CKM Phase Measurements in B decays (Belle II and LHCb)

On behalf of the Belle II and LHCb collaborations

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Conference on Flavor Physics and CP Violation (FPCP2021)

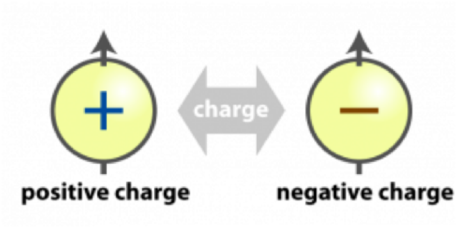
Fudan University, Shanghai, China

Outline

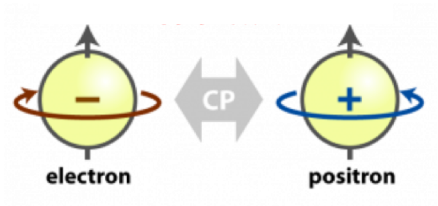
- **Introduction**
- **Recent highlights on CKM angle γ measurements**
- **Status of β and α measurements**
- **New physics hunting with ϕ_s**
- **Conclusion**

Fundamental questions on CP violation

C: Matter ⇔ Antimatter



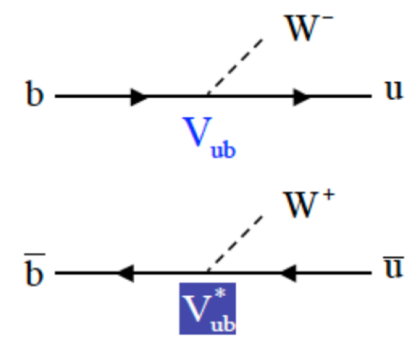
C + Parity



- CP violation in SM is described by CKM mechanism
- Can explain all experimental results
- However, matter-antimatter asymmetry offered by CKM mechanism orders of magnitude smaller than observed in Universe (Why human beings exist?)
- New CP violation mechanism needed: what are they?
- Precision test of CKM mechanism

CKM Physics

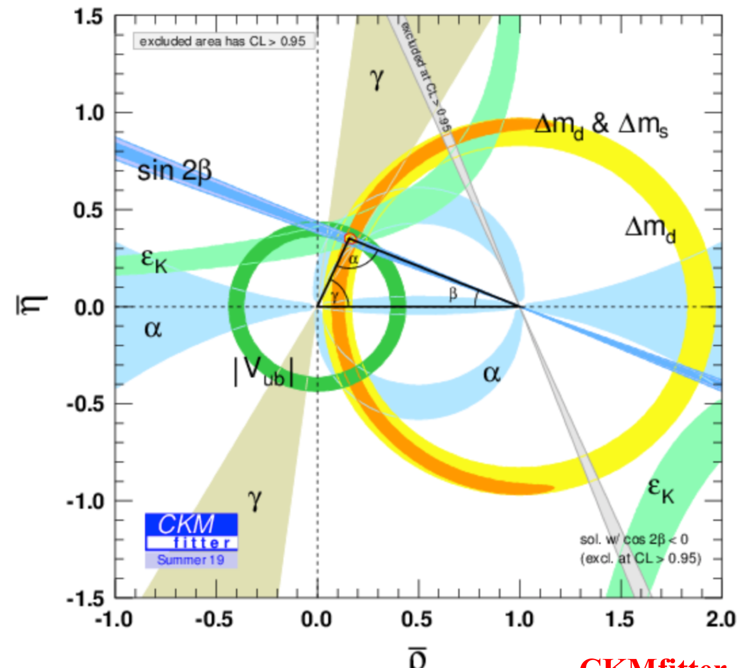
$$V_{\text{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$



- A single complex phase in CKM matrix generate CP violation
- With unitary condition, four parameters can describe the matrix

$A\sim 0.8,\qquad \lambda\sim 0.2,\qquad \rho\sim 0.15,\qquad \eta\sim 0.35$

- Triangles from unitary condition
- All well crossed a single point, though still space for New Physics;
- New particles/forces can modify the picture
- Precision needed to see them



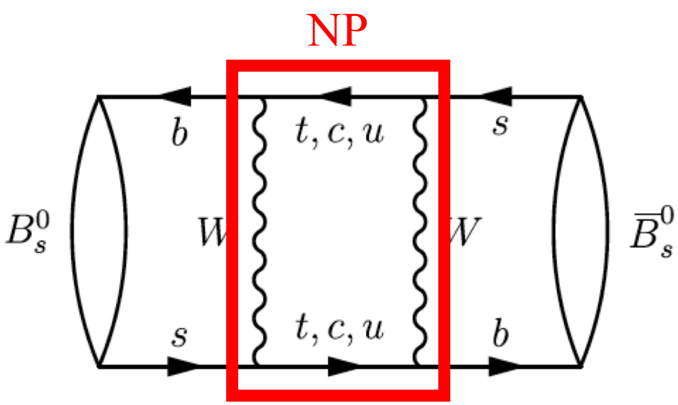
CKMfitter

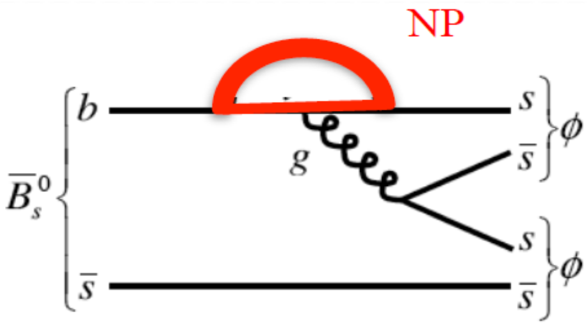
Precision test at flavor sector

- Sensitive to New Physics scale much higher than direct search: 1-10^4 TeV

Couplings $\mathcal{O}(1)$ to avoid fine tuning

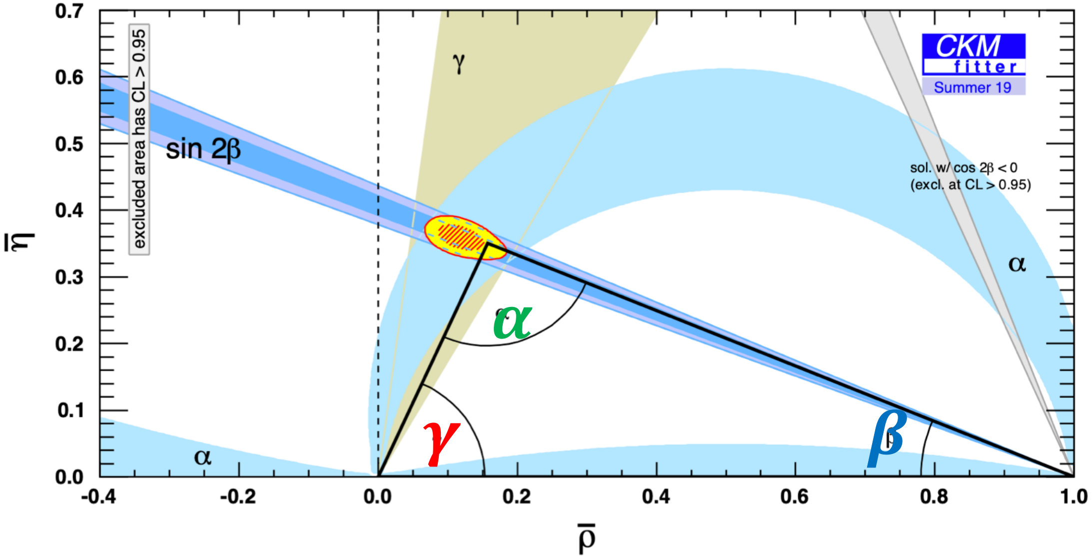
$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum \frac{c_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)}(\text{SM fields}).$$

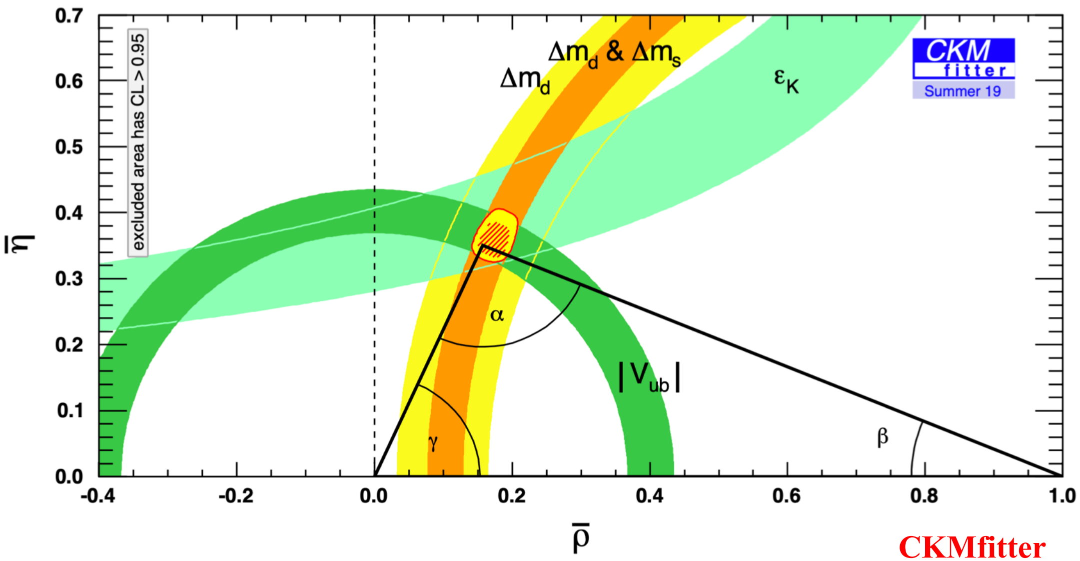




- Statistics or precision is key for flavor program: New Physics scale, i.e. Dim = 6, proportional to $\sqrt[4]{\text{statistics}}$ or $1/\sqrt{\text{Uncertainty}}$,

Unitary constrain with and without angles





CKMfitter

- Most famous triangle: (db) quarks

$$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right),$$

$$\alpha = \phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right),$$

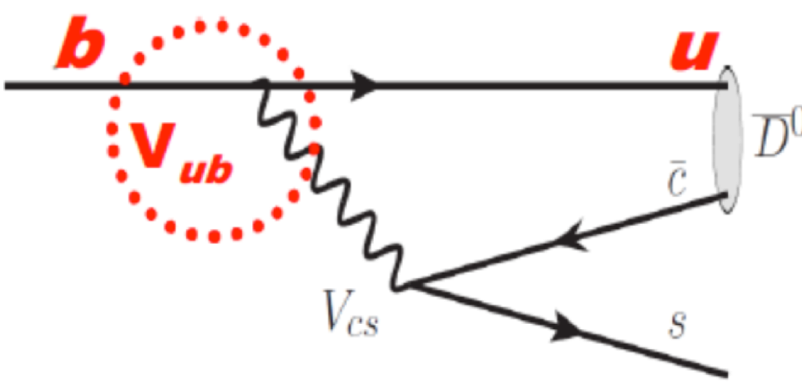
$$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right).$$

- Comparable sensitivities
- Offer constrains to unitary in different ways (tree, loops etc.)

Angle γ

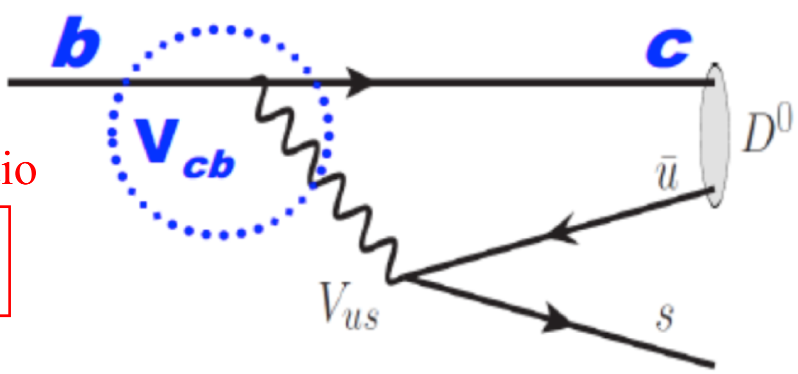
$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

- Angle γ is the phase which enters in $b \to uW^-$
- Indirect measurements give: $\gamma = (65.7^{+1.0}_{-2.5})^\circ$ [CKMfitter19]
- Directly measured through $b \to u$ and $b \to c$ interference with $B \to D^{(*)} K^{(*)}$ etc., theoretically clean [JHEP 1401 (2014) 051]

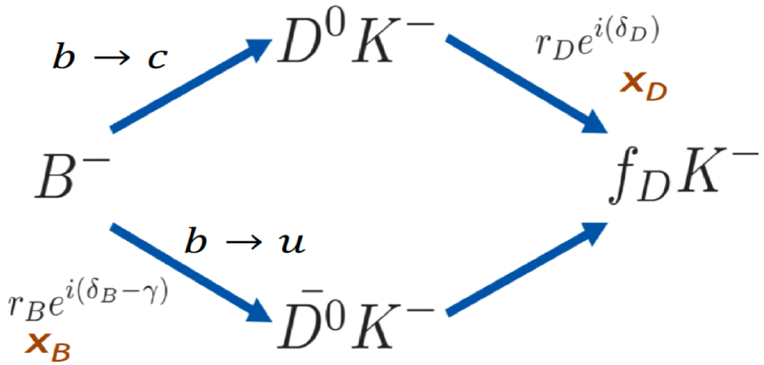


Amplitude ratio

$$r_B e^{i\delta_B}$$



Probe γ in different methods



D^0 and $\overline{D}^0$ decay to same final states to interference

GLW: D = CP eigenstates, e.g. KK, ππ — PLB 253 (1991) 483; PLB 265 (1991) 172

ADS: D = quasi-flavour-specific states e.g. Kπ — PRL 78 (1997) 3257

GGSZ: D = self-conjugate multi(3)-body states e.g. $K_s\pi\pi$ — PRD 68 (2003) 054018

GLS: ADS variant with singly Cabbibo-suppressed decay $D \to K_s K\pi$ — PRD 67 (2003) 071301

time-dependent $B_s \to D_s K$, $B^0 \to D\pi$ etc — Nucl. phys. B 672 (2003) 459

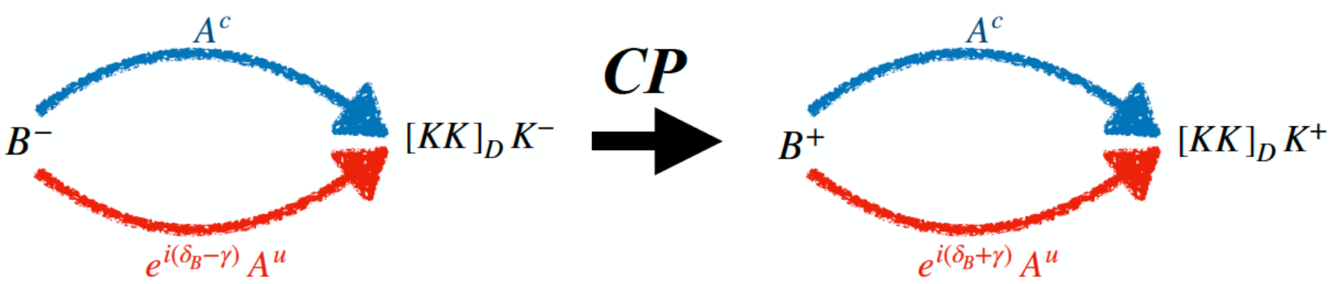
Dalitz (GW) method: $B^0 \to DK\pi$ — PRD 79 (2009) 051301

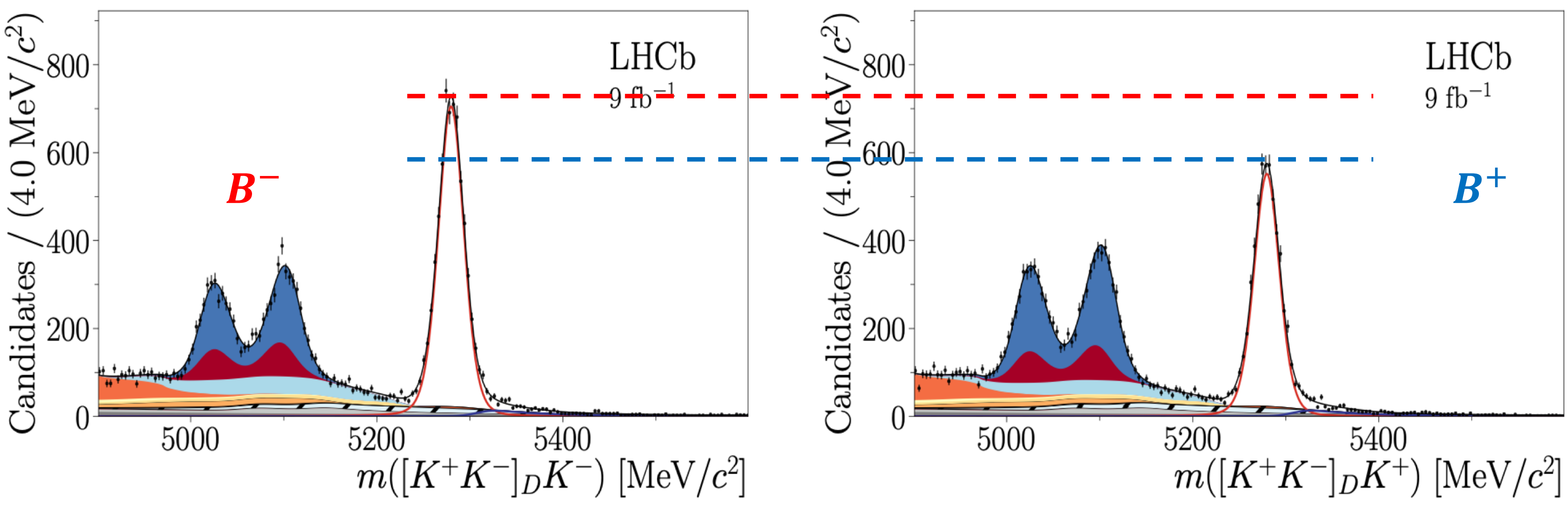
Sensitivities of γ from many channels, important to measure as many as possible

Two-body D decays

JHEP 04 (2021) 081

- GLW/ADS measurements now performed with LHCb full Run1+Run2 data, for $B \to DK, D\pi$ and partially reconstructed $B \to D^*K, D^*\pi$

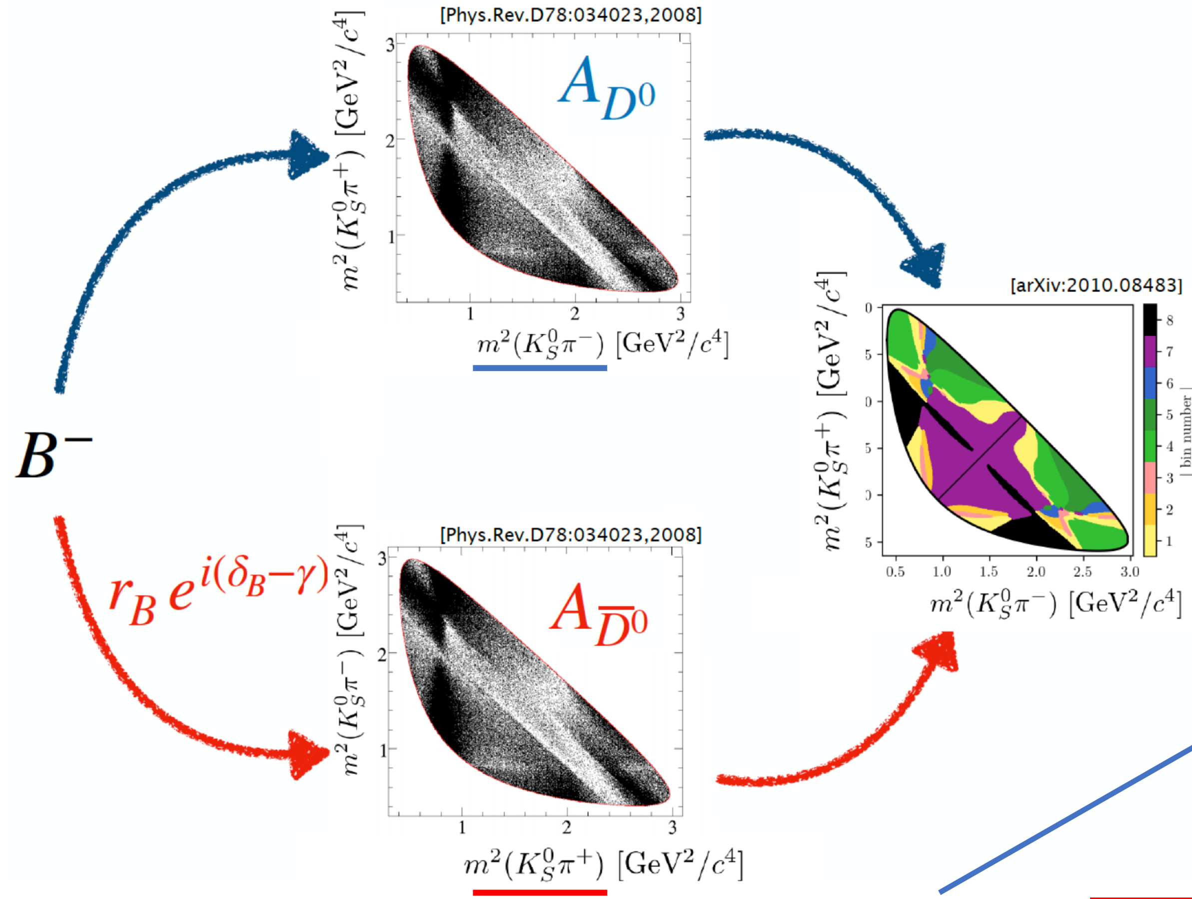




Three-body D decays

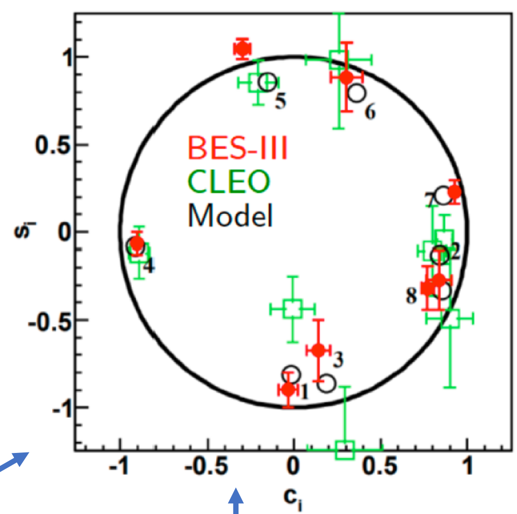
JHEP 02 (2021) 169

- BPGGSZ (GLW/ADS over Dalitz plot) measurements now performed with LHCb full Run1+Run2 data, for $B \to DK, D \to Ks\pi\pi, KsKK$



New charm input from BES-III (4 * CLEO-c stat)

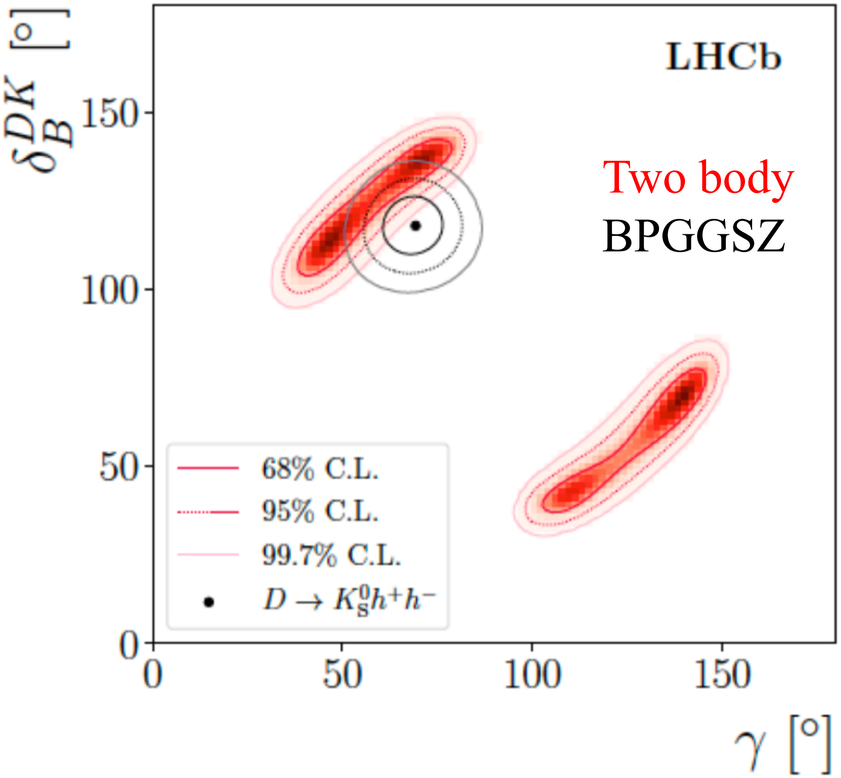
[PRD101, 112002(2020)]

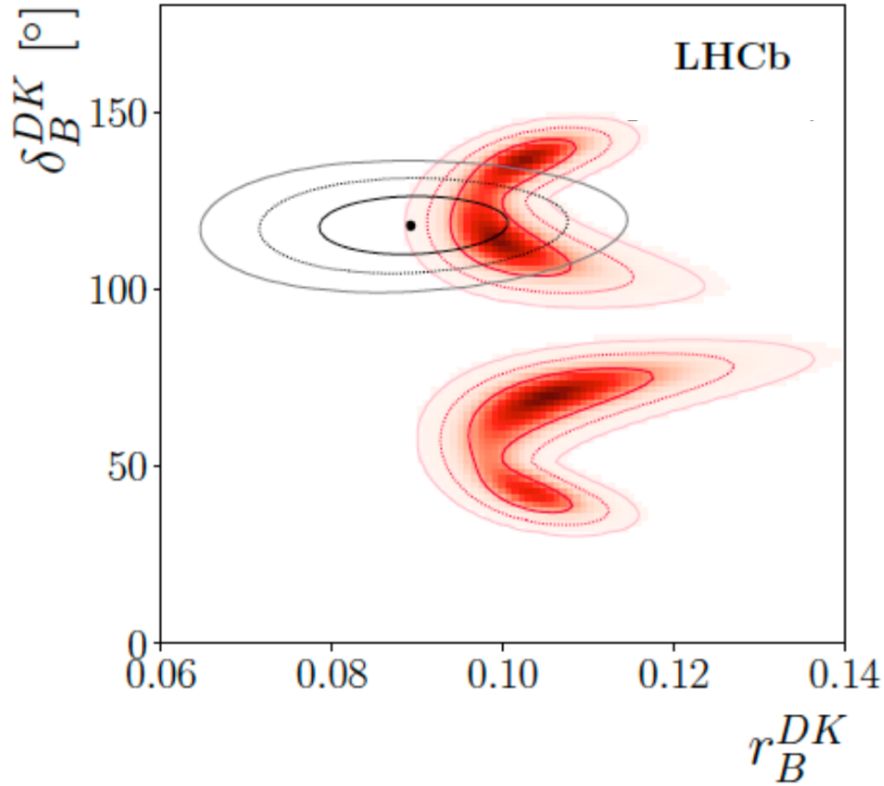


$$A_{B\mp}(m^2_{K_s\pi^+}, m^2_{K_s\pi^-}) = A_{D^0}(m^2_{K_s\pi^+}, m^2_{K_s\pi^-}) + r_B\, e^{i(\delta_B \mp \gamma)} A_{D^0}(m^2_{K_s\pi^-}, m^2_{K_s\pi^+})$$

Combination between the two

JHEP 04 (2021) 081

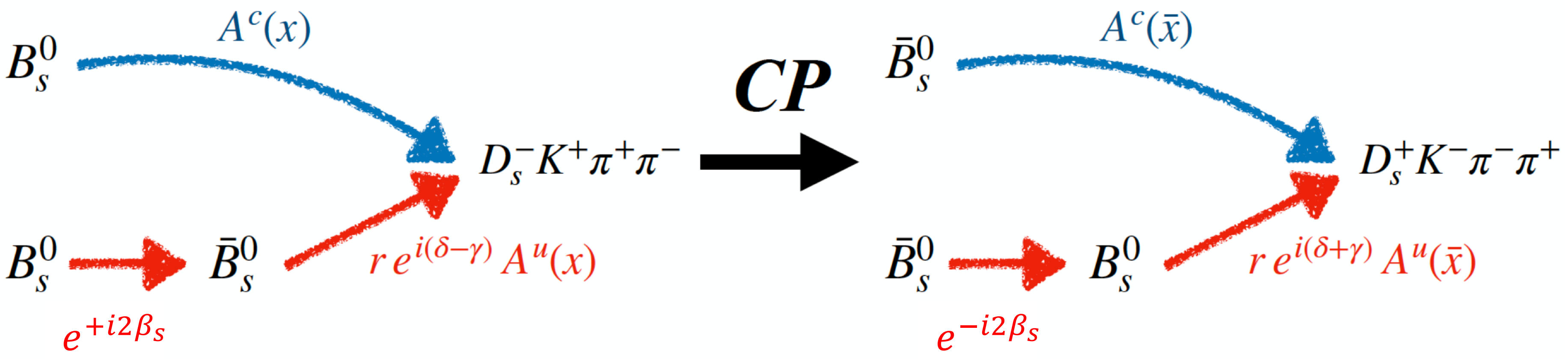




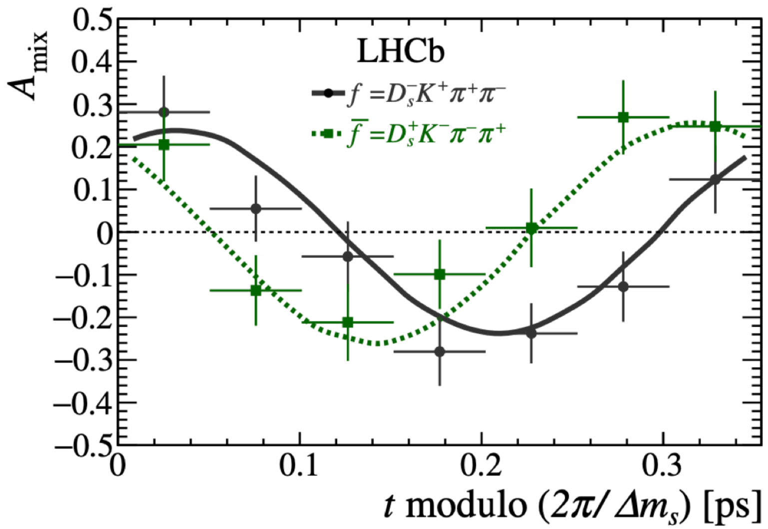
- Good agreement between the two modes (expected)
- Much better sensitivity when combined ➔ key feature for γ measurements
- Important to add more channels and compare between them

New story from B_s decays

JHEP 03 (2021) 137



- $b \to u$ and $b \to c$ interference can also came with B_s mixing
- Measured using LHCb full Run1+Run2 data



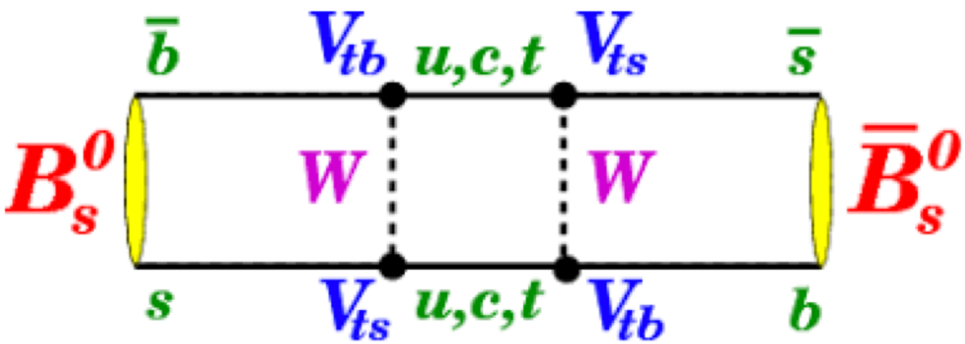
r	$0.56 \pm 0.05 \pm 0.04 \pm 0.07$
κ	$0.72 \pm 0.04 \pm 0.06 \pm 0.04$
$\delta\ [^\circ]$	$-14 \pm 10 \pm 4 \pm 5$
$\gamma - 2\beta_s$	$42 \pm \underbrace{10}_{\text{stat}} \pm \underbrace{4}_{\text{sys}} \pm \underbrace{5}_{\text{model}}$

$$A^f_{\mathrm{mix}}(t) = \frac{N_f(t) - \bar{N}_f(t)}{N_f(t) + \bar{N}_f(t)}$$

$$A^{\bar{f}}_{\mathrm{mix}}(t) = \frac{\bar{N}_{\bar{f}}(t) - N_{\bar{f}}(t)}{\bar{N}_{\bar{f}}(t) + N_{\bar{f}}(t)}$$

Mixing parameter

JHEP 03 (2021) 137
arXiv:2104.04421

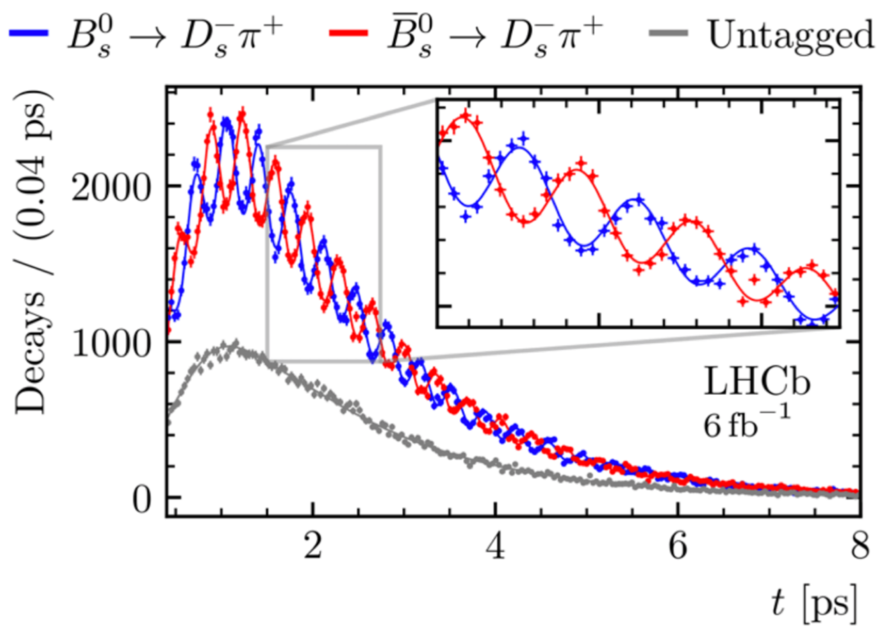


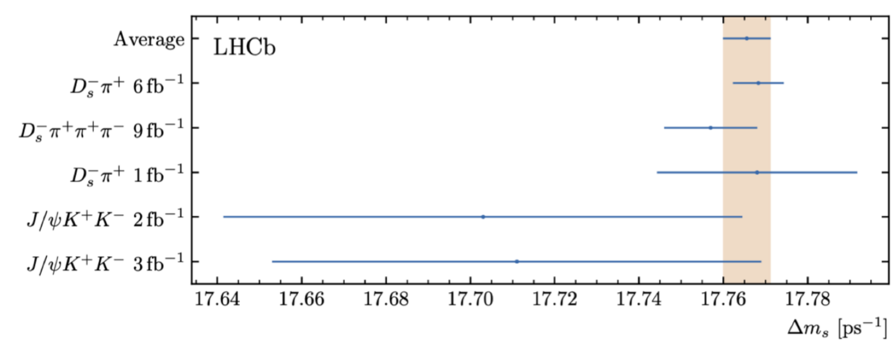
Together with $B_s^0 \to D_s^- \pi^+$, yields the most precise determination of oscillation frequency!!!

Better precision from lattice needed

See Michele Veronesi's talk for details

- Mass eigenstates different from flavor eigenstates: Δm_s

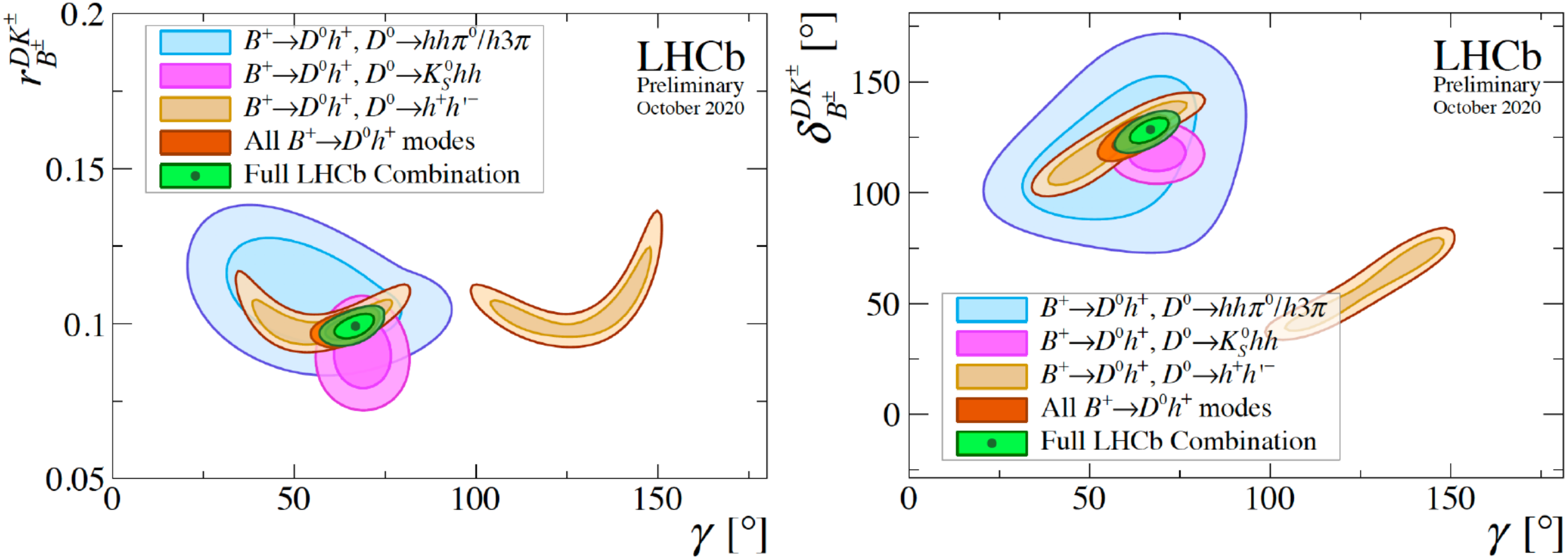




$$17.7656 \pm 0.0057\,\mathrm{ps}^{-1}$$

New γ combination

LHCb-CONF-2020-003

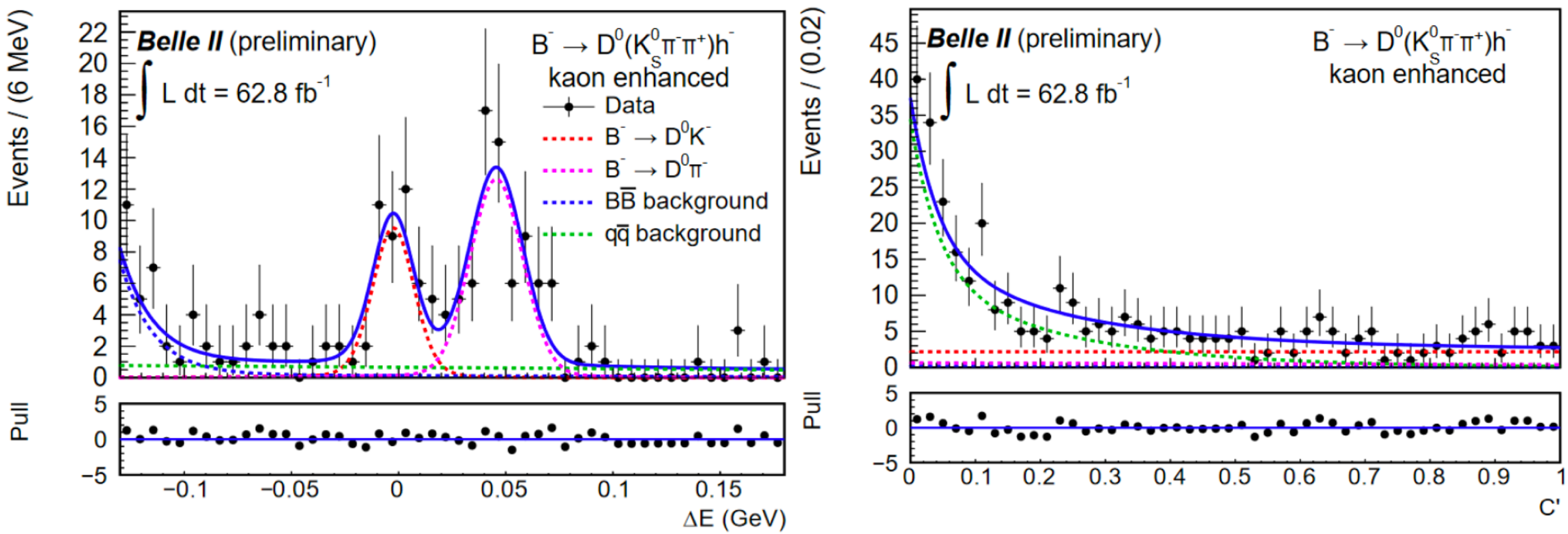


- Now precision mainly from B$^+$ decays, large potential from other b hadrons
- New average on γ from LHCb: $\gamma = (67 \pm 4)°$, compared to 14° in B-factories
- Also now much closer to indirect determination: $\gamma = (65.7^{+1.0}_{-2.5})°$

Belle II starts to see signals

- Signal enhanced with $M_{bc} = \sqrt{E_{beam}^2 - (P_B c)^2} > 5.27$ GeV/c²
- PID enhanced and clear BPGGSZ channel seen

~63 fb⁻¹



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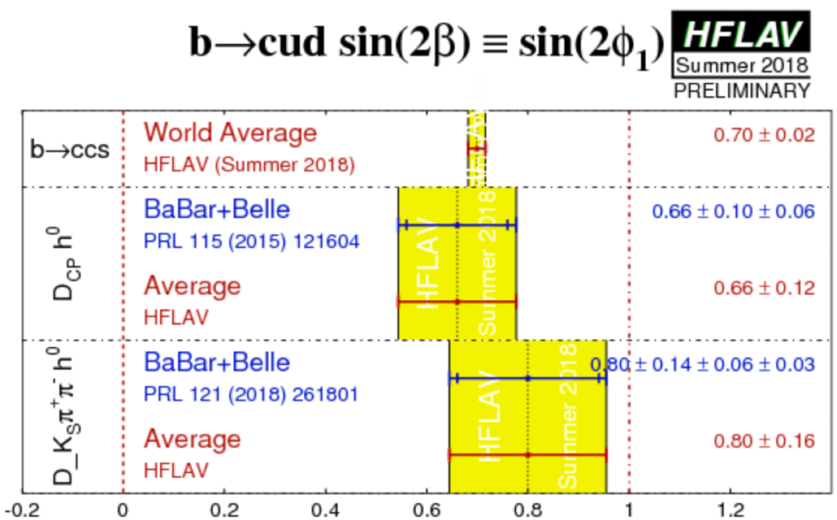
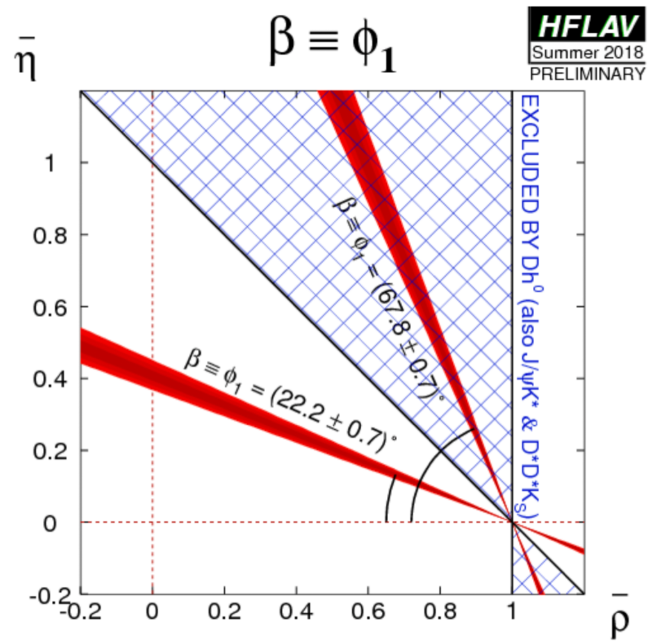
Angle β

$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

- Sensitivities on sin2β driven by B →charmonium+$K^0_{S,L}$: 0.699 ± 0.017 (HFLAV)
- $b \rightarrow c\bar{u}d$ penguin free
- Two fold ambiguity solved using $B^0 \rightarrow Dh^0, D \rightarrow K^0_S h^+ h^-$ decays

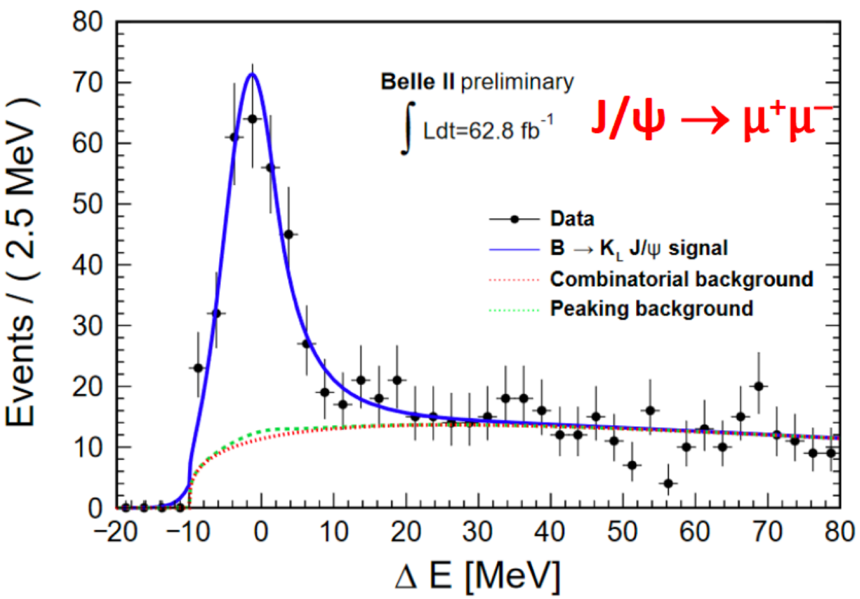


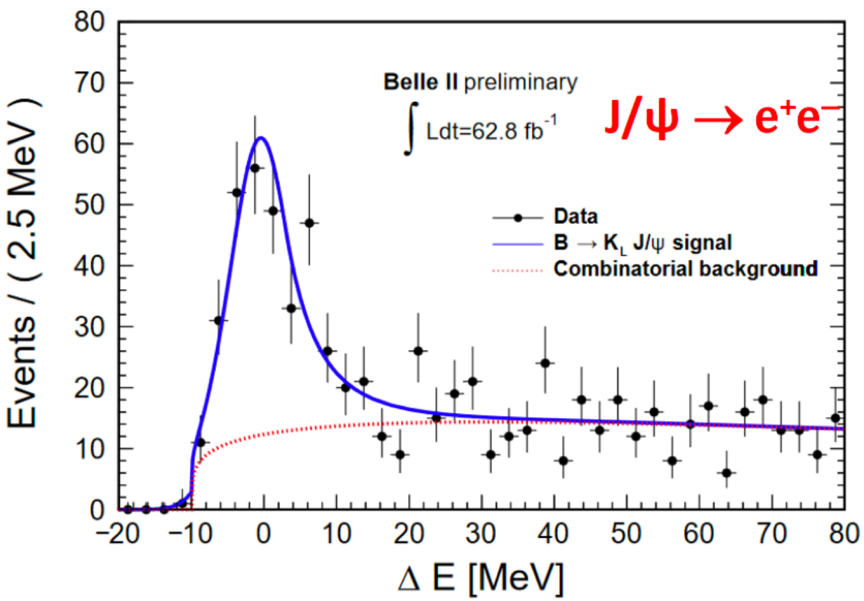


Belle II warms up on β measurements

- $B^0 \to J/\psi K_L^0$ provides additional information on β
- K_L^0 reconstructed using K_L^0 and μ detector
- Very good purity

~63 fb^{-1}





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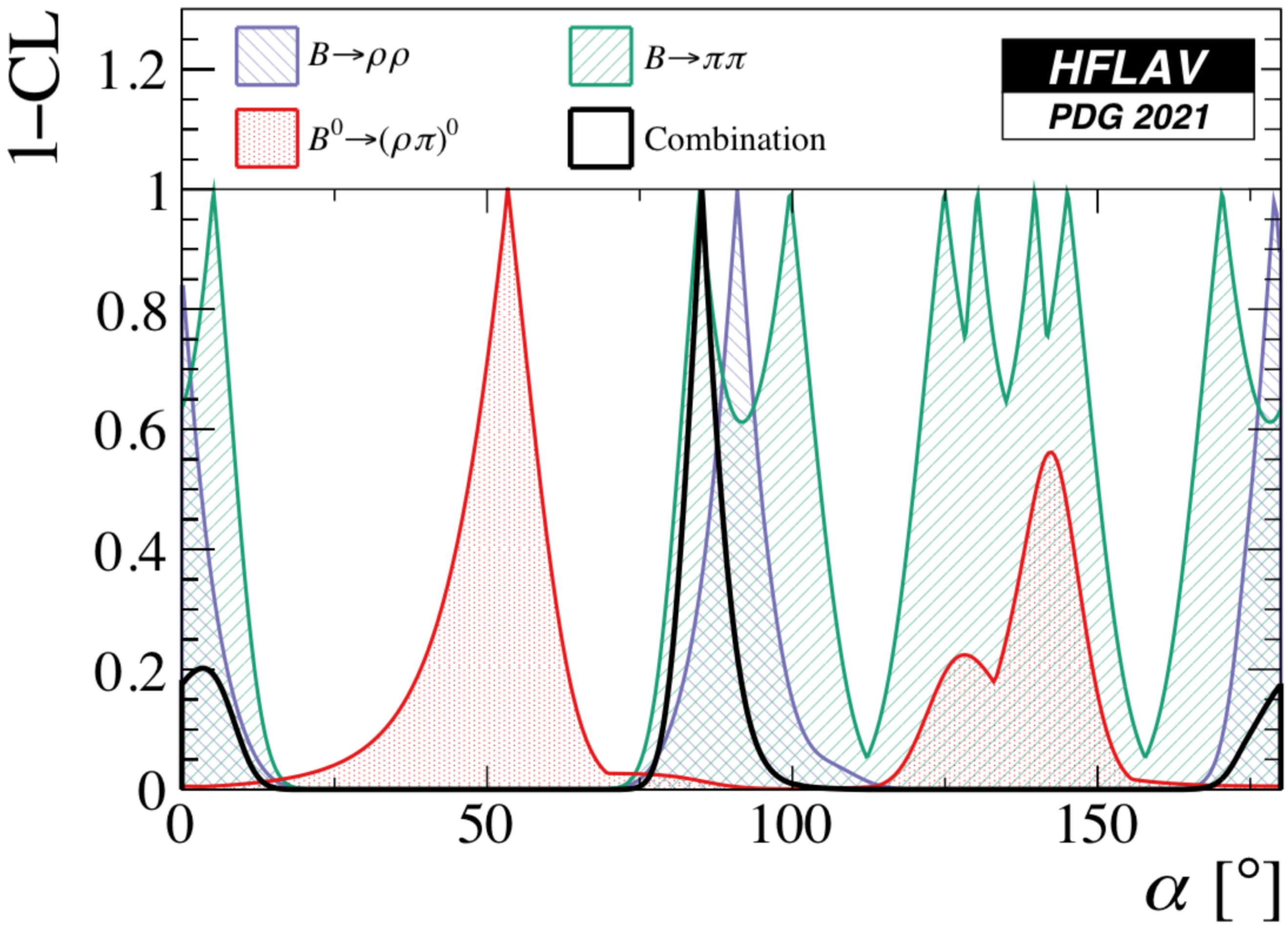
Angle α and related

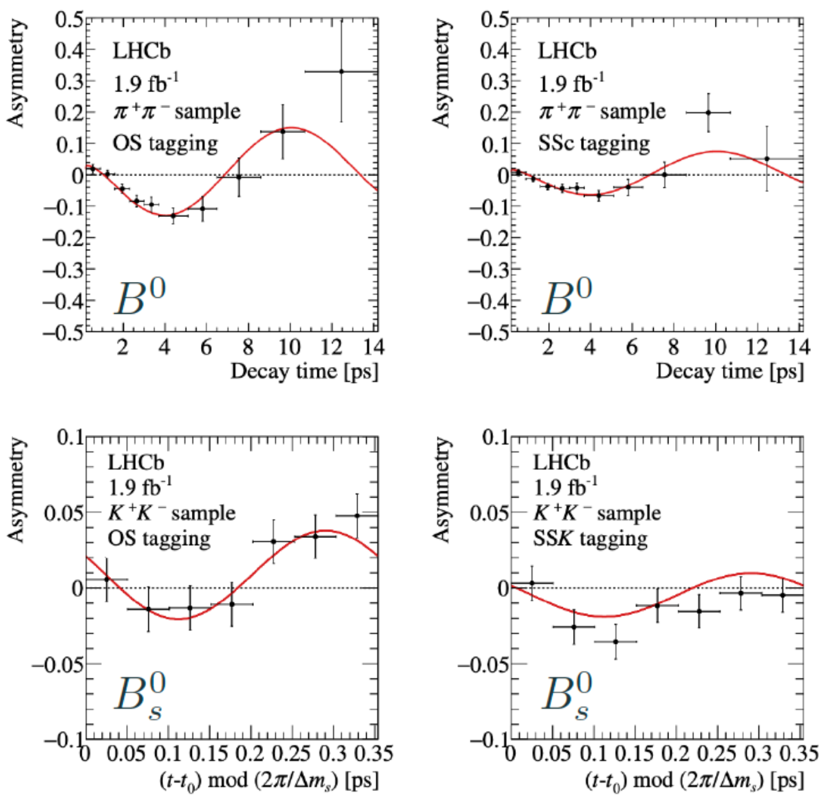
HFLAV



- Obtained using Isospin analyses of $B \to \pi\pi, \rho\pi, \rho\rho$ systems
- Current precision： $(85.2^{+4.8}_{-4.3})°$

CP violation measurements in $B_{(s)} \to h^+h^-$ JHEP 03(2021) 075

- $B^0 \to \pi^+\pi^-$: inputs for α measurements
- $B_s^0 \to K^+K^-$: U spin analysis with $B^0 \to \pi^+\pi^-$ offering $-2\beta_s$ and γ
- $B^0 \to K^+\pi^-$: inputs to understand $B \to K\pi$ puzzle, see William Parker's talk for details
- Now performed with 1.9 fb^{-1} of LHCb Run2 data



Combining with LHCb Run1 results:

$$
\begin{aligned}
C_{\pi\pi} &= -0.320 \pm 0.038,\\
S_{\pi\pi} &= -0.672 \pm 0.034,\\
A_{CP}^{B^0} &= -0.0831 \pm 0.0034,\\
A_{CP}^{B_s^0} &= 0.225 \pm 0.012,\\
C_{KK} &= 0.172 \pm 0.031,\\
S_{KK} &= 0.139 \pm 0.032,\\
\mathcal{A}_{KK}^{\Delta\Gamma} &= -0.897 \pm 0.087
\end{aligned}
$$

First observation of time-dependent CP violation in B_s^0 decays!

Belle II warms up: α measurement

- $B^0 \to \pi^0\pi^0$ driven α sensitivity with $B \to \pi\pi$ system
- $\mathcal{B}(B^0 \to \pi^0\pi^0)\times 10^6 = (1.83 \pm 0.21 \pm 0.13)$ (BaBar), $(1.31 \pm 0.19 \pm 0.18)$ (Belle)
- Some predictions

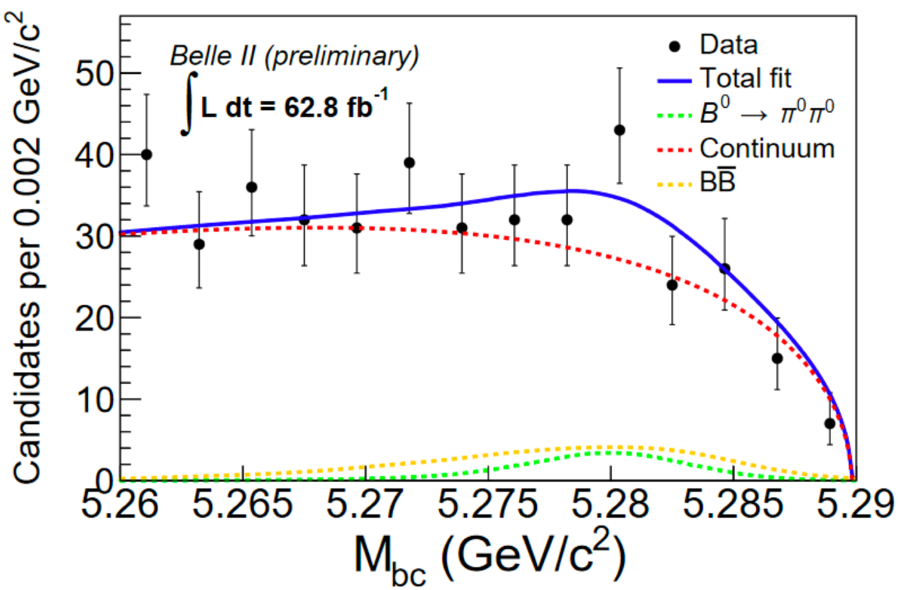
$$Br(B^0 \to \pi^0\pi^0) = [0.23^{+0.08}_{-0.05}(\omega_b)^{+0.05}_{-0.04}(f_B)^{+0.04}_{-0.03}(a_2^\pi)] \times 10^{-6},$$ **PRD 90 (2014) 014029**

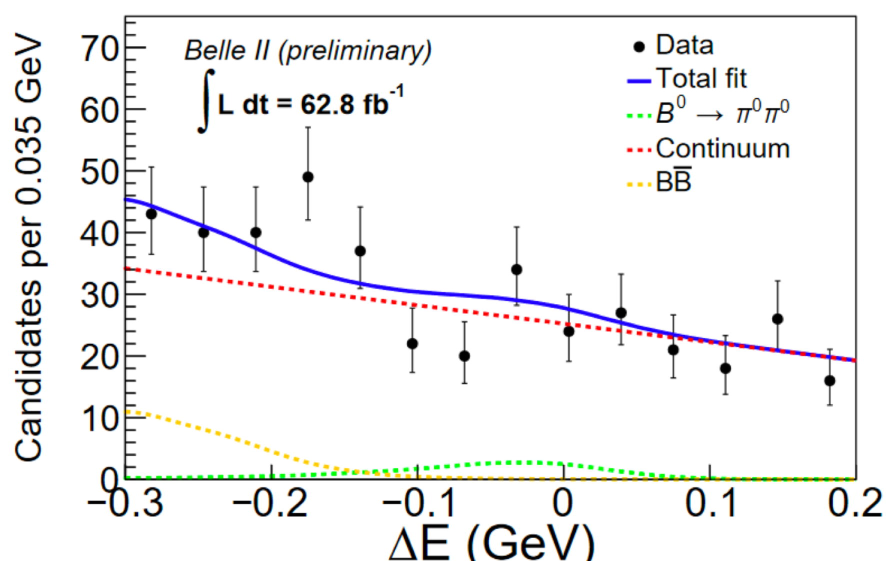
$$\mathcal{B}(B_d \to \pi^0\pi^0)|_{\mathrm{PMC}} = \left(0.98^{+0.44}_{-0.31}\right) \times 10^{-6},$$ **PLB 749 (2015) 422**

$$\mathrm{Br}(\bar{B}^0(B^0) \to \pi^0\pi^0) = (1.17^{+0.11}_{-0.12}) \times 10^{-6}.$$ **PRD 95 (2017) 034023**

- Tensions seen and Belle II is approaching to solve that

~63 fb^{-1}





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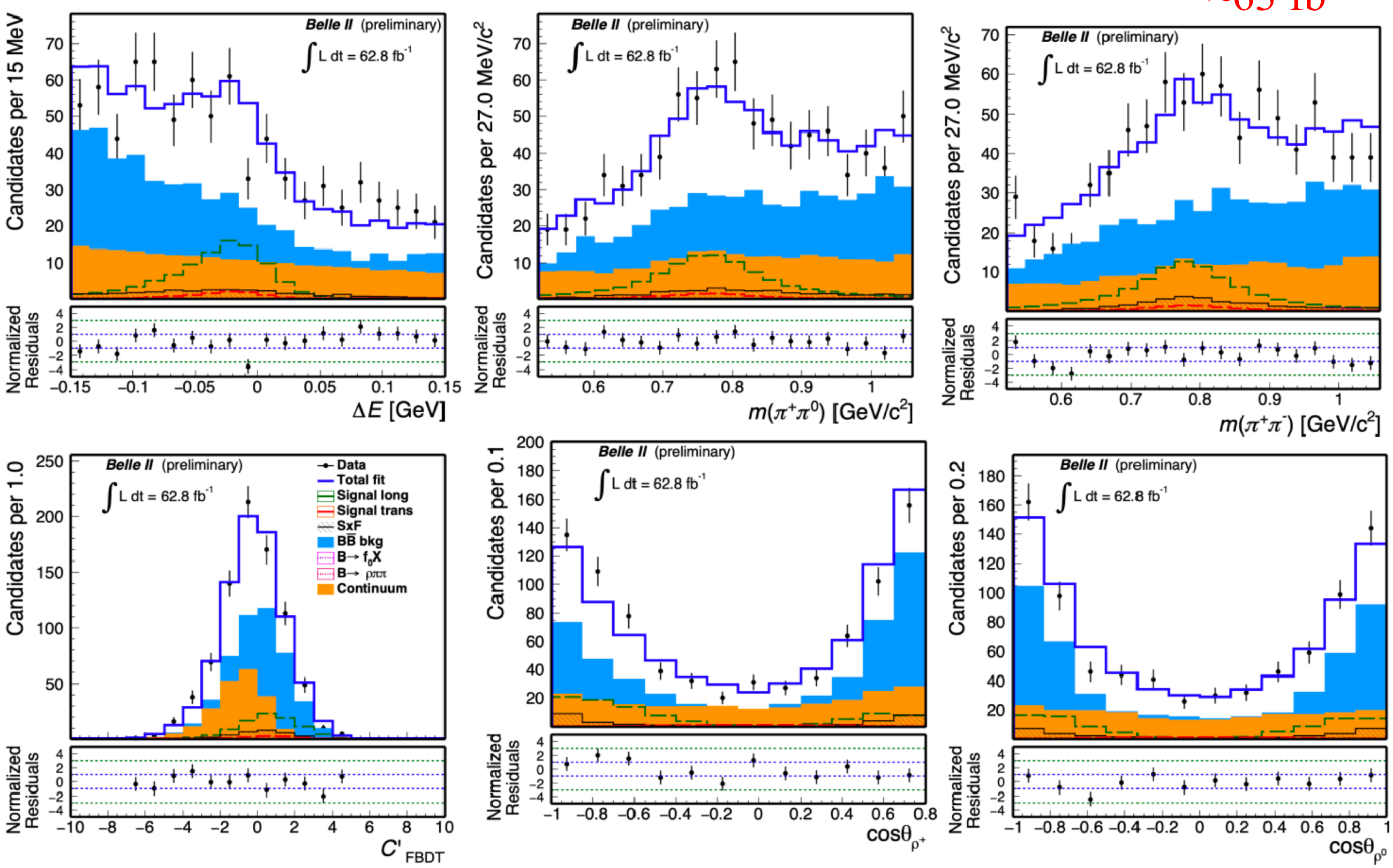
Belle II warms up: α measurement

- Rediscovery of $B^0 \to \rho^+\rho^0$
- $\mathcal{B}(B^0 \to \rho^+\rho^0) = (20.6 \pm 3.2 \pm 4.0)\times 10^{-6}, f_L = 0.936^{+0.049}_{-0.041} \pm 0.021$ can already be achieved!

~63 fb^{-1}



Generic B
Longitudinal
Transverse
Continuum

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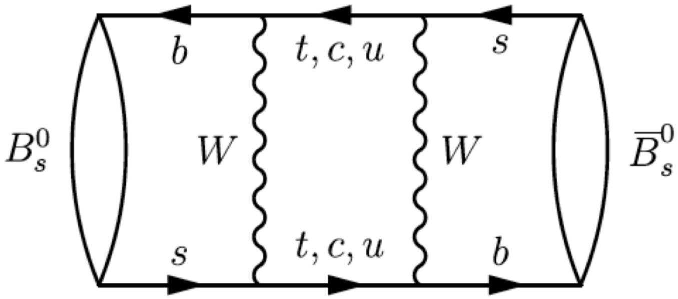
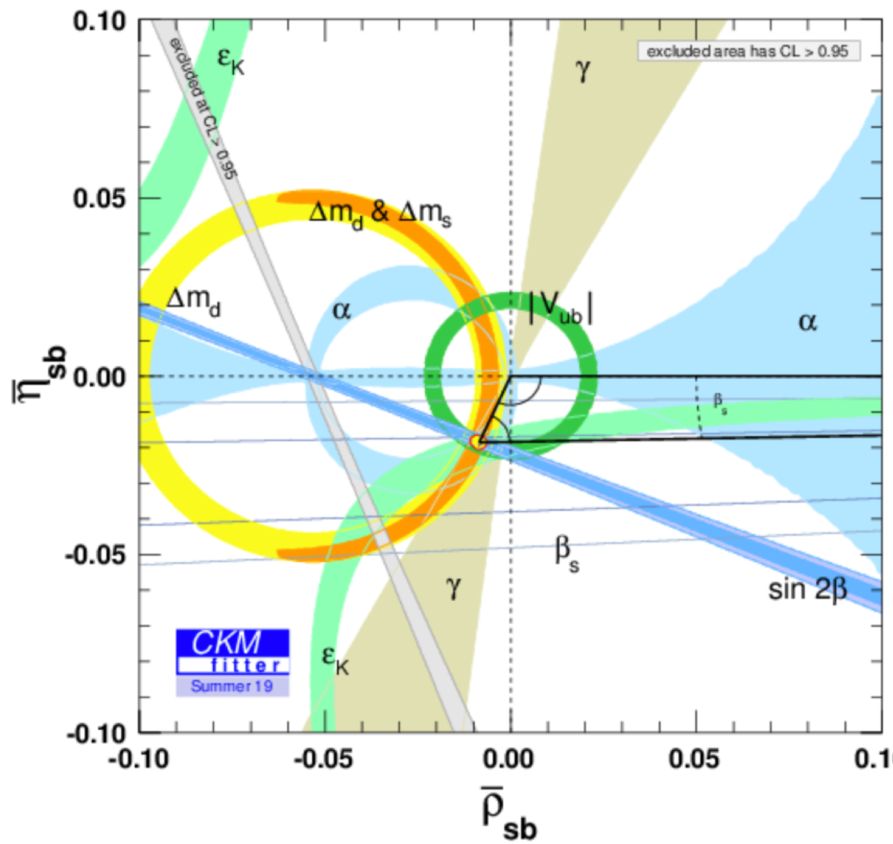
New physics hunting in ϕ_s

CKMfitter
JHEP 11 (2015) 082
PLB 742 (2015) 38

- Analogous triangle from unitary conditions, but with (sb) quarks instead of (db) quarks
- Triangle squeezed, thus β_s very small
- Sensitive to new physics in loop





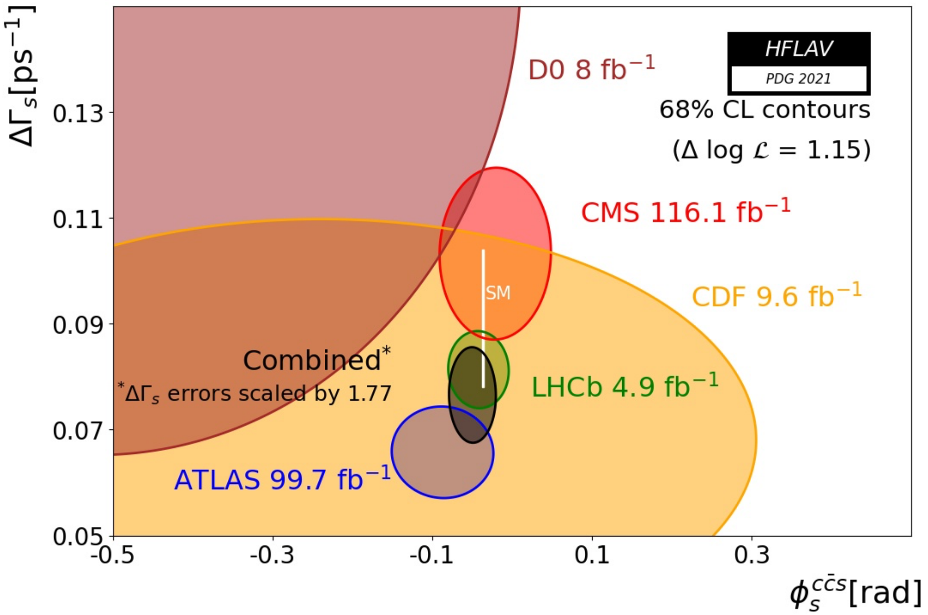
- $\phi_s^{\text{meas.}} = -2\beta_s + \Delta\phi_s^{\text{peng}} + \delta^{\text{NP}}$

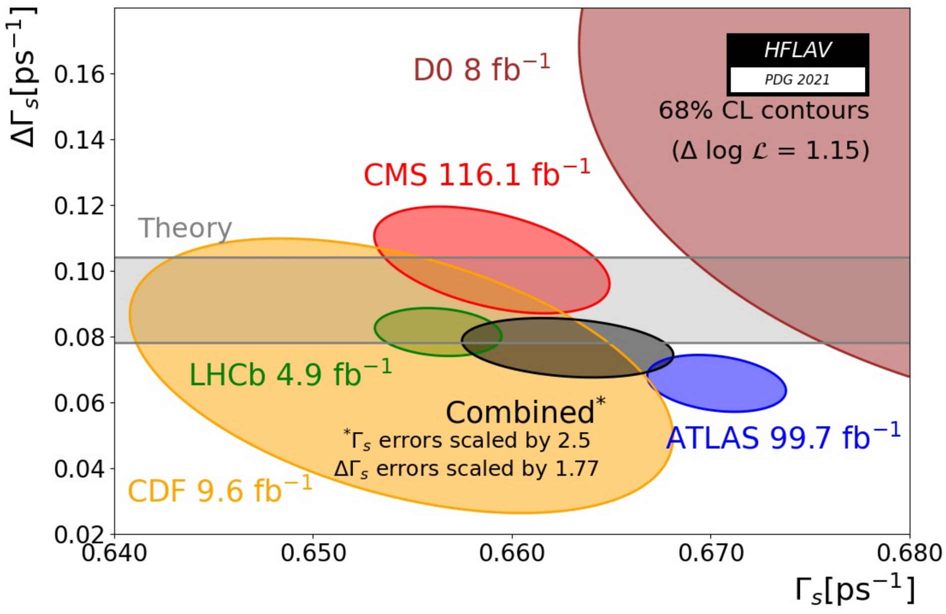
SM prediction for $-2\beta_s$: -0.03696 $\pm$0.0004 [CKMfitter]

Well under control with $B_s^0 \to J/\psi \overline{K}^{*0}$ and $B^0 \to J\psi\rho^0$

Status of $\phi_s^{c\bar{c}s}$

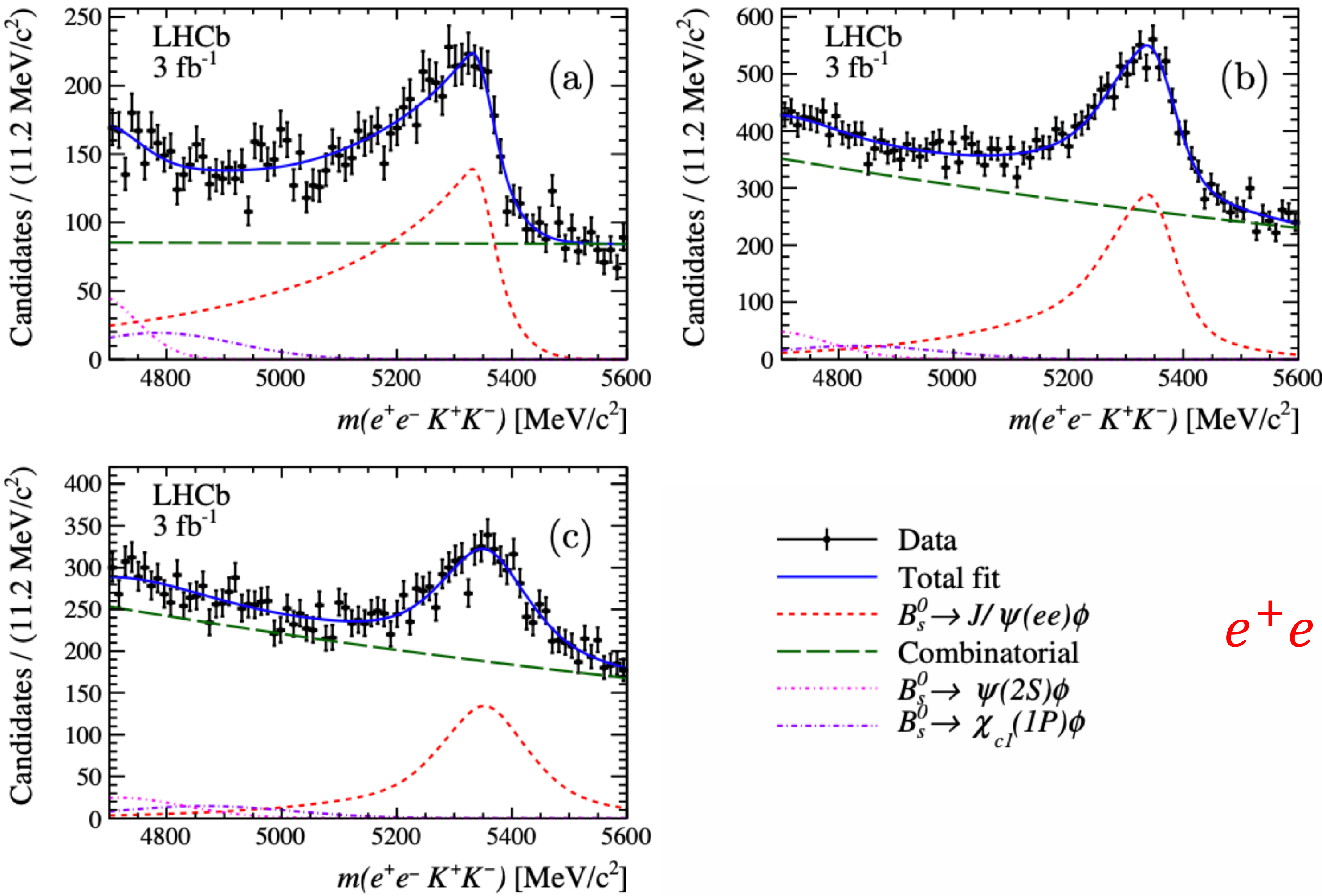
- Tensions seen between measurements for Γ_s and $\Delta\Gamma_s$, scale factors on errors applied: 2.5 and 1.77, respectively
- $B_s^0 \to J/\psi\phi$: CDF, D0, ATLAS, CMS, LHCb
- LHCb: $B_s^0 \to J/\psi K^+K^-, m(K^+K^-) > 1.5$ GeV, $B_s^0 \to J/\psi\pi^+\pi^-$, $B_s^0 \to \psi(2S)\phi, D_s^+D_s^-$ [JHEP 08 (2017) 037, Phys. Lett. B797 (2019) 134789, Phys. Lett. B762 (2016) 253, Phys. Rev. Lett. 113 (2014) 211801]
- Average: $\phi_s^{c\bar{c}s} = -0.050 \pm 0.019$, SM prediction for -2$\beta_s$: -0.03696 $\pm$0.0004





New stories of $\phi_s^{c\bar{c}s}$ measurements

LHCb-PAPER-2020-042

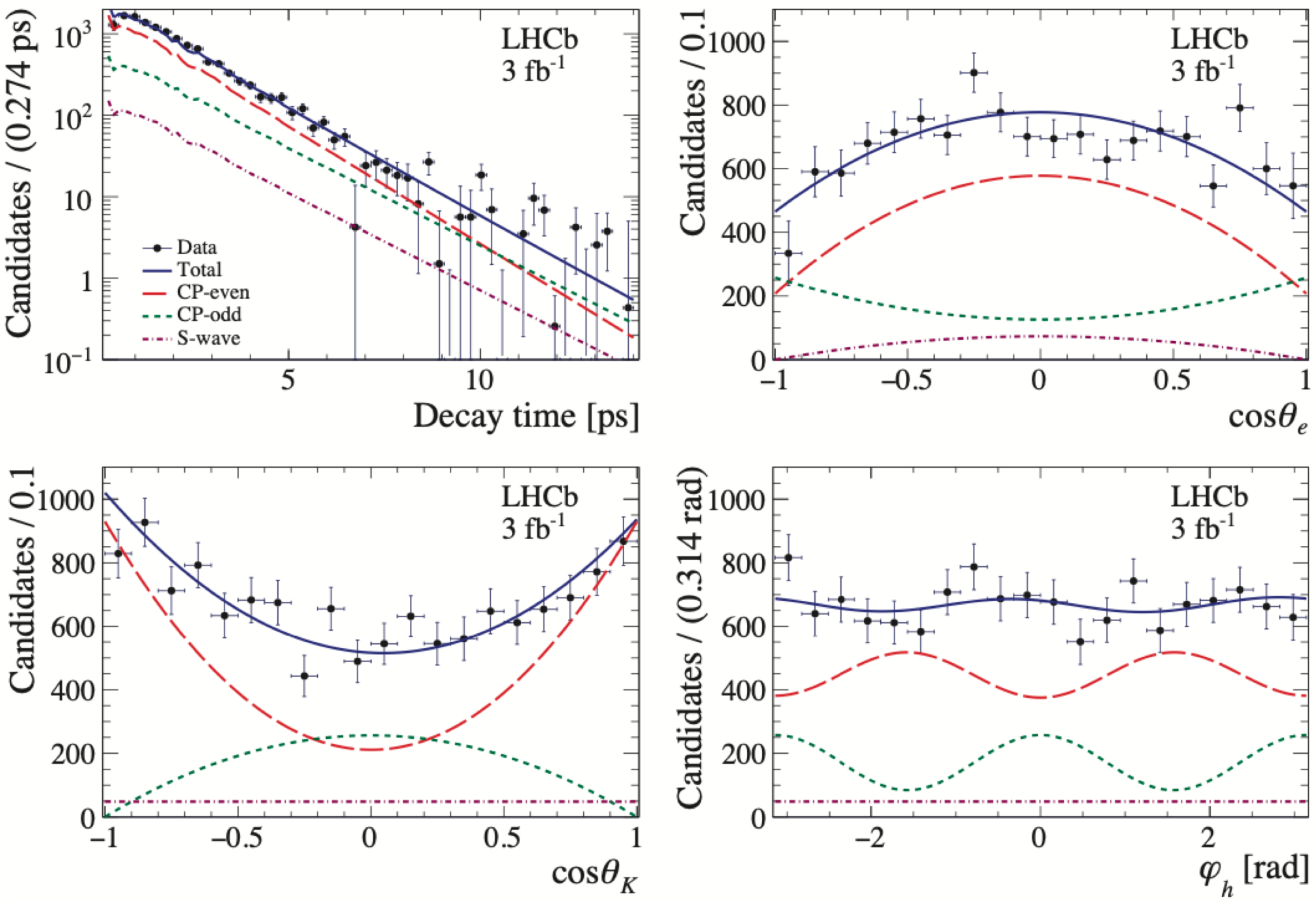


e^+e^- modes

- Reconstructed using $B_s^0 \to J/\psi(e^+e^-)\phi$ using LHCb Run1 data (3 fb^{-1})
- Zero (a), one (b) or both electrons (c) with bremsstrahlung correction

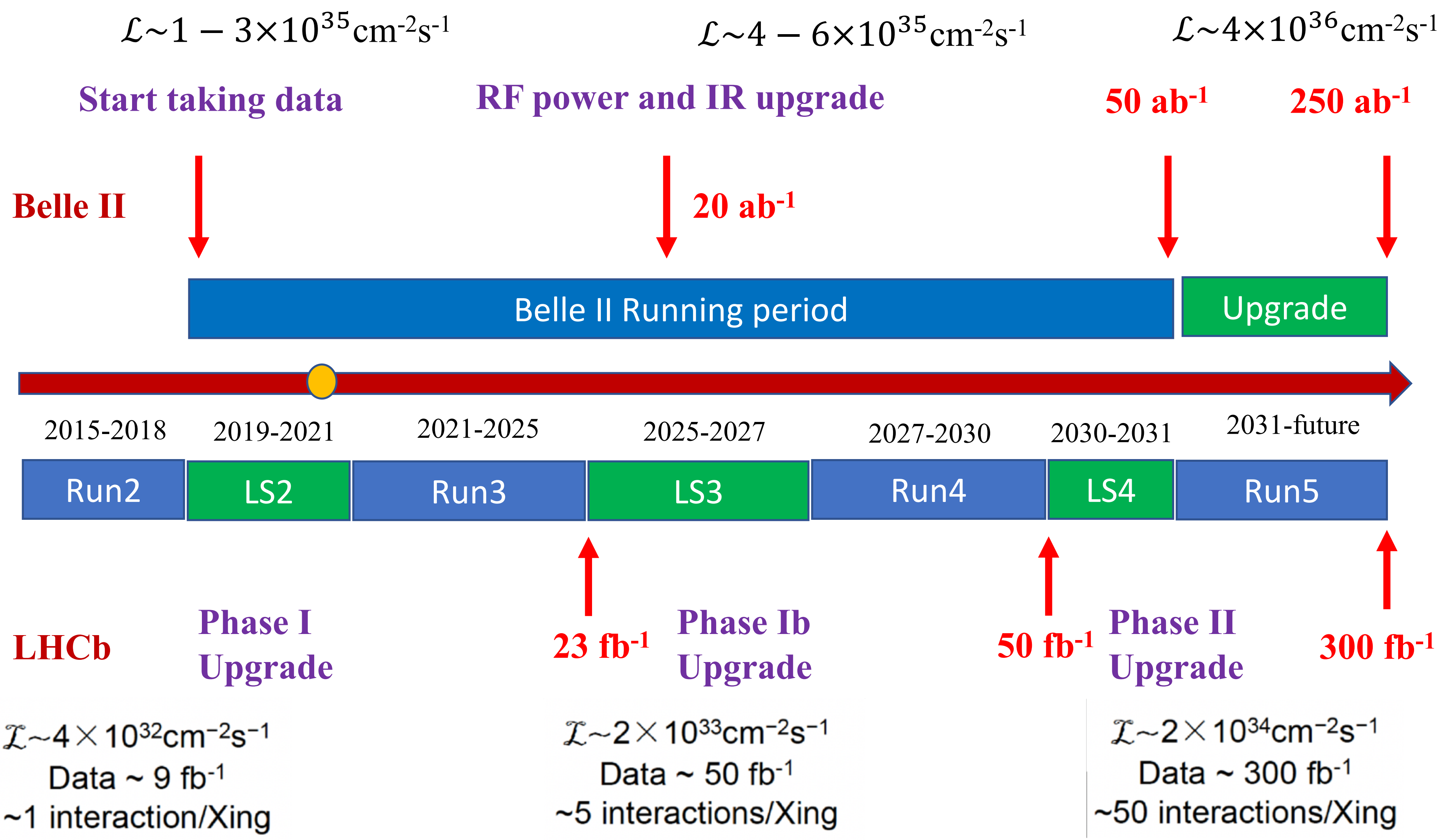
New stories of $\phi_s^{c\bar{c}s}$ measurements

LHCb-PAPER-2020-042



- Full time-dependent angular analysis performed to disentangle CP states
- ϕ_s measured to be $0.00 \pm 0.28 \pm 0.05$ rad, consistent with other results

Future data taking plans



See LHCb upgrade talk from Sheldon Stone, Belle II status from Minakshi Nayak

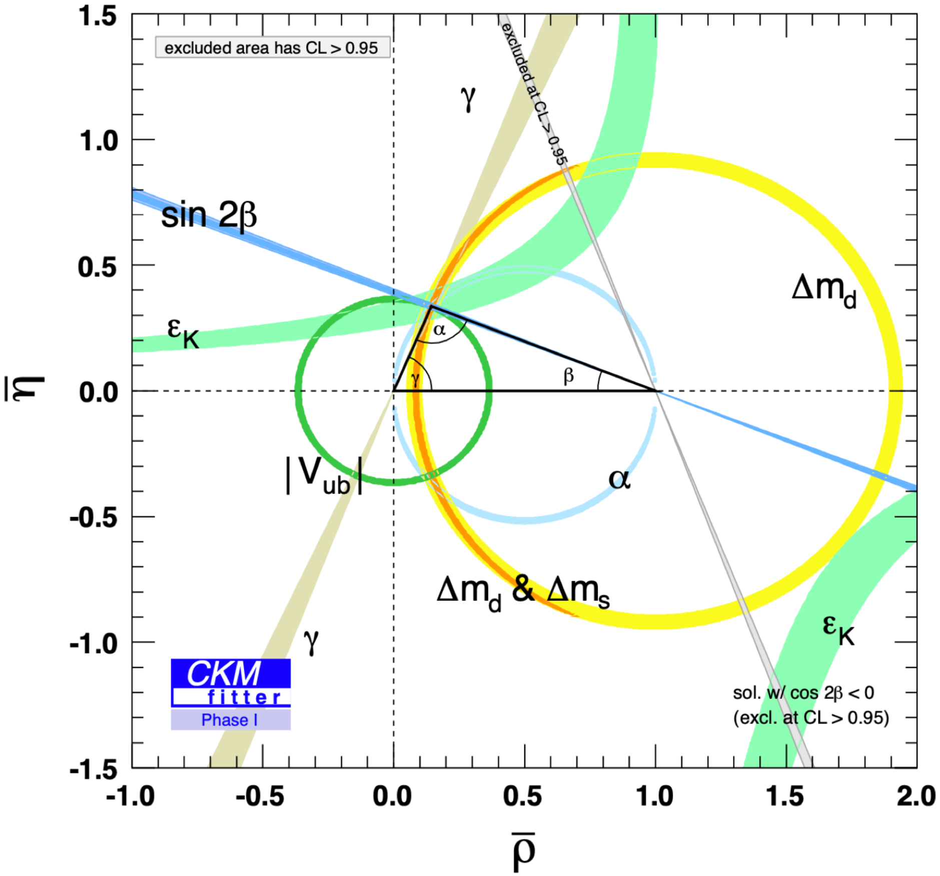
CKM angle potential in near future

Observable	LHCb 2025	Belle II (2025)	> 2030
γ/ϕ_3	1.5°	1.5°	<0.35°
Sin2β/sin2ϕ_1	0.011	0.005	<0.003
α/ϕ_2	-	1.5°	-
ϕ_s, with $B_s^0 \to J/\psi\phi$	14 mrad	-	4 mrad
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	35 mrad	-	9 mrad
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	39 mrad	-	11 mrad

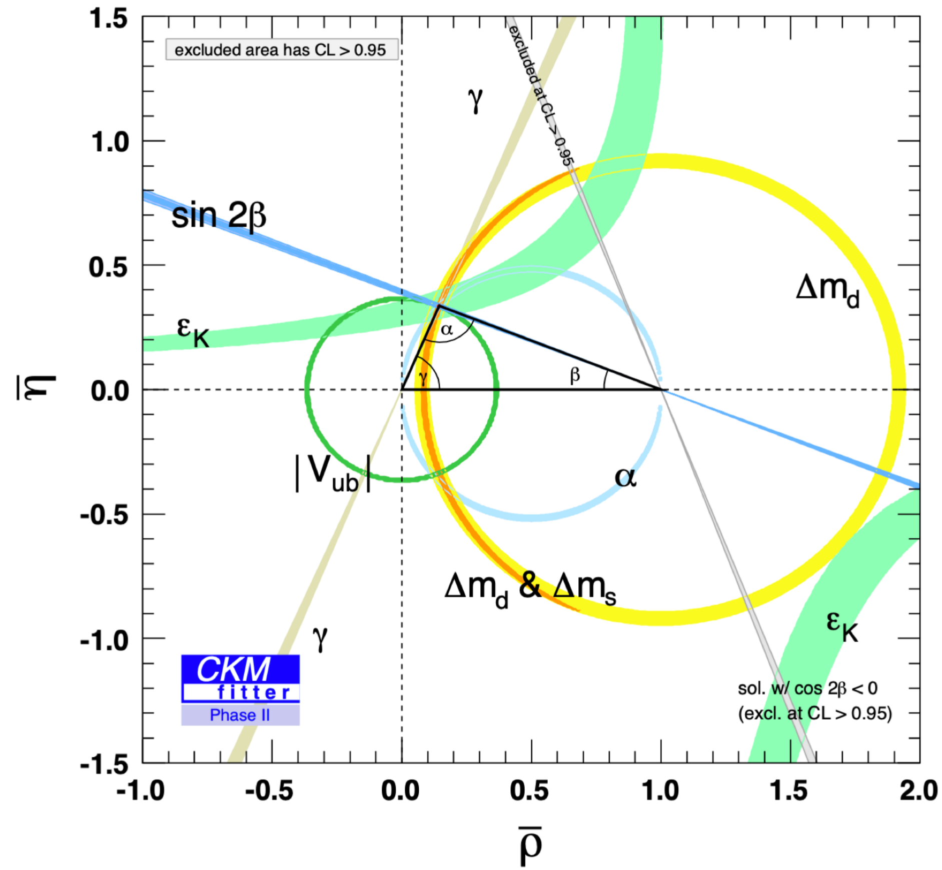
Belle II Physics Book
LHCb upgrade II physics case

CKM triangles in two decades

Phase I



Phase II

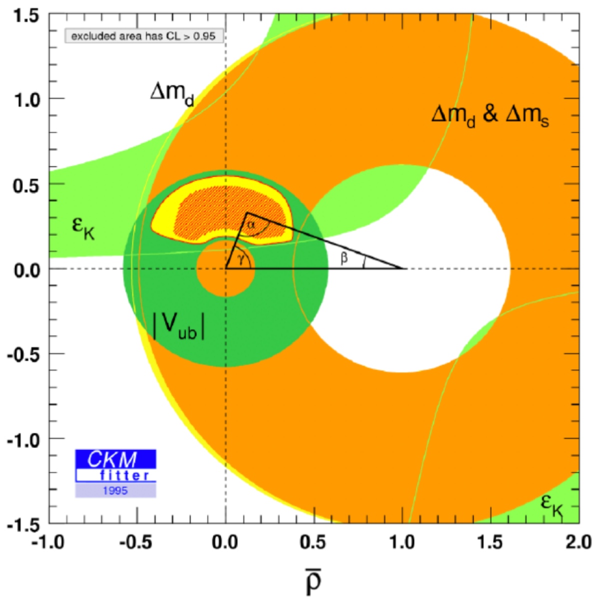


- With assumptions on improvements on lattice
- Central values at current fit values

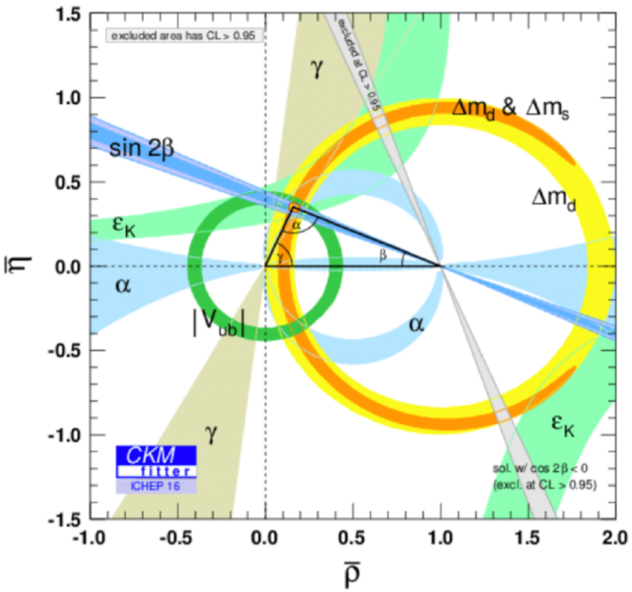
See V_{cb}, V_{ub} talk from Michel De Cian

Conclusion

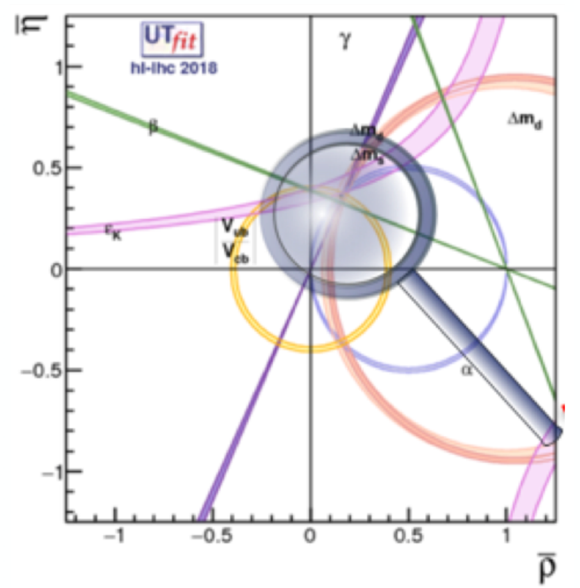
1995



2016



future



Spectrum of H, n=3 → n=2