Recent CP violation results from LHCb

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重味物理前沿论坛研讨会

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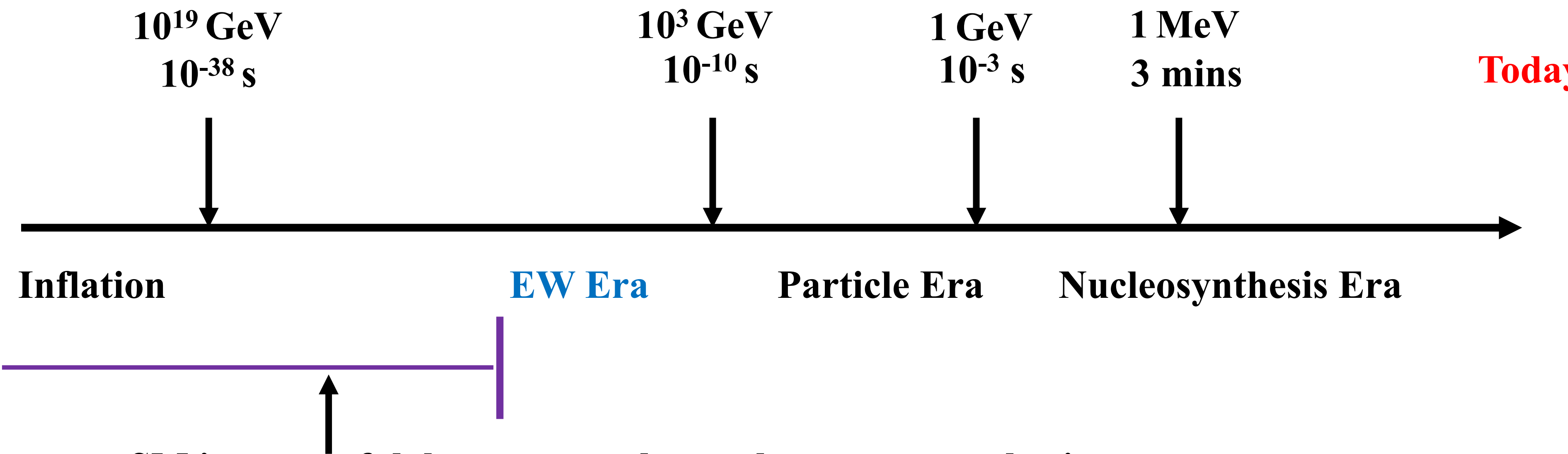
Outline

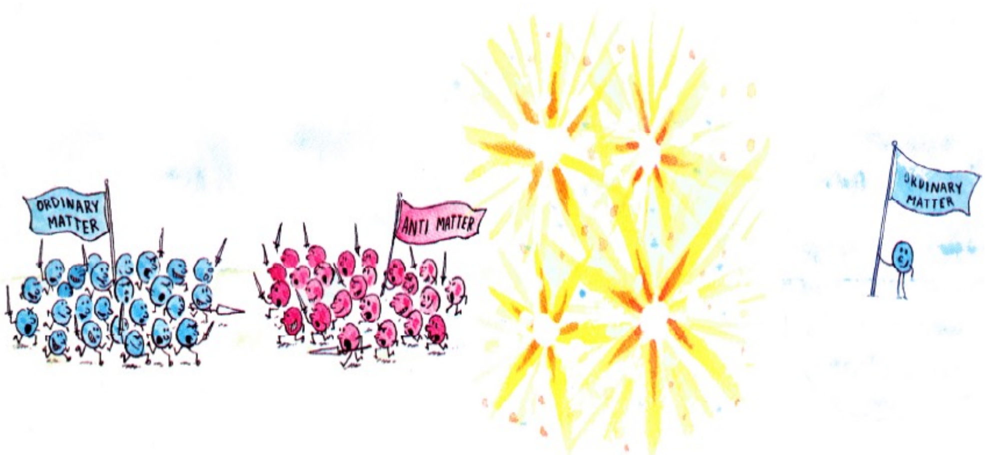
- Introduction
- Recent results on γ and β measurements
- New physics probes
- Conclusions

New Physics



- **SM is successful, however, we know there are new physics**
- **Matter dominated universe**

$$\frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} \sim 10^{-10}$$



- **SM model gives 10^{-17}, not enough**
- **Need extra sources of CP violation**

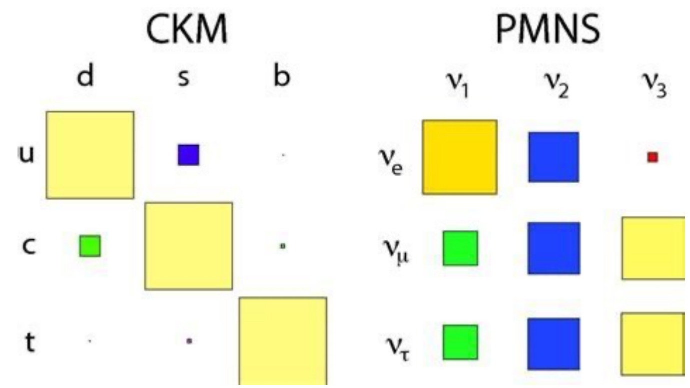
CP violation in SM

- **Complex phases in CKM matrix and PMNS matrix**
- **CKM matrix：unitary matrix connecting interaction and mass eigenstates**

幺正矩阵，标准模型唯一限制条件

$$\begin{pmatrix} d^I \\ s^I \\ b^I \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Interaction eigenstates **Mass eigenstates**



- **Matrix pattern very different**
- **Jarlskog invariant:**

$J_{exp} \sim 3\text{x}10^{-5}$ $J_{max} = 1/6\sqrt{3} \sim 0.1$

$$\begin{pmatrix} \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}}e^{\pm i\pi} \\ -\frac{1}{\sqrt{3}}e^{i\pi/6} & \frac{1}{\sqrt{3}}e^{-i\pi/6} & \frac{1}{\sqrt{3}} \\ \frac{1}{\sqrt{3}}e^{-i\pi/6} & -\frac{1}{\sqrt{3}}e^{i\pi/6} & \frac{1}{\sqrt{3}} \end{pmatrix}$$

matrix with maximum CPV

- **Related to mass hierarchy? Forth generation?**

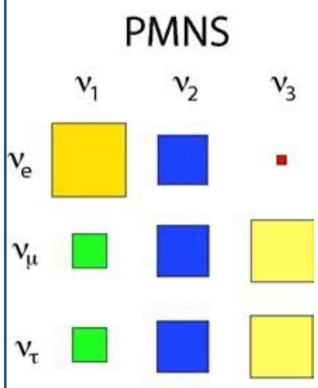
CP violation in SM

- **Complex phases in CKM matrix and PMNS matrix**
- **CKM matrix：unitary matrix connecting interaction and mass eigenstates**

幺正

$$\begin{pmatrix} d^I \\ s^I \\ b^I \end{pmatrix}$$

Interaction eige



Mysterious and suspicious
The more we know, the more we don't know

- **Matri**
- **Jarlskog invariant:**

$J_{exp} \sim 3\text{x}10^{-5}$

$J_{max} = 1/6\sqrt{3} \sim 0.1$

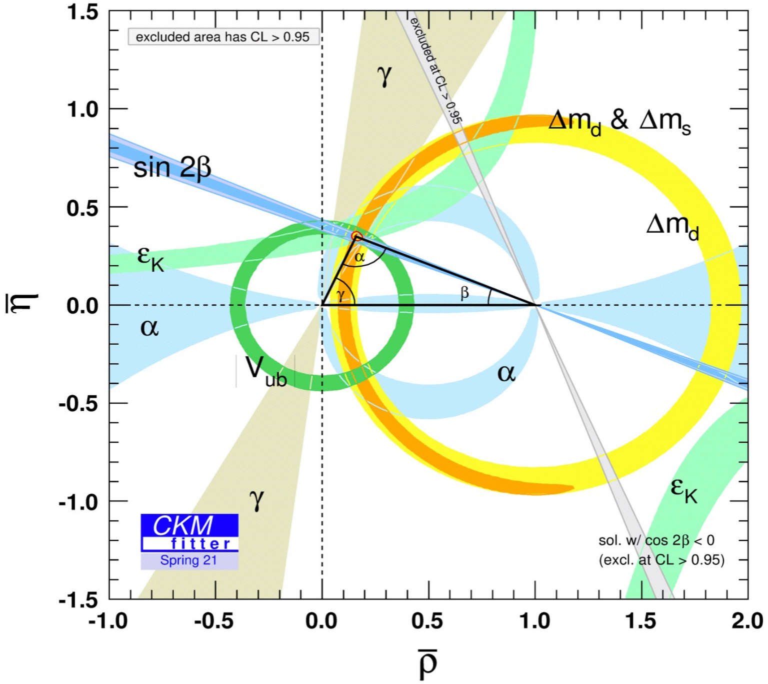
$$\begin{pmatrix} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}}e^{\pm i\pi} \\ -\frac{1}{\sqrt{3}}e & \frac{1}{\sqrt{3}}e^{-i\pi/6} & \frac{1}{\sqrt{3}} \\ \frac{1}{\sqrt{3}}e^{-i\pi/6} & -\frac{1}{\sqrt{3}}e^{i\pi/6} & \frac{1}{\sqrt{3}} \end{pmatrix}$$

matrix with maximum CPV

- **Related to mass hierarchy? Forth generation?**

Unitary test

- **Closure test of unitary triangle etc** $\sum_i V_{ij}^* V_{ij} = 1$ $\sum_i V_{ij}^* V_{ik} = 0$
- **All measurements consistent with each other? Yes**
- **Is current precision enough? No**



10^{-5}

$$V_{ud}V_{ud}^* + V_{us}V_{us}^* + V_{ub}V_{ub}^* - 1$$

$$= -0.00230^{+0.00218}_{-0.00023}\ (1\sigma)$$

$$-0.00230^{+0.00237}_{-0.00044}\ (2\sigma)$$

$$-0.00230^{+0.00242}_{-0.00065}\ (3\sigma)$$

Direct measurements:

$$\boldsymbol{\alpha + \beta + \gamma = (179^{+7}_{-6})^\circ}$$

Global fits:

$$\boldsymbol{\alpha + \beta + \gamma = (179.9^{+1.9}_{-1.7})^\circ}$$

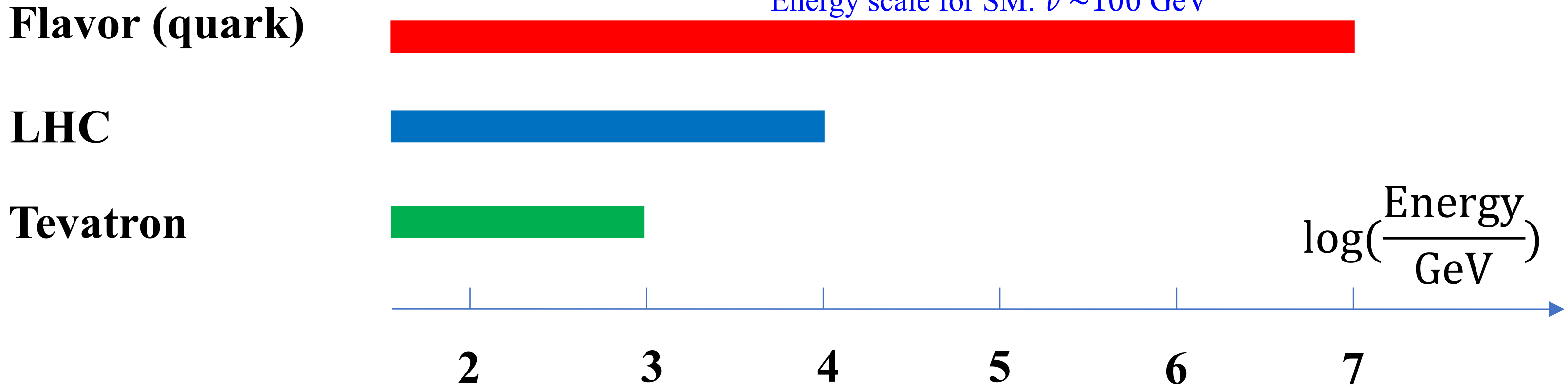
Energy scale

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

$$\mathcal{A}(\psi_i \to \psi_j + X) = \mathcal{A}_0 \left(\frac{c_{\rm SM}}{v^2} + \frac{c_{\rm NP}}{\Lambda^2} \right)$$

NP scale: Λ

Energy scale for SM: v ~100 GeV

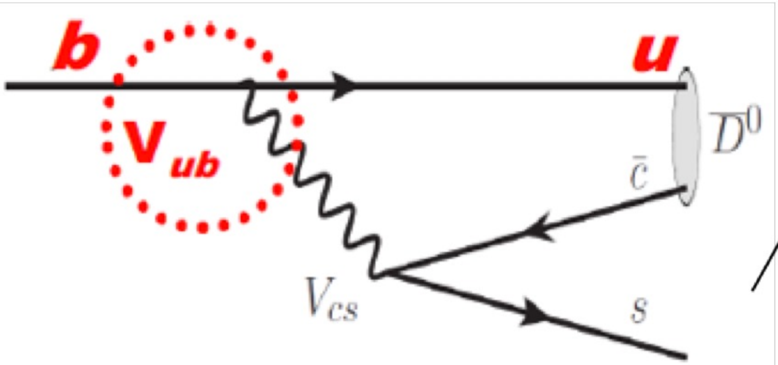


- **Statistics or precision is key for flavor program: New Physics scale, i.e. Dim = 6, proportional to $\sqrt[4]{\text{statistics}}$ or $1/\sqrt{\text{Uncertainty}}$**
- **Also "tasteful", not only can tell there is New Physics, but also tell properties of New Physics based on flavor it couples to**

CKM angle γ

- Measured through $b \to c$ and $b \to u$ interference

$$\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$



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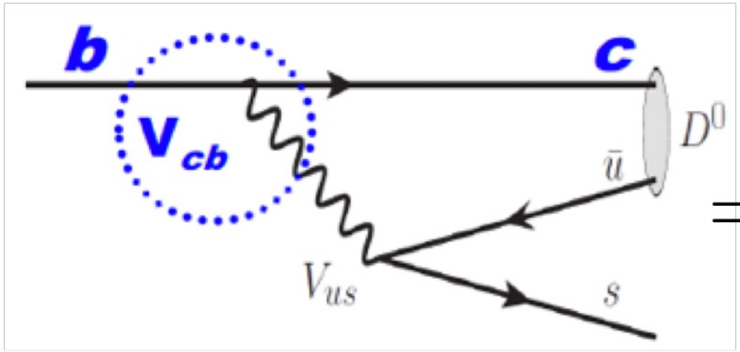


$= r_B e^{i\delta_B}$

$$A = a_1 e^{i(\delta_1+\phi_1)} + a_2 e^{i(\delta_2+\phi_2)} \qquad \bar{A} = a_1 e^{i(\delta_1-\phi_1)} + a_2 e^{i(\delta_2-\phi_2)}$$

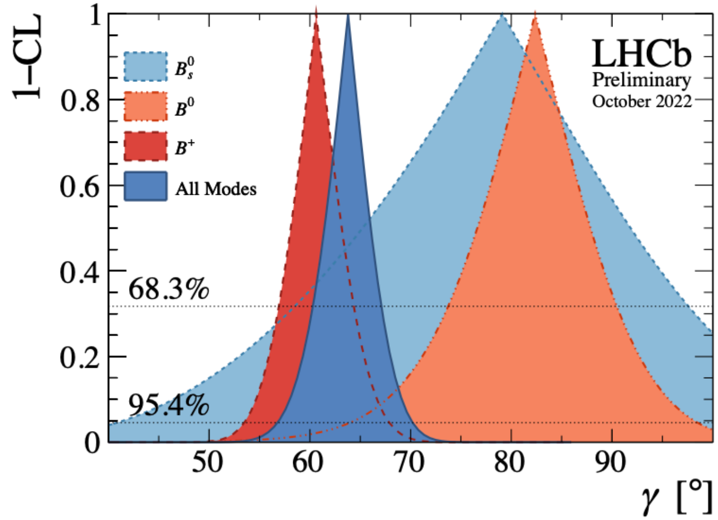
$$A_{CP} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} \propto \sin(\delta_1 - \delta_2)\sin(\phi_1 - \phi_2)$$

- Tree level processes → SM candle, NP normally enters loop diagrams
- Loop level processes suppressed, theoretically clean, $\delta\gamma/\gamma \sim 10^{-7}$

JHEP 1401 (2014) 051

- All QCD parameters (hard to calculate) obtained from experimental measurements (global fit)

Global combination results

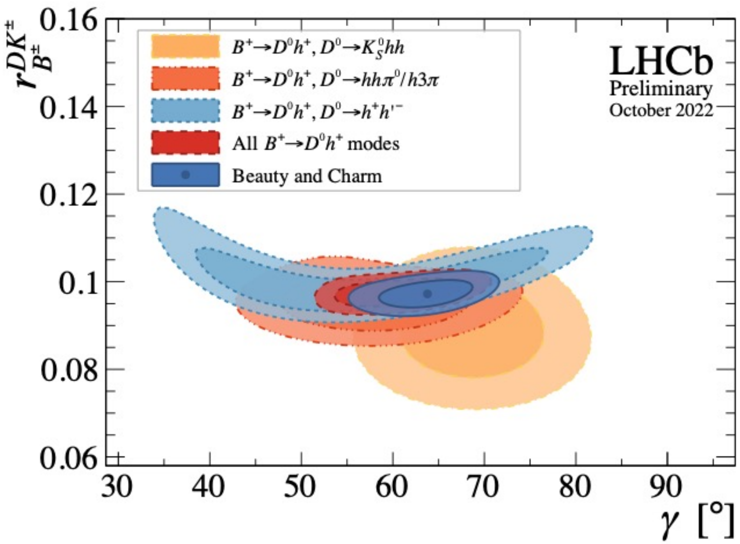


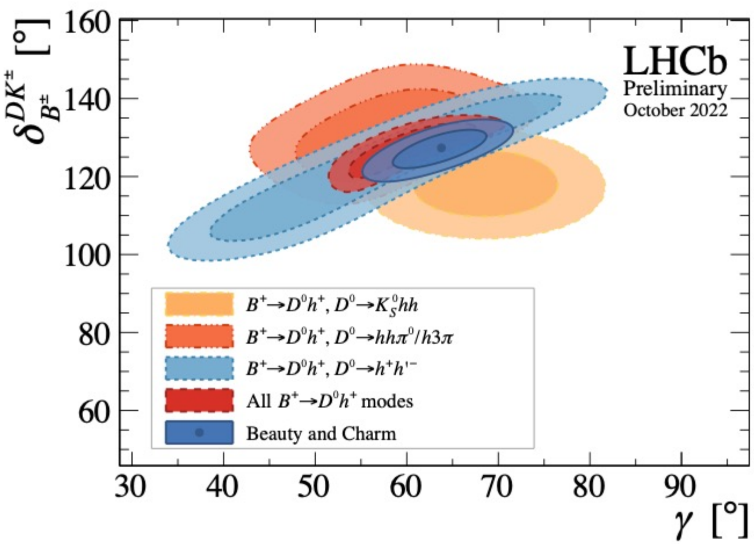
$$\gamma = (63.8^{+3.5}_{-3.7})^\circ$$

- **Compatible with indirect determination**

$$\gamma = (65.5^{+1.1}_{-2.7})^\circ$$ CKMfitter

- **Dominant by B^+ decays**
- **Different decays contribute differently, global combination gives best sensitivity**



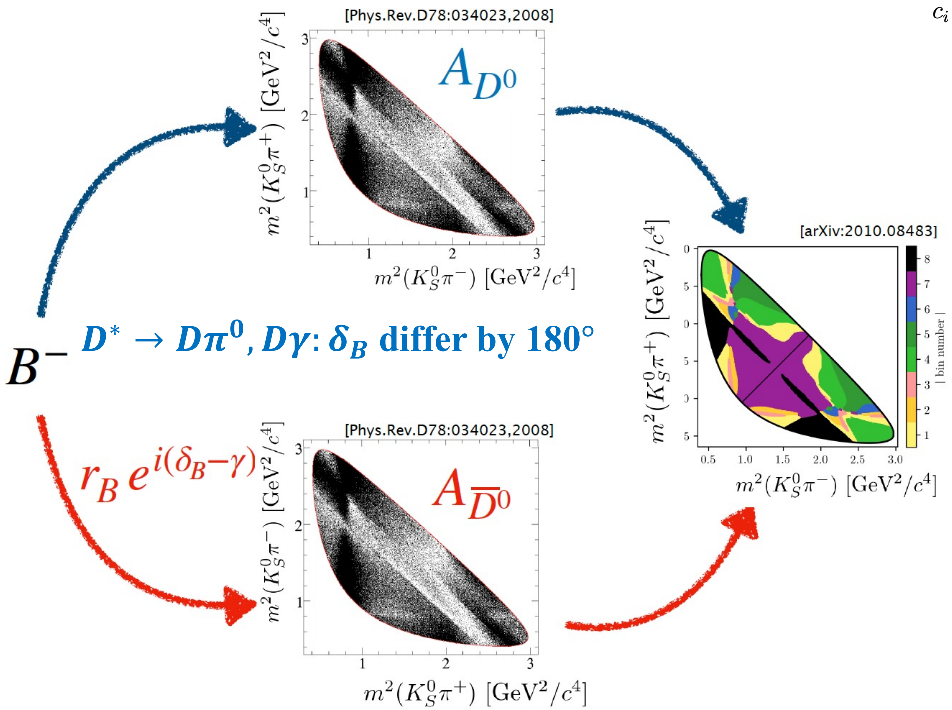


CKM angle γ : results

- Binned method (BPGGSZ) for $B^+ \to D^* K^+, D^* \to D\pi^0, D\gamma$, $D \to K_S^0 h^+ h^-$
- Uncertainties from BaBar and Belle around 26°
- First measurements from LHCb, using fully reconstructed method

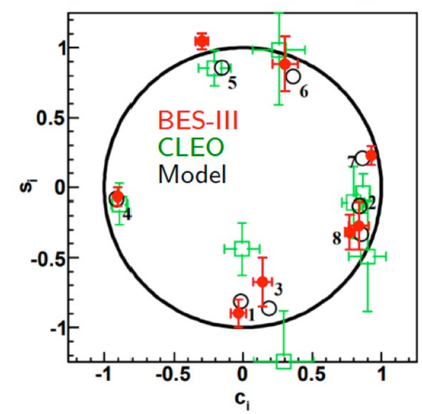
s_i sin

$$c_i = \frac{\int_i ds_+ ds_- |A_D(s_-, s_+)|^2 \cos[\Delta\delta_D(s_-, s_+)]}{\sqrt{\int_i ds_- ds_+ |A_D(s_-, s_+)|^2}\sqrt{\int_i ds_+ ds_- |A_D(s_+, s_-)|^2}},$$



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

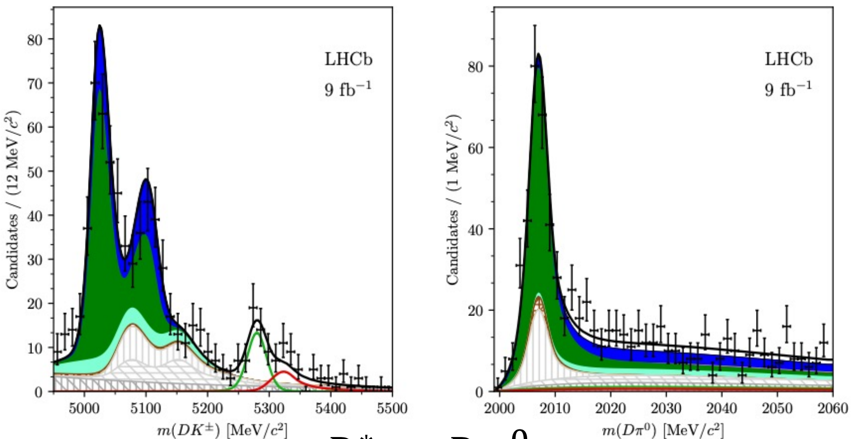
[PRD101, 112002(2020)]



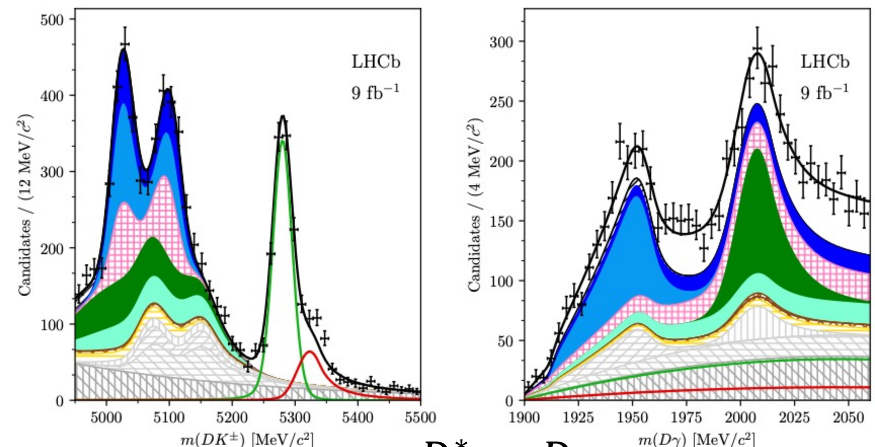
$$A(B^- \to D^* h^-) \propto A_D(s_-, s_+) + f_{D^*} A_{\overline{D}}(s_-, s_+) r_B^{D^* h} e^{i(\delta_B^{D^* h} - \gamma)},$$

CKM angle γ : results

LHCb-PAPER-2023-012

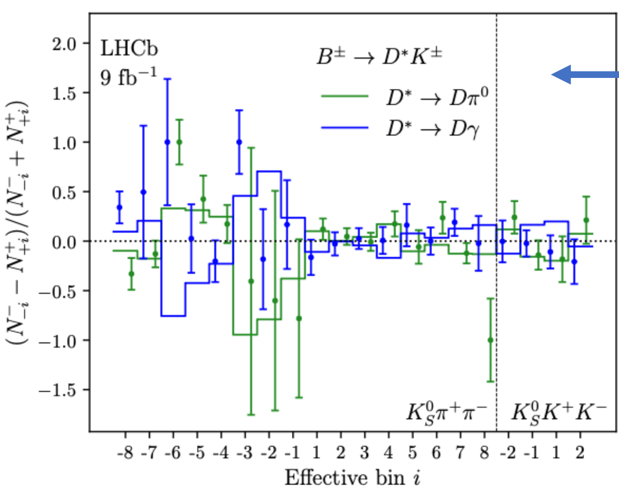


$D^* \to D\pi^0$



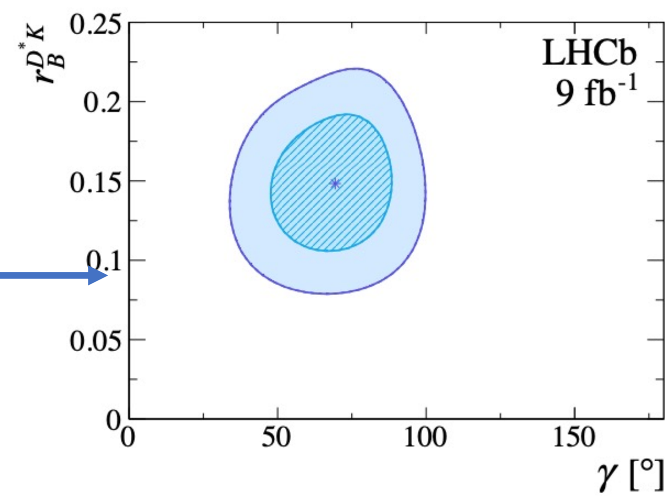
$D^* \to D\gamma$

- **CKM angle γ extracted using number of events in each D Dalitz bins** $\gamma = 69 \pm 14\,^\circ$



CPV in each bin

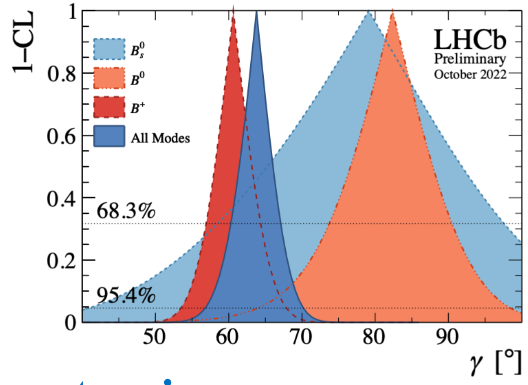
γ vs r_B



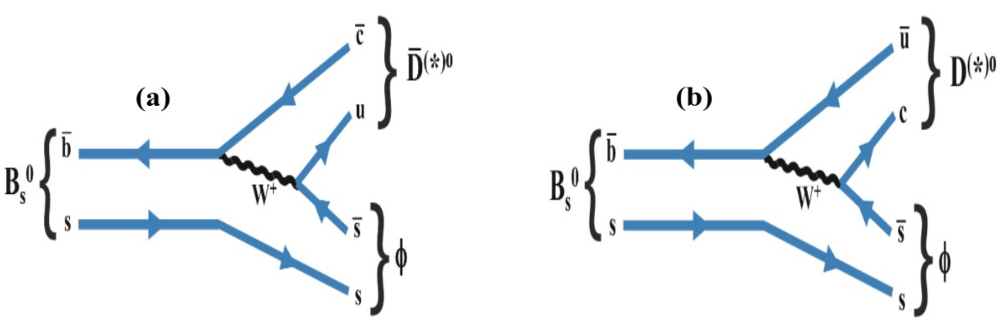
$B^0_{(s)} \to D\phi$ measurements

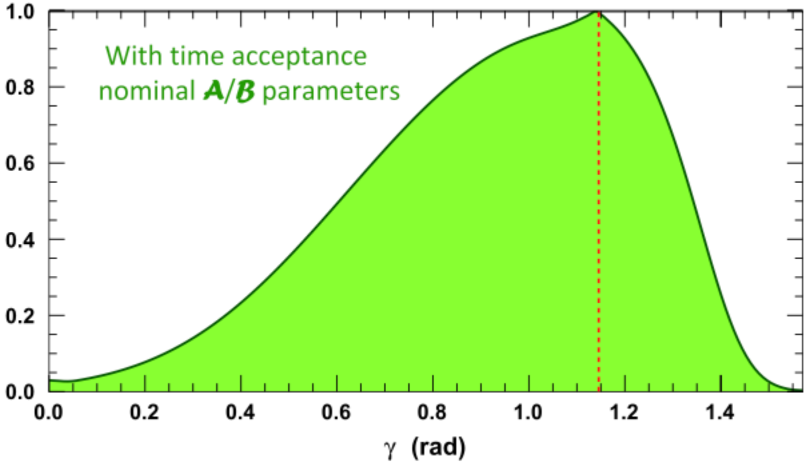
LHCb-CONF-2023-004
CPC 45 (2021) 023003

- Important to understand the difference of angle γ from B^0_s and B^+
- Recently, LHCb updates its measurement from $B^0_s \to D^{\mp}_s K^{\pm}$ and gives $\gamma = (74 \pm 11)^\circ$



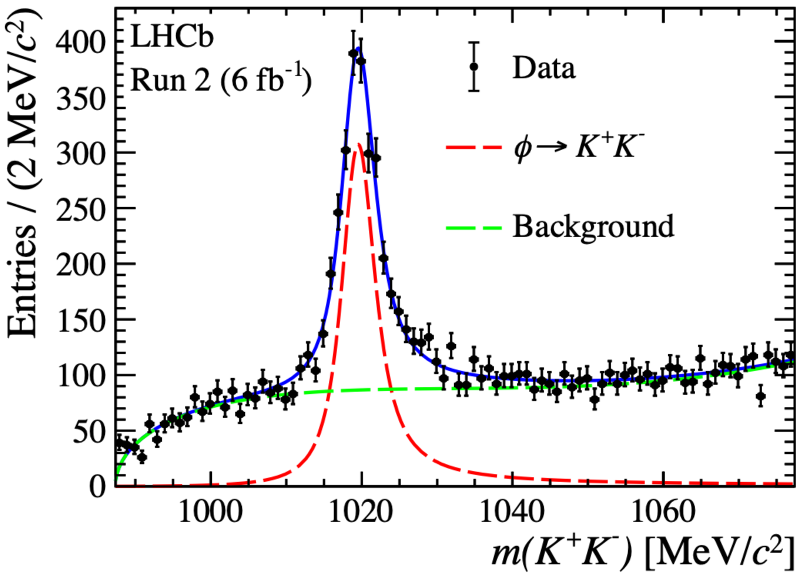
- Important to measure in B^0_s decays, not depending on flavor tagging
- $B^0_s \to D^*\phi$: untagged, time-integrated measurements, predicted to have sensitivity with LHCb Run 1 and 2 data around $8-19^\circ$

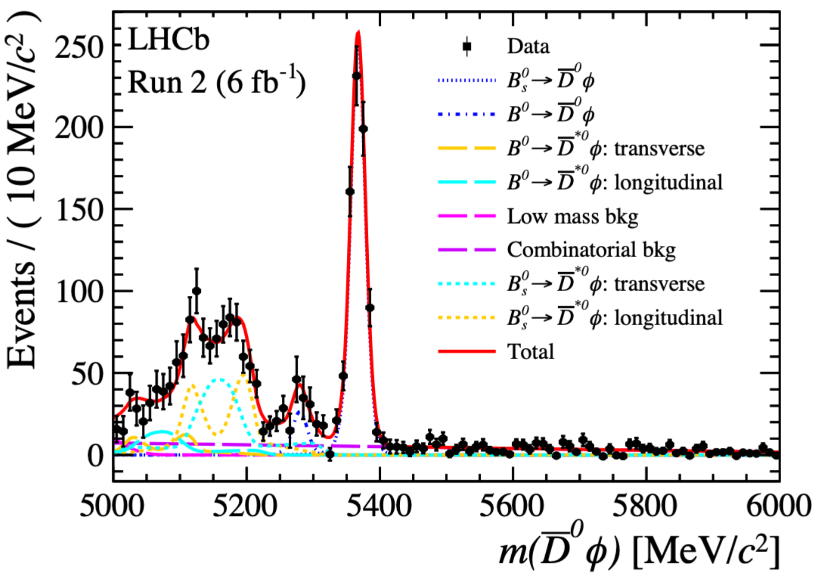




$B^0_{(s)} \to D\phi$ measurements

- **First step: precise measurements of the branching fractions**
- **Sweights to extract ϕ signals and then extract B^0_s yields**





$$\mathcal{B}(B^0_s \to \overline{D}^0\phi) = (2.30 \pm 0.10 \pm 0.11 \pm 0.20) \times 10^{-5},$$
$$\mathcal{B}(B^0_s \to \overline{D}^{*0}\phi) = (3.17 \pm 0.16 \pm 0.17 \pm 0.27) \times 10^{-5}.$$

stat. sys. control

$B^0_{(s)} \to D\phi$ measurements

LHCb-PAPER-2023-003

- $B^0 \to D^{(*)}\phi$: OZI suppressed, but can happen through $\omega - \phi$ mixing

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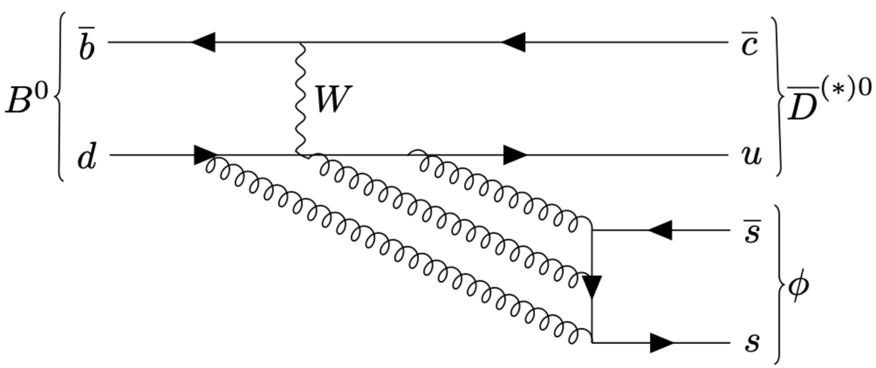
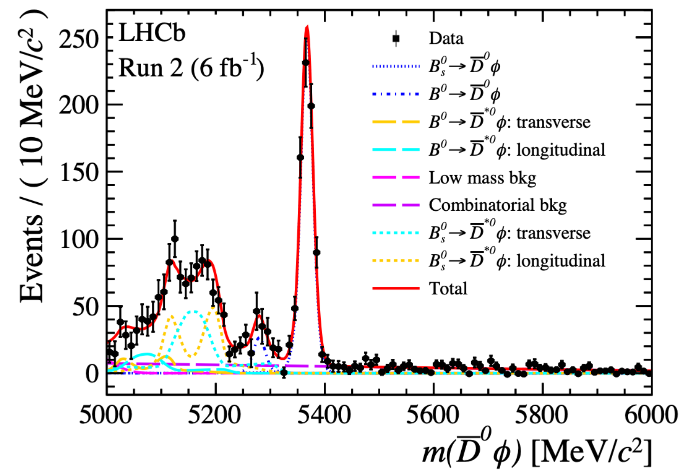
- Predictions: $B^0 \to D^0\phi$, $(2.1 \pm 0.3)\times 10^{-6}$, $B^0 \to D^{0*}\phi$, $(1.8 \pm 0.5)\times 10^{-6}$





$$\mathcal{B}(B^0 \to \overline{D}^0\phi) = (7.7 \pm 2.1 \pm 0.7 \pm 0.7) \times 10^{-7},$$

$$\mathcal{B}(B^0 \to \overline{D}^{*0}\phi) = (2.2 \pm 0.5 \pm 0.2 \pm 0.2) \times 10^{-6}.$$

stat. sys. control

- Mixing angle extracted to be:

$[3.1, 3.8]^\circ$ @ 68.3% C. L.

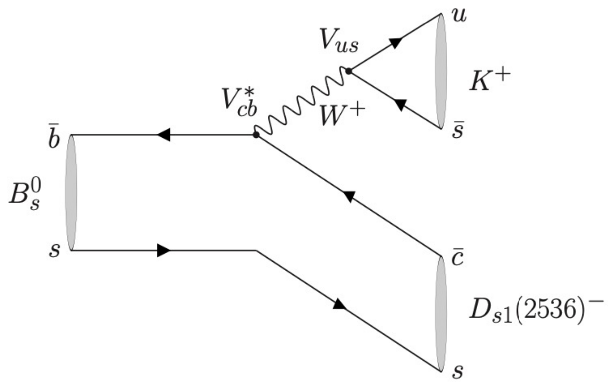
$$\omega^I \equiv (u\bar{u} + d\bar{d})/\sqrt{2} \qquad \phi^I \equiv s\bar{s}.$$

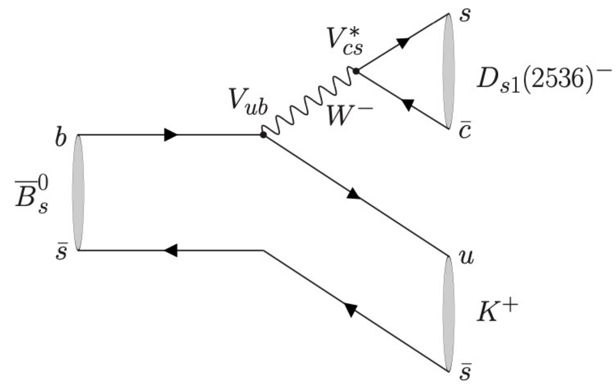
$$\begin{pmatrix} \omega \\ \phi \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} \omega^I \\ \phi^I \end{pmatrix}$$

Observation of $B^0_{(s)} \to D_{s1}(2536)^{\mp}K^{\pm}$

LHCb-PAPER-2023-014

- **Offers another possibility to measure CKM angle γ using TD measurement**

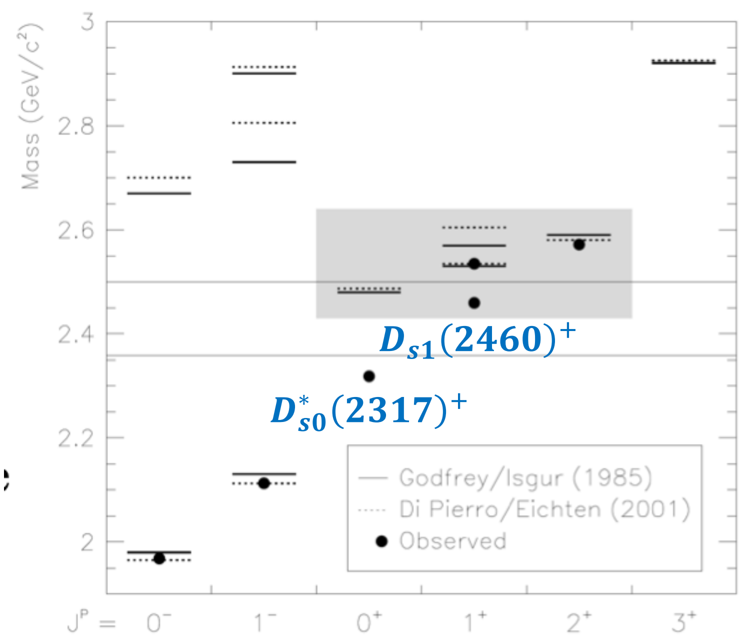




- **Also add additional channel to study recent anomalies found in $B^0 \to D^{(*)-}K^+, B^0_s \to D_s^{(*)-}\pi^+$**

**EPJC80 (2020) 951,
JHEP10 (2021) 235,
JHEP01 (2022) 147,
PRD106 (2022) 056004**

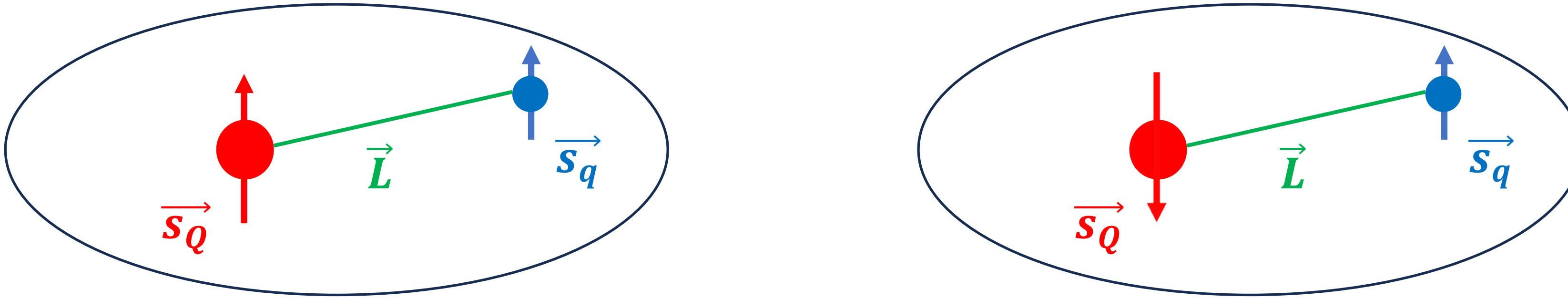
- **Understanding orbitally excited D_s^* mesons ($D^*_{s0}(2317)^+, D_{s1}(2460)^+, D_{s1}(2536)^+$ etc.), where $D_{s1}(2460)^+$ may possibly have exotic nature**



Observation of $B^0_{(s)} \to D_{s1}(2536)^{\mp}K^{\pm}$

LHCb-PAPER-2023-014

- **Under HQSS, $\vec{j} = \vec{s_Q} + (\vec{L} + \vec{s_q}) = \vec{s_Q} + \vec{s_l}$, $Q = c, b$, $q = u, d, s$**



$\vec{s_l}$	J^P	Meson	Mass (MeV)	Meson	Mass (MeV)	Difference (MeV)
1/2	0^-	$D^{0(\pm)}$	1864.83 (1869.58)	$D_s^{\pm}$	1968.27	103.44 (98.69)
	1^-	$D^{*0(\pm)}$	2006.85 (2010.26)	$D_s^{*\pm}$	2112.1	105.25 (101.84)
1/2	0^+	$D_0^*(2400)^{0(\pm)}$	2318 (2351)	$D_{s0}^*(2317)^{\pm}$	2317.7	−0.3(−33.3)
	1^+	$D_1(2430)^0$	2427	$D_{s1}(2460)^{\pm}$	2459.5	32.5
3/2	1^+	$D_1(2420)^{0(\pm)}$	2420.8 (2423.2)	$D_{s1}(2536)^{\pm}$	2535.10	114.3(111.9)
	2^+	$D_2^*(2460)^{0(\pm)}$	2460.57(2465.4)	$D_{s2}^*(2573)$	2569.1	108.53 (103.7)

- **Possible mixing between two 1^+ states**

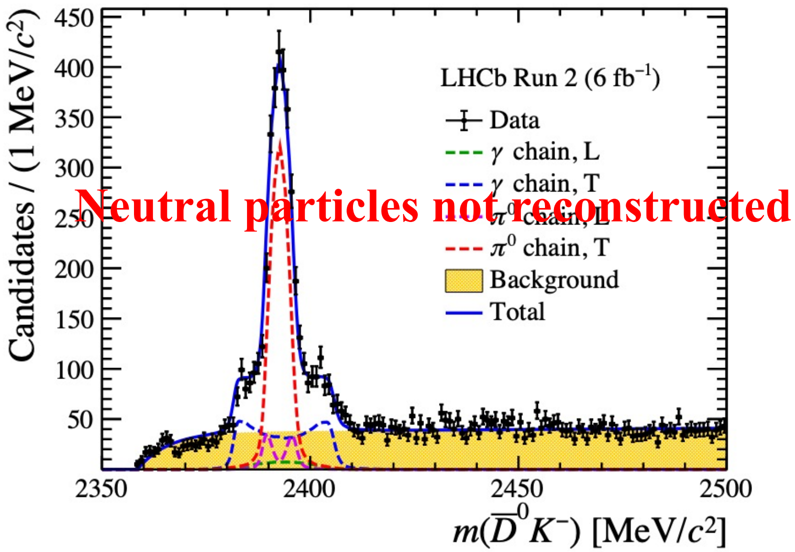
$$|D_{s1}(2460)^+\rangle = \cos\theta \, |^{1/2}E_1\rangle + \sin\theta \, |^{3/2}E_1\rangle,$$
$$|D_{s1}(2536)^+\rangle = -\sin\theta \, |^{1/2}E_1\rangle + \cos\theta \, |^{3/2}E_1\rangle,$$

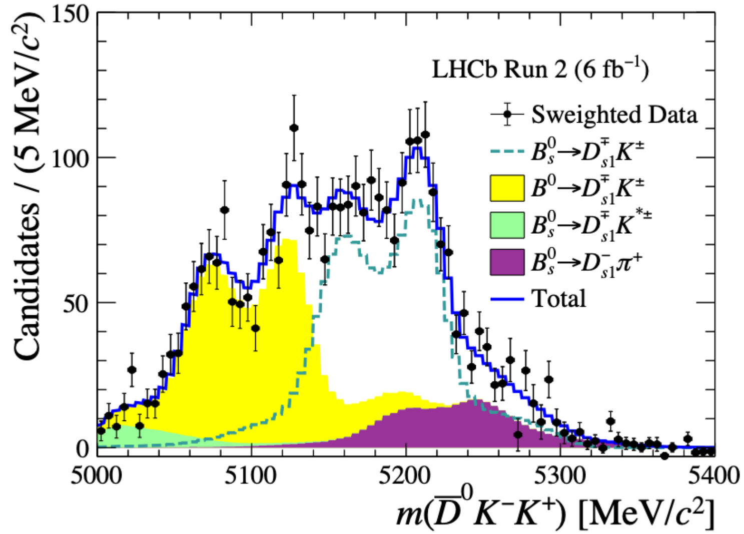
$D_{s1}(2536)^+ \to D^{*0}K^+$:

$|^{1/2}E_1>$: **S wave**

$|^{3/2}E_1>$: **D wave**

Observation of $B^0_{(s)} \to D_{s1}(2536)^{\mp} K^{\pm}$





$D_{s1}(2536)^+ \to D^{*0} K^+, D^{*0} \to D^0\pi^0/D^0\gamma$

$B^0 \to D^{\mp}_{s1} K^{\pm}$:~1500 $\quad B^0_s \to D^{\mp}_{s1} K^{\pm}$:~2000

$$\mathcal{B}(B^0_s \to D_{s1}(2536)^{\mp} K^{\pm}) \times \mathcal{B}(D_{s1}(2536)^- \to \overline{D}^{*0} K^-) = (2.49 \pm 0.11 \pm 0.12 \pm 0.25 \pm 0.06) \times 10^{-5},$$

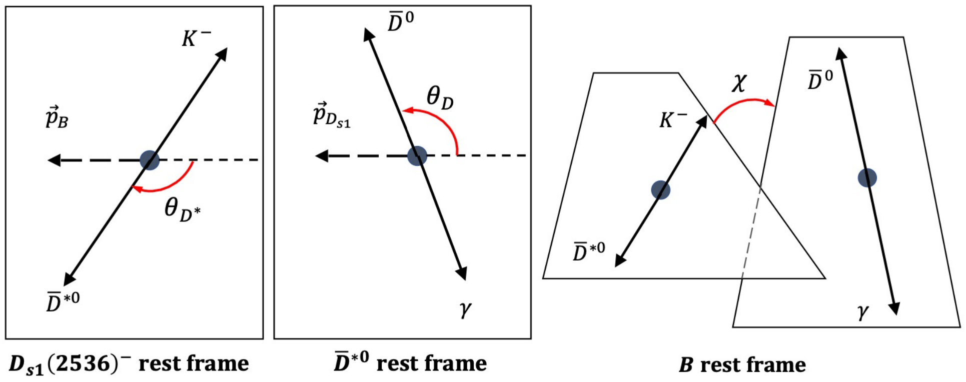
fs/fd

$$\mathcal{B}(B^0 \to D_{s1}(2536)^{\mp} K^{\pm}) \times \mathcal{B}(D_{s1}(2536)^- \to \overline{D}^{*0} K^-) = (0.510 \pm 0.021 \pm 0.036 \pm 0.050) \times 10^{-5},$$

stat. sys. control

Observation of $B^0_{(s)} \to D_{s1}(2536)^{\mp}K^{\pm}$

- Angular information reflects on the invariant mass distributions



$$\frac{d^3\Gamma}{d\cos\theta_{D^*}\, d\cos\theta_D\, d\chi} \propto \omega_{\rm long}(\theta_{D^*}, \theta_D)|H_0|^2 + \omega_{\rm tran}(\chi, \theta_{D^*}, \theta_D)|H_+|^2 + \omega_{\rm int}(\chi, \theta_{D^*}, \theta_D)\Re(H_0^* H_+),$$

$$ke^{i\phi} = H_+/H_0$$

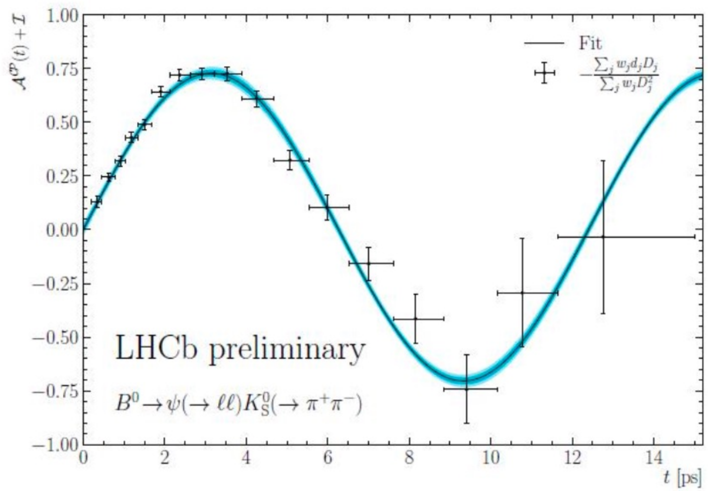
$$k = 1.89 \pm 0.24 \pm 0.06, \quad |\phi| = 1.81 \pm 0.20 \pm 0.11 \ \text{rad},$$

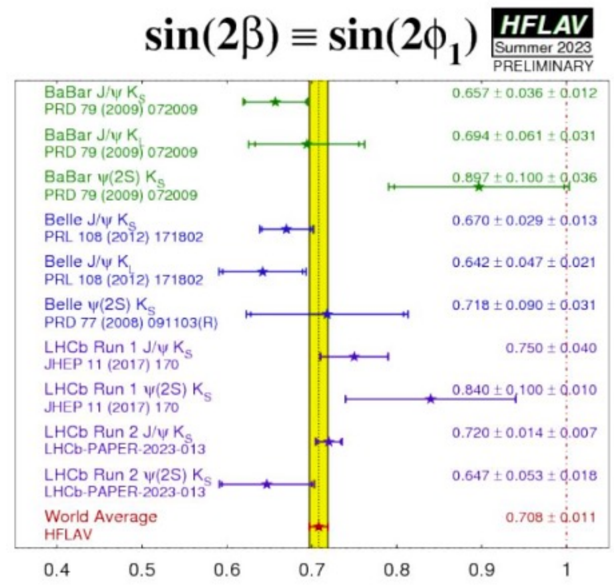
- S-wave fraction: $(55 \pm 7 \pm 3)\%$， allows to calculate mixing angle and understand the nature of these orbitally excited states

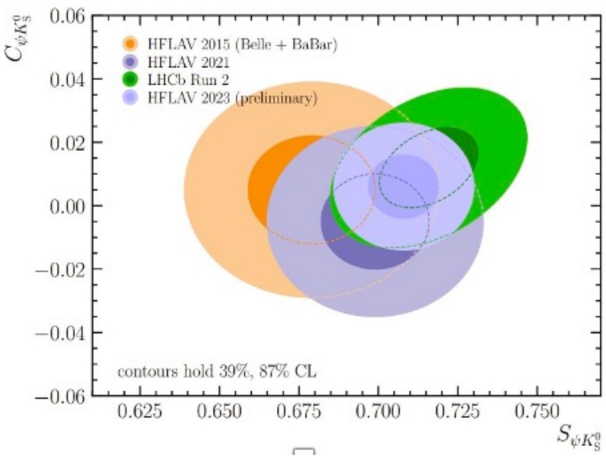
CKM angle β

$$\mathcal{A}^{CP}(t) = \frac{\Gamma(\overline{B}^0(t) \to \psi K^0_S) - \Gamma(B^0(t) \to \psi K^0_S)}{\Gamma(\overline{B}^0(t) \to \psi K^0_S) + \Gamma(B^0(t) \to \psi K^0_S)} \approx \underbrace{D_{\Delta t} D_{FT}}_{\text{Experimental dilution factors}} S \sin(\Delta m_d t)$$

$$S^{\text{Run 2}}_{\psi K^0_S} = 0.716 \pm 0.013\,(\text{stat}) \pm 0.008\,(\text{syst})$$
$$C^{\text{Run 2}}_{\psi K^0_S} = 0.012 \pm 0.012\,(\text{stat}) \pm 0.003\,(\text{syst})$$







[HFLAV to update]

- **Most precise measurement**

HFLAV 2021 ⇒ HFLAV 2023

$$sin(2\beta) = 0.699 \pm 0.017 \Rightarrow 0.708 \pm 0.011$$
$$C_{CP} = 0.005 \pm 0.015 \Rightarrow 0.006 \pm 0.010$$

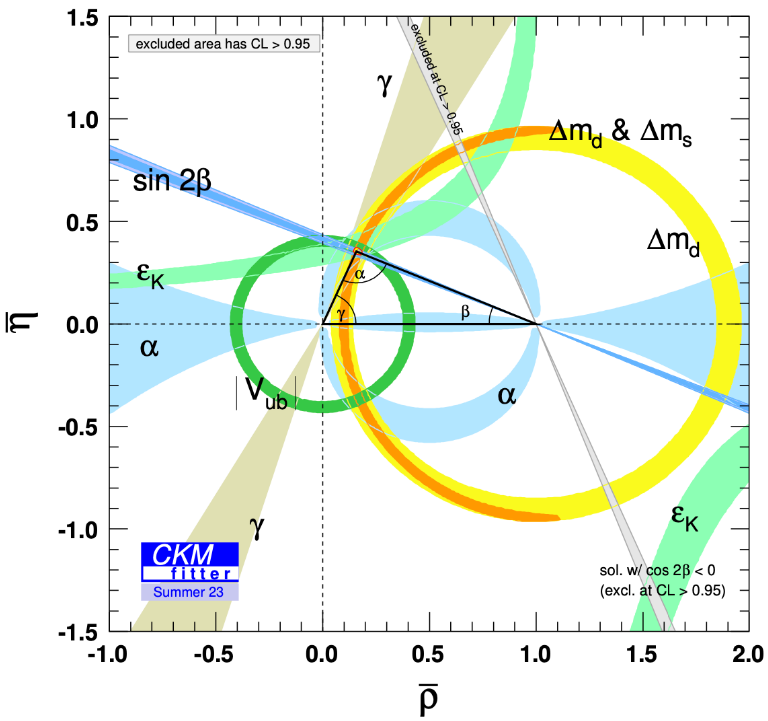
Global fit 2023

- With all these measurements and theoretical inputs from Lattice QCD, new updates on global fit performed

$$A = 0.8215\,^{+0.0047}_{-0.0082}\ (0.8\%\ \text{unc.})$$
$$\lambda = 0.22498\,^{+0.00023}_{-0.00021}\ (0.1\%\ \text{unc.})$$
$$\bar{\rho} = 0.1562\,^{+0.0112}_{-0.0040}\ (4.9\%\ \text{unc.})$$
$$\bar{\eta} = 0.3551\,^{+0.0051}_{-0.0057}\ (1.5\%\ \text{unc.})$$

68% C.L. intervals

$\bar{\rho}, \bar{\eta}$: $\sim$ 20% more precise



- Better constrain due to improved measurements of CKM angle γ and β
- Global consistency looks good

CKM'21: p-value $\sim$ 29% (1.1σ) $\rightarrow$ **CKM'23**: p-value $\sim$ 67% (0.4σ)

- Offers precise predictions on New Physics sensitive processes

CKM angle $\phi_s^{c\bar{c}s}$

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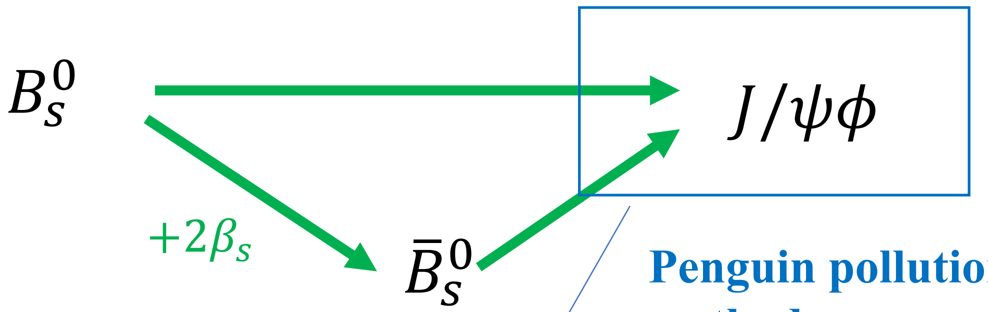
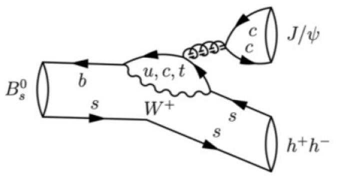
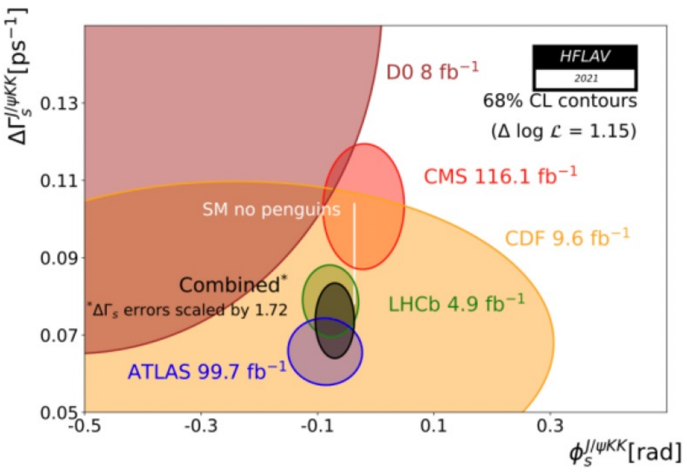
- **Using predictions with CKM parameters, probe new physics in sensitive decays**





Penguin pollution: Data-driven method

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



Very small value

Very small value

$+2\beta_s$:

$36.8^{+0.9}_{-0.6}$ mrad [CKMfitter]

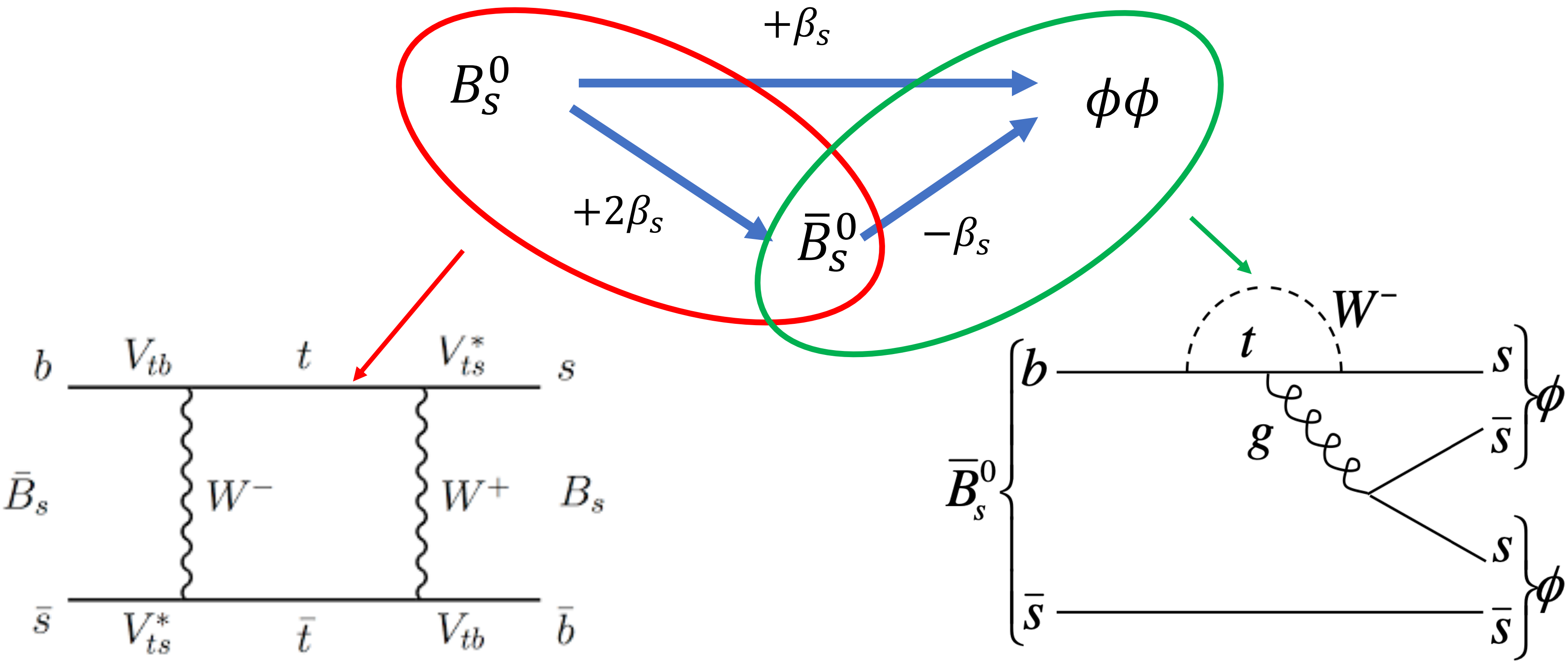
(37 ± 1) mrad [UTFIT]

$\phi_s^{c\bar{c}s} = (-50 \pm 19)$ **mrad** $\quad \Delta\Gamma_s = (0.082 \pm 0.005)$ **ps**$^{-1}$

Global combination

CKM angle $\phi_s^{s\bar{s}s}$

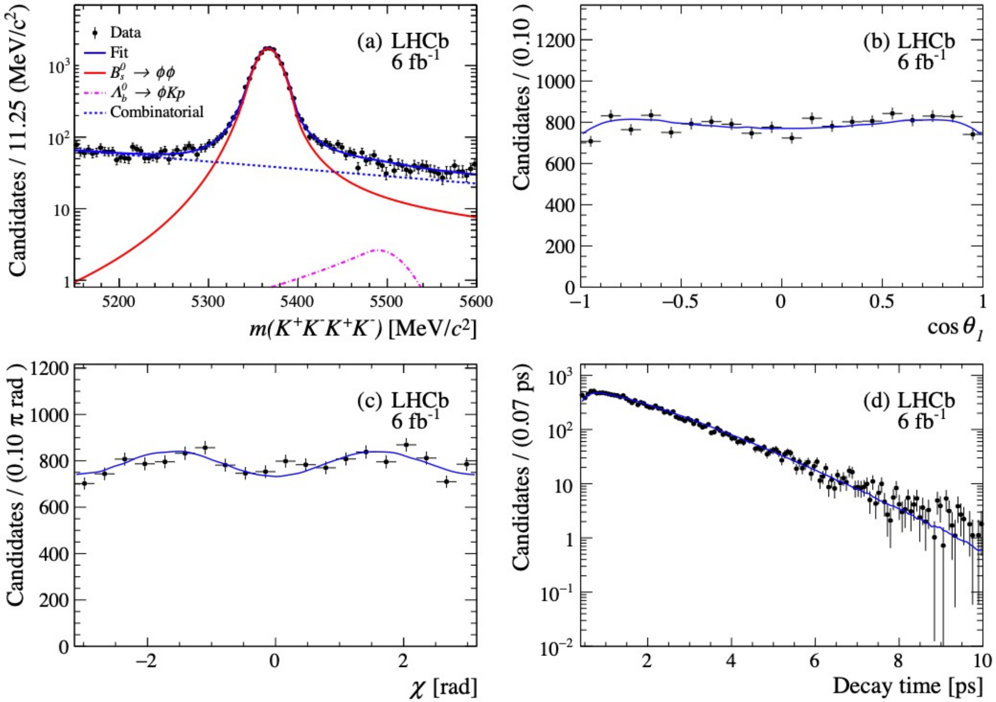
- **Very sensitive to new physics in B_s mixing and in penguin**



$$\phi_s^{s\bar{s}s} \sim 0 \quad \textbf{(SM)}$$

CKM angle $\phi_s^{s\bar{s}s}$

- Very sensitive to new physics in B_s mixing and in penguin
- Time-dependent angular analysis to probe CP violation： distinguish flavor, resonant contributions



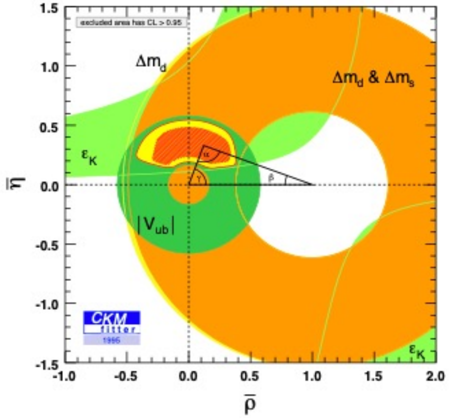
Mixing angle:

$$\phi_s^{s\bar{s}s} = -0.042 \pm 0.075 \pm 0.009 \text{ rad},$$

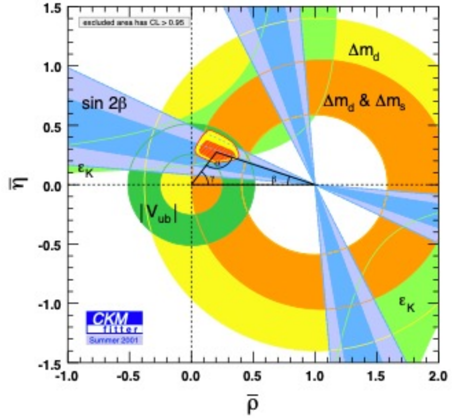
Direct CP violation parameter:

$$|\lambda| = 1.004 \pm 0.030 \pm 0.009,$$

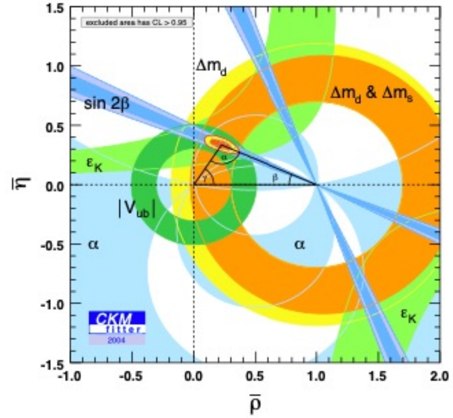
CKM status over years



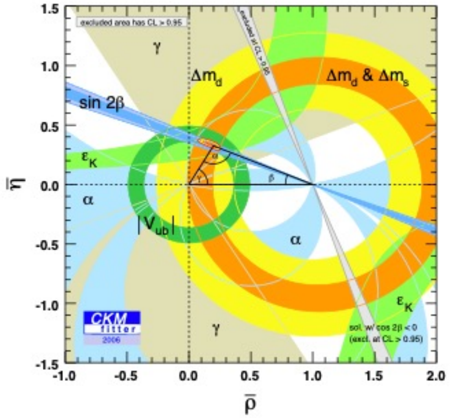
1995



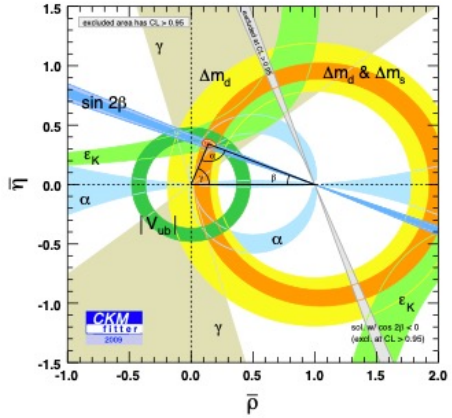
2001



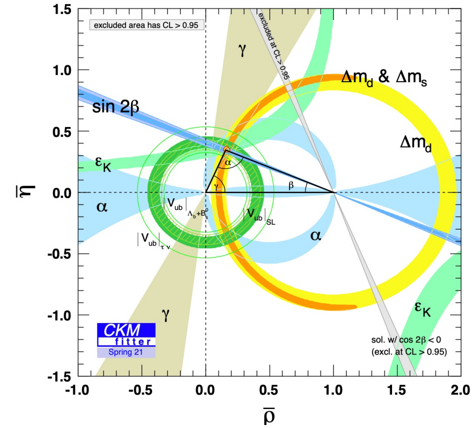
2004



2006

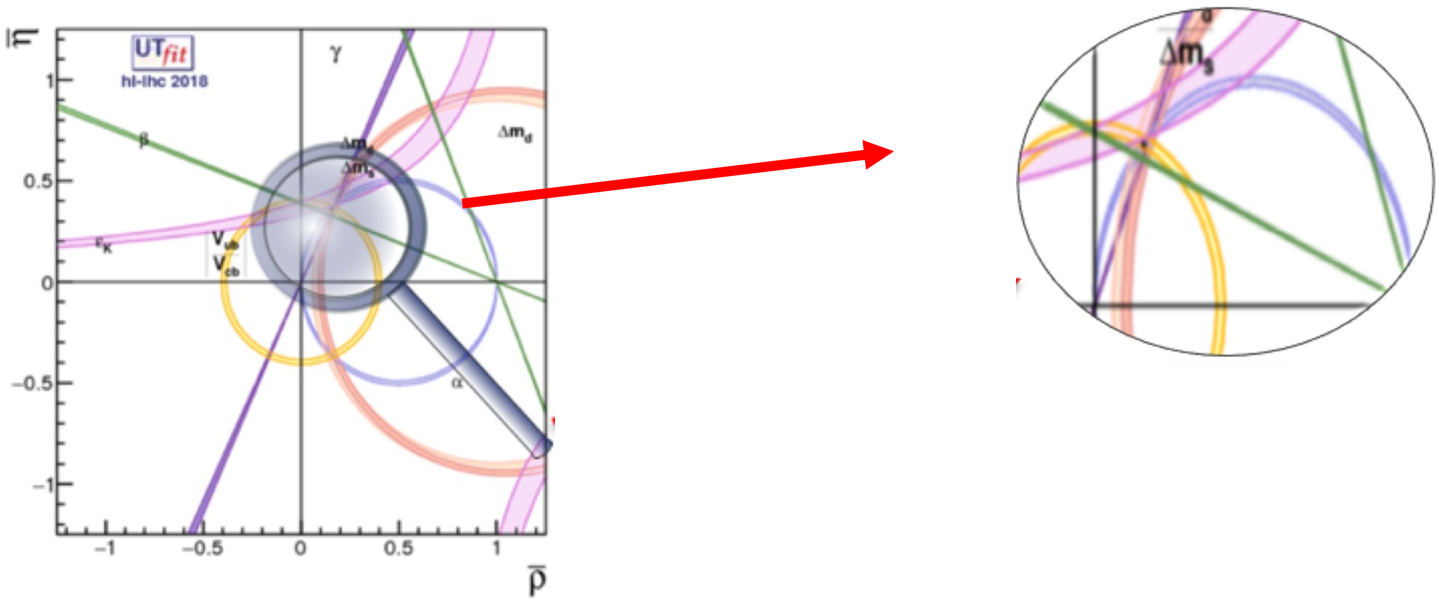


2009

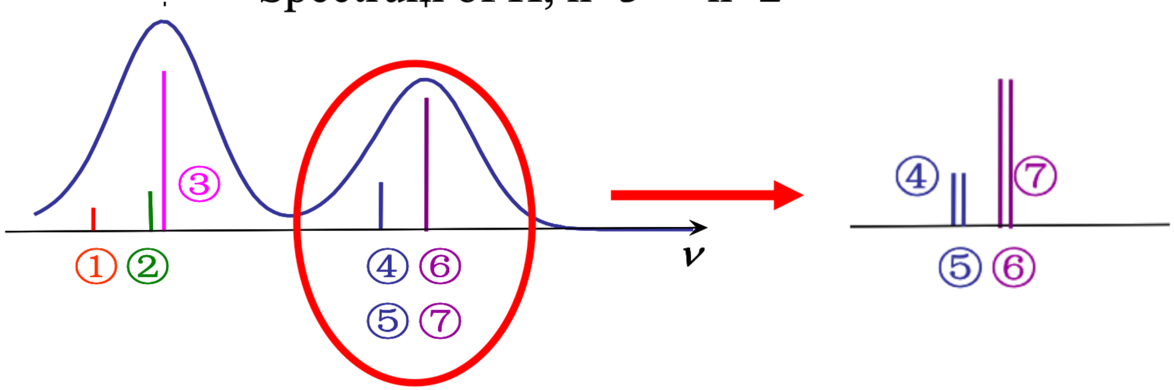


2021

Conclusion



Spectrum of H, n=3 → n=2



Thank You for Your Attention