University of Chinese Academy of Sciences

Latest Charm Physics at LHCb

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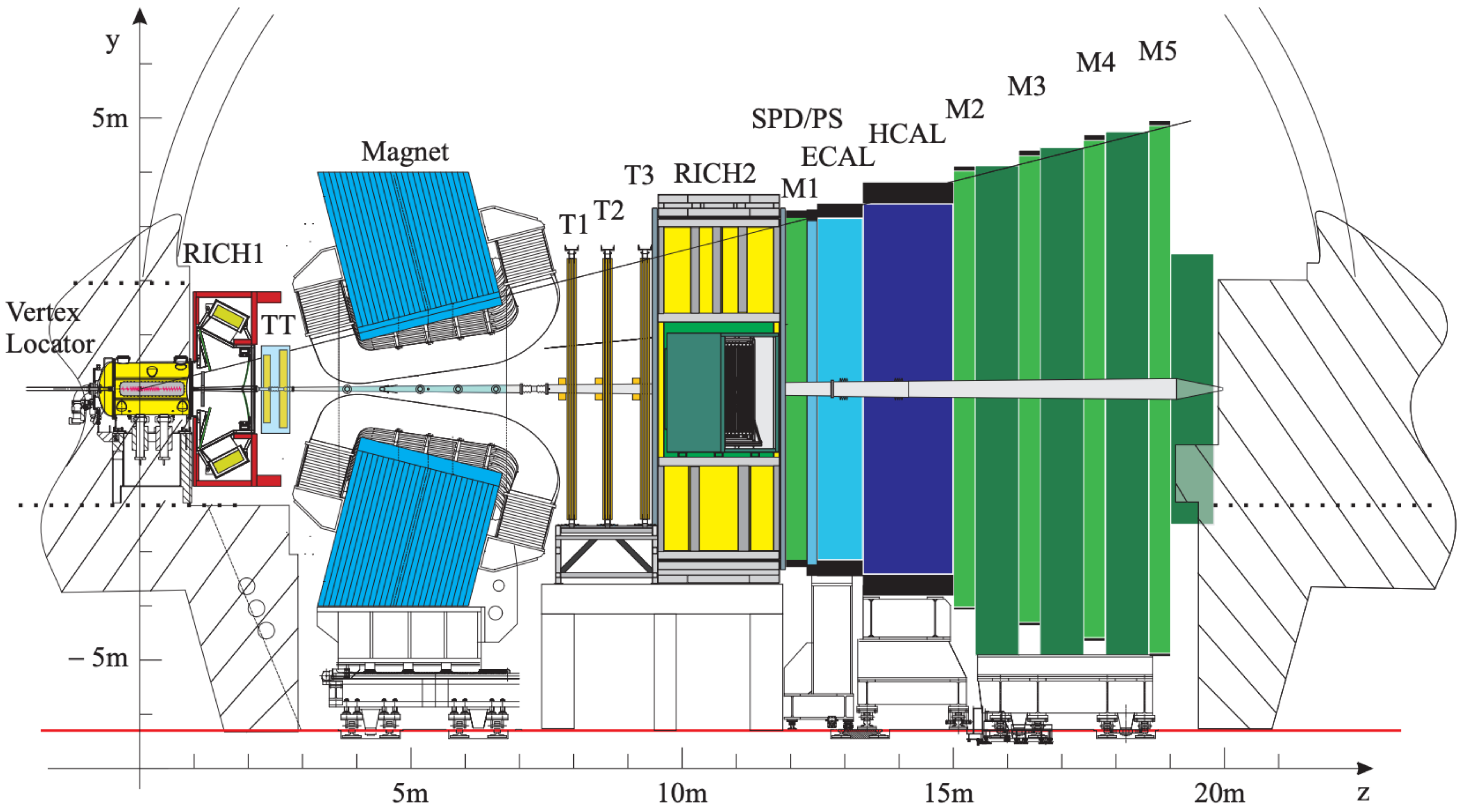
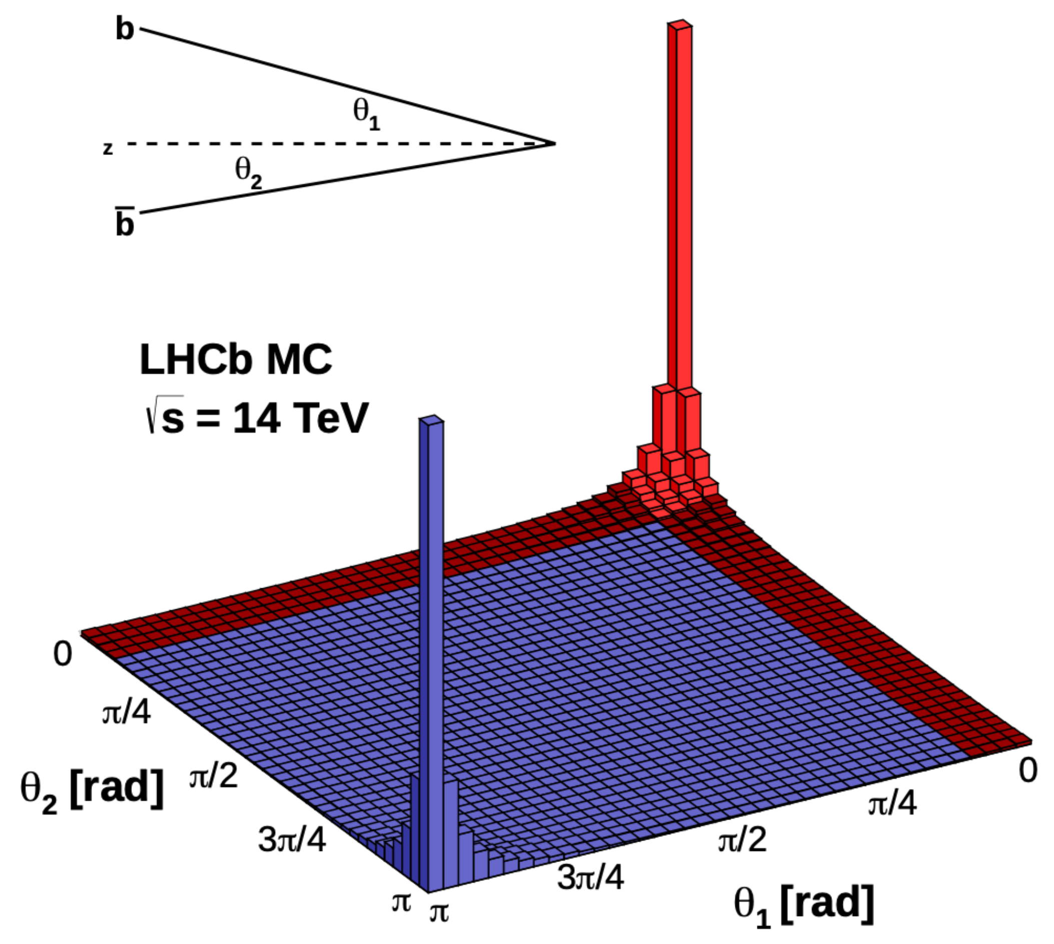
BESIII-BelleII-LHCb Charm Workshop
2025.06.28，长沙

LHCb detector

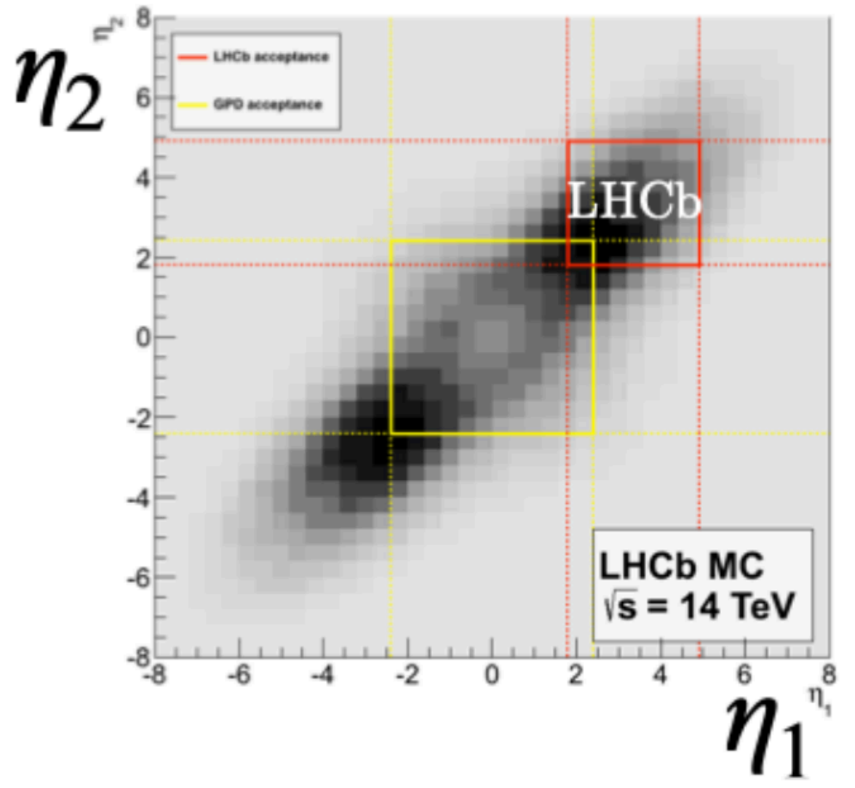
General purpose detector specialised in beauty and charm hadrons

proton beam





$2 < \eta < 5$

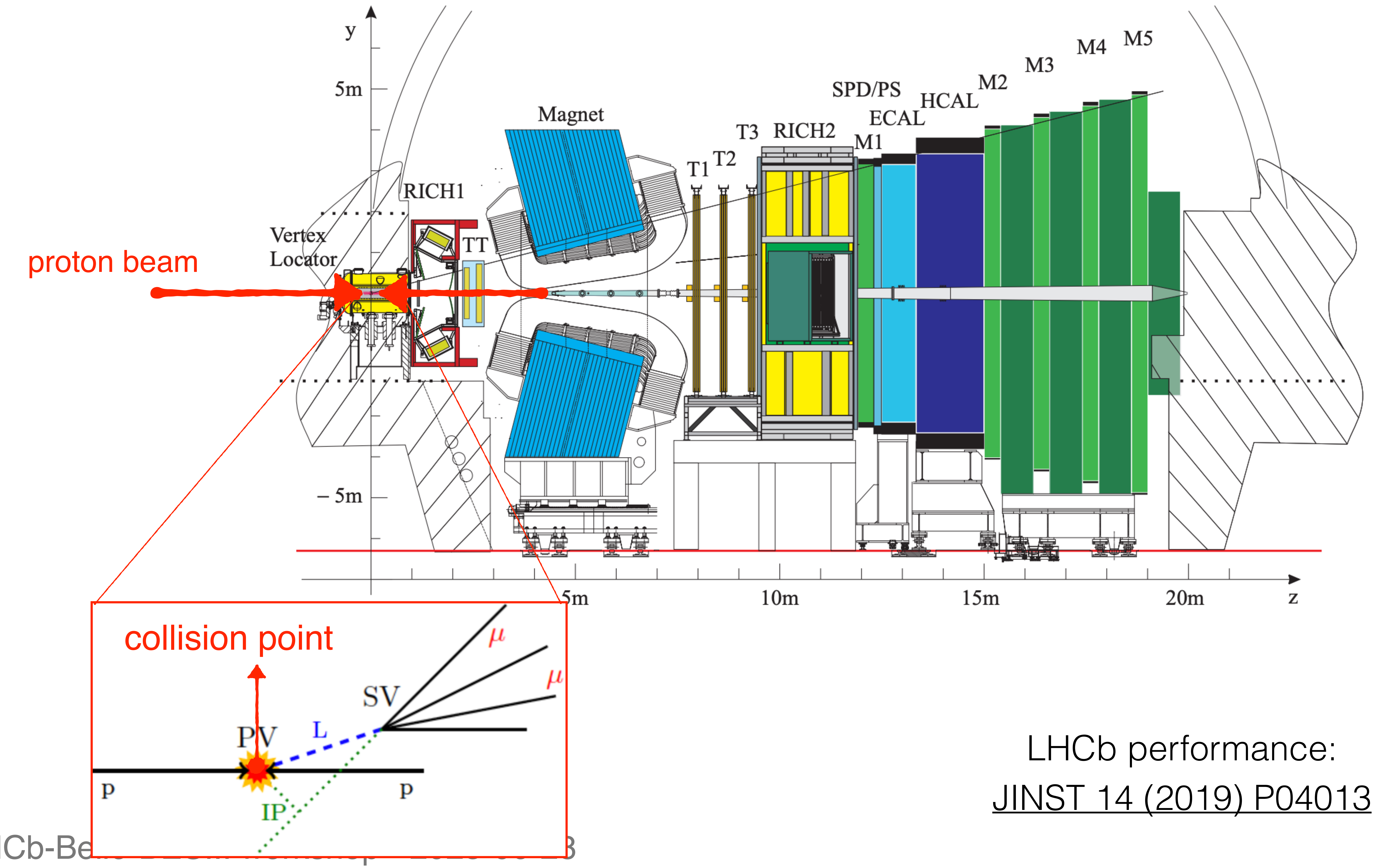


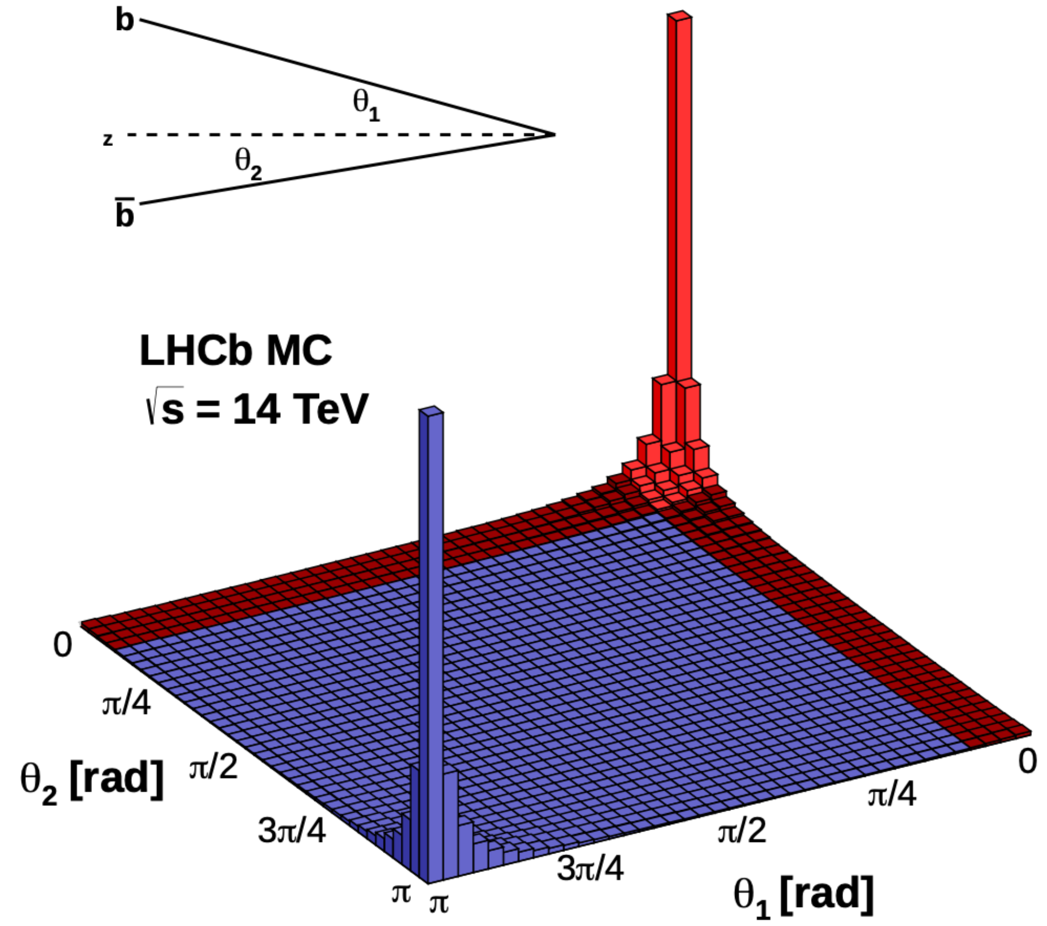
LHCb performance:
JINST 14 (2019) P04013

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





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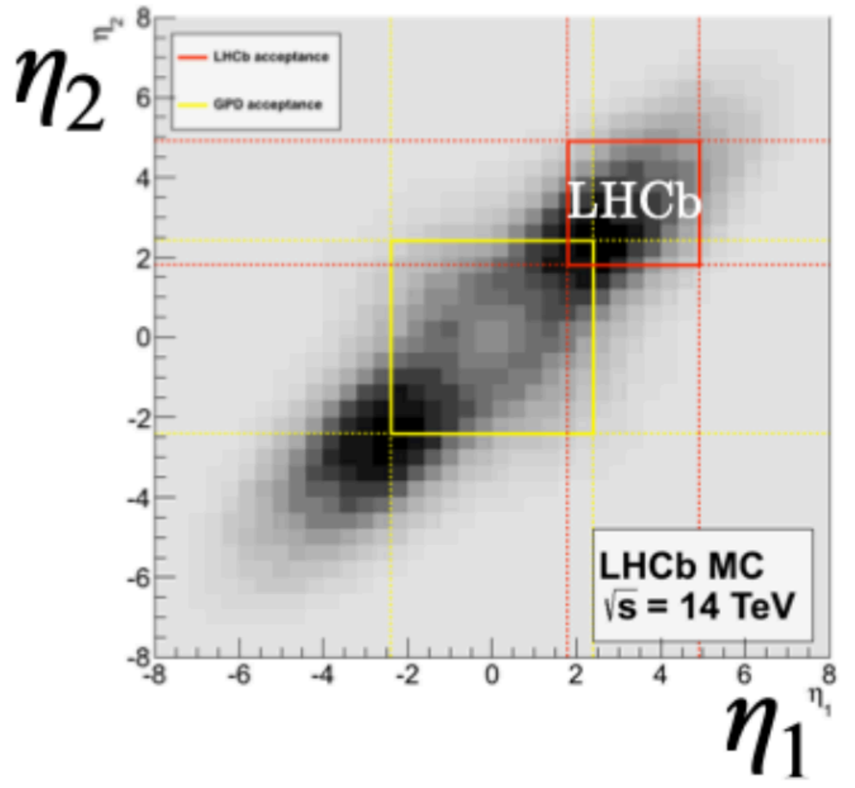

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LHCb detector

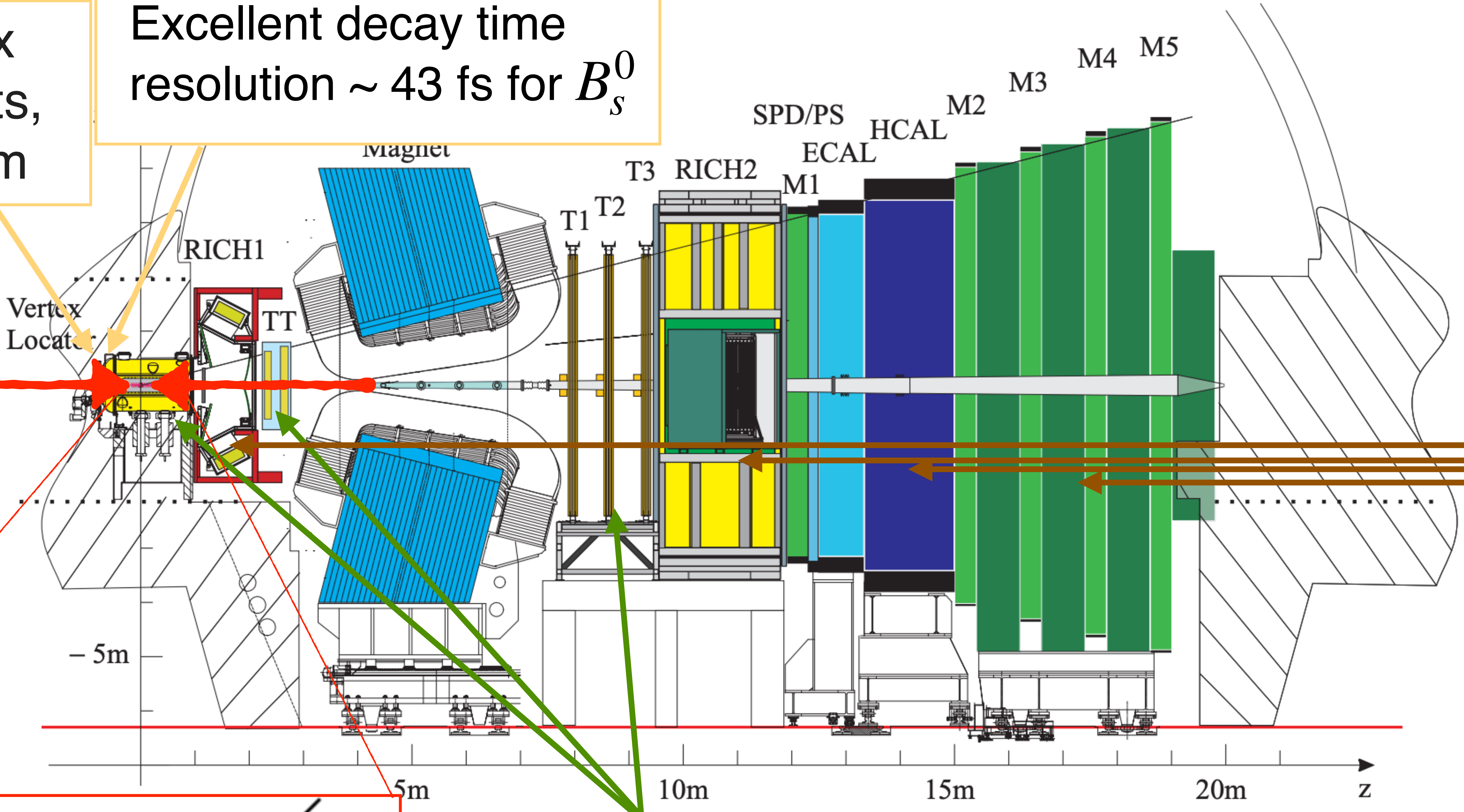
General purpose detector specialised in beauty and charm hadrons

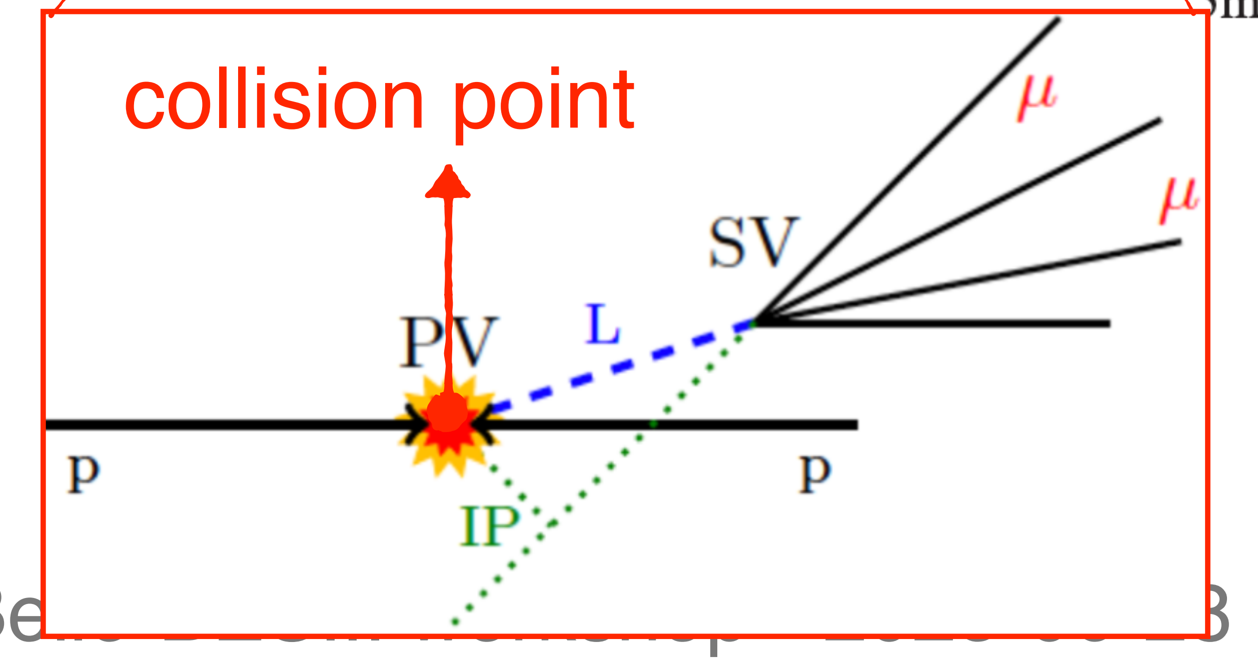
- Daughters of b & c hadron decays: $p_T \sim \mathcal{O}(1\ \mathrm{GeV}/c)$, flight distance L~1mm

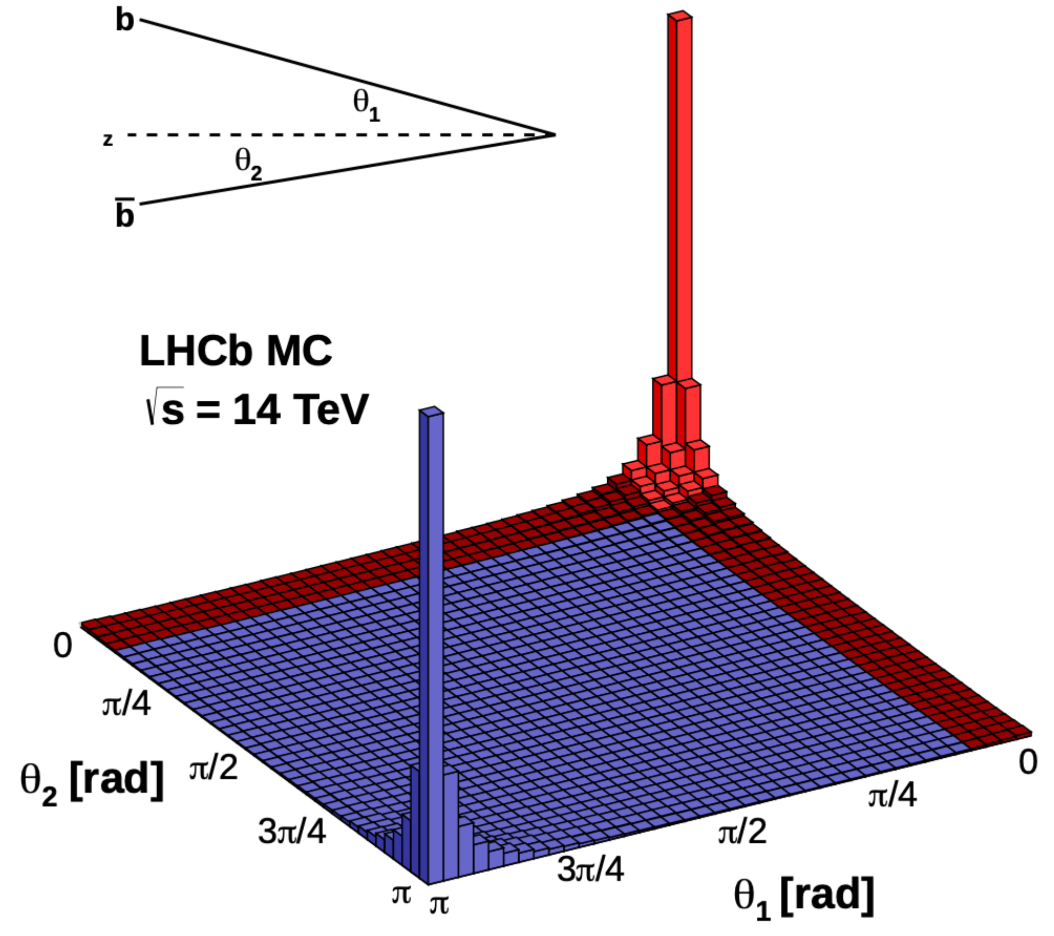
Precise vertex measurements, $\sigma(IP_x)$~ 35 μm

Excellent decay time resolution ~ 43 fs for B_s^0

proton beam





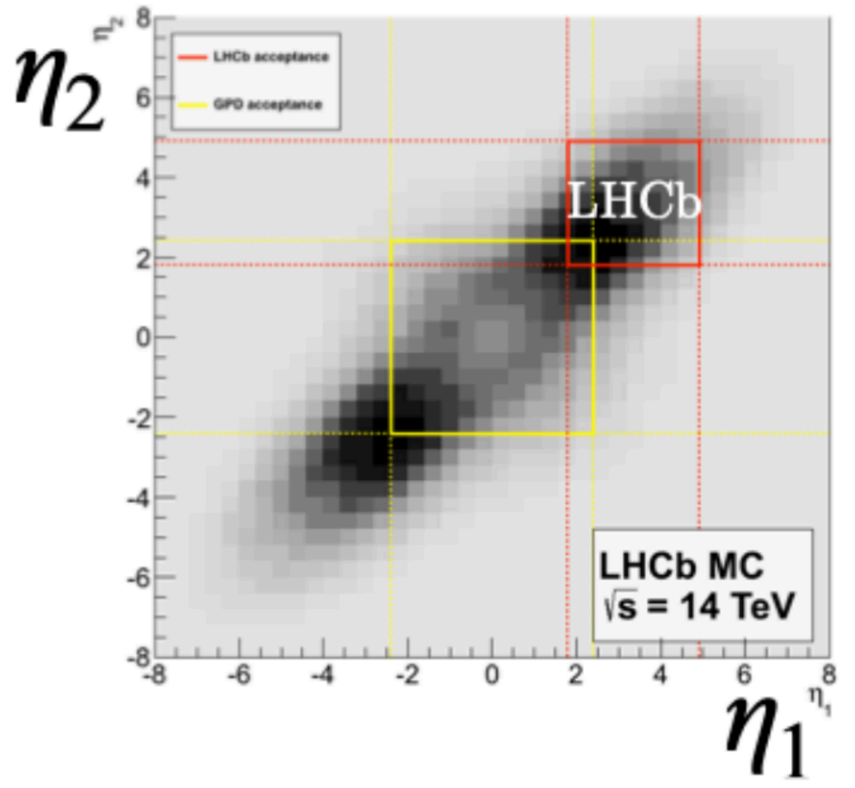


$2 < \eta < 5$

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

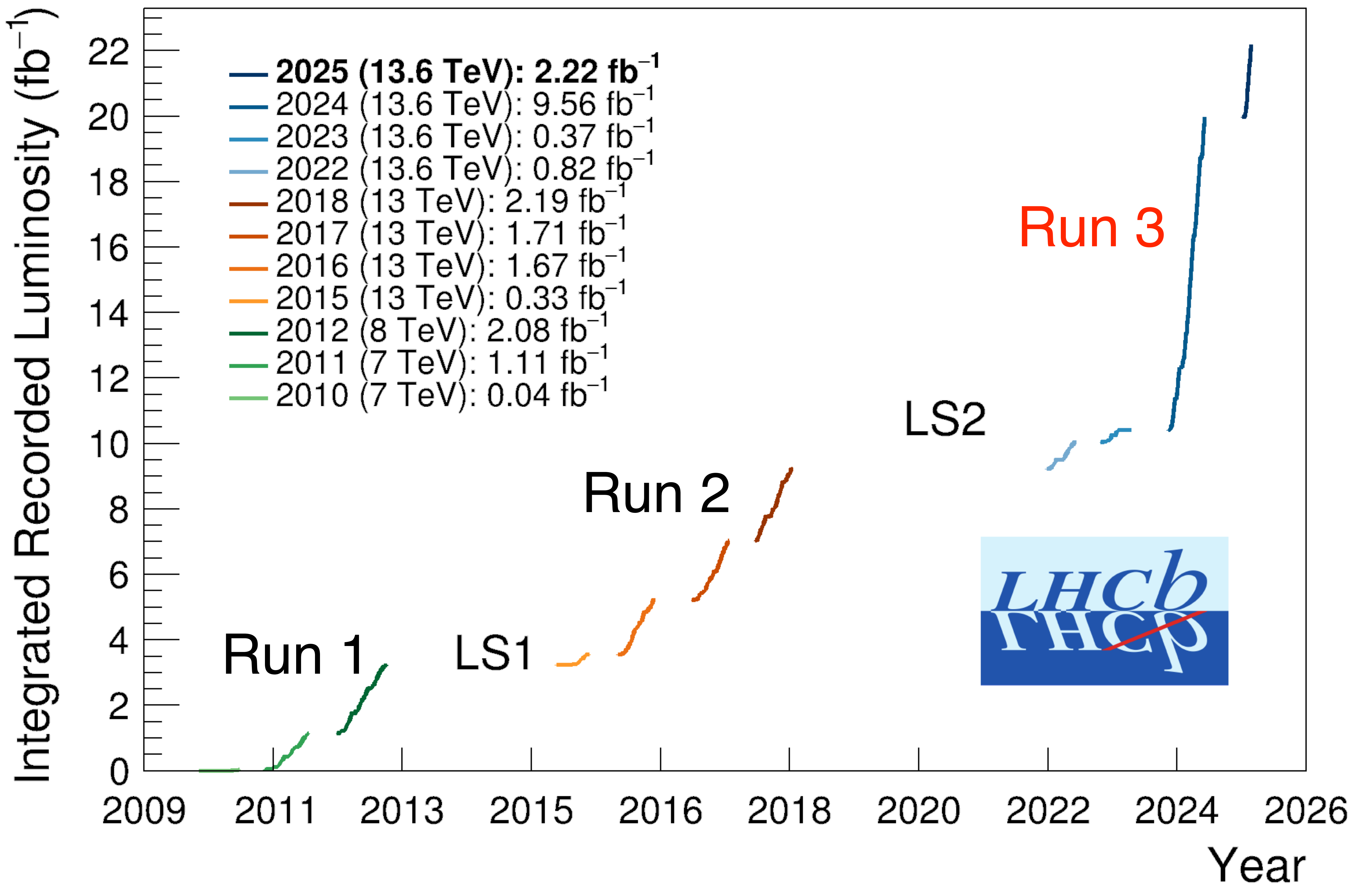
Excellent momentum resolution ~ 0.5-1% for $p \in (0,\ 20)$ GeV

LHCb performance:
JINST 14 (2019) P04013



Luminosity

- Run 1: 2011+2012, 7, 8 TeV
- Run 2: 2015-2018, 13 TeV
- Run 3: 2022-2026, 13.6 TeV



- Run 1 + Run 2: 9 fb^{-1}
- Run 3 : 23 fb^{-1} (expected)

$\sigma(pp \to c\bar{c}X) = 2369 \pm 192\ \mu$b at 13 TeV $\quad 1 < p_T < 8$ GeV/c & $2 < y < 4.5$

Data sets

$\mathscr{L}$, $\sigma_{c\bar{c}}$, acceptance, trigger efficiencies

		$\sqrt{s}$	Yield $D^0 \to KK$	Coverage	Flight distance	σ_t
Charm factory (e^+e^-)	BESIII	3.7 - 4.6 GeV	3fb^{-1}: 0.06M @20 fb^{-1}: 0.5M*	Almost full	/	/
B factory (e^+e^-)	Belle	10.6 GeV	0.25 M	Almost full	~200 μm	~200 fs
	Belle II	10.6 GeV	@50 ab^{-1}: 25M*	Almost full	~200 μm	70-90 fs
Hadron (pp)	LHCb	Run3: 13 TeV Run2: 13 TeV Run1: 7,8 TeV	@23 fb^{-1}: 500M* Run2: 60M Run1: 8M	4% of solid angle; catching ~40% of $\sigma_{Q\bar{Q}}$	0.4 -1 cm	50 fs

*extrapolations

Charm factory

- Background-free
- Lowest statistics
- No boost
- Quantum coherence ★
- Inclusive charm, neutrals and neutrinos
- Absolute branching fractions

B factory

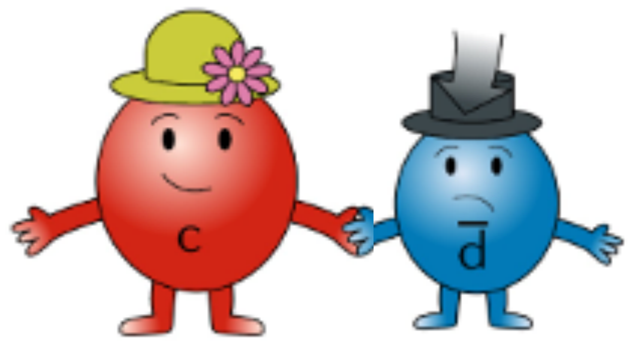
- Low background
- Low statistics
- Low boost
- Good for neutrals and neutrinos ★
- (Some) absolute branching fractions

Hadron collider

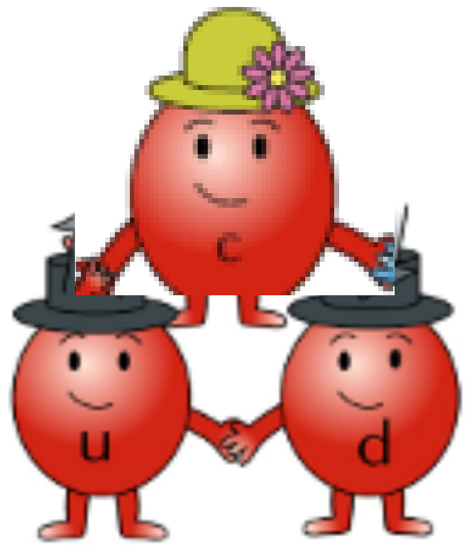
- High background
- High statistics ★
- High boost
- Challenging for neutrals and neutrinos
- Complex and biasing triggers

credit: Tara Nanut

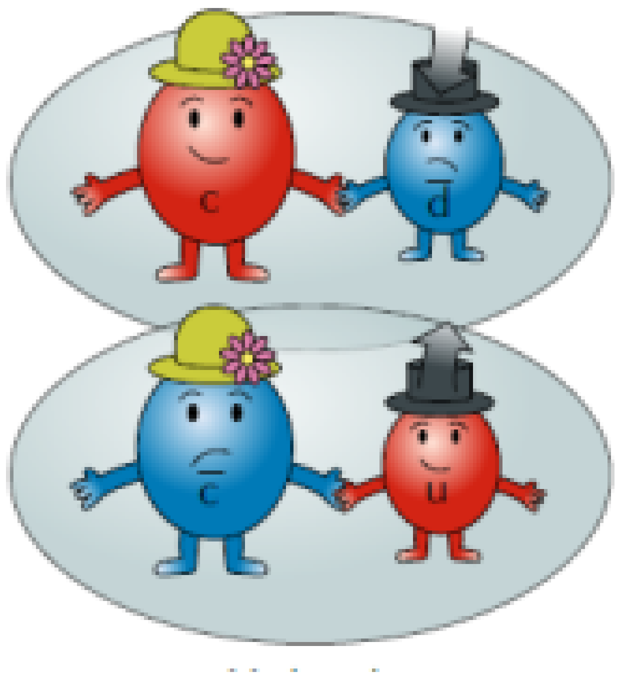
Charm physics at LHCb



Mesons
$D_{(s)}$, charmonium



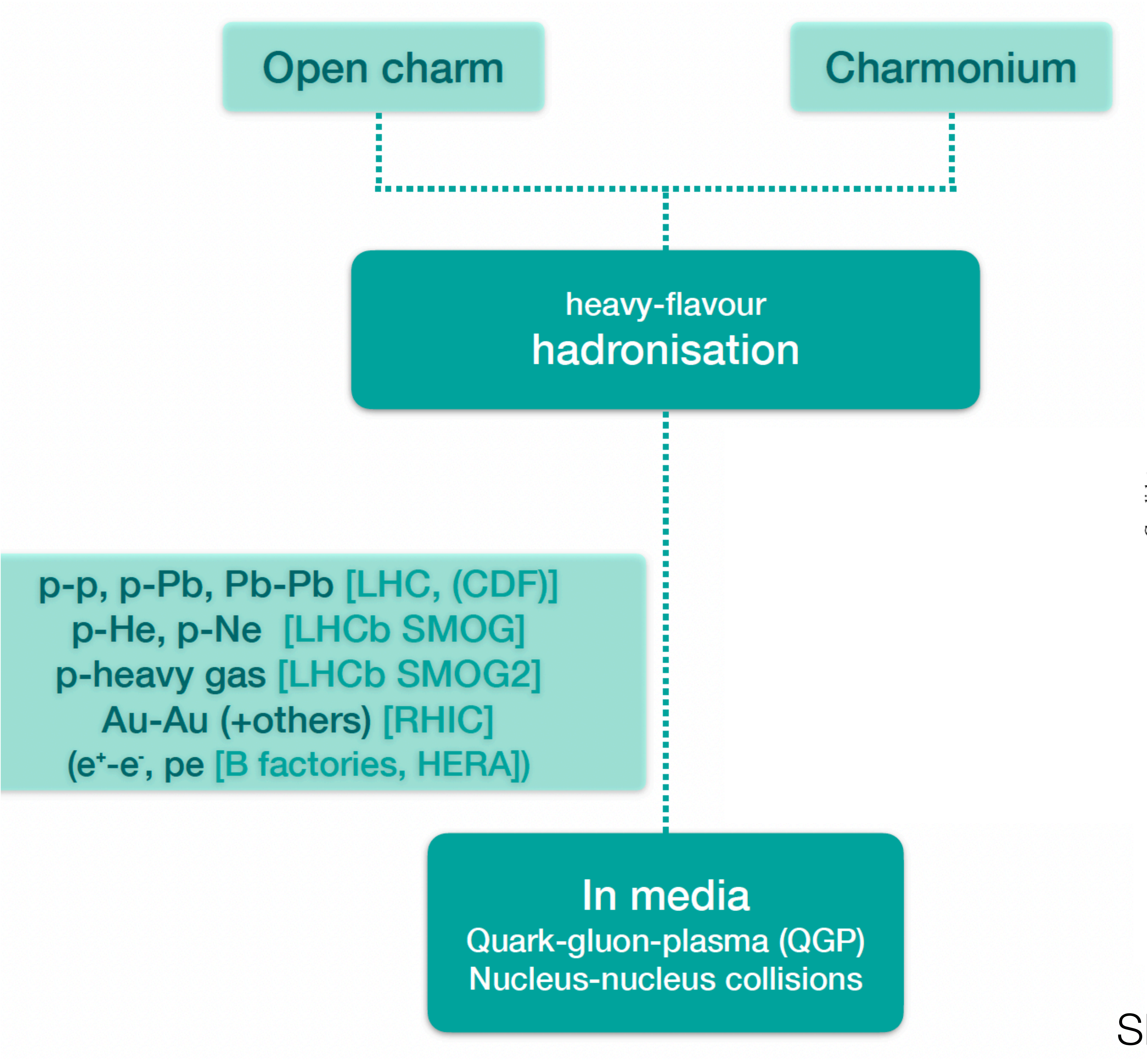
Baryons
singly, doubly
charmed



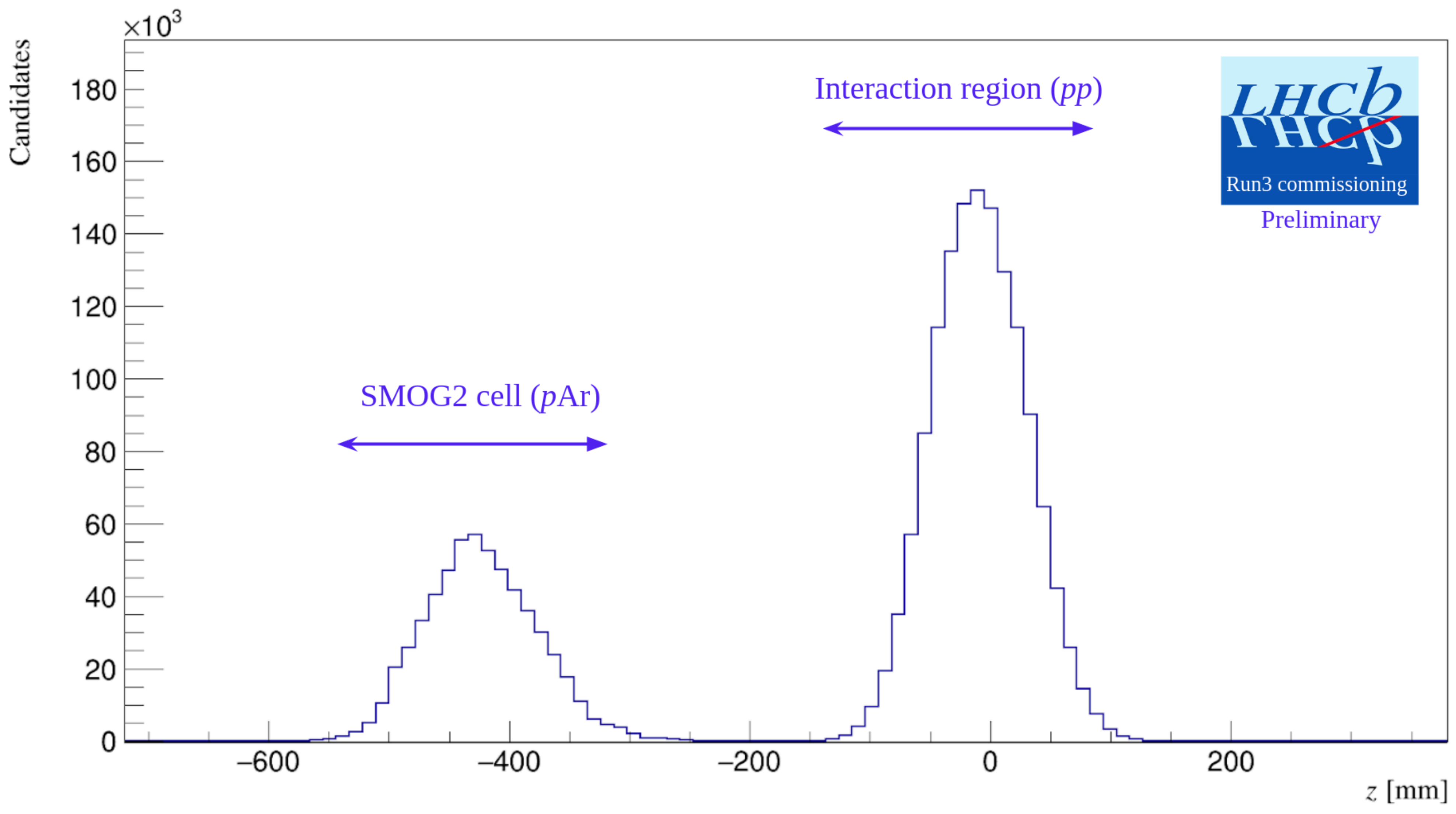
exotic states
$c(\bar{c}) + X$

- Production
- Lifetimes
- Spectroscopy
- CP violation
- Rare decays

Production



- Hadronisation: perturbative QCD with factorisation approach: many sub-models
- QGP properties
- Experiment constantly challenges theoretical predictions



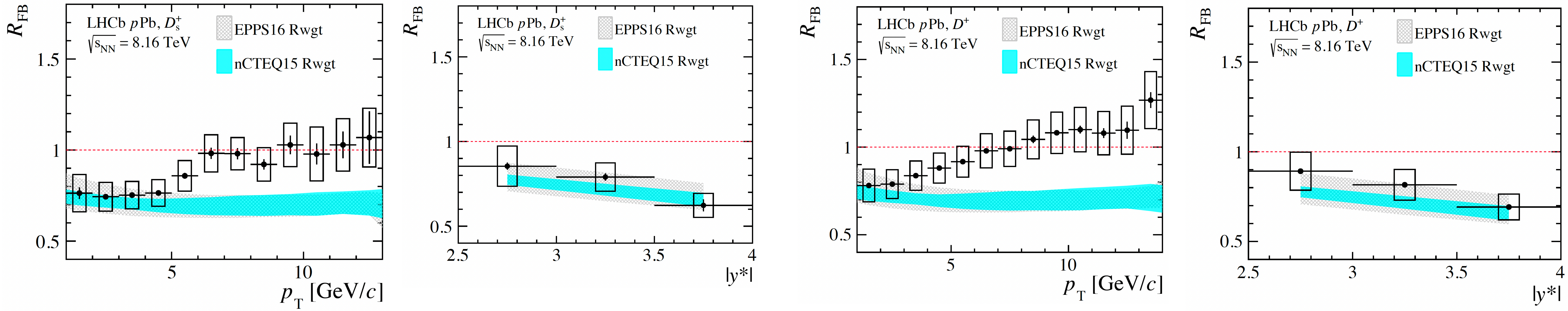
SMOG2 can take data simultaneously to LHCb pp collision!

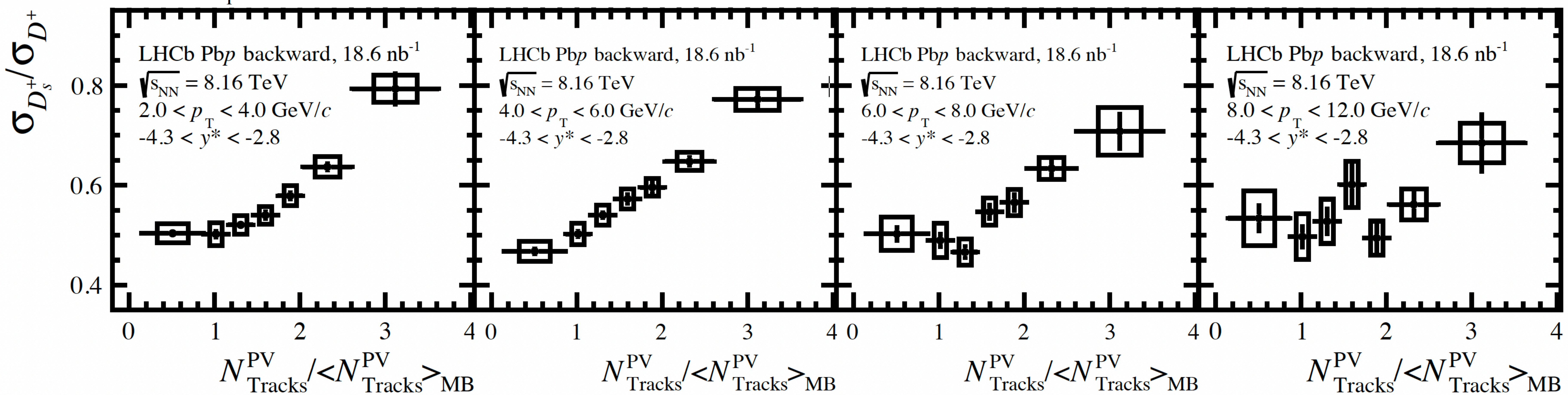
Enhanced production in high-multiplicity pPb collisions

PRD110, L031105 (2024)

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

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

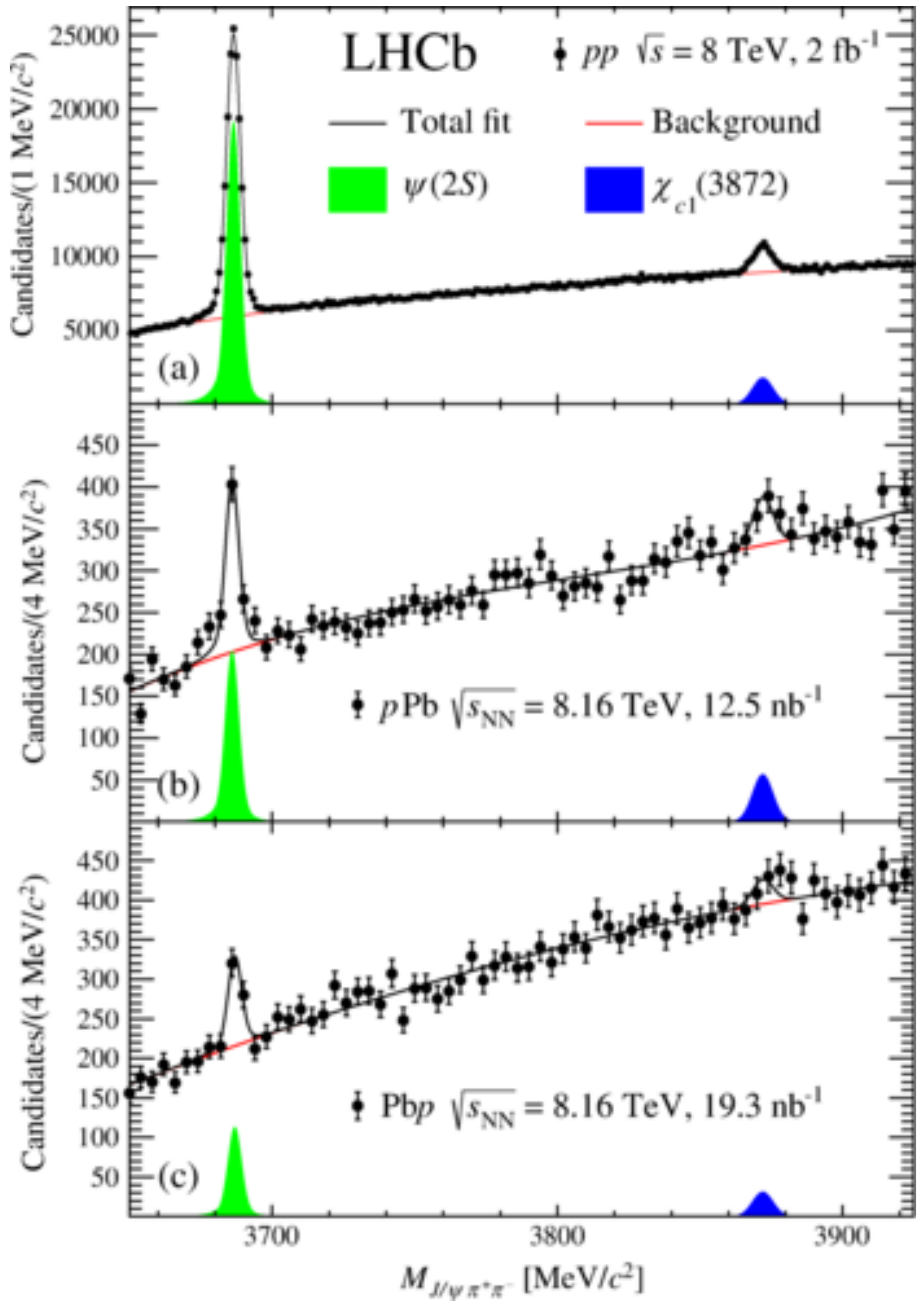




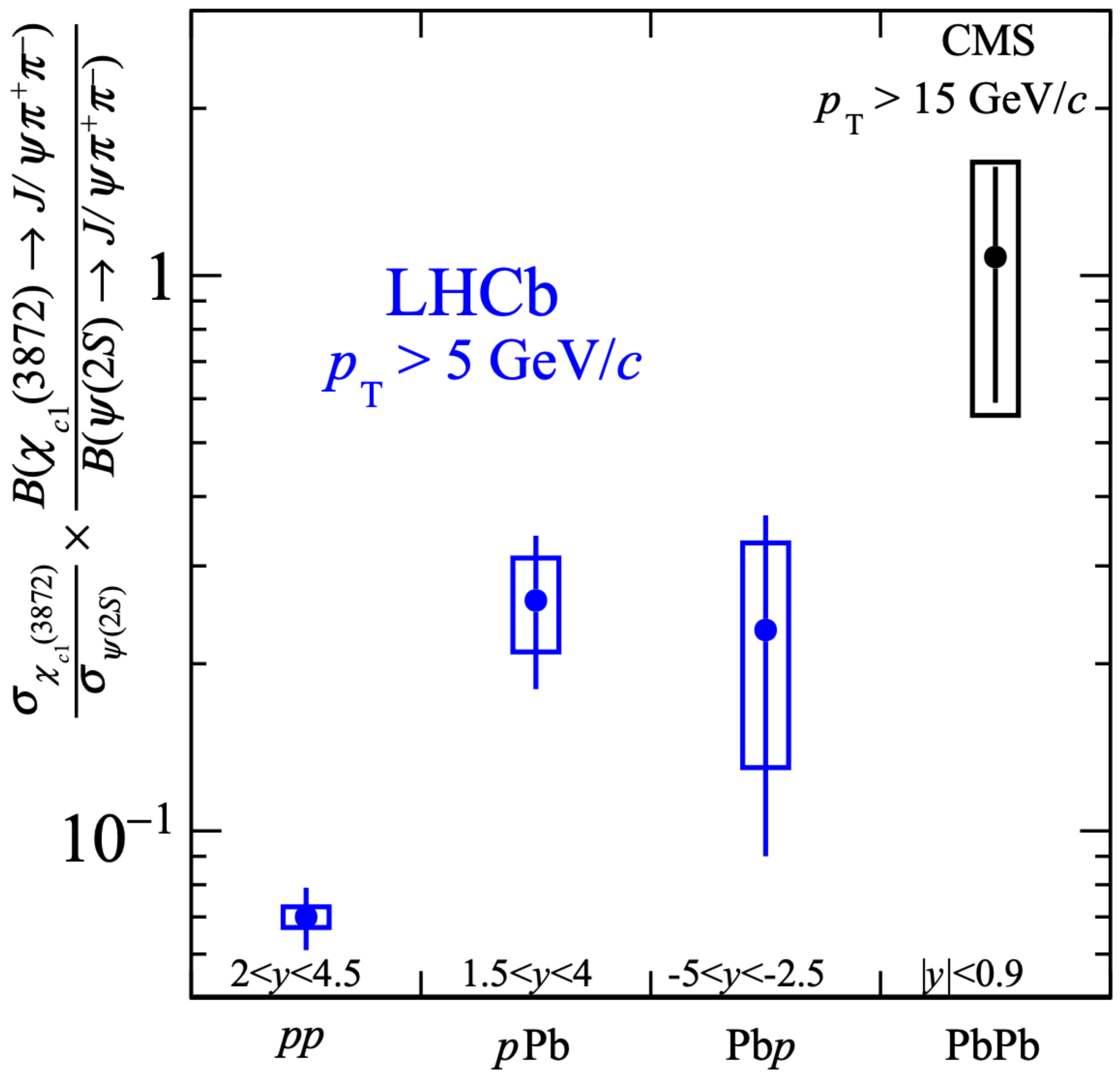
Production cross section of charmonium-(like) states

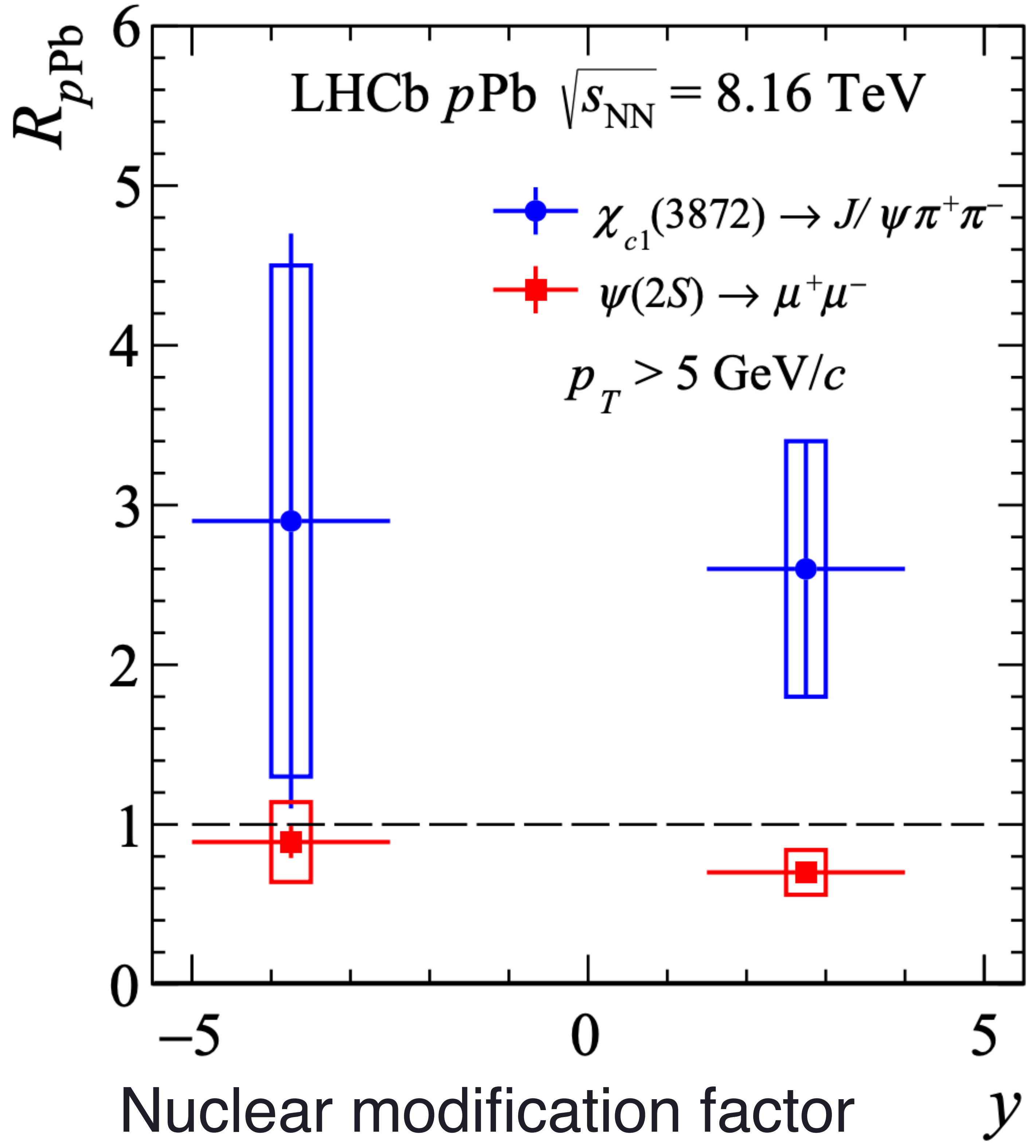
PRL132(2024)242301

- $\chi_{c1}(3872)$ may experience different dynamics in the nuclear medium than the conventional charmonia
- First measurement of the nuclear modification factor of an exotic hadron



$$R_{pA}^{\chi_{c1}(3872)} = \frac{\sigma_{pA}^{\chi_{c1}(3872)}}{208\times\sigma_{pp}^{\chi_{c1}(3872)}} = \frac{1}{208}\frac{\sigma_{pA}^{\chi_{c1}(3872)}}{\sigma_{pp}^{\chi_{c1}(3872)}}\frac{\sigma_{pA}^{\psi(2S)}}{\sigma_{pp}^{\psi(2S)}}\frac{\sigma_{pp}^{\psi(2S)}}{\sigma_{pA}^{\psi(2S)}} = R_{pA}^{\psi(2S)}\frac{\sigma_{pA}^{\chi_{c1}(3872)}/\sigma_{pA}^{\psi(2S)}}{\sigma_{pp}^{\chi_{c1}(3872)}/\sigma_{pp}^{\psi(2S)}}$$





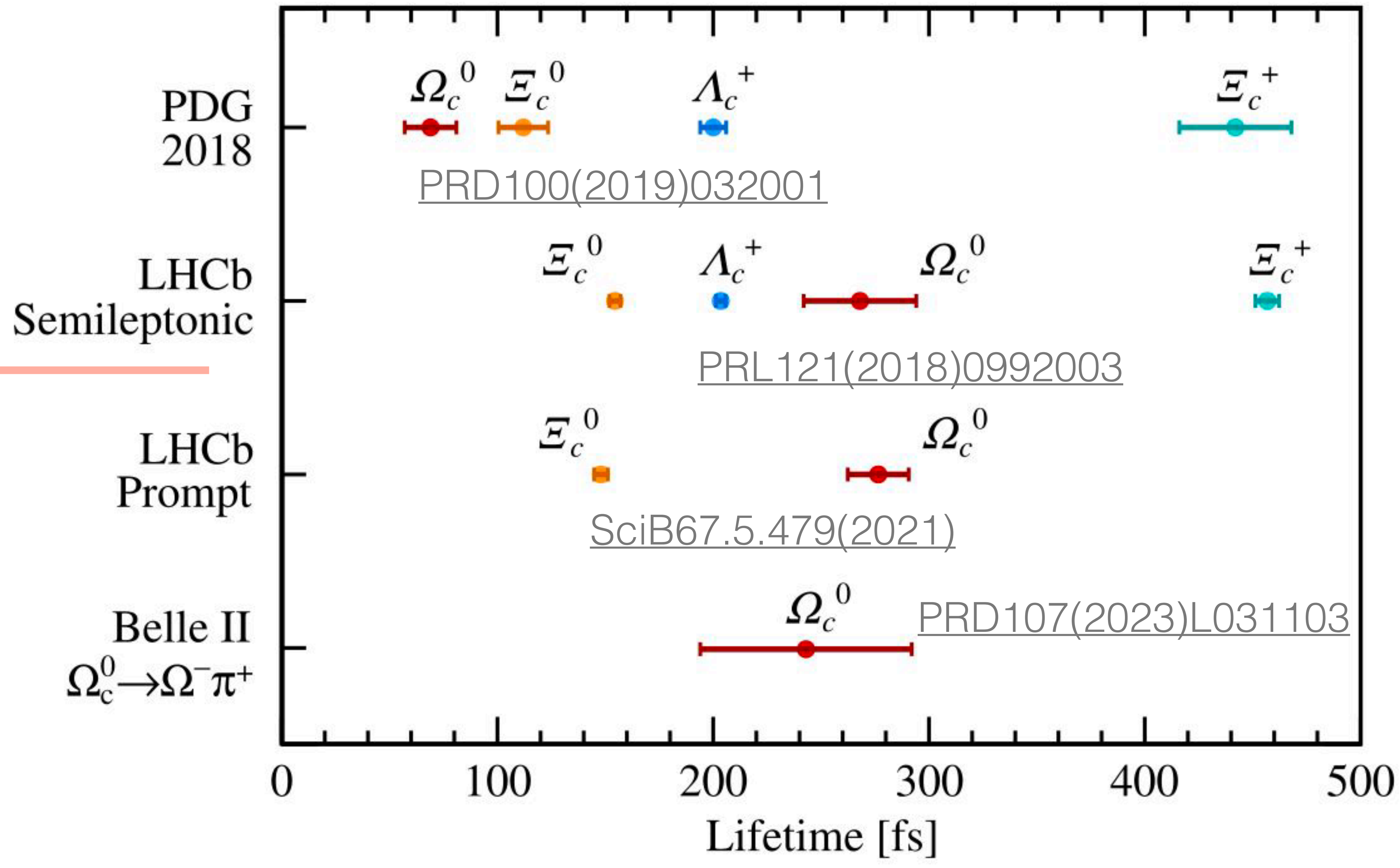
Nuclear modification factor

Charmed baryon lifetimes

- Computed through Heavy Quark Expansion (HQE)
- Differences arise from higher-order effects involving spectator quarks
- Studied since the 1990s with first measurement by E687, WA89, FOCUS: $\tau_{\Omega_c^0} = 69 \pm 12\ \mathrm{fs}$
- Early results supported the expected hierarchy:

$$\tau_{\Xi_c^+} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0} > \tau_{\Omega_c^0}$$

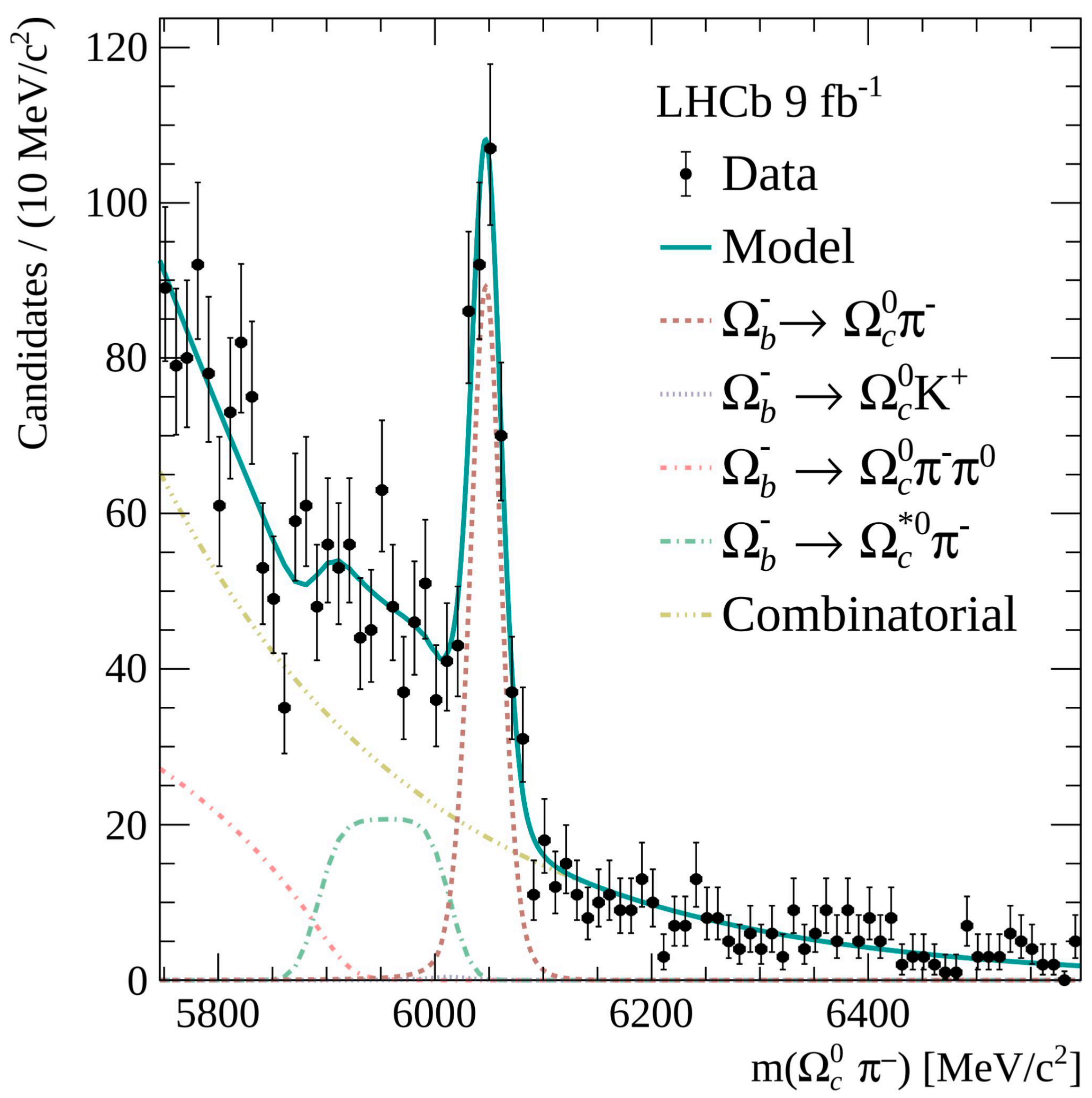
$$\tau_{\Xi_c^+} > \tau_{\Omega_c^0} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0}$$

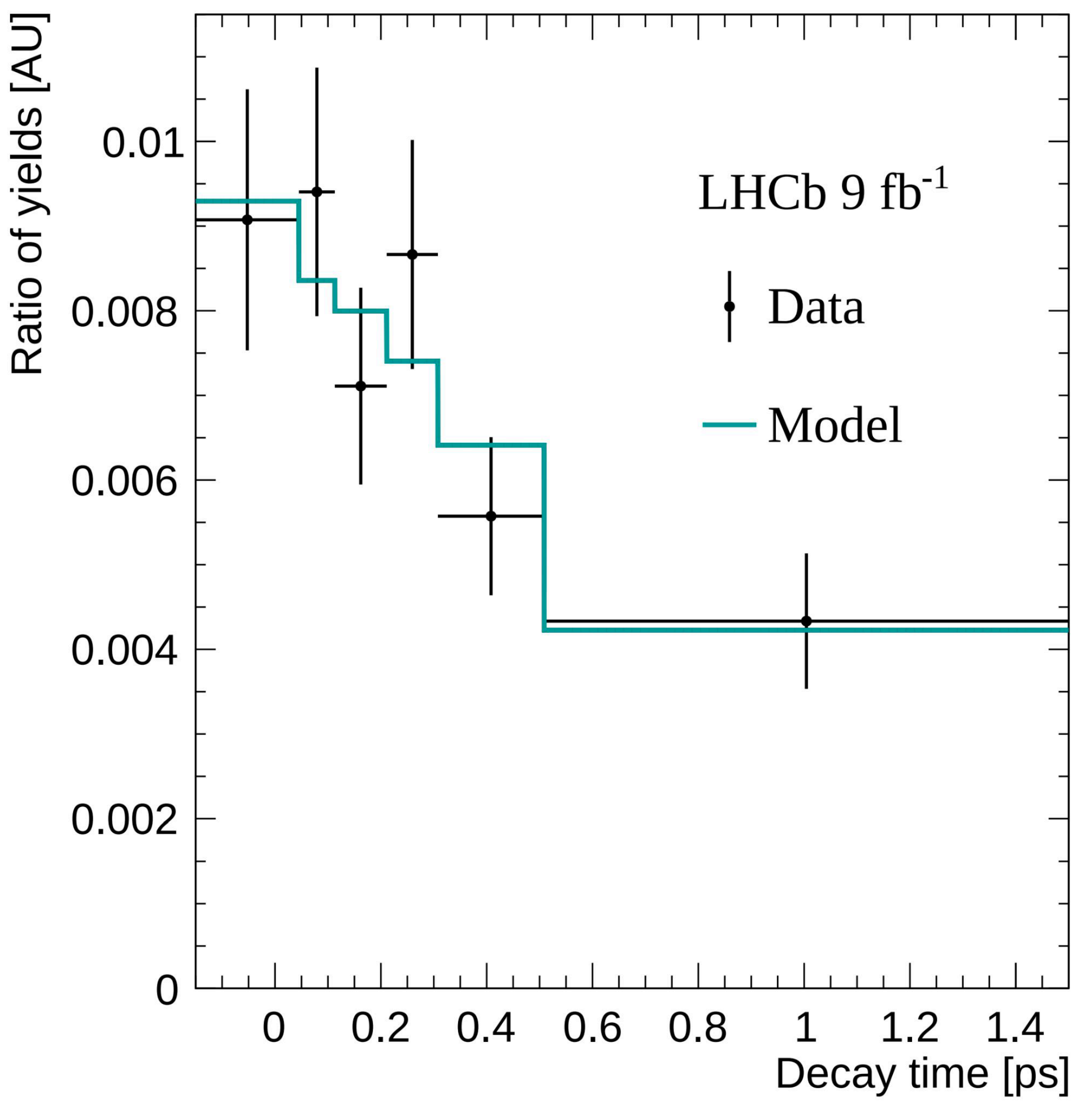


Lifetimes in hadronic decay

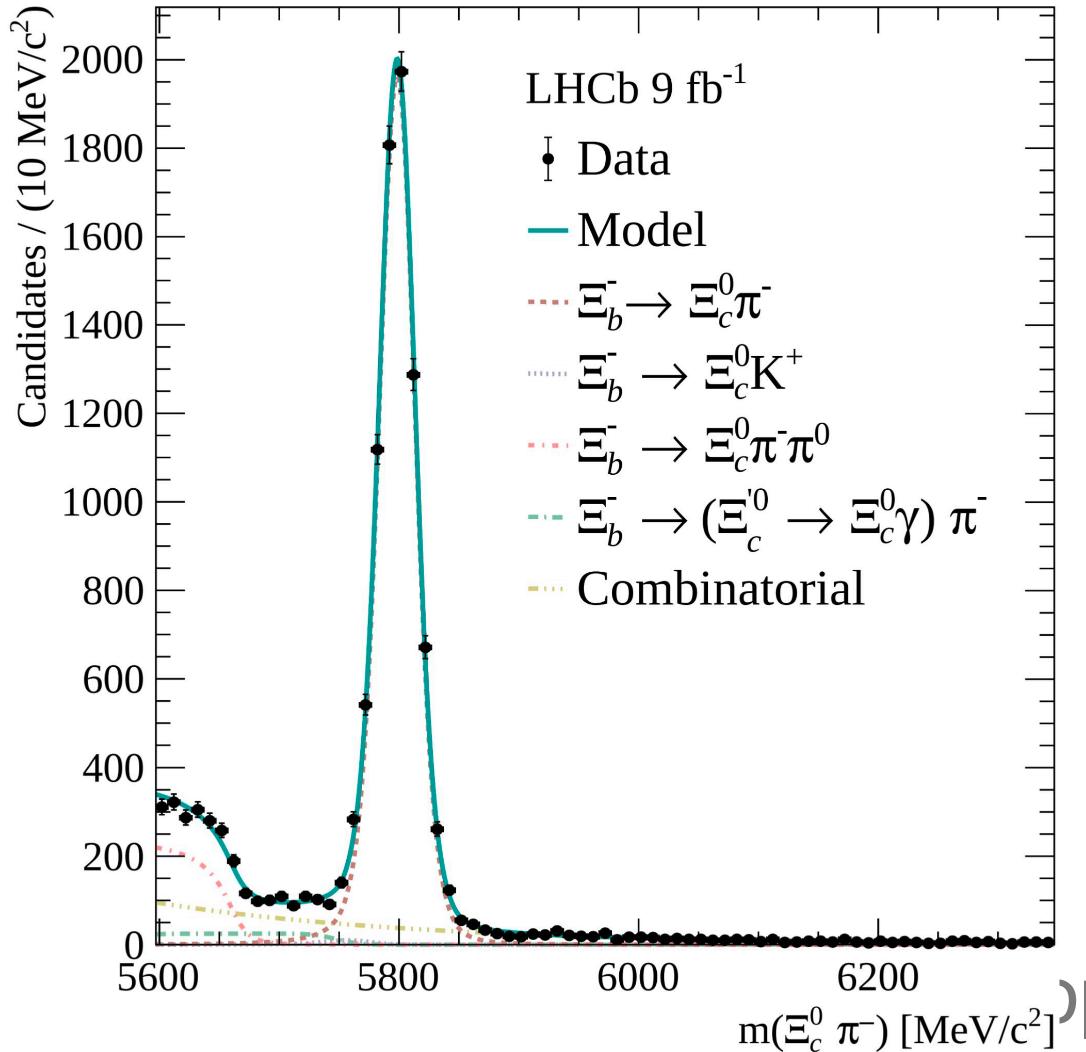
arXiv: 2506.13334

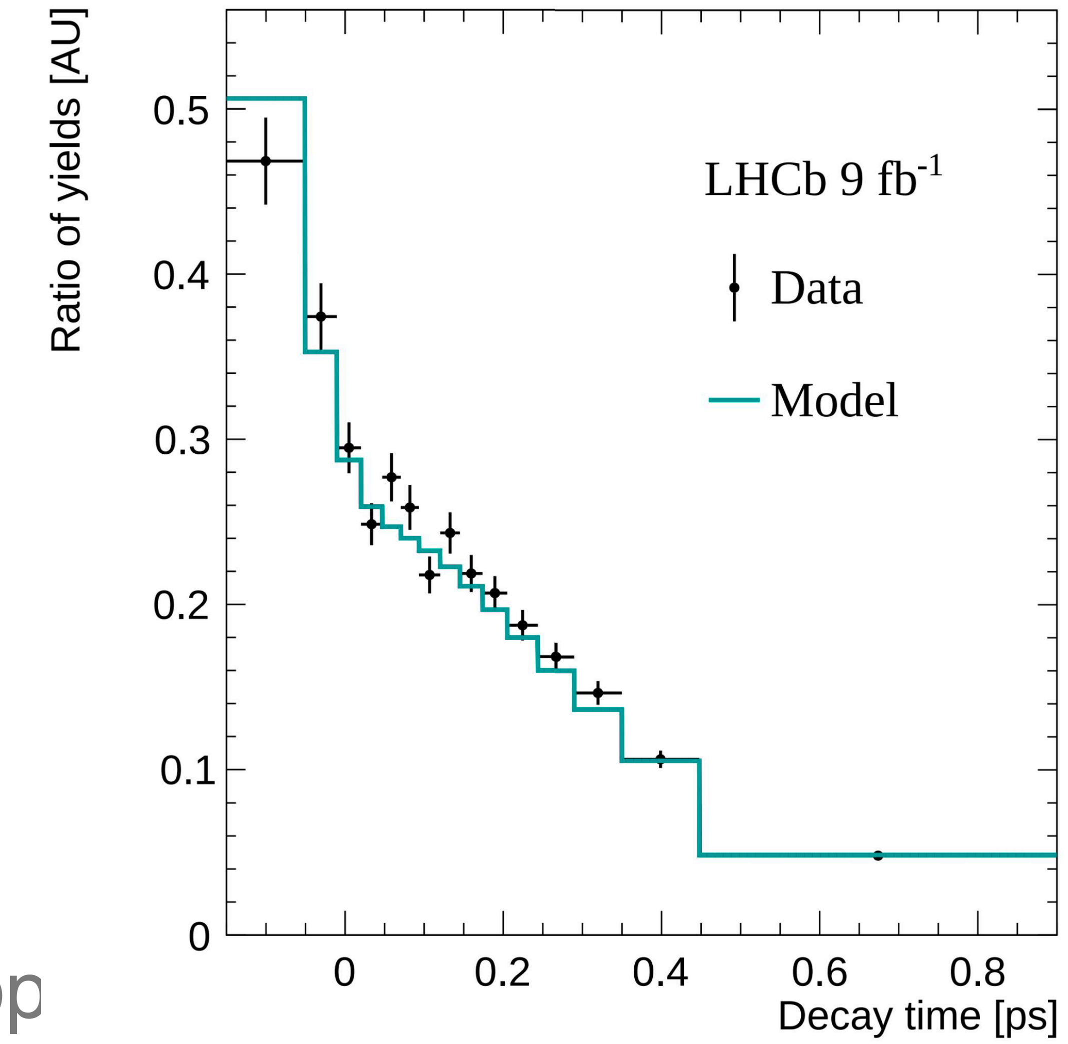
350 events $\Omega_b^- \to (\Omega_c^0 \to pK^-K^-\pi^+)\,\pi^-$





8.2k events $\Xi_b^- \to (\Xi_c^0 \to pK^-K^-\pi^+)\,\pi^-$

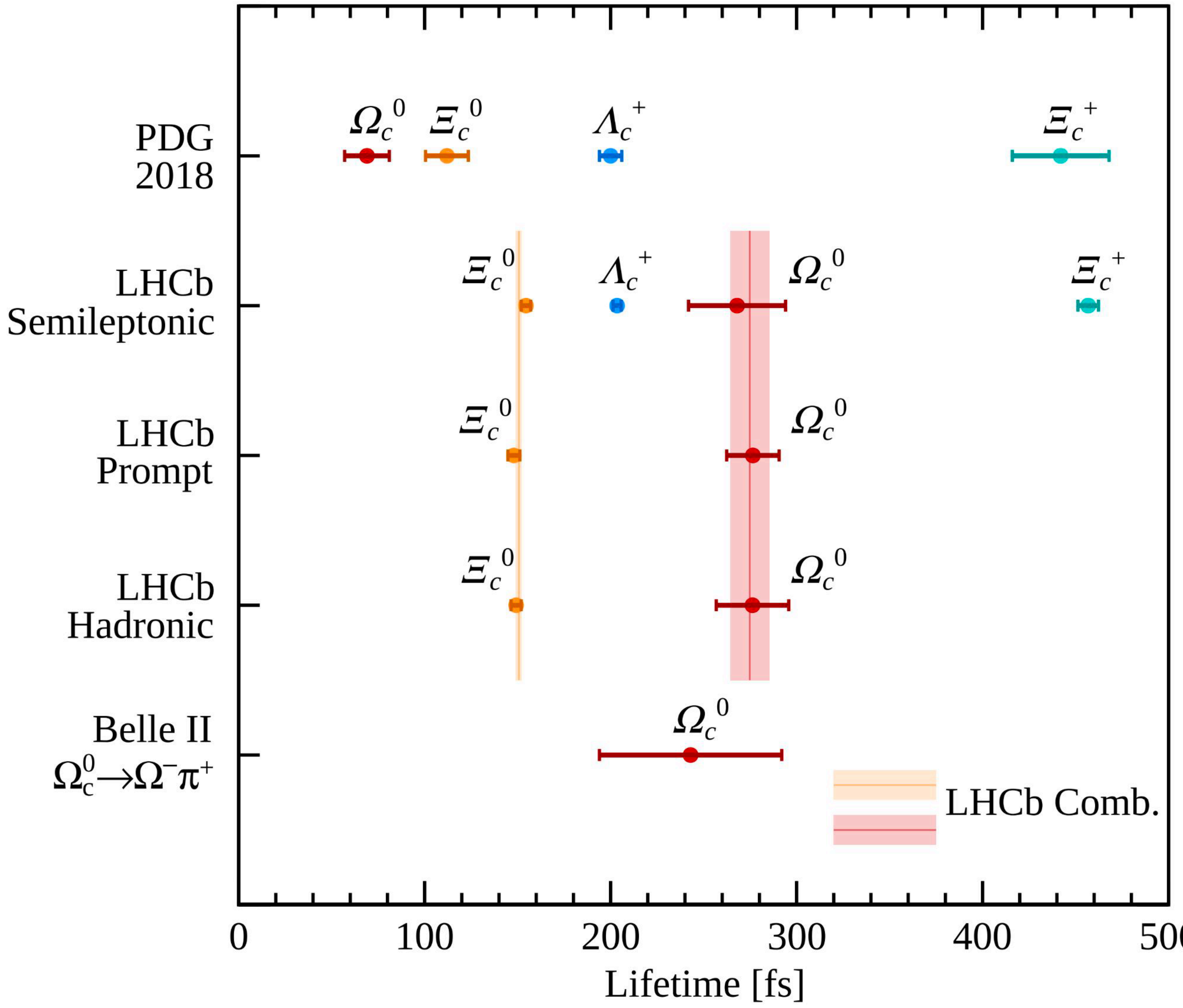




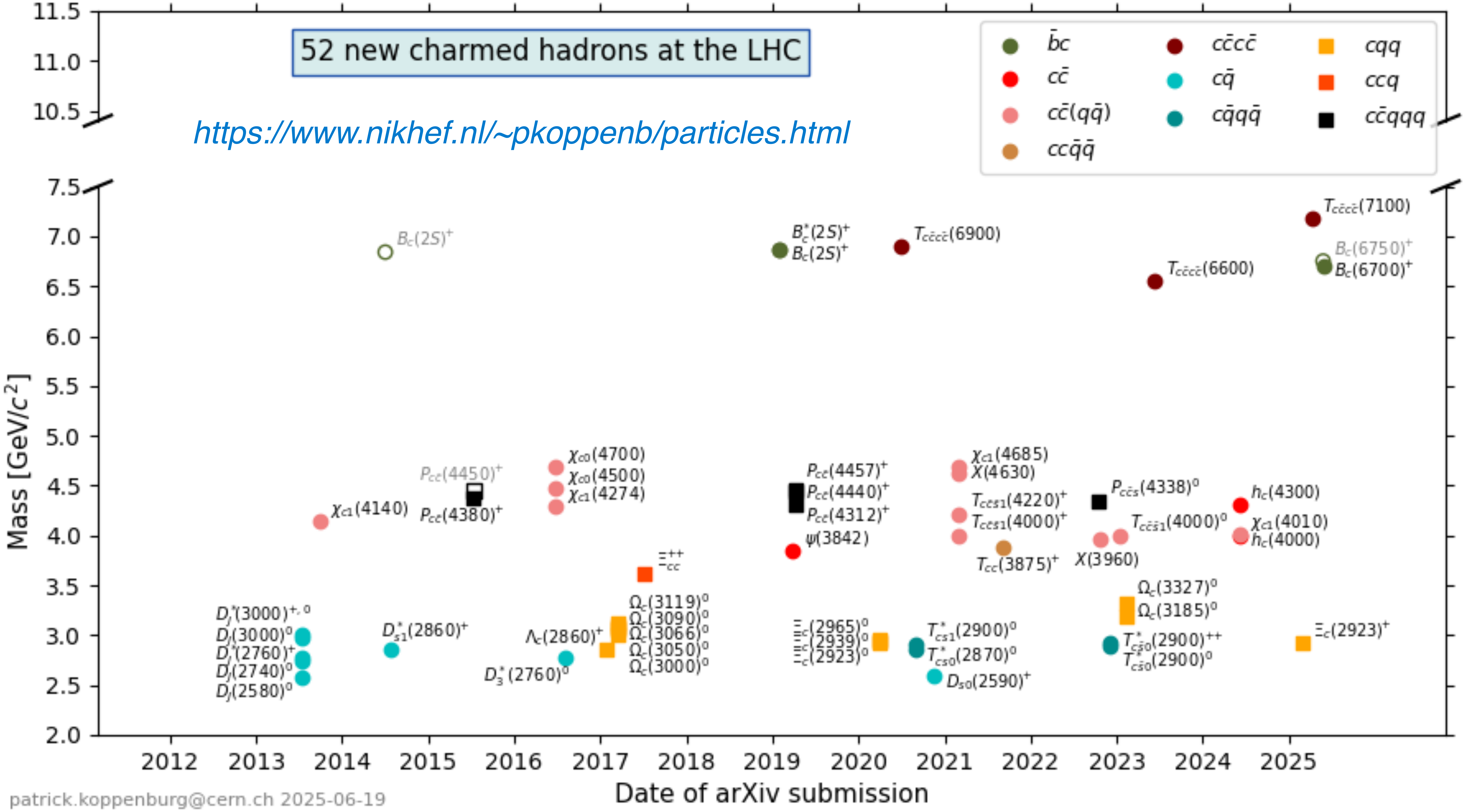
- Fits to decay time ratio w.r.t control mode

$$B^- \to (D^0 \to K^-K^+\pi^-\pi^+)\,\pi^-$$

$$\tau_{\Omega_c^0} = 274.8 \pm 10.5 \text{ fs}$$
$$\tau_{\Xi_c^0} = 150.7 \pm 1.6 \text{ fs}$$

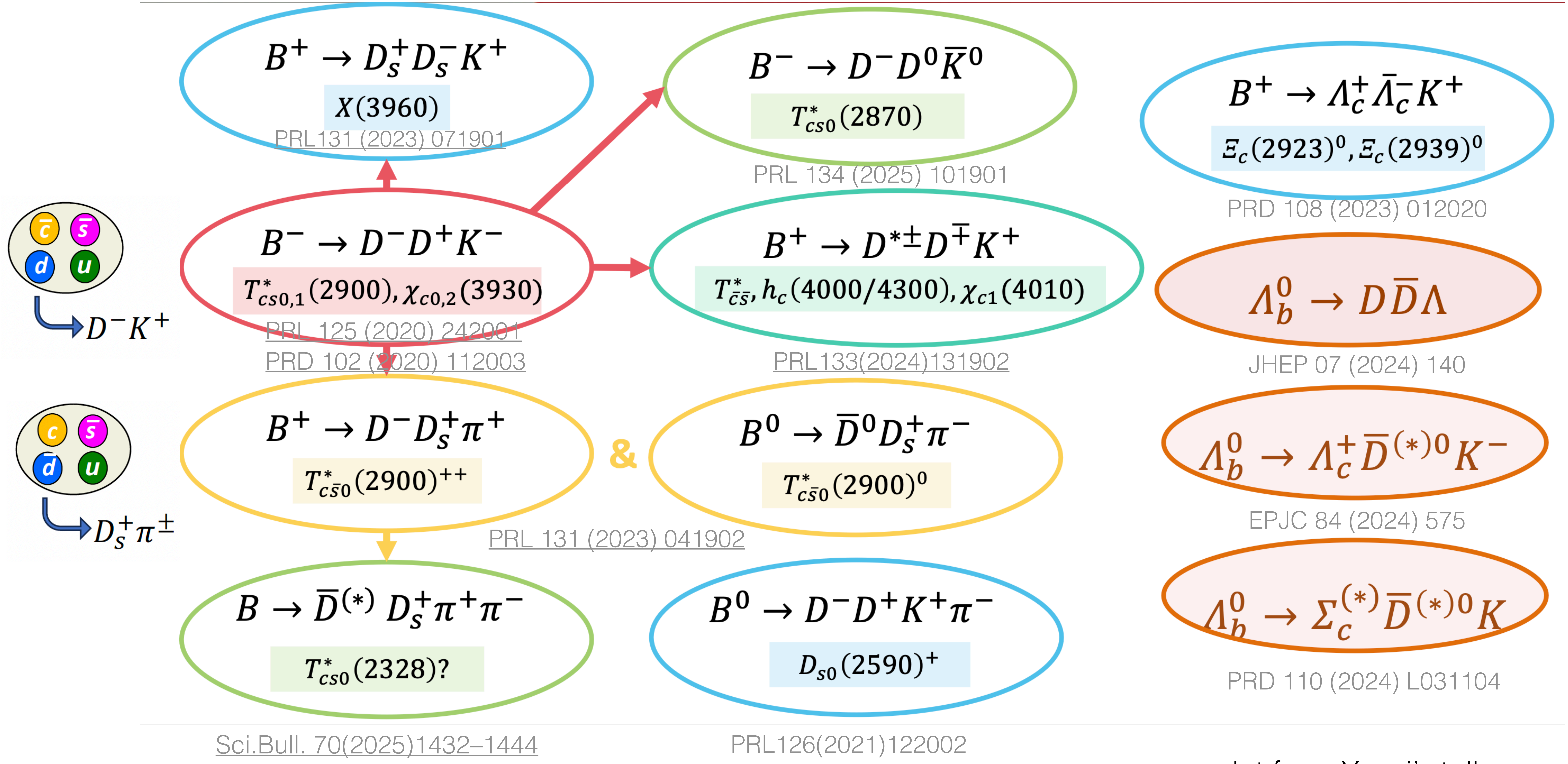


Spectroscopy



More in Chenjia’s talk

Study of $B \to D^{(*)}\bar{D}h(h)$

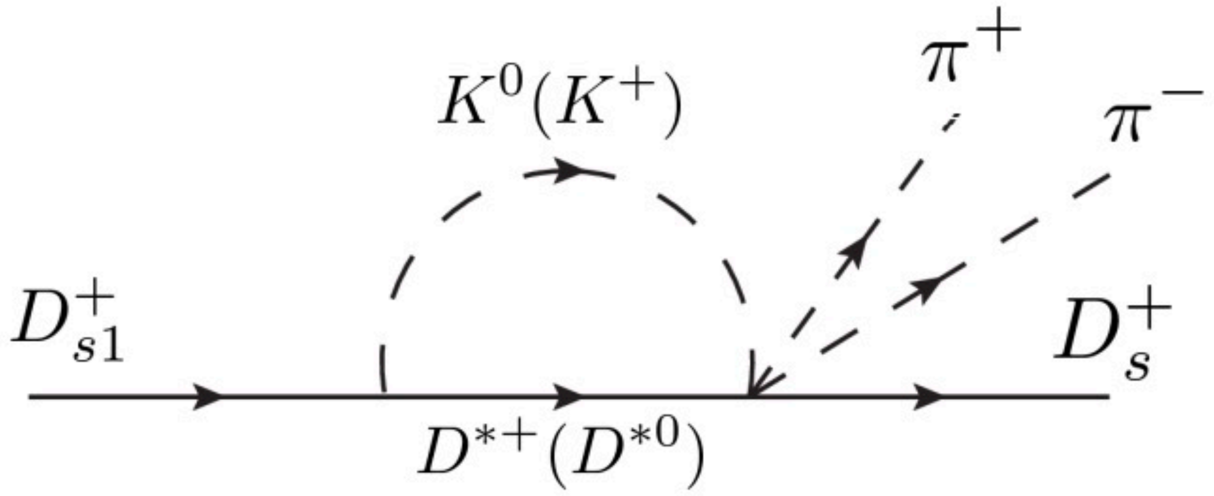


plot from Yanxi's talk

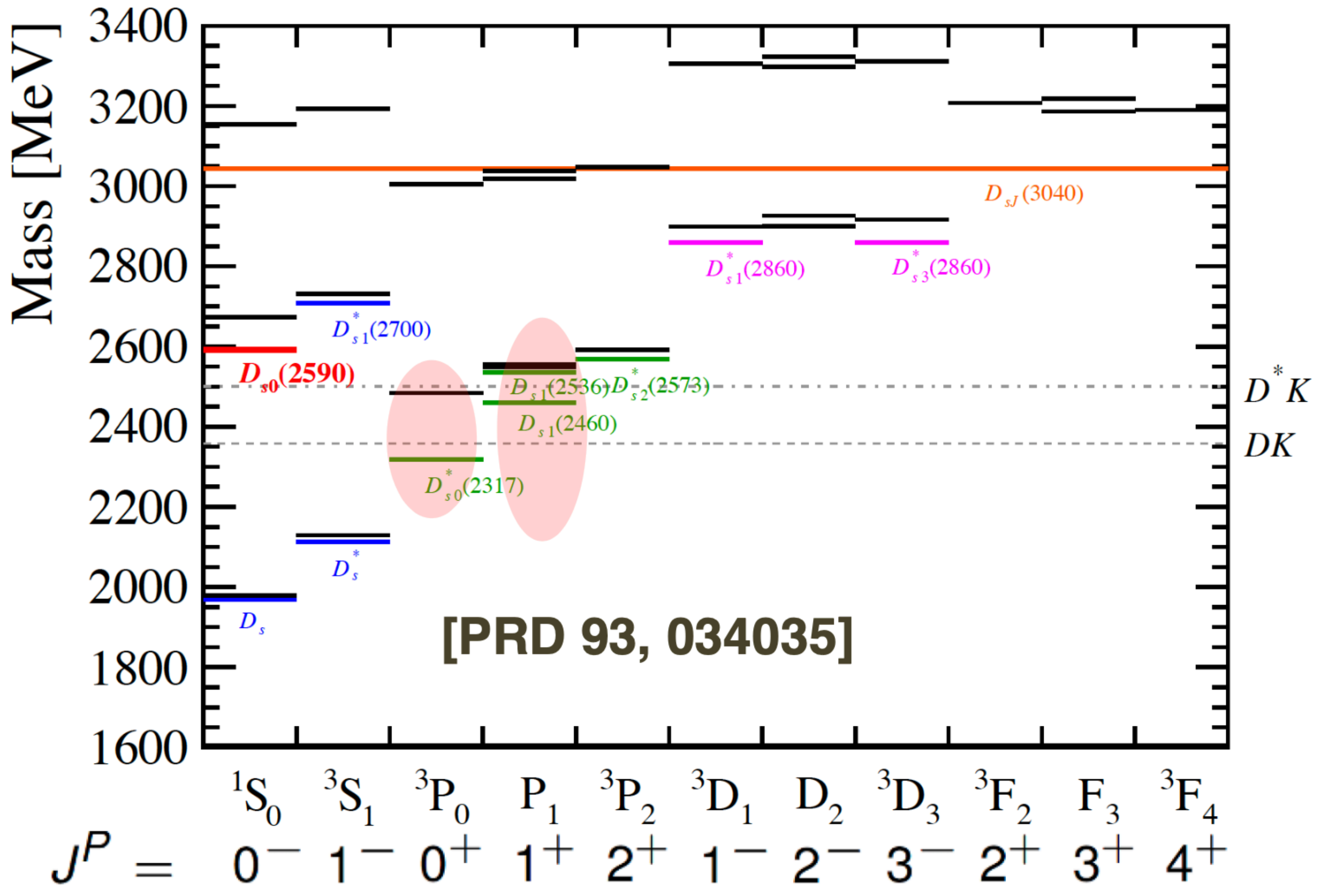
Study of $D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$

Sci.Bull. 70(2025)1432–1444

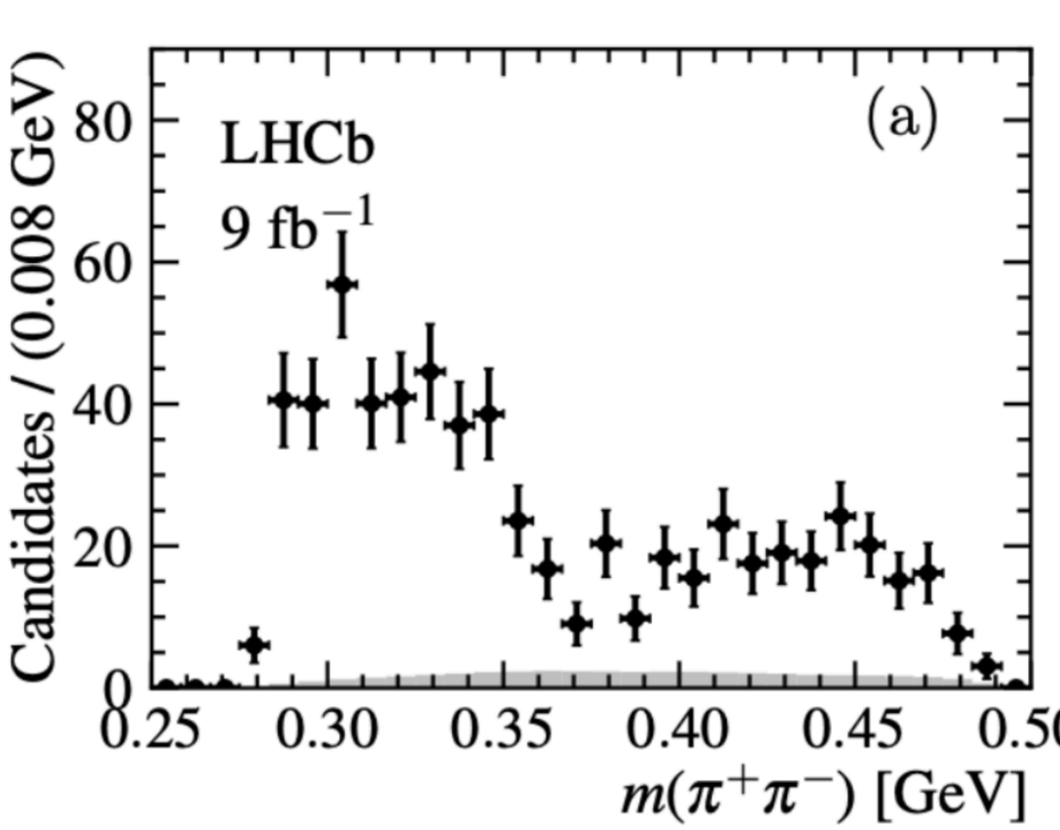
- Unexpected properties for $D_{s0}^*(2317)^+$ and $D_{s1}(2460)^+$
  - Masses ~100 MeV below predictions
  - Isospin-violating decay $D_s^{(*)+}\pi^0$
- Double-bump line shape $m(\pi\pi)$ if $D_{s1}(2460)^+$ is a D^*K molecule

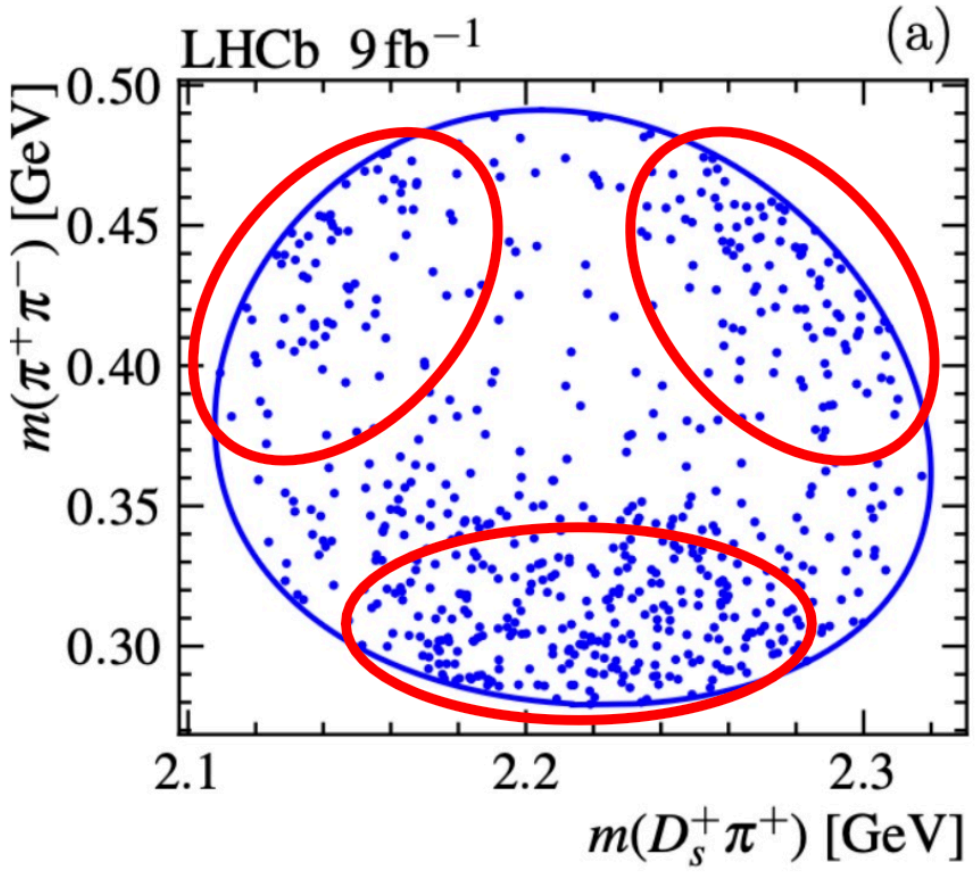


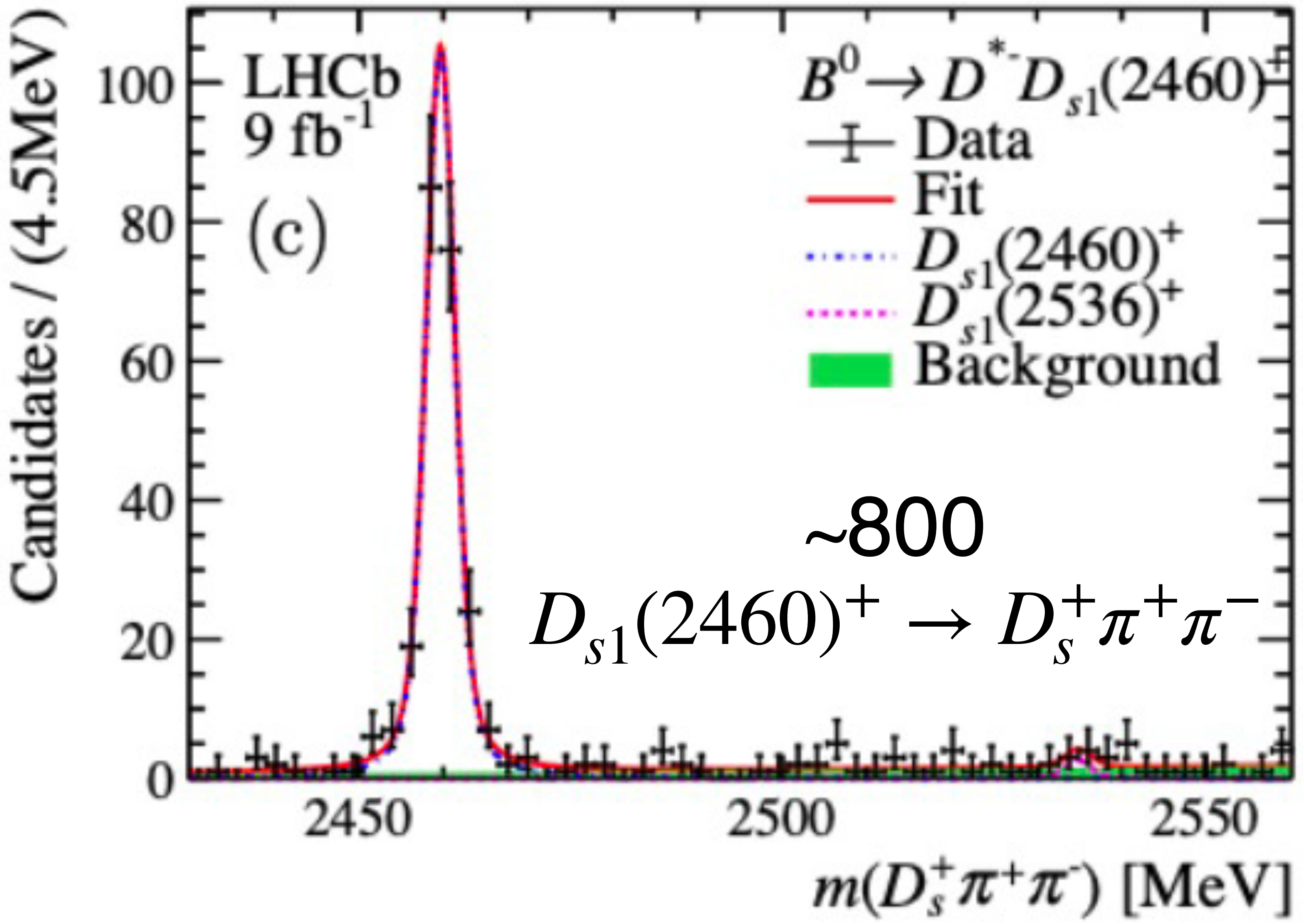
[Commun. Theor. Phys. 75 055203]



- $D_{s0}(2317)^+$ as tetraquark: isospin partners proposed inspired by $T_{c\bar{s}}(2900)^{++/0} \to D_s^+\pi^{+/0}$ [PRD 110, 034014]







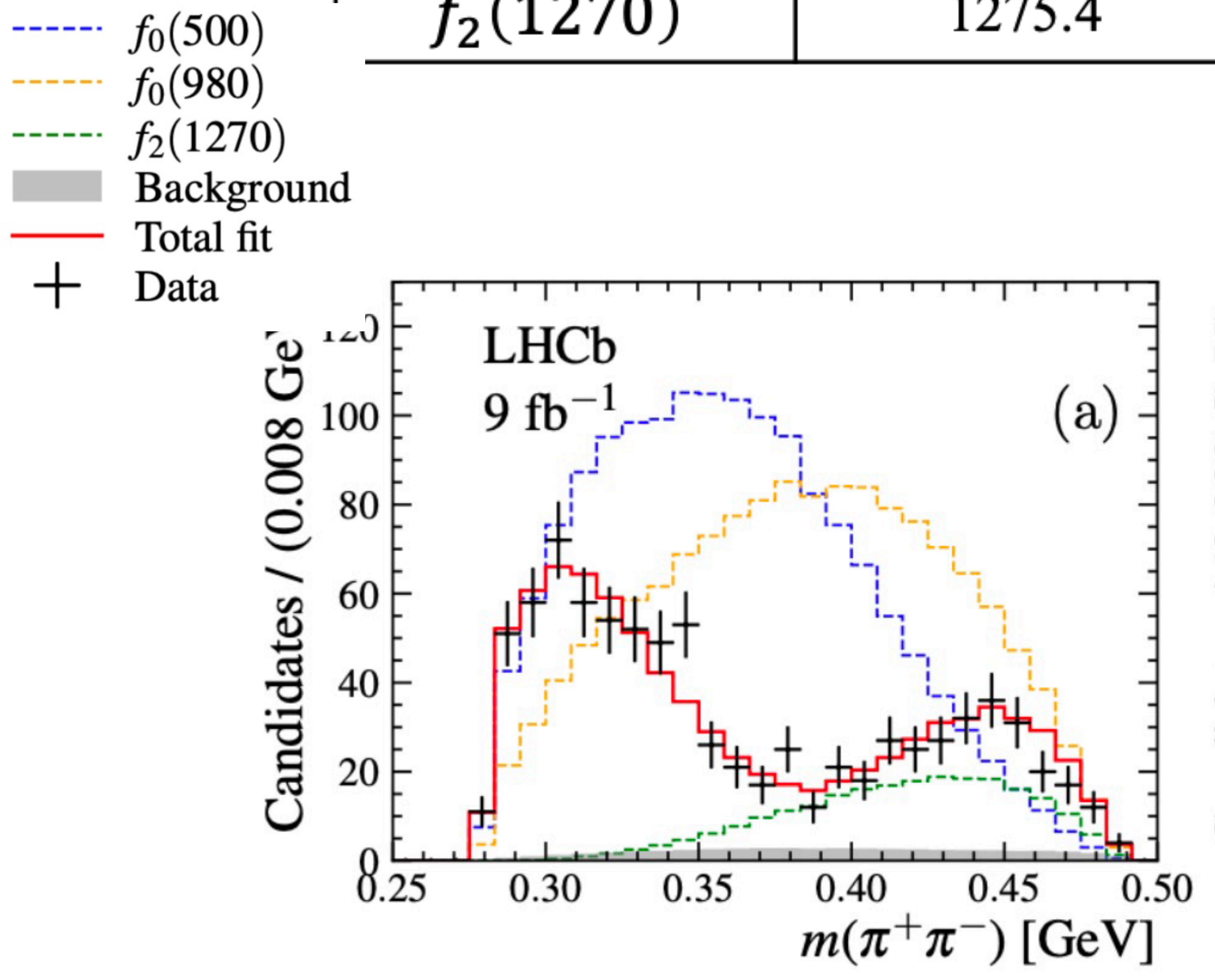
Study of $D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$

Sci.Bull. 70(2025)1432–1444

Two model describe data equally well!

- $f_0(500) + f_0(980) + f_2(1270)$
  - Large contribution from $f_0(980)$ and $f_2(1270)$ despite beyond phase space limit
  - Can't be rejected, but implausible

Resonance	Mass (MeV)	Width (MeV)	FF (%)
$f_0(500)$	$376 \pm 9 \pm 16$	$175 \pm 23 \pm 16$	$197 \pm 35 \pm 23$
$f_0(980)$	945.5	167	$187 \pm 38 \pm 43$
$f_2(1270)$	1275.4	186.6	$29 \pm 2 \pm 1$



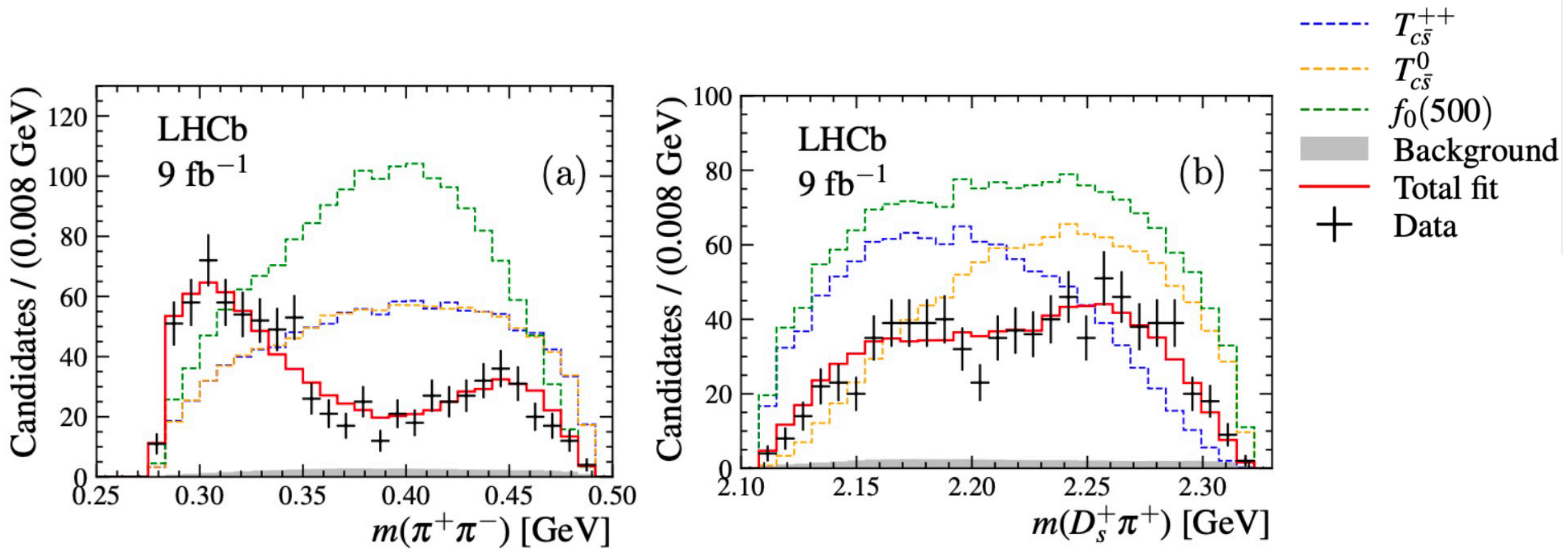
- $f_0(500) + T_{c\bar{s}}^{++} + T_{c\bar{s}}^{0}$ (new exotics)

$T_{c\bar{s}}^{++} \to D_s^+\pi^+$, $T_{c\bar{s}}^{0} \to D_s^+\pi^-$

Consistent with isospin symmetry

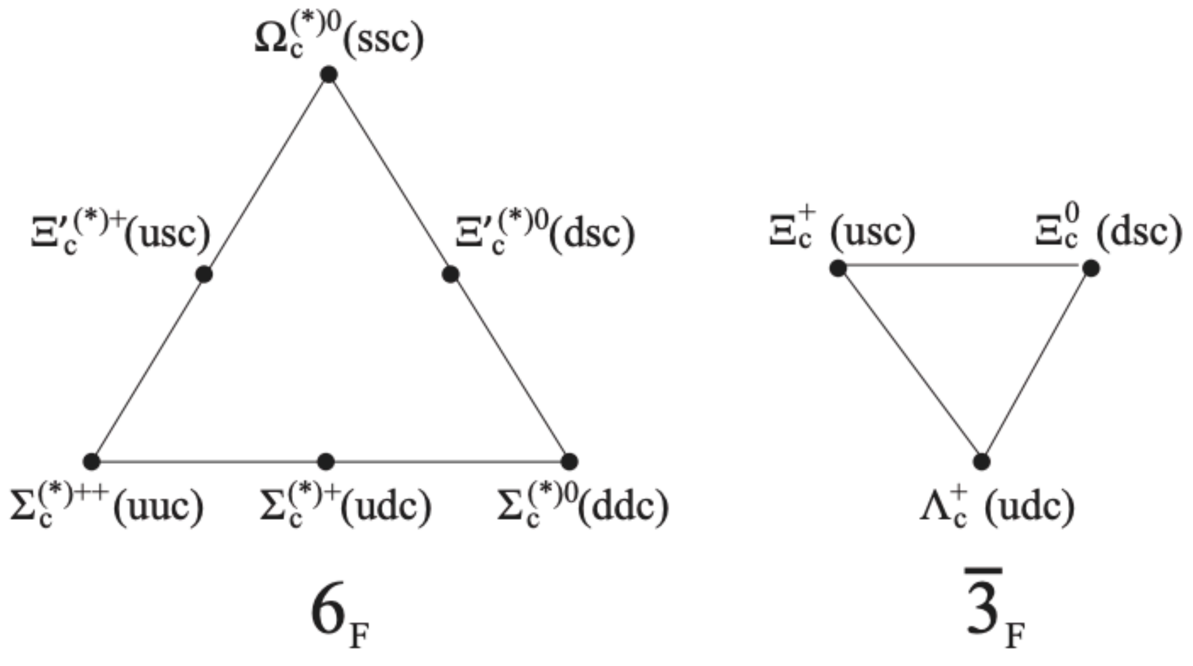
$T_{c\bar{s}}$ masses ~ $D_{s0}^*(2317)^+$, but different widths

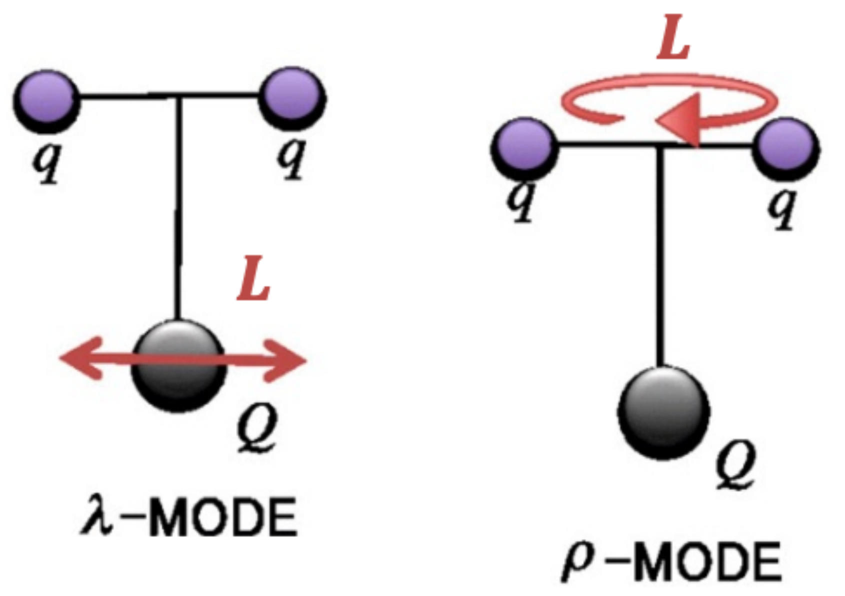
Resonance	Mass (MeV)	Width (MeV)	FF (%)
$f_0(500)$	$472 \pm 32 \pm 19$	$226 \pm 24 \pm 18$	$237^{+51}_{-43} \pm 42$
$T_{c\bar{s}}$	$2328 \pm 12 \pm 12$	$96 \pm 16^{+170}_{-23}$	$151^{+31}_{-33} \pm 25$



Observation of Ξ_c^{**+} in $\Xi_c^- \pi^+ \pi^-$

arXiv:2502.18987





- Rich spectrum in charmed baryons: ideal for non-perturbative QCD
- Angular excitation in λ mode and ρ mode (not observed yet)

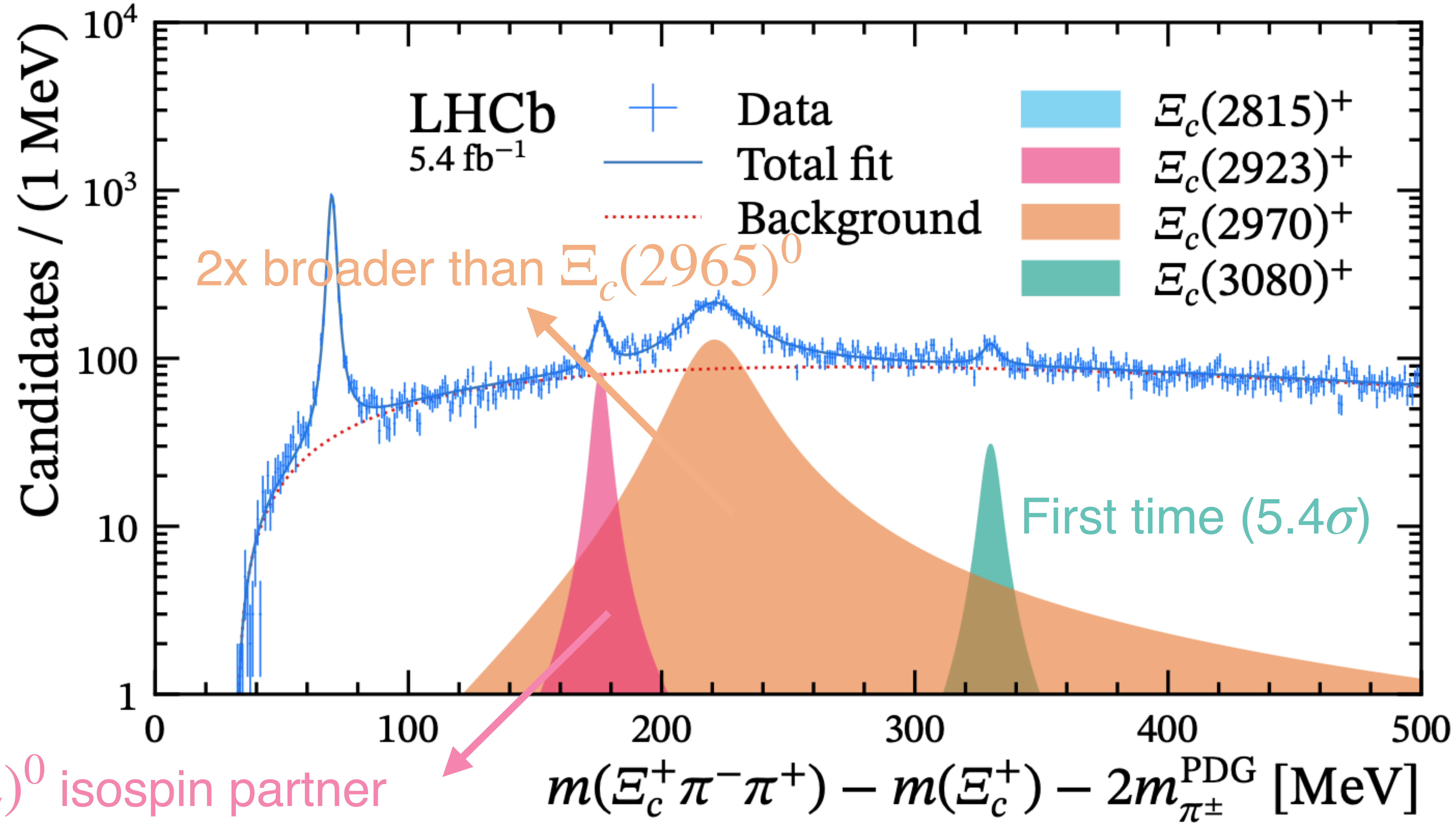
$$m[\Xi_c(2815)^+] = 2816.65 \pm 0.03 \pm 0.03 \pm 0.23\,\text{MeV},$$
$$\Gamma[\Xi_c(2815)^+] = 2.07 \pm 0.08 \pm 0.12\,\text{MeV},$$

$$m[\Xi_c(2923)^+] = 2922.8 \pm 0.3 \pm 0.5 \pm 0.2\,\text{MeV},$$
$$\Gamma[\Xi_c(2923)^+] = 5.3 \pm 0.9 \pm 1.4\,\text{MeV},$$

$$m[\Xi_c(2970)^+] = 2968.6 \pm 0.5 \pm 0.5 \pm 0.2\,\text{MeV},$$
$$\Gamma[\Xi_c(2970)^+] = 31.7 \pm 1.7 \pm 1.9\,\text{MeV},$$

$$m[\Xi_c(3080)^+] = 3076.8 \pm 0.7 \pm 1.3 \pm 0.2\,\text{MeV},$$
$$\Gamma[\Xi_c(3080)^+] = 6.8 \pm 2.3 \pm 0.9\,\text{MeV},$$

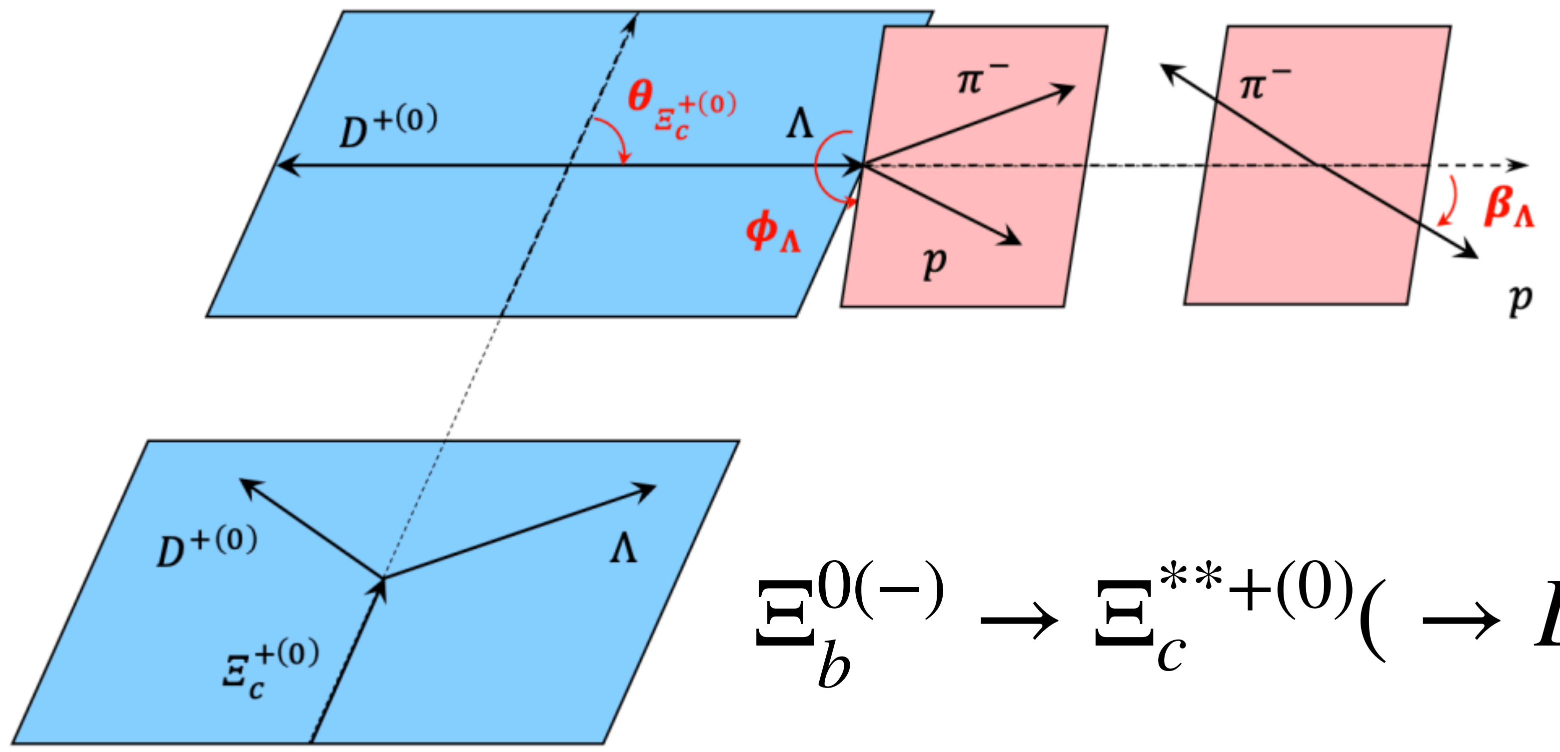
$$\Xi_c^{**+} \to \Xi_c(2645)^0(\to \Xi_c^+ \pi^-)\pi^+$$



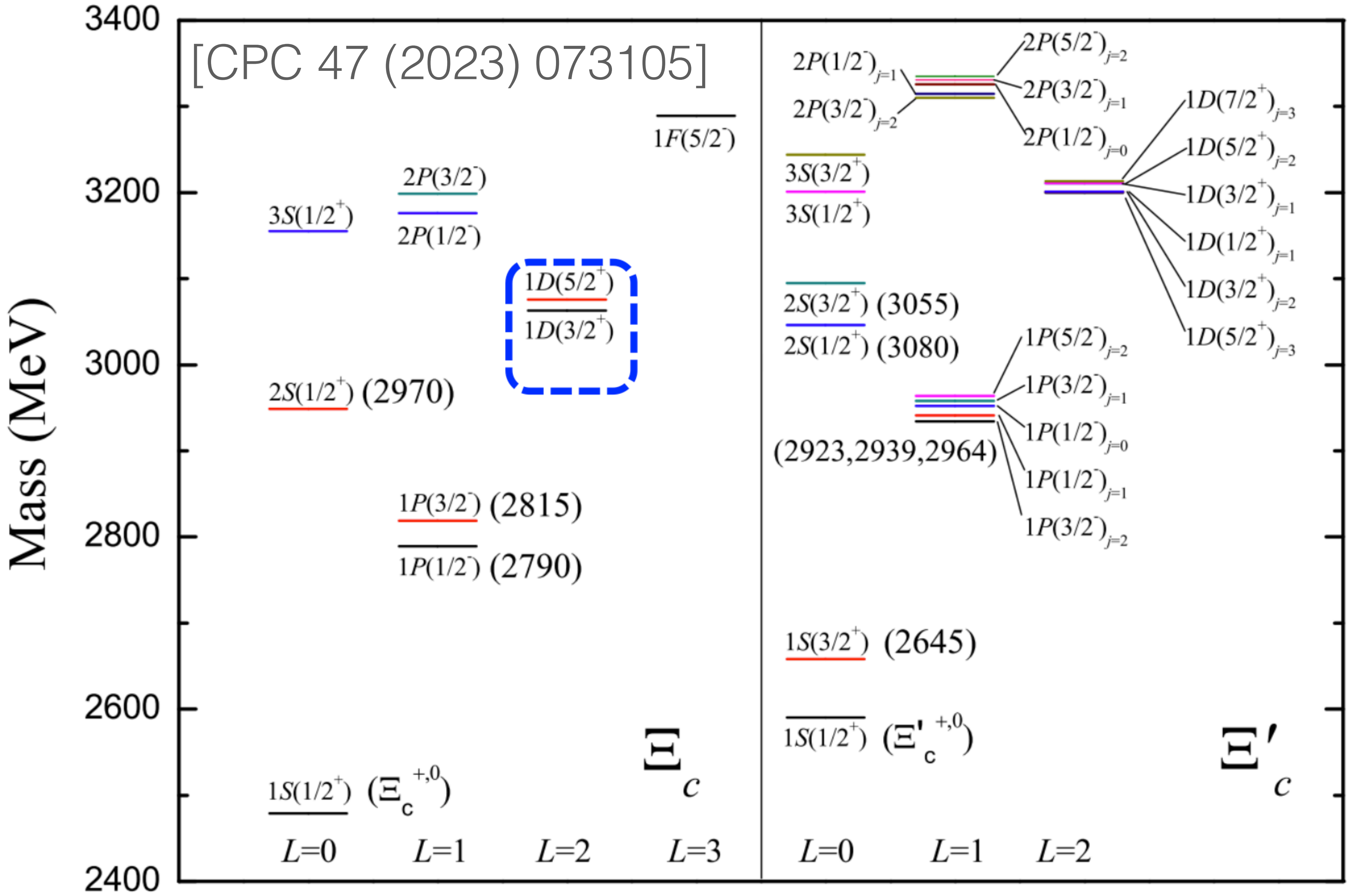
Spin parity of $\Xi_c(3055)^{+(0)}$

PRL134(2025)081901

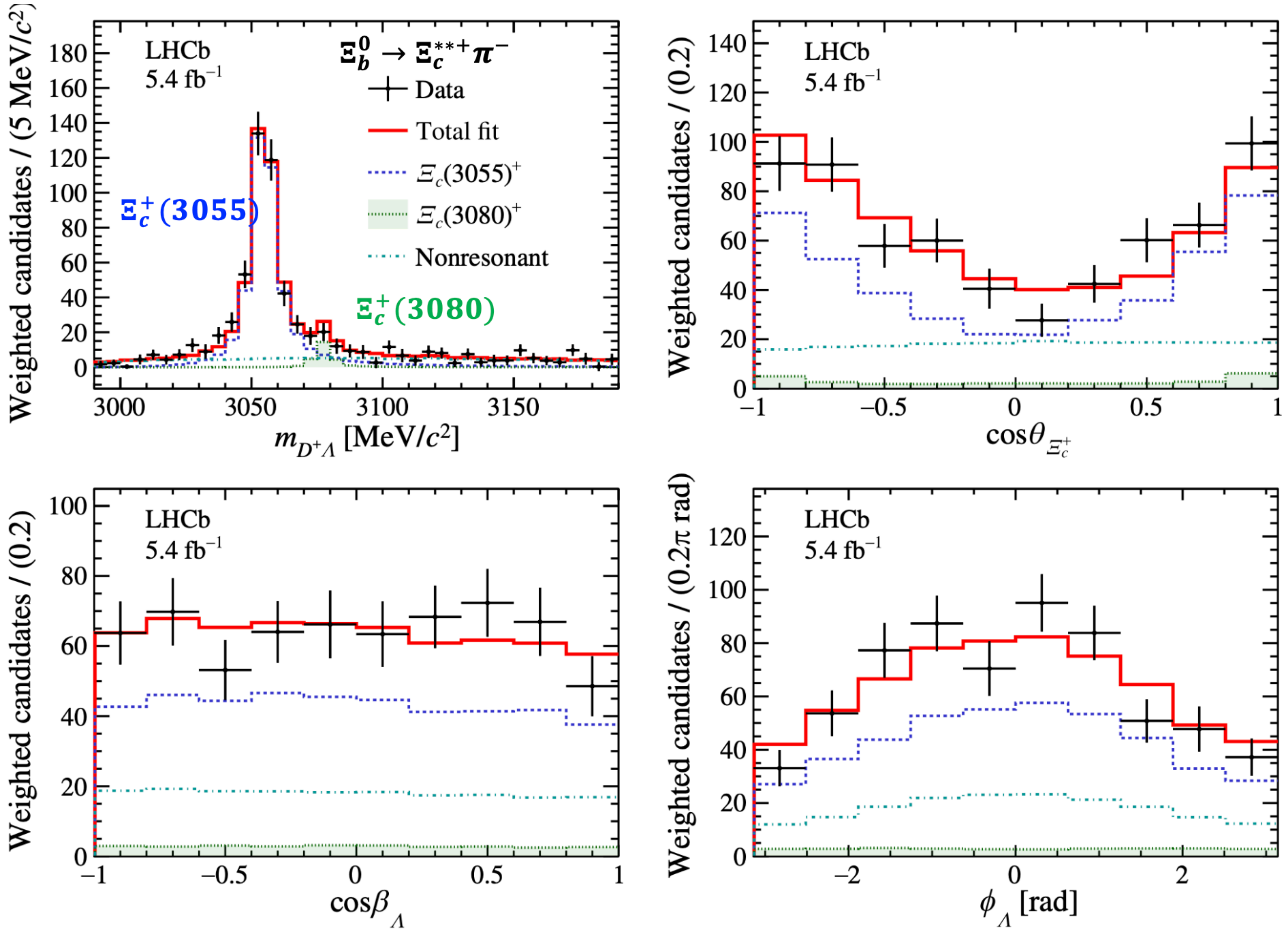
- $J^P(\Xi_b(3055))$ determined to be $3/2^+$ (6.5 σ), $\Xi_c(3080)$ favoured as $5/2^+$ but not significant
- Favor $\Xi_c(3055)^{+(0)}$ as a 1D λ-mode excitation of flavor antitriplet



$$\Xi_b^{0(-)} \to \Xi_c^{**+(0)}(\to D\Lambda)\pi^-$$

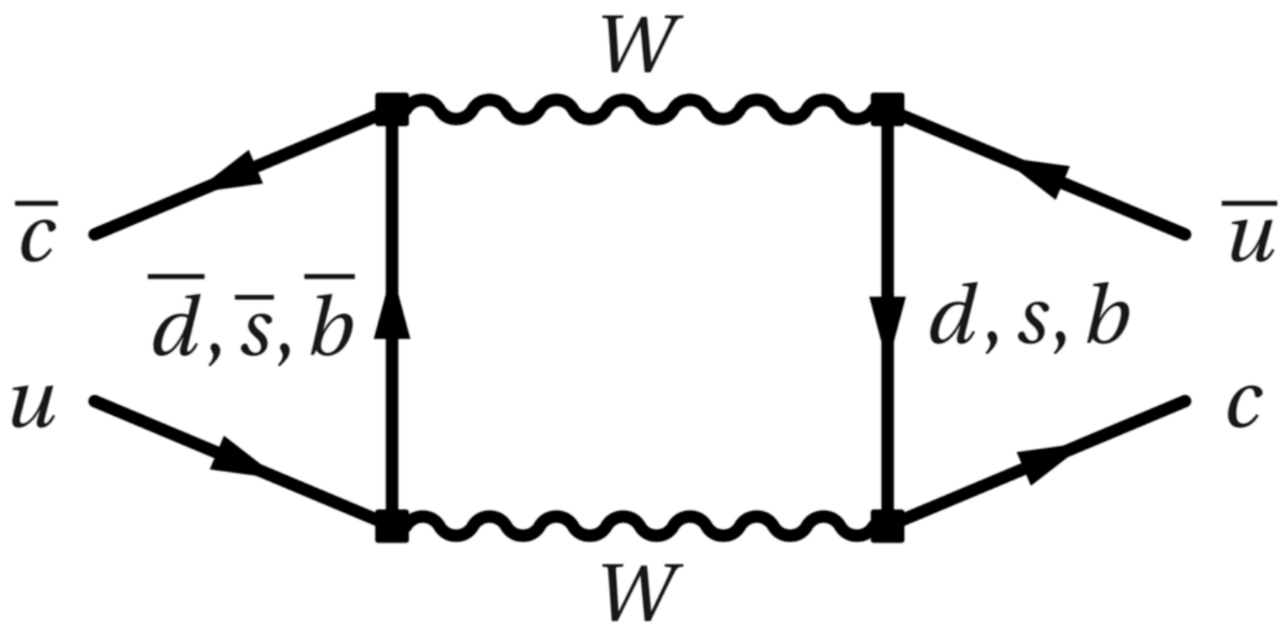


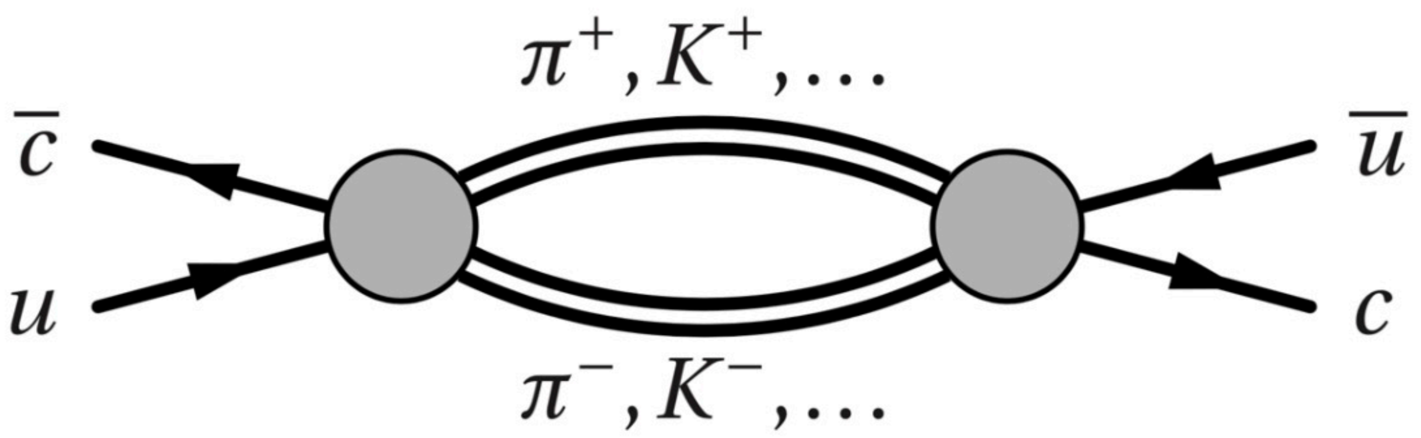
Quantity	$\Xi_c(3055)^+$	$\Xi_c(3055)^0$
m [MeV/c^2]	$3054.52 \pm 0.36 \pm 0.17$	$3061.00 \pm 0.80 \pm 0.23$
Γ [MeV/c^2]	$8.01 \pm 0.76 \pm 0.34$	$12.4 \pm 2.0 \pm 1.1$
α	$-0.92 \pm 0.10 \pm 0.05$	$-0.92 \pm 0.16 \pm 0.22$
$R_\mathcal{B}$	$0.045 \pm 0.023 \pm 0.006$	$0.14 \pm 0.06 \pm 0.04$



CP violation in Charm

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





Direct CPV in mesons

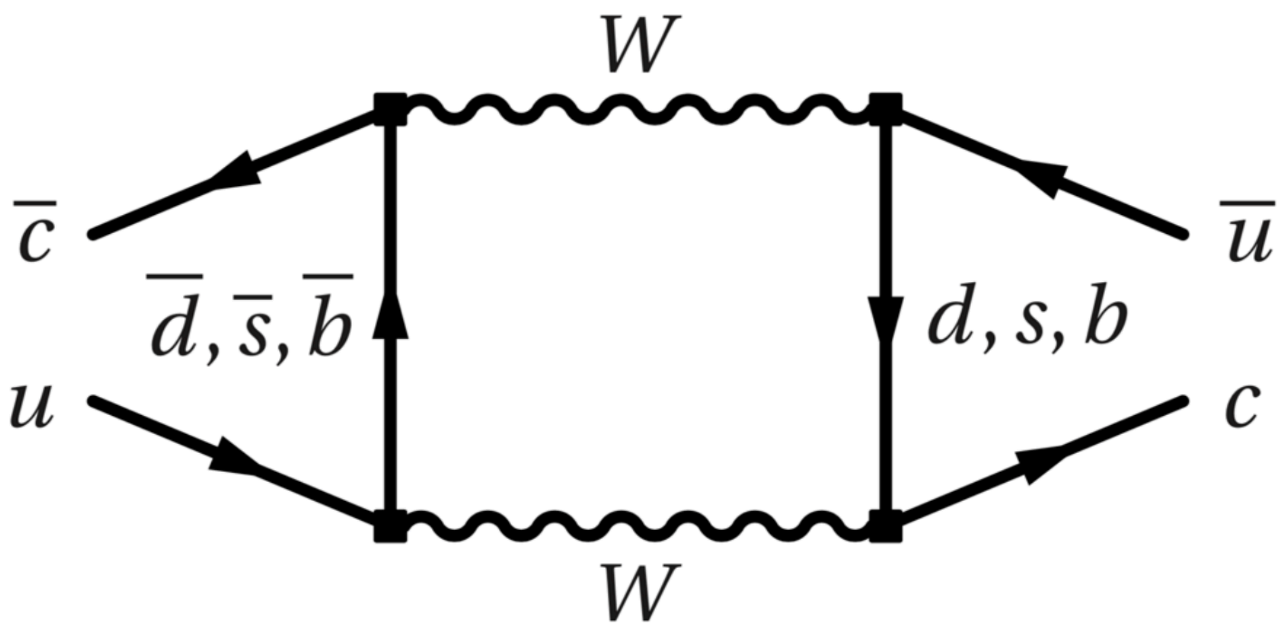
Mixing-induced CPV

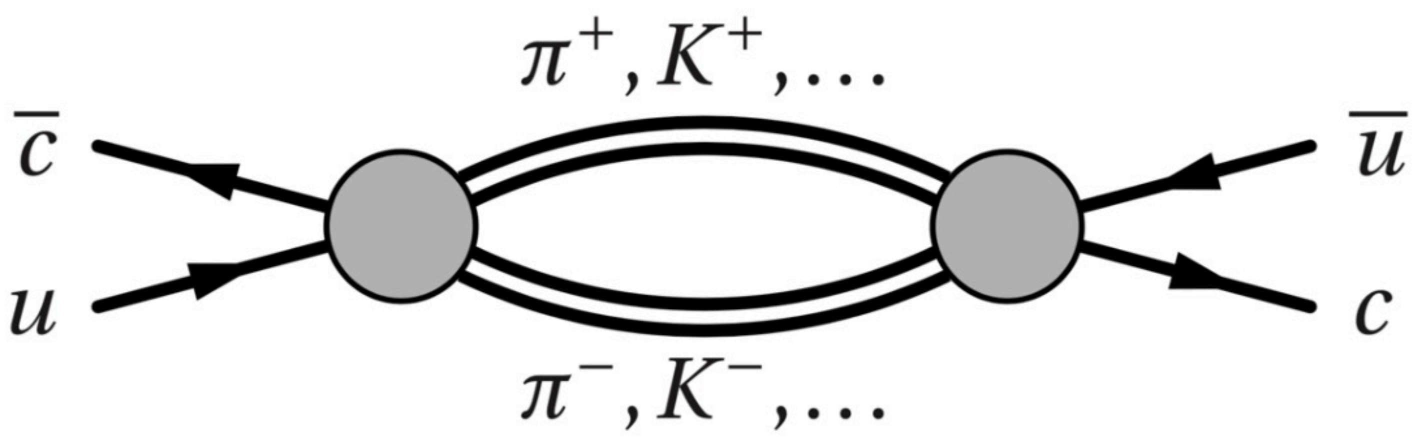
CPV in Baryonic decays

More details in the afternoon session

CP violation in Charm

- GIM mechanism very effective for charm decays, SM loops highly suppressed
- Tiny weak phases in first two generations of CKM matrix ($< \lambda_b \sim 0.1\%$)
- 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]

Direct CPV in mesons

Mixing-induced CPV

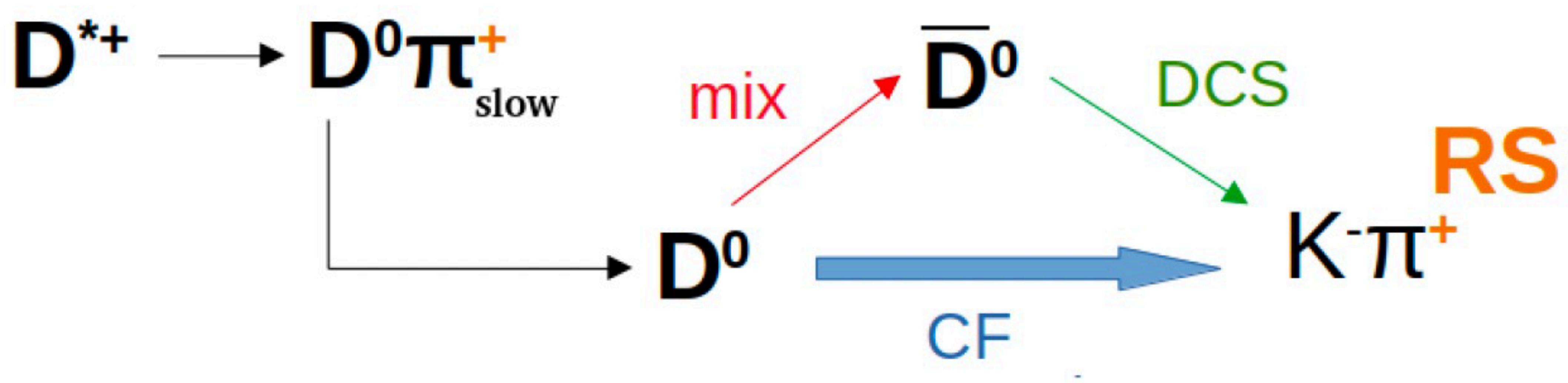
CPV in Baryonic decays

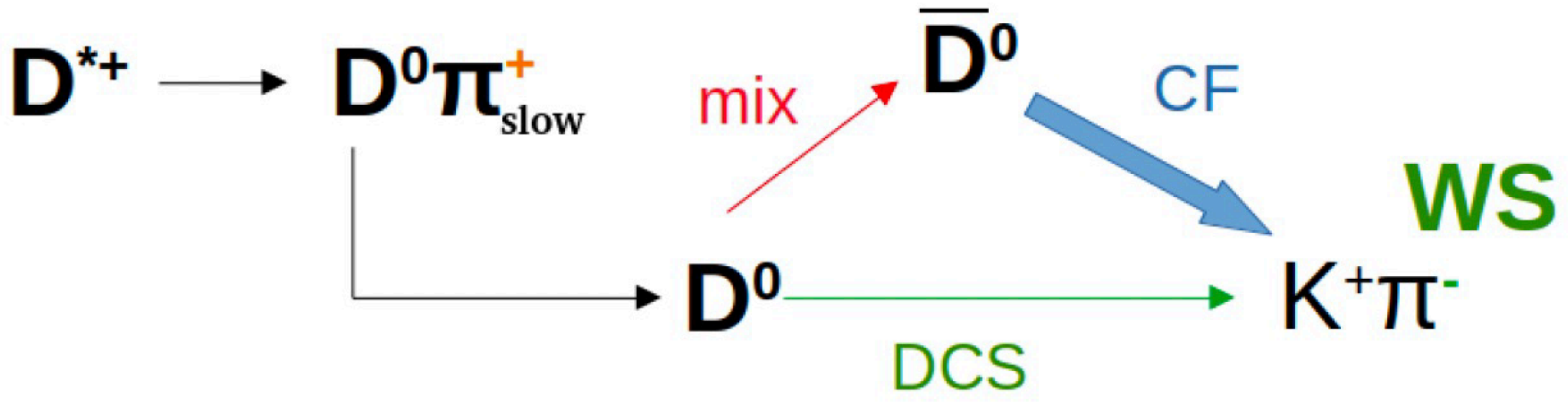
More details in the afternoon session

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

Phys. Rev. D 111 (2025) 012001

- 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

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

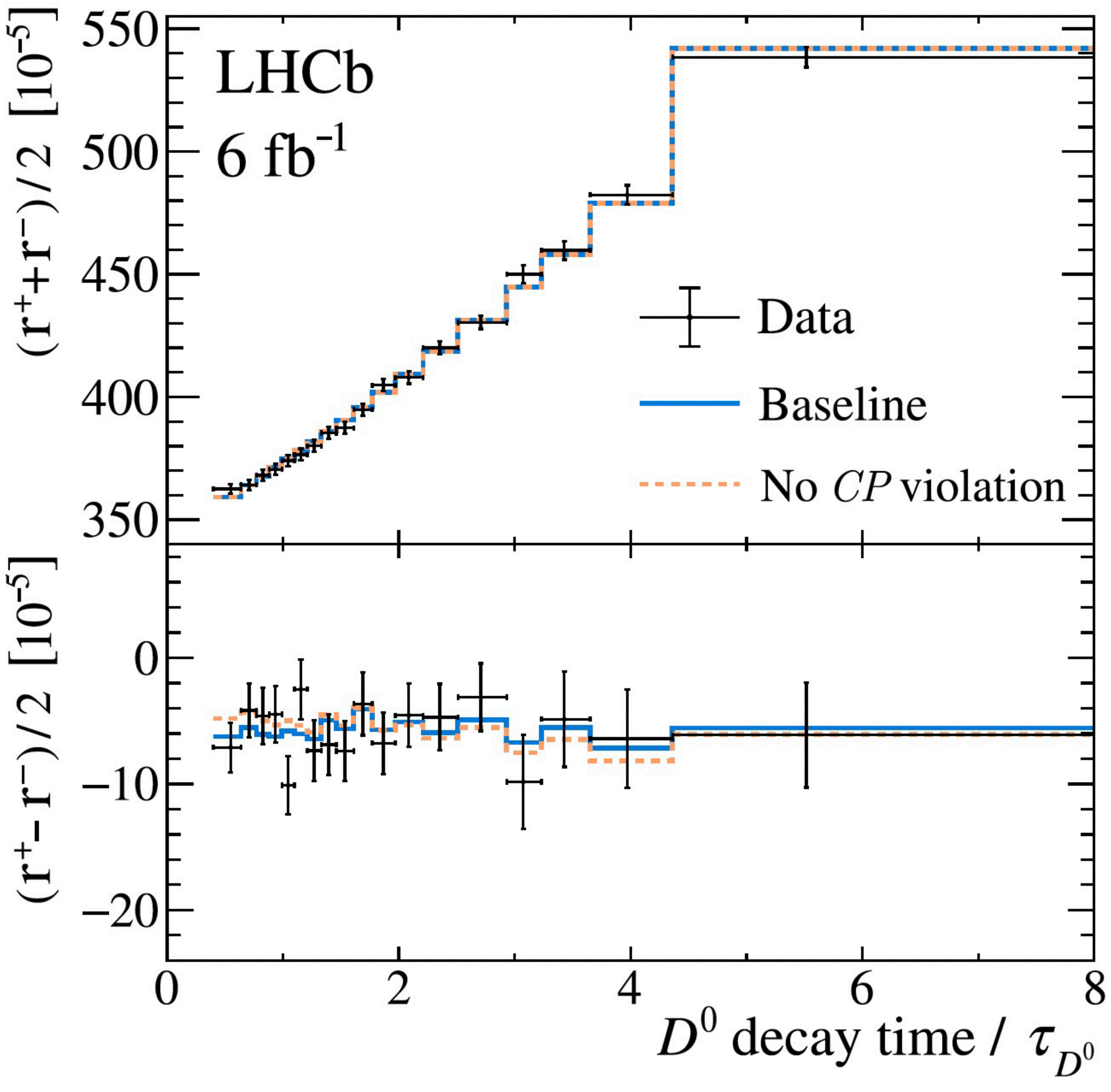
CPV observables: $A_{K\pi}$ (in decays), $\Delta c_{K\pi}$ (in interference), $\Delta c'_{K\pi}$ (in mixing).

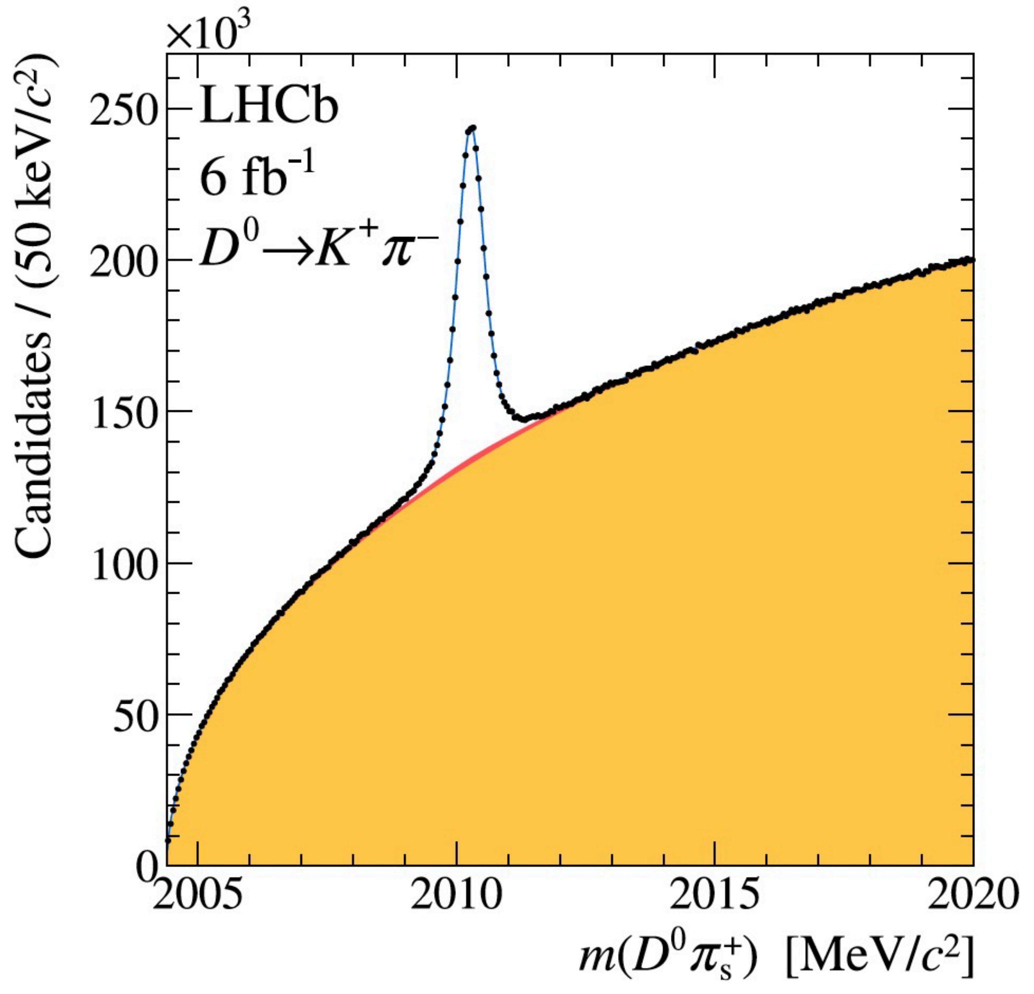
Mixing observables: $c_{K\pi}$, $c'_{K\pi}$

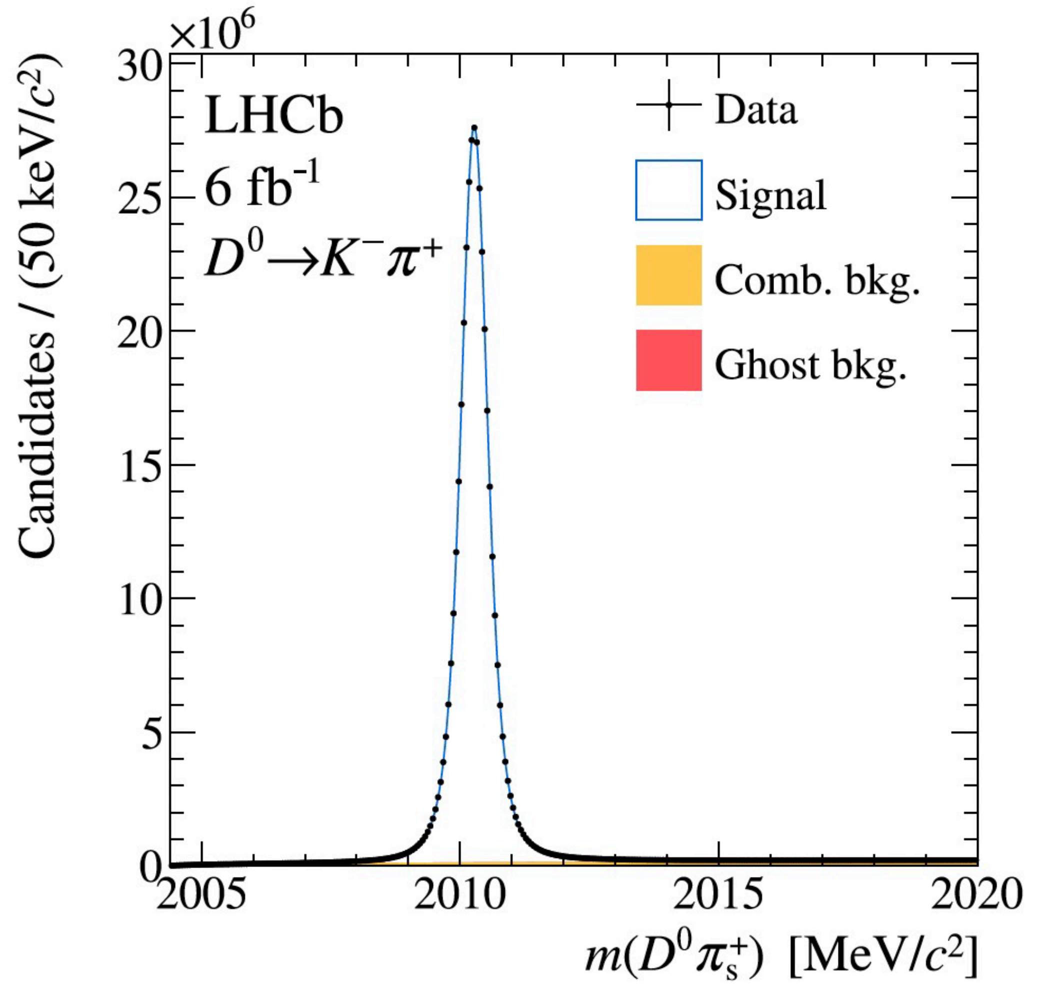
Time-dependent CP violation in $D^0 \to K\pi$

Phys. Rev. D 111 (2025) 012001

Yields: RS ~400 M, WS ~1.6 M







$R_{K\pi}$	$(343.1 \pm 2.0) \times 10^{-5}$	
$c_{K\pi}$	$(51.4 \pm 3.5) \times 10^{-4}$	Mixing parameter
$c'_{K\pi}$	$(13.1 \pm 3.7) \times 10^{-6}$	Evidence of non 0
$A_{K\pi}$	$(-7.1 \pm 6.0) \times 10^{-3}$	No CPV
$\Delta c_{K\pi}$	$(3.0 \pm 3.6) \times 10^{-4}$	No CPV
$\Delta c'_{K\pi}$	$(-1.9 \pm 3.8) \times 10^{-6}$	No CPV

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

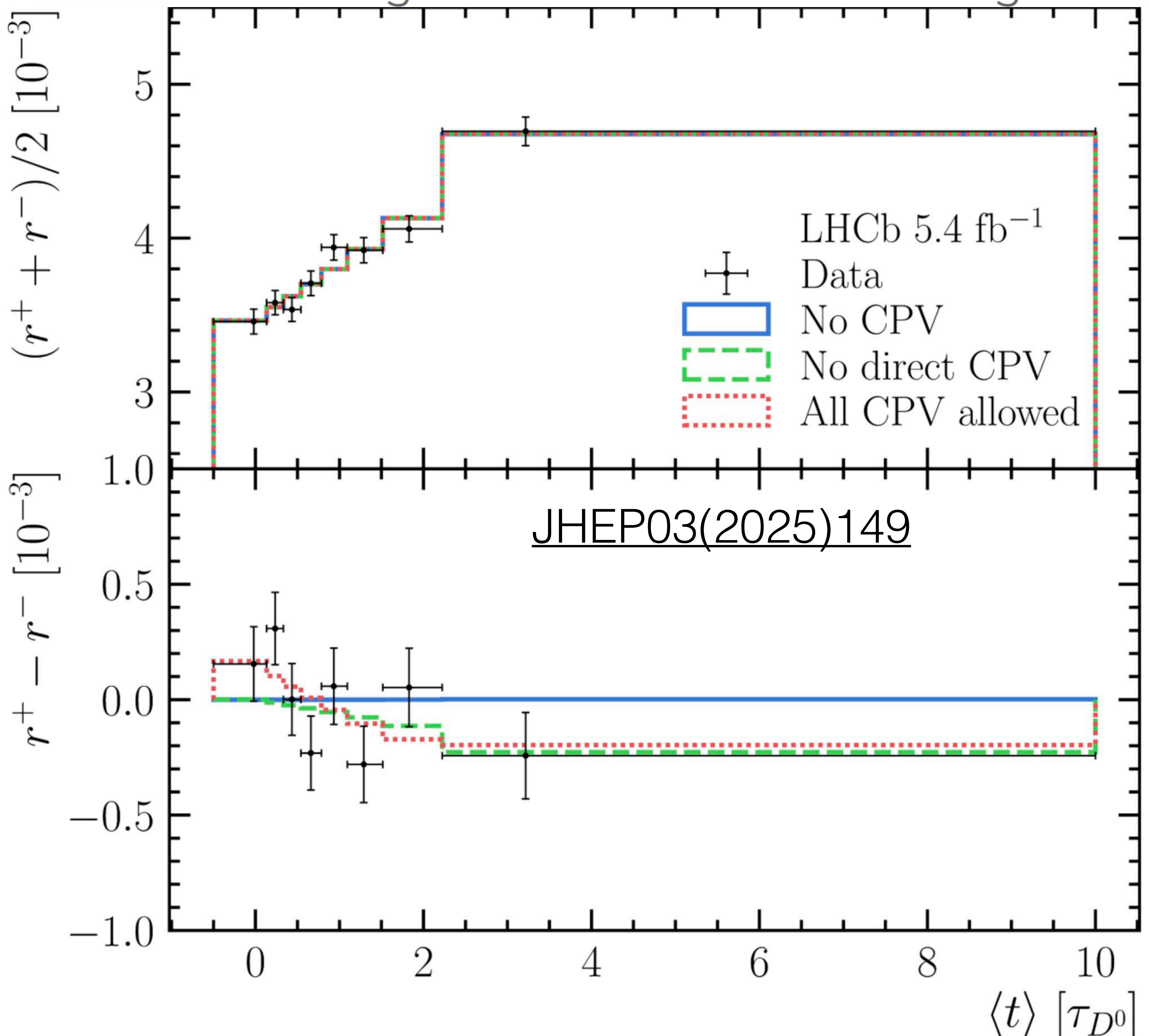
Time-dependent CP violation in $D^0 \to K\pi$

JHEP2025.149

Doubly-tagged b-hadron decays

$\Rightarrow B^- \to D^{*+}(\to D^0 \pi_s^+)\, \mu^- \nu_\mu$ vs. $B^+ \to D^{*-}(\to \overline{D}^0 \pi_s^-)\, \mu^+ \nu_\mu$

✓high eff. at low t ✓low bkg



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

JHEP2025.149

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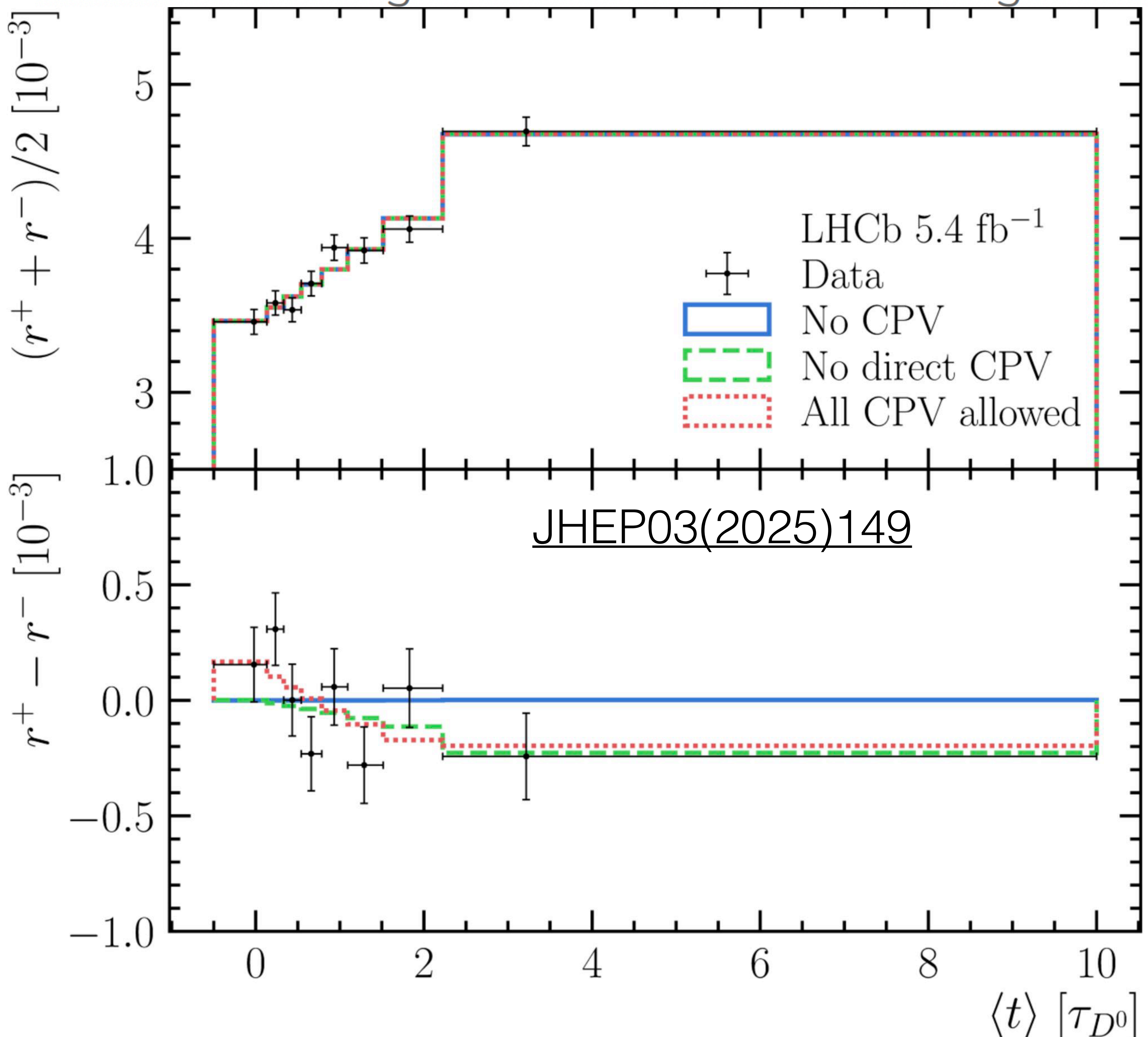
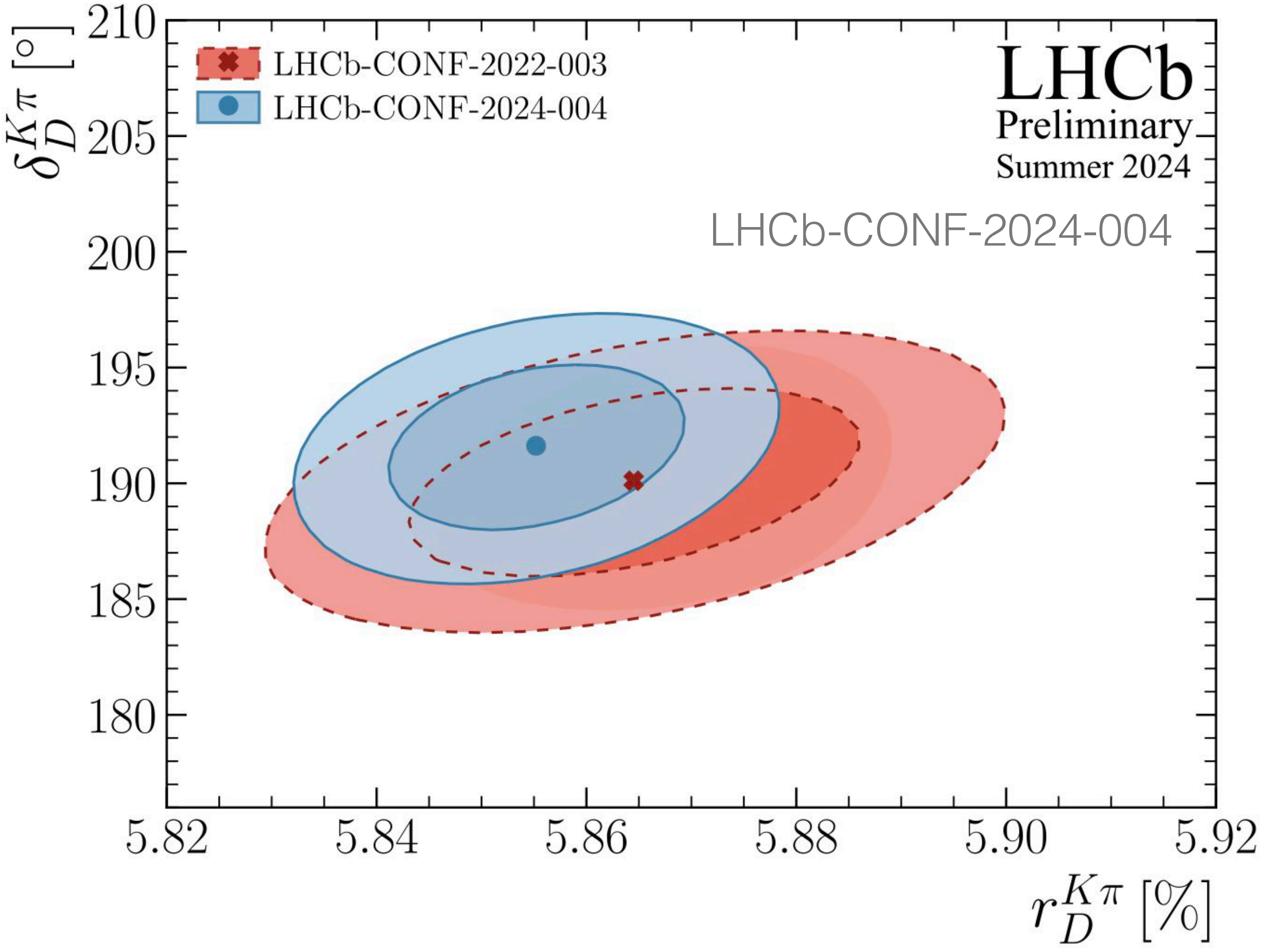
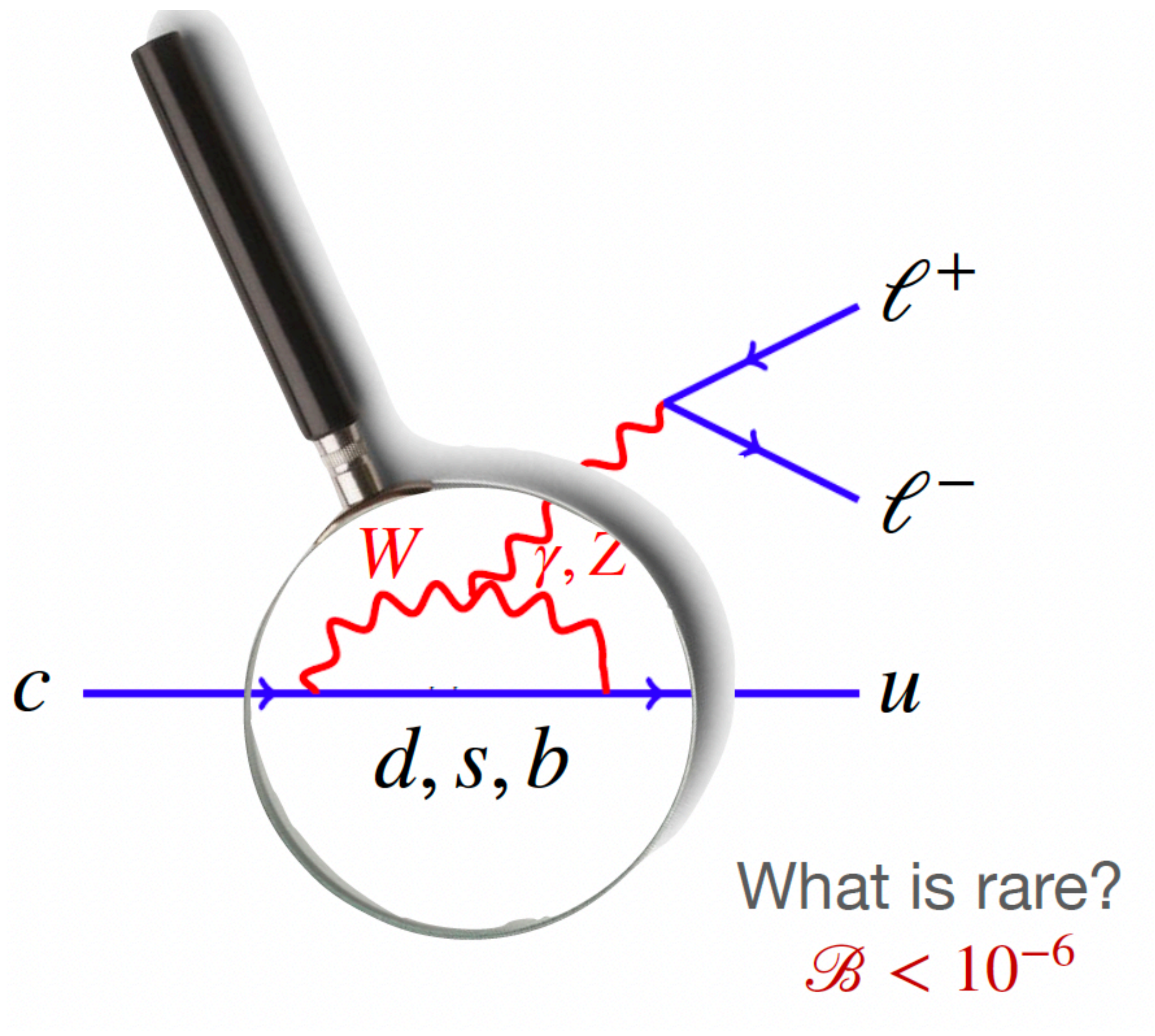


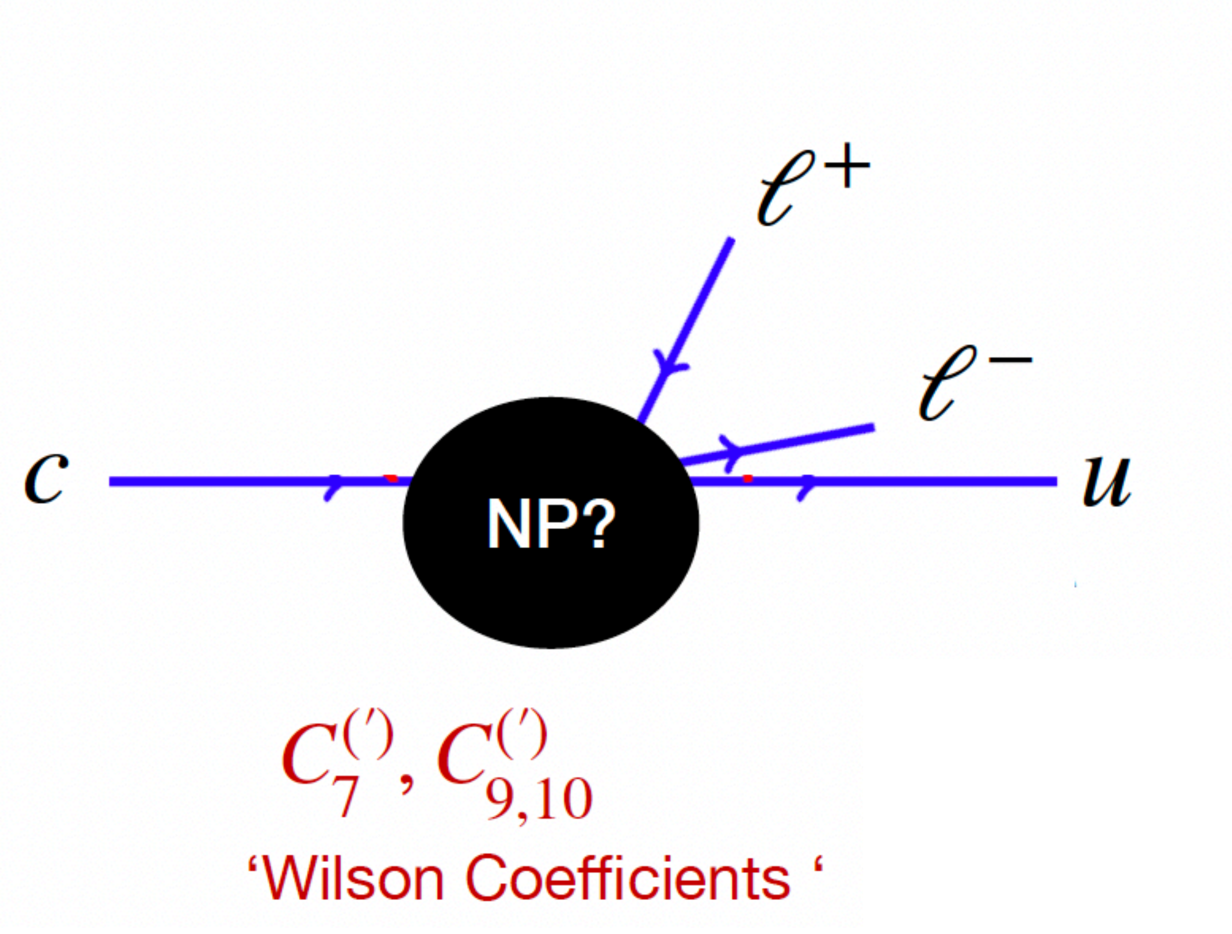
$$c_{K\pi} \approx y_{12} + x_{12}\,\Delta_{K\pi}$$

Combining with LHCb measurements:
4σ U-spin symmetry breaking

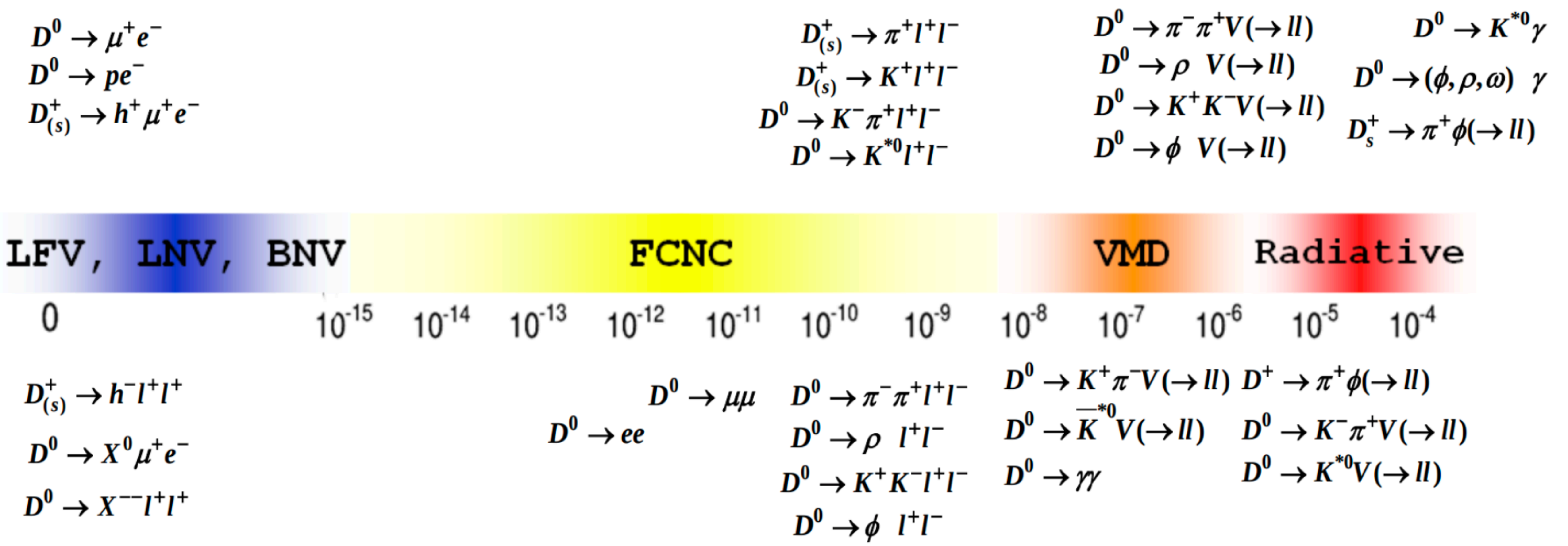


Rare decays





- Sensitive to tiny contributions of heavy BSM (>multi TeV) particles
- Testing different couplings than b and s quark systems



Search for rare or forbidden decays

Angular analyses & CPV searches

Lepton University

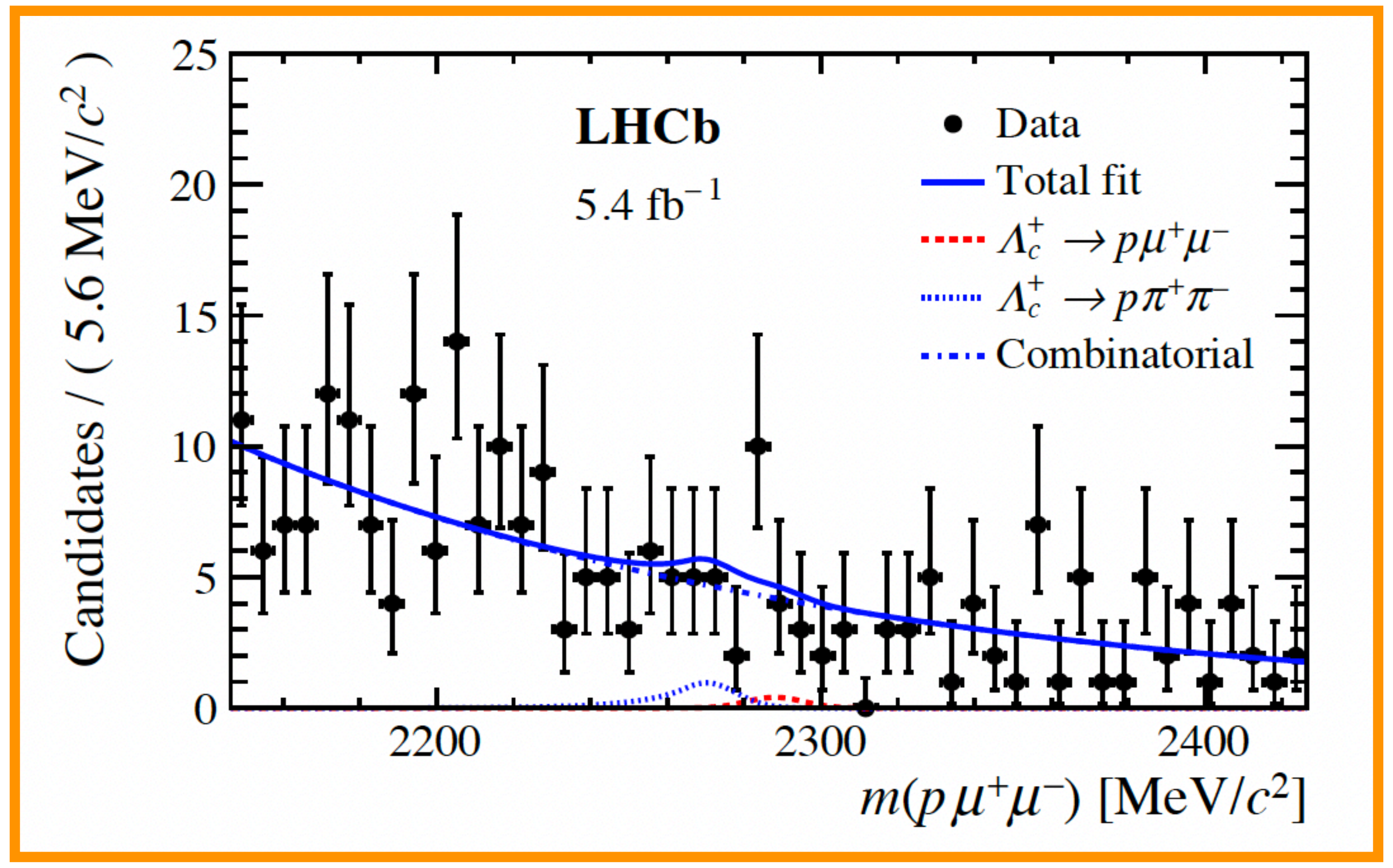
More in Liang Sun's talk

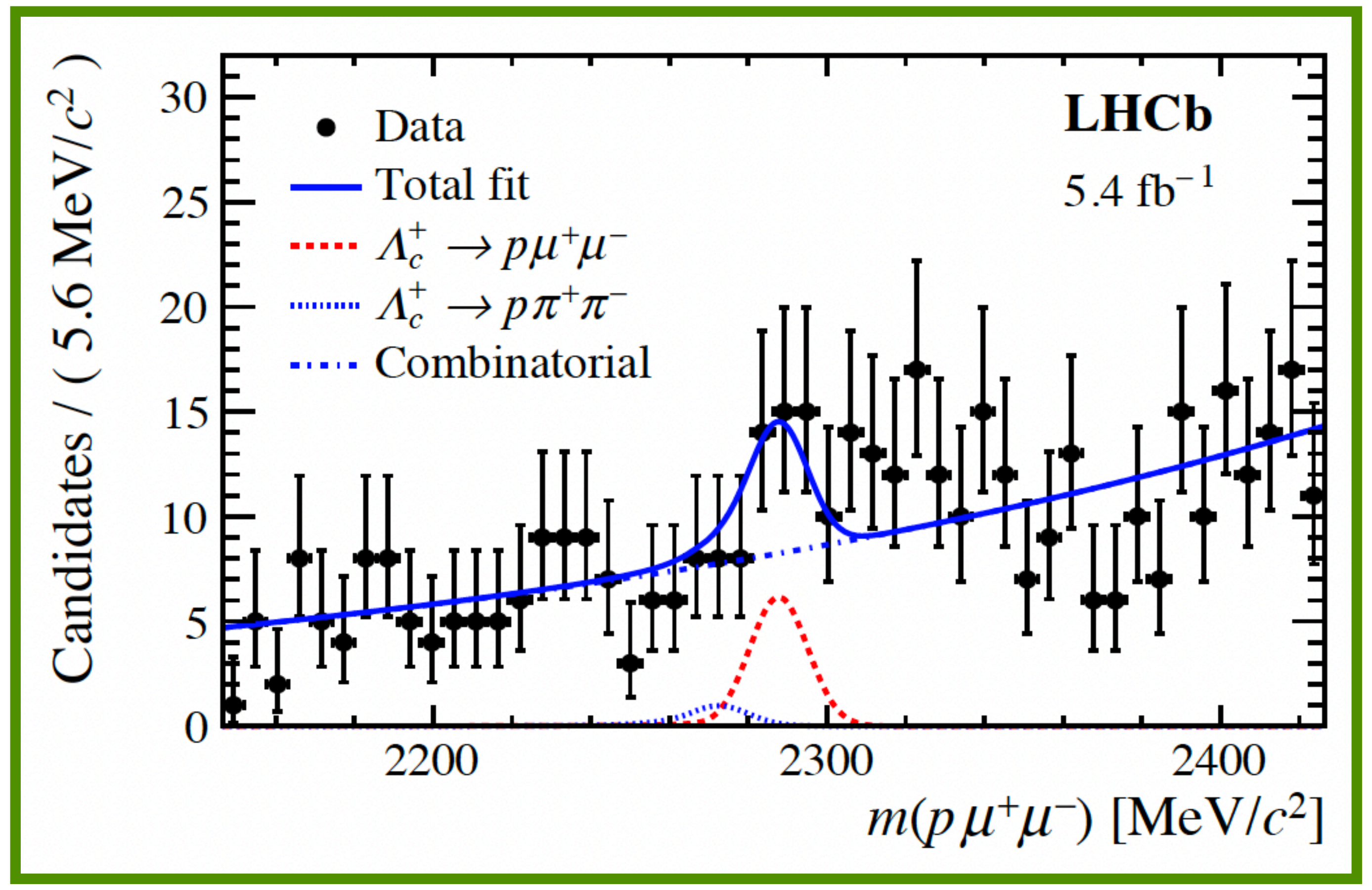
Search for $\Lambda_c^+ \to p\mu^+\mu^-$

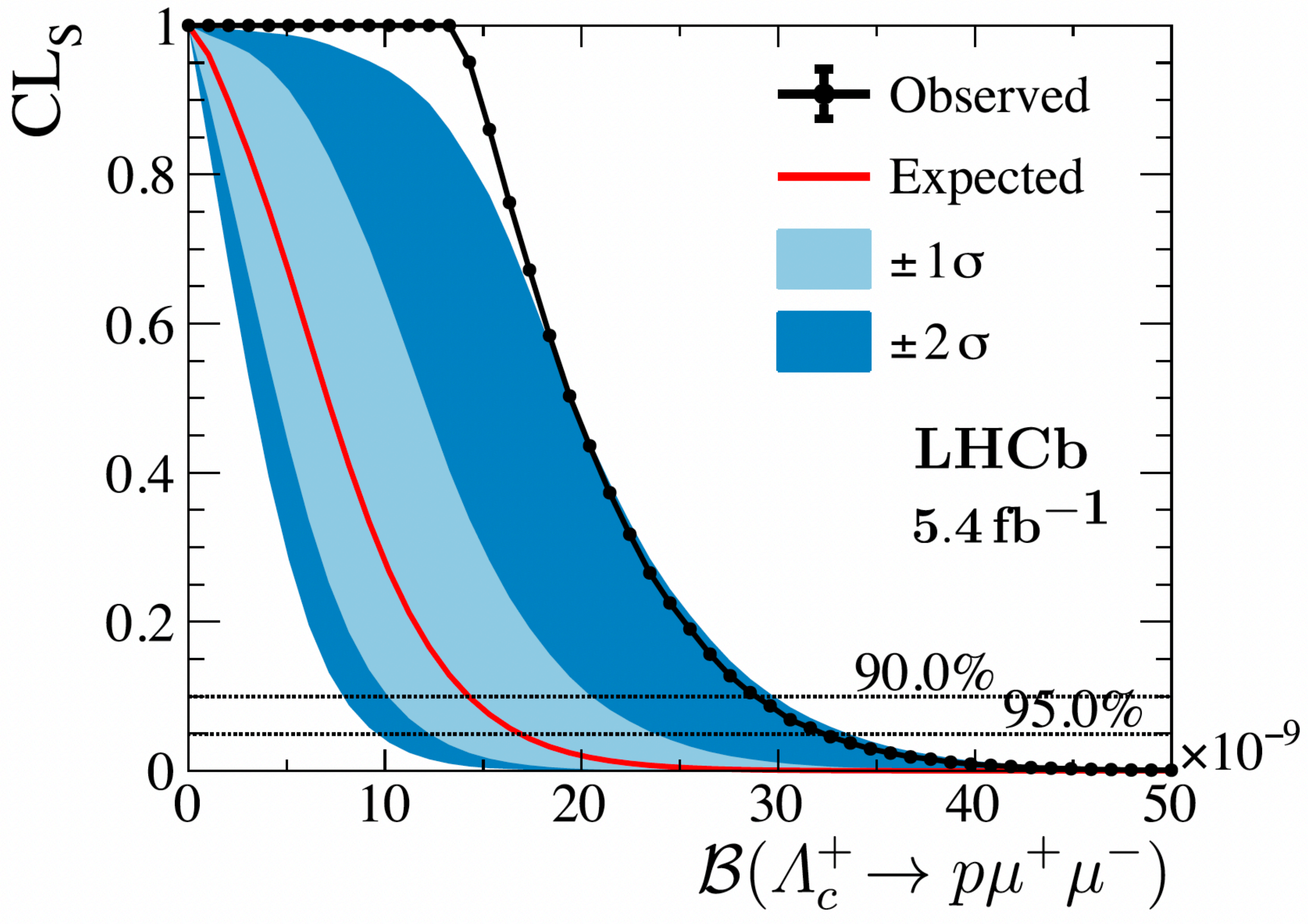
arXiv:2407.11474

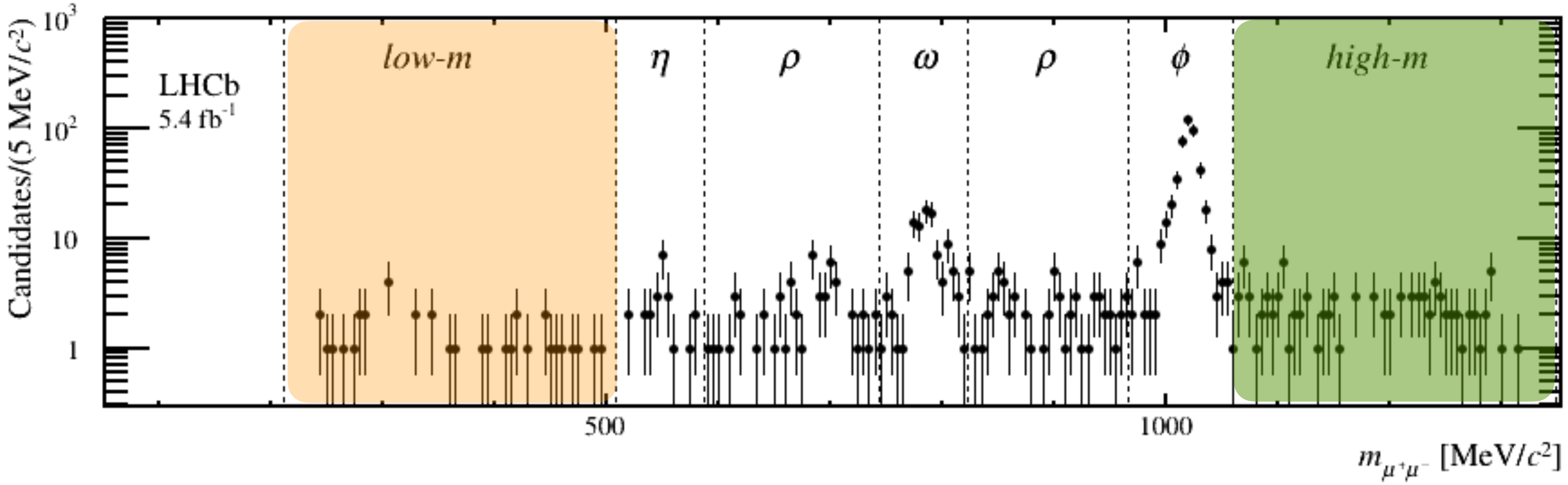
$$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 0.93\ (1.1) \times 10^{-8} \quad \text{at} \quad 90\%\ (95\%)\ \text{CL}\ (low\text{-}m)$$

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









$$\frac{\mathcal{B}(\Lambda_c^+ \to p\omega(\to \mu^+\mu^-))}{\mathcal{B}(\Lambda_c^+ \to p\phi(\to \mu^+\mu^-))} = 0.240 \pm 0.030\ (\text{stat.}) \pm 0.018\ (\text{syst.})$$

$$\frac{\mathcal{B}(\Lambda_c^+ \to p\rho(\to \mu^+\mu^-))}{\mathcal{B}(\Lambda_c^+ \to p\phi(\to \mu^+\mu^-))} = 0.229 \pm 0.051\ (\text{stat.}) \pm 0.022\ (\text{syst.})$$

$$\frac{\mathcal{B}(\Lambda_c^+ \to p\eta(\to \mu^+\mu^-))}{\mathcal{B}(\Lambda_c^+ \to p\phi(\to \mu^+\mu^-))} = 0.032 \pm 0.013\ (\text{stat.}) \pm 0.004\ (\text{syst.})$$

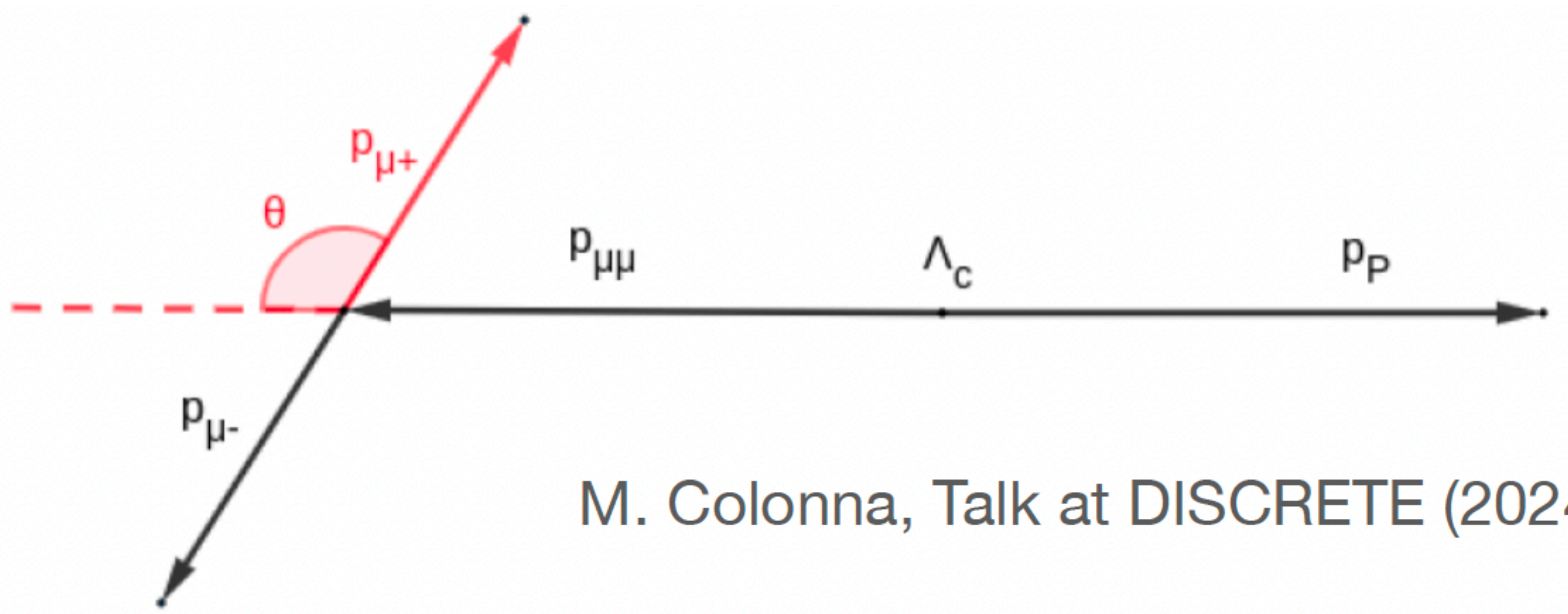
Angular and CP asymmetries

arXiv:2502.04013

$$\frac{d^2\Gamma}{dq^2 d\cos\theta_\ell} = \frac{3}{2}\left(K_{1ss}\sin^2\theta_\ell + K_{1cc}\cos^2\theta_\ell + K_{1c}\cos\theta_\ell\right)$$

K_{1c}~C_{10} (Null test!)

$$A_{FB}(\propto K_{1c}) = \frac{1}{\Gamma}\left[\int_0^1 d\cos\theta_\mu - \int_{-1}^0 d\cos\theta_\mu\right]\frac{d\Gamma}{d\cos\theta_\mu}$$



M. Colonna, Talk at DISCRETE (2024)

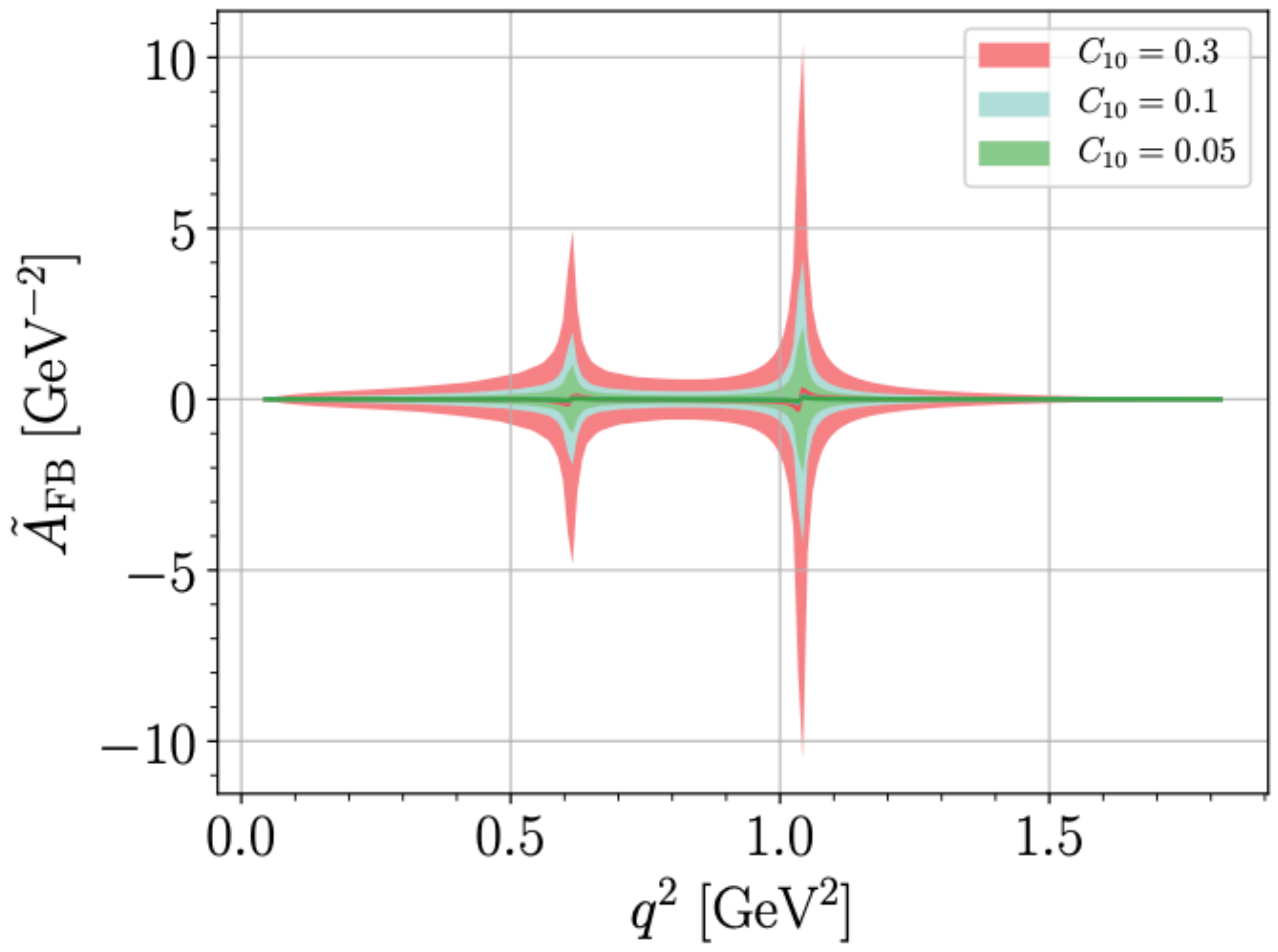
- First study of angular & CP asymmetry in rare baryonic charm decay

Search for resonance-enhanced effects

$$A_{FB} = \frac{\Gamma(\cos\theta_\mu > 0) - \Gamma(\cos\theta_\mu < 0)}{\Gamma(\cos\theta_\mu > 0) + \Gamma(\cos\theta_\mu < 0)}$$

$$A_{CP} = \frac{\Gamma(\Lambda_c^+ \to p\mu^+\mu^-) - \Gamma(\Lambda_c^- \to \bar{p}\mu^+\mu^-)}{\Gamma(\Lambda_c^+ \to p\mu^+\mu^-) + \Gamma(\Lambda_c^- \to \bar{p}\mu^+\mu^-)}$$

Null tests!



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arXiv:2502.04013

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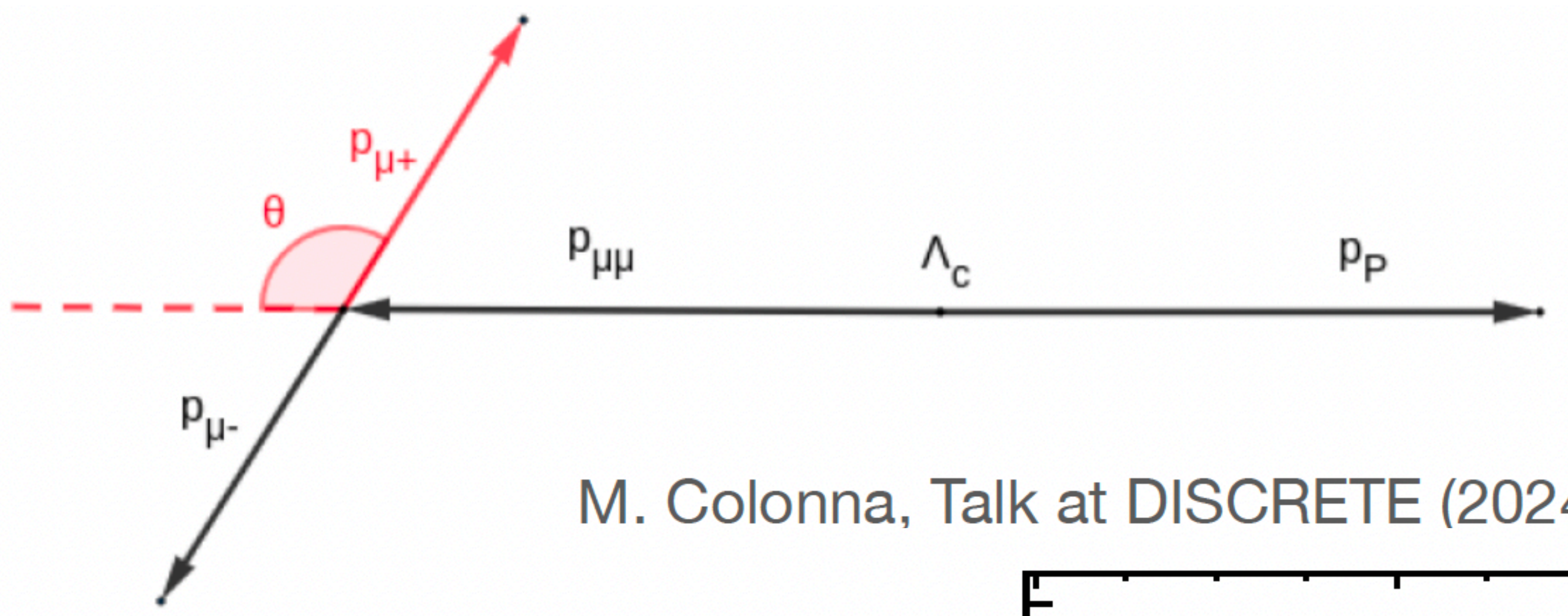
$K_{1c} \sim C_{10}$ (Null test!)

$$A_{FB}(\propto K_{1c}) = \frac{1}{\Gamma}\left[\int_0^1 d\cos\theta_\mu - \int_{-1}^0 d\cos\theta_\mu\right]\frac{d\Gamma}{d\cos\theta_\mu}$$



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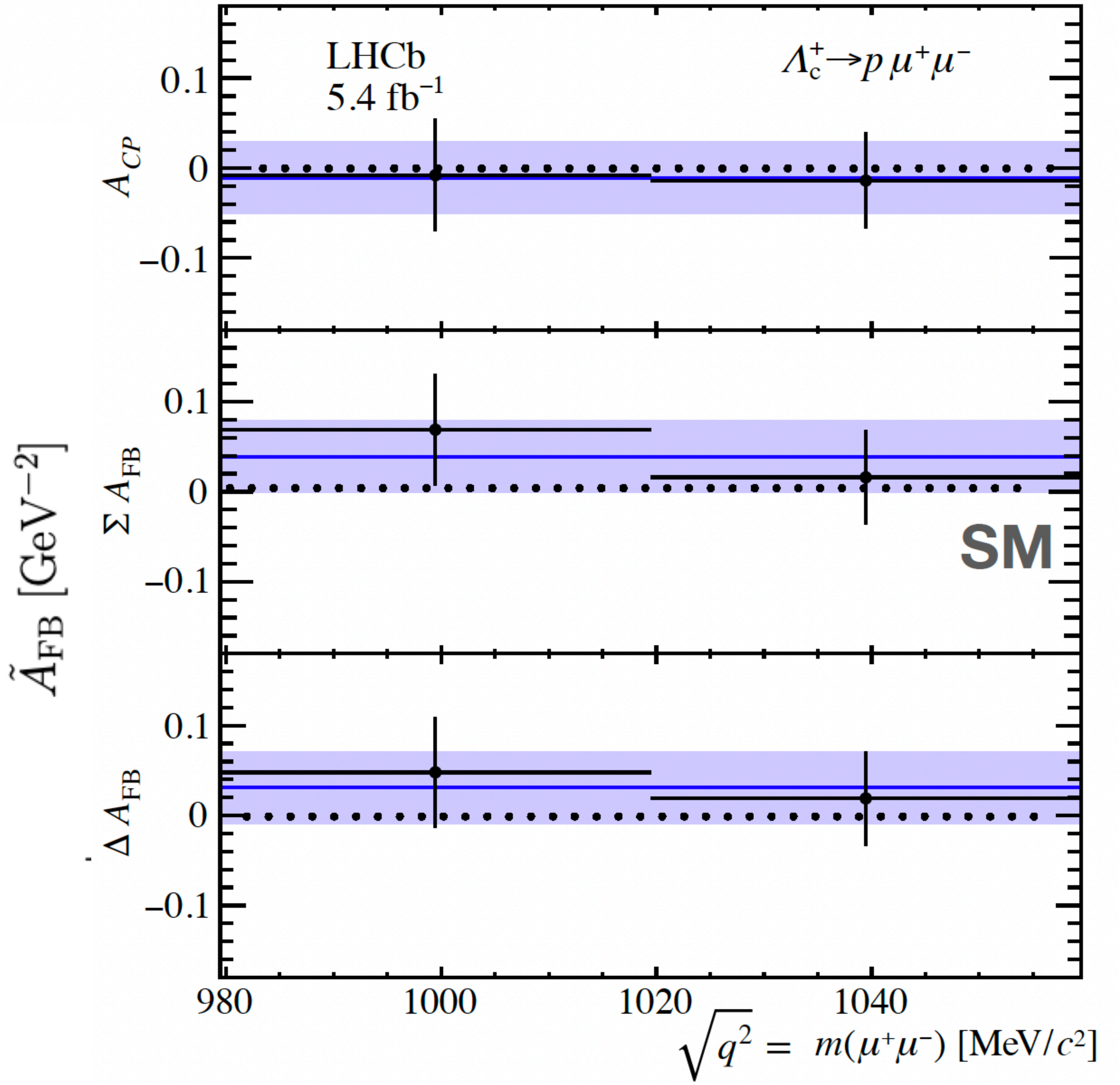
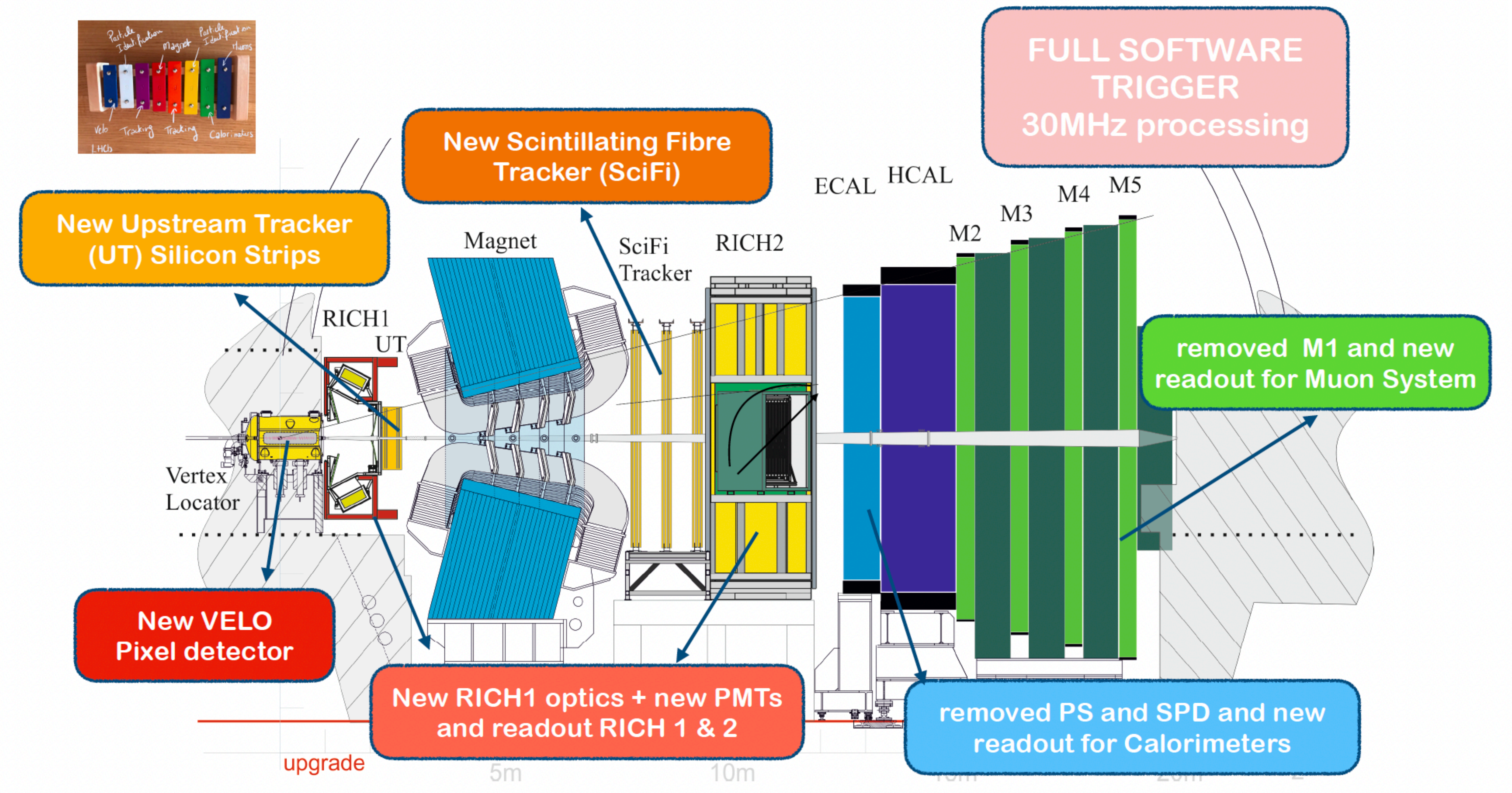
Null tests!



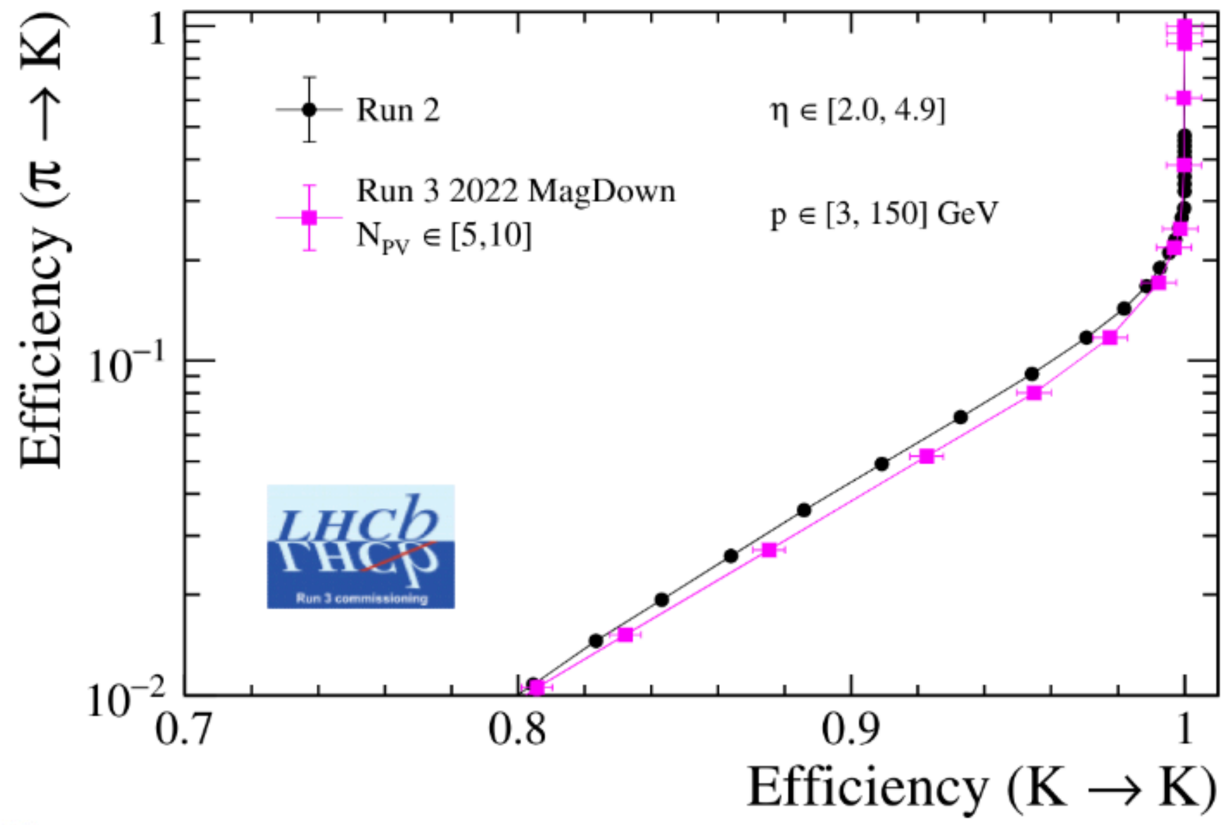
Run 3 in data taking

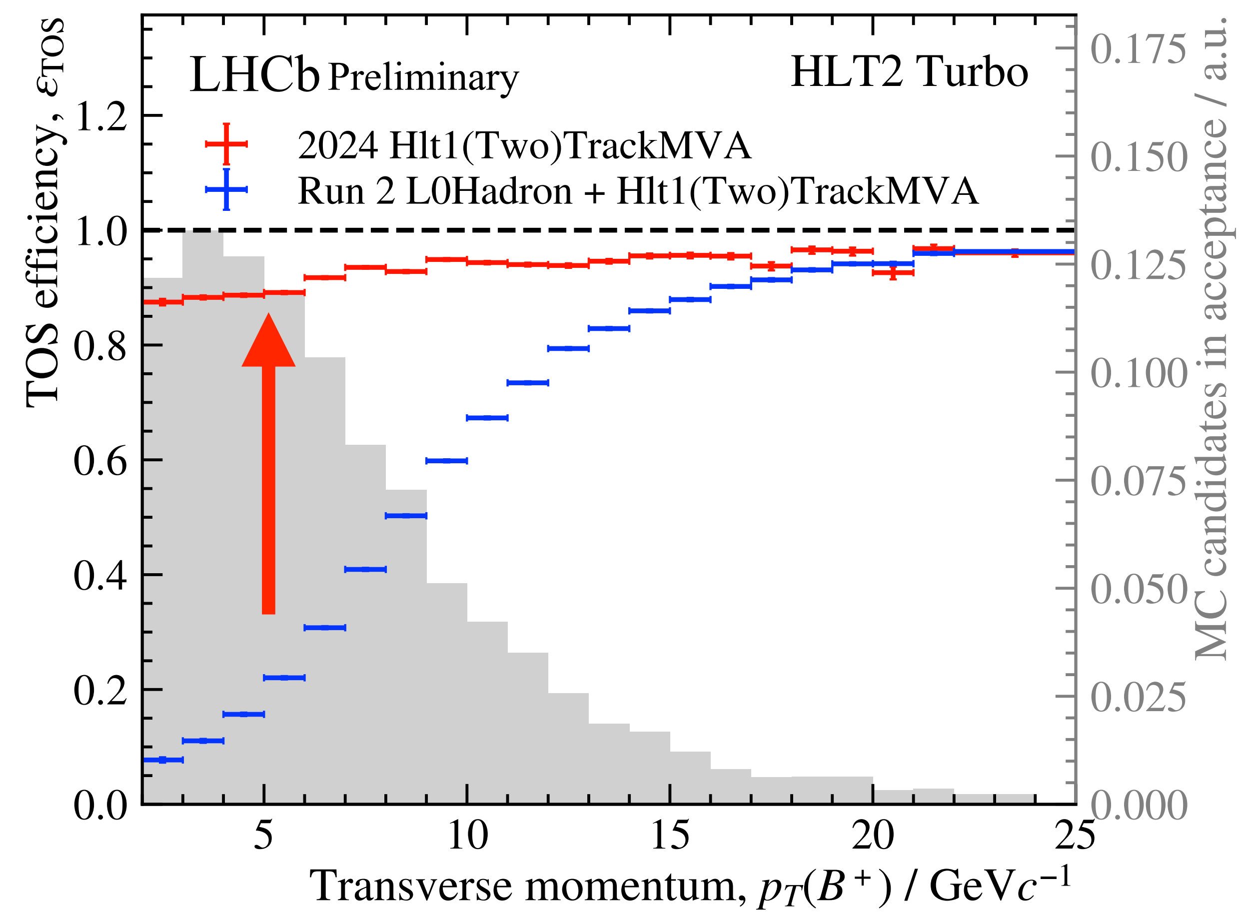


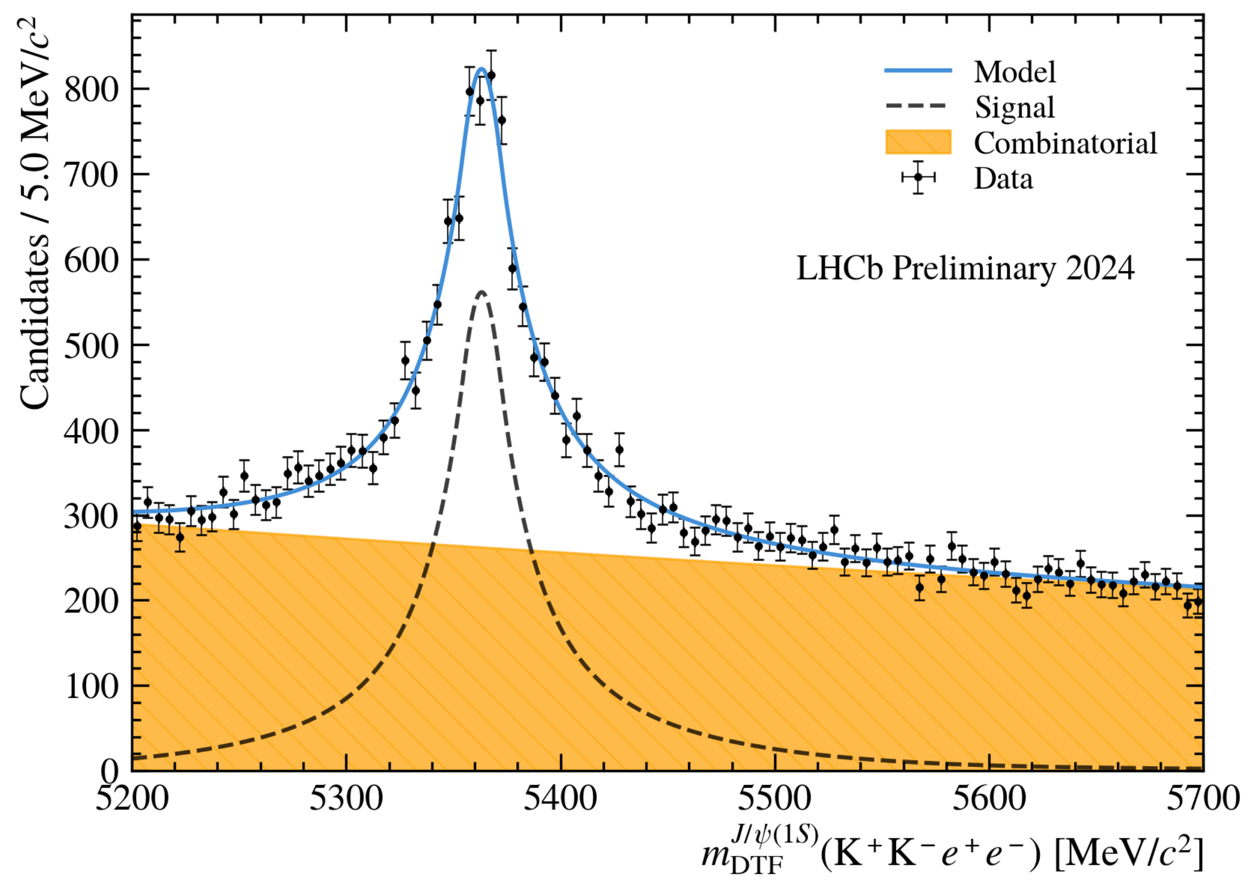
Major upgrade of all sub-detectors and readout

12

The LHCb Upgrade I arXiv:2305.10515





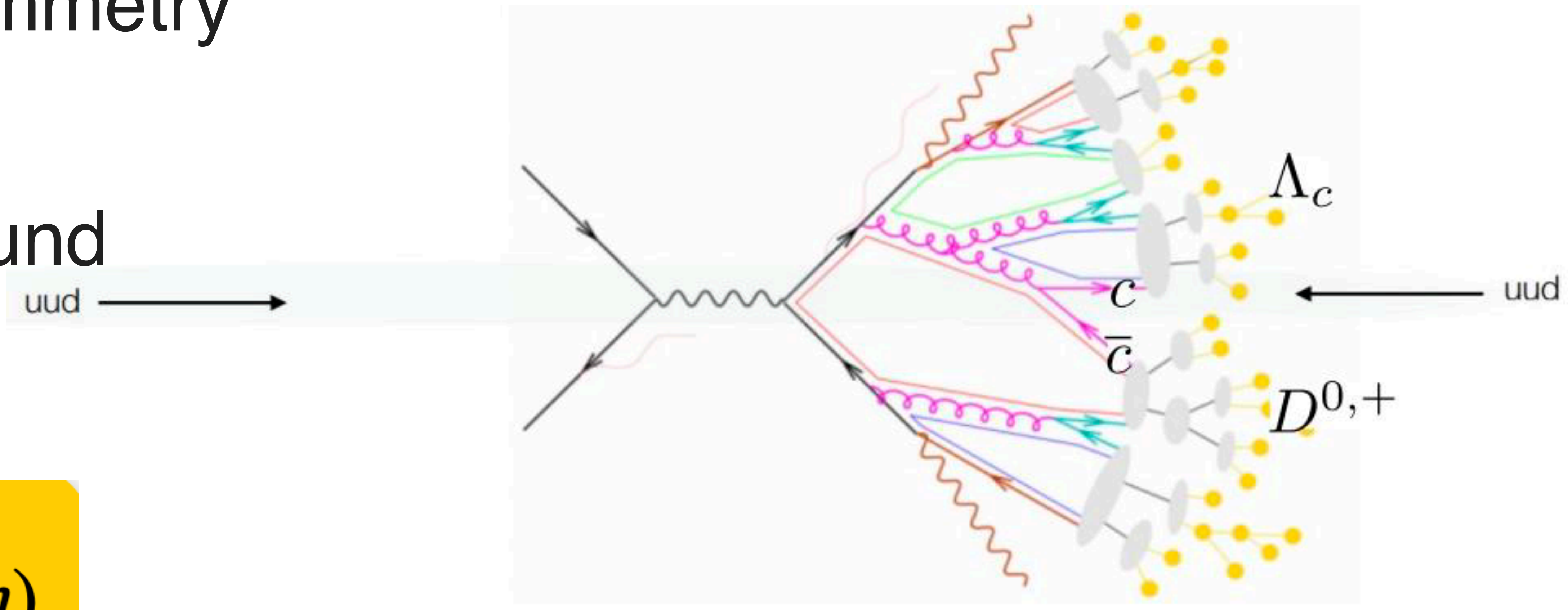


More in Yiming's talk

Production asymmetry of Charm in Run 3

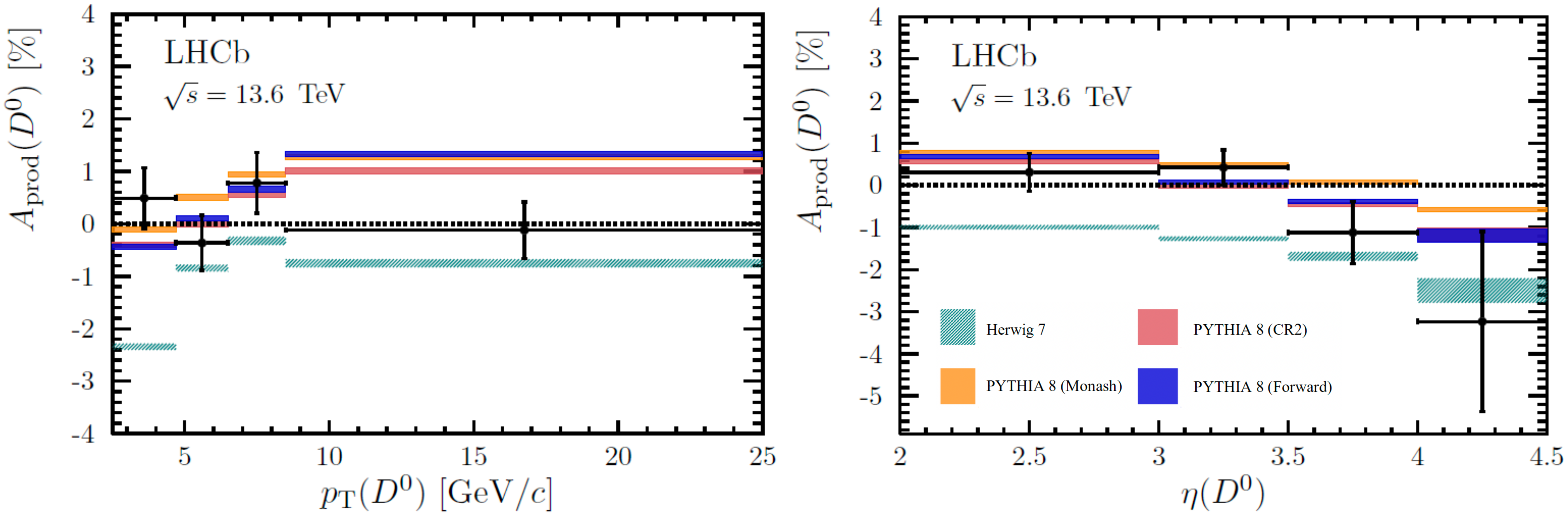
arXiv:2505.14494

- In pp collisions, c and $\bar{c}$ produced in pairs BUT the symmetry disrupted in the hadronisation.
- Test hadronisation models to tune event generators (Lund string model, cluster hadronisation model…)



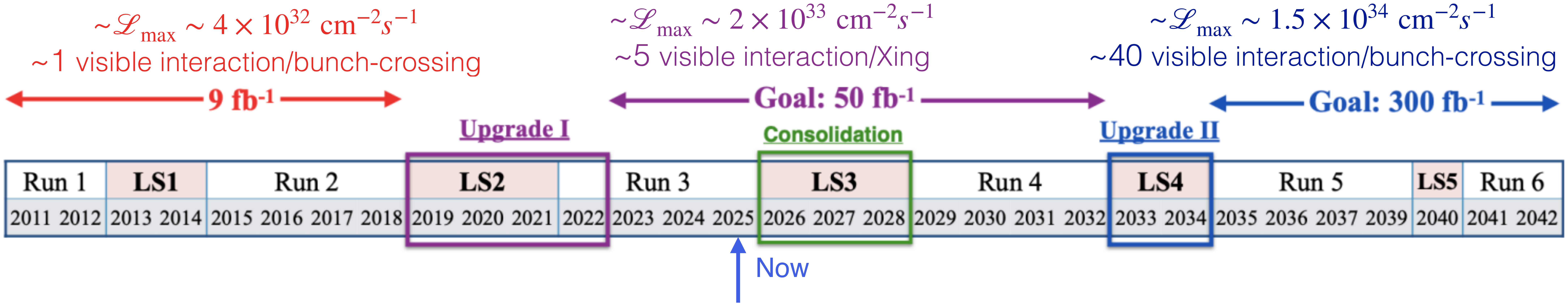
$$A_{\text{prod}}(X_c) = \frac{\sigma(X_c) - \sigma(\bar{X}_c)}{\sigma(X_c) + \sigma(\bar{X}_c)} = f_{X_c}(\sqrt{s}, p_{\text{T}}, \eta)$$

First result using Run 3 data!



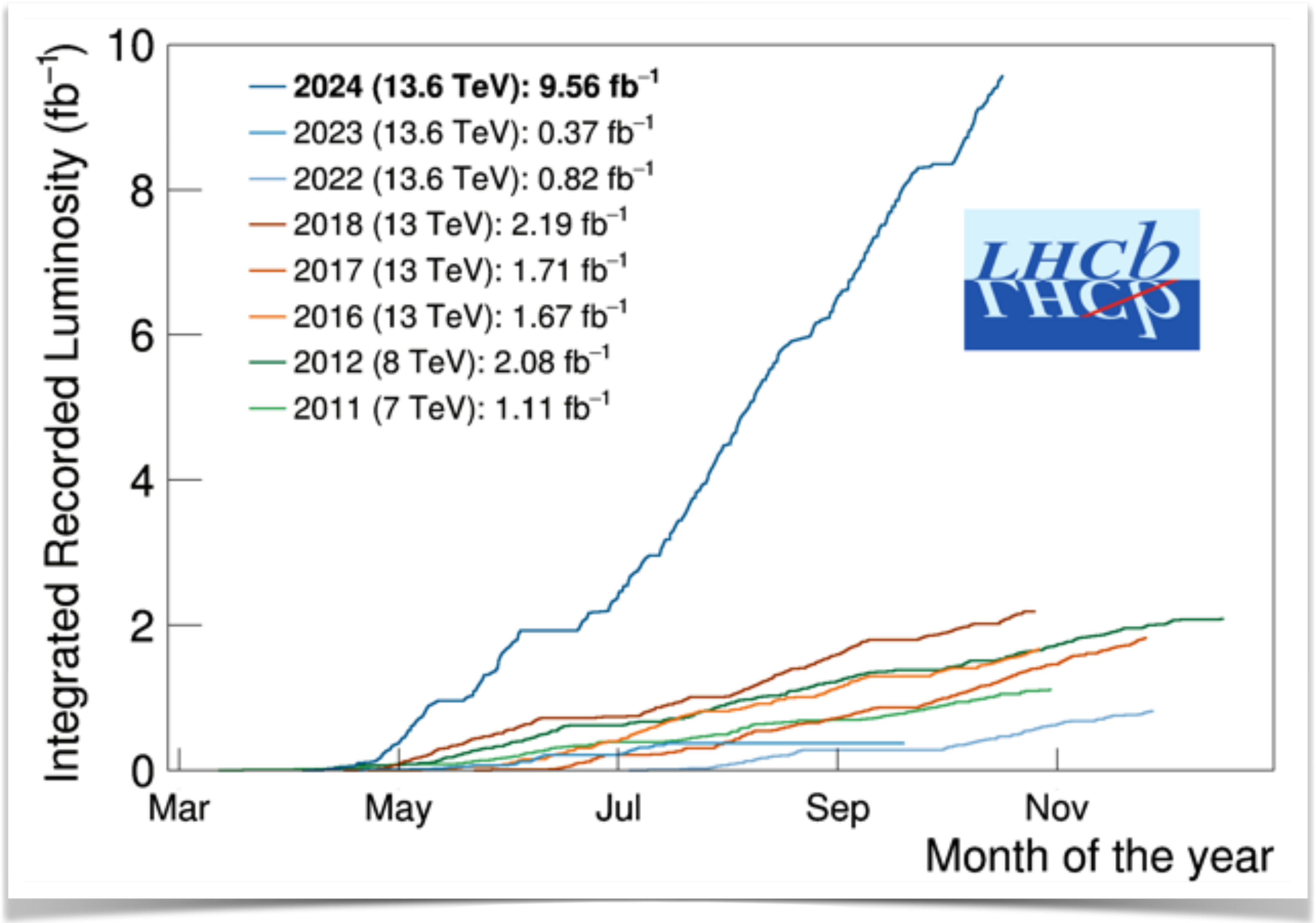
- No significant asymmetry observed
- Comparable statistical uncertainty as Run 1 with ~1/15 integrated luminosity

Summary & prospects



- ✓ Largest statistics at LHCb for all kinds of charm hadrons
- ✓ Rich physics and measurements in charm sector
- ✓ More data coming in Run 3 with 2~4x higher trigger efficiency

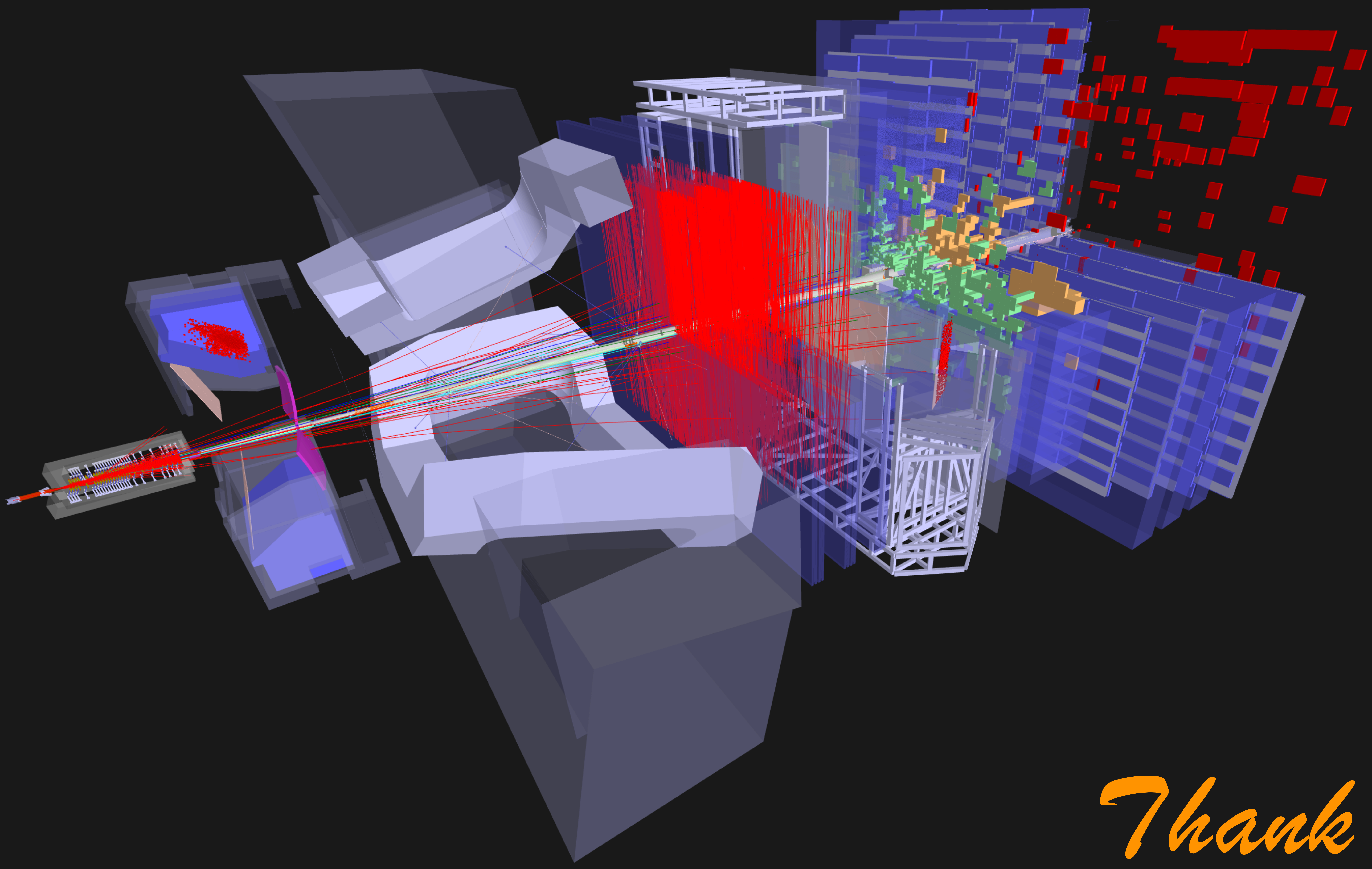
A lot of new results to come soon!



LHCb Experiment at CERN

Run / Event: 255623 / 300064

Data recorded: 2022-11-25 09:40:16 GMT

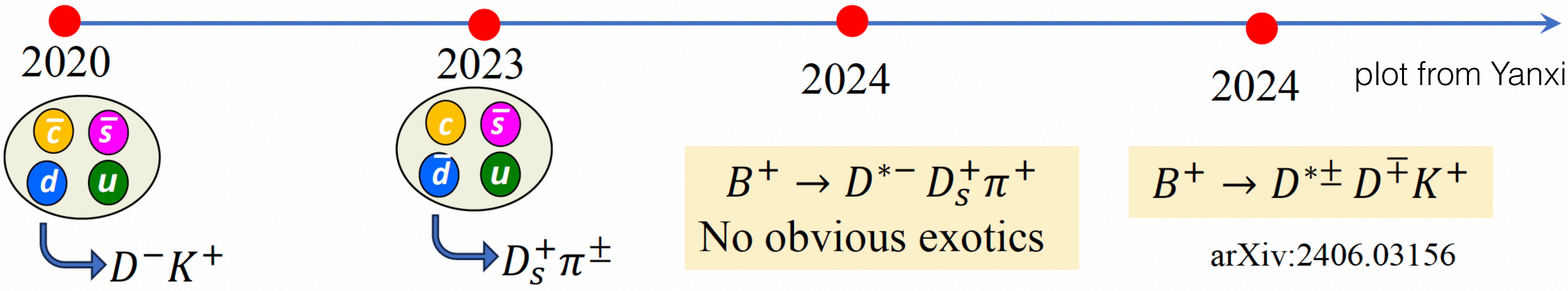


Thank you

Back up slides

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

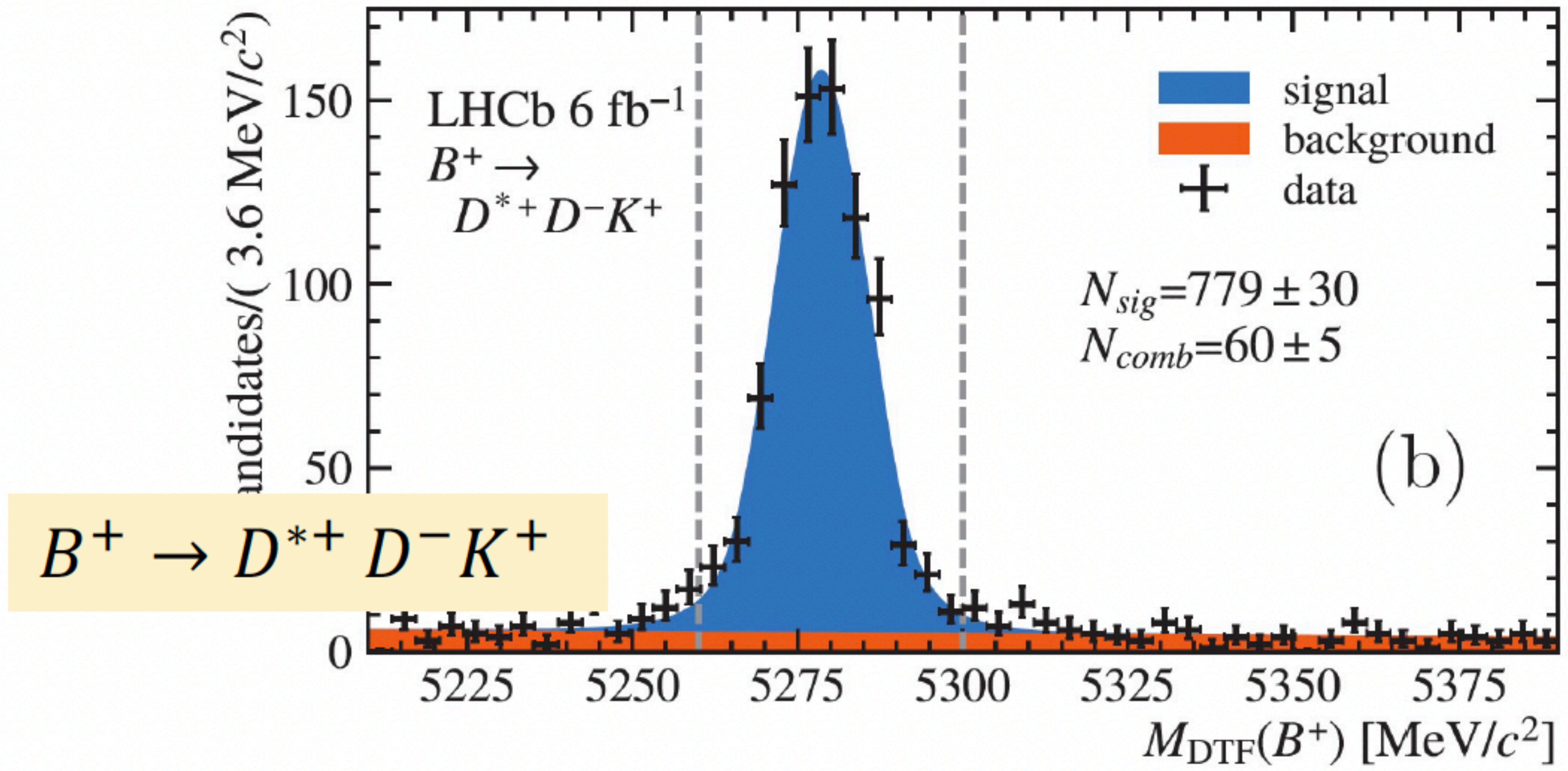
Phys. Rev. Lett. 133 (2024) 131902



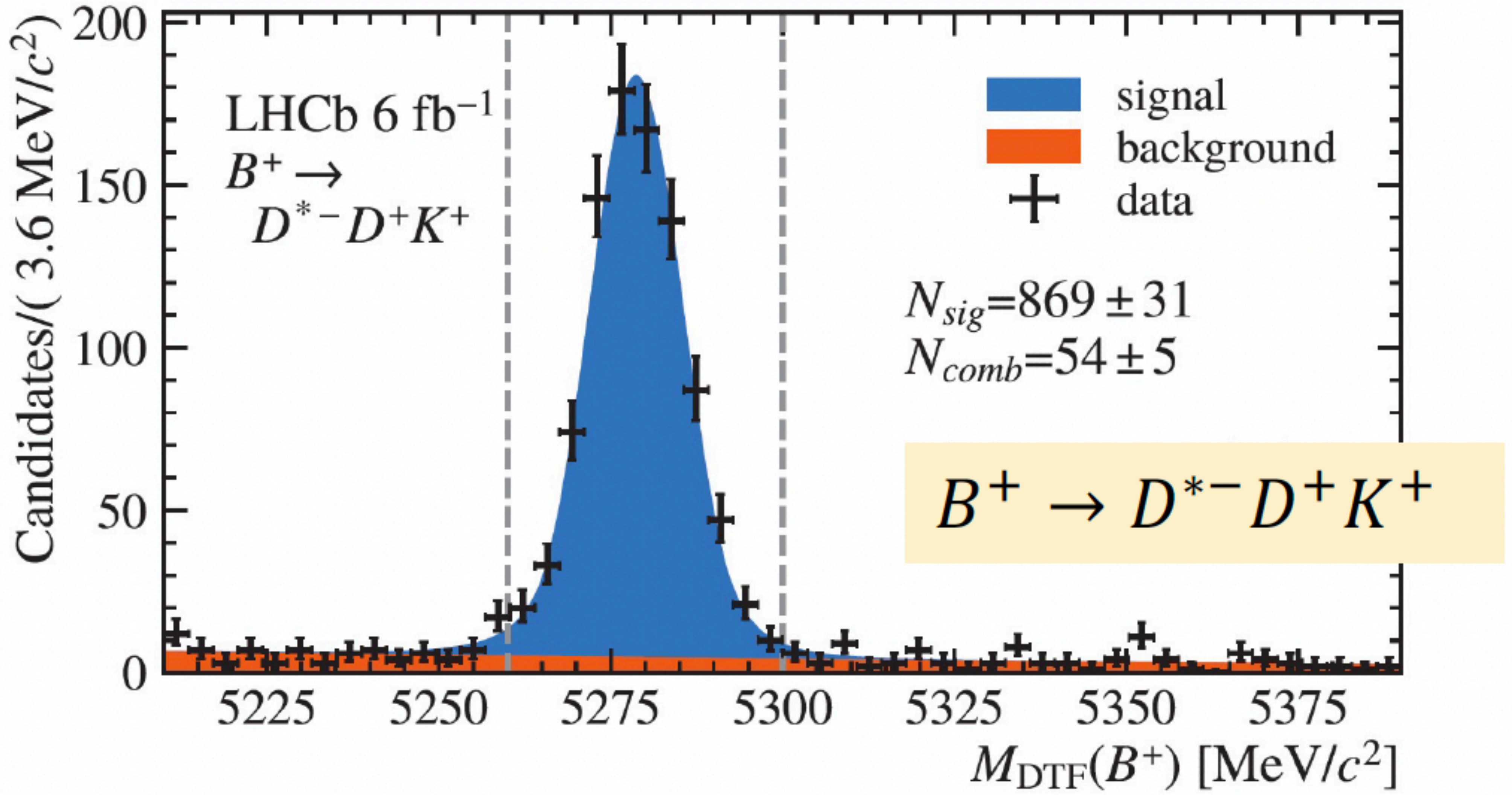
plot from Yanxi's talk

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

About 1700 signals



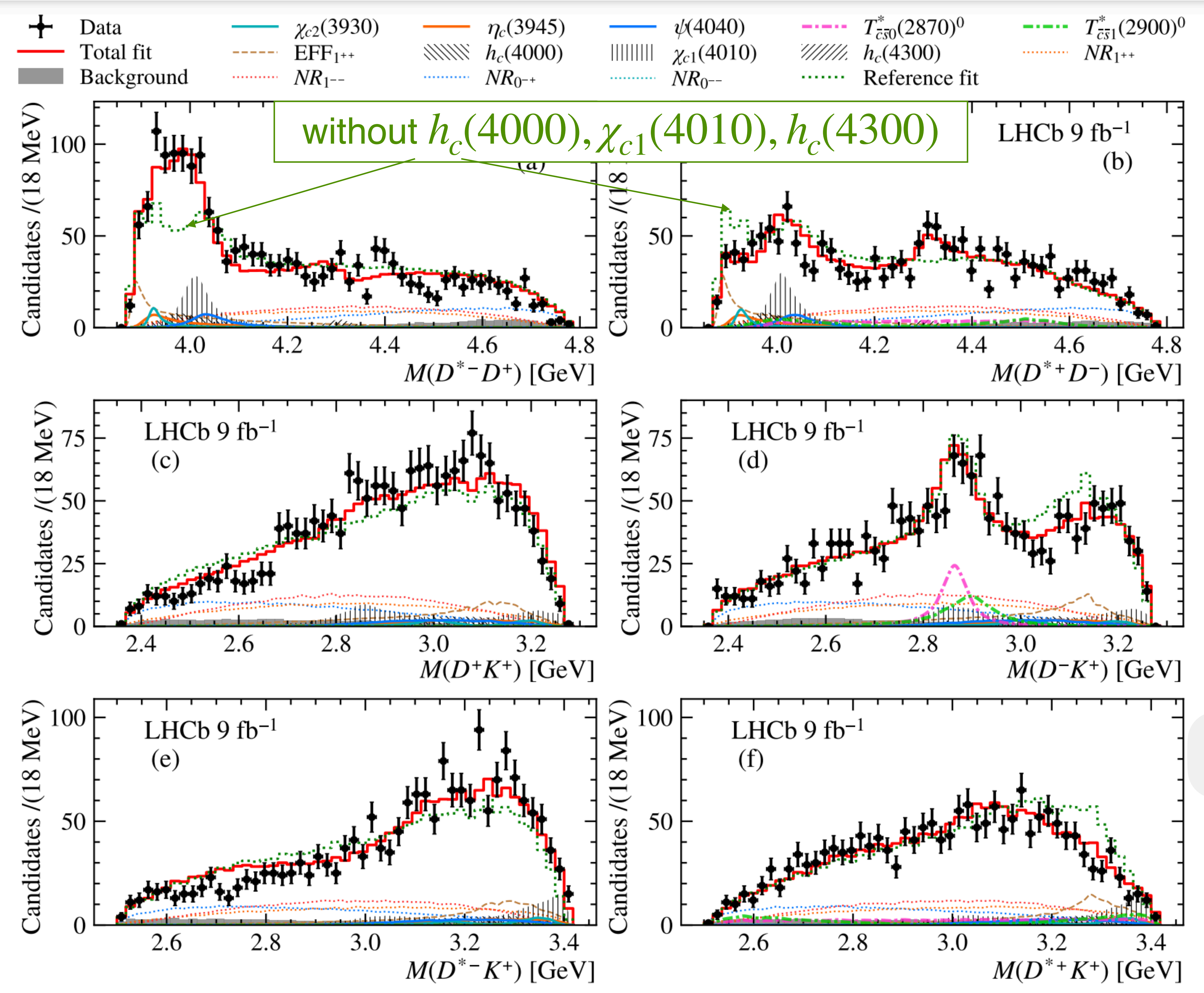
About 1700 signals



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

Phys. Rev. Lett. 133 (2024) 131902

- 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 $B^+ \to R(D^{*\pm}D^{\mp})K^+$
- $T^*_{\bar{c}\bar{s}0}(2870)^0$ and $T^*_{\bar{c}\bar{s}0}(2900)^0$ confirmed in $B^+ \to D^{*+}T^{*0}_{\bar{c}\bar{s}0,1}$



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

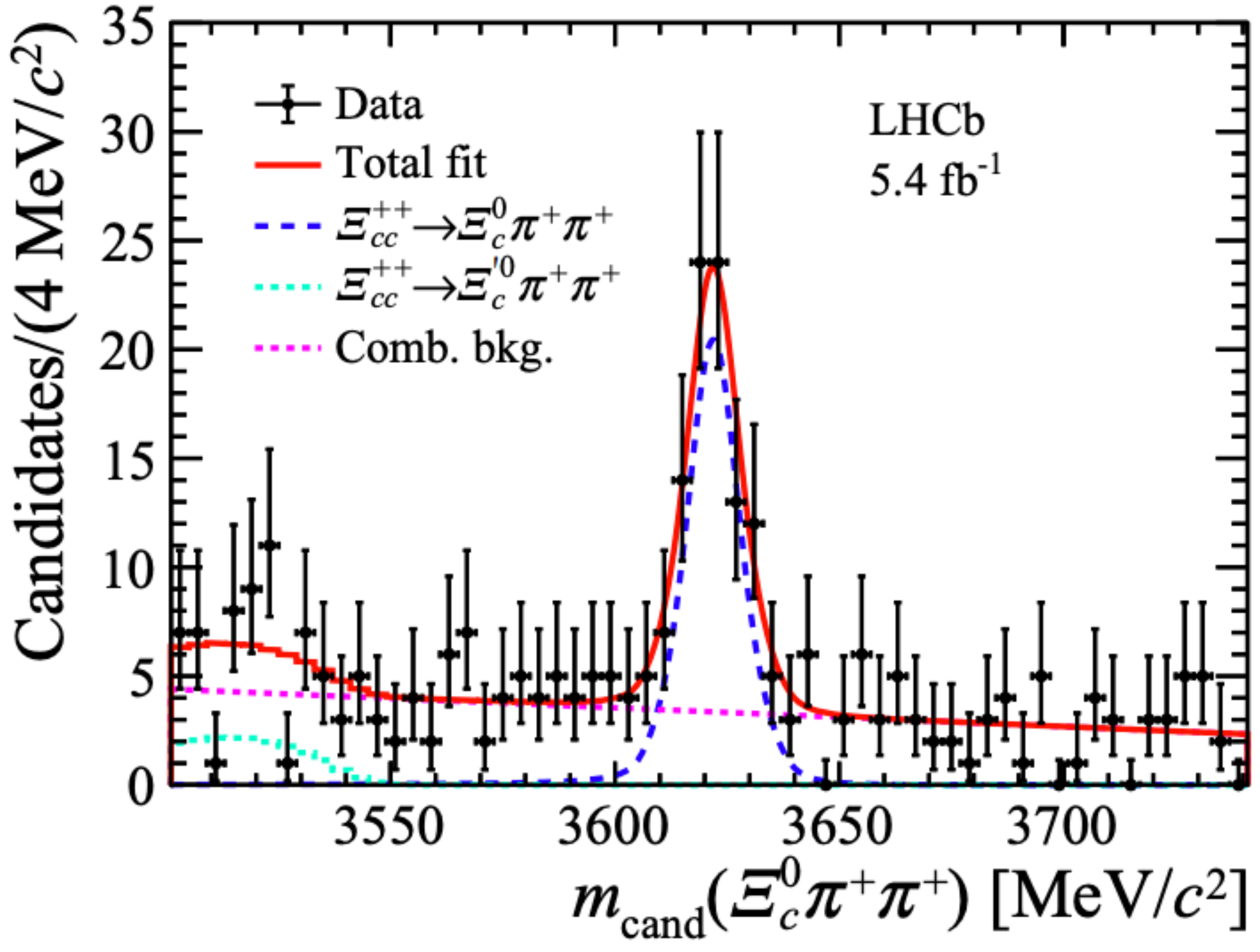
This work		Known states [6]		$c\bar{c}$ prediction [34]	
$\eta_c(3945)$	$J^{PC} = 0^{-+}$	$X(3940)$ [9,10]	$J^{PC} = ?^{??}$	$\eta_c(3S)$	$J^{PC} = 0^{-+}$
$m_0 = 3945\,^{+28}_{-17}\,^{+37}_{-28}$	$\Gamma_0 = 130\,^{+92}_{-49}\,^{+101}_{-70}$	$m_0 = 3942 \pm 9$	$\Gamma_0 = 37\,^{+27}_{-17}$	$m_0 = 4064$	$\Gamma_0 = 80$
$h_c(4000)$	$J^{PC} = 1^{+-}$	$T_{c\bar{c}}(4020)^0$ [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]	$J^{PC} = 1^{++}$	$\chi_{c1}(3P)$	$J^{PC} = 1^{++}$
		$m_0 = 4294 \pm 4\,^{+6}_{-3}$	$\Gamma_0 = 53 \pm 5 \pm 5$	$m_0 = 4317$	$\Gamma_0 = 39$

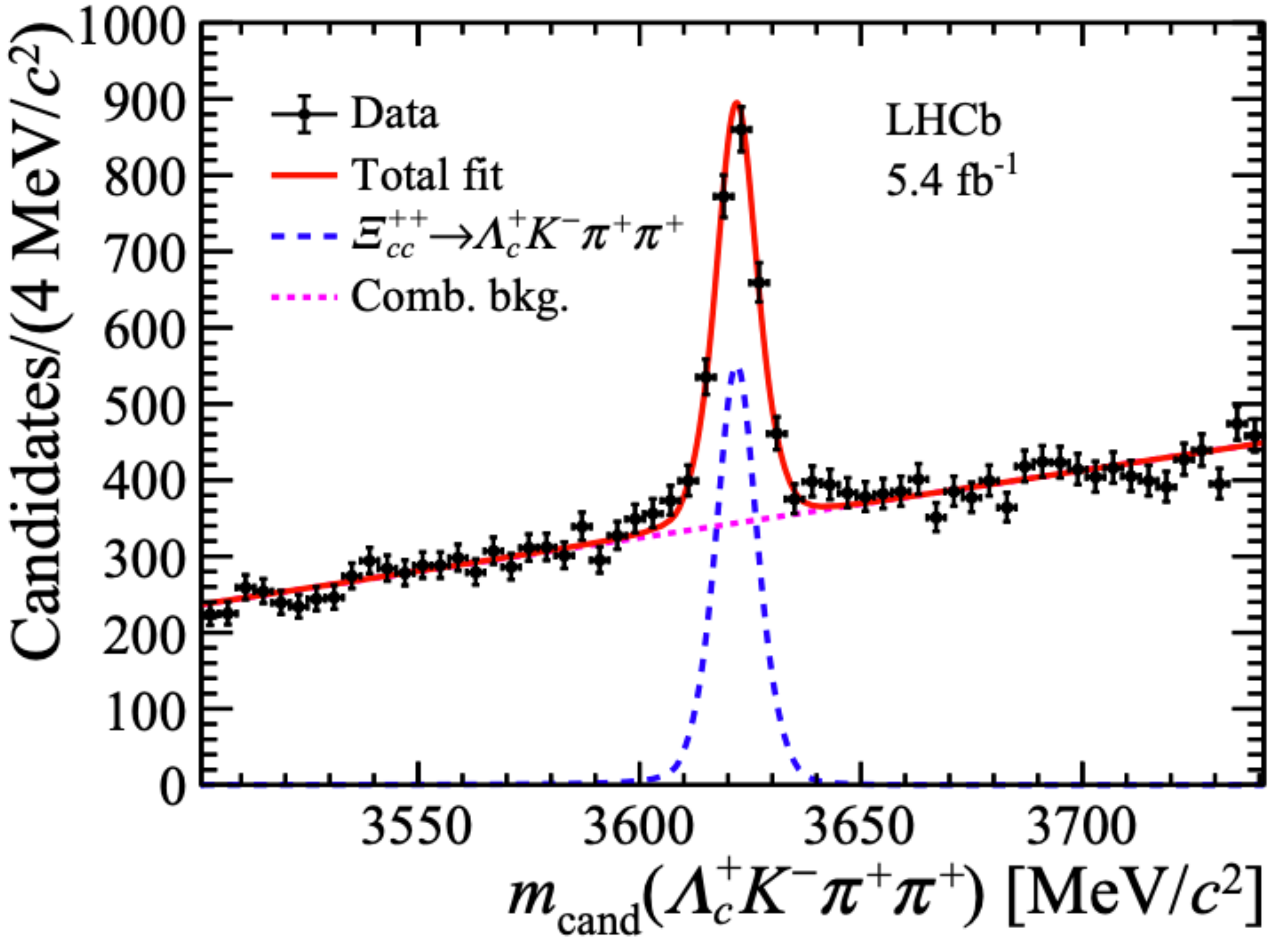
Doubly charmed baryon

arXiv:2504.05063

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^0 \pi^+ \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)} = 1.37 \pm 0.18(\text{stat}) \pm 0.09(\text{syst}) \pm 0.35(\text{ext}),$$

$\Xi_{cc}^{++} \to \Xi_c^0 (\to \Lambda_c^+ K^-) \pi^+ \pi^+$

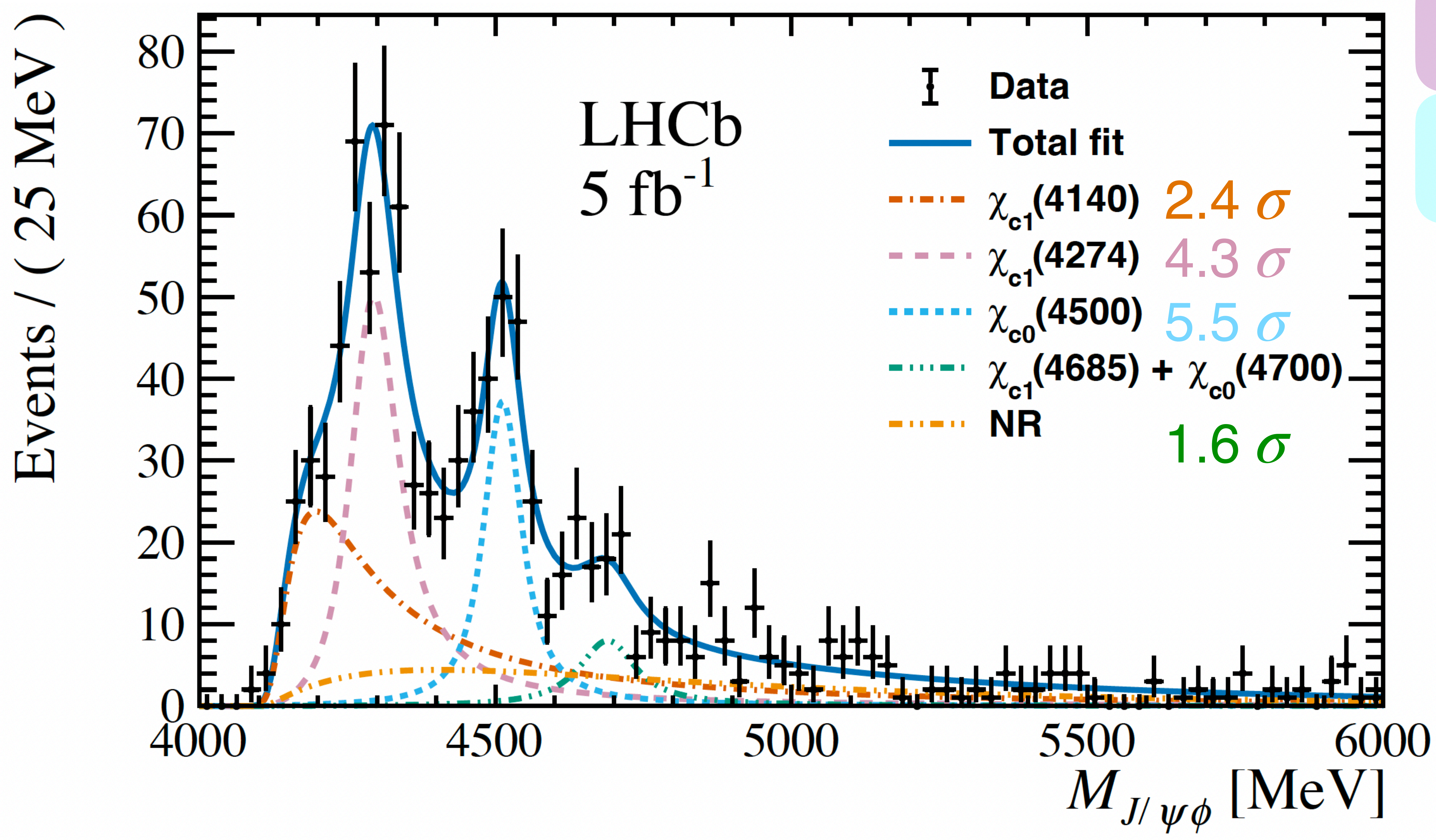




Observation of exotic $J/\psi\phi$ resonance in diffractive process

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

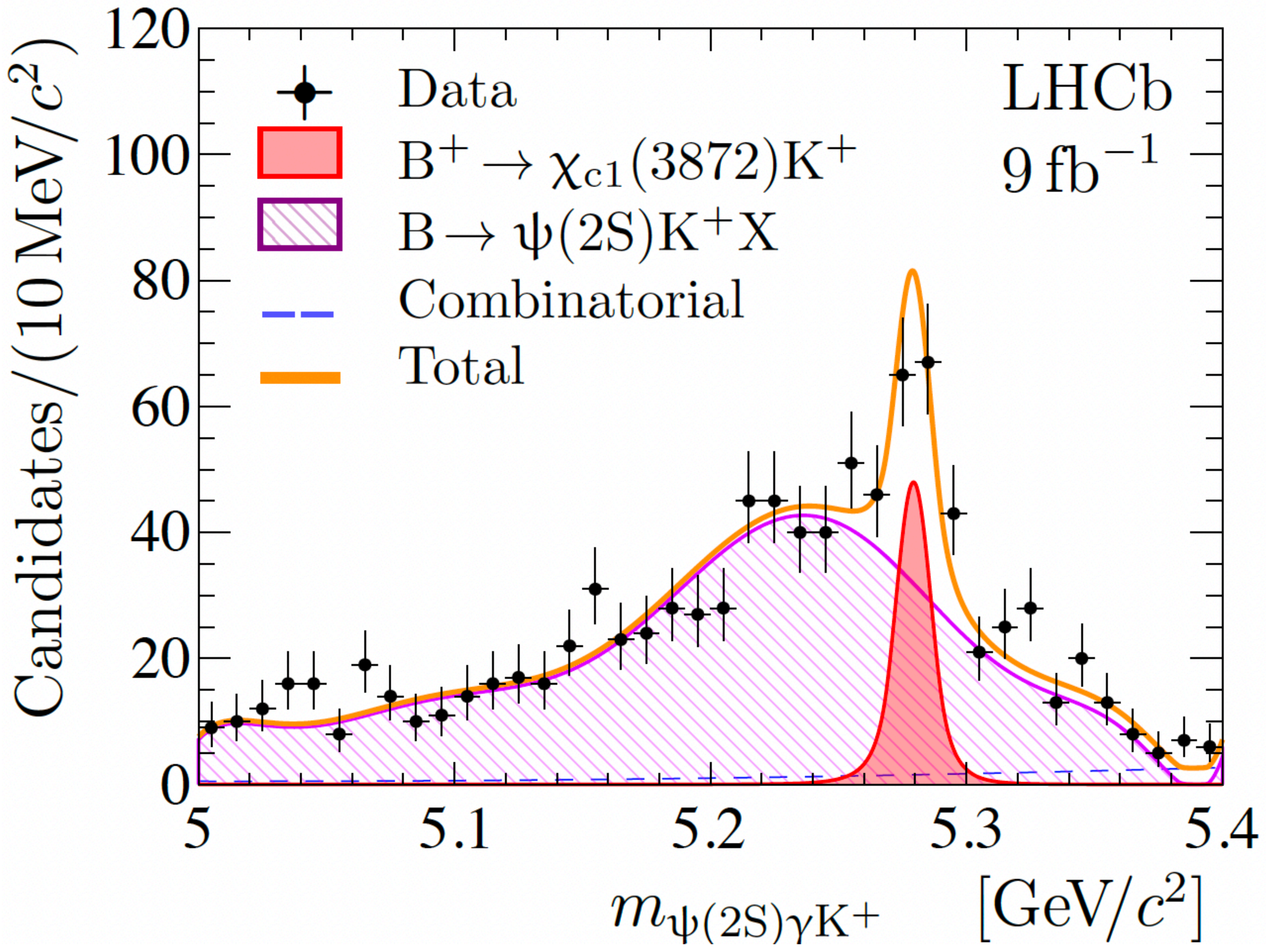
$$\sigma_{\chi_{c1}(4140)} \times \mathcal{B}_{\rm eff}^{\chi_{c1}(4140)} = (0.80 \pm 0.15 \pm 0.28)\ \text{pb},$$
$$\sigma_{\chi_{c1}(4274)} \times \mathcal{B}_{\rm eff}^{\chi_{c1}(4274)} = (0.73 \pm 0.08 \pm 0.17)\ \text{pb},$$
$$\sigma_{\chi_{c0}(4500)} \times \mathcal{B}_{\rm eff}^{\chi_{c0}(4500)}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

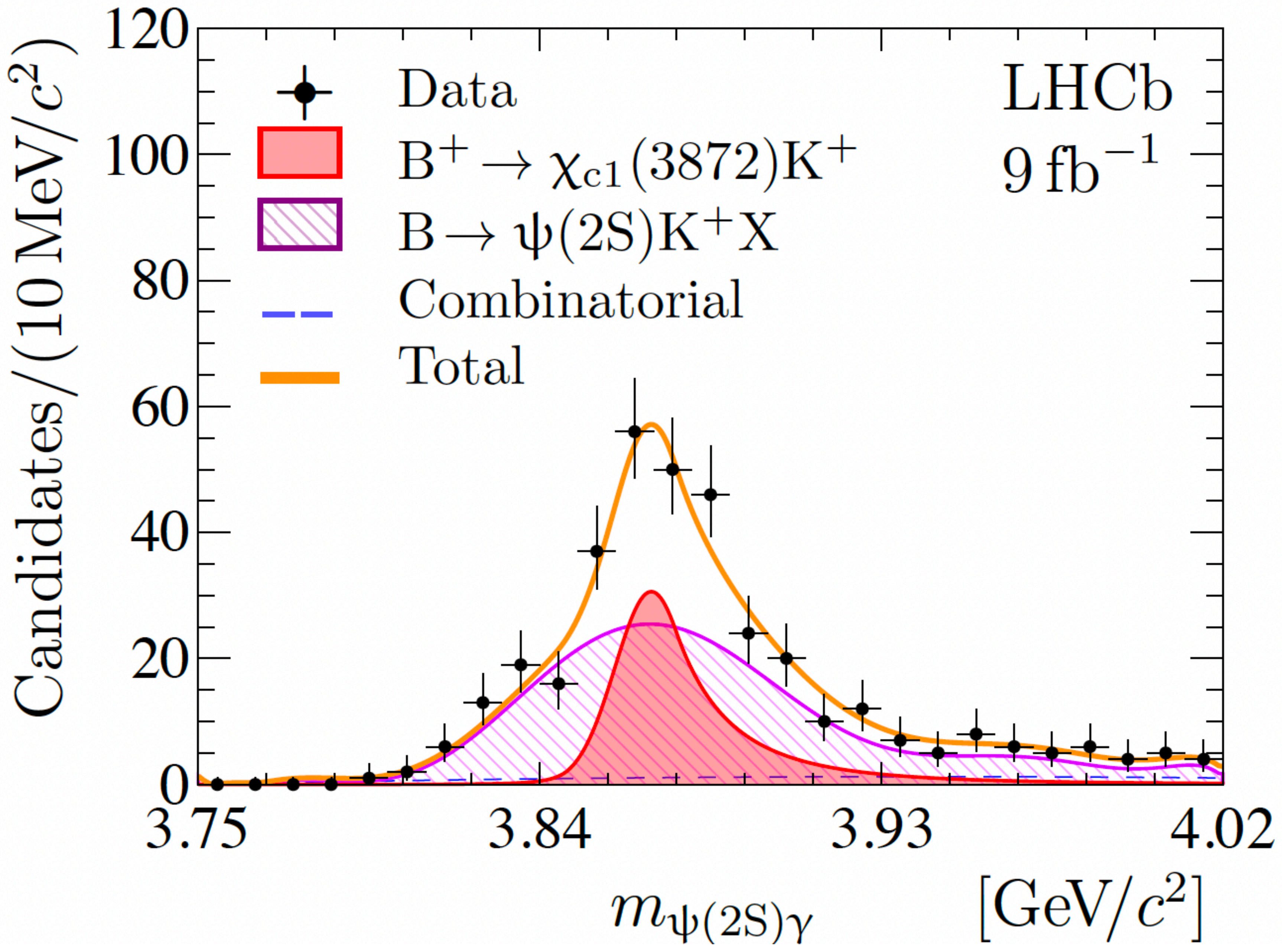
Observation of $\chi_{c1}(3872) \to \gamma\psi(2S)$

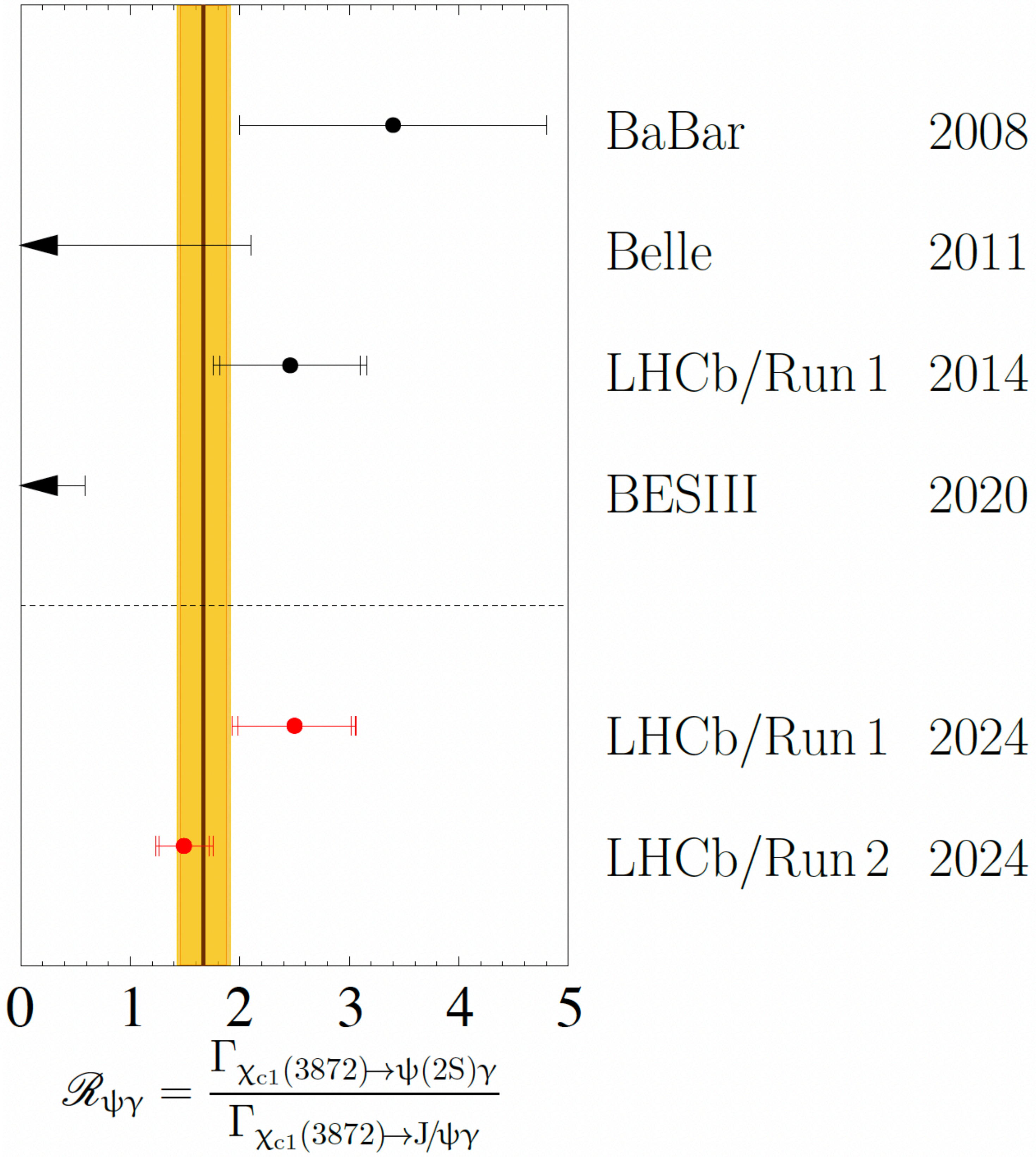
arXiv:2406.17006

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

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







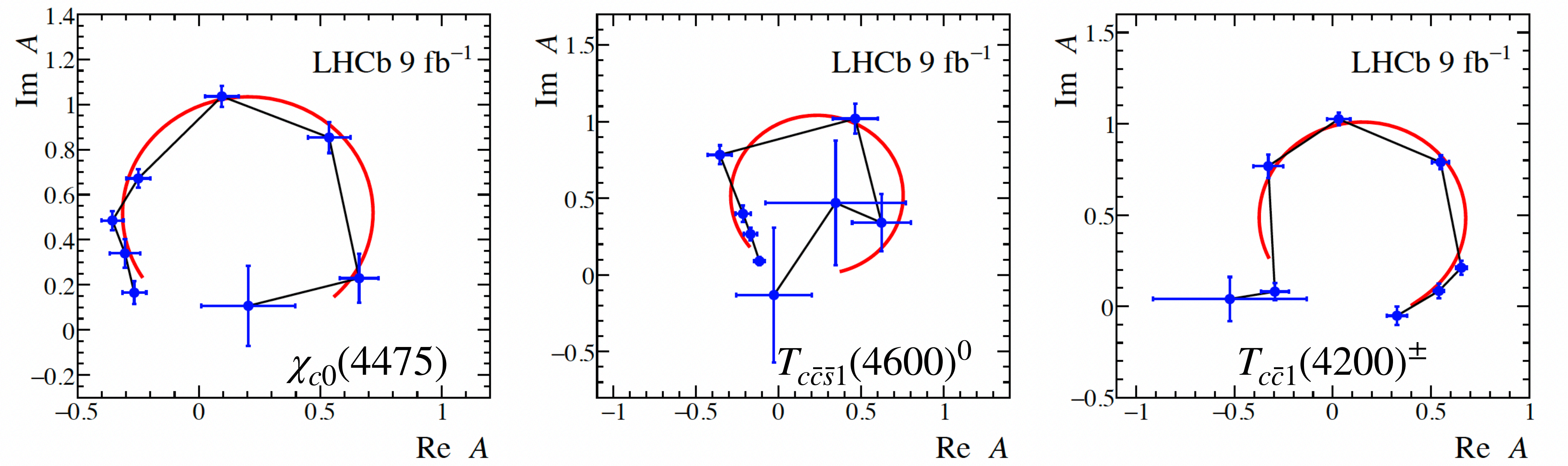
Amplitude analysis of $B^+ \to \psi(2S)K^+\pi^+\pi^-$

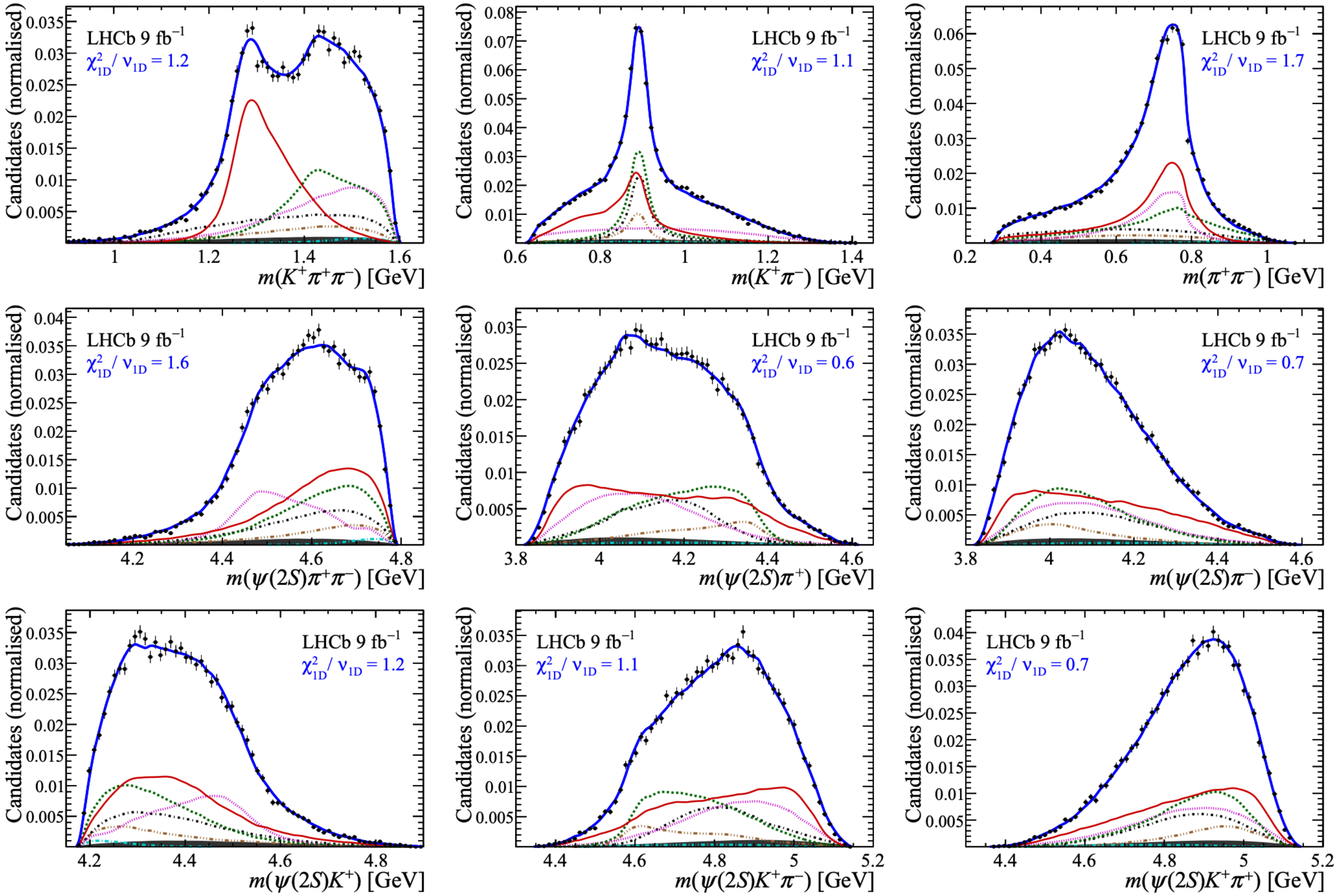
arXiv:2407.12475

- 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





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
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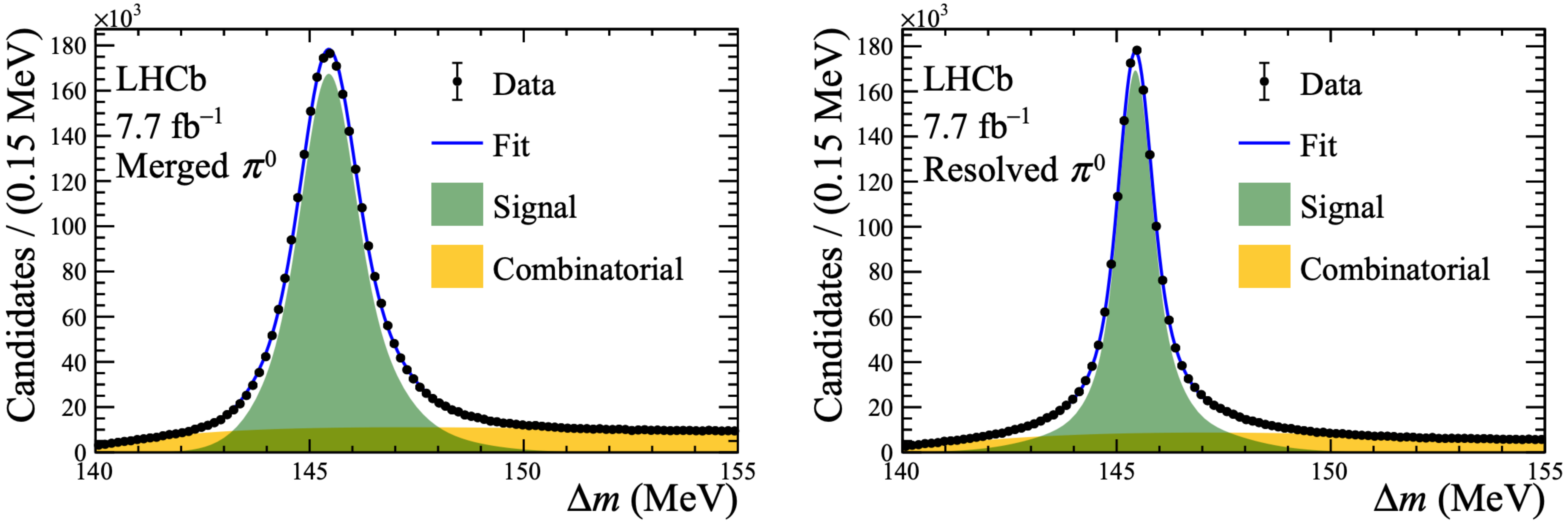
Resonance	J^P	m_0 [MeV]	Γ_0 [MeV]	Sign. [σ]	Res. PDG	m_0 [MeV]	Γ_0 [MeV]
$\chi_{c0}(4475)$	0^+	$4475\pm 7\pm 12$	$231\pm 19\pm 32$	> 20 (19)	$\chi_{c0}(4500)$	4474 ± 4	77^{+12}_{-10}
$\chi_{c1}(4650)$	1^+	$4653\pm 14\pm 27$	$227\pm 26\pm 22$	15 (13)	$\chi_{c1}(4685)$	4684^{+15}_{-17}	126 ± 40
$\chi_{c0}(4710)$	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

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

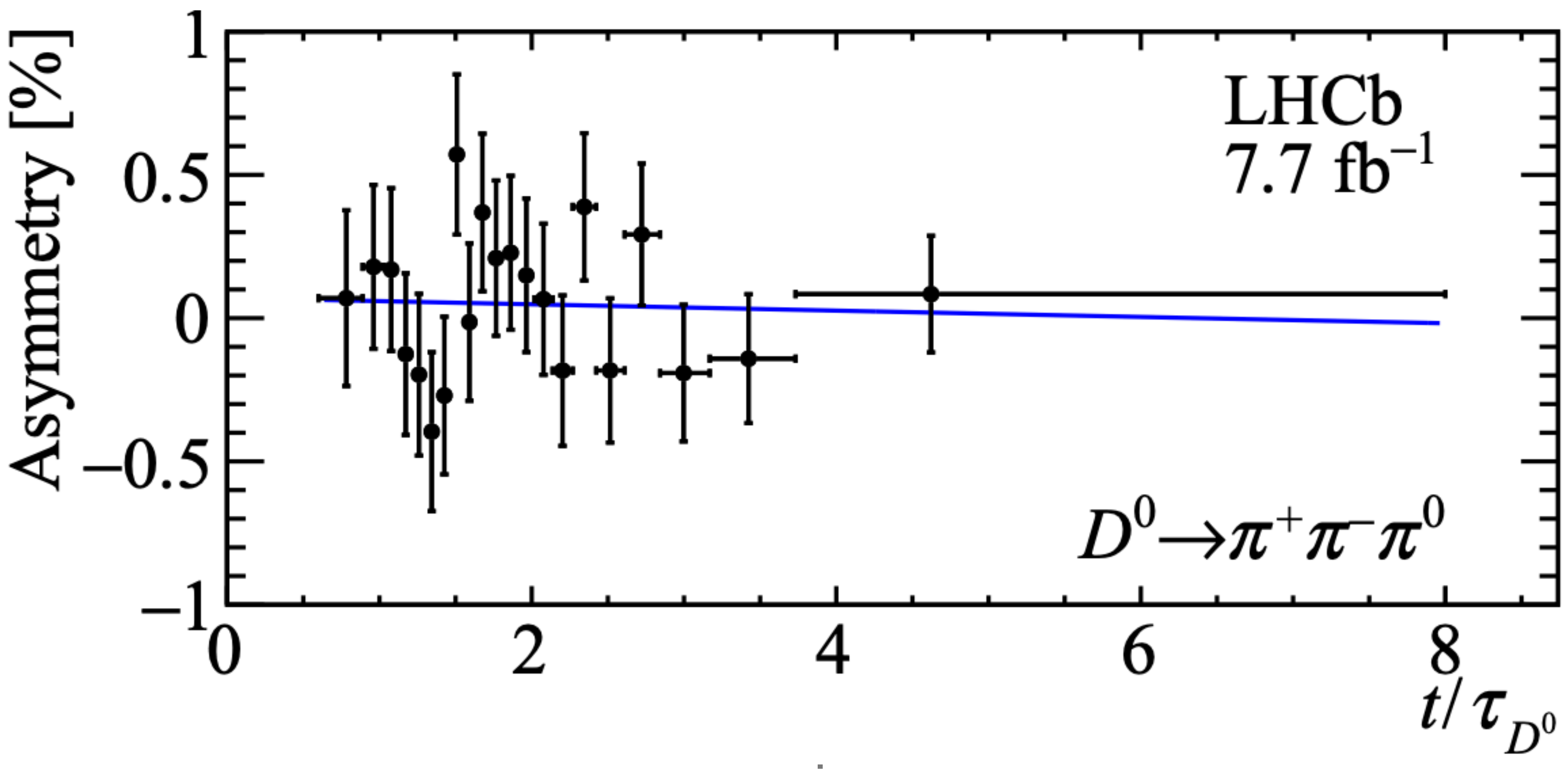
arXiv:2405.06556

- First measurement of time-dependent CP violation in SCS mode



$$A_{CP}(f_{CP}, t) \equiv \frac{\Gamma_{D^0\to f_{CP}}(t) - \Gamma_{\bar{D}^0\to f_{CP}}(t)}{\Gamma_{D^0\to f_{CP}}(t) + \Gamma_{\bar{D}^0\to f_{CP}}(t)} \approx a^{\mathrm{dir}}_{f_{CP}} + \Delta Y_{f_{CP}} \frac{t}{\tau_{D^0}}.$$

$$A_{\mathrm{meas}}(\langle t/\tau_{D^0}\rangle_i) \equiv \frac{N^i_{D^0} - N^i_{\bar{D}^0}}{N^i_{D^0} + N^i_{\bar{D}^0}}$$



$$\Delta Y_{f_{CP}} \approx \frac{\eta_{f_{CP}}}{2}\left[\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x \sin\phi - \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y \cos\phi\right]$$

- No evidence for time-dependent CP violation, constant with world average

$$\Delta Y \equiv \eta_{CP}\Delta Y_{f_{CP}} = (-1.3 \pm 6.3 \pm 2.4) \times 10^{-4}$$