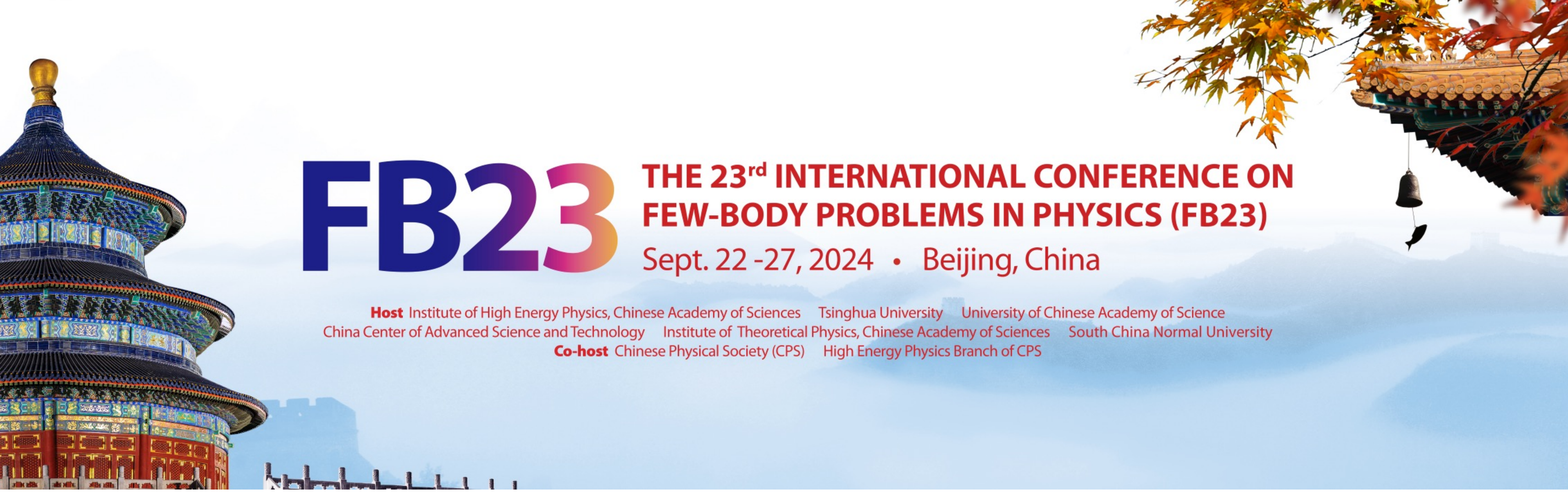


Progress on hadron physics from LHCb

Liupan An

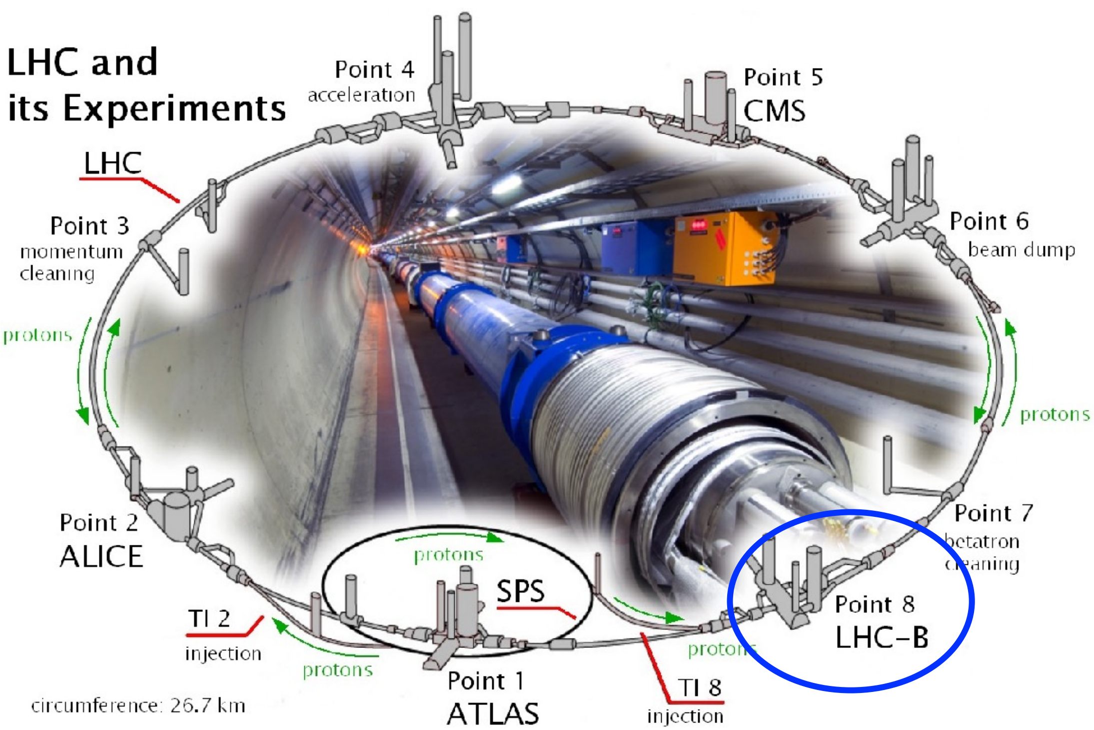
On behalf of the LHCb collaboration

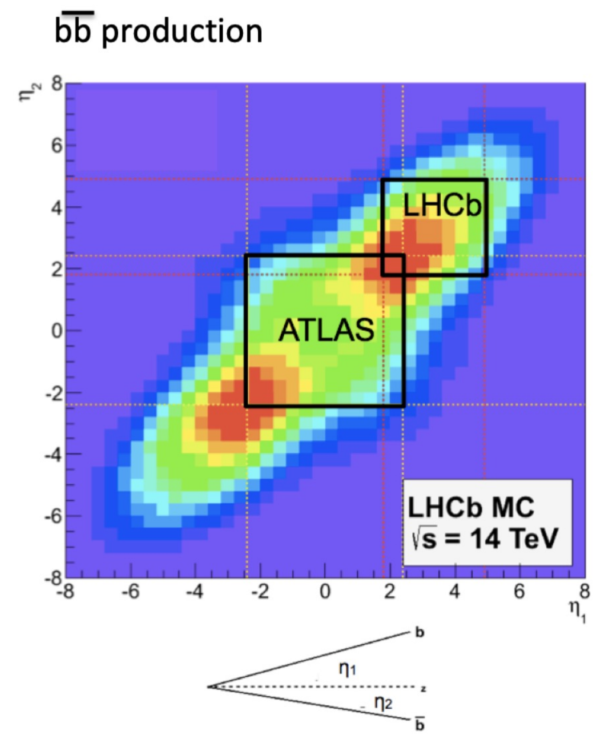
Peking University

23rd International Conference on Few-Body problems in Physics @ Beijing, 2024.09.23

The LHCb experiment

- The LHCb experiment is one of the four large experiments at the LHC, dedicated to heavy flavor physics
  - ✓ LHC has the largest production cross-sections of b- and c-hadrons ever
    - $\sigma(b\bar{b}) \approx 500$ μb @ 13 TeV & $\sigma(c\bar{c}) \approx 20\times\sigma(b\bar{b})$ in pp collisions
  - ✓ A great variety of b and c hadron species are accessible
  - ✗ Too many additional tracks

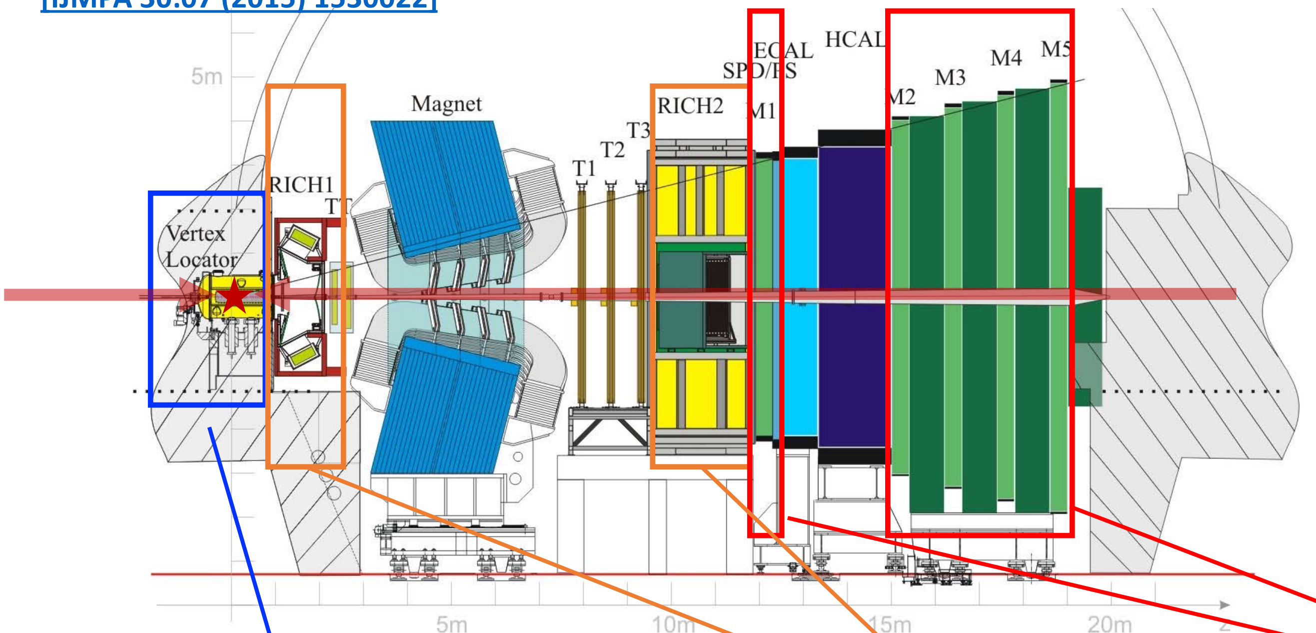




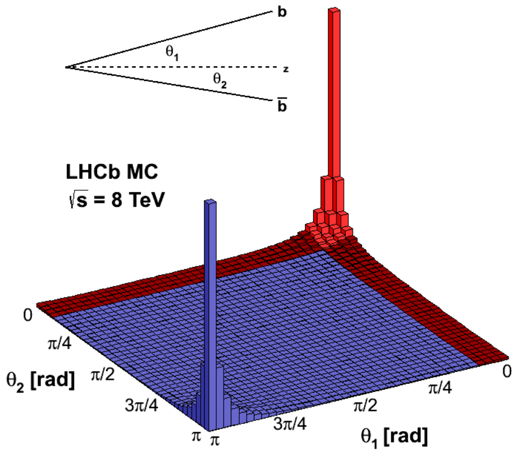
The LHCb detector in Run 1 & 2

➢LHCb is a single-arm forward region spectrometer covering $2 < \eta < 5$, with excellent ***vertexing***, ***tracking*** and ***particle identification (PID)*** performance

[JINST 3 (2008) S08005]
[IJMPA 30:07 (2015) 1530022]



2.4% 4π angle
$\Rightarrow 25\%$ $b\bar{b}$



Vertex Locator: high precision; capable of separating b/c hadron production and decay vertices

$\sigma_{\text{PV},x/y} \sim 10\ \mu\text{m}$, $\sigma_{\text{PV},z} \sim 60\ \mu\text{m}$

RICHs: efficient identification of pions, kaons and protons

$\varepsilon(K \rightarrow K) \sim 95\%$
@ misID rate $(\pi \rightarrow K) \sim 5\%$

Muon system (M1-M5): efficient muon identification and trigger

$\varepsilon(\mu \rightarrow \mu) \sim 97\%$
@ misID rate $(\pi \rightarrow \mu) \sim 1 - 3\%$

The LHCb detector in Run 3

[JINST 19 (2024) P05065]

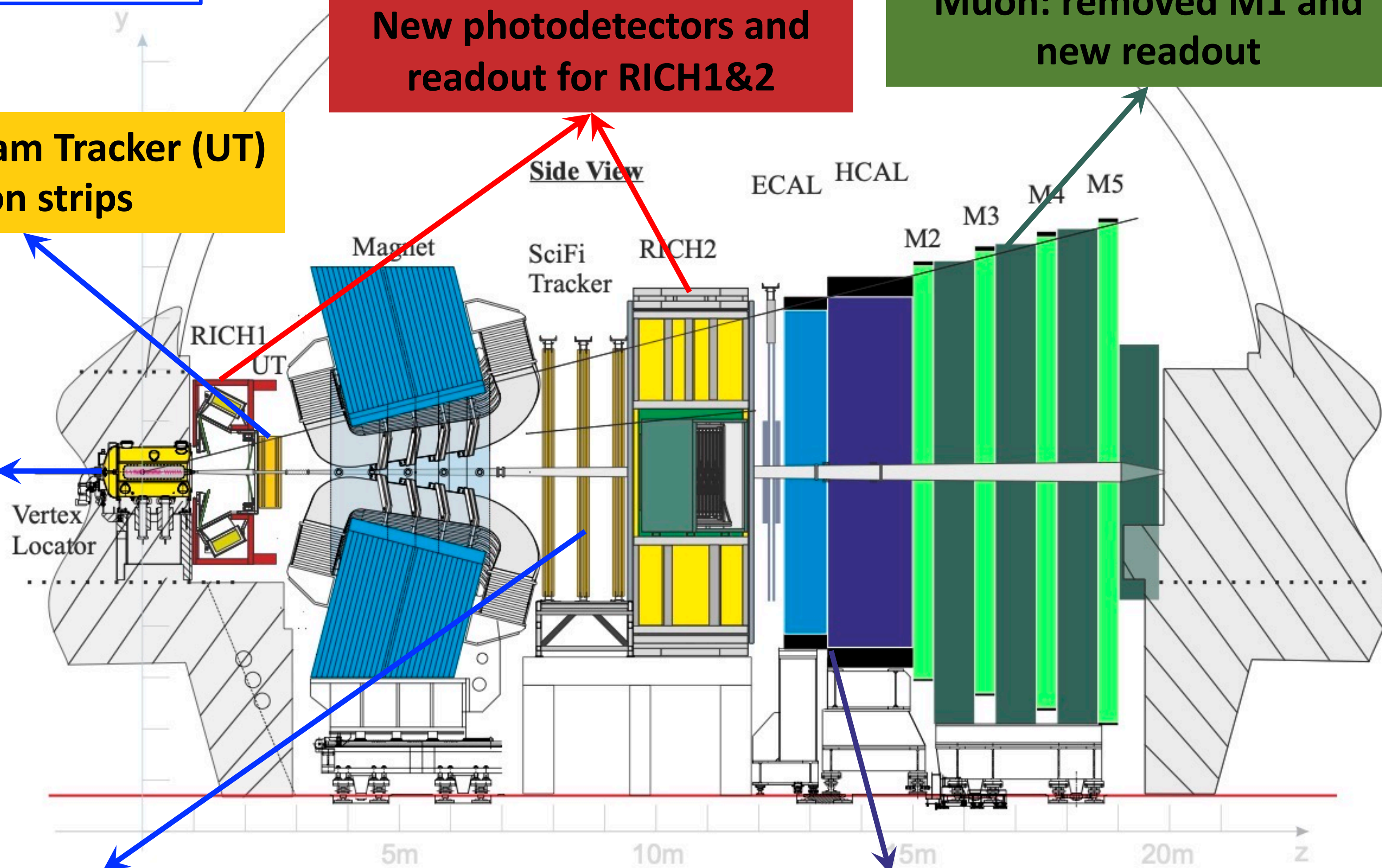
Software-only trigger

New RICH1 optics
New photodetectors and readout for RICH1&2

Muon: removed M1 and new readout

New Upstream Tracker (UT)
Silicon strips

New VELO
Pixel detector

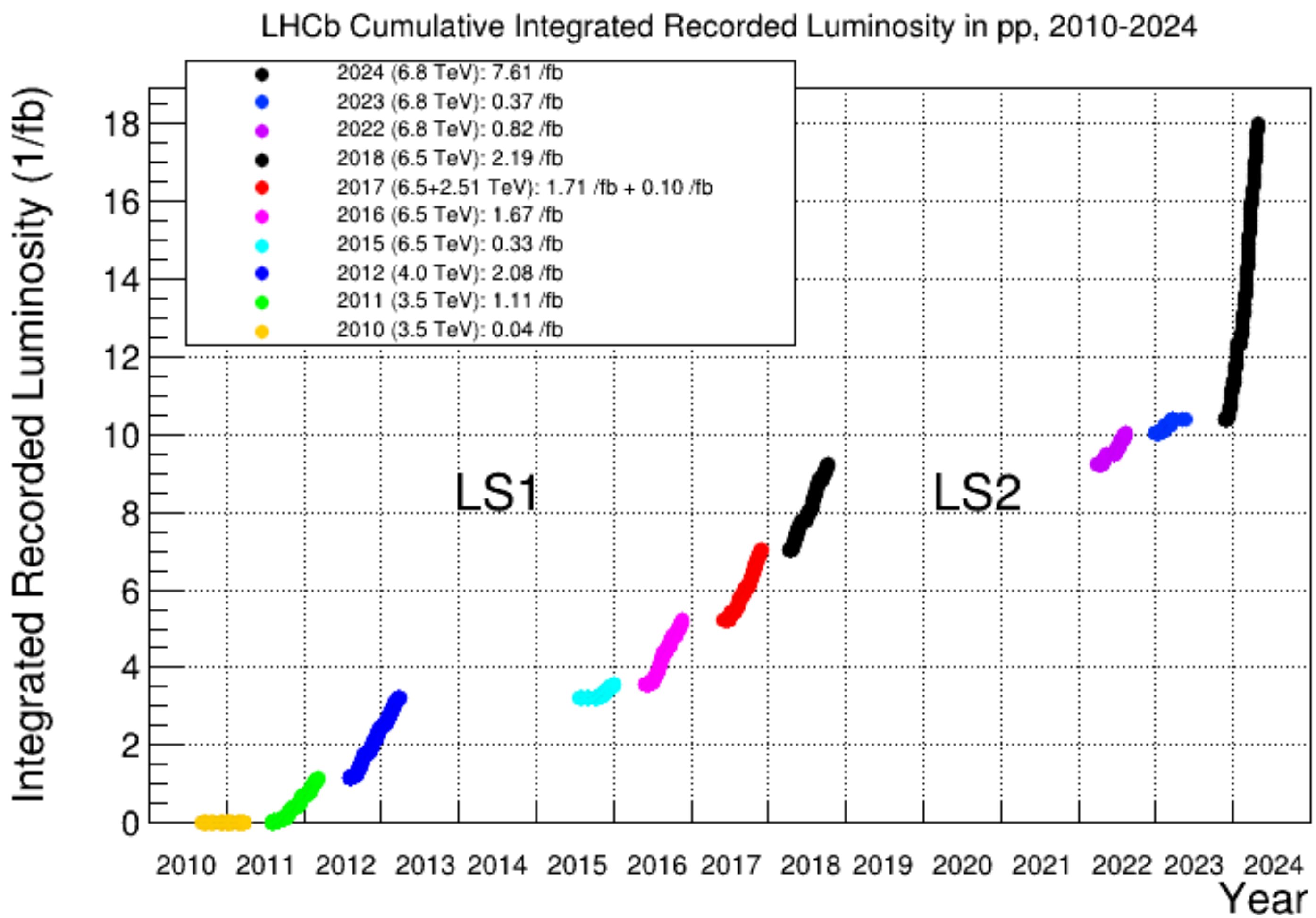


New SciFi Tracker
Scintillating fibres

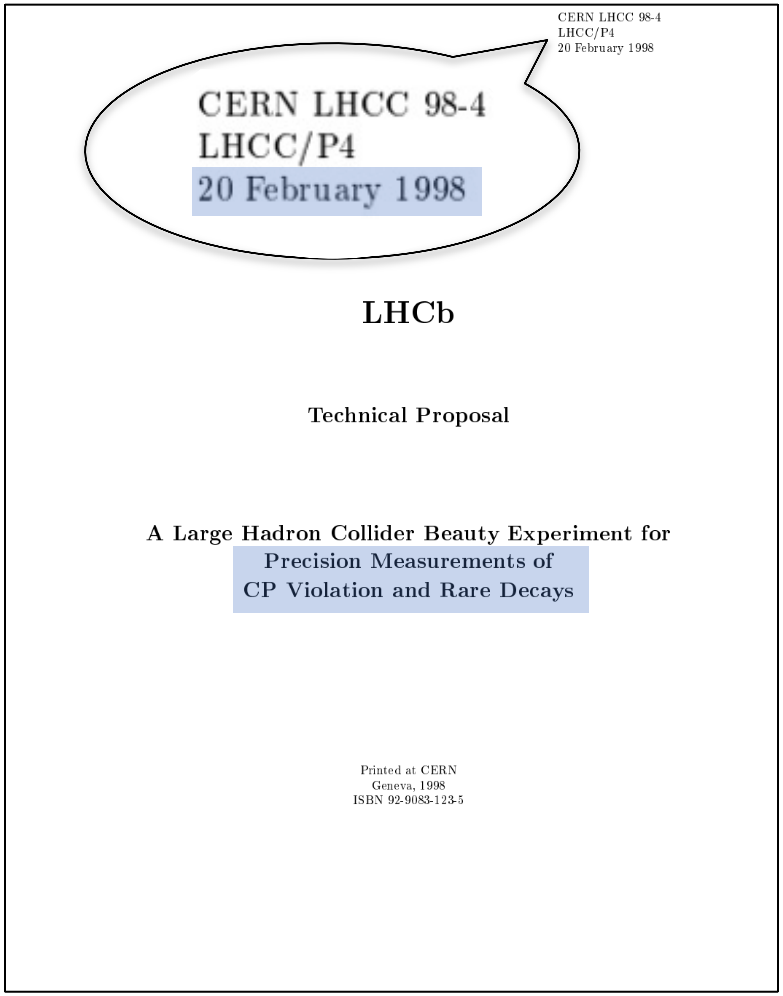
Calorimeters: removed PreShower (PS) and Scintillating Pad Detector (SPD), new readout

LHCb data taking

- Run 1 (2011-2012): $\mathcal{L}_{\text{int}} = 1\ \text{fb}^{-1}$ @ 7 TeV & 2 fb^{-1} @ 8 TeV
- Run 2 (2015-2018): $\mathcal{L}_{\text{int}} = 6\ \text{fb}^{-1}$ @ 13 TeV
- Run 3: rapidly growing @ 13.6 TeV



LHCb physics scheme


CERN LHCC 98-4
LHCC/P4
20 February 1998

CERN LHCC 98-4
LHCC/P4
20 February 1998

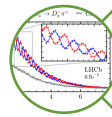
LHCb

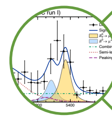
Technical Proposal

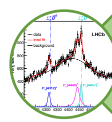
A Large Hadron Collider Beauty Experiment for
Precision Measurements of
CP Violation and Rare Decays

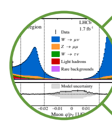
Printed at CERN
Geneva, 1998
ISBN 92-9083-123-5

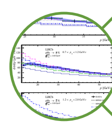
- LHCb has become a general purpose detector nowadays

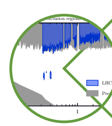

CP violation


Rare decays


Hadron physics: spectroscopy & production

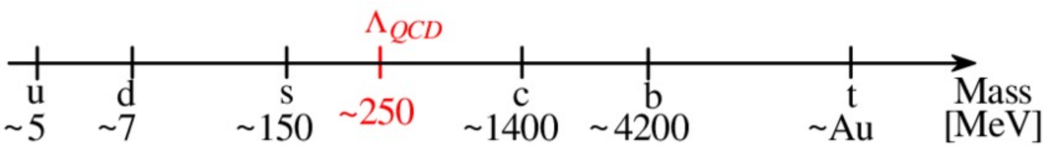

Electroweak

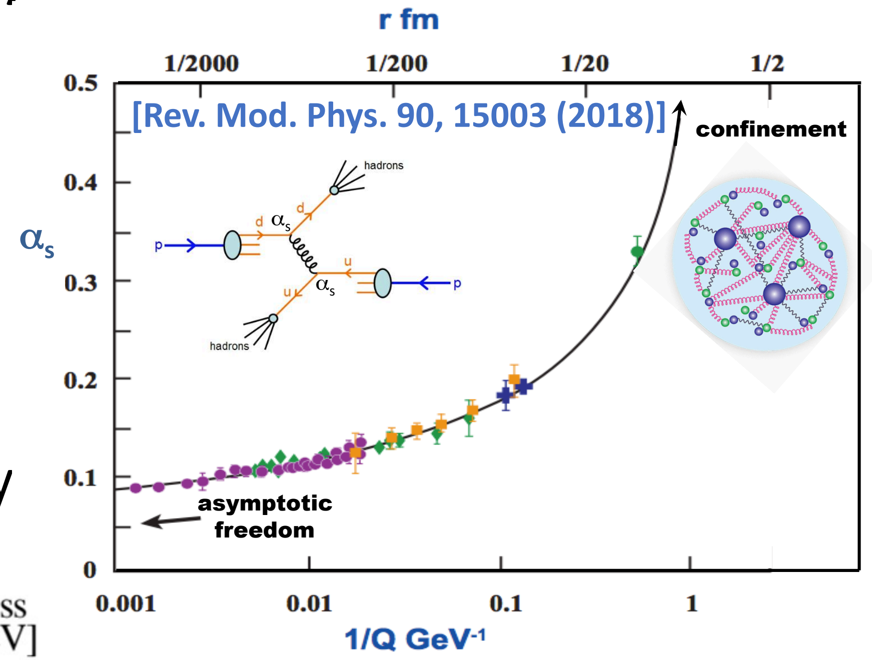

Heavy ions & fixed target


Dark sector ...

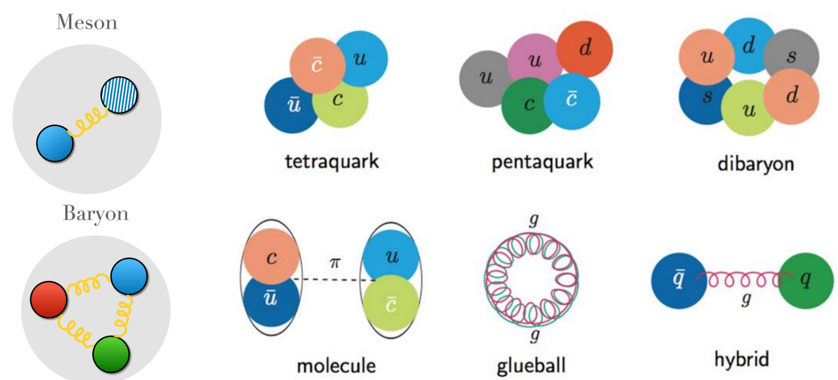
Hadron physics

- ➢ ***QCD dilemma***: understanding the non-perturbative property of QCD at low-energy scale
- ➢ ***Hadron***: a main tool to probe QCD at low-energy regime
  - ✓ ***heavy quarks*** bring advancements both experimentally and theoretically





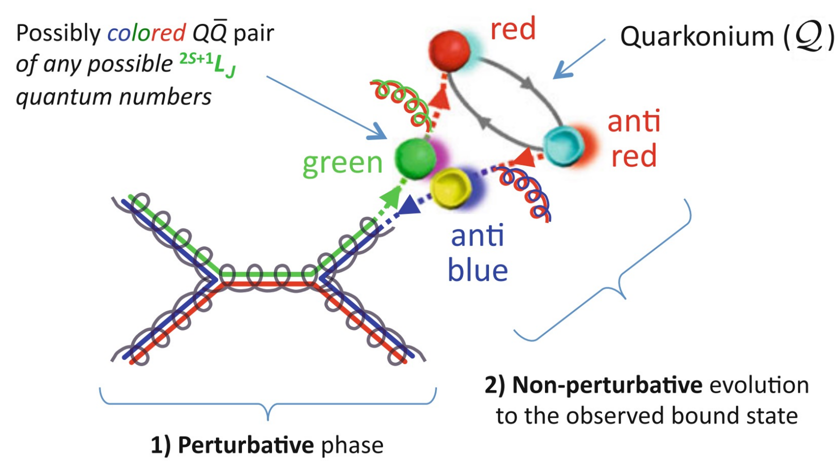
Hadron spectroscopy



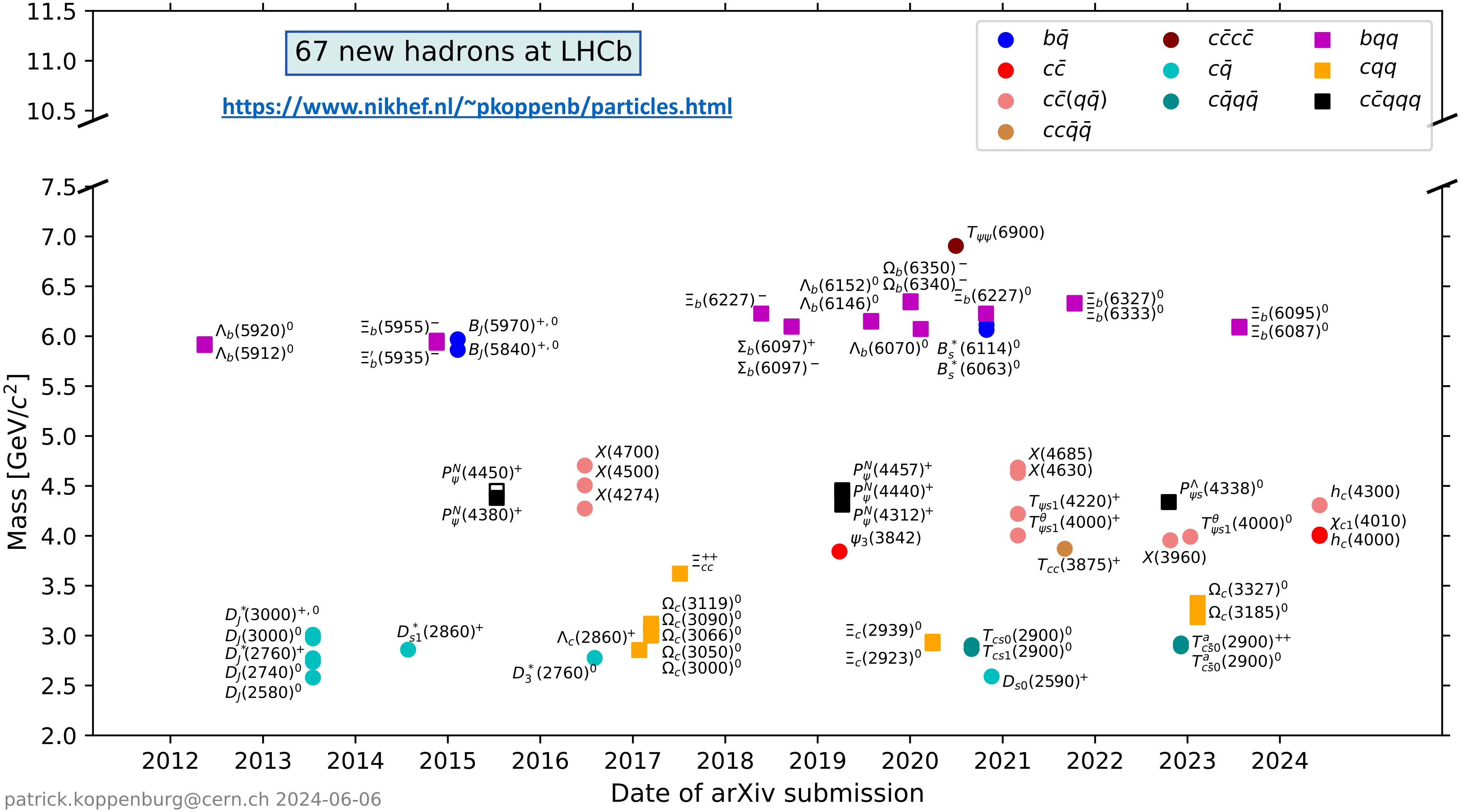
conventional

exotic

Hadron production



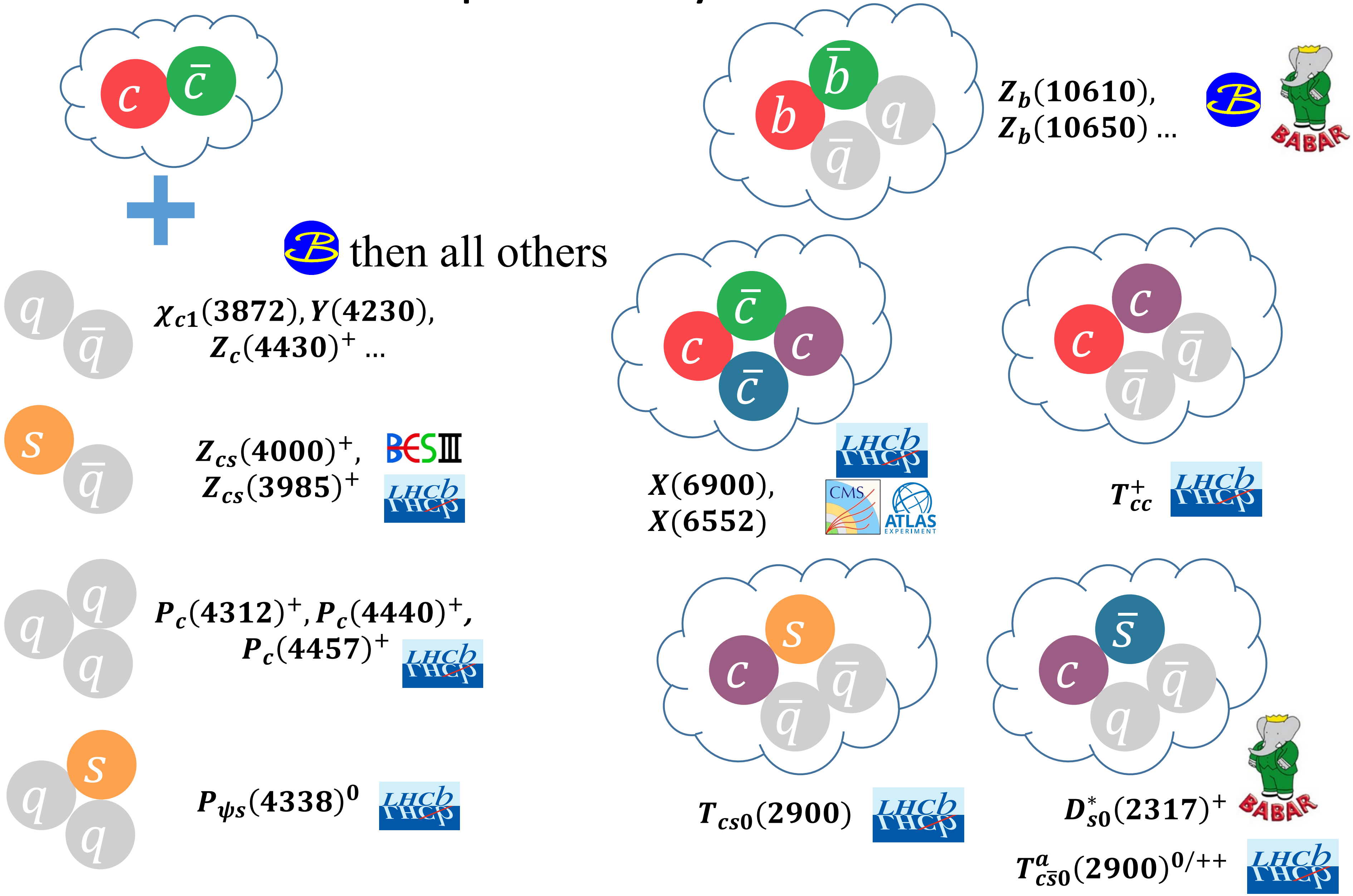
Hadrons observed at LHCb



Exotic hadron spectroscopy

Map of heavy exotics

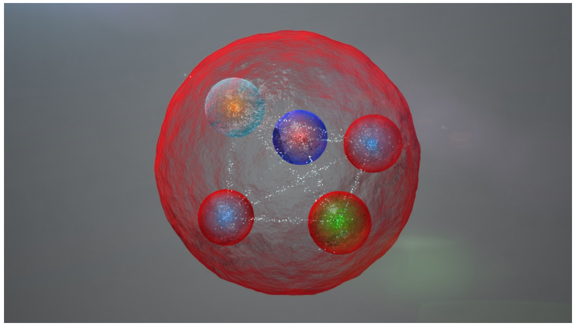
Inspired by Ivan Polyakov



Theoretical scenarios

- Two main players for multiquark state modelling:

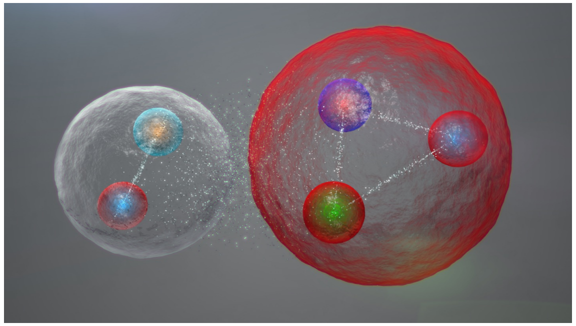
Compact multiquark



(Di-)quarks bound via color forces

- Typical size $\mathcal{O}(1\ \mathrm{fm})$
- Mass proximity to threshold **accidental**
- $SU(3)_{flavor}$ multiplets from combinations of **(di-)quarks**
- No (strong) hierarchy of couplings

Hadron molecule



Hadrons bound via mesonic exchange

- Typical size $> 1\ \mathrm{fm}$
- Mass proximity to threshold **natural**
- $SU(3)_{flavor}$ multiplets from combinations of **component hadrons**
- Fall-apart decay **dominant**

- Other possible scenarios: hadro-quarkonium, hybrid …
- ***Experimental studies*** essential to test various theoretical models

Selected new measurements

- **Pentaquark study**:

  Search for prompt production of pentaquarks in open charm final states

  [PR D110 (2024) 032001]

- **Tetraquark study in $B \to D\bar{D}h$ modes**:

  Amplitude analysis of $B^+ \to D^{*\pm}D^{\mp}K^+$ [arXiv: 2404.19510]

- **Exotic hadrons in diffractive processes**:

  [arXiv: 2407.14301]

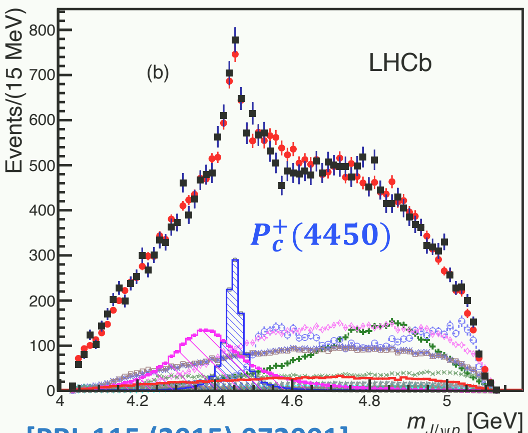
  Observation of exotic $J/\psi\phi$ resonances in diffractive processes in pp collisions

- Amplitude analysis of $B^+ \to \psi(2S)K^+\pi^+\pi^-$ [arXiv: 2407.12475]
- Study of radiative decays of $\chi_{c1}(3872)$ [arXiv: 2406.17006]
- Amplitude analysis of $B^+ \to D^{*-}D_s^+\pi^+$ [JHEP 09 (2024) 165]
- Modification of $\chi_{c1}(3872)$ production in pPb collisions [PRL 132 (2024) 242301]
- ……

- Recent studies of pentaquark states at LHCb ***by Zhenwei Yang*** [link]
- Recent studies of tetraquark states at LHCb ***by Zhihong Shen*** [link]

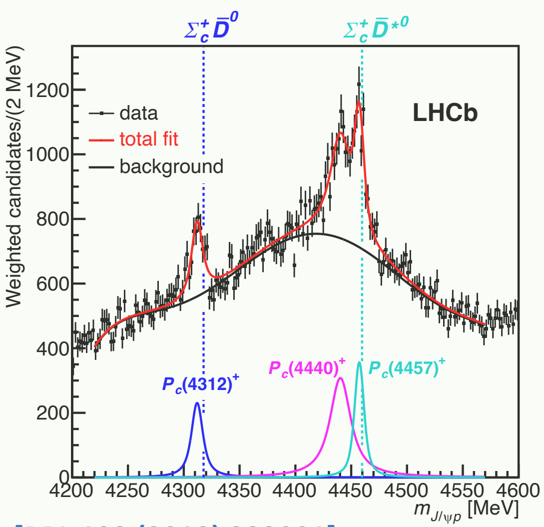
Pentaquark studies at LHCb

$\Lambda_b^0 \to [J/\psi\, p]K^-$



[PRL 115 (2015) 072001]

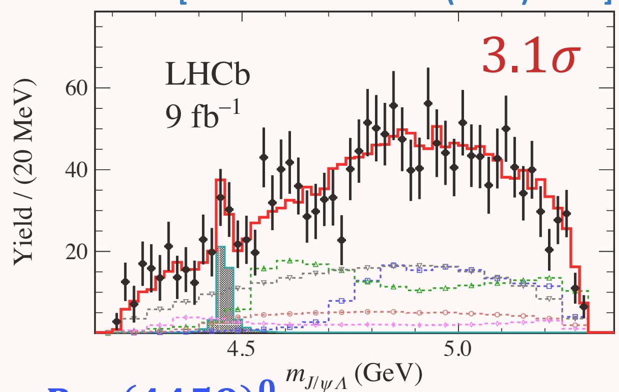
$P_{c\bar{c}}^+$ observation



[PRL 122 (2019) 222001]

$\Xi_b^- \to [J/\psi\Lambda]K^-$

[Science Bulletin 66 (2021) 1278]



$P_{c\bar{c}s}(4459)^0$

$P_{c\bar{c}s}^0$ evidence

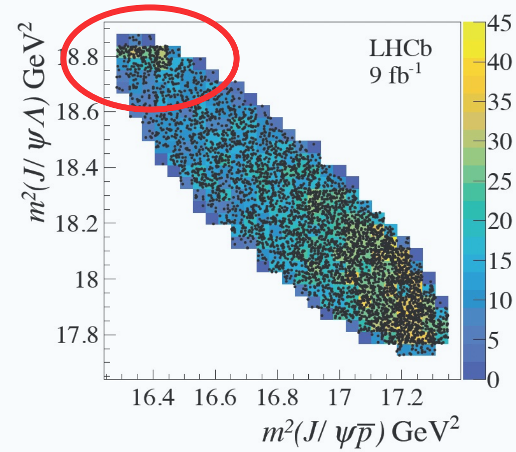
binding scheme

↓

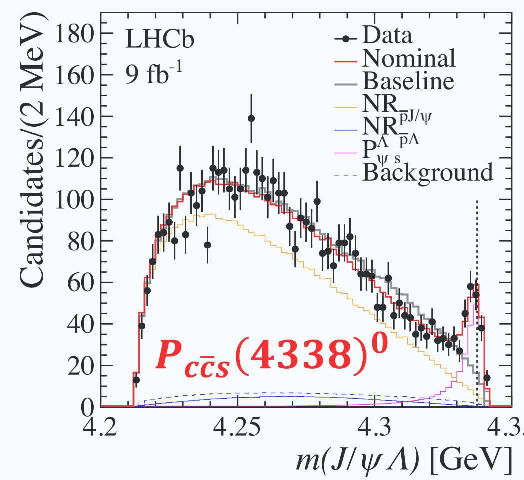
decay modes

⇒ search for pentaquarks through open charm modes

$B^- \to [J/\psi\Lambda]\bar{p}$



$P_{c\bar{c}s}^0$ observation



[PRL 131 (2023) 031901]

Pentaquark search via open charm

[PR D110 (2024) 032001]

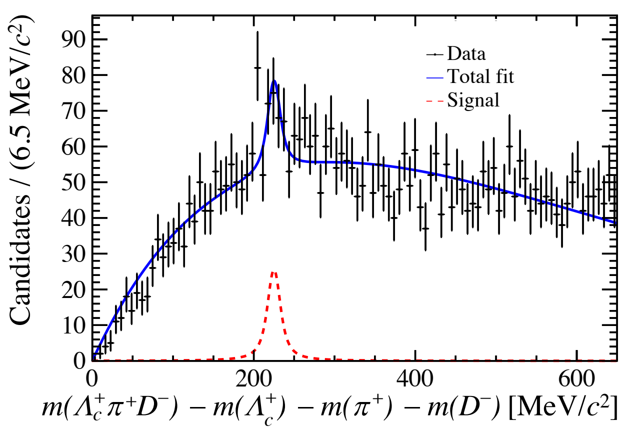
✓hidden-charm pentaquarks

Hadron 1	Hadron 2	Charge	I_3	Y	C	Limit Set
Λ_c^+	$\bar{D}^0$	+1	1/2	1	0	✓
Λ_c^+	D^-	0	−1/2	1	0	✓
Λ_c^+	D^{*-}	0	−1/2	1	0	✓
Σ_c^{++}	$\bar{D}^0$	+2	3/2	1	0	✓
Σ_c^{++}	D^-	+1	1/2	1	0	✓
Σ_c^{++}	D^{*-}	+1	1/2	1	0	×
Σ_c^0	$\bar{D}^0$	0	−1/2	1	0	✓
Σ_c^0	D^-	−1	−3/2	1	0	✓
Σ_c^0	D^{*-}	−1	−3/2	1	0	×
Σ_c^{*++}	$\bar{D}^0$	+2	3/2	1	0	✓
Σ_c^{*++}	D^-	+1	1/2	1	0	✓
Σ_c^{*++}	D^{*-}	+1	1/2	1	0	✓
Σ_c^{*0}	$\bar{D}^0$	0	−1/2	1	0	✓
Σ_c^{*0}	D^-	−1	−3/2	1	0	✓
Σ_c^{*0}	D^{*-}	−1	−3/2	1	0	✓

✓doubly-charmed pentaquarks & excited Ξ_{cc}

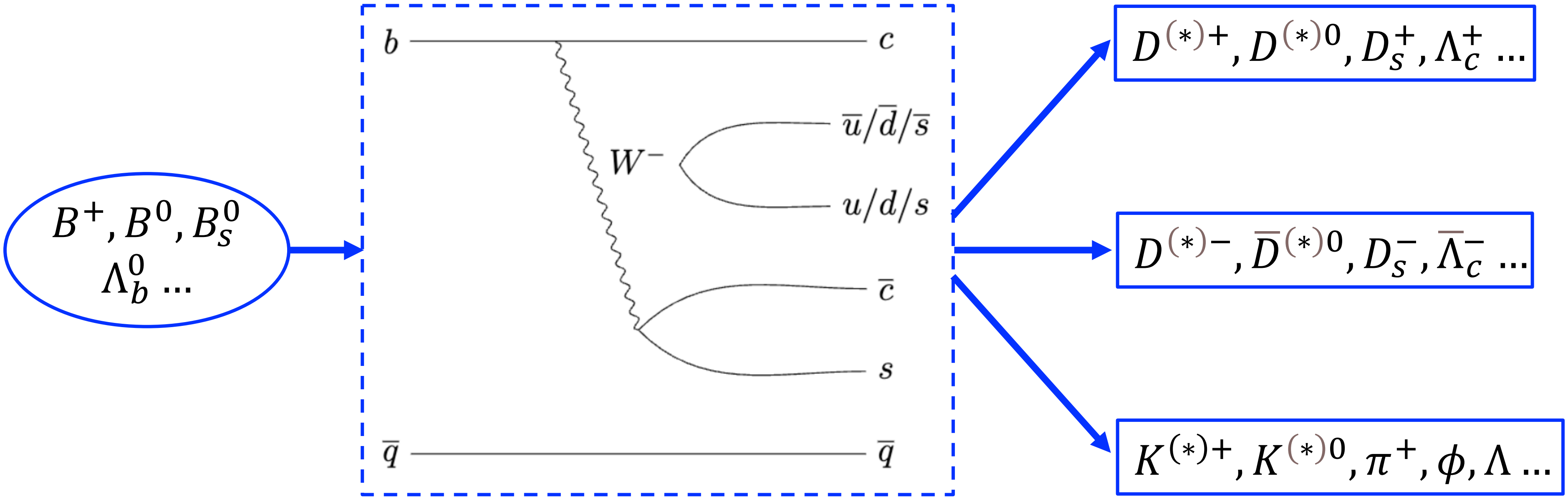
Hadron 1	Hadron 2	Charge	I_3	Y	C	Limit Set
Λ_c^+	D^0	+1	−1/2	3	2	✓
Λ_c^+	D^+	+2	1/2	3	2	✓
Λ_c^+	D^{*+}	+2	1/2	3	2	✓
Σ_c^{++}	D^0	+2	1/2	3	2	×
Σ_c^{++}	D^+	+3	3/2	3	2	×
Σ_c^{++}	D^{*+}	+3	3/2	3	2	×
Σ_c^0	D^0	0	−3/2	3	2	×
Σ_c^0	D^+	+1	−1/2	3	2	×
Σ_c^0	D^{*+}	+1	−1/2	3	2	×
Σ_c^{*++}	D^0	+2	1/2	3	2	✓
Σ_c^{*++}	D^+	+3	3/2	3	2	✓
Σ_c^{*++}	D^{*+}	+3	3/2	3	2	×
Σ_c^{*0}	D^0	0	−3/2	3	2	✓
Σ_c^{*0}	D^+	+1	−1/2	3	2	✓
Σ_c^{*0}	D^{*+}	+1	−1/2	3	2	×

- No significant signals
- Known P_c^+ states tested and yields all agree with 0



*Largest deviation from bkg. shown in $\Lambda_c^+\pi^+D^-(c\bar{c}uud)$ @ $M\sim4520.69$ MeV

$B \to D\overline{D}h$ studies



- Rich opportunities for heavy spectroscopy study
  - ✓ **charmonium(-like)** states in $D^{(*)}\overline{D}^{(*)}, \Lambda_c^+\overline{D}^{(*)}, \Lambda_c^+\overline{\Lambda}_c^-$ ...
  - ✓ **excited $D^+, D^0, D_s^+, \Lambda_c^+$** states from $D^{(*)}h, \Lambda_c^+ h$ ...
  - ✓ **exotic** states from $D^{(*)}h, \Lambda_c^+ h$ ...
- Useful for studies of semi-leptonic decays for search of New Physics

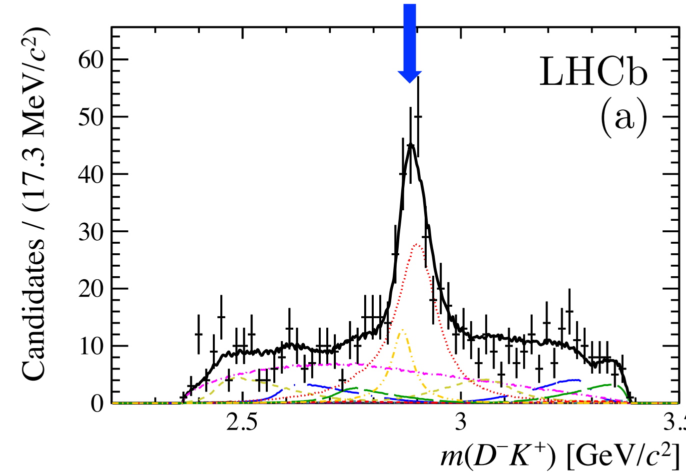
Exotic hadrons in $B \to D\bar{D}h$ at LHCb

$B^+ \to D^+ D^- K^+$

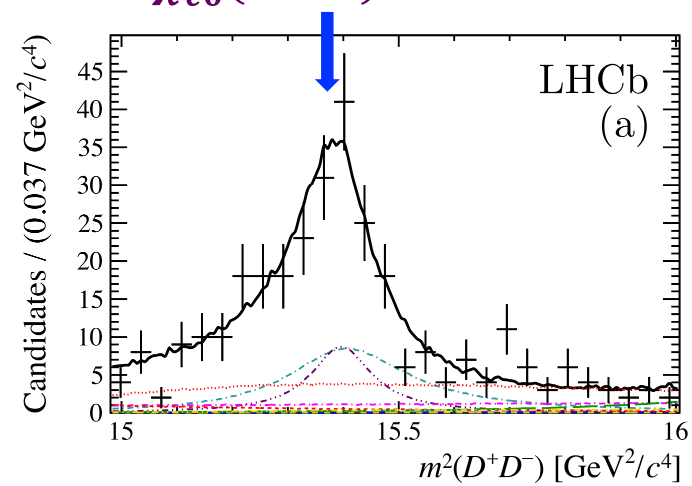
$T^*_{cs0/1}, \chi_{c0}(3930)$

$T^*_{\bar{c}\bar{s}0}(2870)^0 \to D^- K^+$

$T^*_{\bar{c}\bar{s}1}(2900)^0 \to D^- K^+$



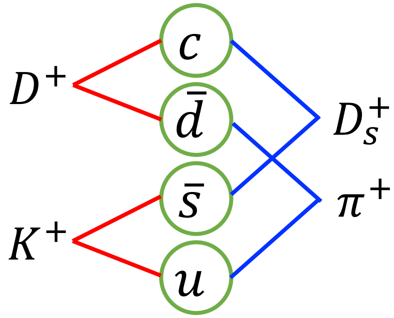
$\chi_{c0}(3930) \to D^+ D^-$



- First discovery of open-charm tetraquarks with four different flavors $[cs\bar{u}\bar{d}]$!

[PRL 125 (2020) 242001]
[PR D102 (2020) 112003]

Exotic hadrons in $B \to D\bar{D}h$ at LHCb



$B^+ \to D^+ D^- K^+$

$T^*_{cs0/1}, \chi_{c0}(3930)$

$B^+ \to D^- D_s^+ \pi^+$

$T^a_{c\bar{s}0}(2900)^{++}$

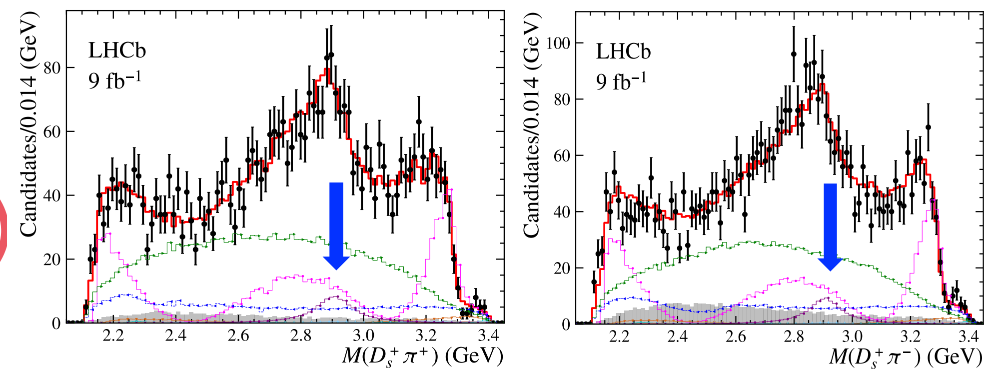
&

$B^0 \to \bar{D}^0 D_s^+ \pi^-$

$T^a_{c\bar{s}0}(2900)^0$

isospin symmetry

$T^a_{c\bar{s}0}(2900)^{++} \to D_s^+\pi^+$ **$T^a_{c\bar{s}0}(2900)^0 \to D_s^+\pi^-$**



[PRL 131 (2023) 041902]

Exotic hadrons in $B \to D\bar{D}h$ at LHCb

[PRL 131 (2023) 071901]

$B^+ \to D_s^+ D_s^- K^+$

$X(3960)$

$B^+ \to D^+ D^- K^+$

$T^*_{cs0/1}, \chi_{c0}(3930)$

$B^+ \to D^- D_s^+ \pi^+$

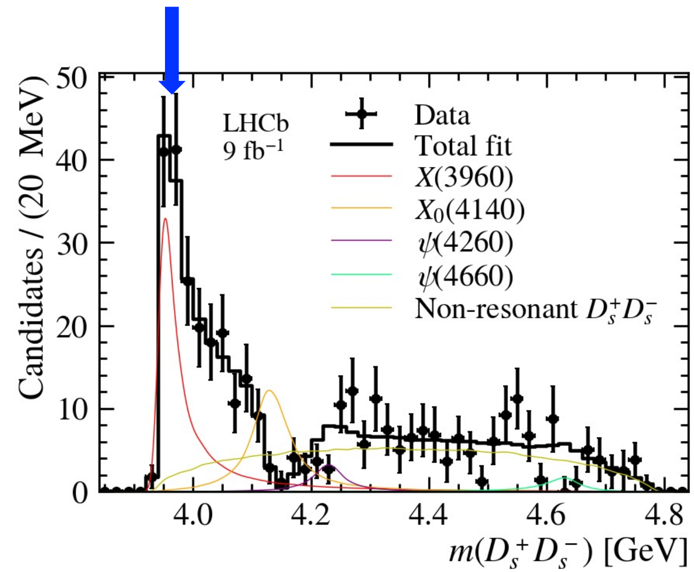
$T^a_{c\bar{s}0}(2900)^{++}$

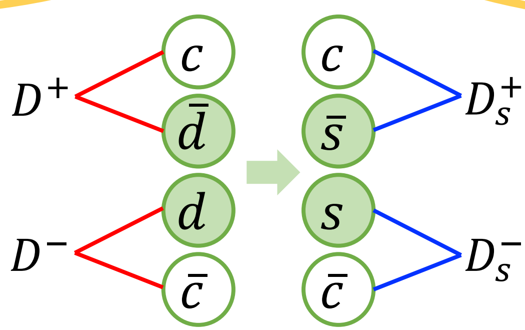
&

$B^0 \to \bar{D}^0 D_s^+ \pi^-$

$T^a_{c\bar{s}0}(2900)^0$

$X(3960) \to D_s^+ D_s^-$





Exotic hadrons in $B \to D\bar{D}h$ at LHCb

$B^+ \to D_s^+ D_s^- K^+$

$X(3960)$

$B^+ \to D^+ D^- K^+$

$T^*_{cs0/1}, \chi_{c0}(3930)$

$B^+ \to D^- D_s^+ \pi^+$

$T^a_{c\bar{s}0}(2900)^{++}$

&

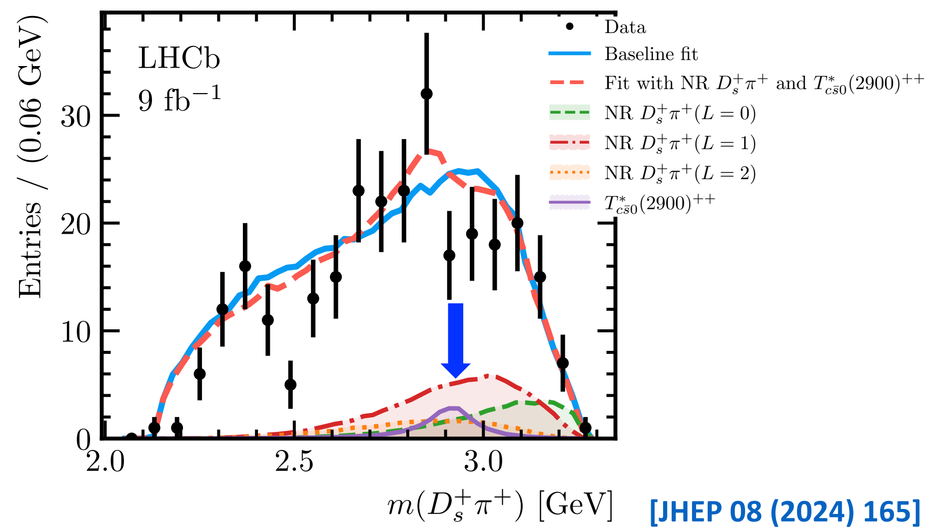
$B^0 \to \bar{D}^0 D_s^+ \pi^-$

$T^a_{c\bar{s}0}(2900)^0$

$B^+ \to D^{*-} D_s^+ \pi^+$

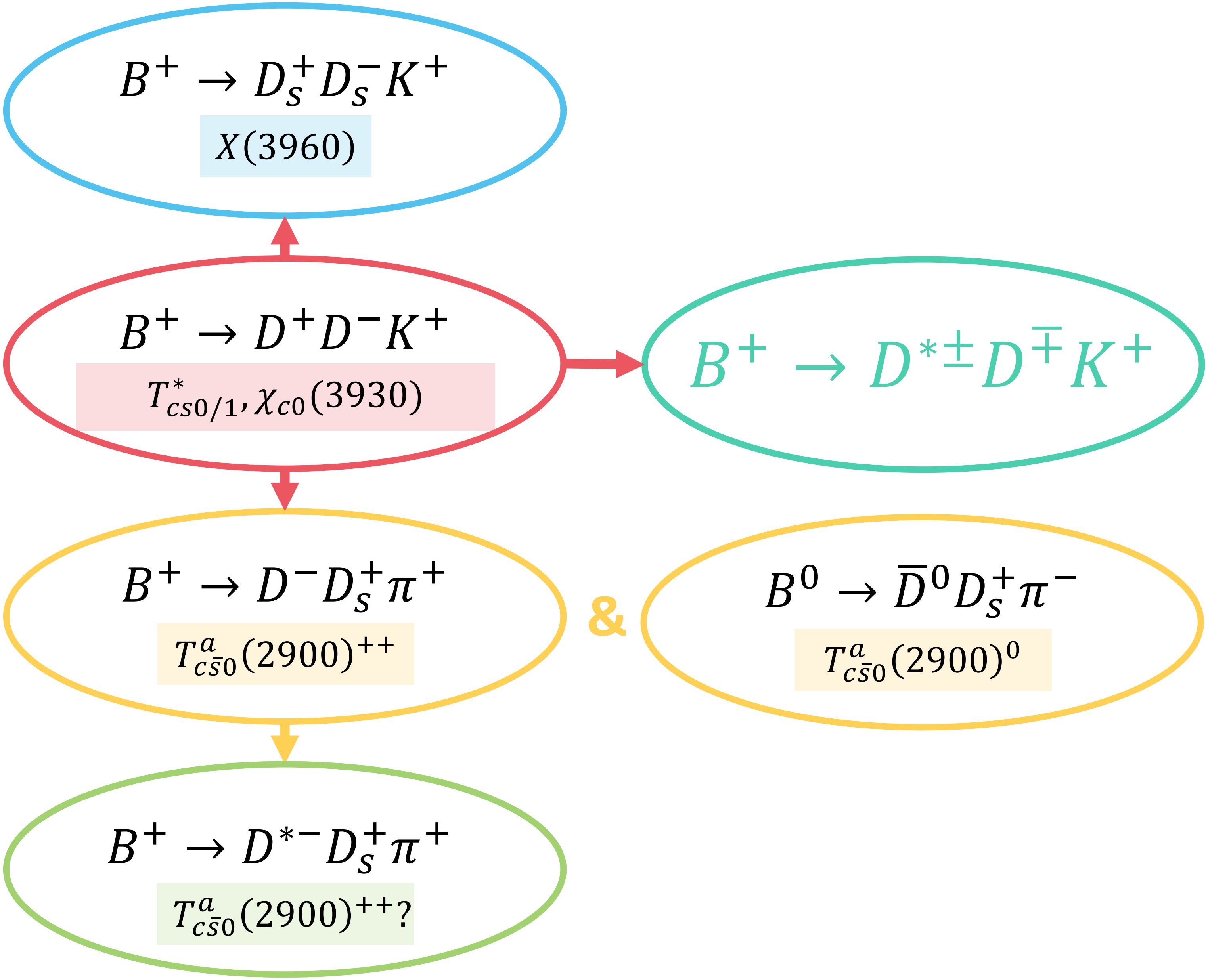
$T^a_{c\bar{s}0}(2900)^{++}?$

$T^a_{c\bar{s}0}(2900)^{++} \to D_s^+ \pi^+$ (below 3σ)



[JHEP 08 (2024) 165]

Exotic hadrons in $B \to D\bar{D}h$ at LHCb

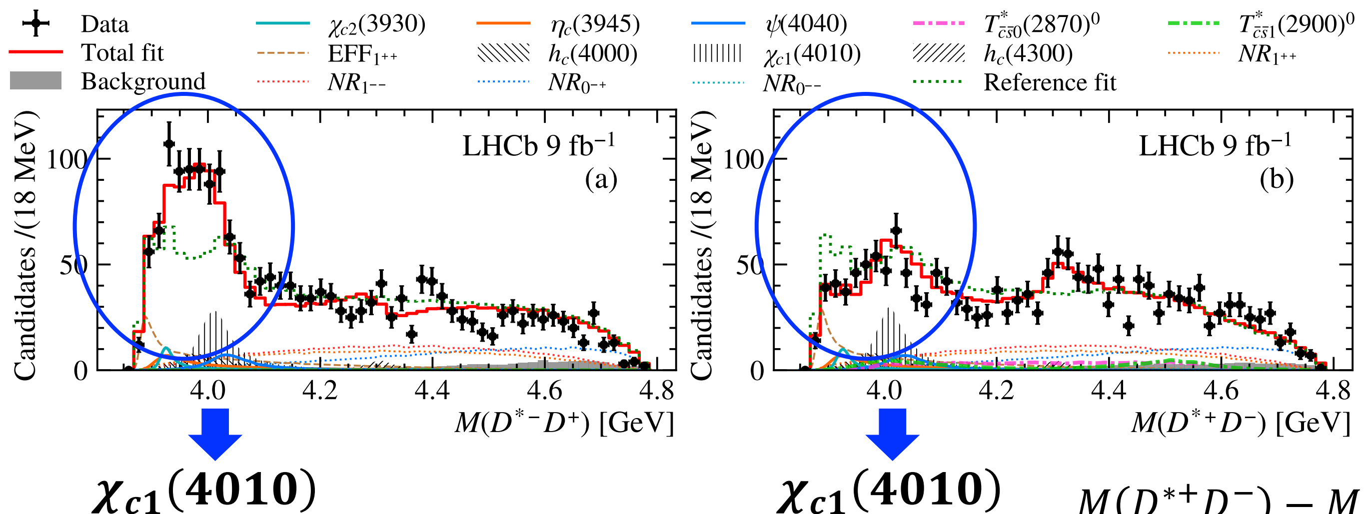


$B^+ \to D^{*\pm} D^{\mp} K^+$: $D^{*\pm} D^{\mp}$ system

[arXiv: 2406.03156]

$B^+ \to R(D^{*+}D^-)K^+$ vs $B^+ \to R(D^{*-}D^+)K^+$

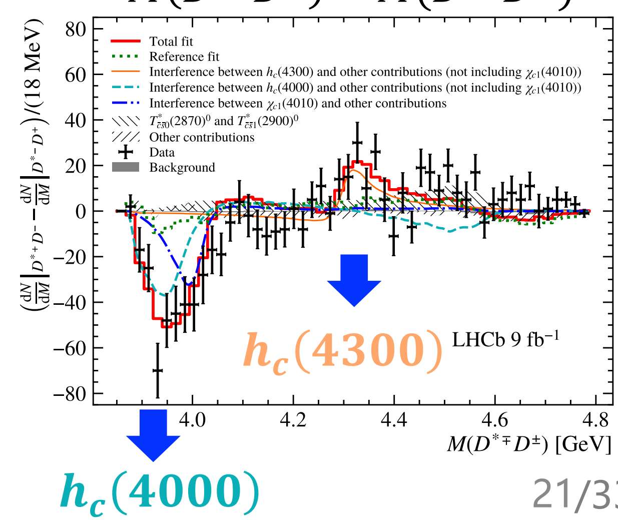
- Same contribution from charmonium(-like) resonances R
- But interference pattern can be largely different due to different ***C*-parity**



✓Three new charmonium(-like) states observed

- ◆ $h_c(4000), J^{PC} = 1^{+-}$
- ◆ $\chi_{c1}(4010), J^{PC} = 1^{++}$
- ◆ $h_c(4300), J^{PC} = 1^{+-}$

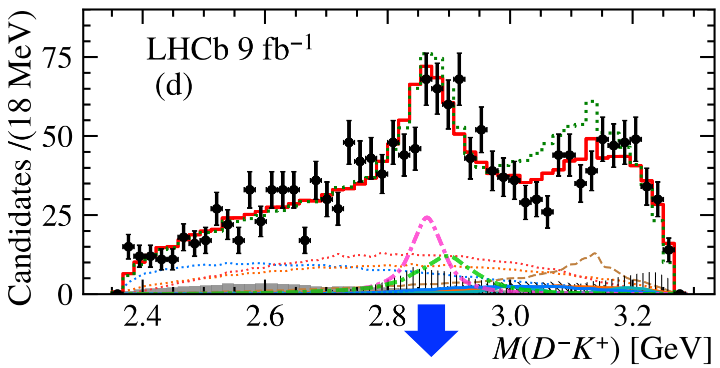
$M(D^{*+}D^-) - M(D^{*-}D^+)$



$B^+ \to D^{*\pm} D^{\mp} K^+$: $T^*_{\bar{c}\bar{s}}$ states

[arXiv: 2406.03156]

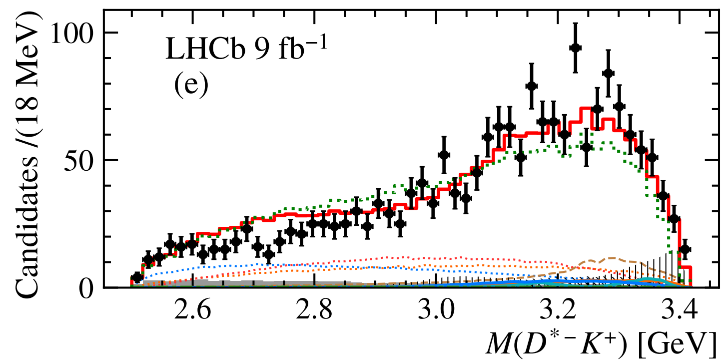
- $B^+ \to D^{*+} D^- K^+$



$T^*_{\bar{c}\bar{s}0}(2870)^0 \to D^- K^+$

$T^*_{\bar{c}\bar{s}0}(2900)^0 \to D^- K^+$

- $B^+ \to D^{*-} D^+ K^+$



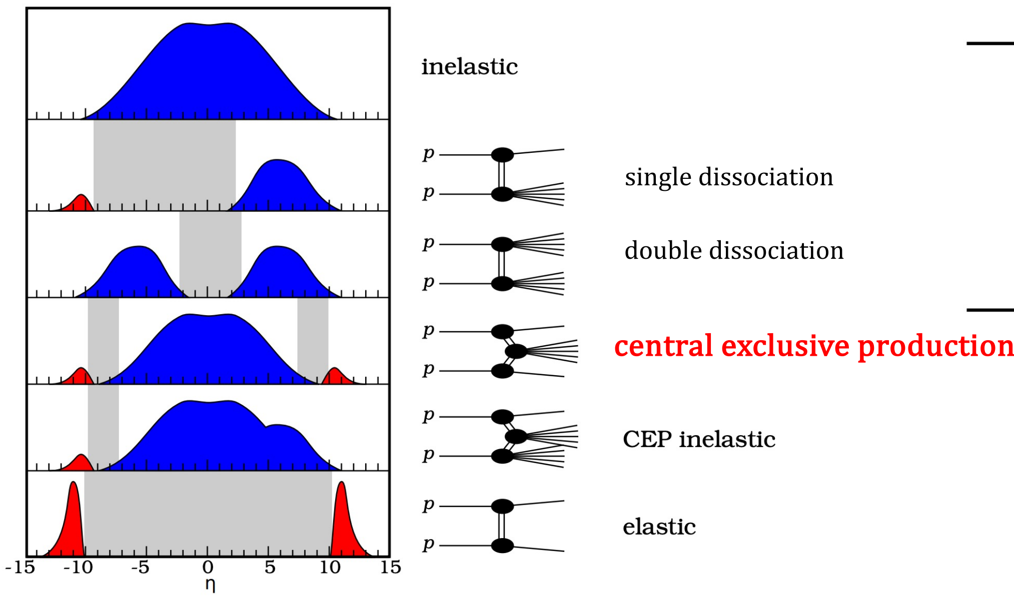
✓ $T^*_{\bar{c}\bar{s}0}(2870)^0 \to D^{*-} K^+$ forbidden

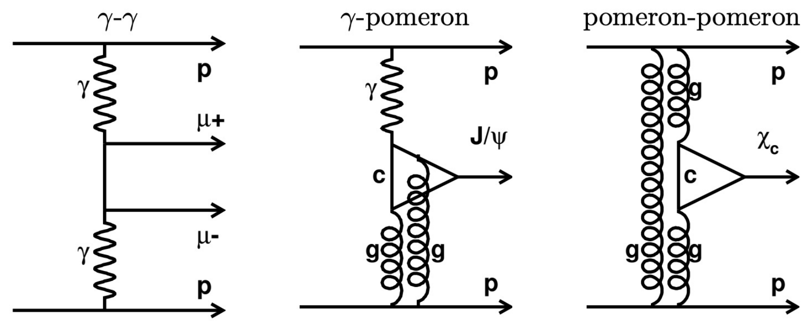
✓ $T^*_{\bar{c}\bar{s}1}(2900)^0 \to D^{*-} K^+$ not seen

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

2σ

$X \to J/\psi\phi$ in diffractive processes





✓Experimentally clean even @LHC
✓Spin-parity option narrowed down
✘ Much smaller rate

✓Rich $X \to J/\psi\phi$ resonances in $B^+ \to J/\psi\phi K^+$, with several reachable in CEP

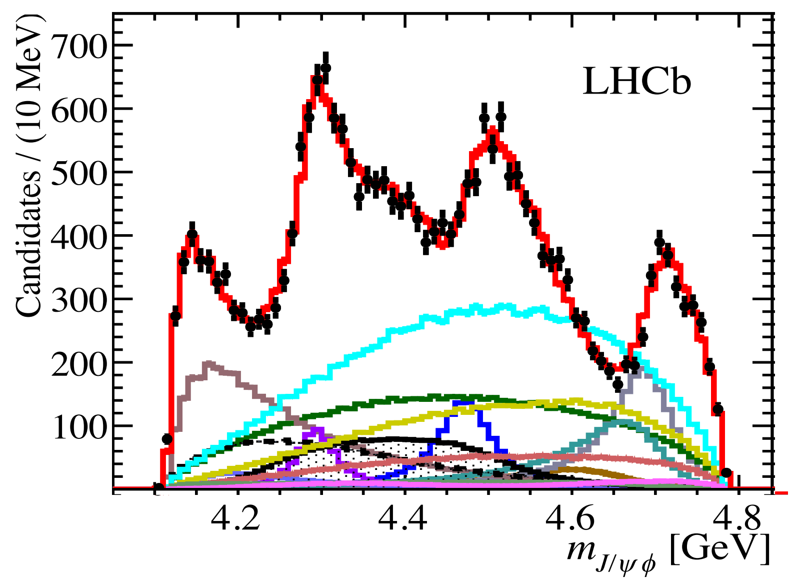
- $\chi_{c0}(4500)$
- $\chi_{c0}(4700)$

$J^P = 0^+$

- $\chi_{c1}(4140)$
- $\chi_{c1}(4274)$
- $\chi_{c1}(4685)$

$J^P = 1^+$

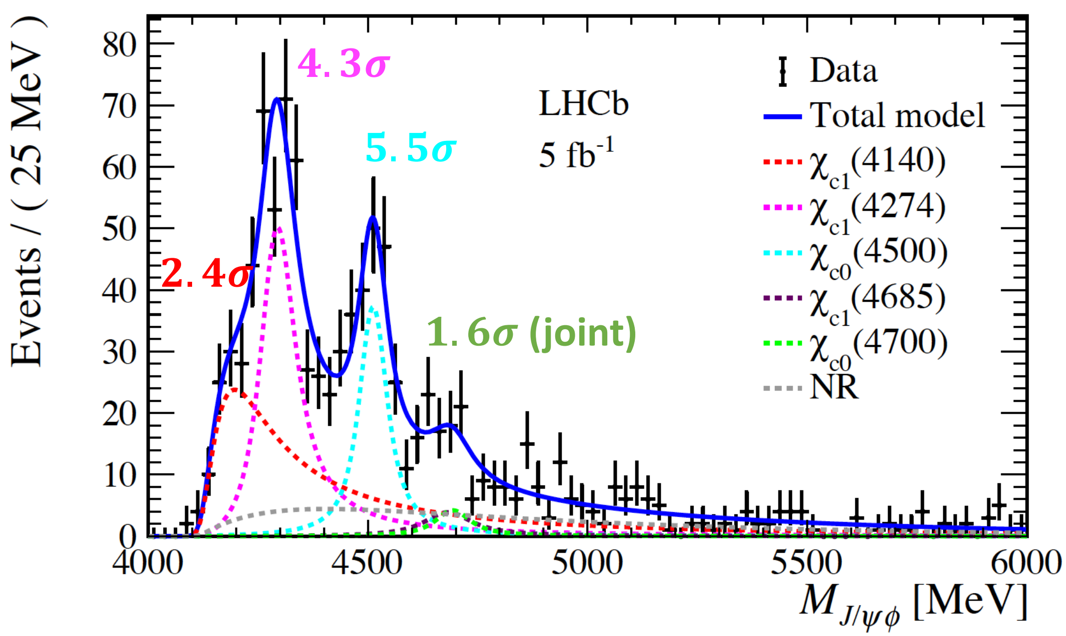
[PRL 127 (2021) 082001]



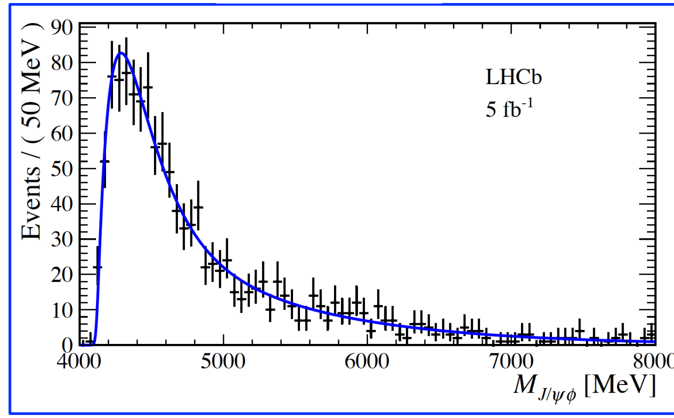
$X \to J/\psi\phi$ results

= 4 tracks

[arXiv: 2407.14301]



> 4 tracks



✓Mass & width measurement:
slightly higher mass of $\chi_{c0}(4500)$

Parameter (MeV)	This Letter	Ref. [12]
$M_{\chi_{c1}(4274)}$	$4298 \pm 6 \pm 9$	$4294 \pm 4^{+3}_{-6}$
$\Gamma_{\chi_{c1}(4274)}$	$92^{+22}_{-18} \pm 57$	$53 \pm 5 \pm 5$
$M_{\chi_{c0}(4500)}$	$4512.5^{+6.0}_{-6.2} \pm 3.0$	$4474 \pm 3 \pm 3$
$\Gamma_{\chi_{c0}(4500)}$	$65^{+20}_{-16} \pm 32$	$77 \pm 6^{+10}_{-8}$

✓Cross-section measurement:

$$\sigma_{\chi_{c1}(4140)} \times \mathcal{B}_{\rm eff}^{\chi_{c1}(4140)} = (0.85 \pm 0.16 \pm 0.30)\,\text{pb},$$
$$\sigma_{\chi_{c1}(4274)} \times \mathcal{B}_{\rm eff}^{\chi_{c1}(4274)} = (0.77^{+0.14}_{-0.13} \pm 0.18)\,\text{pb},$$
$$\sigma_{\chi_{c0}(4500)} \times \mathcal{B}_{\rm eff}^{\chi_{c0}(4500)} = (0.44^{+0.09}_{-0.08} \pm 0.07)\,\text{pb},$$
$$\sigma_{\chi_{c1}(4685)+\chi_{c0}(4700)} \times \mathcal{B}_{\rm eff}^{\chi_{c1}(4685)+\chi_{c0}(4700)} = (0.14^{+0.07}_{-0.06} \pm 0.06)\,\text{pb},$$
$$\sigma_{NR} \times \mathcal{B}_{\rm eff}^{NR} = (0.46^{+0.25}_{-0.19}\,{}^{+0.21}_{-0.22})\,\text{pb},$$

➢First exotic hadron measurement in diffractive processes!

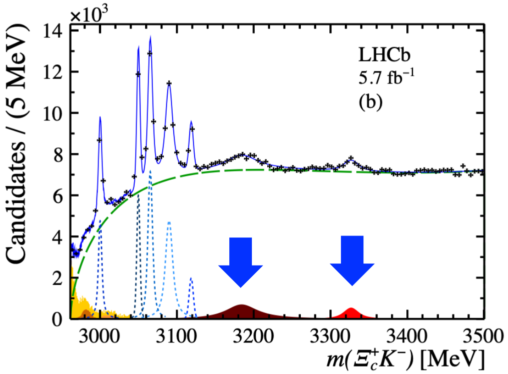
Conventional hadron spectroscopy

- Conventional hadron spectroscopy at LHCb ***by Yuhao Wang*** [link]
- Beauty baryon decays at LHCb ***by Shuqi Sheng*** [link]

Selected new results

New states

✓ Observation of new $\Omega_c^0 \to \Xi_c^+ K^-$



$\boldsymbol{\Omega_c(3185)^0}$

$\boldsymbol{\Omega_c(3327)^0}$

[PRL 131 (2023) 131902]

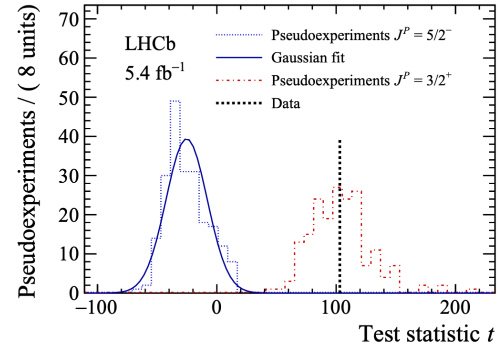
Spin-parity

✓ First J^{PC} determination of $\Xi_c(3055)^{+,0}$

$\Xi_b^{0(-)} \to \Xi_c(3055)^{+(0)}\pi^-$

$\downarrow$

$D^{+(0)}\Lambda$



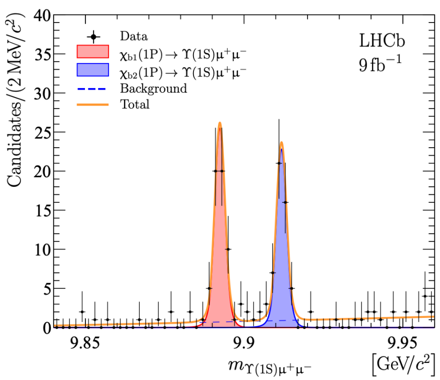
[arXiv: 2409.05440]

$J^P = 3/2^+$

Mass

[arXiv: 2408.05134]

✓ Precise spectroscopy of χ_b states



First observ. of muonic decays

&

Most precise mass results

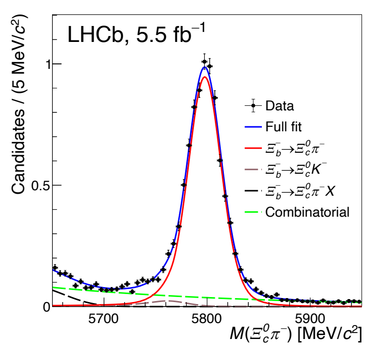
$$m_{\chi_{b1}(1P)} = 9\,892.50 \pm 0.26 \pm 0.10 \pm 0.10\,\text{MeV}/c^2$$
$$m_{\chi_{b2}(1P)} = 9\,911.92 \pm 0.29 \pm 0.11 \pm 0.10\,\text{MeV}/c^2$$

Lifetime/width

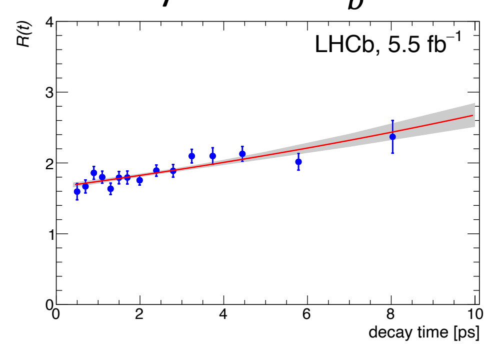
[arXiv: 2406.12111]

✓ Ξ_b^- lifetime measurements

$N = 8303 \pm 107$



yield wrt Λ_b^0

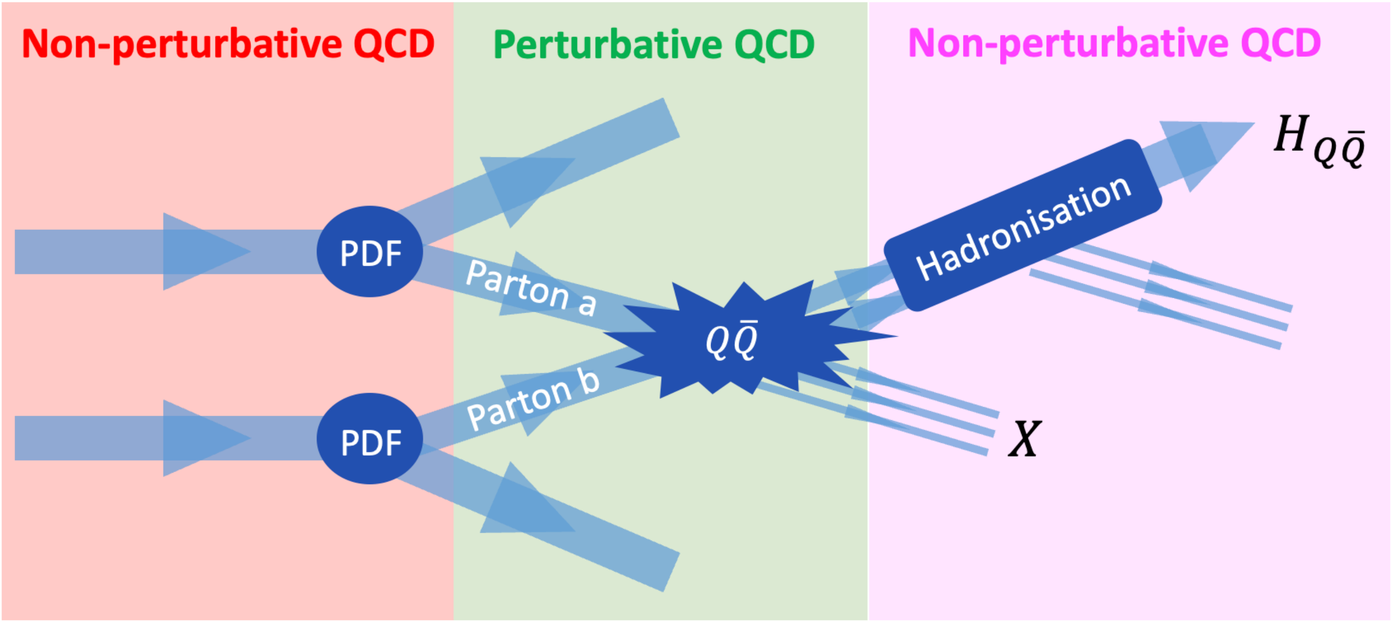


$$\tau_{\Xi_b^-}^{\text{Run 1,2}} = 1.578 \pm 0.018 \pm 0.010 \pm 0.011\ \text{ps}$$

Hadron production

Quarkonium production mechanism

- ***Heavy quarkonium***: ideal system to study hadronization mechanism
- Yet not able to coherently describe prod.&pol. measurements in all collision systems



✓ excellent tool to study gluon PDF

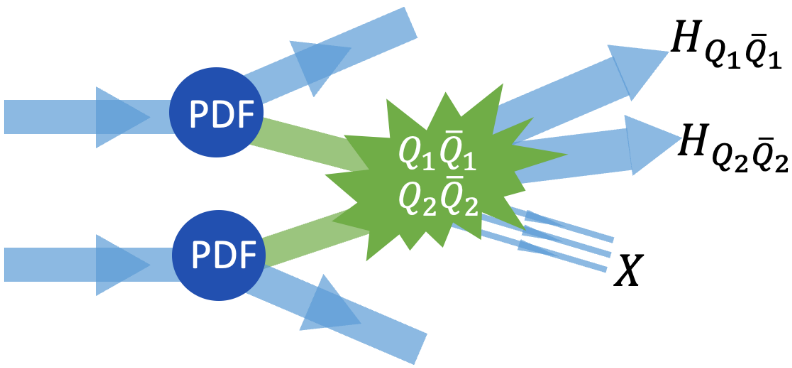
$$\sigma(H_{Q\bar{Q}}) = \sum_{a,b,n} \int \mathrm{d}x_1 \mathrm{d}x_2 \boldsymbol{f}_{\boldsymbol{a/p}}(\boldsymbol{x_1}) \boldsymbol{f}_{\boldsymbol{b/p}}(\boldsymbol{x_2}) |\mathcal{A}(\boldsymbol{ab} \to \boldsymbol{Q\bar{Q}}[\boldsymbol{n}] + \boldsymbol{X})|^2 \times \langle \mathcal{O}^H(\boldsymbol{n}) \rangle$$

✓ LDMEs: extracted from measurements & process independent

$$|J/\psi\rangle = \boldsymbol{O}(\boldsymbol{1}) \left| c\bar{c}\left[\,{}^3S_1^{(1)}\right] \right\rangle + \boldsymbol{O}(\boldsymbol{v}) \left| c\bar{c}\left[\,{}^3P_J^{(8)}\right] + g \right\rangle + \boldsymbol{O}(\boldsymbol{v^{3/2}}) \left| c\bar{c}\left[\,{}^1S_0^{(8)}\right] + g \right\rangle + \cdots$$

Associated quarkonium production

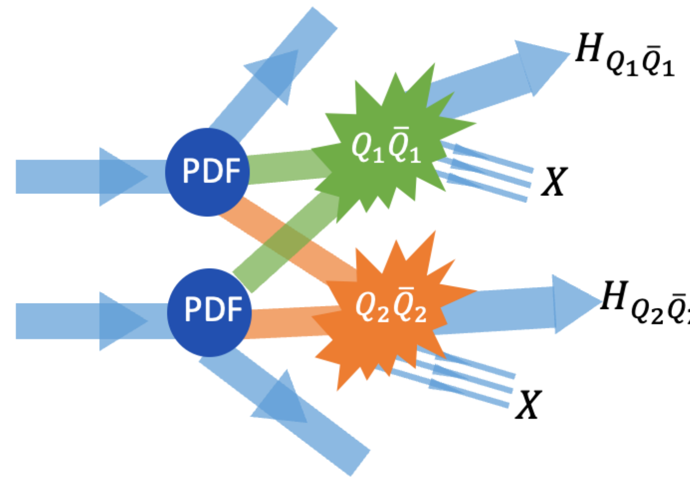
Single-parton scattering (SPS)



- ✓To probe the quarkonium production mechanism puzzle
- ✓Golden channel to probe gluon transverse momentum dependent (TMD) PDFs

gluon / proton	unpolarized	circular	linear
unpolarized	f_1^g		$h_1^{\perp g}$
longitudinal		g_{1L}^g	
transverse	$f_{1T}^{\perp g}$	g_{1T}^g	$h_{1T}^g, h_{1T}^{\perp g}$

Double-parton scattering (DPS)



- ✓To provide information on parton transverse profile & correlations in colliding hadrons

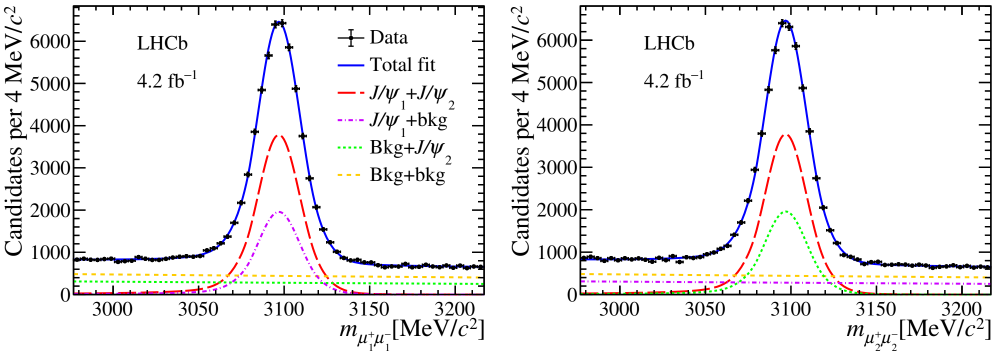
$$\sigma_{Q_1 Q_2}^{\text{DPS}} = \frac{1}{1+\delta_{Q_1 Q_2}} \frac{\sigma_{Q_1}\sigma_{Q_2}}{\boldsymbol{\sigma_{\text{eff}}}}$$

- σ_{eff} is universal under naïve factorisation assumptions

Di-J/ψ @ 13 TeV

[JHEP 03 (2024) 088]

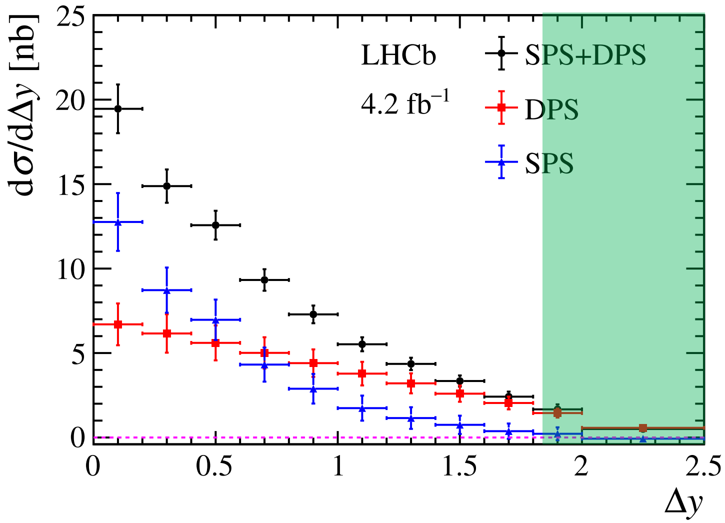
- Fiducial region: $2 < y(J/\psi) < 4.5$, $p_{\mathrm{T}}(J/\psi) < 14$ GeV



$N = (2.187 \pm 0.020)\times 10^4$

$\sigma = 16.36 \pm 0.28(\mathrm{stat}) \pm 0.88(\mathrm{syst})$ nb

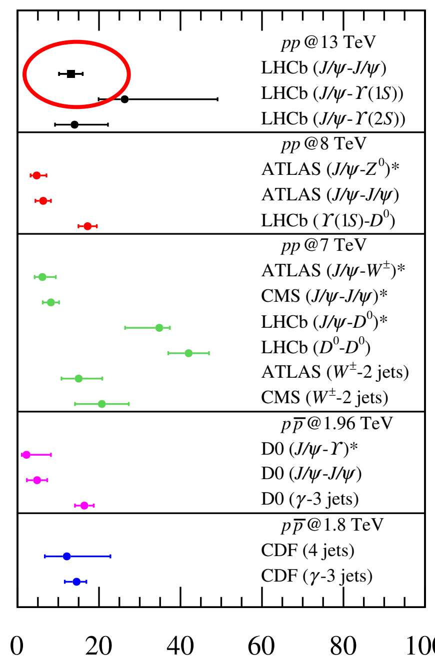
- Data-driven SPS&DPS separation



$\sigma_{\mathrm{DPS}} = 8.6 \pm 1.2(\mathrm{stat}) \pm 1.0(\mathrm{syst})$ nb

$\sigma_{\mathrm{SPS}} = 7.9 \pm 1.2(\mathrm{stat}) \pm 1.1(\mathrm{syst})$ nb

$\sigma_{\mathrm{eff}} = 13.1 \pm 1.8(\mathrm{stat}) \pm 2.3(\mathrm{syst})$ mb



σ_{eff} [mb]

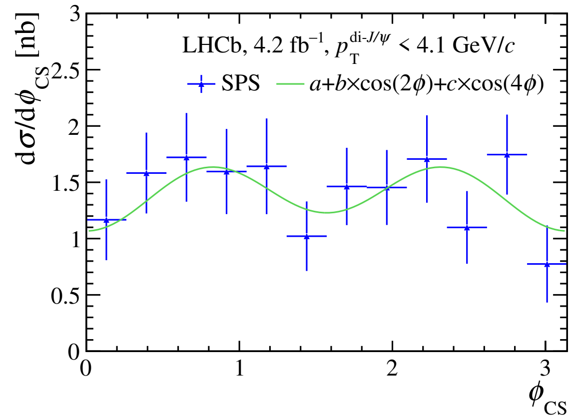
[PoS (LHCP2020) 172; arXiv: 2009.12555]

Gluon TMD PDFs study with di-J/ψ

[JHEP 03 (2024) 088]

- There is almost no experimental info on gluon TMD PDFs
- $h_1^{\perp g}(x, \boldsymbol{k}_\mathrm{T}^2, \mu) \Rightarrow$ azimuthal asymmetry **$\mathrm{d}\sigma/\mathrm{d}\phi_\mathrm{CS} = a + b\times\cos(2\phi_\mathrm{CS}) + c\times\cos(4\phi_\mathrm{CS})$**

$$a = F_1\mathcal{C}[f_1^g f_1^g] + F_2\mathcal{C}[w_2 h_1^{\perp g} h_1^{\perp g}],$$
$$b = F_3\mathcal{C}[w_3 f_1^g h_1^{\perp g}] + F_3'\mathcal{C}[w_3' h_1^{\perp g} f_1^g],$$
$$c = F_4\mathcal{C}[w_4 h_1^{\perp g} h_1^{\perp g}],$$

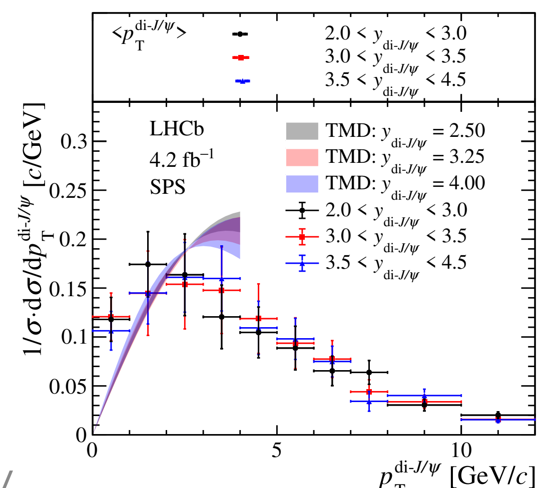


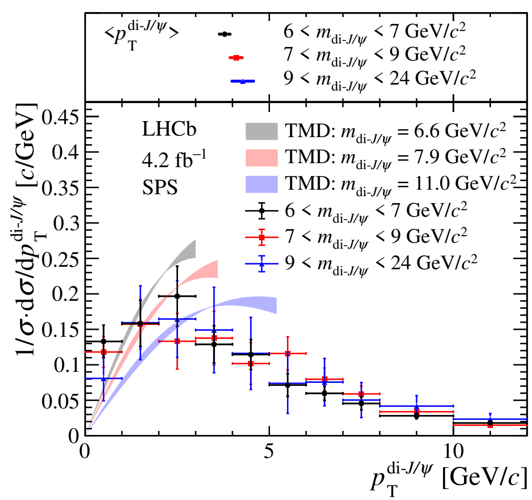
$$\langle\cos(2\phi_\mathrm{CS})\rangle = b/2a = -0.029 \pm 0.050 \pm 0.009$$
$$\langle\cos(4\phi_\mathrm{CS})\rangle = c/2a = -0.087 \pm 0.052 \pm 0.013$$

- $f_1^g(x, \boldsymbol{k}_\mathrm{T}^2, \mu)$: affect p_T spectrum
  - ✓ p_T shape shows no dependence on y

[EPJC 80 (2020) 87]

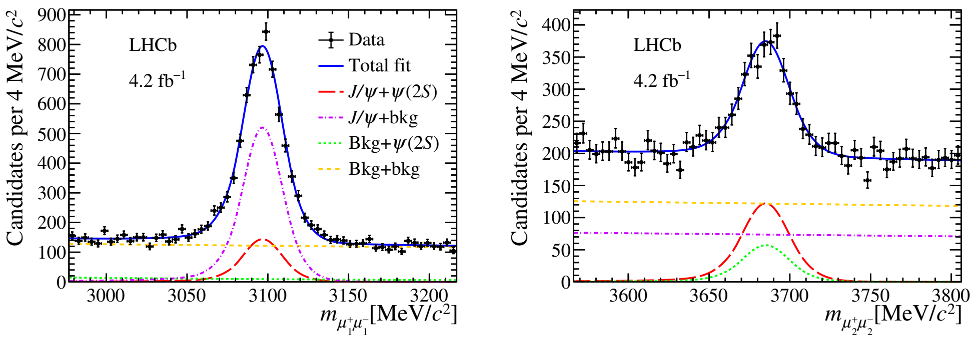
✓ No obvious broadening of p_T spectrum wrt increasing m given large uncertainties





Other new di-quarkonium results

- J/ψ-$\psi(2S)$ @ 13 TeV: $2 < y(\psi) < 4.5$, $p_{\mathrm{T}}(\psi) < 14$ GeV [JHEP 05 (2024) 259]



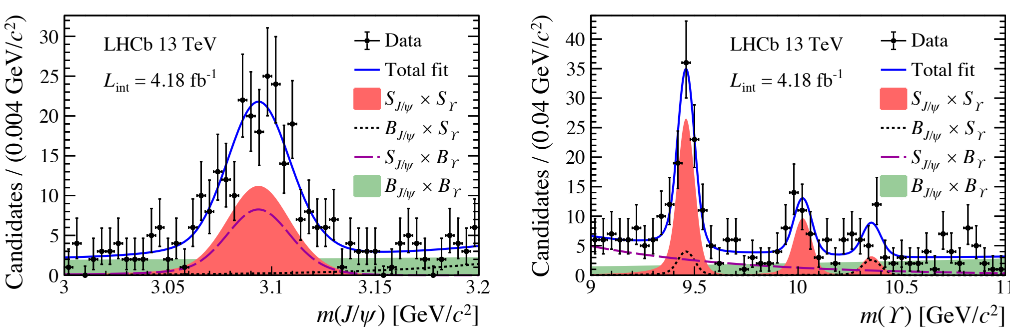
$N = 629 \pm 50$

$\sigma = 4.49 \pm 0.71(\mathrm{stat}) \pm 0.26(\mathrm{syst})$ nb

$$\sigma_{\mathrm{eff}}(\text{lower limit}) = \frac{\sigma(J/\psi)\sigma(\psi(2S))}{\sigma(J/\psi-\psi(2S))} = 7.1 \pm 1.1(\mathrm{stat}) \pm 0.8(\mathrm{syst})\ \mathrm{mb}$$

[JHEP 08 (2023) 093]

- J/ψ-Υ @ 13 TeV: $2 < y(J/\psi, \Upsilon) < 4.5$, $p_{\mathrm{T}}(J/\psi) < 10$ GeV, $p_{\mathrm{T}}(\Upsilon) < 30$ GeV



Signal	Raw yields	Significances
J/ψ–$\Upsilon(1S)$	76 ± 12	$7.9\,\sigma$
J/ψ–$\Upsilon(2S)$	30 ± 7	$4.9\,\sigma$
J/ψ–$\Upsilon(3S)$	10 ± 6	$1.7\,\sigma$

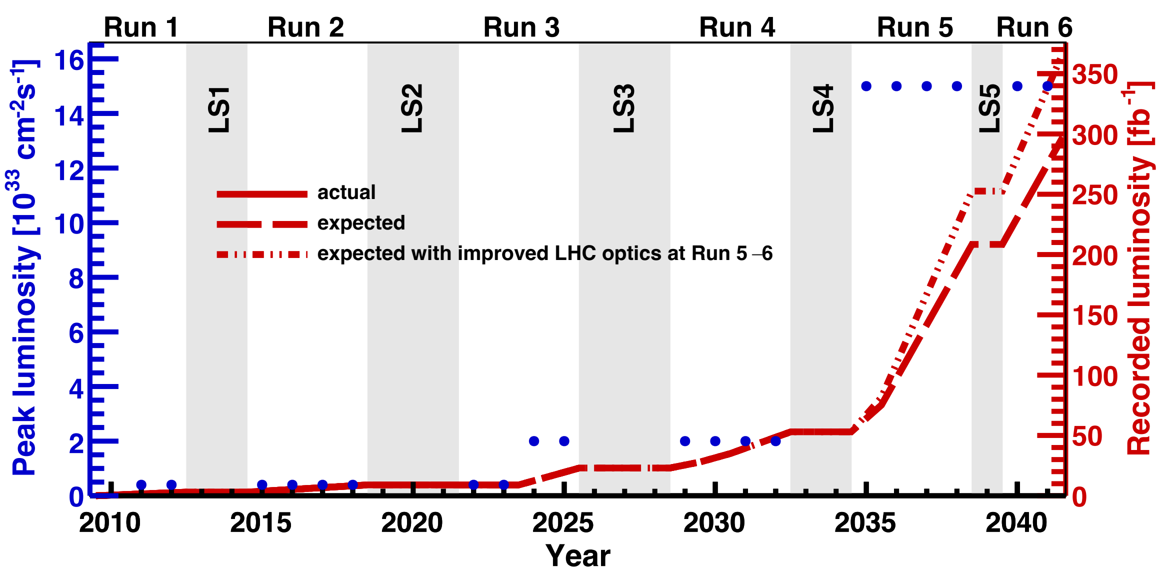
$\sigma(J/\psi - \Upsilon(1S))$
$= 133 \pm 22(\mathrm{stat}) \pm 7(\mathrm{syst}) \pm 3(\mathcal{B})$ pb

✓By subtracting theoretical input of $\sigma_{\mathrm{SPS}}(J/\psi - \Upsilon(1S)) = 20^{+52}_{-15}$ pb [PRL 117 (2016) 062001]

$$\sigma_{\mathrm{eff}}(J/\psi - \Upsilon(1S)) = 26 \pm 5(\mathrm{stat}) \pm 2(\mathrm{syst})\ {}^{+22}_{-3}(\mathrm{th})\ \mathrm{mb}$$

Summary and prospects

- LHCb keeps making important contributions to hadron physics
  - Exotic hadron spectroscopy: pentaquark search; $B \to D\bar{D}h$ studies; first exotic study in diffractive processes…
  - Conventional hadron spectroscopy: new Ω_c^{**0} states; J^P of $\Xi_c(3055)^{+,0}$; χ_b spectroscopy; Ξ_b^- lifetime…
  - Hadron production: di-J/ψ, J/ψ-$\psi(2S)$ and J/ψ-Υ; first study of gluon TMD PDFs with di-J/ψ…
- In Run 3, upgraded sub-detectors & software-only trigger system
  - ✓ trigger efficiency for fully hadronic modes largely improved



- ✓ Run 1-2: 9 fb^{-1}
- ✓ Run 3: $> 20\ \text{fb}^{-1}$
- ✓ Run 4: $\sim 50\ \text{fb}^{-1}$

More data, more chances!

Back up

$B^+ \to D^{*\pm}D^{\mp}K^+$: amplitude analysis [arXiv: 2406.03156]

- Amplitudes of $B^+ \to R(D^{*+}D^-)K^+$ and $B^+ \to R(D^{*-}D^+)K^+$ linked by ***C*-parity**
  $\Rightarrow$ allowing determination of C-parities of R resonances

$$\mathcal{A}(x) = \frac{1+d}{2}\left\{\sum_{j\in R(D^{*\pm}D^{\mp})} \boxed{c_j A_j(x)} + \sum_{k\in R(D^{*-}K^+,\ D^+K^+)} c_k A_k(x)\right\} + \frac{1-d}{2}\left\{\sum_{j\in R(D^{*\pm}D^{\mp})} \boxed{C_j \times c_j A_j(x)} + \sum_{l\in R(D^{*+}K^+,\ D^-K^+)} c_l A_l(x)\right\}$$

✓ $d=1$ for $B^+ \to D^{*-}D^+K^+$; $d=-1$ for $B^+ \to D^{*+}D^-K^+$

- R resonances with $J^P = 1^+$: S-wave & D-wave

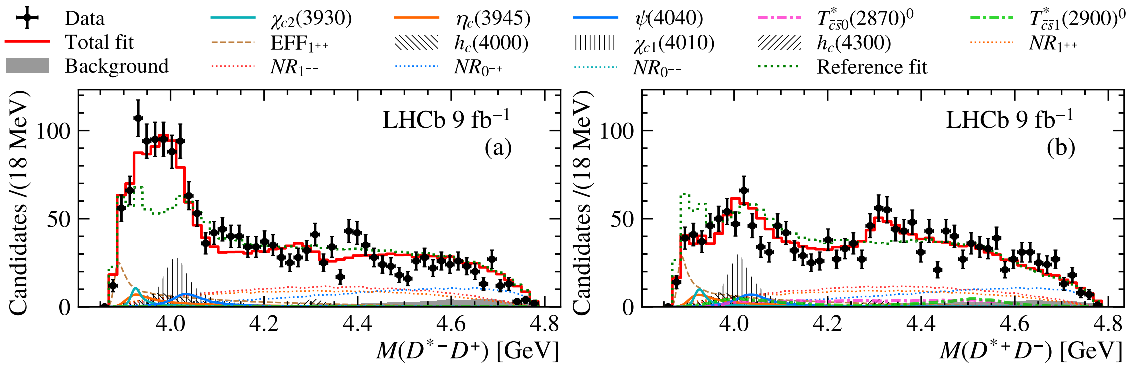
$$f_{R,S/D}(m) = \frac{\gamma_{S/D}}{m_0^2 - m^2 - i m_0[\gamma_S^2\Gamma_S(m) + \gamma_D^2\Gamma_D(m)]}$$

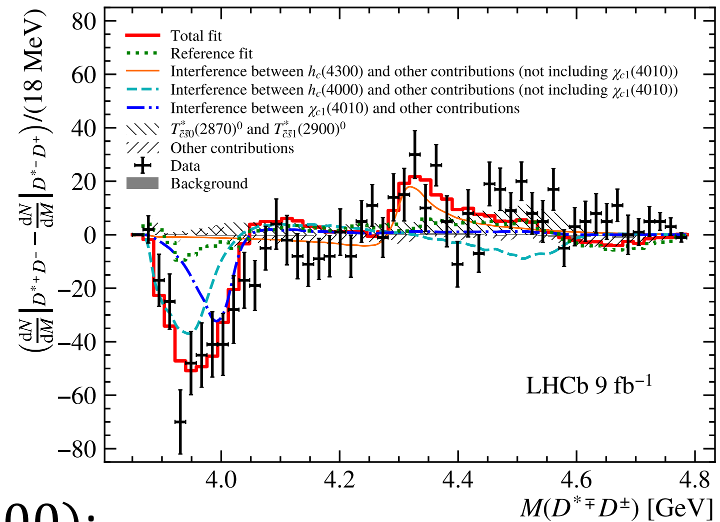
- Other resonances: Breit-Wigner
- Nonresonant contributions to $D^{*\pm}D^{\mp}$:
  $f_R(m) = e^{(\alpha+\beta i)(m^2-m_0^2)}$ for $NR_{0^{-+}}$; otherwise $f_R(m) = 1$

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

[arXiv: 2406.03156]

➢Amplitudes of $B^+ \to R(D^{*+}D^-)K^+$ and $B^+ \to R(D^{*-}D^+)K^+$ linked by ***C*-parity**





✓Reference fit without $h_c(4000), \chi_{c1}(4010), h_c(4300)$: necessary to describe discrepancy between $M(D^{*-}D^+)$ and $M(D^{*+}D^-)$

new: $h_c(4000)$, $\chi_{c1}(4010)$, $h_c(4300)$

This work		Known states [6]		$c\bar{c}$ prediction [34]	
$\eta_c(3945)$	$J^{PC}=0^{-+}$	$X(3940)$ [9, 10]	$J^{PC}=?^{??}$	$\eta_c(3S)$	$J^{PC}=0^{-+}$
$m_0=3945\,^{+28}_{-17}\,^{+37}_{-28}$	$\Gamma_0=130\,^{+92}_{-49}\,^{+101}_{-70}$	$m_0=3942\pm9$	$\Gamma_0=37^{+27}_{-17}$	$m_0=4064$	$\Gamma_0=80$
$h_c(4000)$	$J^{PC}=1^{+-}$	$T_{c\bar{c}}(4020)^0$ [35]	$J^{PC}=?^{?-}$	$h_c(2P)$	$J^{PC}=1^{+-}$
$m_0=4000\,^{+17}_{-14}\,^{+29}_{-22}$	$\Gamma_0=184\,^{+71}_{-45}\,^{+97}_{-61}$	$m_0=4025.5\,^{+2.0}_{-4.7}\pm3.1$	$\Gamma_0=23.0\pm6.0\pm1.0$	$m_0=3956$	$\Gamma_0=87$
$\chi_{c1}(4010)$	$J^{PC}=1^{++}$			$\chi_{c1}(2P)$	$J^{PC}=1^{++}$
$m_0=4012.5\,^{+3.6}_{-3.9}\,^{+4.1}_{-3.7}$	$\Gamma_0=62.7\,^{+7.0}_{-6.4}\,^{+6.4}_{-6.6}$			$m_0=3953$	$\Gamma_0=165$
$h_c(4300)$	$J^{PC}=1^{+-}$			$h_c(3P)$	$J^{PC}=1^{+-}$
$m_0=4307.3\,^{+6.4}_{-6.6}\,^{+3.3}_{-4.1}$	$\Gamma_0=58\,^{+28}_{-16}\,^{+28}_{-25}$			$m_0=4318$	$\Gamma_0=75$
		$\chi_c(4274)$ [36]	$J^{PC}=1^{++}$	$\chi_{c1}(3P)$	$J^{PC}=1^{++}$
		$m_0=4294\pm4\,^{+6}_{-3}$	$\Gamma_0=53\pm5\pm5$	$m_0=4317$	$\Gamma_0=39$

Double Parton Scattering

$$\sigma^{\rm DPS}_{Q_1Q_2} = \frac{1}{1+\delta_{Q_1Q_2}}\sum_{i,j,k,l}\int {\rm d}x_1{\rm d}x_2{\rm d}x_1'{\rm d}x_2'{\rm d}^2\mathbf{b_1}{\rm d}^2\mathbf{b_2}{\rm d}^2\mathbf{b}$$

$$\times\Gamma_{ij}(x_1,x_2,\mathbf{b_1},\mathbf{b_2})\times\hat{\sigma}^{Q_1}_{ik}(x_1,x_1')\hat{\sigma}^{Q_2}_{jl}(x_2,x_2')\times\Gamma_{kl}(x_1',x_2',\mathbf{b_1}-\mathbf{b},\mathbf{b_2}-\mathbf{b})$$

Generalized double parton PDF

SPS parton-level cross-section

Assuming:

✓ factorization of trans. & long. components

$$\Gamma_{ij}(x_1,x_2,\boldsymbol{b}_1,\boldsymbol{b}_2) = D_{ij}(x_1,x_2)T_{ij}(\boldsymbol{b}_1,\boldsymbol{b}_2)$$

✓ no correlation between two sets of partons

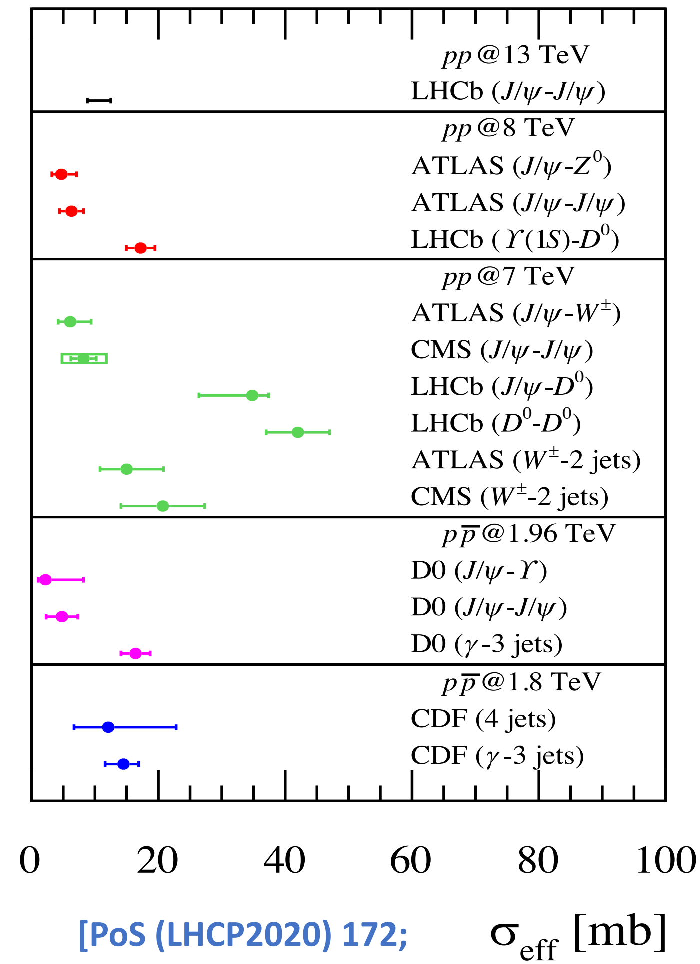
$$D_{ij}(x_1,x_2) = f_i(x_1)f_j(x_2), T_{ij}(\boldsymbol{b}_1,\boldsymbol{b}_2) = T_i(\boldsymbol{b}_1)T_j(\boldsymbol{b}_2)$$

⇒

$$\sigma_{Q_1Q_2} = \frac{1}{1+\delta_{Q_1Q_2}}\frac{\sigma_{Q_1}\sigma_{Q_2}}{\sigma_{\rm eff}}$$

$$\sigma_{\rm eff} = 1/\left[\int d^2\boldsymbol{b}F(\boldsymbol{b})^2\right], F(\boldsymbol{b}) = \int T(\boldsymbol{b}_i)T(\boldsymbol{b}_i-\boldsymbol{b})d^2\boldsymbol{b}_i$$

expected to be universal under the given assumptions



[PoS (LHCP2020) 172; arXiv: 2009.12555]