PANIC Lisbon, Portugal, September 2021
Particles and Nuclei International Conference

Searching for New Physics with $B_s^0 \rightarrow D_s^{\pm} K^{\mp}$ Decays

Eleftheria Malami
Nikhef, Theory Group

Nikhef-2021-017

Based on the following paper

Using $B_s^0 \to D_s^{\mp} K^{\pm}$ Decays as a Portal to New Physics

Robert Fleischer [a,b] **and Eleftheria Malami** [a]

[a] *Nikhef, Science Park 105, NL-1098 XG Amsterdam, Netherlands*
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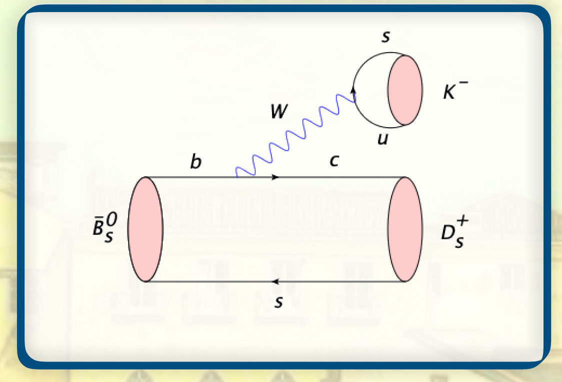

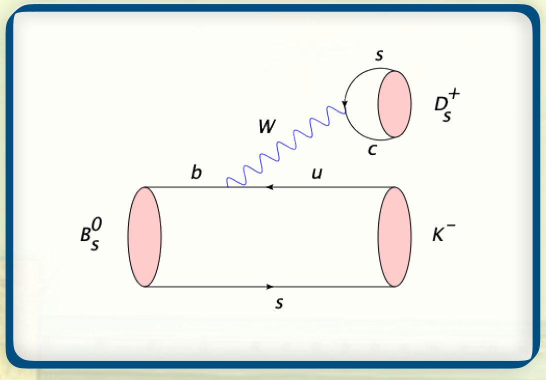

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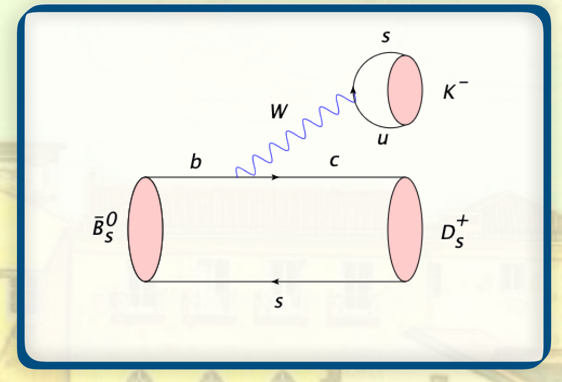

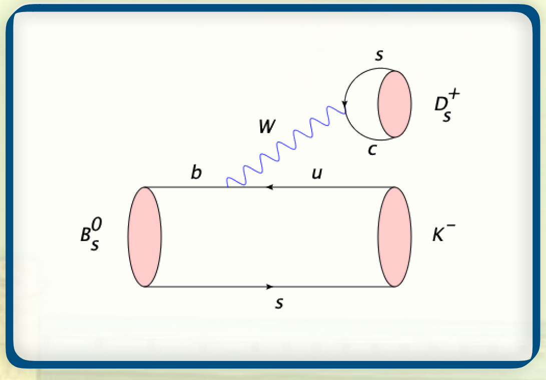

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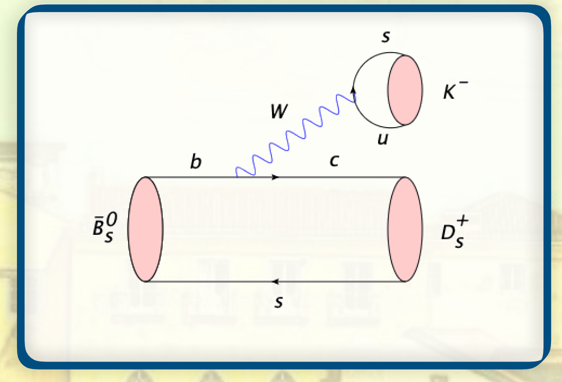

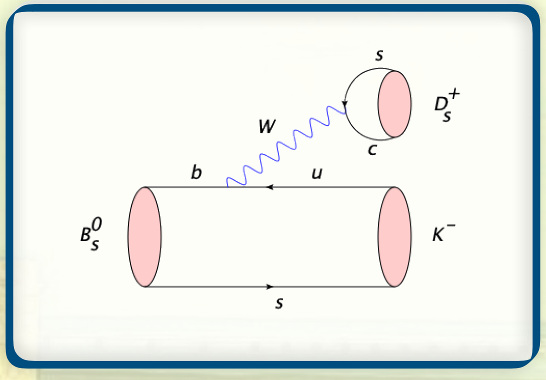

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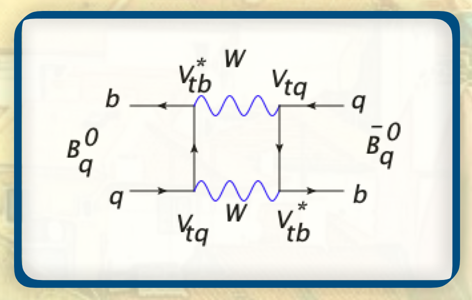

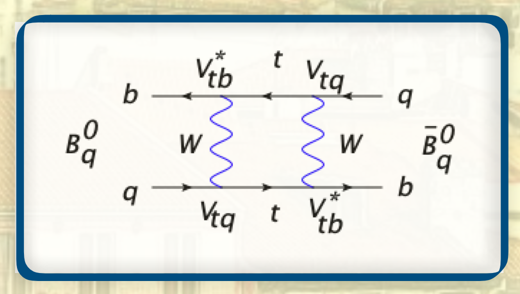

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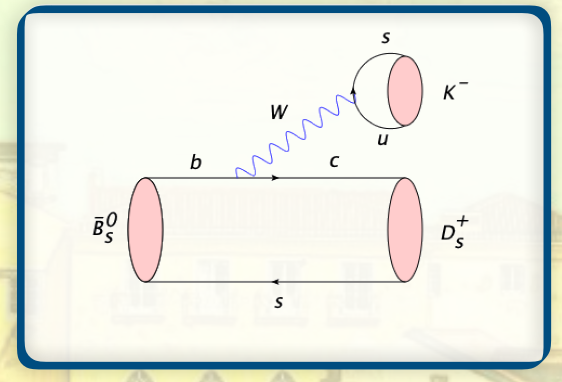

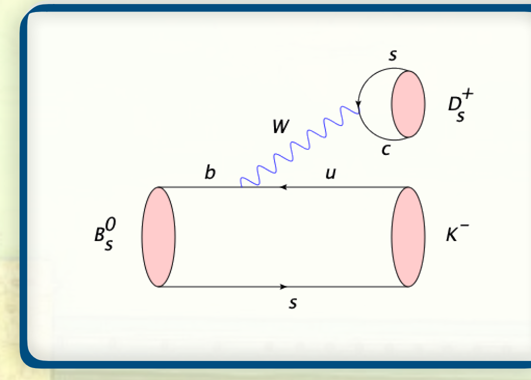

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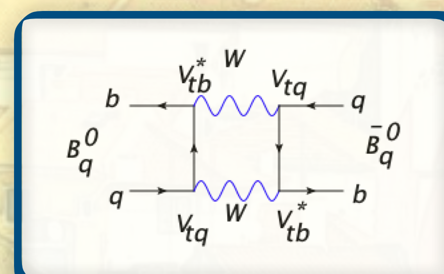

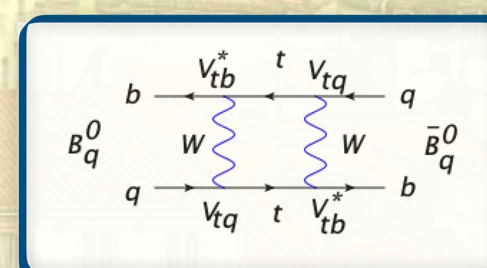

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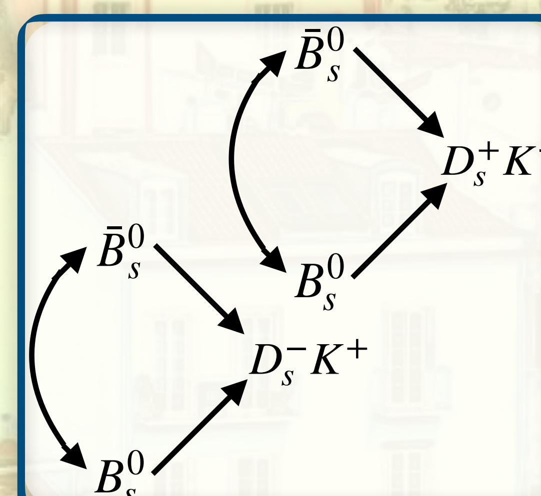

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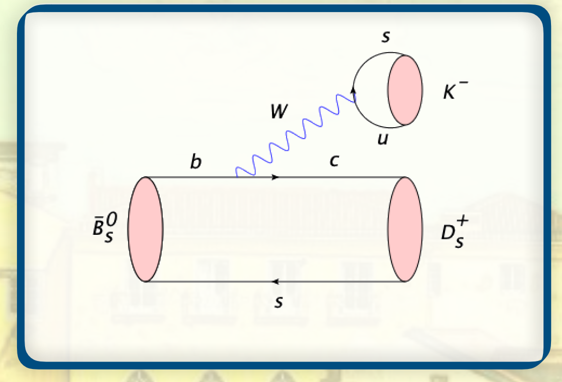

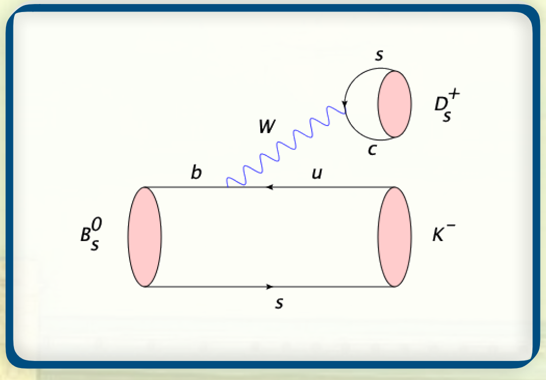

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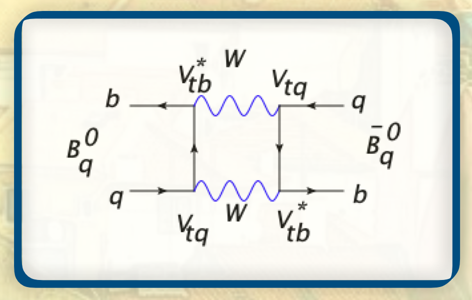

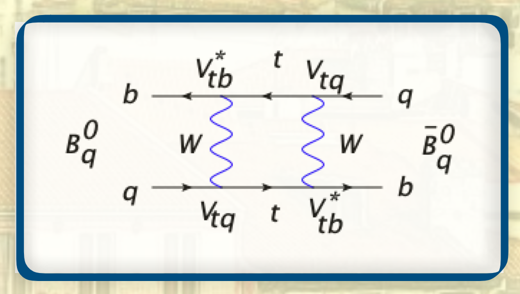

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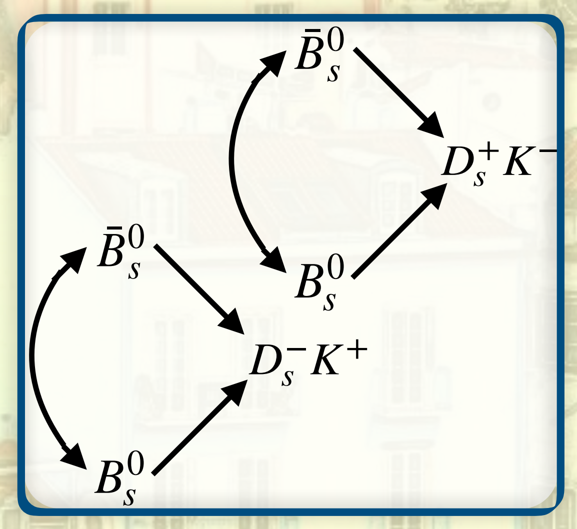

- Allows a theoretically **clean determination** of the Unitarity Triangle (UT) **angle γ**

Motivation

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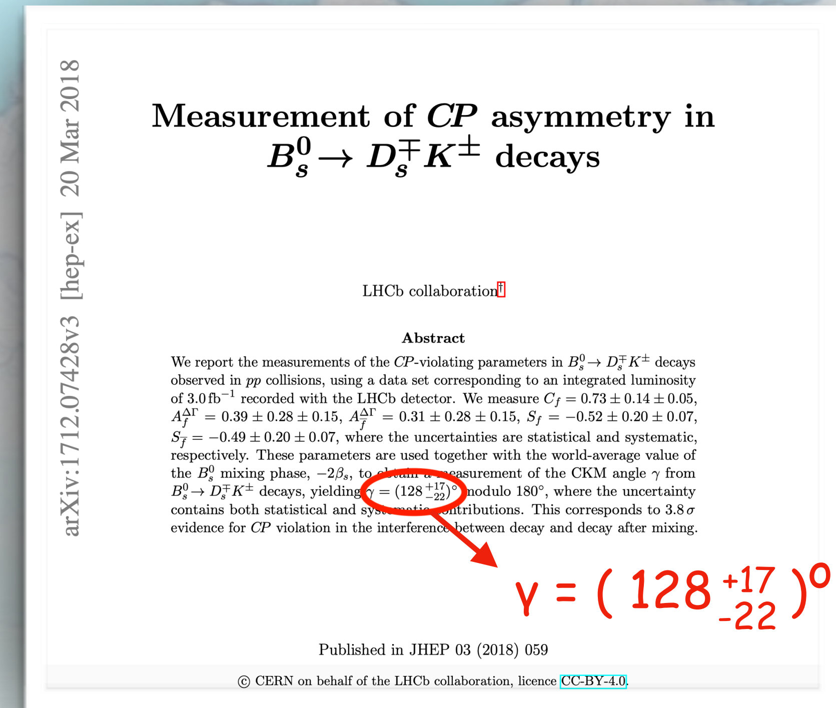
Intriguing value of γ


arXiv:1712.07428v3 [hep-ex] 20 Mar 2018

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LHCb collaboration†

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Published in JHEP 03 (2018) 059

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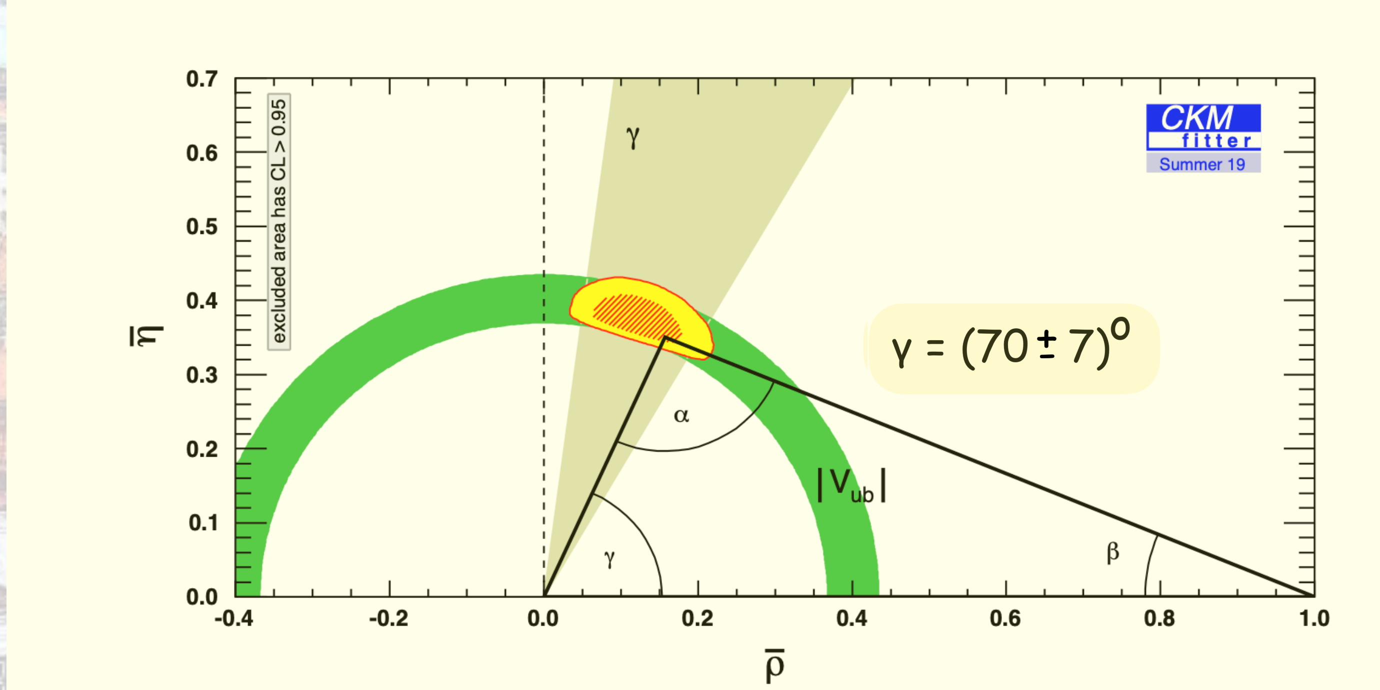

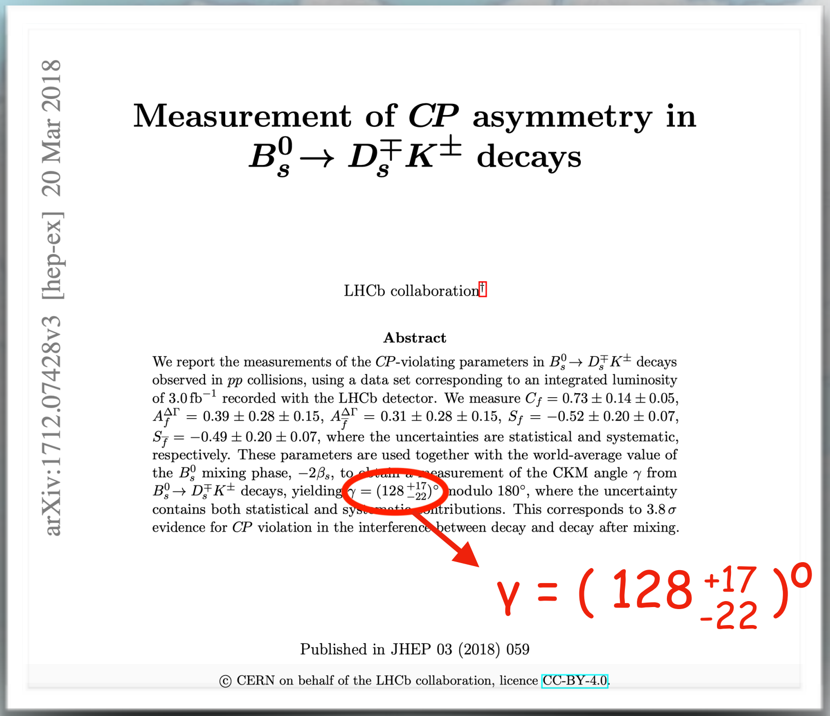

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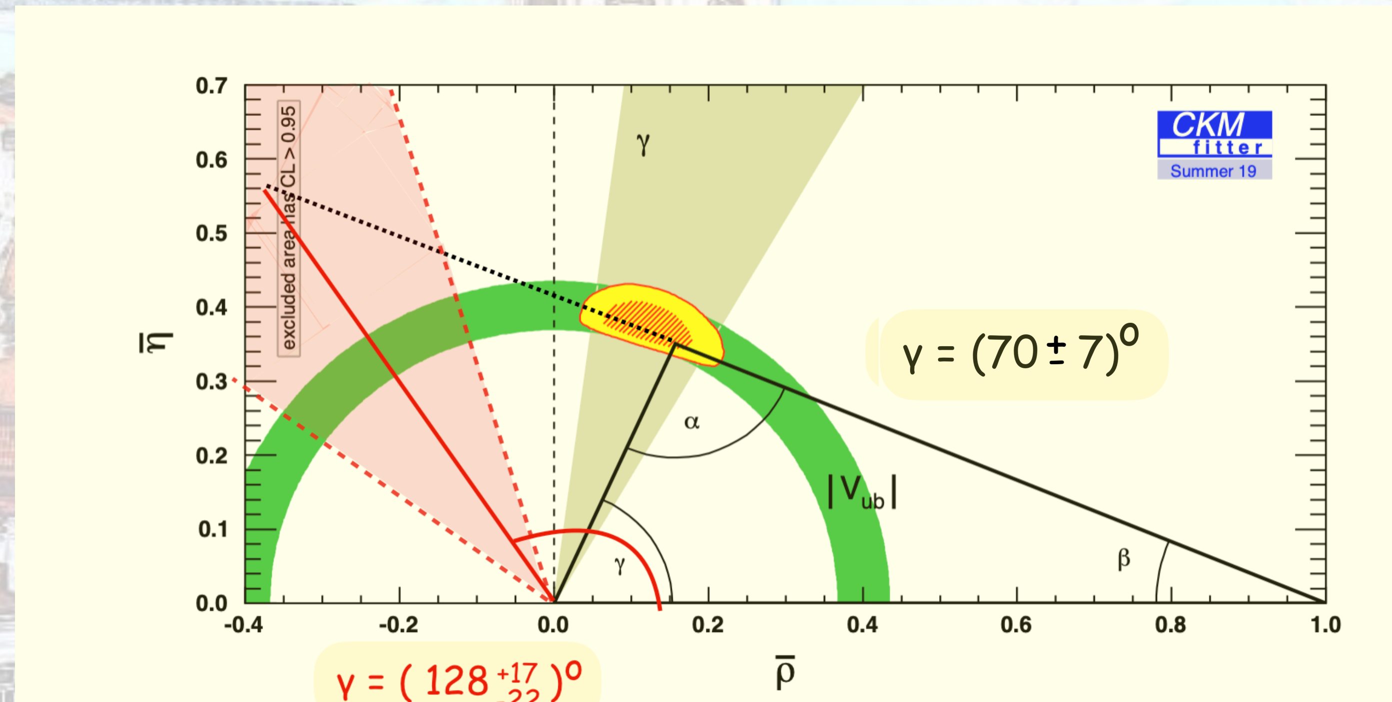

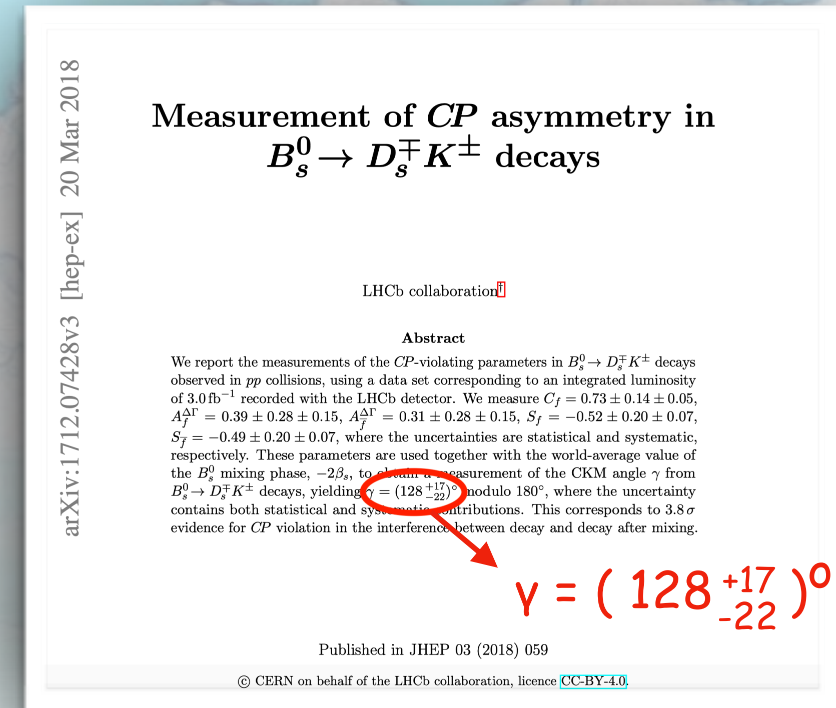

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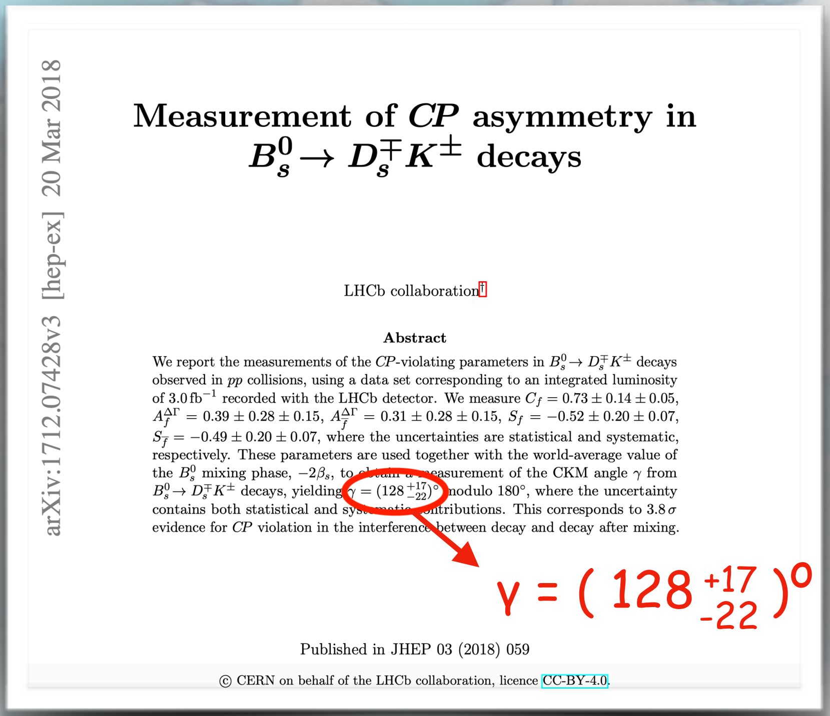

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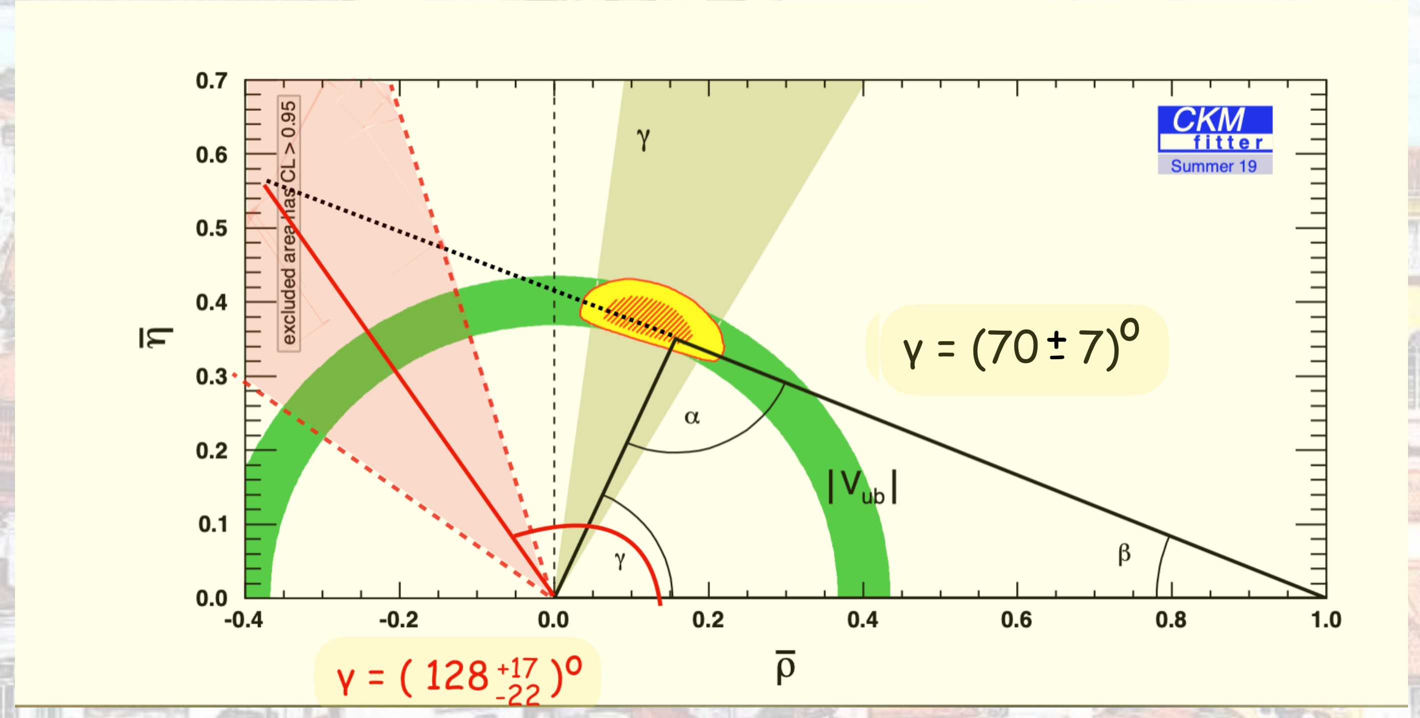

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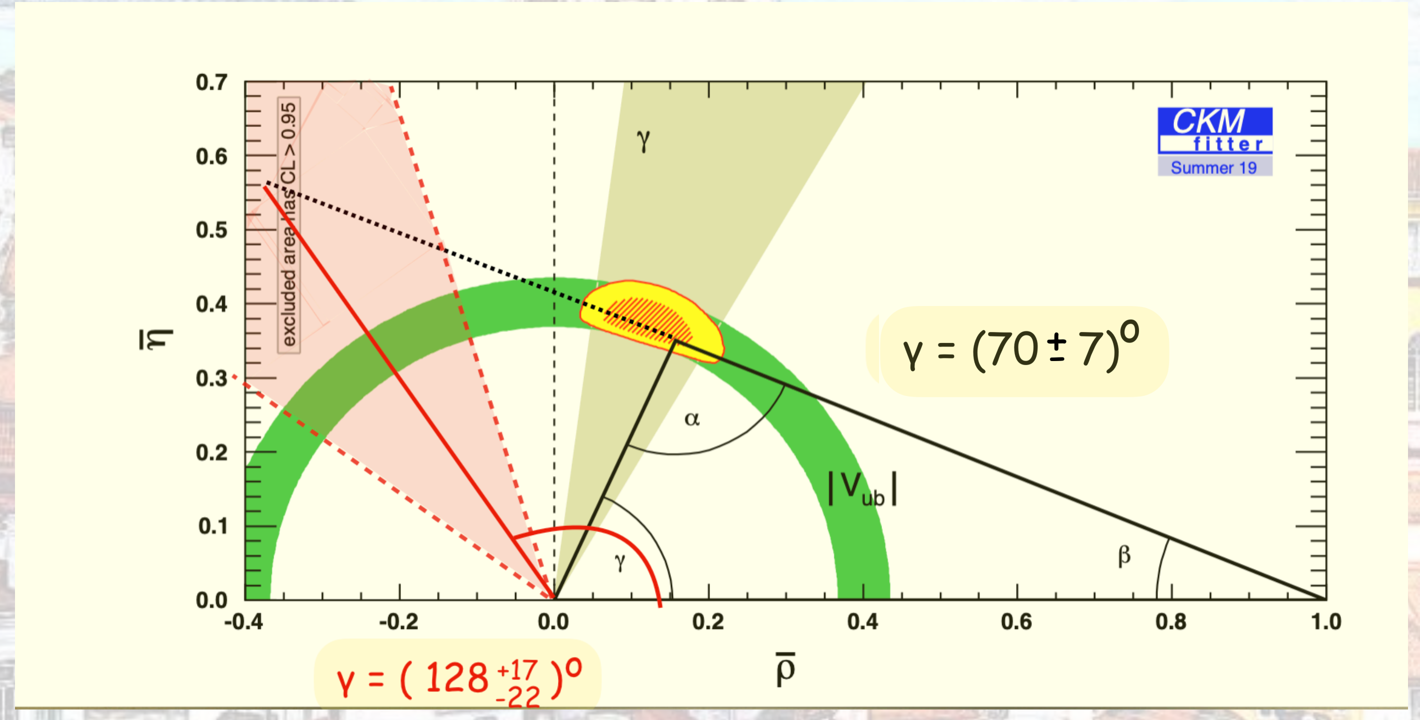

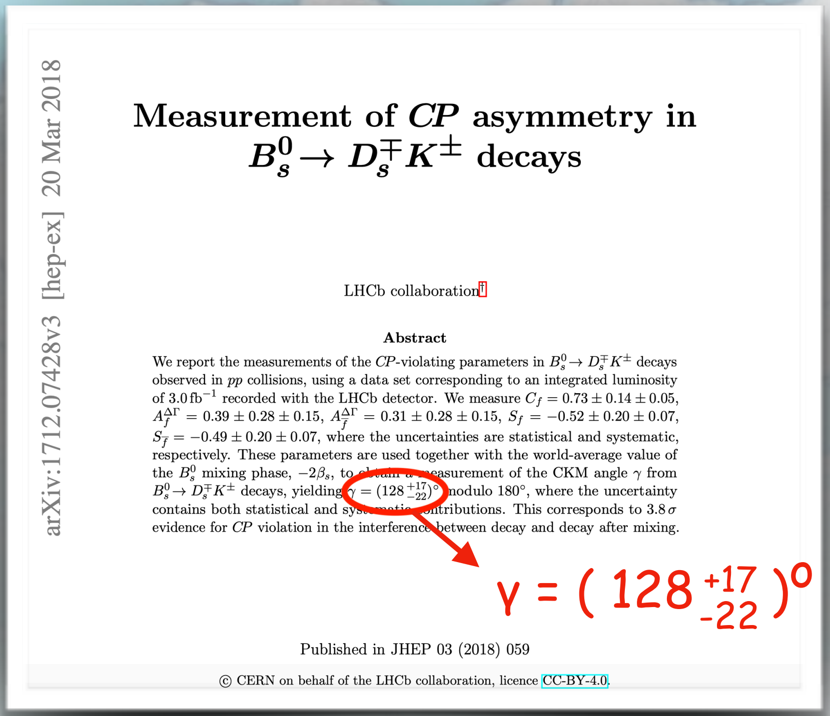

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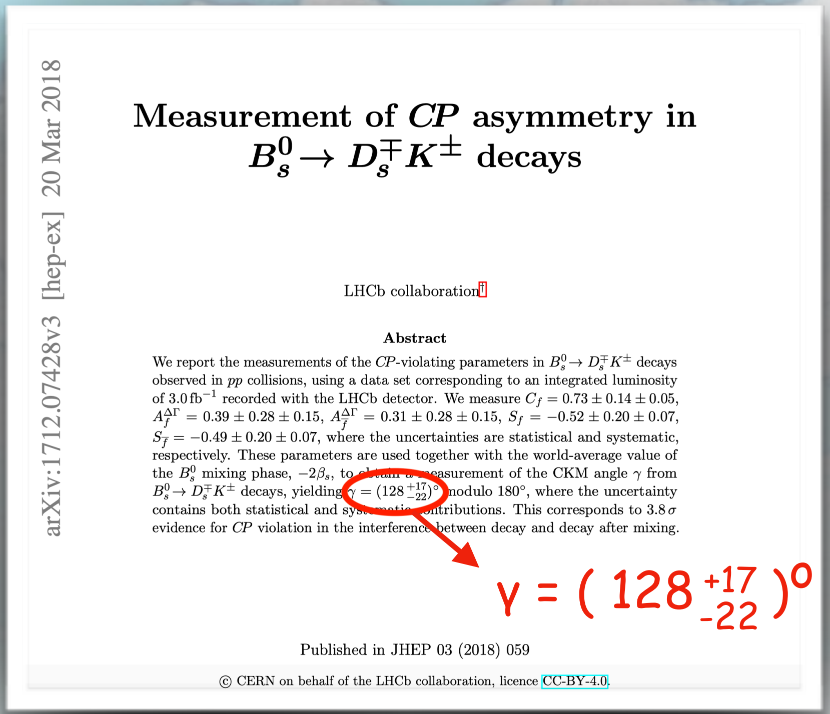

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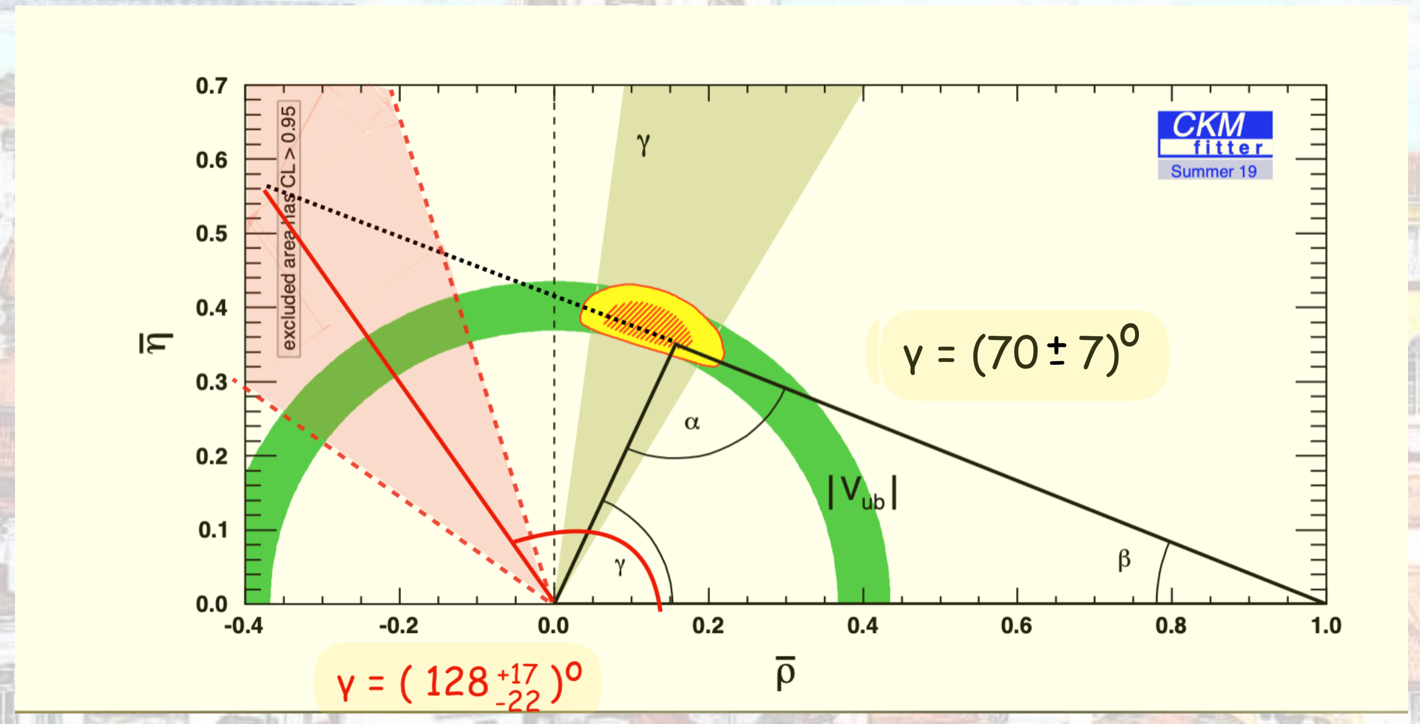

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↓

which we also obtain in other decays with similar dynamics

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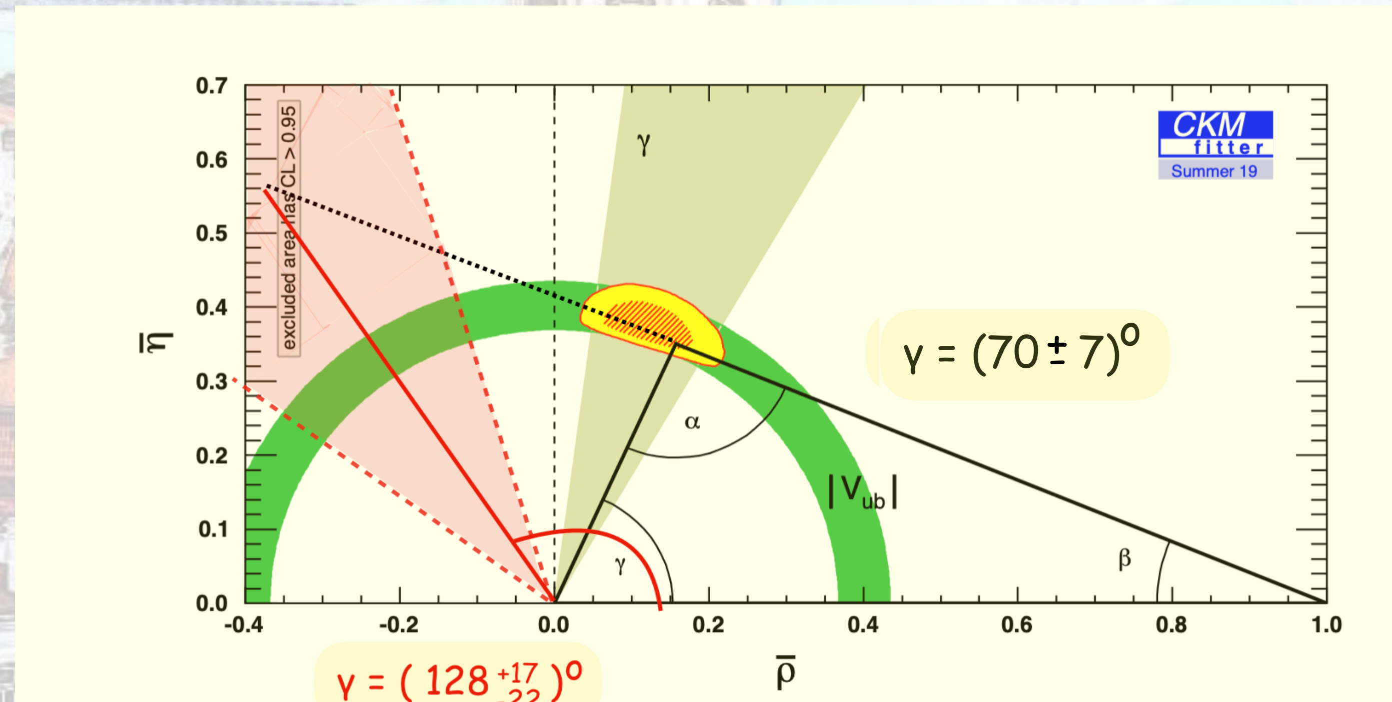

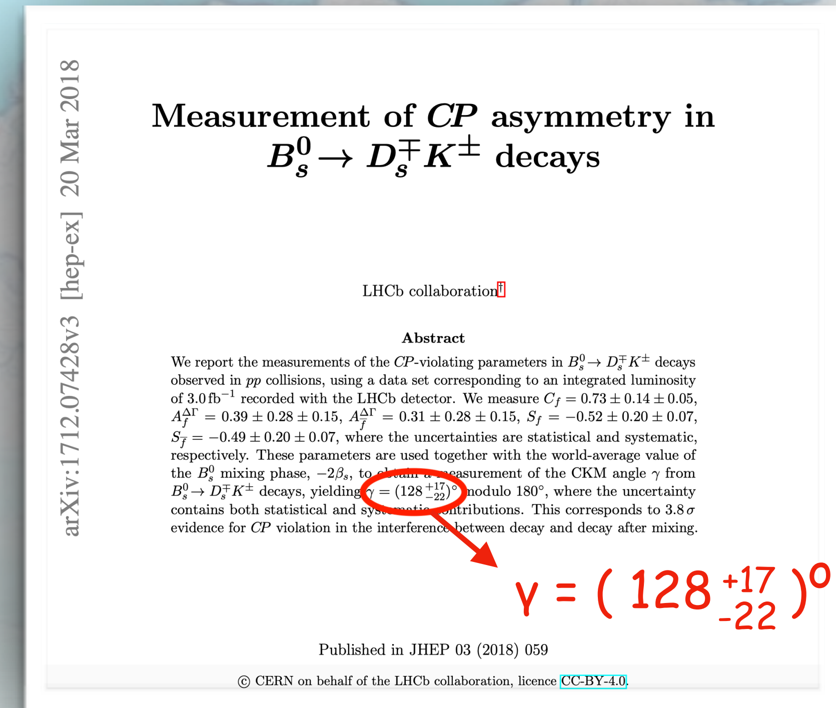

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We need to shed more light on the situation!

Determining angle γ

CP Violation

CP Violation

Time dependent CP Asymmetry

$$\frac{\Gamma(B_s^0(t) \to f) - \Gamma(\overline{B}_s^0(t) \to f)}{\Gamma(B_s^0(t) \to f) + \Gamma(\overline{B}_s^0(t) \to f)} = \left[\frac{C \cos(\Delta M_s\, t) + S \sin(\Delta M_s\, t)}{\cosh(\Delta\Gamma_s\, t/2) + \mathscr{A}_{\Delta\Gamma} \sinh(\Delta\Gamma_s\, t/2)} \right]$$

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With the help of the amplitudes, we introduce the observable, which measures the strength of the interference effects

$$\xi_s = -\,e^{-i\phi_s}\left[e^{i\phi_{CP}}\frac{A(\overline{B}_s^0 \to D_s^+ K^-)}{A(B_s^0 \to D_s^+ K^-)}\right]$$

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Relying on the SM structure of the amplitudes, we obtain:

$$\xi_s = -\, e^{-i(\phi_s+\gamma)} \left[\frac{1}{x_s e^{i\delta_s}}\right]$$

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Correcting for the current value of ϕ_s we calculate the value of $\gamma = \left(131^{+17}_{-22}\right)^\circ$

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$C = -0.73 \pm 0.15$	$\overline{C} = +0.73 \pm 0.15$
$S = +0.49 \pm 0.21$	$\overline{S} = +0.52 \pm 0.21$
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- The **conversion** between the two definitions is the following:

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where $y_s \equiv \frac{\Delta\Gamma_s}{2\,\Gamma_s} = 0.062 \pm 0.004$

- Thus, with the experimental branching ratio, we determine $\mathcal{B}_{\text{th}}$

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- Due to lack of information, we cannot test these SM relations through separate measurements of experimental Branching ratios

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- However, there are measurements of the average:

$$\mathscr{B}_{\Sigma}^{\textsf{exp}} \equiv \mathscr{B}_{\textsf{exp}} + \bar{\mathscr{B}}_{\textsf{exp}} = (2.27 \pm 0.19) \times 10^{-4} \,.$$

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- We may determine the theoretical branching ratios of

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which are equal to their CP conjugates due to our assumptions

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$$\mathcal{B}_{\Sigma}^{\text{exp}} \equiv \mathcal{B}_{\text{exp}} + \bar{\mathcal{B}}_{\text{exp}} = (2.27 \pm 0.19) \times 10^{-4}\,.$$

- Assuming the SM framework, as LHCb does, we obtain:

$$\mathcal{B}_{\text{th}} = \bar{\mathcal{B}}_{\text{th}} = \left[\frac{1 - y_s^2}{1 + y_s \langle \mathcal{A}_{\Delta\Gamma} \rangle_+}\right] \langle \mathcal{B}_{\text{exp}} \rangle$$

$$\langle \mathcal{B}_{\text{exp}} \rangle \equiv \frac{1}{2}\left(\mathcal{B}_{\text{exp}} + \bar{\mathcal{B}}_{\text{exp}}\right) = \frac{1}{2}\mathcal{B}_{\Sigma}^{\text{exp}}$$

- We may determine the theoretical branching ratios of

$$\bar{B}_s^0 \to D_s^+ K^- \qquad B_s^0 \to D_s^+ K^-$$

which are equal to their CP conjugates due to our assumptions

- We can check whether these values are consistent with the branching ratio of similar decays

Branching Ratio Consistency

$\bar{B}_d^0 \to D^+K^-$ and $B_d^0 \to D_s^+\pi^-$ decays,

- Different spectator quark
- Originate from similar quark level processes
- Do not receive contributions from exchange topologies

- We determine the ratios

T: tree topologies
E: exchange topologies

$$\left|\frac{T_{D_sK}}{T_{DK}}\right|^2 \left|1+\frac{E_{D_sK}}{T_{D_sK}}\right|^2 = \frac{\tau_{B_d}}{\tau_{B_s}}\frac{m_{B_s}}{m_{B_d}}\left[\frac{\Phi(m_D/m_{B_d}, m_K/m_{B_d})}{\Phi(m_{D_s}/m_{B_s}, m_K/m_{B_s})}\right]\left[\frac{\mathcal{B}(\bar{B}_s^0 \to D_s^+K^-)_{\rm th}}{\mathcal{B}(\bar{B}_d^0 \to D^+K^-)}\right]$$

$$\left|\frac{T_{KD_s}}{T_{\pi D_s}}\right|^2 \left|1+\frac{E_{KD_s}}{T_{KD_s}}\right|^2 = \frac{\tau_{B_d}}{\tau_{B_s}}\frac{m_{B_s}}{m_{B_d}}\left[\frac{\Phi(m_{D_s}/m_{B_d}, m_\pi/m_{B_d})}{\Phi(m_{D_s}/m_{B_s}, m_K/m_{B_s})}\right]\left[\frac{\mathcal{B}(B_s^0 \to D_s^+K^-)_{\rm th}}{\mathcal{B}(B_d^0 \to D_s^+\pi^-)}\right]$$

SU(3) flavour

$$T_{D_sK} \approx T_{DK}, \quad T_{KD_s} \approx T_{\pi D_s},$$

$$\left|\frac{T_{D_sK}}{T_{DK}}\right| \left|1+\frac{E_{D_sK}}{T_{D_sK}}\right| = 1.02 \pm 0.08$$

$$\left|\frac{T_{KD_s}}{T_{\pi D_s}}\right| \left|1+\frac{E_{KD_s}}{T_{KD_s}}\right| = 1.18 \pm 0.34.$$

- Consistent with the smallest impact of the exchange topologies

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$\bar{B}_d^0 \to D^+\pi^-$ and $\bar{B}_s^0 \to D_s^+\pi^-$ U spin symmetry $\bar{B}_s^0 \to D_s^+K^-$ and $\bar{B}_d^0 \to D^+K^-$

- Working with similar ratios, we obtain consistent results within uncertainties

Factorisation

- Within the SM, we may write the decay amplitude of $\bar{B}_s^0 \to D_s^+ K^-$ as

$$A^{\text{SM}}_{\bar{B}_s^0 \to D_s^+ K^-} = \frac{G_{\text{F}}}{\sqrt{2}} V_{us}^* V_{cb} \; f_K \; F_0^{B_s \to D_s}(m_K^2) \; (m_{B_s}^2 - m_{D_s}^2) \; a_{1\,\text{eff}}^{D_s K}$$

$$a_{1\,\text{eff}}^{D_s K} = a_1^{D_s K} \left(1 + \frac{E_{D_s K}}{T_{D_s K}}\right)$$

describes the deviation from naive factorisation

non-factorisable exchange topologies

non- factorisable effects entering the colour-allowed tree amplitude $T_{D_s K}$

- The state-of-the-art results

$$|a_1^{DK}| = 1.0702^{+0.0101}_{-0.0128} \qquad |a_1^{D_d\pi}| = 1.073^{+0.012}_{-0.014} \qquad |a_1^{D_s\pi}| = 1.0727^{+0.0125}_{-0.0140} \qquad |a_1^{D_s K}| = 1.07 \pm 0.02$$

- Can be used to calculate the ratios of colour allowed tree amplitudes we mentioned in the previous slide

$$\left|\frac{T_{D_s K}}{T_{DK}}\right| = \left[\frac{F_0^{B_s \to D_s}(m_K^2)}{F_0^{B_d \to D_d}(m_K^2)}\right] \left[\frac{m_{B_s}^2 - m_{D_s}^2}{m_{B_d}^2 - m_{D_d}^2}\right] \left|\frac{a_1^{D_s K}}{a_1^{DK}}\right| = 1.03 \pm 0.03$$

$$\left|\frac{T_{D_d\pi}}{T_{D_s\pi}}\right| = \left[\frac{F_0^{B_d \to D_d}(m_\pi^2)}{F_0^{B_s \to D_s}(m_\pi^2)}\right] \left[\frac{m_{B_d}^2 - m_{D_d}^2}{m_{B_s}^2 - m_{D_s}^2}\right] \left|\frac{a_1^{D\pi}}{a_1^{D_s\pi}}\right| = 0.99 \pm 0.03,$$

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- No anomalous behaviour of exchange diagrams
- Consistency

Factorisation

$\bar{B}^0_s \to K^+ D^-_s$ decay, the heavy-quark argument for QCD factorisation for the $b \to c$ tree-level decays not apply in this case

we may expect larger non-factorisable effects in this case

- extract the $|a_1|$ parameters of the $\bar{B}^0_s \to D^+_s K^-$ and $\bar{B}^0_s \to K^+ D^-_s$ from the data in the cleanest possible way

- useful tool $\longrightarrow$ semileptonic decays

to handle
- V_{CKM} elements and
- hadronic form factors

Semi-leptonic Decays

- We can calculate $|a_1^{D_sK}|$

  With the help of the rates of the Branching ratios with the semi-leptonic decays

$$R_{D_s^+K^-} \equiv \frac{\mathscr{B}(\bar{B}_s^0 \to D_s^+ K^-)_{\text{th}}}{\mathrm{d}\mathscr{B}\left(\bar{B}_s^0 \to D_s^+ \ell^- \bar{\nu}_\ell\right)/\mathrm{d}q^2|_{q^2=m_K^2}}$$

$$R_{D_s^+K^-} = 0.08 \pm 0.01,$$

$$R_{D_s^+K^-} = 6\pi^2 f_K^2 |V_{us}|^2 |a_{1\,\text{eff}}^{D_sK}|^2 X_{D_sK}$$

$$X_{D_sK} = \frac{(m_{B_s}^2 - m_{D_s}^2)^2}{[m_{B_s}^2 - (m_{D_s} + m_K)^2][m_{B_s}^2 - (m_{D_s} - m_K)^2]} \left[\frac{F_0^{B_s \to D_s}(m_K^2)}{F_1^{B_s \to D_s}(m_K^2)}\right]^2$$

$$|a_{1\,\text{eff}}^{D_sK}| = 0.81 \pm 0.07.$$

$$|a_1^{D_sK}| = 0.82 \pm 0.09.$$

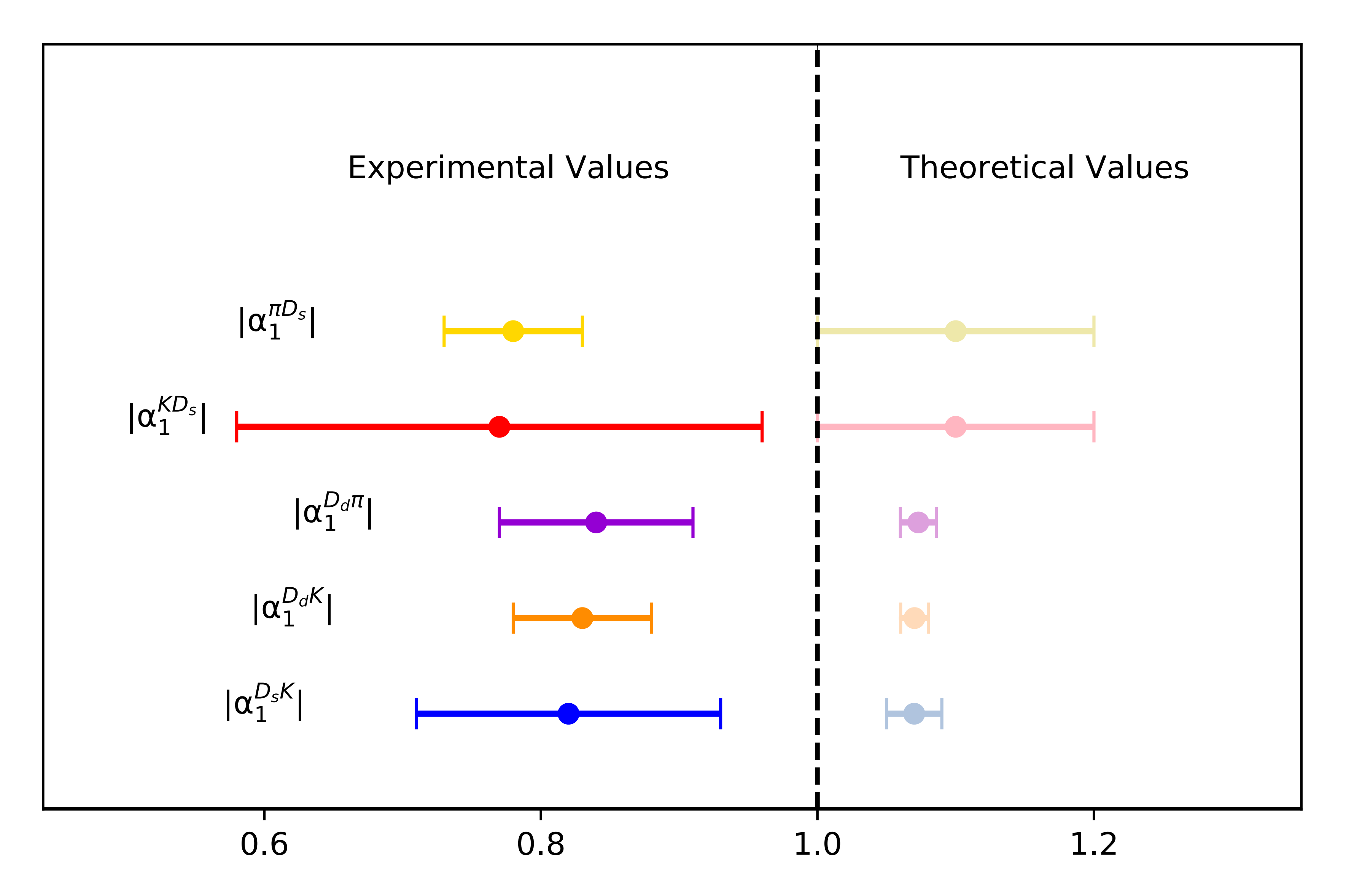
- Similarly, you calculate $|a_1^{KDs}|$

$$|a_{1\,\text{eff}}^{KD_s}| = 0.77 \pm 0.18$$

$$|a_1^{KD_s}| = 0.77 \pm 0.19.$$

- Similar pattern
- Although factorisation may not work that well

Puzzling Patterns
Parameter α_1



In view of

- the intriguing value of γ and
- the puzzling picture following from branching ratios

we extend our analysis and
we search for physics beyond the Standard Model

Searching for New Physics

Generalising the Amplitudes

Generalising the Amplitudes

- The New Physics amplitudes can be written as:

$$A(\bar{B}_s^0 \to D_s^+ K^-) = A(\bar{B}_s^0 \to D_s^+ K^-)_{\textsf{SM}} \left[1 + \bar{\rho}\, e^{i\bar{\delta}} e^{+i\bar{\varphi}} \right]$$

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strong NP phase

weak NP phase

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strength of NP contributions with respect to the SM amplitudes

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- We can introduce the direct CP Asymmetries:

$$\mathscr{A}_{\text{CP}}^{\text{dir}} \equiv \frac{|A(B_s^0 \to D_s^+ K^-)|^2 - |A(\bar{B}_s^0 \to D_s^- K^+)|^2}{|A(B_s^0 \to D_s^+ K^-)|^2 + |A(\bar{B}_s^0 \to D_s^- K^+)|^2}$$

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No direct CP Violation in SM

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NP may generate Direct CP Asymmetries $\neq 0$

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- The generalised ratios with the semi-leptonic decays take the form:

Generalising the Amplitudes

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$$\langle R_{KD_s}\rangle \equiv \frac{\mathcal{B}(\bar{B}_s^0 \to K^+D_s^-)_{\rm th} + \mathcal{B}(B_s^0 \to K^-D_s^+)_{\rm th}}{\left[\mathrm{d}\mathcal{B}\left(\bar{B}_s^0 \to K^+\ell^-\bar{\nu}_\ell\right)/\mathrm{d}q^2 + \mathrm{d}\mathcal{B}\left(B_s^0 \to K^-\ell^+\nu_\ell\right)/\mathrm{d}q^2\right]|_{q^2=m_{D_s}^2}}$$

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$$\bar{b} \equiv \frac{\langle R_{D_sK}\rangle}{6\pi^2 f_K^2\,|\,V_{us}\,|^2\,|\,a_{1\,\mathrm{eff}}^{D_sK}\,|^2\,X_{D_sK}} = \frac{\langle \mathcal{B}(\bar{B}_s^0 \to D_s^+K^-)_{\mathrm{th}}\rangle}{\mathcal{B}(\bar{B}_s^0 \to D_s^+K^-)_{\mathrm{th}}^{\mathrm{SM}}} = 1 + 2\,\bar{\rho}\cos\bar{\delta}\cos\bar{\varphi} + \bar{\rho}^2$$

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- Key relation for studying CP Violation:

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$$\gamma_{\mathrm{eff}} \equiv \gamma + \frac{1}{2}(\Delta\Phi + \Delta\bar{\Phi})$$

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$$\gamma_{\rm eff} \equiv \gamma + \frac{1}{2}\left(\Delta\Phi+\Delta\bar{\Phi}\right) = \gamma - \frac{1}{2}\left(\Delta\varphi+\Delta\bar{\varphi}\right)$$

New Physics Parameters Correlations

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- Collecting the previous relations:

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$$\Delta\varphi = \Delta\bar{\varphi} = \gamma - \gamma_{\mathrm{eff}}$$

- And with the following expressions:

$$\bar{\rho} = -\cos\bar{\varphi} \pm \sqrt{\bar{b} - \sin^2\bar{\varphi}}$$

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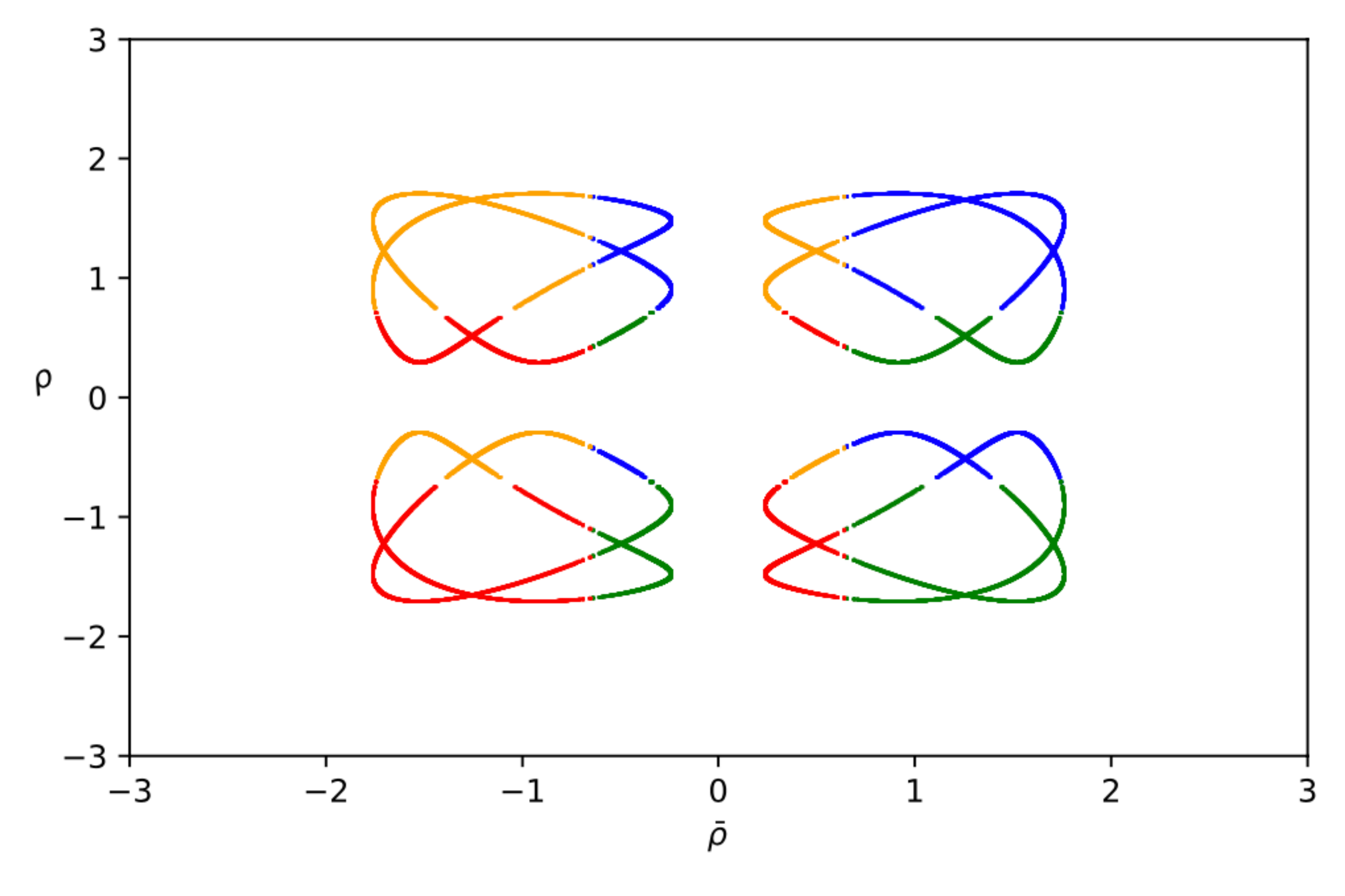
assuming that the strong phase δ=0, we get correlations between the NP parameters

New Physics Parameters Correlations



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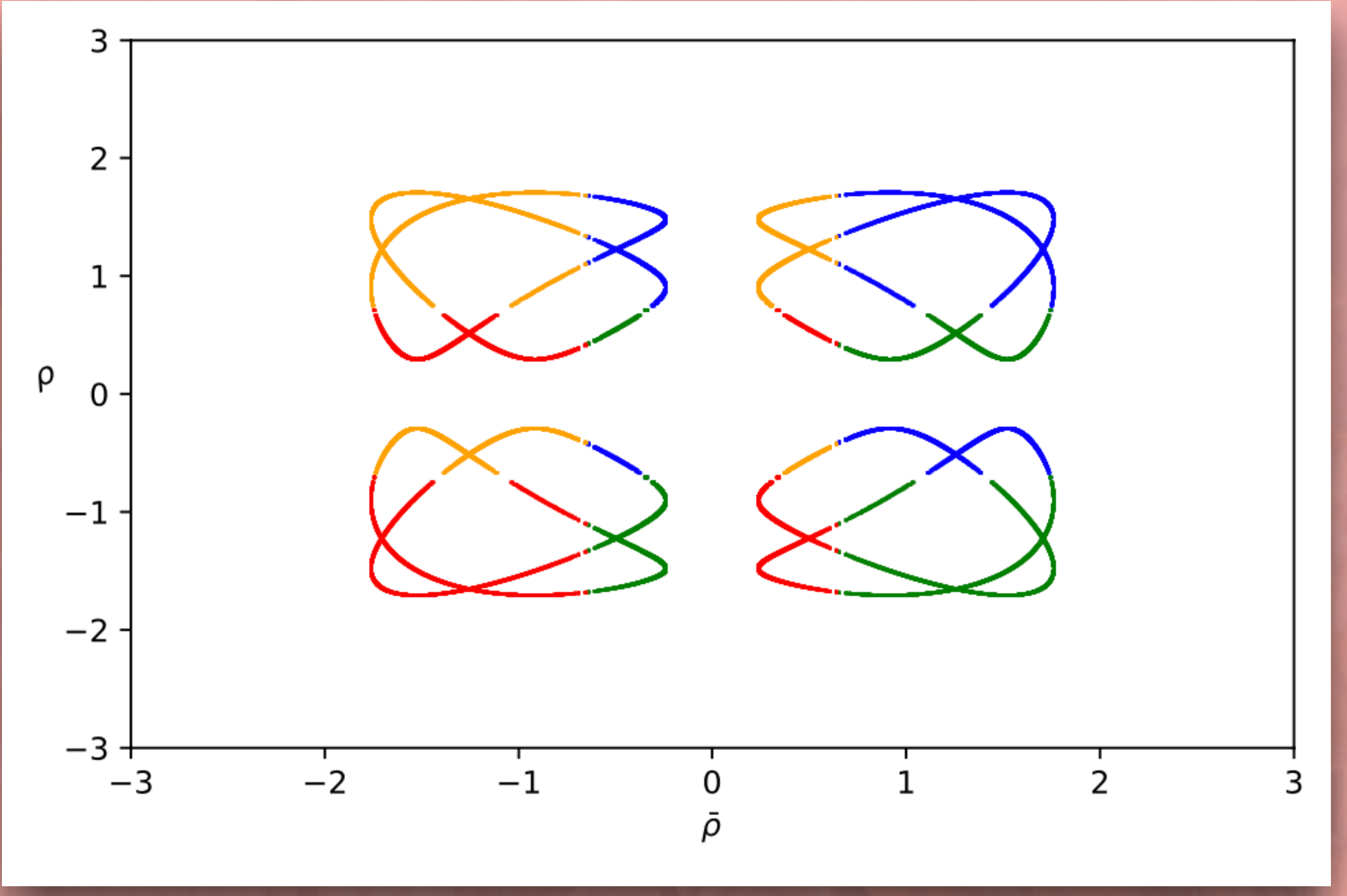

- We can get such values of γ without having enormously large NP contributions

Final Remarks

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- Clean and unambiguous determination of the UT angle γ
- Determination of the individual Branching ratios of $\bar{B}_s^0 \to D_s^+ K^-$ and $B_s^0 \to D_s^+ K^-$ from data
  - Properly accounting for neutral mixing effects
- Generalization of the LHCb assumption that direct CP Violation vanishes in $B_s^0 \to D_s^{\pm} K^{\mp}$
- Determination of α_1 parameters using rates with semileptonic decays
- Generalization of the expressions of the branching ratios
- Moderate NP contributions to accommodate the current data

High precision frontier of precision physics is ahead:

Can we pin down new sources of CP Violation?


Thank you!