Production of *Exotic* Hadrons and Perspectives for Heavy Ion Collisions

QUARK MATTER
KRAKÓW
2022

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Los Alamos NATIONAL LABORATORY

Outline

- Exotic Hadrons
  - What do we mean by exotic?
  - How do we know if something is exotic vs conventional?
- Why study exotics in heavy ion collisions?
- First data on exotics in QCD medium
  - X(3872) in *pp, p*Pb, PbPb
  - Tcc and X(6900)
- Perspectives
- Summary

Quark Model of Hadrons

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\bar{q})$ similarly gives just **1** and **8**.

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

G. Zweig *)
CERN - Geneva

8182/TH.401
17 January 1964

In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}$AAAA, $\bar{A}\bar{A}$AAAAA, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}$A, $\bar{A}\bar{A}$AA etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}$A and AAA, that is, "deuces and treys".

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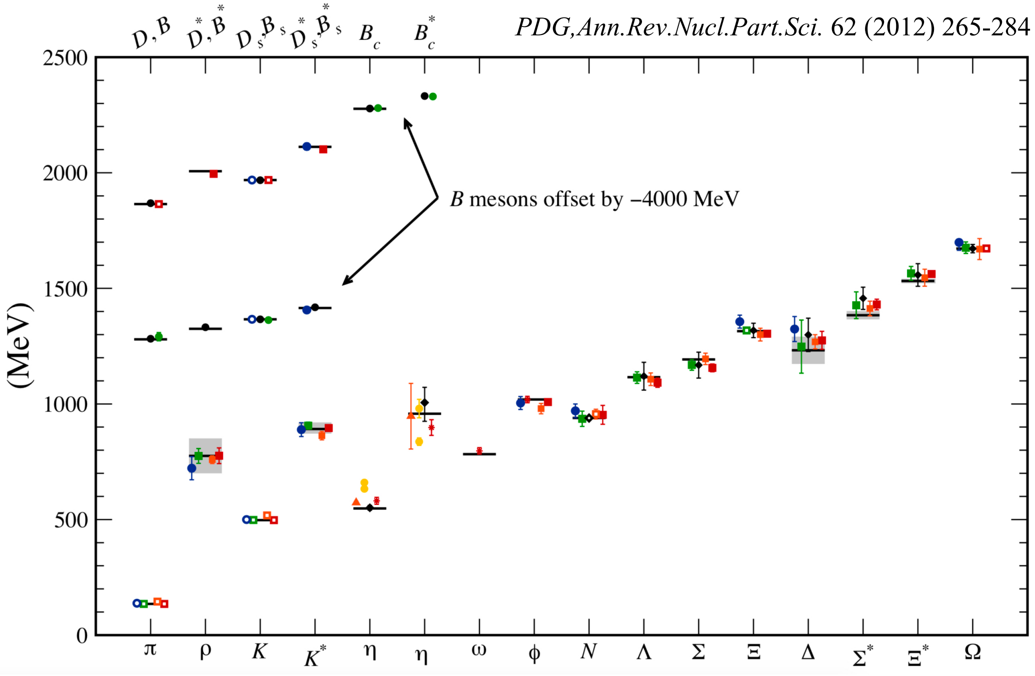
Exotic = hadrons with >3 valence quarks

Expected since first days of quark model

Conventional hadron spectroscopy

Before claiming a particle is ***exotic,*** we must account for **conventional** hadrons.



- Lattice QCD is an effective tool for light quark spectroscopy
- Uncertainties on masses typically ~10%
- **Decades of controversy on status of potential light quark exotics**

See talk by Neelima Agrawal, Weds

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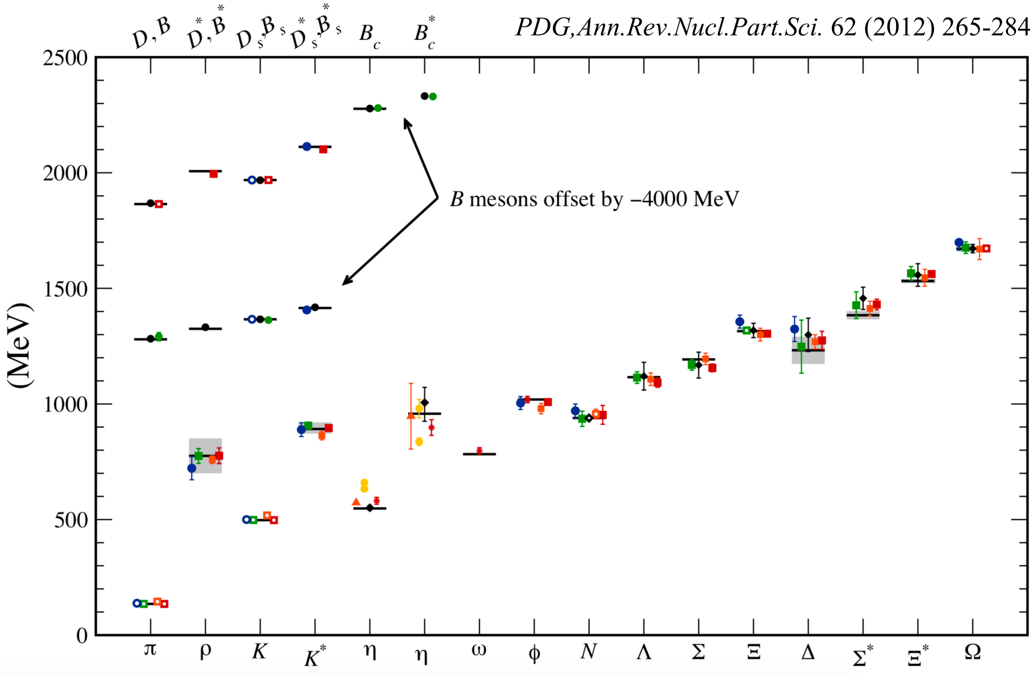

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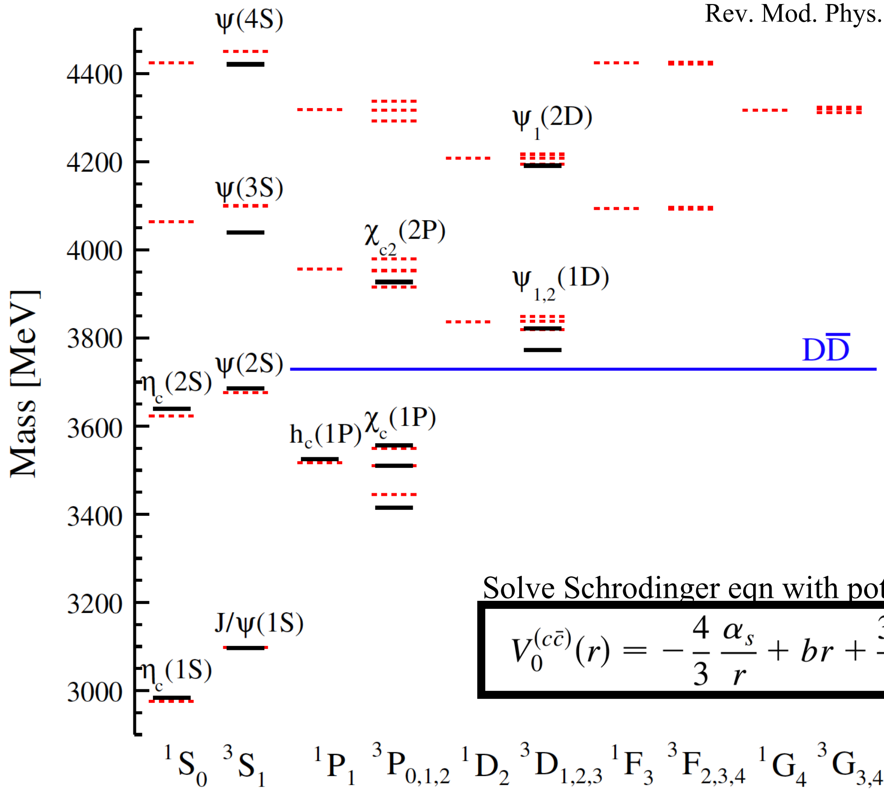

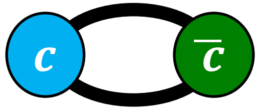

Solve Schrodinger eqn with potential:

$$V_0^{(c\bar{c})}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\tilde{\delta}_\sigma(r)\vec{S}_c \cdot \vec{S}_{\bar{c}}$$

- Charm/bottom produced through perturbative QCD processes
- Potential models produce all known quarkonia states
- Predictive: masses typically within <1% of measurements
- **Conventional heavy quarkonia spectrum well understood**

Hadrons discovered at LHC

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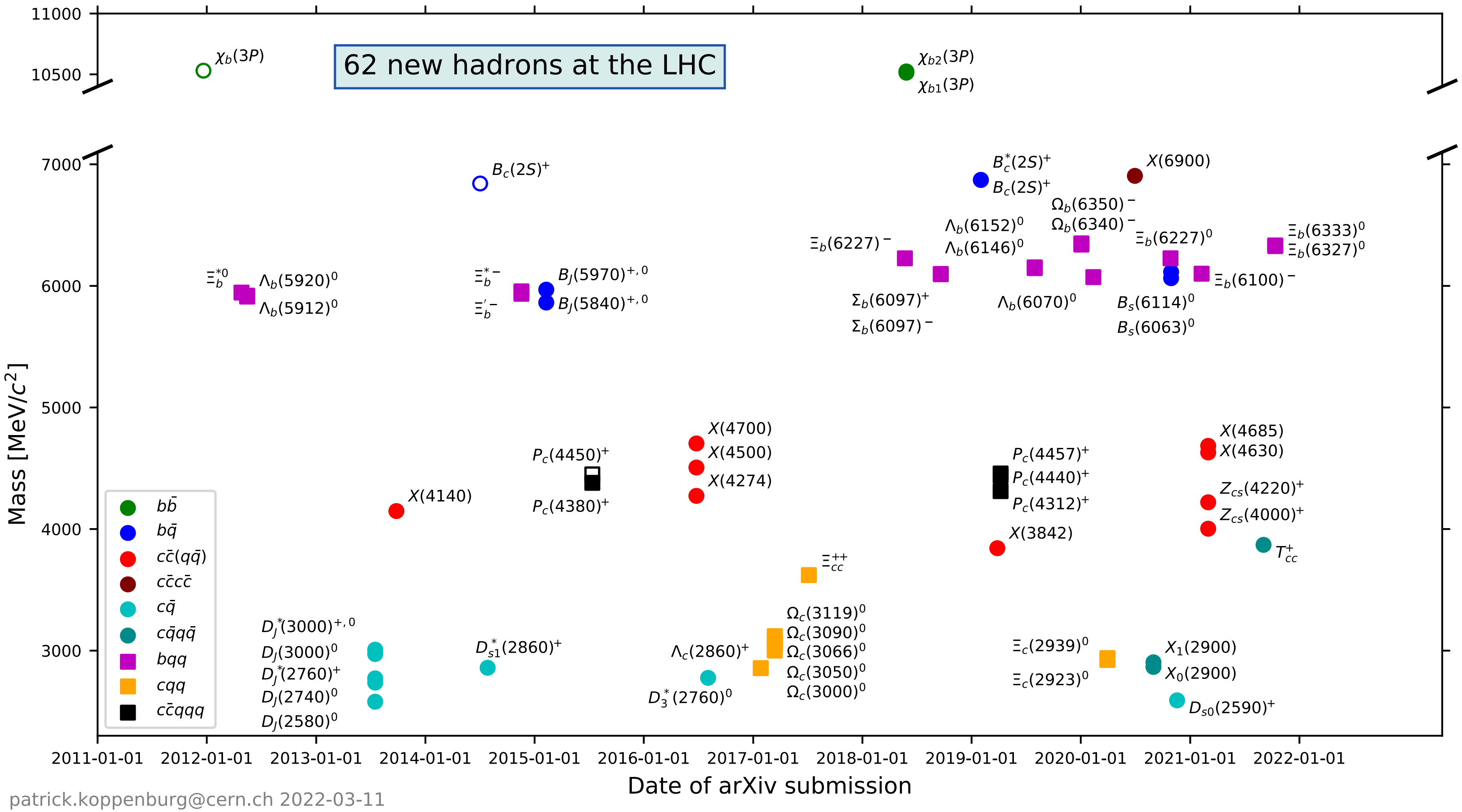

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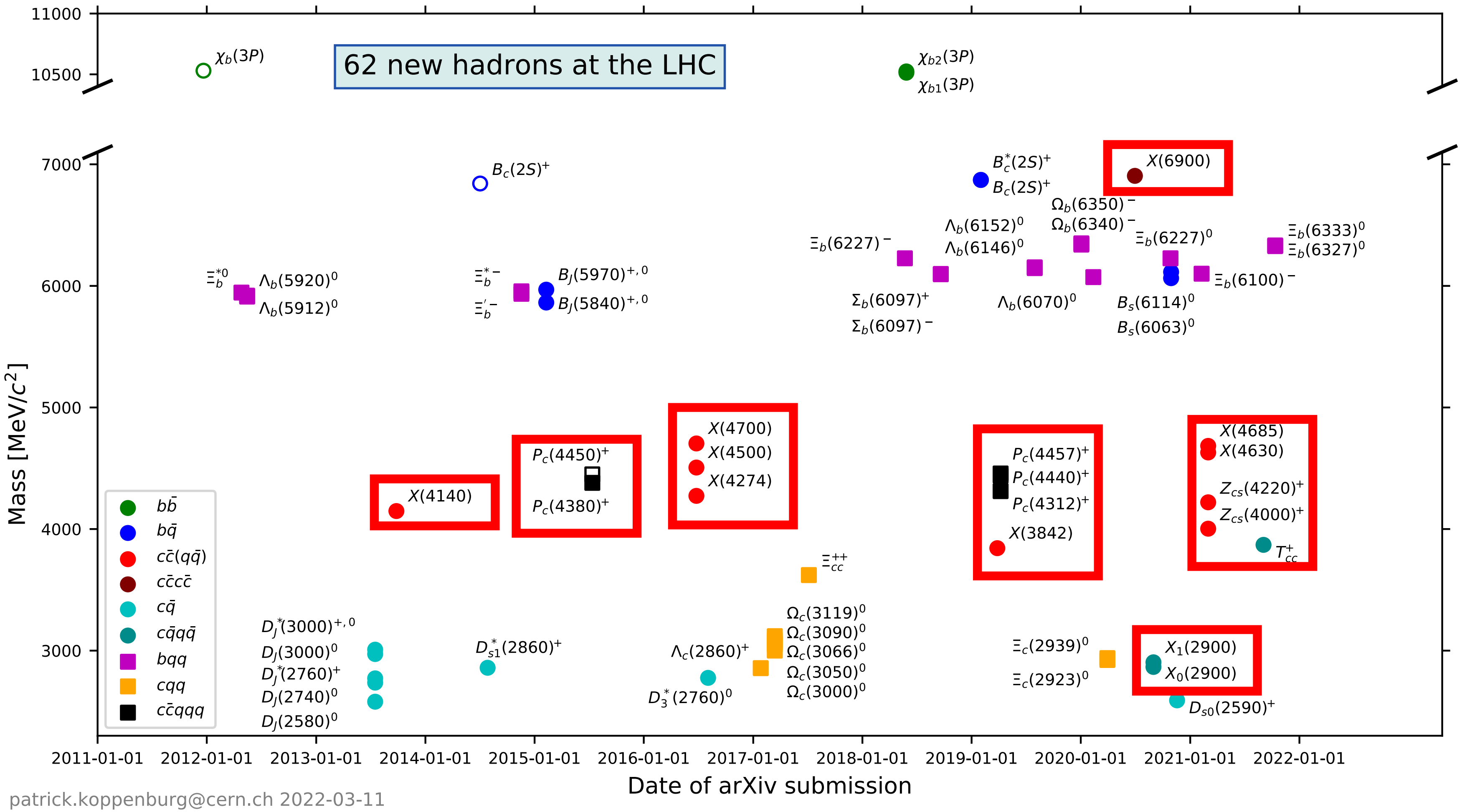
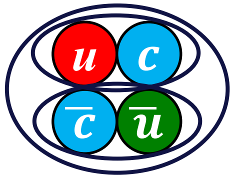
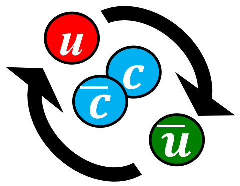


The quark model is rapidly expanding:
study of exotics states largely driven by experiment

Compact tetraquark/pentaquark

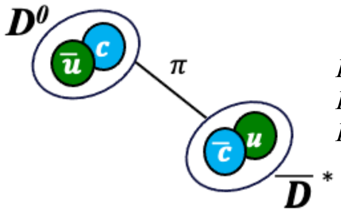


Diquark-diantiquark
PRD 71, 014028 (2005)
PLB 662 424 (2008)



Hadrocharmonium/ adjoint charmonium
PLB 666 344 (2008)
PLB 671 82 (2009)

Hadronic Molecules



PLB 590 209 (2004)
PRD 77 014029 (2008)
PRD 100 0115029(R) (2019)

Mixtures

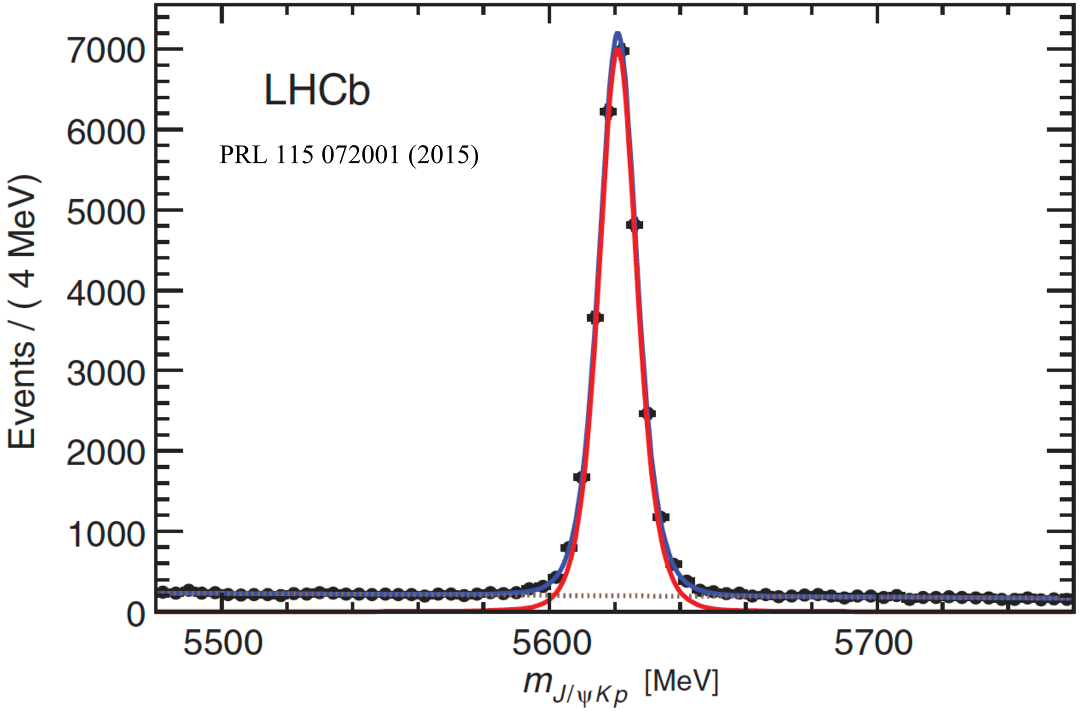
$$X = a\,|c\bar{c}\rangle + b\,|c\bar{c}q\bar{q}\rangle$$

PLB 578 365 (2004)
PRD 96 074014 (2017)

Example: $P_c^{\pm}$ pentaquarks

Select daughters from the decay

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



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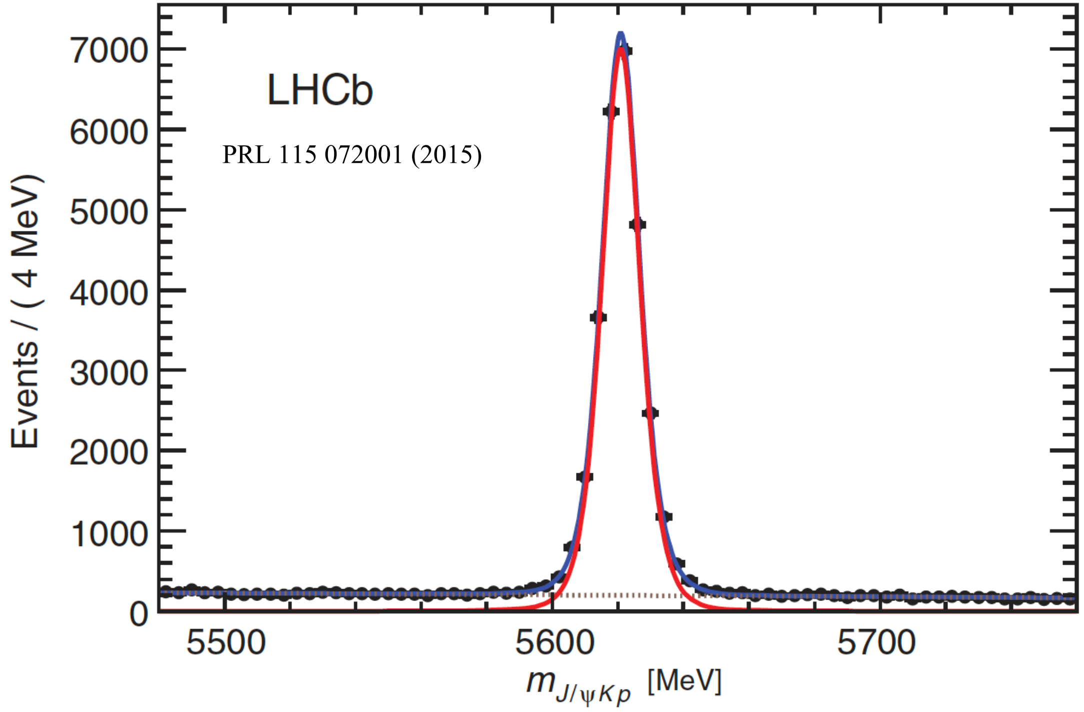

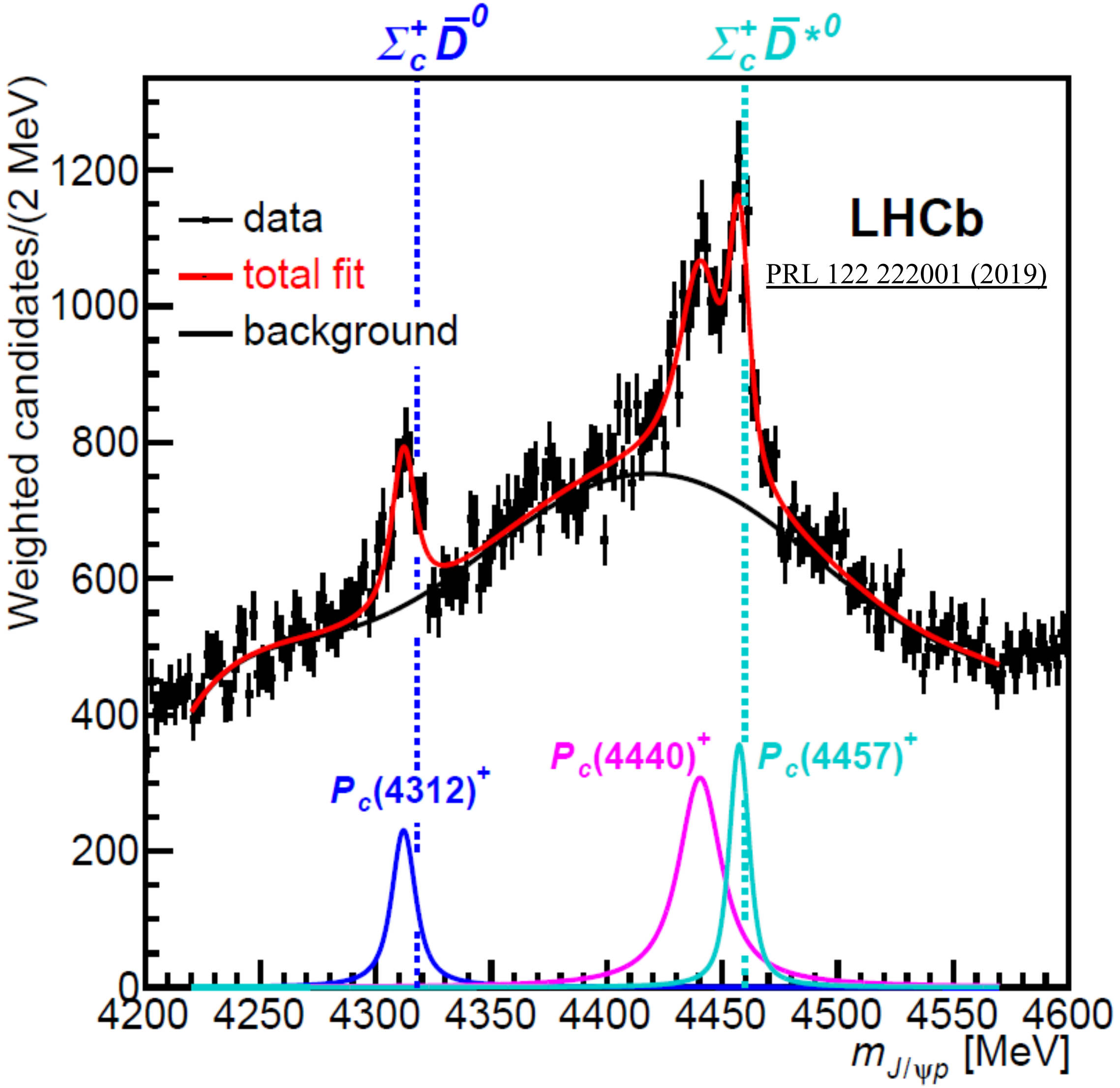

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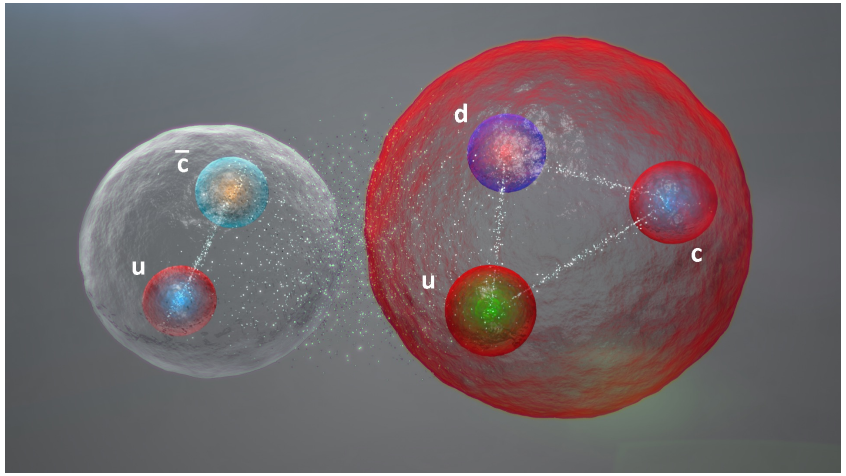
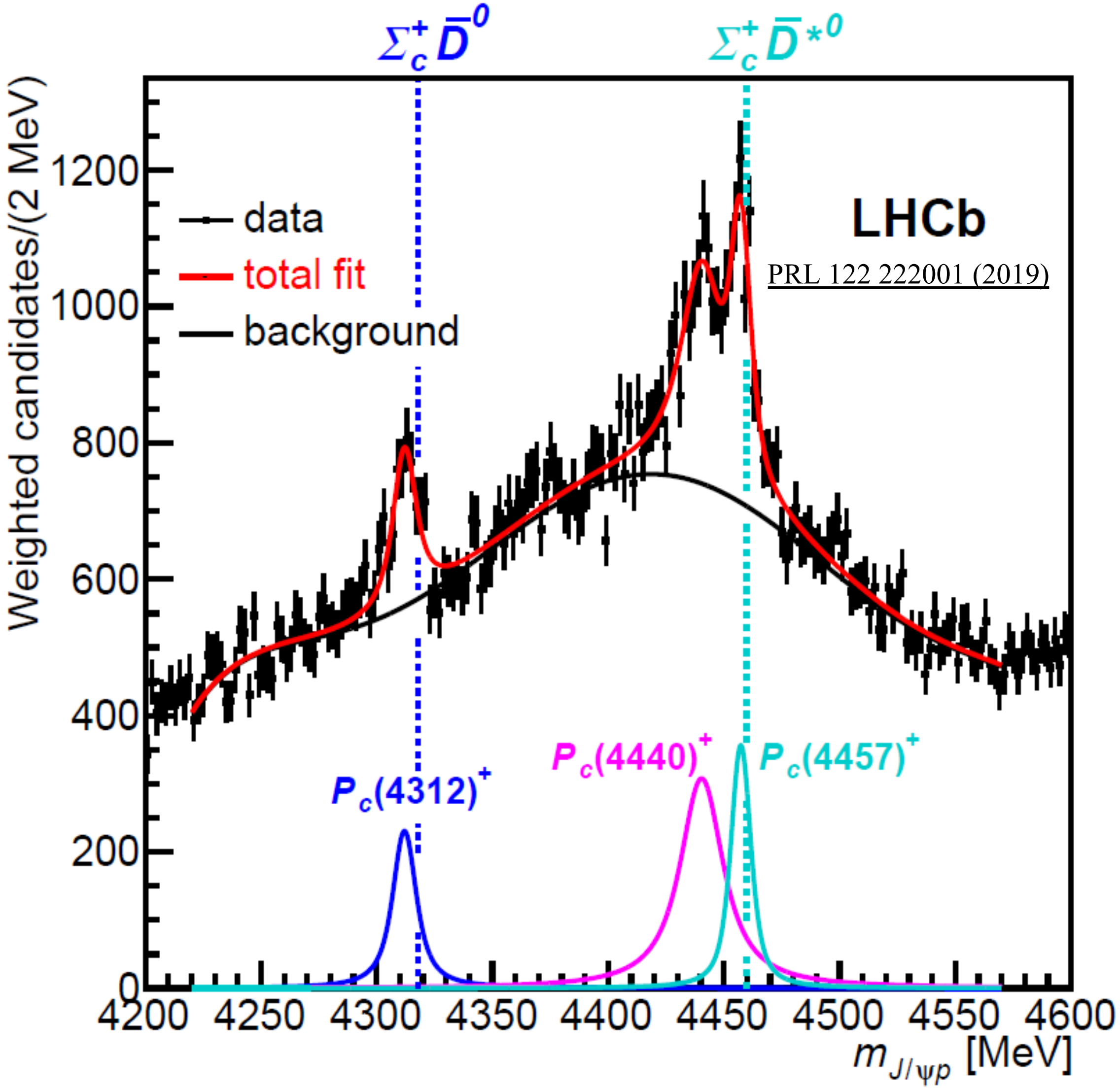
Masses are close to meson+baryon thresholds: candidate hadronic molecule

PRL 22 242001 (2019)



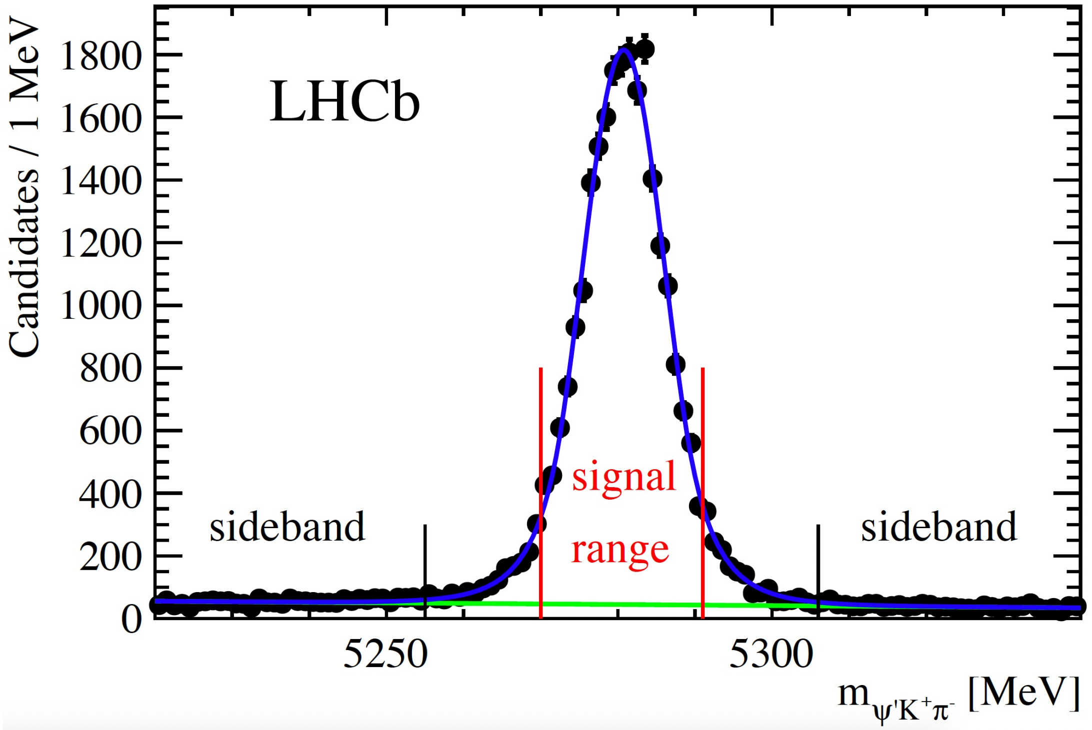
Also interpreted as hadrocharmonium: MPL A 35 250151 (2020)
or compact states: PLB 793 (2019) 365-371



Example: Charged Tetraquark $Z_c^{\pm}(4430)$

Select daughters from the decay

$$B^0 \rightarrow \psi(2S)K^+\pi^-$$



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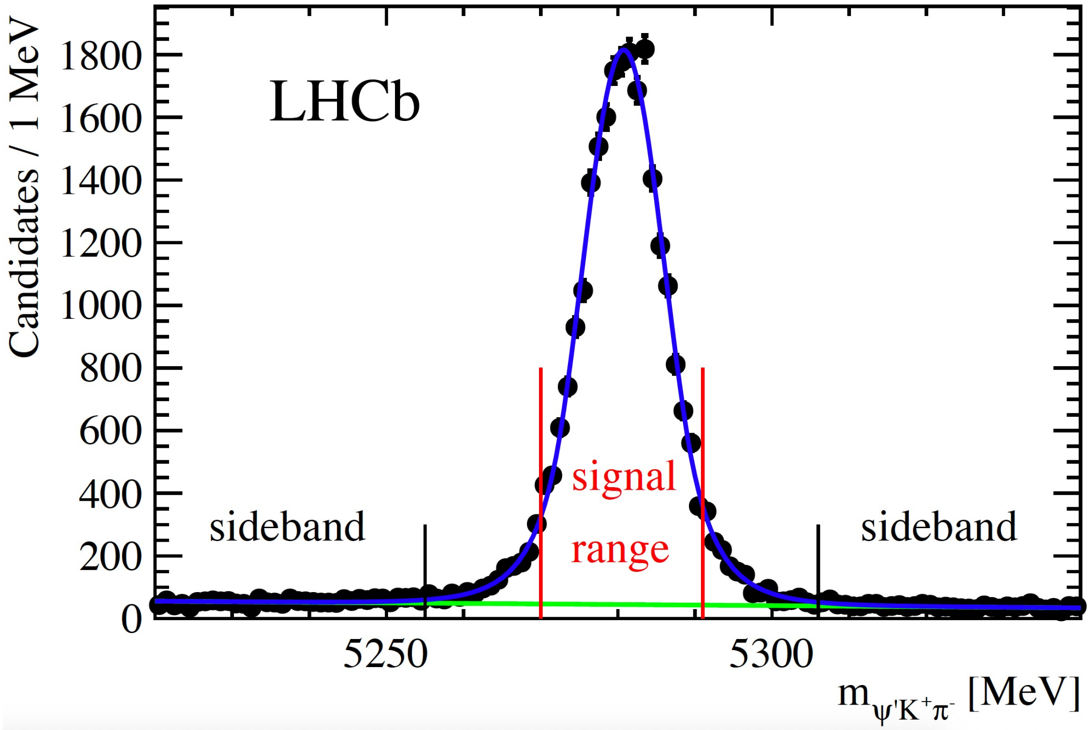
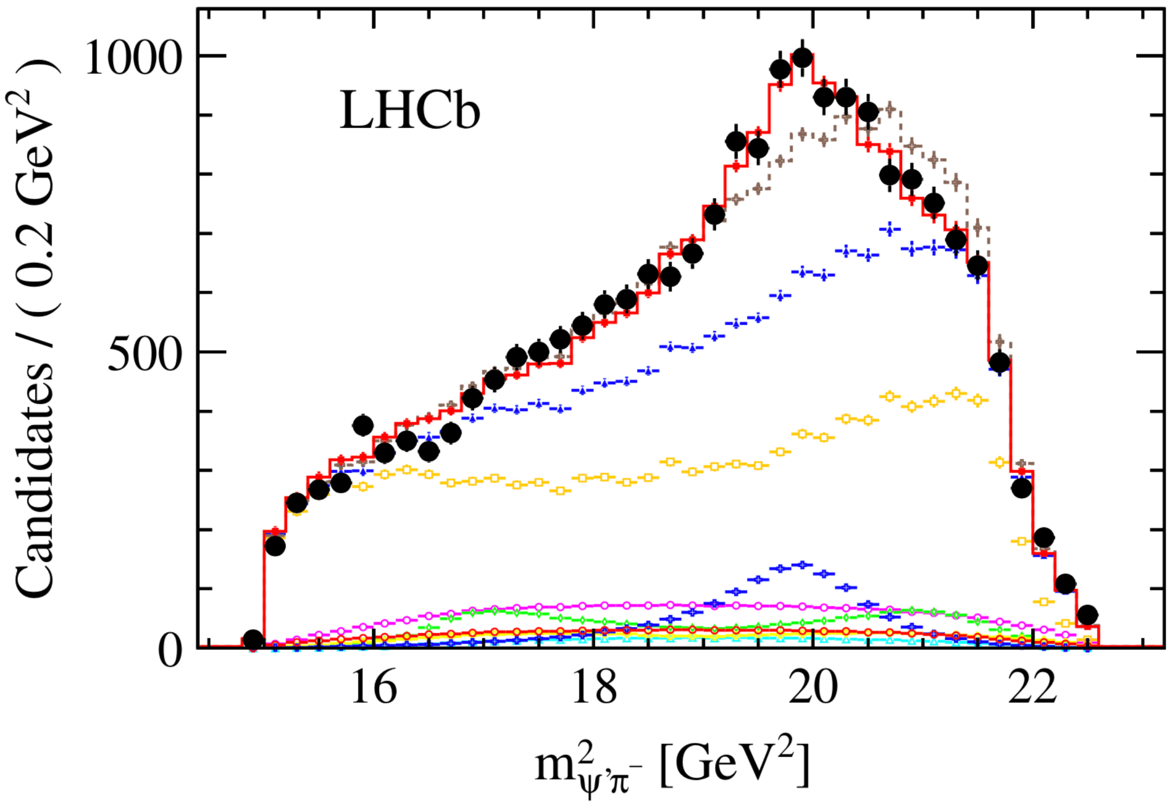
PRL 112 222002 (2014)





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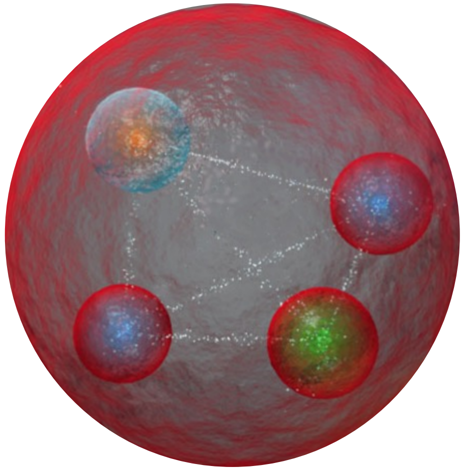
Charged and contains $c\bar{c}$ pair: "manifestly exotic"
minimal quark content $c\bar{c}q\bar{q}$

Mass not close to any known hadron+hadron threshold: candidate compact tetraquark

Diquark model: PRD 89 114010 (2014)



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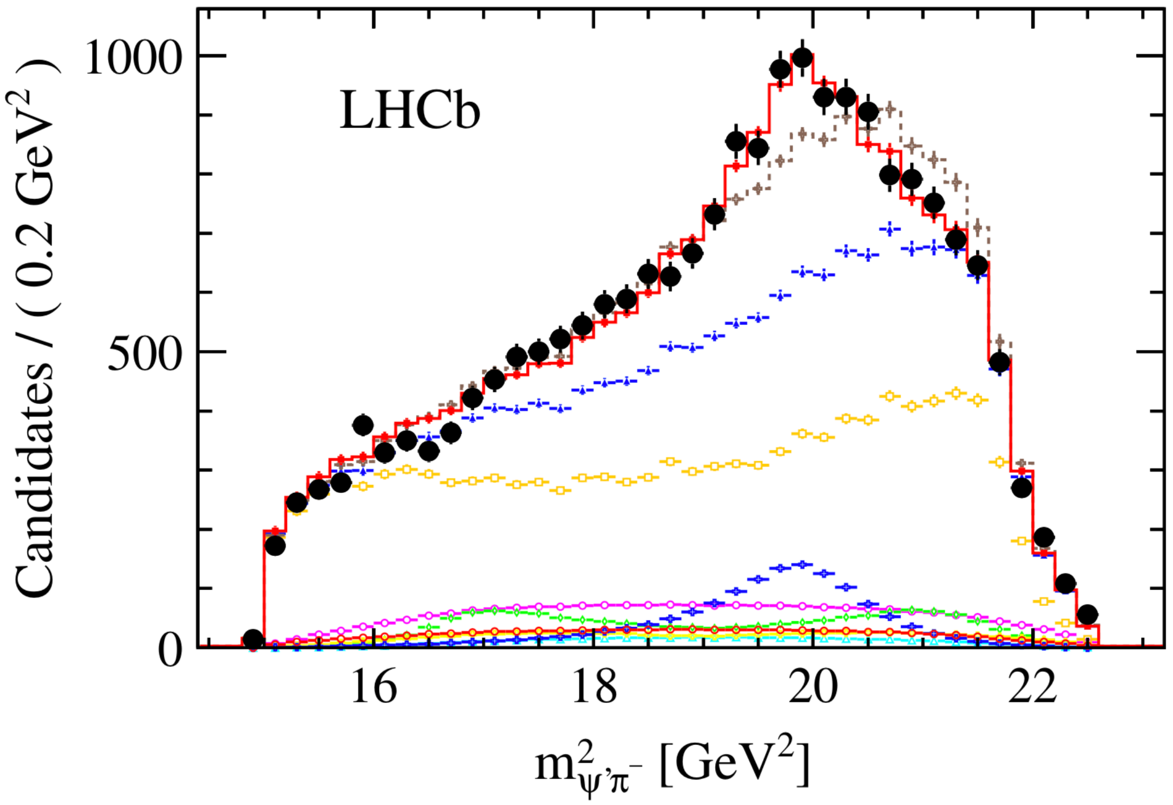
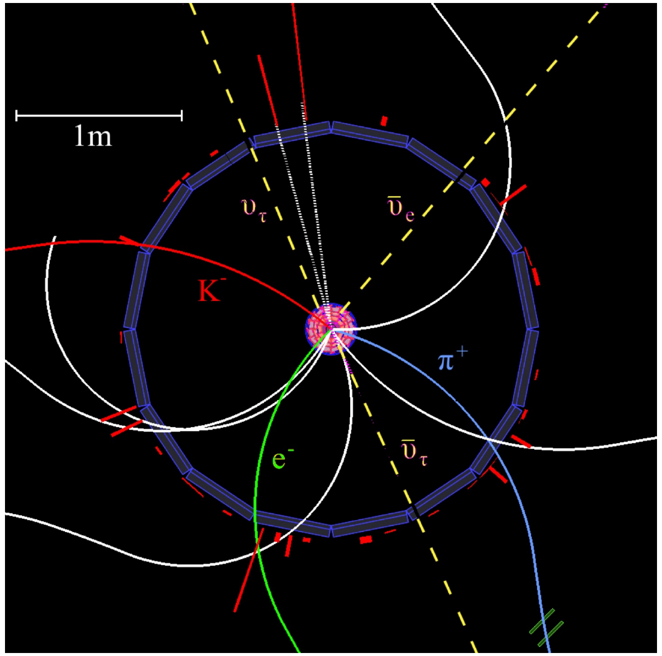


Exotics in the QCD medium

$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$ event from Belle



B decays are a great way to discover exotics and measure some properties:

- Well constrained initial state
- Low backgrounds
- Not all states accessible
- After 20 years, fundamental questions about exotics remain unanswered

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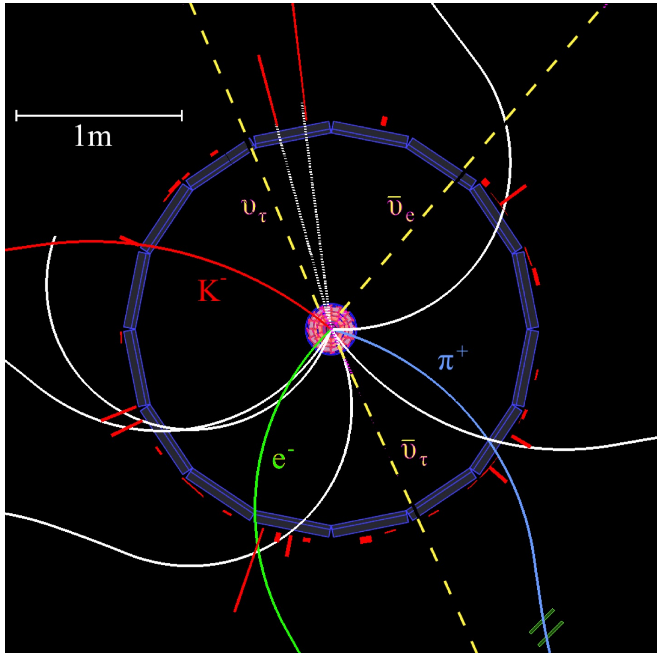

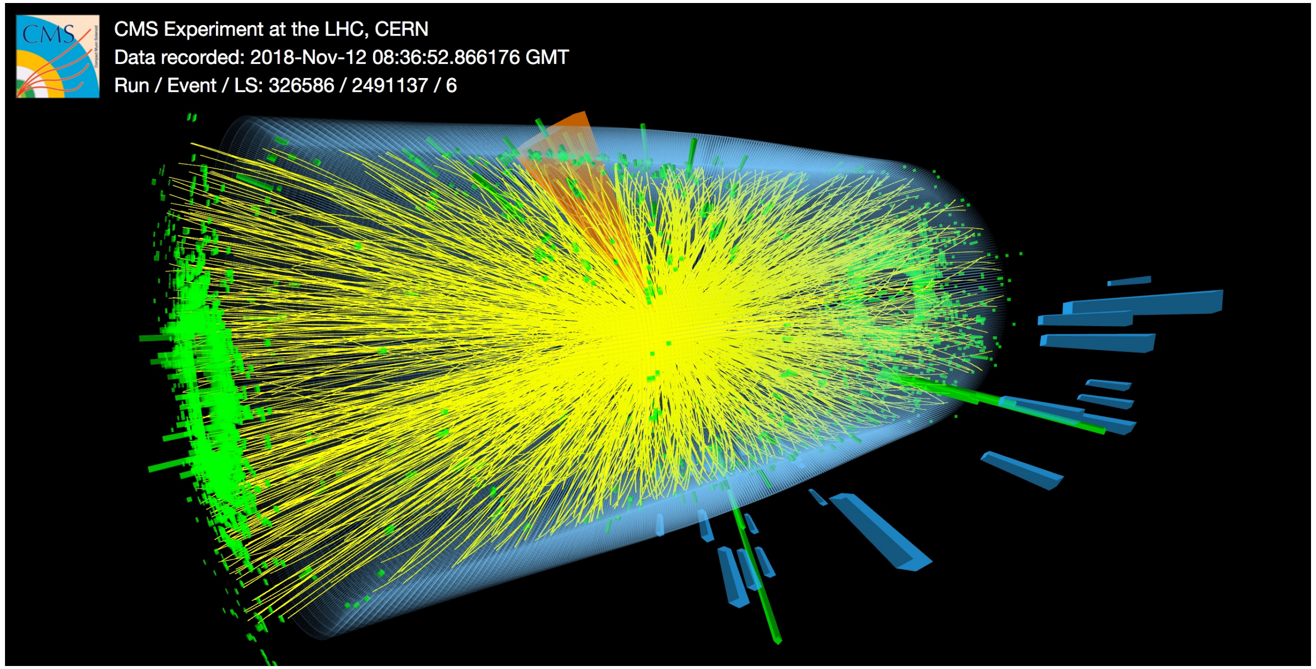

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- Breakup with comoving particles
- Collectivity
- Production via coalescence/recombination
- Signal extraction can be COMPLICATED

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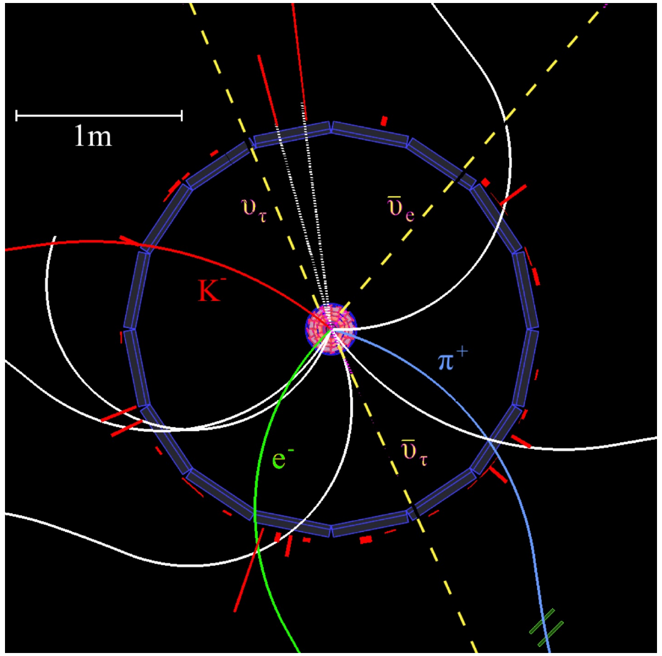

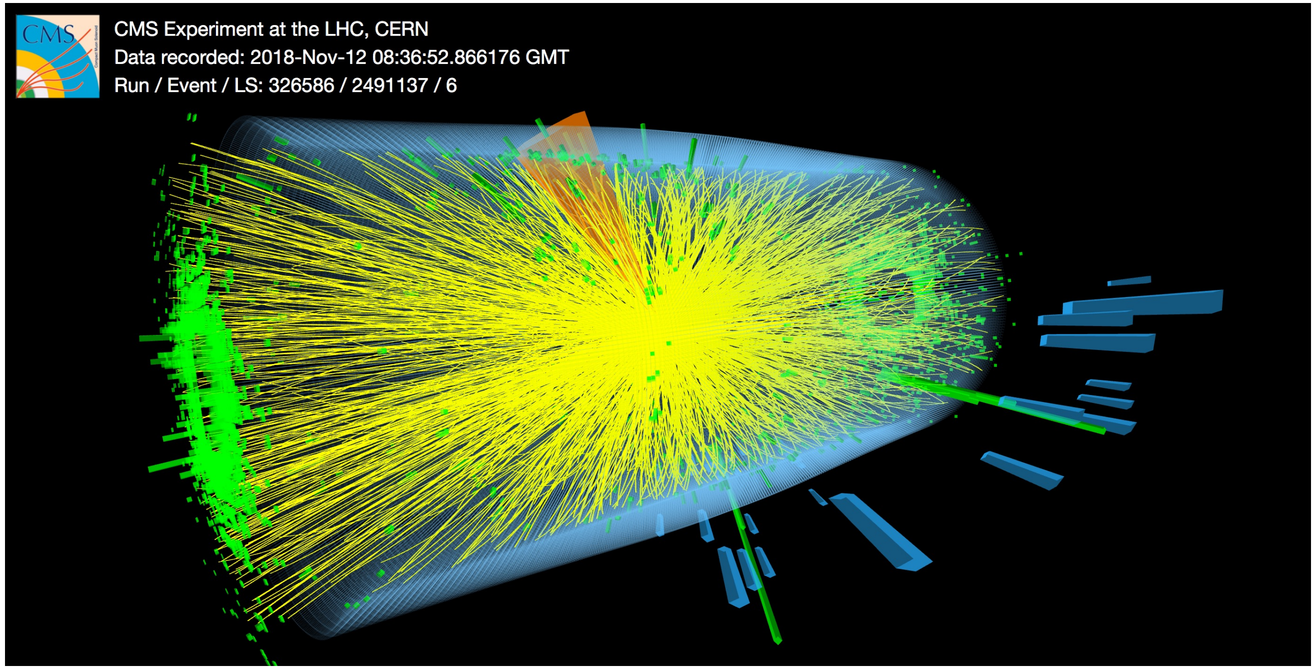

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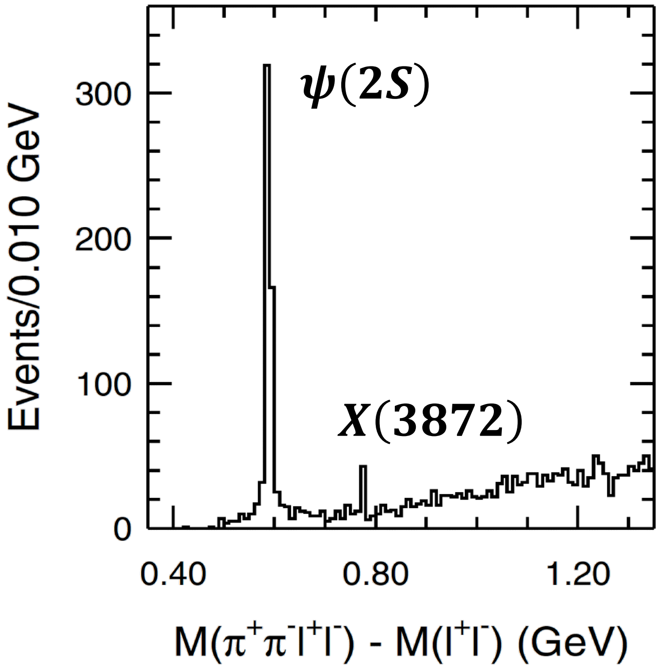
Effects are sensitive to ***size/binding energy of bound state*** and ***density of medium***

Exotic states provide ***new tests of models*** in an ***expanded range of*** n_{cq}

The first heavy quark exotic: X(3872)

Belle Collaboration
PRL 91 262001 (2003)



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- LHCb measured quantum numbers (PRL 110 222001 2013)
  - **Incompatible** with charmonium states expected from potential model

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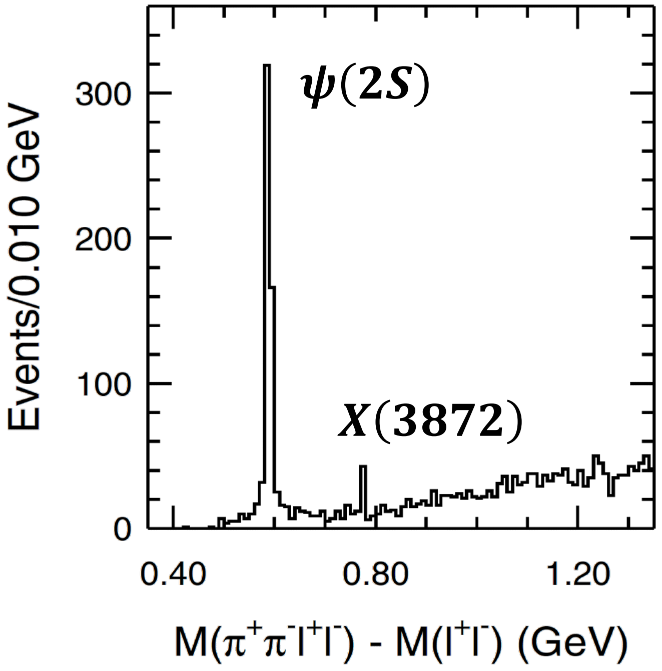

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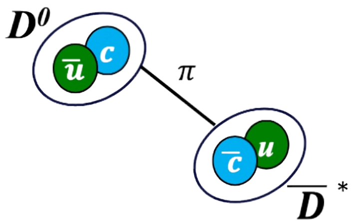
$$\left(M_{D^0} + M_{\bar{D}^{*0}}\right) - M_{\chi_{c1}(3872)} = 0.07 \pm 0.12 \text{ MeV}/c^2$$

$D^0\overline{D}^*$ *Molecule*



VERY **small binding energy**
VERY **large radius, ~5-10 fm**

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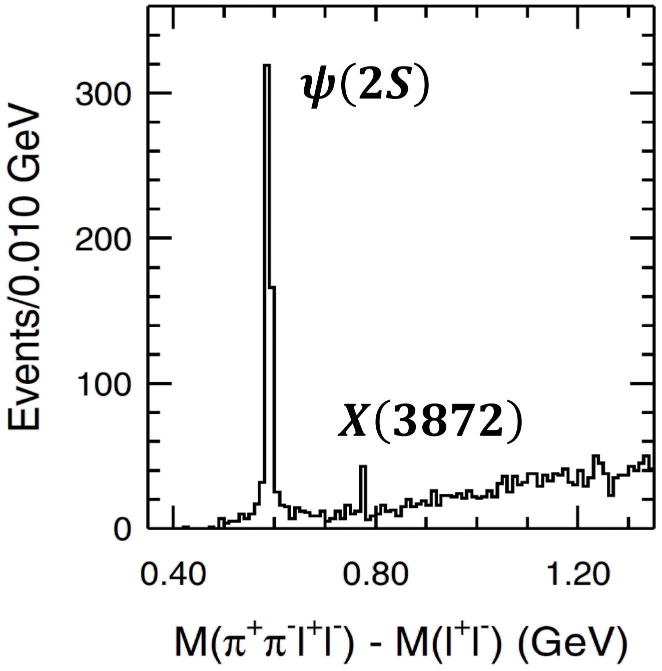

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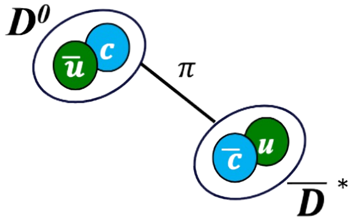
- Large prompt production fraction (~80%) – inconsistent with D meson coalescence in pp*

$D^0\overline{D}^*$ *Molecule*



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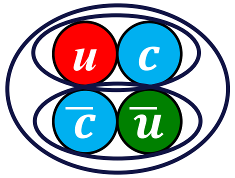
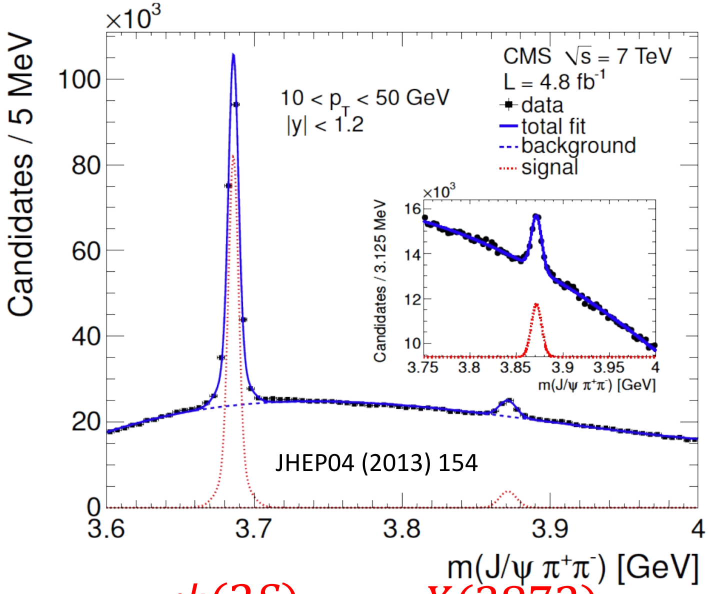
Compact tetraquark



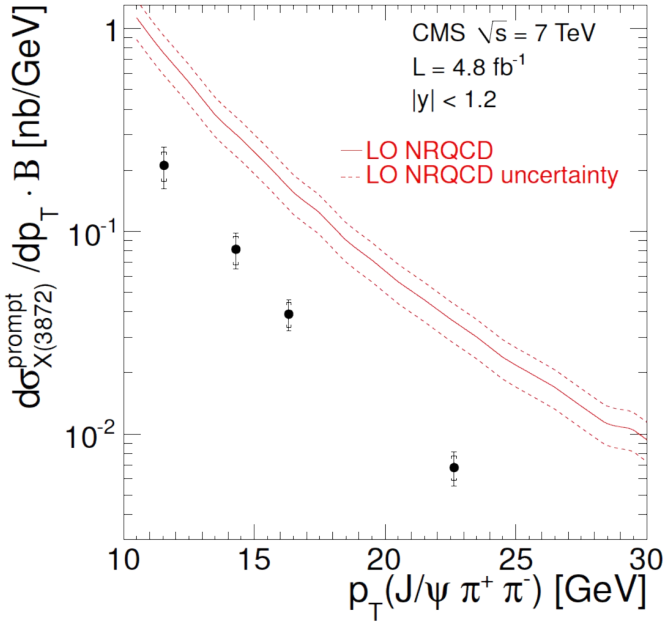
Tightly bound via color exchange between diquarks
***Small* radius, ~1 fm**

***Tension in theoretical literature:**
c.f. Bignamini, Grinstein et al
PRL 103 162001 (2009)
Artoisenet, Braaten
PRD 81 114018 (2010)

X(3872) production in *pp*

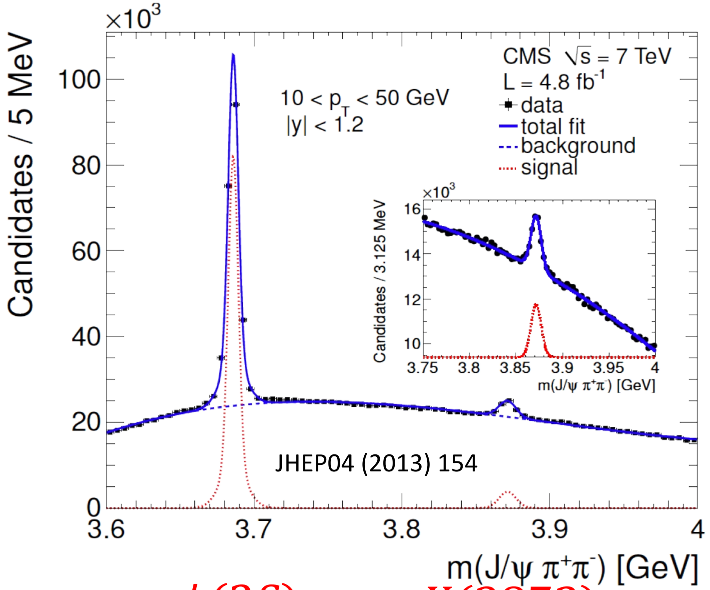


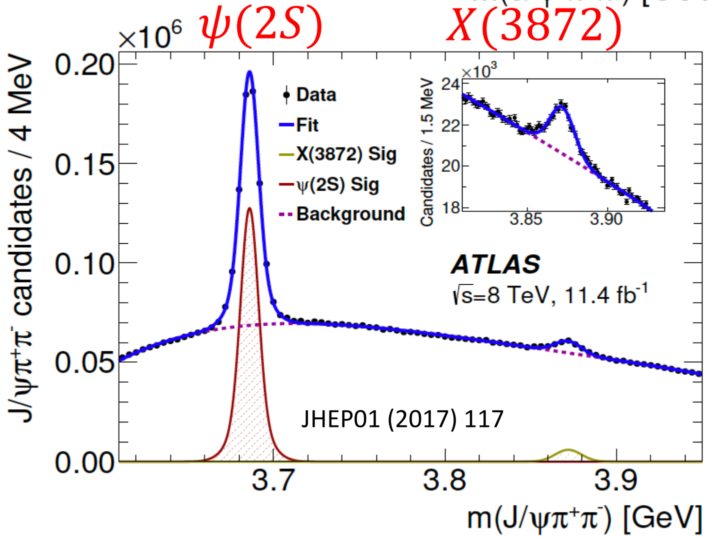
$\psi(2S)$ $X(3872)$

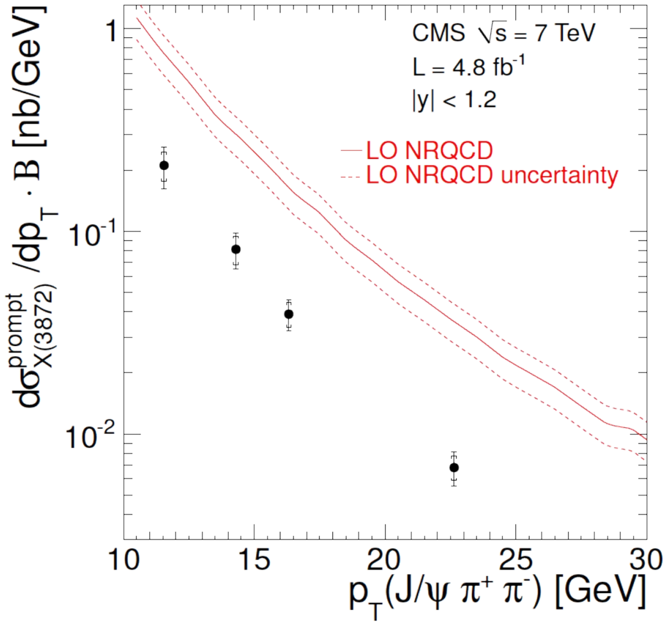


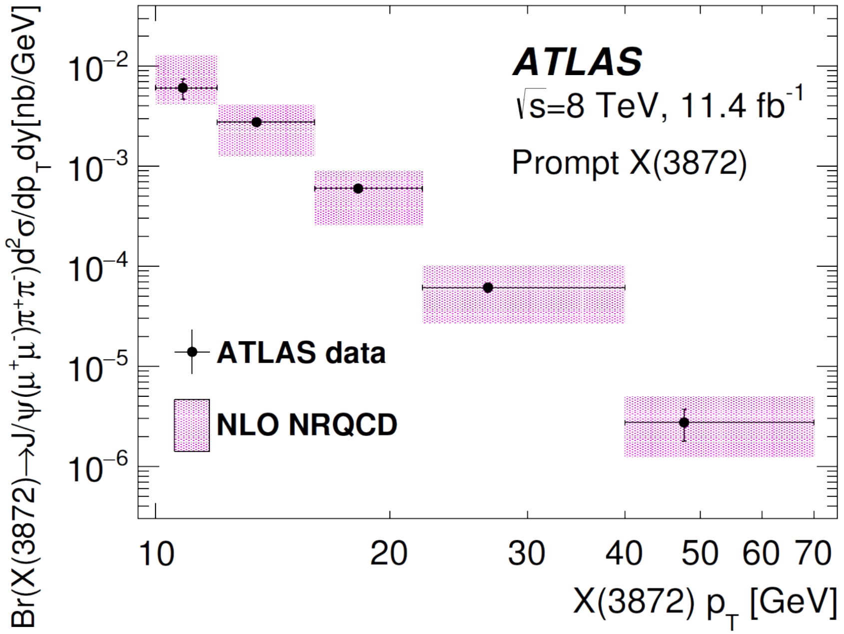
- NRQCD calculation assumes DD molecule, tuned to Tevatron data
- Significantly overpredicts yield
- Distribution shape looks reasonable

X(3872) production in *pp*









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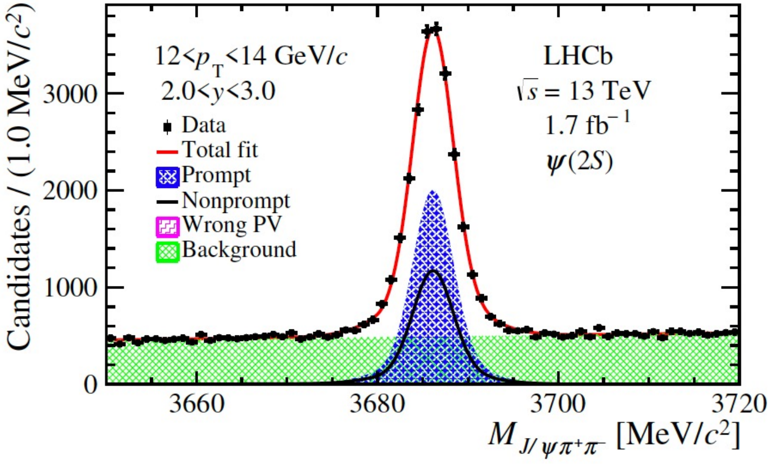
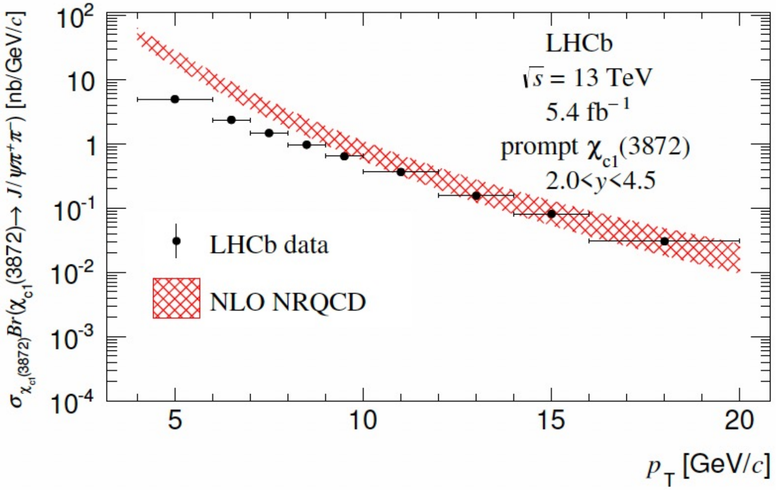
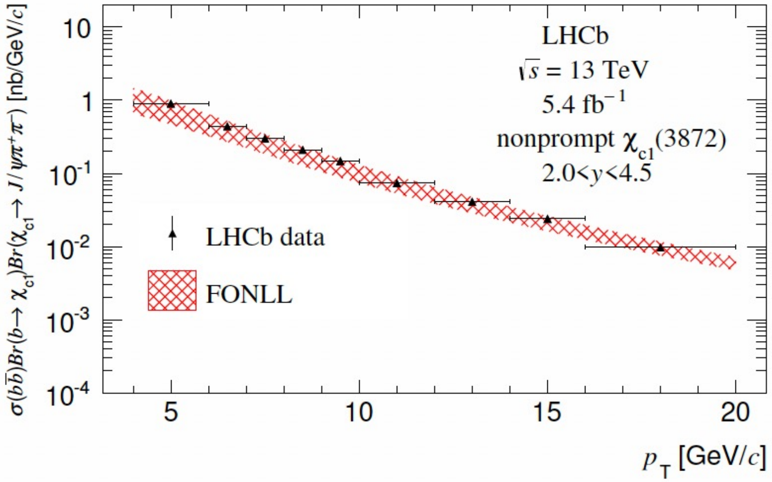
- Updated NRQCD calculation models X(3872) as mixture of DD molecule and conventional quarkonia state
- Calculation normalized to CMS data…

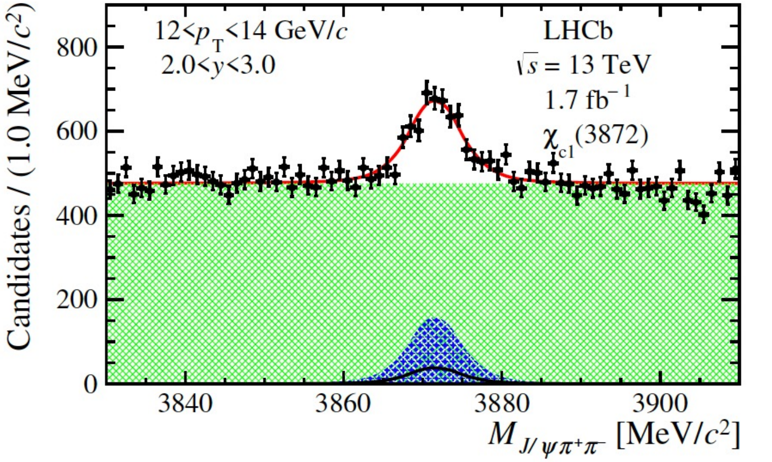
X(3872) production in *pp*

JHEP01 (2022) 131









- Similar NRQCD calculation matches high-p_T data well
- Overpredicts yield at lower p_T
- Room for additional effects?

- FONLL describes non-prompt X(3872) production well (also at ATLAS and CMS)

Examine X(3872)/ψ(2S) ratio for direct comparison between exotic hadron and well-known conventional charmonium

X(3872)/ψ(2S) vs multiplicity

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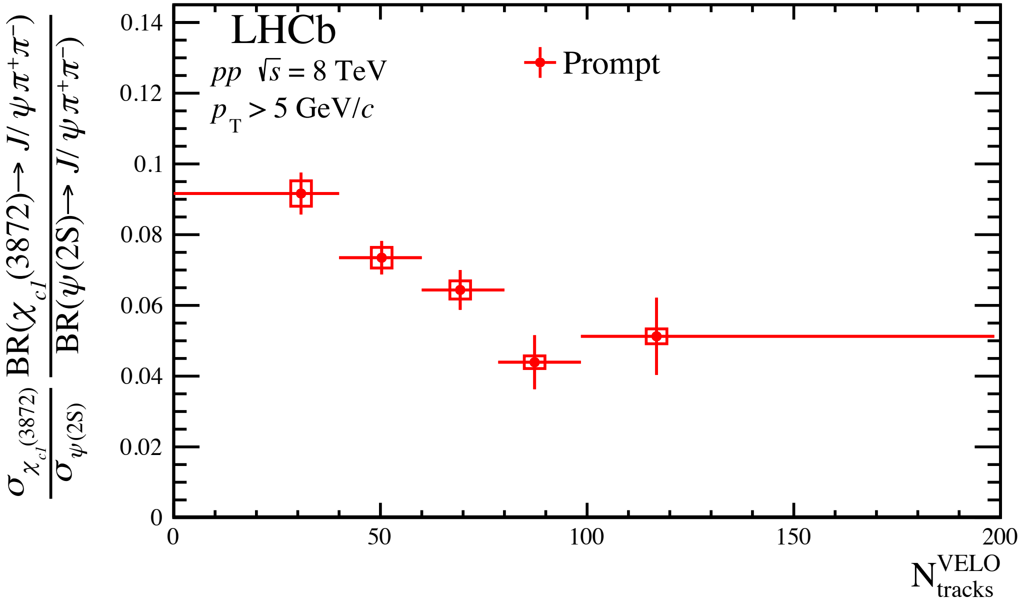
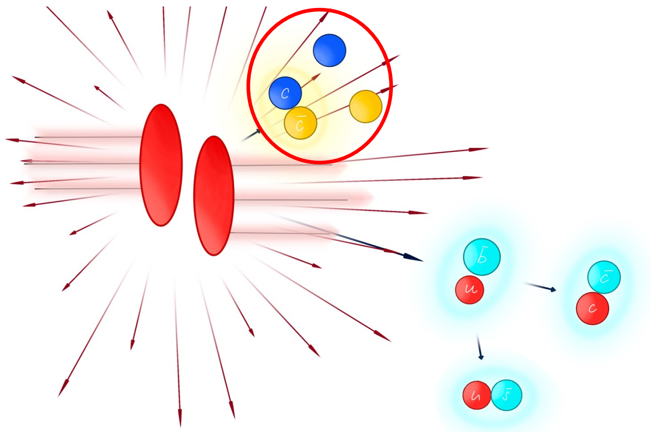
PRL 126 092001 (2021)





Prompt component:

Increasing suppression of $\mathbf{X(3872)}$ production relative to $\boldsymbol{\psi(2S)}$ as multiplicity increases

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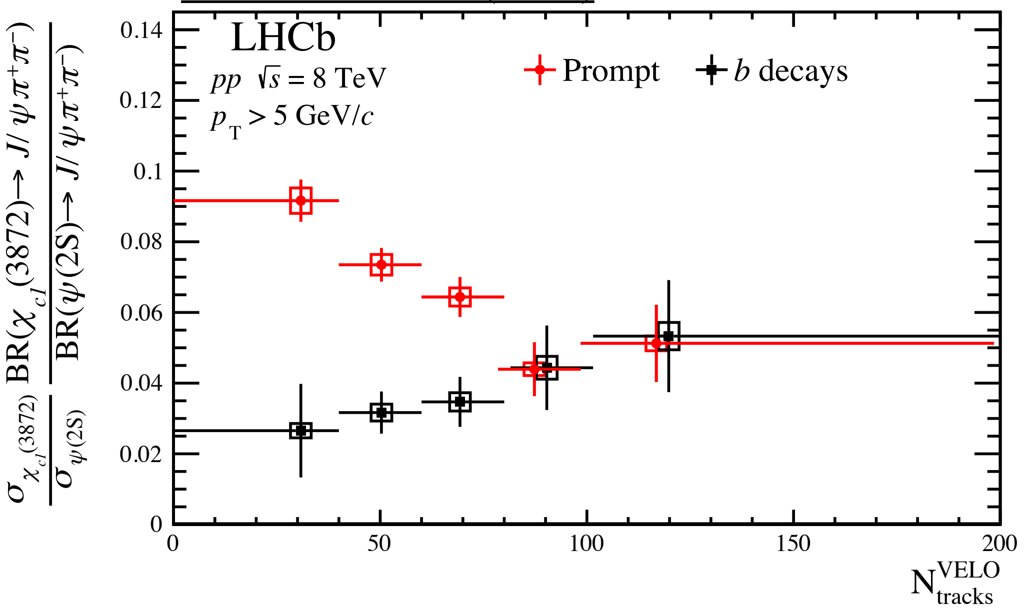

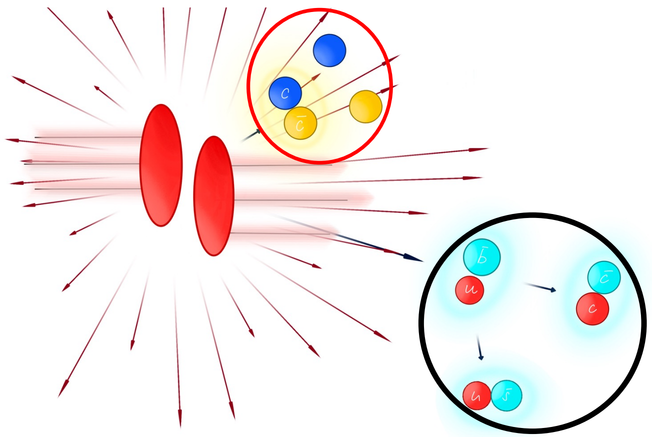

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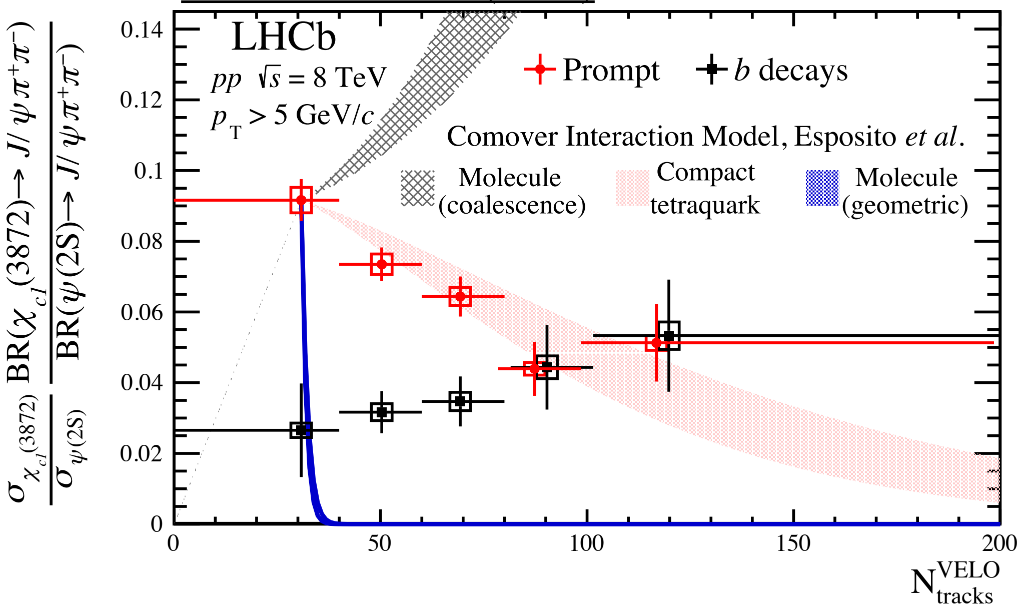
$\boldsymbol{b}$-decay component:

Totally different behavior: no significant change in relative production, as expected for decays in vacuum. Ratio is set by $\boldsymbol{b}$ decay branching ratios.

X(3872)/ψ(2S) vs multiplicity

PRL 126 092001 (2021)

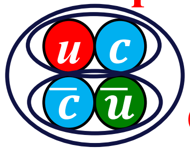


Geometric comover model:

$$\langle v\sigma\rangle_{\mathcal{Q}} = \sigma^{\rm geo}_{\mathcal{Q}} \left\langle \left(1 - \frac{E^{\rm thr}_{\mathcal{Q}}}{E_c}\right)^n \right\rangle$$

Molecular X(3872) immediately broken up

Compact X(3872) gradually dissociated



Data is consistent with **compact tetraquark** model.

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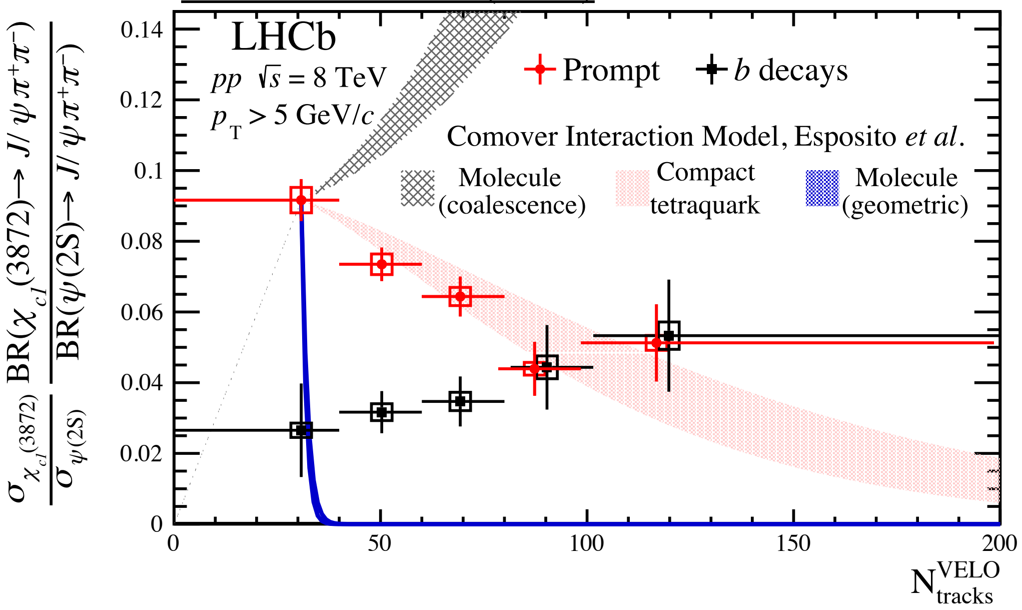

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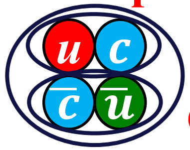

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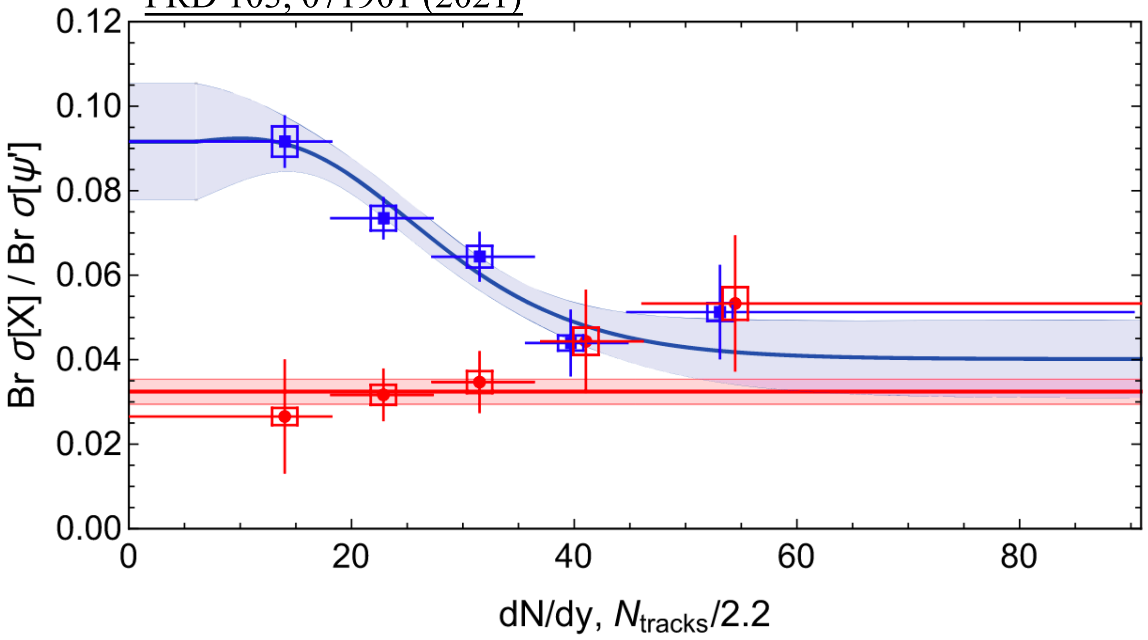
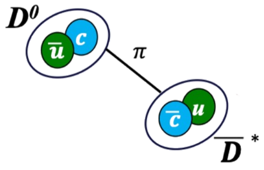
PRD 103, 071901 (2021)



Constituent comover model:

$$\sigma^{incl}[\pi X] \approx \frac{1}{2}(\sigma[\pi D^0] + \sigma[\pi \bar{D}^0] + \sigma[\pi D^{*0}] + \sigma[\pi \bar{D}^{*0}])$$



Data is consistent with **hadronic molecule** model.

X(3872)/ψ(2S) in PbPb

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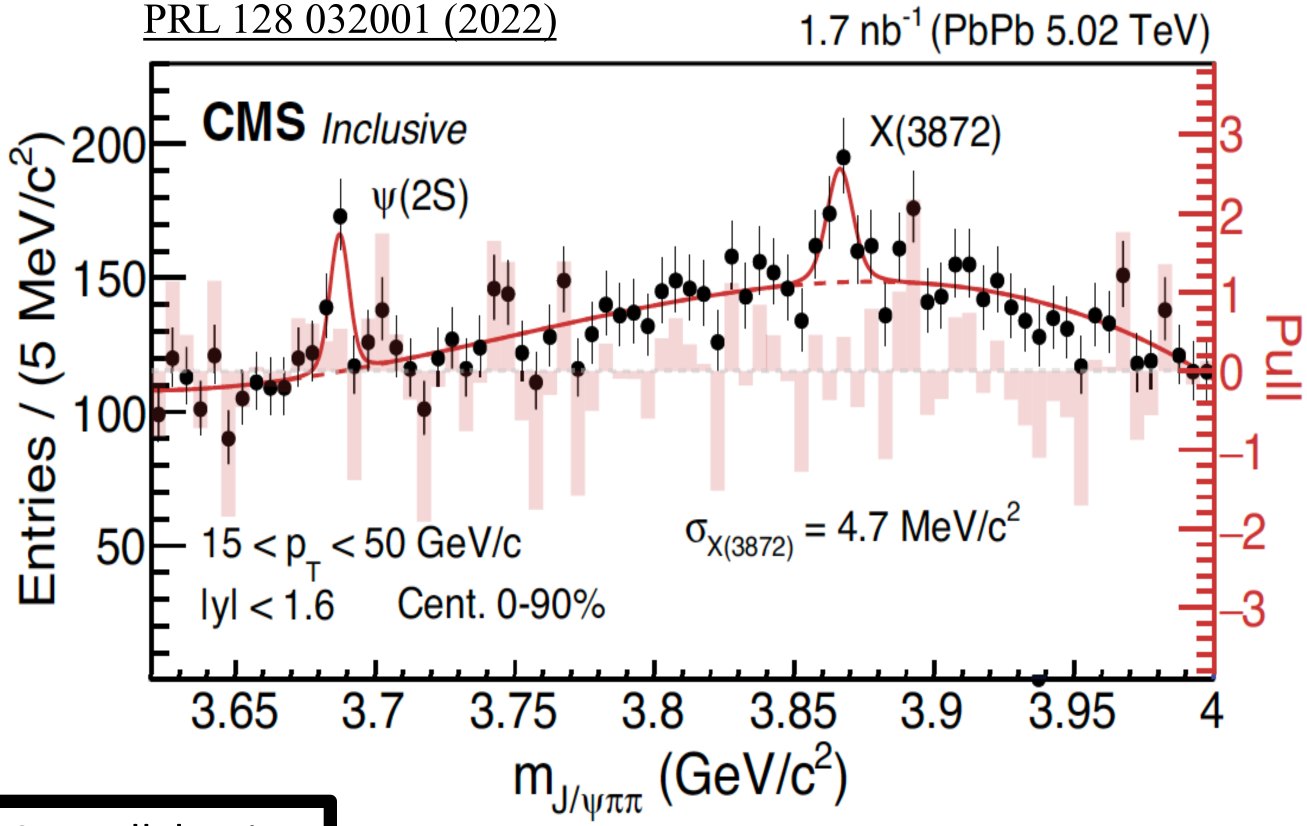
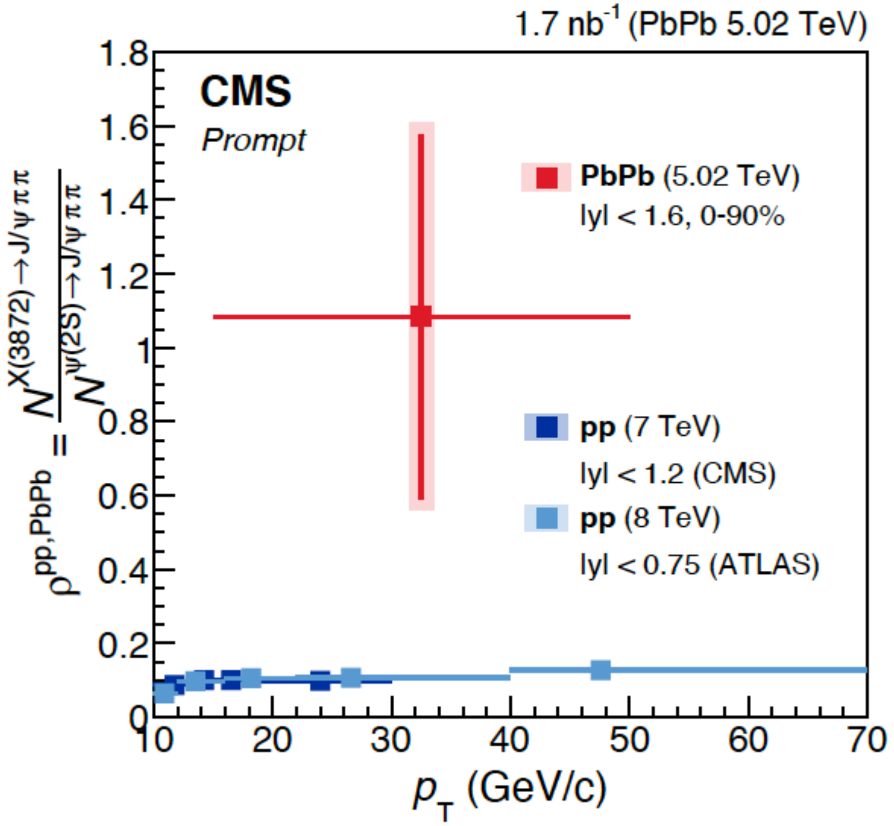
PRL 128 032001 (2022)





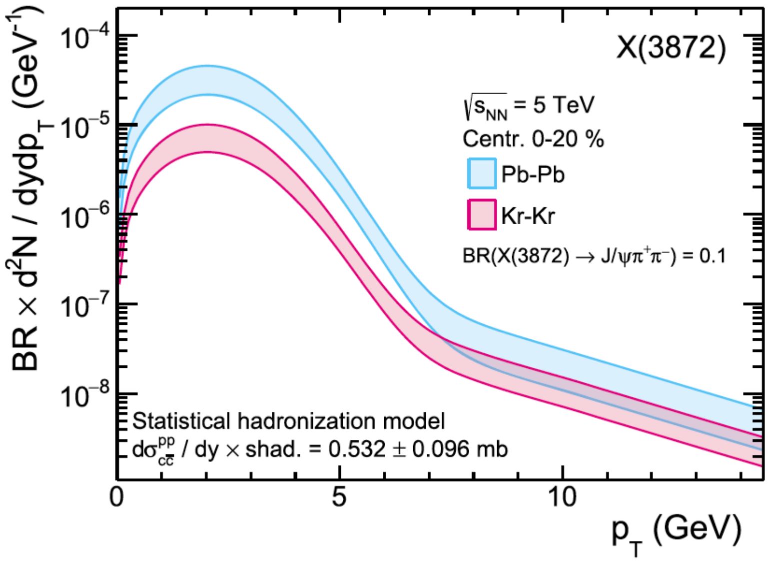
See talk by Jing Wang, Thurs

Prompt X(3872)/ ψ(2S) = 1.10 ± 0.51 ± 0.53 in PbPb at 5 TeV

Prompt X(3872)/ ψ(2S) ≈ 0.1 in pp at 8 TeV

X(3872) in PbPb

PLB 797 (2019) 134836

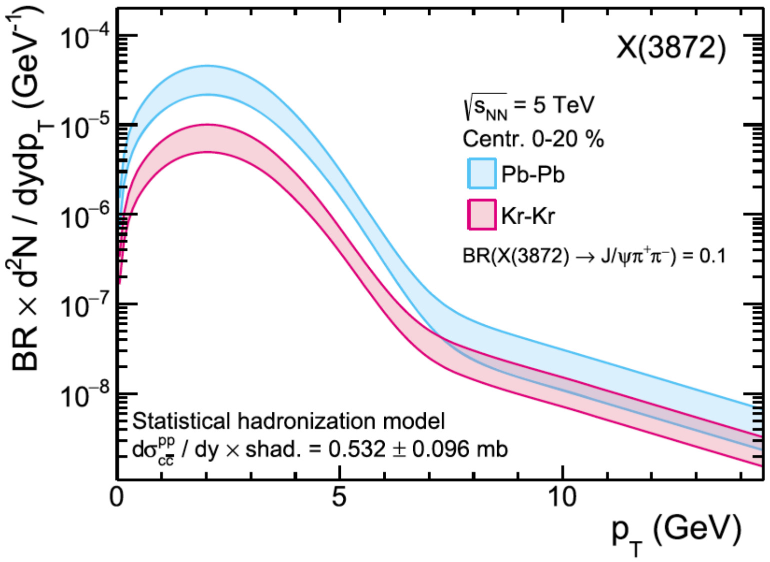


SHMC model:
Significant increase in X(3872) predicted for central AA collisions

Yield reaches up to ~1% of J/ψ yield

X(3872) in PbPb

PLB 797 (2019) 134836



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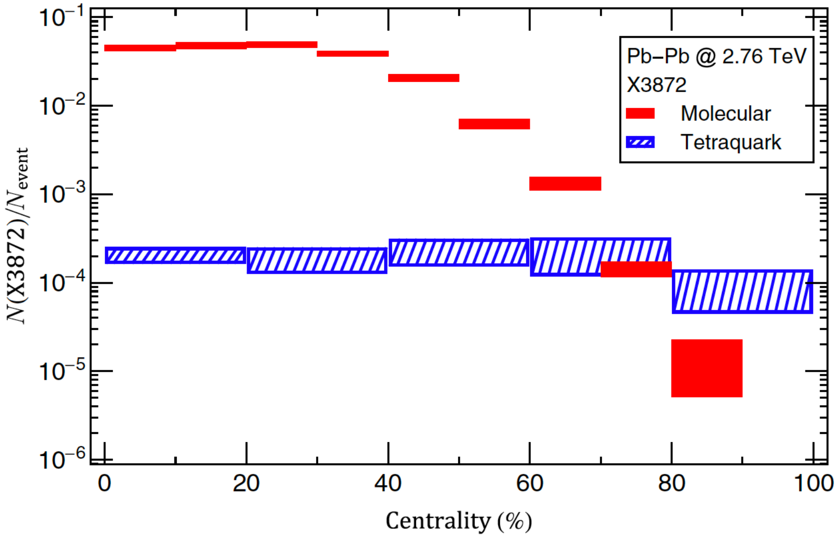
PRL 126 012301 (2021)

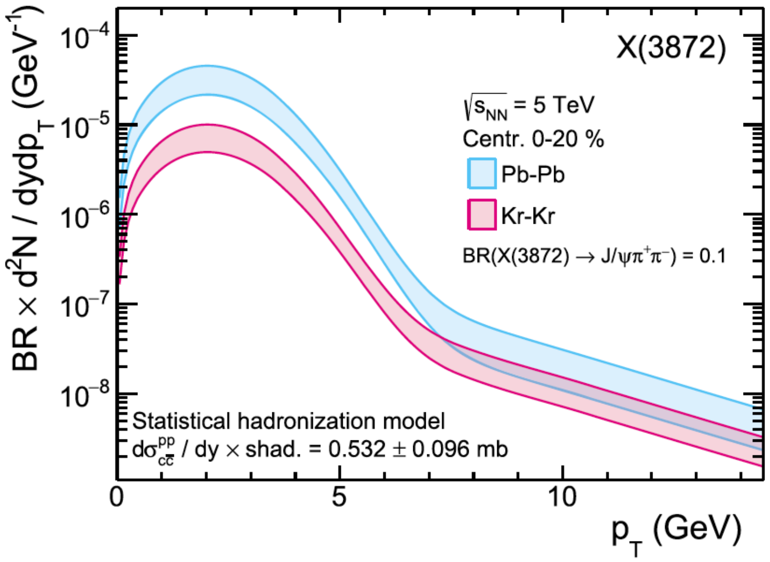


AMPT model:
difference in molecule vs diquark-diquark coalescence gives dramatically different yields and centrality dependence:

$N_{molecule} > N_{tetraquark}$

X(3872) in PbPb

PLB 797 (2019) 134836



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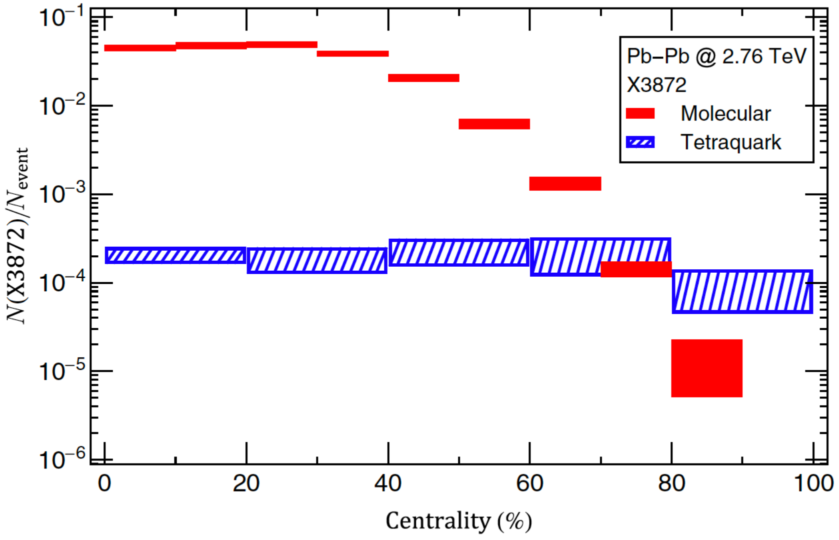

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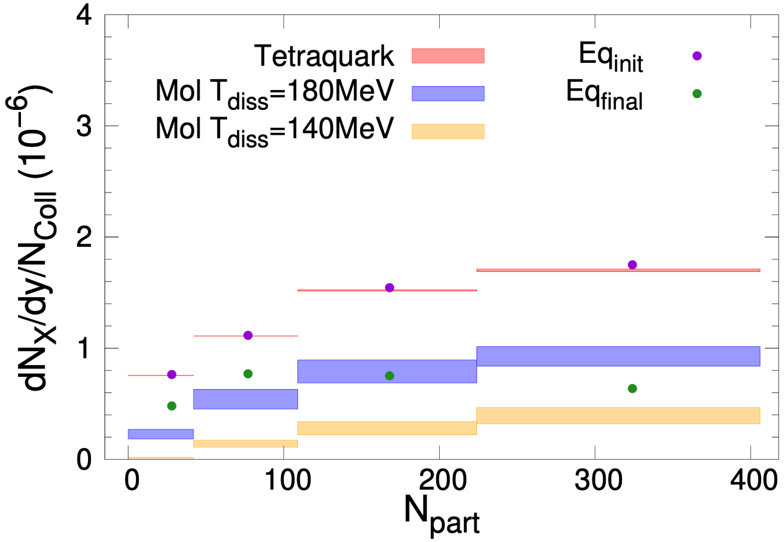
EPJA 57 122 (2021)

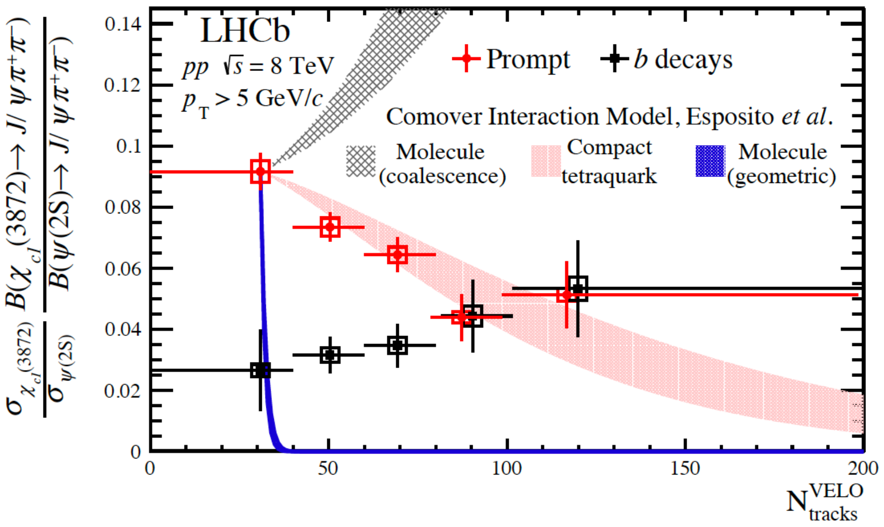


Transport calculation:
molecules have larger reaction rate, formed later in fireball evolution
$N_{tetraquark} > N_{molecule}$

X(3872) in medium

Diffuse medium → Increasing T, N_{ch} → Dense medium

PRL 126 092001 (2021)

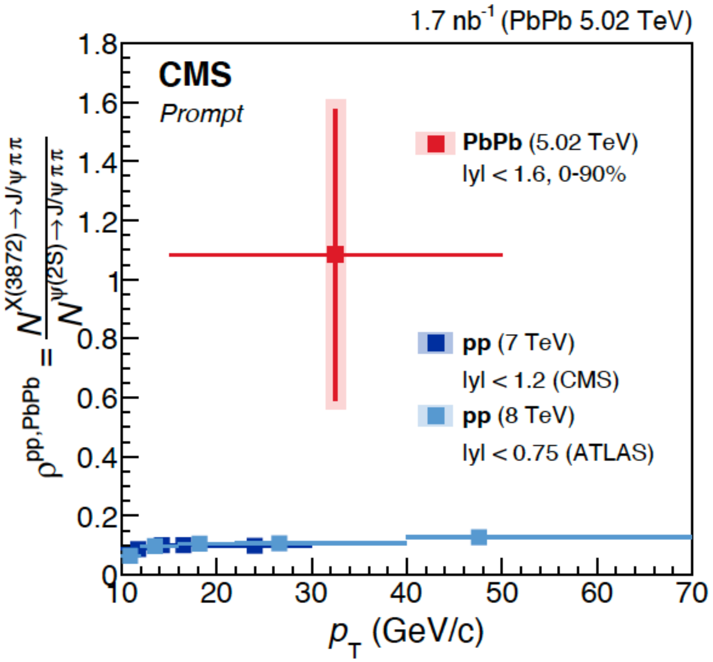


Prompt $\frac{\sigma_{X(3872)}}{\sigma_{\psi(2S)}}$ suppressed with multiplicity in pp

Dominated by comover breakup:

PRD 103 (2021) 7 , EPJC 81 (2021) 669

PRL 128 032001 (2022)



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PLB 797 (2019) 134836, EPJA 57 122 (2021)

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Diffuse medium → Increasing T, N_{ch} → Dense medium

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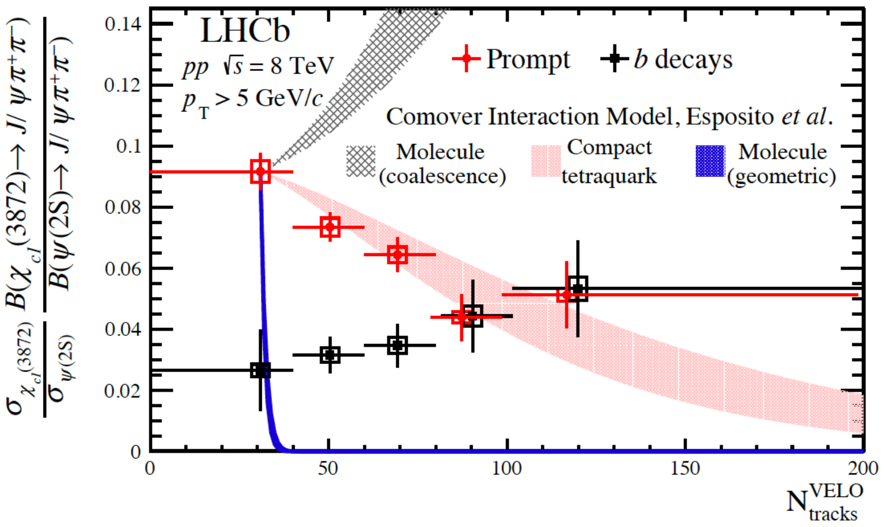

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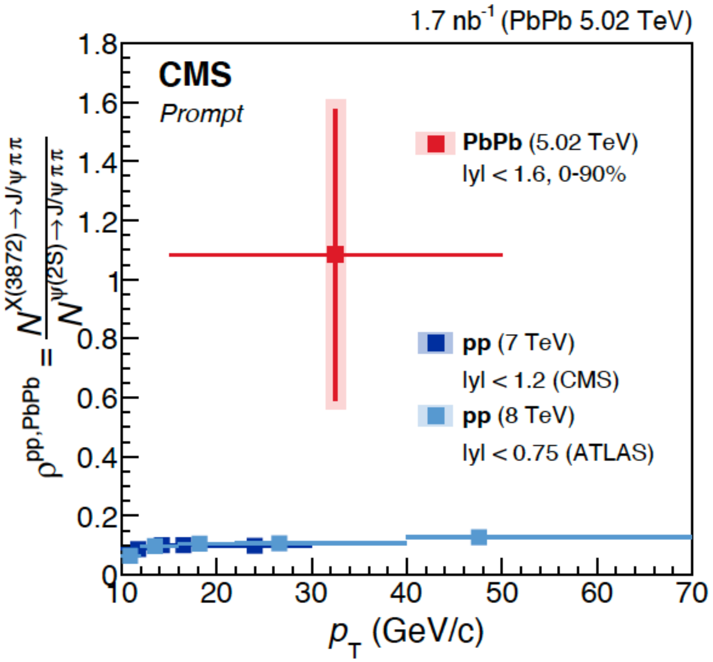
pPb data new for QM2022

PRL 128 032001 (2022)



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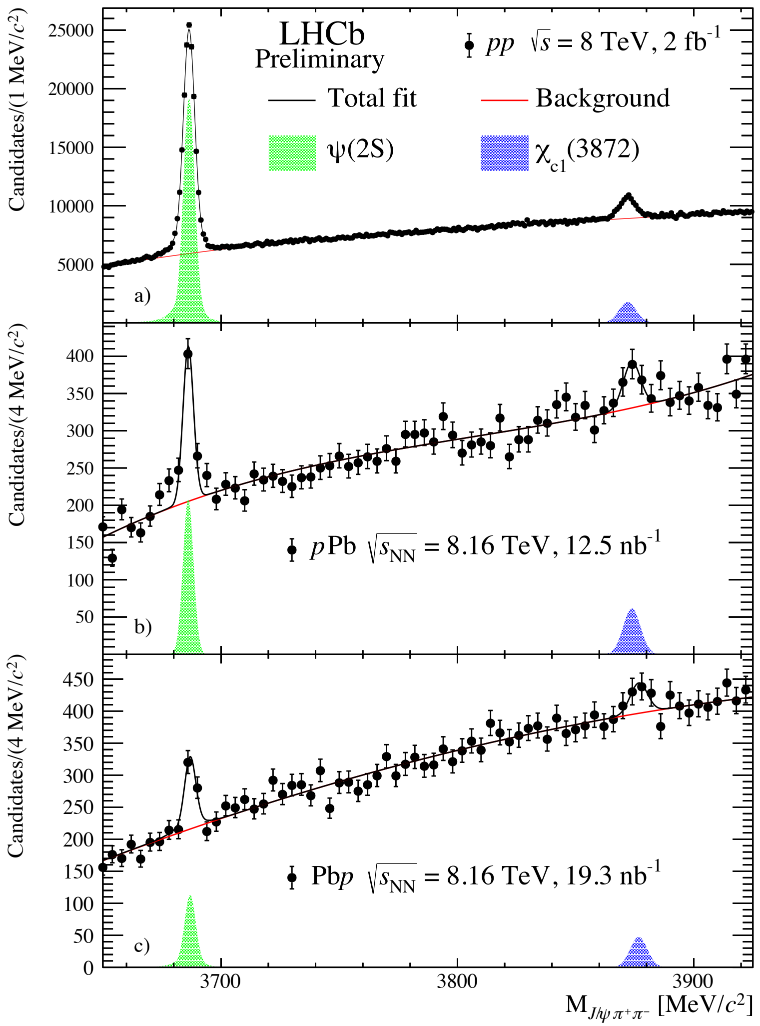
Dominated by comover breakup:
PRD 103 (2021) 7 , EPJC 81 (2021) 669

Where is the crossover?

Dominated by coalescence:
PLB 797 (2019) 134836, EPJA 57 122 (2021)

X(3872) /ψ(2S) in *p*Pb

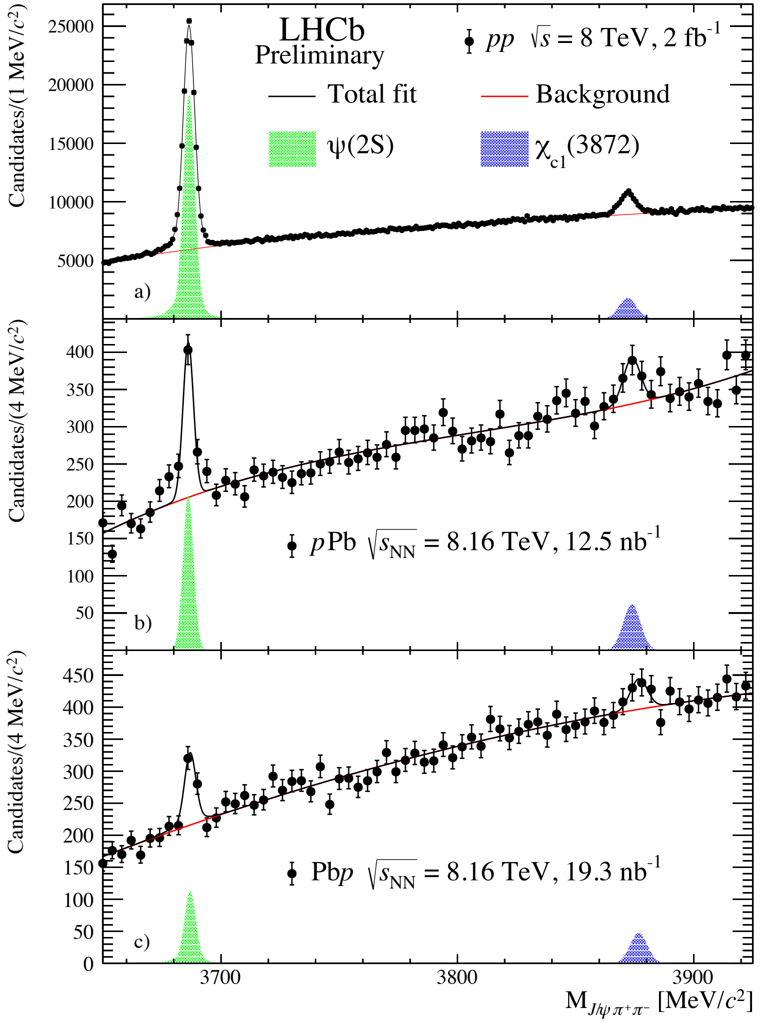
LHCb-CONF-2022-001



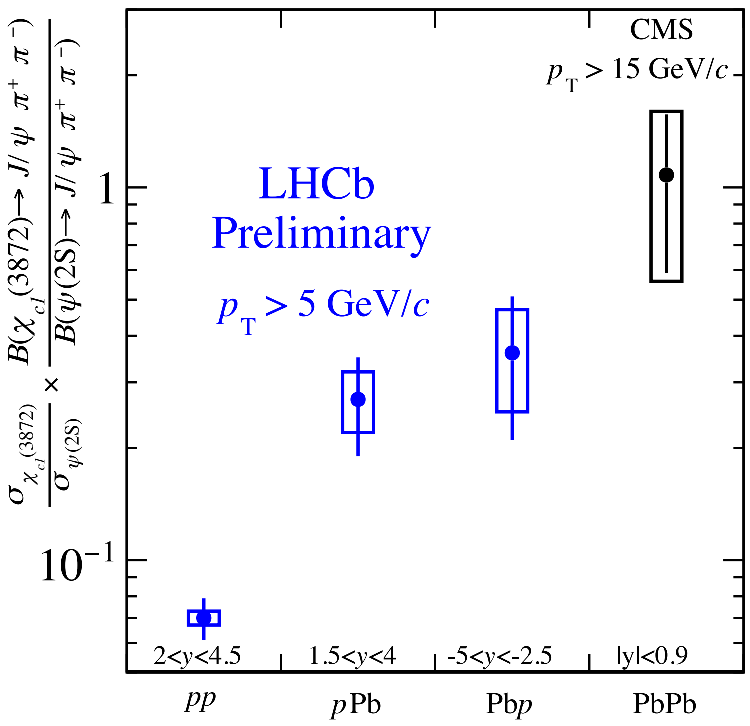
See talk by Eliane Epple, Thurs

X(3872) /ψ(2S) in *p*Pb

LHCb-CONF-2022-001



See talk by Eliane Epple, Thurs



- Comparison between X(3872) and *ψ*(2S) suggests ***something different*** may be happening to exotic vs conventional hadrons in medium
- Initial state effects (eg shadowing) should largely cancel in ratio
- Enhancing effects start to out compete breakup?

Prompt X(3872)/ *ψ*(2S) = 0.27 ± 0.08 ± 0.05 in forward pPb

Prompt X(3872)/ *ψ*(2S) = 0.36 ± 0.15 ± 0.11 in backward pPb

Falls between pp (~0.1) and PbPb (~1.0)

X(3872) /ψ(2S) in *p*Pb

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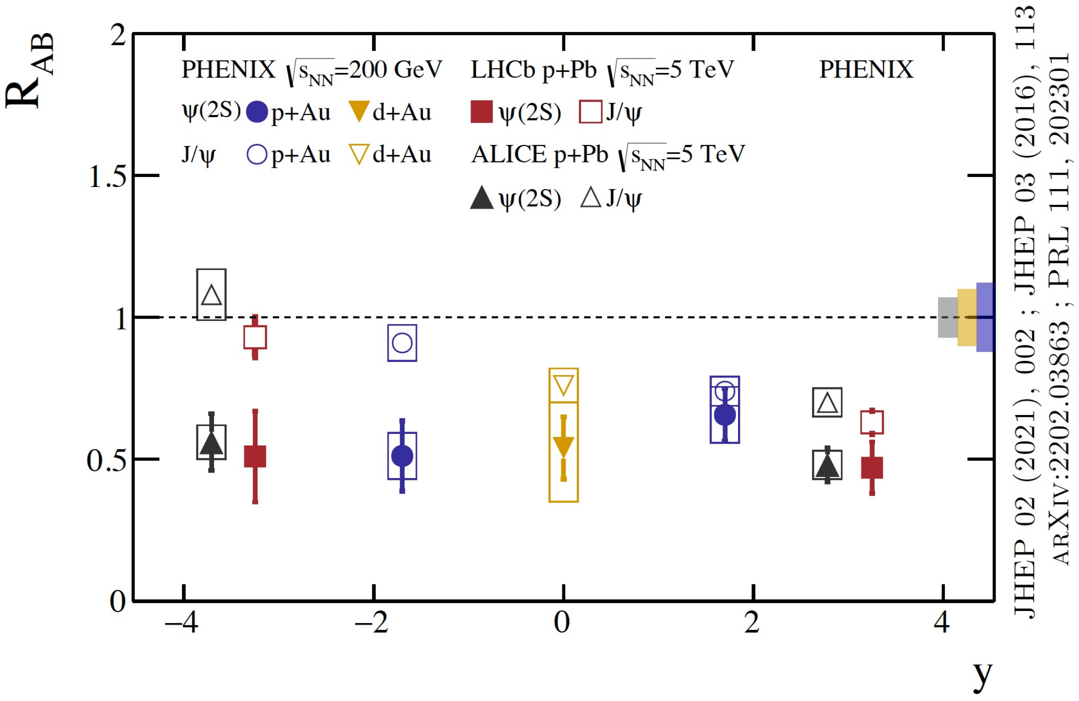
We know $\psi(2S)$ is suppressed in pA collisions:



See talk by Krista Smith, Weds

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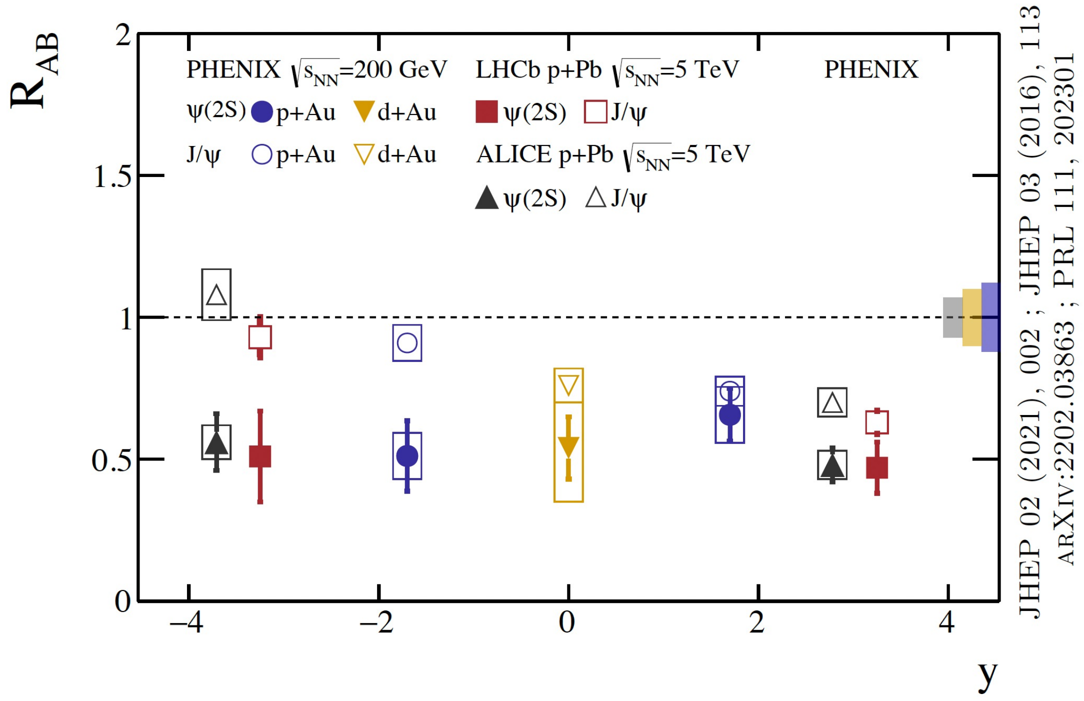


See talk by Krista Smith, Weds

2017 PREDICTION: X(3872) enhanced in pA

Nuclear effects on tetraquark production by double parton scattering

F. Carvalho (Diadema, Sao Paulo Fed. U.), F.S. Navarra (Sao Paulo U.)
2017

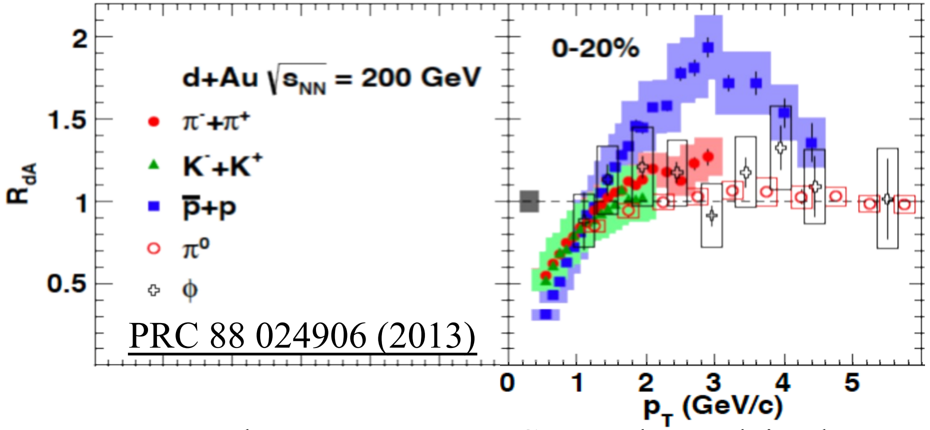
8 pages
Part of Proceedings, 12th Conference on Quark Confinement and the Hadron Spectrum (Confinement XII) : Thessaloniki, Greece
Published in: *EPJ Web Conf.* 137 (2017) 06004
Contribution to: Confinement XII
Published: 2017
DOI: 10.1051/epjconf/201713706004

Abstract. In this work we study the nuclear effects in exotic meson production. We estimate the total cross section as a function of the energy for *pPb* scattering using a version of the color evaporation model (CEM) adapted to Double Parton Scattering (DPS). We fond that the cross section grows significantly with the atomic number, indicating that the hypothesis of tetraquark states can be tested in pA collisions at LHC.

Enhanced DPS has since been observed in pPb:
PRL 125 212001 (2020)

Both of these effects drive X(3872)/ψ(2S) ratio upwards

Coalescence in small systems (?)



Baryon enhancement at RHIC – can be explained by coalescence: PRL 93, 082302 (2004)

Coalescence in small systems (?)

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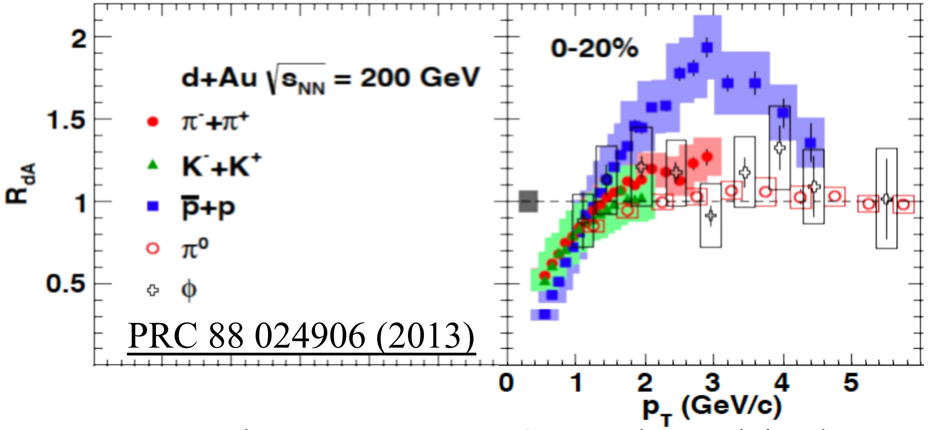

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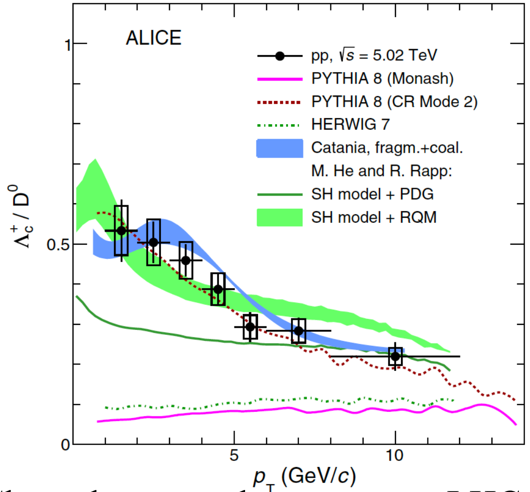
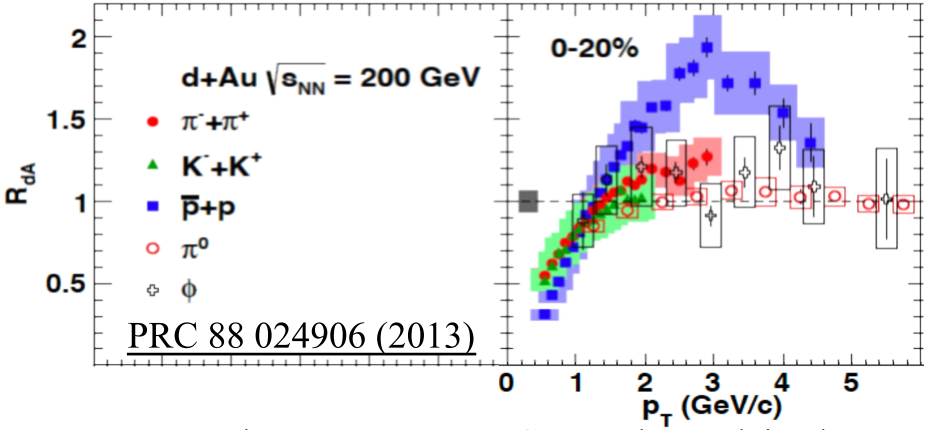


Charm baryon enhancement at LHC relative to e^+e^- – can be explained by coalescence

Mattia Faggin, Thurs

Coalescence in small systems (?)

Los Alamos NATIONAL LABORATORY



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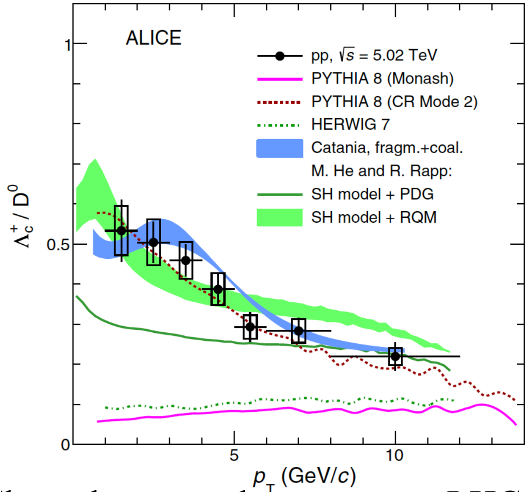

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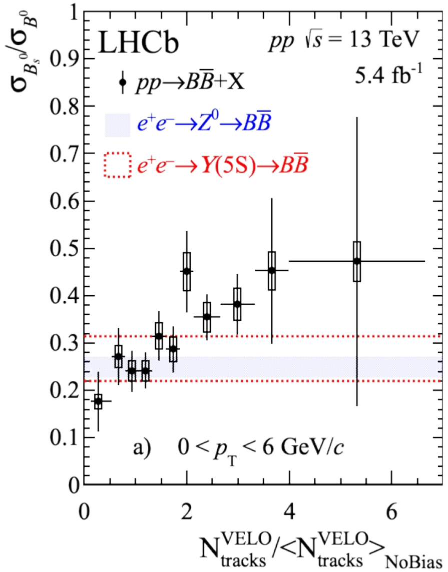
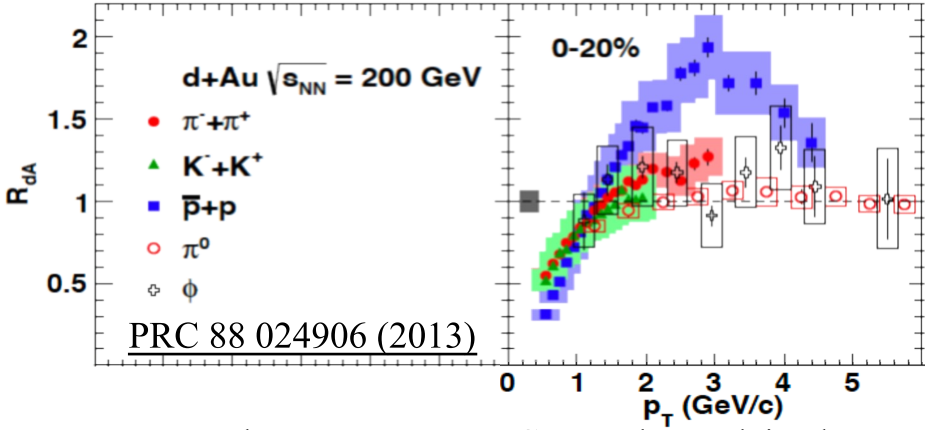


B_s / B^0 enhancement at high mult – expected from coalescence?

Ben Audurier, Thurs

Coalescence in small systems (?)

Los Alamos NATIONAL LABORATORY



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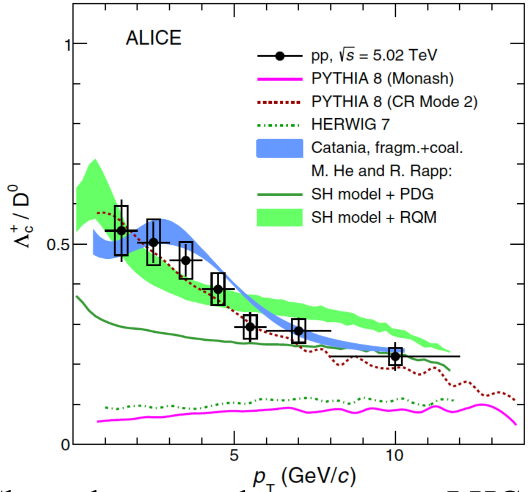

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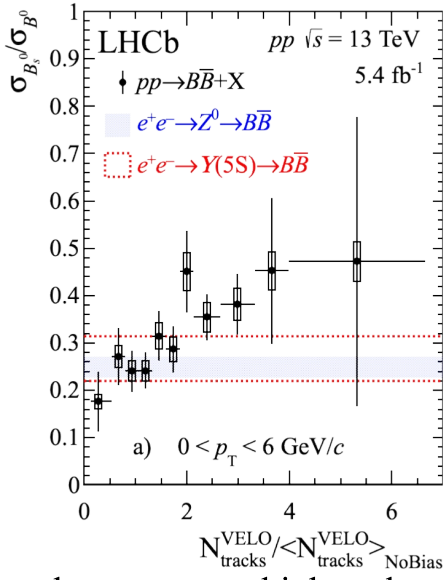

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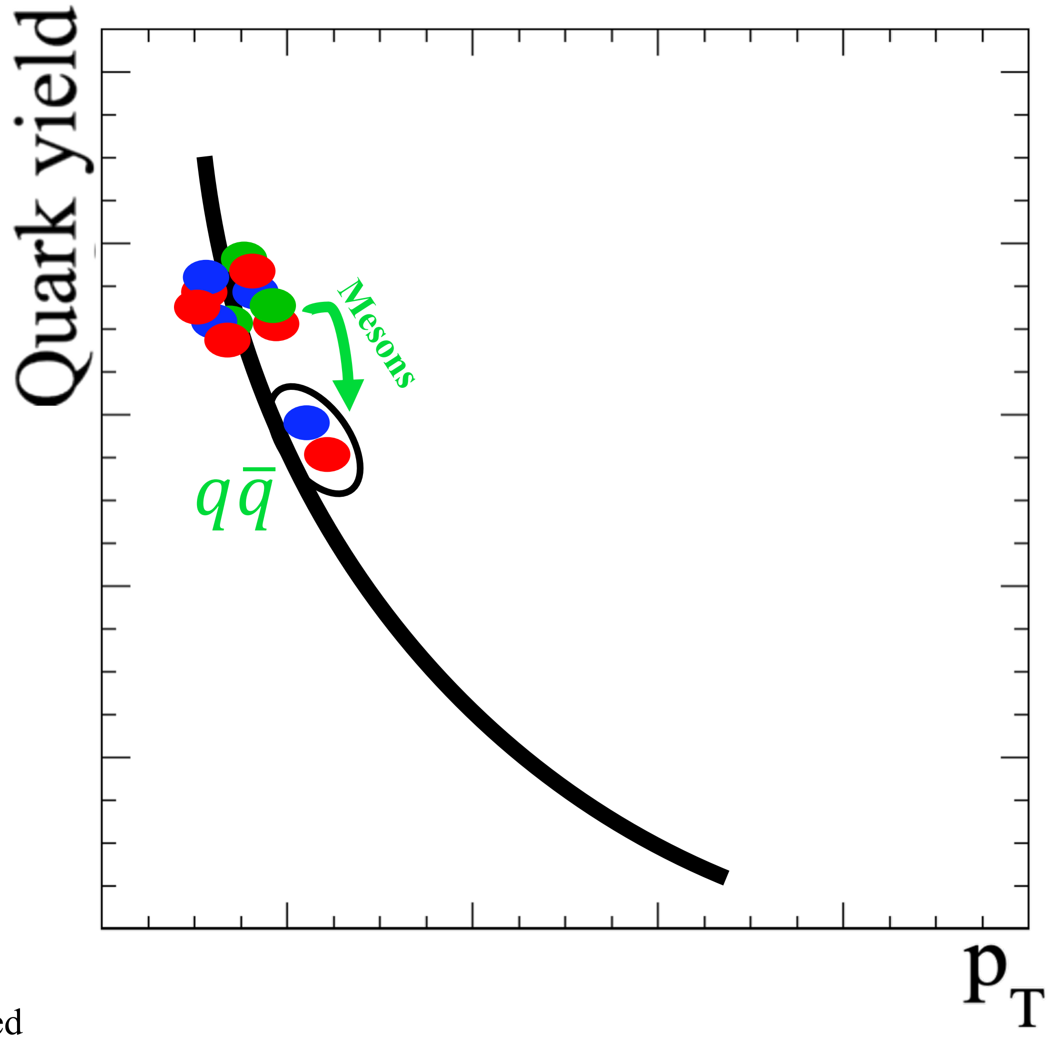

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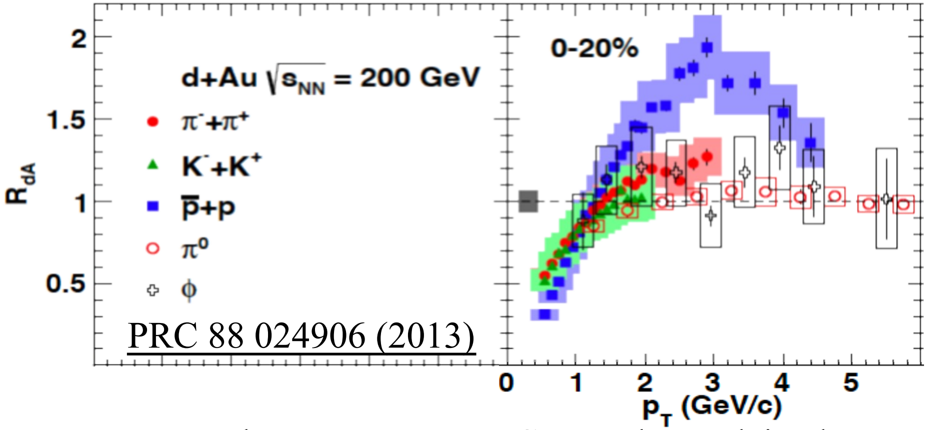

PRC 88 024906 (2013)

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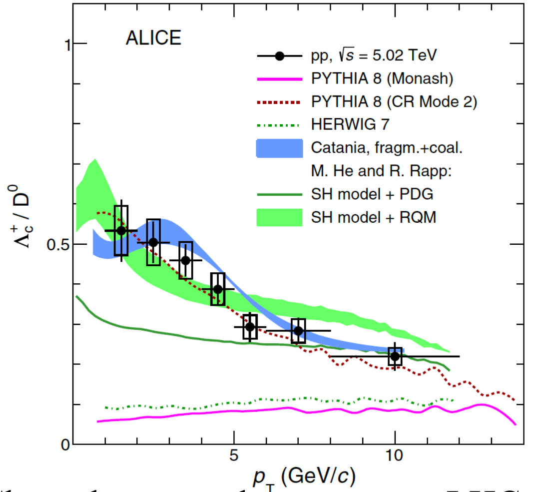

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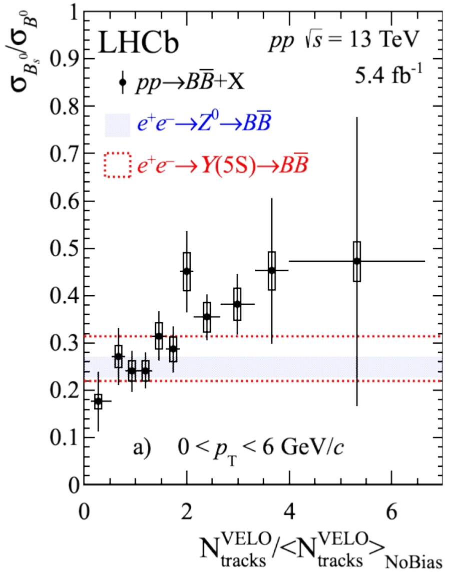

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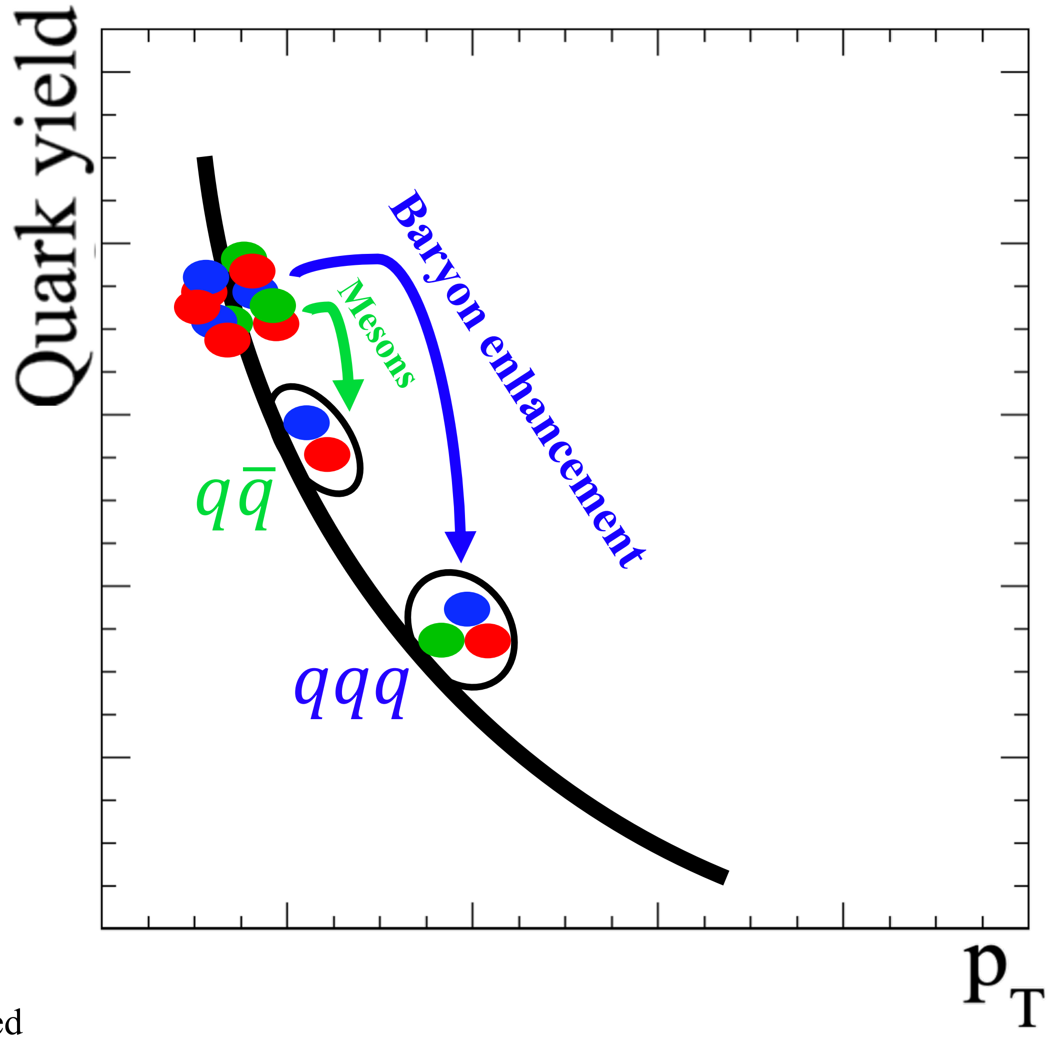

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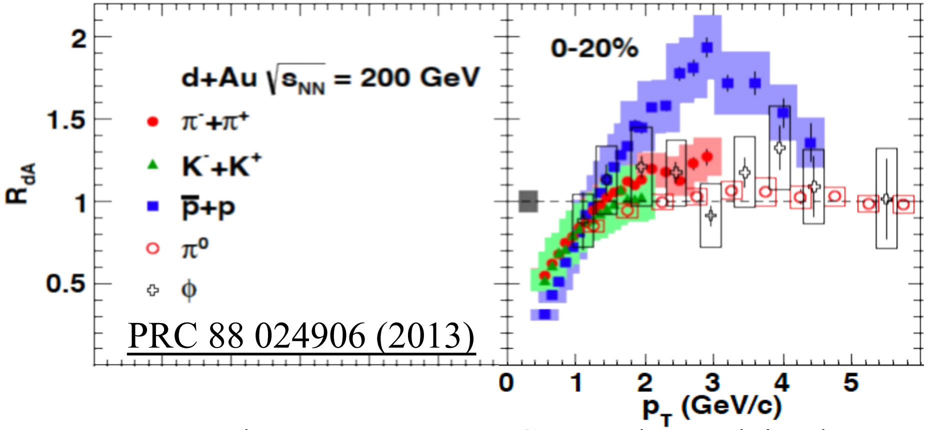

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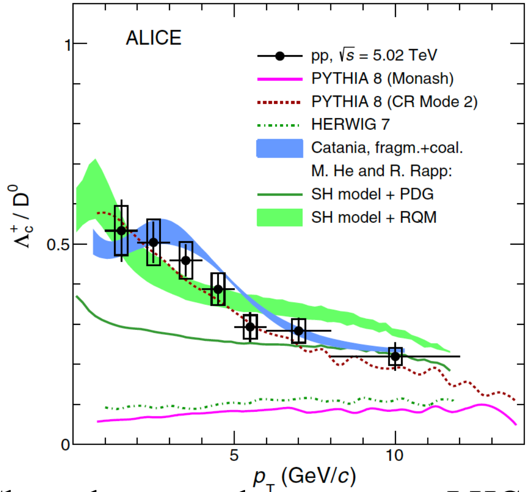

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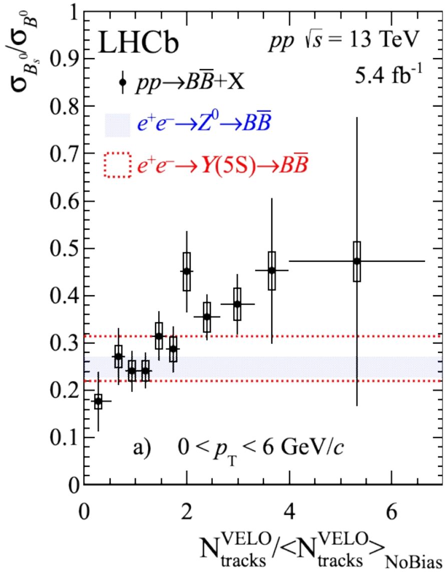

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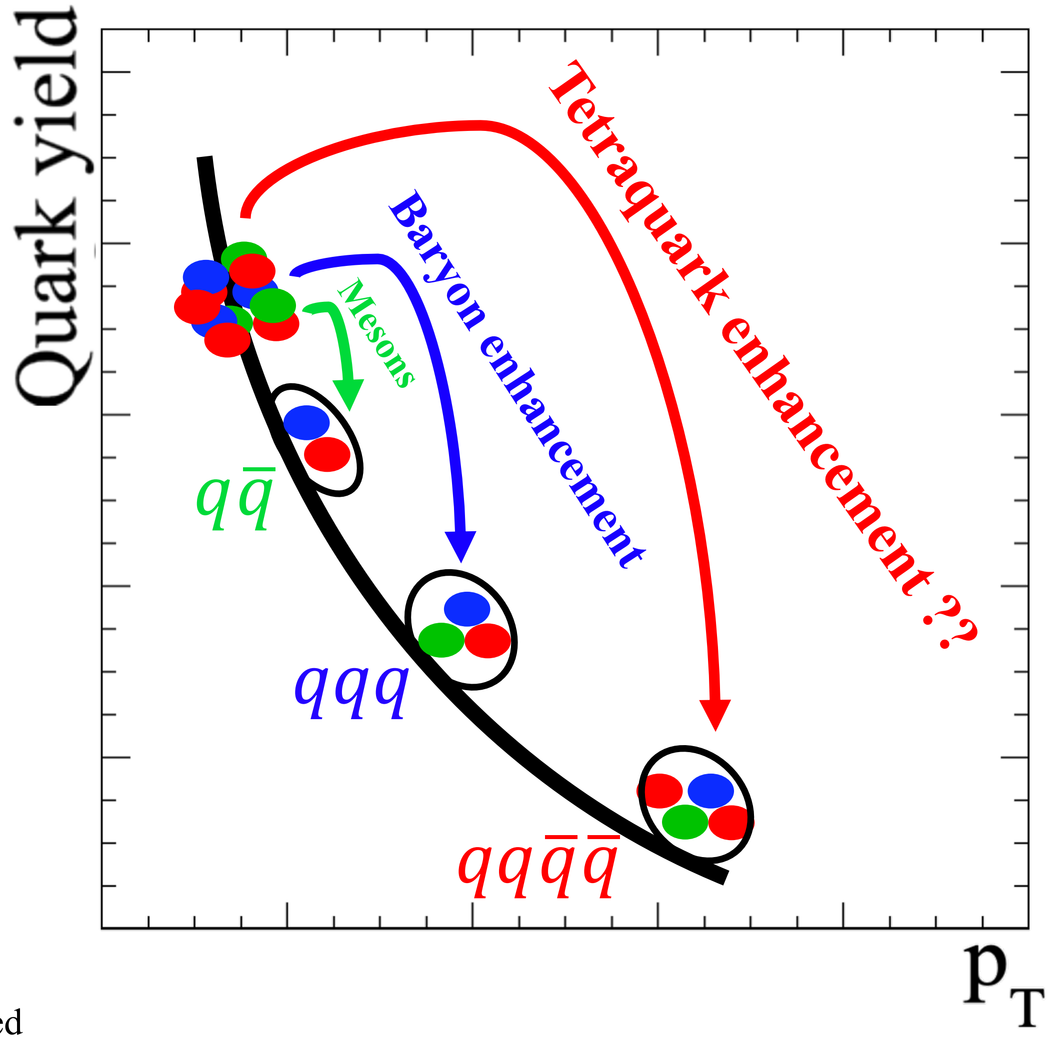
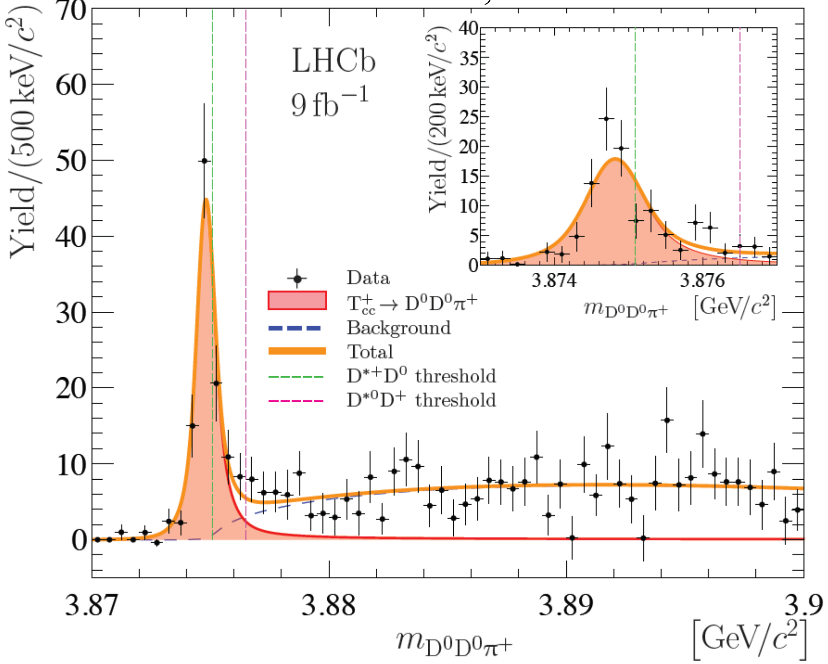


Newest exotic: T_{cc}^{+}

arXiv: 2109.01038, 2109.01056



New state consistent with $cc\bar{u}\bar{d}$ tetraquark recently found:

Similar to X(3872), mass quite close to DD threshold
Big difference: contains cc or $\bar{c}\bar{c}$, rather than $c\bar{c}$

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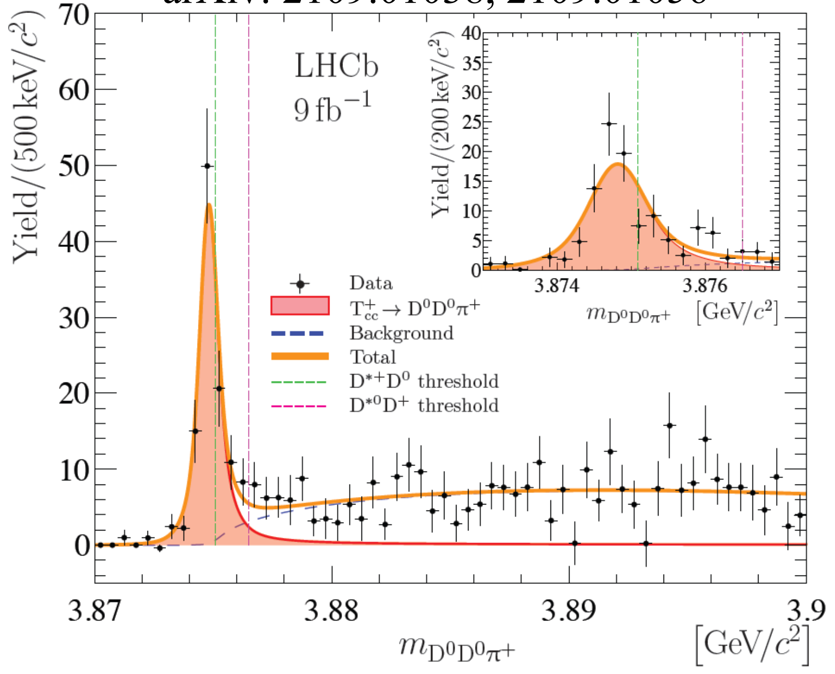

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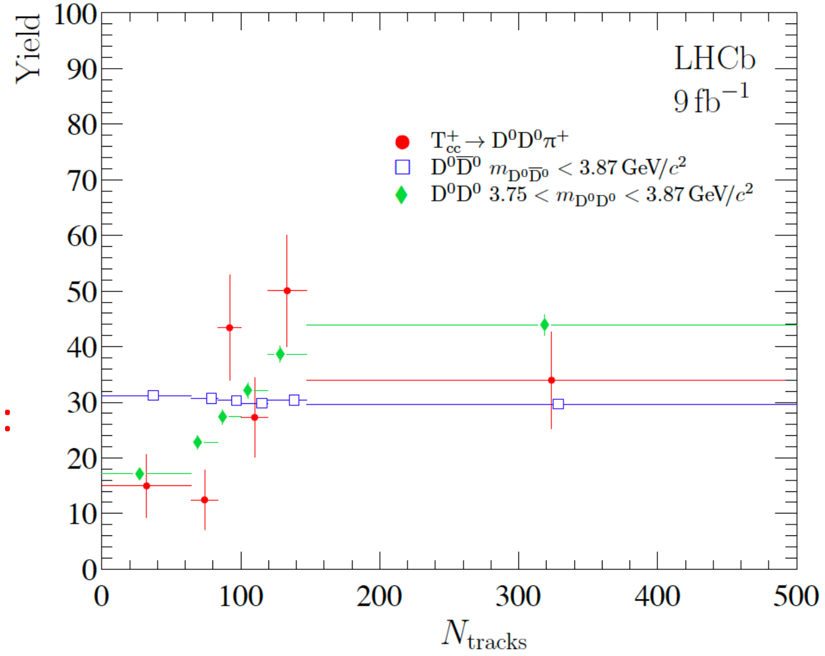

Compare T_{cc}^{+} multiplicity dependence with:

$D\bar{D}$ distribution, dominated by SPS

DD distribution, dominated by DPS

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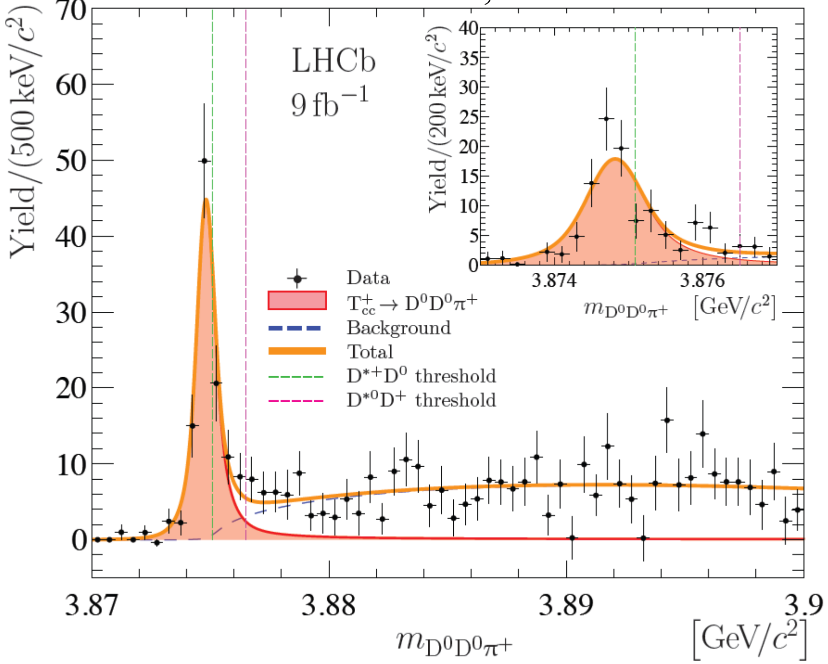

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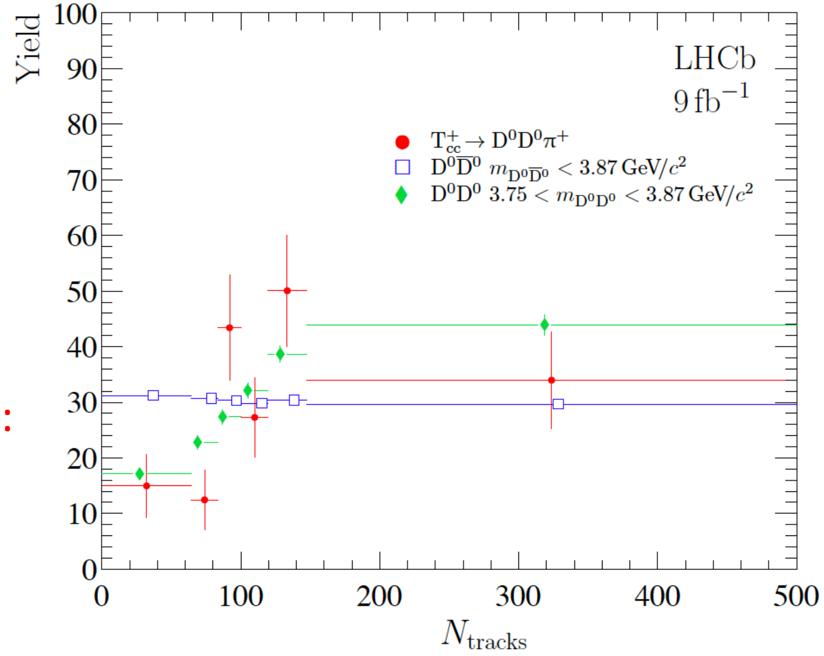

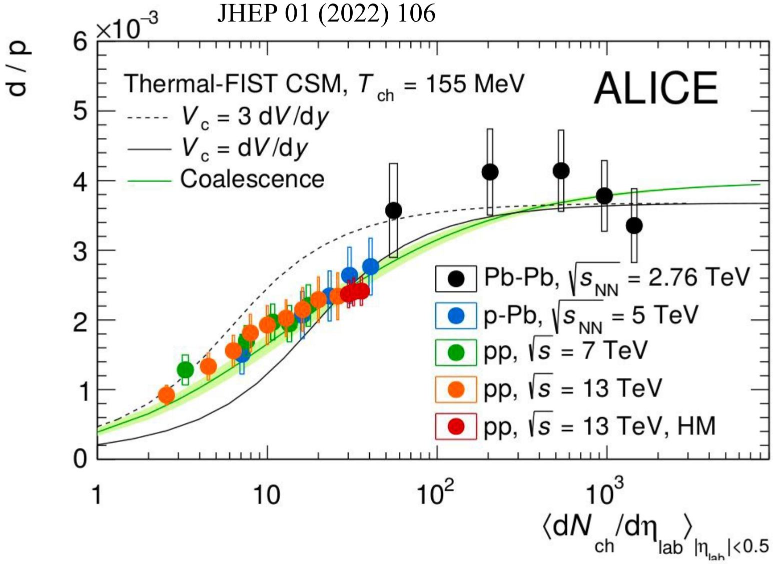

Yield favors higher multiplicity collisions, reminiscent of deuteron.

Evidence for hadronic molecule structure?

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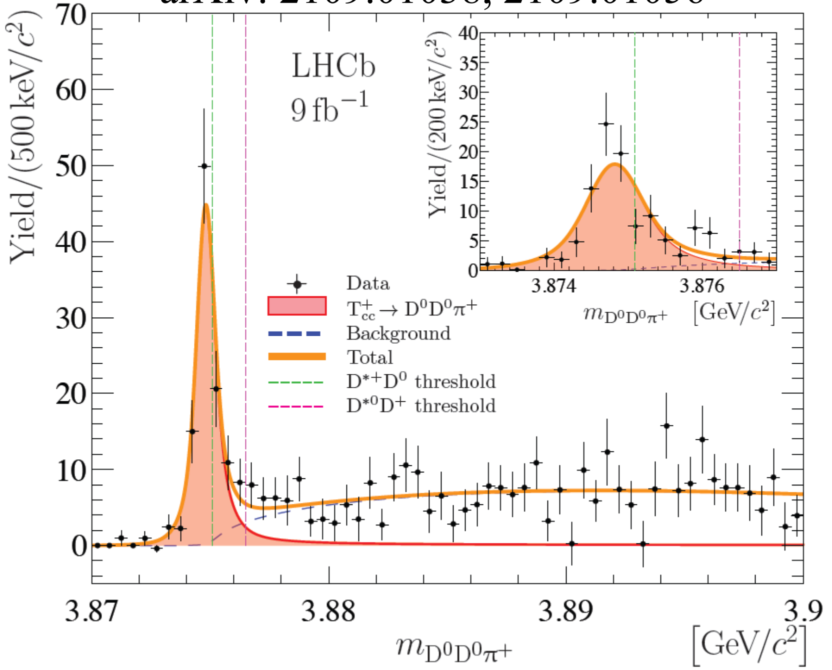

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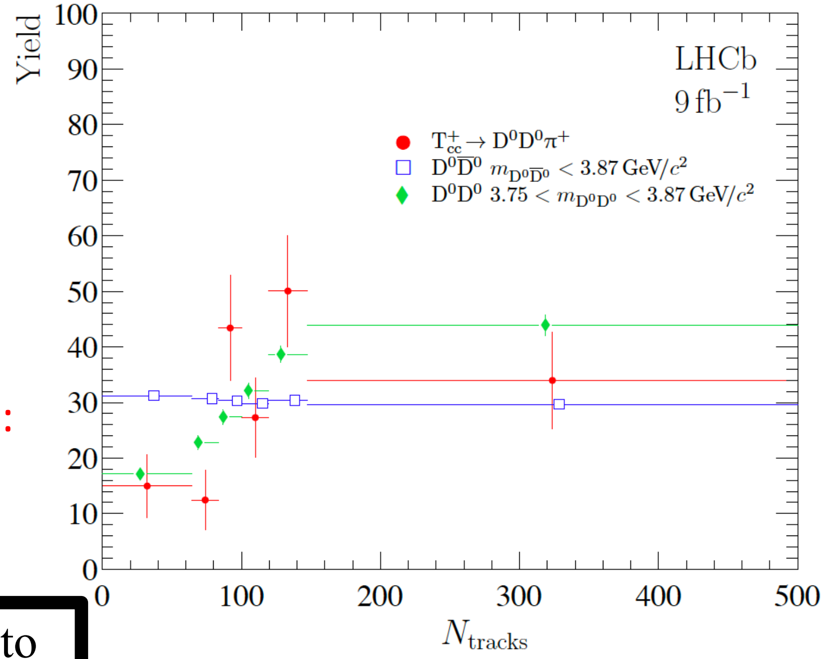

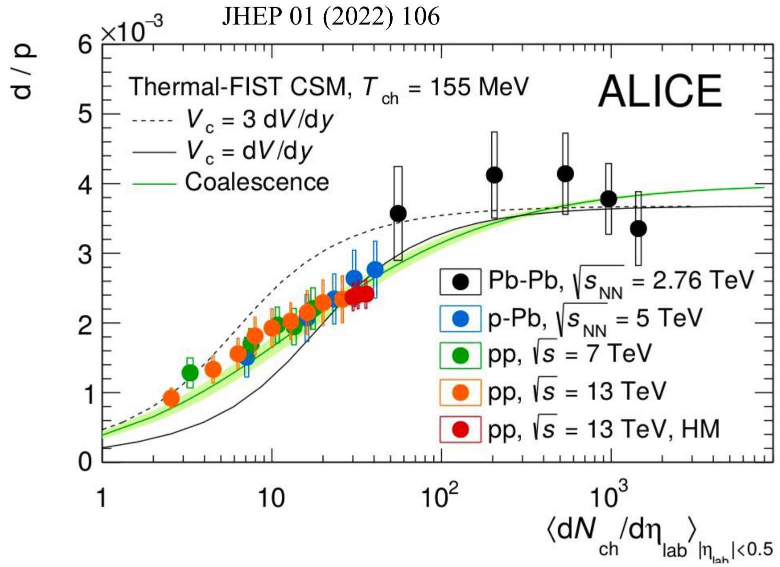

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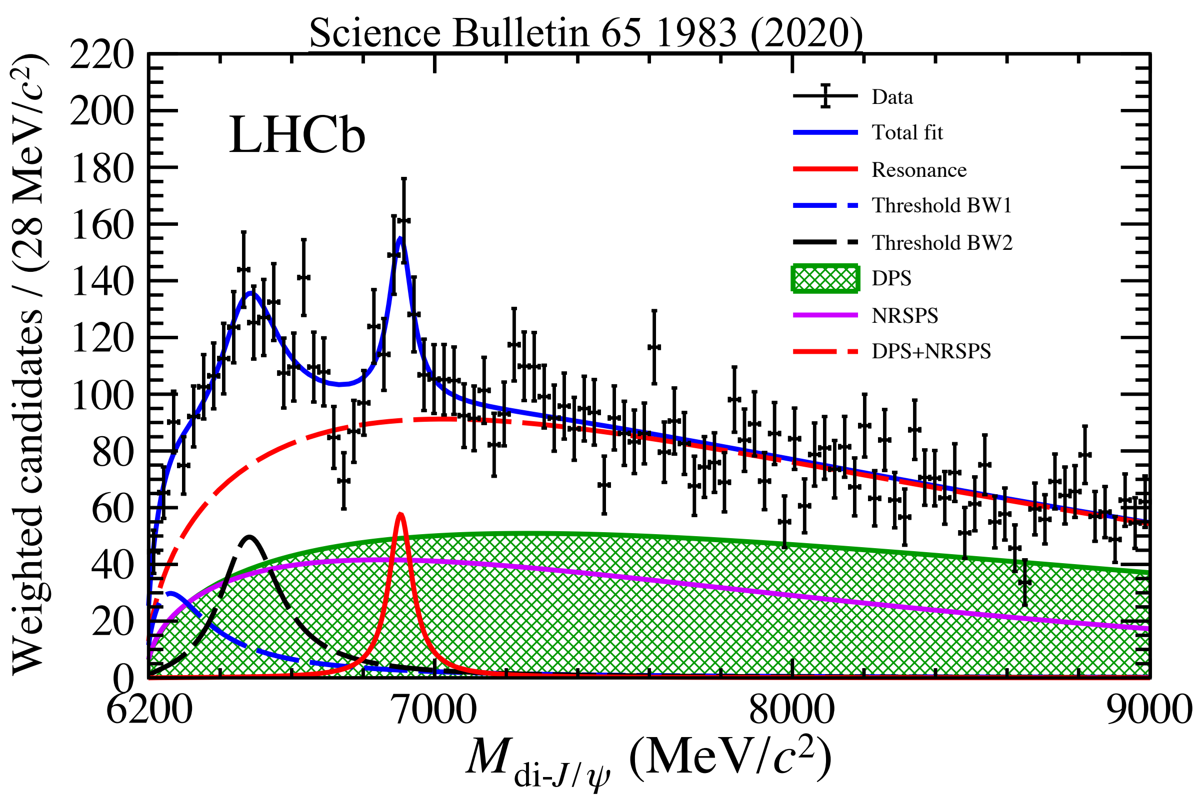
DD distribution, dominated by DPS

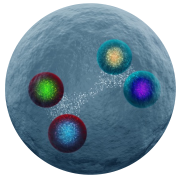
HUGE enhancement expected in PbPb due to recombination: PRD 104 L111502 (2021)

Yield favors higher multiplicity collisions, reminiscent of deuteron.
Evidence for hadronic molecule structure?

“Fully charmed” exotic: X(6900)



- At least one resonant structure observed in di- J/ψ mass spectrum from pp collisions
- Quickly interpreted as all-charm tetraquark
- Evidence for other structure near threshold
  - Another $cc\bar{c}\bar{c}$ state?
  - Could be partially reconstructions of higher charmonia, eg $X \rightarrow \chi_c(\rightarrow J/\psi\gamma)\, J/\psi$ where γ is not reconstructed



“Fully charmed” exotic: X(6900)

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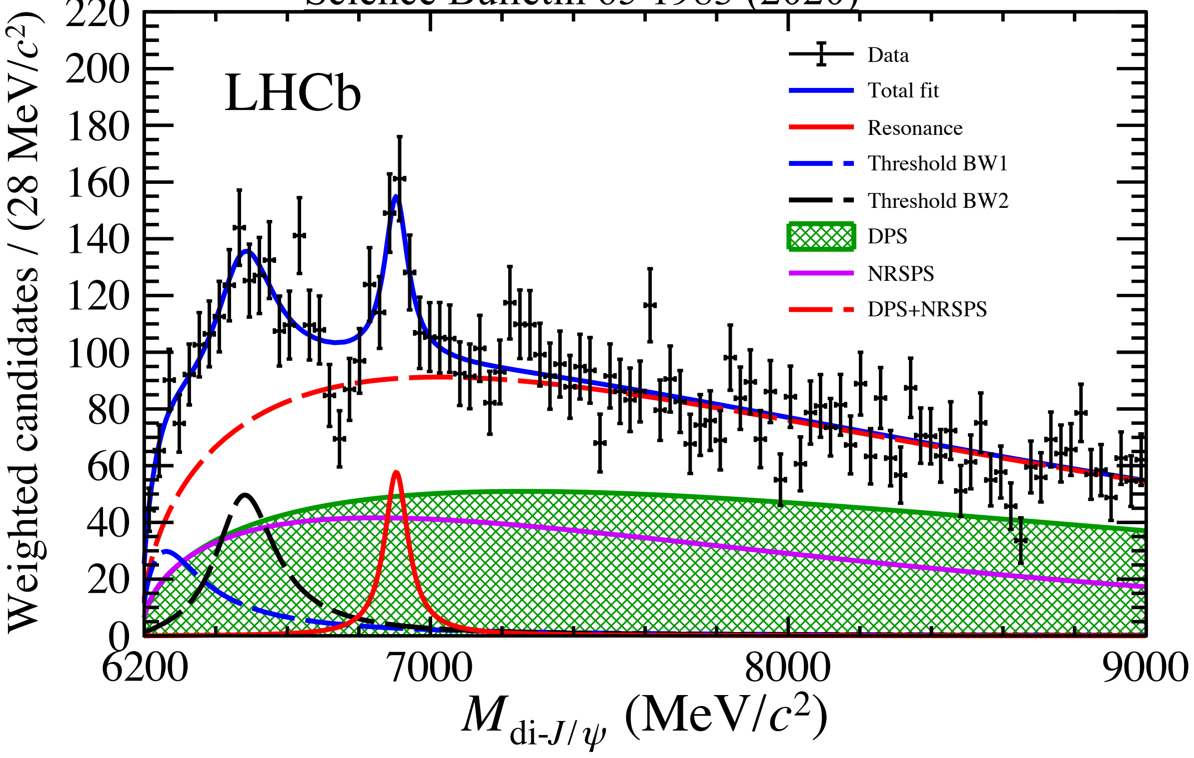
Science Bulletin 65 1983 (2020)



- At least one resonant structure observed in di- J/ψ mass spectrum from pp collisions
- Quickly interpreted as all-charm tetraquark
- Evidence for other structure near threshold
  - Another $cc\bar{c}\bar{c}$ state?
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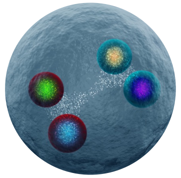
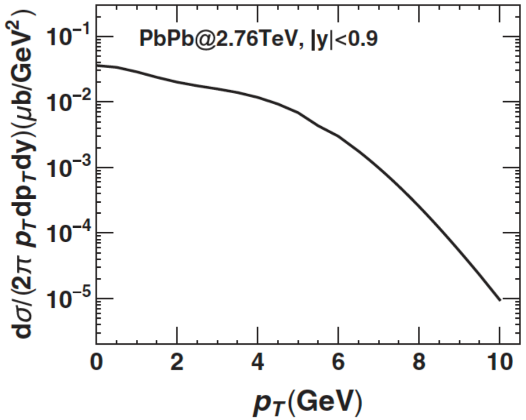


Coalescence model predicts significant enhancement at low p_T

PRD 102 114001 (2020)



Ultimate test for charm coalescence/recombination models in AA

Exotics in Ultra-Peripheral Collisions

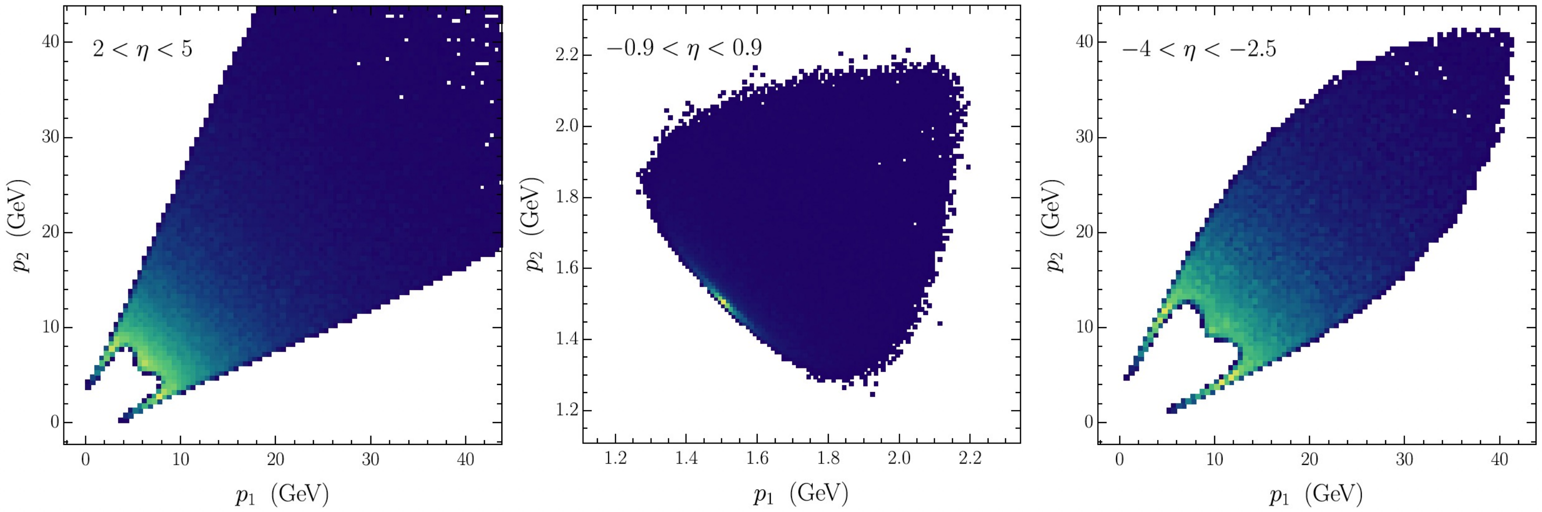
PHYSICAL REVIEW D **104,** 114029 (2021)

Hunting for tetraquarks in ultraperipheral heavy ion collisions

Angelo Esposito,[1,2,*] Claudio Andrea Manzari,[3,4,†] Alessandro Pilloni,[5,6,7] and Antonio Davide Polosa[5,8]

See also: PRD 94 094024 (2016), PRC 100 024620 (2019)

- UPCs may provide a new source of exotics particles
- Very low backgrounds, potentially large cross sections in PbPb
- New source of all-charm exotics: $X(6900) \to J/\psi J/\psi$



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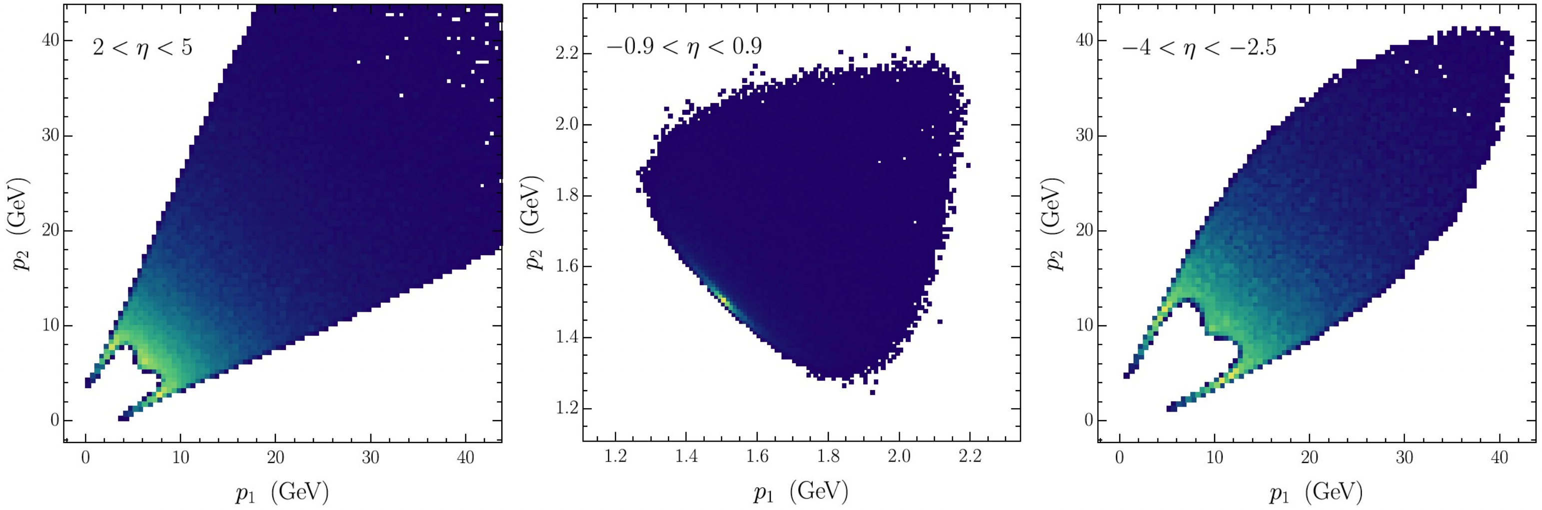
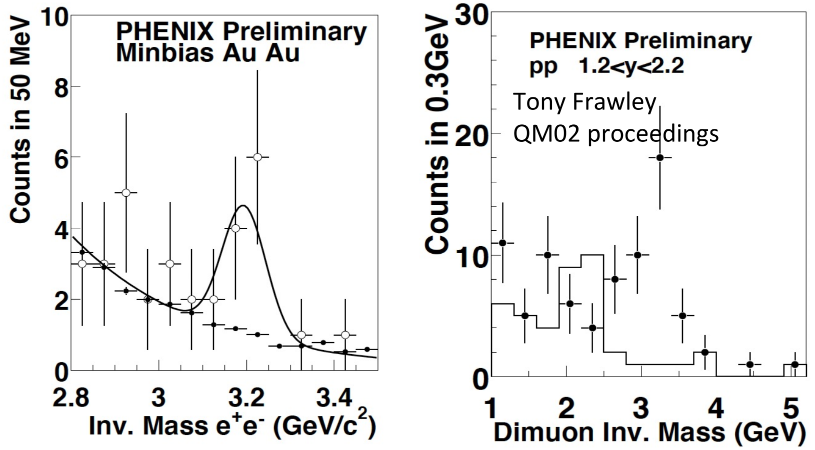


EVERY experiment measures J/ψ

Perspective

Charmonia status, QM 2002



Perspective

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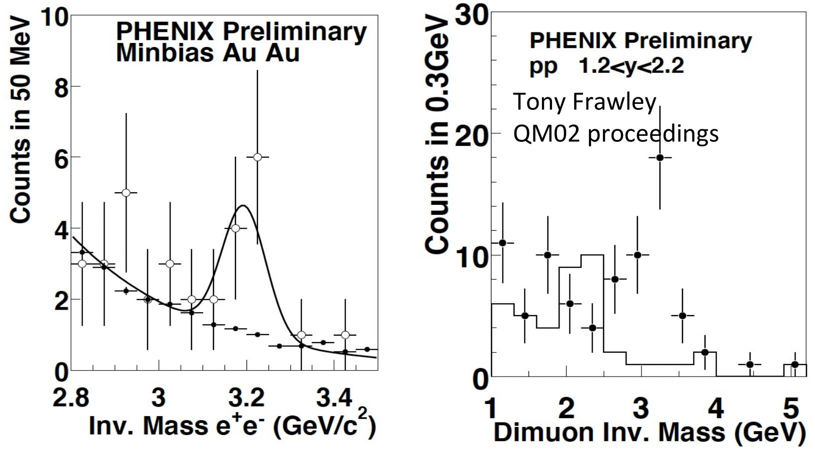
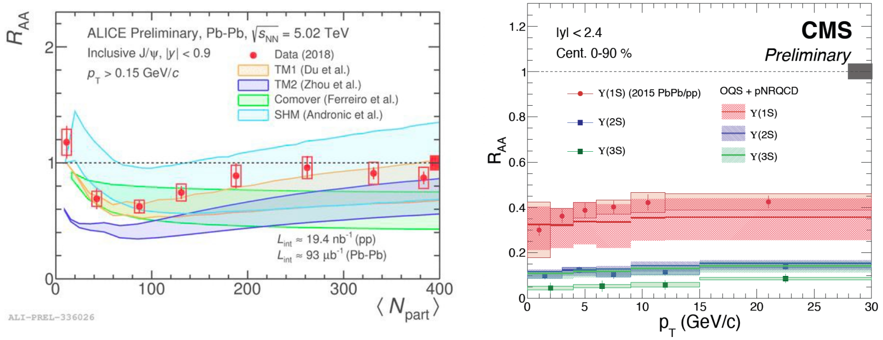


Charmonia status, QM 2022



Precise data and ***advanced*** calculations

Cristine Terrevoli and Min He, Sat

Perspective

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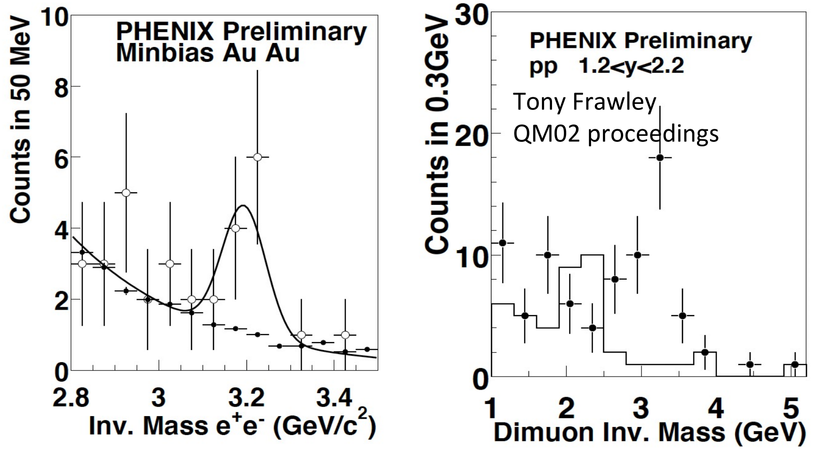

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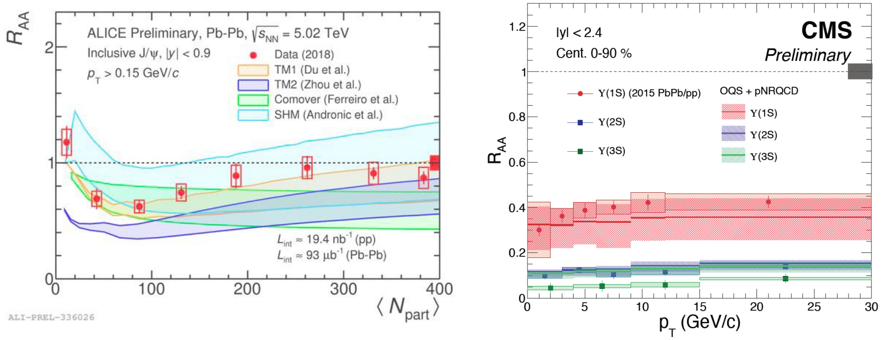

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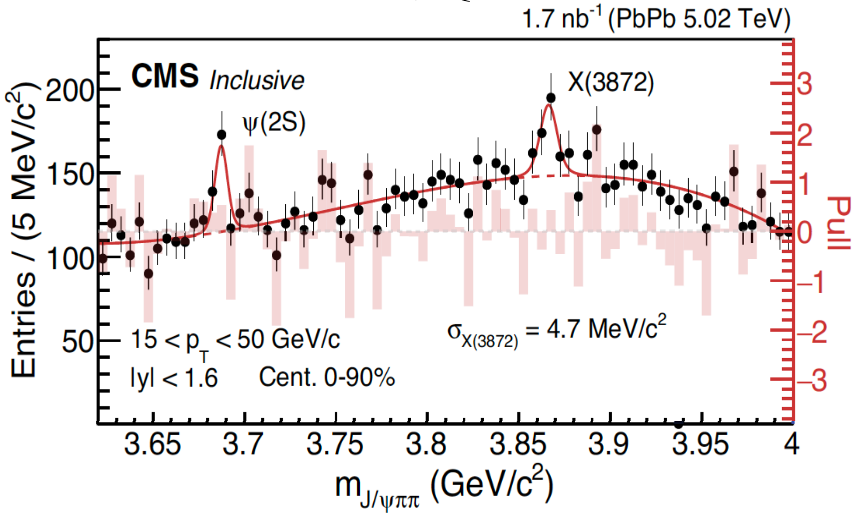
Exotic status, QM 2022



Perspective

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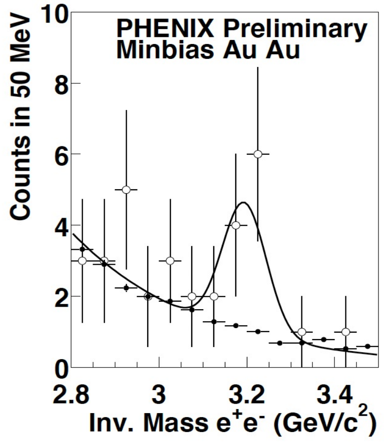
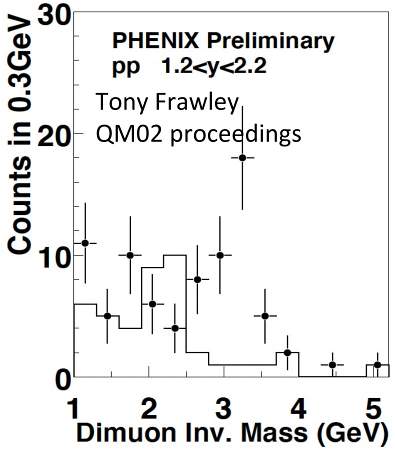
Charmonia status, QM 2002





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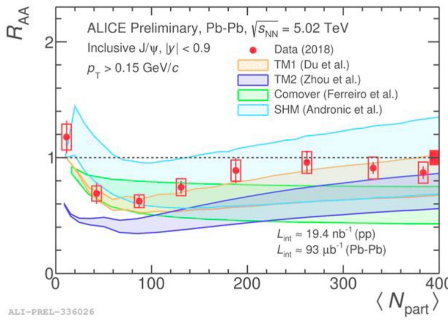

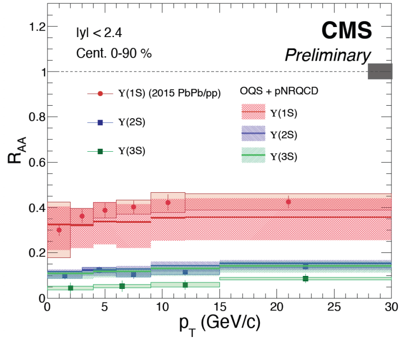

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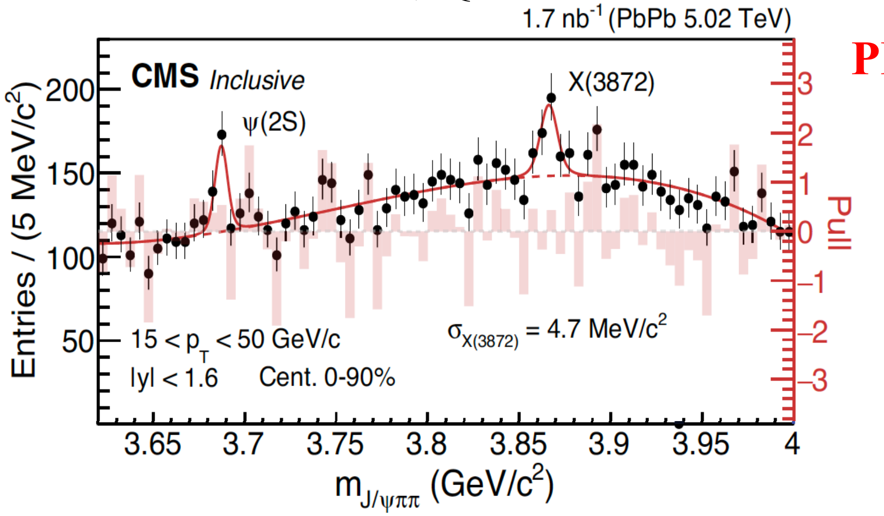
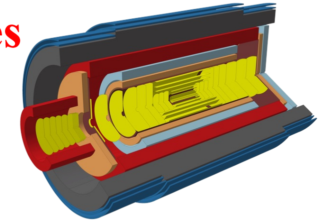


PHENIX and STAR have decades of data on tape
sPHENIX coming soon

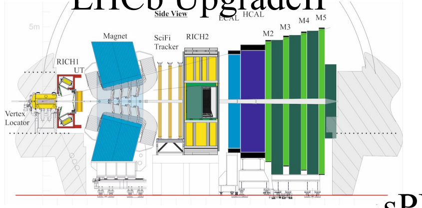
ALL **LHC experiments are implementing relevant upgrades**

See talk by Jochen Klein, Sun

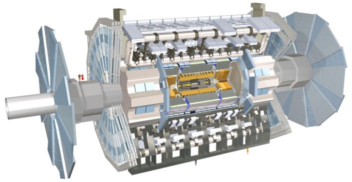
ALICE3



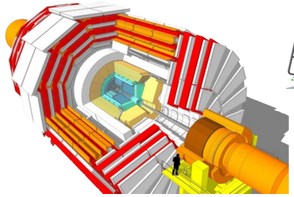
LHCb UpgradeII



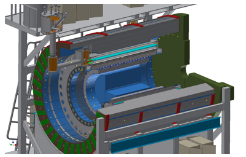
ATLAS Phase II



CMS Phase II



sPHENIX



Summary

- Exotic hadrons are just now becoming measurable in heavy ion collisions
  - First studies of X(3872) production in pA and AA collisions now available – limited precision
  - No theoretical consensus on production, breakup, or coalescence of X(3872)

- Measurements give new constraints on quark transport and hadronization, as well as providing new insight into fundamentally allowed bound states of quarks

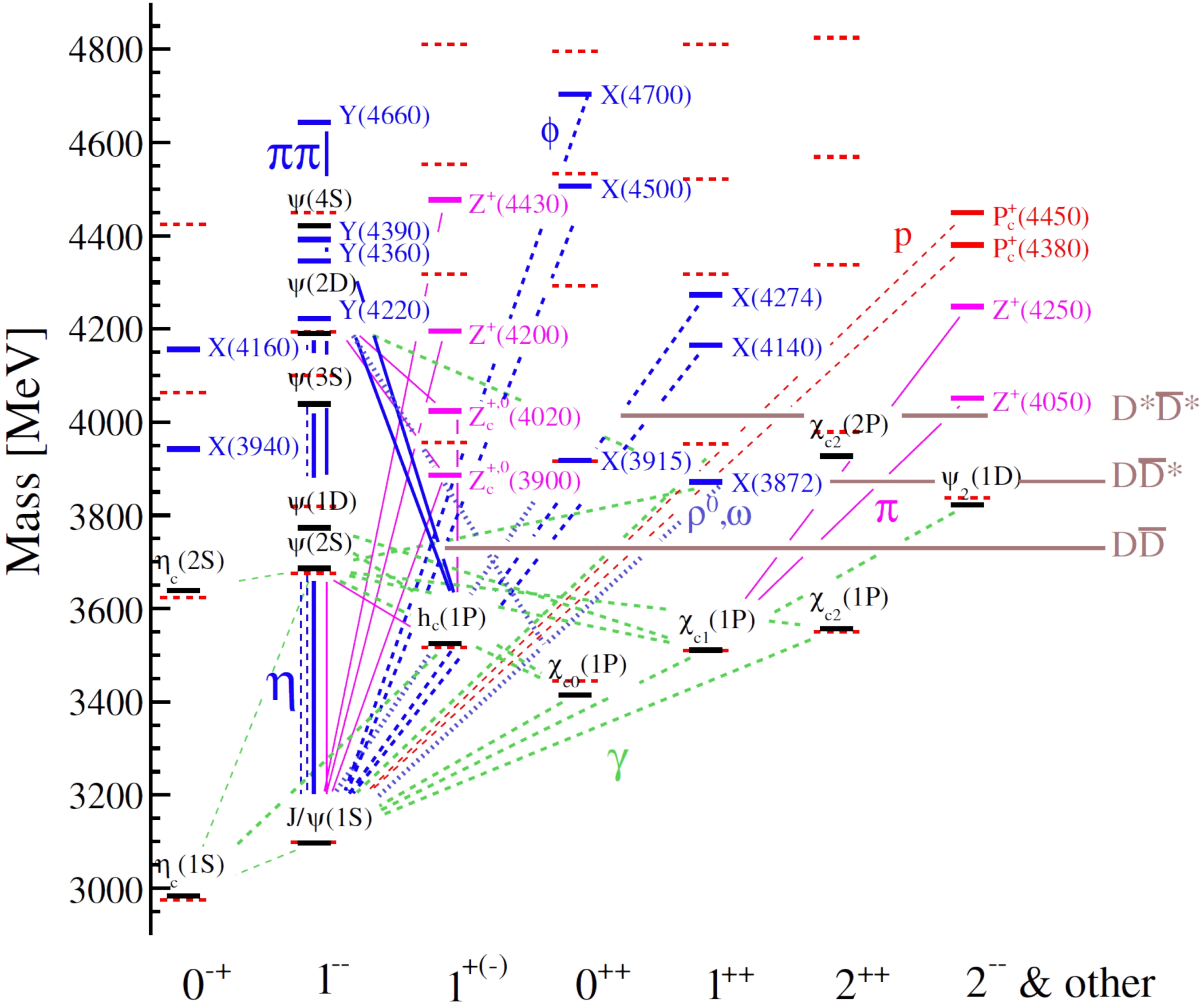
- New discovery channels are being explored, with multiple relevant experimental upgrades underway

Los Alamos National Laboratory is supported by the US Dept. of Energy/Office of Science/Nuclear Physics and DOE Early Career Awards

BACKUPS

Joseph Allen Maldonado-Passage, exotics enthusiast

Rev. Mod. Phys. 90, 015003 (2018)



(Ideal) detector requirements for exotics program in heavy ions

- Hadron ID
  - Hadronic decays of exotic states can have complicated topology
  - Reduces combinatorial backgrounds

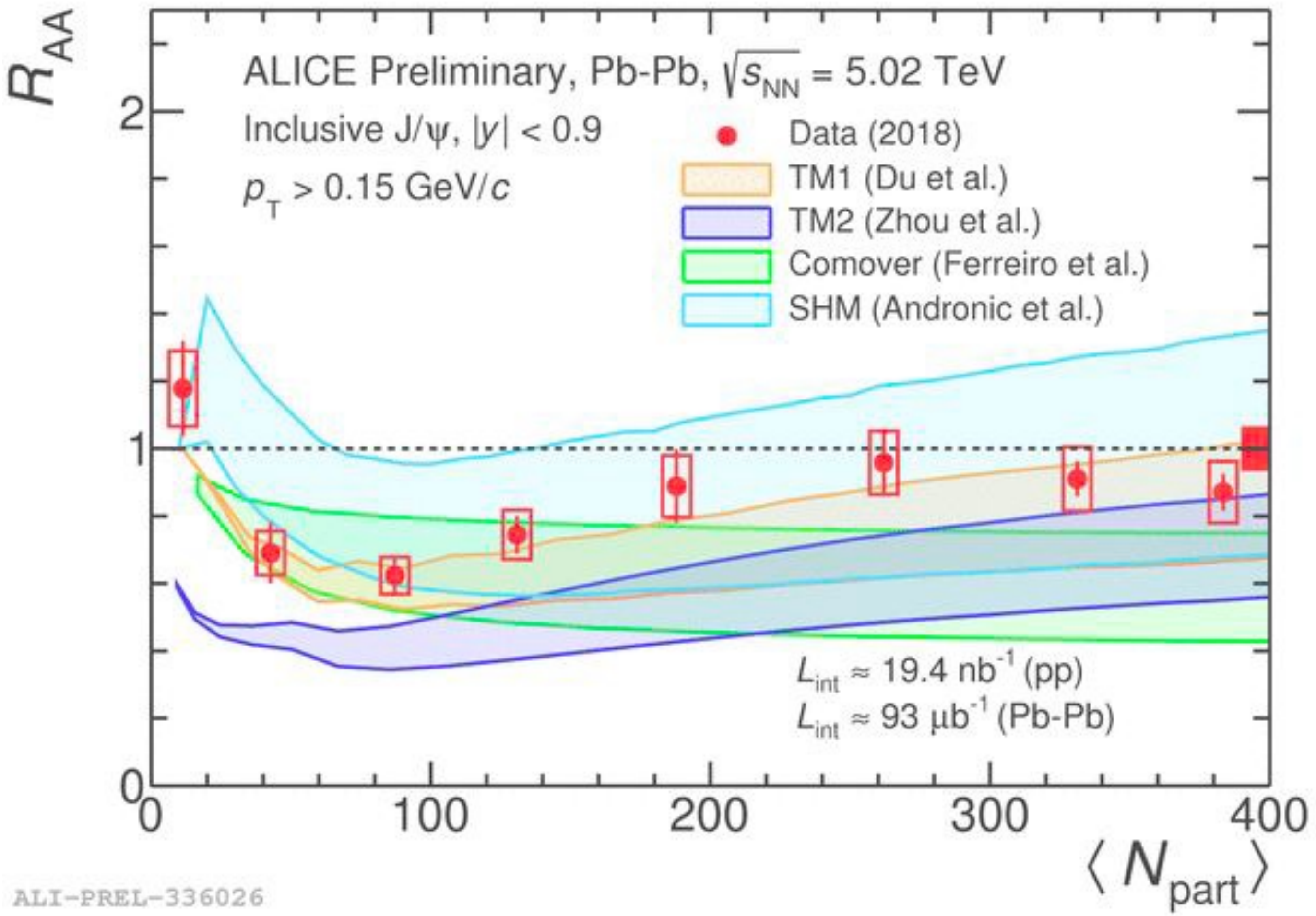
- Precision Vertexing
  - Removes component produced away from vertex in *b*-decays

- Low pt coverage
  - Sensitive to largest breakup/recombination effects

- High sampling rate across full centrality
  - Access to multiquark states with relatively low cross sections in central collisions

Currently, no experiment has all these capabilities

ALL LHC experiments have relevant upgrades ongoing


ALICE Preliminary, Pb-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
Inclusive J/ψ, |y| < 0.9
p_T > 0.15 GeV/c
Data (2018)
TM1 (Du et al.)
TM2 (Zhou et al.)
Comover (Ferreiro et al.)
SHM (Andronic et al.)
L_{int} ≈ 19.4 nb^{-1} (pp)
L_{int} ≈ 93 μb^{-1} (Pb-Pb)
R_{AA}
⟨N_{part}⟩
0
1
2
100
200
300
400
ALI-PREL-336026

A light quark exotic candidate: f(980)

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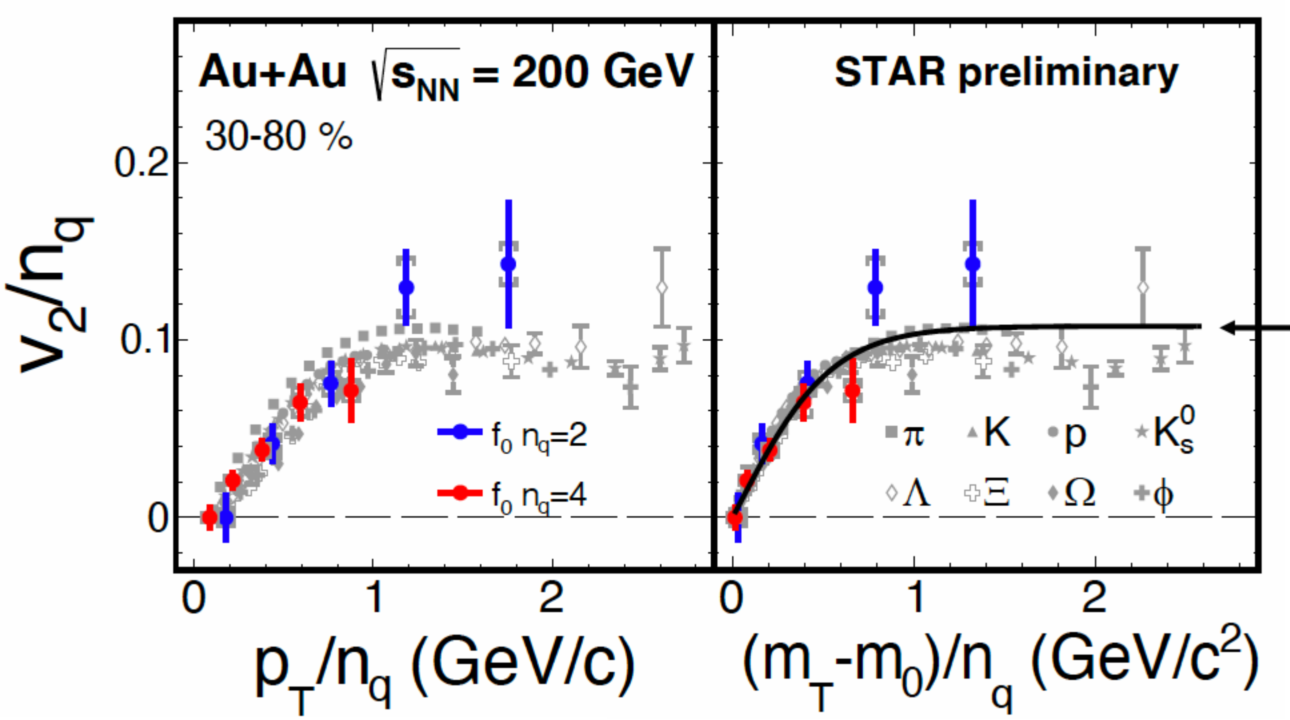
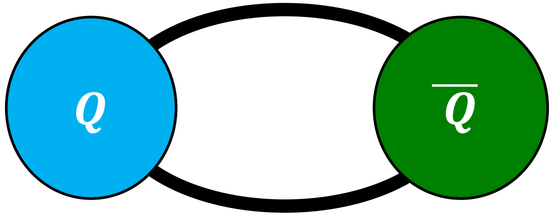
[Jie Zhao for STAR, SQM 2021]



Fit to other hadrons

$n_q(f_0(980)) = 3.0 +/- 0.7 +/- 0.5$

Hadron spectroscopy



$$V_0^{(c\bar{c})}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\tilde{\delta}_\sigma(r)\vec{S}_c\cdot\vec{S}_{\bar{c}}$$

Phys. Rev. D 72, 054026 (2005)

- Fantastically successful for heavy quarkonia states
  - Reproduces all known quarkonia states
  - Predictive: mass of newly discovered $\psi_3(1^3D_3)$ within <1% of model LHCb JHEP (2019) 35
- Works well for heavy open charm and bottom mesons
- Works ~okay for light quark states