CMS Experiment at the LHC, CERN

Experimental Study of the QGP with Quarkonia and the Exploration of Small Systems

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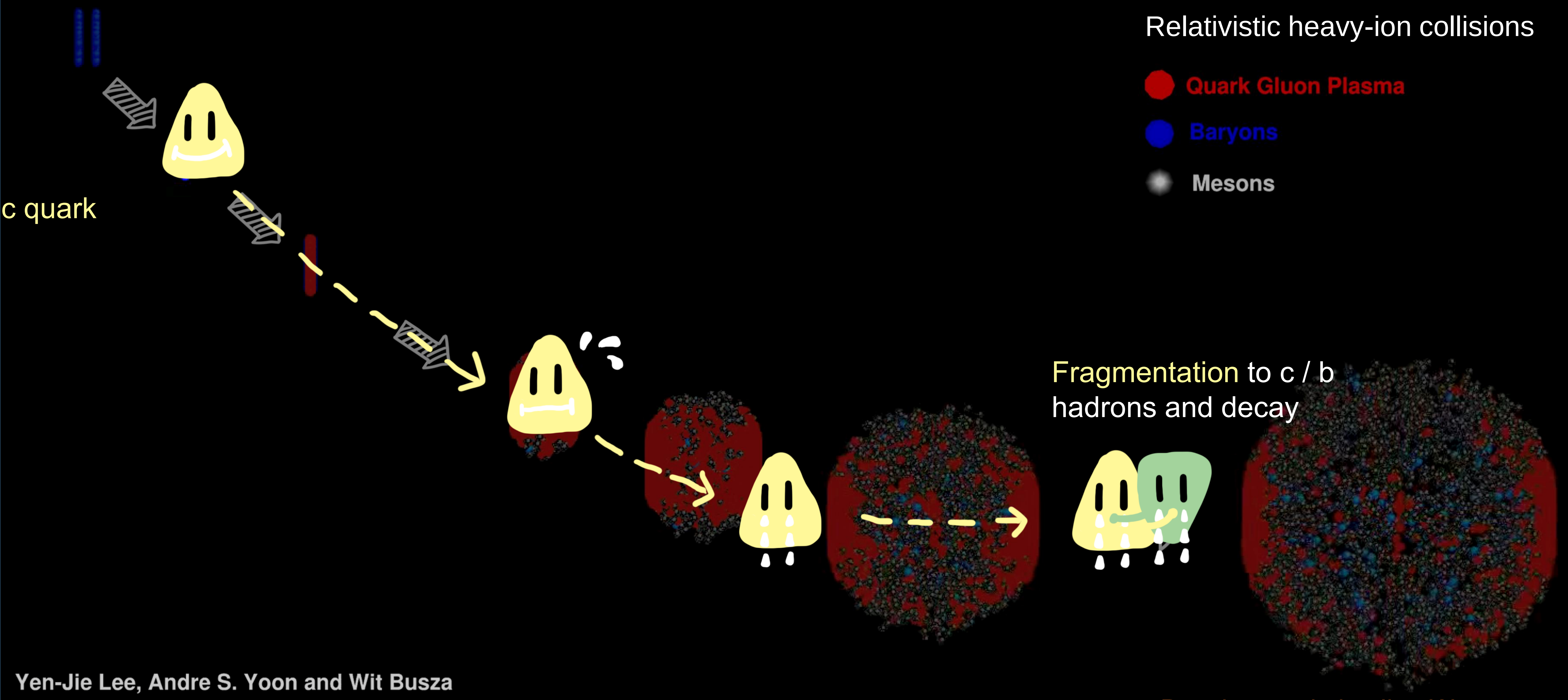
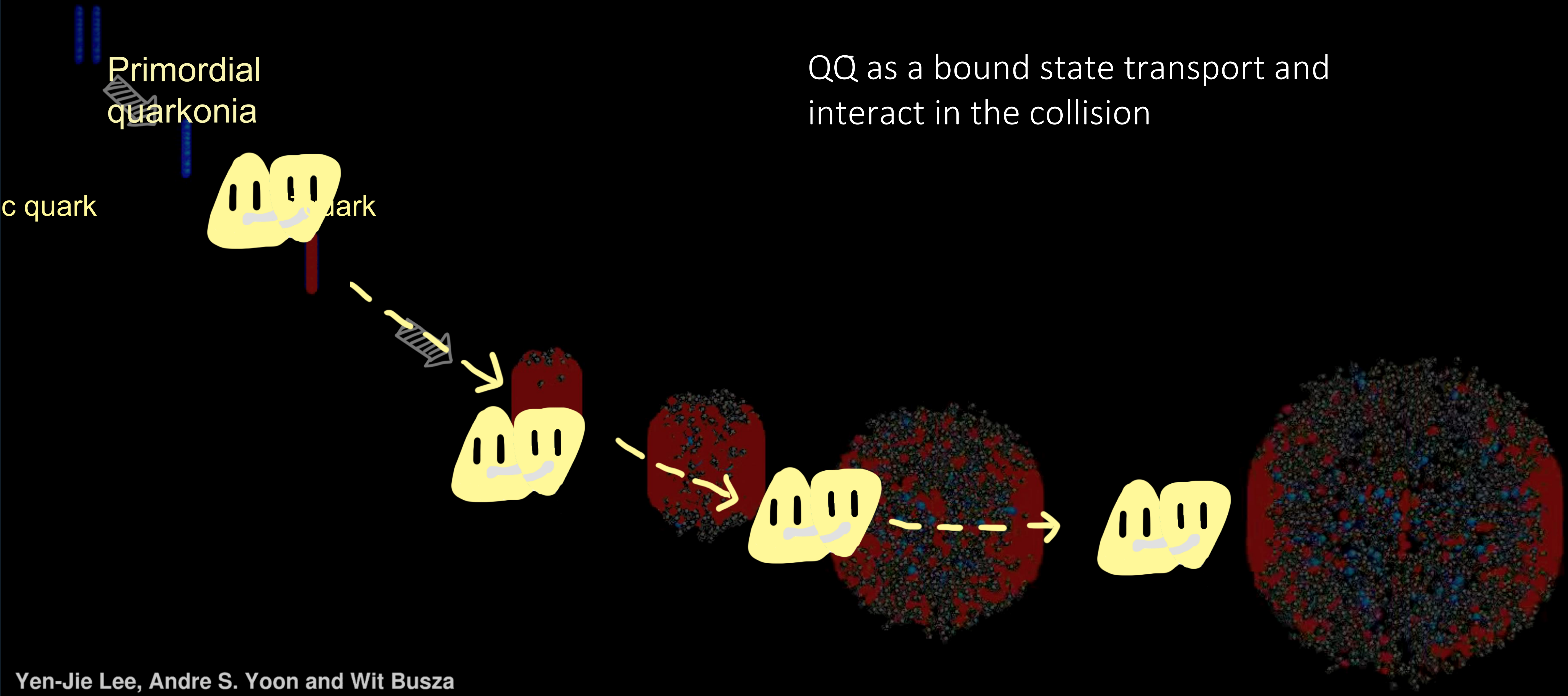
Recall: Open HF hadron in HIC



Drawing made by Jing Wang

Life of a Lucky Heavy Quarkonium in HIC

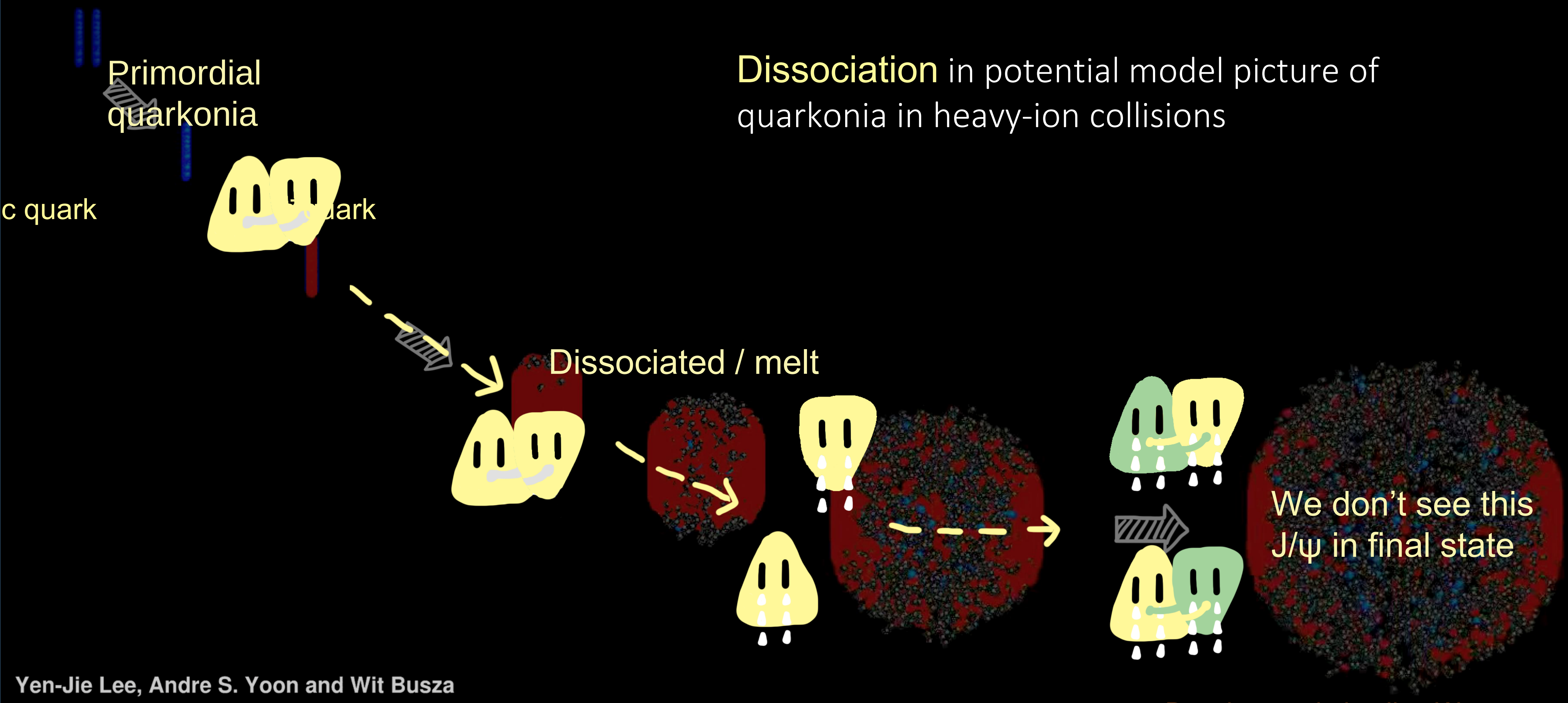
$Q\bar{Q}$ as a bound state transport and interact in the collision



Drawing made by Jing Wang

Life of an Unlucky Quarkonium in HIC

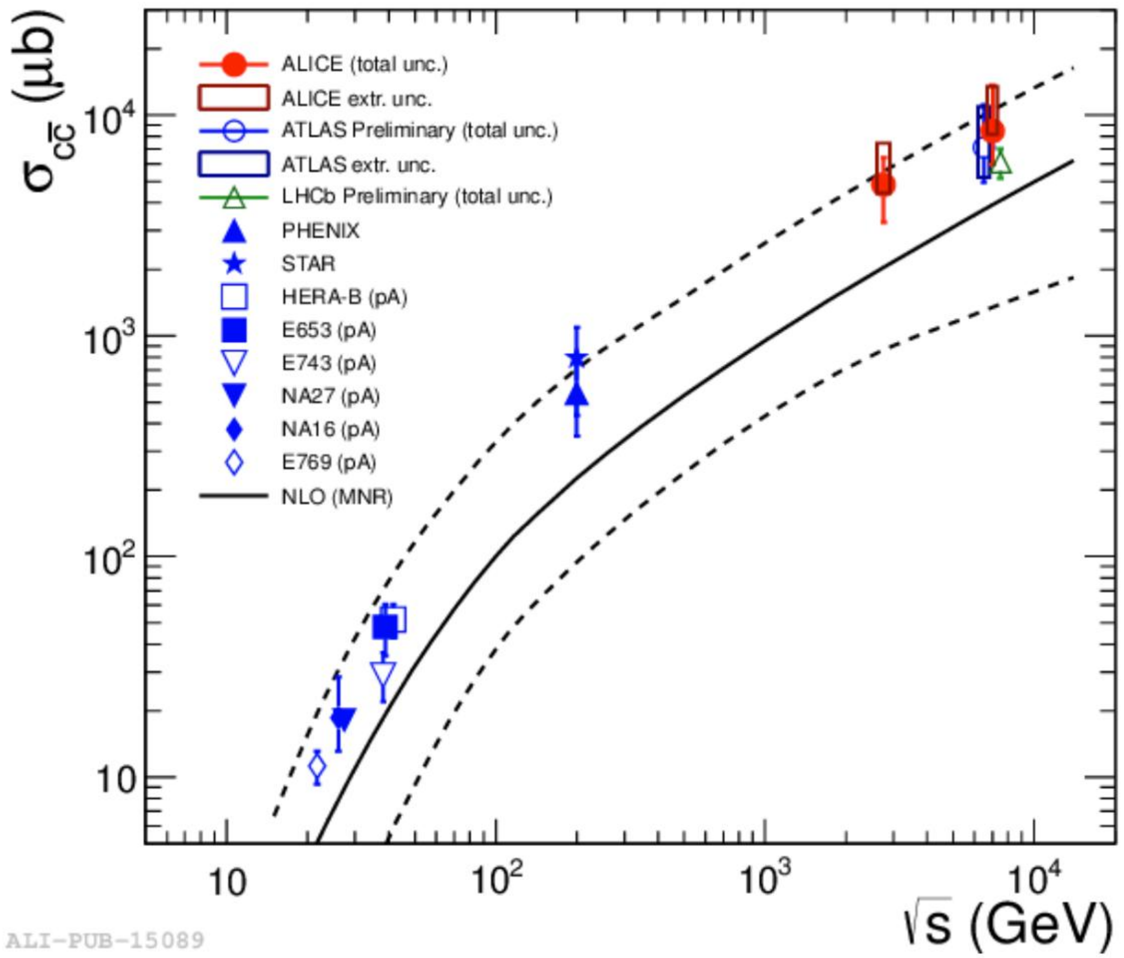
Dissociation in potential model picture of quarkonia in heavy-ion collisions

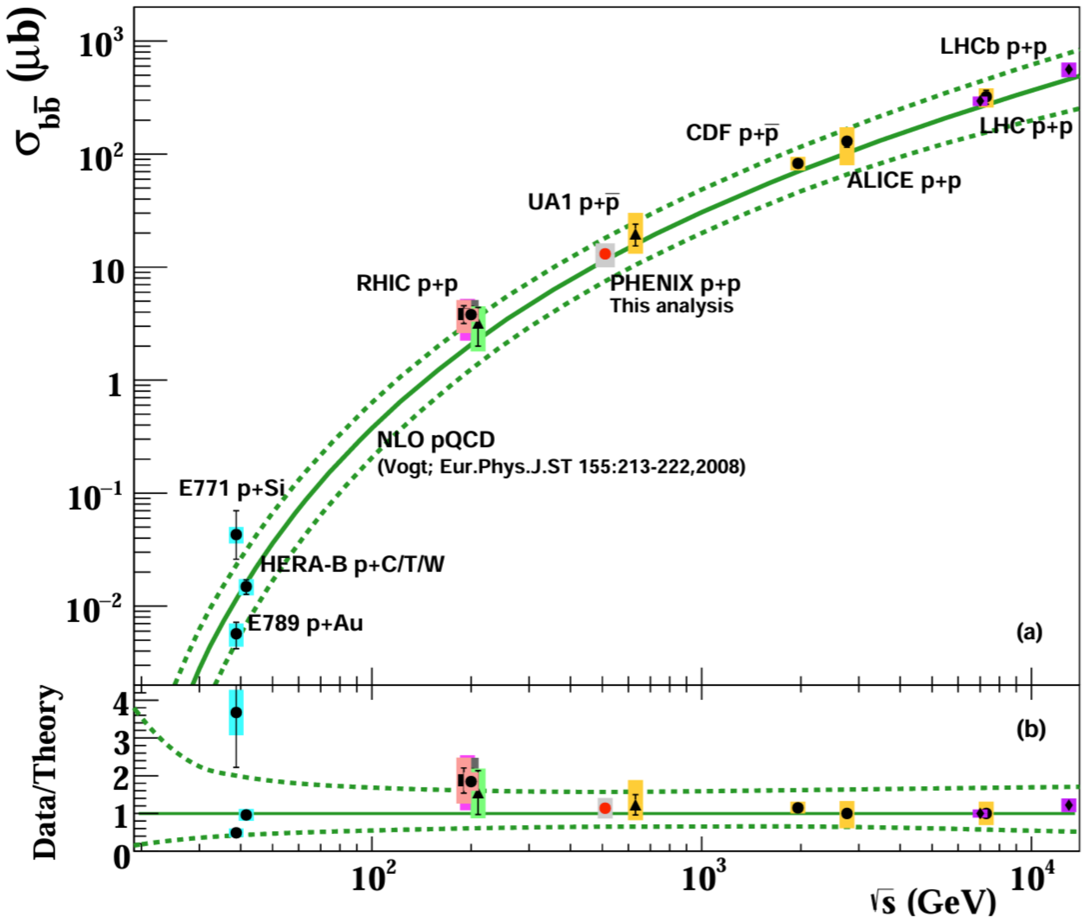


Drawing made by Jing Wang

How many $c\bar{c}$ and $b\bar{b}$ are produced OO vs. PbPb?

Estimation with pp and pA total cross-section





~ 15 pairs of $c\bar{c}$ in 0-5% AuAu at 0.2 TeV

~ 200 pairs of $c\bar{c}$ in 0-5% PbPb at 5 TeV

~ 1.7 pair of $c\bar{c}$ in inclusive OO at 5.36 TeV

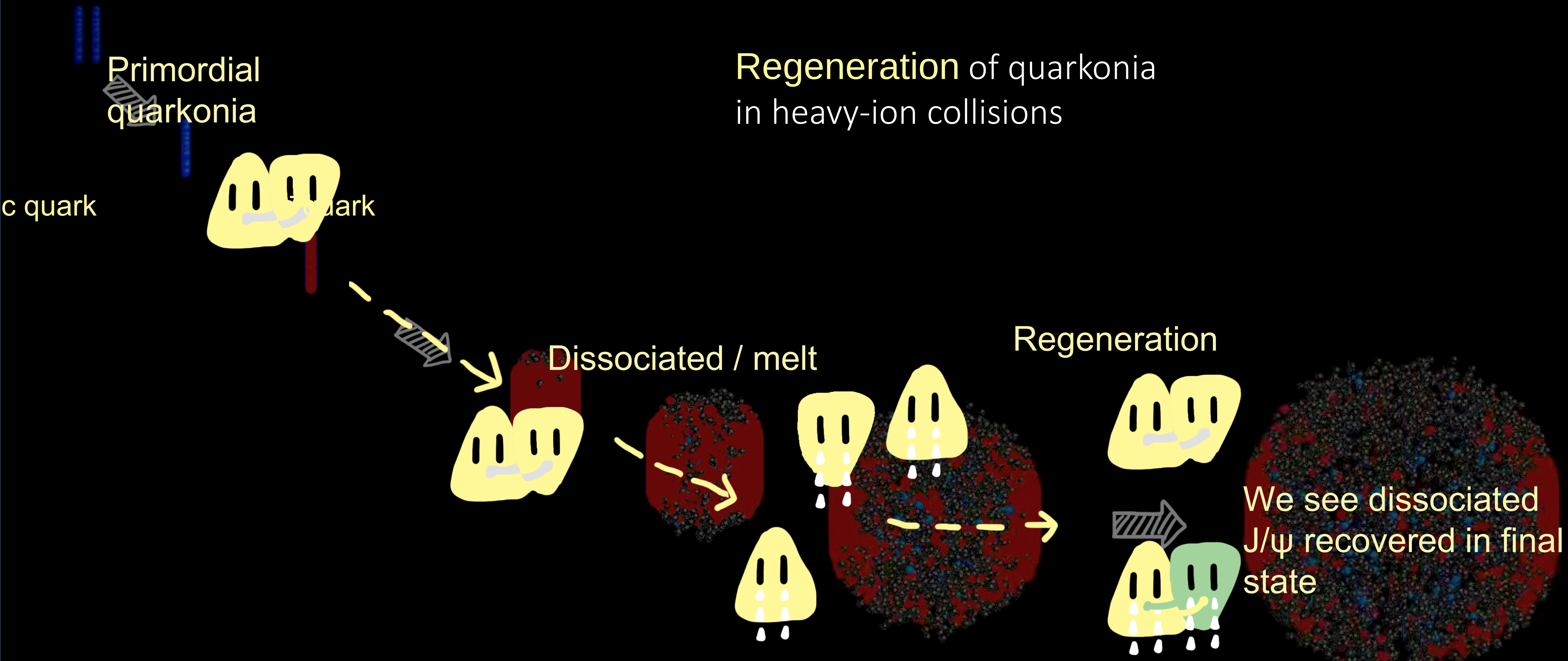
~ 0.75 pairs of $b\bar{b}$ in 0-5% AuAu at 0.2 TeV

~ 7 pairs of $b\bar{b}$ in central PbPb at 5 TeV

~ 0.05 pairs of $b\bar{b}$ in inclusive OO at 5.36 TeV

Life of a Lucky Quarkonium in HIC

Regeneration of quarkonia in heavy-ion collisions



Yen-Jie Lee, Andre S. Yoon and Wit Busza

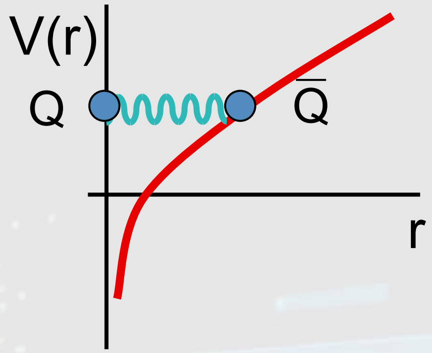
Drawing made by Jing Wang

QGP Temperature

- One interesting tool: the Bottomonium states!
- Bottomonium are rare probes

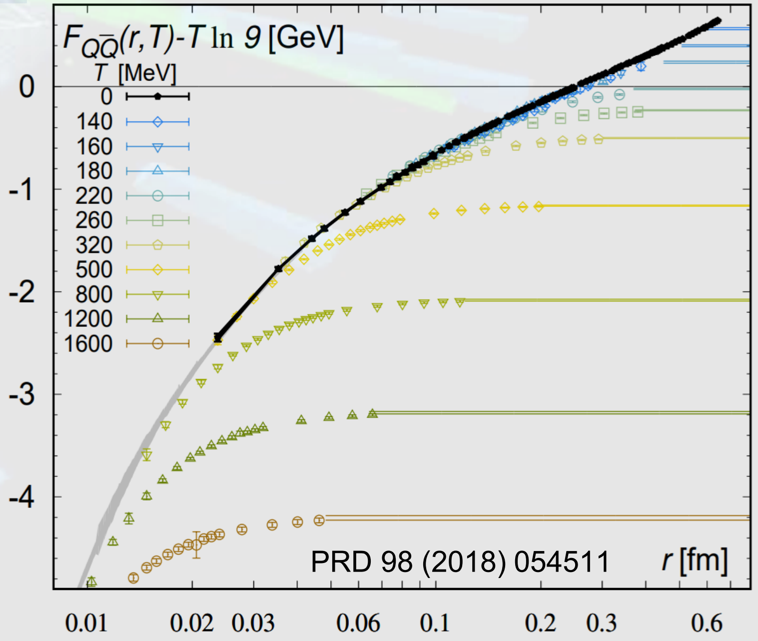
$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$

- Can be described by non-relativistic Schrödinger Equation



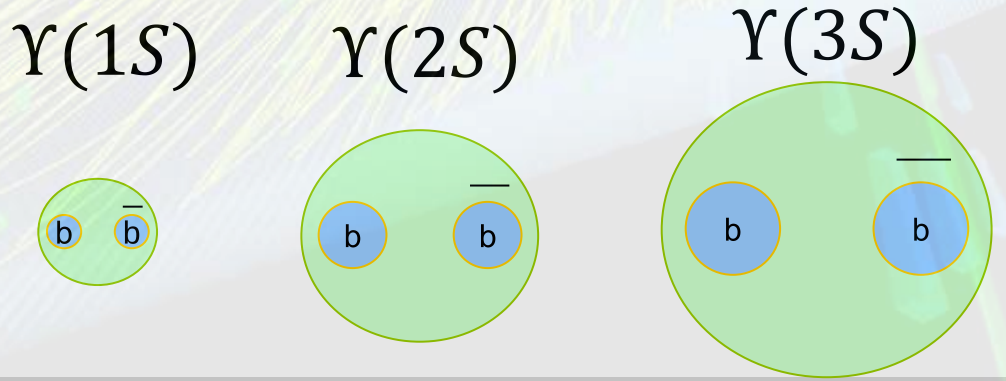
$b\bar{b}$ State	$\Upsilon(1S)$	$\chi_{bJ}(1P)$	$\Upsilon(2S)$	$\chi_{bJ}(2P)$	$\Upsilon(3S)$
Mass [GeV]	9.46	9.90	10.02	10.26	10.36
ΔE to $B\bar{B}$ threshold[GeV]	1.10	0.67	0.54	0.31	0.20
r_0 [fm]	0.28	0.44	0.56	0.68	0.78

Color Screening from LQCD

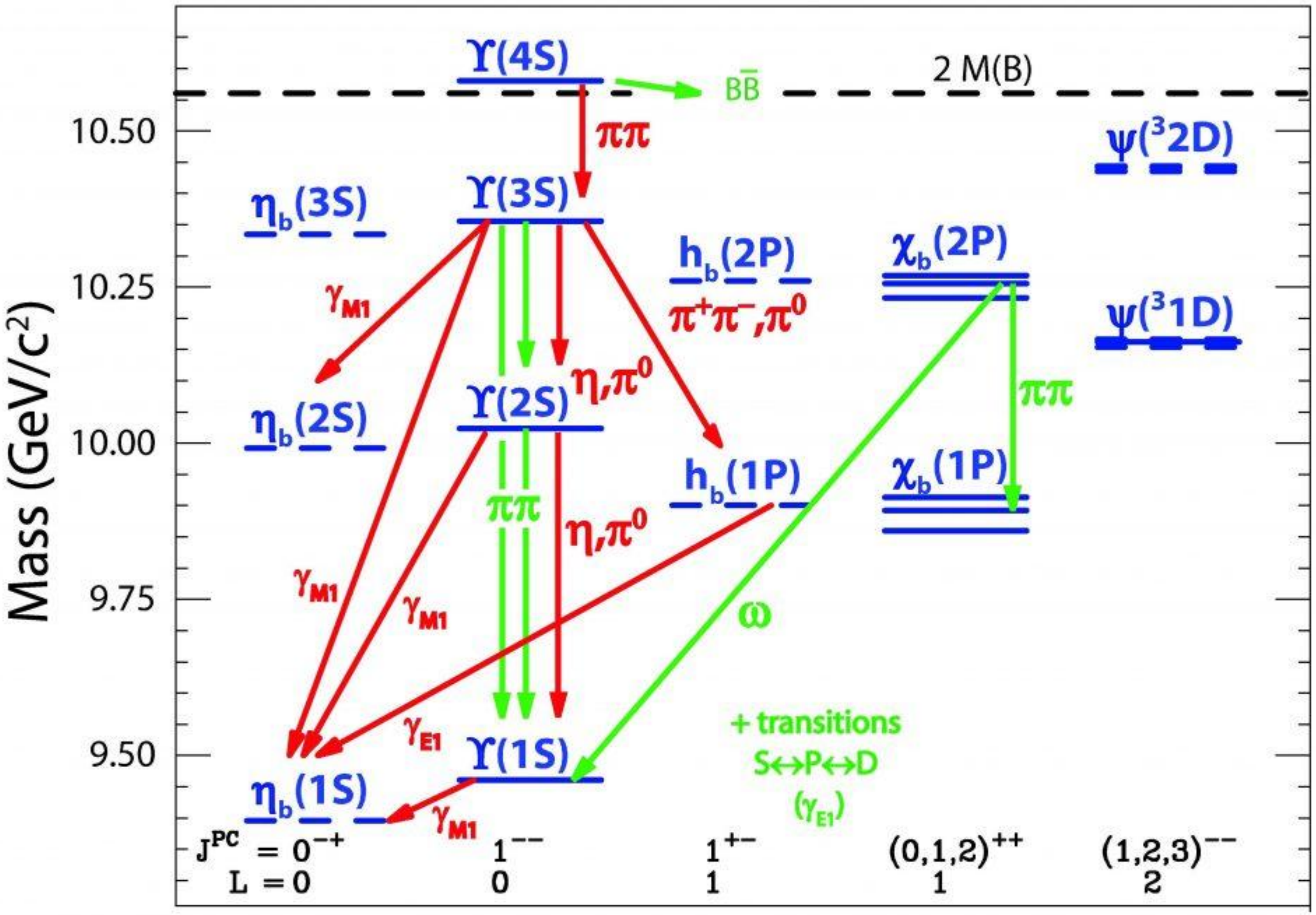


Tightly bound
Small in radius

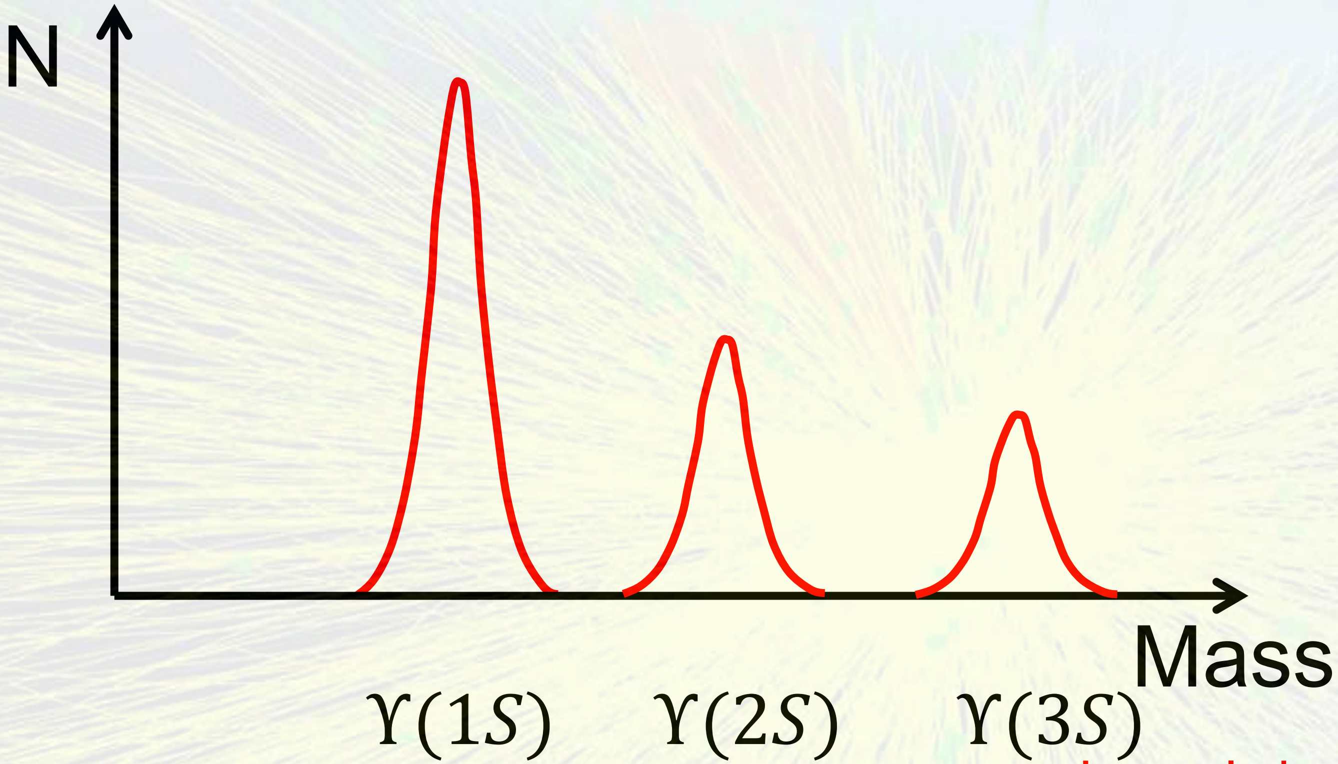
Loosely bound
Large in radius



Bottomium Family



In Vacuum (pp)



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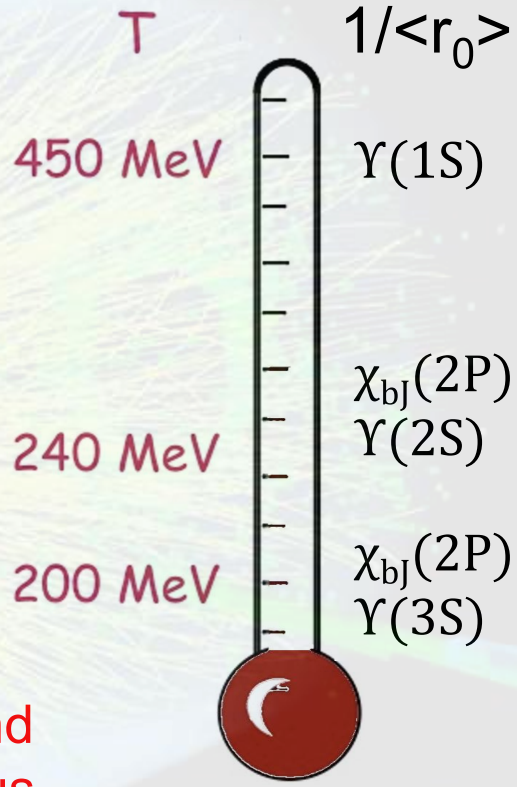
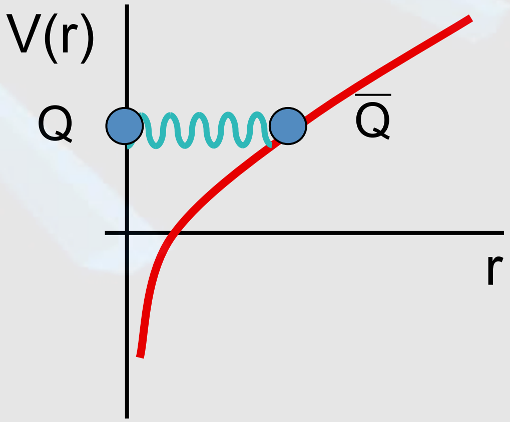
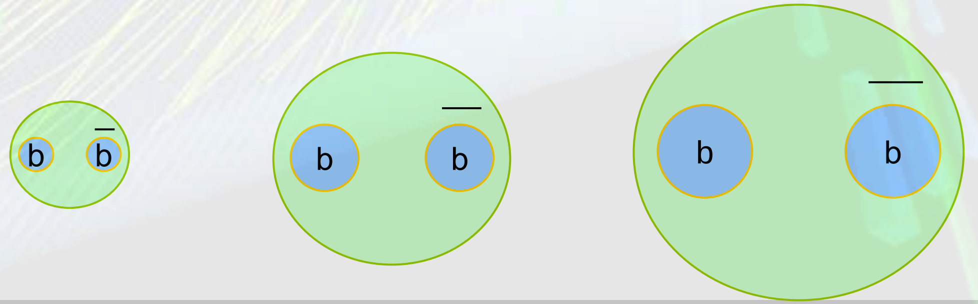
Artist's impression

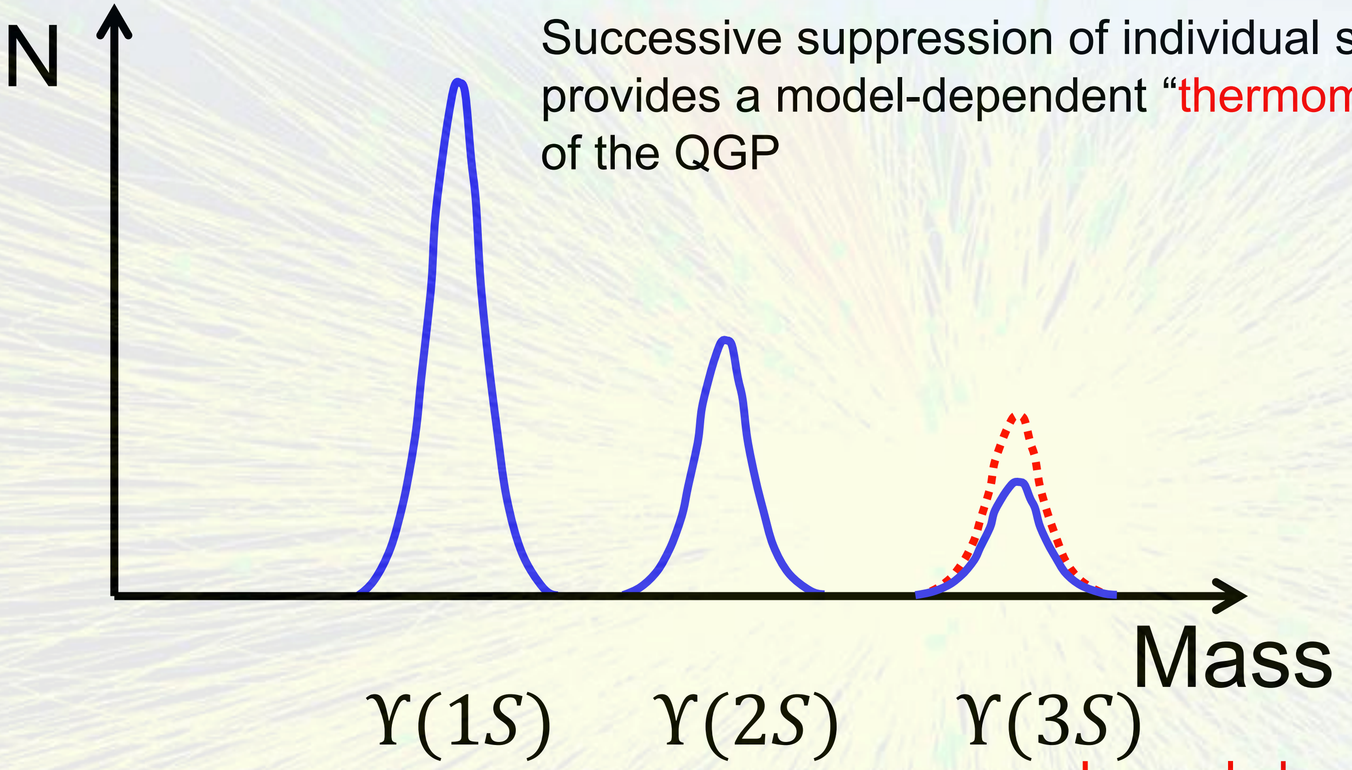


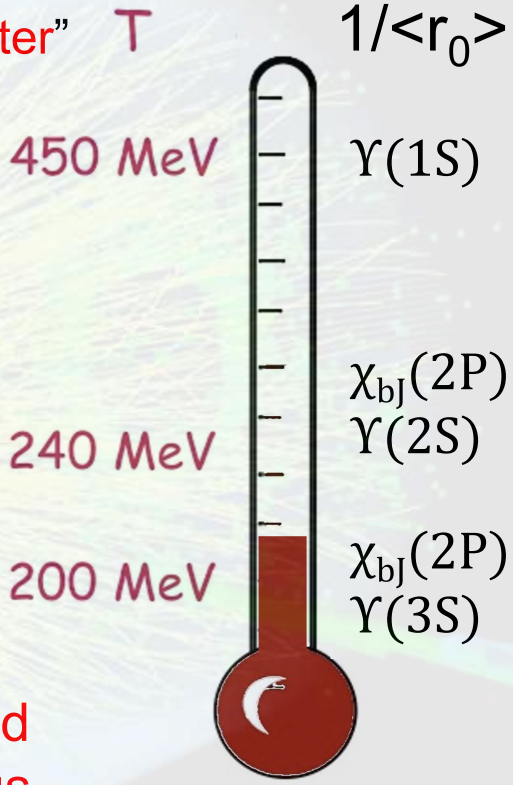




In QGP (lower Energy AA collisions / Peripheral AA)

Successive suppression of individual states provides a model-dependent "thermometer" of the QGP





Artist's impression

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Loosely bound
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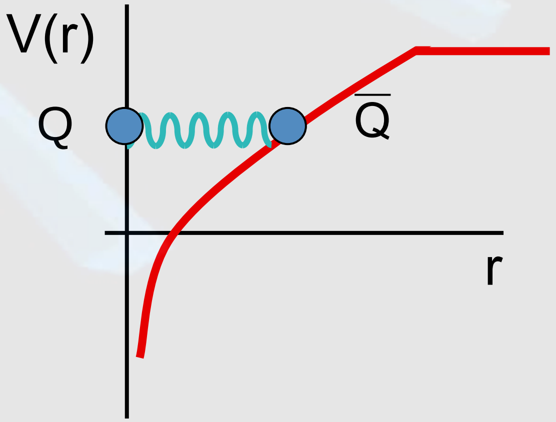
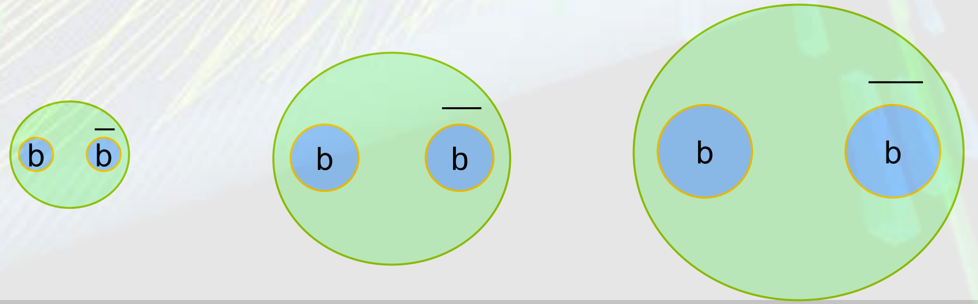
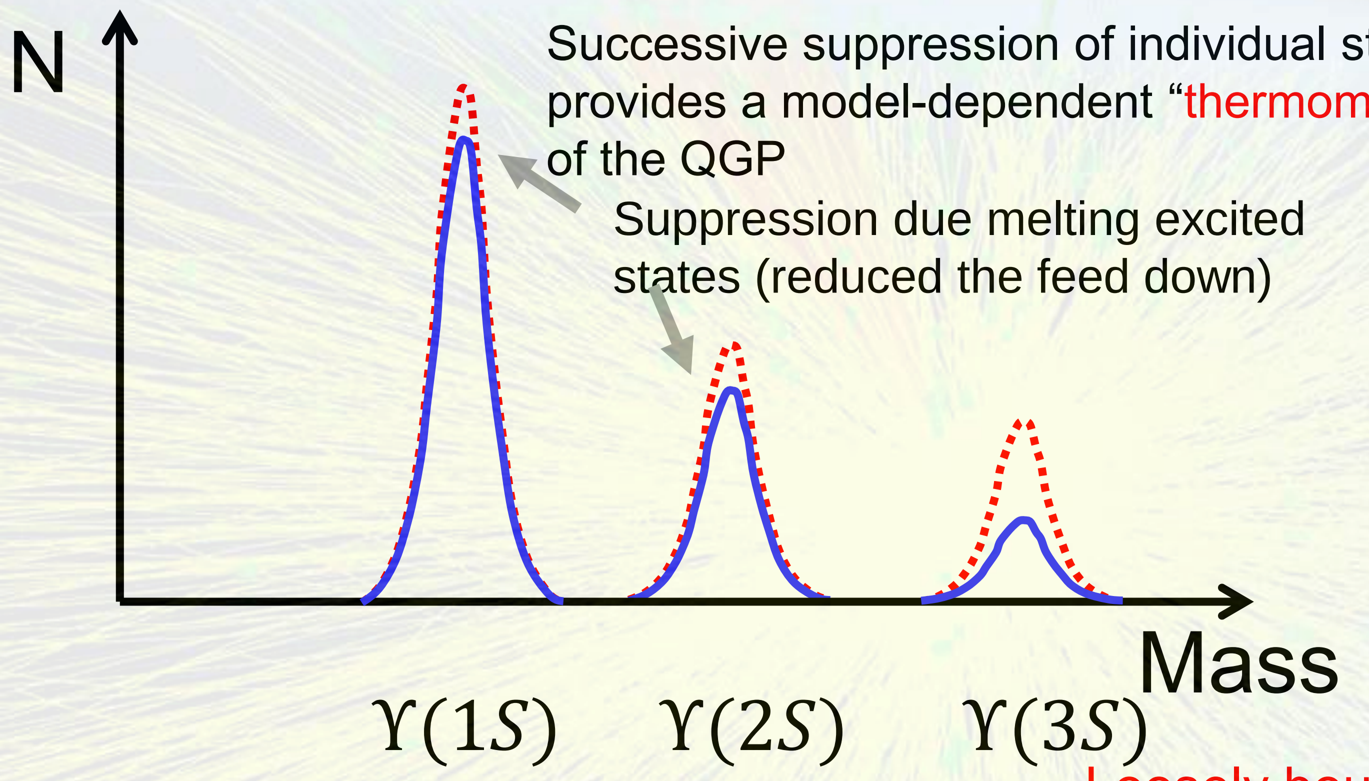




In QGP (AA collisions)

Successive suppression of individual states provides a model-dependent "thermometer" of the QGP

Suppression due melting excited states (reduced the feed down)



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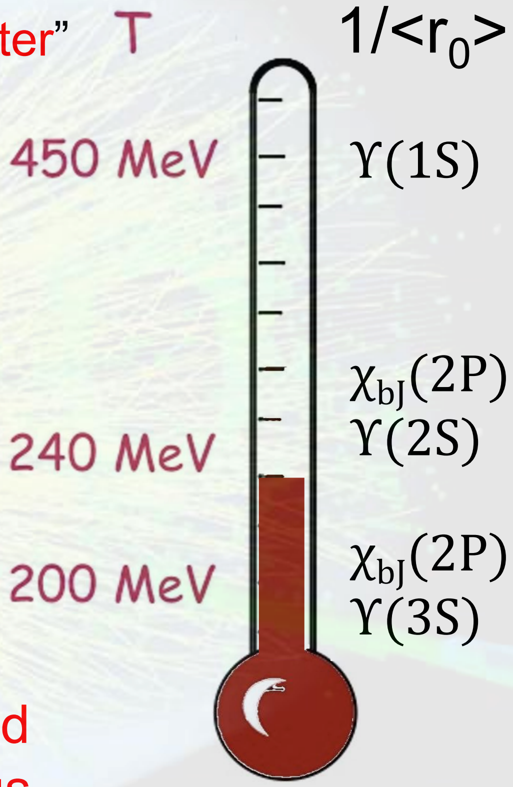
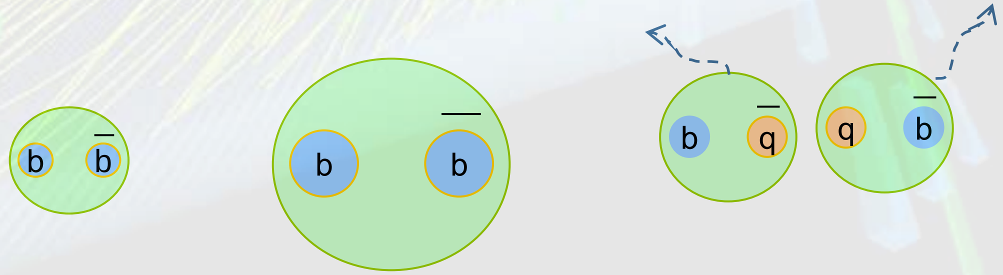
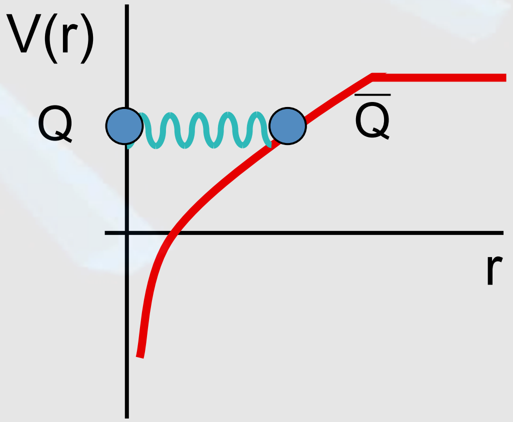
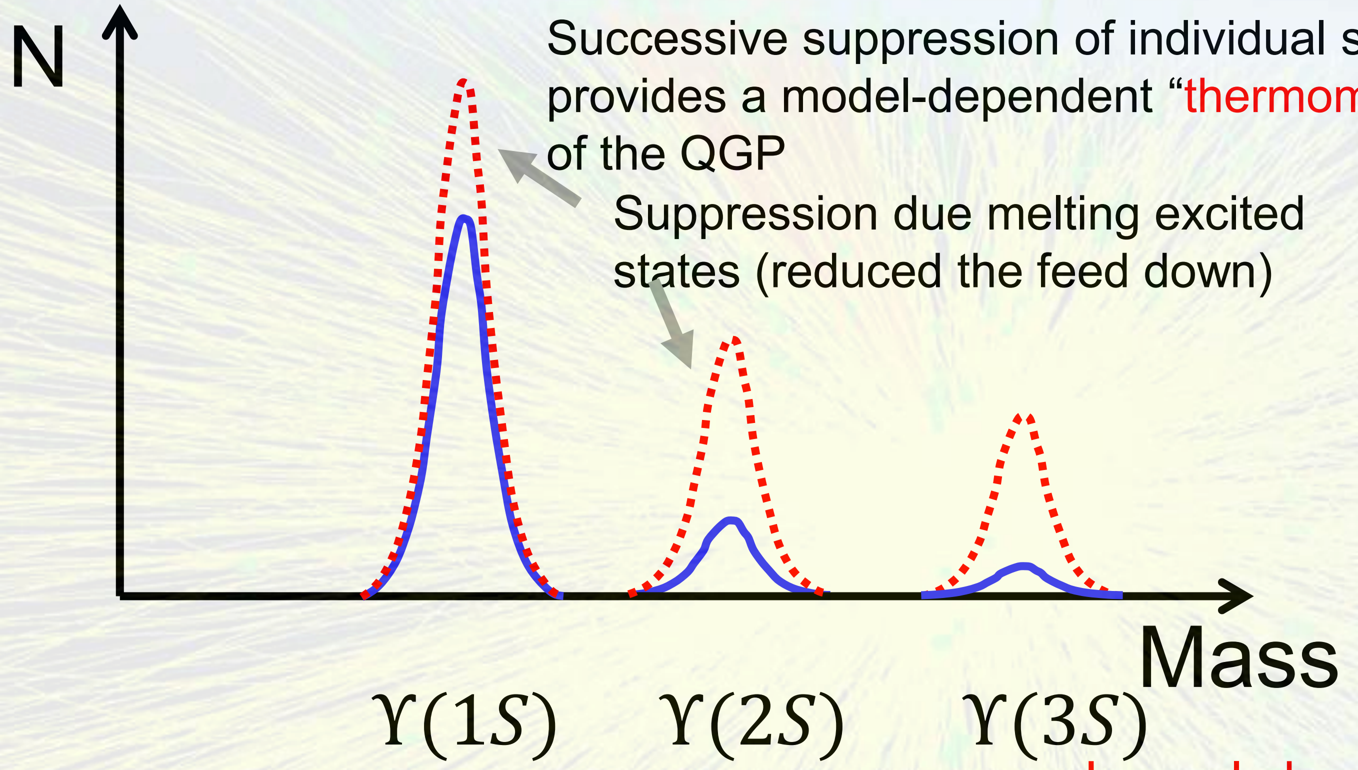






In QGP (AA collisions)



Successive suppression of individual states provides a model-dependent "thermometer" of the QGP

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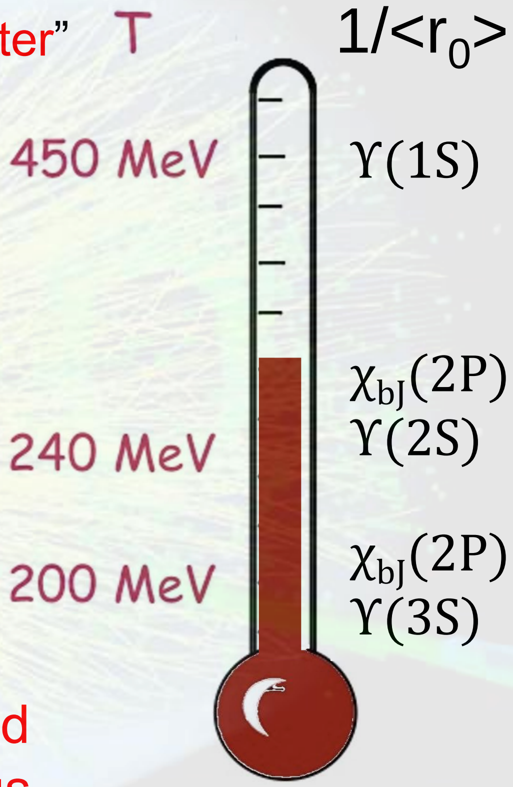

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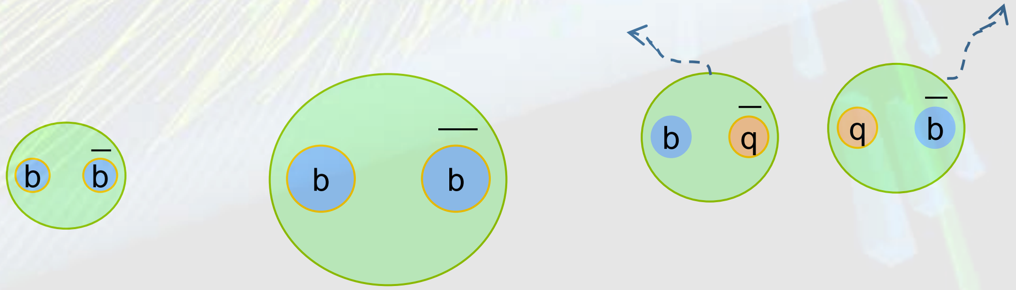
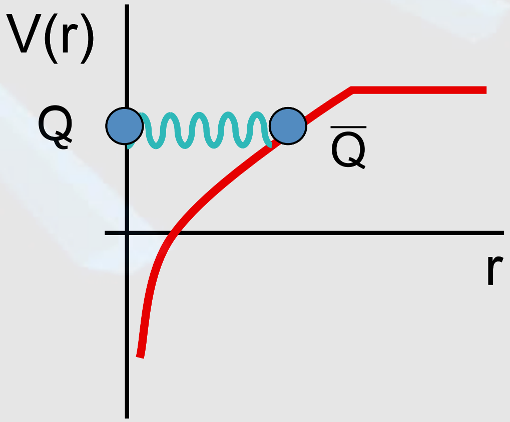
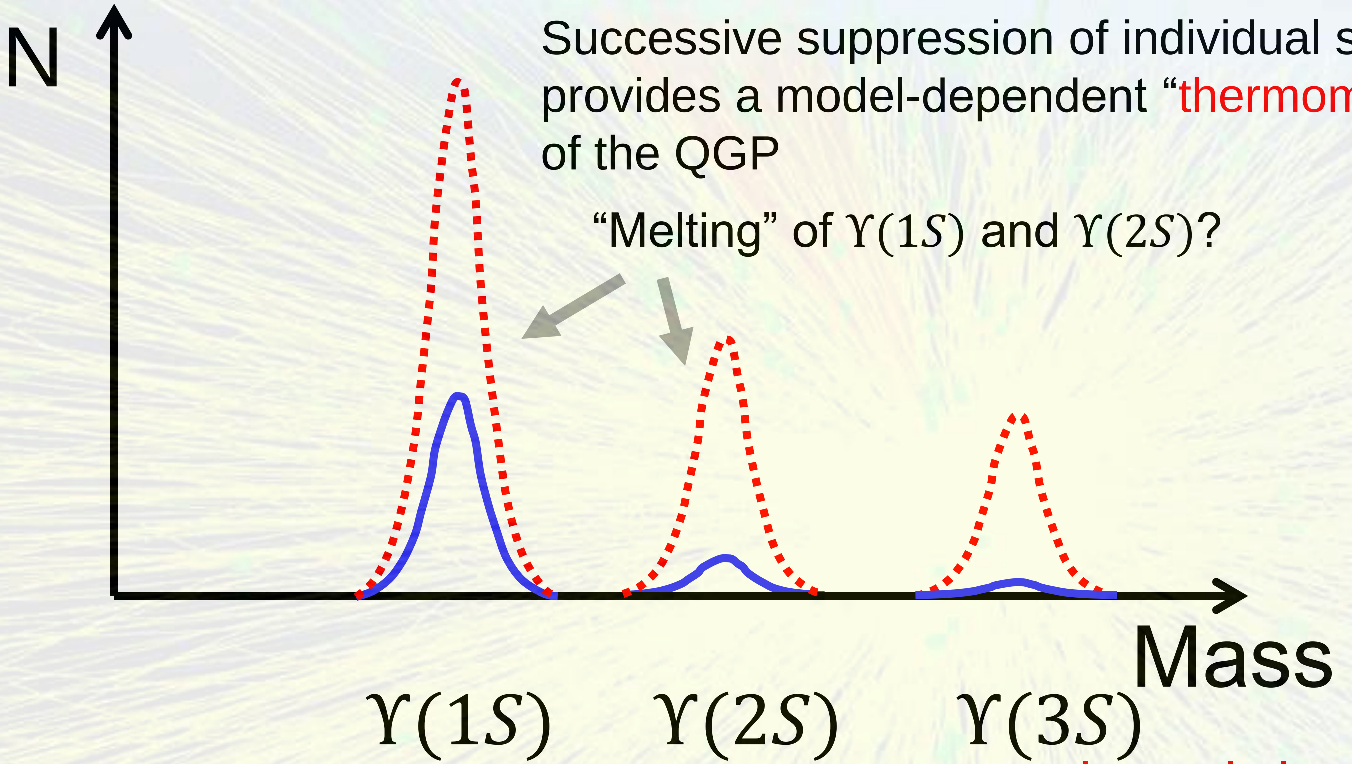


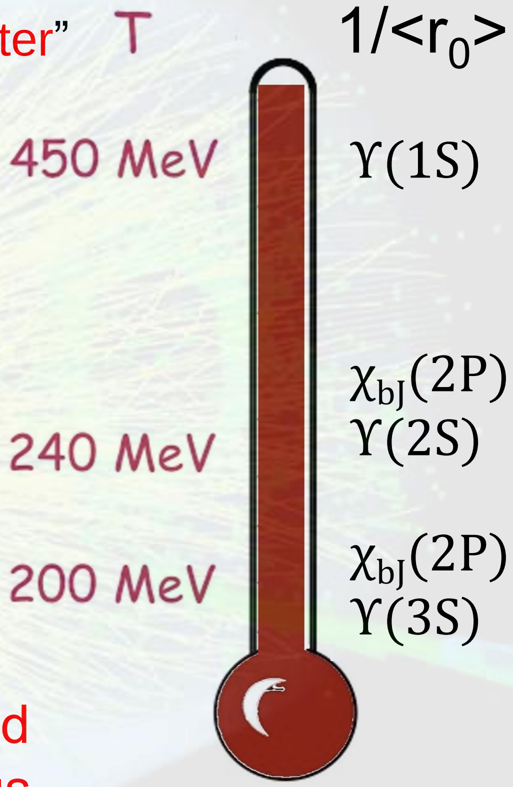


In QGP (AA collisions at LHC)

Successive suppression of individual states provides a model-dependent "thermometer" of the QGP

"Melting" of $\Upsilon(1S)$ and $\Upsilon(2S)$?





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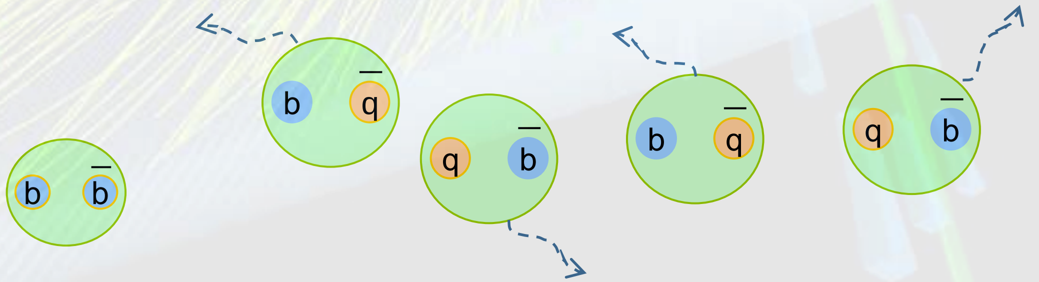
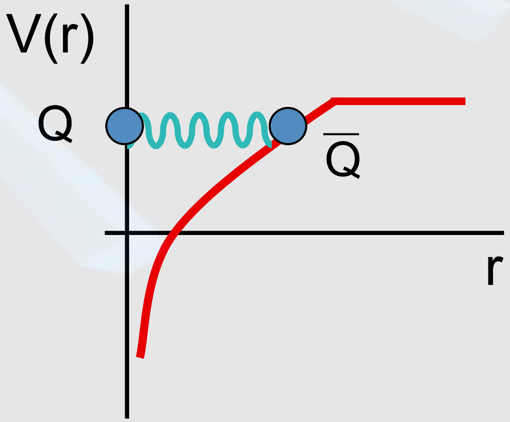
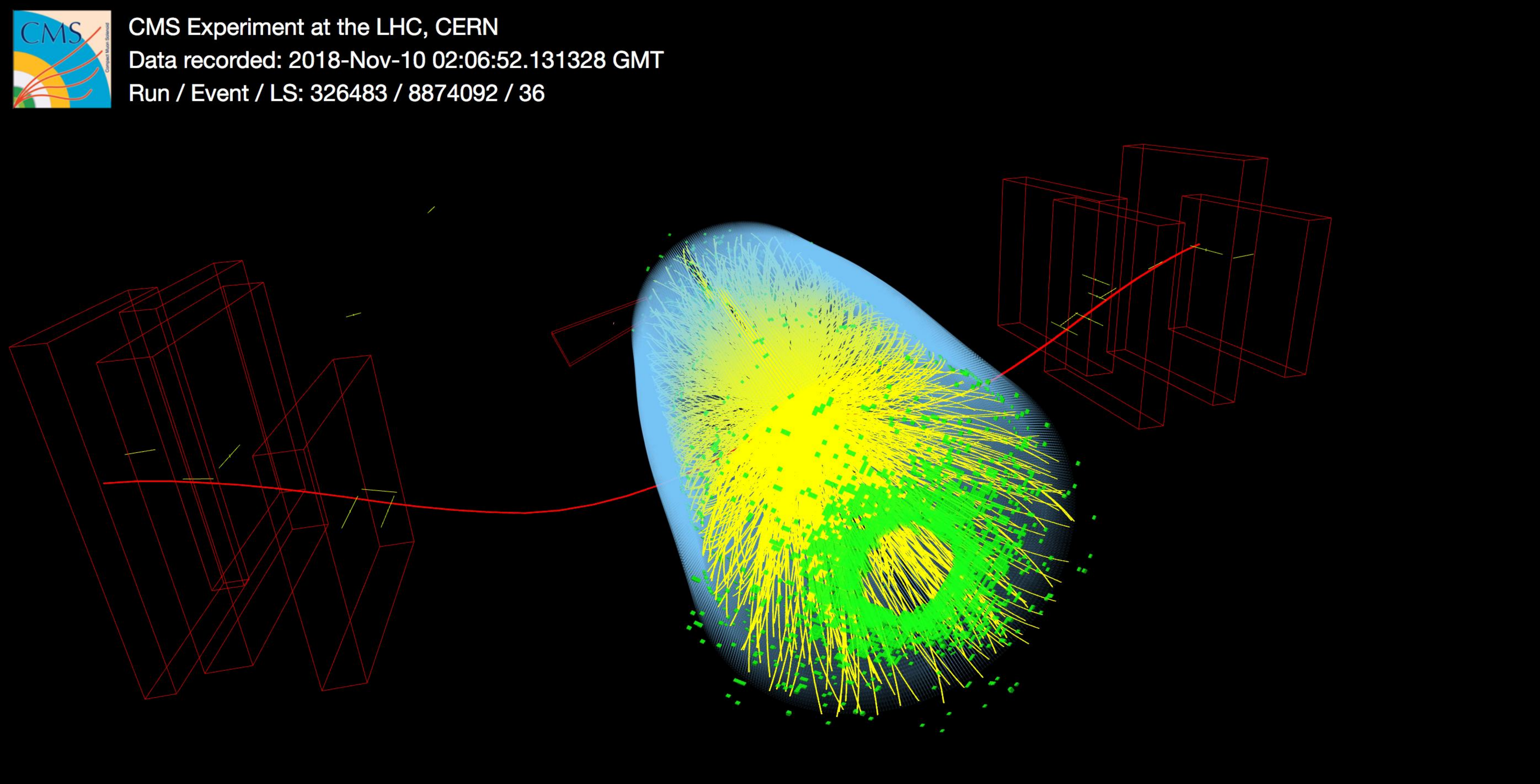
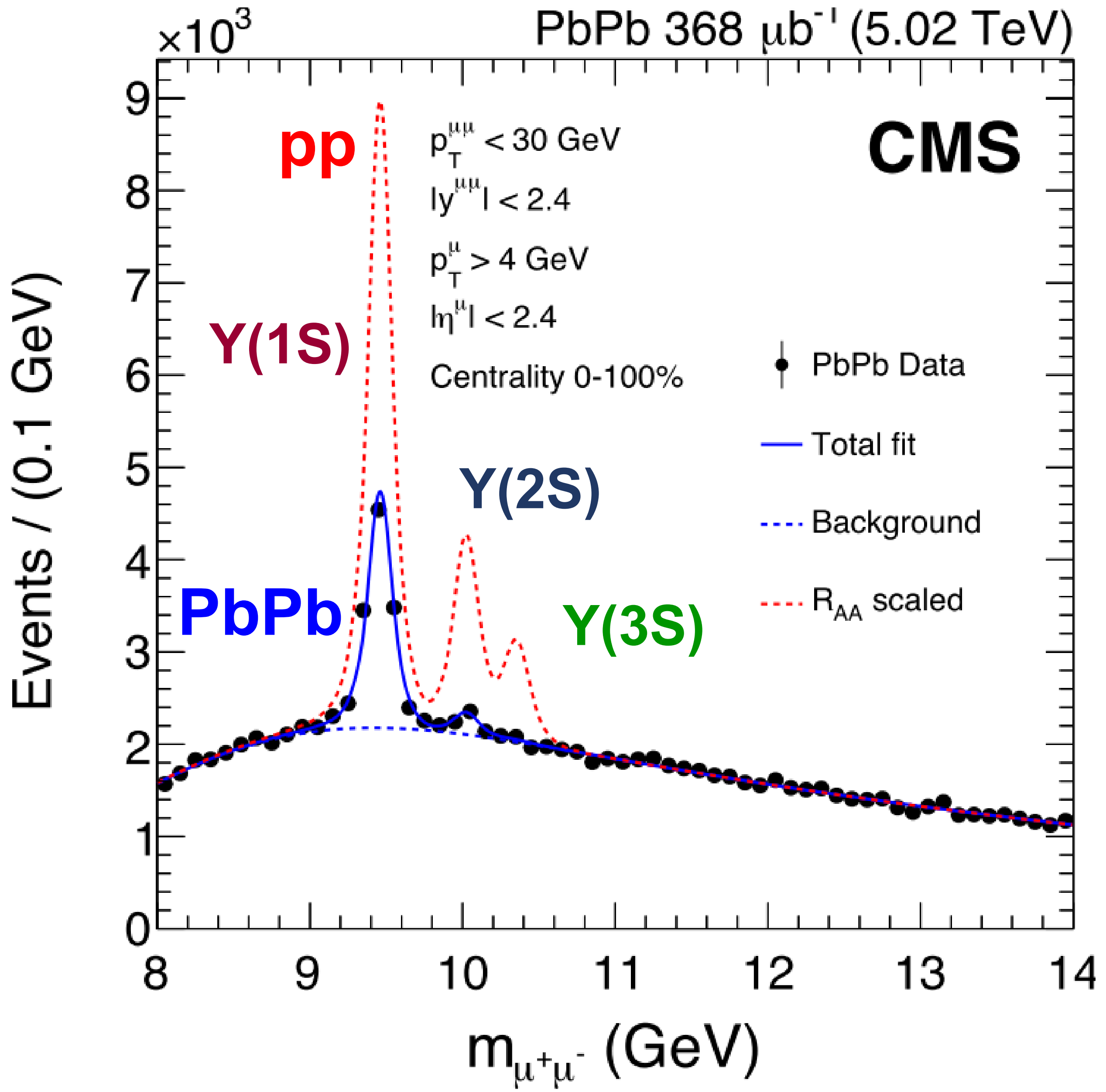


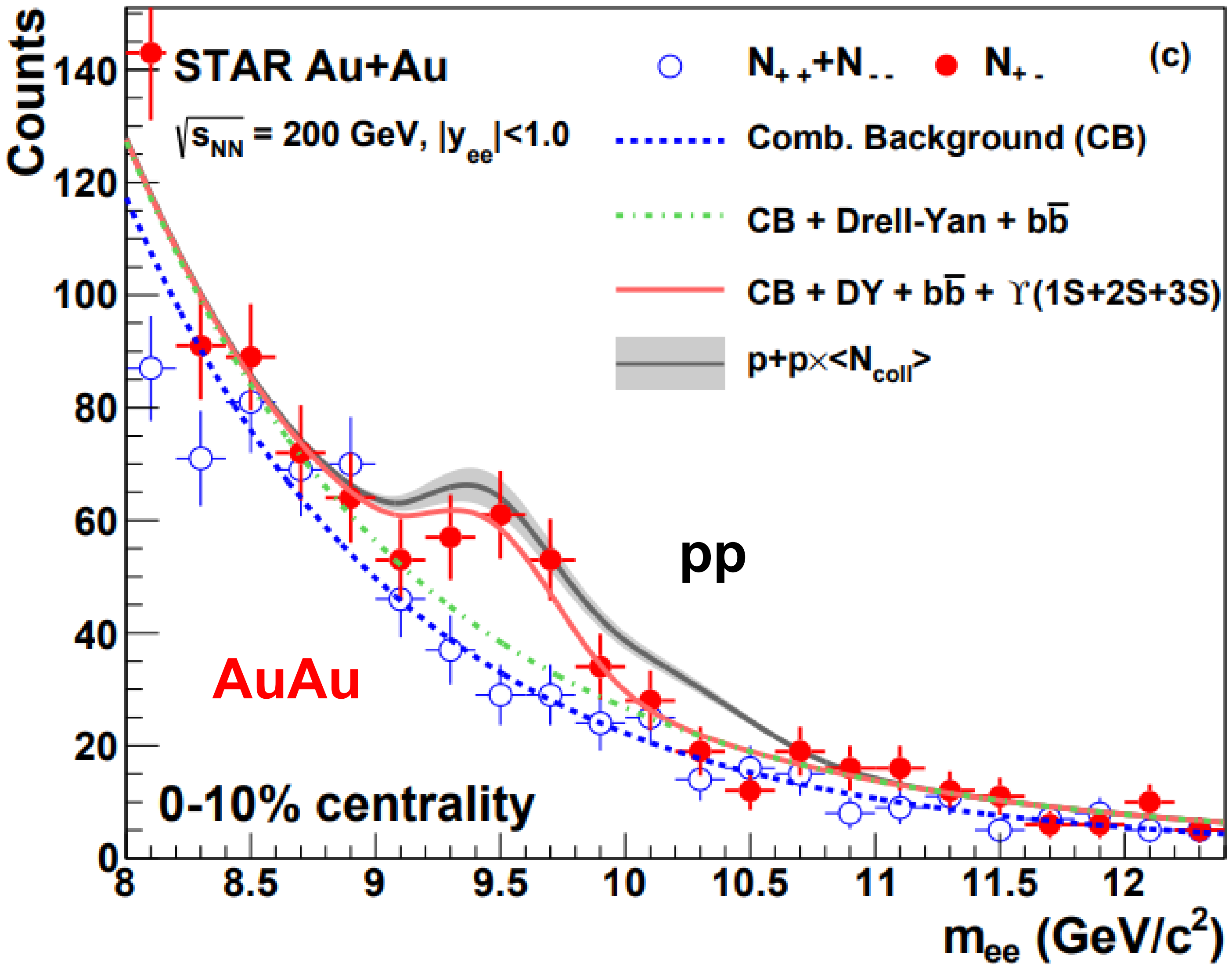


Upsilon to Di-muon in 5.02 TeV PbPb Collision



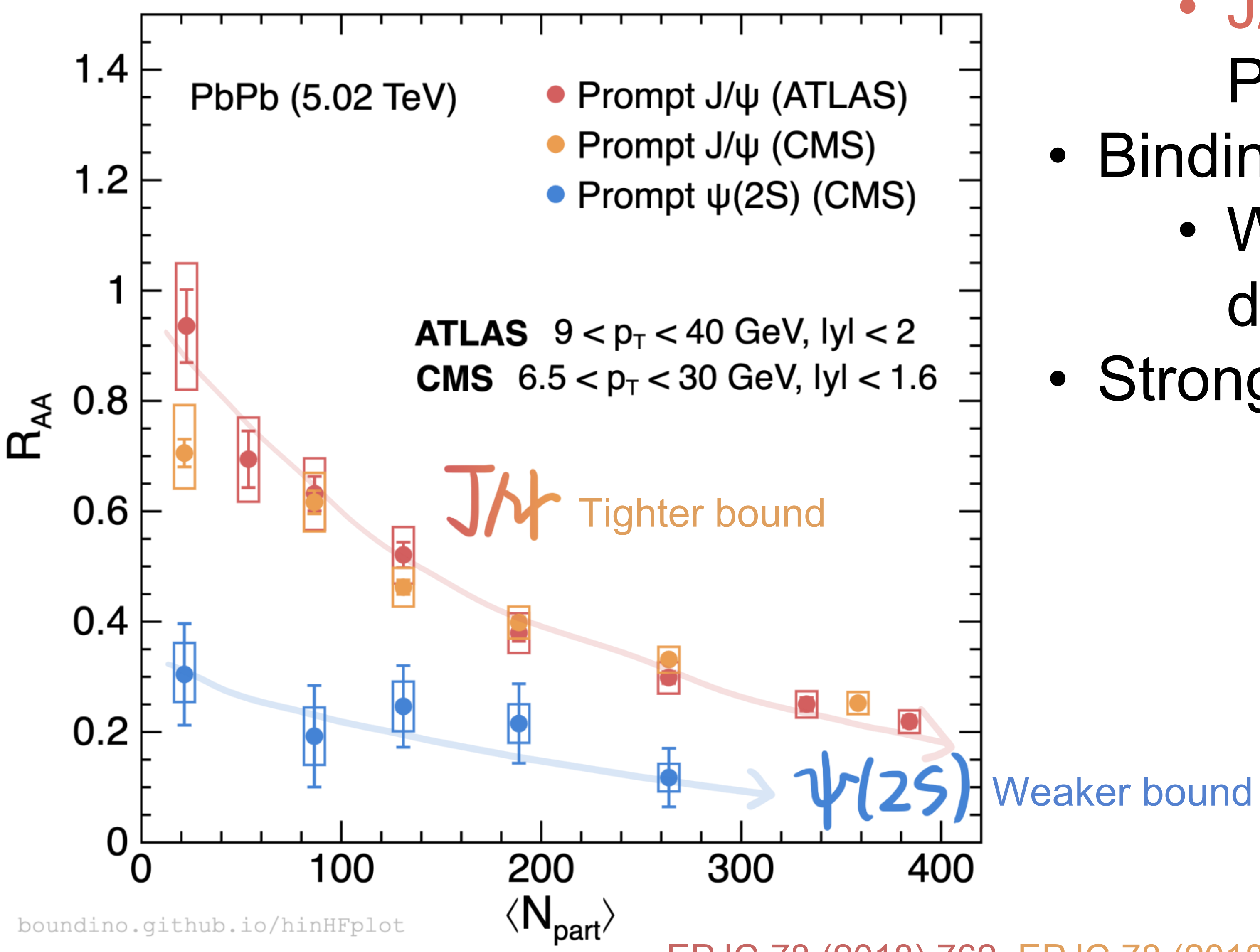
Y(nS)→Dilepton Yield Extraction



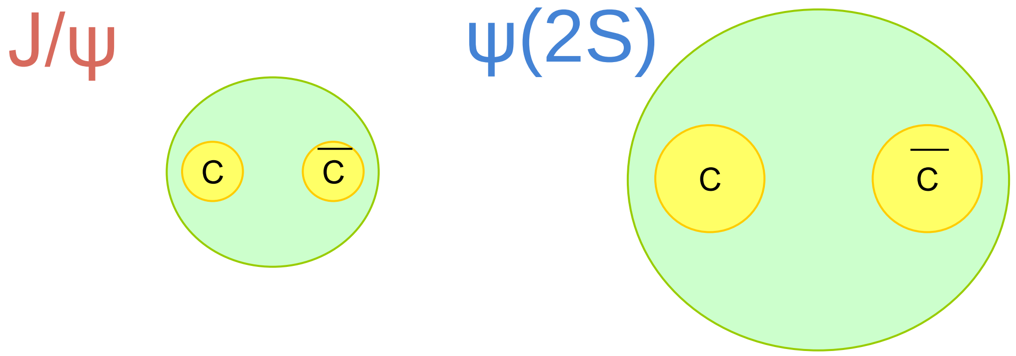


Mass resolution very important for separating the Y states

Charmonia in QGP Sequential Melting

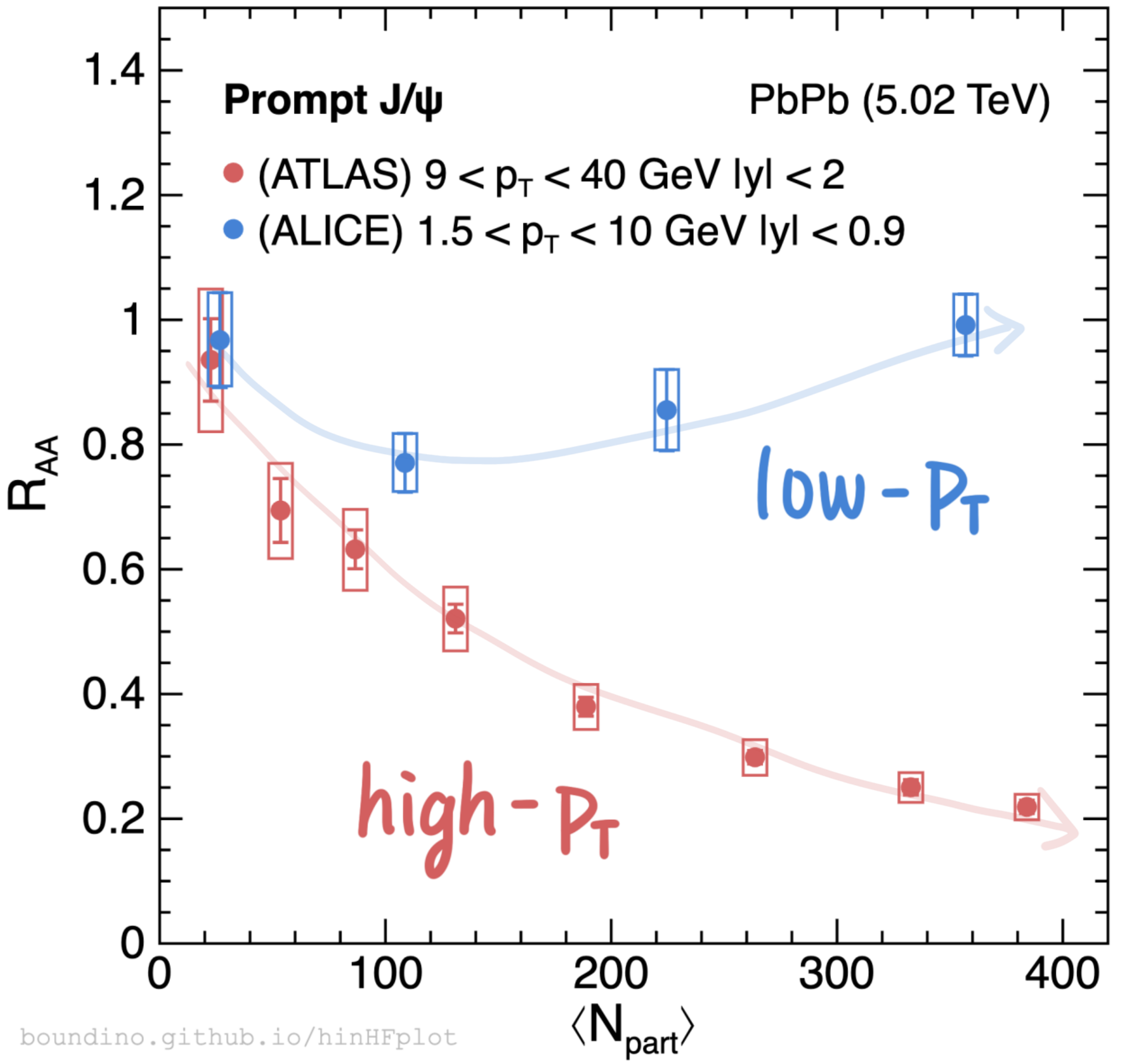


- Sequential melting of charmonium states
  - J/ψ and ψ(2S) strongly suppressed in PbPb collisions
- Binding energy hierarchy:
  - Weaker bound state easier to be dissociated
- Stronger suppression in central events



EPJC 78 (2018) 762 EPJC 78 (2018) 509 EPJC 78 (2018) 509

Charmonia in QGP Regeneration

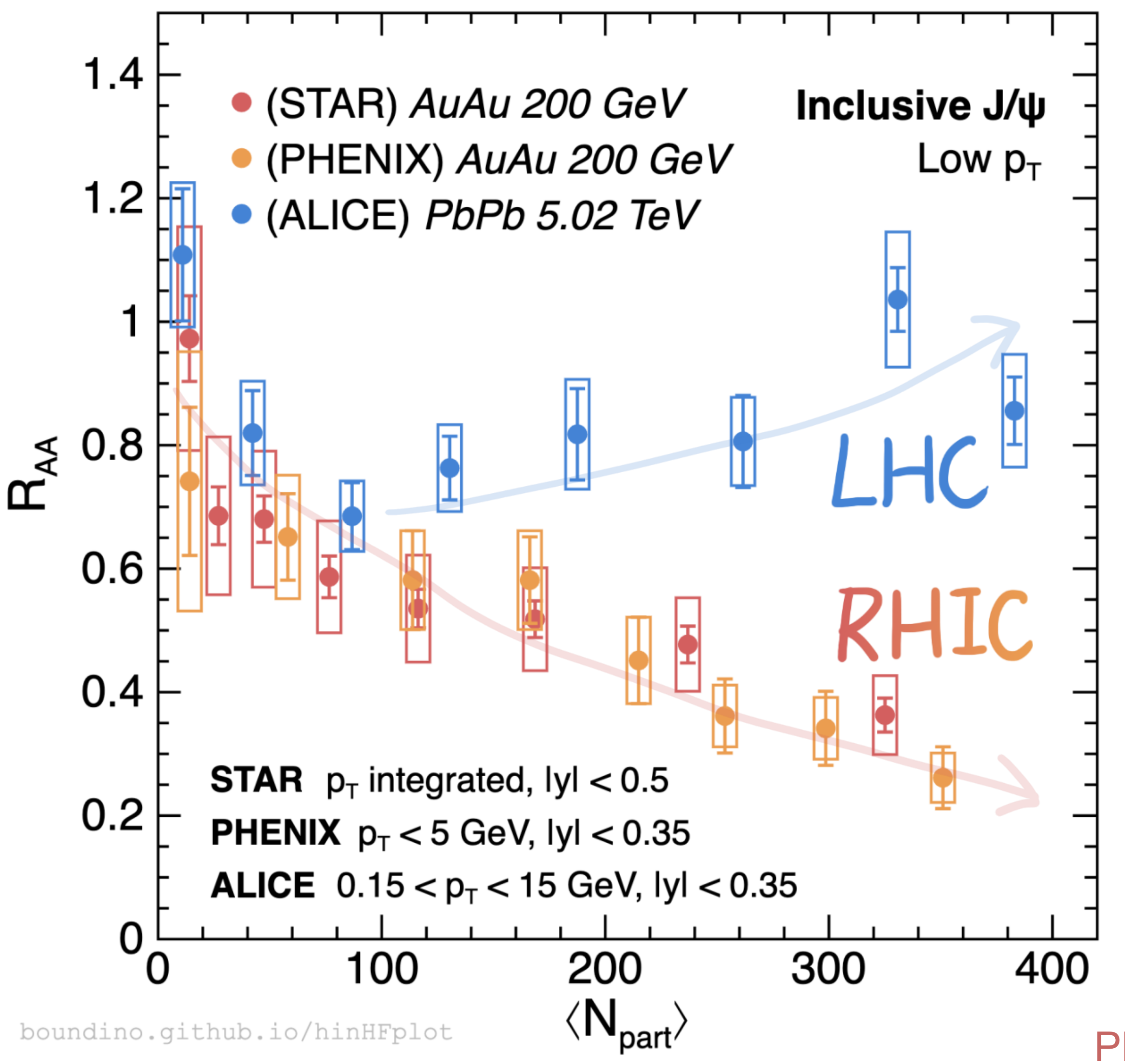


Regeneration

- Uncorrelated $Q\bar{Q}$ in QGP regenerate quarkonia
- At the LHC: Increasing R_{AA} at low p_T towards central events
    - Central events have larger $\sigma_{c\bar{c}}$

EPJC 78 (2018) 762 JHEP 02 (2024) 066

Regeneration of Charmonium in QGP

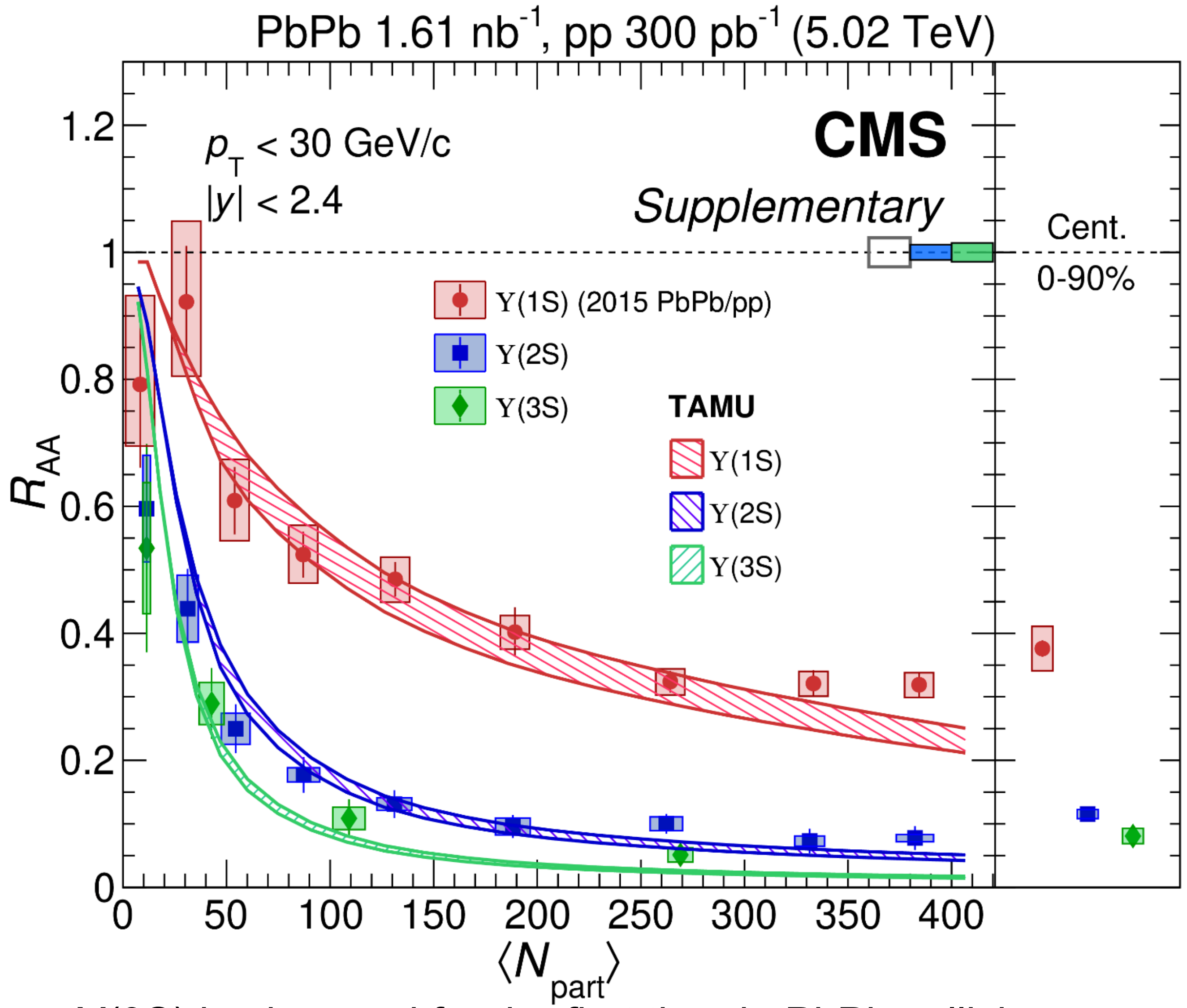


Regeneration picture:

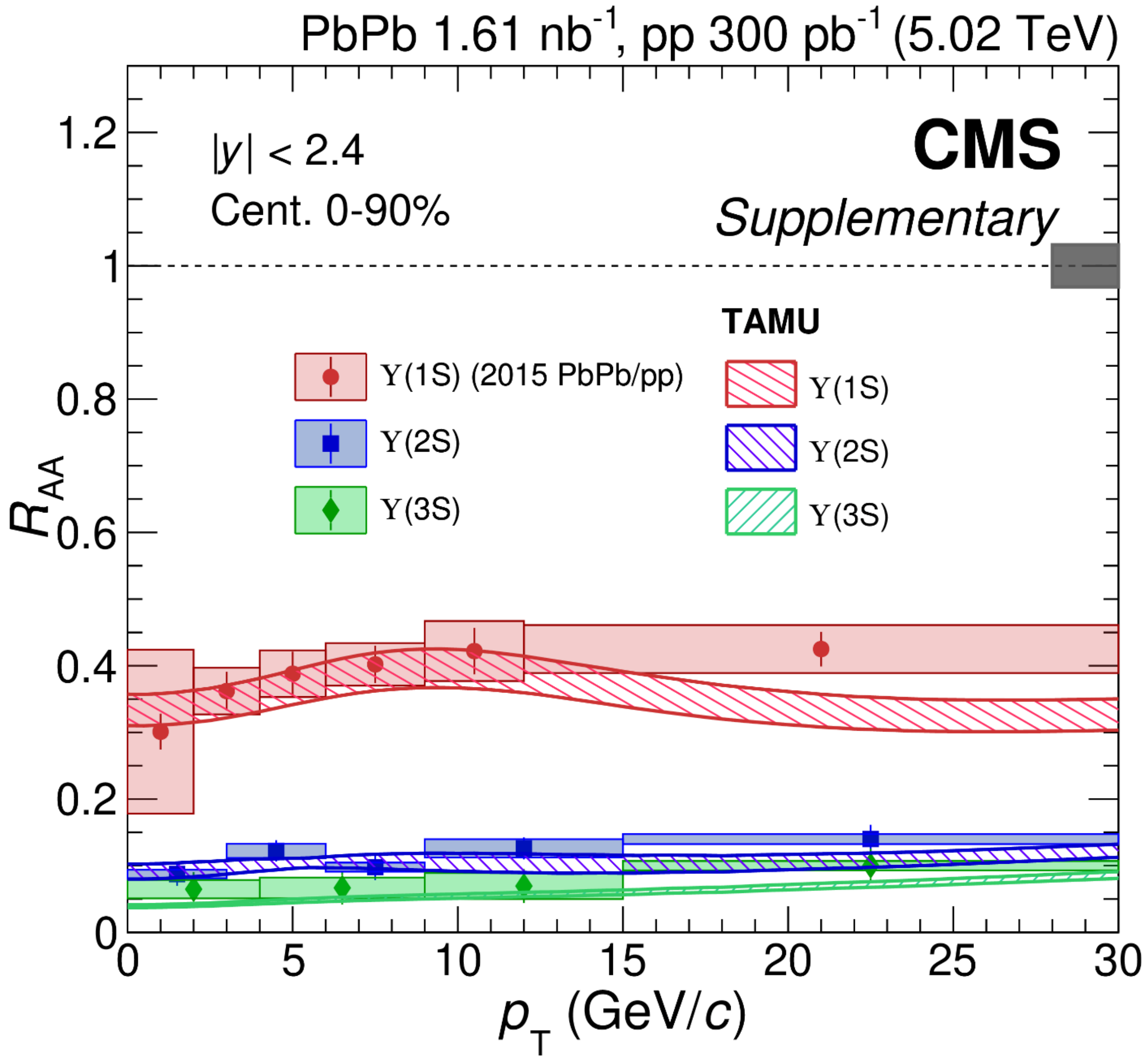
- Uncorrelated $Q\bar{Q}$ in QGP regenerate Quarkonia
- At the LHC: Increasing R_{AA} at **low p_T** towards central events
  - Central events have larger $\sigma_{c\bar{c}}$
- Significant enhancement at the **LHC** but not at the **RHIC**
  - Higher collision energy has larger $\sigma_{c\bar{c}}$, enhances the probability of uncorrelated regeneration

PLB 797 (2019) 134917 PRL 98 (2007) 232301 PLB 849 (2024) 138451

Υ(nS) Suppression

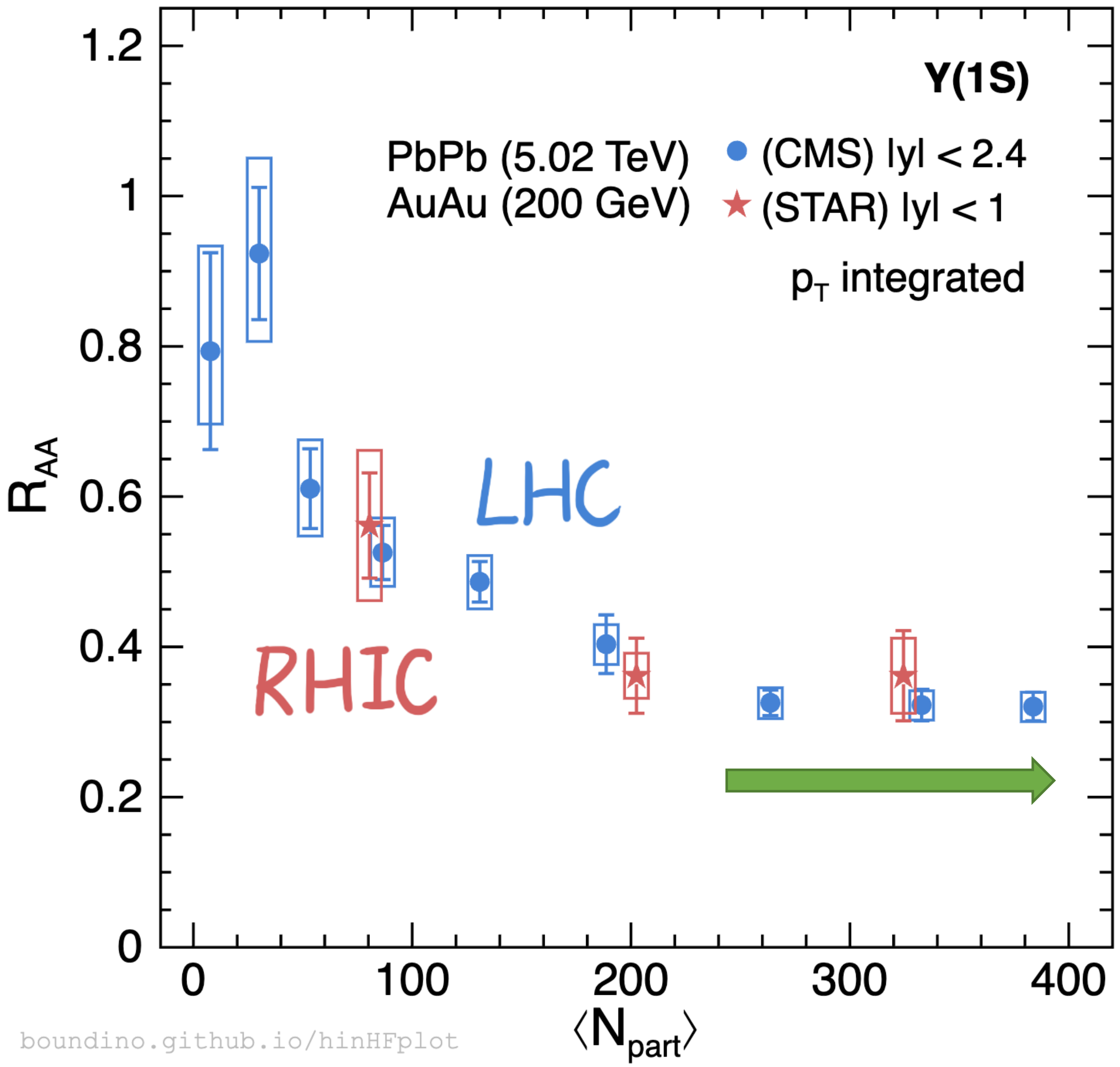


- Υ(3S) is observed for the first time in PbPb collisions
- Reasonable but not perfect description from TAMU, tends to overpredict the suppression in central PbPb



- Is there a “flow bump”?
- Do we have room for uncorrelated regeneration?

Dissociation + Regeneration Picture: Challenge

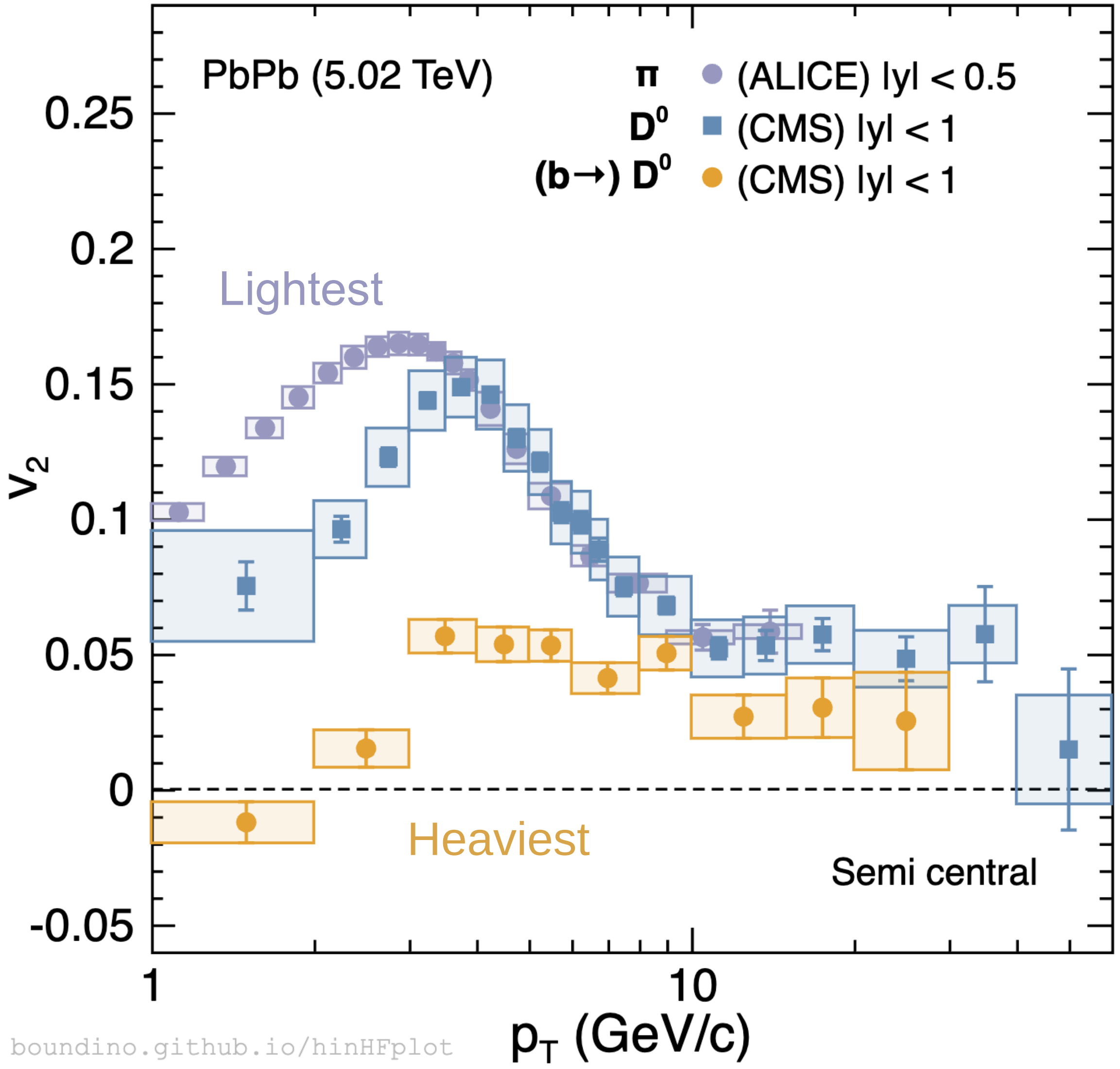


Dissociation + regeneration picture has worked reasonably well, however…

- Why is Y(1S) suppression so similar between **LHC** and **RHIC**?
  - Regeneration at the LHC compensated the effect from higher initial temperature?
- Why does Y(1S) R_{AA} not continue decreasing in most central events?
  - Most models with regeneration still don't describe it well

PLB 790 (2019) 270 PRL 130 (2023) 112301

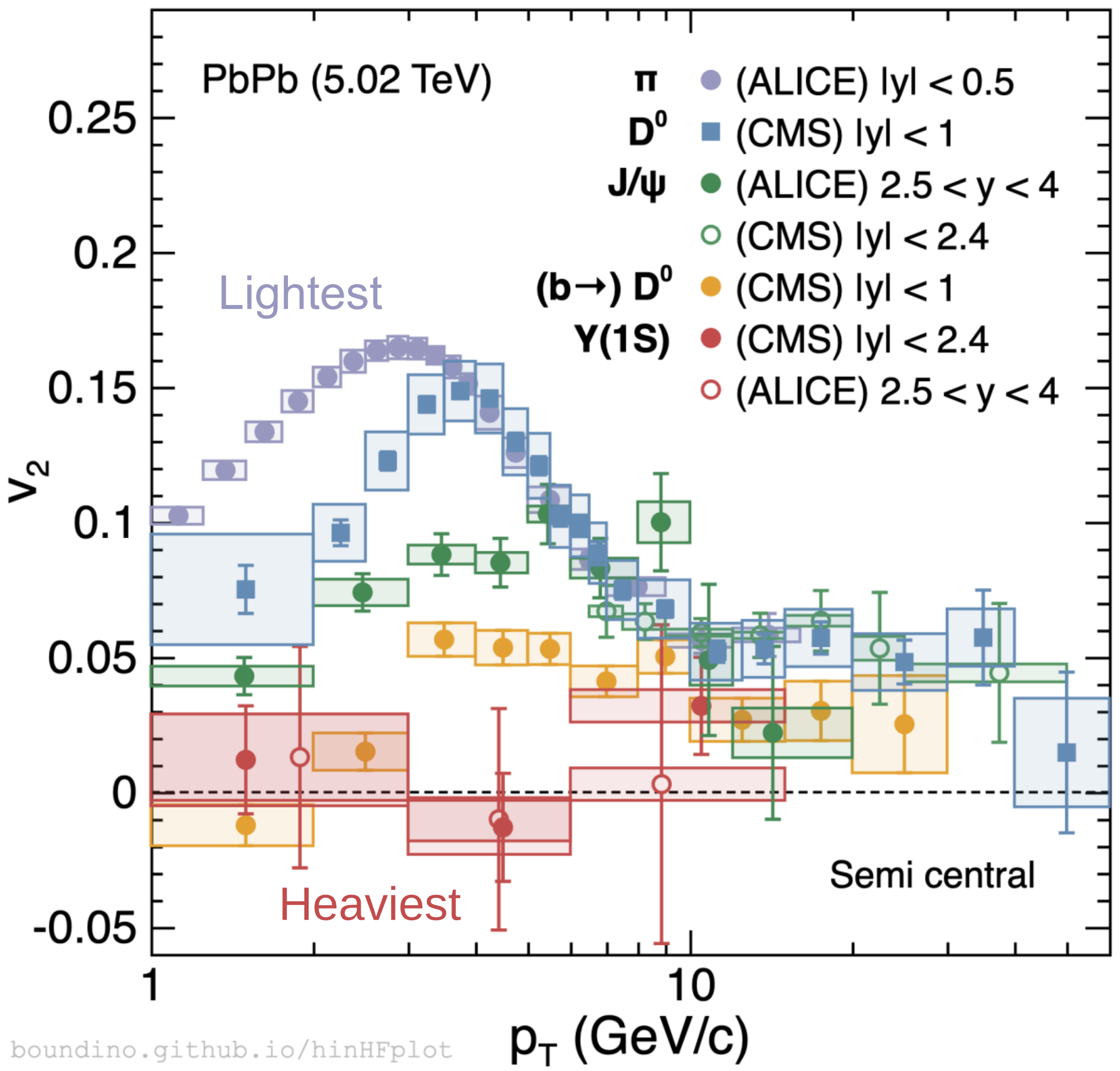
Collective Flow: Mass Hierarchy

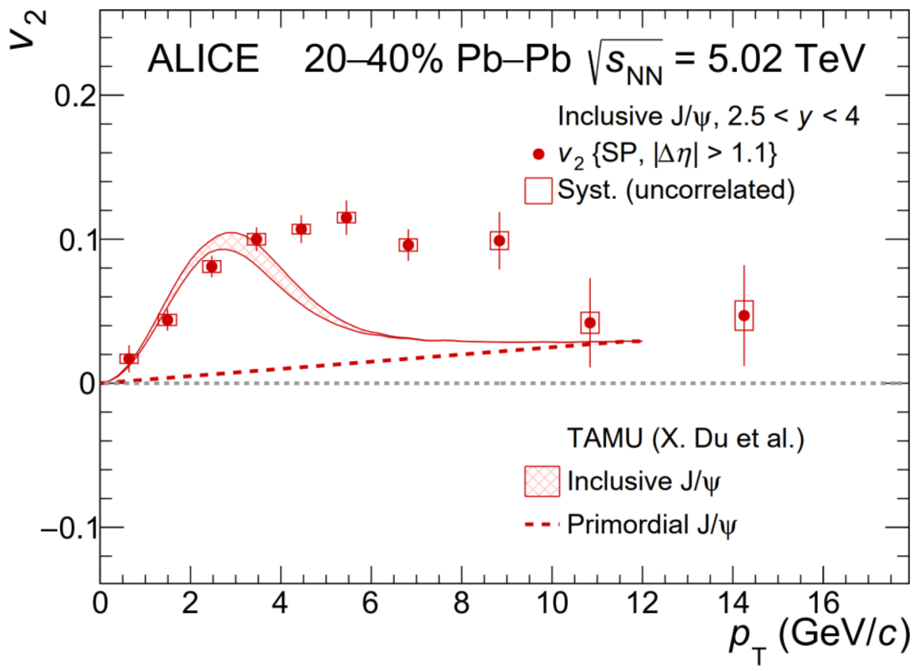


- Recall: v_2 hierarchy from lightest to heaviest hadrons

Collective Flow Mass Hierarchy Including Quarkonia

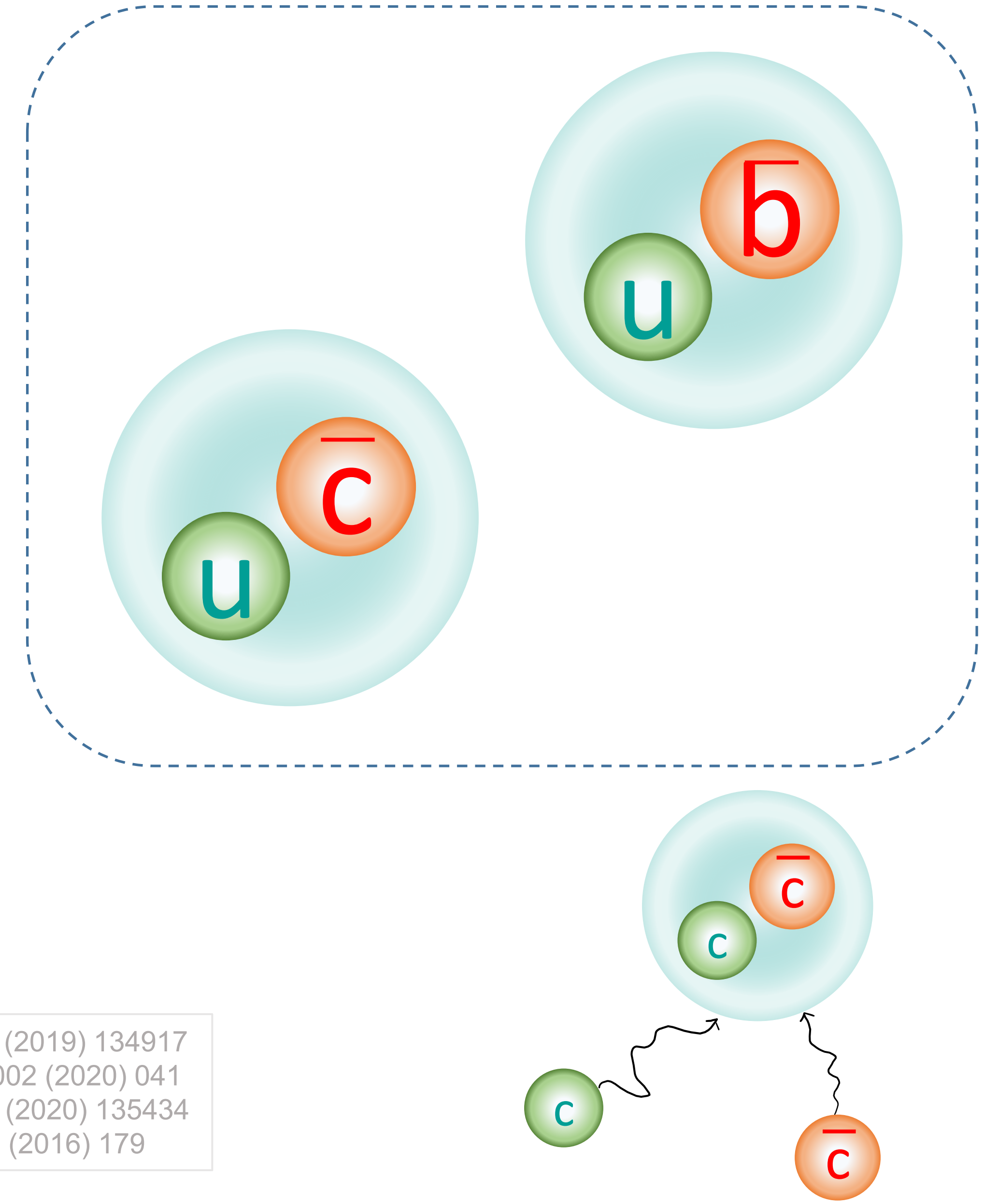
JHEP 10 (2020) 141 JHEP 10 (2023) 115 PLB 819 (2021) 136385
PRL 123 (2019) 192301



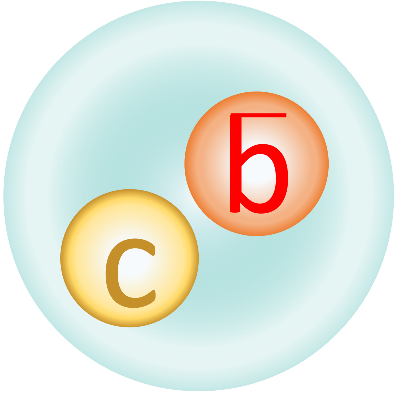


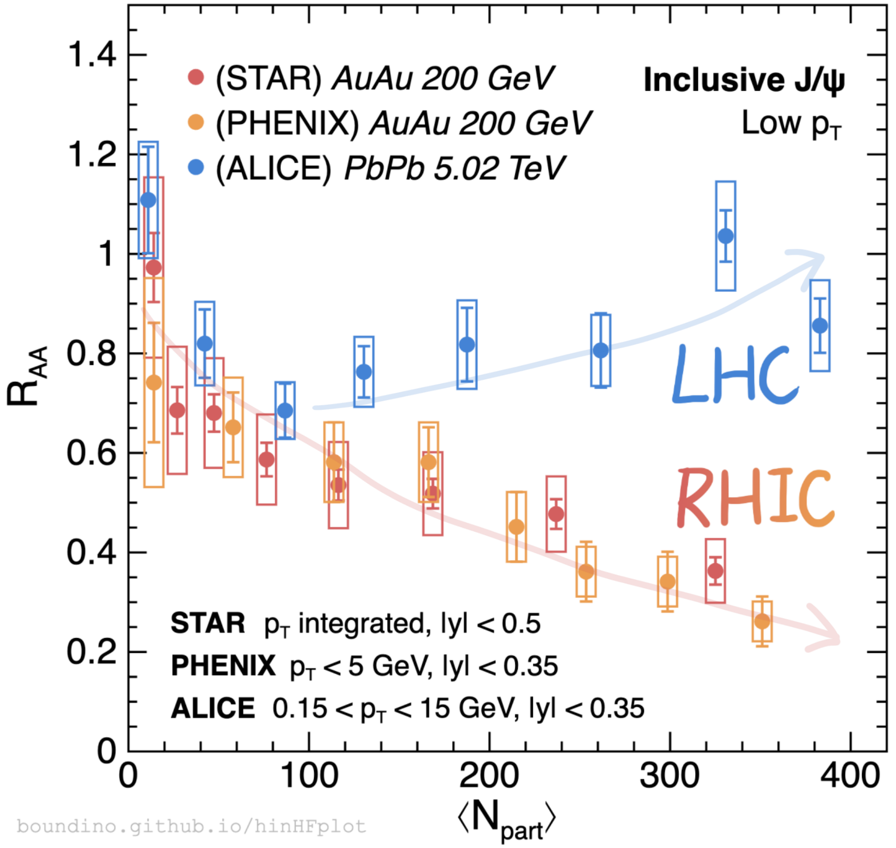
- Recall: v_2 hierarchy from lightest to heaviest hadrons
- Significant J/ψ v_2: contribution from regeneration effect
- Υ(1S) v_2 consistent with 0
  - Limited contribution from uncorrelated

Beyond the Studies of Quarkonia, B and D: B_c



Charmed beauty hadron

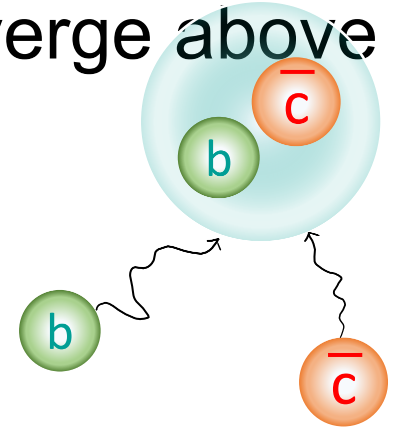


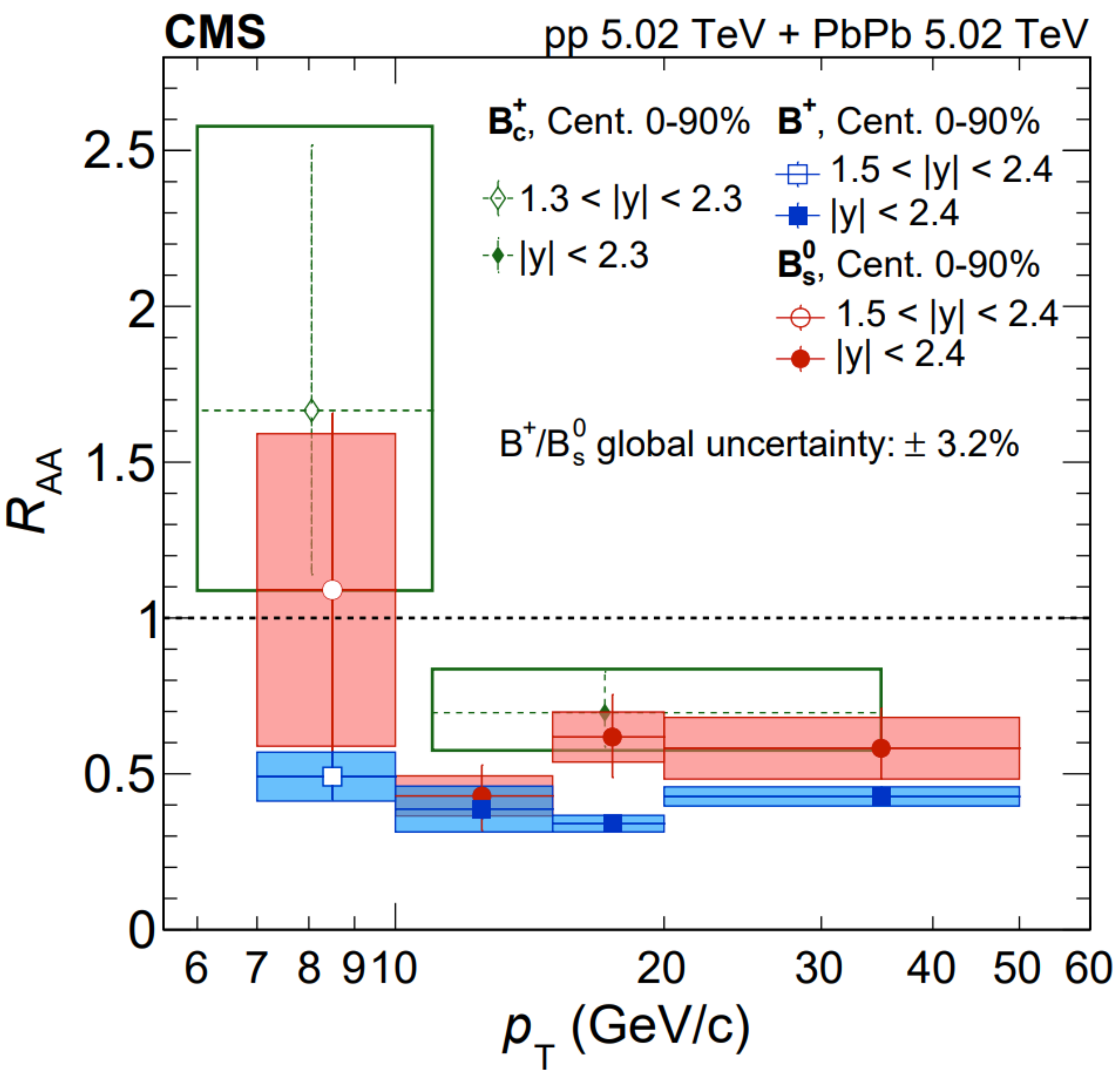


STAR PLB 797 (2019) 134917
ALICE JHEP 2002 (2020) 041
PLB 805 (2020) 135434
JHEP 05 (2016) 179

B_c^+ R_{AA} Compared to B_s and B^+

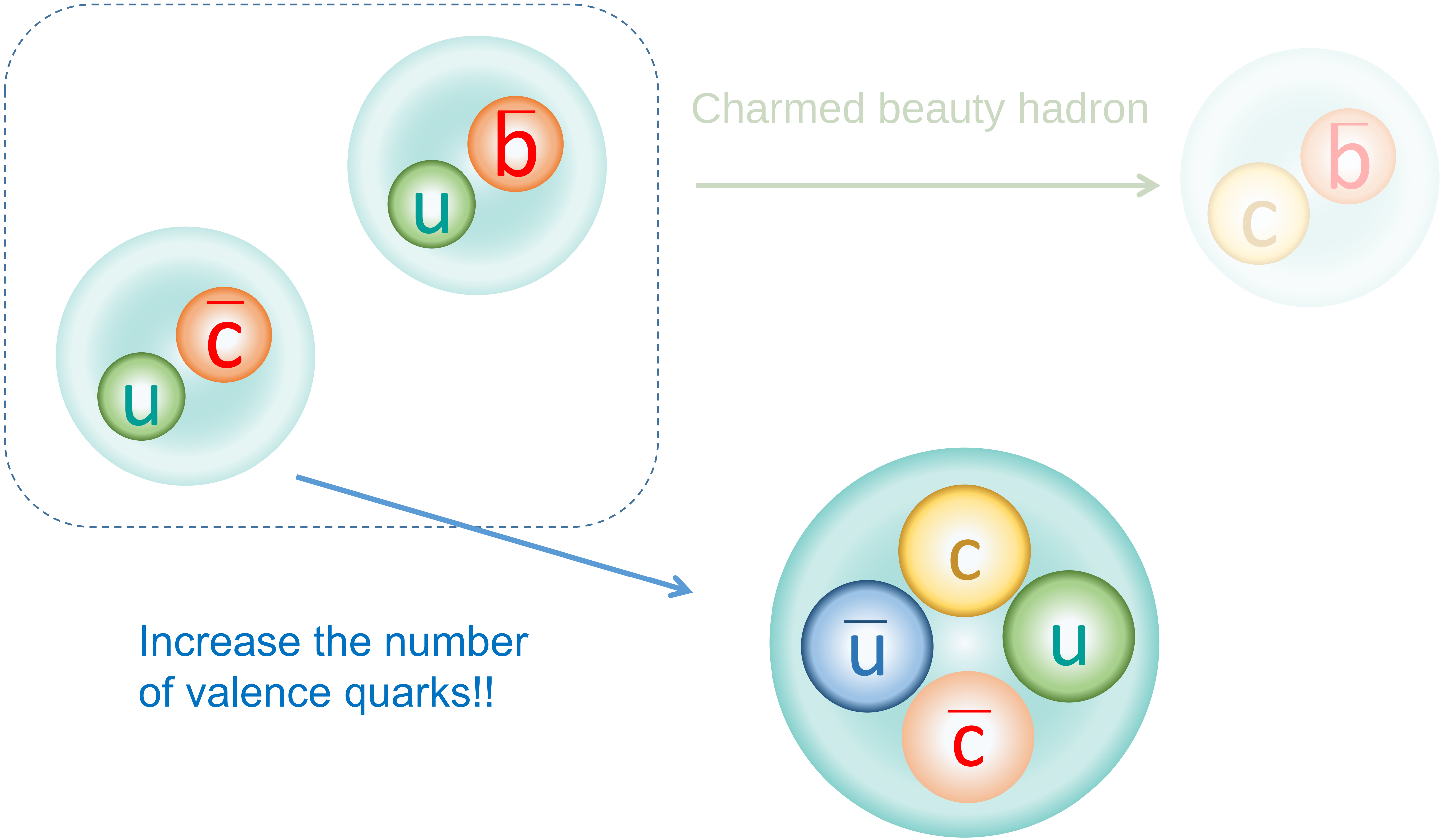
- At low p_T: the B_c^+ R_{AA} central value is higher than **B_s and B^+**
- At high p_T: similar suppression
  - Mass dependent medium modifications such as dead-cone and hadronization effects reduce at high p_T
  - R_{AA} of all flavor identified hadrons seem to converge above ~ 20-30 GeV





PRL 128 (2022) 25, 252301

Beyond the Studies of Quarkonia, B and D: X(3872)



Increase the number
of valence quarks!!

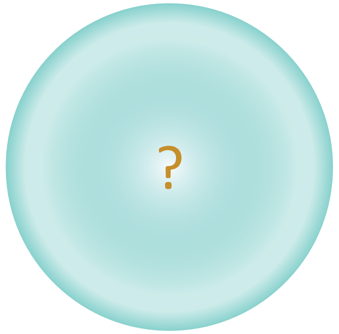
X(3872)

X(3872): Observed by Belle (2003), its internal structure is still under debate

- Quantum number determined by CDF and LHCb data: **J^{PC}=1^{++}**
- **Charmonium** interpretation: **abandoned**, predict wrong mass with J^{PC}=1^{++}
- Remaining possibilities:
  - D-$\overline{D}^*$ hadron molecule: mass X(3872) ≈ D(1875)$\overline{D}^*$(2007), large & extended state
  - **Tetraquark:** a compact four quark state
  - **Hybrid**: mixed molecule-charmonium state

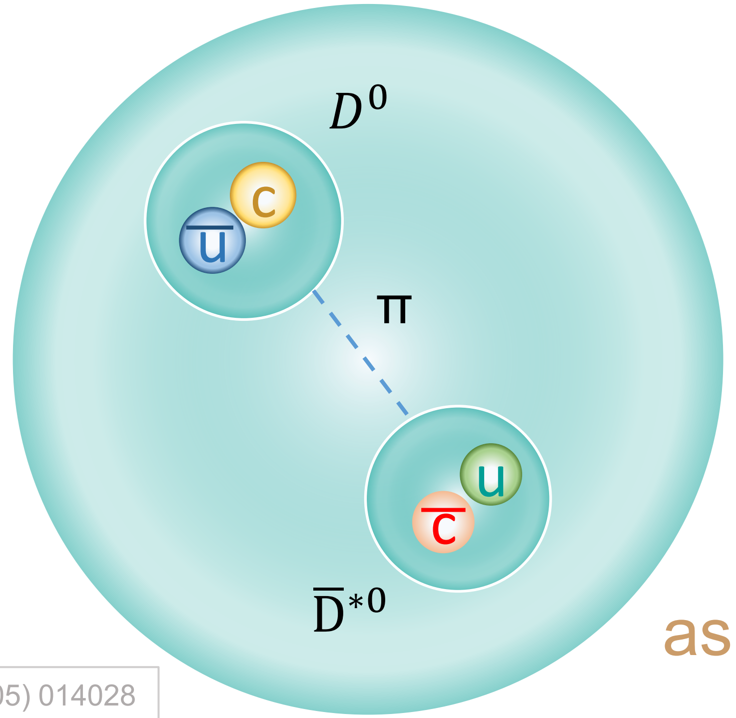
BELLE PRL 91, 262001 (2003)
CDF PRL 98, 132002 (2007)
LHCb PRL 110, 222001 (2013)

Hybrid



EPJA47 (2011) 101

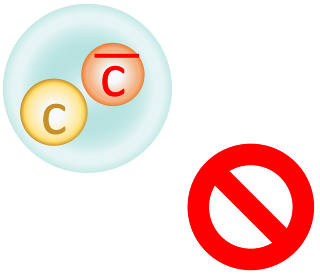
$D^0 - \overline{D}^{*0}$ molecule



$r_{molecule}$ as large as 5 fm

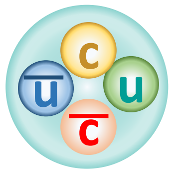
PRD71 (2005) 014028

Charmonium



PLB 590 209-215 (2004)

Tetraquark (4q)



$r_{4q} \approx r_{c\overline{c}}$
≈ 0.3 fm

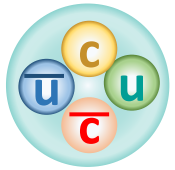
PRD 71 (2005) 014028

Probe the Nature of X(3872)

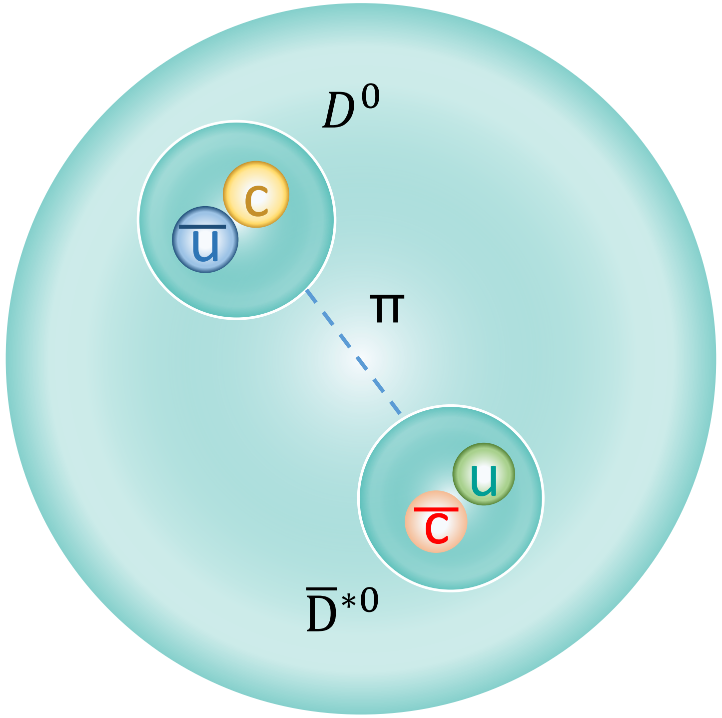
Tightly bound

Loosely bound

Tetraquark (4q)



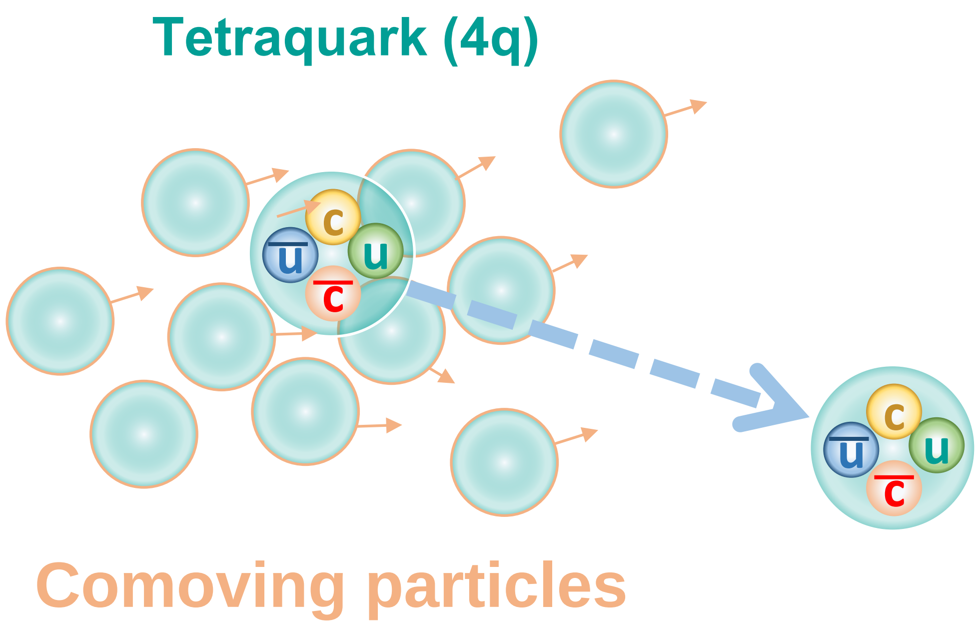
$D^0 - \bar{D}^{*0}$ molecule



- However, the lifetime of X(3872) is extremely short!

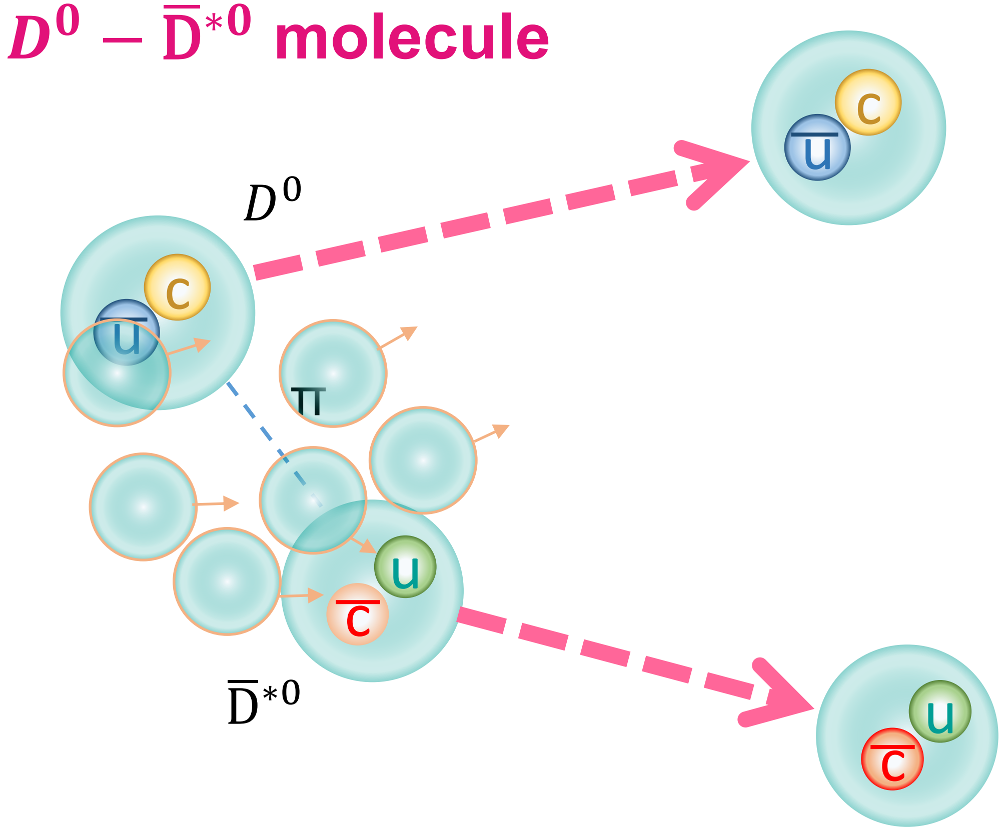
Probe the Nature of X(3872) with Comoving Particles

Tightly bound



Smaller dissociation probability

Loosely bound



Larger dissociation probability

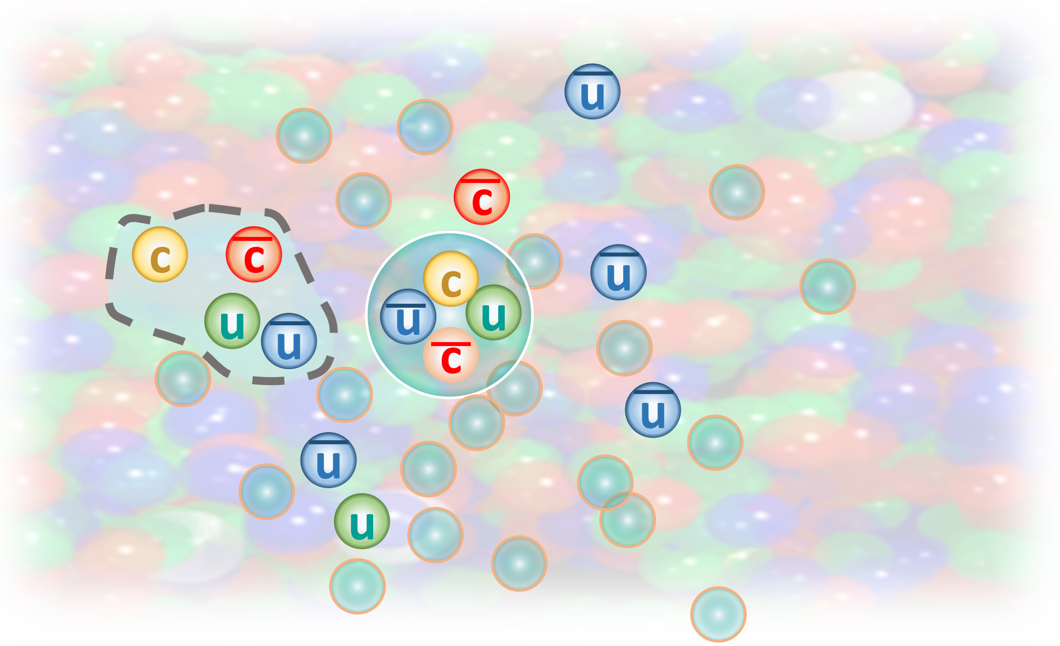
Esposito et al, arXiv: 2006.15044

Production of X(3872) in Heavy Ion Collisions

Jinfeng Liao + collaborators
PRL 126 (2021) 1, 012301

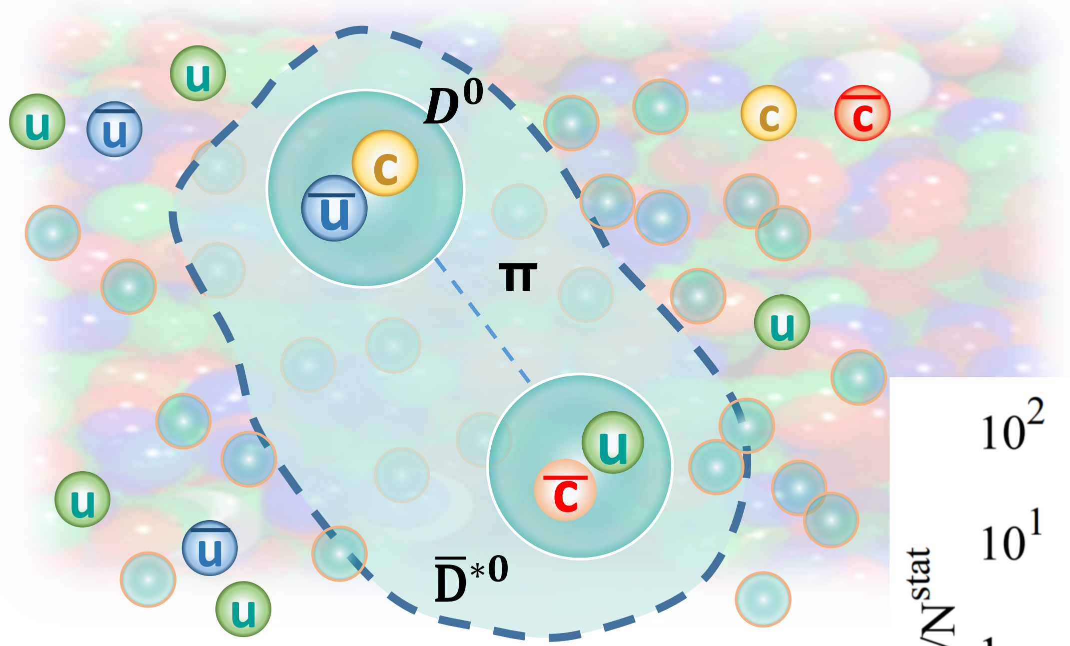
Tightly bound

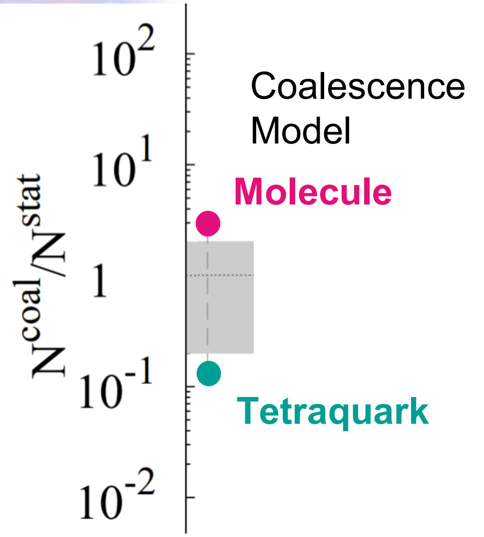
Tetraquark (4q)



Loosely bound

$D^0 - \bar{D}^{*0}$ molecule



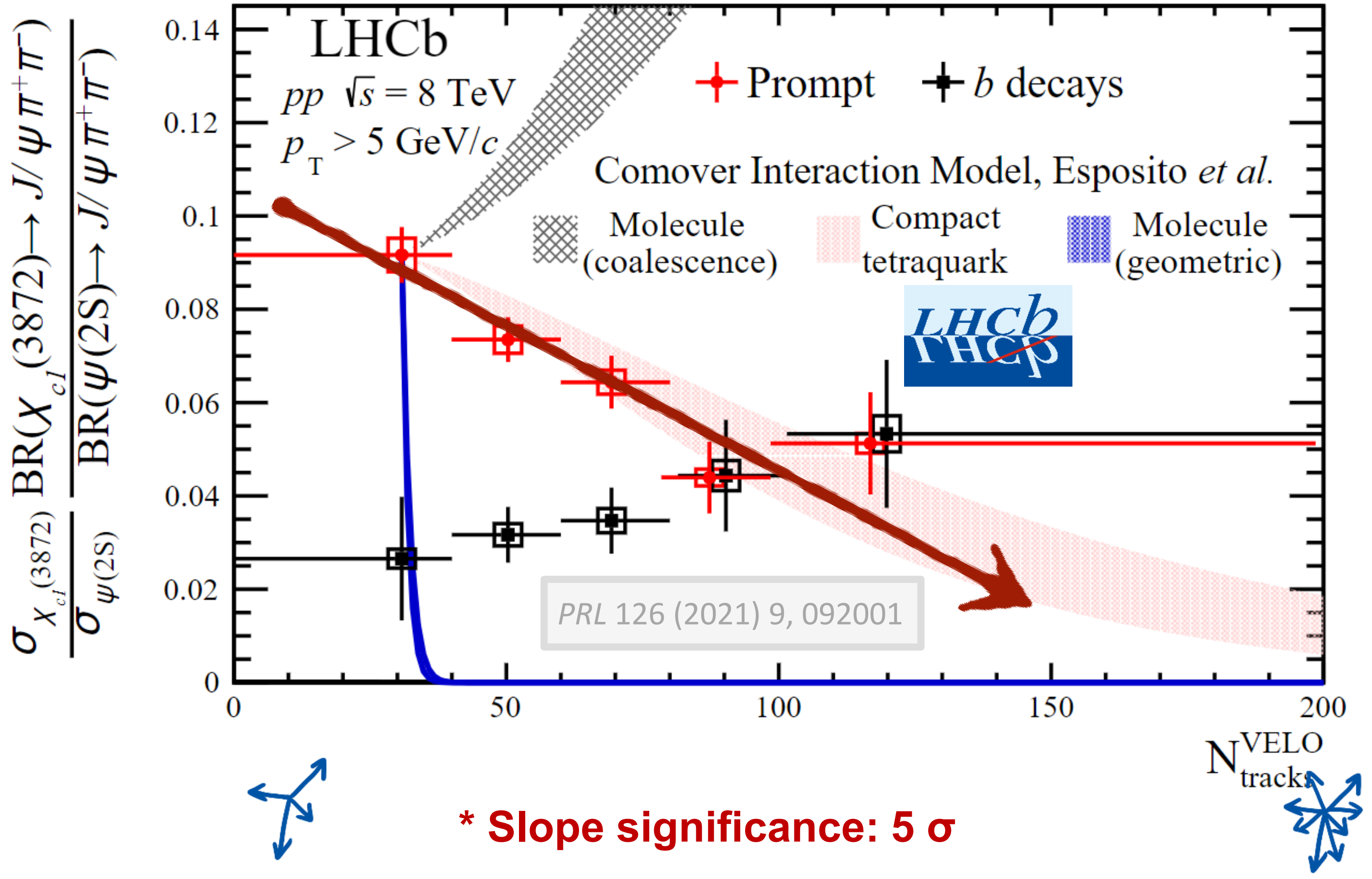


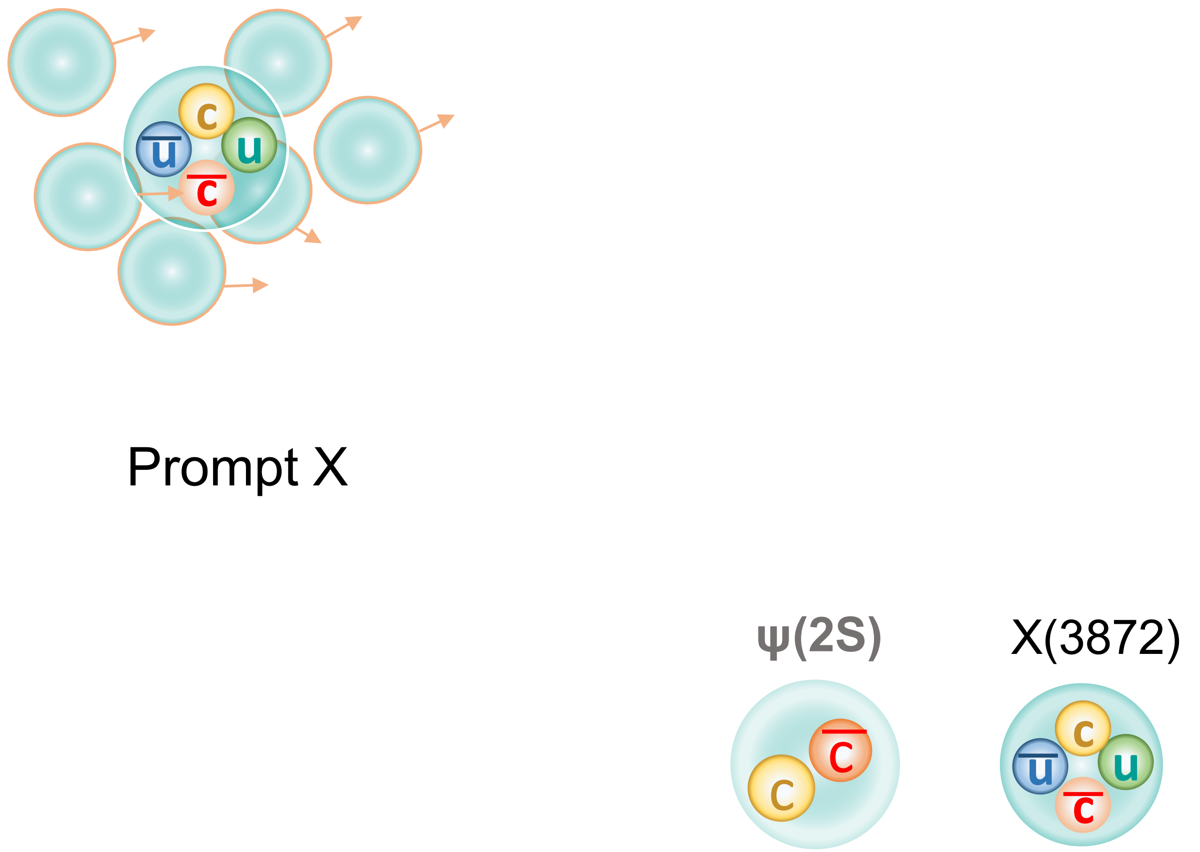
Production of X(3872) in QGP may depend on its inner structure

ExHIC Collaboration
PRL 106 (2011) 212001

X(3872) in High Multiplicity pp from LHCb

Prompt X(3872)/ψ(2S) vs. multiplicity in pp



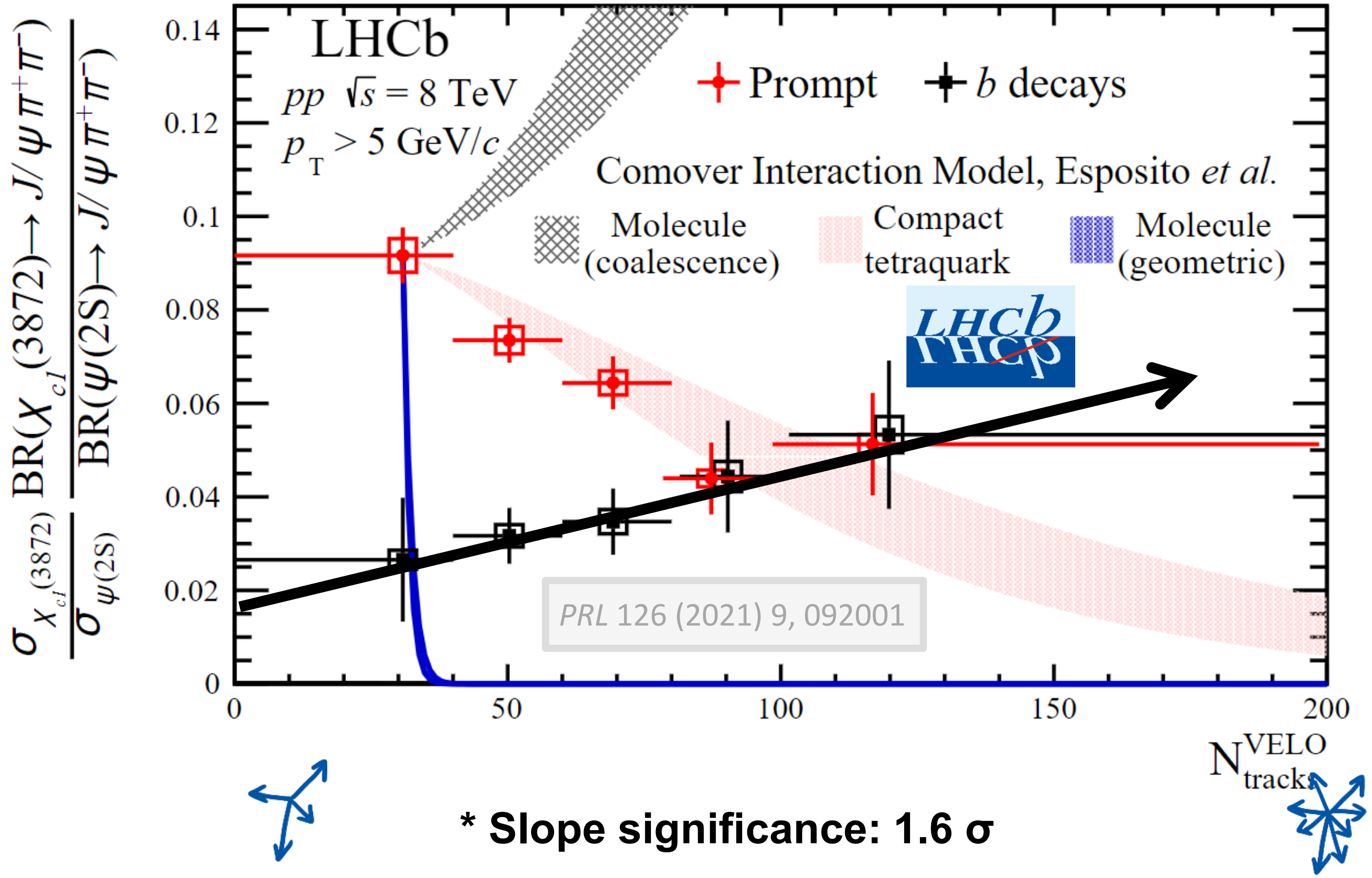


* Slope significance: 5 σ

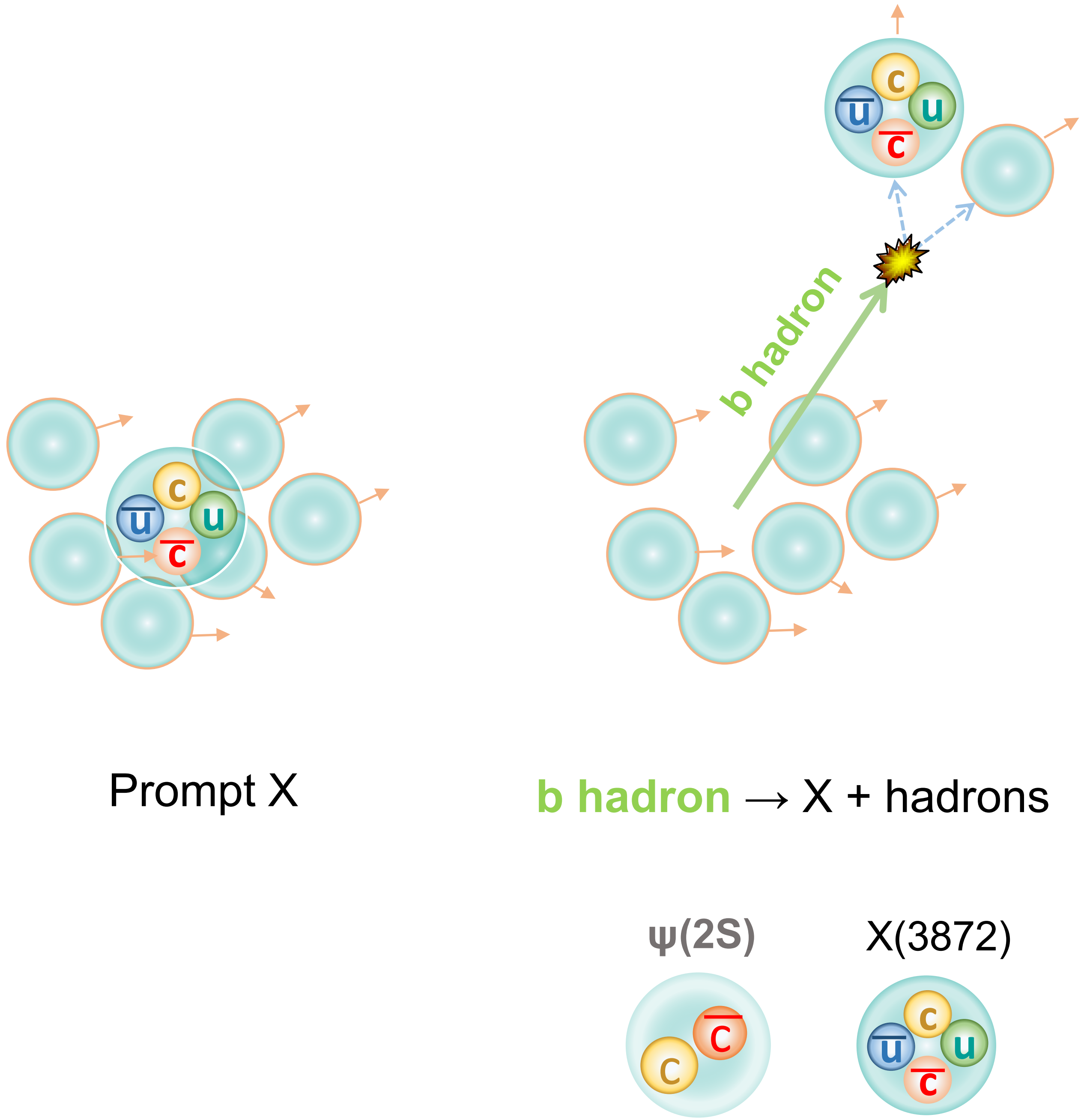
- Destroyed by interactions with other hadrons due to smaller binding energy?

Non-prompt X(3872) in pp from LHCb

Prompt X(3872)/ψ(2S) vs. multiplicity in pp



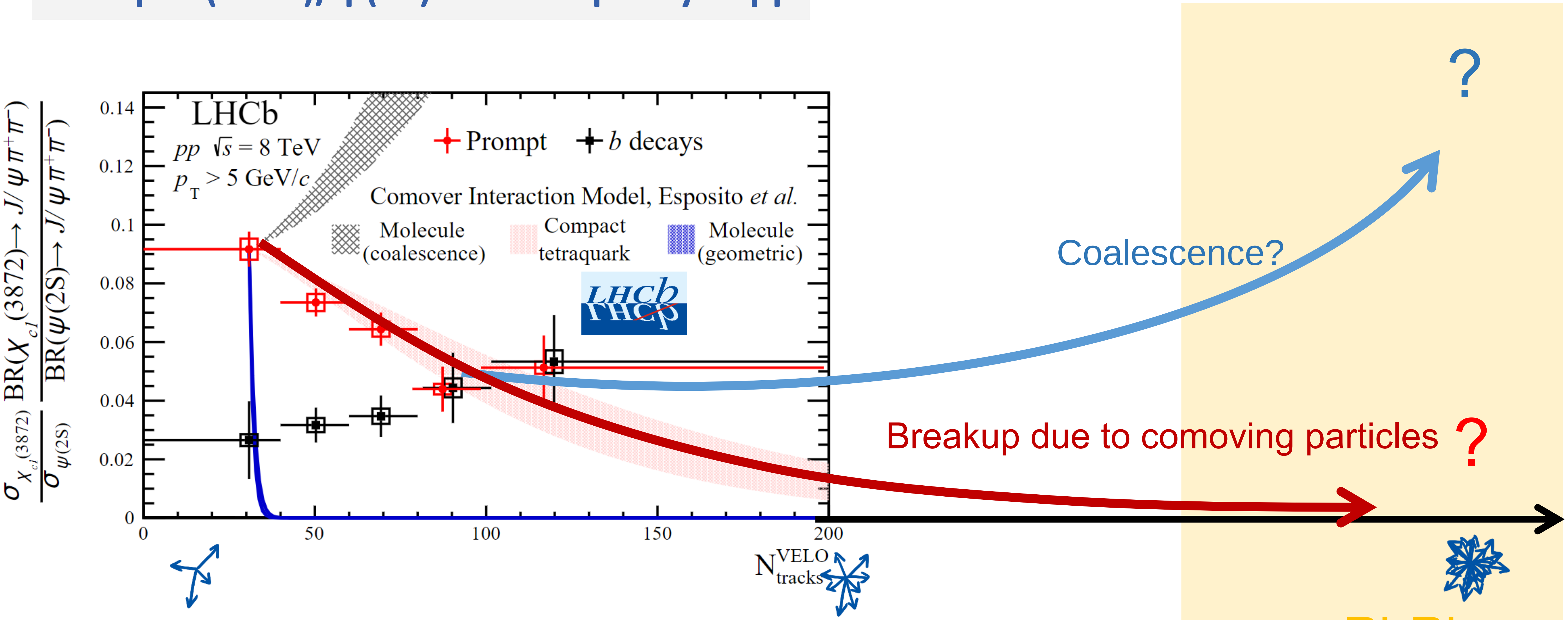
*** Slope significance: 1.6 σ**



- X(3872) from b decays seems to follow a different trend

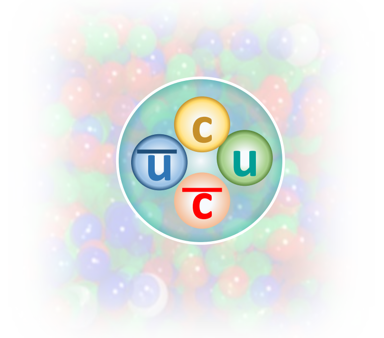
X(3872) in Lead-Lead collision?

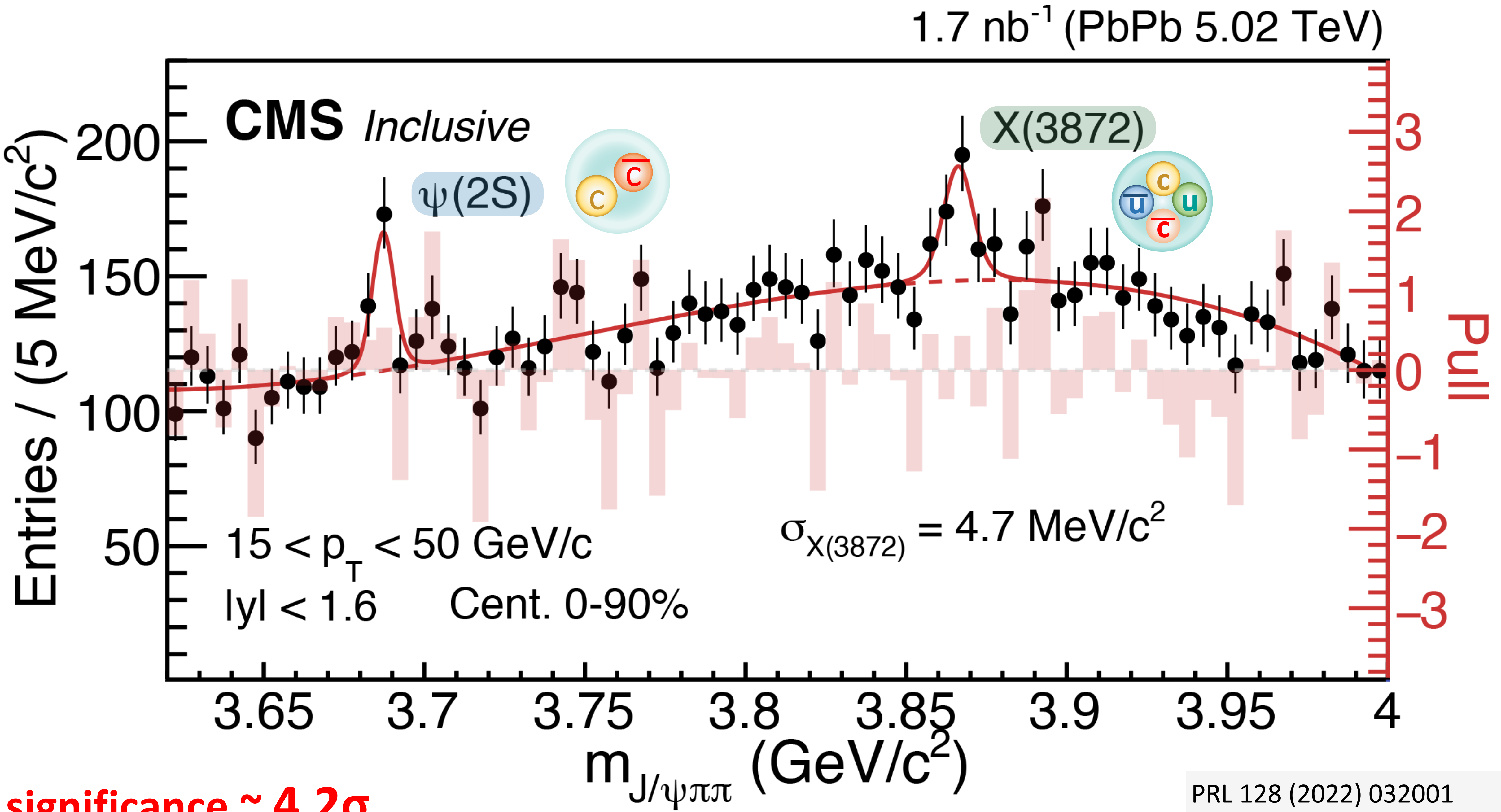
Prompt X(3872)/ψ(2S) vs. multiplicity in pp

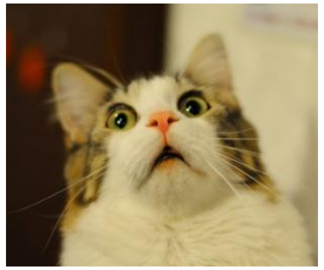


INSTITUTE for NUCLEAR THEORY

The First Evidence of X(3872) in PbPb Collision







PRL 128 (2022) 032001

Statistical significance ~ 4.2σ

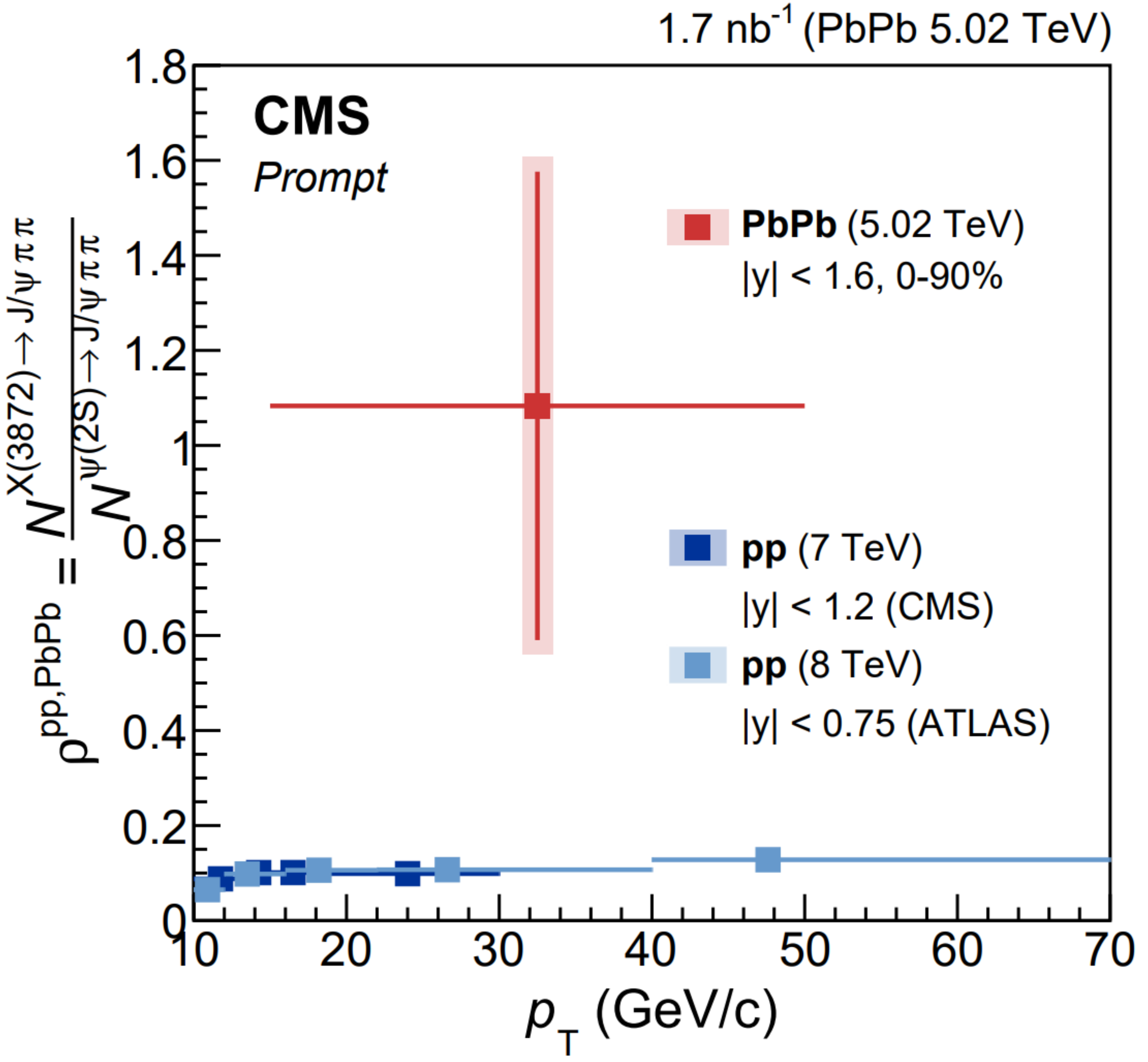
Ratio of X(3872) to ψ(2S) Yields in pp and PbPb

$$\rho = N^{(\mathrm{Corr})}_{X(3872)} / N^{(\mathrm{Corr})}_{\psi(2S)}$$

In Lead-Lead collisions:

$$\rho^{\mathrm{PbPb}} = 1.08 \pm 0.49\,(\mathrm{stat}) \pm 0.52\,(\mathrm{syst})$$

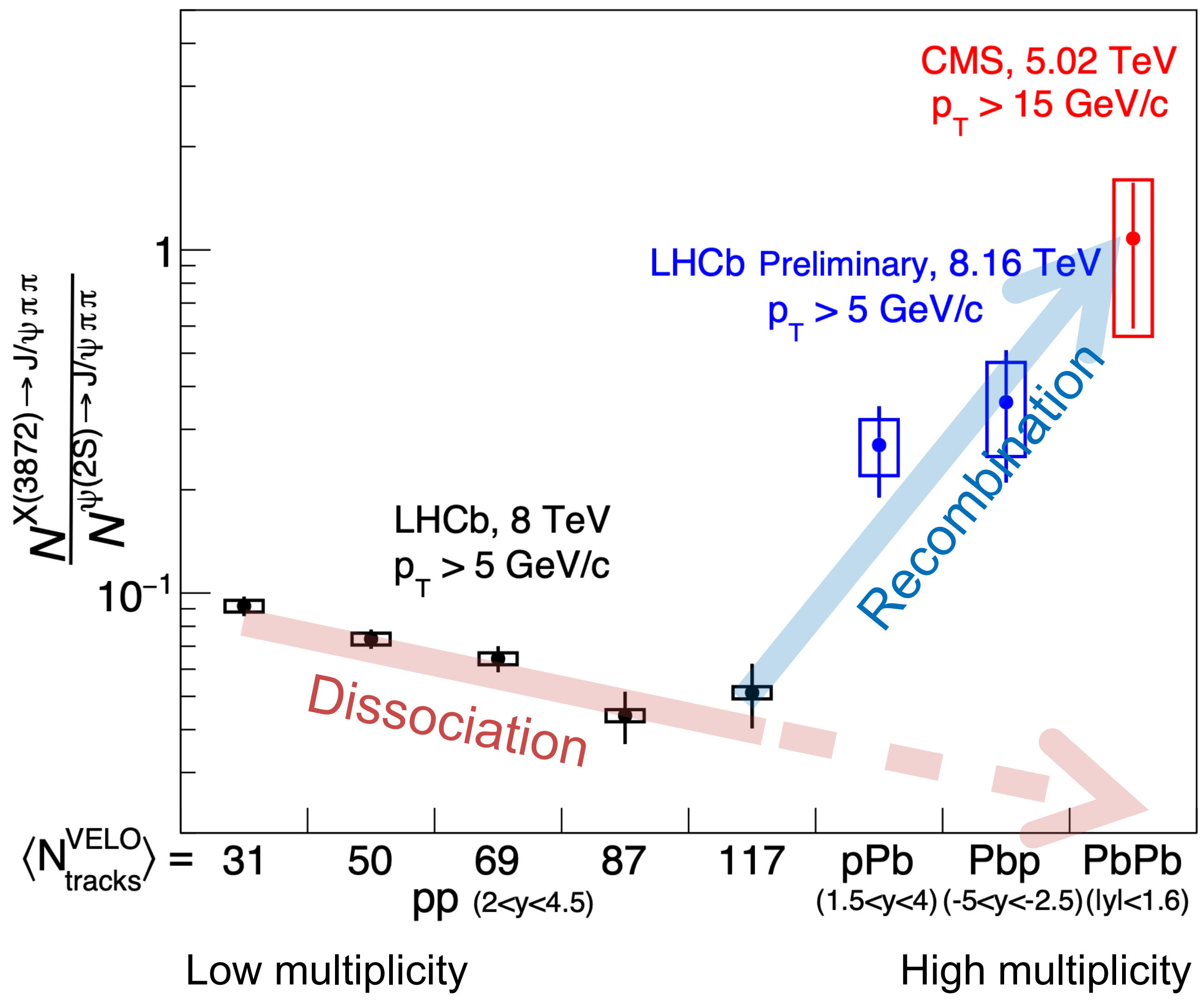
Indication of ρ enhancement in Lead-Lead collisions with respect to **proton-proton collisions** (large uncertainty)



PRL 128 (2022) 032001

Emerging Picture from X(3872) to ψ(2S) Yield Ratio

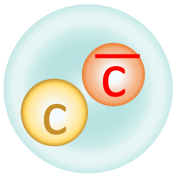
X(3872) / ψ(2S) across collision systems



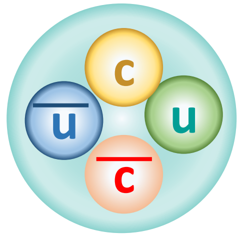
[2402.14975]

X(3872) to ψ(2S) yield ratio across collision systems

- Dissociated by interactions with comovers (**pp**, pPb) or medium (PbPb)
- Different binding energy
- Enhanced via recombination



ψ(2S)



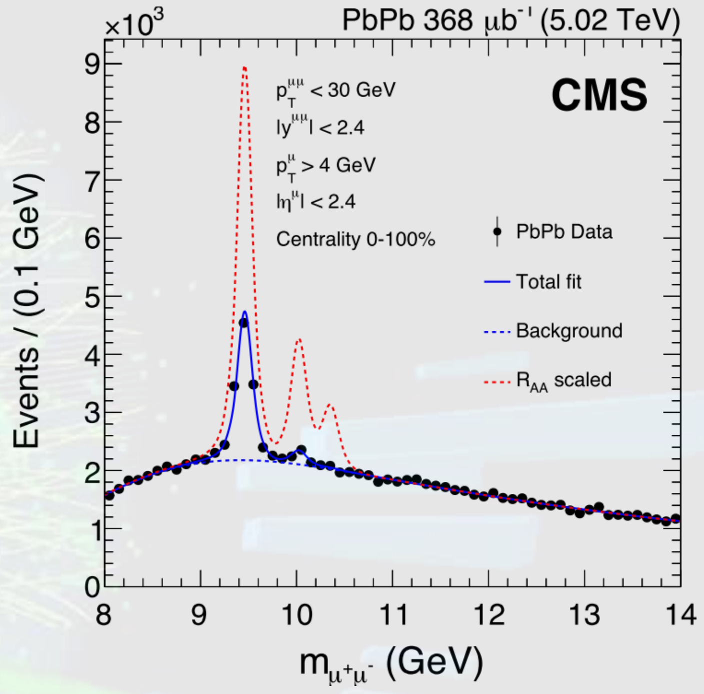
X(3872)

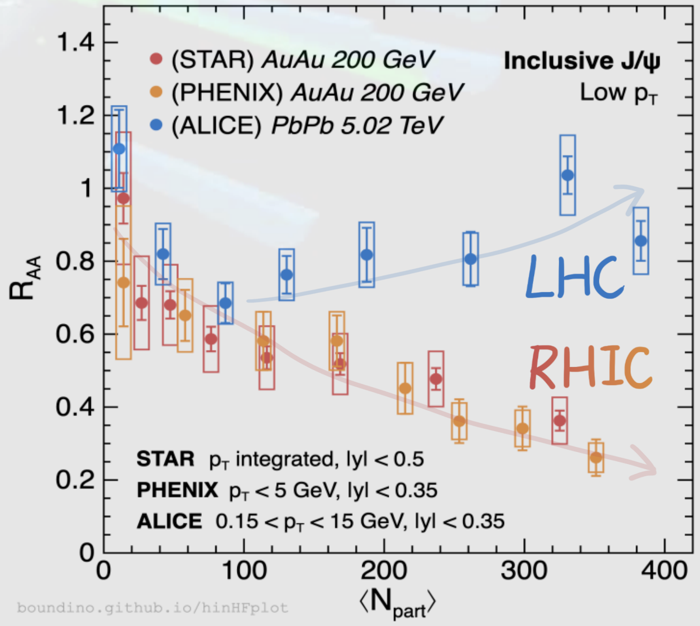
Summary: Quarkonia, B_c and X(3872)

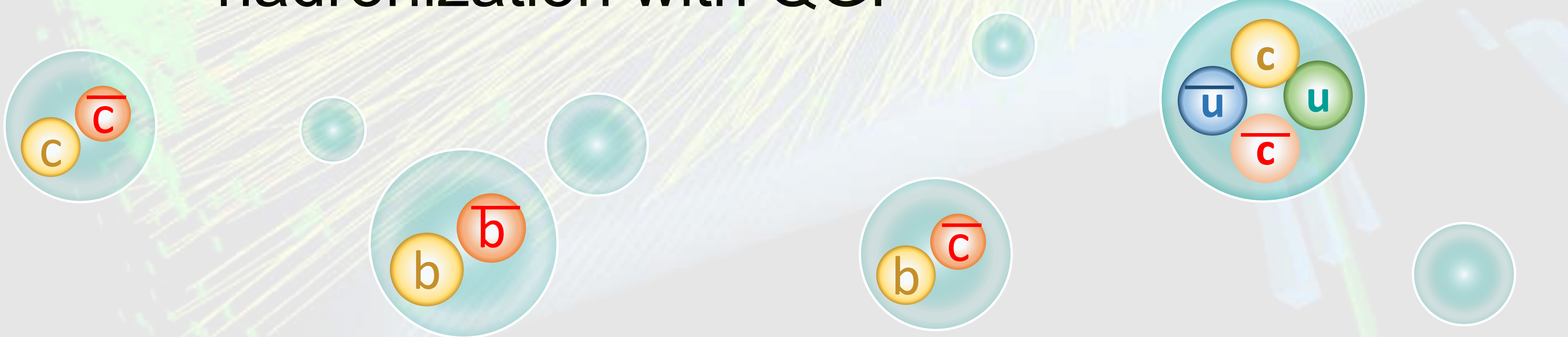
- Study the in-medium dissociation and regeneration, model dependent extraction of QGP temperature

- Sequential Suppression pattern established from R_{AA} of charmonium and bottomonium states

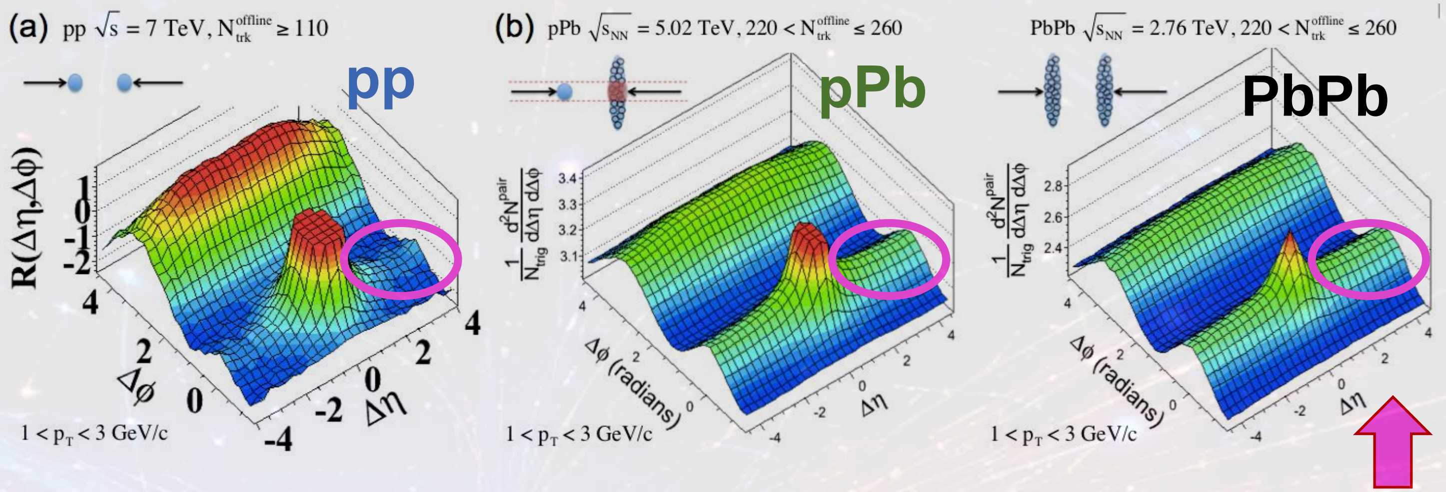
- Significant enhancement of low p_T J/ψ at the LHC, indication of enhanced production of B_c and X(3872)
    - Significant modification of heavy quark hadronization with QGP



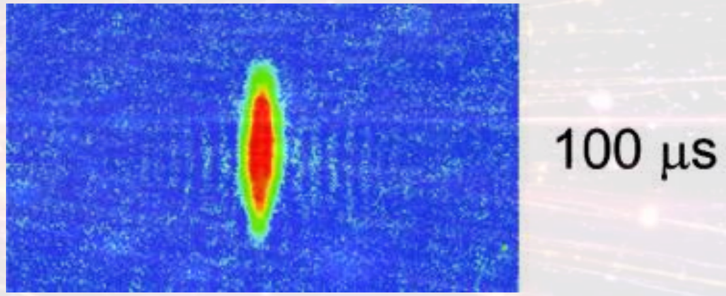




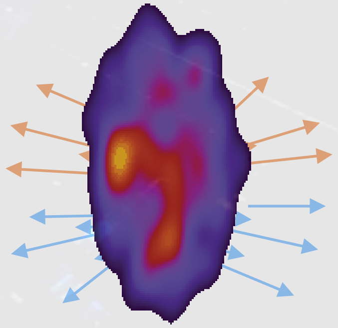
Two-Particle Correlation Function in PbPb Collisions



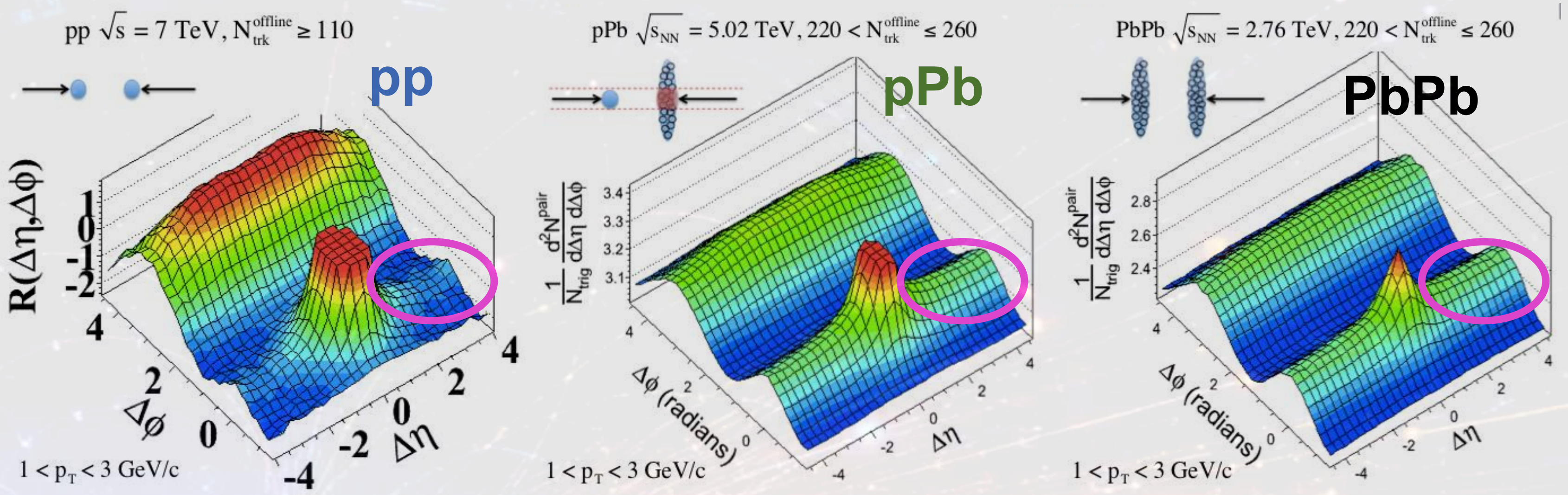
- "Ridge" in **Lead-Lead** collisions: Hydrodynamics Flow



Quark Gluon Plasma



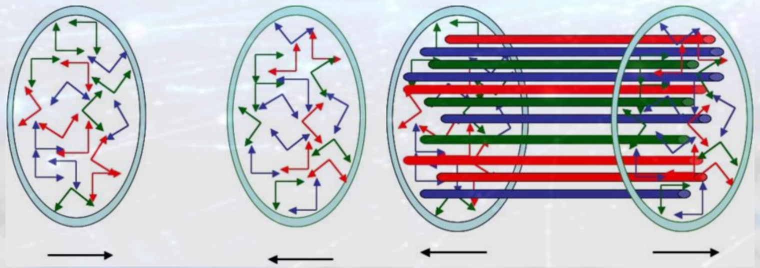
Interpretation of the Ridge Signal



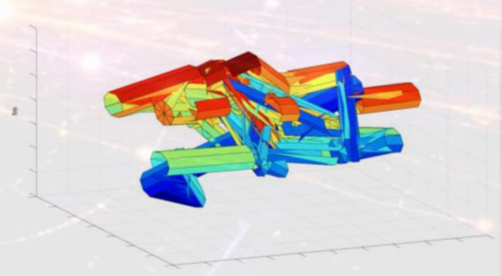
The origin may not be hydrodynamics, possible explanations include:

pp: CMS JHEP 09 (2010) 091
pPb: CMS pPb PLB 718 (2013) 795-814

- Initial state effect (e.g. CGC)

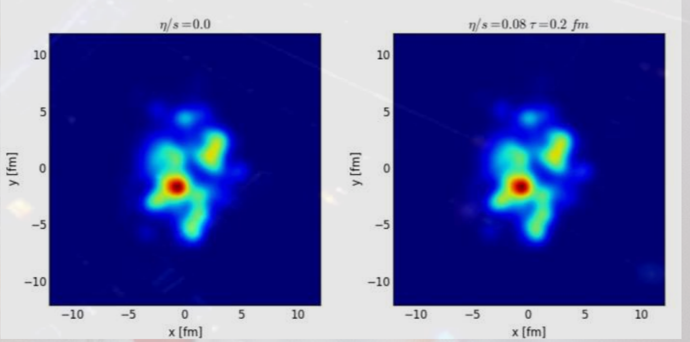


Overlapping strings in PYTHIA



- Escape mechanism / Single or few scatterings (AMPT, PYTHIA with Rope Mechanism, Multi-parton rescattering…)

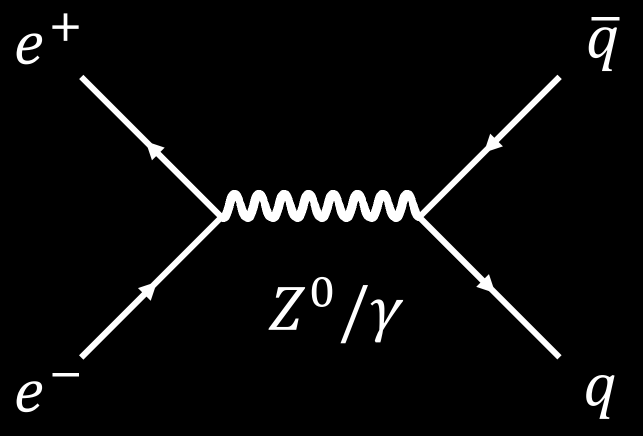
Zi-Wei Lin's talk

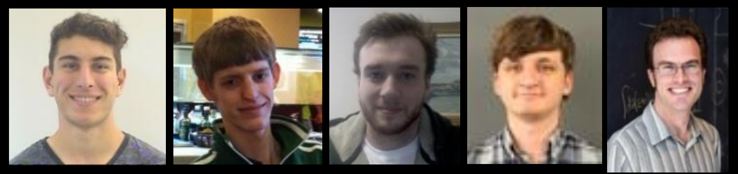


- Final state effect due to mini-QGP production
- …

High Multiplicity Event in e^+e^- Collisions

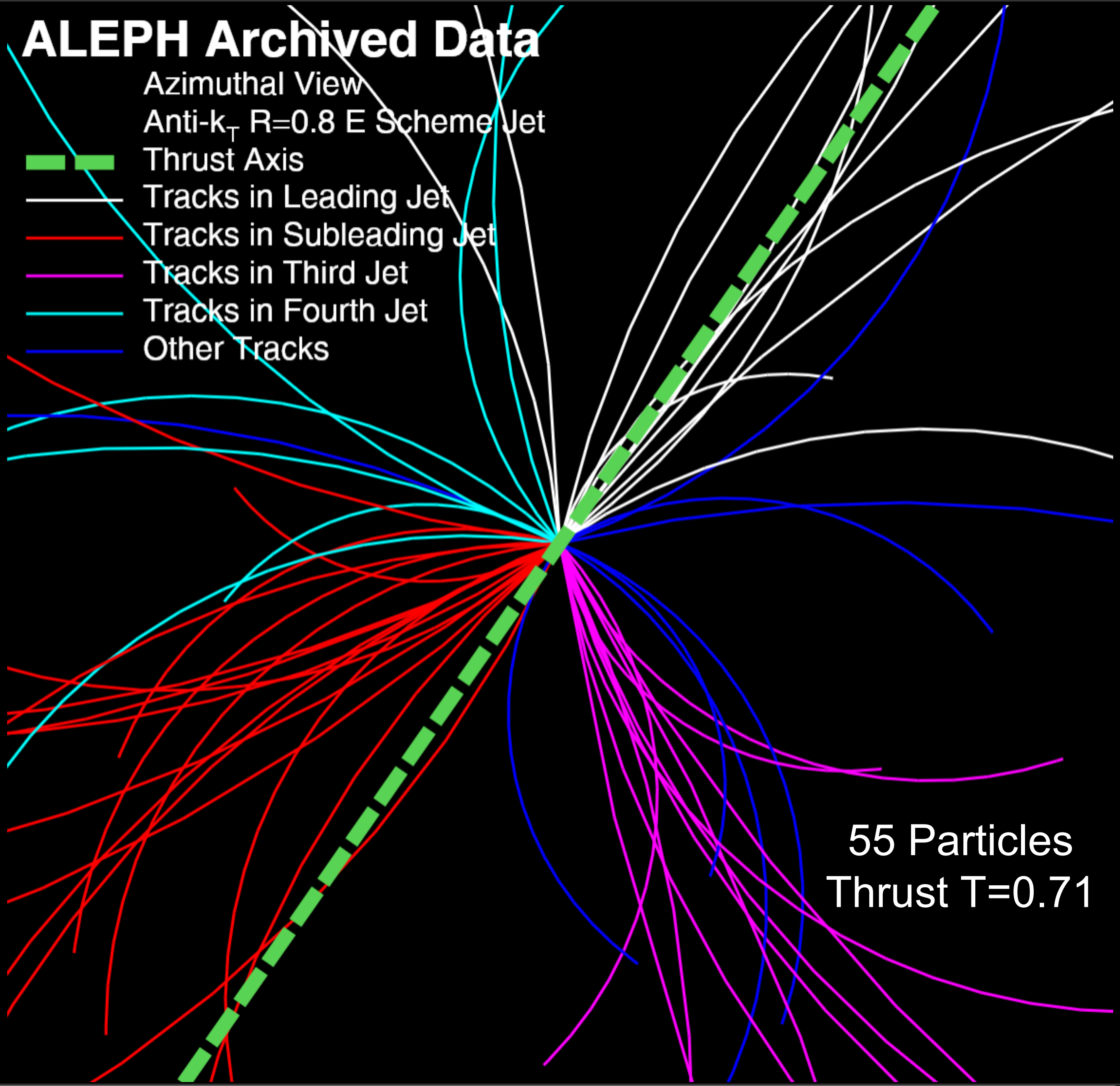
Large Electron Positron Collider 1 (LEP)
1992-1995



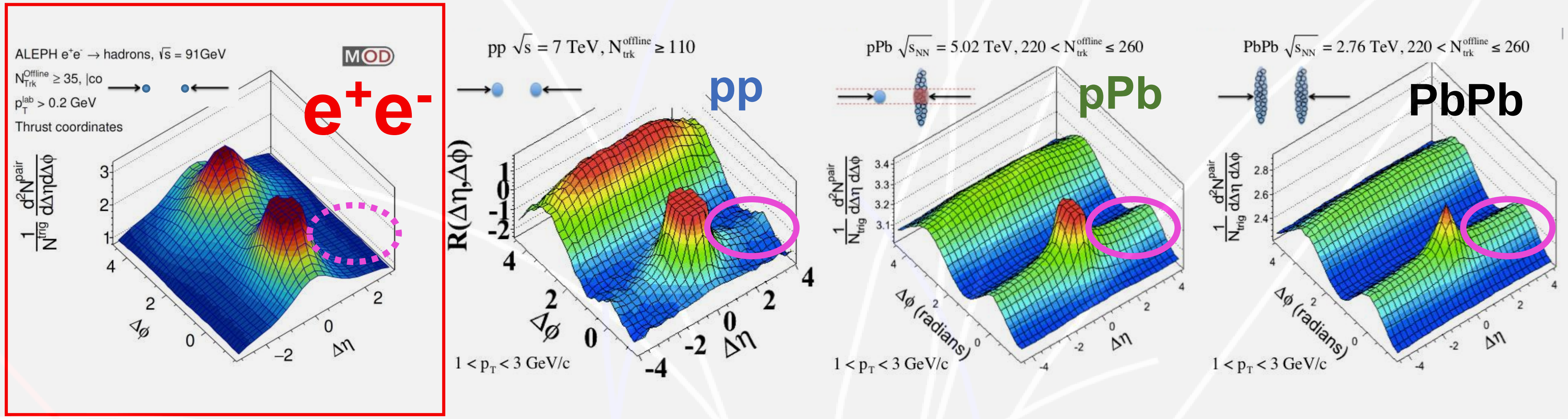


Anthony Badea Austin Baty Chris McGinn Michael Peters Jesse Thaler

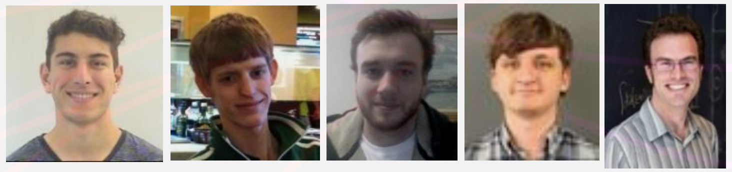
Highest multiplicity event in ALEPH data at Z pole
Collision Energy = 91 GeV



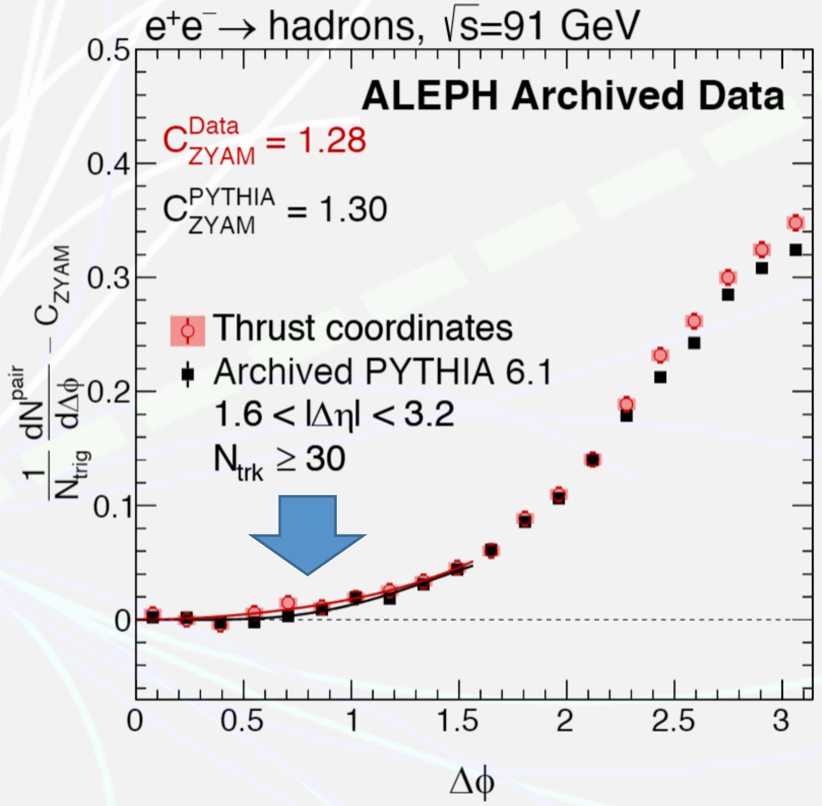
Results from ALEPH e^+e^- at 91 GeV



- No sign of ridge-like signal in single-string electron-positron collisions up to ~ 55 particles per event
- New reference to the collective behavior in small collision systems!



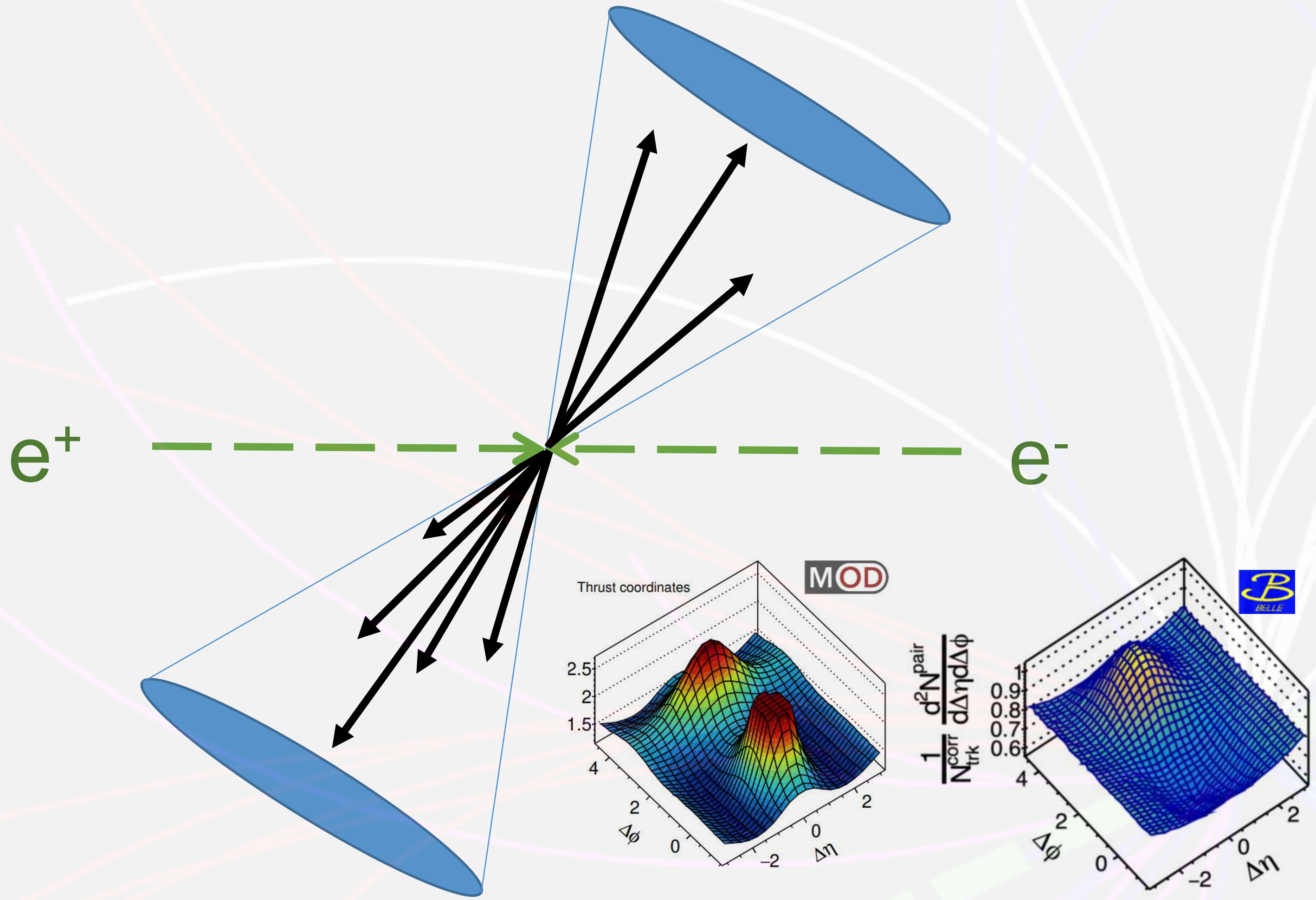
PRL 123, 212002 (2019)

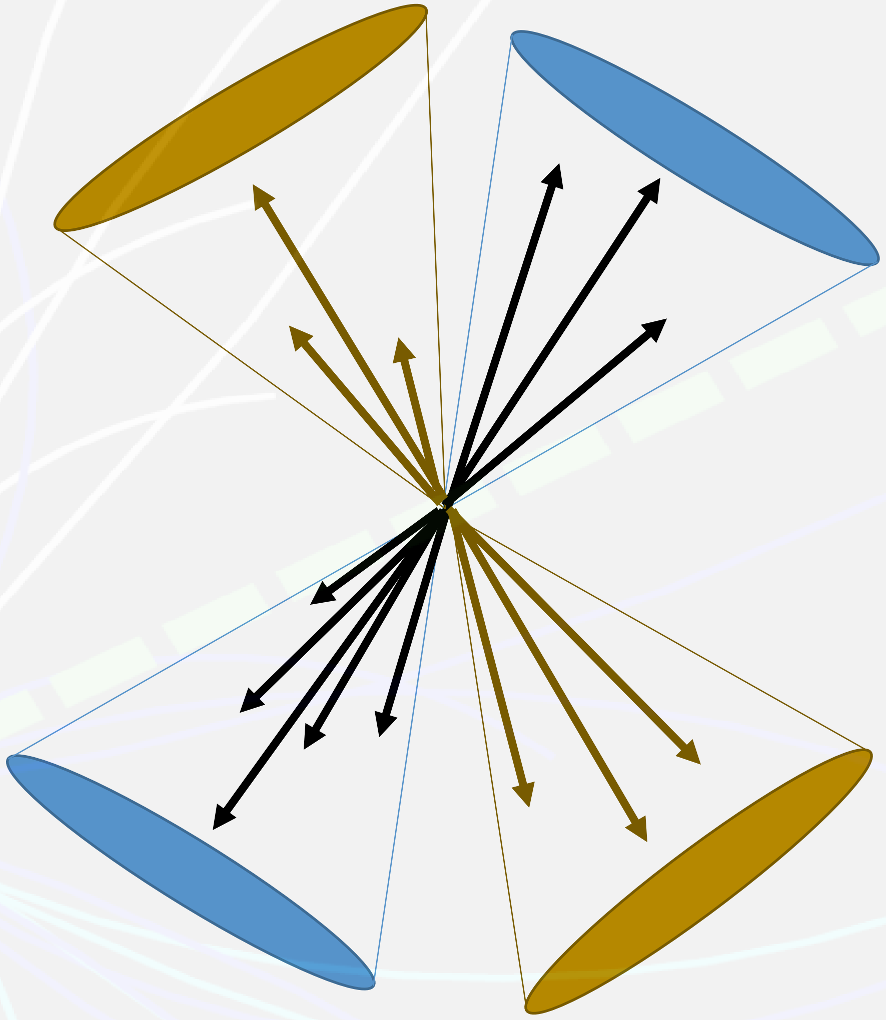


e^+e^- Alliance
http://ee-alliance.org/

Can We Overlap Two Color Strings?

$$e^+e^- \rightarrow q\bar{q}$$





?

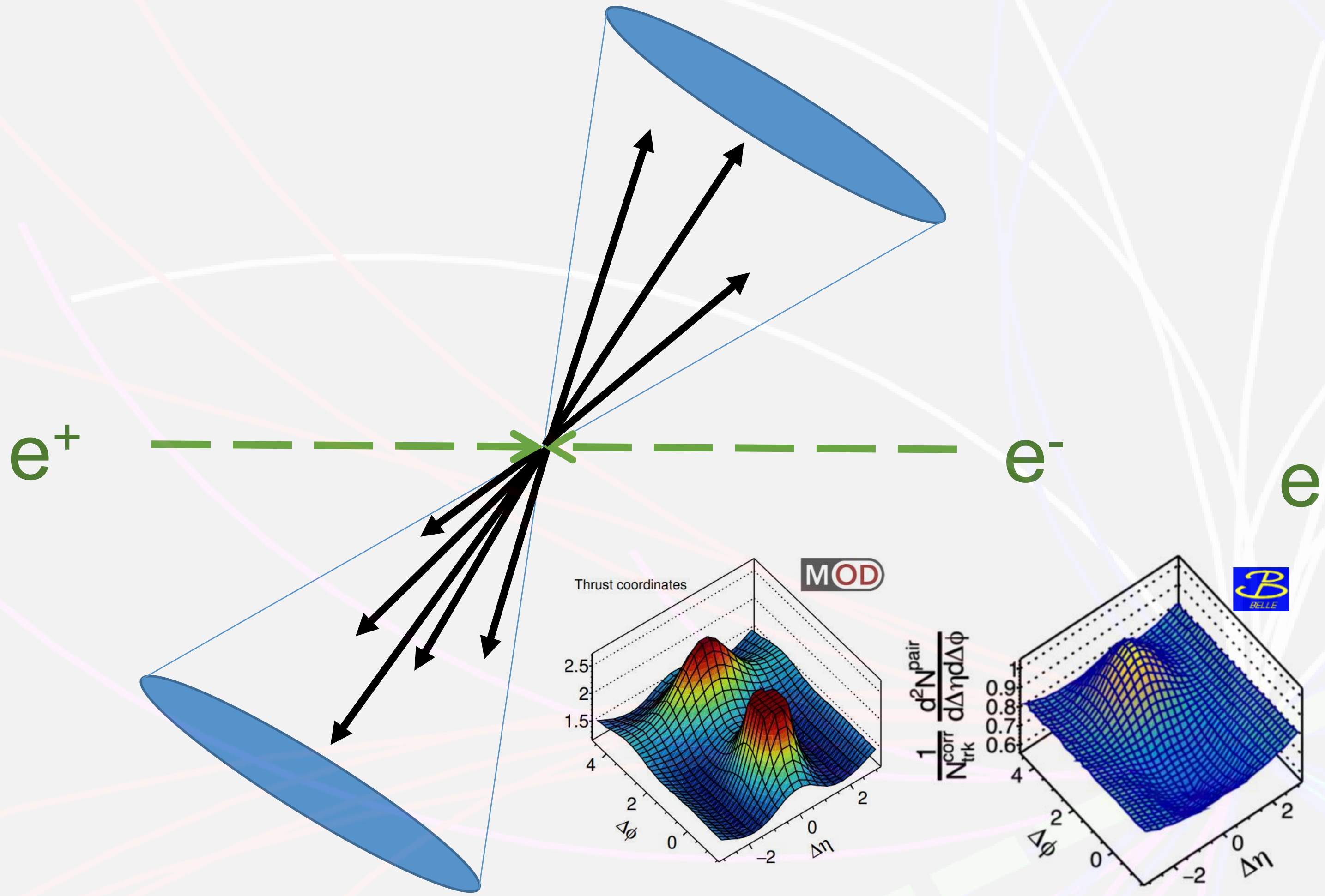
Belle PRL 128 (2022) 14, 142005
Belle JHEP 03 (2023) 171
Electron-Positron Alliance PRL 123, 212002 (2019)

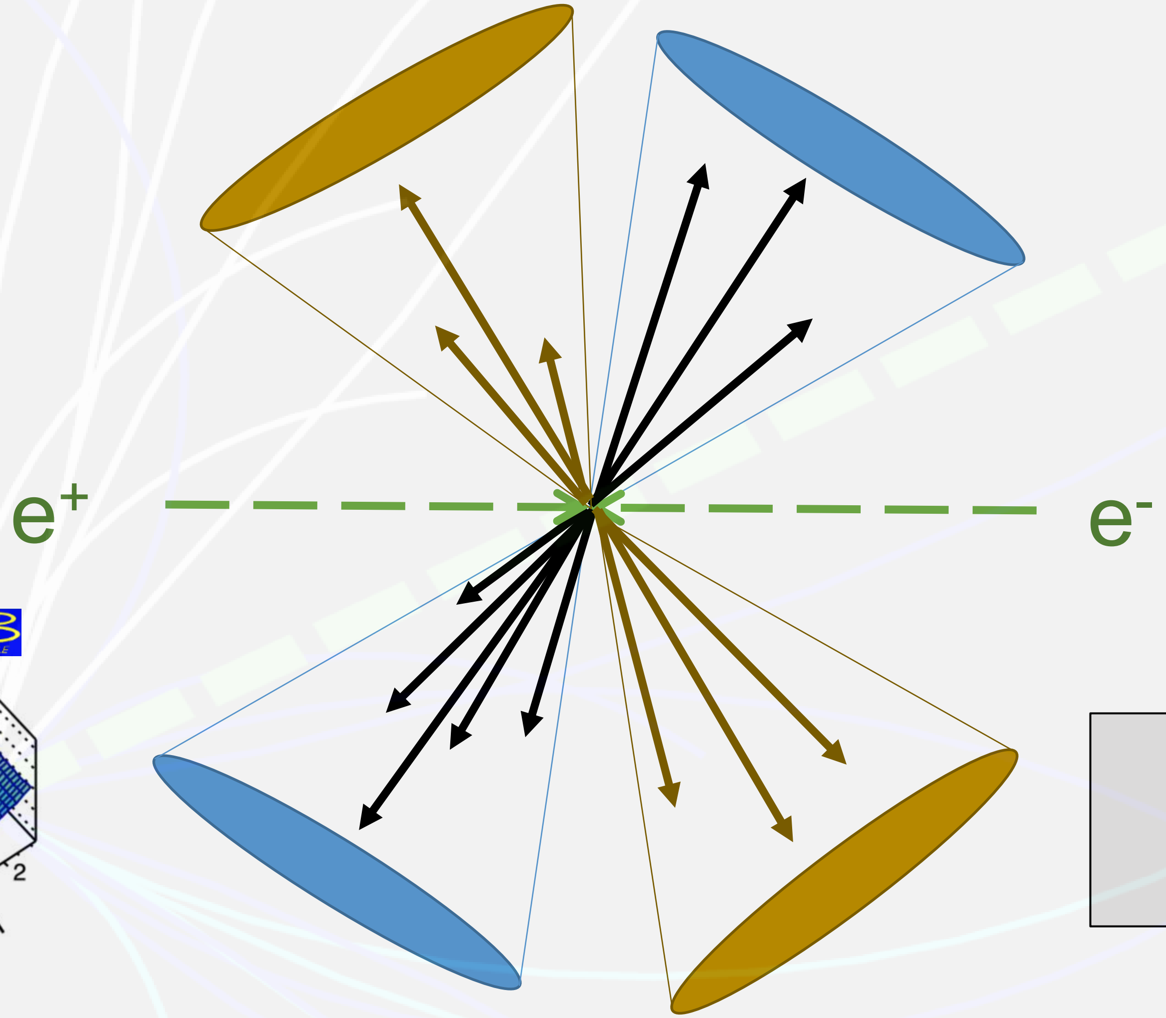
No ridge-like structure

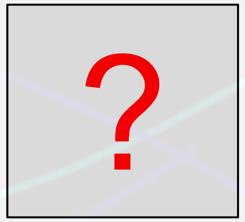
High Multiplicity e^+e^- Event at High Collision Energy !!

$$e^+e^- \to q\bar{q}$$

$$e^+e^- \to W^+W^- \to q\bar{q}q\bar{q}$$



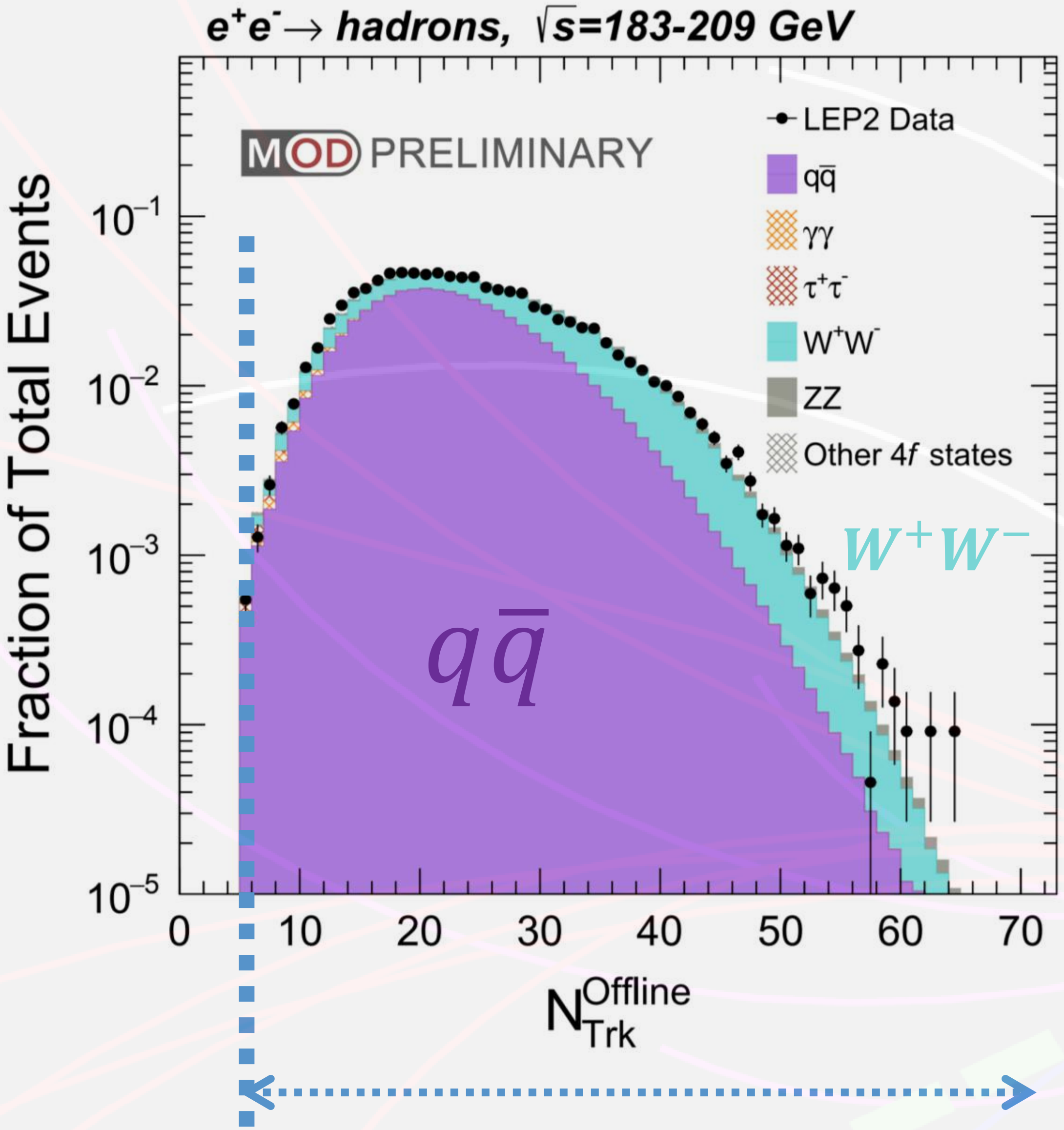


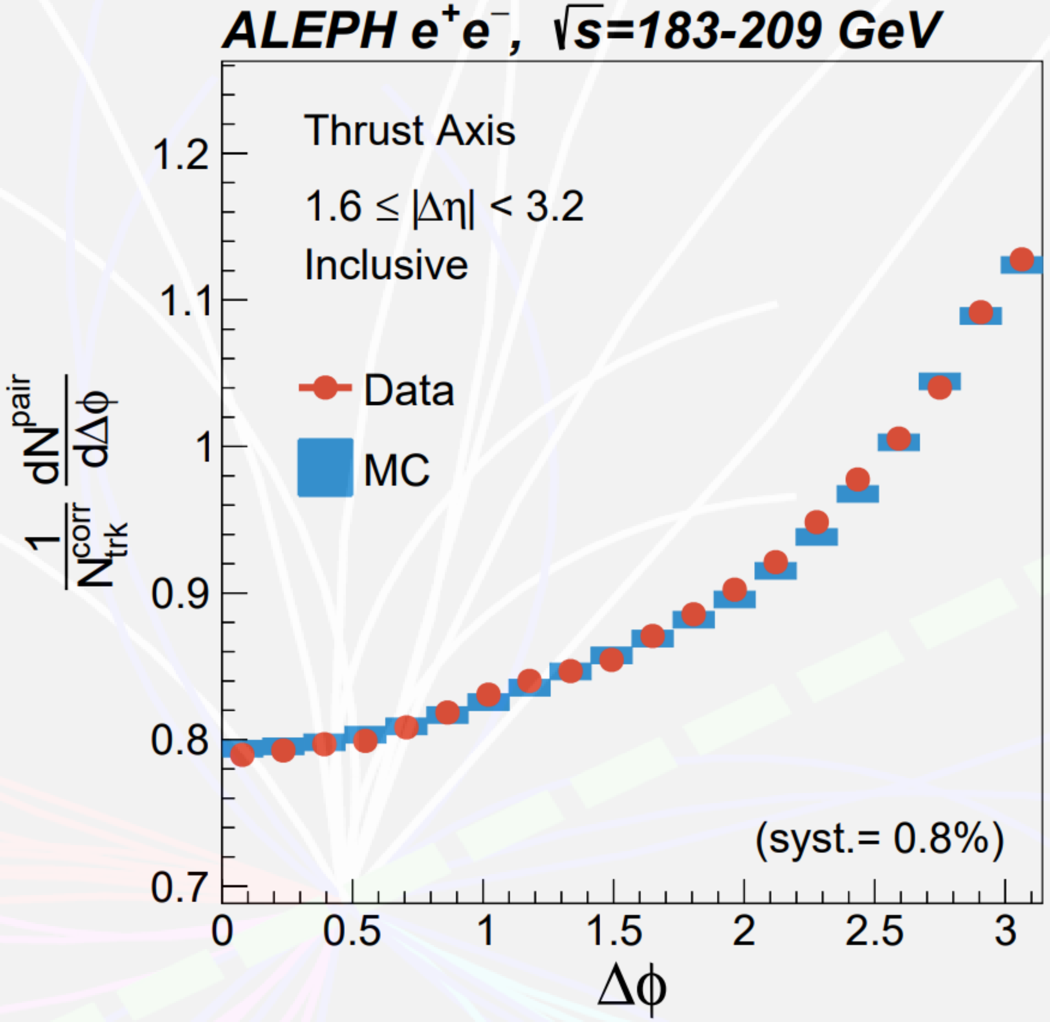


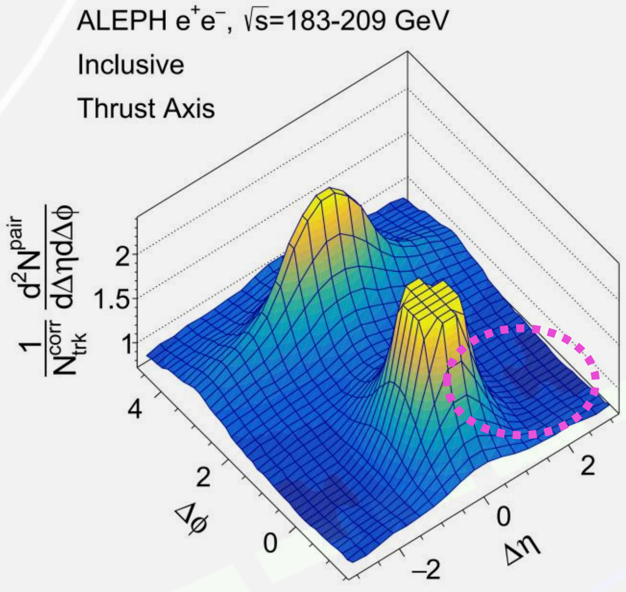
No ridge-like structure

Belle PRL 128 (2022) 14, 142005
Belle JHEP 03 (2023) 171
Electron-Positron Alliance PRL 123, 212002 (2019)

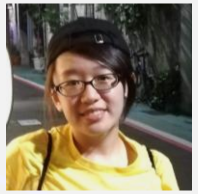
Inclusive Hadronic e^+e^- Events at LEP 2 ($N_{ch} \geq 5$)







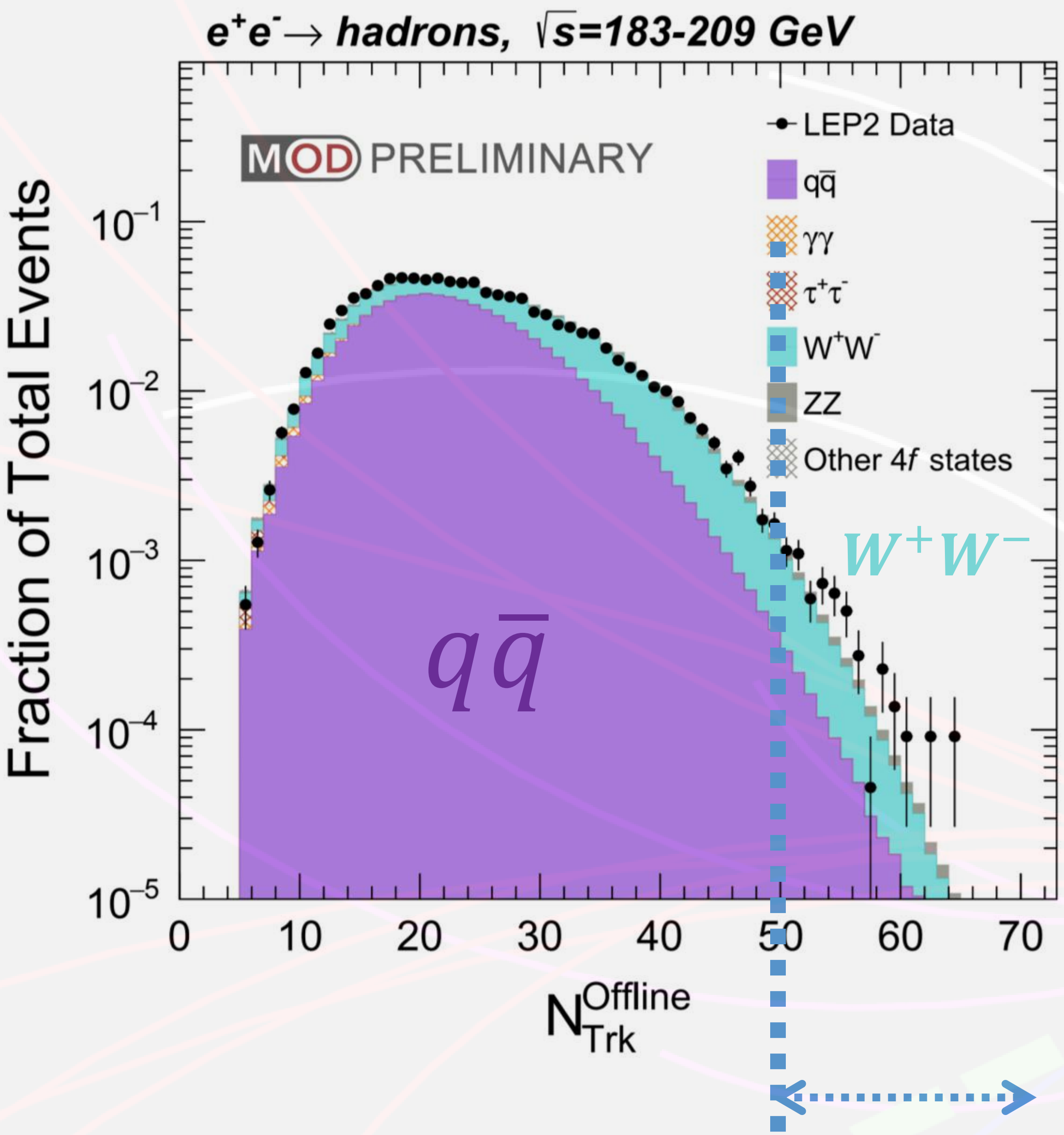
arXiv:2312.05084
PLB 856 (2024) 138957

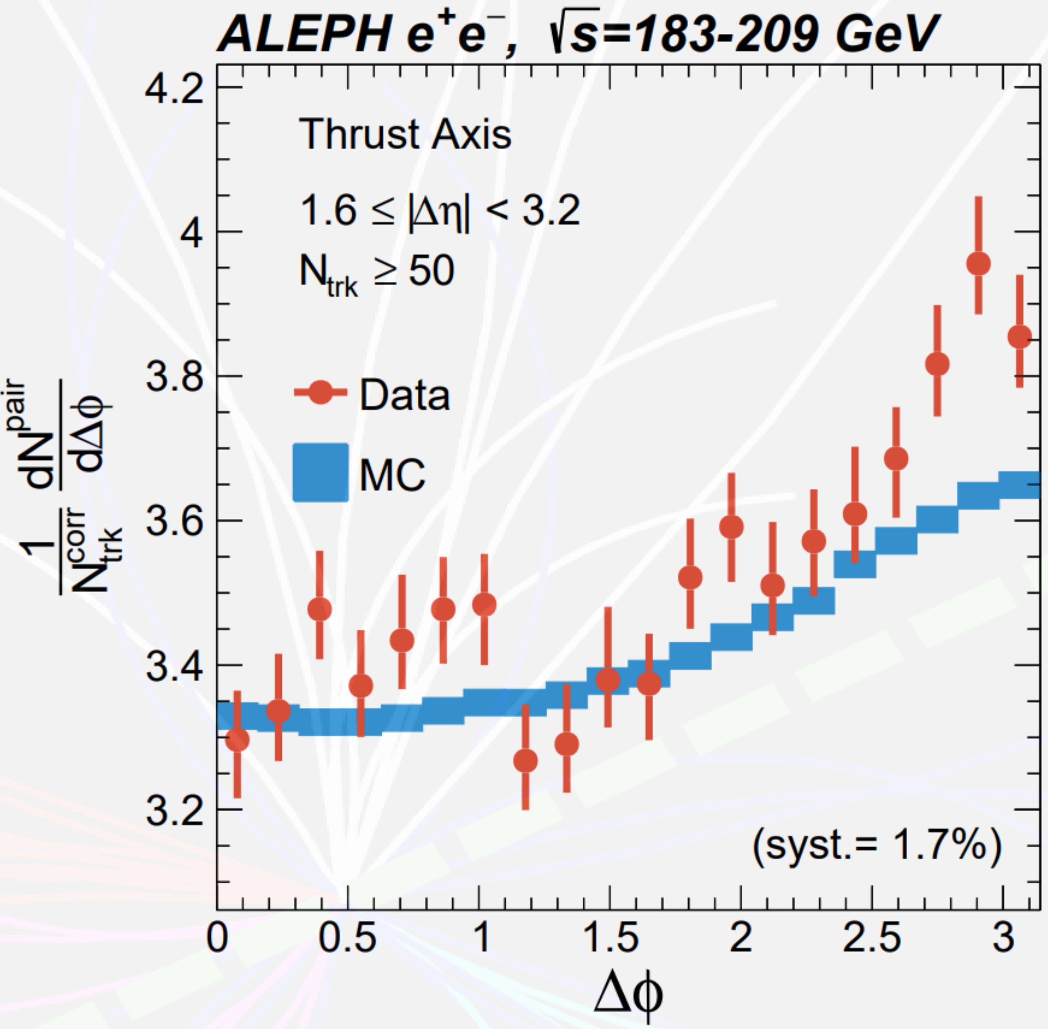


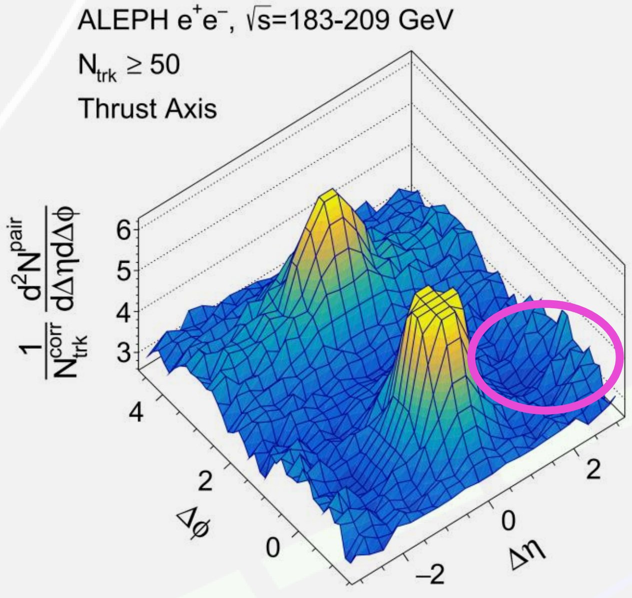
Yu-Chen "Janice" Chen (MIT)

- Excellent agreement between **data** and **simulation (Archived MC)**

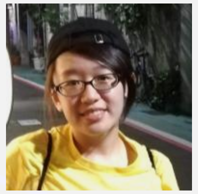
High Multiplicity e^+e^- Events at LEP 2 ($N_{trk} \geq 50$)







arXiv:2312.05084
PLB 856 (2024) 138957

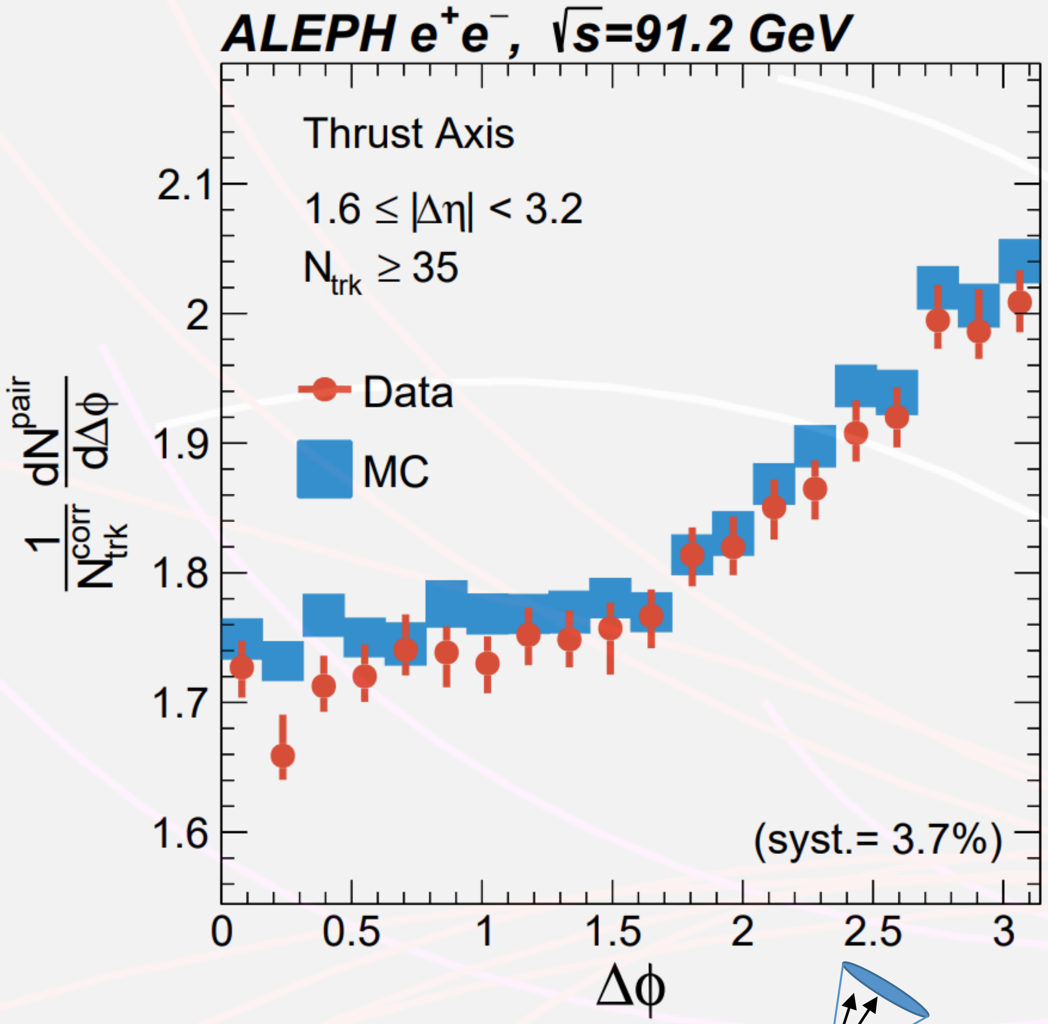


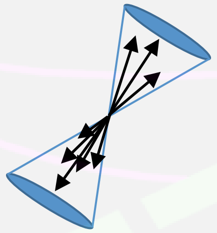
Yu-Chen "Janice" Chen (MIT)

- A long-range near-side correlation signal shows up at high multiplicity!
- Data also feature a narrower away-side spectrum at $\Delta\phi \sim \pi$

High Multiplicity e^+e^- Events at LEP1 vs LEP 2

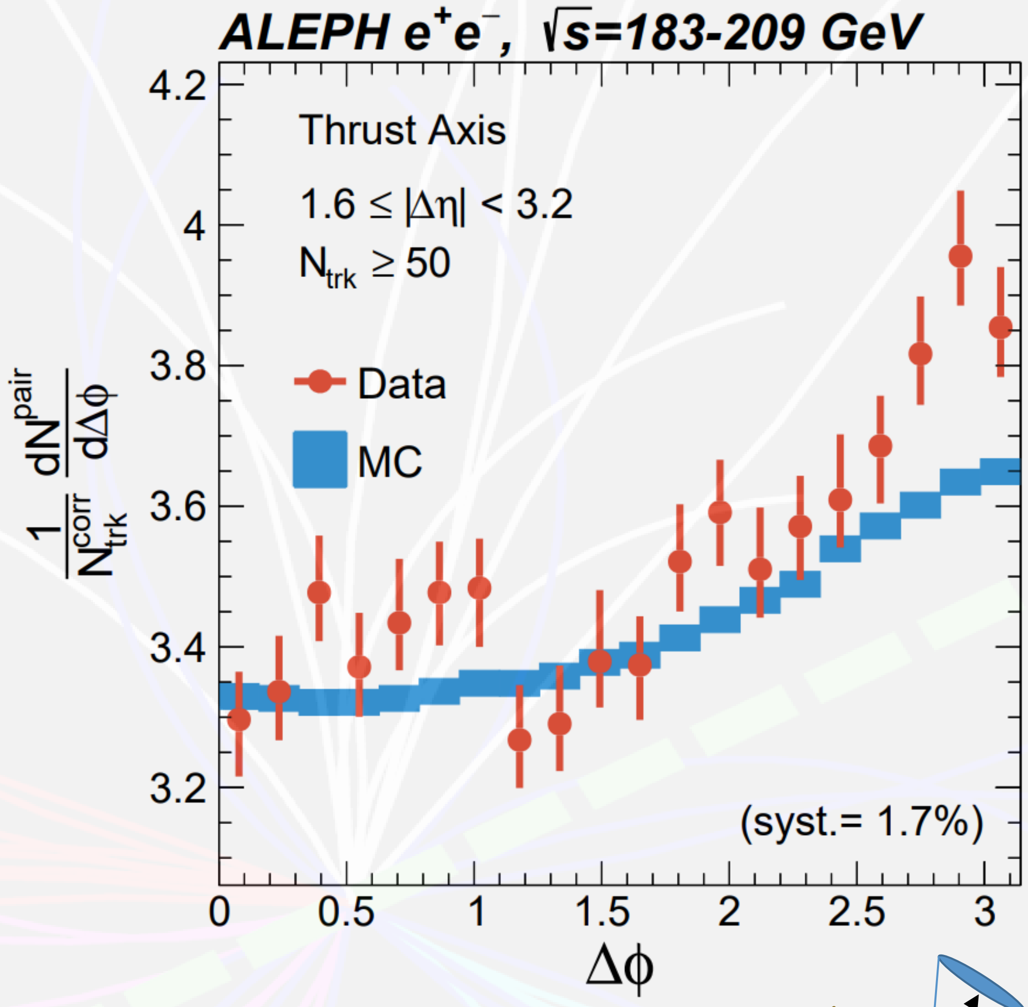
LEP1 N_{trk}>35

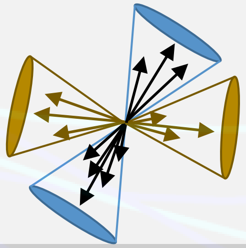




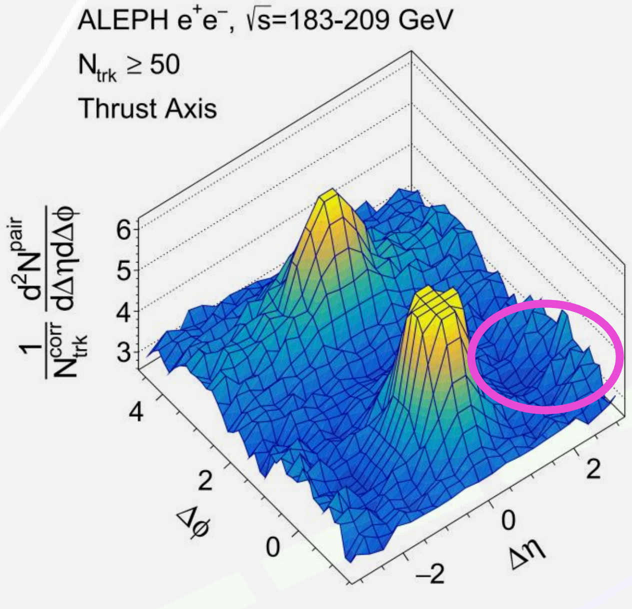
$e^+e^- \rightarrow q\bar{q}(\gamma)$

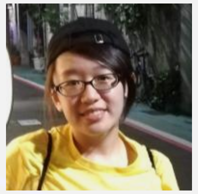
LEP2 N_{trk}>50





$e^+e^- \rightarrow W^+W^-$ enriched

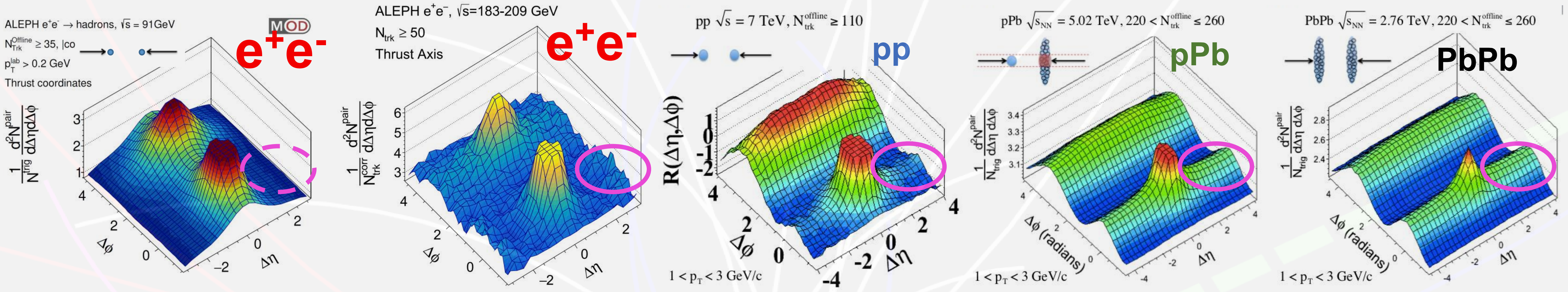


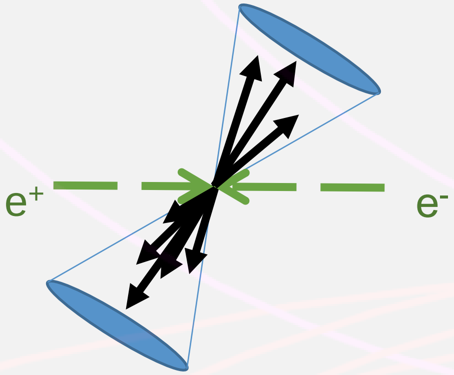


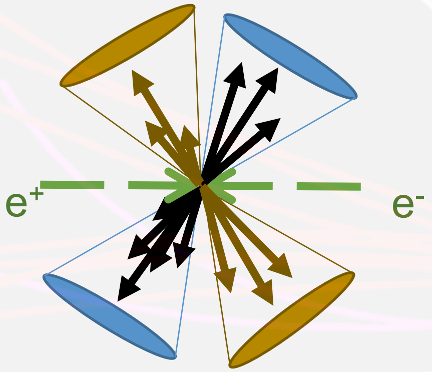
Yu-Chen "Janice" Chen (MIT)

arXiv:2312.05084
PLB 856 (2024) 138957

Emerging Picture

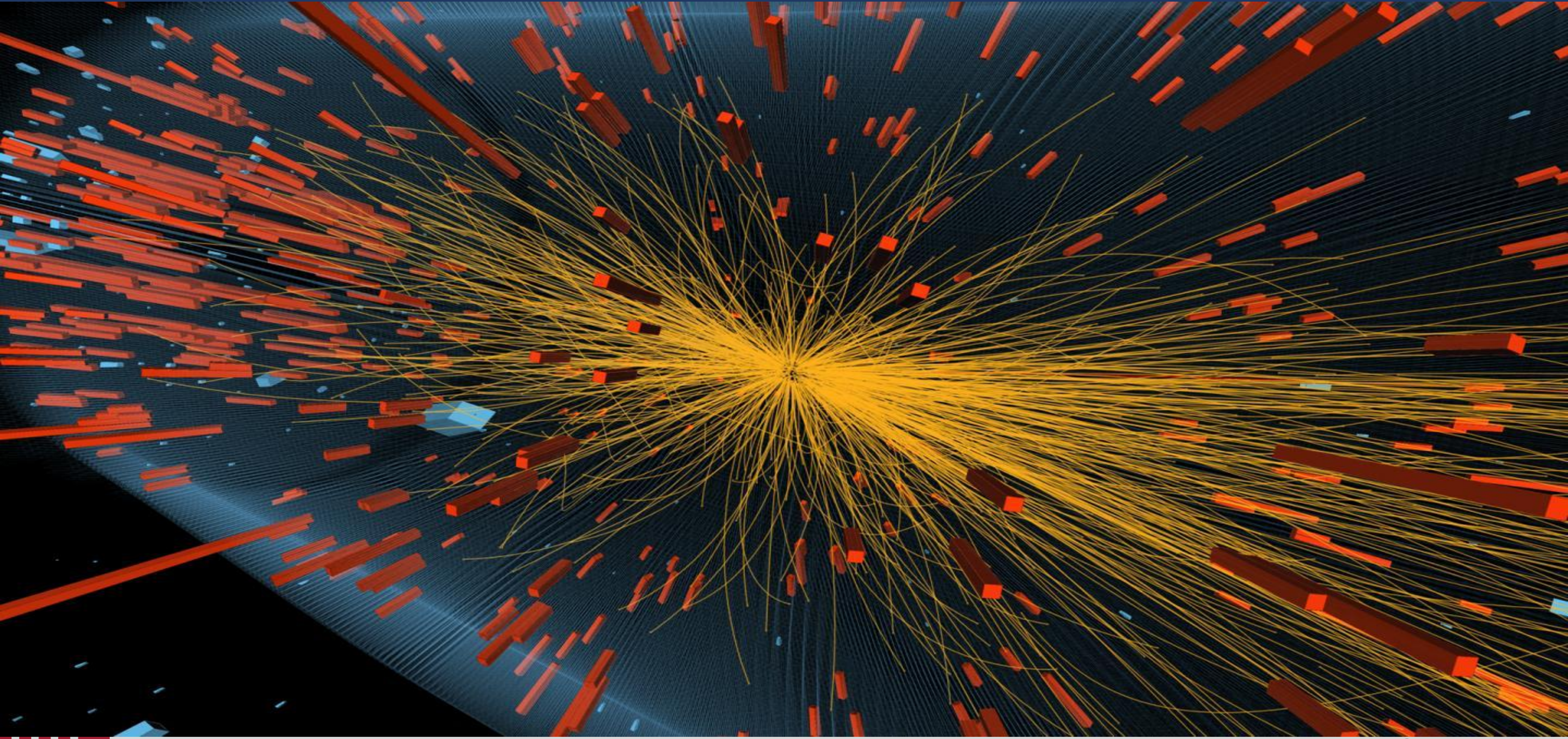




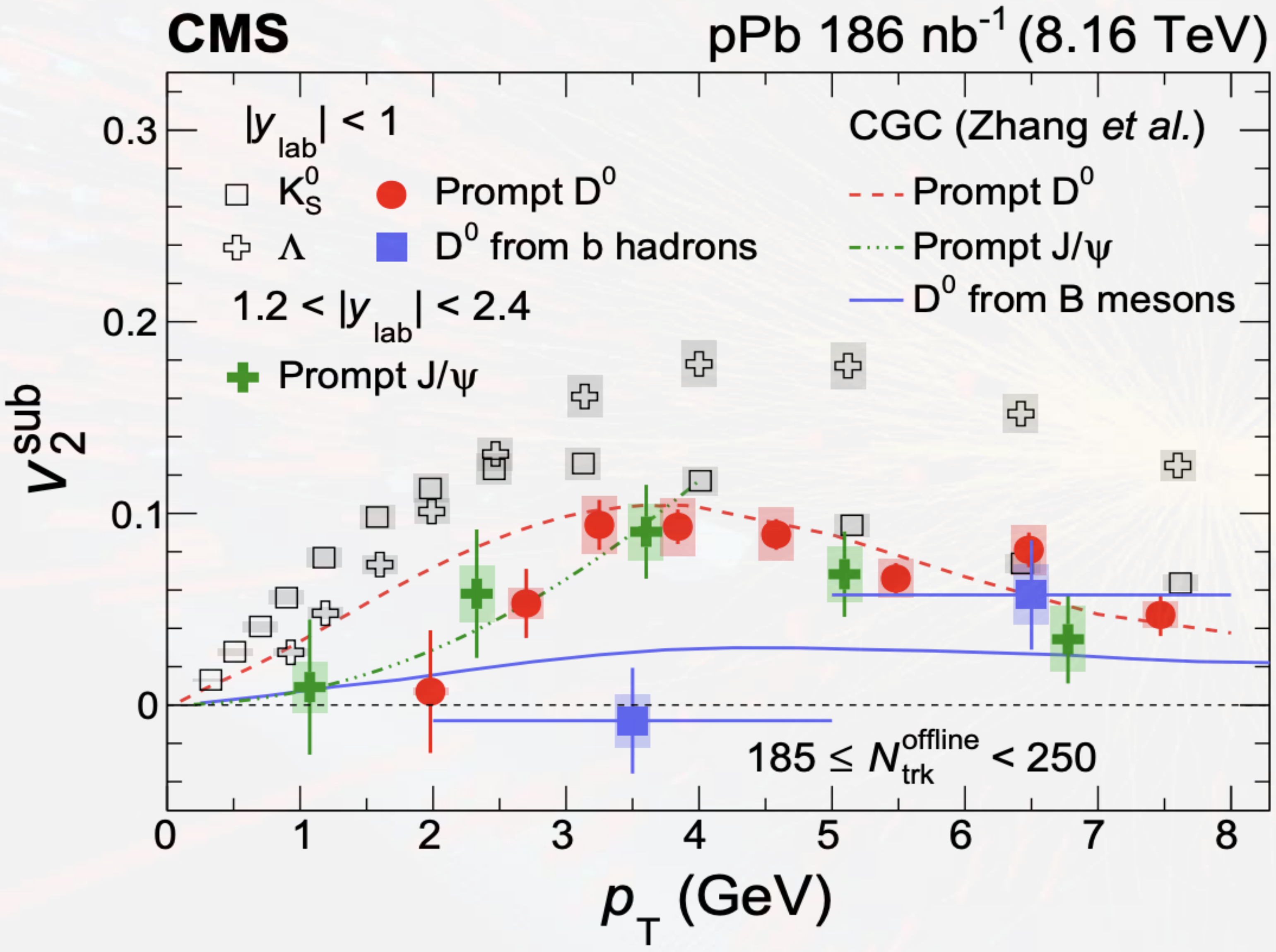


- LEP2 high-multiplicity W^+W^- correlations appear, but **likely not hydrodynamic**.
- Multiplicity is not enough, geometry / color sources matter.

Proton Lead Collisision



Heavy Flavor Hadron v_2 in High Multiplicity pPb



At high multiplicity, significant prompt **D^0** and **J/ψ** v_2 were observed (with nonflow subtraction)

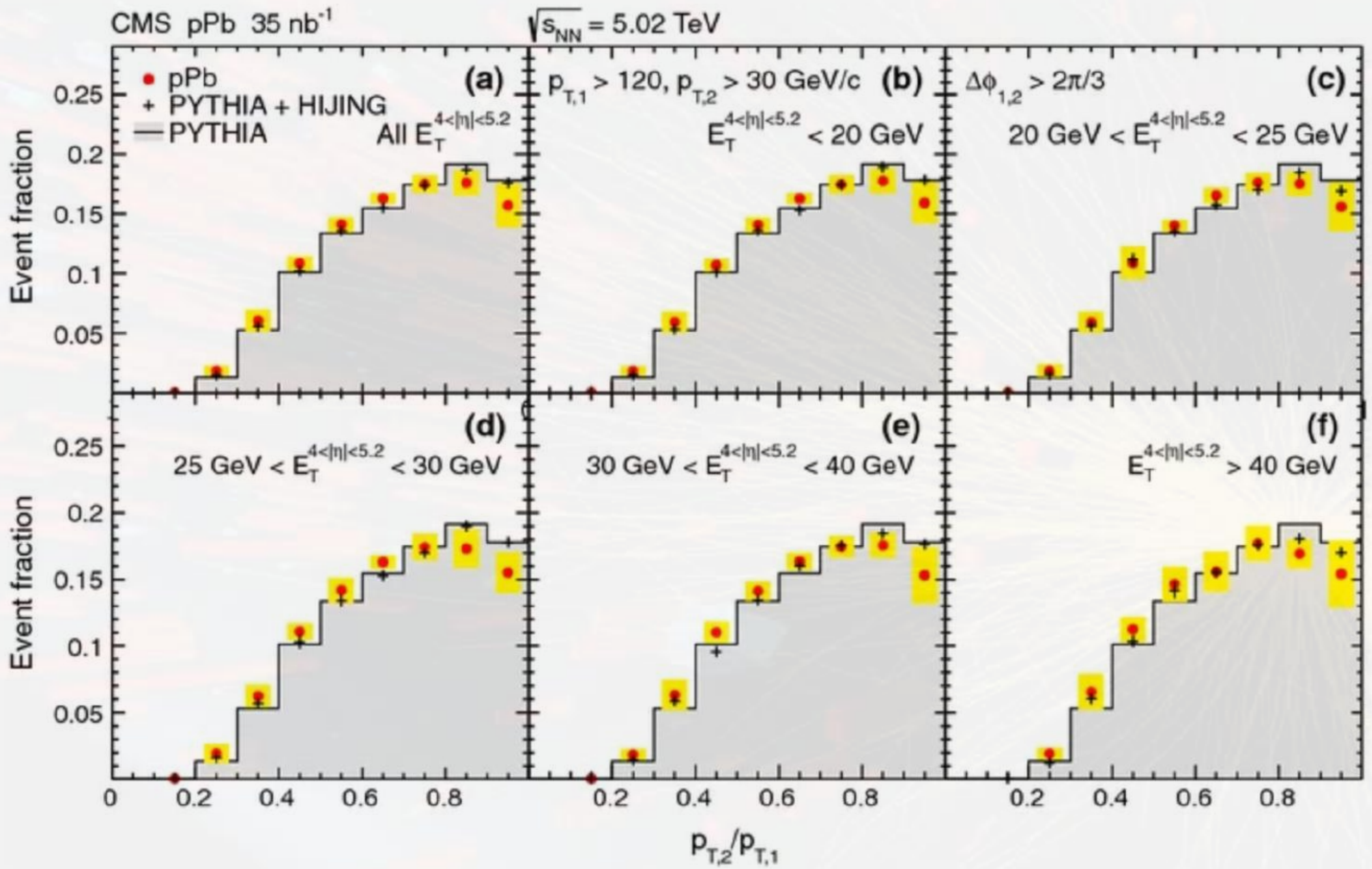
→Charm diffusion in pPb?

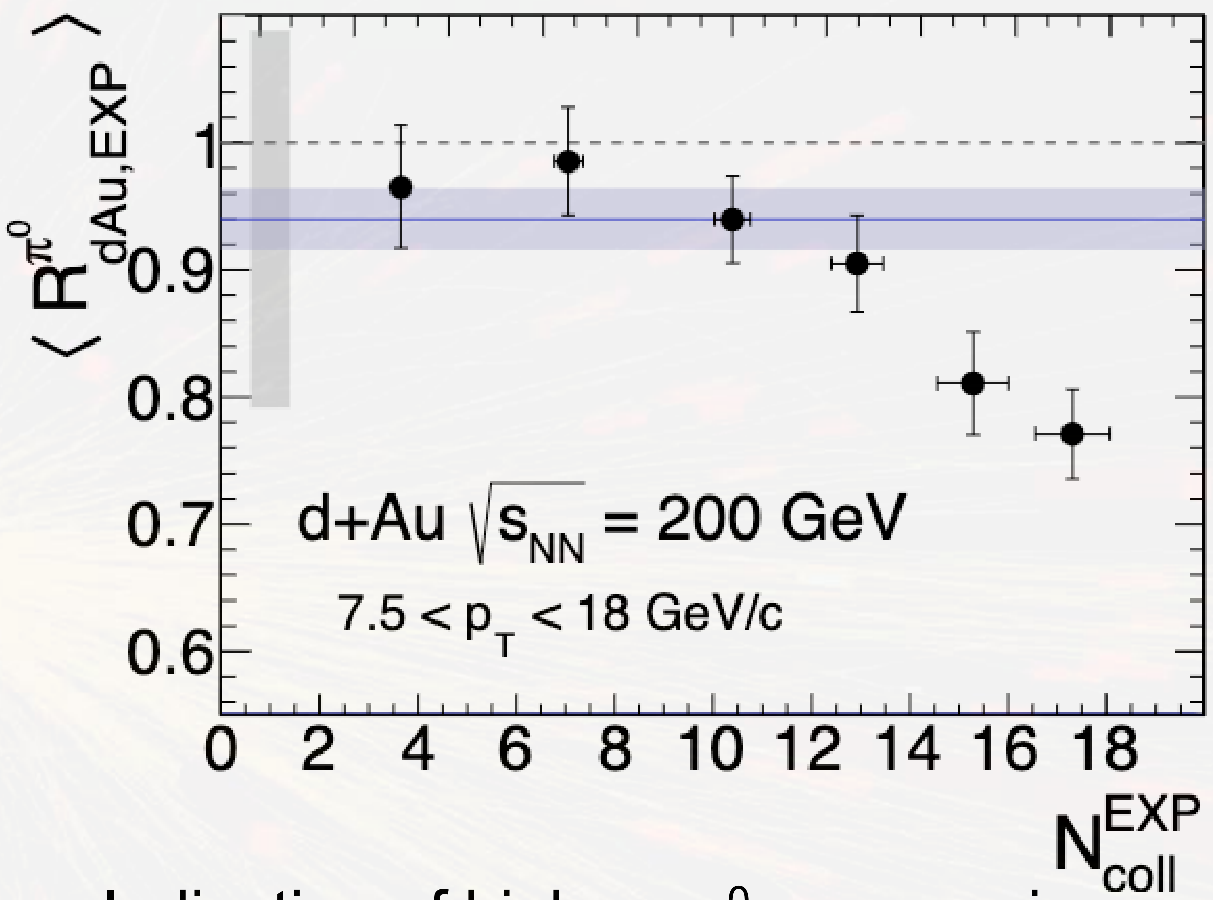
The v_2 values are sizable (as large as 0.09) and remain non-zero up to high p_T (p_T~ 8 GeV)!

→Is this pathlength dependent parton energy loss?

High-multiplicity selection:
What kind of events are we studying?

How about Jet Quenching?



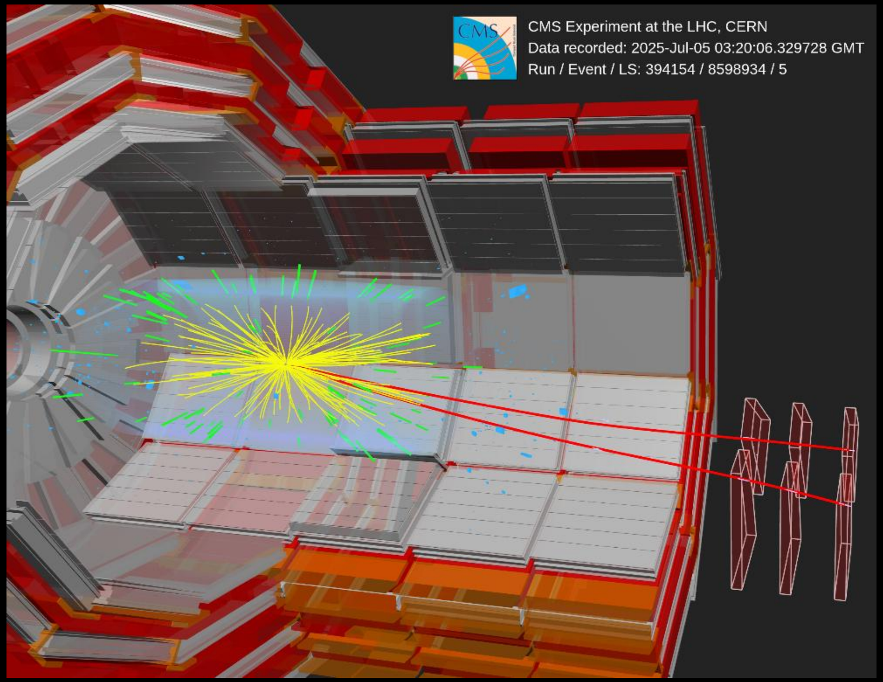


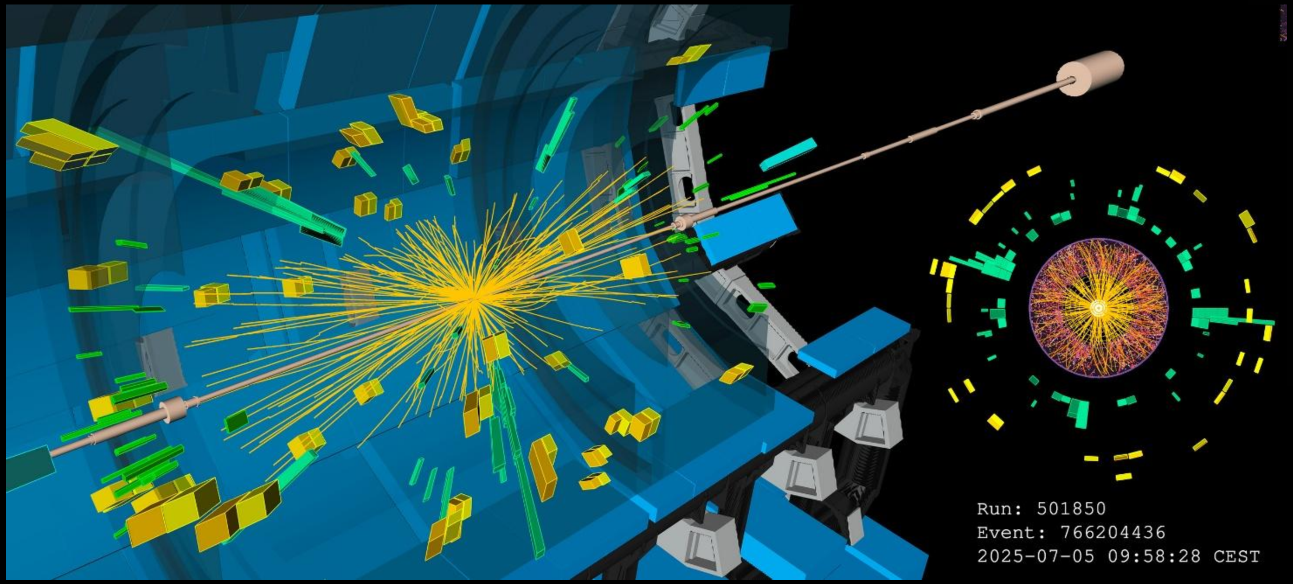
No significant dijet asymmetry signal in pPb collisions at the LHC

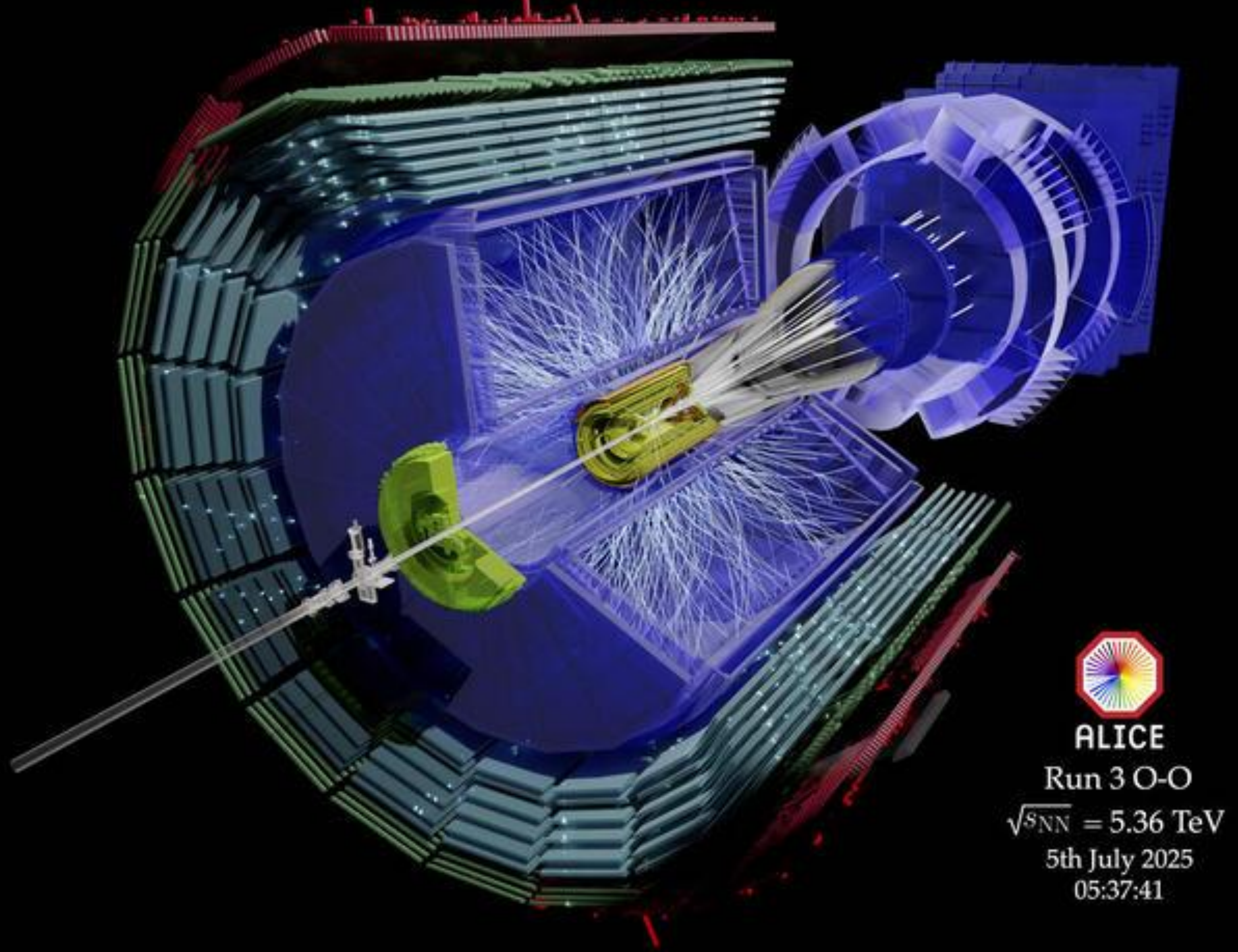
Indication of high p_T π^0 suppression in central dAu collisions (high N_{coll}) at the RHIC

No clear conclusions from various measurements

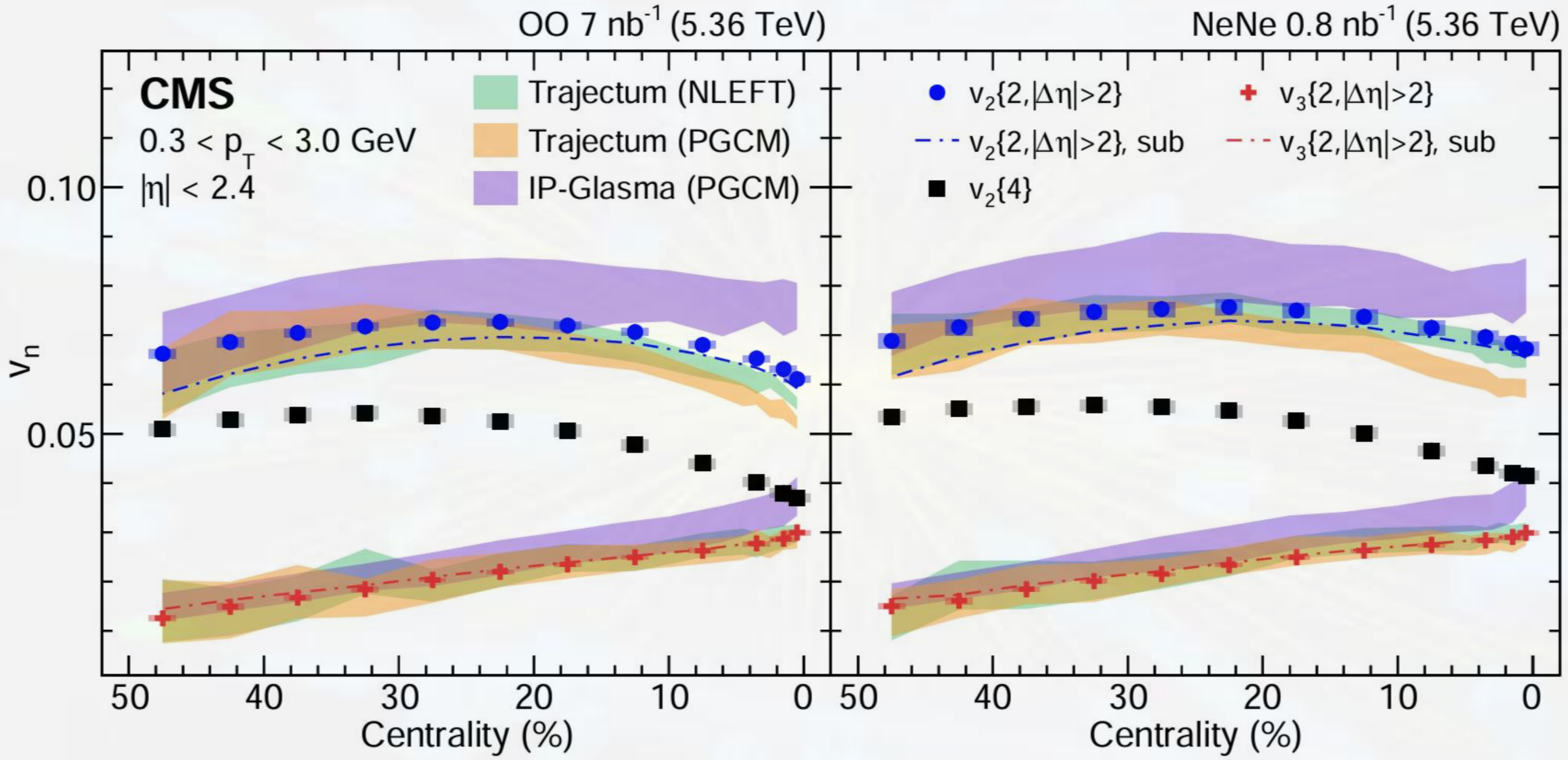
Recent Excitement: Oxygen-Oxygen Collisions





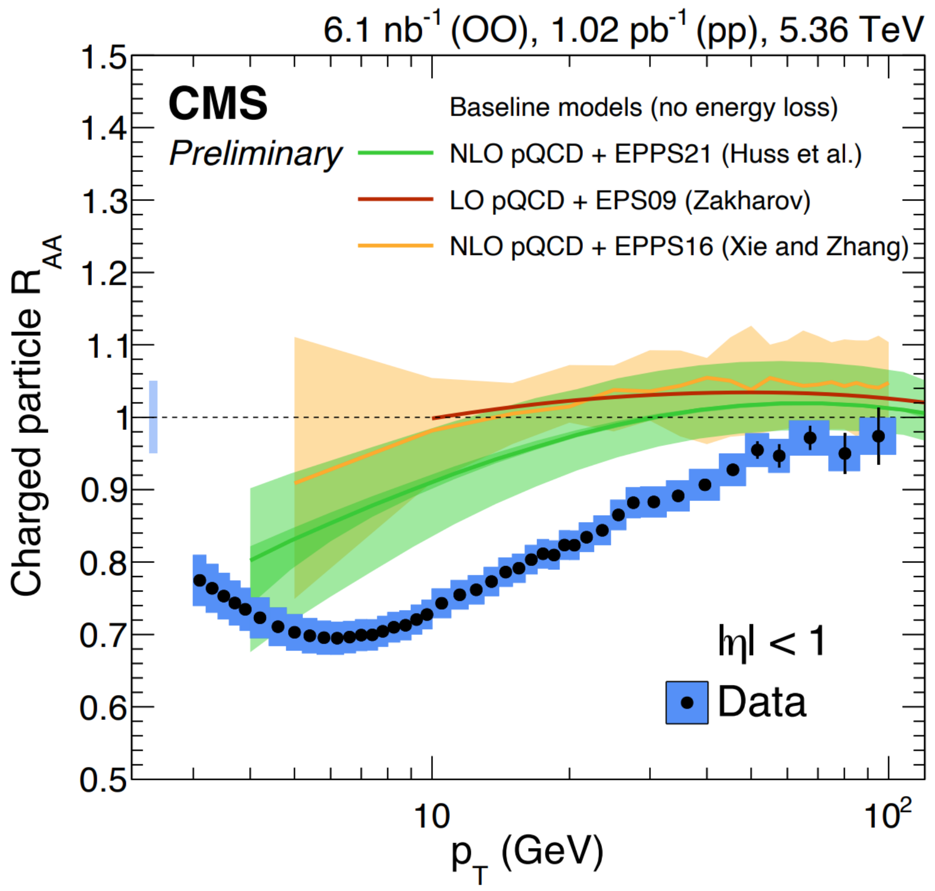


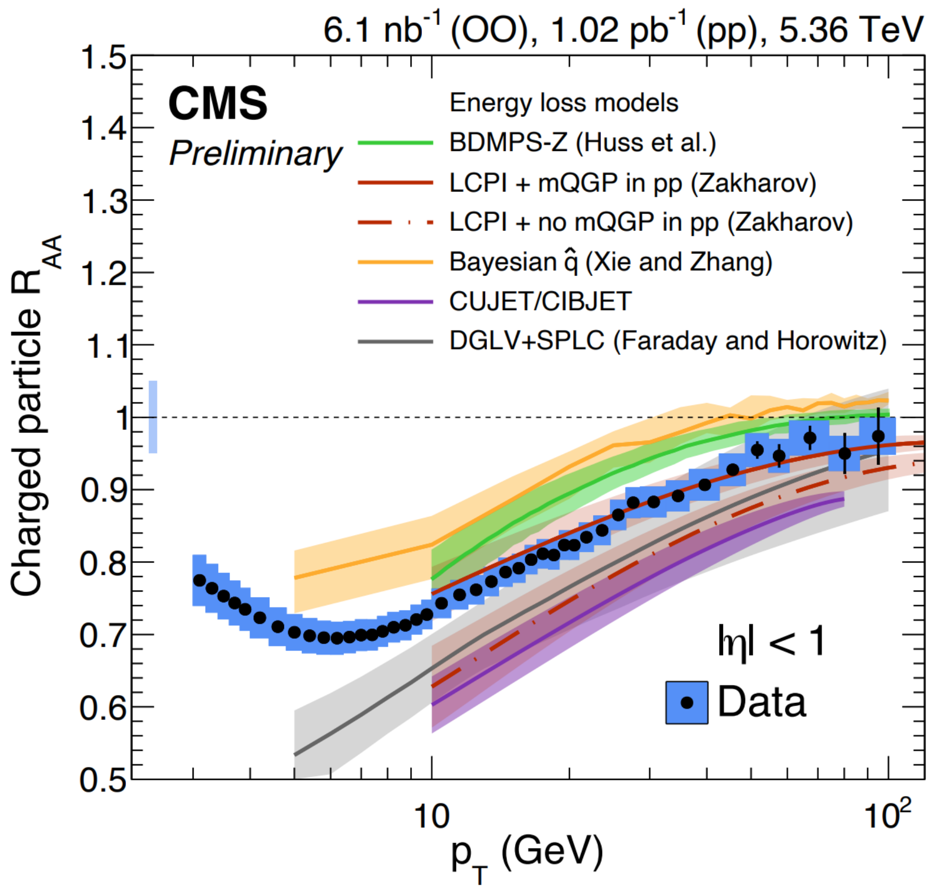
Flow in OO and NeNe Collisions at the LHC

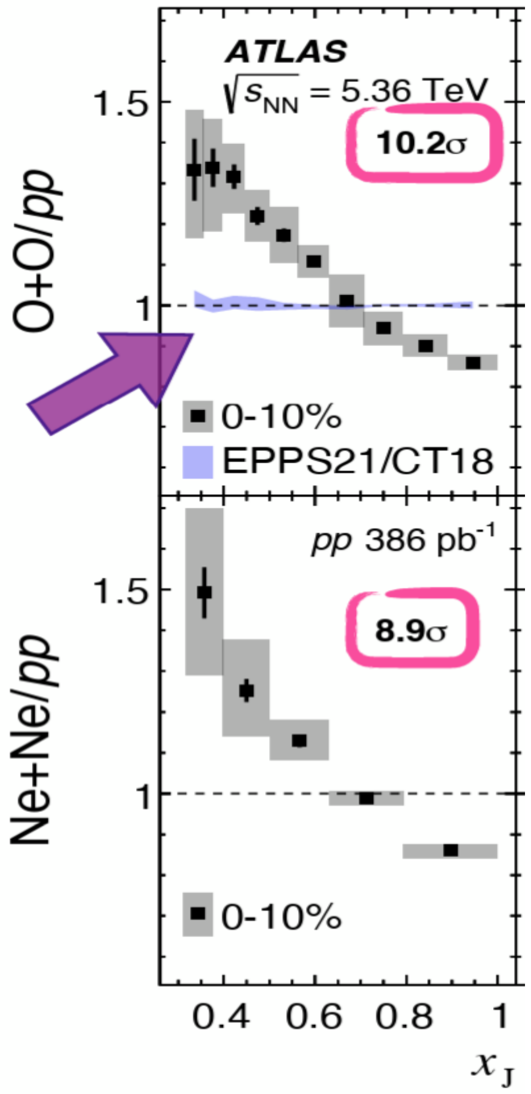


- Significant flow signal in OO and NeNe collisions!
- Elliptic and triangle flow coefficients are described well by the hydrodynamics models

New OO and NeNe Data on Jet Quenching in Small System







- Significant suppression of charged particles observed in **NeNe** and **OO** collisions and dijet asymmetry:
  - The first systems where small-system jet-quenching evidence becomes much more plausible
- In better agreement with models that include jet quenching effect

Heavy Quark Diffusion: D Meson v_2 in OO

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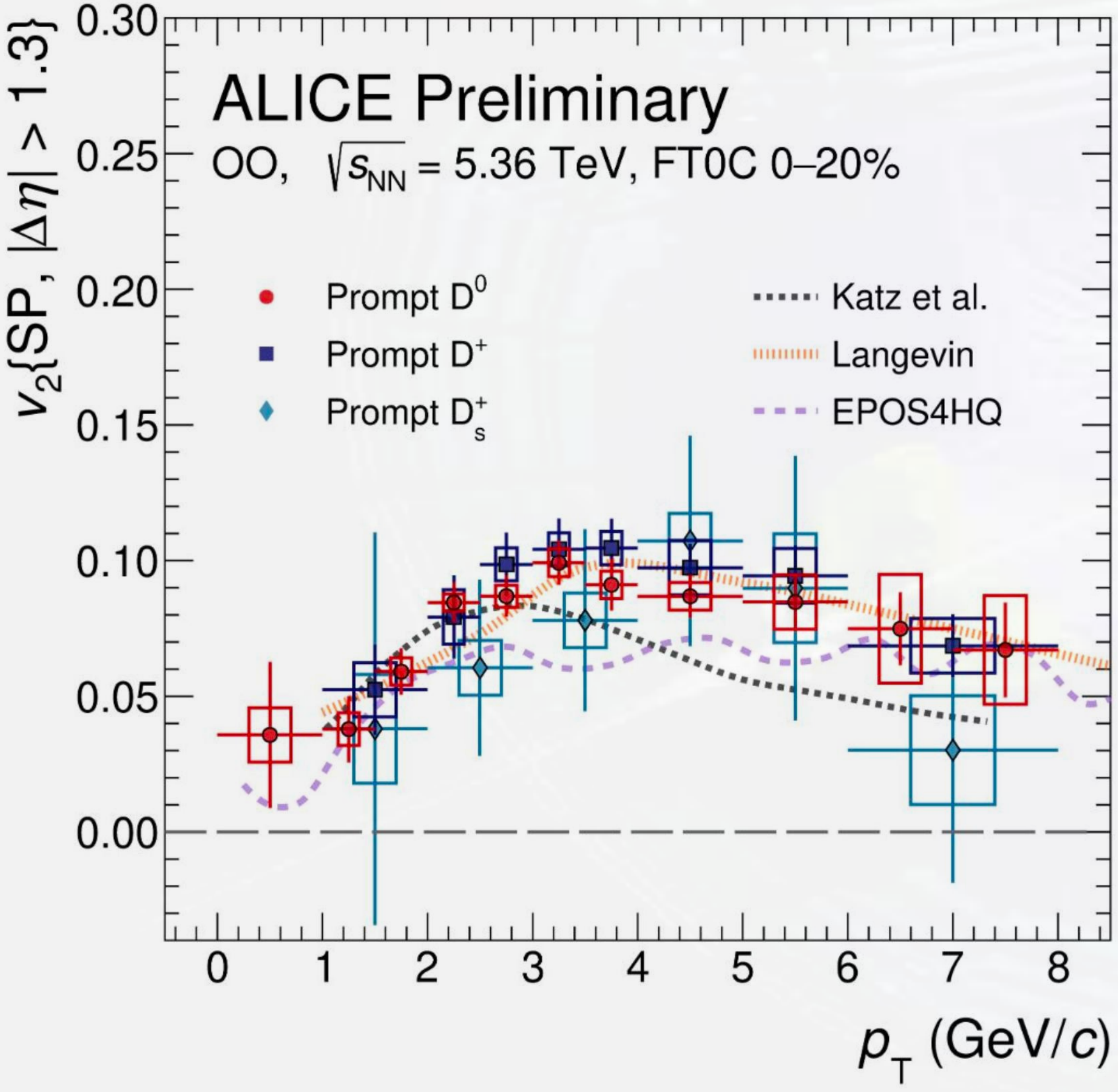
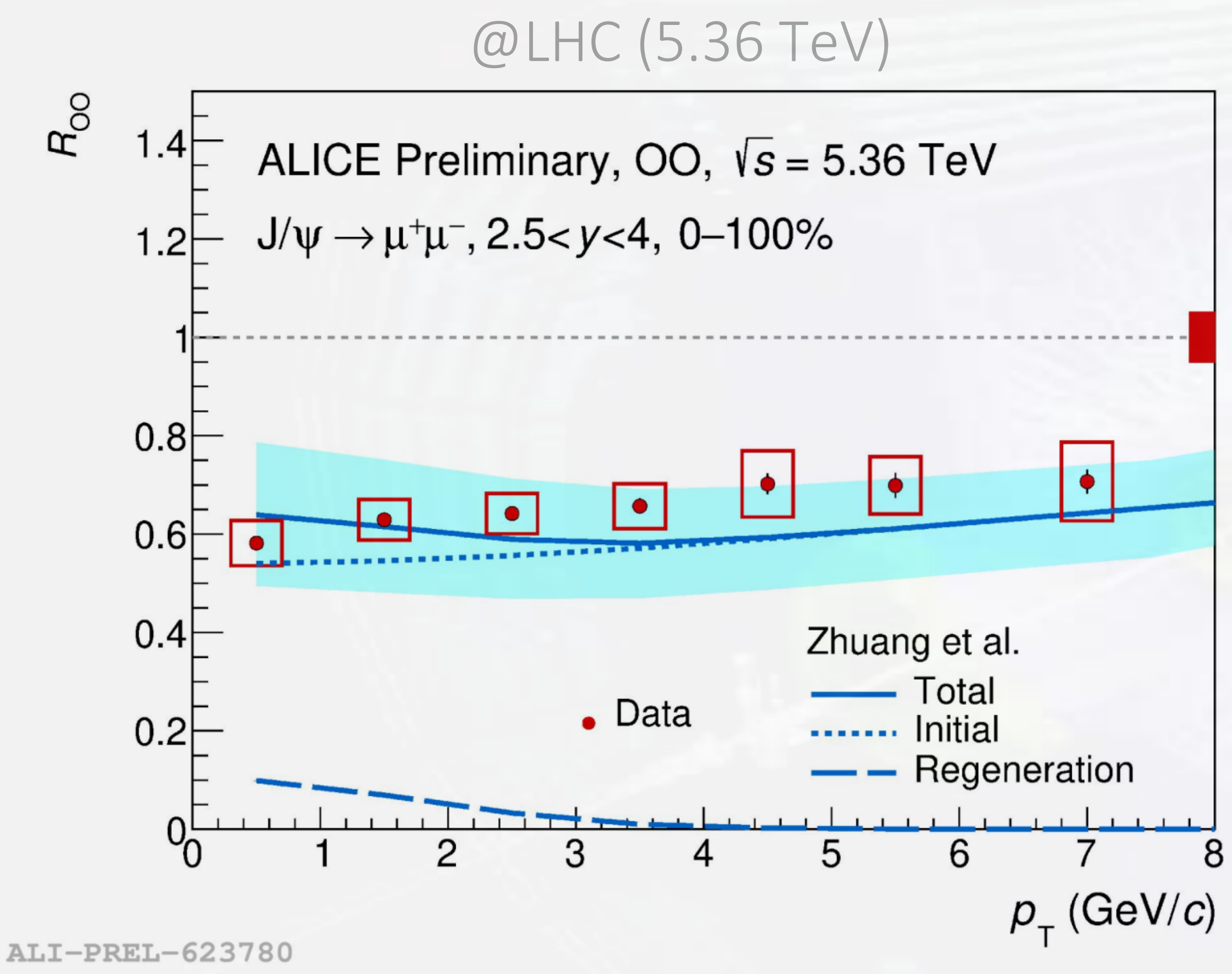
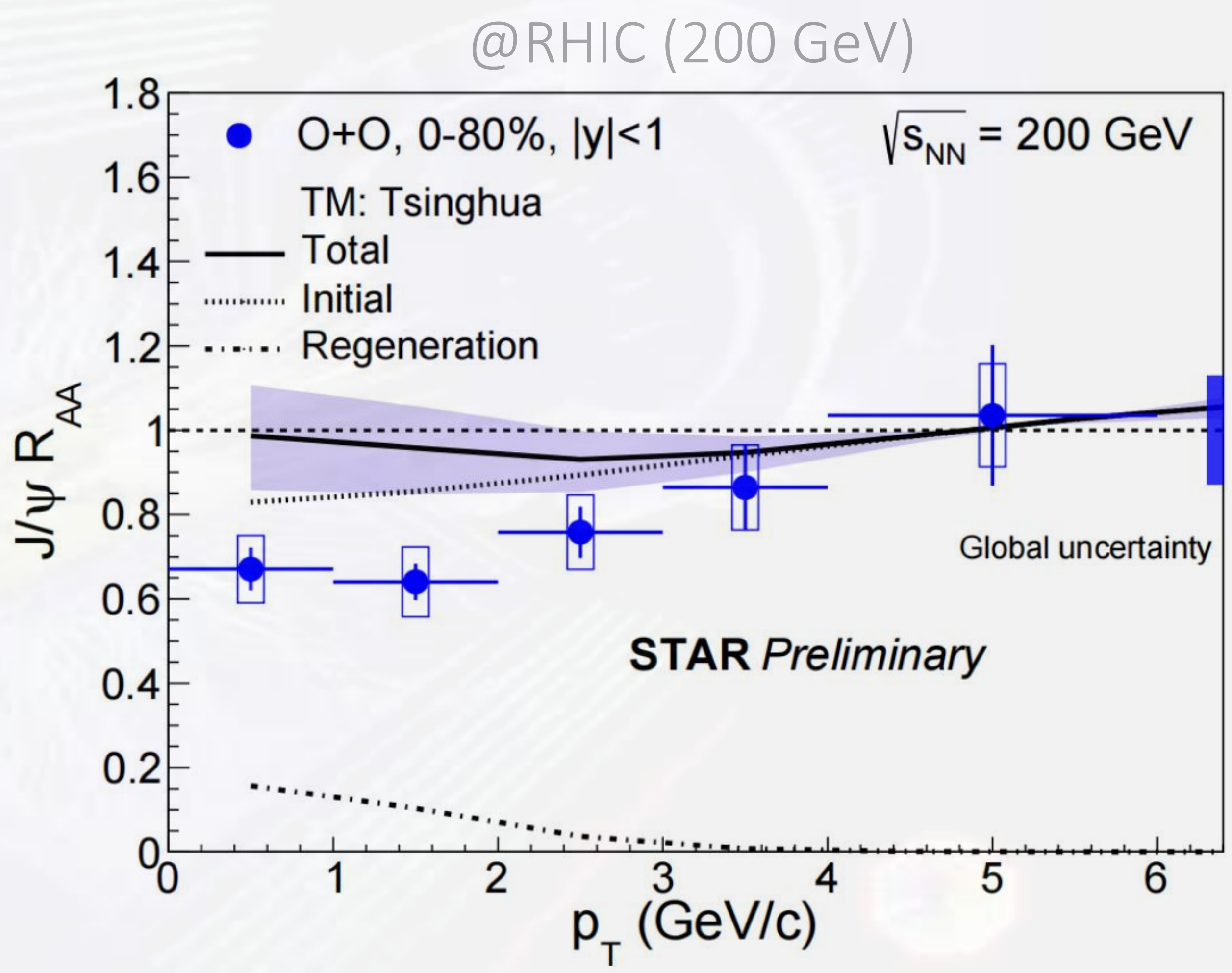


Significant positive v_2 of D mesons in OO

- Charm diffusion and transport picture remains in a small, short-lived QGP droplet
- Hadron gas rescatterings may be relatively more important in OO because the QGP lifetime is shorter
- Data could be reasonably described by transport models

Charmonium Suppression: J/ψ R_{OO} vs Model



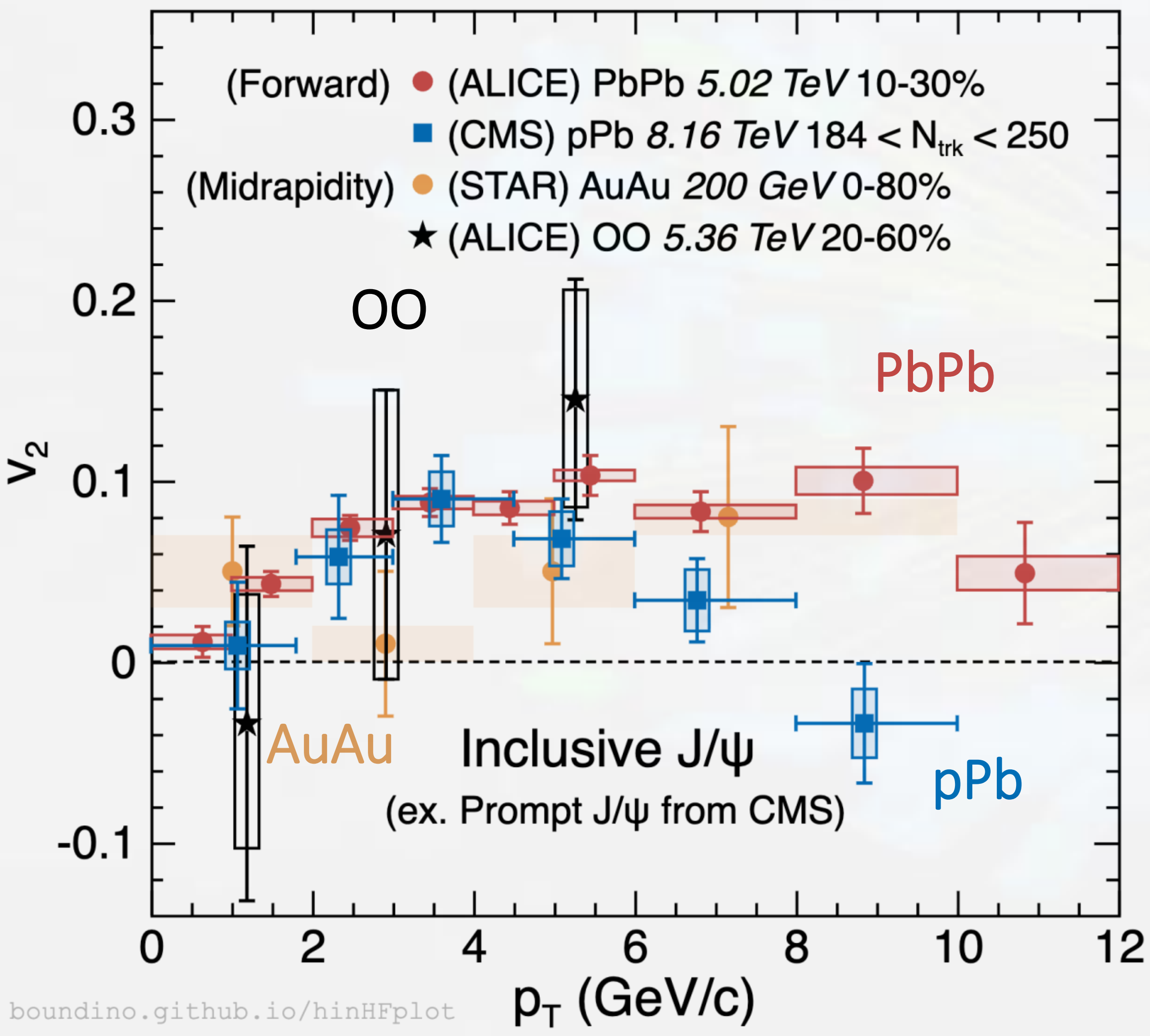


- Regeneration in OO seems to be even weaker than model expectation
- Test models without significant impact from regeneration
- Similar suppression between LHC and RHIC

STAR SQM'26 ALICE SQM'26

Charmonium Production Mechanism J/ψ v_2 in OO

J/ψ v_2



boundino.github.io/hinHFplot

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If J/ψ v_2 comes from partonic flow:

- Charm quarks must acquire sizable collective flow
- J/ψ must form after charm interacts with the medium via regeneration, fragmentation, or late-stage formation

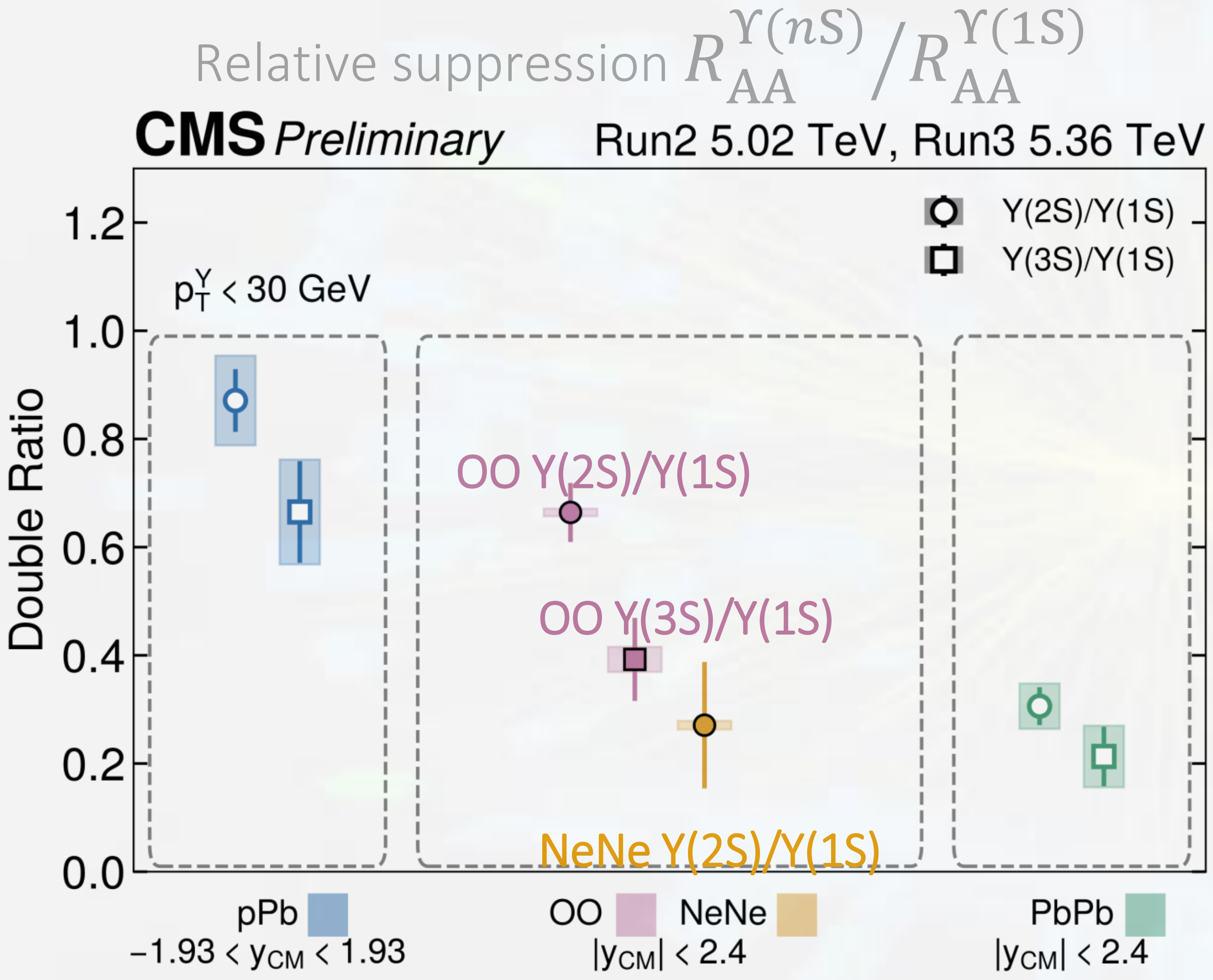
In OO, J/ψ v_2 is not necessarily a charm-flow observable:

- Small regeneration and short-lived medium

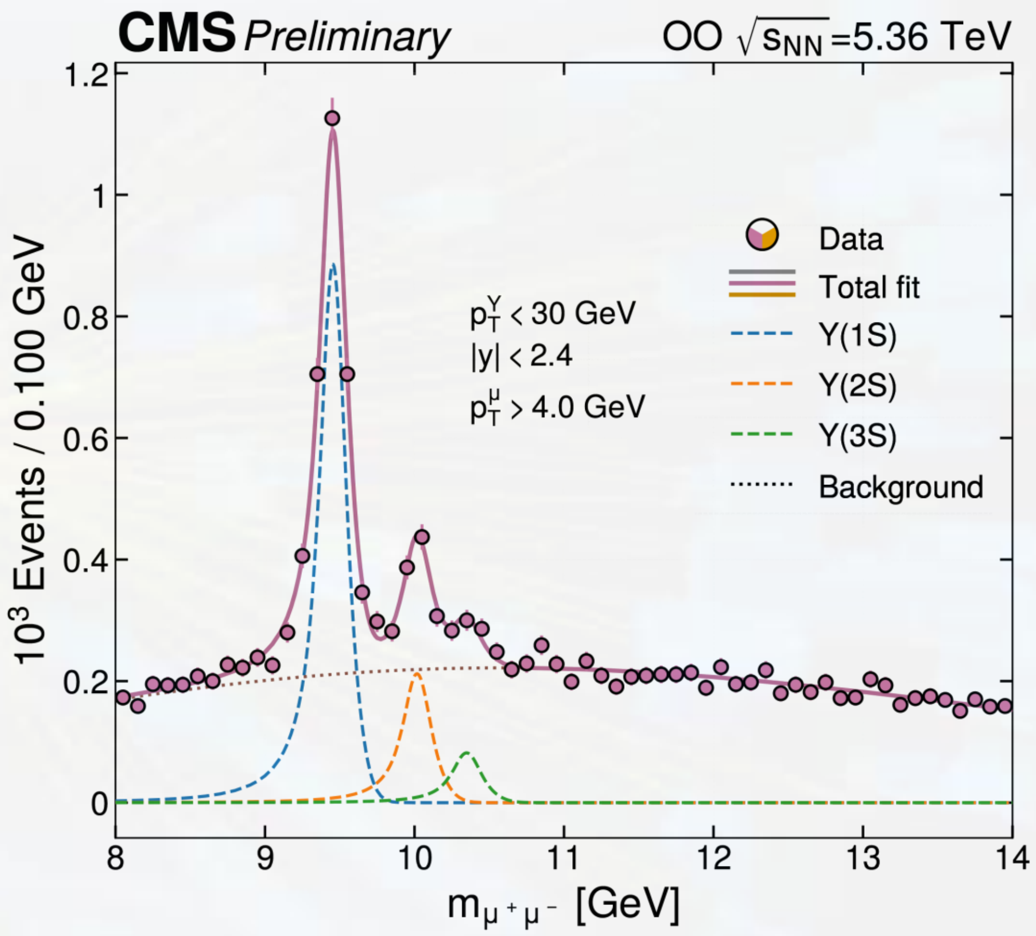
Other mechanism can also generate J/ψ v_2:

- Initial gluon momentum correlation
- Path length dependence of dissociation
- Hadron gas rescattering
- Other nonflow contributions and fluctuations

Sequential Suppression Υ(nS)/Υ(1S) in OO and NeNe



CMS SQM'26

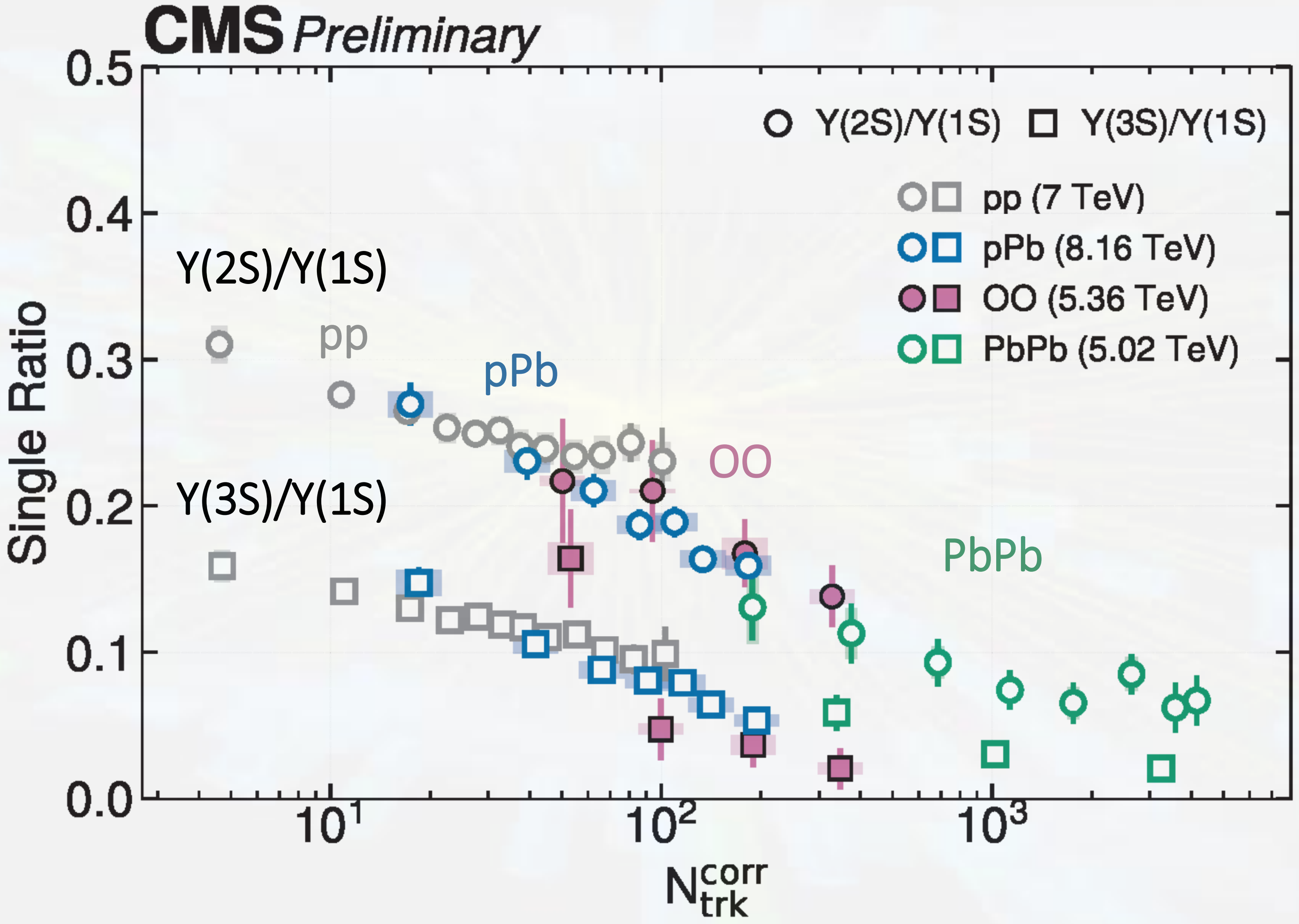


Sequential suppression is observed in OO and NeNe → Excited state Υ(nS) is more suppressed than Υ(1S) due to lower binding energy (negligible regeneration for Υ)

- Double ratios cancel initial state effects (e.g. nPDF) and global uncertainty (e.g. luminosity)

Sequential Suppression Υ(nS)/Υ(1S) vs Systems

CMS SQM'26



- Sequential suppression is smooth and monotonic vs multiplicity across collision systems
- Challenges to models to describe all systems simultaneously

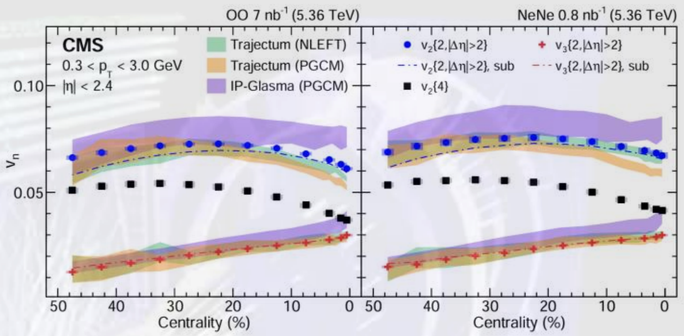
Summary: Small System

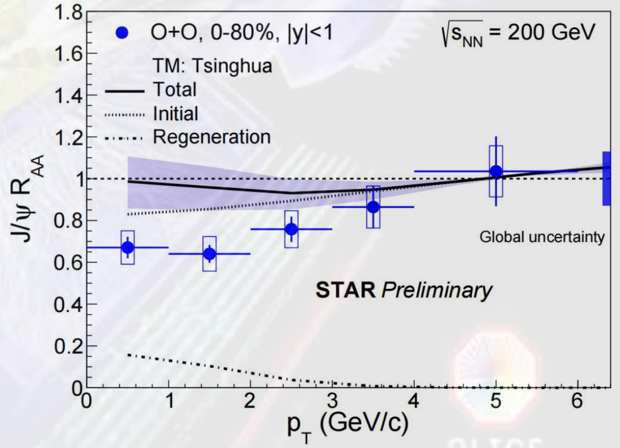
- Significant flow-like signals are observed in high-multiplicity pp and pPb, but their origin is still not settled. Z pole e+e- collision becomes the new baseline.

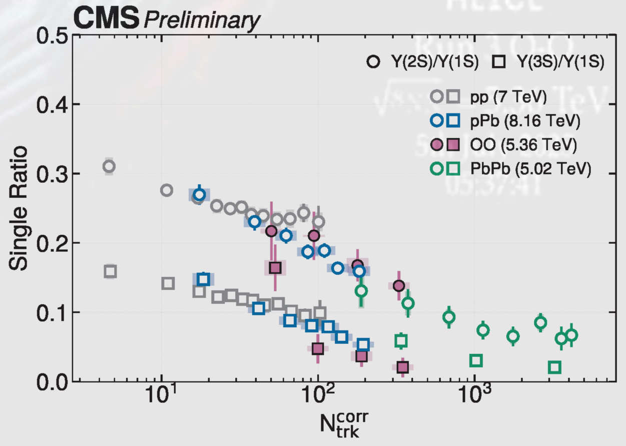
- Jet-quenching signals in pp/pPb remain inconclusive.

- OO and NeNe provide a new bridge between small and large systems: charged-particle suppression, D-meson v_2, and quarkonium suppression all appear in a smaller, shorter-lived system.

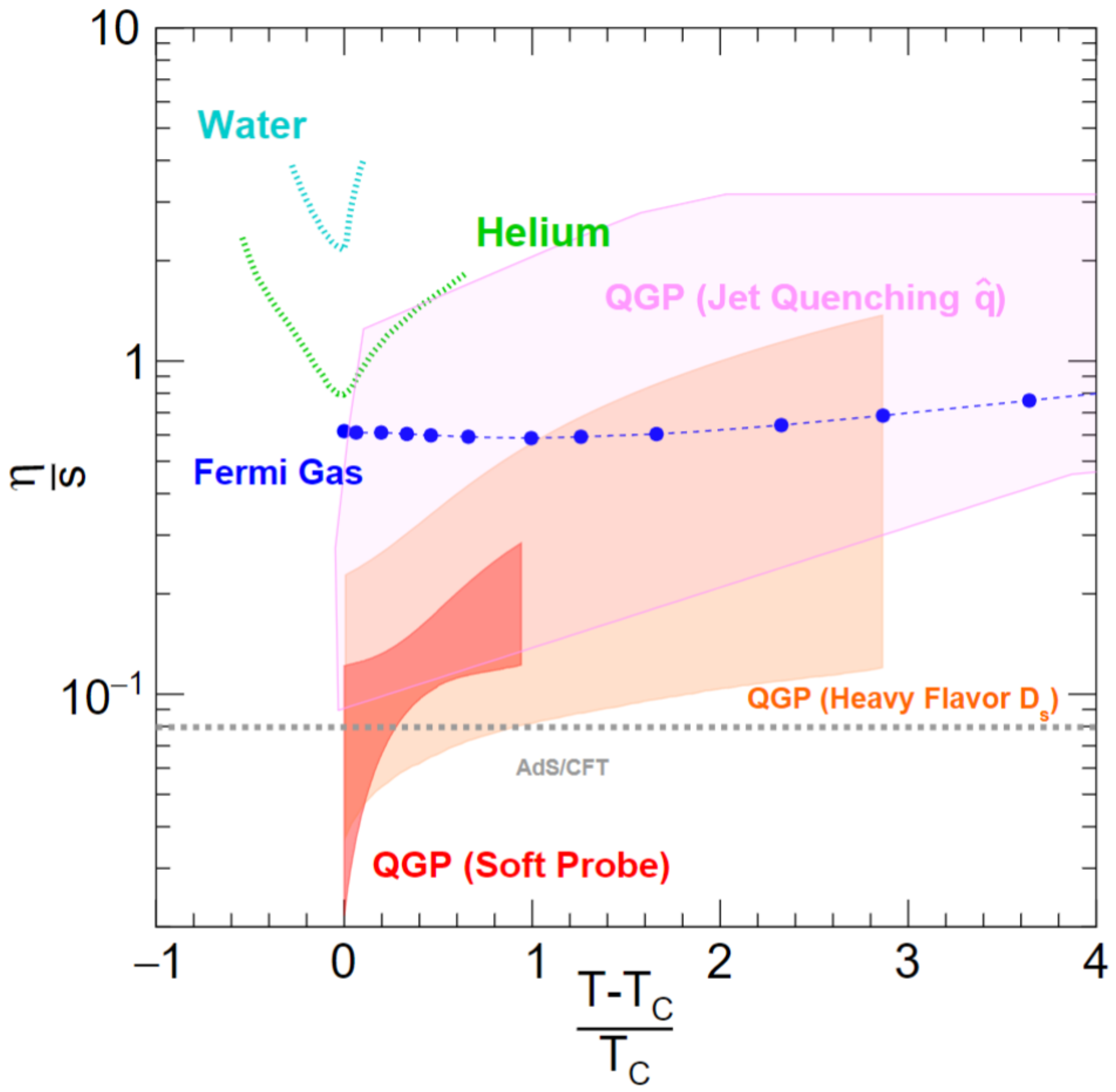
- A smooth evolution from pp/pPb→OO/NeNe→PbPb is emerging for quarkonium modification; the challenge is to describe soft flow, hard energy loss, and quarkonium suppression in **one consistent picture**







Medium Properties from Soft and Hard Probes



Compilation by YJL, Michael Winn, Liliana Apolinario arXiv:2203.16352
Progress in Particle and Nuclear Physics, 103990 (2022)

Specific viscosity has been extracted from **soft probes**

- Via identified hadron dN/dη, $<p_T>$, v_2, v_3 and v_4
- Main uncertainties from initial state and early time dynamics

To get the big picture of the QGP properties with LHC + RHIC data, one could compare the inputs from soft and hard probes:

- **HQ D_s** could be related to specific viscosity by

$$\frac{\eta}{s} = \frac{D_s(2\pi T)}{4\pi k}$$

R. Rapp, H. van Hees, 0903.1096
X. Dong, YJL, R. Rapp, 1903.07709

Where the scale factor k ranges between 1 (strong-coupling limit) and 2.5 (weak coupled)

- **Jet quenching parameter $\hat{q}$** could be related to specific viscosity in the limit of multiple soft scattering by

$$\frac{\eta}{s} = C\frac{T^3}{\hat{q}}$$

Where the scale factor C is varied between 1.25 and 2.5

A. Majumder, B. Muller, Xin-Nian Wang PRL 99 (207) 192301
B. Muller PRD 104 (2021) 7, L071501

Medium properties extracted from **Jet Quenching** and **Open Heavy Flavor** are consistent with the results from **Soft Probes**, but within rather large uncertainties

Probe the Quark Soup!

- How does the strongly interacting medium emerge from an asymptotic free theory?

Start from "un-thermalized" objects and see how they are "thermalized" in the Quark Soup

- Can we see quasi-particles (at some point, quarks and gluons) in the Quark-Gluon Plasma? What is the structure of QGP probed at different length scales?

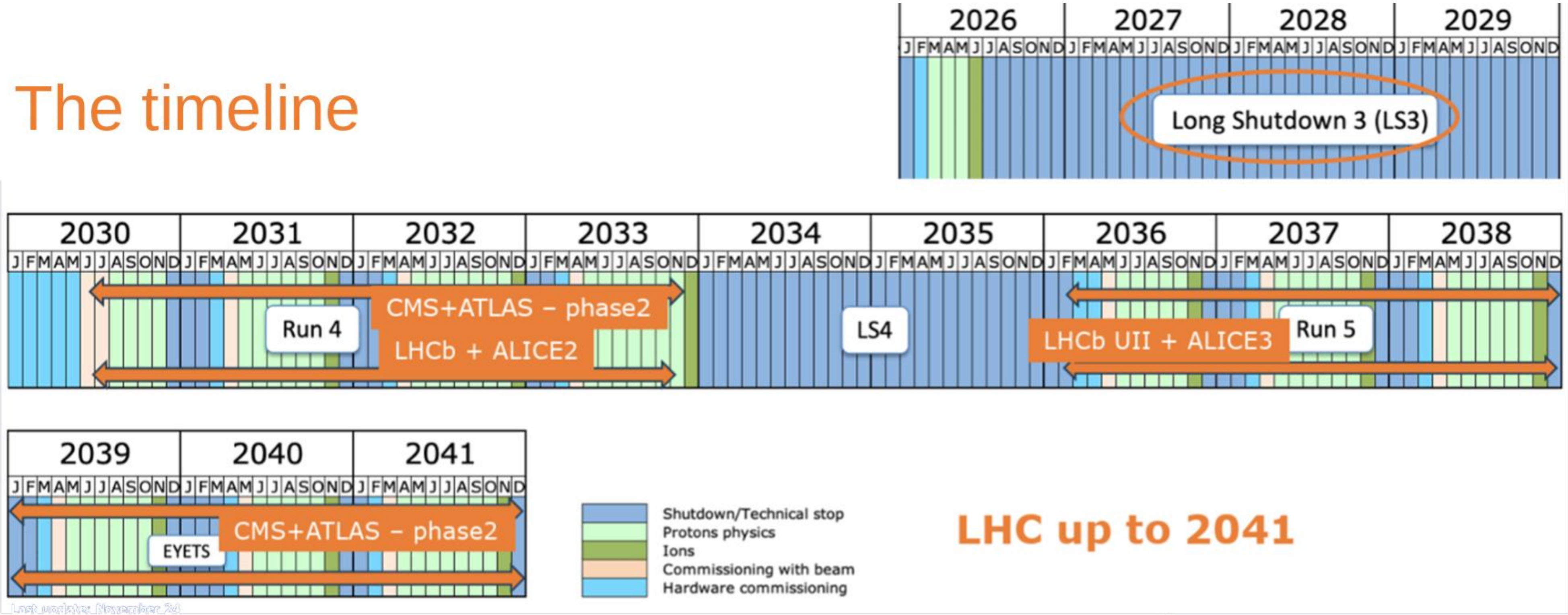
"QGP Rutherford Experiment" and HQ Diffusion

- What are the transport properties of the medium?

Study how Colored Probes are modified by QGP
Study how QGP respond to Colored Probes

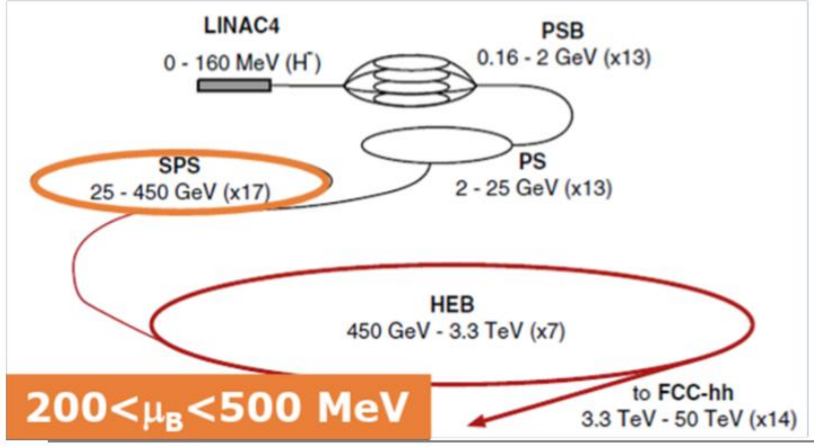
Future Heavy Ion Programs

The timeline



$\mu_B = 0$

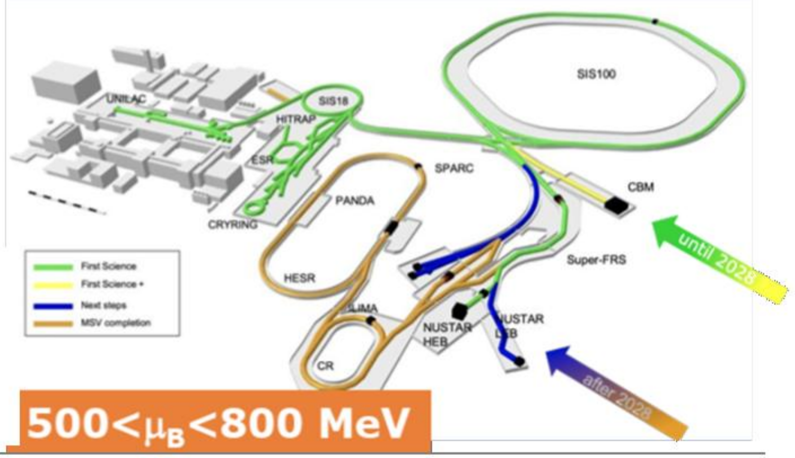
LHC up to 2041



$200 < \mu_B < 500$ MeV

SPS survives beyond LHC age

FAIR to start operation in 2028



$500 < \mu_B < 800$ MeV

Summary

- Quark Gluon Plasma is created in Relativistic Heavy Ion Collision

- What are the properties of QGP?
  - The QGP properties extracted from soft and hard probes (in the multiple soft scattering domain) are consistent, but with large room for improvement.
  - Exciting future investigation to be sensitive to QGP substructure

- How does the hydrodynamization happen and how QGP is created?
  - Slow moving probes moving toward hydrodynamization and fast moving probes quench
  - Direct evidence of QGP **medium response**

- How does hadronization happen in low and high parton density environment?
  - Significant modification of heavy quark hadronization
  - Strong indication of recombination effect (consistent with a deconfined medium)

Exciting future programs trying to answer many of the questions posted in the three lectures!

Thank You!