Overview of recent LHCb results

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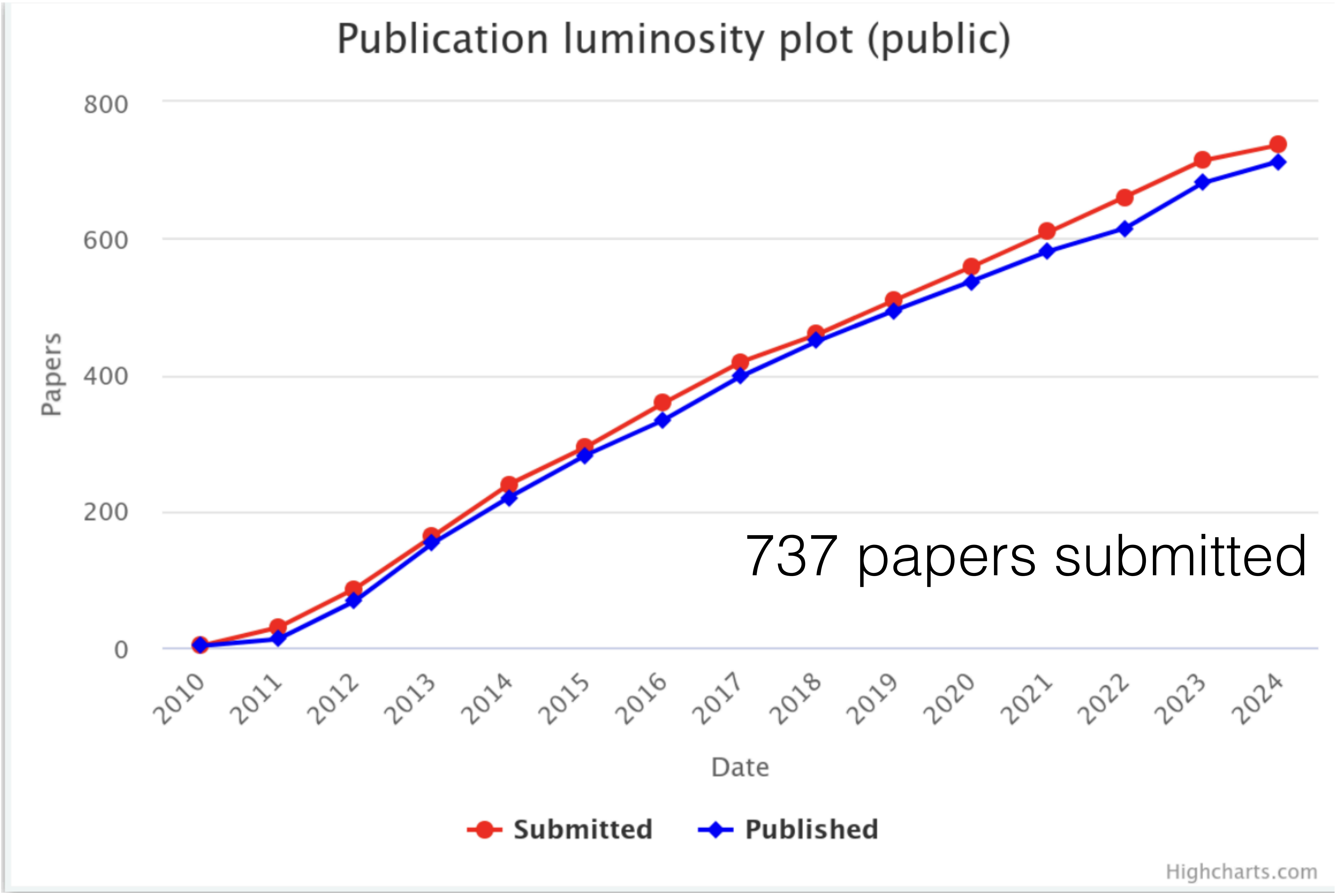
第4届LHCb前沿物理研讨会

2024.07.28，烟台

Outline

- Introduction
- CKM matrix
- Charm physics
- Rare decays
- Flavour anomalies
- Spectroscopy
- Heavy ions



Disclaimer: this talk cannot cover all the recent results; you can refer to the publication page for a full list of LHCb publications

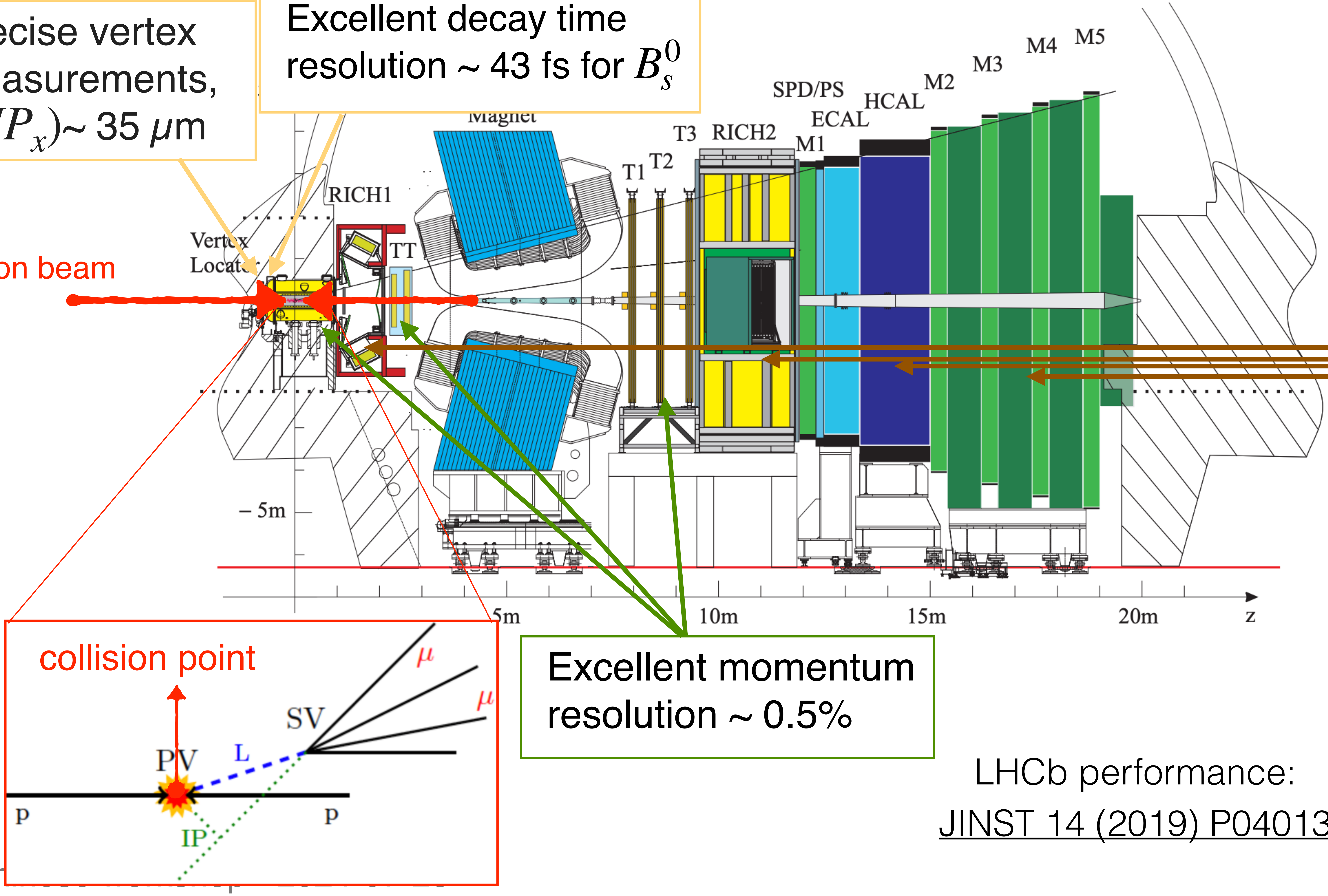
LHCb detector

General purpose detector specialised in beauty and charm hadrons

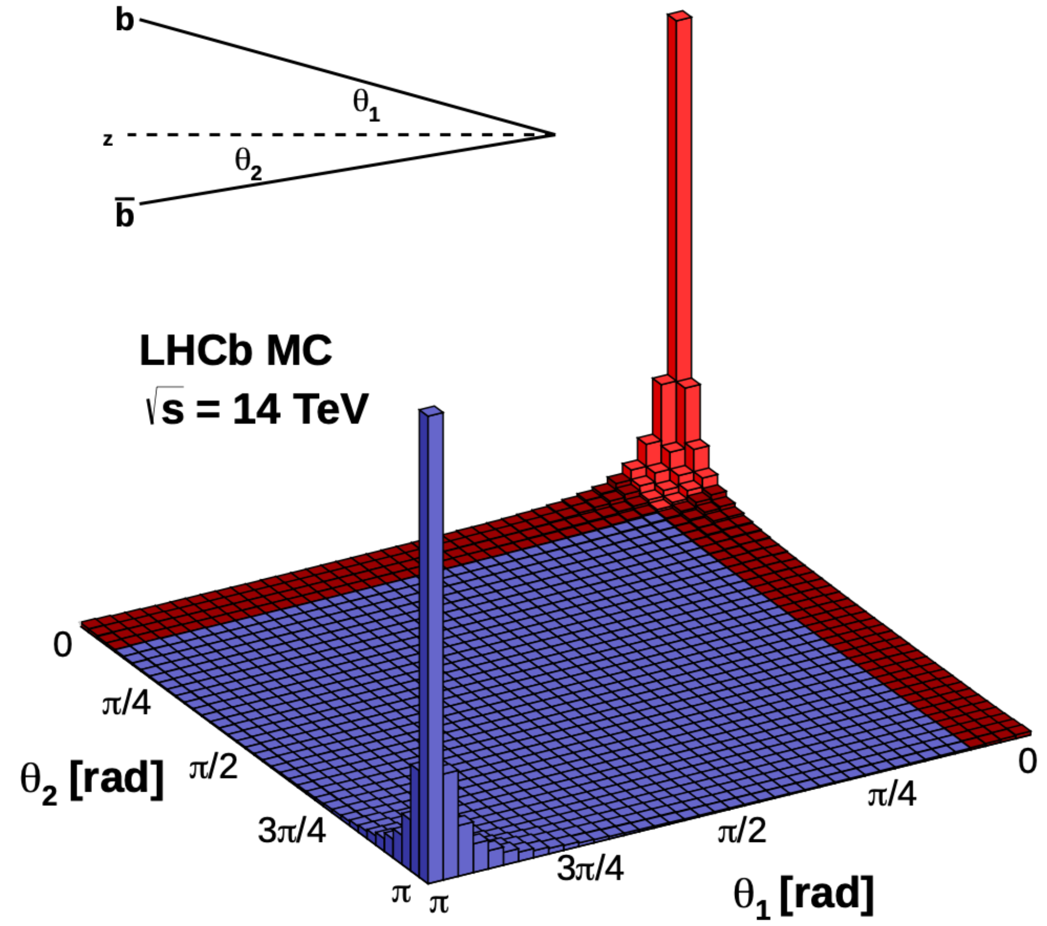
- Daughters of b & c hadron decays: $p_T \sim \mathcal{O}(1\ \mathrm{GeV}/c)$, flight distance L~1mm

Precise vertex measurements, $\sigma(IP_x)$~ 35 μm

Excellent decay time resolution ~ 43 fs for B_s^0

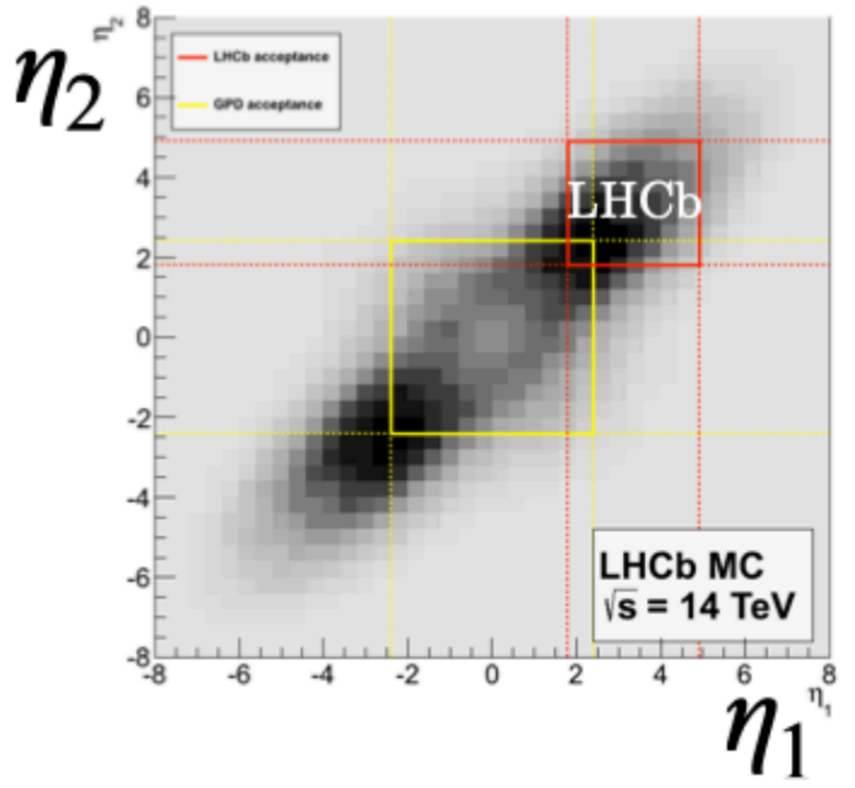


Excellent momentum resolution ~ 0.5%



$2 < \eta < 5$

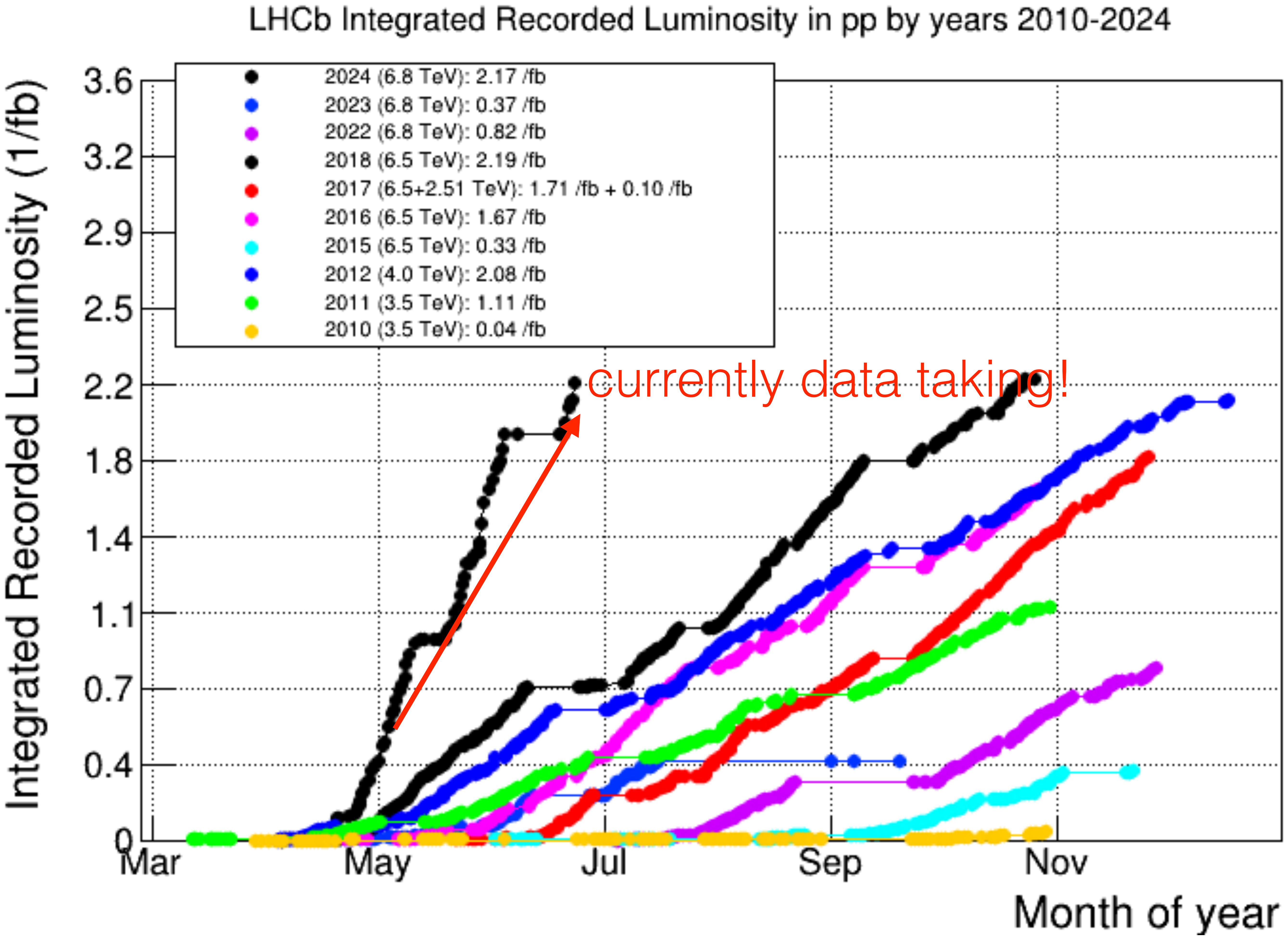
Excellent particle identification
$\epsilon(K) \approx 95\,\%$
misID $p(\pi \to K) \approx 5\,\%$
$\epsilon(\mu) \approx 97\,\%$



LHCb performance:
JINST 14 (2019) P04013

Luminosity

- Run 1: 2011+2012, 7, 8 TeV
- Run 2: 2015-2018, 13 TeV
- Run 3: 2022-2025, 13.6 TeV

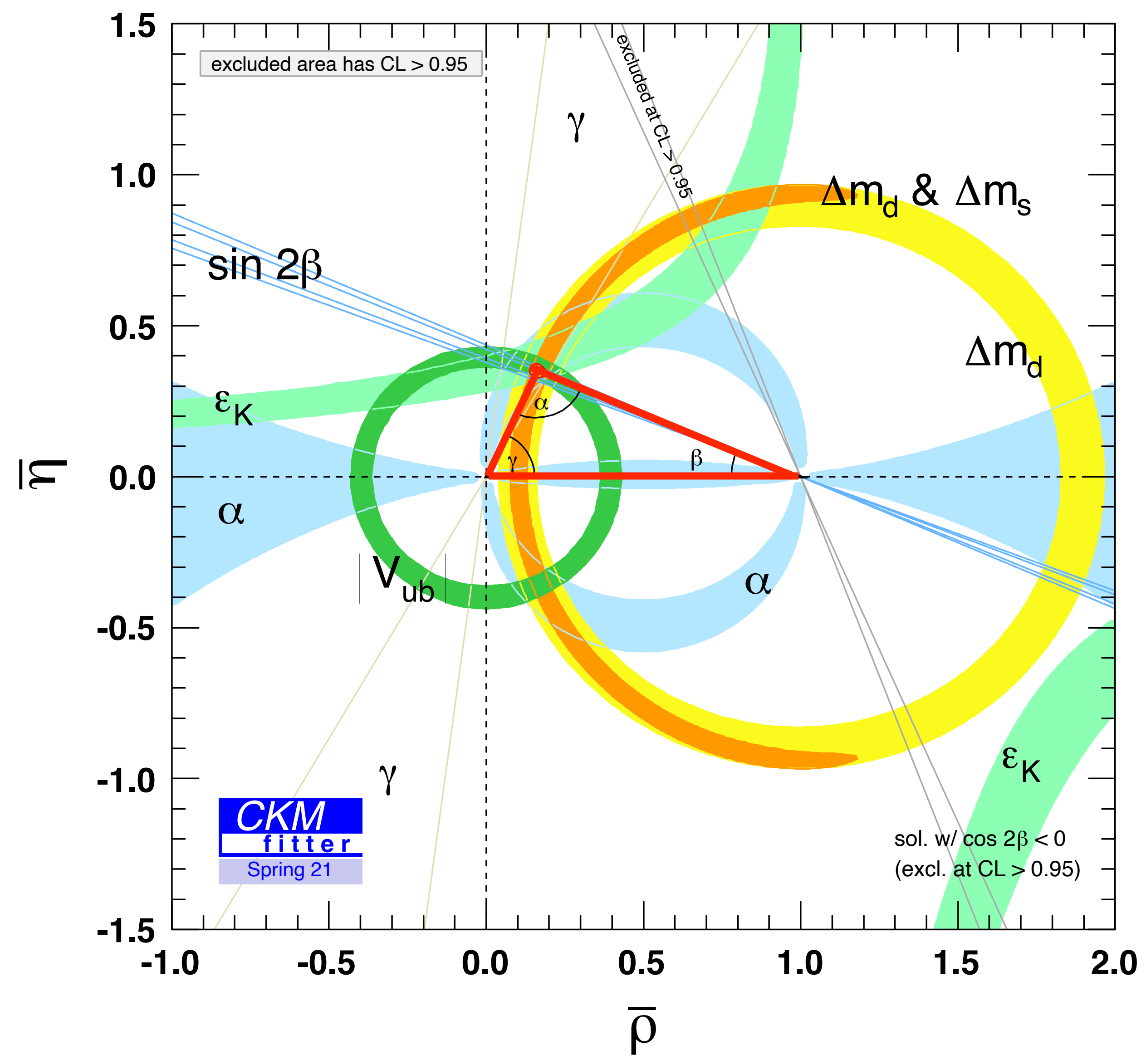


- Run 1(2011+2012): 3 fb^{-1} + Run 2 (2015-2018): 6 fb^{-1}
- Large number of beauty hadrons: [PRL118(2017)052002]

$$\sigma(b\bar{b})(7TeV) = 72.0 \pm 0.3 \pm 6.8\ \mu\text{b},\ \ \sigma(b\bar{b})(13TeV) = 144 \pm 1 \pm 21\ \mu b$$ in $2<\eta<5$

LHCb physics

- Precise measurements of flavour observables of CKM matrix
- Probe new physics through rare decays, FCNC, CP violations etc
  - Complementary to direct detection, possible to probe energy scales beyond collider energy
- Hadron physics to understand the QCD
- Heavy ions & EW physics



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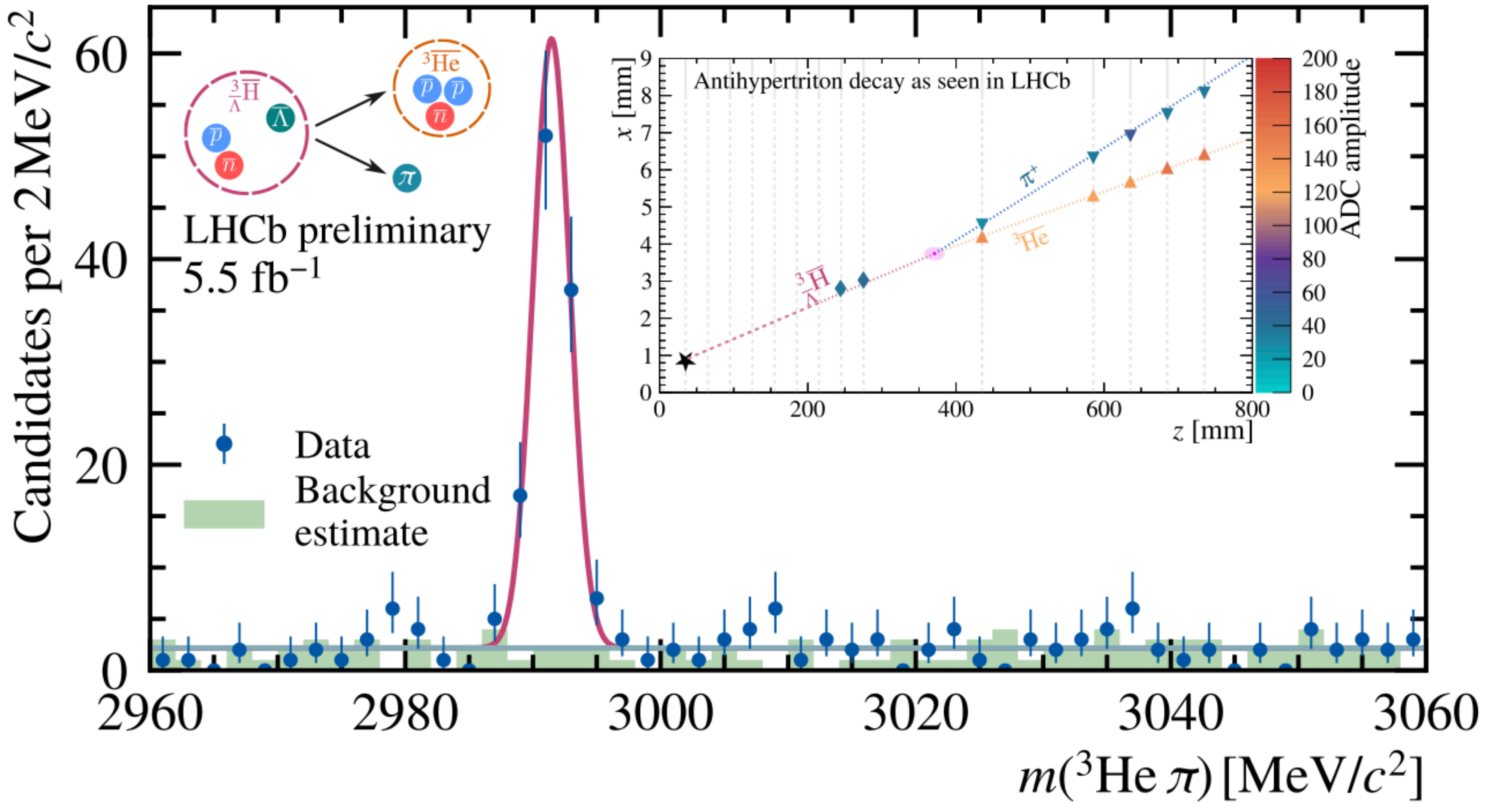
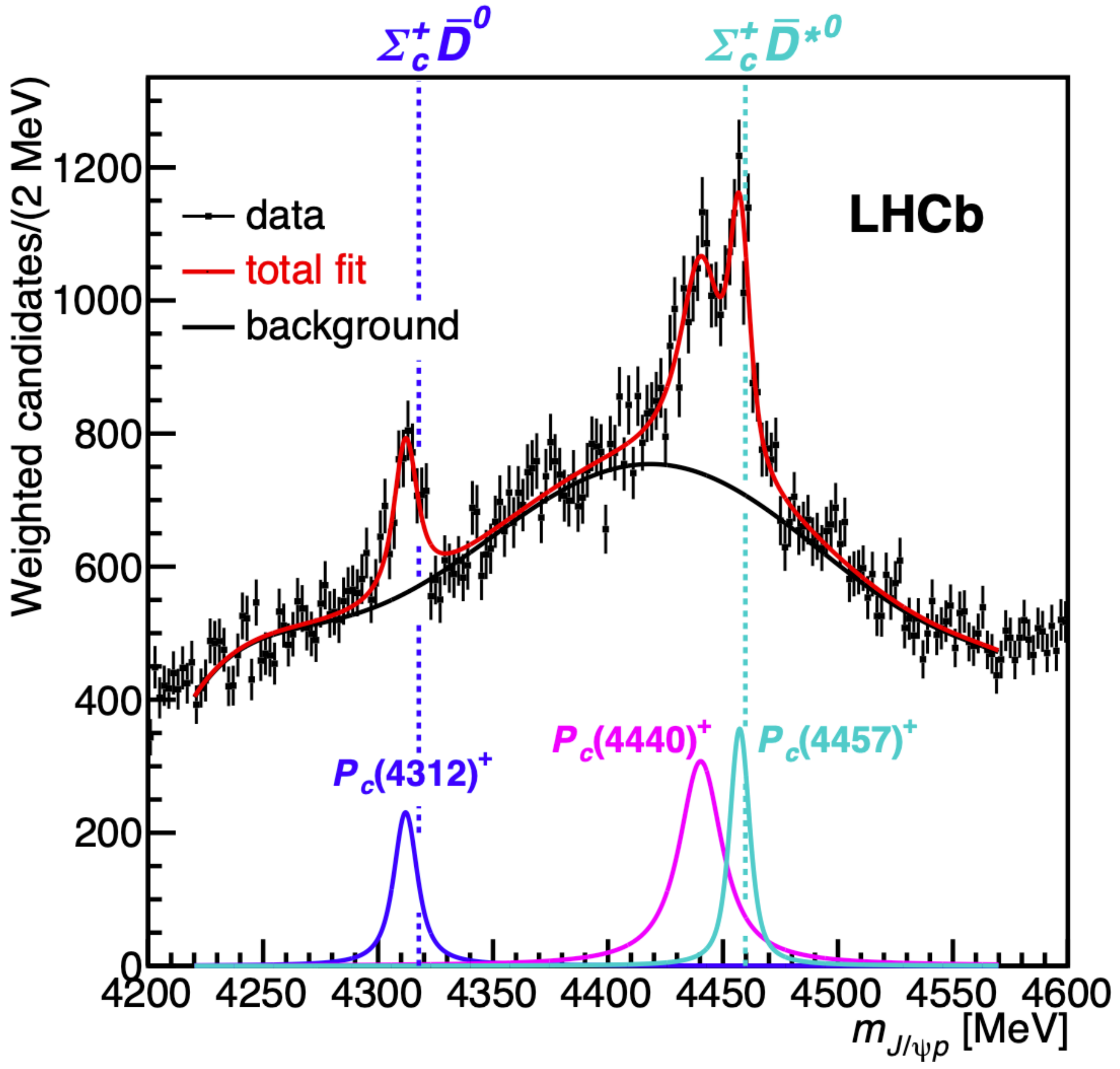
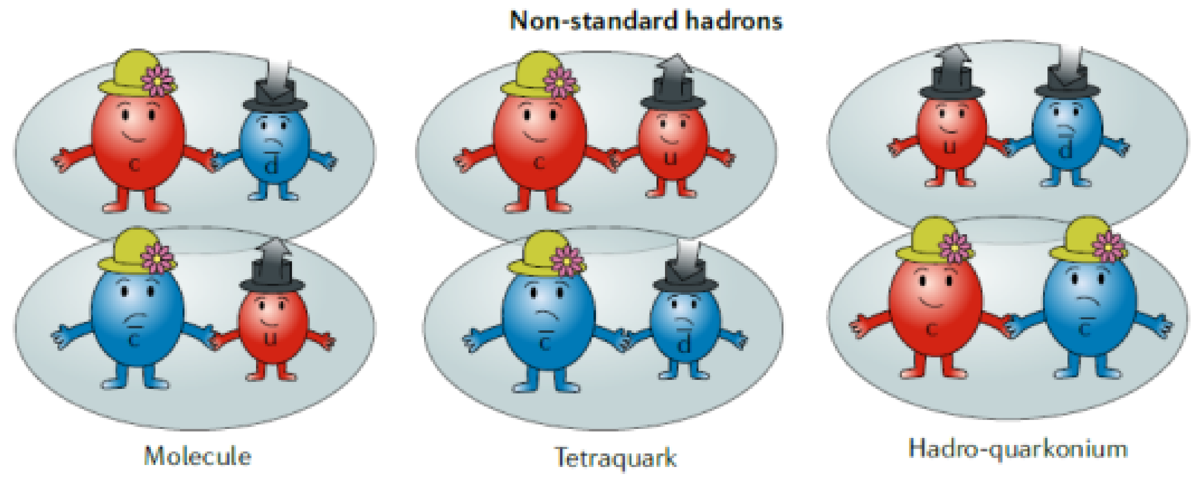
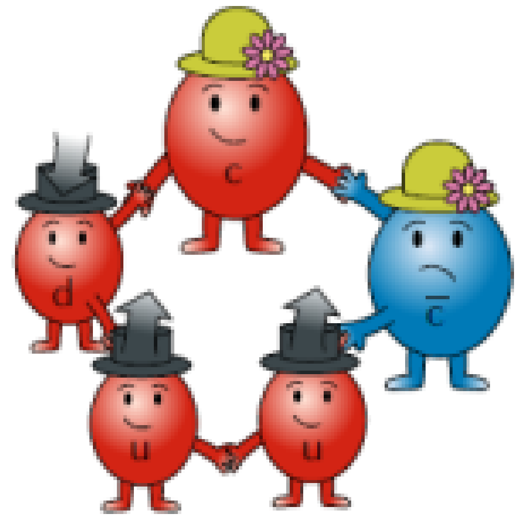




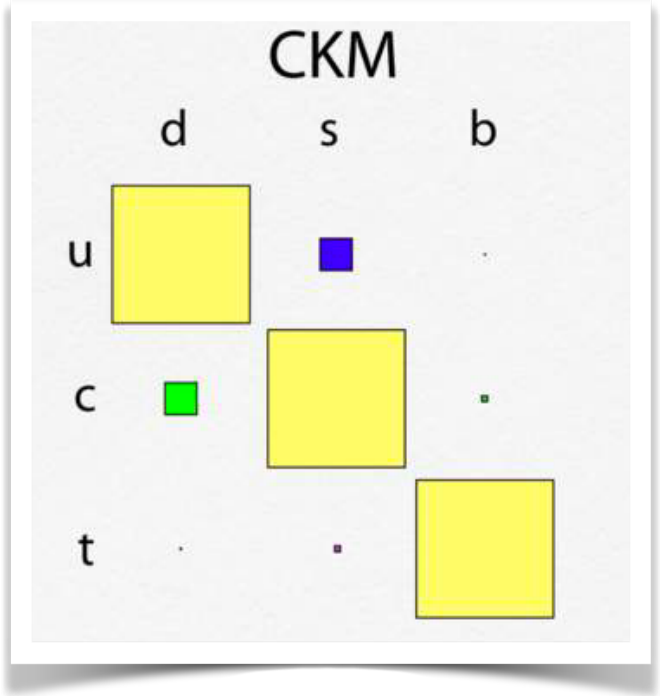




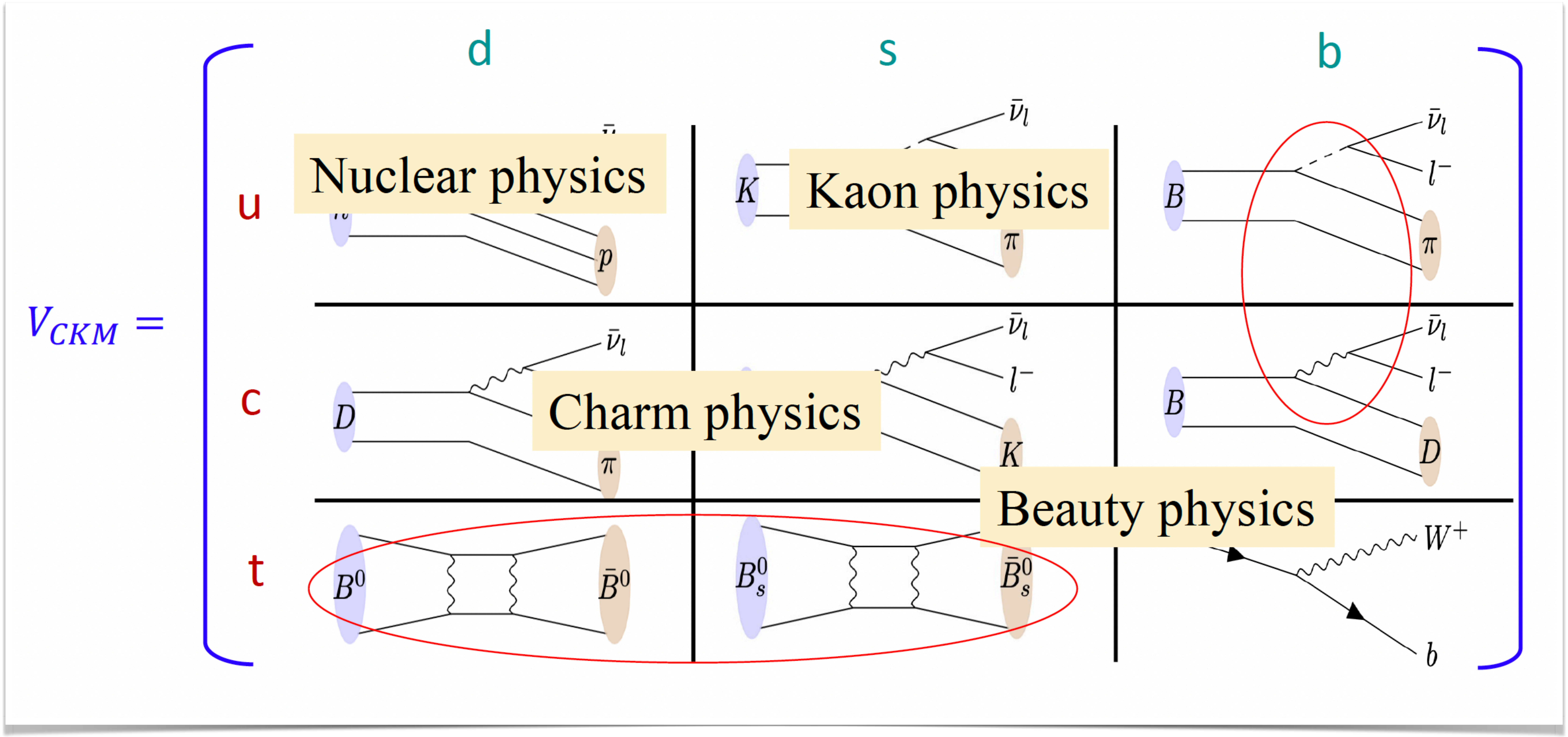
exotic states

CKM matrix

$$V_{\text{CKM}} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



Measurement of CKM matrix



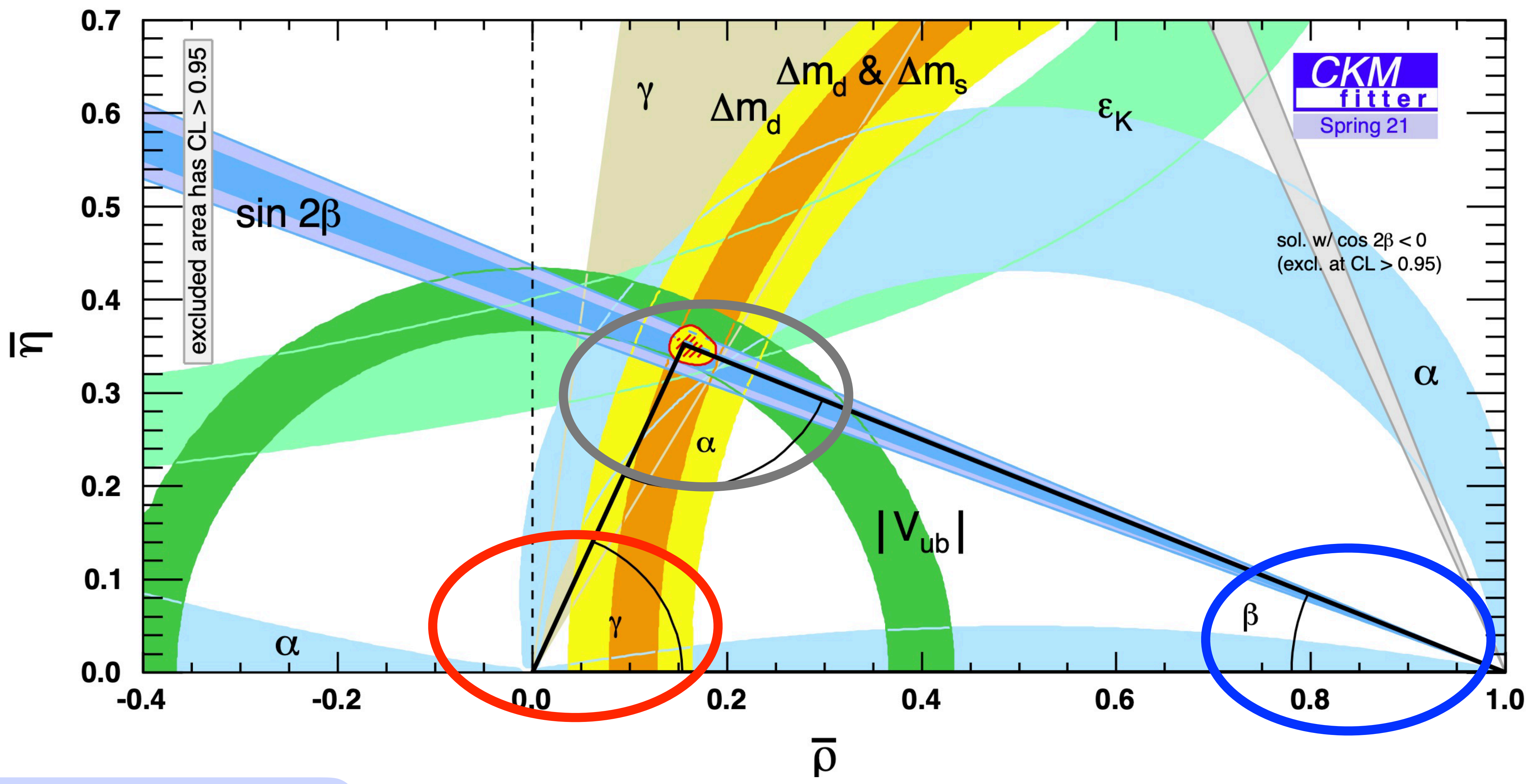
plot borrowed from Yanxi's talk

Measurements of CKM matrix

- Key test of the SM: Verify unitarity of CKM matrix
  - Magnitudes: branching fractions or mixing frequencies
  - Phases: CP violation measurement
- Sensitive probe for new physics

$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix} + \mathcal{O}(\lambda^5)$$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

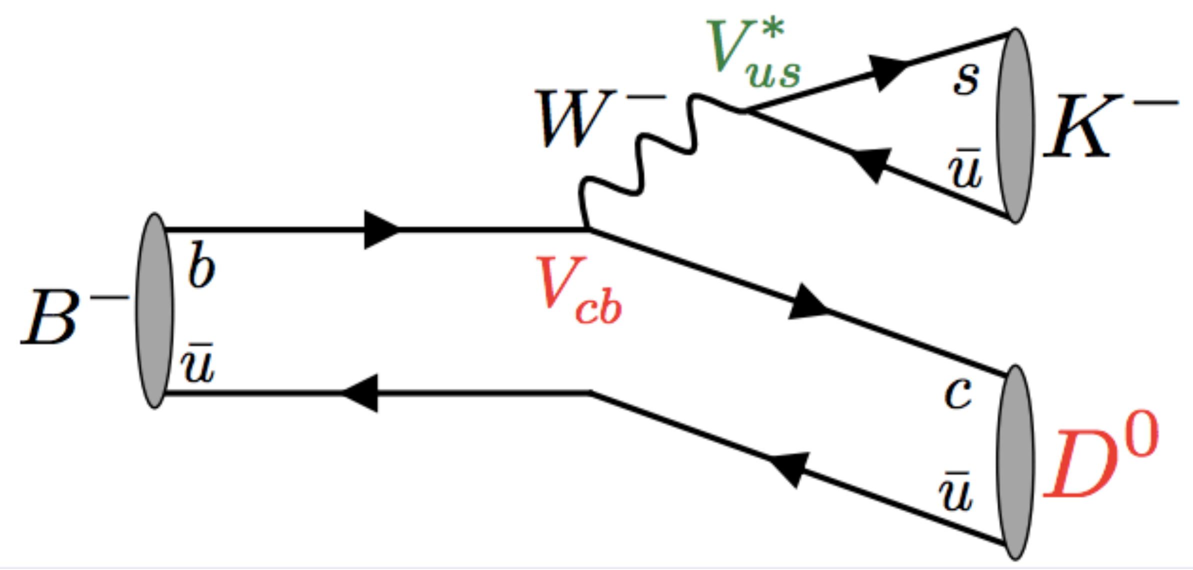


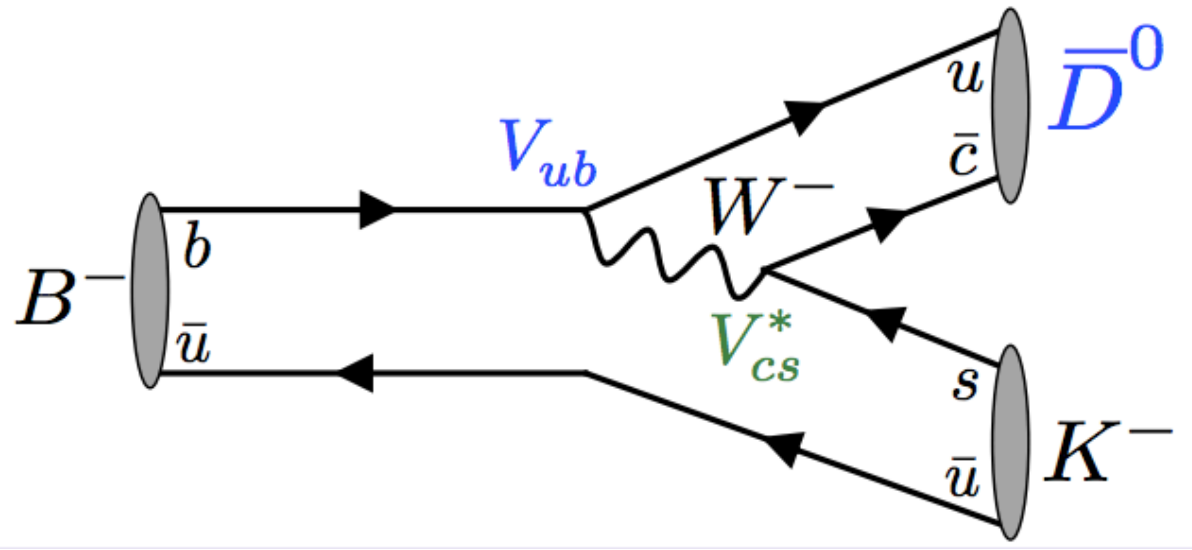
$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right), \beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right), \gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

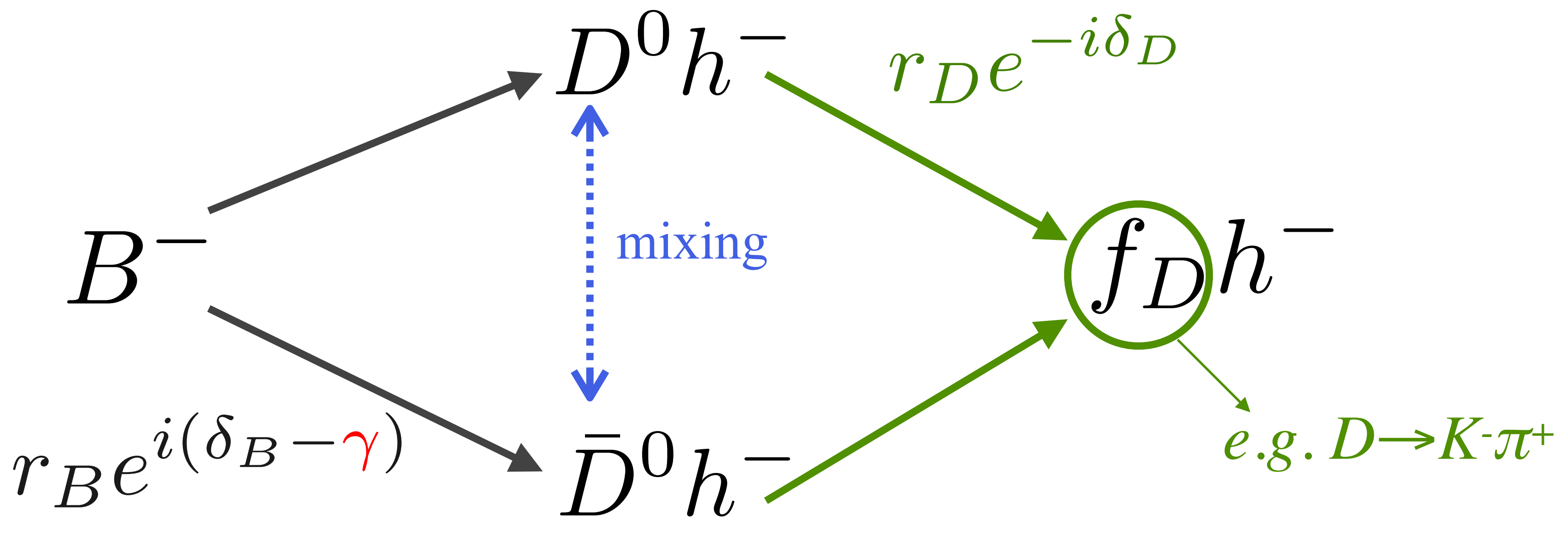
** More discussions later in the morning section on Tuesday*

γ measurements

- Relative weak phase γ in interference between $b \to c\bar{u}s$ and $b \to u\bar{c}s$ transition
- Measured with tree-level decays, theoretically clean observable ($\delta\gamma \sim 10^{-7}$)





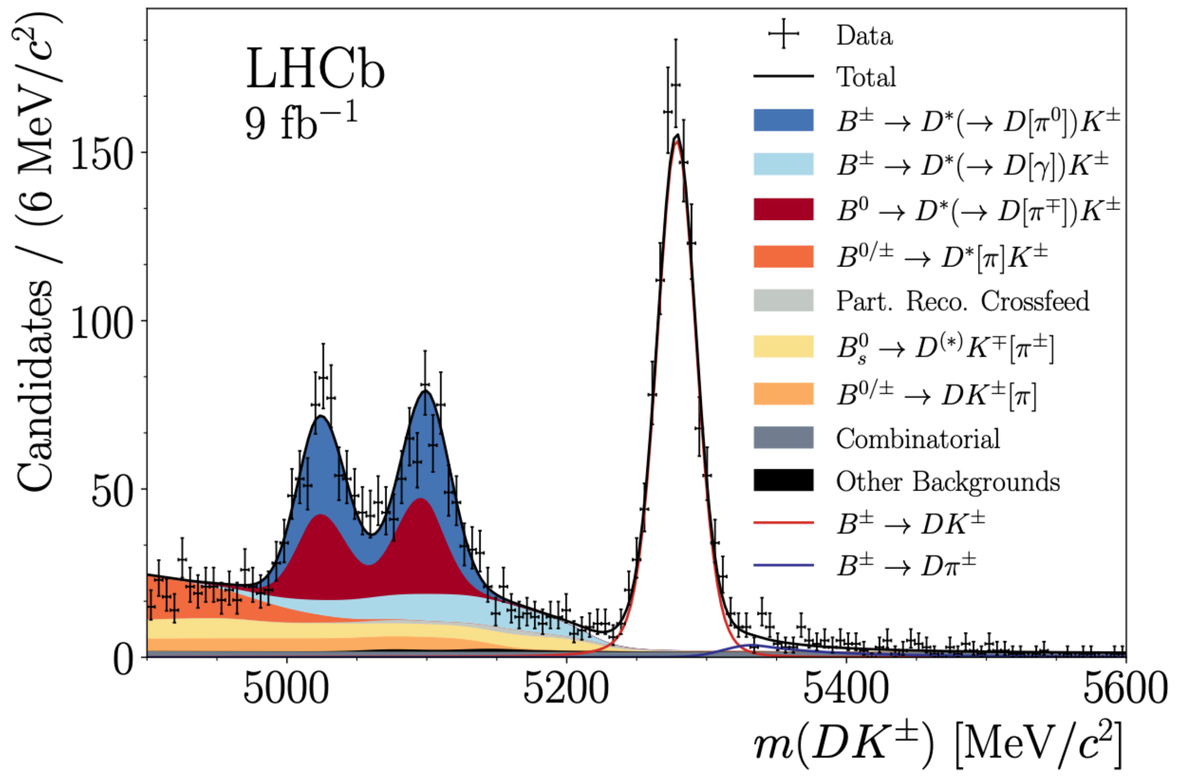


$$\Gamma(B^\pm \to Dh^\pm) \propto |r_De^{-i\delta_D} + r_Be^{i(\delta_B \pm \gamma)}|^2 \Rightarrow r_D^2 + r_B^2 + 2\kappa_D\kappa_B r_D r_B cos(\delta_B + \delta_D \pm \gamma)$$

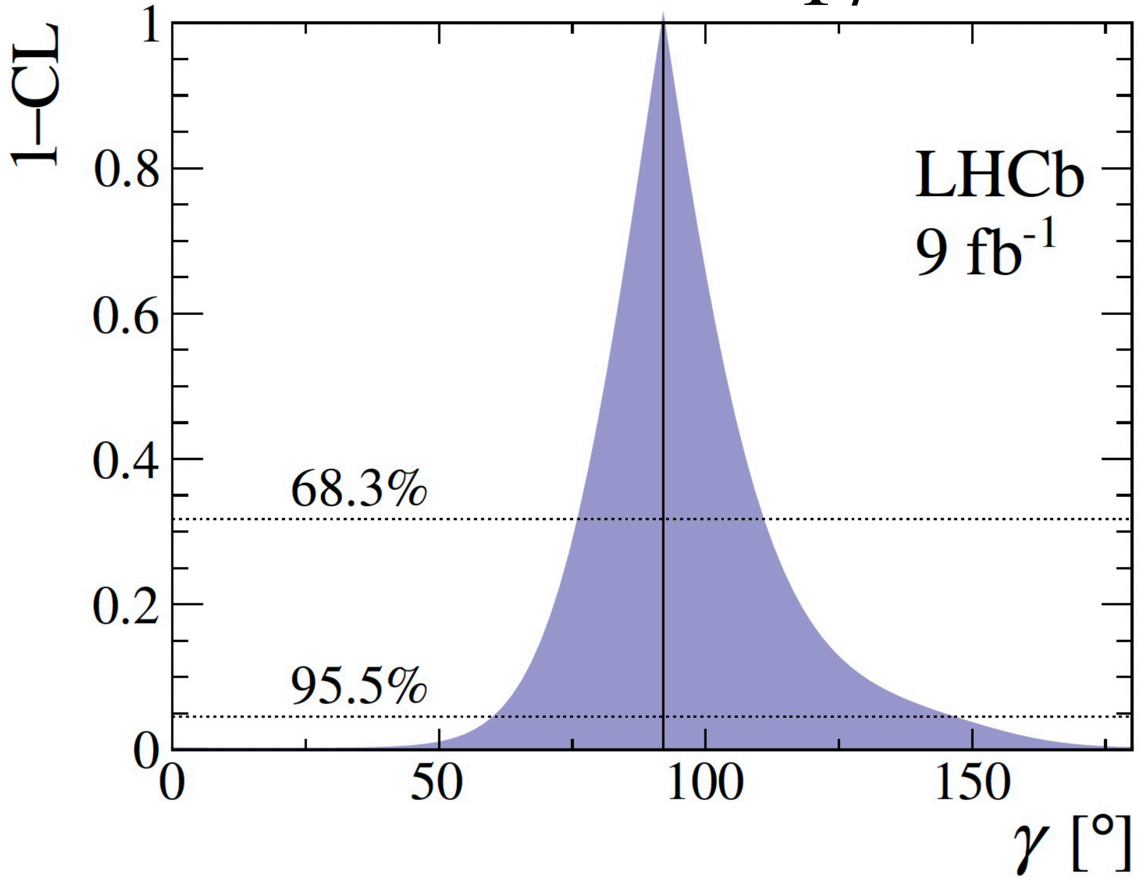
- Interference occurs when D^0 and $\bar{D}^0$ decay to the same final state f
  - ◇ GLW: CP eigenstates, e.g. $D \to KK$, $D \to \pi\pi$
  - ◇ ADS: CF or DCS decays, e.g. $D \to K\pi$
  - ◇ BPGGSZ: self-conjugated 3-body final states, GLW/ADS analysis across the D decay phase space, e.g. $D \to K_s^0\pi\pi$
  - ◇ Time-dependent: $B_s^0 \to D_s^- K^+$ & Dalitz: $B^0 \to \bar{D}^0 K^+ \pi^-$

γ measurements

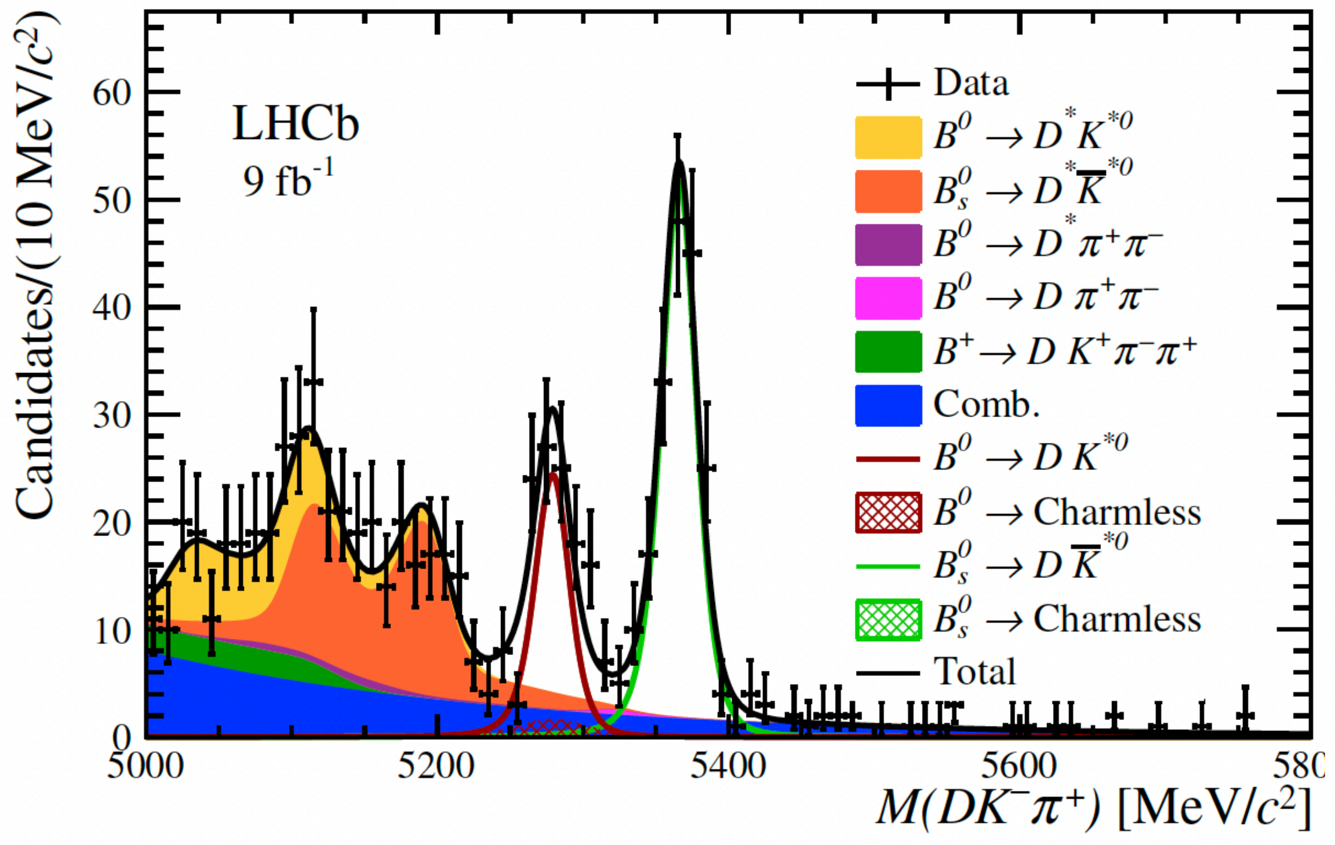
JHEP02(2024)118



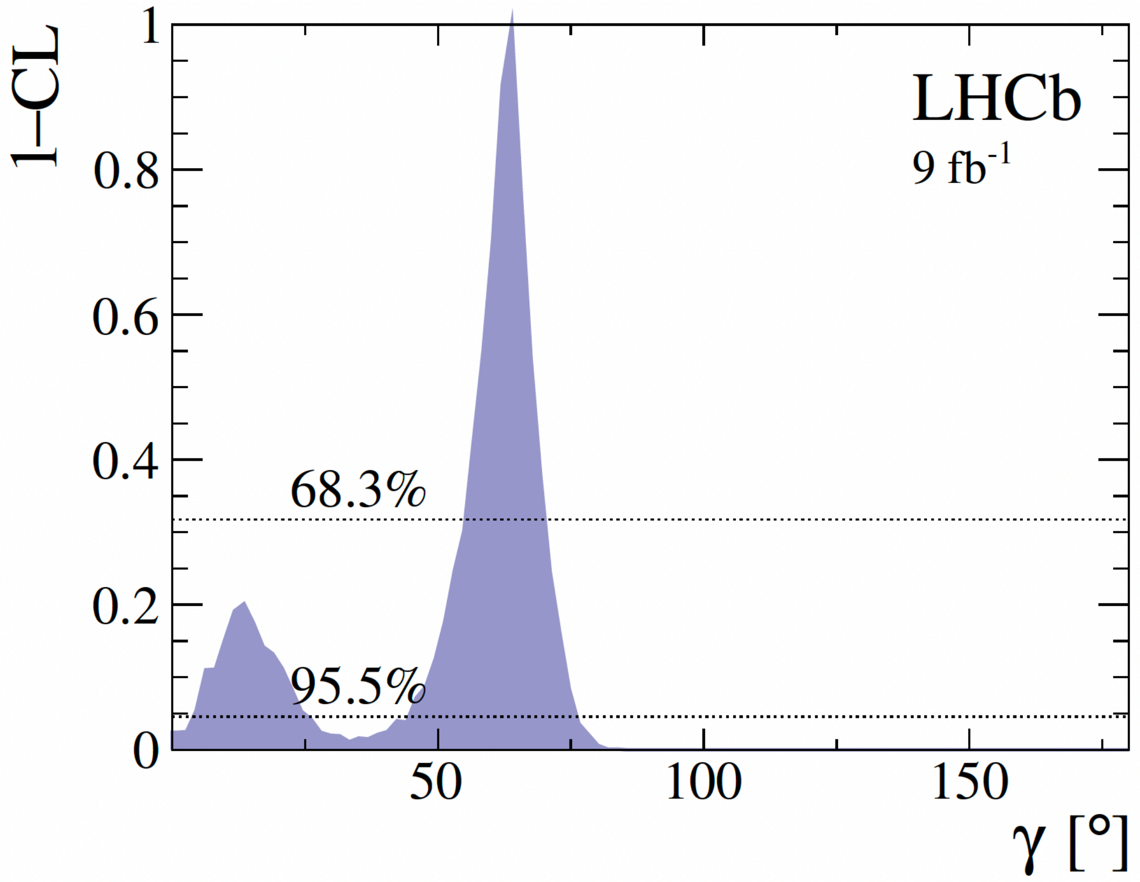
$\gamma = (92^{+21}_{-17})^\circ$



JHEP05(2024)025



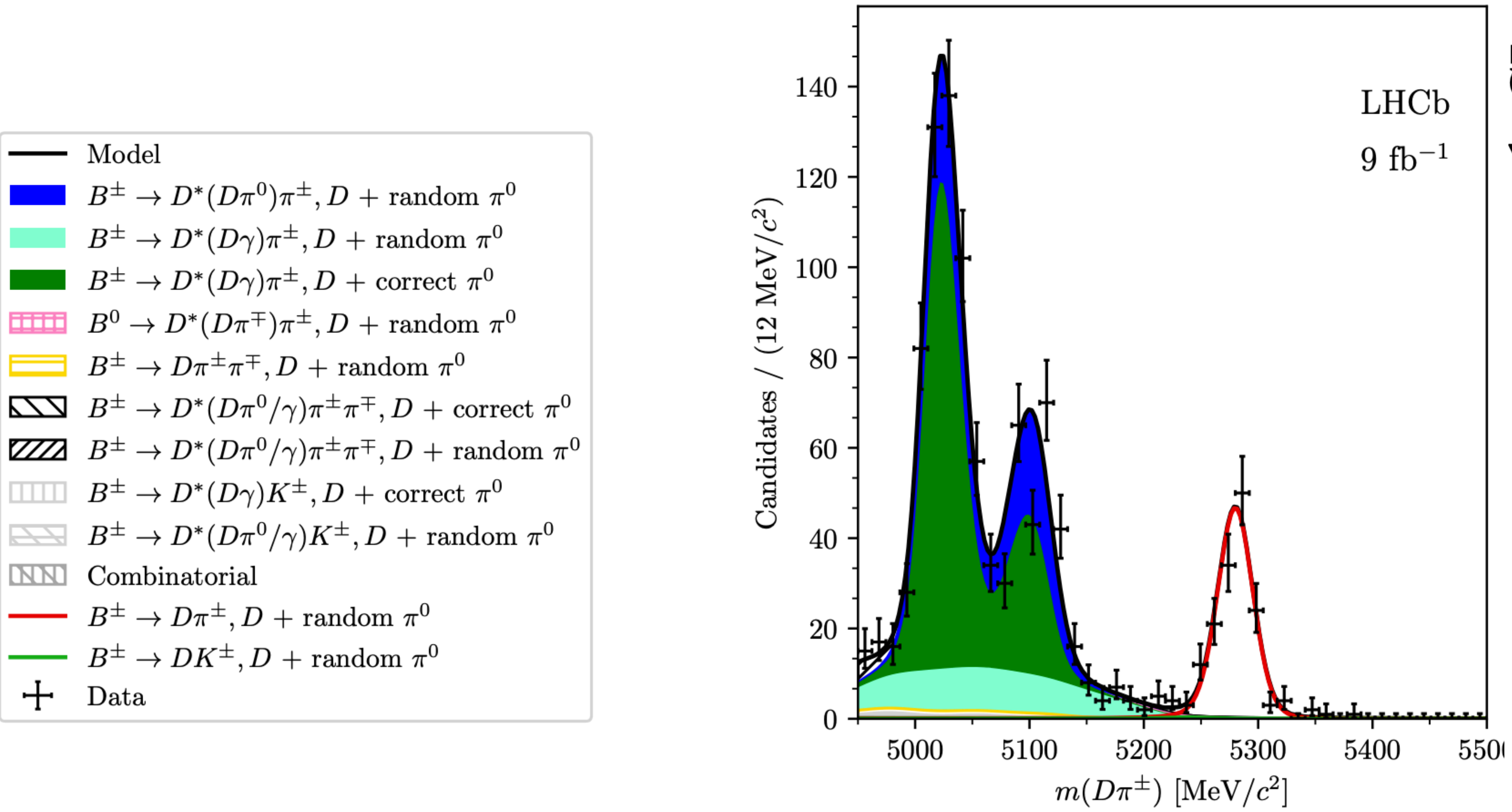
$\gamma = (63.2^{+6.9}_{-8.1})^\circ$



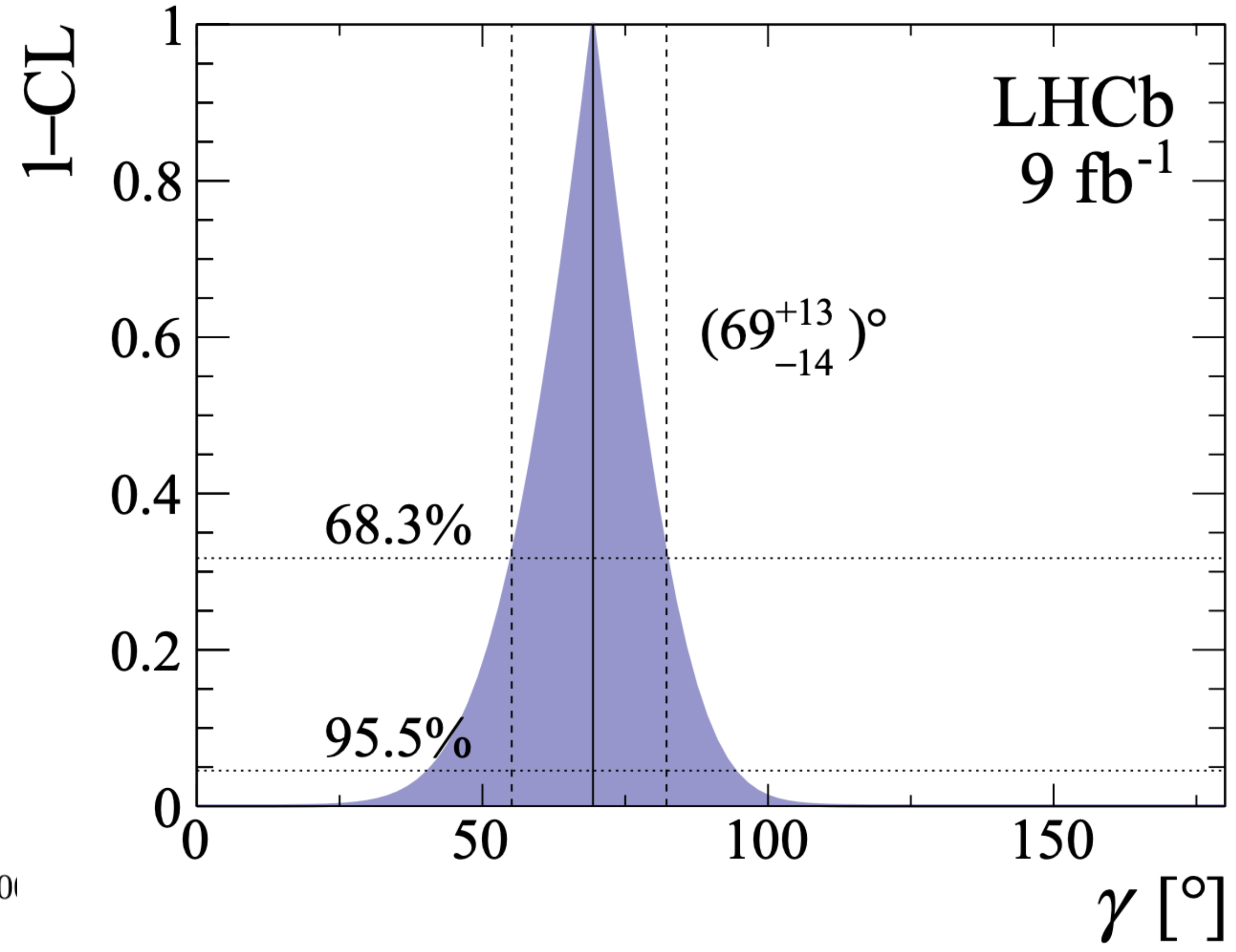
Partial reco. $B^\pm \to D^{*0}h^\pm$ with $D^{*0} \to D(\to K^0_S hh)\gamma/\pi^0$

$B^0 \to D^0 K^*(892)^0$ with $D \to hh$ & $4h$ & $K^0_S hh$

JHEP12(2023)013, *Lei Hao, Wenbin Qian etc*



Full reconstruction of $B^\pm \to D^{*0}K^\pm$ with $D^{*0} \to D(\to K^0_S hh)\gamma/\pi^0$

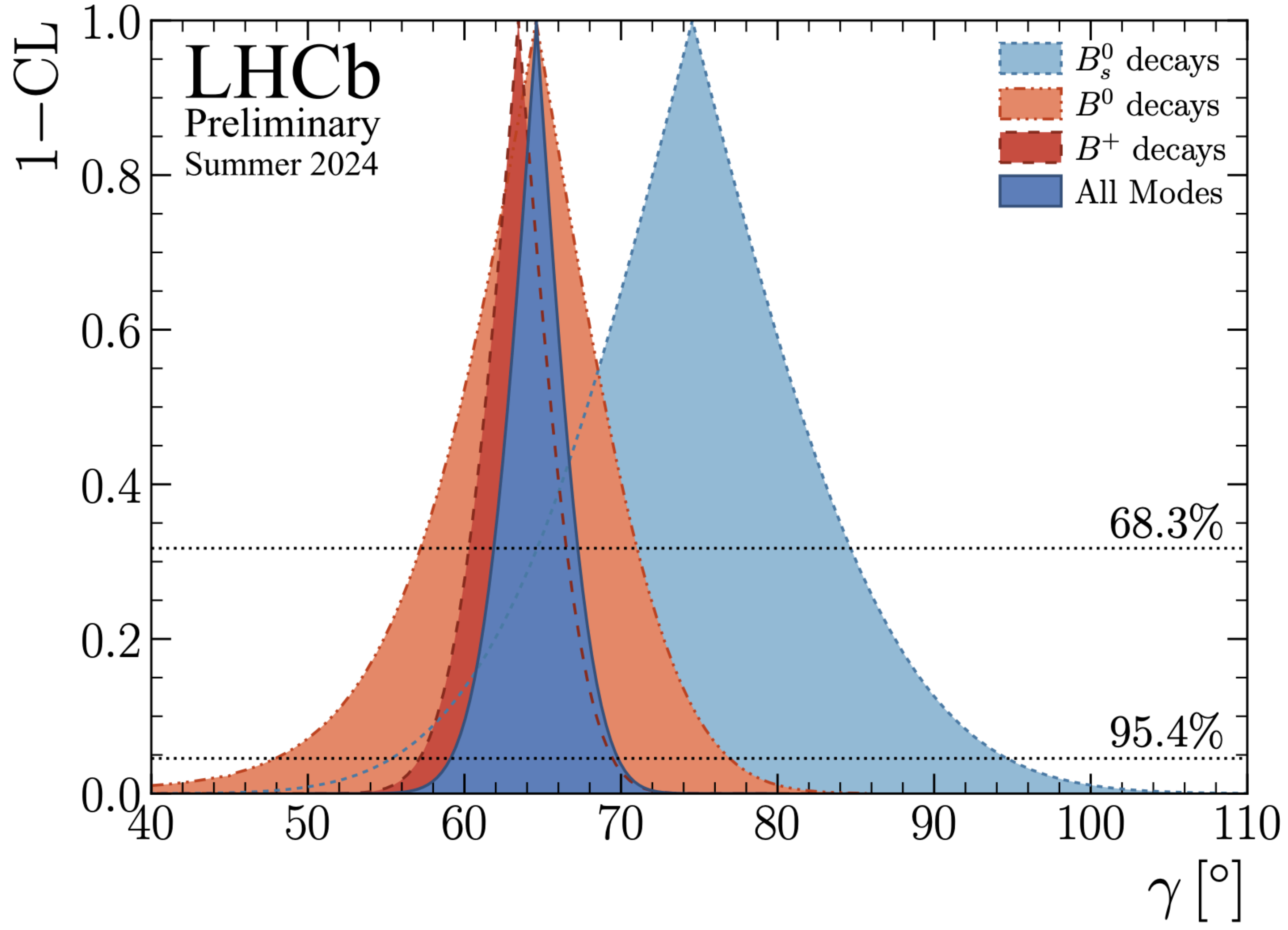


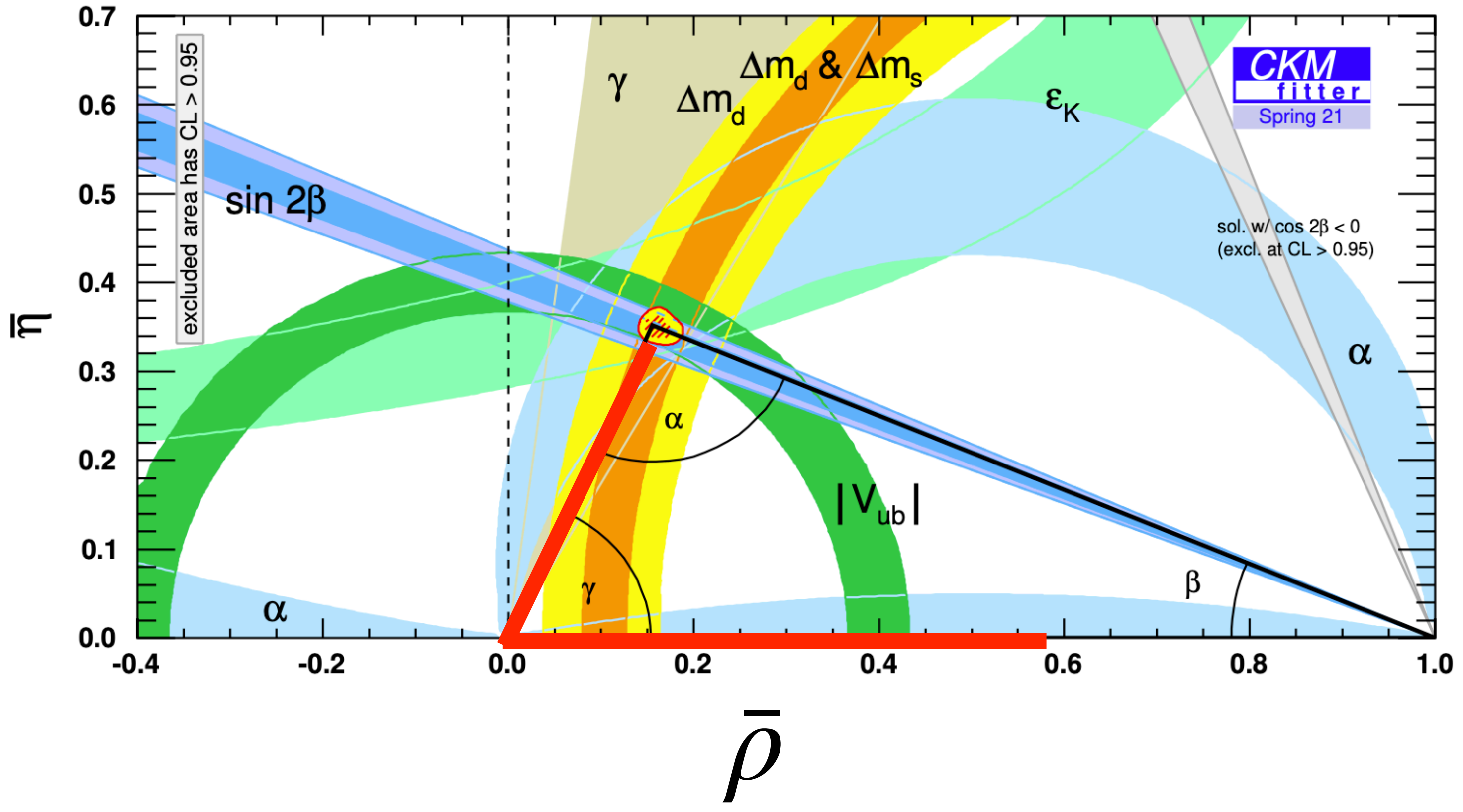
$\gamma = (69^{+13}_{-14})^\circ$

Latest γ combination

LHCb-CONF-2024-004

$$\gamma = (64.6 \pm 2.8)^\circ$$

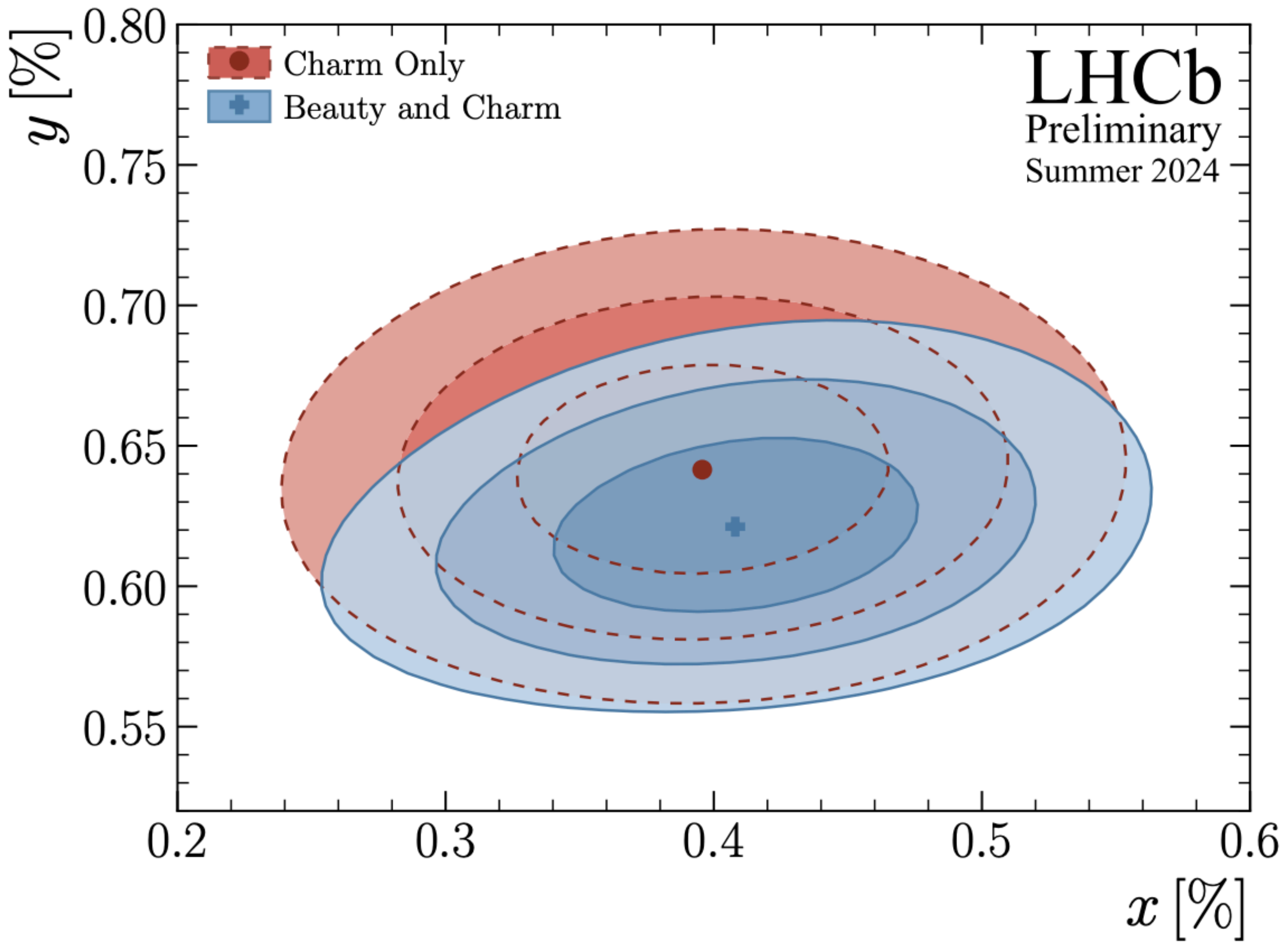


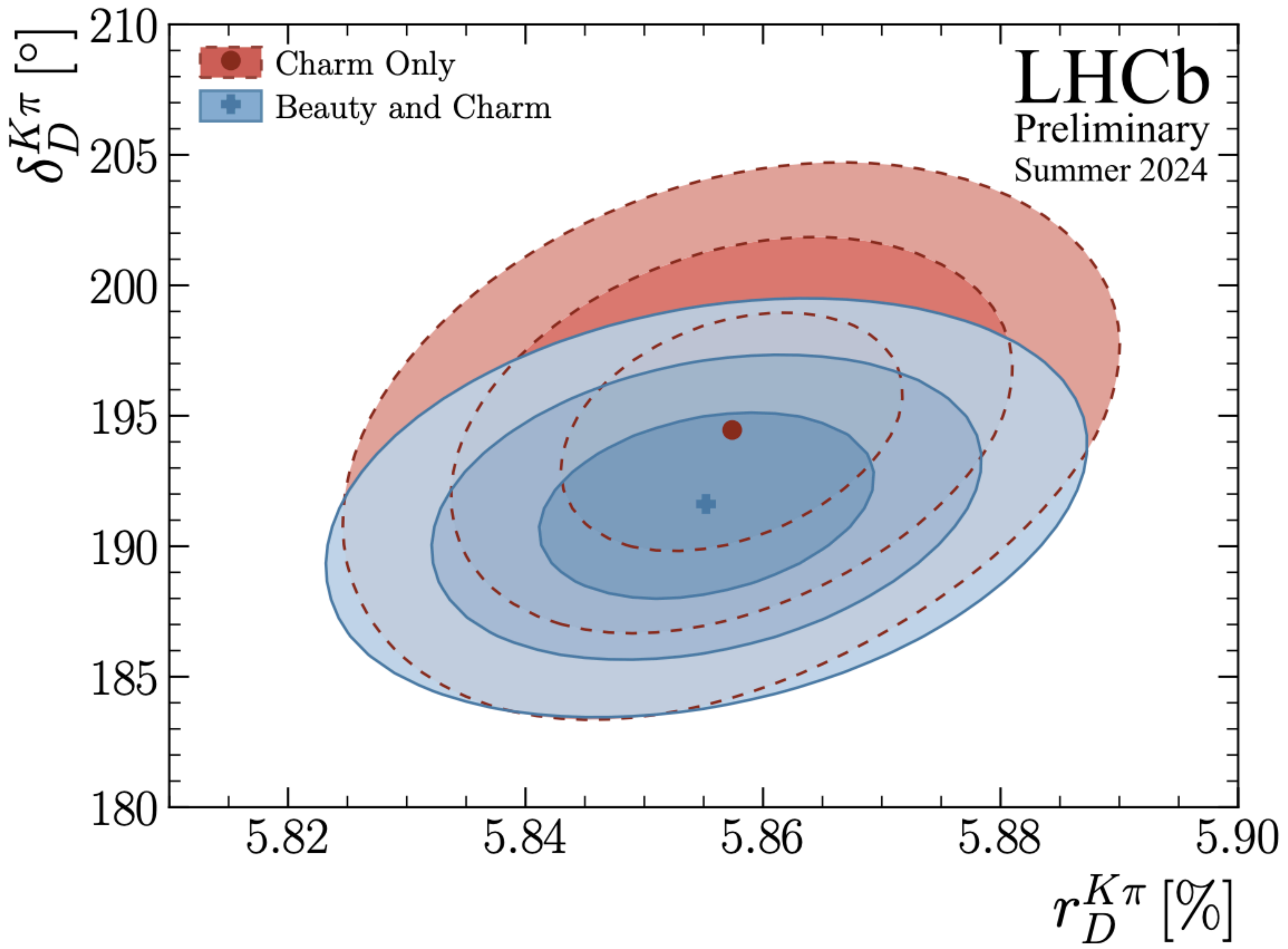


- A combination of all measurements of γ and $D^0 - \bar{D}^0$ mixing and CP asymmetries including 9 new results
- 20% improved precision w.r.t previous combination, consistent with global CKM fit predictions $(65.5^{+0.09}_{-2.65})^\circ$

$$x = (0.41 \pm 0.05)\,\% \qquad |q/p| = 0.989 \pm 0.015$$

$$y = (0.621^{+0.022}_{-0.021})\,\% \qquad \delta_D^{K\pi} = (191.6^{+2.5}_{-.4})^\circ$$



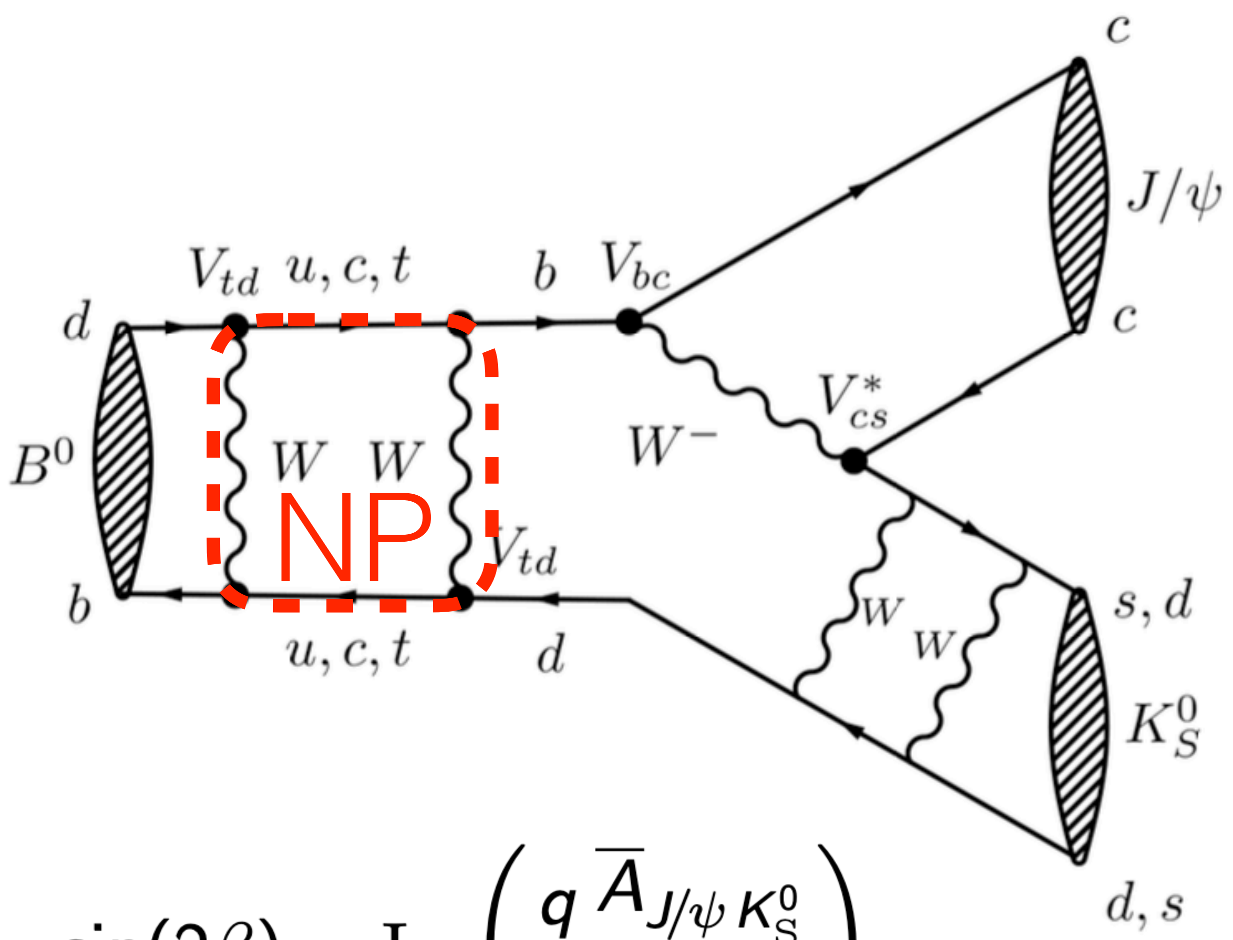


**Find more details for γ measurements in Xiaokang's talk on Tuesday*

$\sin 2\beta$

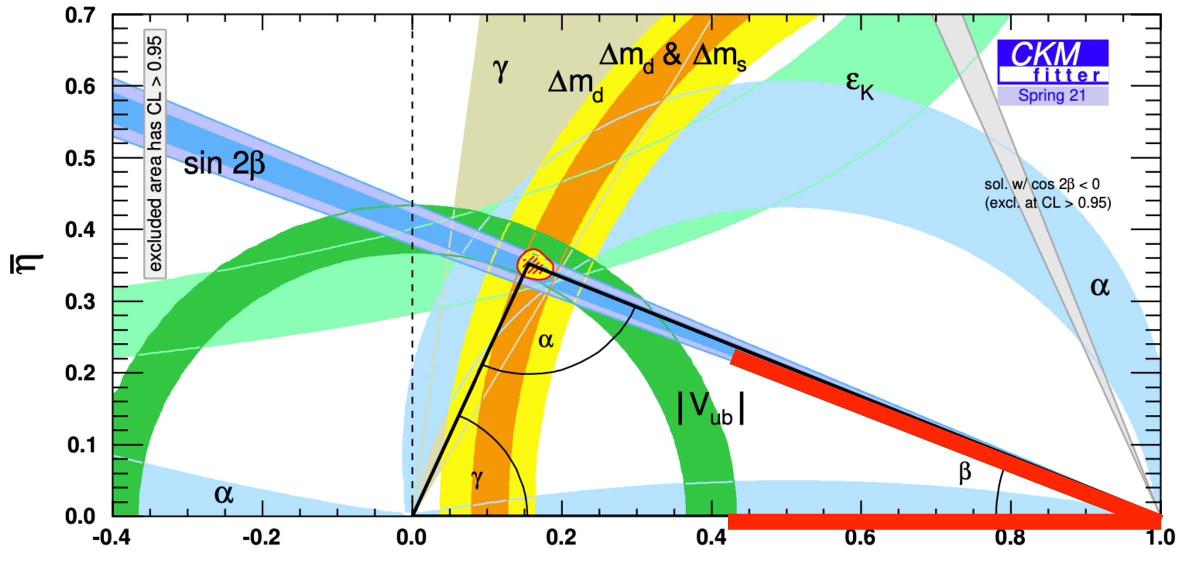
Phys. Rev. Lett. 132 (2024) 021801

- Decay mode $B^0 \to \psi K_S^0$ *(CP-odd only)* offers a theoretically clean access to the CKM angle β



$$\sin(2\beta) = \mathrm{Im}\left(\frac{q}{p}\frac{\bar{A}_{J/\psi K_S^0}}{A_{J/\psi K_S^0}}\right)$$

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



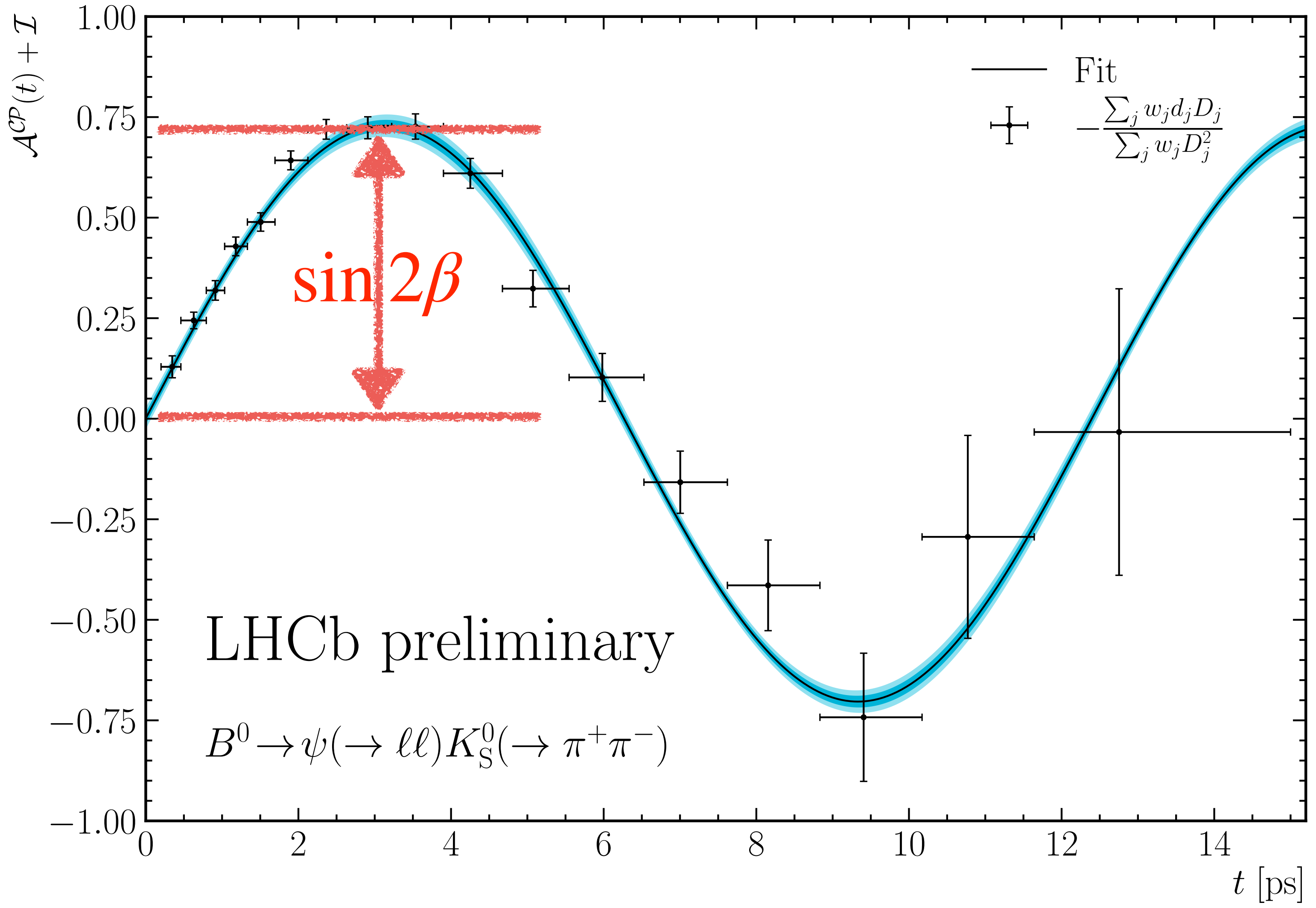
$\sin(2\beta) \neq 0 \Rightarrow$ *CP* violation

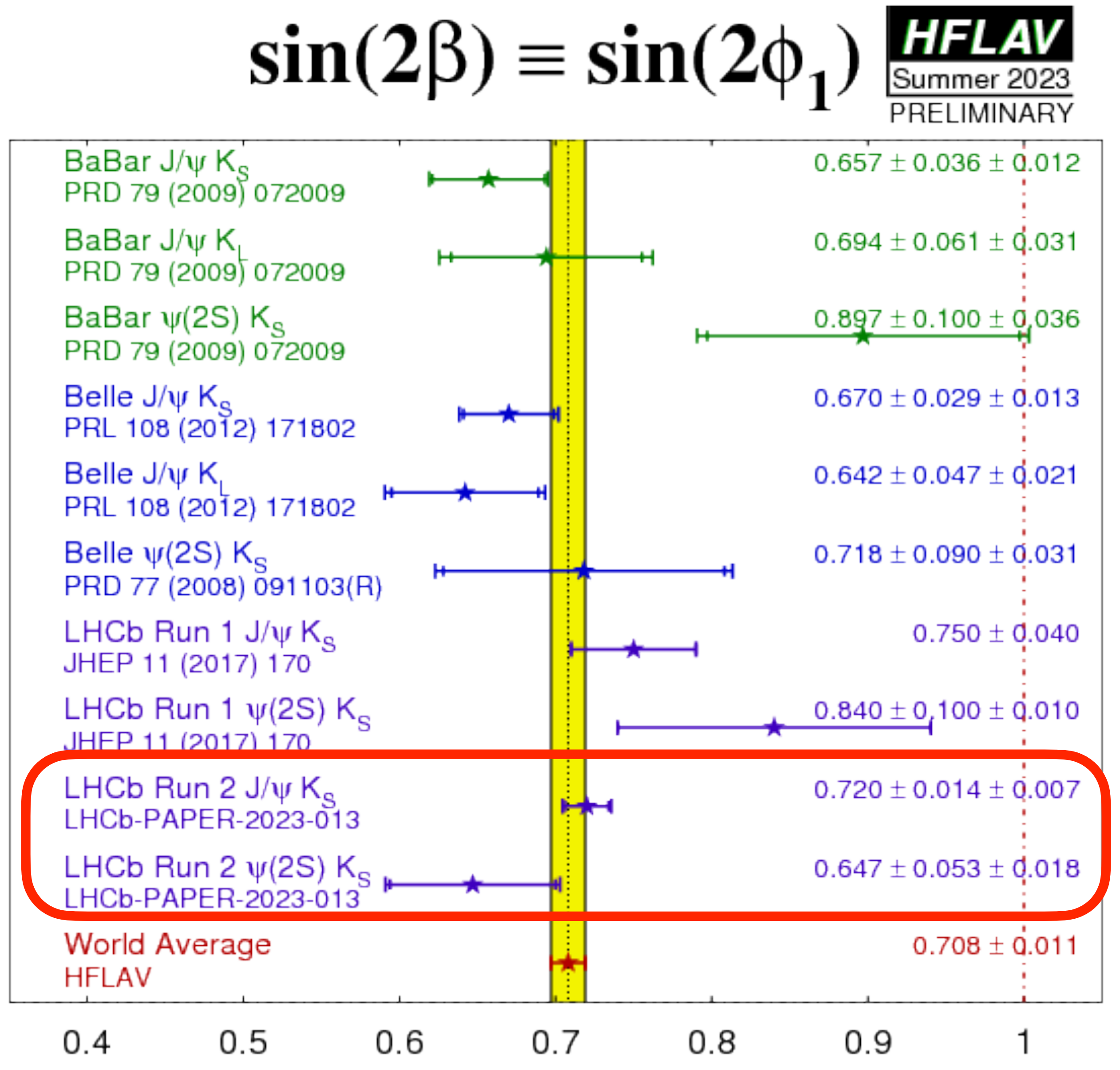
$$A_{CP}(t) = \frac{\Gamma_{\bar{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\bar{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} \propto -\eta_f \cdot \sin 2\beta \cdot \sin(\Delta m_s t)$$

- Consistent with other measurements, still statistical uncertainty limited
- LHCb results dominate the latest World Average

$$S_{\psi K_S^0}^{\text{Run 2}} = 0.716 \pm 0.013 \pm 0.008$$

$$C_{\psi K_S^0}^{\text{Run 2}} = 0.012 \pm 0.012 \pm 0.003$$





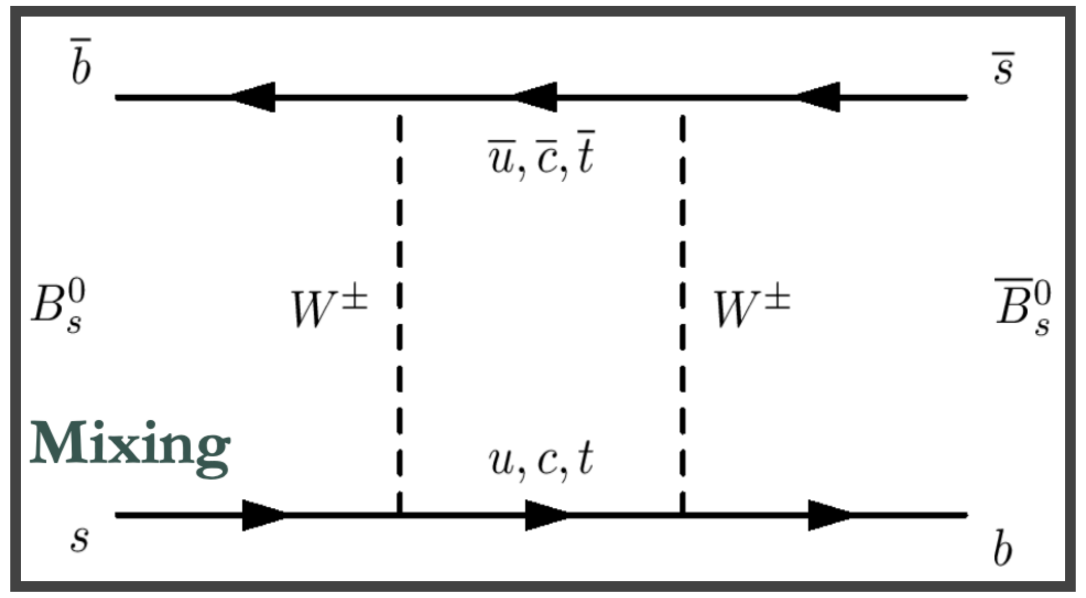
ϕ_s

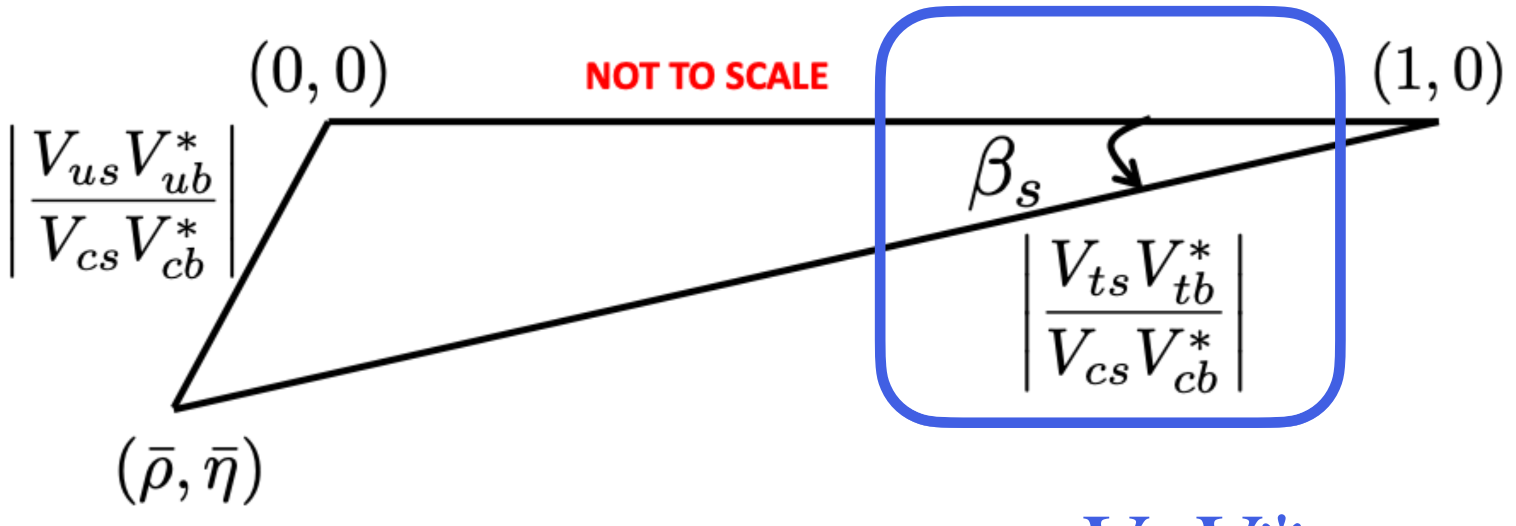
[Phys. Rev. Lett. 132 (2024) 051802](#)

P. Li, Kechen Li, etc

- SM predicts: $\phi_s^{CKMFitter} \approx -2\beta_s = (-0.0368^{+0.0006}_{-0.0009})$ rad
  - Highly suppressed than in B^0 system (β ~22°)
  - Golden mode: $B_s^0 \to J/\psi\phi$

$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$





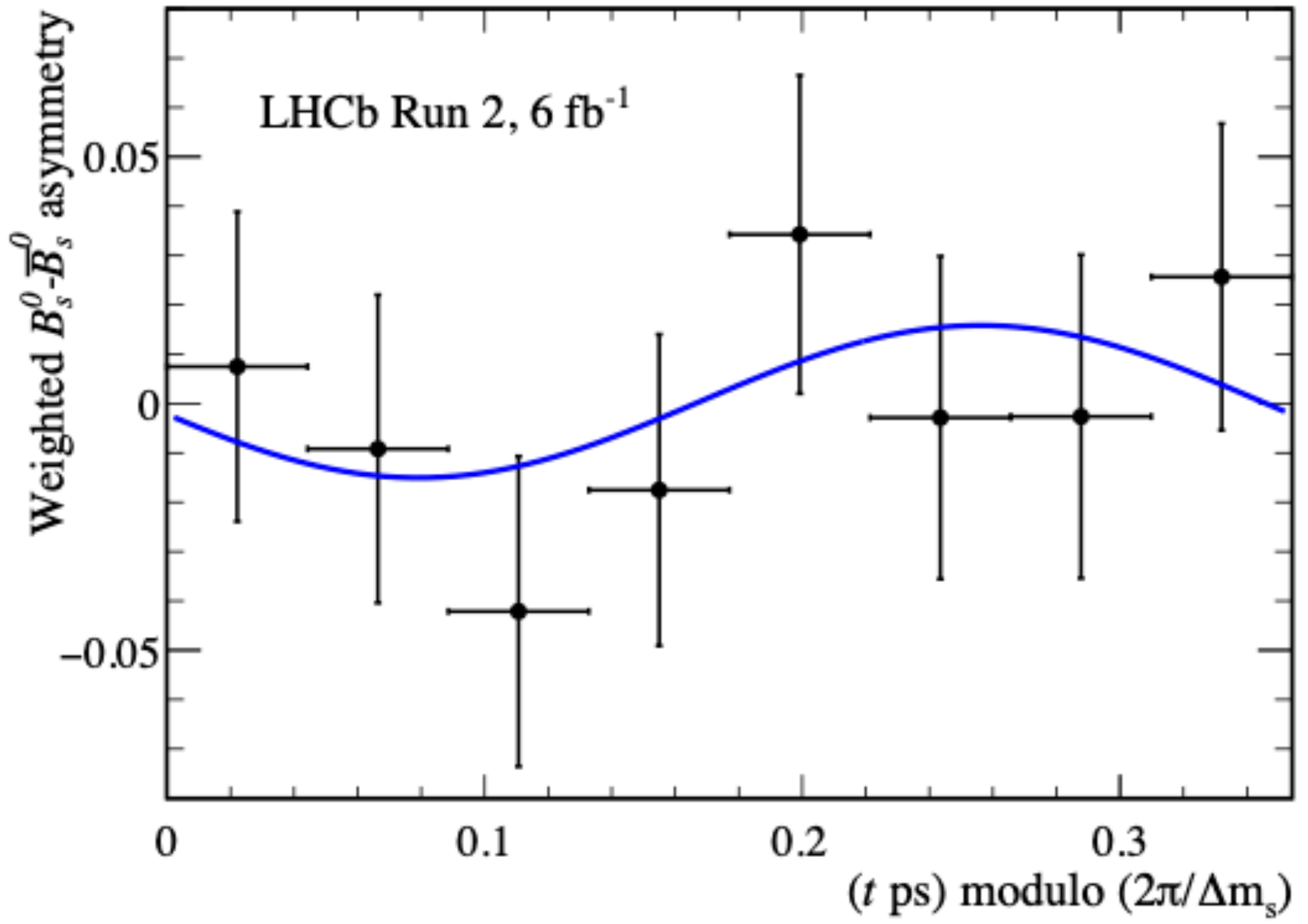
$$\phi_s \approx -2\beta_s = 2arg(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*})$$

(ignoring penguin contribution)

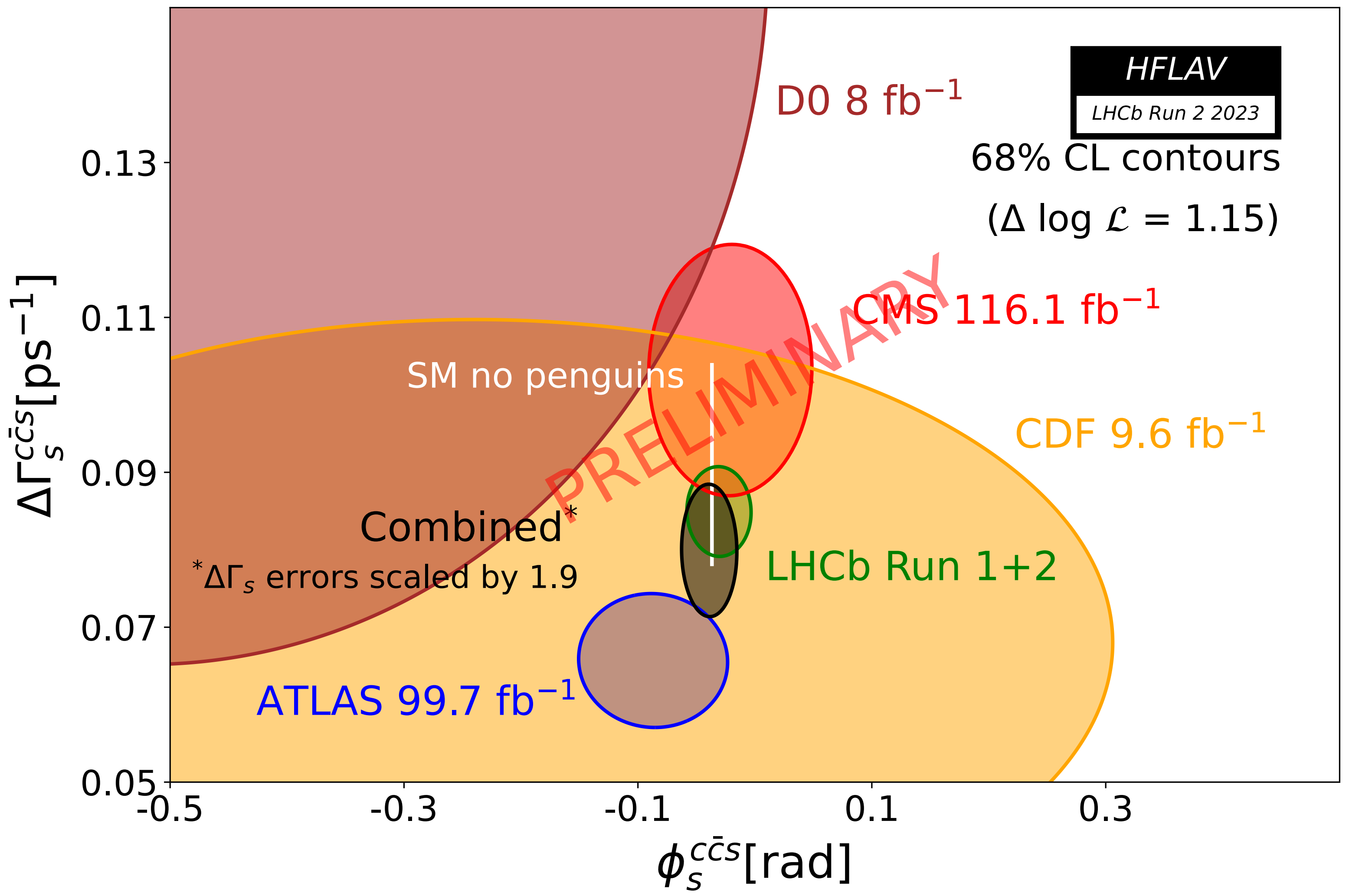
$$A_{CP}(t) = \frac{\Gamma_{\bar{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\bar{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} \propto -\eta_f \cdot \sin\phi_s \cdot \sin(\Delta m_s t)$$

- World-best measurements, consistent with SM predictions
- Still statistical limited

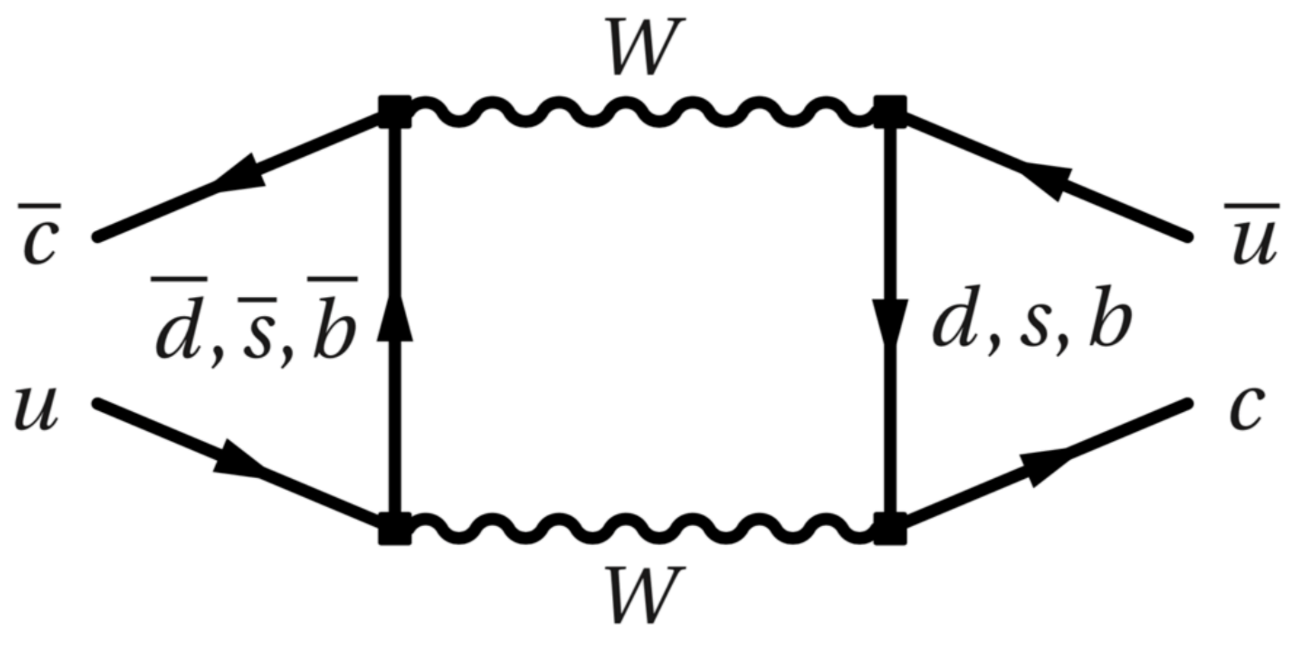
LHCb combination:
$\phi_s^{c\bar{c}s} = -0.031 \pm 0.018$ rad



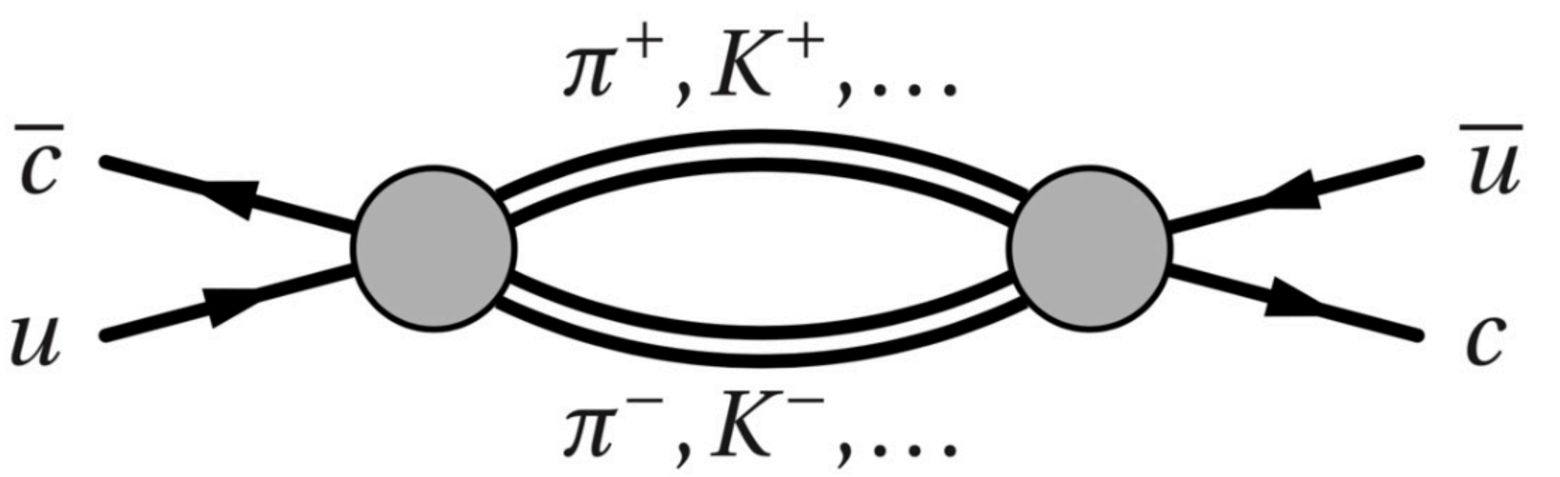
New World Average:
$\phi_s^{c\bar{c}s} = -0.050 \pm 0.016$ rad



CP violation in charm sector



- GIM mechanism very effective for charm decays, SM loops highly suppressed
- Tiny weak phases in first two generations of CKM matrix (< λ_b~ 0.1%)
- Oscillation and CPV ($\lesssim 10^{-3}$)
- Long distance contribution comparable/larger than short distance



Breakthroughs by LHCb thanks to huge statistics:

First observation of CPV in $D^0 \to h^+h^-$ decays

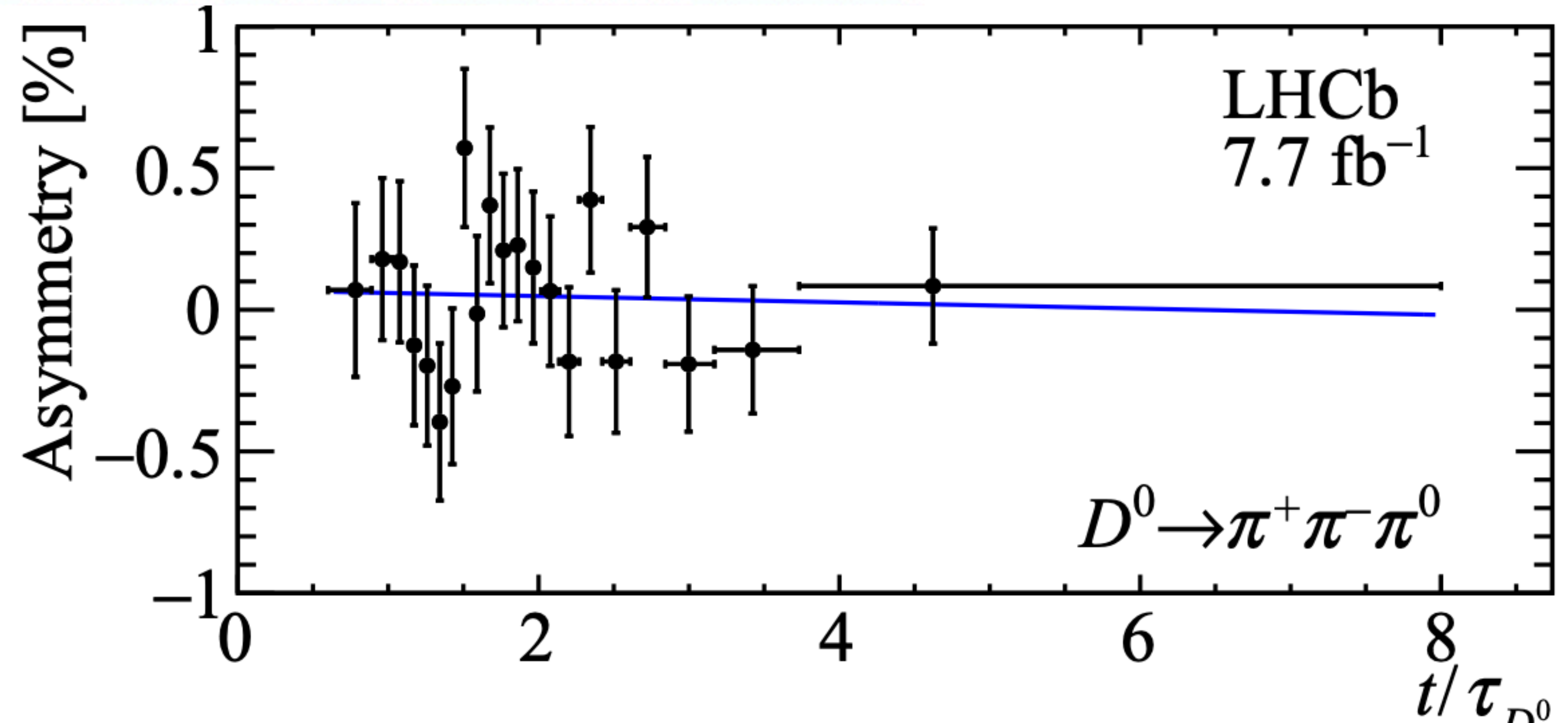
$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-15.4 \pm 2.9)\times 10^{-4}$ [PRL(2019)211803]

Evidence of CPV in $D^0 \to \pi^+\pi^-$ decay

$A_{CP}(\pi^+\pi^-) = (23.2 \pm 6.1)\times 10^{-4}$ (3.8σ) [PRL(2023)211803]

- First measurement of time-dependent CP violation in SCS mode $D^0 \to \pi^+\pi^-\pi^0$
- $\Delta Y \equiv \eta_{CP}\Delta Y_{f_{CP}} = (-1.3 \pm 6.3 \pm 2.4) \times 10^{-4}$, constant with world average, no CPV

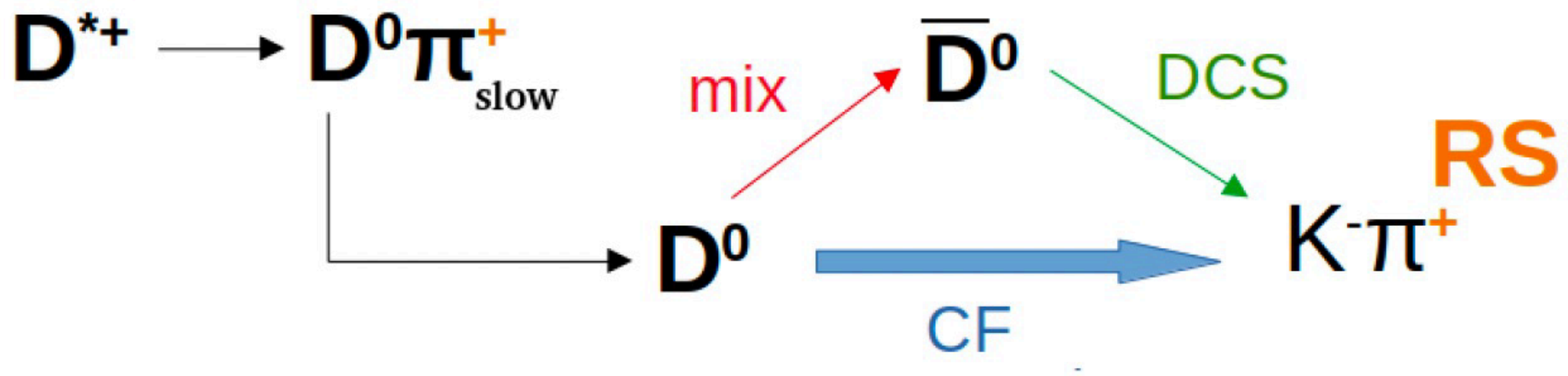
arXiv:2405.06556

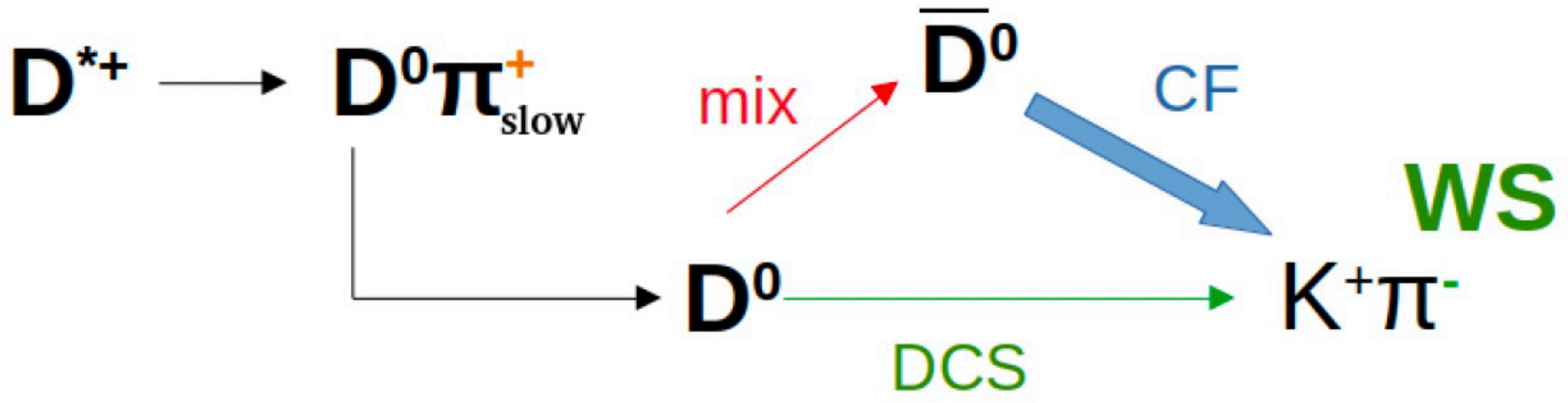


Time-dependent CP violation in $D^0 \to K\pi$

LHCb-PAPER-2024-008

- Interference between mixing and decay for favoured RS and suppressed WS decays





$$R^{+}_{K\pi} = \frac{\Gamma(D^0(t) \to K^+\pi^-)}{\Gamma(\overline{D^0} \to K^-\pi^+)}; \quad R^{-}_{K\pi} = \frac{\Gamma(\overline{D^0}(t) \to K^-\pi^+)}{\Gamma(D^0 \to K^+\pi^-)};$$

DCS over CF amplitude

$$R^{\pm}_{K\pi}(t) \approx \boxed{R_{K\pi}}(1 \pm A_{K\pi}) + R_{K\pi}(1 \pm A_{K\pi})(c_{K\pi} \pm \Delta c_{K\pi})\left(\frac{t}{\tau_{D^0}}\right) + (c'_{K\pi} \pm \Delta c'_{K\pi})\left(\frac{t}{\tau_{D^0}}\right)^2$$

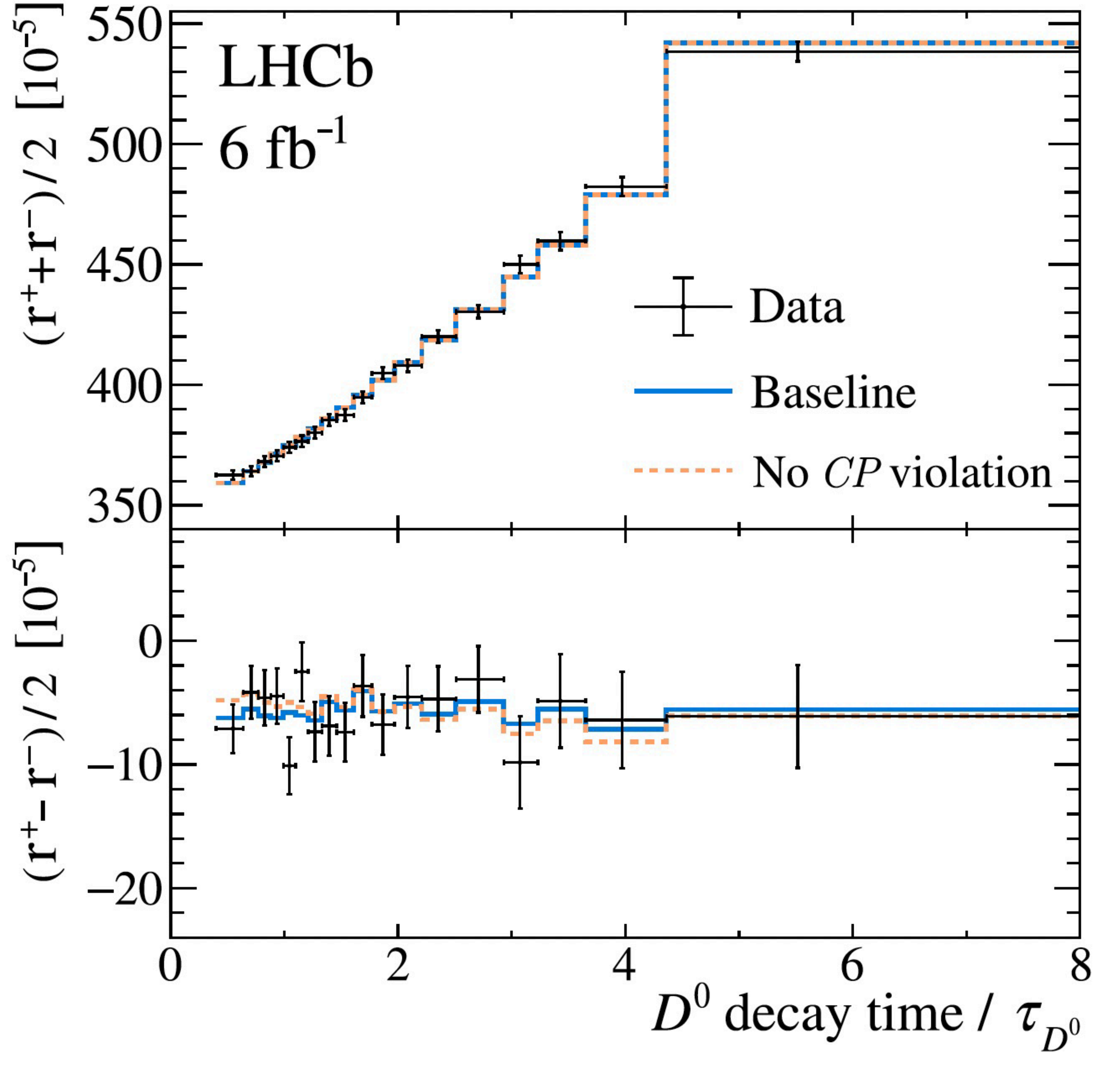
CPV observables: $A_{K\pi}$ (in decays), $\Delta c_{K\pi}$ (in interference), $\Delta c'_{K\pi}$ (in mixing).

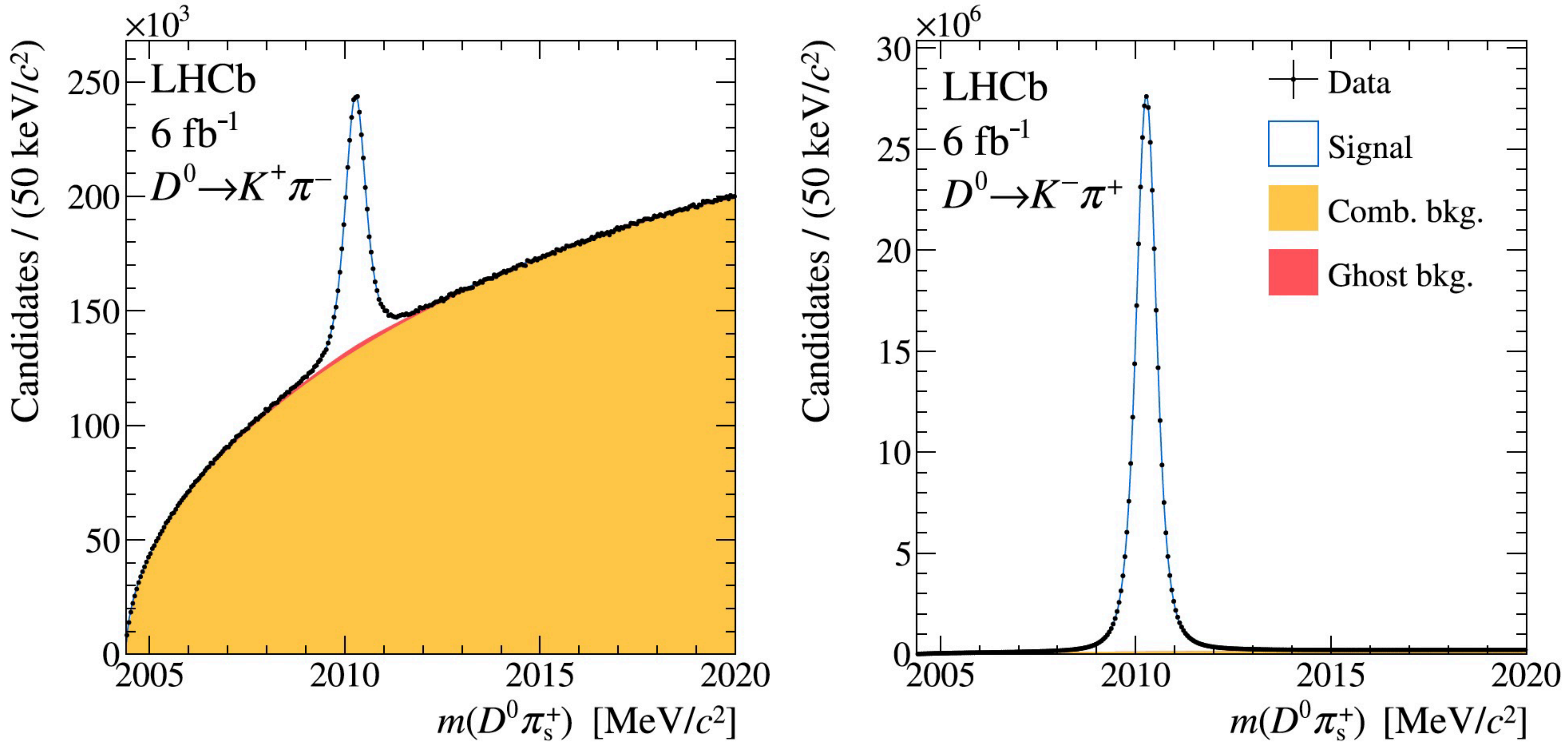
Mixing observables: $c_{K\pi}$, $c'_{K\pi}$

Time-dependent CP violation in $D^0 \to K\pi$

arXiv:2407.18001

- Measured with yields: RS ~400 M, WS ~1.6 M





$R_{K\pi}$	$(343.1 \pm 2.0) \times 10^{-5}$
$c_{K\pi}$	$(51.4 \pm 3.5) \times 10^{-4}$
$c'_{K\pi}$	$(13.1 \pm 3.7) \times 10^{-6}$
$A_{K\pi}$	$(-7.1 \pm 6.0) \times 10^{-3}$
$\Delta c_{K\pi}$	$(3.0 \pm 3.6) \times 10^{-4}$
$\Delta c'_{K\pi}$	$(-1.9 \pm 3.8) \times 10^{-6}$

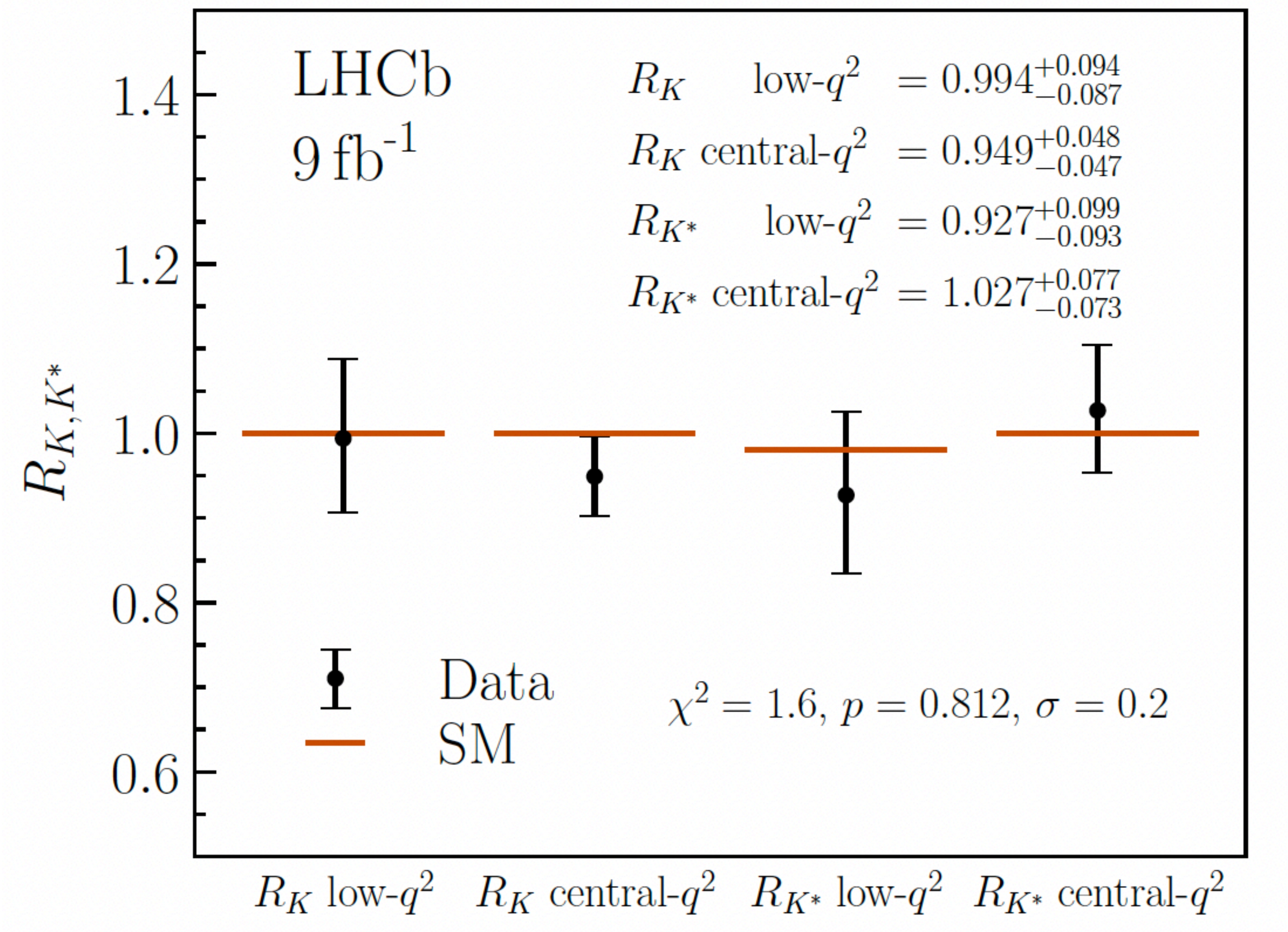
Mixing parameter

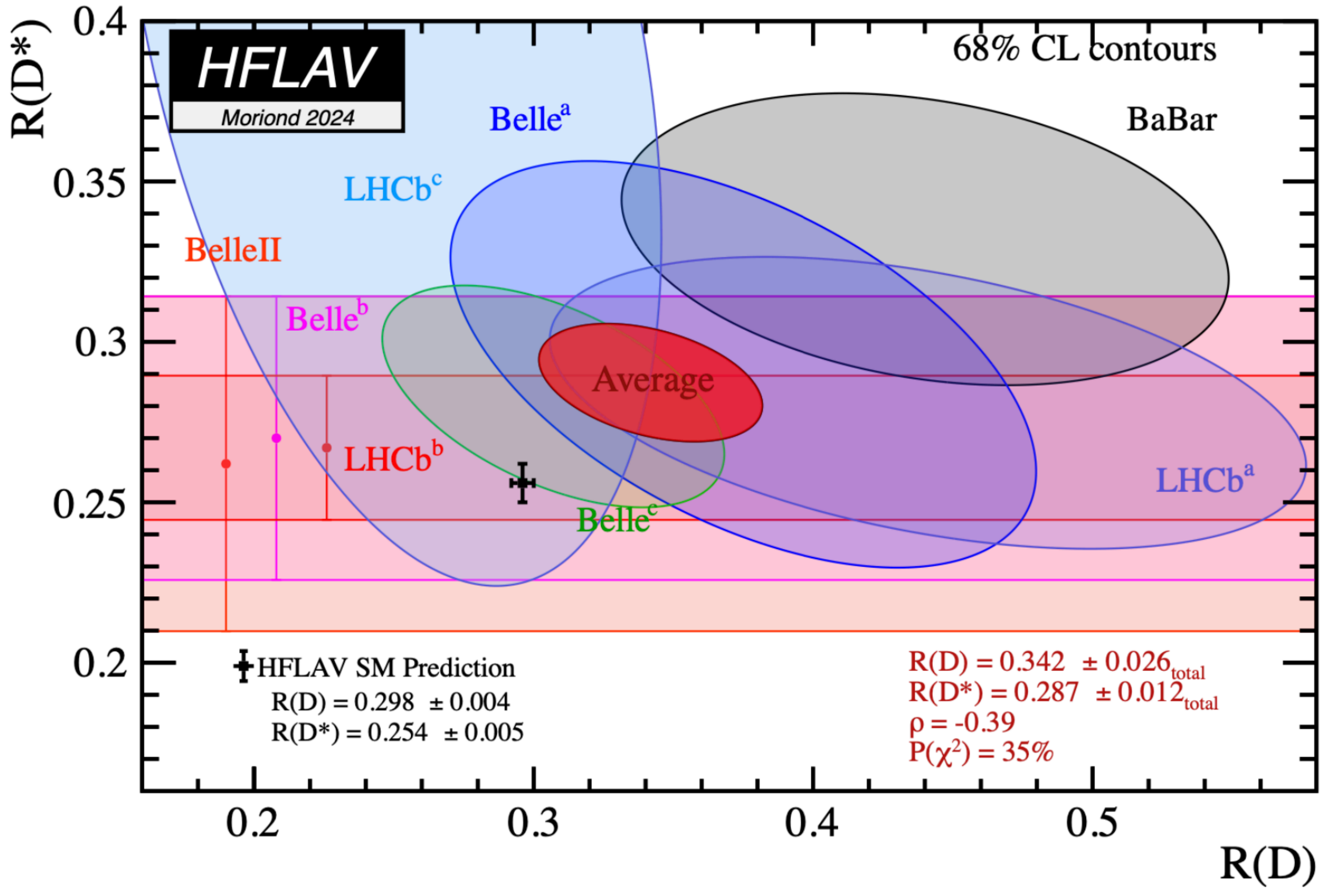
Evidence of non 0

No CPV

$$c_{K\pi} \approx y_{12} \cos\phi_f^{\Gamma} \cos\Delta_f + x_{12} \cos\phi_f^{M} \sin\Delta_f$$

Flavour anomalies

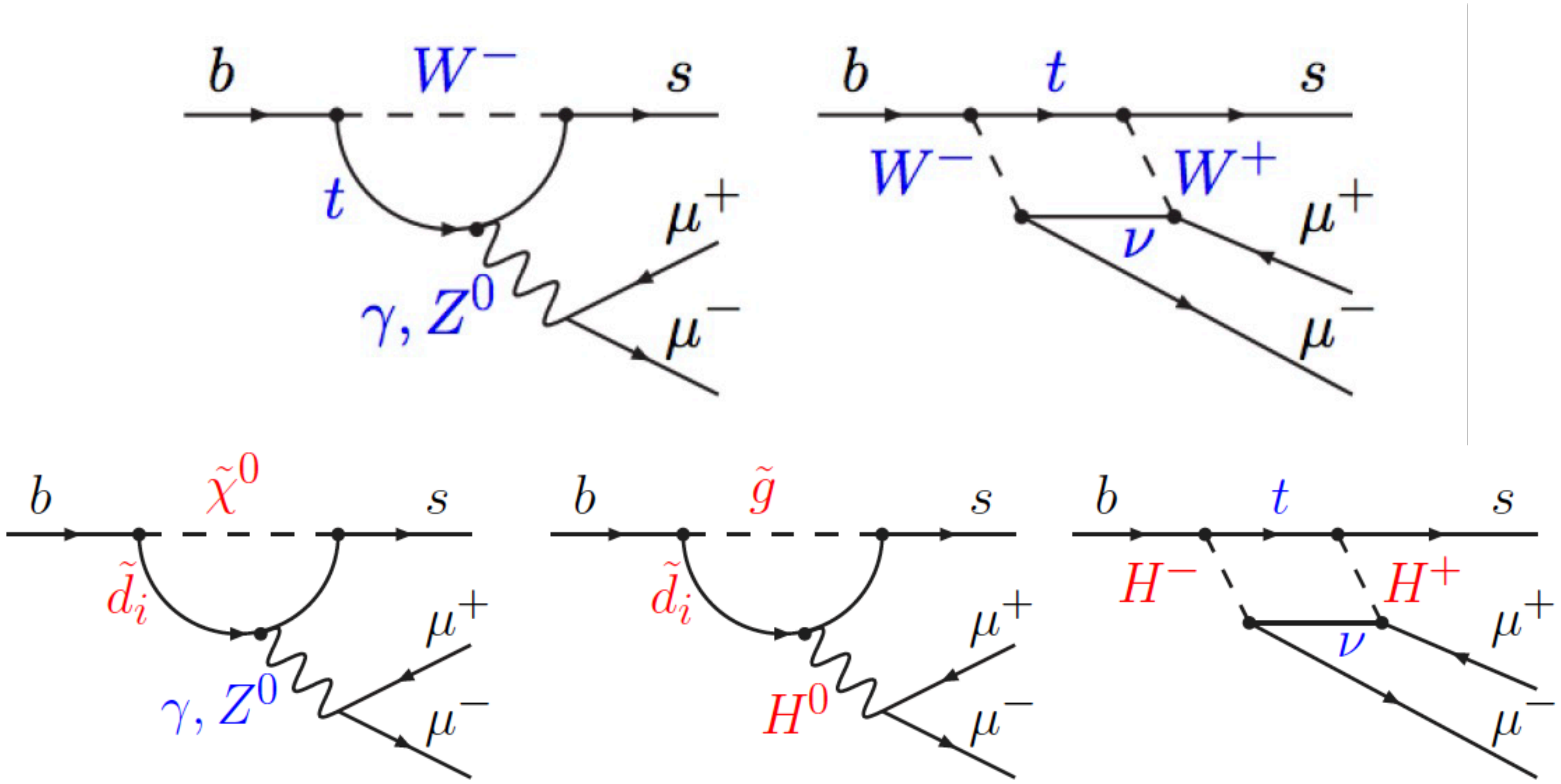




** More dedicated discussions tomorrow morning*

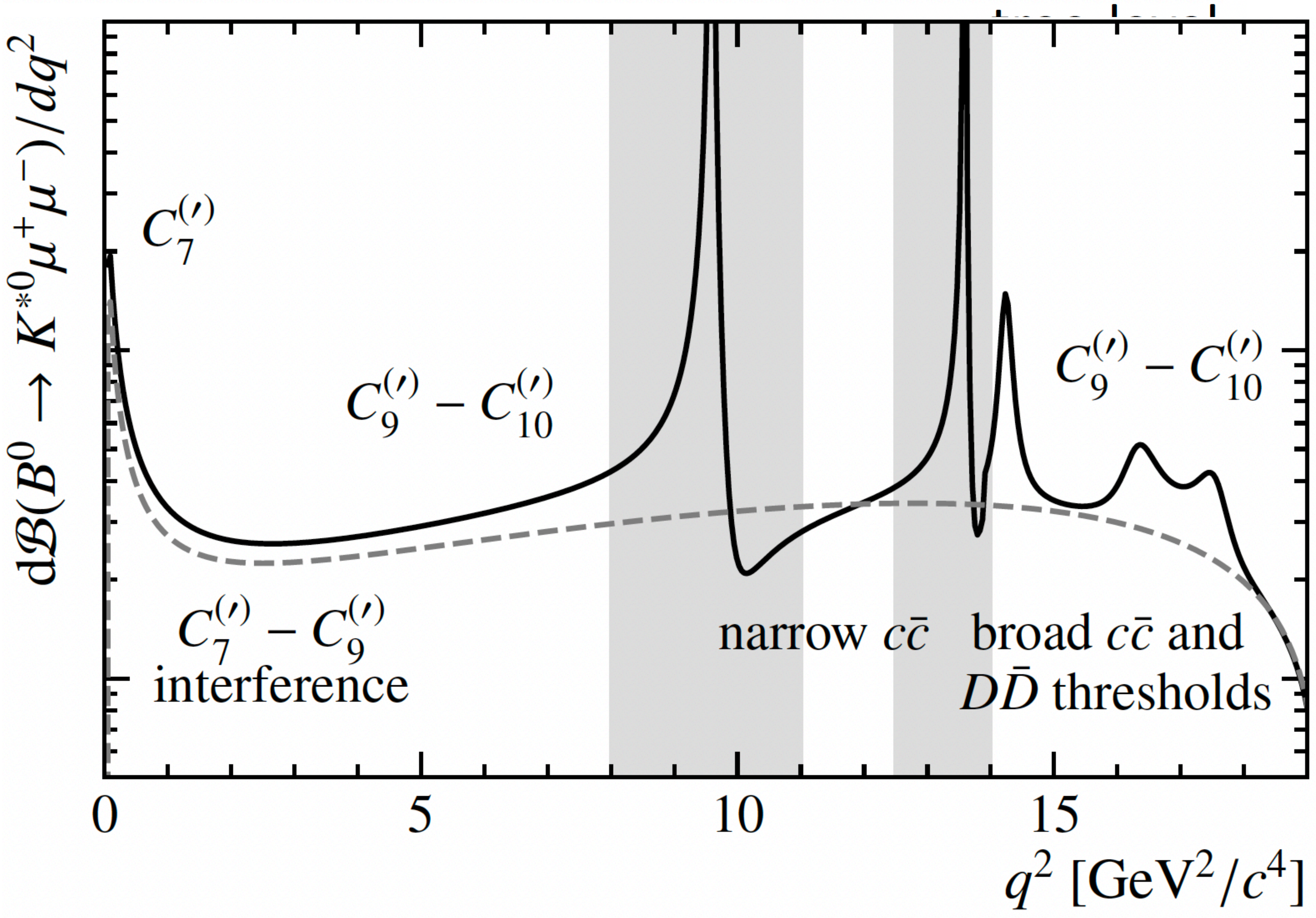
$b \to s\ell^+\ell^-$ decays

- FCNC process involving $b \to s$ transition provides powerful indirect probes for effects beyond the Standard Model (SM)
- Undiscovered particles may transition and deviate the decay rate or the angular distribution, resulting non-universal of lepton flavour



Effective Theory:

$$\mathcal{H}_{\mathrm{WET}} = \frac{-4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_i \mathcal{C}_i^{(\prime)}(\mu)\mathcal{O}_i^{(\prime)}(\mu)$$

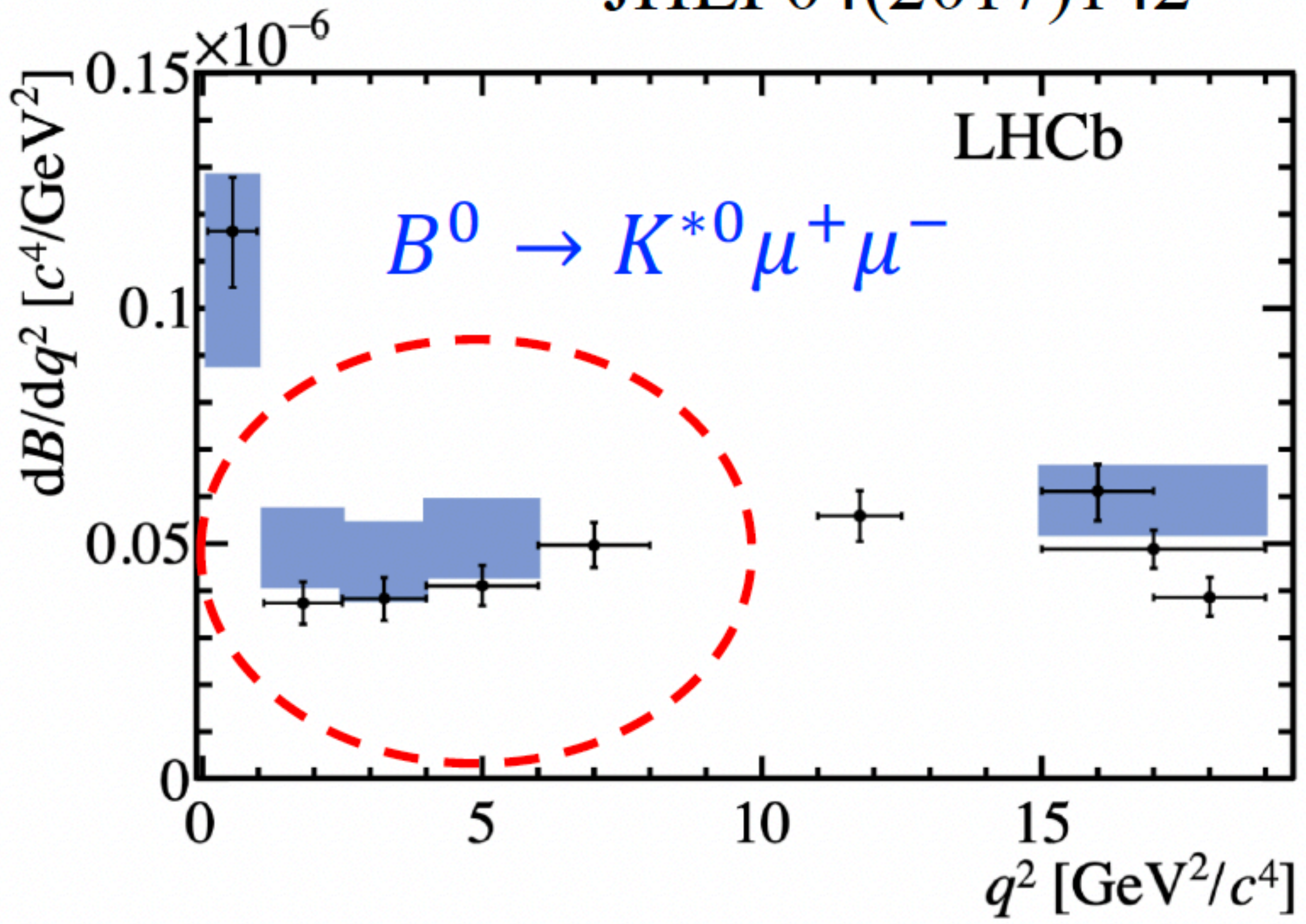


$b \to s\ell^+\ell^-$ decays

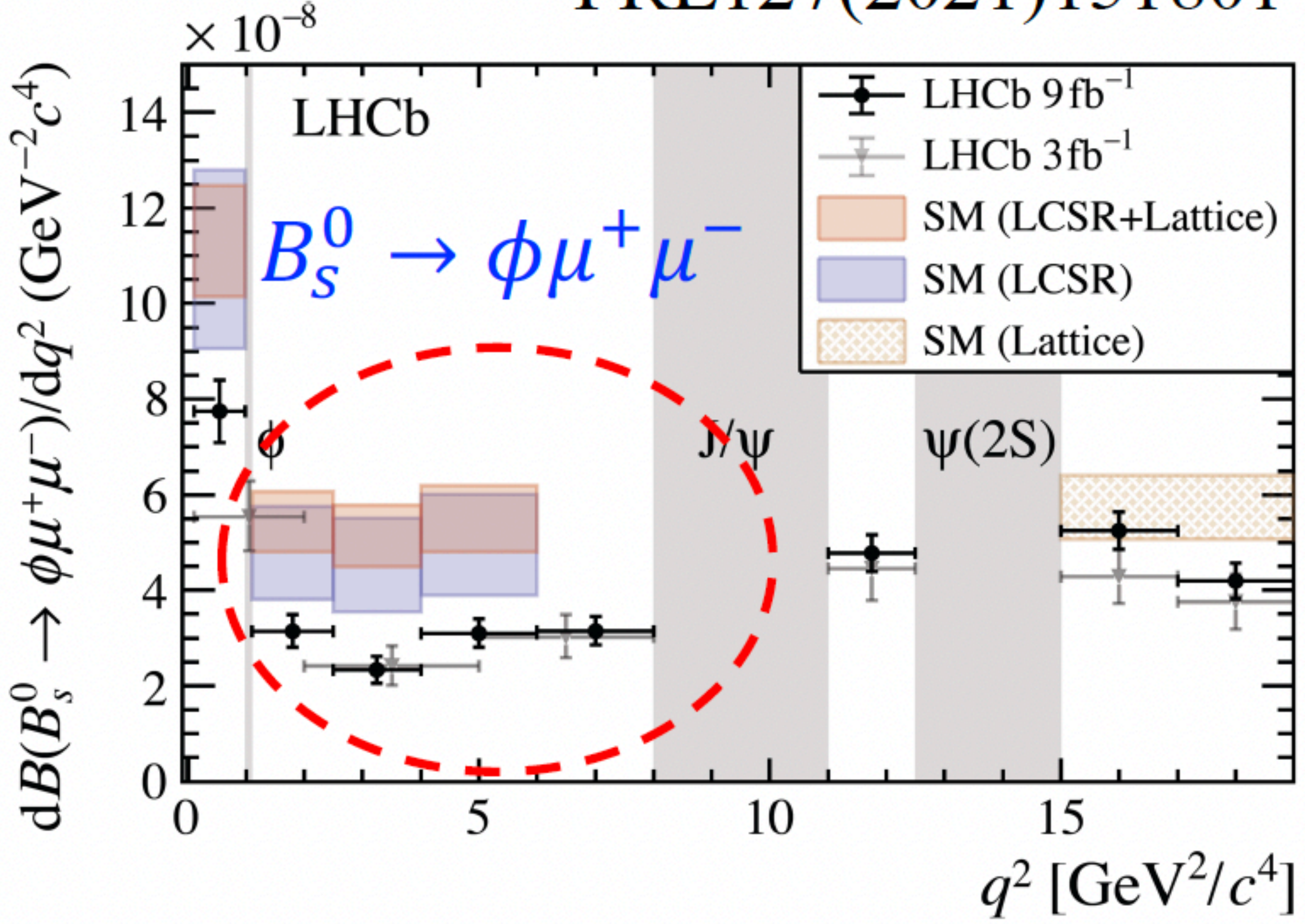
- Anomalous tensions with SM in differential rate

Are these anomalies new physics?

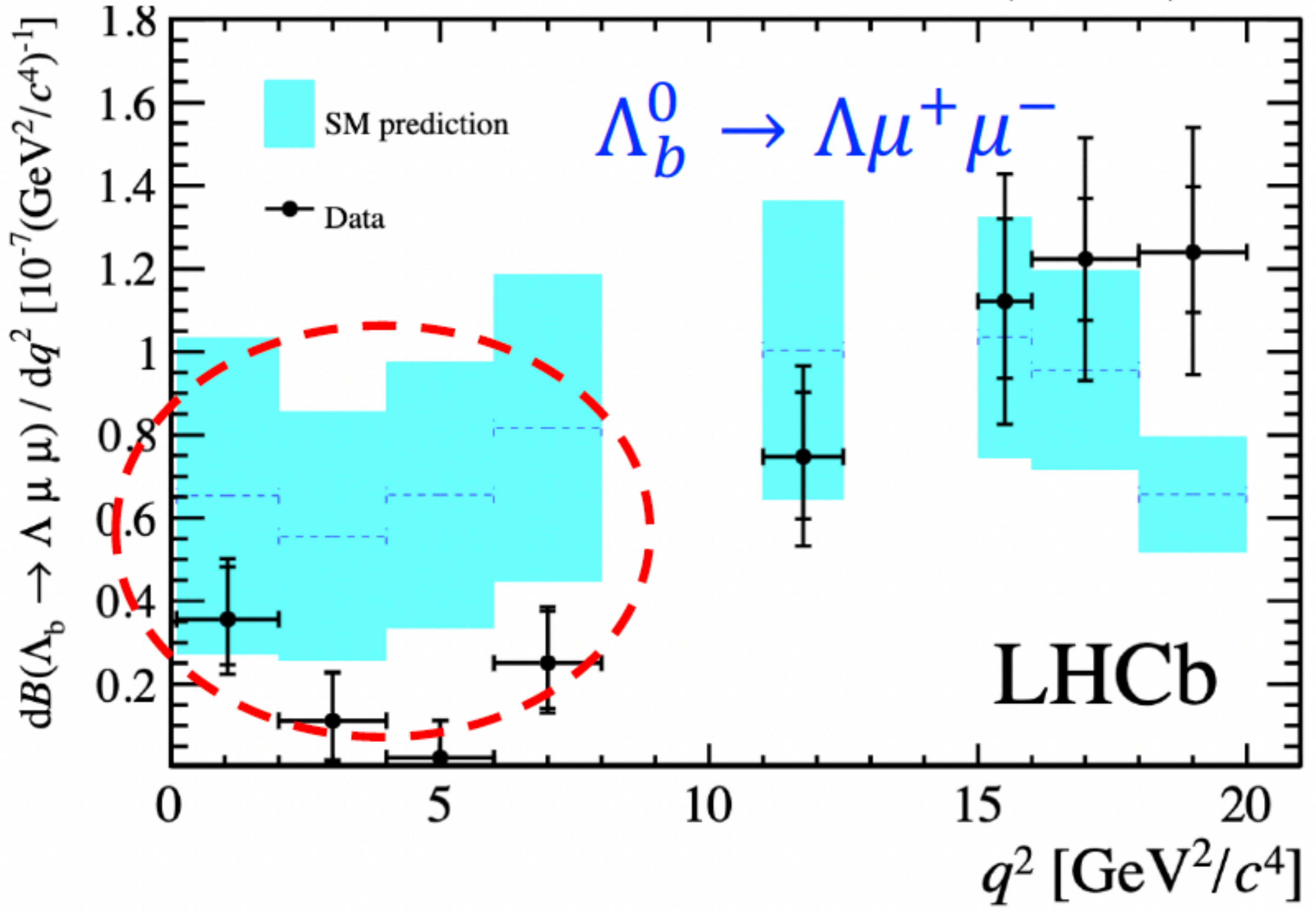
JHEP04(2017)142



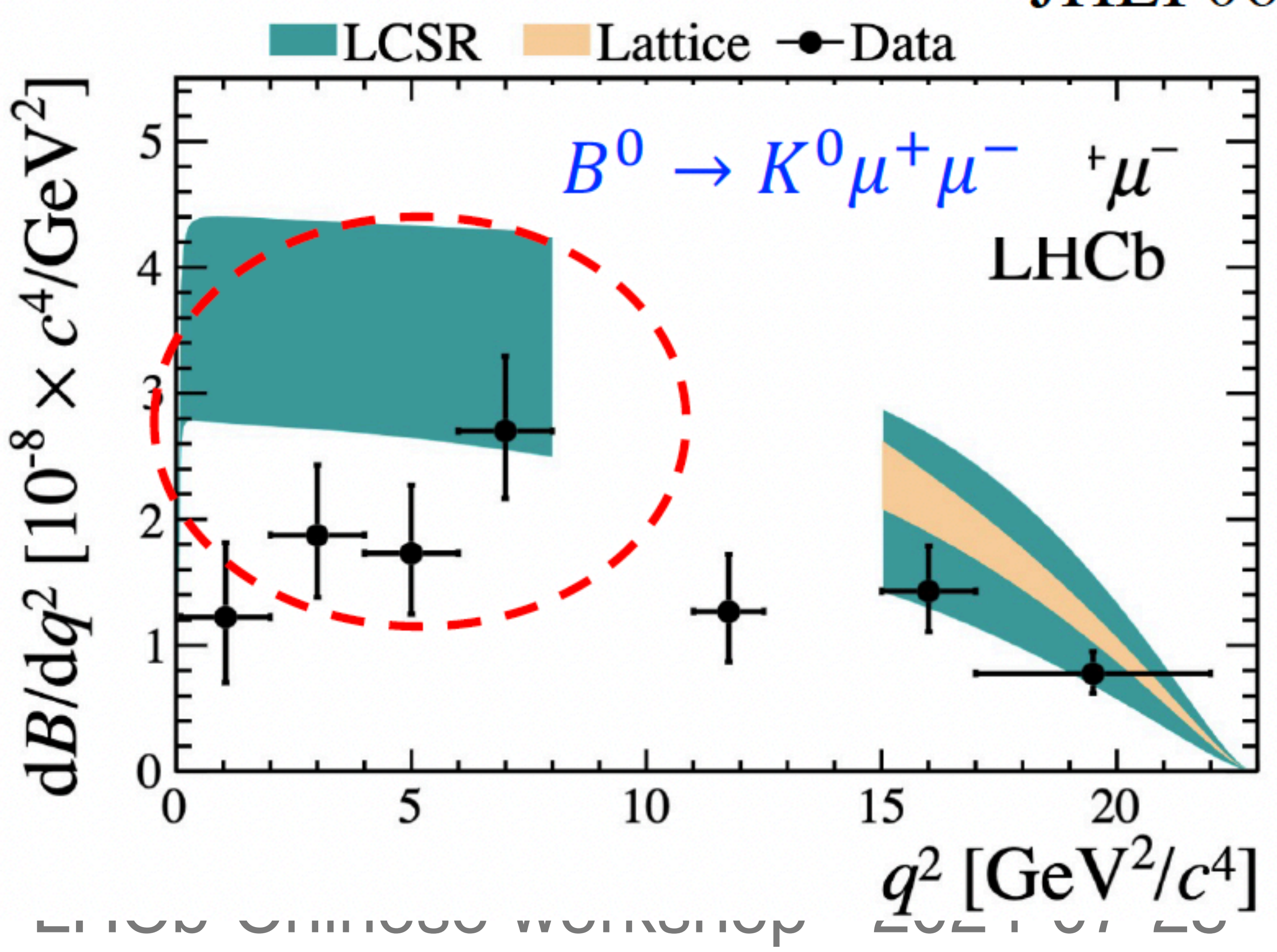
PRL127(2021)151801

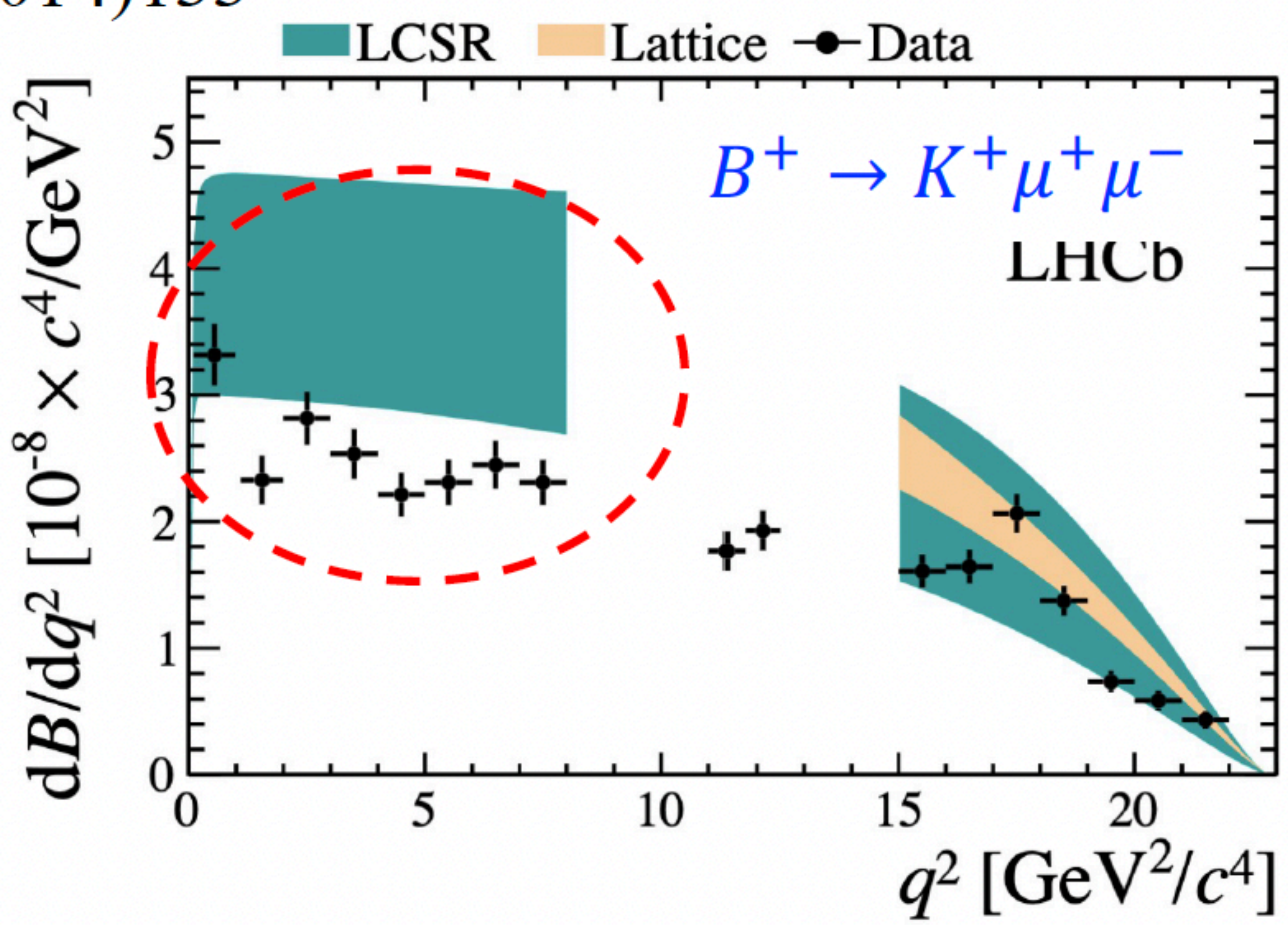


JHEP06(2015)115

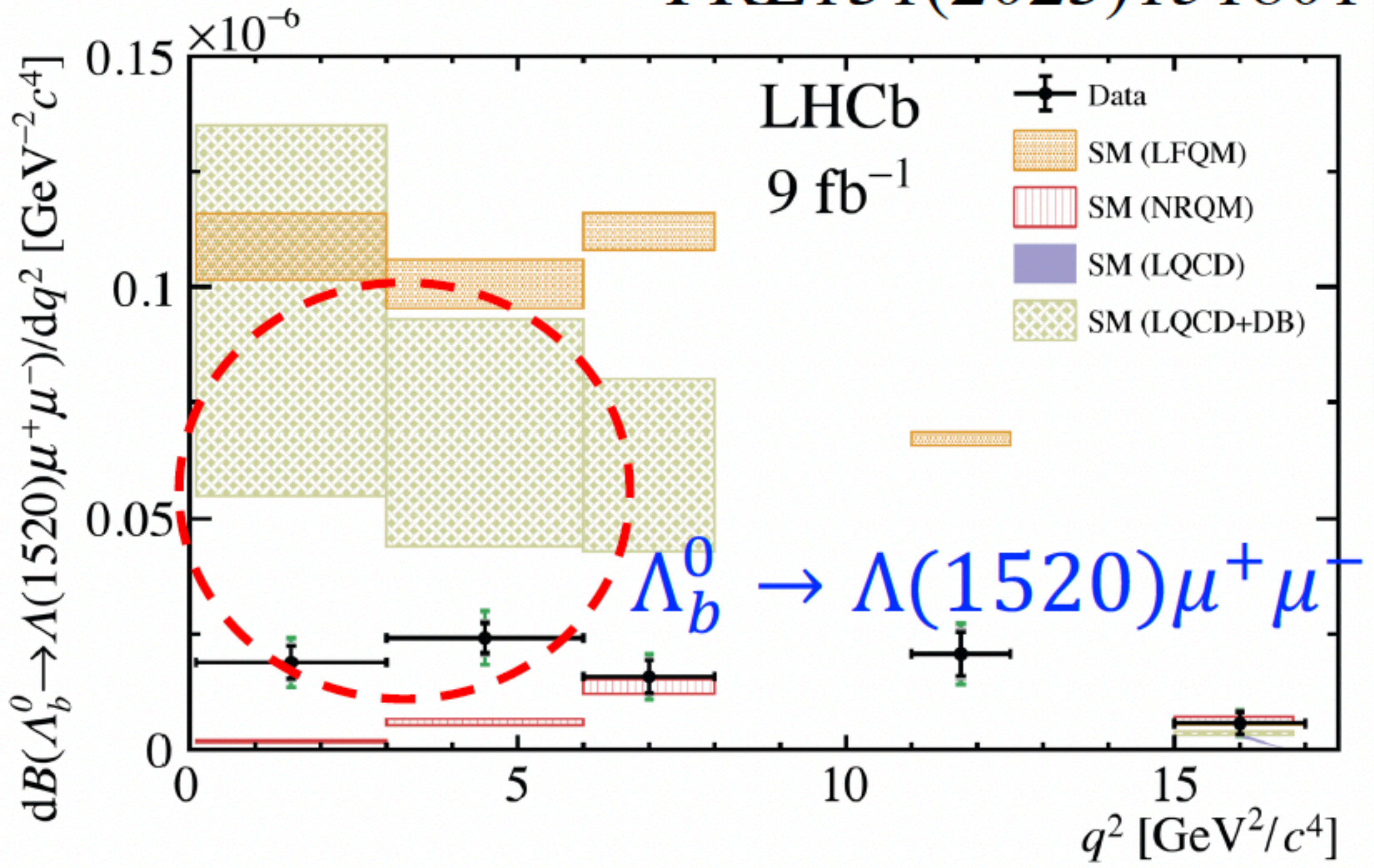


JHEP06(2014)133





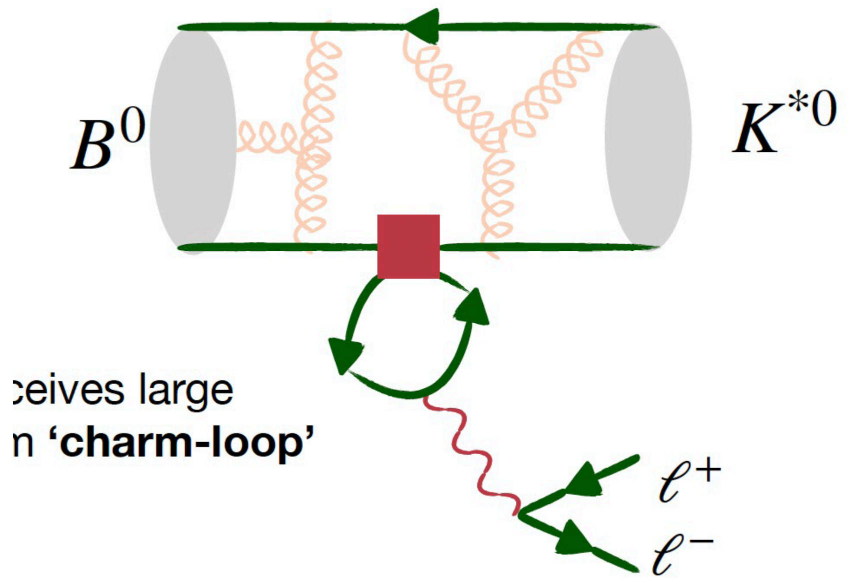
PRL131(2023)151801



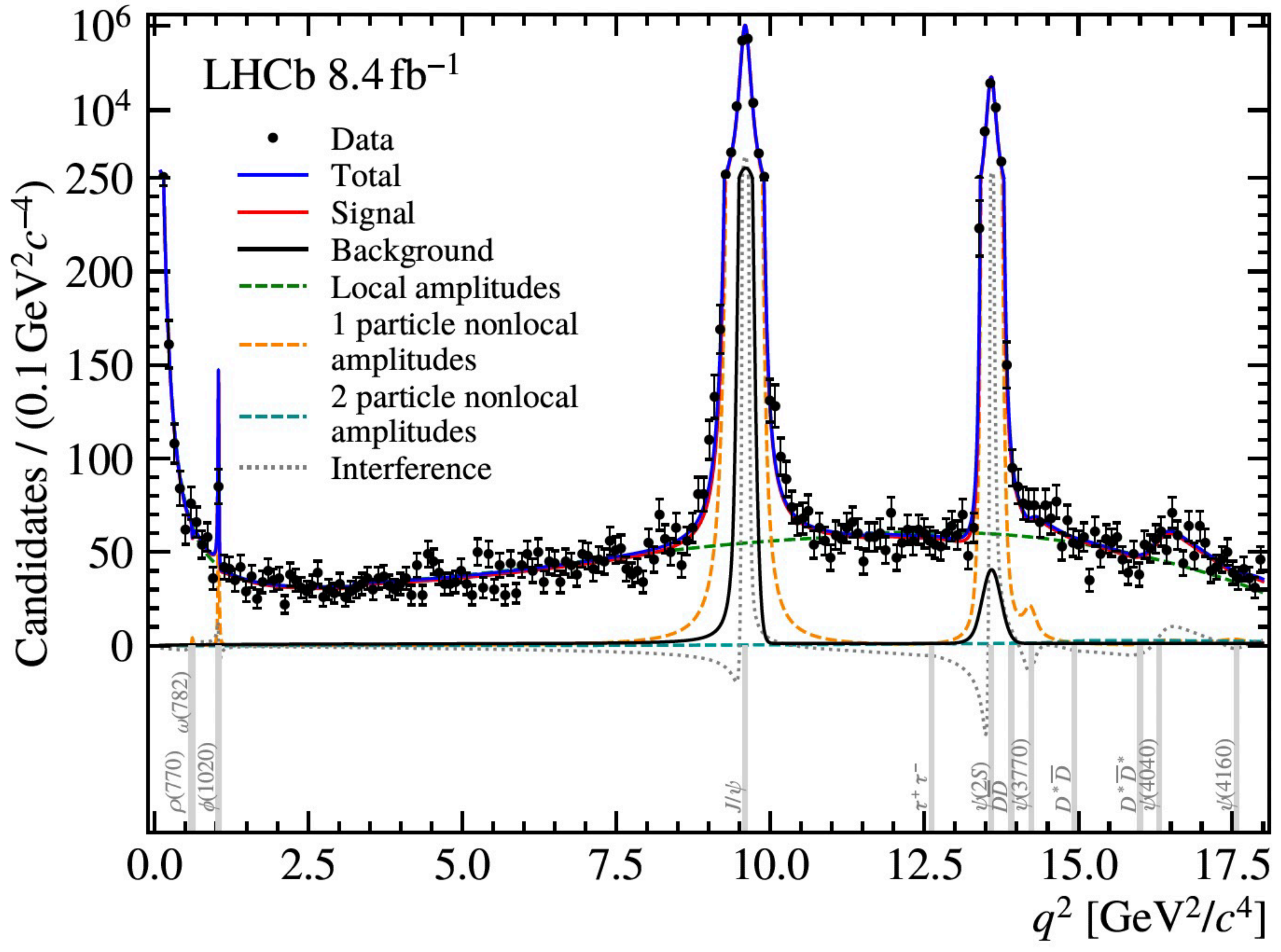
Understanding non-local contributions

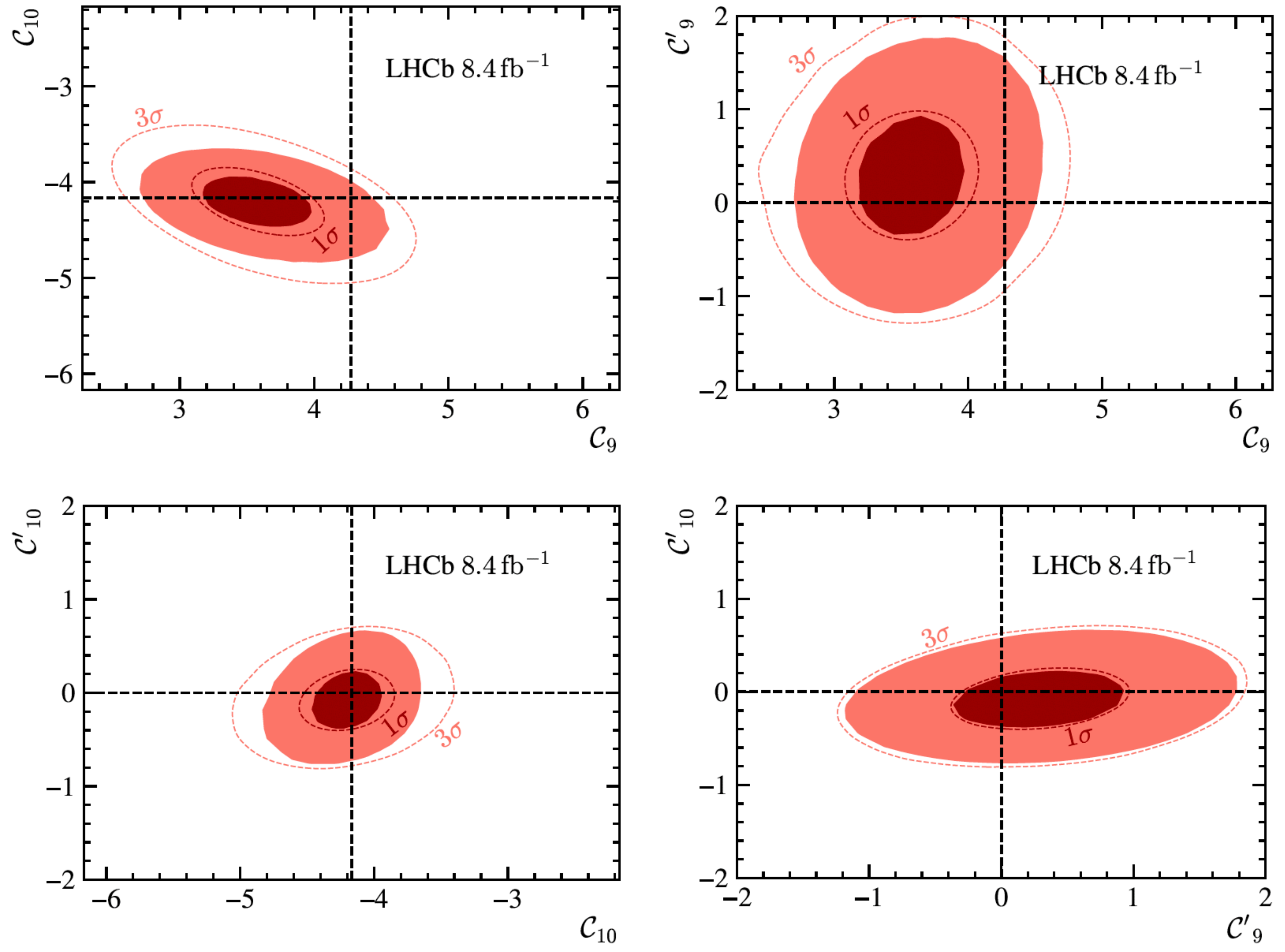
arXiv:2405.17347

- A model combines the local and nonlocal amplitudes ($\omega, \rho, \phi, \psi, D\bar{D}, \tau\tau$) across whole q^2 spectrum (0.1-18.0 GeV²/c⁴) in $B^0 \to K^{*0}\mu^+\mu^-$
  - Simultaneously determine the nonlocal contributions and Wilson coefficients



$$\frac{d^5 \overset{(-)}{\Gamma}(B^0 \to K^+\pi^-\mu^+\mu^-)}{dq^2\, d\vec{\Omega}\, dm^2_{K\pi}} = \frac{9}{32\pi}\sum_i \overset{(-)}{J}_i(q^2) f_i(\cos\theta_\ell, \cos\theta_K, \phi) g_i(m^2_{K\pi})$$





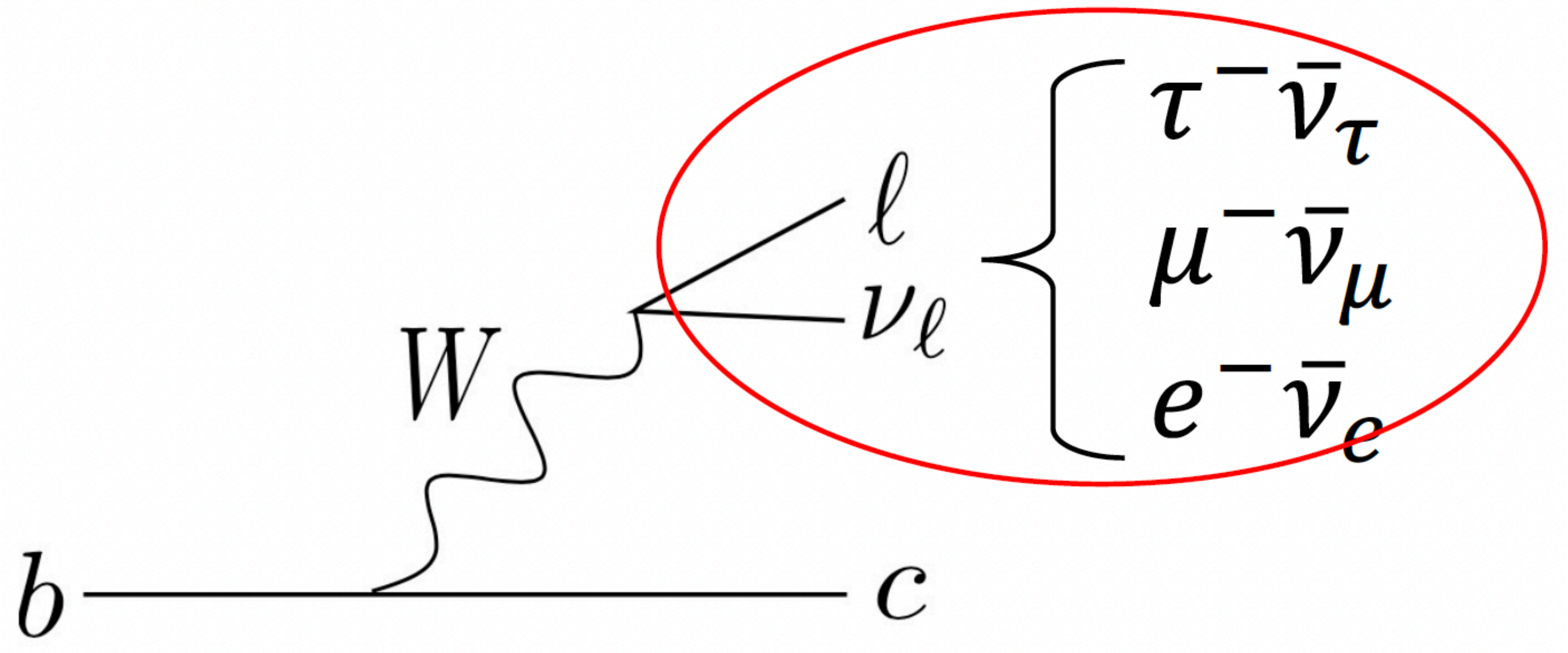
𝒞9: 2.1σ deviation from SM, a slight dependence on local form factor constraint

Wilson Coefficient results	
$\mathcal{C}_9$	$3.56 \pm 0.28 \pm 0.18$
$\mathcal{C}_{10}$	$-4.02 \pm 0.18 \pm 0.16$
$\mathcal{C}'_9$	$0.28 \pm 0.41 \pm 0.12$
$\mathcal{C}'_{10}$	$-0.09 \pm 0.21 \pm 0.06$
$\mathcal{C}_{9\tau}$	$(-1.0 \pm 2.6 \pm 1.0) \times 10^2$

- Interference with nonlocal contributions has a minor impact on the Wilson Coefficients

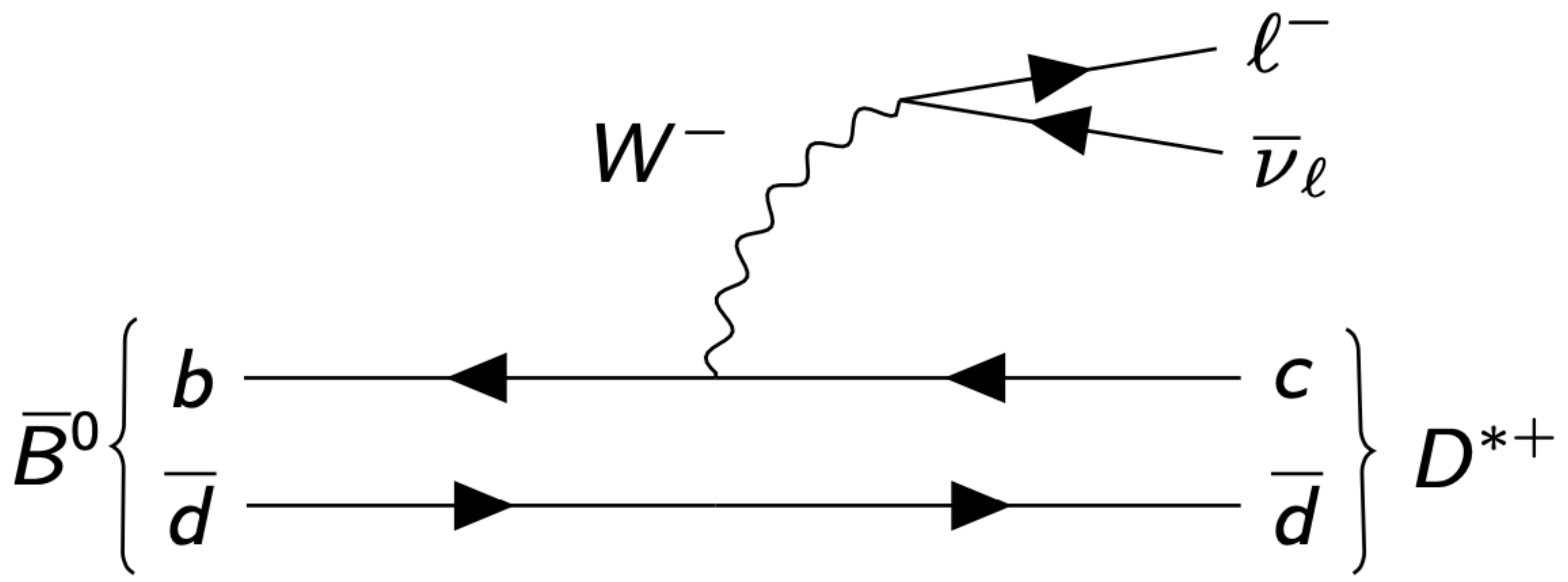
Lepton flavour anomalies in charged current

- $W^{\pm}$ couples equally to three generations of leptons, tested through R(H$_c$) measurements



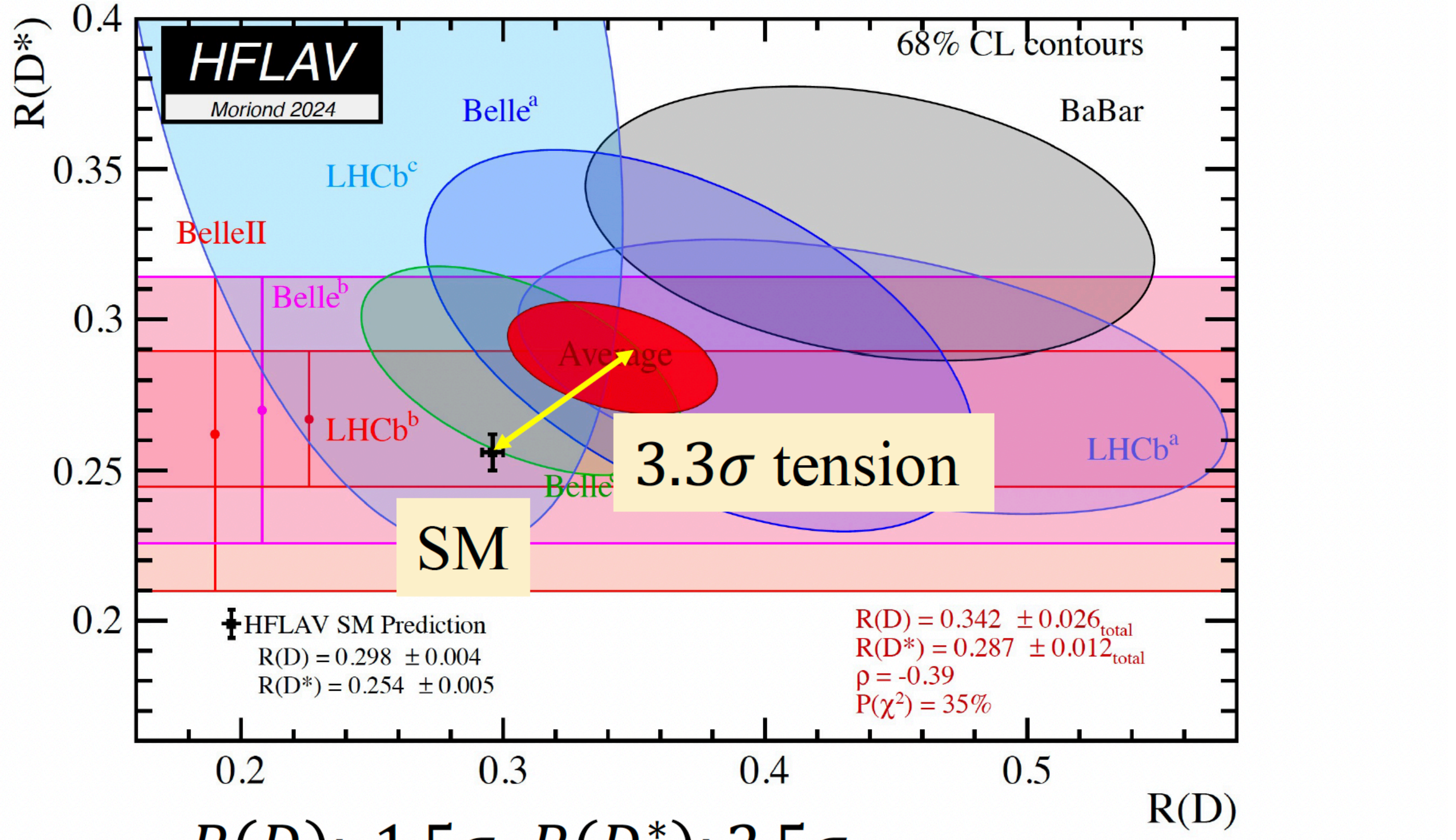
$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau^+ \nu_\tau)}{\mathcal{B}(H_b \to H_c \mu^+ \nu_\mu)}$$

$H_c = D^{(*)+}, D^0, D_s^+, \Lambda_c^+, J/\psi \ldots$



$R(D^{(*)})$ with $\tau \to \mu\nu\nu, \tau \to 3\pi\nu$

PRL131(2023)111802
PRD108(2023) 012018
arXiv:2406.03387



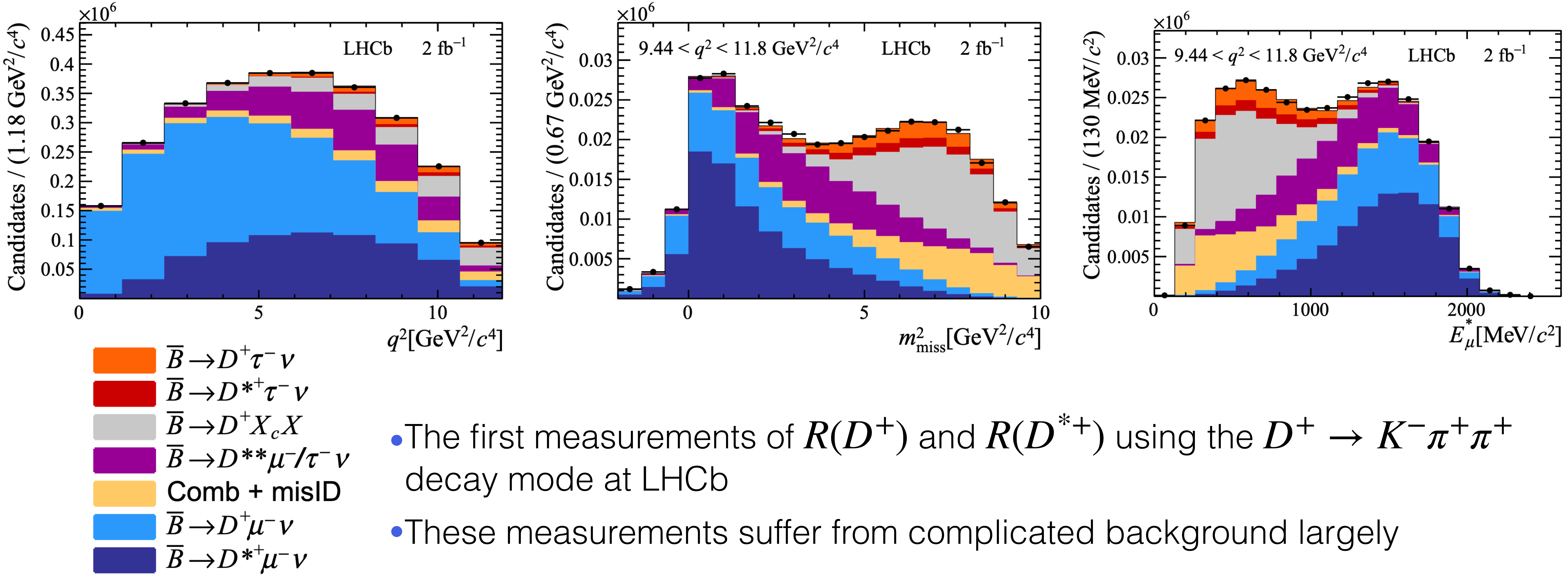
$R(D)$: 1.5σ, $R(D^*)$: 2.5σ

$R(D^+)$ and $R(D^{*+})$ with $D^{*+} \to D^+\pi^0$

- $\bar{B}^0 \to D^{(*)+}\tau^-\bar{\nu}_\tau$
- muonic $\tau \to \mu\nu\nu$ decays

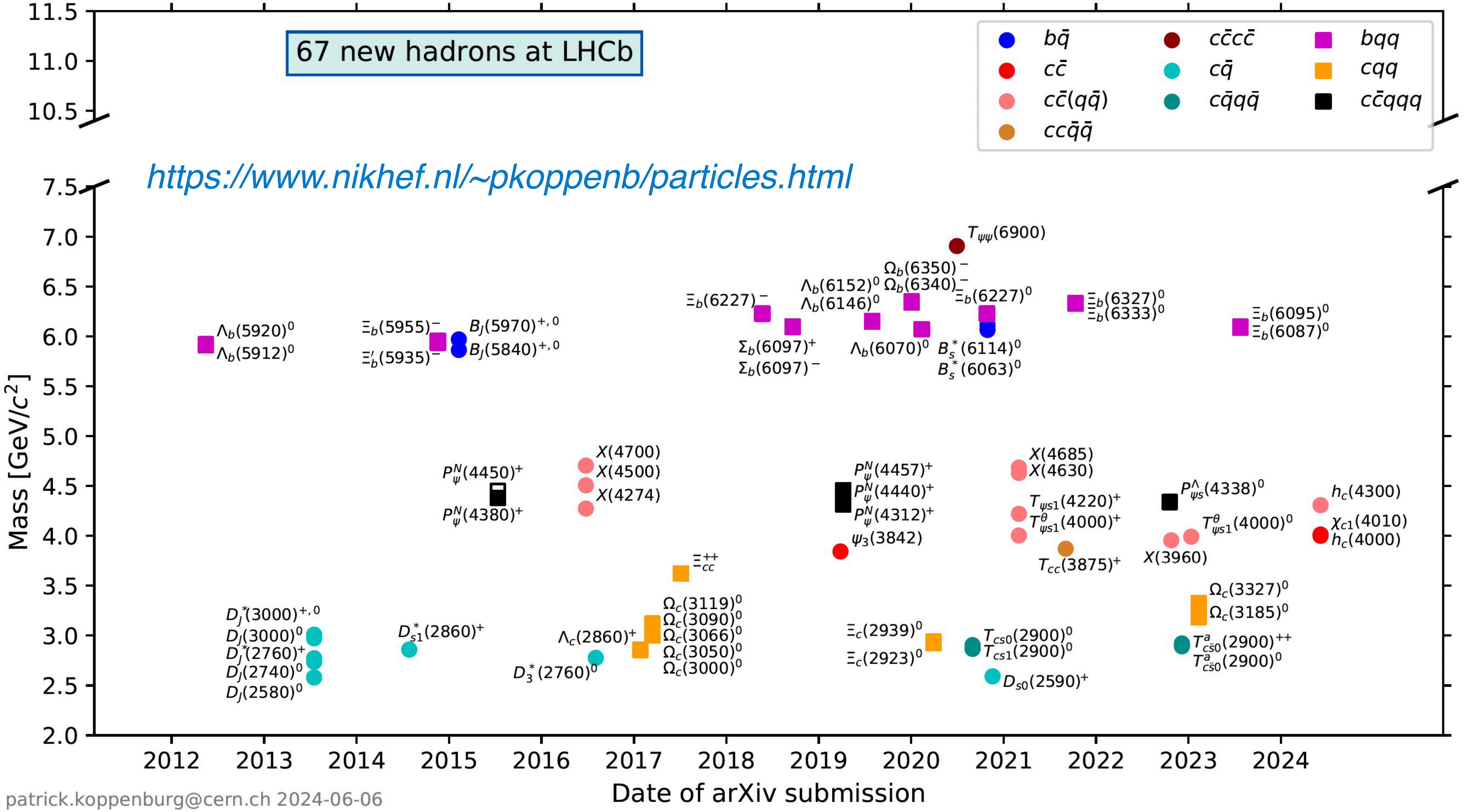
$$R(D^+) = 0.249 \pm 0.043 \pm 0.047$$
$$R(D^{*+}) = 0.402 \pm 0.081 \pm 0.085$$

arXiv:2406.03387



- The first measurements of $R(D^+)$ and $R(D^{*+})$ using the $D^+ \to K^-\pi^+\pi^+$ decay mode at LHCb
- These measurements suffer from complicated background largely

Spectroscopy



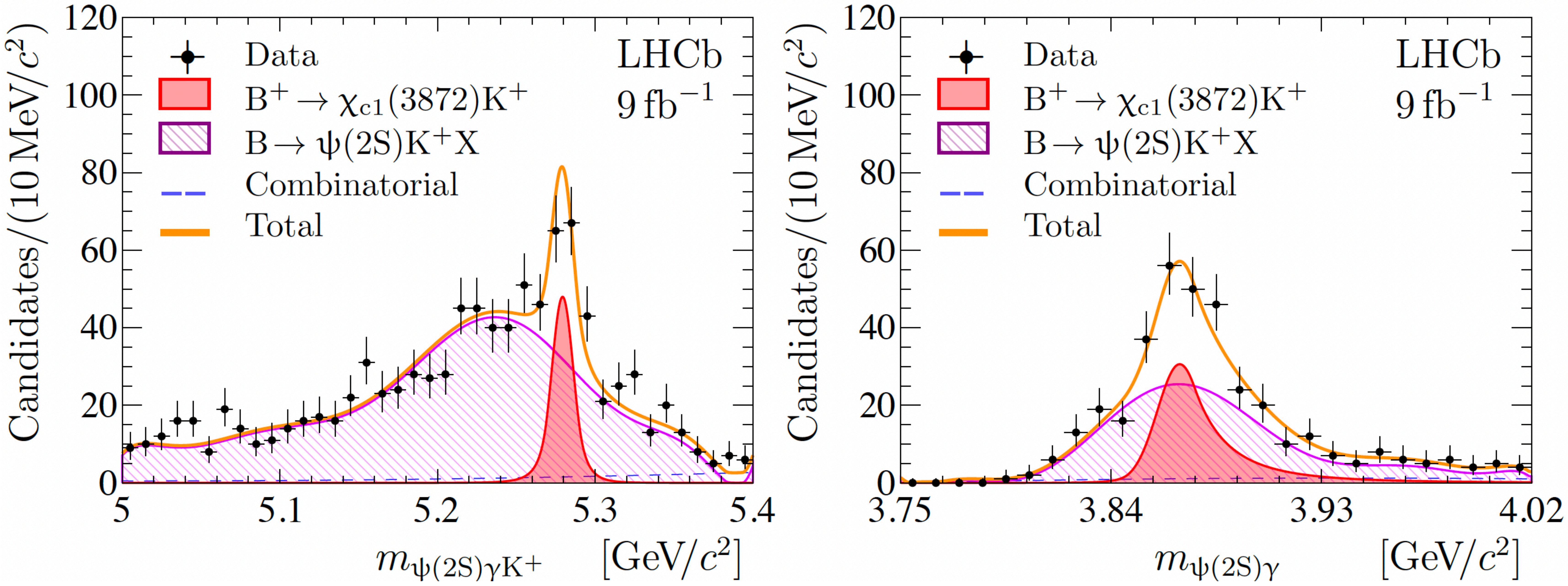
** More results in Liming's talk this afternoon*

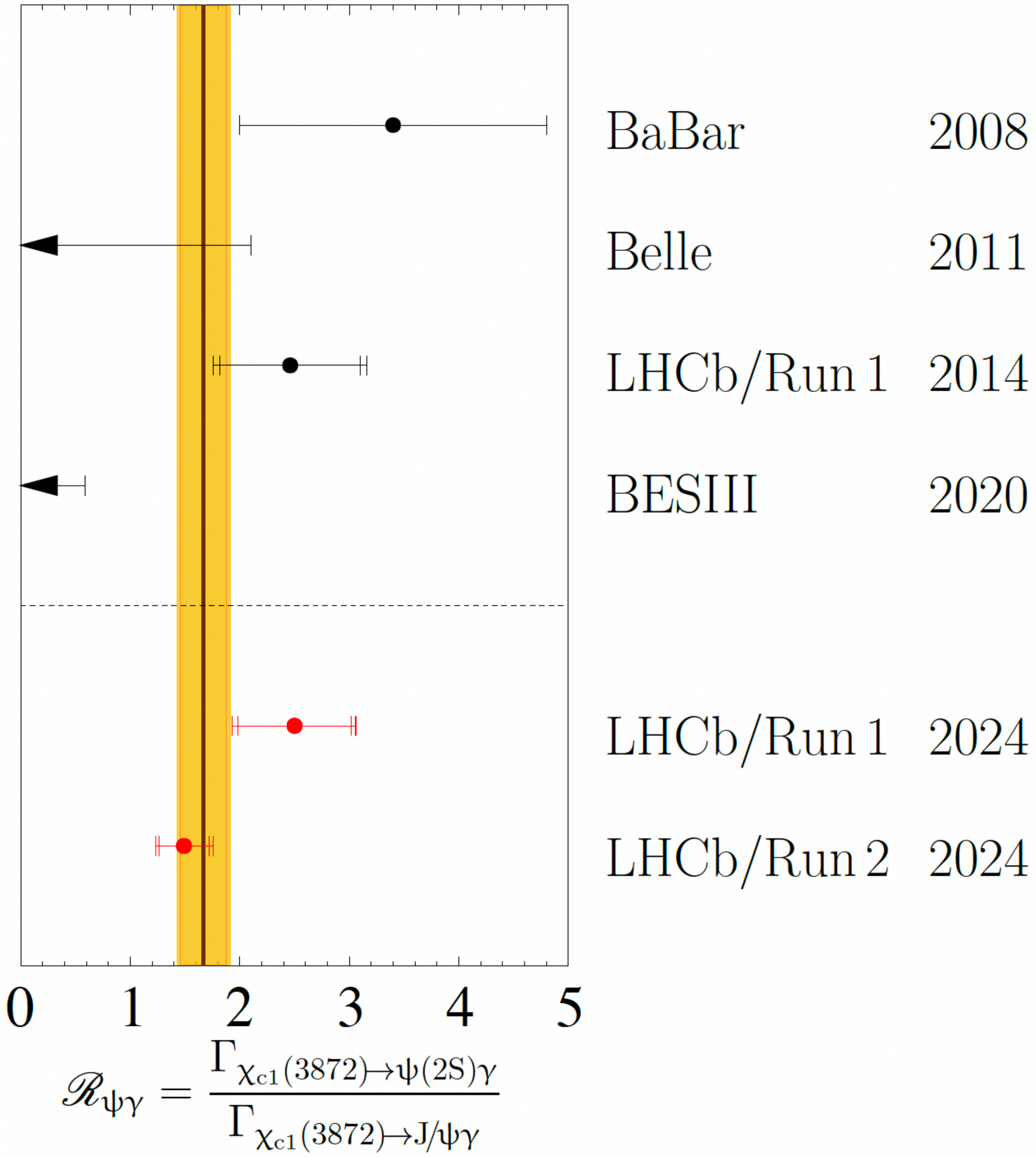
Observation of $\chi_{c1}(3872) \to \gamma\psi(2S)$

arXiv:2406.17006

- $\chi_{c1}(3872) \to \gamma\psi(2S)$ observed in $B^+ \to \chi_{c1}(3872)K^+$ with 9 fb^{-1} pp collision data
- In tension with the upper limit set by BESIII
- Inconsistent with pure $D\bar{D}^*$ molecular hypothesis for $\chi_{c1}(3872)$ but agree with many others

$$\frac{\Gamma_{\chi_{c1}(3872)\to\psi(2S)\gamma}}{\Gamma_{\chi_{c1}(3872)\to J/\psi\gamma}} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04$$





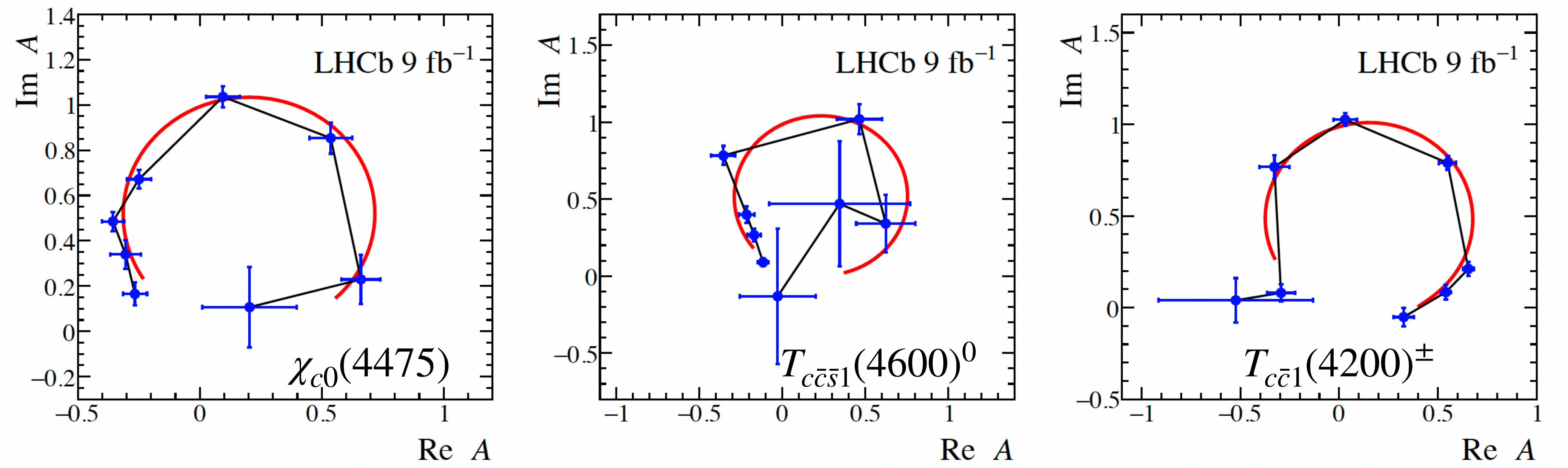
Amplitude analysis of $B^+ \to \psi(2S)K^+\pi^+\pi^-$

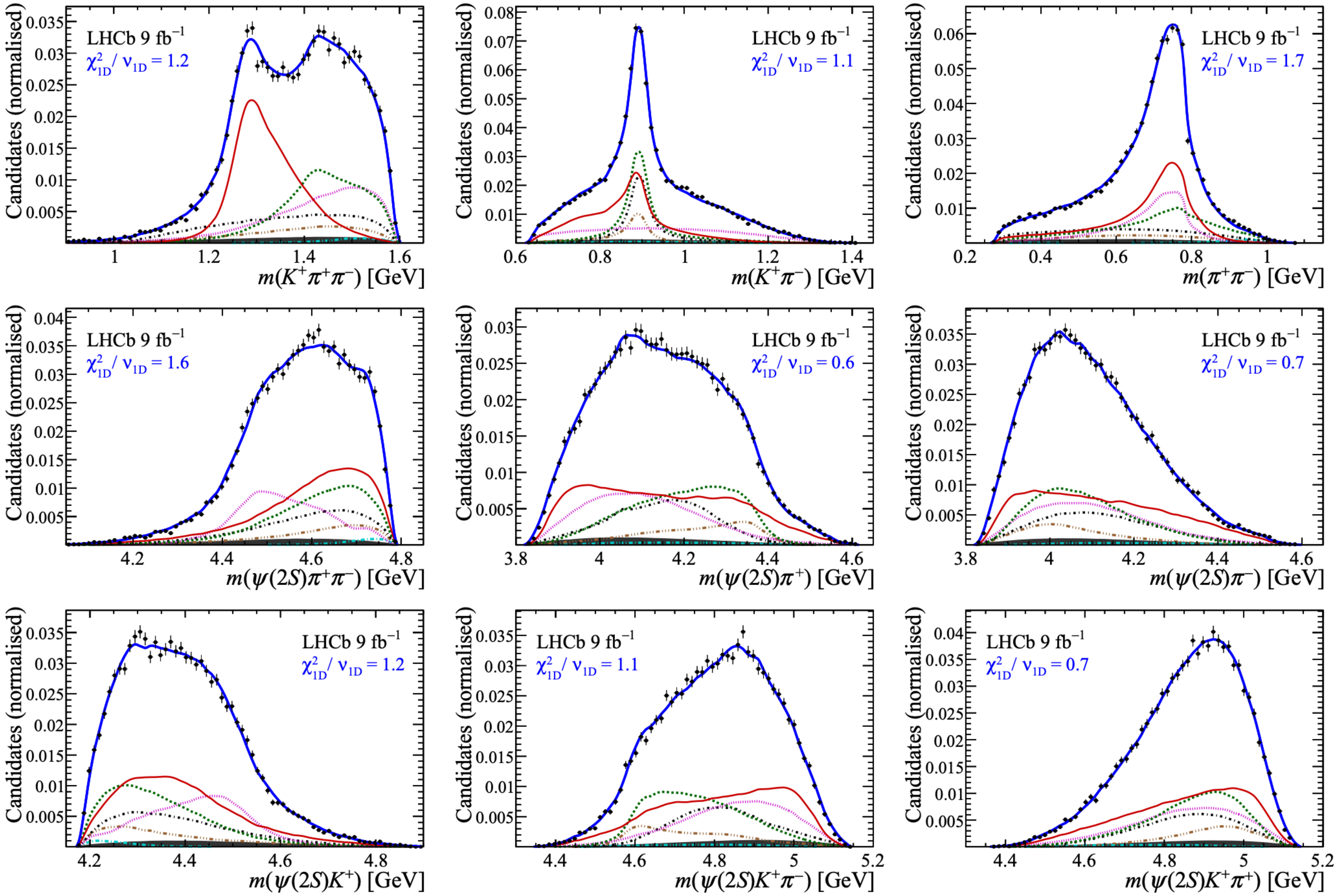
arXiv:2407.12475

- First full 7D amplitude analysis of $B^+ \to \psi(2S)K^+\pi^+\pi^-$ with 9 fb^{-1} pp collision data
- $T_{c\bar{c}1}(4430)^\pm$ resonance confirmed, $J^P(T_{c\bar{c}1}(4200)^\pm) = 1^+$ with a significance $> 5\sigma$
- Hidden-charm exotic states to $\psi(2S)K^+\pi^-$ final sates observed for the first time
- Four $X^0 \to \psi(2S)\pi^+\pi^-$ states identified and shows similarities to $X(J/\psi\phi)$

$\chi_{c0}(4475) \to \rho(770)^0\psi(2S)$	$99.04\pm\ 0.49\pm\ 1.66$
$\chi_{c0}(4475) \to T_{c\bar{c}1}(4200)^-\pi^+$	$0.50\pm\ 0.25\pm\ 0.39$
$\chi_{c0}(4475) \to T_{c\bar{c}1}(4200)^+\pi^-$	$0.50\pm\ 0.25\pm\ 0.39$
Sum $\chi_{c0}(4475)$	$100.03\pm\ 0.02\pm\ 1.42$

$T_{c\bar{c}\bar{s}1}(4600)^0 \to \psi(2S)\ K^*(892)^0$	$50.87\pm\ 7.79\pm11.55$
$T_{c\bar{c}\bar{s}1}(4600)^0 \to T_{c\bar{c}1}(4200)^-K^+$	$16.53\pm\ 3.79\pm12.75$
$T_{c\bar{c}\bar{s}1}(4600)^0 \to T_{c\bar{c}\bar{s}1}(4000)^+\pi^-$	$9.84\pm\ 3.28\pm\ 5.34$
Sum $T_{c\bar{c}\bar{s}1}(4600)^0$	$77.23\pm\ 5.22\pm17.80$
$T^*_{c\bar{c}\bar{s}1}(5200)^0 \to \psi(2S)\ [K^+\pi^-]_S$	$66.28\pm15.03\pm17.35$
$T^*_{c\bar{c}\bar{s}1}(5200)^0 \to T_{c\bar{c}\bar{s}1}(4000)^+\pi^-$	$9.37\pm14.12\pm13.23$
Sum $T^*_{c\bar{c}\bar{s}1}(5200)^0$	$75.65\pm\ 9.18\pm13.39$
$T_{c\bar{c}\bar{s}1}(4900)^0 \to \psi(2S)\ K^*(892)^0$	100





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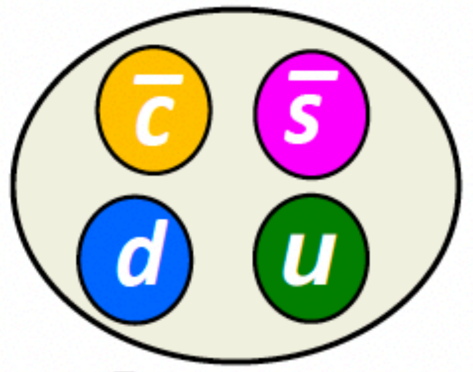
Resonance	J^P	m_0 [MeV]	Γ_0 [MeV]	Sign. [σ]	Res. PDG	m_0 [MeV]	Γ_0 [MeV]
$\chi_{c0}(4475)$	0^+	$4475\pm 7\pm 12$	$231\pm 19\pm 32$	> 20 (19)	$\chi_{c0}(4500)$	4474 ± 4	77^{+12}_{-10}
$\chi_{c1}(4650)$	1^+	$4653\pm 14\pm 27$	$227\pm 26\pm 22$	15 (13)	$\chi_{c1}(4685)$	4684^{+15}_{-17}	126 ± 40
$\chi_{c0}(4710)$	0^+	$4710\pm 4\pm 5$	$64\pm 9\pm 10$	14 (10)	$\chi_{c0}(4700)$	4694^{+16}_{-5}	87^{+18}_{-10}
$\eta_{c1}(4800)$	1^-	$4785\pm 37\pm 119$	$457\pm 93\pm 157$	17 (12)	$X(4630)$	4626^{+24}_{-110}	174^{+140}_{-80}
$T^*_{c\bar{c}1}(4055)^+$	1^-	4054 (fixed)	45 (fixed)	8 (7)	$T_{c\bar{c}}(4055)^+$	4054 ± 3.2	45 ± 13
$T_{c\bar{c}1}(4200)^+$	1^+	$4257\pm 11\pm 17$	$308\pm 20\pm 32$	> 20 (> 20	$T_{c\bar{c}1}(4200)^+$	4196^{+35}_{-32}	370^{+100}_{-150}
$T_{c\bar{c}1}(4430)^+$	1^+	$4468\pm 21\pm 80$	$251\pm 42\pm 82$	15 (8)	$T_{c\bar{c}1}(4430)^+$	4478^{+15}_{-18}	181 ± 31
$T_{c\bar{c}\bar{s}1}(4600)^0$	1^+	$4578\pm 10\pm 18$	$133\pm 28\pm 69$	15 (12)			
$T_{c\bar{c}\bar{s}1}(4900)^0$	1^+	$4925\pm 22\pm 47$	$255\pm 55\pm 127$	12 (8)			
$T^*_{c\bar{c}\bar{s}1}(5200)^0$	1^-	$5225\pm 86\pm 181$	$226\pm 76\pm 374$	10 (8)			
$T_{c\bar{c}\bar{s}1}(4000)^+$	1^+	4003 (fixed)	131 (fixed)	> 20 (14)	$T_{c\bar{c}\bar{s}1}(4000)^+$	4003^{+7}_{-15}	131 ± 30

Study of $B^+ \to D^{*\pm} D^{\mp} K^+$

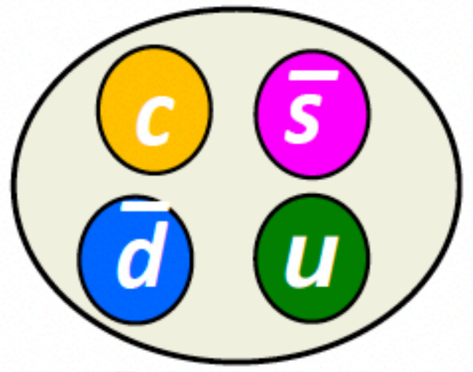
arXiv:2406.03156
Wenbin Qian, Yi Jiang, Huanhuan Liu

2020



$\to D^- K^+$

2023



$\to D_s^+ \pi^\pm$

2024

$B^+ \to D^{*-} D_s^+ \pi^+$
No obvious exotics

2024

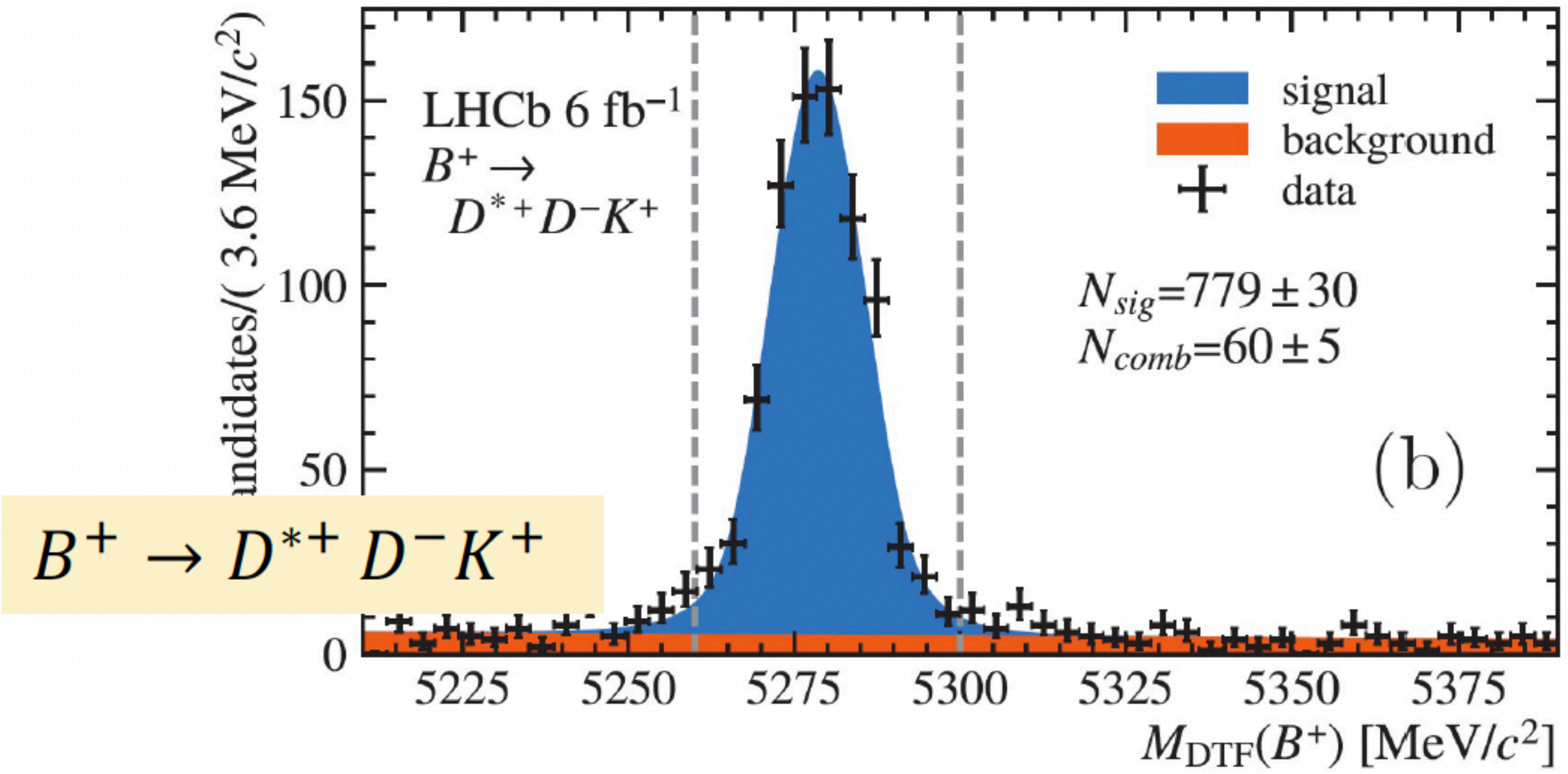
plot from Yanxi's talk

$B^+ \to D^{*\pm} D^{\mp} K^+$

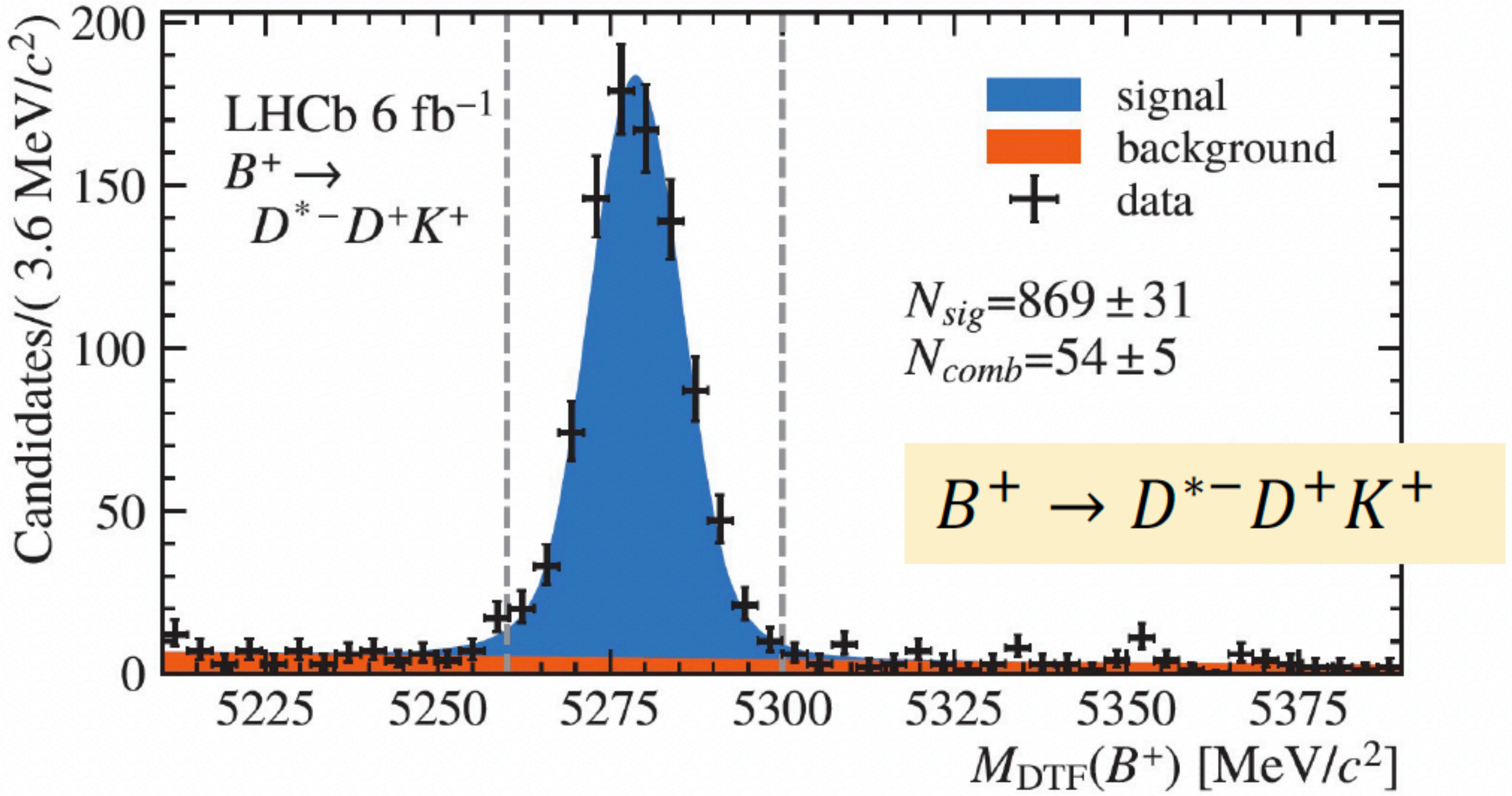
arXiv:2406.03156

$B^+ \to D^{*\pm} D^{\mp} K^+$ topology similar to $B^+ \to D^- D^+ K^+$ decays

About 1700 signals



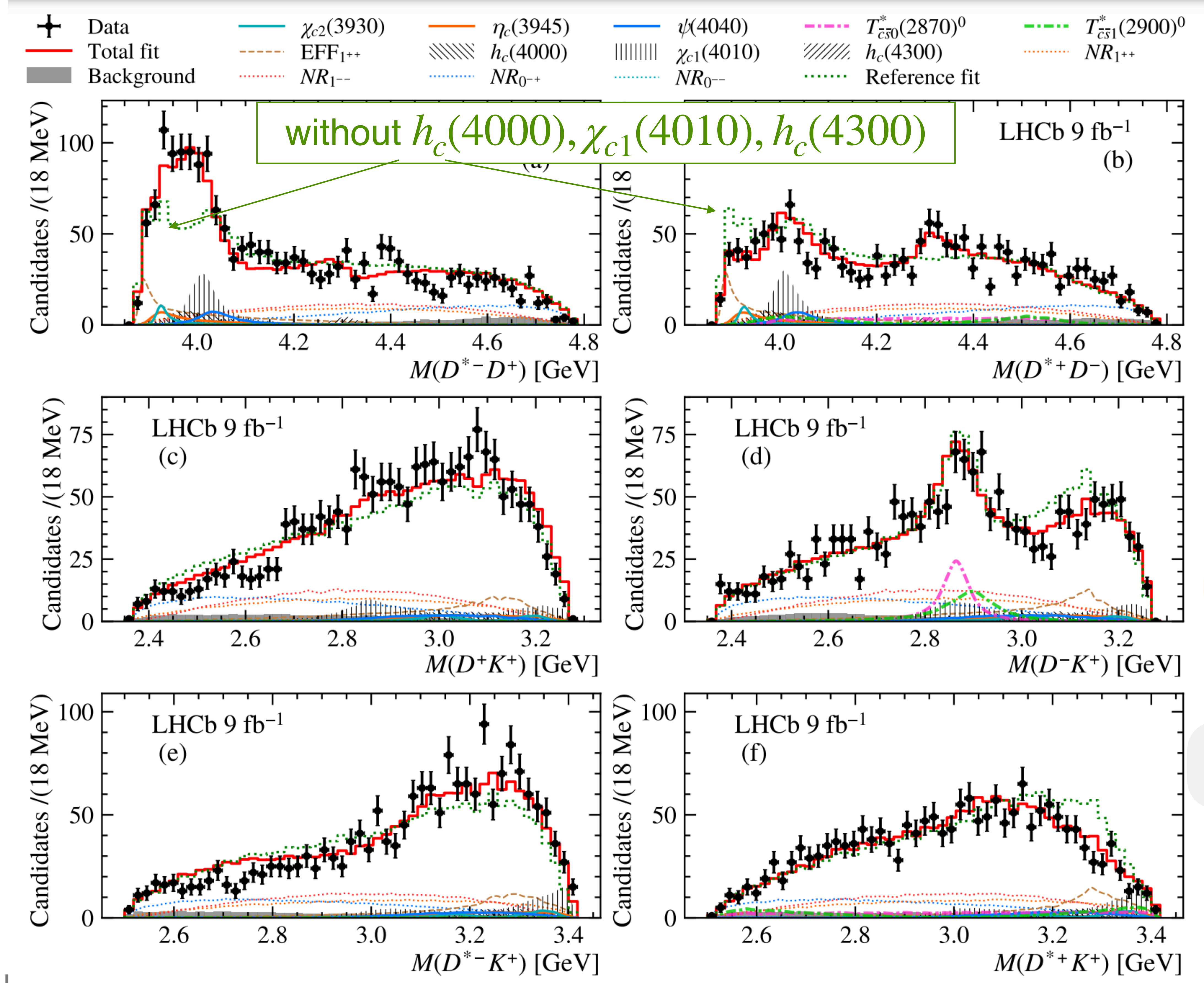
About 1700 signals



Resonant structures in $B^+ \to D^{*\pm}D^{\mp}K^+$

arXiv:2406.03156
Wenbin Qian, Yi Jiang, Huanhuan Liu

- A simultaneous analysis of $B^+ \to D^{*\pm}D^{\mp}K^+$ with 9 fb^{-1} pp collision data
- C-parity conservation considered, requiring equal contribution of $B^+ \to R(D^{*\pm}D^{\mp})K^+$
- Four charmonium(-like) resonances decaying to $D^{*\pm}D^{\mp}$ observed
- Existences of the $T^*_{\bar{c}\bar{s}0}(2870)^0$ and $T^*_{\bar{c}\bar{s}0}(2900)^0$ confirmed in new production channels $B^+ \to D^{*+}T^{*0}_{\bar{c}\bar{s}0,1}$



Property	This work	Previous work
$T^*_{\bar{c}\bar{s}0}(2870)^0$ mass [MeV]	$2914 \pm 11 \pm 15$	2866 ± 7
$T^*_{\bar{c}\bar{s}0}(2870)^0$ width [MeV]	$128 \pm 22 \pm 23$	57 ± 13
$T^*_{\bar{c}\bar{s}1}(2900)^0$ mass [MeV]	$2887 \pm 8 \pm 6$	2904 ± 5
$T^*_{\bar{c}\bar{s}1}(2900)^0$ width [MeV]	$92 \pm 16 \pm 16$	110 ± 12
$\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}0}(2870)^0 D^{(*)+})$	$(4.5\,^{+0.6}_{-0.8}\,^{+0.9}_{-1.0} \pm 0.4) \times 10^{-5}$	$(1.2 \pm 0.5) \times 10^{-5}$
$\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}1}(2900)^0 D^{(*)+})$	$(3.8\,^{+0.7}_{-1.0}\,^{+1.6}_{-1.1} \pm 0.3) \times 10^{-5}$	$(6.7 \pm 2.3) \times 10^{-5}$
$\frac{\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}0}(2870)^0 D^{(*)+})}{\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}1}(2900)^0 D^{(*)+})}$	$1.17 \pm 0.31 \pm 0.48$	0.18 ± 0.05

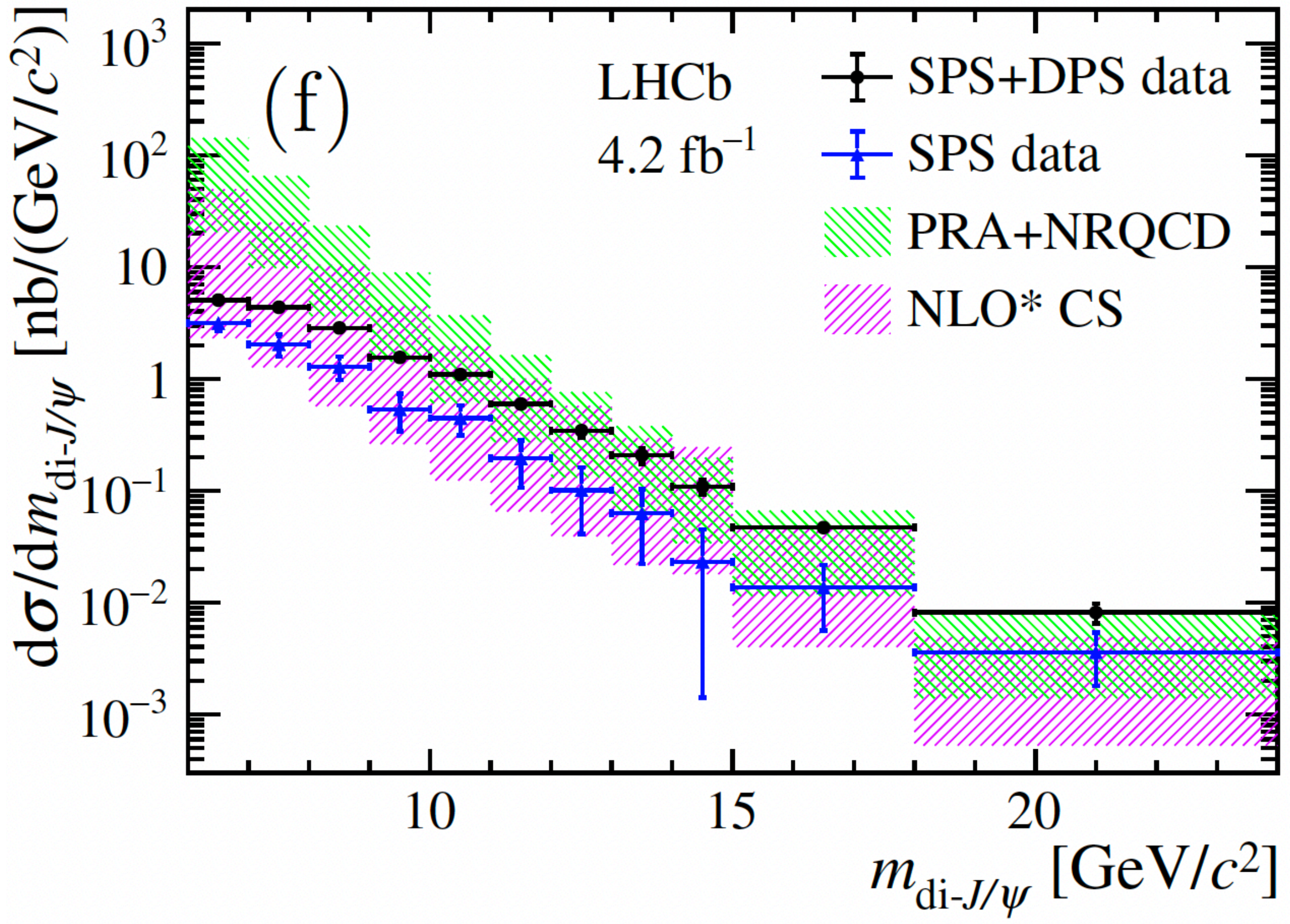
This work		Known states [6]		$c\bar{c}$ prediction [34]	
$\eta_c(3945)$	$J^{PC} = 0^{-+}$	$X(3940)$ [9,10]	$J^{PC} = ??^?$	$\eta_c(3S)$	$J^{PC} = 0^{-+}$
$m_0 = 3945\,^{+28}_{-17}\,^{+37}_{-28}$	$\Gamma_0 = 130\,^{+92}_{-49}\,^{+101}_{-70}$	$m_0 = 3942 \pm 9$	$\Gamma_0 = 37\,^{+27}_{-17}$	$m_0 = 4064$	$\Gamma_0 = 80$
$h_c(4000)$	$J^{PC} = 1^{+-}$	$T_{c\bar{c}}(4020)^0$ [35]	$J^{PC} = ?^{?-}$	$h_c(2P)$	$J^{PC} = 1^{+-}$
$m_0 = 4000\,^{+17}_{-14}\,^{+29}_{-22}$	$\Gamma_0 = 184\,^{+71}_{-45}\,^{+97}_{-61}$	$m_0 = 4025.5\,^{+2.0}_{-4.7} \pm 3.1$	$\Gamma_0 = 23.0 \pm 6.0 \pm 1.0$	$m_0 = 3956$	$\Gamma_0 = 87$
$\chi_{c1}(4010)$	$J^{PC} = 1^{++}$			$\chi_{c1}(2P)$	$J^{PC} = 1^{++}$
$m_0 = 4012.5\,^{+3.6}_{-3.9}\,^{+4.1}_{-3.7}$	$\Gamma_0 = 62.7\,^{+7.0}_{-6.4}\,^{+6.4}_{-6.6}$			$m_0 = 3953$	$\Gamma_0 = 165$
$h_c(4300)$	$J^{PC} = 1^{+-}$			$h_c(3P)$	$J^{PC} = 1^{+-}$
$m_0 = 4307.3\,^{+6.4}_{-6.6}\,^{+3.3}_{-4.1}$	$\Gamma_0 = 58\,^{+28}_{-16}\,^{+28}_{-25}$			$m_0 = 4318$	$\Gamma_0 = 75$
		$\chi_c(4274)$ [36]	$J^{PC} = 1^{++}$	$\chi_{c1}(3P)$	$J^{PC} = 1^{++}$
		$m_0 = 4294 \pm 4\,^{+6}_{-3}$	$\Gamma_0 = 53 \pm 5 \pm 5$	$m_0 = 4317$	$\Gamma_0 = 39$

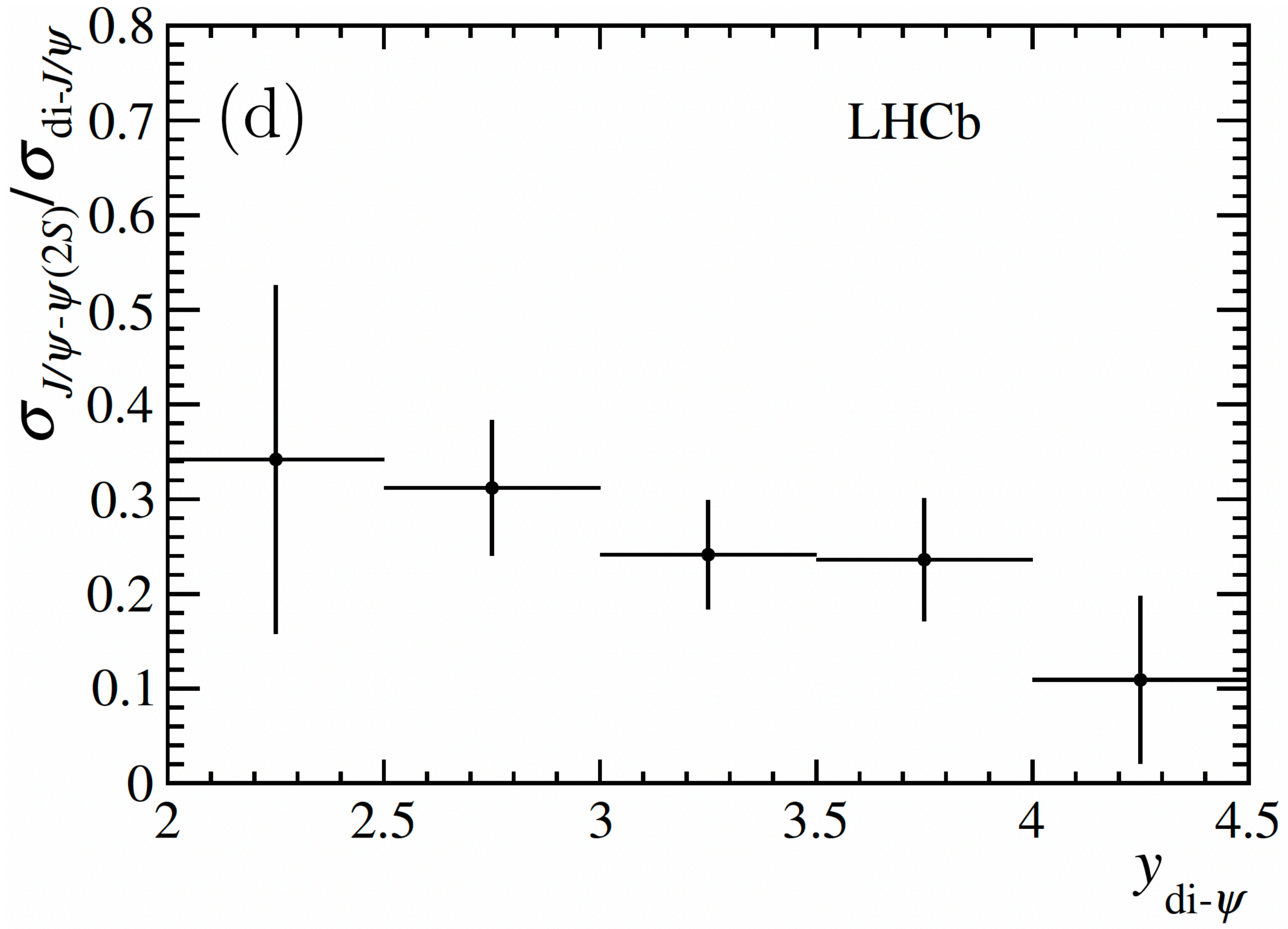
Production cross section of charmonium pairs

JHEP 03 (2024) 088
JHEP 05 (2024) 259
Li Xu, Liupan An etc

- SPS and DPS contributions in J/ψ-pair production cross-section measured separately
- The cross section ratio of $J/\psi - \psi(2S)$ to di-J/ψ is significant smaller than the SPS prediction and consistent with DPS precision

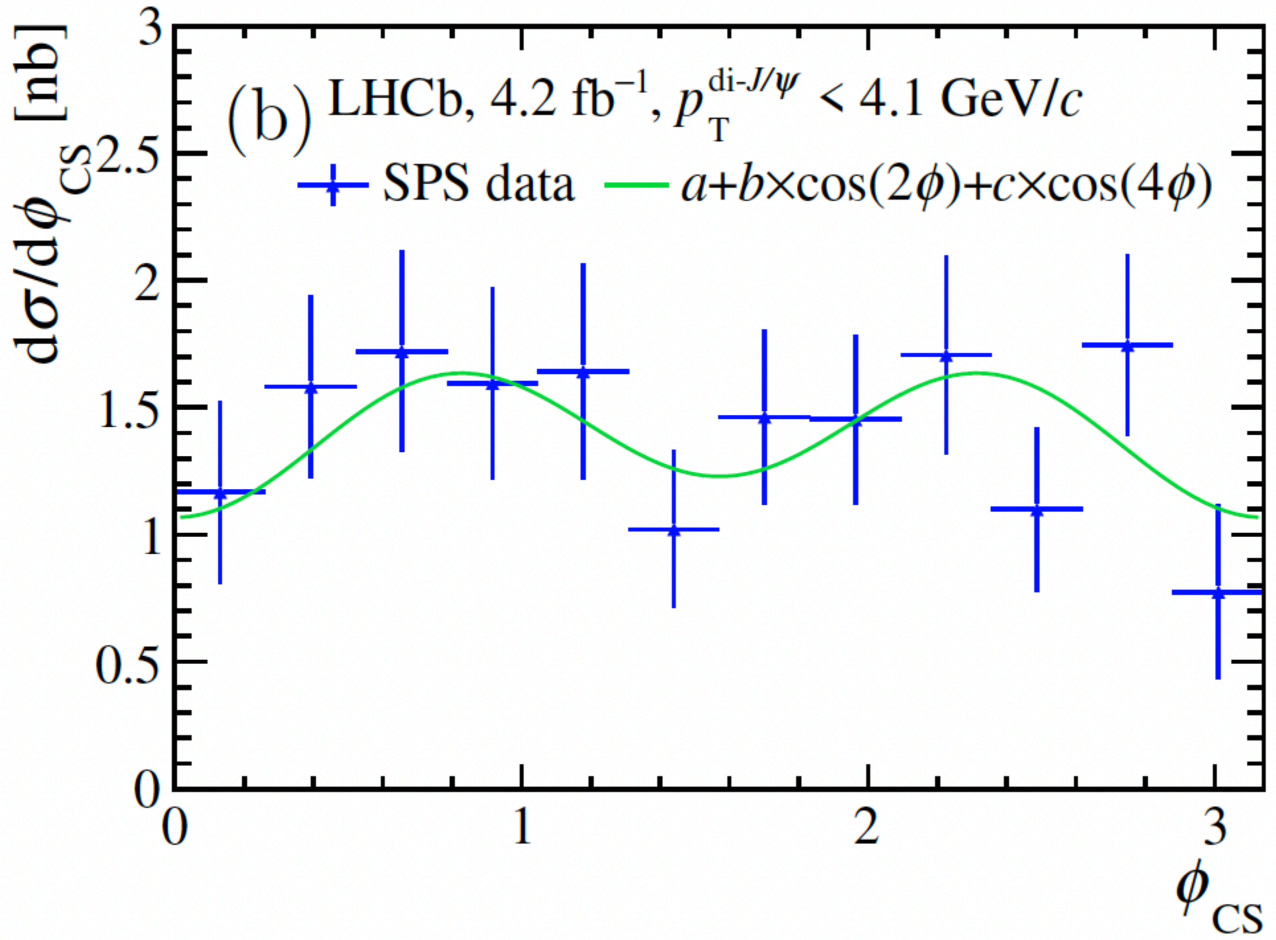
Prediction: 0.94 ± 0.30 for SPS, 0.282±0.027 for DPS

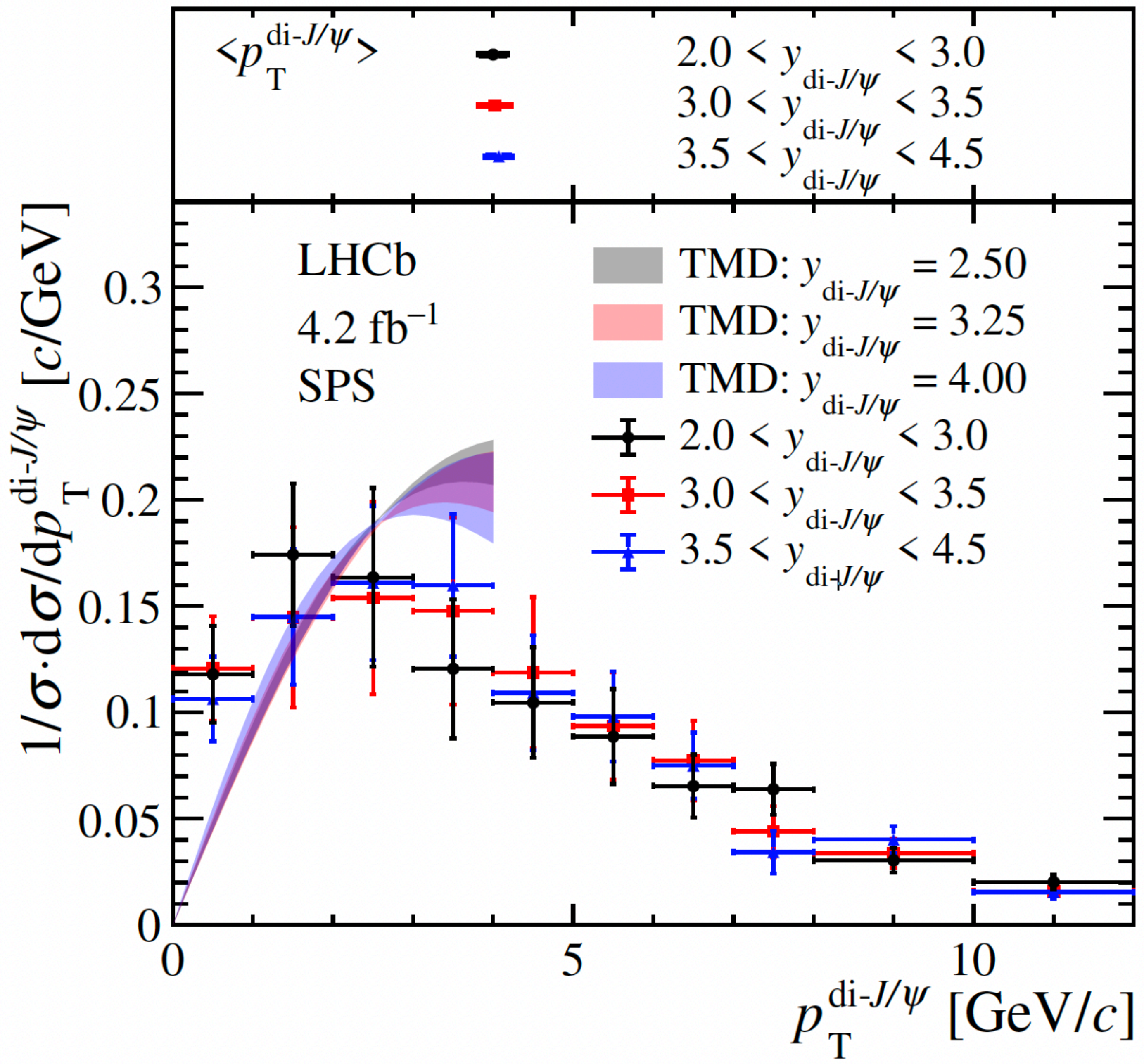




$$\frac{\sigma_{J/\psi-\psi(2S)}}{\sigma_{J/\psi-J/\psi}} = 0.274 \pm 0.044 \pm 0.008$$

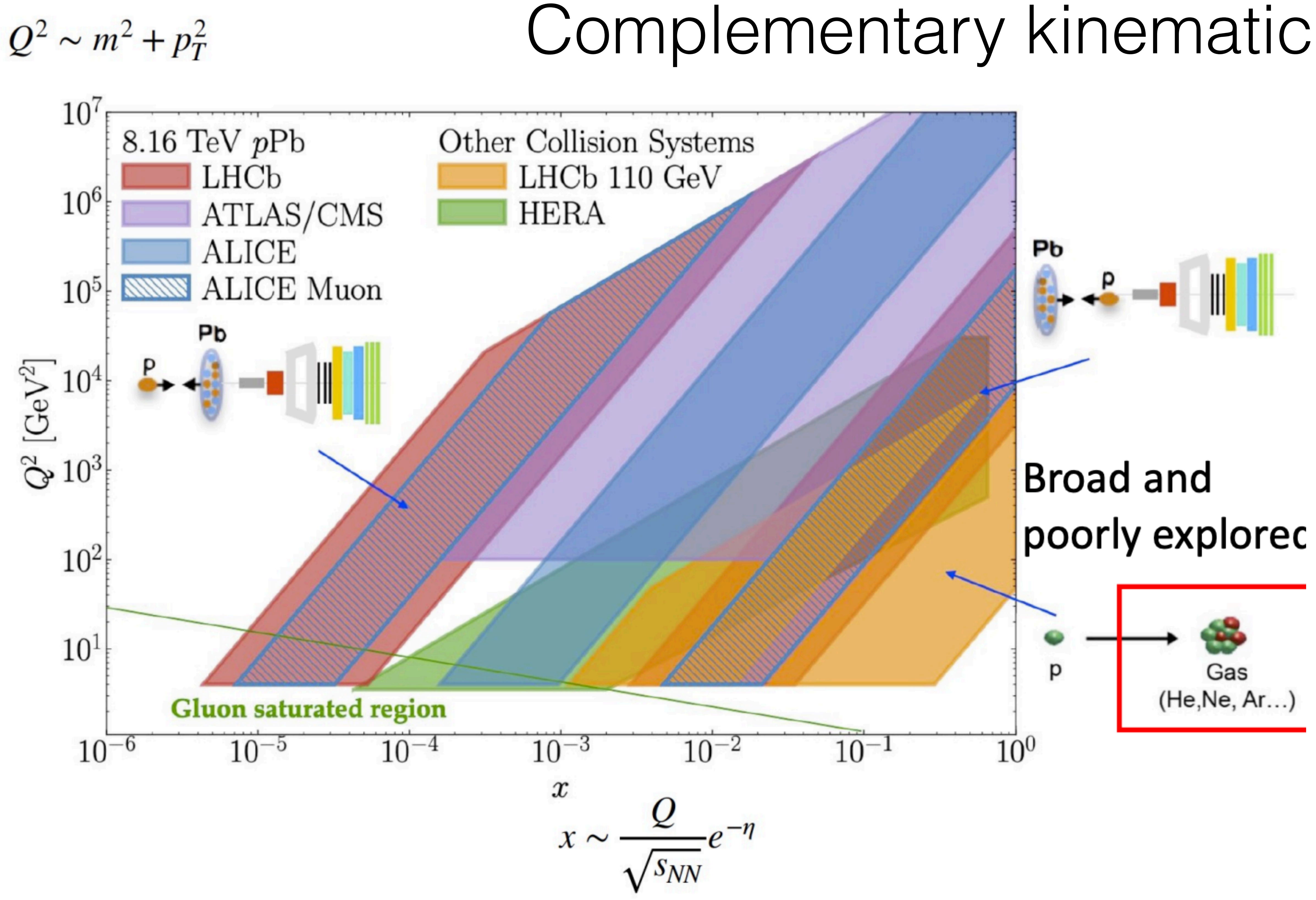
- The gloun TMDs probed via ϕ_{CS} and $p_T^{di-J/\psi}$ spectrum from SPS process





Heavy ions & EW physics

Complementary kinematic regions to ATLAS/CMS



➢A broad physics scheme

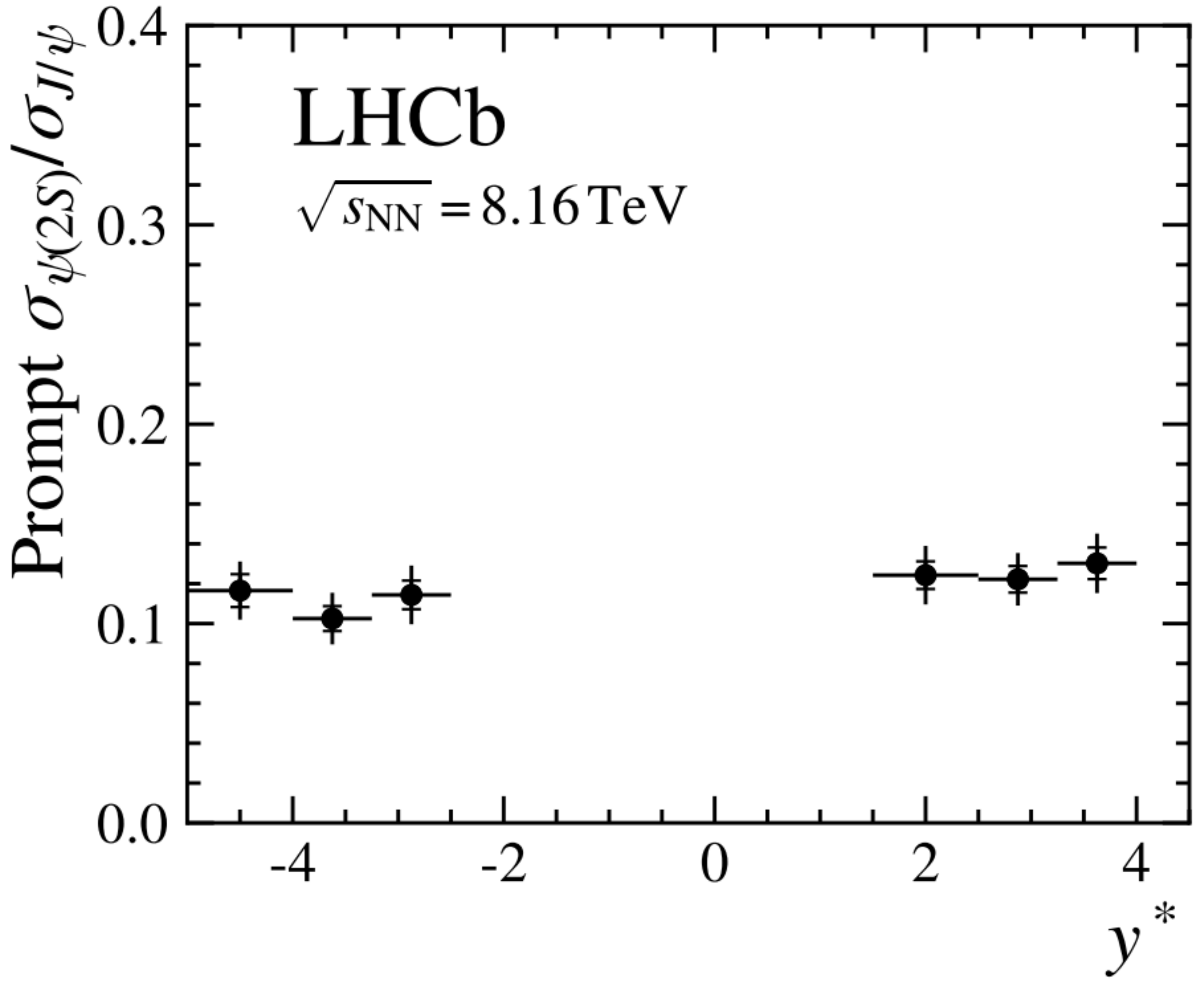
- ✓Hadronization in hot and cold nuclear matter
- ✓Probes for quark-gluon plasma (QGP)
- ✓Constrain nPDF
- ✓Cosmic ray and astro-particle physics
- ✓Ultra-peripheral collisions (UPC)
- ✓Exotic production

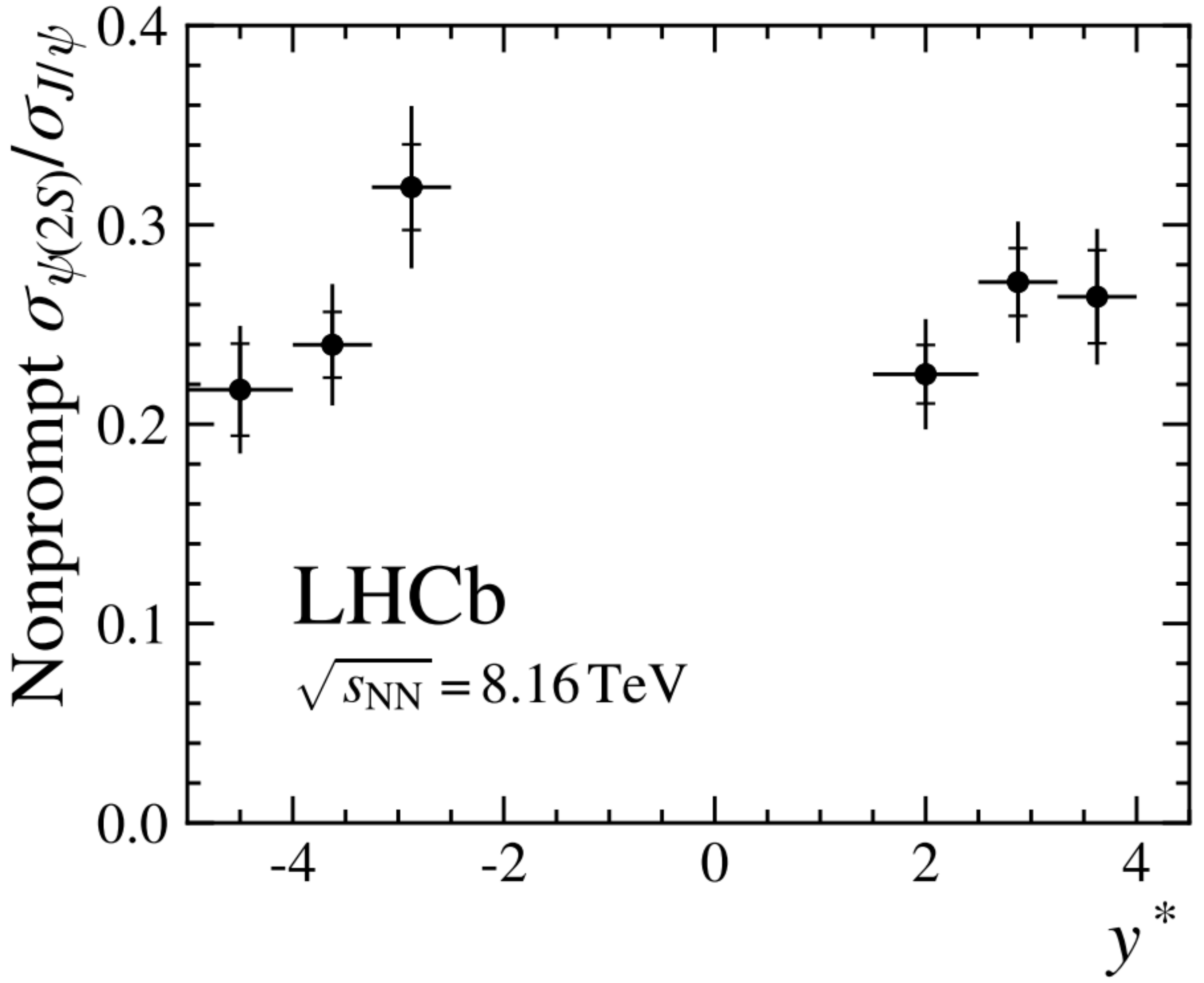
** More details in the morning session on Wednesday*

Production cross section of charmonium-(like) states

- The production of prompt $\psi(2S)$ suppressed than J/ψ

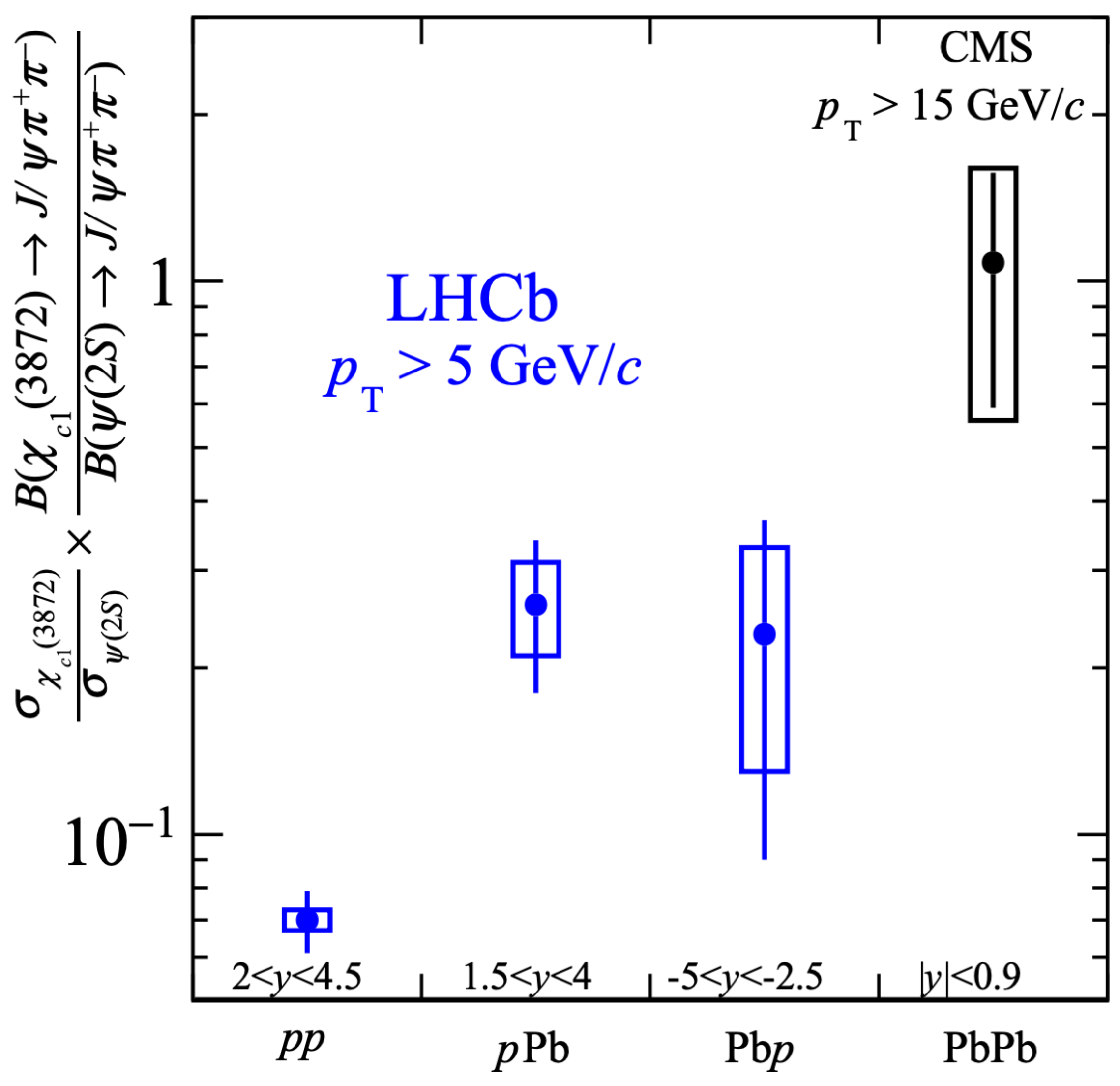
arXiv:2401.11342

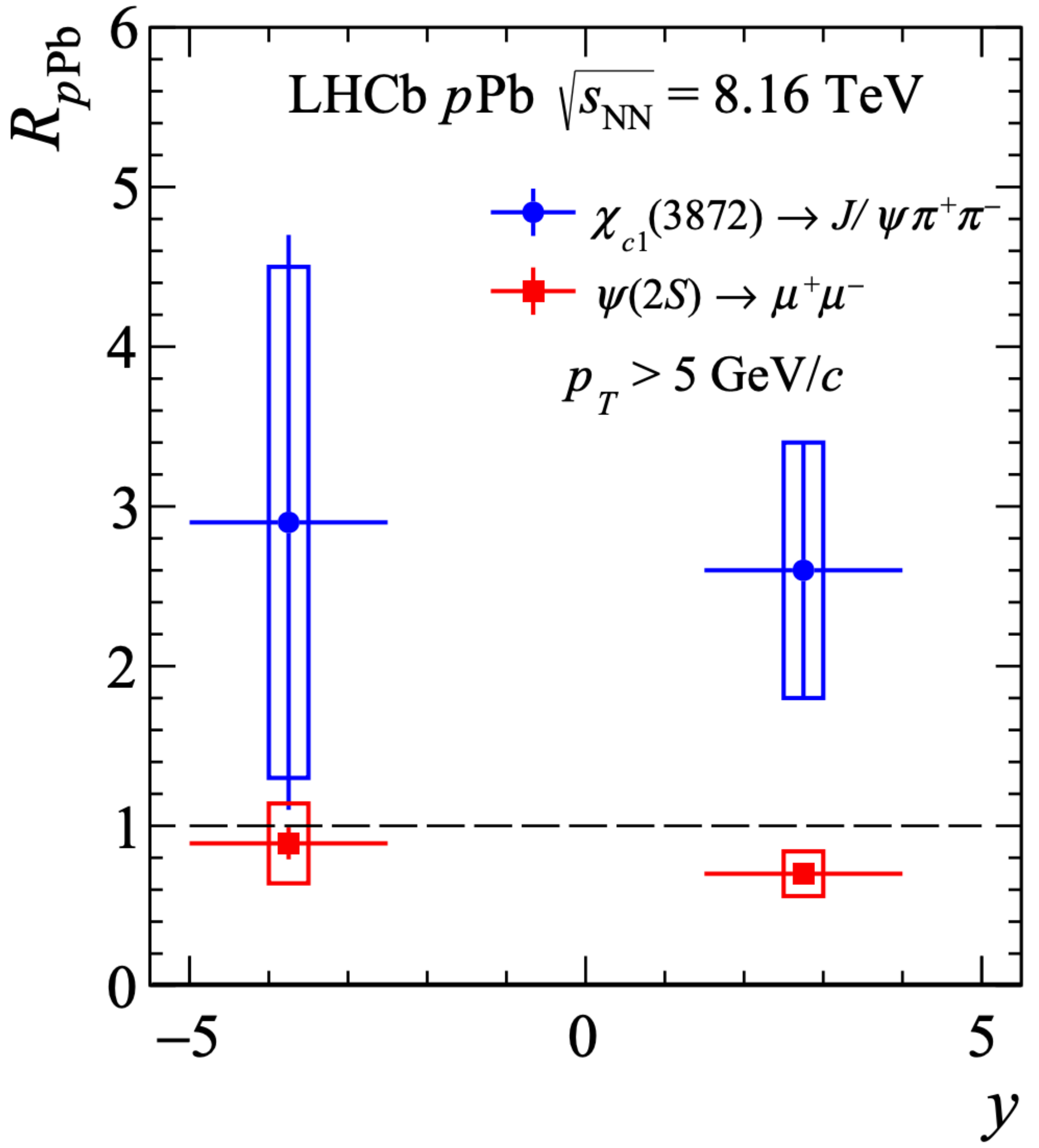




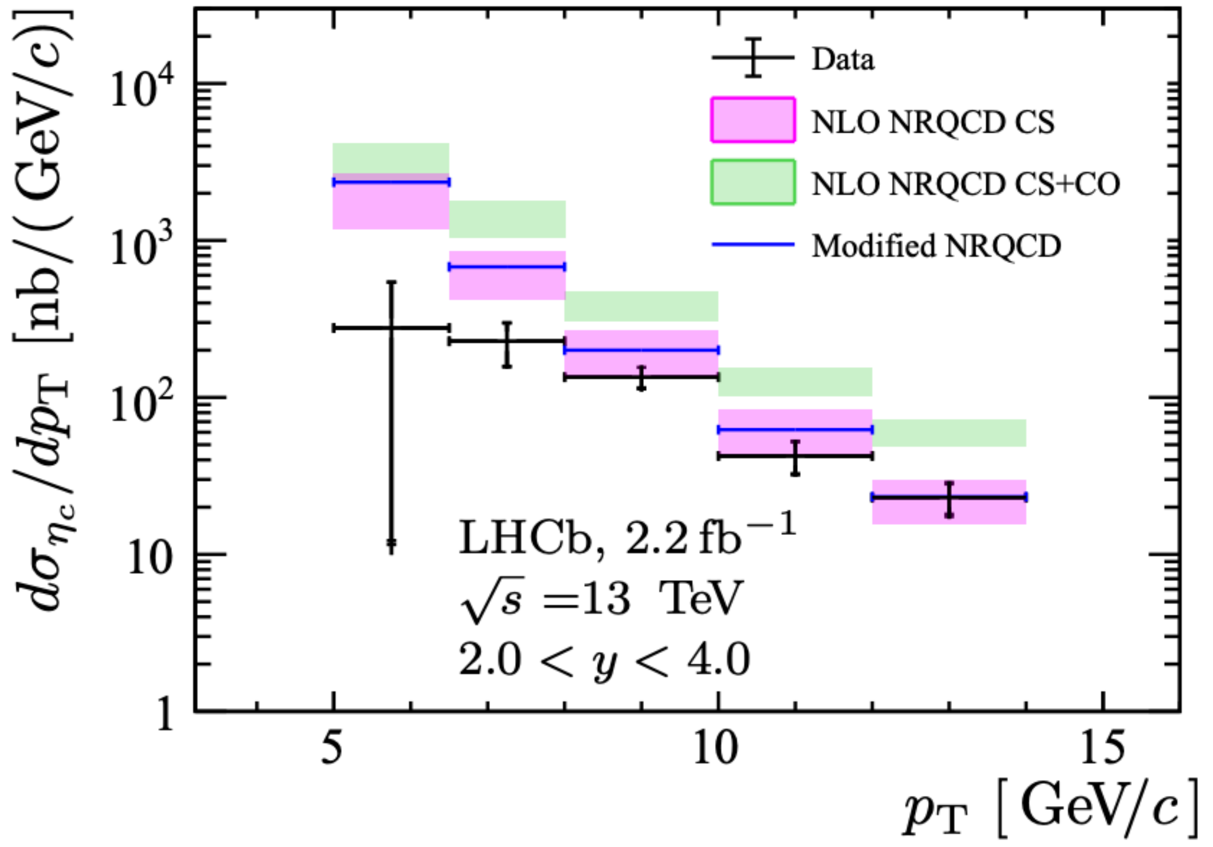
- $\chi_{c1}(3872)$ may experiences different dynamics in the nuclear medium than the conventional charmonia

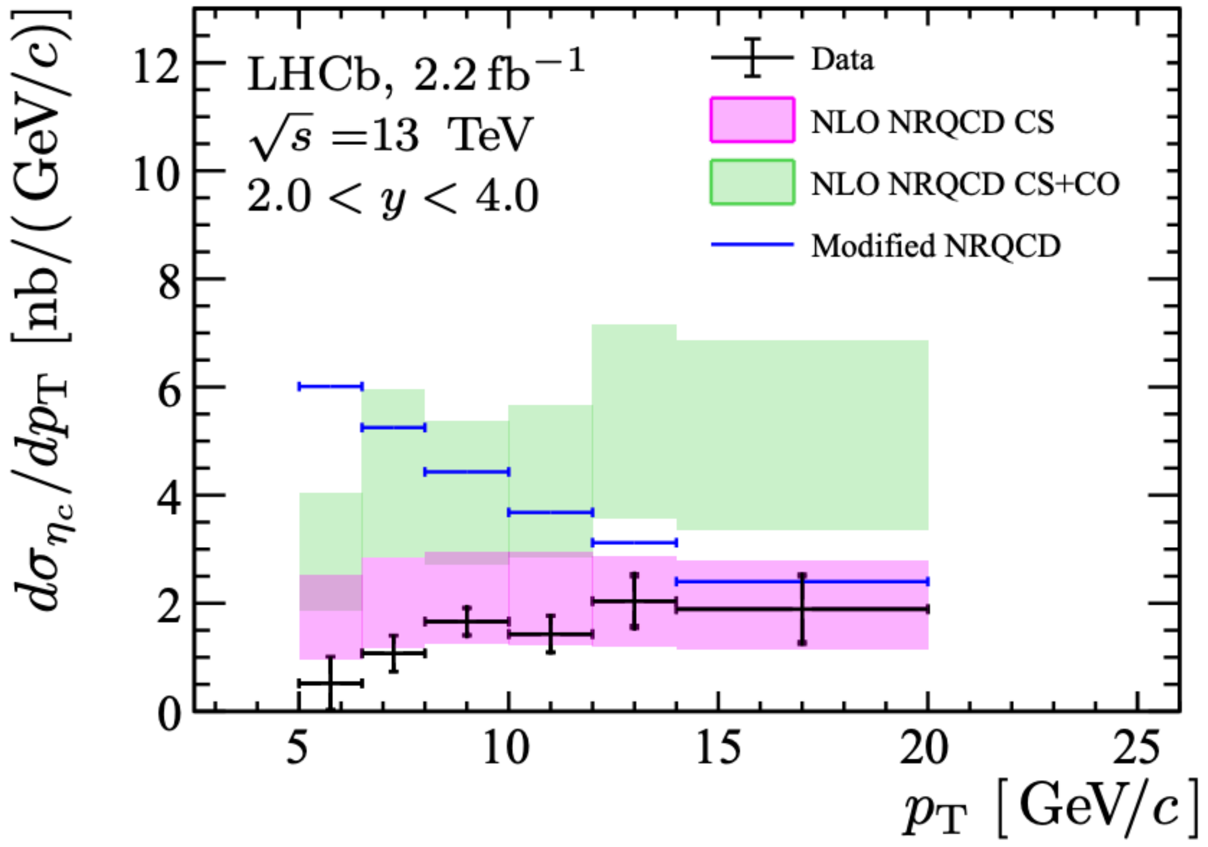
PhysRevLett132(2024)242301





$d\sigma(\eta_c)/dp_T$ arXiv:2407.14261 $d\sigma(\eta_c)/d\sigma(J/\psi)$





$$\frac{(\sigma_{\eta_c(2S)} \times \mathcal{B}_{\eta_c(2S)\to p\bar{p}})}{(\sigma_{J/\psi} \times \mathcal{B}_{J/\psi\to p\bar{p}})} < 0.11\ (0.14)$$

$$\frac{(\sigma_{h_c(1P)} \times \mathcal{B}_{h_c(1P)\to p\bar{p}})}{(\sigma_{J/\psi} \times \mathcal{B}_{J/\psi\to p\bar{p}})} < 0.12\ (0.13)$$

$$(\sigma_{\eta_c}/\sigma_{J/\psi})^{5.0<p_T<20.0\,\mathrm{GeV}/c,\ 2.0<y<4.0} = 1.32 \pm 0.14 \pm 0.09 \pm 0.13.$$

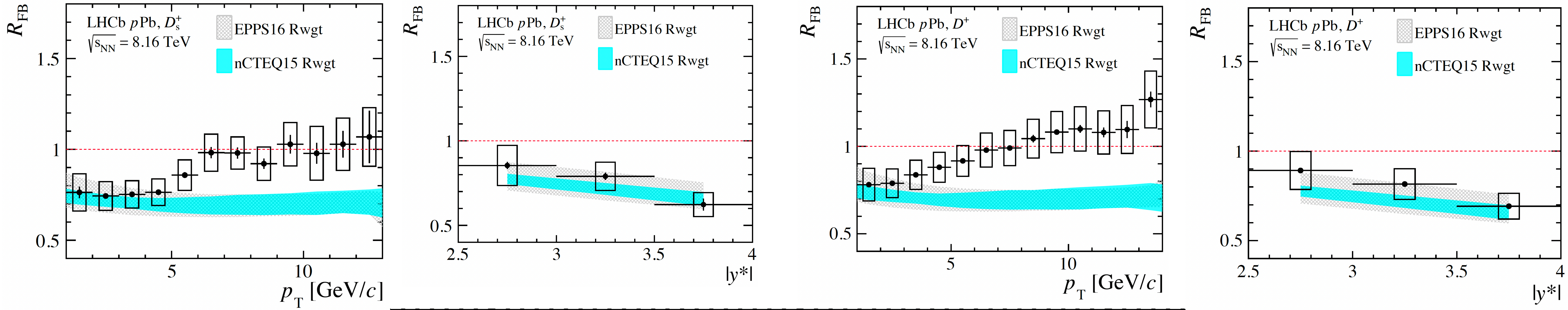
Enhanced production in high-multiplicity pPb collisions

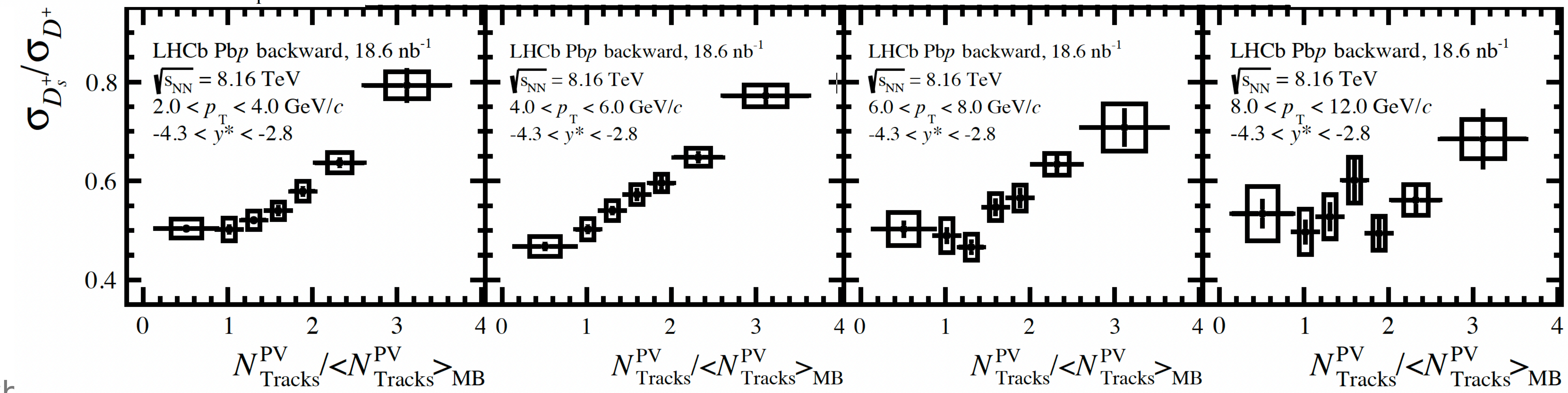
arXiv: 2311.08490

Chenxi Gu, Jiayin Sun etc

- Enhanced D_s^+ to D^+ production in high-multiplicity at $\sqrt{s_{\rm NN}} = 8.16$ TeV
- Qualitatively consistent with expectations arising from quark coalescence as an adjunct charm hadronization mechanism

$$R_{\rm FB}(p_{\rm T}, |y^*|) = \frac{{\rm d}^2\sigma_{p{\rm Pb}}(p_{\rm T}, +|y^*|)/({\rm d}p_{\rm T}{\rm d}y^*)}{{\rm d}^2\sigma_{{\rm Pb}p}(p_{\rm T}, -|y^*|)/({\rm d}p_{\rm T}{\rm d}y^*)}$$

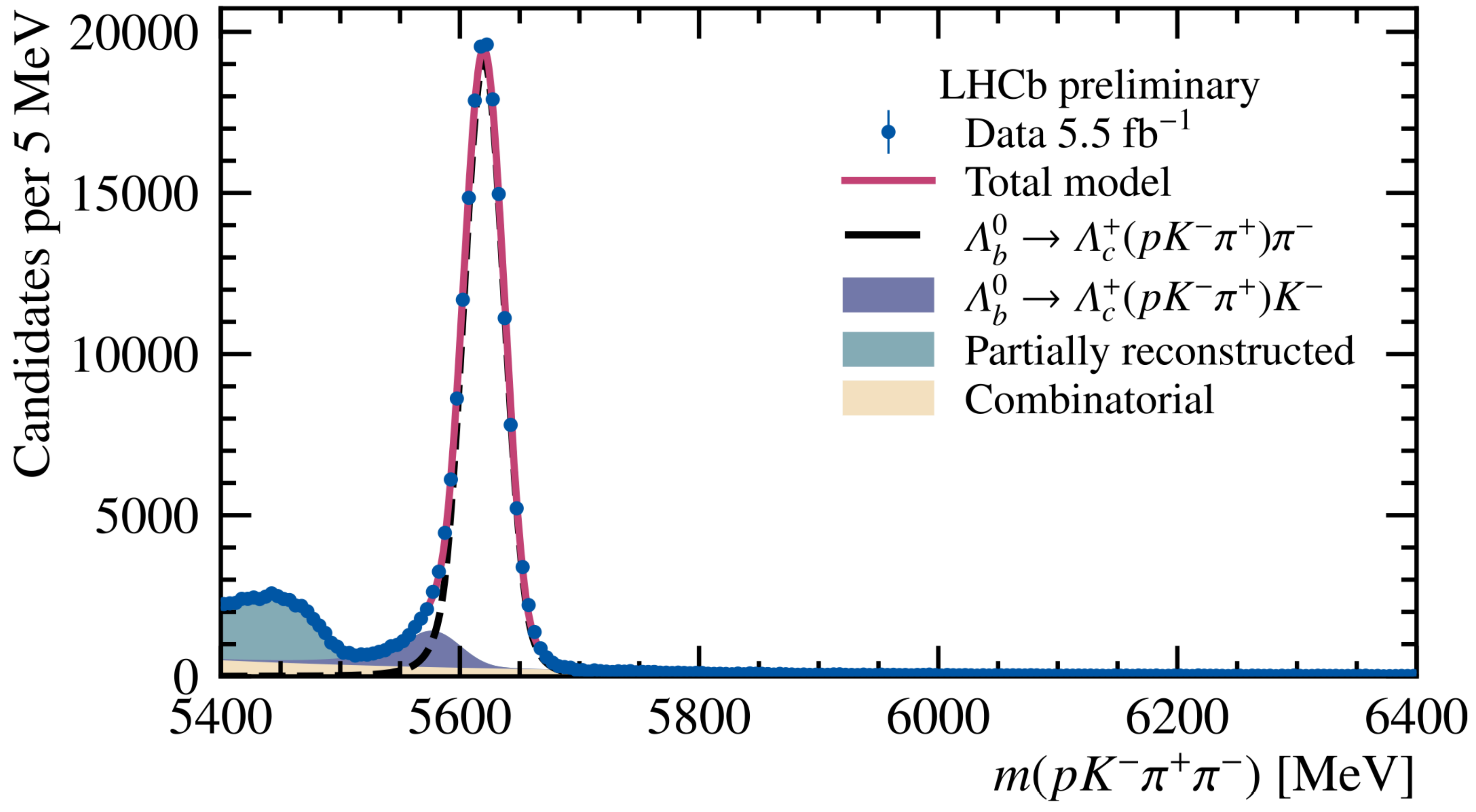




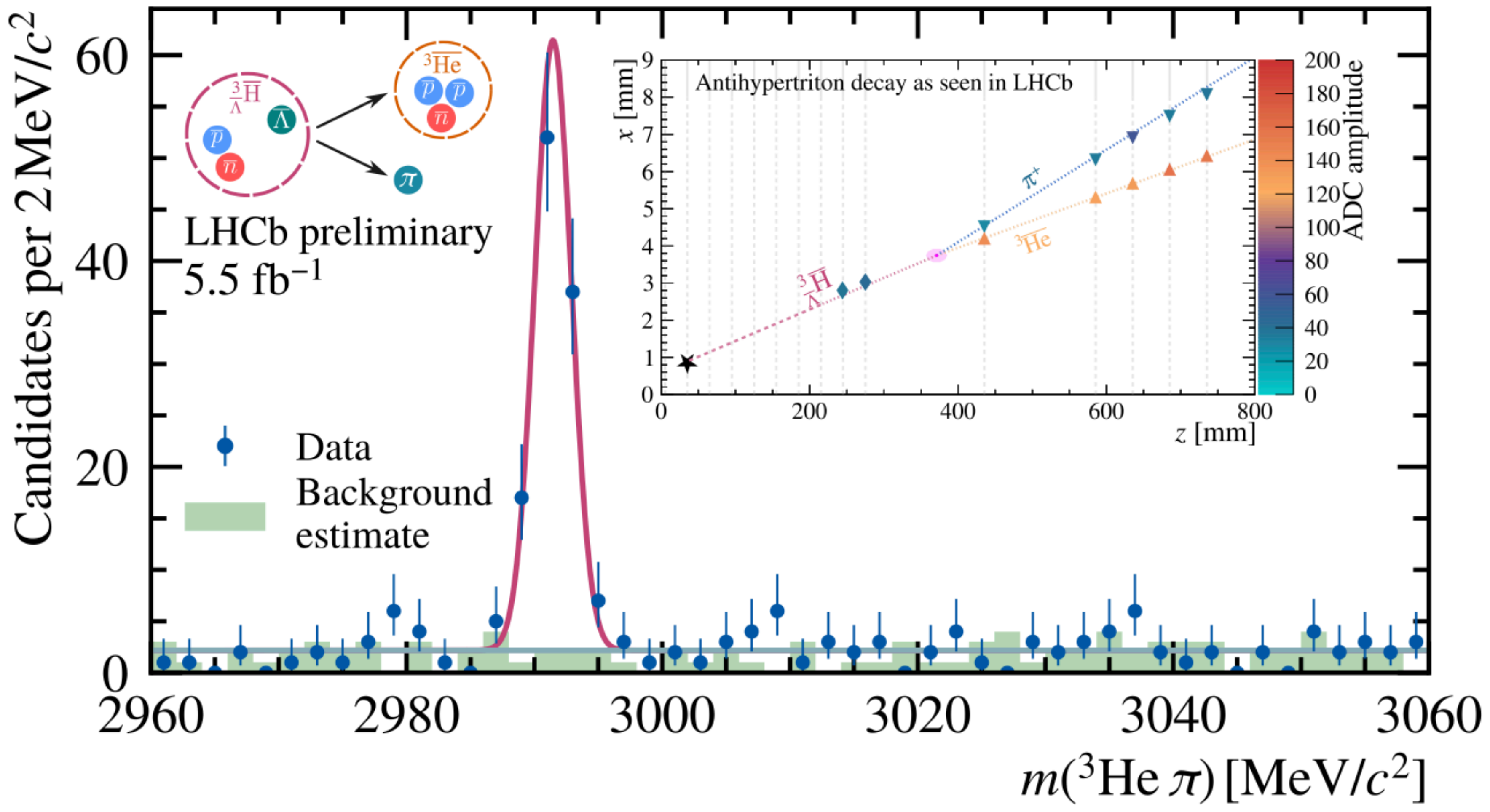
Observation of (anti)helium production in Λ_b decays

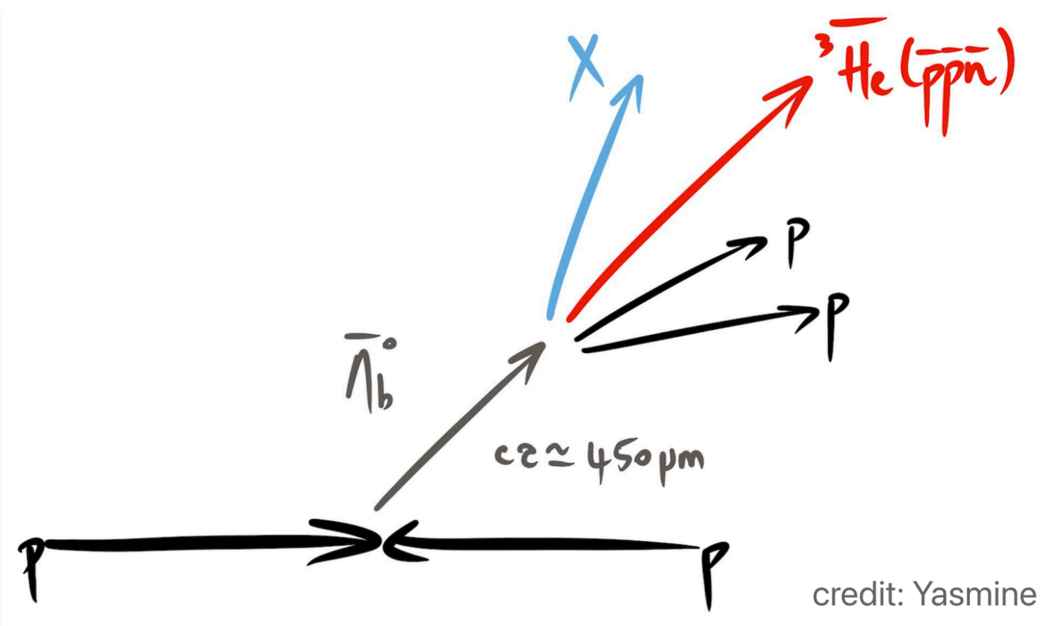
- Observation of antihelium in Cosmic Rays could be a signature of physics beyond the standard model. Interesting scenario where anti-Λ_b are produced in Dark Matter scenario annihilation

LHCb-CONF-2024-005
in preparation

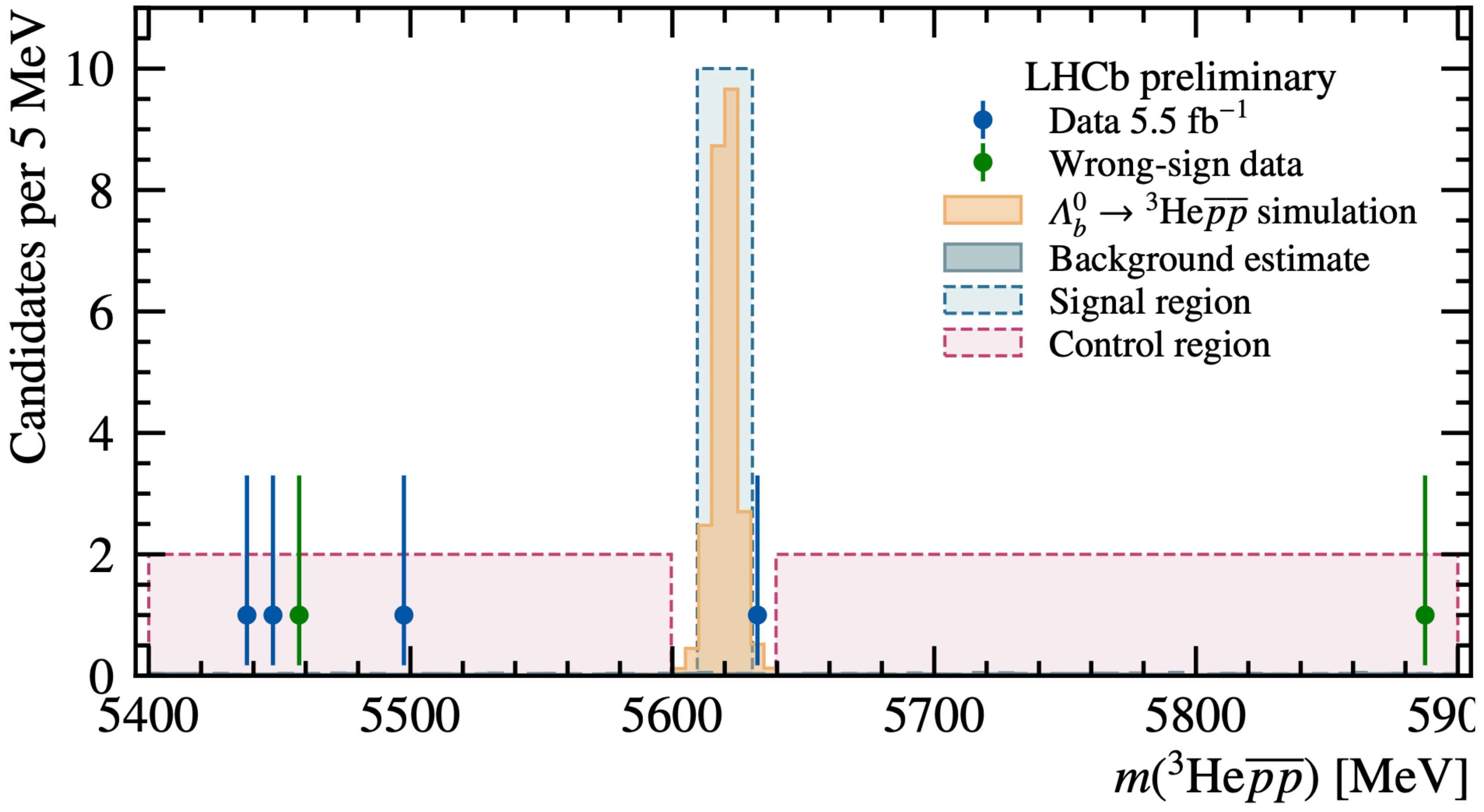


PoS EPS-HEP2023 (2024) 254

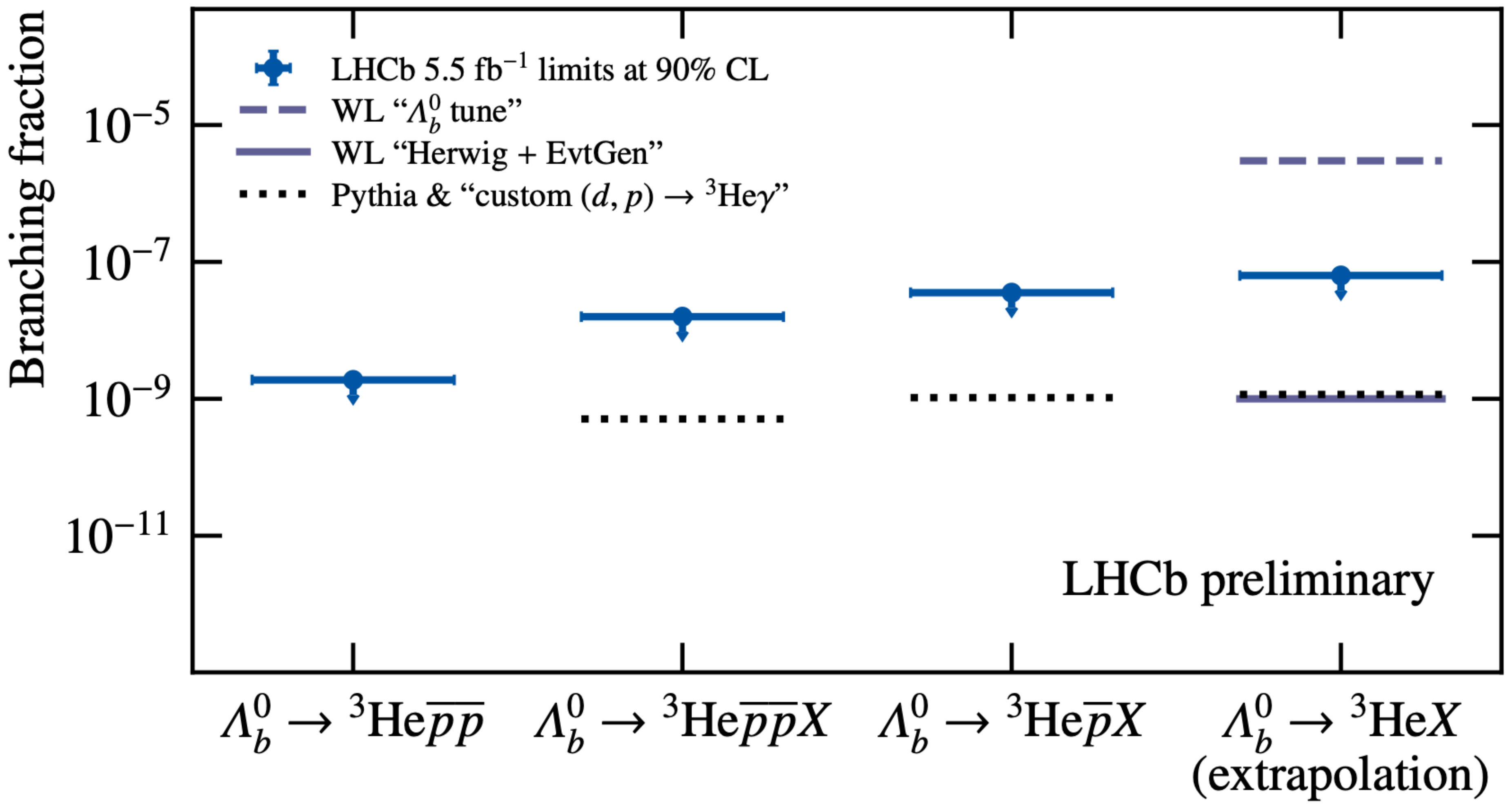




credit: Yasmine

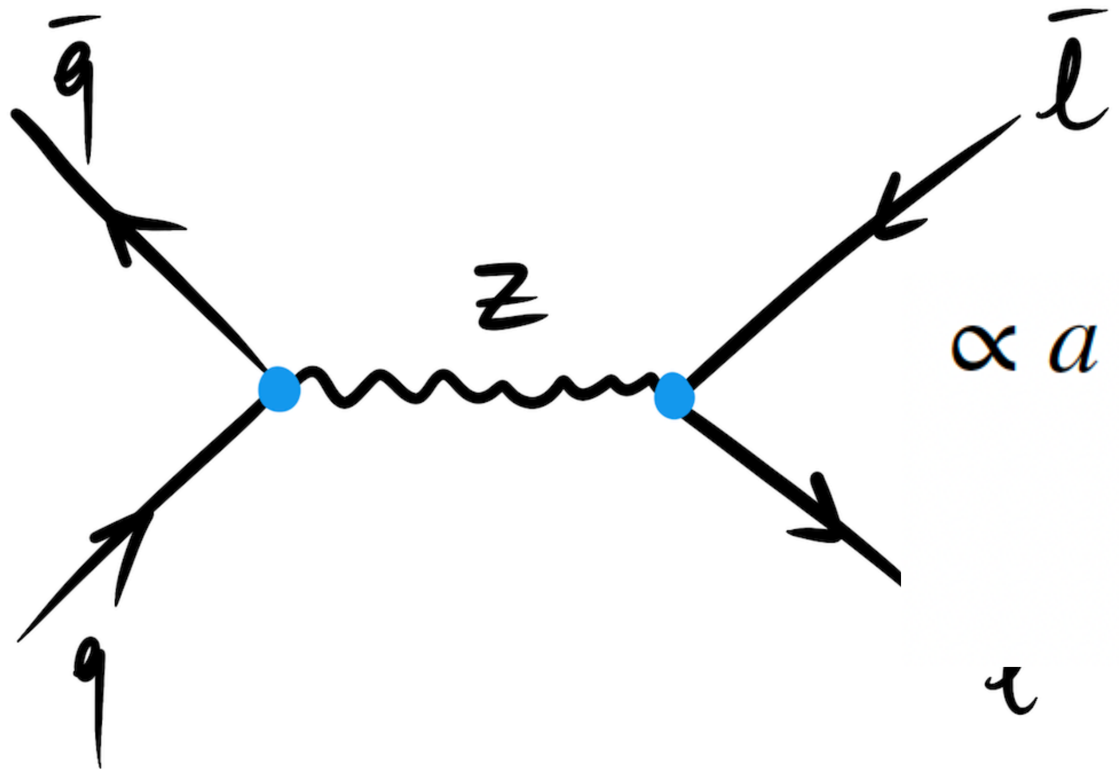


LHCb-CONF-2024-005



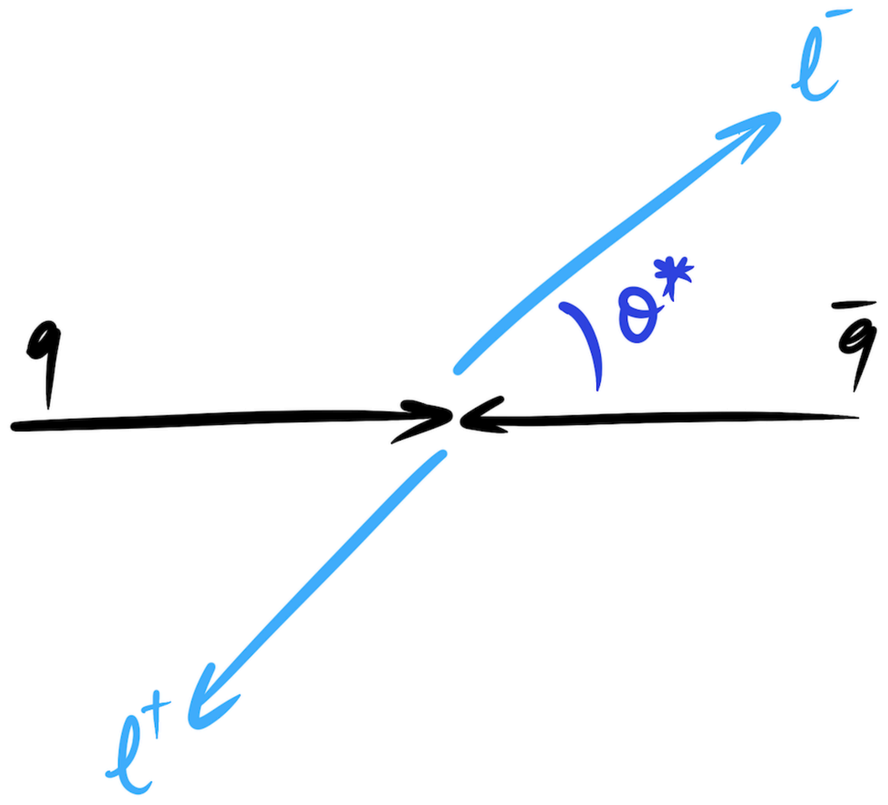
Effective leptonic weak mixing angle

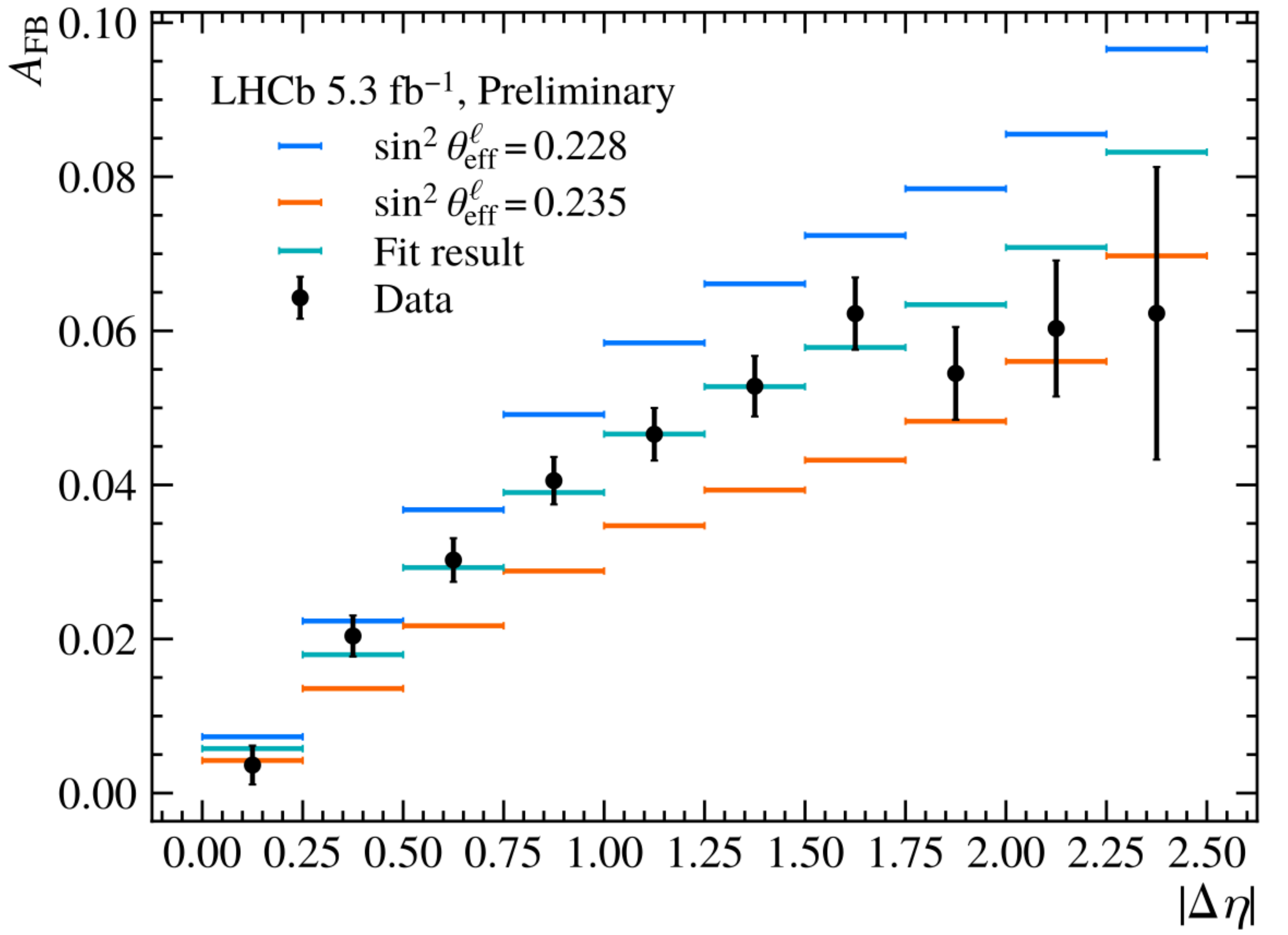
LHCb-PAPER-2024-028
in preparation



$\propto a + \cos^2\theta^* + A\cos\theta^*$

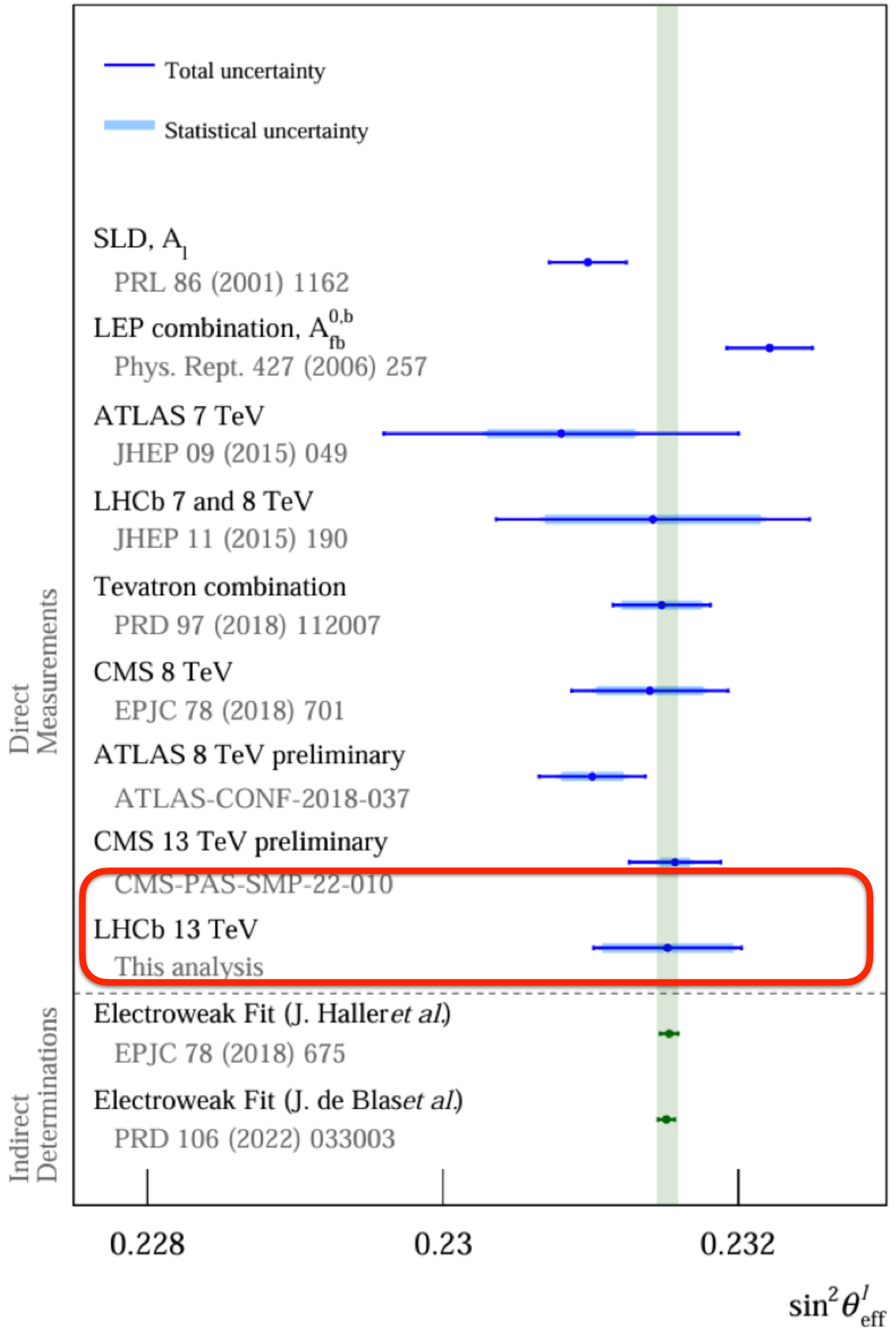
$A \longleftrightarrow A_{FB}$



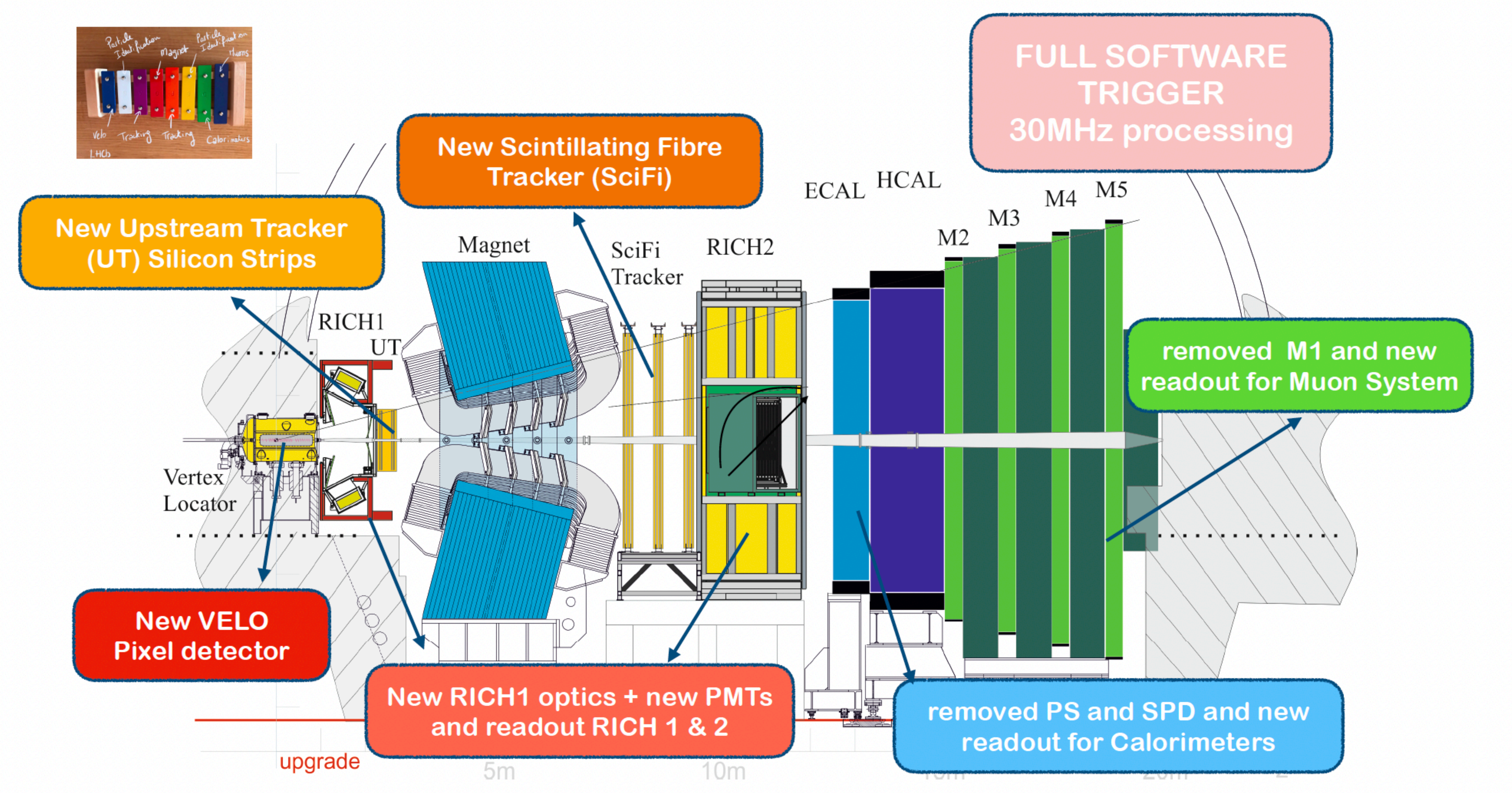


- A_{FB} is compared with predictions to NLO in strong and EW couplings to derive:

$$\sin^2\theta^{\ell}_{eff} = 0.23152 \pm 0.00044 \pm 0.00005 \pm 0.00022$$

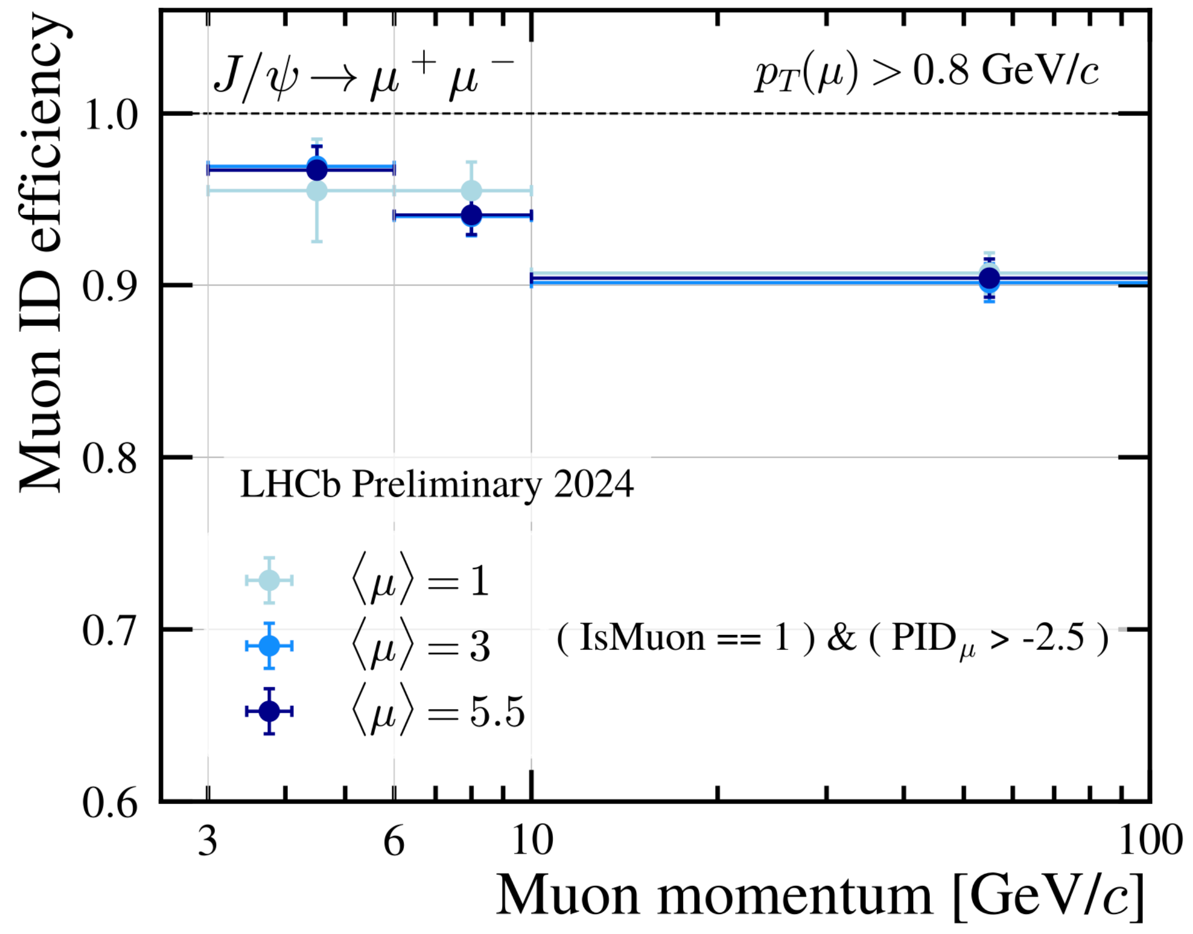


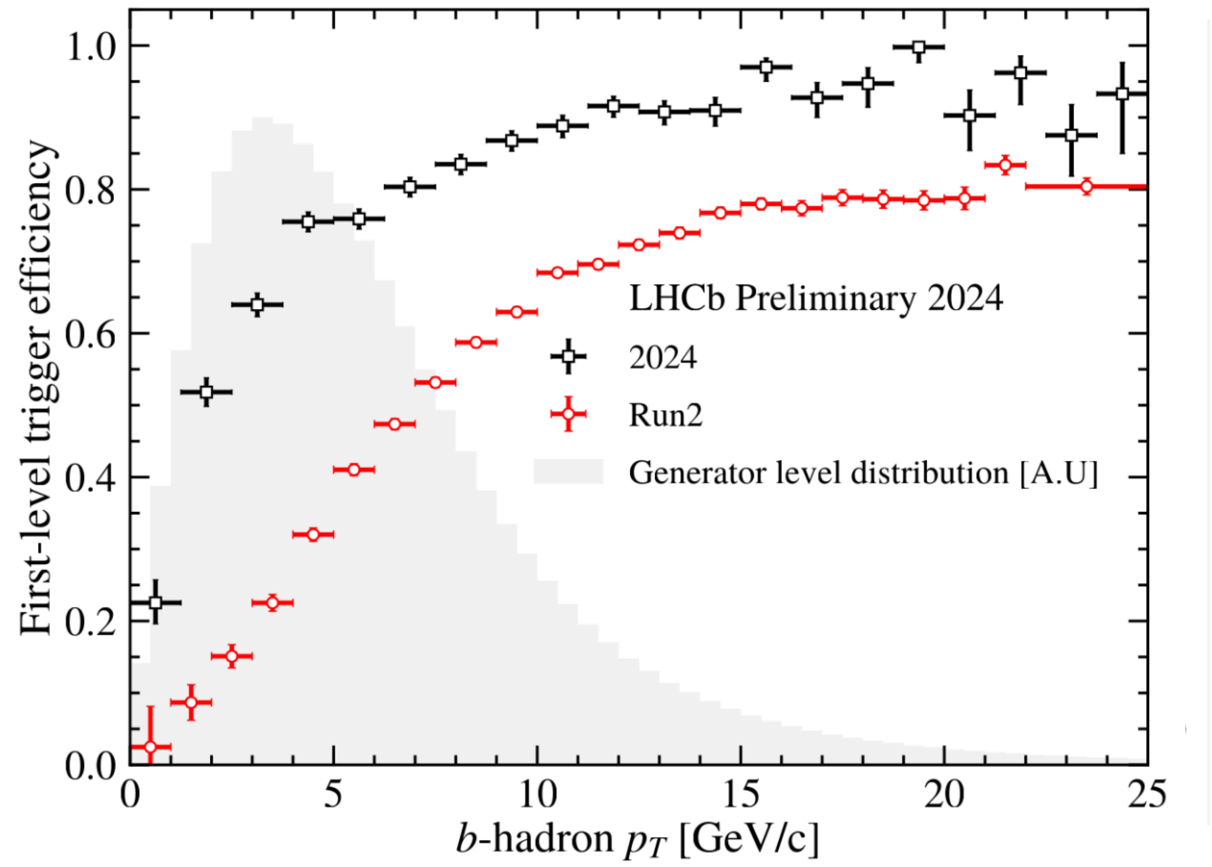
Run 3 in data taking

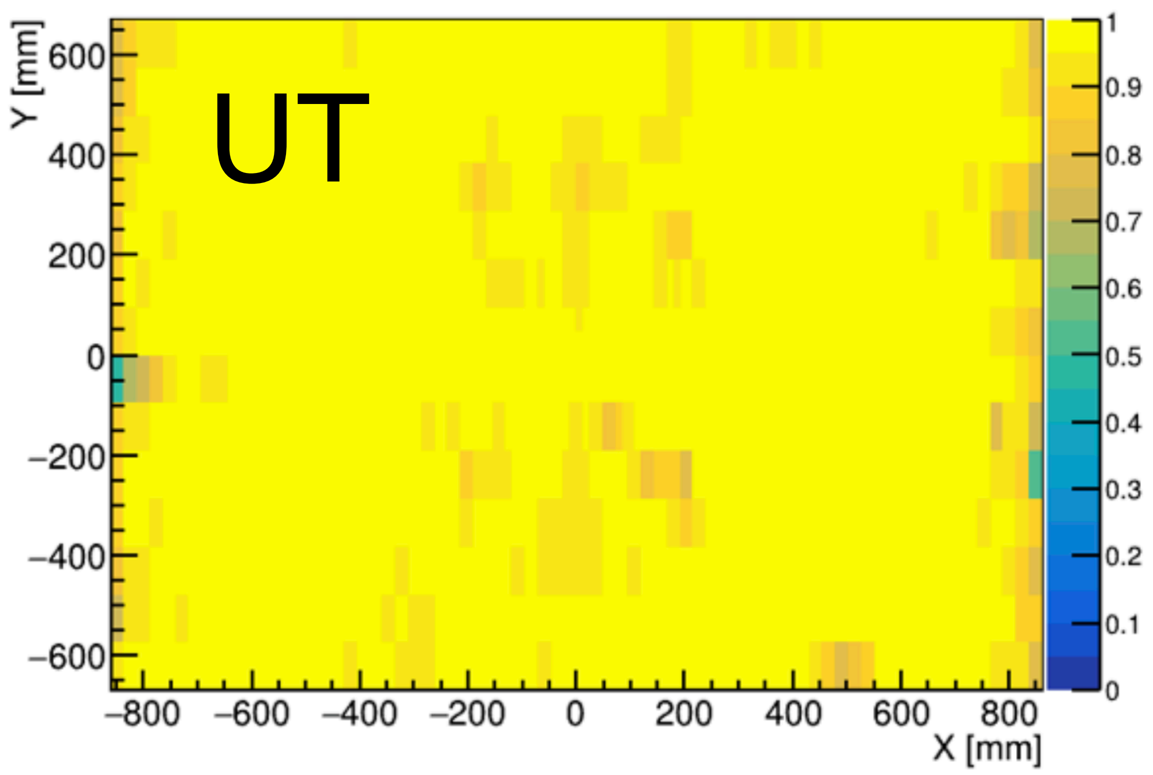


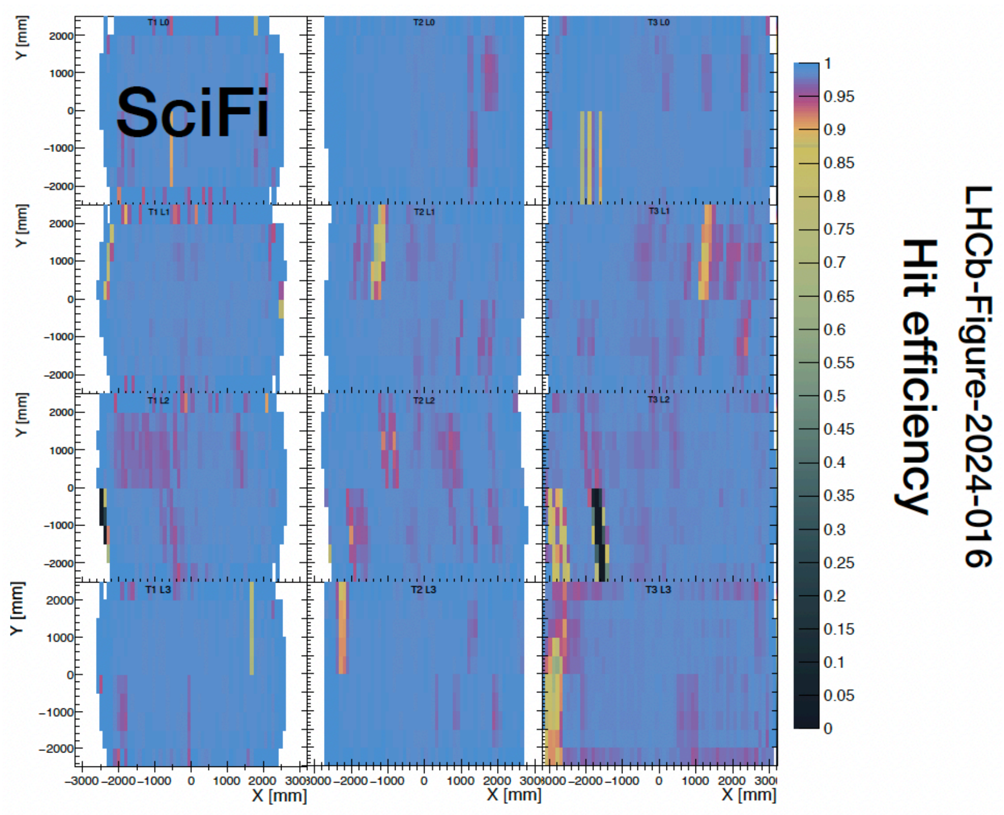
Major upgrade of all sub-detectors and readout

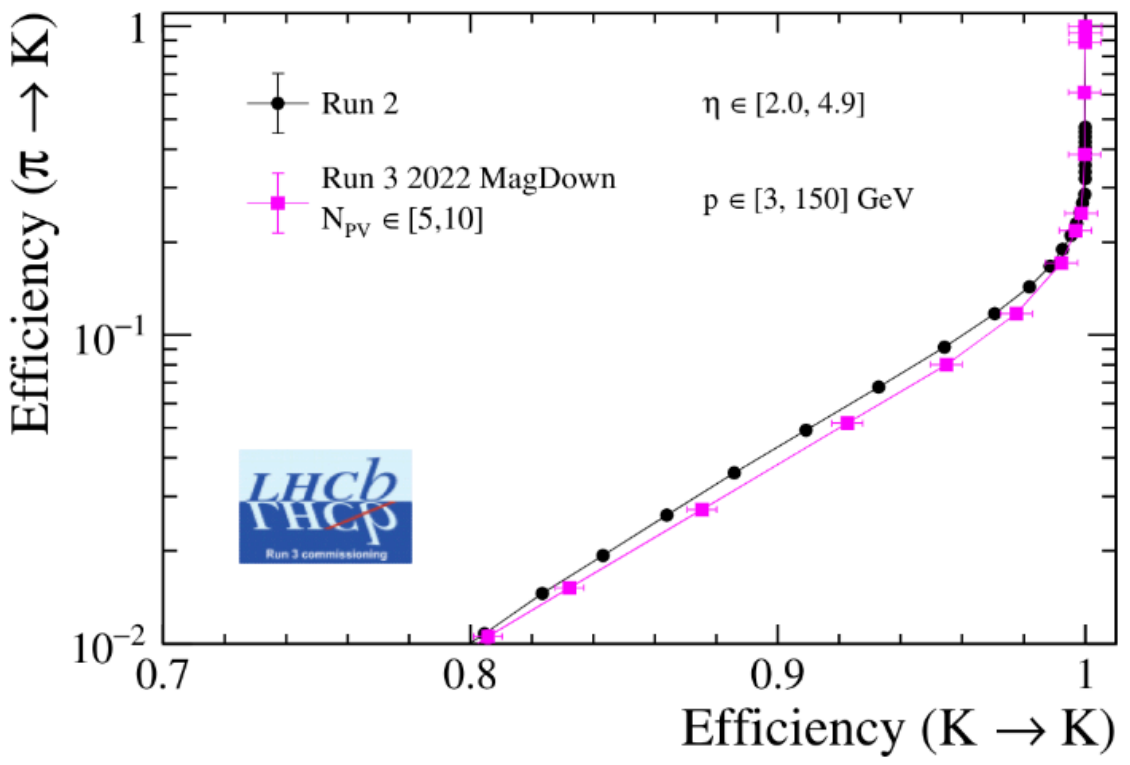
The LHCb Upgrade I arXiv:2305.10515

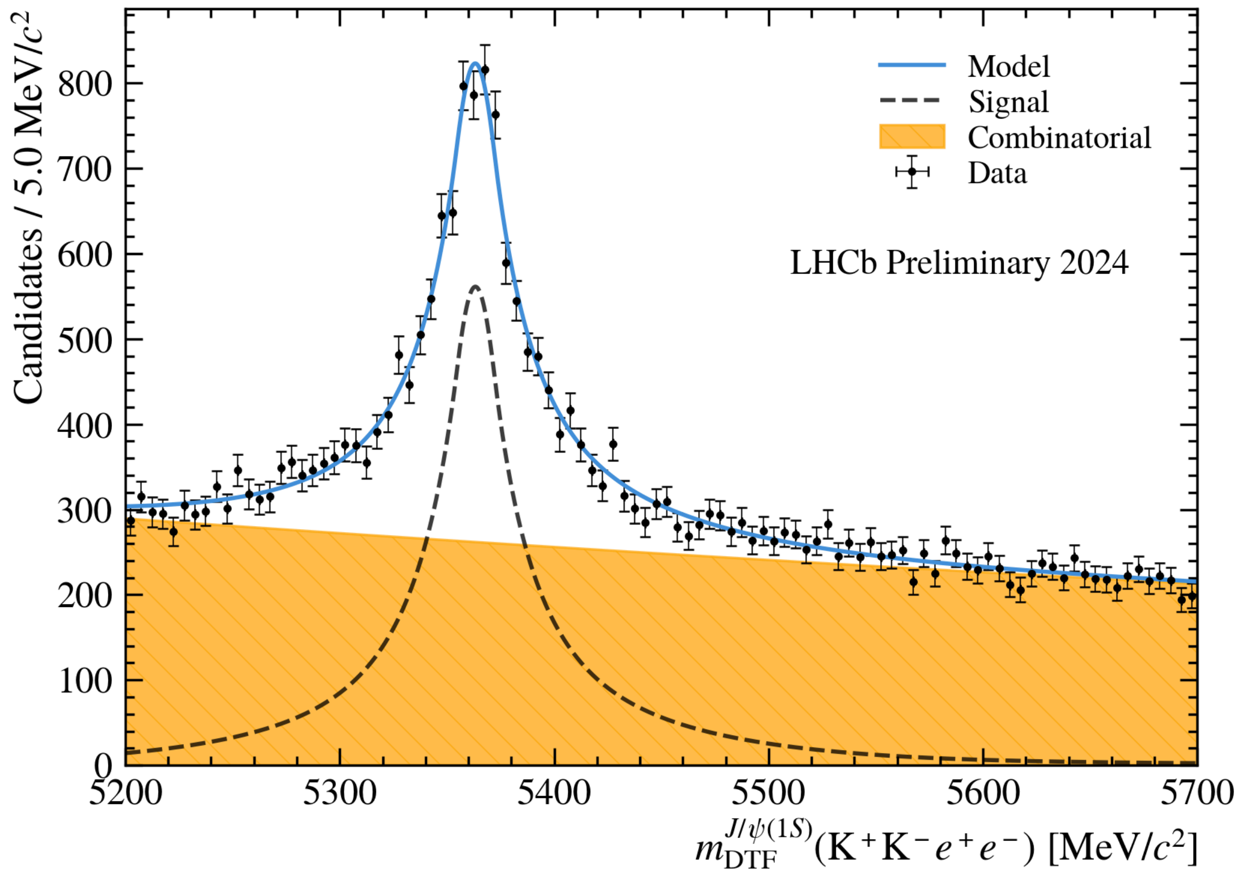




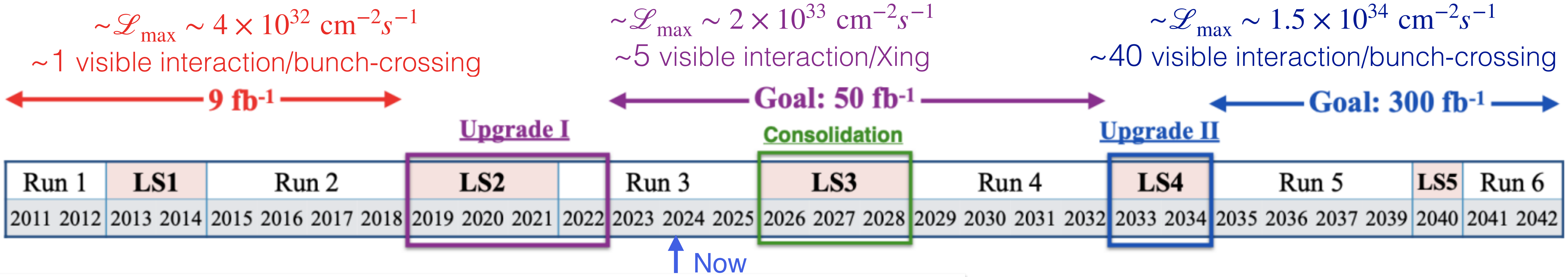








Looking at Run 3 and beyond



Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1<q^2<6\,\text{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1<q^2<6\,\text{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0\to D_s^+K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0\to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0\to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0\to D_s^+D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0\to\phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
$a_{\rm sl}^s$	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$B_s^0, B^0\to\mu^+\mu^-$					
$\mathcal{B}(B^0\to\mu^+\mu^-)/\mathcal{B}(B_s^0\to\mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0\to\mu^+\mu^-}$	22% [264]	8%	–	2%	
$S_{\mu\mu}$	–	–	–	0.2	
$b\to c\ell^-\bar{\nu}_l$ LUV studies					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	
Charm					
$\Delta A_{CP}(KK-\pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	
A_Γ $(\approx x\sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	
$x\sin\phi$ from $D^0\to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	
$x\sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	

LHCb-PUB-2018-009

- Great opportunities for many new discoveries and NP searches

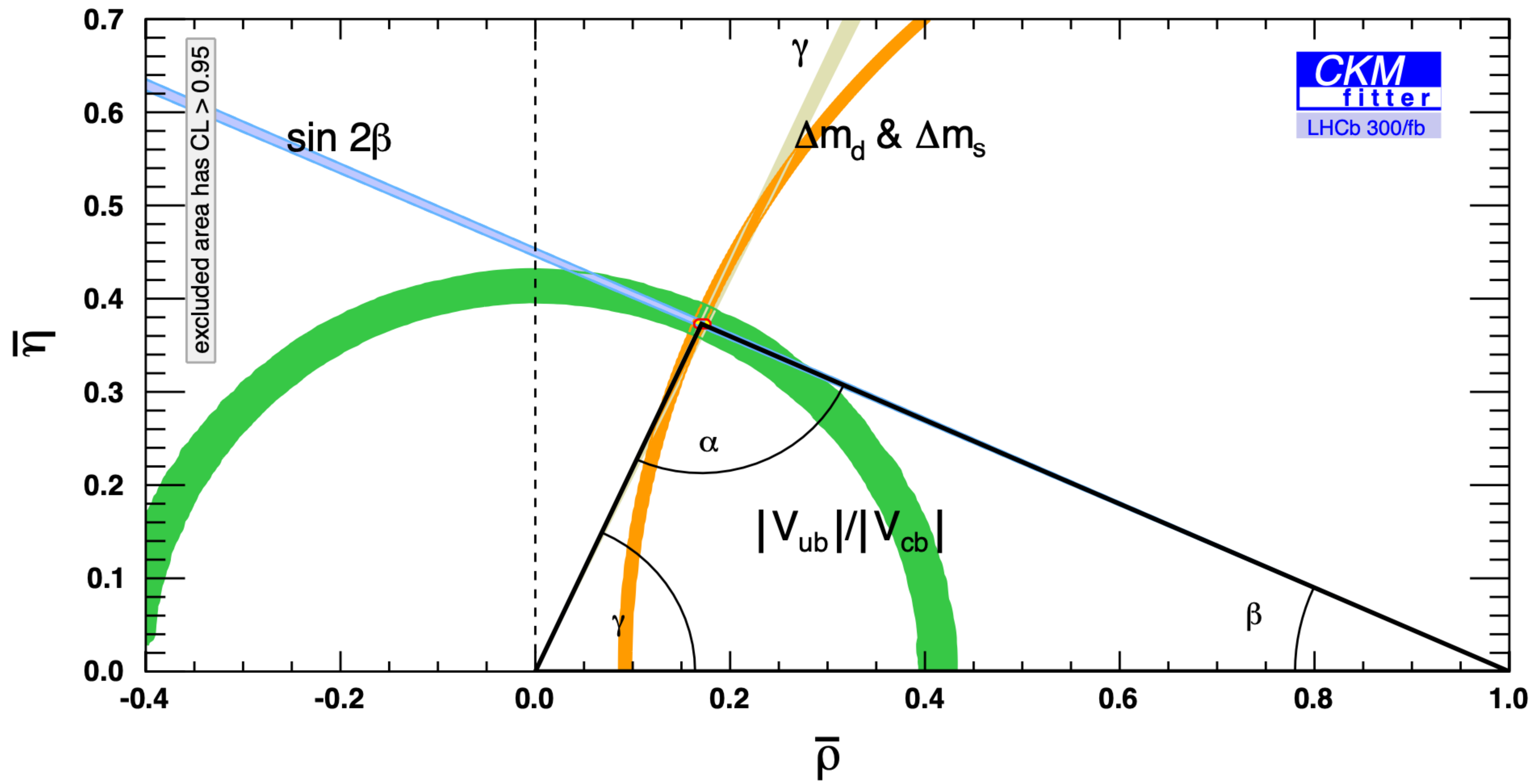
Opportunities beyond flavour

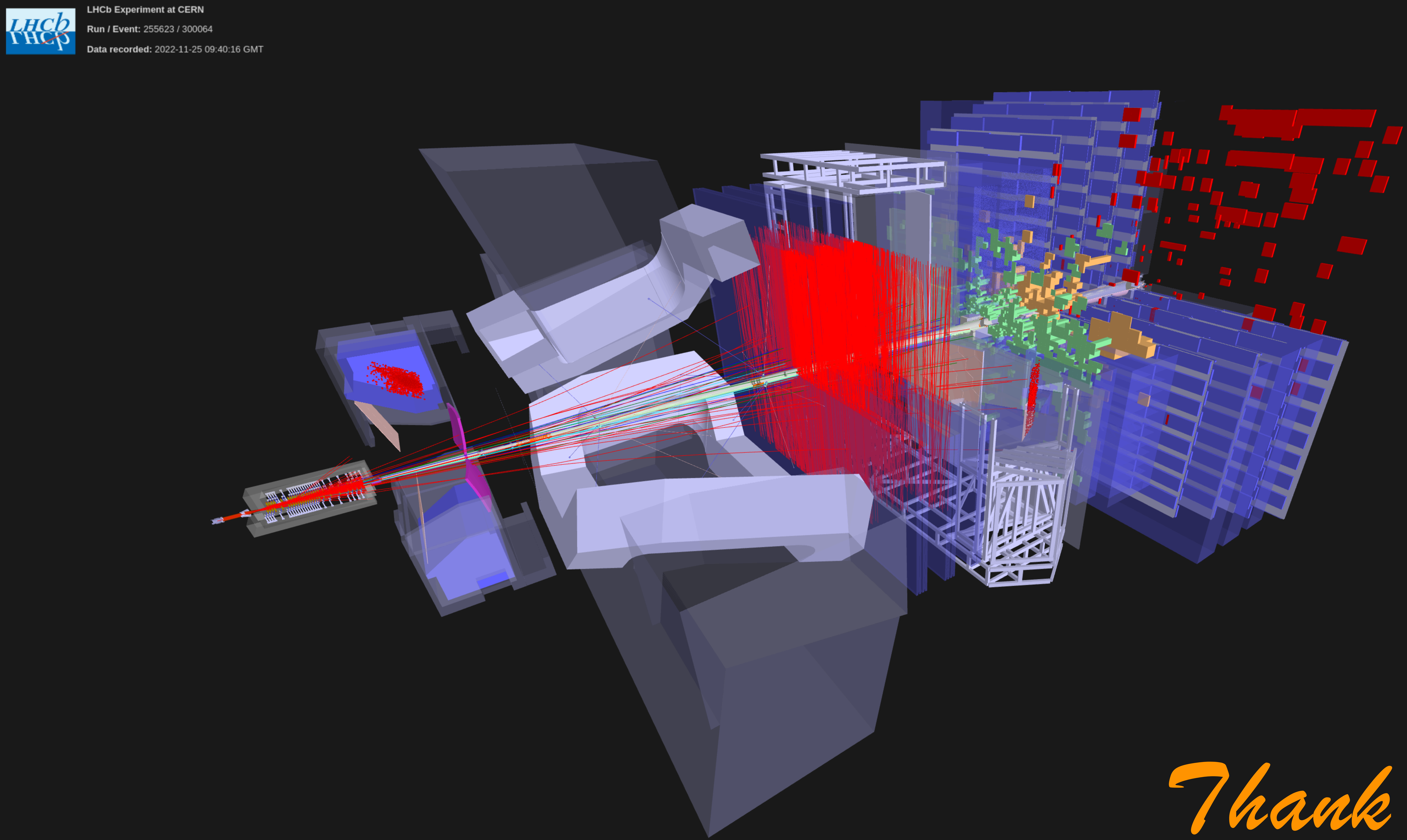
Topic	Comment
Spectroscopy	Enormous yields in gold-plated final states *e.g.* 4M $\Lambda_b^0\to J\psi pK^-$ decays ('pentaquark' mode)
Higgs	Measure Higgs-charm Yukawa within factor 2 to 3 of SM value
$\sin^2\theta_W$	Uncertainty $<10^{-4}$, better than LEP/SLD
Proton structure	Precision probes at extremely low and high Bjorken-x values, with $Q^2>10^5\,\text{GeV}^2$
Hidden sector	Sensitivity to most of relevant parameter space for dark-photon models

Summary

- ✓ LHCb pushes flavour physics to new frontier
- ✓ World-leading precision measurements of CKM matrix: $\beta_{(s)}, \gamma, |V_{qb}|$
- ✓ Anomalies or underestimated QCD effects
- ✓ Charm mixing / CPV / rare decays
- ✓ Various observations of hadron spectroscopy
- ✓ Explorations in Heavy ions and W/Z mass measurements

Run 3 running, a lot of new results to coming!




LHCb Experiment at CERN
Run / Event: 255623 / 300064
Data recorded: 2022-11-25 09:40:16 GMT

Thank you

Back up slides

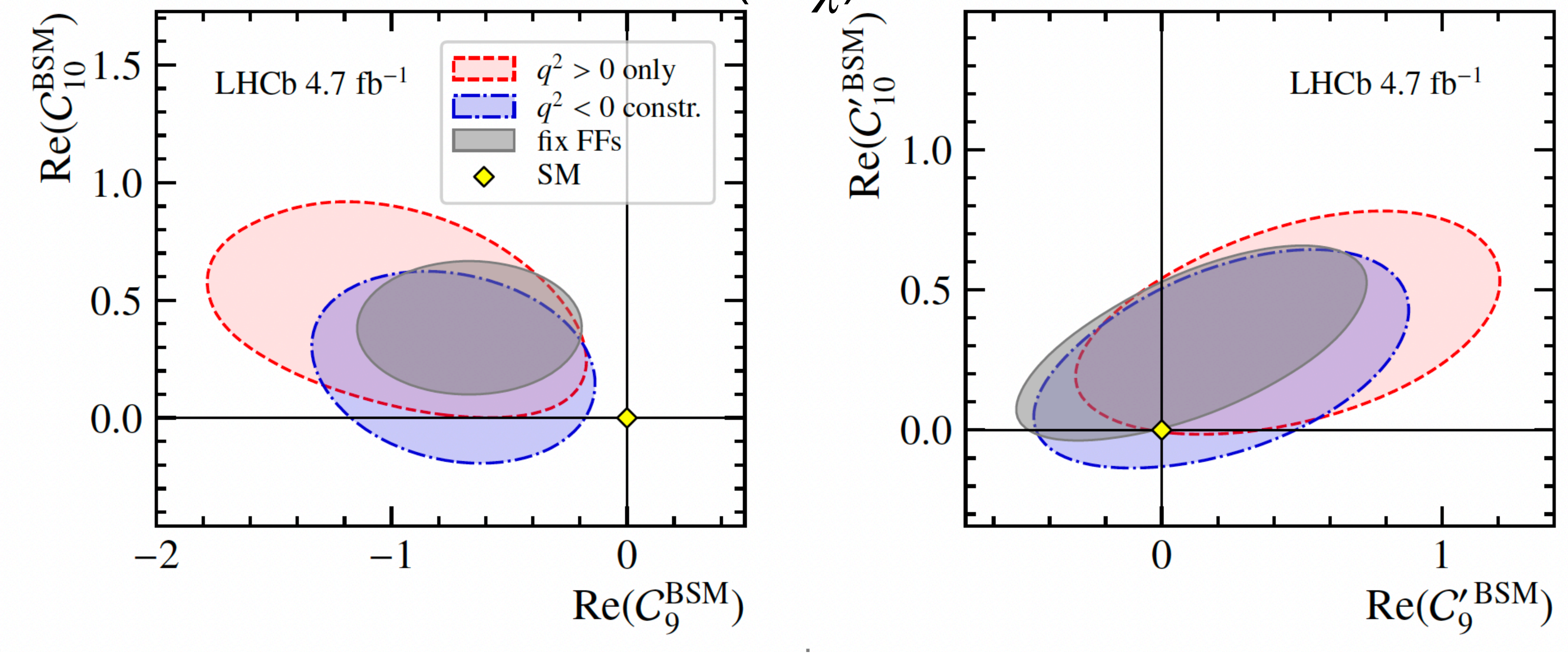
Understanding non-local contributions

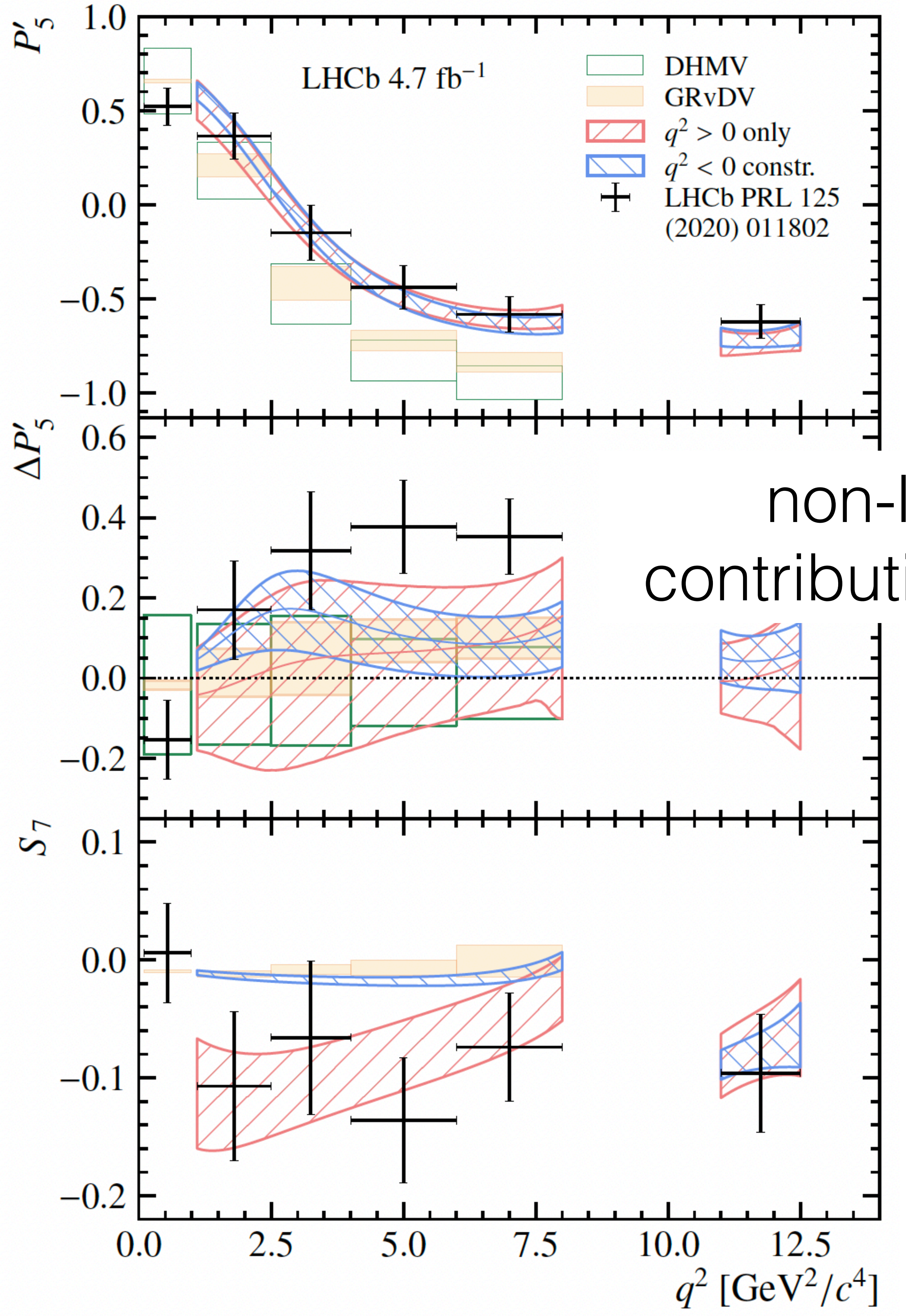
PhysRevLett132(2024)131801

- First unbinned amplitude analysis of $B^0 \to K^{*0}\mu^+\mu^-$ to determine simultaneously the short- and long-distance contributions (from $B^0 \to K^{*0}\psi$ and SM)

$$\mathcal{A}_\lambda^{L,R} = \mathcal{N}\left\{\left[(\mathcal{C}_9 \pm \mathcal{C}_9') \mp (\mathcal{C}_{10} \pm \mathcal{C}_{10}')\right]\mathcal{F}_\lambda(q^2,k^2) + \frac{2m_b M_B}{q^2}\left[(\mathcal{C}_7 \pm \mathcal{C}_7')\mathcal{F}_\lambda^T(q^2,k^2) - 16\pi^2 \frac{M_B}{m_b}\mathcal{H}_\lambda(q^2,k^2)\right]\right\}$$

Theoretical inputs on the determination of non-local effects (H_λ) examined





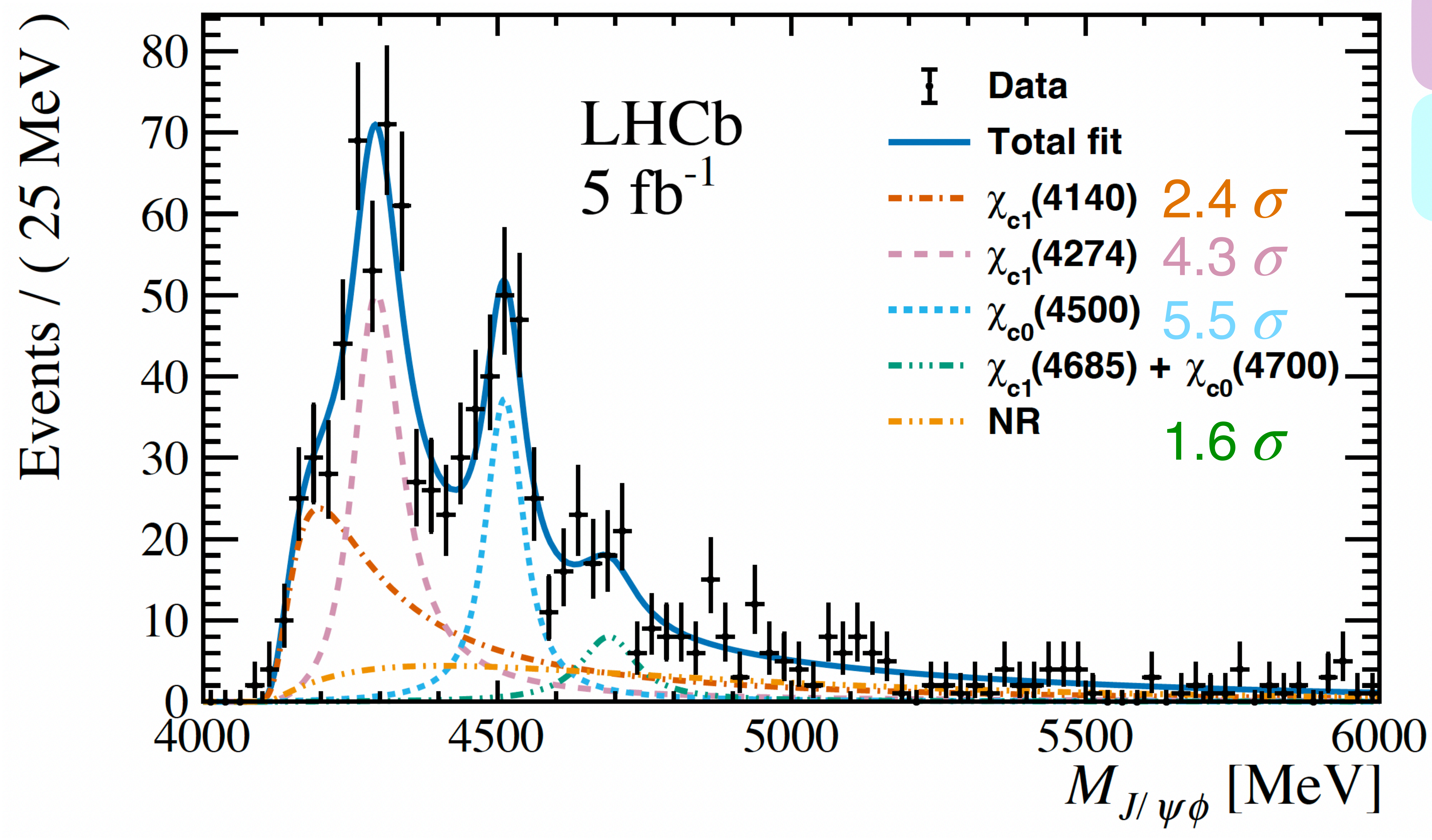
non-local contribution to P_5'

- Explicit inclusion of non-local contribution in the signal amplitude reduce the tension of P_5' to below 2 σ

Observation of exotic $J/\psi\phi$ resonance in diffractive process

arXiv:2404.14301

- First observation of $X \to J/\psi\phi$ production in diffractive processes with 5 resonances
- Helps determine the underlying nature of exotic states



Parameter [MeV]	Current analysis	*PRL127(2021)082001*
$M_{\chi_{c1}(4274)}$	$4298 \pm 6 \pm 9$	$4294 \pm 4^{+3}_{-6}$
$\Gamma_{\chi_{c1}(4274)}$	$92^{+22}_{-18} \pm 57$	$53 \pm 5 \pm 5$
$M_{\chi_{c0}(4500)}$	$4512.5^{+6.0}_{-6.2} \pm 3.0$	$4474 \pm 3 \pm 3$
$\Gamma_{\chi_{c0}(4500)}$	$65^{+20}_{-16} \pm 32$	$77 \pm 6^{+10}_{-8}$

$$\sigma_{\chi_{c1}(4140)} \times \mathcal{B}_{\text{eff}}^{\chi_{c1}(4140)} = (0.80 \pm 0.15 \pm 0.28)\ \text{pb},$$
$$\sigma_{\chi_{c1}(4274)} \times \mathcal{B}_{\text{eff}}^{\chi_{c1}(4274)} = (0.73 \pm 0.08 \pm 0.17)\ \text{pb},$$
$$\sigma_{\chi_{c0}(4500)} \times \mathcal{B}_{\text{eff}}^{\chi_{c0}(4500)} = (0.42^{+0.09}_{-0.08} \pm 0.06)\ \text{pb},$$
$$\sigma_{\chi_{c1}(4685)+\chi_{c0}(4700)} \times \mathcal{B}_{\text{eff}}^{\chi_{c1}(4685)+\chi_{c0}(4700)} = (0.14^{+0.07}_{-0.06} \pm 0.06)\ \text{pb},$$
$$\sigma_{\text{NR}} \times \mathcal{B}_{\text{eff}}^{\text{NR}} = (0.43^{+0.24}_{-0.18} \pm 0.20)\ \text{pb},$$

Wilson Coefficients

$$\mathcal{H}_{\rm WET} = \frac{-4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_i \mathcal{C}_i^{(\prime)}(\mu)\mathcal{O}_i^{(\prime)}(\mu), \qquad (1)$$

where G_F is the Fermi constant and $V_{q_k q_j}$ are elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix corresponding to the $q_j \to q_k$ quark transition. The effective operators $\mathcal{O}_i^{(\prime)}$ describe all possible interactions between ingoing and outgoing particles, while the Wilson Coefficients $\mathcal{C}_i^{(\prime)}$ are the corresponding effective coupling constants. Lastly, μ defines the energy scale.

$$\mathcal{O}_7 = \frac{e}{16\pi^2} m_b \left(\bar{s}_L \sigma^{\mu\nu} b_R\right) F_{\mu\nu}, \qquad \mathcal{O}_7' = \frac{e}{16\pi^2} m_b \left(\bar{s}_R \sigma^{\mu\nu} b_L\right) F_{\mu\nu},$$

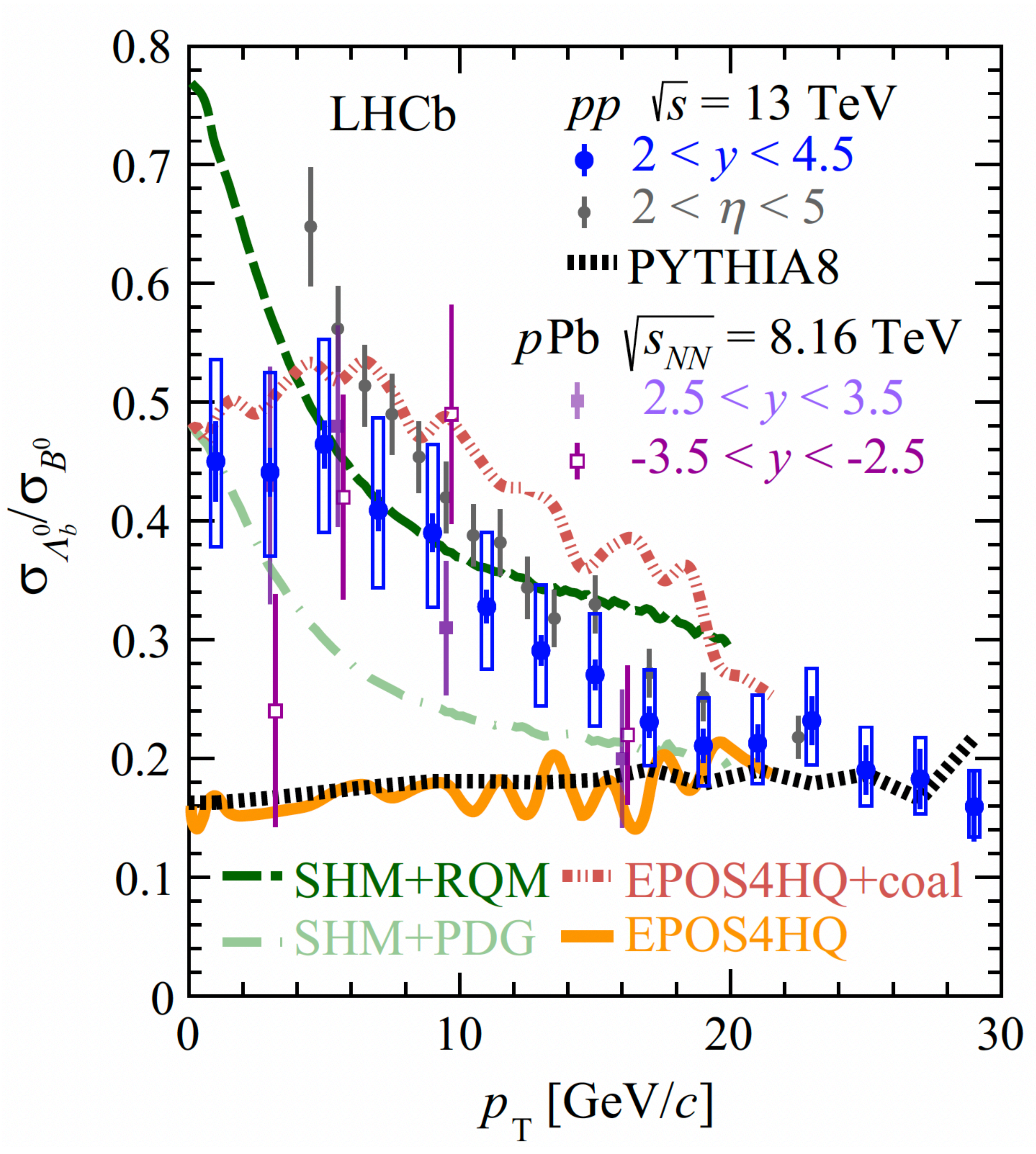
$$\mathcal{O}_{9\ell} = \frac{e^2}{16\pi^2} \left(\bar{s}_L \gamma_\mu b_L\right) \bar{\ell}\gamma^\mu \ell, \qquad \mathcal{O}_{9\ell}' = \frac{e^2}{16\pi^2} \left(\bar{s}_R \gamma_\mu b_R\right) \bar{\ell}\gamma^\mu \ell,$$

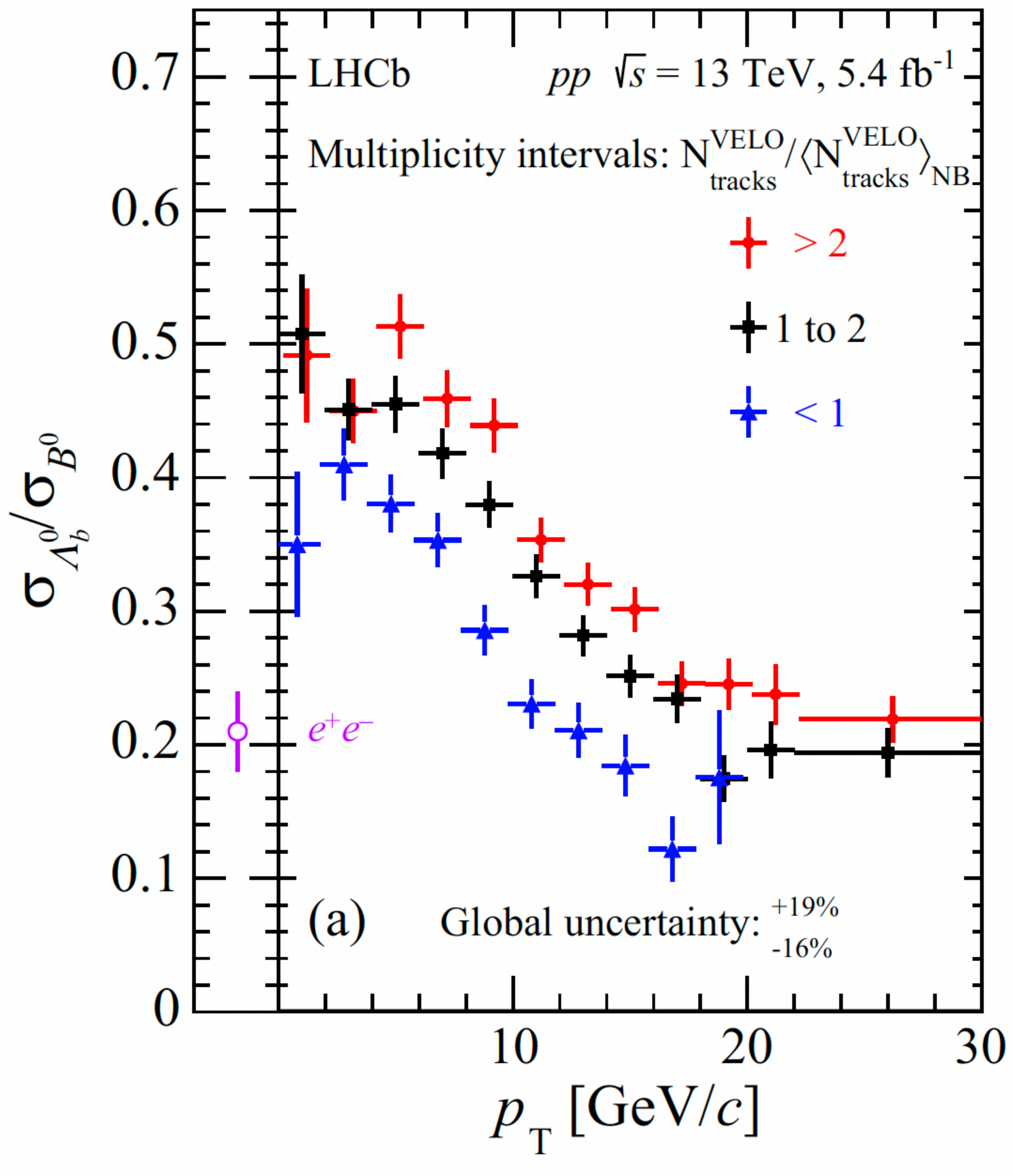
$$\mathcal{O}_{10\ell} = \frac{e^2}{16\pi^2} \left(\bar{s}_L \gamma_\mu b_L\right) \bar{\ell}\gamma^\mu \gamma_5 \ell, \qquad \mathcal{O}_{10\ell}' = \frac{e^2}{16\pi^2} \left(\bar{s}_R \gamma_\mu b_R\right) \bar{\ell}\gamma^\mu \gamma_5 \ell,$$

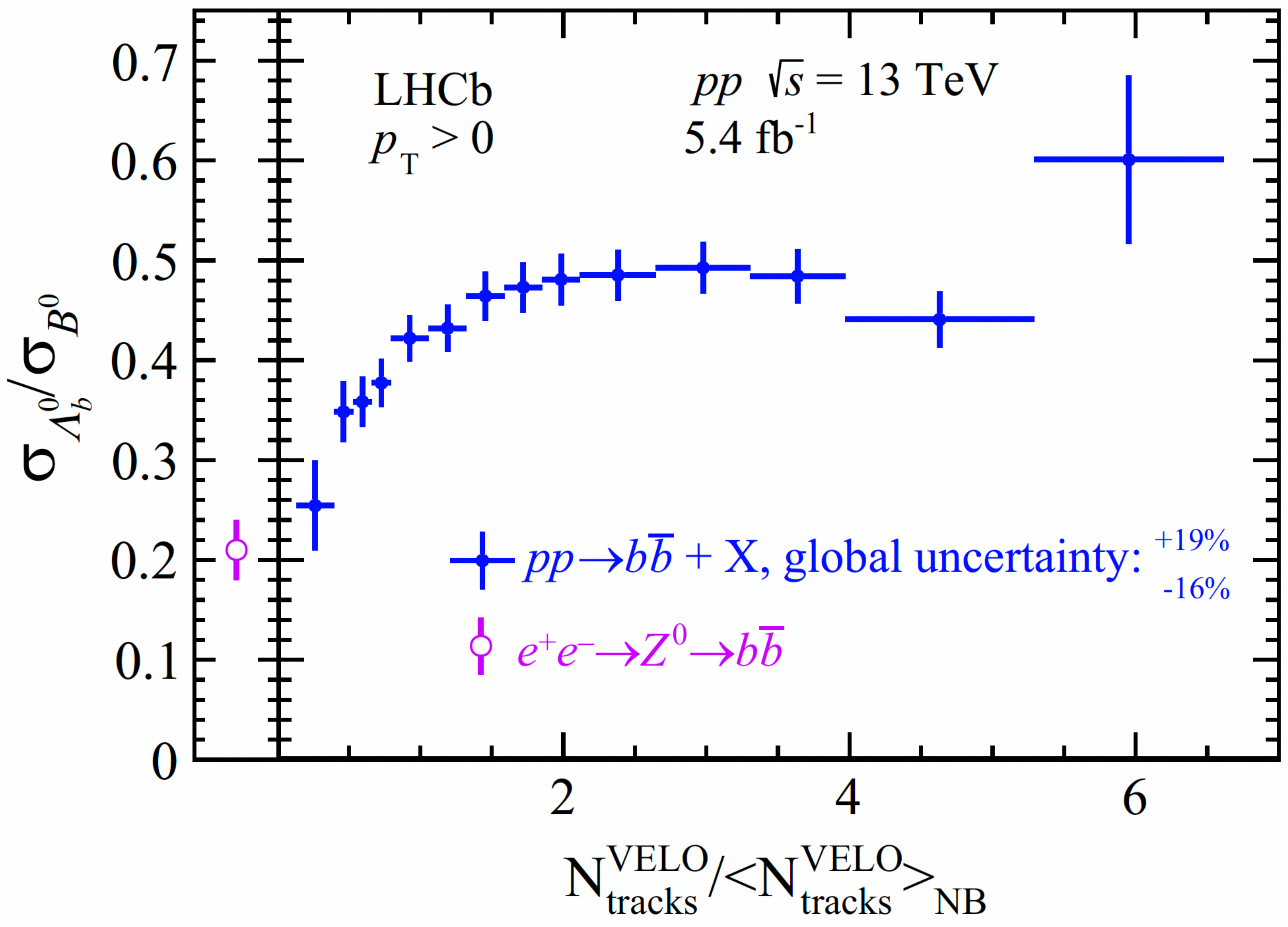
Enhanced production of Λ_b^0 in high-multiplicity pp collisions

- Production cross section ratio of Λ_b^0 to B^0 in pp collisions measured at $\sqrt{s} = 13$ TeV
  - Qualitatively consistent with the emergence of coalescence as an additional baryon production mechanism in high-density hadronic environments.

PhysRevLett.132(2024)081901







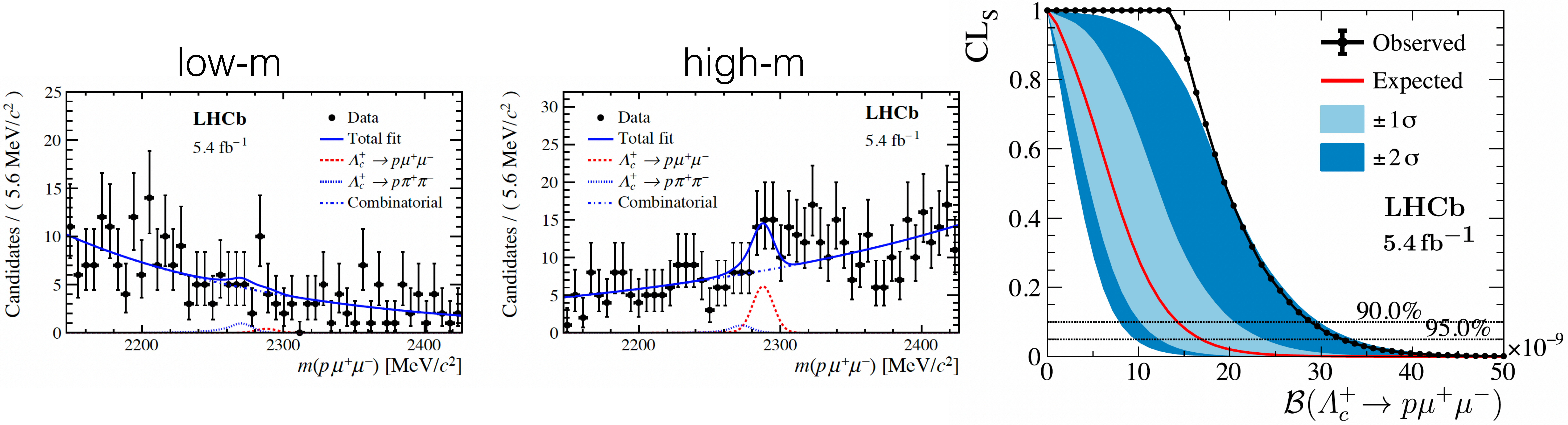
Search of rare charm decay

arXiv:2407.11474

- Flavour-changing neutral-current decay $\Lambda_c^+ \to p\mu^+\mu^-$ heavily suppressed in the SM, forbidden at tree level
- Long-distance processes involving intermediate vector-meson resonances could enhance the BR by 10^{-2}

$$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 0.93\ (1.1) \times 10^{-8} \quad \text{at} \ \ 90\%\ (95\%)\ \text{CL}\ (\textit{low-m})$$

$$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 3.0\ (3.3) \times 10^{-8} \quad \text{at} \ \ 90\%\ (95\%)\ \text{CL}\ (\textit{high-m})$$

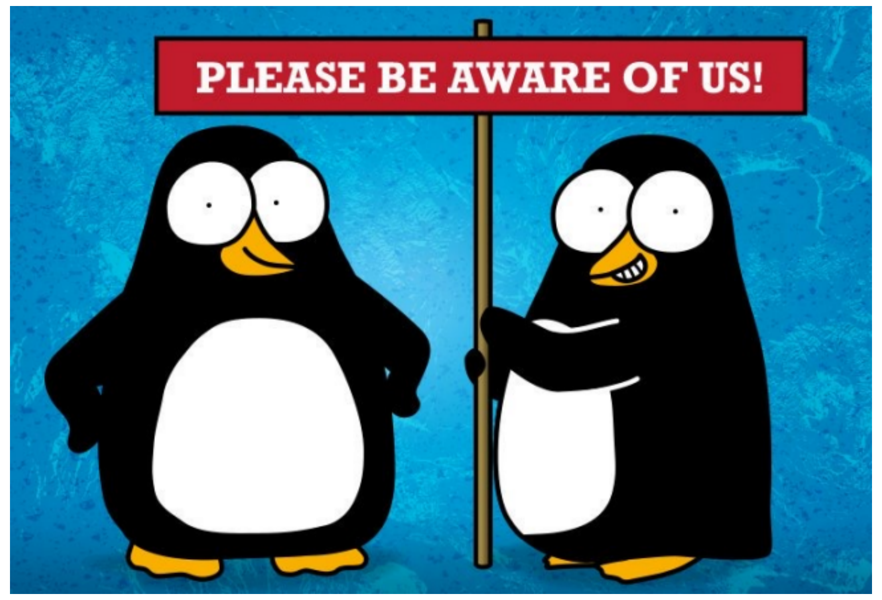


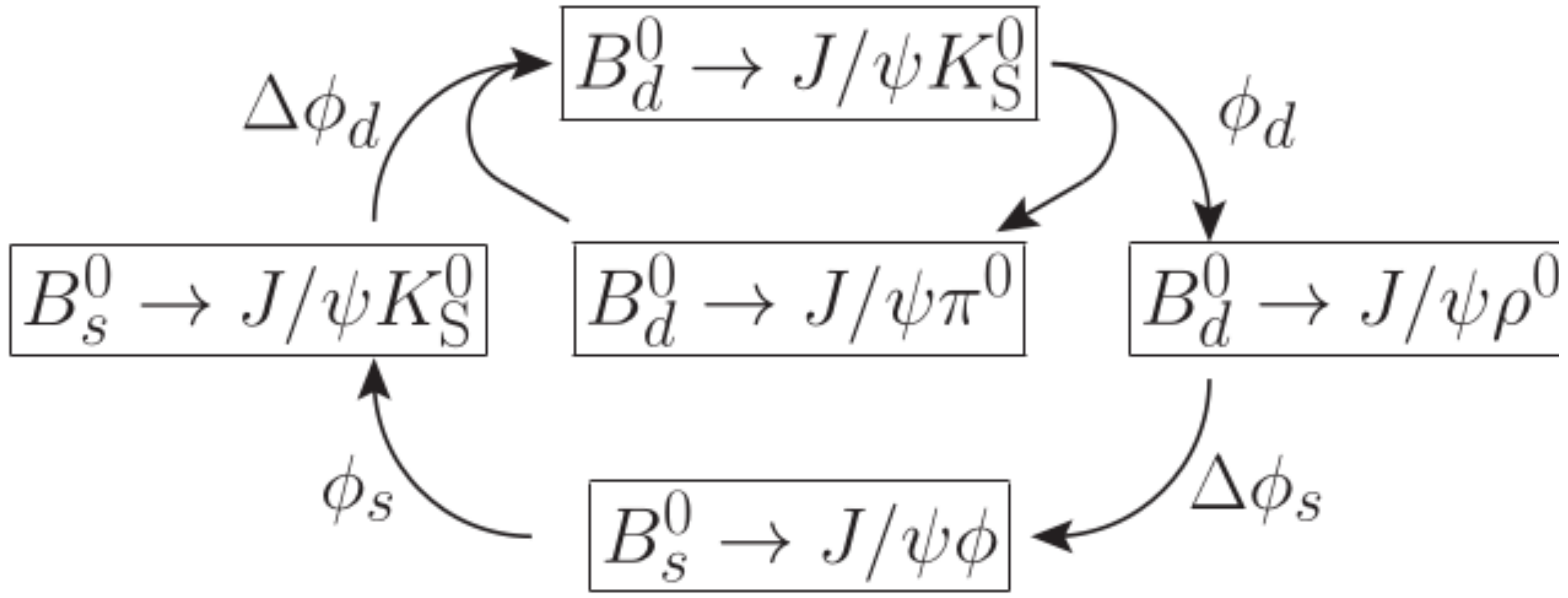
Control of penguin contribution

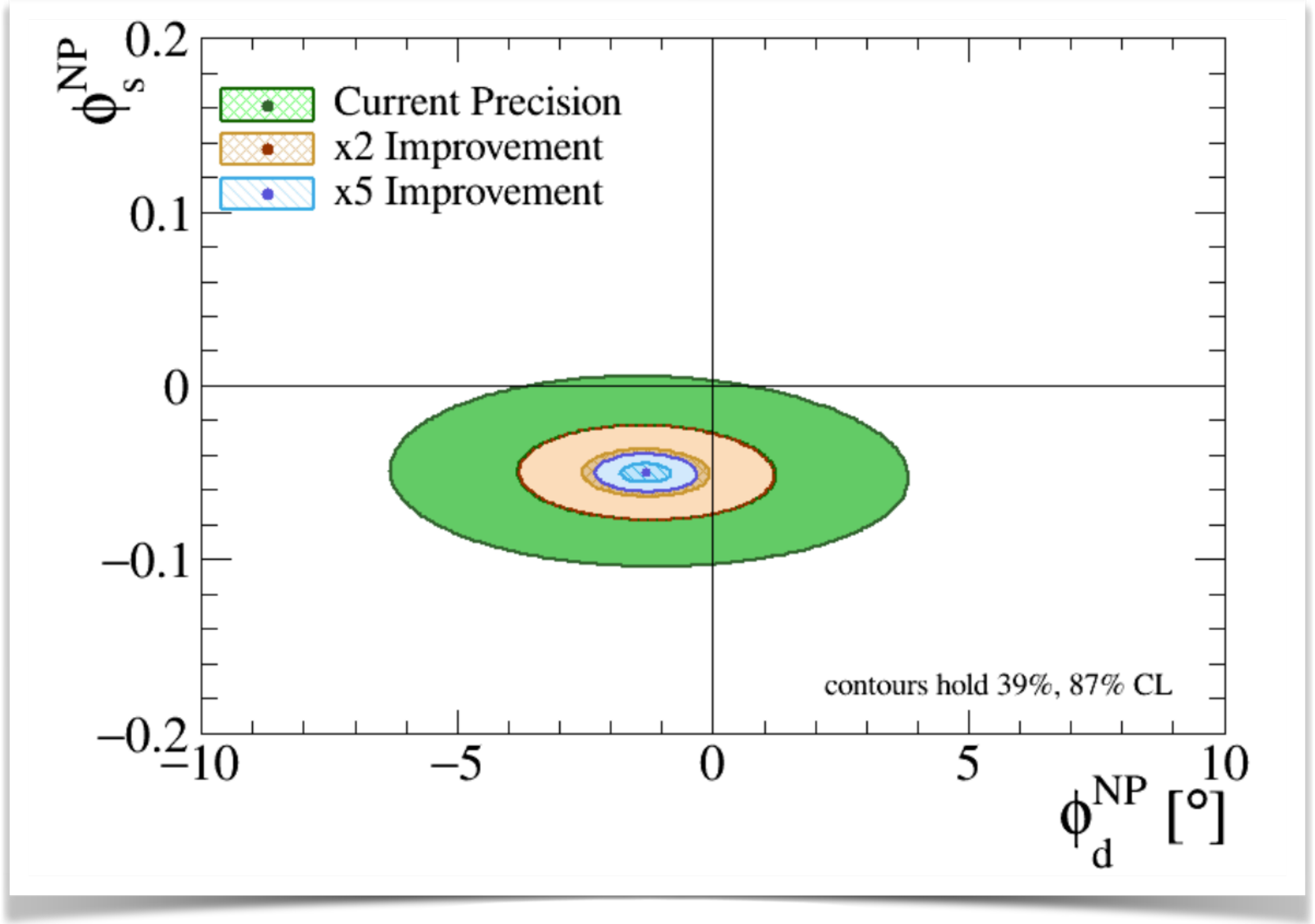
- $\sigma(\phi_s) \sim 0.016$ comparable with the theoretical estimation of $\Delta\phi_s^{penguin} \sim 1^\circ \approx 0.017$, better control of penguin effect necessary
- Combined analysis of penguin contributions in ϕ_s and ϕ_d $(\sin 2\beta)$, using SU(3) flavour symmetry

$$\phi_d = \sin(2\beta^{\text{tree}}) + \Delta\phi_d{}^{\text{penguin}} + \phi_d{}^{\text{NP}}$$

$$\phi_s = \phi_s^{\text{tree}} + \Delta\phi_s^{\text{penguin}} + \phi_s^{NP}$$





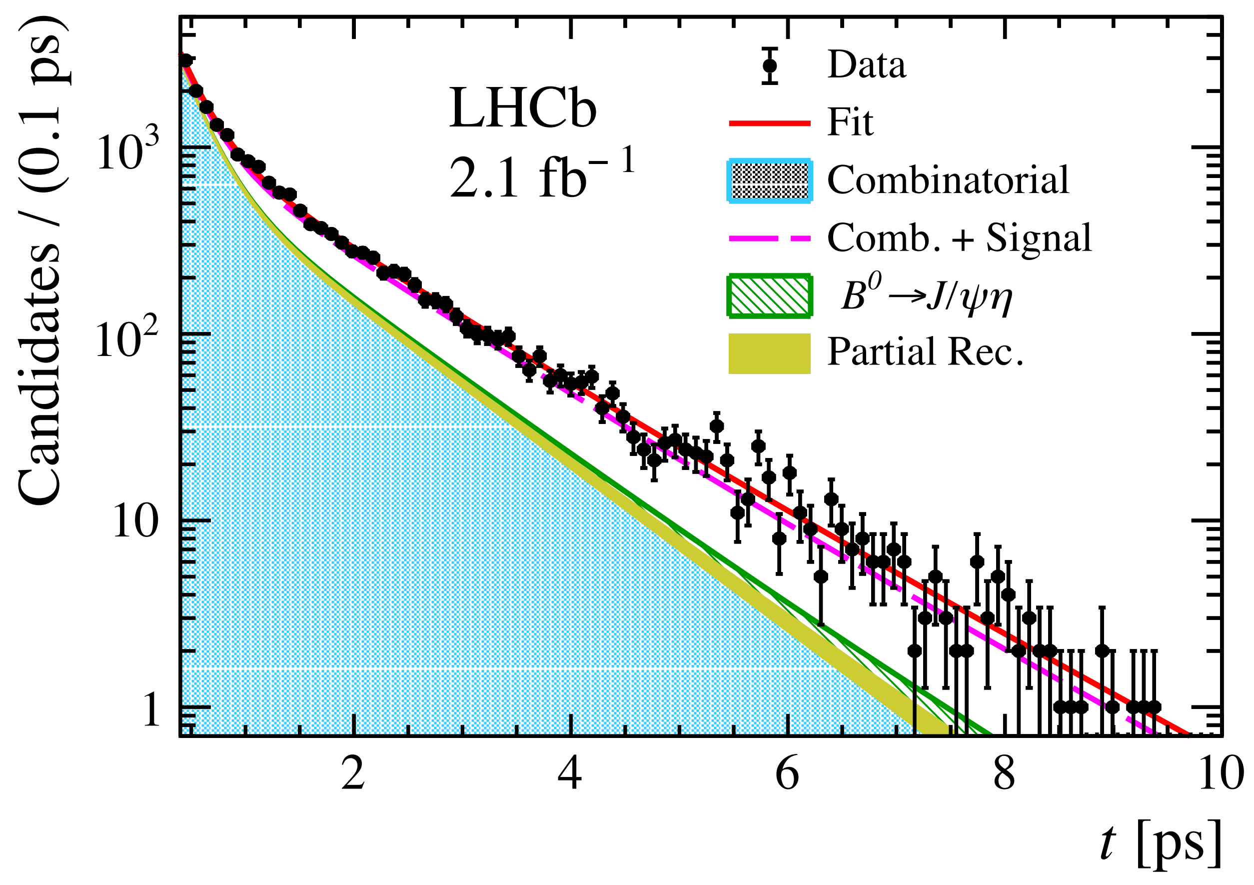


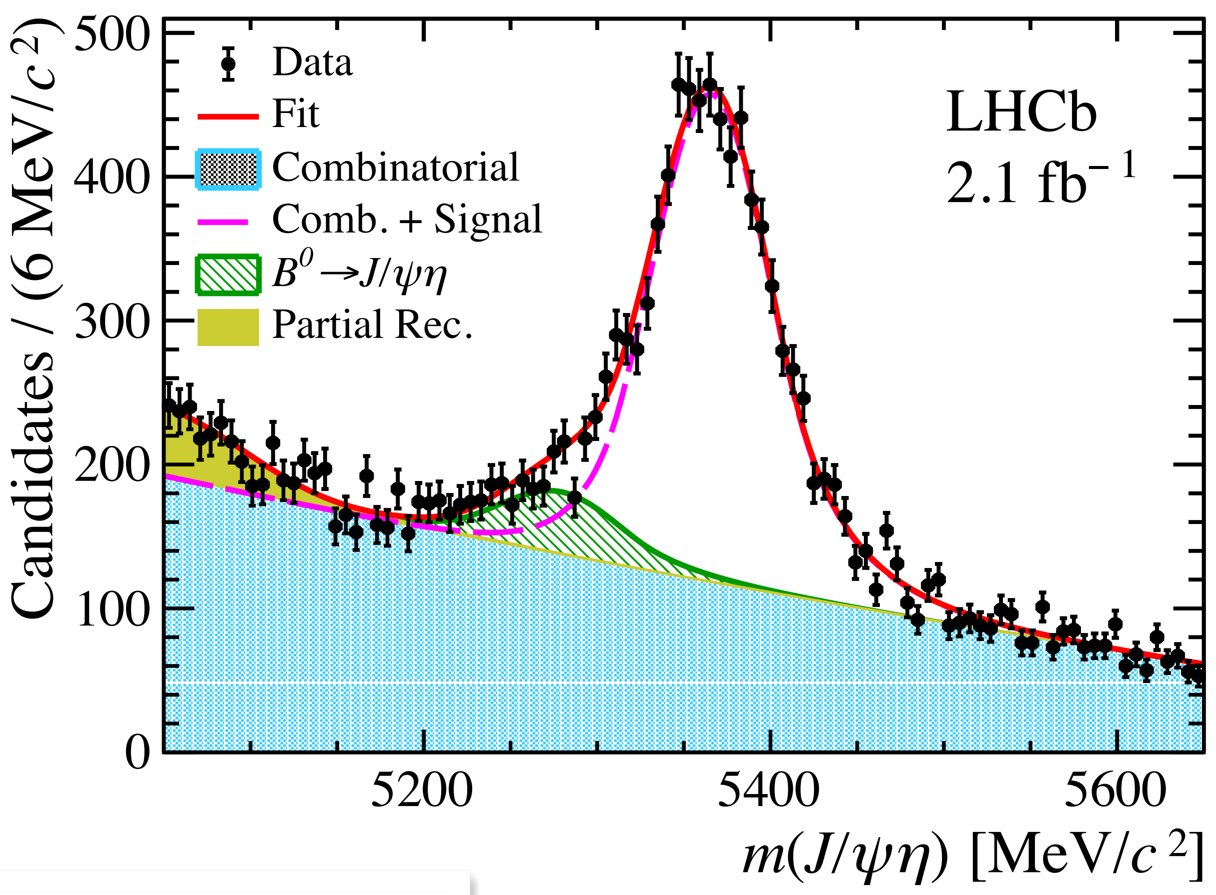
J.Phys.G 48 (2021) 6, 065002

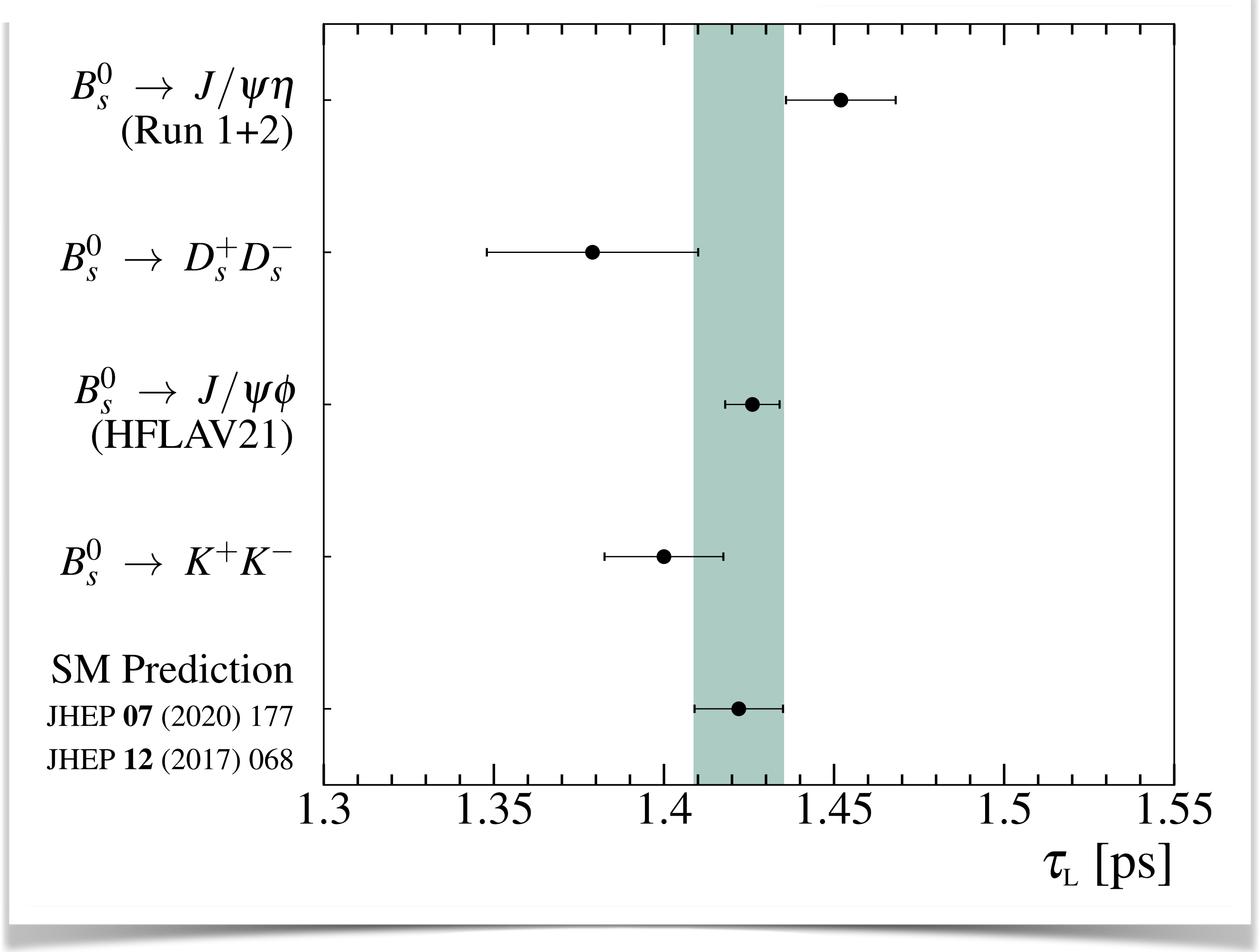
Effective lifetime measurements in $B_s^0 \to J/\psi\eta(\eta')$

EPJC83 (2023) 629

- CP-even decay $B_s^0 \to J/\psi(\mu^+\mu^-)\eta(\gamma\gamma)$ for
  $\tau_L = 1/\Gamma_L = 1.452 \pm 0.014 \pm 0.007 \pm 0.002$ ps

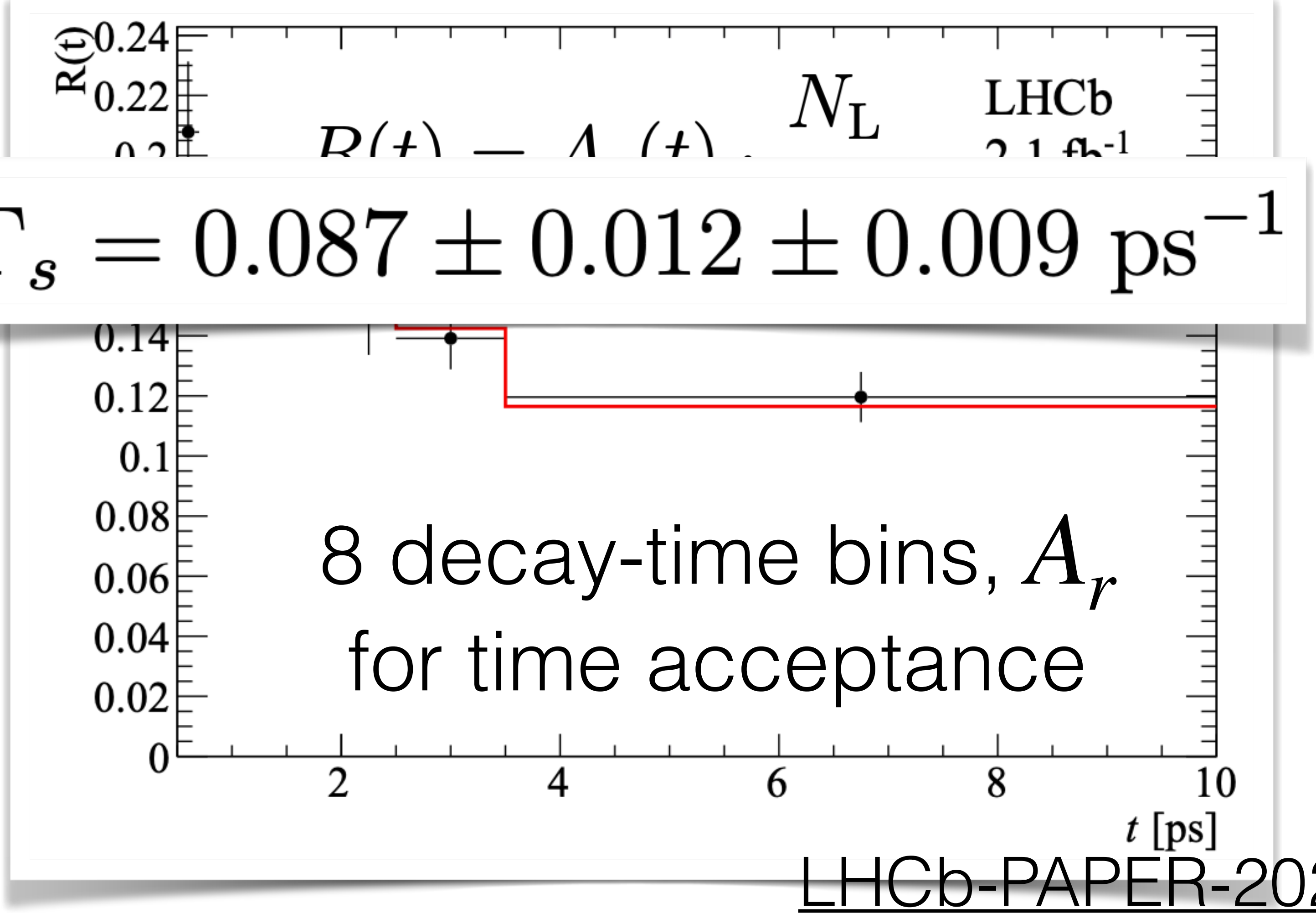






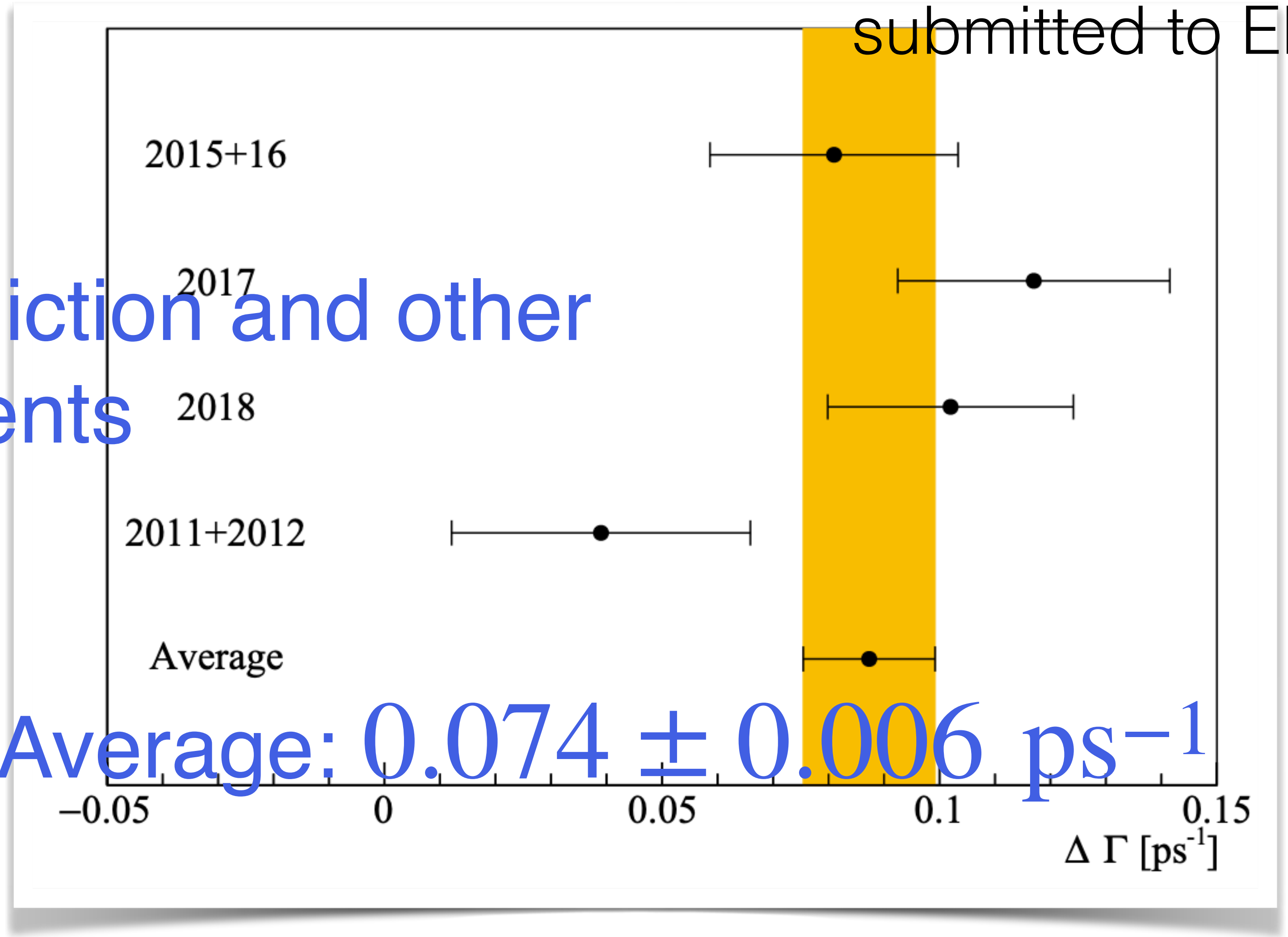
- Simultaneous analysis of CP-odd decay $B_s^0 \to J/\psi\rho^0$ and CP-even decay $B_s^0 \to J/\psi(\mu^+\mu^-)\eta'(\pi^+\pi^-\gamma)$

$\Delta\Gamma_s = 0.087 \pm 0.012 \pm 0.009$ ps^{-1}



8 decay-time bins, A_r for time acceptance

LHCb-PAPER-2023-025
submitted to EPJC



Agree with the SM prediction and other measurements

Agree with the World Average: 0.074 ± 0.006 ps^{-1}