Measurements of the CKM angle γ (and friends) at LHCb

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on behalf of the LHCb collaboration

Science and Technology Facilities Council

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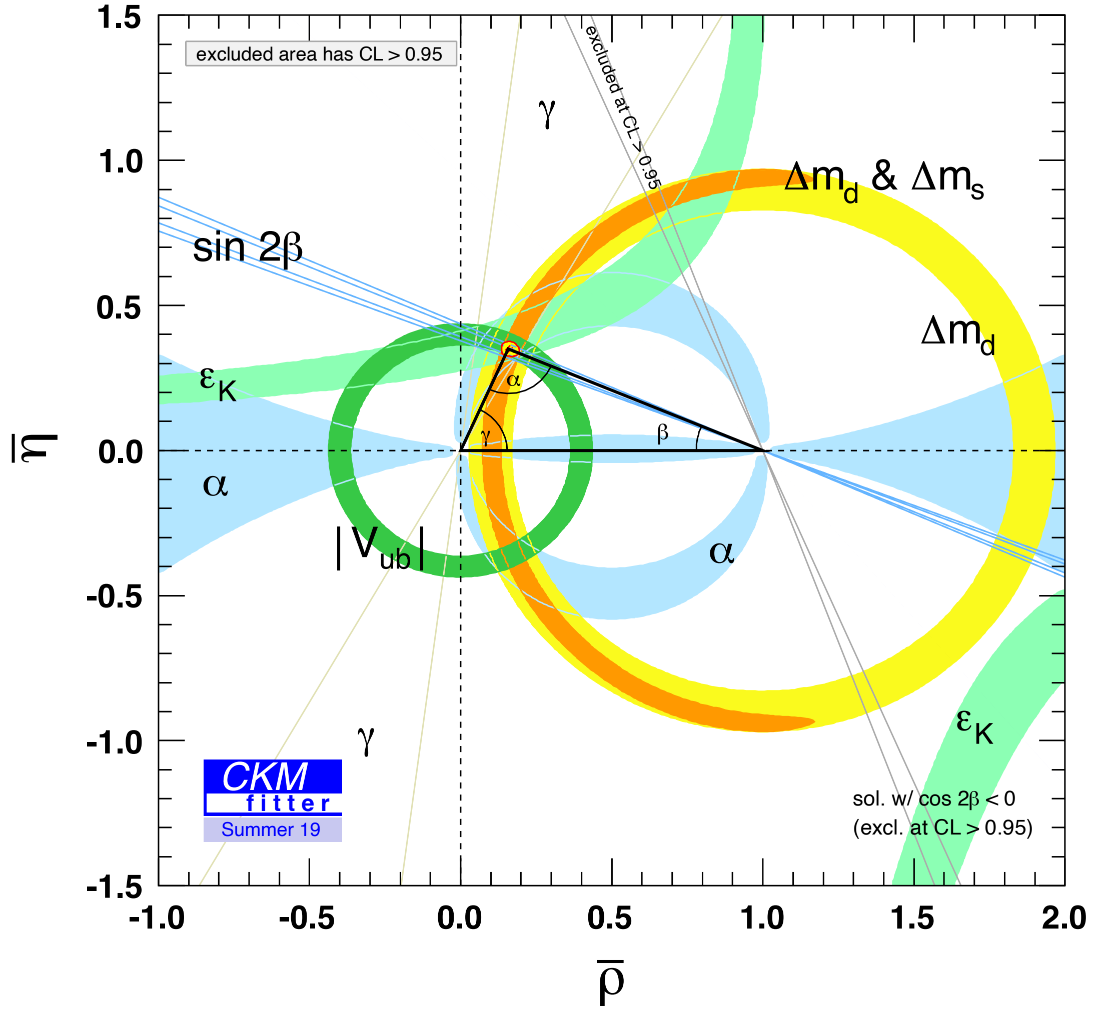
Introduction

- Why are we (still) measuring γ ?
  - Standard candle measurement of the SM
  - Tree-level decays, theoretically simple
  - We really measure γ not $\gamma \pm \Delta_{SM}$
  - Negligible SM uncertainties ~$(10^{-7})^{o}$
  - Still room for some NP though

- Indirect measurements from CKM fits
  - $\gamma = (65.8 \pm 2.2)^{\circ}$, $\gamma = (65.55^{+0.90}_{-2.65})^{\circ}$
  - Previous measurement from LHCb

$$\gamma = (74.0^{+5.0}_{-5.8})^{\circ}$$ LHCb-CONF-2018-002



Measuring γ

- Interference effects
  - Two amplitudes giving the same final state: $b \to cW\ (V_{cb})$ and $b \to uW\ (V_{ub})$
  - Golden mode $B^{\pm} \to DK^{\pm}$

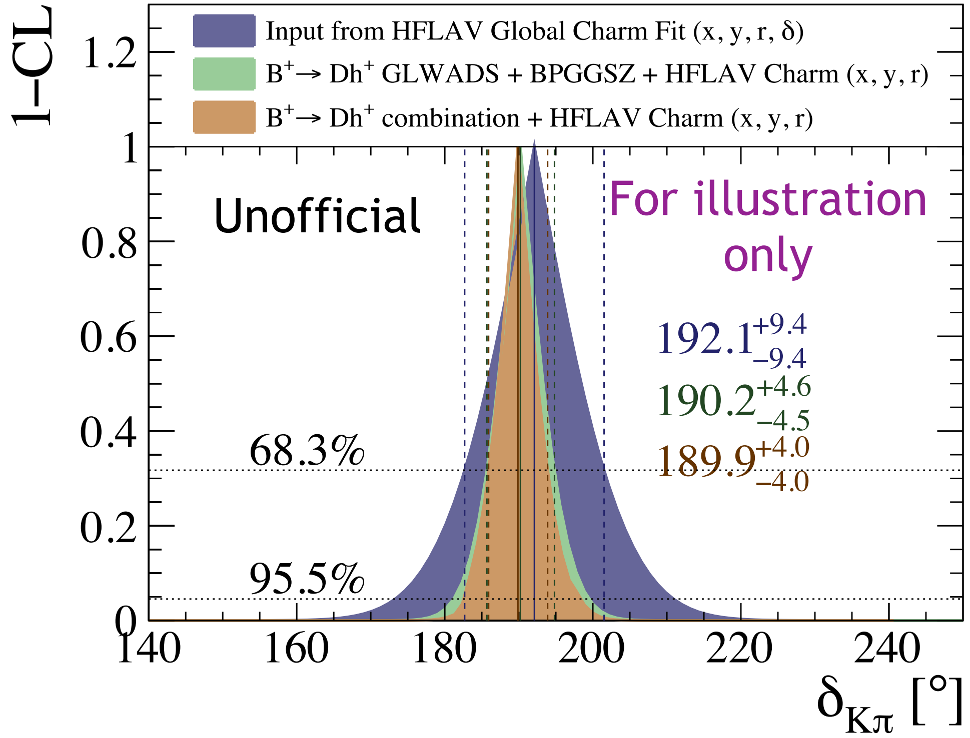
$$
\begin{tikzcd}
 & D^0 K^- \arrow[dr, "r_D e^{i(\delta_D)}"] & \\
B^- \arrow[ur] \arrow[dr, "r_B e^{i(\delta_B - \gamma)}"'] & & f_D K^- \\
 & \bar{D}^0 K^- \arrow[ur] &
\end{tikzcd}
$$

Ratio of magnitudes and phase difference for D decay amplitudes

Ratio of magnitudes and phase difference for B decay amplitudes

LHCb γ (+ charm?) combination

- Historically taken HFLAV global charm fit as an input $(x_D, y_D, r_D, \delta_D)$
  - External constraints for two body D decay modes and mixing corrections across the board
  - $B^- \to Dh^-, D \to K^\pm\pi^\mp$ decays have good sensitivity to $\delta_D^{K\pi}$ (if γ, δ_B are well measured)
- Why not just measure $\delta_D^{K\pi}$?
  - Measuring just $\delta_D^{K\pi}$ requires inputs for x_D, y_D, r_D
  - These in turn depend on the strong phase
  - So, the most robust option is to use LHCb charm + beauty data to constrain all four parameters
  - This combined input can be used by HFLAV etc



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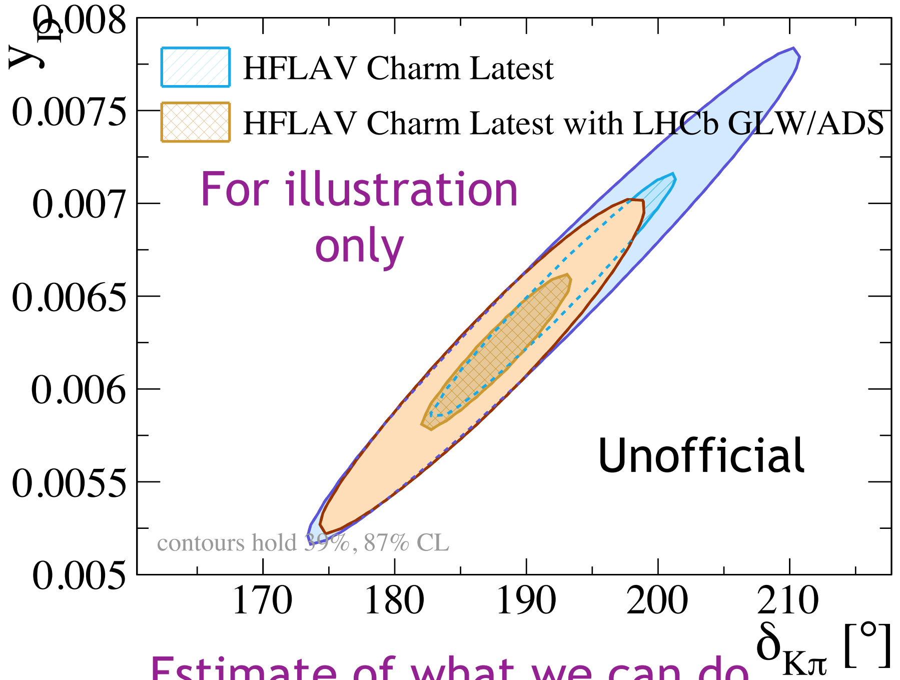
- Strong correlation between y_D and $\delta_D^{K\pi}$
  - Originates from the fact one typically measures $y_D \cos\delta_D^{K\pi}$
  - Allows for a large corresponding improvement in the measurement of y_D

$$y_D \equiv \frac{\Delta\Gamma}{2\Gamma}$$



Estimate of what we can do

LHCb γ and charm combination

- Large update since the previous paper
  - LHCb γ and charm combination
  - Many new and updated inputs
- Follow a frequentist procedure
  - Described in details in the previous paper - JHEP 12 (2016) 087
  - Combine 151 observables
  - Determine 52 parameters

B decay	D decay	Ref.	Dataset	Status since Ref. [22]
$B^\pm \to Dh^\pm$	$D \to h^+h^-$	[24]	Run 1&2	**Updated**
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$	[25]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	[26]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to K^0_S h^+h^-$	[23]	Run 1&2	**Updated**
$B^\pm \to Dh^\pm$	$D \to K^0_S K^\pm\pi^\mp$	[27]	Run 1&2	**Updated**
$B^\pm \to D^*h^\pm$	$D \to h^+h^-$	[24]	Run 1&2(*)	**Updated**
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	[28]	Run 1&2(*)	As before
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$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$	[29]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	[30]	Run 1&2(*)	**Updated**
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[30]	Run 1&2(*)	**New**
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	[31]	Run 1	**Superseded**
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	[32]	Run 1	As before
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[33]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	[34]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm\pi^+\pi^-$	$D^+_s \to h^+h^-\pi^+$	[35]	Run 1&2	**New**
–	$D \to h^+h^-$	[36–38]	Run 1&2	**New**
–	$D \to h^+h^-$	[39]	Run 1	**New**
–	$D \to h^+h^-$	[40–43]	Run 1&2	**New**
–	$D \to K^+\pi^-$	[44]	Run 1	**New**
–	$D \to K^+\pi^-$	[45]	Run 1&2(*)	**New**
–	$D \to K^\pm\pi^\mp\pi^+\pi^-$	[46]	Run 1	**New**
–	$D \to K^0_S\pi^+\pi^-$	[47, 48]	Run 1&2	**New**
–	$D \to K^0_S\pi^+\pi^-$	[49]	Run 1	**New**

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LHCb γ and charm combination

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  - Combine 151 observables
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Most sensitive inputs for γ published last year

JHEP 04 (2021) 081

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JHEP 06 (2020) 058

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$B^0 \to D^{\mp}\pi^{\pm}$	$D^+ \to K^-\pi^+\pi^+$	[33]	Run 1	As before
$B^0_s \to D_s^{\mp}K^{\pm}$	$D_s^+ \to h^+h^-\pi^+$	[34]	Run 1	As before
$B^0_s \to D_s^{\mp}K^{\pm}\pi^+\pi^-$	$D_s^+ \to h^+h^-\pi^+$	[35]	Run 1&2	**New**
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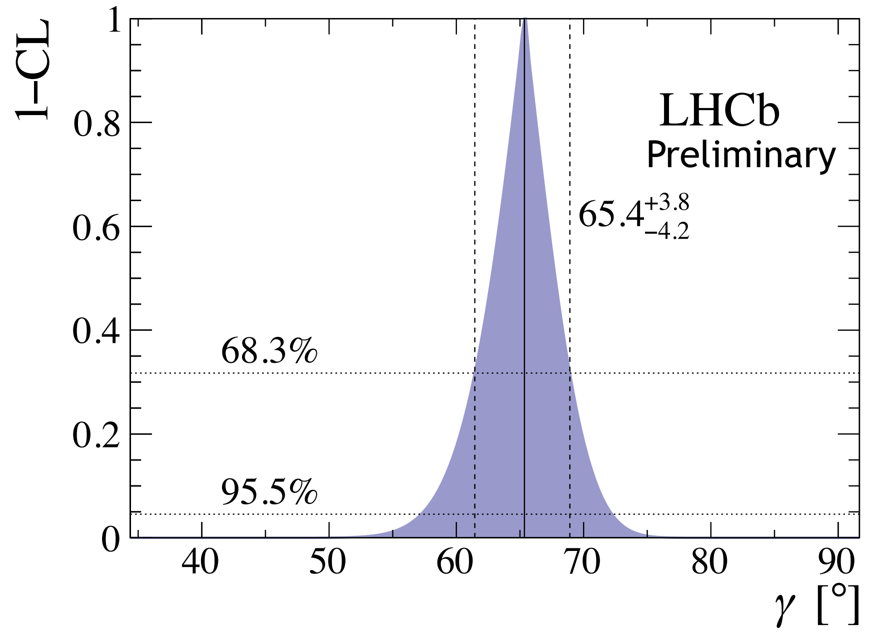
Headline results

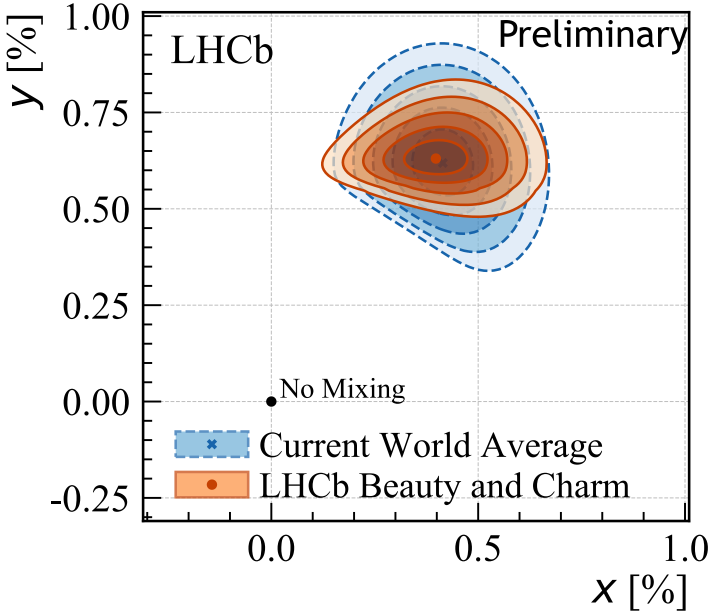
- Results
  - First simultaneous fit for charm and beauty parameters

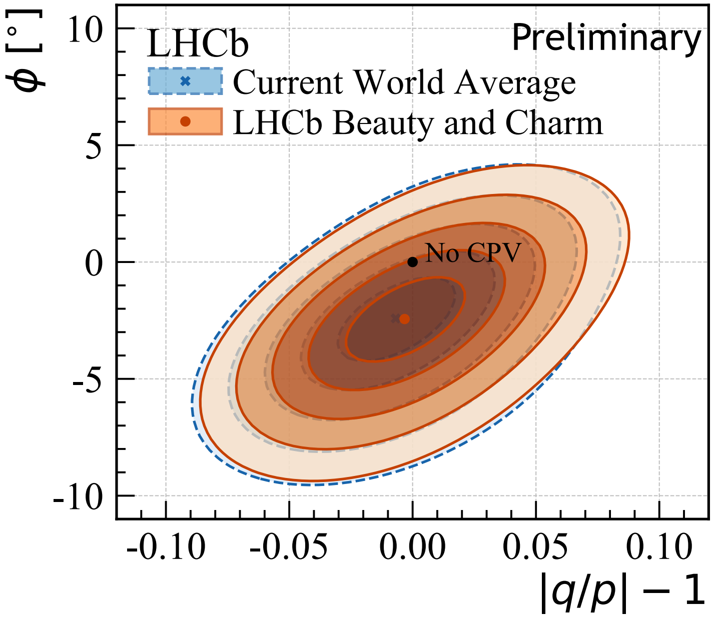
Observables: 151
Parameters: 52
Fit probability: 67%

$$\gamma = (65.4^{+3.8}_{-4.2})^\circ$$



$$x_D = (4.00^{+0.52}_{-0.53}) \times 10^{-3}, y_D = (6.30^{+0.33}_{-0.30}) \times 10^{-3}$$





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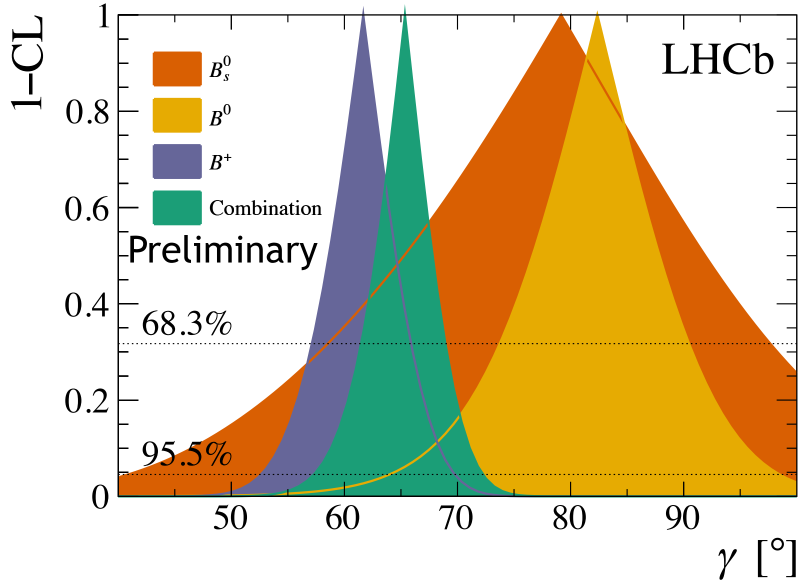
World average (HFLAV) $x_D = (4.09^{+0.48}_{-0.49}) \times 10^{-3}, y_D = (6.15^{+0.56}_{-0.55}) \times 10^{-3}$

Breakdowns

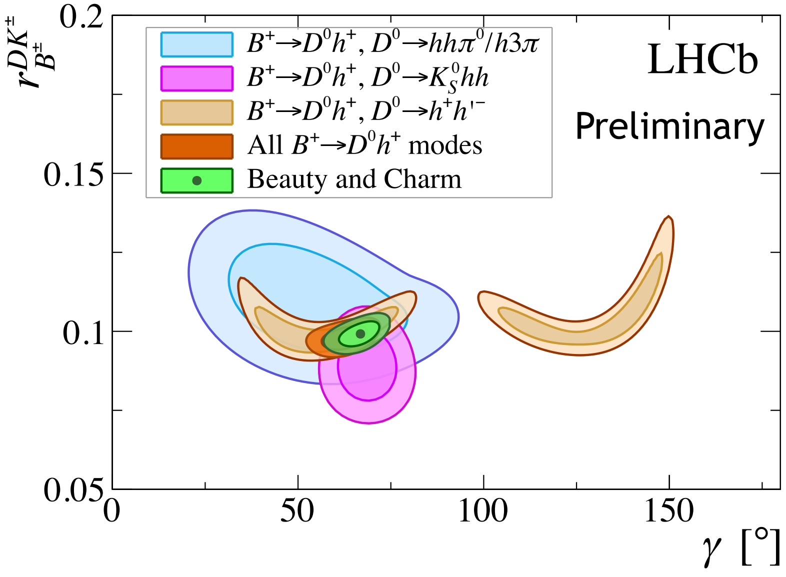
- Interesting to split the combination up into parts

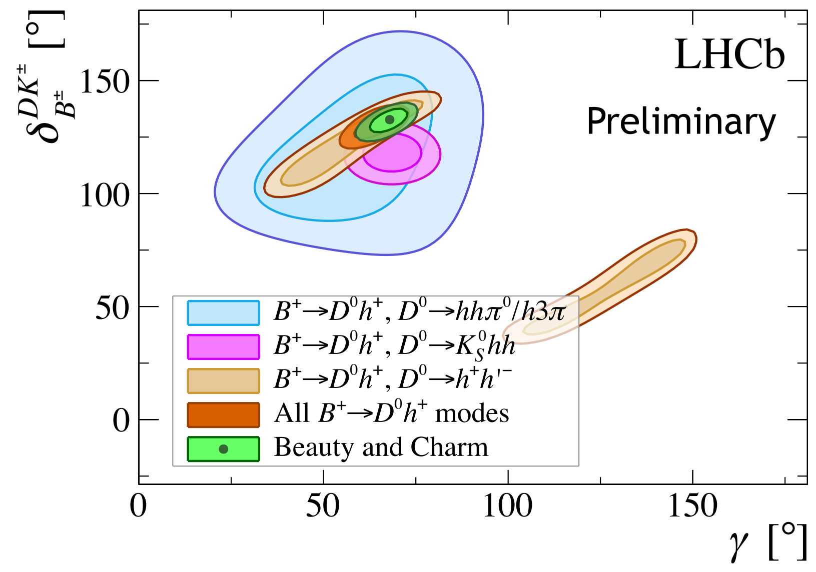
B species



Combination	Value	68.3% CL	95.4% CL
B^+	61.7	[57.1, 65.9]	[52.6, 69.8]
B^0	82.0	[73.7, 90.5]	[64.0, 98.0]
B_s^0	79.0	[59.0, 98.0]	[41.0, 106.0]

B+ decay modes only





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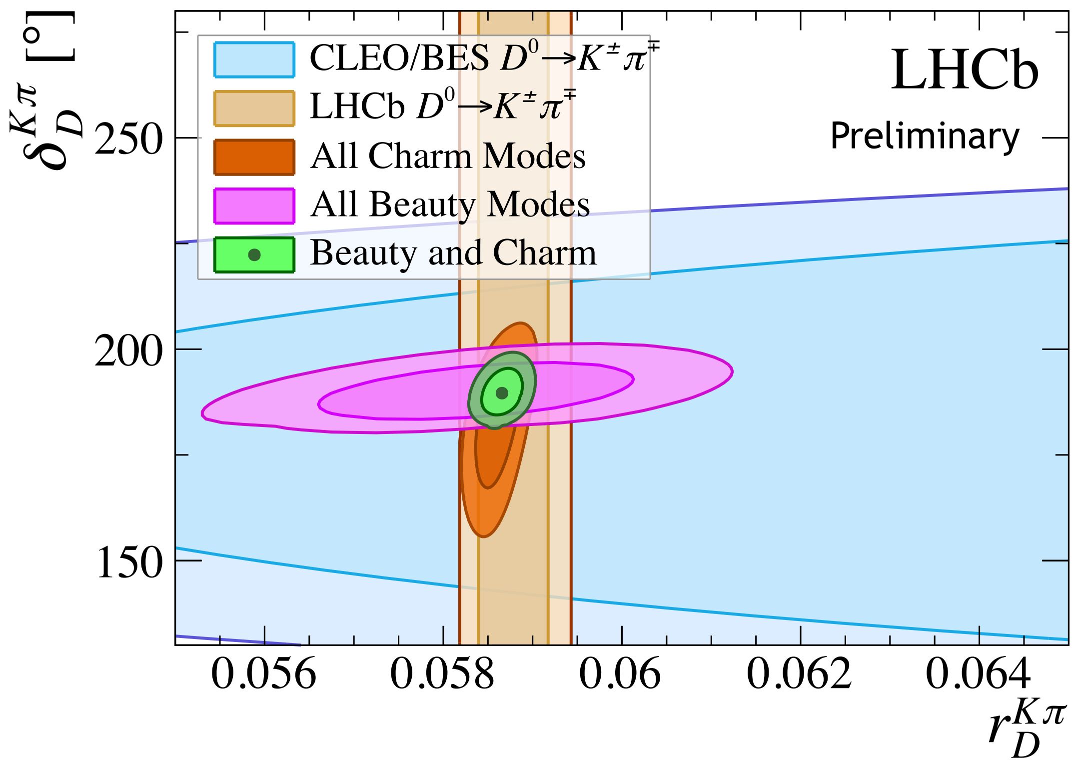
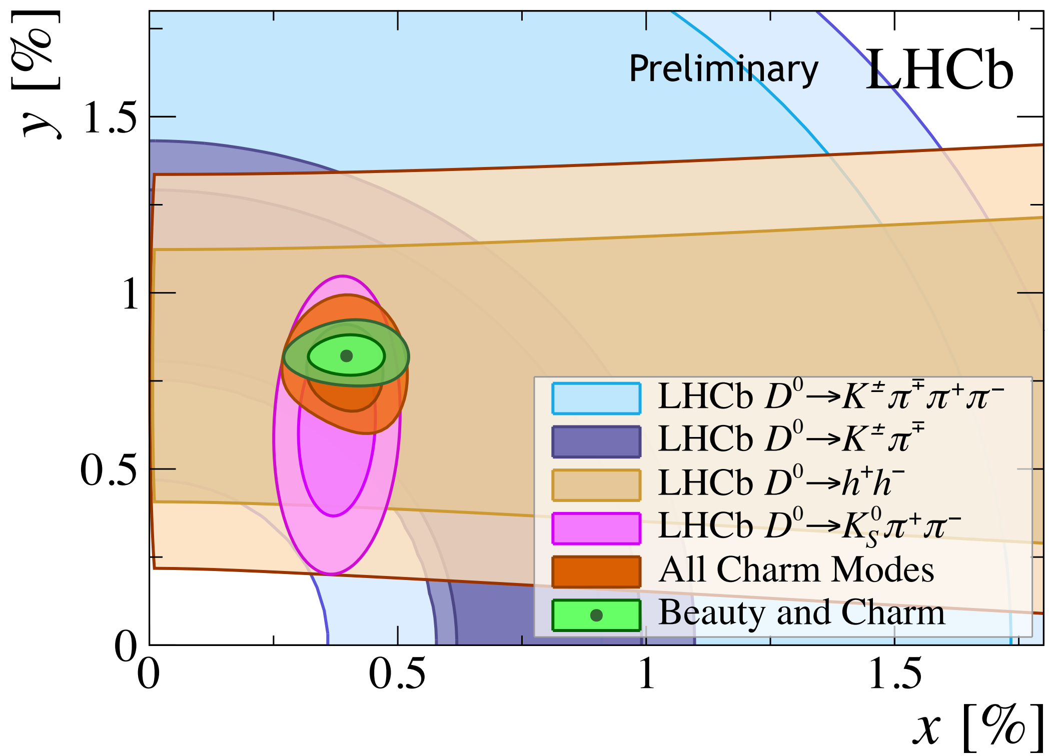
Breakdowns

- Highlights the complementarity of the beauty and charm samples

Charm





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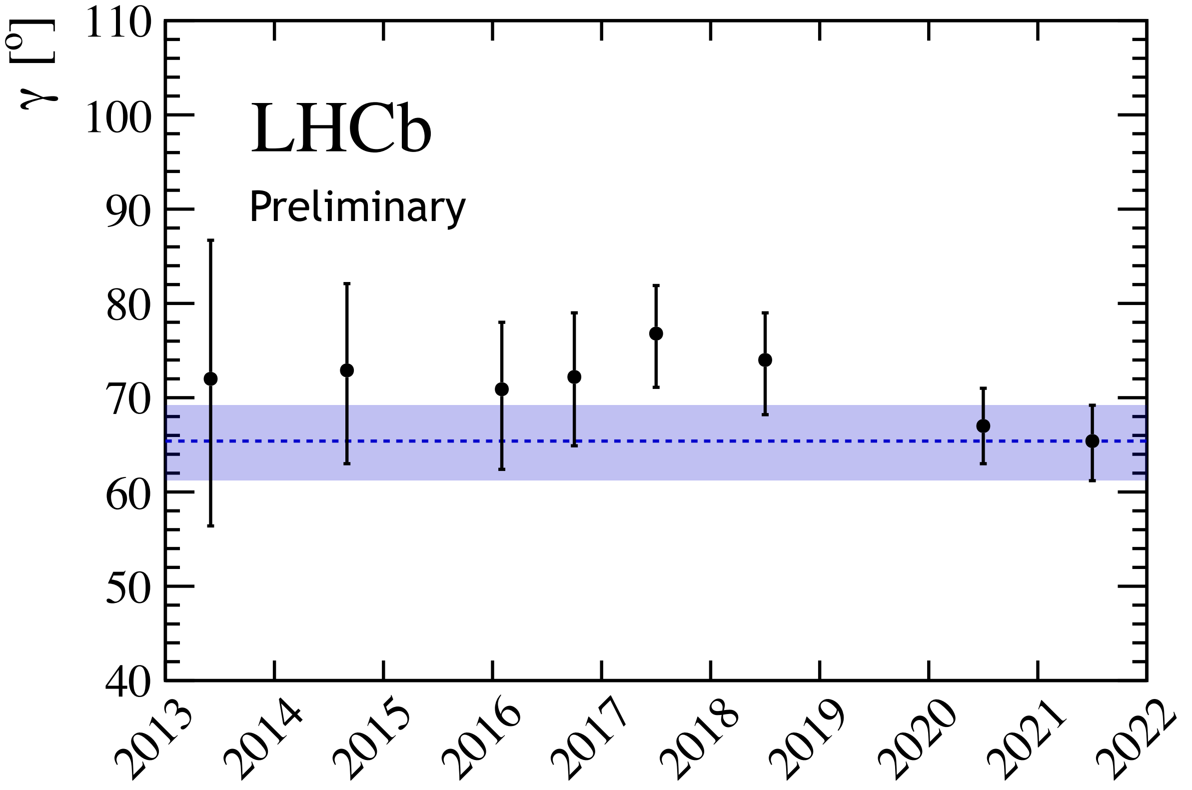
Evolution of γ results

- We've been measuring γ for a while now
  - Last two results around 65 degrees
  - Lower value mostly driven by
    - Run 1+2 $B^- \to Dh^-, D \to K_S^0 h^+ h^-$ updated treatment of backgrounds
    - Run 1+2 $B^- \to Dh^-, D \to K^\pm \pi^\mp$ backgrounds and merging of degenerate solutions
    - 5D compatibility to 2018 result ~2 sigma
  - Excellent agreement with indirect global CKM fitters.

$\gamma = (65.8 \pm 2.2)^\circ$ UT fit

$\gamma = (65.55^{+0.90}_{-2.65})^\circ$ CKMfitter

$\gamma = (65.4^{+3.8}_{-4.2})^\circ$



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Precise measurement of Δm_s

- Oscillation frequency of B_s^0 mesons
  - Powerful constraint on the CKM matrix
  - Reduce systematic uncertainties in CPV measurements
  - Theory predictions available but less precise that experiment

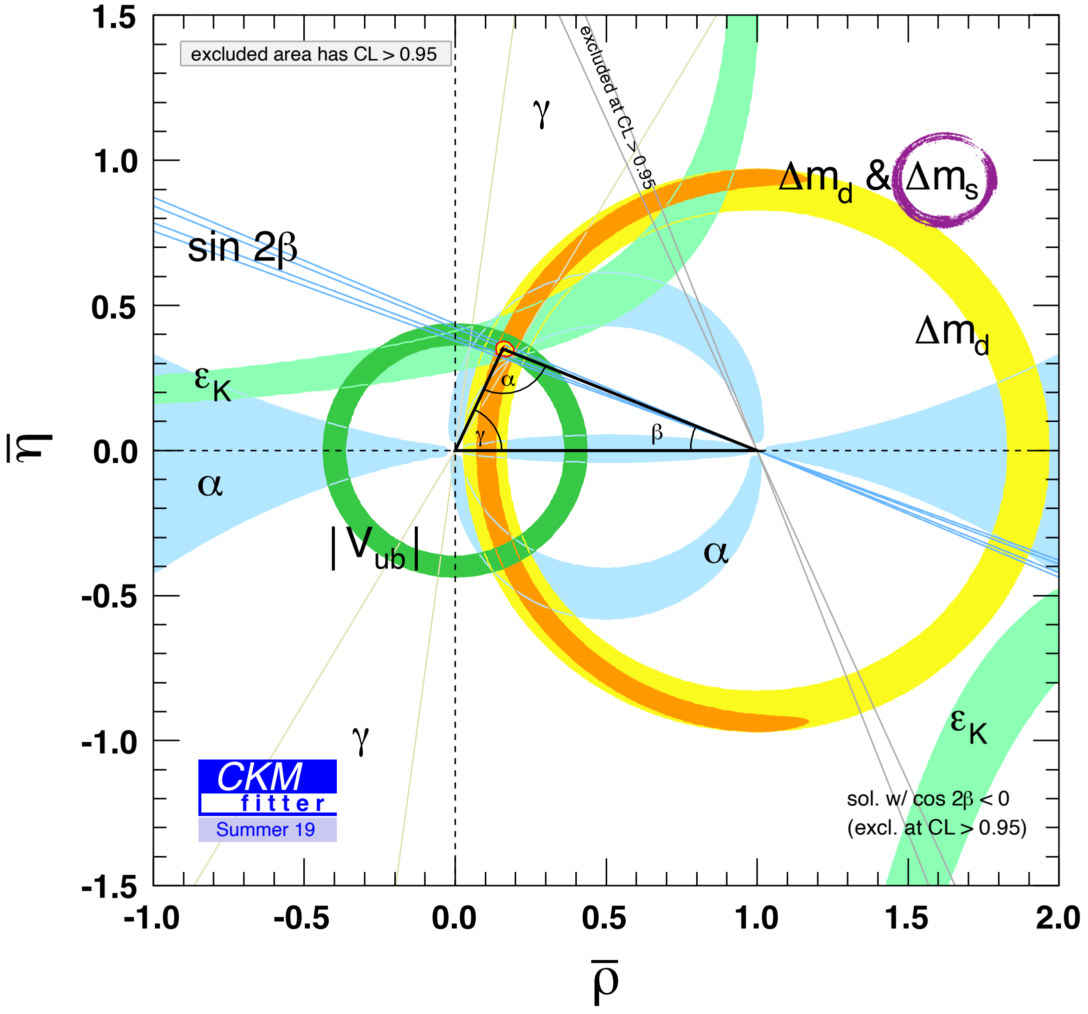
  E.g. Di Luzio, Kirk, Lenz et al. JHEP 12 (2019) 009

- Previous best result from LHCb

  $$\Delta m_s = 17.757 \pm 0.007 \pm 0.008 \ \mathrm{ps}^{-1}$$ JHEP 03 (2021) 137

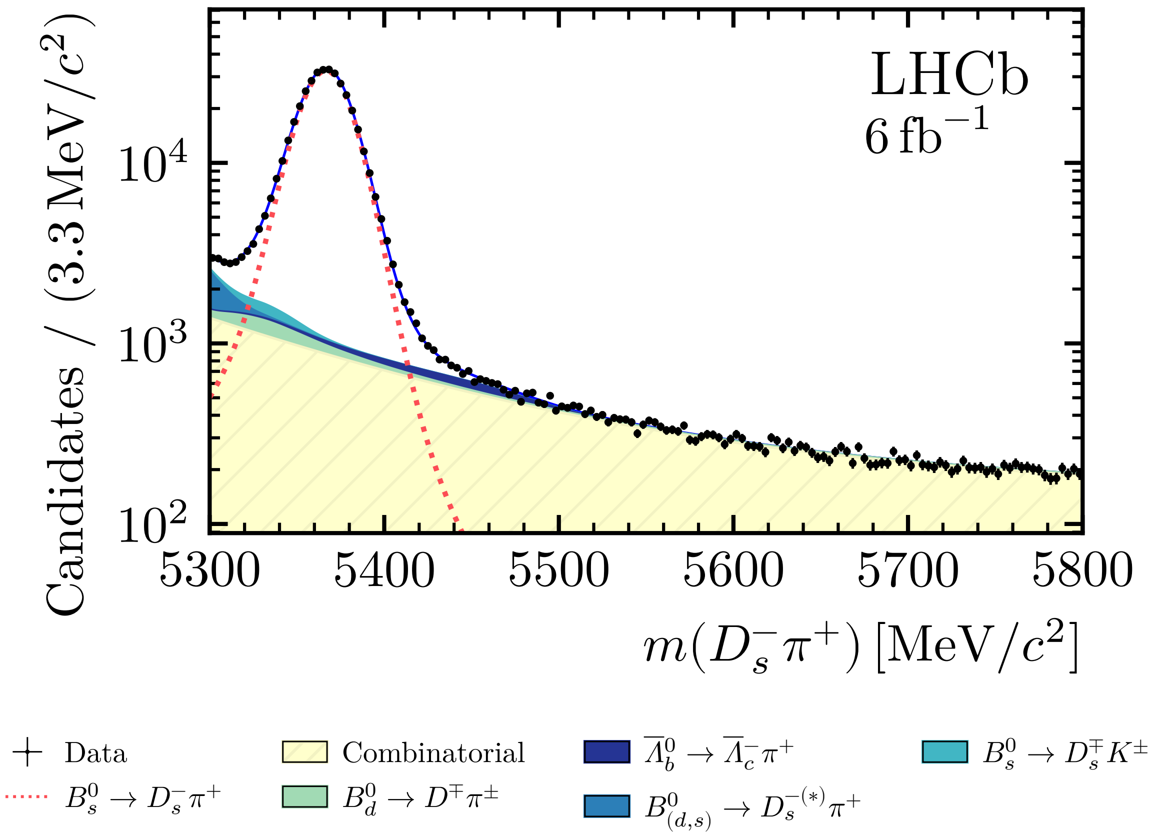
  - Already considerably more precise than the world average (HFLAV)

  $$\Delta m_s = 17.741 \pm 0.020 \ \mathrm{ps}^{-1}$$ Eur. Phys. J. C (2021) 81: 226



Time-dependent analysis of $B_s^0 \to D_s^- \pi^+$ decays

- Full Run 2 data sample, corresponding to $6\ \mathrm{fb}^{-1}$ collected at $13\ \mathrm{TeV}$
  - Use both $D_s^- \to K^+K^-\pi^-, \pi^+\pi^-\pi^-$ final states
  - Mass fit to separate signal and background
  - Signal yield $378\,700 \pm 700$



arXiv:2104.04421 [hep-ex]

- Fit to the decay time distribution
  - Apply sWeights from the mass fit

$$P(t) \sim e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + C \cdot \cos(\Delta m_s t)\right]$$

  - In reality more complicated, resolution and acceptances effects, flavour tagging etc.

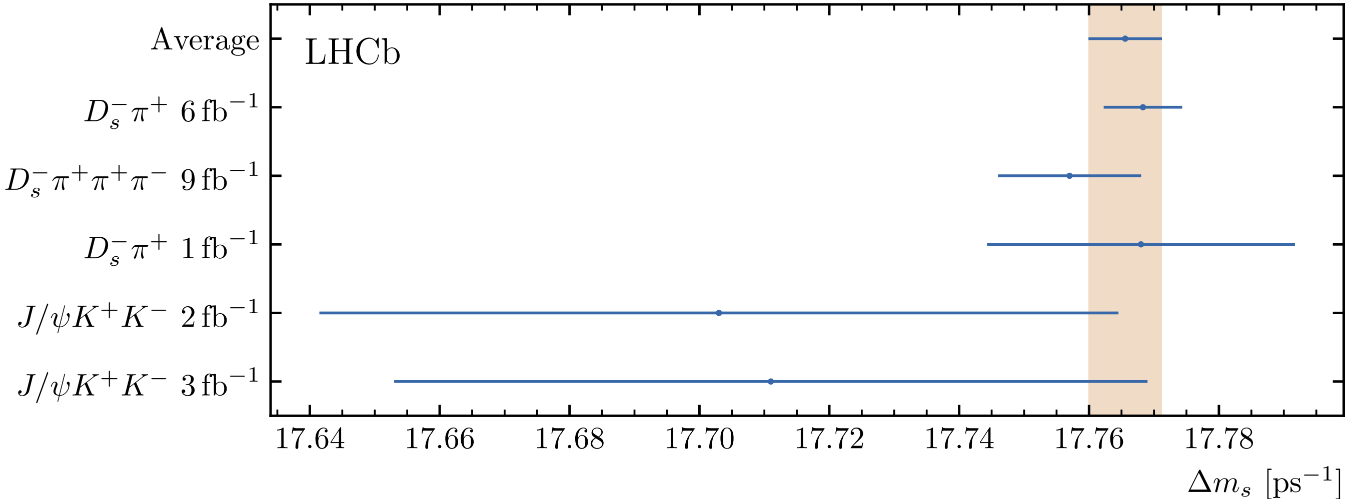
Time-dependent analysis of $B_s^0 \to D_s^-\pi^+$ decays

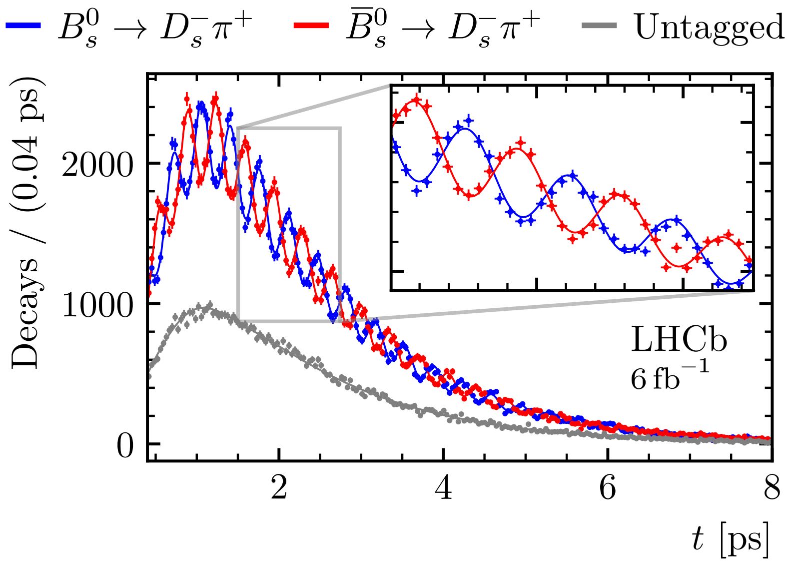
- Fit to the decay time distribution
  - Effective flavour tagging power about 6.1%
  - Factor of two improvement over the previous LHCb result

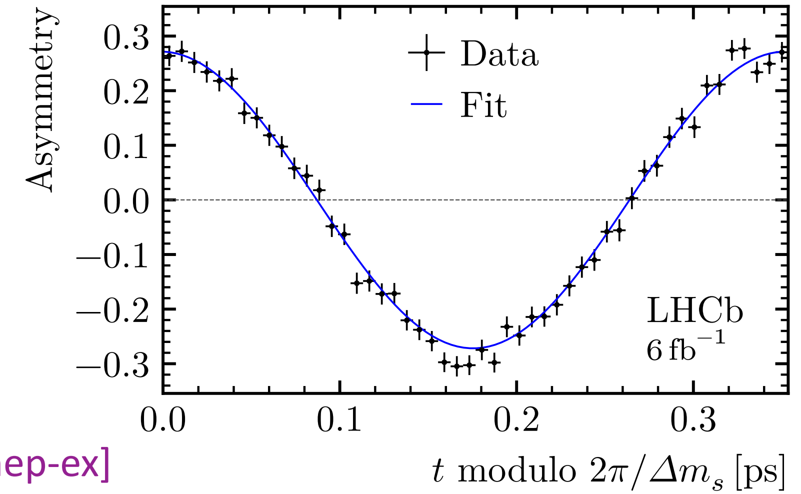
$$\Delta m_s = 17.7683 \pm 0.0051 \pm 0.0032 \text{ ps}^{-1}$$

  - Additionally combine all LHCb results to get

$$\Delta m_s = 17.7656 \pm 0.0057 \text{ ps}^{-1}$$



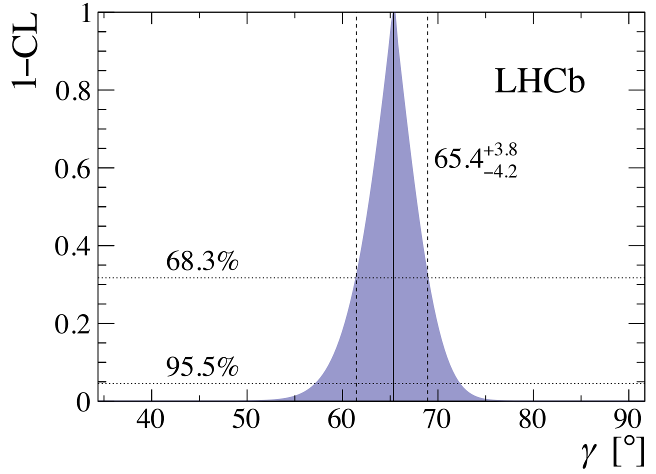




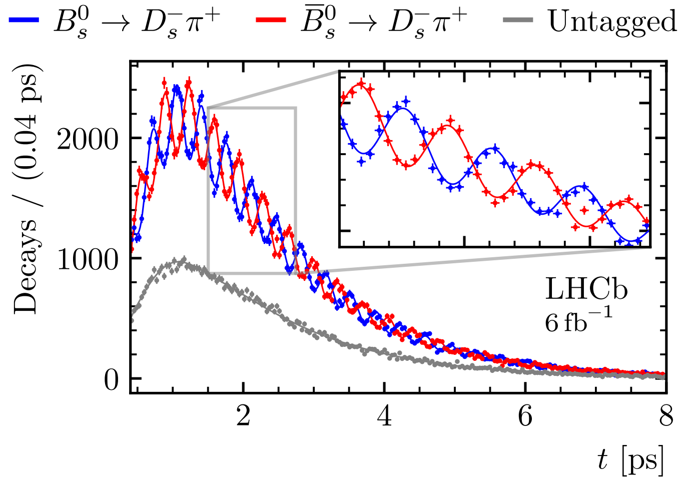
arXiv:2104.04421 [hep-ex]

Summary

- First combination of LHCb beauty and charm observables
  - Excellent precision on γ and a factor of two improvement for y_D



- Very precise new results for Δm_s
  - Improved constraints in the CKM picture



- Still more to come from LHCb
  - Run 1+2 measurements still coming through
  - The upgrade detector has taken shape, looking forward to first data taking next year

Backups

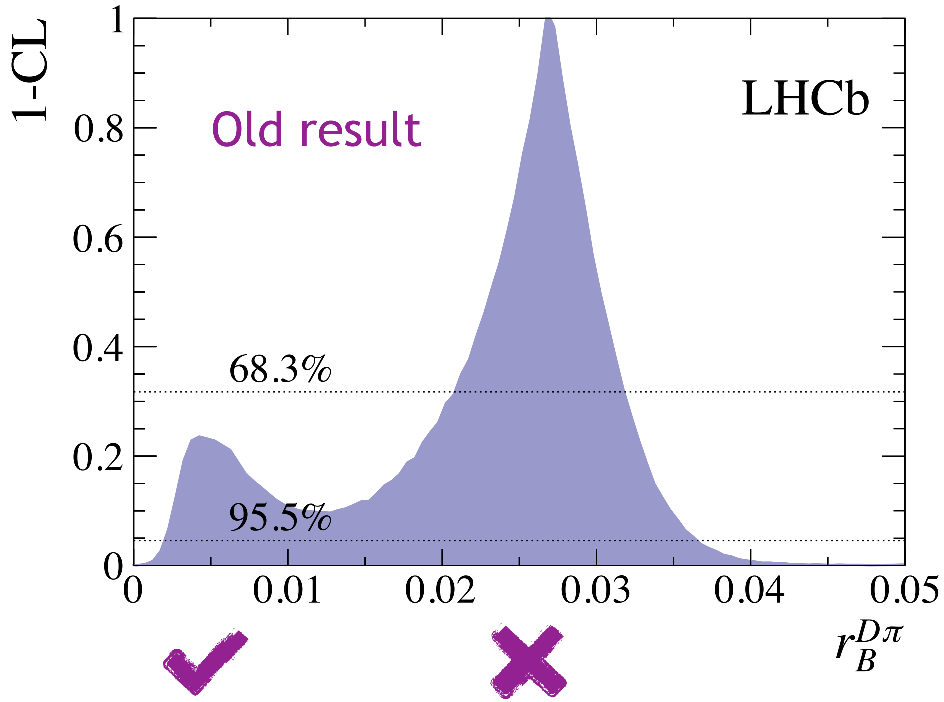
Auxiliary inputs

Decay	Parameters	Source	Ref.	Status since Ref. [22]
$B^\pm \to DK^{*\pm}$	$\kappa_{B^\pm}^{DK^{*\pm}}$	LHCb	[28]	As before
$B^0 \to DK^{*0}$	$\kappa_{B^0}^{DK^{*0}}$	LHCb	[31]	As before
$B^0 \to D^\mp\pi^\pm$	β	HFLAV	[15]	**Updated**
$B_s^0 \to D_s^\mp K^\pm(\pi\pi)$	ϕ_s	HFLAV	[15]	**Updated**
$D \to h^+h^-\pi^0$	$F_{\pi\pi\pi^0}^+$, $F_{K\pi\pi^0}^+$	CLEO-c	[50]	As before
$D \to \pi^+\pi^-\pi^+\pi^-$	$F_{4\pi}^+$	CLEO-c	[50]	As before
$D \to K^+\pi^-\pi^0$	$r_D^{K\pi\pi^0}$, $\delta_D^{K\pi\pi^0}$, $\kappa_D^{K\pi\pi^0}$	CLEO-c+LHCb+BESIII	[46, 51–53]	**Updated**
$D \to K^\pm\pi^\mp\pi^+\pi^-$	$r_D^{K3\pi}$, $\delta_D^{K3\pi}$, $\kappa_D^{K3\pi}$	CLEO-c+LHCb+BESIII	[46, 51–53]	**Updated**
$D \to K_S^0 K^\pm\pi^\mp$	$r_D^{K_S^0 K\pi}$, $\delta_D^{K_S^0 K\pi}$, $\kappa_D^{K_S^0 K\pi}$	CLEO	[54]	As before
$D \to K_S^0 K^\pm\pi^\mp$	$r_D^{K_S^0 K\pi}$	LHCb	[55]	As before

Revisiting the Dh combination

- The full set of Dh inputs last used in the previous PAPER from 2016
  - Subsequent CONFs have focused on the DK-like modes only
  - Mostly due to poor constraints on the Dpi system giving multiple solutions, and favouring one we knew to be incorrect - giving an unrealistically precise one sigma result for γ

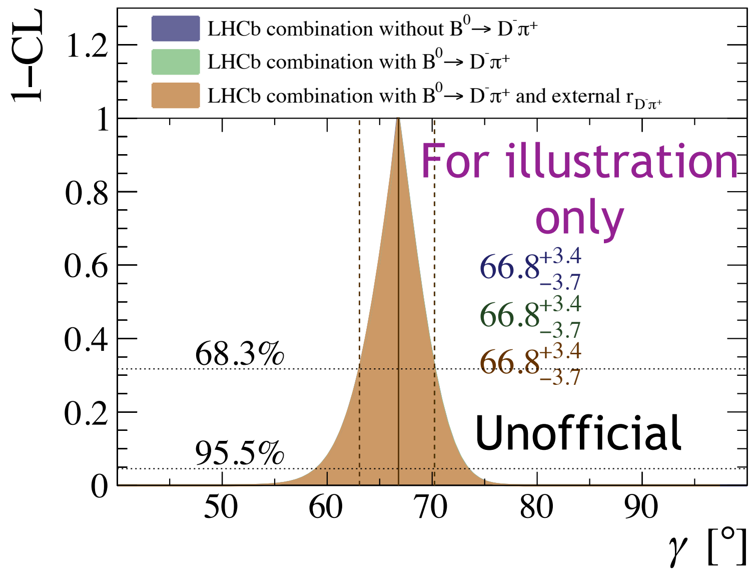
- However, now have some big new results
  - New approach in the BPGGSZ analysis measures CPV in Dpi decays as well
  - Input on $r_B^{D\pi}$ particularly valuable
  - High statistics from the two body analysis also provides some better stability

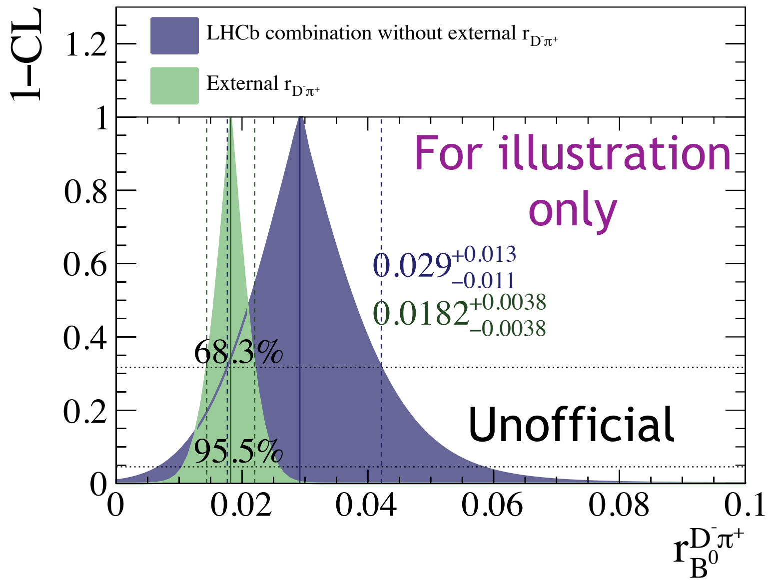


Input from $B^0 \to D^-\pi^+$ decays

- Can measure γ using a time-dependent analysis of this mode
  - However, there are two observables to measure, and three unknowns
  - So previously took $r_B^{D^-\pi^+}$ as an input in order to measure γ
  - This input is the **only** one in the entire combination with a theory assumption - SU(3)

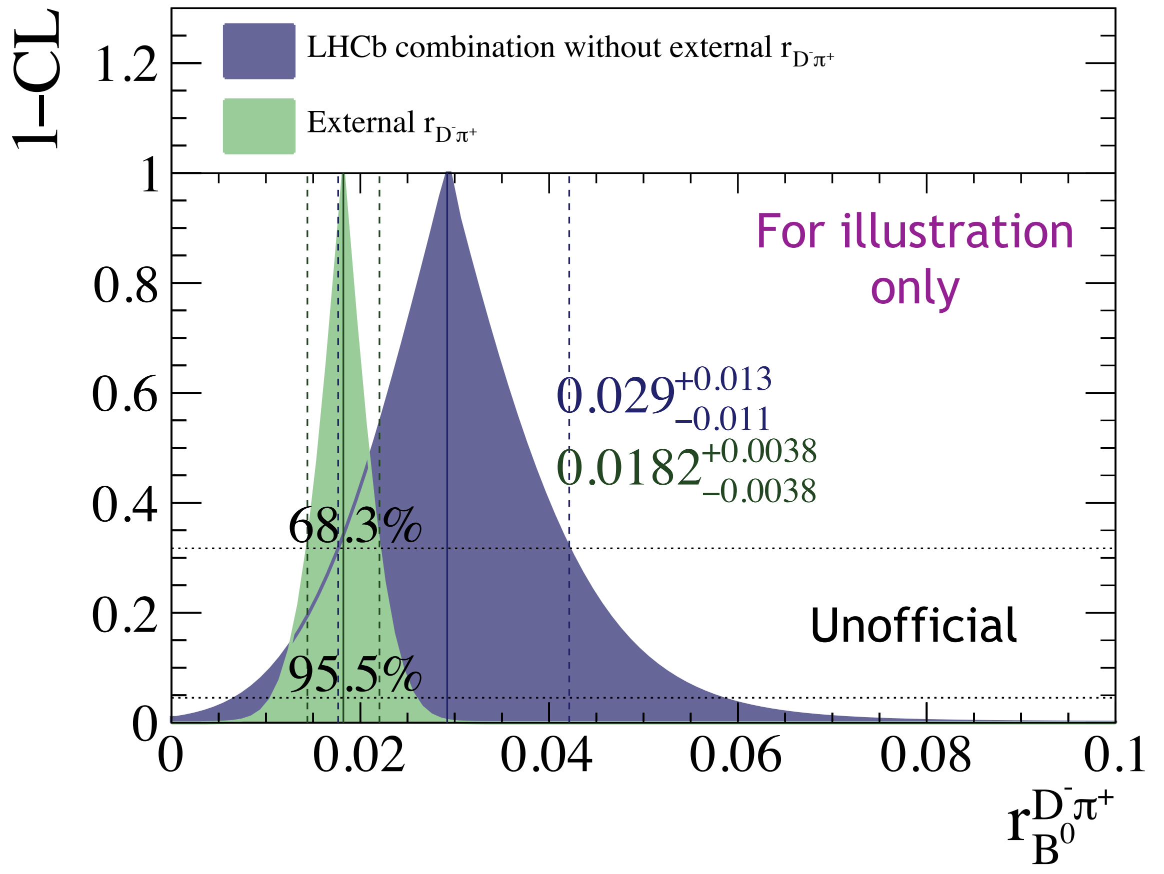
- The plan
  - Keep the experimental results in
  - Remove the external input for $r_B^{D^-\pi^+}$
  - Measure $r_B^{D^-\pi^+}$ in the combination instead





Results - comment on $B^0 \to D^-\pi^+$ decays

- Comparison with and without the old external input
  - Value of γ completely unaffected by the treatment of $r_B^{D^-\pi^+}$
  - Combination measures it to be
    $$r_B^{D^-\pi^+} = 0.029 \pm 0.013$$
  - Consistent with the previous input value of
    $$r_B^{D^-\pi^+}(\text{ext.}) = 0.0182 \pm 0.0038$$
  - Shows the validity of the SU(3) assumptions in this prediction (with uncertainties at least)



Numerical results

Preliminary

Quantity	Value	68.3% CL		95.4% CL	
		Uncertainty	Interval	Uncertainty	Interval
γ [°]	65.4	$^{+3.8}_{-4.2}$	[61.2, 69.2]	$^{+7.5}_{-8.7}$	[56.7, 72.9]
$r_{B^\pm}^{DK^\pm}$	0.0984	$^{+0.0027}_{-0.0026}$	[0.0958, 0.1011]	$^{+0.0056}_{-0.0052}$	[0.0932, 0.1040]
$\delta_{B^\pm}^{DK^\pm}$ [°]	127.6	$^{+4.0}_{-4.2}$	[123.4, 131.6]	$^{+7.8}_{-9.2}$	[118.4, 135.4]
$r_{B^\pm}^{D\pi^\pm}$	0.00480	$^{+0.00070}_{-0.00056}$	[0.00424, 0.00550]	$^{+0.0017}_{-0.0011}$	[0.0037, 0.0065]
$\delta_{B^\pm}^{D\pi^\pm}$ [°]	288	$^{+14}_{-15}$	[273, 302]	$^{+26}_{-31}$	[257, 314]
$r_{B^\pm}^{D^*K^\pm}$	0.099	$^{+0.016}_{-0.019}$	[0.080, 0.115]	$^{+0.030}_{-0.038}$	[0.061, 0.129]
$\delta_{B^\pm}^{D^*K^\pm}$ [°]	310	$^{+12}_{-23}$	[287, 322]	$^{+20}_{-71}$	[239, 330]
$r_{B^\pm}^{D^*\pi^\pm}$	0.0095	$^{+0.0085}_{-0.0061}$	[0.0034, 0.0180]	$^{+0.017}_{-0.0089}$	[0.0006, 0.026]
$\delta_{B^\pm}^{D^*\pi^\pm}$ [°]	139	$^{+22}_{-86}$	[53, 161]	$^{+32}_{-129}$	[10, 171]
$r_{B^\pm}^{DK^{*\pm}}$	0.106	$^{+0.017}_{-0.019}$	[0.087, 0.123]	$^{+0.031}_{-0.040}$	[0.066, 0.137]
$\delta_{B^\pm}^{DK^{*\pm}}$ [°]	35	$^{+20}_{-15}$	[20, 55]	$^{+57}_{-28}$	[7, 92]
$r_{B^0}^{DK^{*0}}$	0.250	$^{+0.023}_{-0.024}$	[0.226, 0.273]	$^{+0.044}_{-0.052}$	[0.198, 0.294]
$\delta_{B^0}^{DK^{*0}}$ [°]	197	$^{+10}_{-9.3}$	[187.7, 207]	$^{+24}_{-18}$	[179, 221]

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Numerical results

Preliminary

$r_{B_s^0}^{D_s^\mp K^\pm}$	0.310	${}^{+0.098}_{-0.092}$	$[0.218, 0.408]$	${}^{+0.20}_{-0.21}$	$[0.10, 0.51]$
$\delta_{B_s^0}^{D_s^\mp K^\pm}$ [°]	356	${}^{+19}_{-18}$	$[338, 375]$	${}^{+39}_{-39}$	$[317, 395]$
$r_{B_s^0}^{D_s^\mp K^\pm \pi^+\pi^-}$	0.460	${}^{+0.081}_{-0.084}$	$[0.376, 0.541]$	${}^{+0.16}_{-0.17}$	$[0.29, 0.62]$
$\delta_{B_s^0}^{D_s^\mp K^\pm \pi^+\pi^-}$ [°]	345	${}^{+13}_{-12}$	$[333, 358]$	${}^{+26}_{-25}$	$[320, 371]$
$r_{B^0}^{D^\mp \pi^\pm}$	0.030	${}^{+0.014}_{-0.012}$	$[0.018, 0.044]$	${}^{+0.036}_{-0.028}$	$[0.002, 0.066]$
$\delta_{B^0}^{D^\mp \pi^\pm}$ [°]	30	${}^{+26}_{-37}$	$[-7, 56]$	${}^{+45}_{-81}$	$[-51, 75]$
$r_{B^\pm}^{DK^\pm \pi^+\pi^-}$	0.079	${}^{+0.028}_{-0.034}$	$[0.045, 0.107]$	${}^{+0.050}_{-0.079}$	$[0.000, 0.129]^*$
$r_{B^\pm}^{D\pi^\pm \pi^+\pi^-}$	0.067	${}^{+0.025}_{-0.029}$	$[0.038, 0.092]$	${}^{+0.040}_{-0.067}$	$[0.000, 0.107]^*$
x [%]	0.400	${}^{+0.052}_{-0.053}$	$[0.347, 0.452]$	${}^{+0.10}_{-0.11}$	$[0.29, 0.50]$
y [%]	0.630	${}^{+0.033}_{-0.030}$	$[0.600, 0.663]$	${}^{+0.069}_{-0.058}$	$[0.572, 0.699]$
$r_D^{K\pi}$	0.05867	${}^{+0.00015}_{-0.00015}$	$[0.05852, 0.05882]$	${}^{+0.00031}_{-0.00030}$	$[0.05837, 0.05898]$
$\delta_D^{K\pi}$ [°]	190.0	${}^{+4.2}_{-4.1}$	$[185.9, 194.2]$	${}^{+8.6}_{-8.3}$	$[181.7, 198.6]$
$\lvert q/p\rvert$	0.997	${}^{+0.016}_{-0.016}$	$[0.981, 1.013]$	${}^{+0.033}_{-0.033}$	$[0.964, 1.030]$
ϕ [°]	-2.4	± 1.2	$[-3.6, -1.2]$	± 2.5	$[-4.9, 0.1]$

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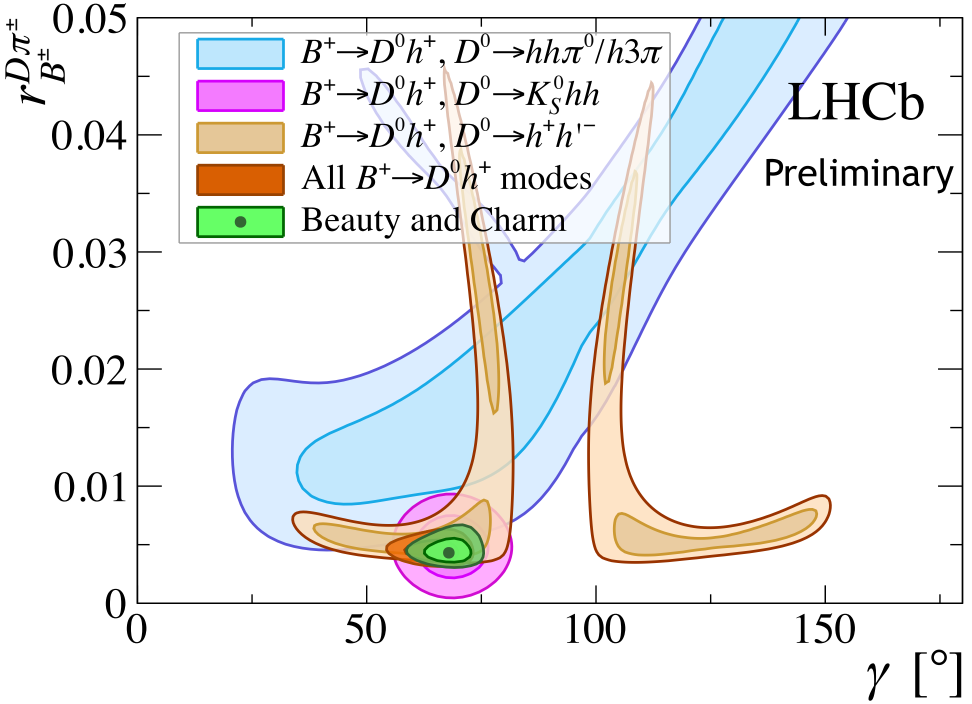
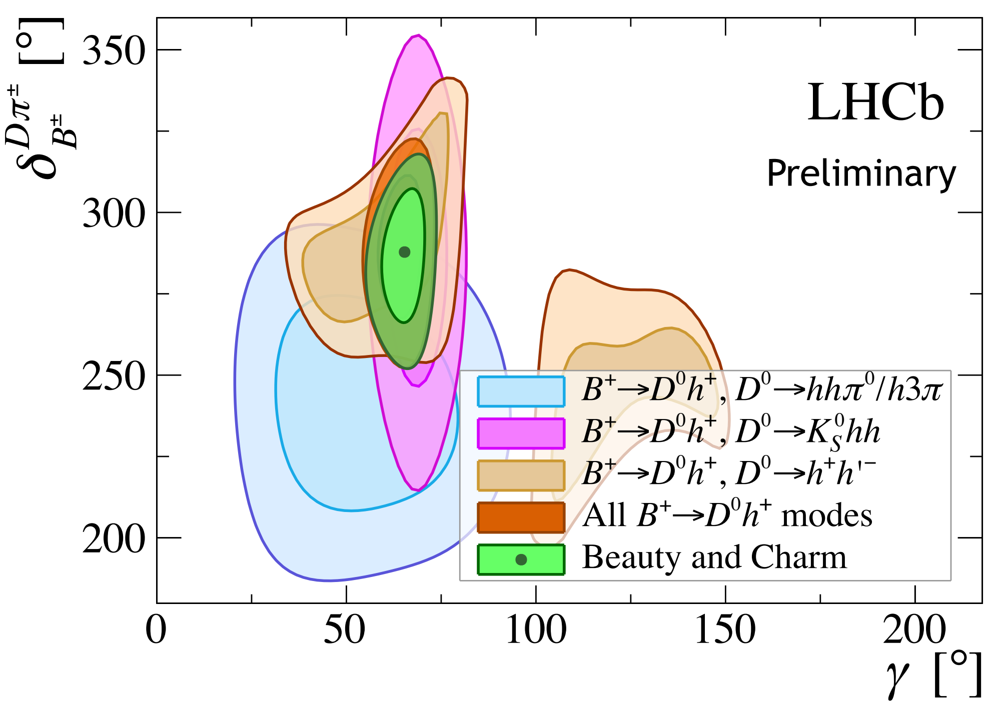
Breakdowns

- Interesting to split the combination up into parts

B+ modes





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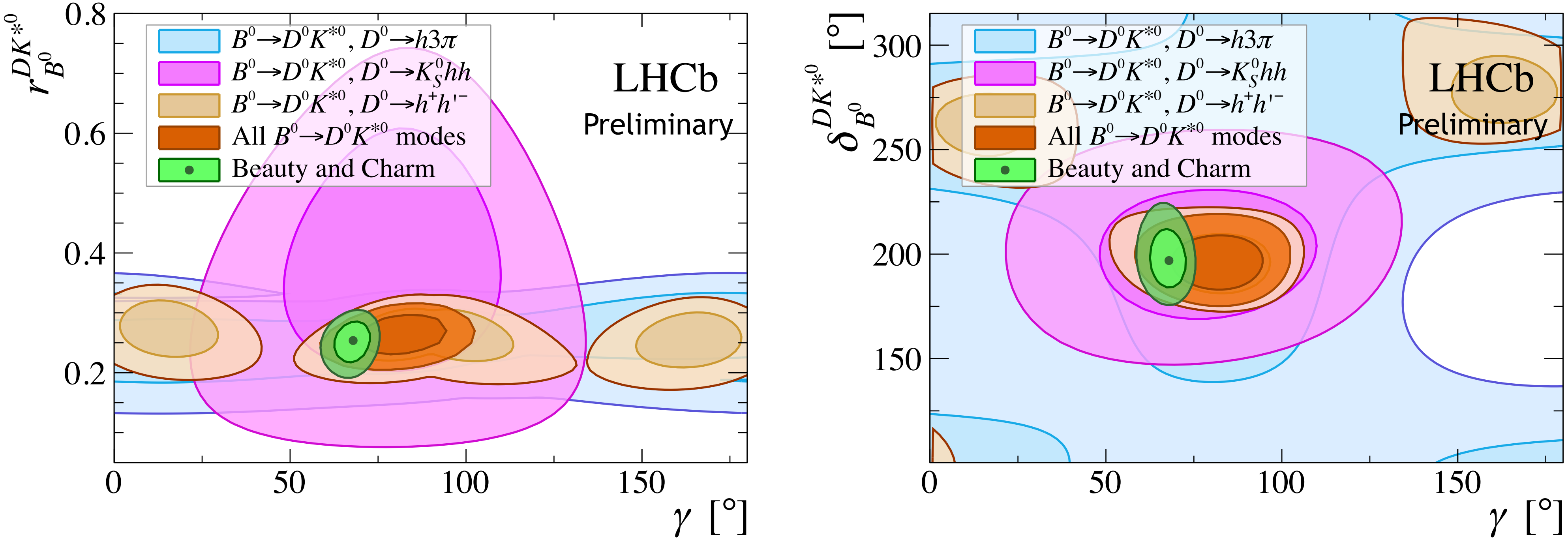
Breakdowns

- Interesting to split the combination up into parts

B0 modes



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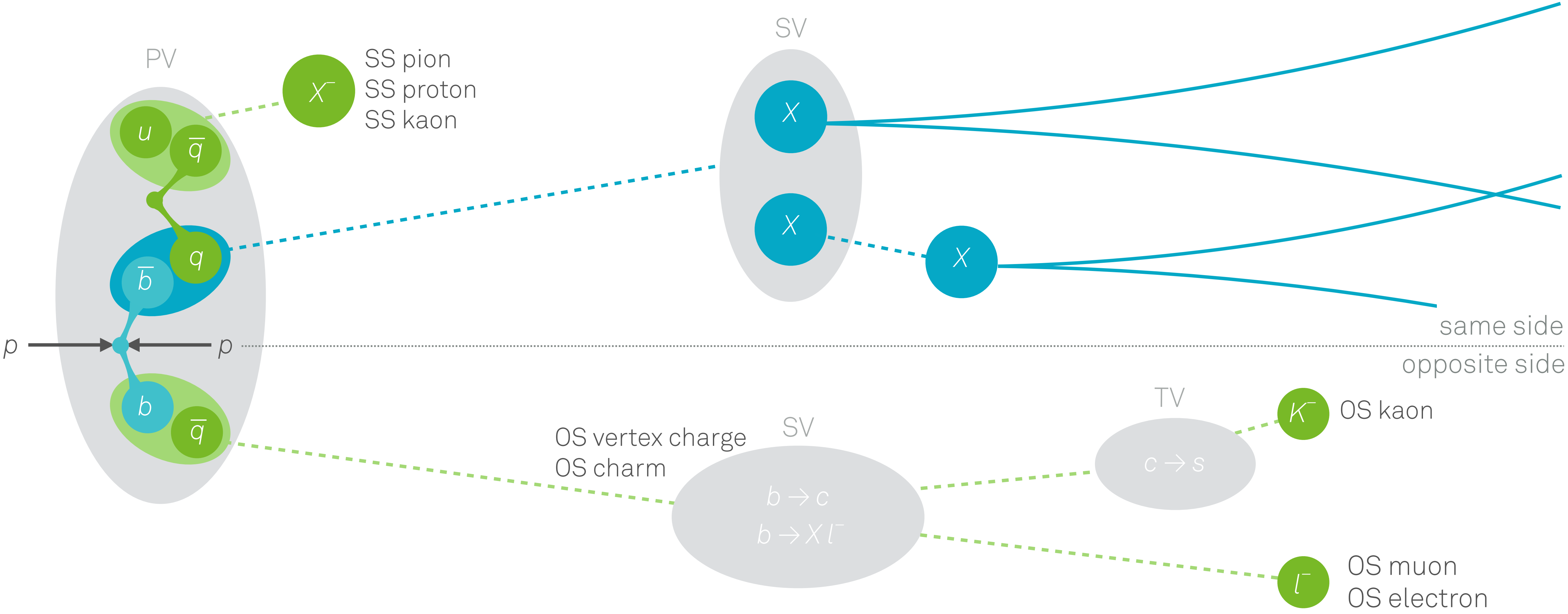
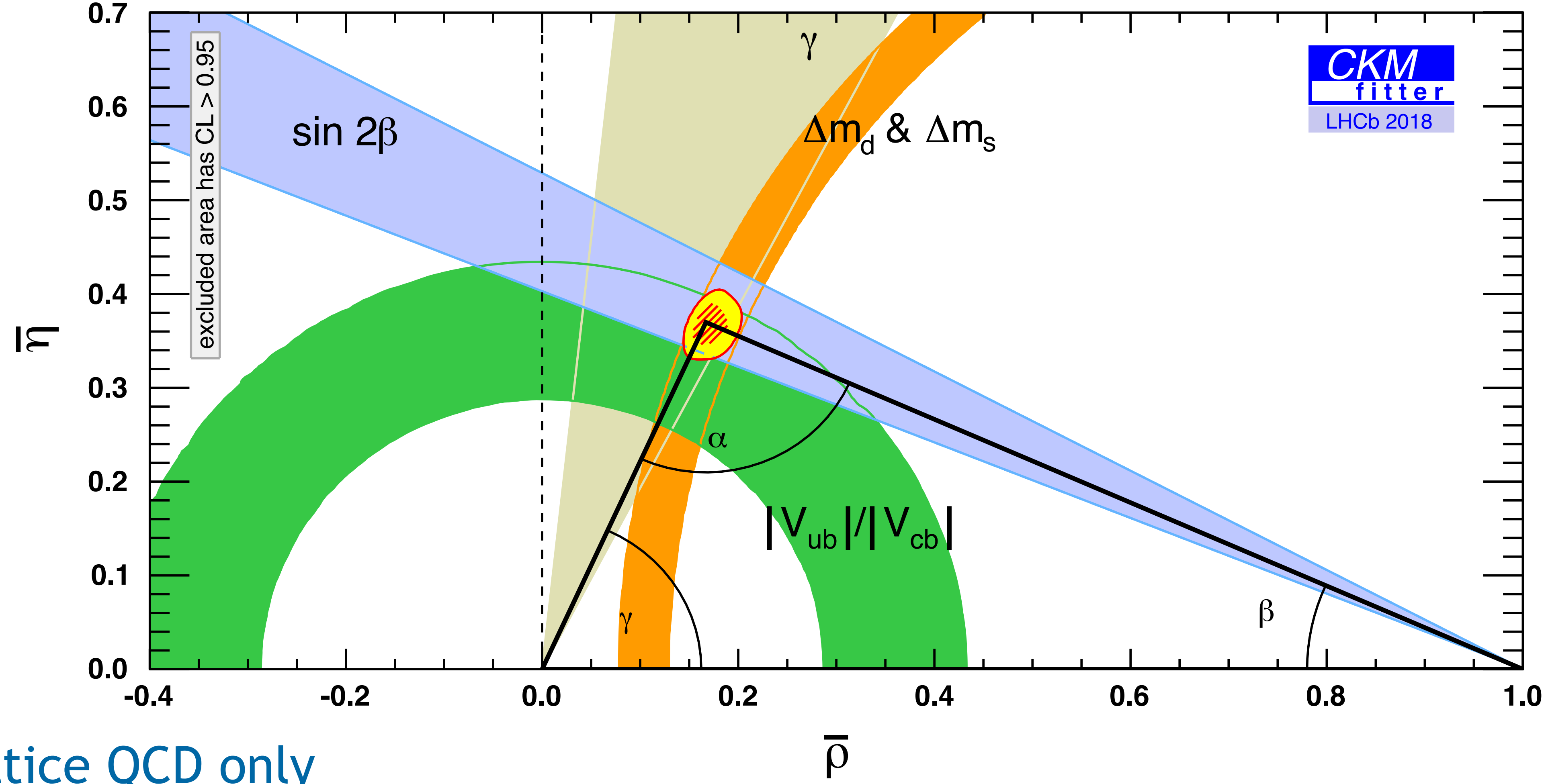
Flavour tagging at LHCb

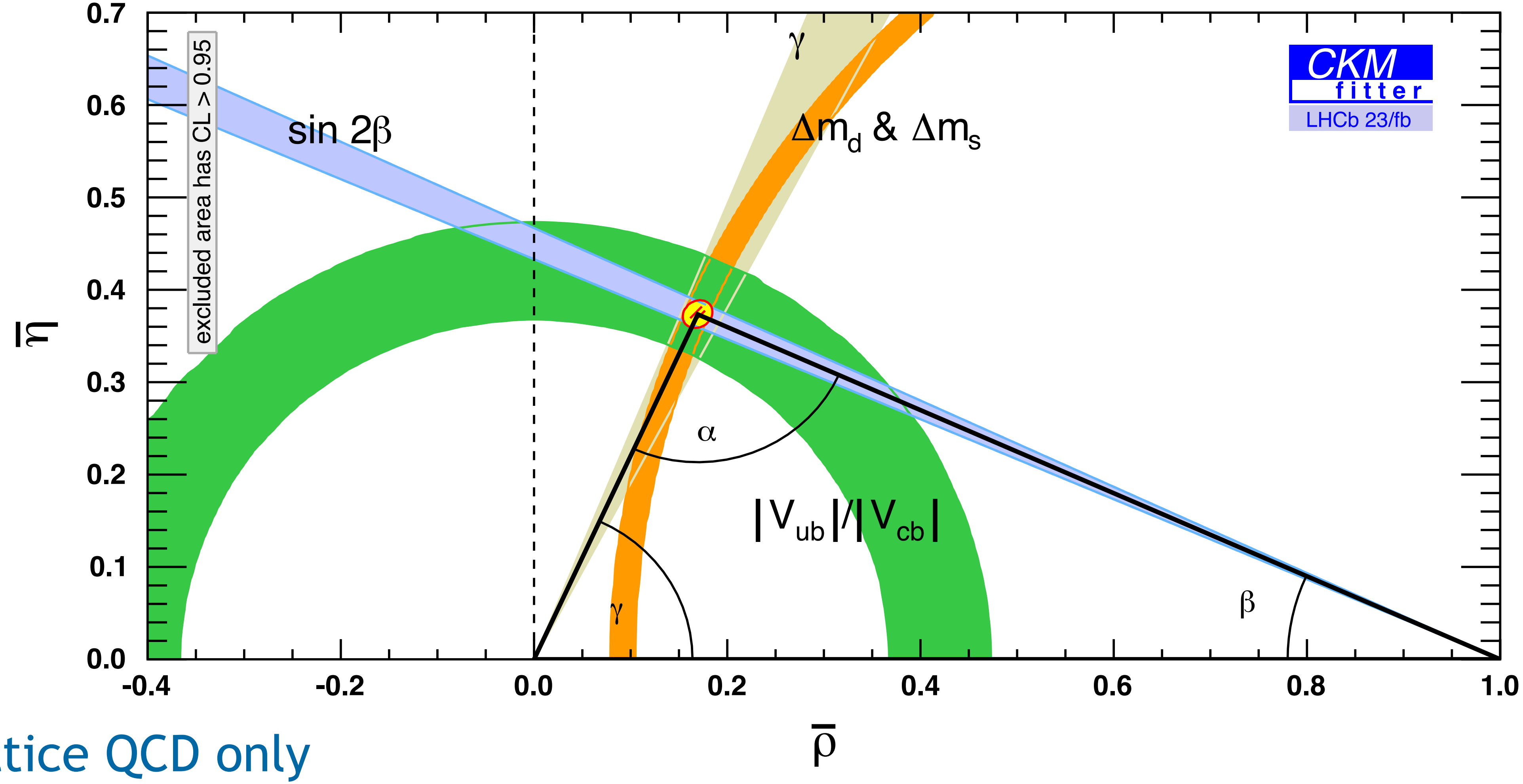


Today



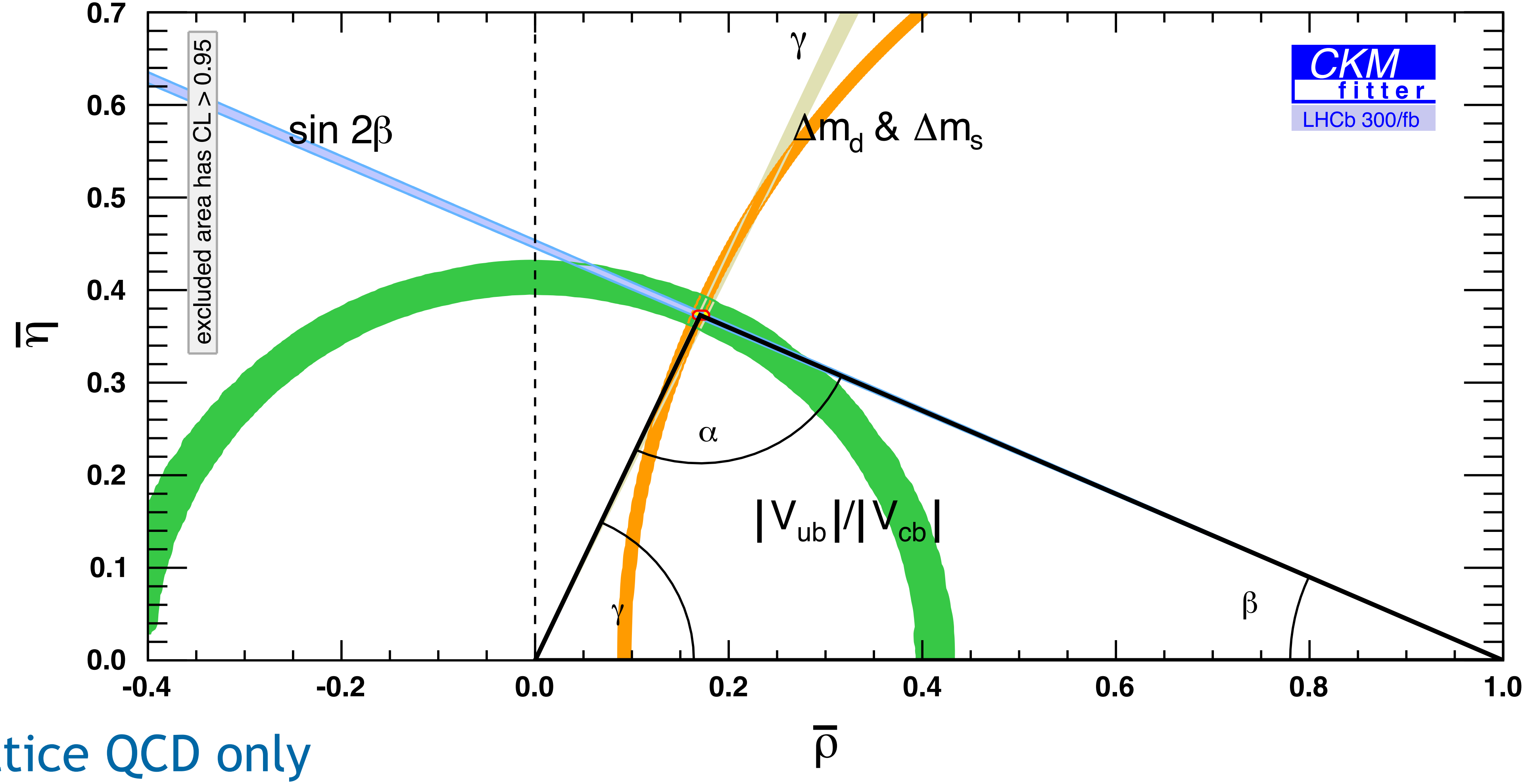
LHCb + lattice QCD only

Pre HL-LHC



LHCb + lattice QCD only

After HL-LHC



LHCb + lattice QCD only