Heavy-ion physics, lecture 2

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September 24th, 2018

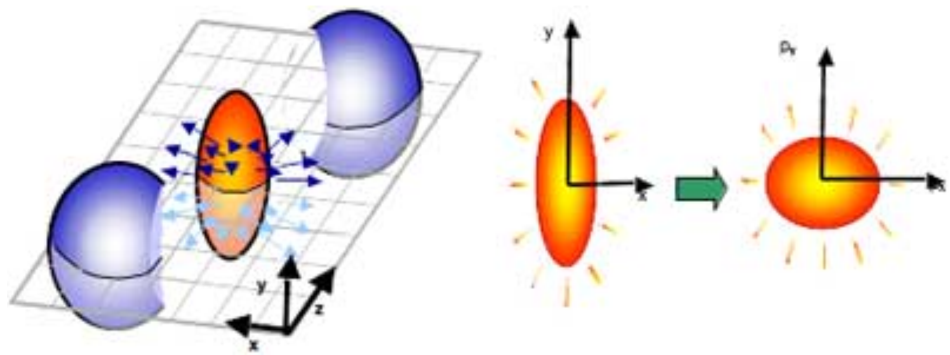
Today

Select probes of the quark-gluon plasma

- Collective flow
- Jet quenching
- Quarkonia melting
- Small systems (time permitting)

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

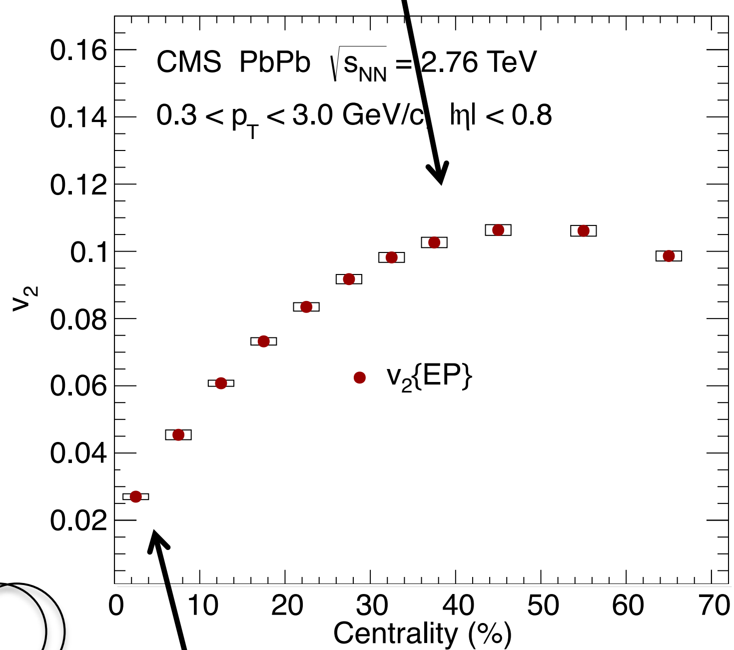
$$E\frac{d^3\sigma}{d\mathbf{p}^3} = \frac{1}{2\pi}\frac{d^2\sigma}{p_\mathrm{T}dp_\mathrm{T}dy}\left(1 + 2\sum_n v_n \cos[n(\phi - \psi_R)]\right)$$

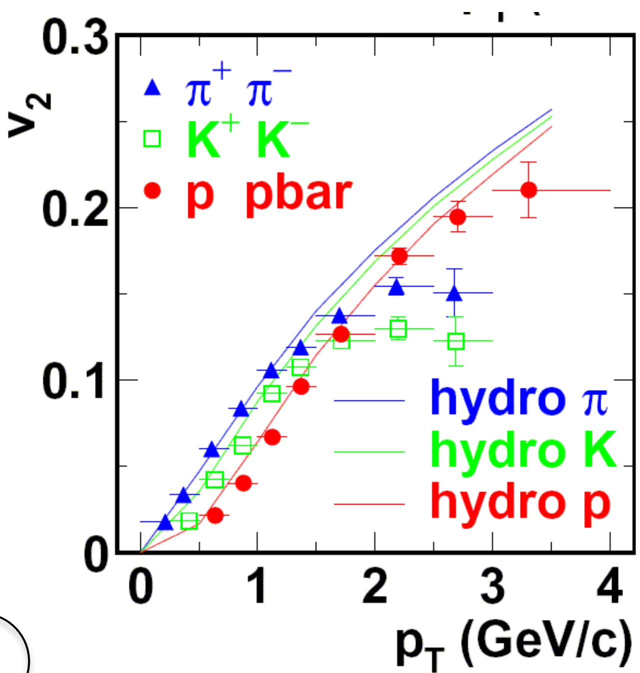
Given the overlap shape, 2nd harmonic v_2 dominates: "elliptic flow"
Naively odd terms not expected to contribute due to symmetry

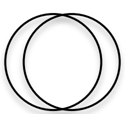
Elliptic flow vs. centrality

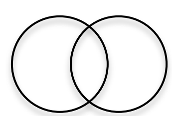
v_2 data conforms to basic expectations: reaches peak in semi-central collisions

Lighter particles more easily swept up in flow







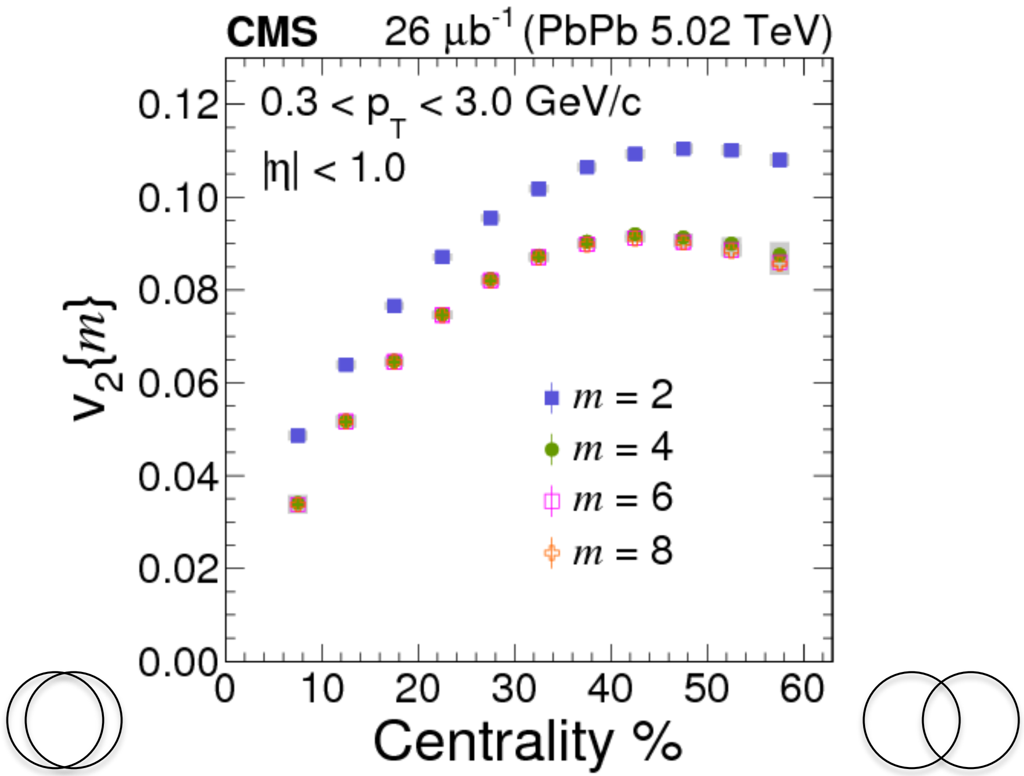


Small in central events due to symmetric overlap

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

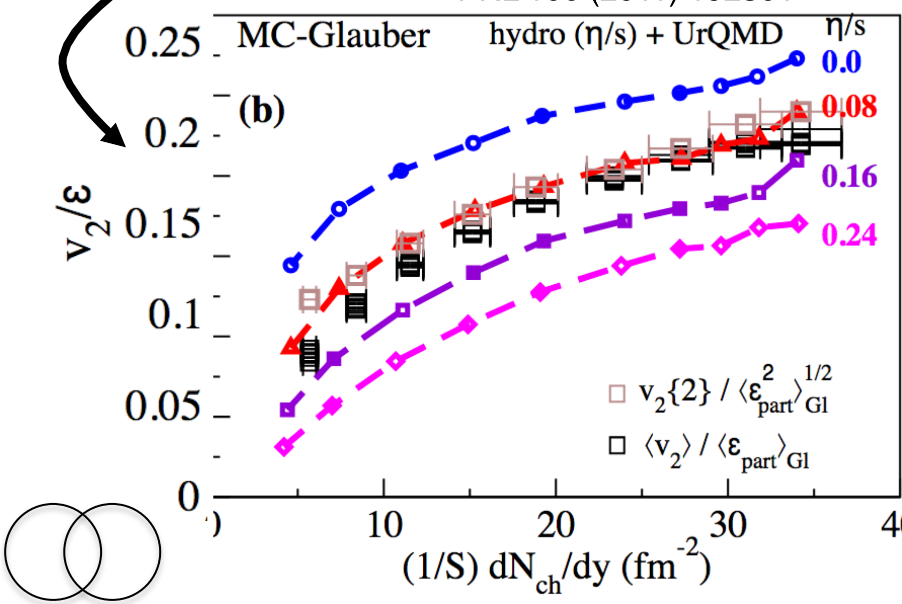


For particle pairs, strong contribution from “non-flow”, e.g, jets
Minimized by studying multiparticle correlations via “cumulants”

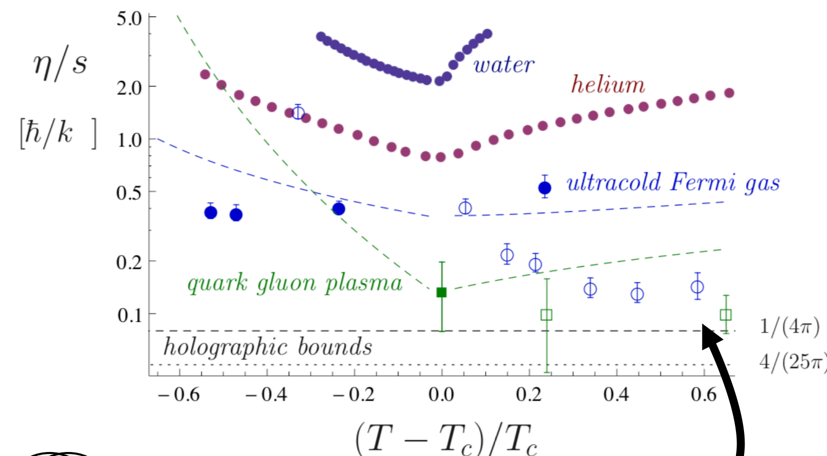
Hydrodynamics

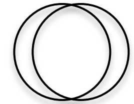
- Collective flow is modeled by relativistic hydrodynamics
- Viscous terms are corrections to ideal hydrodynamics
- Dissipation from shear viscosity would damp elliptic flow
- Sophisticated models couple hydro w/ hadronic rescattering phase

PRL 106 (2011) 192301



New J.Phys. 14 (2012) 115009

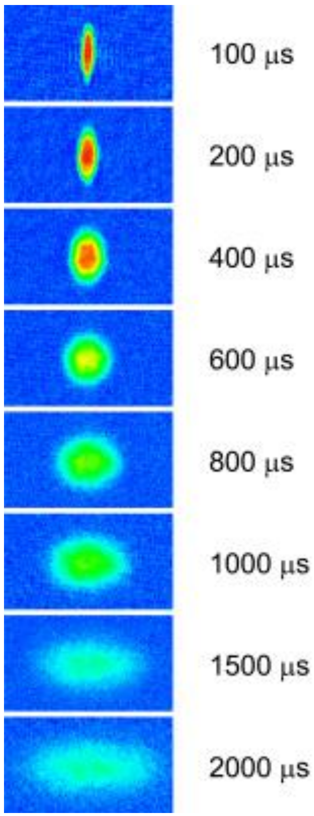




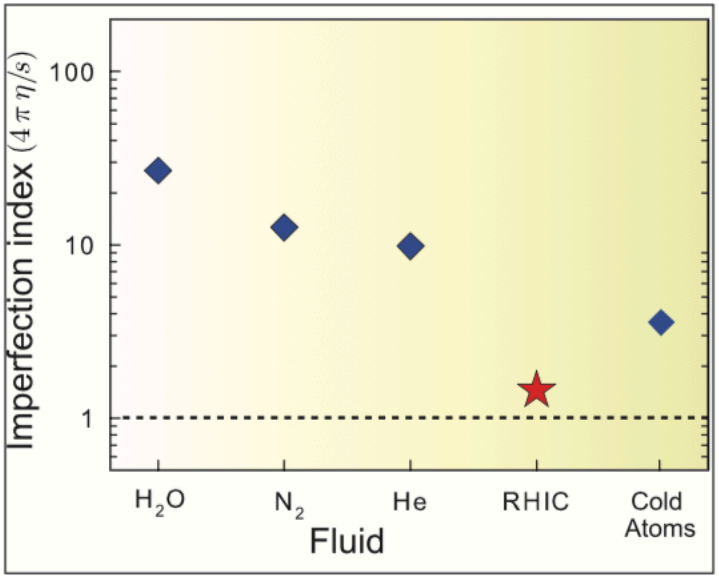
- The ratio η/s is known to have a minimum near phase transition
- Data indicates that viscous corrections are very small → η/s ~ 0.08

Perfect fluidity

Strongly-interacting Fermi gasses display similar anisotropic expansion



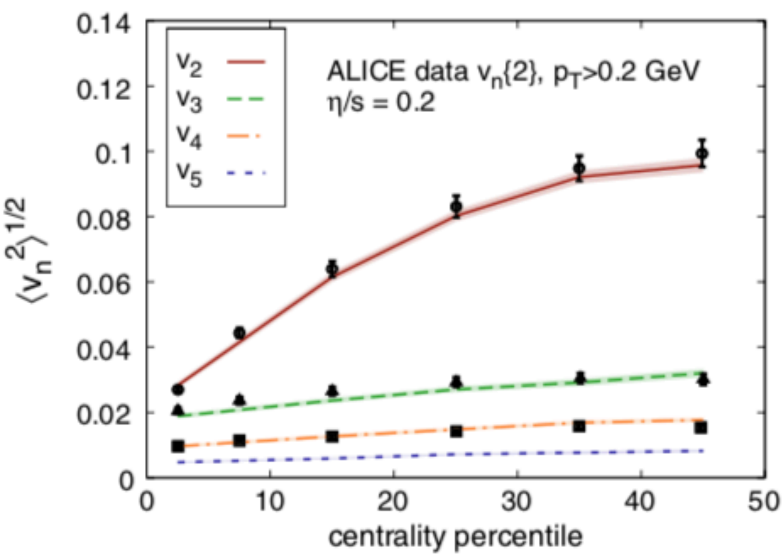
However, viscous corrections are smaller for the QGP than other known systems



Conformal field theory (via *AdS/CFT duality*) gives η/s of 1/4π ~ 0.08
This is conjectured to be a universal lower bound

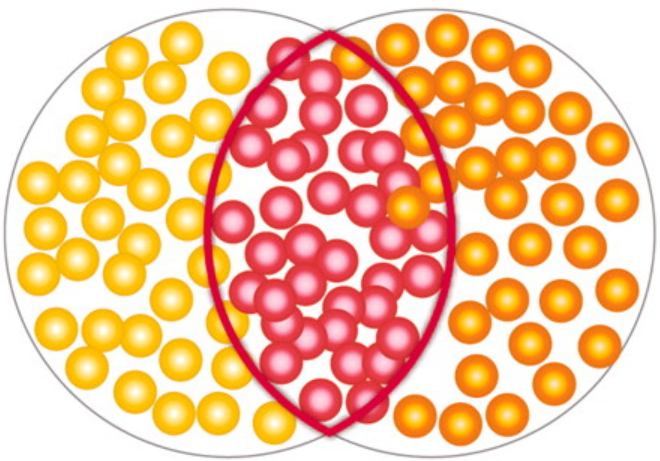
Review on QGP, atomic gasses and AdS/CFT: arXiv:1205.5180

Higher harmonics

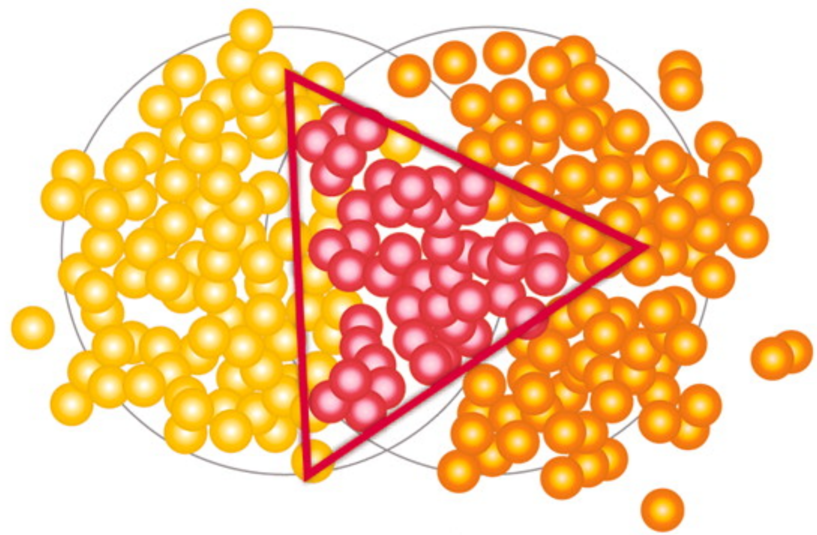


More recently higher harmonics found to be surprisingly large (v_3, v_4)
What is physical picture behind these components of flow?

Geometry fluctuations



Elliptic flow

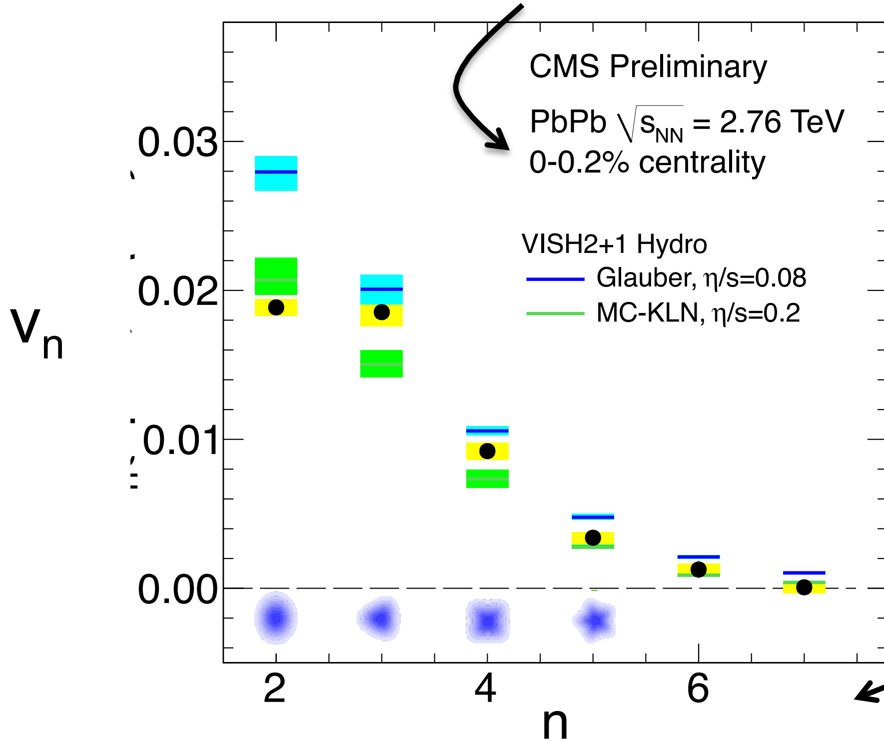


Triangular flow

- 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



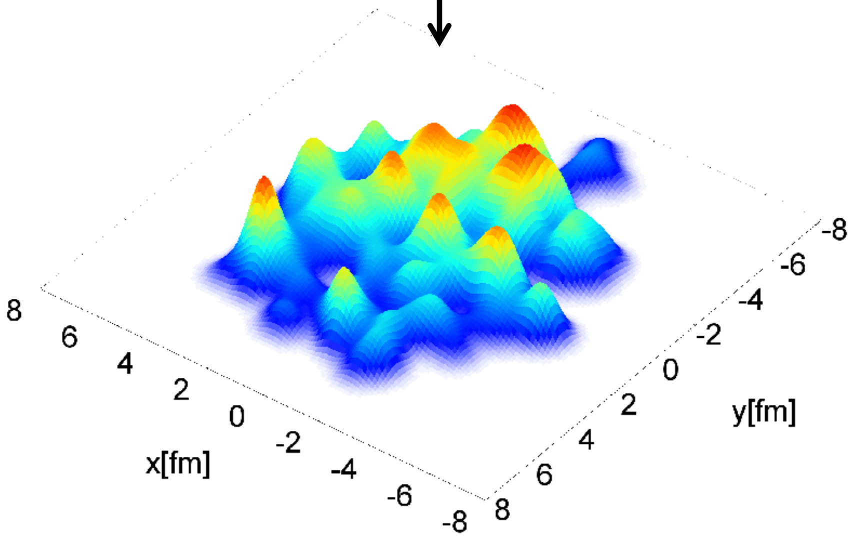
Flow harmonics

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

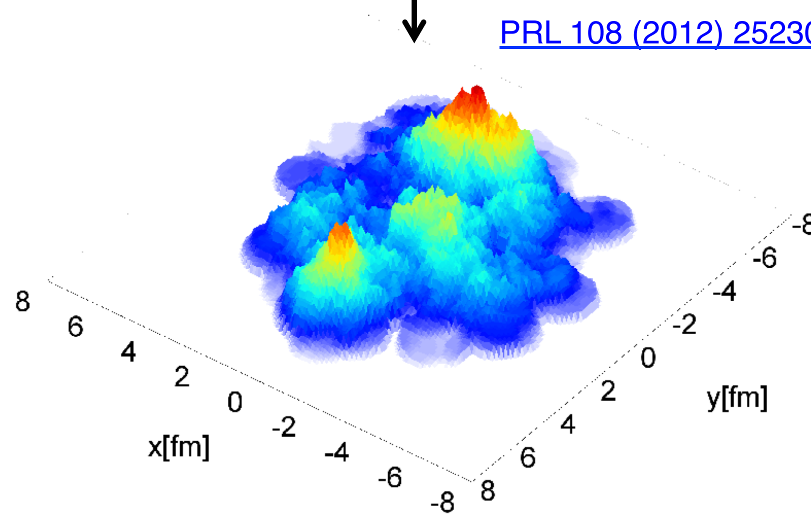
Initial conditions

Initial energy density for a nucleus w/ MC Glauber



Initial energy density for a nucleus w/ MC-KLN, a model w/ sub-nucleonic fluctuations

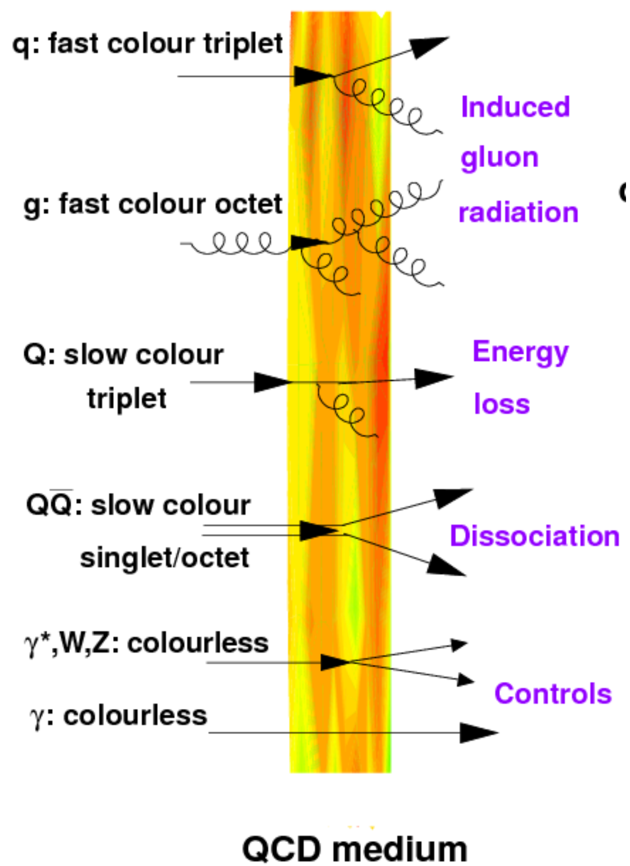
[PRL 108 (2012) 252301](PRL 108 (2012) 252301)



- 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 the particles that are produced in HICs
- 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

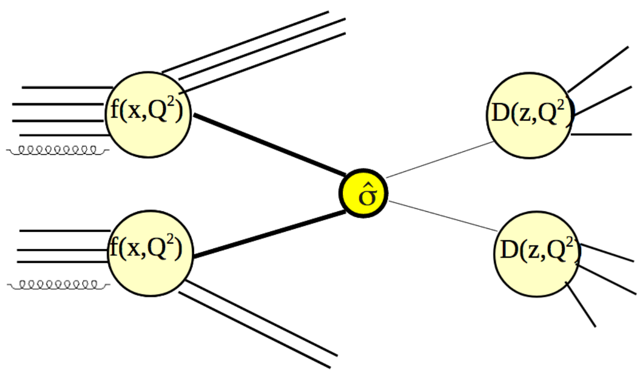


Jets in elementary collisions

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

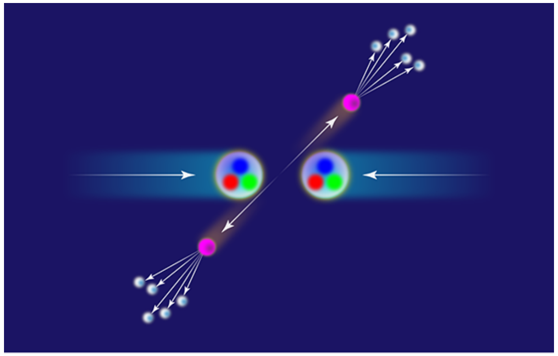
Jet quenching

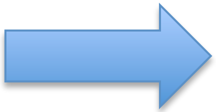
$$d\sigma = f(x_1, Q^2) \otimes f(x_2, Q^2) \otimes d\hat{\sigma} \otimes P(\Delta E) \otimes D(z', Q^2)$$

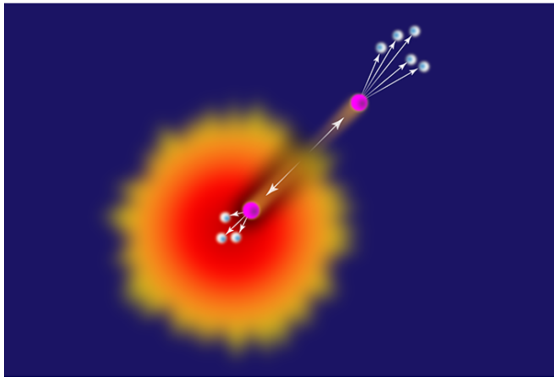
PDFs are modified in nuclei, but relatively small effect

Outgoing parton should lose energy as they cross the QGP

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

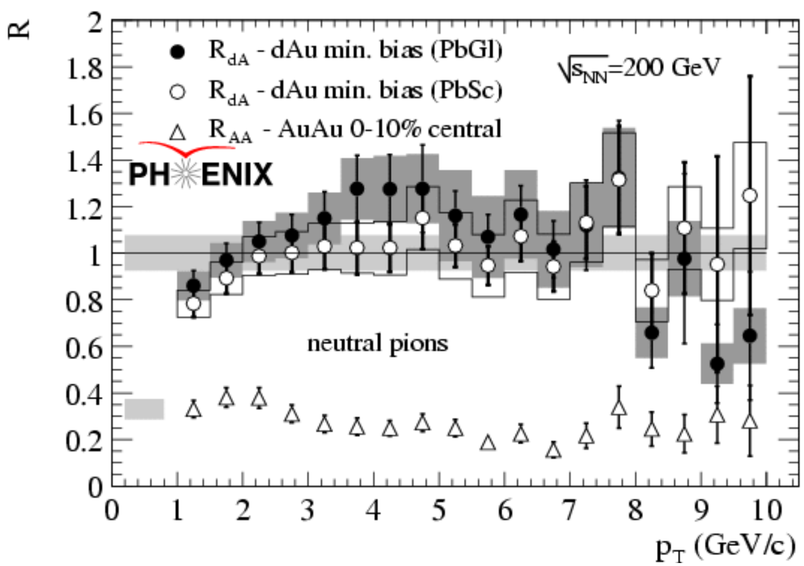






High p_T hadron suppression

PHENIX measured $\pi^0 \rightarrow 2\gamma$
99% branching ratio



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

$$R_{\mathrm{AA}}(p_{\mathrm{T}}) \equiv \frac{dN_{\mathrm{AA}}/dp_T}{\langle N_{\mathrm{coll}}\rangle\, dN_{pp}/dp_T} = \frac{dN_{\mathrm{AA}}/dp_T}{\langle T_{\mathrm{AA}}\rangle\, d\sigma_{pp}/dp_T}$$

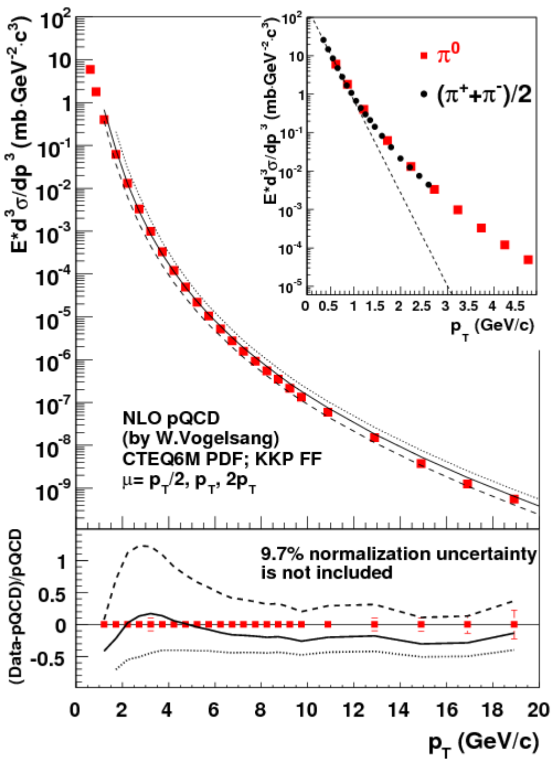
R_{AA} = 1 indicates n_{coll} scaling with no nuclear effects

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

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: $n \approx 7$
LHC: $n \approx 5$

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

then: $$R_{\mathrm{AA}} = (1 - C)^{n-1}$$

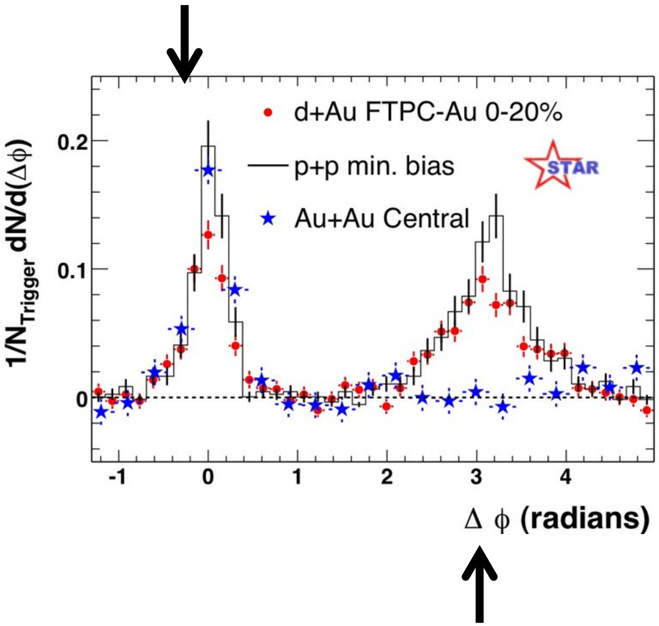
e.g., $R_{AA} = 0.2$ @ RHIC → C = 0.2 (20% e-loss)

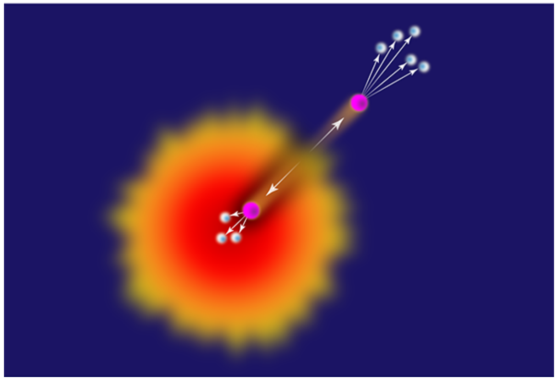
1. Flat R_{AA} consistent with fractional e-loss
2. R_{AA} depends on both e-loss and spectral shape

Dihadron azimuthal correlations

Select *trigger* hadron,
$4 < p_T^{trig} < 6$ GeV
$\Delta\Phi$ to partner hadron,
$2 < p_T < p_T^{trig}$

Small angle correlation from hadrons within a single jet



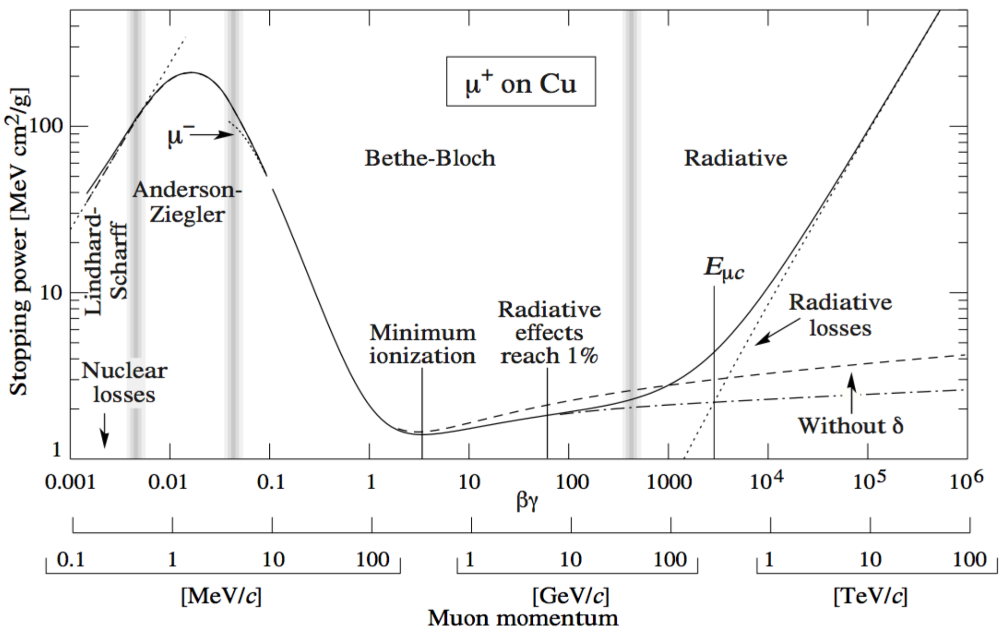


Back-to-back from recoiling jets
Disappears in central Au-Au!

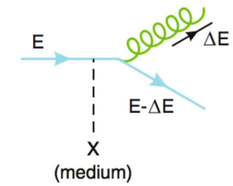
Interpretation: Trigger hadron preferentially produced near surface, while recoil jet traverses the QGP

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

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

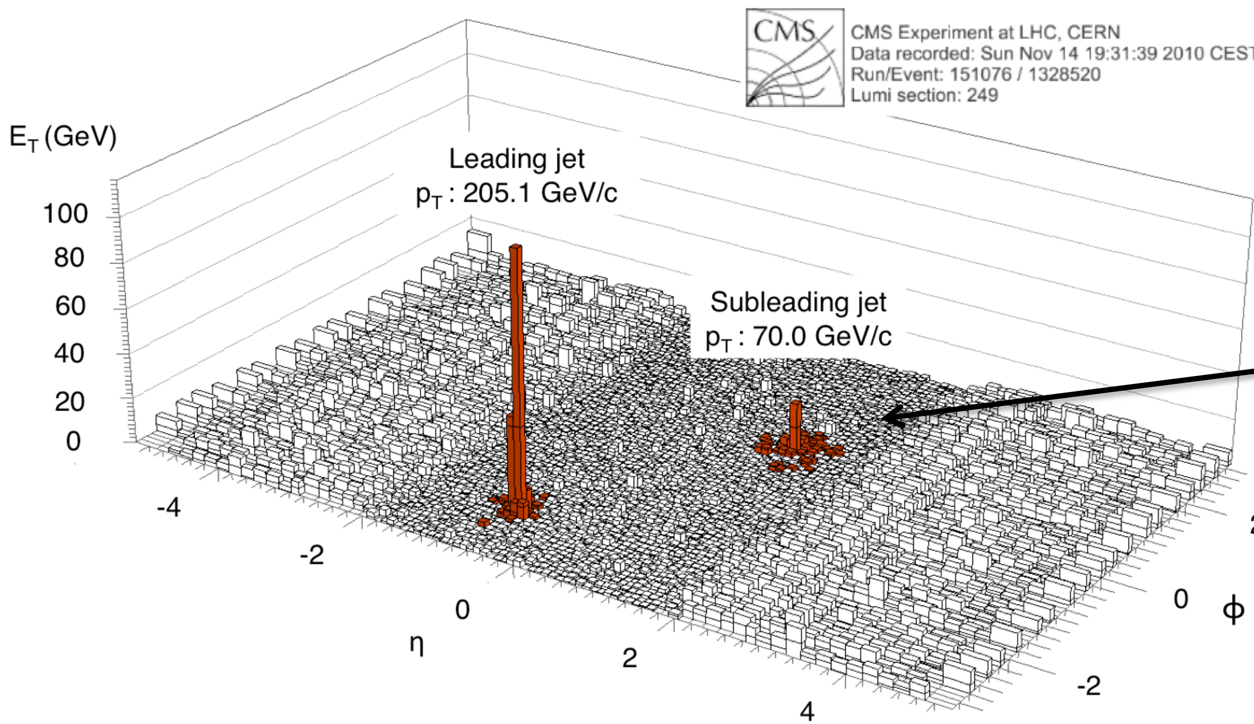
L^2 instead of *L*, due to destructive interference between scattering centers (LPM effect)

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



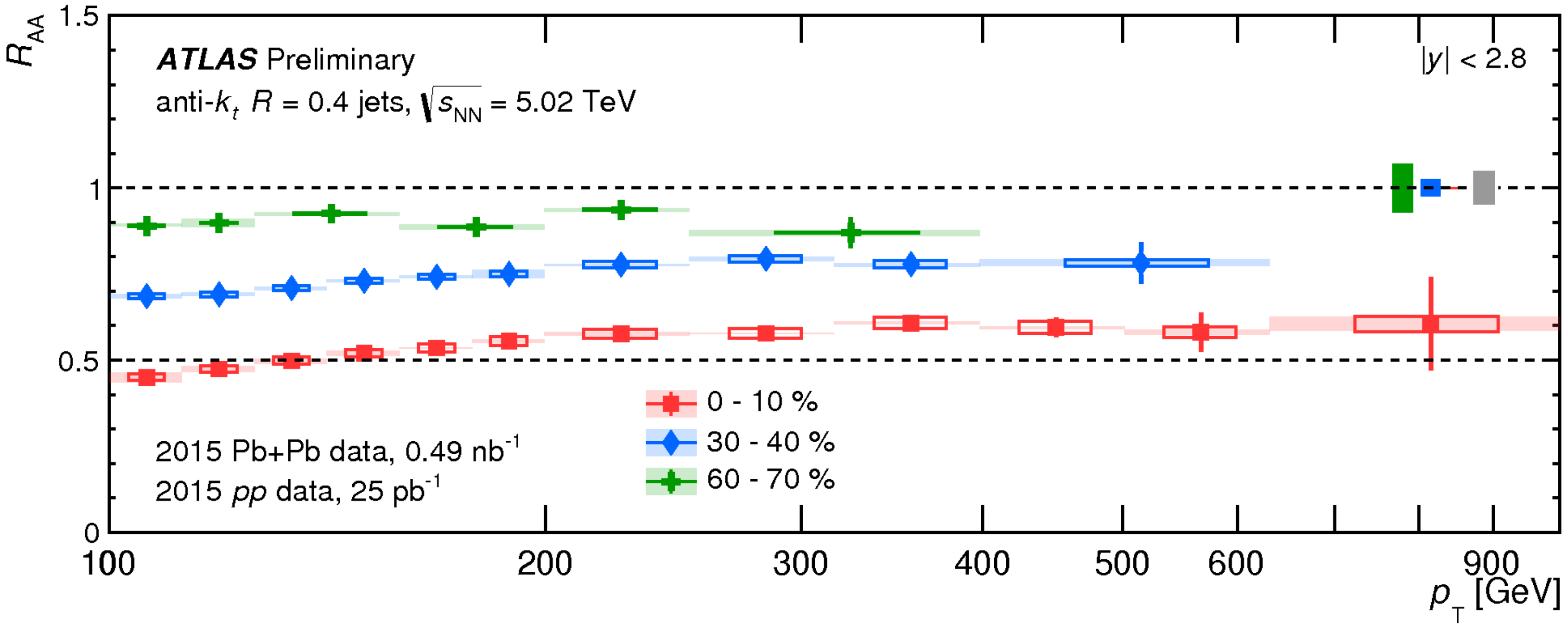
High p_T hadrons are gone, but away jet is still there, albeit with reduced energy

Jet reconstruction become possible at the LHC for the first time

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

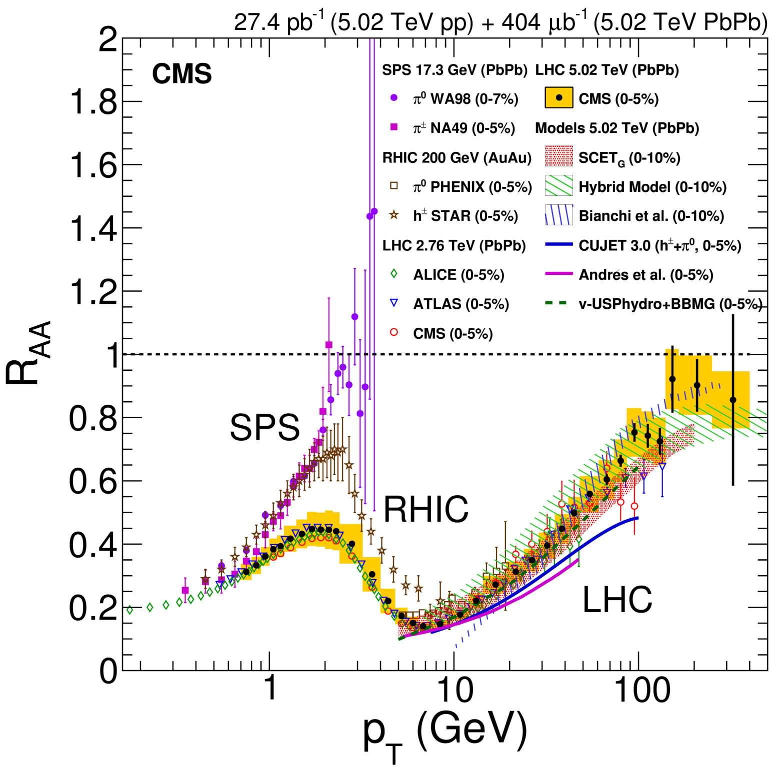
Jet R_{AA}

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?

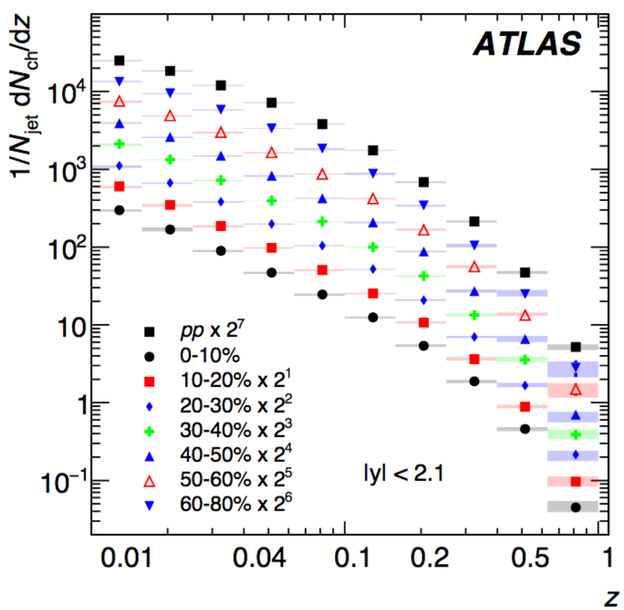
→ Must be dependence of quenching on fragmentation pattern of jet

Jet fragmentation functions

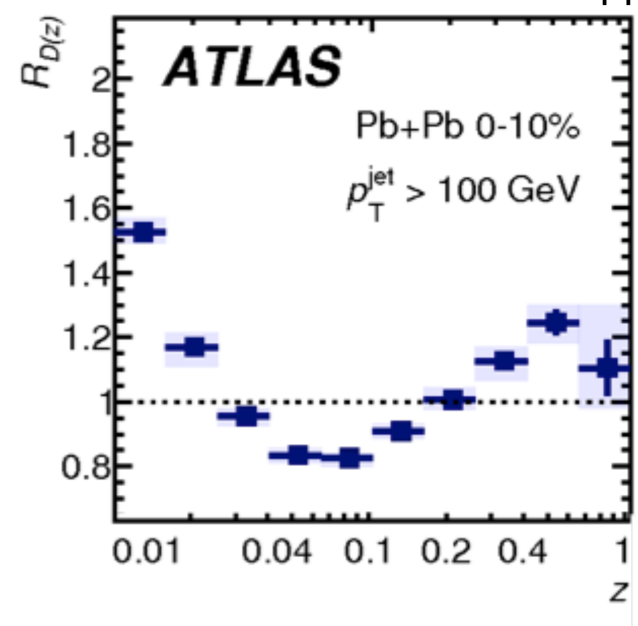
Not a true FF, jet used as proxy for parton $z = p_{T,hadron} / p_{T,jet}$

Not trivial: Quenching may transfer some energy outside jet

dN/dz for different centralities



Ratio of central PbPb to pp



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

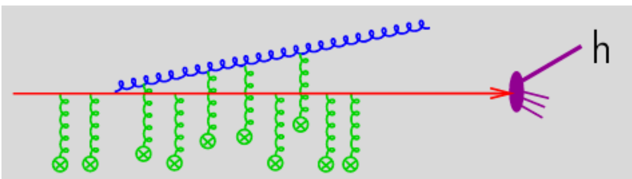
Depletion then excess at intermediate to high *z*:

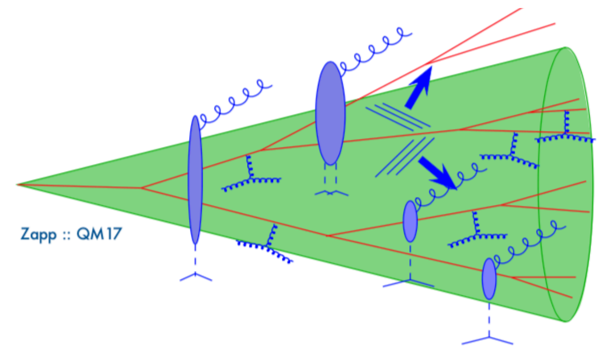
Modification of fragmentation pattern due to quenching?

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



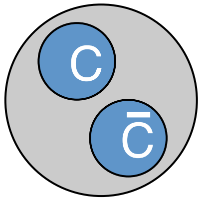


More realistic treatment requires taking into account the entire parton shower

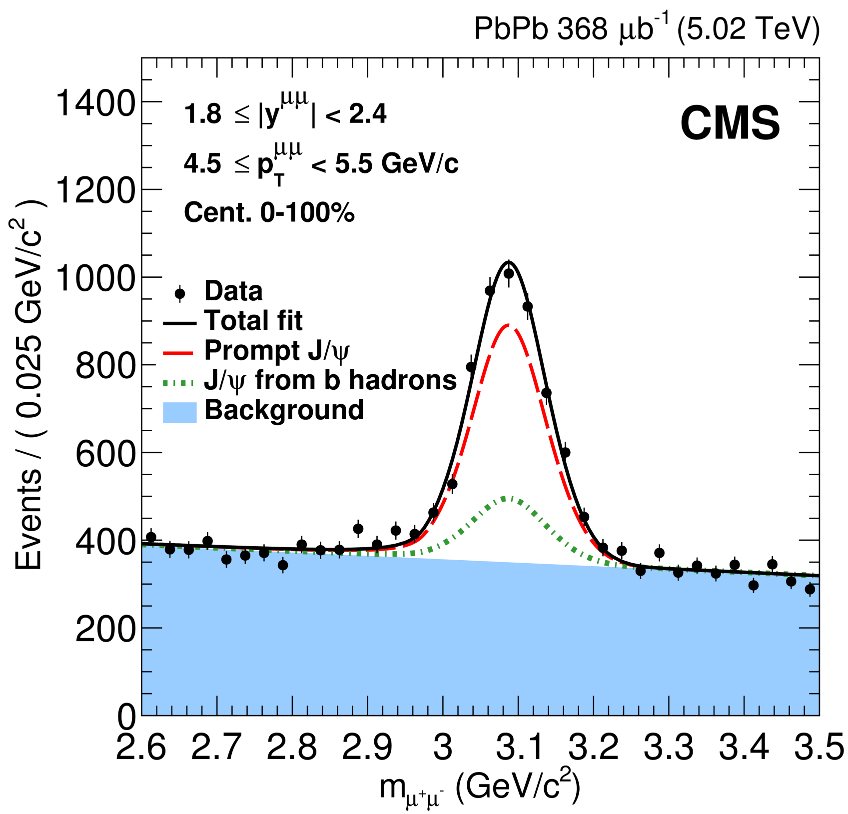
Among the effects currently being studied

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

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

"J/ψ Suppression by QGP Formation"

Matsui & Satz
PLB178 (1986) 416

Cornell potential:

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

Confinement (σr) — Coulomb-like (α/r)

σ and α from fits to onia data

$\sigma \approx 1$ GeV/fm, $\alpha \approx \pi/12$

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

Rest ($2m$) — kinetic ($\frac{1}{2mr^2}$)

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

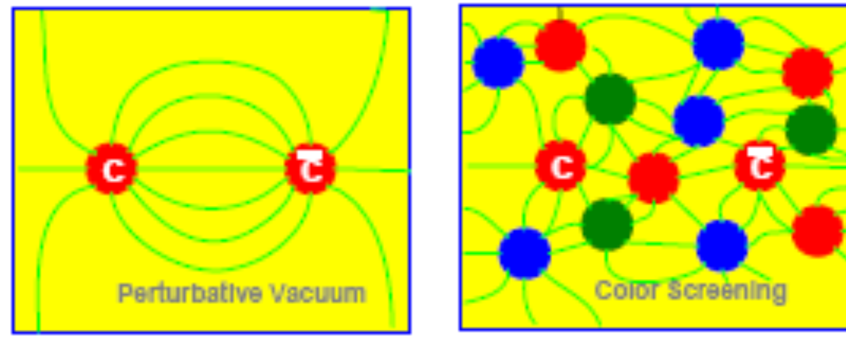
→ Several times smaller than typical light hadrons

Quarkonia melting

Potential is screened in the QGP

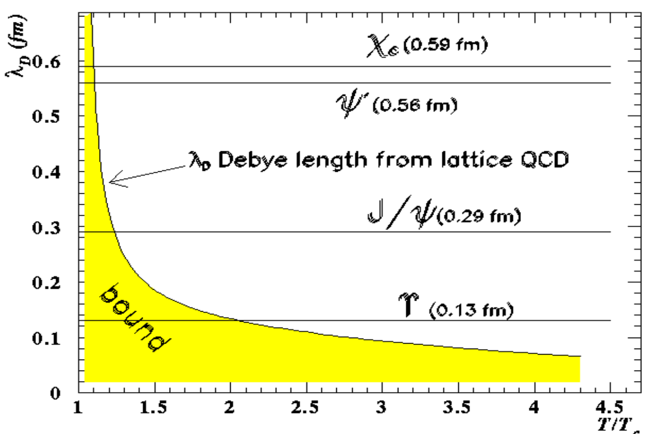
$$V(r) = -\frac{\alpha}{r} e^{r/\lambda_D}$$

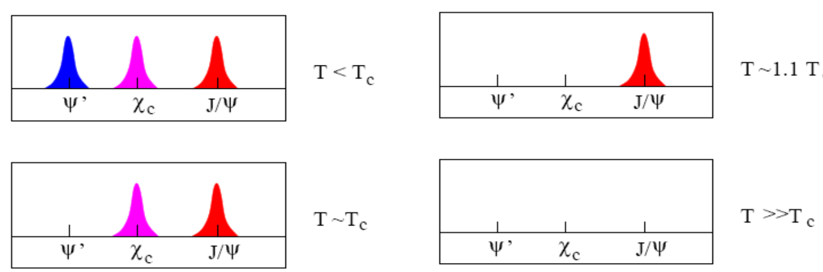
Debye screening length



Besides J/ψ, also excited states ψ' & χ_c
→ Sequential melting vs. binding energy

λ_D provided by lattice QCD





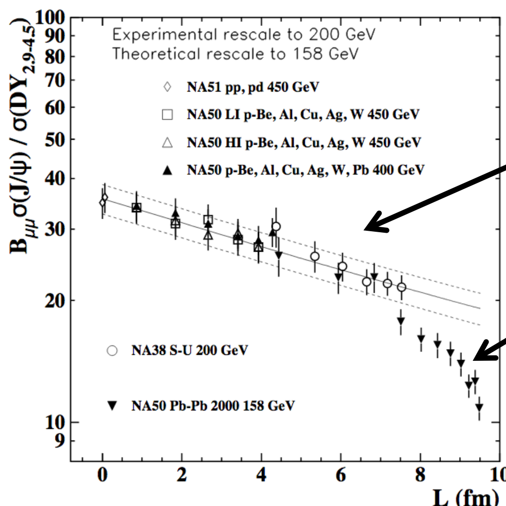
Feed-down complicates matters:
≈10% of J/ψ from ψ'
≈30% of J/ψ from χ_c

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

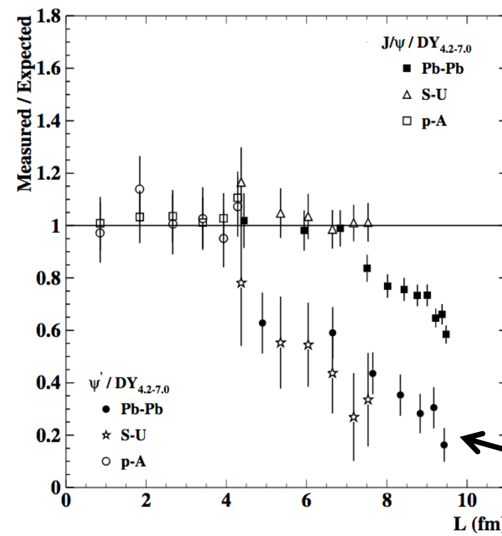


pp & pA

PbPb

Mean nuclear length traversed (L), from Glauber model

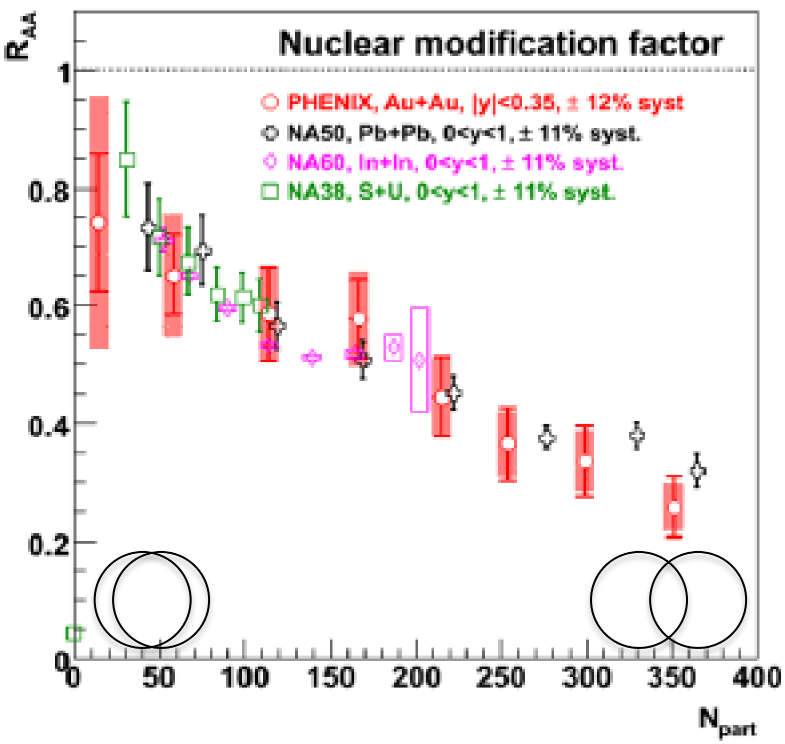
Ratio to nuclear absorption baseline



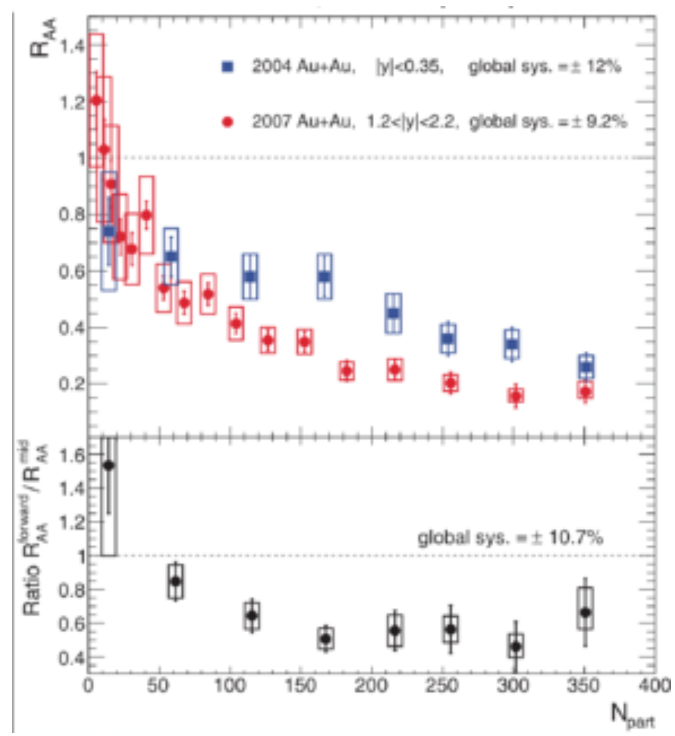
ψ' also studied

- 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



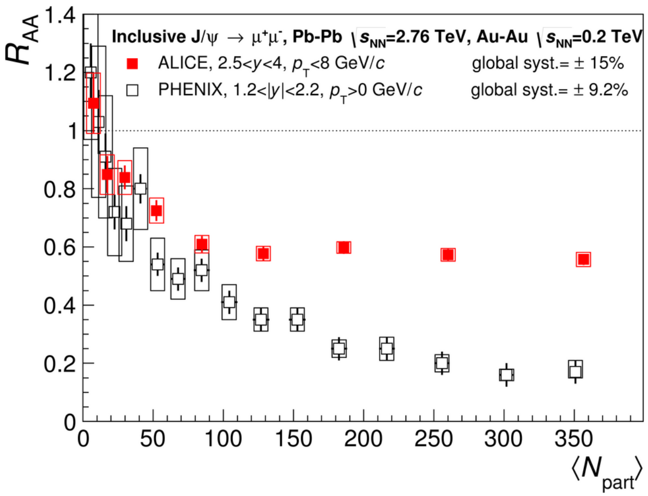
Comparable suppression to SPS
→ Saturation of onia melting?

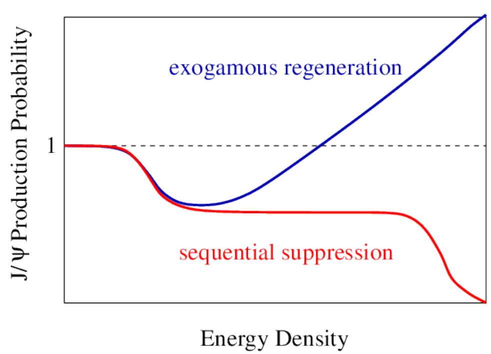


However, larger suppression at forward rapidity → not expected in Debye screening picture

Melting & regeneration

Less suppression at LHC

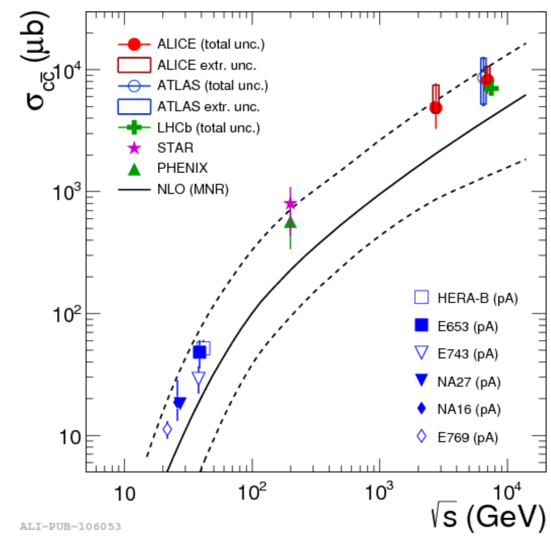




Interpretation: Cancellation of two effects, melting and *regeneration*

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

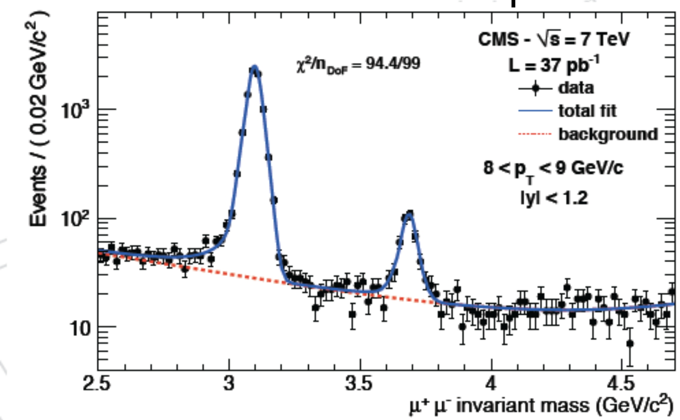
Charm copious enough at high energies to meet other charm in the QGP. Effect ~ N_c^2



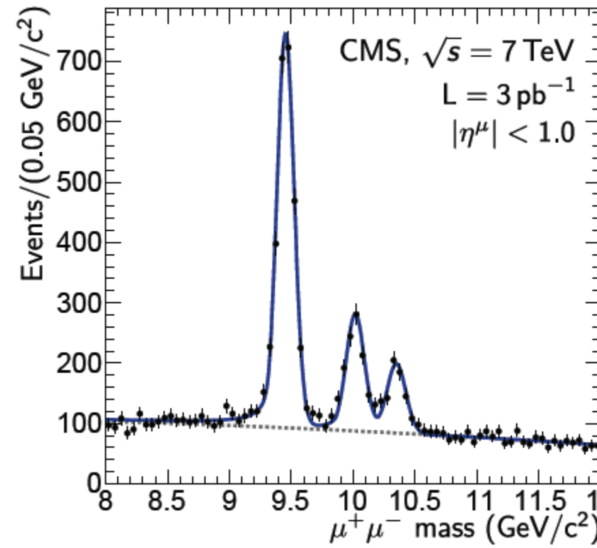
σ(cc) ≈ 5 mb x 1500 coll / 65 mb ≈ 115 cc pairs in a central PbPb collision!

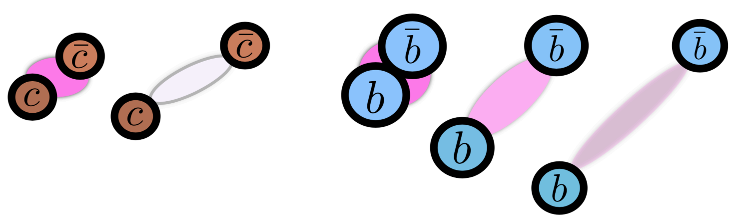
Upsilon spectroscopy

Charmonium dimuon spectrum



Bottomonium dimuon spectrum



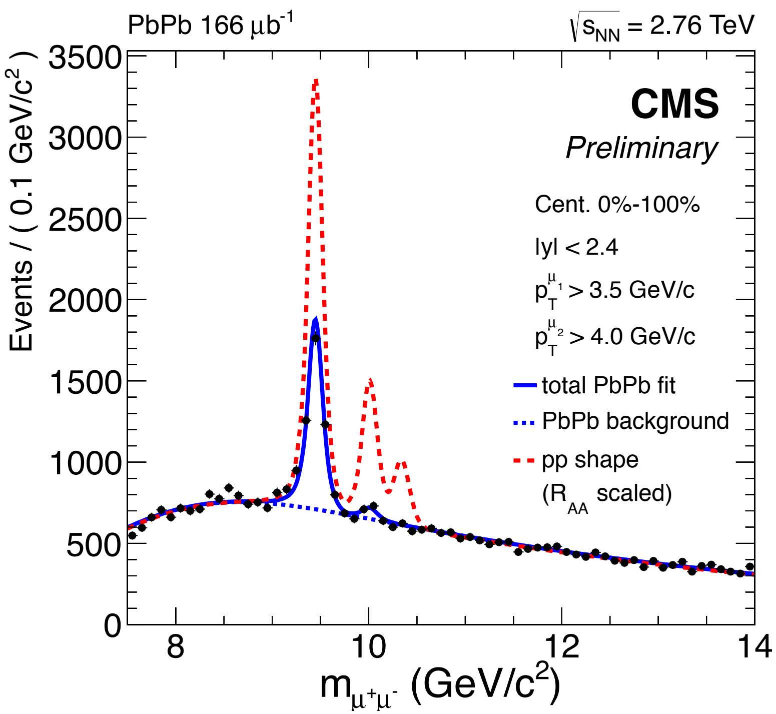


state	J/ψ	ψ'	ϒ	ϒ'	ϒ''
mass (GeV)	3.10	3.68	9.46	10.0	10.4
radius (fm)	0.25	0.45	0.14	0.28	0.39

- 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

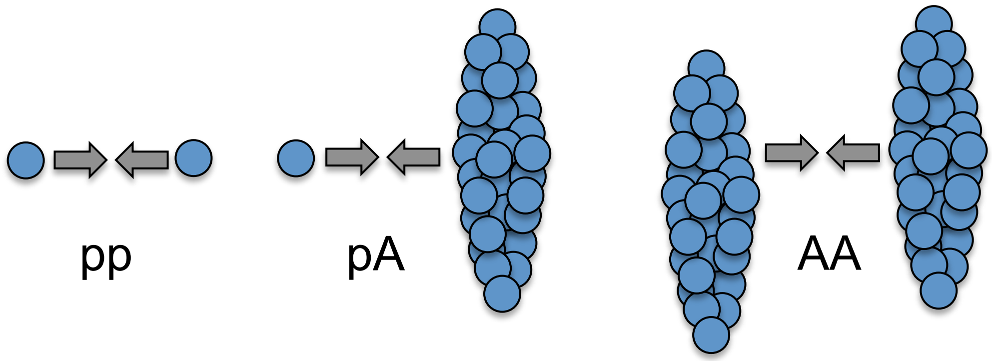


$R_{AA}(\Upsilon(1S)) = 0.453 \pm 0.014 \pm 0.046;$
$R_{AA}(\Upsilon(2S)) = 0.119 \pm 0.028 \pm 0.015;$
$R_{AA}(\Upsilon(3S)) < 0.145$ at a 95% confidence level,

- 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



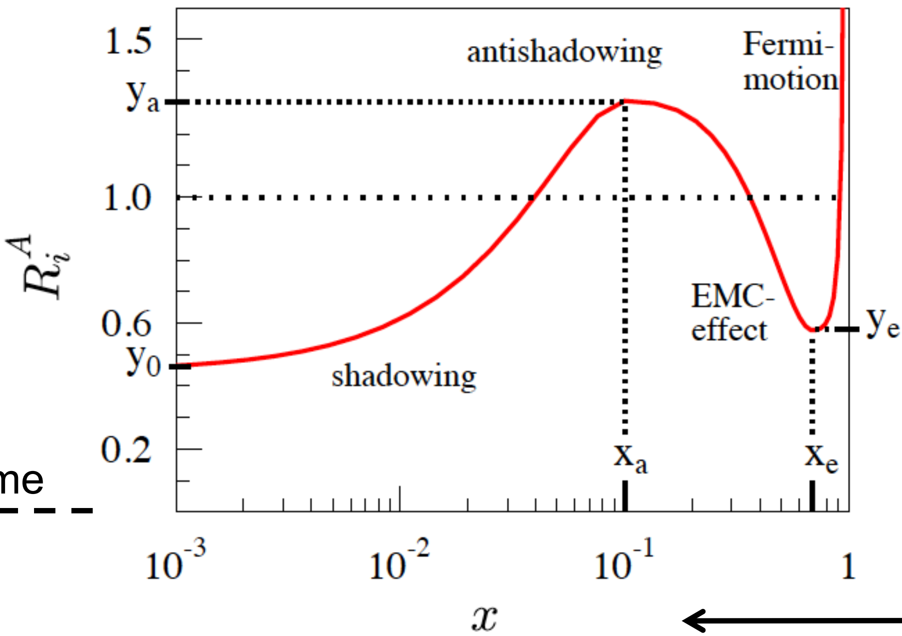
Original paradigm

- 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 ~ decade
Certain effects thought to be tied to deconfinement show up even in smaller systems

Nuclear PDFs

Ratio of nuclear PDF to free proton PDF

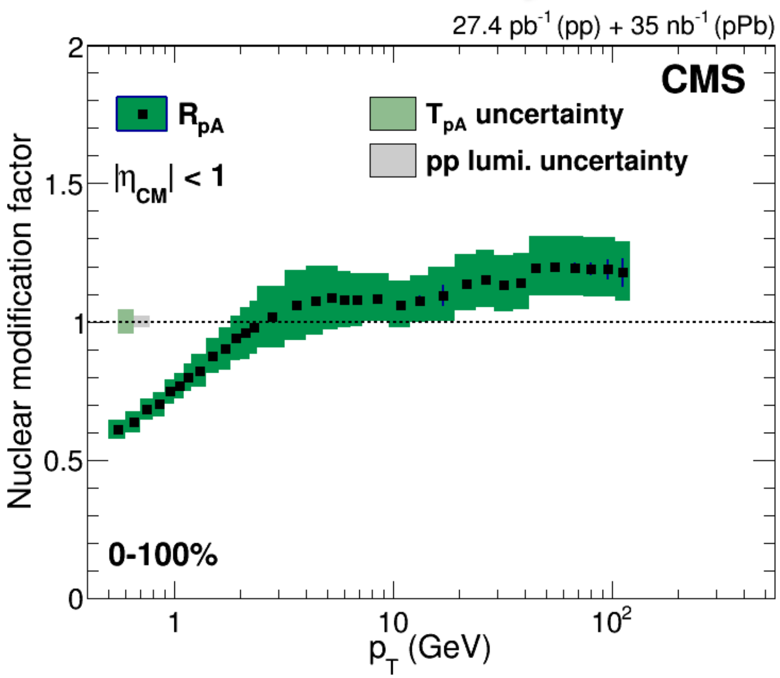


Saturation regime

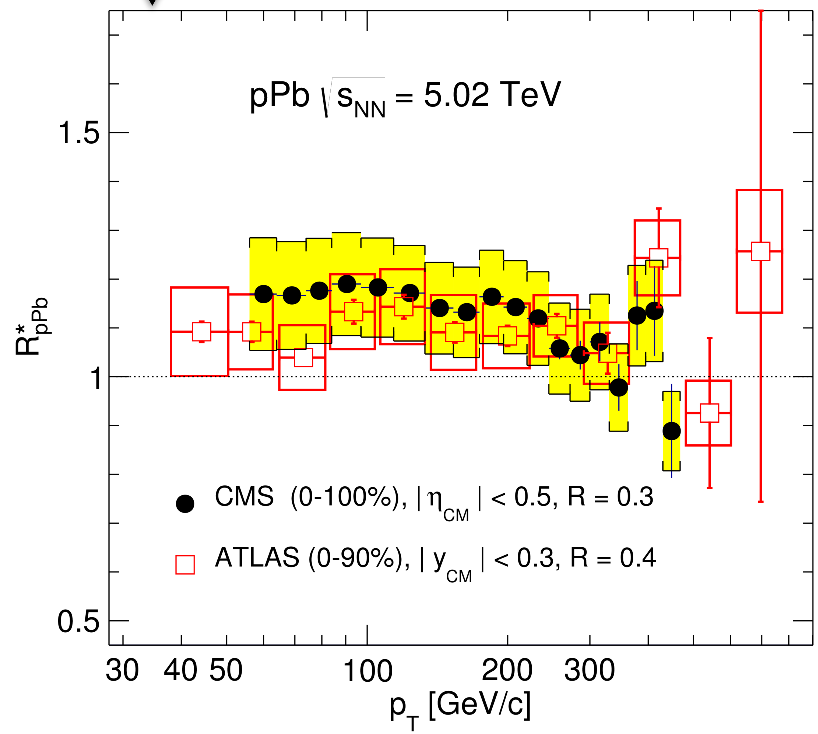
Bjorken x: fraction of nucleon's momentum carried by struck parton

- 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

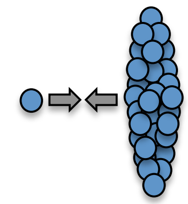


CMS, EPJC 76 (2016) 372

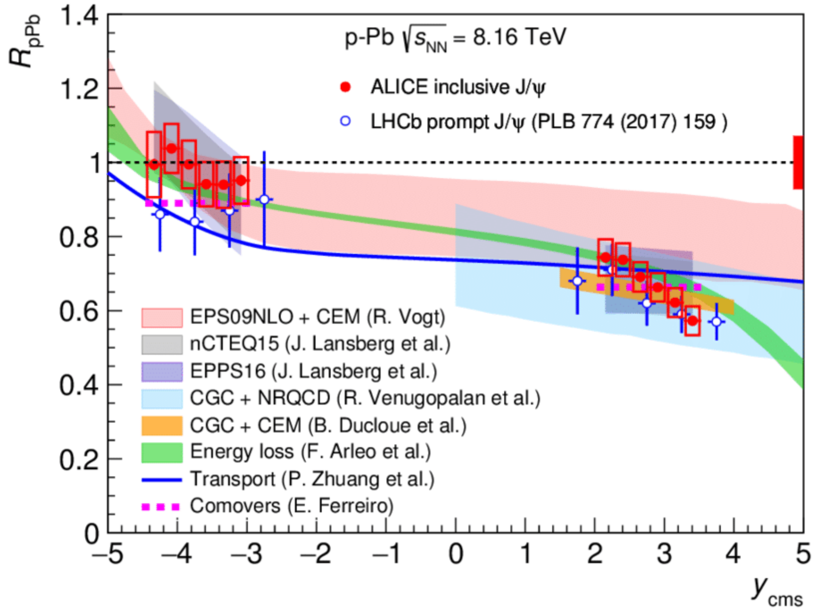
- No suppression as would be expected if jet quenching were present
- Rather, small enhancement due to nuclear parton distributions (anti-shadowing)

Quarkonia R_{pA}

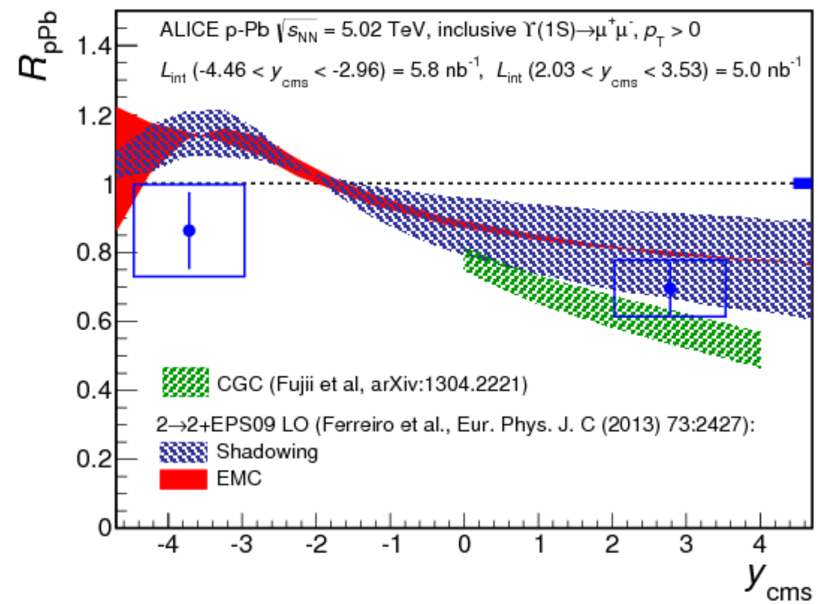
Proton-going direction →



J/ψ



ϒ(1s)



Quarkonia access lower x, where shadowing expected to dominate

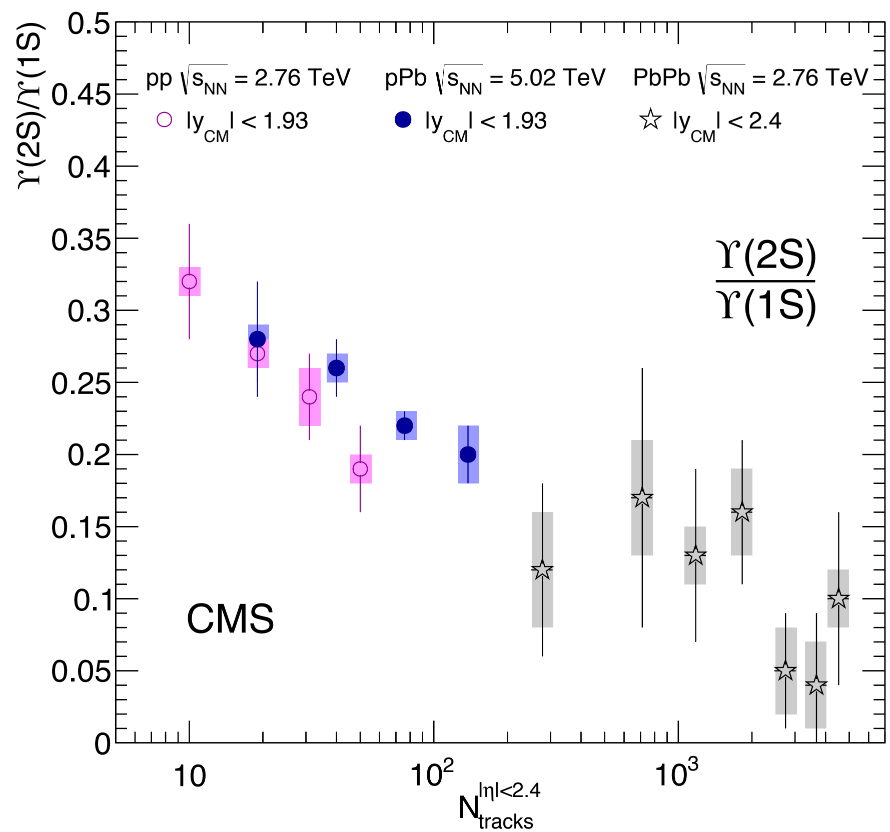
Results consistent with shadowing in proton-going direction

Part of the ϒ suppression is due to PDF effects

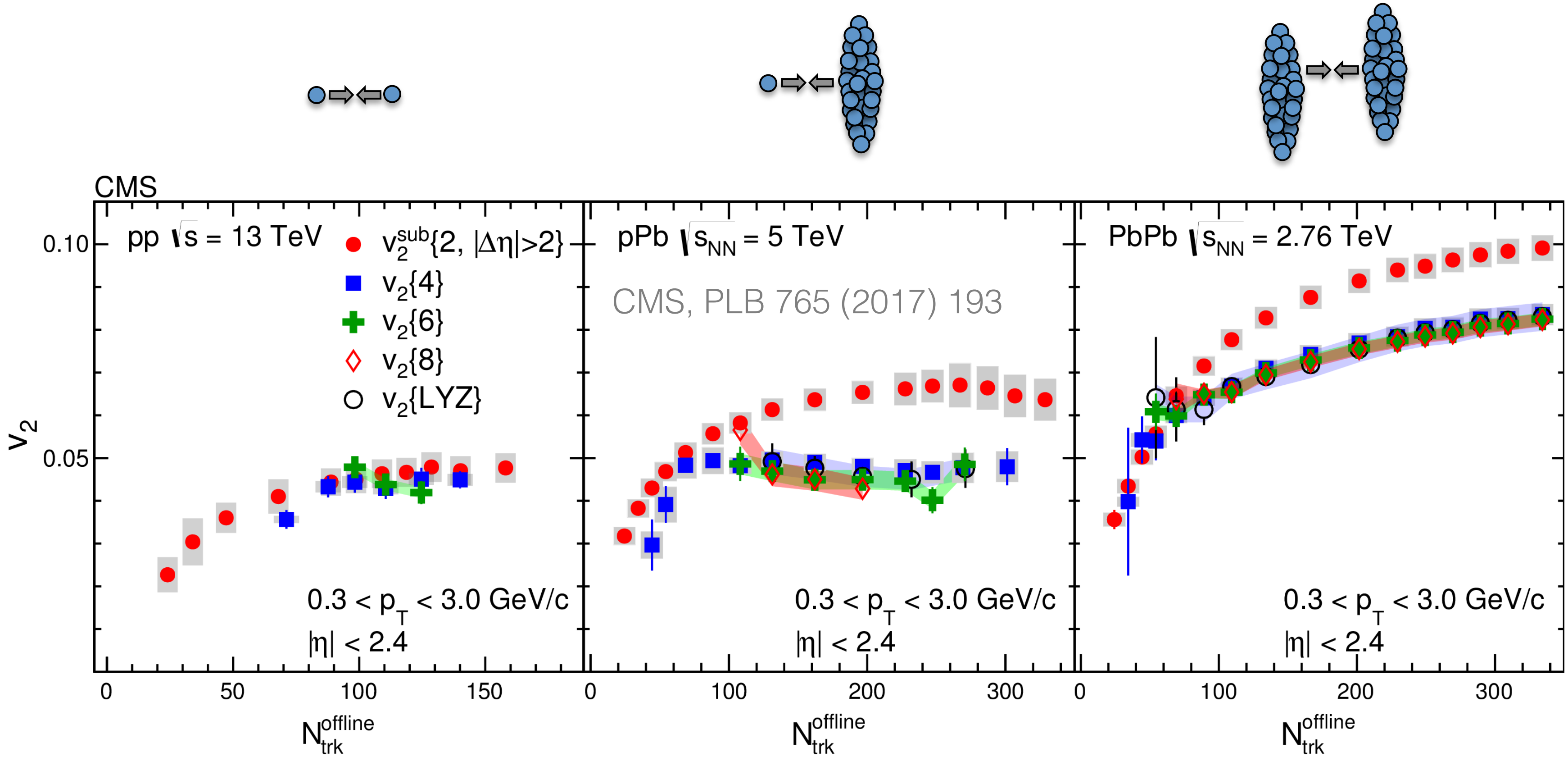
ϒ states vs. multiplicity

- 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



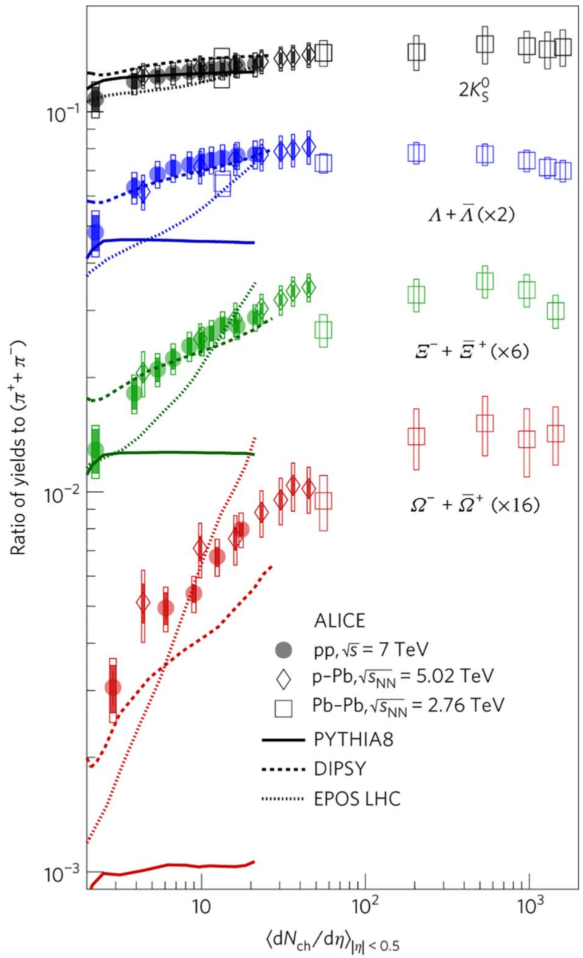
Multiparticle correlations



- 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

Lecture 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

Further reading

- Excellent set of lectures on heavy-ion physics
  https://www.physi.uni-heidelberg.de/~reygers/lectures/2017/qgp/
- Recent Nature article on the statistical hadroproduction
  https://www.nature.com/articles/s41586-018-0491-6.pdf
- Review on the connection between the QGP, cold Fermi gasses & AdS/CFT arXiv:1205.5180