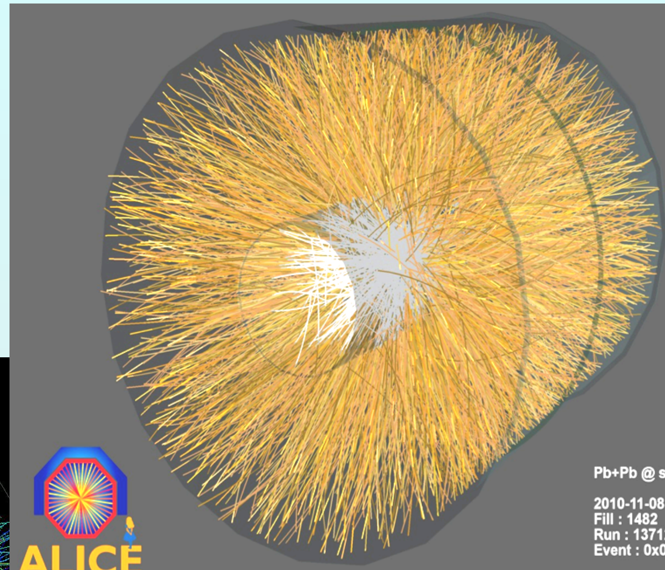
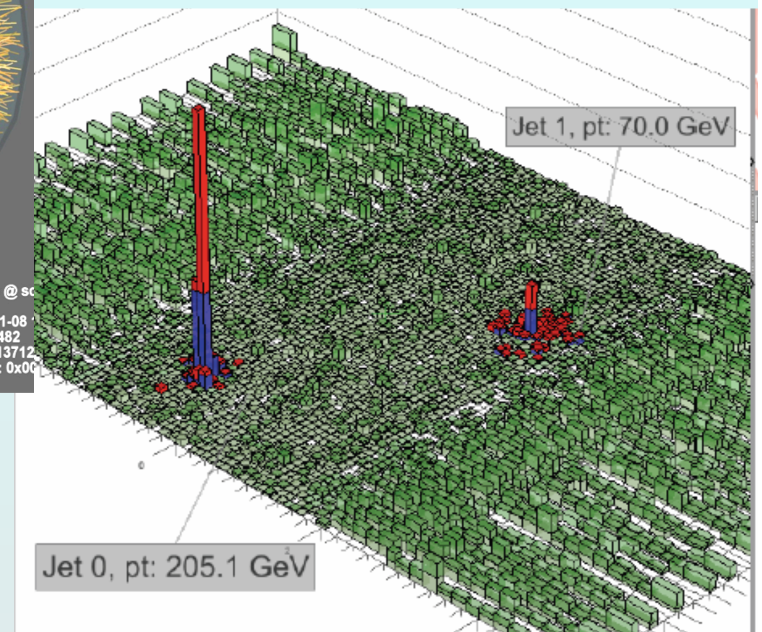
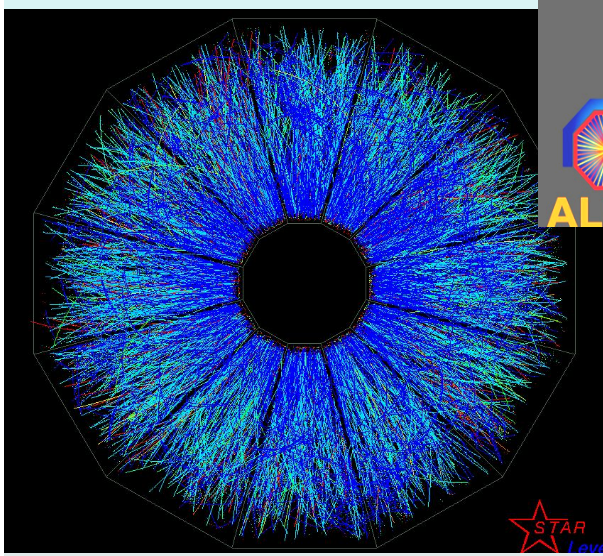
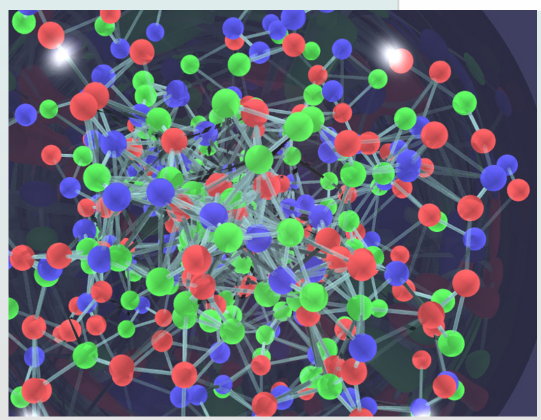
Hot QCD









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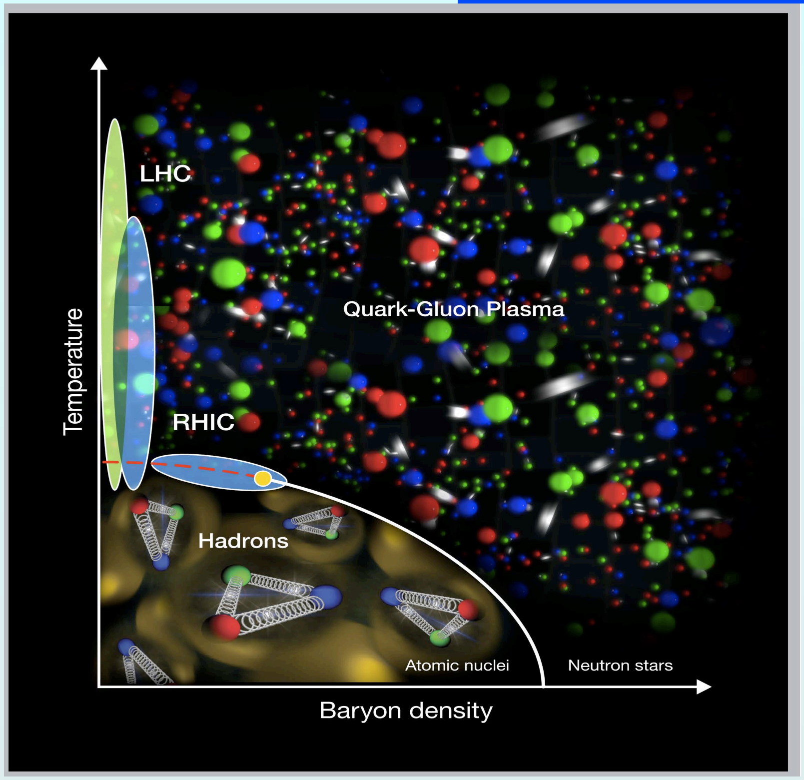
UC Berkeley

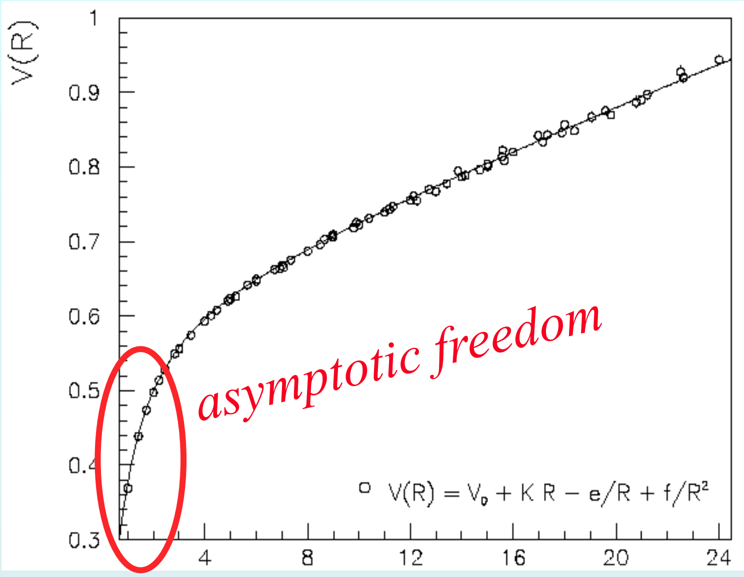
Feb. 17, 2016

outline

- Why hot QCD
- How – and what - we measure
- Controlling the collision
- Collective behavior in QCD
- Parton interactions with quark gluon plasma
- Color screening in quark gluon plasm

Hot, dense QCD matter





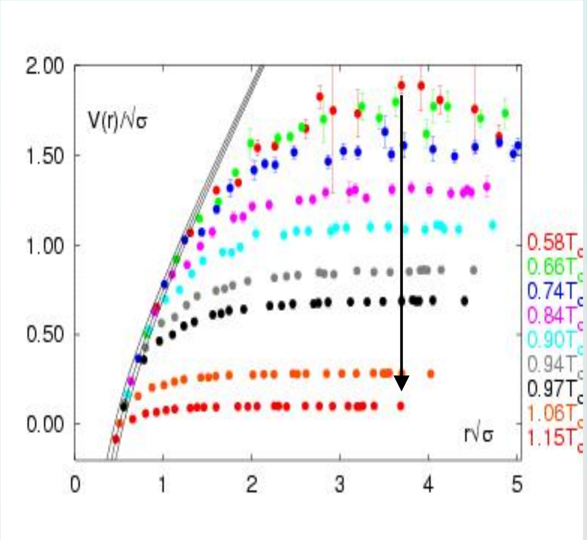
At high temperature/density

screening by produced colored particles

Expect phase transition to

deconfined quark gluon plasma

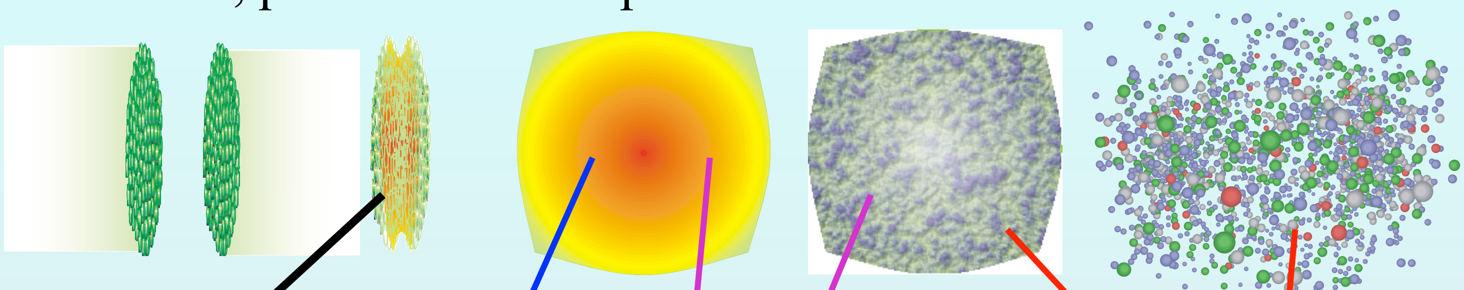
Lattice QCD → T_c ~ 150 MeV



heavy ion collision & diagnostics

time →

ε, pressure builds up



Hard scattered q,g
(short wavelength)
probes of plasma
formed

Hot QGP

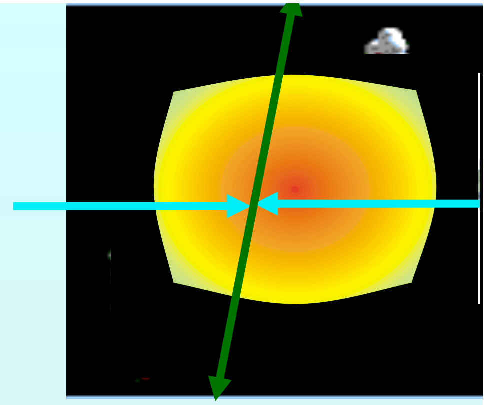
thermal radiation
(γ, γ*→ e^+e^-, μ+μ−)

π, **K**, **p**, **n**, φ, Λ, Δ, Ξ, Ω, **d**,

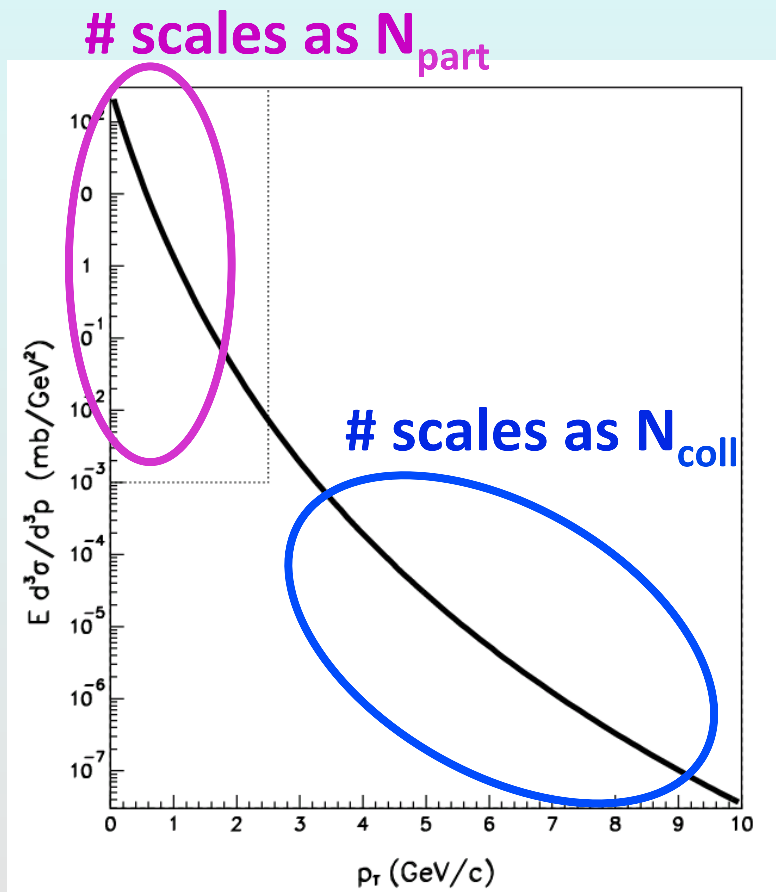
Hadrons qqq baryons & $q\bar{q}$ mesons
reflect (thermal) properties when
inelastic collisions stop

not possible to measure as a function of time
nature integrates over the entire collision history

study plasma with radiated & "probe" particles



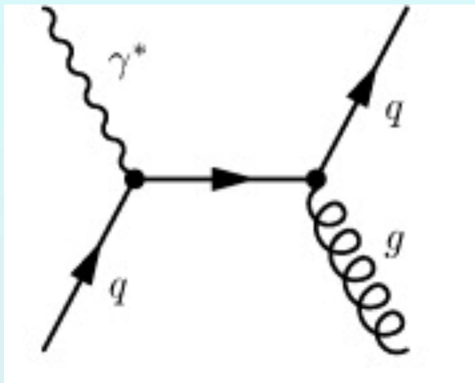
- as a function of transverse momentum
  - 90° is where the action is (max T, ρ)
    - p_L between the two beams: midrapidity
- p_T < 1.5 GeV/c
  - "thermal" particles π,K,p, etc.
  - radiated from bulk medium
  - "internal" plasma probes
- p_T > 3 GeV/c
  - "large E_{tot}" (p_T or M >>T)
  - set scale other than T(plasma)
  - autogenerated "external" probe
  - describe by perturbative QCD
- control probe: photons
  - EM, not strong interaction
  - produced in Au+Au by QCD
    - Compton scattering



Some cool observables

- **Compare p+A to p+p for gluon distribution in A**

  Use QCD Compton scattering



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What to measure to study thermalization (pre-equilib)?

- **Penetrating probes**

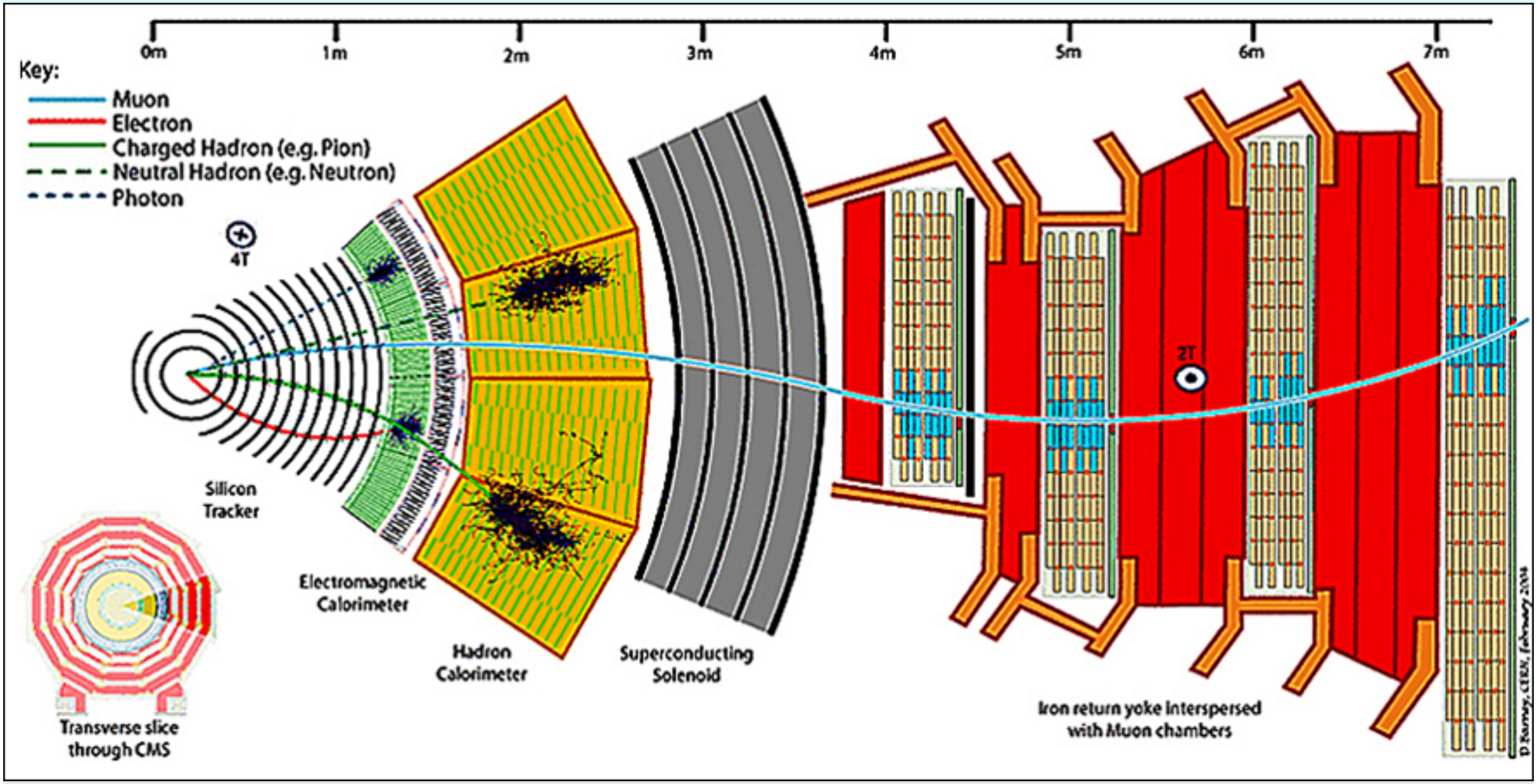
  γ or e^+e^- emitted during thermalization?

- **Lasting probes (which may survive later stages)**

  Correlations and fluctuations among groups of particles

  Pre-equilibrium flow?

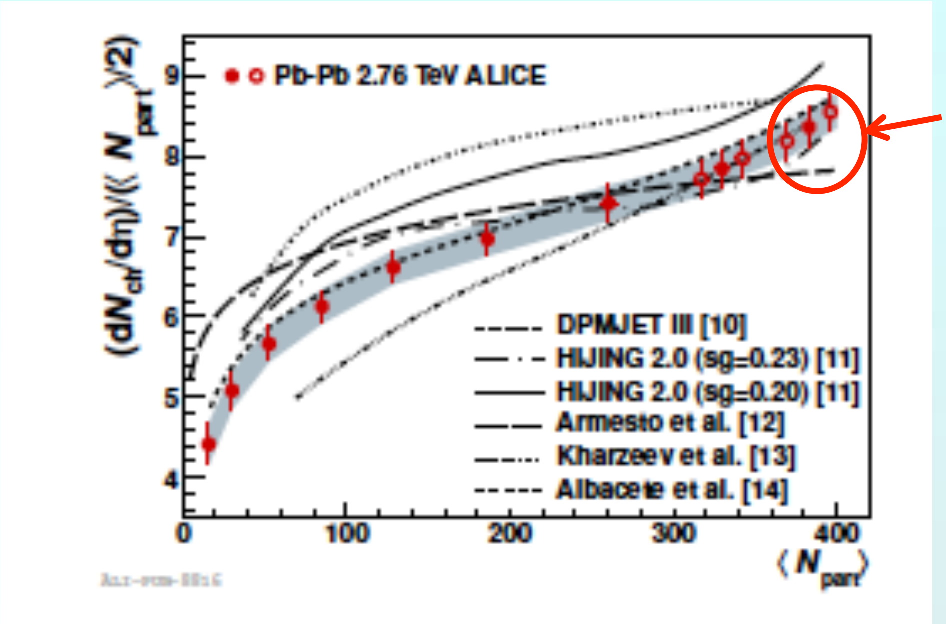
How to measure all this stuff?



+ dE/dx & Time-of-flight: hadron ID + Cherenkov & TRD: electron ID

High granularity to handle high multiplicity

Handling high multiplicities



1700 particles per unit η

Challenge for Si: # of space points

Challenge for TPC: space charge

Trick: reconstruct collision vertex & use it in track reconstruction

Luminosity = frequency$*n_1*n_2/(4\pi\sigma_x\sigma_y)$

higher Z -> lower n

@RHIC $\langle\mathcal{L}\rangle$ in Au+Au /pp ~ 1/600

Just how tough is this?

For p+p collisions, value is about 4 particles per unit η

But, luminosity is much higher!

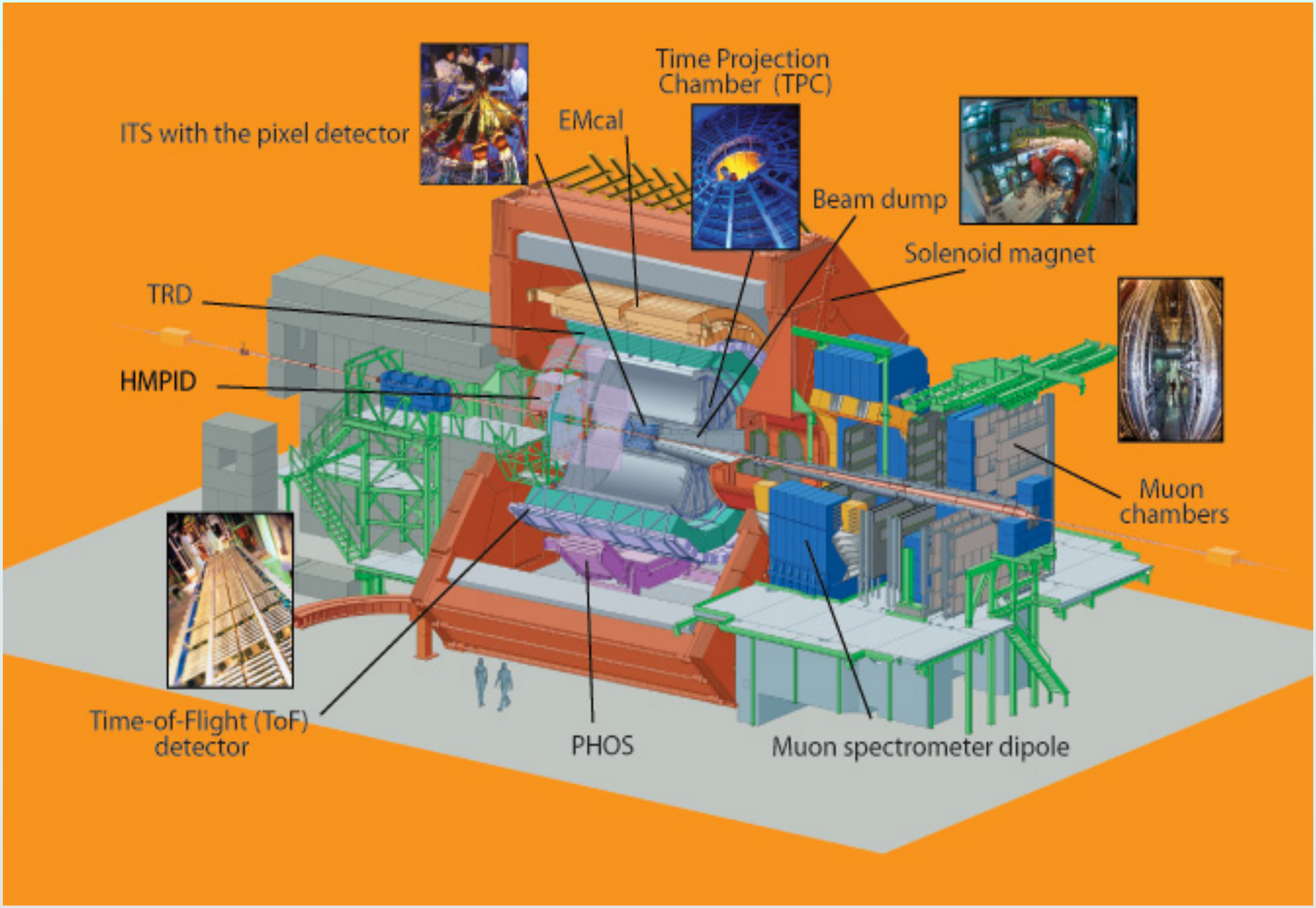
Pileup in high luminosity p+p = 150 events/crossing ($dN/d\eta$ ~ 600)

but these are from different vertices!!

Pile-up rate in ATLAS in 2015?

ATLAS handles a similar tracking problem (it can do HI collisions!)

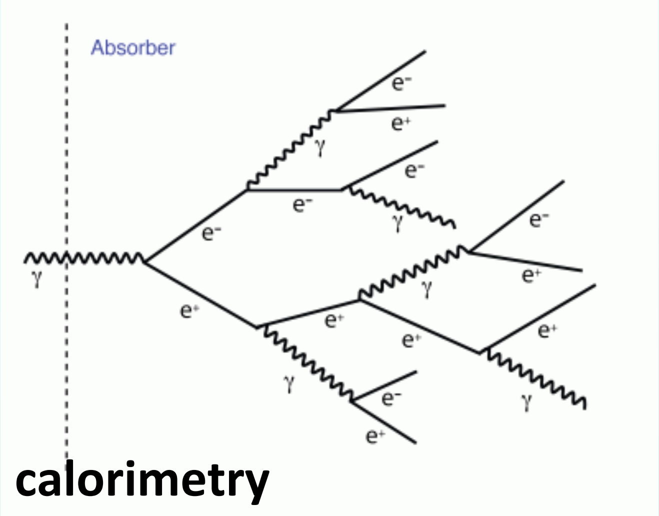
PID in ALICE

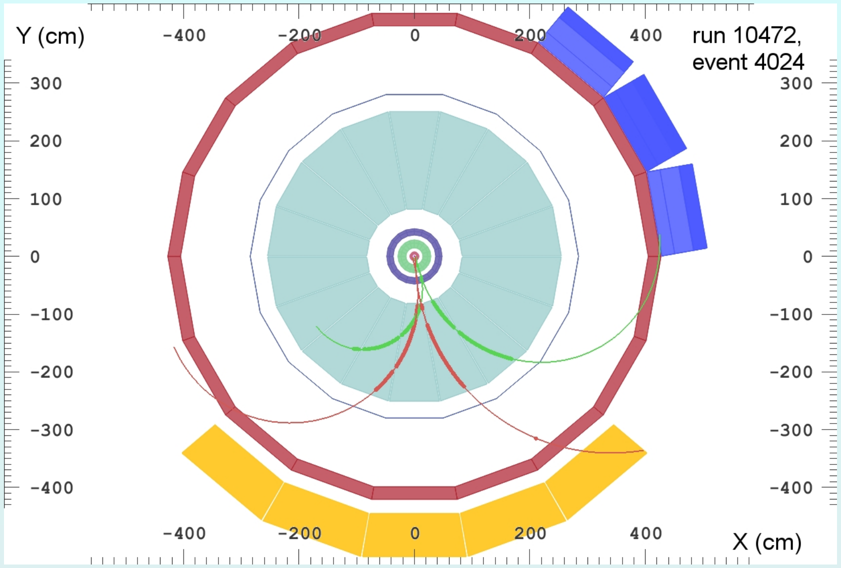


ITS with the pixel detector
EMcal
Time Projection Chamber (TPC)
Beam dump
Solenoid magnet
TRD
HMPID
Muon chambers
Time-of-Flight (ToF) detector
PHOS
Muon spectrometer dipole

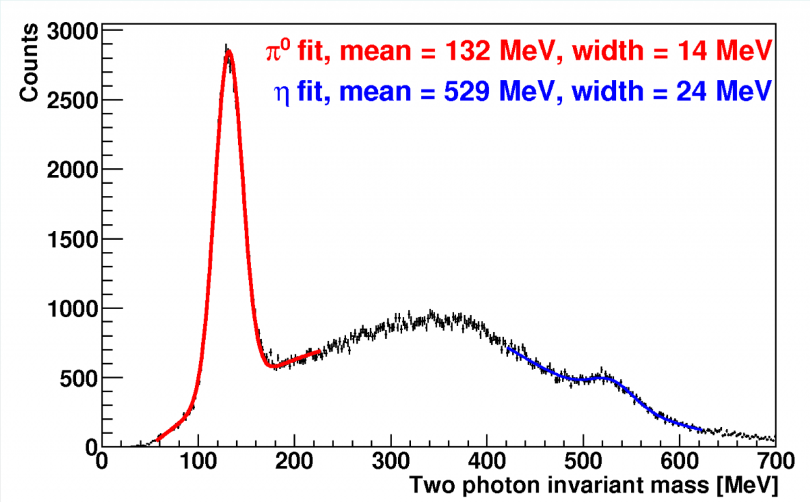
Measuring photons

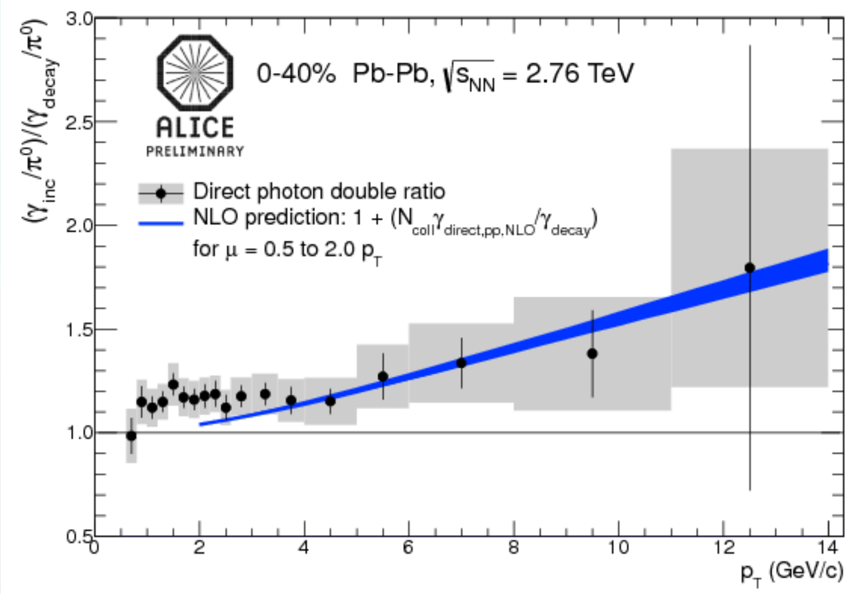
- **Two ways to measure photons**



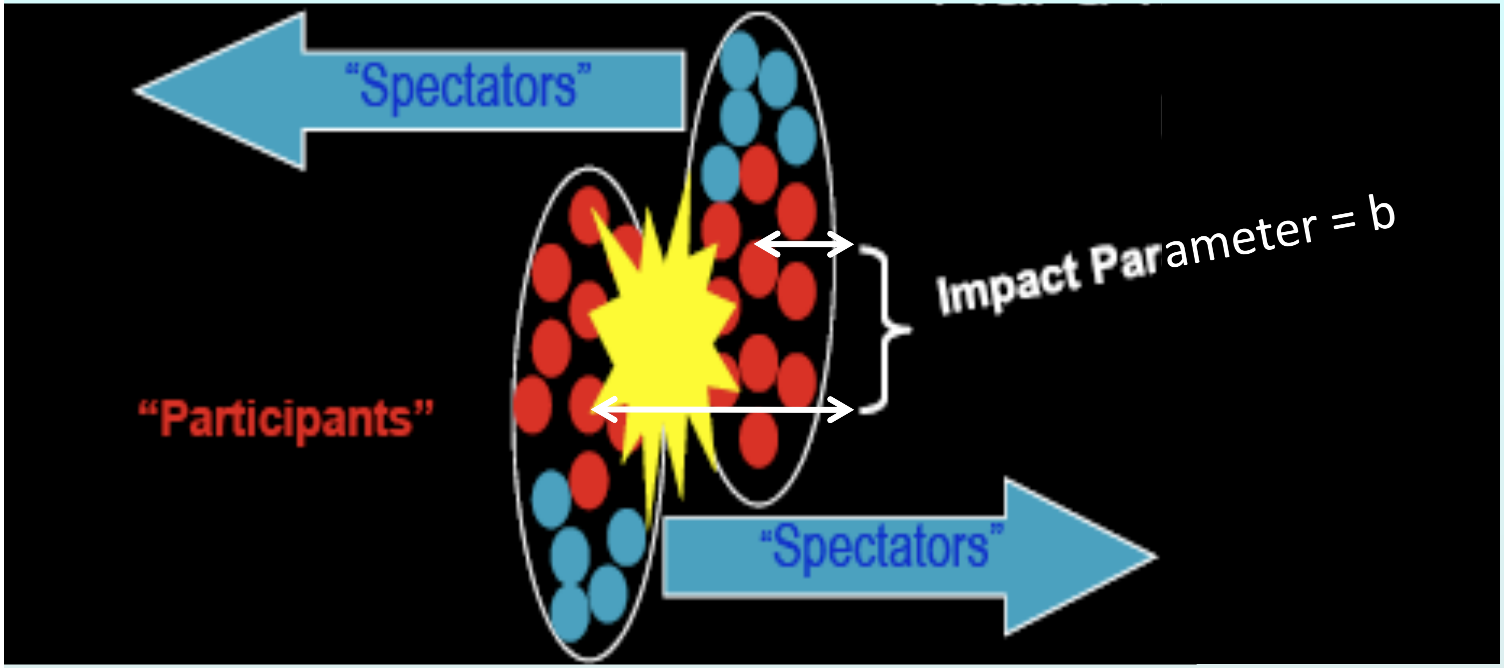


- **Big backgrounds**





Geometry of heavy ion collisions

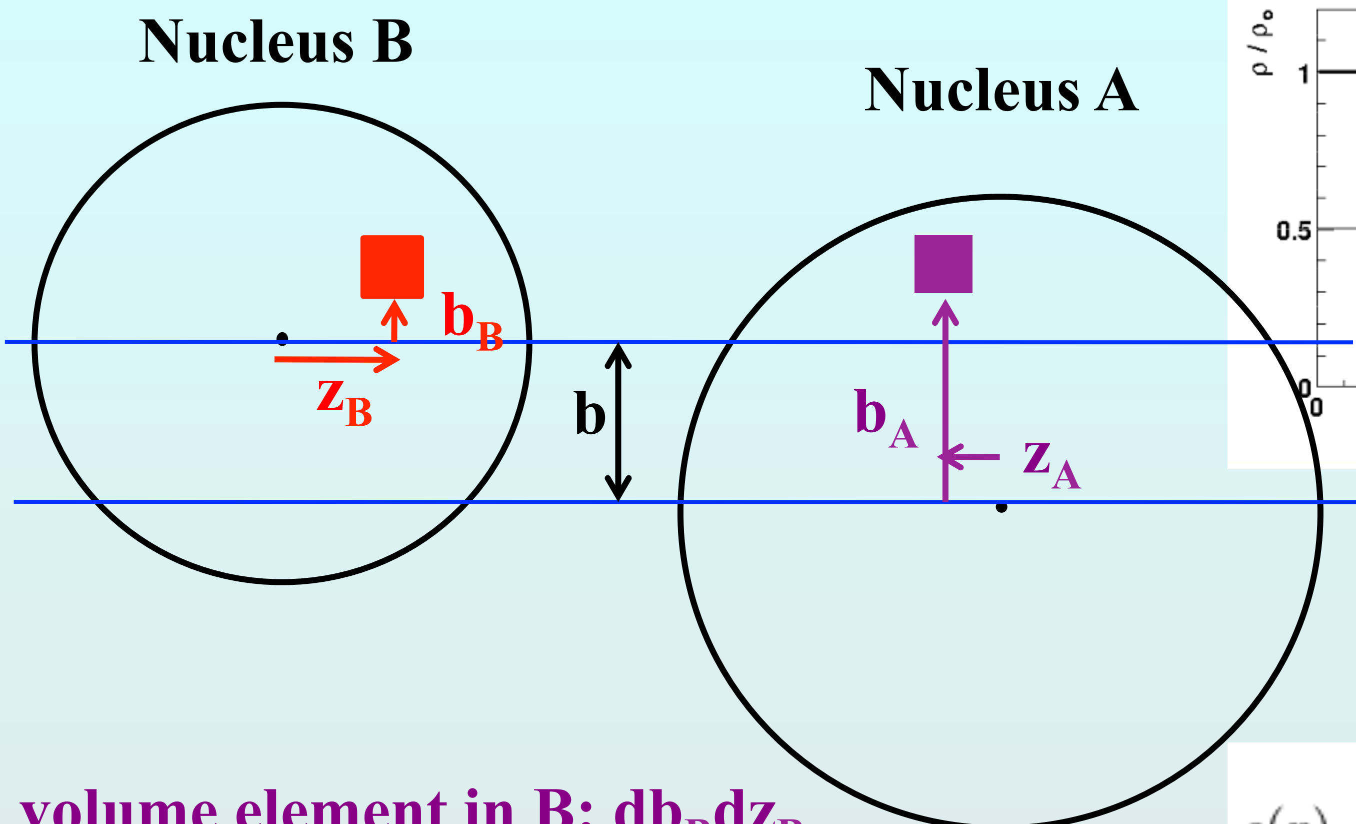


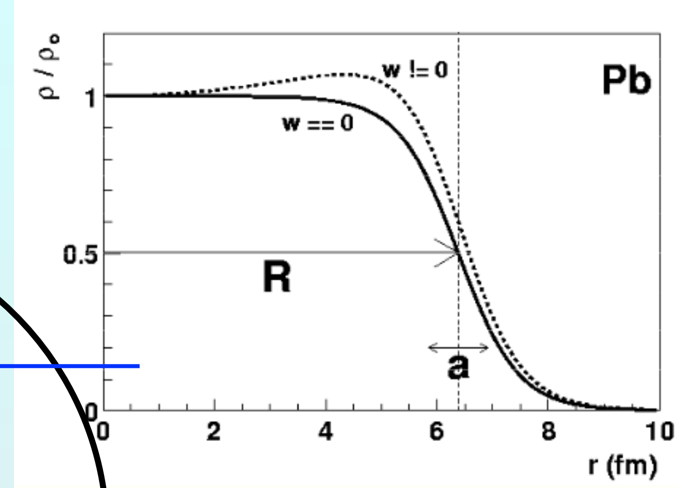
Use Glauber model of nucleons in nuclei

calculate # of participant nucleons N_{part}

# of binary NN collisions N_{coll}

Glauber model: calculate probabilities





Woods-Saxon nuclear density profile:

$$\rho(r) = \frac{\rho_0 \left(1 + wr^2/R^2\right)}{1 + \exp((r - R)/a)}$$

volume element in B: $db_B dz_B$

volume element in A: $db_A dz_A$

Probability of finding a nucleon in volume element A =

$\rho_A(b_A, z_A)\, db_A dz_A$ (ρ_A is nuclear density * nucleons in A)

Probability of n interactions

Thickness function in nucleus A: $\hat{T}_A(\mathrm{s}) = \int \hat{\rho}_A(\mathrm{s}, z_A) dz_A$

s measures transverse overlap – given by b and nucleus R

Thickness function for A+B: $\hat{T}_{AB}(\mathrm{b}) = \int \hat{T}_A(\mathrm{s}) \hat{T}_B(\mathrm{s}-\mathrm{b}) d^2 s$

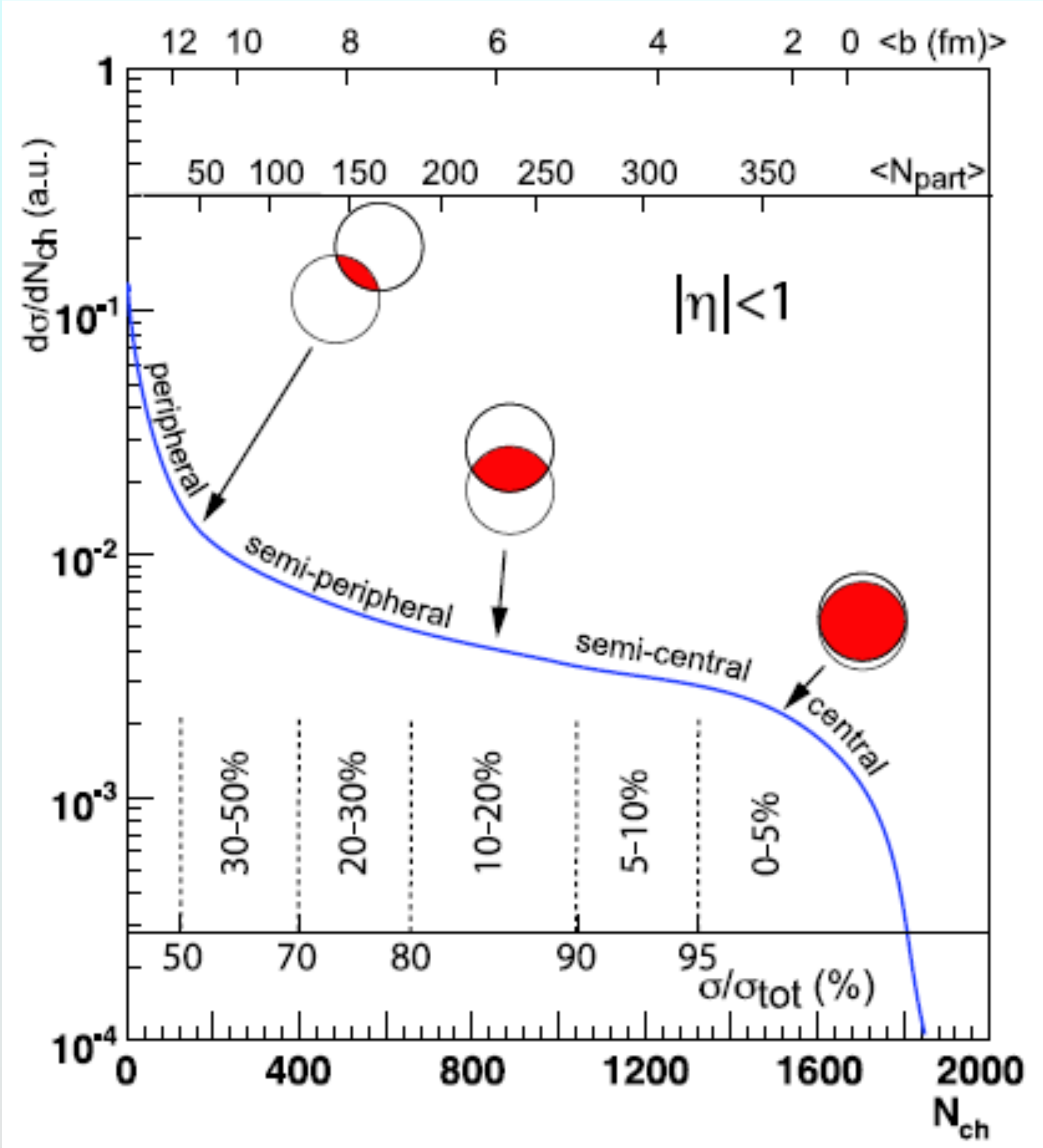
Probability of n interactions is given by binomial distribution:

$$P(n, \mathrm{b}) = \binom{AB}{n} \left[\hat{T}_{AB}(\mathrm{b}) \sigma_{\mathrm{inel}}^{\mathrm{NN}}\right]^n \left[1 - \hat{T}_{AB}(\mathrm{b}) \sigma_{\mathrm{inel}}^{\mathrm{NN}}\right]^{AB-n}$$

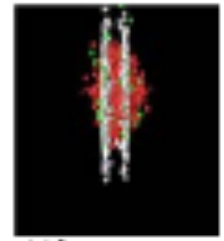
Number of nucleon-nucleon collisions:

$$N_{\mathrm{coll}}(b) = \sum_{n=1}^{AB} n P(n, b) = AB \hat{T}_{AB}(b) \sigma_{\mathrm{inel}}^{\mathrm{NN}}$$

Collision centrality



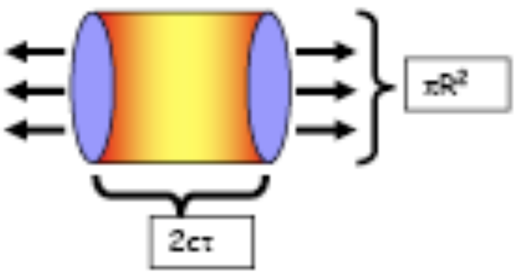
Energy Density

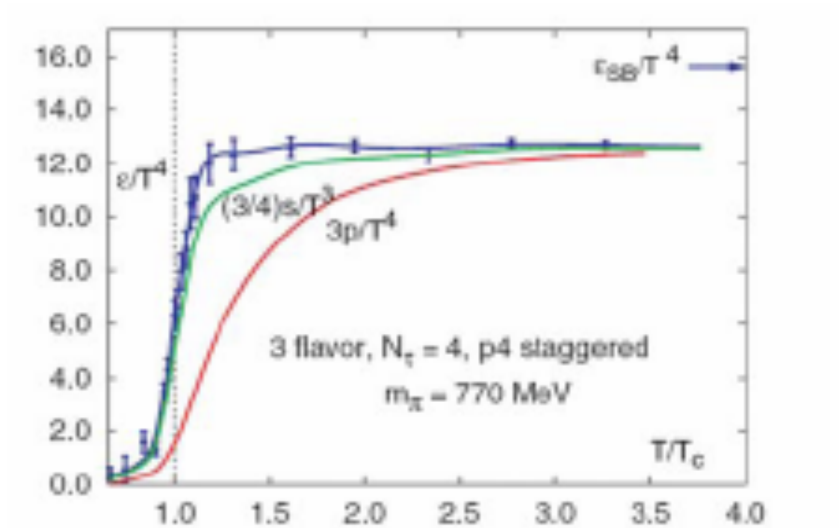


Energy density far above transition value predicted by lattice.

$$\varepsilon_{Bj} = \frac{1}{\pi R^2} \frac{1}{2c\tau} \left(2 \frac{dE_T}{dy} \right)$$

R~7fm





Lattice: T_C~190 MeV (ε_C ~ 1 GeV/fm³)

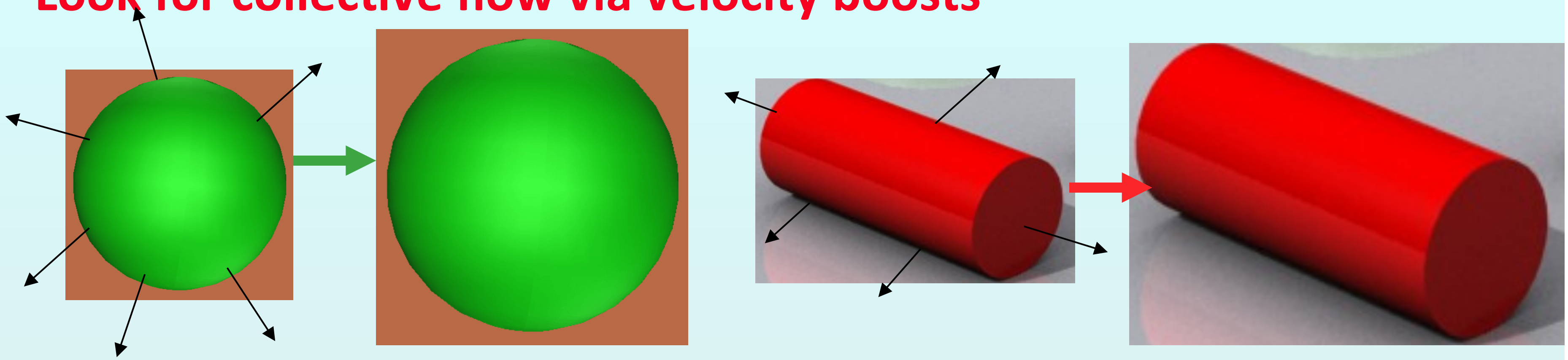
PHENIX: Central Au-Au yields

$$\left\langle \frac{dE_T}{d\eta} \right\rangle_{\eta=0} = 503 \pm 2\,GeV$$

$$\varepsilon \sim 15 \frac{GeV}{fm^3} \;@\; \tau = 0.6\,fm/c\ (thermalization)$$

Does the matter exhibit collectivity?

Look for collective flow via velocity boosts



Model expansion of the system with fluid dynamics

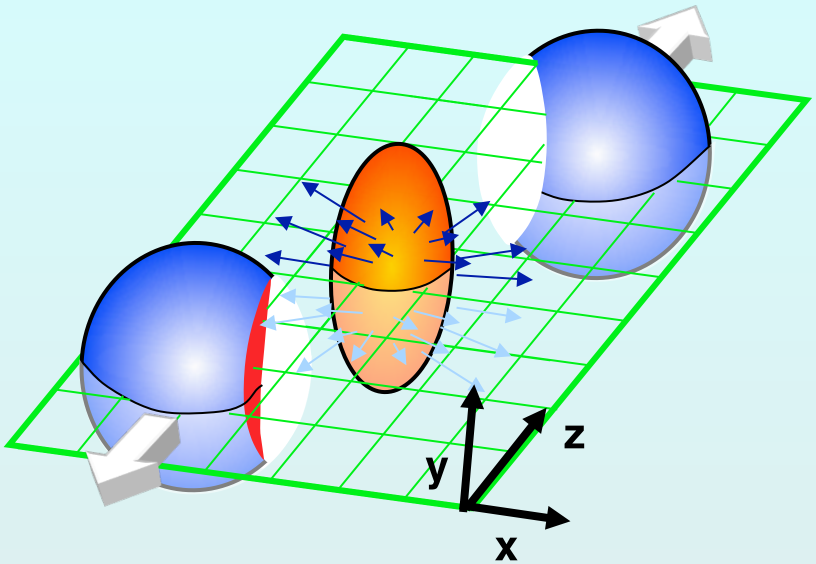
$$\partial_t \begin{pmatrix} \rho \\ \rho u \\ \rho v \\ e \end{pmatrix} + \partial_x \begin{pmatrix} \rho u \\ \rho u^2 + p \\ \rho u v \\ u(e+p) \end{pmatrix} + \partial_y \begin{pmatrix} \rho v \\ \rho u v \\ \rho v^2 + p \\ v(e+p) \end{pmatrix} -$$

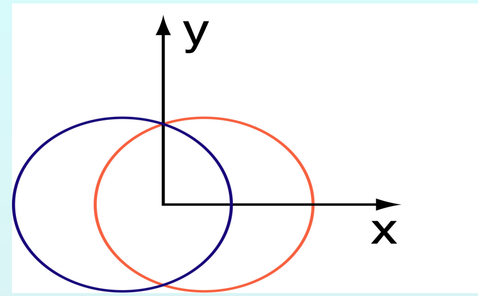
$$\partial_x \begin{pmatrix} 0 \\ \tau_{11} \\ \tau_{12} \\ \tau_{11} u + \tau_{12} v + k \partial_x \Theta \end{pmatrix} - \partial_x \begin{pmatrix} 0 \\ \tau_{21} \\ \tau_{22} \\ \tau_{21} u + \tau_{22} v + k \partial_y \Theta \end{pmatrix} = 0 \,,$$

where u and v are the components of the velocity, ρ the density, p the pressure, e total energy density, τ_{ij} the components of the viscous part of the stress tensor, Θ the absolute temperature and k is the heat conductivity.

Nuclear theorists have found solutions for 3-D viscous hydro!

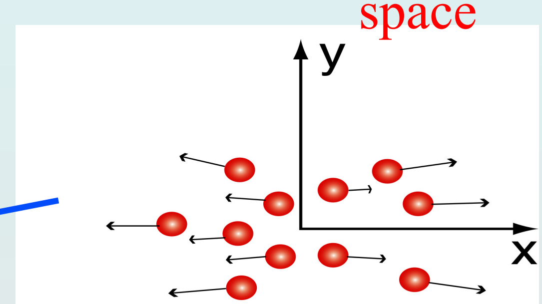
Collective motion & elliptic flow (v_2)

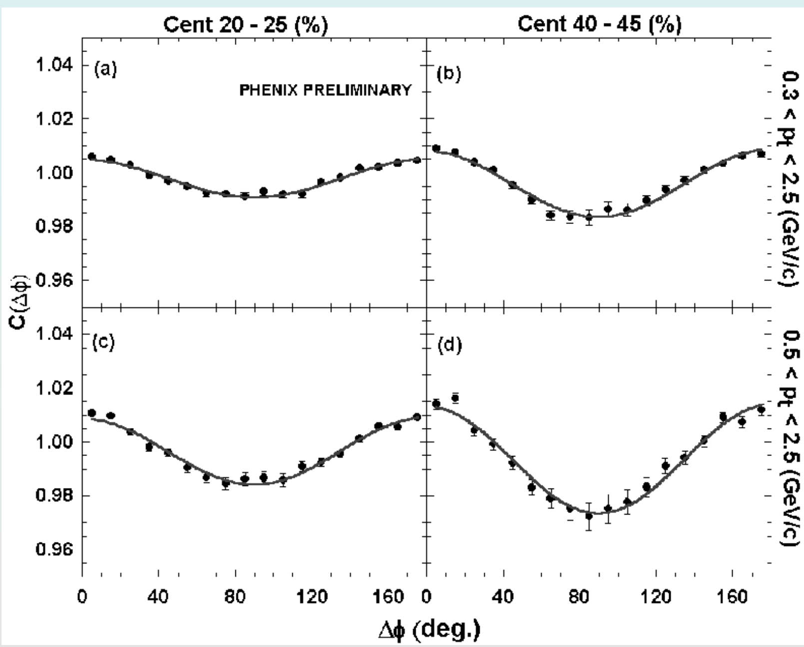




Almond shape overlap region in coordinate space

momentum space

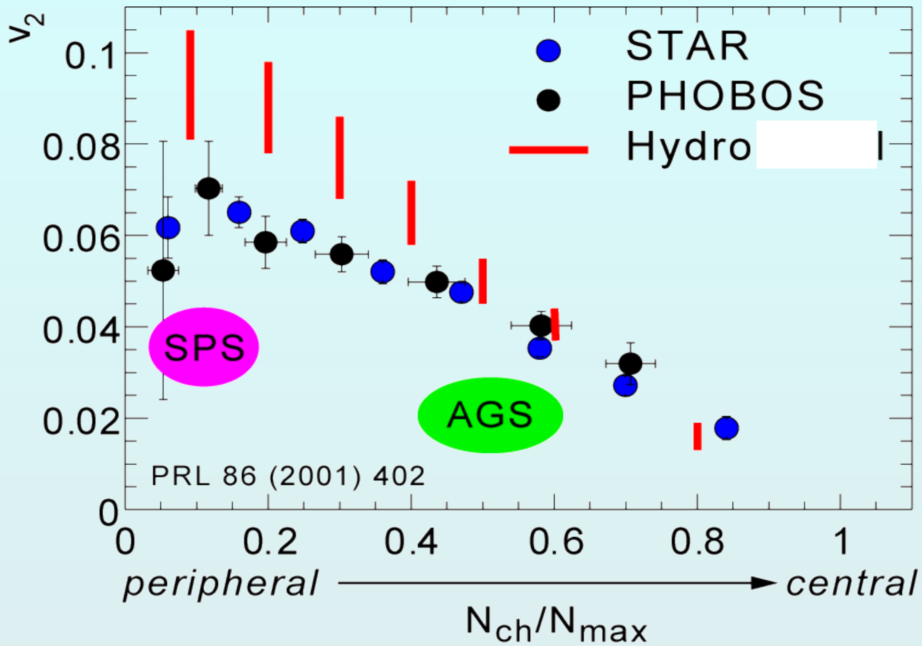




$dN/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \ldots$

hydrodynamics works!

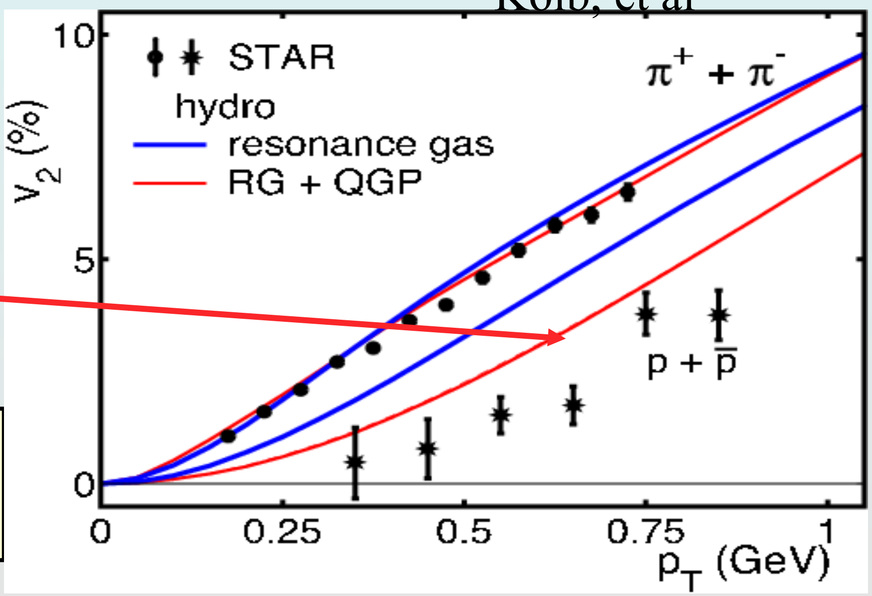
Surprise: matter flows like a liquid



- huge pressure buildup
- large anisotropy → it all happens fast
- efficient equilibration mechanism??

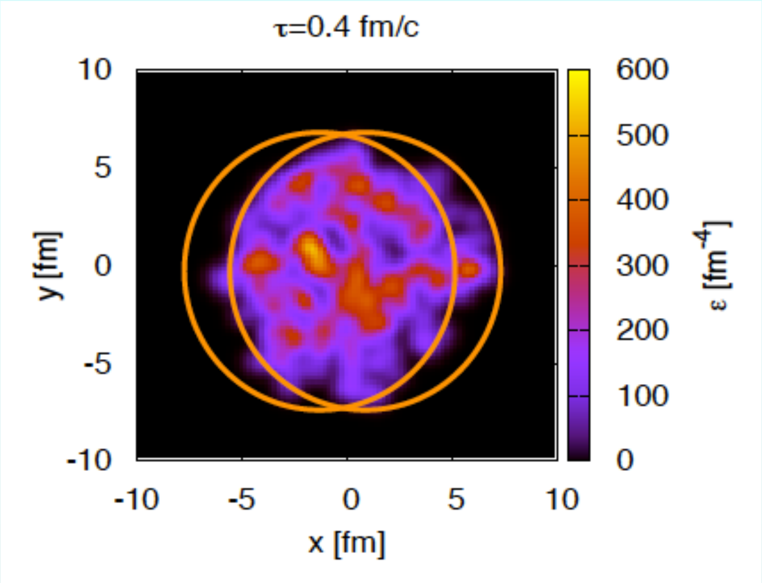
Hydrodynamics reproduces elliptic flow of q-$\overline{q}$ and 3q states
Mass dependence requires
soft EOS, NOT gas of hadrons

Kolb, et al



only works with low viscosity/entropy
"perfect" liquid (D. Teaney, PRC68, 2003)

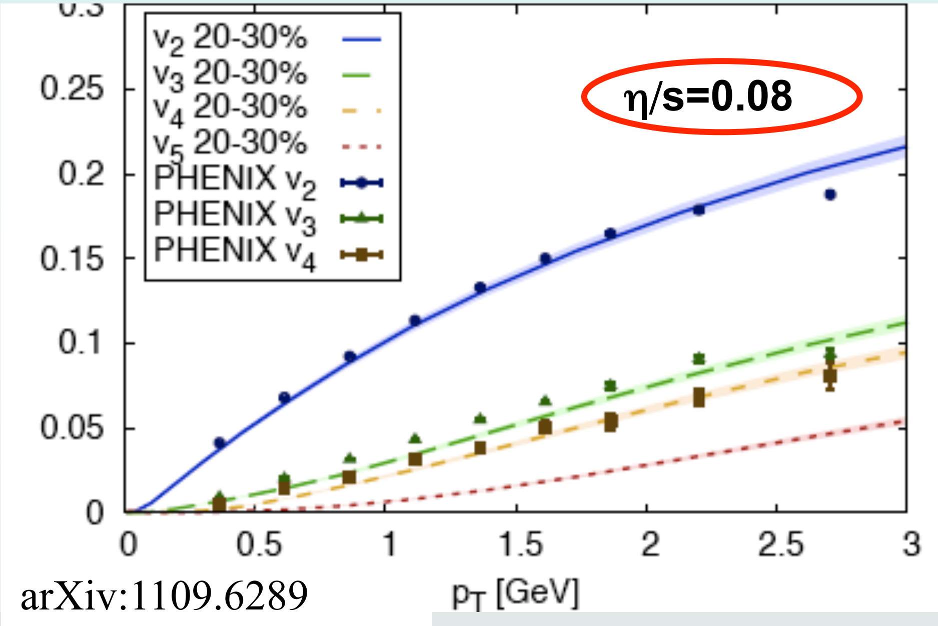
Fluctuations matter!



- Nucleons move around inside the nucleus

-> locations of NN scattering fluctuate

-> apparent symmetry effects yielding only even harmonics not realistic

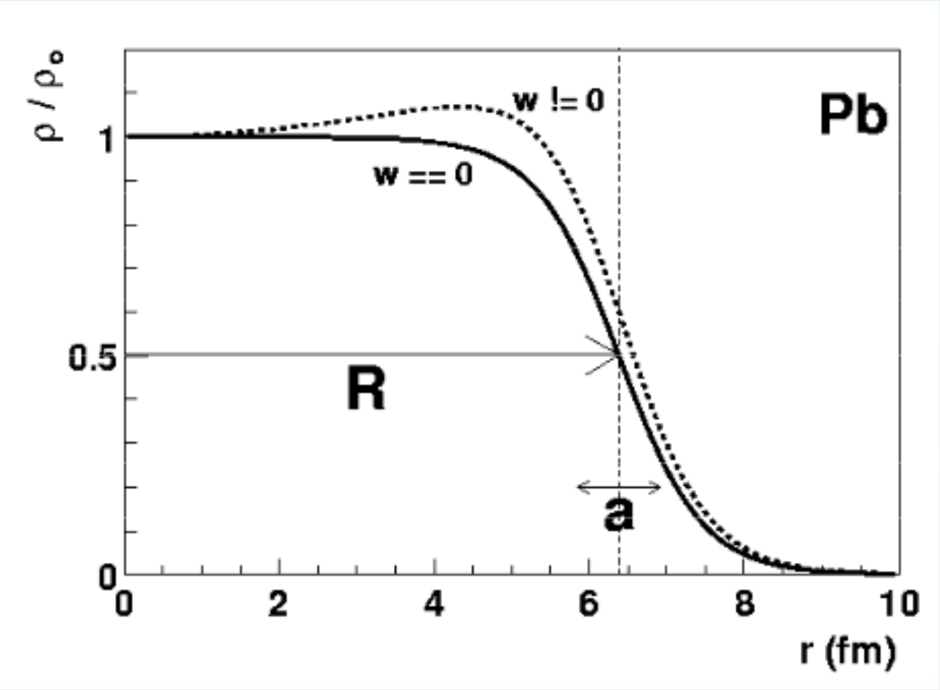


- Reproduce with hydro
- IF include fluctuating initial conditions
- Provides a tool to better pin down the viscosity/ entropy ratio

Hydro including event-by-event fluctuations

- **Use the same Glauber model**
- **MC to allow nucleon positions to fluctuate**

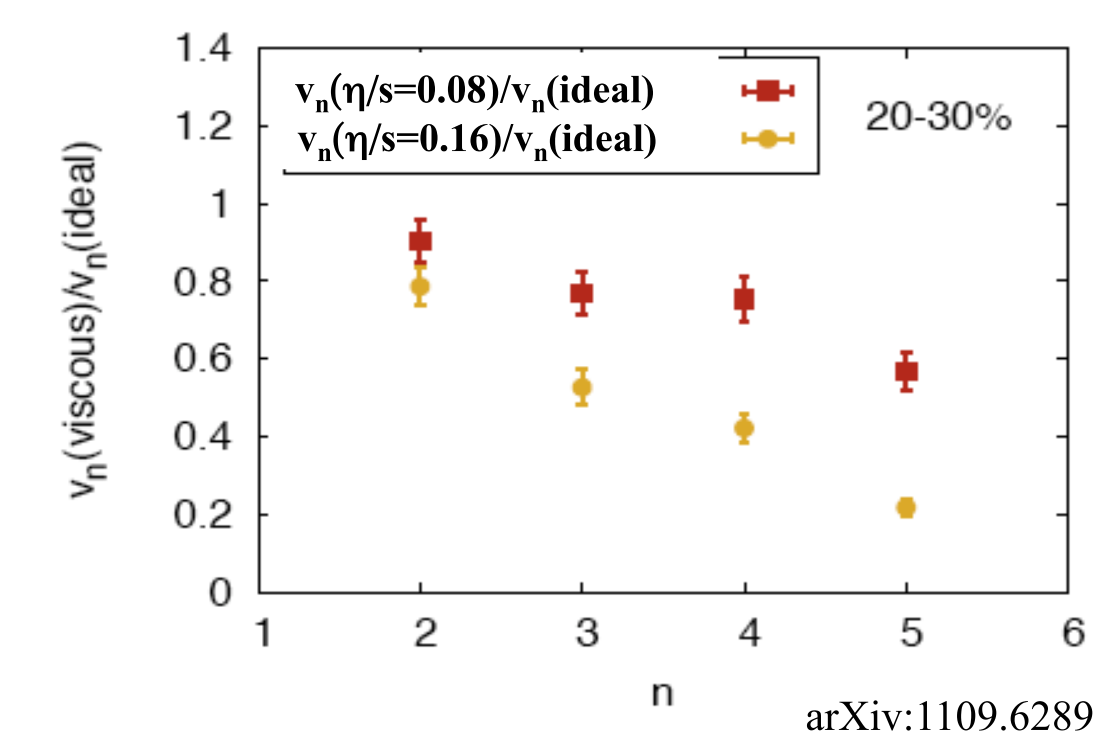
  Generate an ensemble of hydro calculations with different initial states



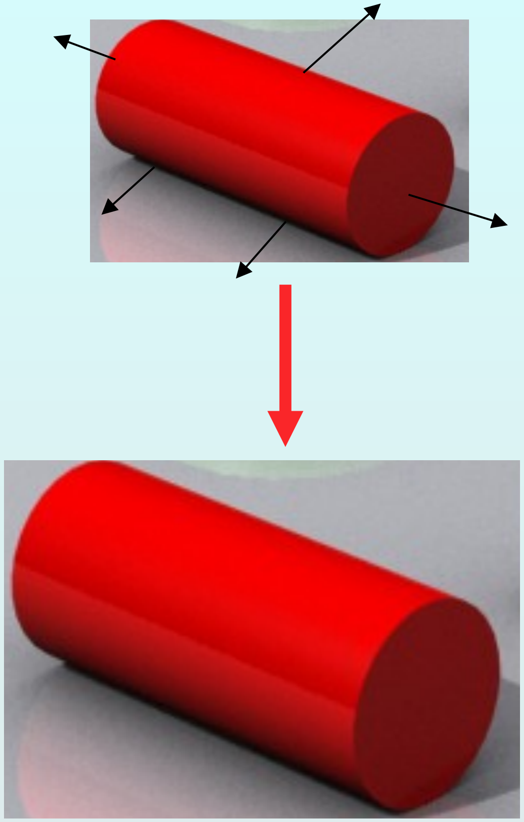
Woods-Saxon nuclear density profile:

$$\rho(r) = \frac{\rho_0 \left(1 + wr^2/R^2\right)}{1 + \exp((r - R)/a)}$$

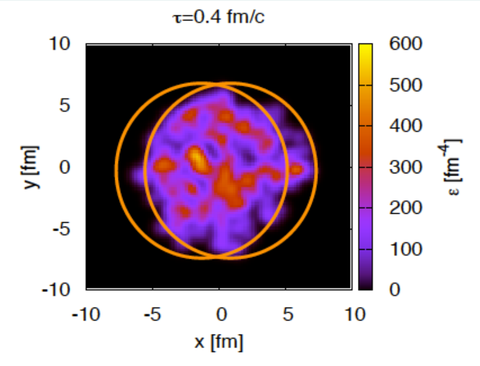
Higher moments more sensitive to viscosity



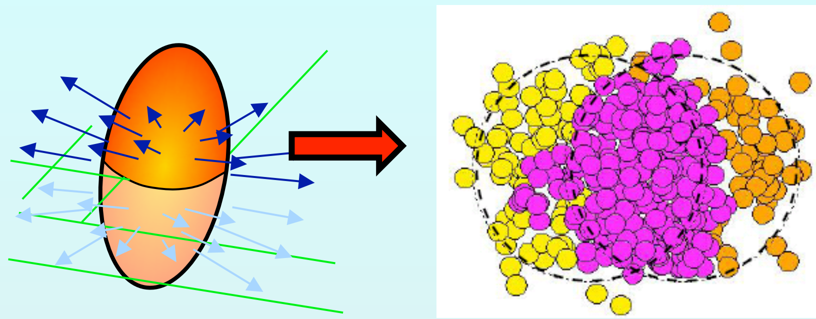
arXiv:1109.6289

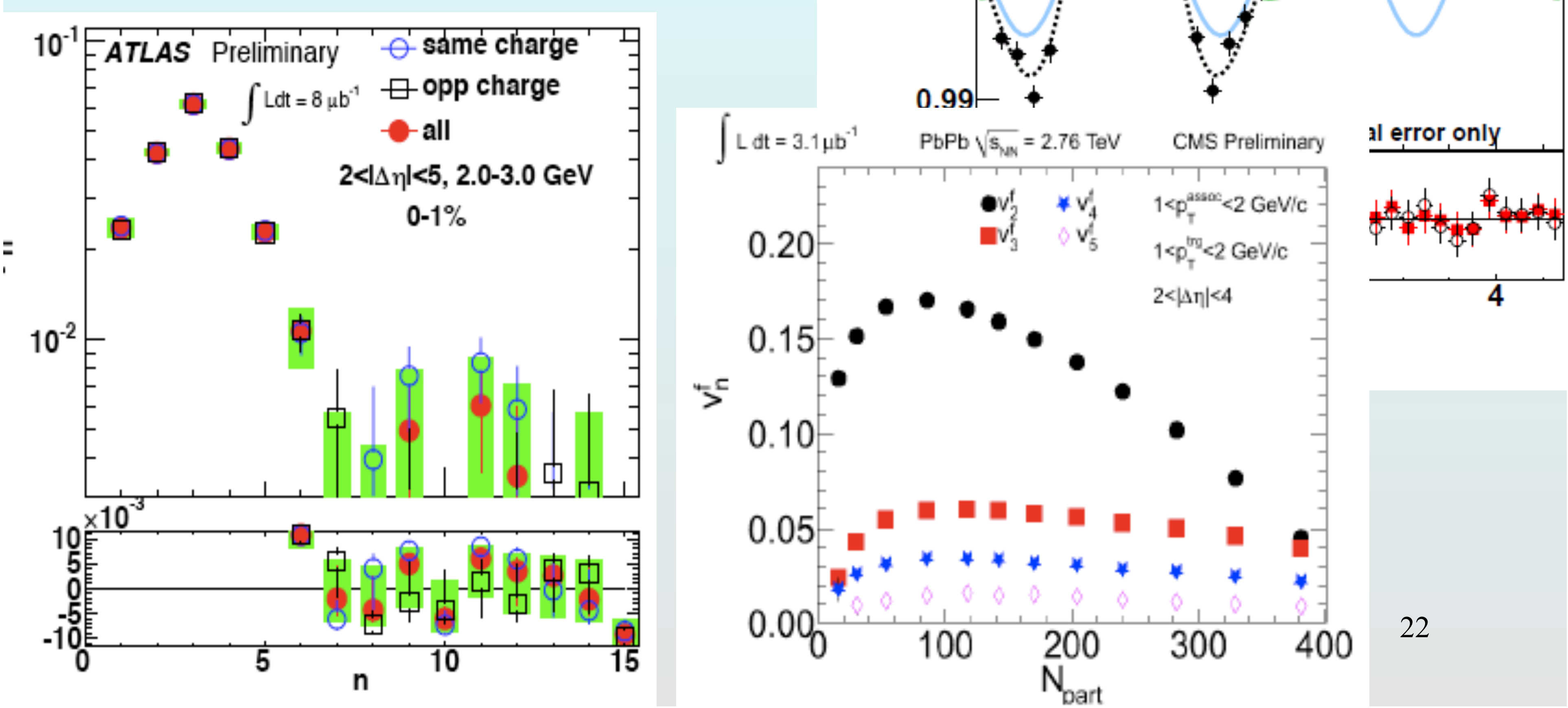


- Longitudinal expansion at v ~ c
- "freezes in" small shape perturbations
  e.g. triangular fluctuations (v_3)
- Viscosity is like friction!

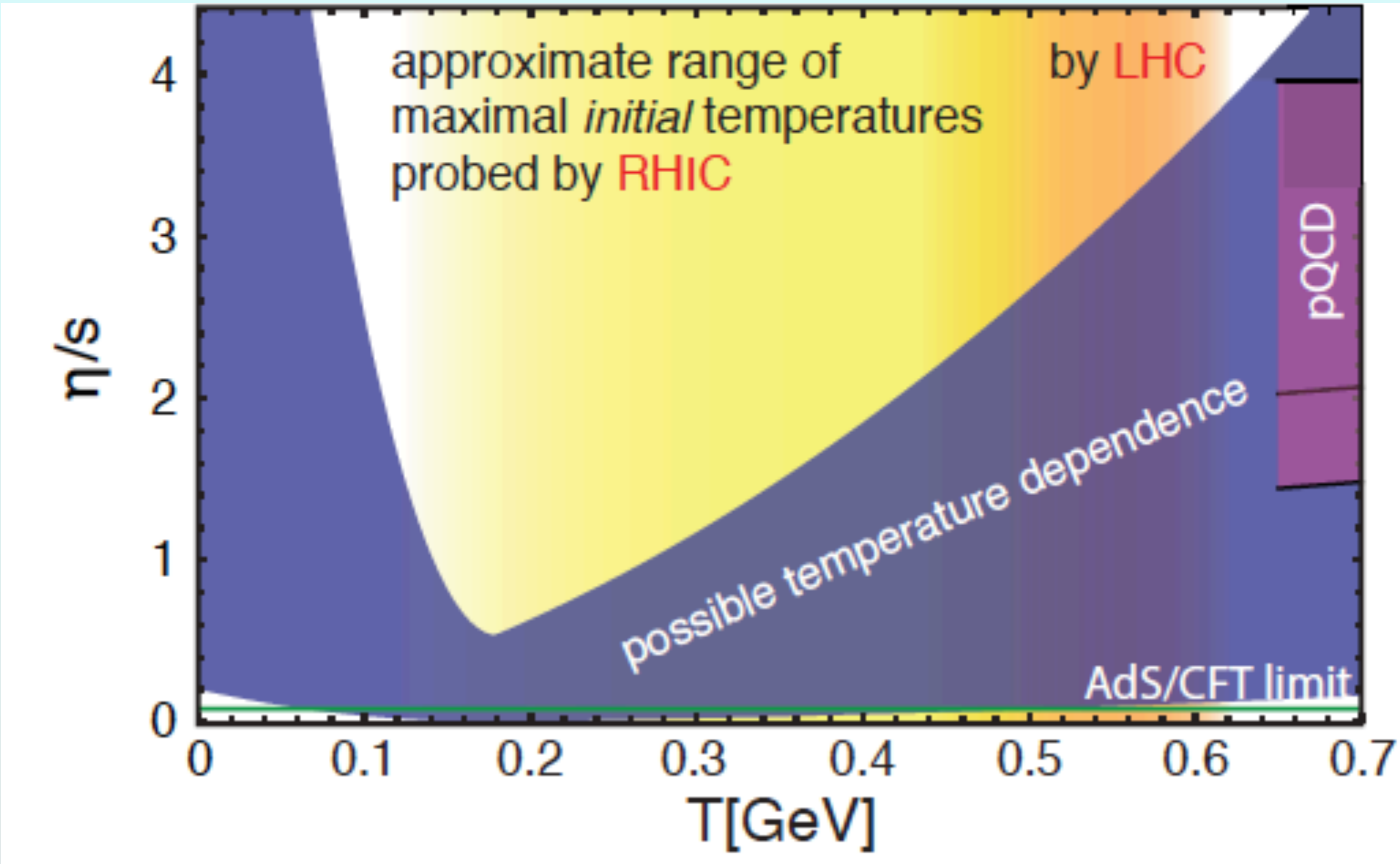


LHC data

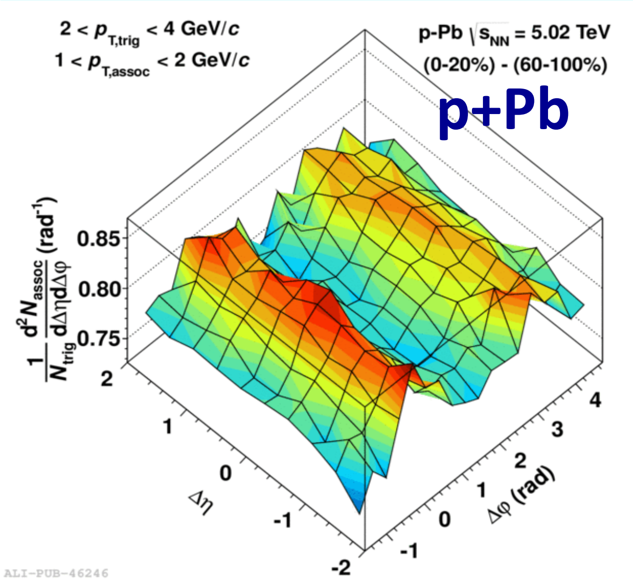


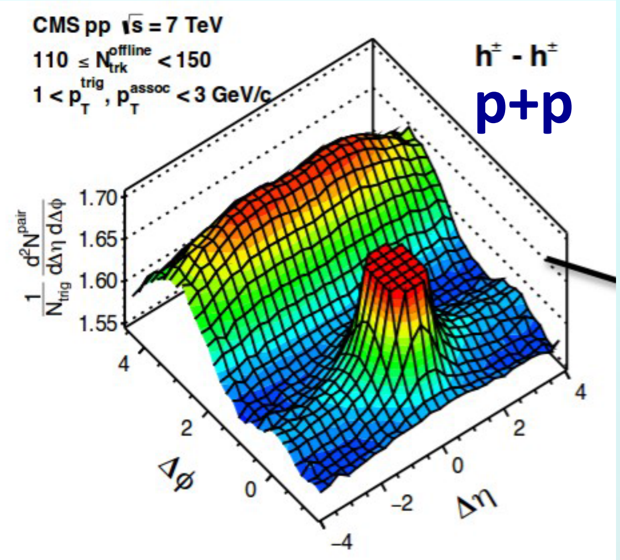

|Δη| > 0.8
p_T^{trig} 2-2.5 GeV/c
p_T^{assoc} 1.5-2 GeV/c
Pb+Pb 0-
ALICE
v_3
v_2
1.01
1
0.99
C(Δφ)
al error only
4
ATLAS Preliminary
∫Ldt = 8 μb⁻¹
same charge
opp charge
all
2<|Δη|<5, 2.0-3.0 GeV
0-1%
n
∫L dt = 3.1μb⁻¹
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
CMS Preliminary
$1<p_T^{assoc}<2$ GeV/c
$1<p_T^{trig}<2$ GeV/c
2<|Δη|<4
v_n^f
N_{part}

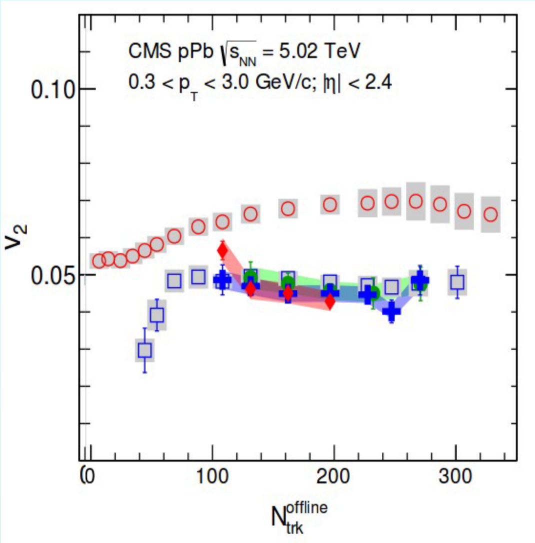
Shear viscosity depends on temperature



Collective flow in small systems?







Significant v_N (n=2 to 5) with "familiar" ordering + shape in p_T

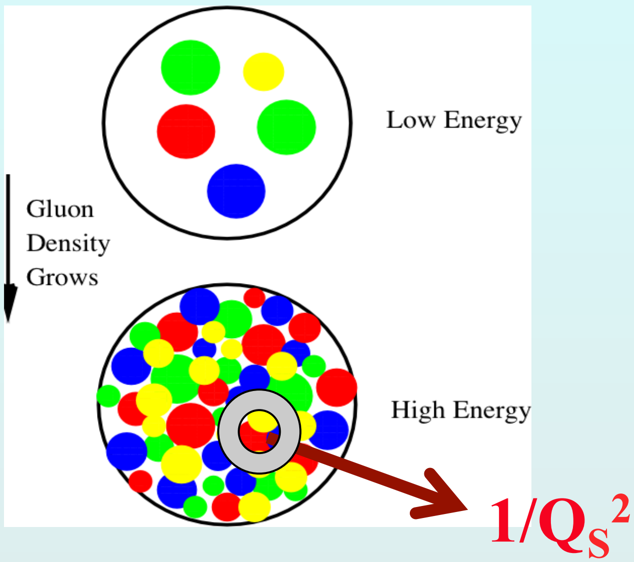
Multi-particle correlations (v2{4}≈v2{6}≈v2{8}≈v2{LYZ})

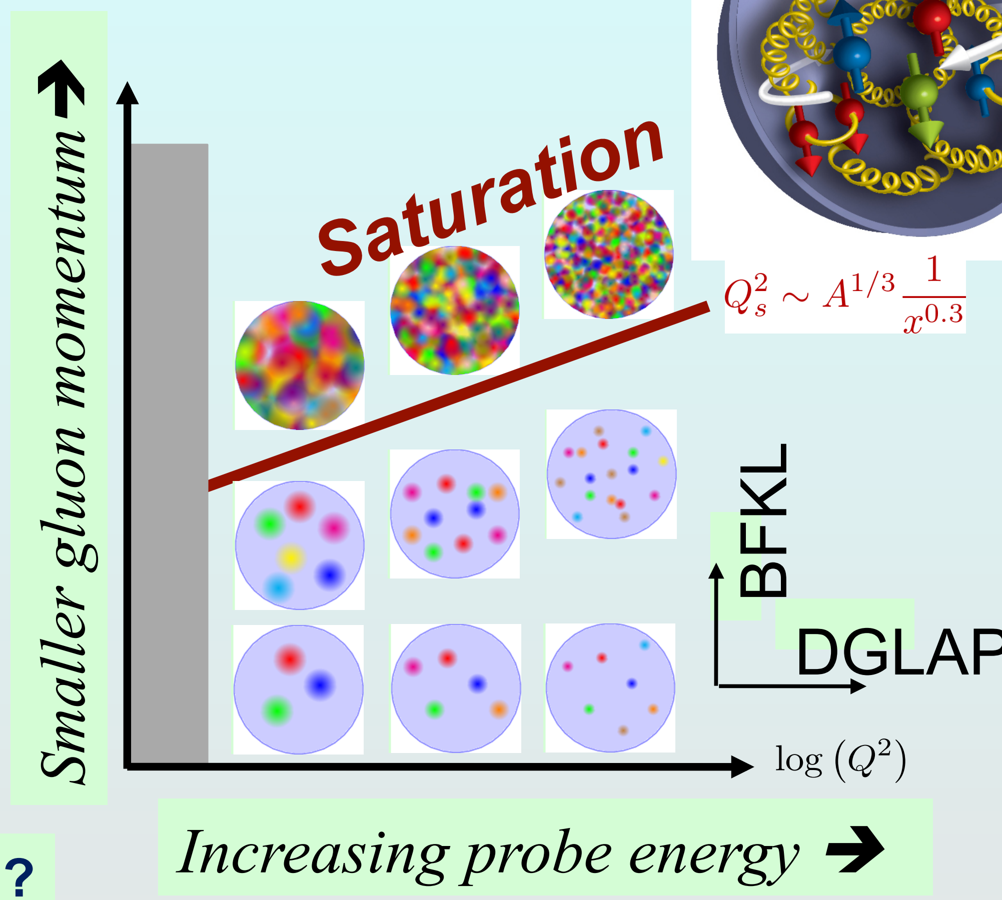
- ***What is going on?***

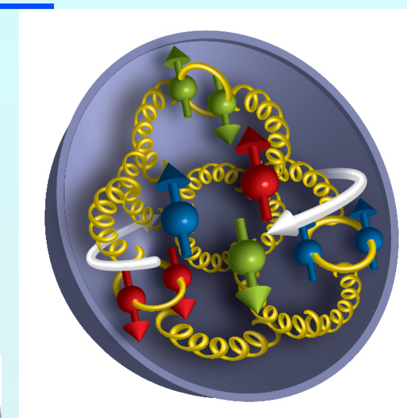
  Hydrodynamics in small(ish) systems? Correlations between particles produced in initial state? Radial flow an artefact of constant temperature freezeout surface?

Hot, dense gluonic matter is surprising
Are cold dense gluons wierd too?

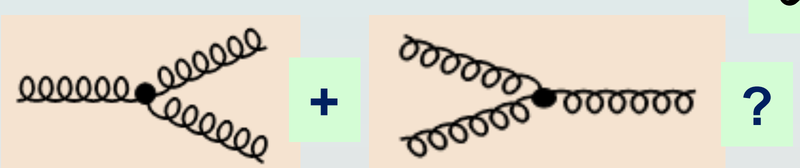
- **Look deep in a nucleus: gluons are numerous**







- ***At high density***
  what then?



➢ **This is our initial state in heavy ion collisions!**

Probe with e+A

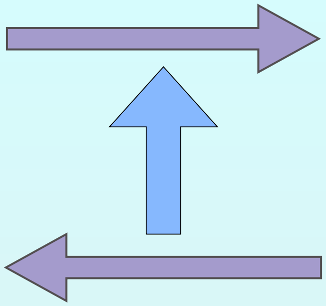
Surprise: viscosity/entropy is small

Viscosity: *inability* to transport momentum & sustain a wave

low η → large σ, transports disturbances

Viscosity/entropy near 1/4π limit from quantum mechanics!

∴ liquid at RHIC is "perfect"



$$\eta \approx \frac{1}{3} n \bar{p} \lambda_f$$

$$\bar{p} \sim T$$

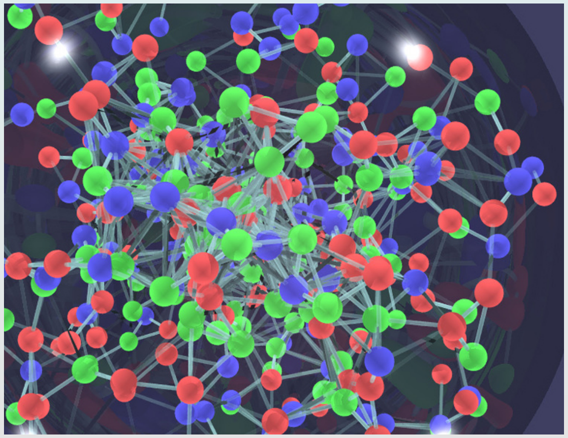
Example: milk. Liquids with higher viscosities will not splash as high when poured at the same velocity.

Good momentum transport: neighboring fluid elements "talk" to each other

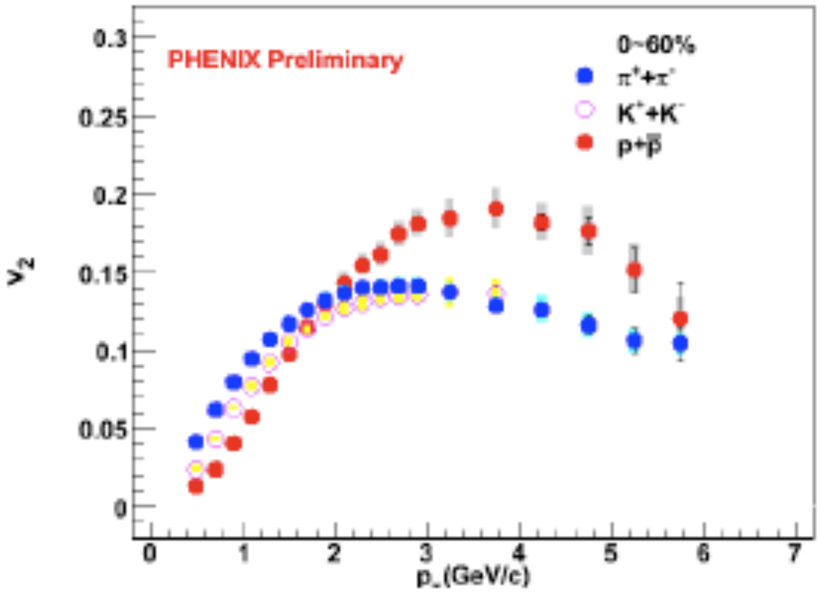
→ QGP is strongly coupled

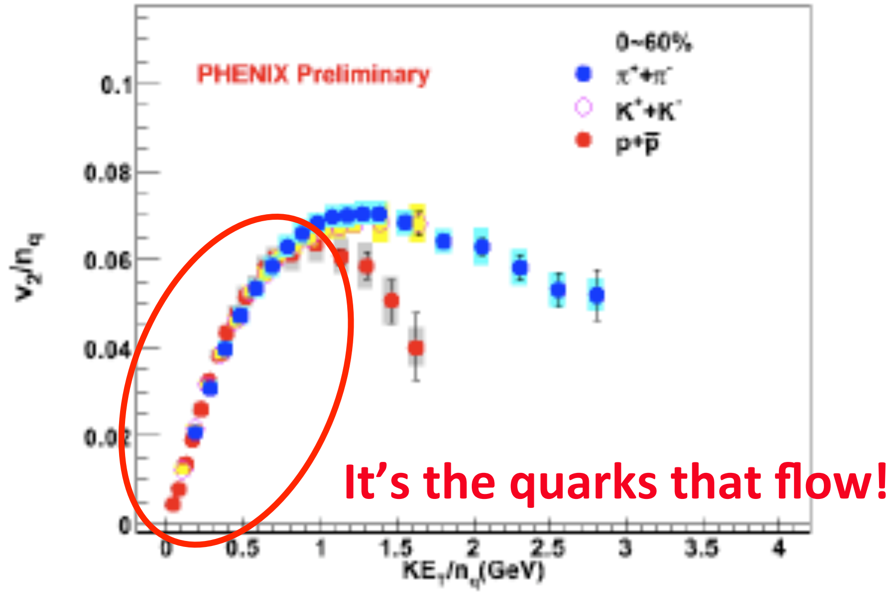
Should be opaque:

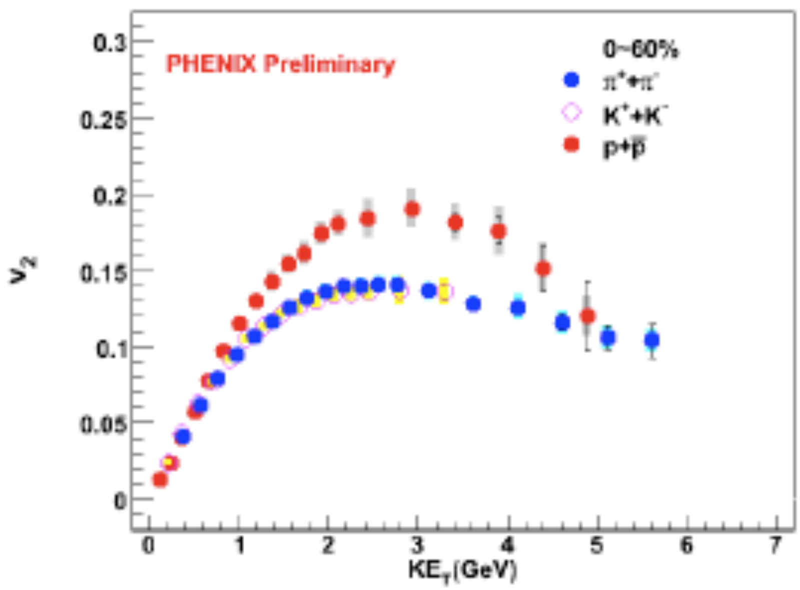
e.g. q,g collide with "clumps" of gluons, not individuals



p_T dependence of v_2







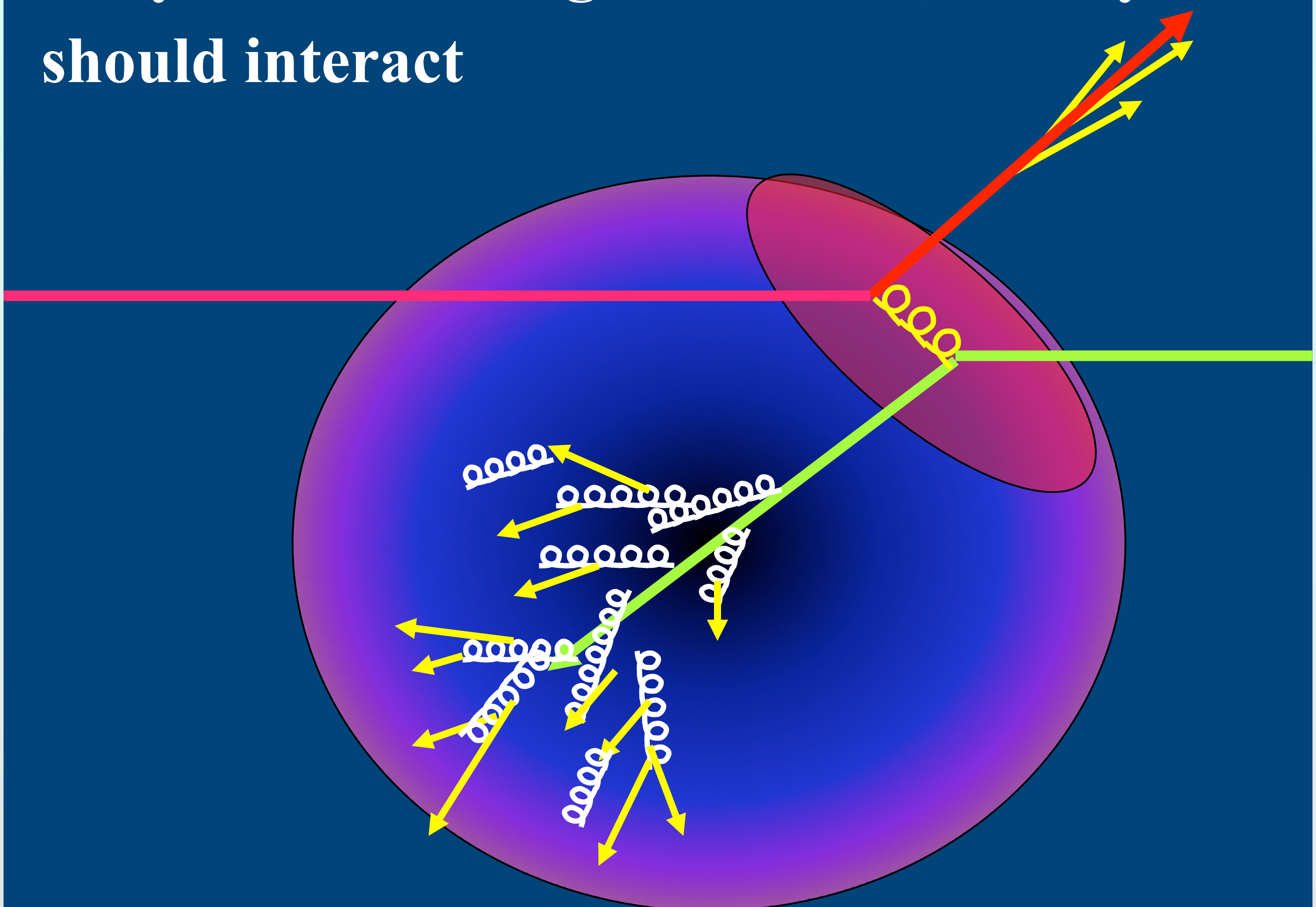
- *KE_T/n_q< 1GeV – soft physics*

  Hydrodynamic flow

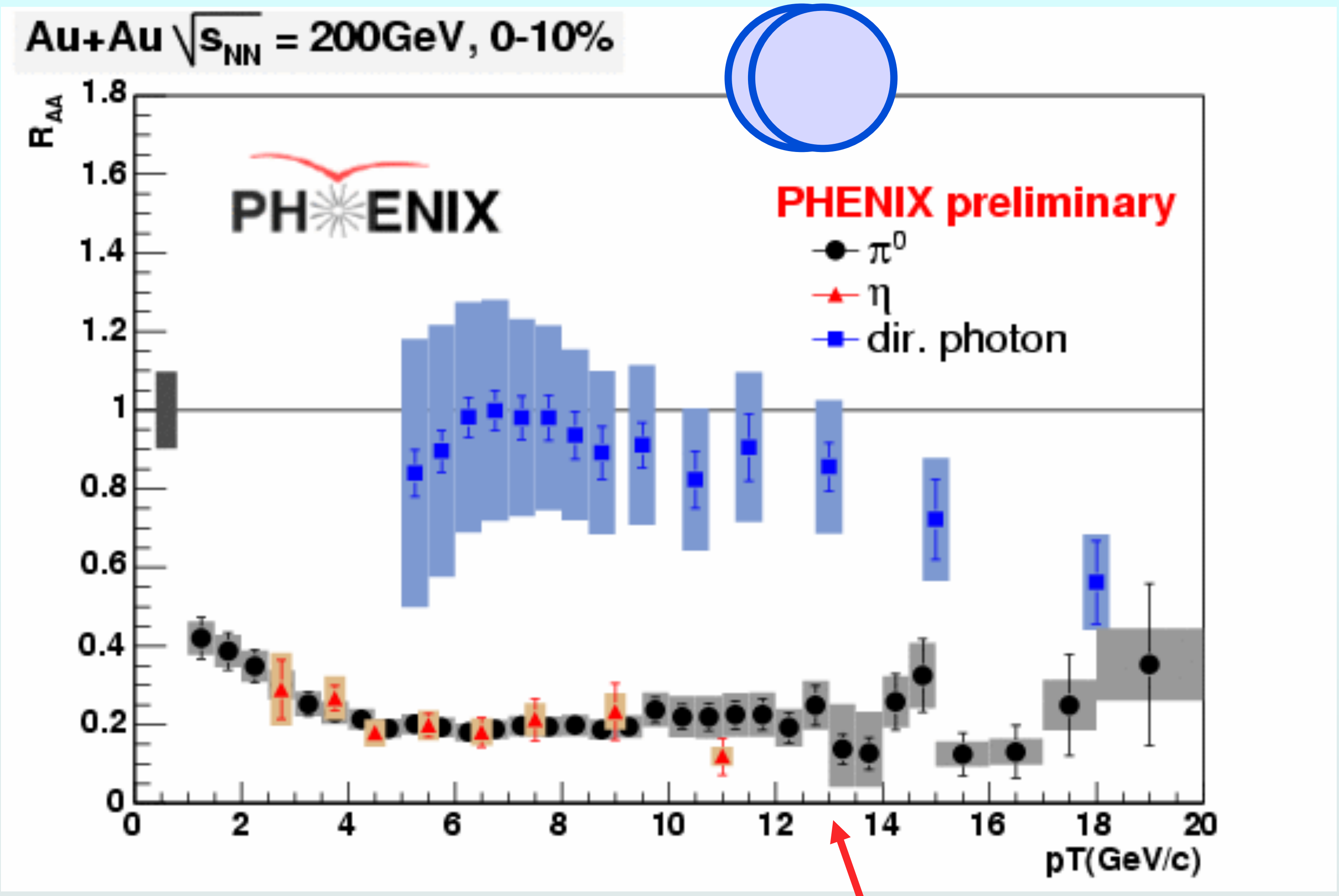
- *Interplay soft-hard 3.0 < p_T< 5 GeV/c ?*
- *Hard dominates: p_T> 5 GeV/c*

Do fast quarks & gluons escape the plasma?

They feel the strong interaction, so they should interact



colored objects lose energy, photons don't

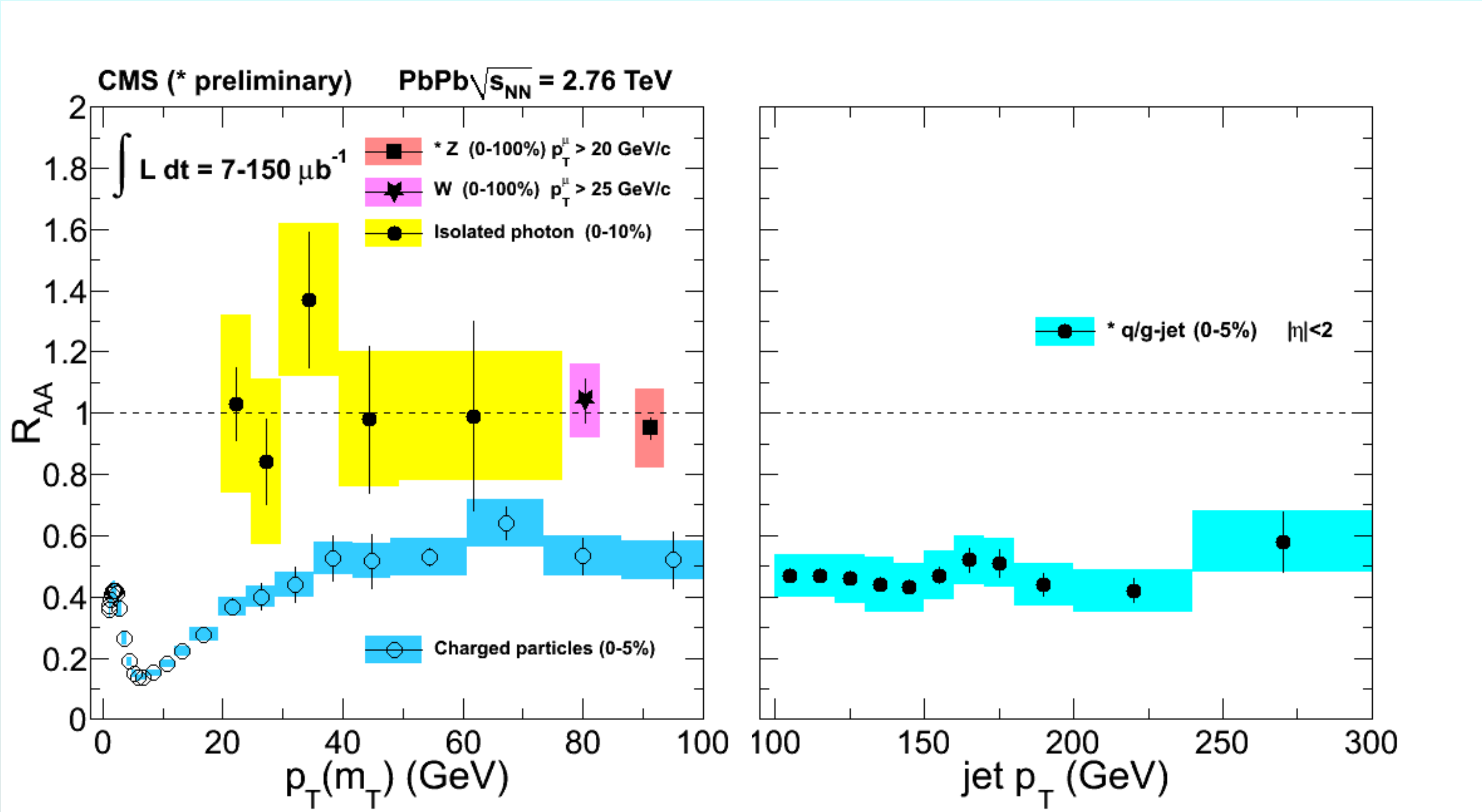


Nuclear modification factor:

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

VERY opaque! Lots of gluon radiation (bremsstrahlung)

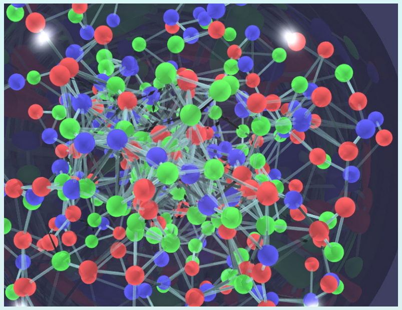
Energy loss even by very energetic q & g



- **LHC experiments reach to 300 GeV!**

Energy loss depends on medium density

- In dilute medium
  - Independent processes: bremsstrahlung & scattering
  - Calculate probabilities and add them up
  - Independent radiations follow Bethe-Heitler



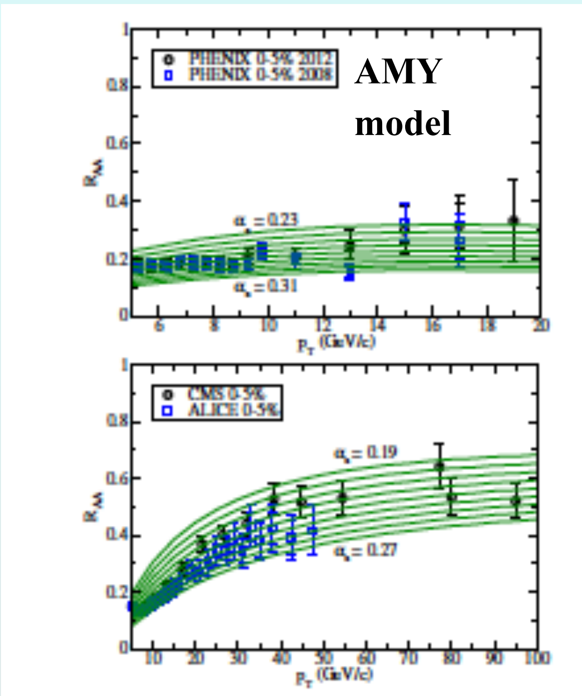
- In dense medium
  - Mean free path is short: $\lambda = \sigma/\rho$
  - Formation time of radiated gluon: $\tau = \omega/k_T^2$
  - Transverse momentum of radiated gluon: $k_T^2=n\mu^2$
    - # of collisions $n=L/\lambda$, μ=typical p_T transfer in 1 scattering
    - λ,μ are properties of the medium, combine to $\hat{q}= \sqrt{\mu^2/\lambda}$
- Coherence in the dense medium!
  - Next scattering takes place faster than gluon formation
  - Add amplitudes for all multiple scatterings
  - In QCD this increases the energy loss!
    - *some evidence for coherence already in cold matter!*

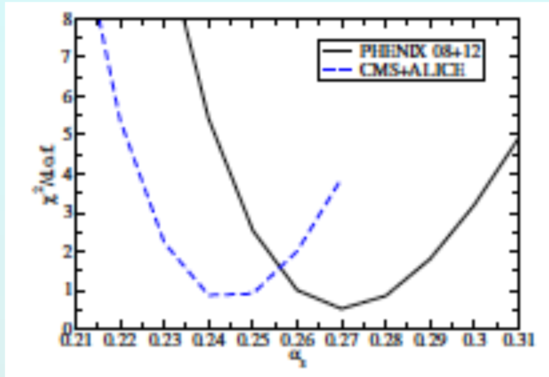
Fit R_{AA} at different √s

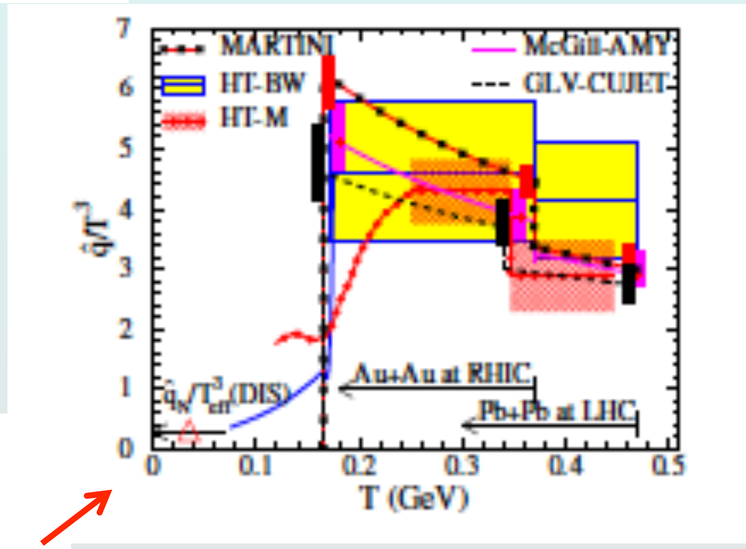
arXiv:1312.5003

JET collaboration fit all data with multiple calculations

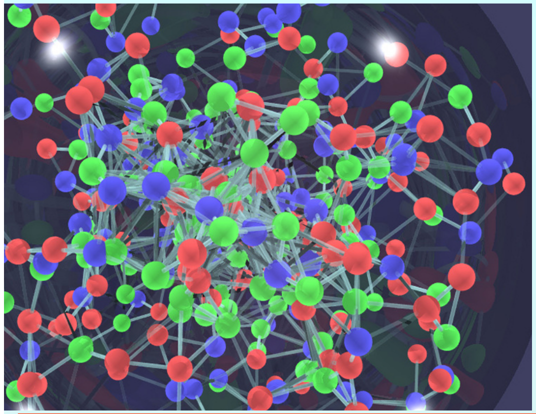
minimize $\chi 2$ for best fit to strong coupling parameter or $\hat{q}$







Put together all the calculations

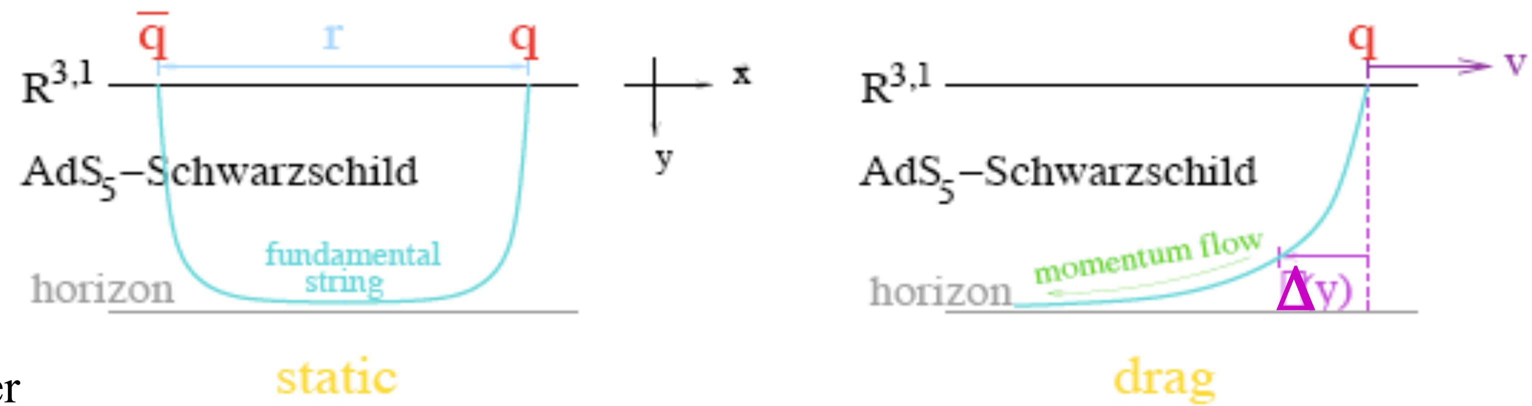


Interactions with plasma?

- radiation (bremsstrahlung)
- collisional energy loss

In plasma: interactions among charges of multiple particles
charge is spread, screened in characteristic (Debye) length, λ_D
also the case for strong, rather than EM force … Effect on collisions?

- **AdS/CFT says QGP is a strongly interacting field, model as ∞ strong**
  Interact with this QGP as with a tiny black hole
  No particles to hit, none can survive inside. Eloss → collective excitations



S. Gubser

Figure 2: *Left: a screened attraction between static quark arises from a string dipping into AdS_5-Schwarzschild. Right: a drag force arises from a string tailing behind a moving quark.*

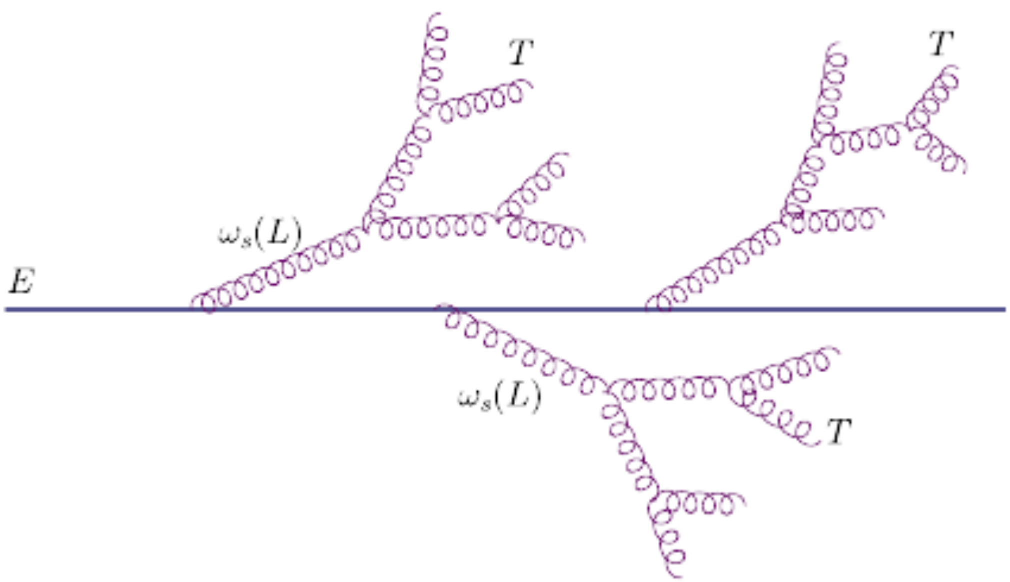
Back to QCD…

Jet versus mini-jets

- At the LHC, the energy E of the leading particle is much higher

$$E \geq 100\,\text{GeV} \;\gg\; \omega_{\text{br}} = \alpha_s^2 \hat{q} L^2 \simeq 4 \div 16 \text{ GeV for } L = 3 \div 6 \text{ fm}$$

  - the leading particle cannot suffer democratic branchings
  - it abundantly emits primary gluons with $p \lesssim \omega_{\text{br}}(L)$
  - these primary gluons generate 'mini-jets' via democratic branchings
  - the energy flows from one parton generation to the next one

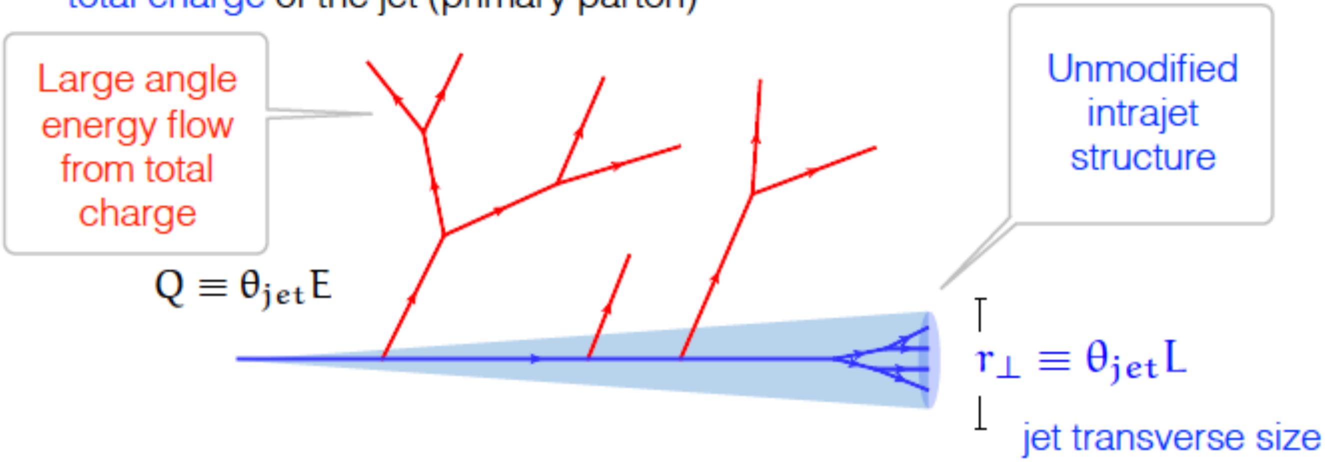


$$\Delta E_{\text{flow}} \simeq 2.5\,\omega_{\text{br}}(L)$$

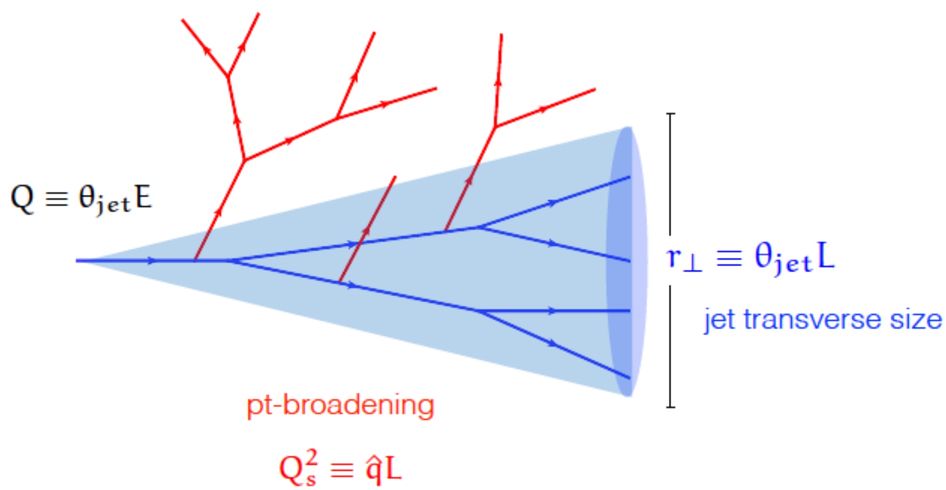
- 'absorbed by the medium'
- is the medium a 'perfect sink' ?
- is the branching process affected by thermalization ?

- When the transverse size $r_\perp$ of the jet is smaller than medium resolution scale Q_s^{-1} the medium interacts "effectively" with the total charge of the jet (primary parton)

coherent limit



Subsequent splittings drive color de-coherence of 1st generation emitted gluons & softer leading partons



How this is calculated

- There is a great paper comparing vacuum DGLAP evolution to an in-medium cascade (BDMPS), which depends on $\hat{q}$.
- See Blaizot and Mehtar-Tani:

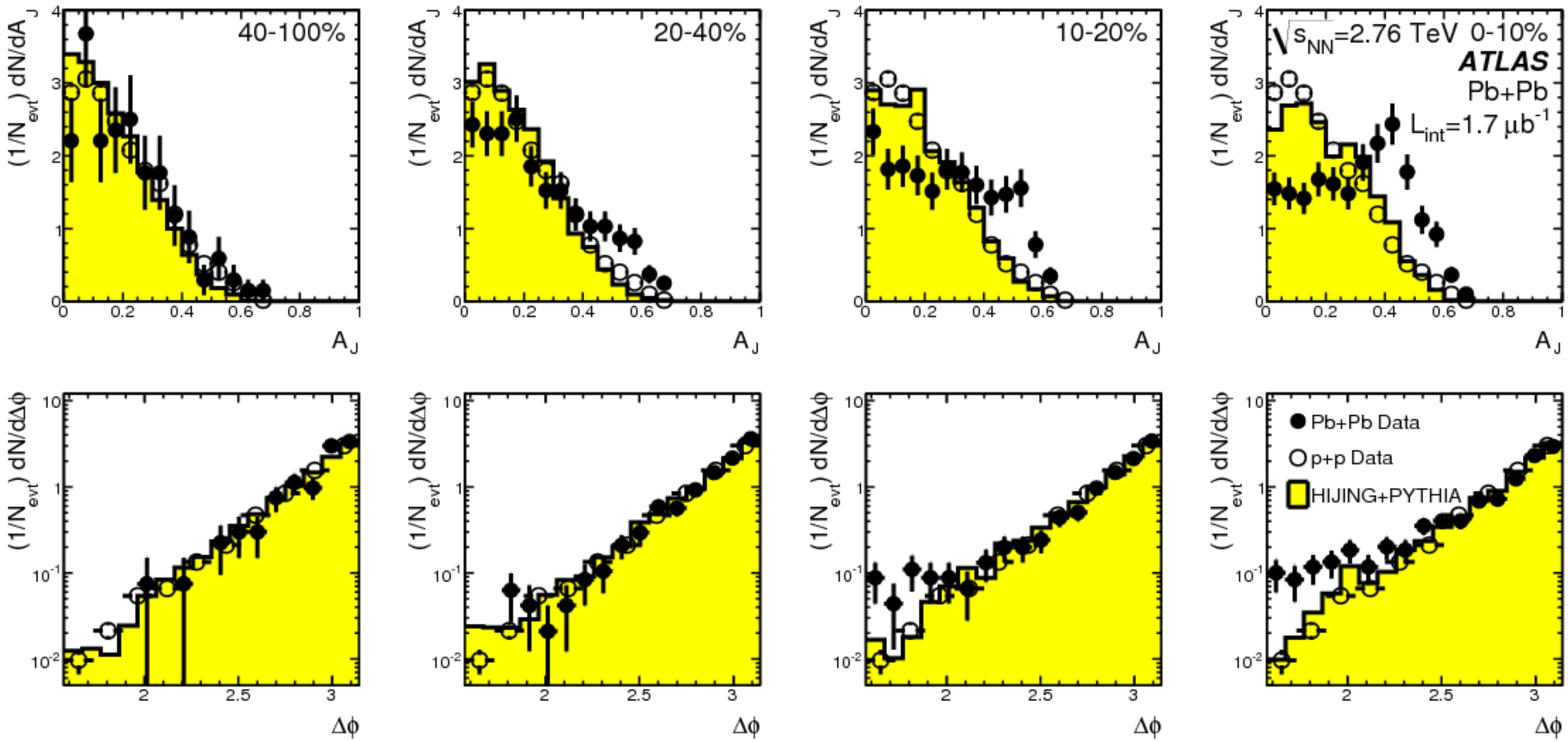
  http://arxiv.org/pdf/1501.03443v1.pdf

- In medium cascade results in energy flow to x~0 due to multiple branchings. DGLAP has an infrared cutoff. DGLAP branching time is constant, while in BDMPS it decreases along the cascade. This allows transport of energy to very soft gluons in a finite amount of time. Result looks a lot like wave turbulence

A good topic for a (somewhat technical) QCD talk!

Jet asymmetry

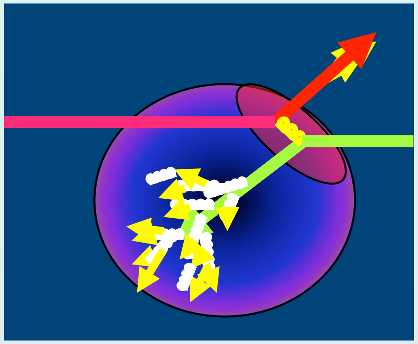
$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \Delta\phi > \frac{\pi}{2}$$



Where does the lost energy go?

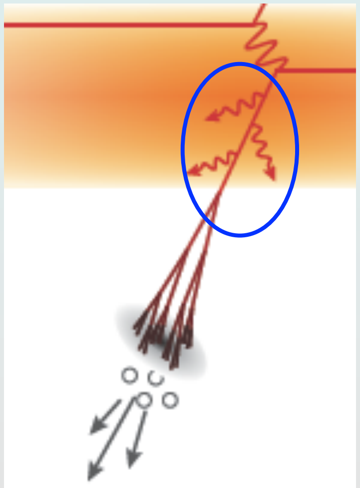
- We don't know yet!
- Medium enhances gluon radiation/splitting:

extra gluons at small angles (in/near jet cone)

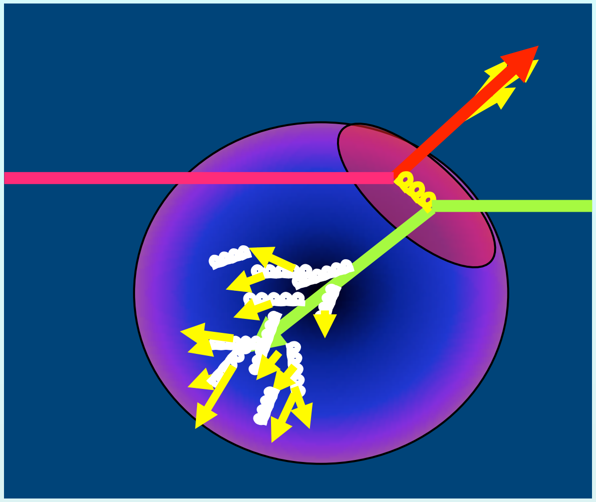


radiated gluons thermalize in medium (i.e. they're gone!)

remain correlated with leading parton, but broaden/change jet

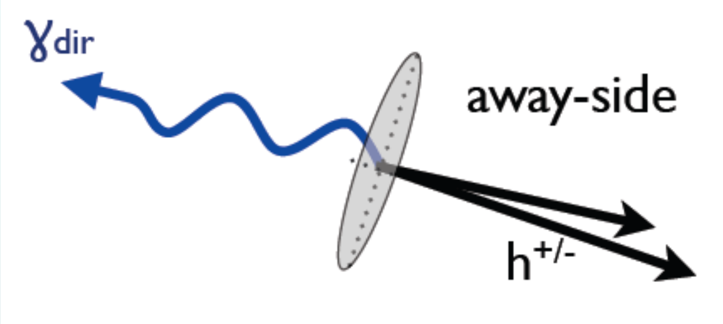


Jet Fragmentation function



$D(z) = 1/N_{jet}\, dN(z)/dz;\; z = p_{had}/p_{jet}$

Measure: count partners per trigger as fraction of trigger momentum



$z_T = p_{Ta}/p_{Tt} \sim z$ for γ trigger

$\xi = \ln(1/z_T)$

Modification factor similar to R_{AA}:

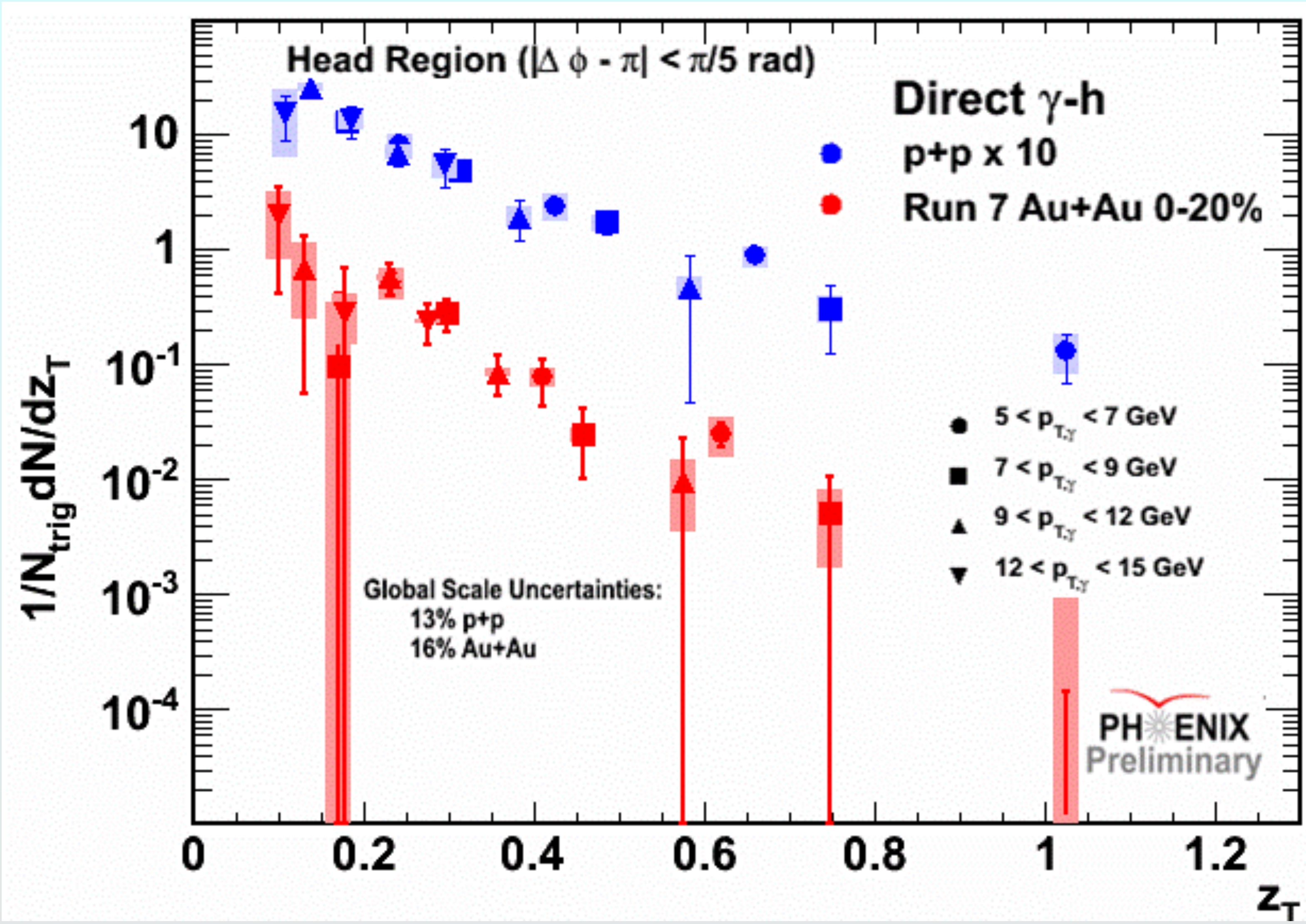
$$I_{AA} \equiv \frac{(1/N_{trig} dN/d\xi)_{AA}}{(1/N_{trig} dN/d\xi)_{pp}}$$

FFn experimental challenge:

measure the parton p

Use trigger γ or jet

Modified in AA vs. p+p



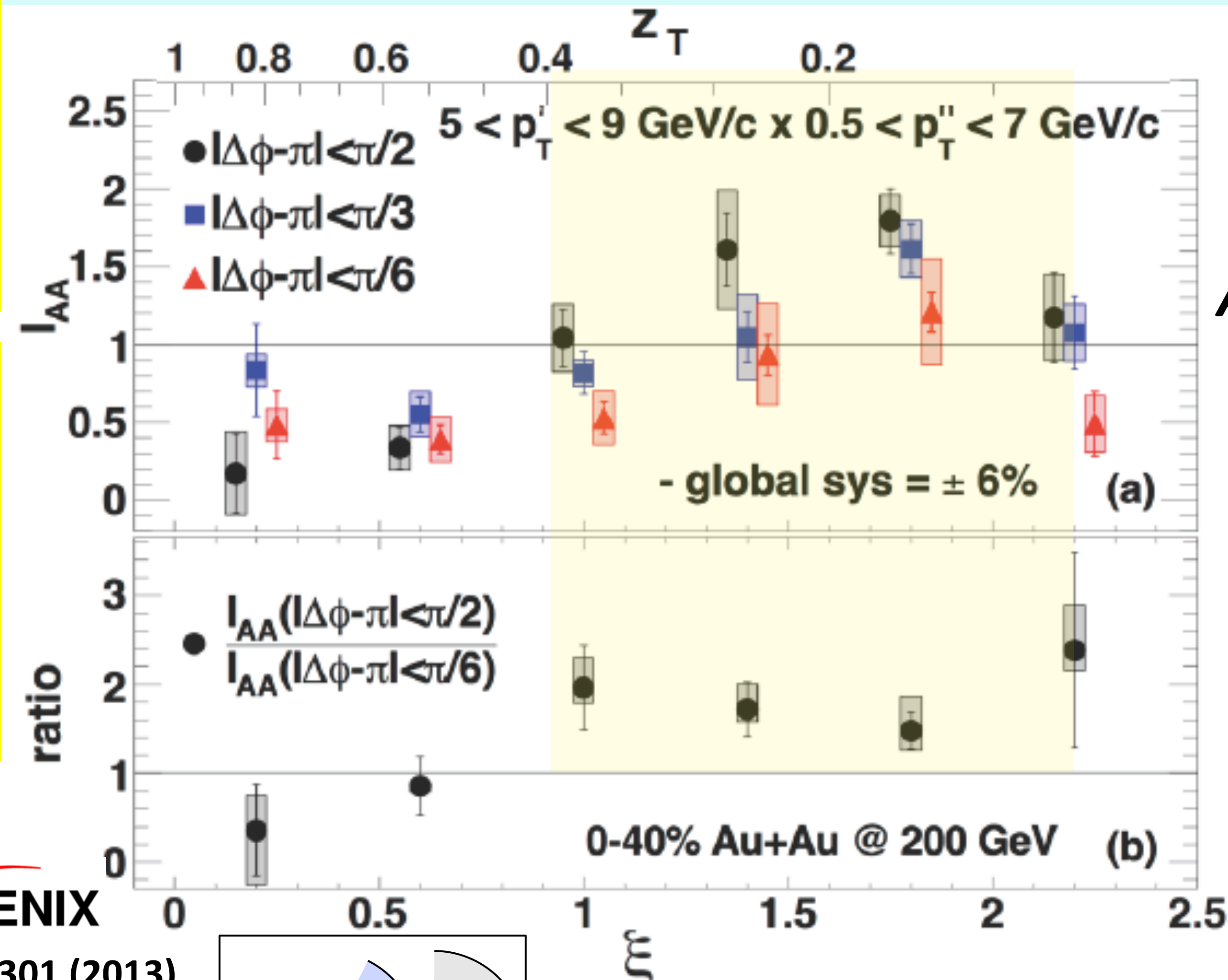
PHENIX: FFn via γ-h correlation

γ: parton energy, h: fragmentation fn.

"Extra" soft particles at larger angles near the away side jet

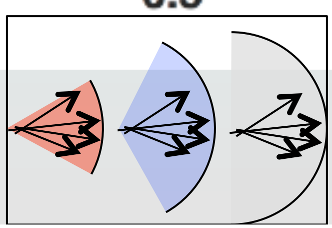
Provide constraints on gluon splitting

Perturbative?



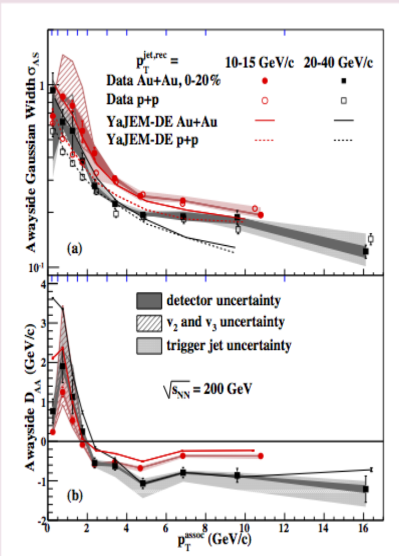
Au+Au/ p+p

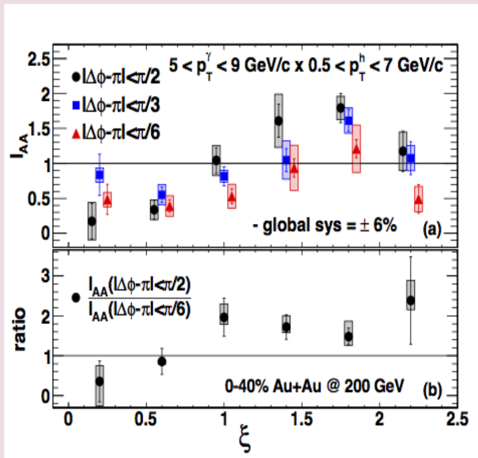
PRL 111, 032301 (2013)



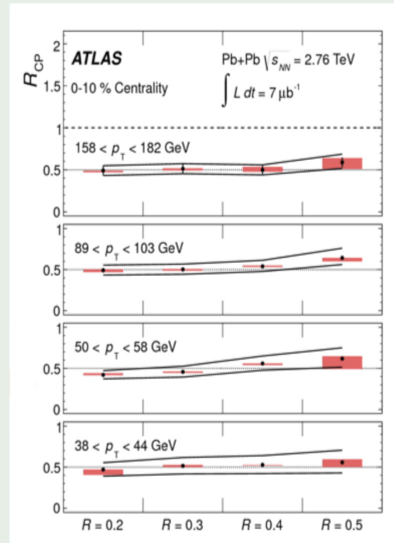
G. Roland

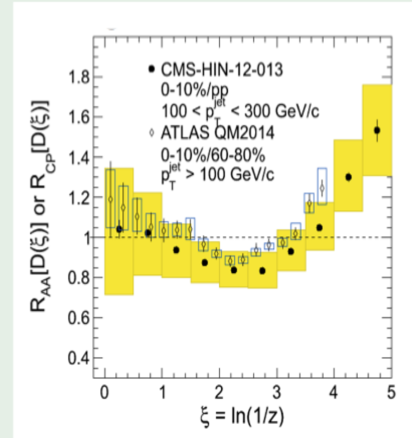
Jets @ RHIC

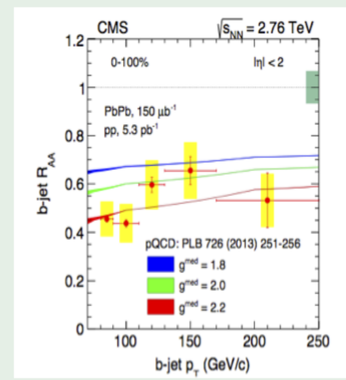


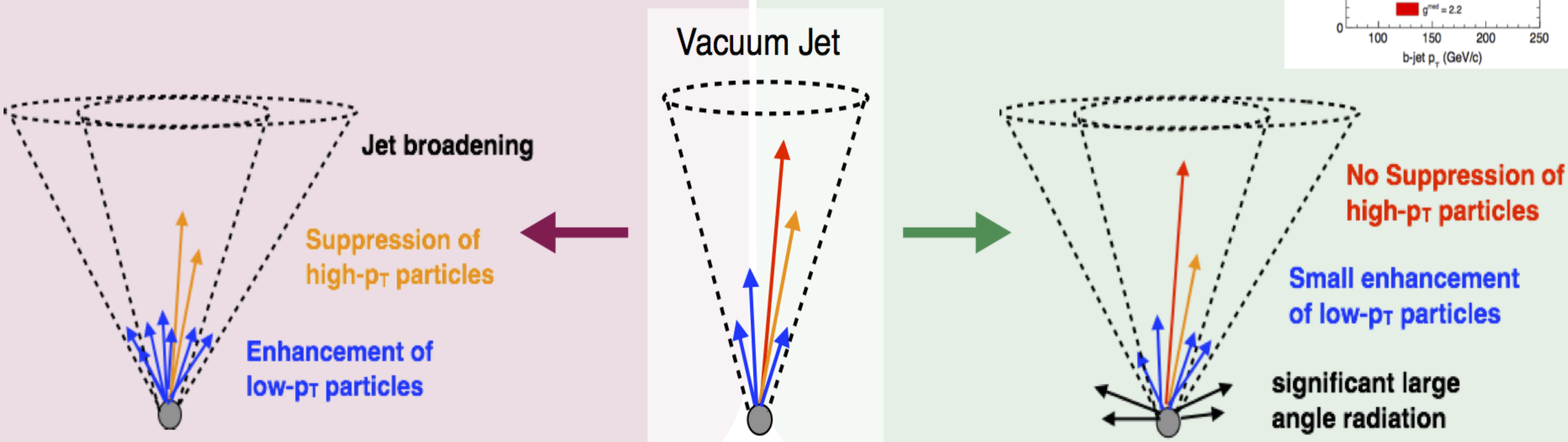


Jets @ LHC









A jet is a partonic probe

It's not a photon…

- It can lose energy before the hard scattering
- It can lose energy after the hard scattering
- It can experience multiple scattering
- These may not be independent!

These are not just "background"

Higher-twist physics is interesting, not well understood, as well as relevant to parton-plasma interaction !

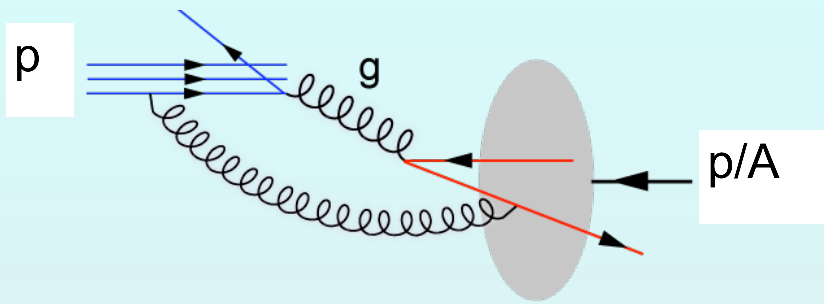
Should measure γ-h correlations in cold nuclear matter!

this is underway in p+A!

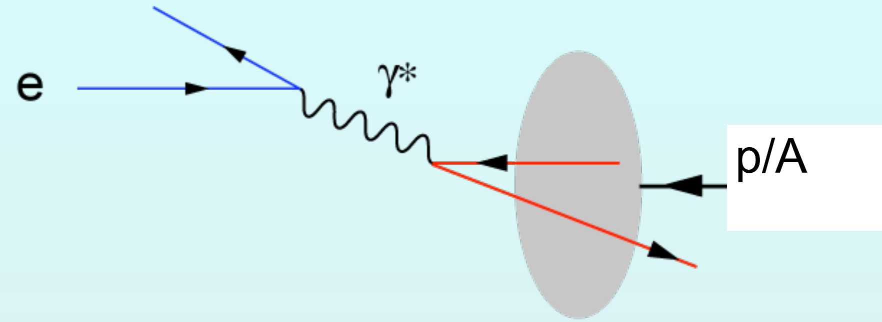
Change the probe! pA vs. eA

T. Ullrich

Hadron-Hadron



Electron-Hadron (DIS)

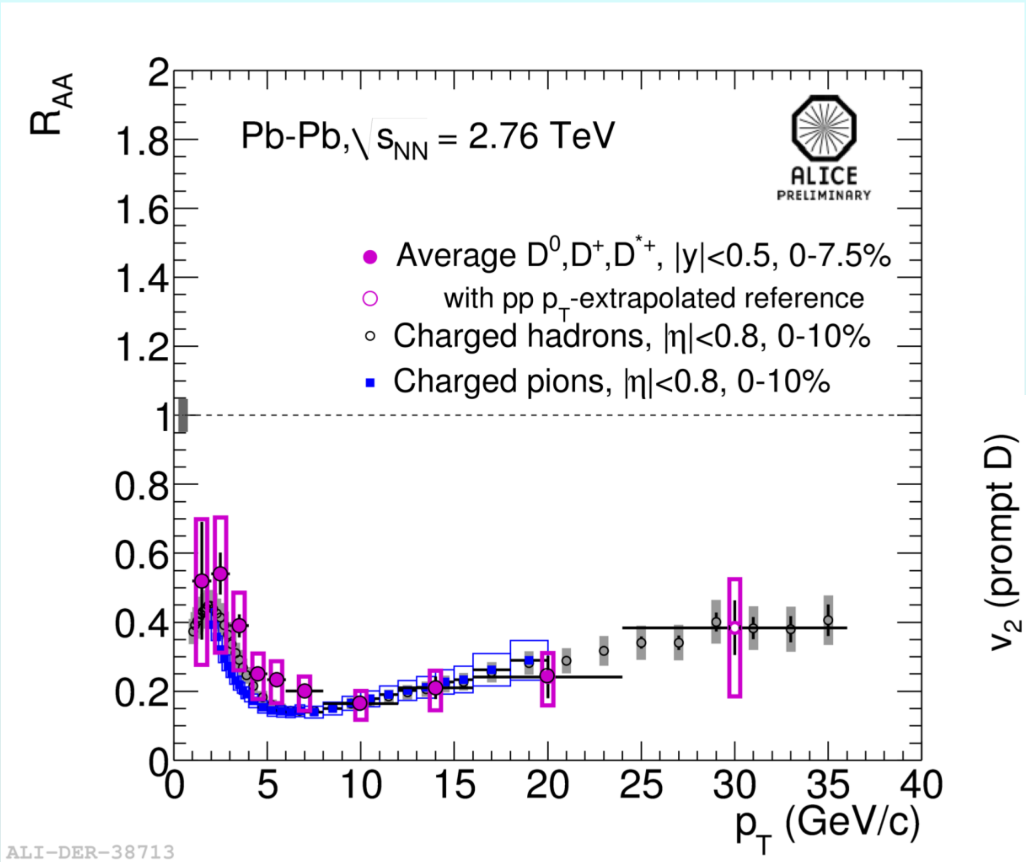


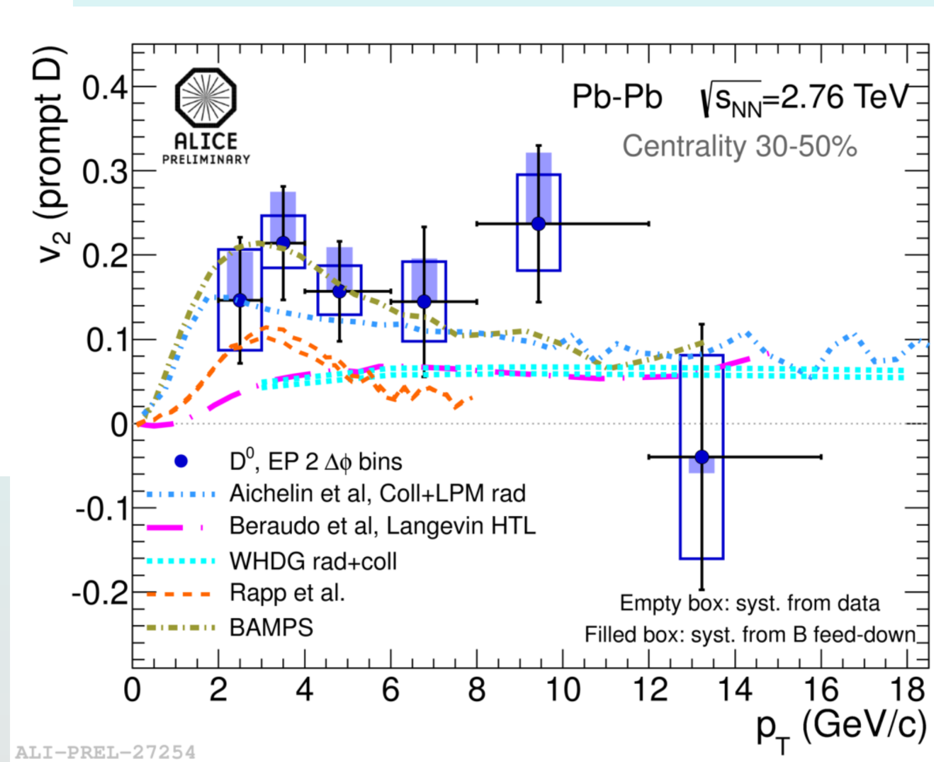
- More direct information on the response of a nuclear medium to gluon probe
- Probe has structure as complex as the "target"
- Soft color interactions before the collision can alter the nuclear wave function and destroy universality of parton properties (break factorization)

- Point-like probe
- Dominated by single photon exchange ⇒ no direct color interaction ⇒ preserve the properties of partons in the nuclear wave function
- High precision & access to partonic kinematics
- Nuclei always "cold" nuclear matter (CNM)

Heavy quark probes of QGP

Charm quarks also lose energy and flow!



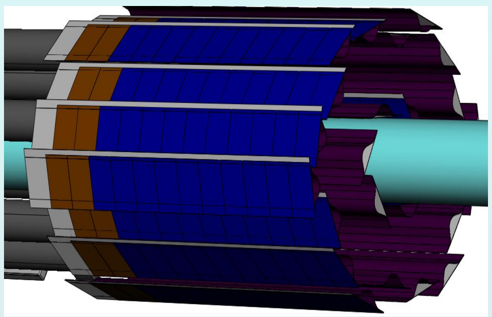


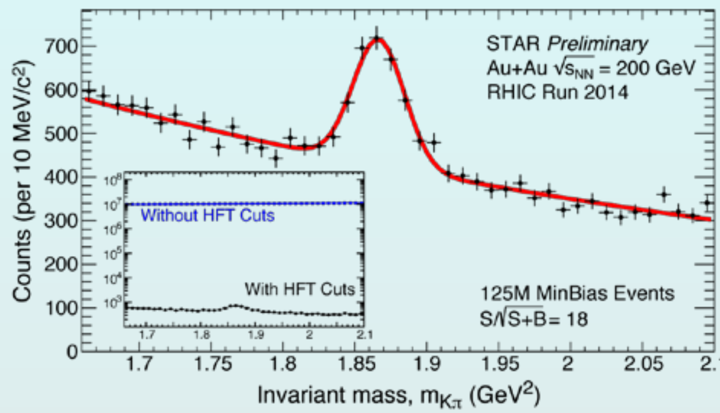
- Charm quarks diffusing through strongly coupled QGP
- Collisions drive energy loss and push charm along with the bulk

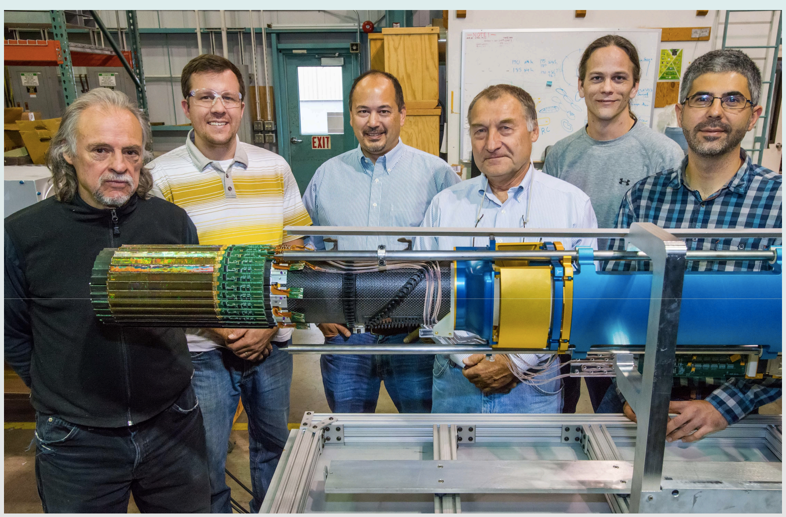
Upgrade ALICE for heavy quark probes in Run3

- **Silicon detector arrays around beam pipe**
  - **Tag displaced vertex to separate c,b**
  - **Reconstruct D & B mesons from their decay hadrons**

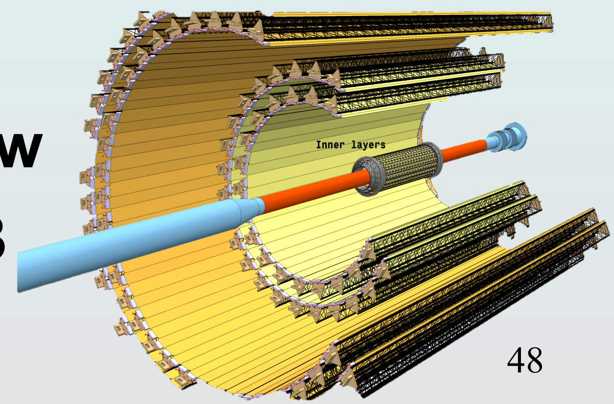
MAPS technology used for STAR at RHIC



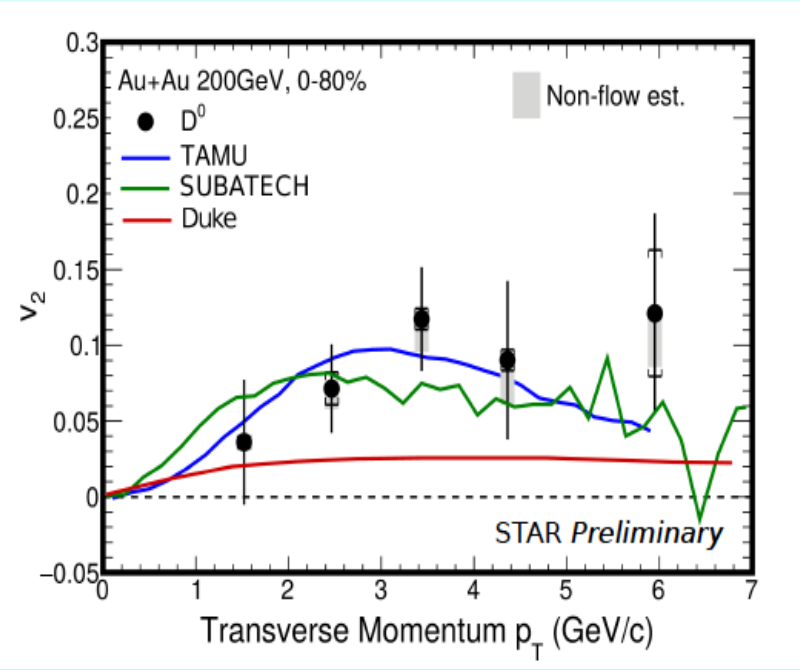


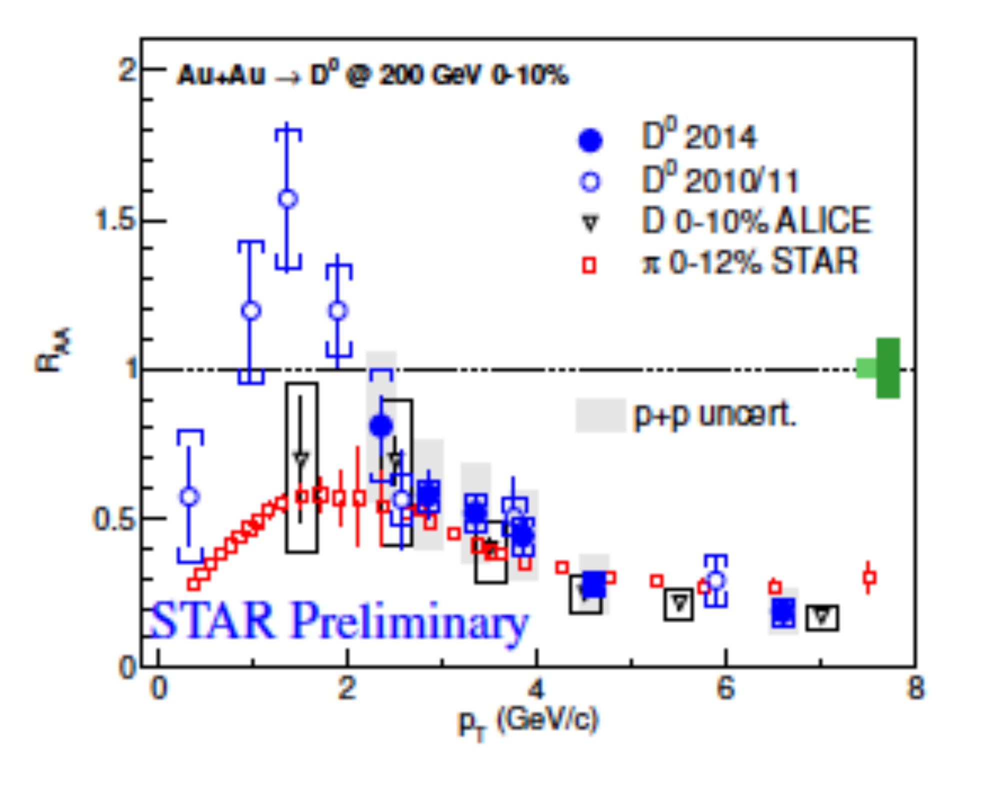


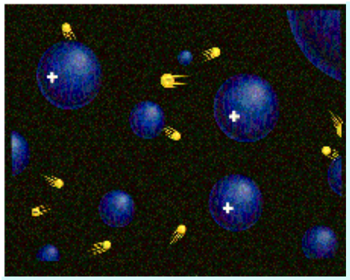
ALICE build now for Run3 (2020)



Flow and suppression as for light quarks





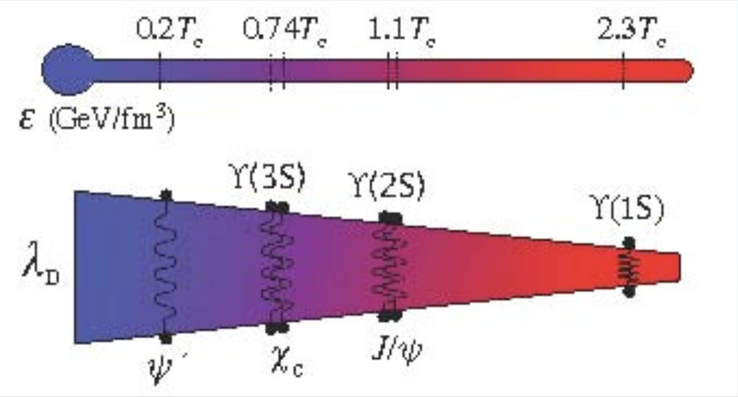


Is there a relevant screening length?

- Plasma: interactions among charges of multiple particles
  spreads charge into characteristic (Debye) length, λ_D
  particles inside Debye sphere screen each other

- Strongly coupled plasmas: few (~1-2) particles in Debye sphere
  Partial screening -> liquid-like properties
  sometimes even crystals!

- *Test* QGP *screening with heavy quark bound states*
  $c + \bar{c}$ and $b + \bar{b}$: J/ψ & Y
  Do they survive?
  All? None? Some? Which size?



Color screening in quark gluon plasma

- **q-qbar potential in vacuum:** $$V(r) = \sigma r - \frac{\alpha}{r}$$

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

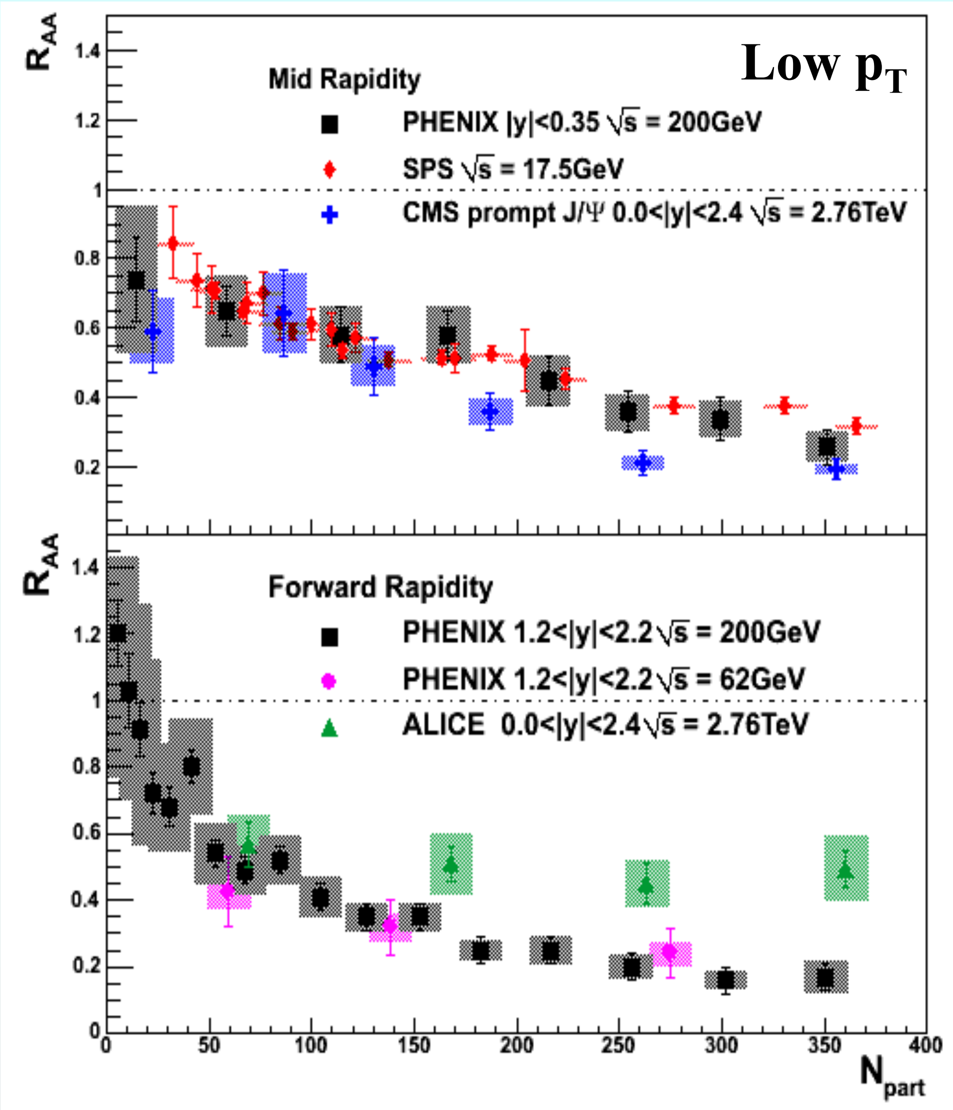
- **Screening length in EM plasma:** $$\lambda_D = \sqrt{\frac{T}{8\pi\alpha\rho}}$$

  in (ideal) QGP, particle density $\rho \propto T^3$ **so:** $$\lambda_D \sim \frac{1}{\sqrt{8\pi\alpha}T}.$$

- **For α_s ~ 0.2, find:**

Bound state	χ_c	ψ'	J/ψ	$\Upsilon(2S)$	χ_b	$\Upsilon(1S)$
T_d	$\lesssim T_c$	$\lesssim T_c$	$\sim 1.2T_c$	$\sim 1.2T_c$	$\sim 1.3T_c$	$\sim 2.0T_c$

J/ψ vs. system size, √s



No clear suppression pattern with √s, T!

Why more suppression at y=2?

Late break-up?

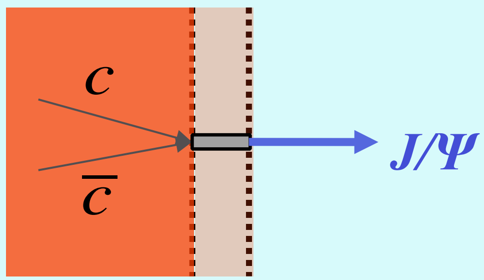
Final state coalescence of $q\bar{q}$?

J/ψ R_{AA} ~same from 17.5-200 GeV!

2.76 TeV direct J/ψ lower at mid-y, inclusive above at forward y

Lose some and gain some

- QGP screens primordial c-cbar and b-bbar
  - Melting depends on binding energy (i.e. size of bound state)
  - Look at J/ψ vs. ψ' vs. Υ states
- quarks find one another when system cools to T~150 MeV
  - coalesce to form the hadrons we observe
- Occasionally a c can find a cbar
  - "regeneration" or "coalescence"
  - Probability increases with c-cbar pairs
  - Increases with beam energy
  - Confuses measurements of melting



- ➢ Measure energy & quark mass dependence to sort out
  - ➢ b's are rare, so Υ is a good screening probe
- ➢ Initial state affects c&b production – so must measure p+A!

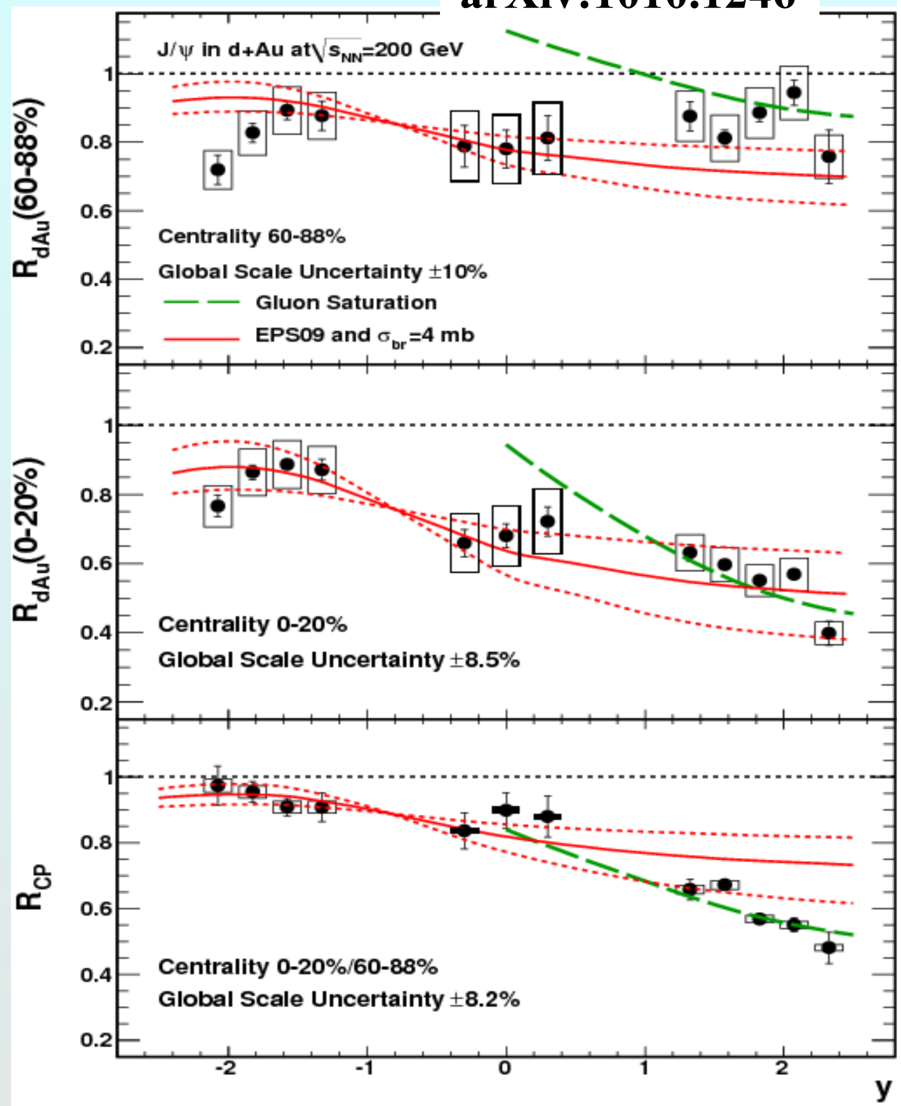
Suppression pattern ingredients

arXiv:1010.1246

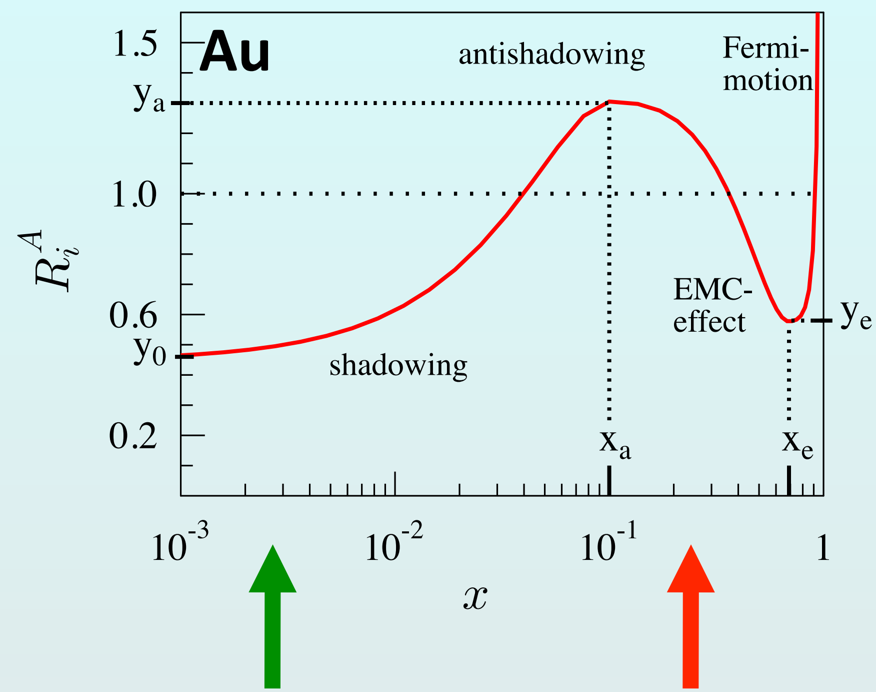
- Color screening
- Final state coalescence

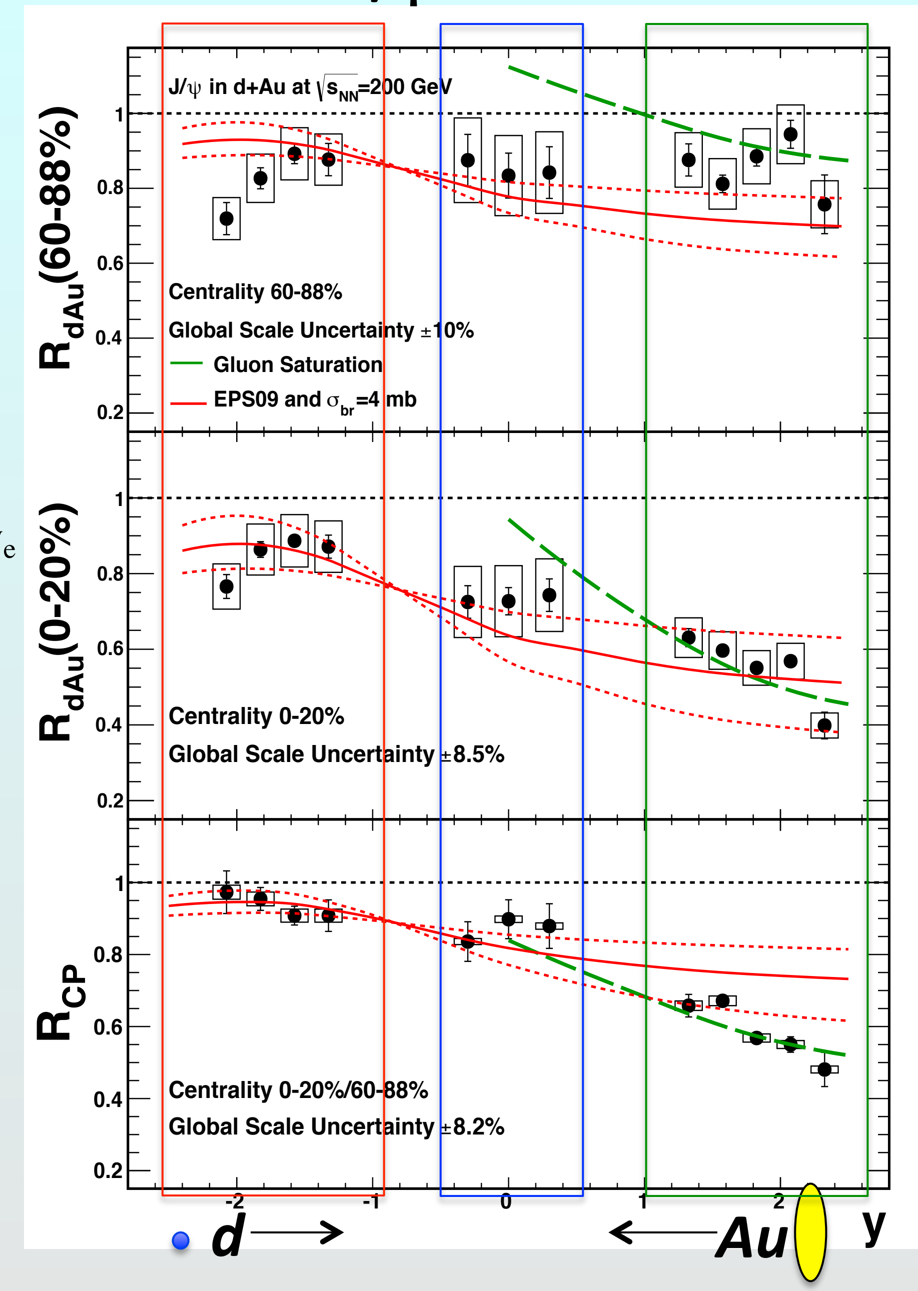
- **Initial state effects**
  Shadowing or saturation of incoming gluon distribution
  Initial state energy loss
  (calibrate with p+A or e+A)

- **Final state effects**
  Breakup of quarkonia due to co-moving hadrons
  (calibrate with A & centrality dependence)



d+Au -> J/ψ from PHENIX



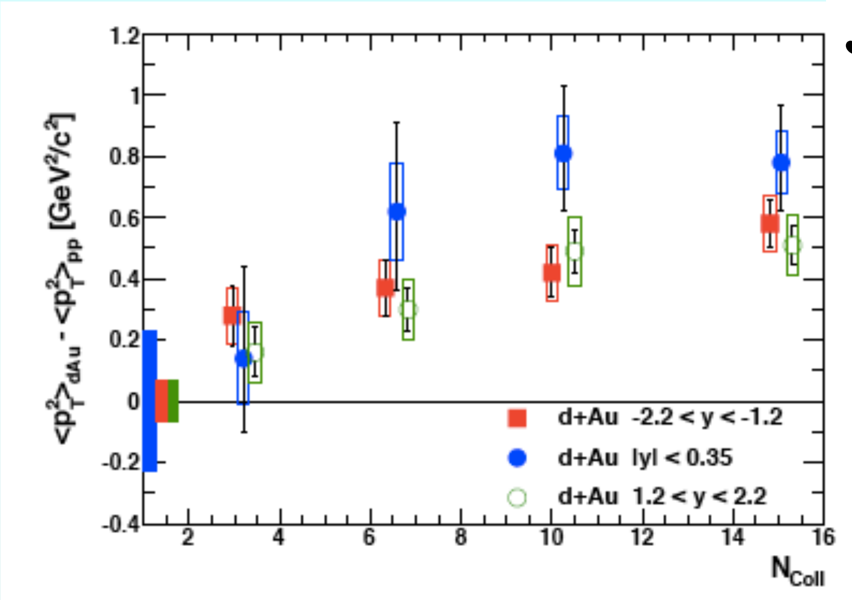


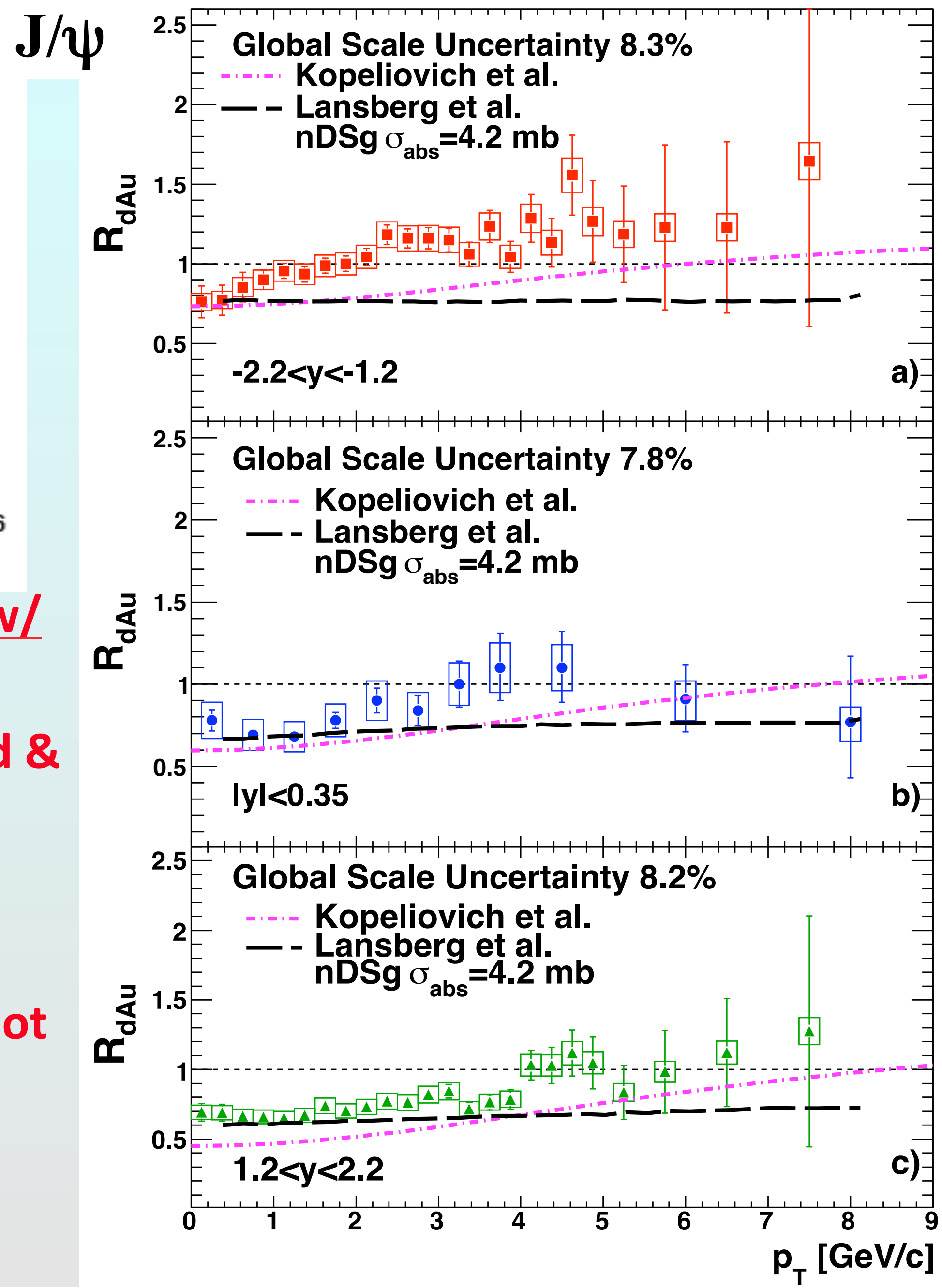
Forward
+ y
d-going

Backward
- y
Au-going

Shadowing, breakup & Cronin effect

PRC87, 034911 (2013)



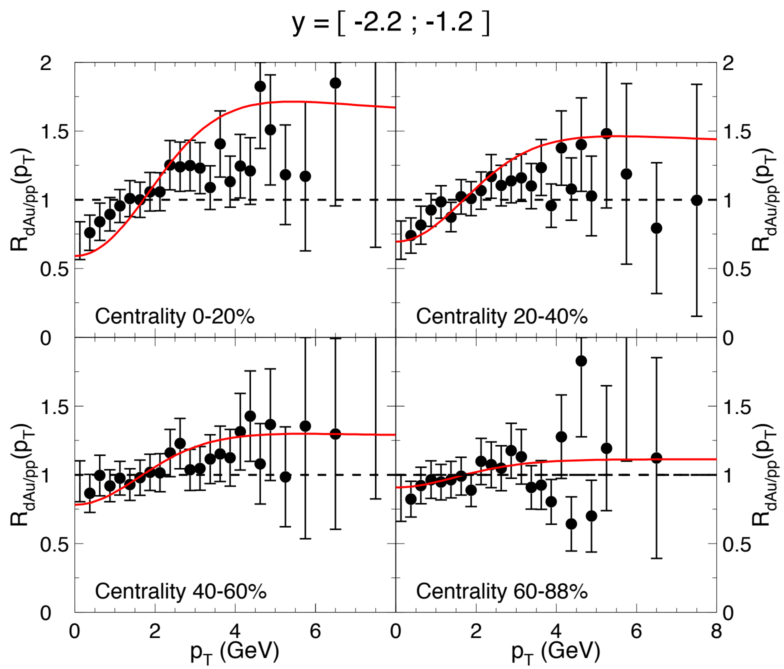


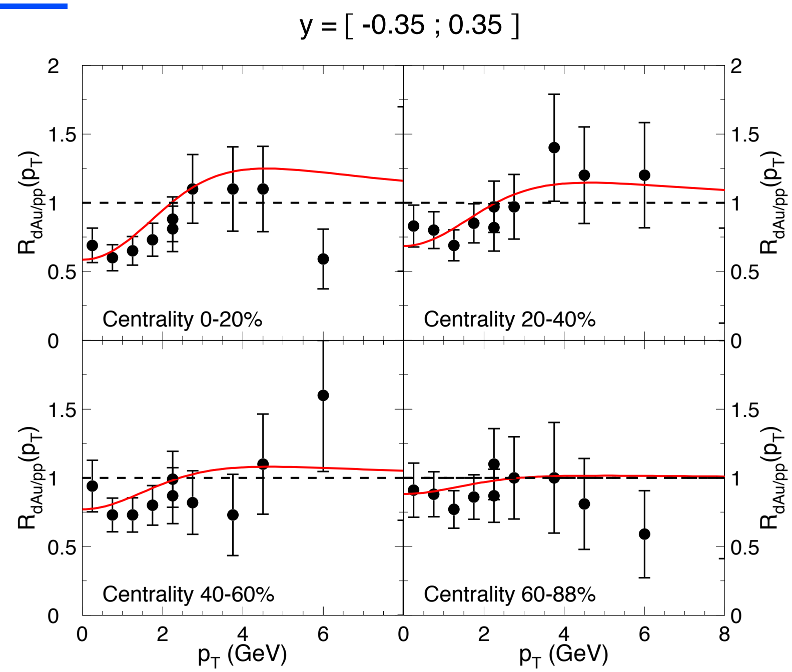
- ✦ p_T broadens (multiple scattering) w/ N_{coll}; effect stronger at y=0
- ✦ J/ψ suppressed to higher p_T @ mid & forward y (lower x in Au);
- ✦ R_{dA}>1 at high p_T backward (Cronin effect in Au nucleus)
- ✦ p_T, y, centrality dependence was not reproduced by the models

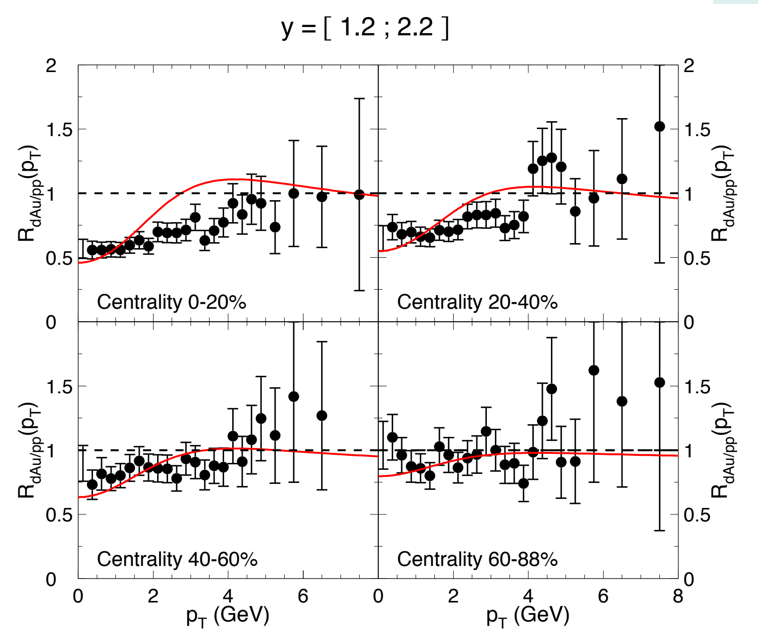
d+Au -> J/ψ

but

Arleo, et al 1304.090







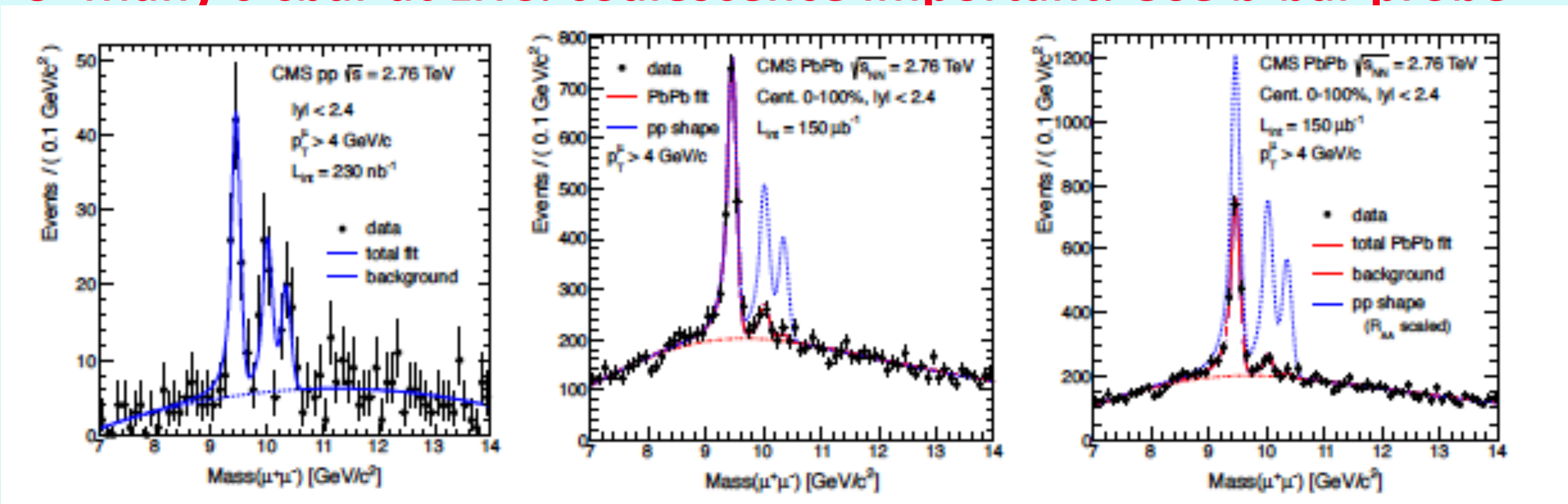
coherent parton energy loss and p_T broadening from multiple scattering ir the nucleus is consistent with data!

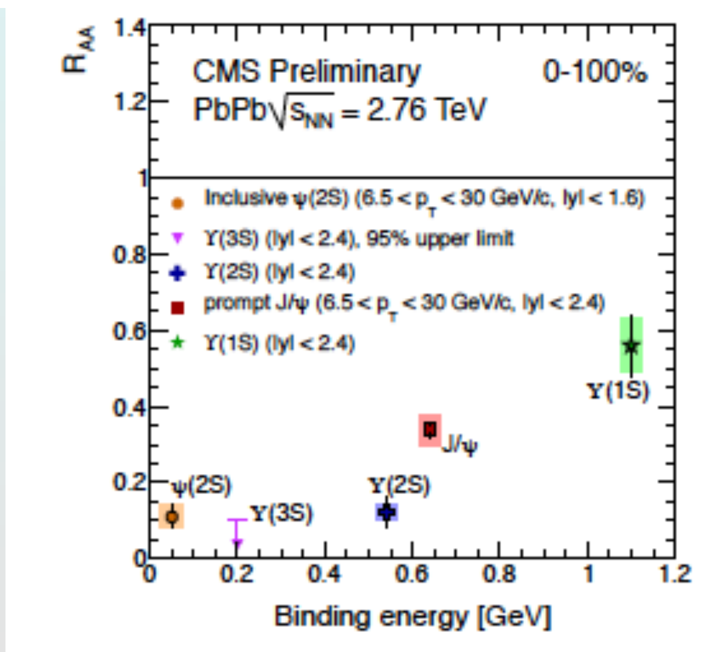
$\hat{}q_0 = 0.075$ GeV^2/fm

Dynamics of the probe & structure of the medium mix!!

b-bar bound states at the LHC

- **Many c-cbar at LHC: coalescence important. Use b-bar probe**

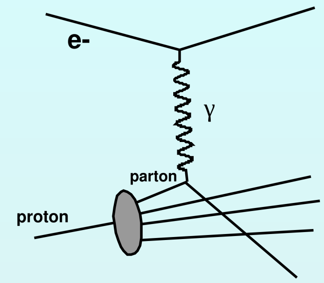




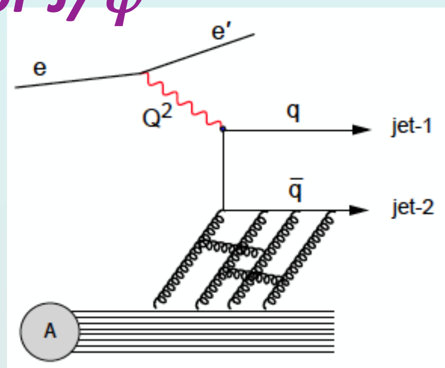
Υ (2S,3S) suppressed

Probe nucleons & nuclei with electrons

- **How many gluons are there?**
  Measure e+p, e+A → e

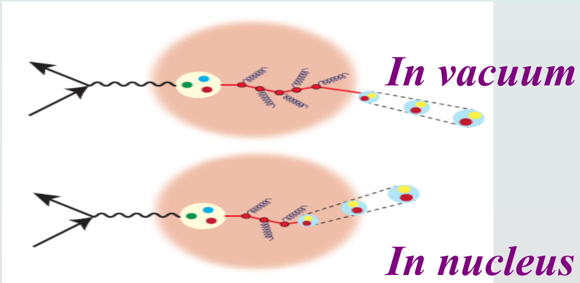


- **How are they distributed?**
  In space? In momentum?
  Measure e+p, e+A → e + hadrons, e + γ or J/ψ



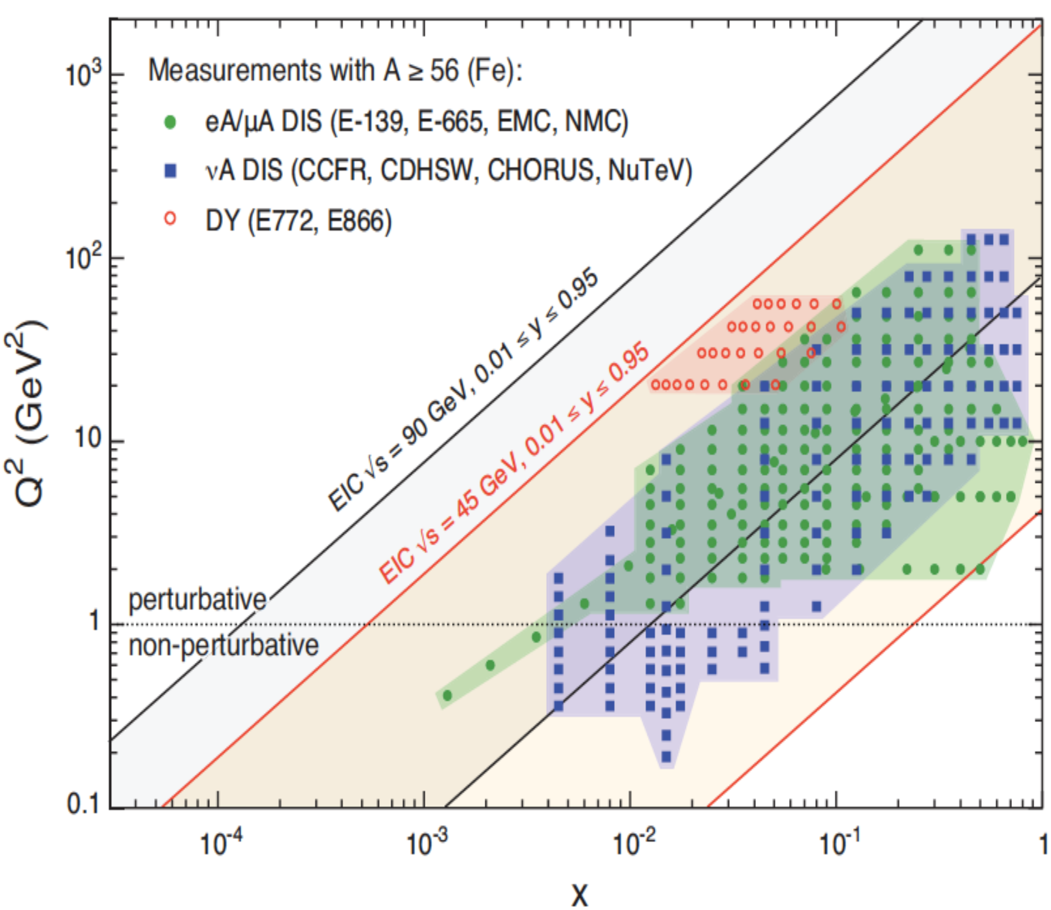
- **How are they correlated inside nucleus?**
  Measure e+p, e+A →
  e + ≥ 2 hadrons

- **What's gluon range inside a nucleus?**
  Measure hadron production

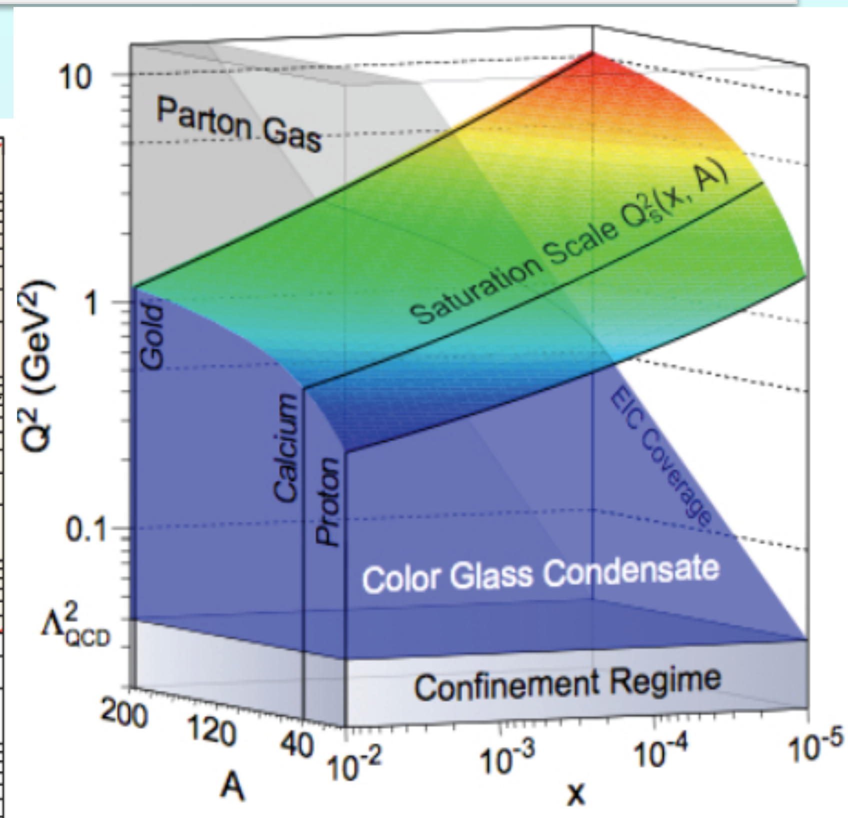


EIC kinematic reach

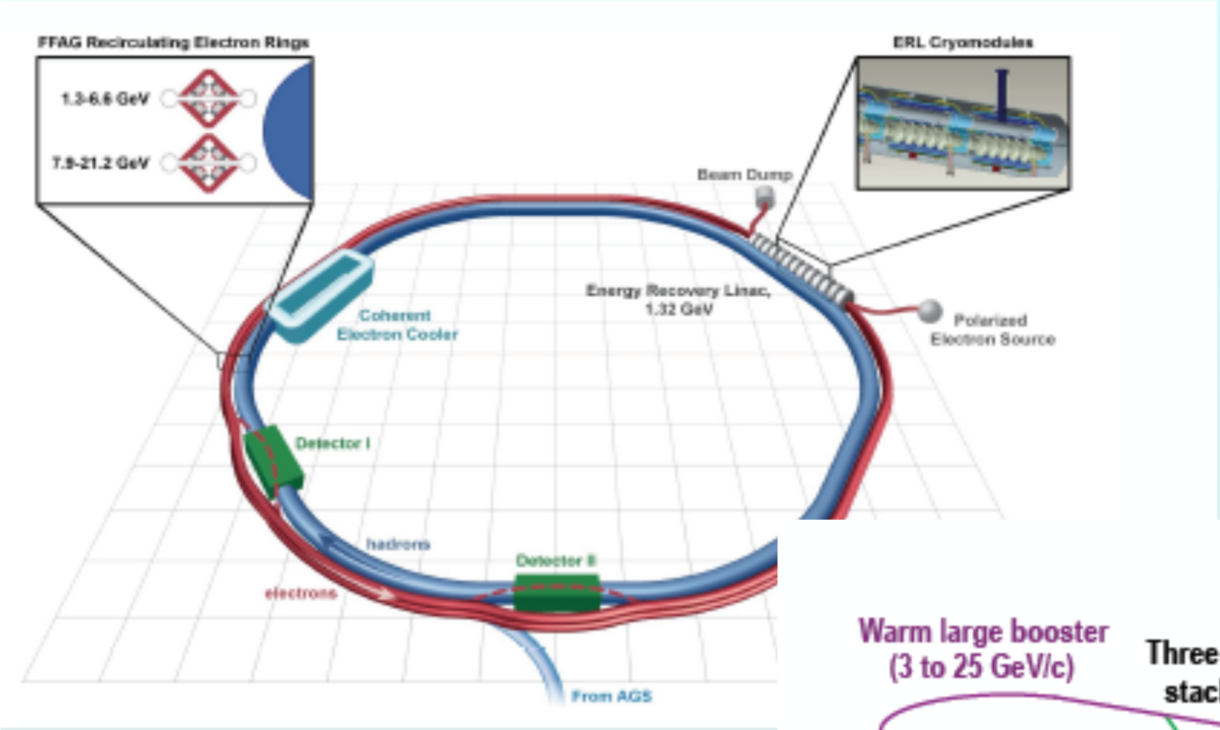
An electron-ion collider probe structure directly

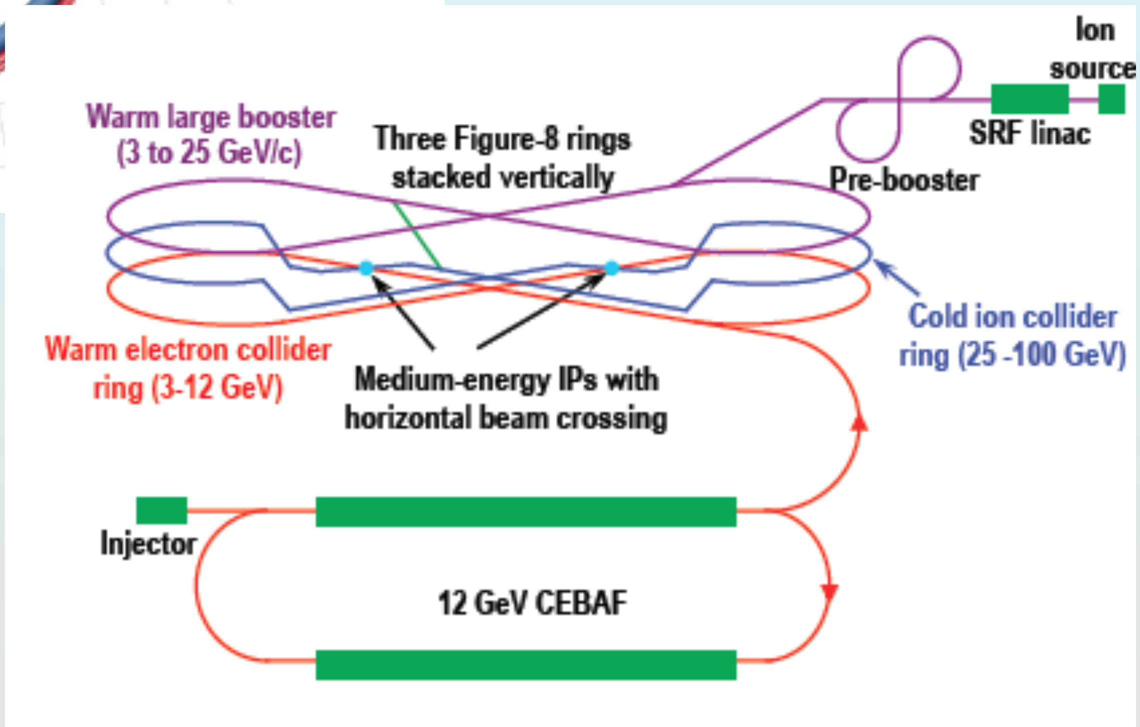


Enhance Q_S with A, not energy



Electron-ion collider





- **backup slides**

Questions

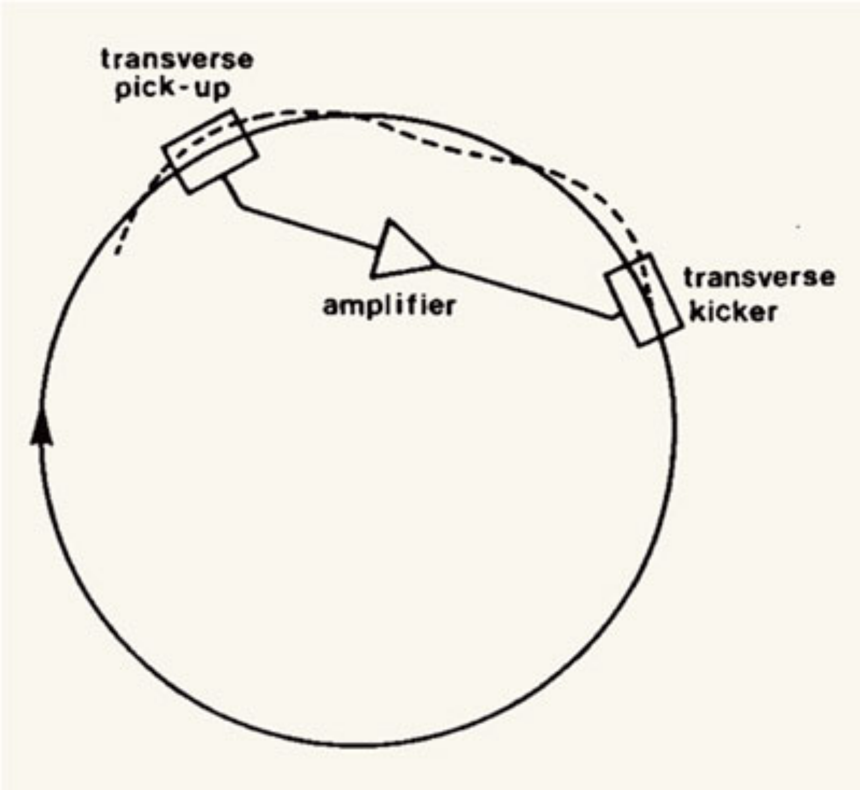
- Can we create quark gluon plasma in the lab?
- thermodynamic properties (equilibrium)
  T, P, ρ
  Equation Of State (relation btwn T, P, V, energy density)
  v_{sound}, static screening length
- transport properties (non-equilibrium)*
  particle number, energy, momentum, charge
  diffusion *sound* *viscosity* *conductivity*

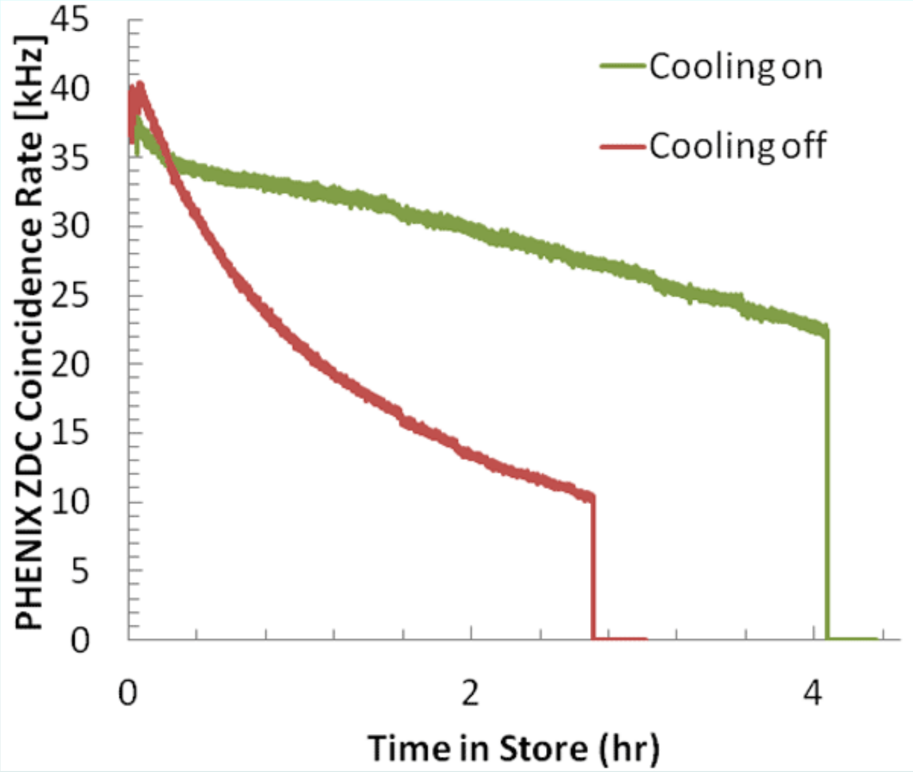
In plasma: interactions among charges of multiple particles
charge is spread, screened in characteristic (Debye) length, λ_D
also the case for strong, rather than EM force

***measuring these is new for nuclear/particle physics!**

Stochastic cooling keeps bunches tight

- *Coulomb interactions among highly charged ions blow up the beam bunches*
- *Measure and send correcting kick to outliers (at each go-round)*





➢ ***Huge increase in beam lifetime and luminosity!***

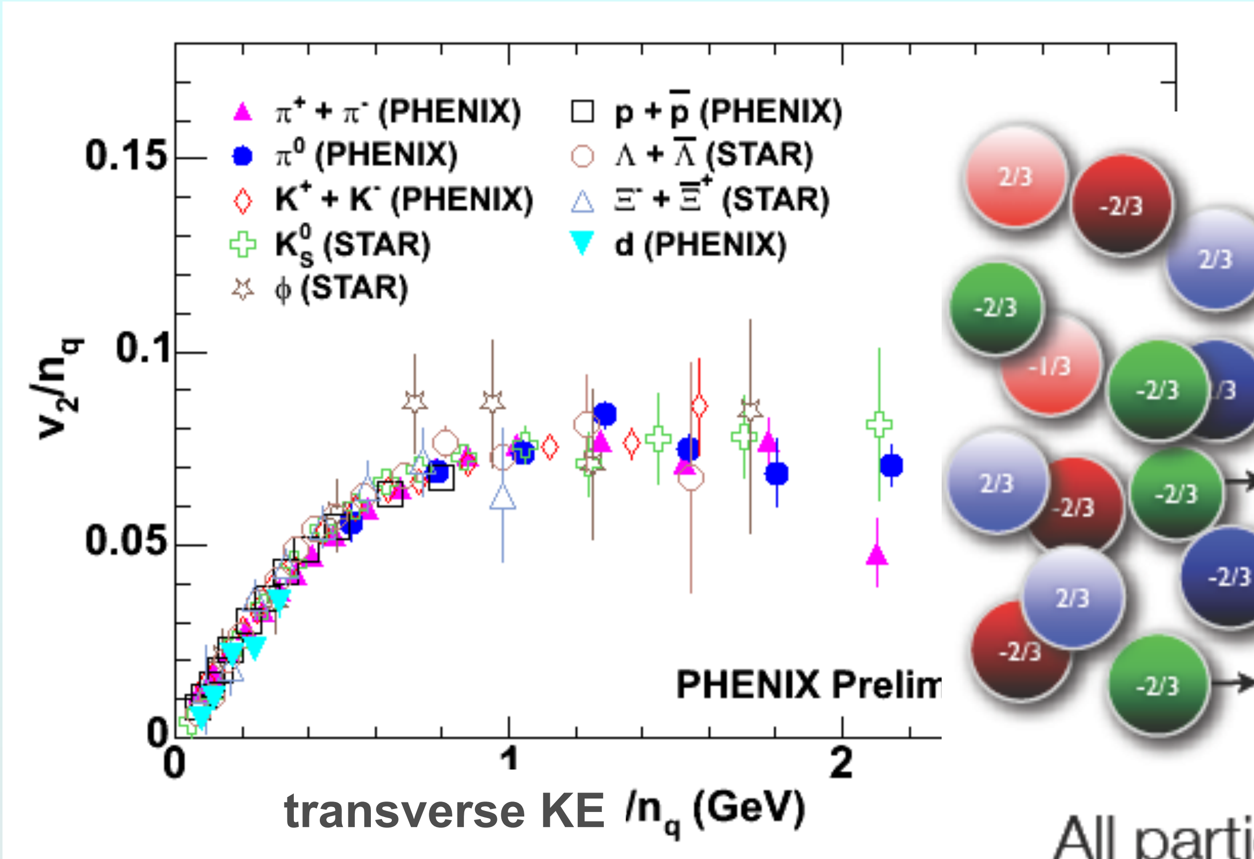
Mechanism for fast thermalization?

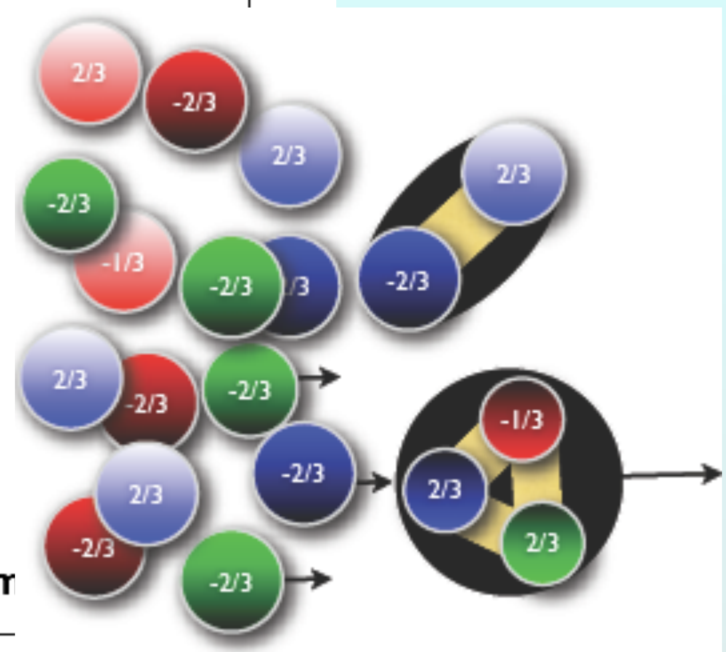
- Must be thermalized in < 1 fm/c!
  Otherwise v_2 smaller than in the data

- Can this be achieved with gg, qg, and qq binary scatterings?
  NO!
  Making this picture yield sufficient v_2, requires boosting the pQCD parton-parton cross sections by a factor of ~50!

- Mechanism not known yet. Perhaps start out with correlated gluonic matter at small x?

Elliptic flow scales with number of quarks





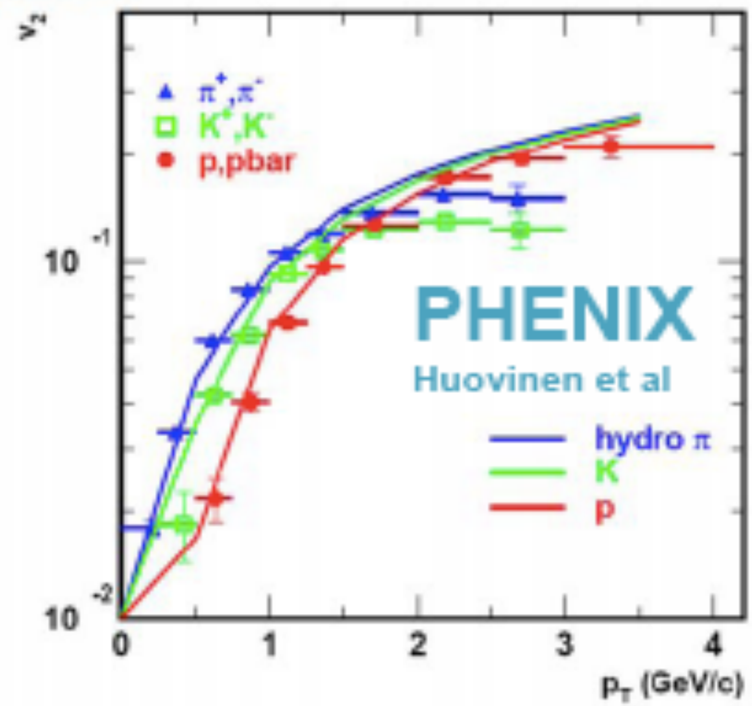
All particles flow as if frozen out from a flowing soup of constituent quarks

implication: valence quarks, not hadron

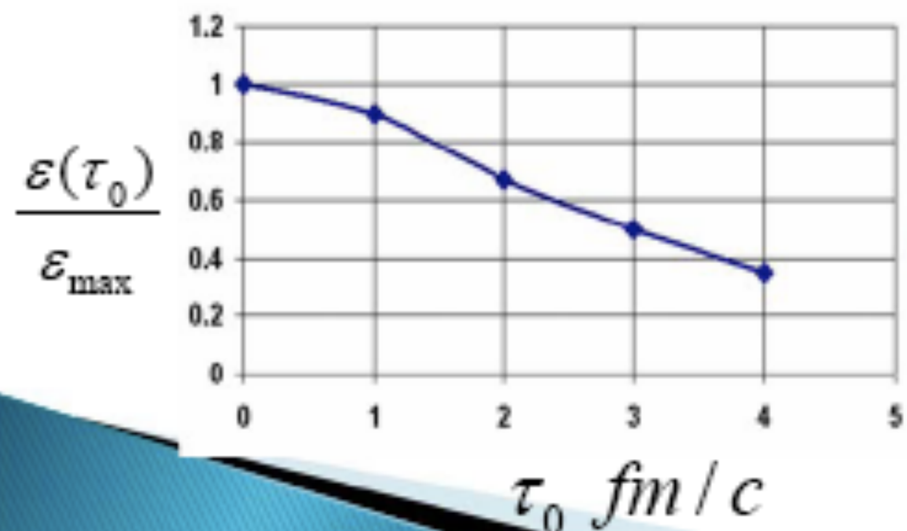
pressure builds early, dressed quarks ar

Strong flow Implies early thermalization

- If system free streams
  - spatial anisotropy is lost
  - v_2 is not developed



Eccentricity: $\varepsilon = \dfrac{\langle y^2\rangle - \langle x^2\rangle}{\langle y^2\rangle + \langle x^2\rangle}$



detailed hydro calculations (QGP+mixed+RG, zero viscosity)

- $\tau_0 \sim 0.6 - 1.0$ fm/c
- $\varepsilon \sim 15\text{–}25$ GeV/fm^3
- (ref: cold matter 0.16 GeV/fm^3)

Calculating transport in QGP

weak coupling limit

perturbative QCD

kinetic theory, cascades

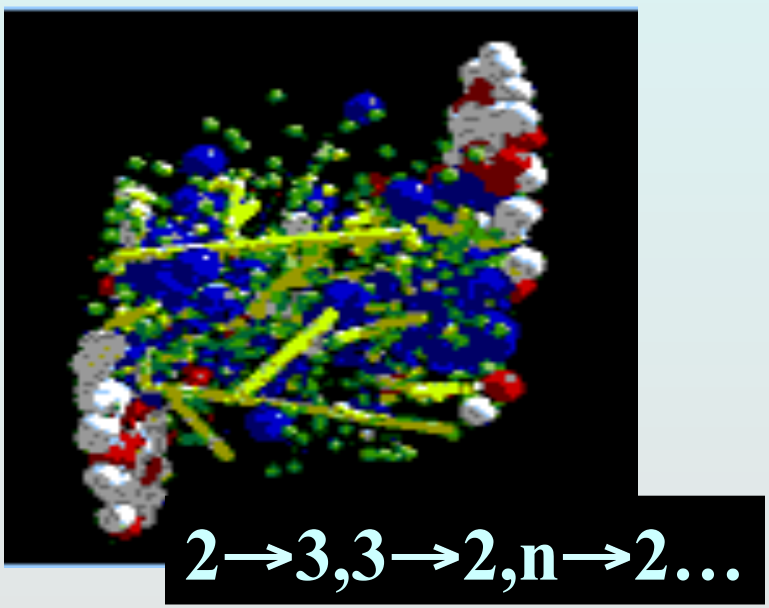
interaction of particles

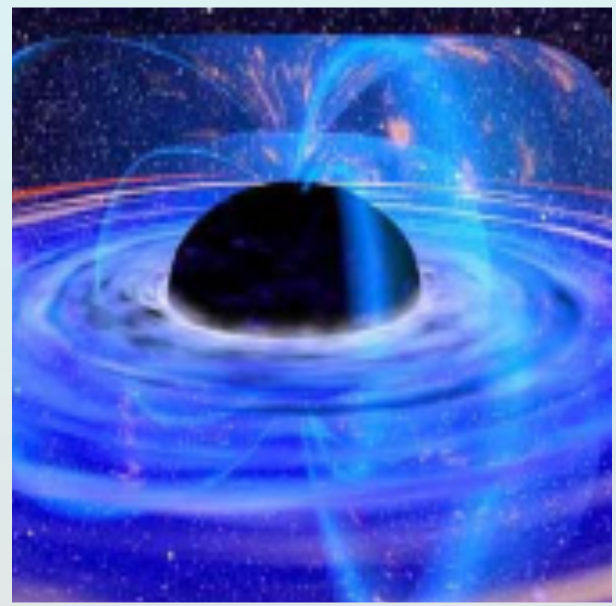
∞ strong coupling limit

not easy! Try a pure field…

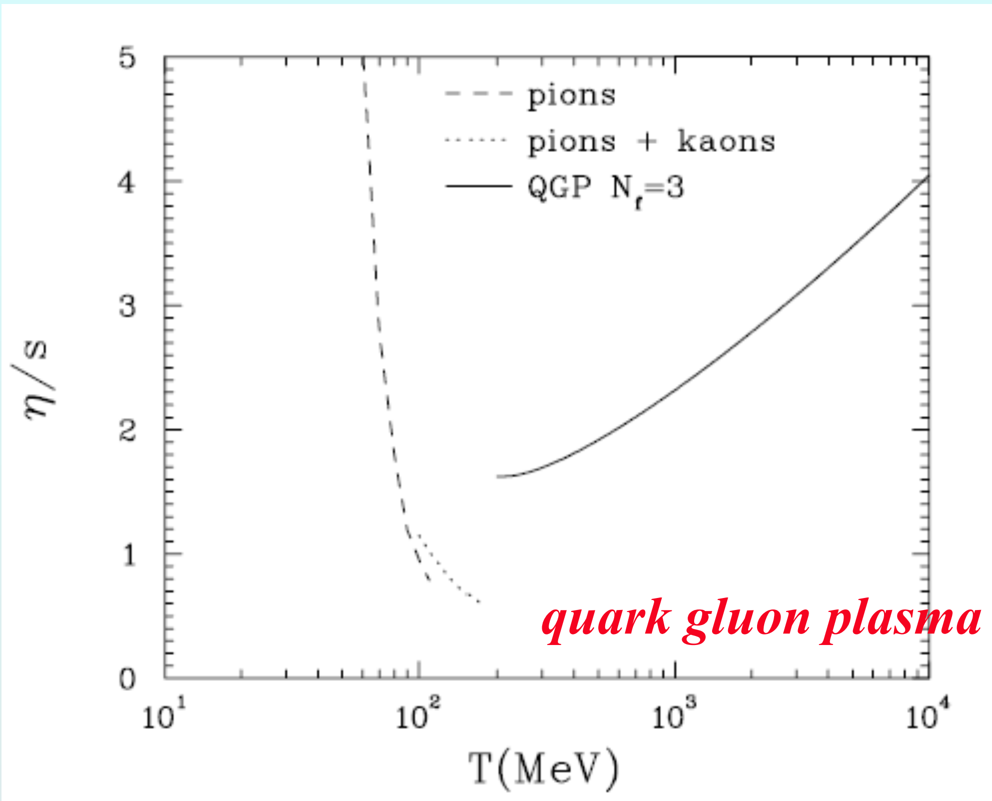
gravity ↔ supersym 4-d

(AdS/CFT)



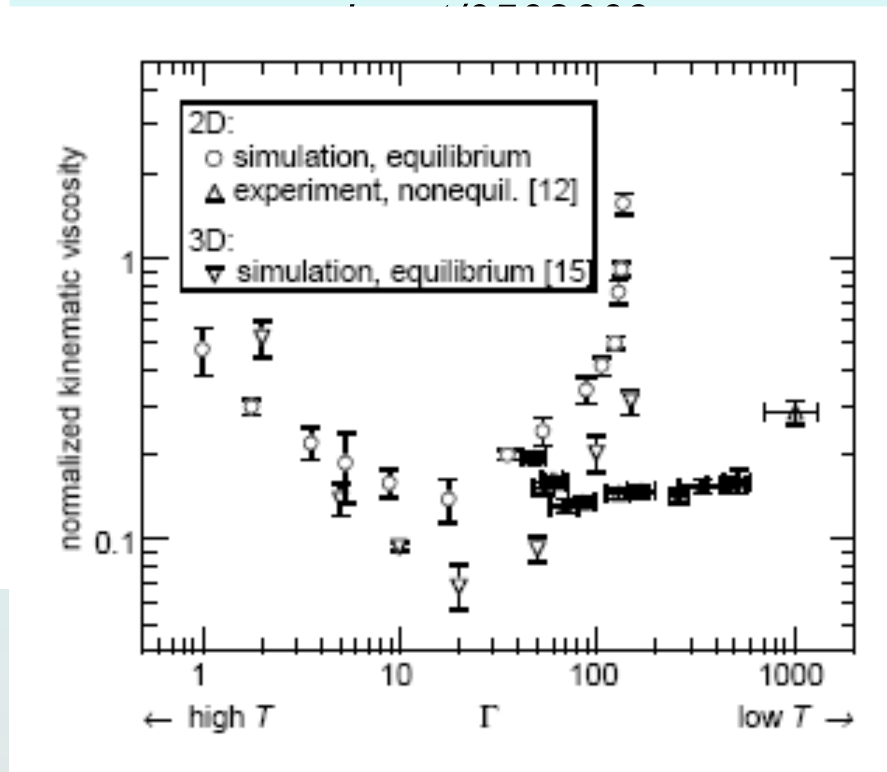


minimum η at phase boundary?



strongly coupled dusty plasma

B. Liu and J. Goree,

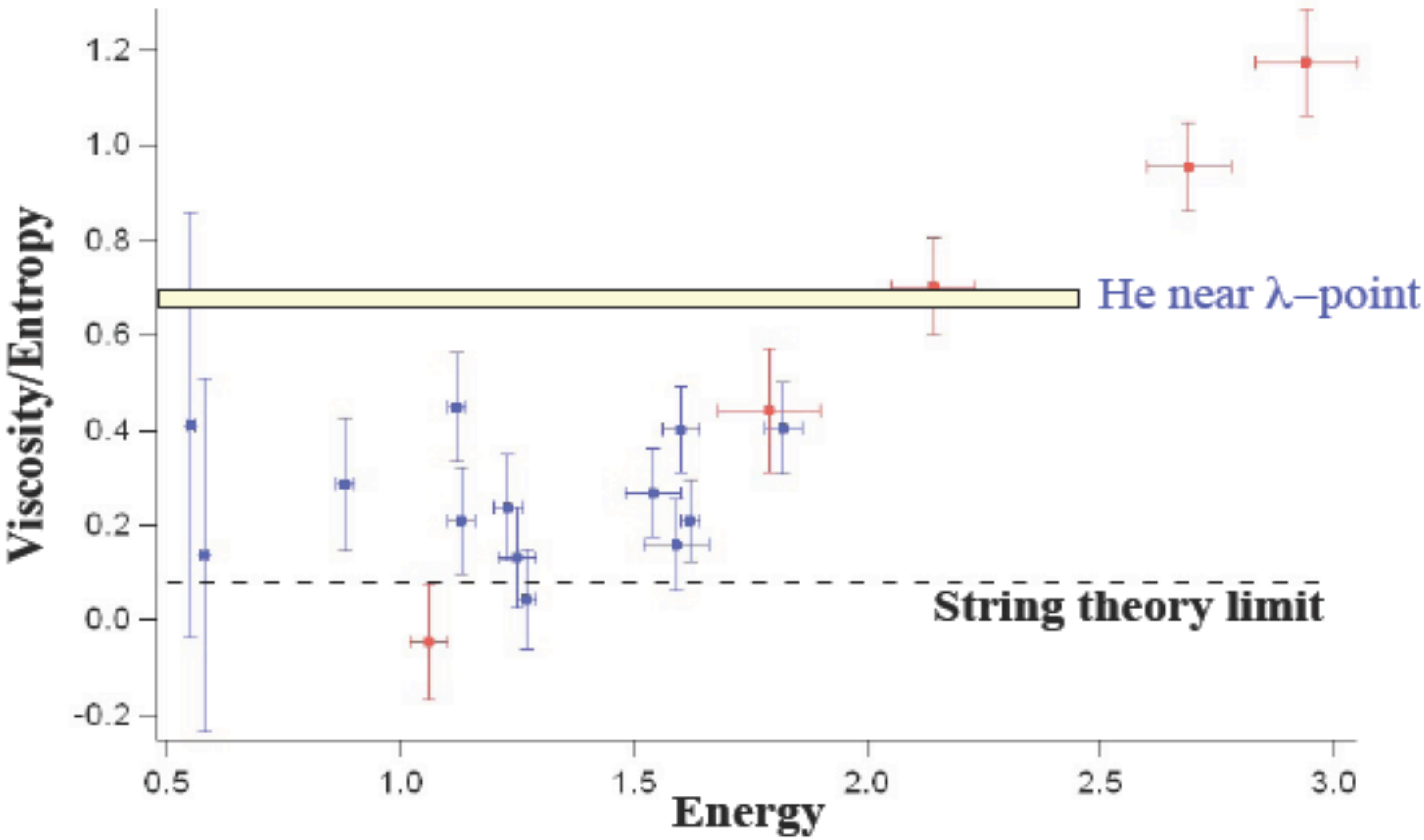


Csernai, Kapusta & McLerran
PRL97, 152303 (2006)

minimum observed in other strongly coupled systems –
kinetic part of η decreases with Γ while potential part increases

Viscosity/Entropy (natural units)

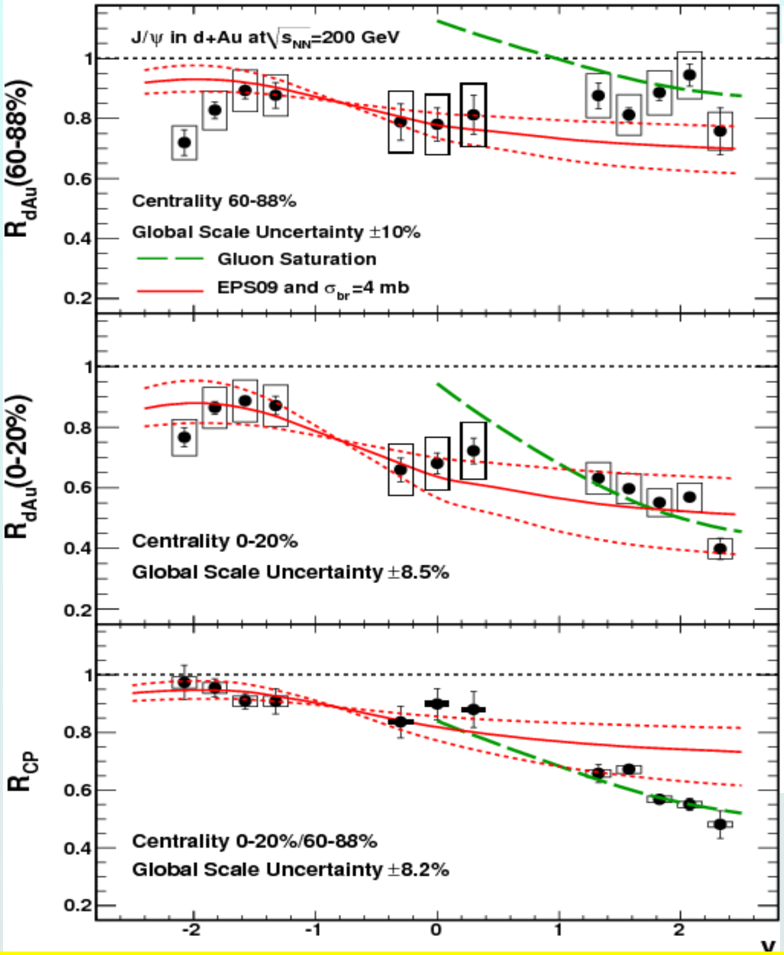
Duke Physics
Atom Cooling and Trapping

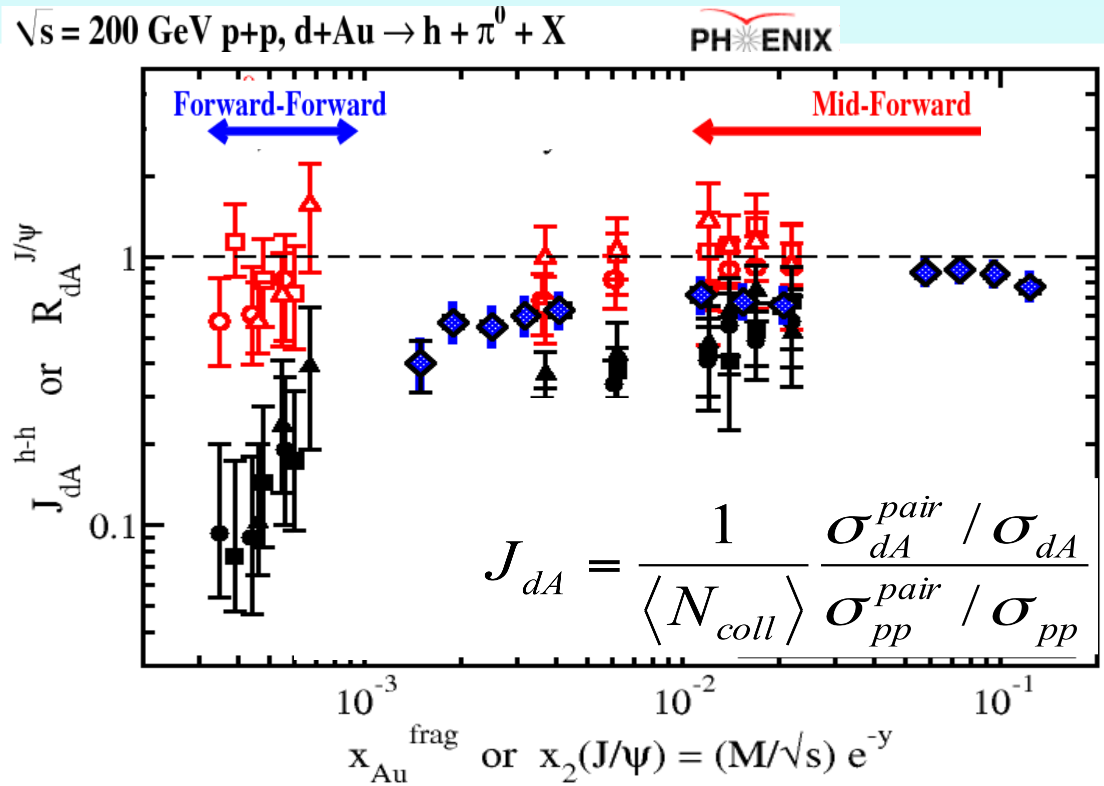


Dense gluonic matter (d+Au, forward y): large effects observed

arXiv:1010.1246

arXiv:1105.5112





Di-hadron suppression at low x

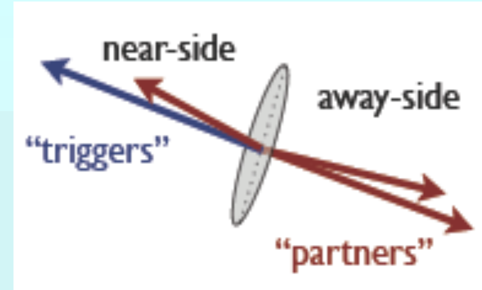
pocket formula (for 2➔2):

$$x_{Au}^{frag} = \frac{< p_{T1} > e^{-<\eta_1>} + < p_{T2} > e^{-<\eta_2>}}{\sqrt{s}}$$

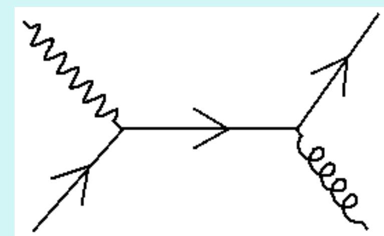
Shadowing/absorption stronger than linear w/nuclear thickness

trend as, e.g. in CGC …

More jet probes = more insight



- **Hadrons**
  - **Single high p_T hadrons (leading jet fragments)**
  - **di-hadron correlations**
- **Reconstructed jets (*depend on reco algorithm, compare to theory)***
  - **Single jets**
  - **<di-jets> or jet-h correlations**
- **Gamma-jet correlations (*photon tags jet energy)***
  - **γ-h correlations**
  - **<γ-reconstructed jet>**



- **Construct the variables: R_{AA}, I_{AA}, A_J, q-hat**

Nuclear modification:

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

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

Jet asymmetry:

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \Delta\phi > \frac{\pi}{2}$$

Jet transport coefficient: $\hat{q} = \mu^2/\lambda$; μ = <p_T transfer> in 1 scattering