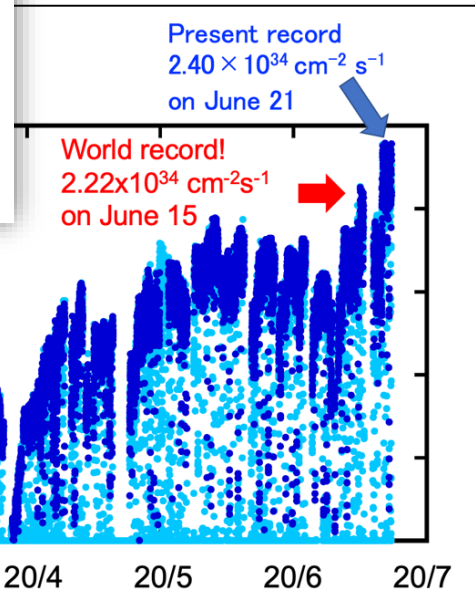
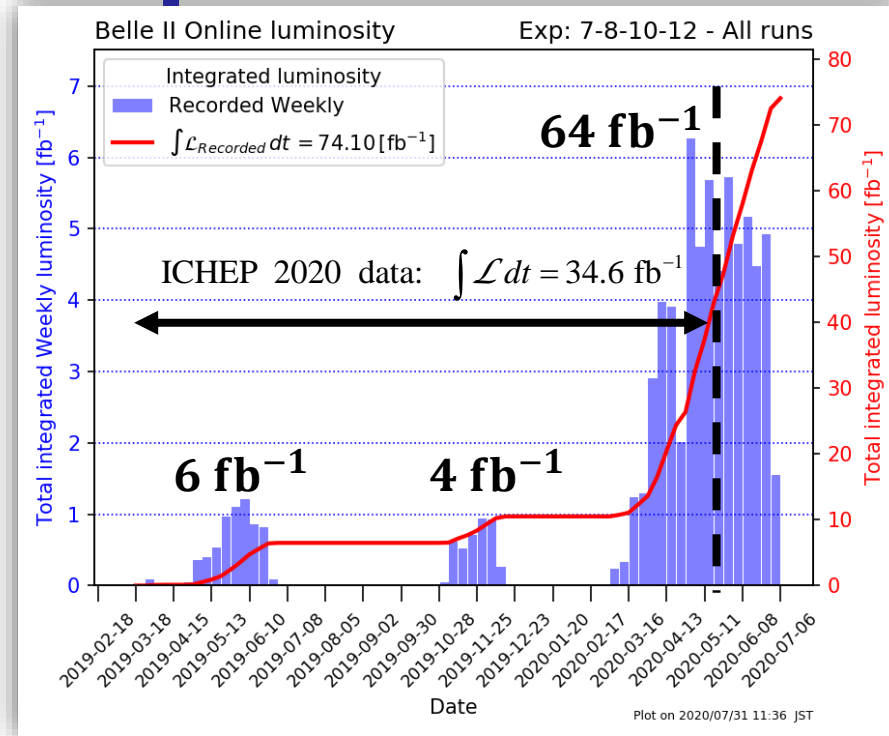
# NEWS FROM BELLE II



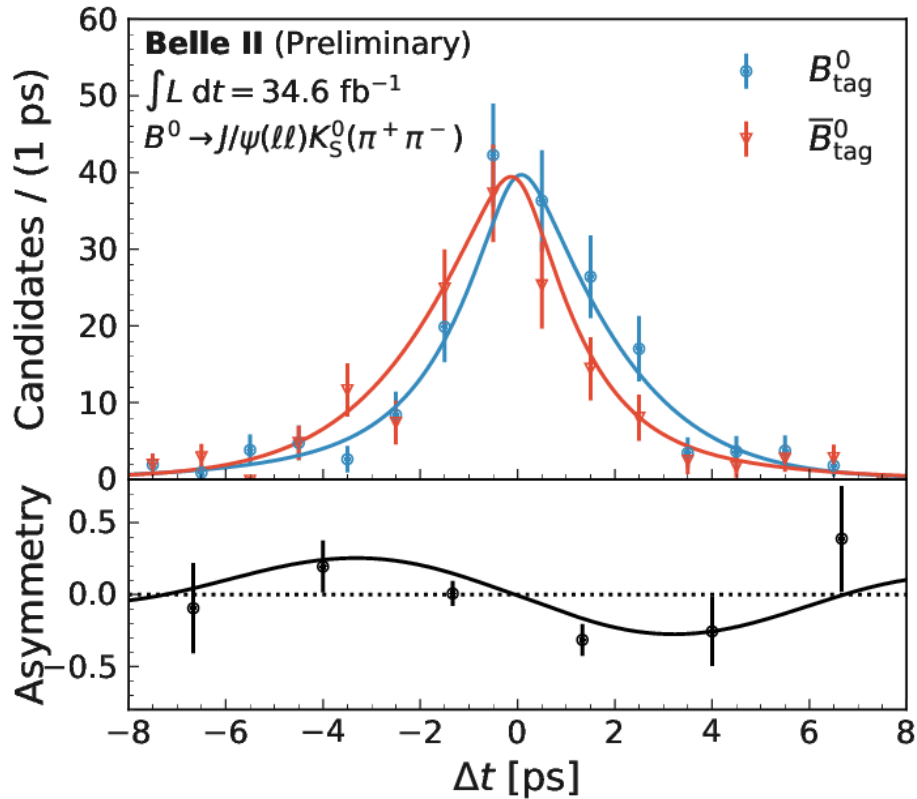
# Belle II Luminosity: Proposed Plan and Status



- 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

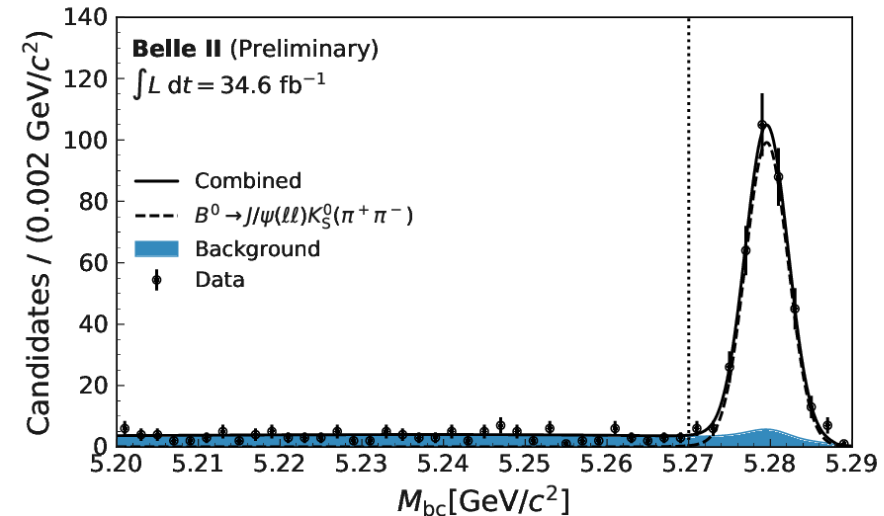


Belle II:  $S_f \approx \sin 2\phi_1 = 0.55 \pm 0.21 \pm 0.04$ .

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

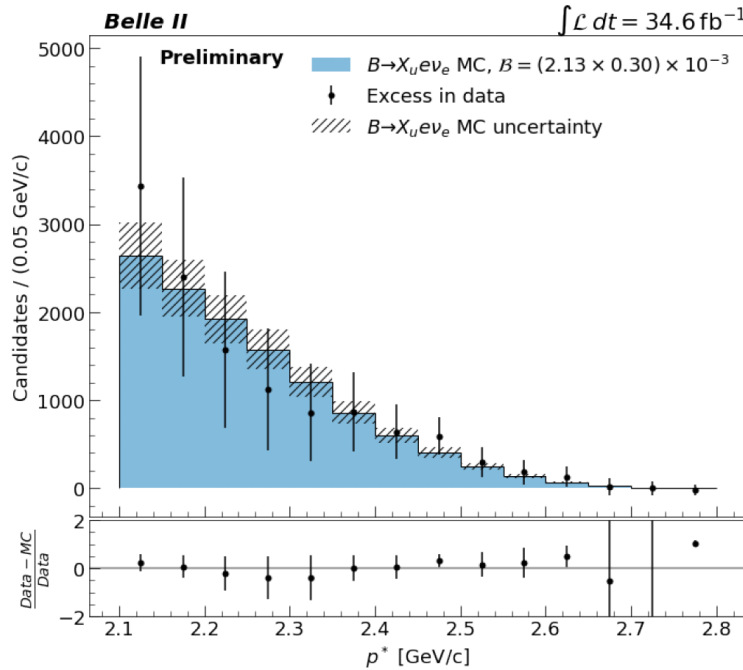
- The golden channel  $B^0 \rightarrow J/\psi(\ell\ell)K_S^0(\pi^+\pi^-)$  is studied and the time dependent CPV parameter  $\sin 2\phi_1$  is extracted.
- CPV is assumed only from the  $B^0$  mixing ( $A_{CP} = 0$ ).
- The wrong sign tag ratio  $w = (20.9 \pm 2.1)\%$  is obtained from the  $B^0 \rightarrow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

(Talk Rout, July 30<sup>th</sup>)

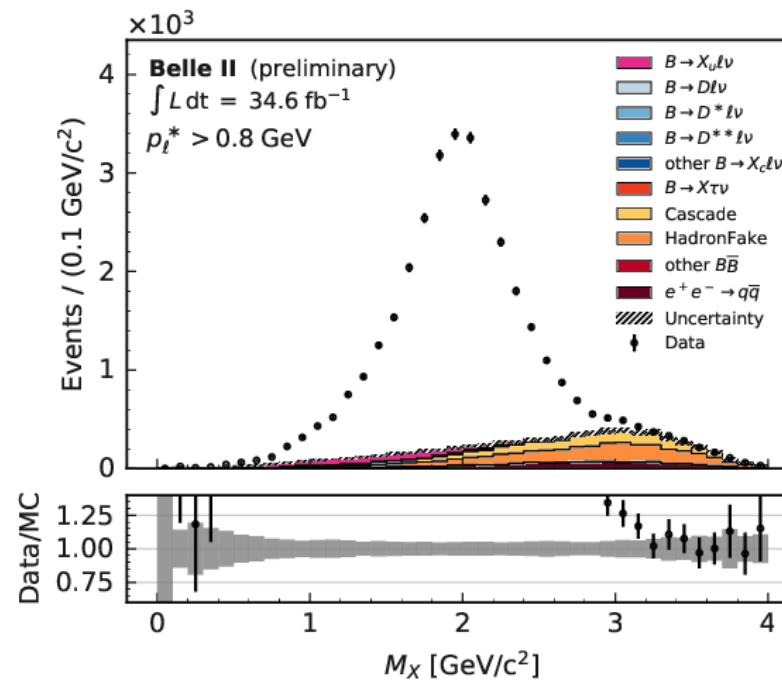


# Toward $V_{cb}$ and $V_{ub}$ : Semi-Leptonic Decays

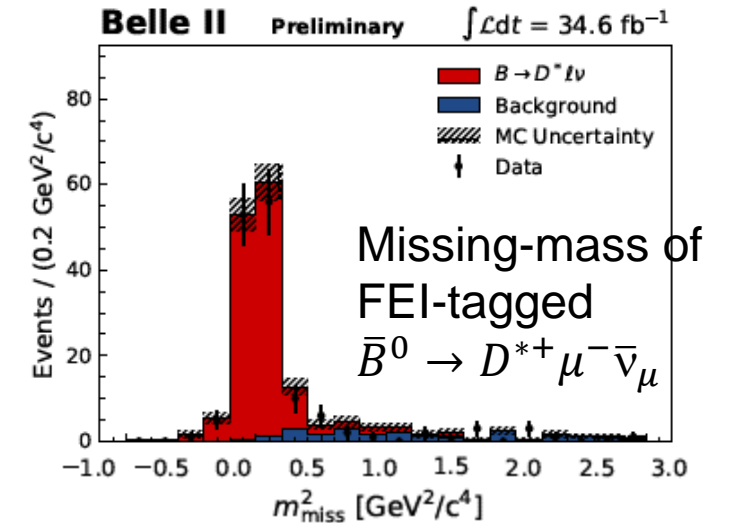
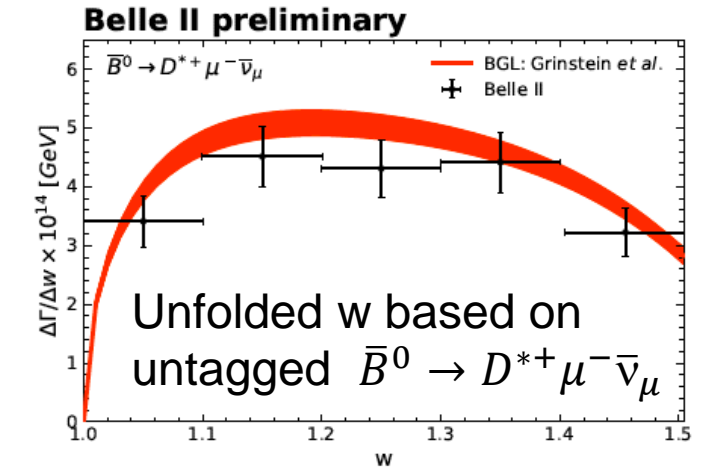
(Talk Cheaib, July 29<sup>th</sup> & poster Granderath, July 29<sup>th</sup>)



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



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



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

# Summary

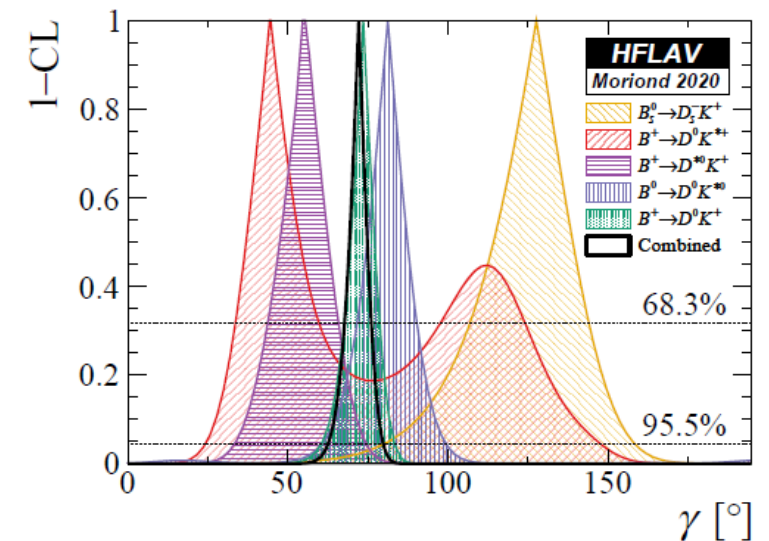
- Measurement on  $\gamma$  slowly enters the precision area.
  - Inputs from charm/beauty experiments are needed.
- The CKM elements are being updated relentlessly.
  - (semi)-leptonic decay modes are leading the efforts.
- Belle II started generating comparable physics results.
- The CKM/CPV is a great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



# EXTRA

# Final D Category for Measurement of $\gamma$

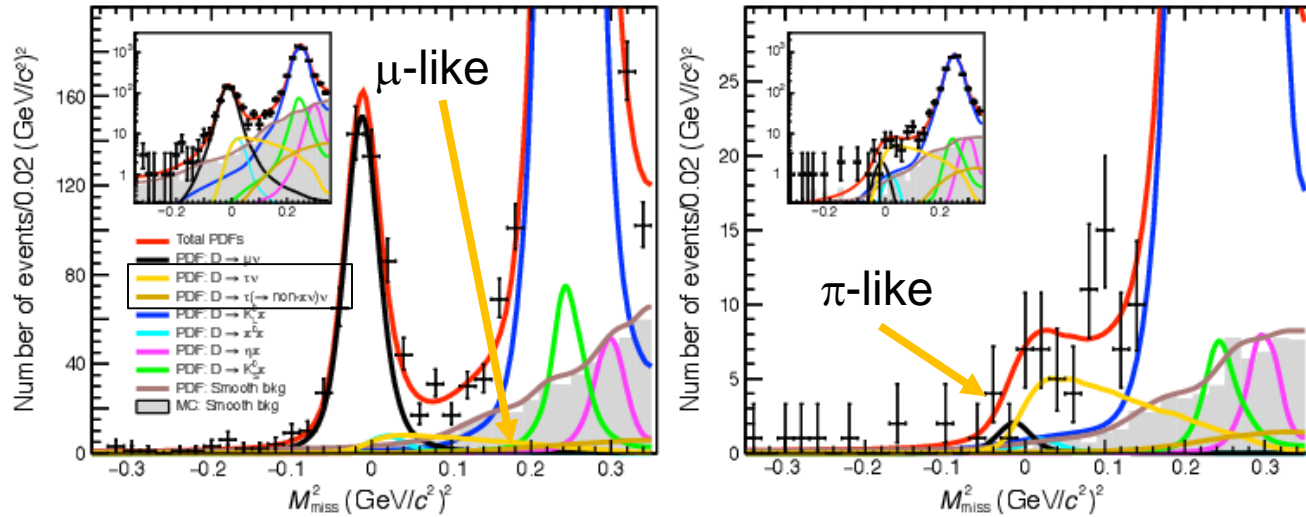
- GLW: CP eigenstate D decays
  - $D \rightarrow KK, D \rightarrow \pi\pi$ . Phys. Lett. B 253, 483 (1991), Phys. Lett. B 265, 172 (1991)
- ADS: CF or DCS D decays
  - $D \rightarrow K\pi$ . Phys. Rev. Lett. 78, 3257 (1997), Phys. Rev. D63, 036005 (2001)
- BPGGSZ: D to 3 body final states
  - $D \rightarrow K_S^0 \pi\pi$ . 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)

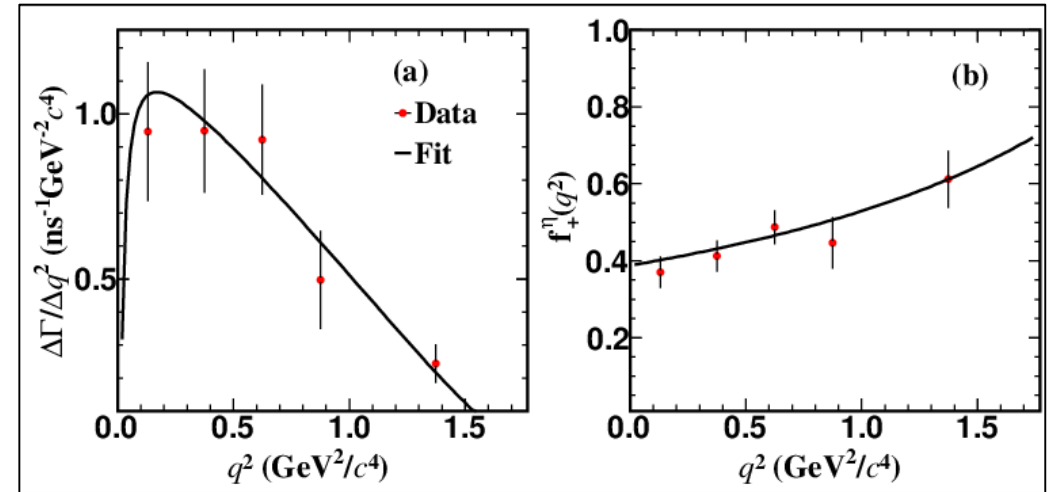
# Other (Semi)-Leptonic Decays

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