# Heavy Flavor Physics at the EIC

## from a heavy ion perspective

Matt Durham

Los Alamos NATIONAL LABORATORY EST. 1943

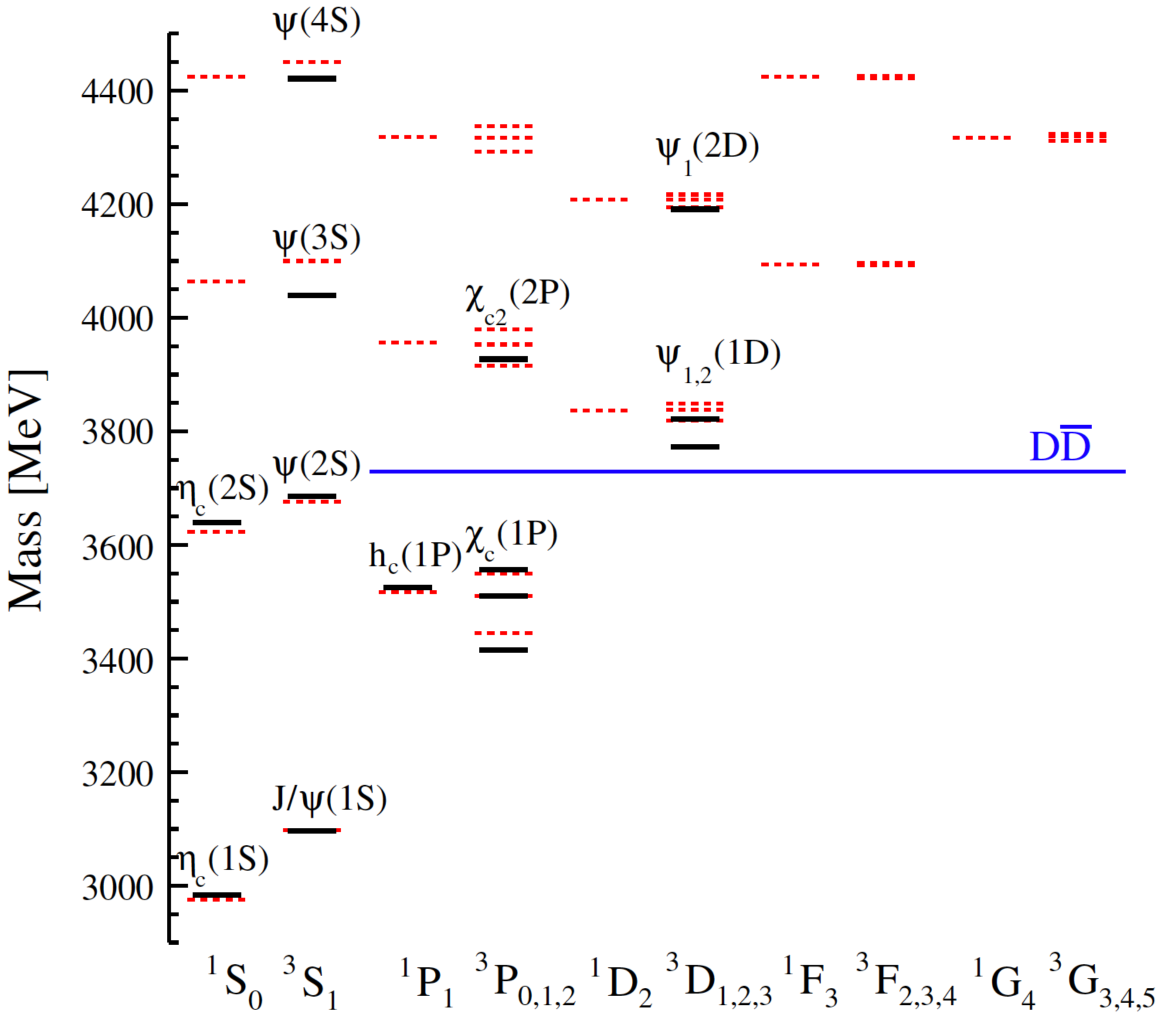
LPC Workshop on Physics Connections between the LHC and EIC

13-15 November 2019

Fermilab, Wilson Hall

America/Chicago timezone

# Charmonium Production in Vacuum




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

Nonrelativistic potential model: solve Schrodinger equation with the potential

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

Barnes, Godfrey, Swanson,
Phys. Rev. D 72, 054026 (2005)

New charmonium states still being found: LHCb observed state consistent with $\psi_3(1^3D_3)$ found in $\boldsymbol{D\bar{D}}$ and $\boldsymbol{D^+D^-}$ mass spectra in 2019 **JHEP (2019) 2019:35**

Rich structure, accessible experimentally and theoretically

# Charmonium in Heavy Ion collisions

Volume 178, number 4 PHYSICS LETTERS B 9 October 1986

**>2900 citations**

## J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

T. MATSUI
*Center for Theoretical Physics, Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

and

H. SATZ
*Fakultät für Physik, Universität Bielefeld, D-4800 Bielefeld, Fed. Rep. Germany and Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA*

Received 17 July 1986

If high energy heavy ion collisions lead to the formation of a hot quark–gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, the temperature dependence of the screening radius, as obtained from lattice QCD, is compared with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark–gluon plasma formation.

**"unambiguous signature of QGP formation"**

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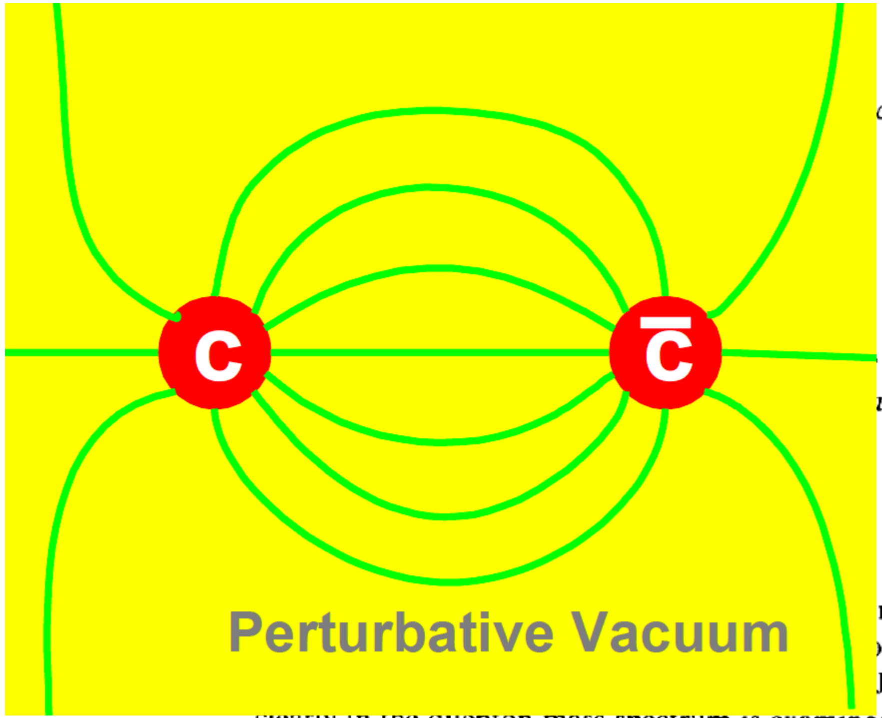


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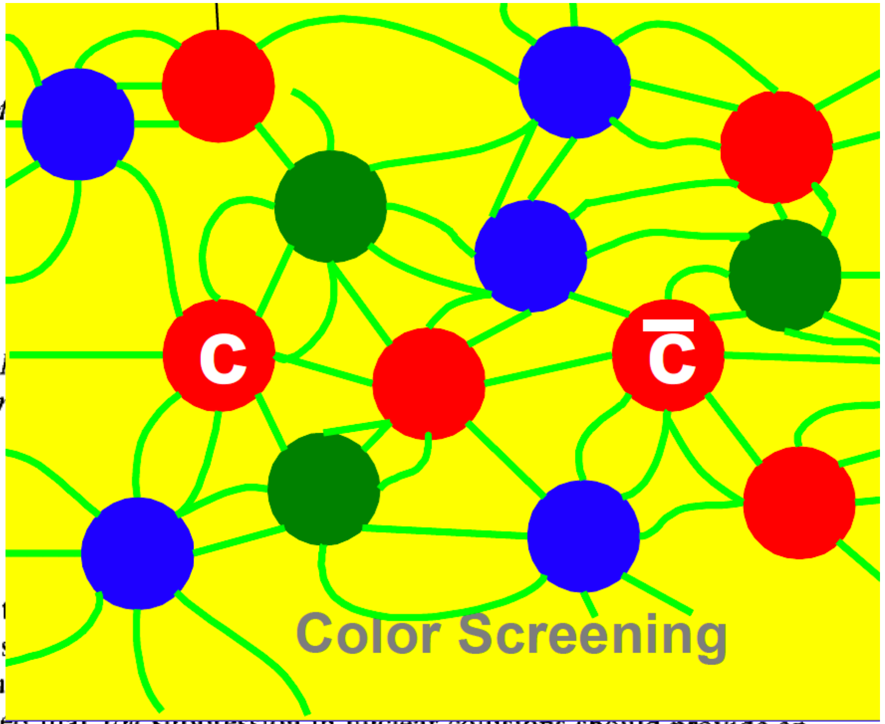


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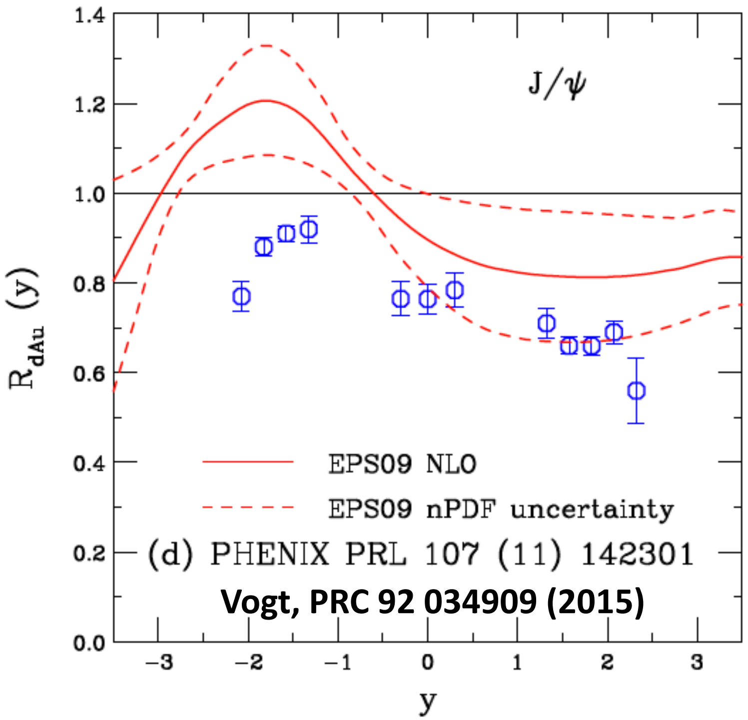
# Charmonium in Heavy Ion collisions

### PDF Modifications




PHYSICS LETTERS B 9 October 1986

**PHENIX d+Au J/ Ψ data from PRL 107, 143301 (2011)**

JON PLASMA FORMATION ☆


*clear Science, Massachusetts Institute of Technology,*

*Bielefeld, Fed. Rep. Germany*
*iboratory, Upton, NY 11973, USA*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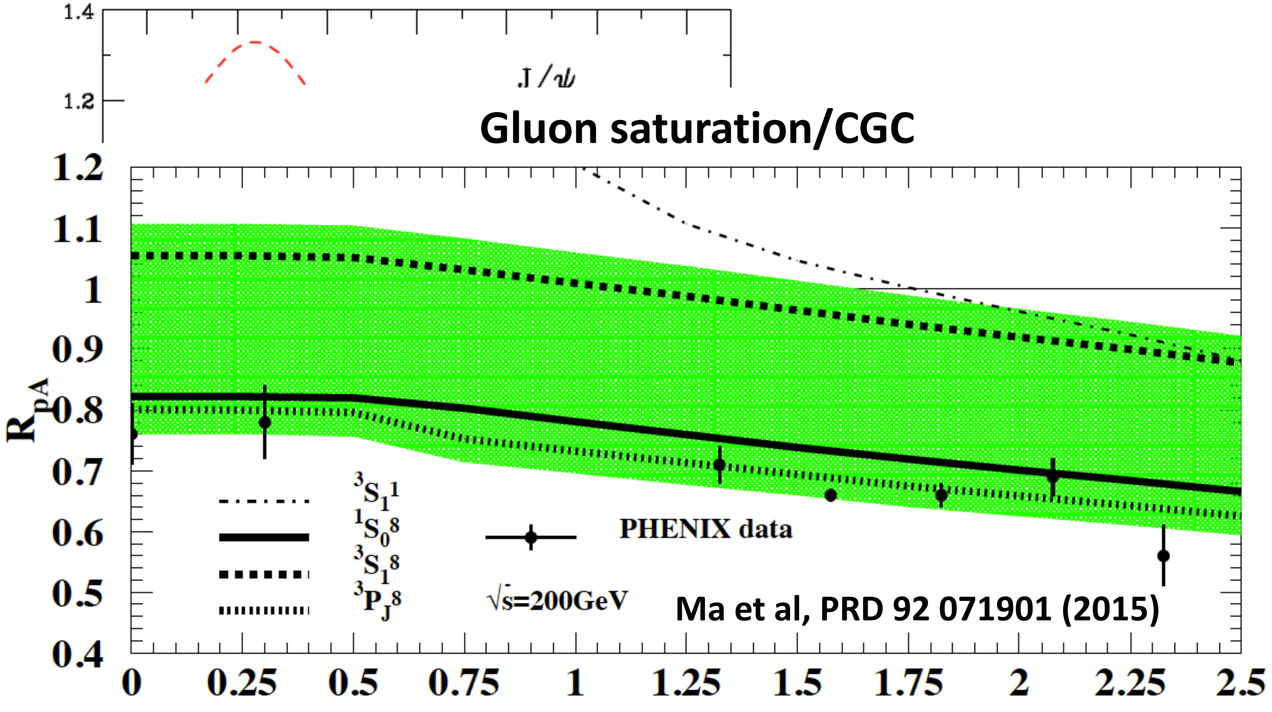


☆

Technology,

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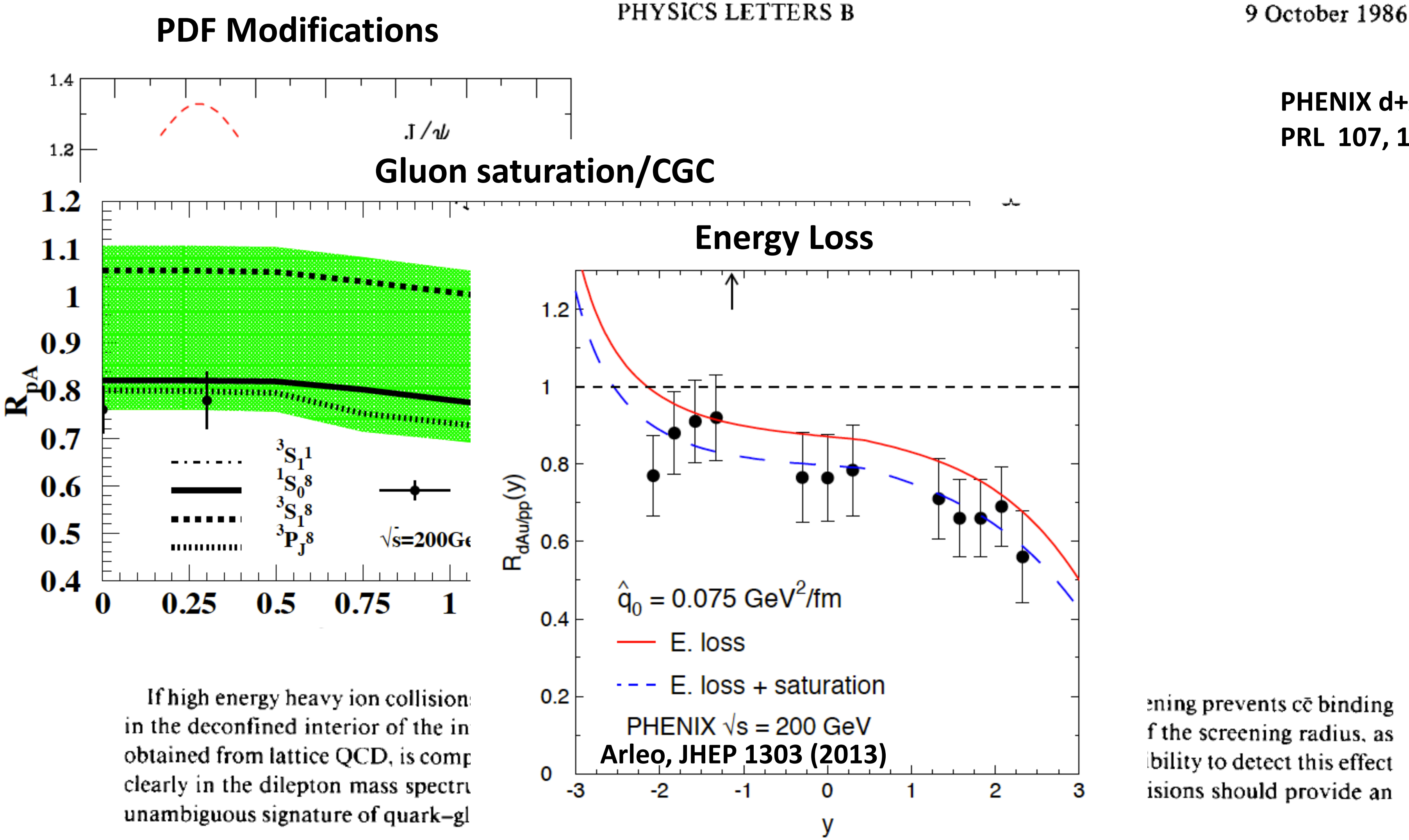


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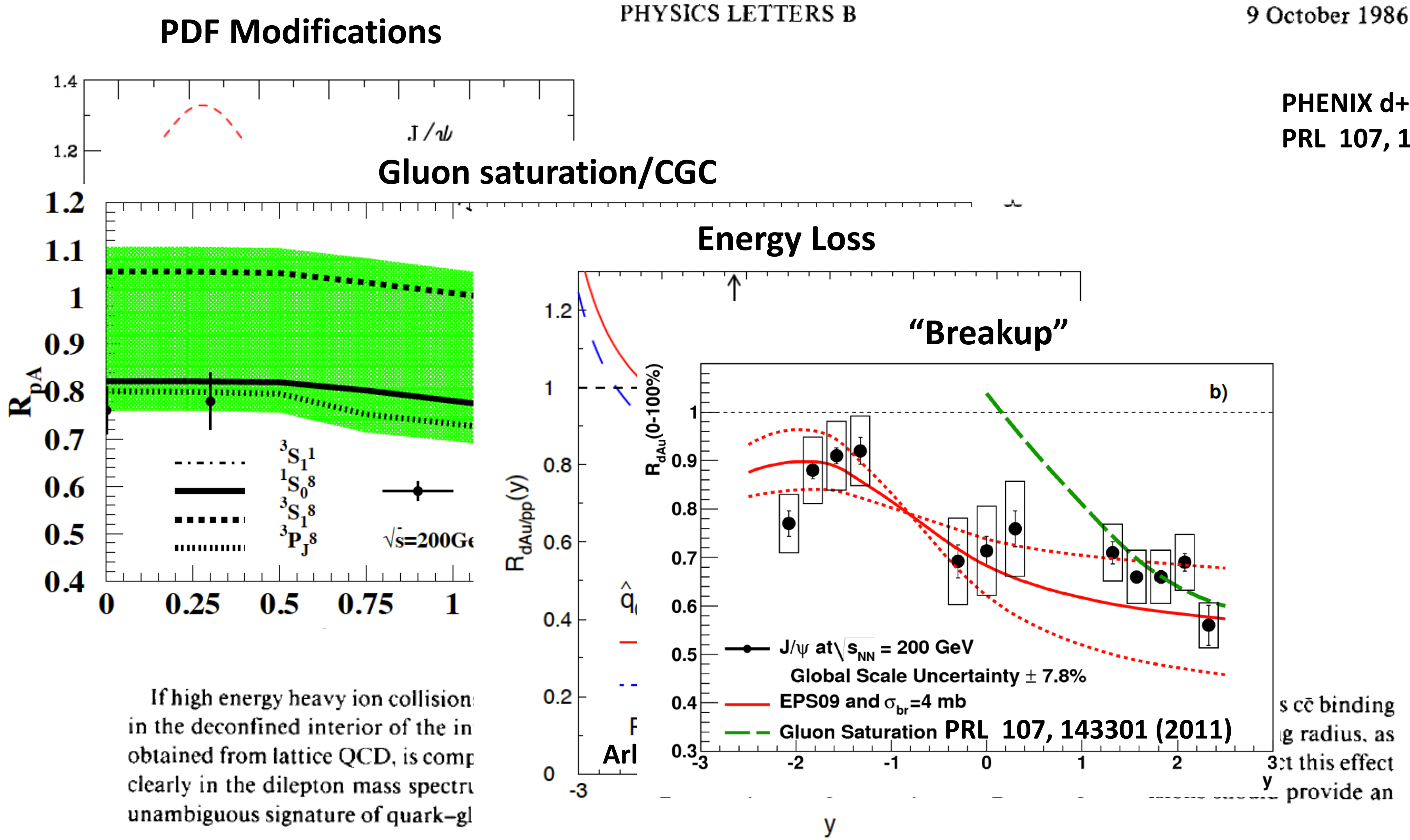


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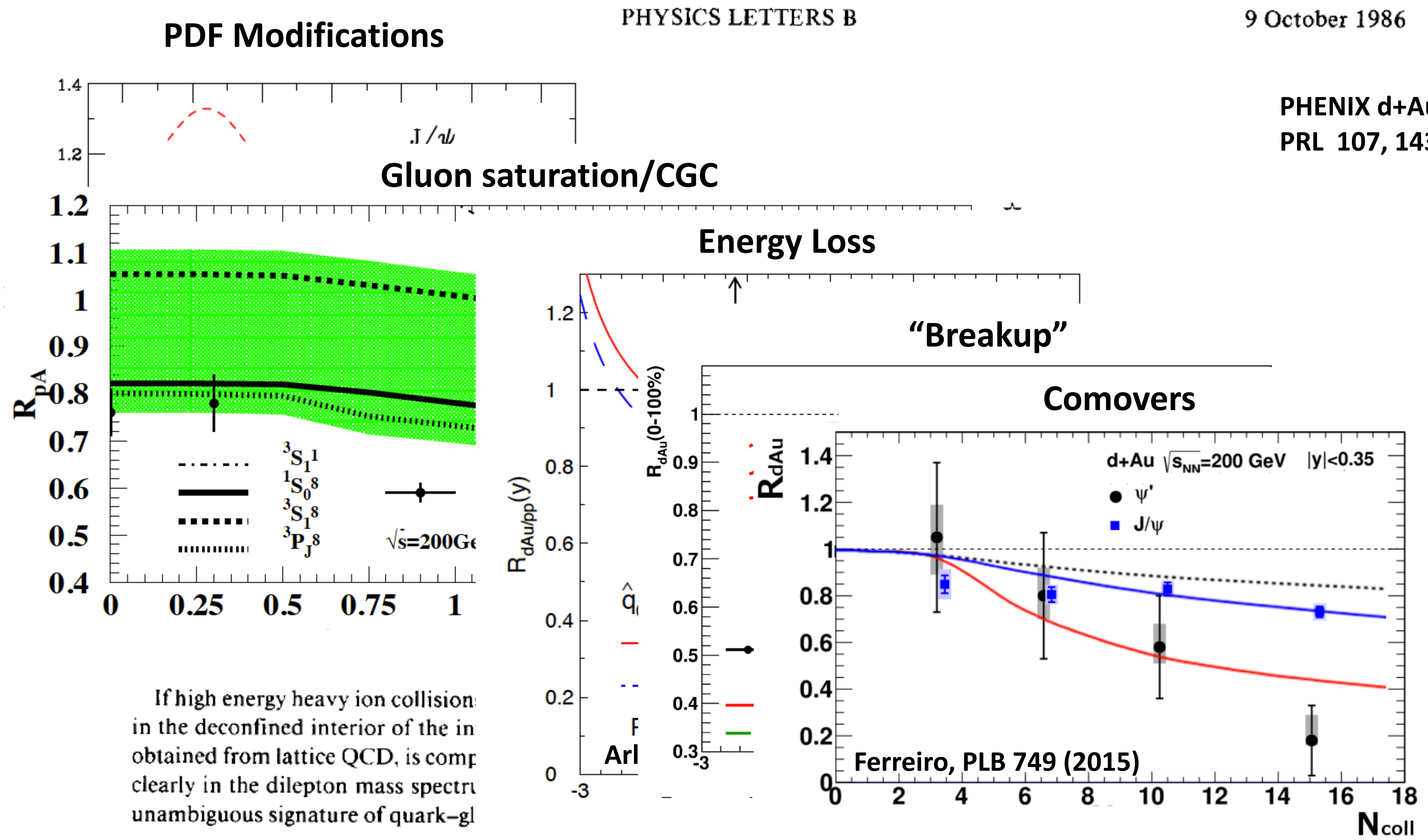


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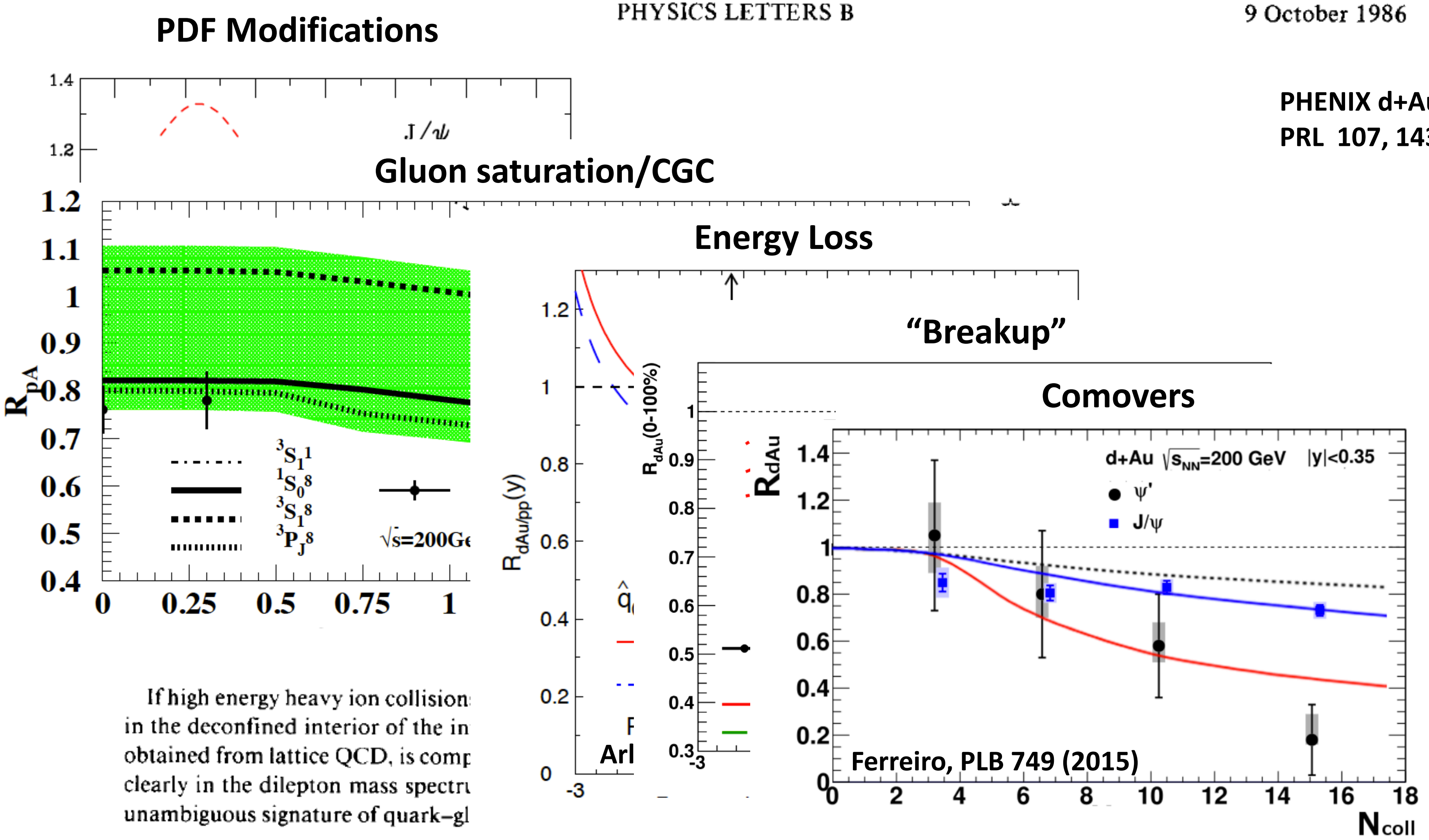
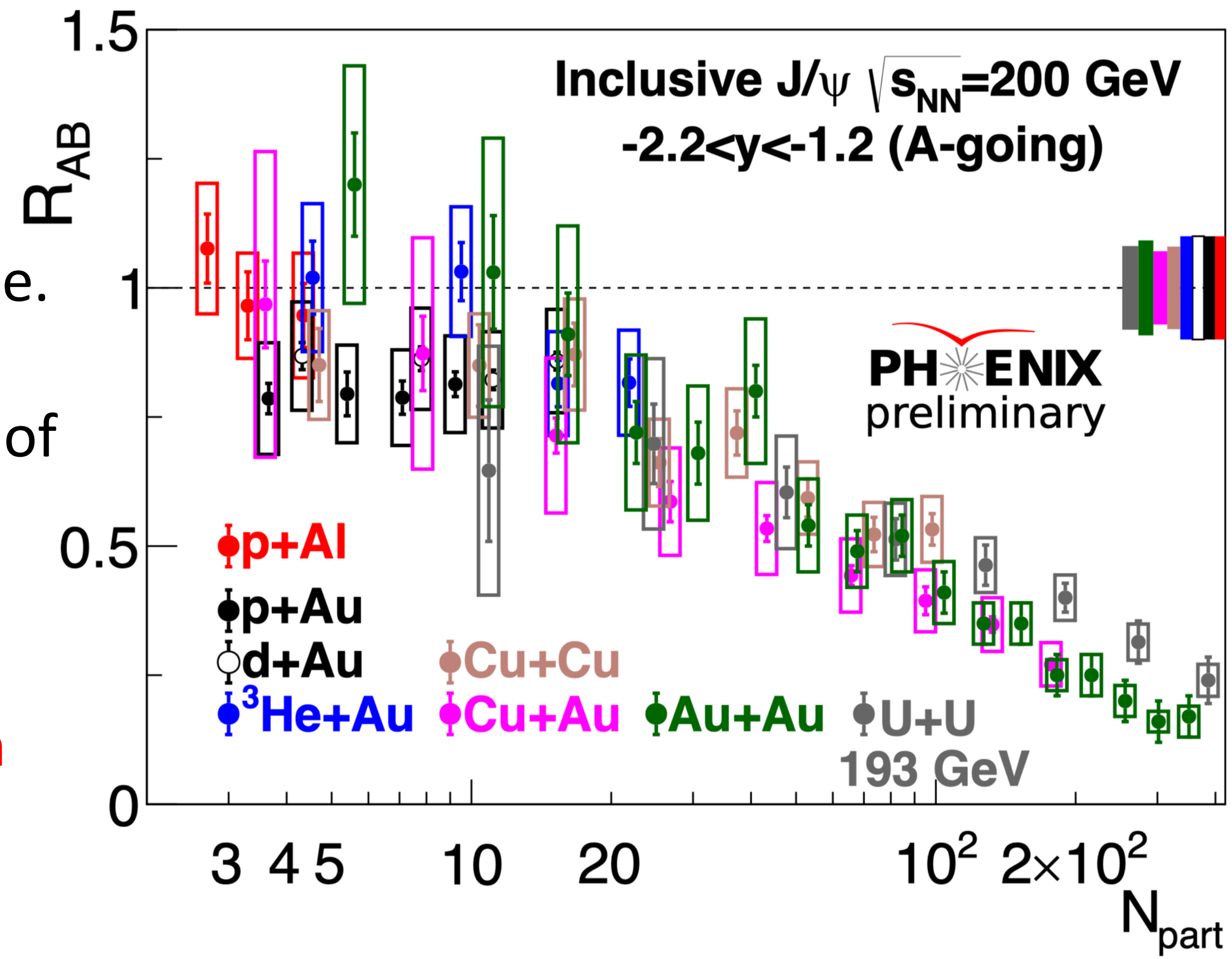



HIGHLY ✗ "unambiguous signature of QGP formation"

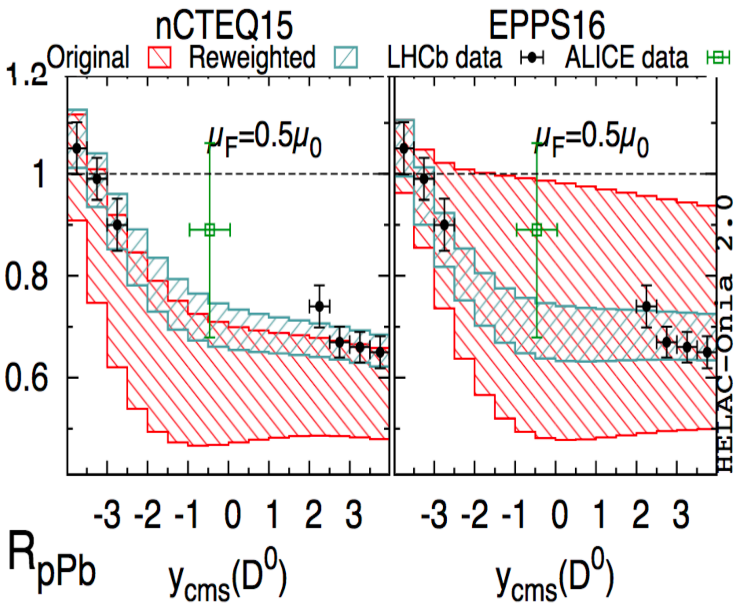
# Charmonia in Heavy Ion Collisions – system scan

$$R_{AB} = \frac{1}{\langle N_{coll} \rangle} \frac{d^2N^{AB}/dydp_T}{d^2N^{pp}/dydp_T}$$

- Multiple effects of varying significance.
- Smooth transition across large range of system sizes.
- EIC allows us to constrain initial state effects: nPDF, energy loss, absorption



# Example: Heavy Quark Production Constrains nPDF




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

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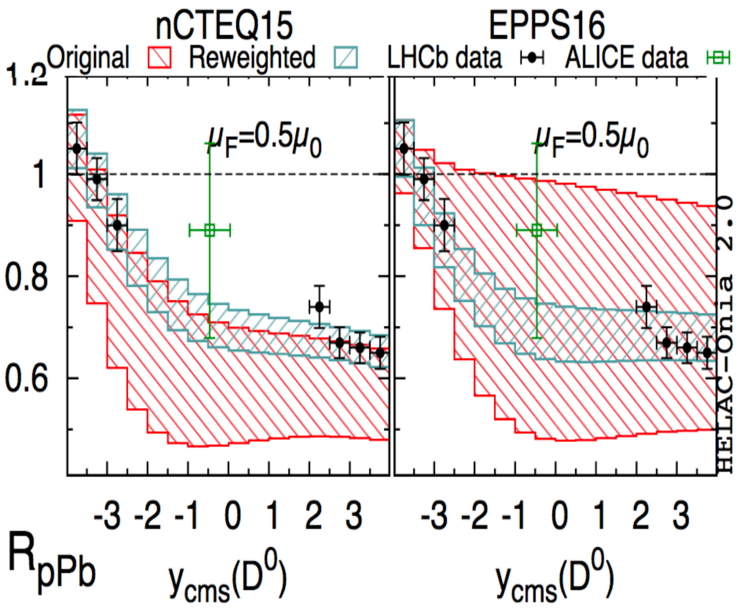


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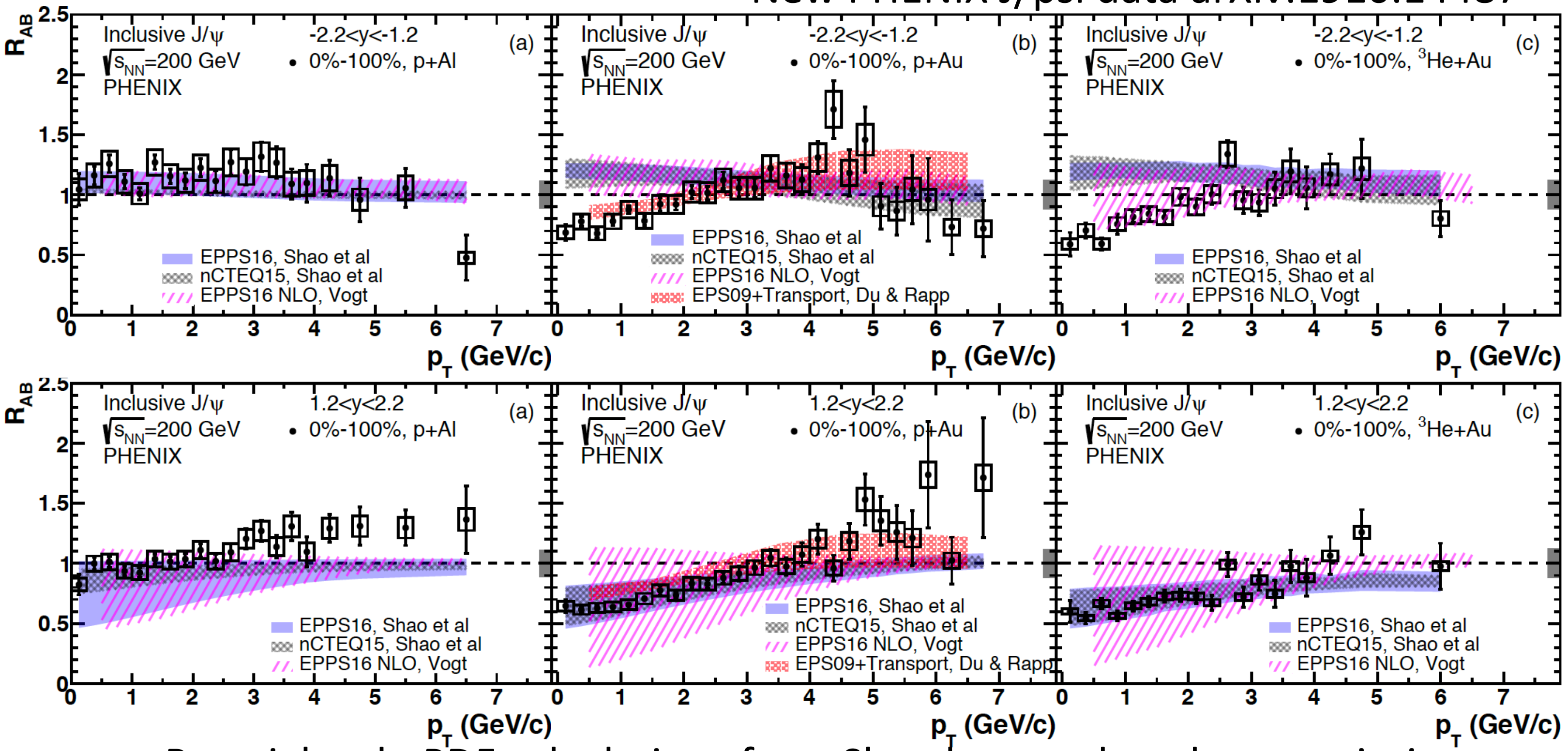
New PHENIX J/psi data arXiv:1910.14487




Reweighted nPDF calculations from Shao have reduced uncertainties

Able to describe features of RHIC data after reweighting using LHC data, revealing effects which are not due to nPDF modification.

- **Precision heavy flavor data from EIC can further constrain nPDFs**

# Detector R&D by LANL for EIC –funded by LDRD

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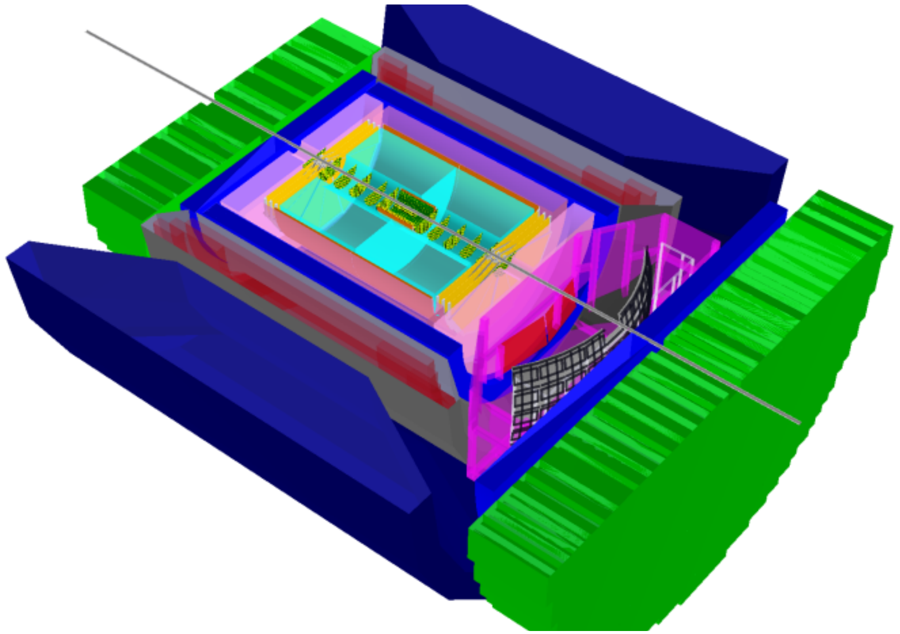
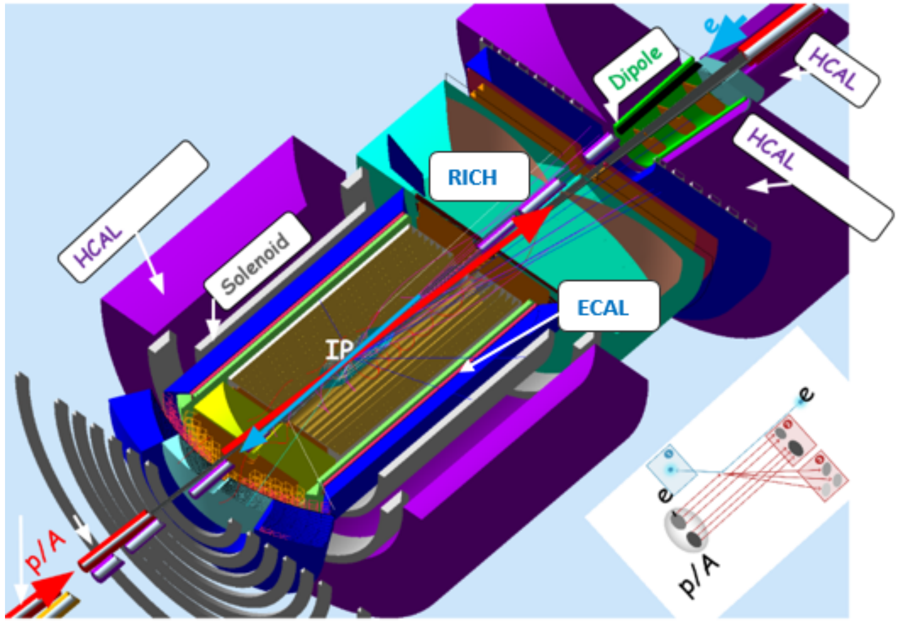
- To measure heavy flavor products, jets and their correlations in the hadron/nuclei going (forward) direction at the EIC, a Forward Silicon Tracking (FST) detector is needed.

**Brookhaven EIC detector concept: BEAST**



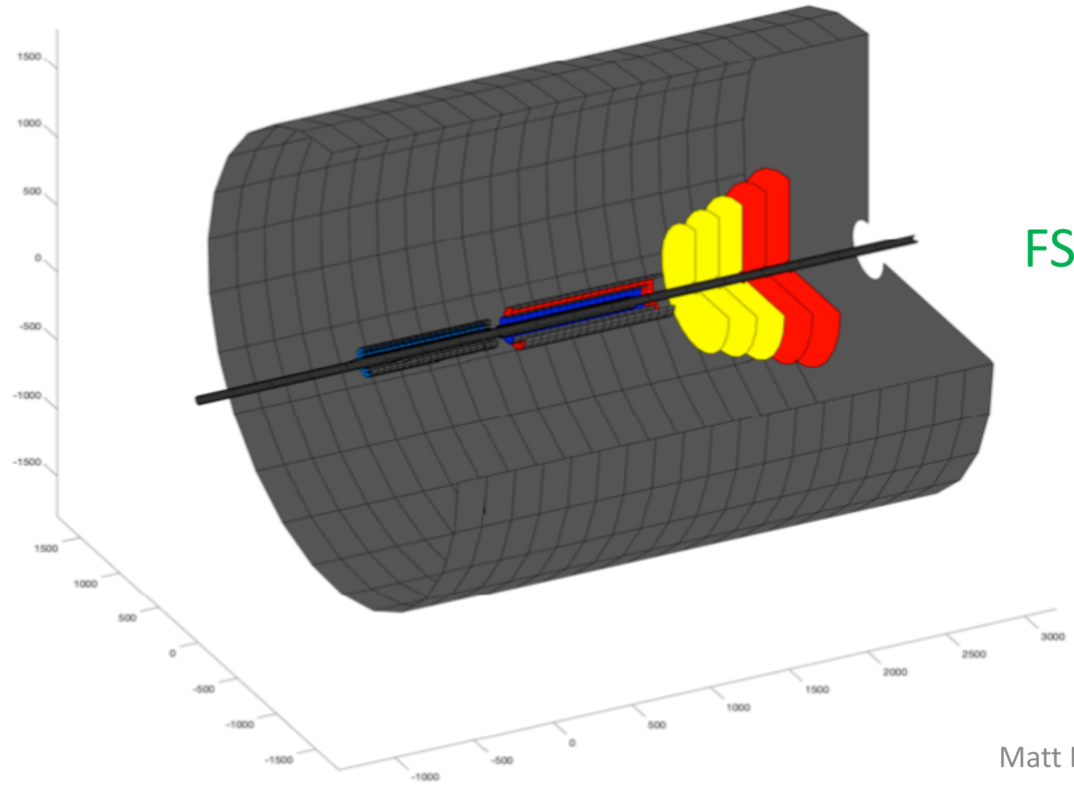
**Jefferson lab EIC detector concept: JLEIC**



# EIC studies at Los Alamos

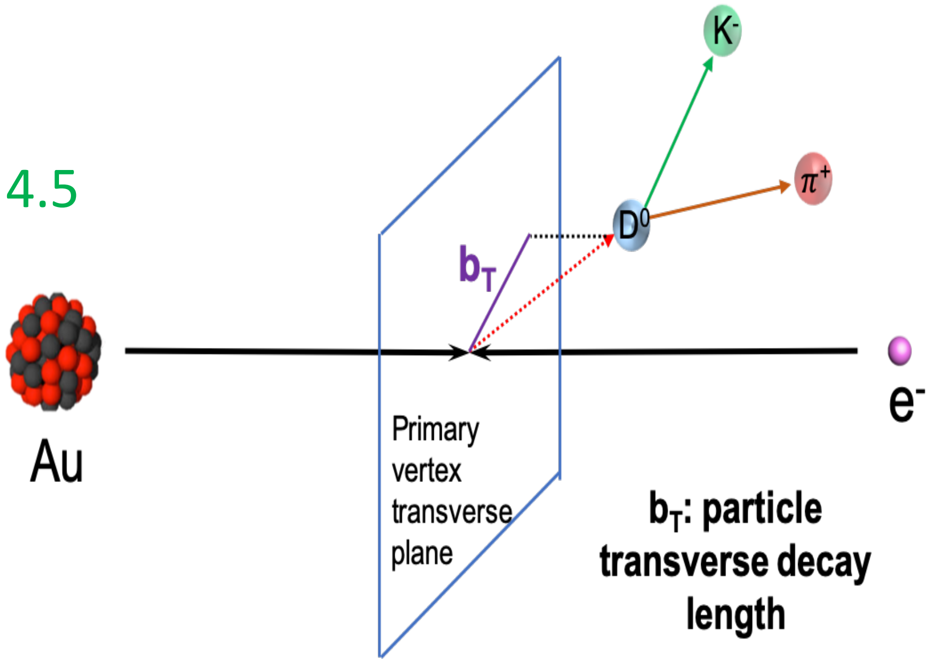
**Slide from Xuan Li**

- Detector design in fast simulation:
  - Mid-rapidity silicon vertex detector: 3 barrel layers of Monolithic Active Pixel Sensor (MAPS) type detector.
  - Forward-rapidity silicon tracking detector (FST): 3 barrel layers of MAPS + other silicon detector and 5 forward planes of MAPS + other silicon detector.



B = 3T

FST: $1.0 < \eta < 4.5$



# EIC studies at Los Alamos

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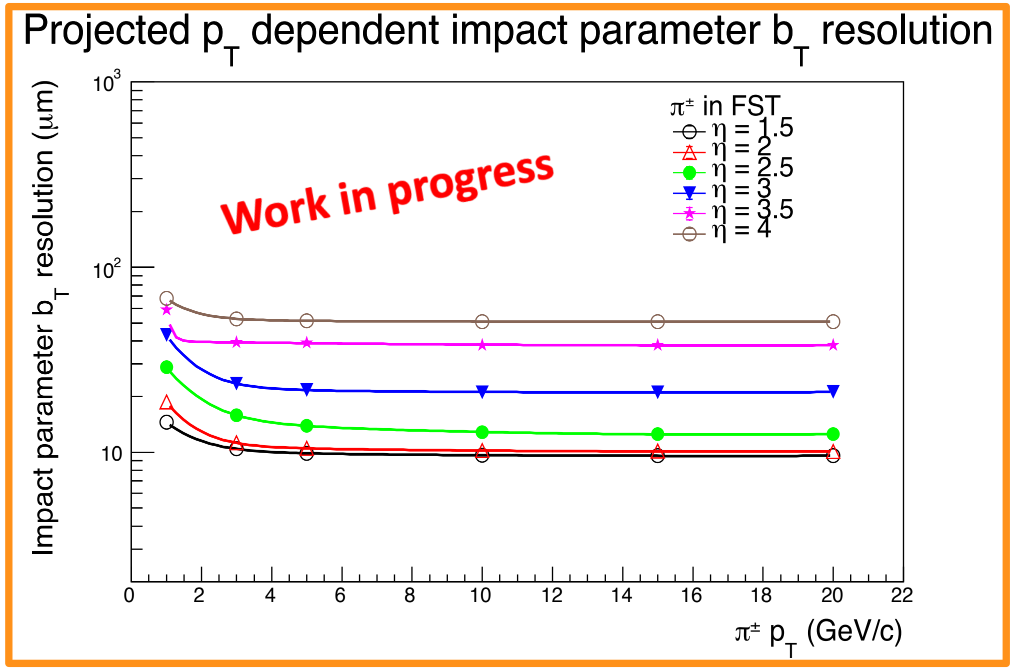
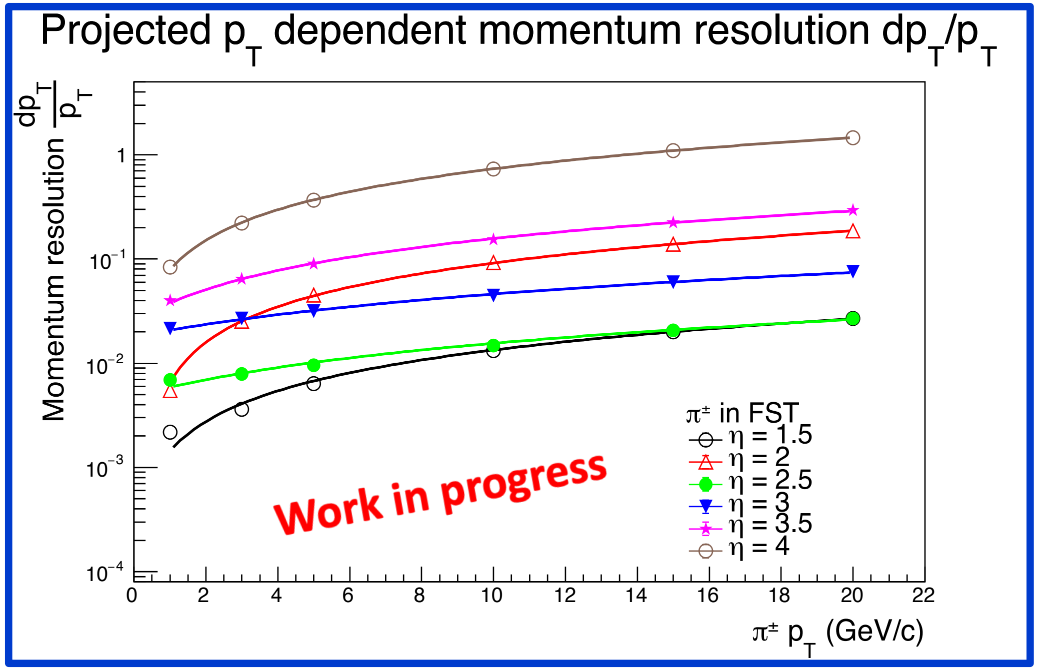
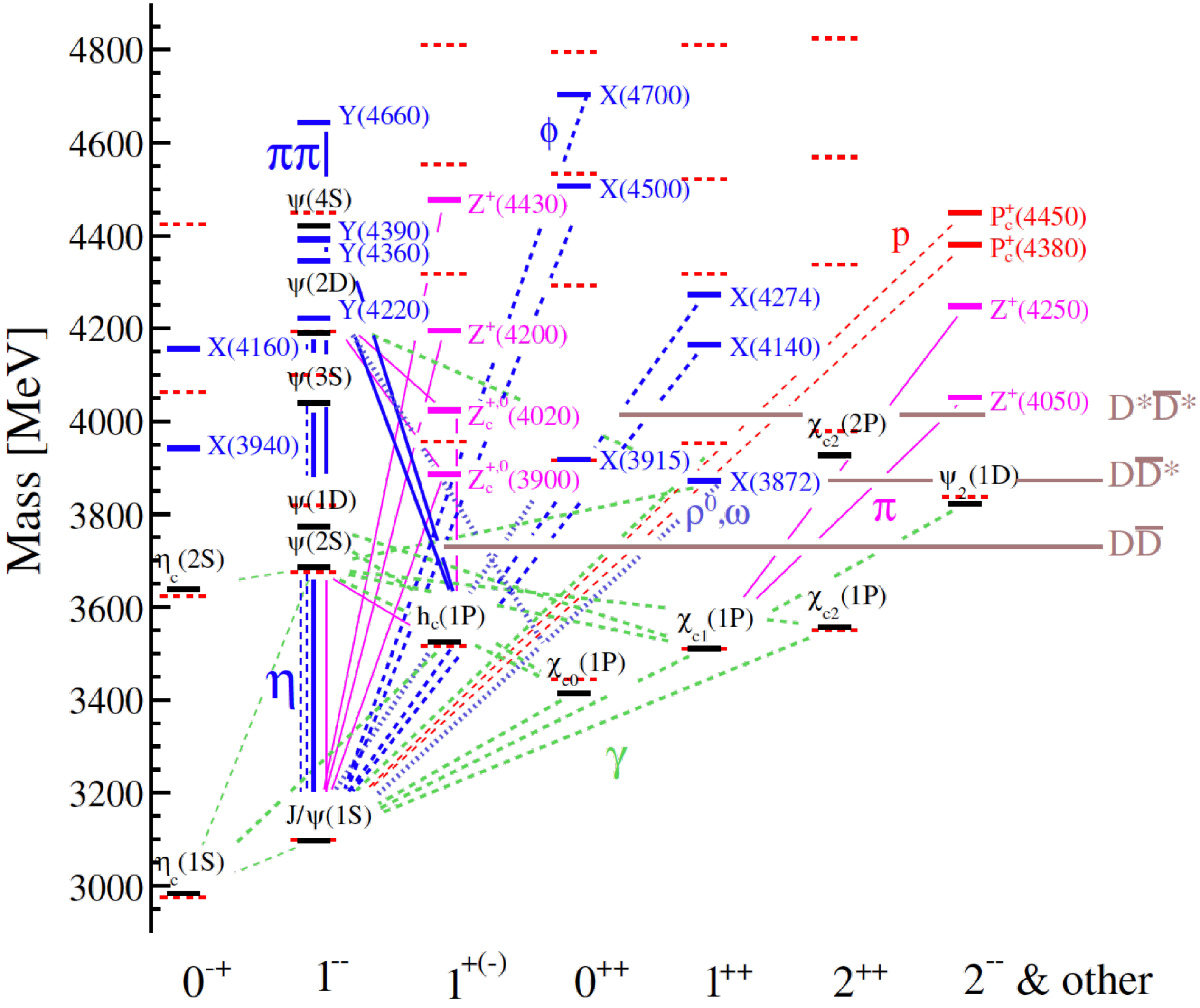
- Evaluated FST track performance from the fast simulation:




- Better than 70 $\mu$m resolution can be achieved by the initial FST design for the transverse decay length $b_T$ measurements for tracks with $p_T > 1$ GeV/c over the $1.5<\eta<4.0$ region.
- The momentum resolution $dp_T/p_T$ are better than or consistent with the forward tracking requirements from the EIC detector handbook.

# Exotic Charmonium Production

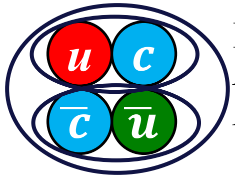



Rev. Mod. Phys. 90, 015003 (2018)

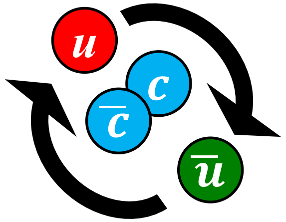
**20+ states containing $c\bar{c}$ have been discovered since 2003 that do not fit in the picture of typical charmonium: Collectively known as "*XYZ*" particles**

**Multiple explanations explored in literature:**

**Compact tetraquark/pentaquark**

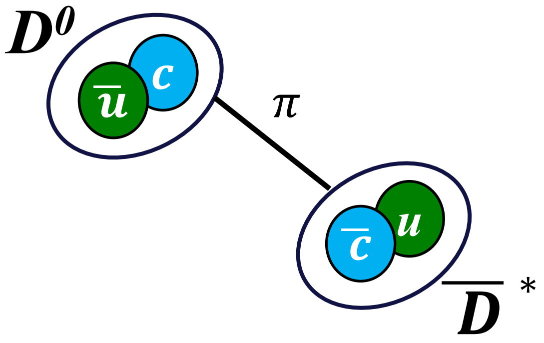


**Diquark-diquark**
*PRD 71, 014028 (2005)*
*PLB 662 424 (2008)*



**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 of exotic + conventional states**

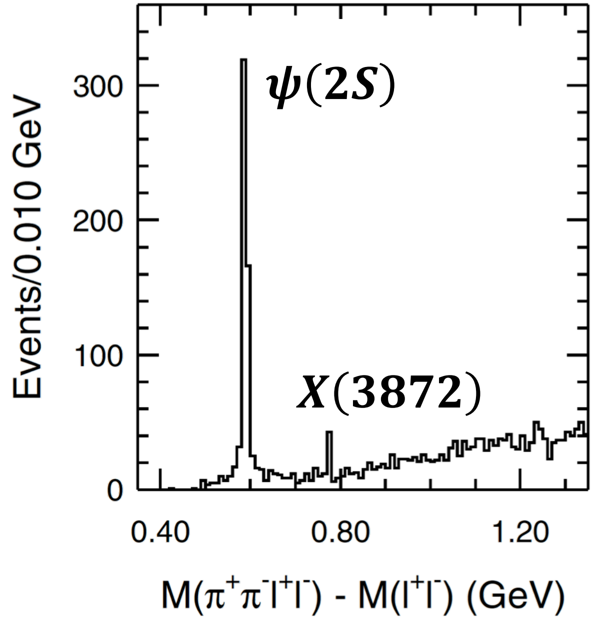
$$X = a|c\bar{c}\rangle + b|c\bar{c}q\bar{q}\rangle$$

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

# X(3872) - a puzzle

Recently renamed $\chi_{c1}(3872)$ by PDG

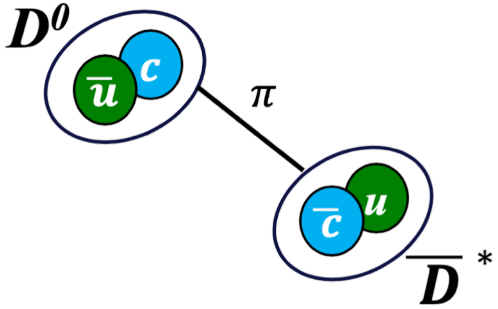
Belle Collaboration
PRL 91 262001 (2003)




- The first exotic hadron – discovered in $J/\psi\pi^+\pi^-$ mass spectrum from B decays by Belle in 2003
- LHCb measured quantum numbers (PRL 110 222001 2013)
  - Incompatible with expected charmonium states
- Mass is consistent with sum of $D^0$ and $\overline{D}^{*0}$ masses:

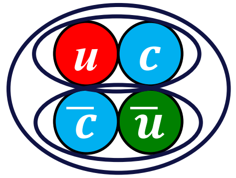
$$M_{\chi_{c1}(3872)} - (M_{D^0} + M_{\bar{D}^{*0}}) = 0.01 \pm 0.27 \text{ MeV}$$

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



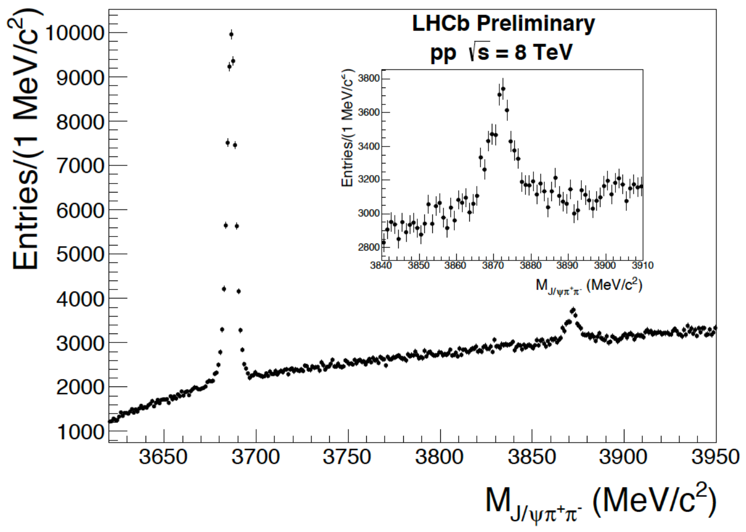

***VERY* small binding energy**
***VERY* large radius, ~7 fm**

***Compact tetraquark***




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

# X(3872) at LHCb – hints of breakup

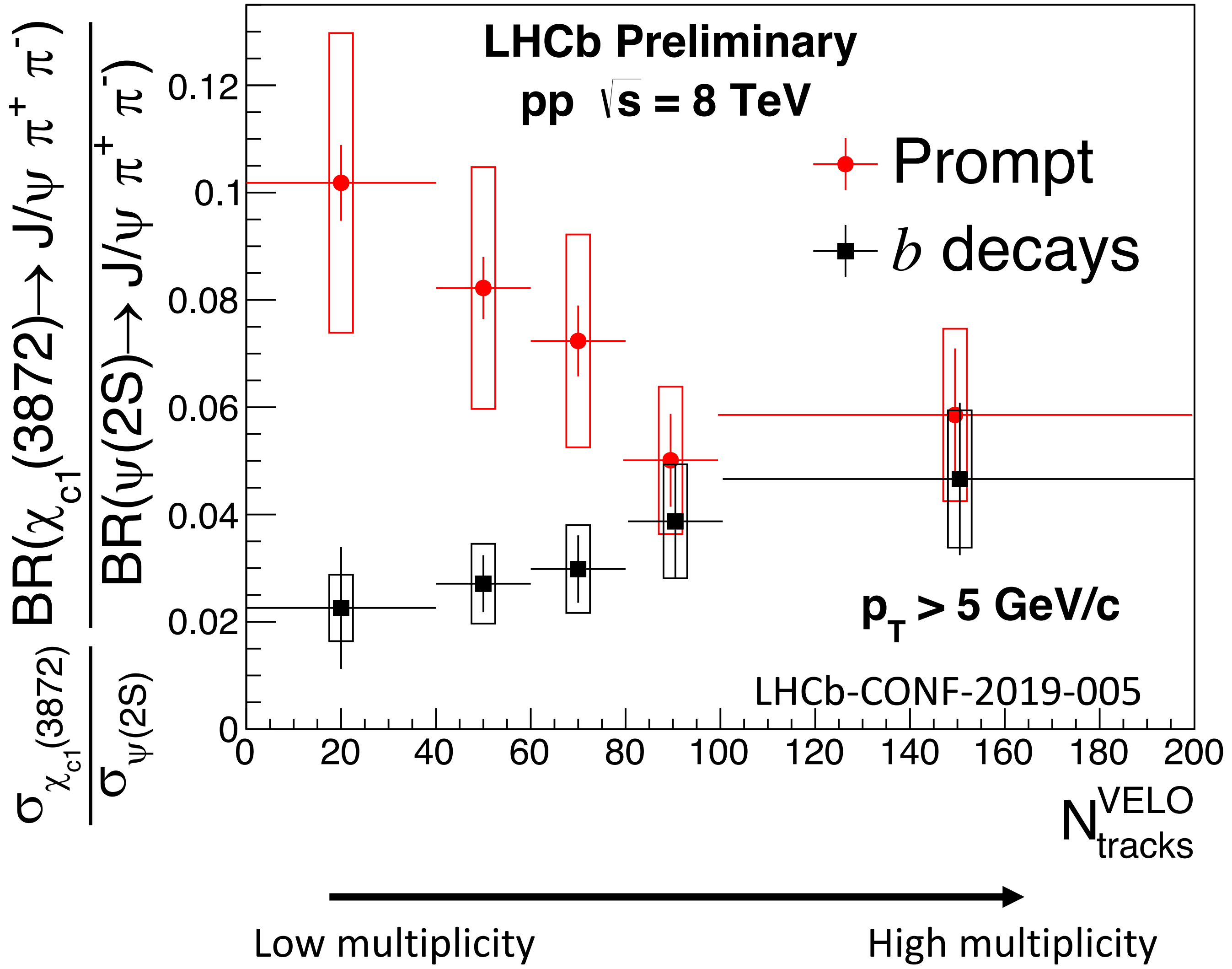



Prompt X(3872) may be disrupted via late-stage interactions with hadrons

Production via b-decays in vacuum are NOT subject to further effects

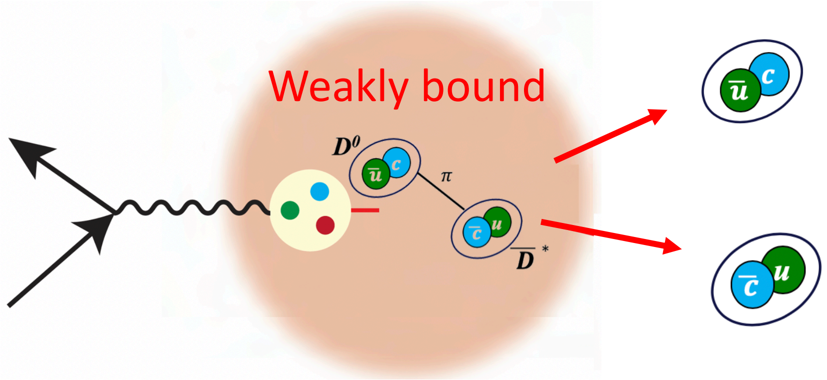
This is the first look at probing exotics via their interactions with other hadrons

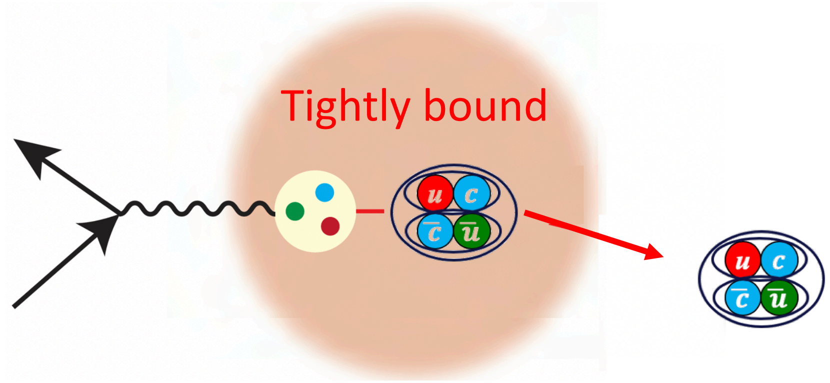
https://cds.cern.ch/record/2701519



# X(3872) Production Inside the Nucleus at EIC

- Many exotic hadrons have only been observed as products of B decays
  - Reconstruction can be significantly more complicated than $J/\psi \rightarrow \mu\mu$
  - EIC provides high rate, low background environment – necessary for precise measurements of direct production of exotics
- Production inside the nucleus exposes exotics to a dense QCD environment – potentially disrupting formation. Different nuclei give different path lengths.
- Effects are suspected to depend highly on binding energy: for X(3872), this may give discrimination between molecular and compact tetraquark pictures



# Summary

- Heavy quarks provide an appealing probe of QCD:
  - Production rates are calculable by pQCD
  - D,B states measurable via displaced decay vertices
  - Rich spectrum of quarkonia is accessible experimentally and theoretically

- Exotic States are not understood
  - Comparisons between production in a dense nuclear target vs production in proton and b-decays give new constraints on structure

- EIC gives us new tools to isolate and understand various effects

**Thanks to Los Alamos National Lab LDRD program for support**

# EIC Postdoc Positions Open at LANL

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https://labs.inspirehep.net/jobs/1757484

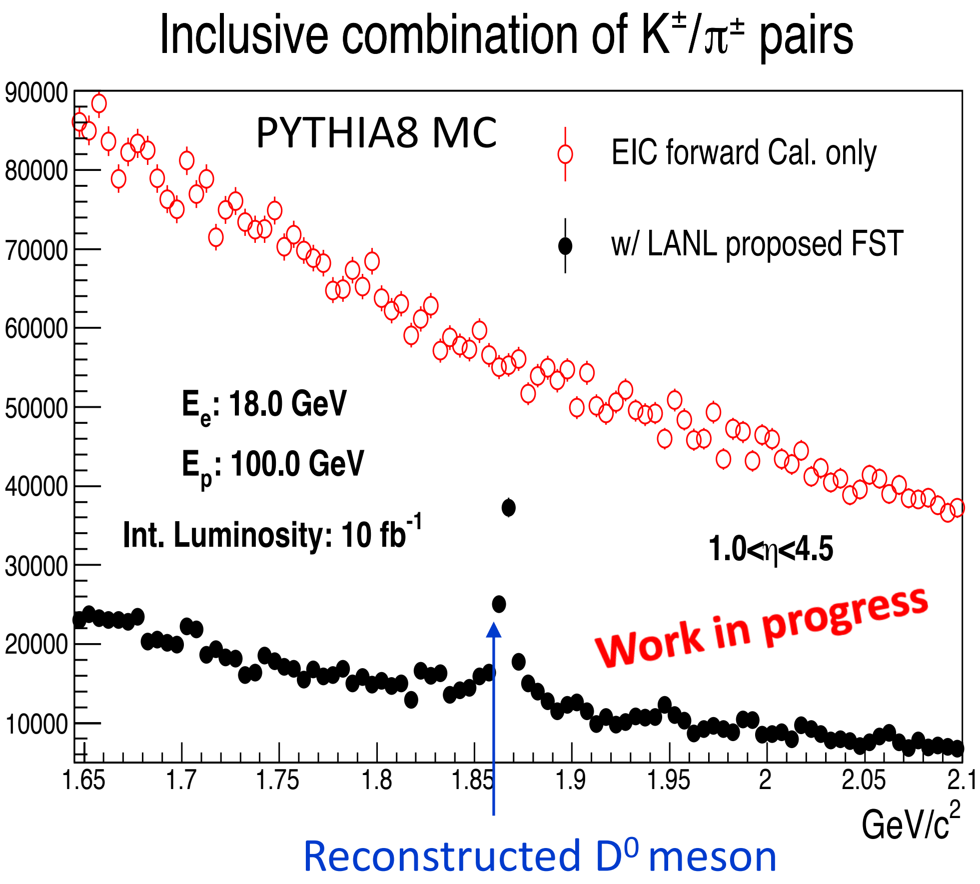
https://labs.inspirehep.net/jobs/1746549

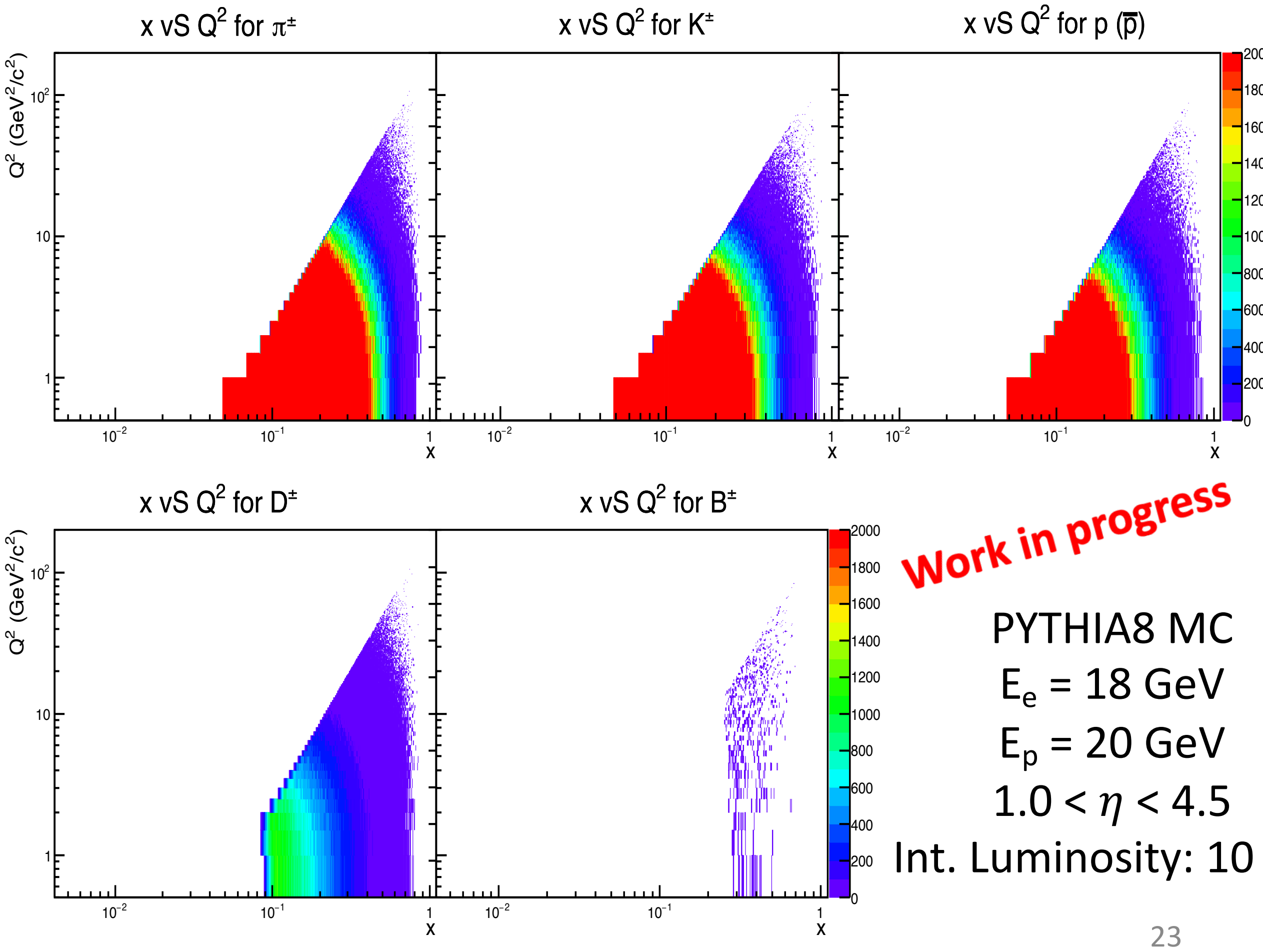
Work on developing EIC physics and advanced silicon detector R&D in conjunction with work in our existing physics programs: E1039/SpinQuest, PHENIX, sPHENIX, LHCb

# EIC studies at Los Alamos

**Slide from Xuan Li**

- The FST can clearly identify heavy flavor hadrons (such as $D^0$ meson) in a wide kinematic region and significantly reduce the combinatorial background the reconstruction.




PYTHIA8 MC
$E_e$ = 18 GeV
$E_p$ = 20 GeV
$1.0 < \eta < 4.5$
Int. Luminosity: 10 $fb^{-1}$

# Theory connection at LANL

**Slide from Xuan Li**

- Competing models of nuclear modification in DIS reactions with nuclei (e.g HERMES data). Differentiation not possible with light hadrons.
  - Hadronization inside nuclear matter (dashed lines).
  - Energy loss of partons, hadronization outside (solid lines).
- Heavy mesons have very different fragmentation functions and formation times
  - Easy to discriminate between larger suppression for D/B mesons (in-medium hadronization) and strong/intermediate z enhancement (E-loss).
  - Enhanced sensitivity to the transport properties of nuclei.

Projection in $\sqrt{s}$ = 69 GeV e+A collisions