Quarkonium: experimental overview

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Los Alamos NATIONAL LABORATORY EST. 1943

10th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions

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The University of Texas at Austin

Outline

- Introduction
- $Q\bar{Q}$ in Small Systems → Large Systems
  - Focus on medium interactions
- Exotic hadrons containing $Q\bar{Q}$
  - X(3872) in the QCD medium
- Brief look to the future

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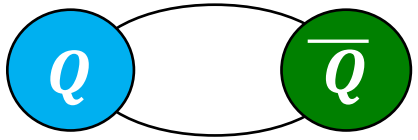
Heavy $Q\bar{Q}$ states in vacuum



Solve Schrodinger equation with the potential

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

Phys. Rev. D 72, 054026 (2005)

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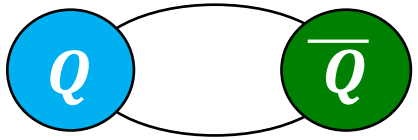

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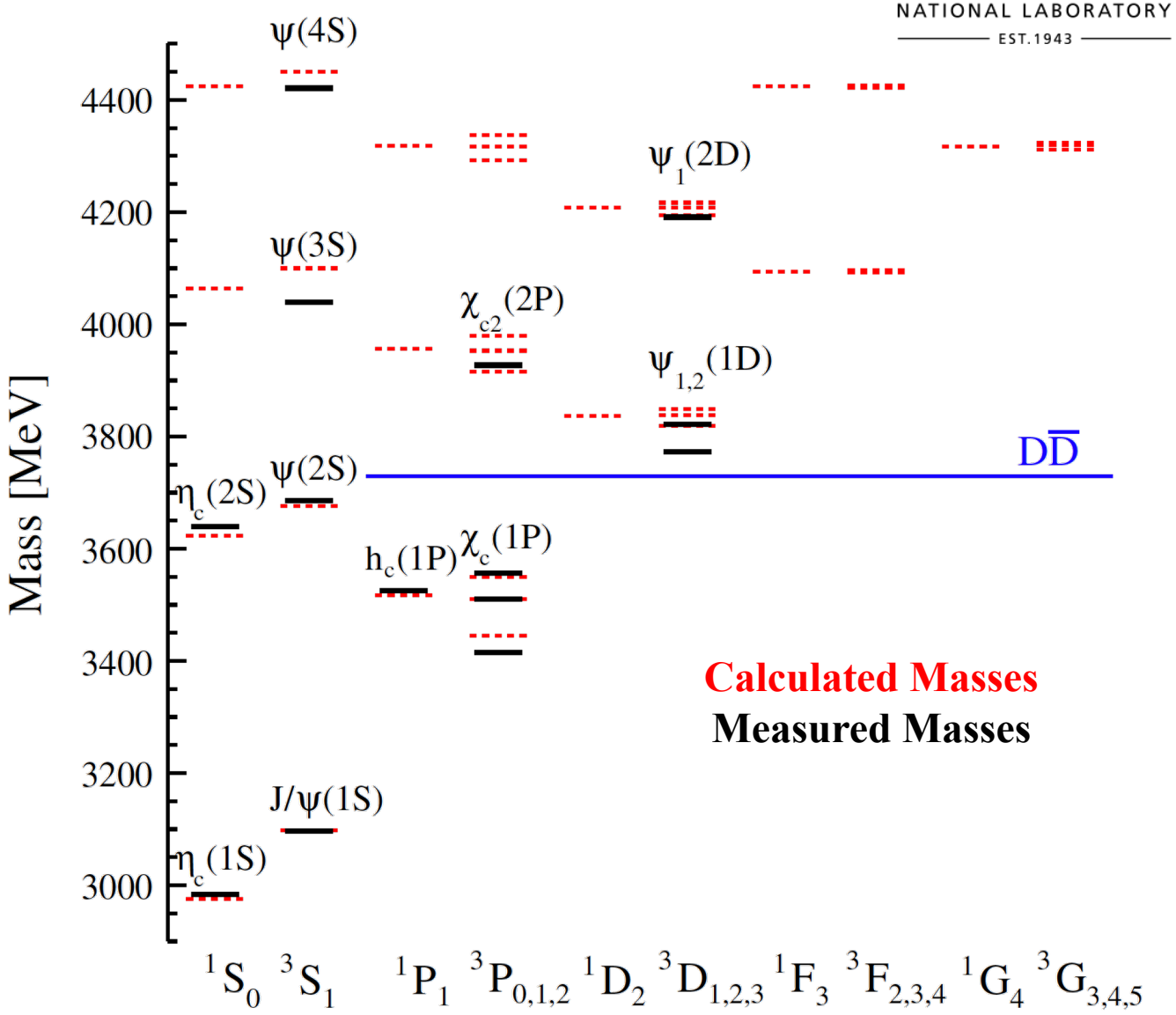

Rev. Mod. Phys. 90, 015003 (2018)

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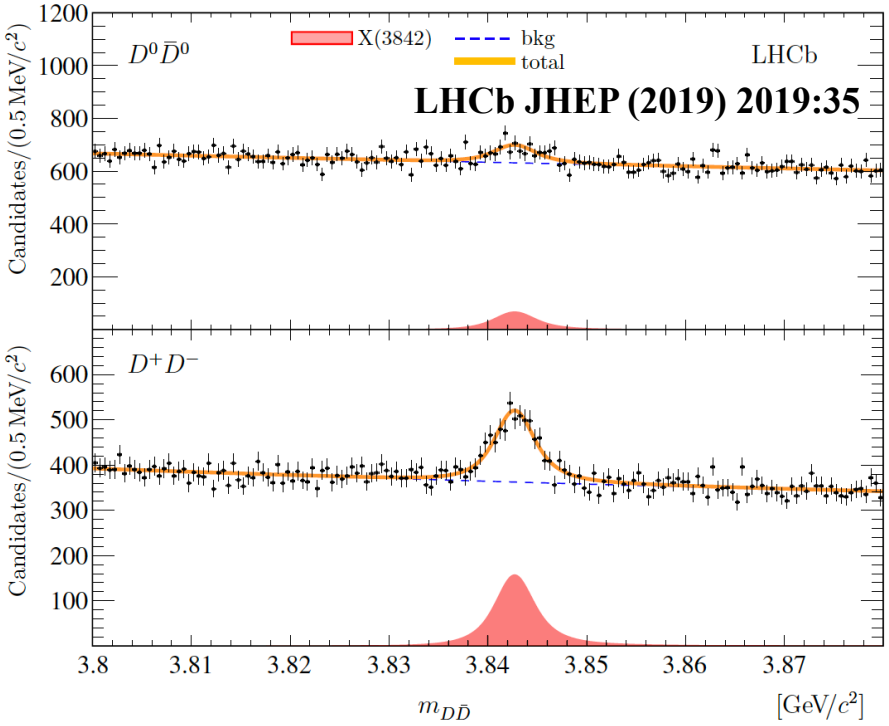
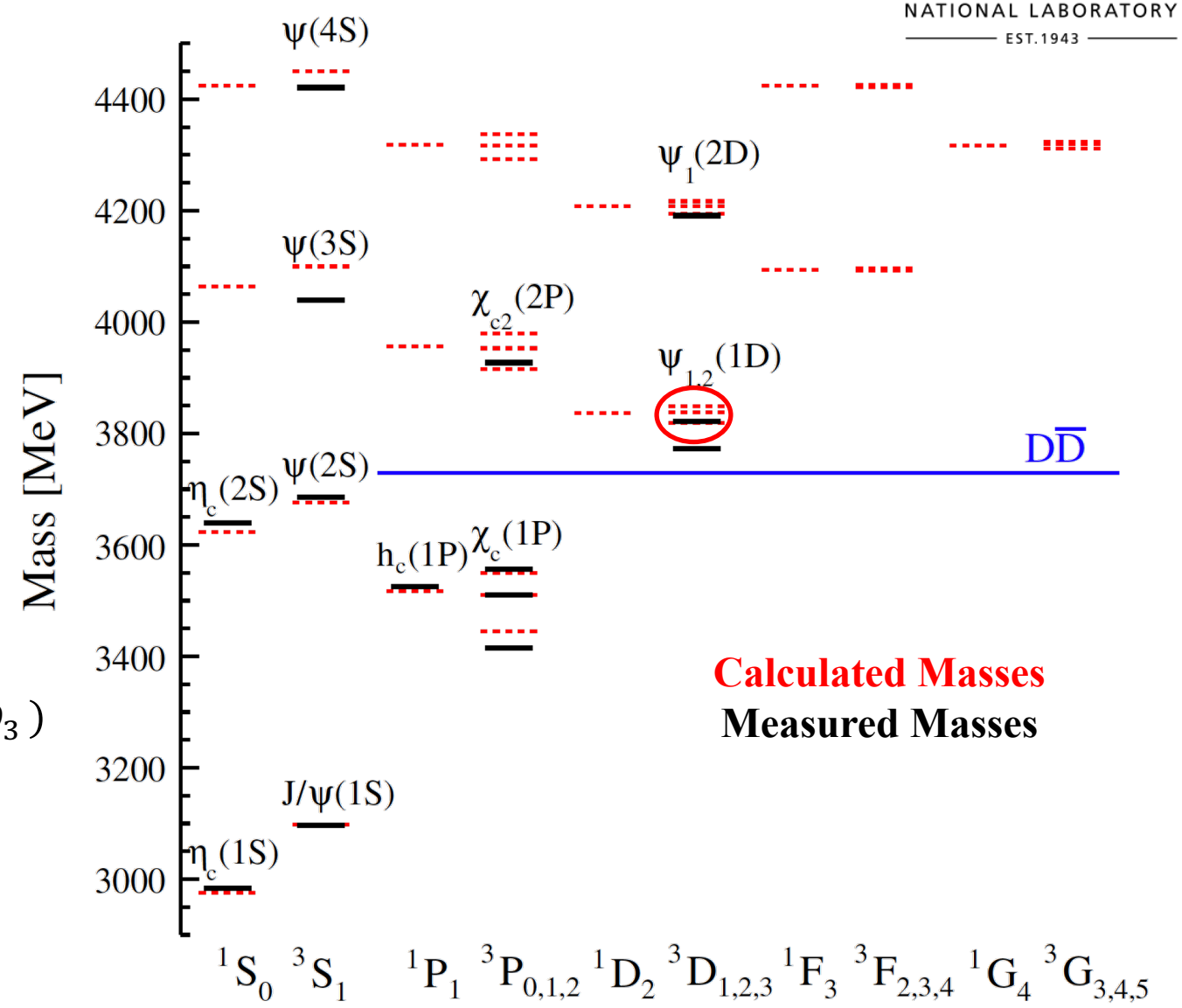


The most recently discovered charmonium state: $\psi_3(1^3D_3)$

Measured mass: $3842.71 \pm 0.16 \pm 0.12$ MeV
Predicted mass: 3849 MeV

Incredibly rich structure, accessible theoretically and experimentally



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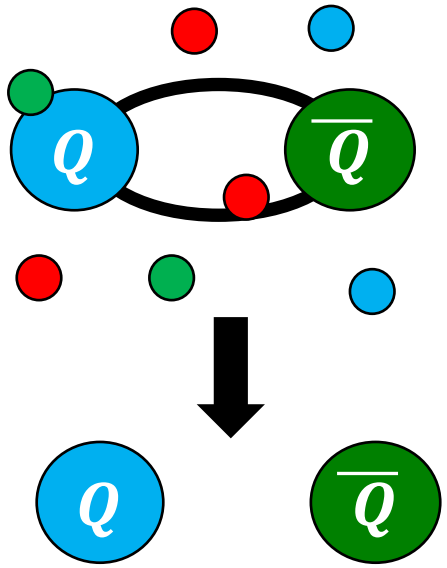
Heavy $Q\bar{Q}$ states in the QCD medium

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



Dissociation via interactions with comoving particles

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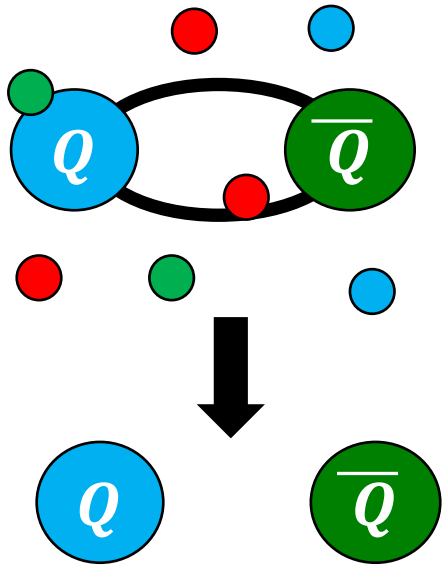

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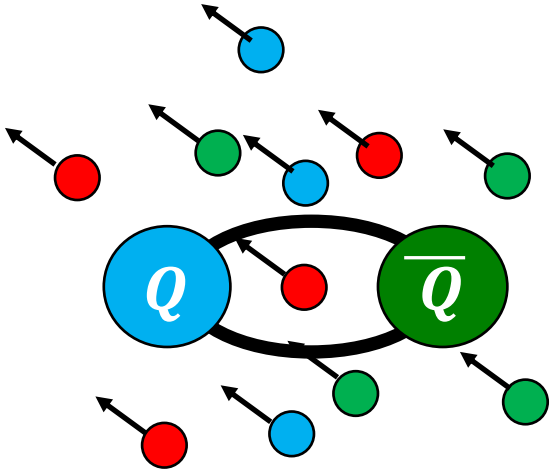

Hydrodynamic flow induced by pressure gradients (initial state?)

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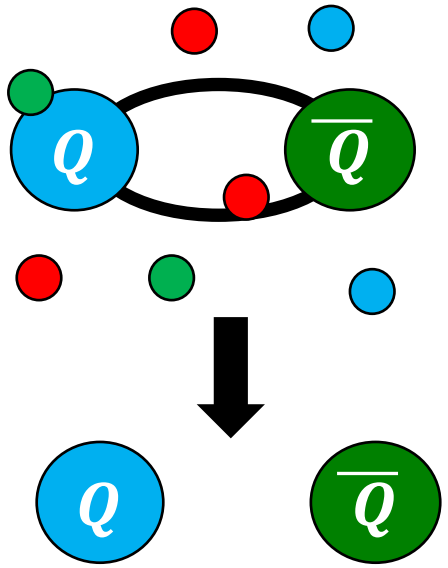

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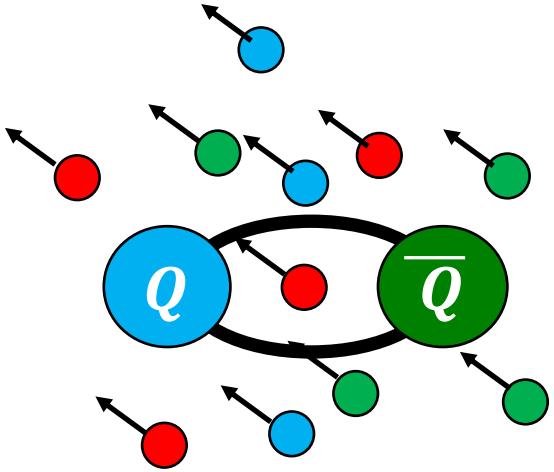

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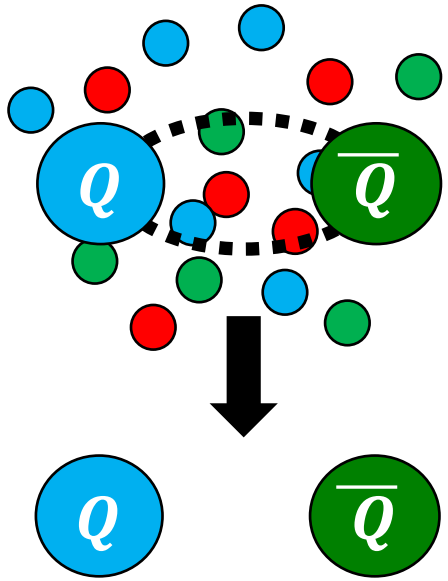

Suppression via color screening

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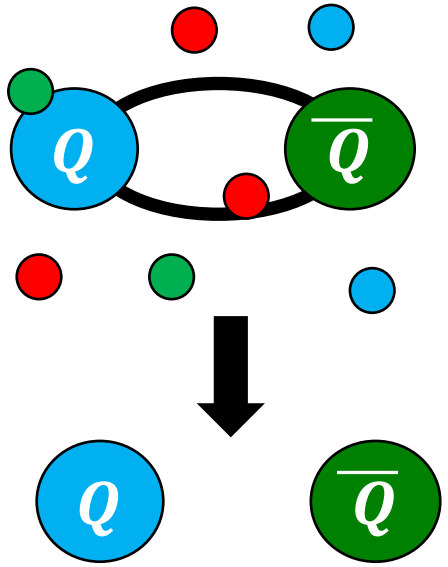

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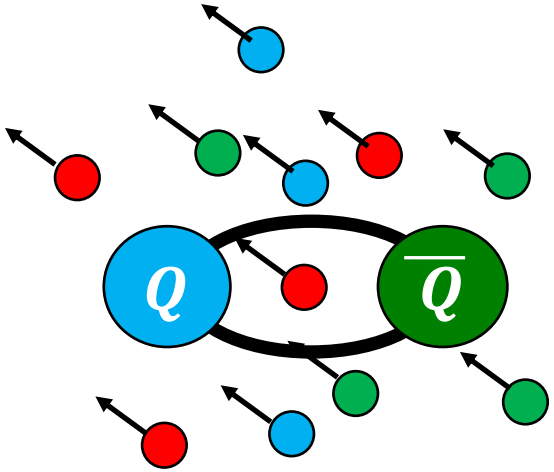

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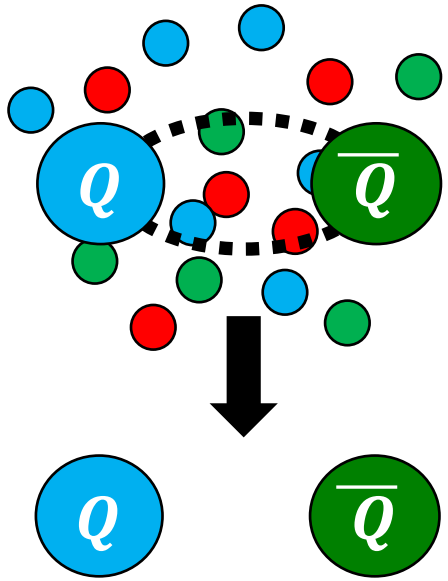

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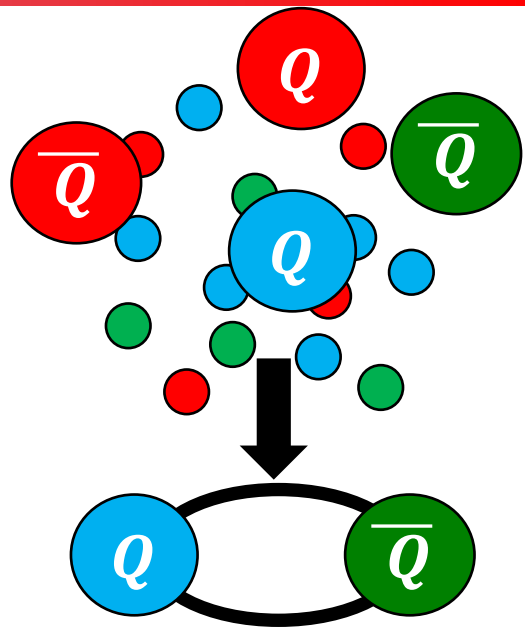

Production via coalescence

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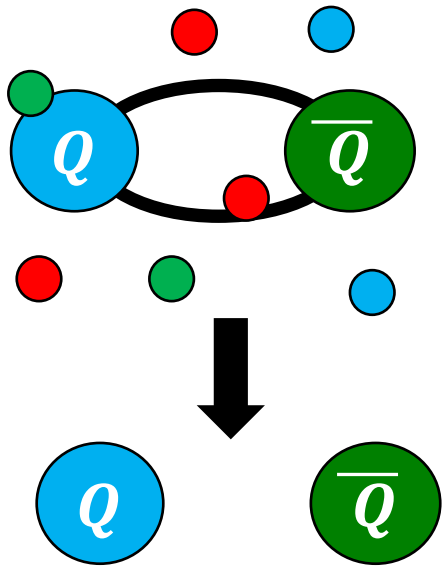

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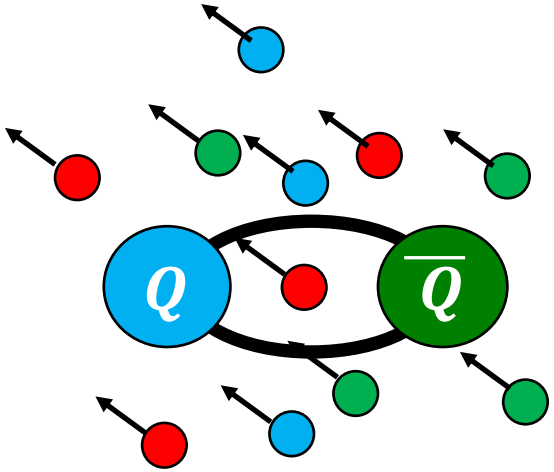

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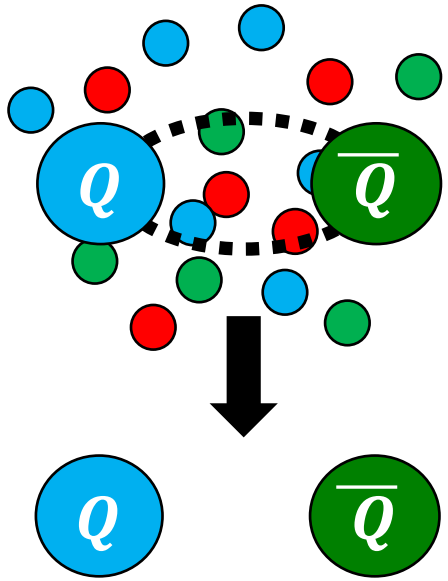

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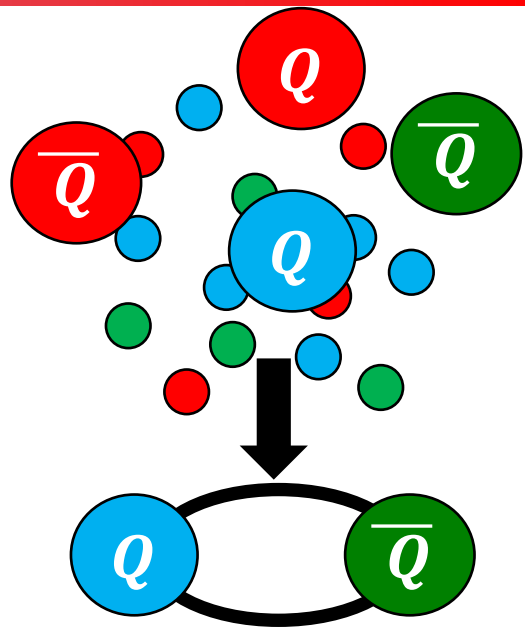


Production via coalescence

*Additional initial state effects from modified nPDF and energy loss can also be significant in collisions with nuclei.

Experimentally, we use different collision systems/kinematic regions to prepare environments where different effects dominate for different probes.

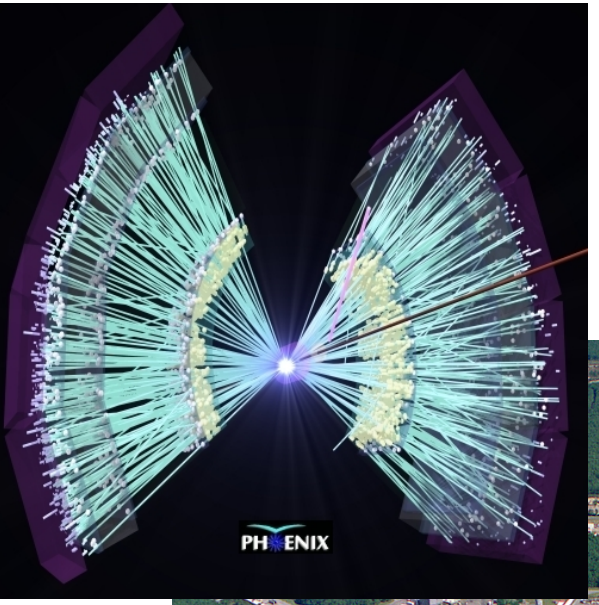
Every experiment contributes to quarkonia physics

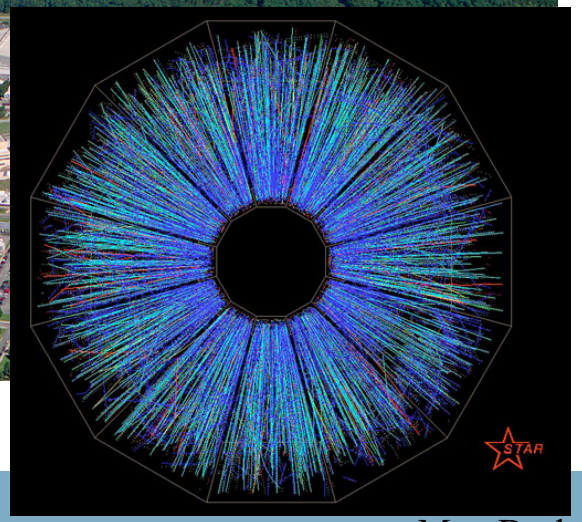
Taken together:

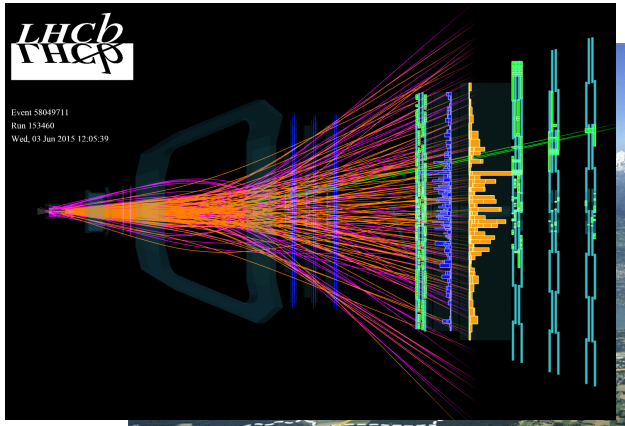
$-5 < y < 5$

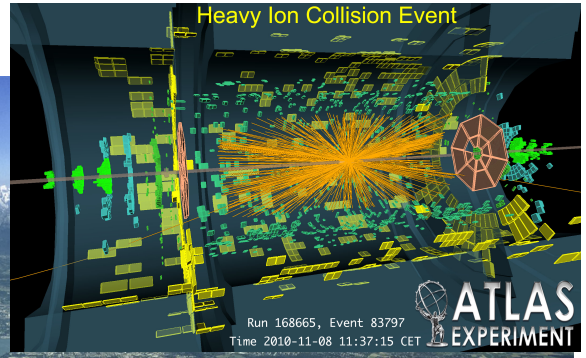
$0 < p_T <$ several hundred GeV

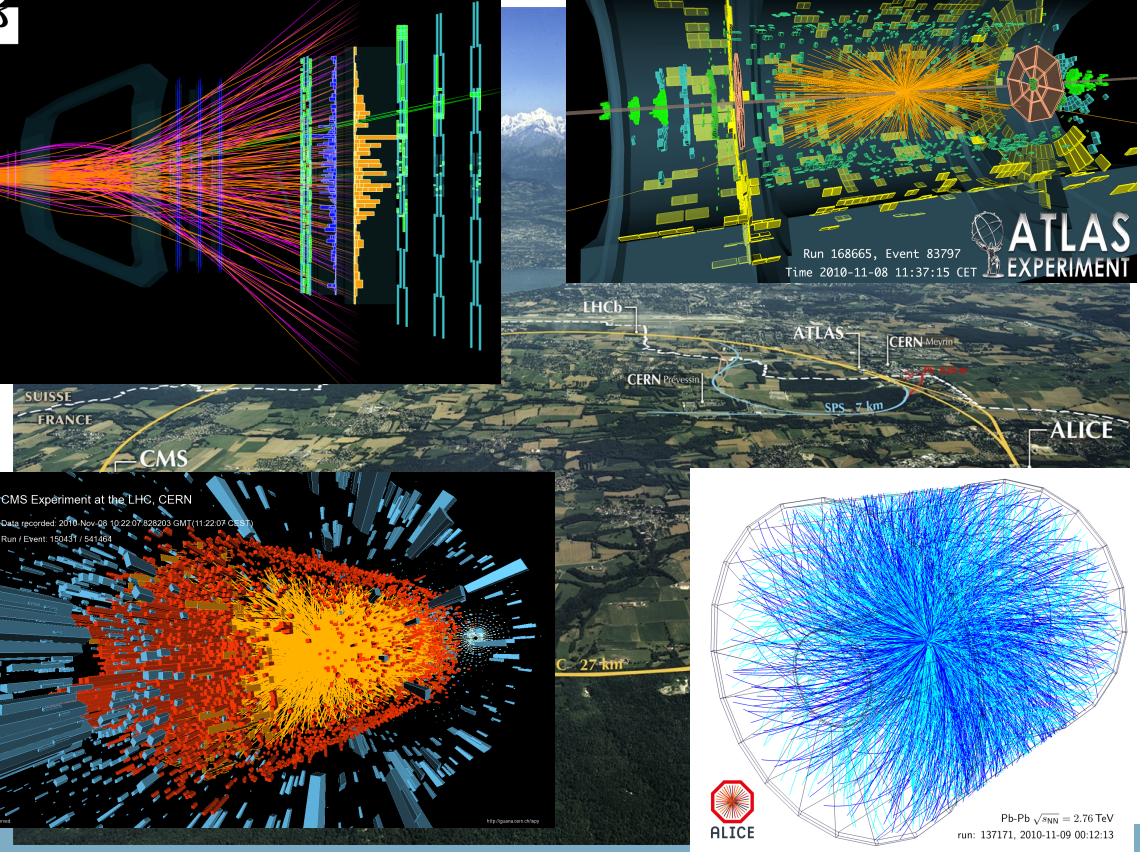
$\sim 0 < T <$ hundreds of MeV











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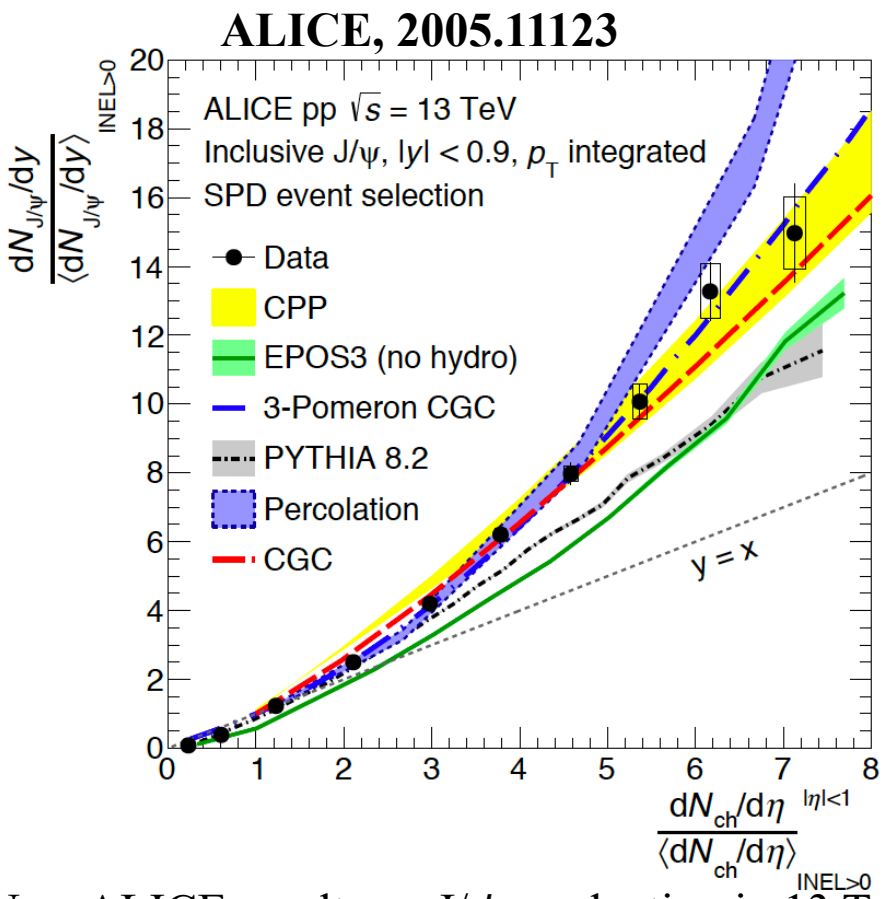
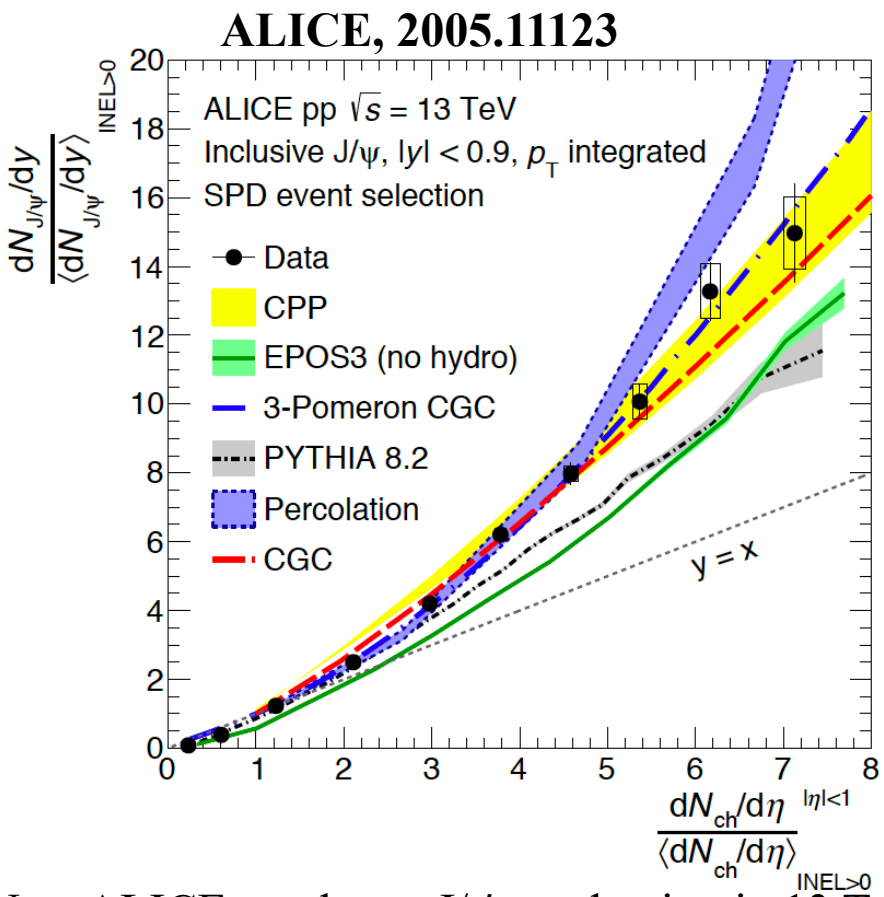
Charmonium in *pp* vs. multiplicity

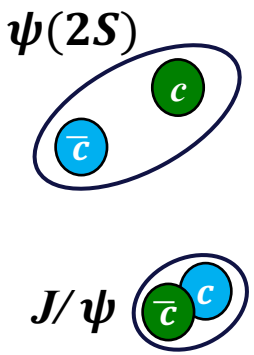


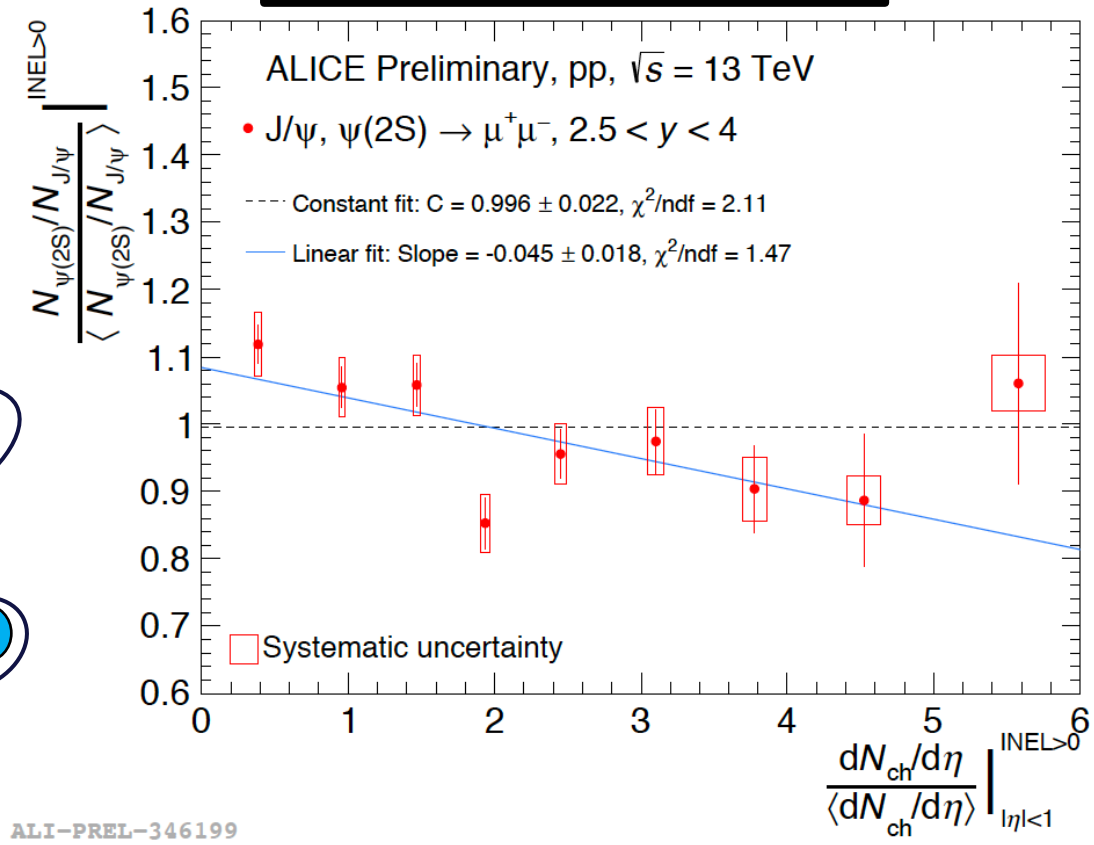
New ALICE results on J/ψ production in 13 TeV pp shows faster-than-linear growth with multiplicity: various CGC calculations match data

Charmonium in *pp* vs. multiplicity

Manuel Guittiere, Tues 11:00





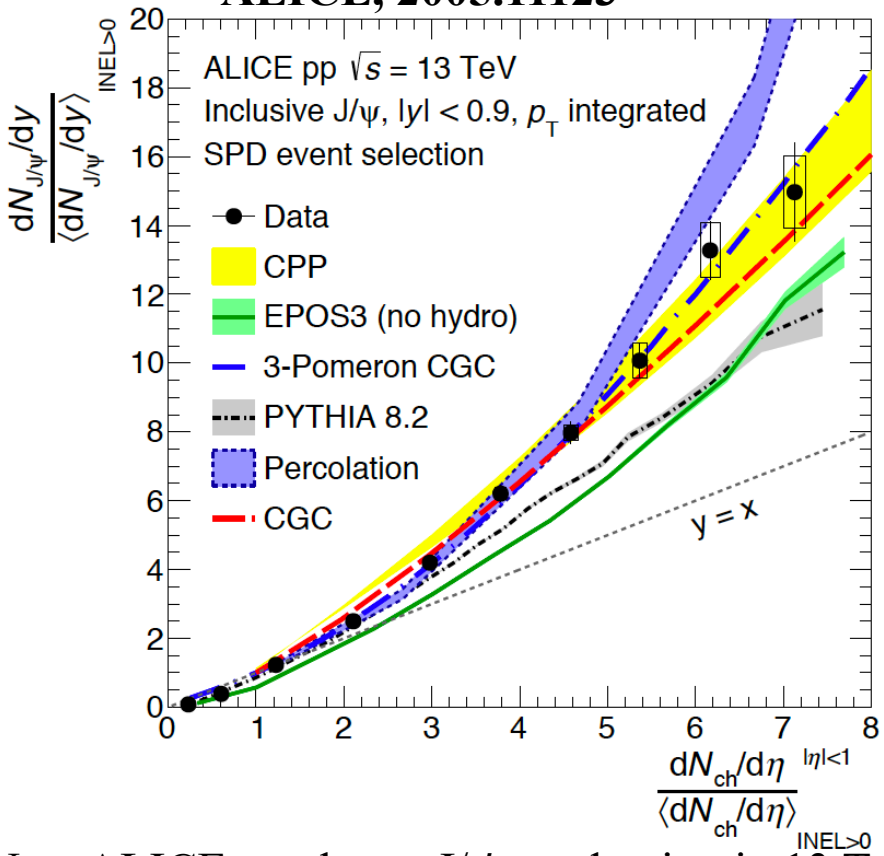


New ALICE results on J/ψ production in 13 TeV pp shows faster-than-linear growth with multiplicity: various CGC calculations match data

Hints that ψ(2S) production does now grow as fast as J/ψ with multiplicity – initial state models should give similar trend for both. Final state effect suppressing ψ(2S) in *pp*?

Charmonium in *pp* vs. multiplicity

ALICE, 2005.11123



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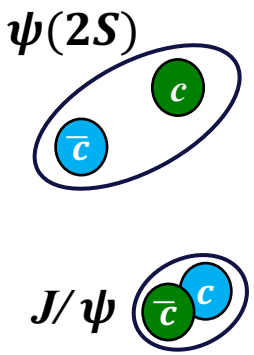

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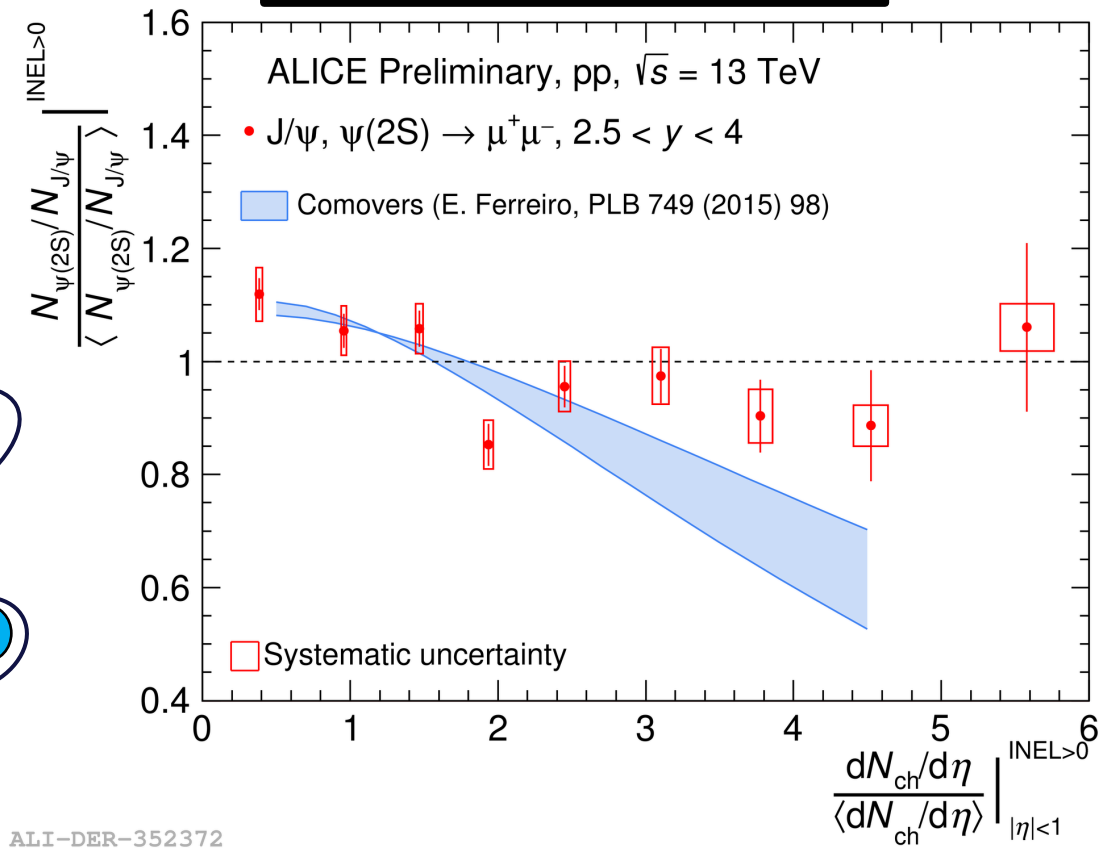

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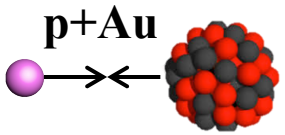
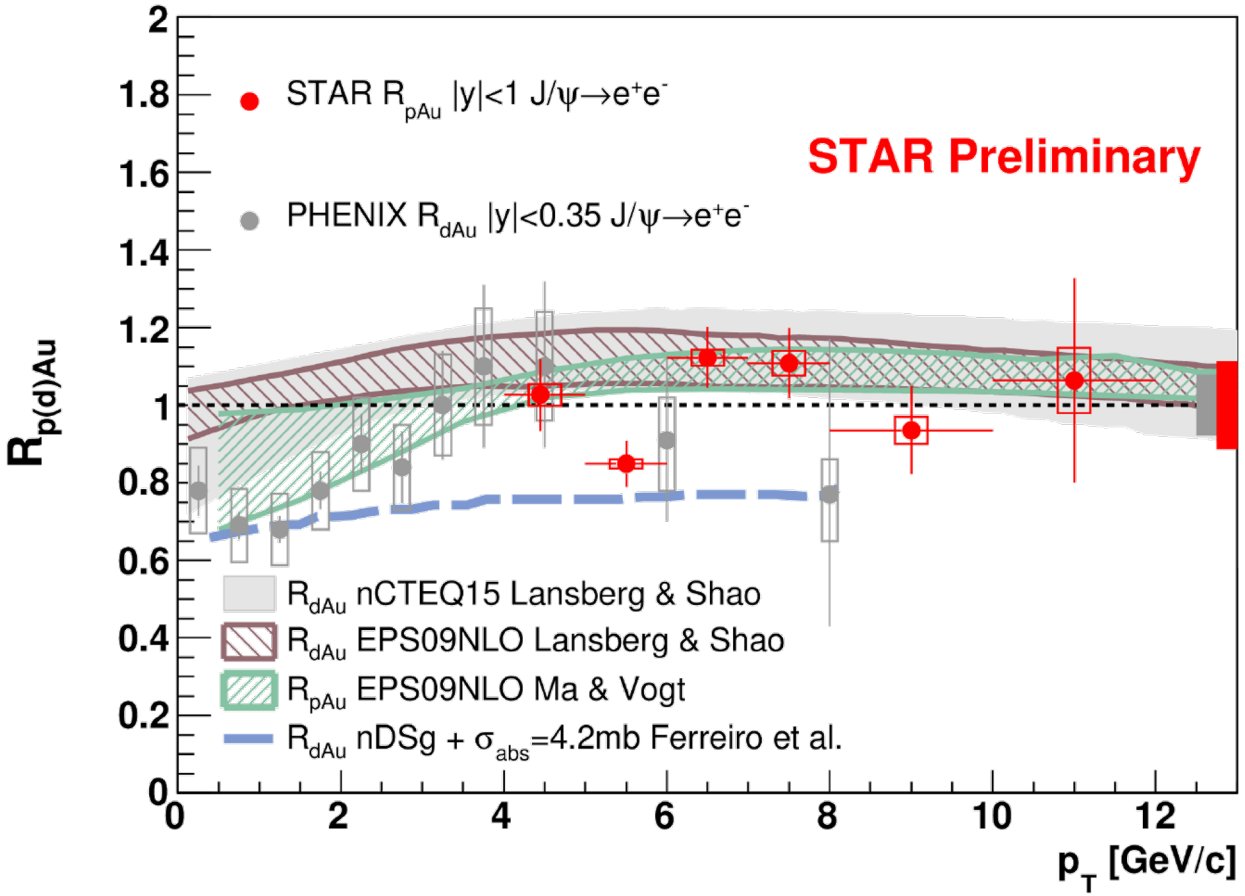
J/ψ in small systems at RHIC

Ziyue Zhang, Monday 12:20





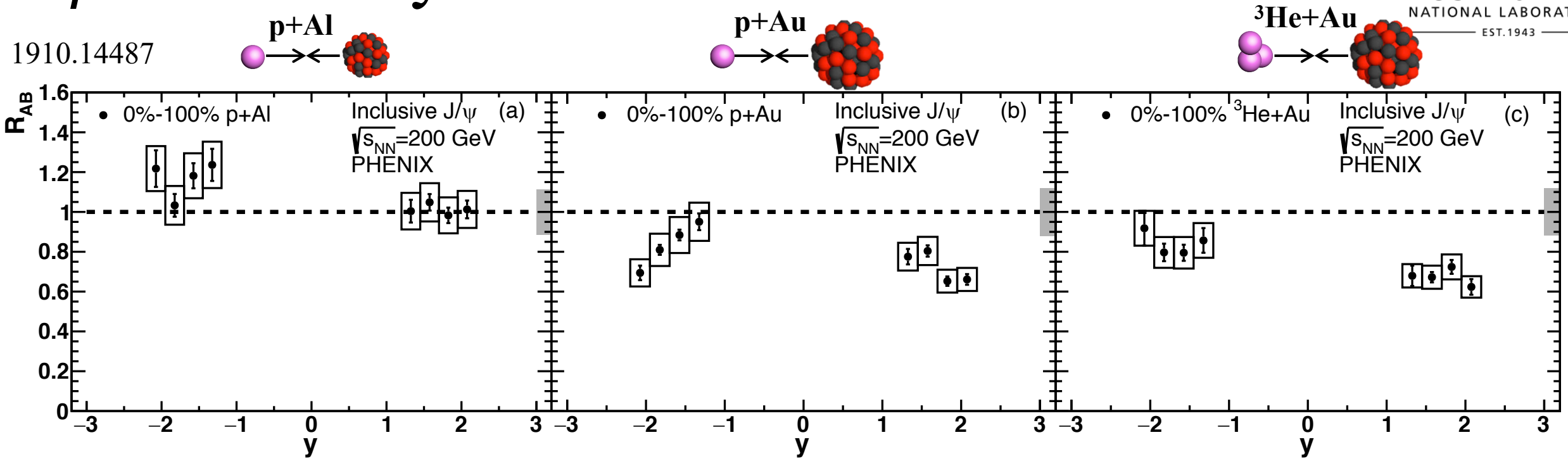
Midrapidity STAR data shows little J/ψ modification at intermediate p_T:

- Consistent with nPDF calculations
- Consistent with PHENIX d+Au data
- CNM not dominant effect in AA in this range

J/ψ in small systems at RHIC

Sanghoon Lim, Tues 11:20

1910.14487



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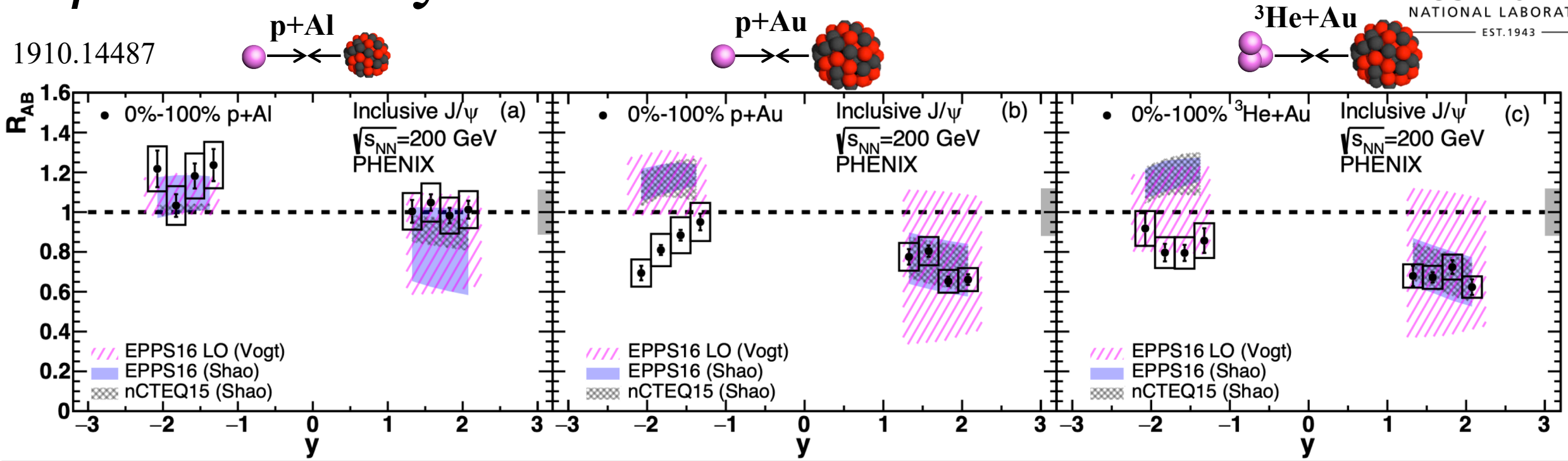

Forward rapidity (p or 3He-going direction):

- Data generally in agreement with nPDF calculations

Backward rapidity (A-going direction):

- Data from Au nucleus is **inconsistent with nPDF calculation**:
  - Additional effects *required* to explain data

Significantly improved precision in state-of-the art nPDF calculations, which include D, J/ψ, and ϒ(1S) LHC data

Kusina, Lansberg, Schienbein, Shao, Phys. Rev. Lett. 121, 052004 (2018)

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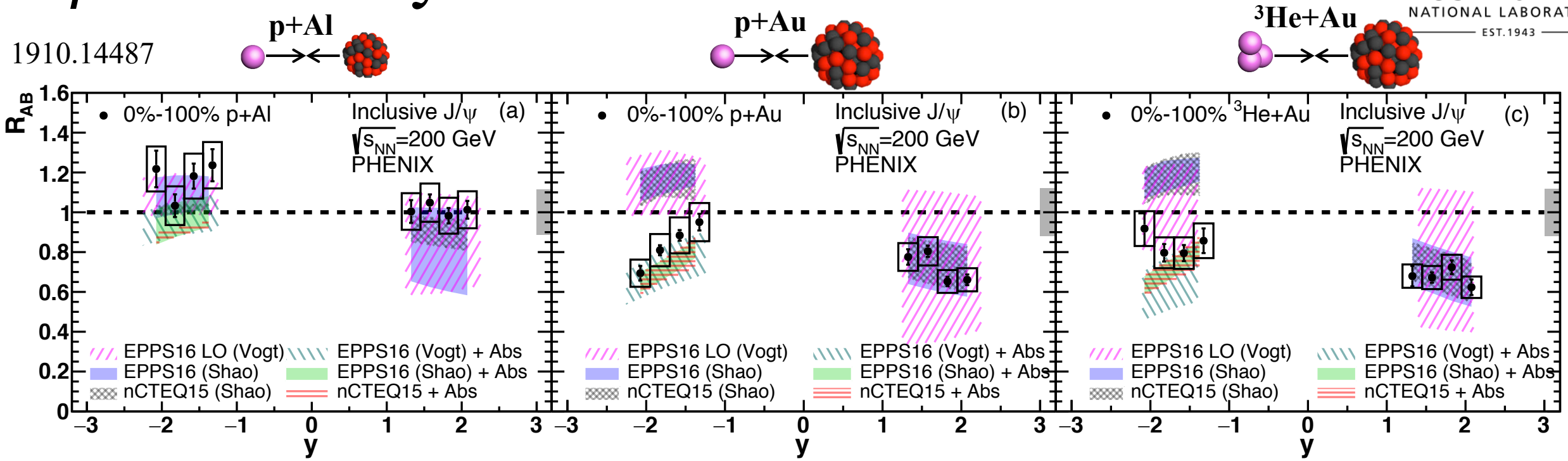

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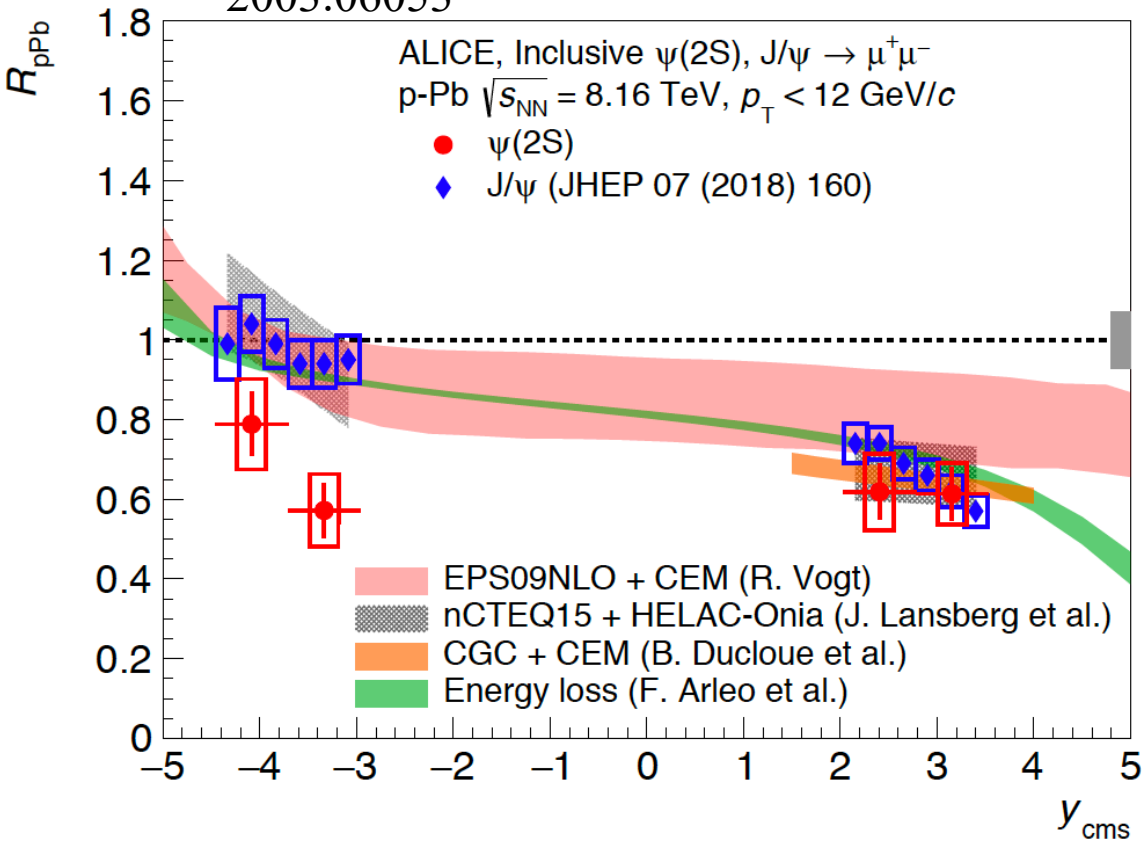
$Q\bar{Q}$ in pPb

2003.06053



Florian Damas, Mon 1:35

At both forward and backward rapidity, J/ψ well described by nPDF calculations: initial state dominates

- **Marked difference from PHENIX data, where additional effects are required to match backwards J/ψ data**
- J/ψ breakup smaller at LHC - smaller crossing time

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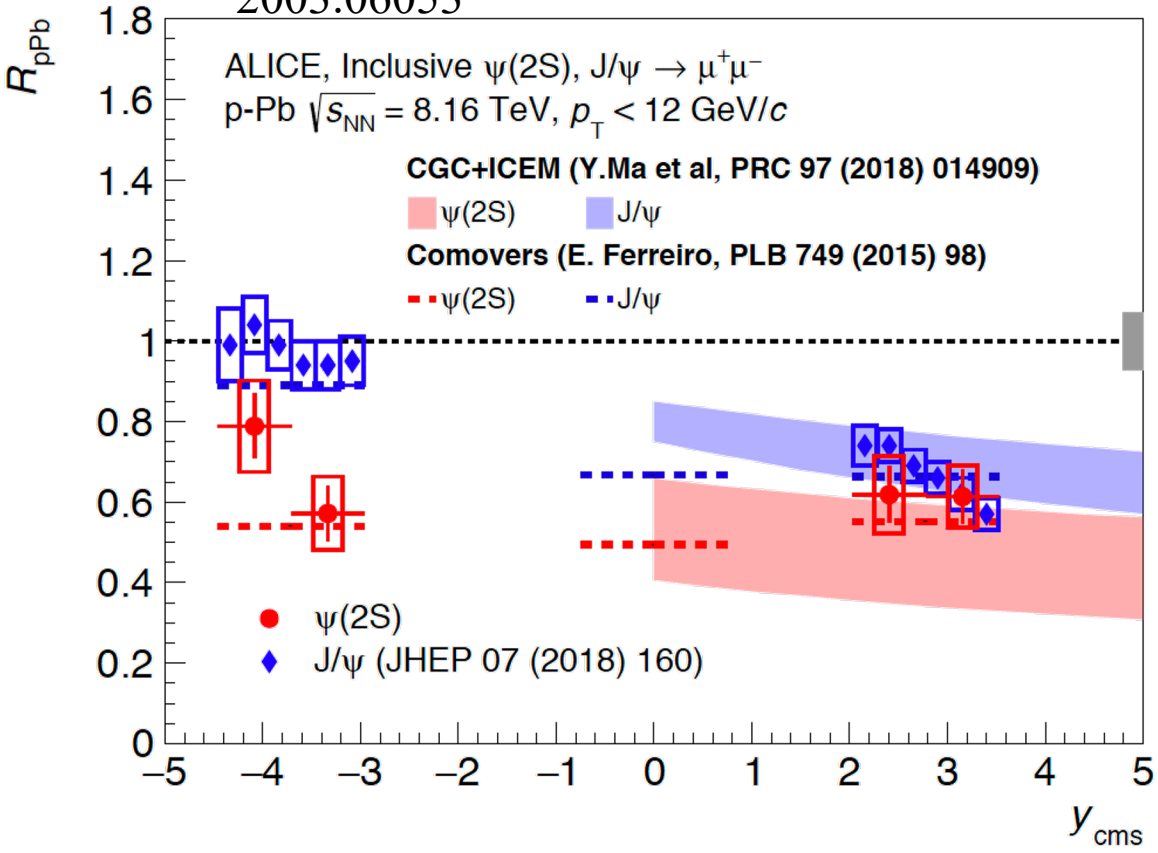

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Similar effects previously observed by PHENIX, ALICE, LHCb
Similar sequential suppression of Υ(nS) also observed in pPb

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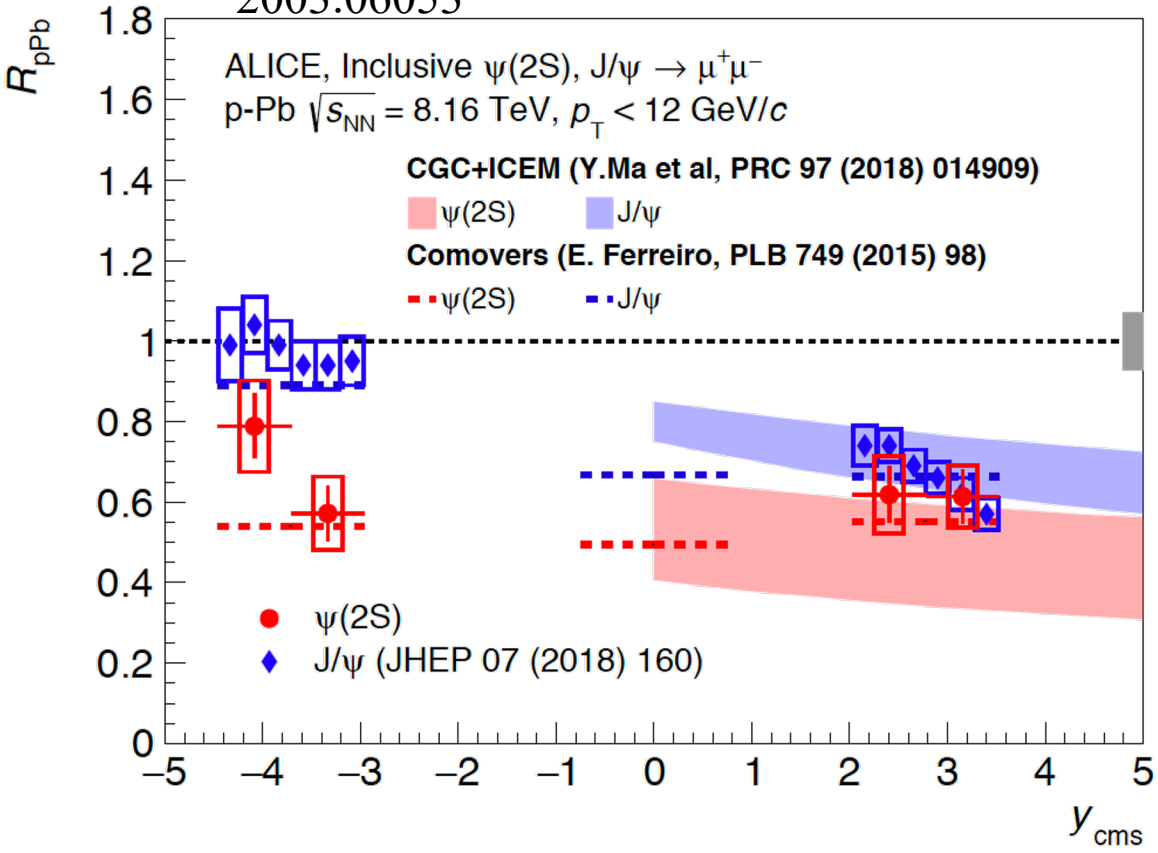

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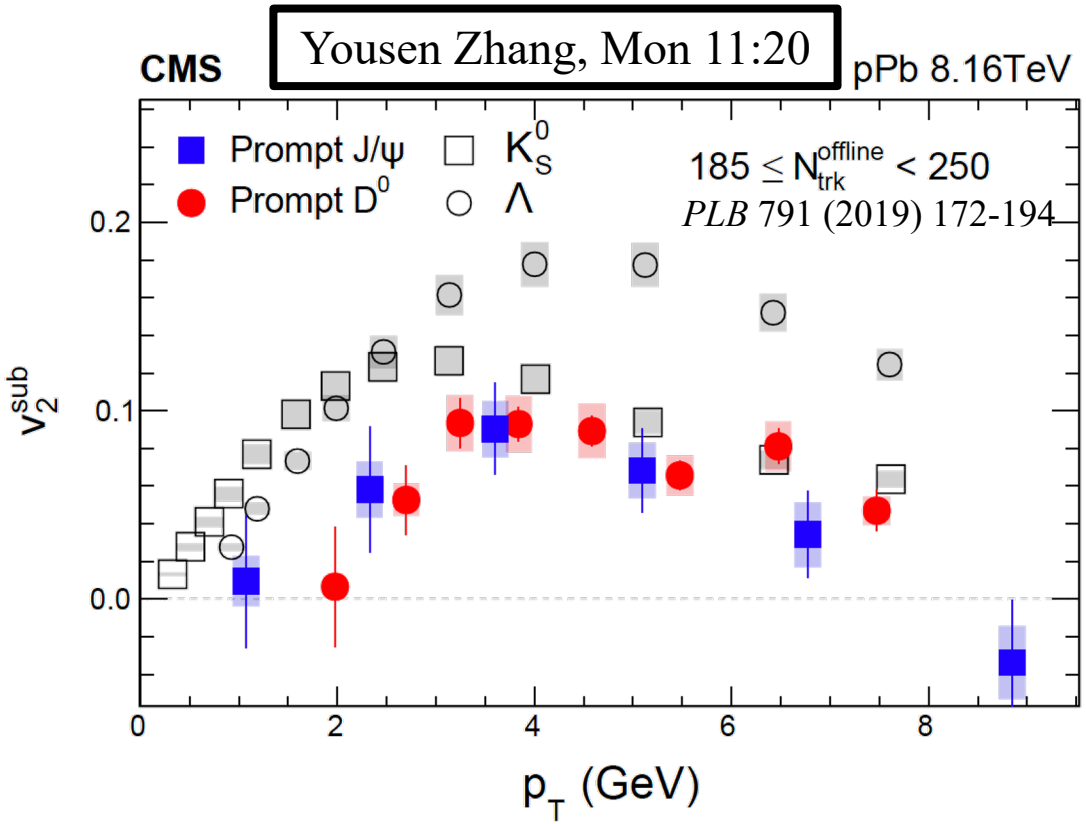
J/ψ flow

Data on J/ψ production is consistent with nPDF, however: Significant J/ψ v_2 observed in pPb collisions



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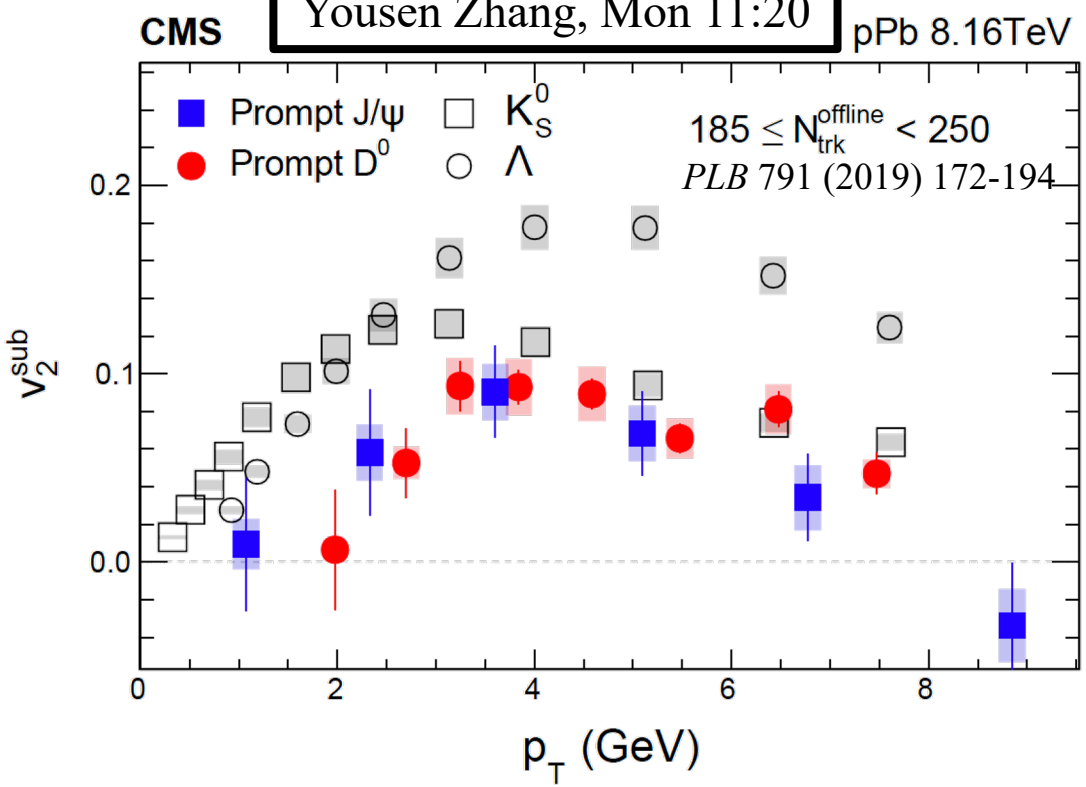
Yousen Zhang, Mon 11:20



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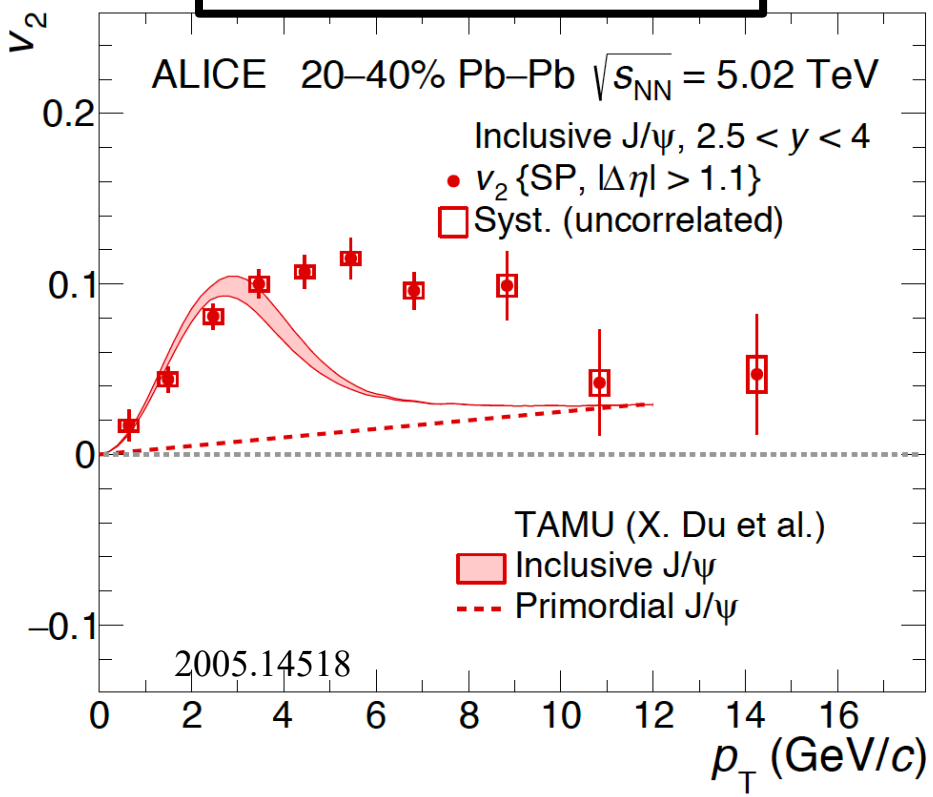

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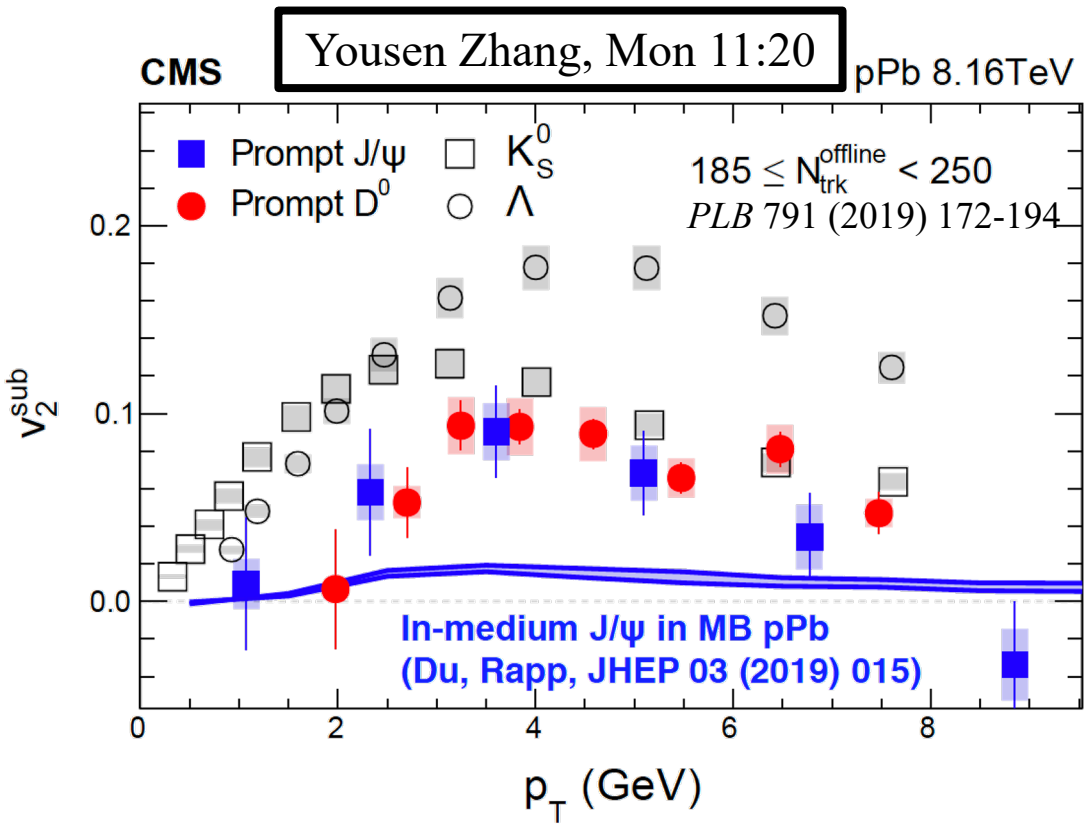

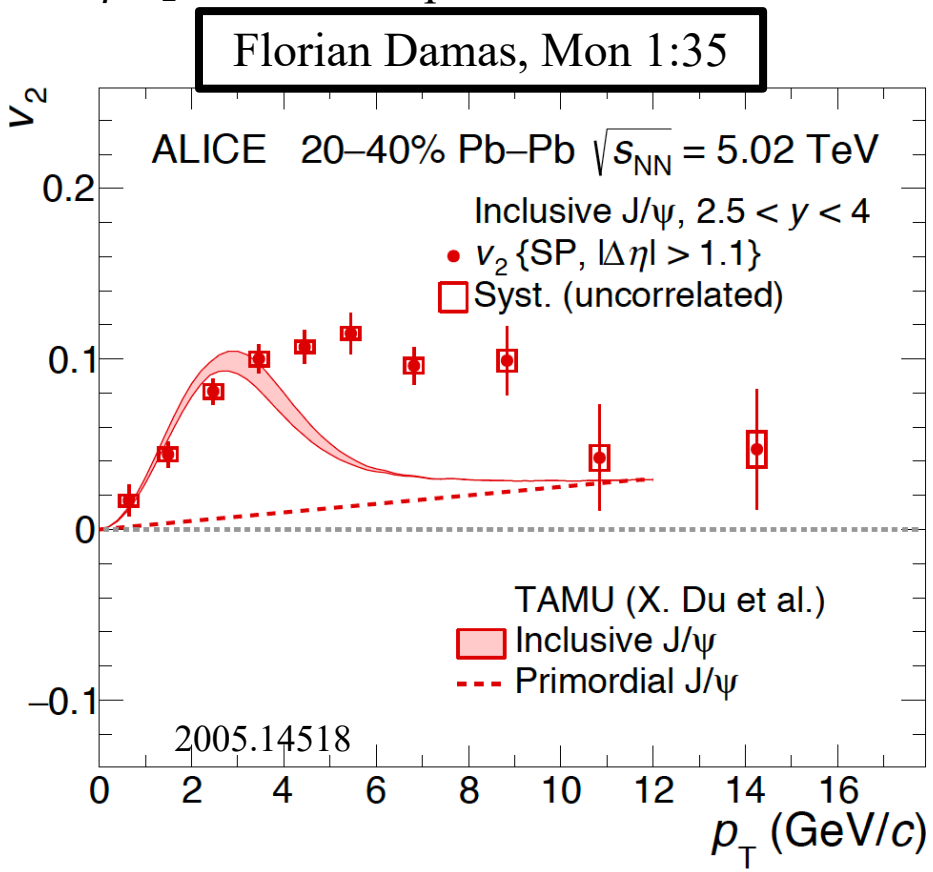

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- **Transport model with short lived plasma phase in pPb does not give large v2 in pPb (does describe low pT PbPb)**

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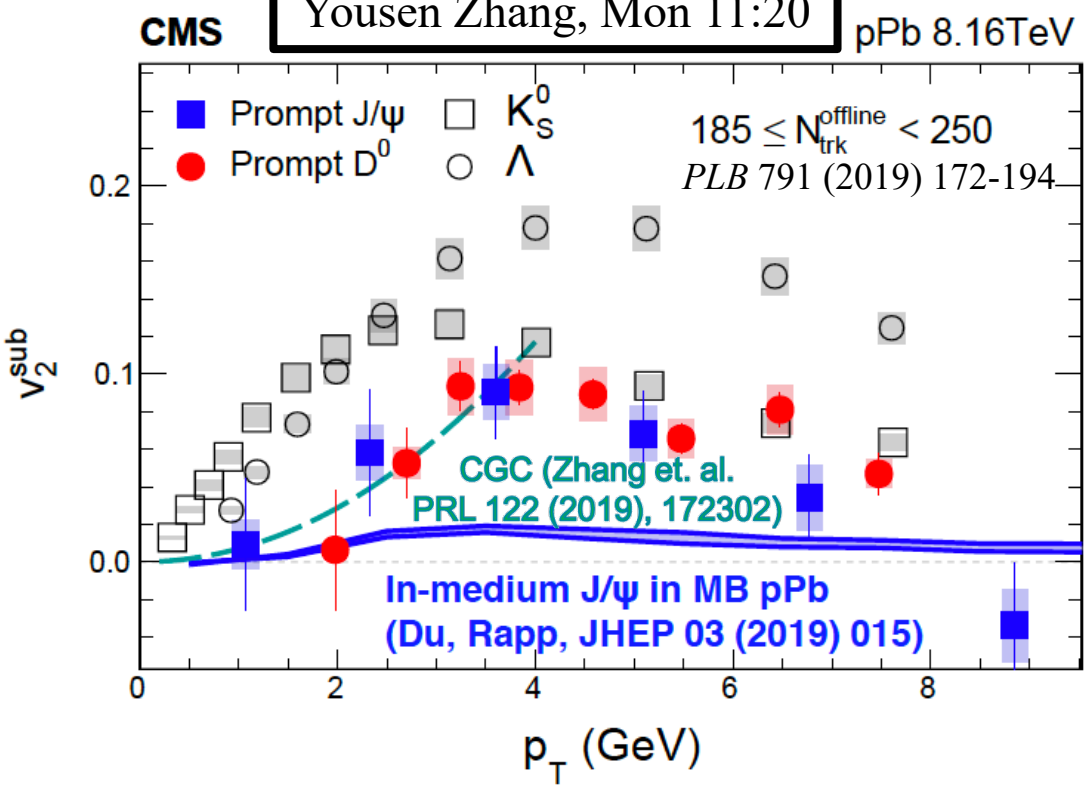
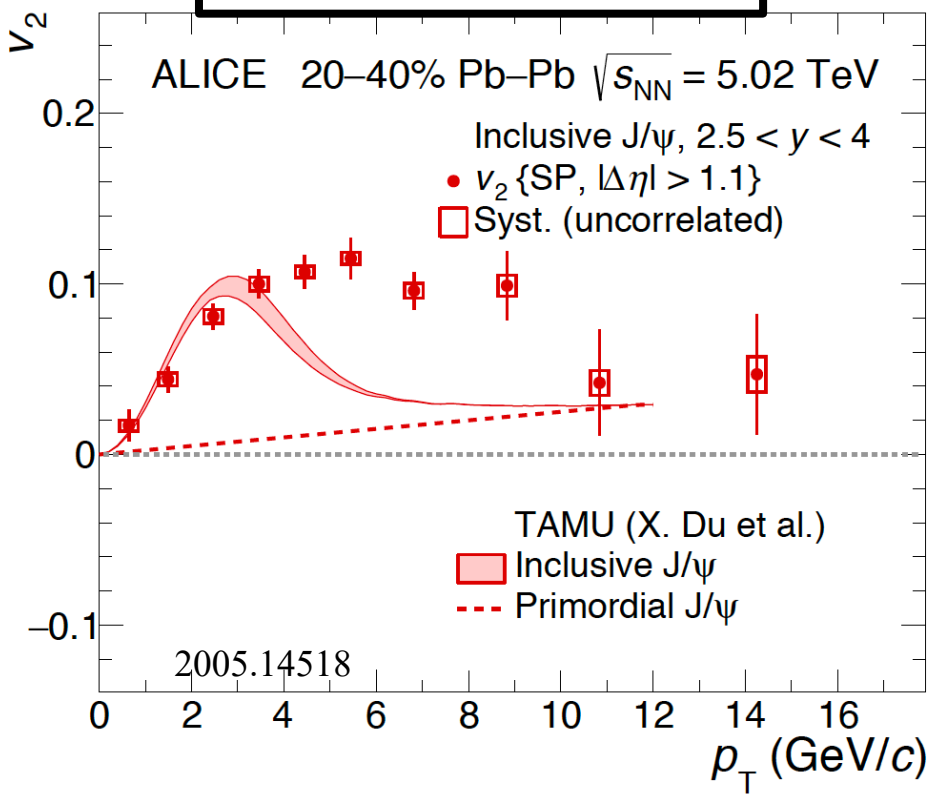


Florian Damas, Mon 1:35

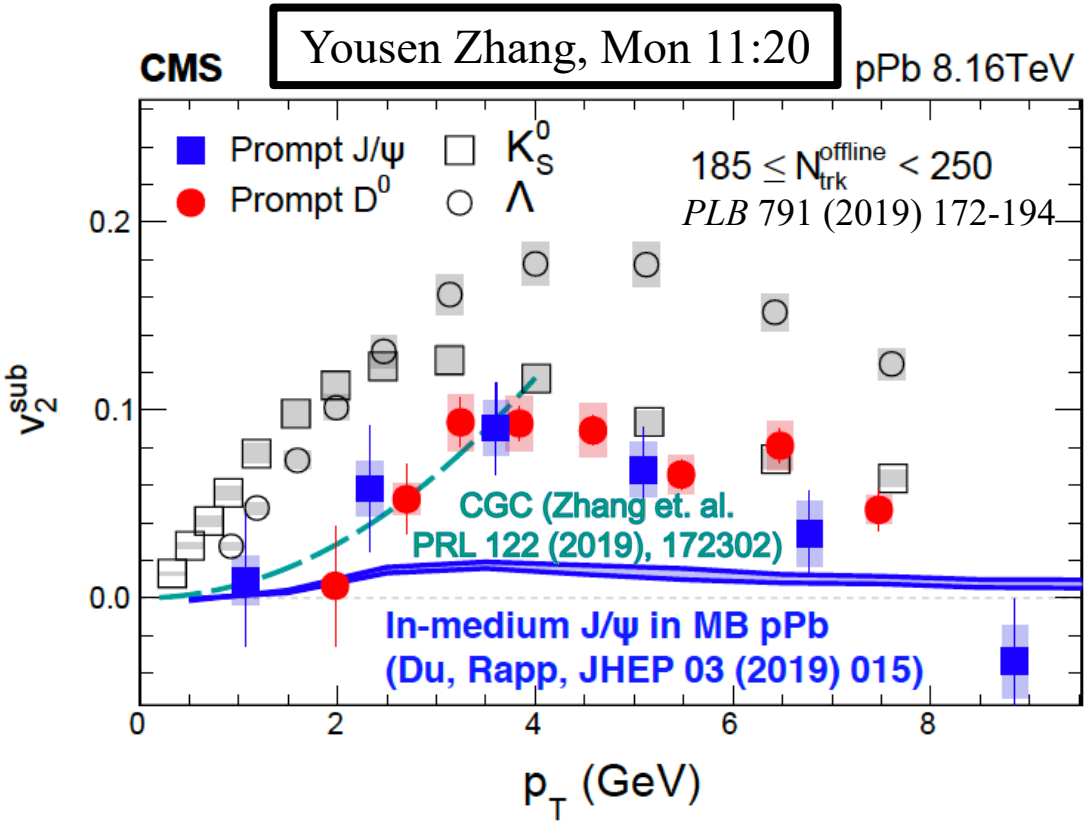


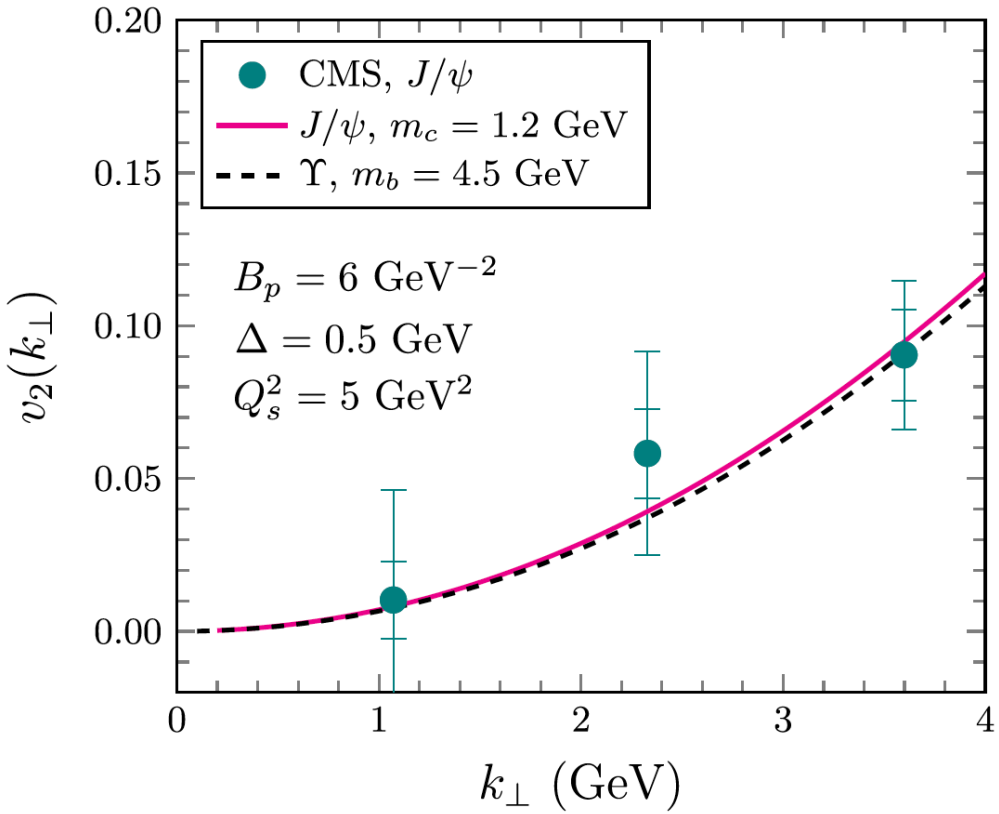
- Similar to PbPb; some differences observed at high pt, typically attributed to *L* dependent energy loss, not present in pPb
- **Transport model with short lived plasma phase in pPb does not give large v2 in pPb (does describe low pT PbPb)**
- **CGC calculation describes part of pPb v2; however CGC has mixed results describing light sector v2**

MAJOR OPEN QUESTION

J/ψ flow

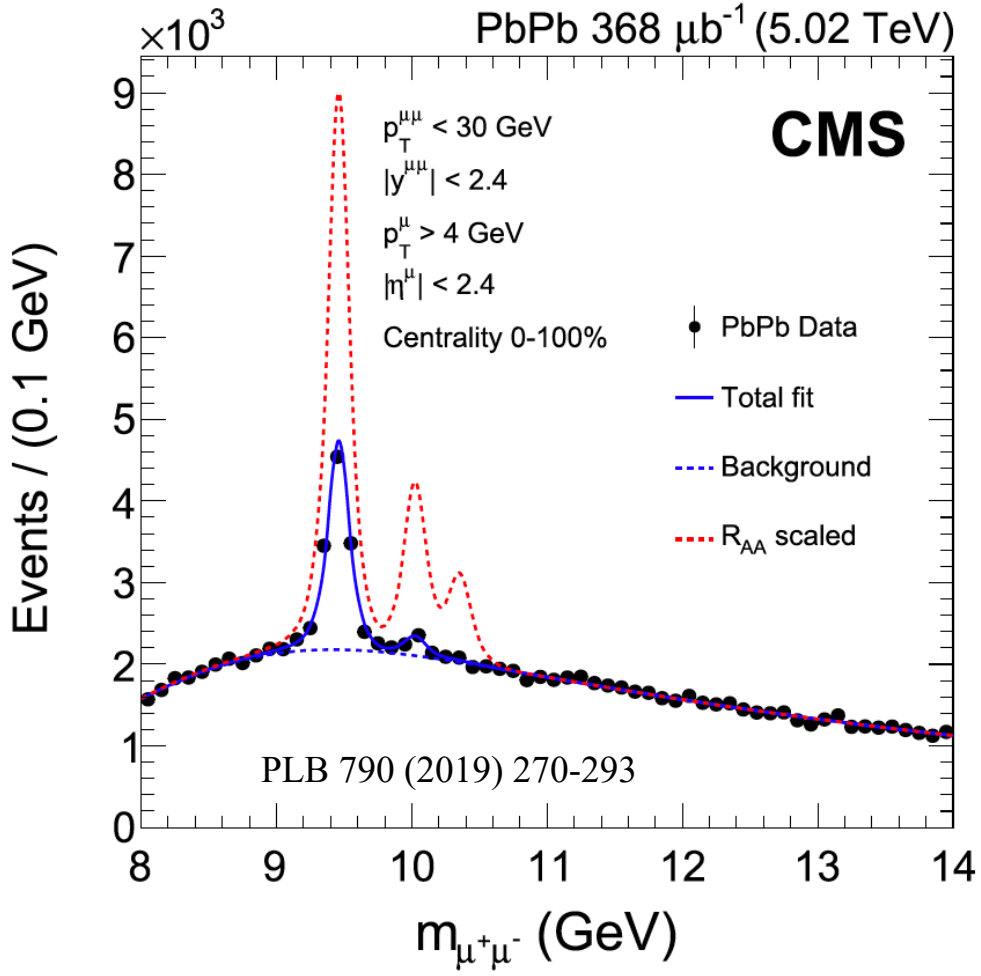
Data on J/ψ production is consistent with nPDF, however: Significant J/ψ v_2 observed in pPb collisions



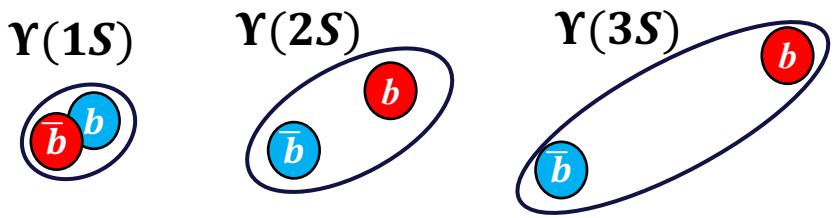


- **CGC calculation gives very similar v2 for Upsilon states on pPb: next challenge for experiments**

Υ(nS) in PbPb

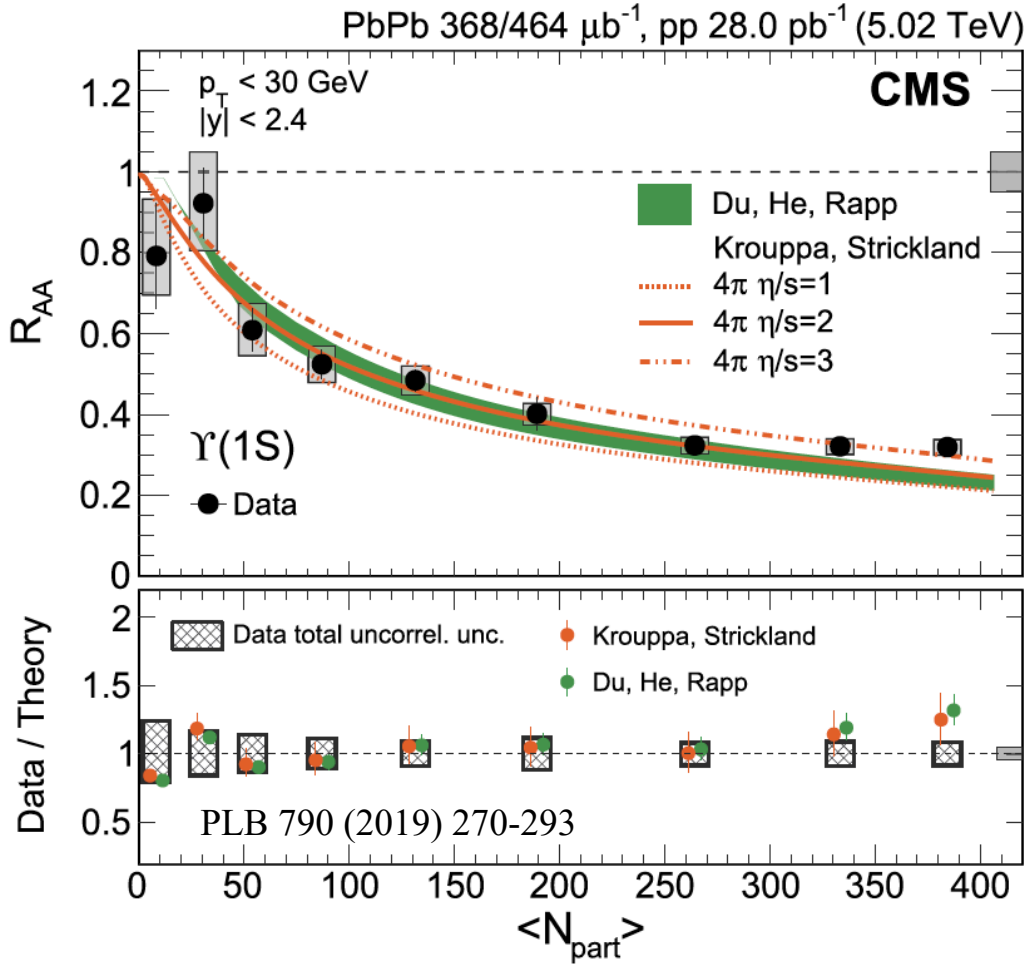


Textbook example of color screening

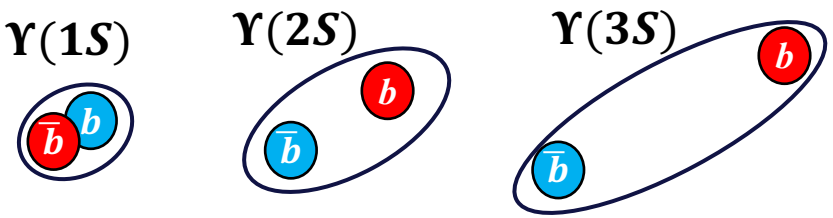


- Three well defined state observable in $\mu^+\mu^-$
- Bottom density relatively low – expect minimal effects from recombination

Υ(nS) in PbPb



Textbook example of color screening
Well described by models



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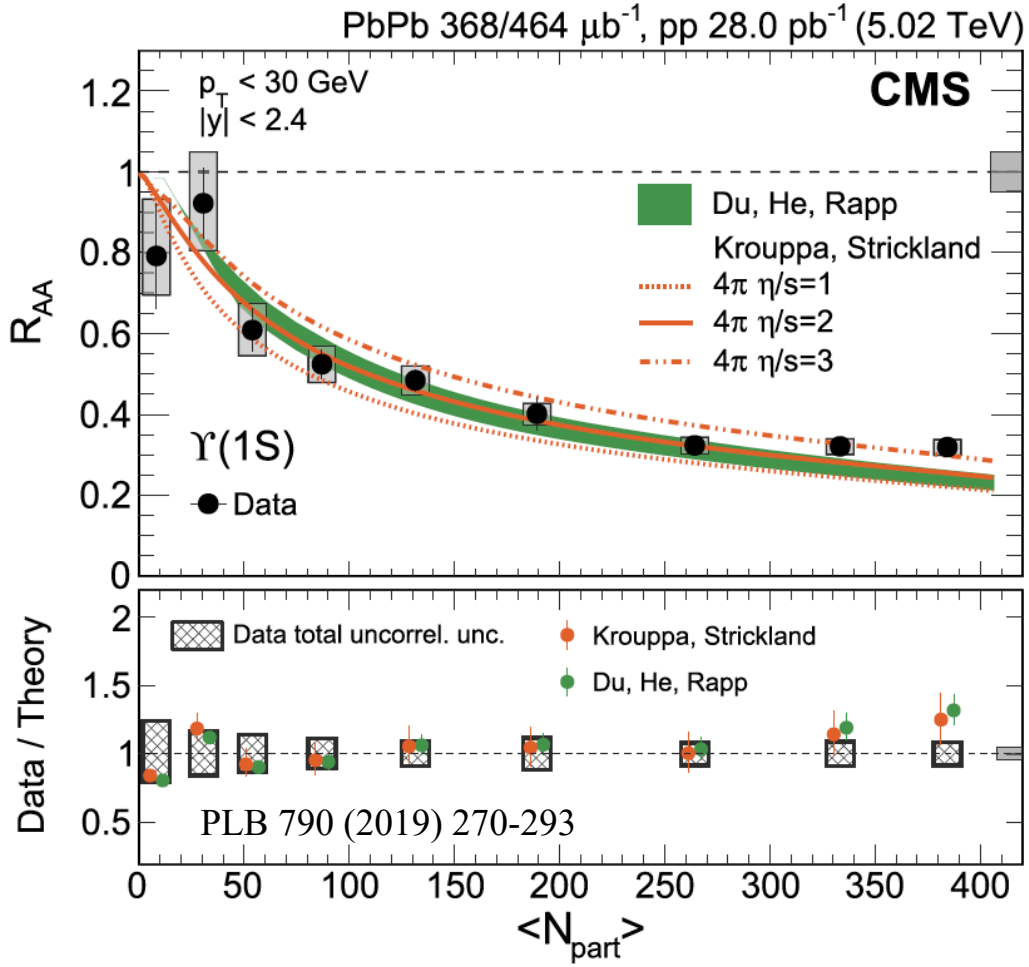
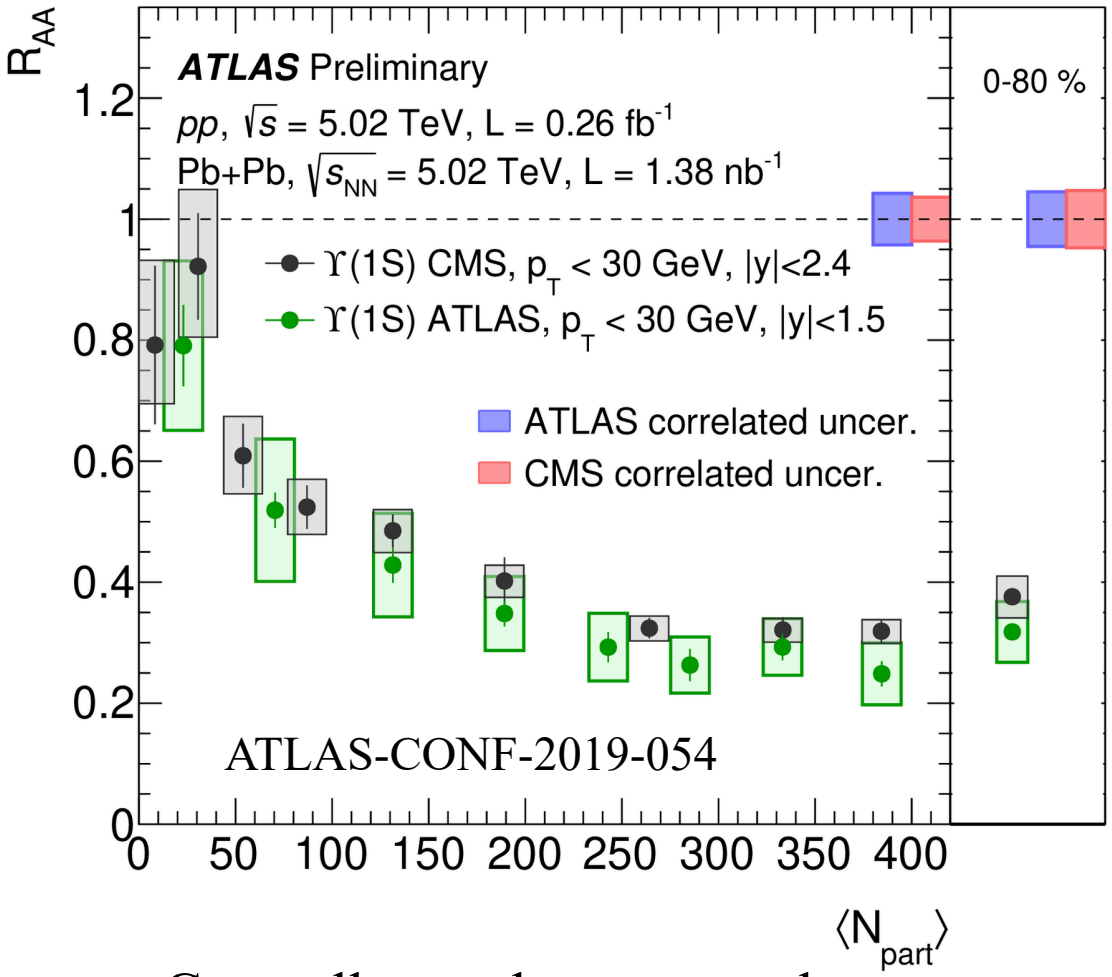


Textbook example of color screening
Well described by models

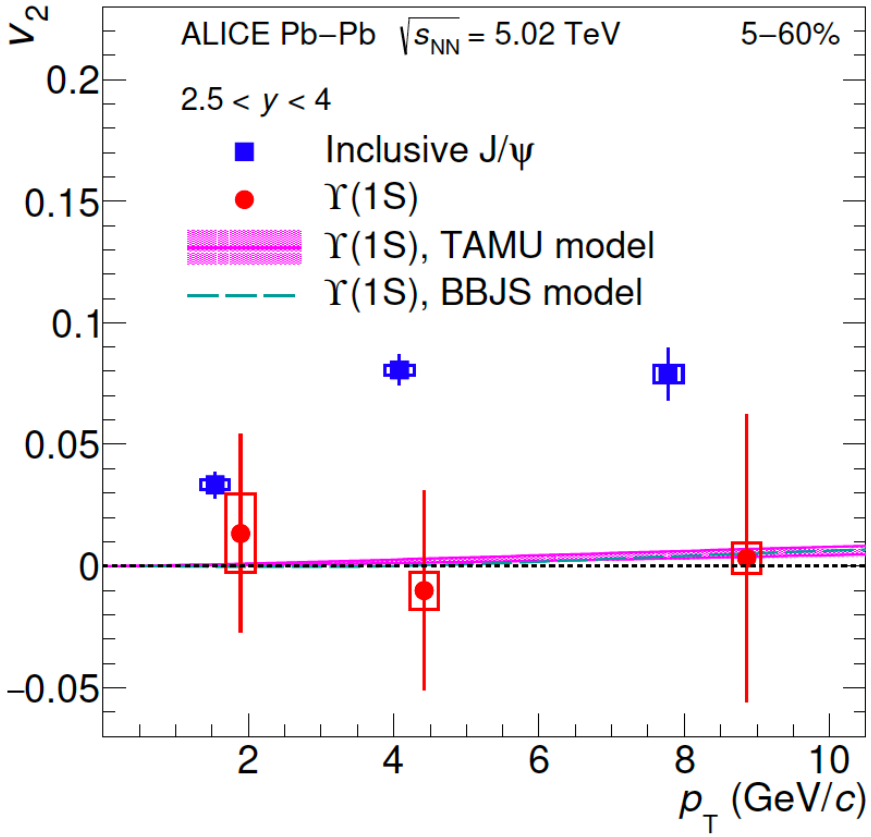
Songkyo Lee, Mon 1:15

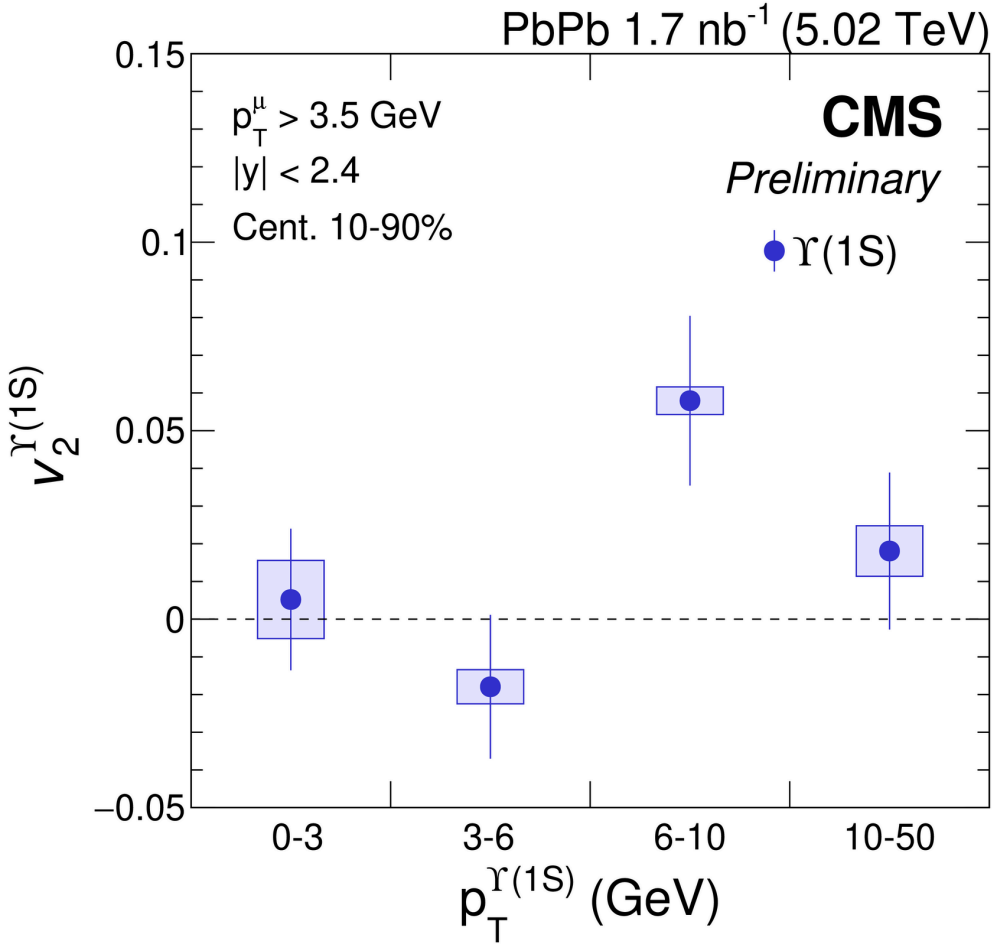


Generally good agreement between
ATLAS and CMS

$Q\bar{Q}$ flow in PbPb

ALICE PRL





In contrast to J/ψ, no significant v_2 is observed for Υ(1S) by ALICE or CMS.
Little or no recombination due to relative low *b* density in QGP, as expected from models.

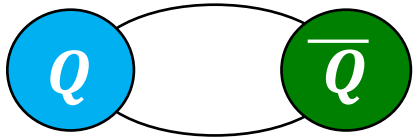
Outline

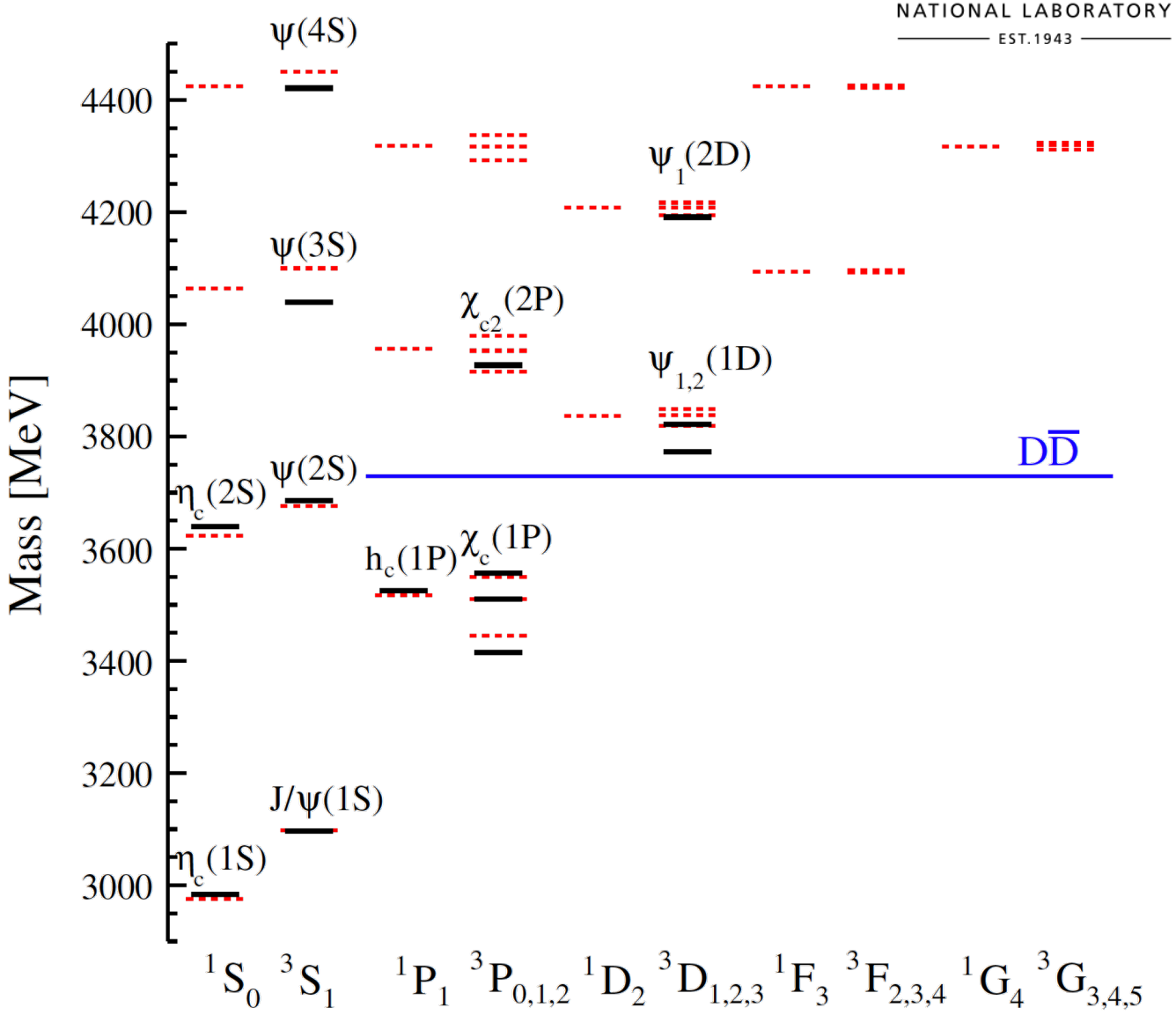
- Introduction
- $Q\bar{Q}$ in Small Systems → Large Systems
  - Focus on medium interactions
- Exotic hadrons containing $Q\bar{Q}$
  - X(3872) in the QCD medium
- Brief look to the future

Hard Probes 1-9: 0 talks devoted to X(3872)

Hard Probes 10: 4 talks! 2 experiment, 2 theory

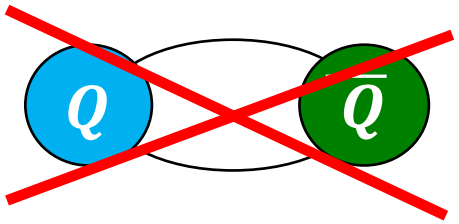
Exotic $Q\bar{Q}$ states: XYZ





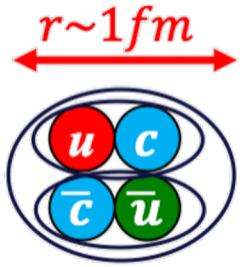
Rev. Mod. Phys. 90, 015003 (2018)

Exotic $Q\bar{Q}$ states: XYZ

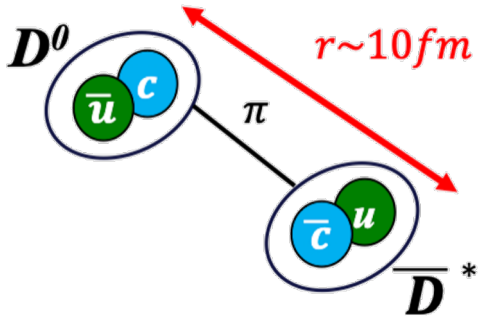


Dozens of states containing $c\bar{c}$ and $b\bar{b}$ have been discovered that are not predicted by any $Q\bar{Q}$ potential model

Compact tetraquark

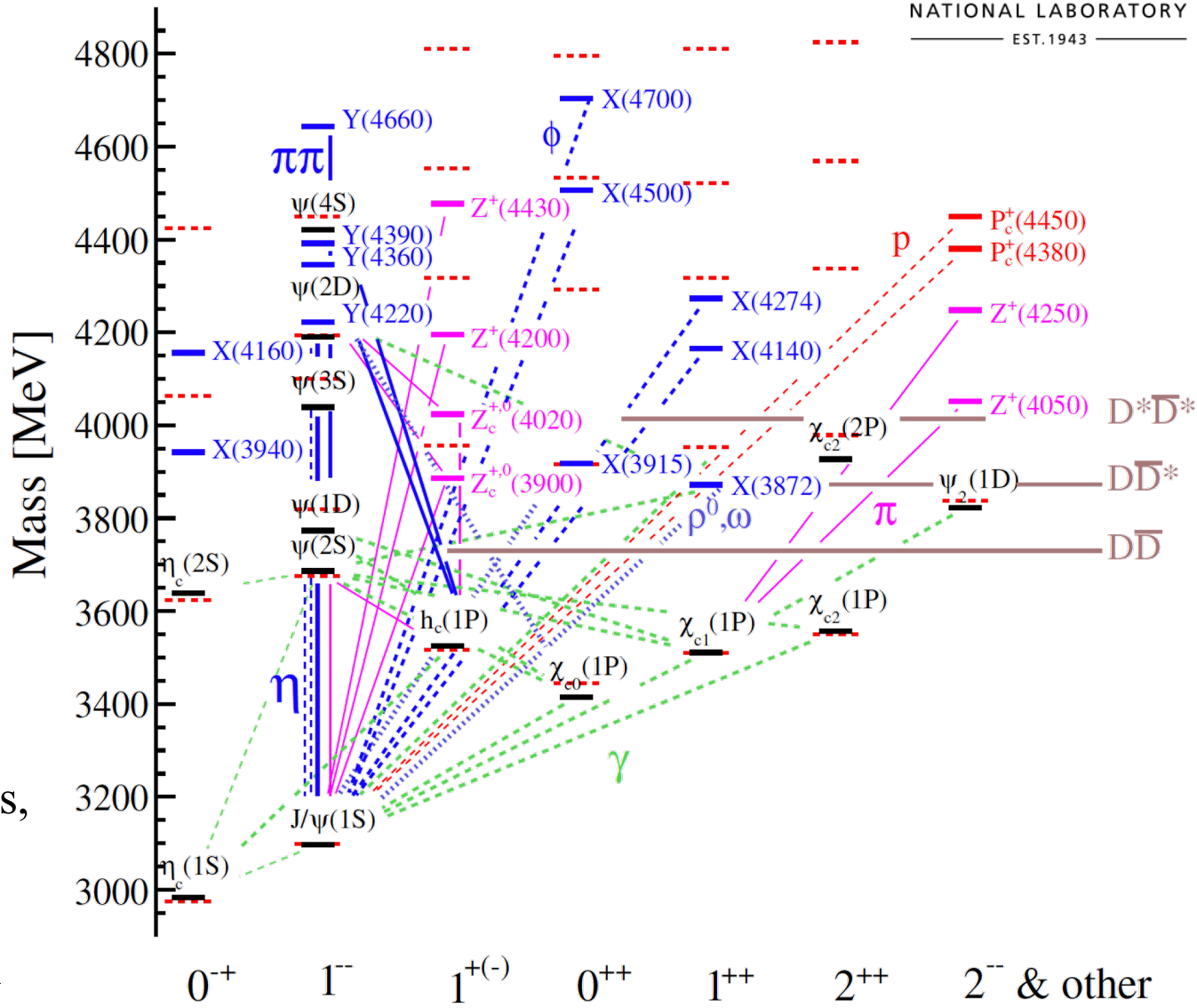


Hadronic molecule



Thousands of theory papers exploring possible structures, but no consensus on even the first exotic, X(3872)

Primarily measured as products of b decays in vacuum



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

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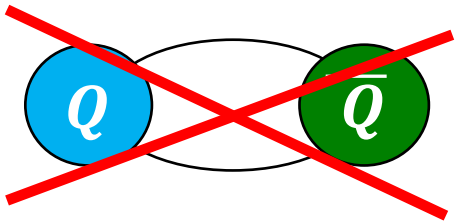

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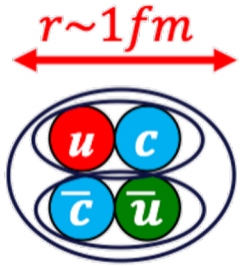
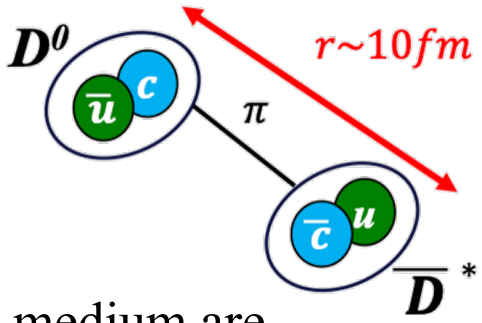


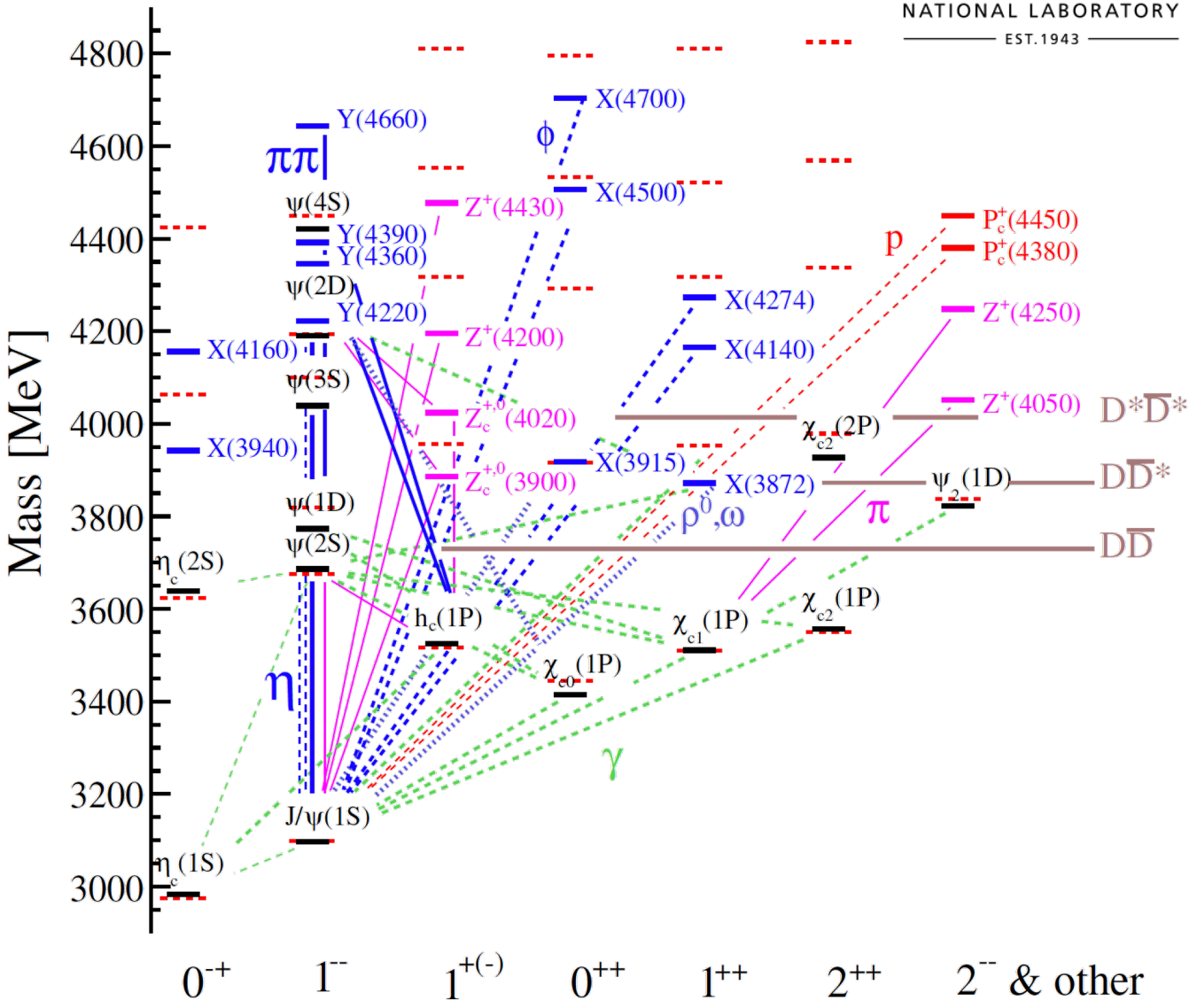
Hadronic molecule



Interactions in QCD medium are dependent on binding energy/structure

⇕

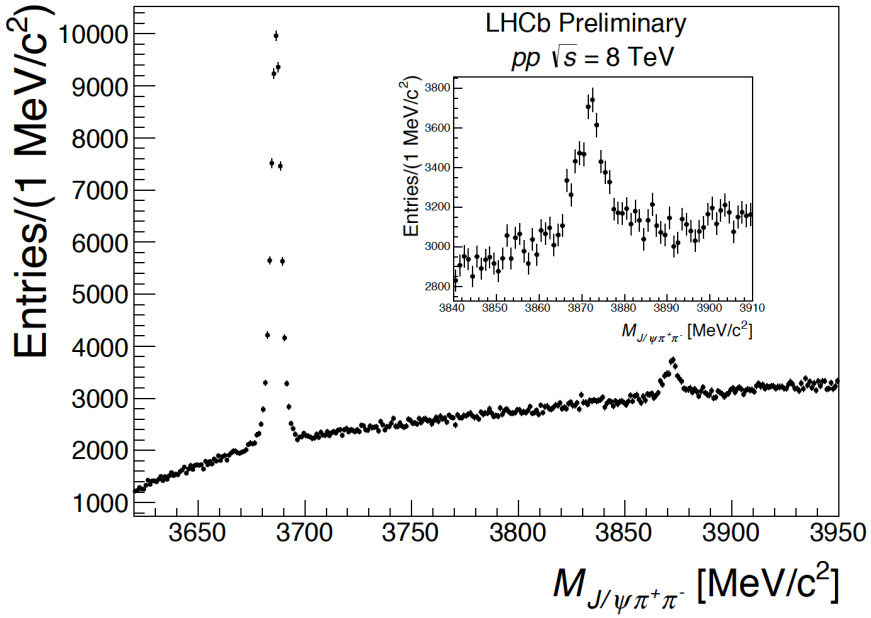
Production of multiquark exotics is especially sensitive to recombination/coalescence effects that are expected in heavy ion collisions

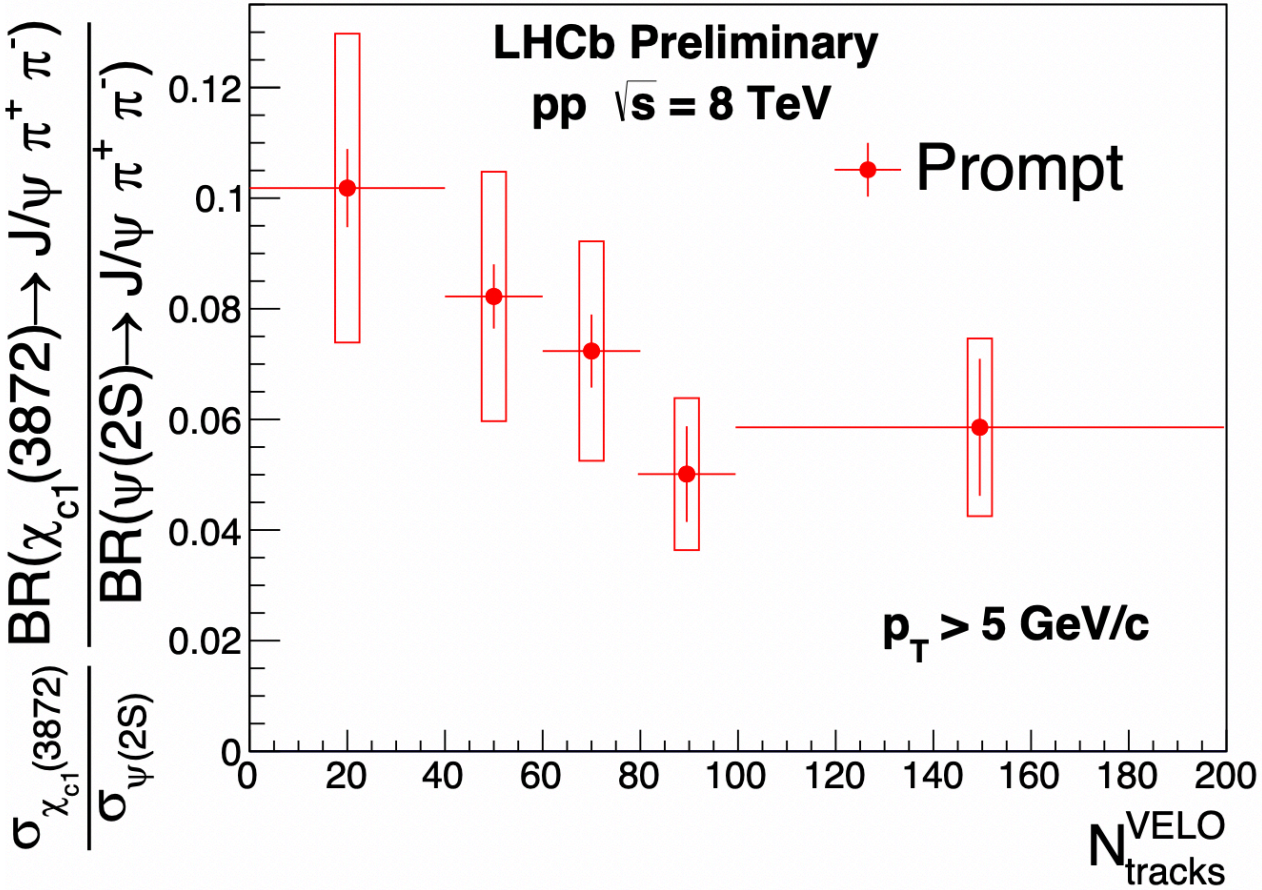


Rev. Mod. Phys. 90, 015003 (2018)

Exotic X(3872) in diffuse medium (8 TeV *pp*)

LHCb-CONF-2019-005





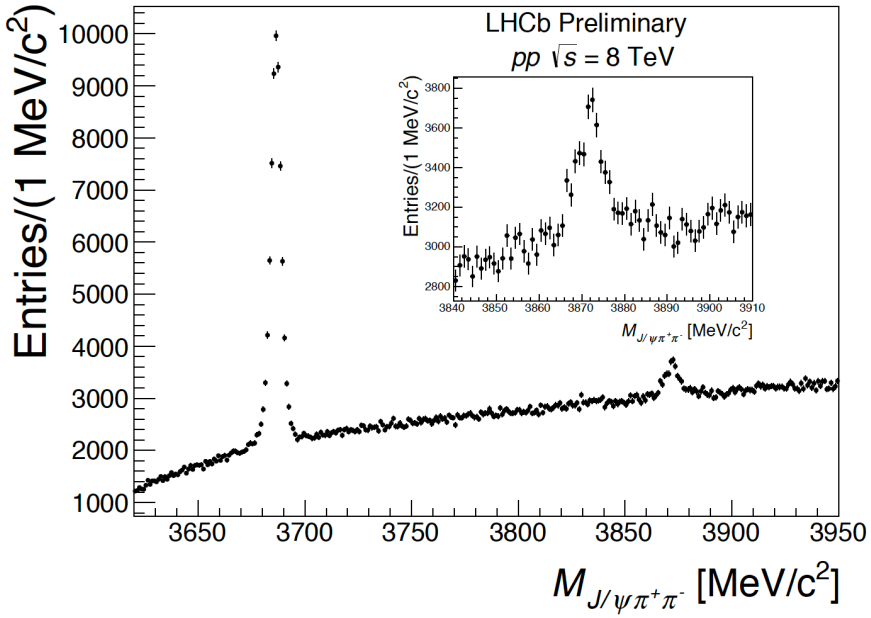
- Prompt X(3872)/ ψ(2S) decreases with activity
  - X(3872) suppressed more than ψ(2S)

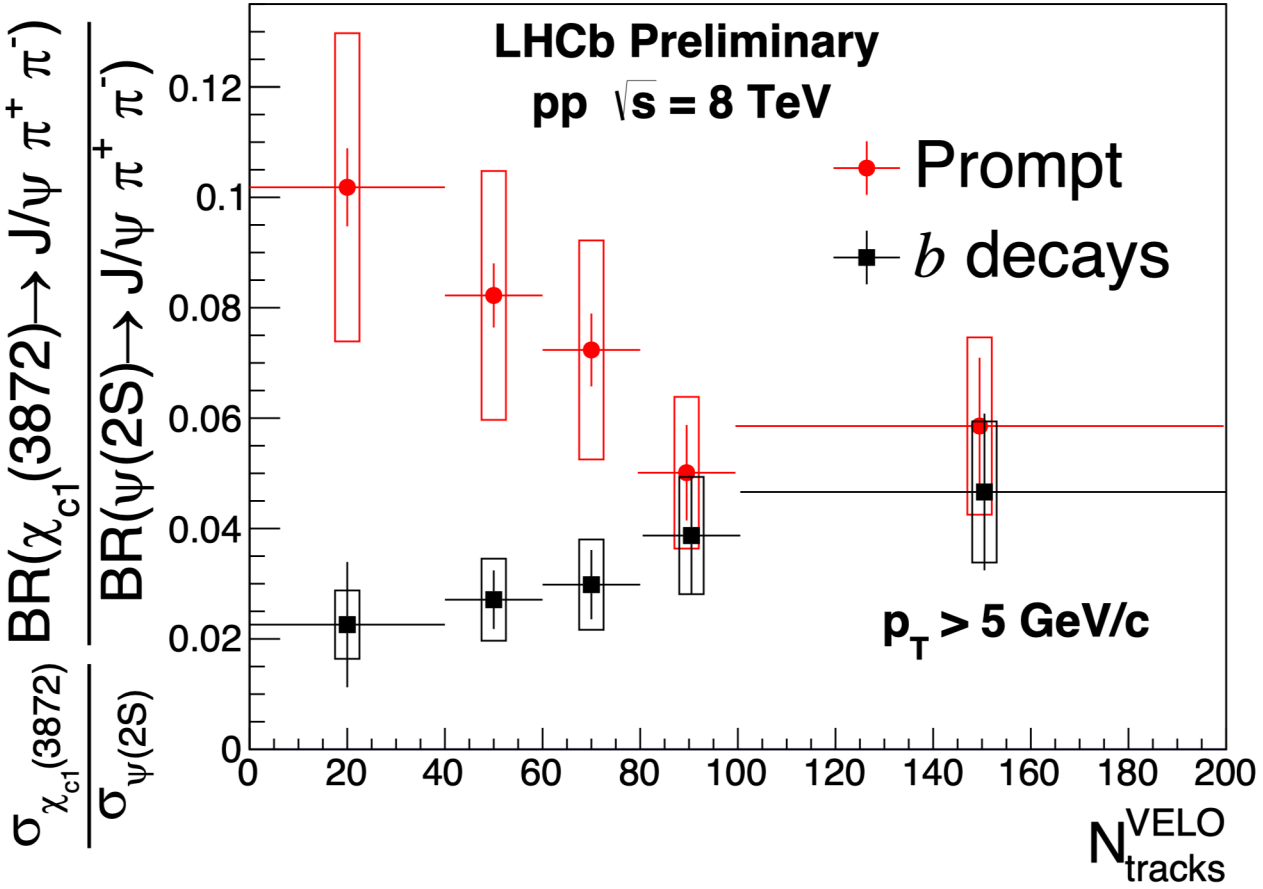
Systematic uncertainty box fully correlated point-to-point

Cameron Dean, Wed 12:25

Exotic X(3872) in diffuse medium (8 TeV *pp*)

LHCb-CONF-2019-005





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- *B*-decay component consistent with constant
  - Production in vacuum unaffected

Cameron Dean, Wed 12:25

Systematic uncertainty box fully correlated point-to-point

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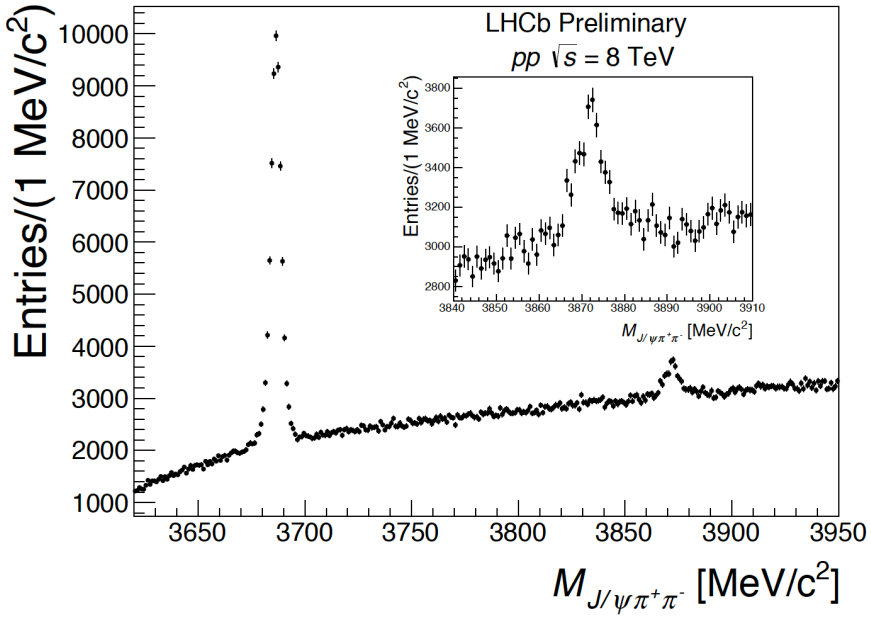
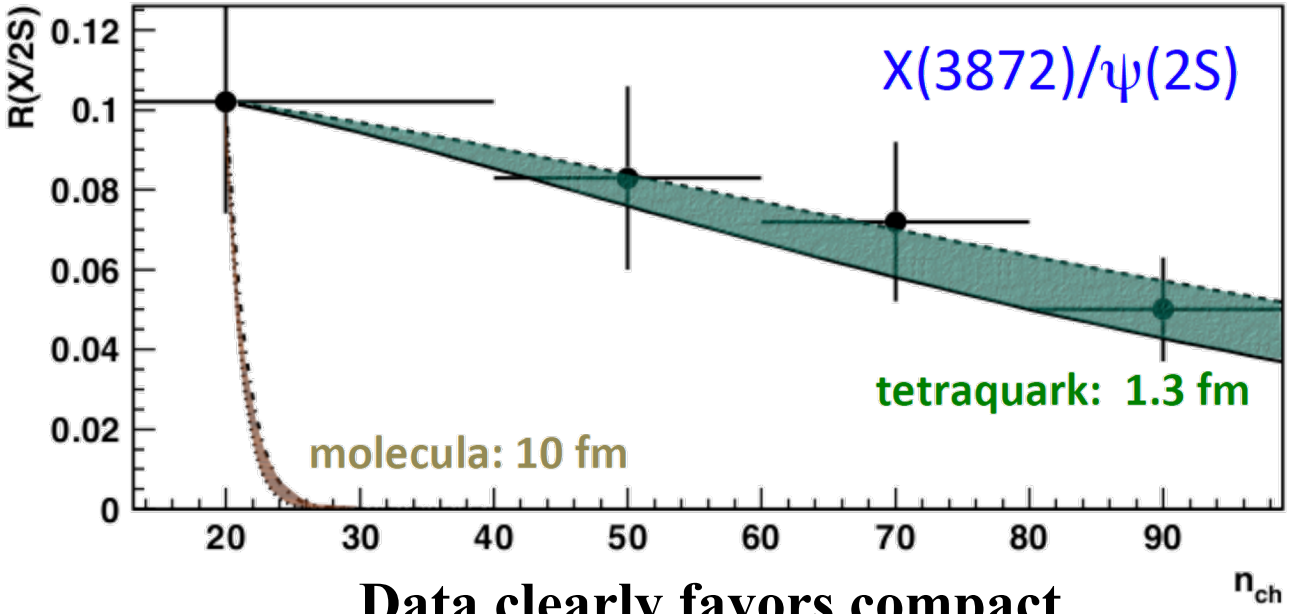
LHCb-CONF-2019-005



$$\sigma^{\mathrm{co}-\mathcal{Q}}(E^{\mathrm{co}}) = \sigma^{\mathcal{Q}}_{\mathrm{geo}} \times \left(1 - \frac{E^{\mathcal{Q}}_{\mathrm{thr}}}{E^{\mathrm{co}}}\right)^{n}$$

Directly probes size σ_{geom} and binding energy



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  - Production in vacuum unaffected

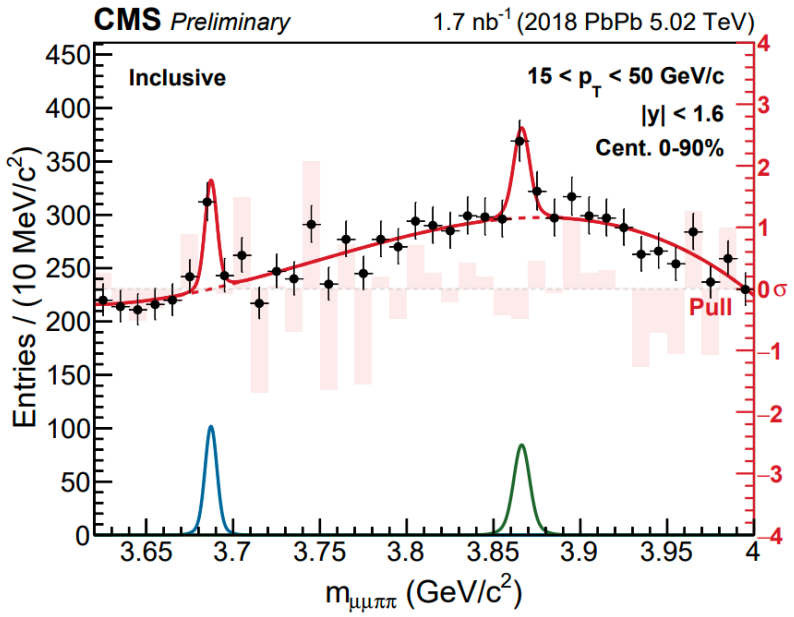
Cameron Dean, Wed 12:25

Data clearly favors compact tetraquark interpretation

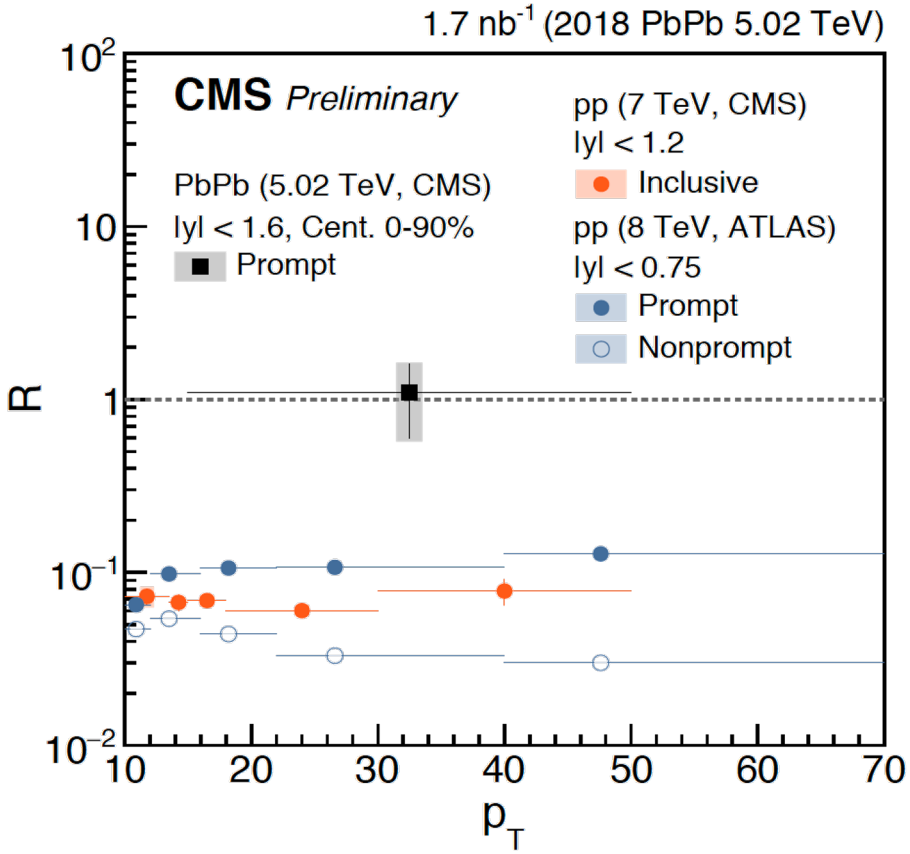
Elena Ferreiro, Wed 1:05

Exotic X(3872) in dense medium (PbPb)

CMS-PAS-HIN-19-005



Jing Wang, Wed 12:45



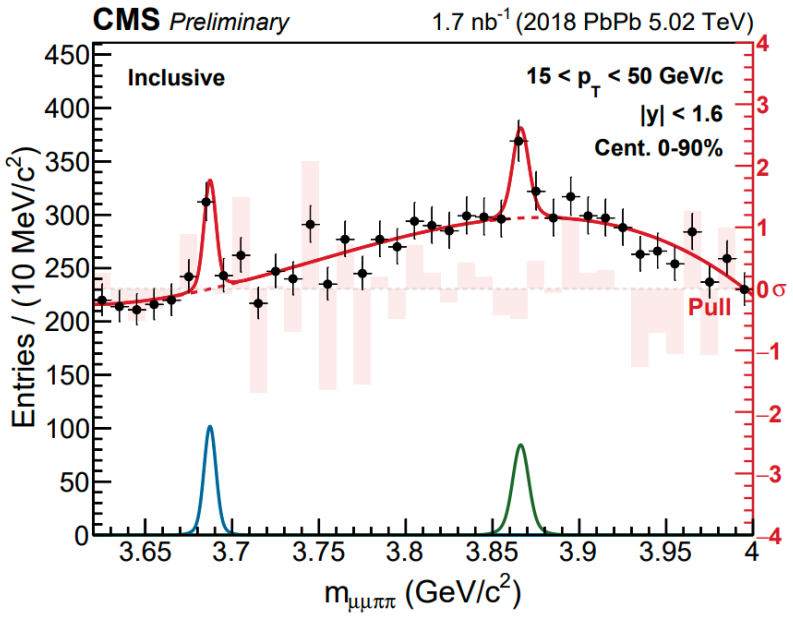
Recombination of X(3872) at pT > 15 GeV?

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

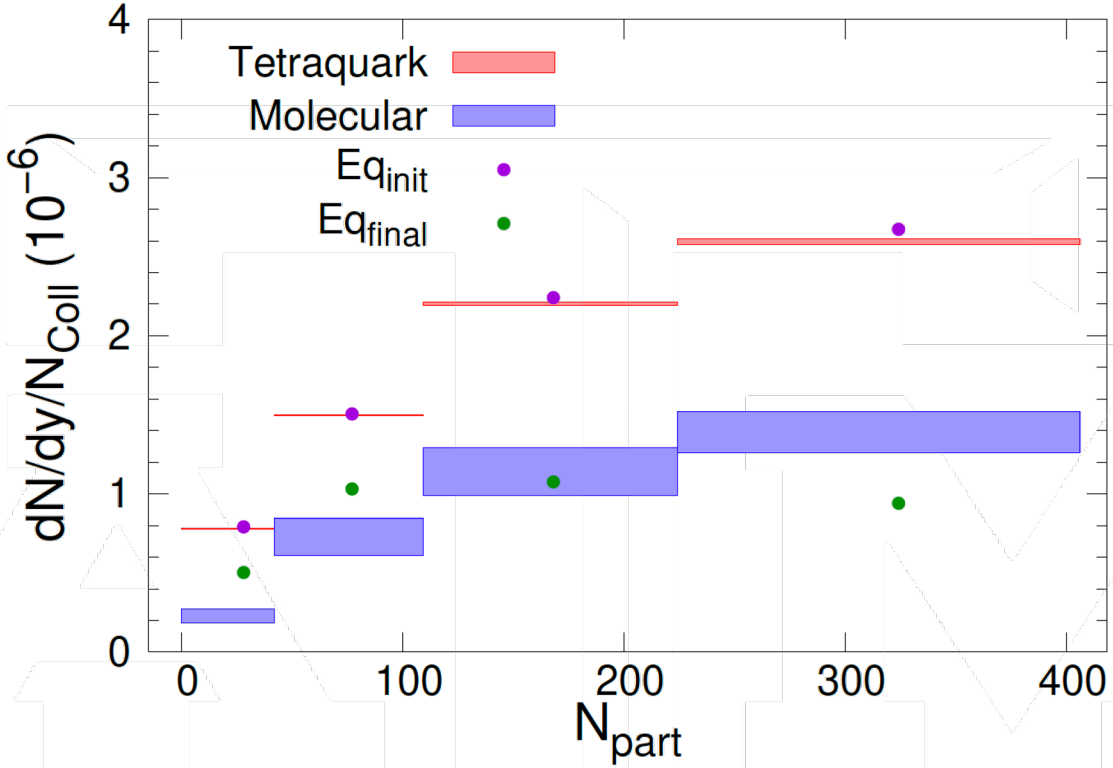
Exotic X(3872) in dense medium (PbPb)

CMS-PAS-HIN-19-005



Jing Wang, Wed 12:45

Biaogang Wu, Wed 1:25



Transport model gives larger yield for compact tetraquark vs. molecule by factor of ~2 in PbPb

Will be tested with future PbPb data sets.

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

Intriguing data! Inconclusive with these uncertainties.

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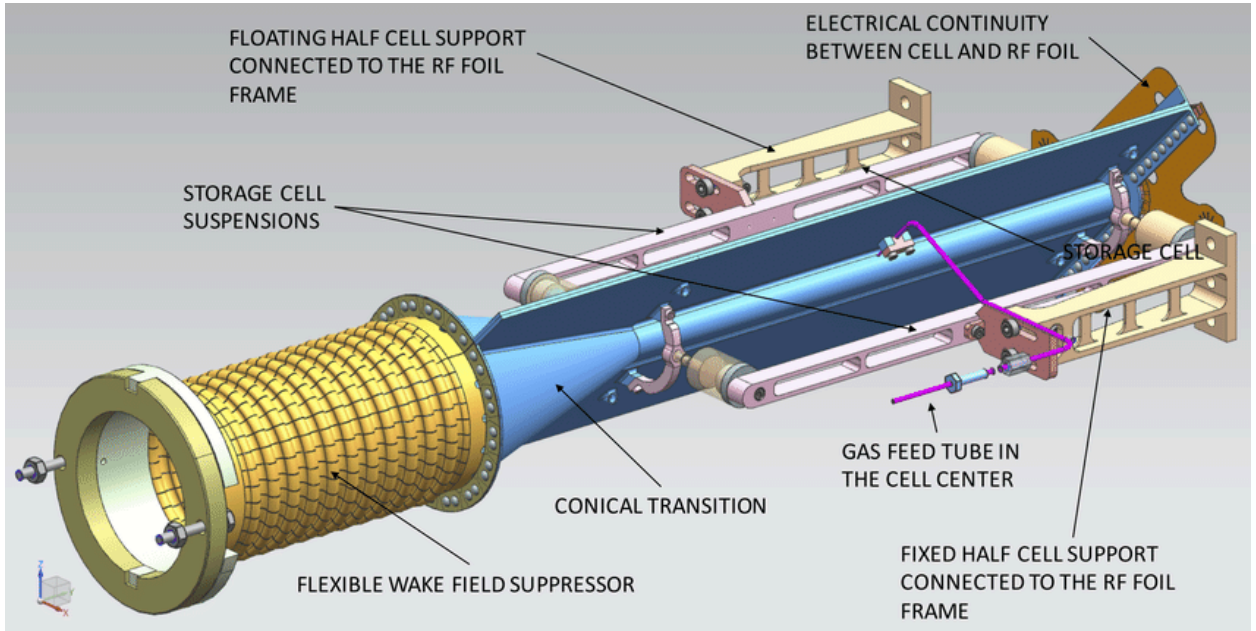
Fixed target at LHCb: SMOG II



https://cds.cern.ch/record/2673690/files/LHCB-TDR-020.pdf

Upgraded SMOG system at LHCb allows greatly increased rates of beam+injected gas collisions

No centrality limitations in p+gas or Pb+gas at LHCb

Barbara Trzeciak (AFTER physics program), Wed 1:55

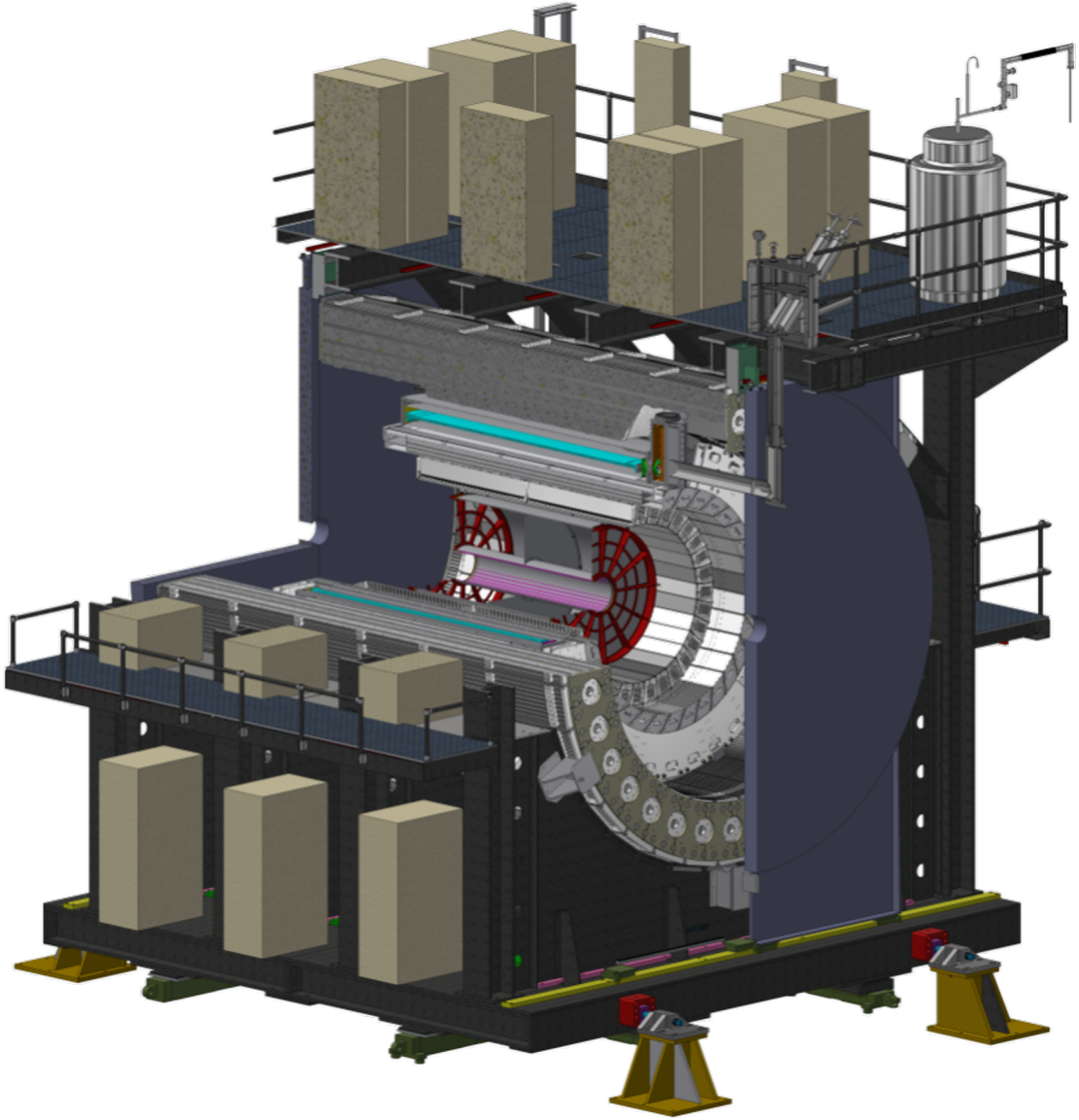
Samuel Belin (Future of LHCb), Thurs 10:55

Example SMOG2 pAr at 115 GeV for one year

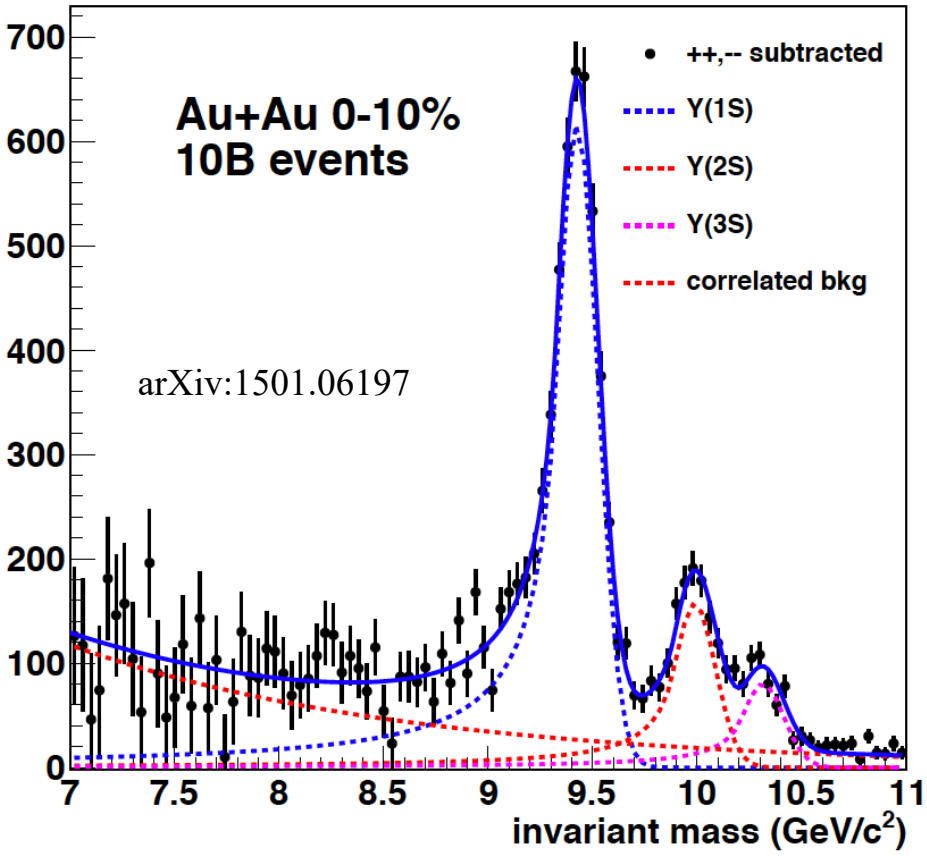
Int. Lumi.		80 pb^{-1}
Sys.error of J/Ψ xsection		~3%
J/Ψ	yield	28 M
D^0	yield	280 M
Λ_c	yield	2.8 M
Ψ'	yield	280 k
$\Upsilon(1S)$	yield	24 k
$DY\ \mu^+\mu^-$	yield	24 k

Large heavy flavor samples
Access to exotic states near RHIC energies

New detector at RHIC: sPHENIX

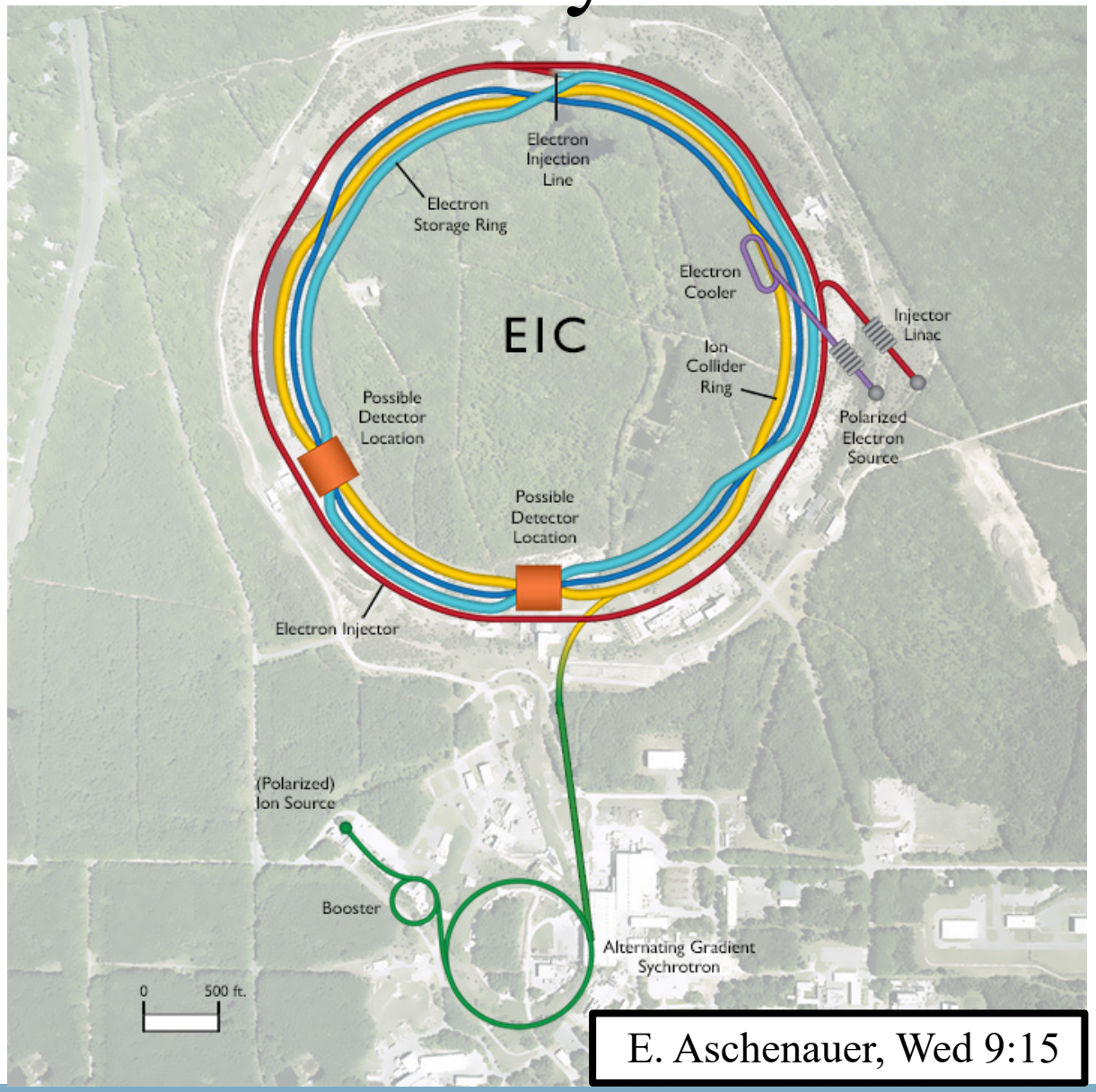


Rosi Reed, Fri 8:00



Precision bottomonium measurements at RHIC are a major focus of sPHENIX

Future facility: electron-ion collider



E. Aschenauer, Wed 9:15

EIC site selection at BNL announced Jan 2020

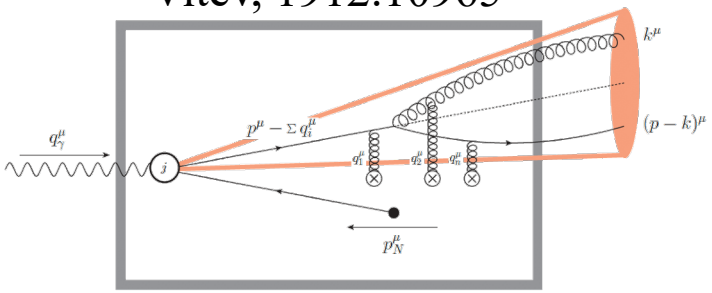
Charm production inside the nucleus probes:

- Parton structure of nucleons
- nPDF modifications
- QCD energy loss

Xuan Li, Thurs 10:35

In the kinematic range accessed by the EIC, hadronization ***inside the nucleus*** becomes an important effect on observables

Vitev, 1912.10965



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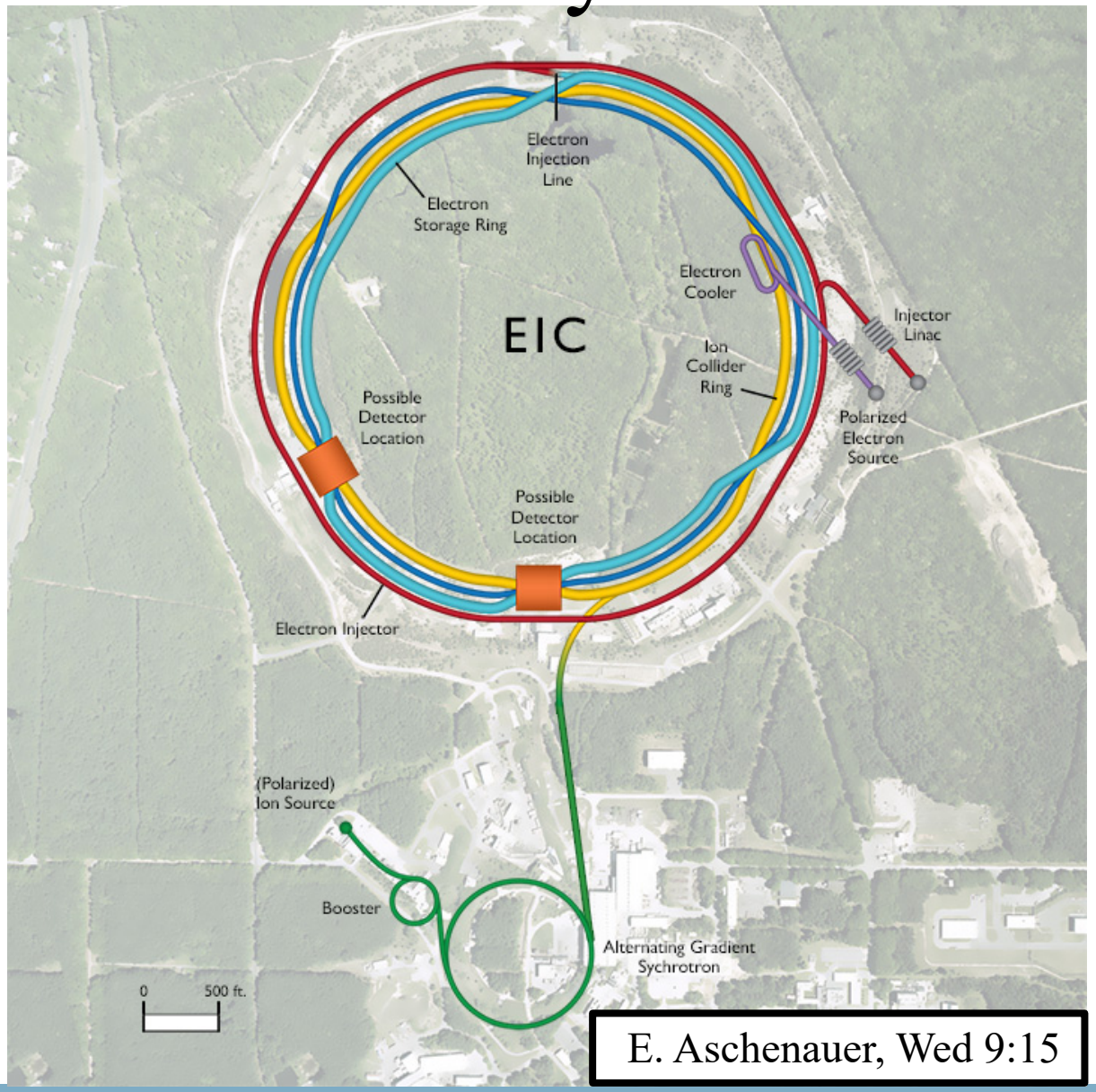


E. Aschenauer, Wed 9:15

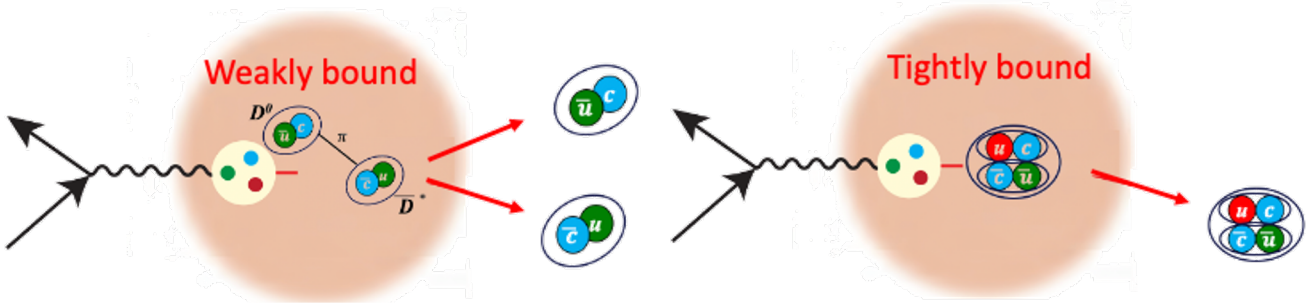
EIC site selection at BNL announced Jan 2020

Charm production inside the nucleus probes:

- Parton structure of nucleons
- nPDF modifications
- QCD energy loss

Xuan Li, Thurs 10:35

e+A collisions have relatively low backgrounds – well suited for studies of higher charmonia and exotics: $P_c^+, Z_c^+, \chi_c, \ldots$



Summary

- Quarkonia remains a major focus of heavy ion physics 34 years after Matsui and Satz
  - Contributions from all experimental collaborations – a wealth of data
  - Strong synergy with theory community

- The lines between small and large systems are continually becoming blurred
  - Final state suppression manifests in many systems at high multiplicity
  - Universal understanding of J/ψ flow from small to large systems remains elusive

- Exotic multiquark states are becoming accessible in a QCD medium
  - Medium probes exotic properties ⇔ Exotics probe medium properties

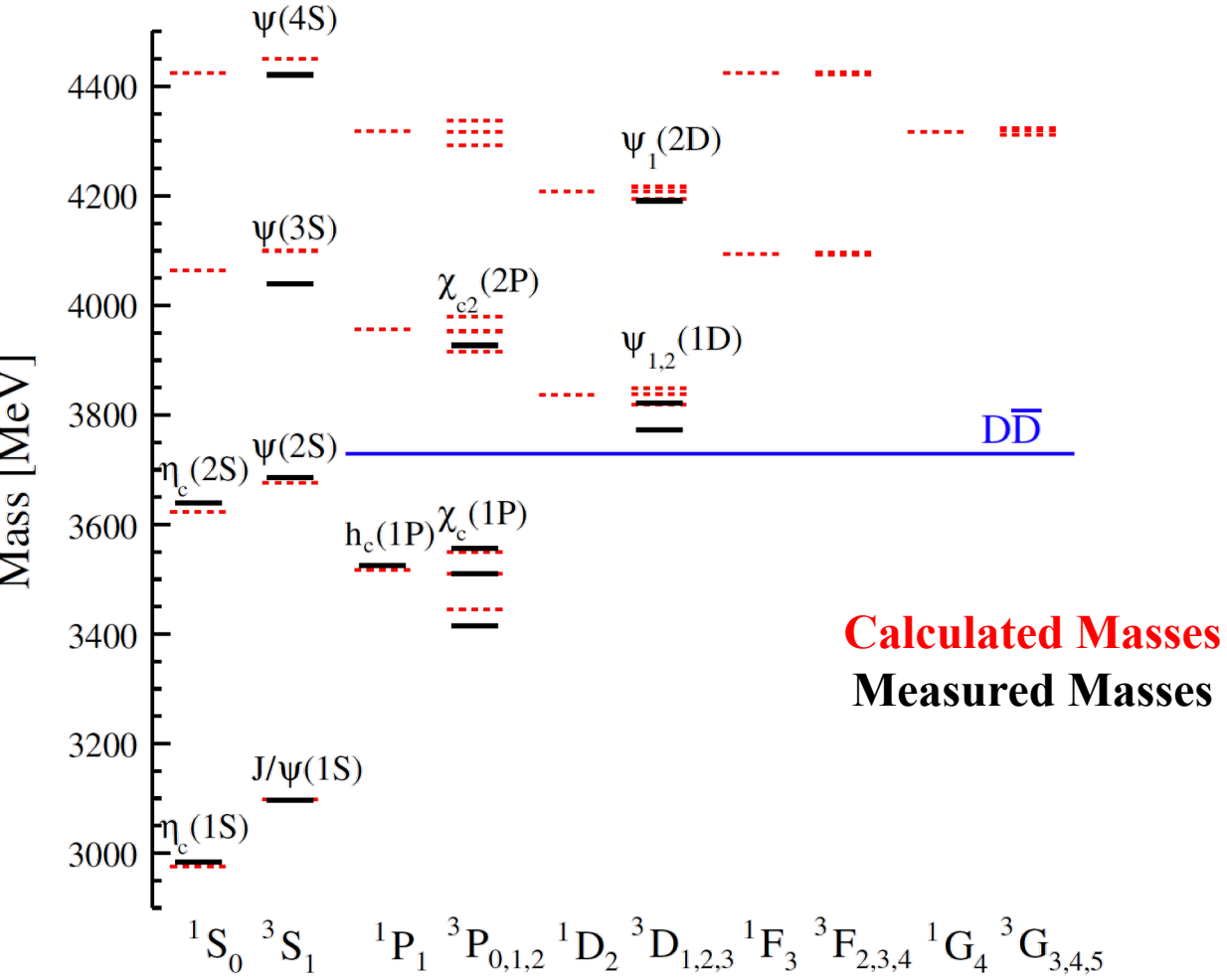
- Exciting future programs of in-medium quarkonia studies at LHC/RHIC/EIC to come

Los Alamos is supported by the US Dept. of Energy/Office of Science/Office of Nuclear Physics

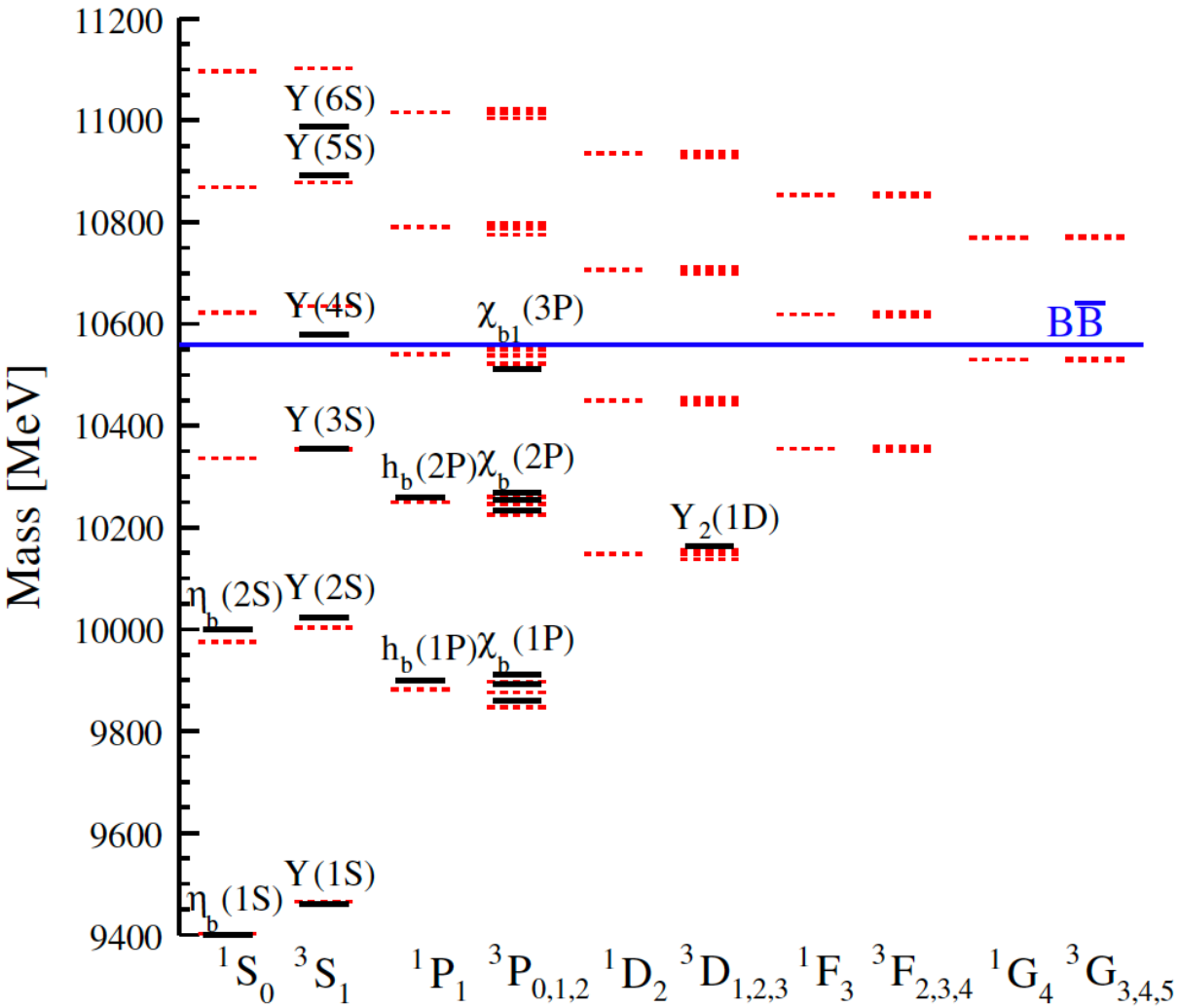
BACKUPS

We have only measured 2 charmonium states in heavy ion collisions at LHC.

We have only measured 3 bottomonium states in heavy ion collisions at LHC.



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



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 (q q q), (q q q q $\bar{q}$), etc., while mesons are made out of (q $\bar{q}$), (q q $\bar{q}$ $\bar{q}$), etc. It is assuming that the lowest baryon configuration (q q q) 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

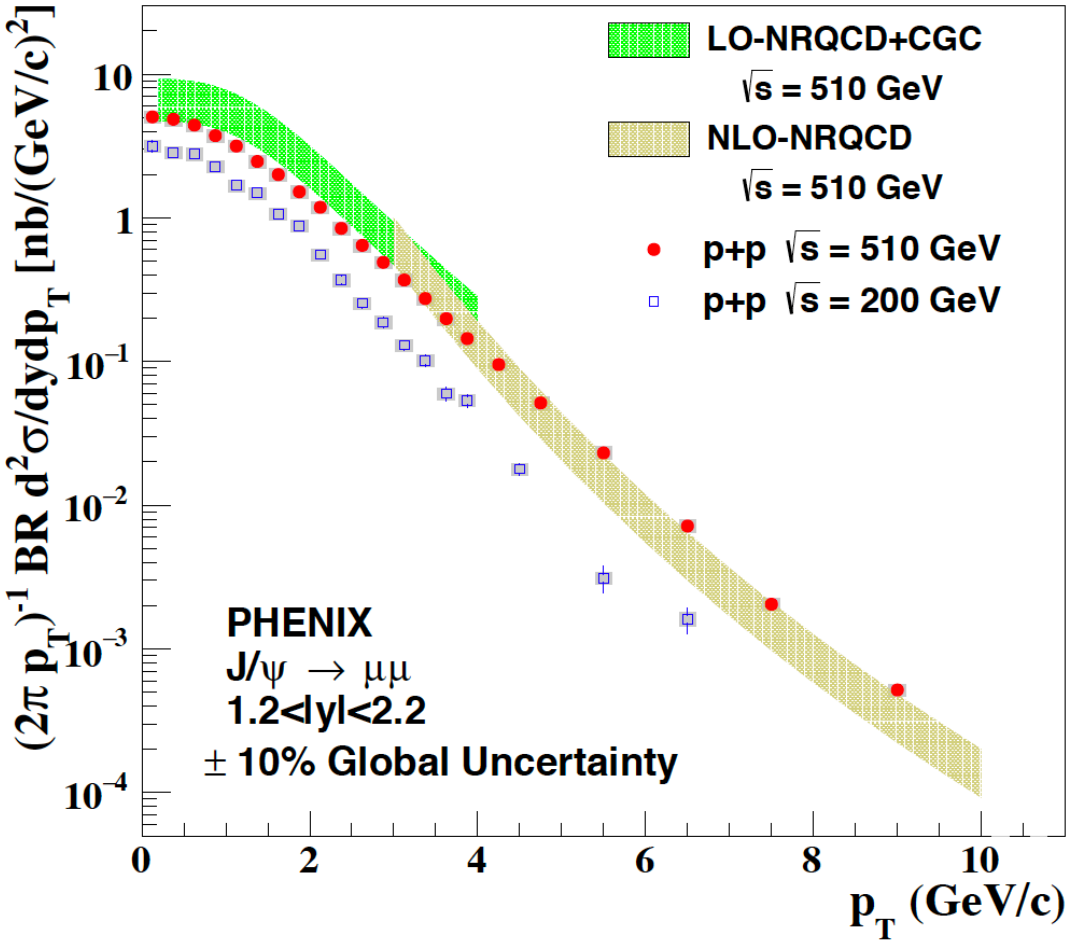
8182/TH.401
17 January 1964

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".

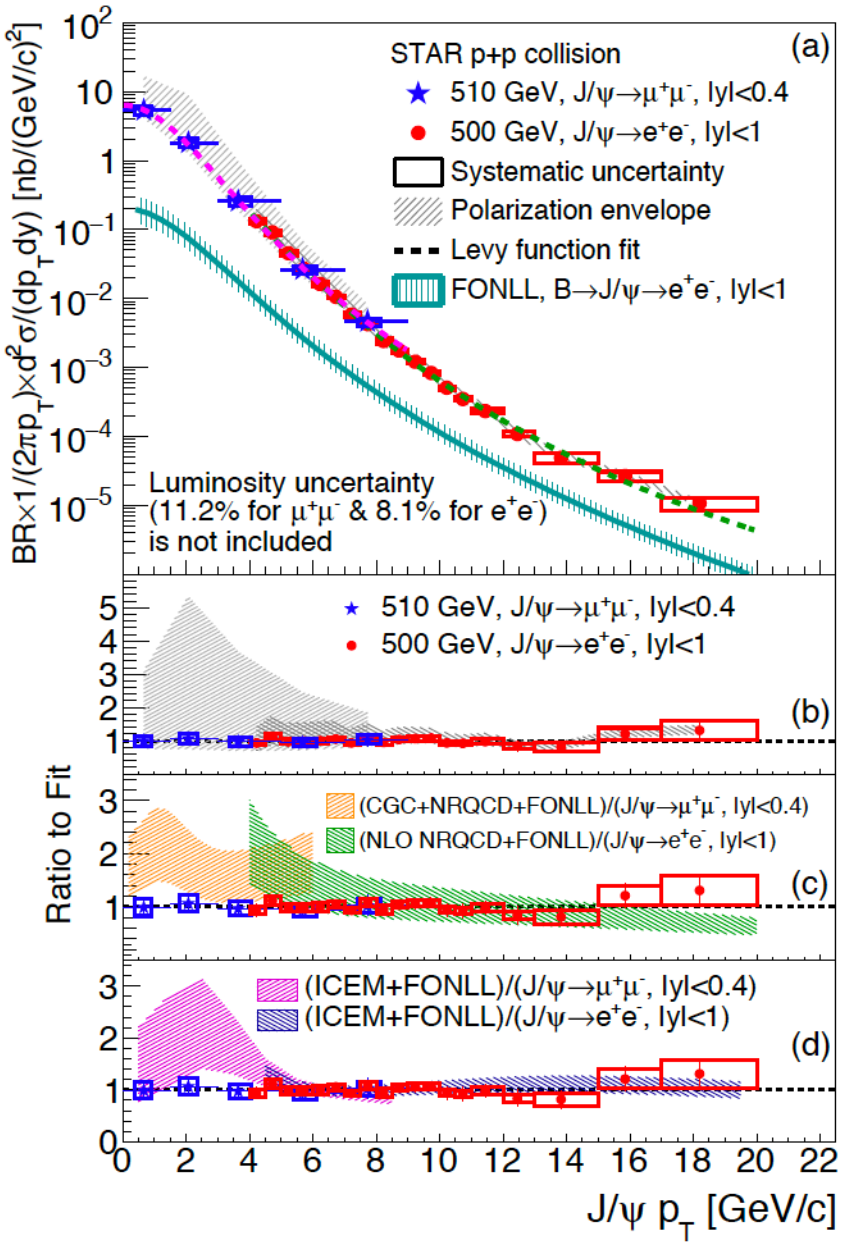
States with >3 quarks have been expected since the beginning of the quark model

Charmonium in *pp* - RHIC

PHENIX: PRD 101 (2020) 5, 052006



Agreement with calculations across entire p_T range



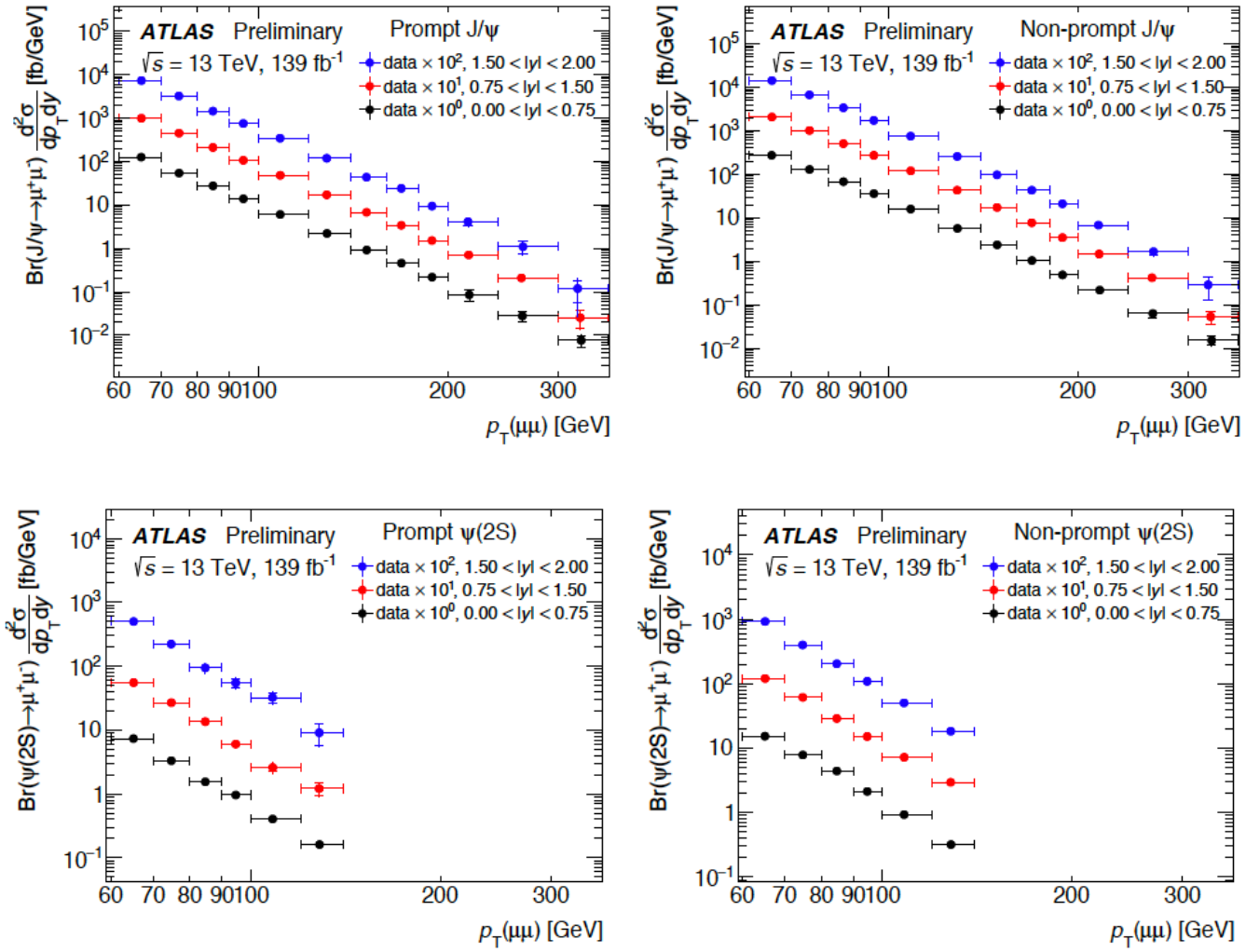
STAR, *PRD* 100 (2019) 5, 052009

Charmonium in *pp* - LHC

ATLAS-CONF-2019-047

Preliminary result from ATLAS:

J/ψ measured up to 360 GeV
ψ(2S) measured up to 140 GeV



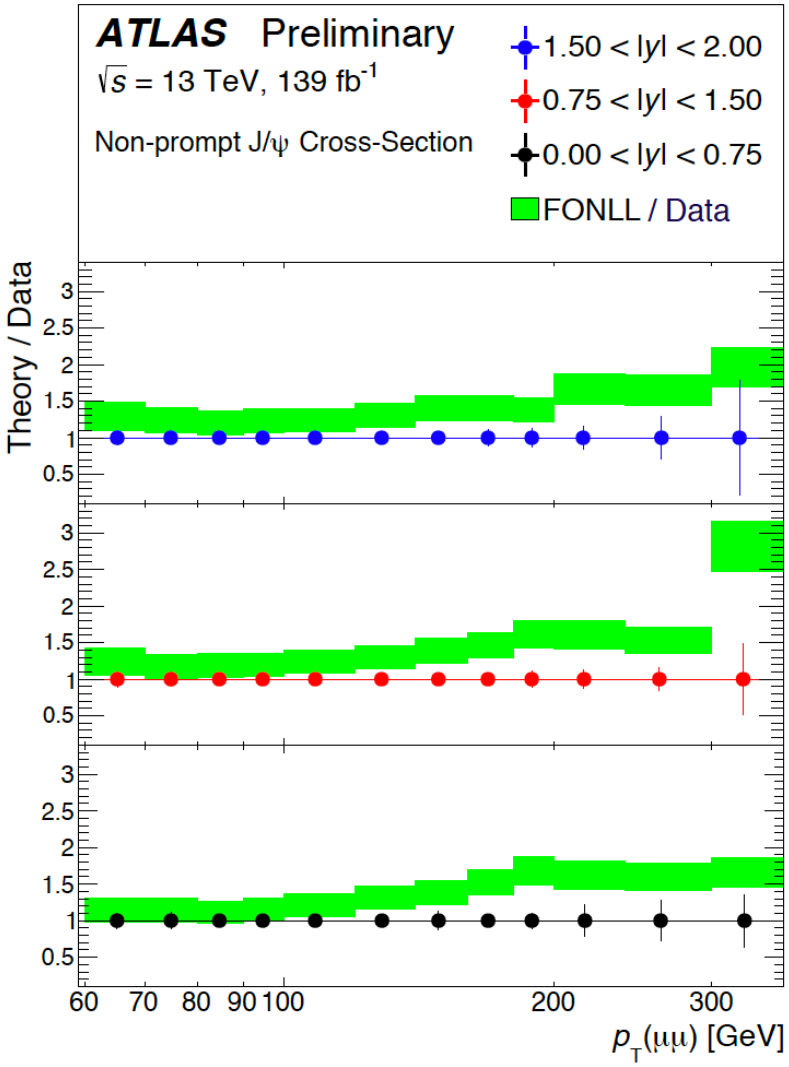
Charmonium in *pp* - LHC

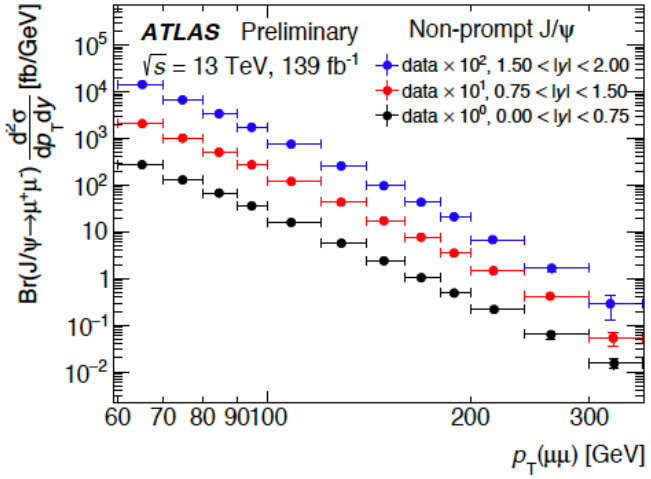
ATLAS-CONF-2019-047

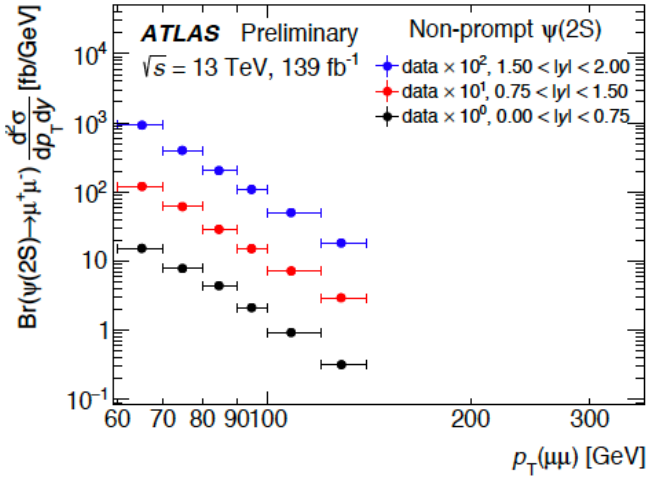
Preliminary result from ATLAS:

J/ψ measured up to 360 GeV
ψ(2S) measured up to 140 GeV

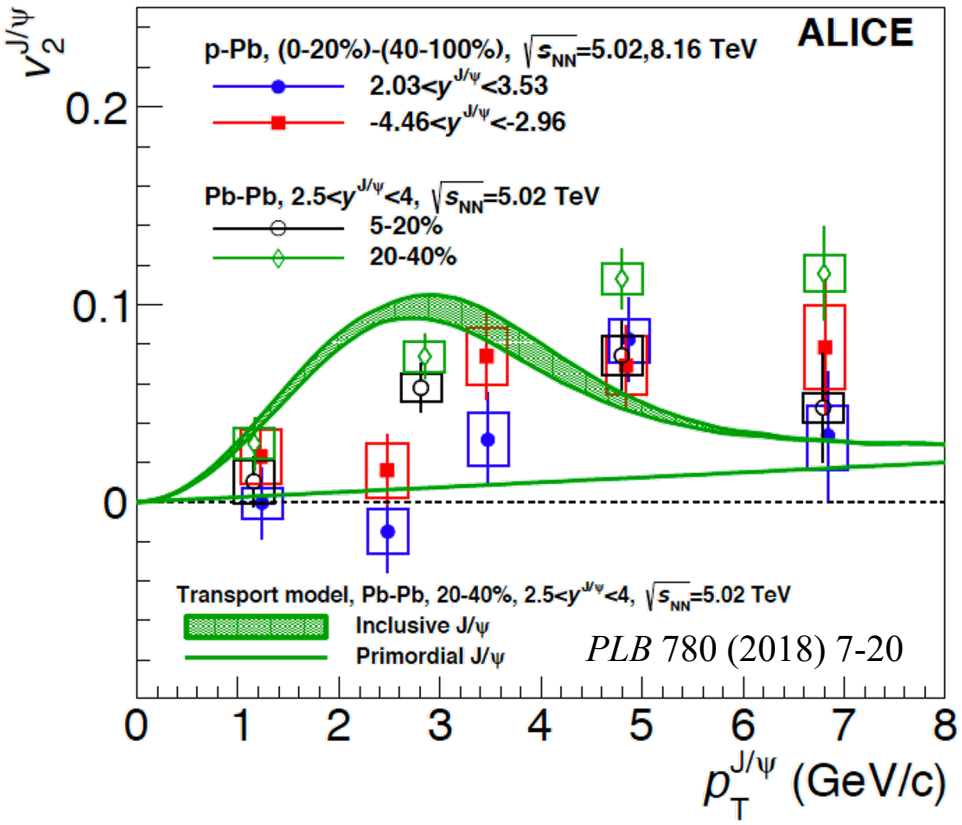
Non-prompt component (from *b* decays) diverges from FONLL calculations for $p_T > 100$ GeV



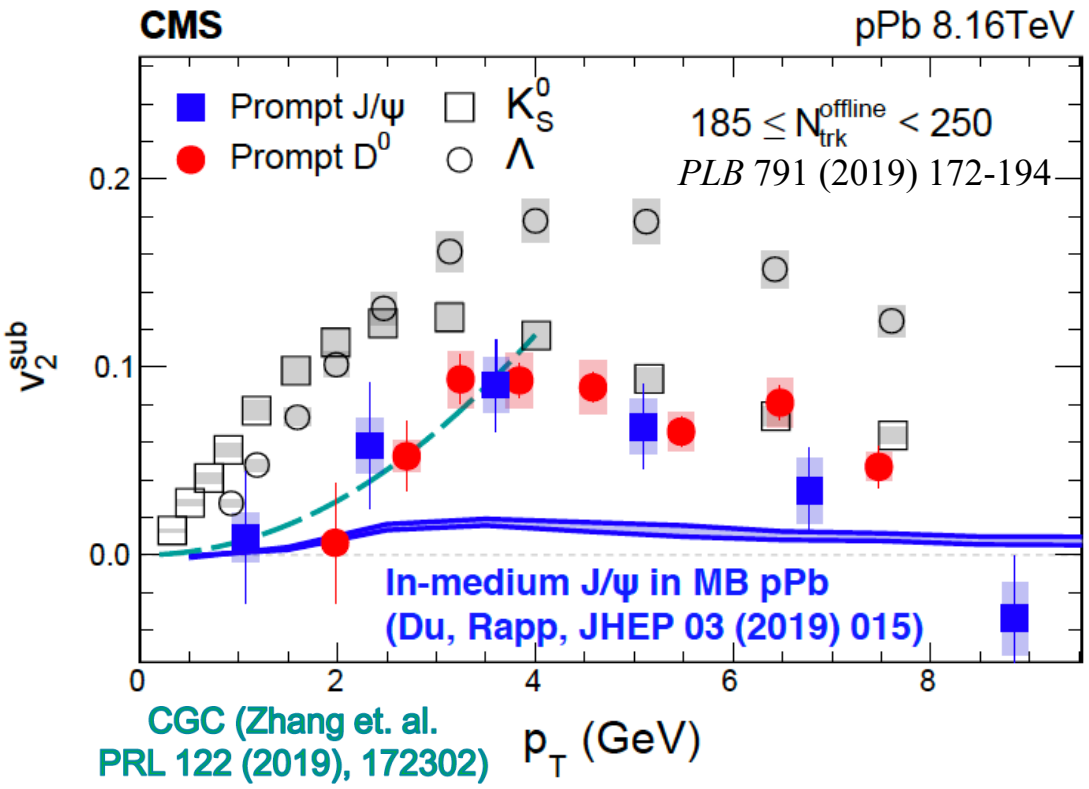




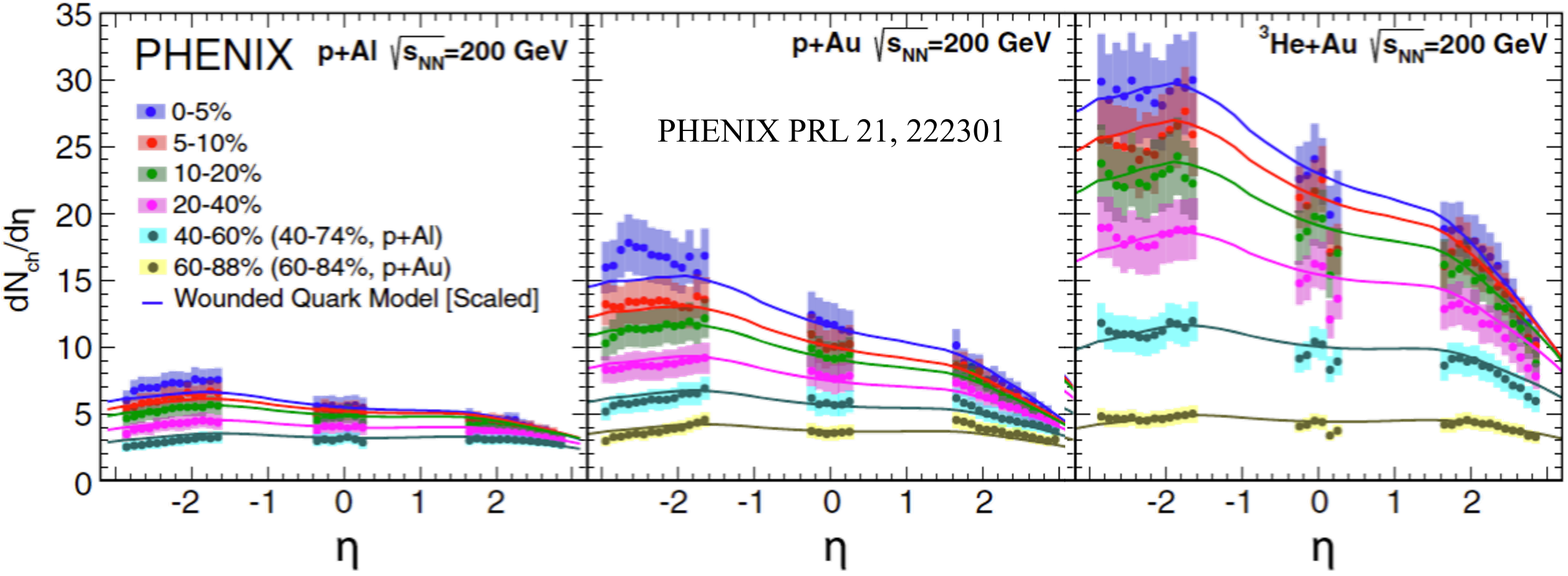
J/ψ flow: pPb and PbPb



PLB 780 (2018) 7-20

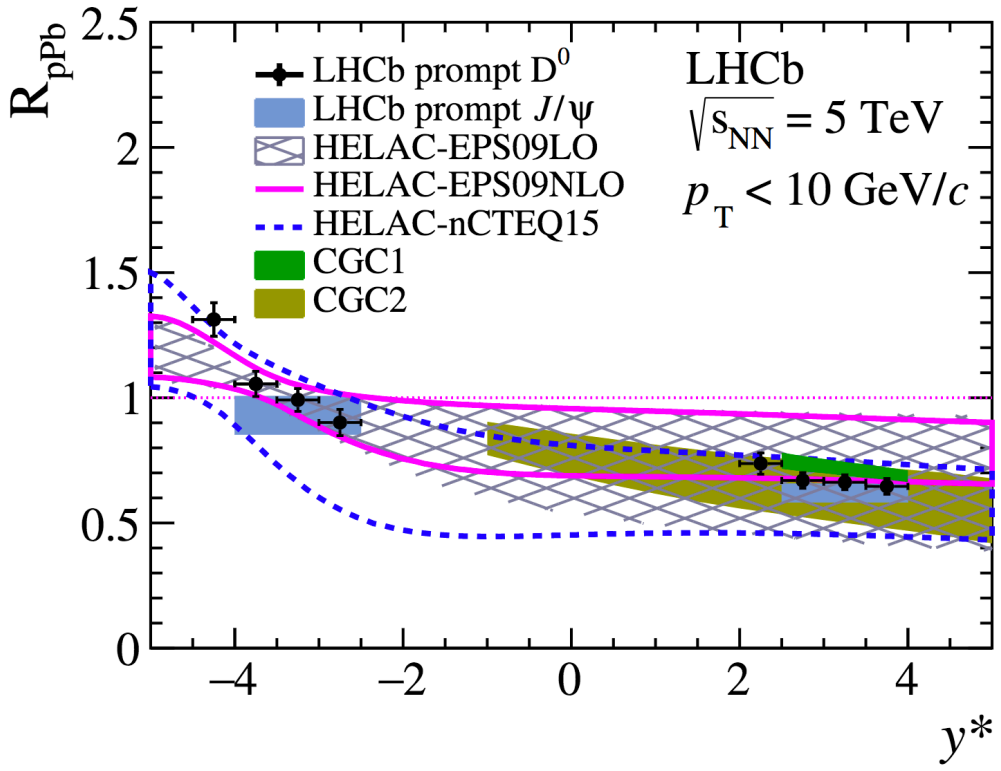


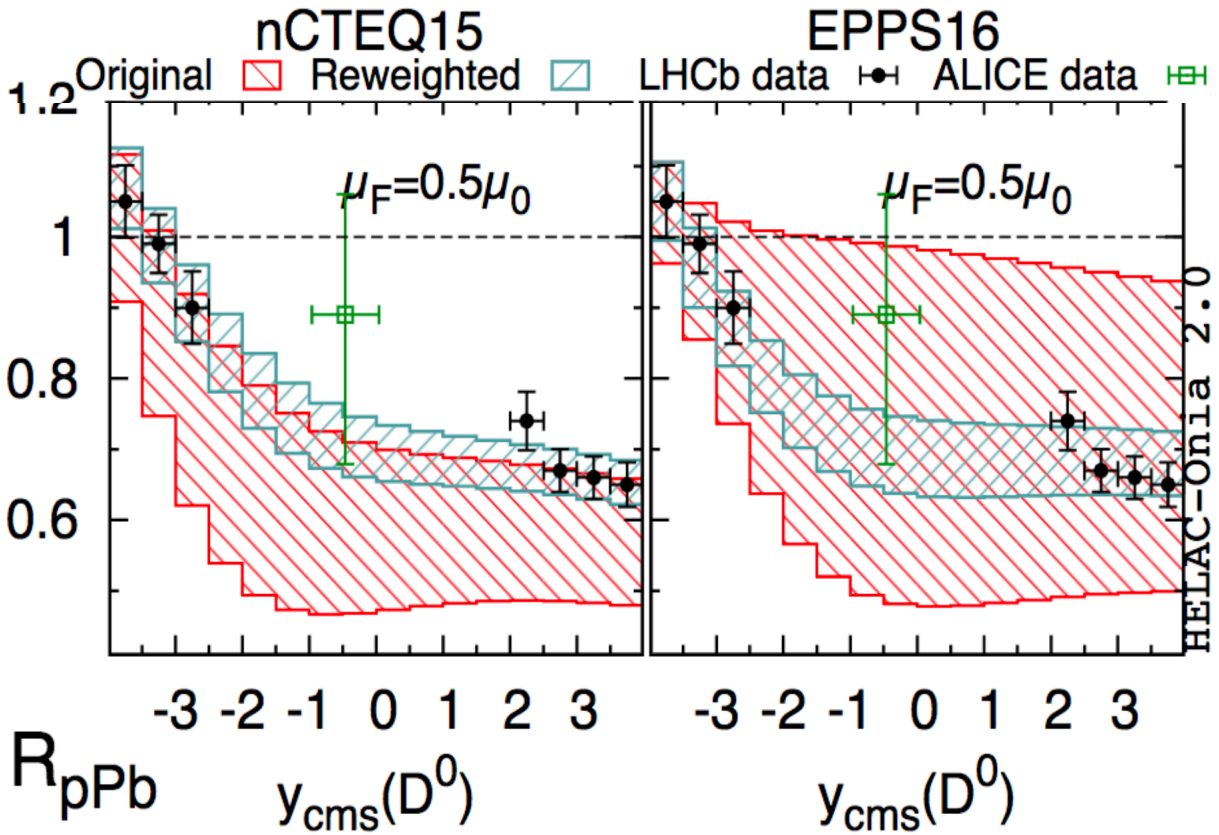
PLB 791 (2019) 172-194



PHENIX PRL 21, 222301

Improved nPDF extraction

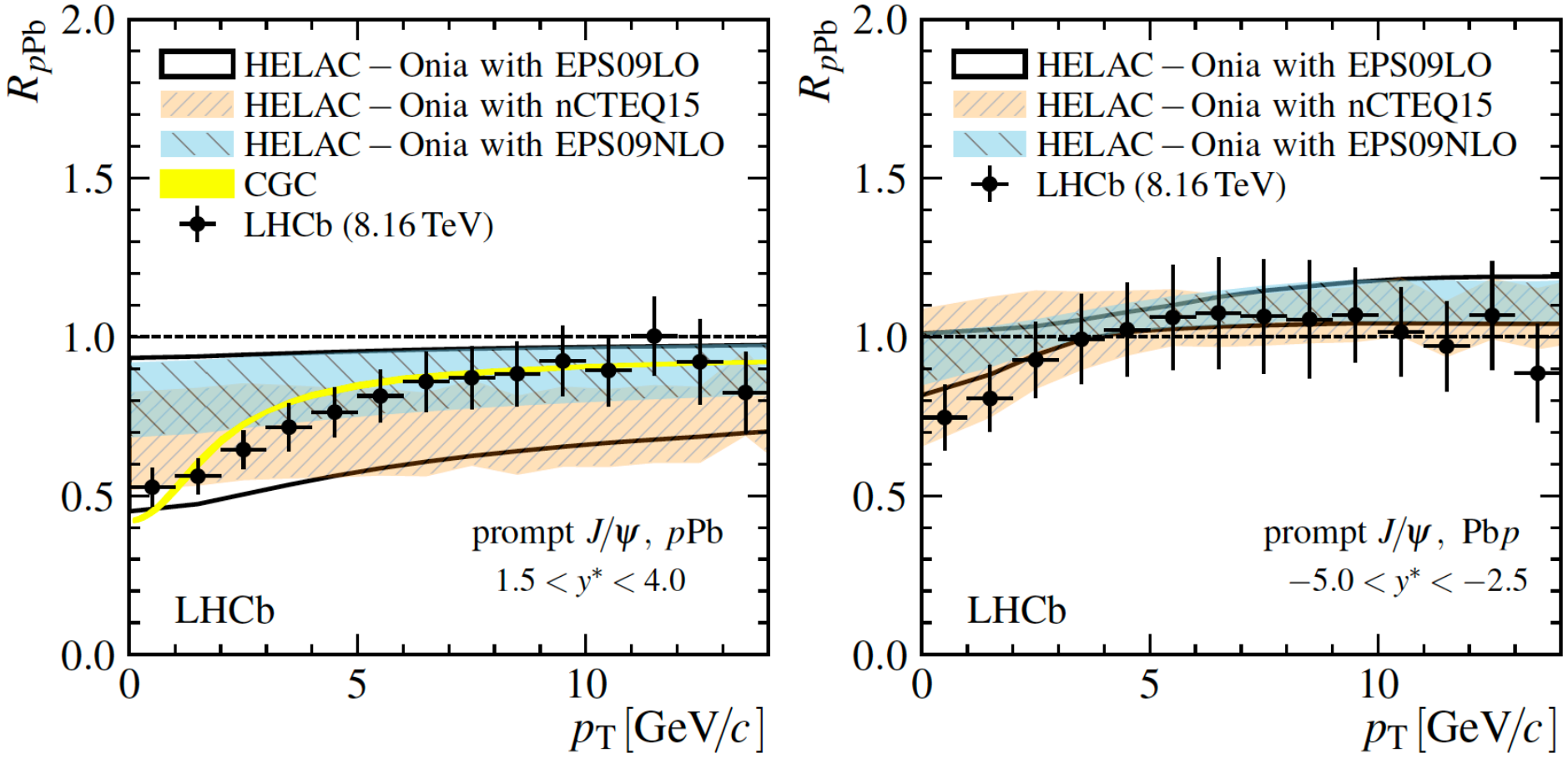




This data is already being used to constrain the gluon nPDF down to x~5x10^{-6}

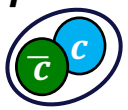
Kusina, Lansberg, Schienbein, Shao,
Gluon shadowing and antishadowing in heavy-flavor production at the LHC
Phys. Rev. Lett. 121, 052004 (2018)

Phys. Lett. B Volume 774, 10 November 2017, Pages 159-178

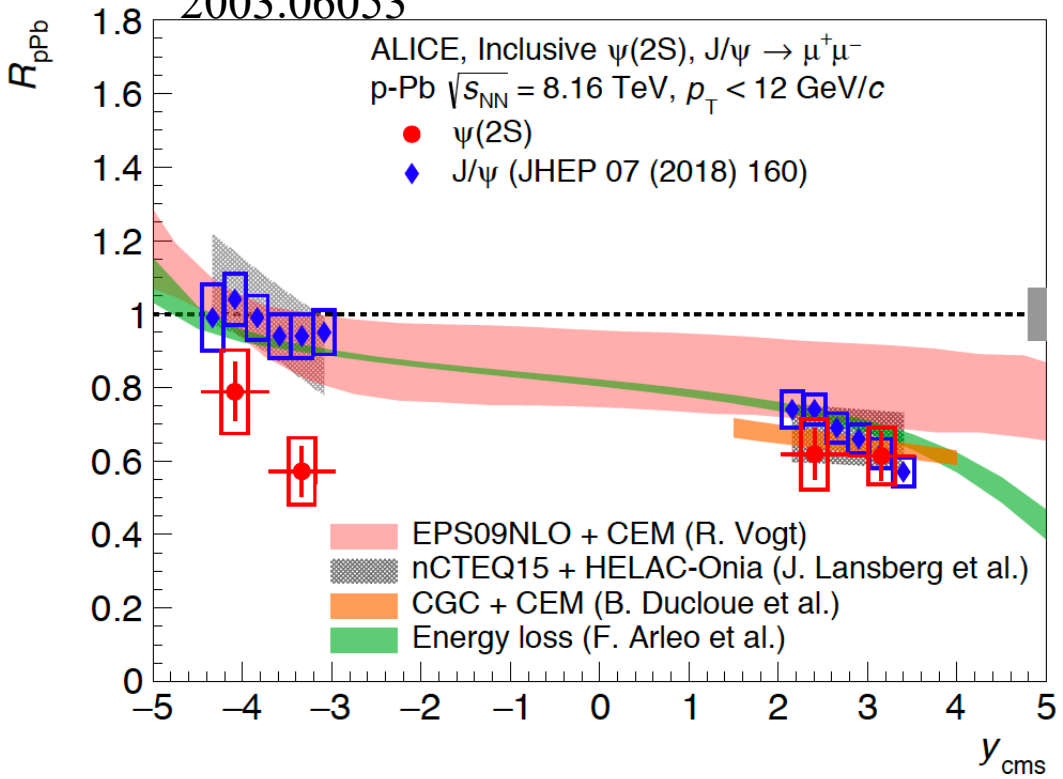


$Q\bar{Q}$ in pPb

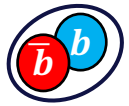
J/ψ

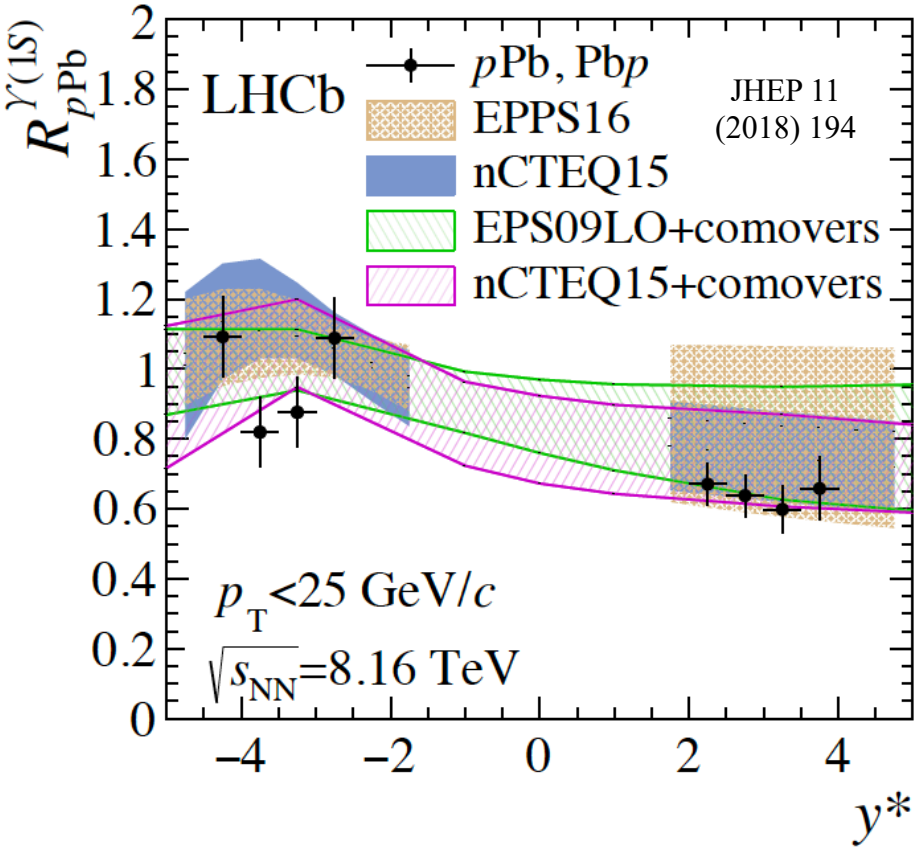


2003.06053



$\Upsilon(1S)$

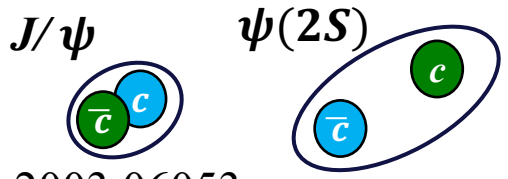


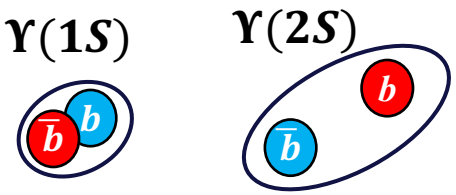


At both forward and backward rapidity, J/ψ and Υ(1S) states are well described by nPDF calculations: initial state dominates

- **Marked difference from PHENIX data, where additional effects beyond nPDF were required to match backwards data**

$Q\bar{Q}$ in pPb





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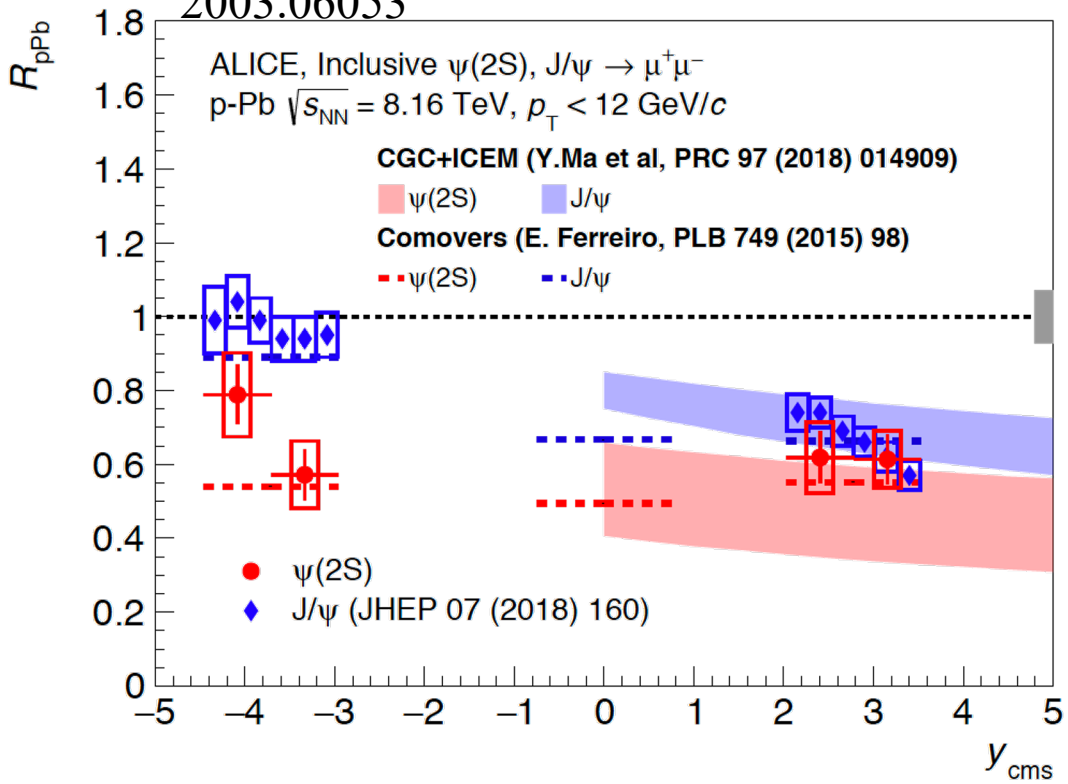
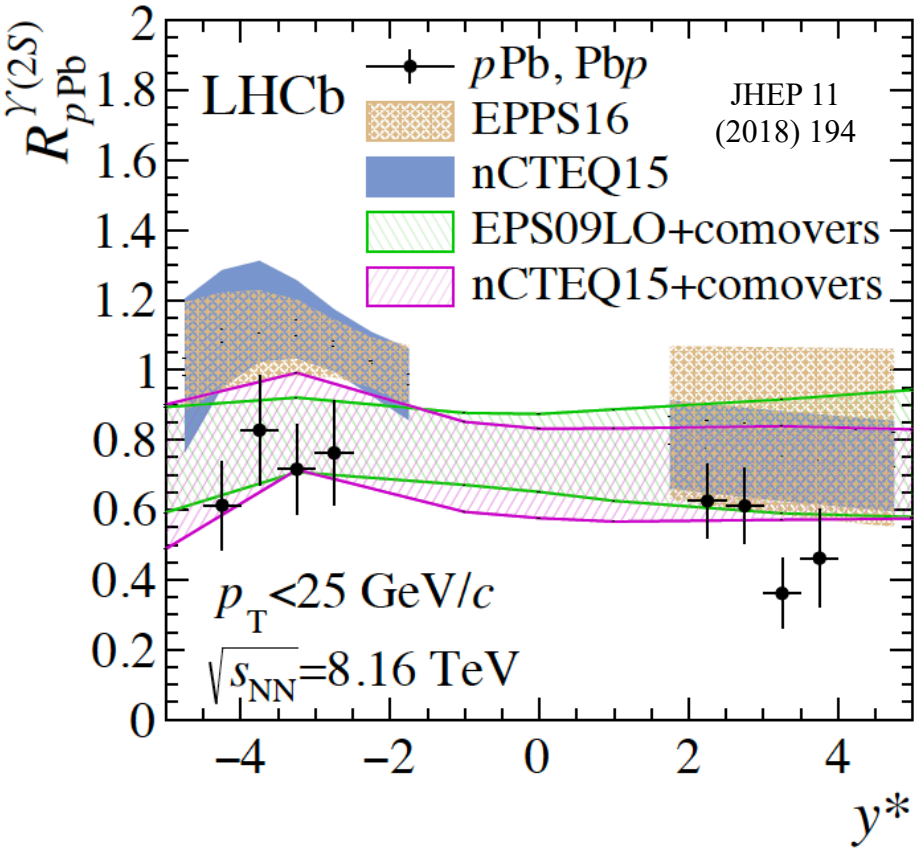




At both forward and backward rapidity, J/ψ and Υ(1S) states are well described by nPDF calculations: initial state dominates

Final state effects *required* to explain suppression of excited states at backwards rapidity

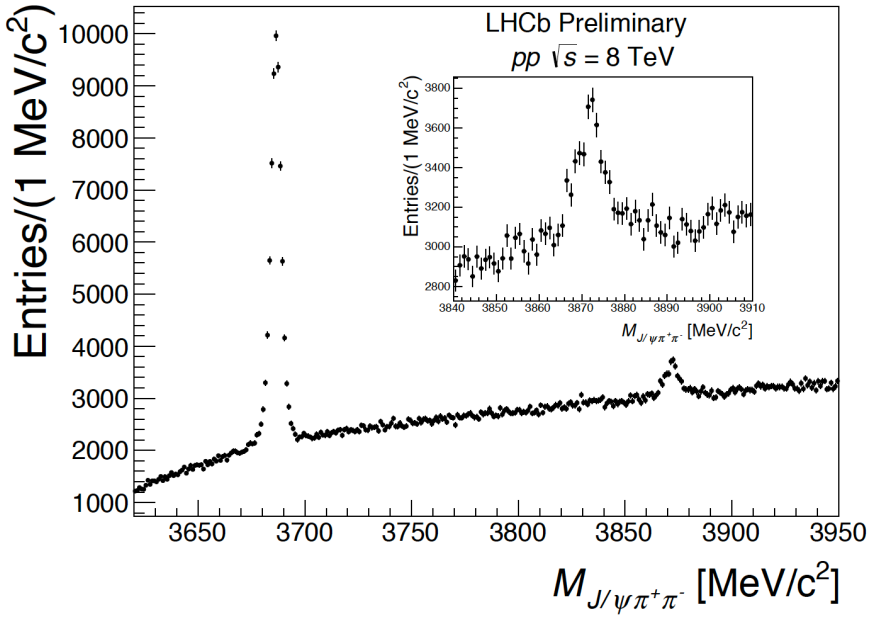
$D\overline{D}^*$ ***Molecule***

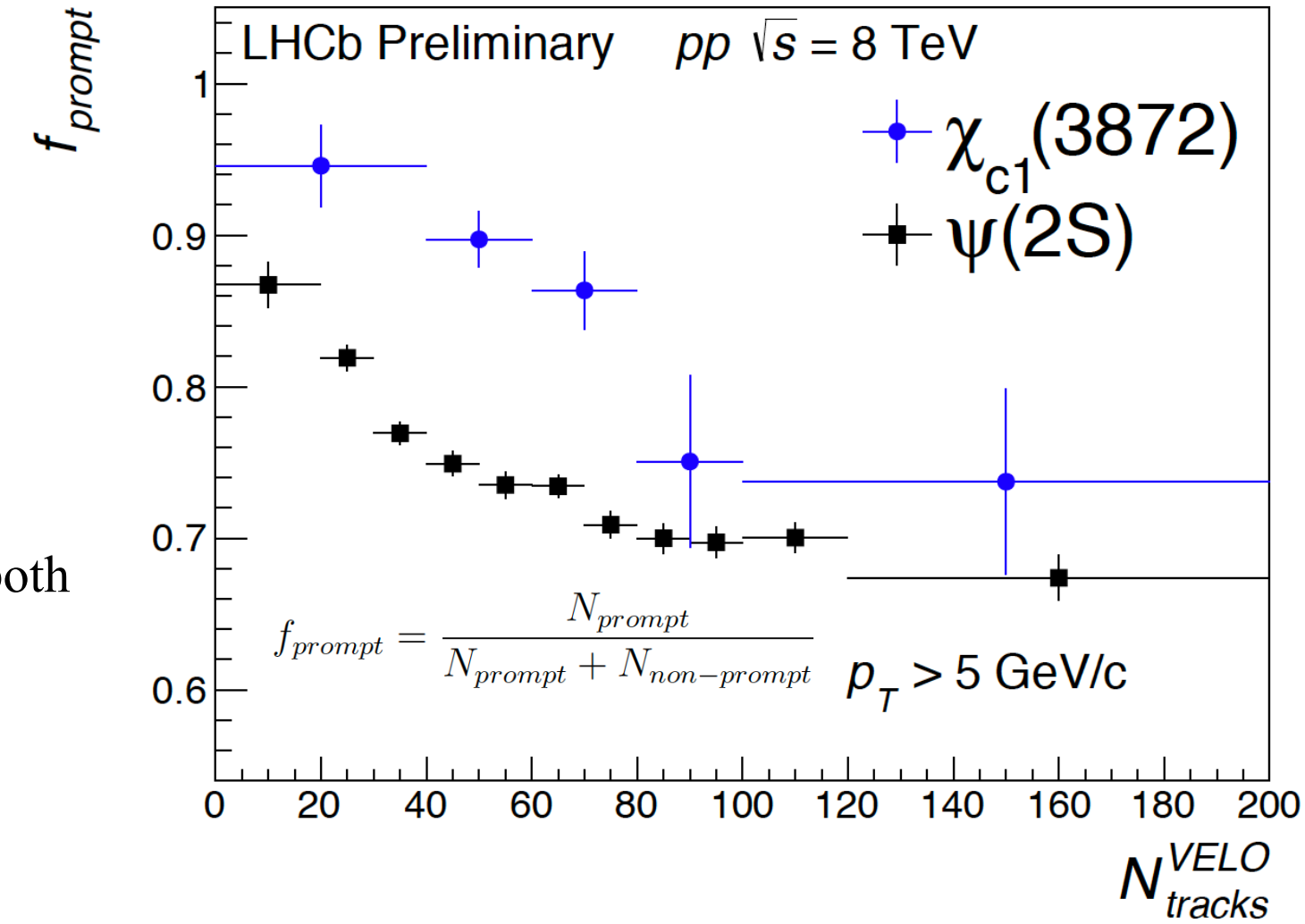
state	η_c	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	ψ'	X(3872)
mass [GeV]	2.98	3.10	3.42	3.51	3.56	3.69	3.872
ΔE [GeV]	0.75	0.64	0.32	0.22	0.18	0.05	0.00001± 0.00027

Satz, J. Phys. G 32 (3) 2006

Exotic X(3872) in diffuse medium (8 TeV *pp*)

LHCb-CONF-2019-005





Prompt fraction of X(3872) and ψ(2S) both drop as function of event activity:

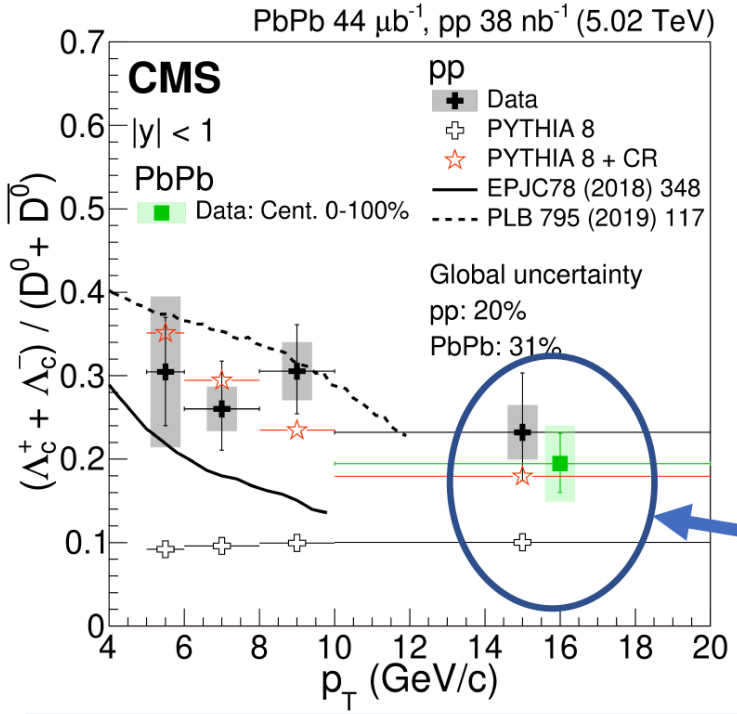
- Increasing *b* component?
- Suppressed prompt component?
  i.e. final state effect in *pp*?

Cameron Dean, Wed 12:25

“No significant contribution from coalescence” at pT > 10 GeV/c for charm baryons

Charm quark coalescence?

PLB 803 (2020) 135328
Milan Stojanovic, Wed 13:45



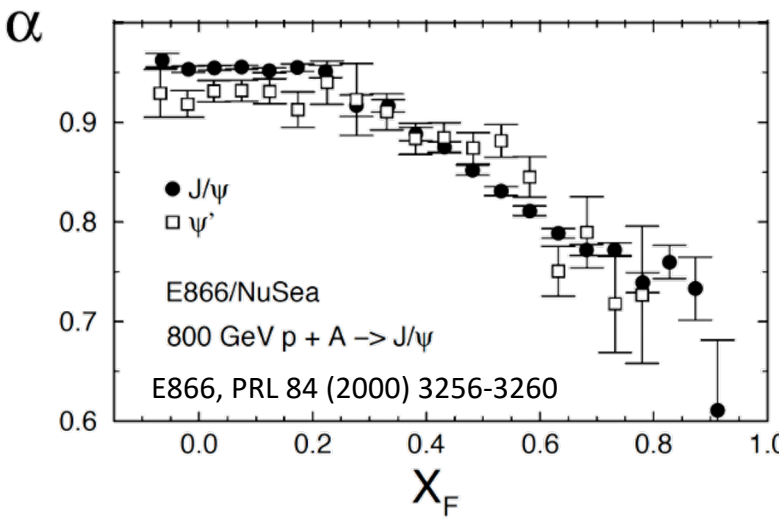
Good agreement between pp data and PYTHIA8 with color reconnection

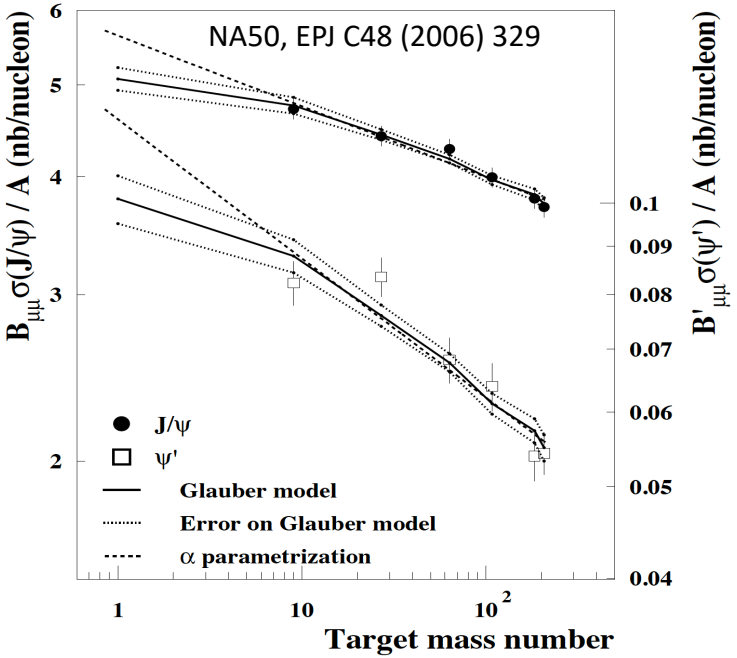
Lack of an enhancement in PbPb:
No significant contribution from coalescence

Daniel Tapia Takaki | Hard Probes 2020 – *Austin, Texas* | June 1, 2020 | 14

Quarkonia inside the nucleus

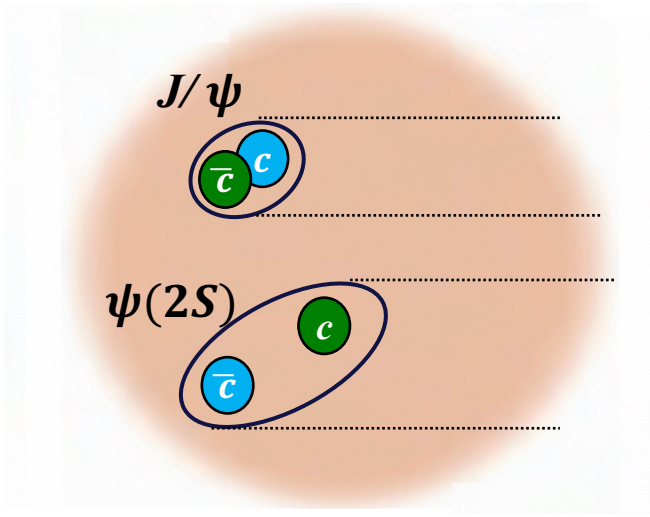
Fixed target p+A experiments also operated in a kinematic region where quarkonia hadronized inside the nucleus – similar to EIC



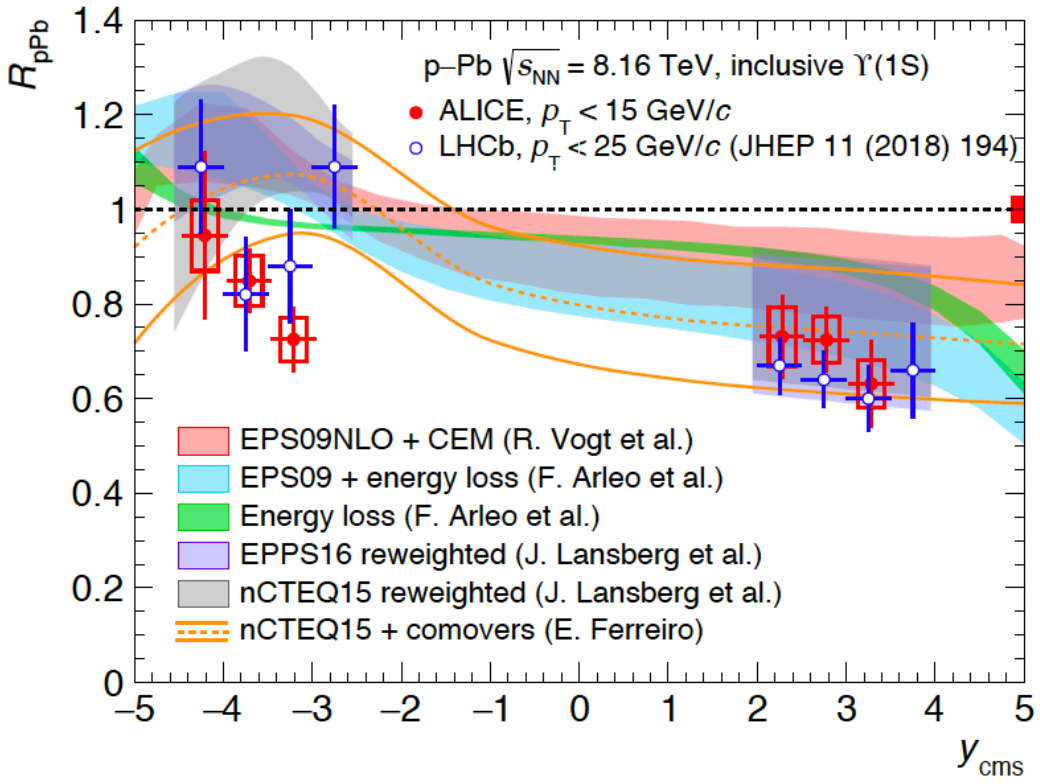


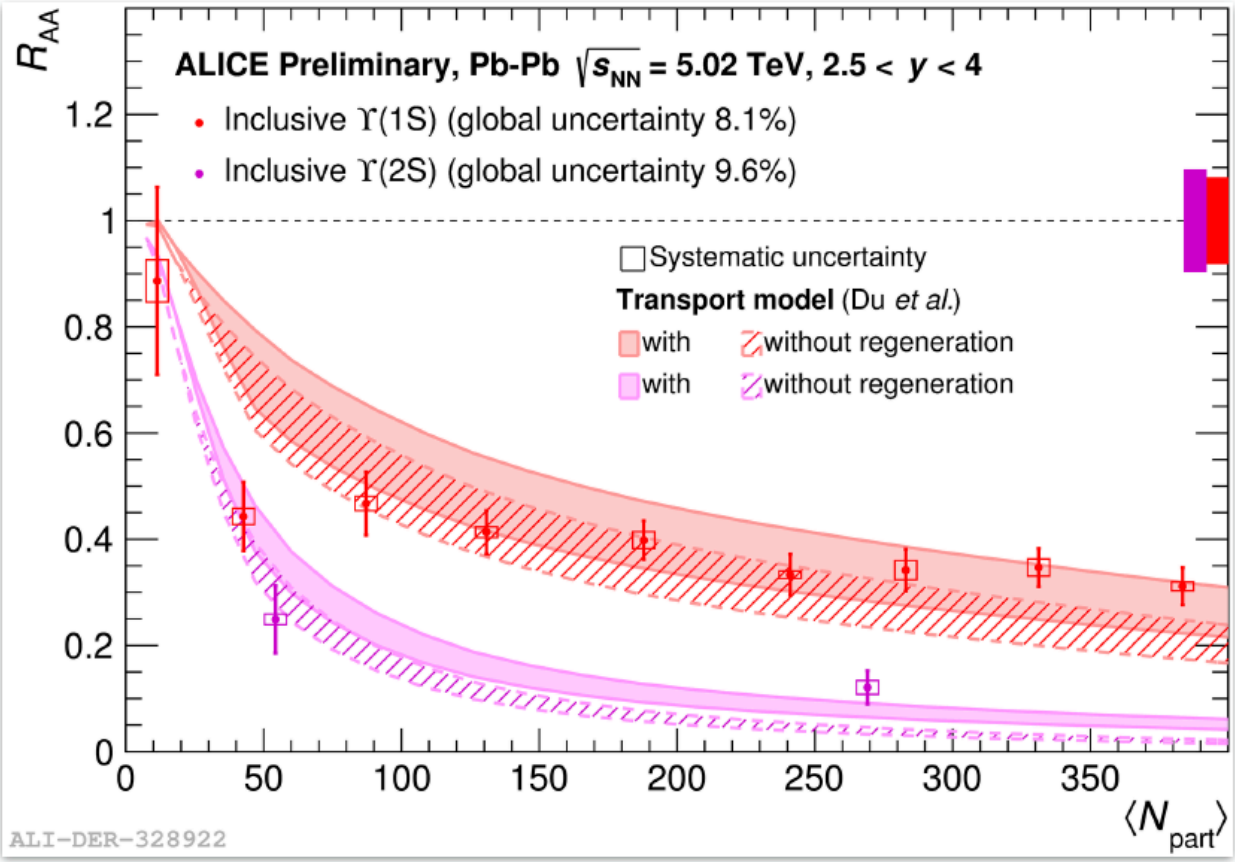
Natural explanation based on size: Larger (weakly bound) states sample a larger volume of the nucleus while passing through – larger absorption cross section

Arleo, Gossiaux, Gousset, Aichelin PRC 61 (2000) 054906



Significant differences observed between states with same quark content, but different binding energies


R_{pPb}
p–Pb $\sqrt{s_{NN}}$ = 8.16 TeV, inclusive ϒ(1S)
ALICE, p_T < 15 GeV/c
LHCb, p_T < 25 GeV/c (JHEP 11 (2018) 194)
EPS09NLO + CEM (R. Vogt et al.)
EPS09 + energy loss (F. Arleo et al.)
Energy loss (F. Arleo et al.)
EPPS16 reweighted (J. Lansberg et al.)
nCTEQ15 reweighted (J. Lansberg et al.)
nCTEQ15 + comovers (E. Ferreiro)
y_{cms}

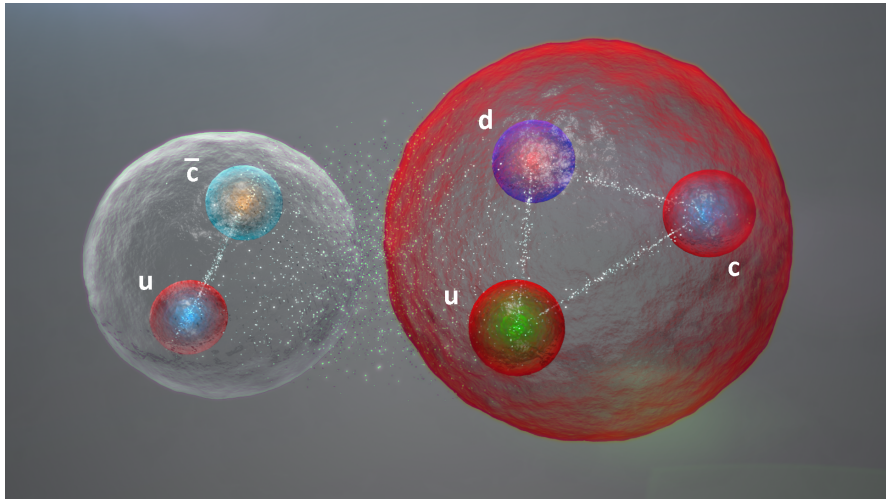

R_{AA}
ALICE Preliminary, Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV, 2.5 < y < 4
Inclusive ϒ(1S) (global uncertainty 8.1%)
Inclusive ϒ(2S) (global uncertainty 9.6%)
Systematic uncertainty
Transport model (Du et al.)
with
without regeneration
with
without regeneration
$\langle N_{part} \rangle$
ALI-DER-328922

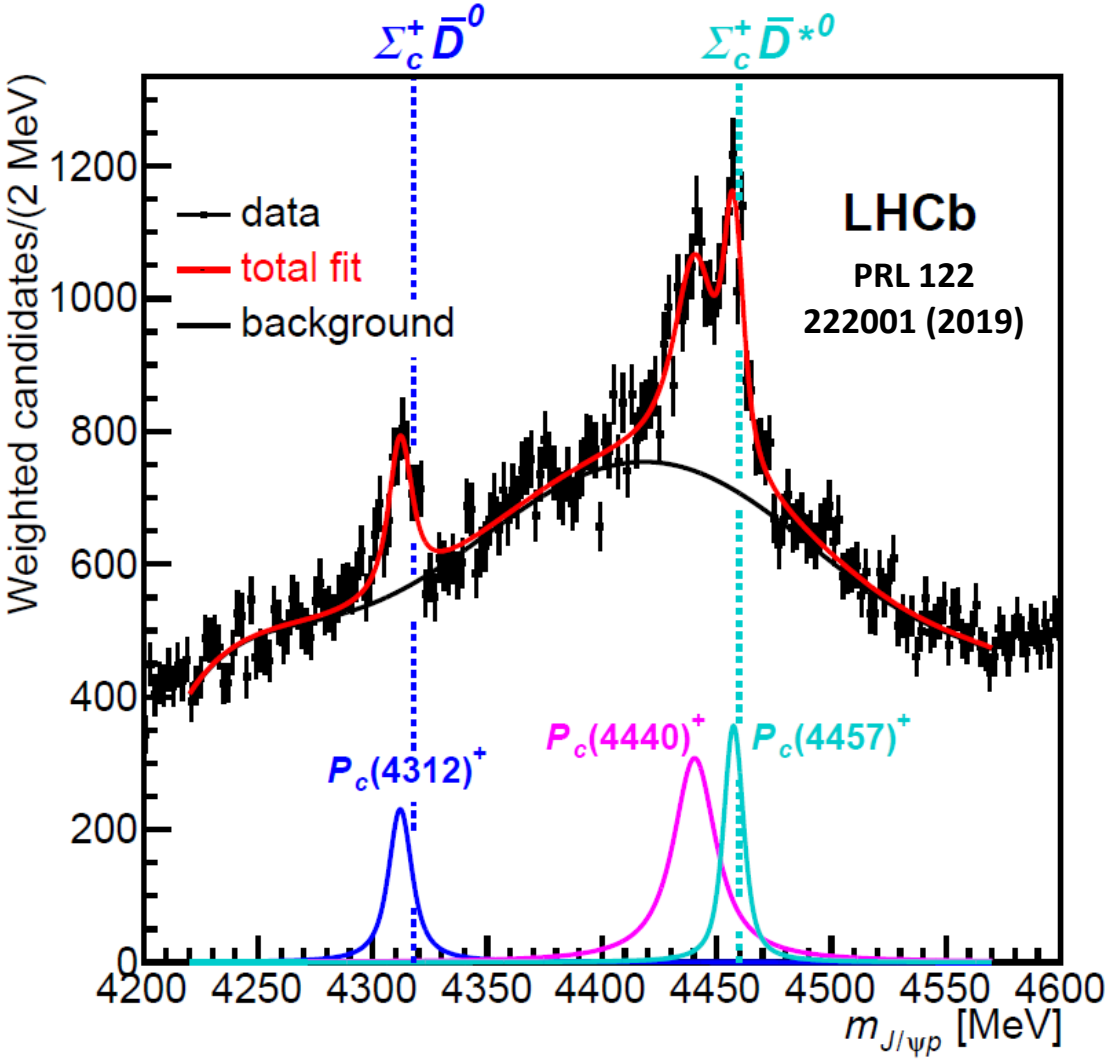
Recent LHCb Discovery – P_c States

Select daughters from the decay

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

Masses are close to meson+baryon thresholds – candidate for hadronic molecule

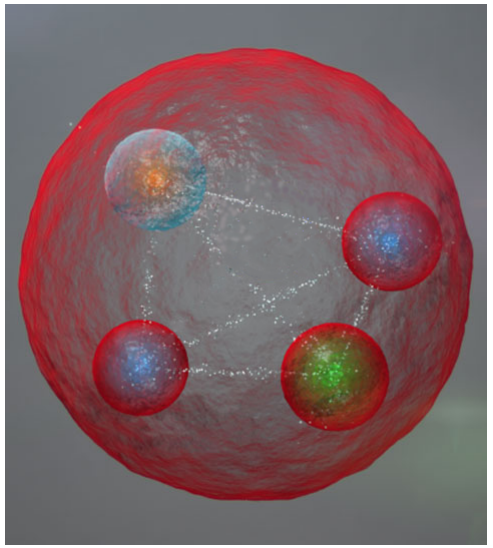




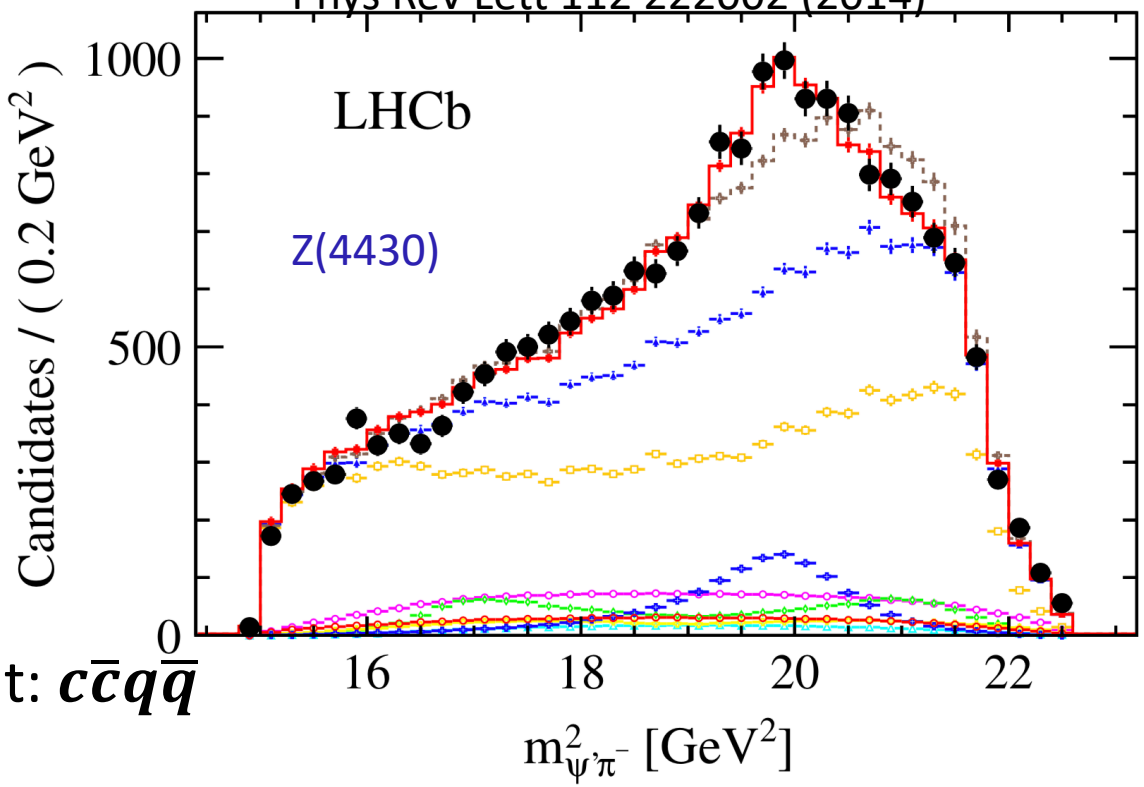
Charged Exotic – Z_c State

Select daughters from the decay

$$B^0 \rightarrow \psi' K^+ \pi^-$$



Phys Rev Lett 112 222002 (2014)



Charged and contains $c\bar{c}$: Minimal 4 quark content: $c\bar{c}q\bar{q}$

Mass is NOT close to any hadron+hadron threshold – candidate for compact tetraquark