Open-flavor tetraquarks from LHCb

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13/11/2024

Experiment

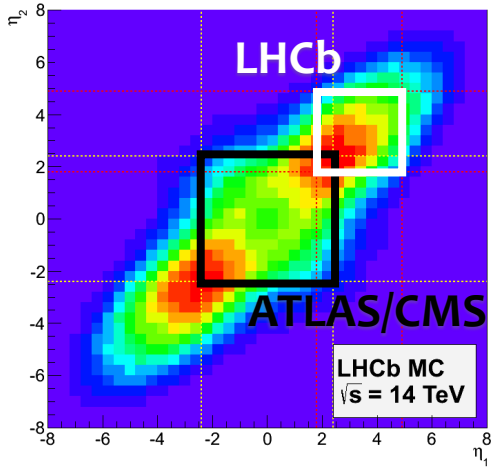
LHCb@CERN: heavy flavor quarks factory

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

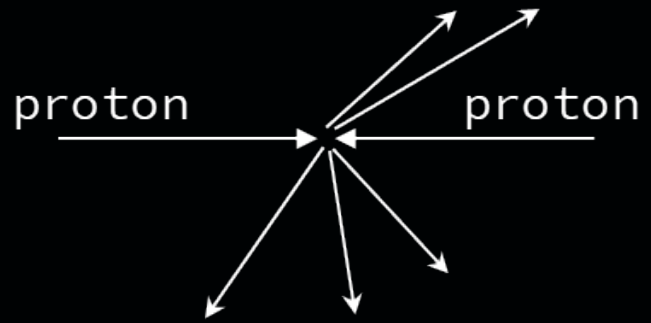
High track multiplicity



b-quark product cross-section

[detector, performance, event display]

The LHCb experiment



VeLo RICH1 Tracker Magnet RICH2 Tracker Calorimeters Muon stations

Upgraded detector

Software only trigger

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

New RICH2 optics
new sensors and readout for RiCH

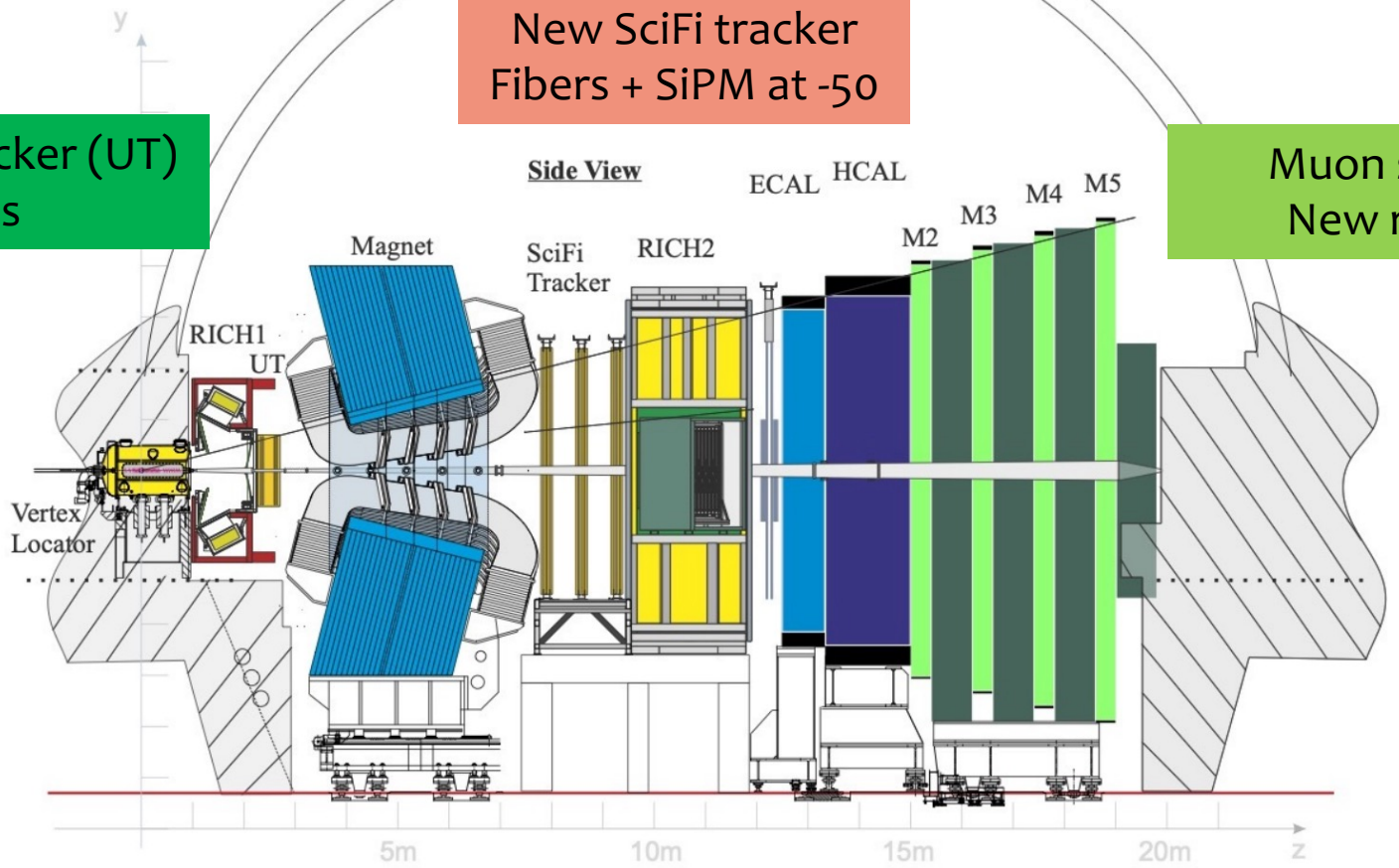
Calo: removed preshawer,
Scintillating Pad Detector, new readout

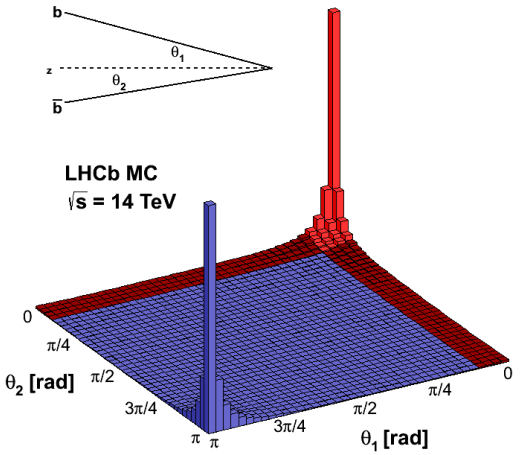
New SciFi tracker
Fibers + SiPM at -50

New Upstream Tracker (UT)
Silicon strips

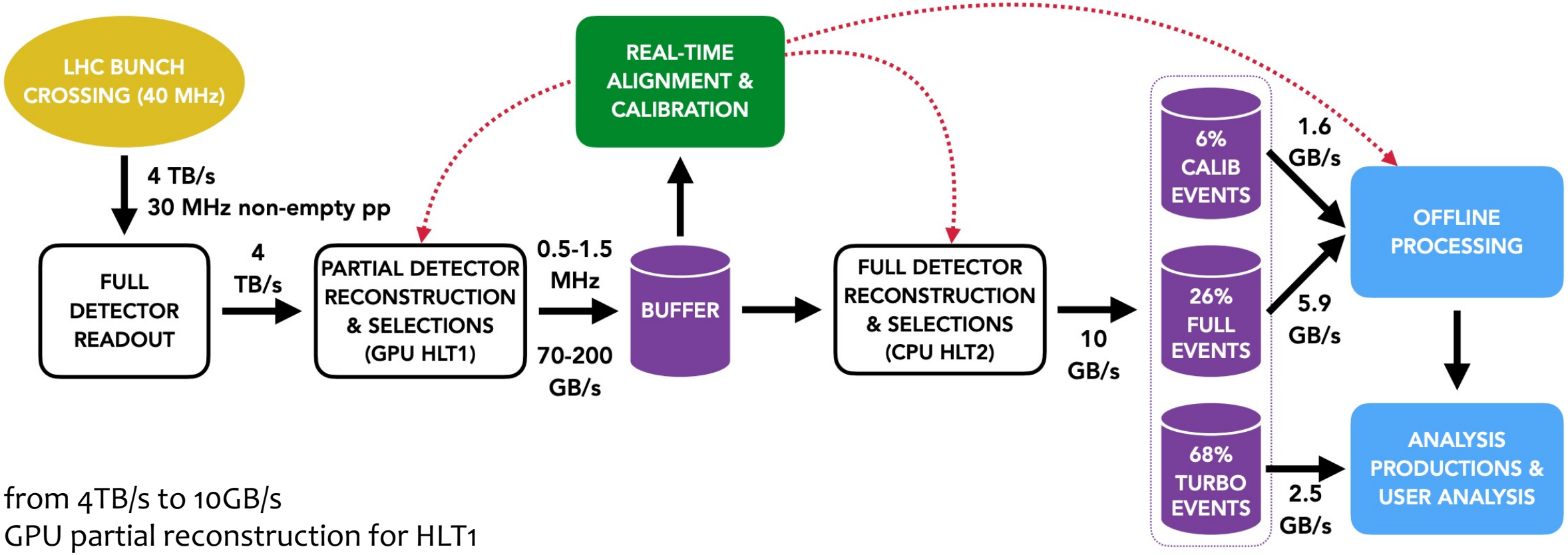
Muon stations:
New readout

New VeLo
Pixel detector





Trigger



from 4TB/s to 10GB/s
GPU partial reconstruction for HLT1
CPU full reconstruction for HLT2

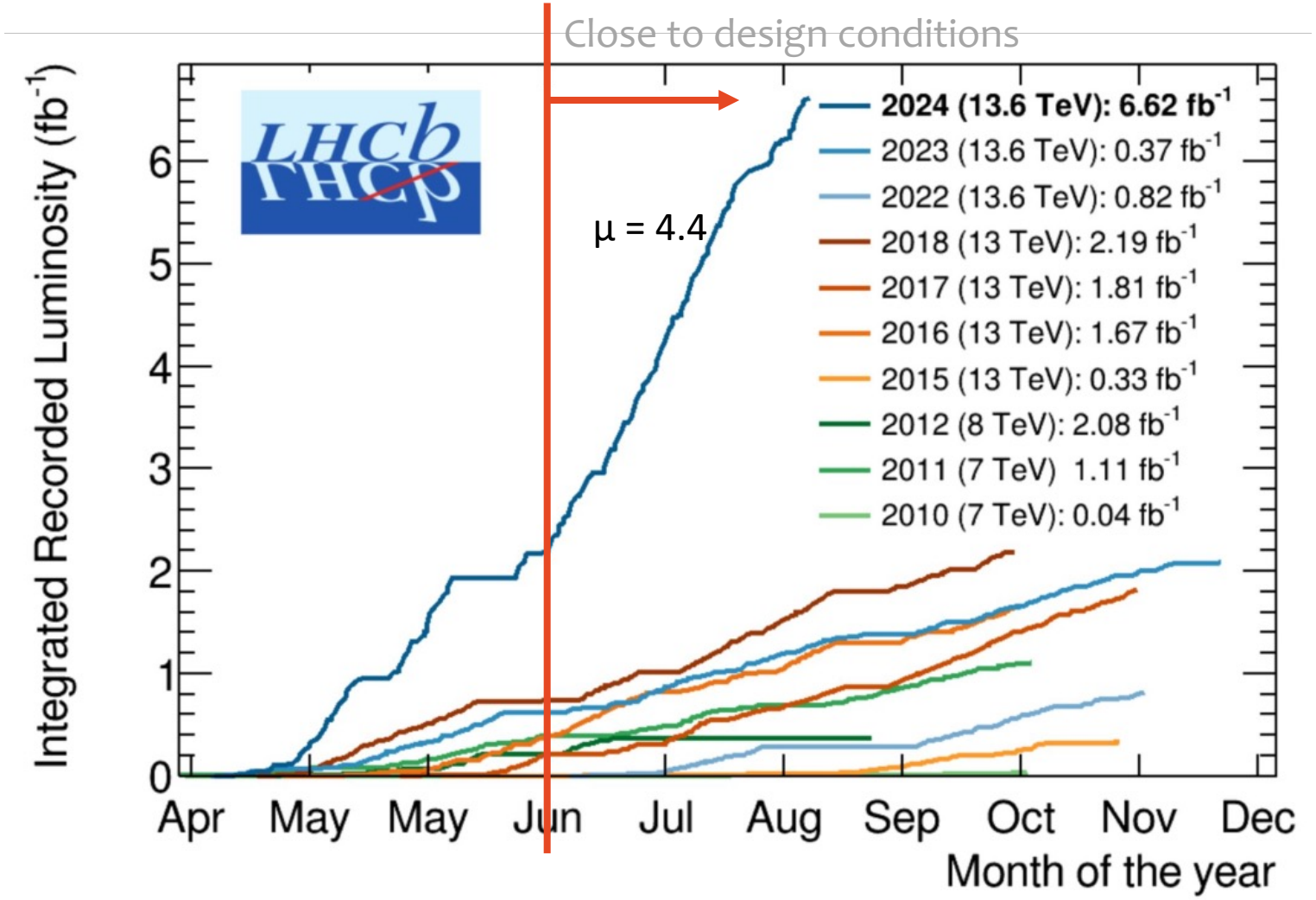
Data taking at LHCb

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

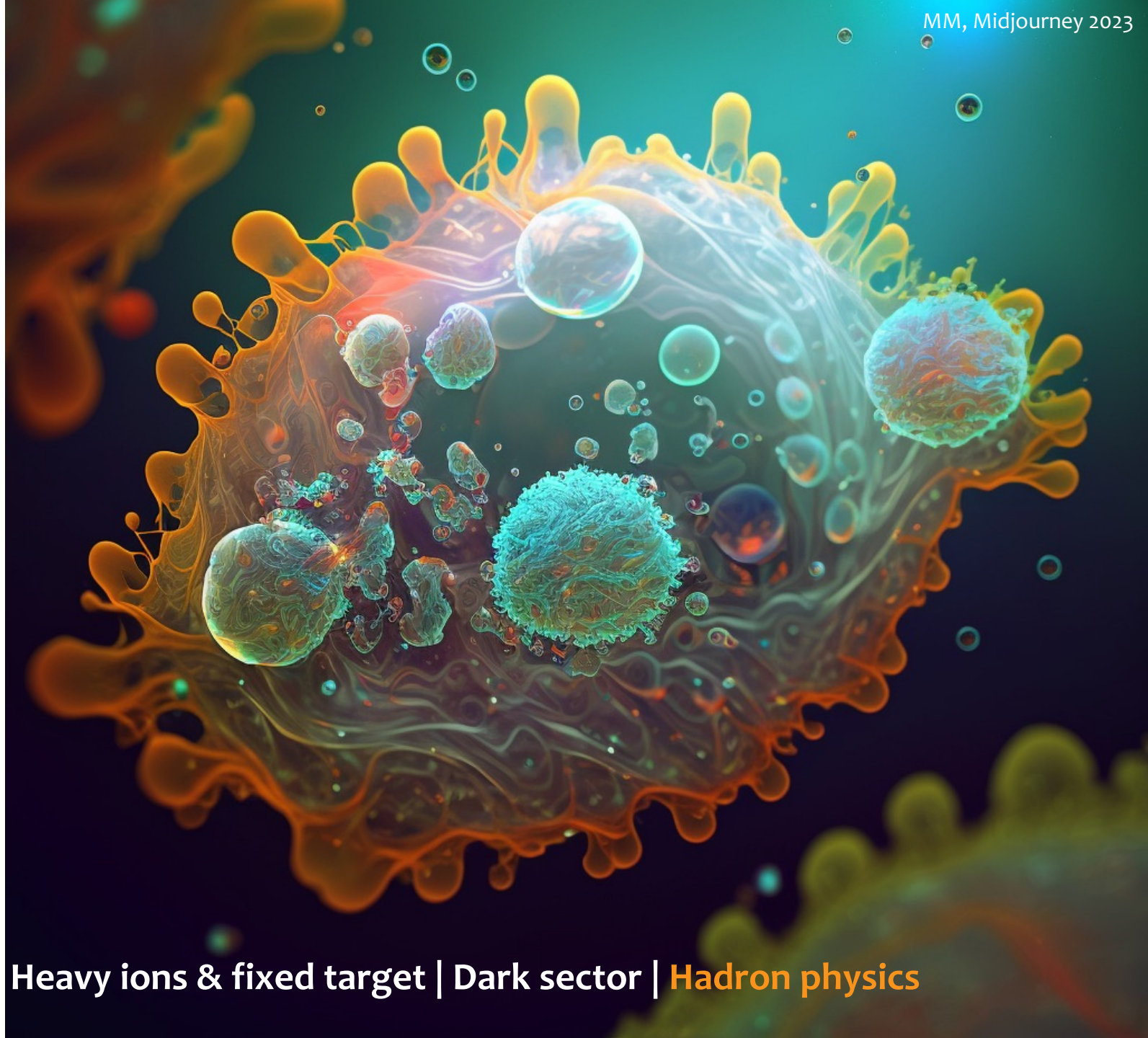
Run 2: (2015-2018):
$\mathcal{L}_{\text{int}} = 6\ \text{fb}^{-1}$ @ 13 TeV

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

Target of $7\ \text{fb}^{-1}$ is archived in September



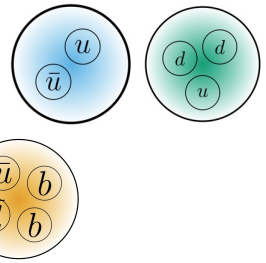
Physics



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

Possible configurations of hadrons

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

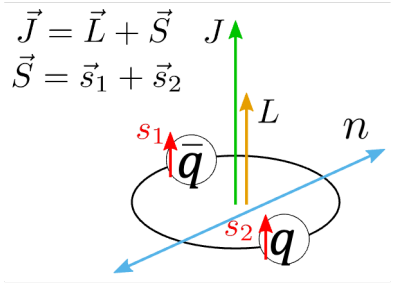


Bigger Quark Model $(q\bar{q}q\bar{q}, qqqq\bar{q}, \dots)$

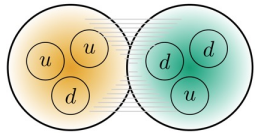
Conventional Hadronic Molecules = Nuclei: $(qqq)(qqq)$

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

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



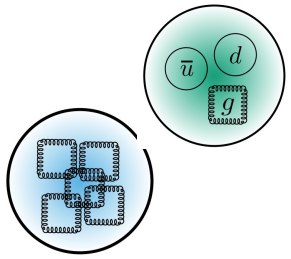
+ excitations



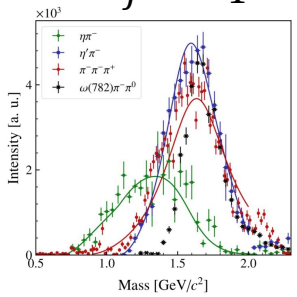
+ nuclei chart

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

Glueballs: $g{\sim}g$



$J^{PC} = 1^{-+}$



[P.Haas, HADRON2023]

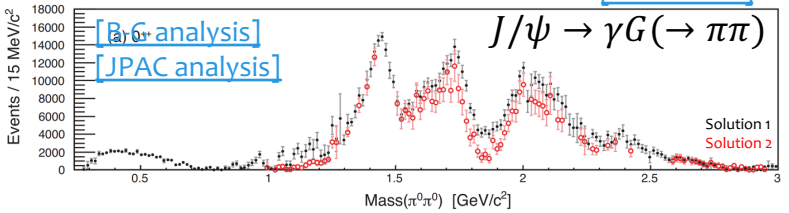
[D. Spülbeck, B3 / 194]

[BESIII data]

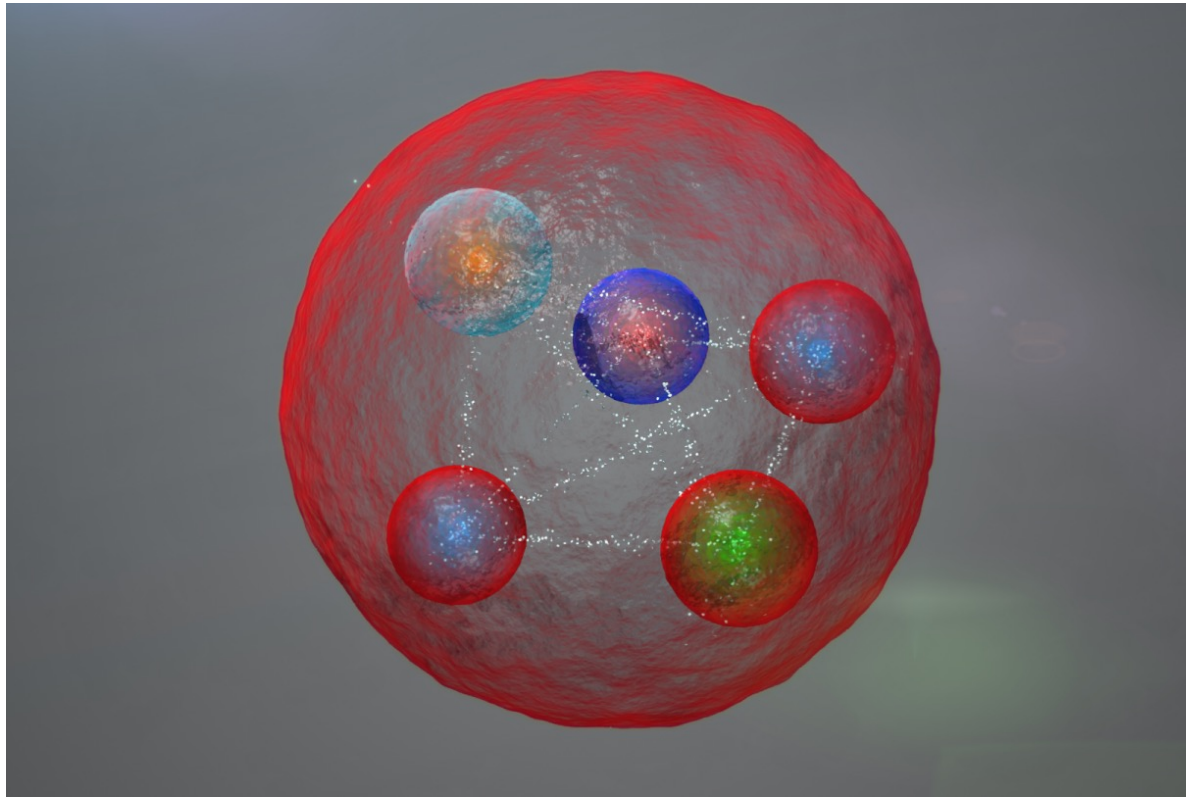
[BGS analysis]

[JPAC analysis]

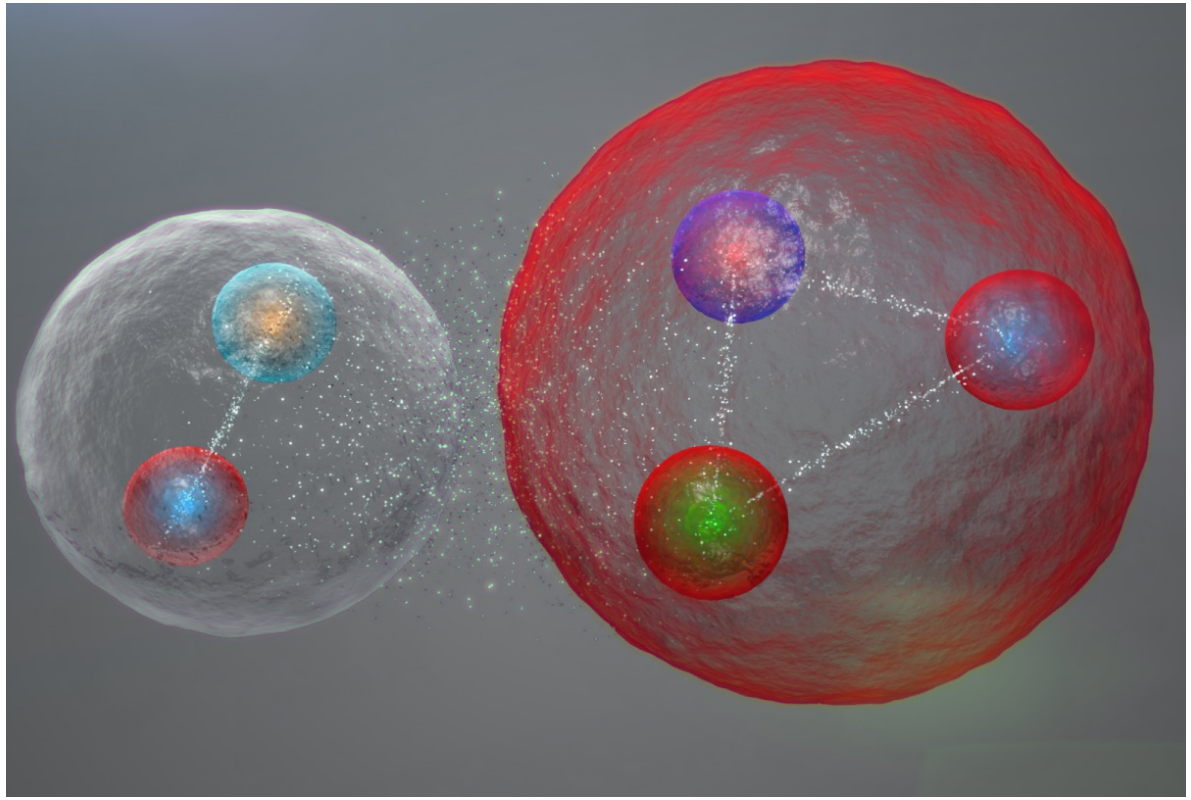
$J/\psi \rightarrow \gamma G(\rightarrow \pi\pi)$



“Compact pentaquark”



“Hadronic molecule”

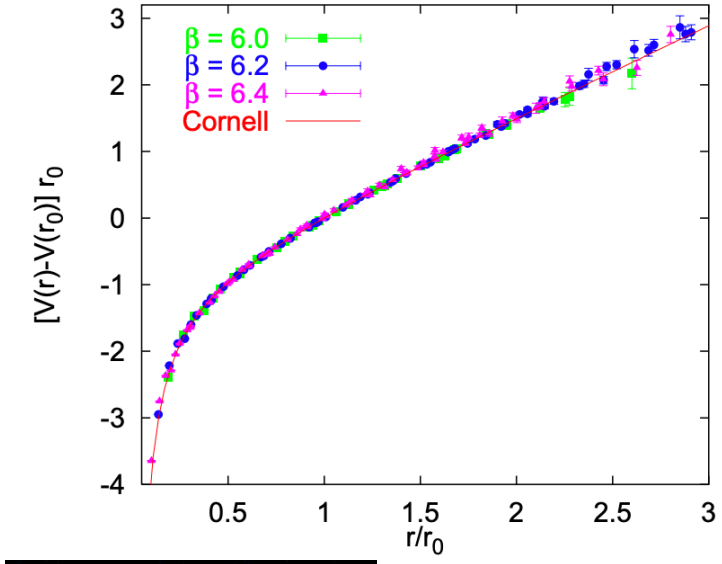


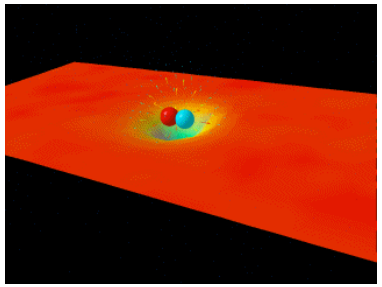
In fact, **quark-model states** are coupled to **continuum** (hadron-hadron),
and have ~100% of wave function as a molecule if near threshold.
Q: does meson-exchange interaction provide sufficient binding? (molecules in absence of contract QM seed)

Effect of string breaking

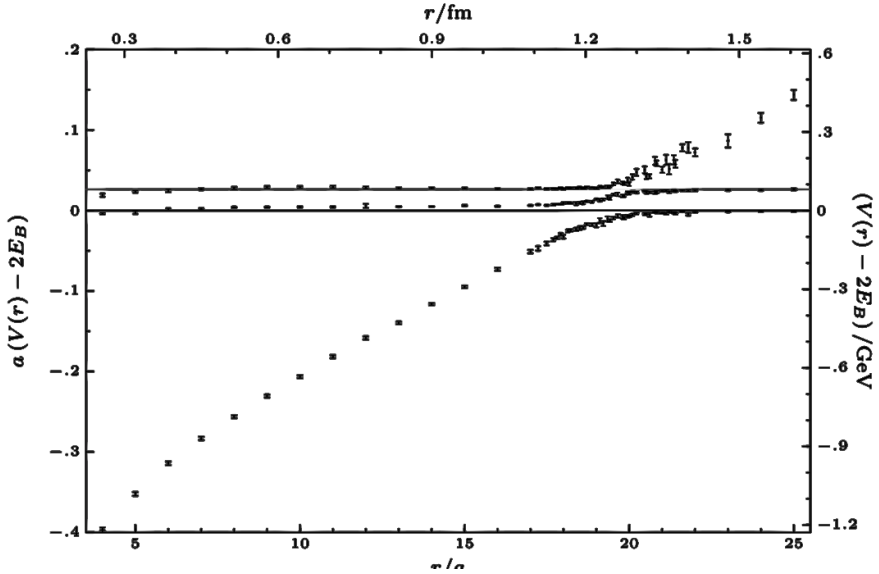
[G.S.Bali, PR 343 (2001) 1-136]
[D. Leinweber, CSSM, Adelaide]
[J. Bulava et al., PLB 793 (2019) 493-498]

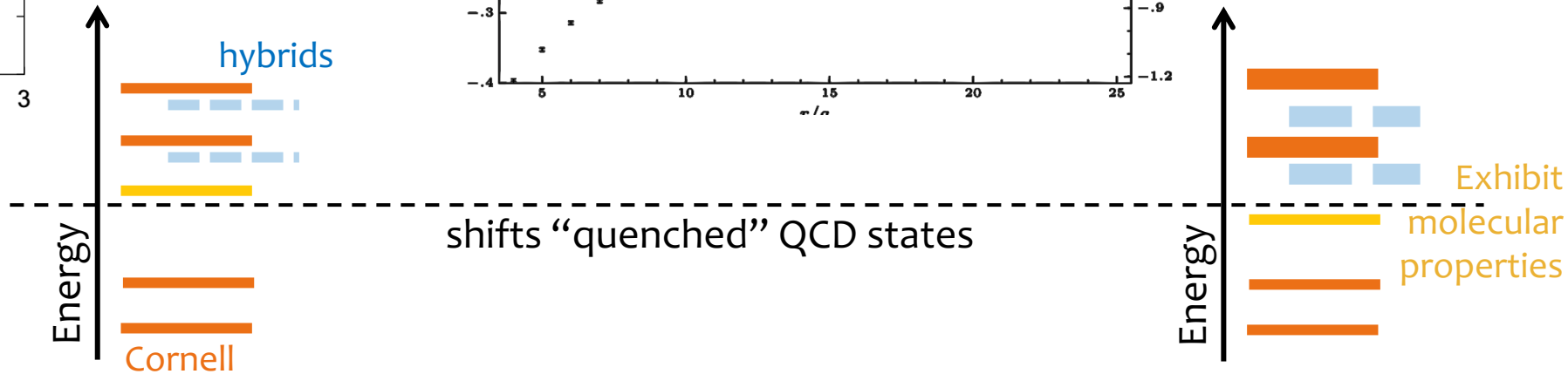
The quenched potential (no breaking)





The unquenched potential (breaking)



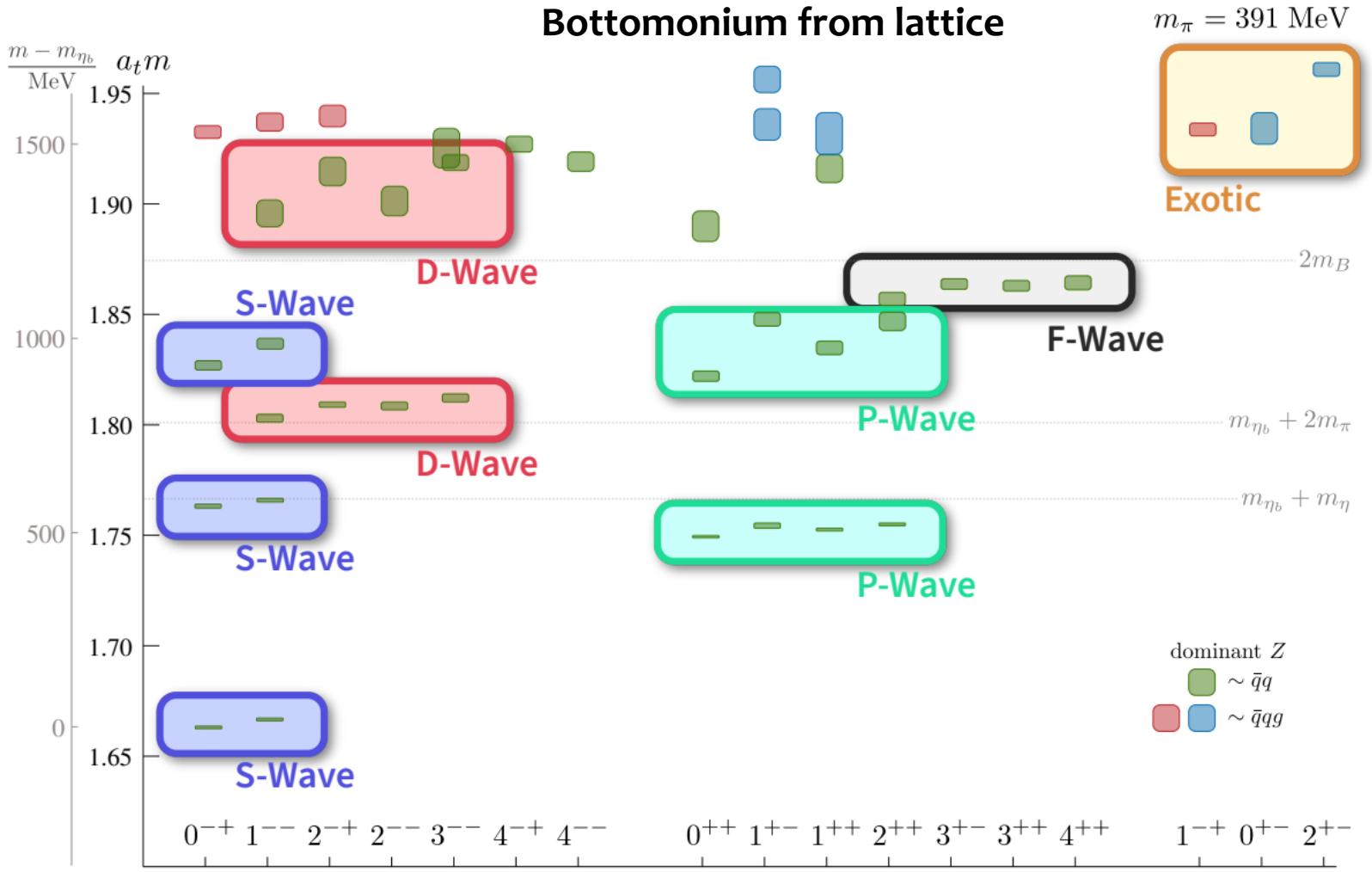


[HadSpec, JHEP 02 (2021) 214]

Pattern of meson excitation

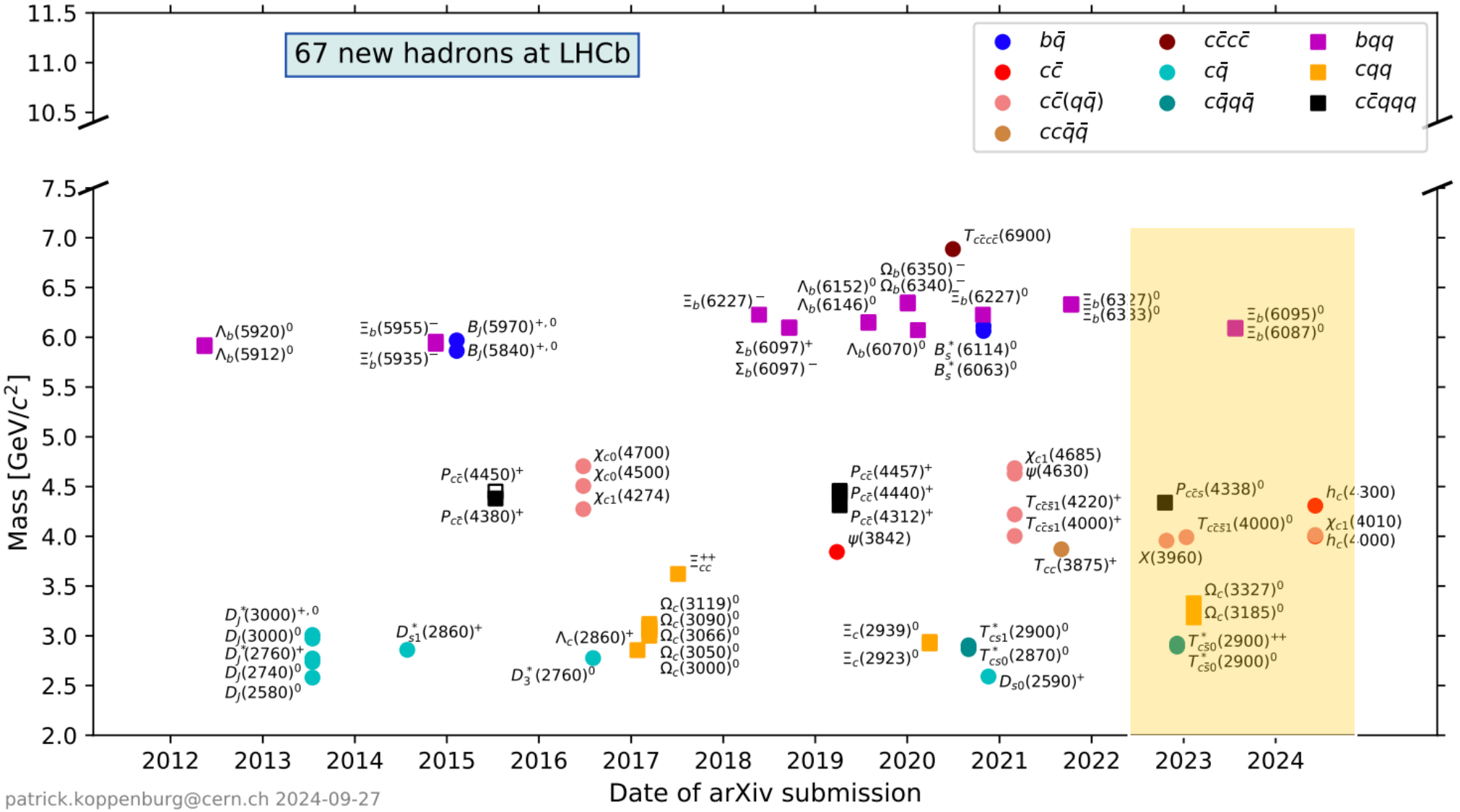
Same patter for all mesons:

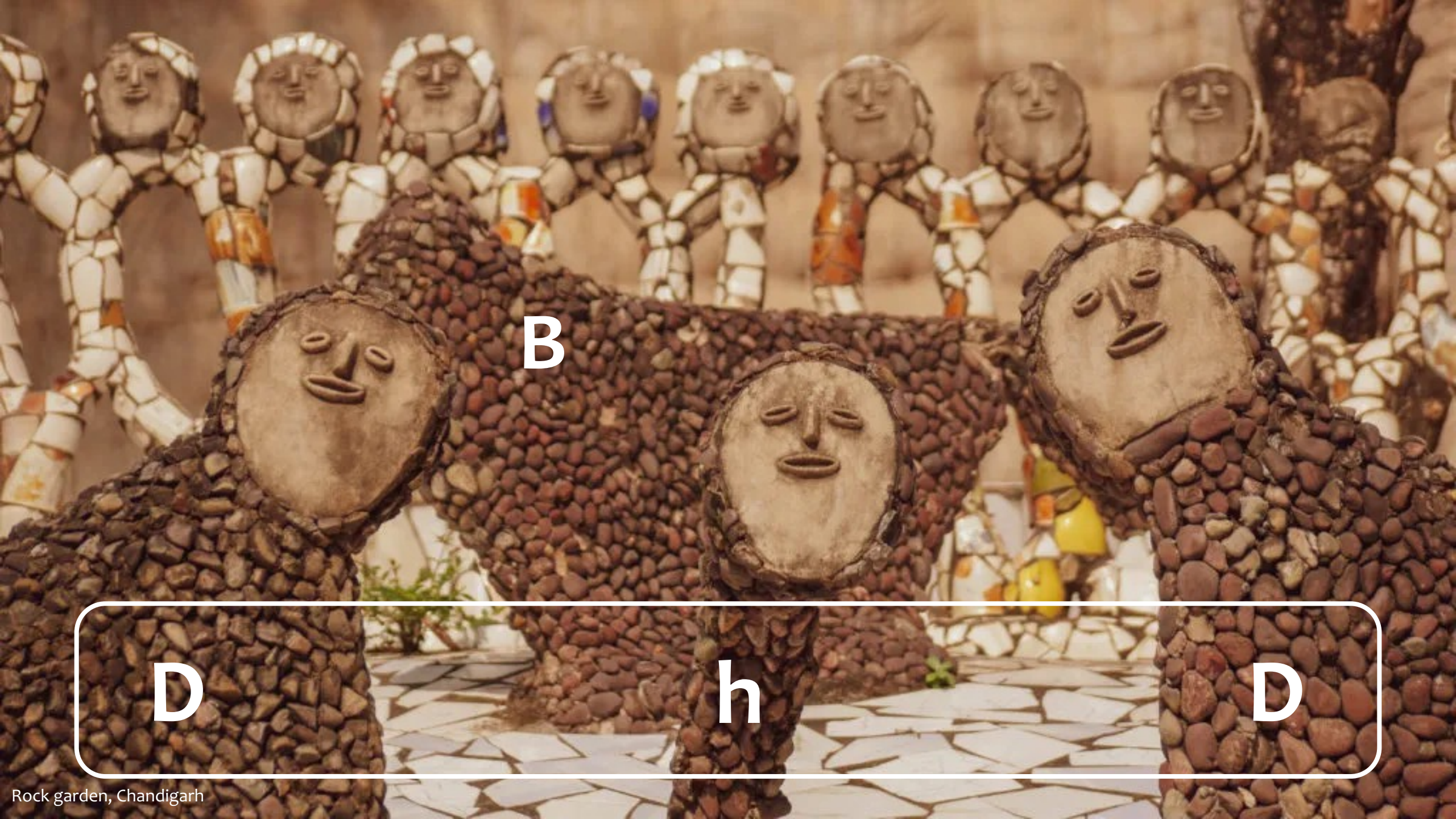
- Radial excitation
- Orbital excitation
- Hyper-fine splitting within every multiplet
  - 2 line for S-wave,
  - 4lines for L>0



New particles

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

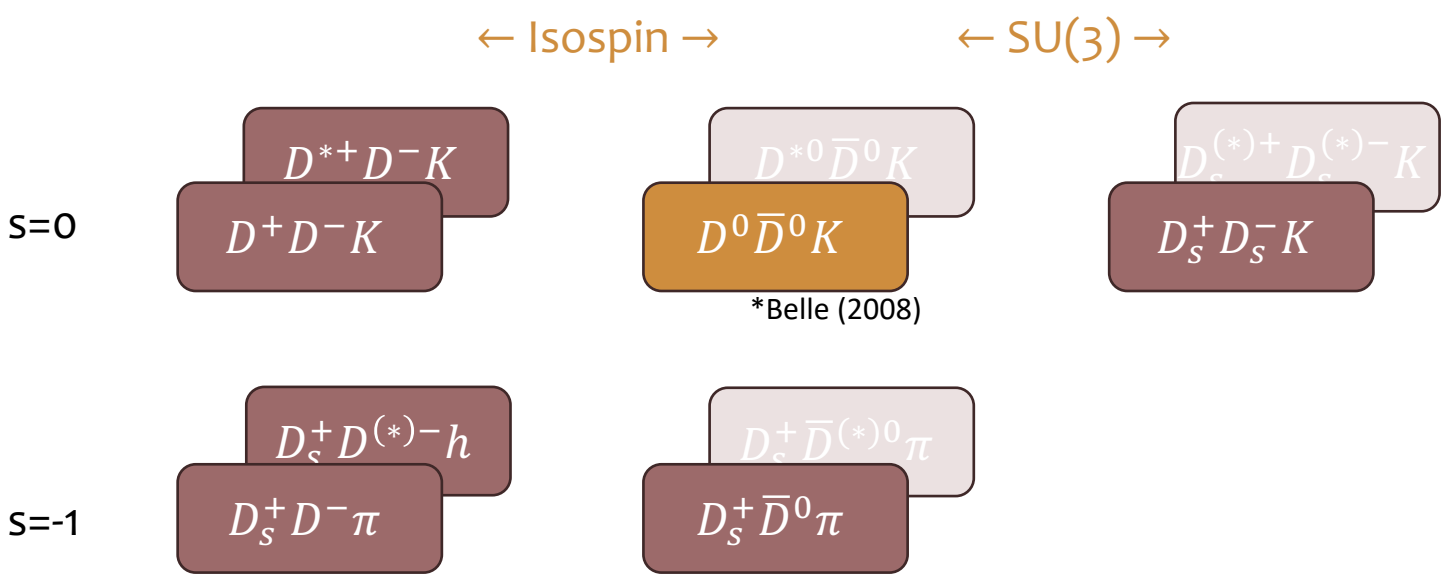




Rock garden, Chandigarh

B → D D h studies

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



*Belle (2008)

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

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

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

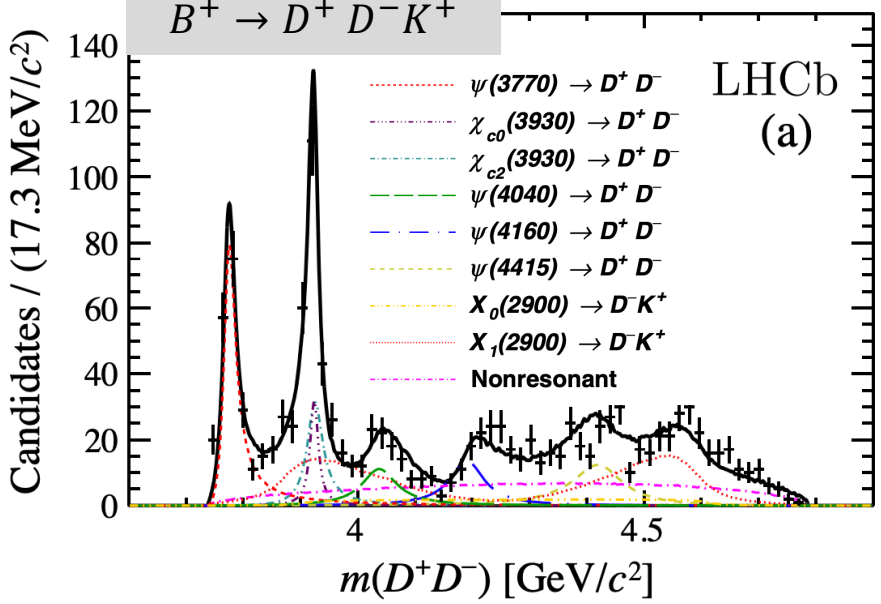
2. excited D states:
$D^{+}\pi^{-} : D_s^{+}\,K^{-}$

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

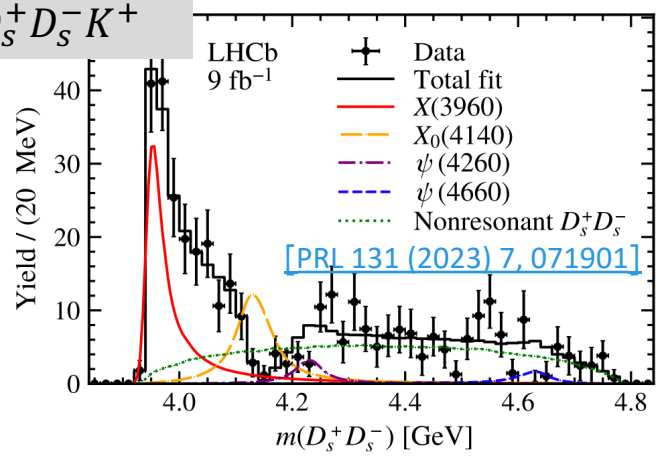
4. exotic T_{cs} states:
$D^{+}K^{-}$

Charmonium

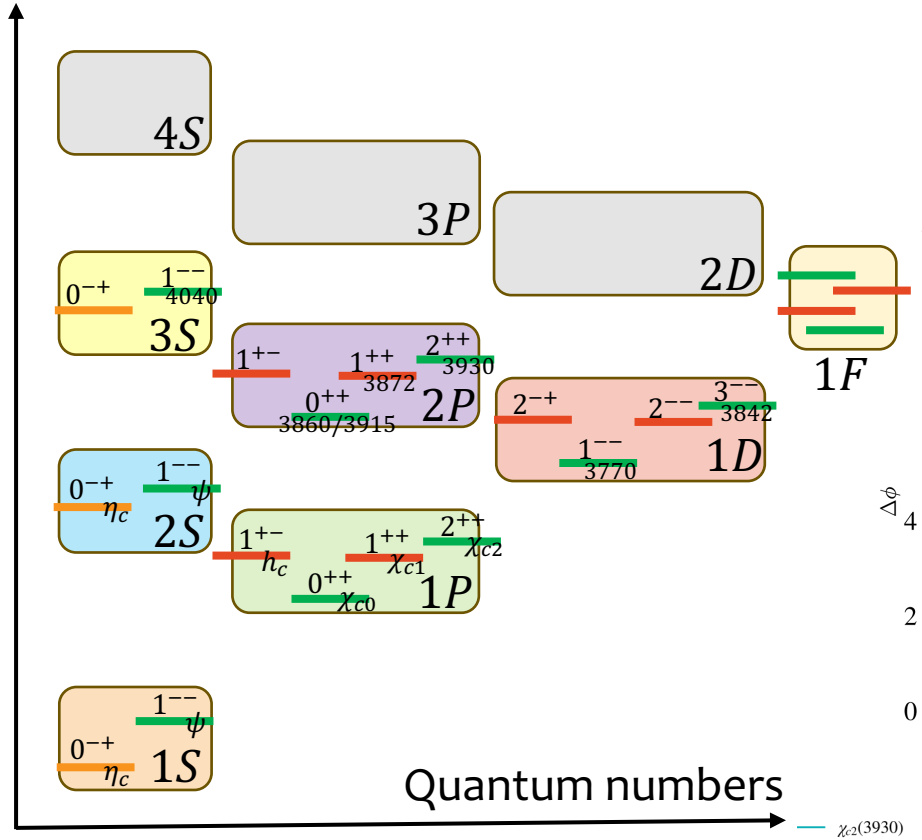
$B^+ \to D^+ D^- K^+$ [PRD 102 (2020) 112003]



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



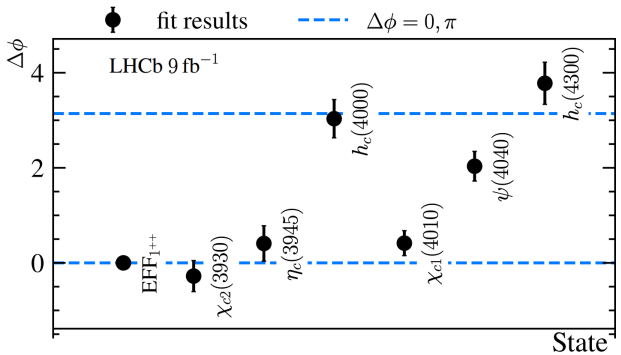
[PRL 131 (2023) 7, 071901]



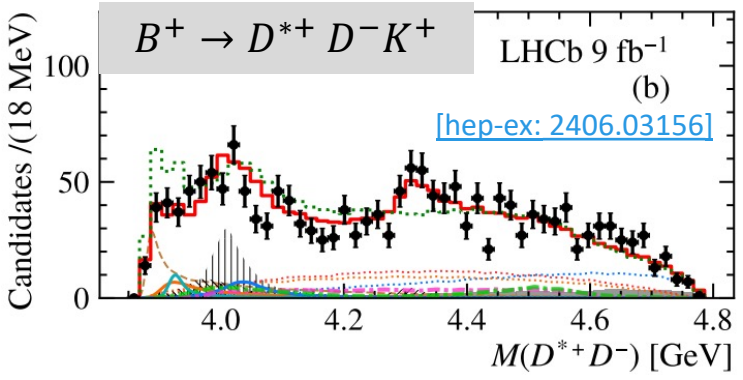
D^+D^-: $0^{++}, 1^{--}, 2^{++}, 3^{--}$

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

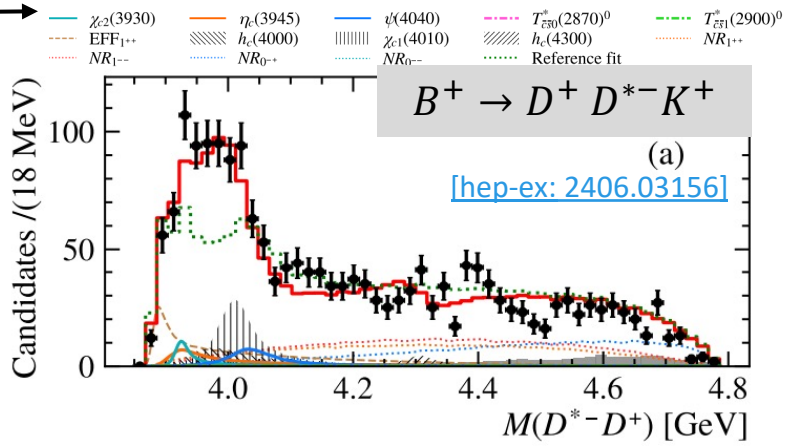
$$|D^*\bar{D}> = \frac{D^{*+}D^- + e^{i\Delta\phi} D^{*-}D^+}{2}$$



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



[hep-ex: 2406.03156]



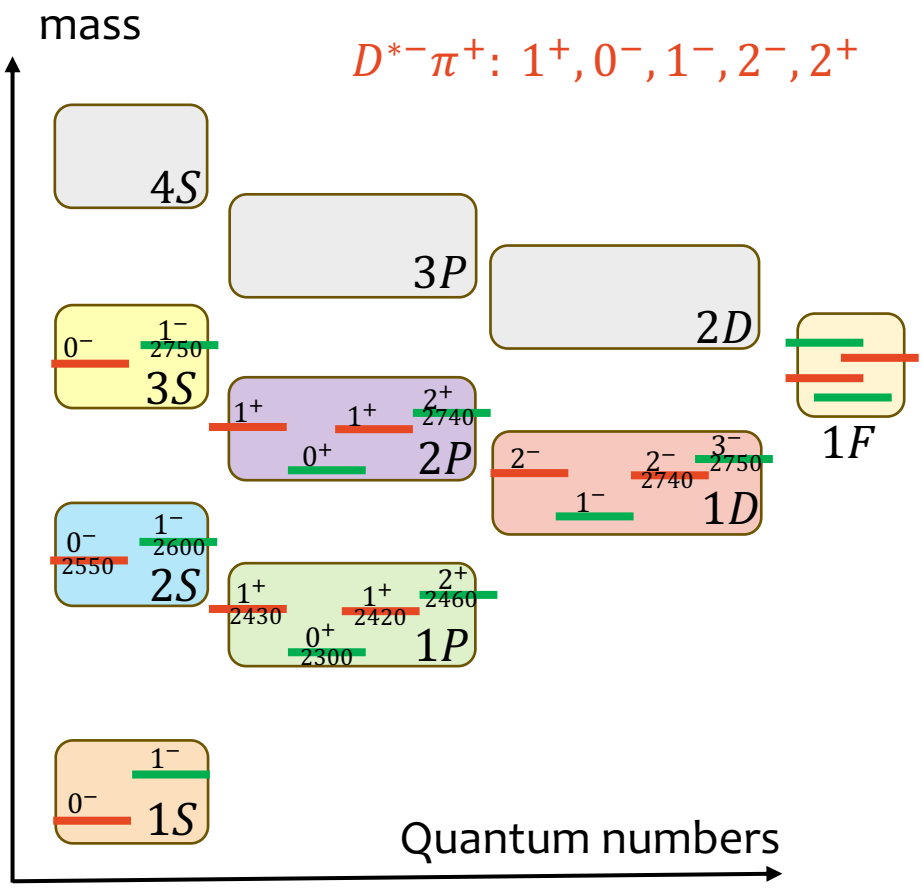
$B^+ \to D^+ D^{*-} K^+$

[hep-ex: 2406.03156]

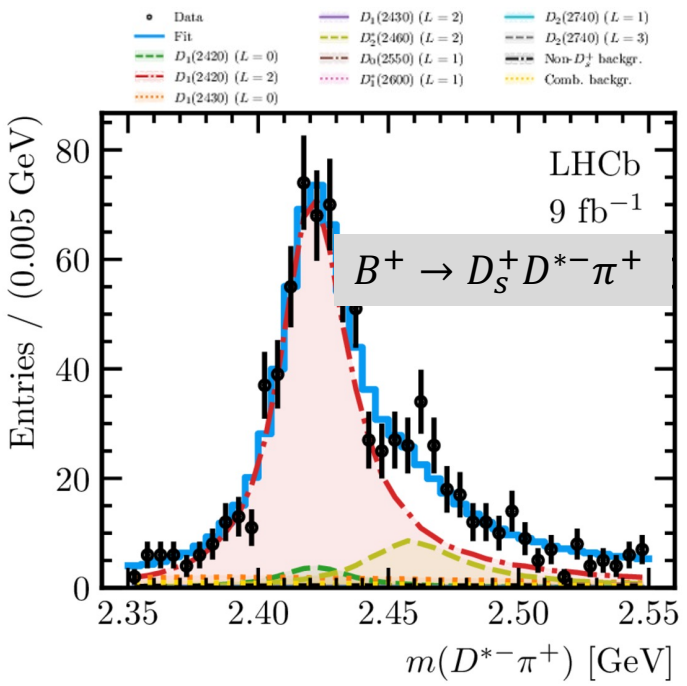
D-meson spectroscopy

$D^-\pi^+$: $0^+, 1^-, 2^+, 3^-$

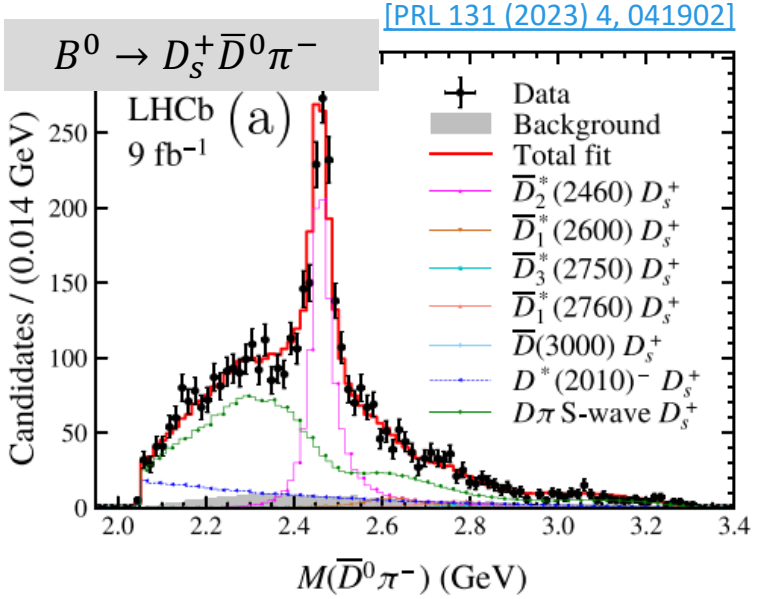
$D^{*-}\pi^+$: $1^+, 0^-, 1^-, 2^-, 2^+$

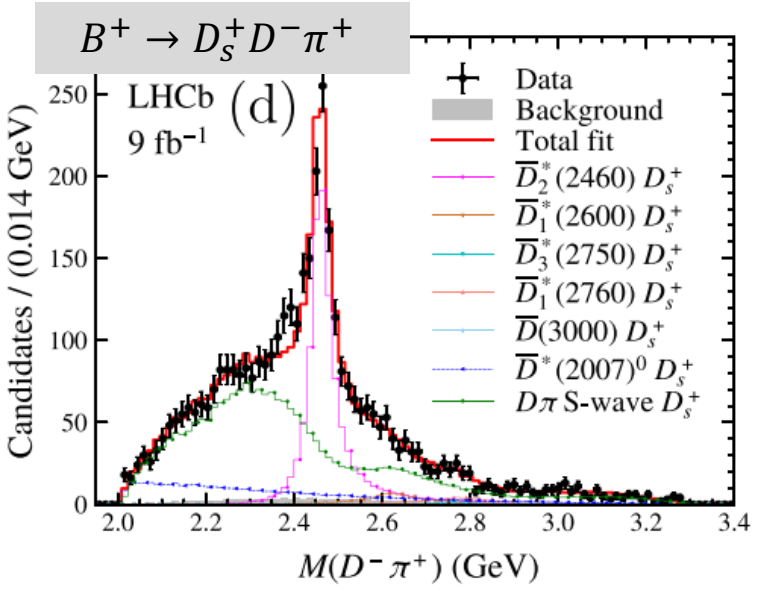


[JHEP 08 (2024) 165]

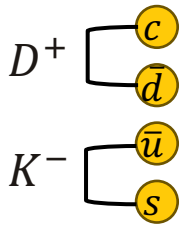


[PRL 131 (2023) 4, 041902]



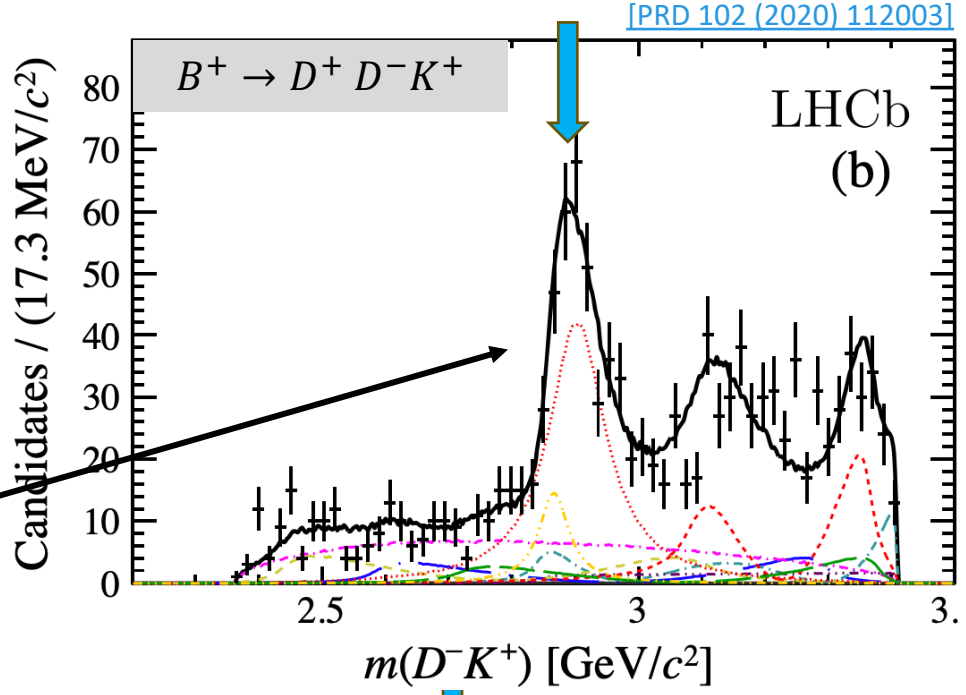


Exotic T_{cs} states

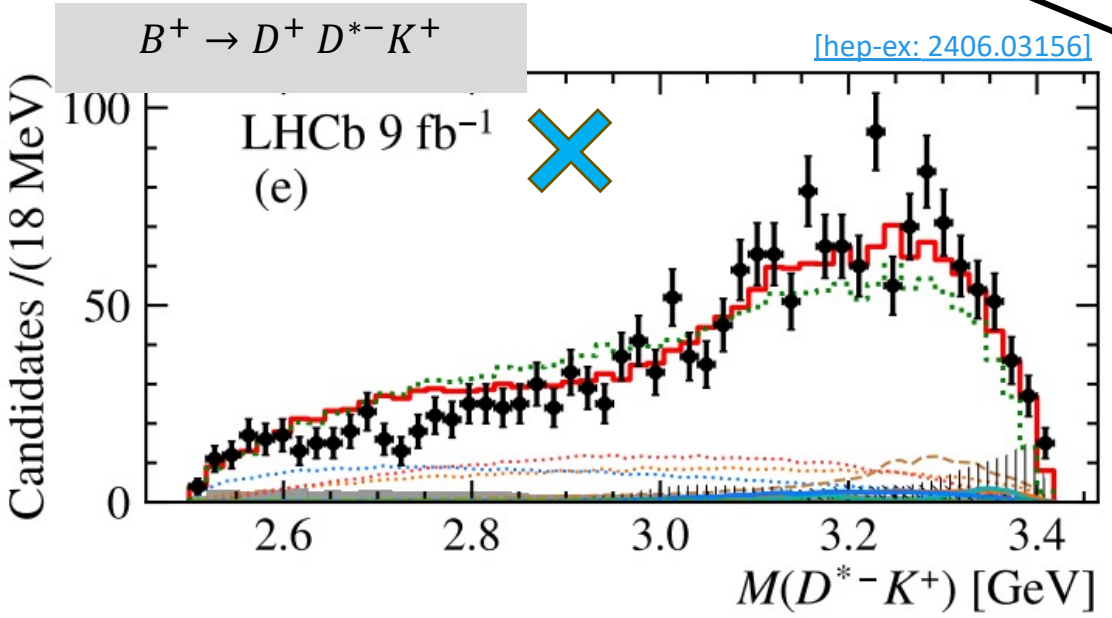


Property	This work	Previous work
$T^*_{\bar{c}s0}(2870)^0$ mass [MeV]	$2914 \pm 11 \pm 15$	2866 ± 7
$T^*_{\bar{c}s0}(2870)^0$ width [MeV]	$128 \pm 22 \pm 23$	57 ± 13
$T^*_{\bar{c}s1}(2900)^0$ mass [MeV]	$2887 \pm 8 \pm 6$	2904 ± 5
$T^*_{\bar{c}s1}(2900)^0$ width [MeV]	$92 \pm 16 \pm 16$	110 ± 12

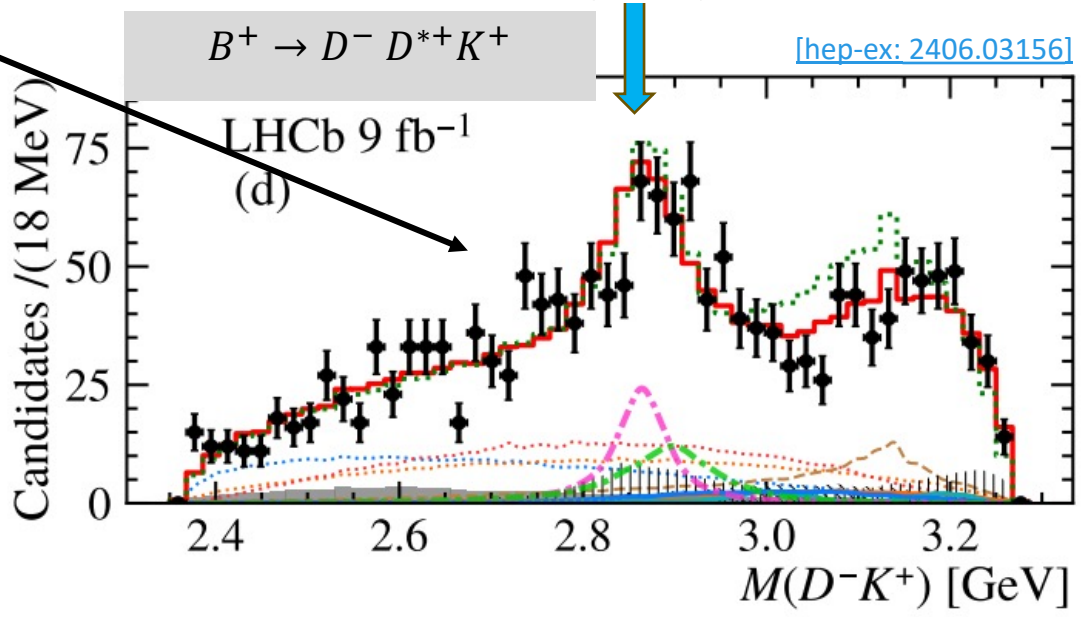
[PRD 102 (2020) 112003]



[hep-ex: 2406.03156]



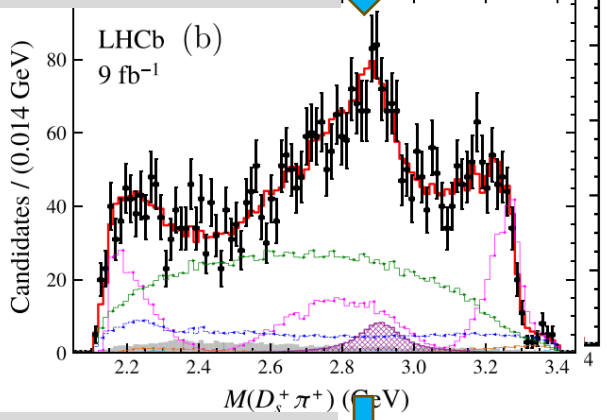
[hep-ex: 2406.03156]



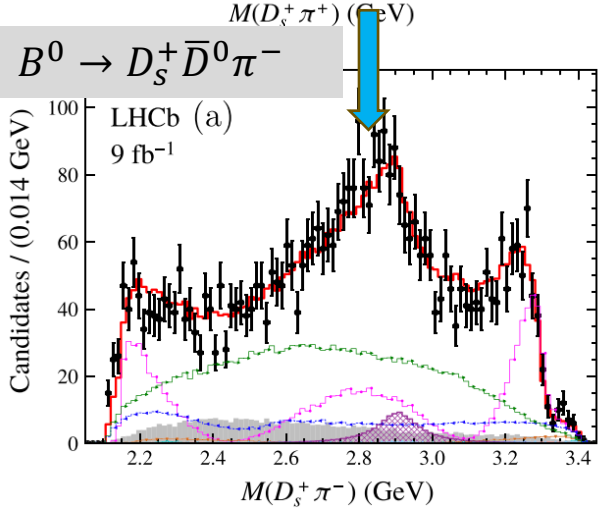
Exotic $T_{c\bar{s}}$ states

[PRL 131 (2023) 4, 041902]

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

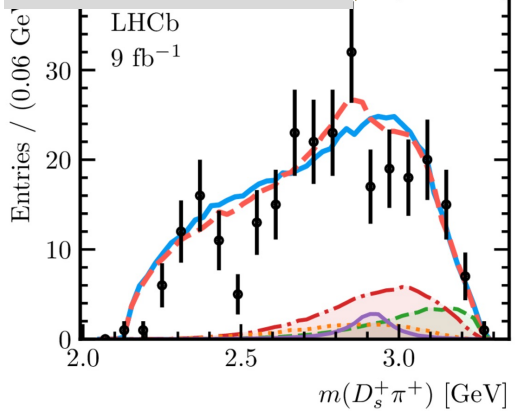


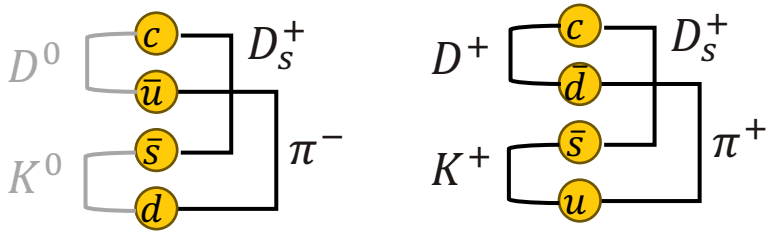
$B^0 \to D_s^+ \bar{D}^0 \pi^-$



[JHEP 08 (2024) 165]

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

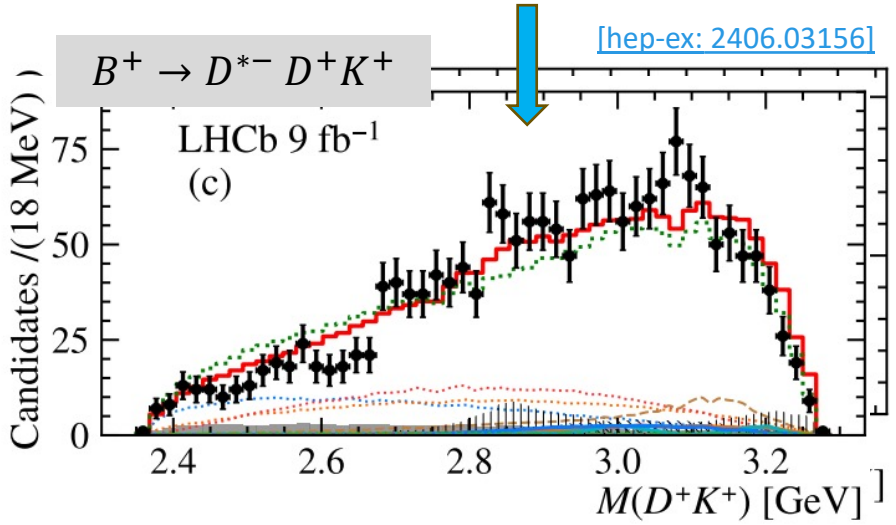




$T_{c\bar{s}}$: $T^0_{c\bar{s}}(c\bar{s}d\bar{u}), T^+_{c\bar{s}}(c\bar{s}d\bar{d}), T^{++}_{c\bar{s}}(c\bar{s}u\bar{d})$

[hep-ex: 2406.03156]

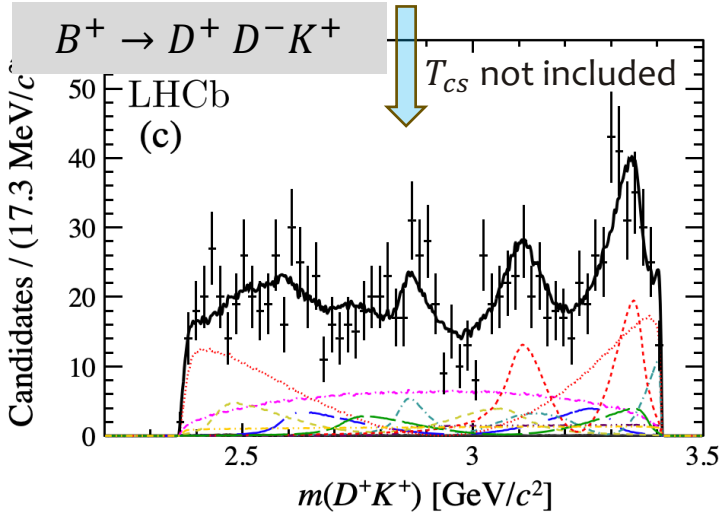
$B^+ \to D^{*-} D^+ K^+$

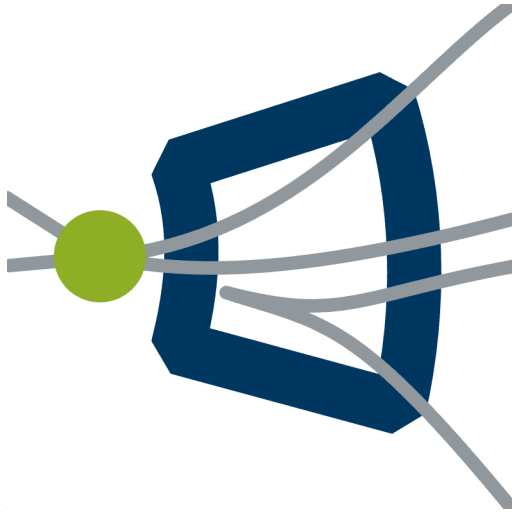


[PRD 102 (2020) 112003]

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

T_{cs} not included





$J/\psi\,\varphi$ states

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

Rich spectrum of previous-unseen states

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

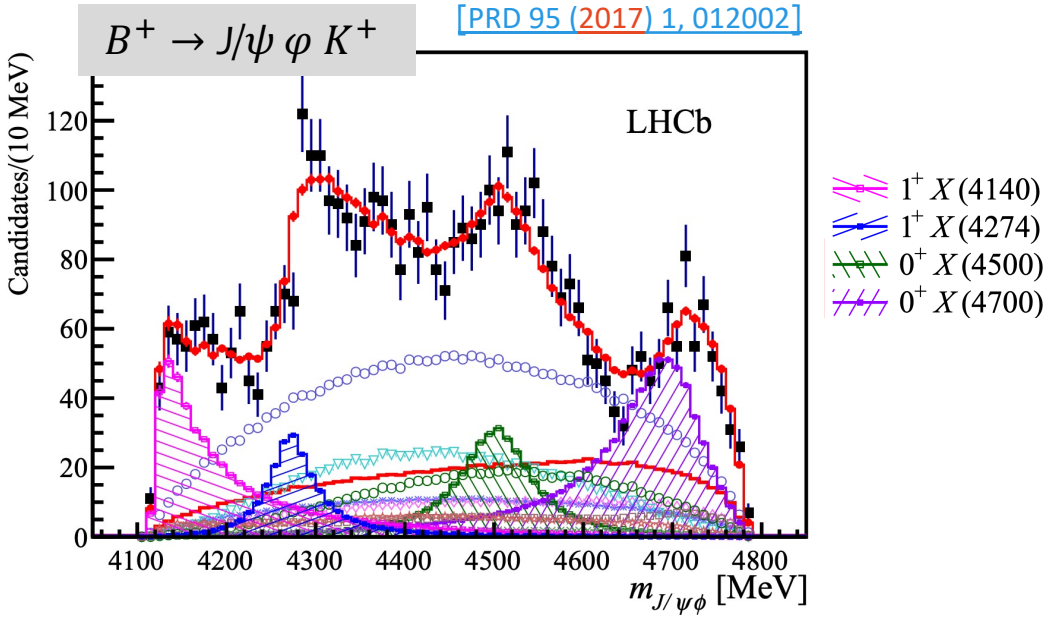
(2017) four babies 0^+ & 1^+

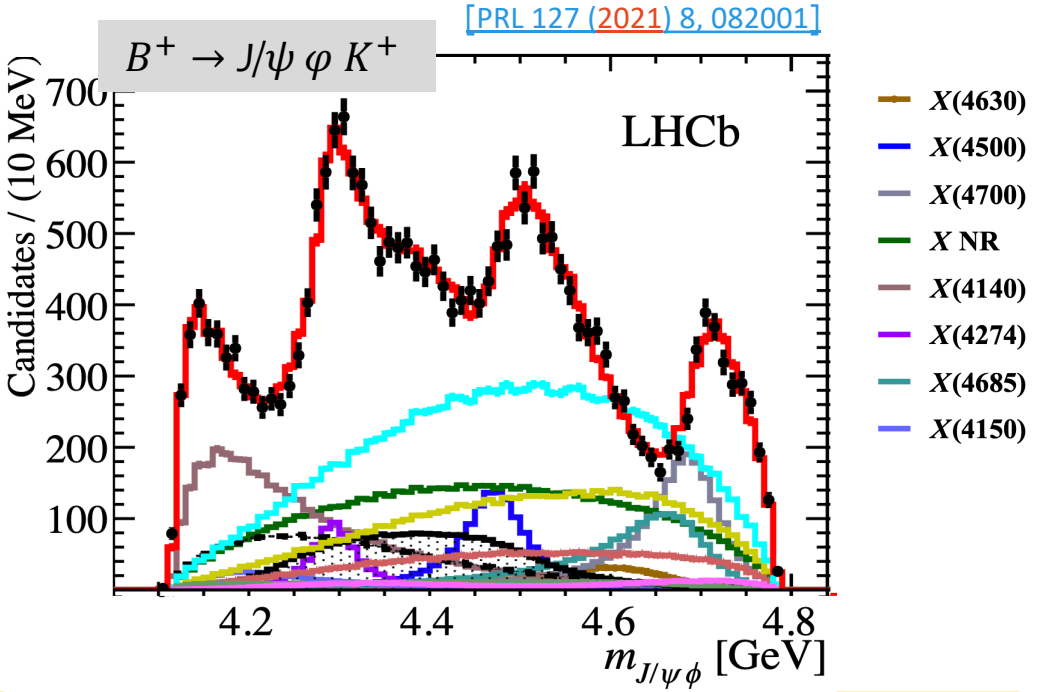
"I wonder if they'll be a doctor or an artist."
- some are probably charmonia, but some are exotic

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

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

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



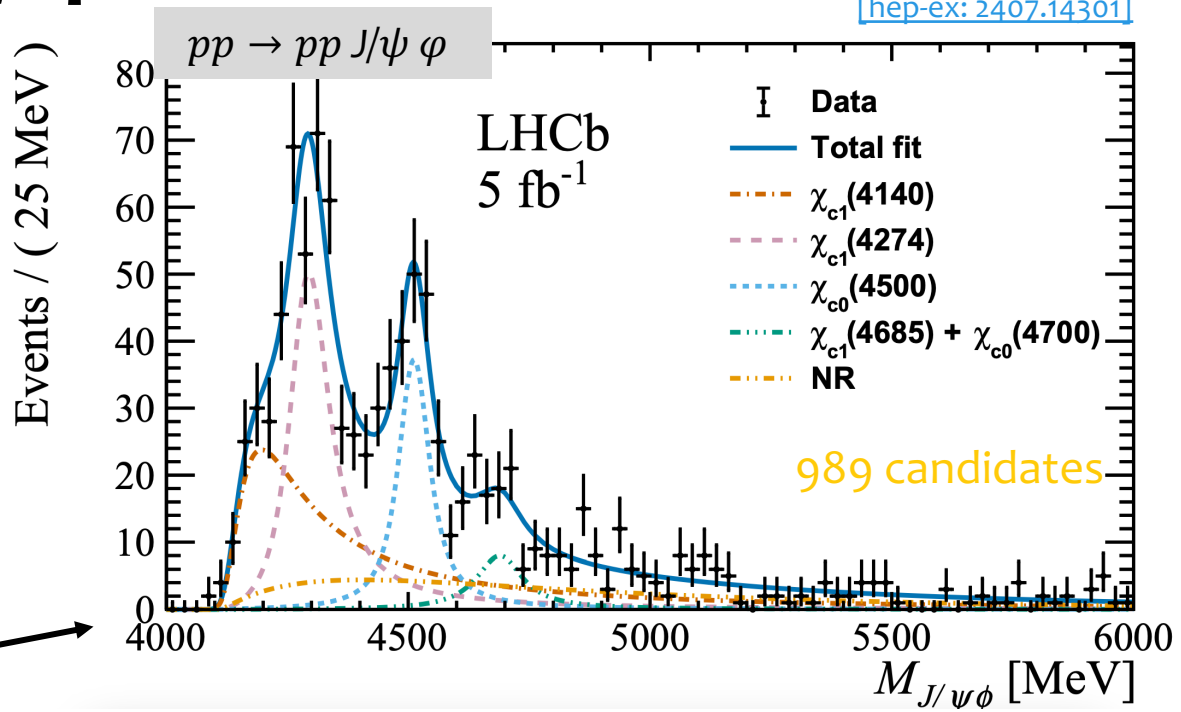


New results on diffractive $J/\psi\,\varphi$ production

[hep-ex: 2407.14301]

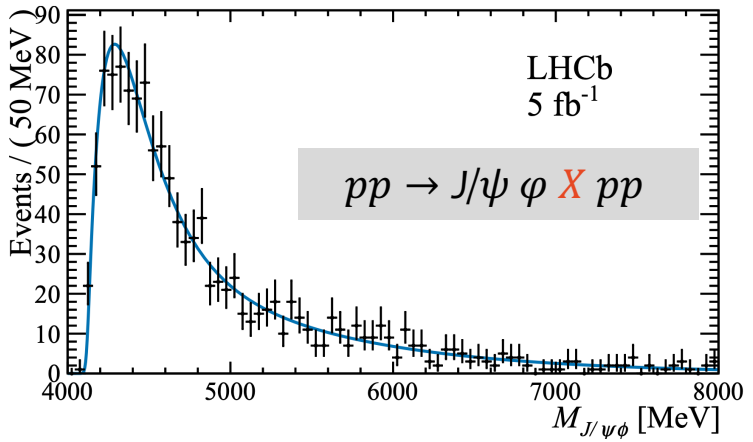
For diffractive studies,
the acceptance is extended with HeRSChel,
$5 < |\eta| < 10$
=> cross section measurement

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

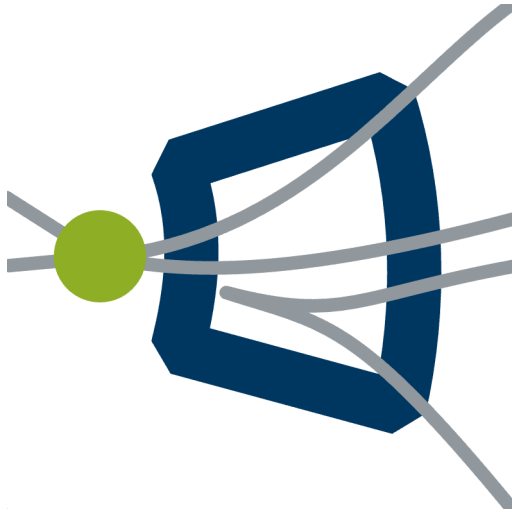


For selection, #track in VeLo is used

- only four tracks
- with additional tracks



Hm, strong couplings to gluons?



Future of LHCb

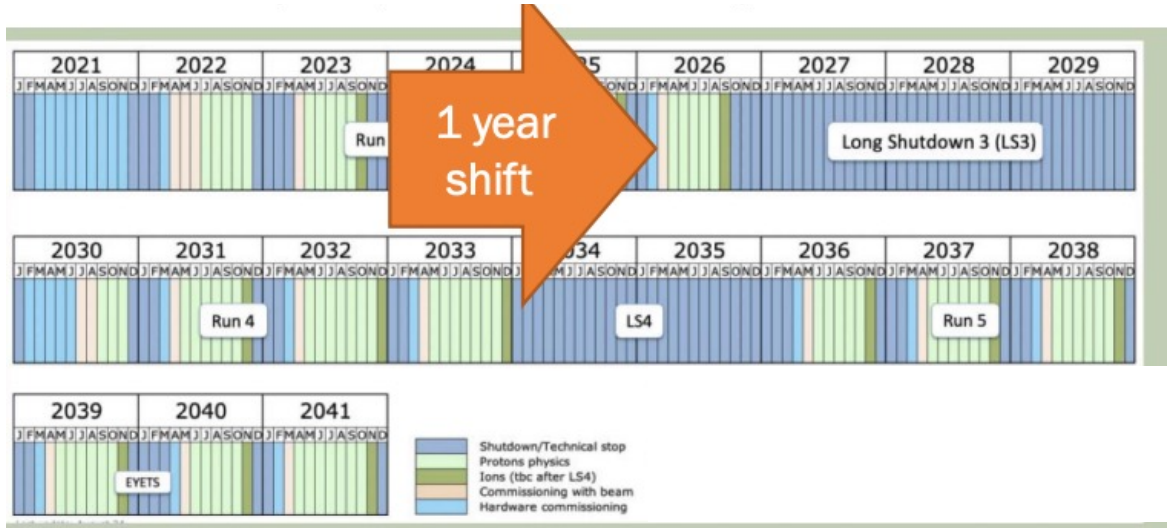
Upgrade II

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

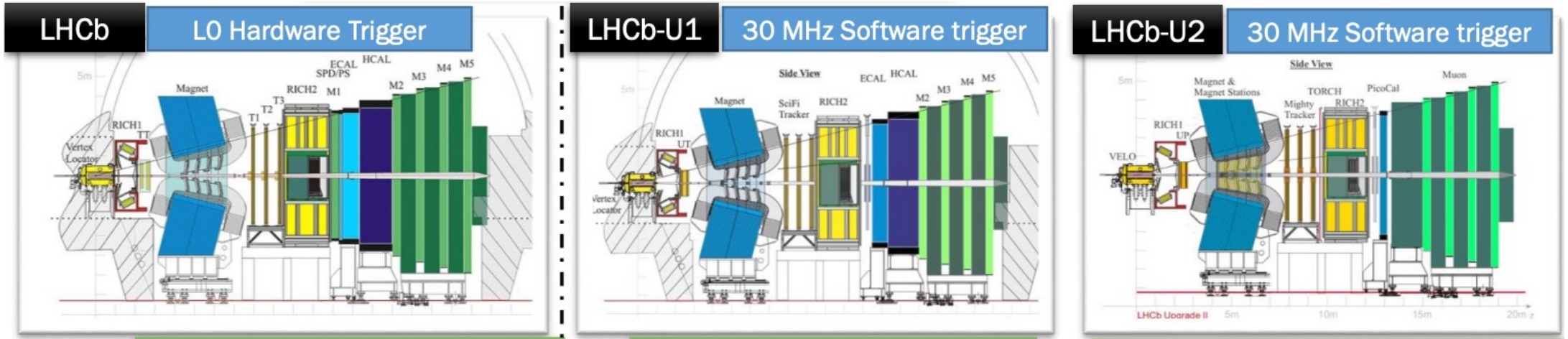
LS3: no major changes at LHCb

Run4: 2030-2033

LS4: Upgrade II, 2036-2041 start of data taking



Comparison courtesy Blake Leverington



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 ($T_{c\bar{s}}$ ~ "neutral D_s")

The Run-3 has started:

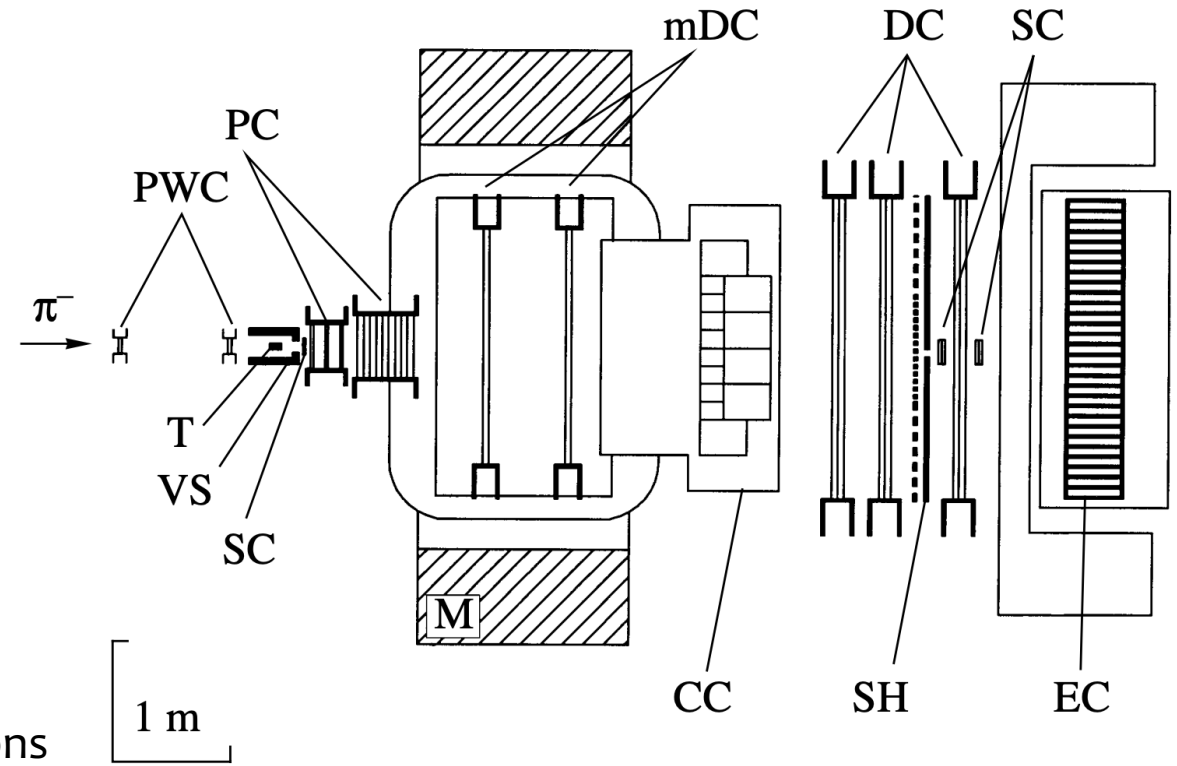
- already more B mesons than in Run-2.
- running for 2 more years
- Run4: 2030-2033

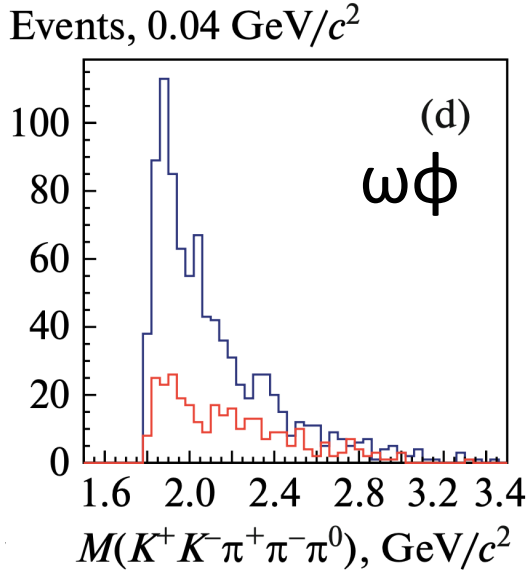
Upgrade 2 operation time: 2036-2045

A note on 30 GeV setup

VES experiment at IHEP, Protvino, Russia:

- **30 GeV pion beam on beryllium target**
- **Integrated flux, $1.73 \cdot 10^{11}$ protons on target**





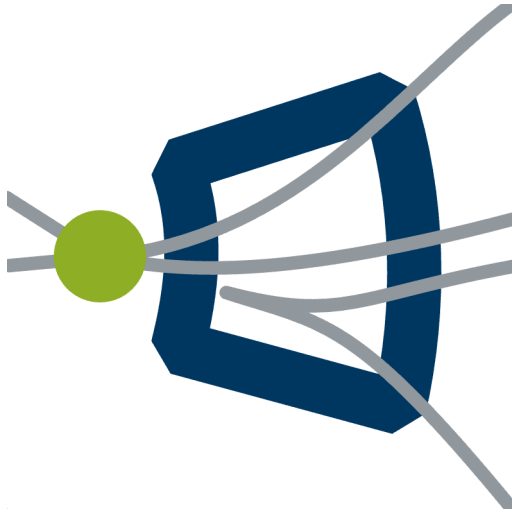
Physics program and reach

- Exclusive multi-pion reactions
- Multi-kaon reactions (phi)

[Phys.Atom.Nucl. 83 (2020) 11, 1602-1606]

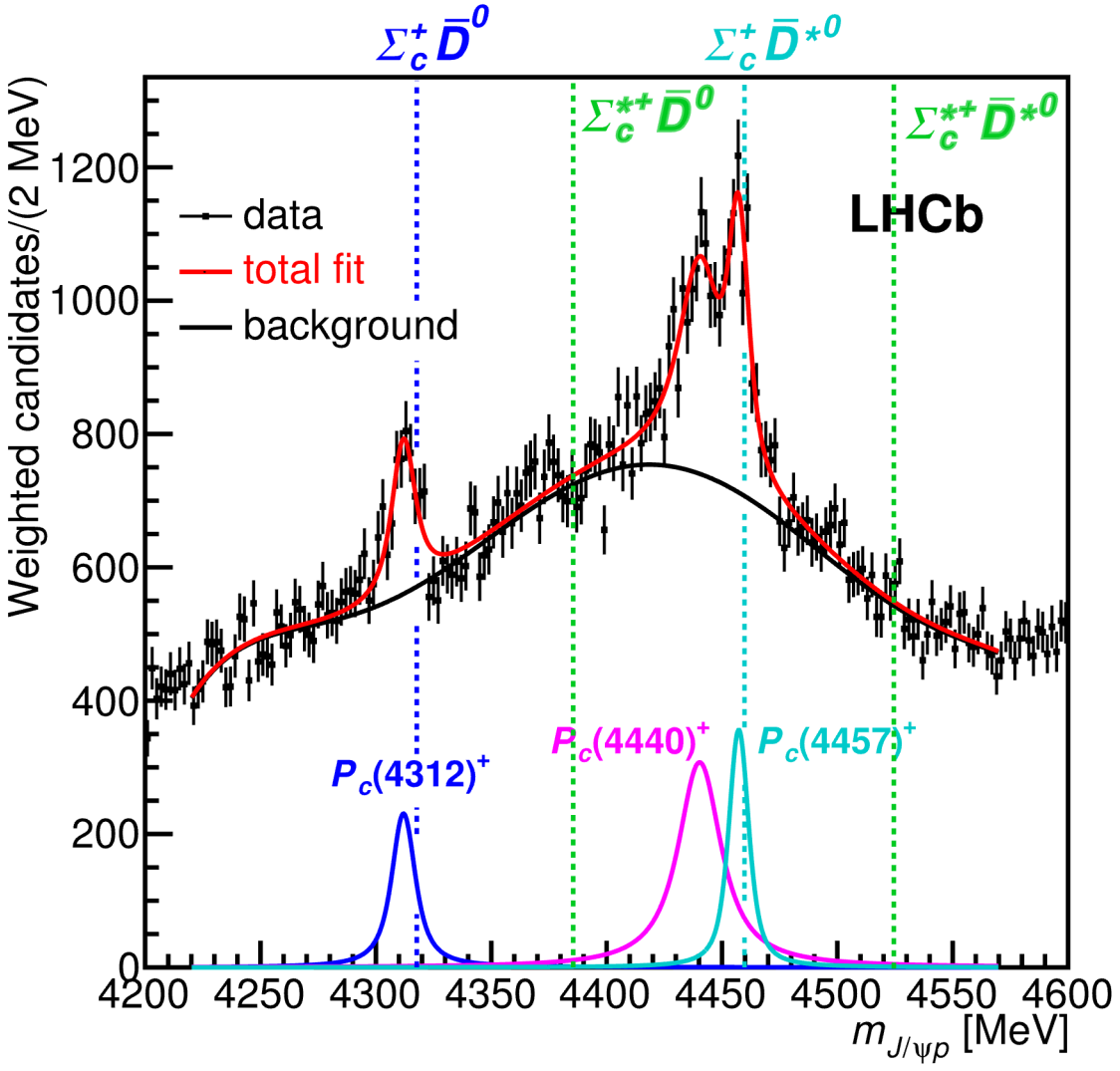
Search for Scalar Resonance in the ωϕ System in the Pion-Nuclear Interaction at Momentum of 29 GeV/*c*

Backup



Pentaquarks

In prompt



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

Near threshold

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

Multiplicity matches threshold-states spin algebra

No observation in other final states so far

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

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

[naming scheme for hadrons, PDG2023]

New search of Pentaquarks in open-flavor decays

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

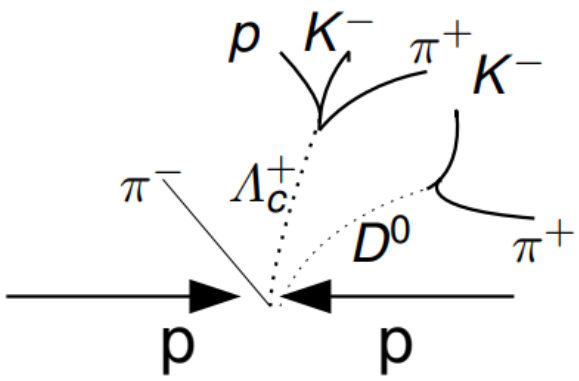
$$\Sigma_c^{(*)++} D^{(*)-}$$
$$\Sigma_c^{(*)+} \overline{D}^{(*)0}$$
$$\Sigma_c^{(*)+} D^{(*)-}$$
$$\Sigma_c^{(*)0} D^{(*)0}$$
$$\Lambda_c^+ D^{(*)-}$$
$$\Lambda_c^+ \overline{D}^{(*)0}$$

New search in prompt production is performed in many systems of

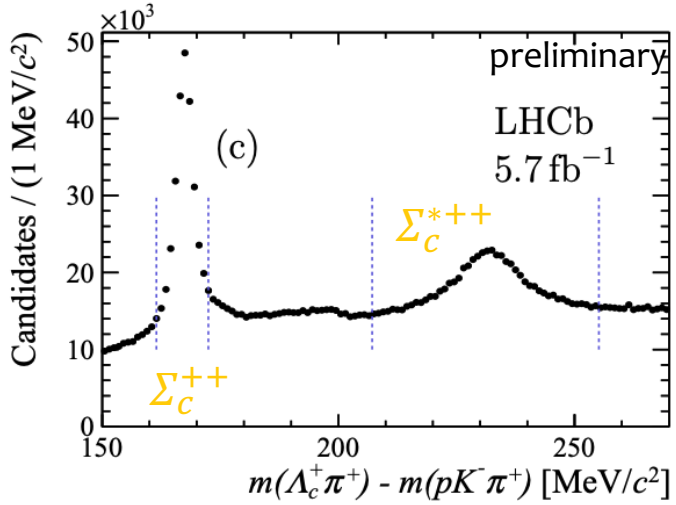
$$\Lambda_c^+ \overline{D}\, \pi^\pm$$

combinations

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



[courtesy G. Robertson (LHCb)]



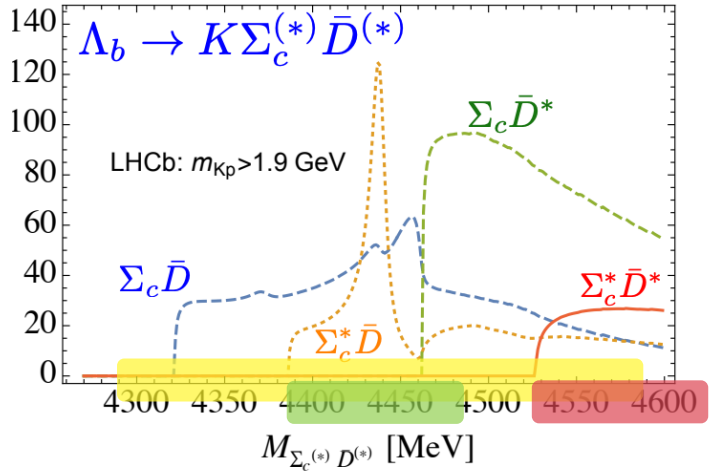
$\Sigma_c^{++}\bar{D}^0$	~~$\Sigma_c^{++}D^0$~~	$\Sigma_c^{++}D^-$	~~$\Sigma_c^{++}D^+$~~	~~$\Sigma_c^{++}D^{*-}$~~	~~$\Sigma_c^{++}D^{*+}$~~
$\Sigma_c^{0}\bar{D}^0$	~~$\Sigma_c^{0}D^0$~~	$\Sigma_c^{0}D^-$	~~$\Sigma_c^{0}D^+$~~	~~$\Sigma_c^{0}D^{*-}$~~	~~$\Sigma_c^{0}D^{*+}$~~
$\Sigma_c^{*++}\bar{D}^0$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

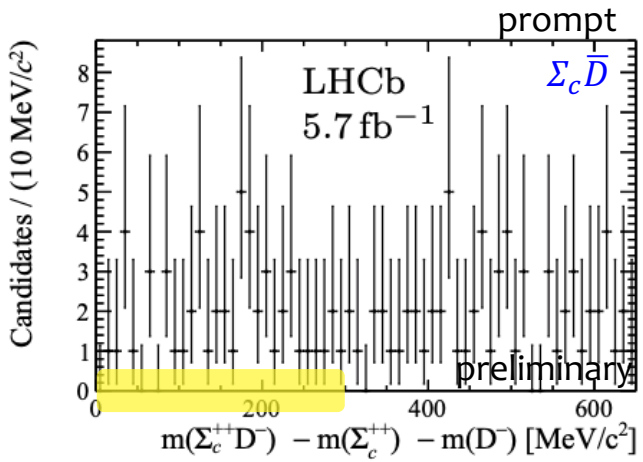
[X] : too small statistics for limit setting

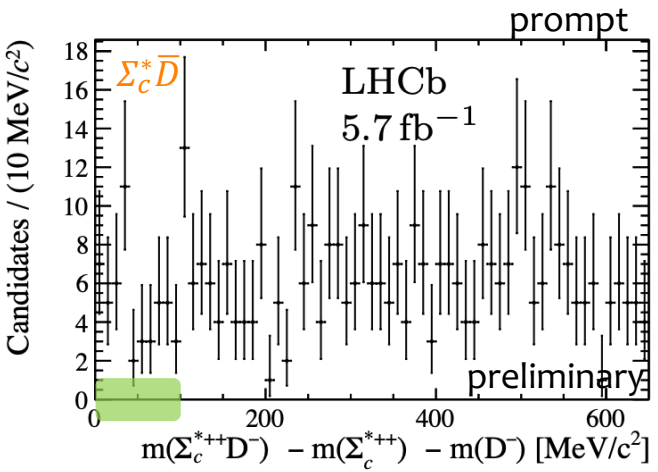
Search for pentaquarks: $\Sigma_c \bar{D}^{(*)}$

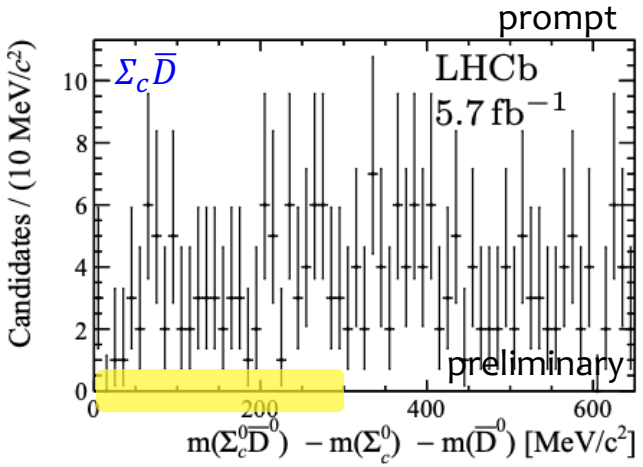
[LHCb-PAPER-2023-018, in preparation]

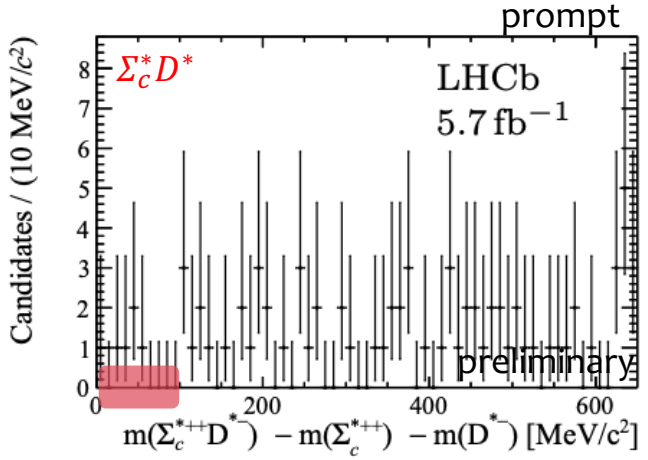
[Meng-Lin Du et al.]









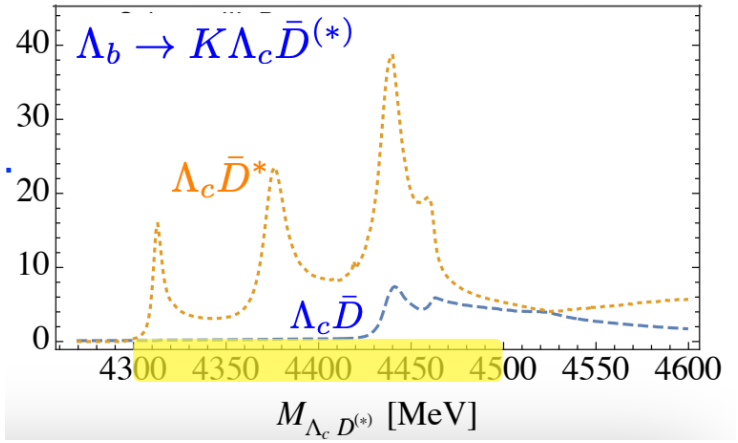


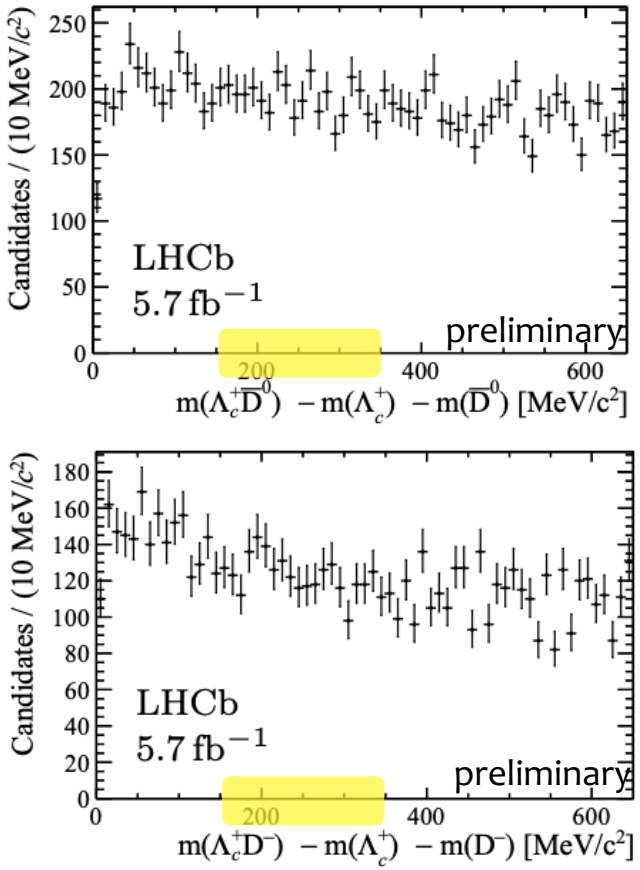
Statistically limited

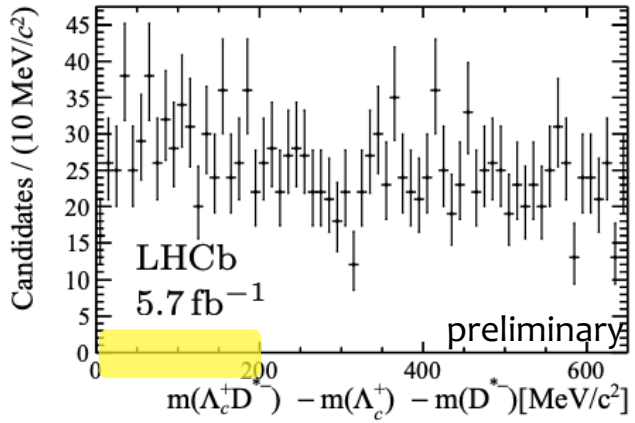
Search for pentaquarks: $\Lambda_c^+ \bar{D}$

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

[Meng-Lin Du et al.]



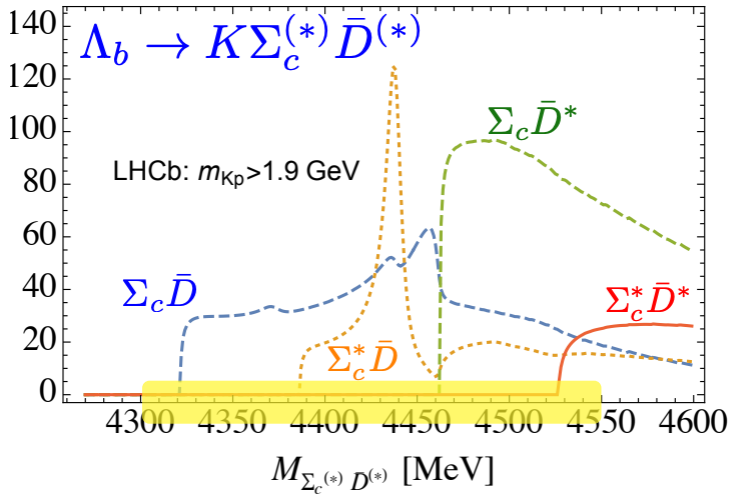


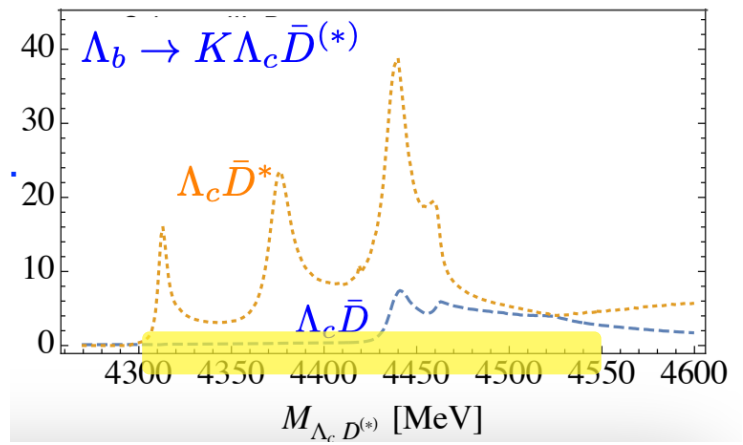


No obvious peaks

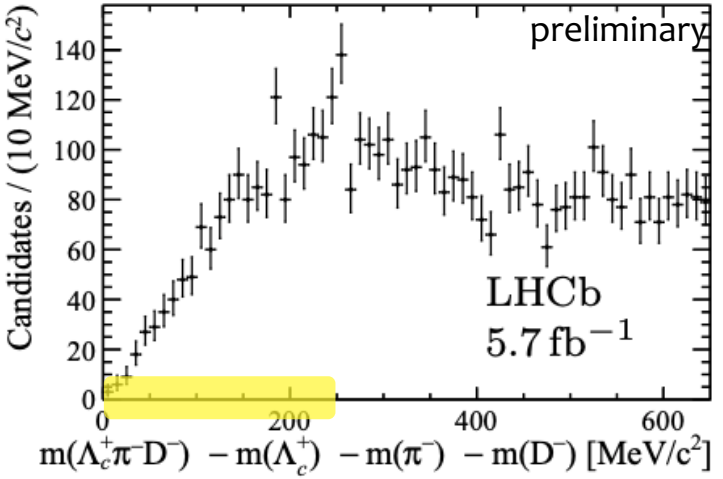
Search for pentaquarks: $\Lambda_c^+ \bar{D}\,\pi$

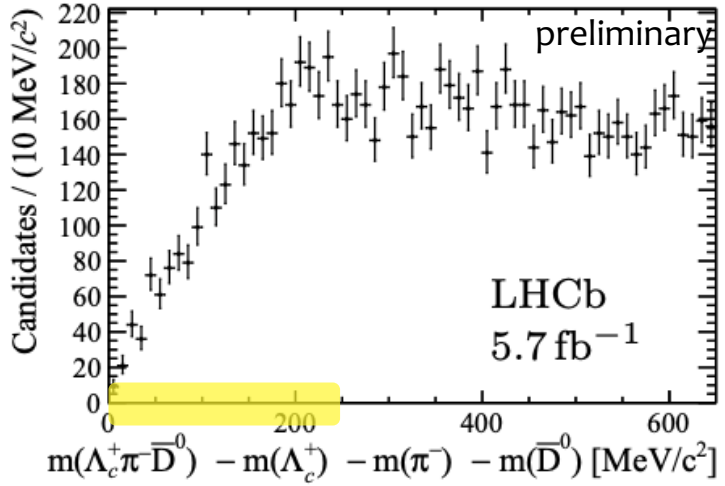
[LHCb-PAPER-2023-018, in preparation]

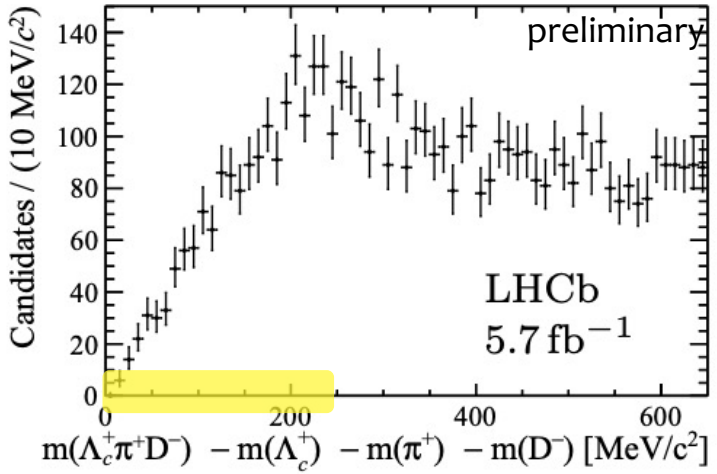




[Meng-Lin Du et al.]







Some peaking structures that might become pentaquarks with more statistics

[LHCb-PAPER-2023-034]

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

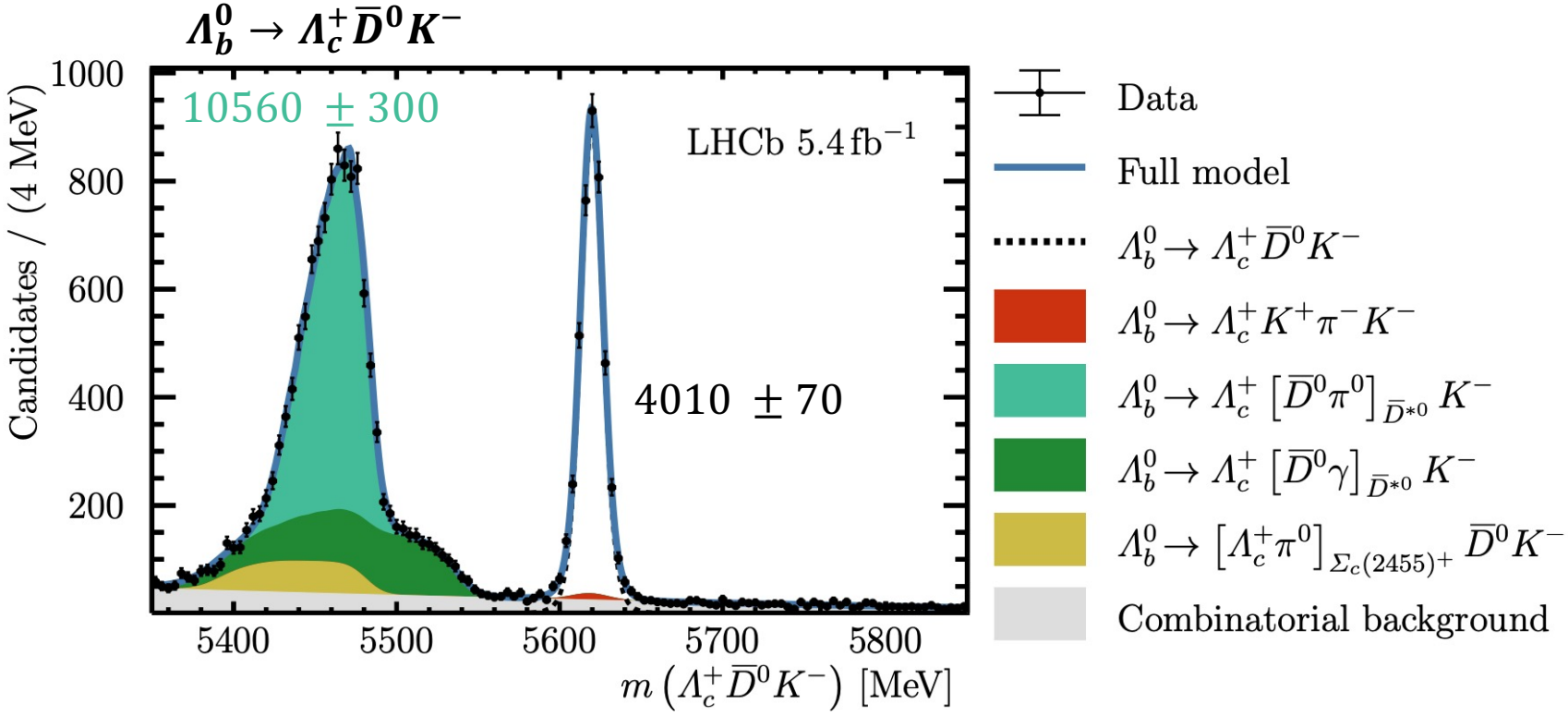
The decays $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^0 K^-$ are observed.

Dalitz plot is populated by

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

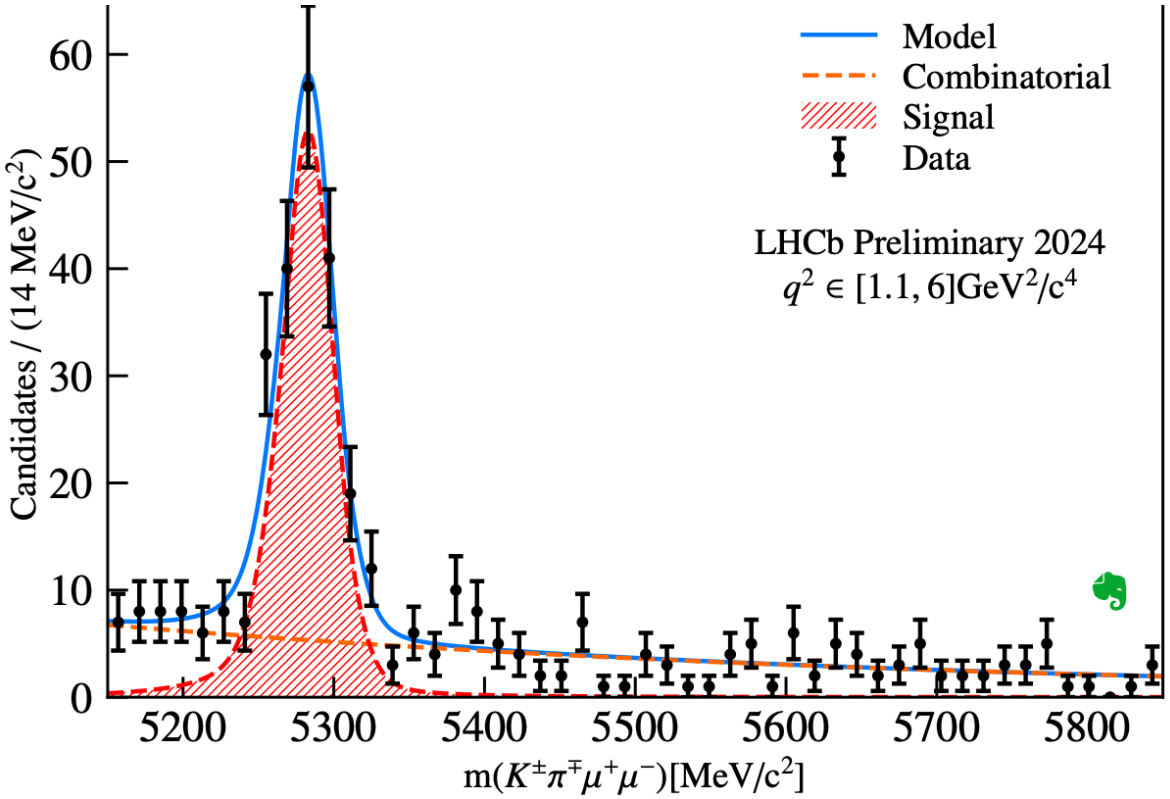
states

Searches for pentaquark contributions are ongoing.

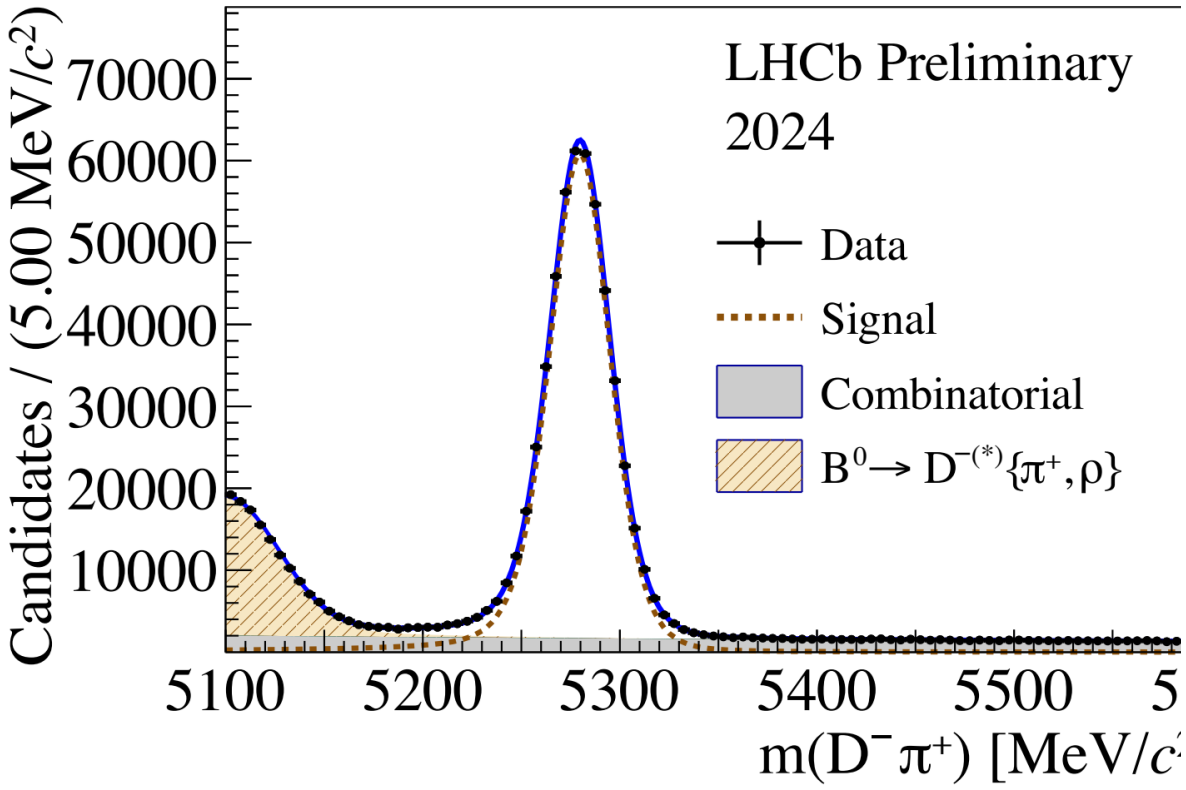


More on B->DDh

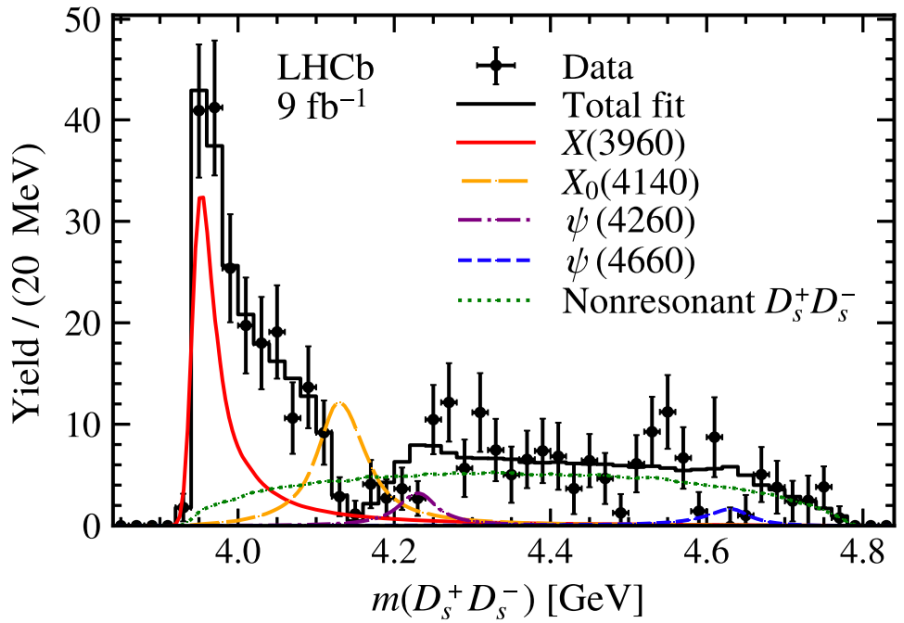
$B^0 \to K^{*0}\mu^+\mu^-$

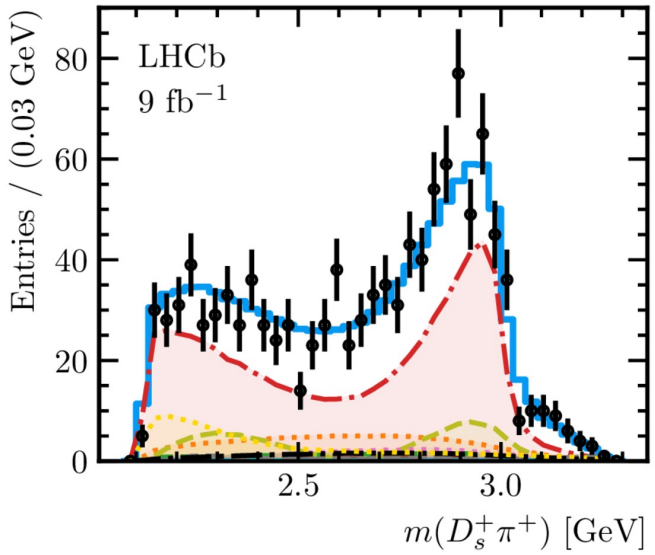


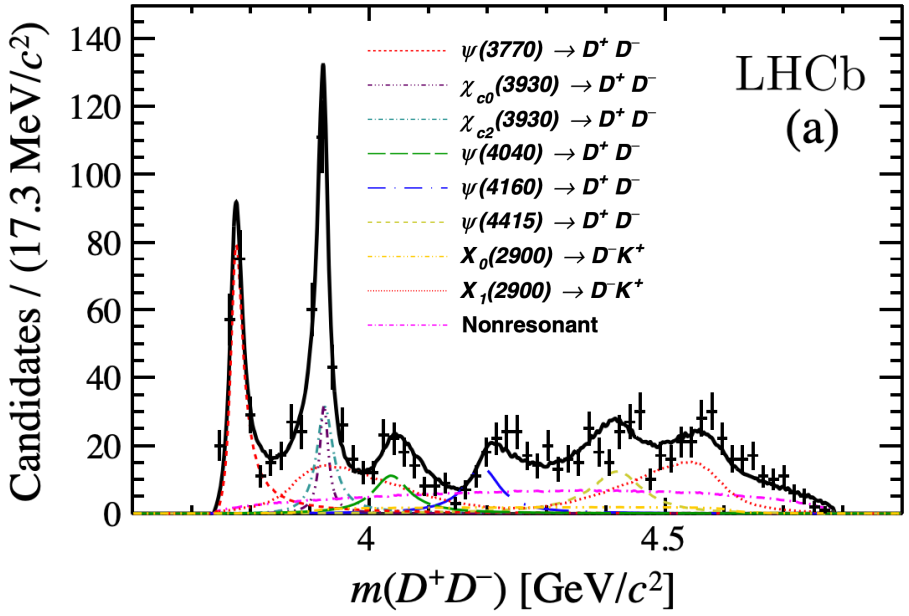
$B^0 \to D^-(K^+\pi^-\pi^-)\pi^+$

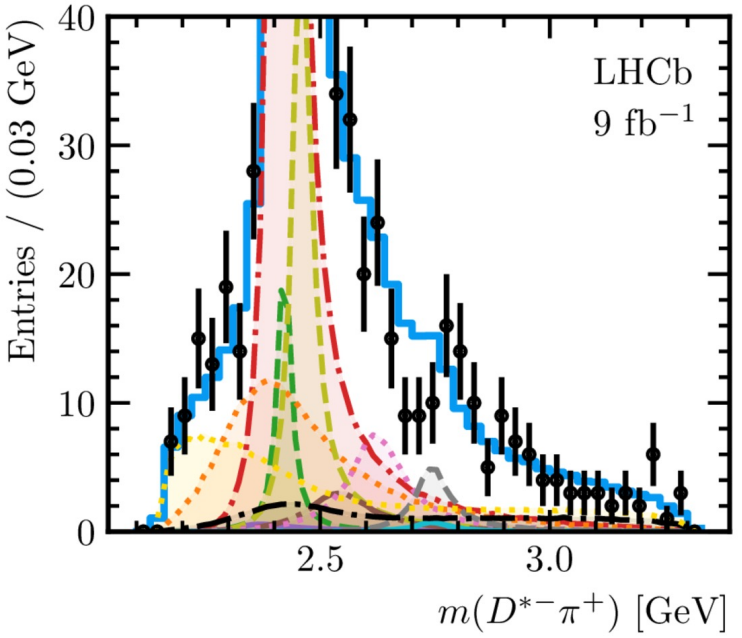


[PRL 125 (2020) 242001]
[*Phys.Rev.D* 102 (2020) 112003]
[JHEP 08 (2024) 165]



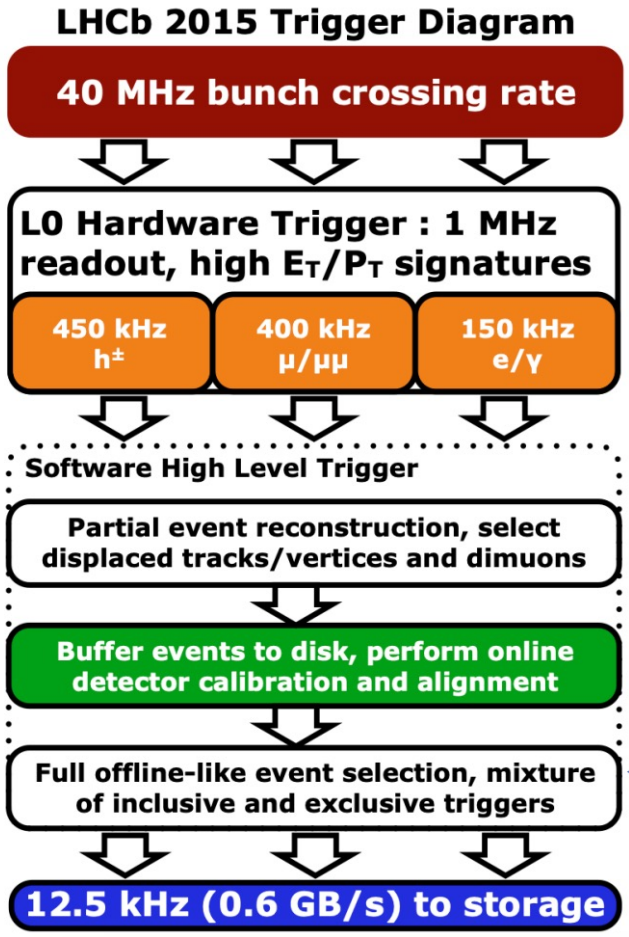






No level zero hardware trigger anymore

Run2 (2014-2018)



L0

HLT1

HLT2

Run3 (2022-2026)