From Heavy-Ion Collisions to Quark-Gluon matter

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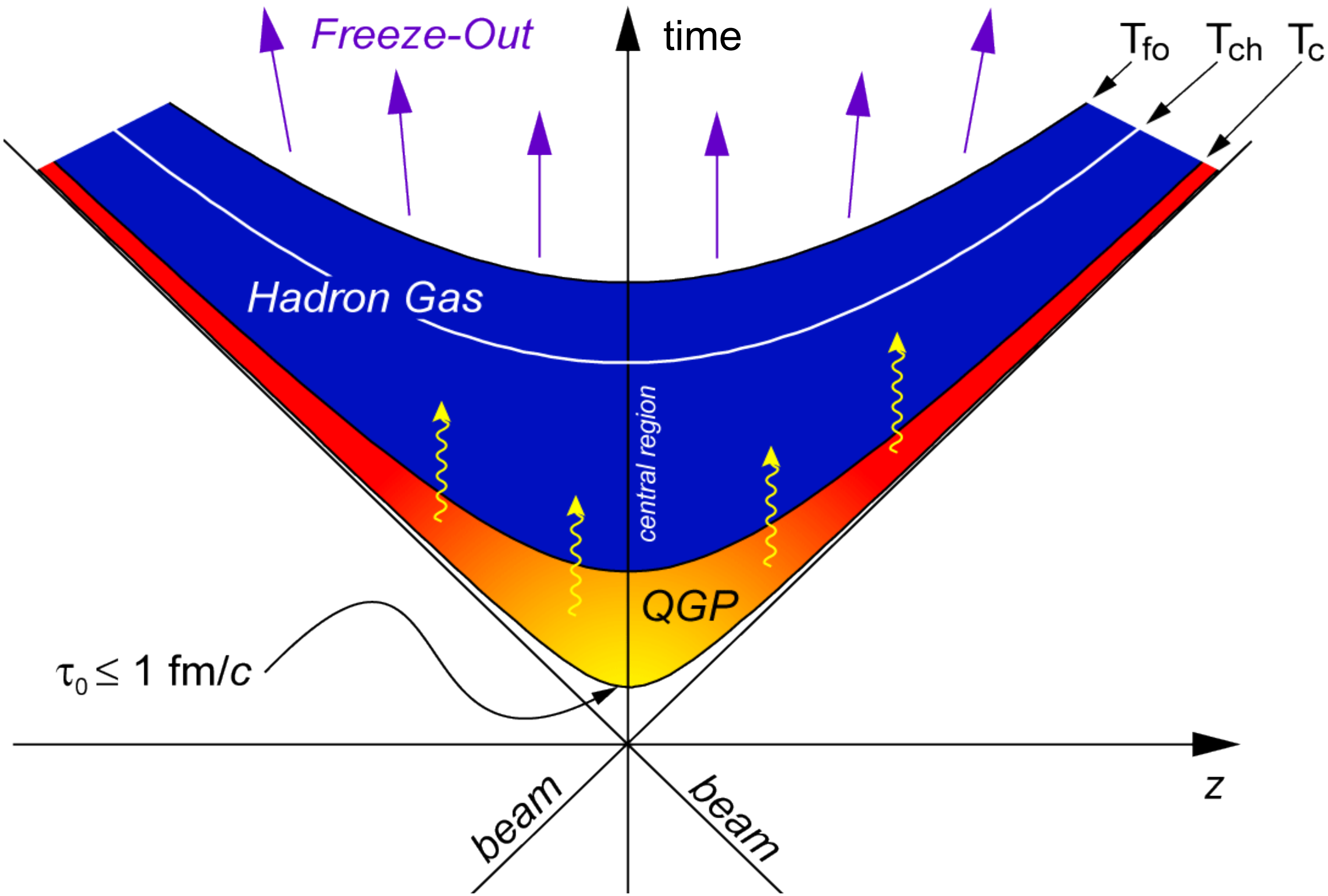
(LBNL)

- Part I: Introduction and background
- Part II: Results mainly related to bulk properties
- Part III: Results mainly related to hard probes

CERN summer student programme 2016

Study QCD bulk matter at high temperature

(Recap part I)



Particle detection ($t \approx 10^{15}$fm/c)

Kinetic freeze-out (t=10fm/c)

Chemical freeze-out

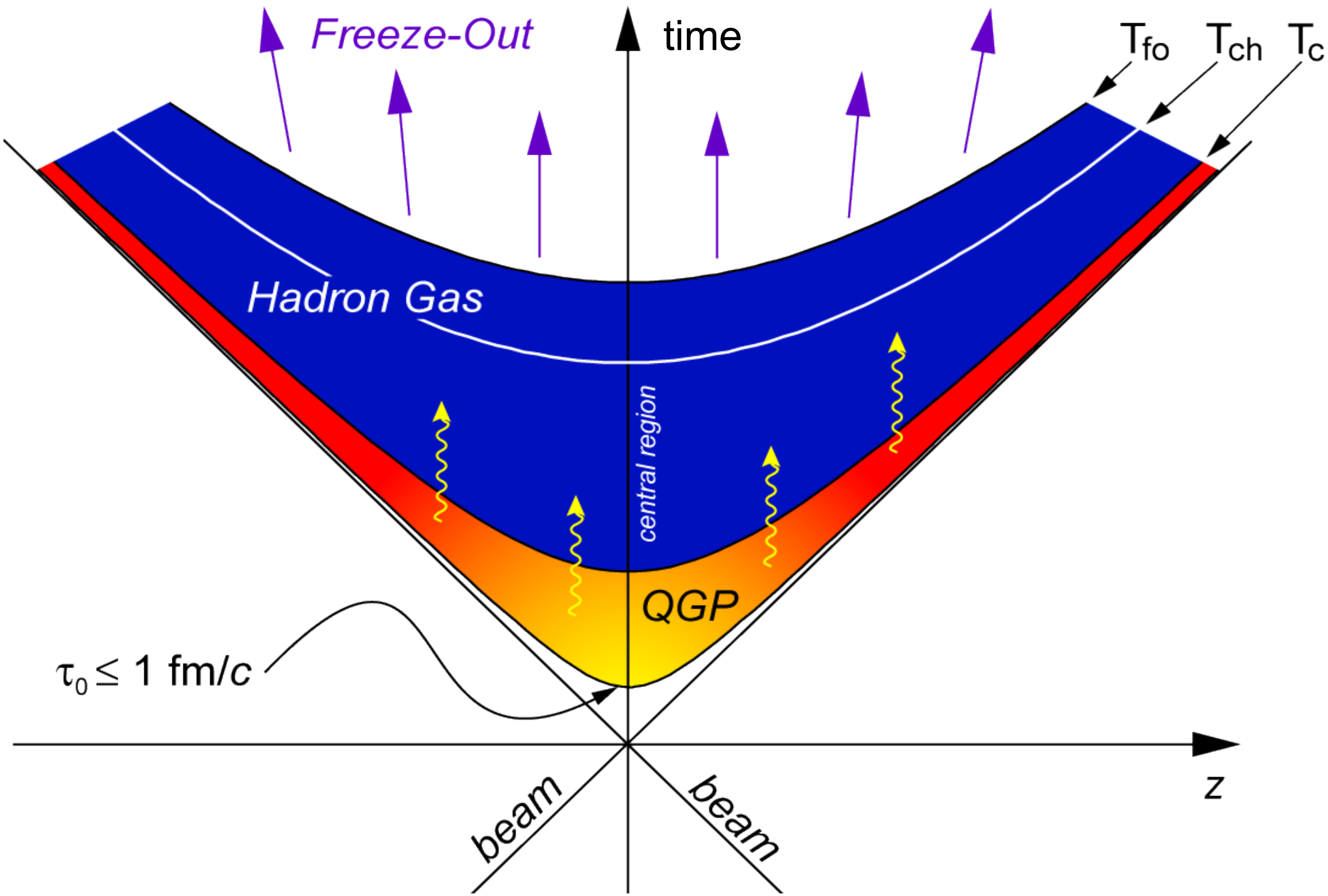
Hydrodynamic evolution (t~0.5fm/c)

Pre-equilibrium

Collision (t=0fm/c)

Different stages of the collision process

What quantities to measure?



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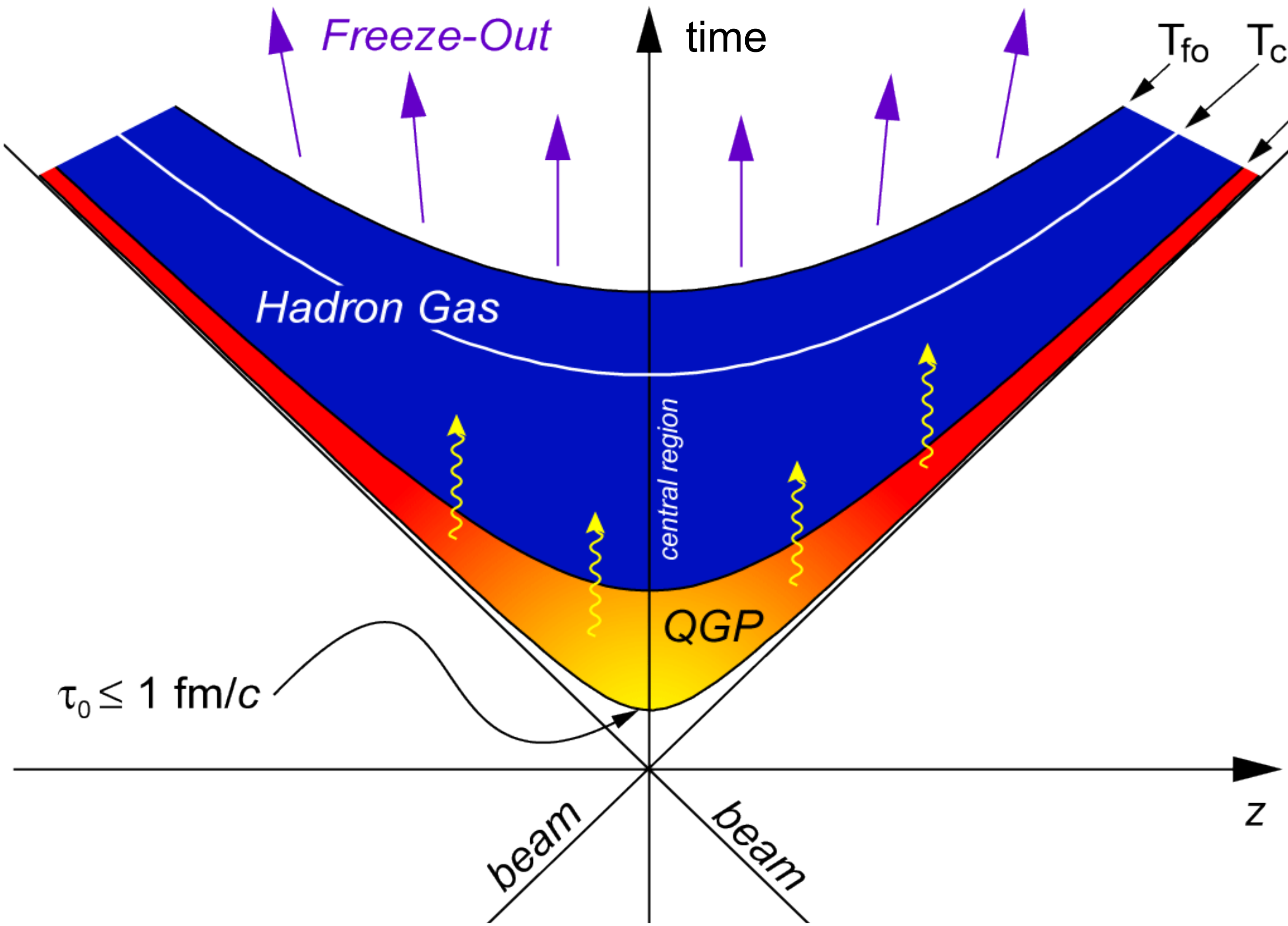


Observables

Multiplicity
HBT
Particle yields
Particle spectra

Transverse flow
Thermal photons

Hard probes
(jets, heavy flavor, EW bosons)

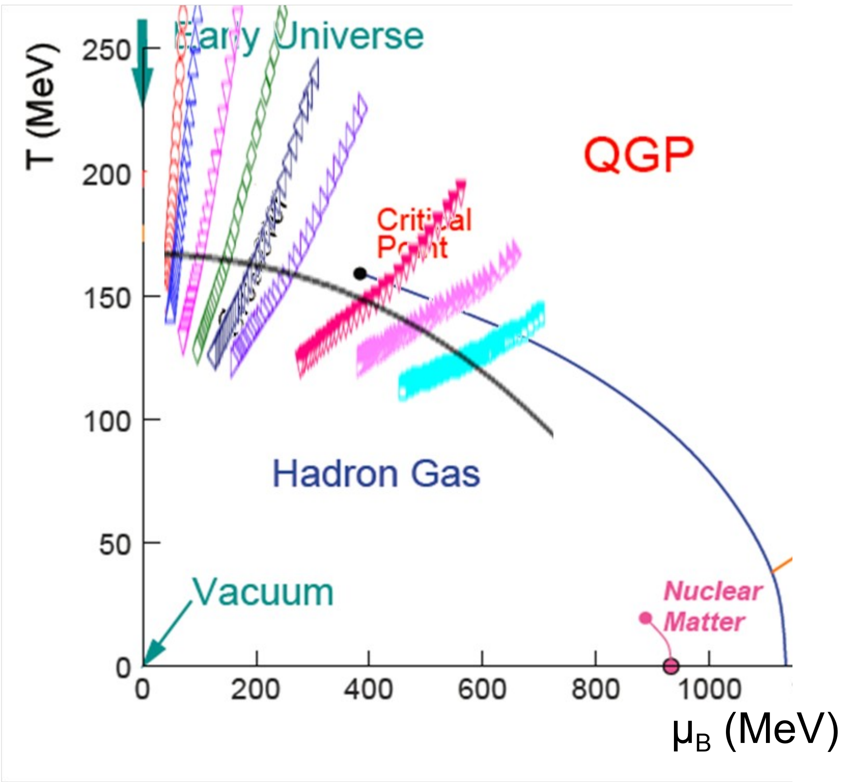
Experimental approach is to study various observables with different sensitivity to the different stages of the collision

External control parameters

External parameters: Collision energy

Collision energy

Initial conditions
and freeze-out paths



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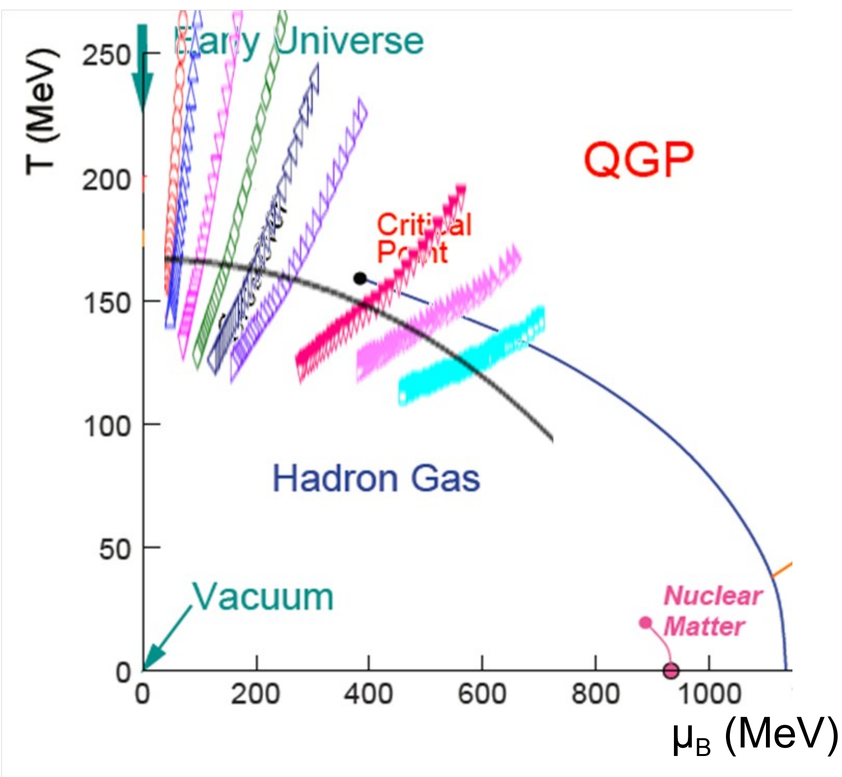
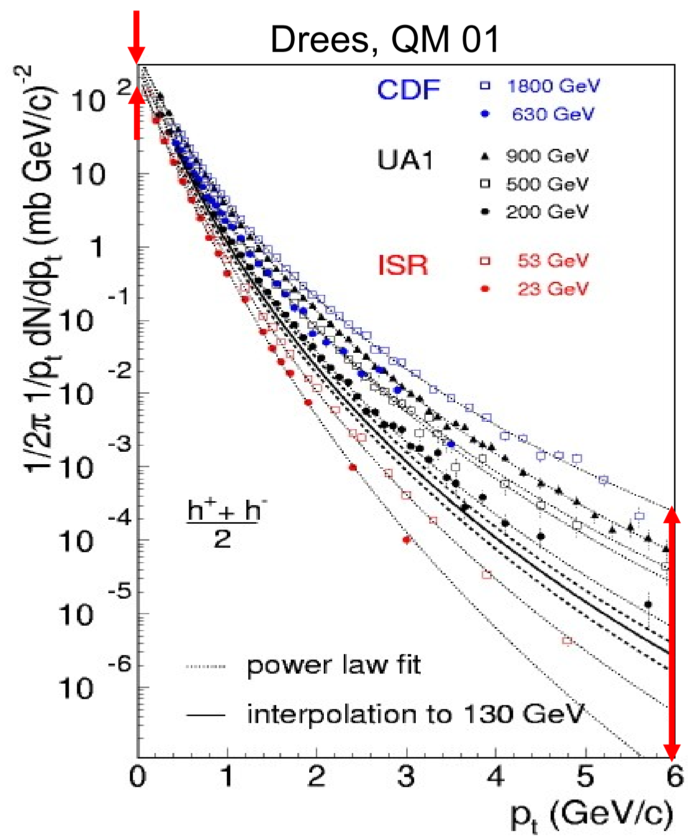
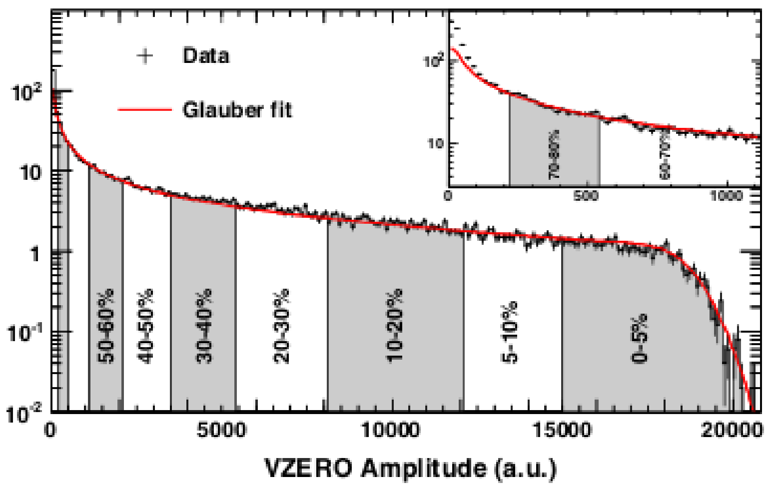


Ratio of “soft” to “hard”
processes



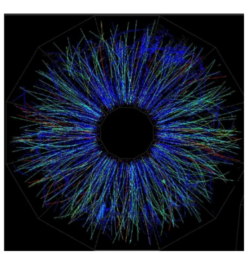
External parameters: Collision centrality

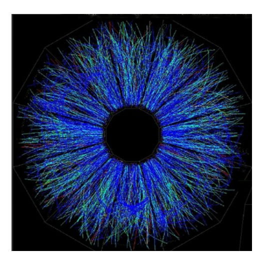
Nuclear cross-section classes
(by slicing in bins of multiplicity)

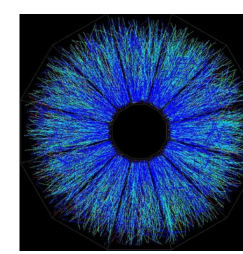


Cross-section percentile (in %)

Collision energy







Collision centrality

arXiv:1301.4361

External parameters: Collision centrality

Collision energy

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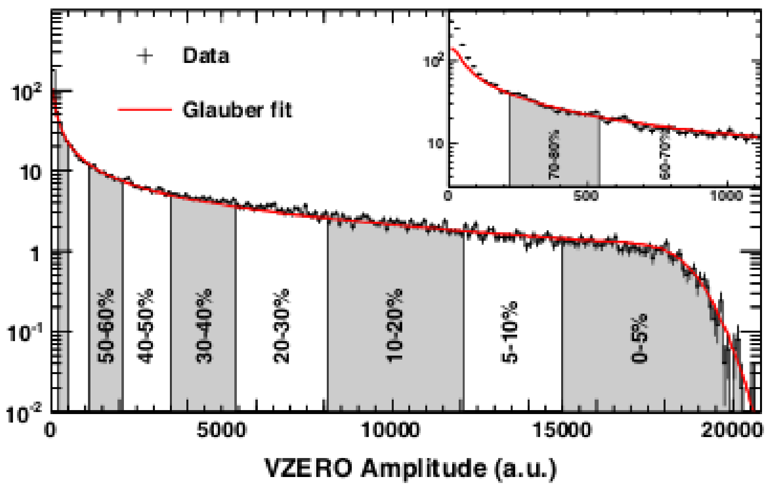
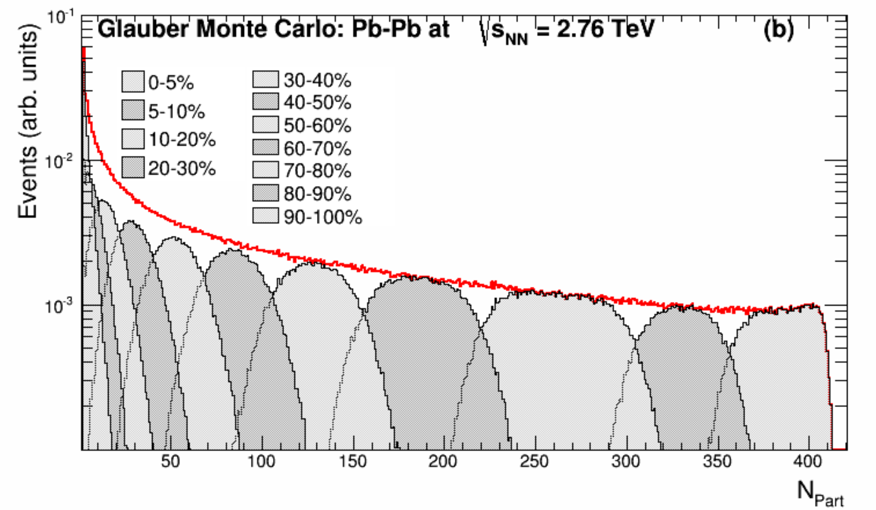
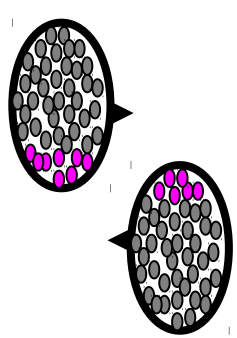


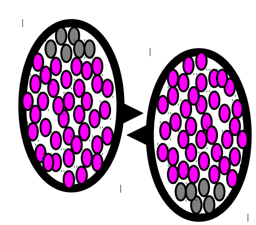
Glauber model



Via model

Cross-section percentile (in %) ⟷ Number of participants (or collisions)

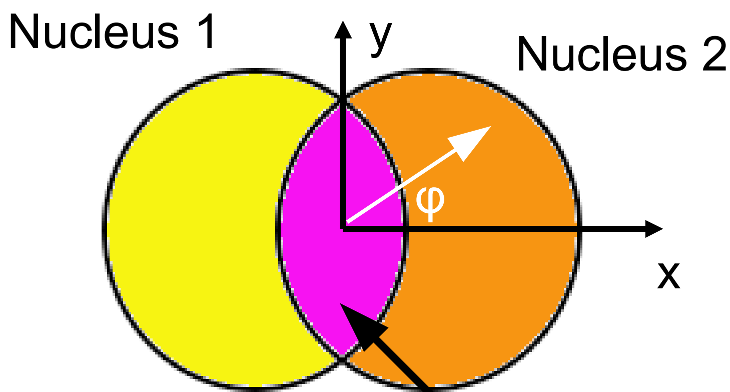




Collision centrality

arXiv:1301.4361

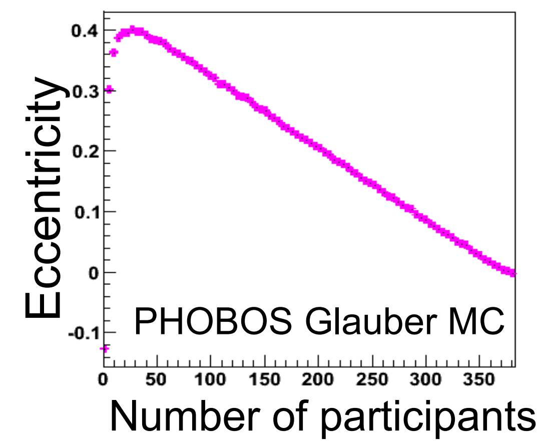
External parameters: Transverse geometry



Overlap (participant) region is asymmetric in azimuthal angle

$$\epsilon_{\mathrm{std}} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}$$

Initial state eccentricity



Center of mass energy

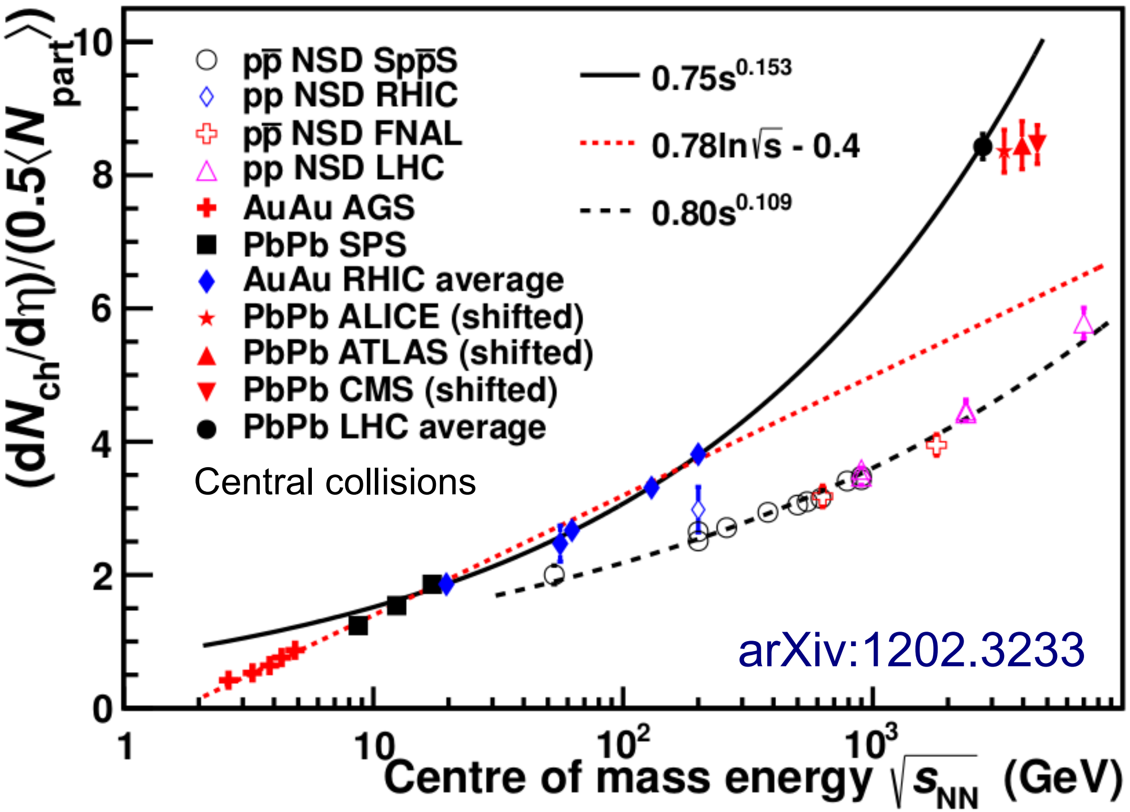
Collision centrality

arXiv:0711.3724

Multiplicity and transverse energy

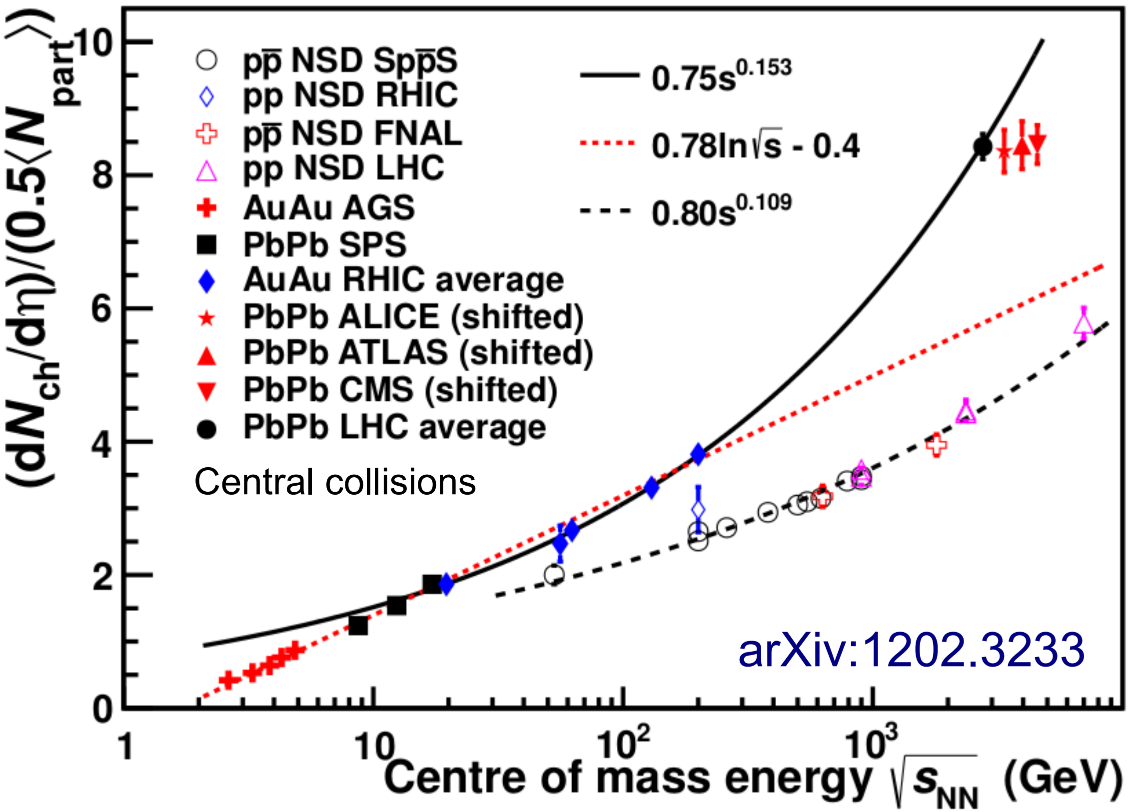
(Estimate of energy density and related to entropy)

Energy dependence of dN/dη and dE_T/dη

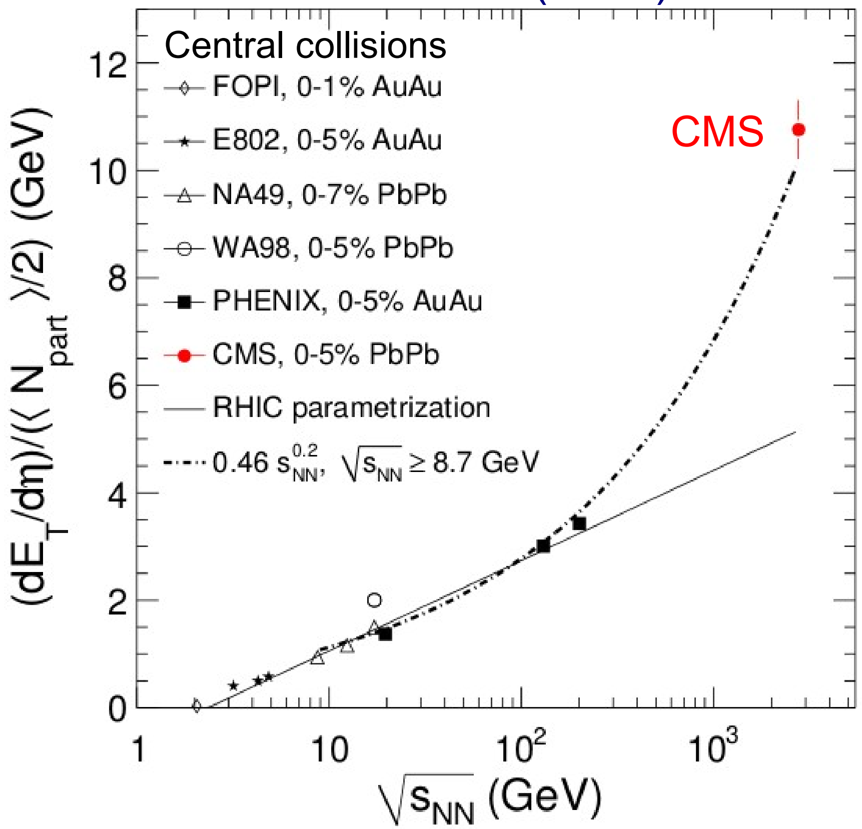


Up dN/dη ≈ 1600 charged particles in central PbPb at LHC

Energy dependence of dN/dη and $dE_T/d\eta$



PRL 109 (2012) 152303



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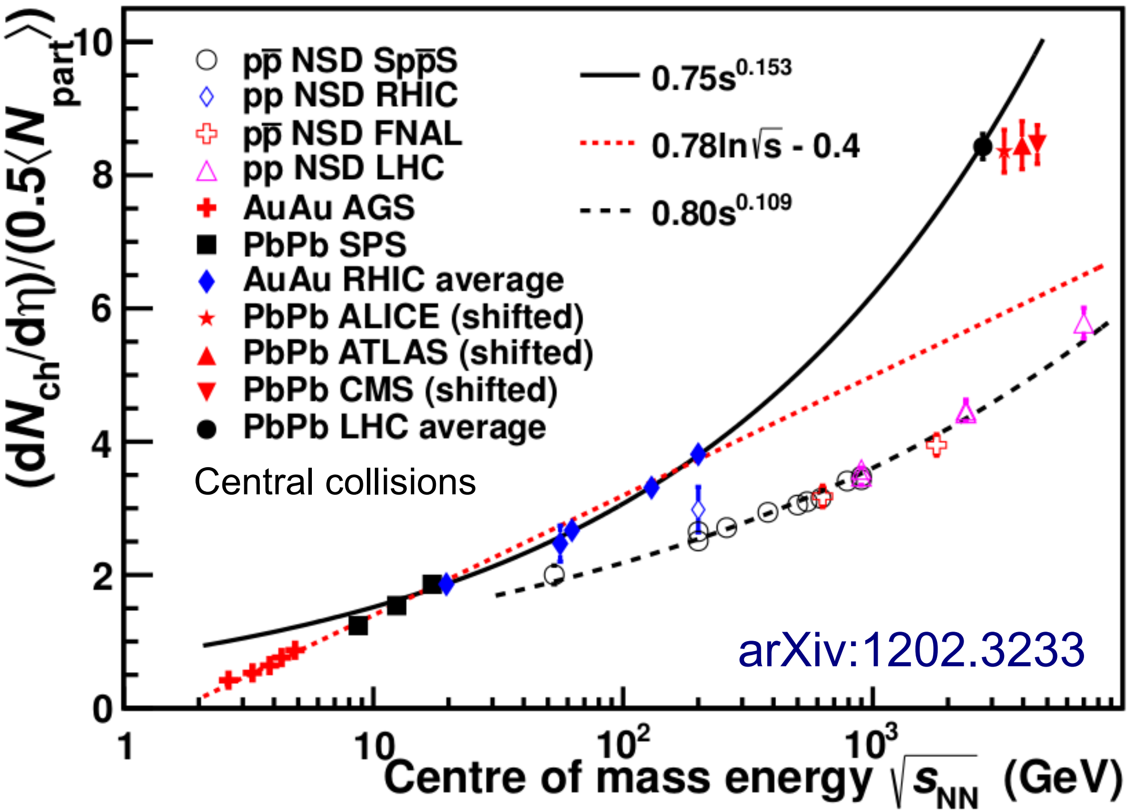
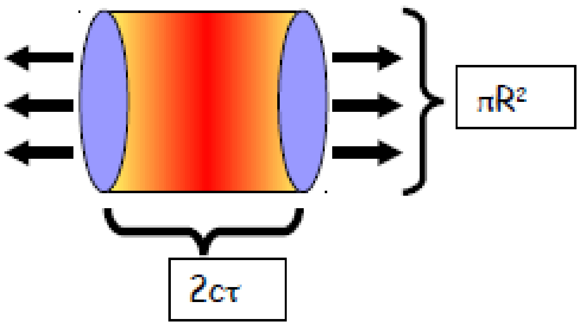
Energy dependence of dN/dη and dE_T/dη



Bjorken estimate:



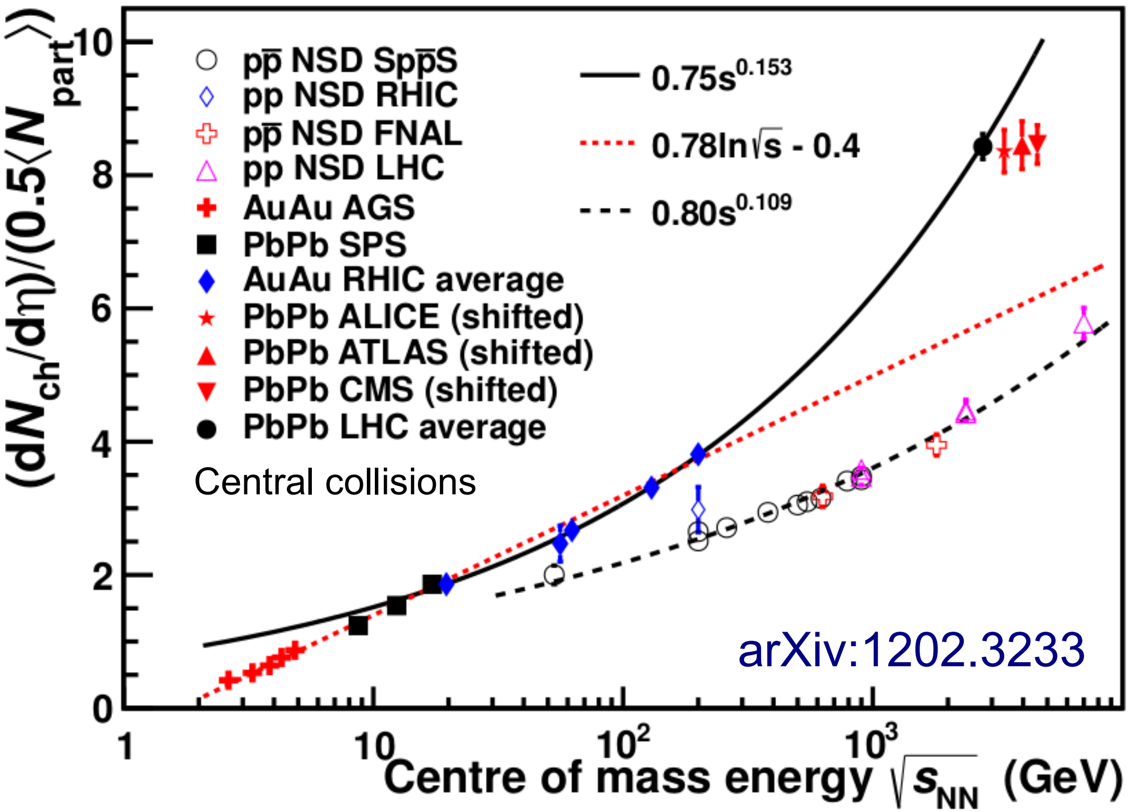
$$\langle \varepsilon \rangle (\tau) = \frac{1}{\tau\, \pi R^2} \frac{\mathrm{d}E_\mathrm{T}}{\mathrm{d}y}$$

Bjorken, PRD 27 (1983) 140

Up dN/dη ≈ 1600 charged particles in central PbPb at LHC

Use these measurements to get an estimate of the energy density

Estimate of energy density from dN/dη



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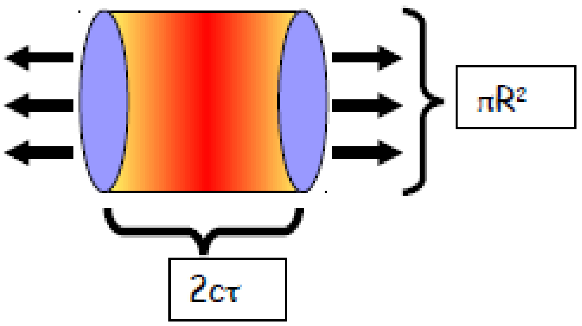


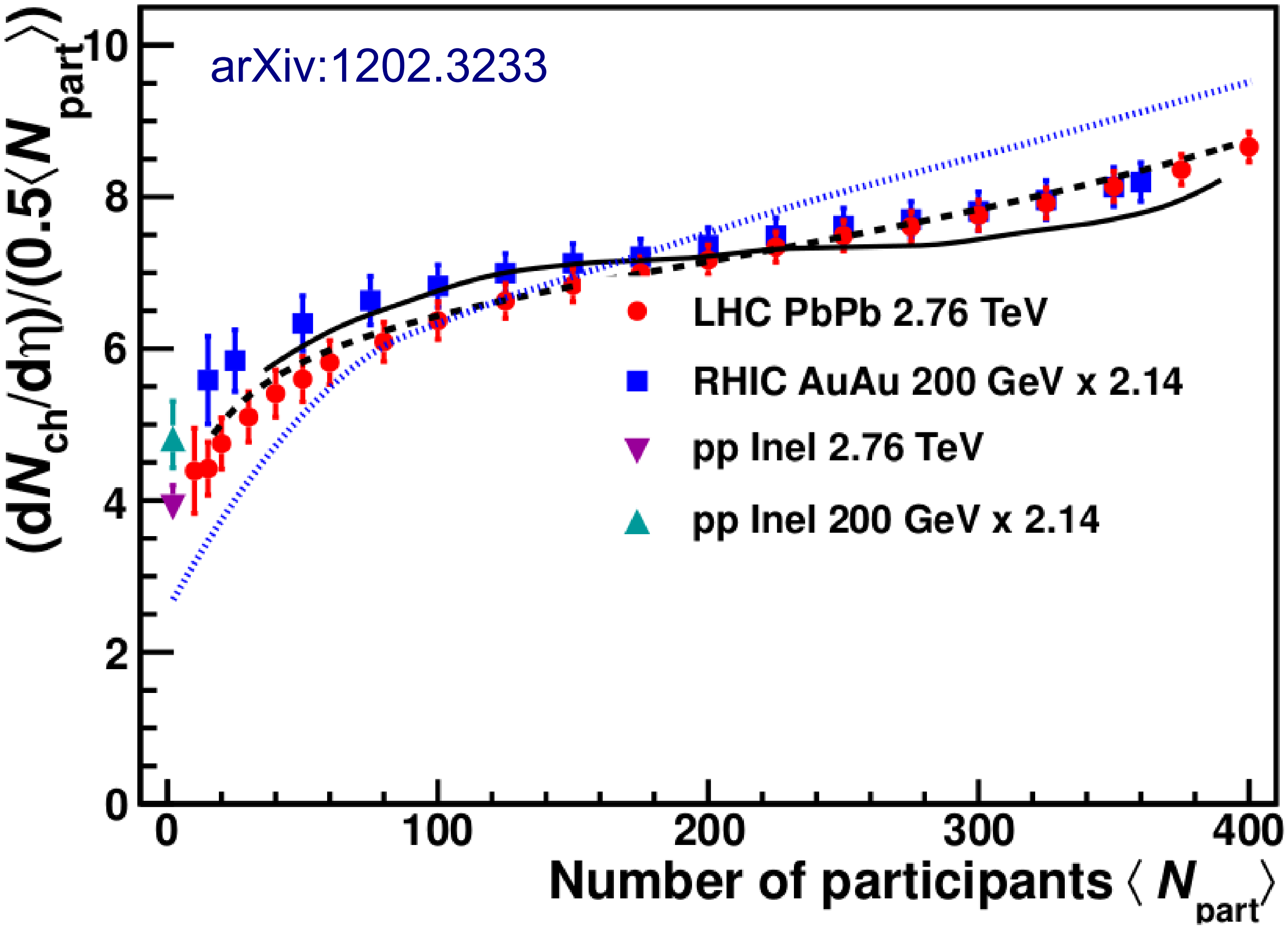
$$\langle \varepsilon \rangle (\tau) = \frac{1}{\tau \pi R^2} \frac{dE_T}{dy}$$

Bjorken, PRD 27 (1983) 140

- System undergoes rapid evolution
  - Using 1 fm/c as an upper limit for the time needed to “thermalization”
  - Leads to densities above the transition region (also for AGS)
    - However, only necessary not sufficient condition for QPG

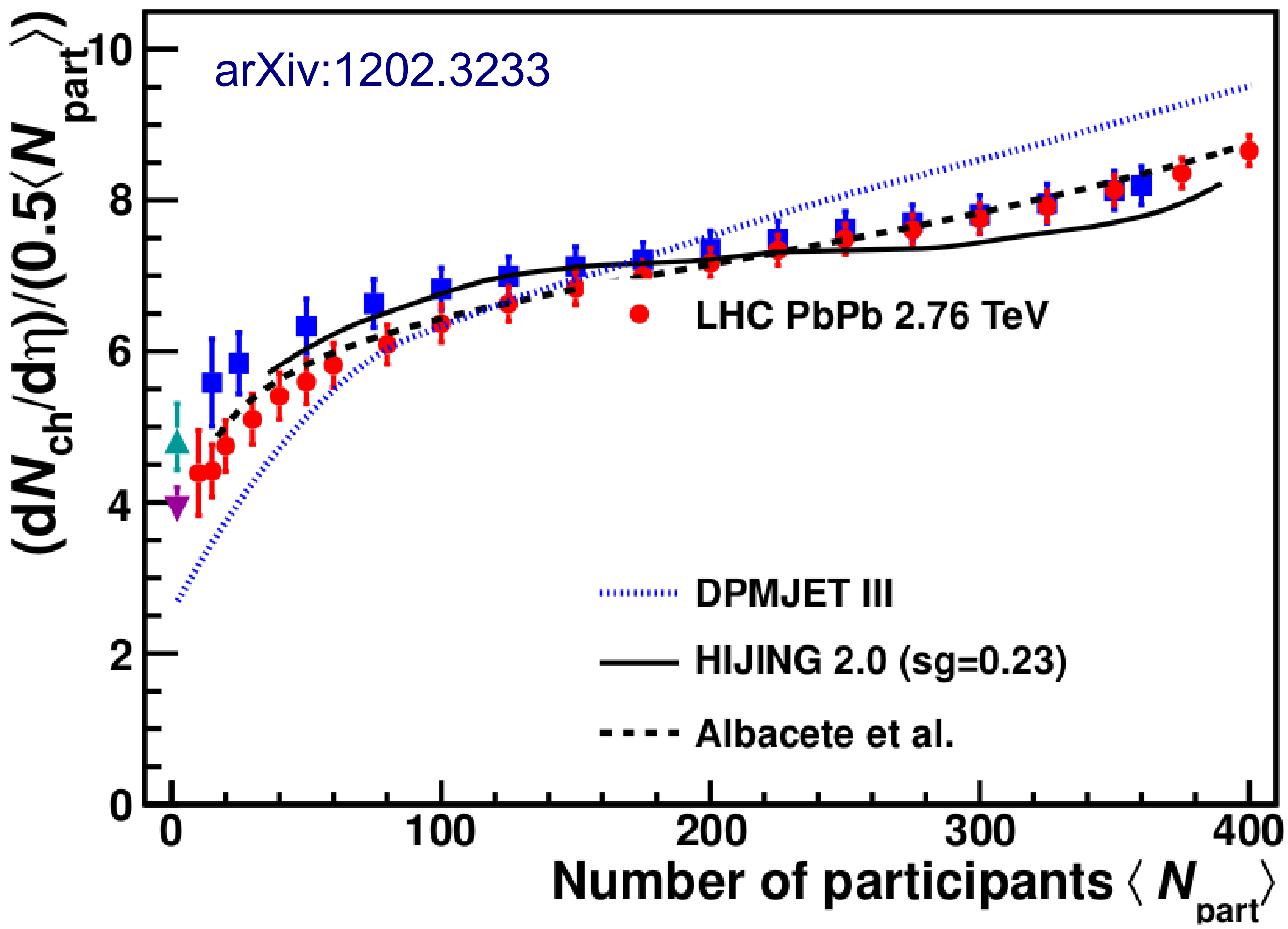
$$\varepsilon_{BJ} = 1.5\,\mathrm{GeV/fm^3} \text{ for } \sqrt{s_{NN}} = 5\,\mathrm{GeV}$$
$$\varepsilon_{BJ} = 2.9\,\mathrm{GeV/fm^3} \text{ for } \sqrt{s_{NN}} = 17\,\mathrm{GeV}$$
$$\varepsilon_{BJ} = 5.4\,\mathrm{GeV/fm^3} \text{ for } \sqrt{s_{NN}} = 200\,\mathrm{GeV}$$
$$\varepsilon_{BJ} = 15\,\mathrm{GeV/fm^3} \text{ for } \sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$$

Centrality dependence of dN/dη



Factorization in energy and centrality:
Shape is strikingly similar to RHIC

Centrality dependence of dN/dη and models



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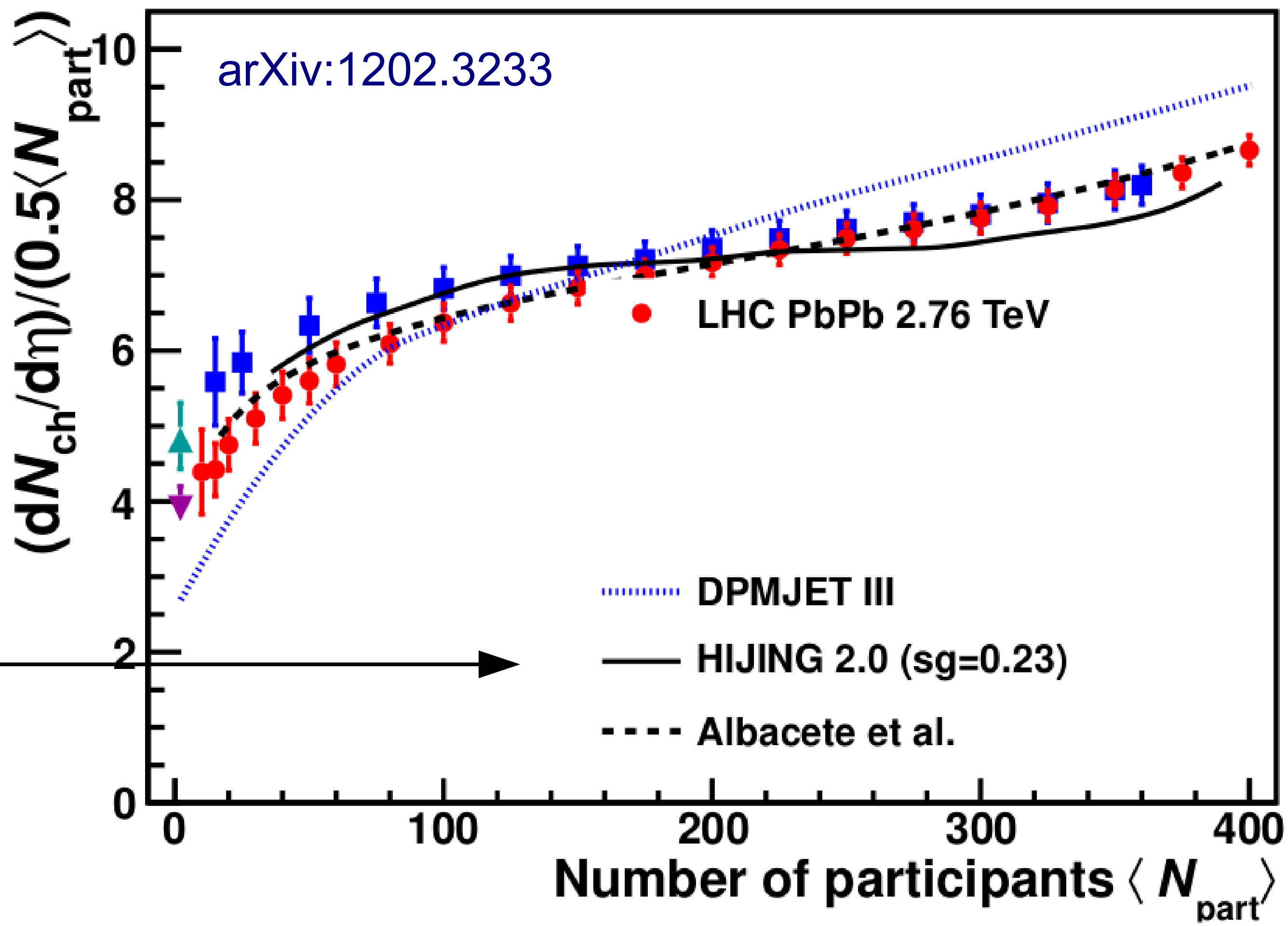
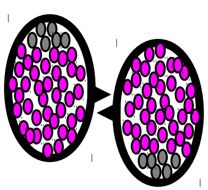


Glauber IC

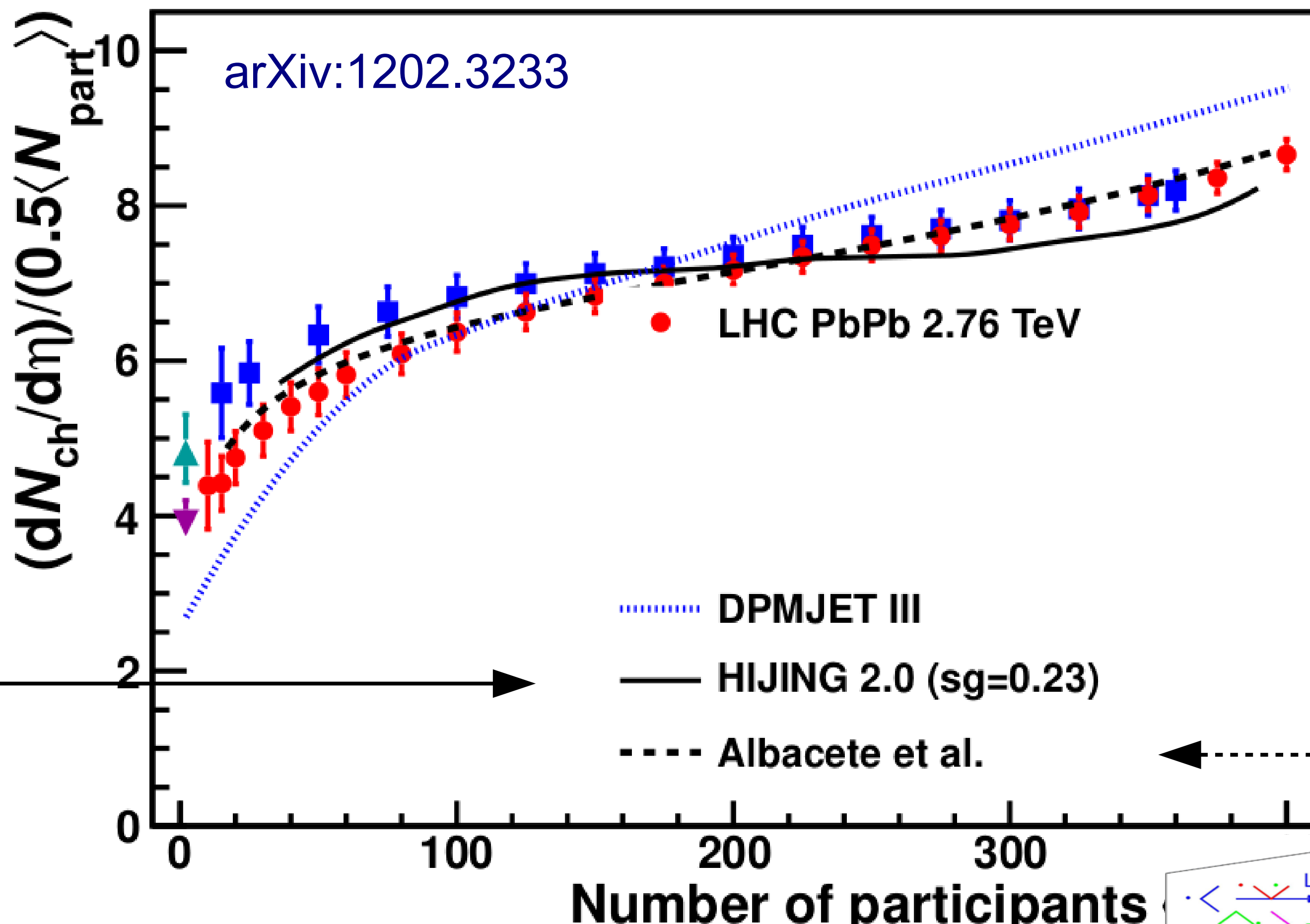


Glauber IC
Two-component model

$$\frac{dN}{d\eta} = \frac{dN}{d\eta^{pp}}\left((1-x)N_{coll} + x\,N_{part}/2\right)$$

PRC 70 021902 (2004)

Centrality dependence of dN/dη and models



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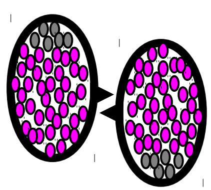
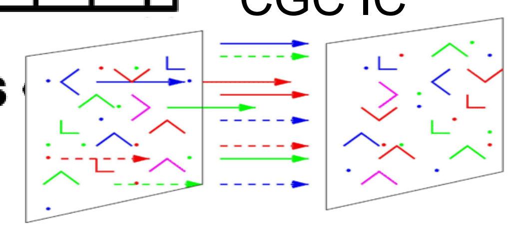


CGC IC



Glauber IC
Two-component model

$$\frac{dN}{d\eta} = \frac{dN}{d\eta}^{pp}((1-x)N_{coll} + x N_{part}/2)$$

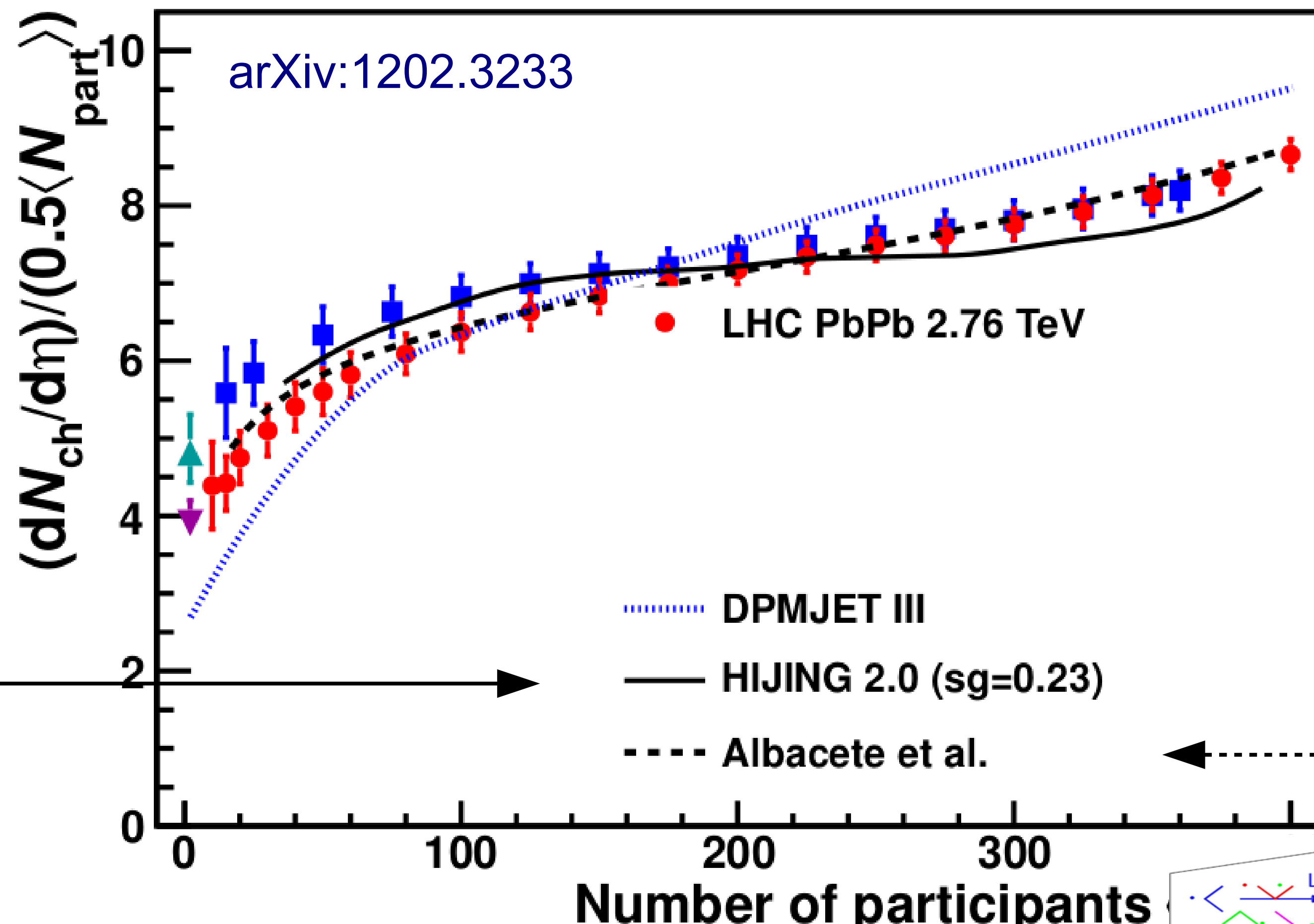
PRC 70 021902 (2004)

CGC IC
Color glass condensate

$$\frac{dN}{d\eta} \propto N_{part}^{\alpha} \sqrt{s}^{\lambda}$$

PRL 94 022002 (2005)

Centrality dependence of dN/dη and models



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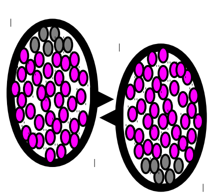

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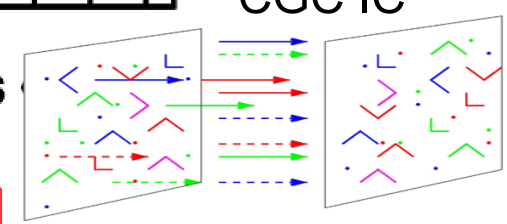

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Two-component model

$$\frac{dN}{d\eta} = \frac{dN}{d\eta^{pp}}((1-x)N_{coll} + x\,N_{part}/2)$$

PRC 70 021902 (2004)

Two-component models need to incorporate strong nuclear modification. Saturation models more naturally incorporate factorization!

CGC IC
Color glass condensate

$$\frac{dN}{d\eta} \propto N_{part}^{\alpha}\sqrt{s}^{\lambda}$$

PRL 94 022002 (2005)

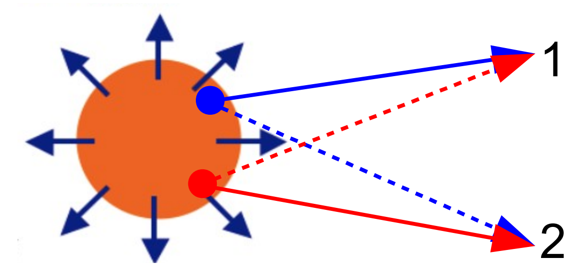
Hanbury Brown Twiss

(Measurement of size of homogeneity region)

Intensity interferometry (HBT)

- Two particles whose production or propagation are correlated show wave properties in their relative momentum difference
  - First used with photons by Hanbury Brown and Twiss to measure size of star Sirius

    HBT, Nature 178 (1956) 1046
- Bose-Einstein Correlations: Enhancement of correlation for identical bosons
  - From uncertainty principle
    - $\Delta q \, \Delta x \sim 1$
    - Need $\Delta q \sim 200$ MeV to be sensitive to fm scale
- Fit to correlation function with assumed shape of source (eg. Gauss, Exponential, etc)

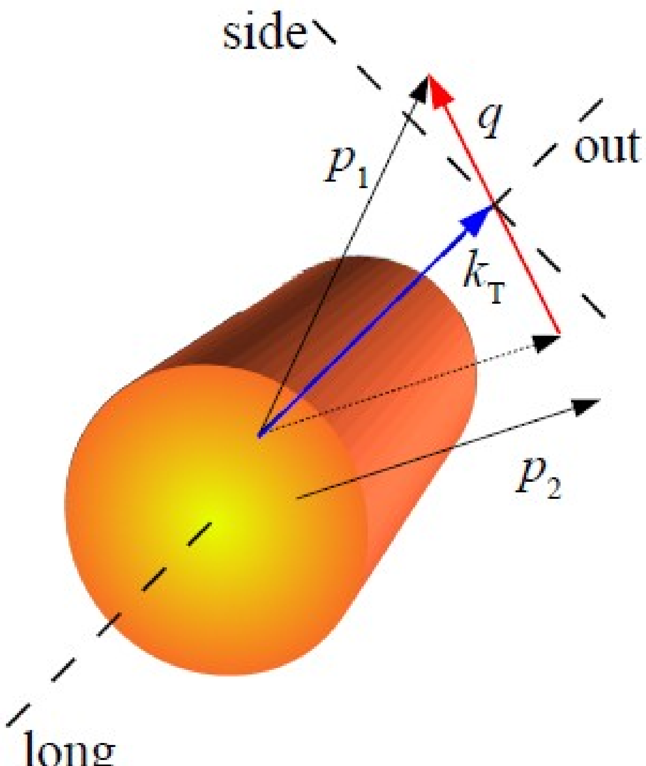


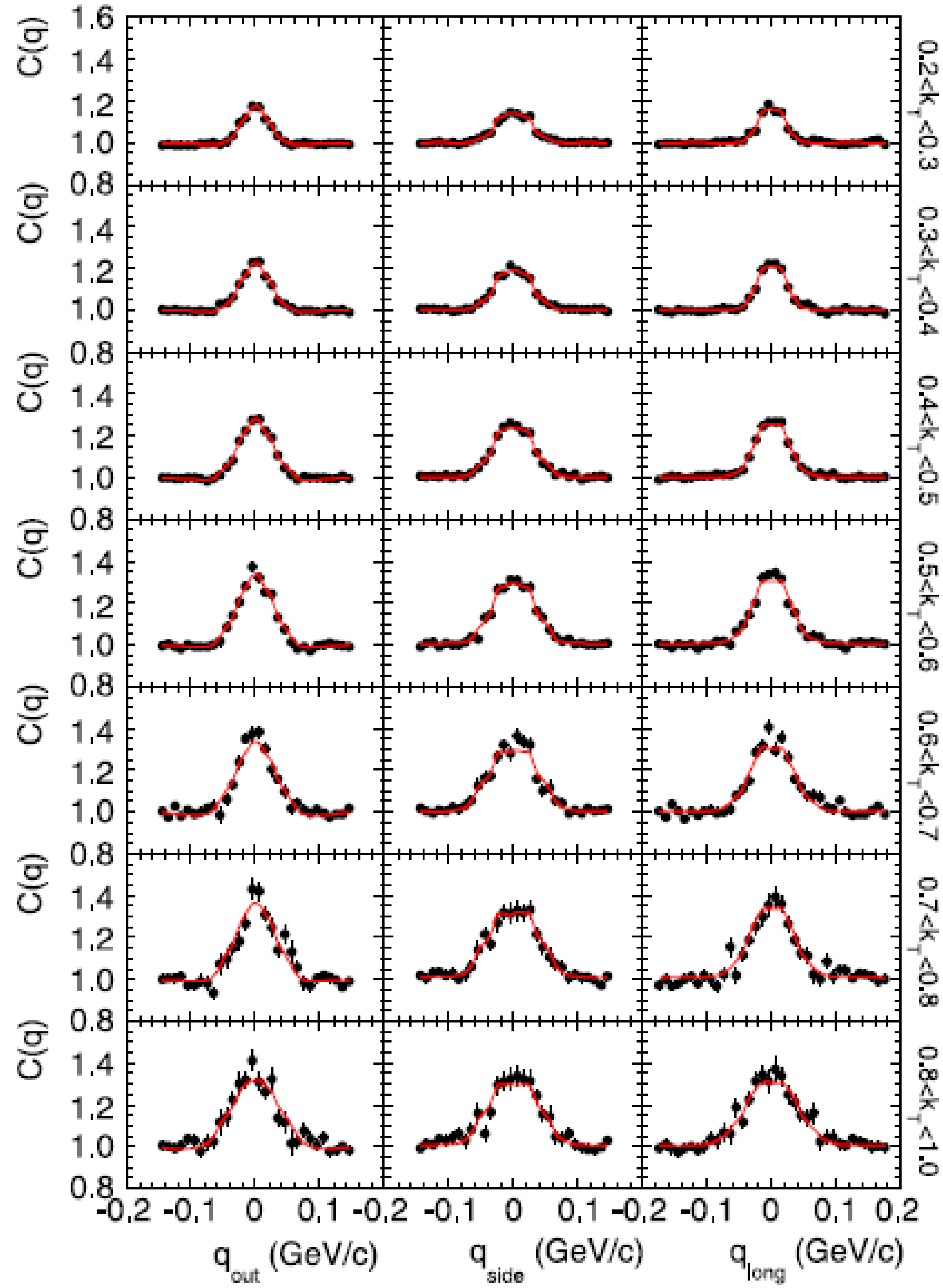
$$C_f(\mathbf{q}) = \int S(r,\mathbf{q})|\Psi(\mathbf{q},r)|^2 d^4r$$

$q = p_1 - p_2 \quad r = r_1 - r_2$

Intensity interferometry (HBT)

- In LCMS ($p_{L,1}+p_{L,2}=0$), can decompose correlation function in three directions
  - Longitudinal direction
  - Outward (along k_T direction)
  - Sideward (orthogonal) direction

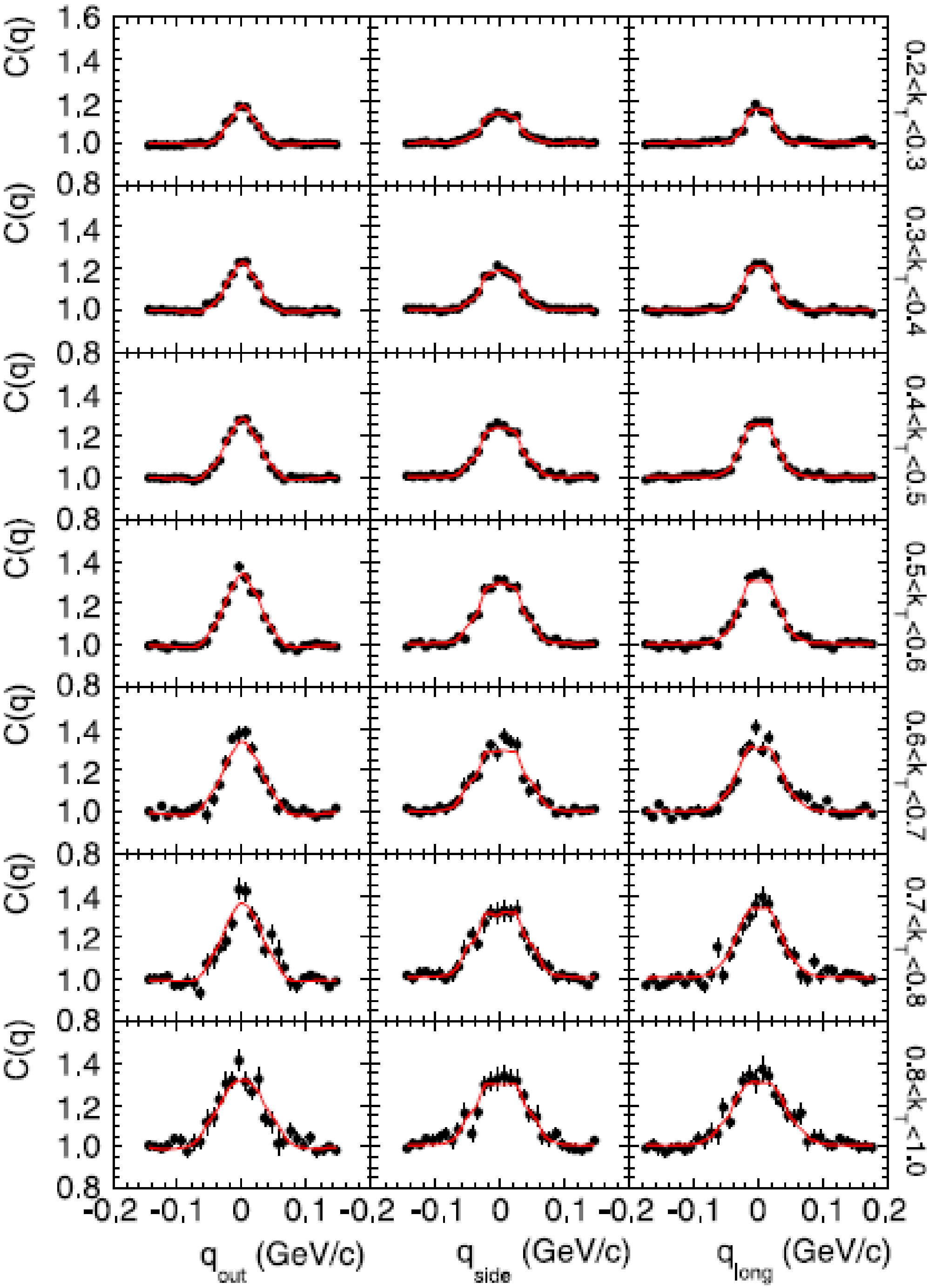




Intensity interferometry (HBT)

- In LCMS ($p_{L,1}+p_{L,2}=0$), can decompose correlation function in three directions
  - Longitudinal direction
  - Outward (along k_T direction)
  - Sideward (orthogonal) direction
- Three components of C(q) for pairs of identical pions in 8 intervals of the pair transverse momentum $k_{\mathrm{T}} = 0.5\,(\vec{p}_1 + \vec{p}_2)_T$
- Assuming Gaussian

$$C_2(q) \propto 1 + \exp\left(-R^2_{\mathrm{out}}q^2_{\mathrm{out}} - R^2_{\mathrm{side}}q^2_{\mathrm{side}} - R^2_{\mathrm{long}}q^2_{\mathrm{long}}\right)$$



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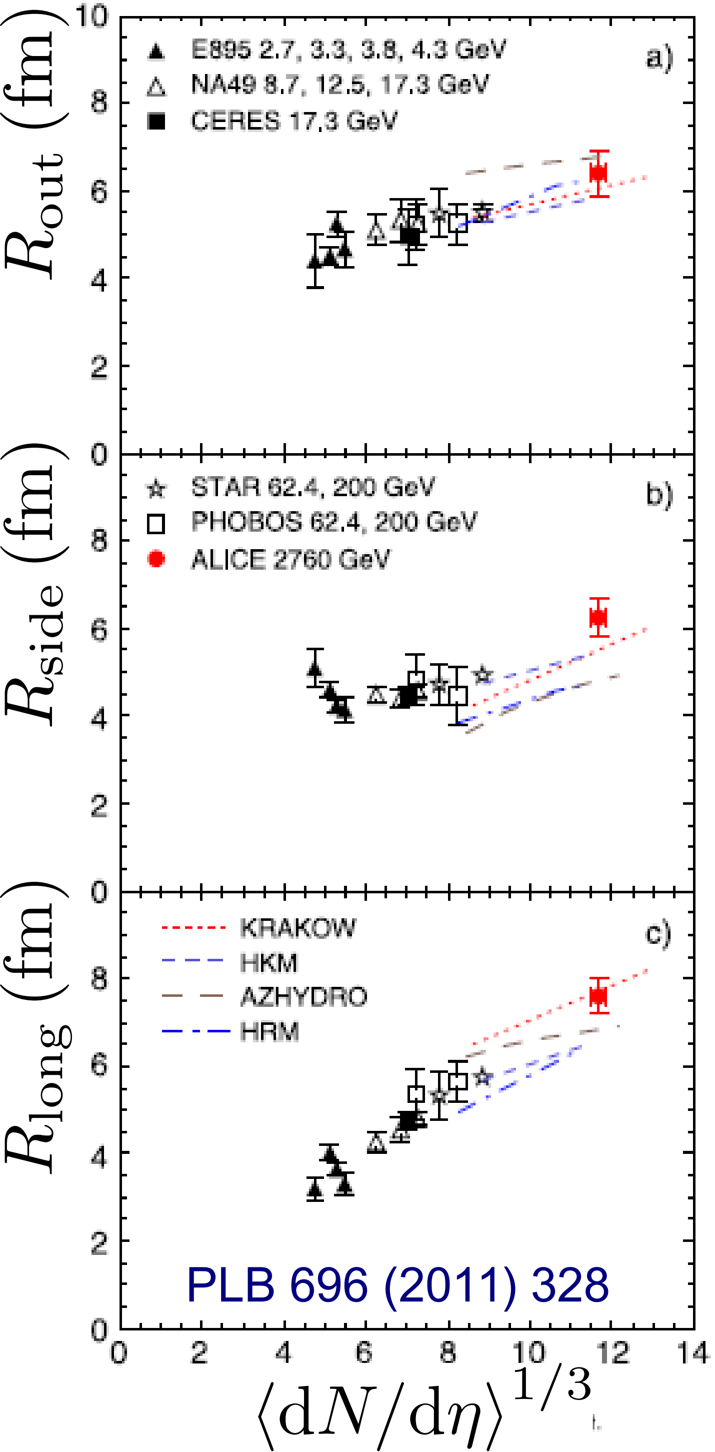
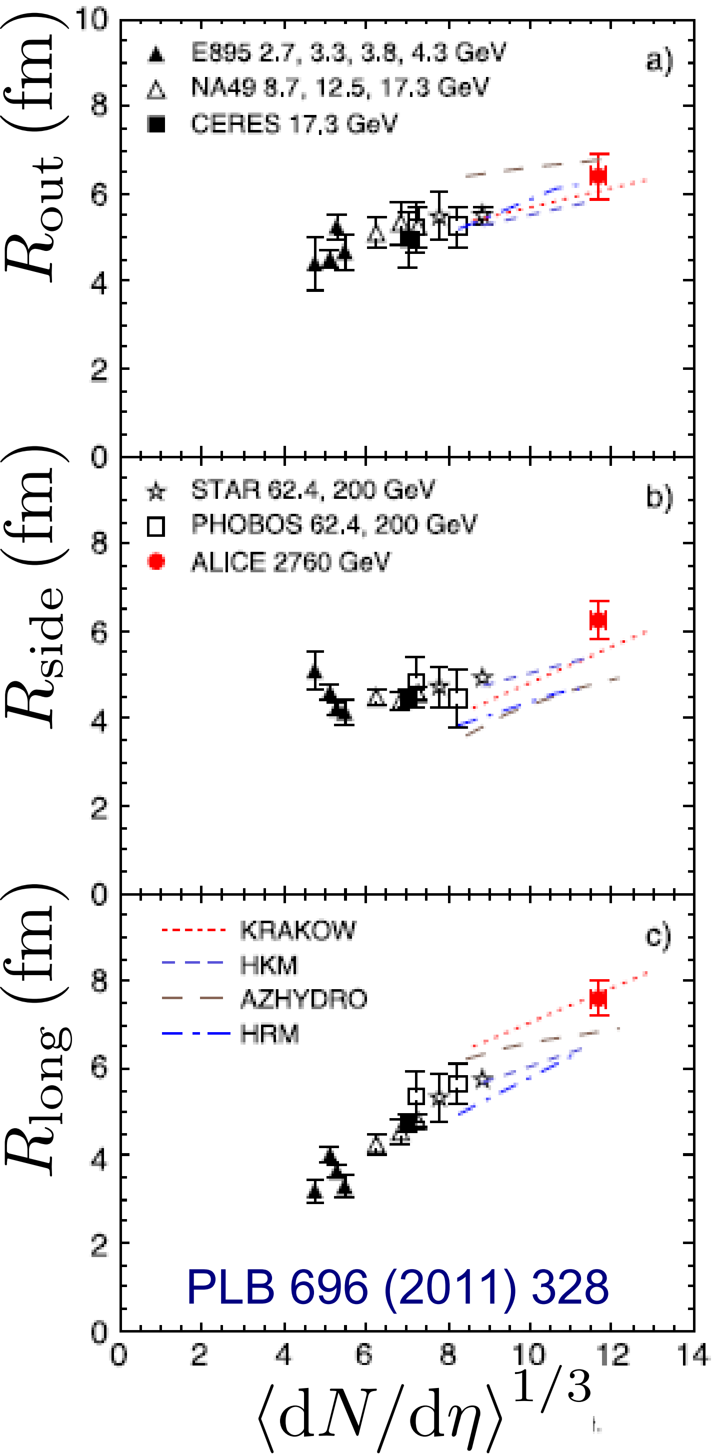


From RHIC to LHC

- Increase of radii in all directions
  - Out, side and long

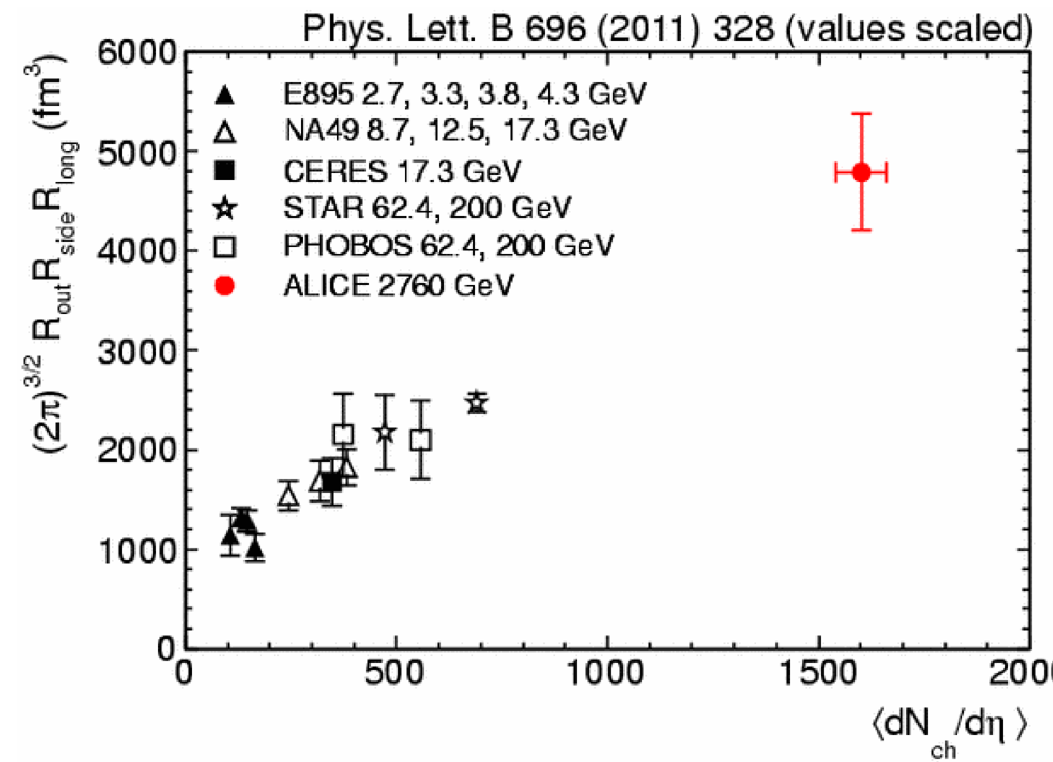
Intensity interferometry (HBT)



PLB 696 (2011) 328

From RHIC to LHC

- Increase of radii in all directions
  - Out, side and long
- "Homogeneity" volume: 2x RHIC



- Substantial expansion
  - For comparison: R(Pb) ~ 7fm → V~1500fm^3
  - Lifetime (extr. from R_{long}) ~ 10fm/c

Chemical equilibrium

(Are particles produced with relative abundances as
expected for a grand-canonical ensemble in equilibrium?)

Statistical models

- Statistical models of hadronization
  - Use hadron resonance gas with masses < 2 GeV/c
    - Well known hadron spectra and decay chains
- Yield per species for a grand-canonical ensemble

$$N_i = V \frac{g_i}{2\pi^2} \int \frac{p^2 \, \mathrm{d}p}{e^{(E_i - \mu_\mathrm{B} B_i - \mu_\mathrm{s} S_i - \mu_3 I_{3i})/T} \pm 1}$$

  - Here, E_i is the energy and g_i is the degeneracy of the species i, and μ_B, μ_S, μ_3 are baryon, strangeness and isospin chemical potentials, respectively
  - In principle, 5 unknowns but also have information from initial state about Ns neutron and Zs stopped protons

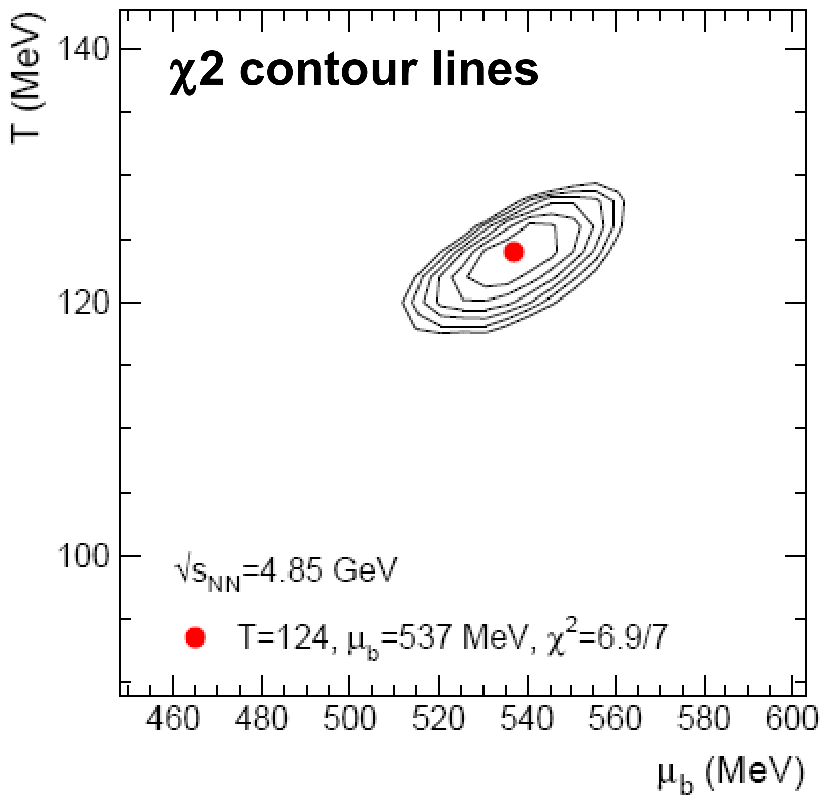
$$V \sum n_i I_{3i} = \frac{Z_\mathrm{S} - N_\mathrm{S}}{2}$$
$$V \sum n_i B_i = Z_\mathrm{S} + N_\mathrm{S}$$
$$V \sum n_i S_i = 0$$

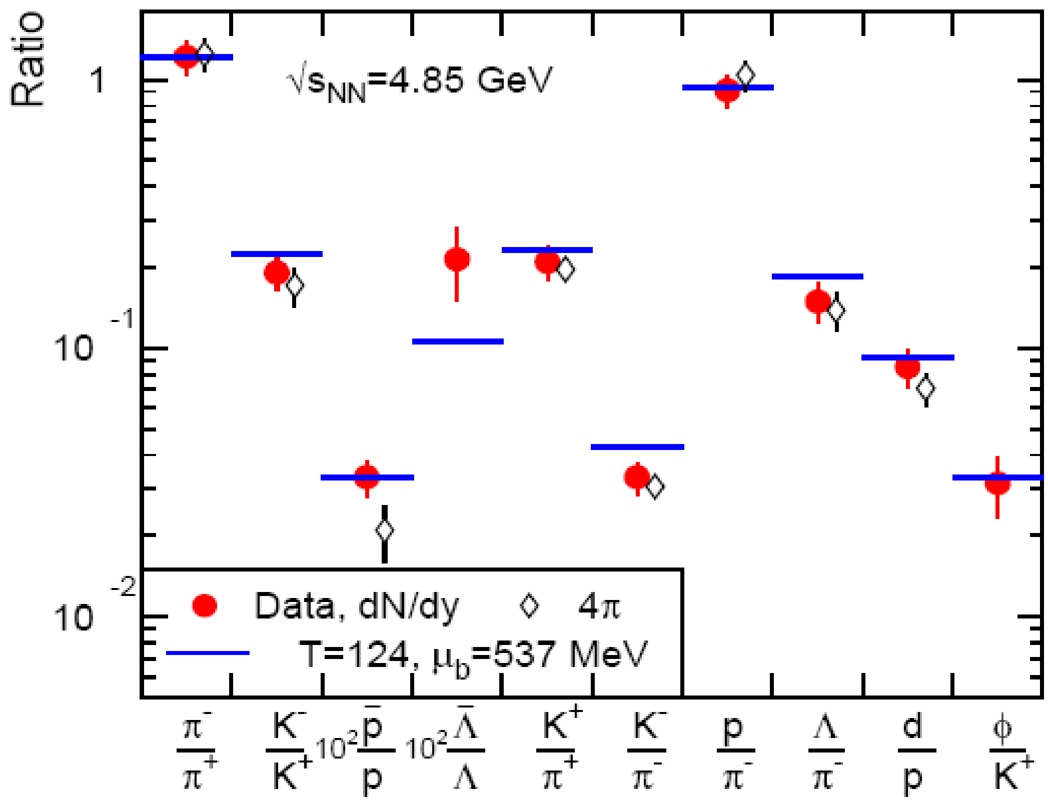
  - Only three parameters remain: V, μ_B and T
  - Typically use ratio of particle yields between various species to determine μ_B and T

Particle ratios at the AGS

Au+Au: E_{beam} = 10.7 GeV/nucleon ↔ $\sqrt{s_{NN}}$=4.85 GeV

Minimum χ^2 for : T_{ch} = 124±3 MeV and μ_B = 537±10 MeV

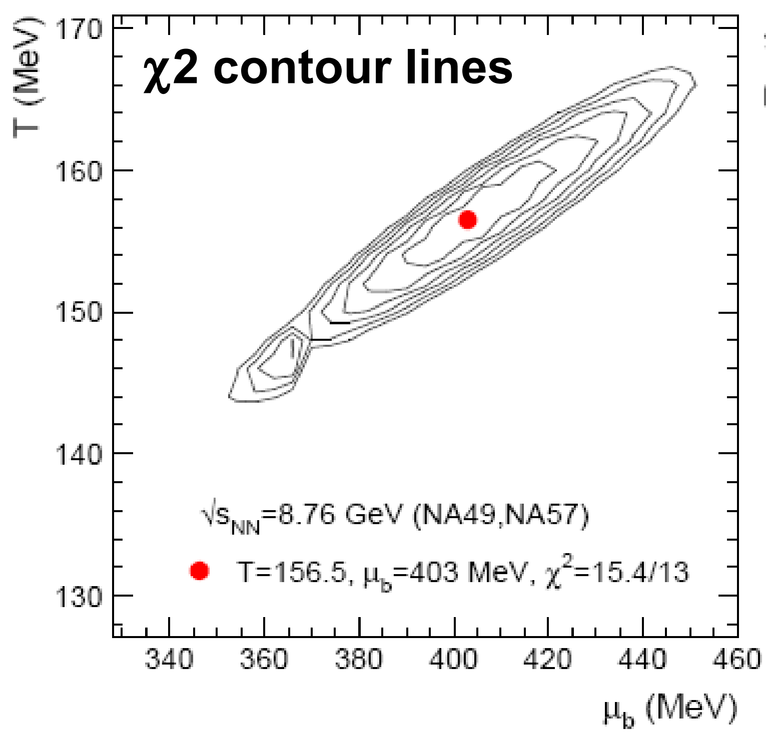


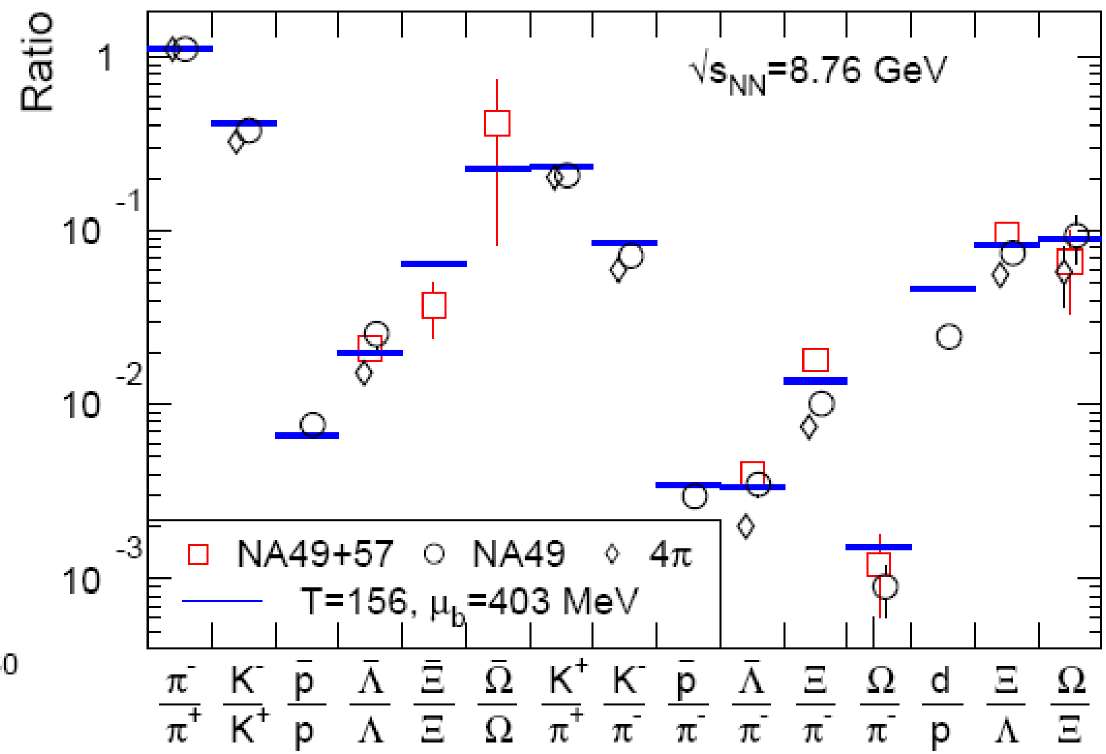


NPA 772 (2006) 167

Particle ratios at the SPS

Pb+Pb: E_{beam} = 40 GeV/nucleon ↔ $\sqrt{s_{NN}}$=8.77 GeV
Minimum χ^2 for : T_{ch} = 156±3 MeV and μ_B = 403±18 MeV





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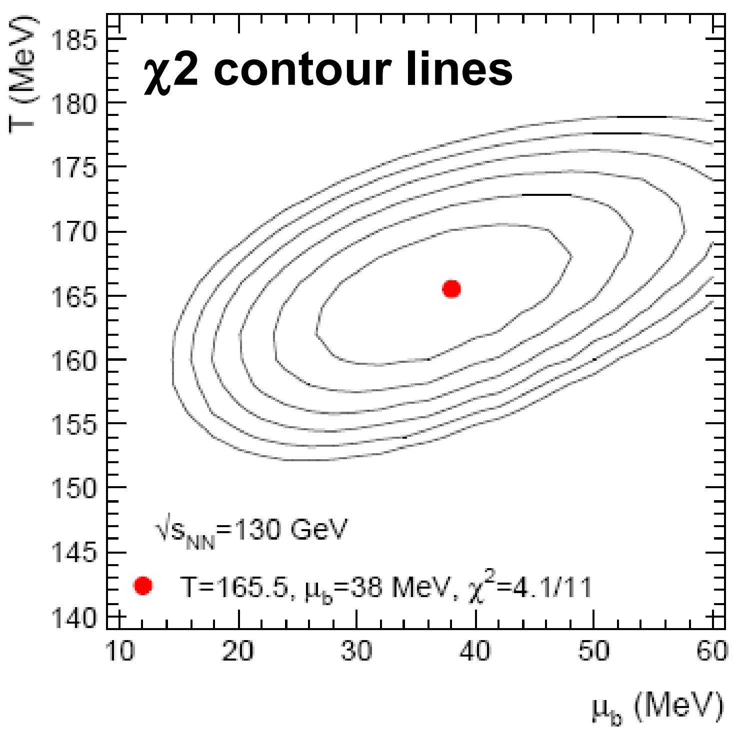
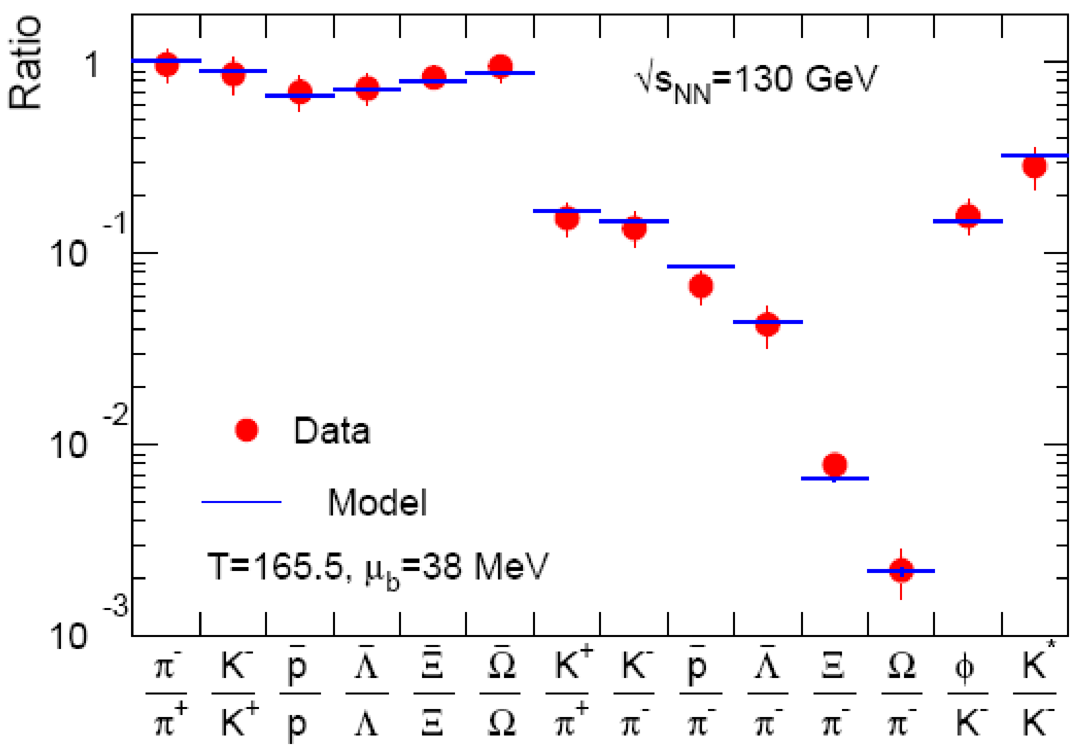
Particle ratios at RHIC

Au+Au: $\sqrt{s_{NN}}$=130 GeV

Minimum χ^2 for : T_{ch} = 166±5 MeV and μ_B = 38±11 MeV





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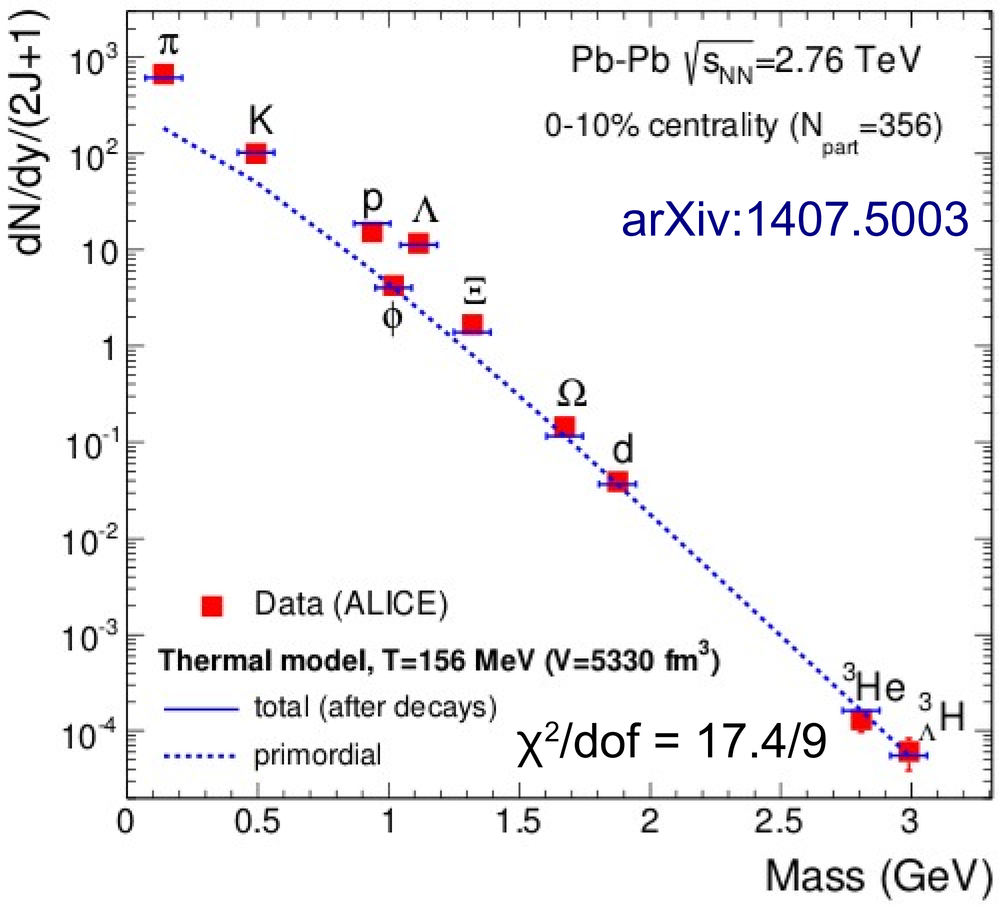
Particle ratios at the LHC

Pb+Pb: $\sqrt{s_{NN}}$=2.76 TeV

Minimum χ^2 for : T_{ch} = 156±2 MeV and μ_B = 0 MeV (fixed)

- Ratios except p/π well described
- Disagreement for p/π may point to the relevance of other effects at LHC like
  - Rescattering in hadronic phase
  - Non-equilibrium effects
  - Flavor-dependent freeze-out



Kinetic equilibrium

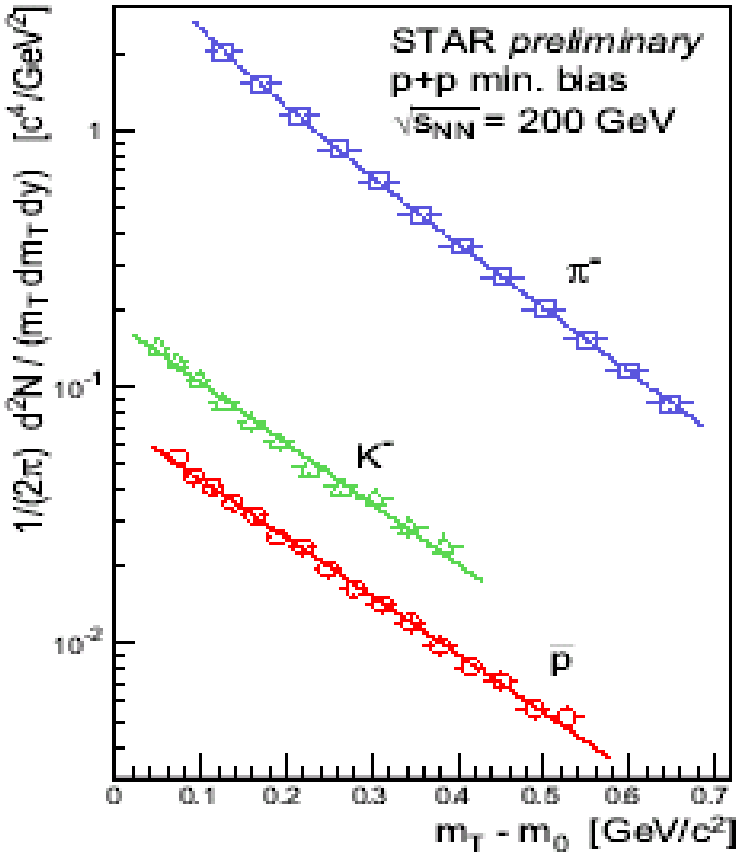
(Are the p_T distributions of particle species at low p_T described by a thermal distribution?)

Transverse mass (m_T) scaling in pp collisions

- Exponential behavior at low p_T, in pp collisions
  - Identical for all hadrons
  - Transverse mass (m_T) scaling

$$\frac{\mathrm{d}N}{m_\mathrm{T}\mathrm{d}m_\mathrm{T}} \propto e^{-\frac{m_\mathrm{T}}{T_\mathrm{slope}}} \; (m_\mathrm{T}^2 = m_0^2 + p_\mathrm{T}^2)$$

  - T_{slope} ~ 170 MeV for all particles



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  - Transverse mass (m_T) scaling

$$\frac{dN}{m_T dm_T} \propto e^{-\frac{m_T}{T_{\mathrm{slope}}}} \quad (m_T^2 = m_0^2 + p_T^2)$$

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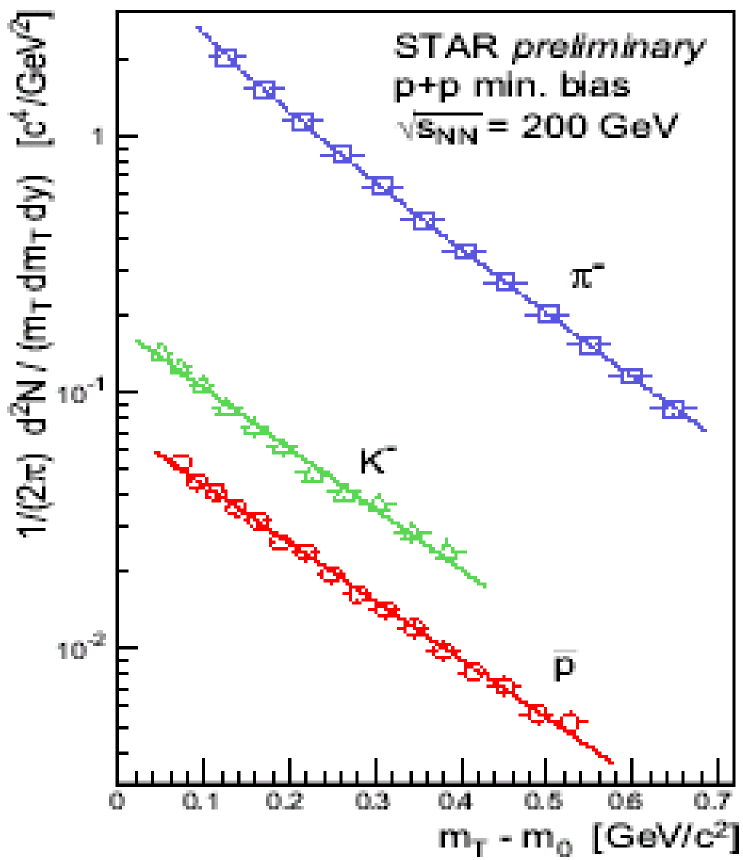
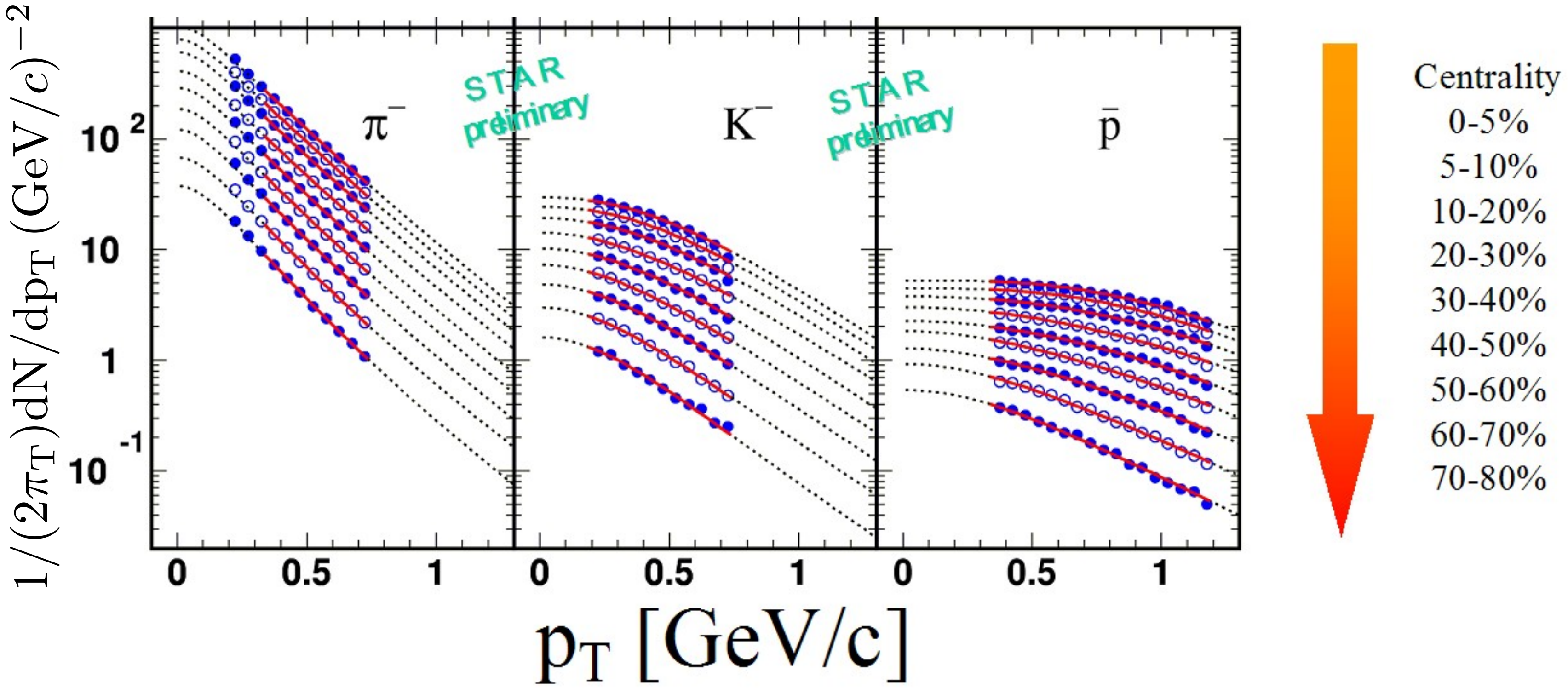


- These distributions look like thermal spectra
  - T_{slope} can be interpreted as the temperature at the time when kinetic interactions between particles ended
  - Kinetic freeze-out temperature (T_{fo})

Breaking of m_T scaling in A+A collisions



- Harder spectra (i.e. larger T_{slope}) for larger masses
- Consistent with a shift towards larger p_T for heavier particles
    - Remember $p_T = m_0 v_T$

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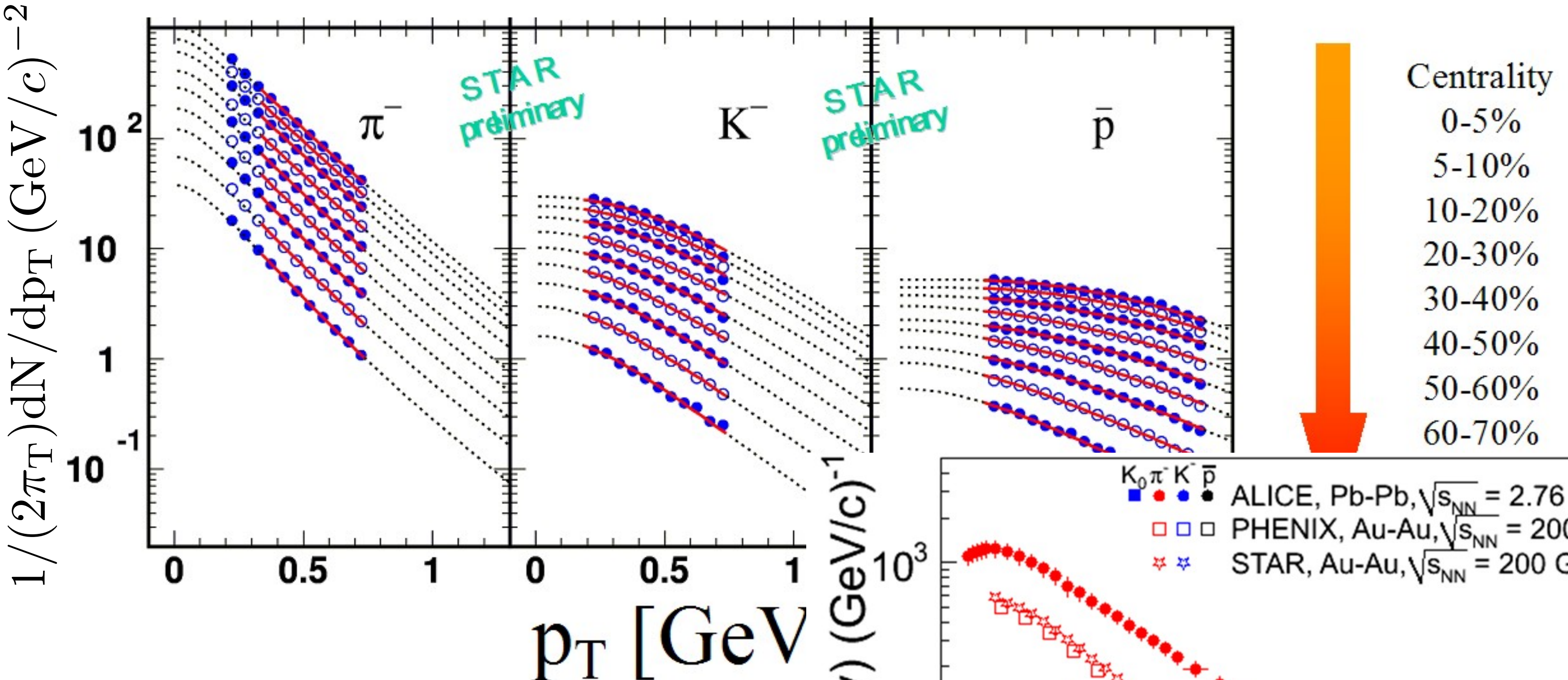

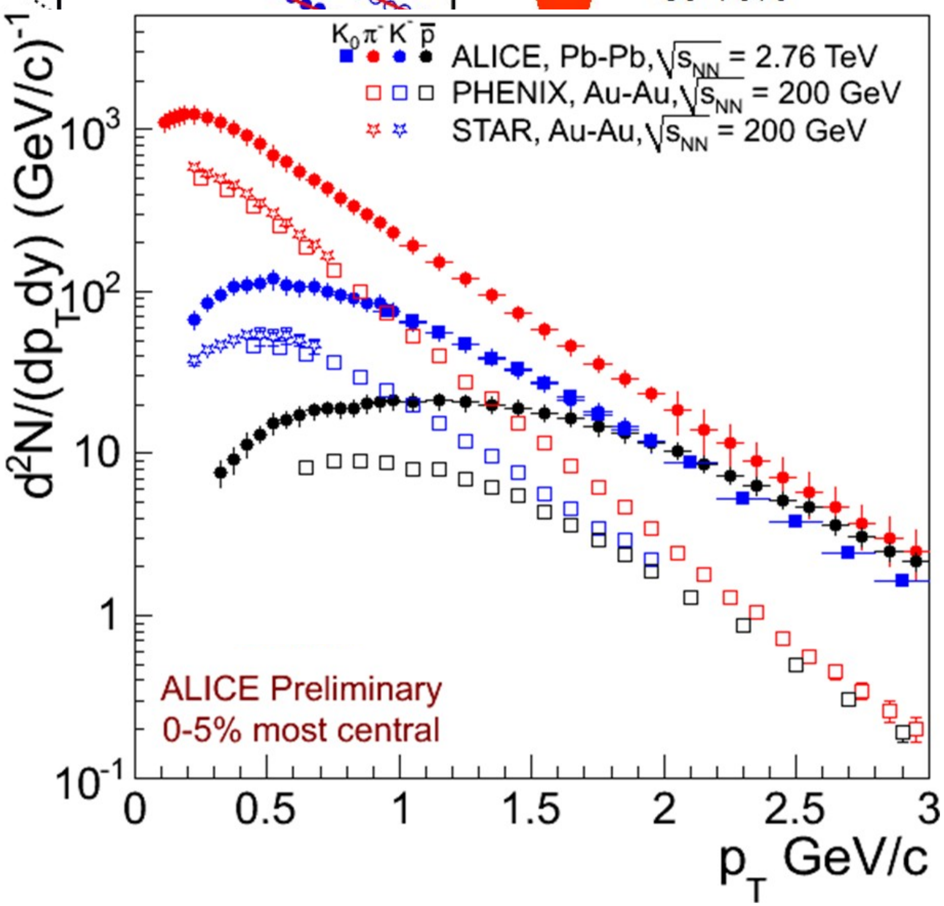

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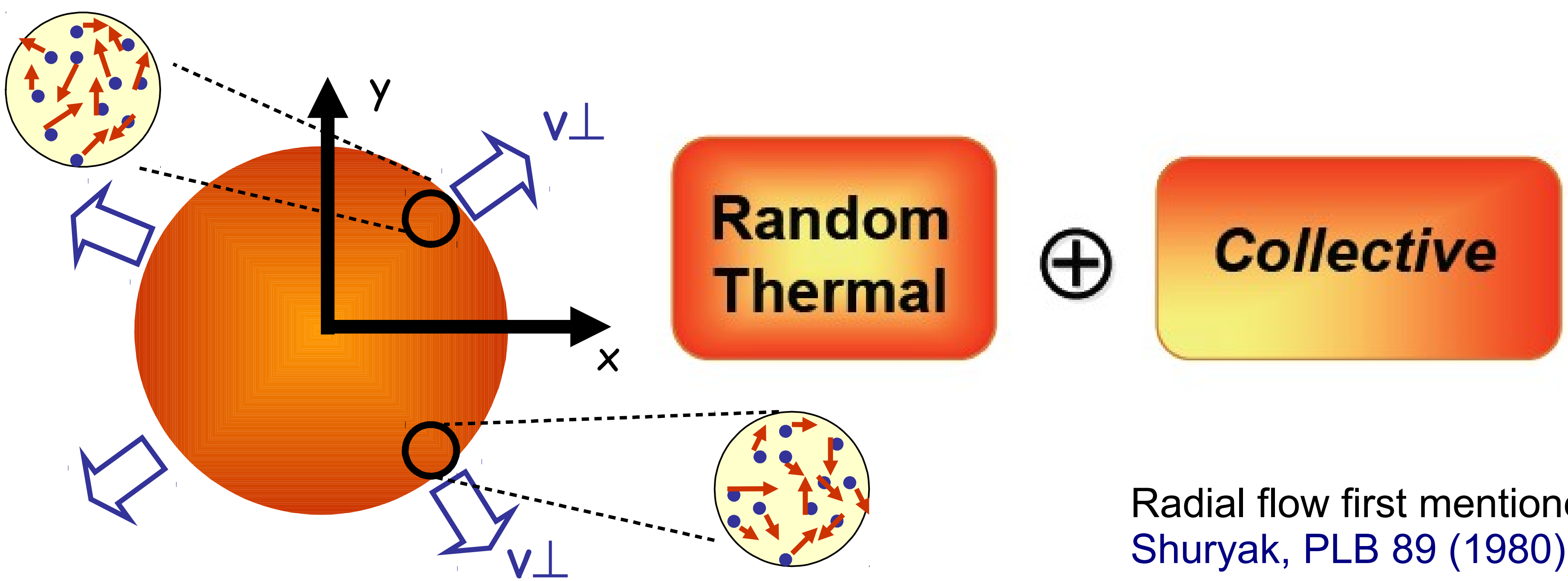
Flow in A+A collisions

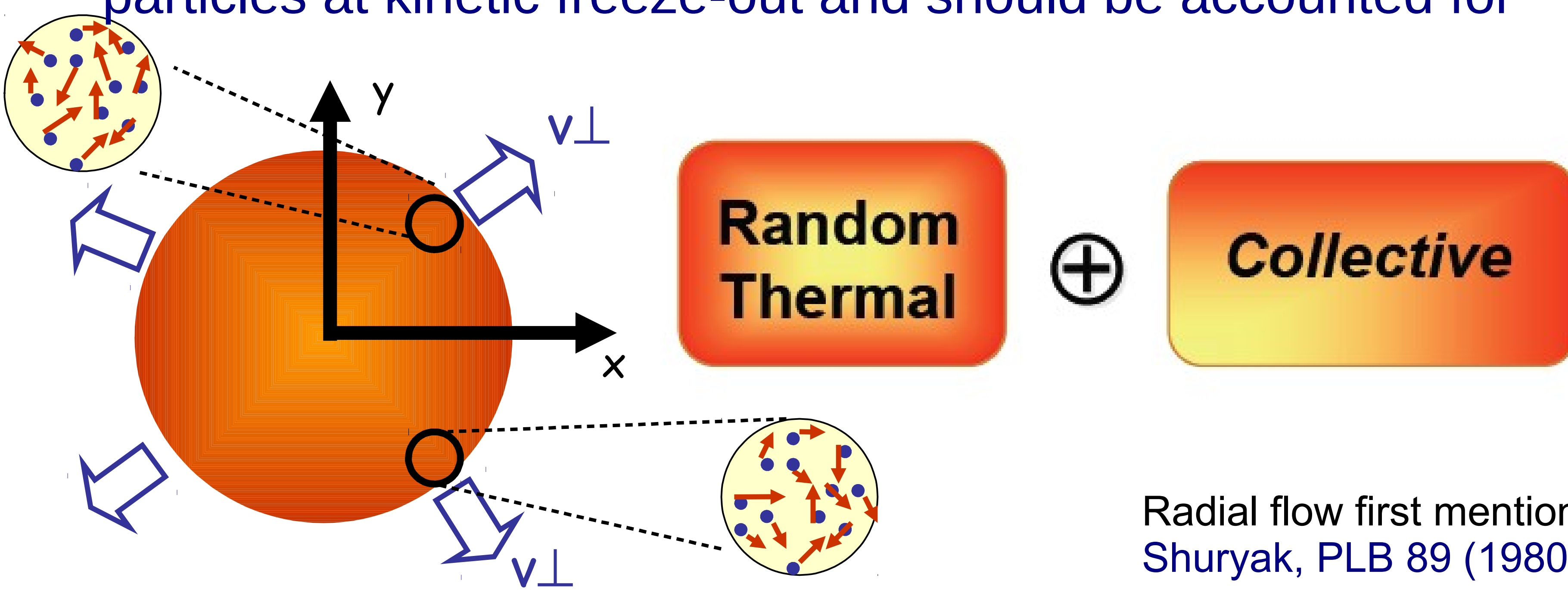
- Interpretation in the flow picture:
  Collective motion of particles superimposed to thermal motion



Radial flow first mentioned:
Shuryak, PLB 89 (1980) 253

Flow in A+A collisions

- Interpretation in the flow picture:
  Collective motion of particles superimposed to thermal motion
- For any interacting system of particles expanding into vacuum, radial flow is a natural consequence
  - During the cascade process, one naturally develops an ordering of particles with the highest common underlying velocity at the outer edge
  - This motion complicates the interpretation of the momentum of particles at kinetic freeze-out and should be accounted for



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Shuryak, PLB 89 (1980) 253

Decoupling motion: Blast wave description

- Consider a thermal Boltzman source

$$E\frac{\mathrm{d}^3N}{\mathrm{d}p^3} \propto E\,e^{-E/T} \qquad\qquad E = m_\mathrm{T}\cosh(y)$$

Schnedermann et al., PRC 48 (1993) 2462

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- Boost source radially with a velocity β and evaluate at y=0

$$\frac{1}{m_\mathrm{T}}\frac{\mathrm{d}N}{\mathrm{d}m_\mathrm{T}} \propto m_\mathrm{T}\, I_0\left(\frac{p_\mathrm{T}\sinh(\rho)}{T}\right)\, K_1\left(\frac{m_\mathrm{T}\cosh(\rho)}{T}\right)$$

with $\rho = \tanh^{-1}(\beta)$

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with $\rho = \tanh^{-1}(\beta)$

- Simple assumption: Consider uniform sphere of radius R

$$\frac{1}{m_\mathrm{T}}\frac{\mathrm{d}N}{\mathrm{d}m_\mathrm{T}} \propto \int_0^R r\mathrm{d}r\, m_\mathrm{T}\, I_0\left(\frac{p_\mathrm{T}\sinh(\rho(r))}{T}\right)\, K_1\left(\frac{m_\mathrm{T}\cosh(\rho(r))}{T}\right)$$

and parametrize surface velocity as

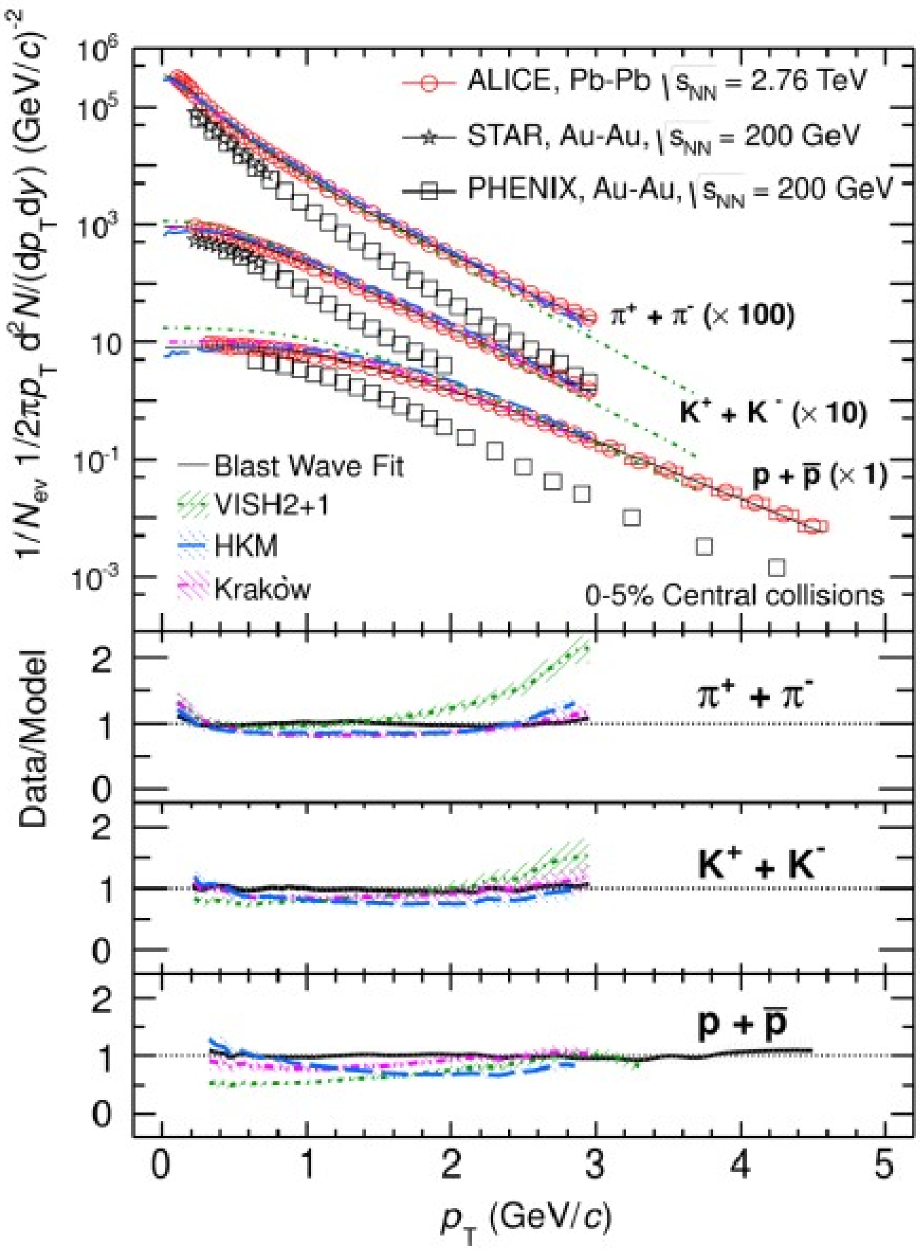
$$\beta(r) = \beta_\mathrm{s}\,(r/R)^n$$

Three parameters: T,β_s and n
(sometimes n=2 is fixed)

Schnedermann et al., PRC 48 (1993) 2462

Radial flow and kinetic freeze-out

PRL 109 (2012) 252301



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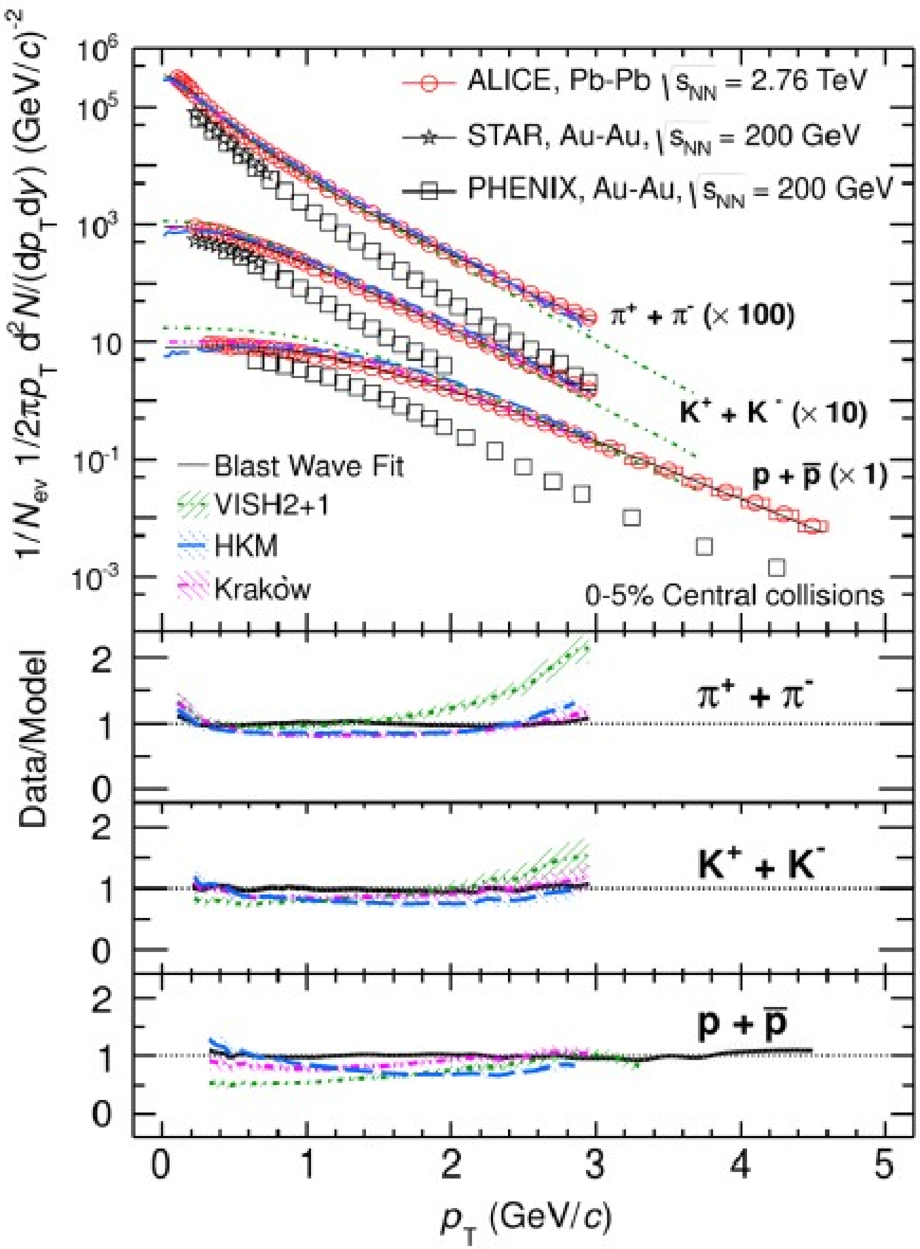
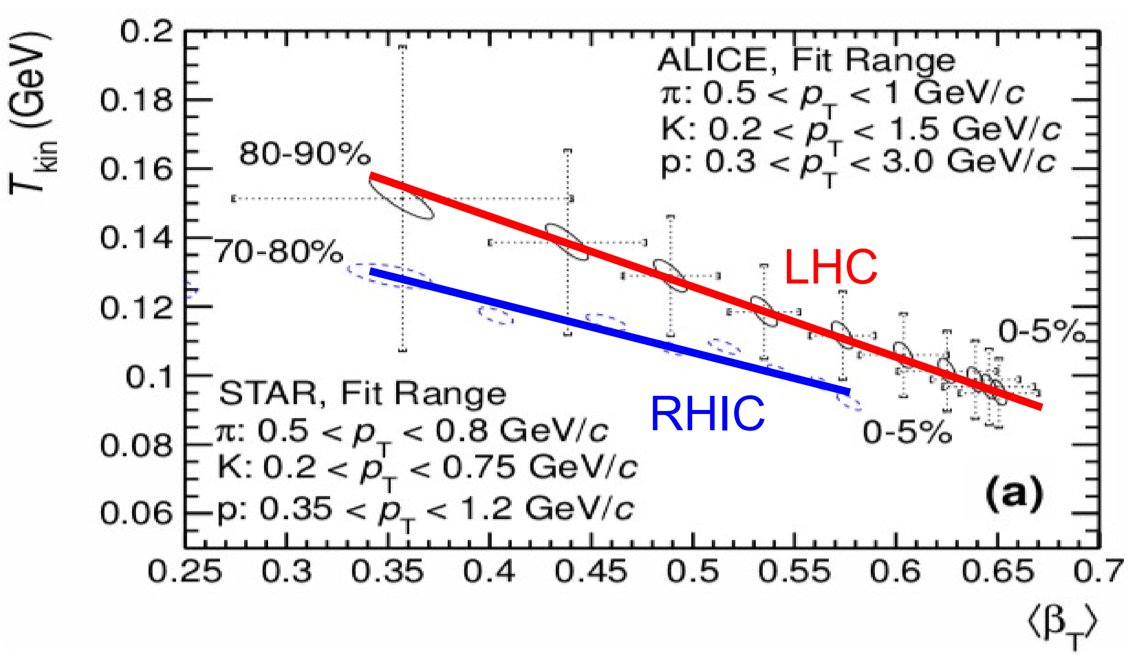
PRL 109 (2012) 252301



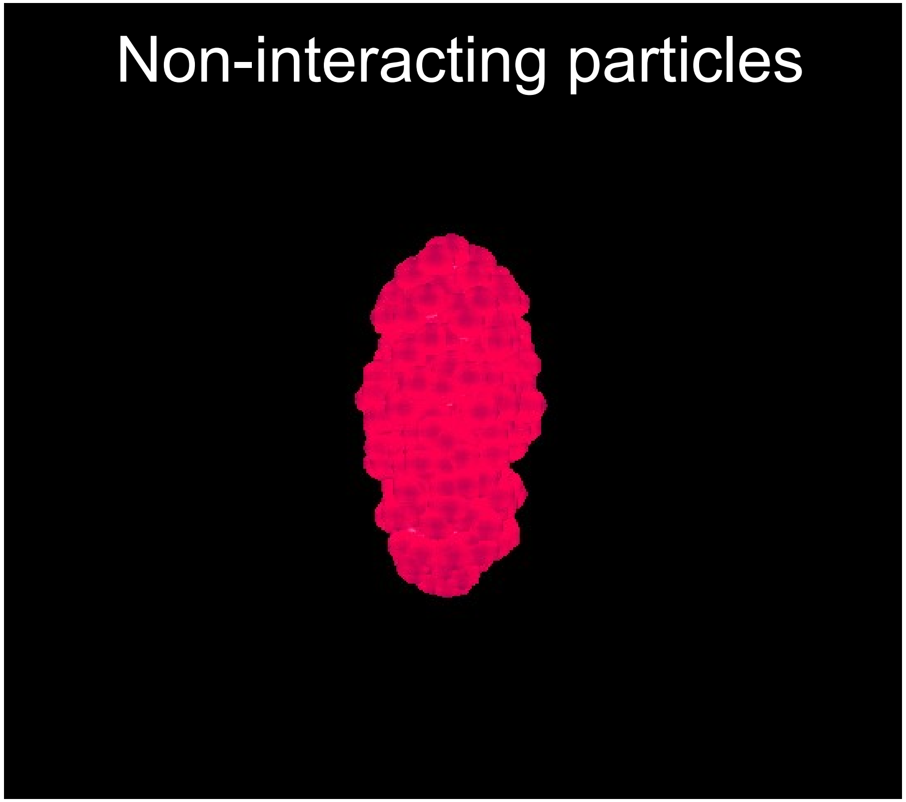


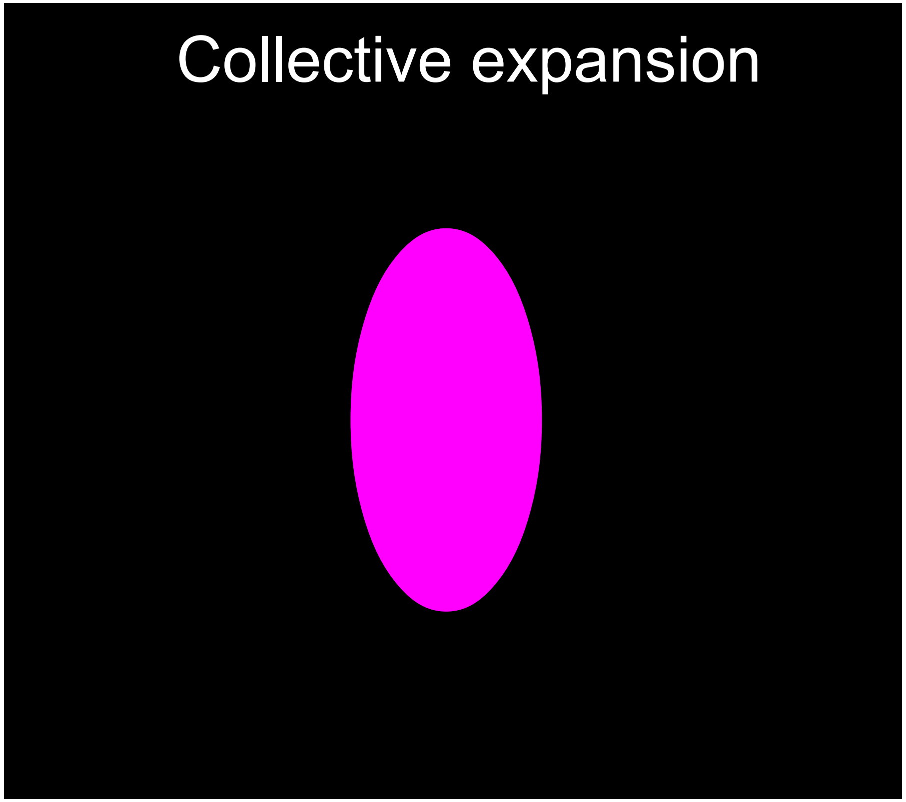
- Strong radial flow up to $\beta_{LHC,central} = 0.65c$
  - $\beta_{LHC,central} = 1.1\ \beta_{RHIC,central}$
- Similar kinetic freeze-out $T_{kin} \approx 100$ MeV

Elliptic flow

(Do we indeed make matter?)

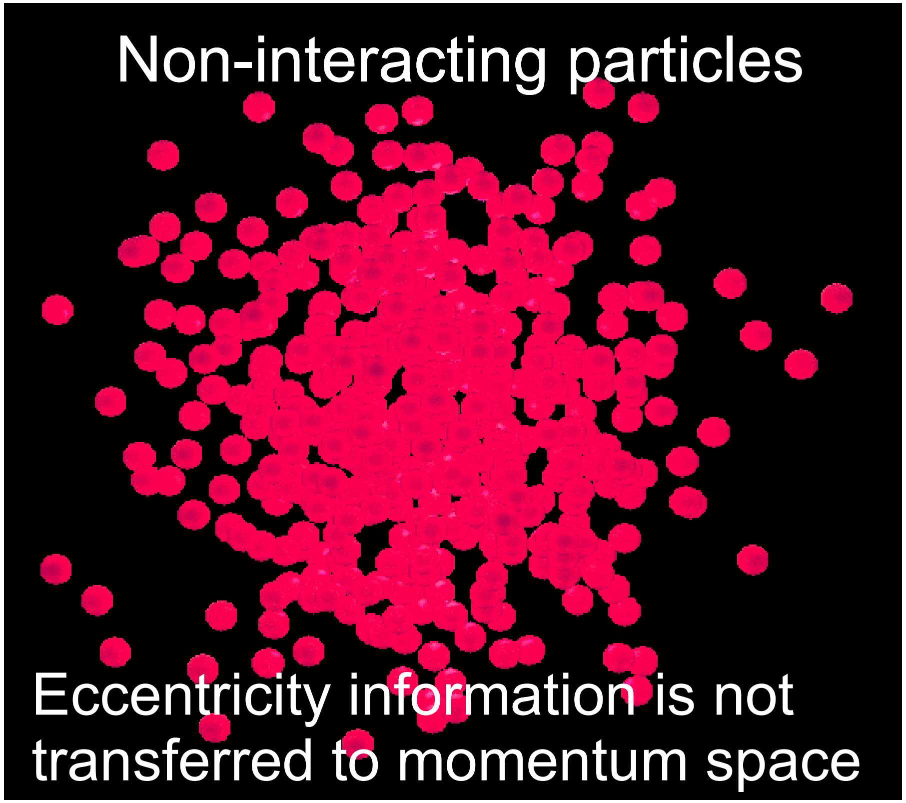
How do we prove that we make “matter”?

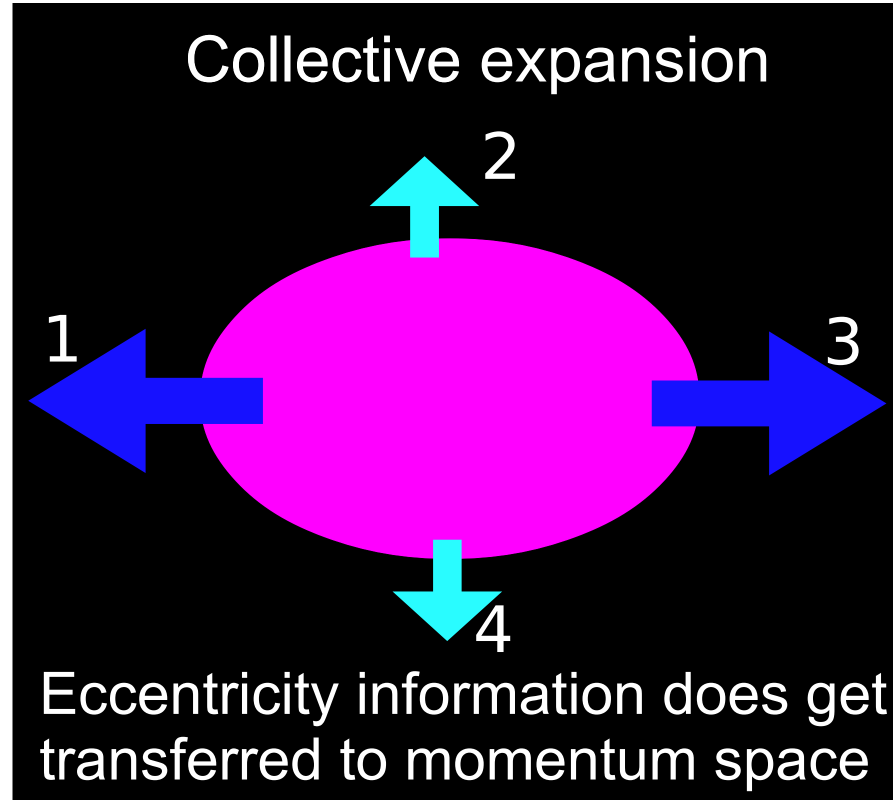


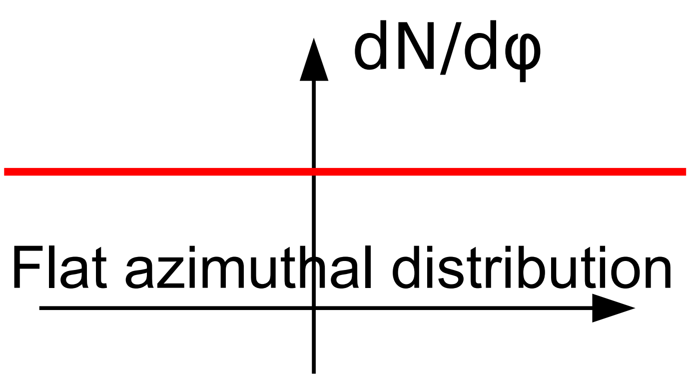


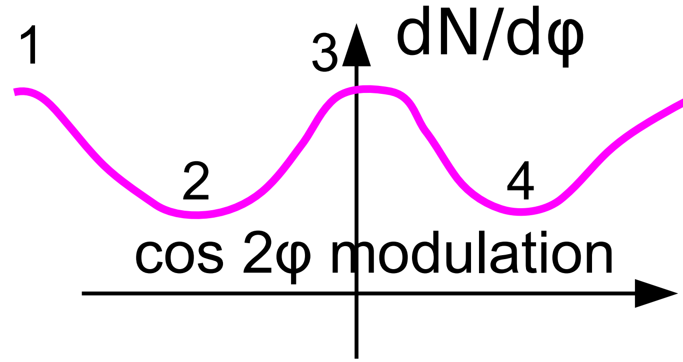
What happens to the shape (eccentricity) information during the expansion?

How do we prove that we make "matter"?

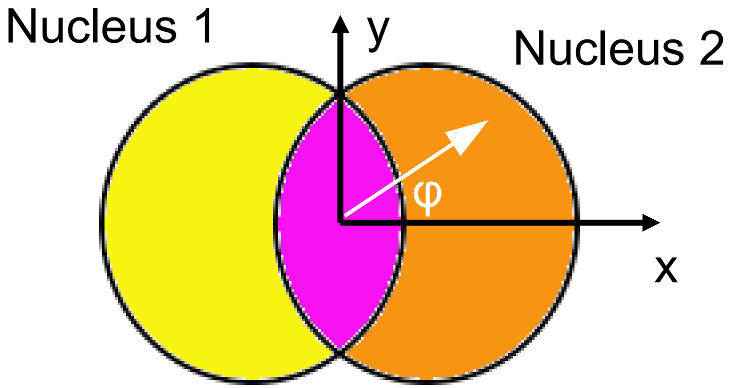




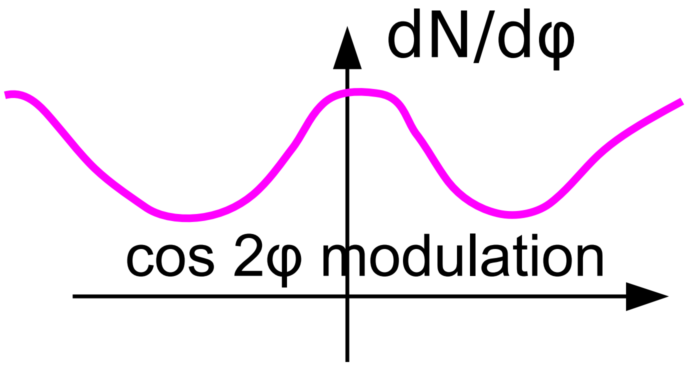




Initial and final state anisotropy



(ψ_R=0 , ie. along x)



$$\frac{dN}{d\varphi} \sim 1 + 2 v_2 \cos[2(\varphi - \psi_R)] + \ldots$$

Initial spatial anisotropy:
Eccentricity

Interactions present early

Momentum space anisotropy:
Elliptic flow

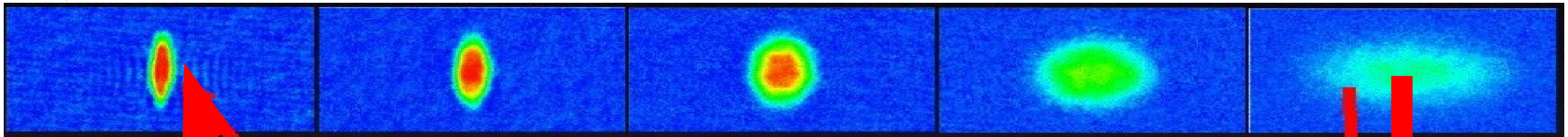
$$\epsilon_{std} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}$$

$$v_2 = \langle \cos(2\varphi - 2\Psi_R) \rangle$$

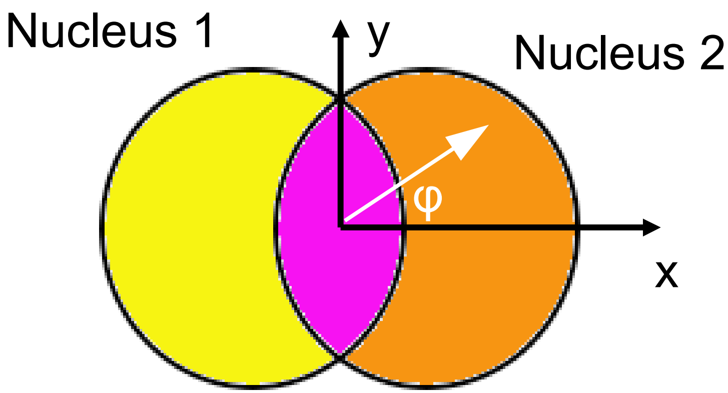
Initial and final state anisotropy

Time

Illustration with liquid ^{6}Li, Science 298 5601 (2002) 2179-2182



(Process is self quenching)



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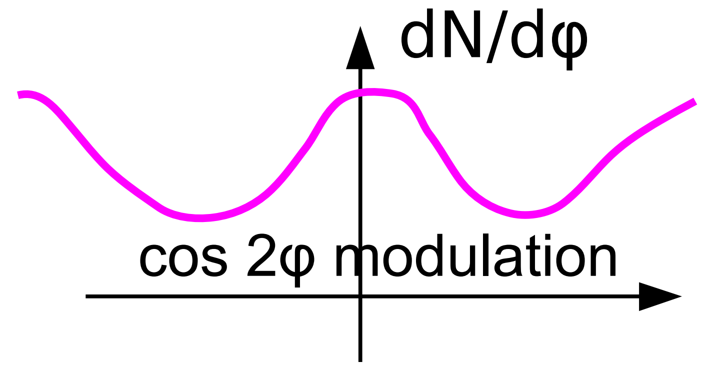

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$$v_2 = \langle \cos\left(2\varphi - 2\Psi_R\right) \rangle$$

Flow methods

$$v_2 = \langle \cos(2\varphi - 2\Psi_R) \rangle$$

Extract from data or
use only relative angles

Ollitrault, Poskanzer, Voloshin
PRC 80 80 014904 (2009)

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$$v_2 = \langle \cos(2\varphi - 2\Psi_R) \rangle$$

Extract from data or
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Two-particle cumulant

$$v\{2\} = \sqrt{\langle \cos(2\varphi_1 - 2\varphi_2) \rangle}$$

Can suppress "non-flow"
by employing cuts in |Δη|
If p_T cuts are used:
$v\{2\} = \sqrt{v(p_{T,1})v(p_{T,2})}$

Measures:

$$v\{2\}^2 = \langle v \rangle^2 + \sigma_{v_2}^2 + \delta$$

$$v \gg 1/\sqrt{M}$$

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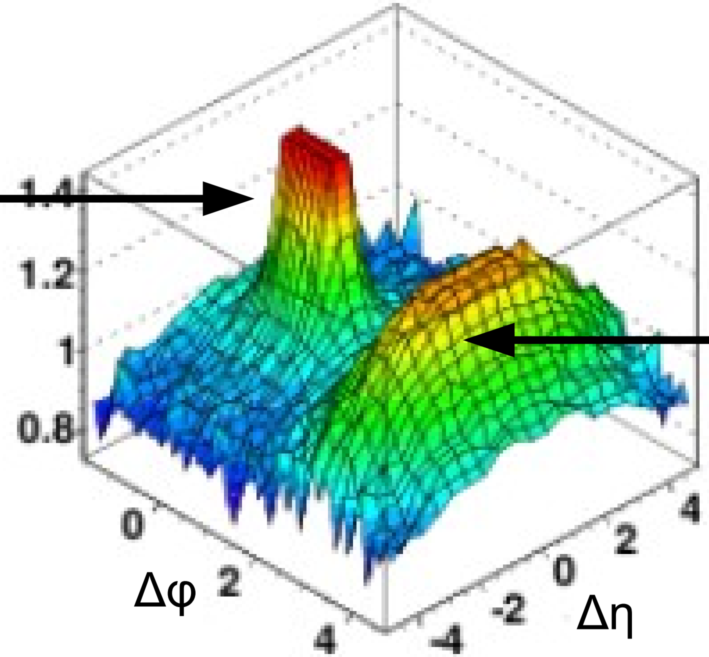
Jet
(Near-side region)

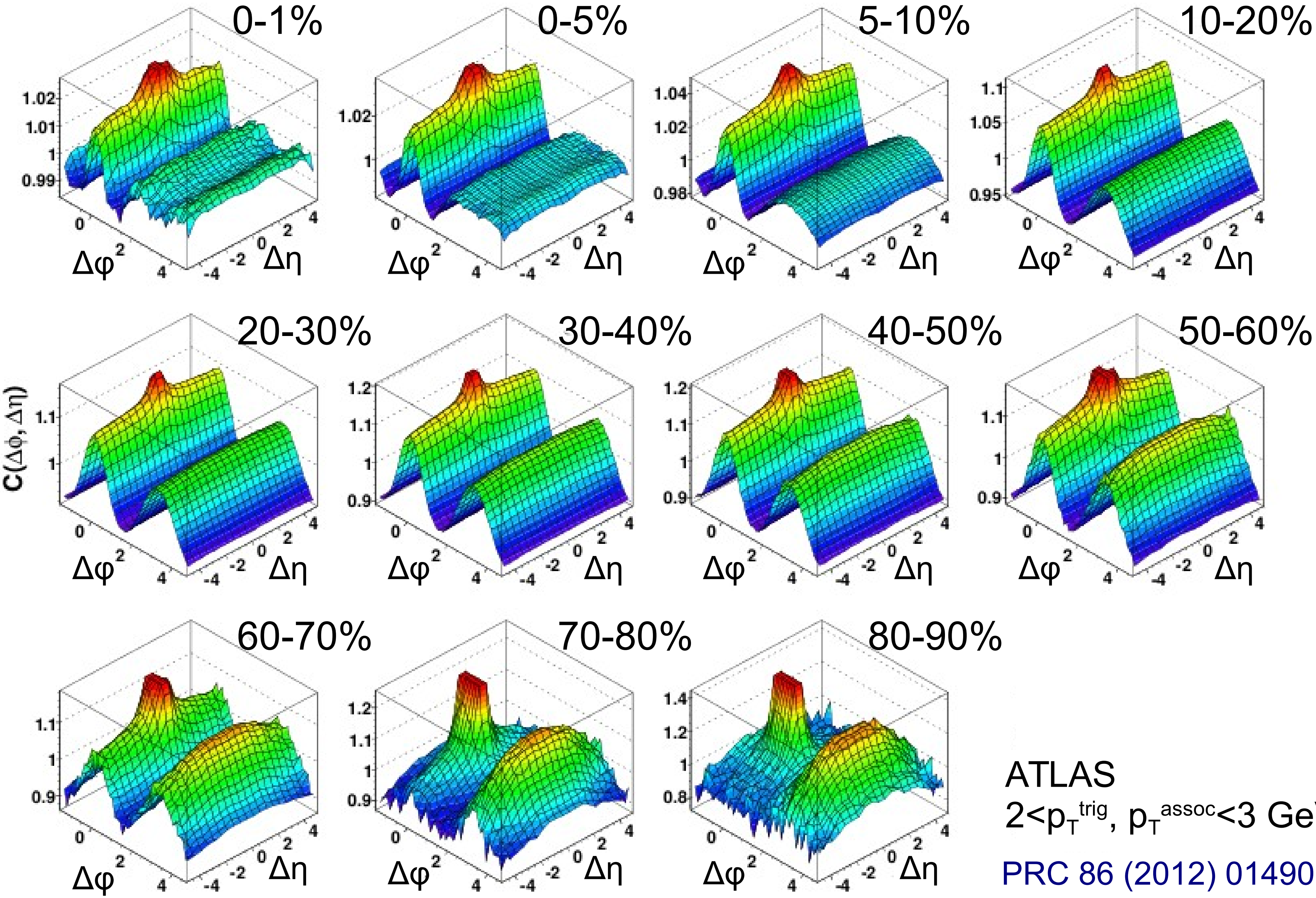


Recoil-jet
(Away-side region)

Often multi-particle cumulants are used, see arXiv:1010.0233

Ollitrault, Poskanzer, Voloshin
PRC 80 80 014904 (2009)

Two-particle angular correlations

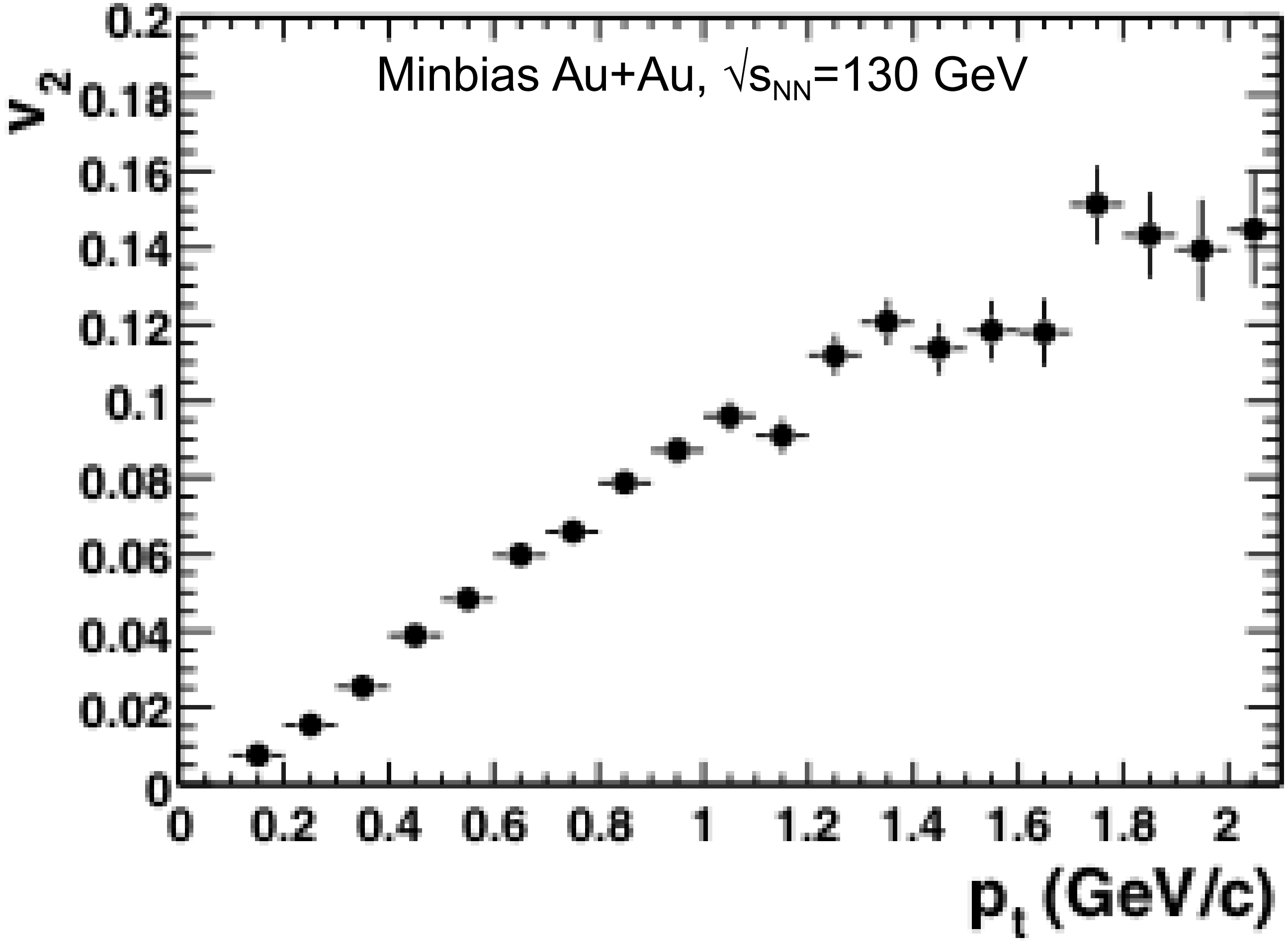


ATLAS
$2<p_T^{trig}, p_T^{assoc}<3$ GeV/c

PRC 86 (2012) 014907

Measuring the v_2 coefficient

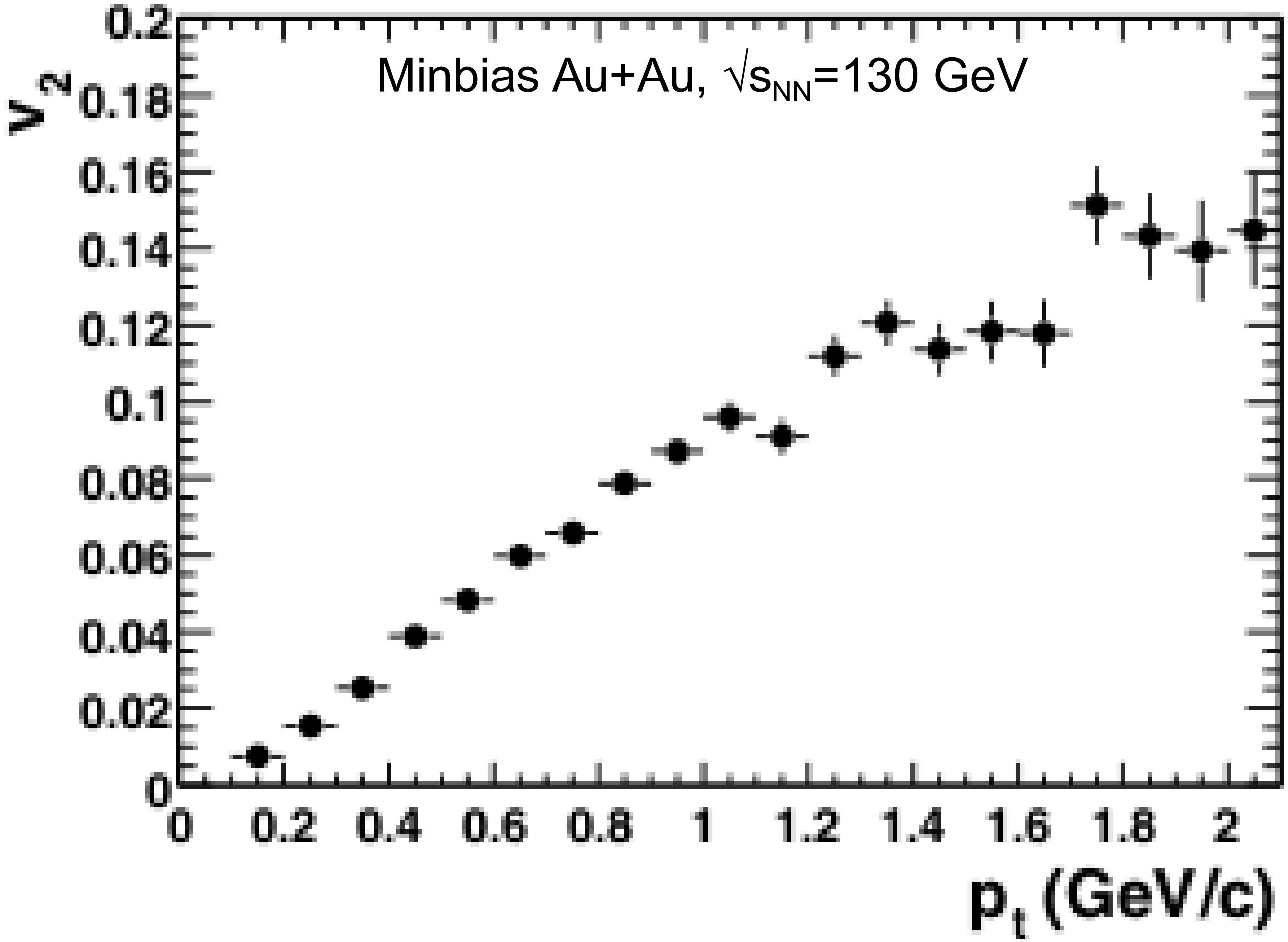
STAR, PRL 86 (2001) 402



Huge elliptic flow coefficients!

Measuring the v_2 coefficient

STAR, PRL 86 (2001) 402



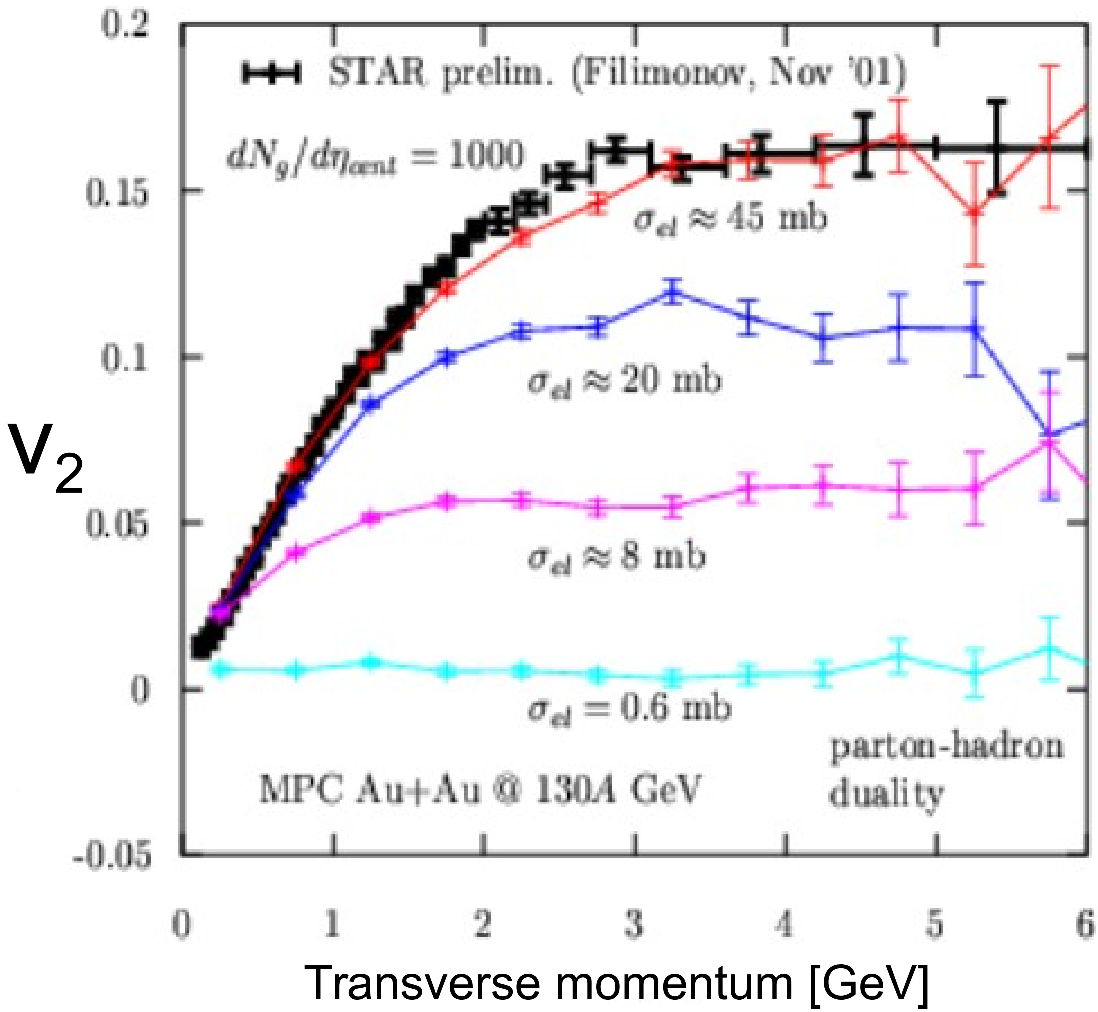
Huge elliptic flow coefficients!

$$\frac{dN}{d\varphi} \sim 1 + 2\, v_2 \cos\left[2\left(\varphi - \psi_R\right)\right] + \ldots$$

At 1 GeV: 20% modulation

How to explain the large elliptic flow?

What's needed partonically to get v_2?



Parton transport model: Bolzmann equation with 2-to-2 gluon processes

D.Molnar, M.Gyulassy
NPA 697 (2002)

Need large opacity to describe elliptic flow, ie elastic parton cross sections as large as inelastic the proton cross-section

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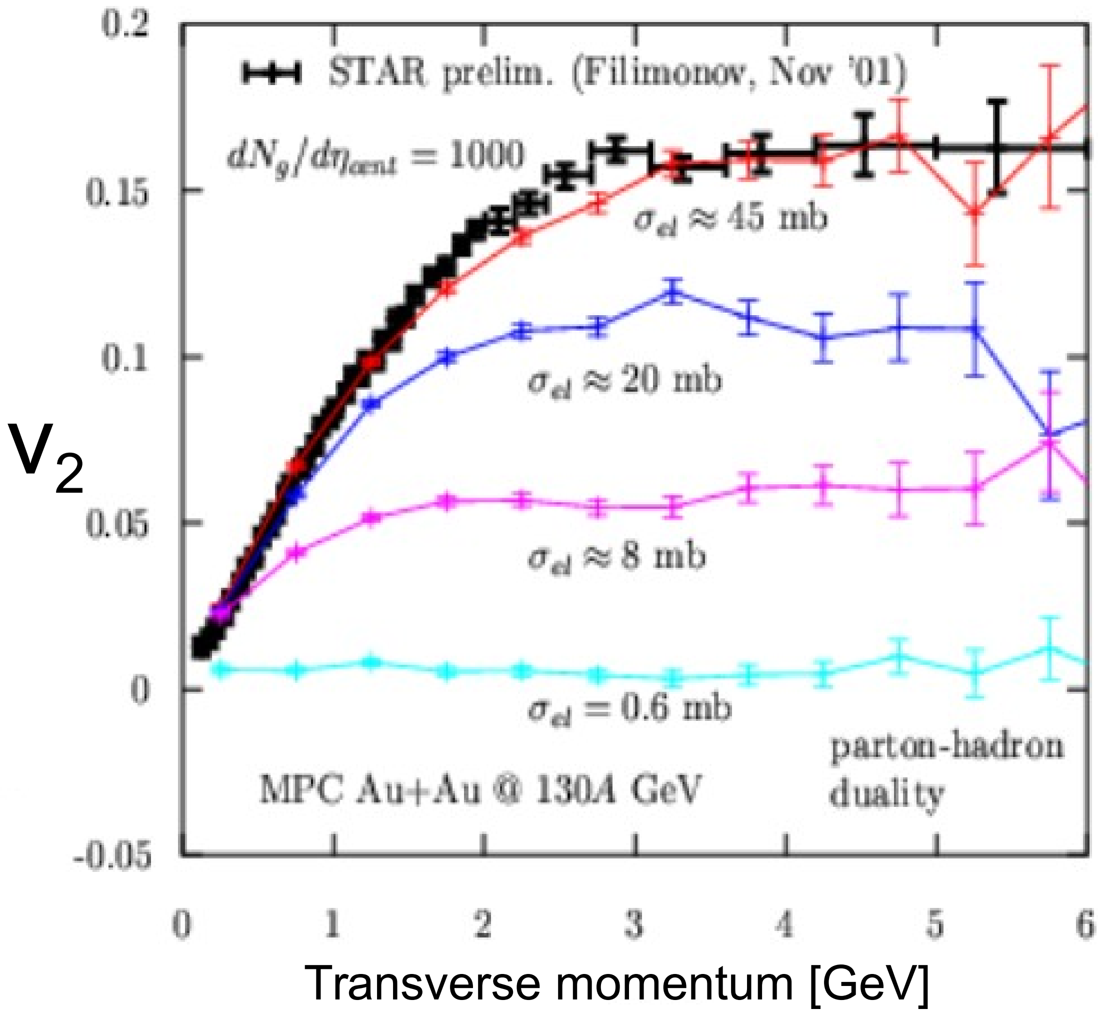

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D.Molnar, M.Gyulassy
NPA 697 (2002)

HUGE (hadronic) cross sections needed to describe v_2

Macroscopic description possible?

$$1/\lambda = n\sigma$$
$$Kn = \lambda/L \ll 1$$

Need large opacity to describe elliptic flow, ie elastic parton cross sections as large as inelastic the proton cross-section

Hydrodynamical model calculations

Heinz, arXiv:0901.4355

Hydrodynamics: conservation

$$\partial_\mu T^{\mu\nu} = 0$$

Generally:

$$T^{\mu\nu} = (\epsilon + P) u^\mu u^\nu - P g^{\mu\nu}$$

$$\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$$

+ initial conditions

+ freeze-out conditions

+ Equation of State

Today even second order calculations (full Israel-Stewart) calculations are done.

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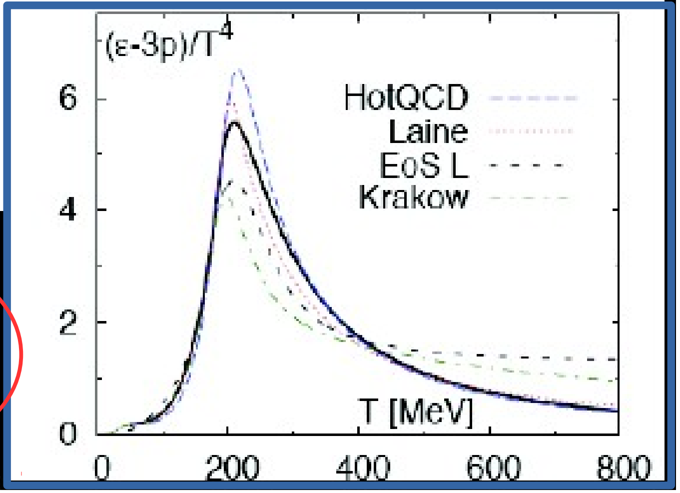

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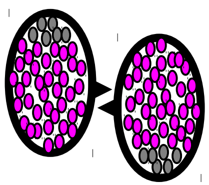
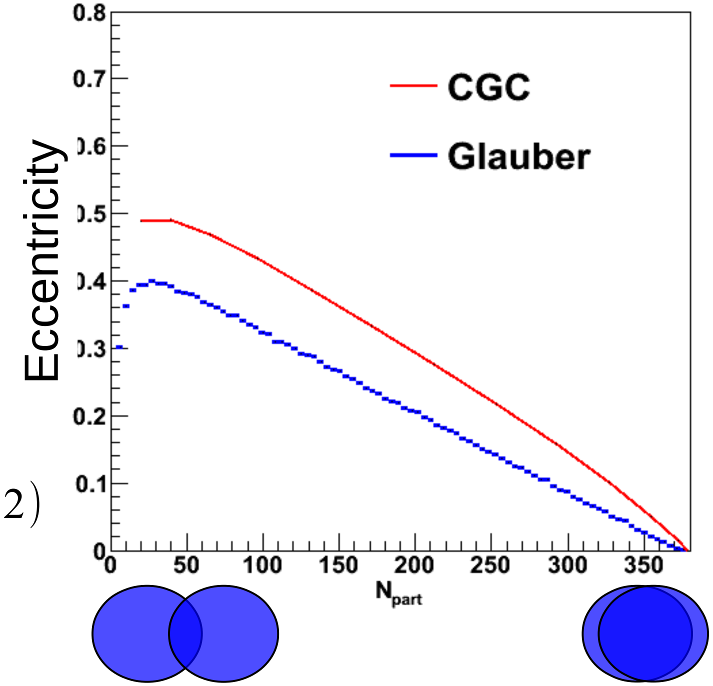
Glauber IC



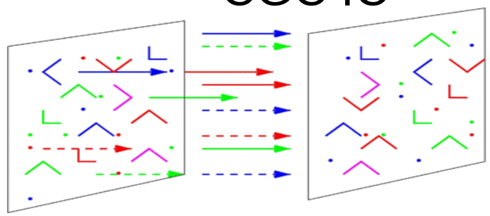
Glauber IC
Two-component model

$$\frac{dN}{d\eta} = \frac{dN}{d\eta^{pp}}\left((1-x)\,N_{coll} + x\,N_{part}/2\right)$$

PRC 70 021902 (2004)



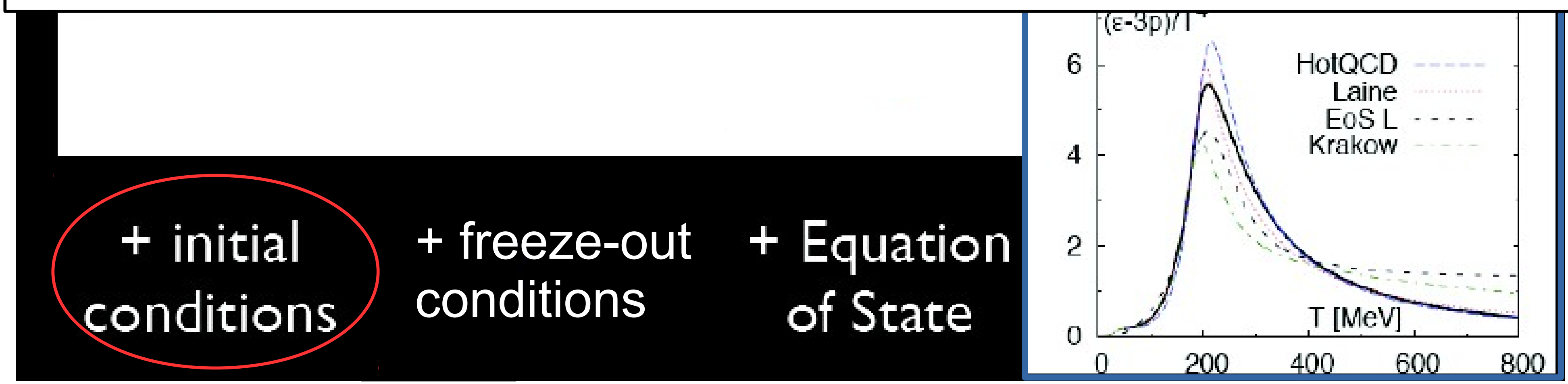
CGC IC



CGC IC
Color glass condensate

$$\frac{dN}{d\eta} \propto N_{part}^{\alpha} \sqrt{s}^{\lambda}$$

PRL 94 022002 (2005)



Today even second order calculations (full Israel-Stewart) calculations are done.

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Heinz, arXiv:0901.4355

Hydrodynamics: conservation

$$\partial_\mu T^{\mu\nu} = 0$$

Generally:

$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu} + \pi^{\mu\nu}.$$

First order Navier Stokes theory:

$$\pi^{\mu\nu} = \pi^{\mu\nu}_{(1)} = \eta(\nabla^\mu u^\nu + \nabla^\nu u^\mu - \tfrac{2}{3}\Delta^{\mu\nu}\nabla_\alpha u^\alpha).$$

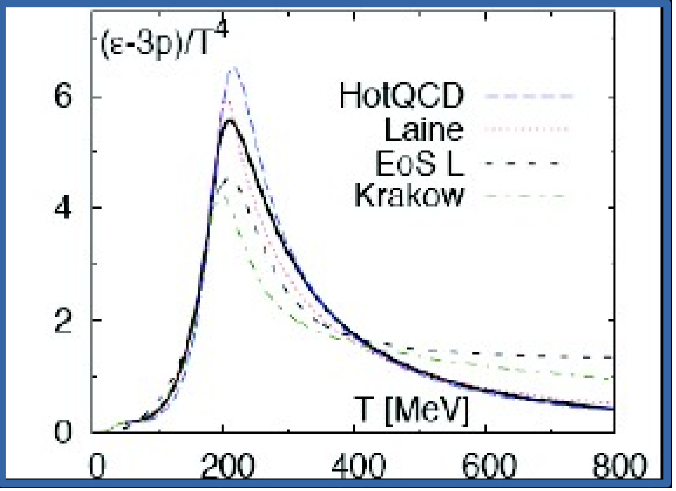
$\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$

η: Shear viscosity
Large shear viscosity → transport of momentum across fluid layers

+ initial conditions

+ freeze-out conditions

+ Equation of State

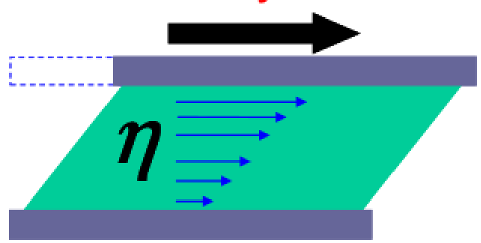


Today even second order calculations (full Israel-Stewart) calculations are done.

Effect of viscosity

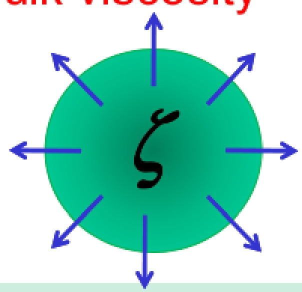
Heinz, arXiv:0901.4355

Shear viscosity – measures the resistance to flow gradients



acts against the buildup of
flow anisotropy

Bulk viscosity – measures the resistance to expansion



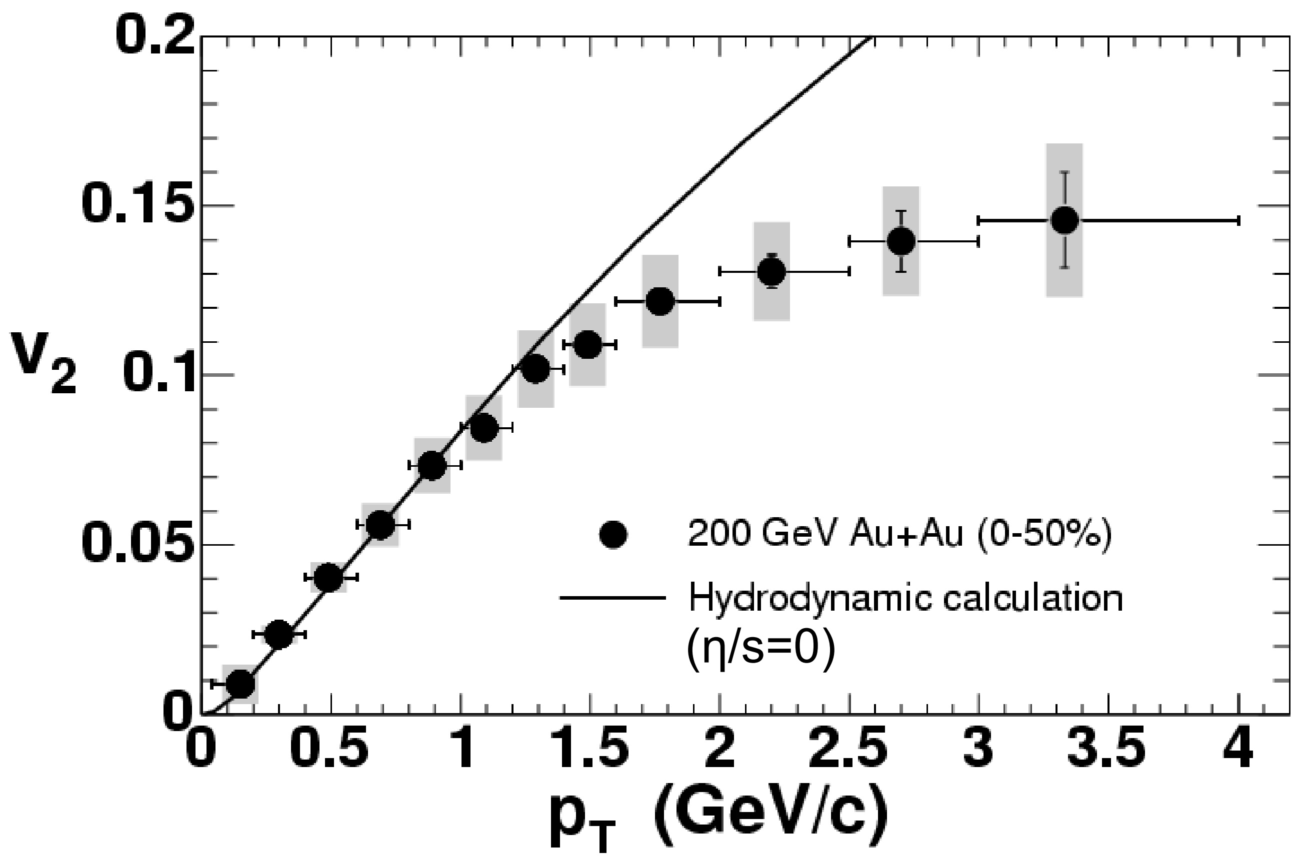
acts against the buildup of
radial flow

Early calculations at RHIC were done with η/s=0.
Today small values between (1-3)/4π used.

KSS bound

$$\eta/s > 1/4\pi \sim 0.08$$

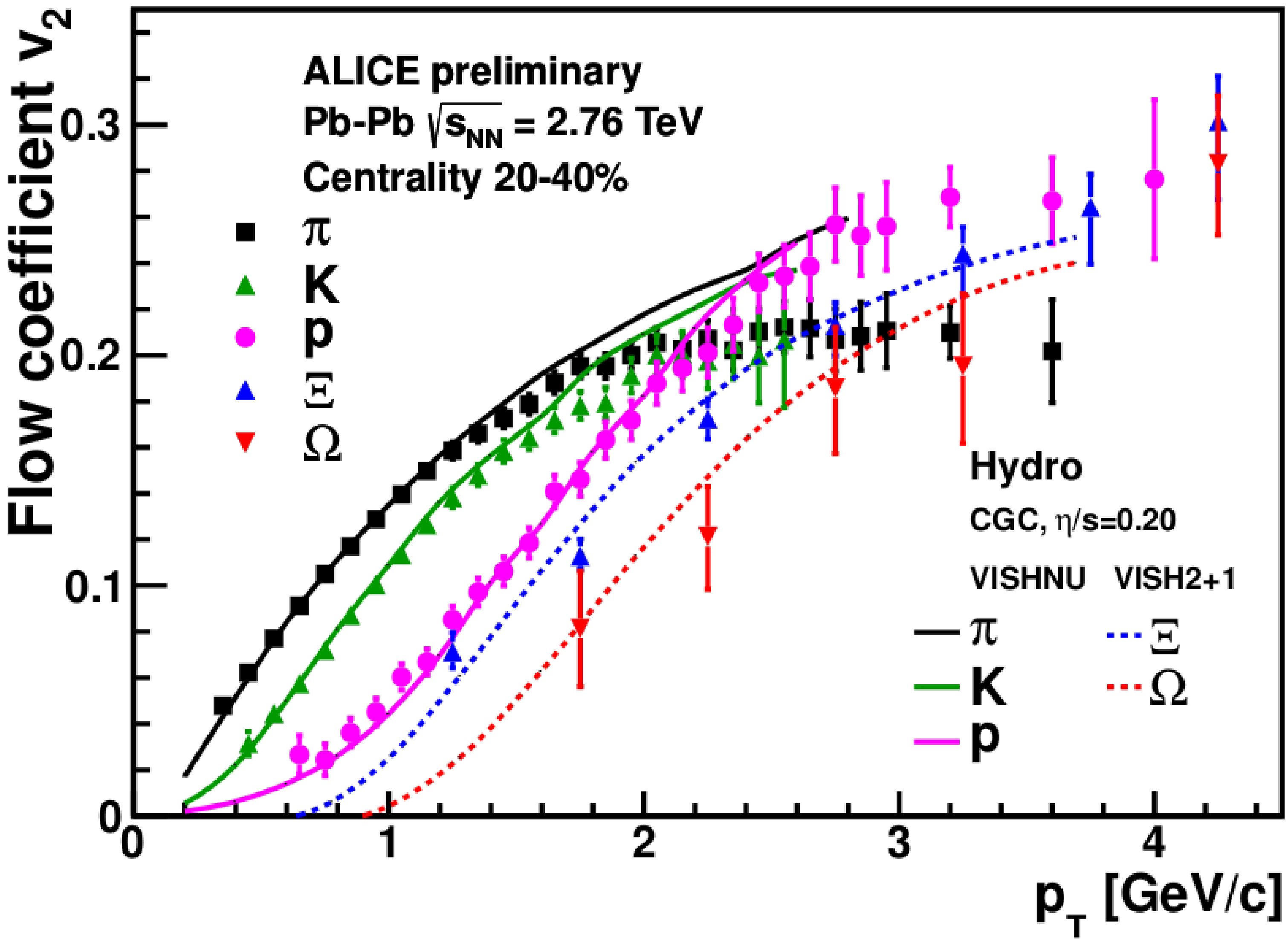
Results on elliptic flow vs p_T (RHIC)



- At low p_T the data is described by hydrodynamics
  - Finite viscosity neglected for early RHIC results
- At high p_T, expect significant deviations, since:
  - High-p_T particles (produced early) are not expected to thermalize
  - Hydrodynamics not expected to be applicable

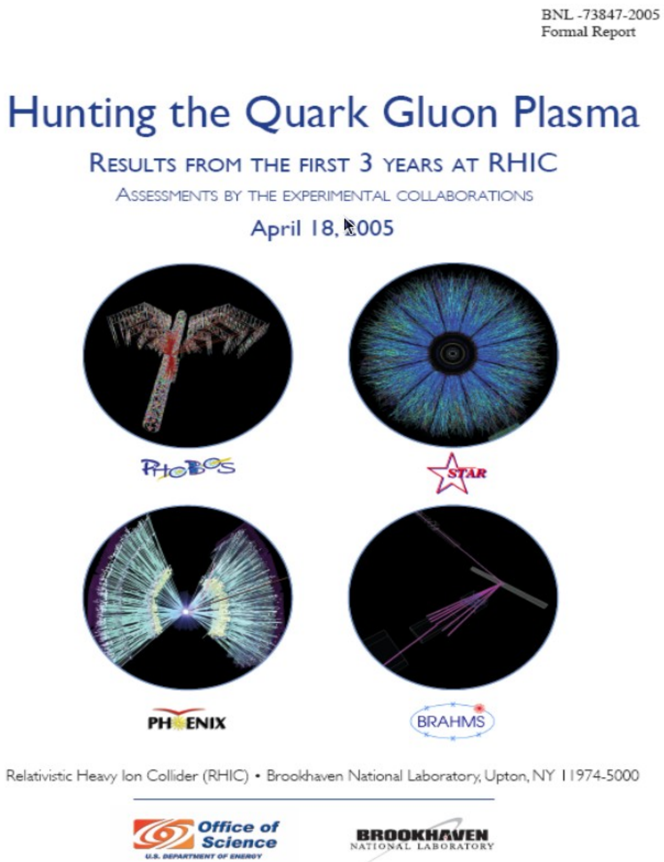
Identified particle v_2 versus p_T (LHC)

arXiv:1202.3233



Observed mass ordering in v_2 due to radial flow can be described by hydrodynamical models

The quark-gluon liquid


BNL -73847-2005
Formal Report

Hunting the Quark Gluon Plasma

RESULTS FROM THE FIRST 3 YEARS AT RHIC

ASSESSMENTS BY THE EXPERIMENTAL COLLABORATIONS

April 18, 2005

PHOBOS STAR

PHENIX BRAHMS

Relativistic Heavy Ion Collider (RHIC) • Brookhaven National Laboratory, Upton, NY 11974-5000

Office of Science U.S. DEPARTMENT OF ENERGY BROOKHAVEN NATIONAL LABORATORY

RHIC whitepapers: NPA 757 1-283 (2005)

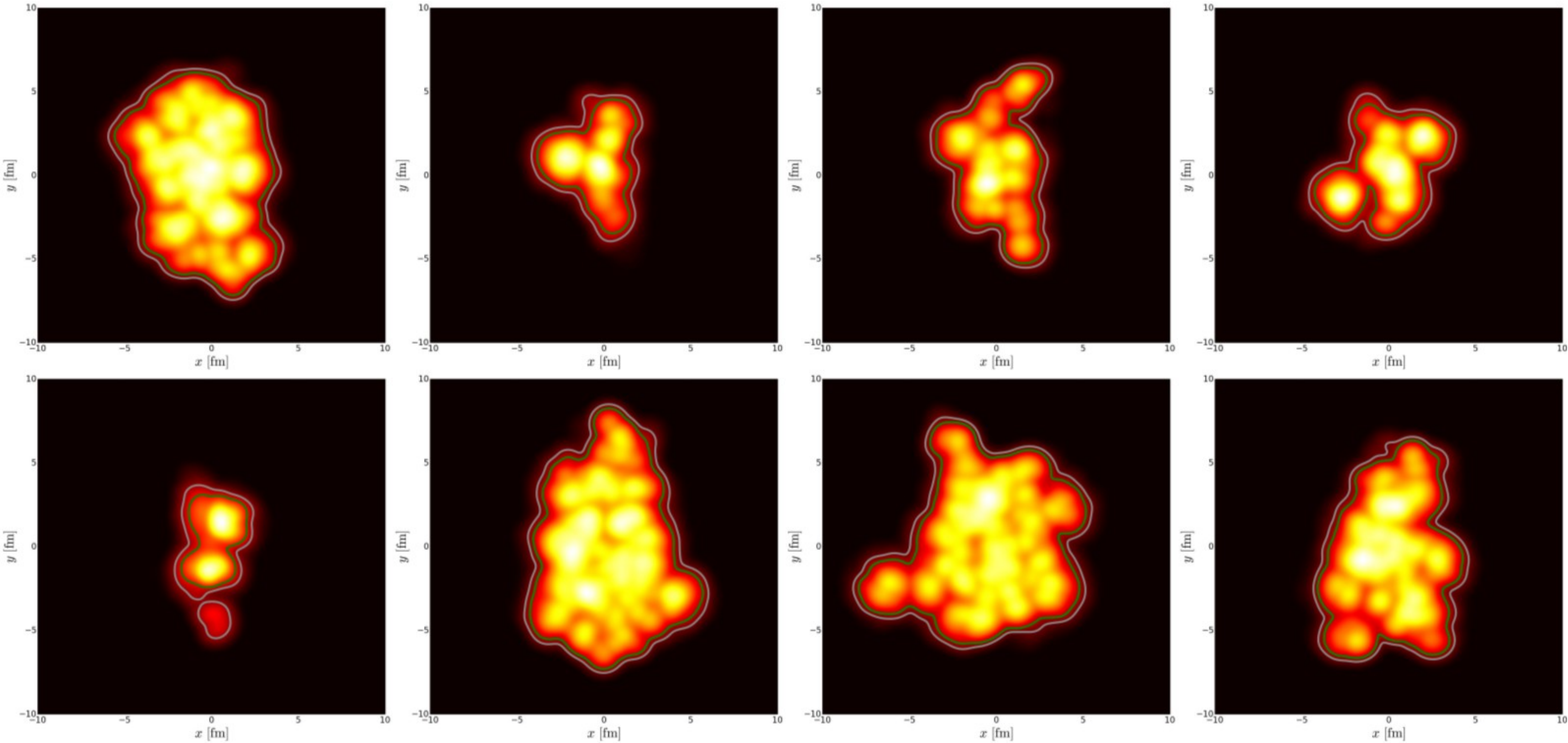
Conjectured in 2005 for RHIC. Picture further substantiated at the LHC

- QGP:
  Not a gas of free quarks and gluons
- Instead, strongly coupled nearly perfect liquid reaching almost the minimum value of shear viscosity to entropy density ratio (η/s)

Initial state fluctuations

Initial and final anisotropy (~2010)

Initial spatial anisotropy not smooth, fluctuates event-by-event and contains other higher harmonics / symmetry planes



Temperature profiles in transverse plane from hydrodynamical calculation (H. Niemi)

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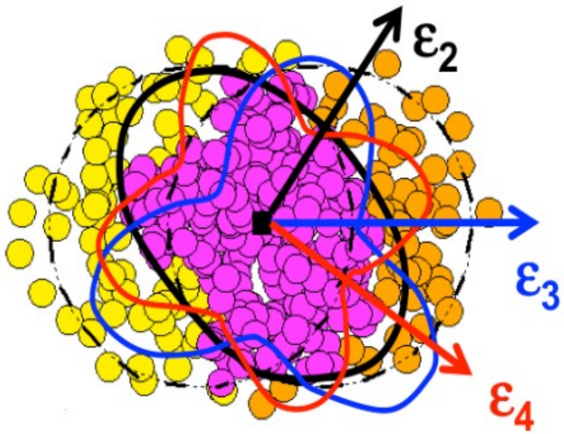


Alver, Roland

$$\frac{dN}{d\varphi} \sim 1 + 2v_2 \cos[2(\varphi - \psi_2)] + 2v_3 \cos[3(\varphi - \psi_3)] + 2v_4 \cos[4(\varphi - \psi_4)] + 2v_5 \cos[5(\varphi - \psi_5)] + \ldots$$

Initial spatial anisotropy: Eccentricity

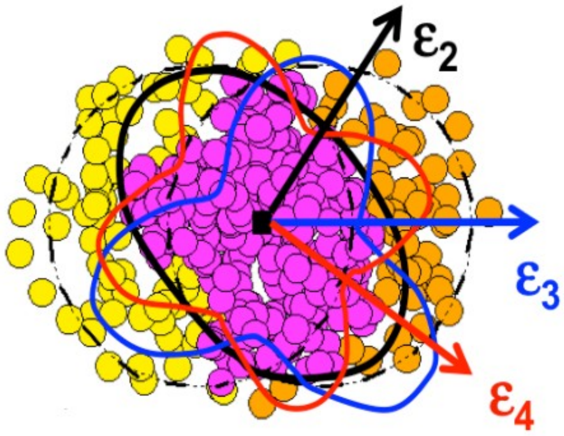
$$\epsilon_n e^{-in\varphi_n}$$

If interactions present early (induces long-range Δη correlations)

Momentum space anisotropy: Flow

$$v_n = \langle \cos(2\varphi - 2\psi_n) \rangle$$

Higher harmonics and viscosity

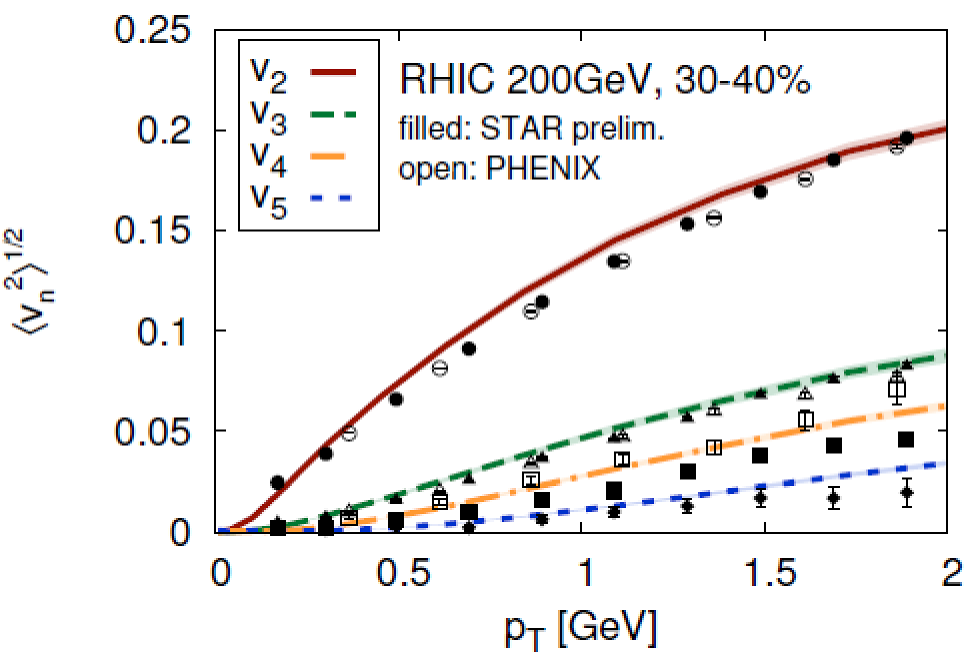


Alver, Roland

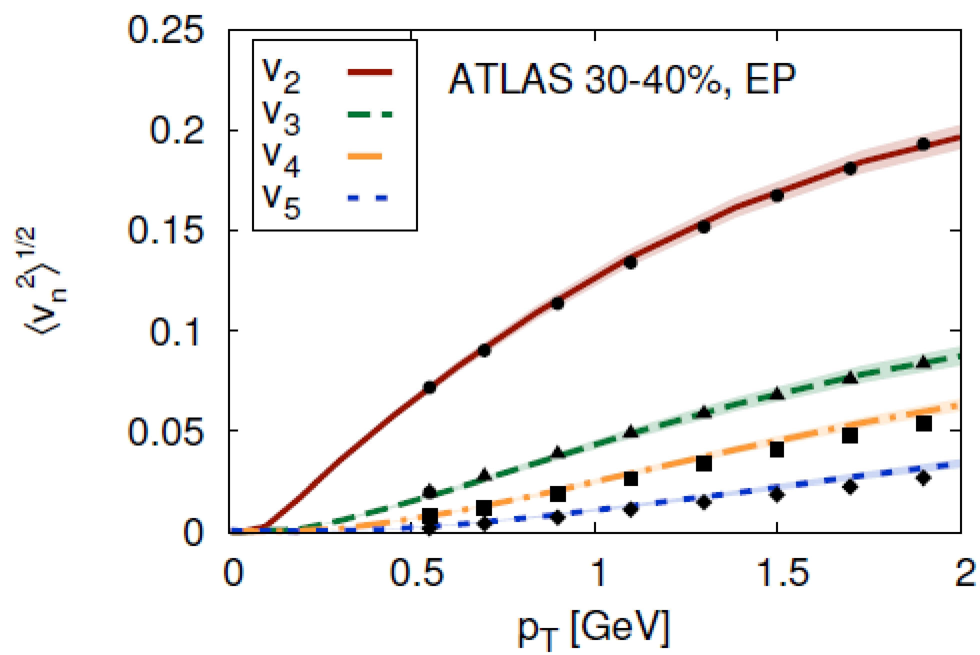
Initial spatial anisotropy not smooth, leads to higher harmonics / symmetry planes.

$$\frac{dN}{d\varphi} \sim 1 + 2v_2 \cos[2(\varphi - \psi_2)] + 2v_3 \cos[3(\varphi - \psi_3)] + 2v_4 \cos[4(\varphi - \psi_4)] + 2v_5 \cos[5(\varphi - \psi_5)] + \ldots$$

RHIC $\eta/s = 0.12$

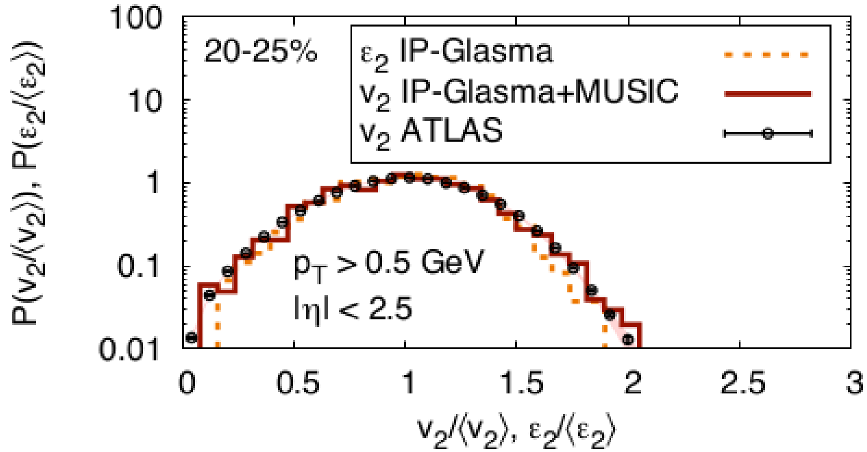


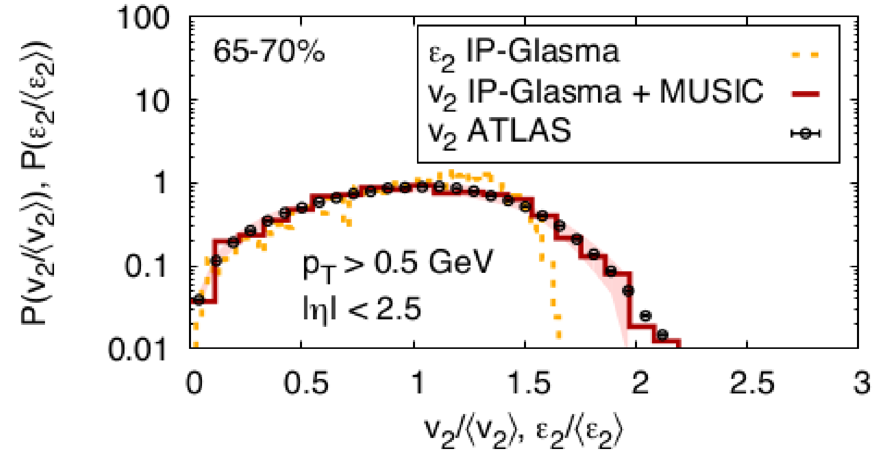
LHC $\eta/s = 0.2$

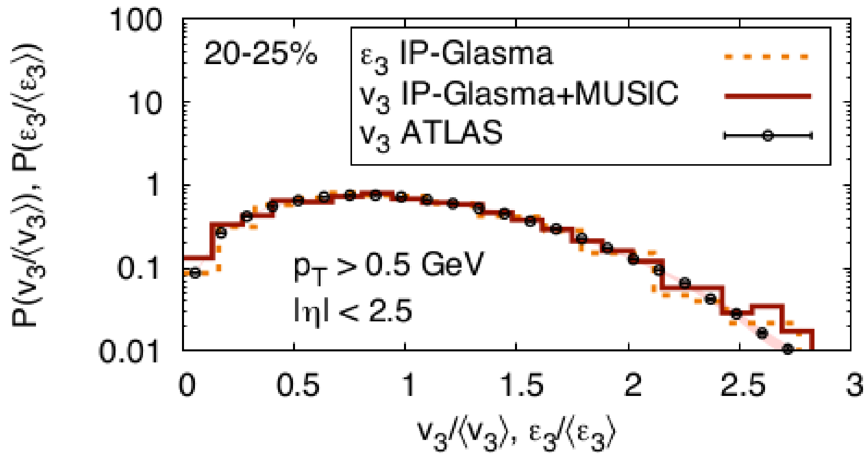


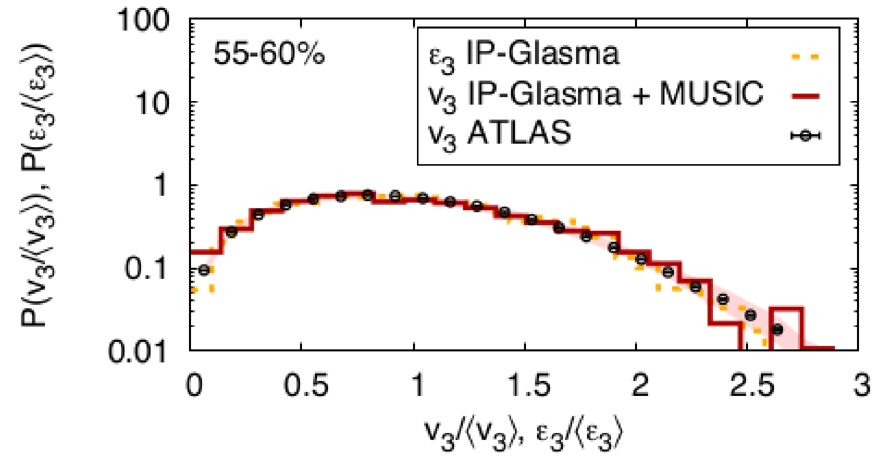
Schenke et al., PRL 110 (2013) 012302

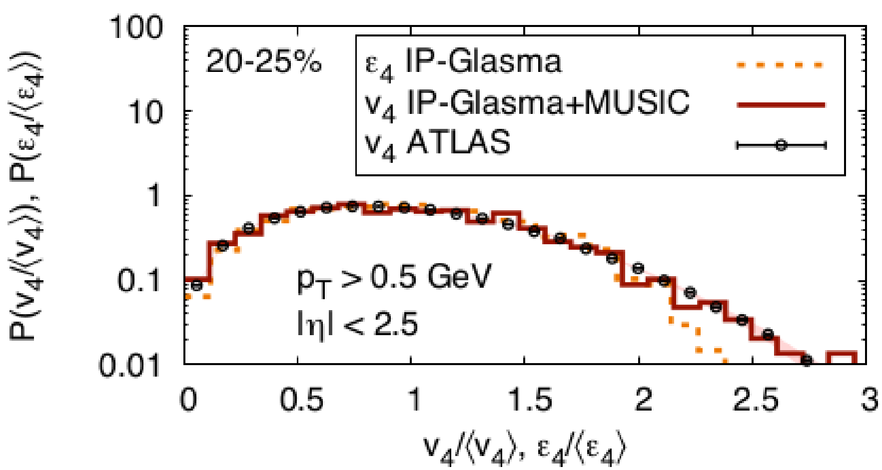
Event-by-event fluctuations











Hydrodynamical calculations can describe event-by-event fluctuations

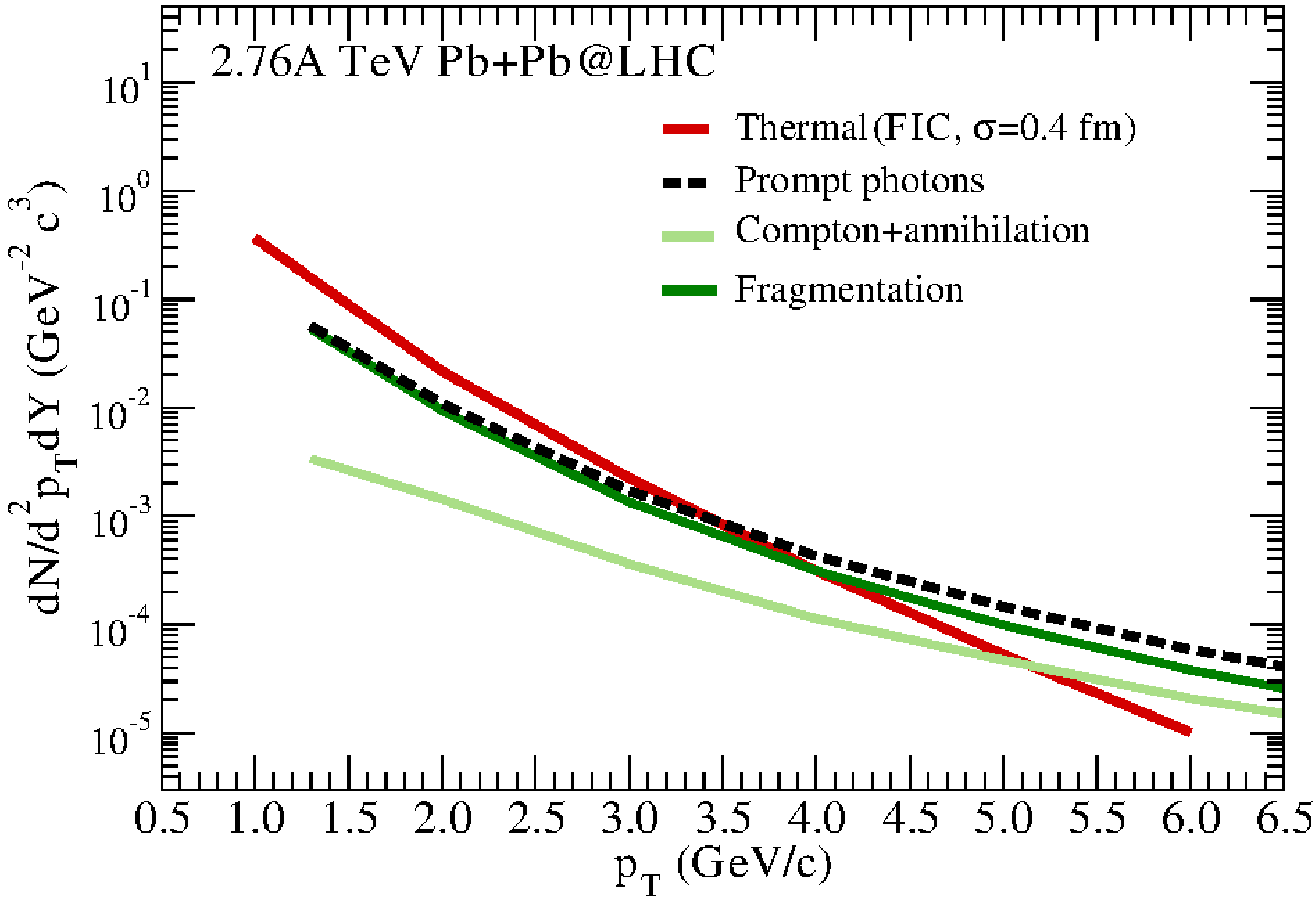
ATLAS, JHEP 11 (2013) 183
Schenke et al., PRL 110 (2013) 012302

Direct photons at low p_T

(Measurement of apparent temperature)

Direct photons

Direct photons: No charge, no color, ie. they do not interact further
Use (at low p_T) to extract temperature of the system.



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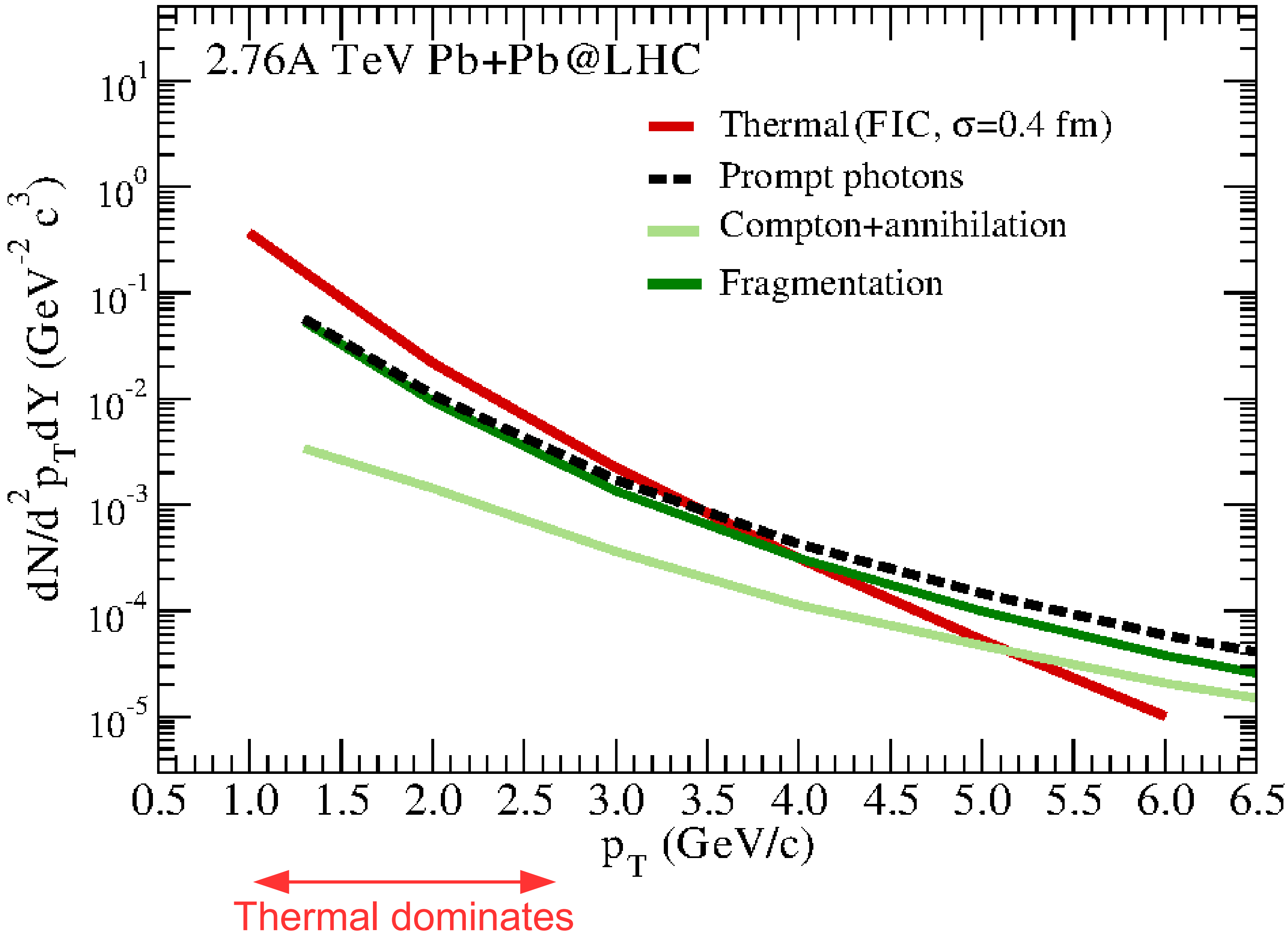

Initial temperature at RHIC

Direct photons: No charge, no color, ie. they do not interact further
Use (at low p_T) to extract temperature of the system.

- Different measurements performed using real and virtual photons
  - E.g. via double ratio $R = \left(\gamma/\pi^0\right)_{\mathrm{inc}} / \left(\gamma/\pi^0\right)_{\mathrm{mc}}$
  - Then $\gamma^{\mathrm{dir}} = (1 - 1/R)\,\gamma^{\mathrm{inc}}$

Initial temperature at RHIC

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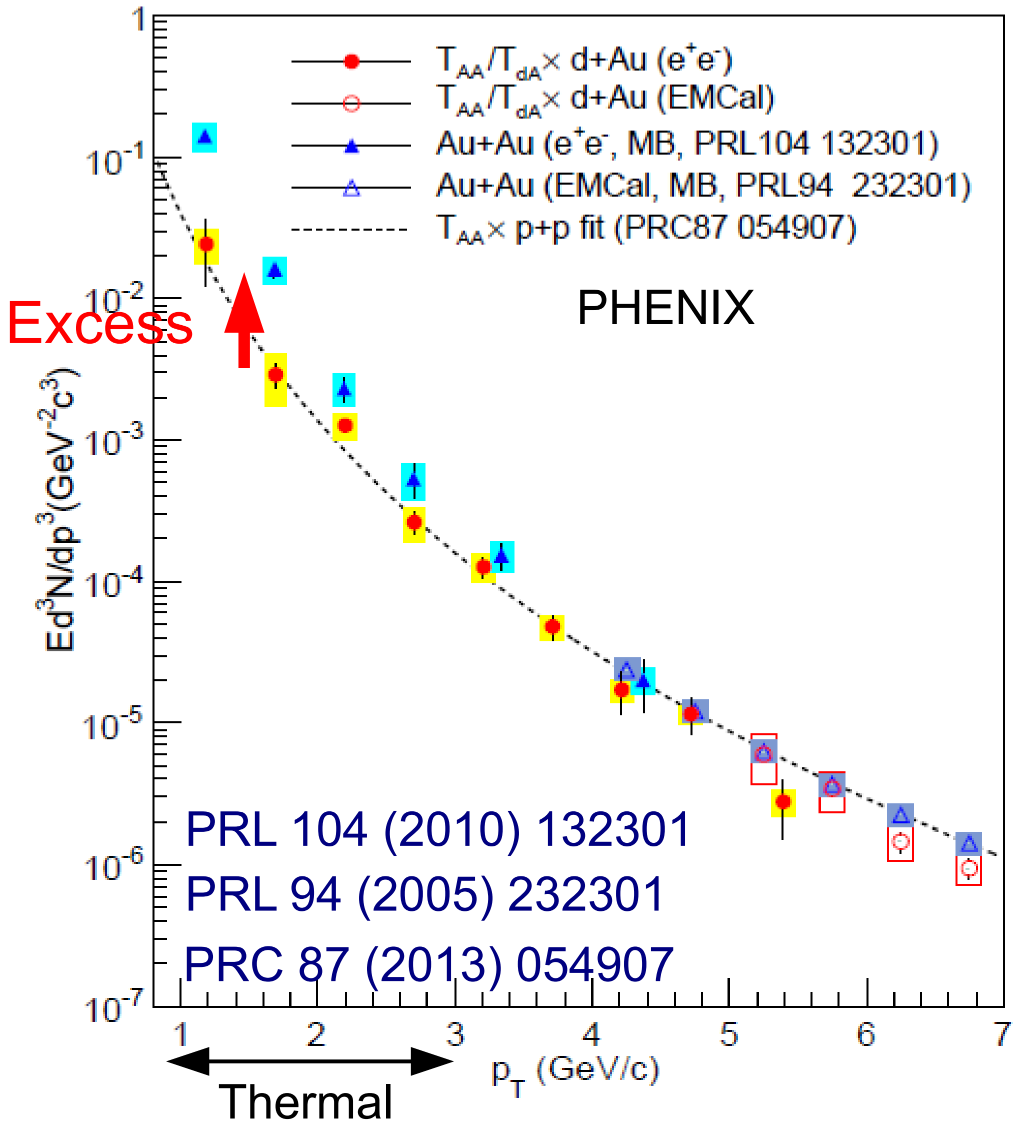

- Different measurements performed using real and virtual photons
  - E.g. via double ratio
    $$R = \left(\gamma/\pi^0\right)_{\rm inc} / \left(\gamma/\pi^0\right)_{\rm mc}$$
- Exponential (thermal) shape with inverse slope of T~220 MeV in excess region
- No excess seen in d+Au (or pp)

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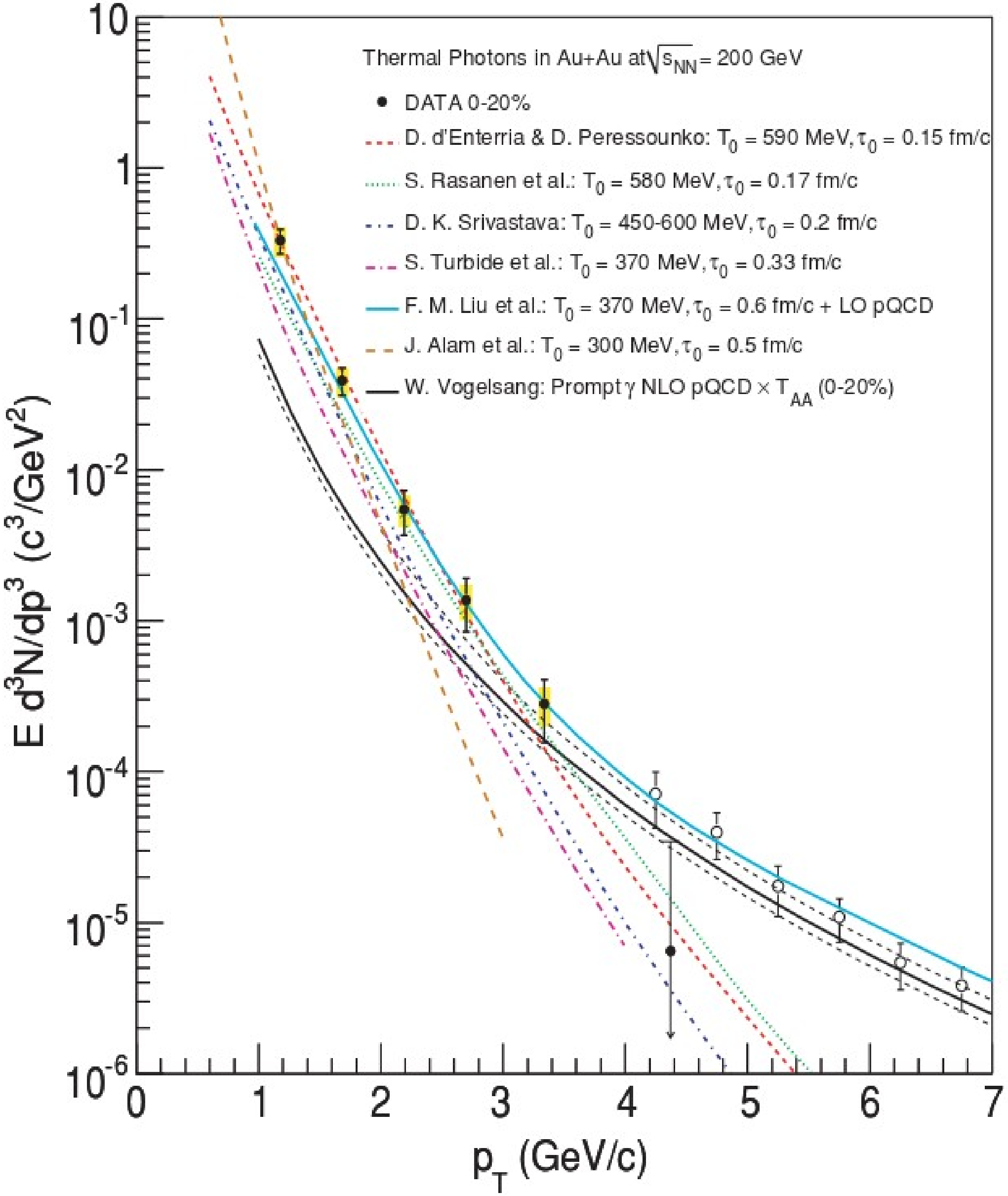

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- Need models to extract T_{init}

Initial temperature at RHIC (also for LHC, see extra slides)

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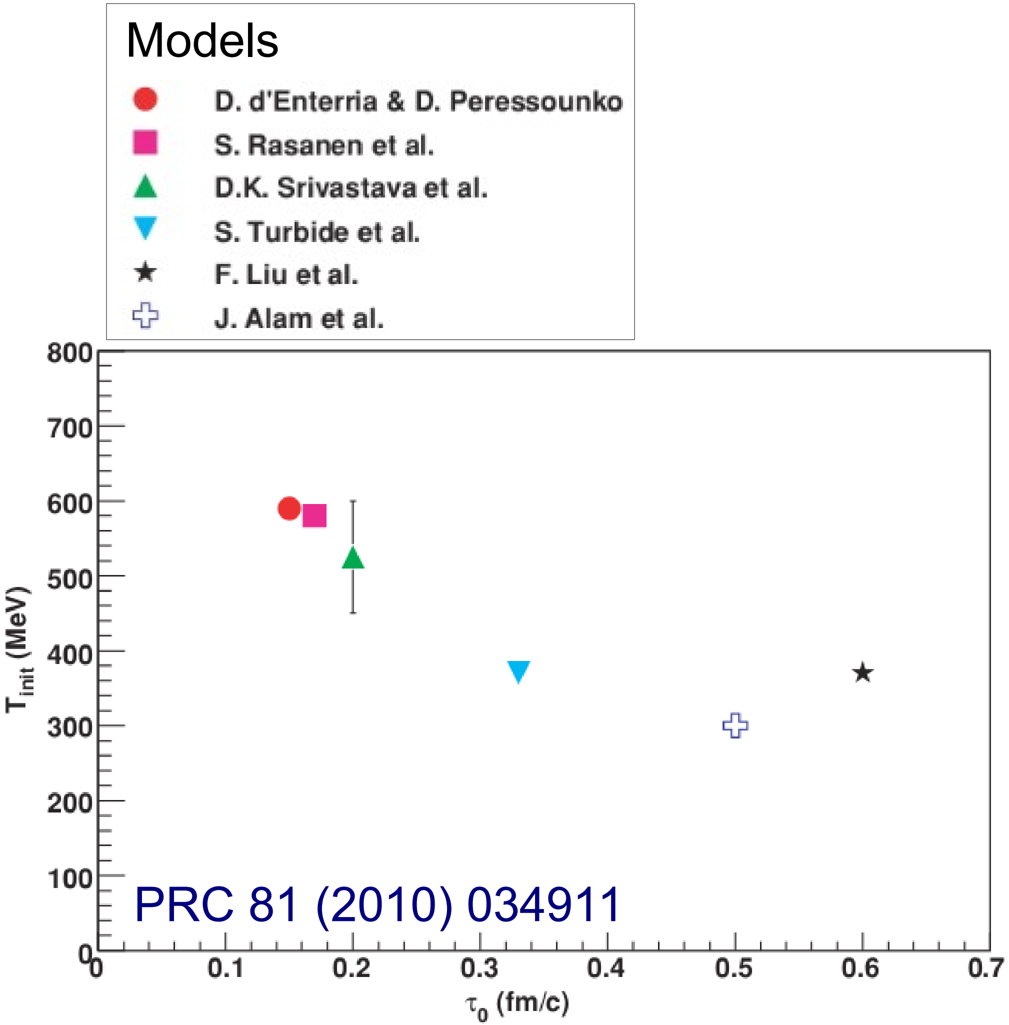
Use (at low p_T) to extract temperature of the system.



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- No excess seen in d+Au (or pp)
- Need models to extract T_{init}
- From models: T_{init} = 300 - 600 MeV (> 2 Tc)

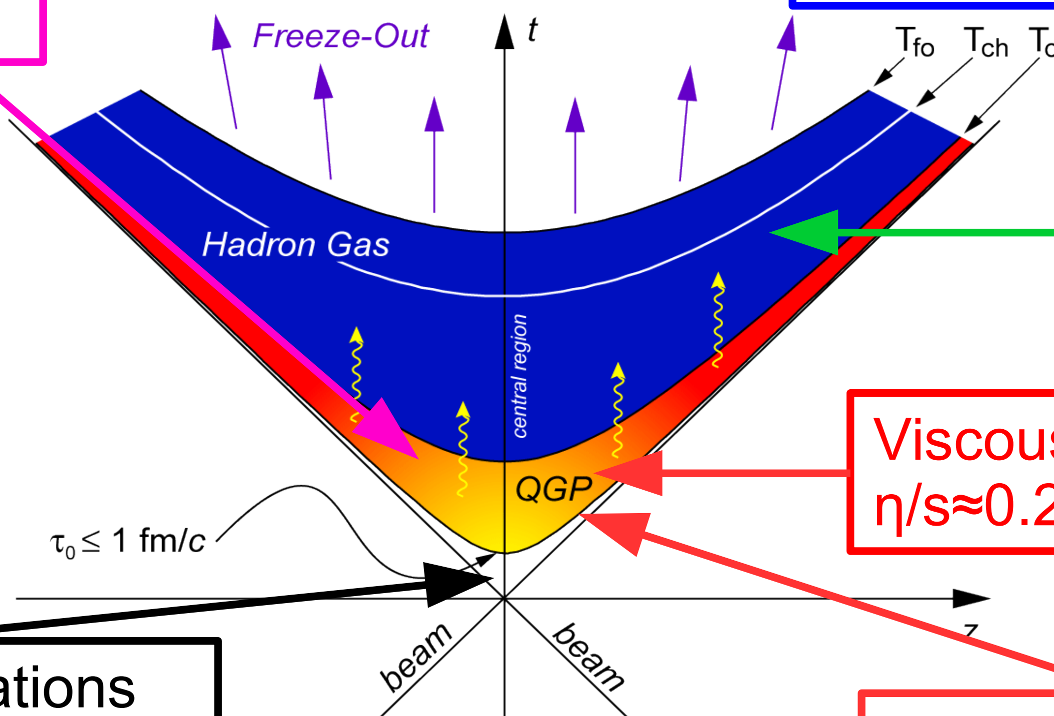
First experimental observation of $T>T_c$

Summary

Harmonic flow v_N
(v_2 up to 0.1)
Mass ordering

$dN/d\eta \approx 1600$
(values for central PbPb at 2.76 TeV)

Kinetic freezeout ≈100 MeV
Radial flow velocity ≈0.65c
Volume ≈ 5000 fm^3
Lifetime ≈10 fm/c



Chemical freeze-out ≈160 MeV
(Grand-canonical)

Viscous hydrodynamics
$\eta/s \approx 0.2$

Initial temperature
>300 MeV

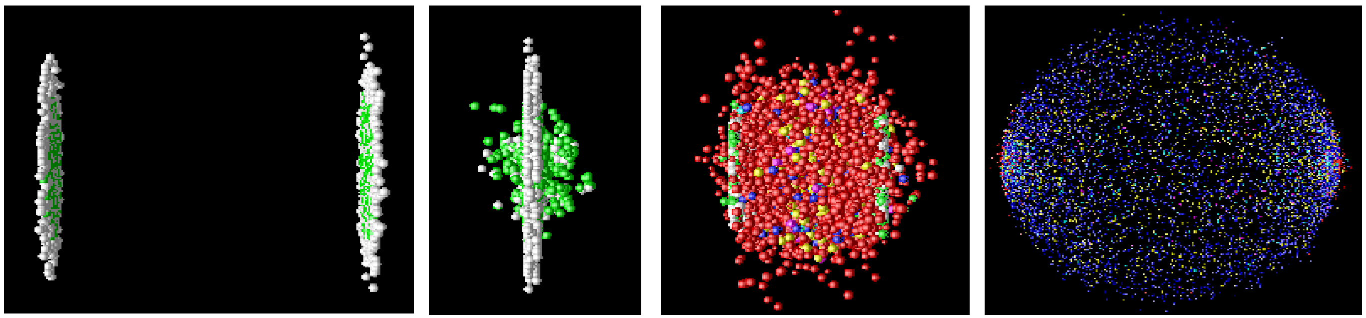
Density fluctuations
↓
Interactions/Pressure
↓
Momentum anisotropies

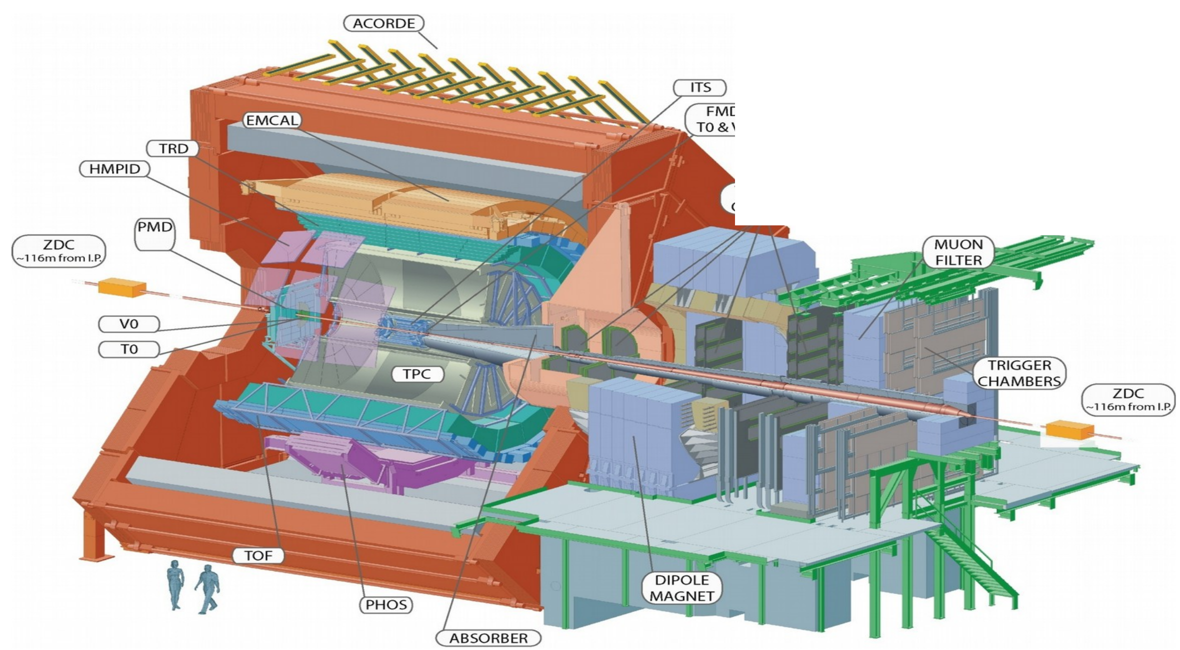
If you have questions about today's lecture please send them to "cloizides at lbl dot gov"

Extra

Nuclear geometry and collision centrality

Nuclei are macroscopic objects:
Characterize collisions via impact parameter





Nuclear geometry and collision centrality

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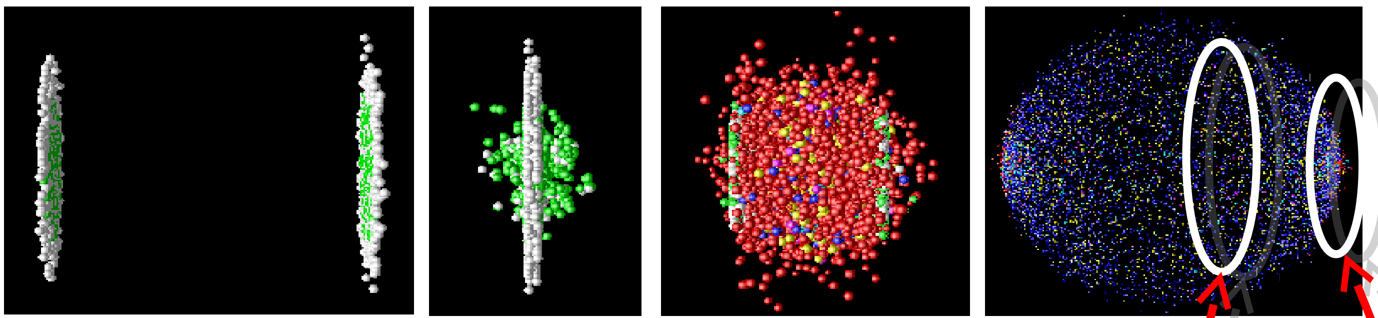
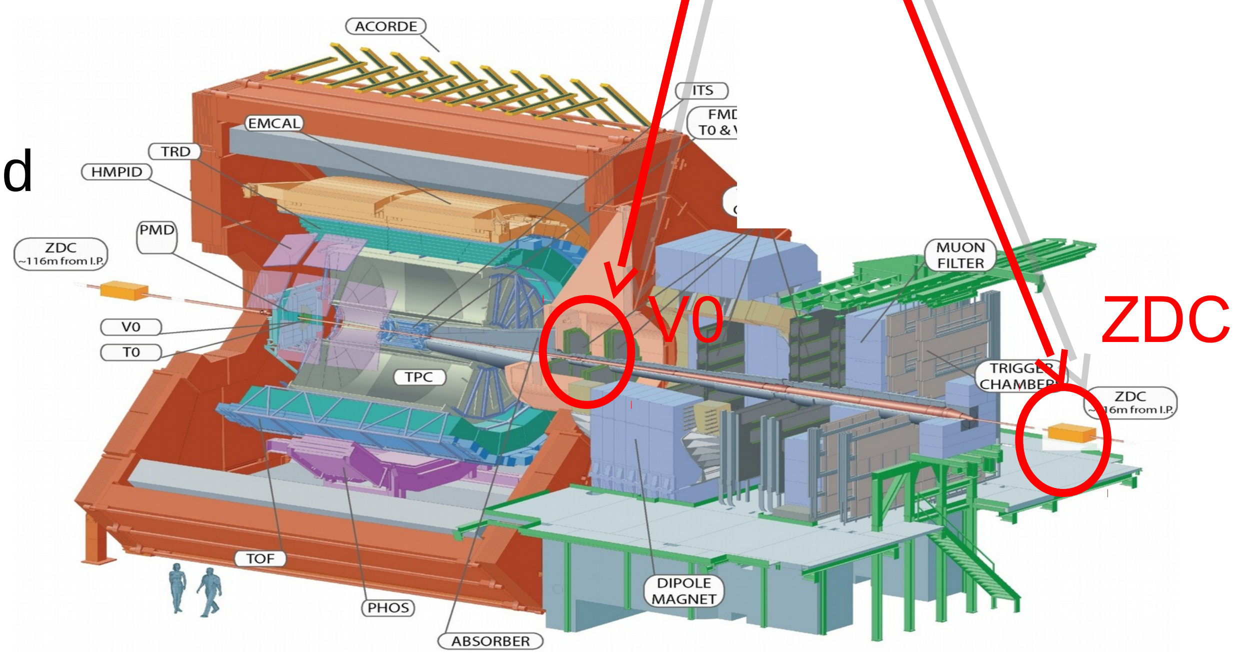
Characterize collisions via impact parameter



Correlate particle yields from ~causally disconnected parts of phase space

→Correlation arises from common dependence on collision impact parameter



Nuclear geometry and collision centrality

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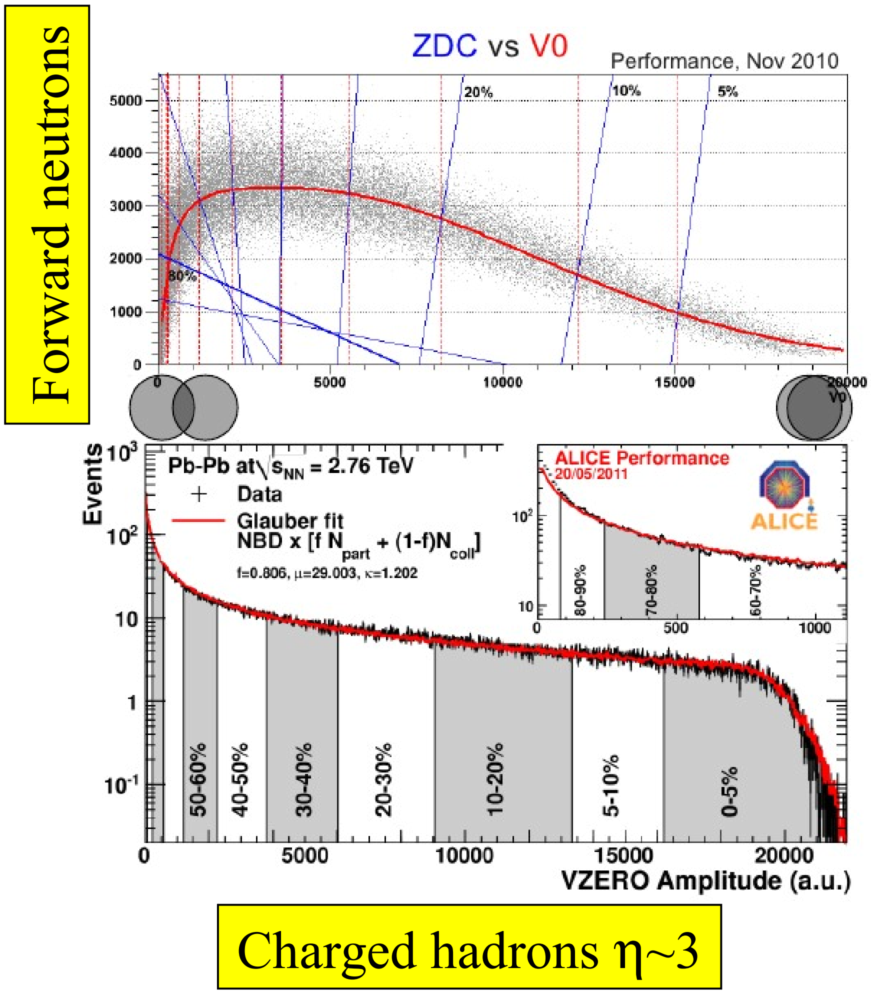


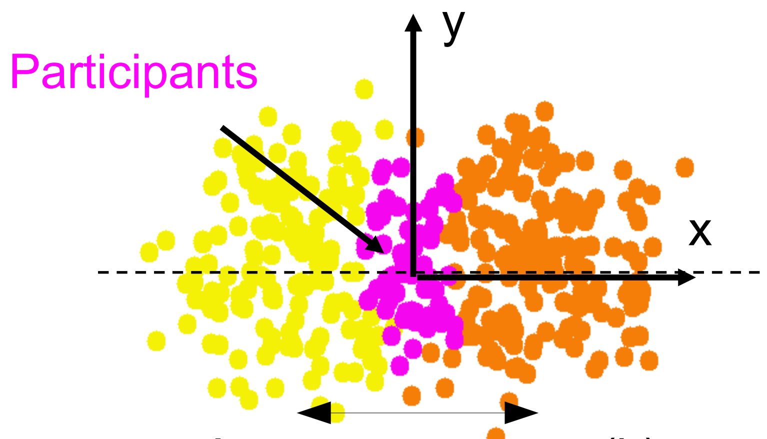
PRC 88 (2013) 044909

- Order events by centrality metric
  - Typically, classify them as “ordered” fraction of total cross section
    - eg. 0-5% most central collisions
  - Not trivial to obtain total cross section as it requires good control of background and trigger efficiency for very peripheral collisions
  - Connect to Glauber theory via particle production model to obtain
    - Number of (inelastically scattered) participating nucleons
    - Number of binary nucleon collisions

Glauber Monte-Carlo model

- Semi-classical model of nucleus+nucleus collision based on incoherent nucleon+nucleon scatters
  - Nucleons distributed according to measured proton charge distribution in nucleus, e.g. Pb nucleus
    - Radius (6.62 ± 6fm)
    - Skin depth (0.546 ± 0.02 fm)
  - Assume repulsion by enforcing inter-nucleon distance (e.g. 0.4 ± 0.4 fm)
- Collision process by assuming
  - Straight-line nucleon trajectories
  - Interaction radius given by inelastic proton-proton cross section (σ_{NN})
  - Equal probabilities for all (including) subsequent scatterings

Ann.Rev.Nucl.Part.Sci. 57 (2007) 205



- Calculate vs impact parameter
  - #Participants ($\langle N_{part} \rangle$)
    - Nucleons struck at least once
  - #NN-collisions ($\langle N_{coll} \rangle$)
    - Total number of collisions
  - Size of interaction area ($\langle S \rangle$)

Thermal equilibrium

- In HI usually two aspects of thermal equilibrium are considered
  - Kinetic Equilibrium
    - Are the p_T distributions of particle species at low p_T described by a thermal distribution?
  - Chemical Equilibrium
    - Are all particle species produced at the right relative abundances?

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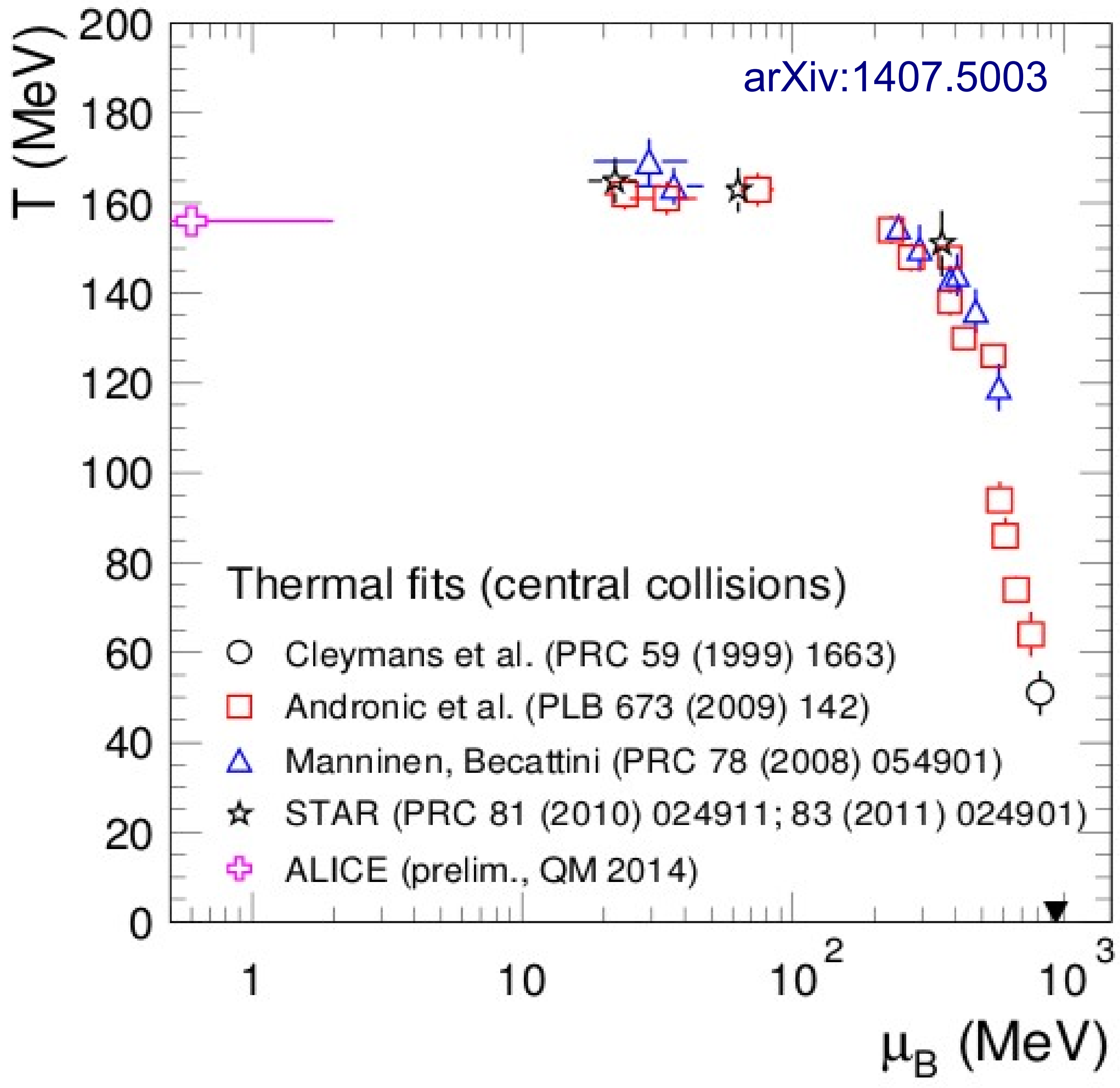
  - Chemical Equilibrium
    - Are all particle species produced at the right relative abundances?
- Chemical equilibrium:
  - Grand Canonical Ensemble: In a large system with many produced particles implement conservation laws in an averaged sense via appropriate chemical potentials
  - Canonical Ensemble: In a small system, conservation laws must be implemented on an event-by-event basis. Leads to severe restriction of available phase space (“Canonical Suppression”)
  - Canonical description is required for
    - Low energy HI collisions
    - High energy e+e- or hh collisions
    - Peripheral high energy HI collisions

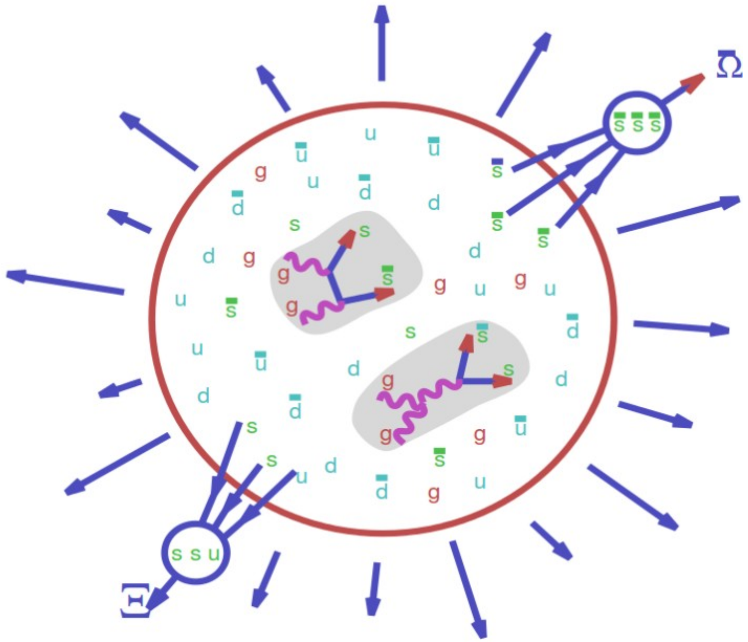
Statistical model parameters vs $\sqrt{s_{NN}}$



Chemical freeze-out points

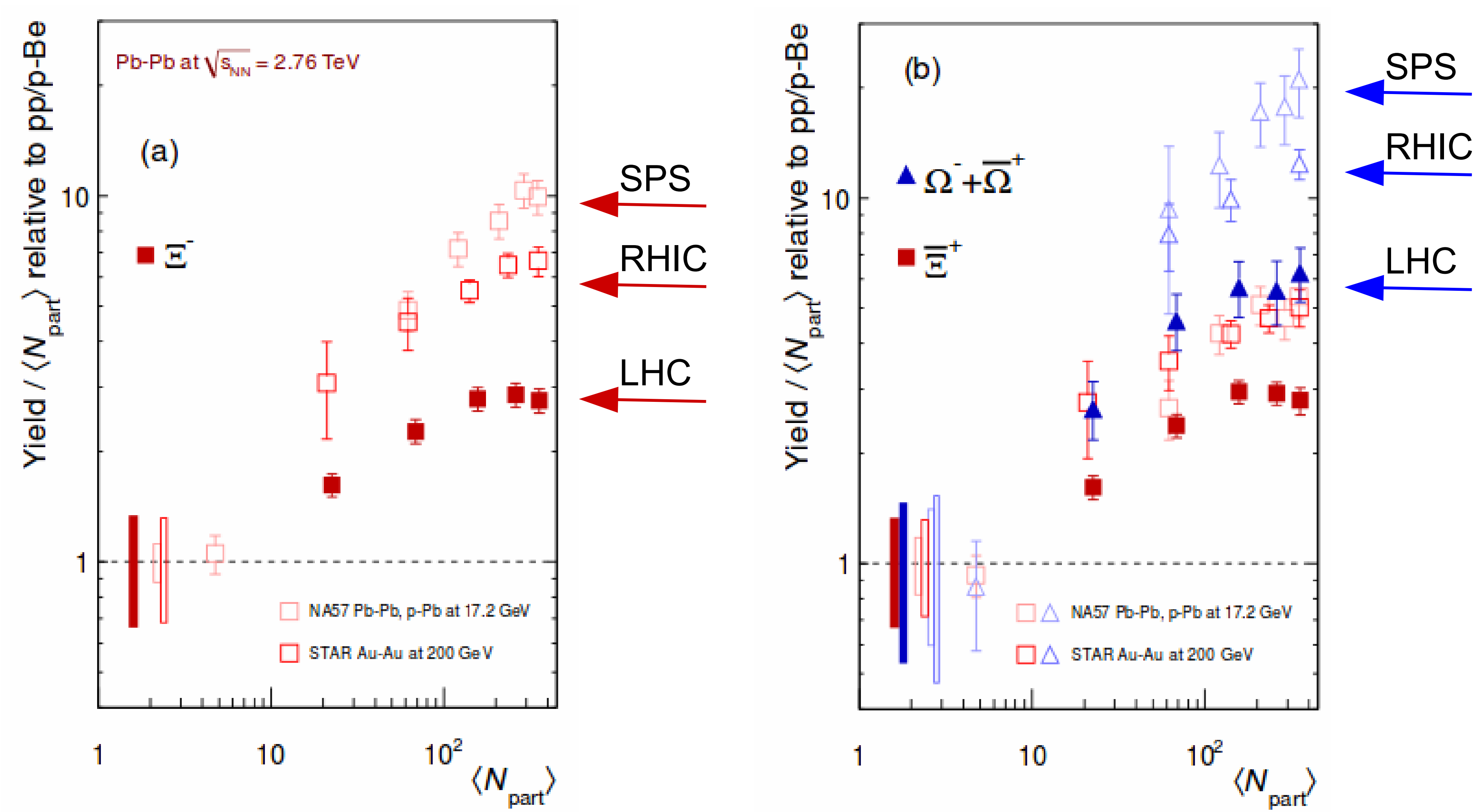
Strangeness enhancement

- Chiral symmetry restoration should lead to increased yield of strange quark production by gluon fusion
  - $m_s \approx 150$ MeV/c^2 ie. below T_c
- For a grand-canonical system effect strongest for multi-strange hadrons due to recombination



(original ideas Rafelski and Mueller, 1982
Koch, Mueller and Rafelski, 1986)

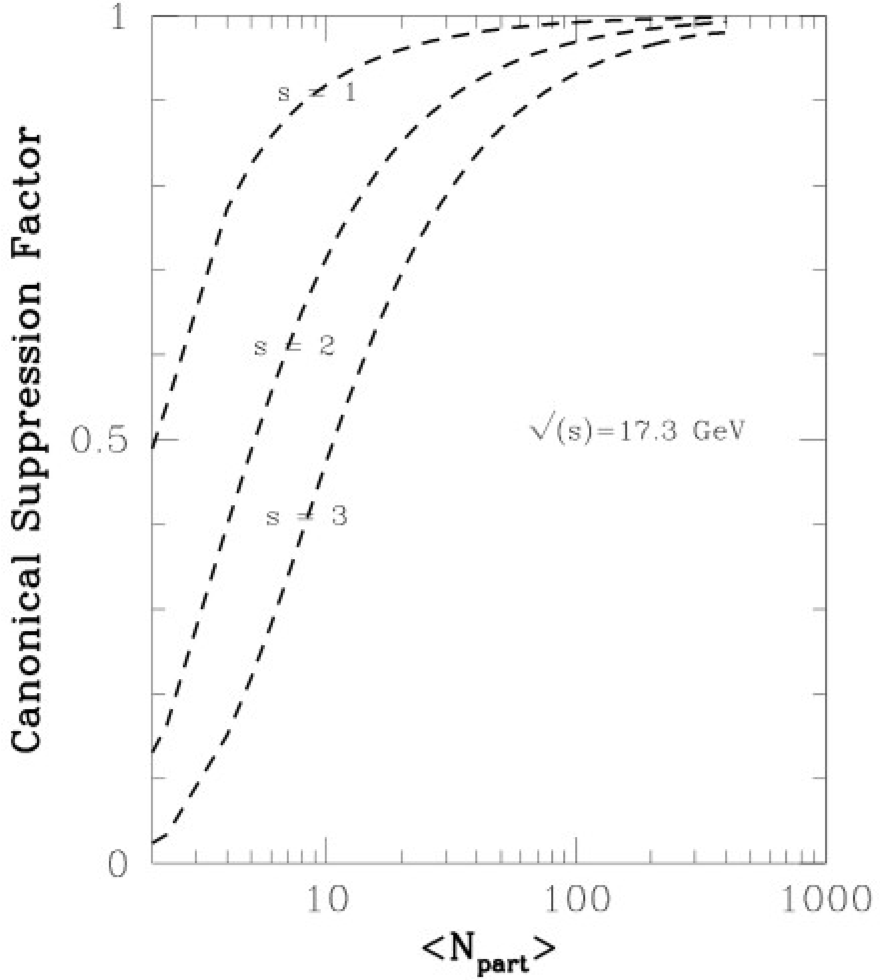
Strangeness enhancement

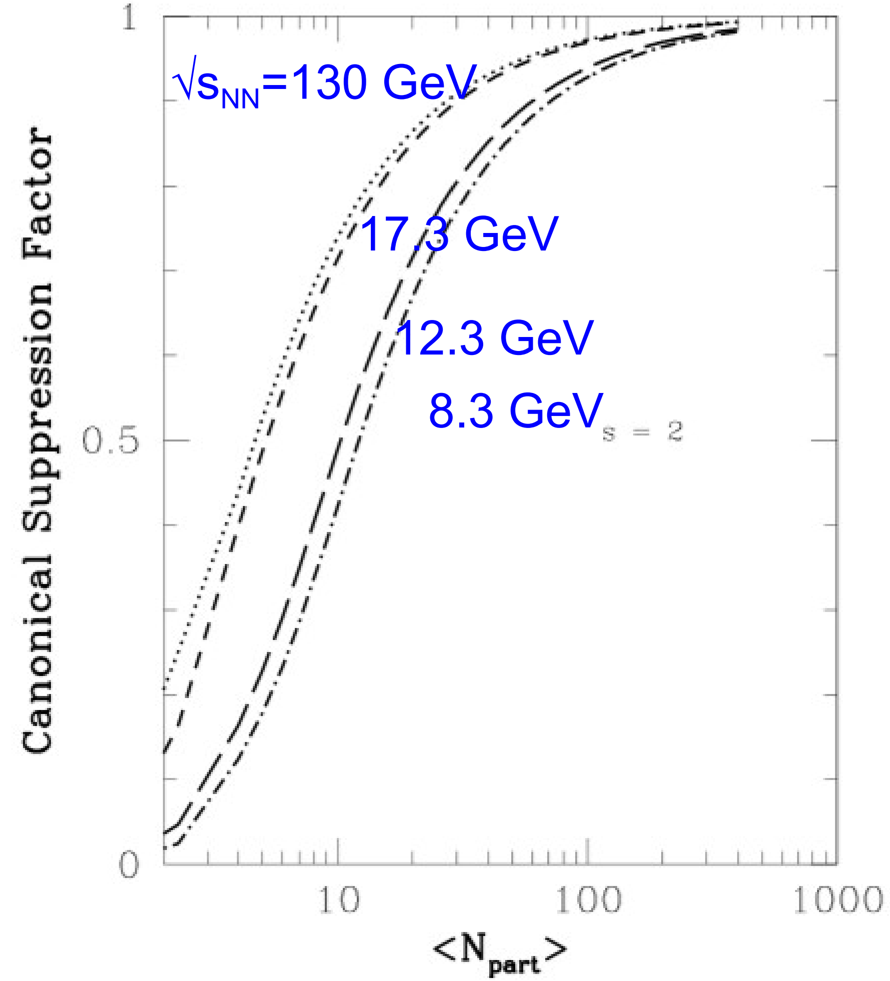


Strangeness enhancement observed, but reduced with increasing collision energy (due to even stronger-increasing yield in pp).
Strangeness enhancement understood as release of small-volume canonical constraints (see R.Stock, arXiv:0312039)

Canonical suppression

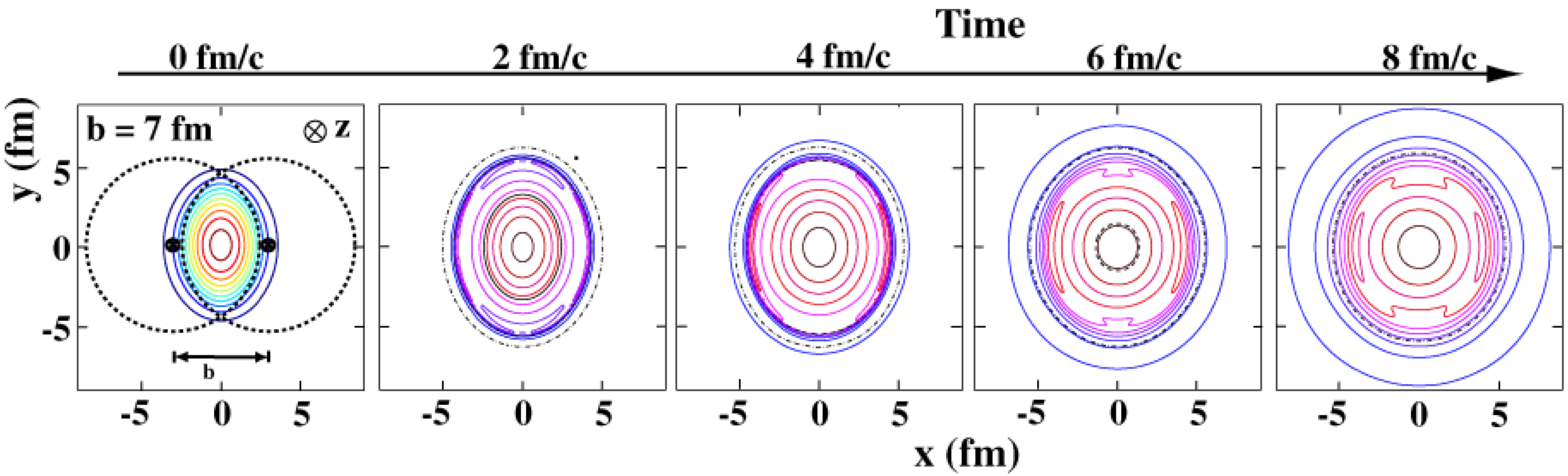
Redlich and Tounsi, hep-ph/0111159





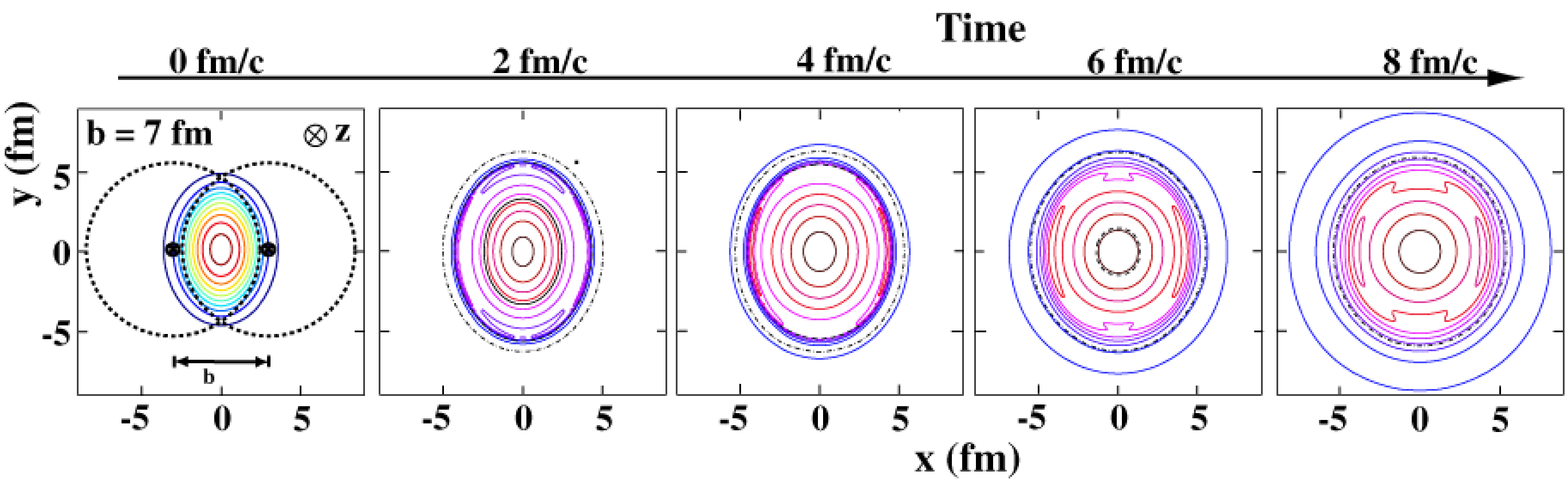
For Npart≥60, Grand Canoncial ok to better than 10%

Elliptic flow: Self quenching

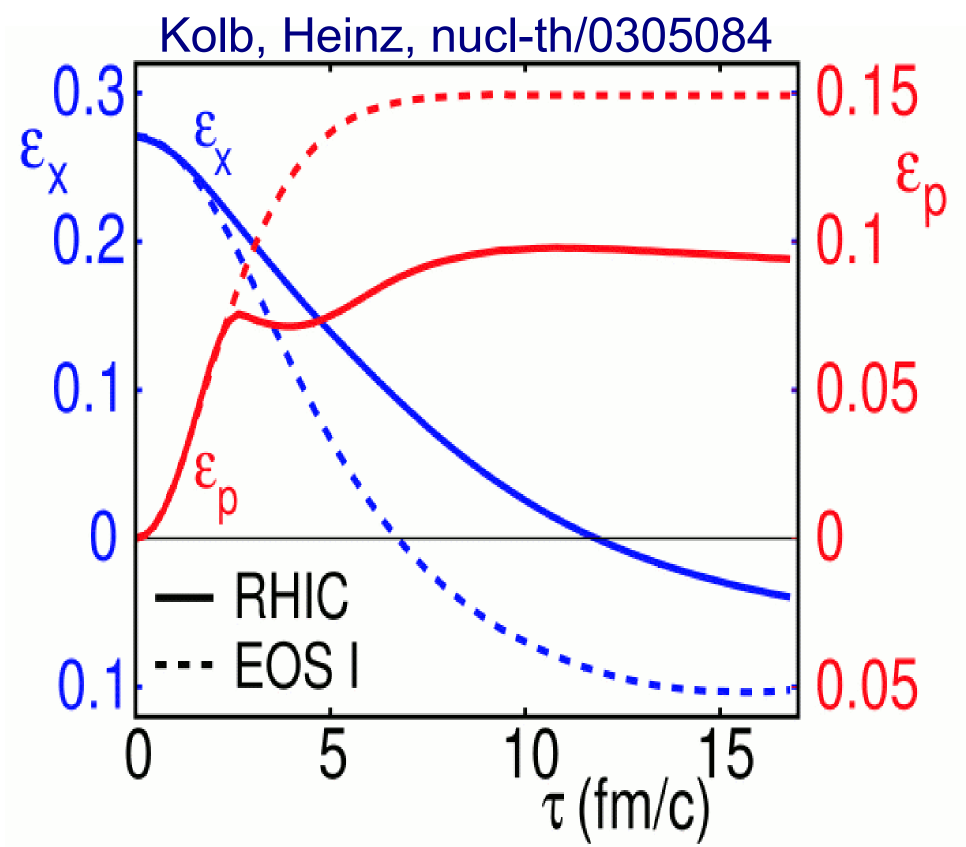


- The geometrical anisotropy, which gives rise to the elliptic flow becomes weaker with the evolution of the system
- Pressure gradients are stronger in the first stages of the collision
- Elliptic flow is therefore an observable particularly sensitive to the early stages of the system

Elliptic flow: Self quenching



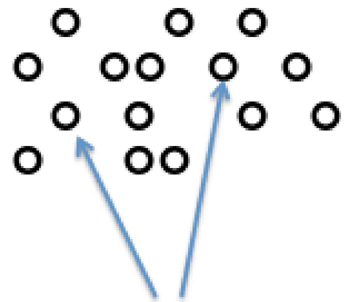
- The picture is supported by a hydrodynamical calculation using two different equations of state
- The momentum anisotropy is dominantly built up in the QGP (τ<2-3fm/c) phase and stays constant in the (first-order) phase transition, and only slightly rises in the hadronic phase



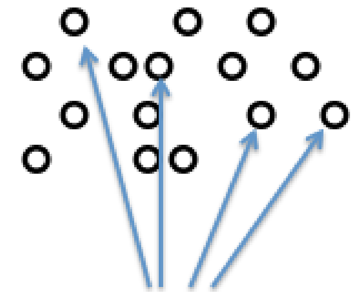
Multi-particle correlations: $v_2\{4\}$ and higher

- Cumulants to extract genuine k-particle correlations excluding those from k-1 particles
- To first order for k=2 k=4
  - $v_2\{2\}^2 = \langle v_2 \rangle^2 + \sigma_{v_2}^2 + \delta_2$
    $v_2 \gg 1/\sqrt{M}$
  - $v_2\{4\}^2 = \langle v_2 \rangle^2 - \sigma_{v_2}^2$
    $v_2 \gg 1/M^{3/4}$
  - eg. for M=100, v_2>>0.03

See arXiv:1010.0233

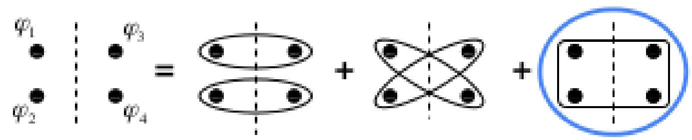


$$\left\langle e^{in(\varphi_1-\varphi_2)} \right\rangle$$



$$\left\langle e^{in(\varphi_1+\varphi_2-\varphi_3-\varphi_4)} \right\rangle$$

Four particle correlations (Q-cumulant method):



$$c_n\{4\} = \langle\langle 4 \rangle\rangle - 2 \cdot \langle\langle 2 \rangle\rangle^2$$

$$v_2\{4\} = \sqrt[4]{-c_n\{4\}}$$

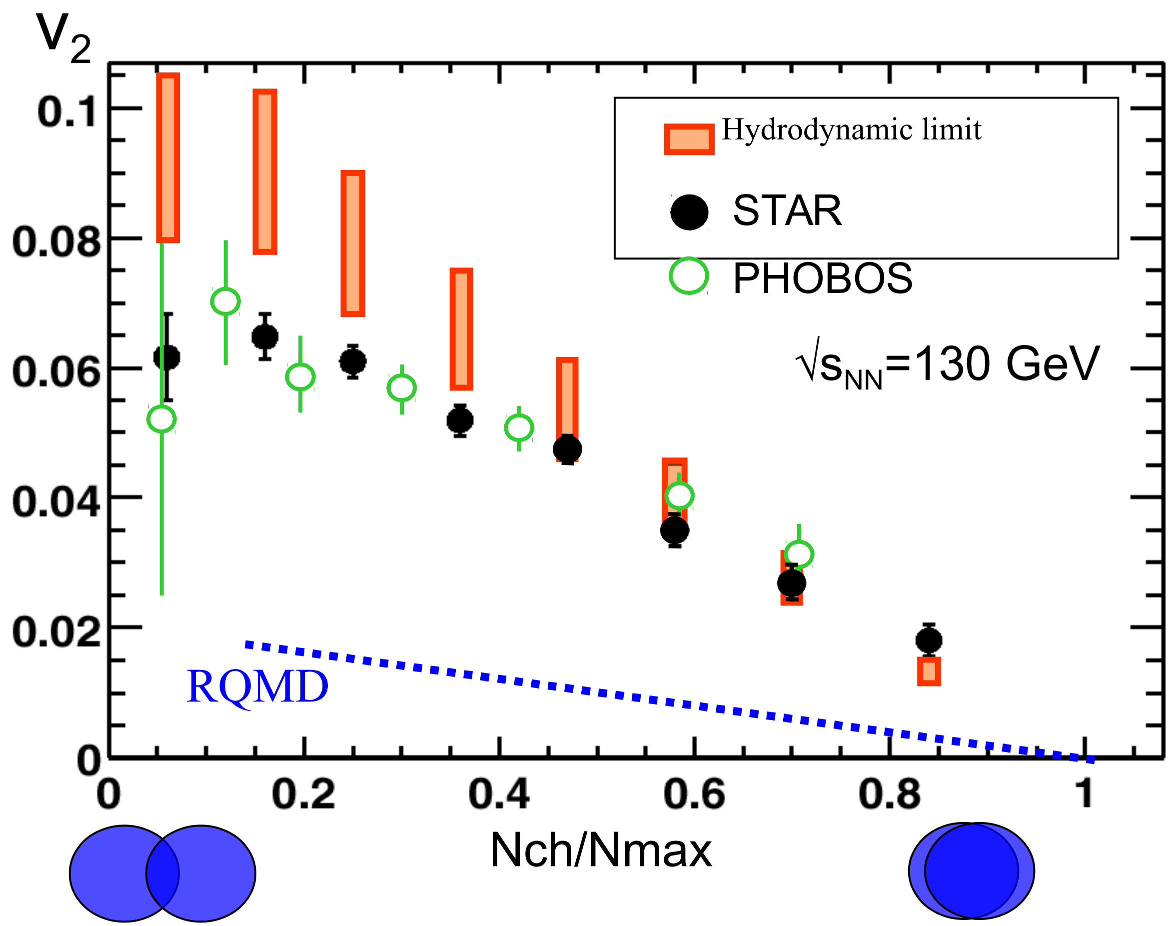
$$\left\langle e^{in(\varphi_1+\varphi_2-\varphi_3-\varphi_4)} \right\rangle - \left\langle e^{in(\varphi_1-\varphi_3)} \right\rangle \left\langle e^{in(\varphi_2-\varphi_4)} \right\rangle - \left\langle e^{in(\varphi_1-\varphi_4)} \right\rangle \left\langle e^{in(\varphi_2-\varphi_3)} \right\rangle$$

(From S. Tuo)

Multi-particle correlations (cumulant) studies extract the genuine multi-particle correlation

Results on integrated elliptic flow (RHIC)

- Elliptic flow depends on
  - Eccentricity of overlap region, which decreases with increasing centrality
  - Number of interactions, which increases with increasing centrality



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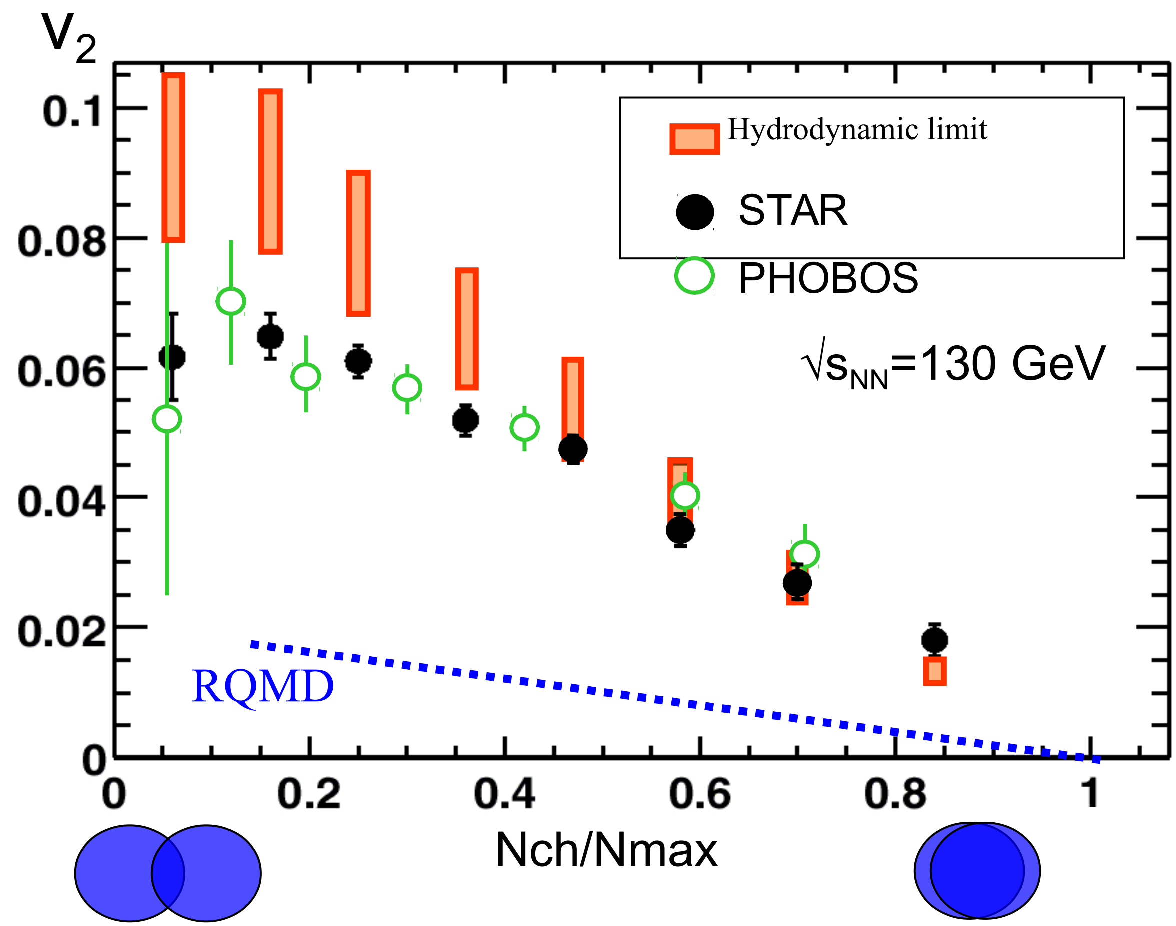

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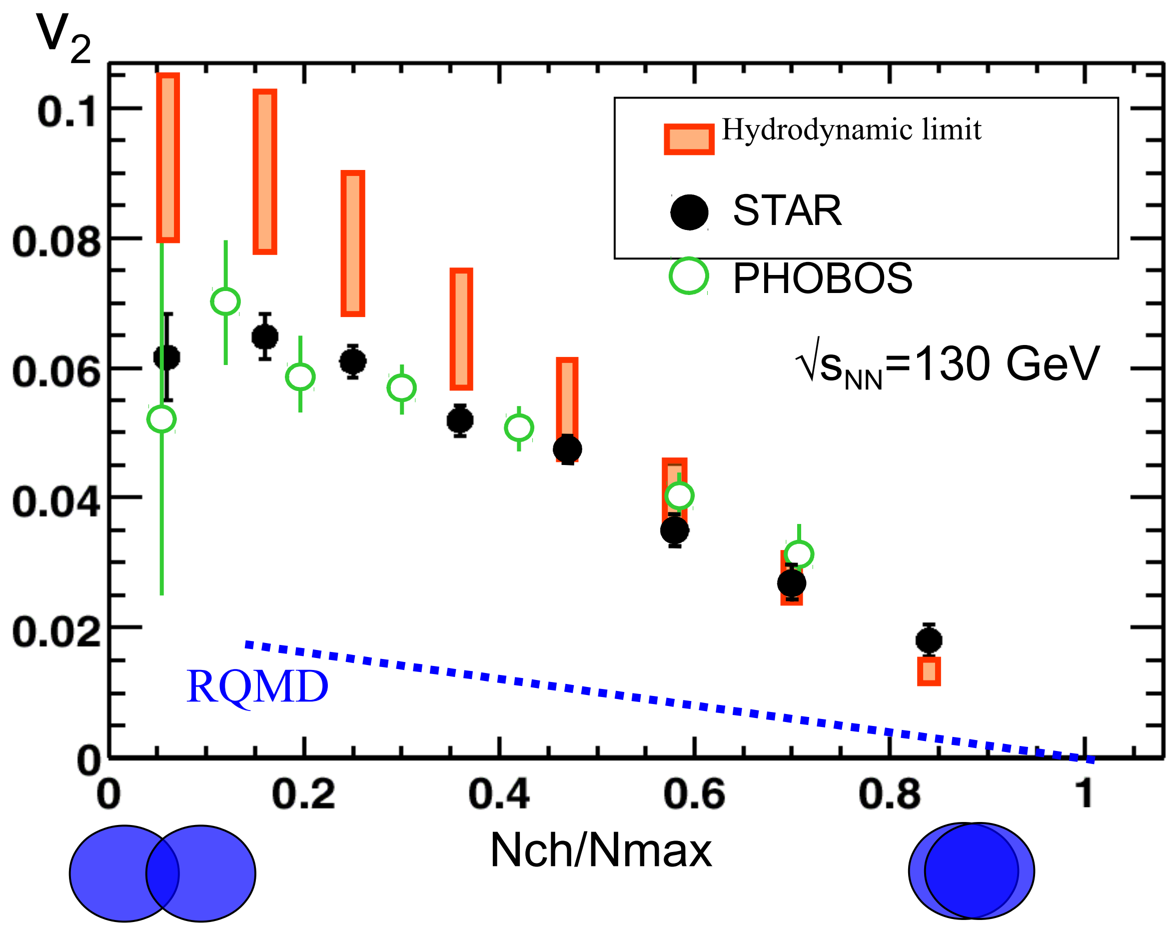
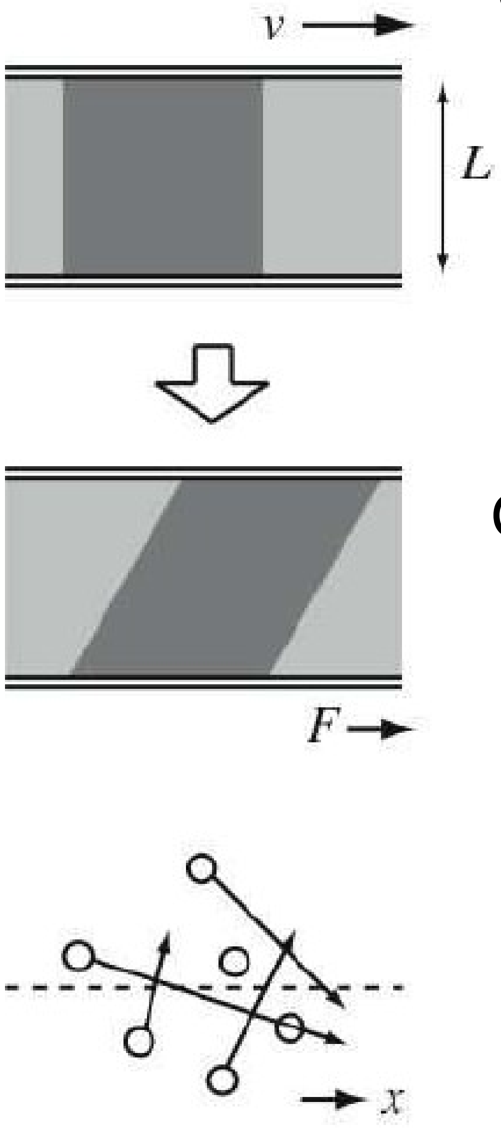


- At RHIC
  - Models based on hadronic cascades, such as RQMD, fail. Hence, v_2 is likely to be built up in the partonic (deconfined) phase
  - Measured v_2 found for the first time in agreement with ideal hydrodynamical calculations (for central and mid-central collisions)
    - Fast (<1fm/c) thermalization with matter (close to) an ideal fluid
    - In more peripheral collisions thermalization is incomplete or slower

Shear viscosity in fluids



Shear viscosity characterizes
the efficiency of momentum transport

$$\frac{F}{A} = \eta \frac{v}{L}$$

$$\eta = \rho \langle v \rangle \lambda_{\mathrm{mfp}} \sim \frac{1}{\sigma}$$

quasi-particle interaction cross section

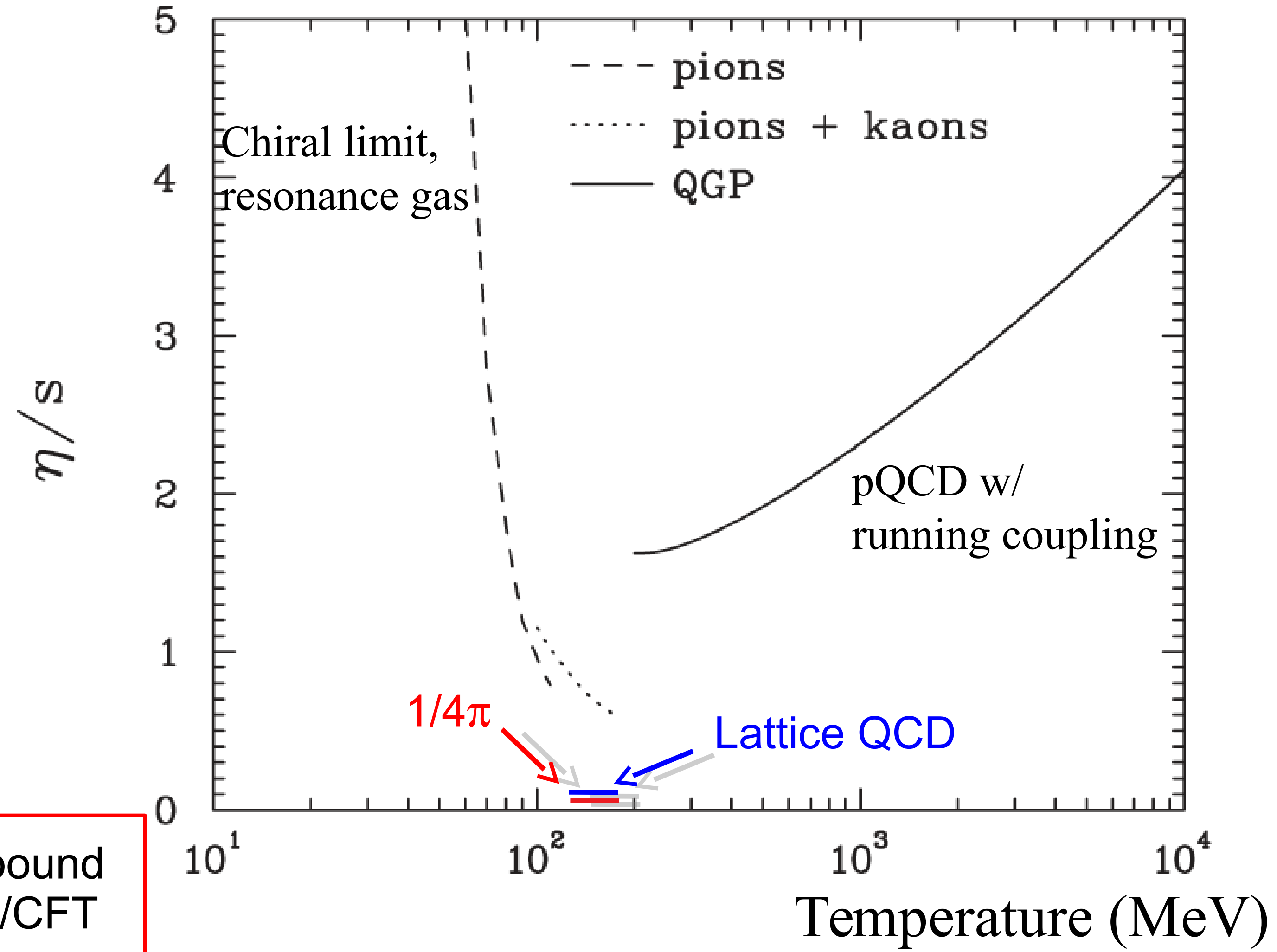
Comparing relativistic fluids: η/s

- s = entropy density
- scaling parameter η/s emergy from hydro equations
- generalization for non-rel. Fluids: η/s (w=enthalpy)
  Liao and Koch, PRC81 (2010) 014902

Large σ → small η/s
→ strongly-coupled matter
→ “perfect liquid”

Shear viscosity in QCD

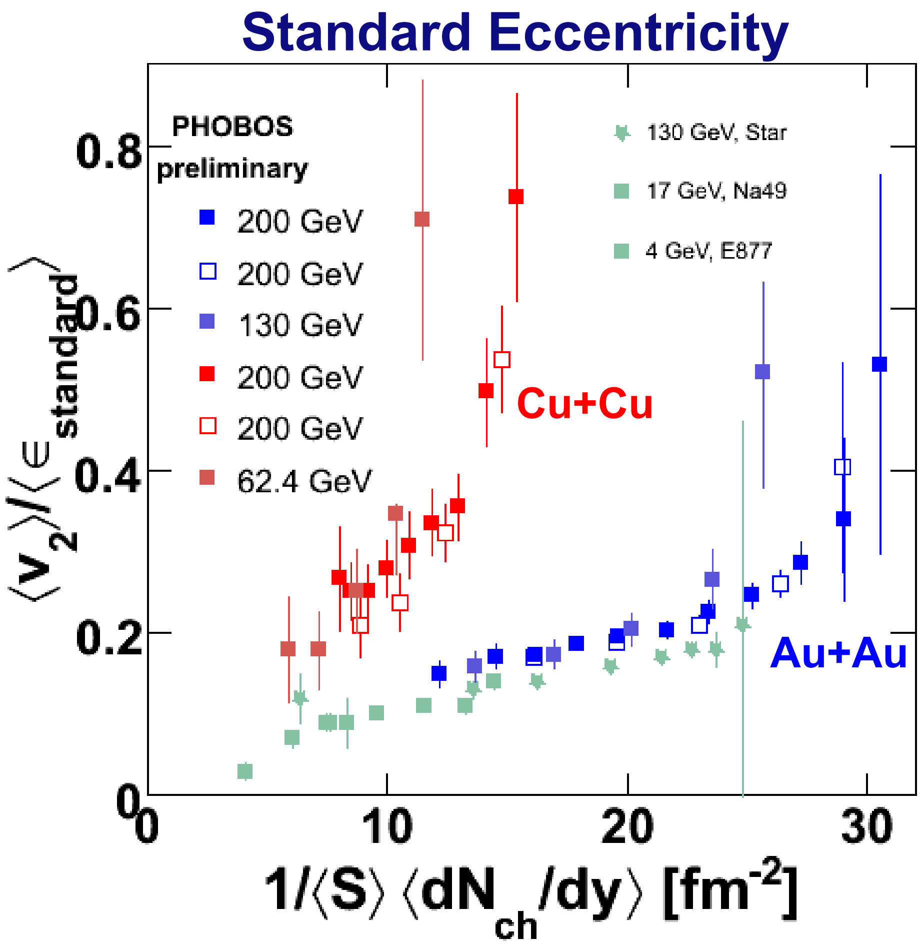
Analytic: Csernai, Kapusta and McClerran PRL 97, 152303 (2006)
Lattice: H. Meyer, PR D76, 101701R (2007)

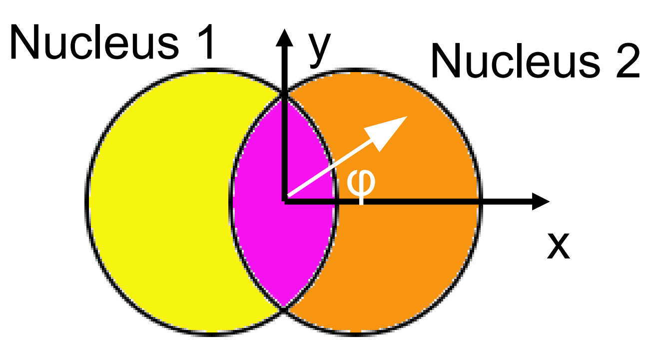


Minimal bound from AdS/CFT

$$\frac{\eta}{s} = \frac{1}{4\pi}$$

Importance of initial state fluctuations





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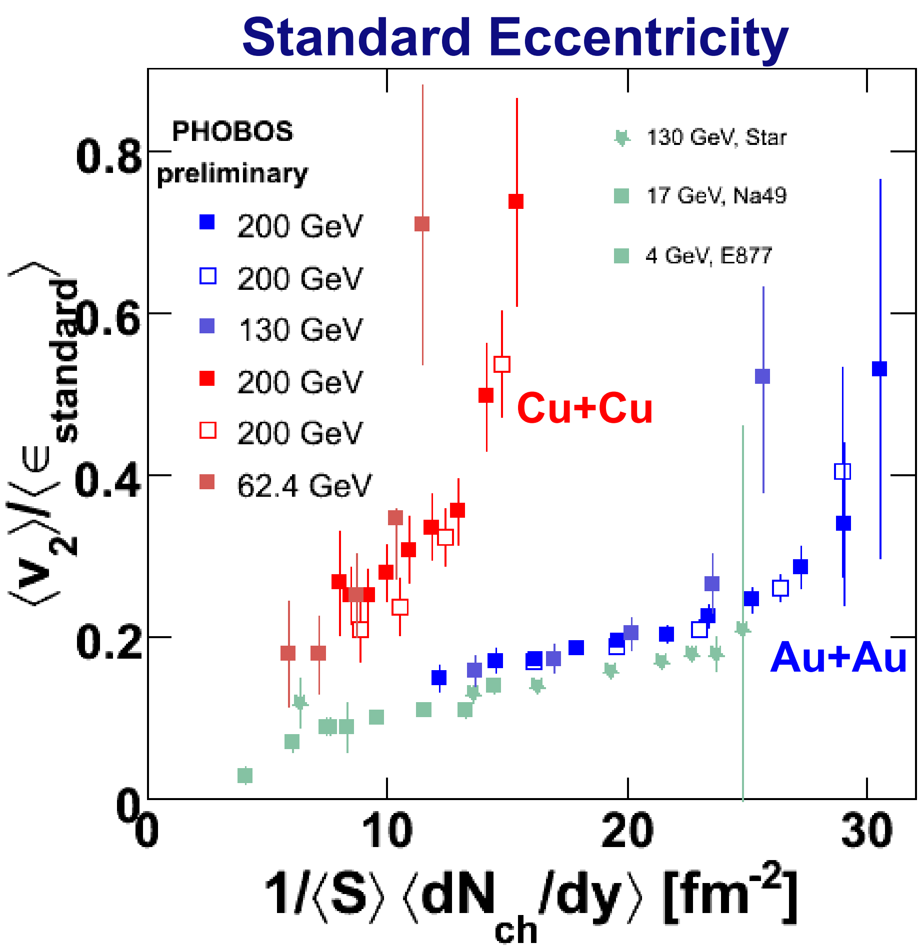
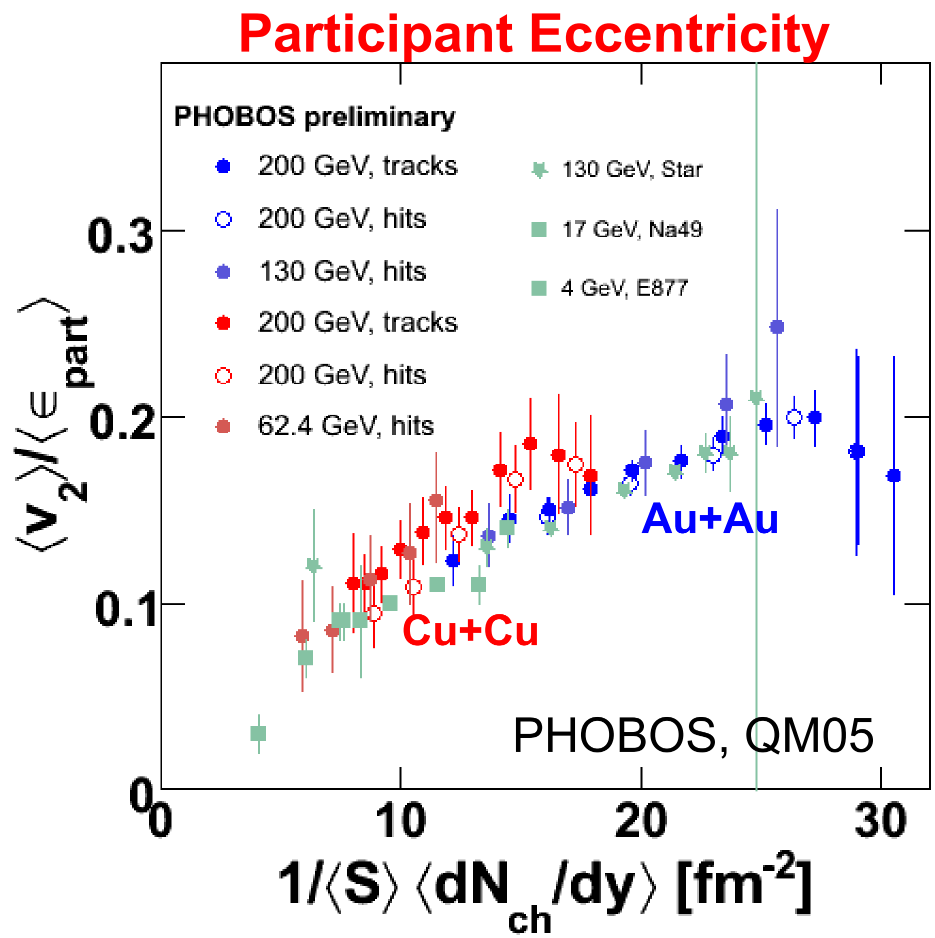
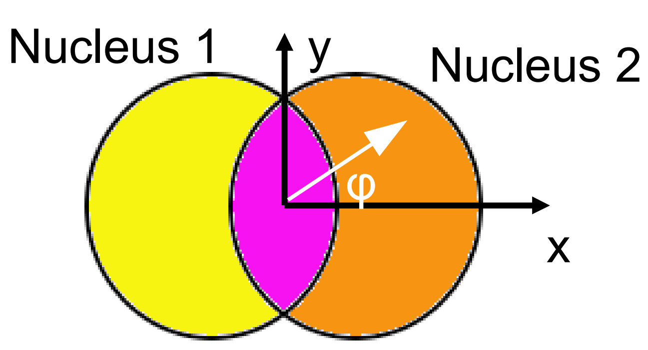
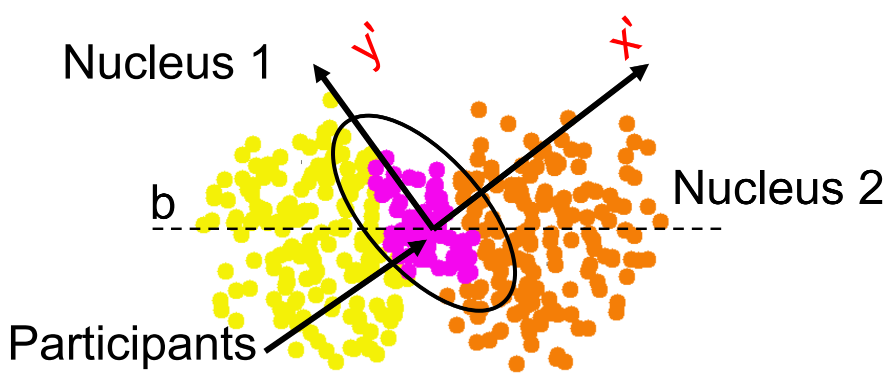
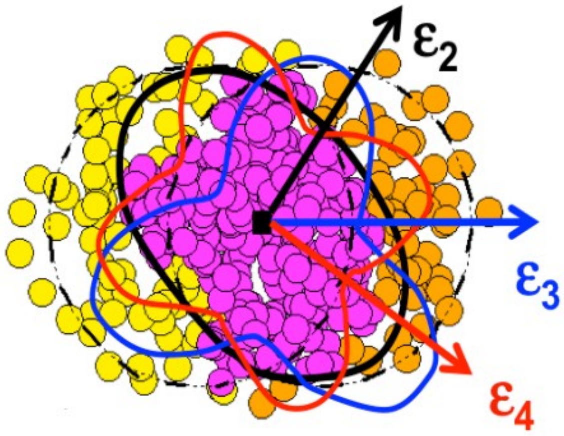








Higher harmonics and viscosity

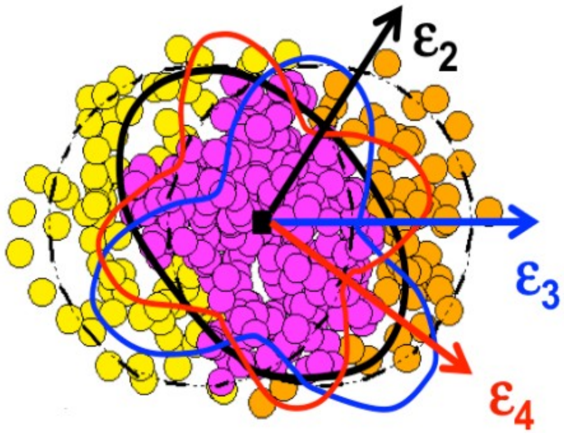


Alver, Roland

Initial spatial anisotropy not smooth, leads to higher harmonics / symmetry planes.

$$\frac{dN}{d\varphi} \sim 1 + 2v_2 \cos[2(\varphi - \psi_2)] + 2v_3 \cos[3(\varphi - \psi_3)]$$
$$+ 2v_4 \cos[4(\varphi - \psi_4)] + 2v_5 \cos[5(\varphi - \psi_5)] + \ldots$$

Higher harmonics and viscosity



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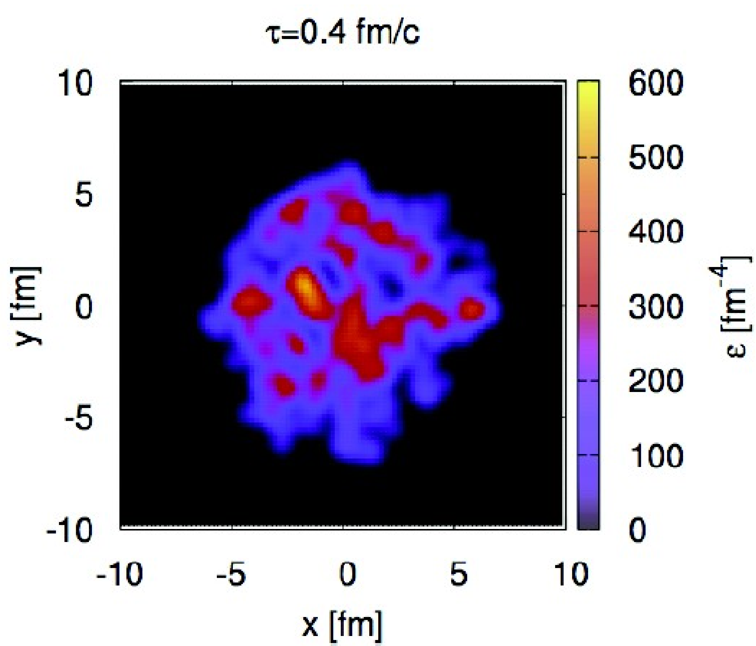
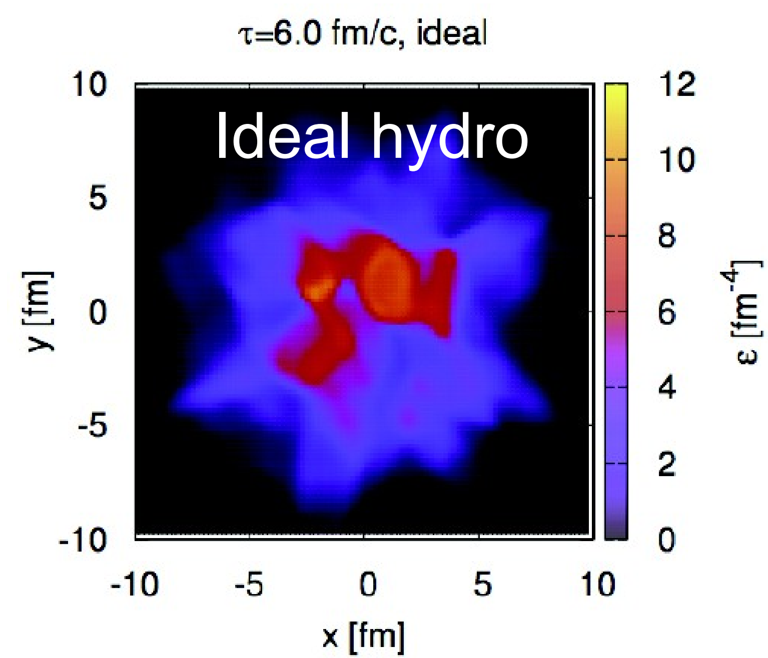
$$+ 2v_4\cos[4(\varphi-\psi_4)] + 2v_5\cos[5(\varphi-\psi_5)] + \ldots$$



e-by-e hydro

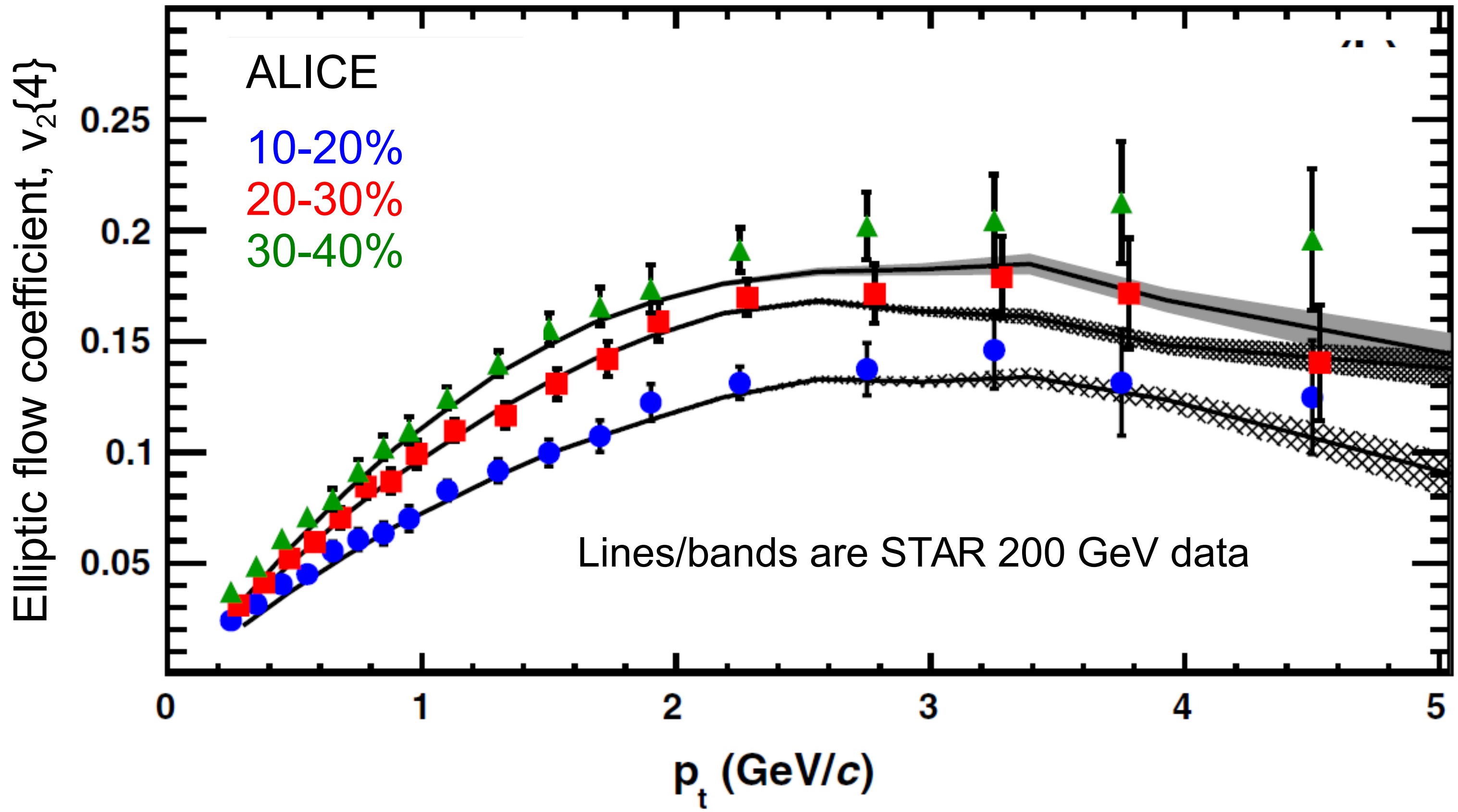
B. Schenke et al.



Ideal hydrodynamical models preserves these “clumpy” initial conditions

Elliptic flow vs p_T (LHC vs RHIC)

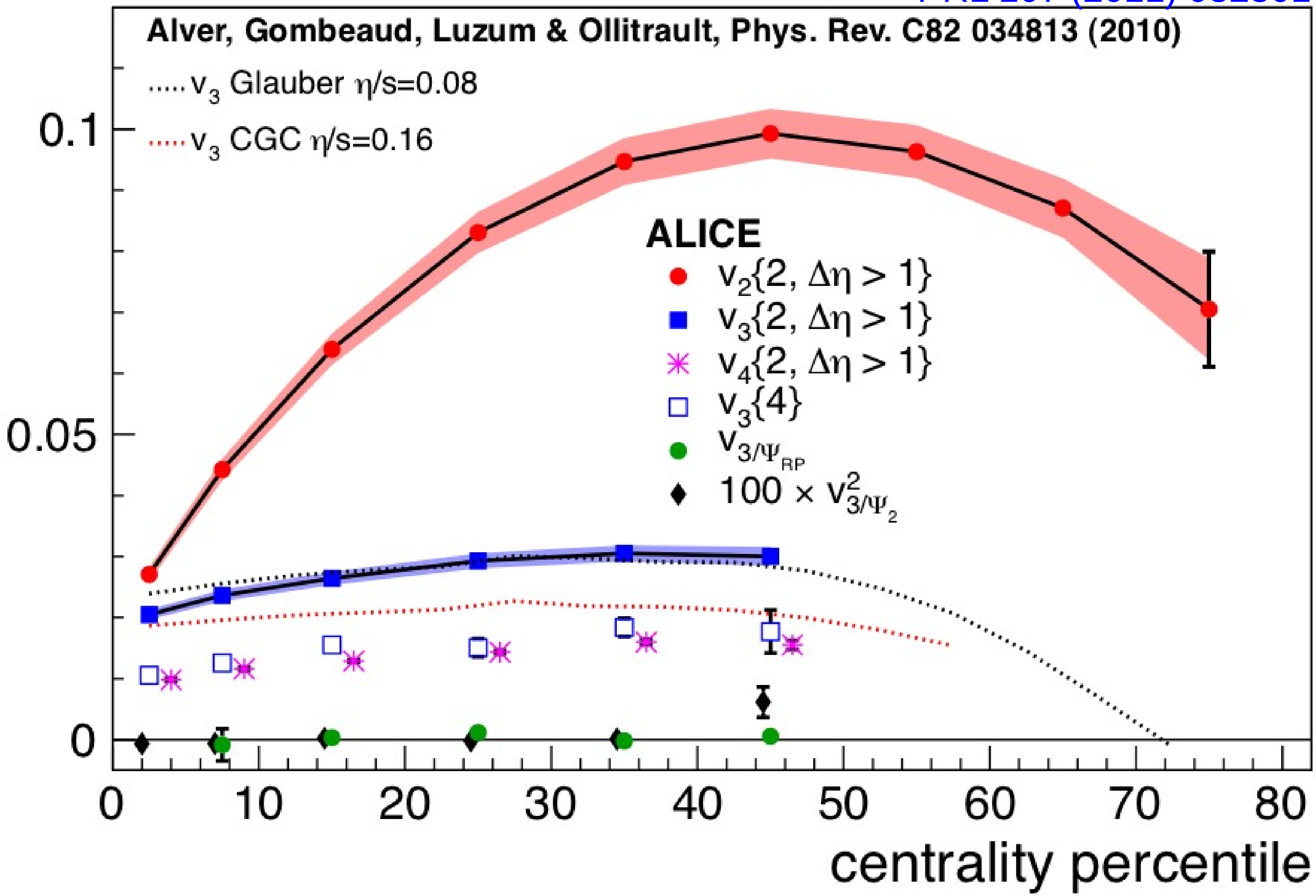
PRL 105 (2010) 252302



Observe $v_2(p_T)_{LHC} \approx v_2(p_T)_{RHIC}$ above 1 GeV to about 5% despite factor 14 increase in energy, but consistent with hydro predictions! (Integrated v_2 30% larger due to radial flow)

Triangular flow

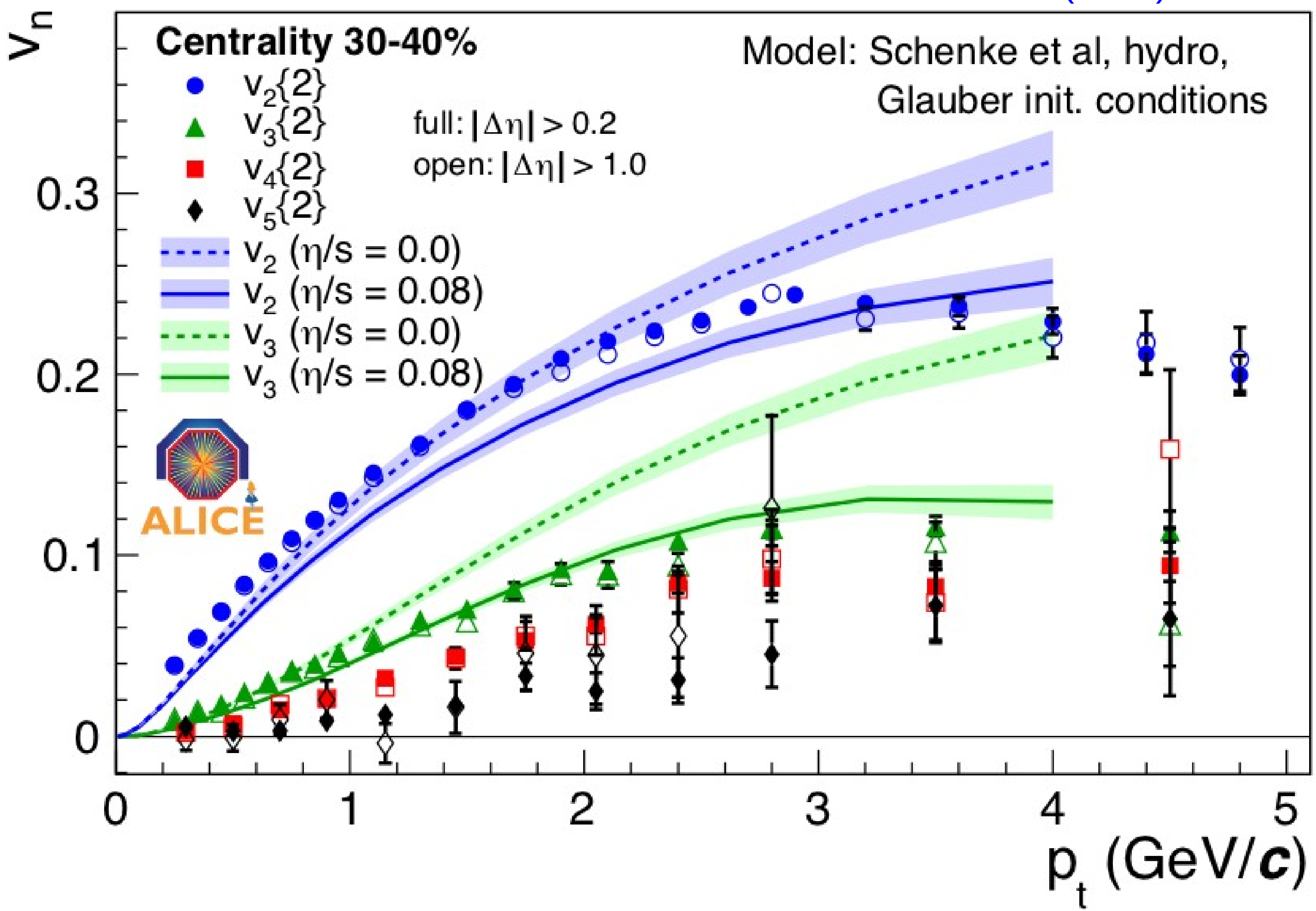
PRL 107 (2011) 032301



Significant triangular flow observed. Centrality dependence is different to that of elliptic flow. Measurements vs reaction plane yield zero as expected if it arises from fluctuations.

Measurement of higher harmonics

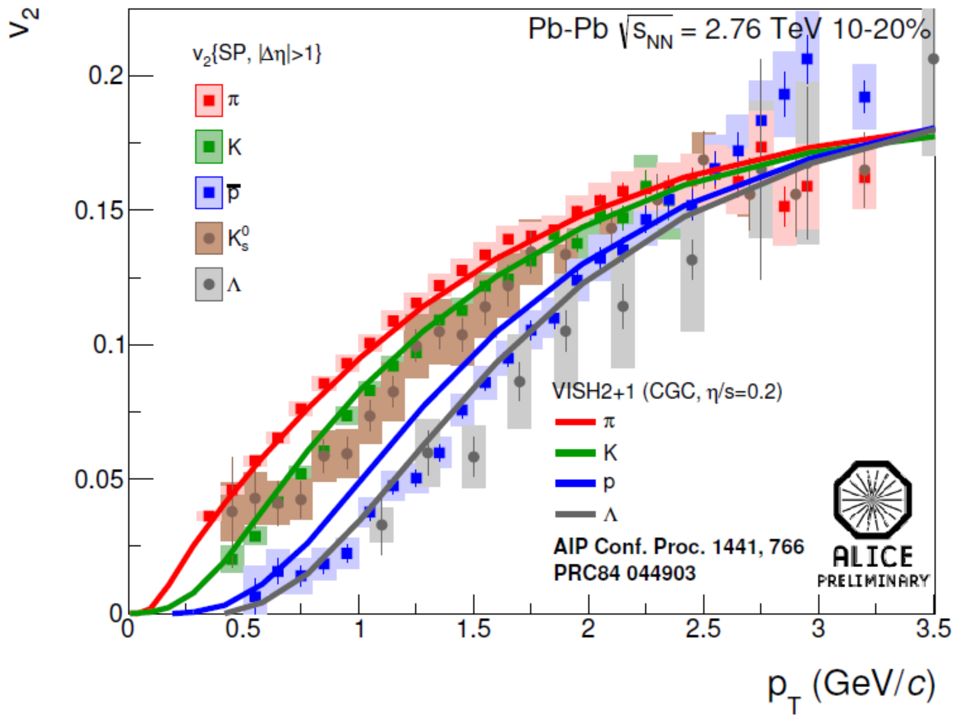
PRL 107 (2011) 032301



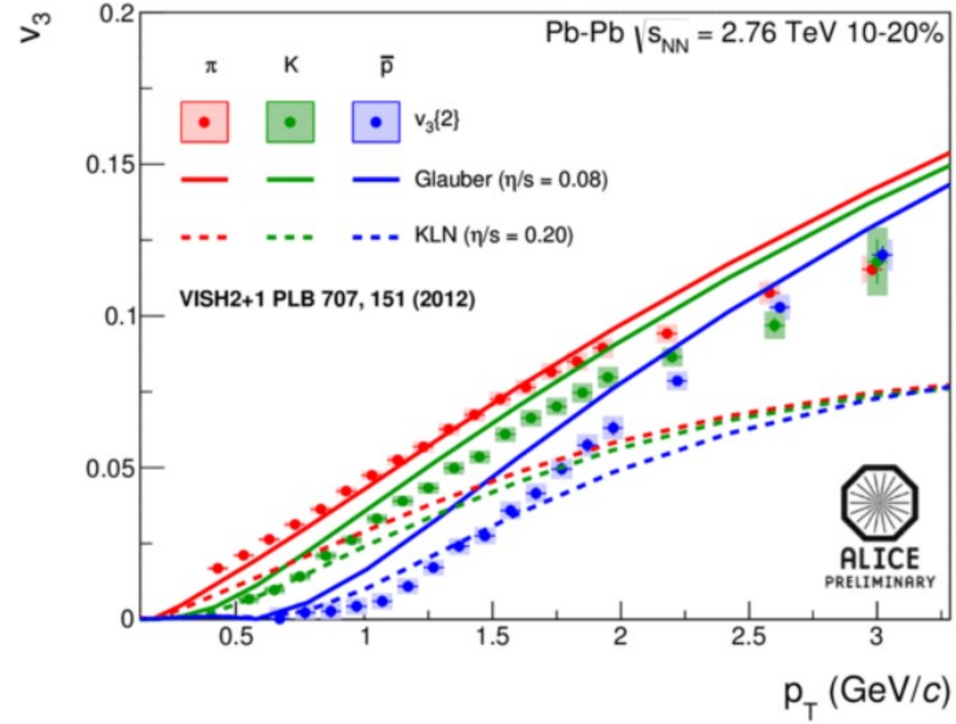
Strong constraints on hydro calculations

Mass-dependent splitting of v_2 and v_3

Elliptic flow



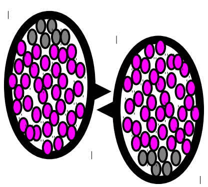
Triangular flow



- Particle mass dependent splitting from radial flow characteristic for v_2
- Can be described by hydrodynamical models (+ hadronic afterburners)

- Similar mass splitting for v_3
- Qualitatively described by hydrodynamical models (+ hadronic afterburners)
- Provides additional constraints on η/s

Description of initial state?

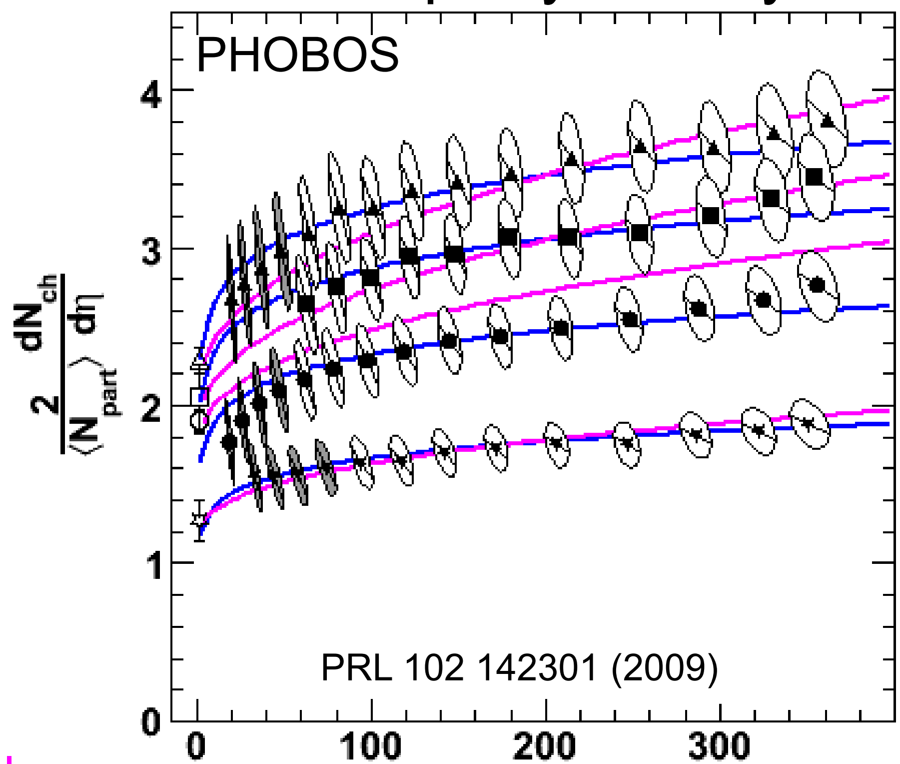


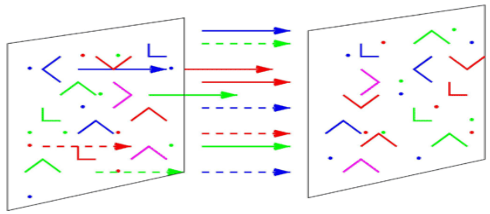
Glauber IC
Two-component model

$$\frac{dN}{d\eta} = \frac{dN}{d\eta^{pp}}((1-x)N_{coll} + x N_{part}/2)$$

PRC 70 021902 (2004)

Mid-rapidity density





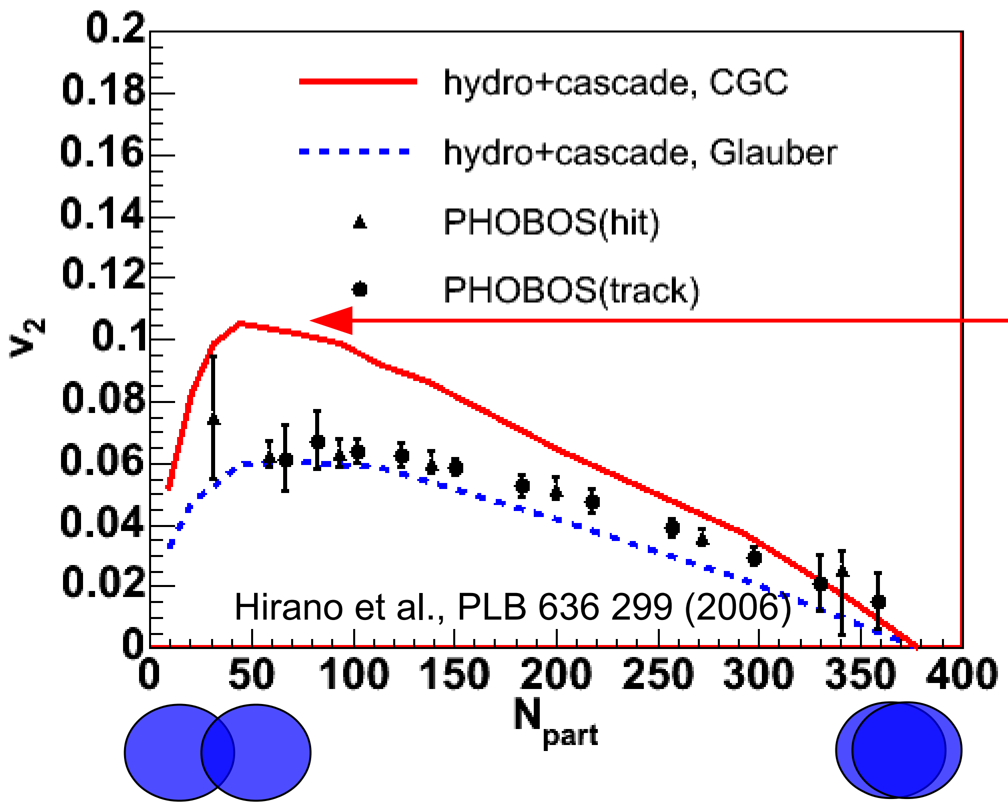
CGC IC
Color glass condensate

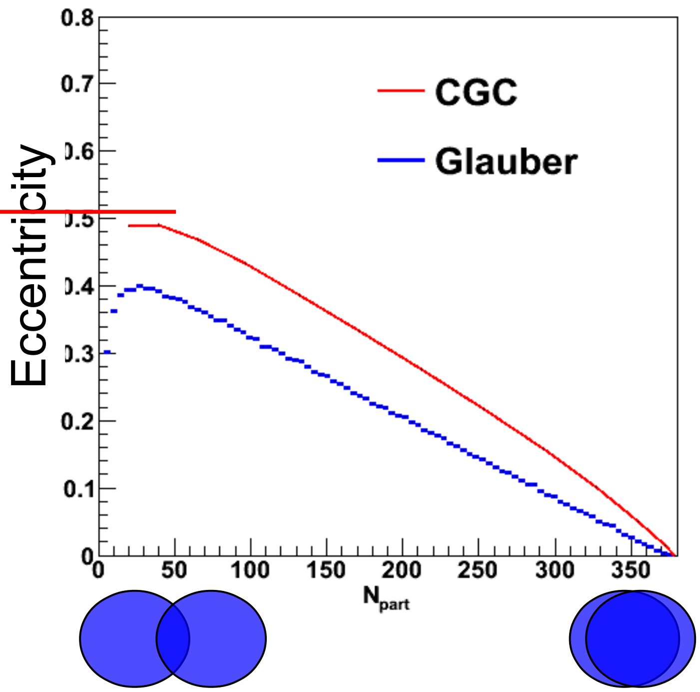
$$\frac{dN}{d\eta} \propto N_{part}^{\alpha} \sqrt{s}^{\lambda}$$

PRL 94 022002 (2005)

Two classes of models describe the multiplicity (believed to be sensitive to initial state) equally well

Ambiguity translates into conclusions

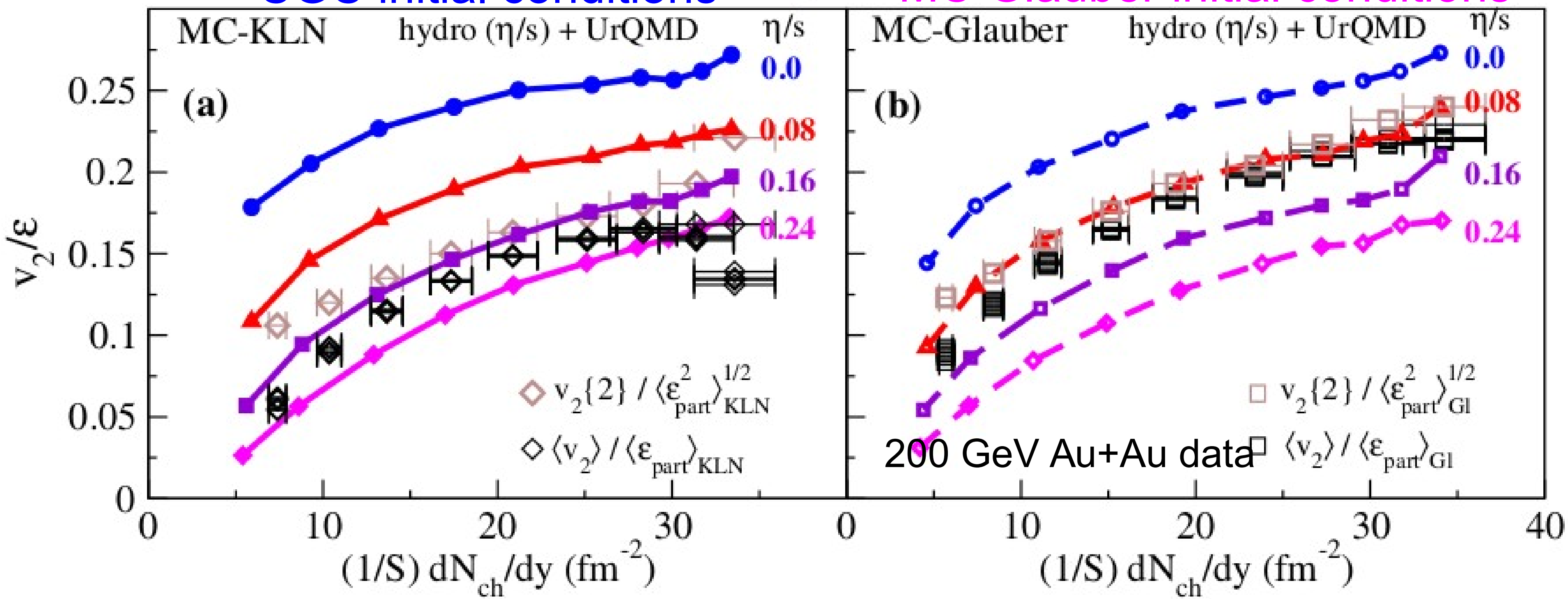




Ambiguity in description of initial state allows for various models:
Size of viscous corrections and/or soft equation of state?

The hot QGP is a nearly perfect fluid ...

CGC initial conditions MC Glauber initial conditions



Combination of many calculations, including state-of-art results from Israel-Stewart theory for a conformal fluid (2+1D), hint to a low shear viscosity to entropy ratio:

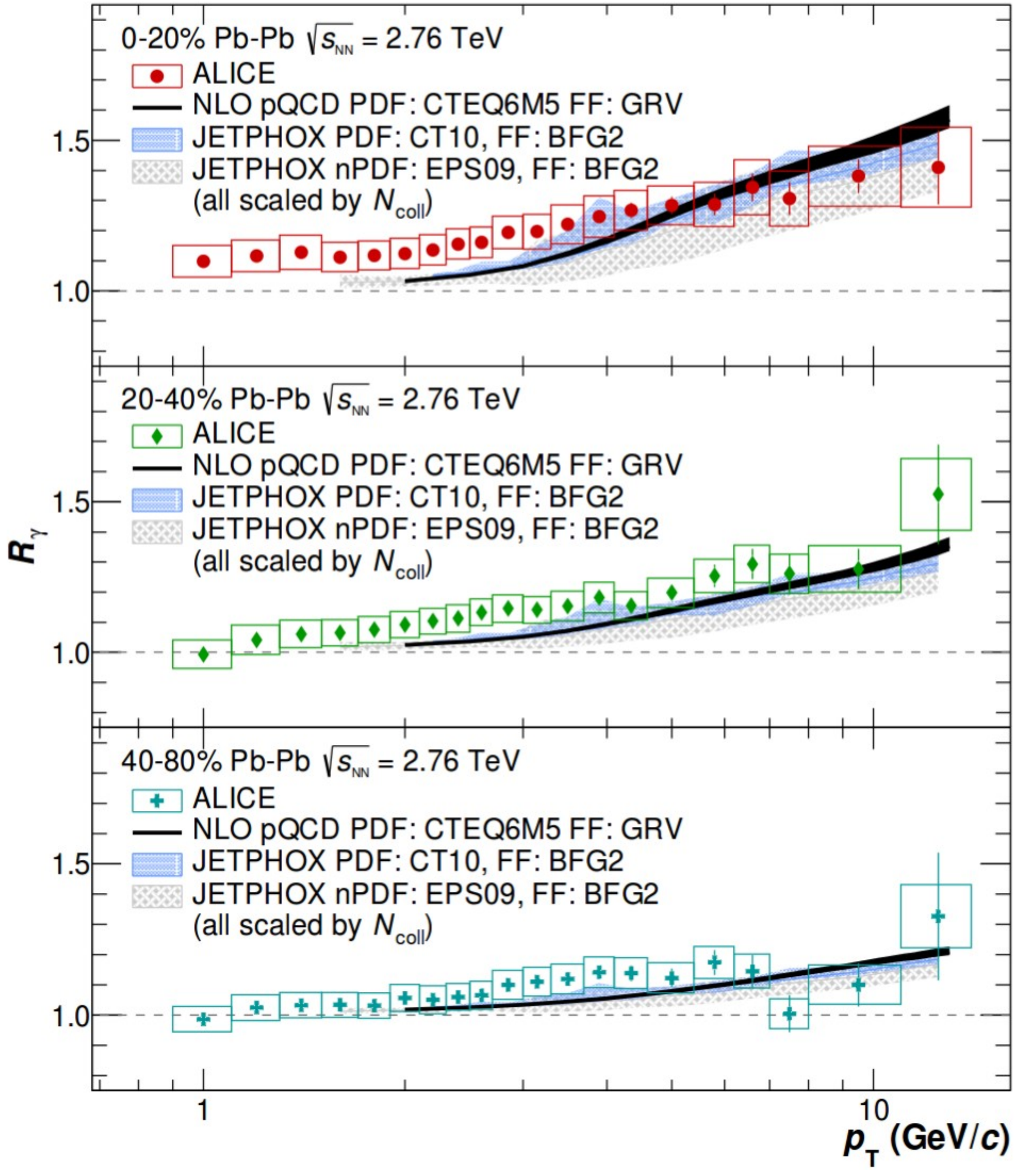
$$\boxed{\frac{1}{4\pi} < \frac{\eta}{s} < \frac{3}{4\pi}}$$

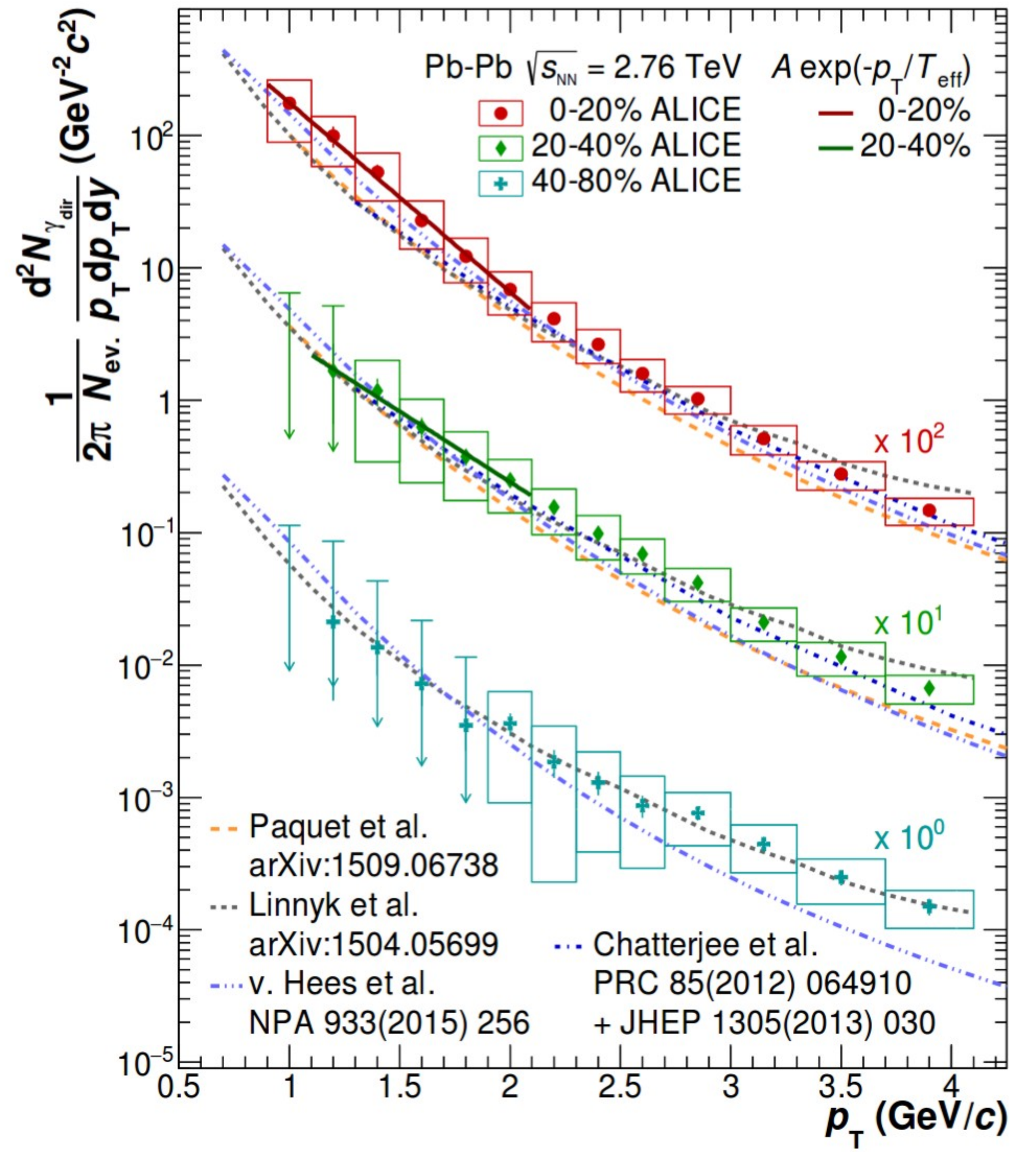
Largest part of uncertainties still from the ambiguity in the description of initial state.

Song et al, PRL 109 (2012) 139904

Initial temperature at LHC

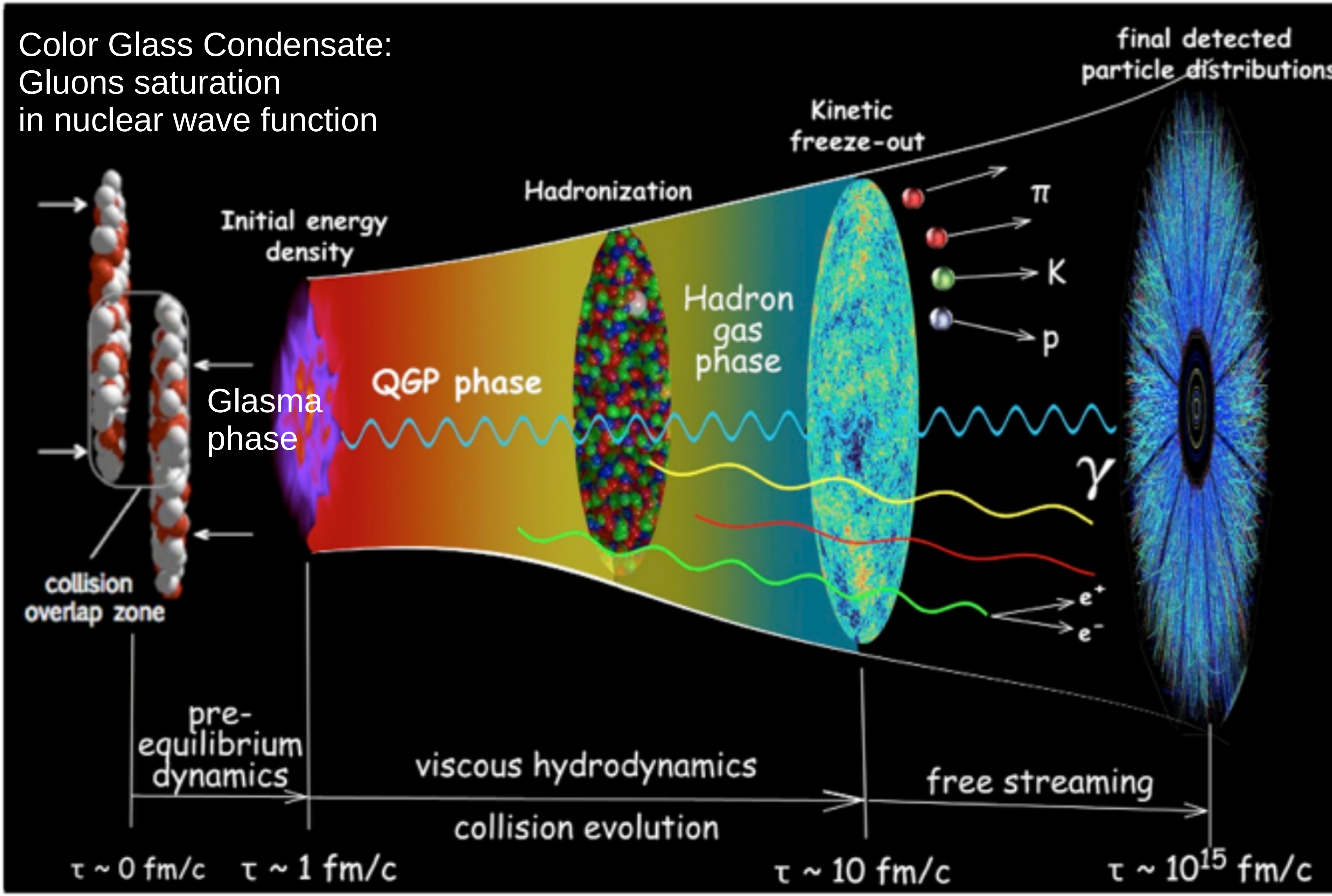
$$R = \left(\gamma/\pi^0\right)_{\text{inc}} / \left(\gamma/\pi^0\right)_{\text{mc}} \qquad \gamma^{\text{dir}} = (1 - 1/R)\,\gamma^{\text{inc}}$$





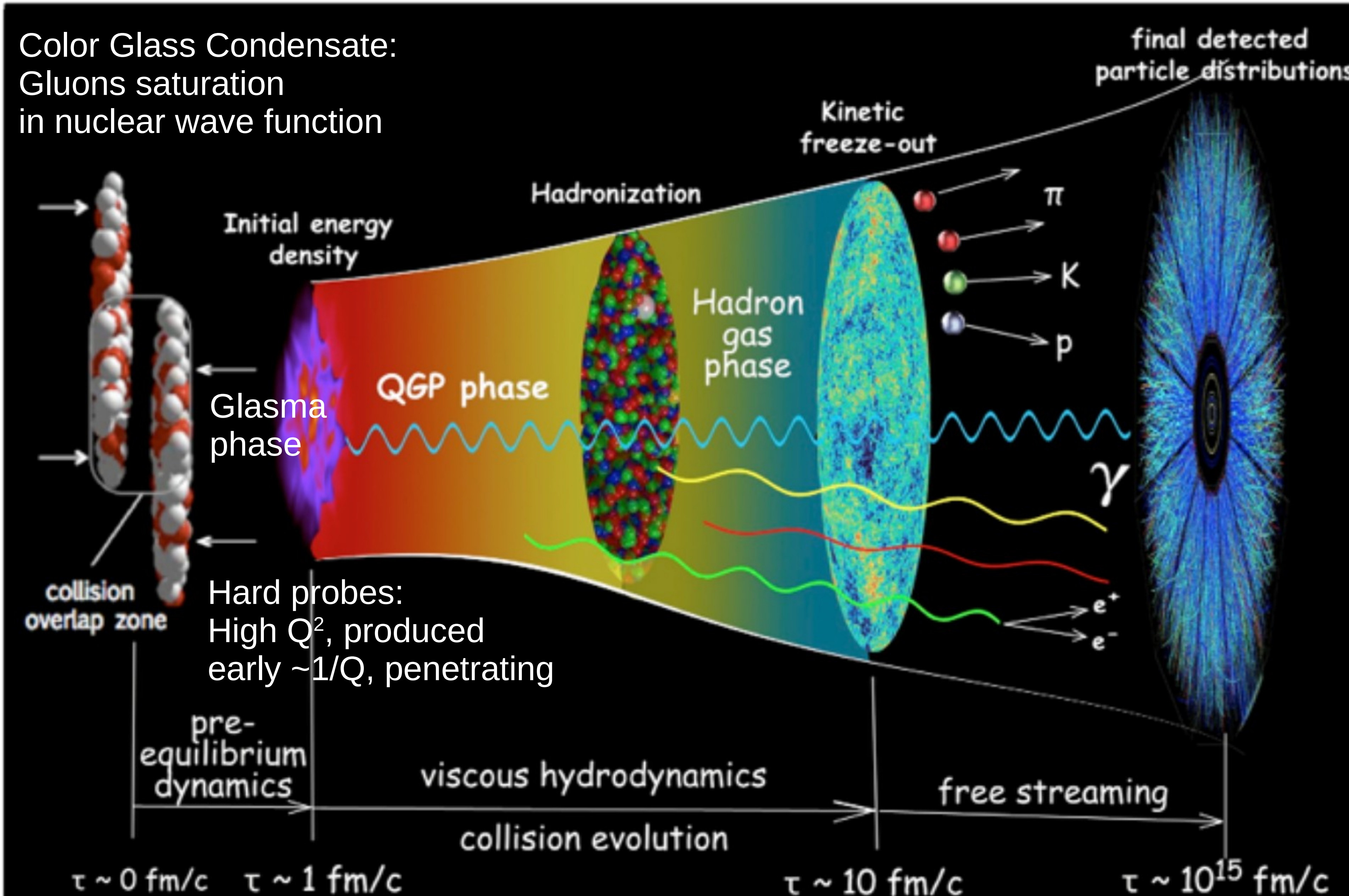
PLB 754 (2016) 235

SM of heavy-ion reaction dynamics



(adapted from C.Shen)

SM of heavy-ion reaction dynamics



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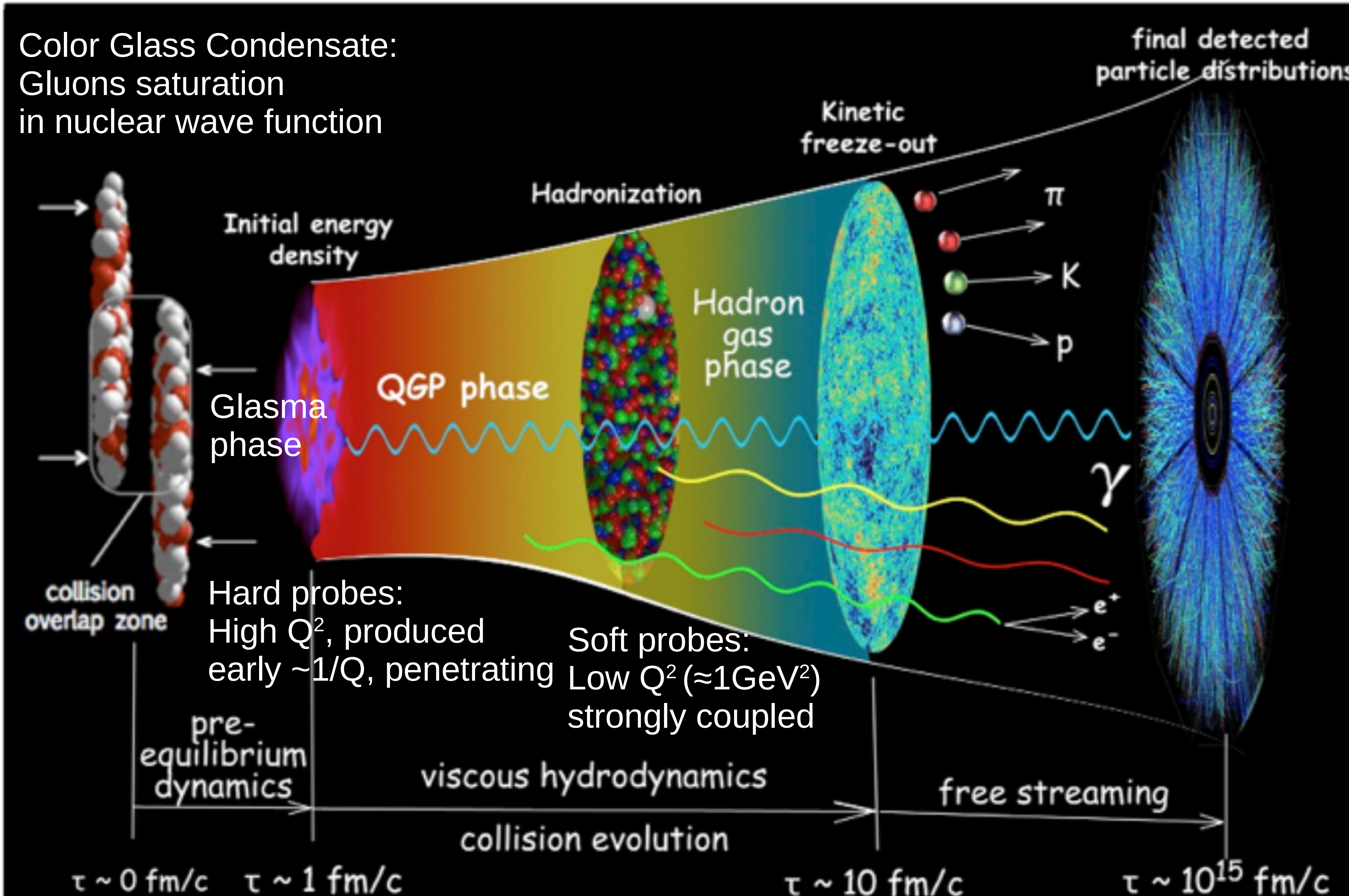
SM of heavy-ion reaction dynamics



(adapted from C.Shen)