HELMHOLTZ INTERNATIONAL SUMMER SCHOOL

Dubna International Advanced School of Theoretical Physics / DIAS-TH

DENSE MATTER 2015

Bogoliubov Laboratory of Theoretical Physics,
Joint Institute for Nuclear Research, 29 June - 11 July

“Some Topics of Relativistic Heavy Ion Physics. Quark Gluon String Model ”

by

Larissa Bravina,
University of Oslo, Norway

“Some Topics of Relativistic Heavy Ion Physics and Quark Gluon String Model”

Content:

1. **Introduction to High Energy Heavy Ion Collisions**

- Quantum Chromodynamics and signatures of QGP phase transition

– Applications of particle intensive interferometry in relativistic heavy-ion collisions

- Strangeness production in hh-, hA- and A+A-collisions

- Hard probes:Jet Quenching, Nuclear Shadowing, High-pt particles

- Electromagnetic signals: Photon and Dilepton Production

- Heavy quark production and J/ψ suppression

- Collective effects: anisotropic flow, shock waves

- Cosmological aspects of QGP formation from Big Bang to Neutron Stars

Lecture:

1) Introduction to Relativistic Heavy Ion Collisions
2) Glauber Model of relativistic heavy Ion collisions
3) Space Time Picture of Relativistic Heavy Ion collisions in Gribov-Regge picture
folk.uio.no/larissa/nuclphys/HotQuarks2006.pdf
4) Quark Gluon String model
folk.uio.no/larissa/nuclphys/Kaidalov_ITEP_school.pdf
5) Particle Anisotropy in pp collisions coming from the string with impact parameter
www.folk.uio.no/larissa/nuclphys/seminar-string.pdf

“Quark Gluon String Model and some topics of Relativistic Heavy Ion Physics ”

Content:

1. **Introduction to High Energy Heavy Ion Collisions**
2. **Nucleon-Nucleon Collisions and Quark Gluon String Model**
    - Particle production in Nucleon-Nucleon Collisions
    - Baryon Energy Loss in Inelastic Collision
    - Hard Processes in Nucleon-Nucleon collision
    - Particle Production in a Strong Field
    - Schwinger mechanism of particle production
    - Production rates
3. **Classical String Models**
    - Yo-Yo and constituent string models of hadrons
    - Lund model for Nucleon-Nucleon collisions
    - Lund Model for Nucleus-Nucleus collisions

Special type of the string with impact parameter

“Quark Gluon String Model and some topics of Relativistic Heavy Ion Physics ”

by Larissa Bravina (University of Oslo, Norway)

Content

1. **Introduction to High Energy Heavy Ion Collisions**
2. **Nucleon-Nucleon Collisions and Quark Gluon String Model**
3. **Classical String Models**
4. **Nucleus-Nucleus Collisions**
    - Multiple Collisions and Nuclear Stopping
    - Glauber Model of Nucleus-Nucleus Collision

Quark Gluon String Model for Nucleus Nucleus Collisions

Conclusions

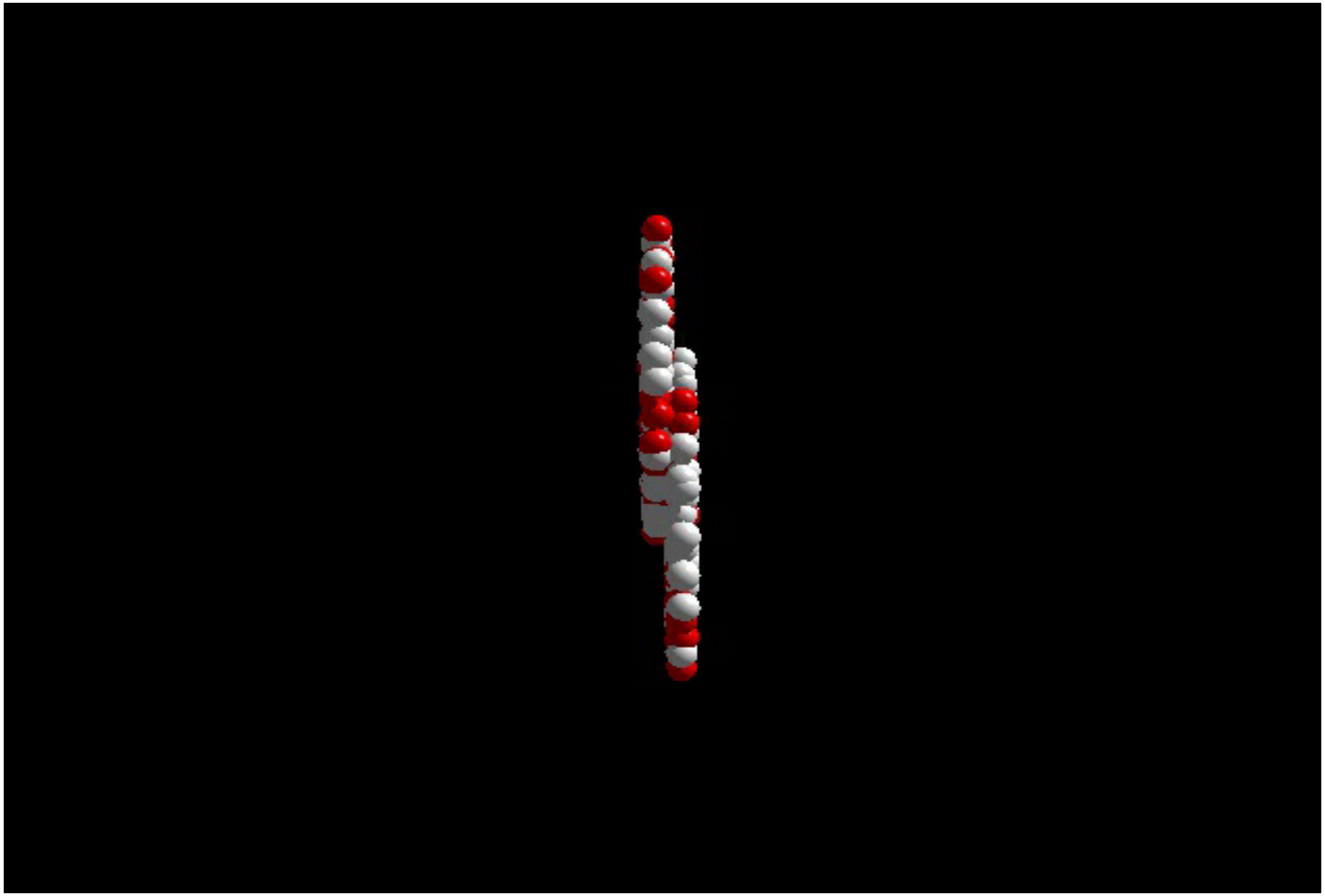
1. Are there undiscovered principles of nature: New symmetries, new physical laws?
2. How can we solve the mystery of dark energy?
3. Are there extra dimensions of space?
4. Do all the forces become one?
5. Why are there so many kinds of particles?
6. What is dark matter?
   How can we make it in the laboratory?
7. What are neutrinos telling us?
8. How did the universe come to be?
9. What happened to the antimatter?

From “Quantum Universe”

Evolved Thinker

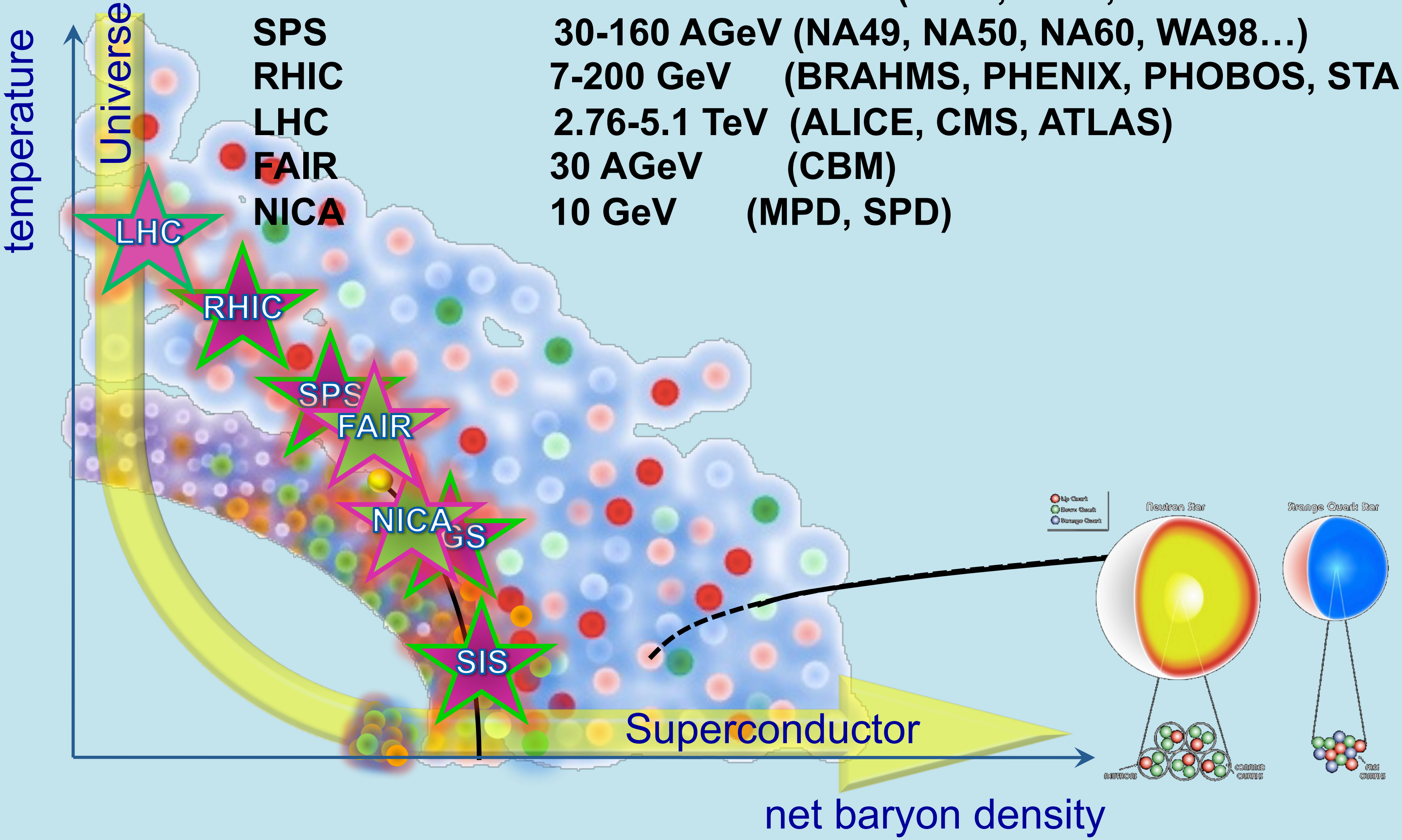
Courtesy: Y.K. Kim

All this can be explored in energetic collisions of ultra-relativistic nucleons or nuclei.

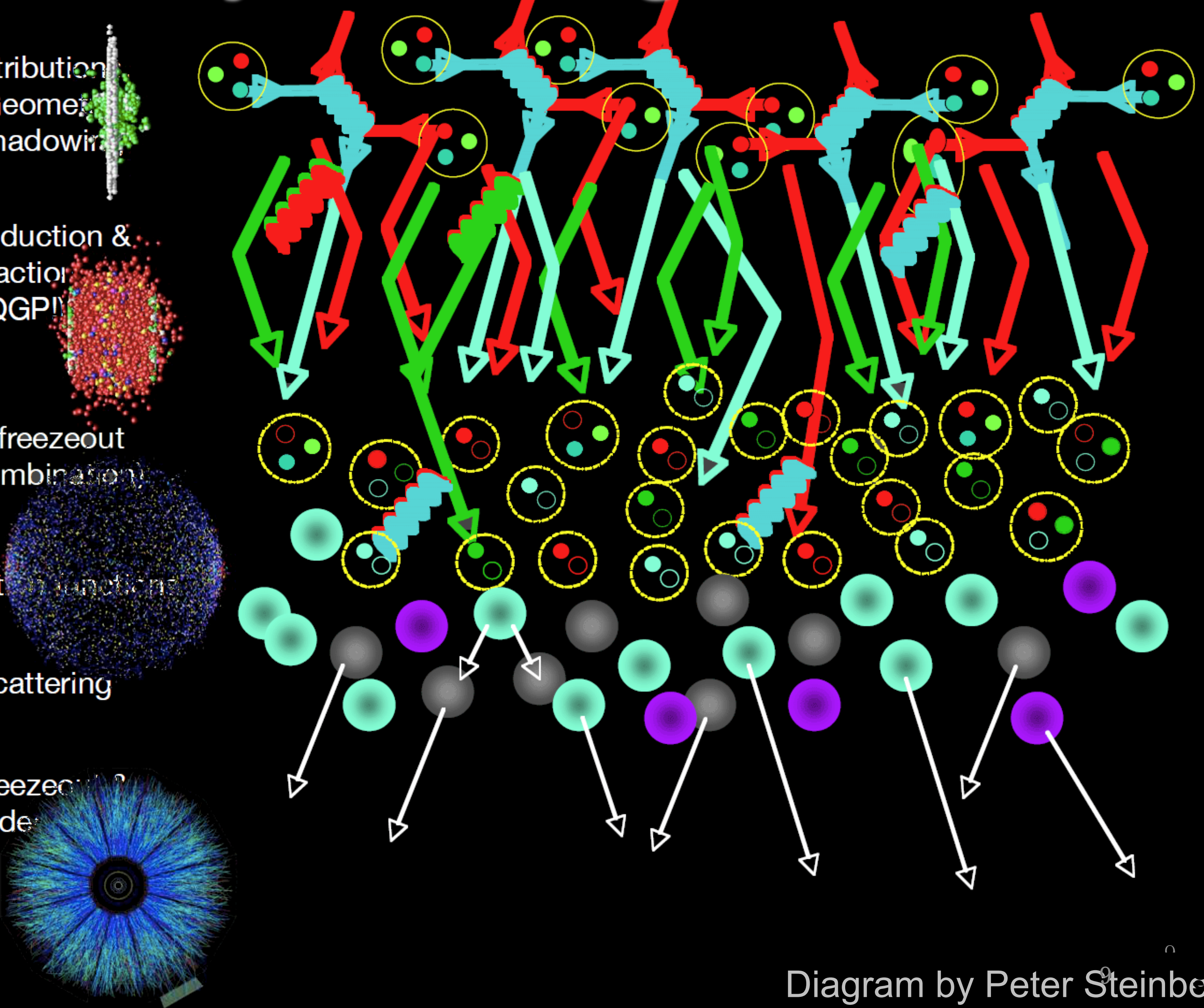


Phase diagram

SIS	**2 AGeV**	**(FOPI, TAPS, HADES)**
AGS	**10 AGeV**	**(E896, E917, E910**
SPS	**30-160 AGeV**	**(NA49, NA50, NA60, WA98…)**
RHIC	**7-200 GeV**	**(BRAHMS, PHENIX, PHOBOS, STAR)**
LHC	**2.76-5.1 TeV**	**(ALICE, CMS, ATLAS)**
FAIR	**30 AGeV**	**(CBM)**
NICA	**10 GeV**	**(MPD, SPD)**



Dynamic Regimes



Parton distribution
Nuclear Geome
Nuclear shadowi

Parton production &
reinteractio
(or, sQGP!)

Chemical freezeout
(Quark recombin

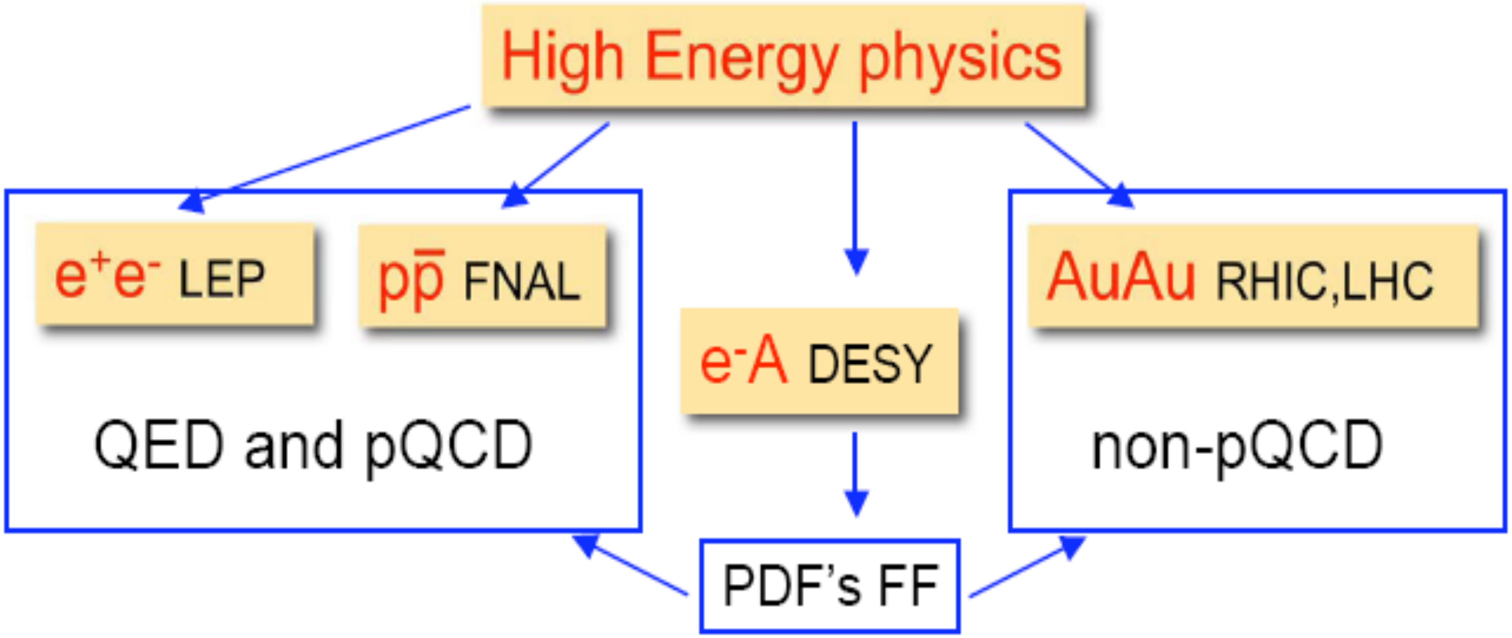
Jet fragmentat

Hadron rescattering

Thermal freezeo
Hadron de

Diagram by Peter Steinberg

High Energy (ultra-relativistic) Heavy Ion physics



High Energy physics

e^+e^- LEP

$p\bar{p}$ FNAL

QED and pQCD

e^-A DESY

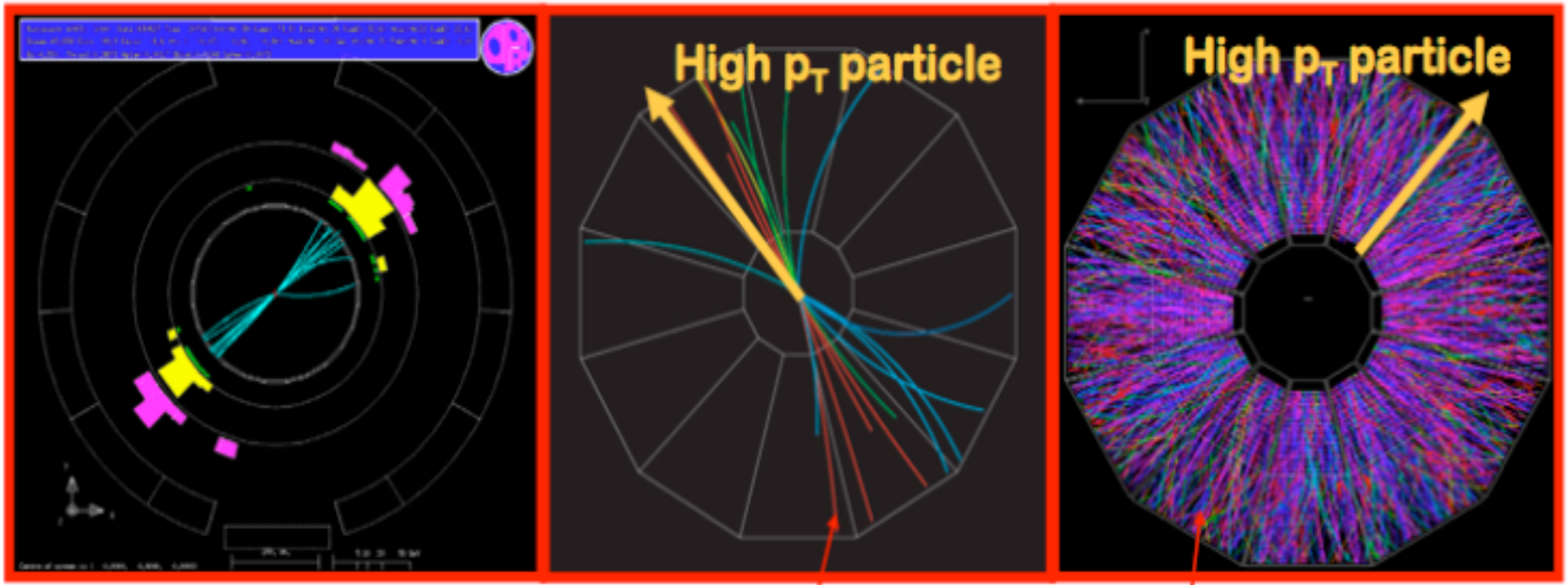
AuAu RHIC,LHC

non-pQCD

PDF's FF

Heavy Ion physics:

- nonperturbative QCD phenomena at high-temperature and high-energy density.
- addresses the properties of QCD vacuum relevant to the structure of the early universe
- the origin of particle masses, QCD phase transition
- thanks to the Maldacena discovery of the duality between super gravity in Anti de Sitter space and conformal field theory, heavy ion physics provides a unique testbed for applied string physics.



$e^+ + e^- \rightarrow$ jet + jet

$p + p \rightarrow$ jet + jet

Au + Au → stuff
+ jet + jet

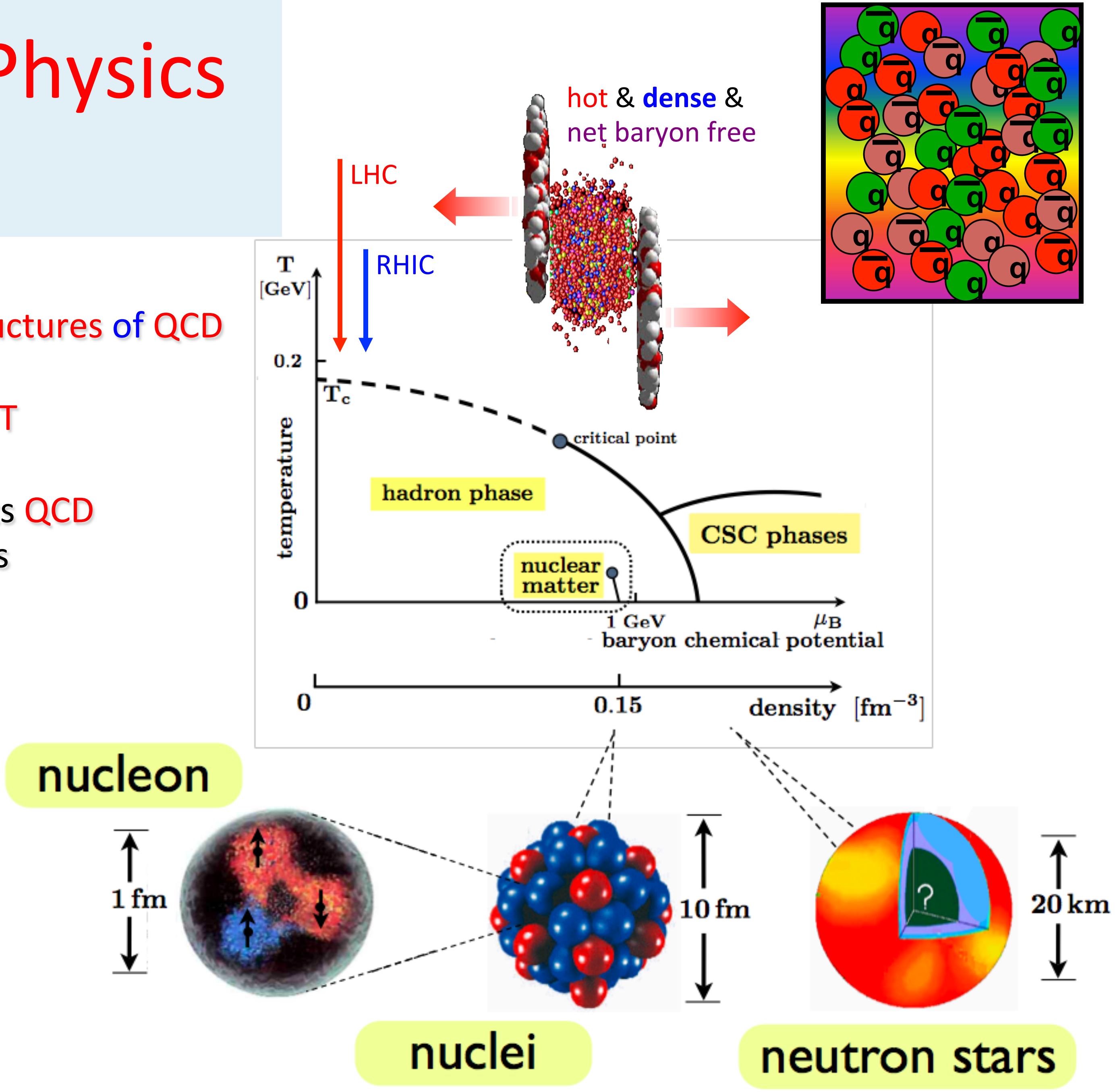
measure these...

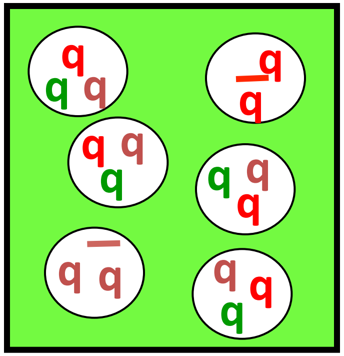
here?!

Heavy Ion Physics

Exploring Phases and Structures of QCD phase diagram

- High temperature T
- High density ε
- Many-body aspects QCD
- Vacuum properties

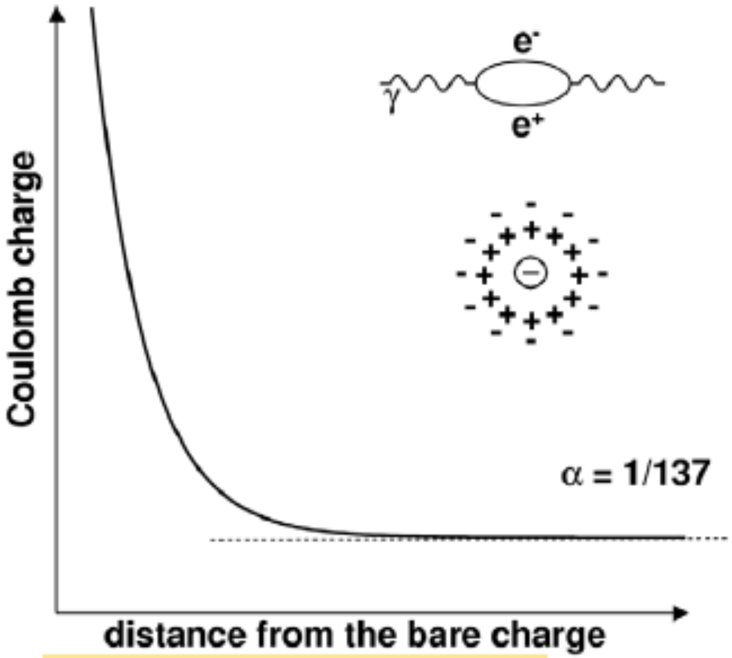




Collider era – quantum field theory

Local gage invariance → two “identical” theories

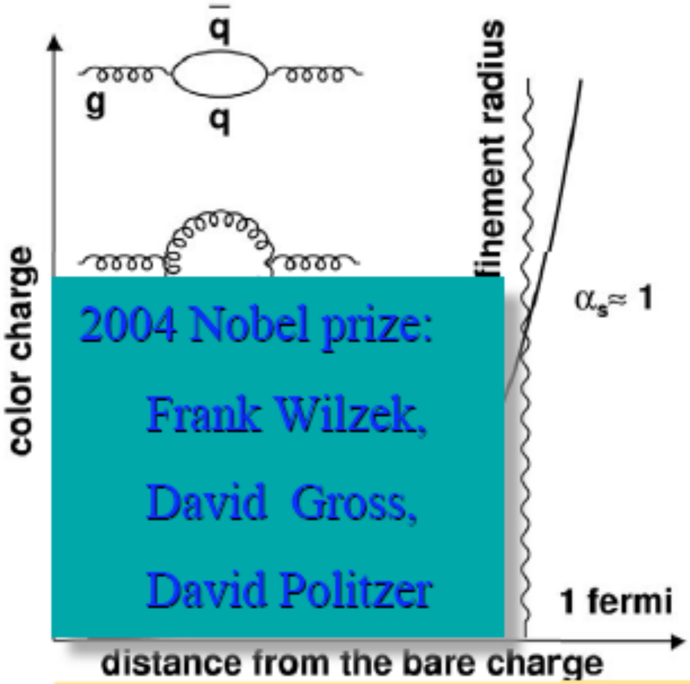
Electroweak interaction QED



$$\alpha(Q^2)=\frac{\alpha(\mu^2)}{1-\frac{\alpha(\mu^2)}{3\pi}\log(\frac{Q^2}{\mu^2})}$$

Landau’s zero charge problem
–vacuum rearrangement ?

Strong interaction QCD



2004 Nobel prize:

Frank Wilzek,

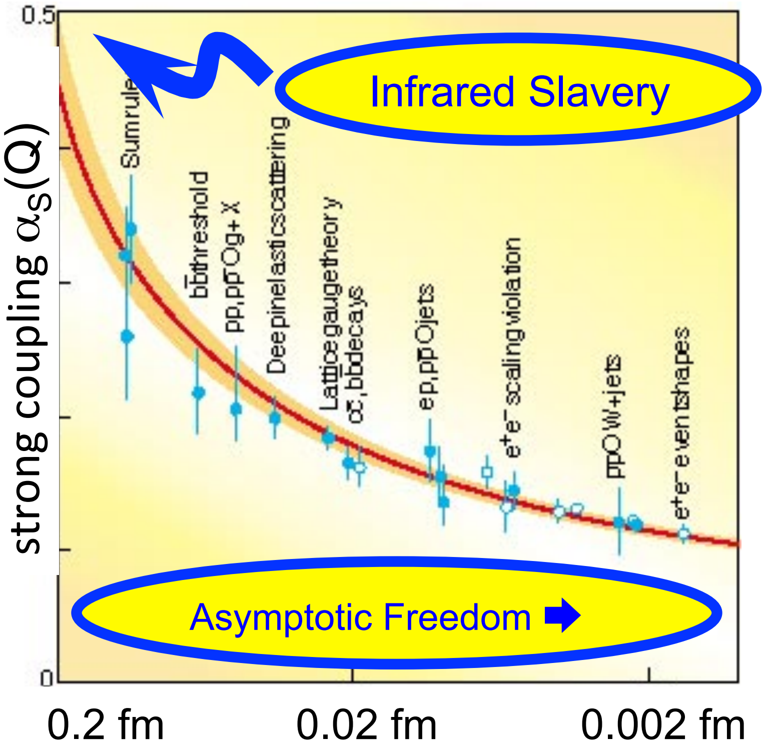
David Gross,

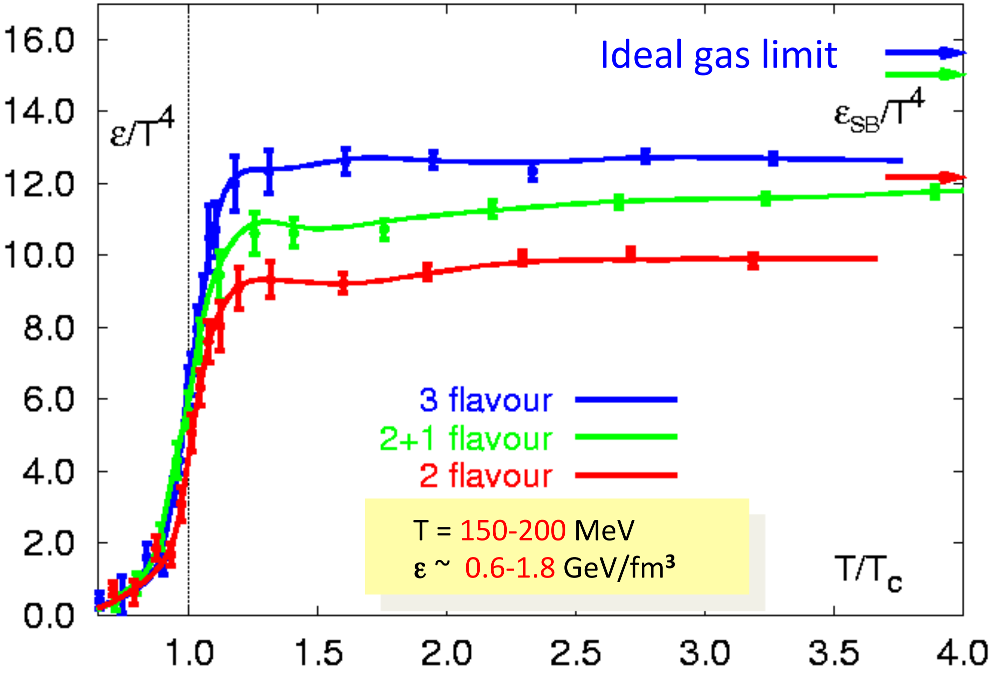
David Politzer

$$\alpha_S(Q^2)=\frac{\alpha_S(\mu^2)}{1+\frac{\alpha_S(\mu^2)}{12\pi}(33-2n_f)\log(\frac{Q^2}{\mu^2})}$$

Heavy ion coll. - QGP problem
–vacuum rearrangement ?

Phase transition in Heavy Ion collisions

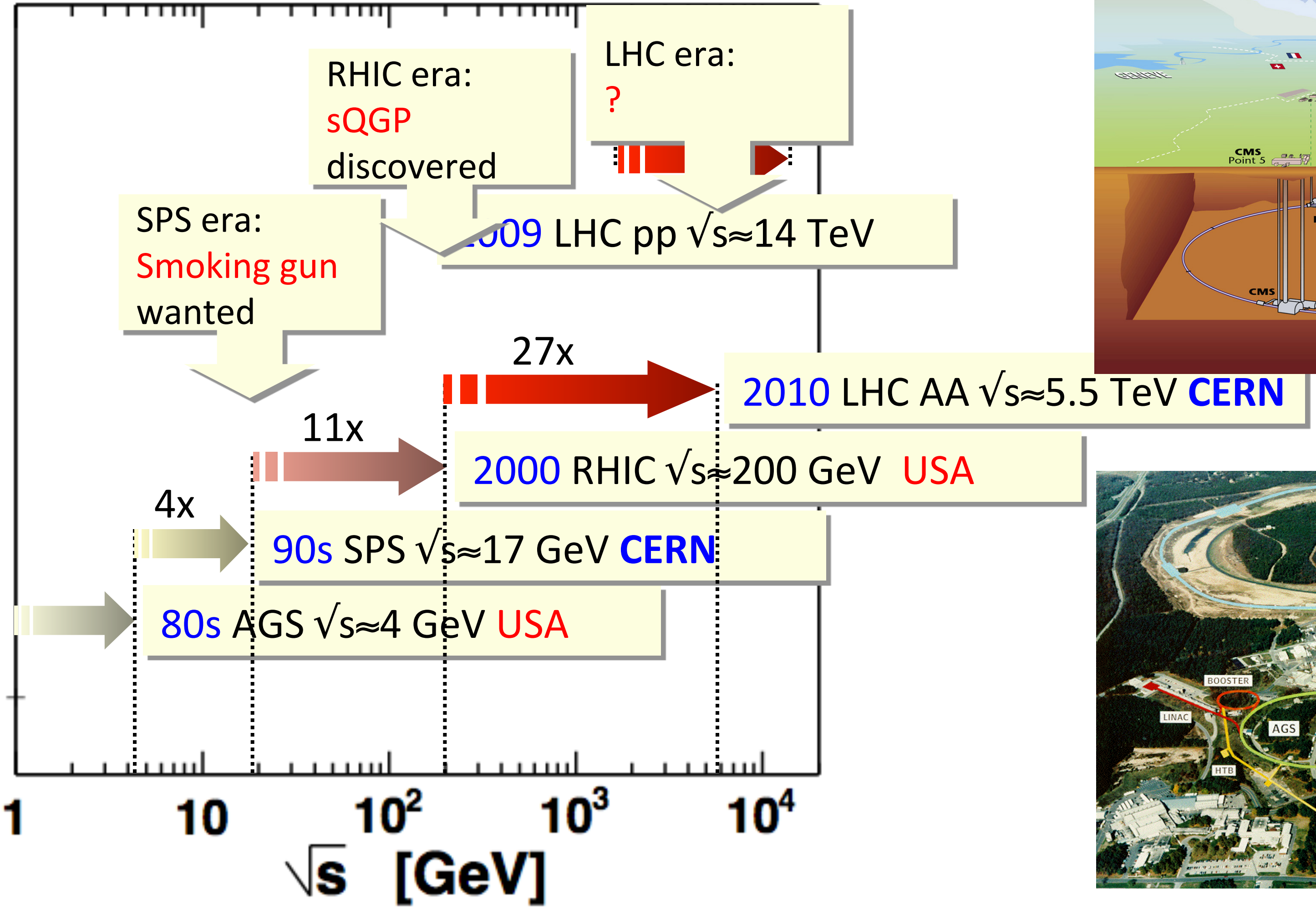




Lattice QCD, *Lect. Notes Phys* ***583****, 209 (2002)*

T.D.Lee (1974) Temporarily restored broken symmetries of the **physical vacuum**
Collins, Perry (1975) Asymptotic freedom in QCD → deconfined quarks/gluons matter
E.V. Shuryak (1978) Invented Quark Gluon Plasma → target of HI community

HI - Center Of Mass Energy regimes



LHC era:
?

RHIC era:
sQGP
discovered

SPS era:
Smoking gun
wanted

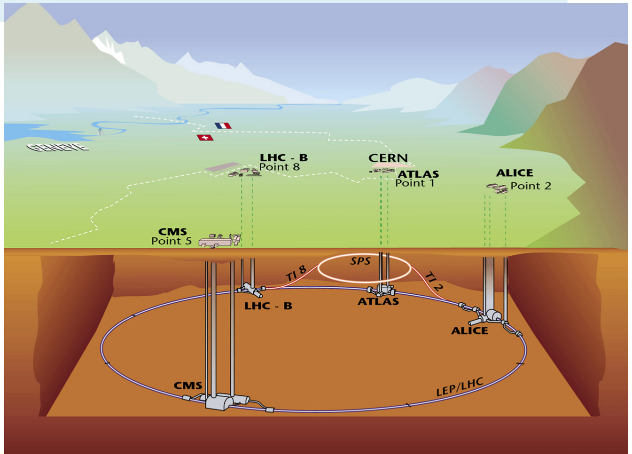
009 LHC pp √s≈14 TeV

2010 LHC AA √s≈5.5 TeV **CERN**

2000 RHIC √s≈200 GeV USA

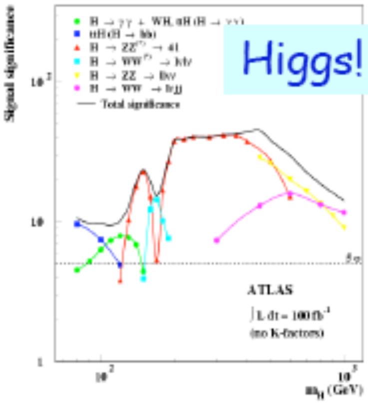
90s SPS √s≈17 GeV **CERN**

80s AGS √s≈4 GeV USA

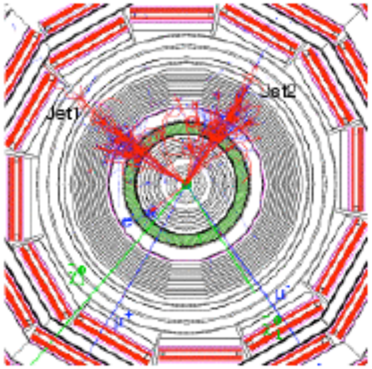


Relativistic **H**eavy **I**on **C**ollider
Brookhaven Nat. Lab. Long Island, USA

Physics at the LHC: pp @ 14 TeV

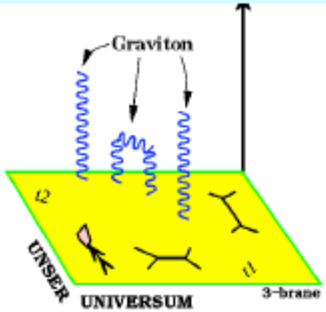


Higgs!

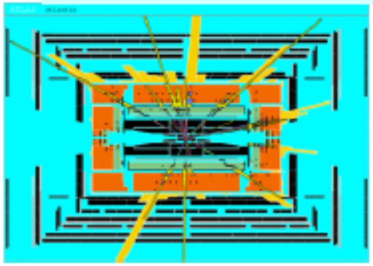


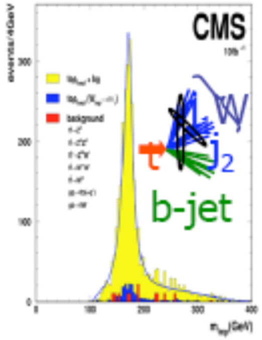
Supersymmetry?

Extra Dimensions?



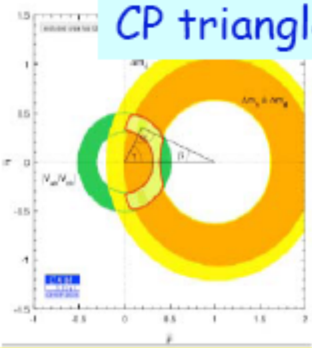
Black Holes???



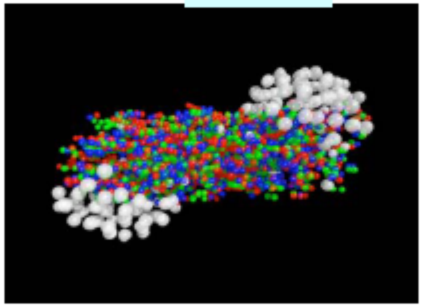


Precision measurements e.g top!

CP triangle!

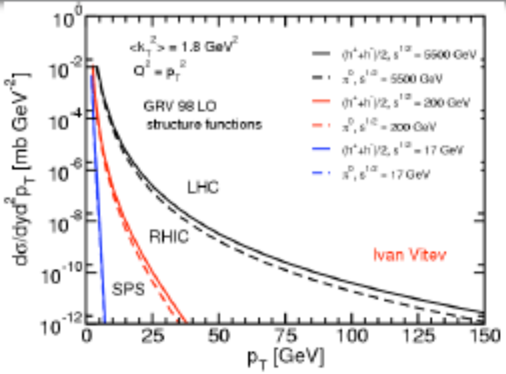


QGP?

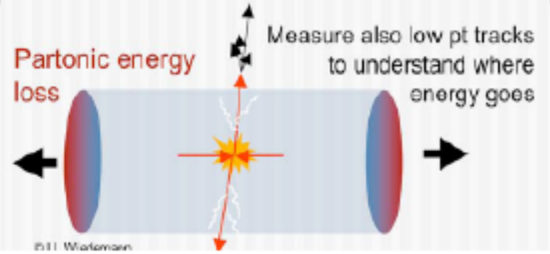


- LHC will explore directly the highly-motivated TeV-scale and say the final word about the SM Higgs mechanism and many TeV-scale New Physics predictions
- Also LHC will be a great machine for: QCD, B-physics, Heavy Ions, EW precision..

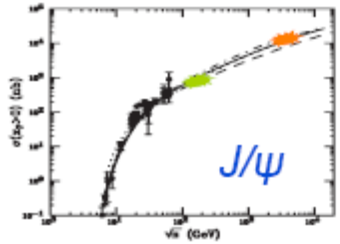
Heavy Ion Physics at the LHC

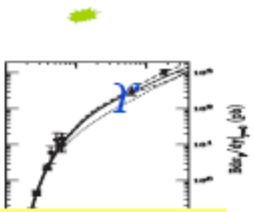


High P_T
particle and
jet production
Jet-quenching



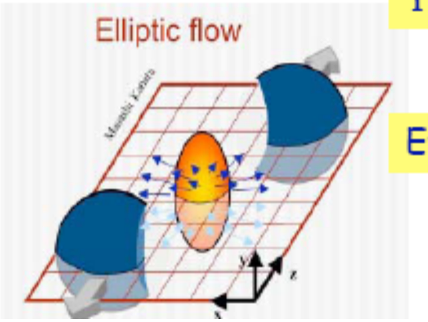
Heavy ions part of the LHC physics program with ALICE, but also CMS and ATLAS





Υ melt down

Size: 16 x 26 meters
Weight: 10,000 tons

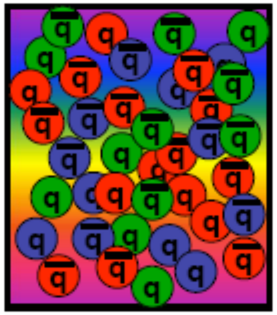


Event shapes

LHC ready for heavy ions in 2008

Properties of the deconfined nuclear medium

RHIC provided a lot of convincing evidences that the deconfined Quark-Gluon Medium (plasma) was created.



It was created also at lower energies - more aboout that later.

Where is the phase transition, location of the Critical End Point

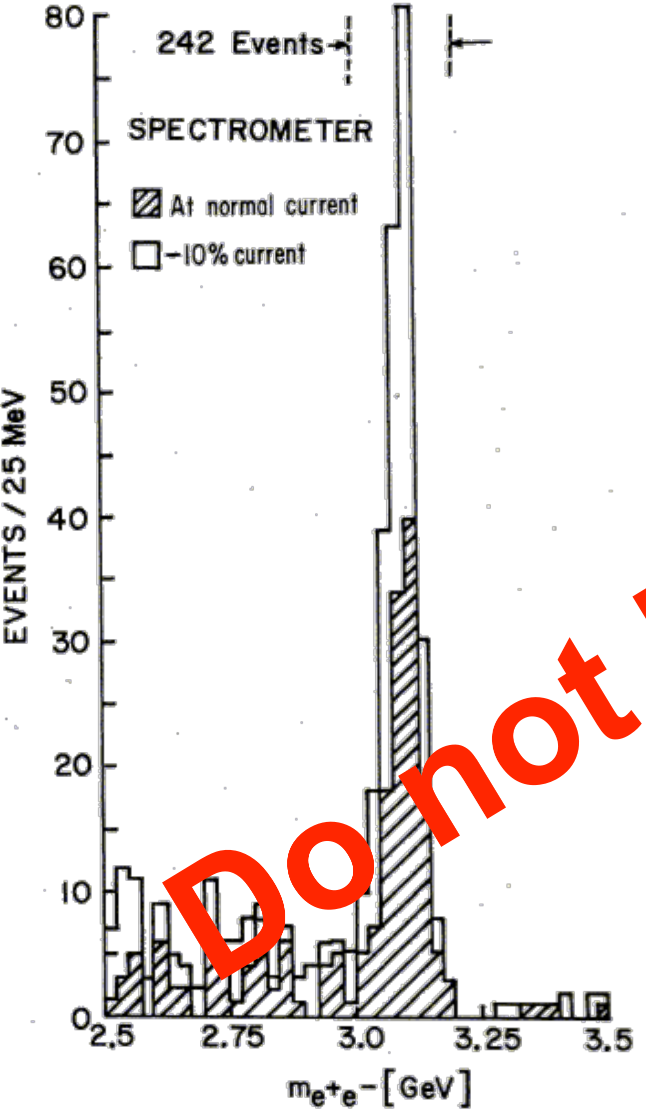
Properties of deconfined medium:

- Equation of state
- Viscosity, fluidity
- Transport properties, interaction with jets (quenching)
- Initial condition - nuclear modification, saturation
- Baryo-chemical potential.

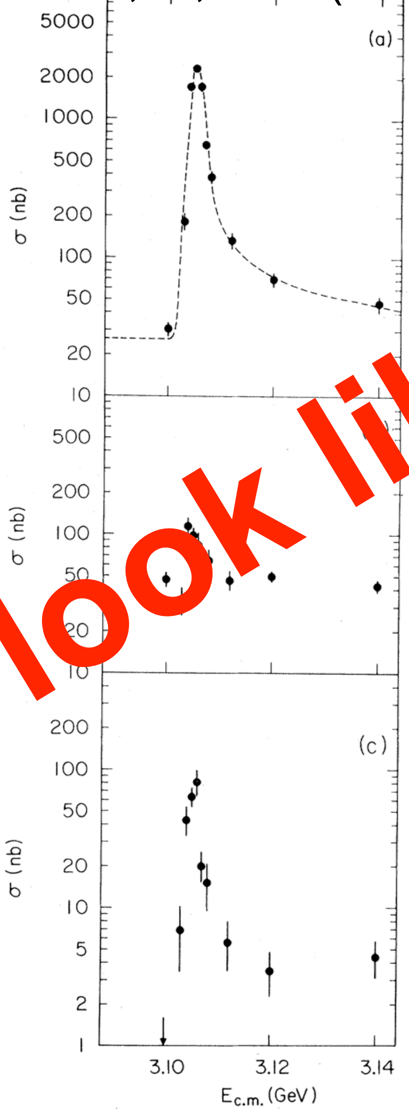
QGP signatures…

Do not look like these …

J-peak
PRL,33,1404 (1974)



Ψ-peak
PRL,33,1406 (1974)



PLB 126 (1983) 398-410

PLB 129 (1983) 130-140

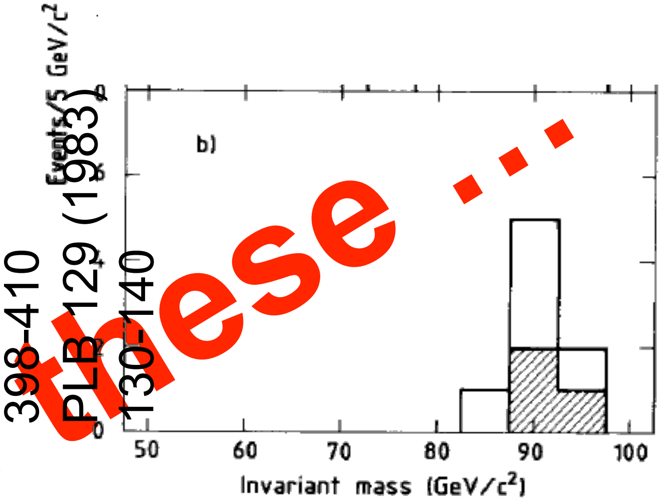
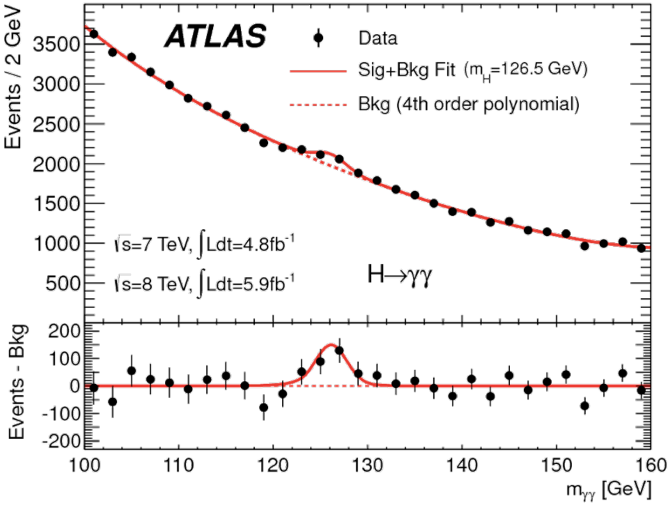
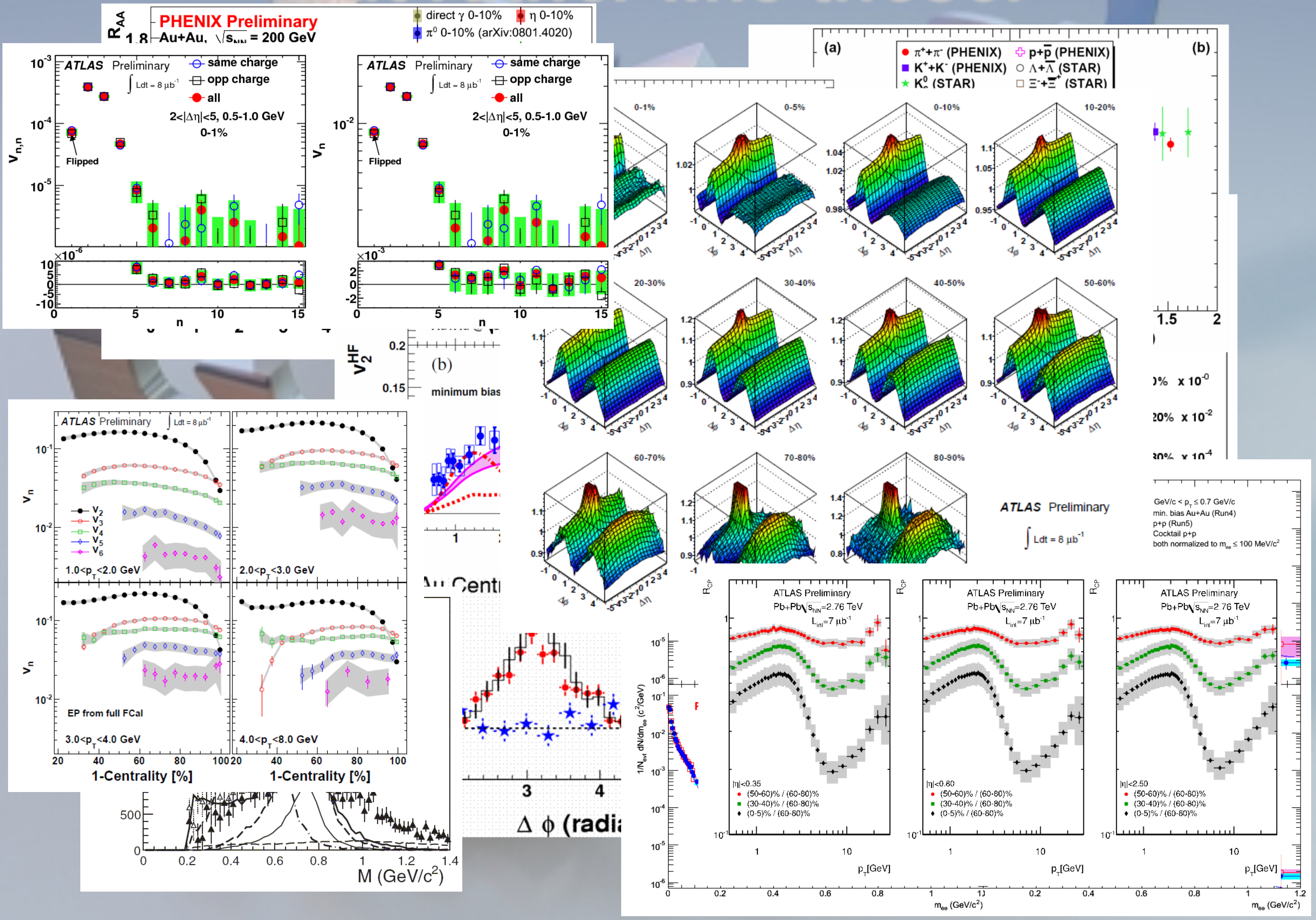


Fig. 2. Invariant mass distributions (a) of the 24 pairs which pass cut 1 of table 1, (b) of the eight of these 24 pairs for which all cuts of table 1 are satisfied by at least one electron. The three events in which both electrons pass all cuts of table 1 are cross-hatched.



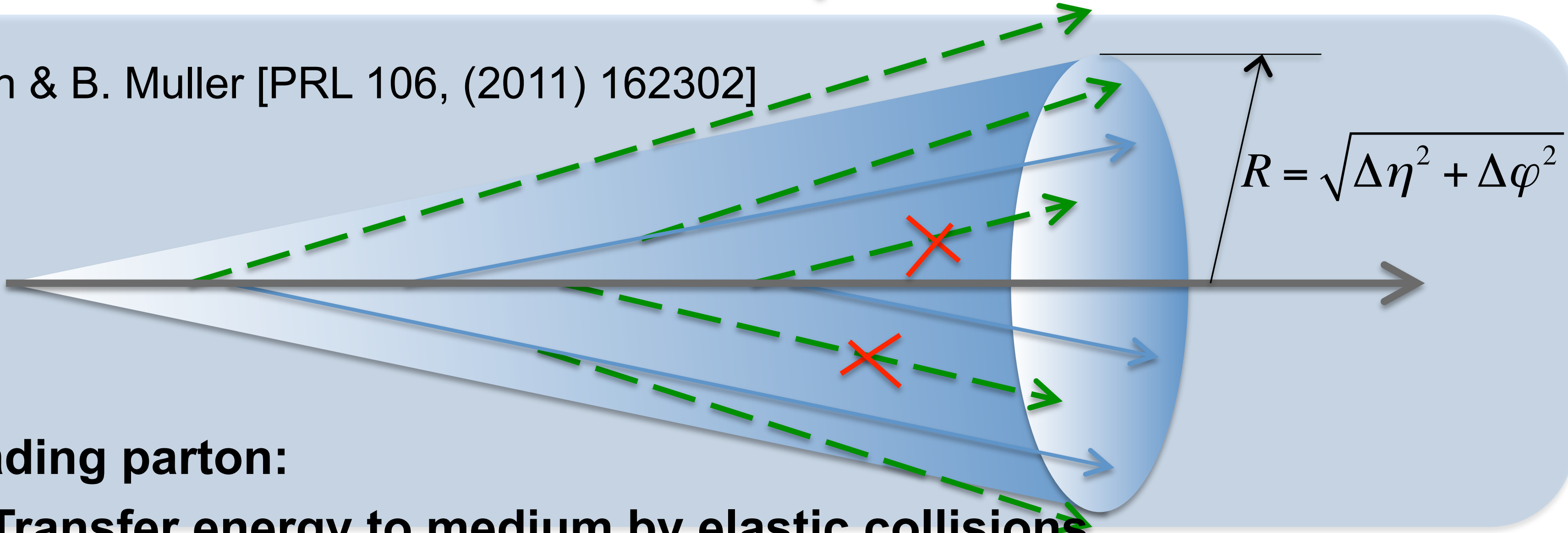
PLB 716 (2012) 1-29

But rather like these:



Jets as a medium probe

G-Y Qin & B. Muller [PRL 106, (2011) 162302]



$R = \sqrt{\Delta\eta^2 + \Delta\varphi^2}$

Leading parton:

- Transfer energy to medium by elastic collisions
- Radiate gluons due to scattering in the medium
  - Inside and out side jet cone

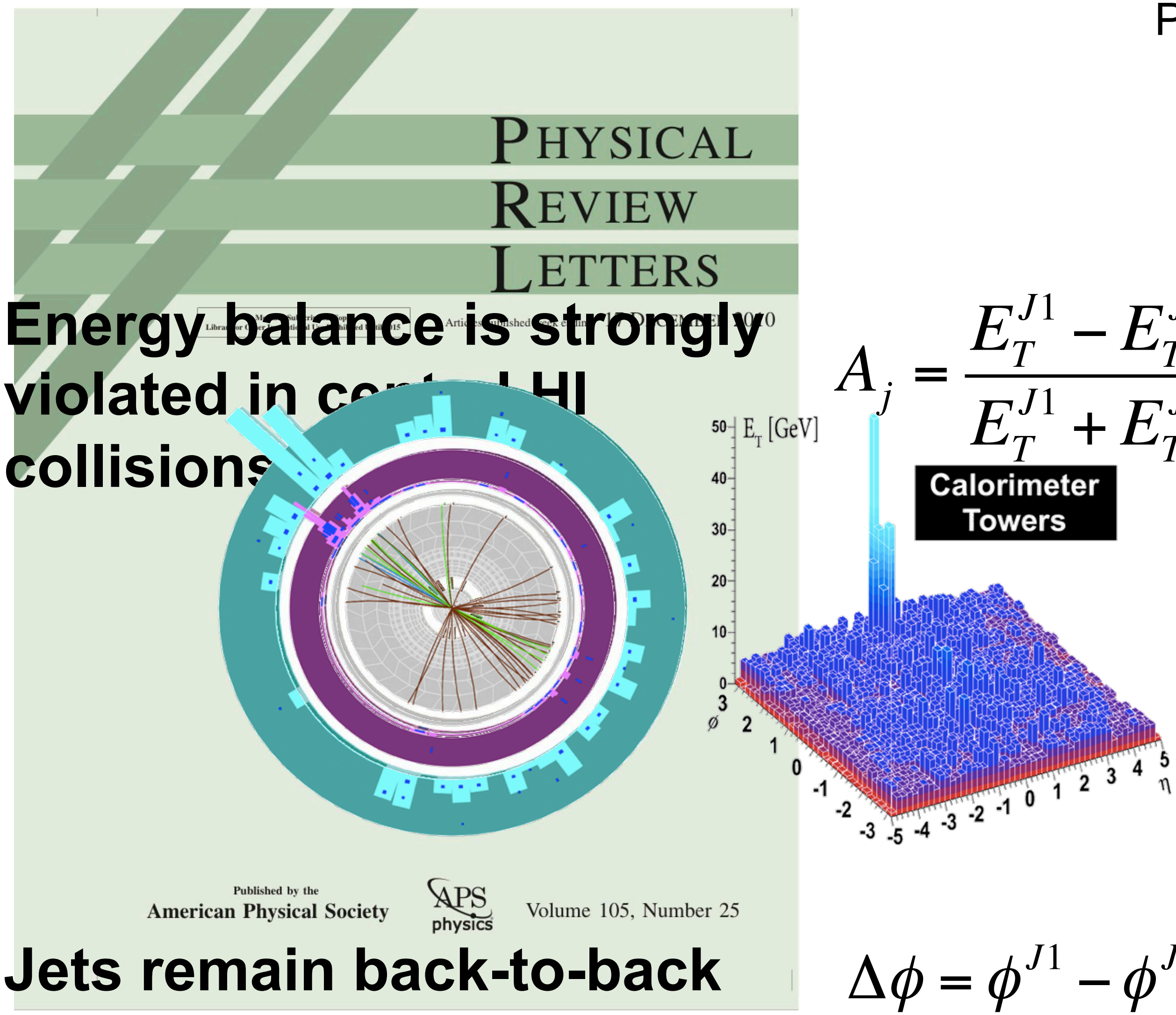
Radiated gluons (vacuum & medium induced):

- Transfer energy to medium by elastic collisions
- Be kicked out of the jet cone by multiple scattering after emission

Different for b-quark, dead cone effect

How we see it?

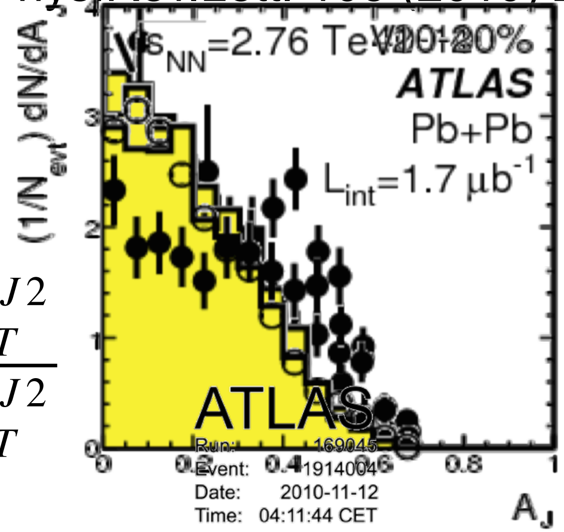
Phys.Rev.Lett. 105 (2010) 252



Energy balance is strongly violated in central HI collisions

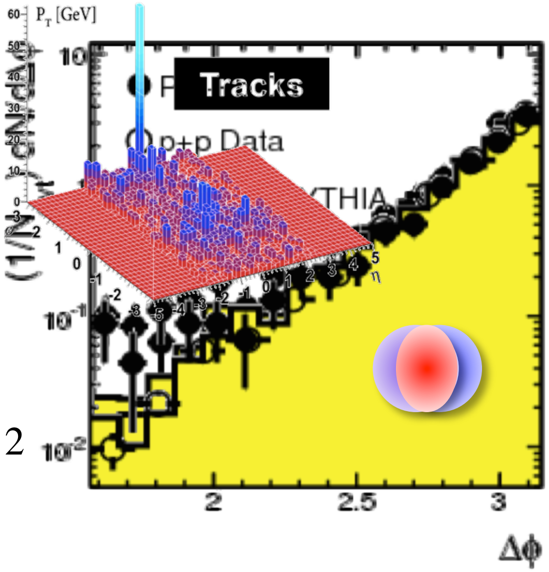
$$A_j = \frac{E_T^{J1} - E_T^{J2}}{E_T^{J1} + E_T^{J2}}$$

Calorimeter Towers



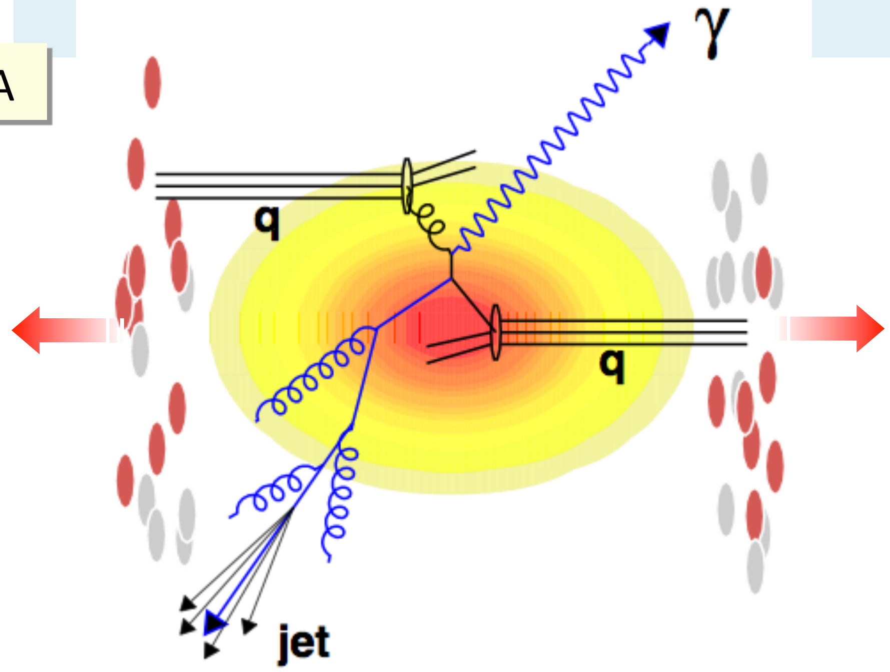
Jets remain back-to-back

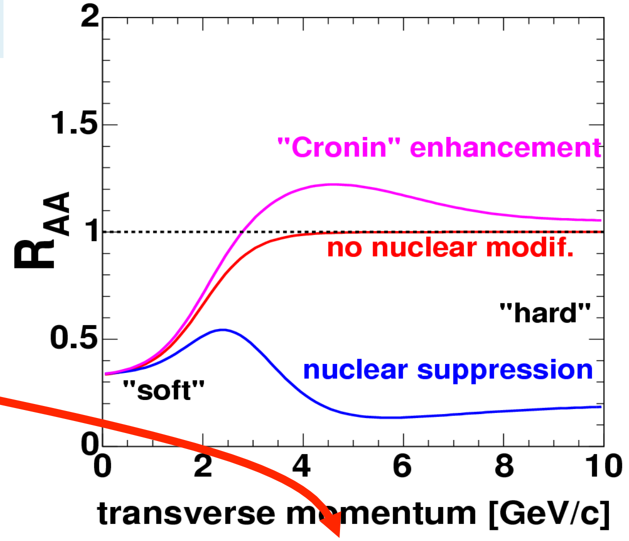
$$\Delta\phi = \phi^{J1} - \phi^{J2}$$



HI collision - Nuclear Modification Factor R_{AA}

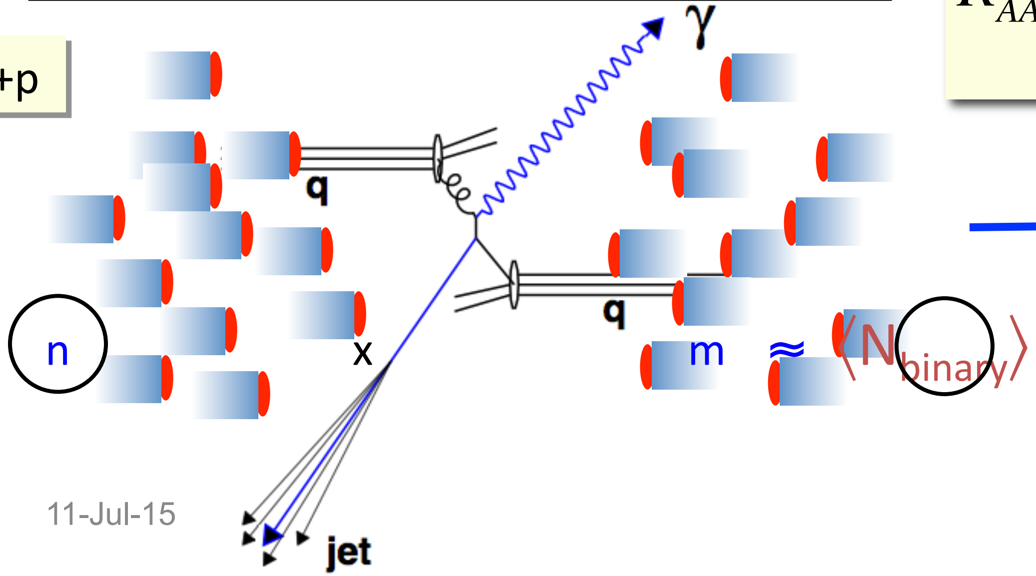
A+A





$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{\langle N_{binary}\rangle d^2N^{pp}/dp_T d\eta}$$

p+p

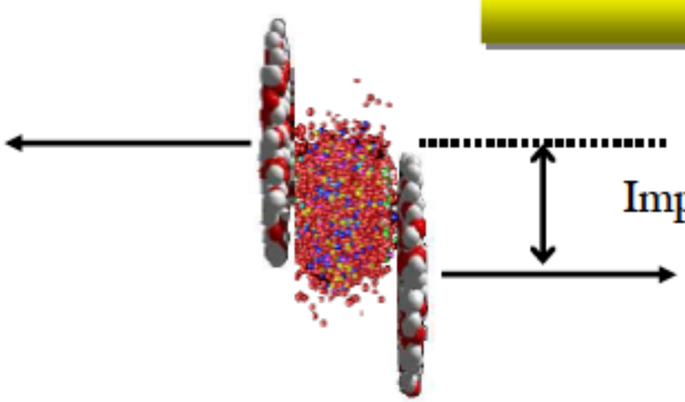


varies with impact parameter ***b***

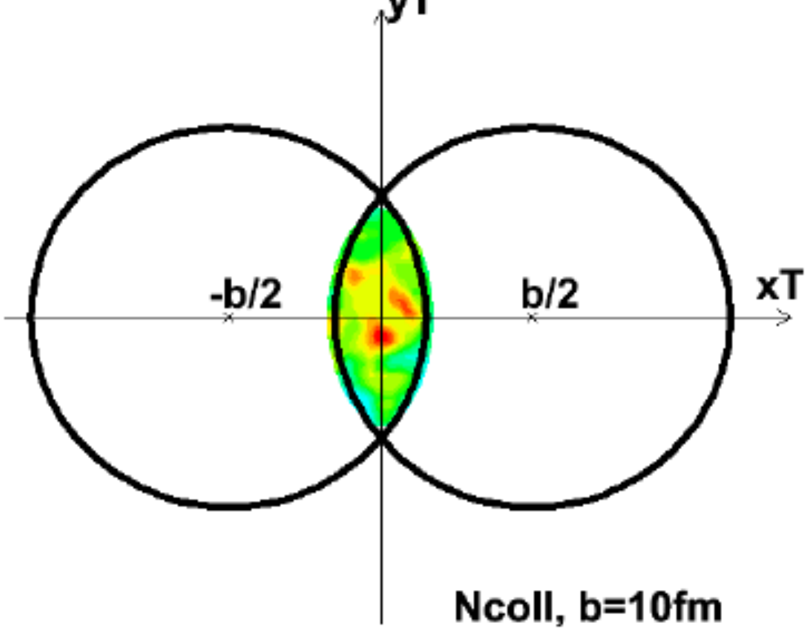
What is N_{col} and how to calculate it ?

Glauber Model

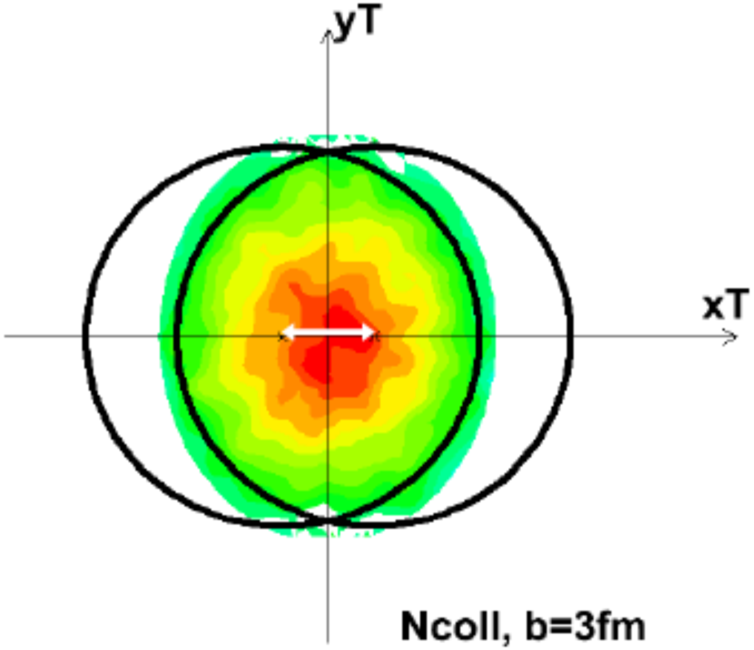
Centrality



Impact parameter = distance of nuclear centers $\vec{b}$



Peripheral collision



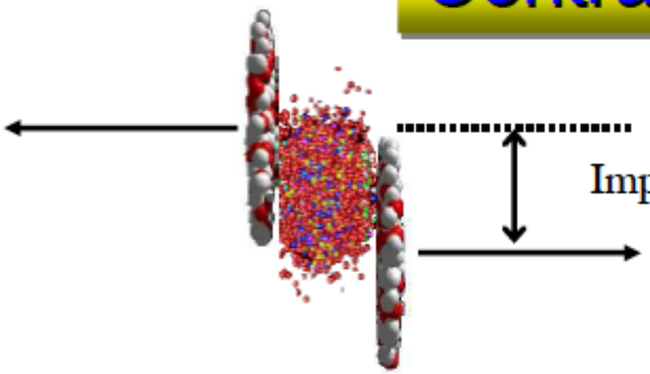
Central collision

On collision centrality

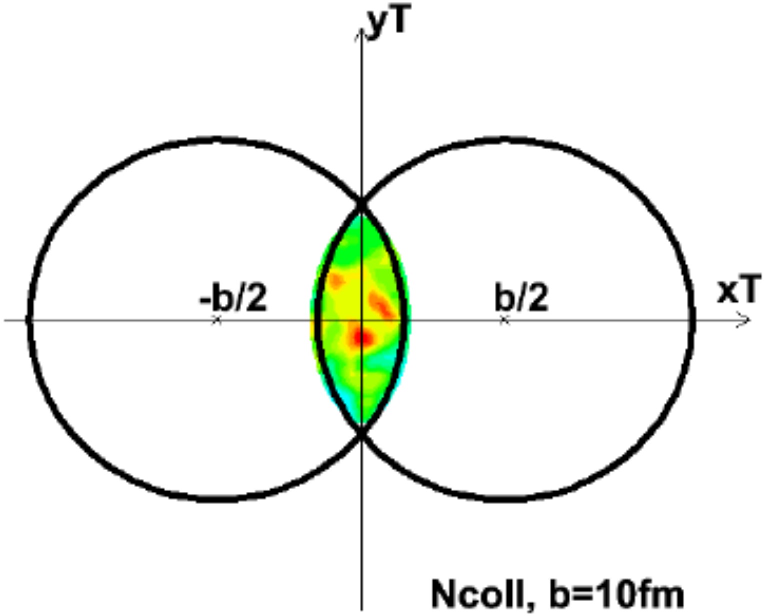
Glauber model

N_{part} N_{coll} scaling

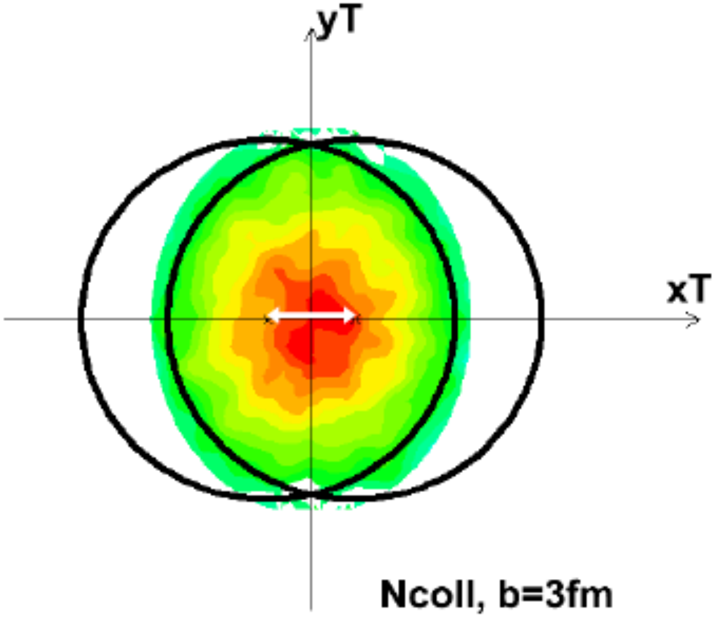
Centrality controls Energy density



Impact parameter = distance of nuclear centers $\vec{b}$

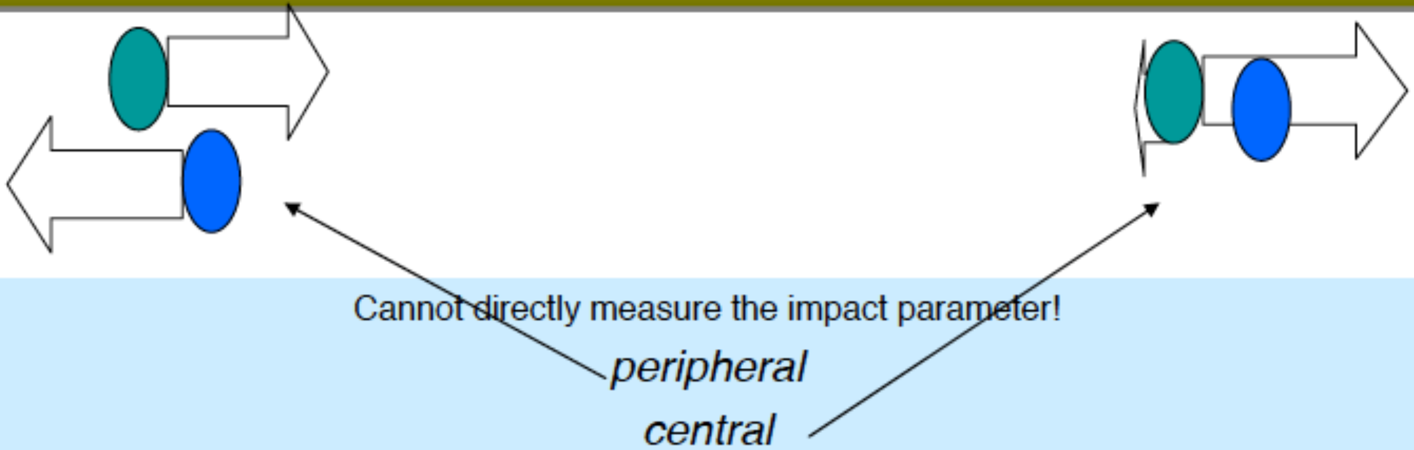


Peripheral collision



Central collision

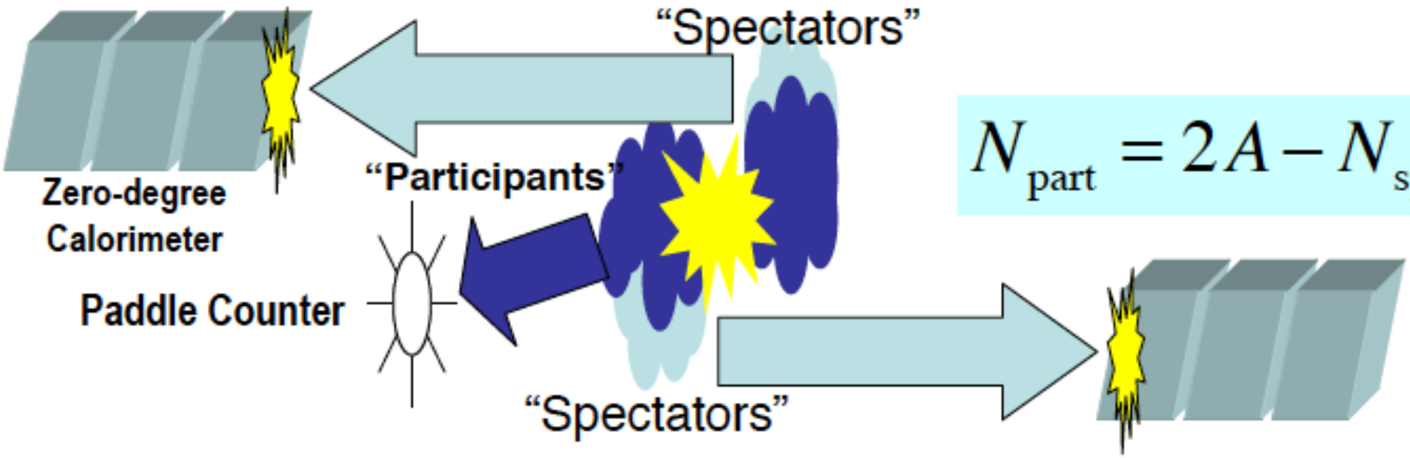
Measuring Centrality



Cannot directly measure the impact parameter!

peripheral

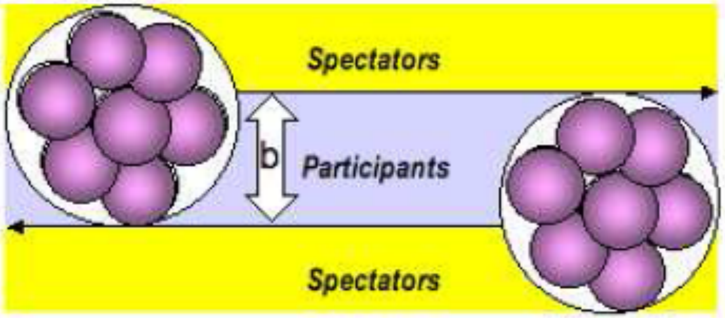
central



$$N_{\text{part}} = 2A - N_{\text{spec}}$$

spectators studied with zero-degree calorimeters, and *participants* via monotonic relationship with produced particles

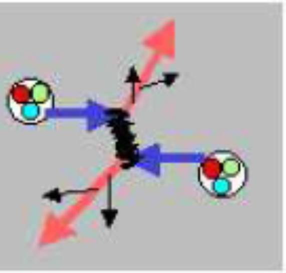
Participants vs Binary collisions

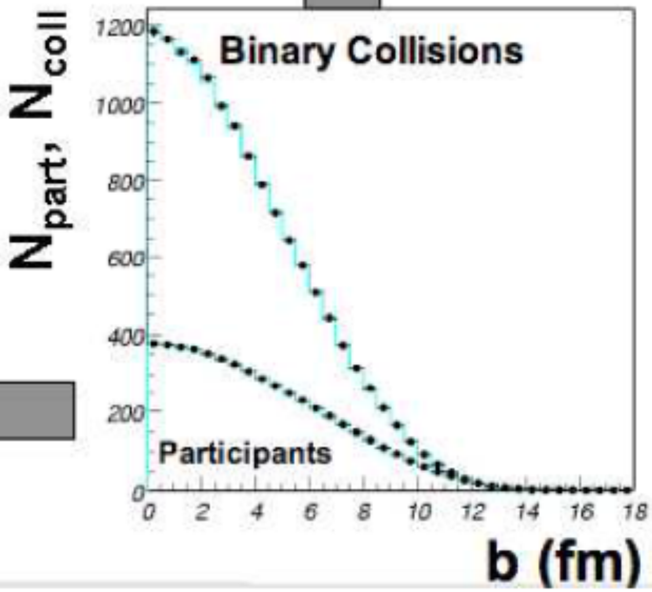


"Glauber" model of AA

Binary Collisions:

1. Jet Production
2. Heavy Flavor





Color Exchange:

1. Soft Hadron Production
2. Transverse Energy

"wounded nucleon model"

Participant = at least one inelastic collision

Binary collision = point like scattering, optical theorem NxM, parton lumin.

How do we calculate N_{part} and N_{coll} ?

$$\begin{aligned} 1\ \text{barn} &= 1000\ \text{mb} \\ 1\ \text{barn} &= 100\ \text{fm}^2 \\ 1\ \text{fm}^2 &= 10\ \text{mb} \\ 1\ \text{fm}^{-2} &= 0.1\ \text{mb}^{-1} \end{aligned}$$

$$n_0 = 0.17\ \text{fm}^{-3},$$

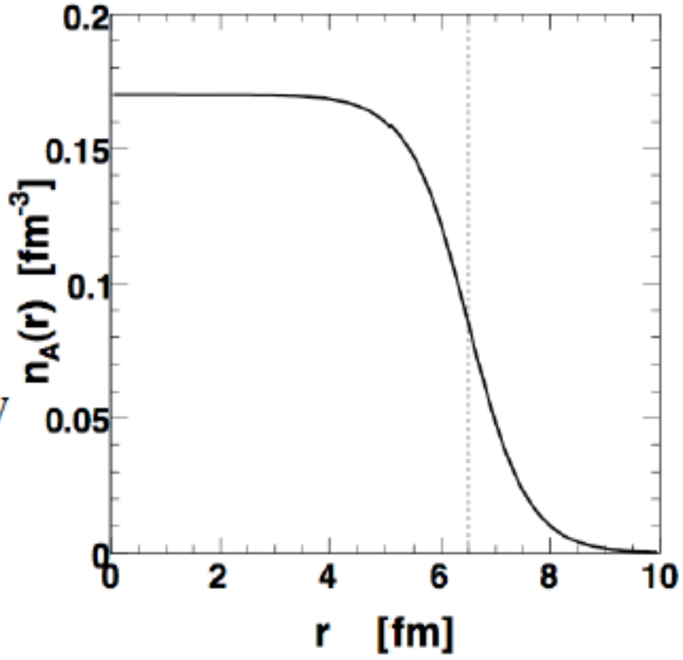
Nuclear density

$$R = \left(\frac{3A}{4\pi \cdot n_0}\right)^{1/3}$$

Nuclear radius

$$n_A(r) = \frac{n_0}{1 + \exp(\frac{r-R}{d})} \cdot$$

Woods-Saxon potential



$$\begin{aligned} R &= (1.12\ A^{1/3} - 0.86\ A^{-1/3})\ \text{fm}, \\ d &= 0.54\ \text{fm}. \end{aligned}$$

Parameterization or 6.5 fm

Skin parameter

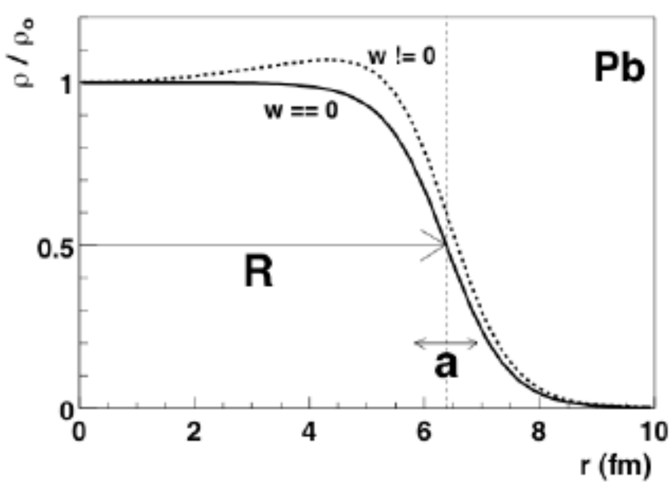
Nucleus Parameters

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

Electron Scattering Measurements

Nucleus	A	R	a	w
C	12	2.47	0	0
O	16	2.608	0.513	-0.051
Al	27	3.07	0.519	0
S	32	3.458	0.61	0
Ca	40	3.76	0.586	-0.161
Ni	58	4.309	0.516	-0.1308
Cu	63	4.2	0.596	0
W	186	6.51	0.535	0
Au	**197**	**6.38**	**0.535**	**0**
Pb	208	6.68	0.546	0
U	238	6.68	0.6	0

H. DeVries, C.W. De Jager, C. DeVries, 1987



$$R = r_0\, A^{1/3}$$

R=nuclear radius 6-7 fm

r_0 = nucleon radius 0.75 fm (use 1fm)

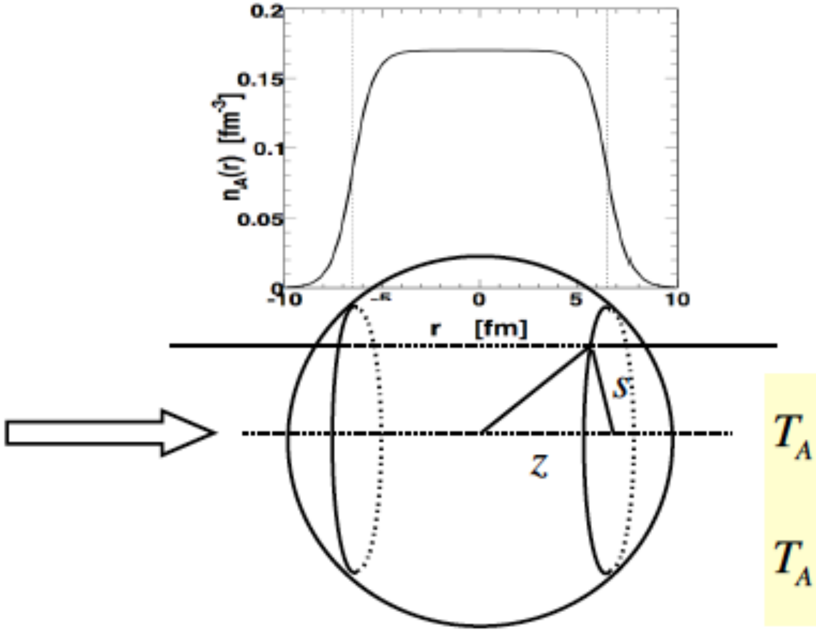
Thickness function

Thickness Function reflects the nuclear density integrated along beam axis

$$T_A(s) = \int_{-\infty}^{\infty} dz\, n_A\left(\sqrt{s^2 + z^2}\right)$$

The integral of the Thickness Function is

$$\int ds^2 T_A(s) = A$$



In the case of p+A collision the cross section:

$$\sigma(b) = \sigma_0 T_A(b)$$

Sharp sphere approx:

$n_A(r<R) = n_0 = A/V$ and $n_A(r>R) = 0$

$$T_A(s) = 2n_0\sqrt{R^2 - s^2} = 2\frac{3A}{4\pi R^3}\sqrt{R^2 - s^2}$$

$$T_A(0) = \frac{3A}{2\pi R^2} = \frac{3A}{2\pi r_0^2 A^{2/3}} = \frac{3}{2\pi r_0^2} A^{1/3} = 0.39 A^{1/3}$$

p+A minimum bias

T_A(b) = nucleon density per unit transverse area

$$\frac{N_{collisions}}{N_{nucleons}=T_A}=\frac{\sigma_{NN}}{\text{unit area}}$$

$$N_{coll}^{MB}=\int_0^{\infty} d^2b\,T_A(b)\cdot\sigma_{NN}=\sigma_{NN}\int_0^{\infty} d^2b\int_{-\infty}^{\infty}\mathrm{dV}\,n(r)=A\sigma_{NN}$$

$T_A(0) = 0.17\ \mathrm{fm}^{-3}\ 2\mathrm{R}_{\mathrm{Au}} = 2.2$ nucleons fm^{-2}

$\sigma_{pA}=\sigma_{pp}$ A for minimum bias

$$\boxed{\sigma_{pA}=\sigma_{pp}\int_{b1}^{b2} d^2b\ \mathrm{T_A}(b)}$$

Overlap function

For a given impact parameter $\vec{b} := \langle \vec{r}_B \rangle - \langle \vec{r}_A \rangle$, the Overlap Function is defined as a product of the $T(b)$'s of the colliding nuclei A and B, integrated over the transverse area:

$$T_{AB}(b) = \int d^2s\; T_A(\vec{s})T_B(\vec{s}-\vec{b})$$

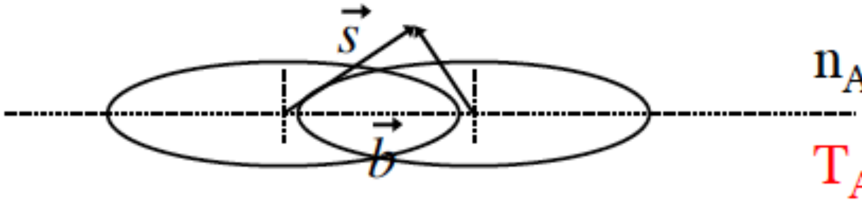
with $\vec{b}$ and $\vec{s}$ being perpendicular to beam direction z. The overlap function can also be calculated directly from densities by four-dimensional integration:

$$T_{AB}(b) = \int d^2s\; dz_A dz_B\; \mathrm{n}_A(\vec{s}, z_A) n_B(\vec{s}-\vec{b}, z_B)$$

The integral over the ovelap function is

$$\int db^2 T_{AB}(b) = AB$$

Transverse plane integral



Sharp sphere approx:

$n_A(r<R)=n_0= A/V$ and $n_A(r>R)=0$

$$T_{AA}(b=0) = \frac{9}{8\pi r_0^2} A^{4/3}$$

where $R = r_0 A^{1/3}$

Thickness f. p+A Overlap f. A+A

$$\boxed{\sigma_{pA} = \sigma_{pp} \int_{b1}^{b2} d^2b \, \mathrm{T_A}(b)}$$

$$\boxed{\sigma_{AA} = \sigma_{pp} \int_{b1}^{b2} d^2b \, \mathrm{T_{AB}}(b)}$$

Total Geometric Cross Section is the xsection in A+B collisions when, at least, on inelastic n+n collision occurs

$$\sigma_G = \int d^2b \left[1 - e^{T_{AB}(b)\sigma_{\mathrm{NN}}}\right]$$

For the Sharp Sphere and in the limit of infinite n+n xsection σ_{NN}

$$\sigma_G = \pi\left(R_A + R_B\right)^2 = \left(\frac{9\pi}{16n_0^2}\right)^{1/3} \left[A^{1/3} + B^{1/3}\right]^2 \approx 3.94\left[A^{1/3} + B^{1/3}\right]^2 \approx 540 \text{ fm}^2 = 5.4 \text{ barn}$$

$$\boxed{\left.\frac{dN^{AB}}{dp_T dy}\right|_{b1-b2} = \frac{dN^{pp}}{dp_T dy} \frac{\sigma_{pp}}{\pi(b_2^2 - b_1^2)} \int_{b1}^{b2} d^2b \, \mathrm{T_{AB}}(b)}$$

Collision probability

$$P(n,b) = \binom{AB}{n} \left(1 - \frac{\sigma_{NN} T_A(b)}{A}\right)^{AB-n} \left(\frac{\sigma_{NN} T_A(b)}{A}\right)^{n}$$

The two terms represents the contributions from the two colliding objects. The factor repeatedly present in these formulas represents a probability for a nucleon to pass through the nucleus without any collision:

$$p(ncol = 0) = \left[1 - \frac{\sigma_{NN}\ T_A(b)}{A}\right]^A \tag{16}$$

This probability is obtained using the binomial distribution of number of binary collisions. A numerically similar result can be obtained using the simpler Poissonian

$$p(ncol = 0) = e^{-\sigma_{NN}\ T_A(b)}. \tag{17}$$

Since the maximum number of collisions is limited to A, the binomial formula seems more appropriate though.

Probability of becoming participant is $p(ncol > 0) = 1 - p(0)$.

Calculating N_{part} and N_{coll}

- Number of participants - thickness function

$$N_{part}^{AB}(b) = \int d^2 s T_A(\vec{s}) \left\{ 1 - \left[1 - \sigma_{NN} \frac{T_B\left(\vec{s} - \vec{b}\right)}{B} \right]^B \right\} + (A \Leftrightarrow B)$$

- Number of collisions - overlap function

$$N_{coll}^{AB}(b) = \sigma_{NN} \int d^2 s T_A(\vec{s}) T_A\left(\vec{s} - \vec{b}\right)$$

Participants are nucleons which have encountered at least one binary collision. The mean number of participants in pA and A+B collisions at an impact parameter b can be calculated via

$$Npart_{pA}(b) = \left\{1-\left[1-\frac{\sigma_{NN}\,T_A(b)}{A}\right]^A\right\} + T_A(b)\,\sigma_{NN} \tag{13}$$

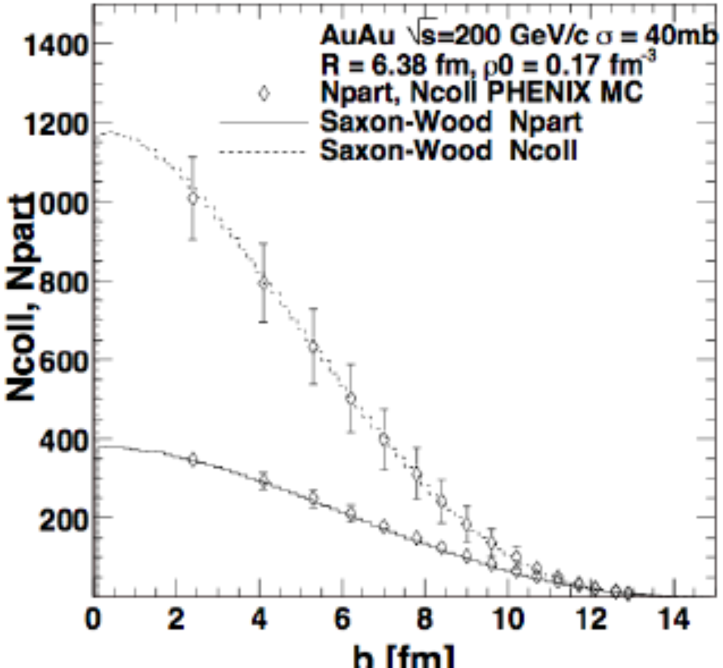
$$\begin{aligned} Npart_{AB}(b) &= \int d^2s\, T_A(\vec{s})\left\{1-\left[1-\frac{\sigma_{NN}\,T_B(\vec{s}-\vec{b})}{B}\right]^B\right\} \qquad (14) \\ &+ \int d^2s\, T_B(\vec{s})\left\{1-\left[1-\frac{\sigma_{NN}\,T_A(\vec{s}+\vec{b})}{A}\right]^A\right\} \qquad (15) \end{aligned}$$

Sharp sphere approx:

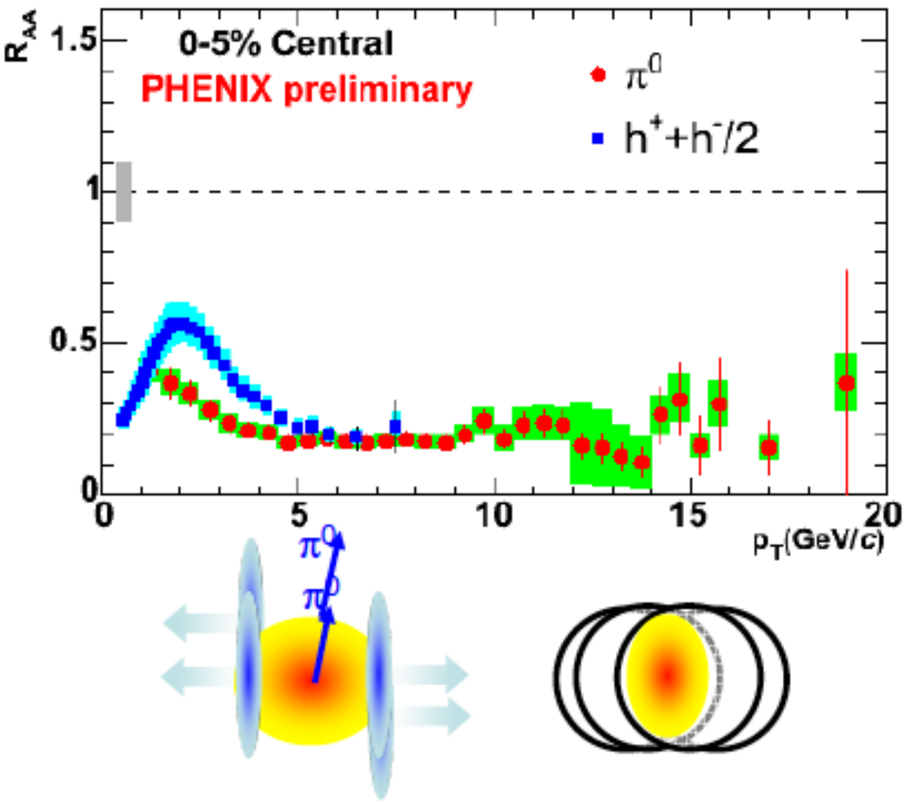
$n_A(r<R)=n_0= A/V$ and $n_A(r>R)=0$

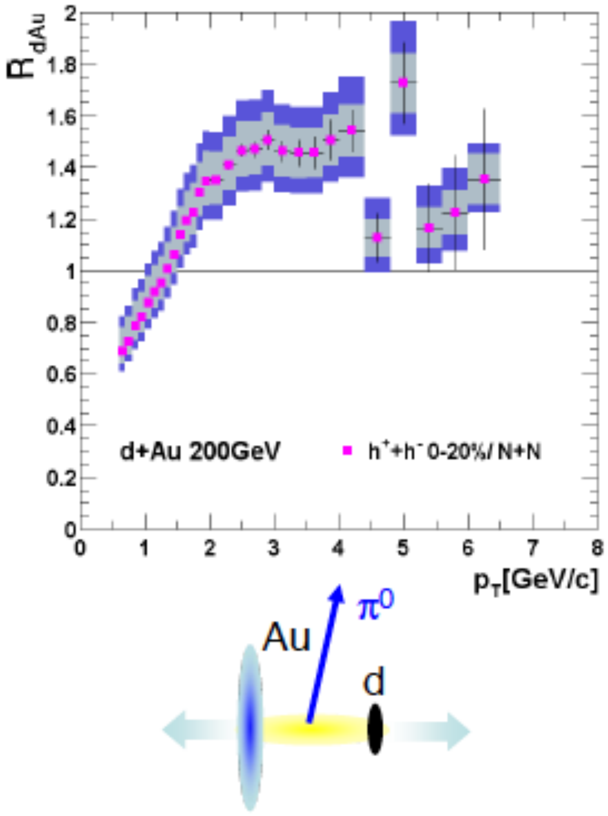
$T_{AA}(b=0) = \dfrac{9}{8\pi r_0^2} A^{4/3}$

$N_{coll}(0) = T_{AA}(0)\sigma_{NN}=1460$ (σ_{NN}=40mb)



RHIC $\sqrt{s} = 200$ π^0 and $h^+ + h^-$ data



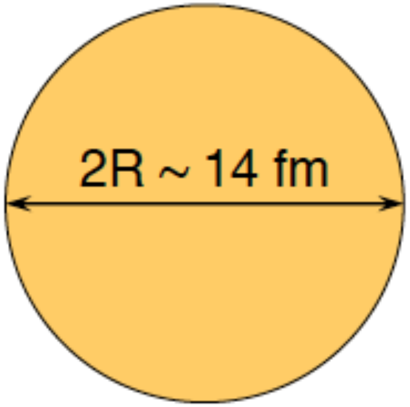


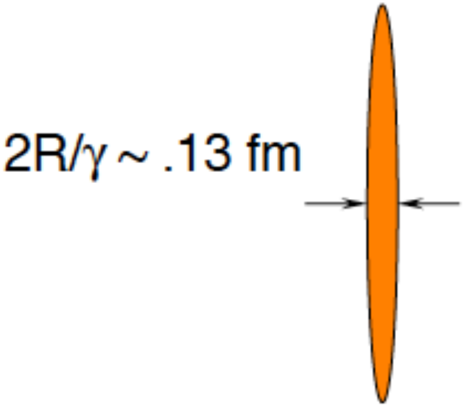
- Strong suppression (x5) in central Au+Au coll.
- No suppression in peripheral Au+Au coll.
- No suppression (Cronin enhancement) in control d+Au exp.

Convincing evidence for the **final state partonic** interaction - emergence of **sQGP**

Energy Density, step 1

Just divide energy by volume, in some frame.





Rest Frame

$\varepsilon = E/V = M/V_0$

$\varepsilon \sim 0.14$ GeV/fm$^3 = \varepsilon_0$

Boosted Frame

$\varepsilon = E/V = \gamma M/(V_0/\gamma) = \varepsilon_0\gamma^2$

$\gamma_{RHIC} = 106$

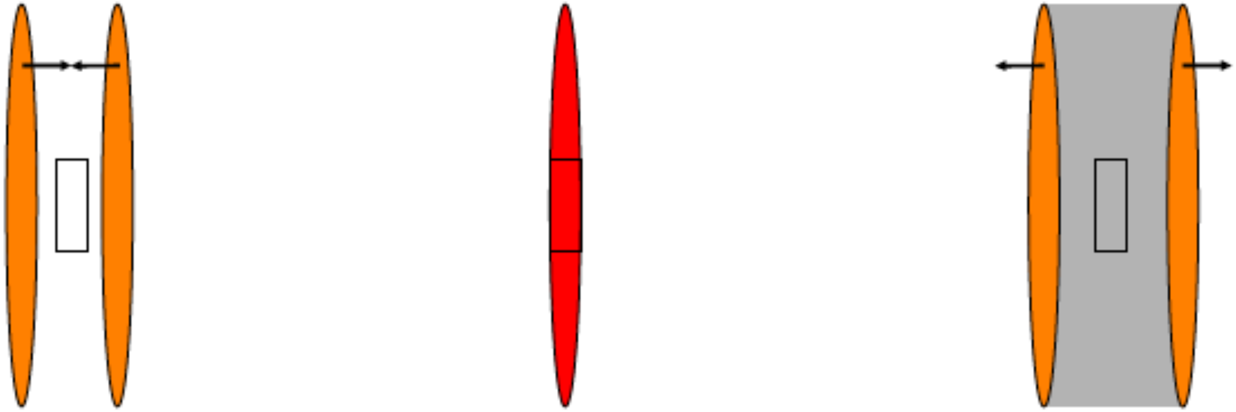
$\varepsilon \sim 1570$ GeV/fm^3 (!!)

$\gamma_{LHC} = 2880$

$\varepsilon \sim 1.2\ 10^6$ GeV/fm^3 (!!!!)

Energy Density, step 2

Examine a box with total momentum zero.



$\varepsilon = 0$

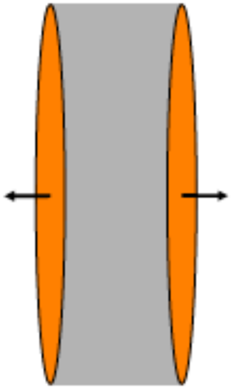
$\varepsilon = 2\gamma^2\varepsilon_0 \sim 3150\ \mathrm{GeV/fm^3}$

$\varepsilon = ?$

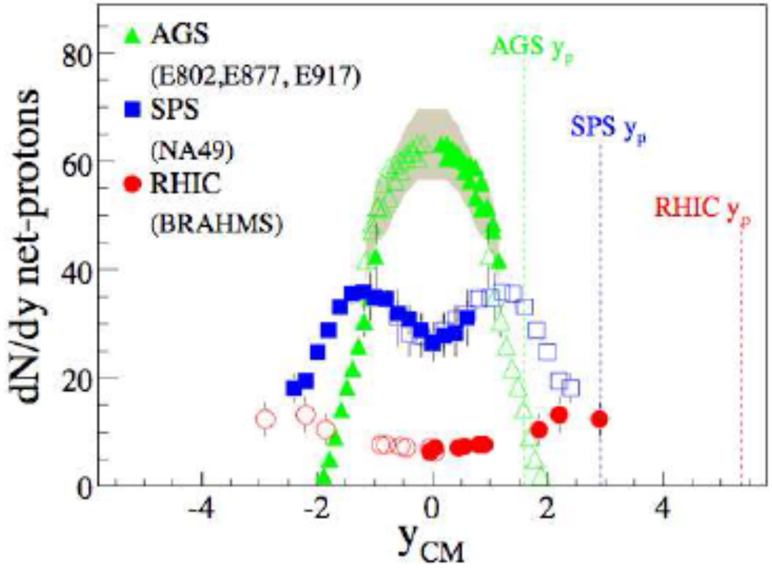
Very high, but
very short-lived!

Energy Density, step 3

Count up energy in *produced* particles/matter.



Define produced as everything at velocities/rapidities intermediate between those of the original incoming nuclei.

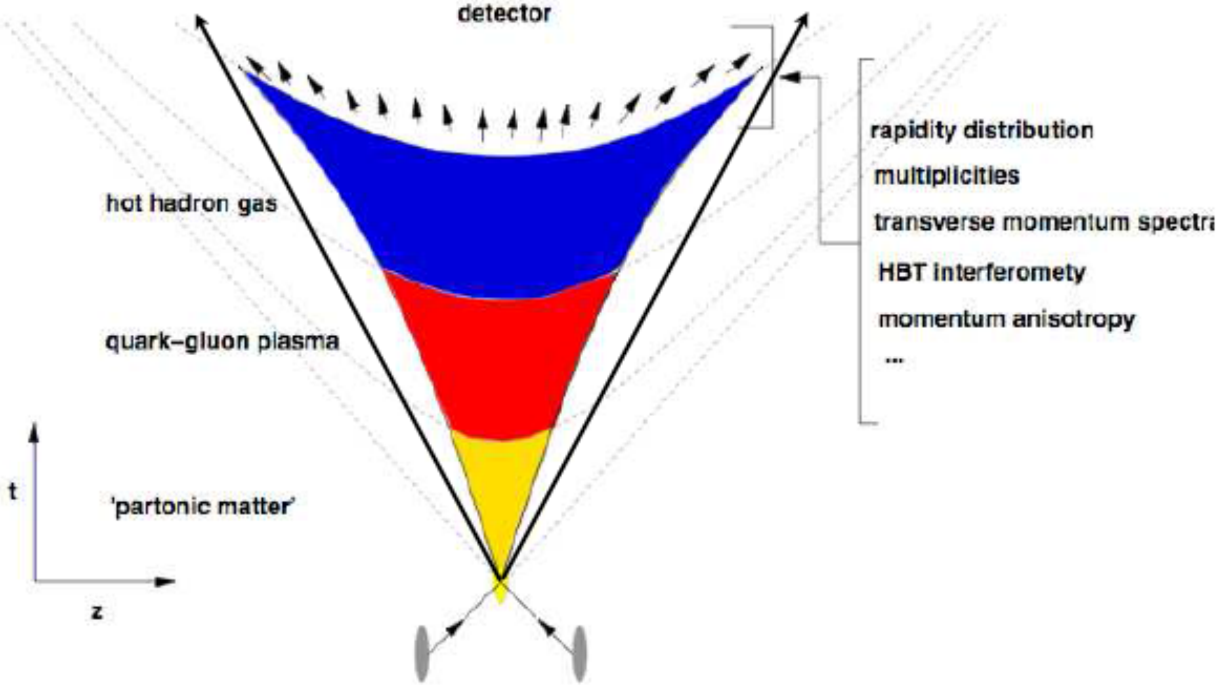


Two extremes:

Full transparency Bjorken

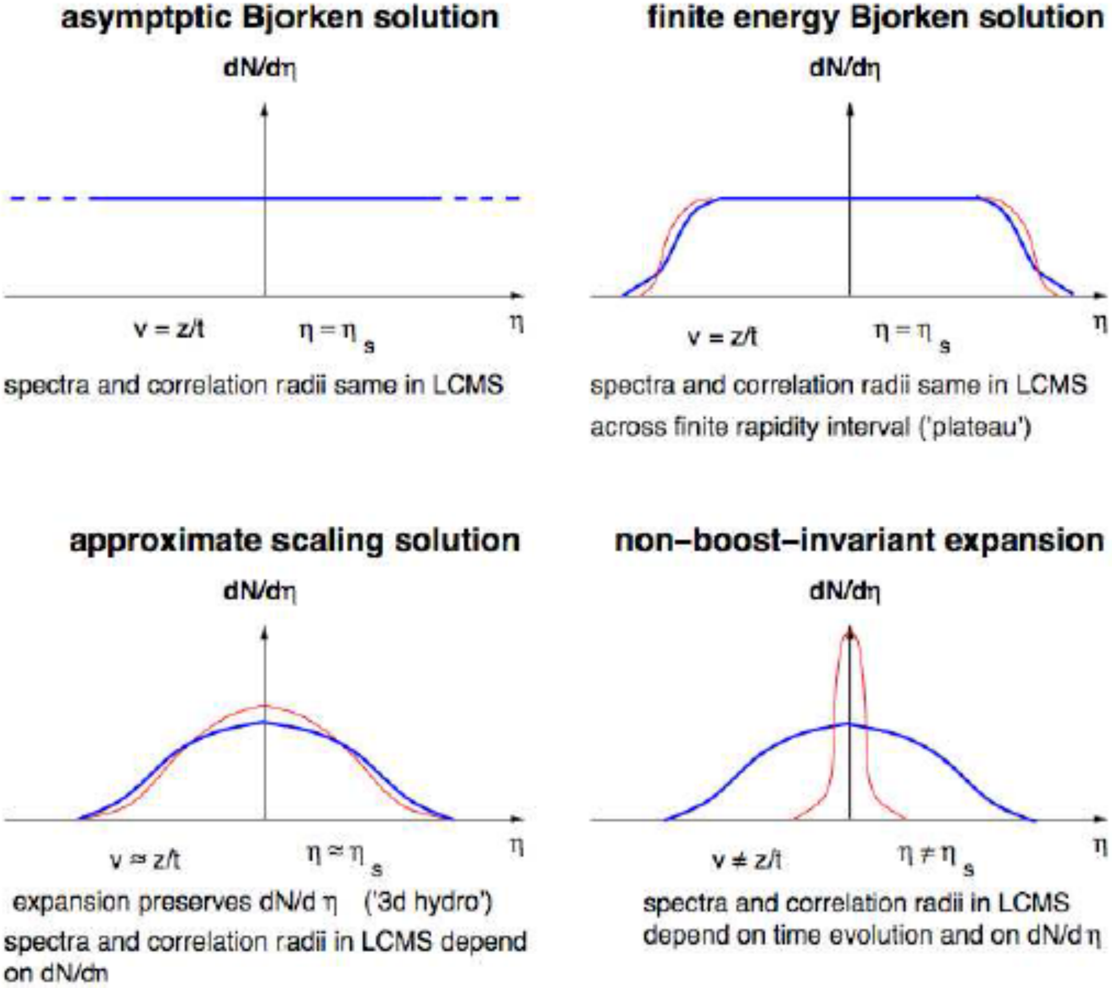
Full stopping Landau

Landau stopping x Bjorken expansion



- access to the final state of the system when collective behavious ends (freeze-out)
- bulk matter probes measured with high precision

What is meant by boost-invariance?



asymptptic Bjorken solution

spectra and correlation radii same in LCMS

finite energy Bjorken solution

spectra and correlation radii same in LCMS across finite rapidity interval ('plateau')

approximate scaling solution

expansion preserves dN/d η ('3d hydro')
spectra and correlation radii in LCMS depend on dN/dη

non–boost–invariant expansion

spectra and correlation radii in LCMS depend on time evolution and on dN/d η

Courtesy of T. Renk

Define (longitudinal) proper time, τ, and space-time rapidity, η

$$\tau = \sqrt{t^2 - z^2}$$

$$\eta_{st} = \eta = \tfrac{1}{2}\ln\left(\tfrac{t+z}{t-z}\right)$$

that gives

$$t = \tau\cosh(\eta)$$

$$z = \tau\sinh(\eta)$$

Exercise: show that t is invariant in longitudinal Lorentz boosts

Boost invariant flow

Boost invariant flow = flow of the matter appears the same in every (longitudinal) frame boosted from z=0

For a start, neglect transverse expansion.
It will be shown that following expression does the job:

$$u^{\mu} = \gamma(1,\vec{v}) = \gamma(1,0,0,\tfrac{z}{t}) = \left(\cosh(\eta),0,0,\sinh(\eta)\right)$$

Hydrodynamical description of HI collisions
= conservation of energy and momentum

Conservation equations: $\partial_{\mu} T^{\mu\nu} = 0$

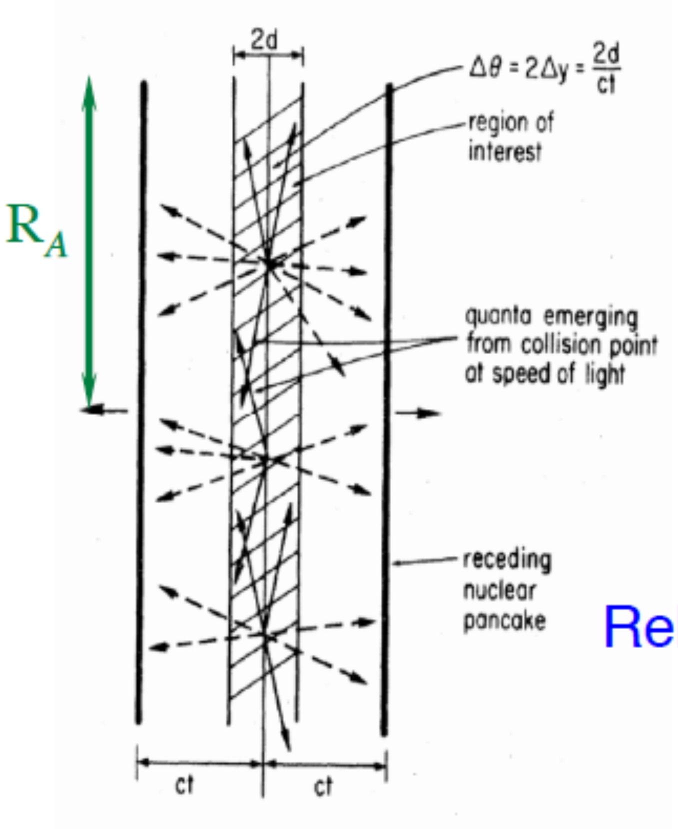
Ideal fluid: $T^{\mu\nu} = (\varepsilon + P)u^{\mu}u^{\nu} - g^{\mu\nu}P$

(Simplified) Equation of State: $P = P(\varepsilon)$

relates energy density ε and pressure P

One dimensional scaling solution

J.D. Bjorken, Phys. Rev. D 27 (1983) 140



With simplified flow presented in previous page, conservation equations boil down to:

$$\frac{\partial\varepsilon}{\partial\tau} + \frac{\varepsilon+P}{\tau} = 0$$

$$\frac{\partial P}{\partial\eta} = 0$$

Two basic scenarios:

Free streaming (FS): $P = P(\varepsilon) \equiv 0$

Relativistic ideal gas (IG): $P = P(\varepsilon) = \frac{1}{3}\varepsilon$

Solve to obtain:

FS: $\varepsilon(\tau) = \varepsilon_0\left(\frac{\tau_0}{\tau}\right)$ and

IG: $\varepsilon(\tau) = \varepsilon_0\left(\frac{\tau_0}{\tau}\right)^{4/3}$

Initial values ε_0 and τ_0

For fixed proper time τ_0: $dz = \frac{\partial z}{\partial \tau} d\tau + \frac{\partial z}{\partial \eta} d\eta = 0 + \tau_0 \cosh(\eta) d\eta$

Estimate volume at z=η=0: $dV \approx \pi R_A^2 dz = \pi R_A^2 \tau_0 d\eta$

Energy density: $\varepsilon = \frac{dE}{dV} \approx \frac{\Delta E}{\Delta V} \approx \frac{\Delta E}{\pi R_A^2 \tau_0 \Delta\eta}$

Energy in the central rapidity region can be approximated:

$$\Delta E \approx \Delta E_T \approx \langle m_T \rangle \frac{dN}{dy} \Delta y$$

where multiplicity dN/dy and average transverse mass <mT> can be measured experimentally. Now boost invariance implies Δy=Δη and hence we obtain

$$\boxed{\varepsilon_{Bjorken} \approx \frac{\langle m_T \rangle}{\pi R_A^2 \tau_0} \frac{dN}{dy} = \frac{1}{A\tau_0} \frac{dE^{measured}}{dy}}$$

What about τ_0?

Initial time τ_0 has two basic limits:

Crossing time of the two nuclei: $\tau_0 \geq \frac{2}{\gamma} R_A$

Formation time: $\tau_0 \geq \tau_{form}$

For many years this $\varepsilon_{\mathrm{Bjorken}}$ formula was used with a nominal $\tau_{\mathrm{Form}}=1.0$ fm/*c* with no real justification, even when it manifestly violated the crossing time limit for validity!

$2R/\gamma = 5.3$ fm/*c* for AGS Au+Au, 1.6 fm/*c* for SPS Pb+Pb.

Note: In hydrodynamical models, it turns out that total multiplicity (related with entropy) essentially fixes the product $\tau_0\varepsilon_0$. Later it turns out that data (for v_2) favours $\tau_0<0.6$ fm/c at RHIC. However, τ_0 and ε_0 are essentially free parameters in hydrodynamical models.

Better formation time estimates

Generic quantum mechanics: a particle can't be considered *formed* in a frame faster than $\hbar / E$

Translation: $\tau_{\text{Form}} \geq 1/m_T \sim 1/\langle m_T \rangle$

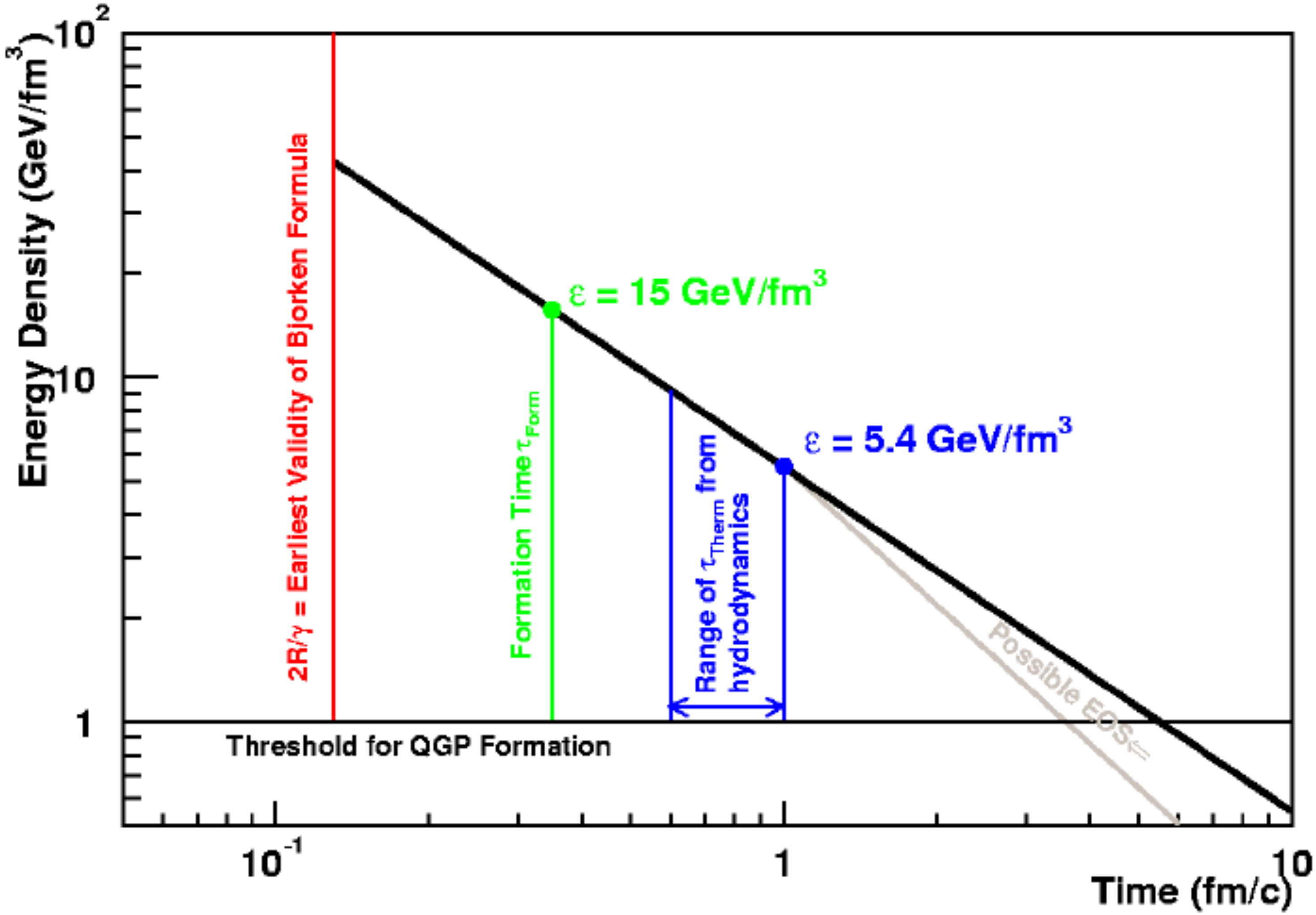
$$\langle m_T \rangle = \frac{dE_T(\tau_{\text{Form}})/dy}{dN(\tau_{\text{Form}})/dy} \approx \frac{dE_T/d\eta}{dN/d\eta} \quad \text{(Final State)}$$

PHENIX Data: $(dE_T/d\eta)/(dN^{ch}/d\eta) \sim 0.85$ GeV

Assuming 2/3 of particles are charged, this implies

$\langle m_T \rangle \sim 0.85 * 2/3 = 0.57$ GeV/(charged+neutral)

$\tau_{\text{Form}} \sim h / \langle m_T \rangle = 0.2/0.57 = 0.35$ fm/c

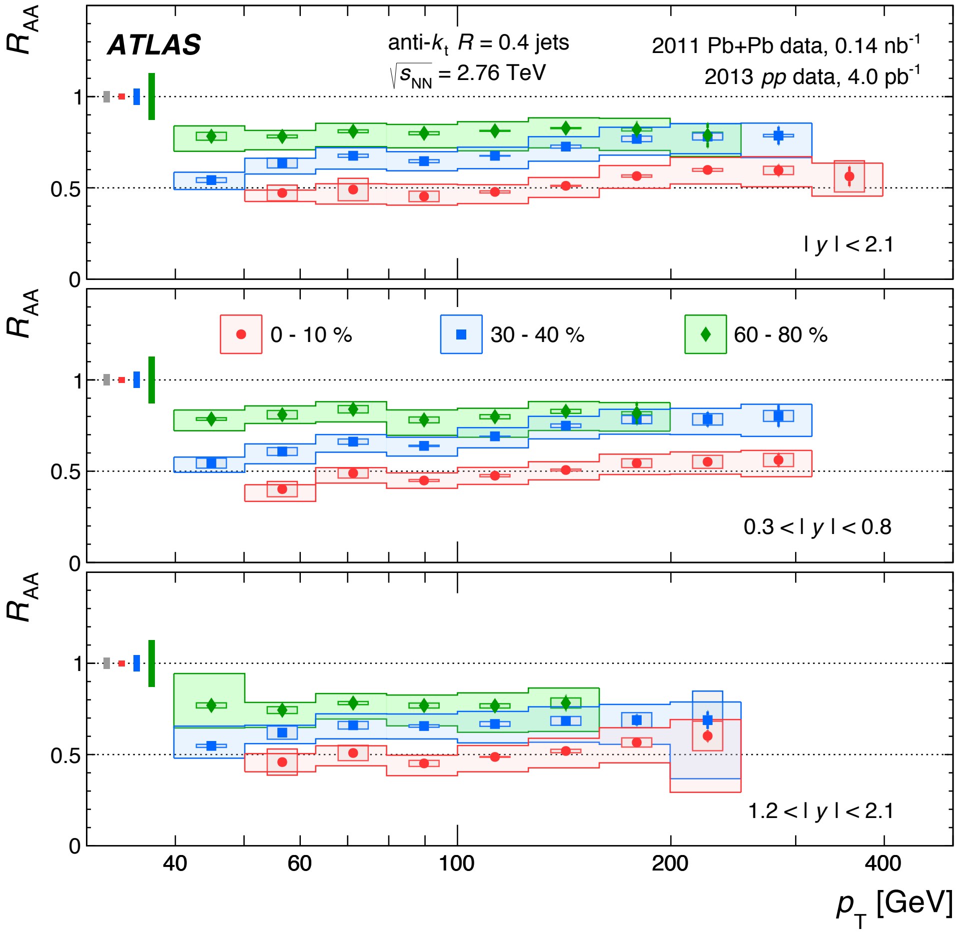


Note: Bjorken estimate corresponds to free streaming case

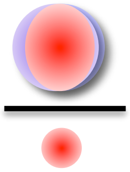
→ It estimates lower limit of initial ε

Jet suppression

Phys. Rev. Lett. 114 (2015) 072302



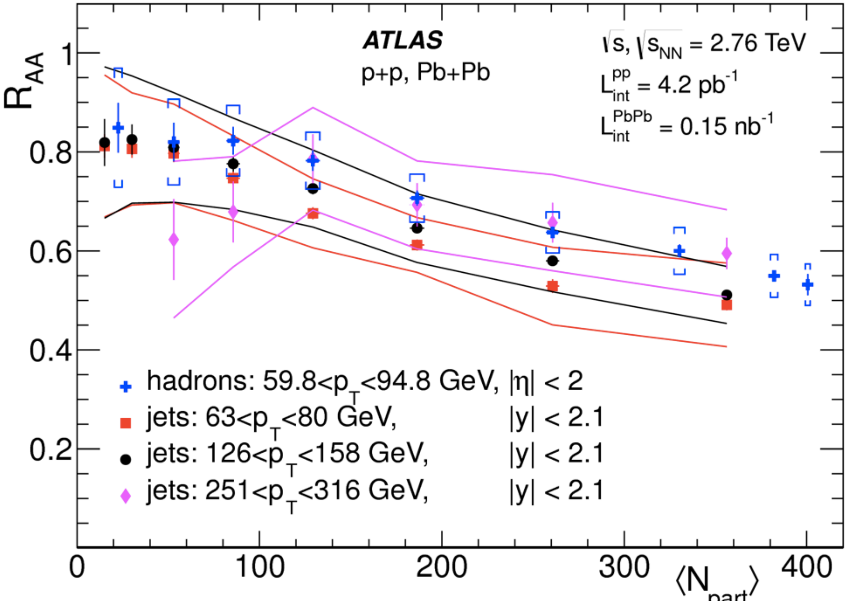
$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{d^2 N_{A+A} / dy dp_T}{d^2 N_{p+p} / dy dp_T}$$



- 4 units of rapidity, 40-400 GeV
- Each color is a different centrality selection
- Each panel is a different y selection
- ~2x suppression in most central events
- Little p_T dependence in this kinematic range

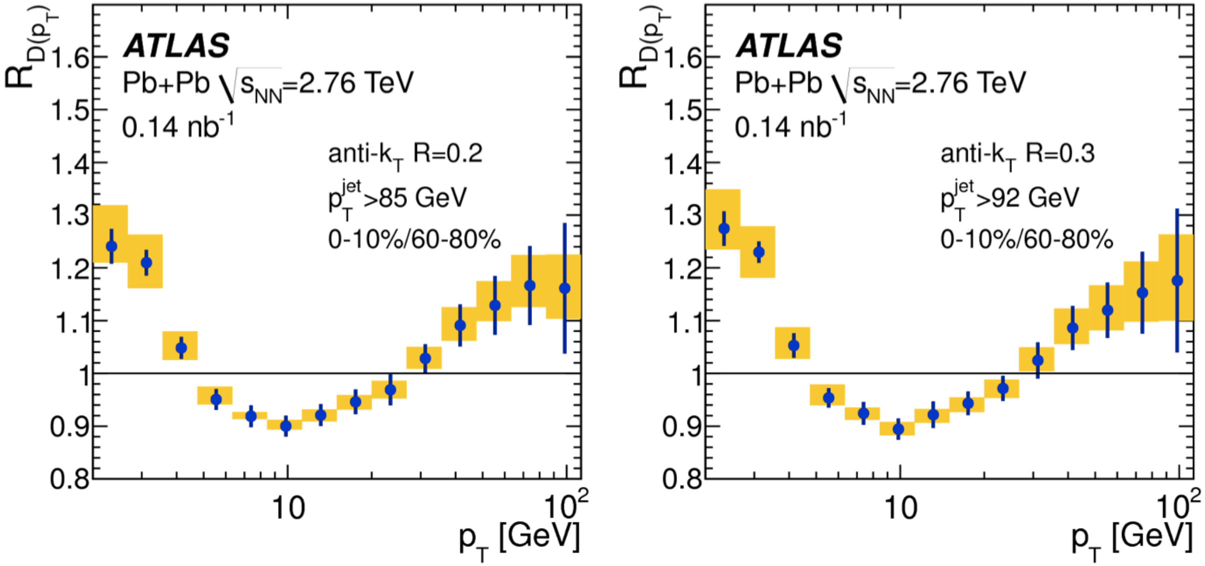
Jet suppression

arXiv:1504.04337



Similar trend for charged particles and jets.

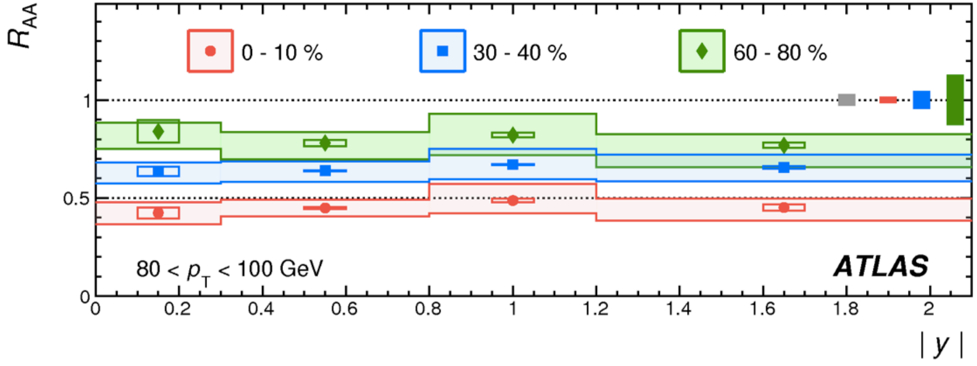
Consistency with ATLAS fragmentation measurement:
enhancement at low z [pT] of ~25%
smaller enhancement at high z
about 10% suppression at intermediate z.



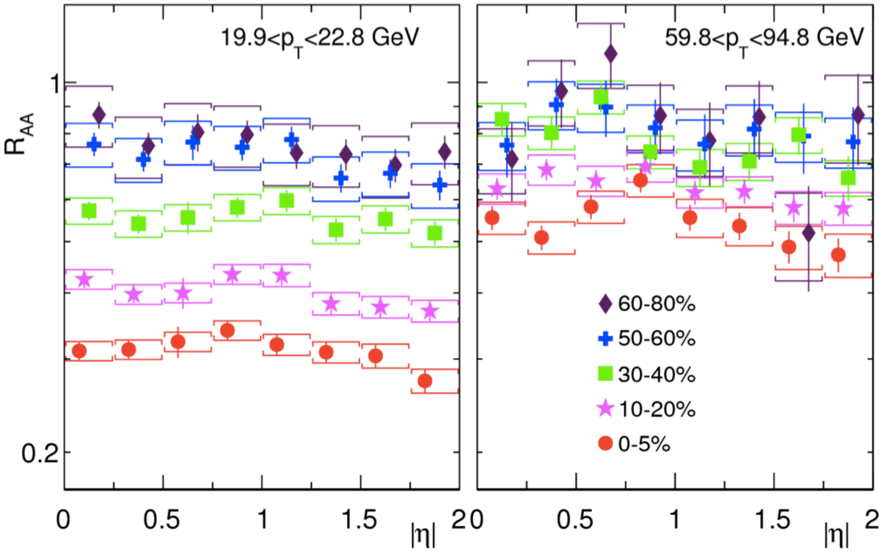
PLB 739 (2014) 320

Jet suppression

Phys. Rev. Lett. 114 (2015) 072302



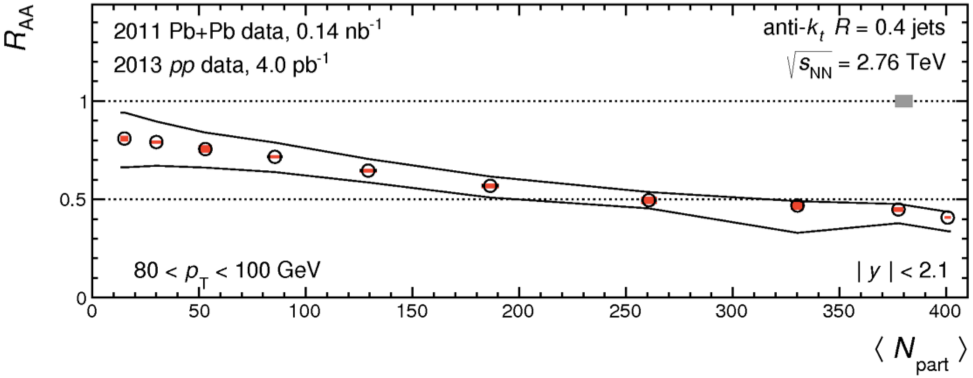
arXiv:1504.04337

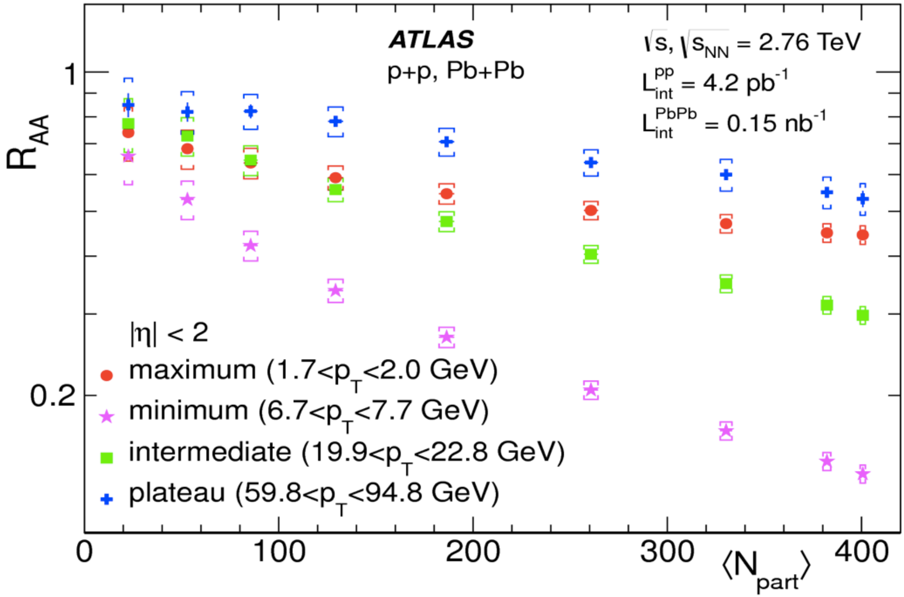


different shape of initial jet spectrum

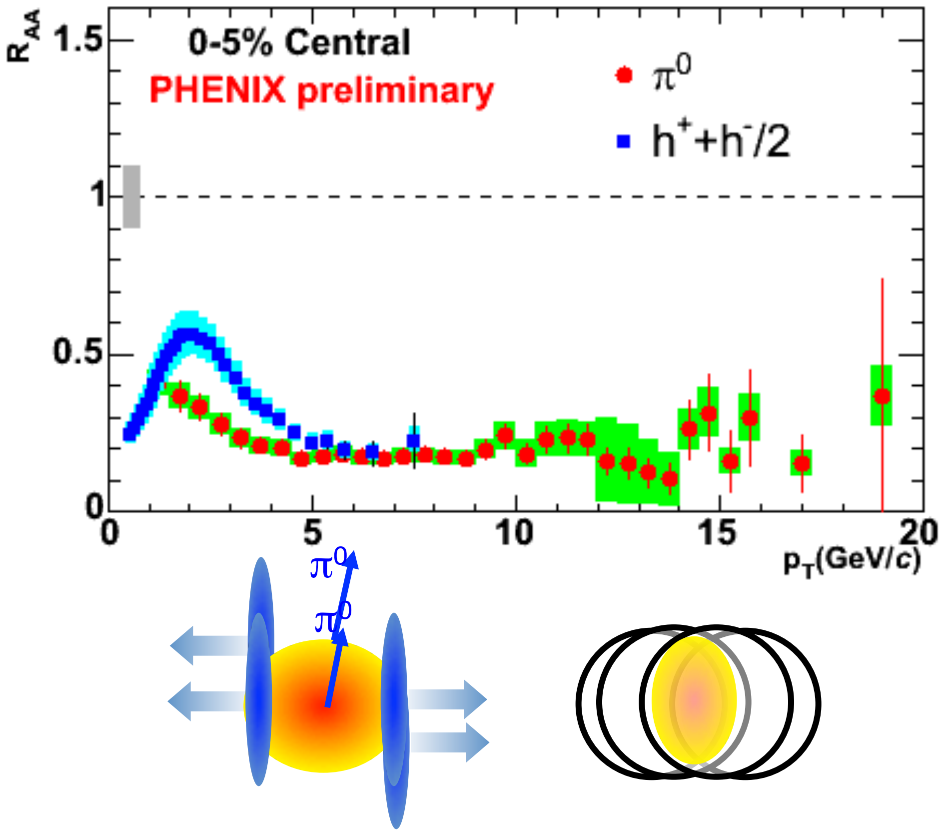
different q/g mixture at fixed p_T

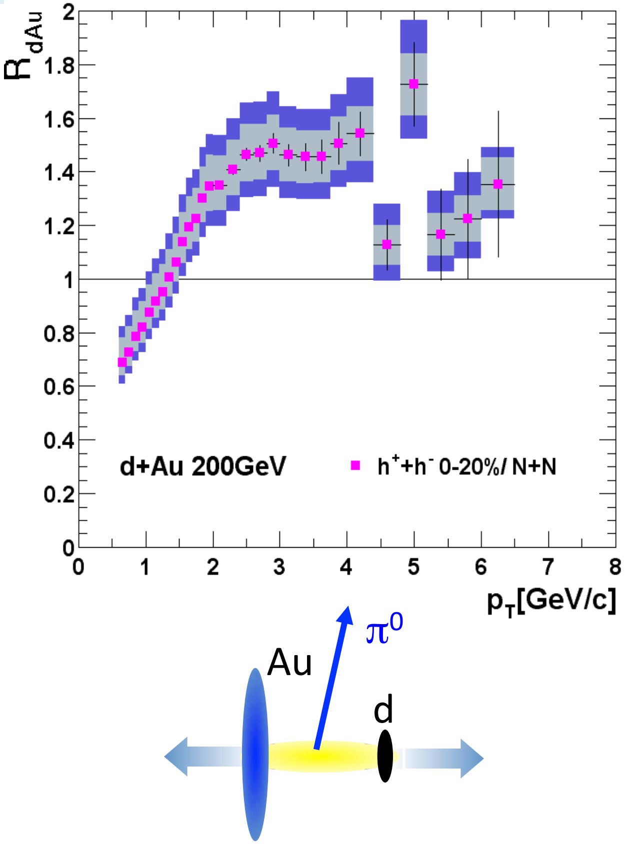
different path length seen by jets





RHIC $\sqrt{s}$ = 200 π^o and $h^+ + h^-$ data





- Strong suppression (x5) in central Au+Au coll.
- No suppression in peripheral Au+Au coll.
- No suppression (Cronin enhancement) in control d+Au exp.

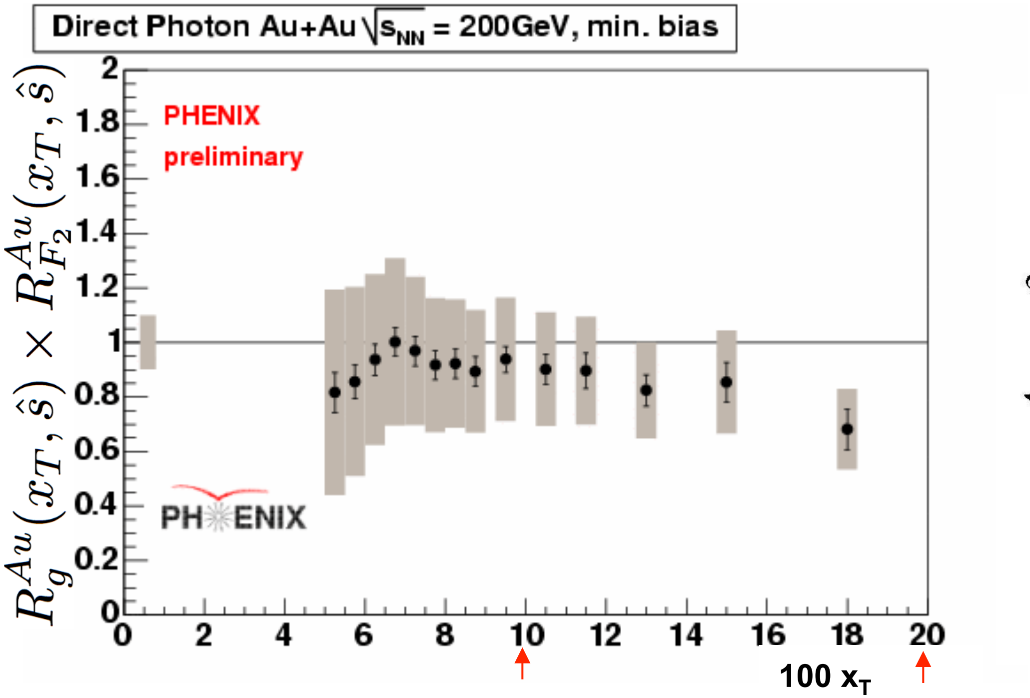
Convincing evidence for the **final state partonic** interaction - emergence of **sQGP**

For Au+Au min bias direct γ R_{AA} is simple

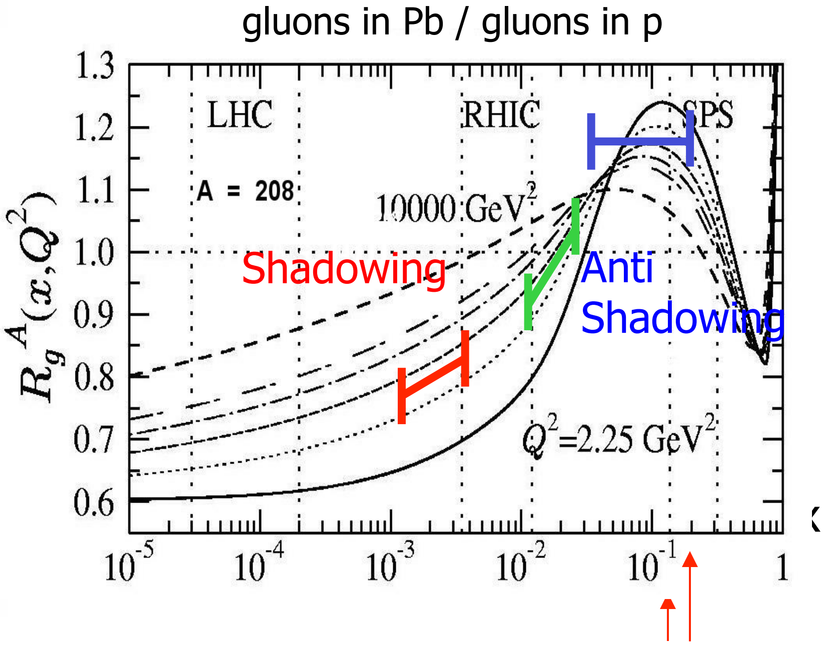
Eskola,Kolhinen,Ruuskanen Nucl. Phys. B**535**(1998)351

Au+Au minimum bias at mid-rapidity

$$R_{AA} = \frac{d^2\sigma_\gamma^{AA}/dp_T^2\,dy_\gamma}{AA\,d^2\sigma_\gamma^{pp}/dp_T^2\,dy_\gamma} \approx \left(\frac{F_{2A}(x_T)}{AF_{2p}(x_T)} \times \frac{g_A(x_T)}{Ag_p(x_T)}\right)$$



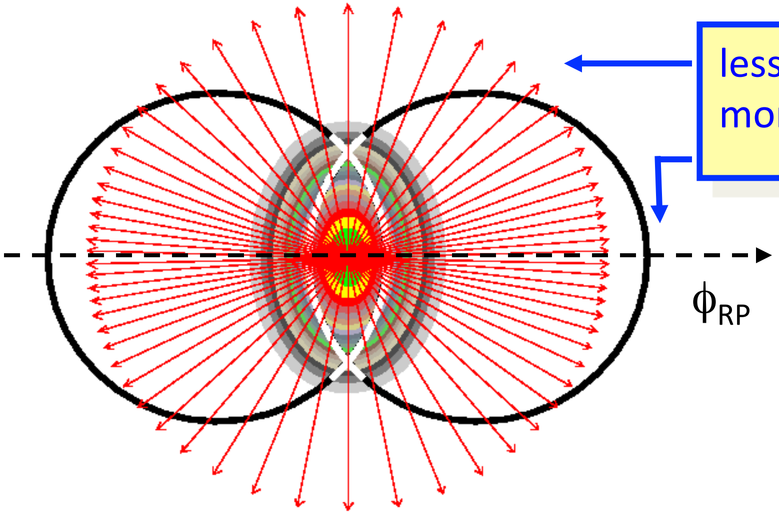
Eskola et al. NPA**696** (2001) 729

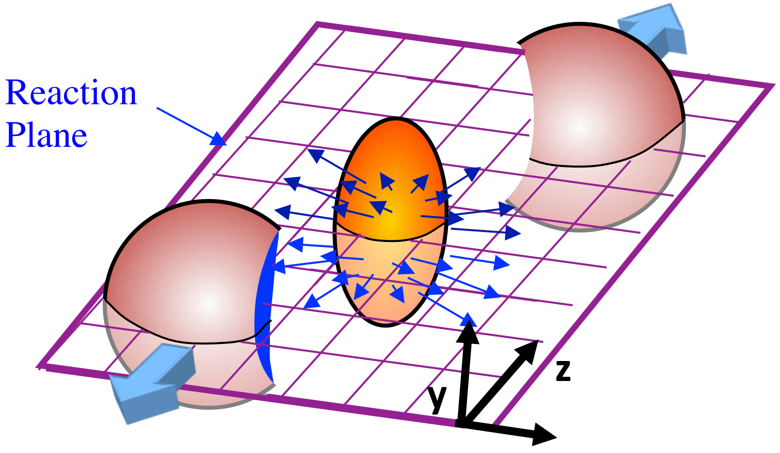


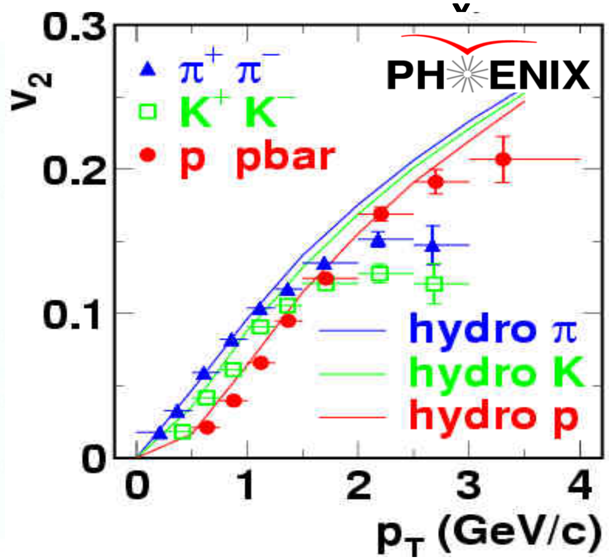
Do the structure function ratios actually drop by ~20% from x=0.1 to x=0.2?

Nuclear Geometry and Hydrodynamic

multiple scattering → larger pressure gradient in plane → less yield out more in plane







Spatial asymmetry

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

Mom. Asymmetry

elliptic flow $v_2 = \dfrac{\langle p_x^2 \rangle - \langle p_x^2 \rangle}{\langle p_x^2 \rangle + \langle p_x^2 \rangle}$

$$\frac{d^3N}{p_T dp_T dy d\varphi} \propto [1 + 2v_2(p_T)\cos 2(\varphi - \phi_{RP}) + \ldots]$$

What are the relevent DOF's in "Flow" ?

"Fine structure" of v2(pT) for different mass particles.

In Ideal "hydro" picture:

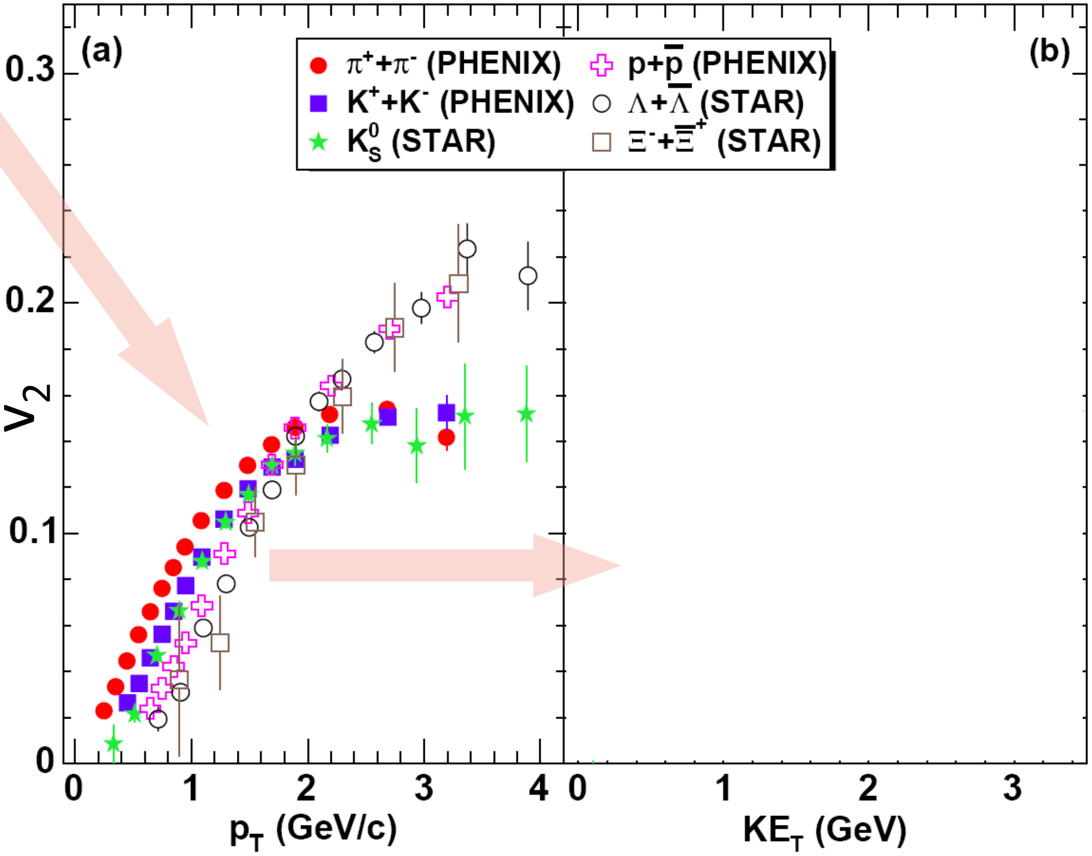
$$\partial_\nu T^{\mu\nu} = 0 \quad \rightarrow \quad \text{Work-energy theorem}$$

$$\rightarrow \int_{vol} \nabla P dV = \Delta E_K =$$

$$= m_T - m_0 \equiv \Delta KE_T$$

$v_2(p_T) \rightarrow v_2(KE_T)$

Phys. Rev. Lett., 2007, 98, 162301

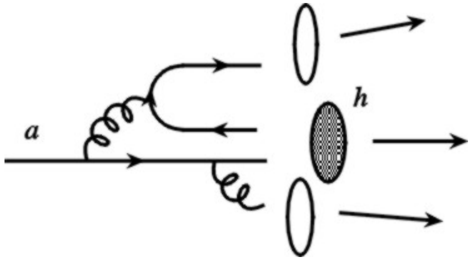


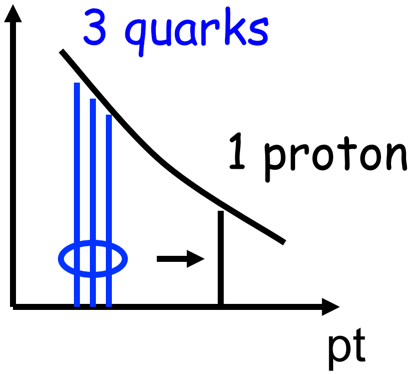
v2(KE_T) universal for baryons
v2(KE_T) universal for mesons

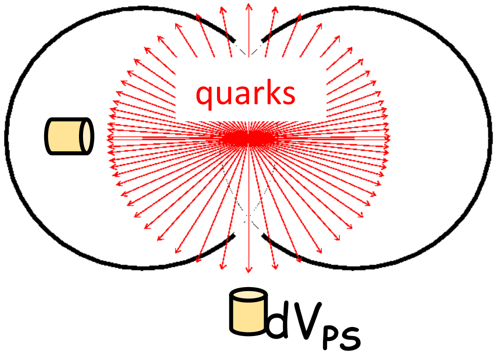
Do we have an even more universal scaling?

QG medium fragmentation-quark recombination

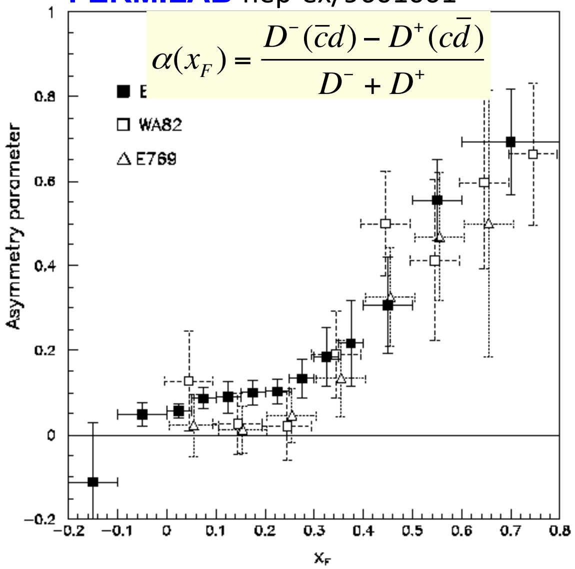
Why is the universal $v_2(KE_T)$ different for meson and baryons?
Exited quark-gluon medium → huge phase-space densities → constituent Quark Recombination / Coalescence







Phys. Lett.,1996,B371,157-162
FERMILAB hep-ex/9601001



$$\alpha(x_F) = \frac{D^-(\bar{c}d) - D^+(c\bar{d})}{D^- + D^+}$$

Phys.Rev.Lett.91:092301,2003

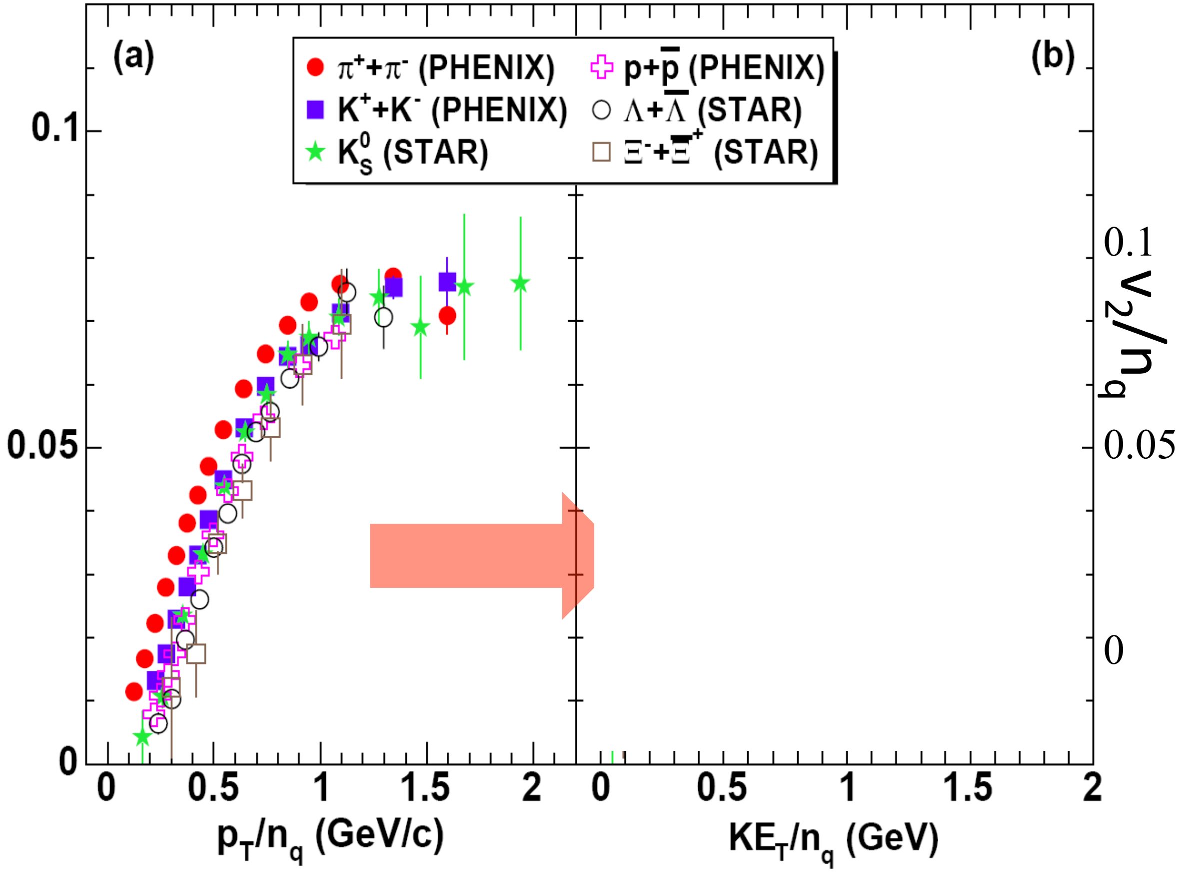
$$v_2^{meson}(p_T) \approx 2 \cdot v_2^{quark}\left(\frac{p_{T,quark}}{2}\right) \qquad v_2^{baryon}(p_T) \approx 3 \cdot v_3^{quark}\left(\frac{p_{T,quark}}{3}\right)$$

The "Flow" Knows Quarks

Assumption:

all bulk particles are coming from recombination of flowing partons

$$v_2(p_T) \rightarrow n_q \cdot v_2\left(\frac{KE_T}{n_q}\right)$$

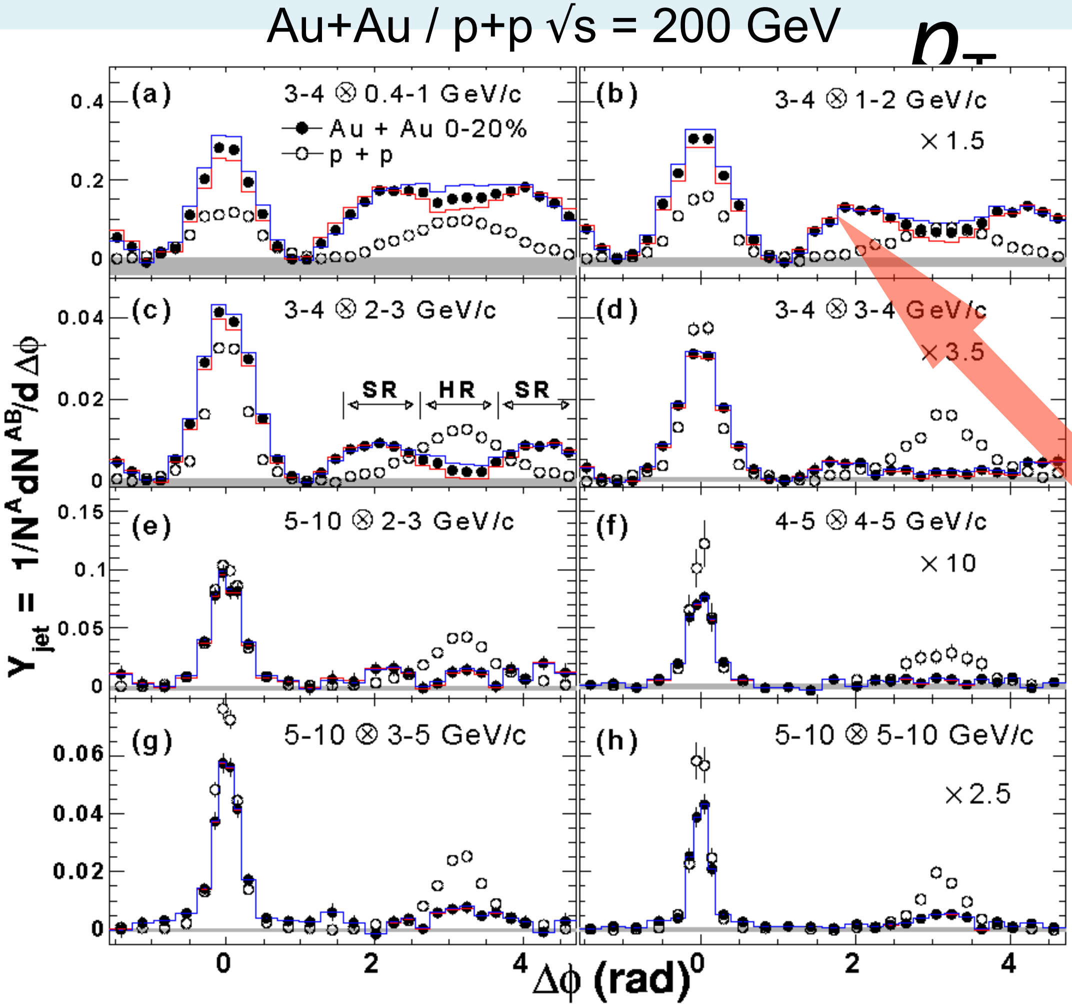


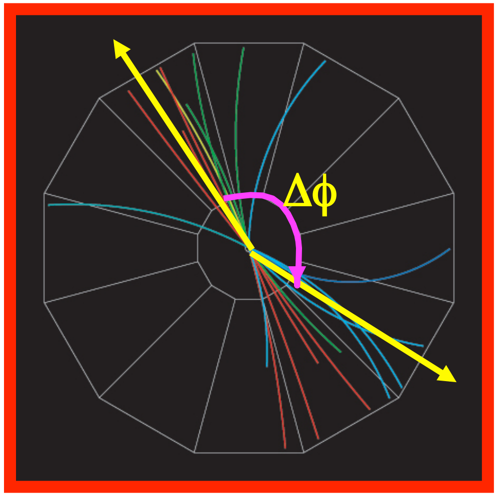
Discovery of universal scaling:

- flow parameters scaled by quark content n_q resolves meson-baryon separation of final state hadrons. Works for strange and even charm quarks.
- strongly suggests the early thermalization and **quark degree of freedom**.

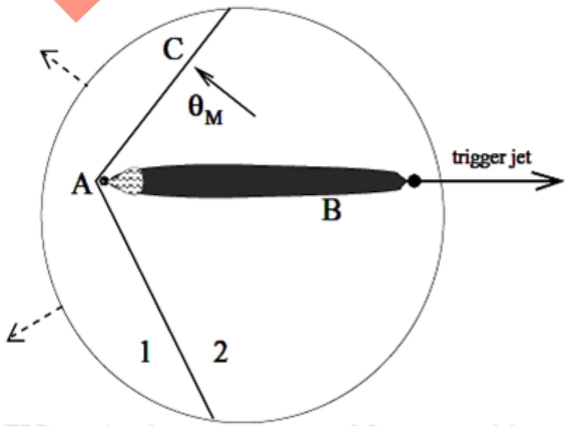
Jet shape evolution with trigger and assoc.

Au+Au / p+p √s = 200 GeV





p + p → jet + jet



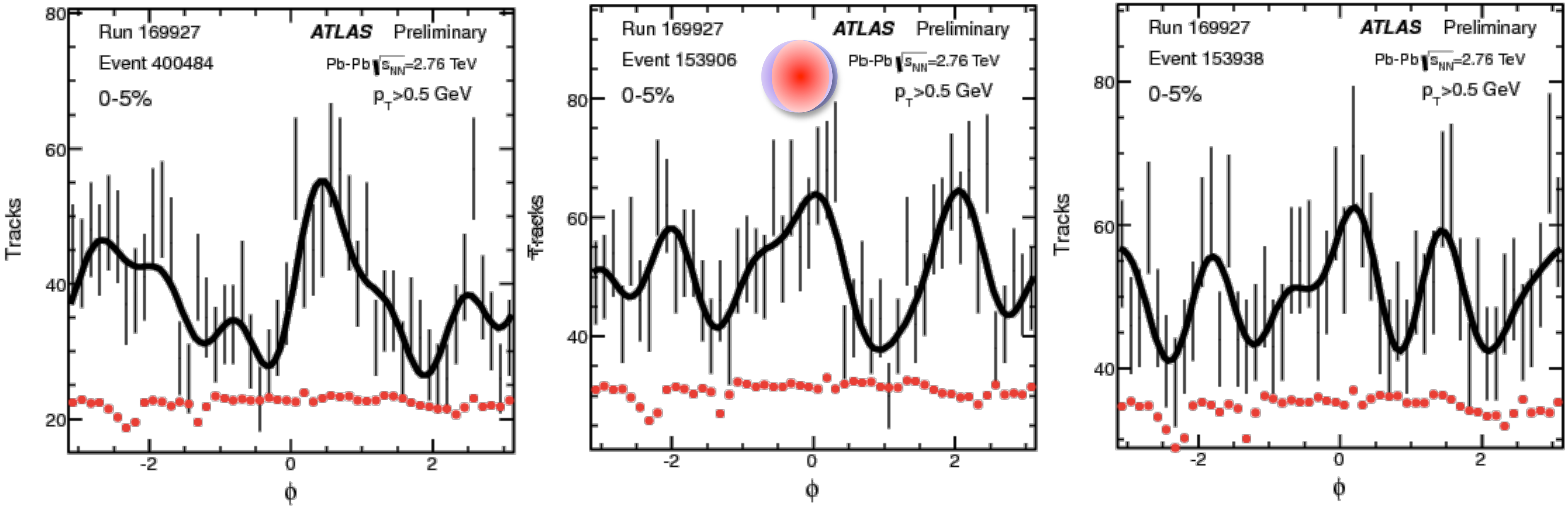
Per-trigger yield vs. $\Delta\phi$ for various trigger and partner p_T ($p^A_T \otimes p^B_T$), arranged by increasing pair momentum ($p^A_T + p^B_T$)

arXiv:0705.3238 [nucl-ex]

Fluctuations

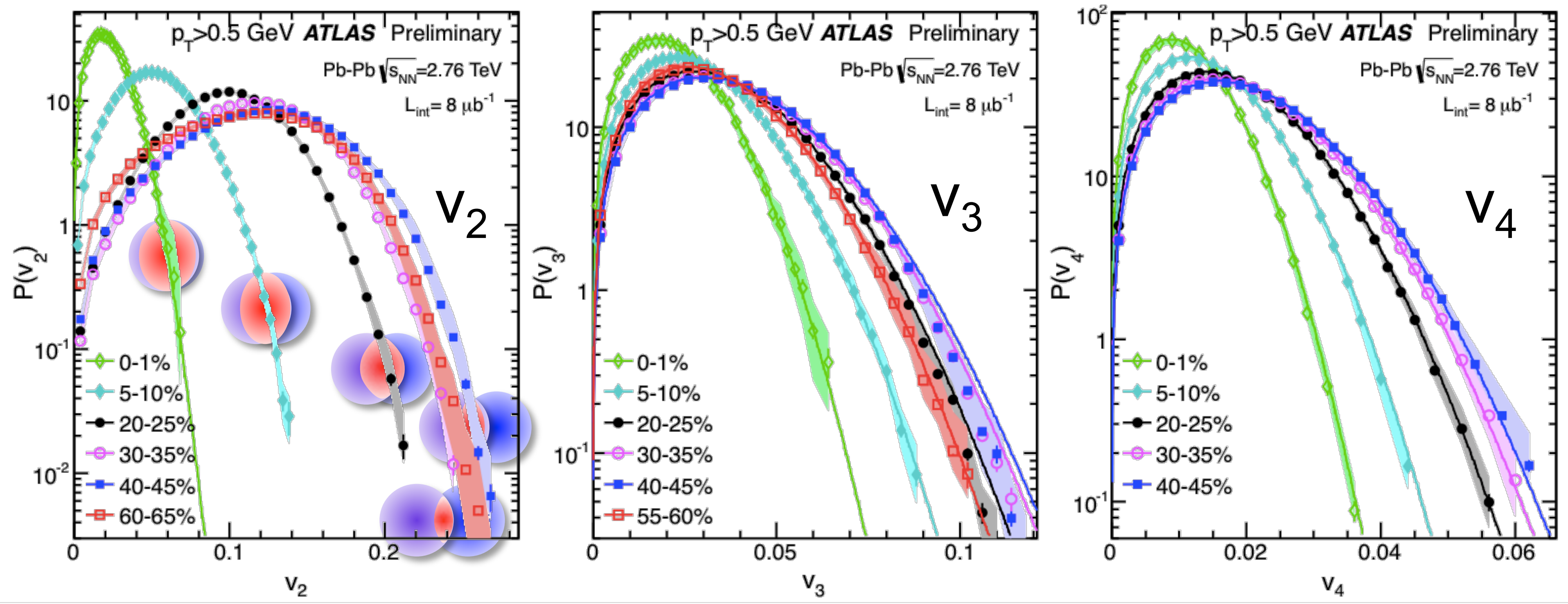
$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n} \mathrm{v}_{\mathrm{n}} \cos n\left(\phi - \Phi_{n}\right)$$

JHEP11(2013)183



Significant fluctuations, factor of ~2
Cannot be explained by detector effects

Flow becomes understood?

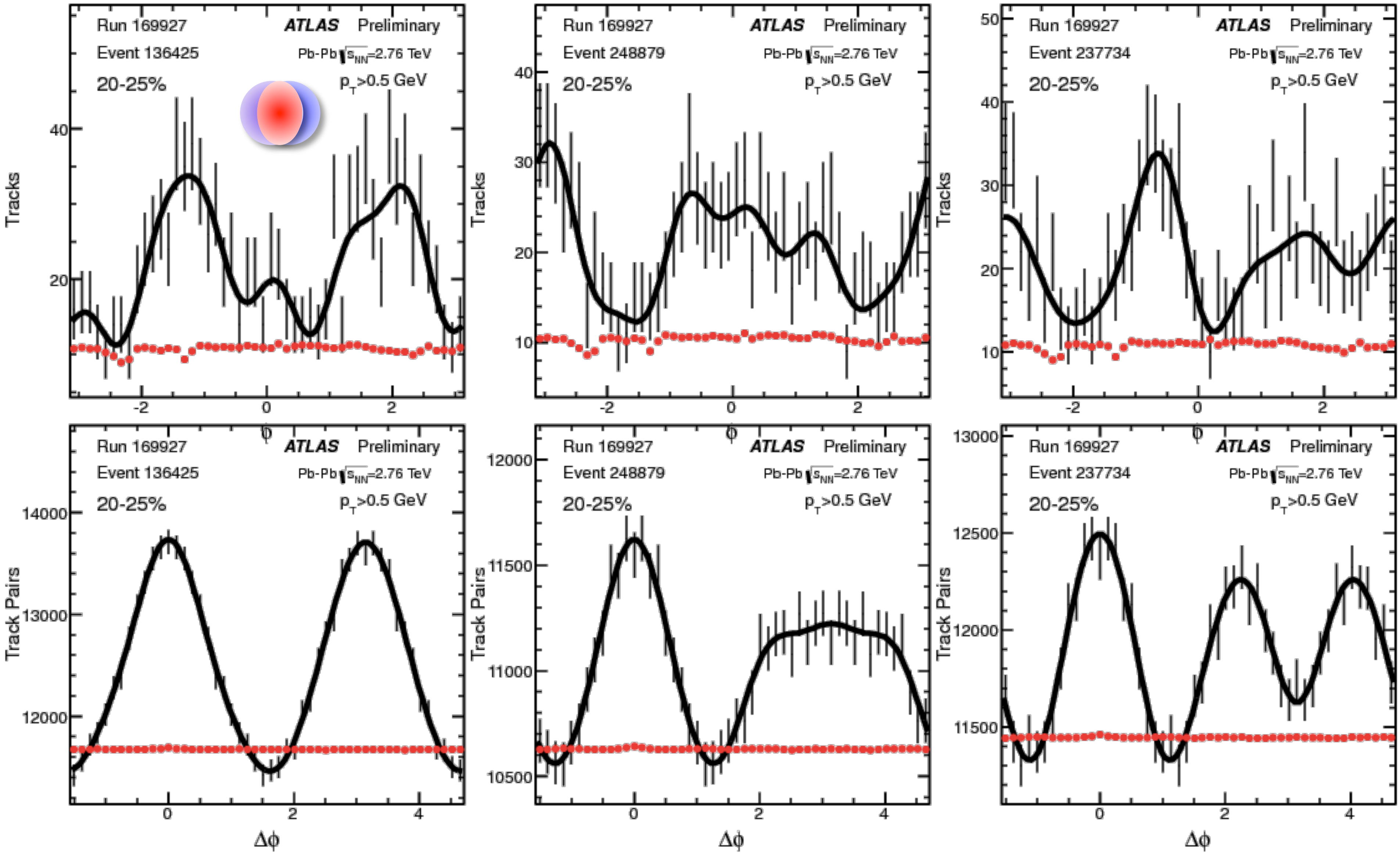


JHEP11(2013)183

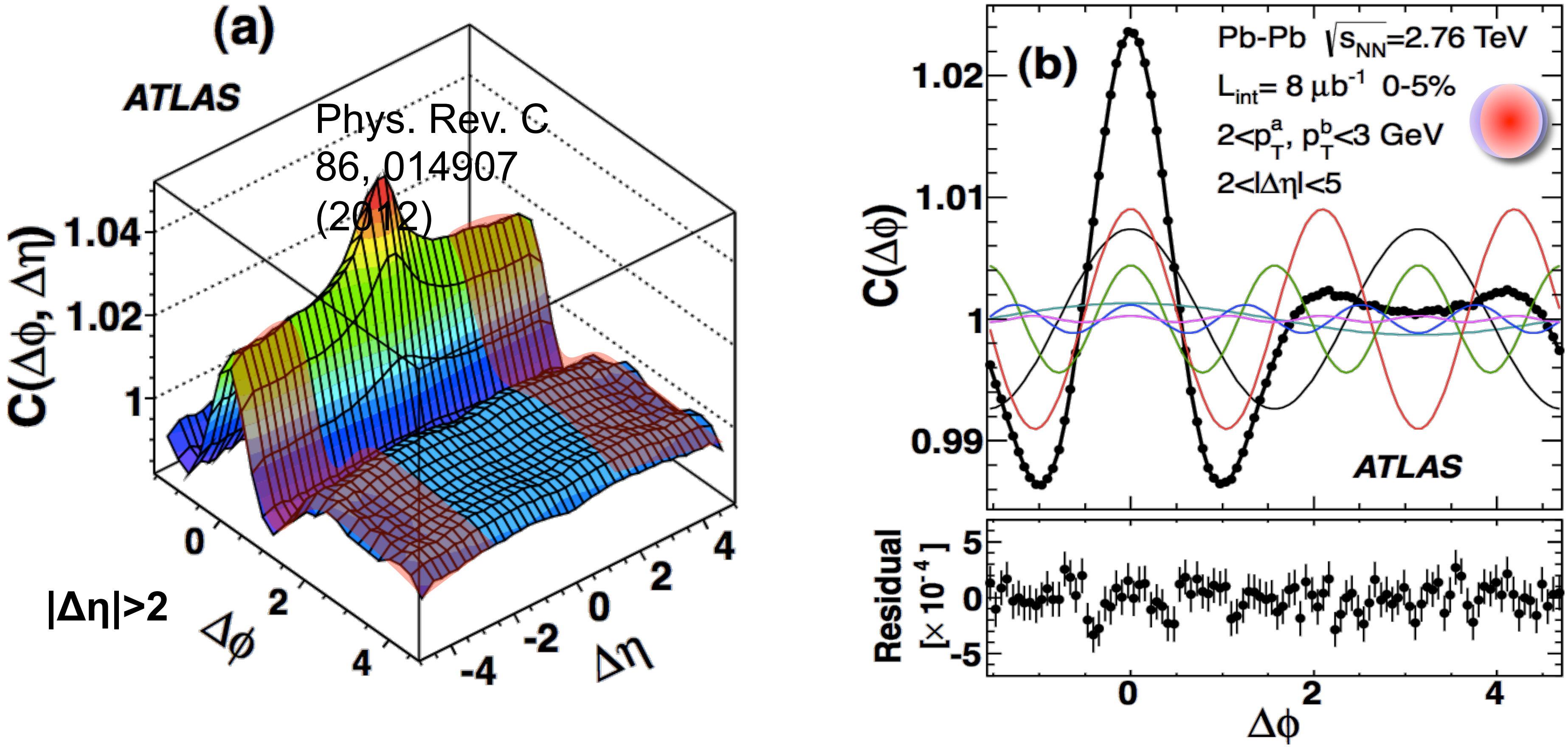
v_n distributions in p_T and centrality

Fully corrected for detector effects an unfolded for limited statistics

2 particle correlations in Pb+Pb



2 particle correlations vs. flow



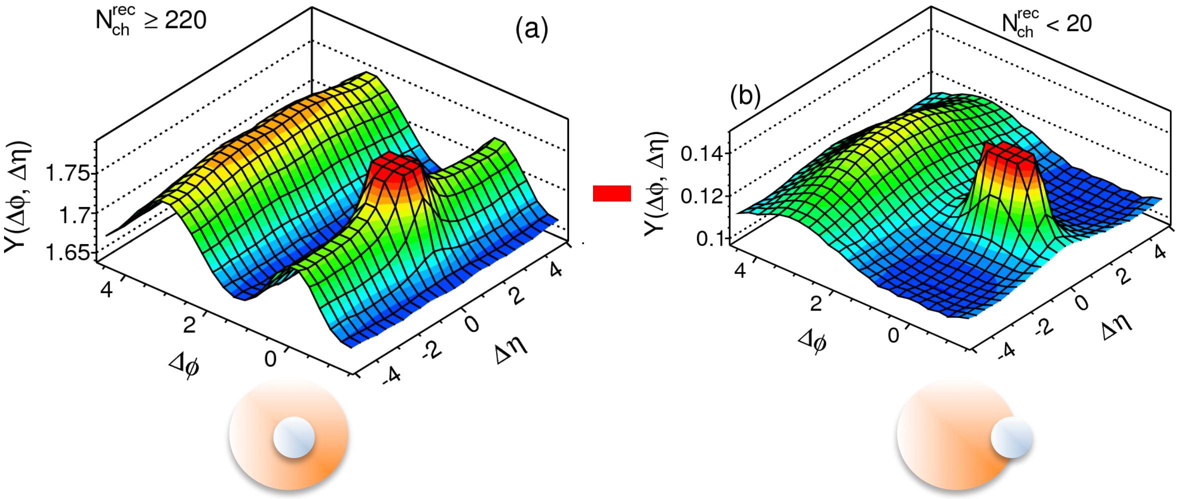
Phys. Rev. C 86, 014907 (2012)

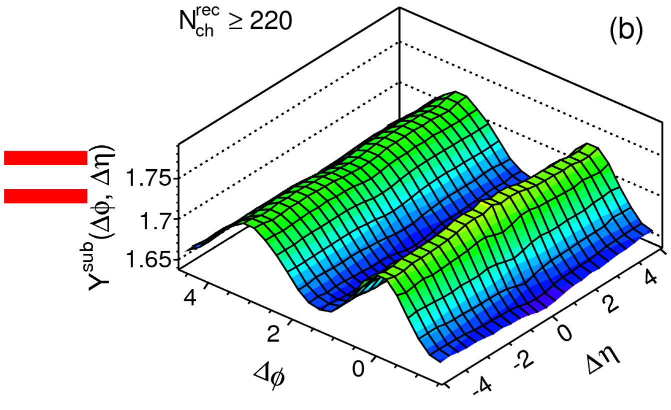
|Δη|>2

Long range structures ("ridge") can be almost entirely described by harmonics $v_{1,1}$-$v_{6,6}$

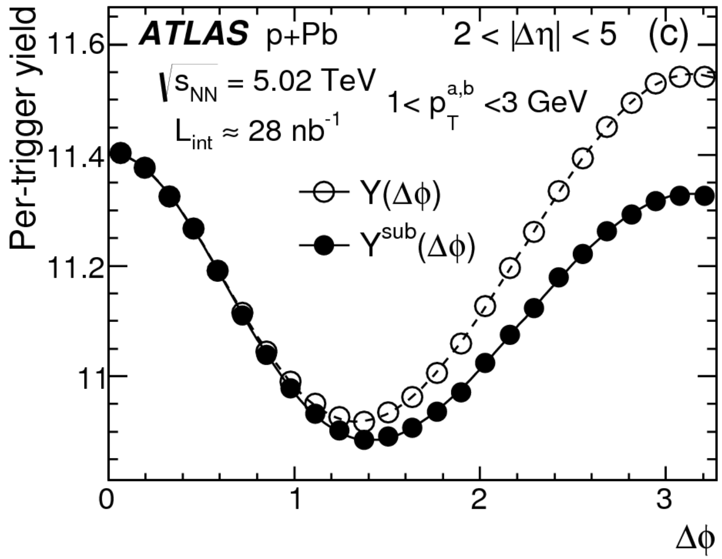
$$v_{n,n}\left(p_T^a, p_T^a\right) = v_n\left(p_T^a\right) v_n\left(p_T^b\right) + non - flow$$

2PC in p+Pb





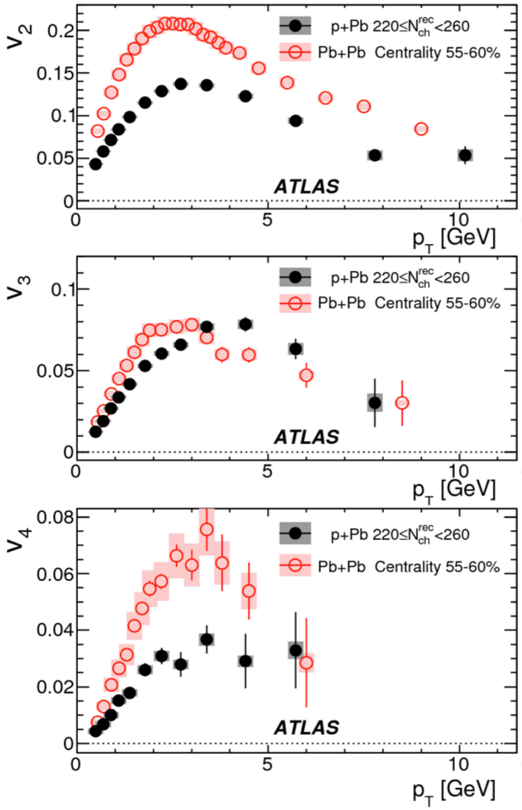
Phys. Rev. C90 (2014) 044906.



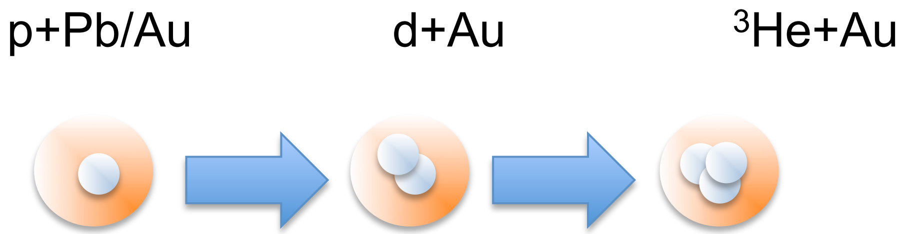
Flow in p+Pb

p_T shapes similar between p+Pb & Pb+Pb

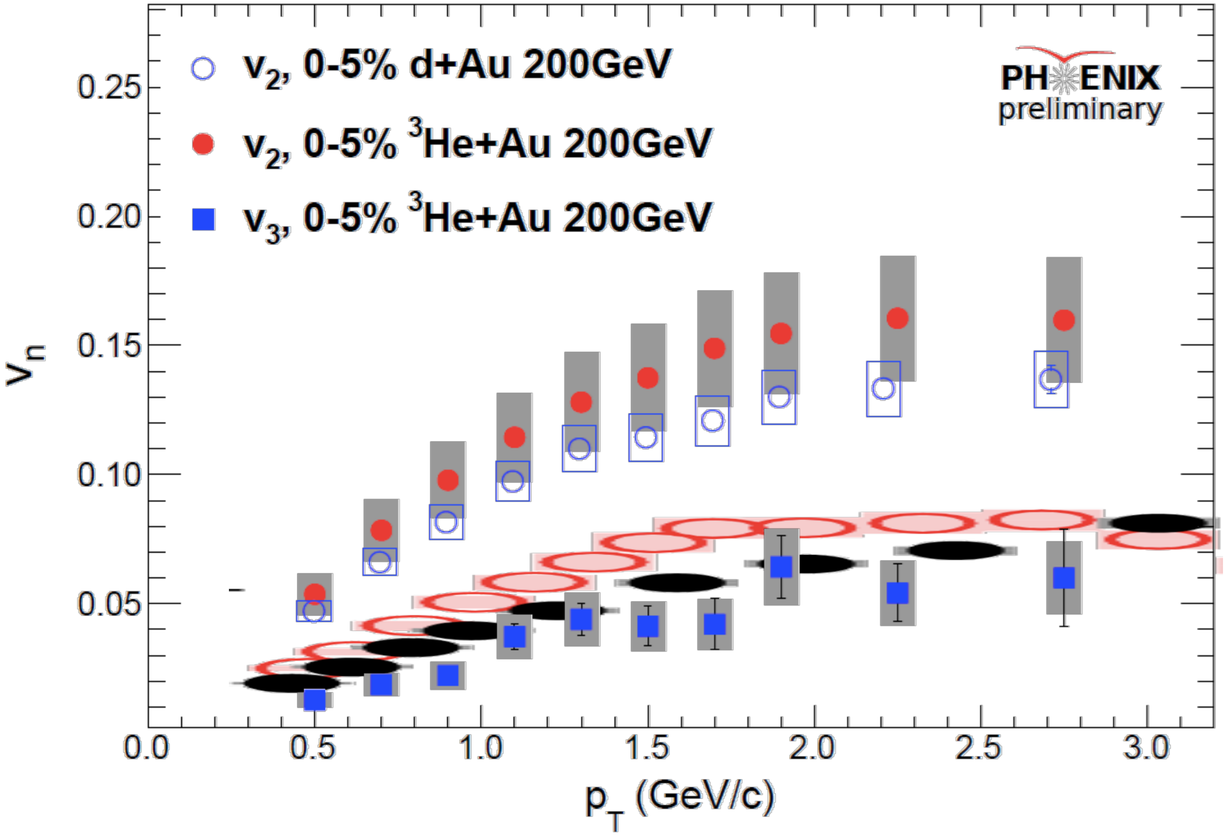
Amplitudes comparable to those seen in Pb+Pb



Boosting triangular flow



p+Pb/Au d+Au ^{3}He+Au



Clear measurements of harmonics in small systems

Magnitudes are similar in different systems

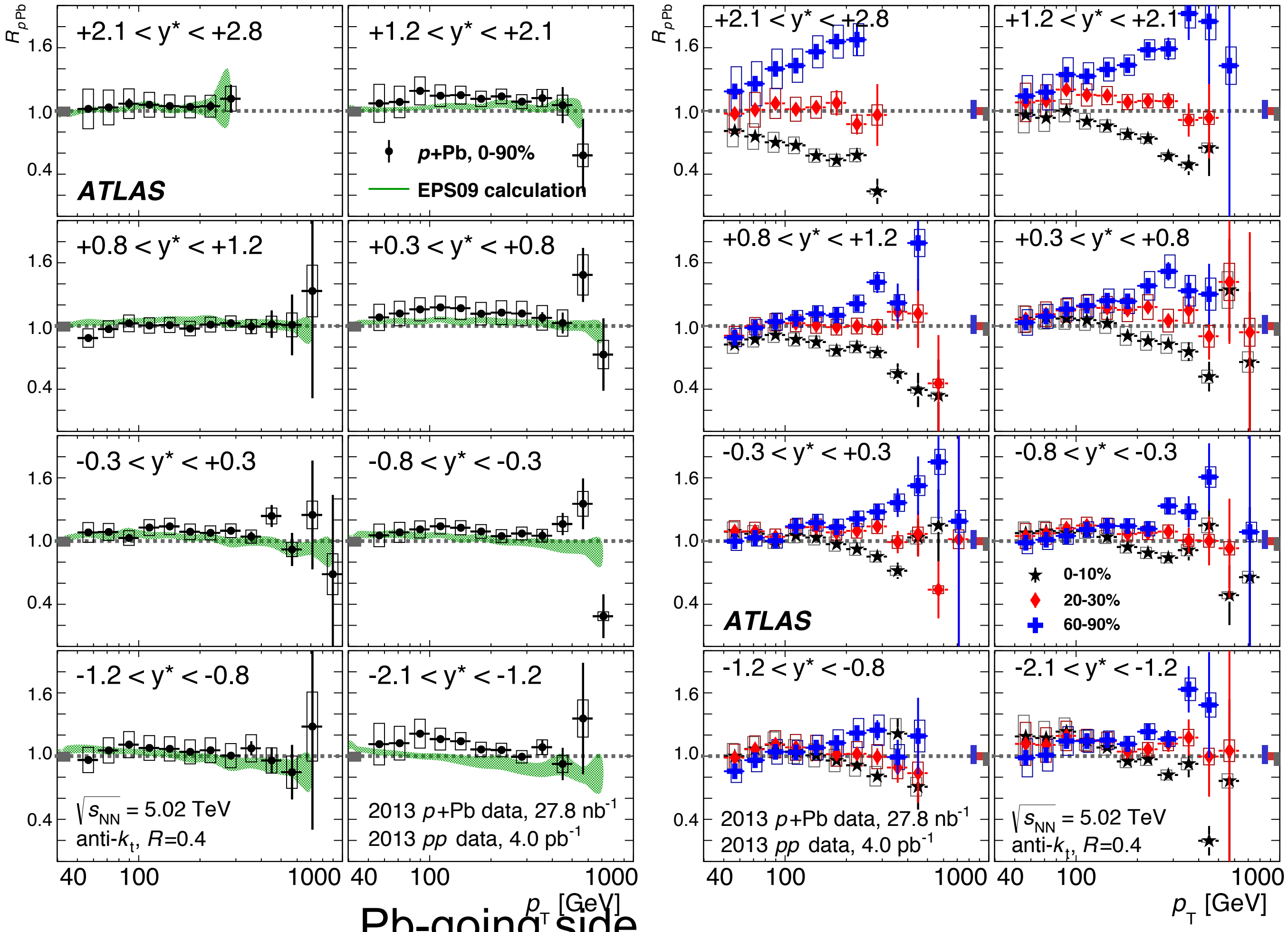
Jets in p+Pb

Overall jet production scales as expected compared to p+p

But when separated into centrality unexpected behavior observed

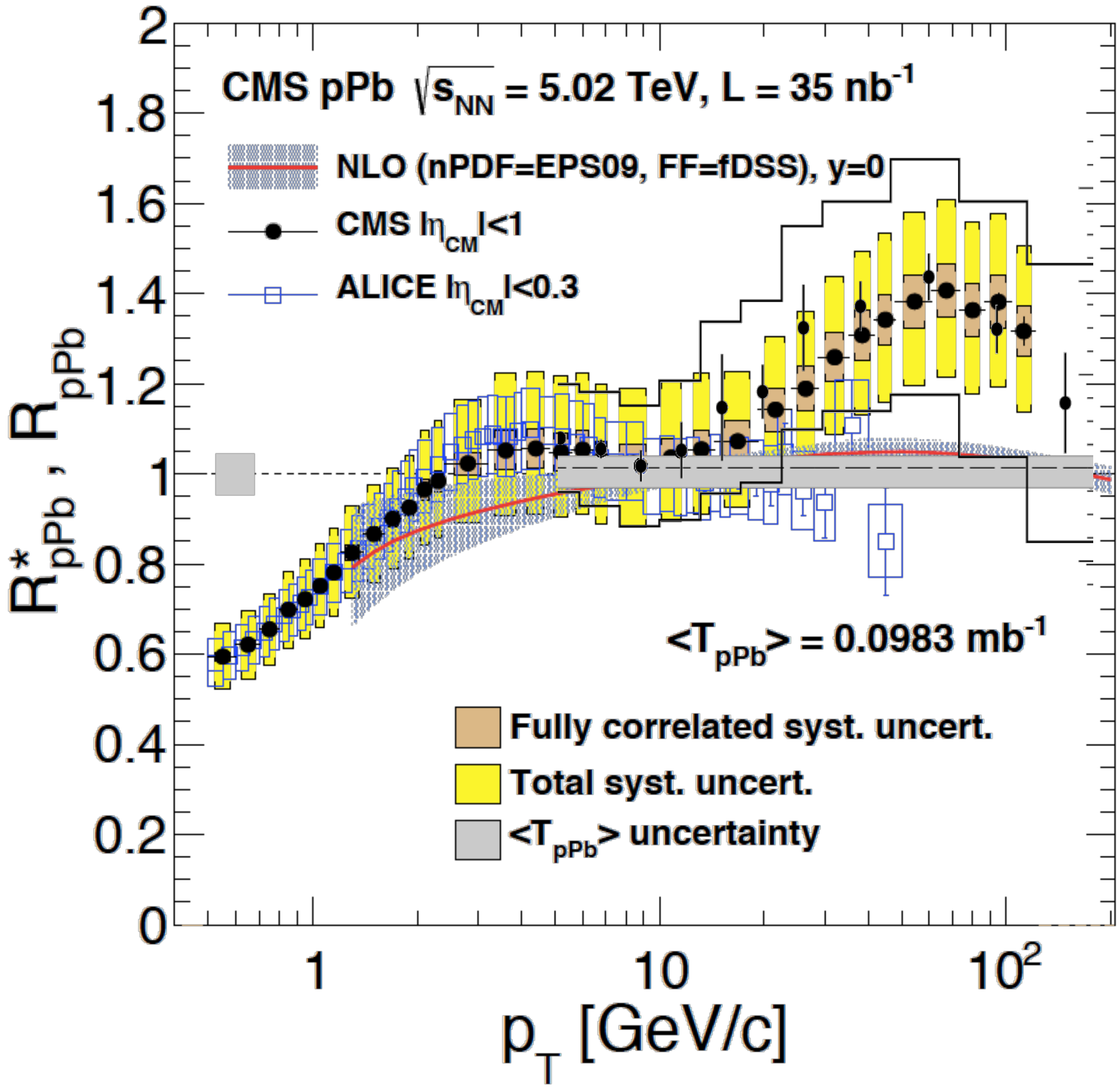
Insight into x-section fluctuations in the nucleon? Effect on centrality?

p-going side



Pb-going side

R_{pPb}

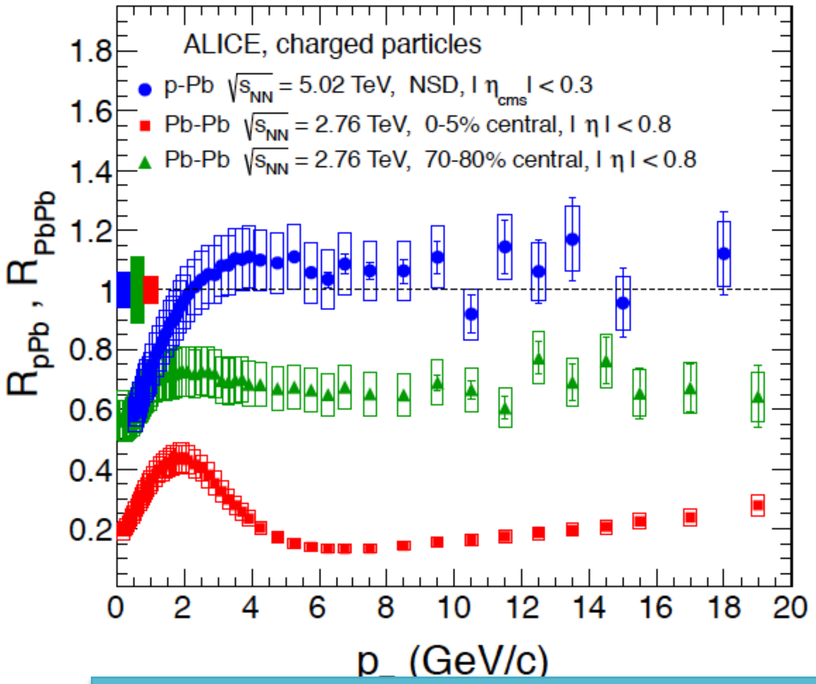


arXiv:1502.05387

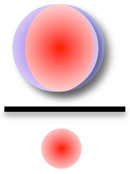
CMS observes anomalous enhancement in R_{pPb}

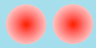
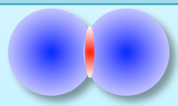
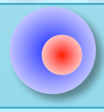
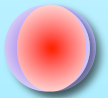
ATLAS measures similar effect

A puzzling plot.



$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{d^2 N_{A+A} / dydp_T}{d^2 N_{p+p} / dydp_T}$$



System	N_{coll}	R_{AA}		
p+p	1			baseline
p+Pb any	~10	1		0% effect
Pb+Pb peripheral	15	0.7		30% effect
Pb+Pb central	1600	0.2		100% effect

Summary

In heavy ion systems:
- jet suppression
- binary scaling demonstration
- quarkonia suppression
- open charm measurements
- flow factorization
- search of the critical point

In lighter systems
- clear evidence of collective behavior
- jet rates modification
- not clear what happens to the initial state
- many open issues with understanding geometry

High expectation to the upcoming run (end of this year)

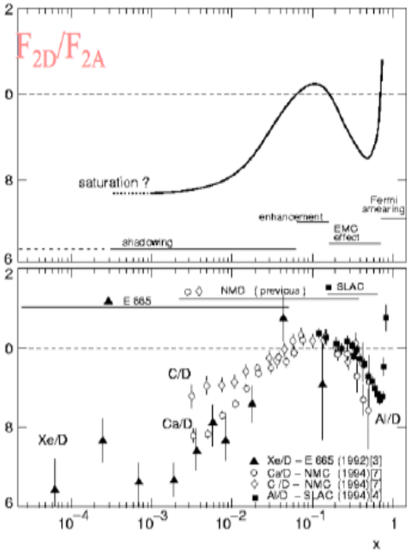
Parton kinematics

$$\frac{d\sigma_{pp}^{h}}{dy d^2 p_T} = K \sum_{abcd} \int dx_a dx_b f_a(x_a, Q^2) f_b(x_b, Q^2) \frac{d\sigma}{d\hat{t}}(ab \to cd) \frac{D_{h/c}^{0}}{\pi z_c}$$

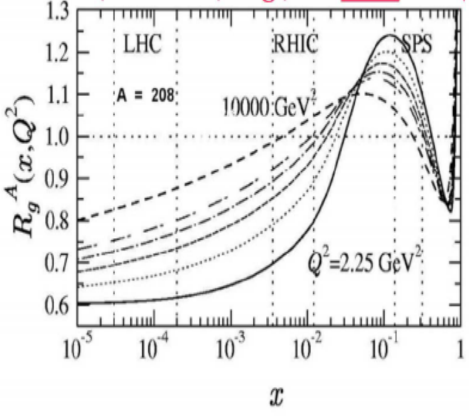
Parton distributions in nucleon and nucleus

Modification of parton momentum distributions of nucleons embedded in nuclei

- shadowing – depletion of low-momentum partons (gluons)
- coherence & dynamical shadowing
- gluon saturation at small x – e.g. color glass condensate



Eskola, Kolhinen, Vogt, NP A696, 729 (2001)



Fragmentation function KKP

$$\frac{d\sigma_{pp}^{h}}{dy d^2 p_T} = K \sum_{abcd} \int dx_a dx_b f_a(x_a, Q^2) f_b(x_b, Q^2) \frac{d\sigma}{d\hat{t}}(ab \to cd) \frac{D_{h/c}^{0}}{\pi z_c}$$

Kniehl, B. A.; Kramer, G. & Potter, B.

Testing the universality of fragmentation functions

Nucl. Phys., **2001**, B597, 337-369

$$D(x, \mu^2) = N x^{\alpha} (1-x)^{\beta} \left(1 + \frac{\gamma}{x}\right)$$

LO FFs for $(\pi^+ + \pi^-)$:

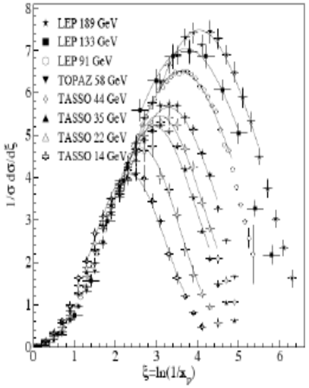
$$D_u^{\pi^\pm}(x, \mu^2) = D_d^{\pi^\pm}(x, \mu^2):$$

$$N = 0.54610 - 0.22946\bar{s} - 0.22594\bar{s}^2 + 0.21119\bar{s}^3$$

$$\alpha = -1.46616 - 0.45404\bar{s} - 0.12684\bar{s}^2 + 0.27646\bar{s}^3$$

$$\beta = 1.01864 + 0.95367\bar{s} - 1.09835\bar{s}^2 + 0.74657\bar{s}^3$$

$$\gamma = -0.01877\bar{s} + 0.02949\bar{s}^2$$



Simple Gaussian fits the ξ distributions.

Biebel, O.; Nason, P. & Webber, B. R.

Jet fragmentation in e+ e- annihilation

Kinematics: extending the reach why?

- Why is it interesting to extend the reach from $Q^2 \approx (10\ GeV)^2$ to $Q^2 \approx (100\ GeV)^2$?
  - better separation of scales

    $$1/Q \ll \Delta r_{medium} \qquad Q \gg T, Q_s$$

  - better separation of hard probes form soft background
  - access to Q^2- evolution in medium

- Why is it interesting to extend the reach from $\ln x \approx -3$ to $\ln x \approx -5$?
  - higher initial density implies longer lifetime, bigger spatial extension, stronger medium effects
  - access to small-x evolution (how) are jets affected by it?