Hard Probes from RHIC to LHC energies

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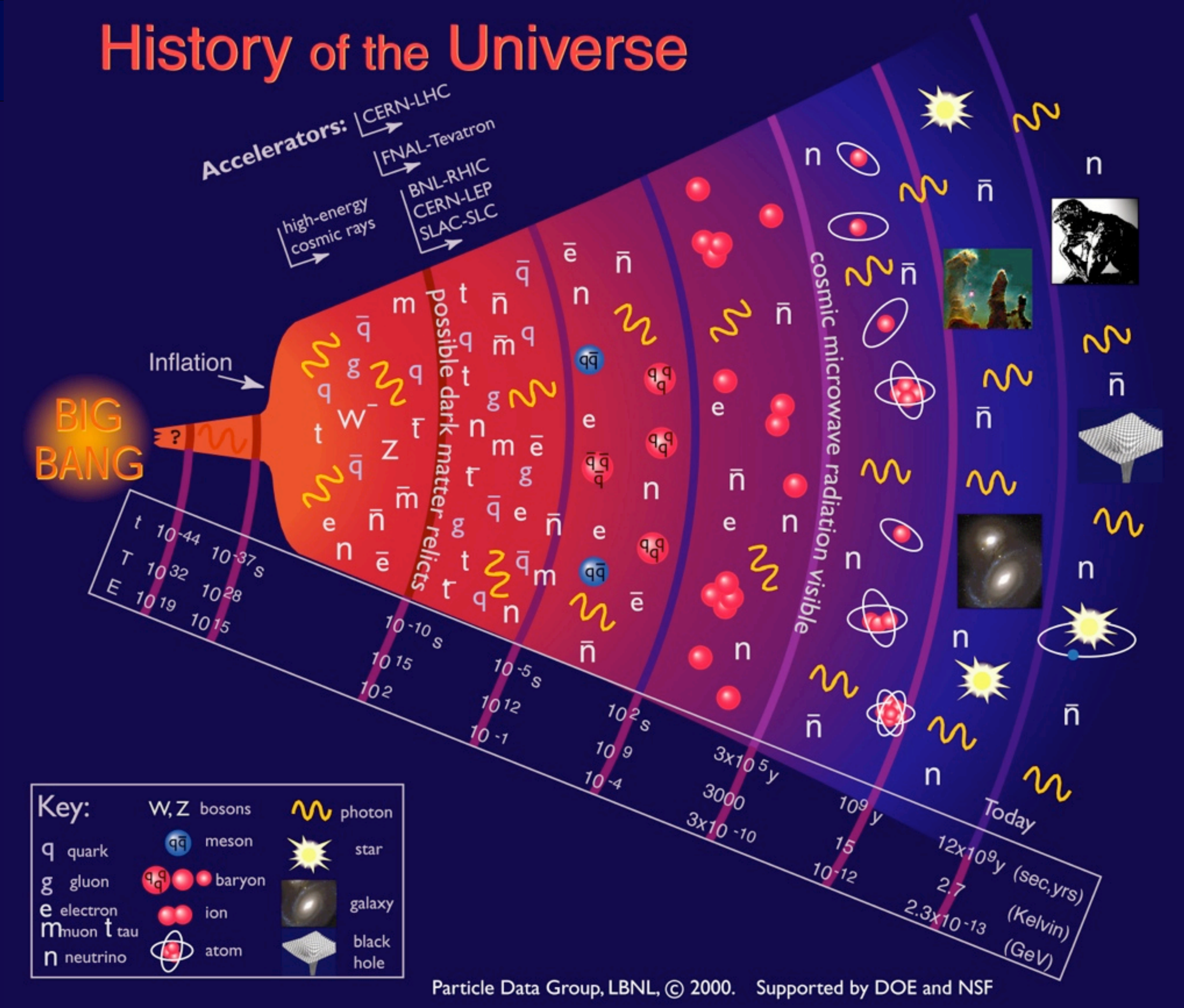
History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s 10-10 s 10-5 s 10 2 s 3x10 5 y 10 9 y Today 12x10 9 y (sec,yrs)
T 10 32 10 28 10 15 10 12 10 9 3000 15 2.7 (Kelvin)
E 10 19 10 15 10 2 10 -1 10 -4 3x10 -10 10 -12 2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon
t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
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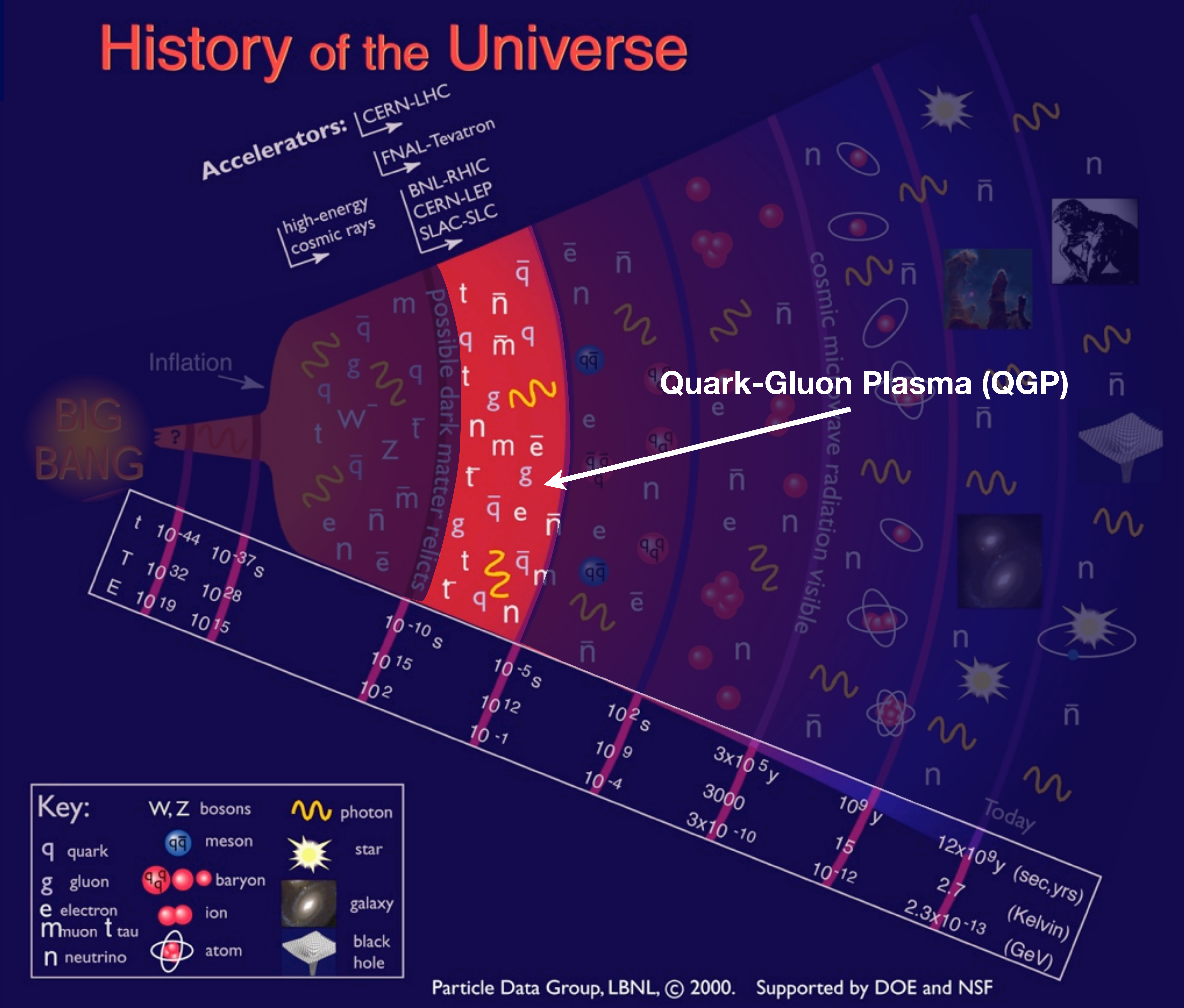
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Quark-Gluon Plasma (QGP)
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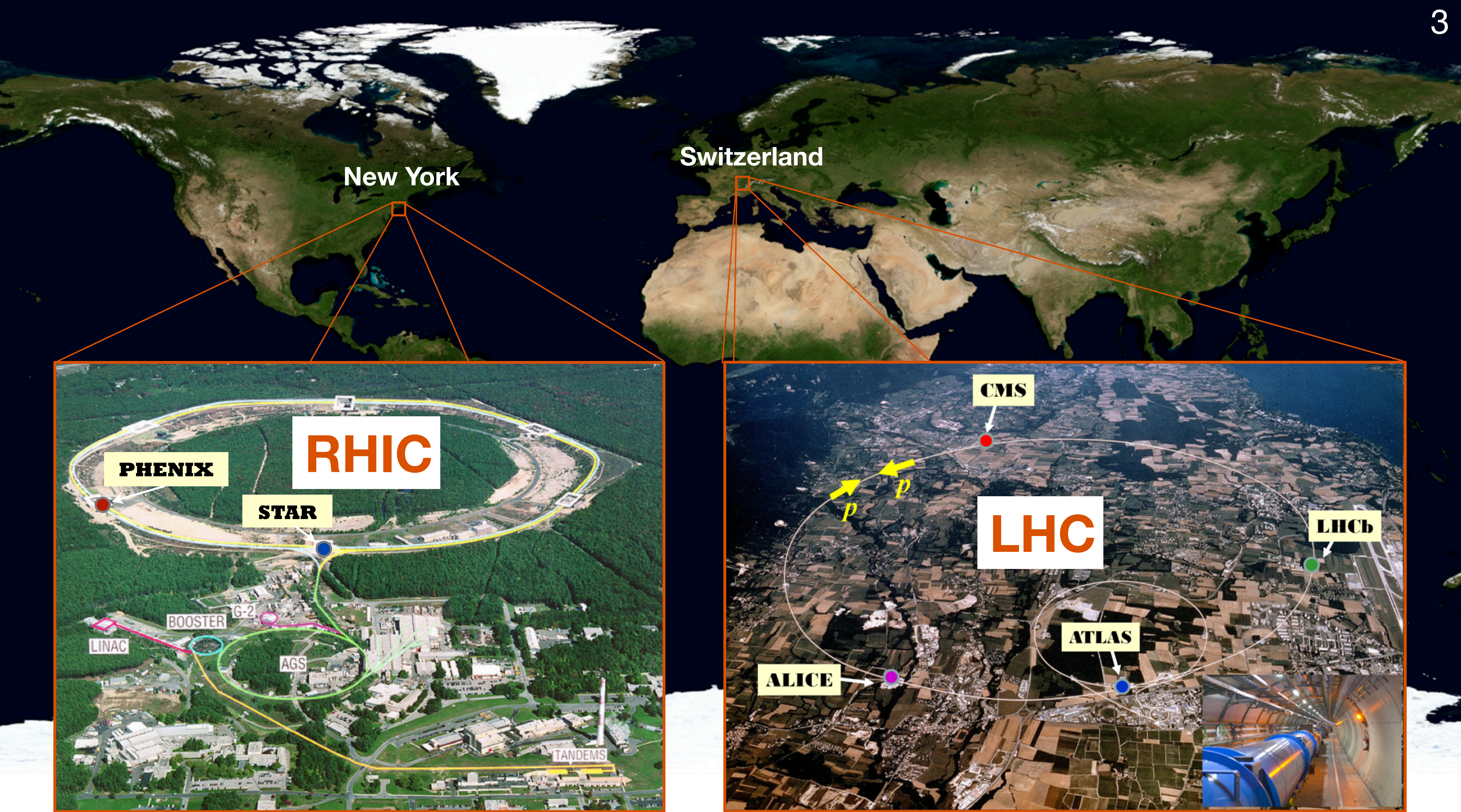


beam	energy
$\vec{p}+\vec{p}$	200 - 510 GeV
d+Au	200 GeV
Cu+Cu	62 - 200 GeV
Cu+Au	200 GeV
Au+Au	7 - 200 GeV
U+U	200 GeV

beam	energy
p+p	7000-8000 GeV
p+Pb	5020 GeV
Pb+Pb	2760 GeV

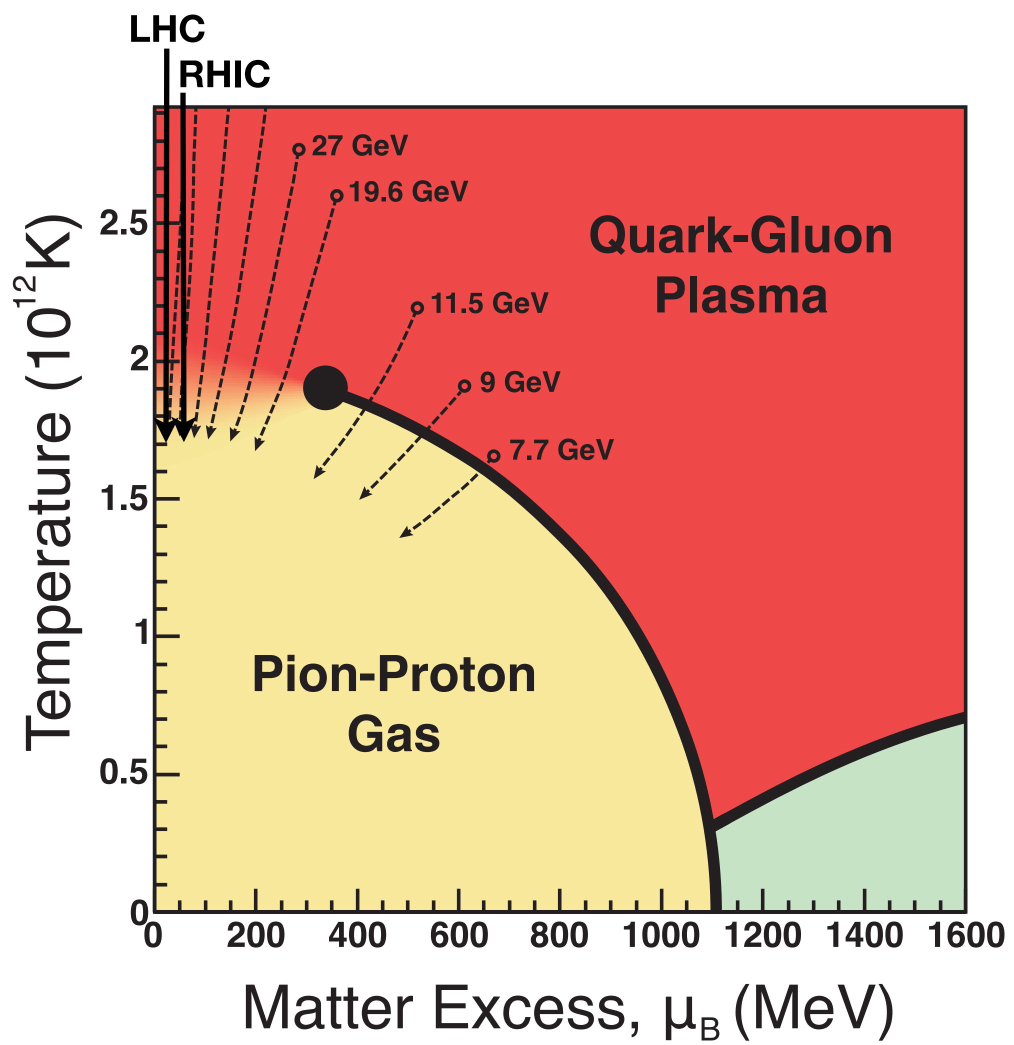
Heavy Ion Collisions

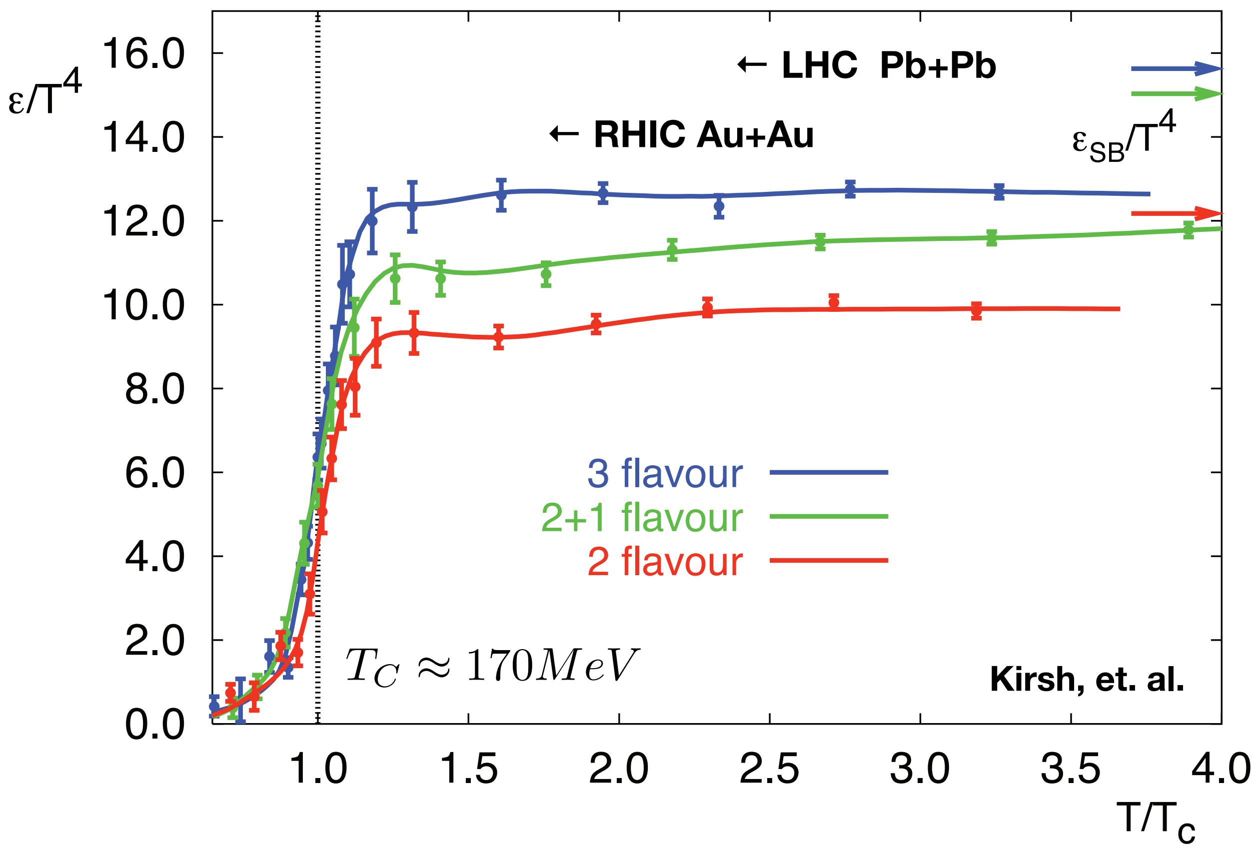
QCD Phase Diagram

Quark-gluon plasma above a few 10^{12} K

Reachable by collider facilities

Critical point being sought





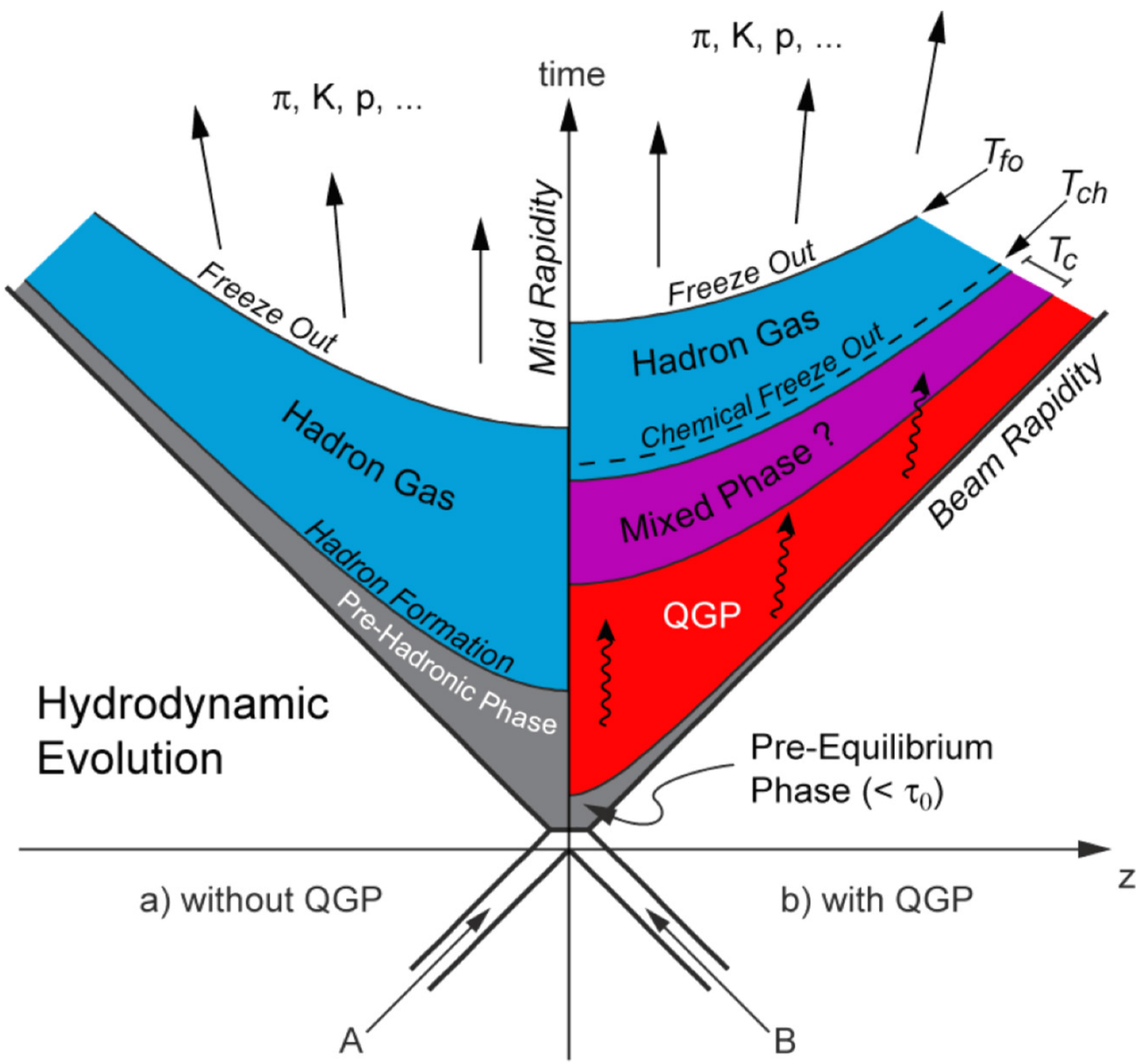
Lattice QCD Calculations

Energy density indicates partonic degrees of freedom open at $T_c \approx 170$ MeV

Ideal gas of quarks and gluons at arbitrarily large T

(Data) Strongly-coupled fluid near T_C

Space-Time Evolution



Kinetic Freeze Out (~10-15 fm/c)

Chemical Freeze Out (~7 fm/c)

Hadron Gas

Phase Transition (~4 fm/c)

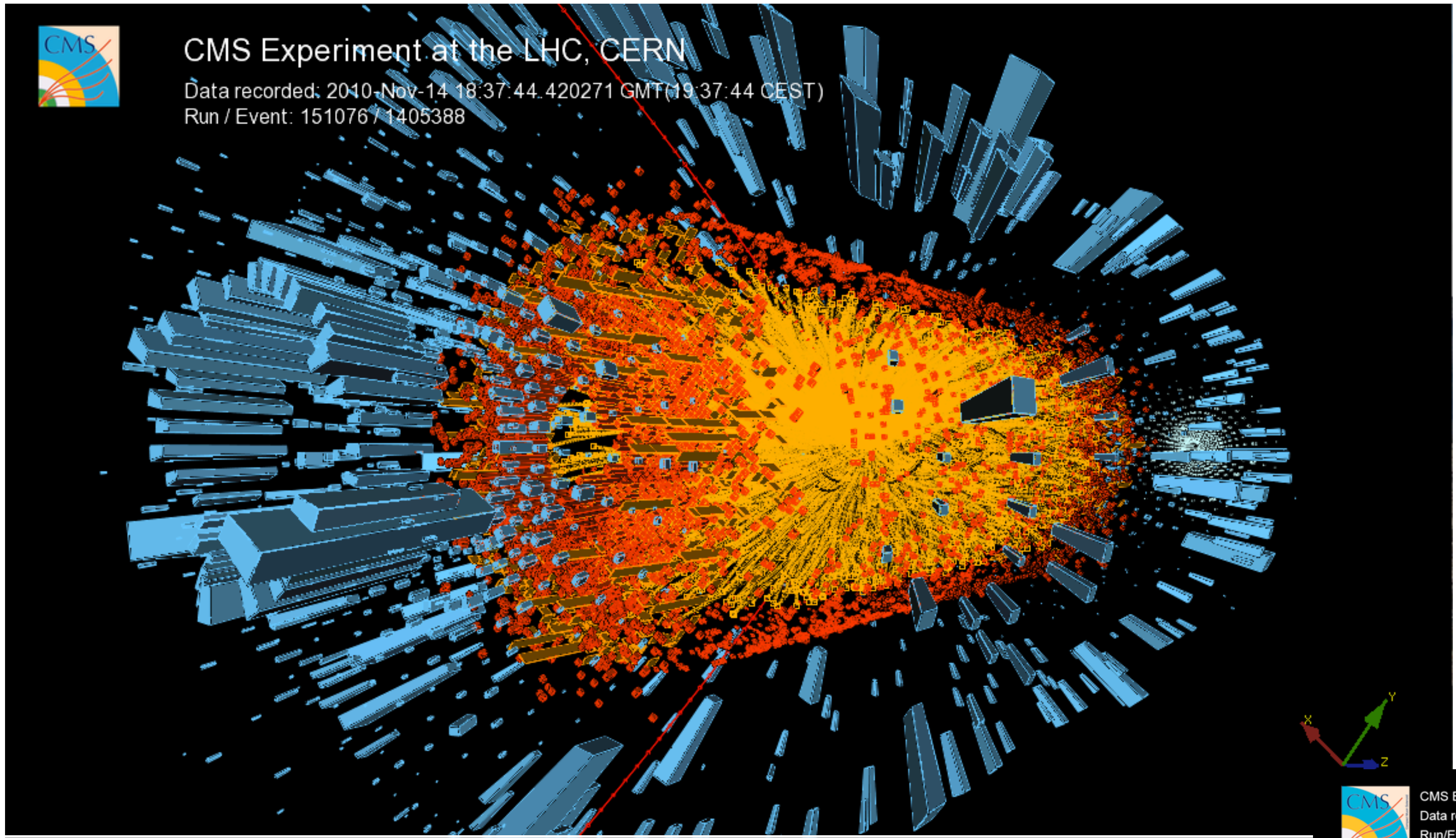
QGP

Thermalization (~0.6 fm/c)

Nuclear Crossing (~0.1 fm/c)

***values for RHIC at 200 GeV**

Events with Large Multiplicity

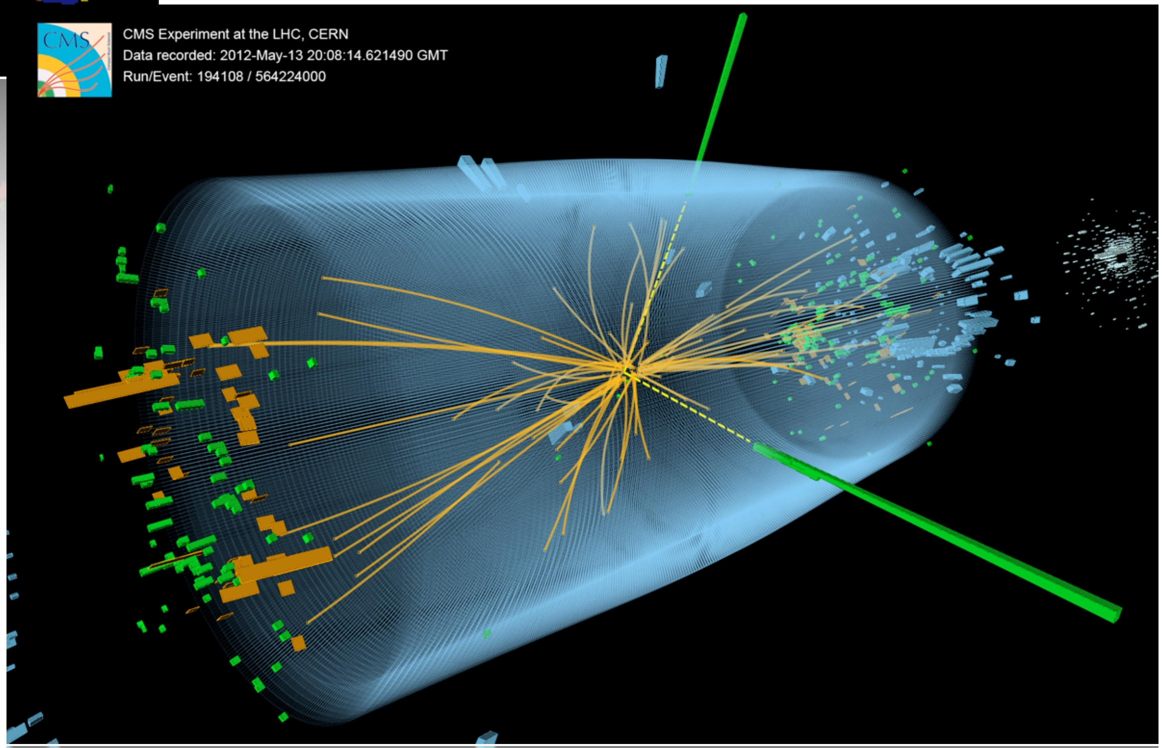


Head-on Heavy Ion Events

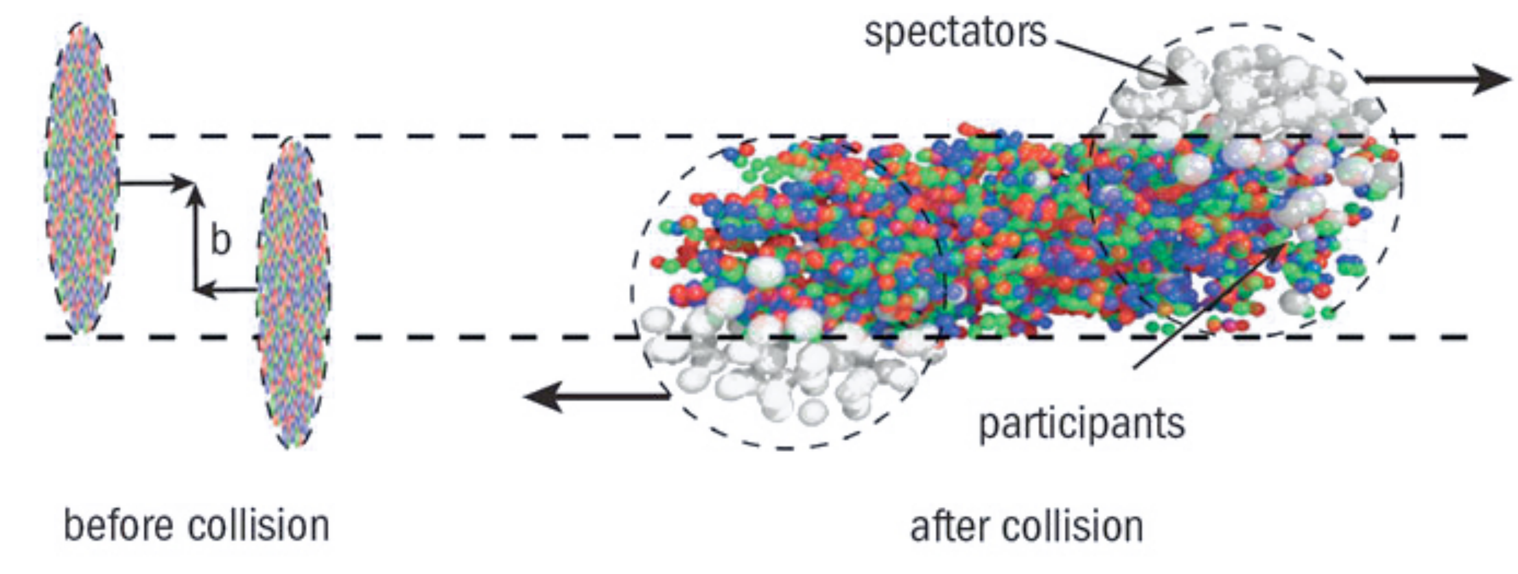
- Many particles produced
- Challenges for detectors
- Provides many analysis channels

for your reference a Higgs Candidate Event in p+p

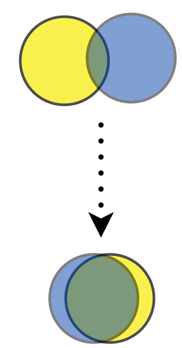
- many times fewer particles



Event Geometry Controls



Impact parameter studied via **centrality** selection



Large impact parameter
→ peripheral events, ≲100%

Small impact parameter
→ central events, ≳0%

Measured at large pseudorapidity

Tool: Glauber Monte Carlo simulation

Simple geometric description of A+A

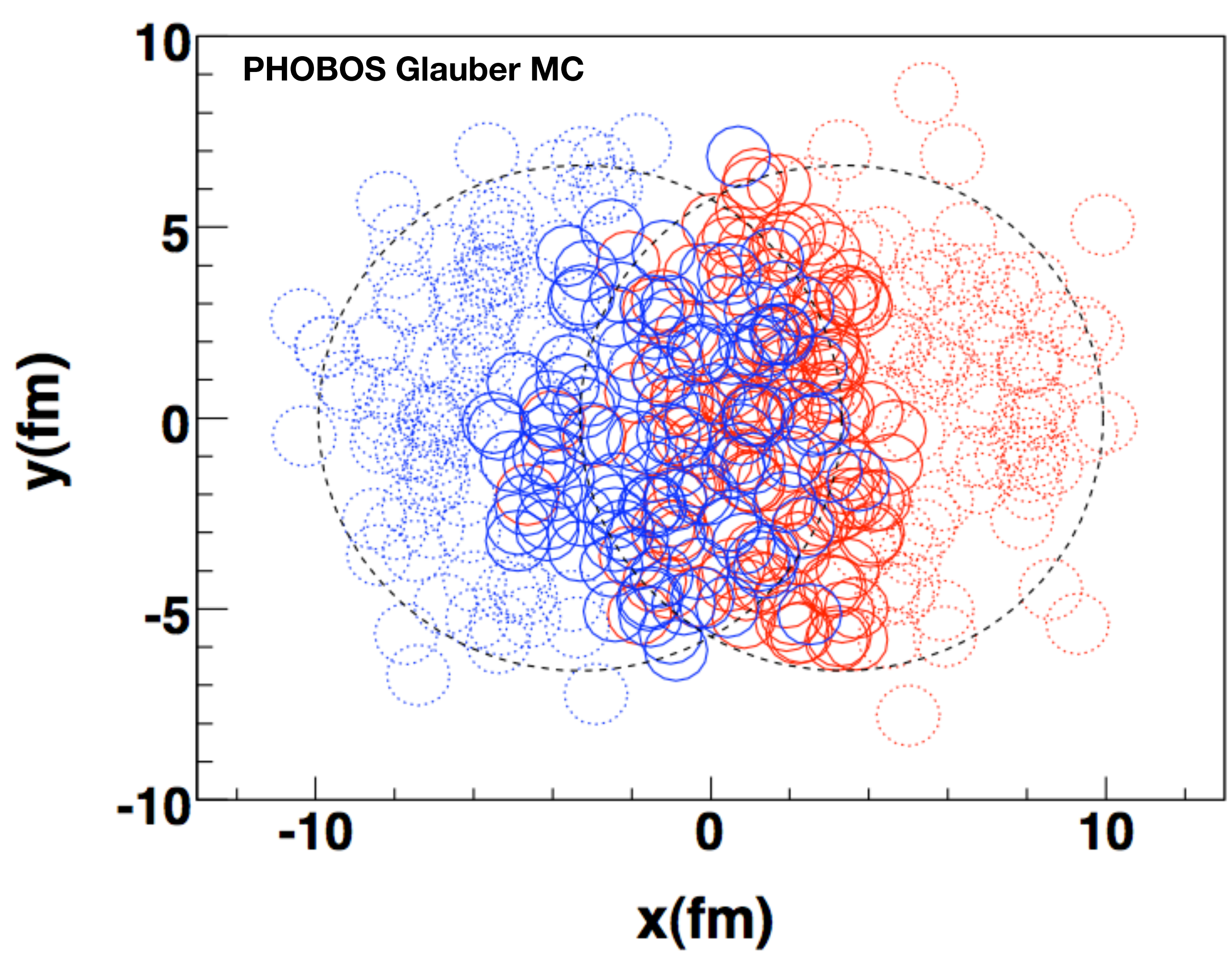
Includes statistical fluctuations

Number of Participating Nucleons, N_{part}

~ system size

Number of Binary Scatterings, N_{coll}

~ hard process cross-section



Probes from Hard Scattering

*"In science, one man's signal is another man's **calibration reference**."*
~ paraphrasing Edward W. Ng

What are **"Hard Probes"** in Nucleus-Nucleus Collisions:

(1) Light particles resulting hard scattering between partons
(jets, jet fragments, prompt photons)

(2) Open heavy flavor
(charm and beauty quarks)

(3) Quarkonia
(Charmonium states: $J/\psi, \psi', \chi_c$; **Bottomonium mesons**: $\Upsilon(1S), \Upsilon(2S), \Upsilon(3S)$, χ_b**)**

What makes a good probe?

Form quickly with long lifetime with respect to the Quark Gluon Plasma
Is **not generated by the QGP** phase
pQCD **calculable** production rates with **experimental verification** in p+p

"Initial state" Nuclear Modification from p+Pb and d+Au measurements

Referred to as "cold nuclear matter" effects
Rich field of study on nuclear structure (gluon saturation, initial state energy loss, etc)

Probes from Hard Scattering II

What physics are we after? (Hint: Hot Nuclear Matter Effects)

Jets → **energy loss via gluon radiation and collisions**

Heavy quarks → **different mix of energy loss**

Quarkonia → **thermal melting**

“Final state” Nuclear Modification from Pb+Pb and Au+Au

Compare p+p scaled up by N_{coll} to measurements in A+A

Workhorse metric for energy loss studies:

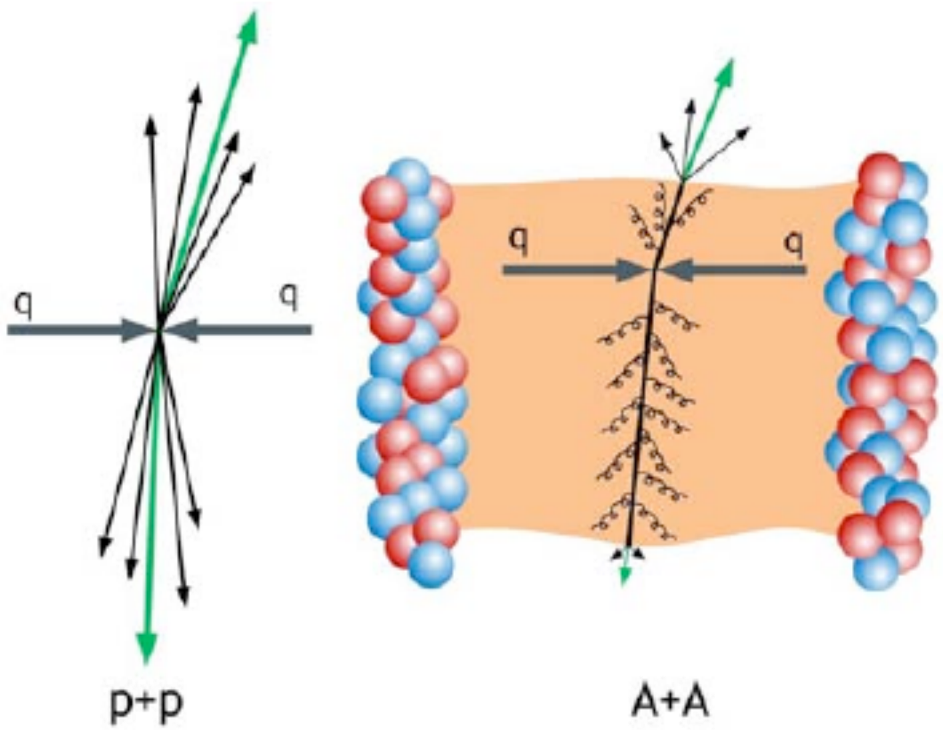
$$R_{AA}\left(p_T\right) \equiv \left(\frac{d\sigma_{AA}}{dp_T}\right) \Big/ \left(T_{AB}\frac{d\sigma_{pp}}{dp_T}\right) = \left(\frac{dn_{AA}}{dp_T}\right) \Big/ \left(N_{coll}\frac{dn_{pp}}{dp_T}\right)$$

In the absence of cold nuclear matter effects:

R_{AA} = 1 indicates no effect from hot nuclear matter

R_{AA} < 1 indicates suppression from hot nuclear matter

Jets and Jet Fragments



Fast partons lose energy escaping the QGP

- Inelastic gluon radiation
- Elastic collisions with medium components

What matters:

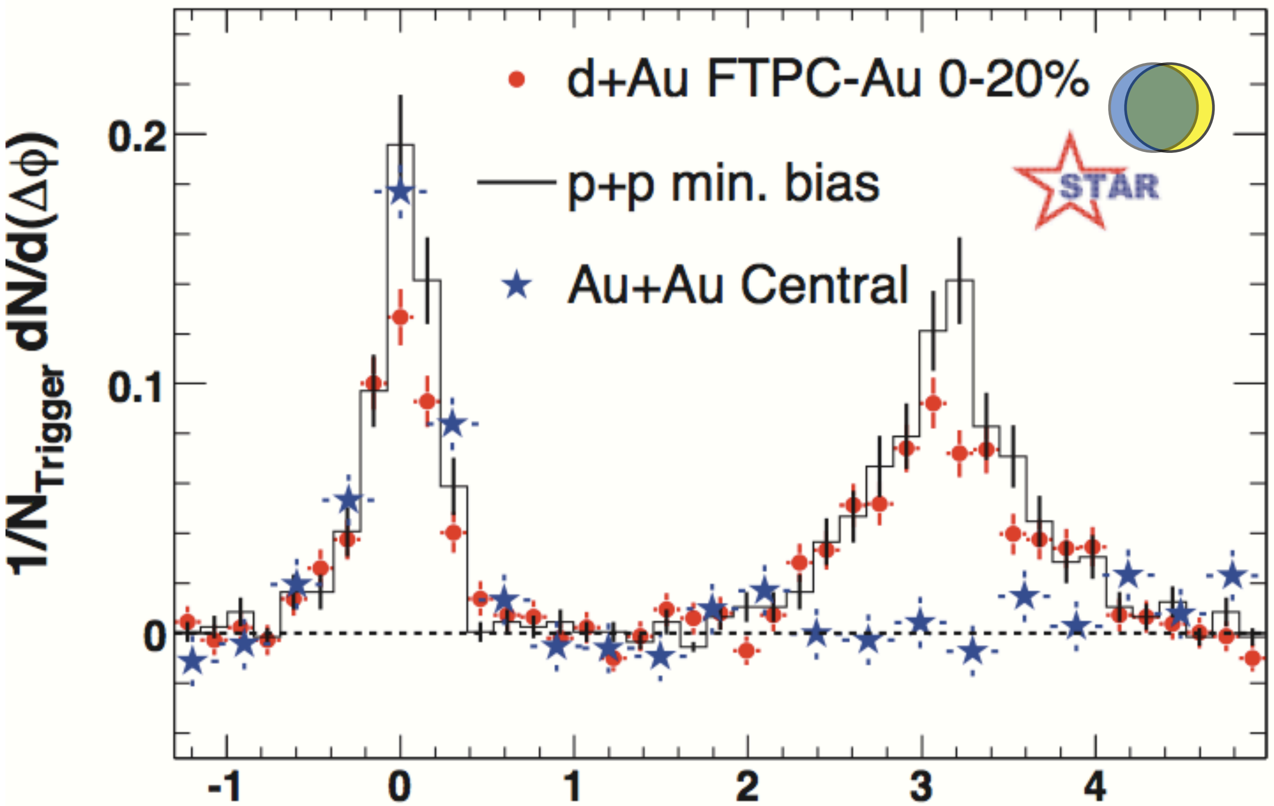
- Fast parton **color charge** type (quark or gluon)
- **Path-length** through the QGP
- QGP macroscopic properties:
  - **density, temperature**
- QGP microscopic structure:
  - **mean-free path**, **internal degrees of freedom**

Classic evidence for "Jet Suppression"

Jets survive if they are near the surface and escape immediately

Momentum balance requires a recoil jet

Recoil jets have a long path through the QGP and are massively suppressed

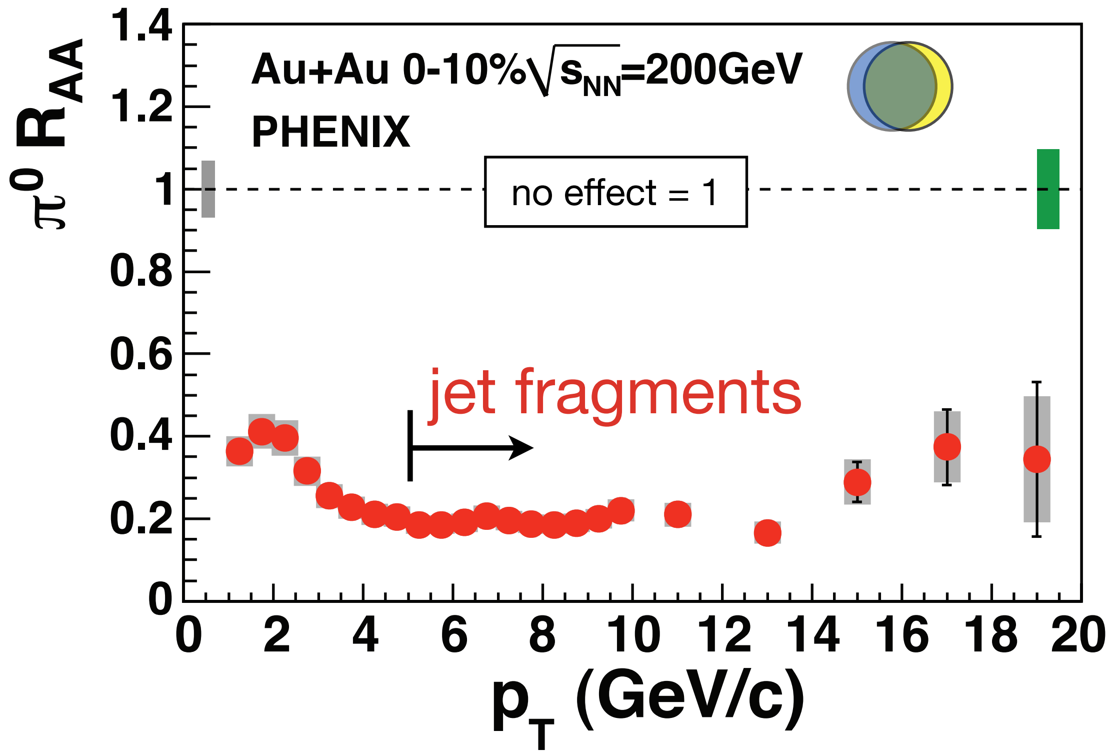


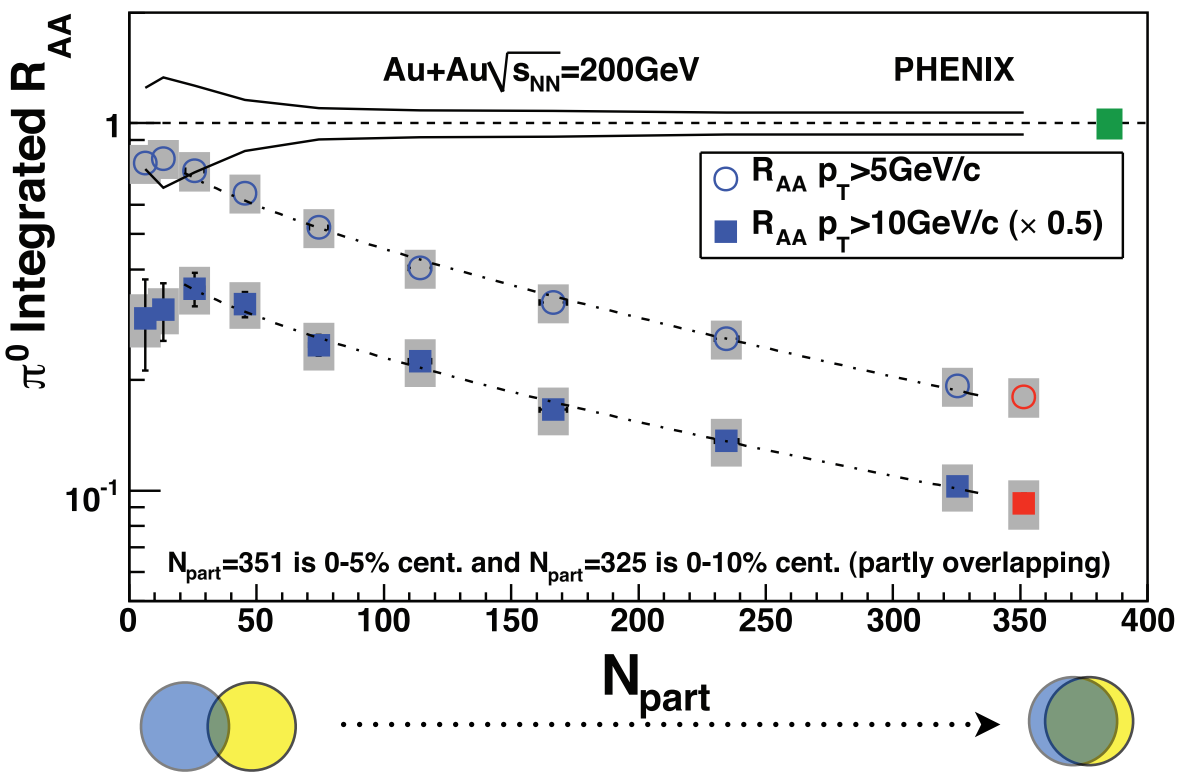
Nuclear Suppression

Very large momentum is not populated by thermal production, only hard scattering

Simplest measure of energy loss is the **rate of energetic particles leaving the collision**

$$R_{AA}(p_T) = \left(\frac{dn_{AA}}{dp_T}\right) \Big/ \left(N_{coll}\frac{dn_{pp}}{dp_T}\right)$$





Large suppression (R_{AA}~0.2) characteristic of energy loss in dense medium

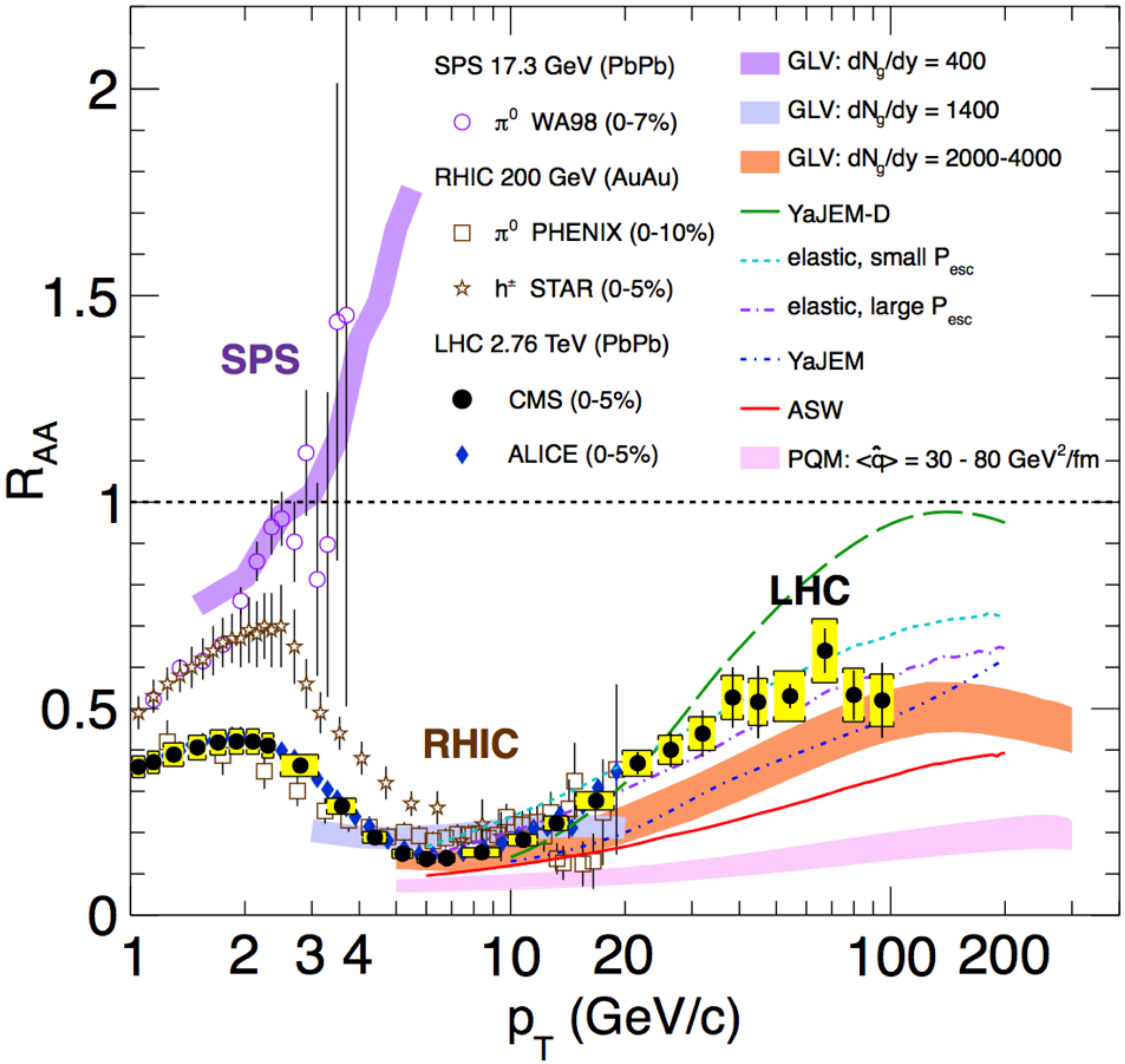
No suppression in peripheral events, grazing events look like p+p

Suppression increases with centrality as overlap region grows

Nuclear Suppression II

Suppression found in all high energy nucleus-nucleus collisions

Larger at LHC energy than RHIC, both much larger than at SPS energy



Rises at larger momentum, long standing prediction of energy loss models

Eliminates complete thin surface bias of survivors

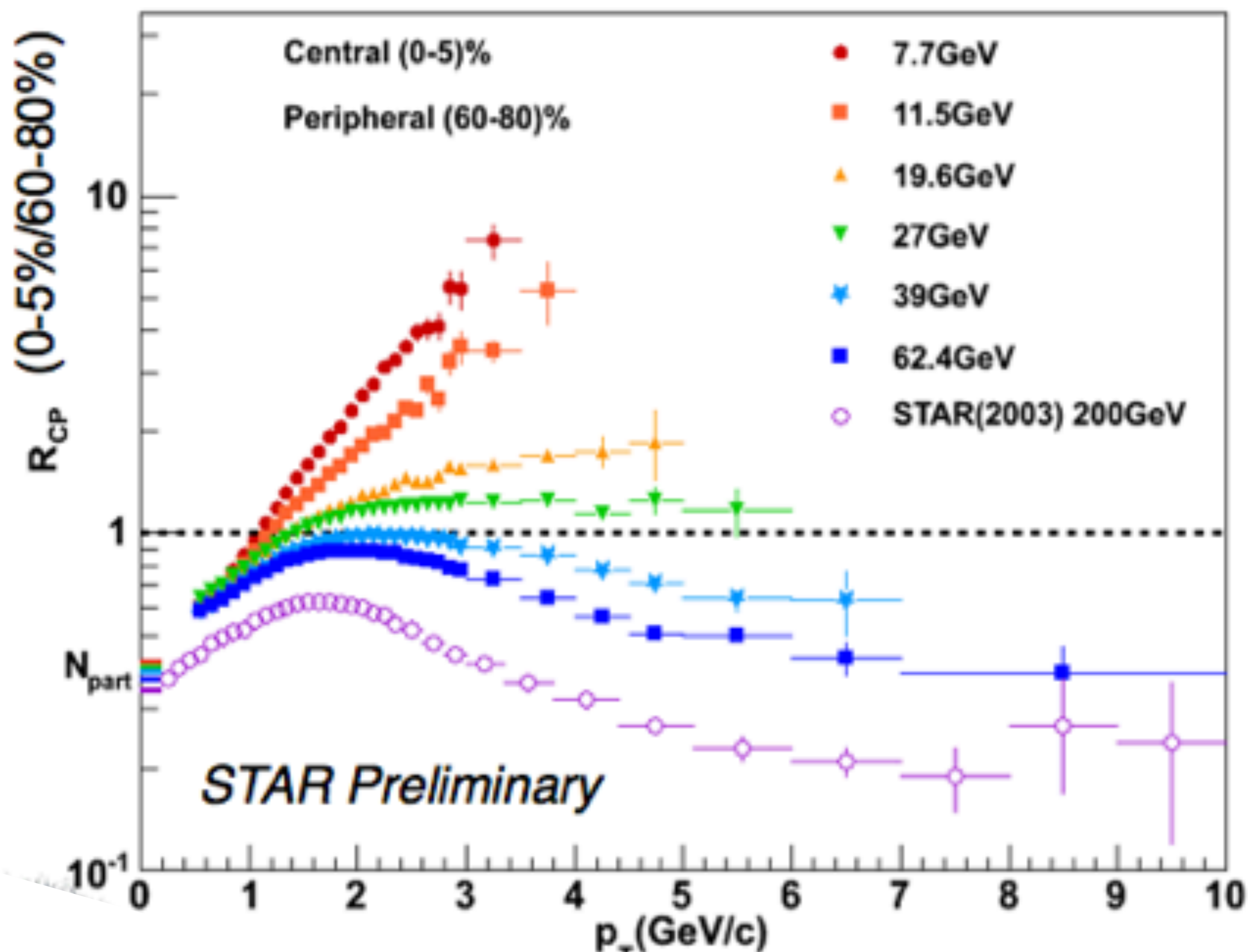
Important data for energy loss model construction

What about lower energies?

RHIC beam energy scan (7.7 GeV - 200 GeV)

R_{cp}: ratio of centralities, useful when p+p reference not available
uses relative N_{coll} to scale between centralities, R_{cp} = 1 = no effect

Nuclear suppression increases with beam energy.



But large values found at lowest energy!

Partons within the beam can scatter as they penetrate a large nucleus before hard scattering

Additional kicks smear spectrum

Should be a small effect at high E

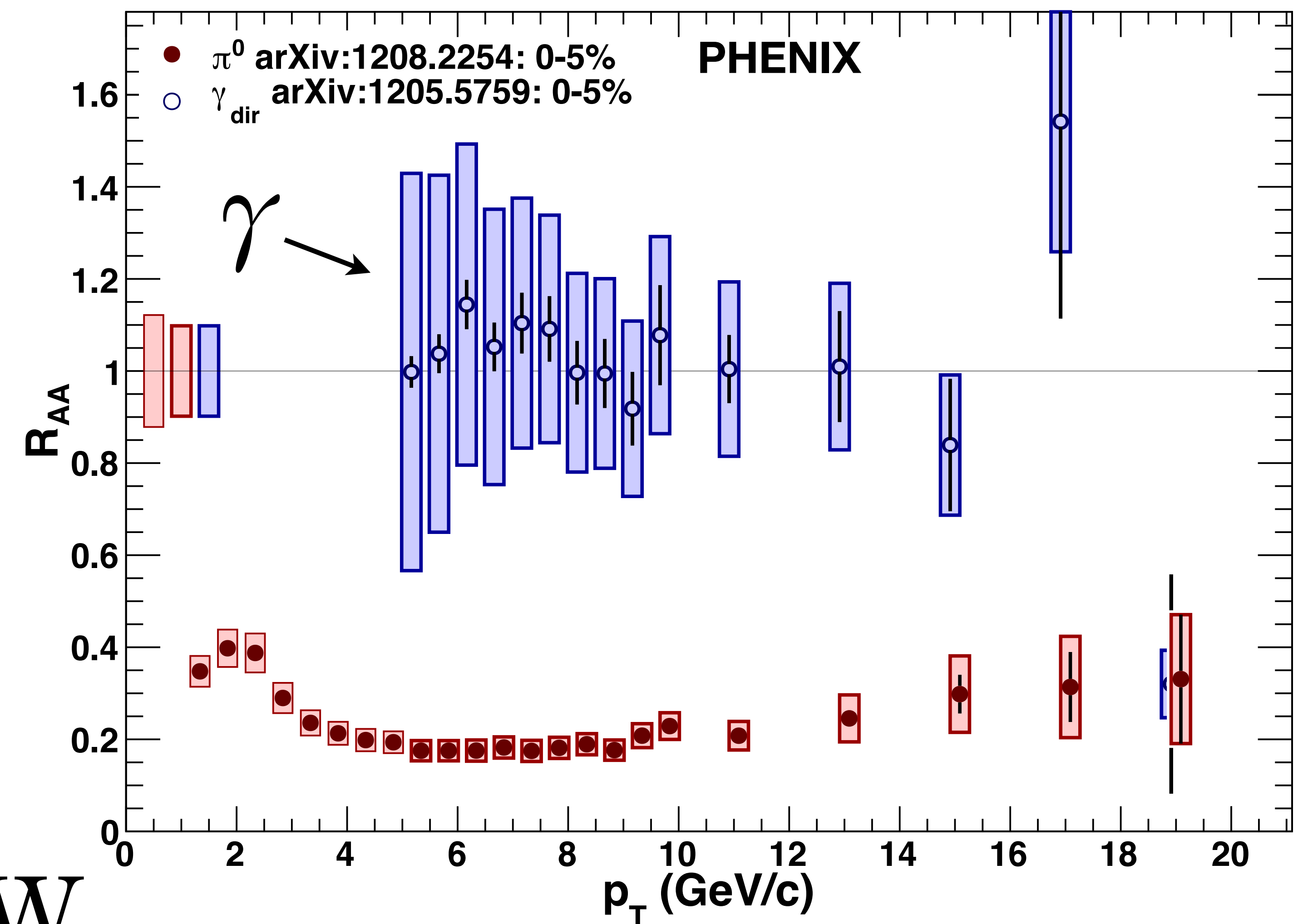
But how have we convinced ourselves we are measuring a hot nuclear matter effect?

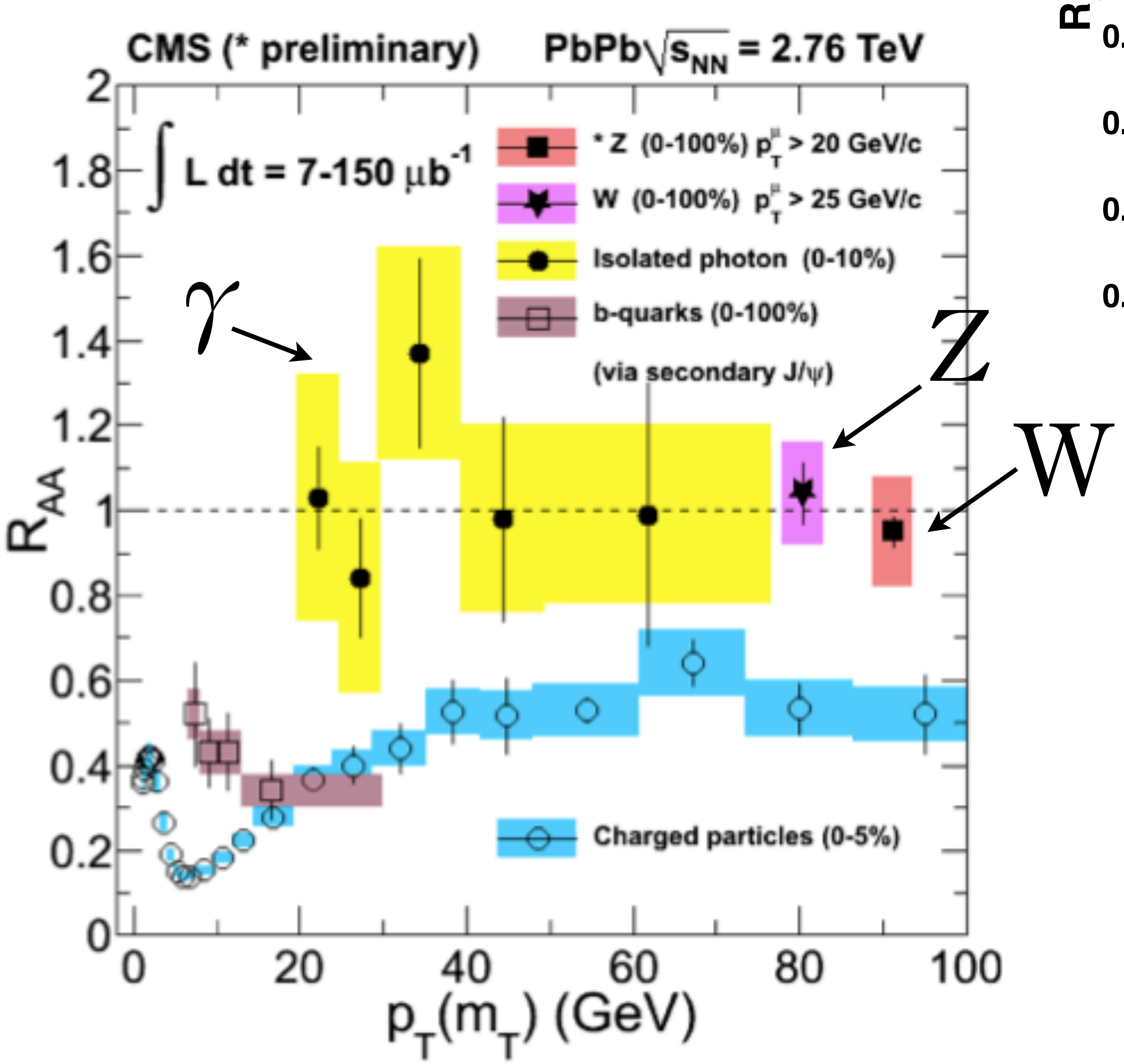
Color-less Probes

Use prompt photons (no color charge):

Sensitive to initial state effects in CNM

Will not lose energy in the QGP



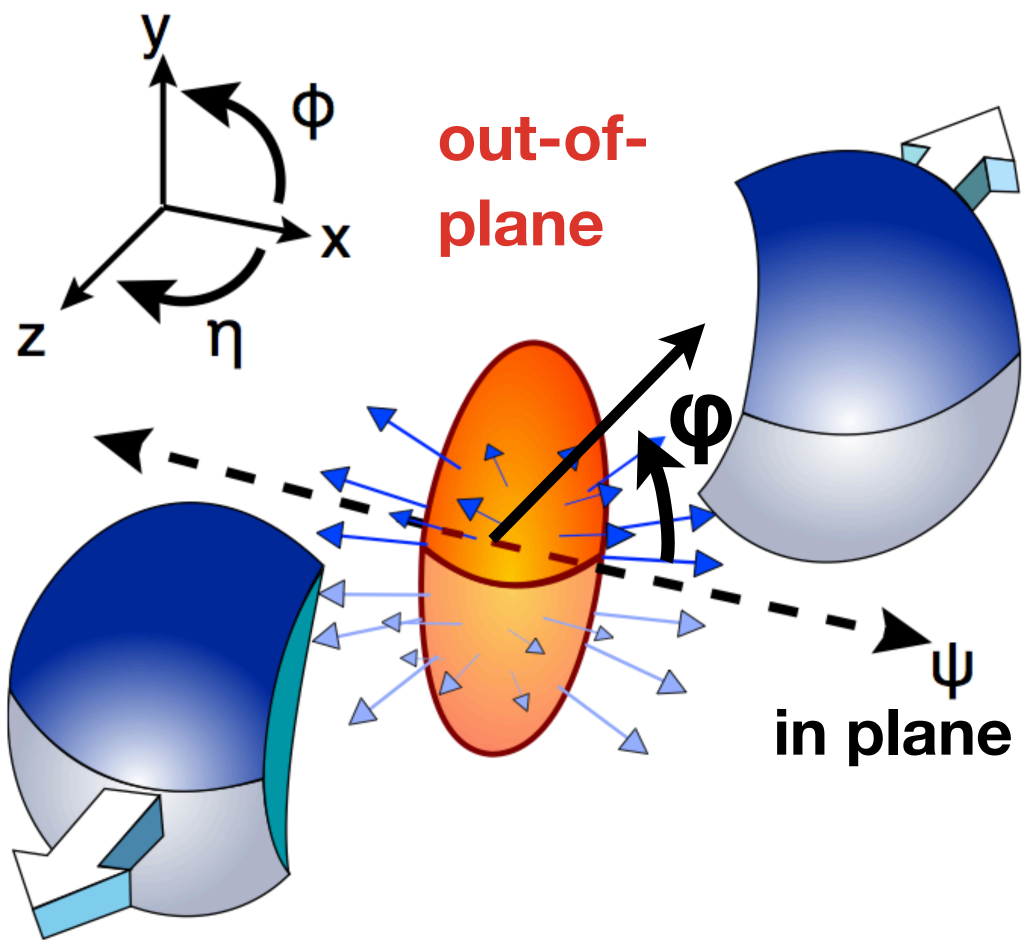


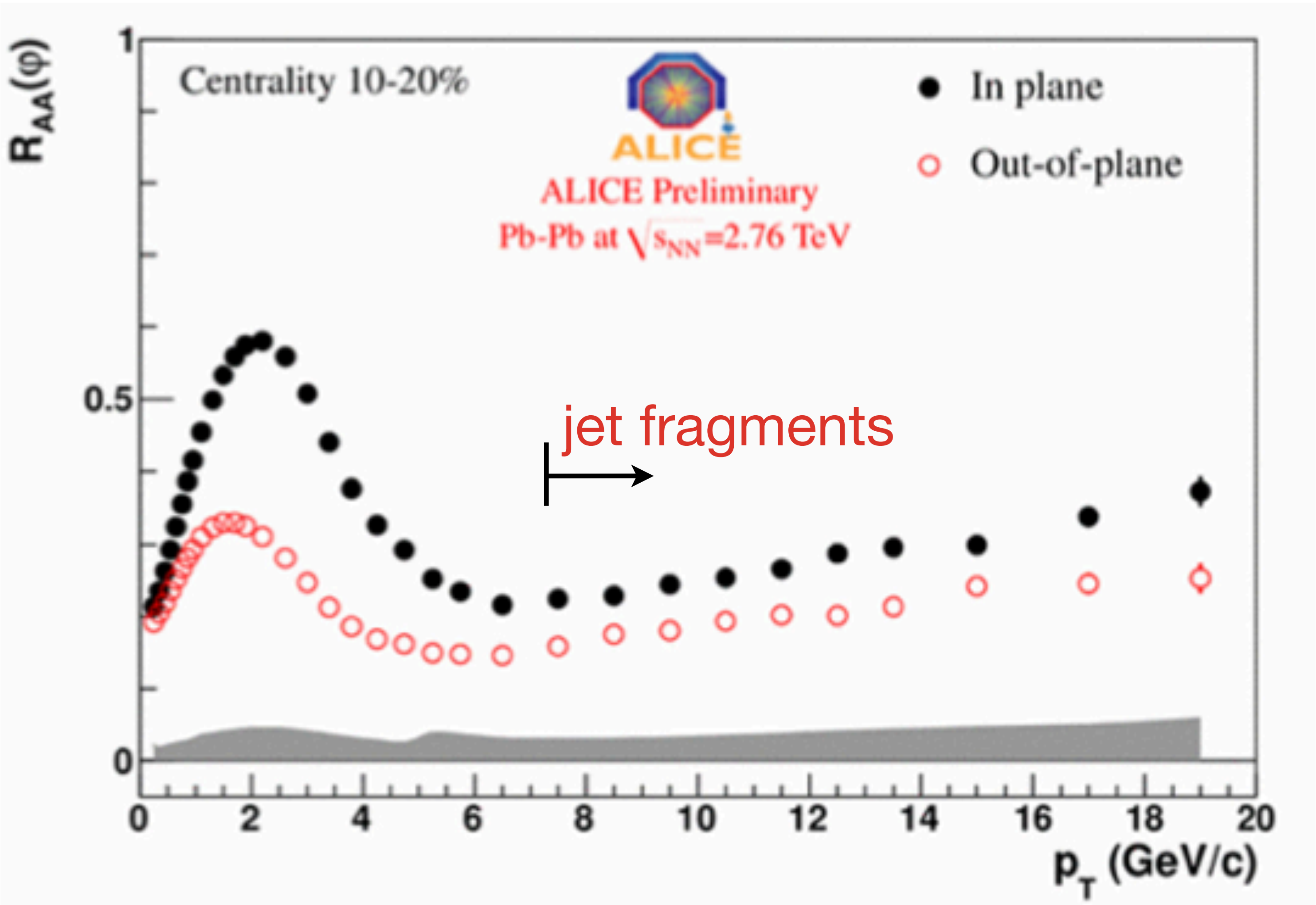
Better S/B at RHIC

LHC can use Z, W as well

Color charge matters!

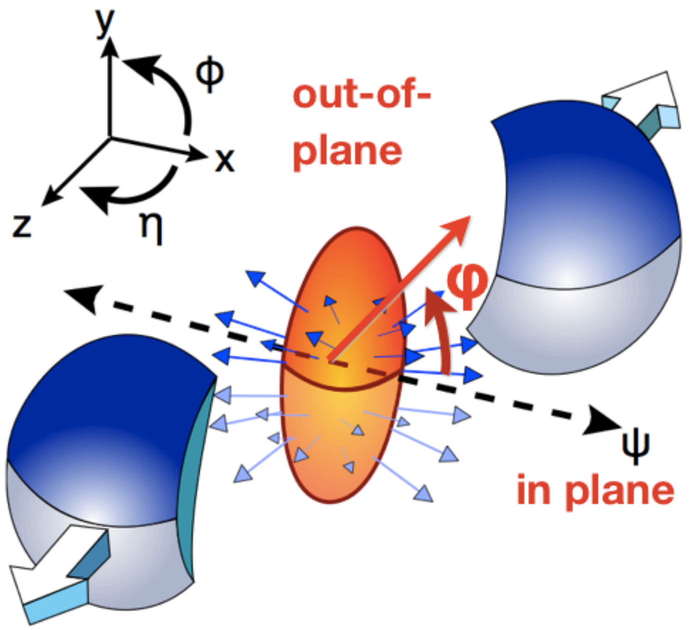
Path-length Dependence





Large increase in suppression as path-length grow out-of-plane

Path-length Dependence II



Analyze the dependence via the **2nd moment, v2**

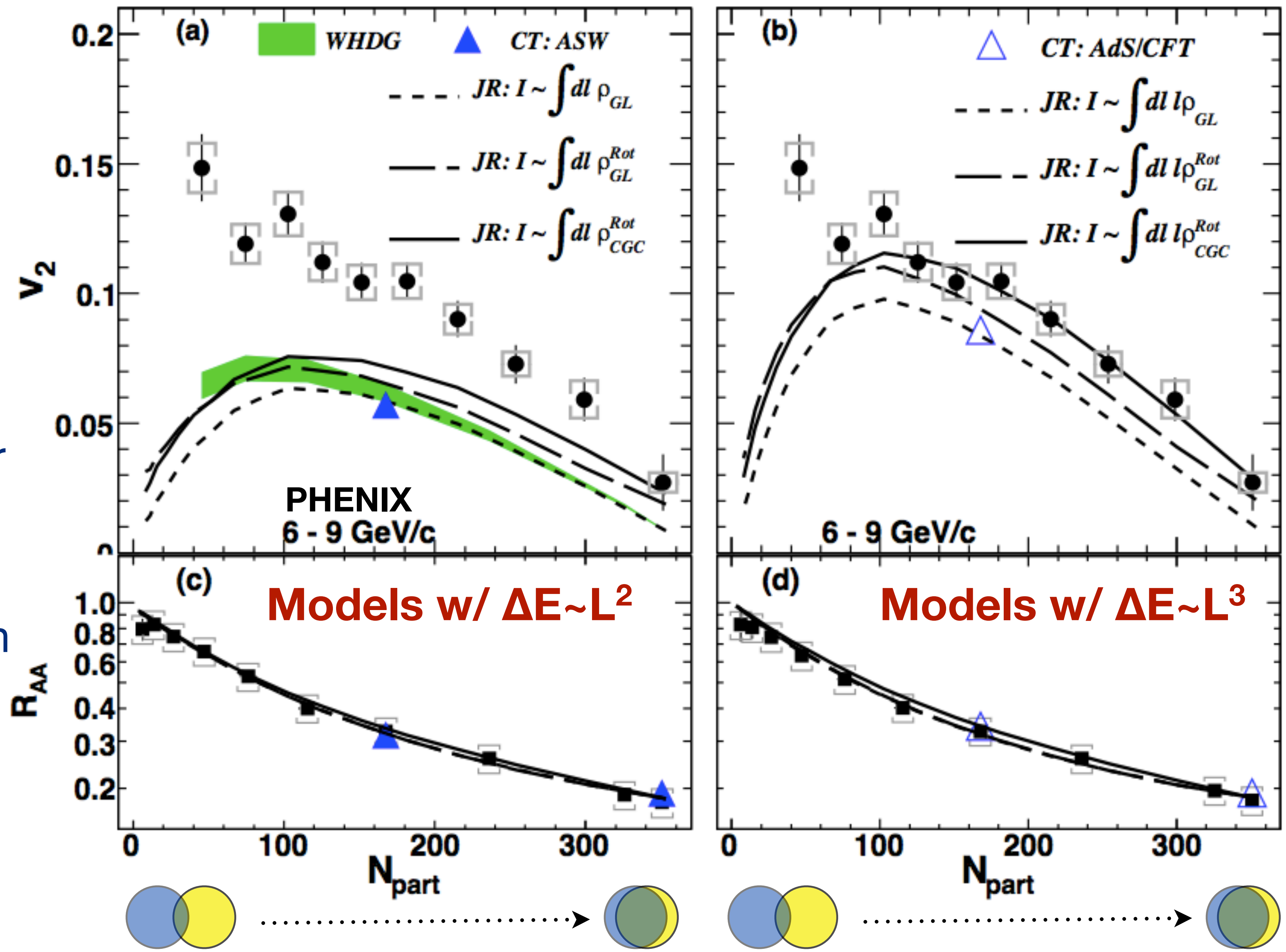
$$\frac{dn}{d\phi} = \frac{n(p_T)}{2\pi}\left(1 + 2v_2(p_T)\cos(2\phi) + 2v_4(p_T)\cos(4\phi) + \ldots\right)$$

"Jet Tomography" of the overlap region

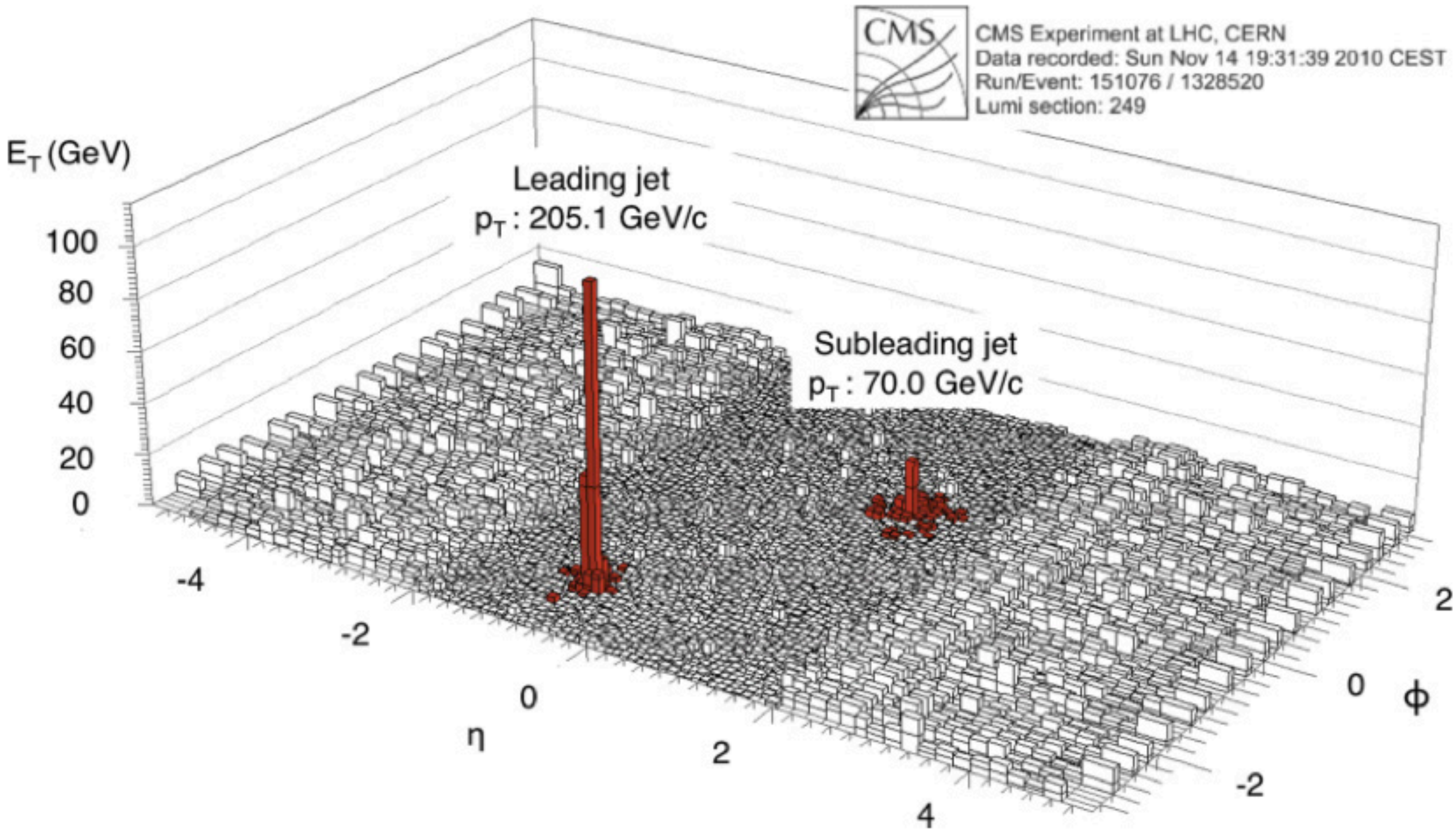
Large anisotropies disappear in central events

R_{AA} alone = no discrimination

Parametrically large path-length dependence needed in models



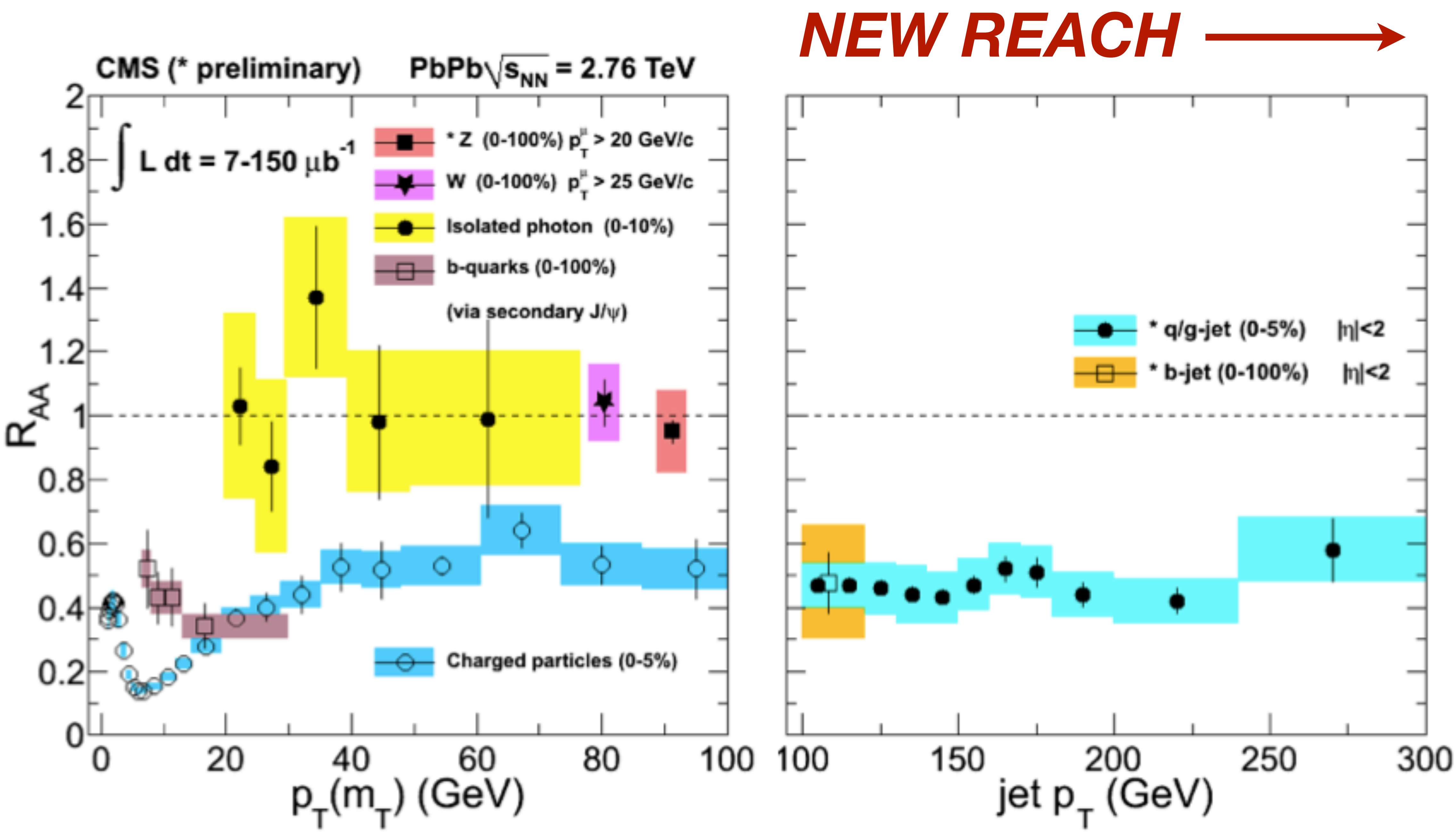
Reconstructed Jets



New channel with LHC lever arm

Extremely large energy losses on recoil jets in fully reconstructed jets at LHC

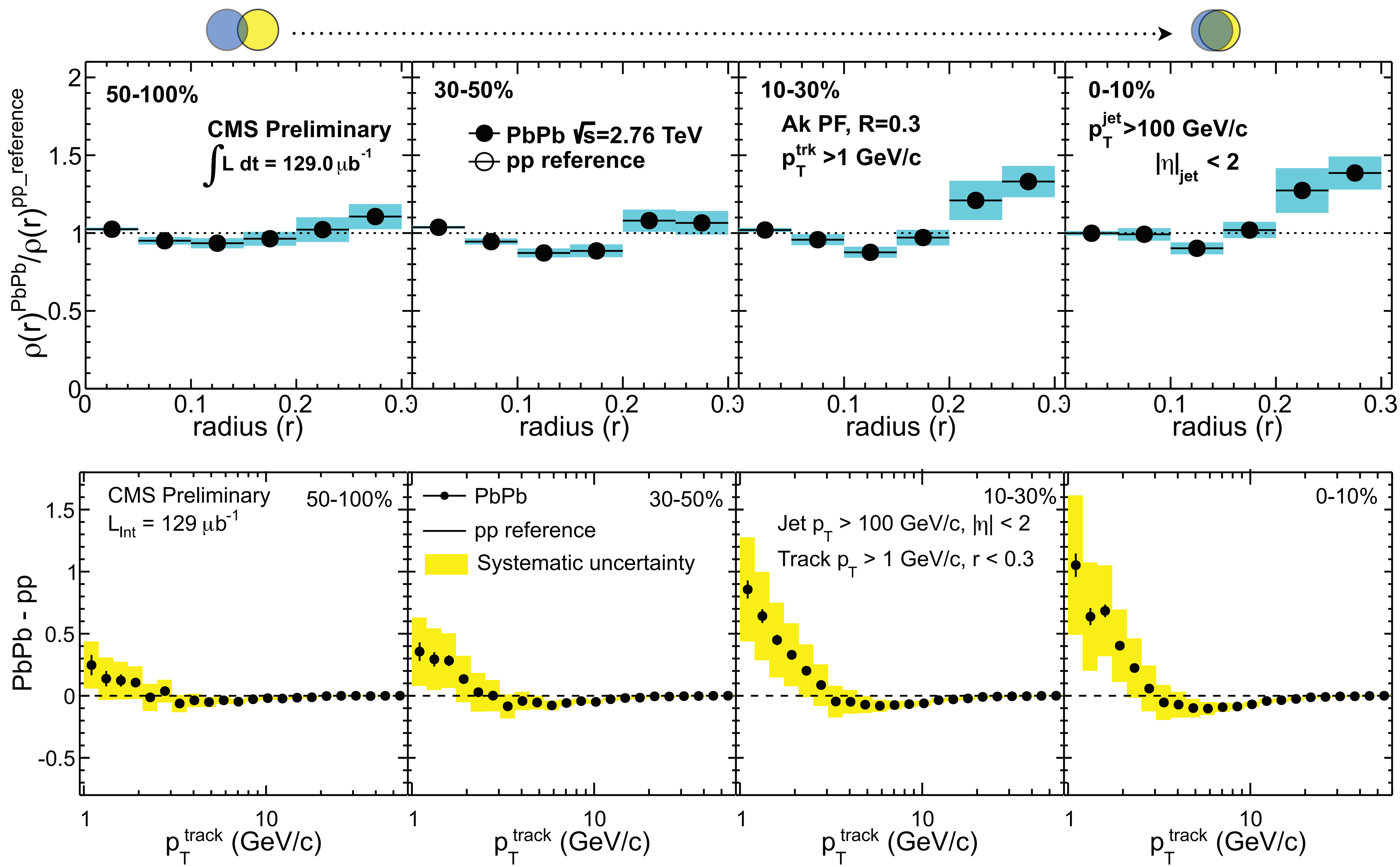
Jet Suppression



Copious jet production allows vast extension of kinematic range

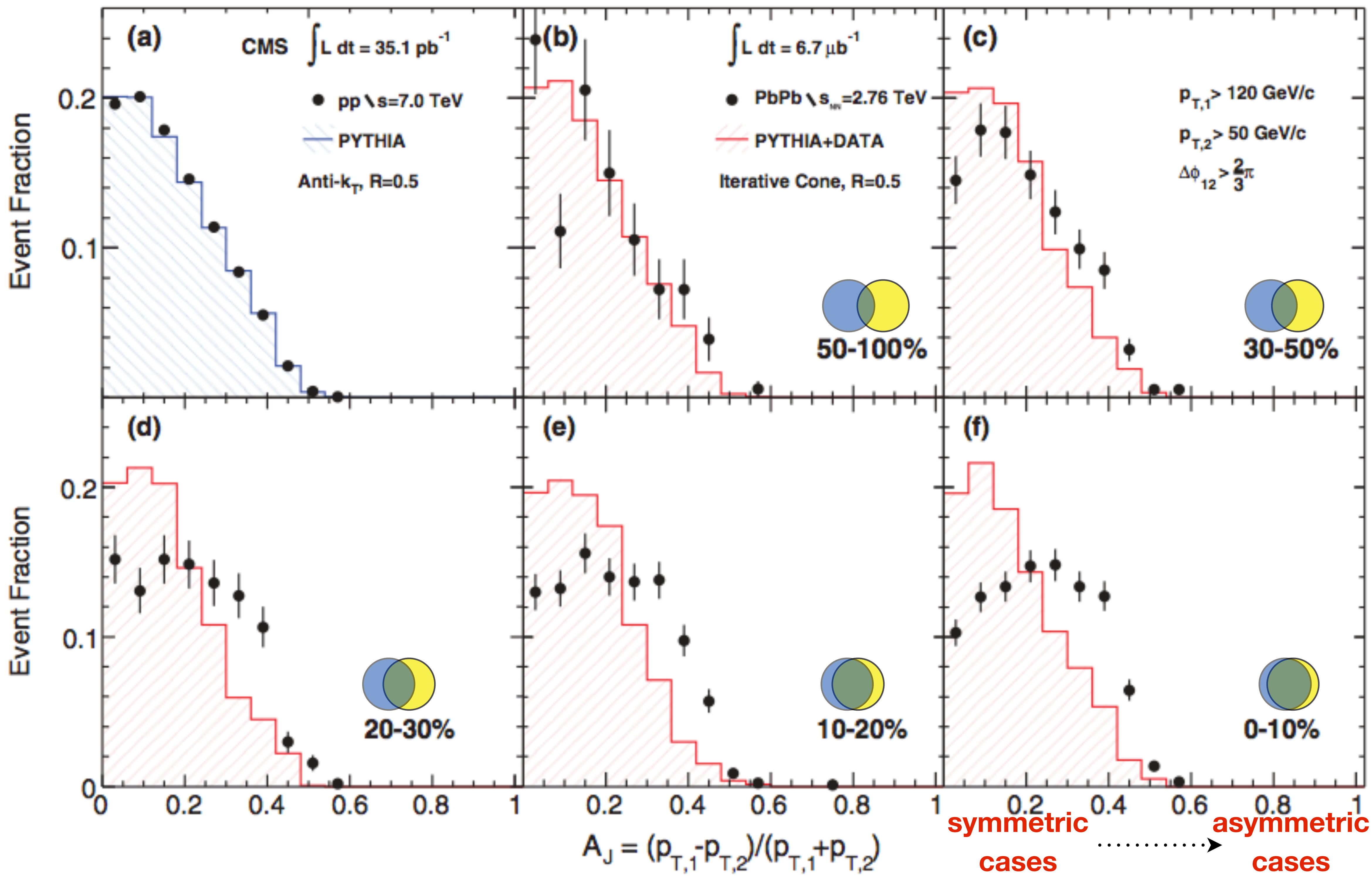
Nuclear suppression persists to extremely large momentum

Jet Internals



Energy loss **widens and softens** jet energy flow in Pb+Pb

Di-jets

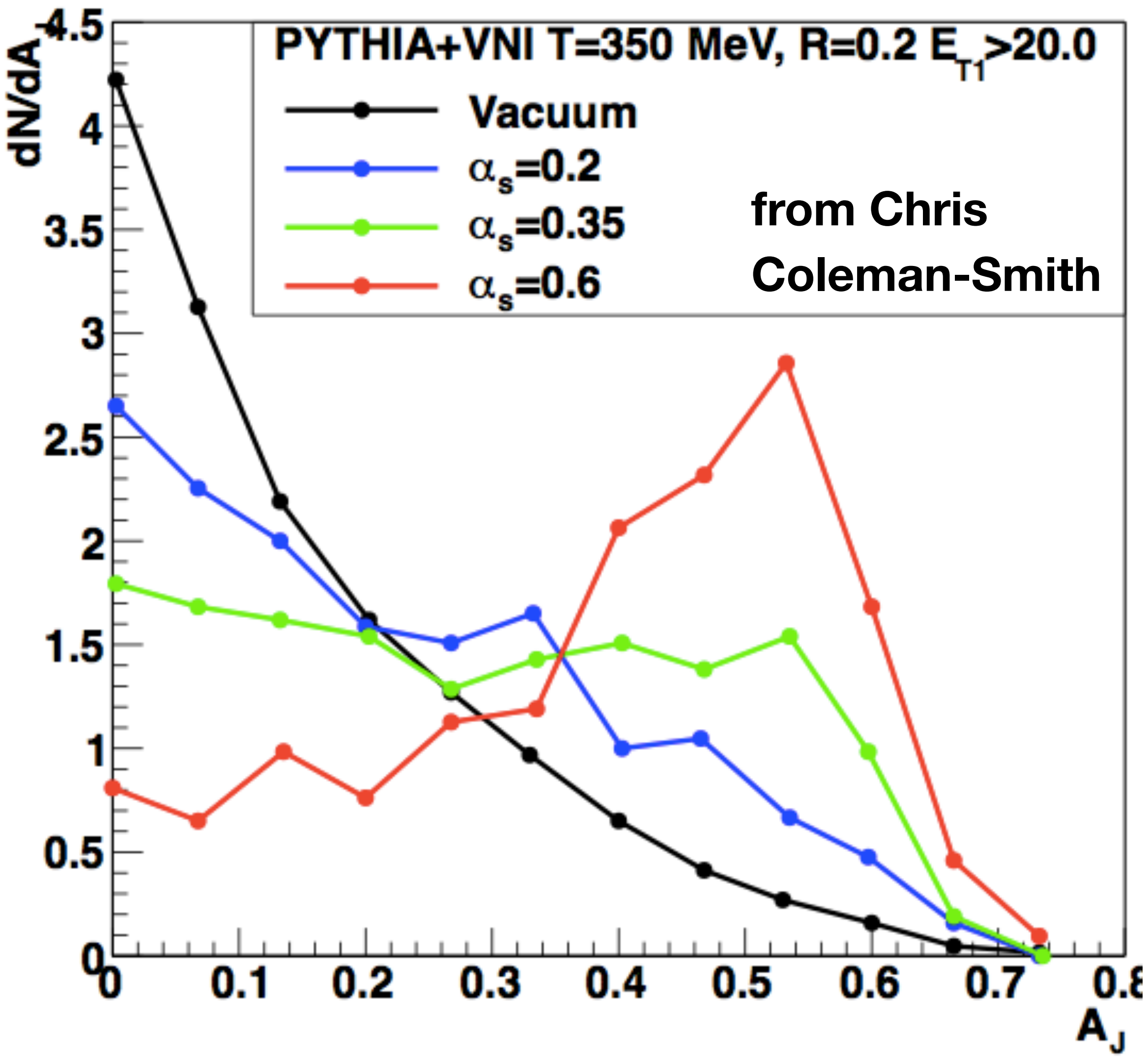


Asymmetric jets are present in p+p but at a very small rate

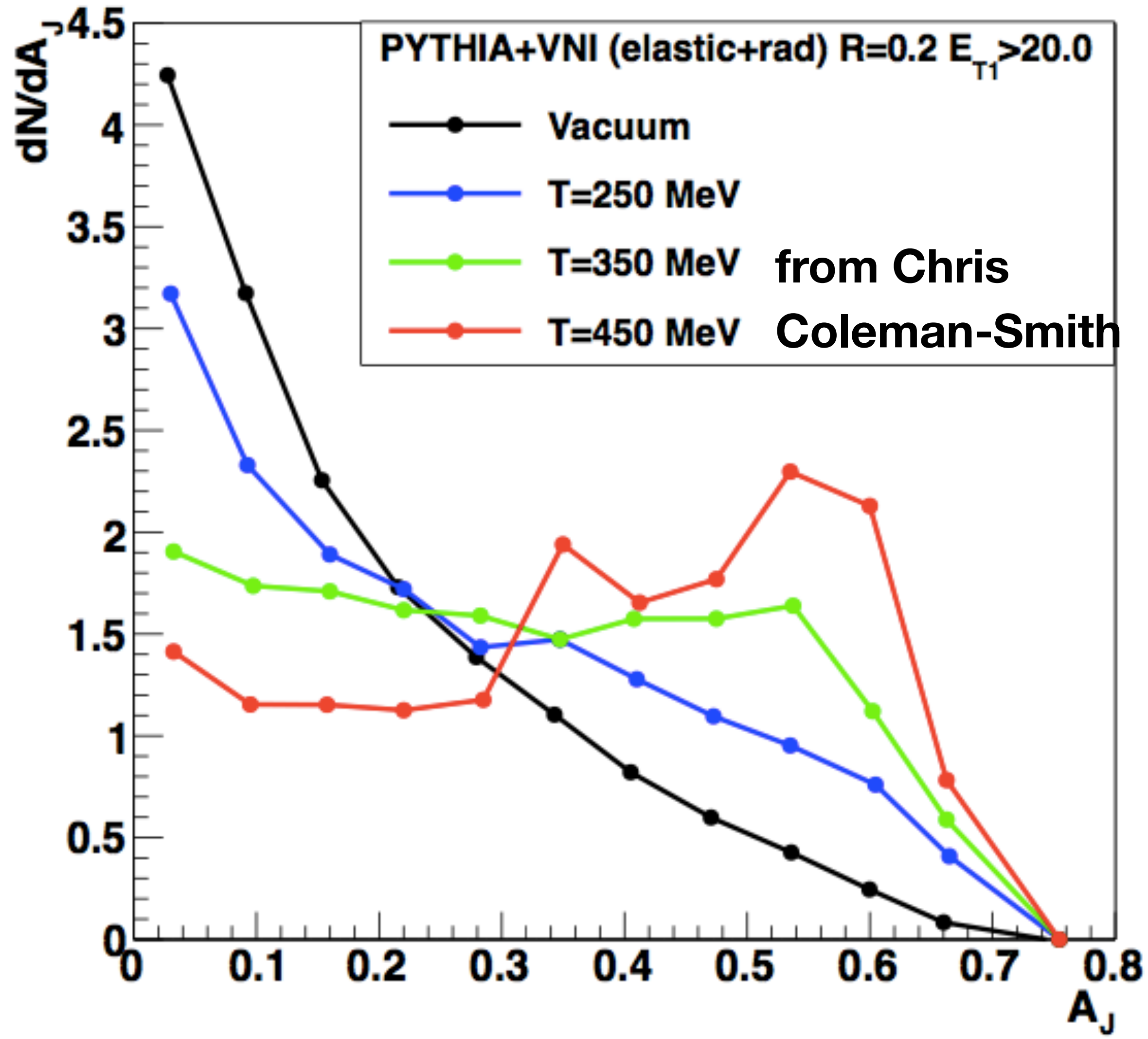
Pb+Pb shows fewer symmetric cases, many more asymmetric cases

Di-jet Balance Asymmetry II

Medium coupling strength



Temperature



A view of the future:

Distributions encode rich information about the QGP

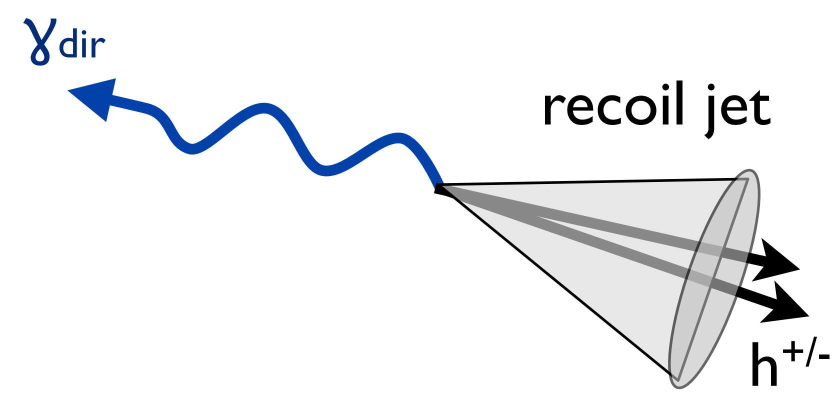
But also quasi-particle mass and other interesting properties

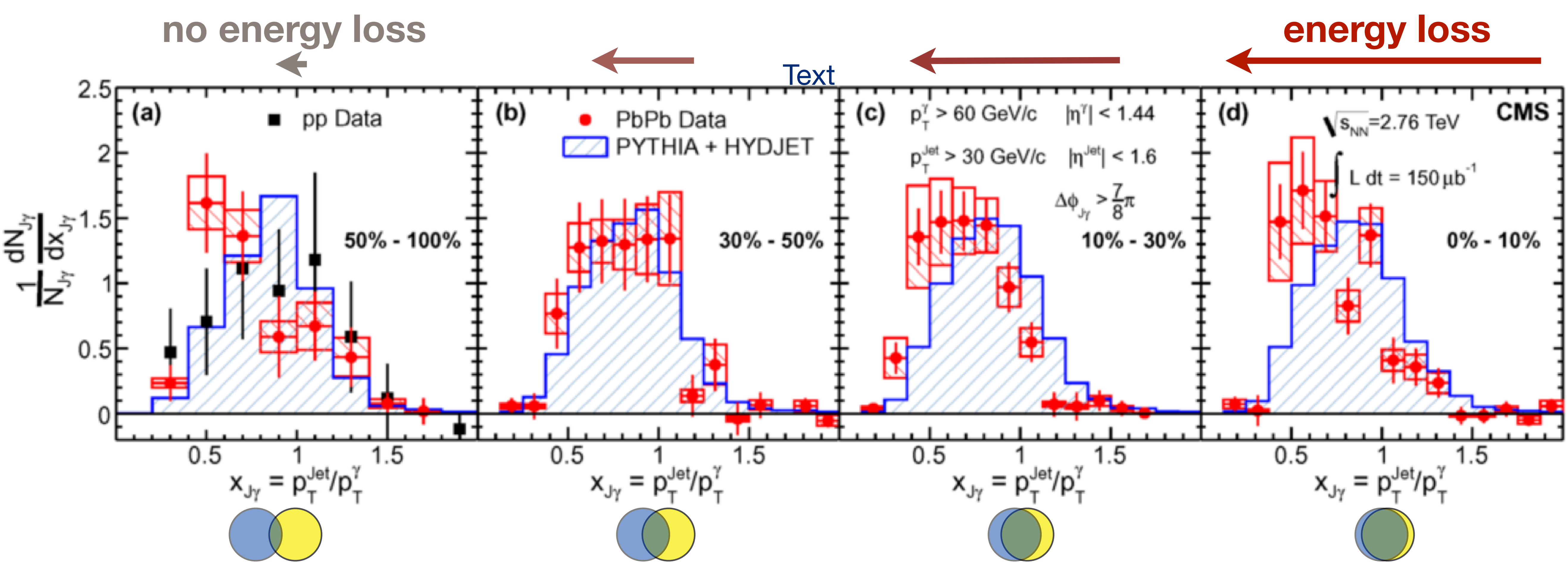
Will require systematic effort to separate these effects and pull out the QGP properties & compare with our collective models

Prompt Photon - Jet

Photons escape medium without energy loss
Provides initial energy of the away-side parton at LO

Considered a **“golden channel”**
for energy loss studies





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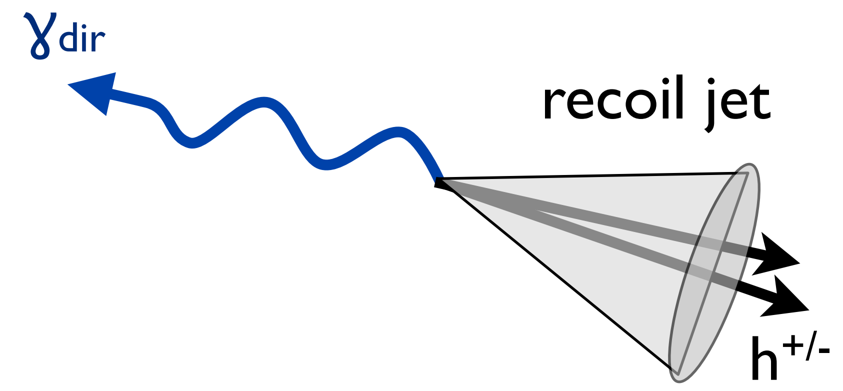
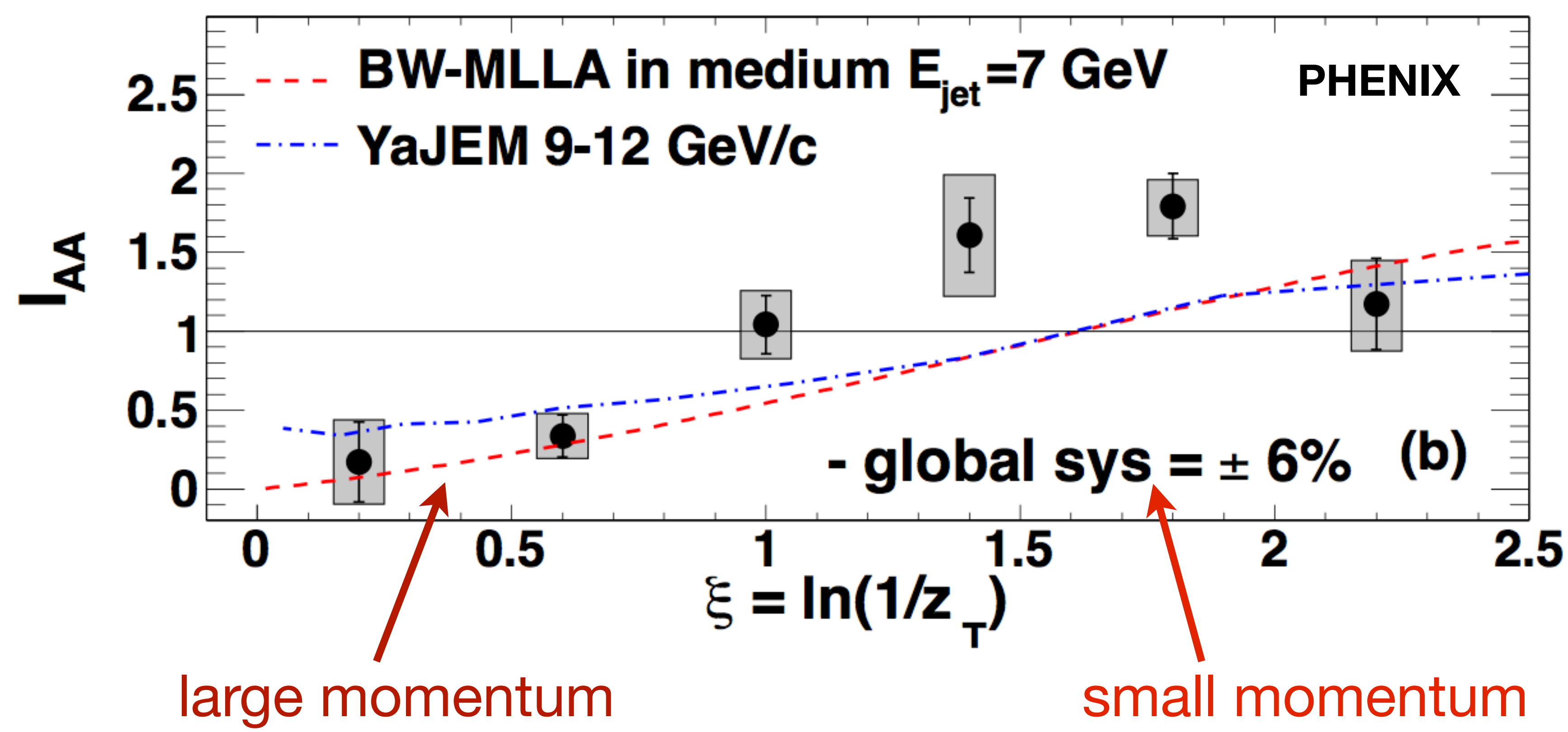


Looking within the jet:

$$I_{AA} \equiv \frac{(1/N_{trig} dN/d\xi)_{AA}}{(1/N_{trig} dN/d\xi)_{pp}}$$

like R_{AA}, no effect = 1



Energy lost recovered at low momentum
Characteristically similar to model predictions
No jet algorithm needed

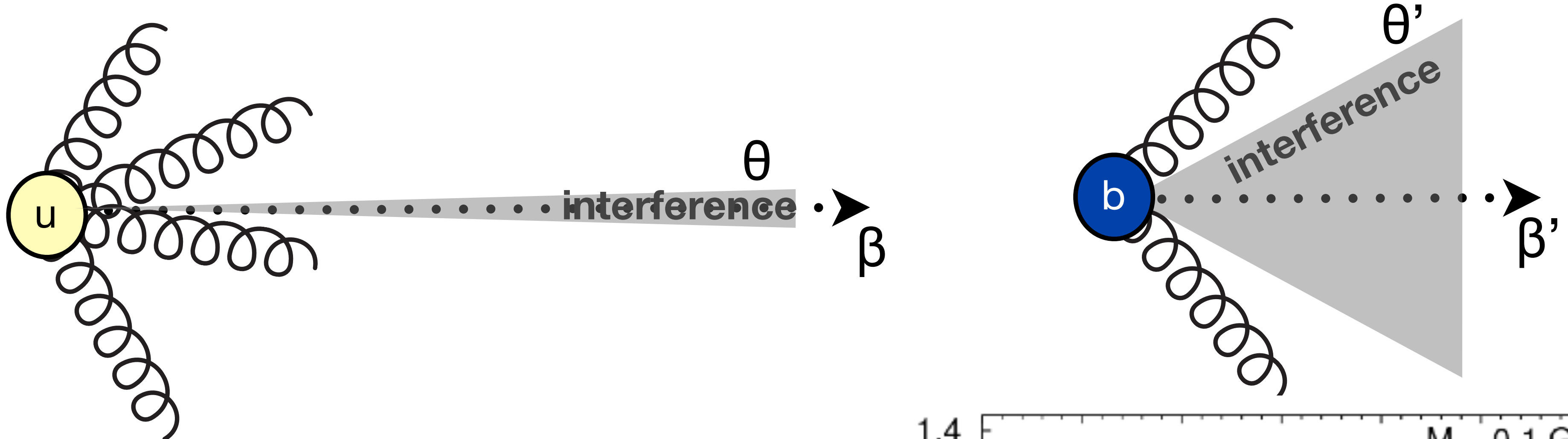
Open Heavy Flavor

Why **Charm and Beauty** Quarks?

- **rapid formation time** exposes probe to full medium evolution: ~1/M
- **differently sensitive** to cold nuclear matter effects impacting quarkonia

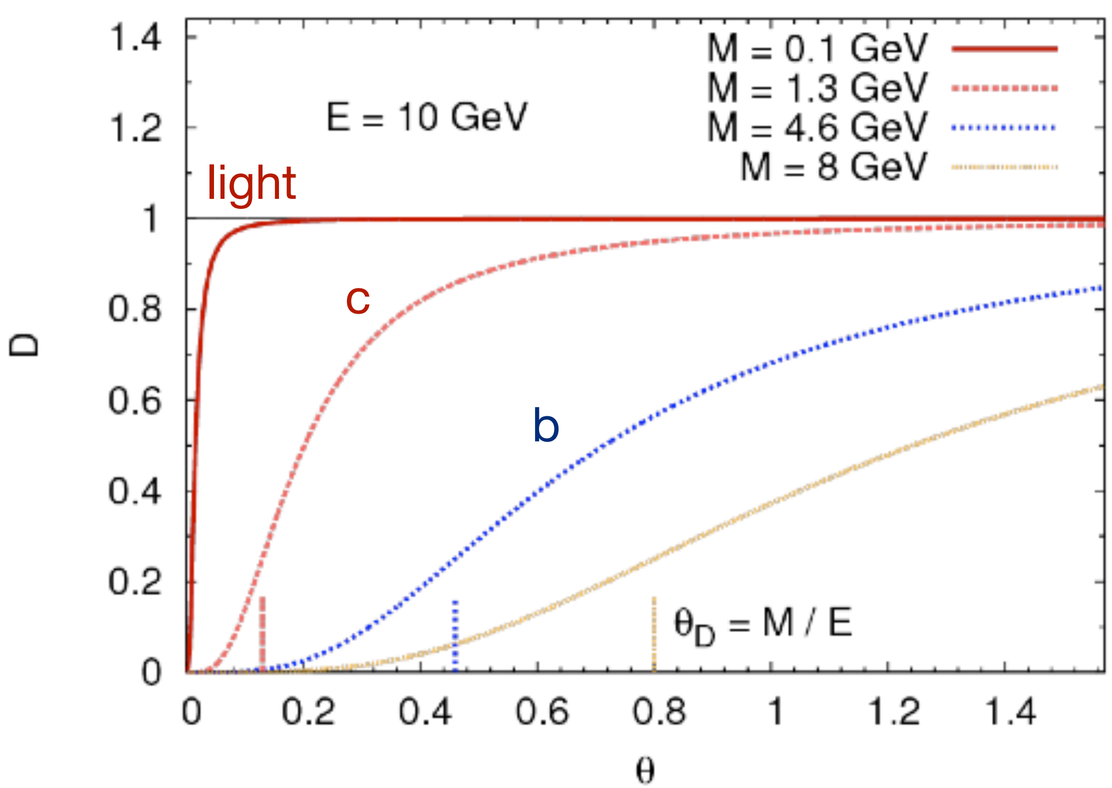
How is energy loss of heavy flavor different?

- **"Dead cone effect"** on gluon radiation (proposed Dokshitzer & Kharzeev, 2001)



importance of destructive gluon interference adds to **mass-ordering of energy loss**

$$\Delta E_g > \Delta E_{u,d} > \Delta E_c > \Delta E_b$$



Cold Nuclear Matter Effects

Gluon fusion process dominates heavy quark production

$$g + g \rightarrow q + \bar{q} + X$$

CNM effects include:

(1) **Gluon shadowing**

penetration into the front face of the nucleus modifies the gluons available for fusion

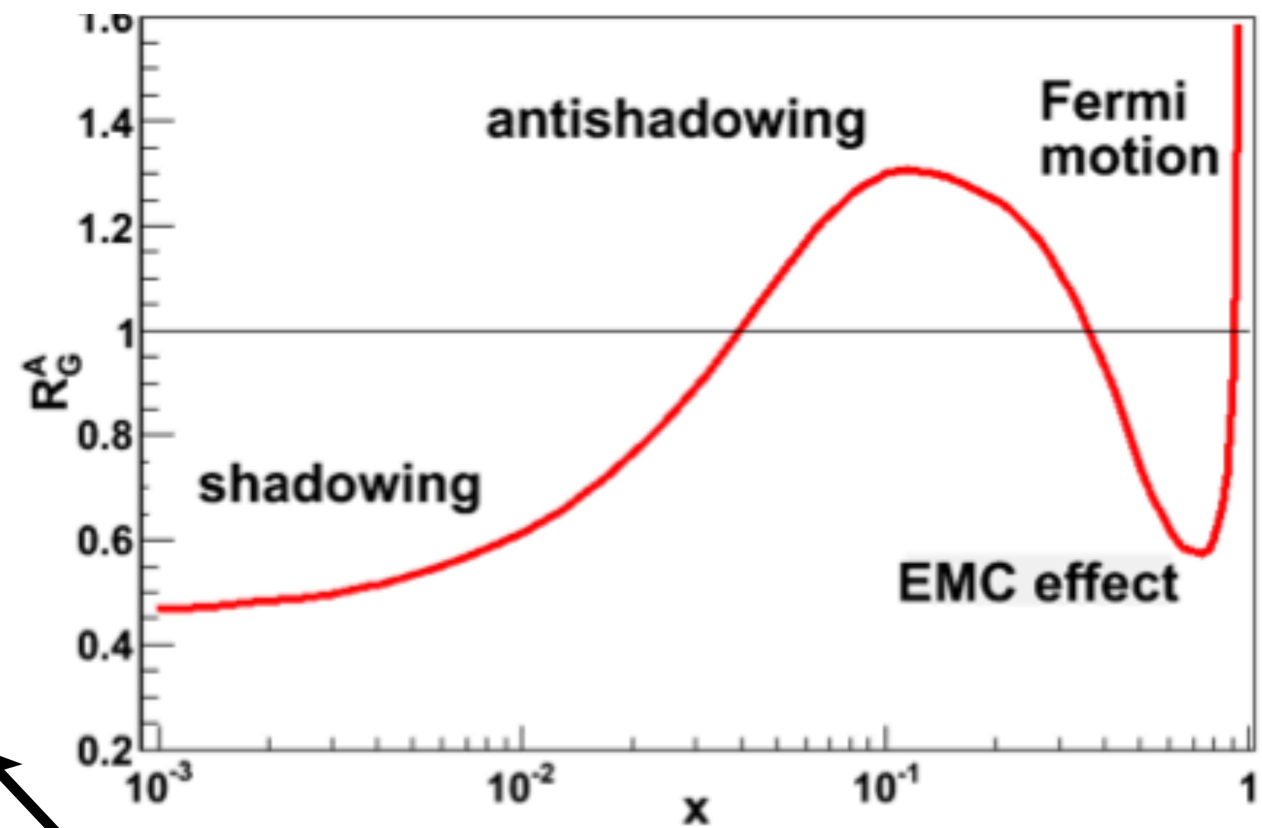
(2) **Gluon saturation**

at extremely low x, gluons should fuse to maintain unity in the PDF, not known where this happens!

*(3) **Nuclear absorption (quarkonia only)***

the bound-state or its predecessor state is "broken up" by reactions with the back-side of the nucleus

nuclear gluon PDF / proton

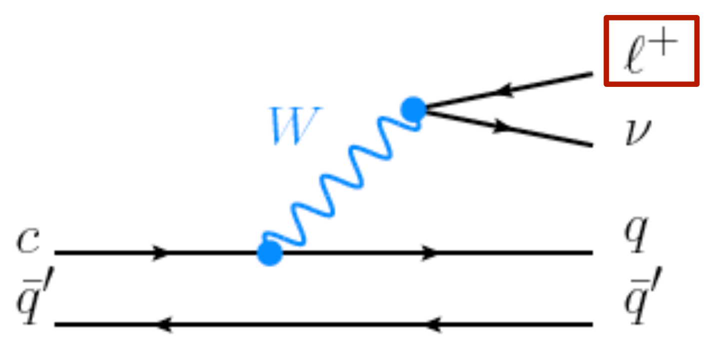


Important at higher energy (low x feature)

Important at lower energy (formation time)

Heavy Flavor Suppression

Early results from
single heavy flavor leptons

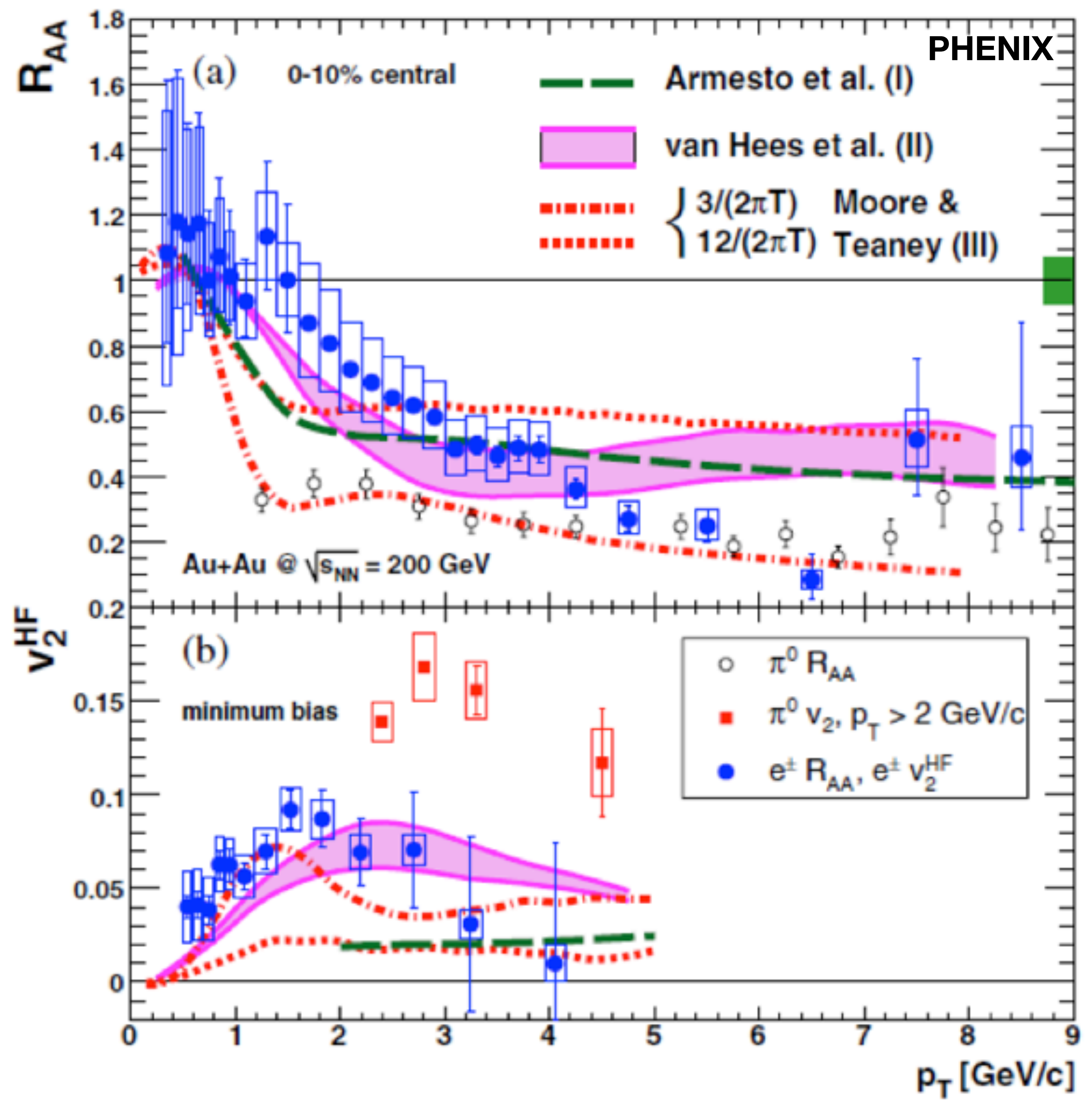


Mixes **charm and bottom**

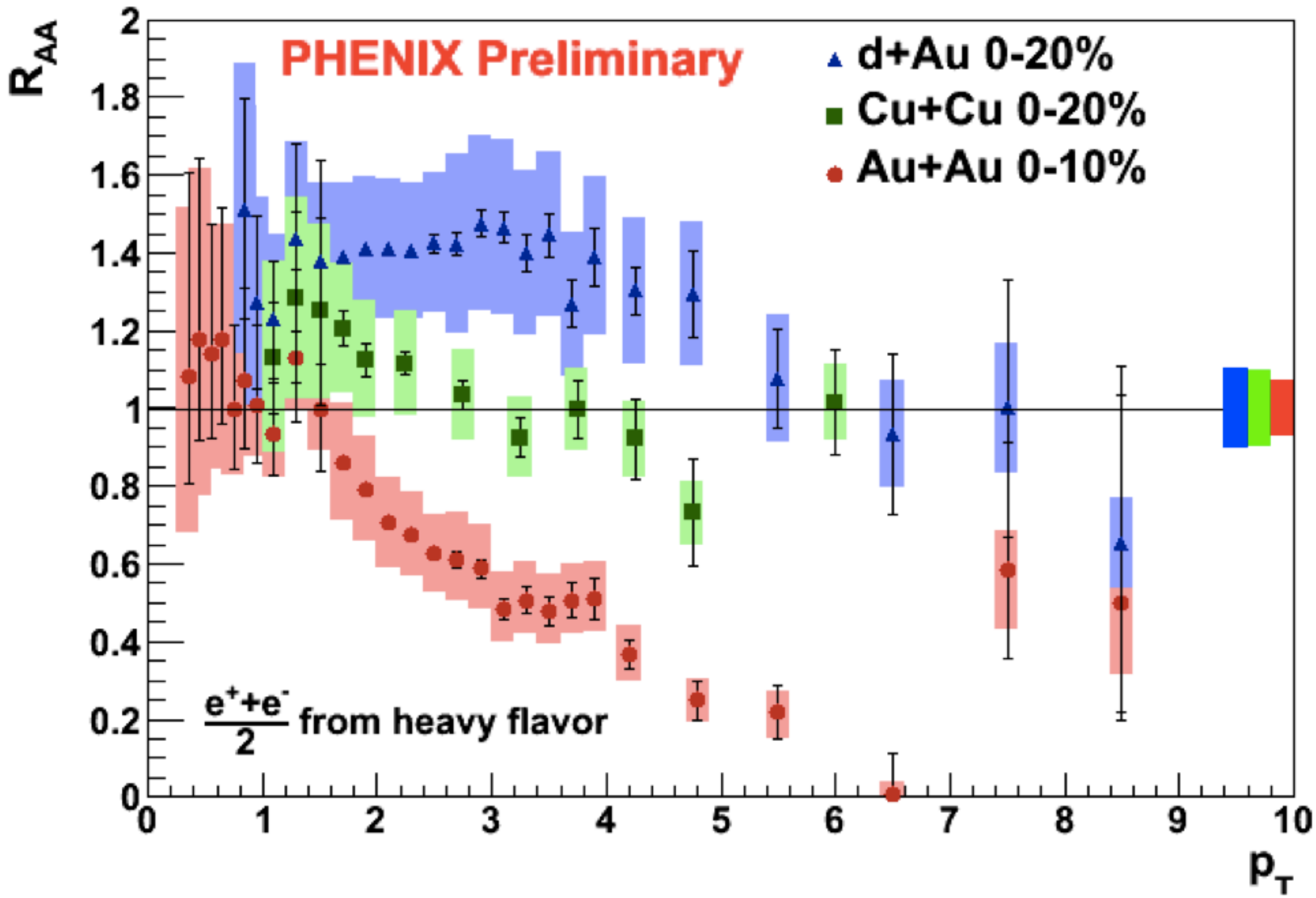
Large suppression at high p_T shows significant energy loss

As expected:
π^0 R_{AA} < c+b R_{AA}

Not obvious if:
c R_{AA} < b R_{AA}



Cold Nuclear Matter Baseline



CNM effects are important for open heavy flavor at RHIC!

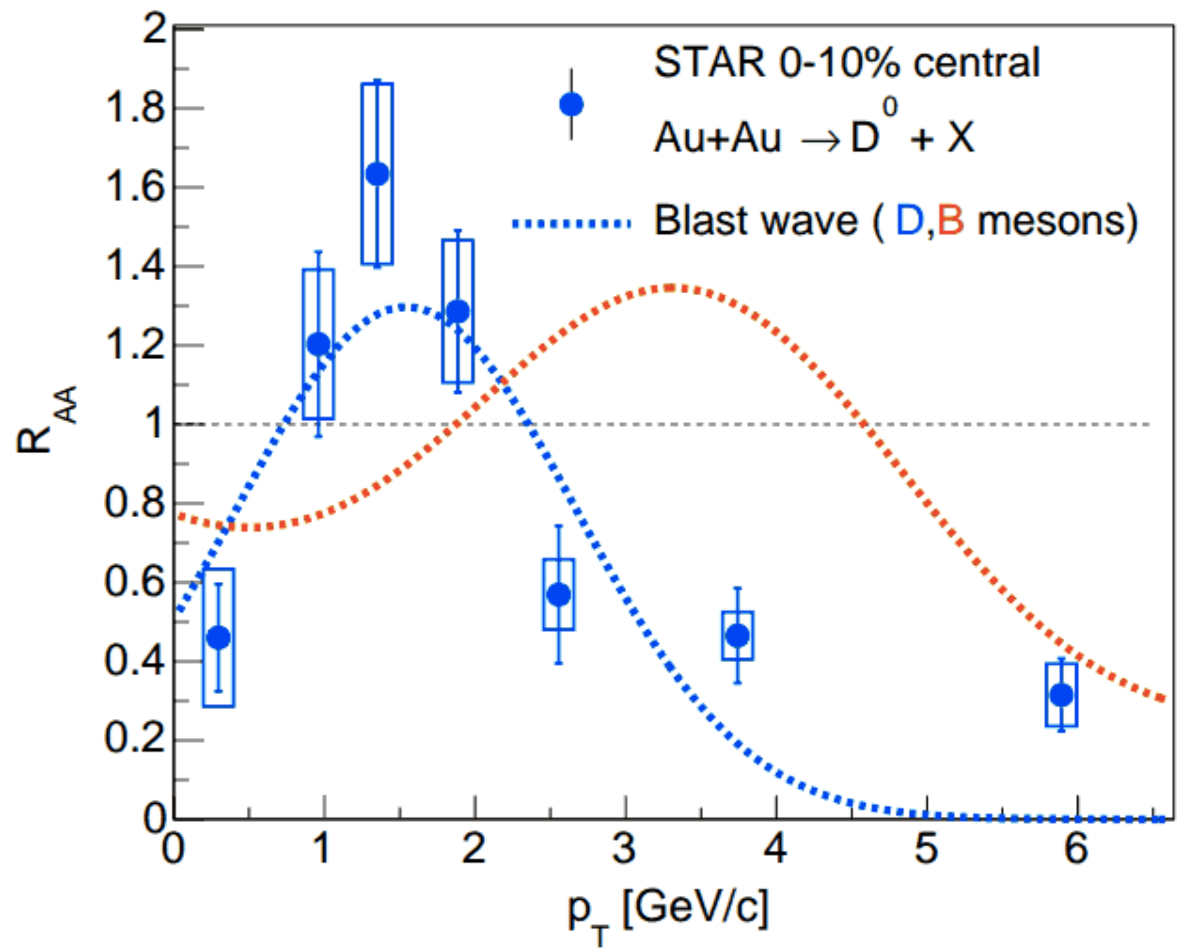
Important for Cu+Cu interpretation

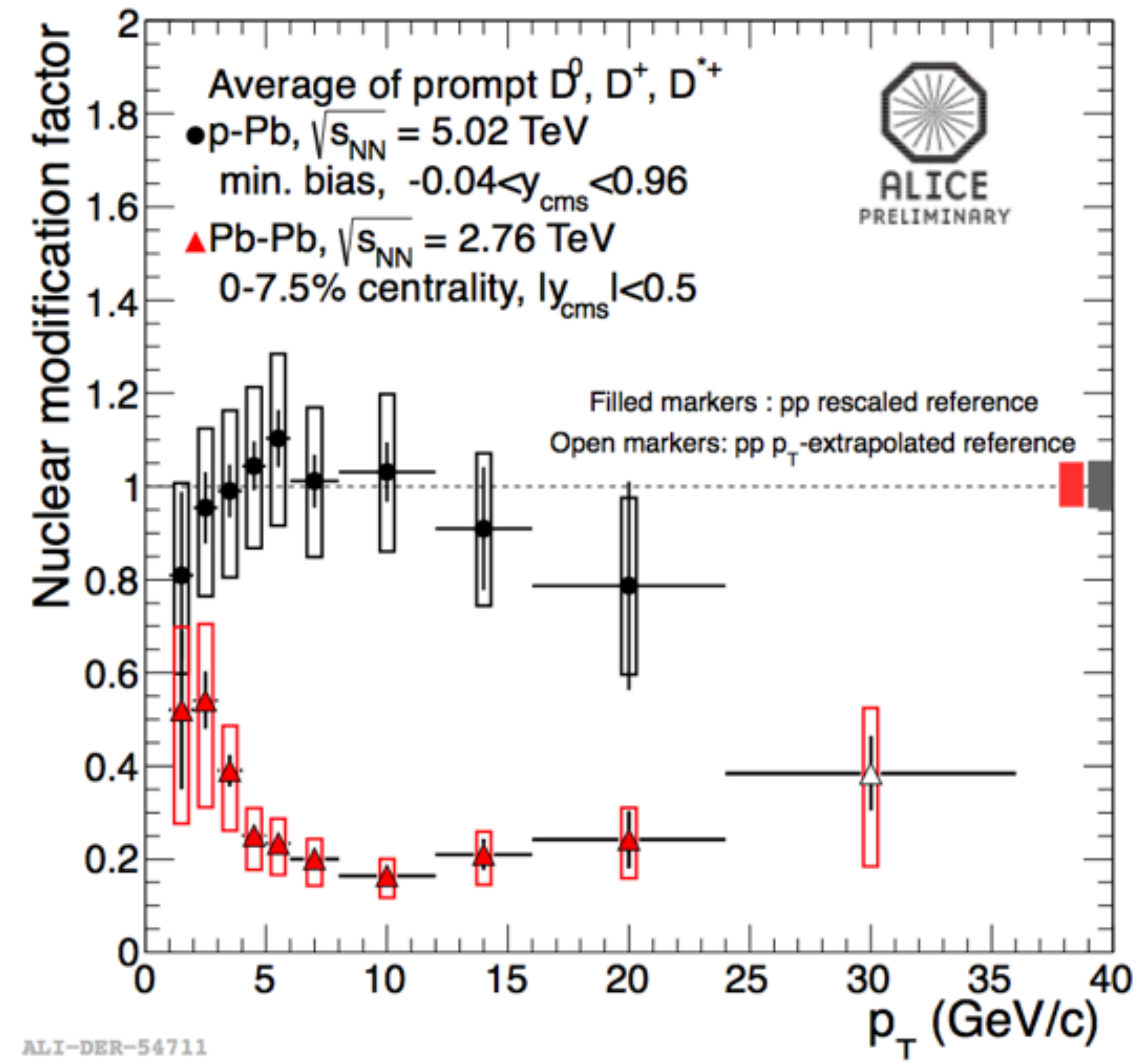
Increases the energy loss needed reproduce the heavy flavor spectrum

D Meson Reconstruction

Better to fully reconstruct the decay kinematics and **separate charm** from bottom

example: $D^0 \rightarrow K^- + \pi^+$





Large charm suppression, comparable with light partons

No significant CNM effect in p+Pb collisions at the LHC

Important input for quarkonia studies

D Meson Reconstruction

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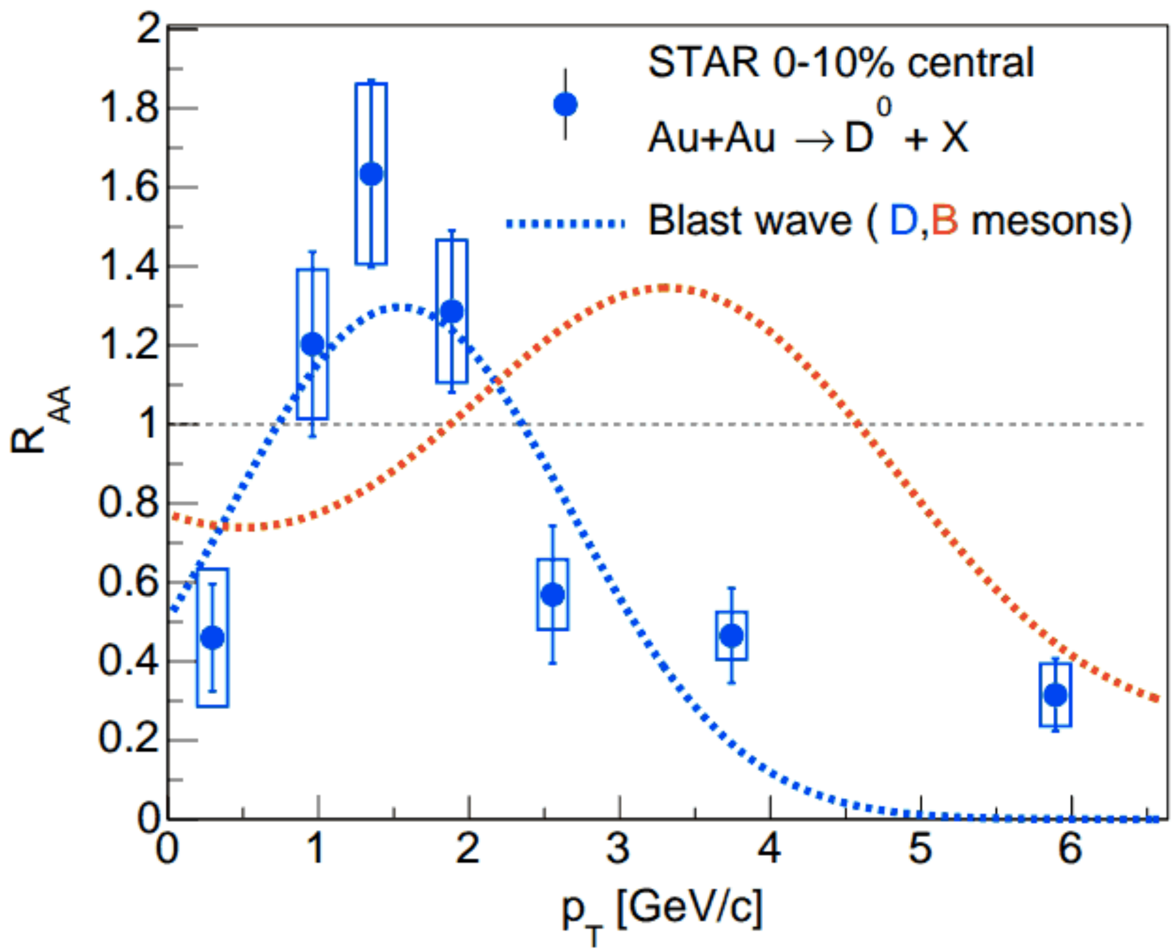

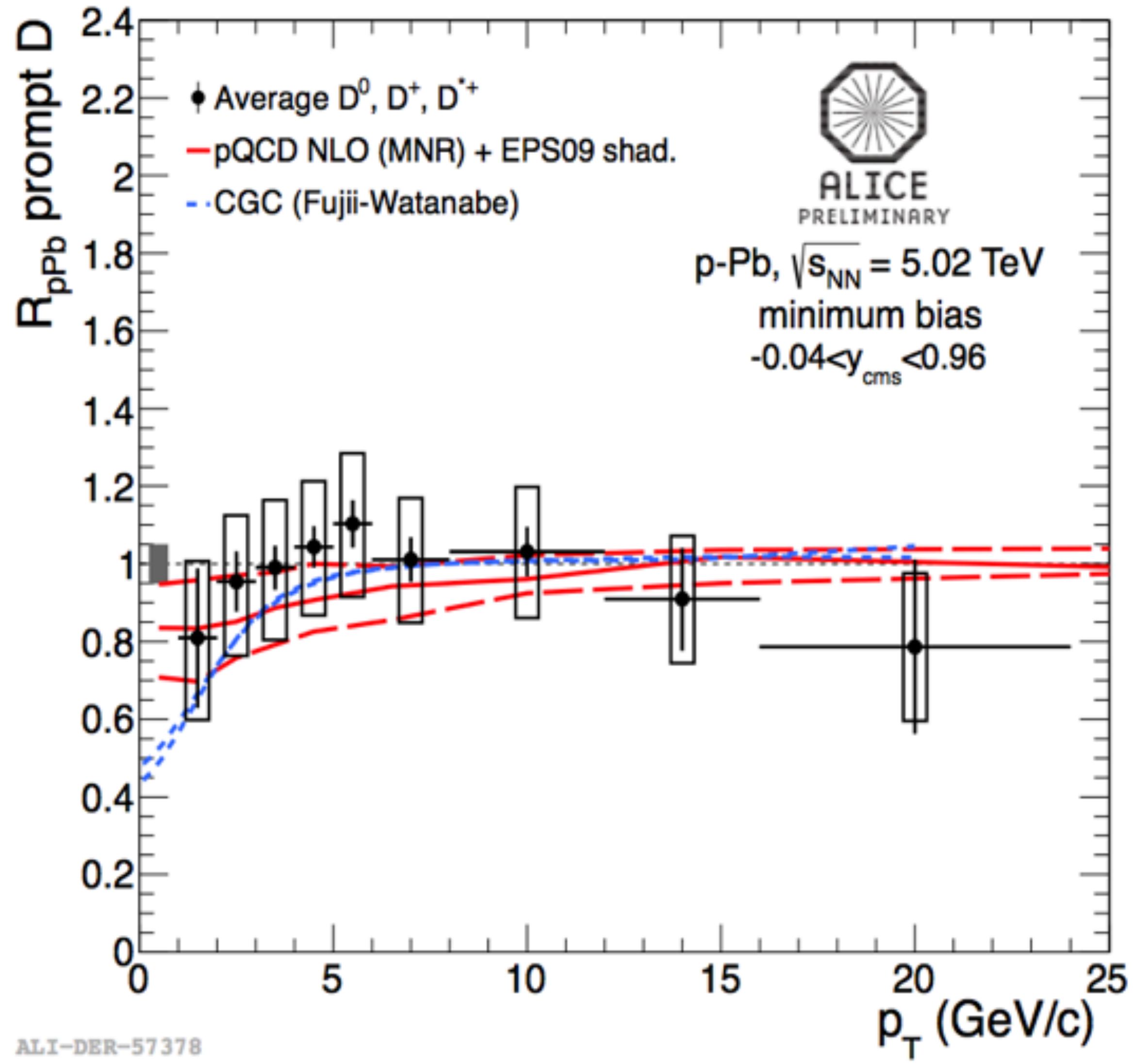

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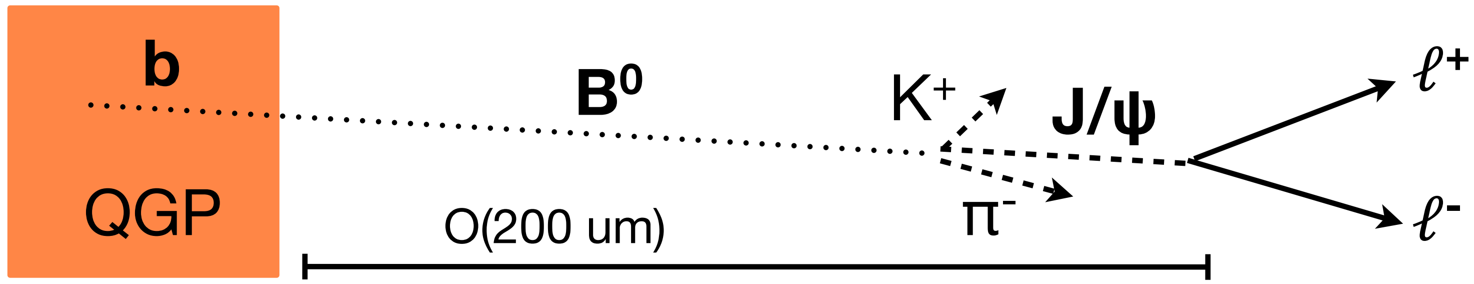
B→J/ψ Suppression



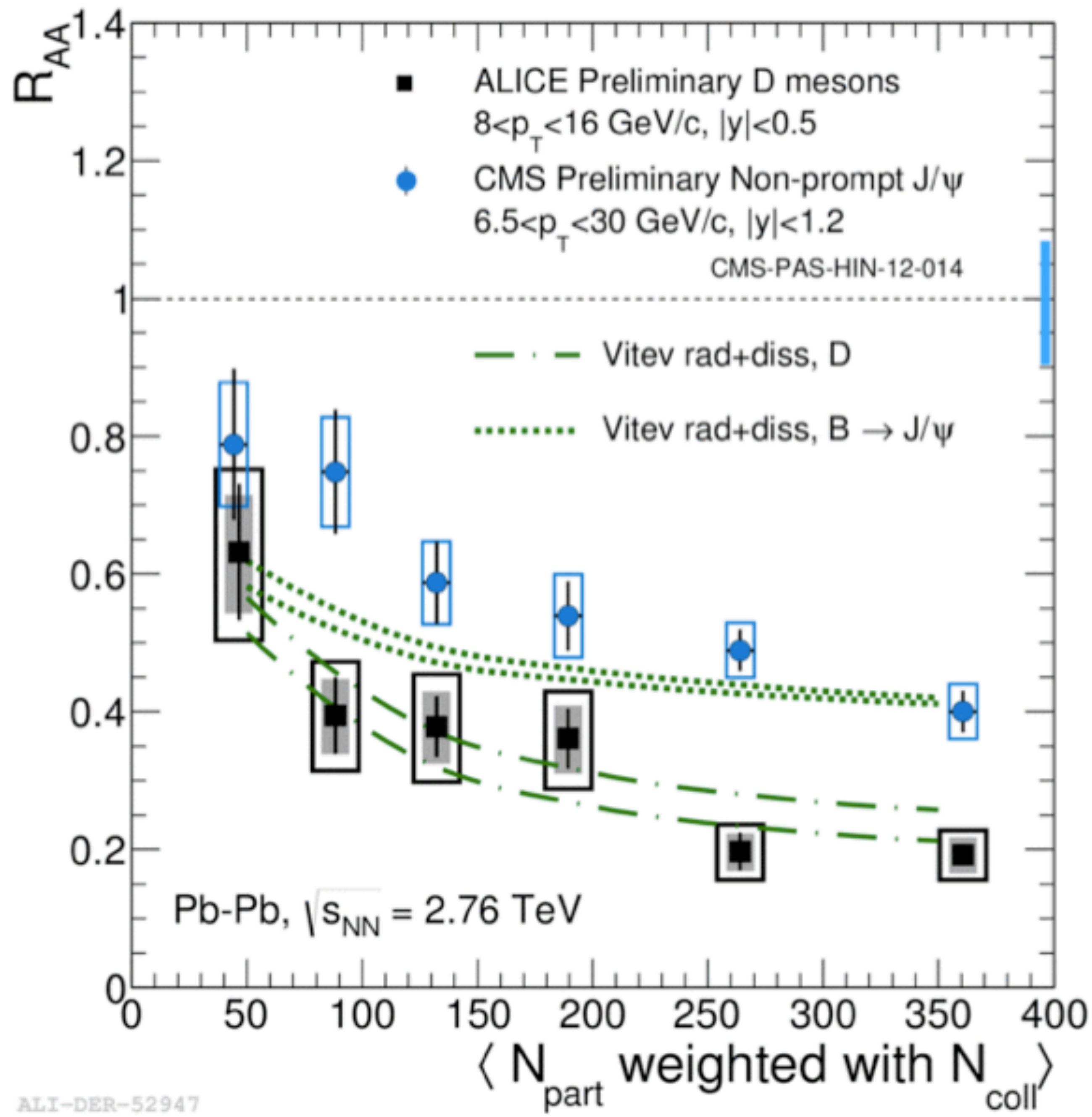
Bottom quark last through the medium expansion, hadronization, and decays in vacuum

Long flight time of beauty hadron = Off vertex decay to J/ψ

Separate into prompt & non-prompt J/ψ with inner tracking

c R_{AA} < b R_{AA}

Difference typically characteristic of model expectations

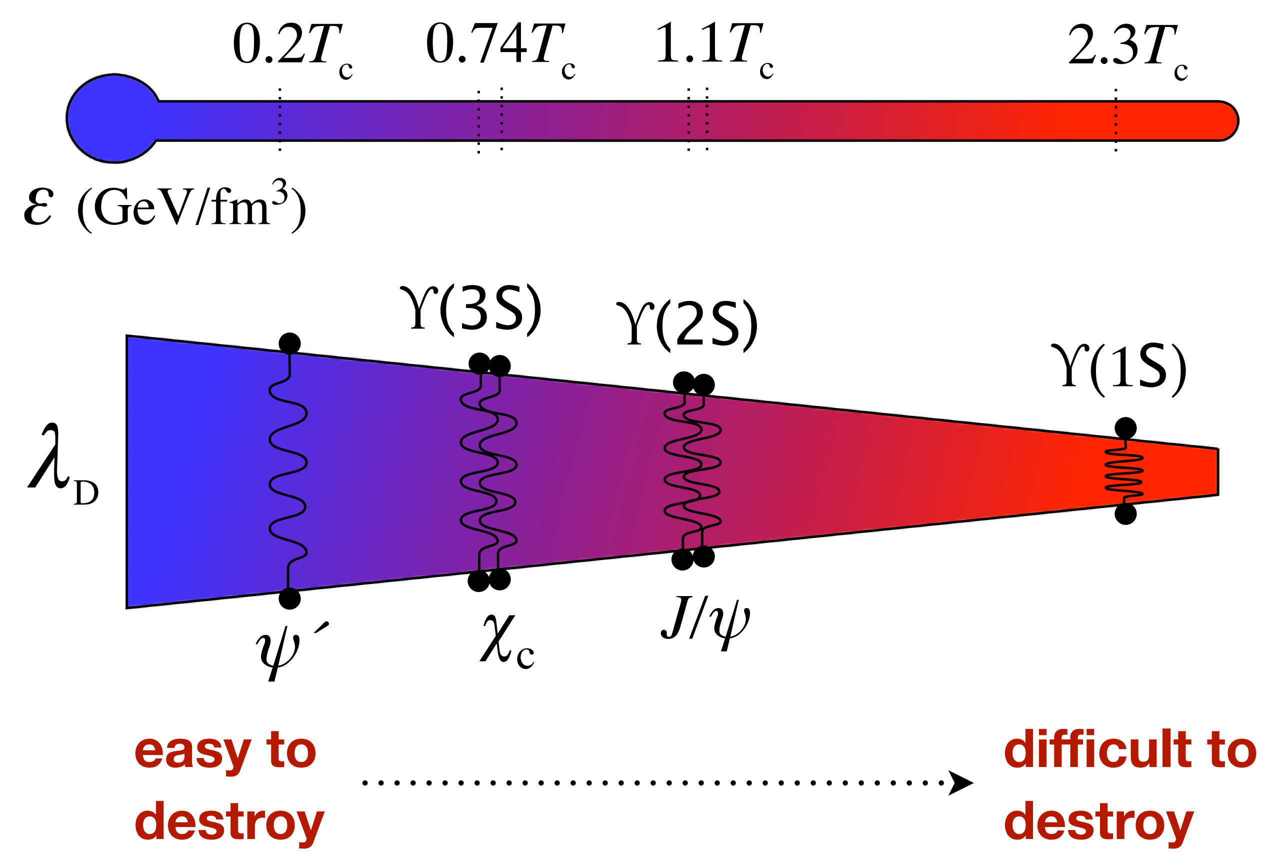


Quarkonia Suppression

Early proposed "smoking gun" channel for Quark-Gluon Plasma

Screening from medium charges dissolves bound state hadrons

Set of remaining states reveal peak temperature in the medium



The idealized picture breaks down rather quickly:

- **Feed-down Contamination**
  - lower mass states produced during decay
- **Cold Nuclear Matter Effects**
  - initial state energy loss, gluon saturation, nuclear breakup
  - dependencies on centrality, pseudorapidity, momentum
- **Recombination at Hadronization**
  - isolated heavy quarks bind after QGP phase
  - worse at lower mass and at higher beam energy

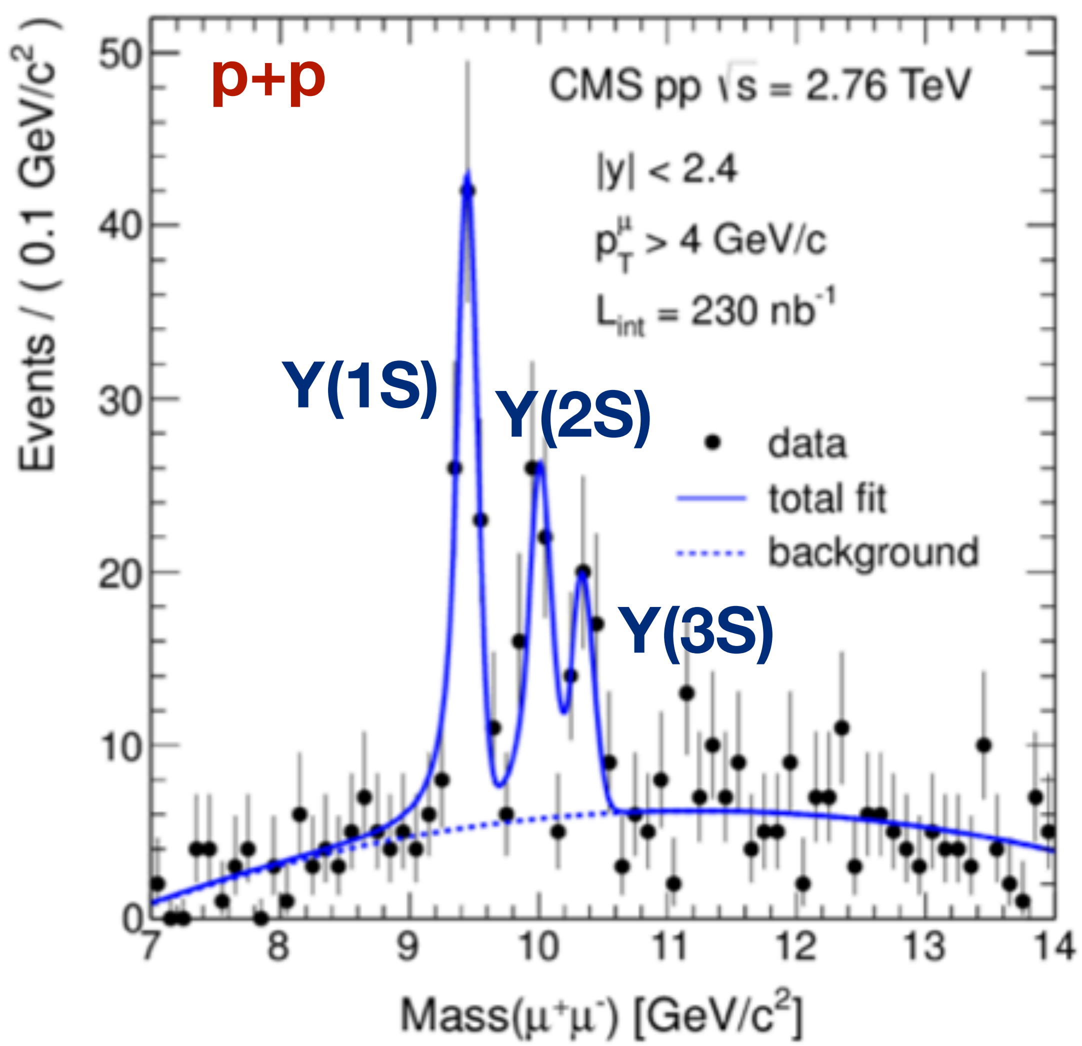
Our challenge:

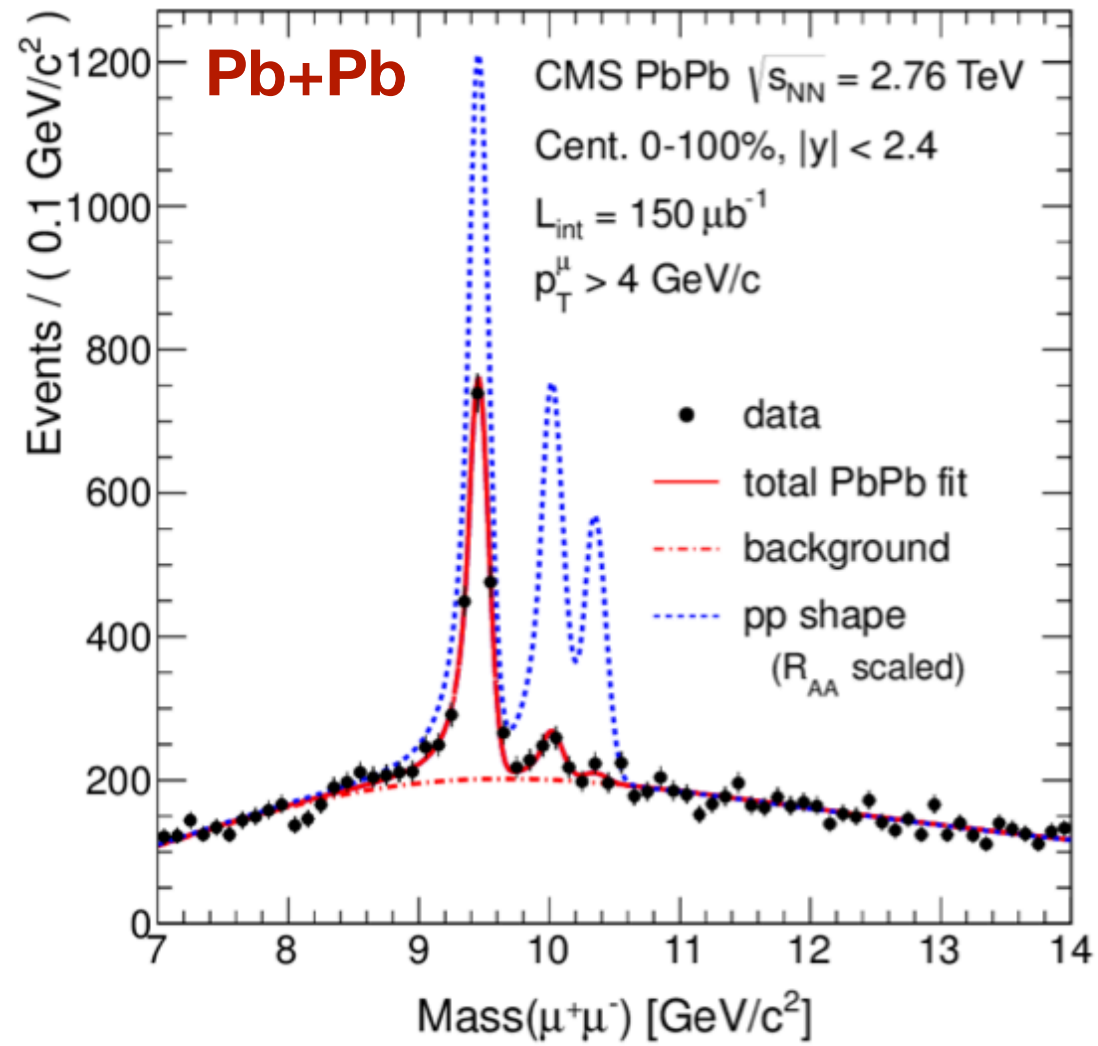
Gather diverse data sets and multiple discriminants to isolate and characterize these effects

Opinion:

puzzle pieces about to come together

Bottomonium

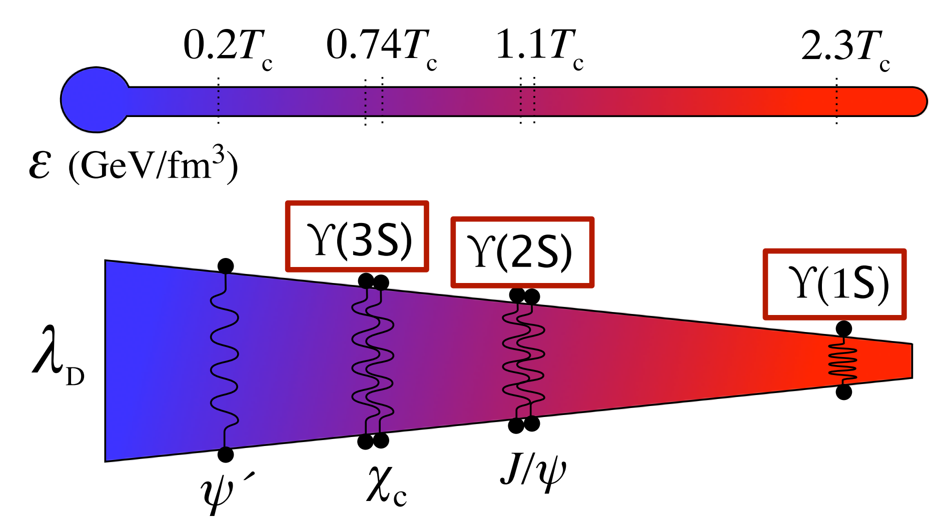




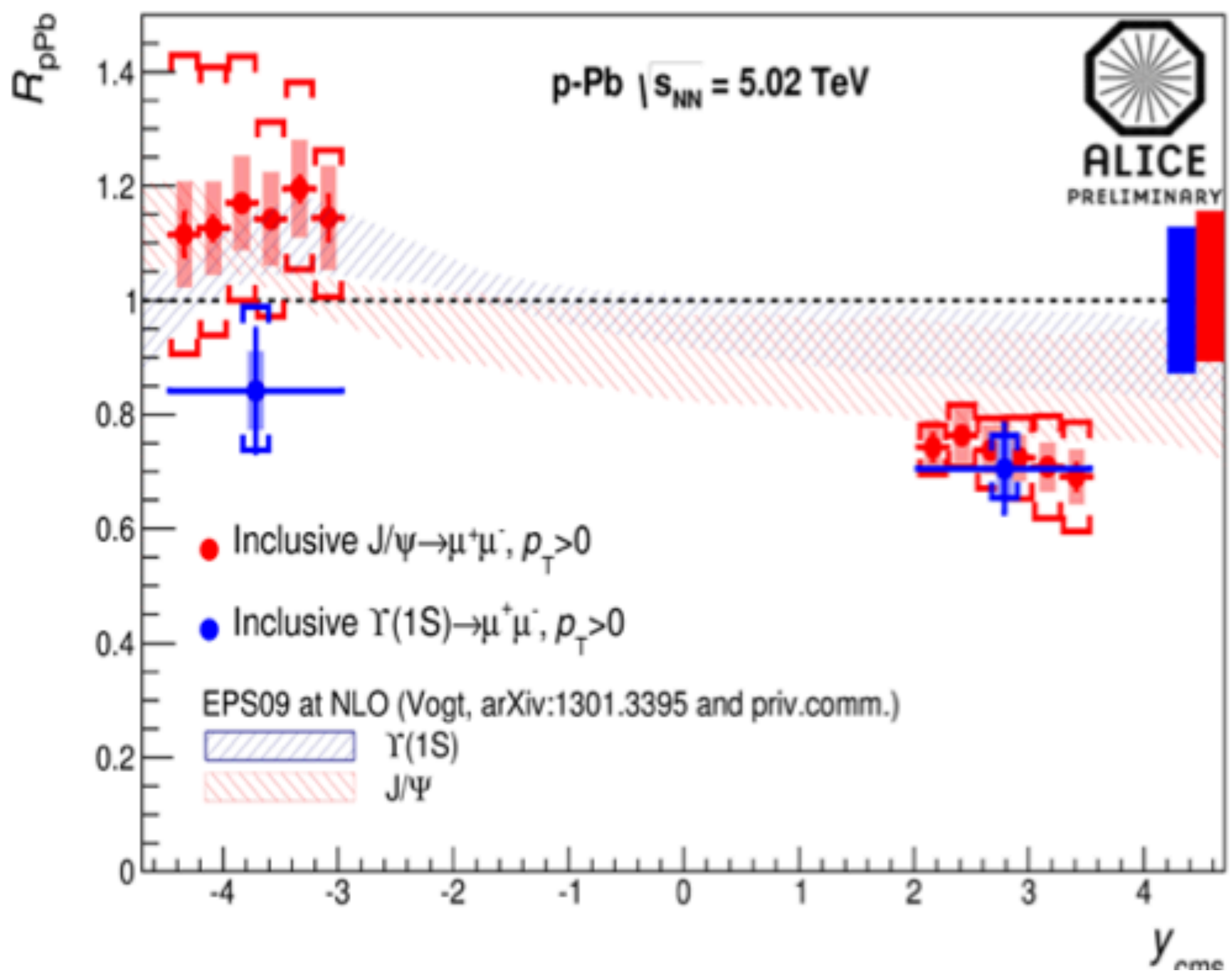
Least sensitive states to feed-down and recombination

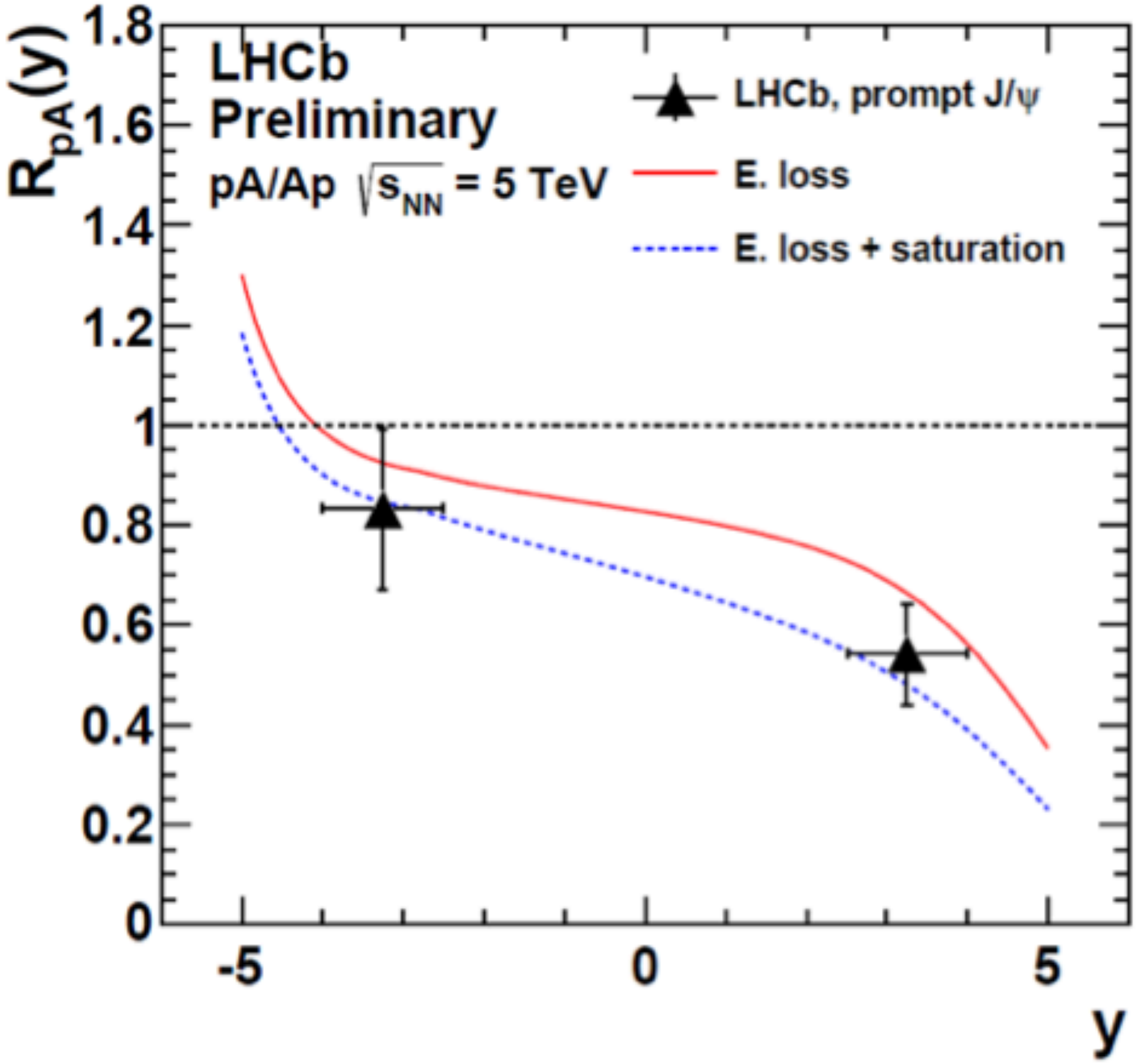
Large suppression even for most robust state, Υ(1S)
Less robust state, Υ(2S), even more suppressed
Υ(3S) disappears completely

Really so simple? but what about CNM effects?



LHC p+Pb Y Reference



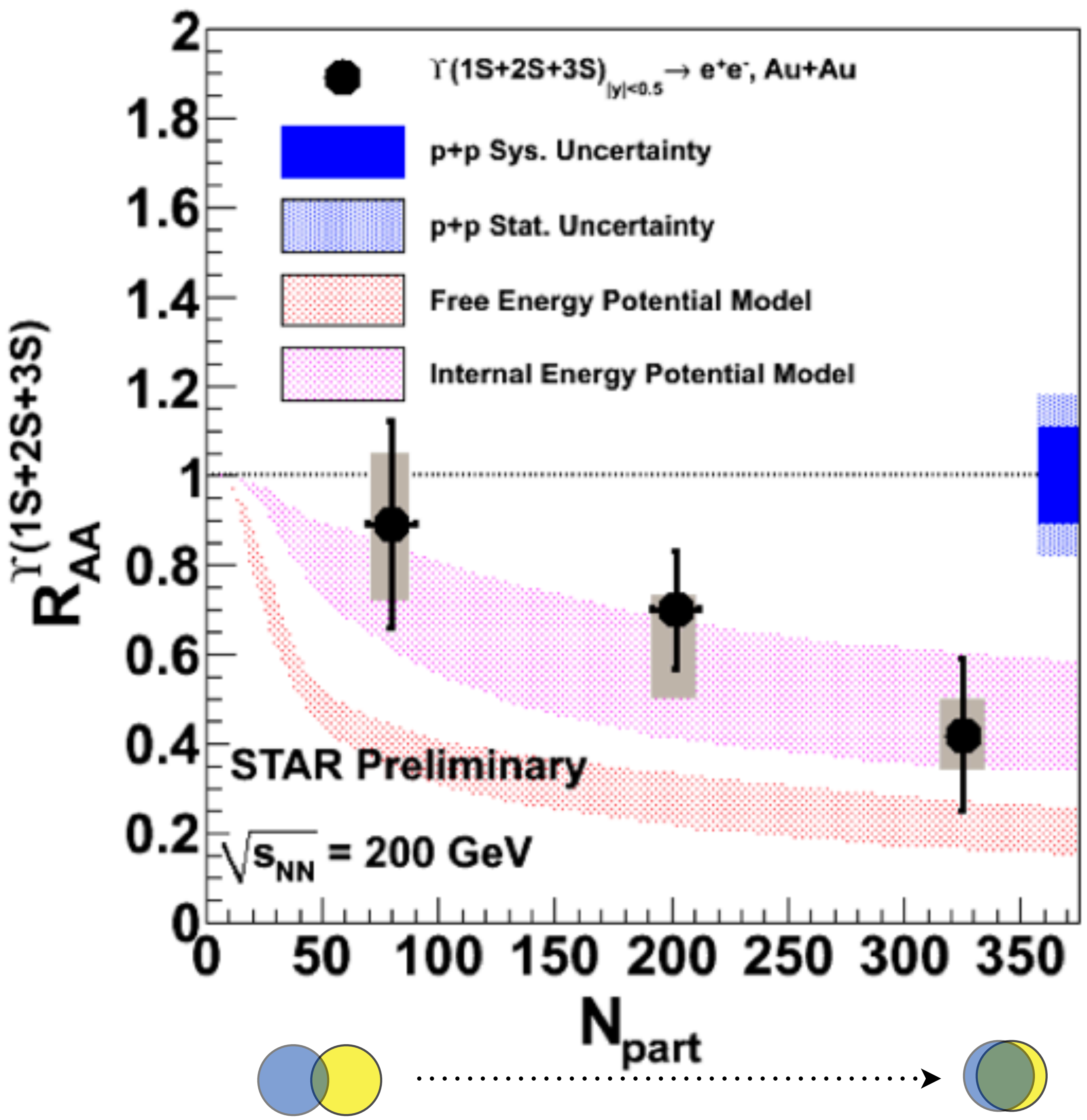


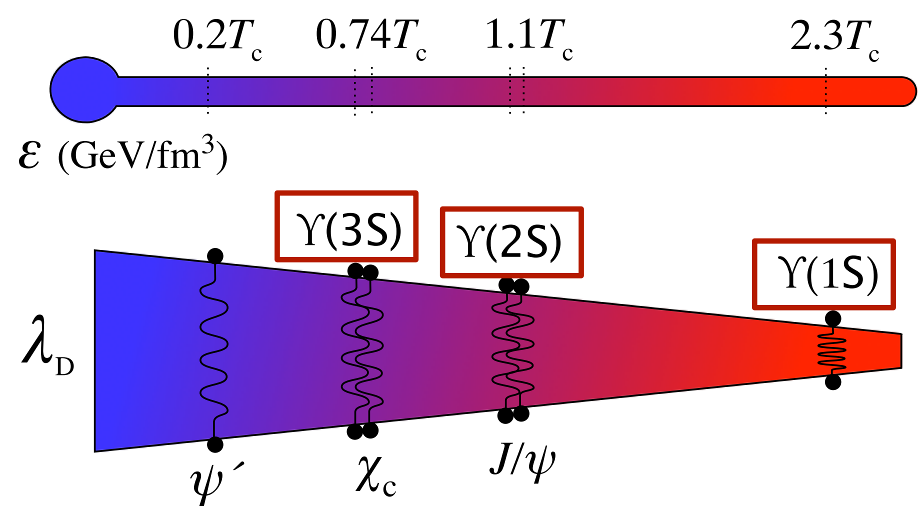
Upsilon production does contain cold nuclear modifications

Implied modifications at mid-rapidity are not negligible, O(20%)

Initial state energy loss is needed, saturation effects may be present

Υ(nS) at RHIC



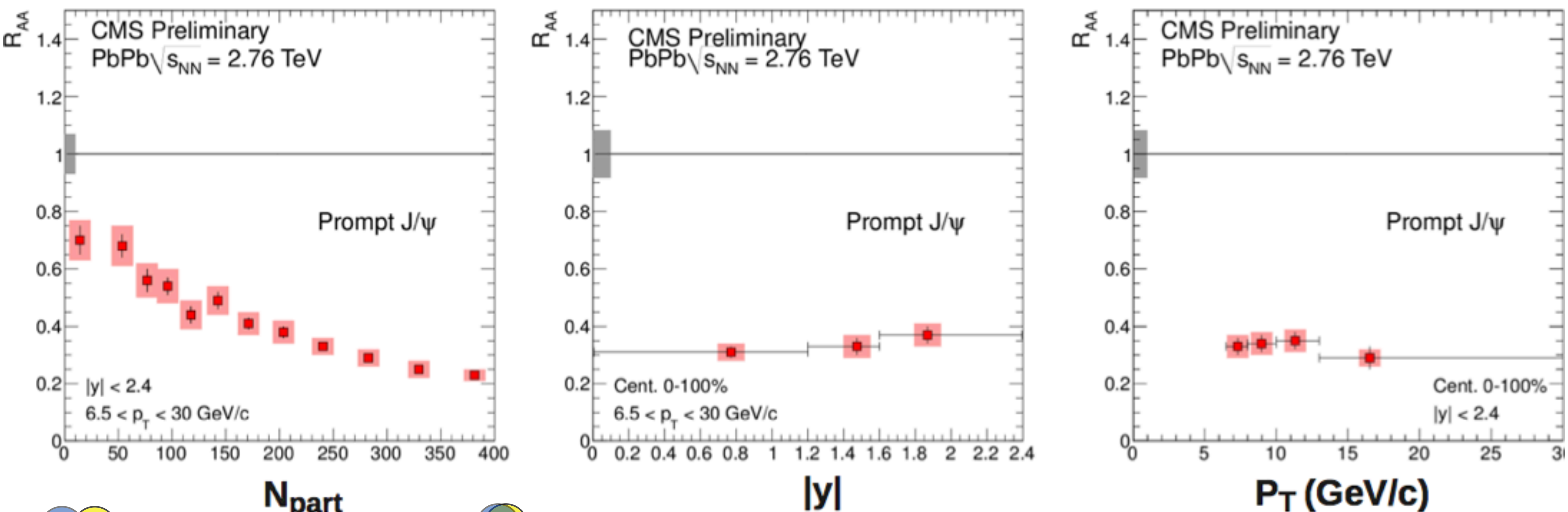


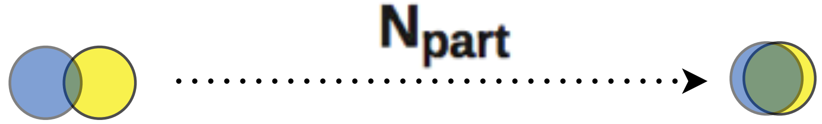
Upsilon family suppressed at RHIC

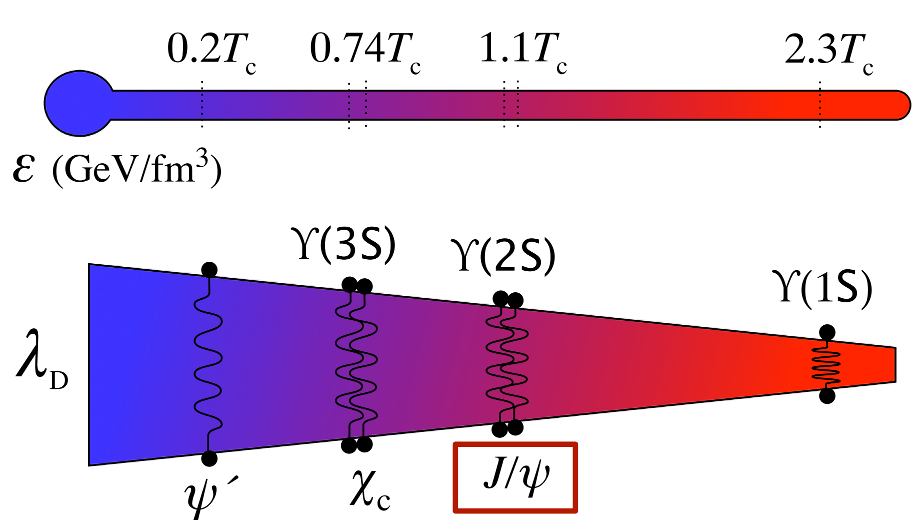
Result is consistent with complete melting of 2S+3S states

Hints that there must be at least some suppression of the 1S at RHIC, but unlikely as much as at the LHC

J/ψ Suppression





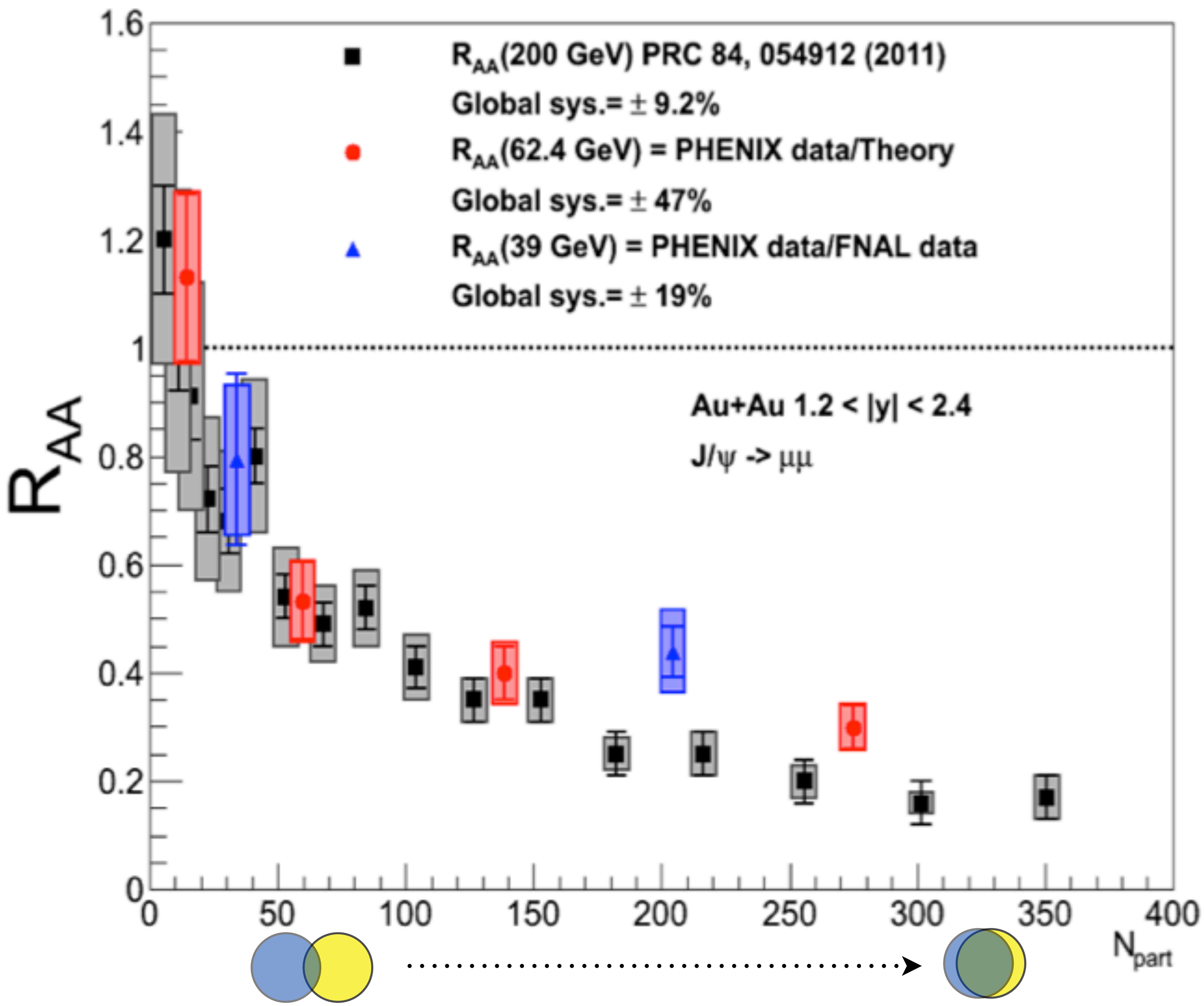


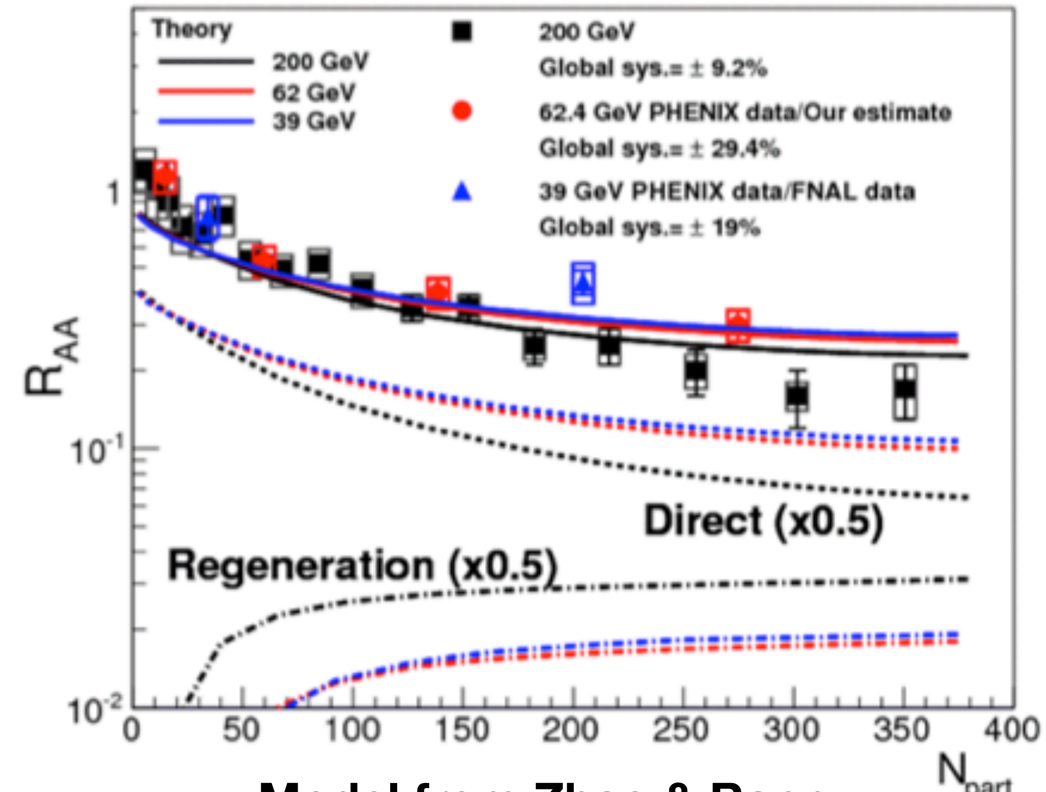
Bountiful charmonium at the LHC but also at RHIC

Also shows a large suppression in central events

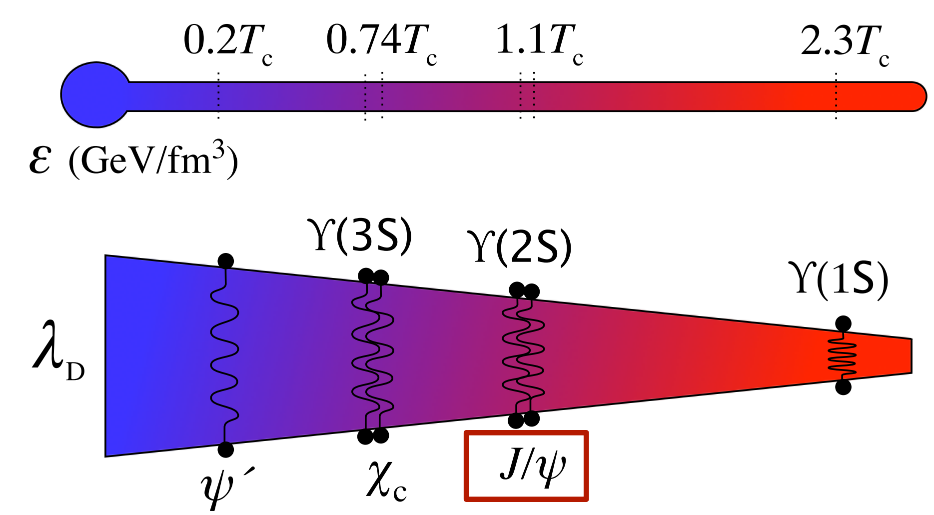
Influenced by more complicating factors, namely recombination

Energy Dependence





Model from Zhao & Rapp

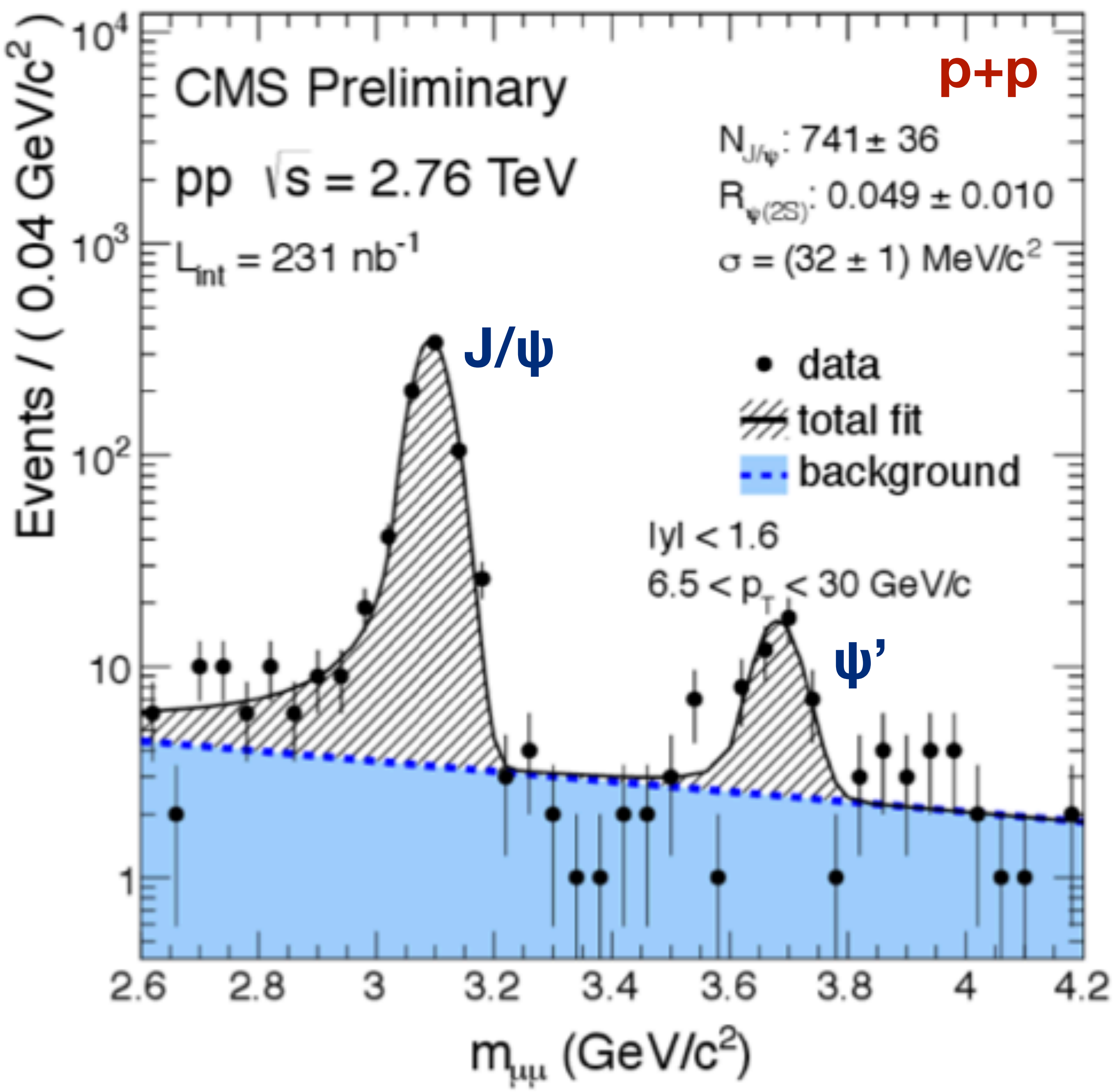


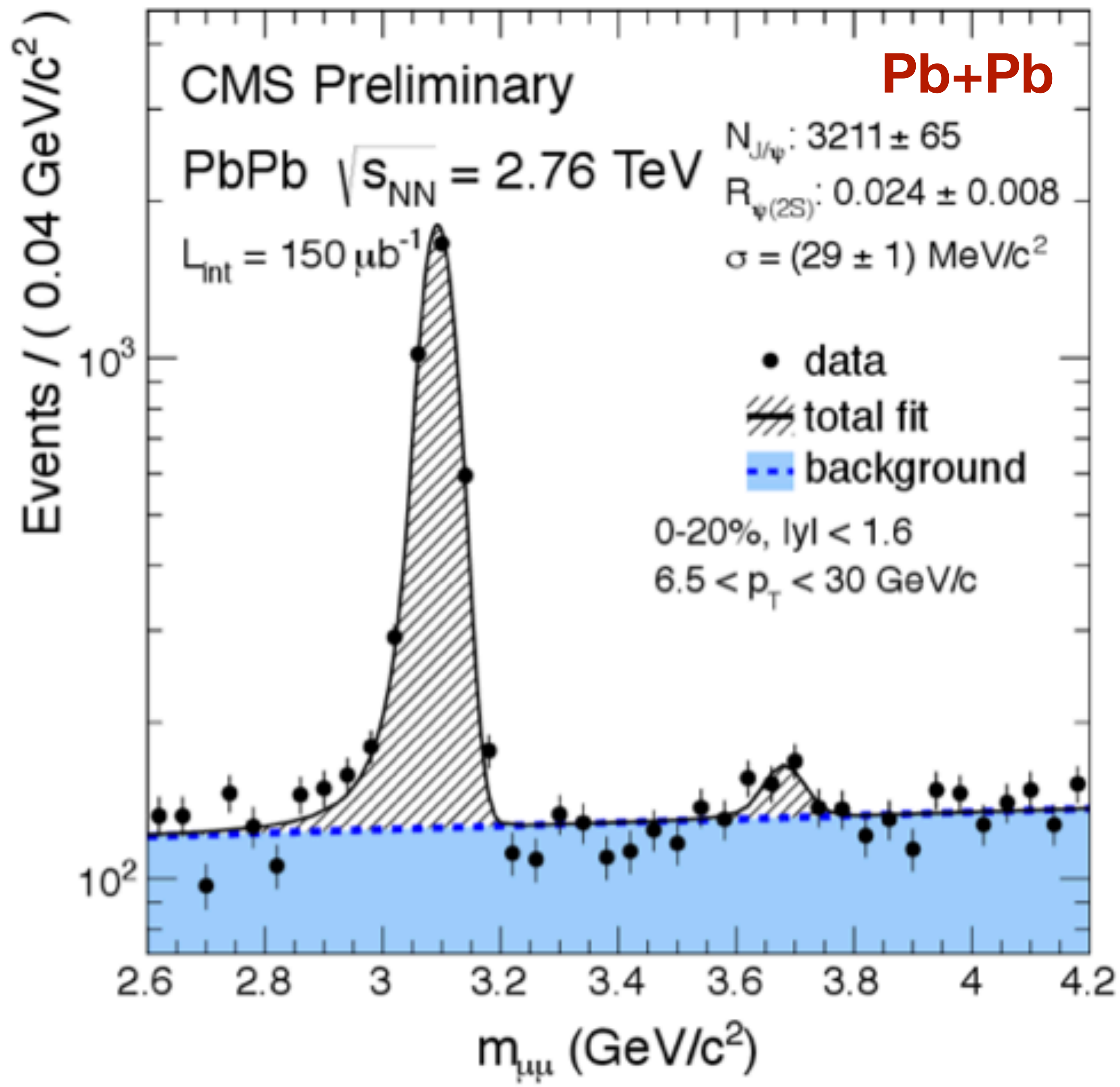
Large suppression in J/psi from 39 GeV - 2.76 TeV

Competition between melting and recombination

CNM matter effects will also vary across this range

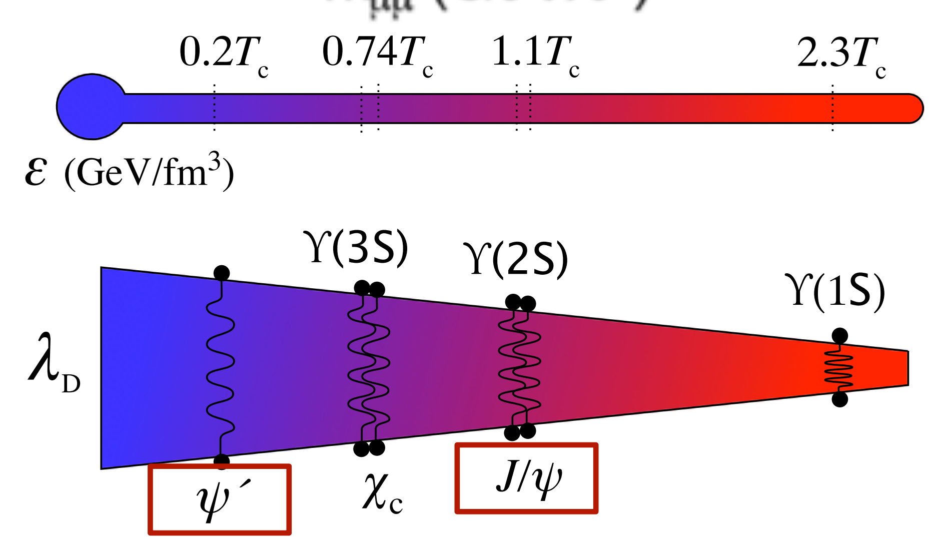
ψ' in Pb+Pb





ψ' suppressed more than the J/ψ

Again in line with expectations of sequential melting



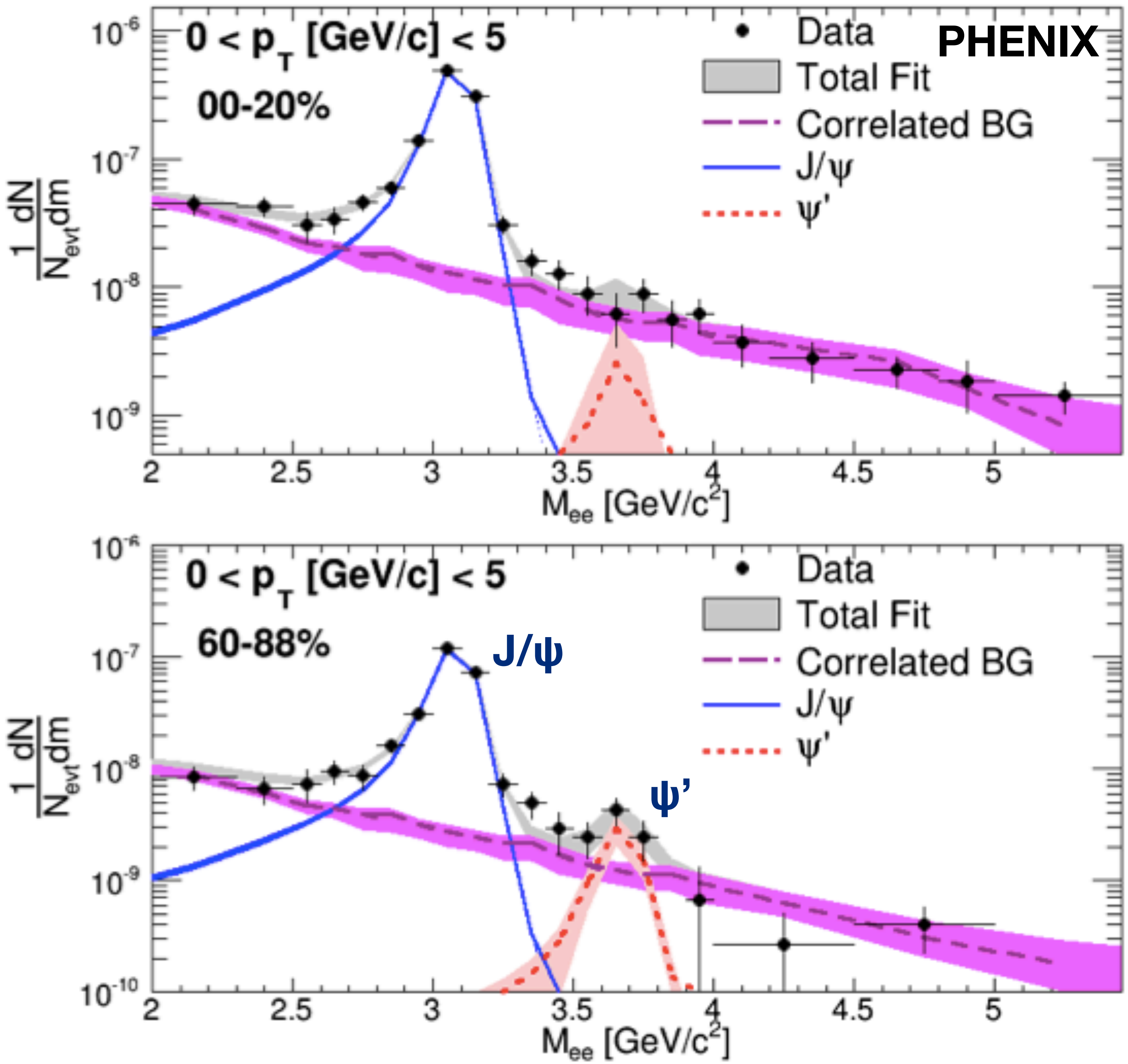
ψ’ in d+Au

CNM Surprise

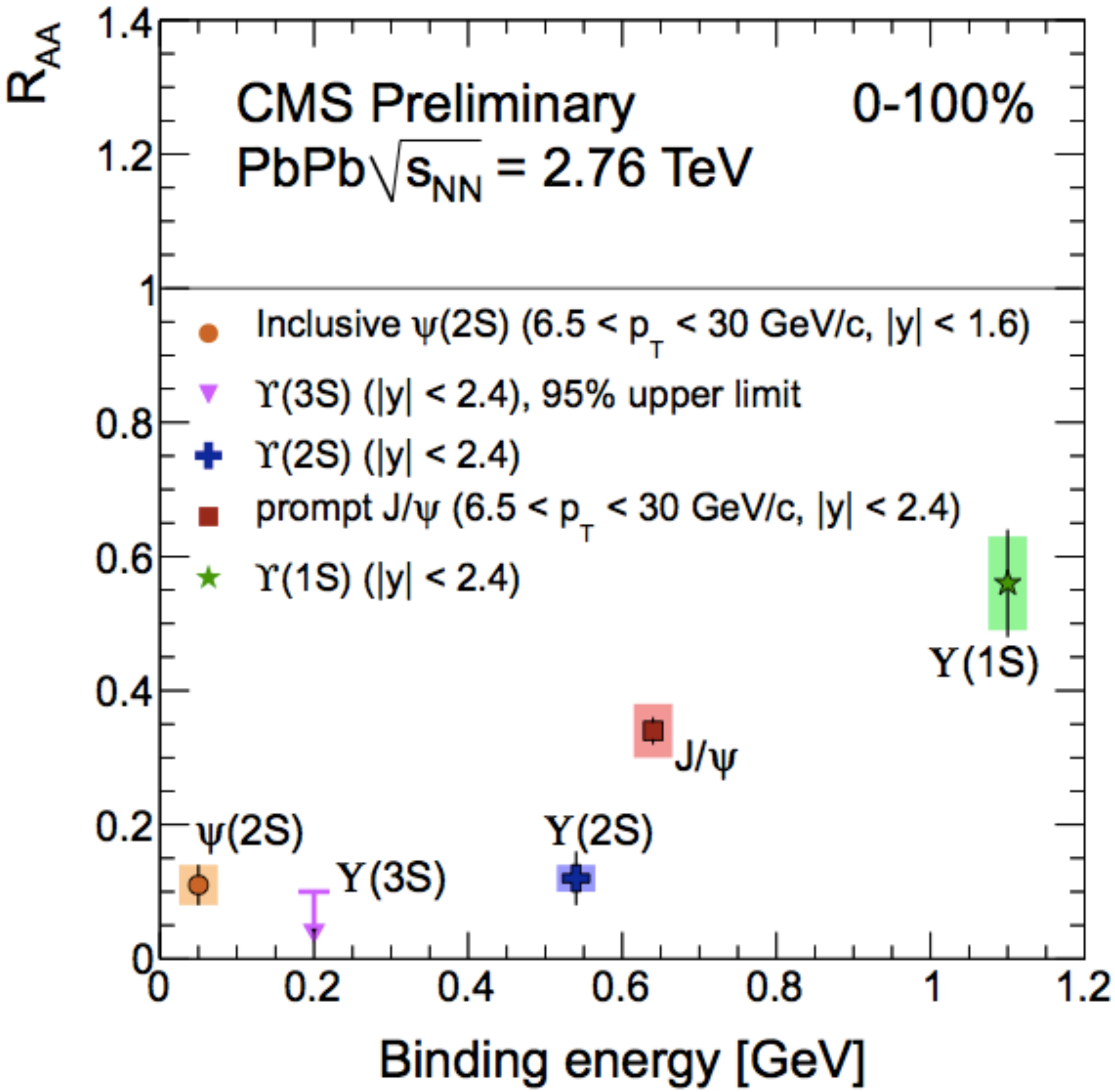
ψ’ completely suppressed in central d+Au at RHIC at mid-rapidity

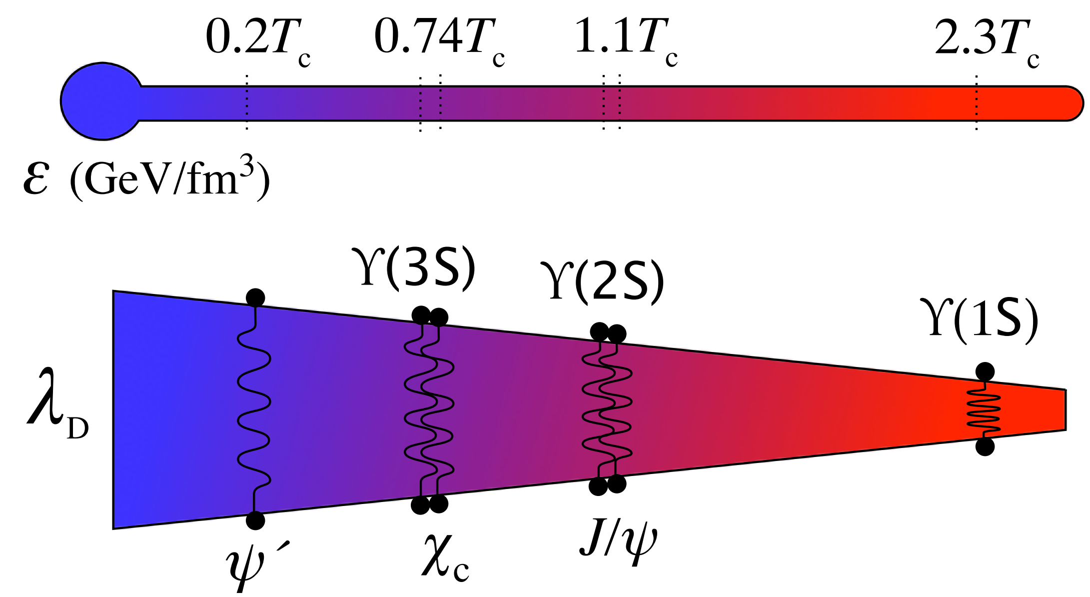
Larger diameter may result in larger breakup cross-section with “back-side” of the nucleus

A+A ψ’ from regeneration almost exclusively



Sequential Melting





Relative suppressions largely understandable via sequential melting

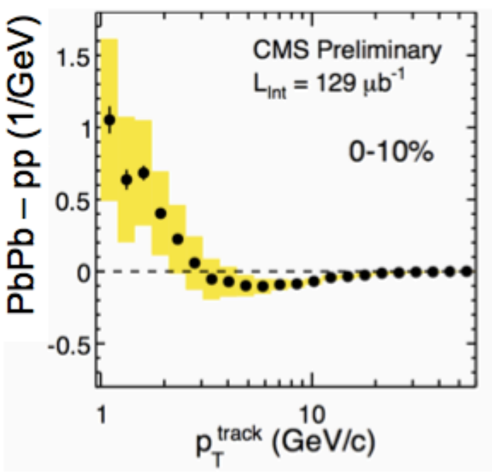
Detailed understanding will only come with model descriptions

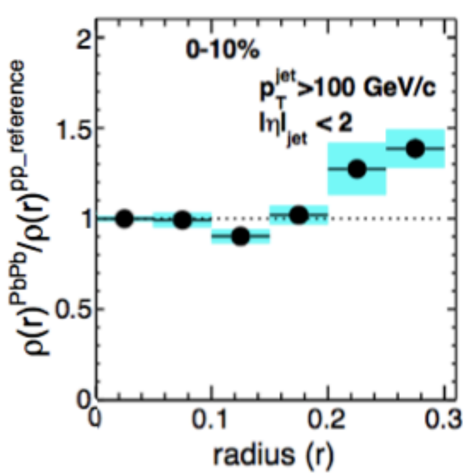
ψ' may be largely populated via recombination

Υ(nS): large melting, small CNM
J/ψ': large melting and some CNM
ψ': large melting, large CNM, large recombination

Take-Home Summary

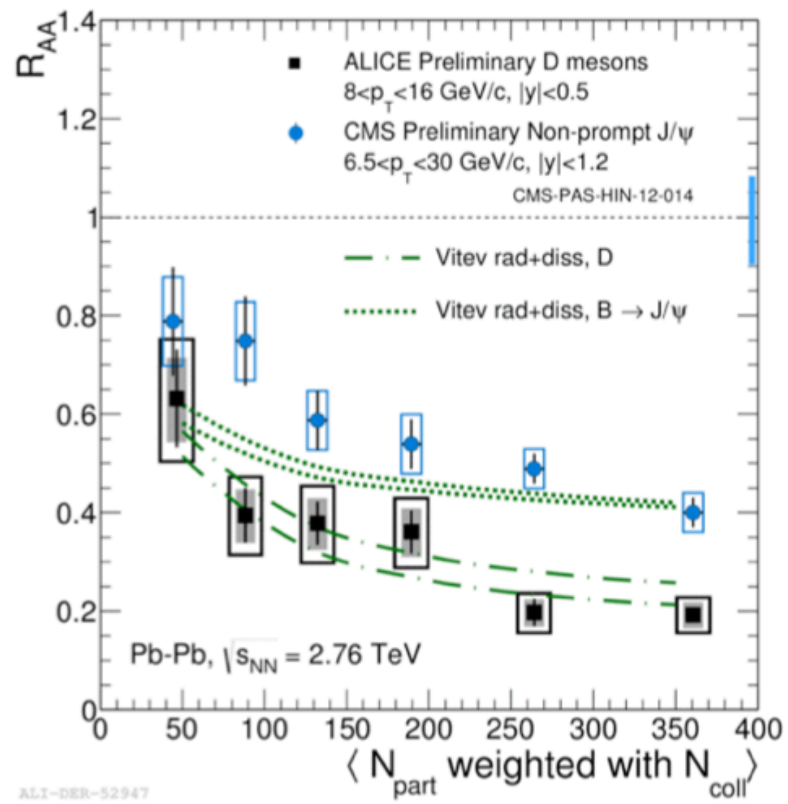
Jets





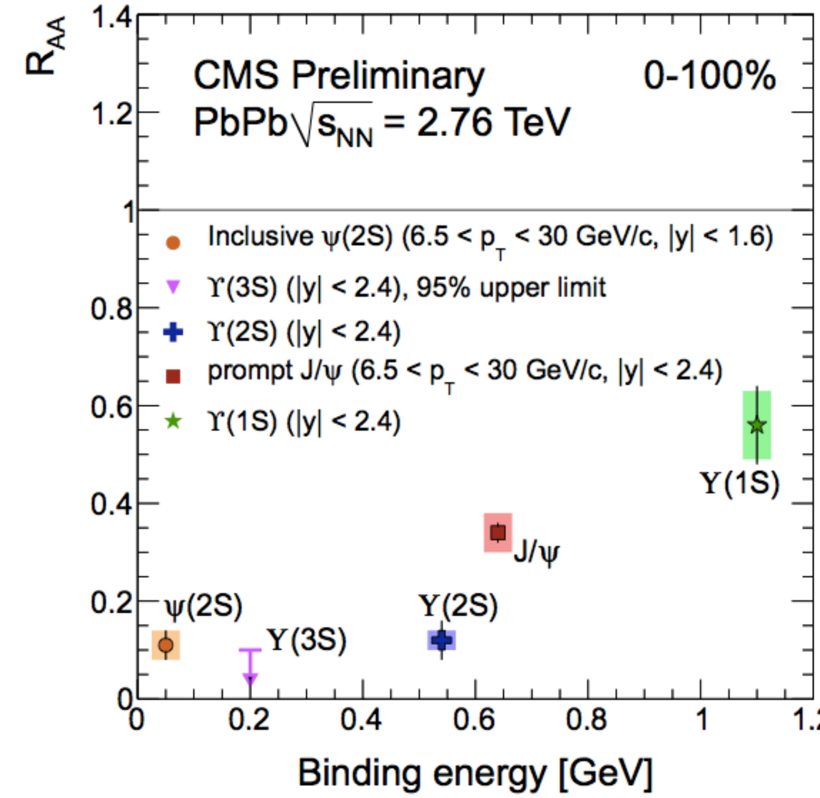
Large energy lost but recovered at large angles and small momentum

Heavy Flavor



Evidence charm is suppressed more than bottom

Quarkonia



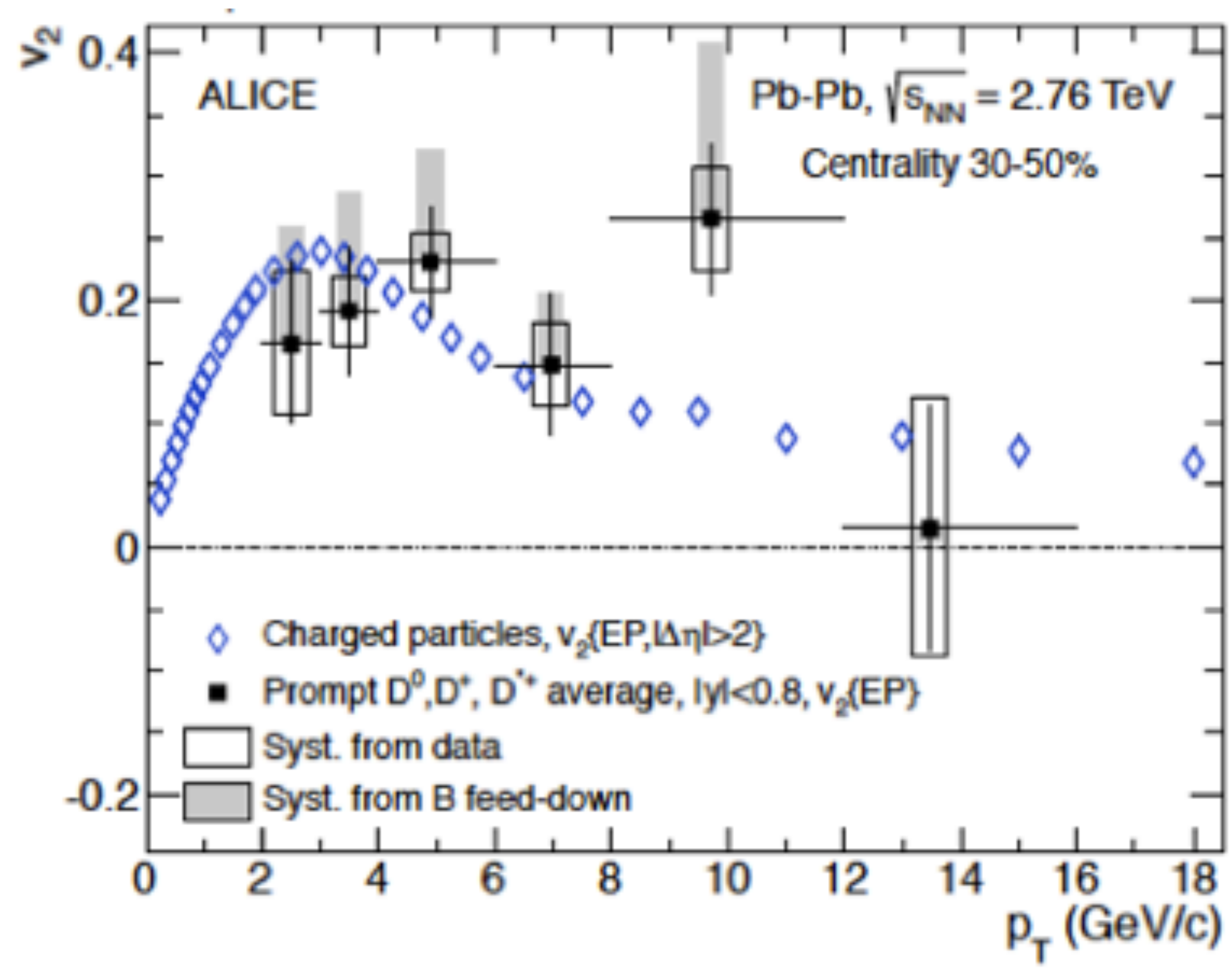
Influence of binding energy measured

Thank you!!! 谢谢!!!

Extras

Aside: Charm and Bottom Flow

Large anisotropy at low pT driven by soft physics:
hydrodynamic expansion

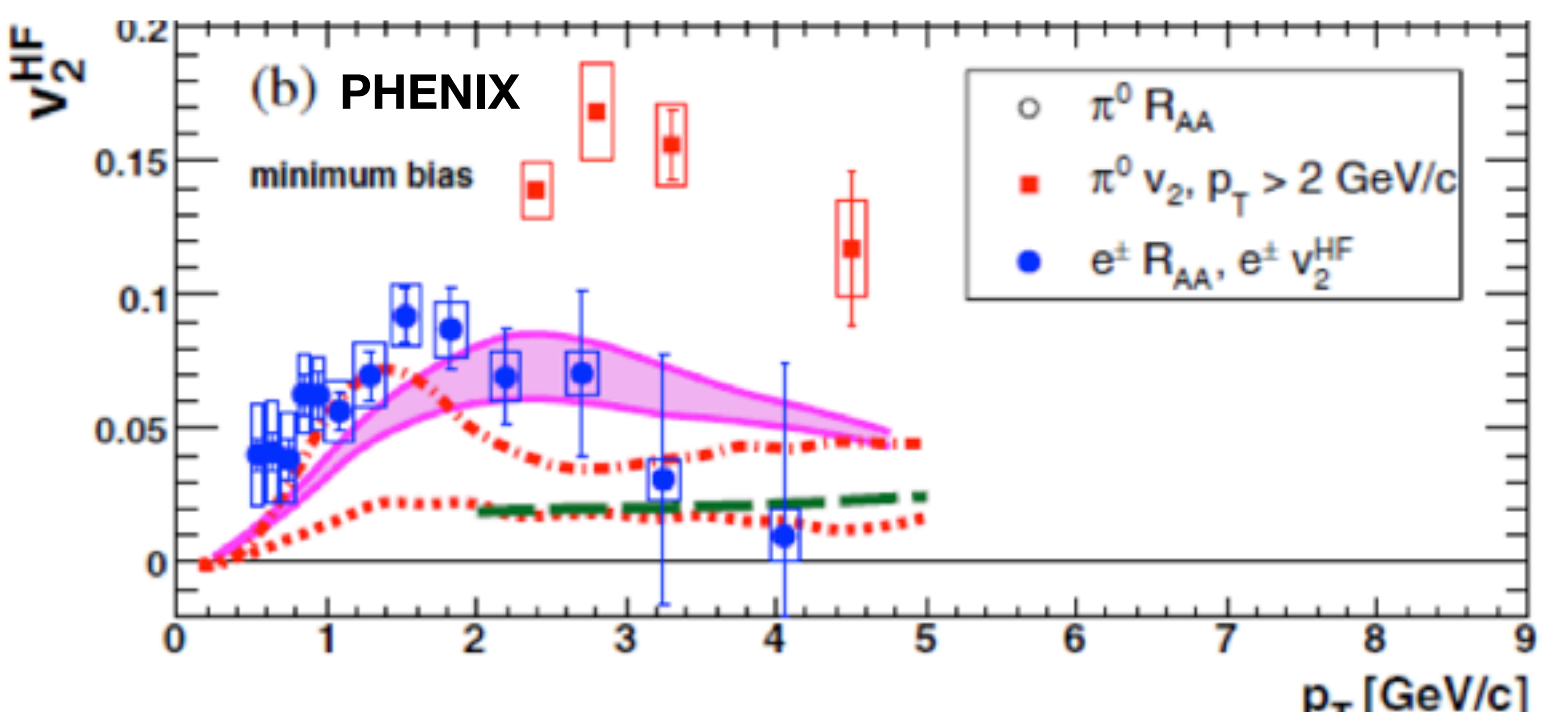


Charm is substantially thermalized and flows like light quarks

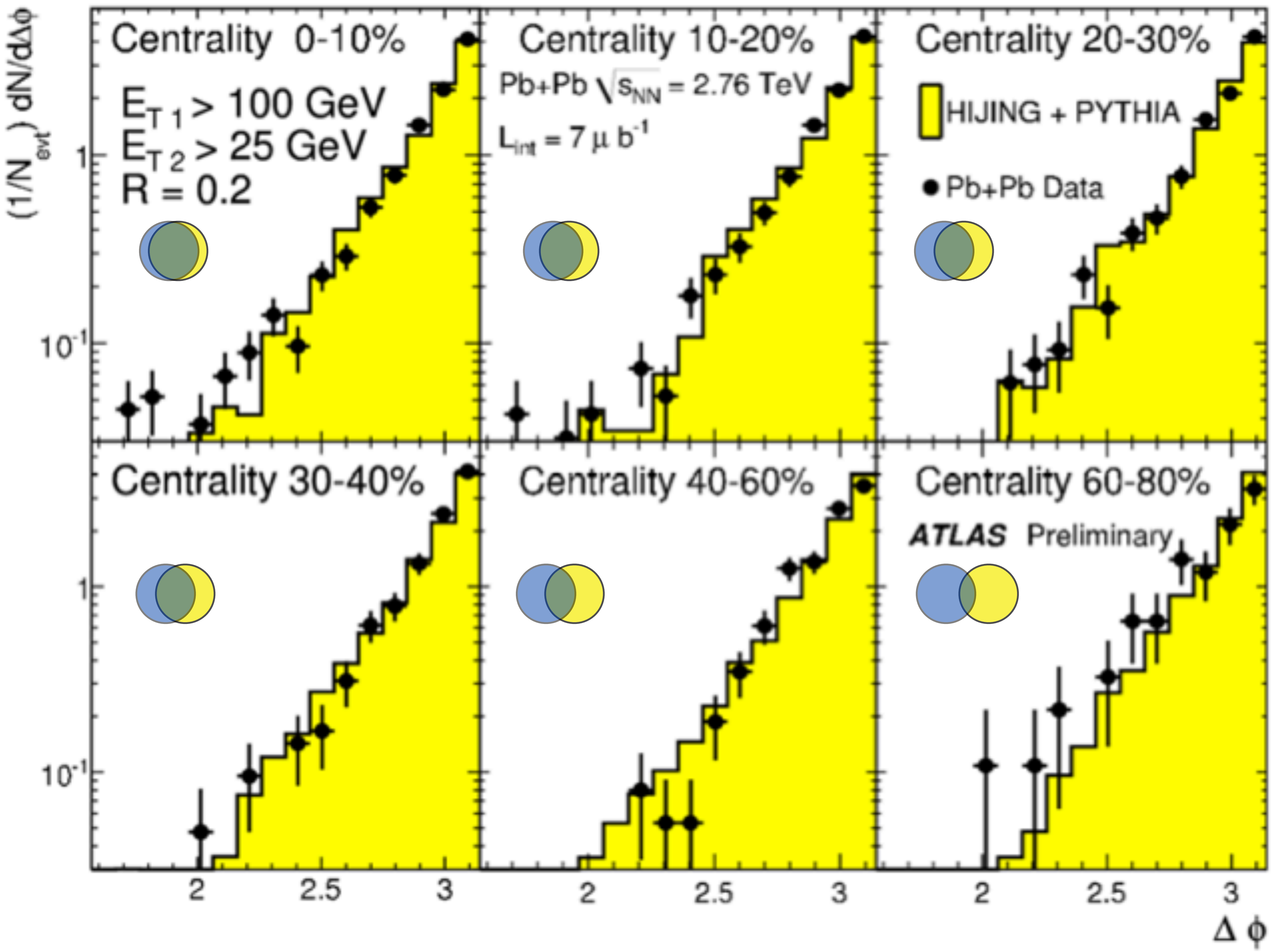
Langevin:

$$\frac{d\vec{p}}{dt} = -\eta_D(p)\,\vec{p} + \vec{\xi}$$

Diffusion rate related to the viscosity of the fluid



Di-jet Angular Correlations

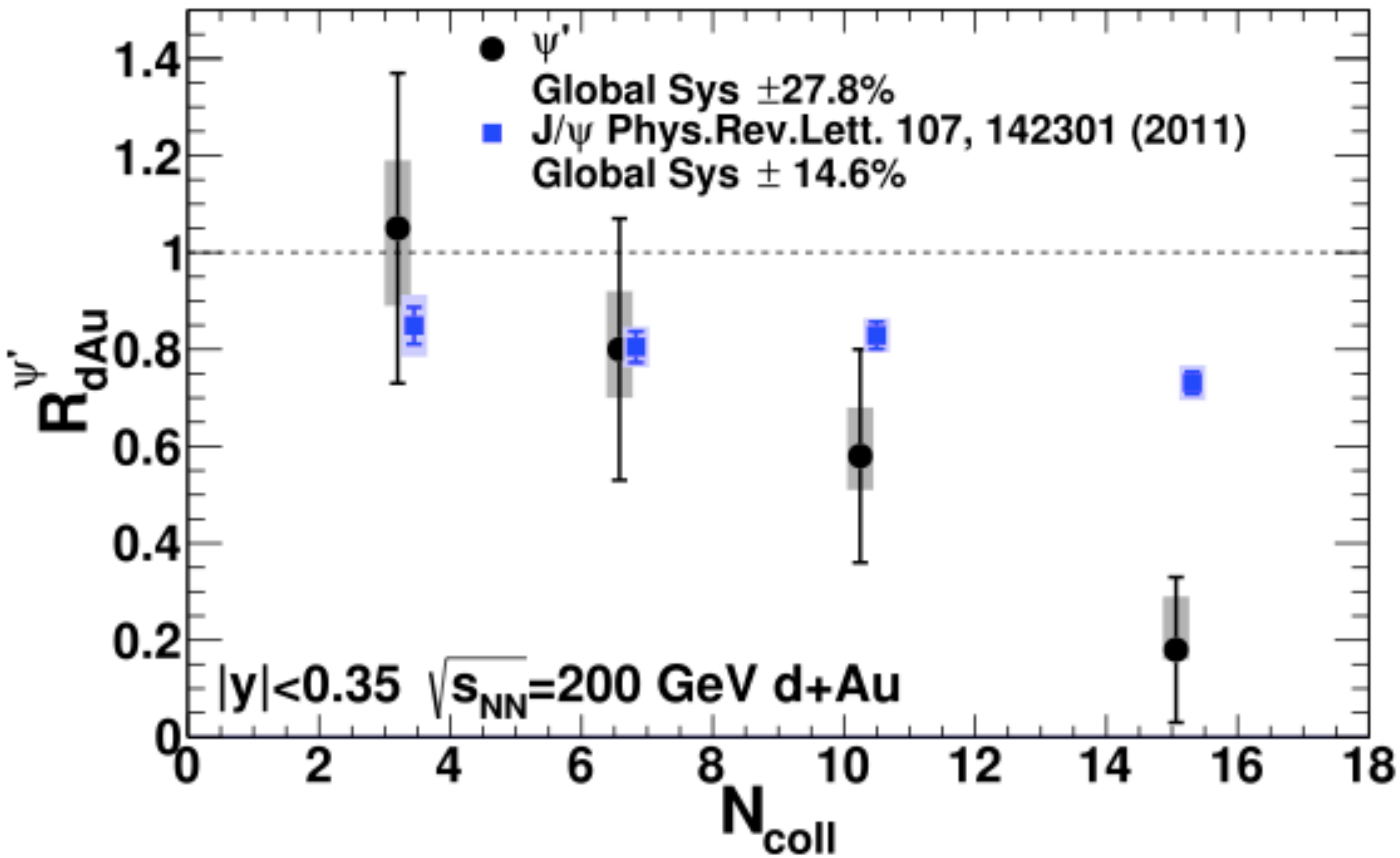


Are the modified jets still typically back-to-back?

No change in recoil direction at large momentum

Energy loss is the result of a many small scatterings with the medium

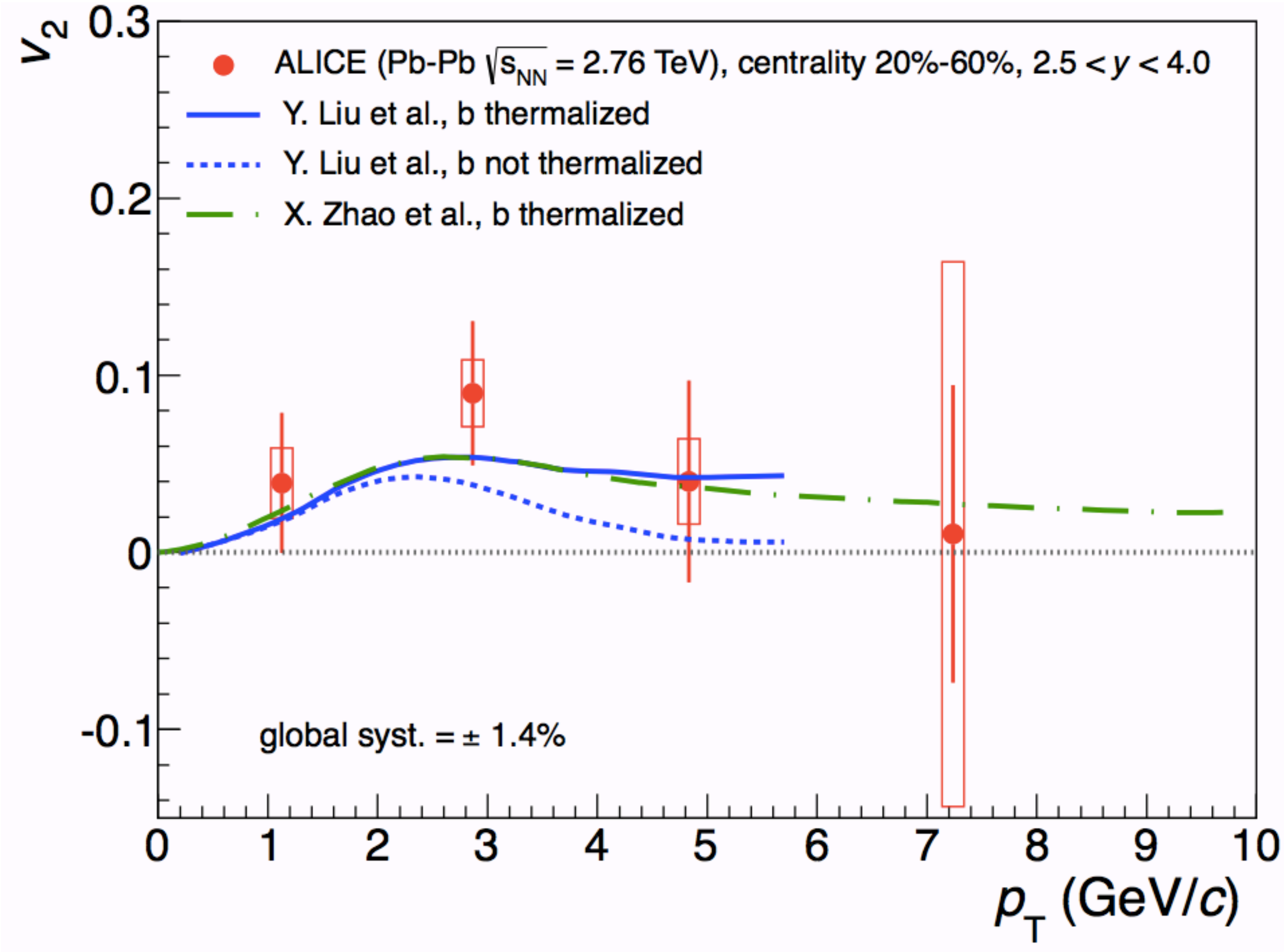
Centrality Dependence



Similar rates of shadowing and Cronin

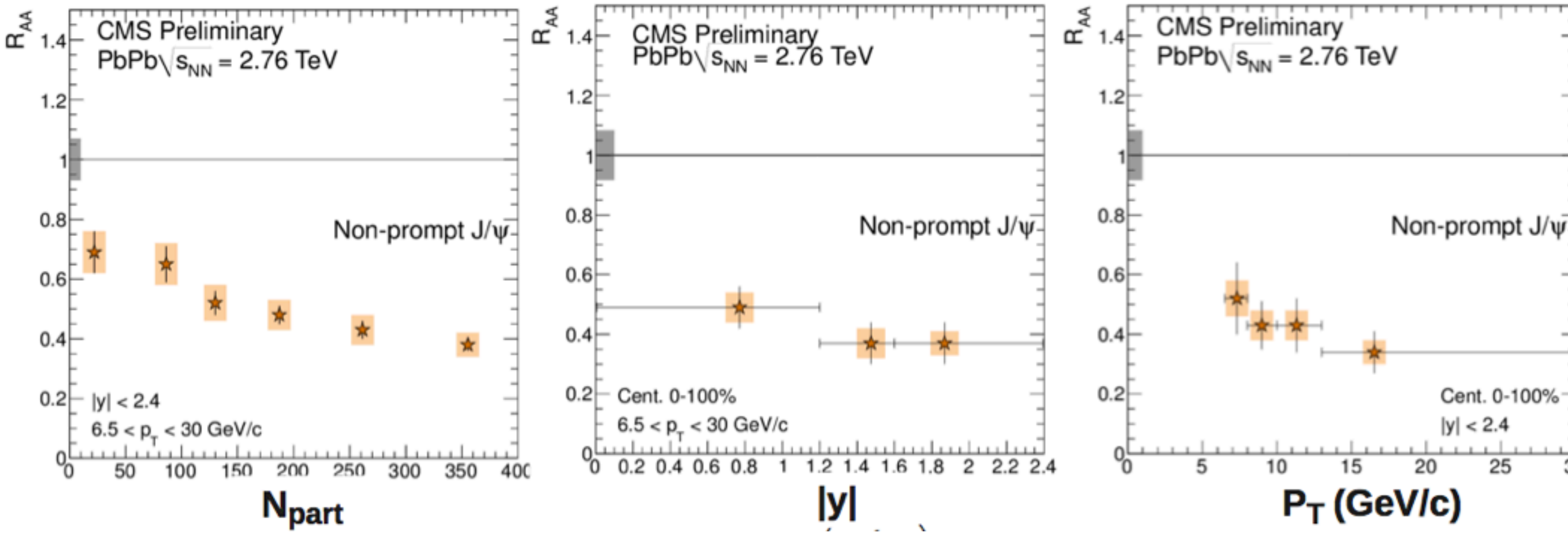
ψ' actually measured in central A+A events will provide a good way to isolate and understand recombination rates

Quarkonia Flow

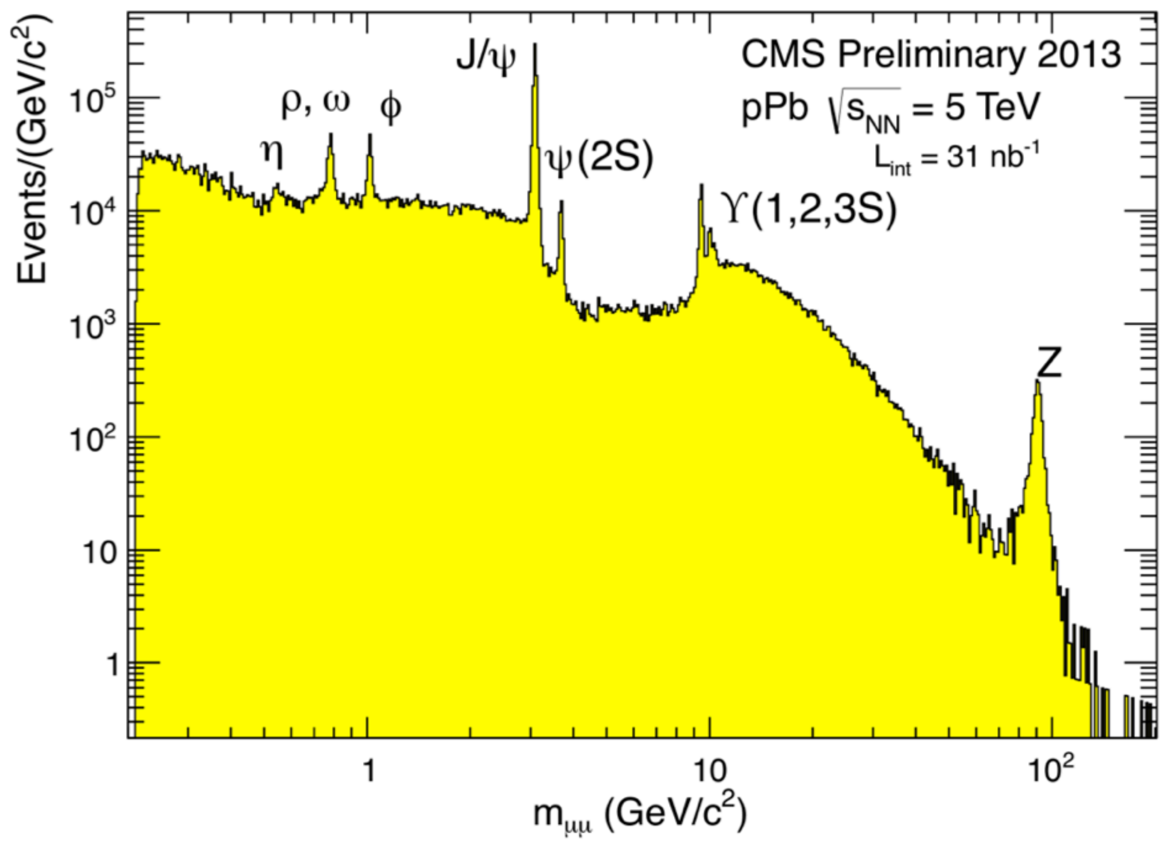


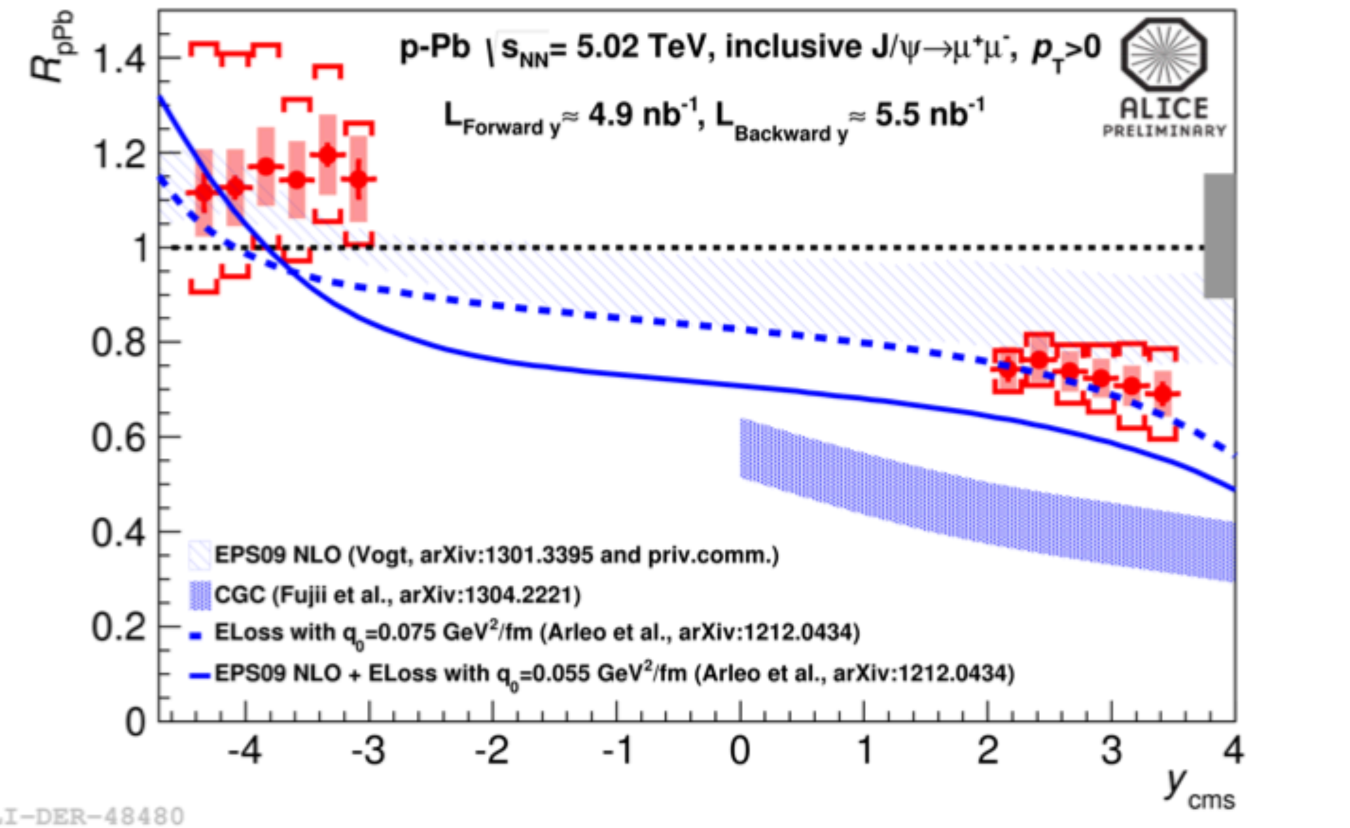
Charm recombination important for J/psi production

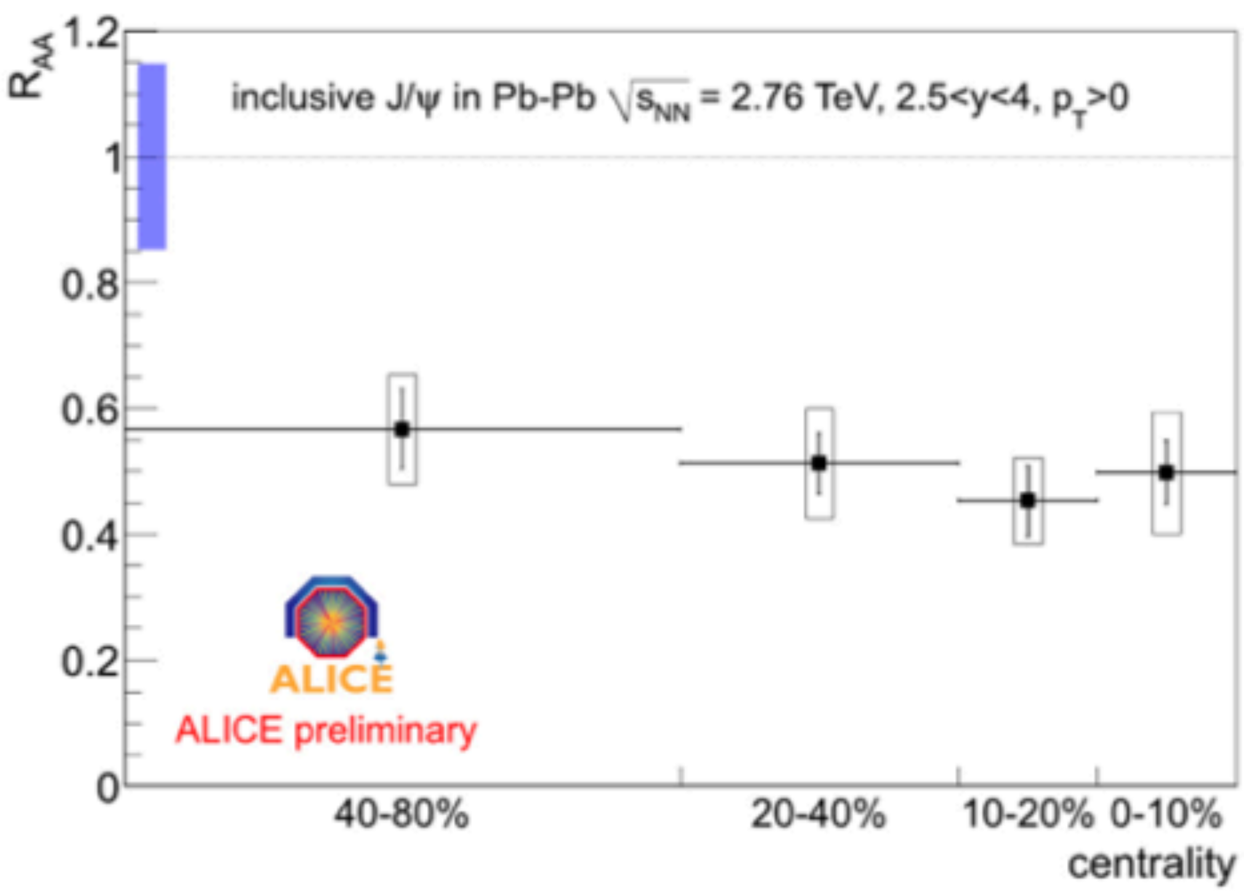
Charm and Bottom Results II

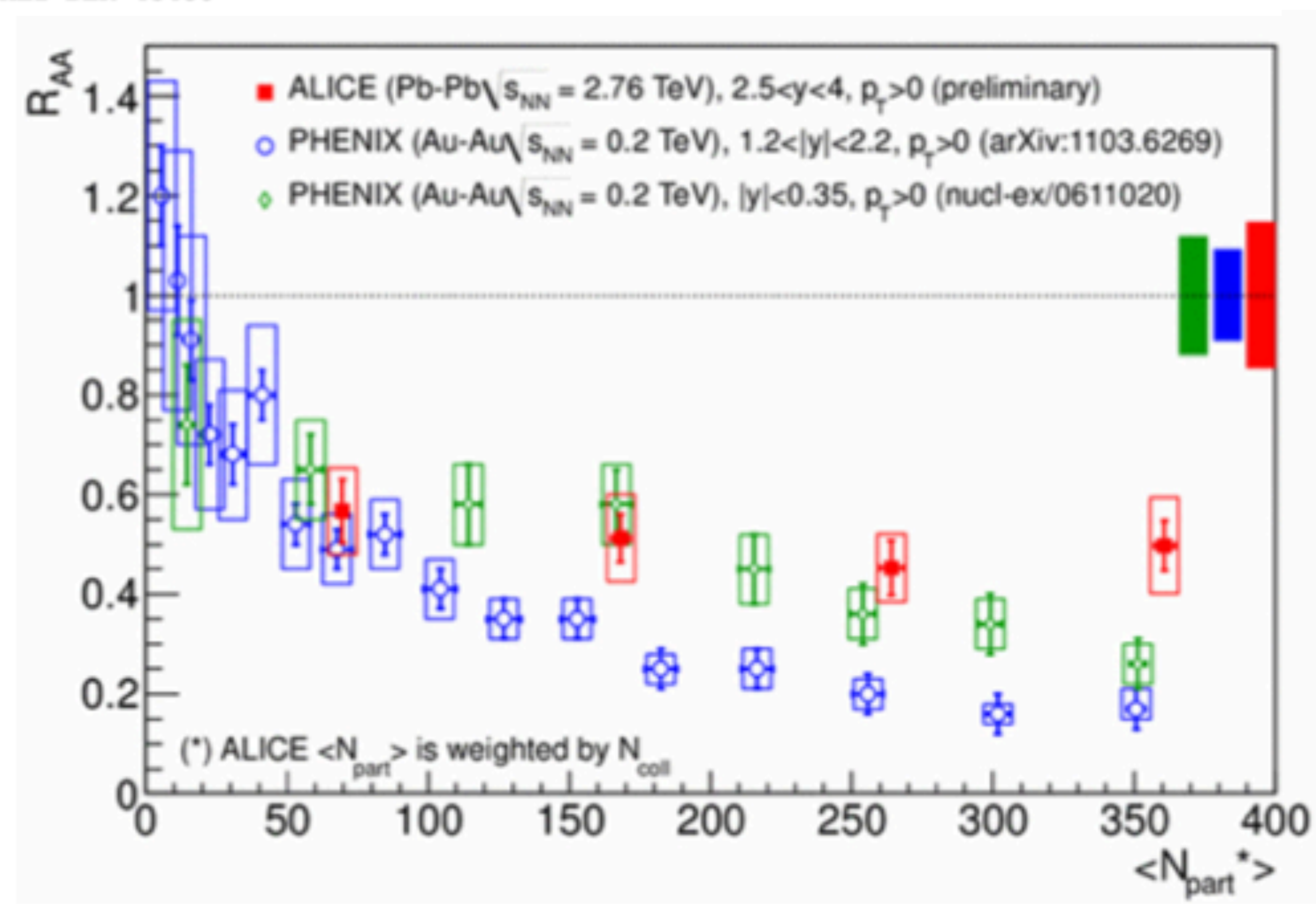


Quarkonia Results I

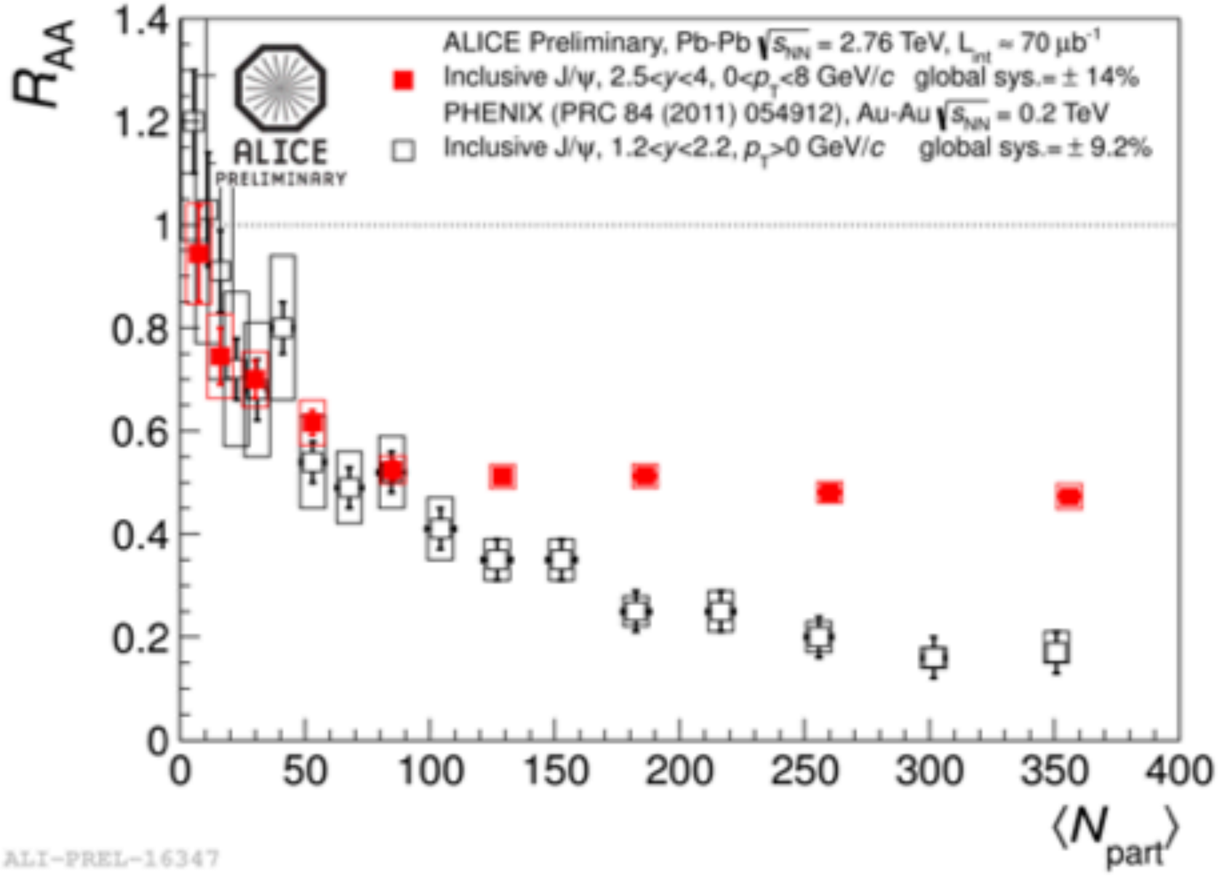


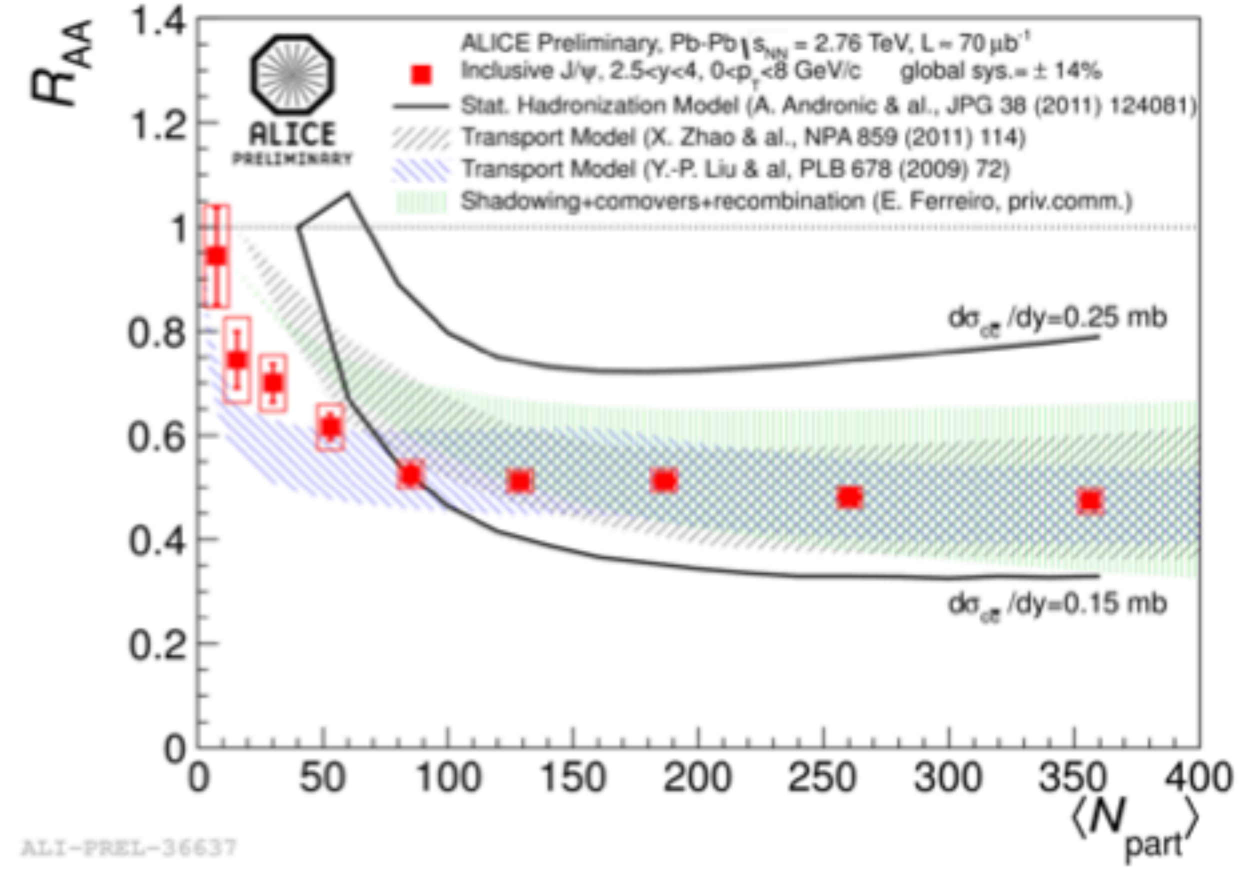






Quarkonia II





Heavy Ion Collisions