LHCb spectroscopy status

Mikhail Mikhasenko, LHCb

Ruhr University Bochum

13/11/2024

Experiment

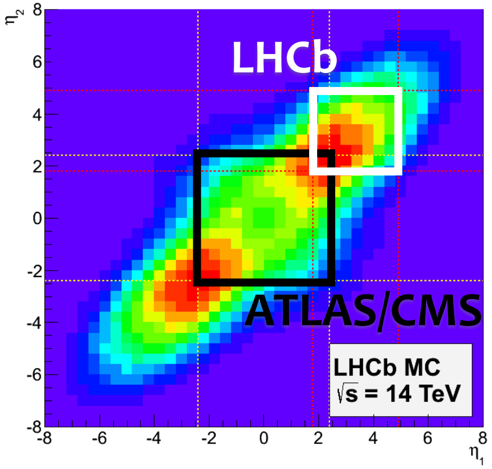
LHCb@CERN: heavy flavor quarks factory

One of four large experiments at LHC

LHCb has the largest production cross-sections of b- and c-hadrons ever

$\sigma(b\bar{b}) \approx 600\mu b$ @ 14TeV
$\sigma(c\bar{c}) \approx 20 \times \sigma(b\bar{b})$ in pp collisions

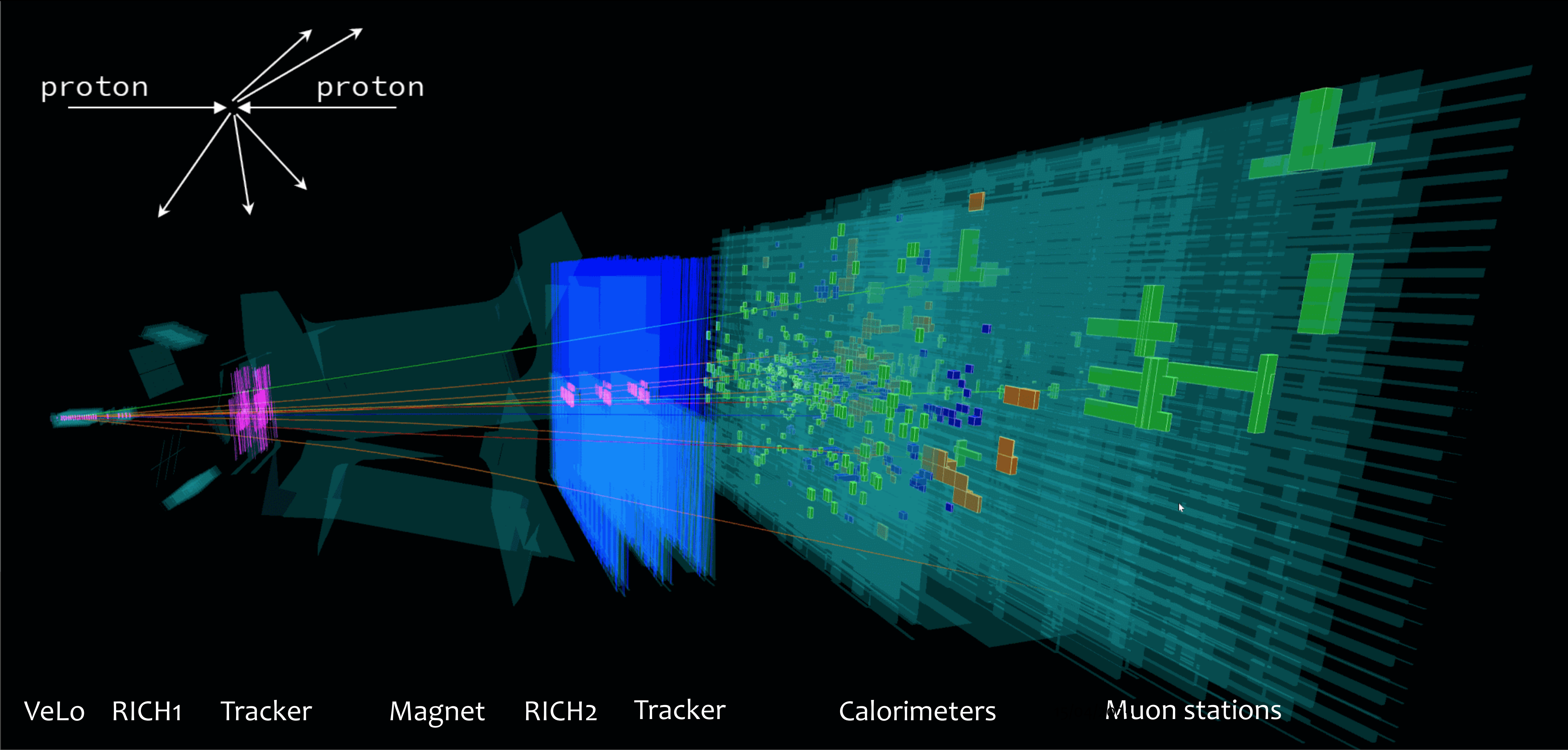
High track multiplicity



b-quark product cross-section

[detector, performance, event display]

The LHCb experiment



[LHCb, JINST **19** (2024) P05065]

Upgraded detector

Software only trigger

New RICH2 optics
new sensors and readout for RiCH

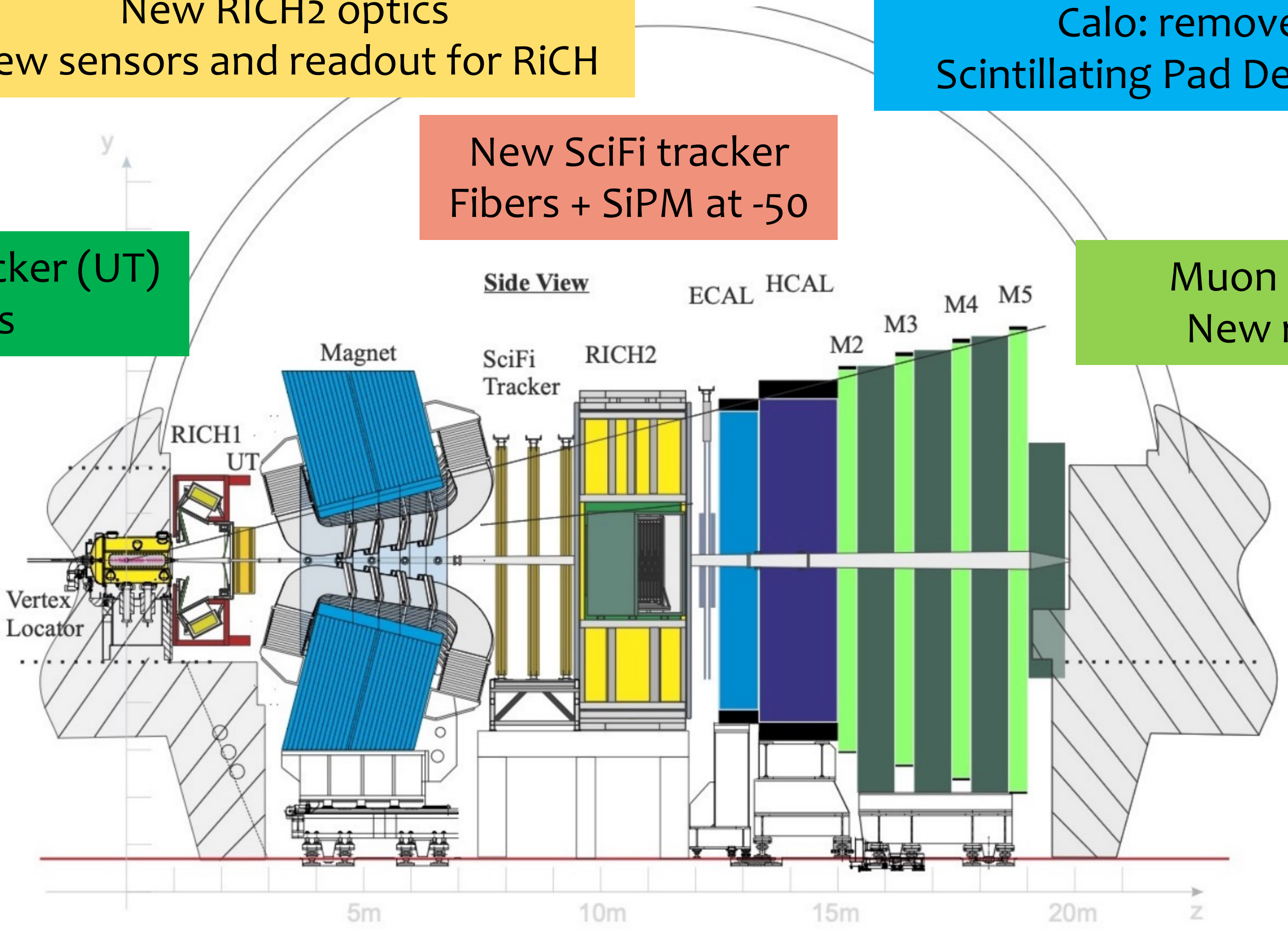
Calo: removed preshawer,
Scintillating Pad Detector, new readout

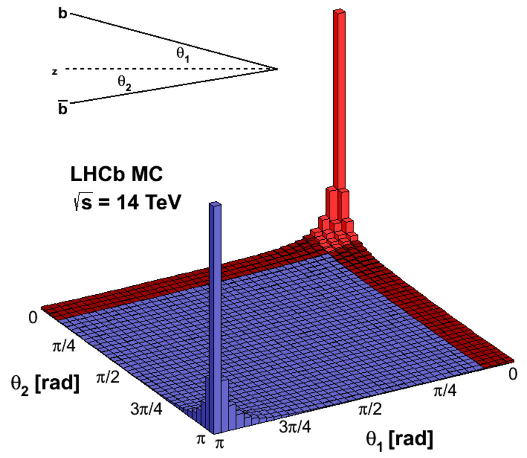
New SciFi tracker
Fibers + SiPM at -50

New Upstream Tracker (UT)
Silicon strips

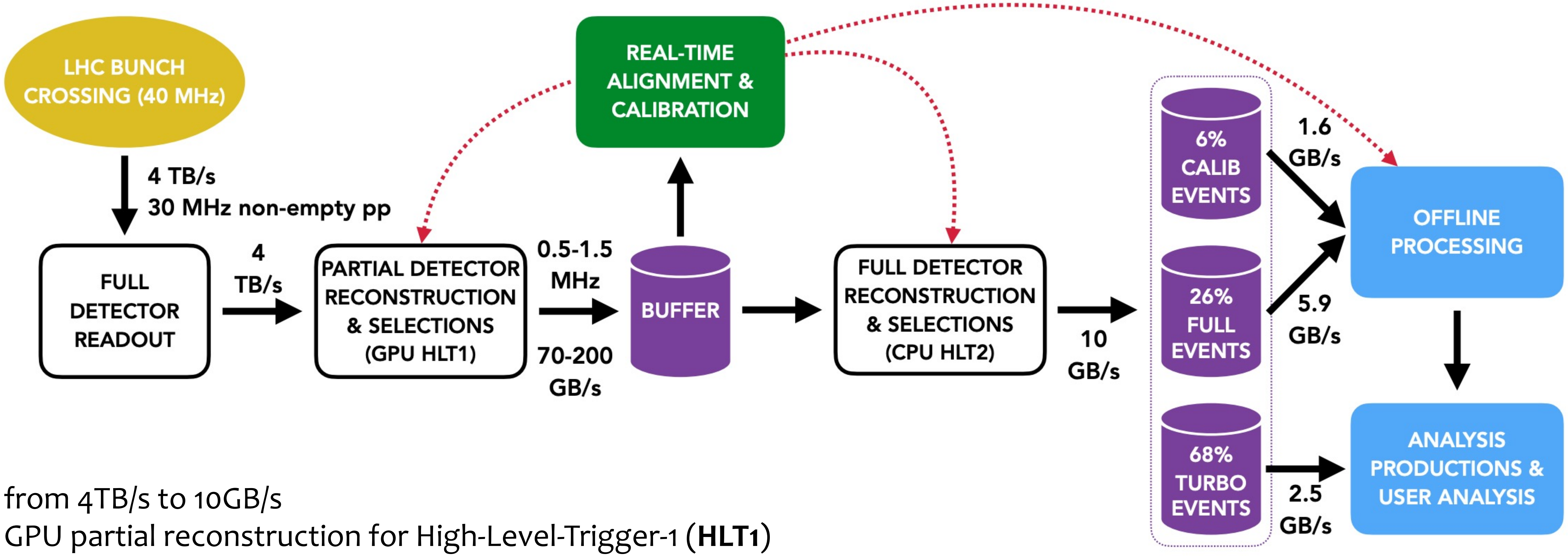
Muon stations:
New readout

New VeLo
Pixel detector





Upgraded Trigger



from 4TB/s to 10GB/s
GPU partial reconstruction for High-Level-Trigger-1 (**HLT1**)
CPU full reconstruction for High-Level-Trigger-2 (**HLT2**)

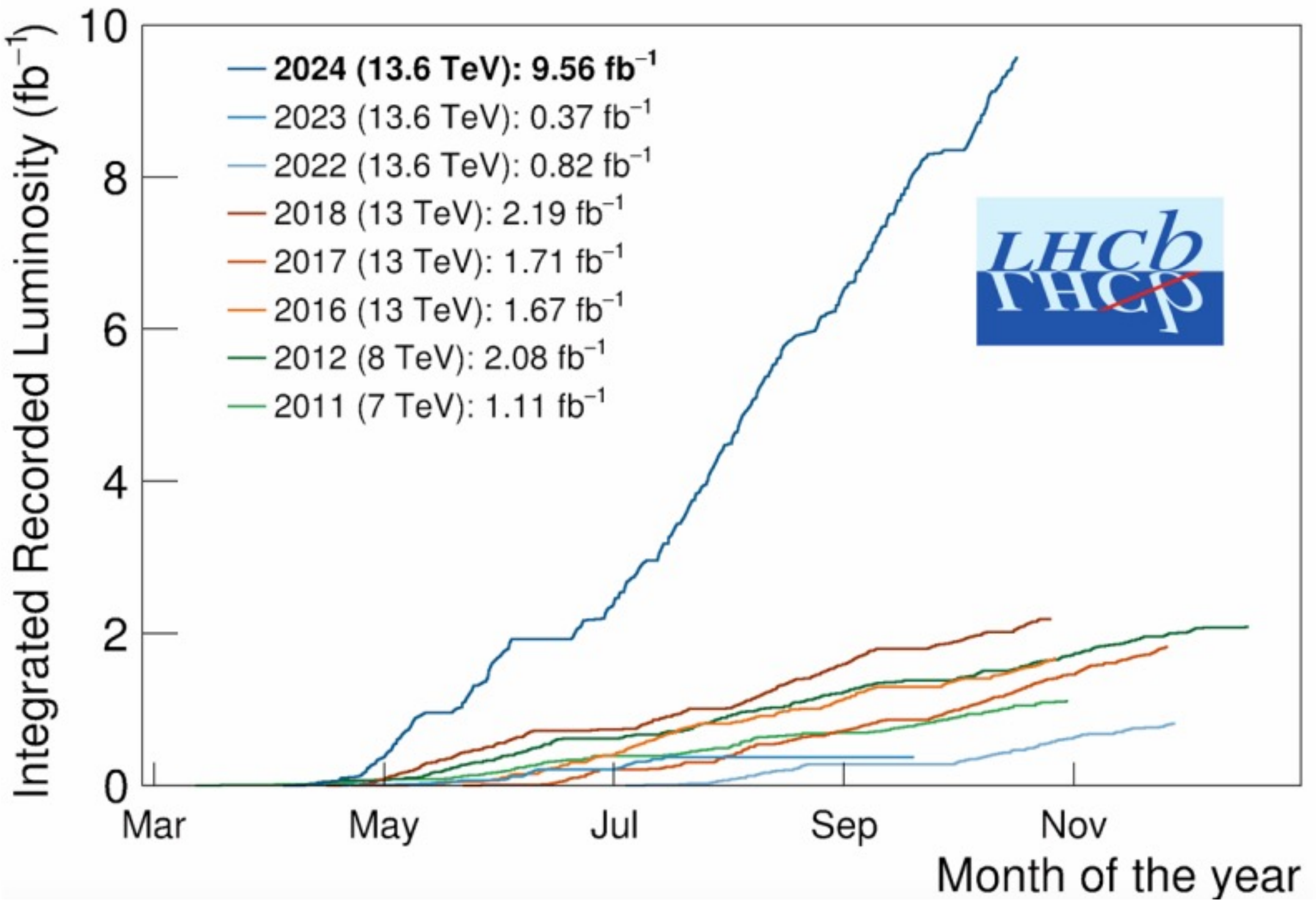
2022-2026 LHCb data taking campaign

Run 1: (2011-2012):
$\mathcal{L}_{\text{int}} = 1\ \text{fb}^{-1}$ @ 7 TeV
$\mathcal{L}_{\text{int}} = 2\ \text{fb}^{-1}$ @ 8 TeV

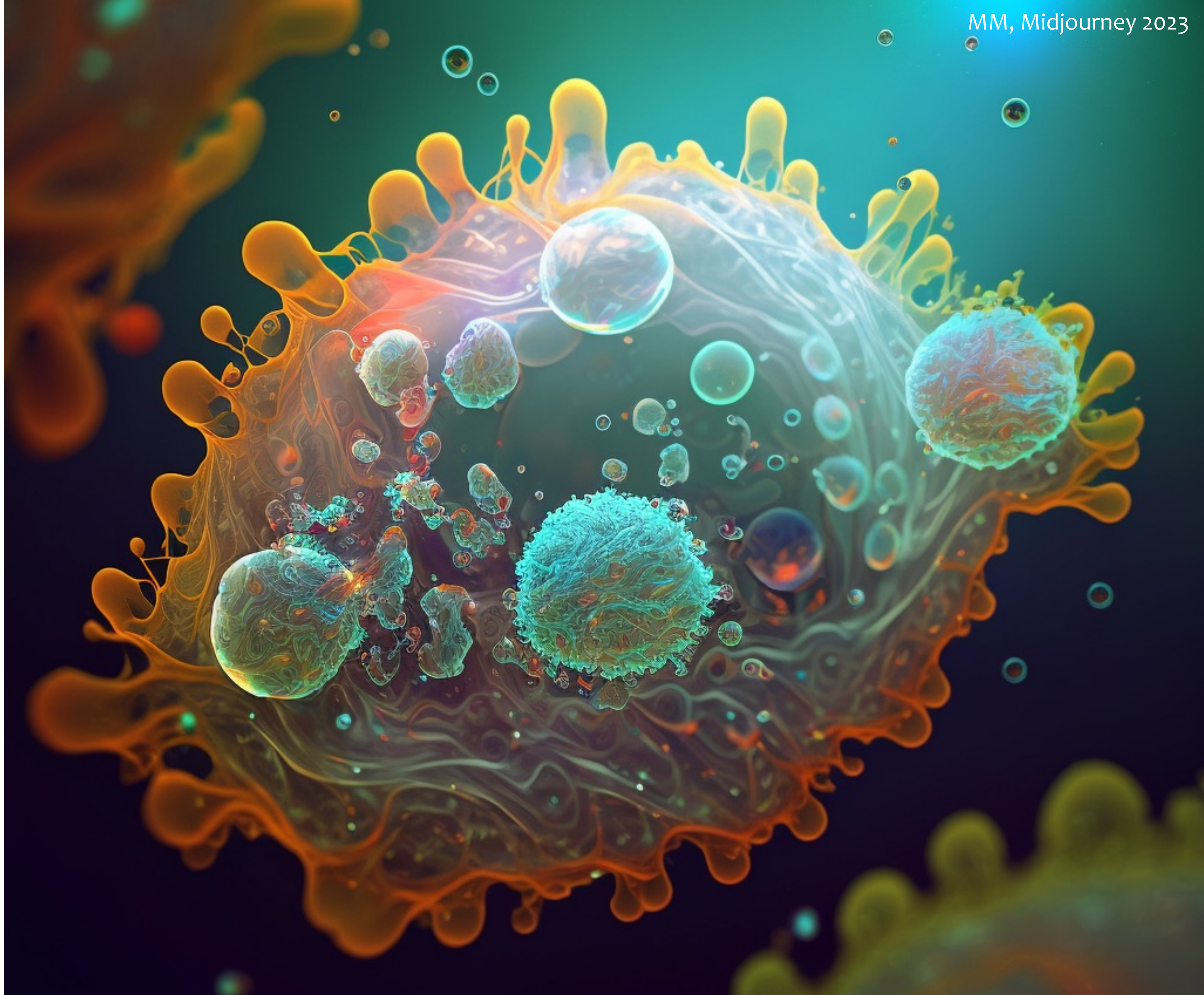
Run 2: (2015-2018):
$\mathcal{L}_{\text{int}} = 6\ \text{fb}^{-1}$ @ 13 TeV

Run 3: (2022-2026):
rapidly growing @ 13.6 TeV
nominal μ = 5.5

Target of $10\ \text{fb}^{-1}$ is archived in September



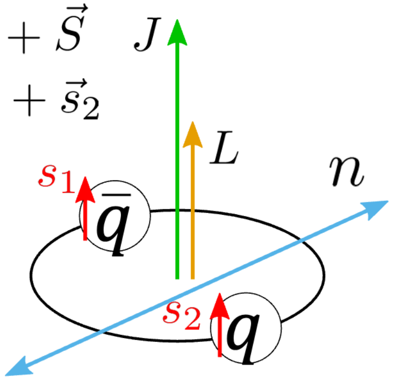
Spectroscopy



CP violation | Rare decays | Electroweak | Heavy ions & fixed target | Dark sector | Hadron physics

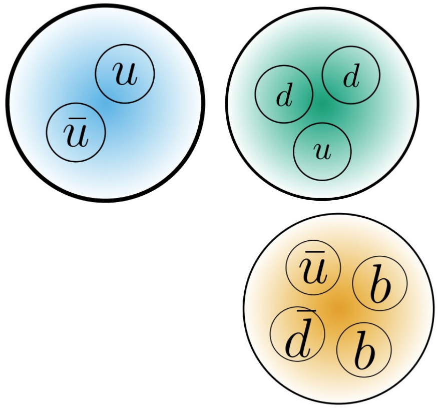
Possible configurations of hadrons

$$\vec{J} = \vec{L} + \vec{S}$$
$$\vec{S} = \vec{s}_1 + \vec{s}_2$$



+ excitations

Conventional Quark Model: $(q\bar{q}, qqq)$

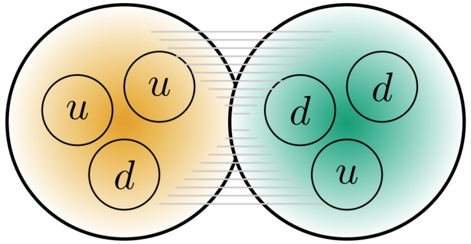


Bigger Quark Model $(q\bar{q}q\bar{q}, qqqq\bar{q}, \dots)$

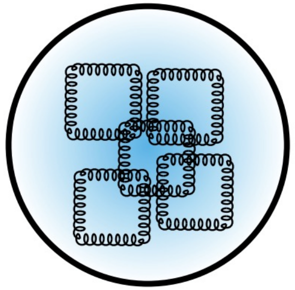
Conventional Hadronic Molecules = Nuclei: $(qqq)(qqq)$

Heavy-Flavor Hadronic Molecules: $(Qqq)(Qqq), (Q\bar{q})(Qqq), \dots$

Admixed Molecules: $q\bar{q} \to (q\bar{q})(q\bar{q})$

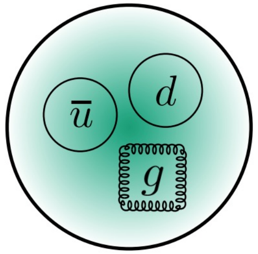


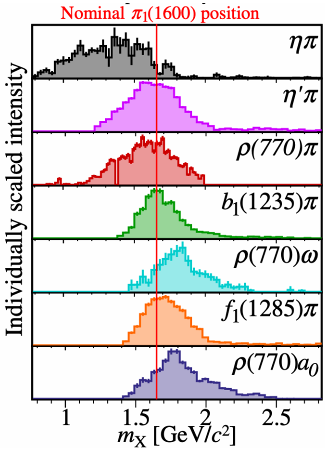
+ nuclei chart



Hybrids: $q{\sim}g{\sim}\bar{q}$

Glueballs: $g{\sim}g$



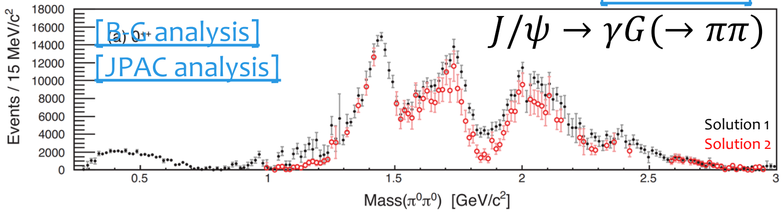


[contesy D.Spüllbeck, COMPASS data]

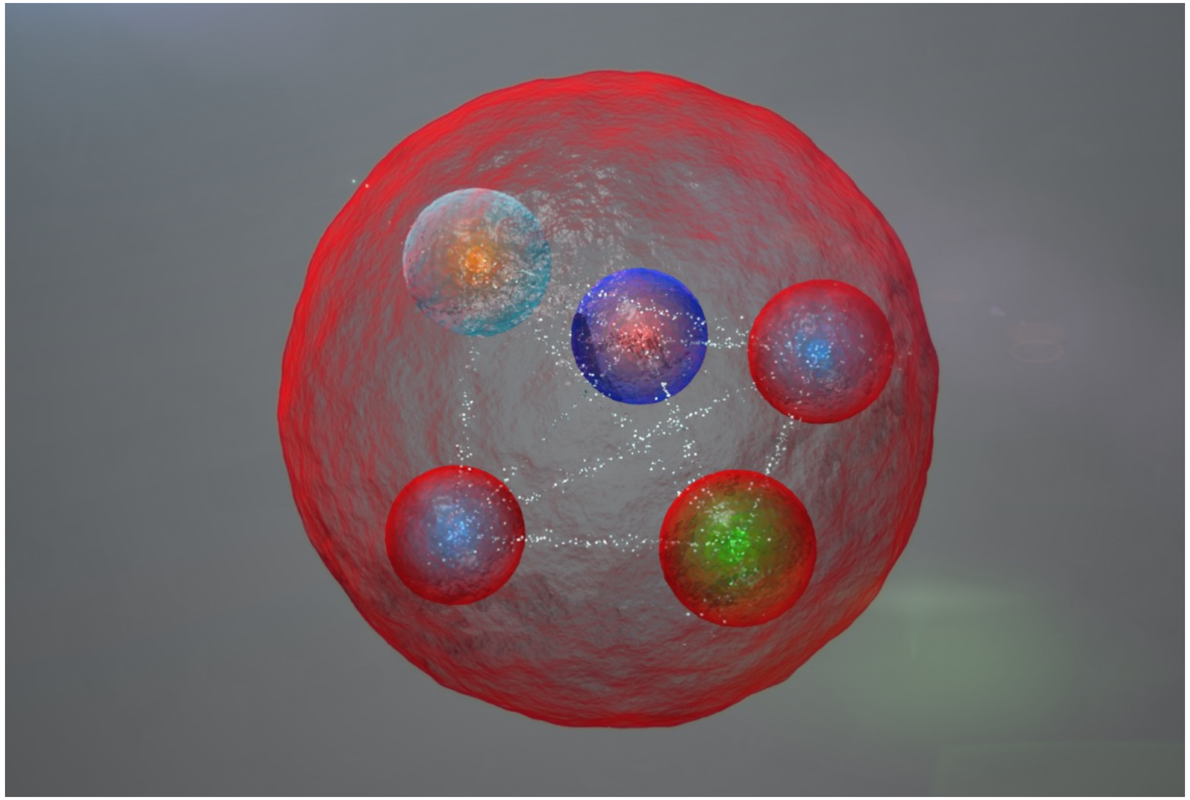
[BESIII data]

[B.G analysis]

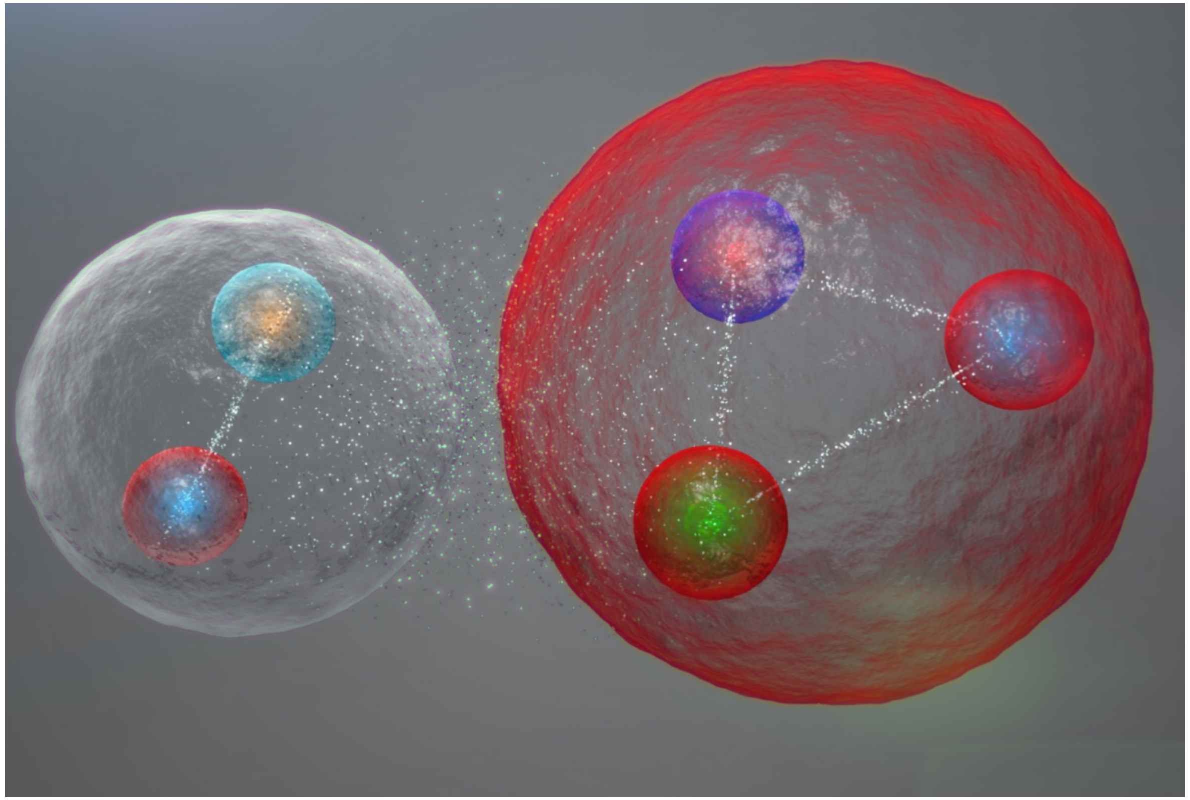
[JPAC analysis]



“Compact pentaquark”



“Hadronic molecule”



In fact, **quark-model states** are coupled to **continuum** (hadron-hadron), and have ~100% of wave function as a molecule if near threshold.

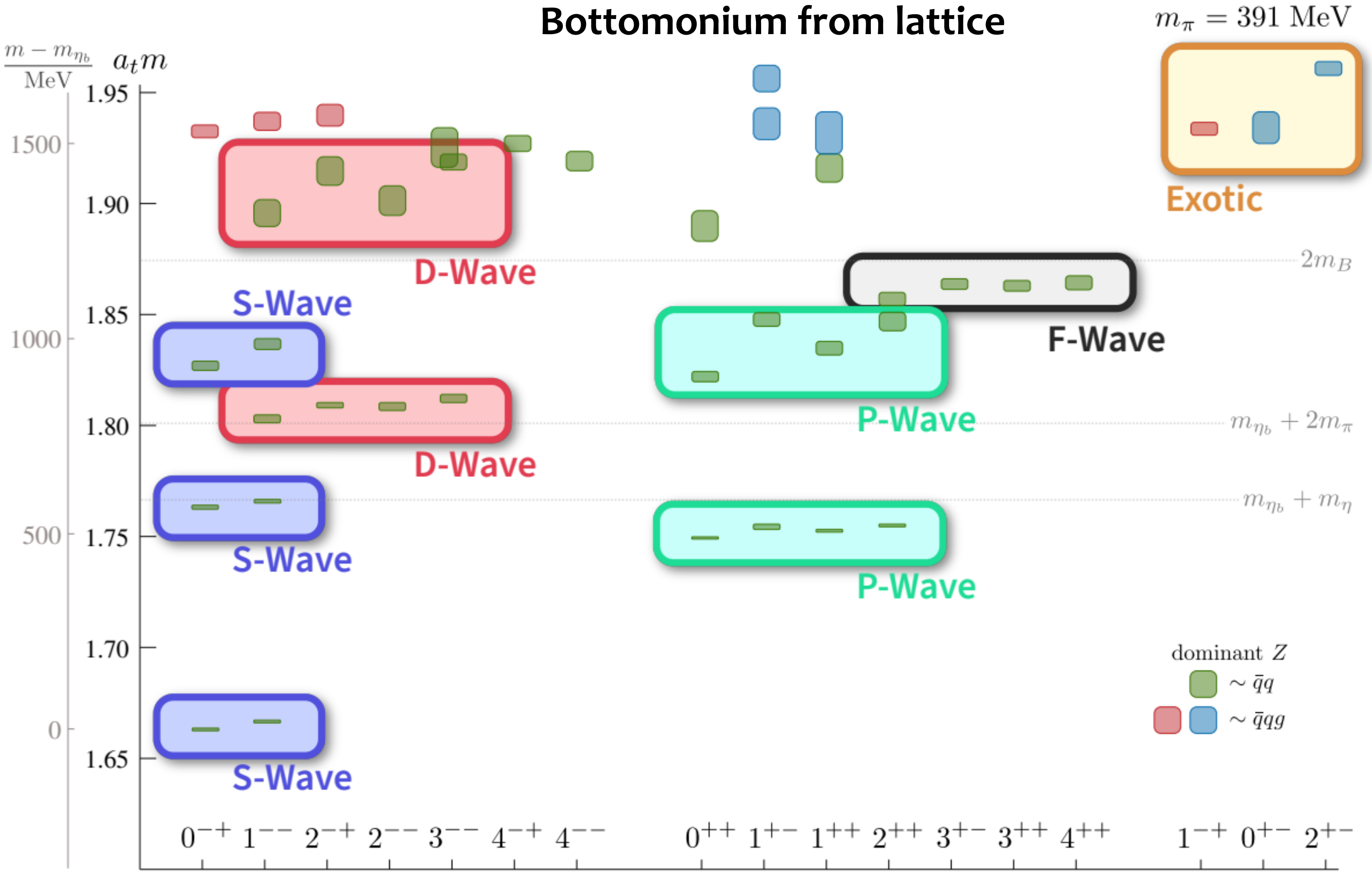
Q: does meson-exchange interaction provide sufficient binding? (molecules in absence of contract QM seed)

[HadSpec, JHEP 02 (2021) 214]

Pattern of meson excitation

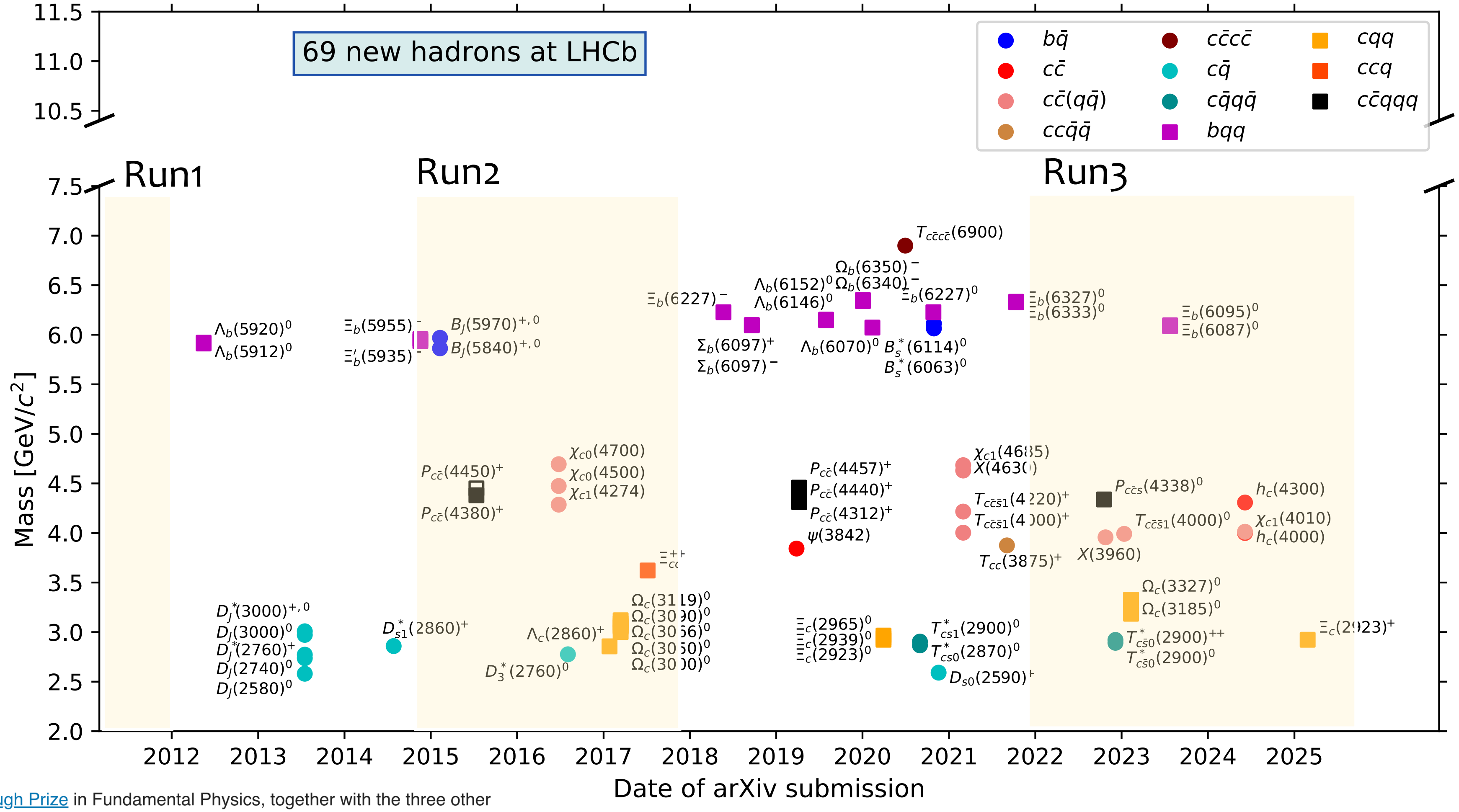
Same patter for all mesons:

- Radial excitation
- Orbital excitation
- Hyper-fine splitting within every multiplet
  - 2 line for S-wave,
  - 4lines for L>0



New particles

https://www.nikhef.nl/~pkoppenb/particles.html



2025 Breakthrough Prize

The LHCb collaboration has been awarded yesterday the 2025 Breakthrough Prize in Fundamental Physics, together with the three other CERN's Large Hadron Collider collaborations: ALICE, ATLAS and CMS, "For detailed measurements of Higgs boson properties confirming the symmetry-breaking mechanism of mass generation, the discovery of new strongly interacting particles, the study of rare processes and matter-antimatter asymmetry, and the exploration of nature at the shortest distances and most extreme conditions at CERN's Large Hadron Collider." The prize has been awarded to all current and former members of the four collaborations who have authored Run-2 data papers by 15 July 2024.

Exotic spectroscopy timeline

Highlights 2008-2020

Anonalous properties of $\chi_{c1}(3872)$

Pentaquarks $P_{c\bar{c}}$

Tetraquarks $T^{+}_{c\bar{c}1}(Z_c)$

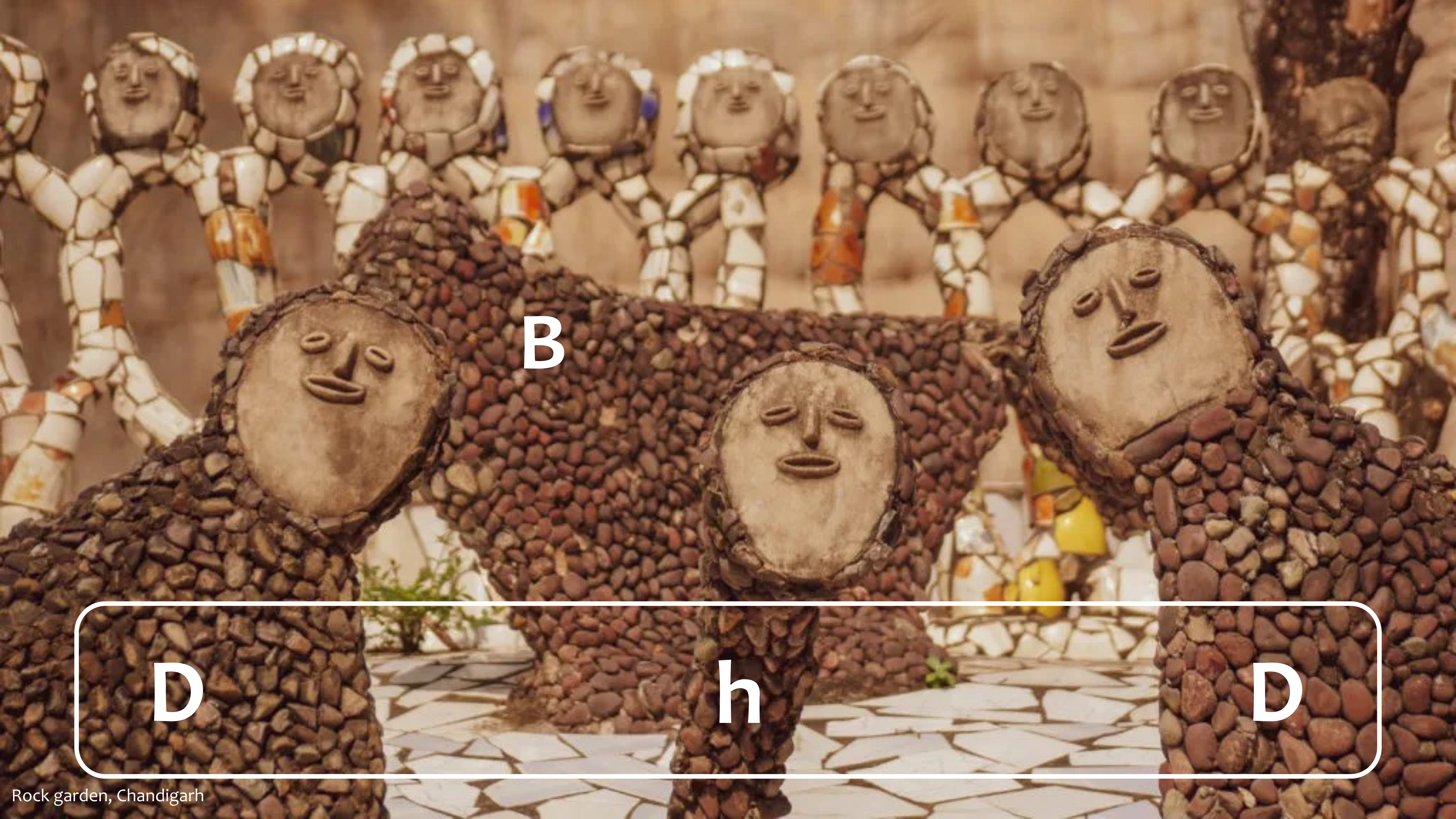
… other XYZ …

Highlights 2020-now

Double-charm tetraquark T^{+}_{cc} ☆

Charm-strange tetraquarks T^{+}_{cs} ☆

Charm-antistrange tetraquarks $T^{+}_{c\bar{s}}$



Rock garden, Chandigarh

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

h is a $K^{\pm}$ or $\pi^{\pm}$

← Isospin → ← SU(3) →

s=0

$D^{*+}D^{-}K$ $D^{*0}\bar{D}^{0}K$ $D_s^{(*)+}D_s^{(*)-}K$

$D^{+}D^{-}K$ $D^{0}\bar{D}^{0}K$ $D_s^{+}D_s^{-}K$

*Belle (2008)

s=-1

$D_s^{+}D^{(*)-}h$ $D_s^{+}\bar{D}^{(*)0}\pi$

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

$T_{c\bar{s}}$: $T_{c\bar{s}}^{0}(c\bar{s}d\bar{u}), T_{c\bar{s}}^{+}(c\bar{s}d\bar{d}), T_{c\bar{s}}^{++}(c\bar{s}u\bar{d})$

T_{cs} : $T_{cs}^{-}(cs\bar{u}\bar{u}), T_{cs}^{0}(cs\bar{u}\bar{d}), T_{cs}^{+}(cs\bar{d}\bar{d})$ (unknow isospin)

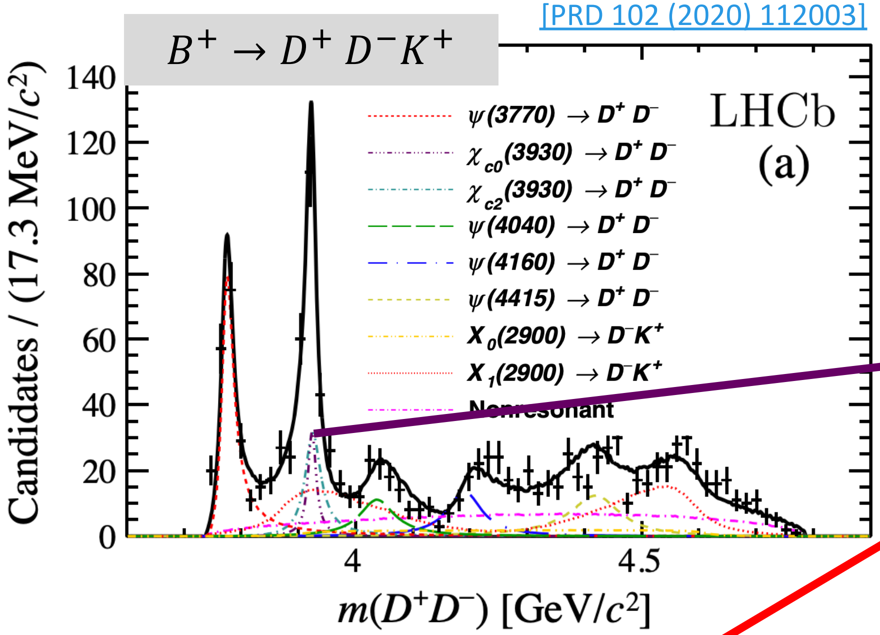
1. $D\bar{D}$: **Studies of charmonium:**
$D^{+}D^{-} : D^{0}\bar{D}^{0} : D_s^{+}D_s^{-}$

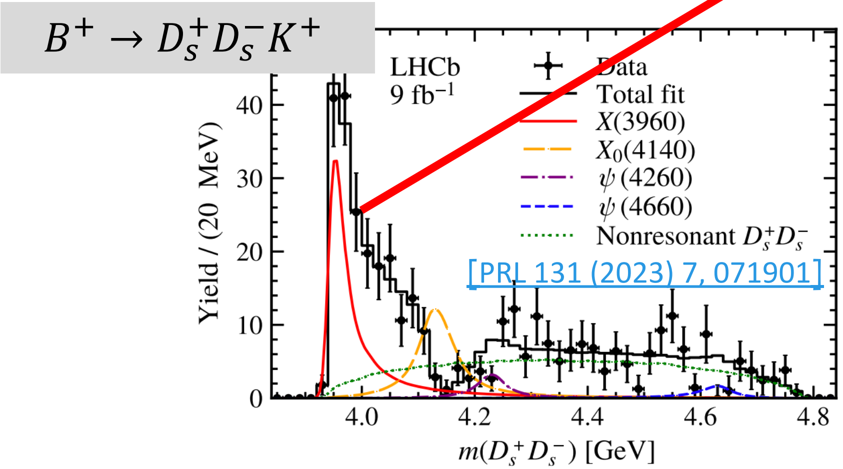
2. $D\bar{h}$ **excited D states:**
$D^{+}\pi^{-} : D_s^{+}K^{-}$

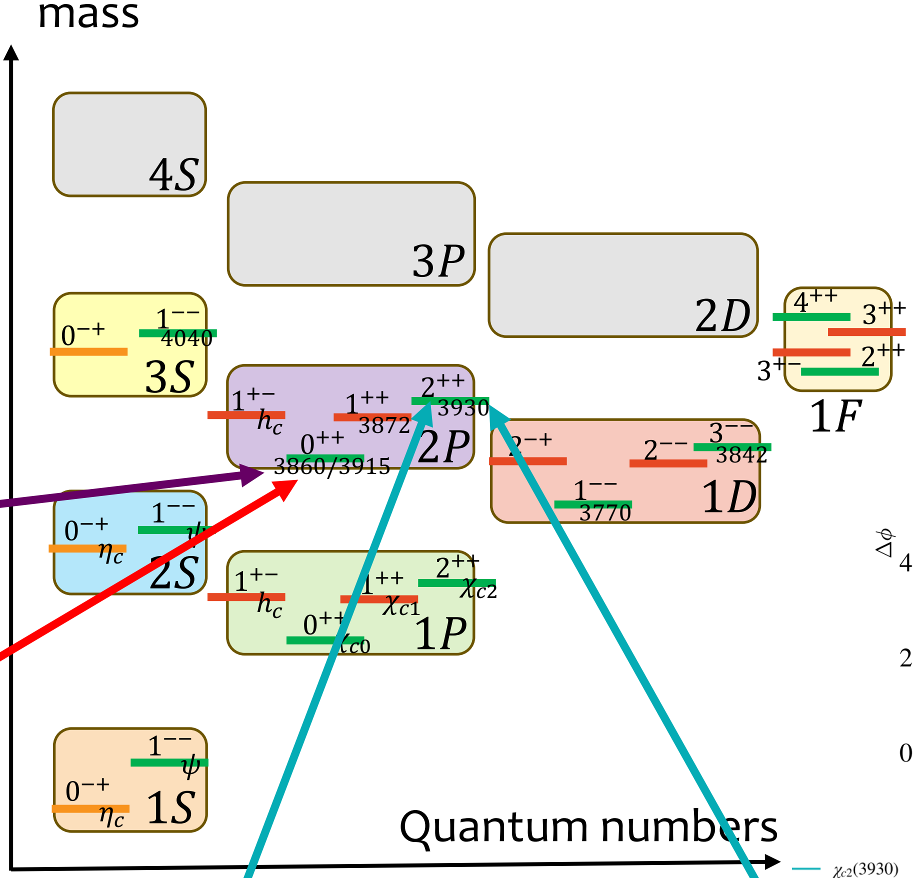
3. Dh **exotic $T_{c\bar{s}}$ states:**
(like D_s^{+} but double charged / neutral)
$D^{+}K^{+} : D_s^{+}\pi^{+}$

4. $D\bar{K}$ **exotic T_{cs} states:**
$D^{+}K^{-}$

Charmonium



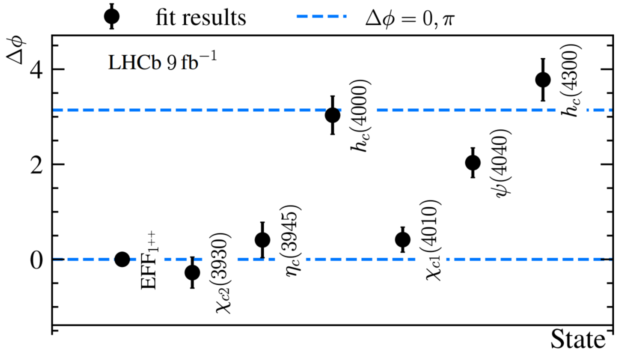


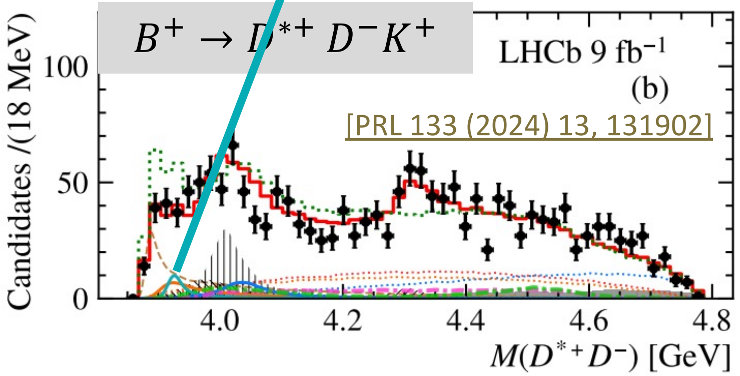


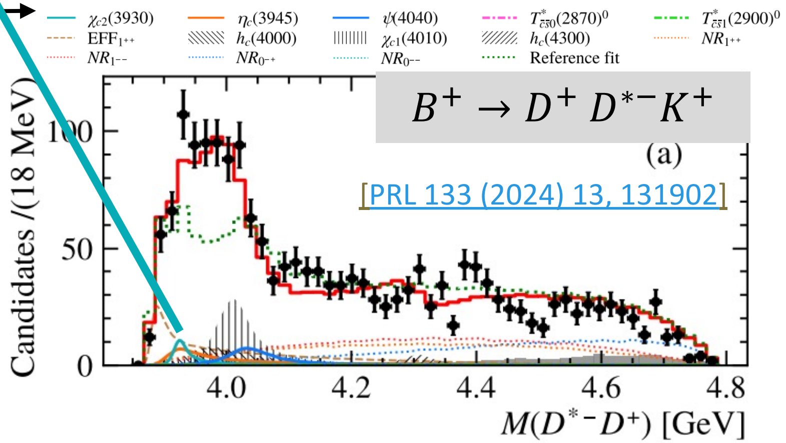
D^+D^-: $0^{++}, 1^{--}, 2^{++}, 3^{--}$

$D^{*+}D^-$: $1^{+x}, 0^{-x}, 1^{-x}, 2^{-x}, 2^{+x}$

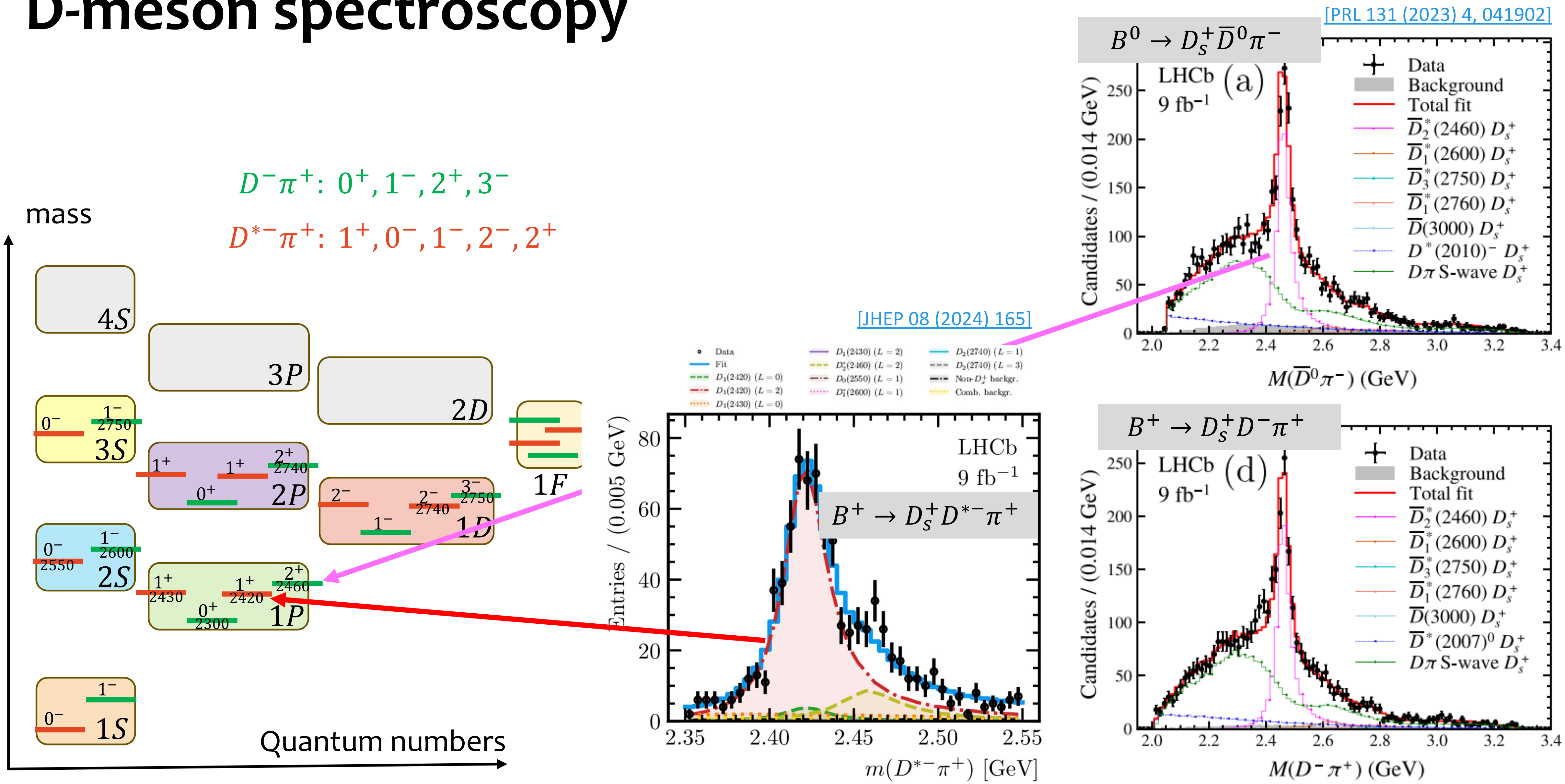
$$|D^*\bar{D}\rangle = \frac{D^{*+}D^- + e^{i\Delta\phi} D^{*-}D^+}{2}$$



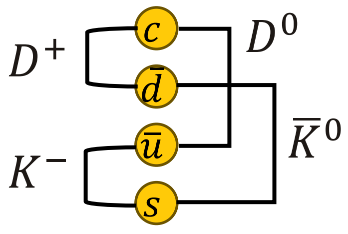




D-meson spectroscopy

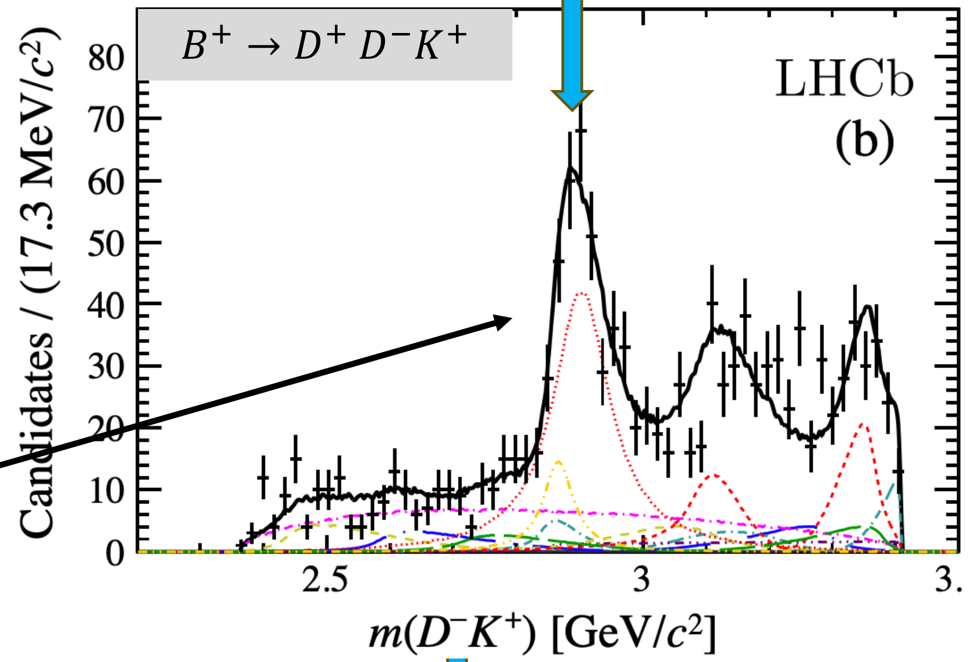


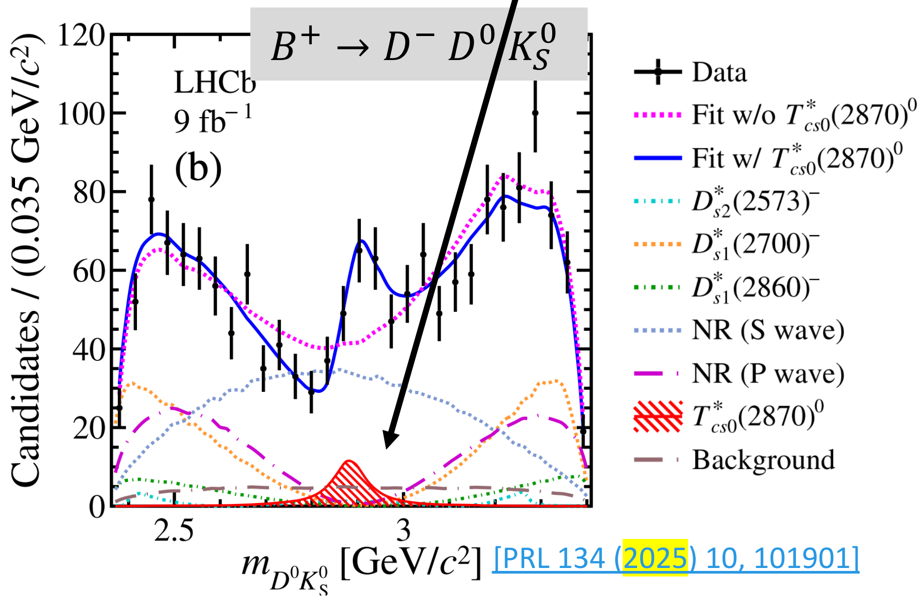
Exotic T_{cs} states



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

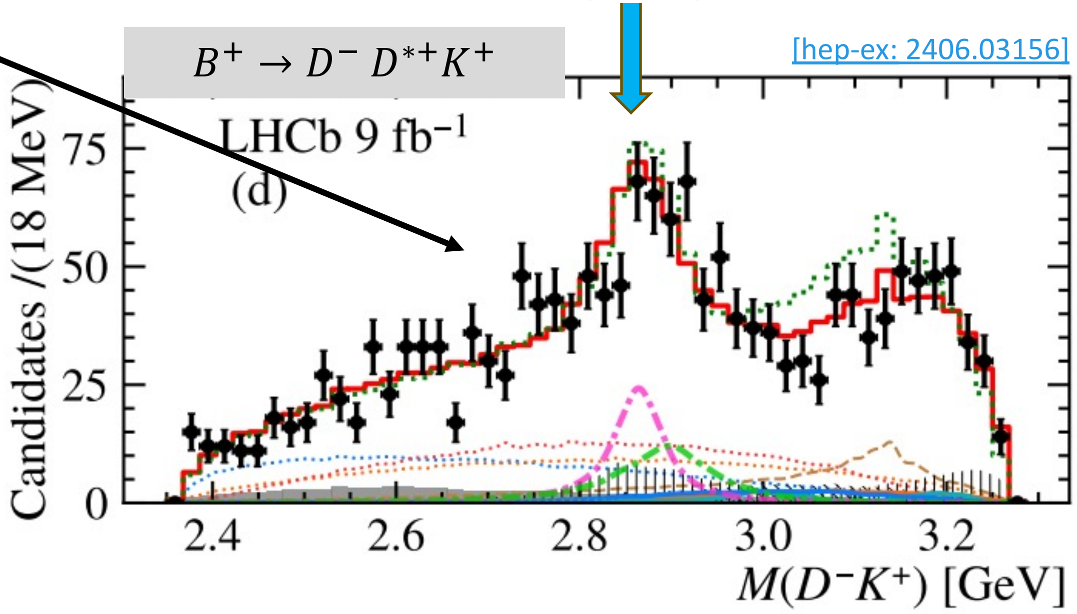
[PRD 102 (2020) 112003]





[PRL 134 (2025) 10, 101901]

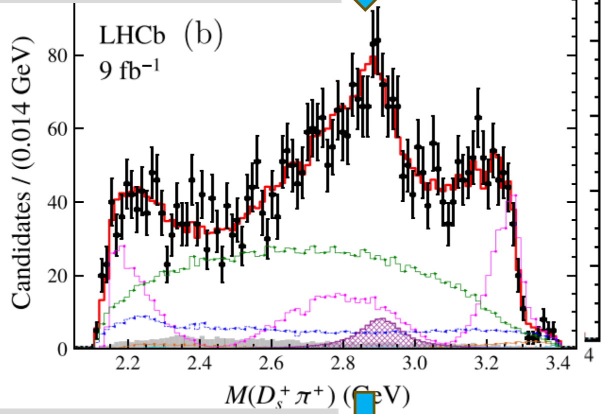
[hep-ex: 2406.03156]



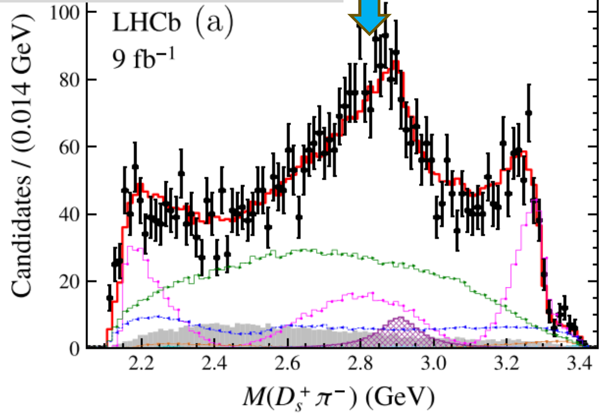
Exotic $T_{c\bar{s}}$ states

[PRL 131 (2023) 4, 041902]

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

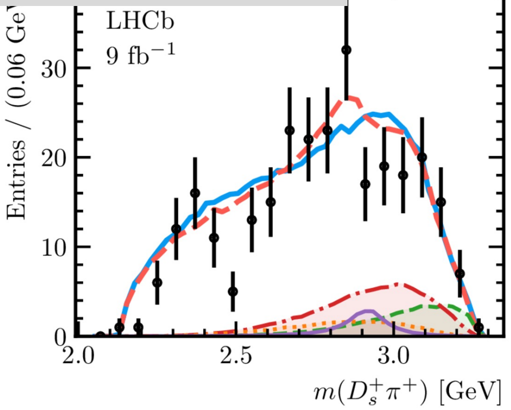


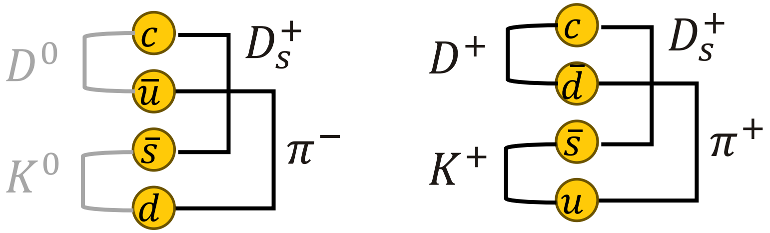
$B^0 \to D_s^+ \bar{D}^0 \pi^-$



[JHEP 08 (2024) 165]

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

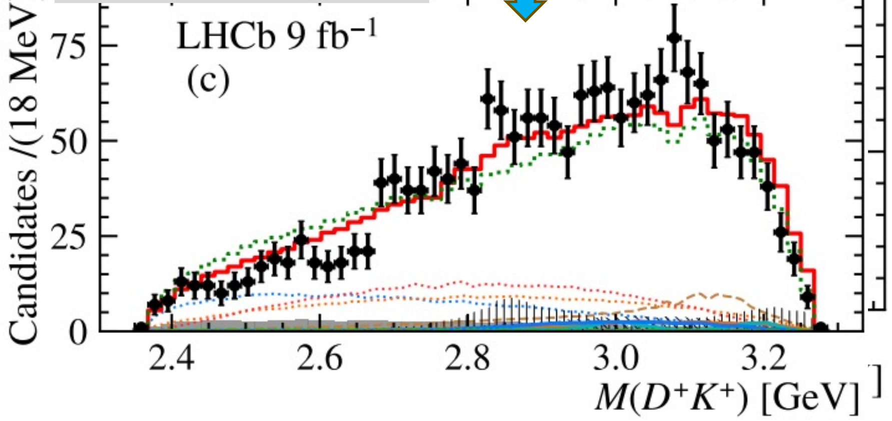




$T_{c\bar{s}}$: $T^0_{c\bar{s}}(c\bar{s}d\bar{u}), T^+_{c\bar{s}}(c\bar{s}d\bar{d}), T^{++}_{c\bar{s}}(c\bar{s}u\bar{d})$

[hep-ex: 2406.03156]

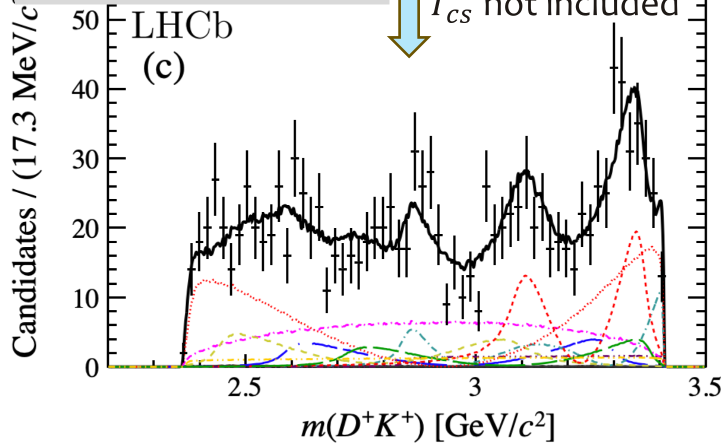
$B^+ \to D^{*-} D^+ K^+$



[PRD 102 (2020) 112003]

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

T_{cs} not included



$J/\psi\ \varphi$ states

Reminder: $J/\psi\ \varphi$ states

Rich spectrum of previous-unseen states

$\chi_{c1}(4140)$
$\chi_{c1}(4274)$
$\chi_{c0}(4500)$
$\chi_{c0}(4700)$

(2017)
four
babies
0^+ & 1^+

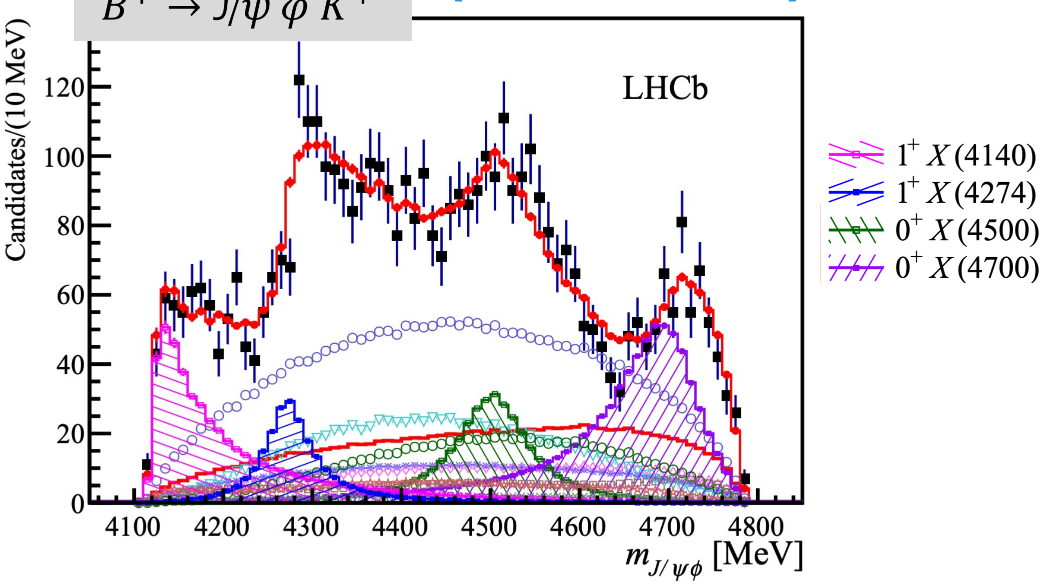
"I wonder if they'll be a doctor or an artist."
- some are probably charmonia, but some are exotic

$\chi_{c1}(4685)$
$\psi\ (4630)$
$X(4150)$

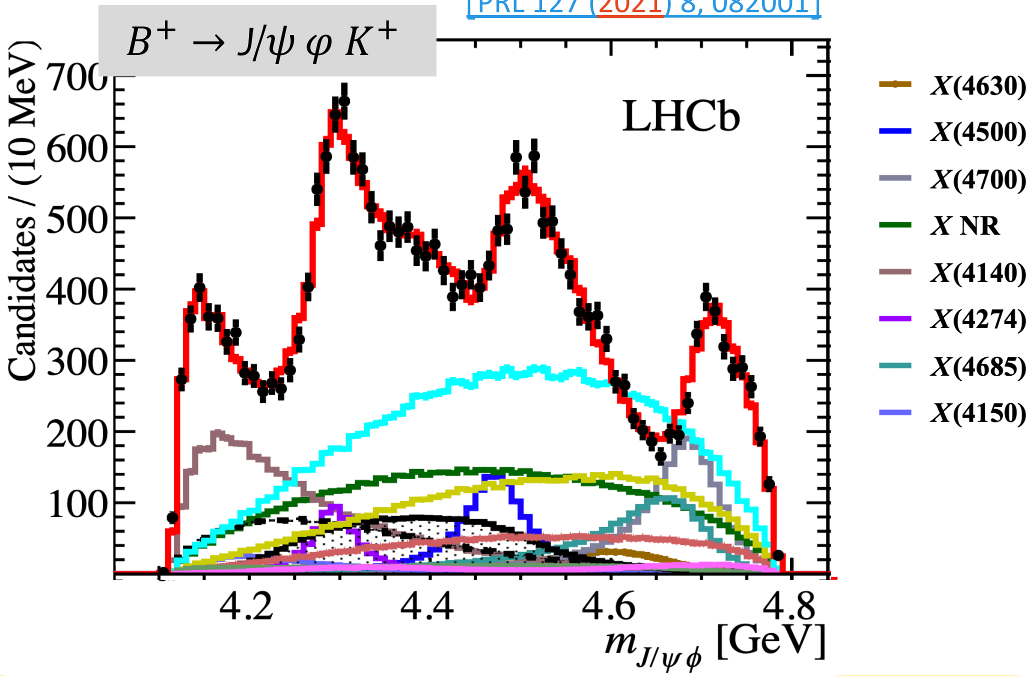
(2021)
three more
1^+ & 1^- & 2^-

Overall, 9 exotic states (7 X + 2 Z_{cs})

[PRD 95 (2017) 1, 012002]



[PRL 127 (2021) 8, 082001]

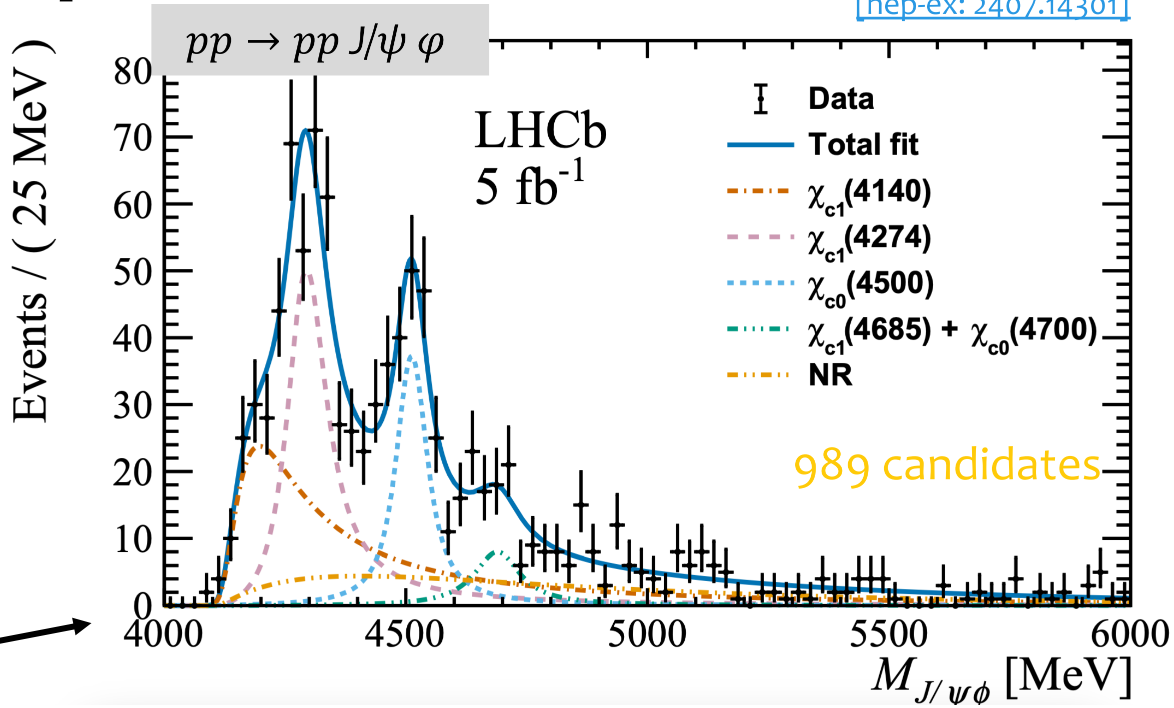


New results on diffractive $J/\psi\ \varphi$ production

[hep-ex: 2407.14301]

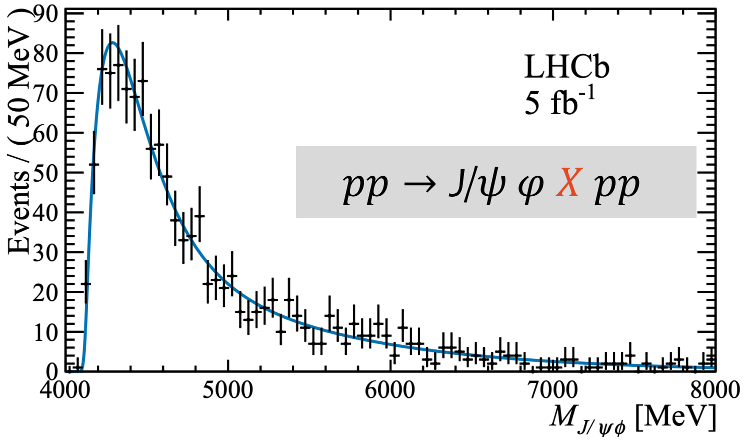
For diffractive studies,
the acceptance is extended with HeRSChel,
$5 < |\eta| < 10$
=> cross section measurement

$$\sigma_{J/\psi\phi} \times \mathcal{B}(J/\psi \to \mu^+\mu^-) \times \mathcal{B}(\phi \to K^+K^-)$$
$$= (2.52 \pm 0.08 \pm 0.12 \pm 0.05)\,\text{pb},$$



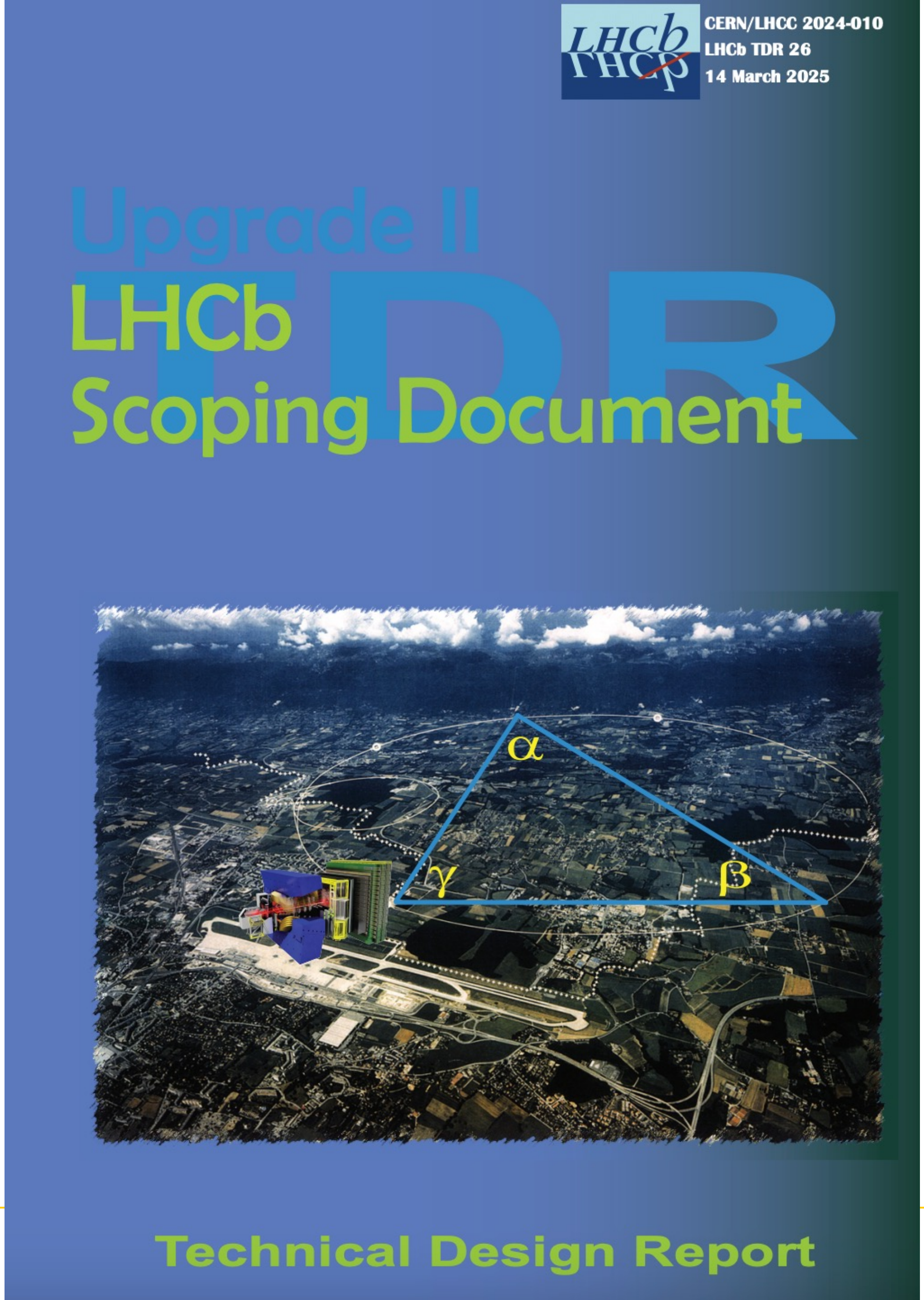
For selection, #track in VeLo is used

- only four tracks
- with additional tracks



Hm, strong couplings to gluons?

Future of LHCb



LHCb Upgrade II Scoping Document (public link)

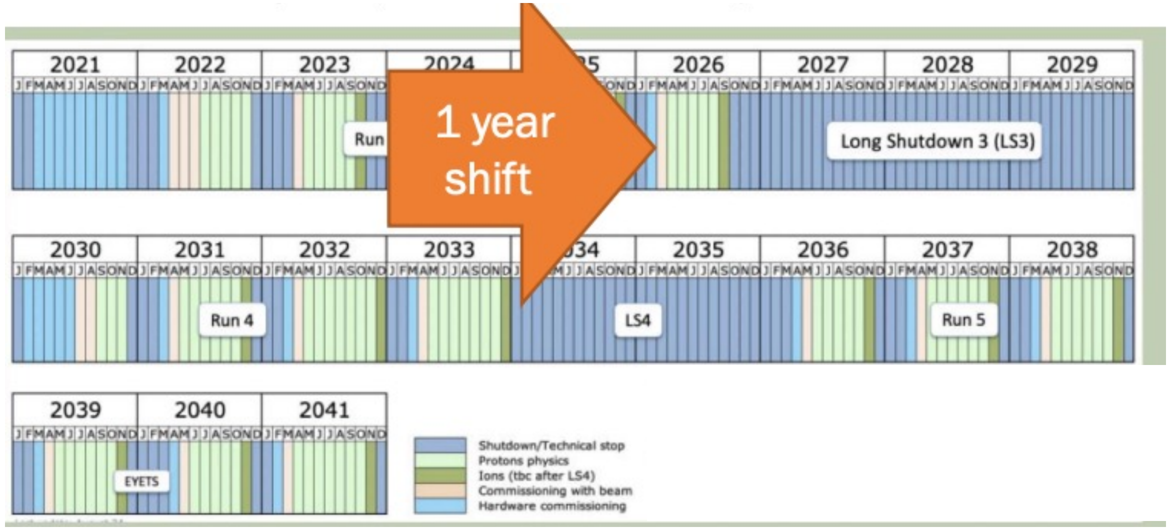
Upgrade II

The current Run is prolongated by 1y (2022-2026)

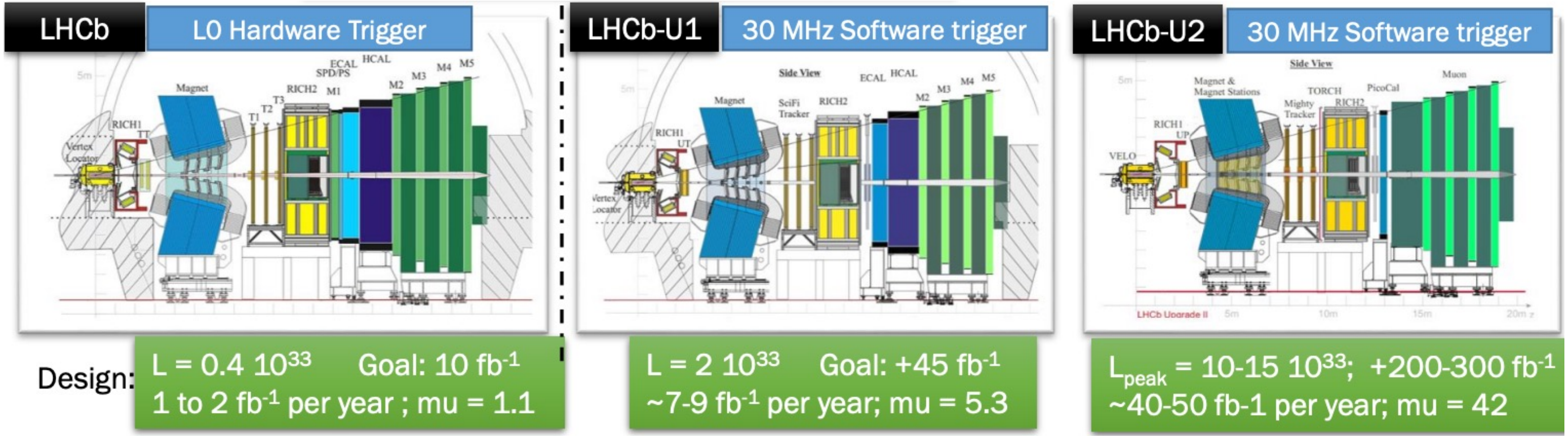
LS3: no major changes at LHCb

Run4: 2030-2033

LS4: Upgrade II, 2036-2041 data taking



Comparison courtesy Blake Leverington



Upgrade II Scoping

(LHCb-CDS)

	Baseline	Middle
$\mathcal{L}_{\text{peak}}$ $(10^{34}\,\text{cm}^{-2}\,\text{s}^{-1})$	1.5	1.0
	(kCHF)	(kCHF)
VELO	16672	15906
UP	8077	7719
Magnet Stations	2592	2234
Mighty-SciFi	21767	21273
Mighty-Pixel	15994	11641
RICH	21450	18415
TORCH	12508	8756
PicoCal	27607	27607
Muon	9785	8266
RTA	18800	11700
Online	11800	9467
Infrastructure	14463	13284
Total	181515	156268

Middle $1.0 \times 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$
RICH1/2
inner:outer $\frac{1}{4}:\frac{3}{4}$
inner 2.0 mm SiPM
outer 2.8 mm SiPM
new optics
469,000 channels
TORCH
12 quartz bars
158,000 channels
PicoCal
40 SpaCal-W
408 SpaCal-Pb
2864 Shashlik
double R/O
30,976 channels
Muon
µ-RWELL in R1/R2
keep old MWPC in R3
keep old MWPC in R4
keep HCAL
608,256 channels

Middle $1.0 \times 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$
VELO
32 stations, $\eta < 4.8$
module 0.8% X_0
RF foil 75 µm
UP
as baseline
Magnet Stations
as baseline
Mighty-Pixel
6 planes pixel $\times 1.3\,\text{m}^2$
Mighty-SciFi
12 planes fibres
shorter, $23.7\,\text{m}^2$/plane

US contributors:

- MIT
- Los Alamos National Laboratory
- University of Maryland
- University of Michigan
- Ohio State University
- University of Cincinnati
- Syracuse University

Summary on LHCb

A lot of exciting physics with open-flavor systems with $D\pi$ and DK

- D-spectroscopy, and D_s spectroscopy
- Exotic states ($T_{c\bar{s}} \sim$ "neutral D_s")
- ***more results to come!***

The Run-3 for two more years:

- already more B mesons than in Run-2.

Run4: 2030-2033

Upgrade 2 operation time: 2036-2045

Backup

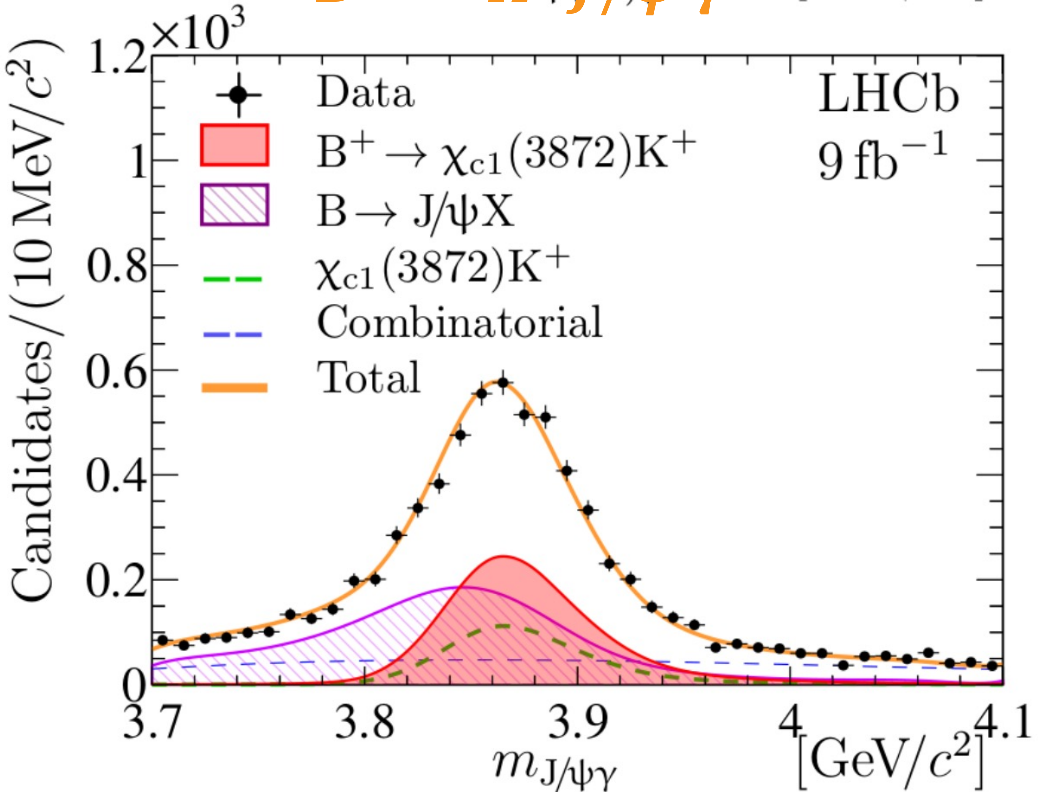
Radiative decays of $\chi_{c1}(3872)$

Radiative decays of $\chi_{c1}(3872)$

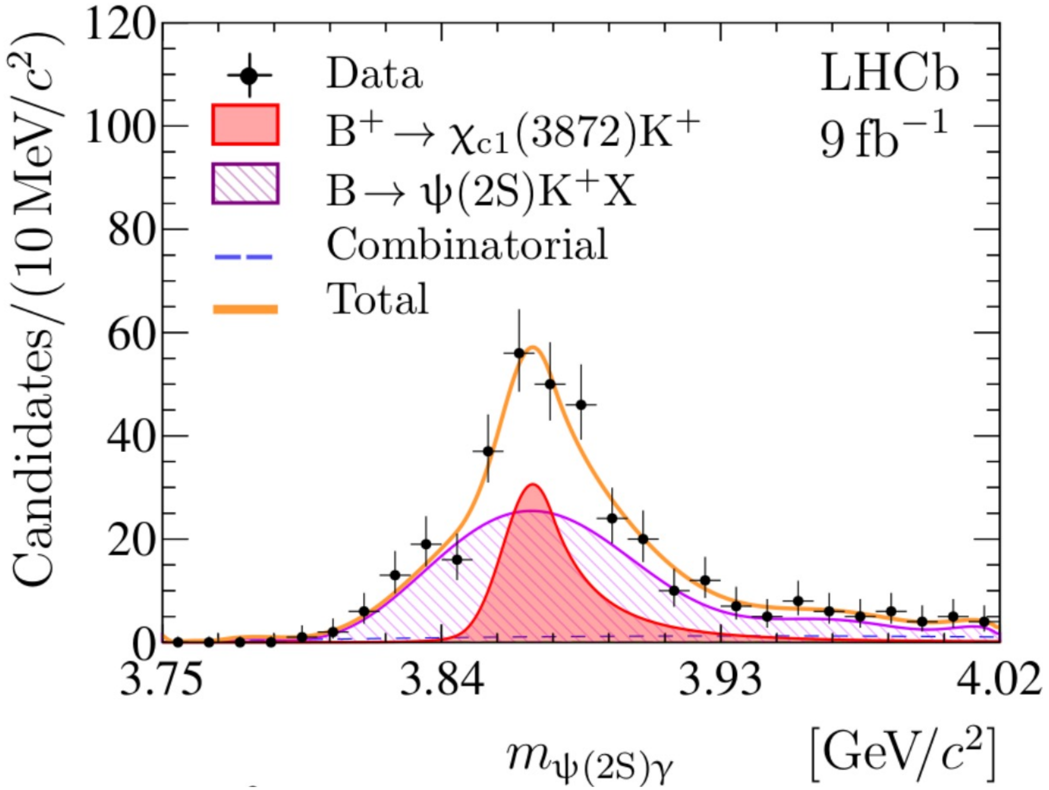
[JHEP 11 (2024) 121]

$$\mathcal{R}_{\psi\gamma} = \frac{\mathcal{B}_{B^+\to(\chi_{c1}(3872)\to\psi(2S)\gamma)K^+}}{\mathcal{B}_{B^+\to(\chi_{c1}(3872)\to J/\psi\gamma)K^+}}$$

$B^+ \to K^+ J/\psi\, \gamma$



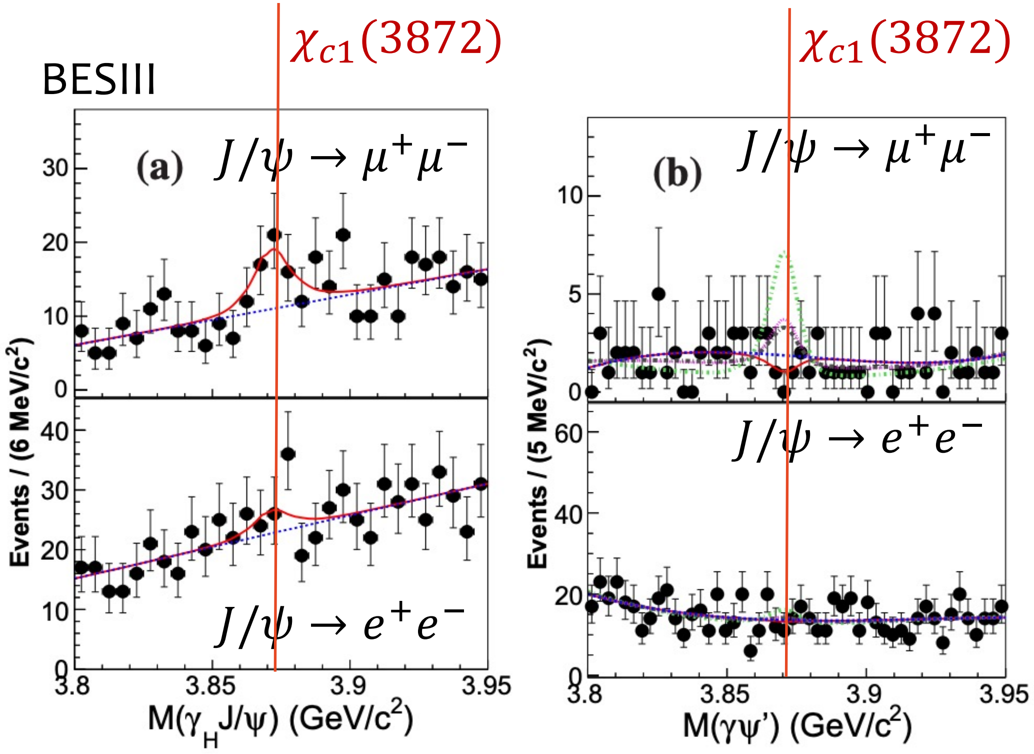
$B^+ \to K^+ \psi\, \gamma$

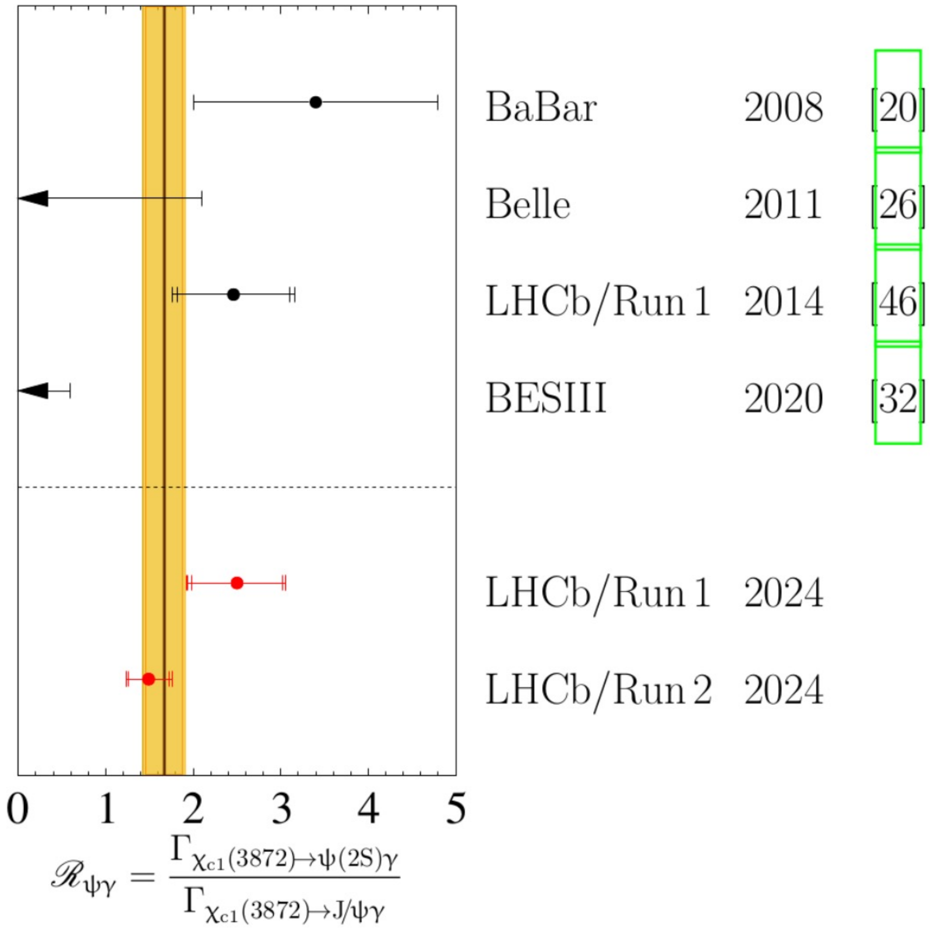


[JHEP 11 (2024) 121]

Radiative X decays

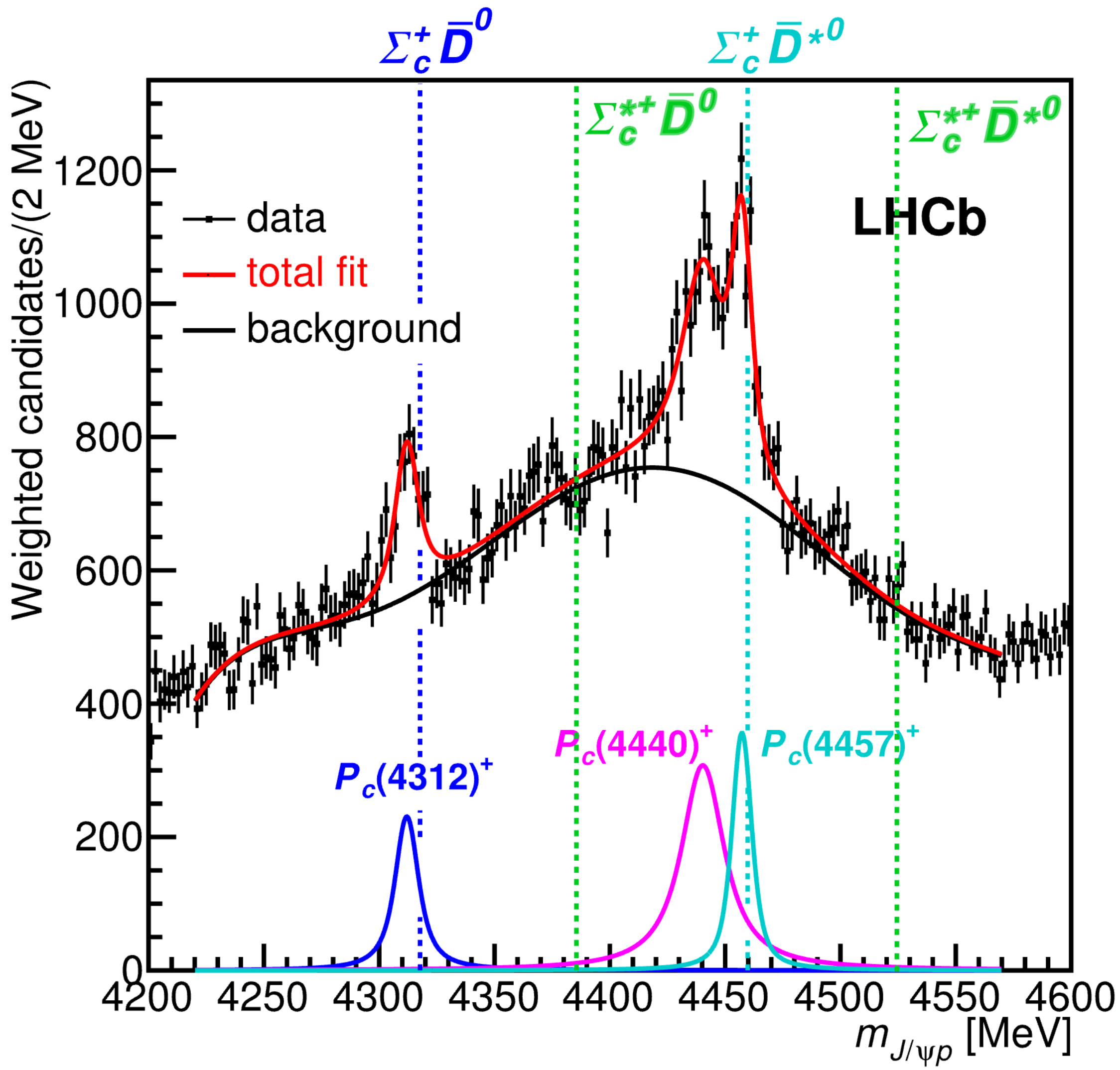
Consistent picture of different measurement excluding BESIII





Pentaquarks

Pentaquarks $P_{c\bar{c}}^{+}$ in $\Lambda_b^0 \to K^-(p\,J/\psi)$



(1D) [LHCb, PRL 122 (2019) 22, 222001]

(AmAn) [LHCb, PRL 115 (2015), 072001]

Near threshold

$\Sigma_c^{(*)+}\bar{D}^{(*)0}$ / $\Sigma_c^{(*)++}D^{(*)-}$

Multiplicity matches threshold-states spin algebra

No observation in other final states so far

[naming scheme for hadrons, PDG2023]

New search of Pentaquarks in open-flavor decays

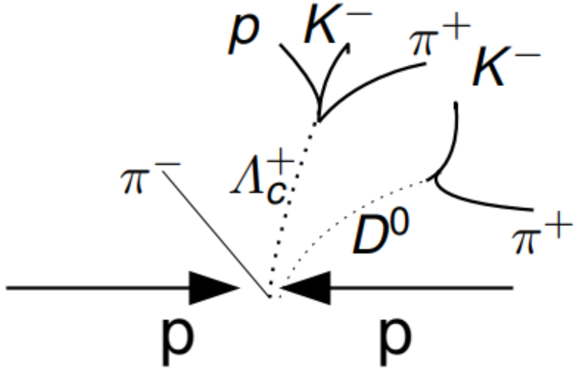
Pentaquark states seen in $J/\psi\, p$ must leave traces in

$$\Sigma_c^{(*)++} D^{(*)-}$$
$$\Sigma_c^{(*)+} \overline{D}^{(*)0}$$
$$\Sigma_c^{(*)+} D^{(*)-}$$
$$\Sigma_c^{(*)0} D^{(*)0}$$
$$\Lambda_c^{+} D^{(*)-}$$
$$\Lambda_c^{+} \overline{D}^{(*)0}$$

New search in prompt production is performed in many systems of

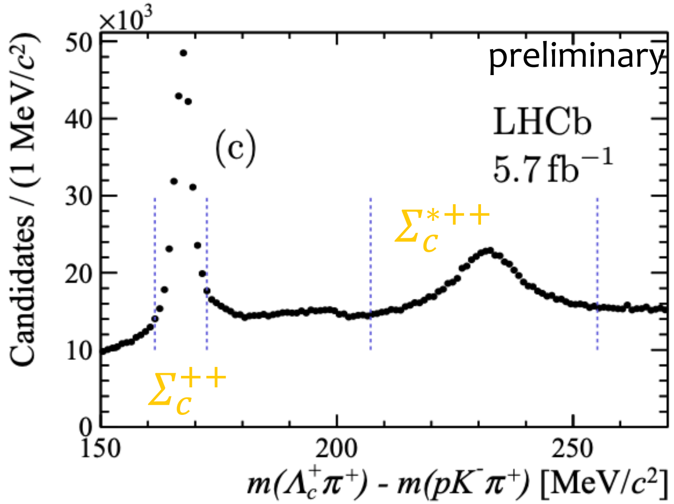
$$\Lambda_c^{+} \overline{D}\, \pi^{\pm}$$

combinations



[courtesy G. Robertson (LHCb)]

[LHCb-PAPER-2023-018, in preparation]



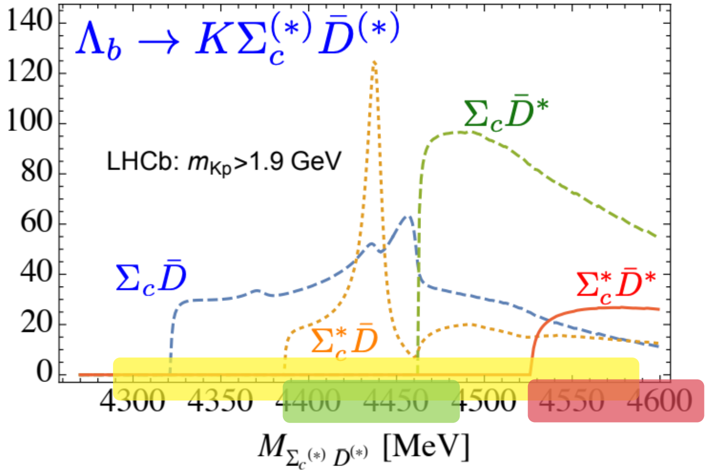
$\Sigma_c^{++}\bar{D}^0$ $\Sigma_c^{0}\bar{D}^0$	$\cancel{\Sigma_c^{++}D^0}$ $\cancel{\Sigma_c^{0}D^0}$	$\Sigma_c^{++}D^-$ $\Sigma_c^{0}D^-$	$\cancel{\Sigma_c^{++}D^+}$ $\cancel{\Sigma_c^{0}D^+}$	$\cancel{\Sigma_c^{++}D^{*-}}$ $\cancel{\Sigma_c^{0}D^{*-}}$	$\cancel{\Sigma_c^{++}D^{*+}}$ $\cancel{\Sigma_c^{0}D^{*+}}$
$\Sigma_c^{*++}\bar{D}^0$ $\Sigma_c^{*0}\bar{D}^0$	$\Sigma_c^{*++}D^0$ $\Sigma_c^{*0}D^0$	$\Sigma_c^{*++}D^-$ $\Sigma_c^{*0}D^-$	$\Sigma_c^{*++}D^+$ $\Sigma_c^{*0}D^+$	$\Sigma_c^{*++}D^{*-}$ $\Sigma_c^{*0}D^{*-}$	$\cancel{\Sigma_c^{*++}D^{*+}}$ $\cancel{\Sigma_c^{*0}D^{*+}}$
$\Lambda_c^+\bar{D}^0$	$\Lambda_c^+D^0$	$\Lambda_c^+D^-$	$\Lambda_c^+D^+$	$\Lambda_c^+D^{*-}$	$\Lambda_c^+D^{*+}$
$\Lambda_c^+\bar{D}^0\pi^+$ $\Lambda_c^+\bar{D}^0\pi^-$	$\Lambda_c^+D^0\pi^+$ $\Lambda_c^+D^0\pi^-$	$\Lambda_c^+D^-\pi^+$ $\Lambda_c^+D^-\pi^-$	$\Lambda_c^+D^+\pi^+$ $\Lambda_c^+D^+\pi^-$	$\Lambda_c^+D^{*-}\pi^+$ $\Lambda_c^+D^{*-}\pi^-$	$\Lambda_c^+D^{*+}\pi^+$ $\Lambda_c^+D^{*+}\pi^-$

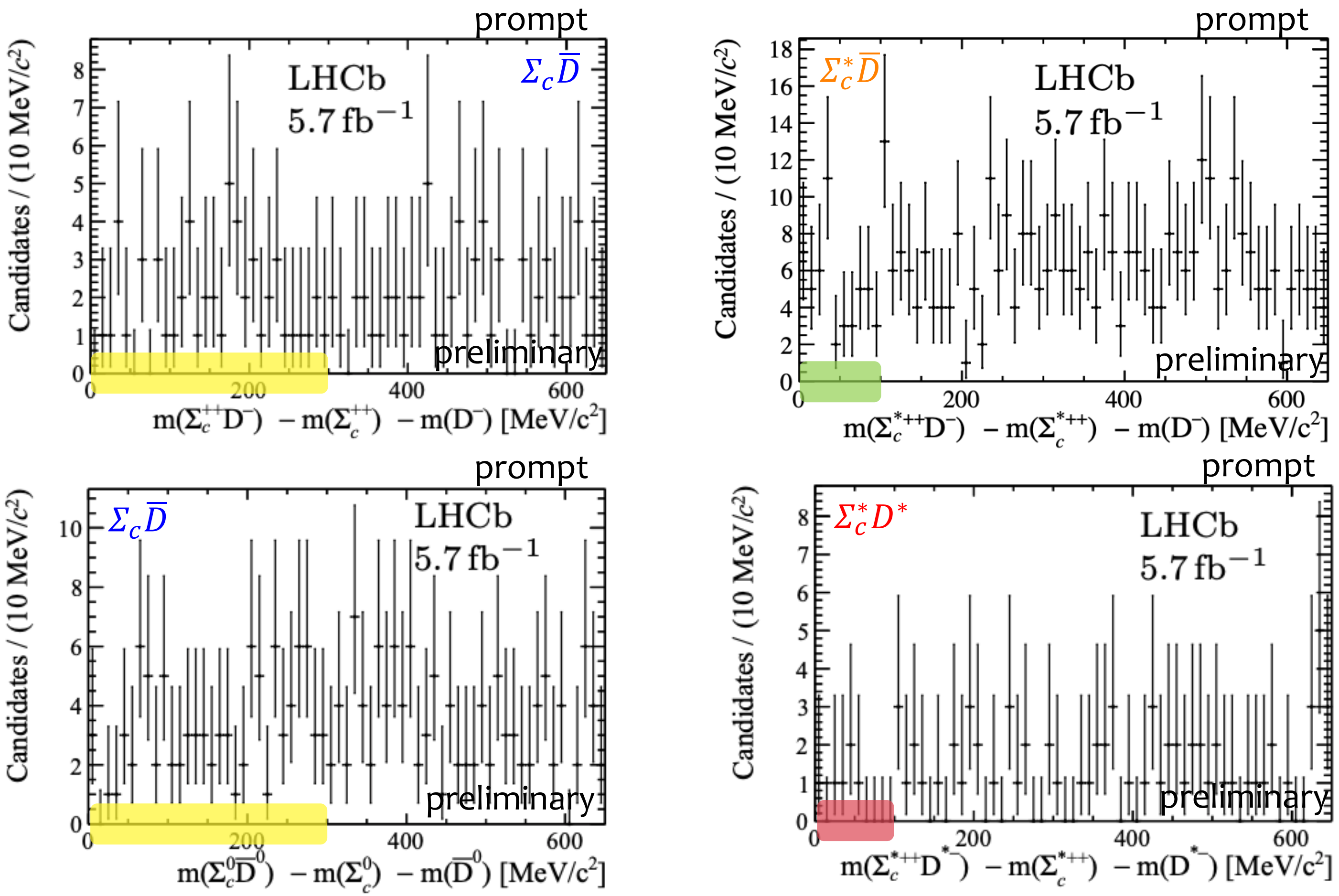
[X] : too small statistics for limit setting

Search for pentaquarks: $\Sigma_c\bar{D}^{(*)}$

[LHCb-PAPER-2023-018, in preparation]

[Meng-Lin Du et al.]



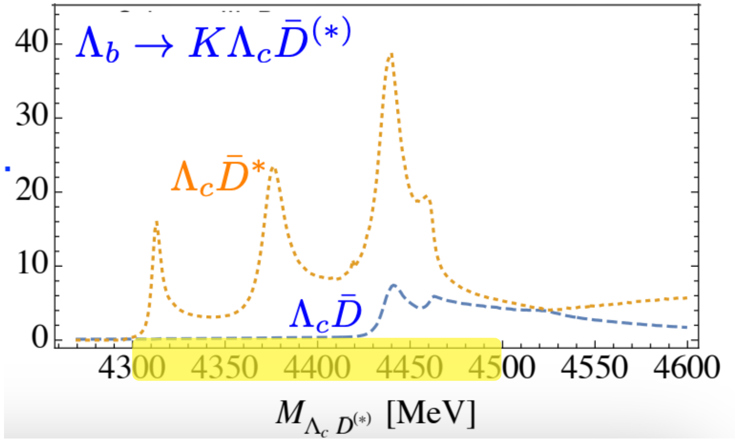


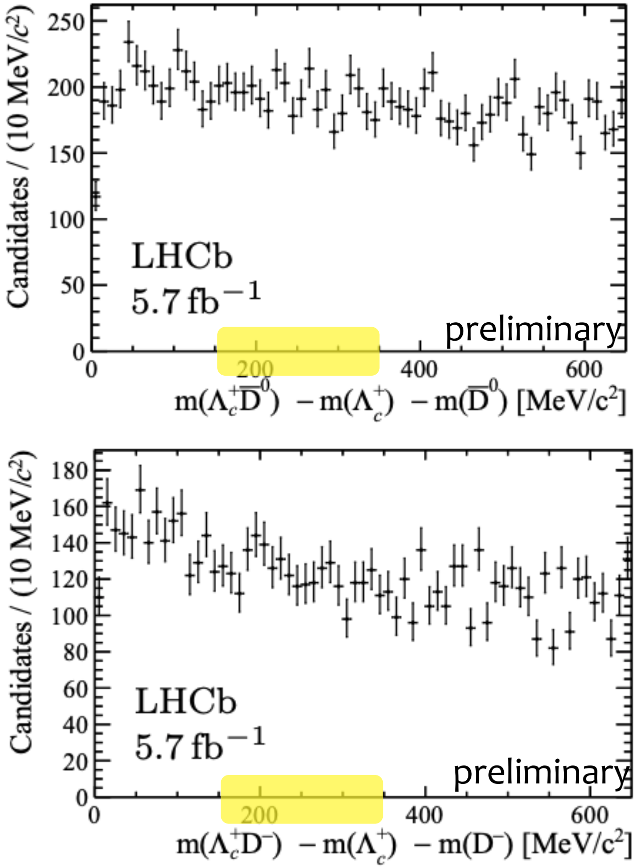
Statistically limited

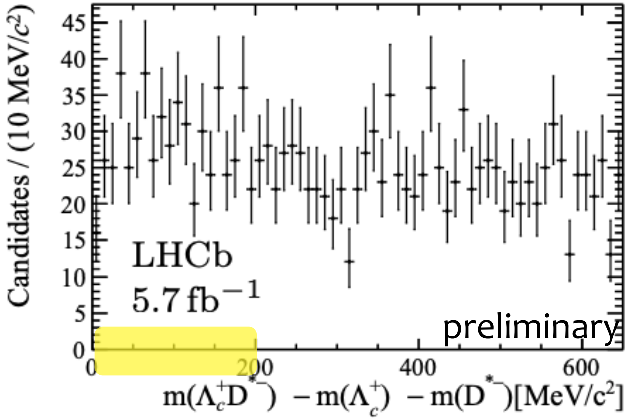
Search for pentaquarks: $\Lambda_c^+ \bar{D}$

[LHCb-PAPER-2023-018, in preparation]

[Meng-Lin Du et al.]



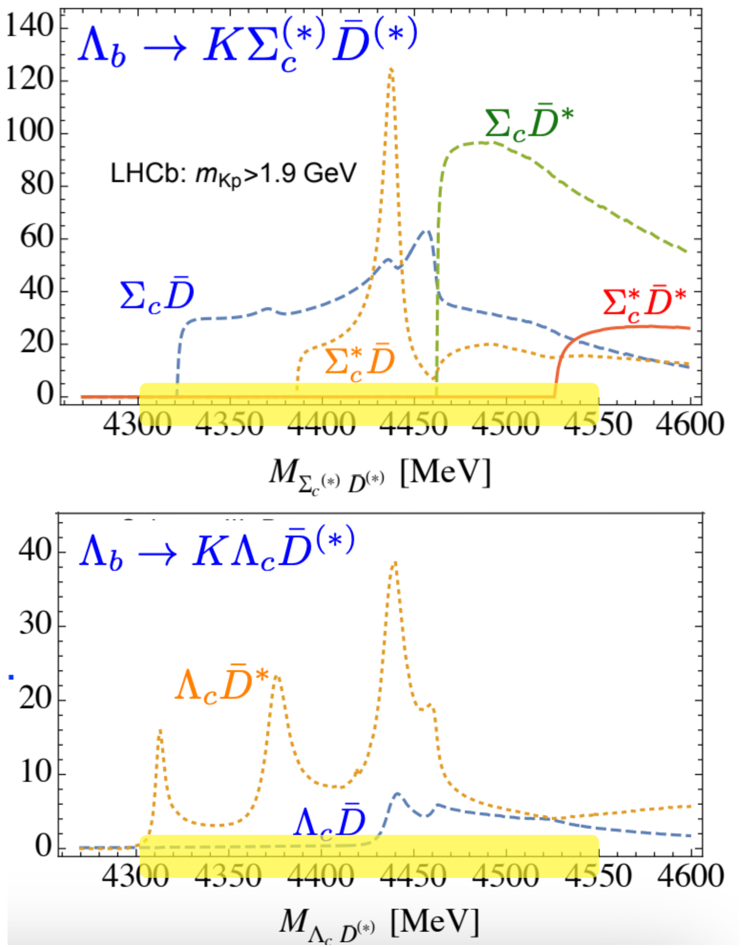




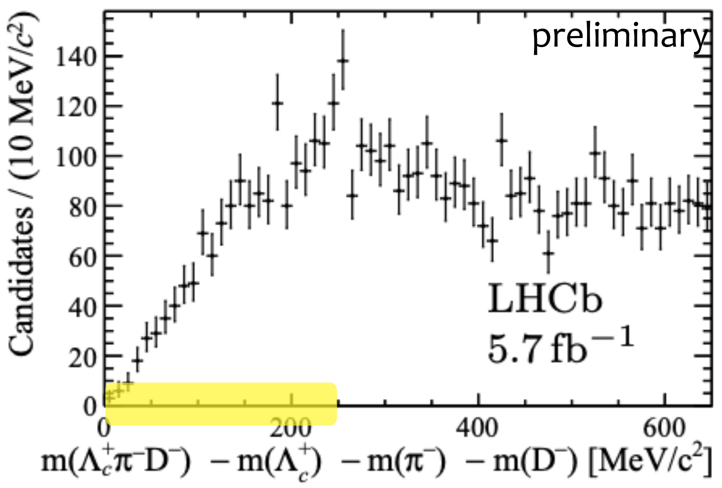
No obvious peaks

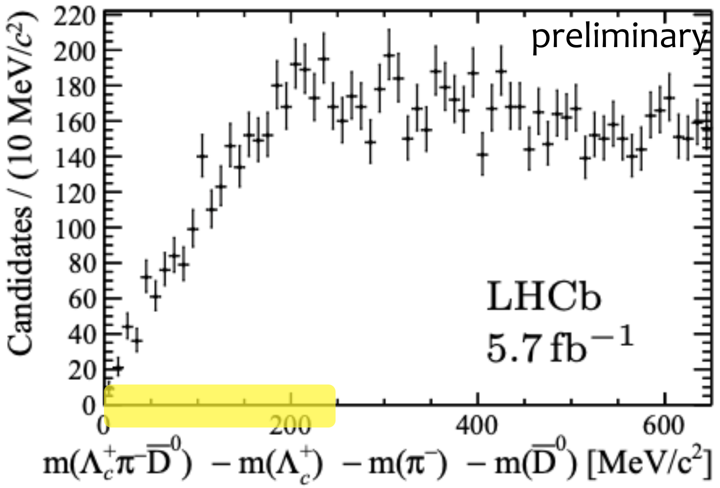
Search for pentaquarks: $\Lambda_c^+ \bar{D}\, \pi$

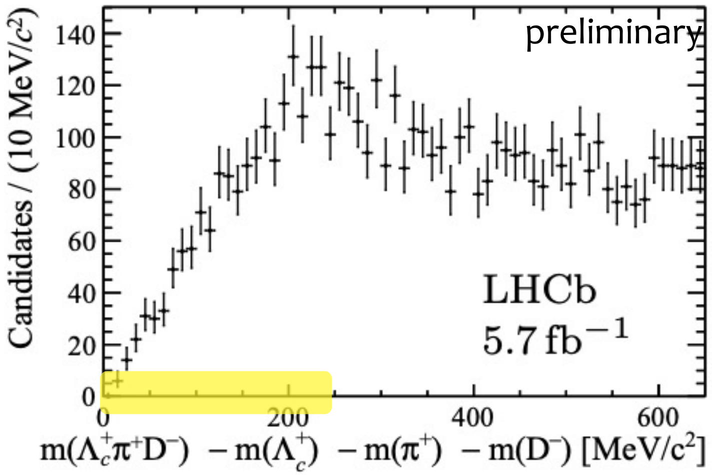
[LHCb-PAPER-2023-018, in preparation]



[Meng-Lin Du et al.]







Some peaking structures
that might become pentaquarks
with more statistics

$\Lambda_c^+ D^0$ in b-decays

The decays $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^-$ are observed.

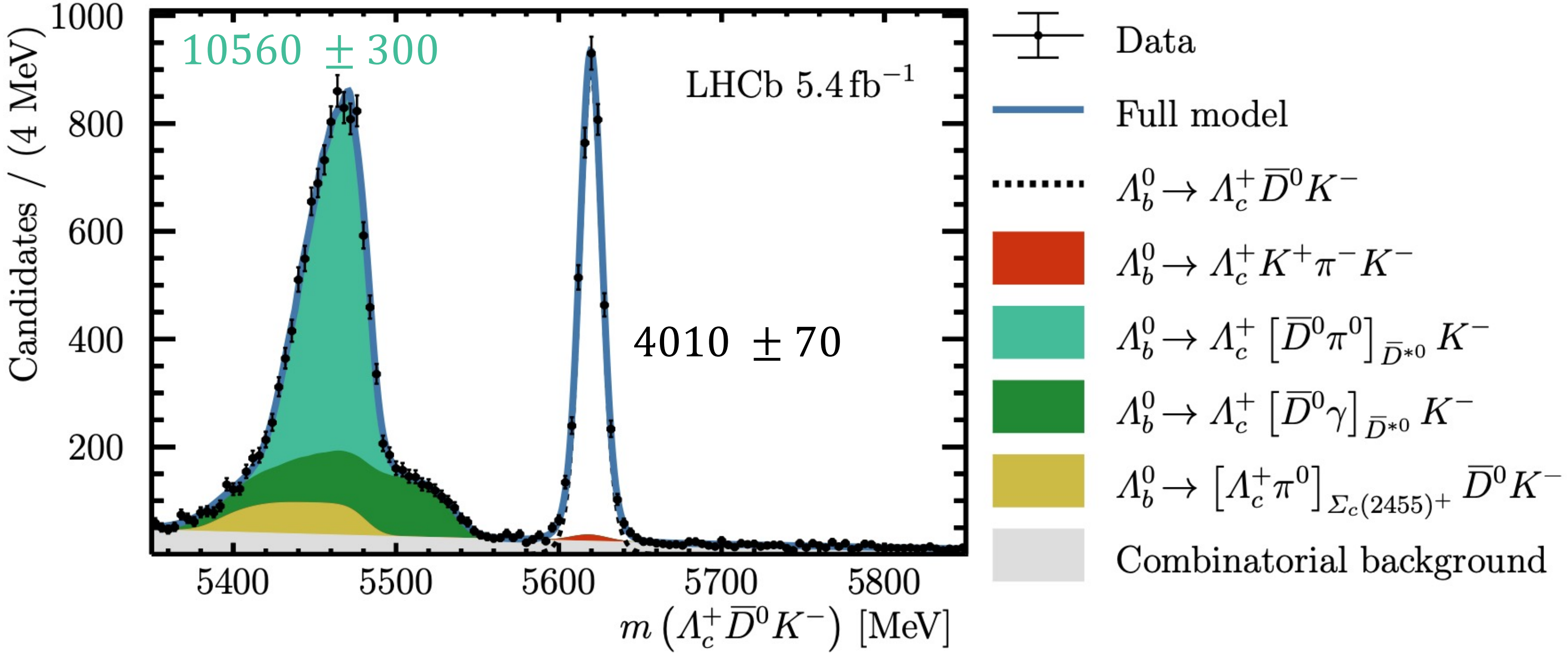
Dalitz plot is populated by

- $D_s^{**-}(\to \overline{D}^0 K^-)$, and
- $\Xi_c^{**0}(\to \Lambda_c^+ K^-)$

states

Searches for pentaquark contributions are ongoing.

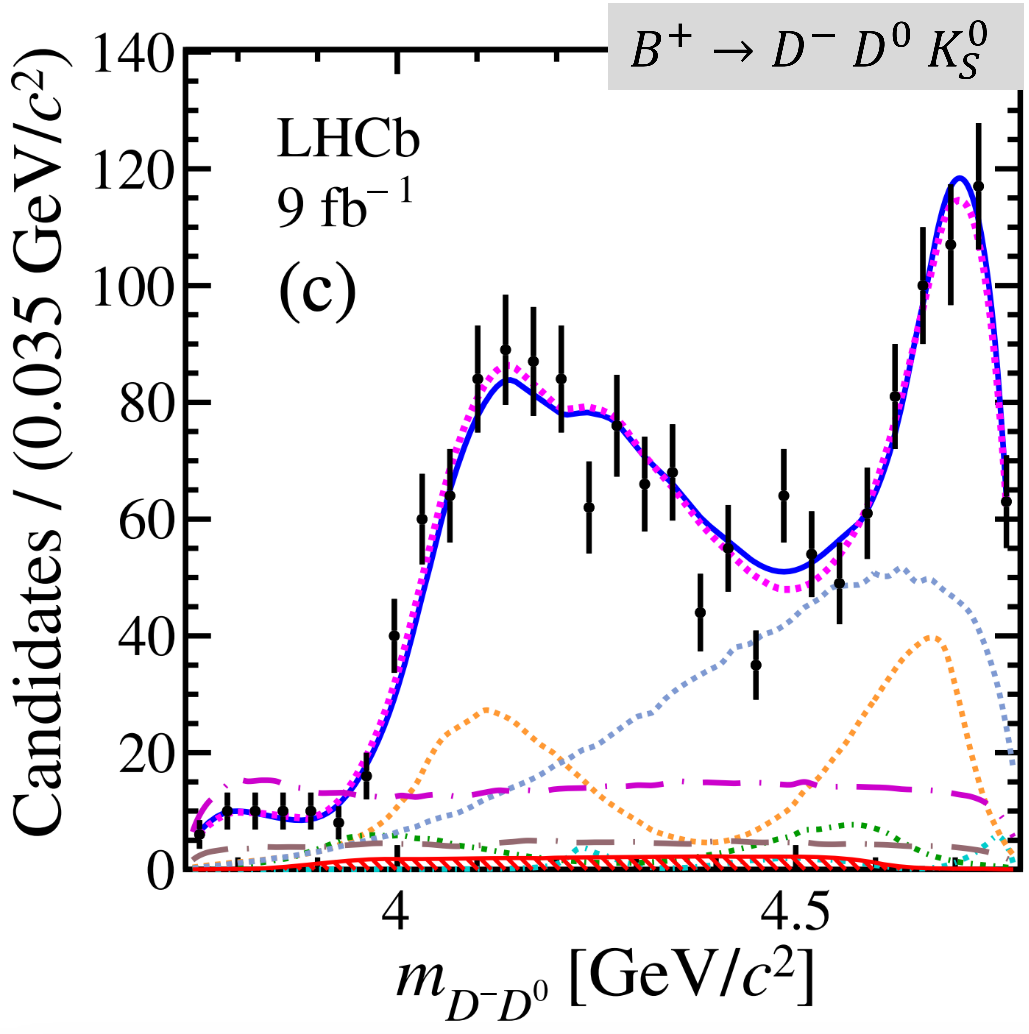
$\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^-$



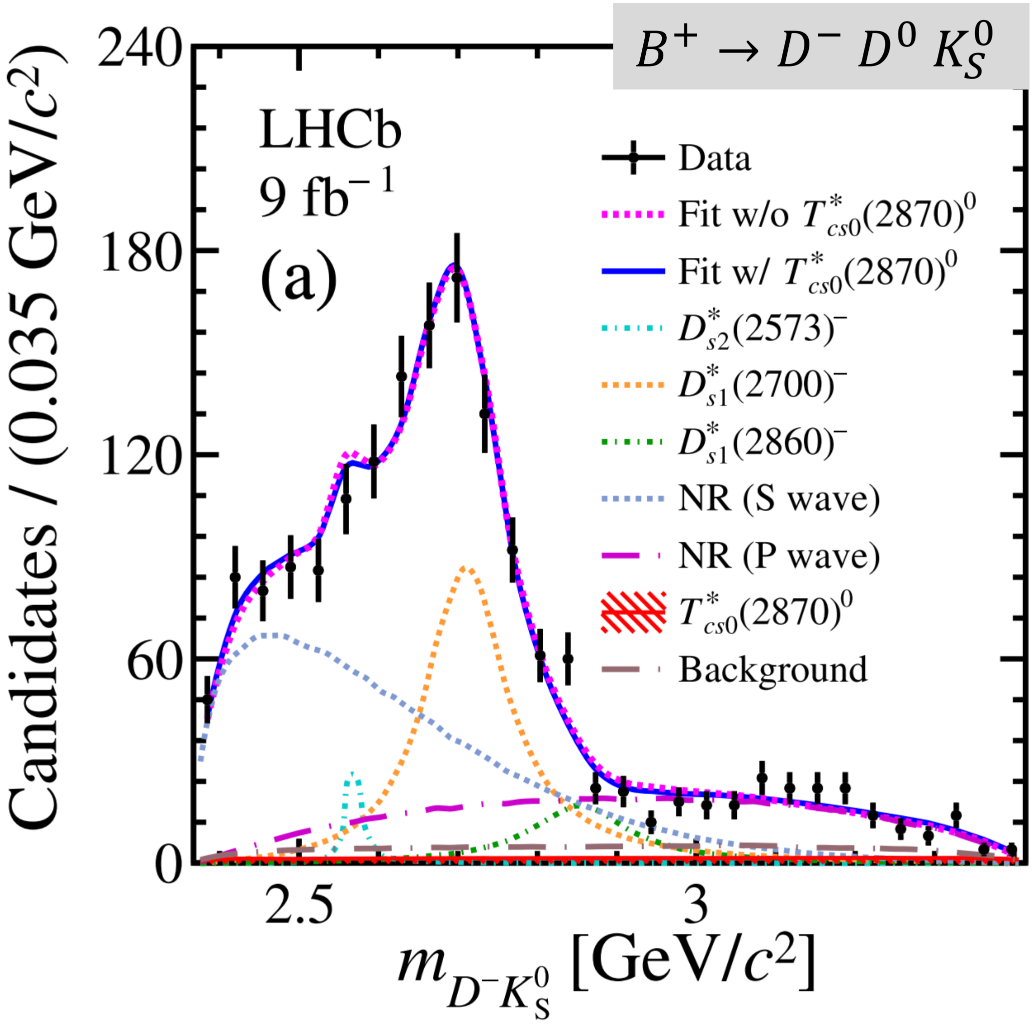
More on B -> DDH

Charmonium and D_s^{**} mesons in $B^+ \to D^- D^0 K_S^0$

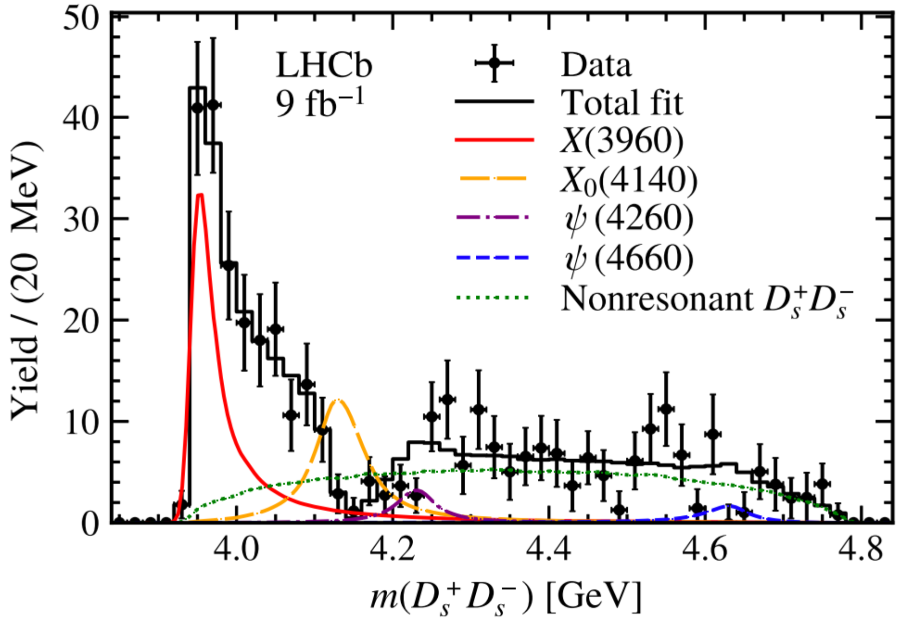
[PRL 134 (2025) 10, 101901]

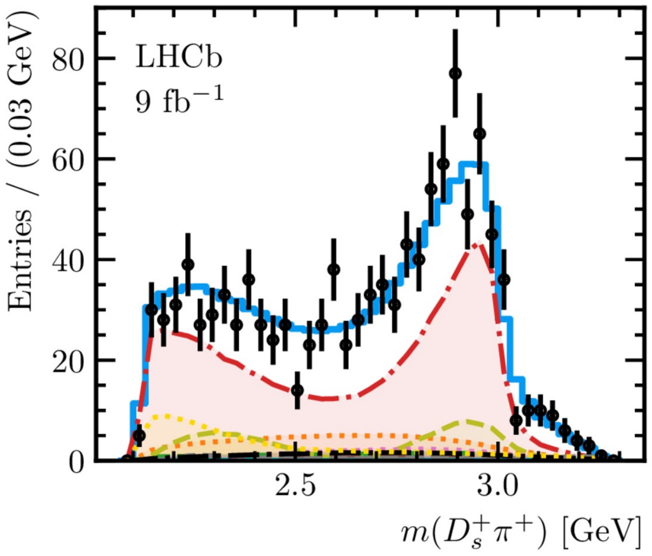


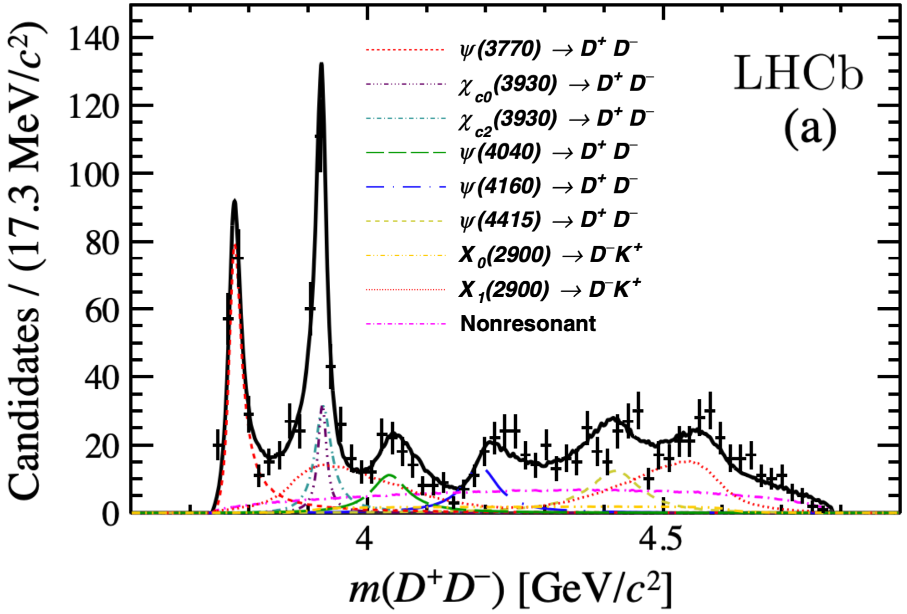
[PRL 134 (2025) 10, 101901]

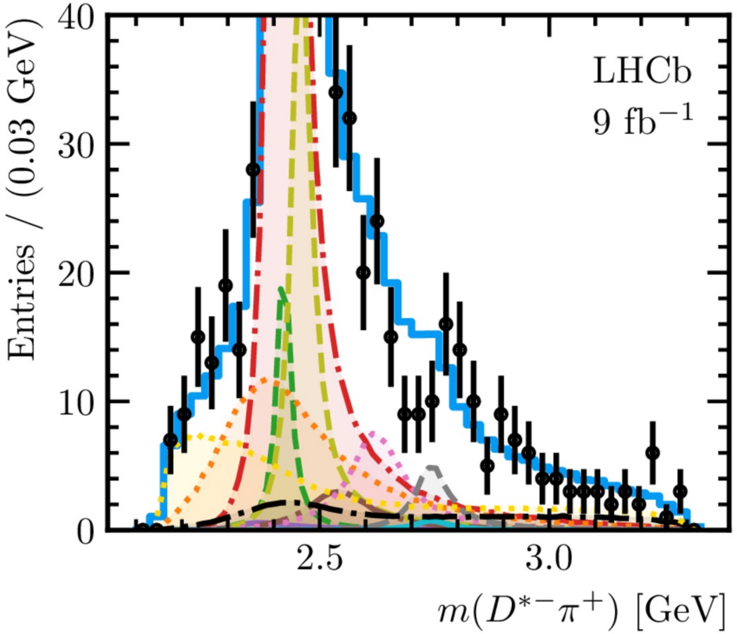


[PRL 125 (2020) 242001]
[Phys.Rev.D 102 (2020) 112003]
[JHEP 08 (2024) 165]









More on trigger

No level zero hardware trigger anymore