Heavy-ion physics, part 2

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March 11th, 2025

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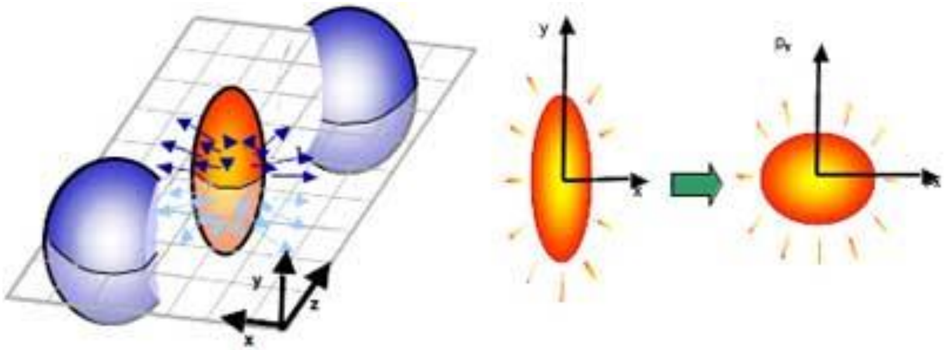
Part 2

Probes of the quark-gluon plasma

- Collective flow
- Jet quenching
- Quarkonia melting

Elliptic flow

In non-central collisions the overlap zone takes an almond shape



Given rapid thermalization, larger pressure along short axis than long one
This *spatial asymmetry* gives rise to a *momentum space anisotropy*

Analyzed by a Fourier decomposition of the particle distribution vs. azimuth

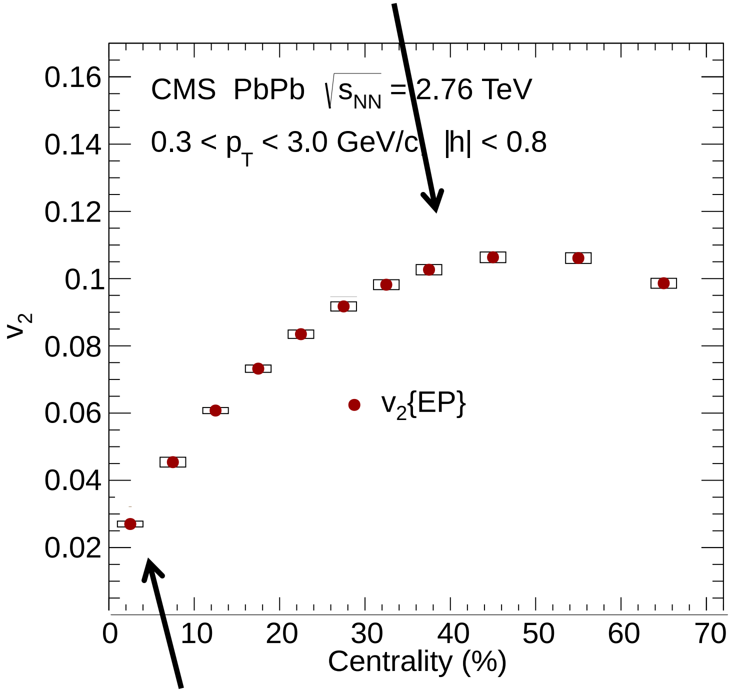
$$E\frac{d^3\sigma}{d\mathbf{p}^3} = \frac{1}{2\pi}\frac{d^2\sigma}{p_{\mathrm{T}}dp_{\mathrm{T}}dy}\left(1 + 2\sum_n v_n \cos[n(\phi - \psi_R)]\right)$$

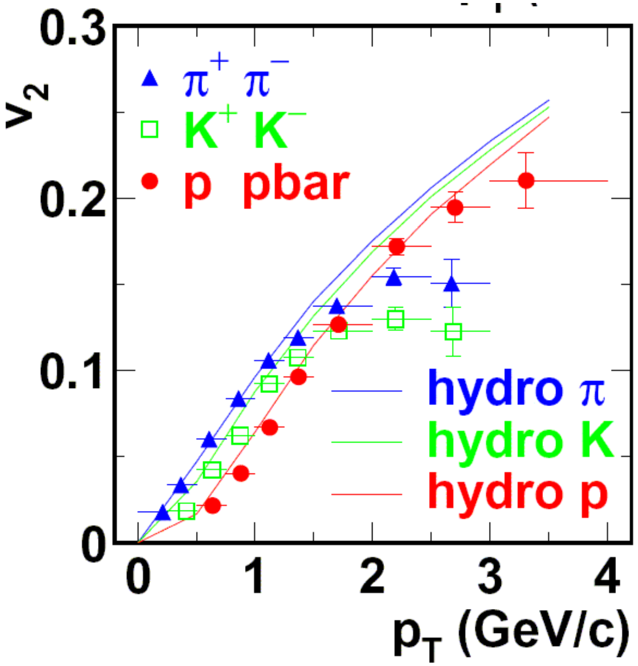
Given the overlap shape, 2nd harmonic v_2 dominates: “elliptic flow”
Naively odd terms not expected to contribute due to symmetry

Elliptic flow vs. centrality

v_2 data conforms to basic expectations: reaches peak in semi-central collisions

Lighter particles more easily swept up in flow



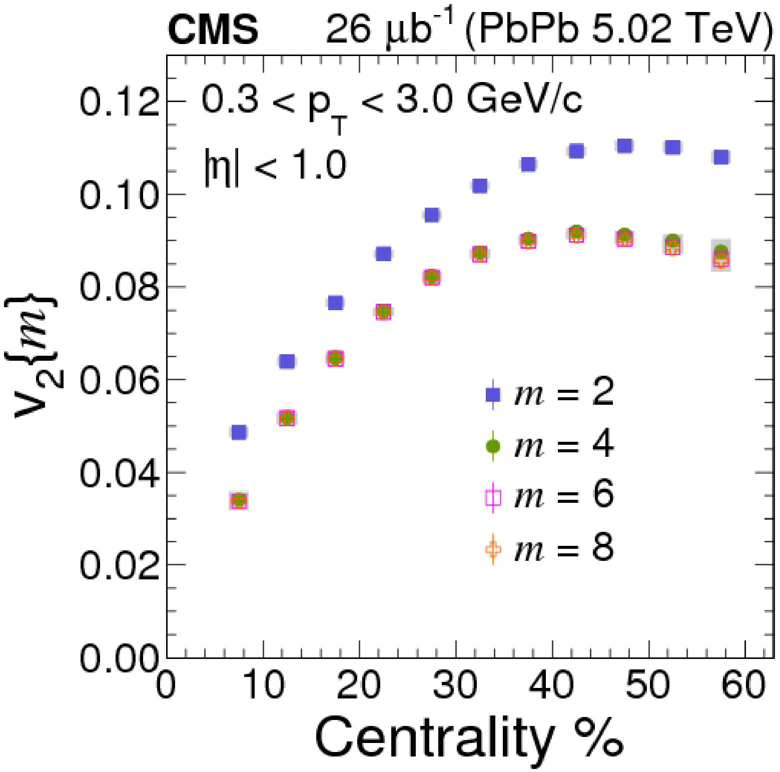


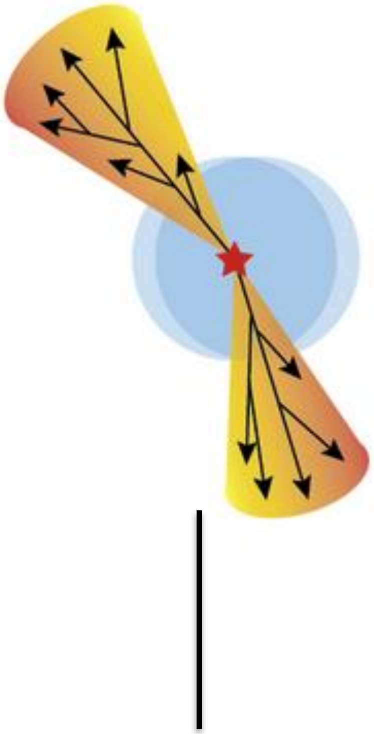
Small in central events due to symmetric overlap

Flow effects dominant until about 2 GeV

Naively, expect elliptic flow to turn off in peripheral events where system should be too small to thermalize

Multiparticle correlations



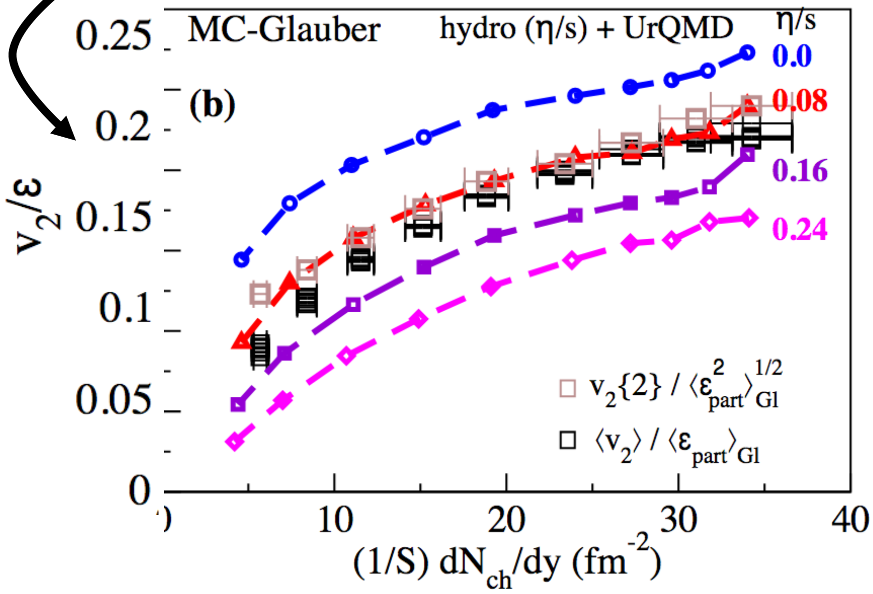


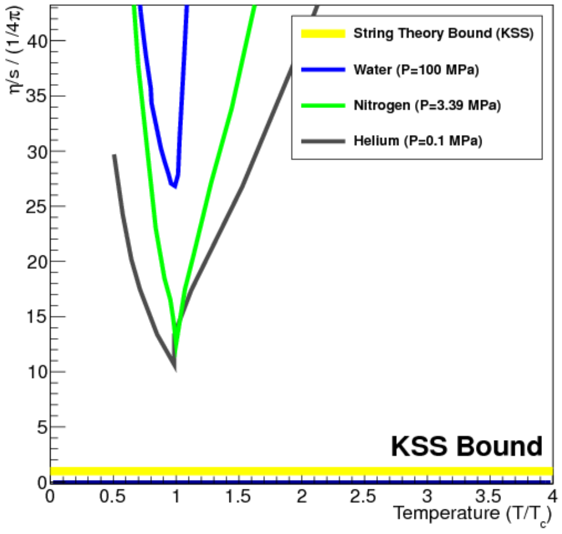
For particle pairs, strong contribution from “non-flow”, e.g, jets

Minimized by studying multiparticle correlations via “cumulants”

Hydrodynamics

- Collective flow is modeled by relativistic hydrodynamics
- Viscous terms are corrections to ideal hydrodynamics
- Dissipation from shear viscosity would damp elliptic flow
- Sophisticated models couple hydro w/ hadronic rescattering phase

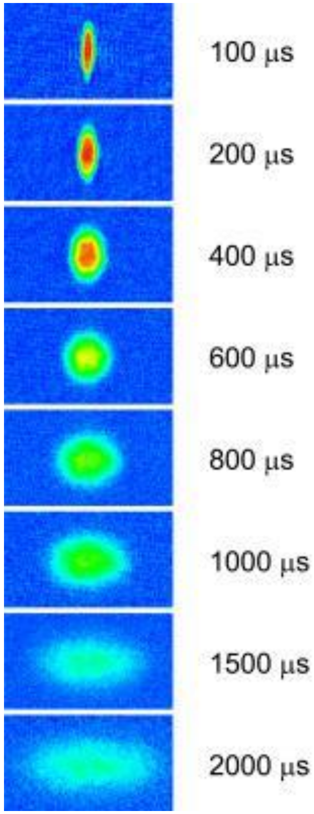




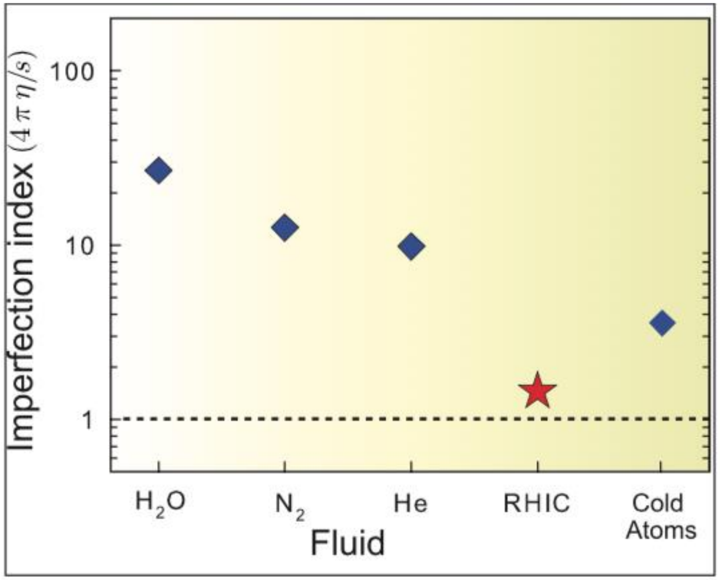
- The ratio η/s is known to have a minimum near phase transition
- Data indicates that viscous corrections are very small → η/s ~ 0.08

Perfect fluidity

Strongly-interacting Fermi gasses display similar anisotropic expansion



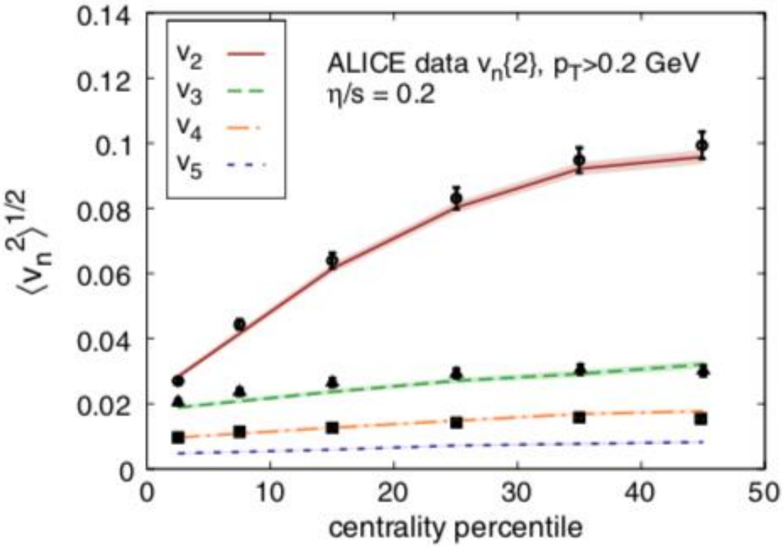
However, viscous corrections are smaller for the QGP than other known systems



Conformal field theory (via *AdS/CFT duality*) gives η/s of 1/4π ~ 0.08

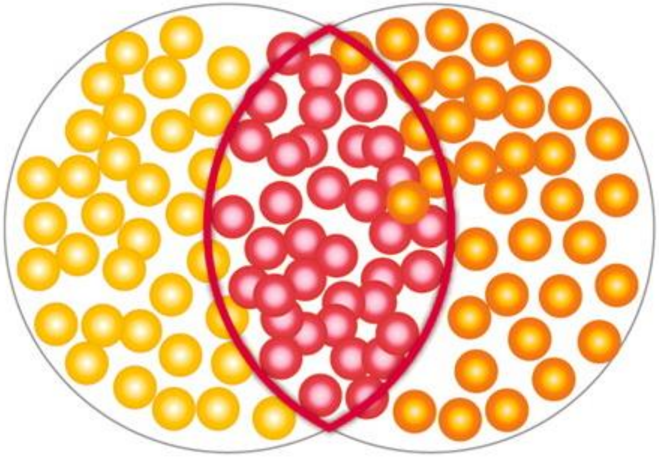
This is conjectured to be a universal lower bound

Higher harmonics

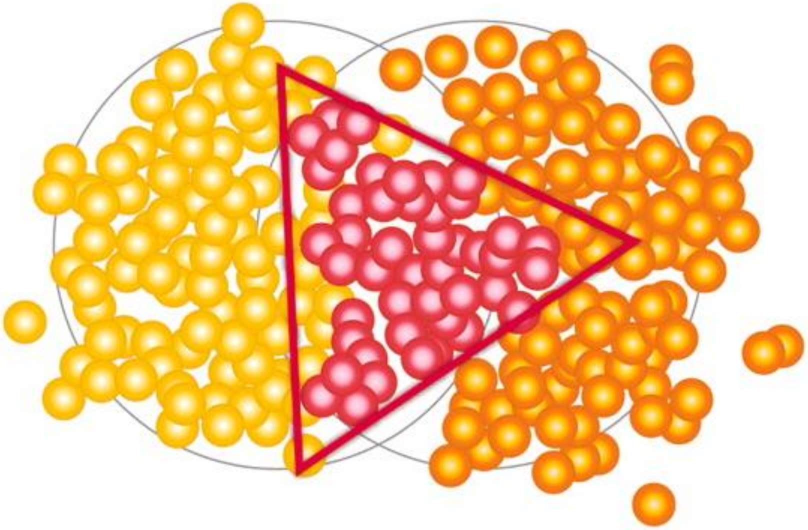


More recently higher harmonics found to be surprisingly large (v_3, v_4)
What is physical picture behind these components of flow?

Geometry fluctuations



Elliptic flow



Triangular flow

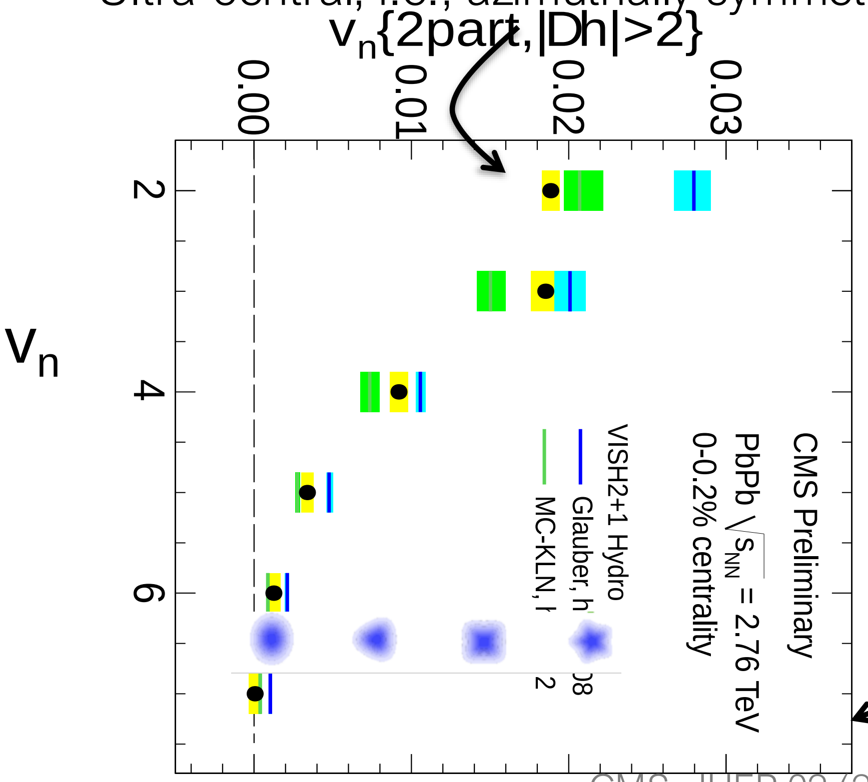
Higher harmonics explained by event-by-event fluctuations of overlap shape

These fluctuations arise naturally in MC implementation of Glauber model

Persist even when collision is azimuthally symmetric

Mapping initial state fluctuations

Ultra-central, i.e., azimuthally symmetric



Flow harmonics

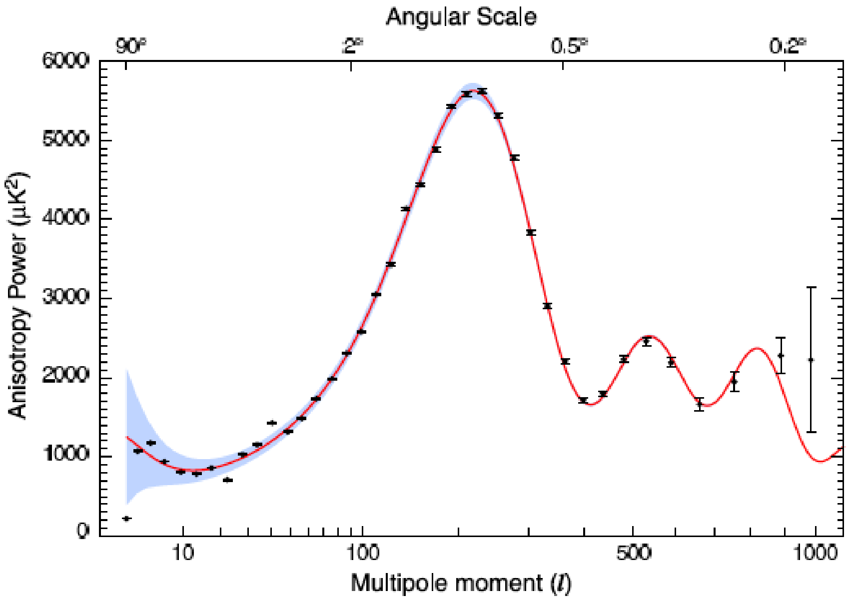
CMS, JHEP 02 (2014) 088

In addition to shear viscosity, higher harmonics sensitive to initial conditions

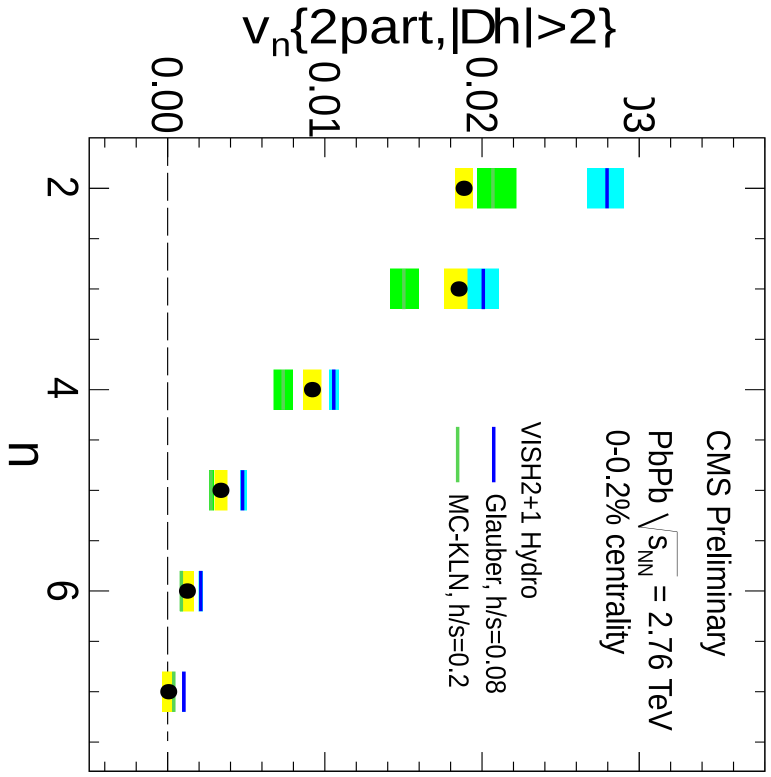
Standard Glauber conditions give very low η/s, close to conjectured bound

But “lumpier” initial conditions in MC-KLN correspond to larger η/s

Analogy to CMB



NASA/WMAP Science team

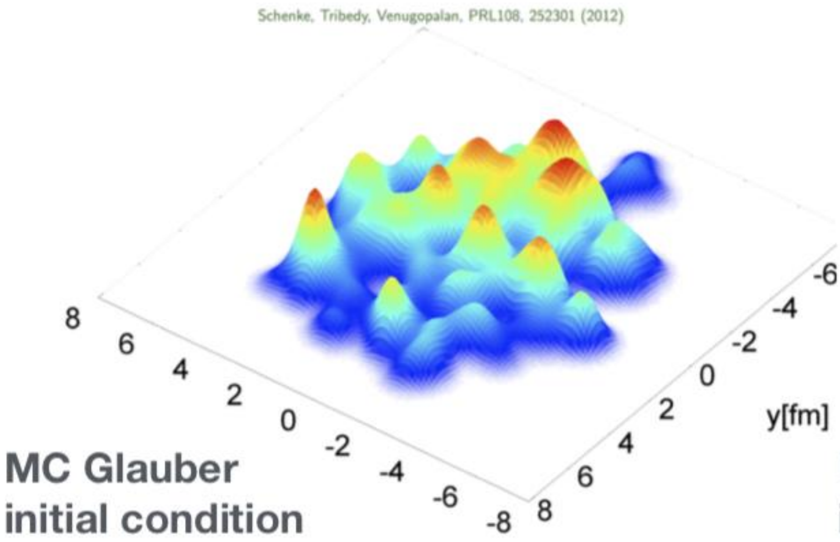


CMS, JHEP 02 (2014) 088

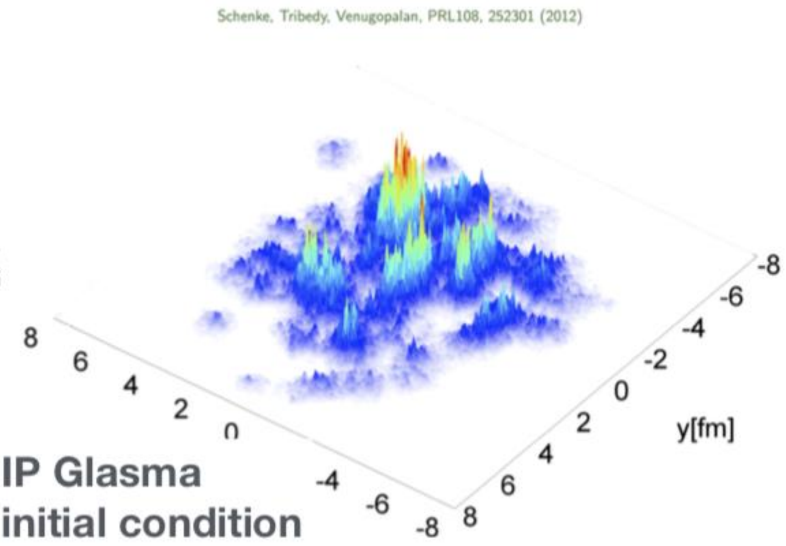
Power spectrum of the cosmic microwave background reflect fluctuations in the density of matter in the early universe before inflation

Fourier harmonics from long-range correlations reflect fluctuations of the initial state of dense QCD matter before hydrodynamic expansion

Initial conditions



Schenke, Tribedy, Venugopalan, PRL108, 252301 (2012)

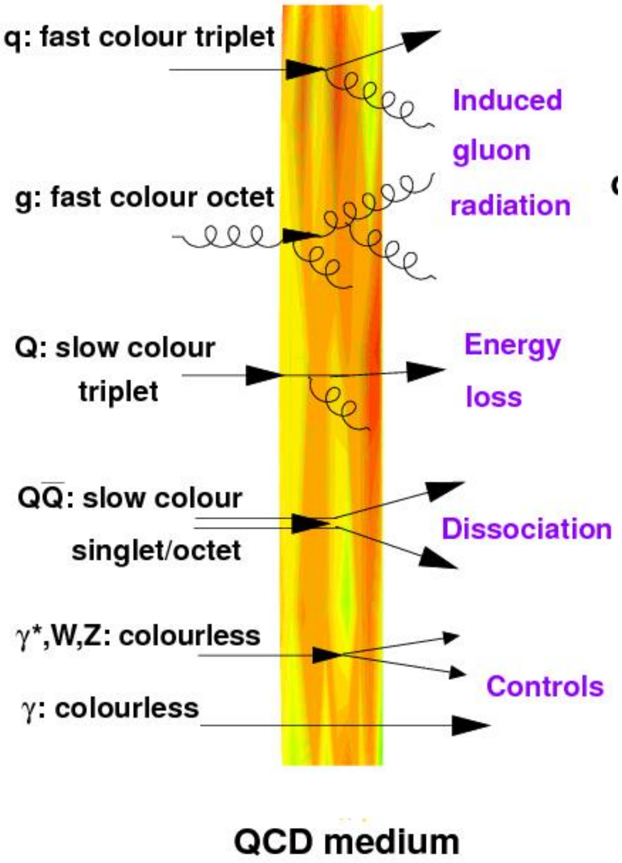


Schenke, Tribedy, Venugopalan, PRL108, 252301 (2012)

- Glauber treatment only considers fluctuations at the scale of the nucleon
- Sub-nuclear fluctuations at the level of the gluon field may be important; such effects should be present in small systems (pA or even pp)

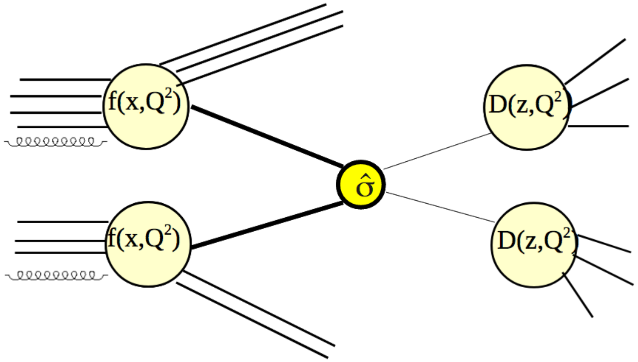
“Hard Probes” of the QGP

- Discussed “bulk observables” that effect the majority of particles that are produced in heavy-ion collisions
- Would be nice to scatter particles off the QGP, à la Rutherford
- Next best thing to a particle gun: hard processes
  - High momentum partons → jets
  - Heavy quarks, not produced thermally
  - Bound states of heavy quarks, whose binding may be screened
  - Colorless probes



Jets in elementary collisions

High p_T particle production calculable via collinear factorization



Parton scattering cross-section

Parton distribution functions

Fragmentation functions

$$d\sigma = f(x_1, Q^2) \otimes f(x_2, Q^2) \otimes d\hat{\sigma} \otimes D(z, Q^2)$$

PDF and FF are not calculable, but are universal

A jet the output of a clustering algorithm, removes sensitivity to hadronization

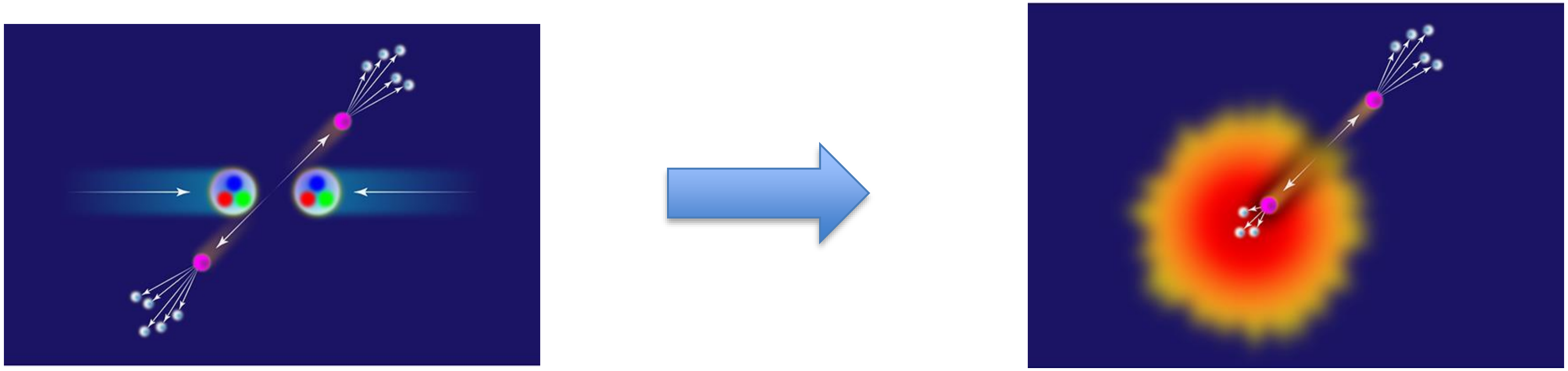
Jet quenching

$$d\sigma = f(x_1, Q^2) \otimes f(x_2, Q^2) \otimes d\hat{\sigma} \otimes P(\Delta E) \otimes D(z', Q^2)$$

PDFs are modified in nuclei, but relatively small effect

Outgoing parton should lose energy as they cross the QGP

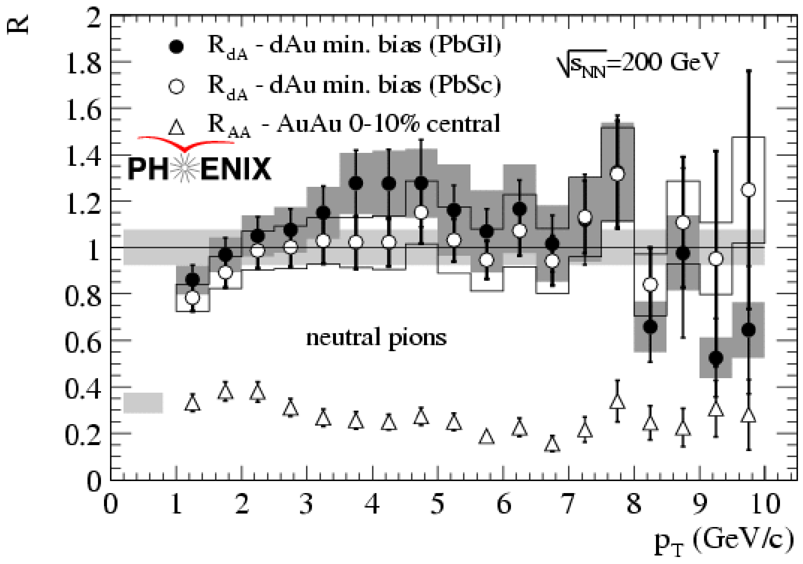
Assuming partons fragment outside QGP, fragmentation unmodified (but shifted)



High p_T hadron suppression

Nuclear Modification Factor: $$R_{AA} \equiv \frac{\mathrm{d}N^{AA}/\mathrm{d}p_T}{\langle N_{coll}\rangle \mathrm{d}N^{pp}/\mathrm{d}p_T} = \frac{\mathrm{d}N^{AA}/\mathrm{d}p_T}{\langle T_{AA}\rangle \mathrm{d}\sigma^{pp}/\mathrm{d}p_T}$$

PHENIX measured π^0 → 2γ
99% branching ratio



R_{AA} = 1 indicates “N_{coll} scaling”, i.e., no nuclear effects

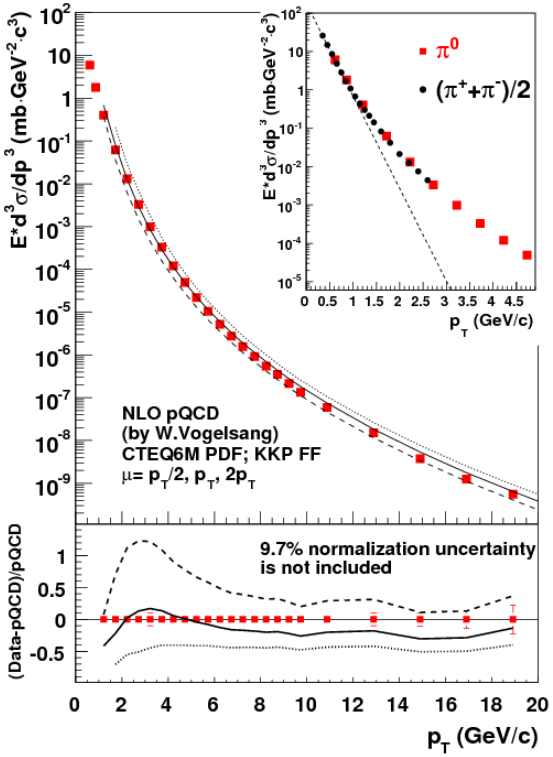
Deuteron-Gold collisions
→ No large parton energy loss
→ No large initial state effects, e.g., modification of parton distribution inside nuclei

Au-Au yield suppressed by factor of 5!
Roughly independent of p_T

Fractional energy loss

What would a flat R_{AA} imply for e-loss?

High p_T spectra typically well-described by a power-law



$$\frac{d\sigma}{dp_\mathrm{T}} \propto \frac{1}{p_\mathrm{T}^n}$$

RHIC: n ≈ 7

LHC: n ≈ 5

Assume *fractional* e-loss: $$\Delta p_T = C \cdot p_T$$

$$R_\mathrm{AA} = C^{n-1}$$

e.g., R_{AA} = 0.2 @ RHIC

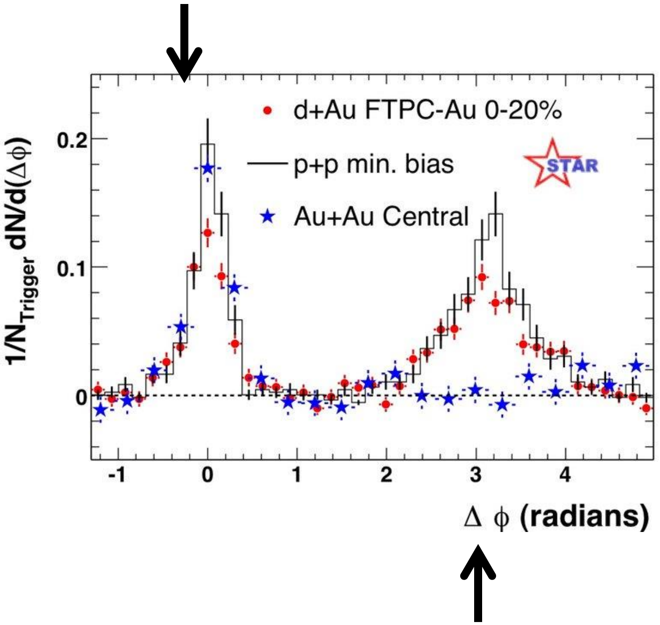
→ C = 0.8 (20% e-loss)

Flat R_{AA} consistent with fractional e-loss

R_{AA} depends on both e-loss and spectral shape

Dihadron azimuthal correlations

Small angle correlation from hadrons within a single jet



Back-to-back from recoiling jets

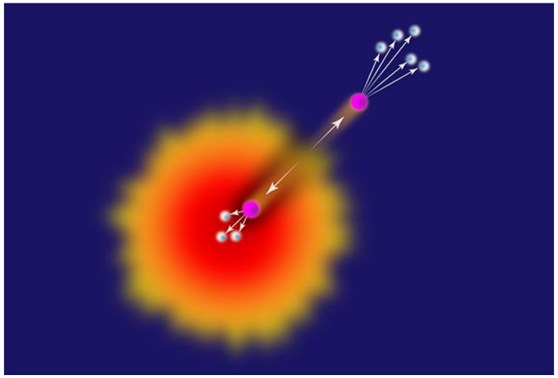
Disappears in central Au-Au!

Select *trigger* hadron,

$4 < p_T^{trig} < 6$ GeV

⊗√ to partner hadron,

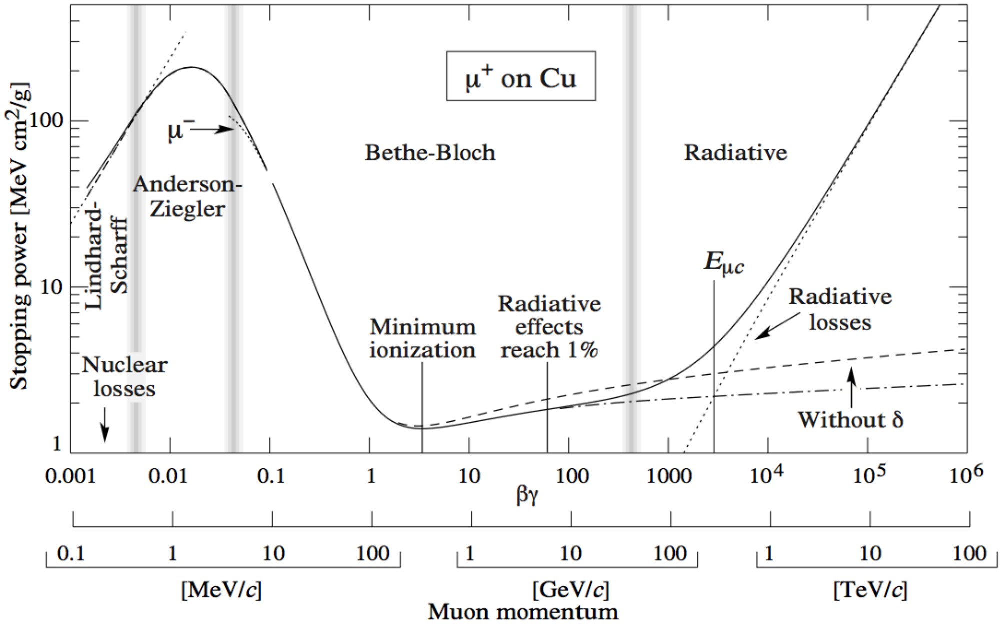
$2 < p_T < p_T^{trig}$



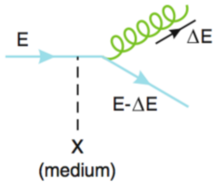
Interpretation: Trigger hadron preferentially produced near surface, while recoil jet traverses the QGP

Energy loss in QCD matter

Passage of particles thru (QED) matter



At large energy radiative e-loss should dominate
→ gluon bremsstrahlung



For mean free path λ << medium size *L* we are in the LPM regime

$$\Delta E \propto \alpha_s C_F \hat{q} L^2$$

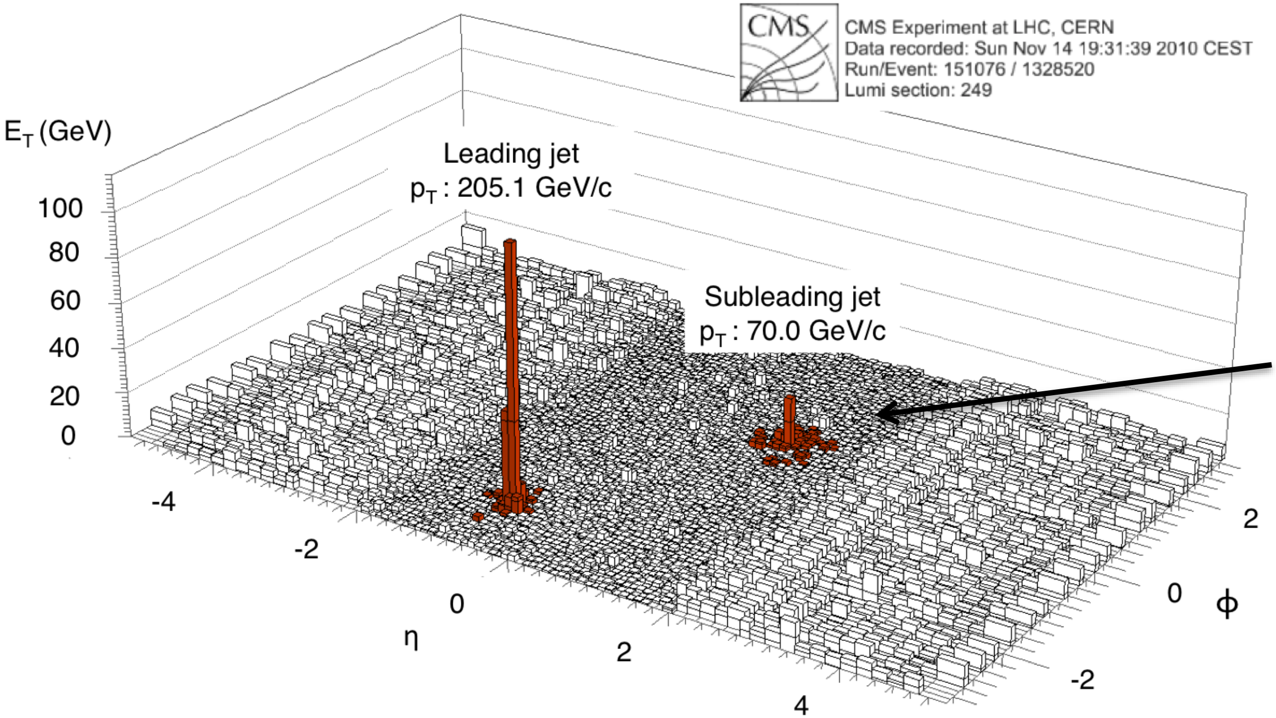
*L*² instead of *L*, due to destructive interference between scattering centers (LPM effect)

Quenching depends on color factor

$$C_F = \begin{cases} 3 & \text{gluon jets} \\ 4/3 & \text{quark jets} \end{cases}$$

Stopping power *q* depends on medium density
→ jets are a tomographic probe of the QGP

Fully reconstructed jets



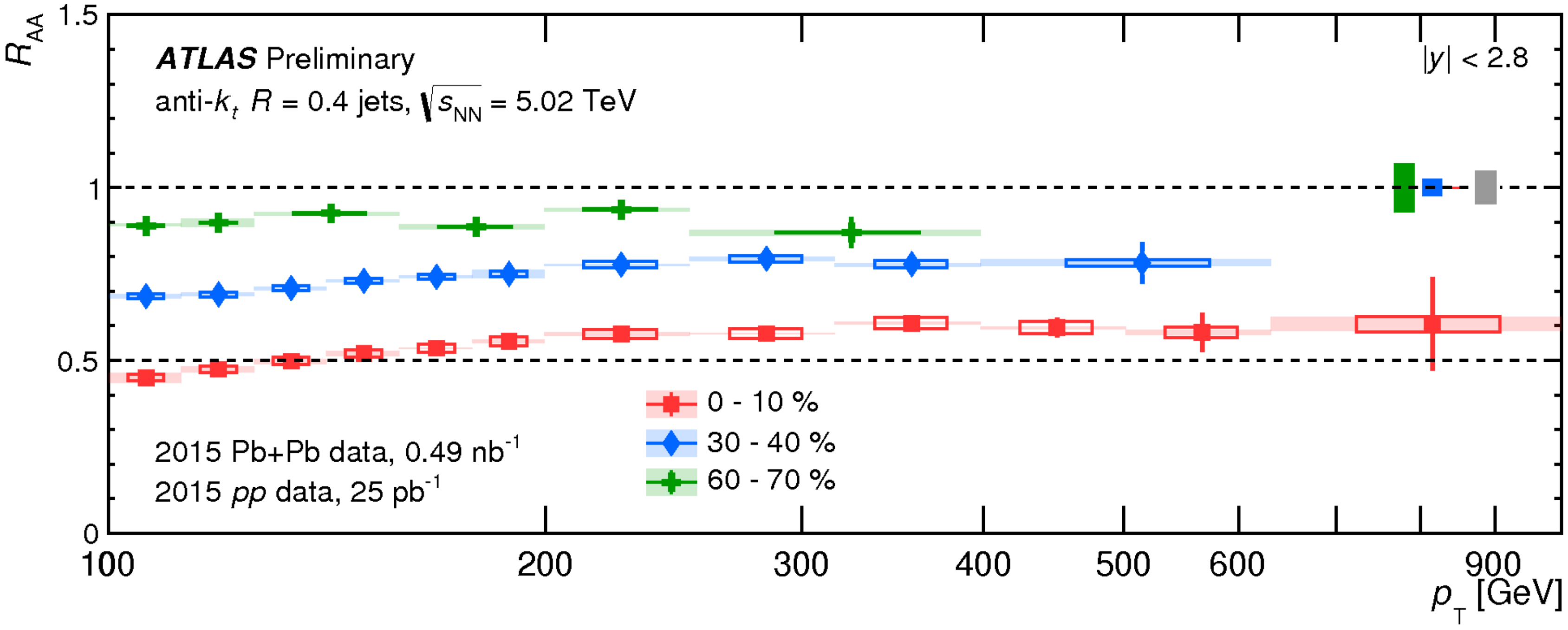
High p_T hadrons are gone, but away jet is still there, albeit with reduced energy

Jet reconstruction become possible at the LHC for the first time in heavy ions

- Hard scattering more abundant at larger collision energy
- Availability of large acceptance, hermetic calorimeters in CMS & ATLAS

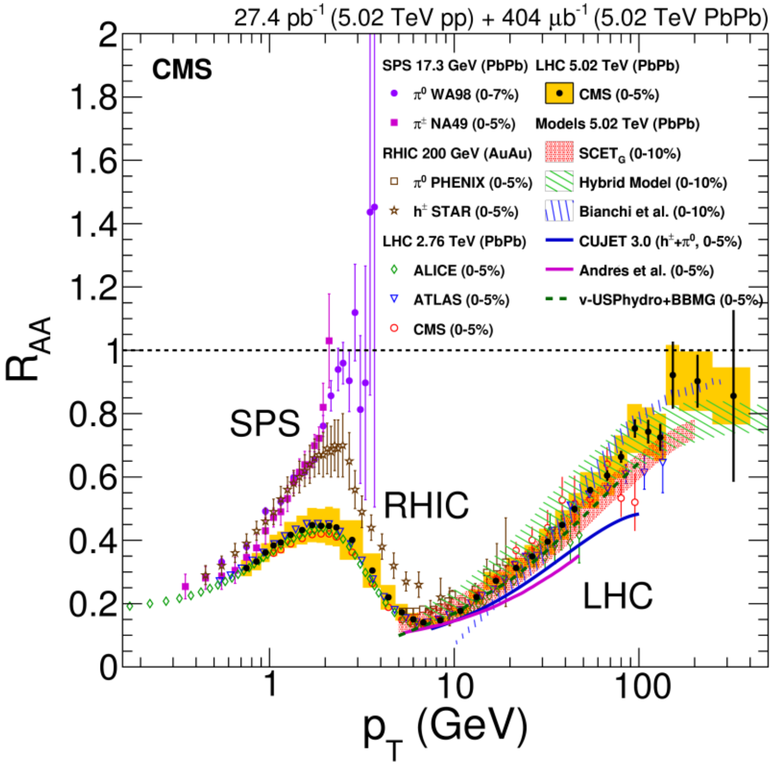
Jet R_{AA}

Wide range of jet momenta probed by PbPb data at the LHC



At large p_T, remarkably flat R_{AA} in central collisions, reminiscent of the hadron suppression at RHIC

Hadrons at the LHC



Not so flat anymore!

Instead a slow but steady rise, showing little suppression at 100 GeV!

How to reconcile charged hadron and jet suppression?

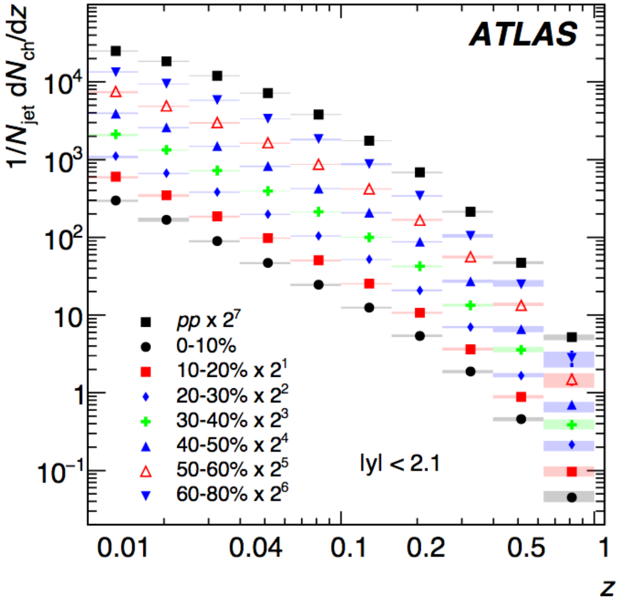
→ Must be dependence of quenching on fragmentation pattern of jet

Jet fragmentation functions

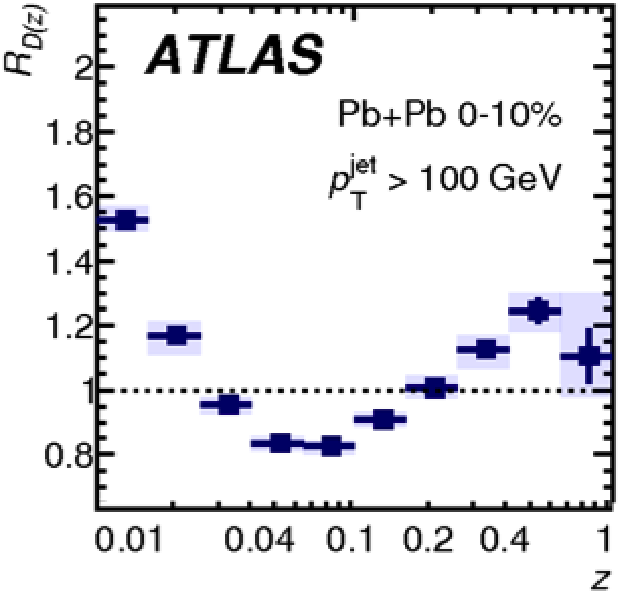
Not a true FF, jet used as proxy for parton $z = p_{T,\mathrm{hadron}} / p_{T,\mathrm{jet}}$

Not trivial: Quenching may transfer some energy outside jet

dN/dz for different centralities



Ratio of PbPb to pp



Excess at low *z*: likely dominated by medium response

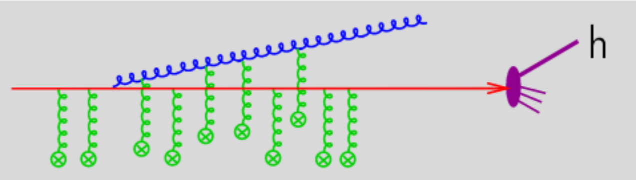
Depletion then excess at intermediate to high *z*:

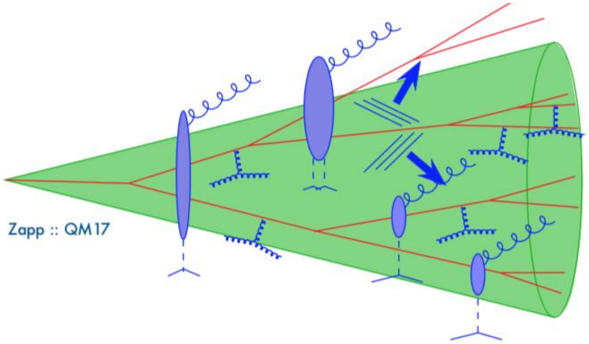
Modification of fragmentation pattern due to quenching?

Preferential quenching of gluon jets over quark jets?

Jet quenching state-of-the-art

Single hard parton traversing QCD matter is very much a 1st approximation



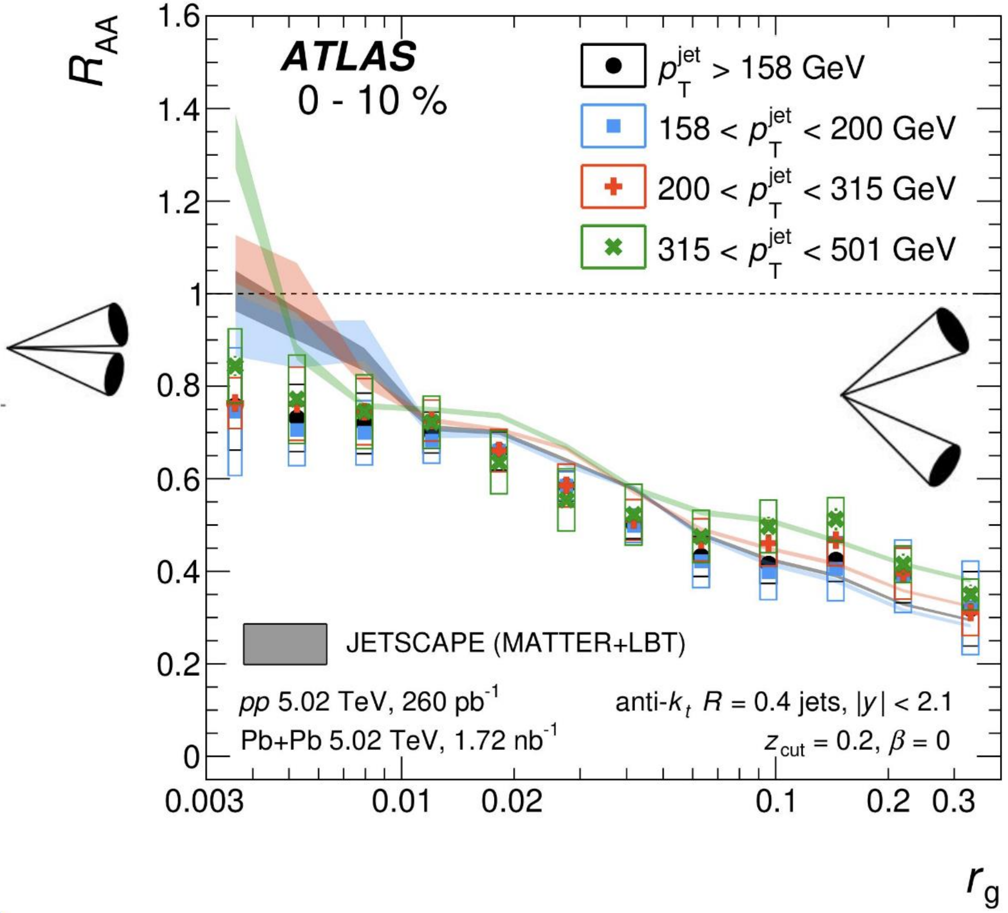


More realistic treatment requires taking into account the entire parton shower

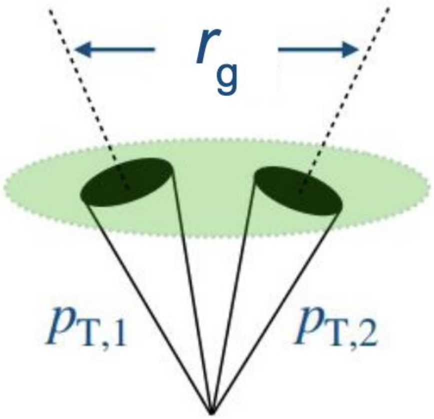
Among the effects currently being studied

- Coherence effects between nearby partons in the shower & jet substructure
- Modeling of recoil “splash”
- Development of full jet quenching MC codes

New: Jet substructure

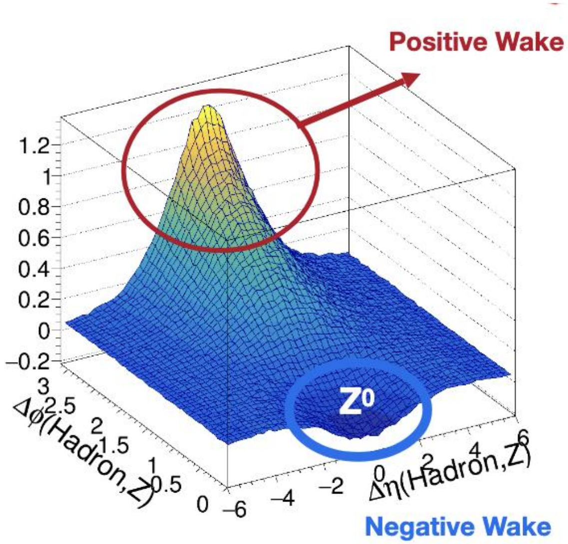


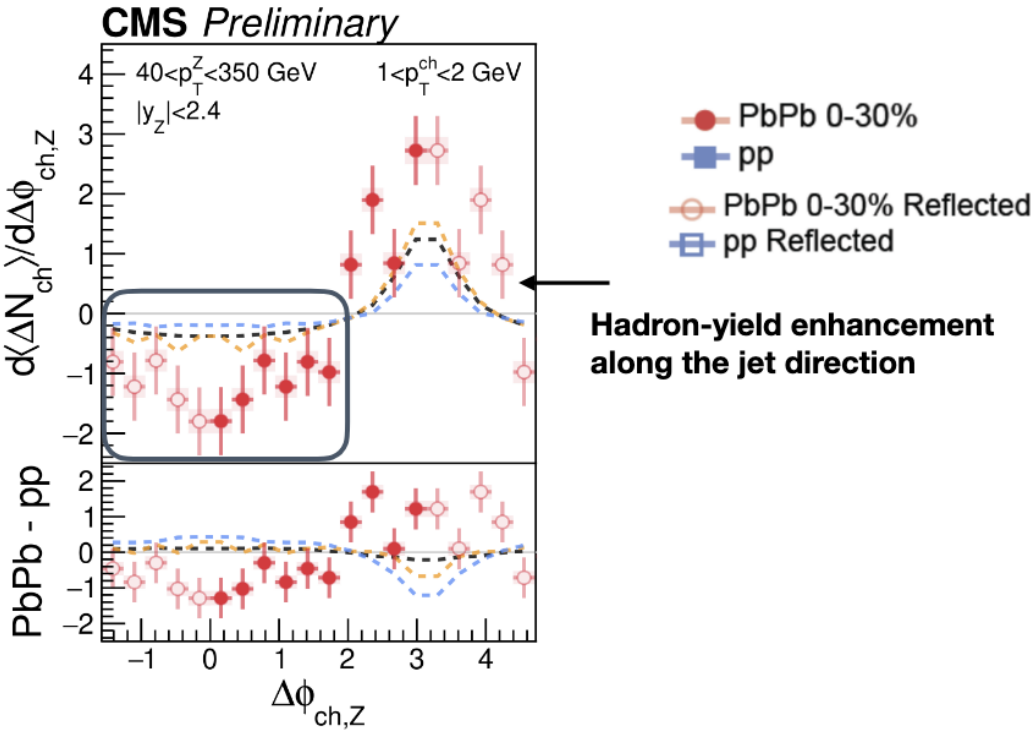
”Decluster” your jets to look at the hardest prongs



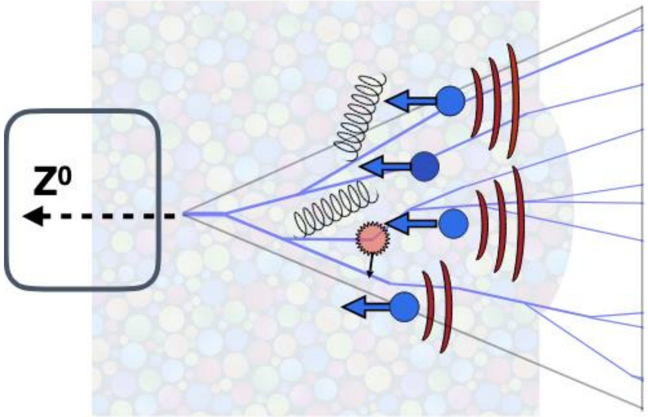
Larger suppression for more separated prongs
→ Coherence effects?

New: jet wake



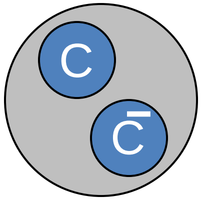


Hadron-yield enhancement along the jet direction

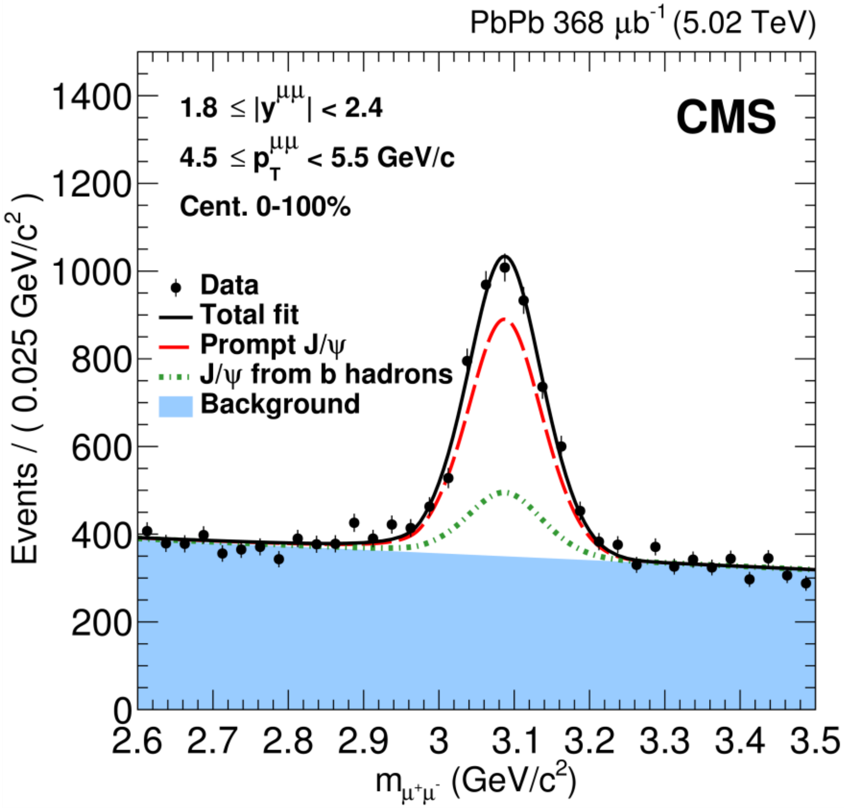


Clear depletion in PbPb on the Z side ($\Delta\phi$=0)

J/ψ meson factsheet



J/ψ mass peak in PbPb collisions, via the dimuon decay channel



- Bound state of c-cbar, most abundant quarkonium state
- 1974 “November revolution”, confirmed 4th quark generation
- Large rate of decays in leptons, 6% into dimuon or dielectron
- Mass = 3.1 GeV (~ 2x charm)

Charm quark above temperate threshold for thermal production
→ produced via hard scattering

Size of the J/ψ

Cornell potential:

$$V(r) = \sigma r - \frac{\alpha}{r}$$

Confinement Coulomb-like

σ and α from spectrum
of onium states

σ ≈ 1 GeV/fm, α ≈ π/12

$$E(r) = 2m + \frac{1}{2mr^2} + V(r)$$

Rest kinetic

Minimizing to get the lowest bound state

$$\frac{dE}{dr} = \frac{1}{mr^3} - \frac{\alpha}{r^2} - \sigma = 0$$

Dominant term is confining one

$$r \approx (m\sigma)^{-1/3}$$

Inserting m = 1.5 GeV

r ≈ 0.3 fm

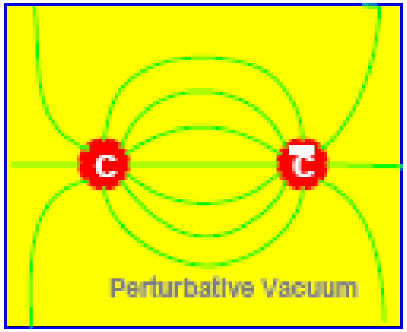
→ Several times smaller
than typical light hadrons

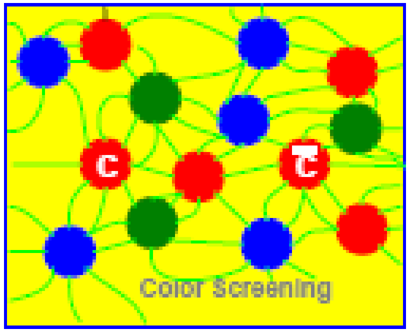
Quarkonia melting

Potential is screened in the QGP

$$V(r) = -\frac{\alpha}{r} e^{r/\lambda_D}$$

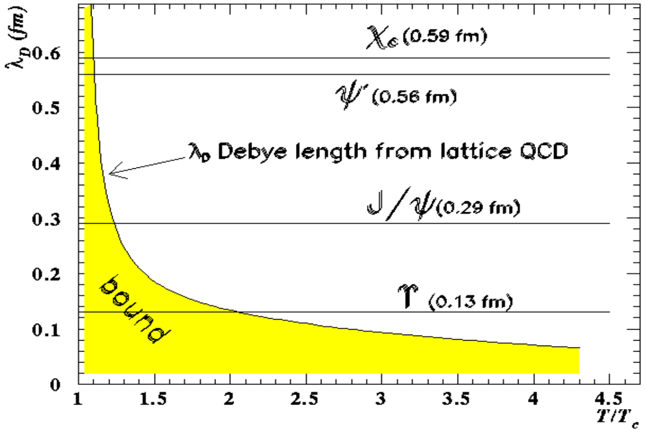
Debye screening length

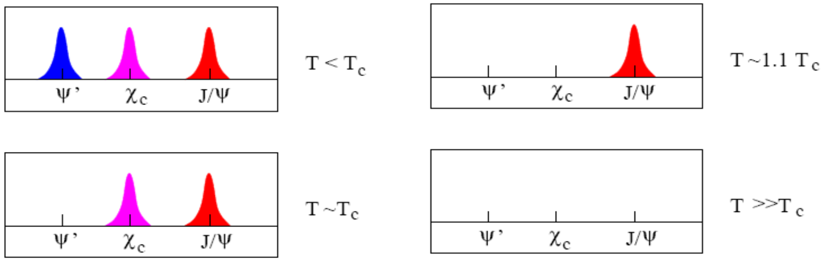




Besides J/ψ, also excited states ψ’ & χ_c
Feed-down: 10% of J/ψ from ψ’
30% of J/ψ from χ_c

λ_D provided by lattice QCD





Sequential melting of states according to binding energy

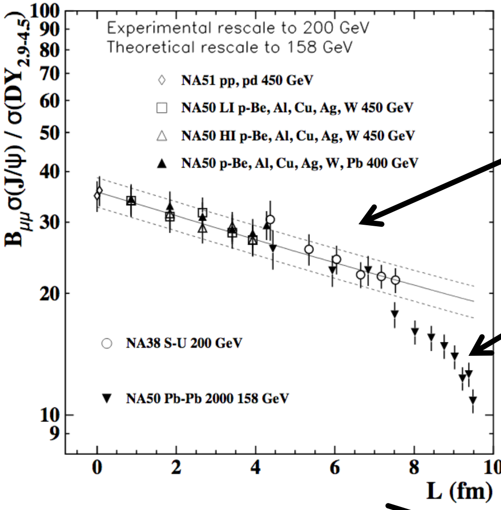
Charmonia @ the SPS

SPS collided Pb ions in fixed target mode at CERN

200 GeV Pb beam

→ $\sqrt{s_{NN}} \approx 17$ GeV

Instead of R_{AA}, ratio to Drell-Yan

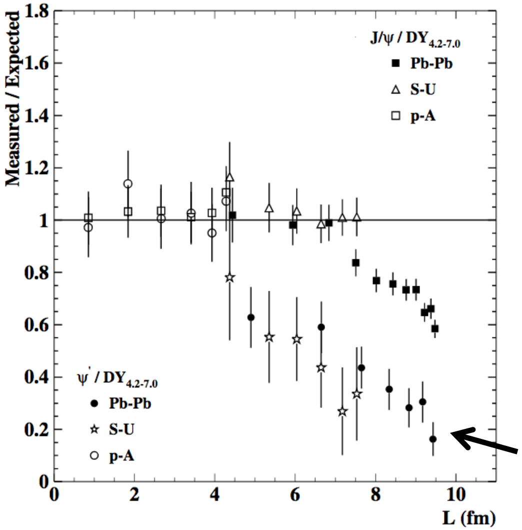


pp & pA

PbPb

Mean nuclear length traversed (L), from Glauber model

Ratio to nuclear absorption baseline



ψ' also studied

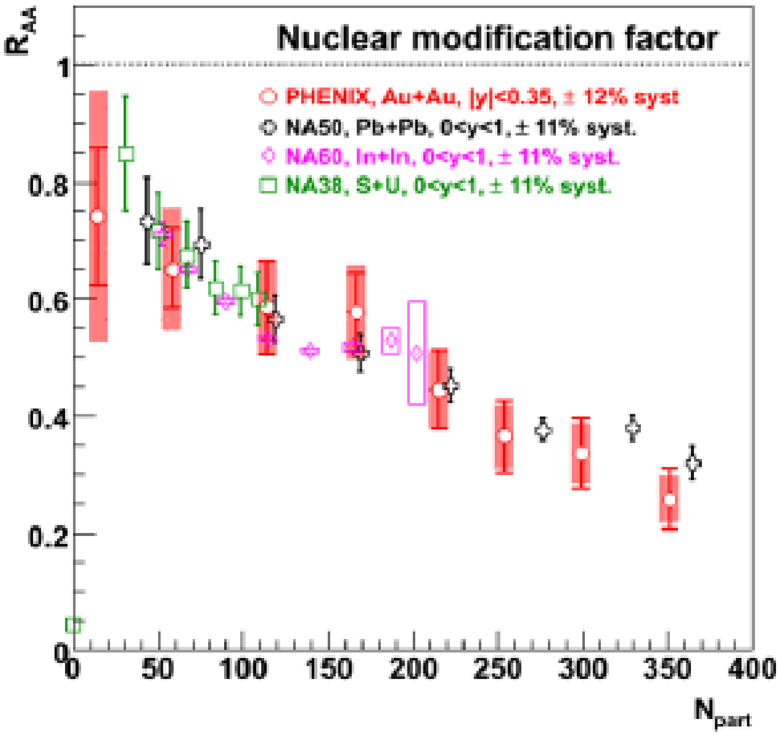
J/ψ suppressed even in light systems due to (pre-resonant) nuclear absorption

However, in central PbPb 'anomalous' suppression observed

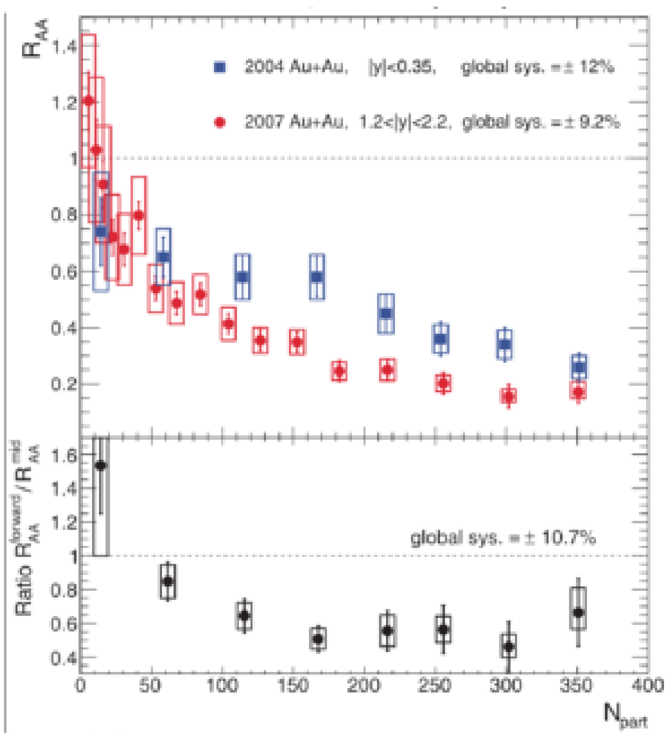
Naïve interpretation: ψ' melts first, then χ_c, while J/ψ remains intact at this energy

Evidence for QGP discovery, although modern interpretation more nuanced

Charmonia @ RHIC $\sqrt{s_{NN}} = 200$ GeV



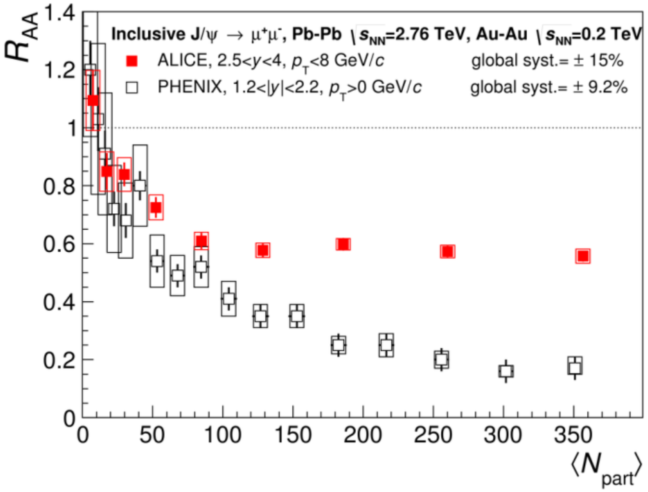
Comparable suppression to SPS
→ Saturation of onia melting?

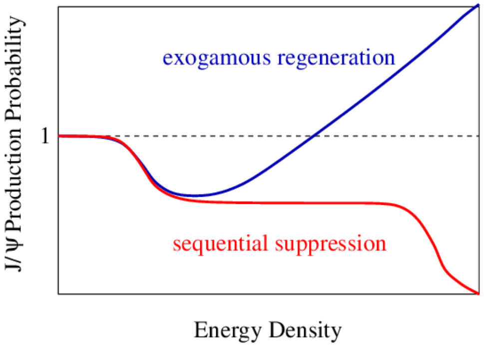


However, larger suppression at forward rapidity → not expected in Debye screening picture

Melting & regeneration

Less suppression at LHC

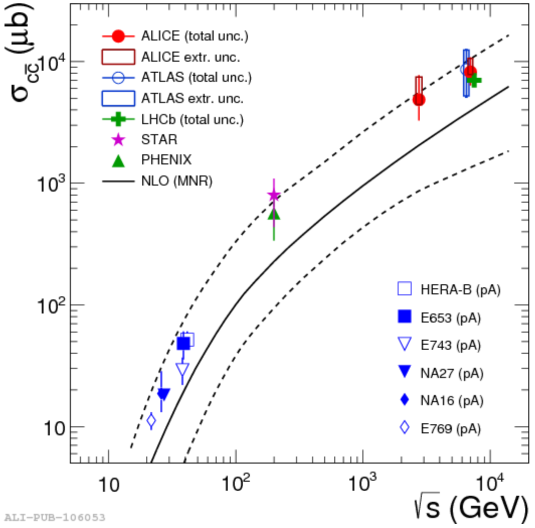




Interpretation: Cancellation of two effects, melting and *regeneration*

LHC: $\sqrt{s_{NN}}$ = 2760 GeV

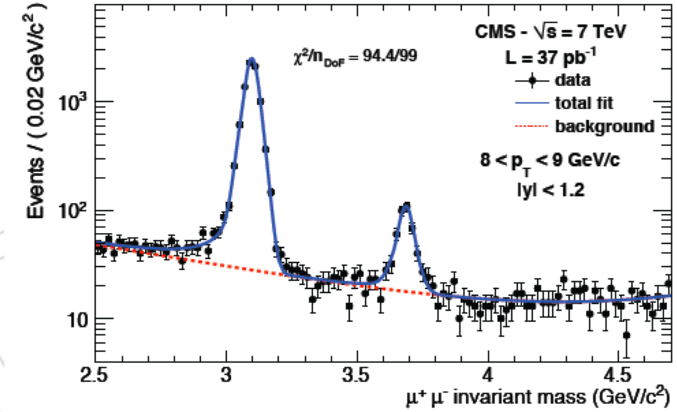
Charm copious enough at high energies to meet other charm in the QGP. Effect ~ N_c^2



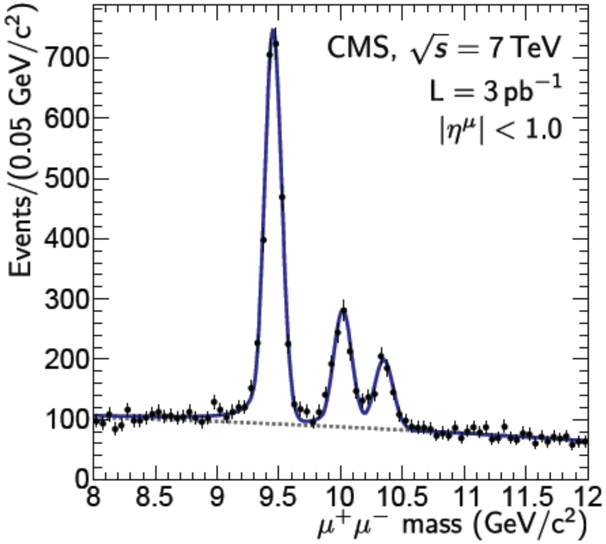
σ(cc) ≈ 5 mb x 1500 coll / 65 mb ≈ 115 cc pairs in a central PbPb collision!

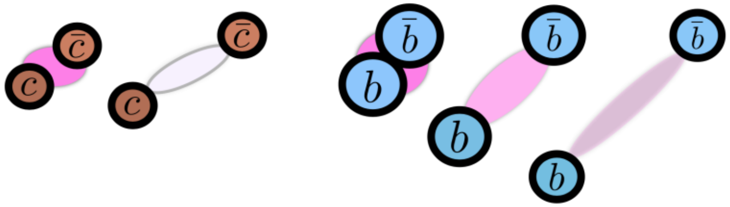
Upsilon spectroscopy

Charmonium dimuon spectrum



Bottomonium dimuon spectrum



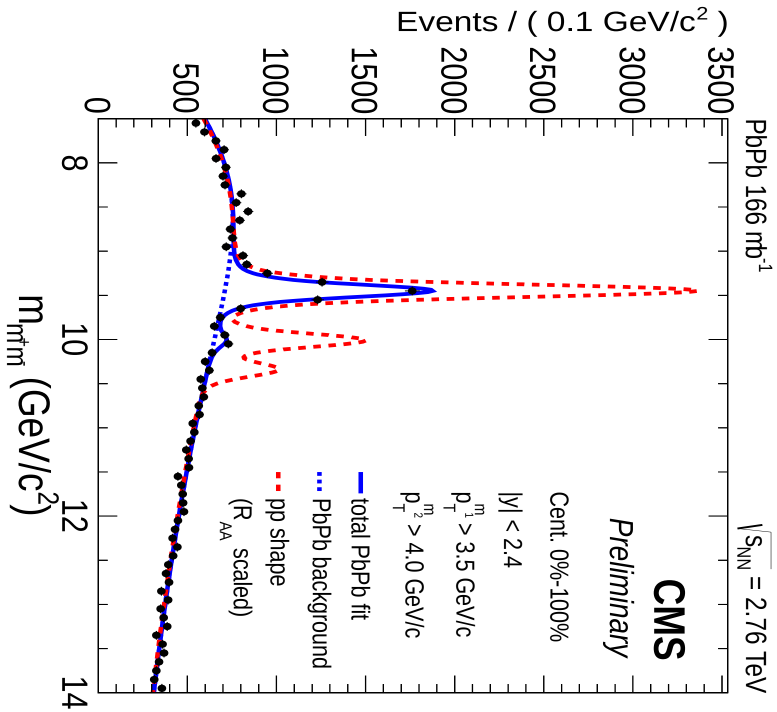


state	J/ψ	ψ'	ϒ	ϒ'	ϒ''
mass (GeV)	3.10	3.68	9.46	10.0	10.4
radius (fm)	0.25	0.45	0.14	0.28	0.39

- 3 ϒ states w/ comparable cross section, but different binding energy
- ϒ(1s) more tightly bound than J/ψ

bb cross section ≈ 0.3 mb → little regeneration expected!

Upsilon melting

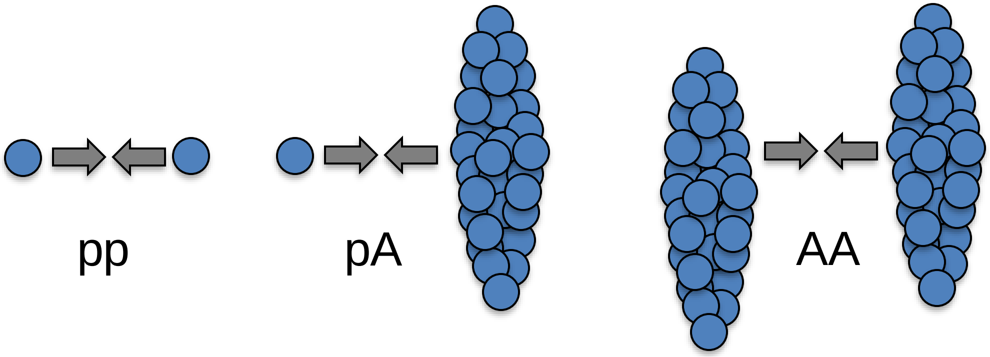


$$R_{AA}(\Upsilon(1S)) = 0.453 \pm 0.014 \pm 0.046;$$
$$R_{AA}(\Upsilon(2S)) = 0.119 \pm 0.028 \pm 0.015;$$
$$R_{AA}(\Upsilon(3S)) < 0.145 \text{ at a 95\% confidence level,}$$

- Υ(1s) suppressed, although ≈ 30% feed-down from excited states
- Υ(2s) more suppressed
- Υ(3s) not even visible

- Naïve interpretation: Excited states melt, while ground state survives
- More likely different states dissociate over different volumes
- Also need to consider the role of *cold nuclear effects*

Addendum: small systems

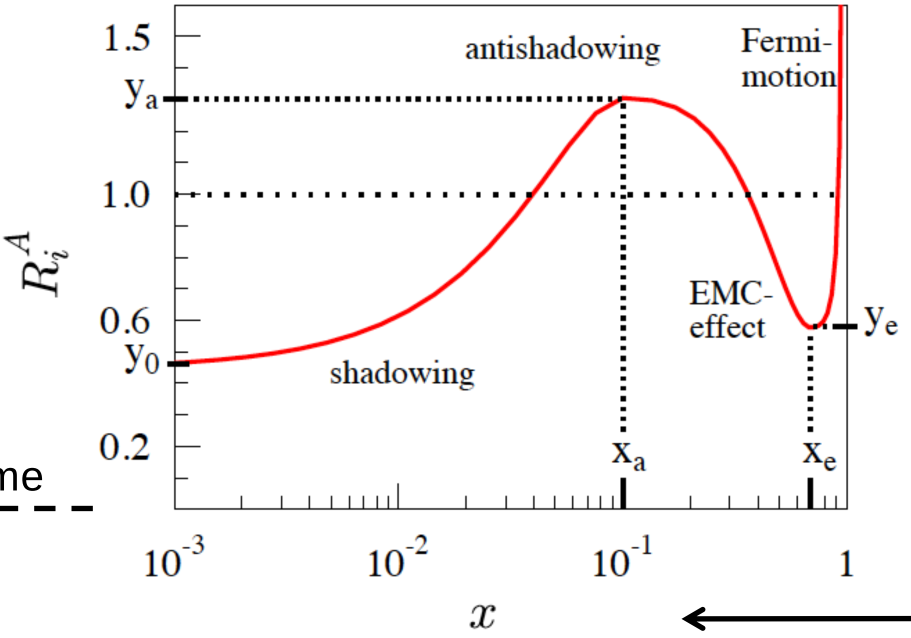


Original paradigm

- pp collisions a baseline for absence of nuclear effects
- pA collisions a baseline for cold nuclear matter effects, i.e., nuclear effects unrelated to the quark-gluon plasma

Paradigm shift over last ~ 15 years
Certain effects thought to be tied to deconfinement
show up even in smaller systems

Nuclear PDFs



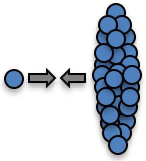
Ratio of nuclear PDF to free proton PDF

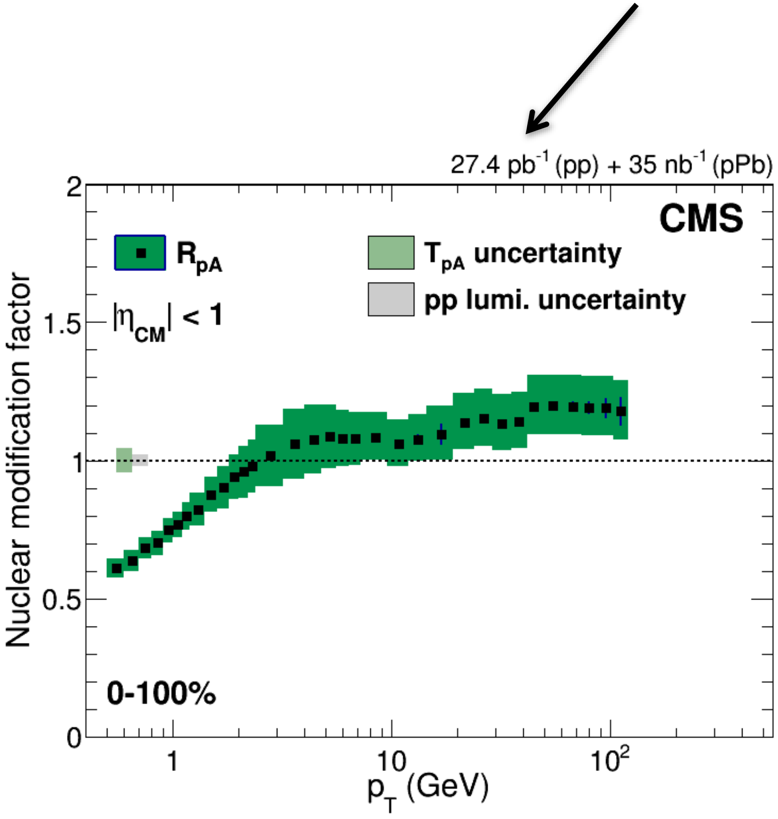
Saturation regime

Bjorken *x*: fraction of nucleon’s momentum carried by struck parton

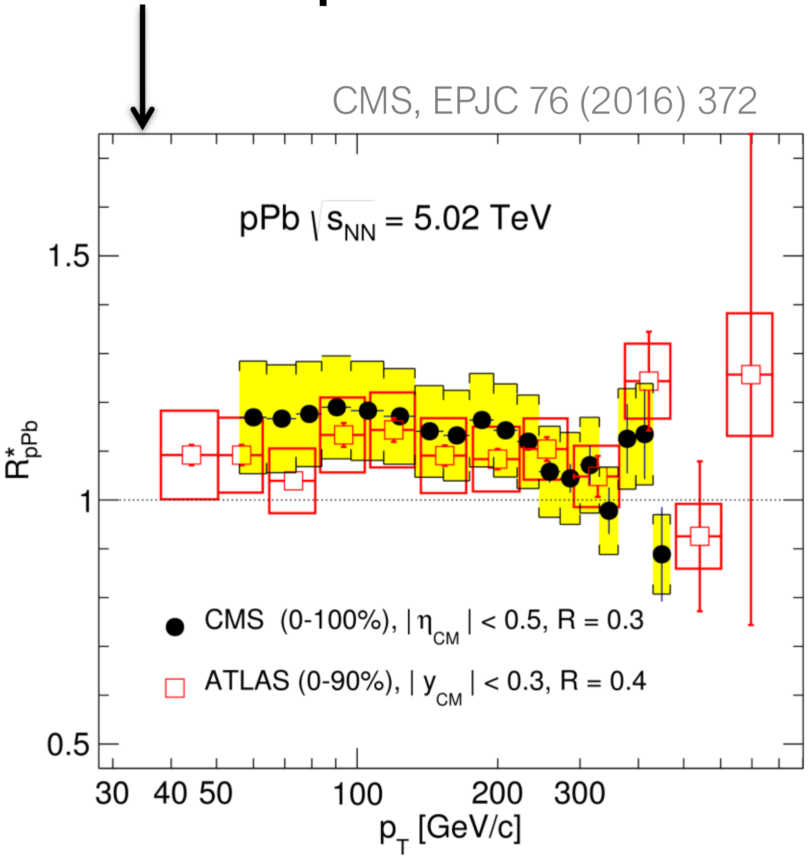
- Modest nuclear effect already expected in pA: modification of parton distributions inside nuclei
- Known from nuclear DIS measurements
- Evolution with Q^2 calculable in QCD via DGLAP equations
- Gluons must saturate at very low x → non-linear evolution

Hadron & jet R_{pA}





CMS, JHEP 04 (2017) 039

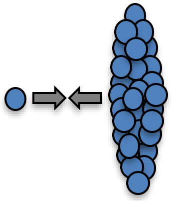


CMS, EPJC 76 (2016) 372

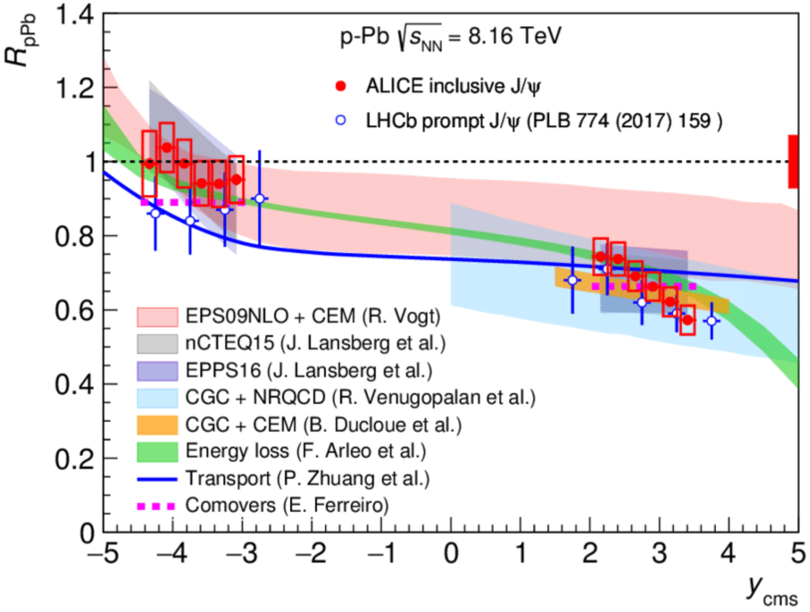
- No suppression as would be expected if jet quenching were present
- Rather, small enhancement due to nuclear parton distributions (anti-shadowing)

Quarkonia R_{pA}

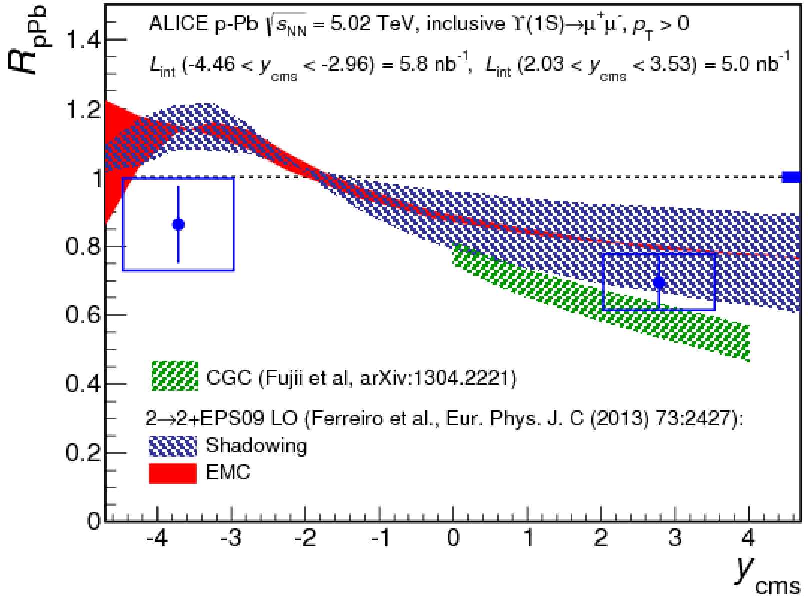
Proton-going direction →



J/ψ



Υ(1s)



Quarkonia access lower x, where shadowing expected to dominate

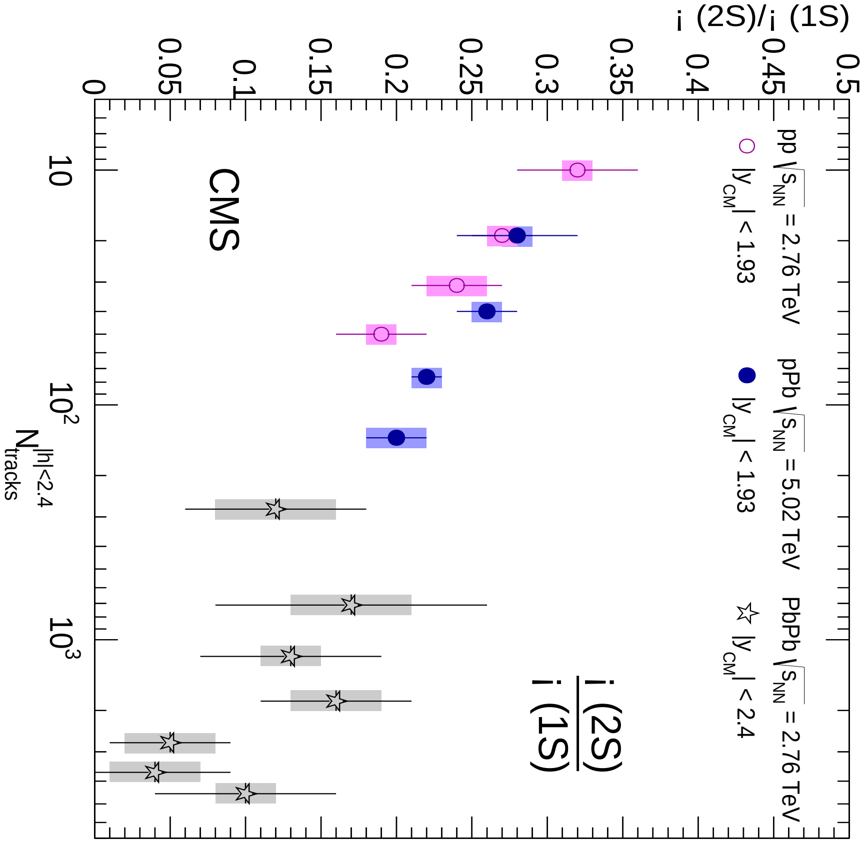
Results consistent with shadowing in proton-going direction

Part of the Υ suppression is due to PDF effects

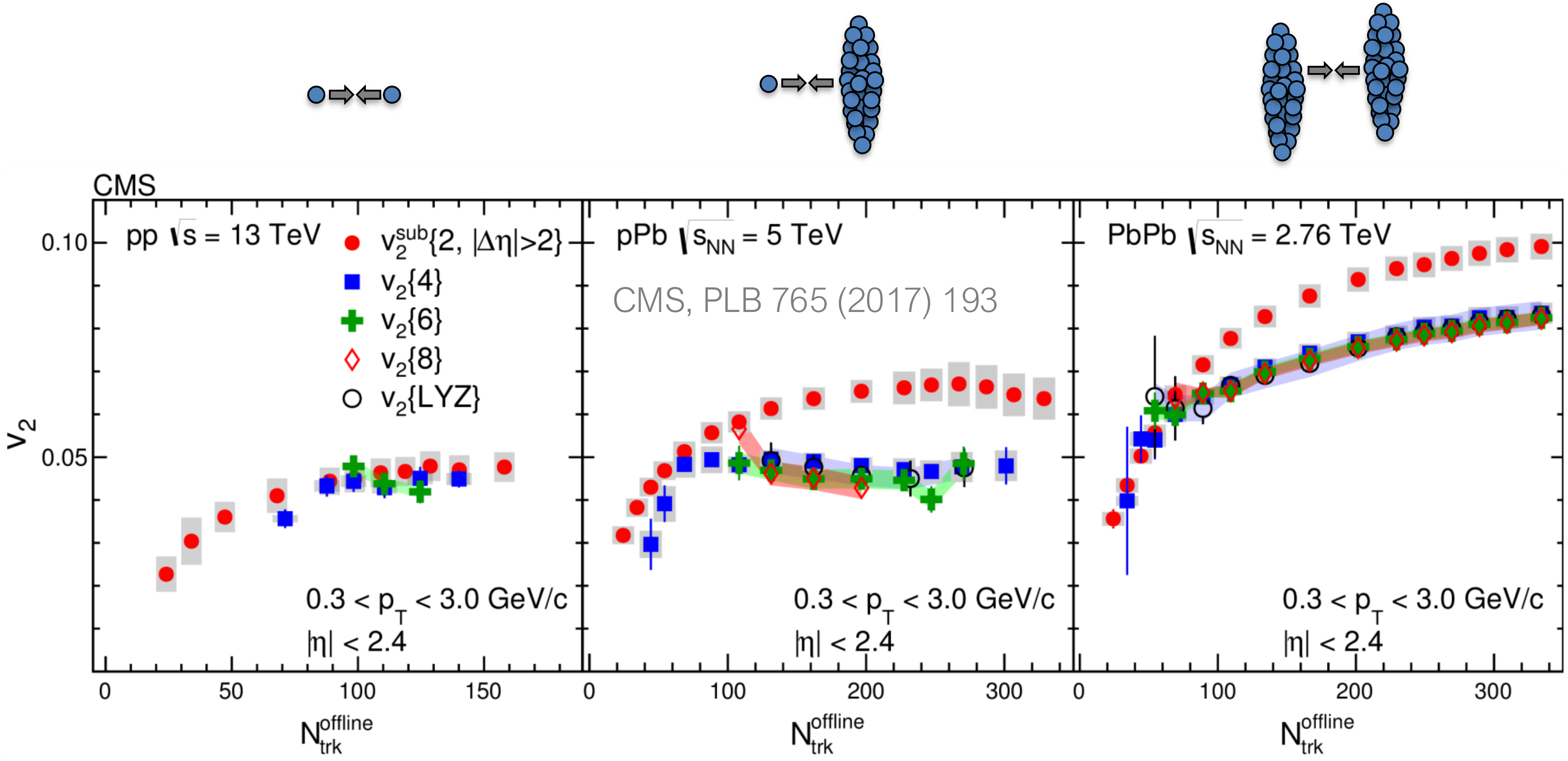
ϒ states vs. multiplicity

- Centrality difficult to define in small systems → multiplicity as a proxy
- Preferential suppression of ϒ(2s) already seen in pp and pPb collisions
- Consistent with a smooth dependence on multiplicity

Ratio of exited to ground state



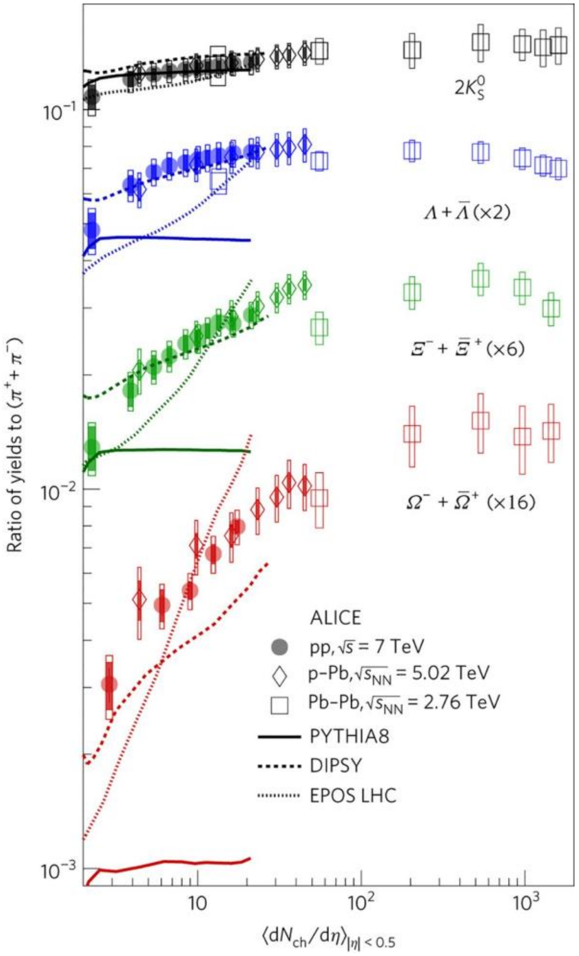
Multiparticle correlations



- No initial asymmetry in small systems, yet elliptic flow observed for mult > 100
- Source suspected to be fluctuations at the sub-nucleonic scale
- Hydrodynamic behavior at relatively small multiplicity is surprising

Strangeness in small systems

- Recall strangeness enhancement indicative of chemical equilibrium over an extended volume
- Effect also present in small systems
- Smooth dependence on multiplicity
- Increases w/ # of strange quarks



Small systems: summary

- Nuclear modification factor (R_{pA}) consistent with no QGP, rather effects from modified nuclear PDFs
- However, with increasing multiplicity, effects thought to relate to QGP formation emerge in pp and pA collisions
  - Preferential suppression of excited ϒ(2s) over ϒ(1s)
  - Flow signals from initial state fluctuations
  - Strangeness enhancement indicating chemical equilibration
- May indicate a QGP droplet is formed in small systems, but very much an ongoing field of study

Part 2, take-home messages

- The QGP is studied with a variety of probes, a few of which have been discussed here
  - Parton energy loss in the QGP via jet quenching
  - Debye screen in the QGP via onia dissociation
  - Collectivity of the QGP via elliptic flow
- Emergence of some of these effects in small systems is an ongoing avenue of investigation