QCD spectroscopy and hadronic structure

LHCP2022

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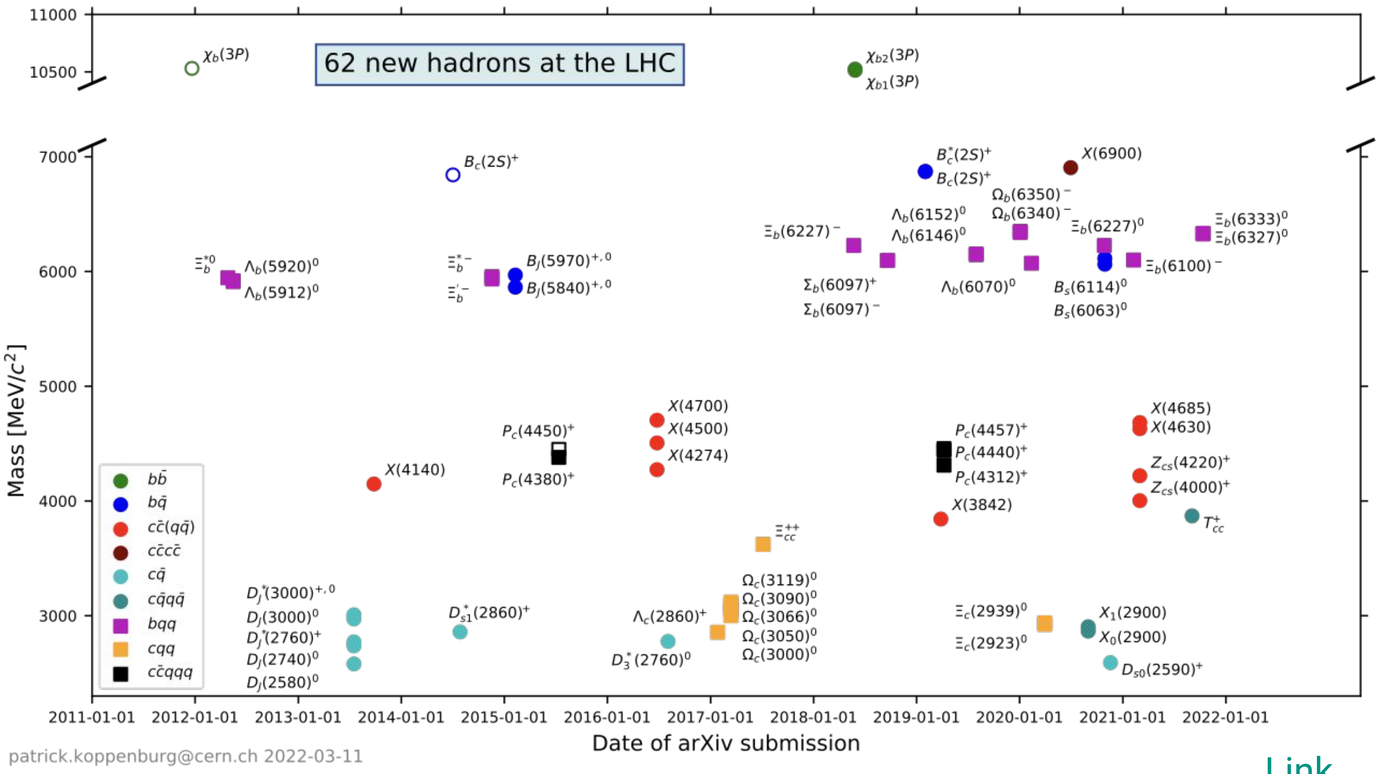
on behalf of the LHC experiments

May 20th, 2022

Spectroscopy at LHC

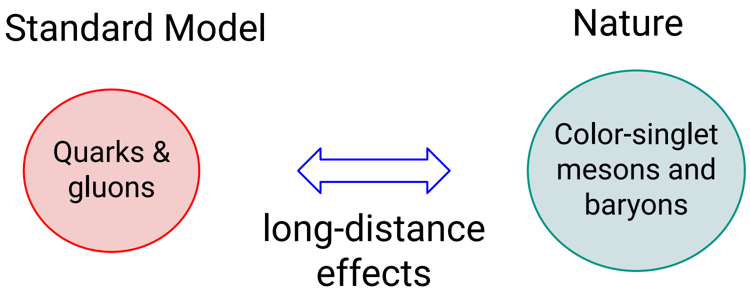
Over the past 10 years more than 60 new hadrons

Observations of new states challenge our current understanding of QCD and the validity of the Heavy quark effective theory (HQET) assumptions



Link

QCD and spectroscopy



Conventional spectroscopy

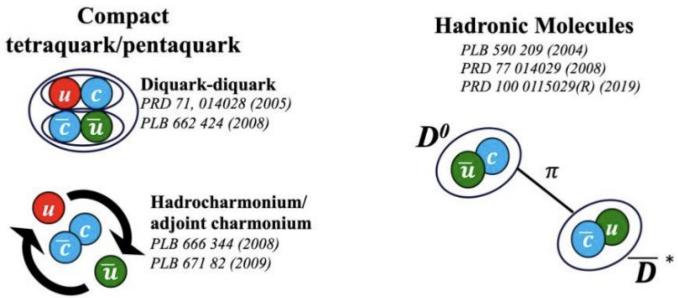
HQET predicts the masses of the heavy hadrons:
- expansion in $\Lambda_{QCD}/m_Q \sim 0$

Need for precise measurements of the excited hadron properties to test the validity of HQET

Exotic spectroscopy

Many states predicted with minimal quark content different from $q\bar{q}$ and qqq

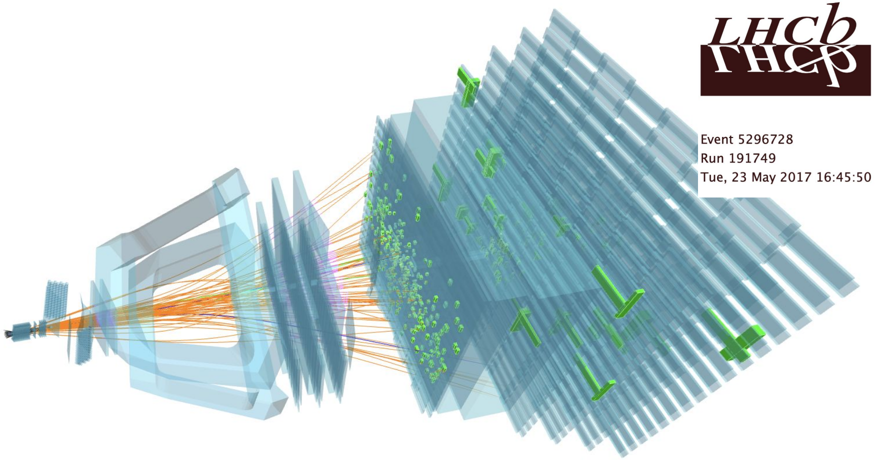
Lots of theoretical models

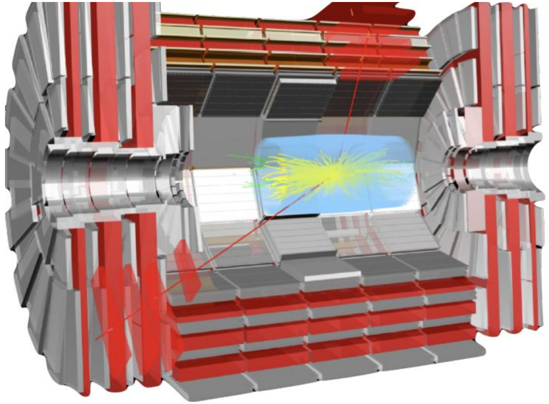


Study of exotics in production and decays to discriminate among models

LHC experiments

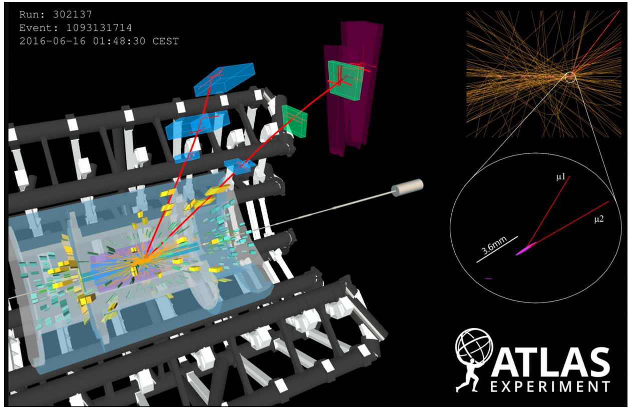
LHCb: the major player in spectroscopy
- unique dedicated design
- high vertex resolution
- RICH detectors for PID





CMS and **ATLAS** are also giving significant contributions to beauty and quarkonium sectors
- Large acceptance for muons |η|<2.4
- Very good dimuon resolution
- Highly flexible trigger

$B_s \rightarrow \mu\mu$ event display



Outline

Conventional spectroscopy

Observation of excited Ξ_b^-, Ξ_b^0 baryons

Search for Ξ_{bc}^0, Ξ_{bc}^+ , Ω_{bc}^0

Exotic spectroscopy

$\chi_{c1}(3872)$ state:

- dipion mass spectrum, lineshape and decay modes
- production in pp, pPb and PbPb

Doubly charm tetraquark

Pentaquark: evidence for a new pentaquark state $P_c(4337)$

more in 'Exotic hadrons at LHC' talk by Paolo Gandini

Conventional spectroscopy

Observation of new excited Ξ_b

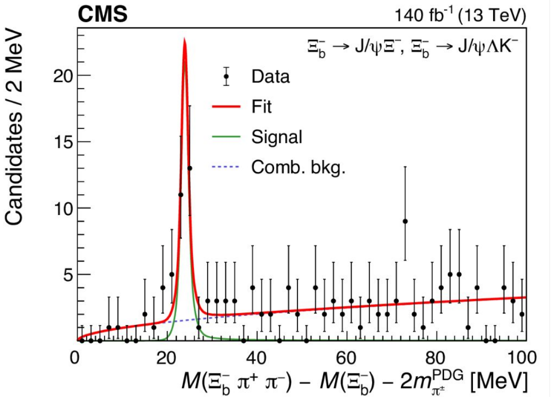
PRL 126 (2021) 252003, PRL 128, 162001 (2022)

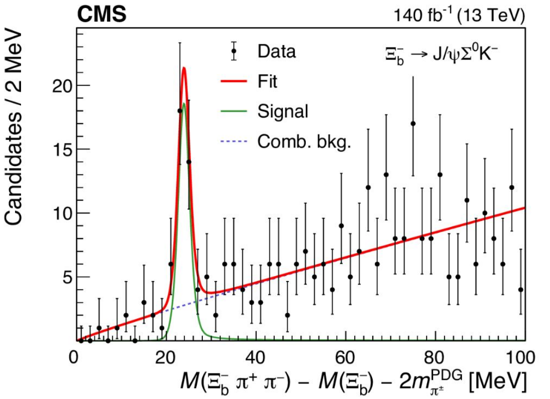
Narrow resonance $\Xi_b(6100)^-$ is observed in $\Xi_b^-\pi^+\pi^-$

- Combination of fully reconstructed and partial reconstructed modes
- UL on width at 95% CL <1.9 MeV
- Consistent with orbitally excited $J^P = 3/2^-$

New $\Xi_b(6327)^0$, $\Xi_b(6333)^0$ states observed in $\Lambda^0_b K^-\pi^+$ final state

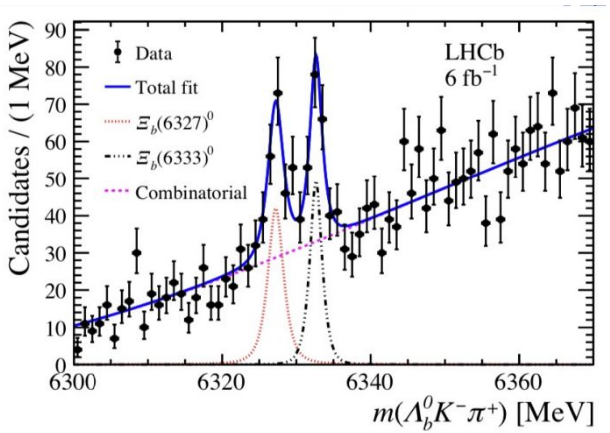
- Widths consistent with mass reso
- 1D doublet, $J^P = 3/2^+$ and $J^P = 5/2^+$





PRL 126 (2021) 252003

Significance: 6.2-6.7σ



PRL 128, 162001 (2022)

Search for Ξ_{bc}^0, Ω_{bc}^0, Ξ_{bc}^+

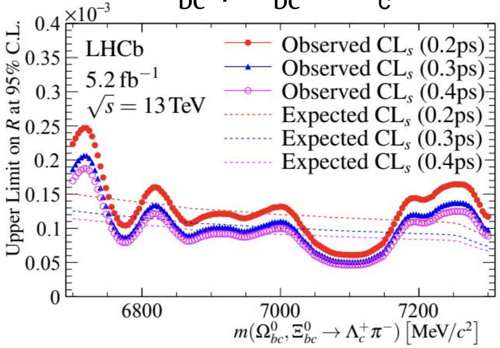
Chin. Phys. C 45 093002, arXiv:2204.09541v1

Search for peaks in the $\Lambda_c^+\pi^-$ / $\Xi_c^+\pi^-$ and $J/\psi\ \Xi_c^+$ final states

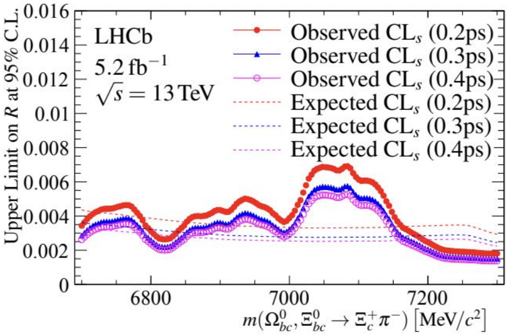
- No obvious peaks
- UL are set at 95% CL

R: production cross-section multiplied by BR and normalised with Λ_b^0/Ξ_b^0 (decays to $\Lambda_c^+\pi^-/\Xi_c^+\pi^-$) and $B_c^+ \to J/\psi\ D_s^+$

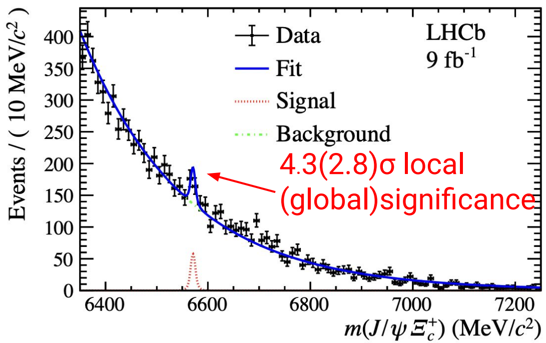
$\Xi_{bc}^0/\Omega_{bc}^0 \to \Lambda_c^+\pi^-$

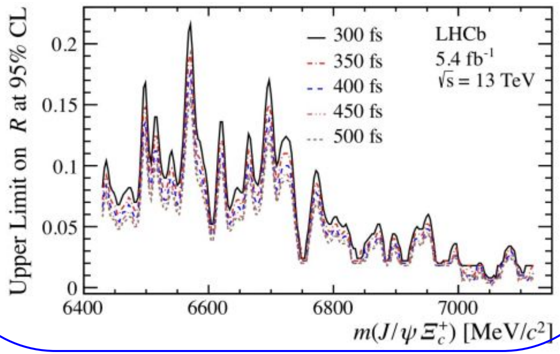


$\Xi_{bc}^0/\Omega_{bc}^0 \to \Xi_c^+\pi^-$



$\Xi_{bc}^+ \to J/\psi\ \Xi_c^+$

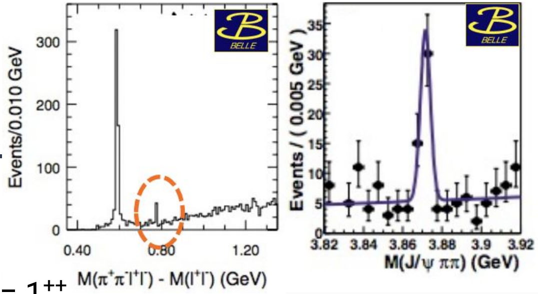




Exotic spectroscopy

$\chi_{c1}(3872)$ state - aka X(3872)

Discovered in 2003 by the Belle collaboration in the
$B \to KX(3872), X(3872) \to \pi^+\pi^- J/\psi$

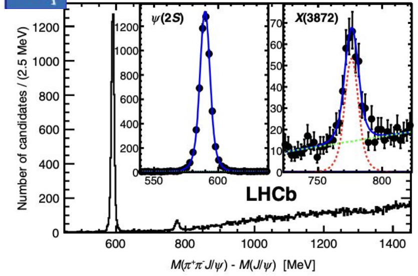


Phys. Rev. Lett. **91**, 262001

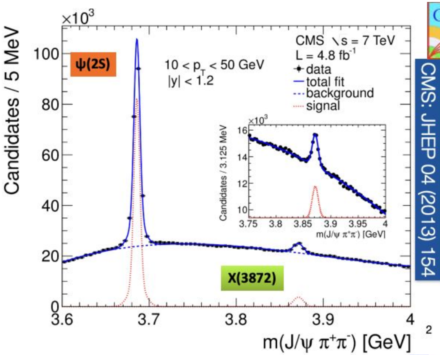
Many experiments contribute to it:

- Spin assignment: $J^{PC} = 1^{++}$
- Mass is consistent with $m(D^0) + m(D^{*0})$
- Width is surprisingly narrow

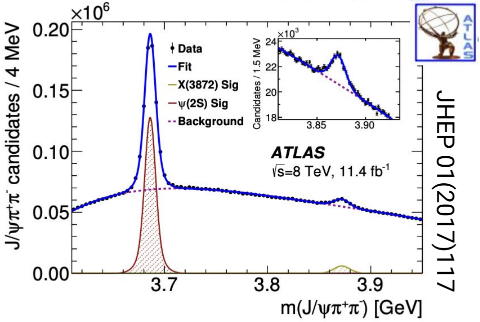
spin assignment: $J^{PC} = 1^{++}$



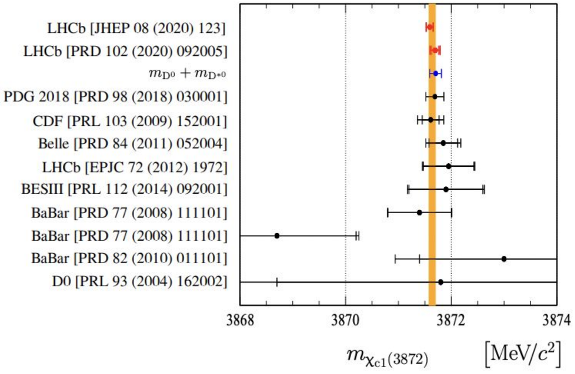
PRL. 110 (2013) 222001

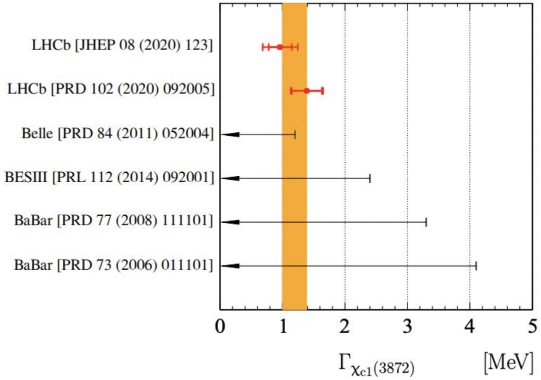


CMS: JHEP 04 (2013) 154



JHEP 01(2017)117





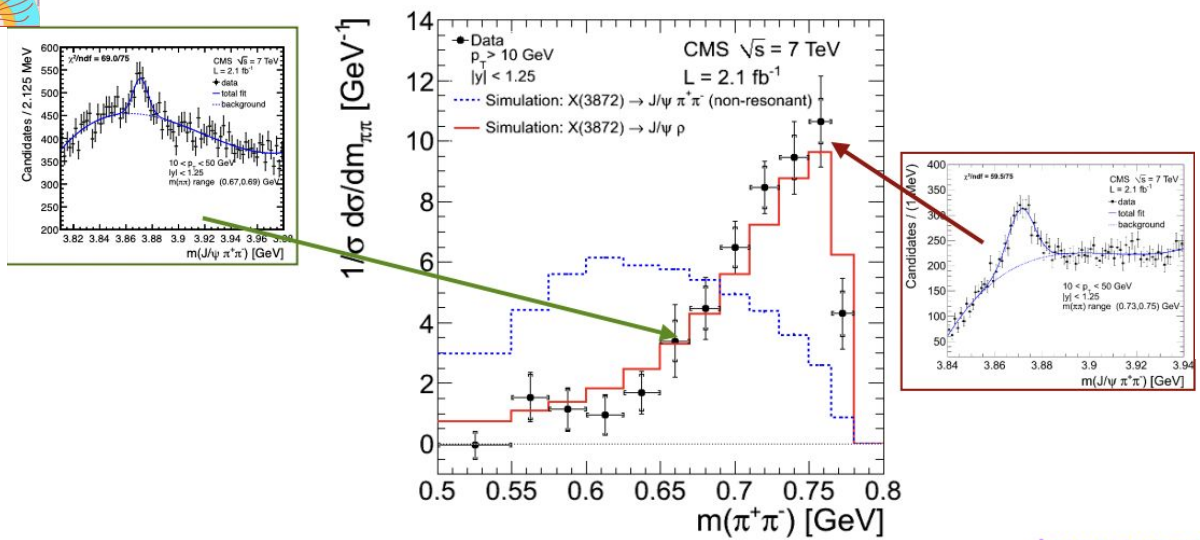
PRD102 (2020) 092005

Dipion mass spectrum

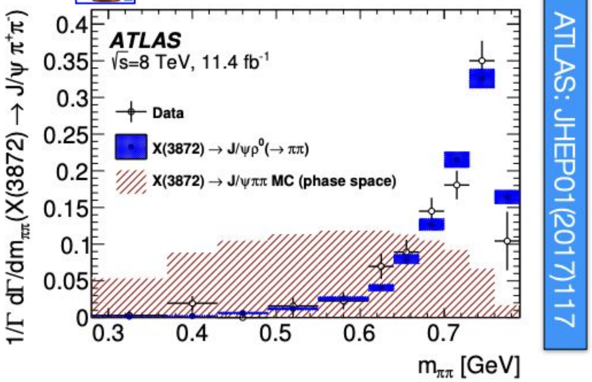
JHEP 04 (2013) 154, JHEP 01(2017)117

Study the $\rho^0(770)$ contamination in the $X(3872) \to J/\psi\pi^+\pi^-$

- fits to $m(J/\psi\pi^+\pi^-)$ in intervals of $m(\pi^+\pi^-)$
- spectrum compared to simulations with and without an intermediate ρ



JHEP 04 (2013) 154

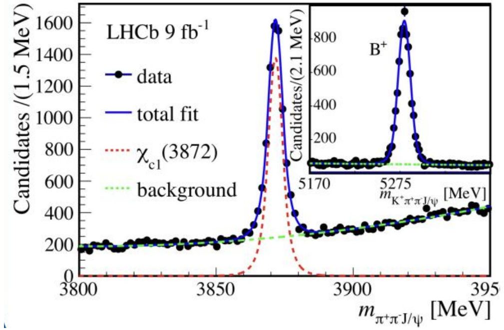


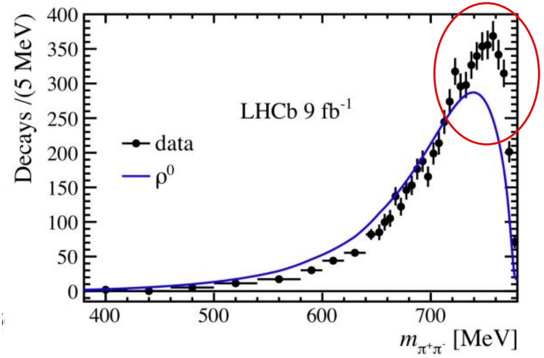
Assumptions with intermediate ρ give better agreement with data
→ compatible with ATLAS and LHCb

Is it all $\chi_{c1} \to \rho^0 J/\psi$?

LHCb-PAPER-2021-045, arXiv:2204.12597v1

2D fits in $m(\pi^+\pi^- J/\psi)$ and $m(\pi^+\pi^-)$ intervals

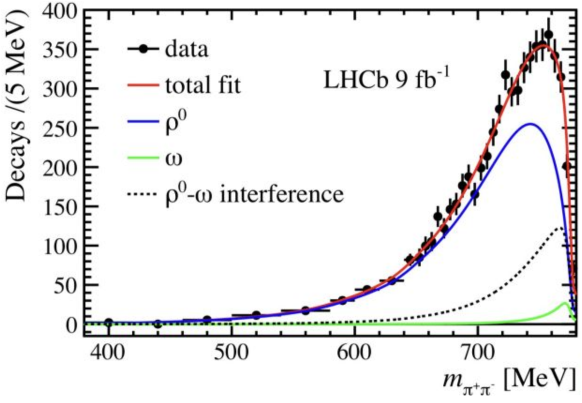




Previous $\chi_{c1}(3872) \to \rho J/\psi$ simulations do not simulate the effects of phase space on resonance masses in a decay sequence

⇒ $p(J/\psi)$ suppression factor missing in the simulations!

ω contribution is small (~2%) but is enhanced by ω-ρ interference (~19%)



Ratio of isospin violating to isospin conserving $\chi_{c1}(3872)$ couplings: much larger than expected for a charmonium state

$$\frac{g_{\chi_{c1}(3872)\to\rho^0 J/\psi}}{g_{\chi_{c1}(3872)\to\omega J/\psi}} = 0.29 \pm 0.04. \qquad \frac{g_{\psi(2S)\to\pi^0 J/\psi}}{g_{\psi(2S)\to\eta J/\psi}} = 0.045 \pm 0.001$$

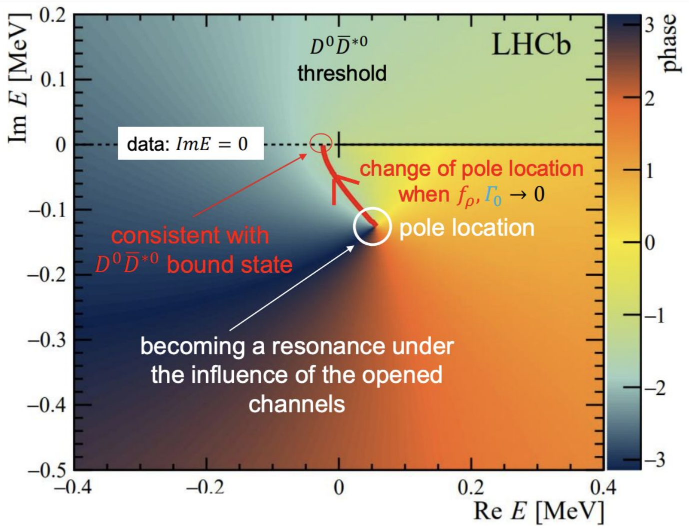
χ_{c1} lineshape: molecular state?

PRD102 (2020) 092005

Study of the analytic structure of the amplitude near $\bar{D}^0D^{*0}$ threshold

- using Flattè formula due to the proximity to $\bar{D}^0D^{*0}$
- considering also D^+D^{*-} threshold (8 MeV above, I=1)

2 poles found: show the one closer to $\bar{D}^0D^{*0}$



Consistent with a **bound state**

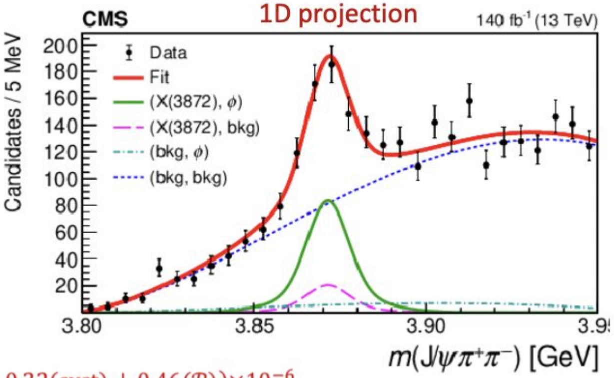
⇒ Molecular interpretation is favored

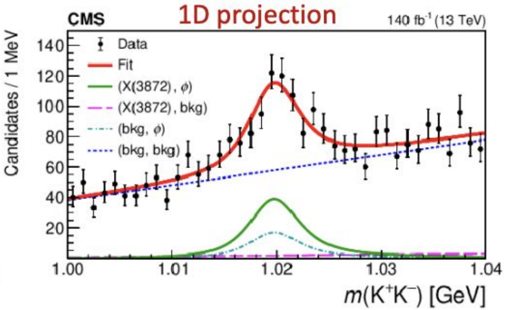
But compact state is not ruled out [PRD 105, L031503 (2022)]

Observation of the new decay mode $B_s^o \rightarrow X(3872)\Phi$

PRL 125 (2020) 152001

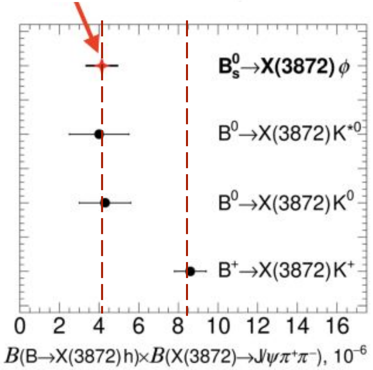
Signal yield determined from a simultaneous 2D fit of the distributions m($\pi^+\pi^-J/\psi$) and m(K^+K^-)

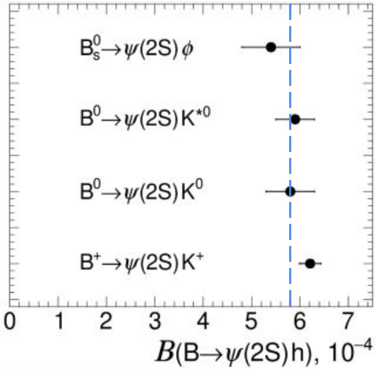




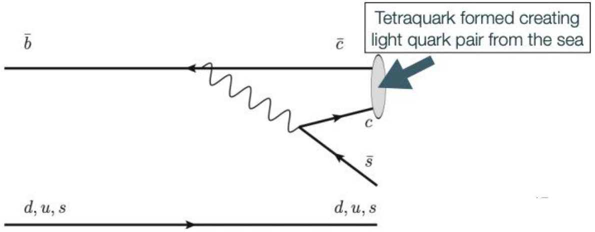
$$\mathcal{B}(B_s^0 \rightarrow X(3872)\phi)\mathcal{B}(X(3872) \rightarrow J/\psi\pi^+\pi^-) = (4.14 \pm 0.54(\text{stat}) \pm 0.32(\text{syst}) \pm 0.46(\mathcal{B}))\times 10^{-6}$$

Comparison of BRs indicates that the X(3872) formation in B meson decays is different from ψ(2S)





This pattern can emerge in compact tetraquark picture



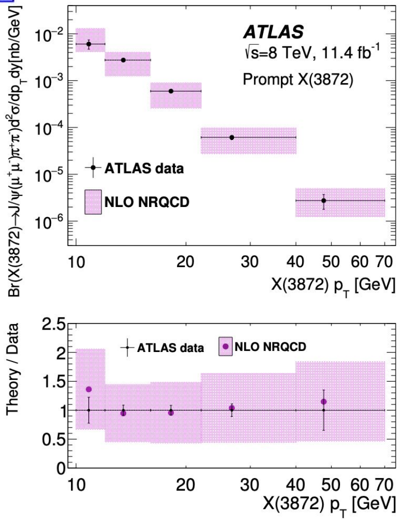
PRD 102 (2020) 3, 034017

χ_{c1} production in pp @ CMS and ATLAS

JHEP 04 (2013) 154, JHEP01(2017)117

CMS and ATLAS studied:

- prompt X(3872) production cross section x *B(X(3872)→J/ψπ⁺π⁻)* @central rapidity as a function of p_T



Model[2] is a mixture of charmononium and molecule

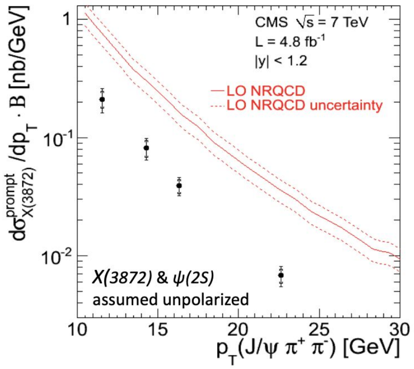
$\chi_{c1}(2P)\,\&\,\bar{D}^0 D^{0*}$

$\chi_{c1}(2P)$: short-distance production

$\bar{D}^0 D^{0*}$: hadronic decays of X(3872) → DDπ, DDγ and J/ψρ and Jψω

→ Good agreement with data! Production dominated by the $\chi_{c1}(2P)$ component

[2] PRD96 (2017) 074014



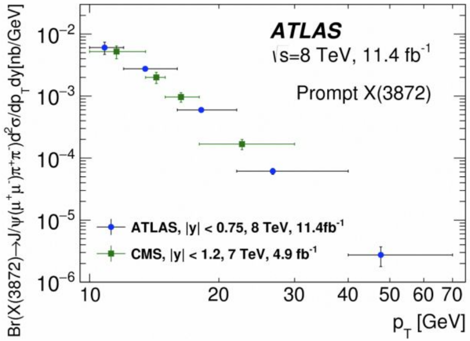
Prediction based on S-wave molecular model[1]

→ cross section is overestimated by over 3σ

Measurement not support S-wave molecular model

[1] PhysRevD.81.114018

Compatible prompt cross sections



ATLAS: JHEP01(2017)117

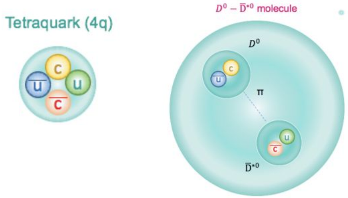
χ_{c1} production in pp @ LHCb

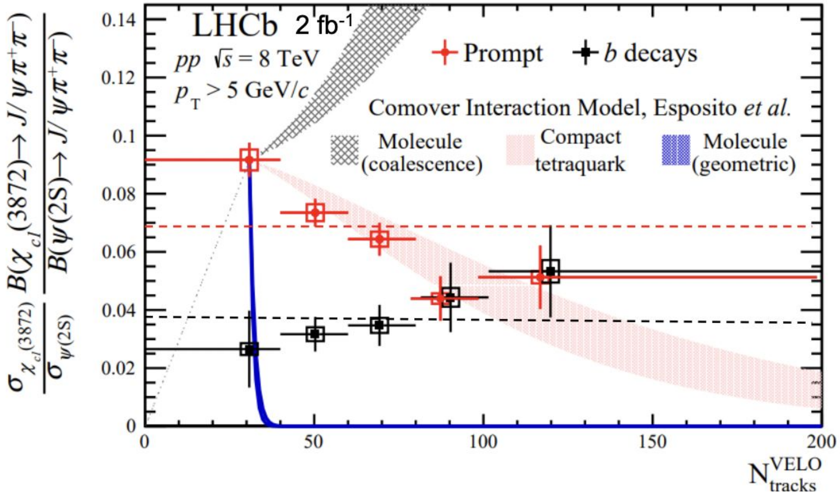
PRL 126 (2021) 092001, JHEP 01 (2022) 131

Differential cross section ratio of $\chi_{c1}(3872)$ relative to $\psi(2S)$

- Both in prompt pp collisions and from b-hadron decays
- Measured as a function of track multiplicity, p_T and y

Separate a compact tetraquark (r<1 fm) from a large-sized molecular state (r~10 fm)





Prompt ratio is suppressed as multiplicity increases (5σ)

→ compact tetraquark model favored

→ Dominated by **comover breakup**[1]:

small radius = decrease of xsection ratio

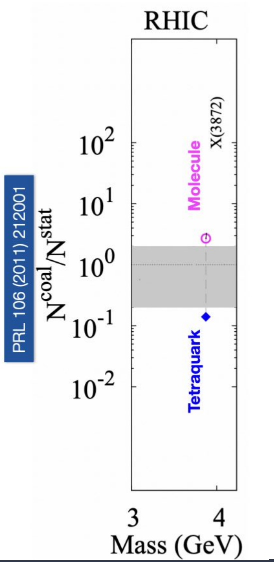
[1]PRD 103 (2021) 7, EPJC 81 (2021) 669

Can we learn more in HI collisions?

PRL 128 (2022) 032001

Formation of QGP could enhance the χ_{c1}(3872) production through the **quark coalescence mechanism**

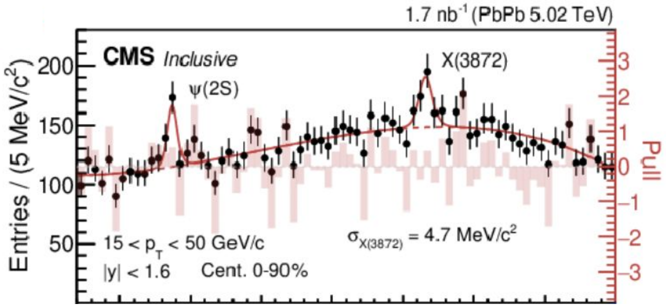
⇒ Molecules are easier to be produced and destroyed than tetraquark



Ratio of hadron yields calculated in the coalescence model to those in the statistical hadronization model

Expected order of magnitude difference!

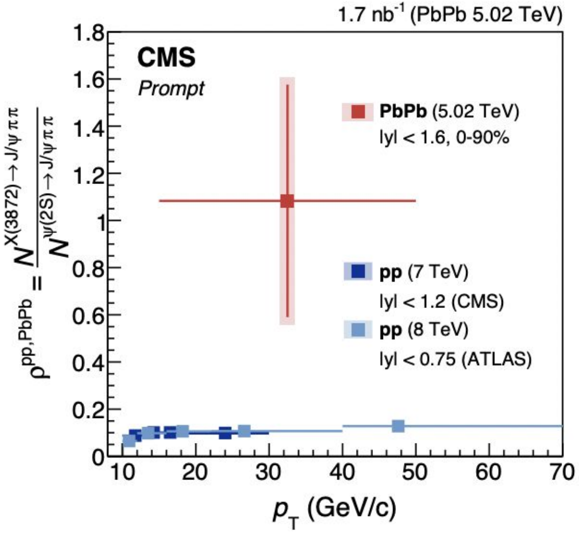
Study inclusive $J/\psi\pi^+\pi^-$ in PbPb collisions



First evidence of X(3872) in HI collisions (4.2 σ)

Can we learn more in HI collisions?

PRL 128 (2022) 032001



Ratio of prompt $\chi_{c1}(3872)$ vs $\psi(2S)$ is enhanced in PbPb wrt pp

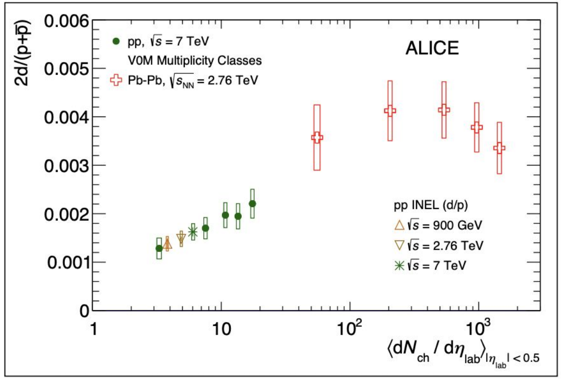
Large uncertainties preclude from drawing conclusions

In pp: $\chi_{c1}(3872)$ suppression due to breakup by coming particles → compact tetraquark

In PbPb: $\chi_{c1}(3872)$ enhancement due to coalescence mechanism → molecule

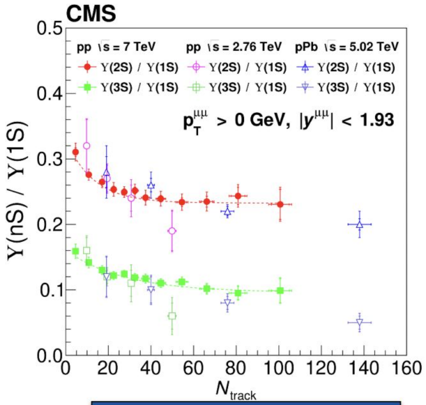
For comparison

Deuteron/proton production increases



ALICE: Phys. Lett. B 794 (2019) 50-63

Quarkonium production rate (excited/ground state) decreases

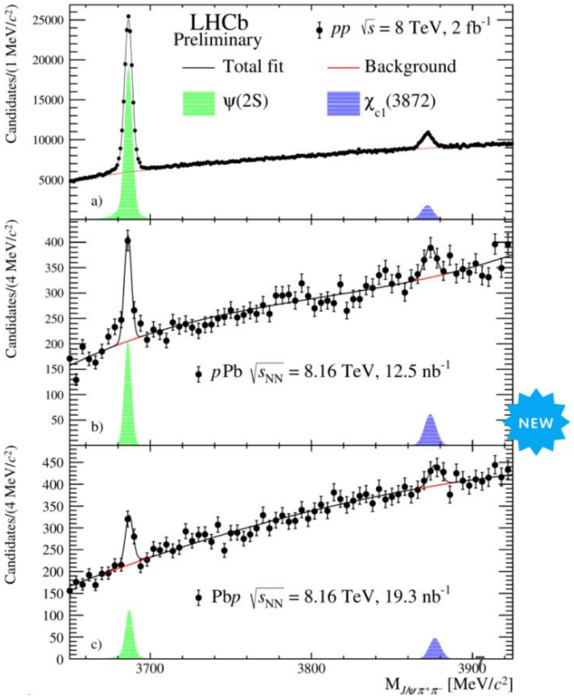


CMS: JHEP 11 (2020) 001

What happens in pPb?

LHCb-CONF-2022-001

Production of χ_{c1}(3872) in pPb collisions to help understand the dynamics

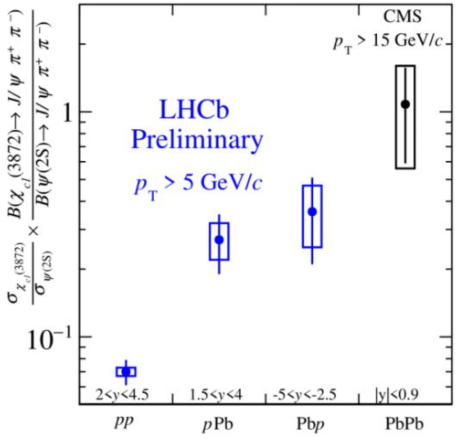


- ψ(2S) is suppressed in pPb and Pbp
- χ_{c1}(3872) production may also be enhanced as in PbPb collisions

⇨ Increasing trend:

at high density quark coalescence can become the dominant mechanism affecting χ_{c1} production

But still large uncertainties



$\propto N_{tracks}$

Molecule, tetraquark or a mixture?

New tetra and pentaquarks

Observation of doubly charm tetraquark

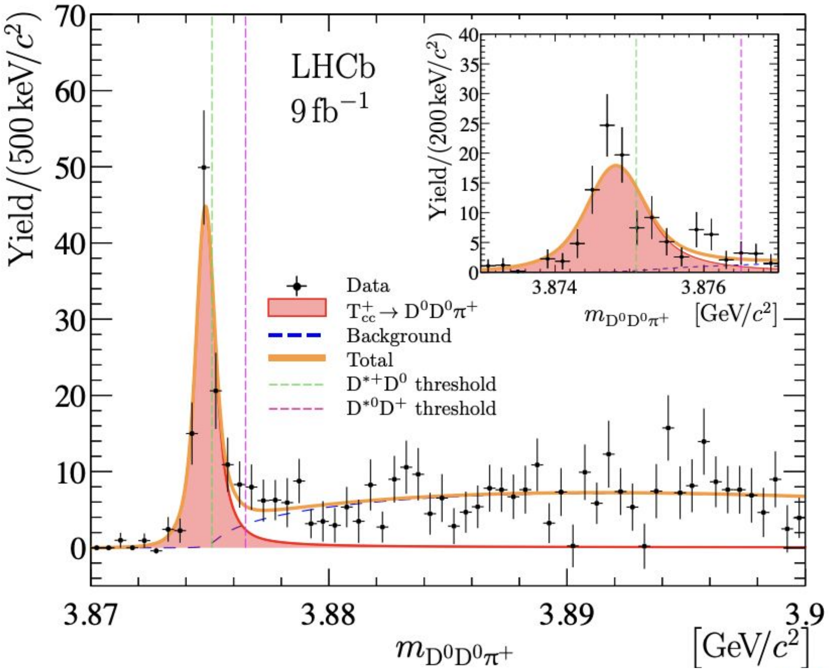
arXiv:2109.01038; arXiv:2109.01056

First observation of same-sign double charmed tetraquark T_{cc}^{+}
⇒ exotic quark content $cc\bar{u}\bar{d}$

Mass close to $D^{*+}D^{0}$ threshold and very narrow

$$\delta m_{\rm BW} = -273 \pm 61(\text{stat}) \pm 5(\text{syst})^{+11}_{-14}(\text{model})\ \text{keV}$$
$$\Gamma = 410 \pm 65(\text{stat}) \pm 43(\text{syst})^{+18}_{-38}(\text{model})\ \text{keV}$$

Consistent with isoscalar $J^P=1^+$



New pentaquark: $P_c(4337)$

PRL 128, 062001 (2022)

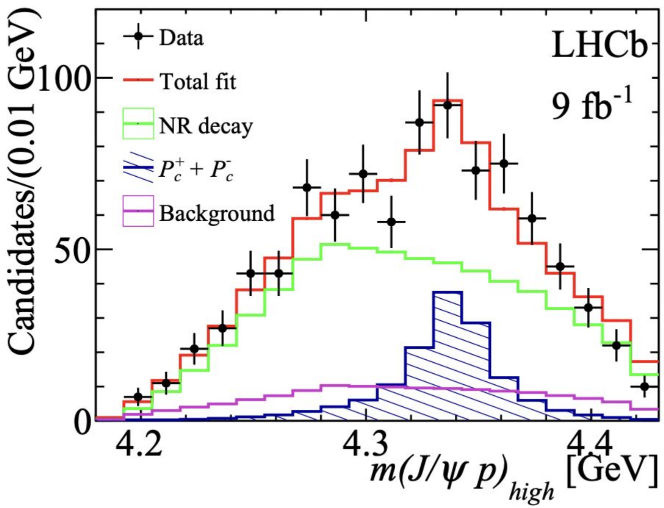
In $B^0_{(s)} \to J/\psi p\bar{p}$ decays: ~800 events

4D amplitude analysis
in $\Phi=(m_{pp}, \cos\theta_l, \cos\theta_V, \varphi)$

Evidence for a structure in $J/\psi p$ and $J/\psi\bar{p}$

$$M_{P_c} = 4337^{+7}_{-4}(\text{stat}) \pm 2(\text{sys})\text{MeV},$$
$$\Gamma_{P_c} = 29^{+26}_{-12}(\text{stat}) \pm 14(\text{sys})\text{ MeV}$$

No evidence
for ***P_c(4312)***
nor for ***f_J(2220)*** glueball[1]



Peculiar that:
- *P_c(4312)* only in Λ_b decays
- *P_c(4337)* only in B_s decays

[1]Eur. Phys. J. C75 (2015), no. 3 101

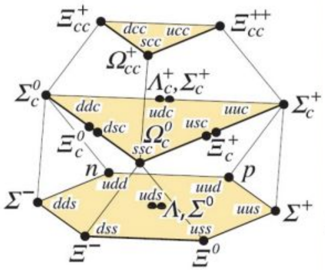
Conclusion & Prospects

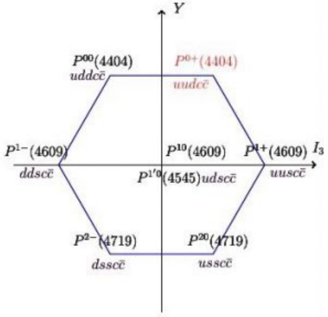
Spectroscopy of heavy hadrons
- excited *b* hadrons
- *bc* searches already started

Exotic contributions
- Nature of $\chi_{c1}(3872)$ still uncertain
- New tetra and pentaquark states observed: T_{cc}^{+} and $P_c(4337)$

With Run 3 data:

Observation of Ξ_{cc}^{+}, Ω_{cc}^{+}?
Access to *bc* tetraquarks and pentaquarks and *bb* spectroscopy
Confirm P_c and P_{cs} states
Search for exotic flavour multiplets





Interesting studies will also come from **ALICE 3**[1] in Run 5-6
- $\chi_{c1}(3872)$ production down to low p_T
- T_{cc} structure by measuring DD* momentum correlation functions in pp and PbPb

Thank you for listening!

[1]CERN-LHCC-2022-009

Backup slides

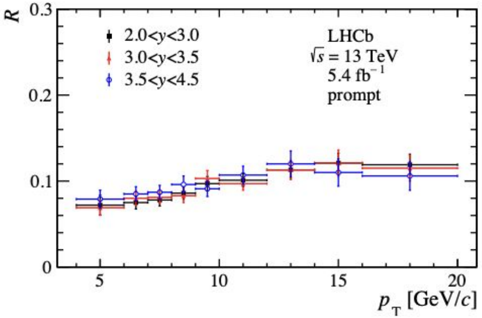
Production in pp

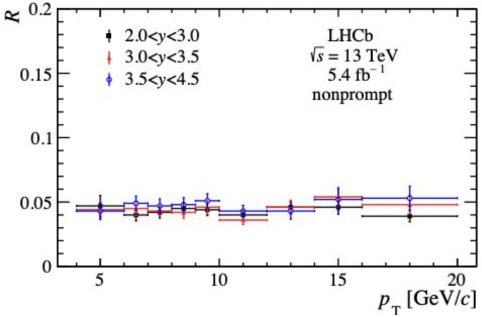
PRL 126 (2021) 092001, JHEP 01 (2022) 131

Differential cross section ratio of $\chi_{c1}(3872)$ relative to ψ(2S)

- Both in prompt pp collisions and from b-hadron decays
- Measured as a function of track multiplicity, p_T and y

Separate a compact tetraquark (r<1 fm) from a large-sized molecular state (r~10 fm)

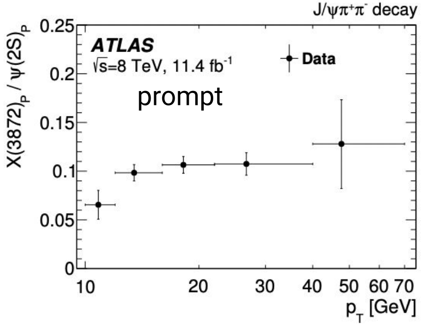




Increase with p_T for prompt

no p_T dependence for b-decays (non-prompt)

also measured by ATLAS



nonprompt