Heavy Ions at the LHC:

First Results

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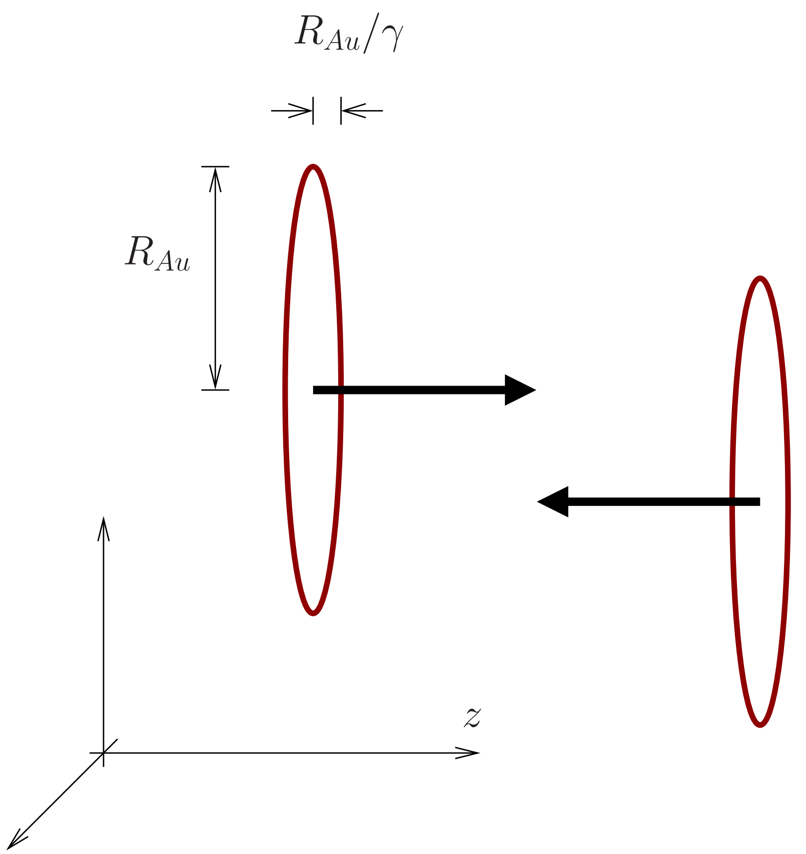
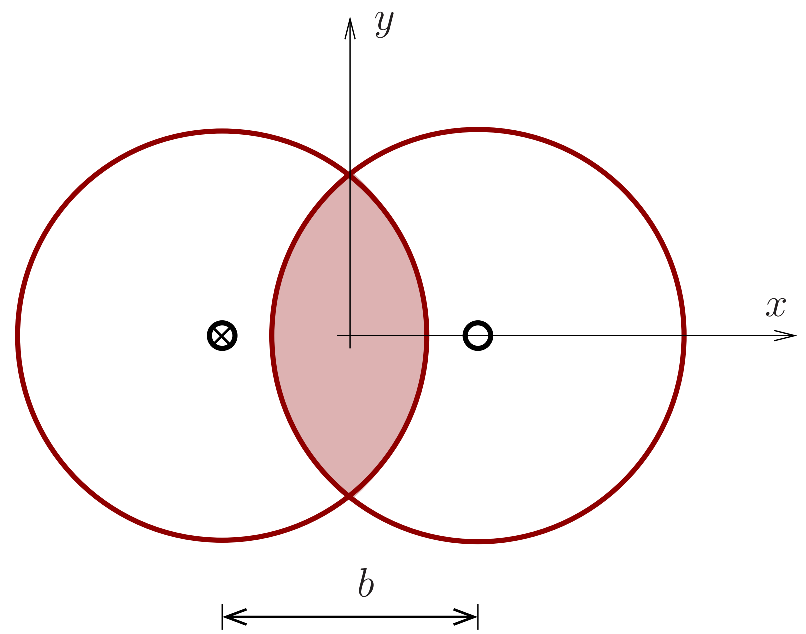
Heavy ion collision: Geometry





$$\text{rapidity}: \ y = \frac{1}{2}\log\left(\frac{E+p_z}{E-p_z}\right)$$

$$\text{transverse momentum}: \ p_T^2 = p_x^2 + p_y^2$$

Bjorken expansion

Experimental observation: At high energy ($\Delta y \to \infty$) rapidity distributions of produced particles (in both pp and AA) are "flat"

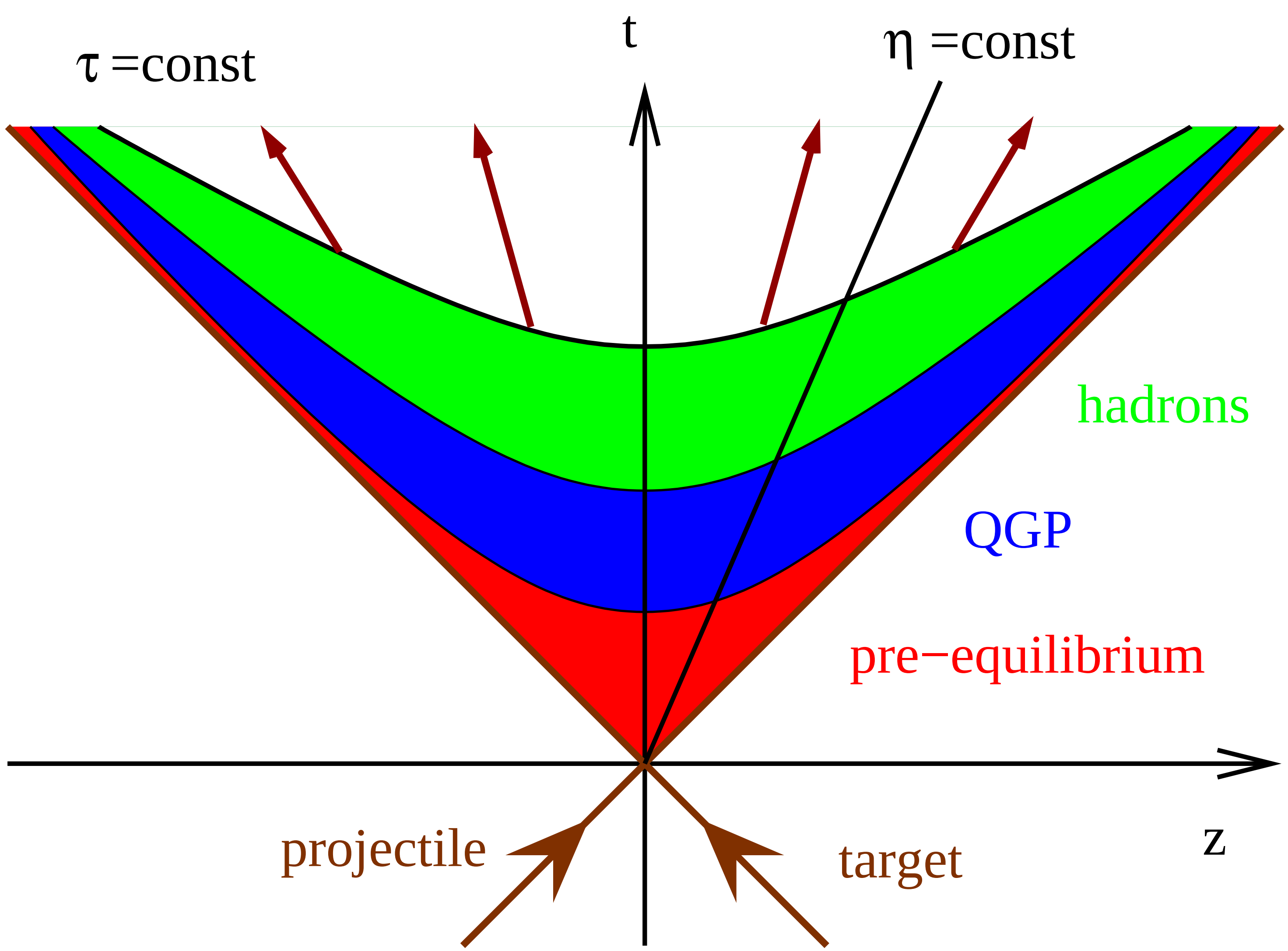
$$\frac{dN}{dy} \simeq const$$

Physics depends on proper time $\tau = \sqrt{t^2 - z^2}$, not on y

All comoving ($v = z/t$) observers are equivalent

Analogous to Hubble expansion

Bjorken expansion



Bjorken expansion: Hydrodynamics

Boost invariant expansion

$$u^\mu = \gamma(1,0,0,v_z) = (t/\tau, 0, 0, z/\tau)$$

solves Euler equation (no longitudinal acceleration)

$$\partial^\mu (s u_\mu) = 0 \qquad \Rightarrow \qquad \frac{d}{d\tau}\left[\tau s(\tau)\right] = 0$$

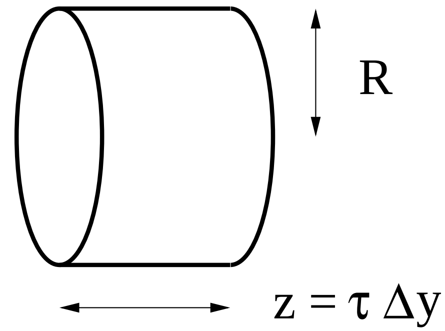
Solution for ideal Bj hydrodynamics

$$\boxed{s(\tau) = \frac{s_0 \tau_0}{\tau}} \qquad\qquad T = \frac{const}{\tau^{1/3}}$$

Exact boost invariance, no transverse expansion, no dissipation, . . .

Numerical estimates

Total entropy in rapidity interval $[y, y + \Delta y]$



$$S = s\pi R^2 z = s\pi R^2 \tau \Delta y = (s_0 \tau_0) \pi R^2 \Delta y$$

$$s_0 \tau_0 = \frac{1}{\pi R^2} \frac{S}{\Delta y}$$

Use $S/N \simeq 3.6$

$$s_0 = \frac{3.6}{\pi R^2 \tau_0} \left(\frac{dN}{dy} \right)$$

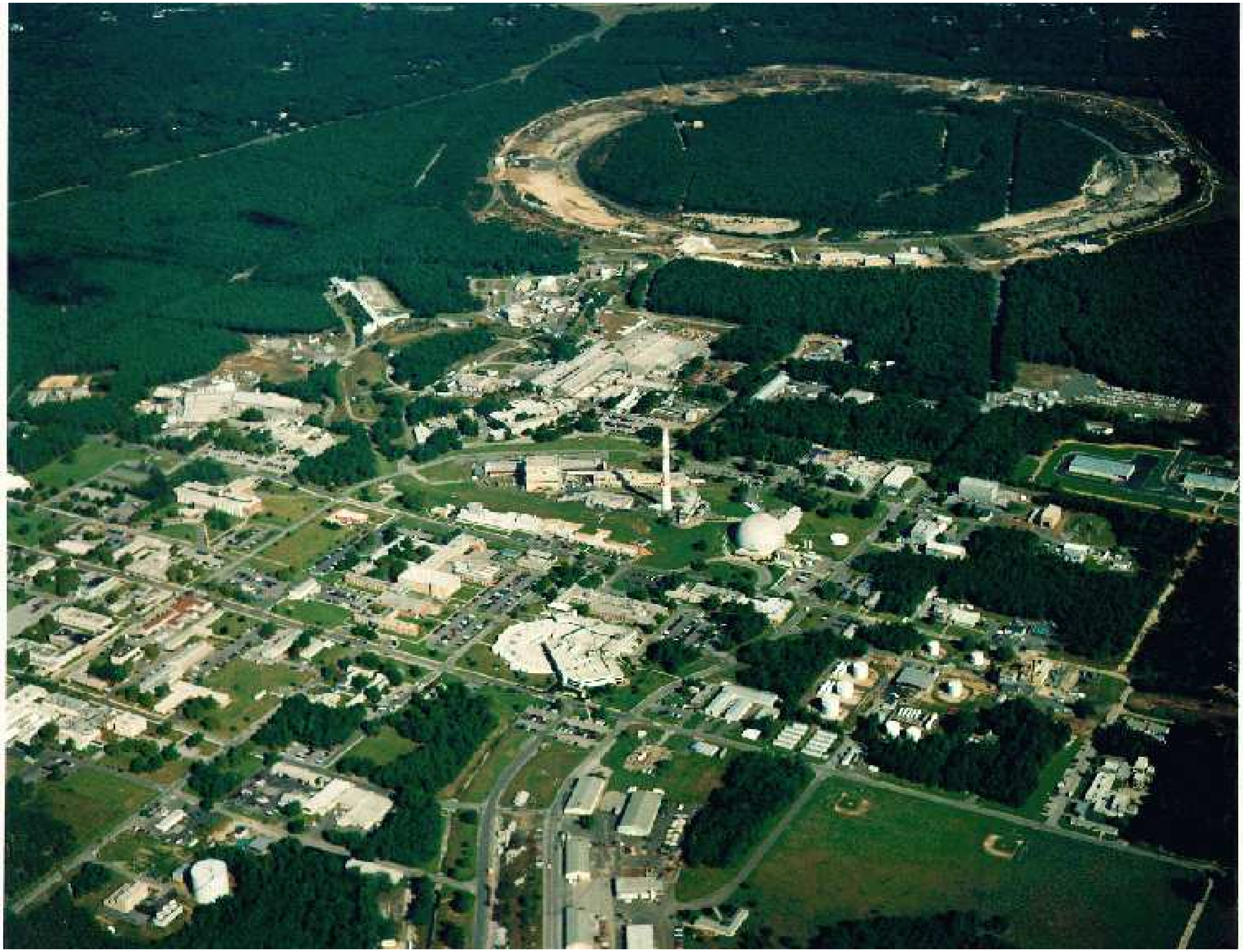
Bj estimate

Depends on initial time τ_0. Assume QGP equation of state

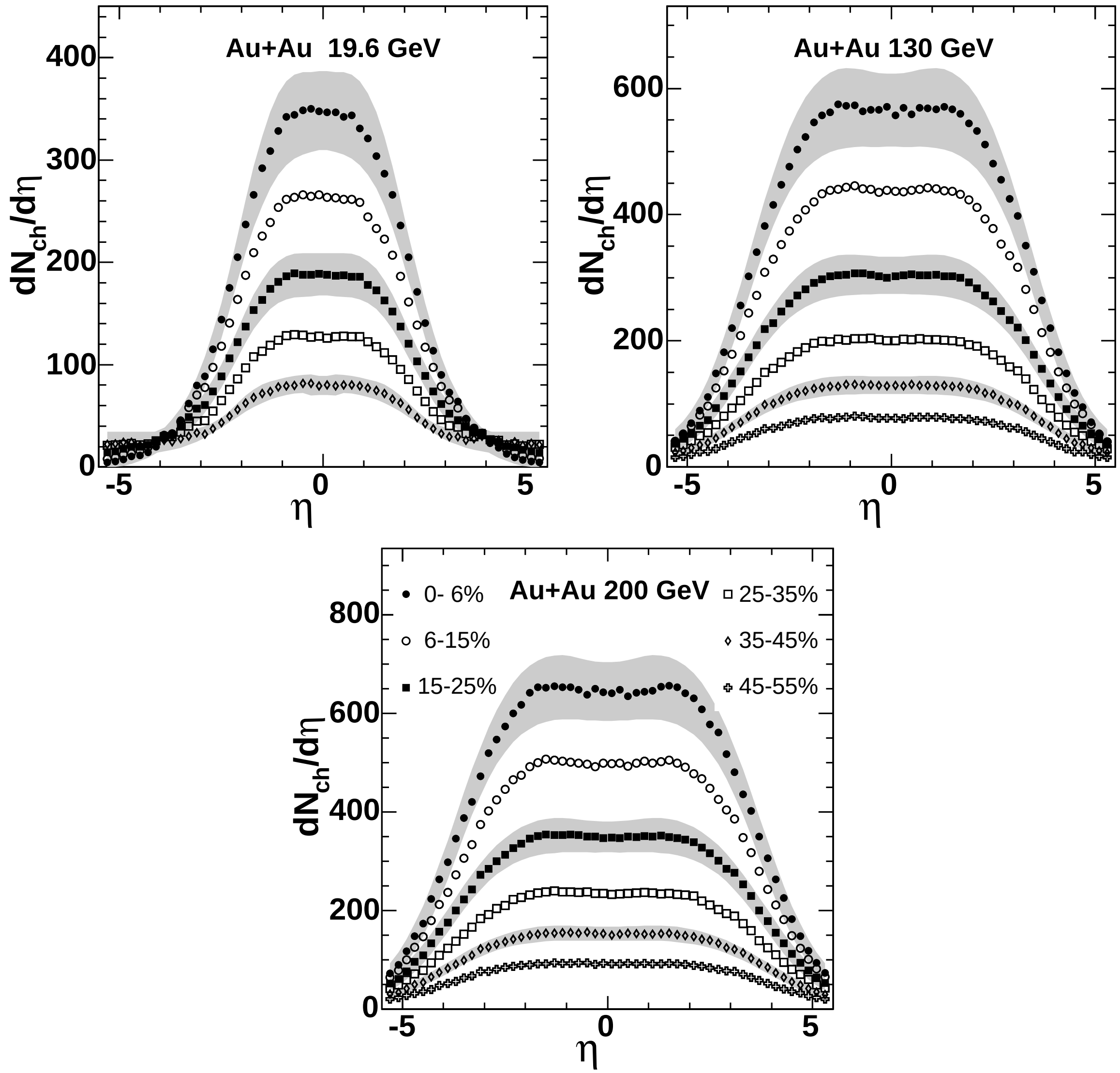
$$s_0 = \frac{2\pi^2}{45} N_d T_0^3$$

Fixes initial temperature (and energy density)

BNL and RHIC

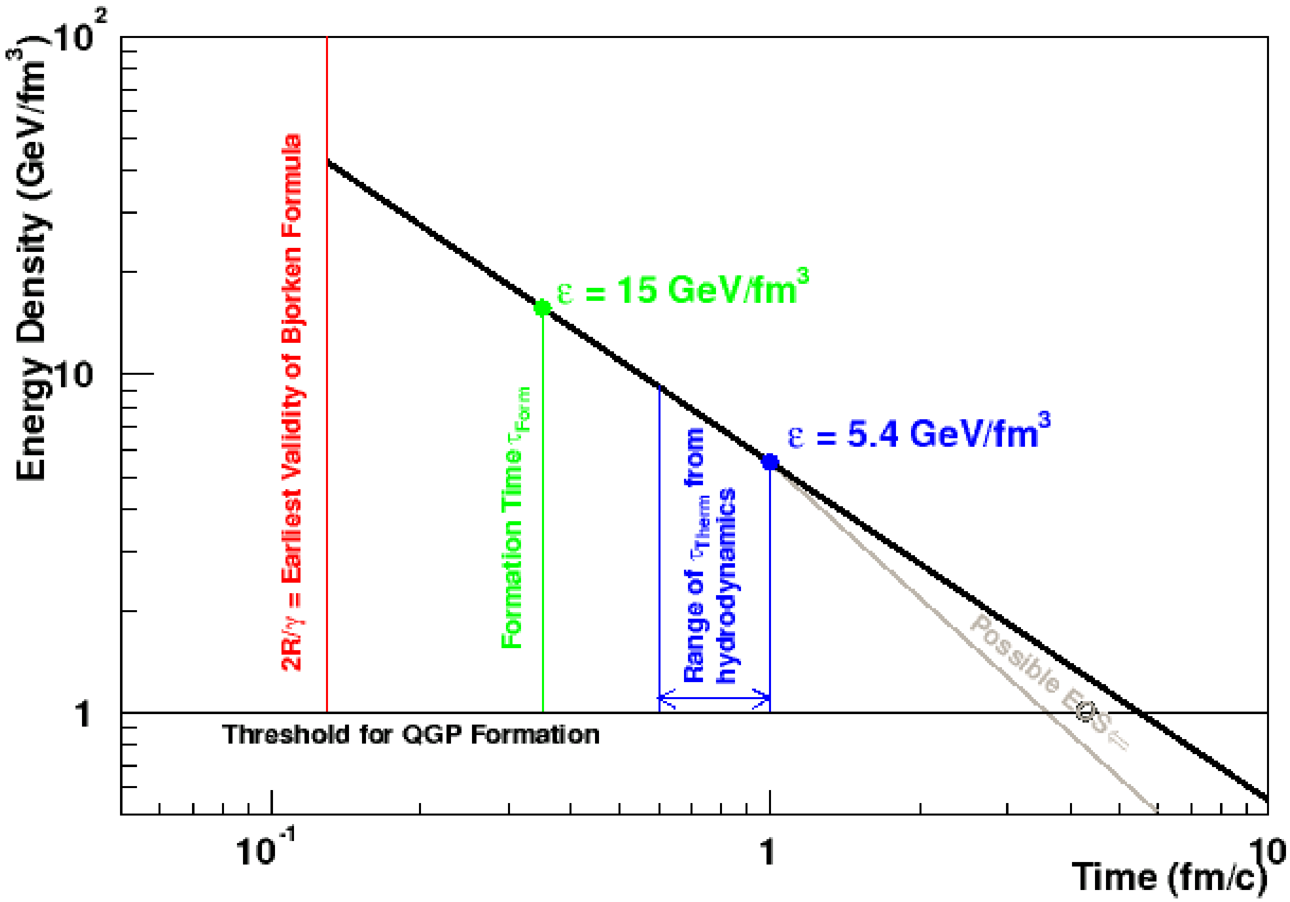


Multiplicities

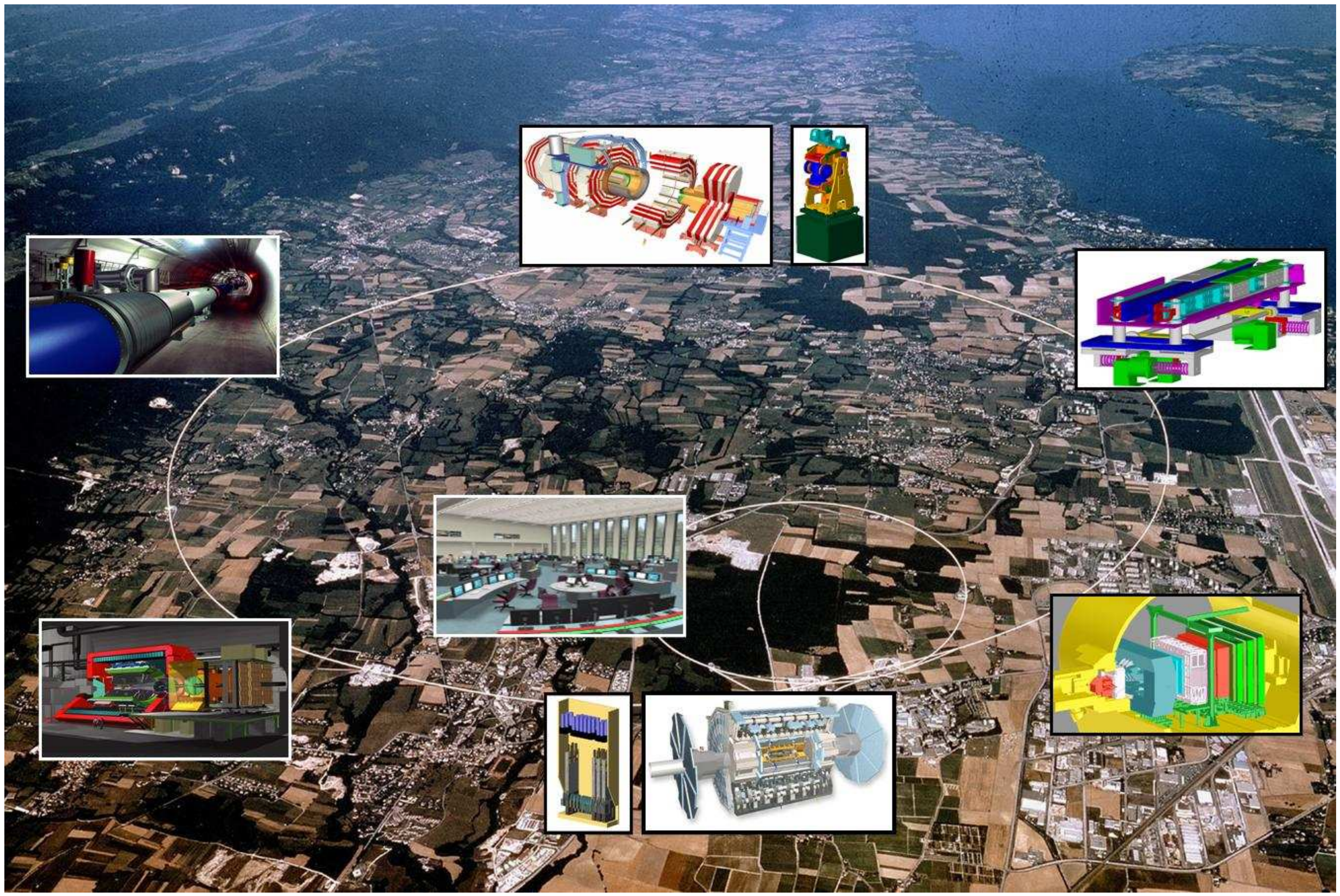


Phobos White Paper (2005)

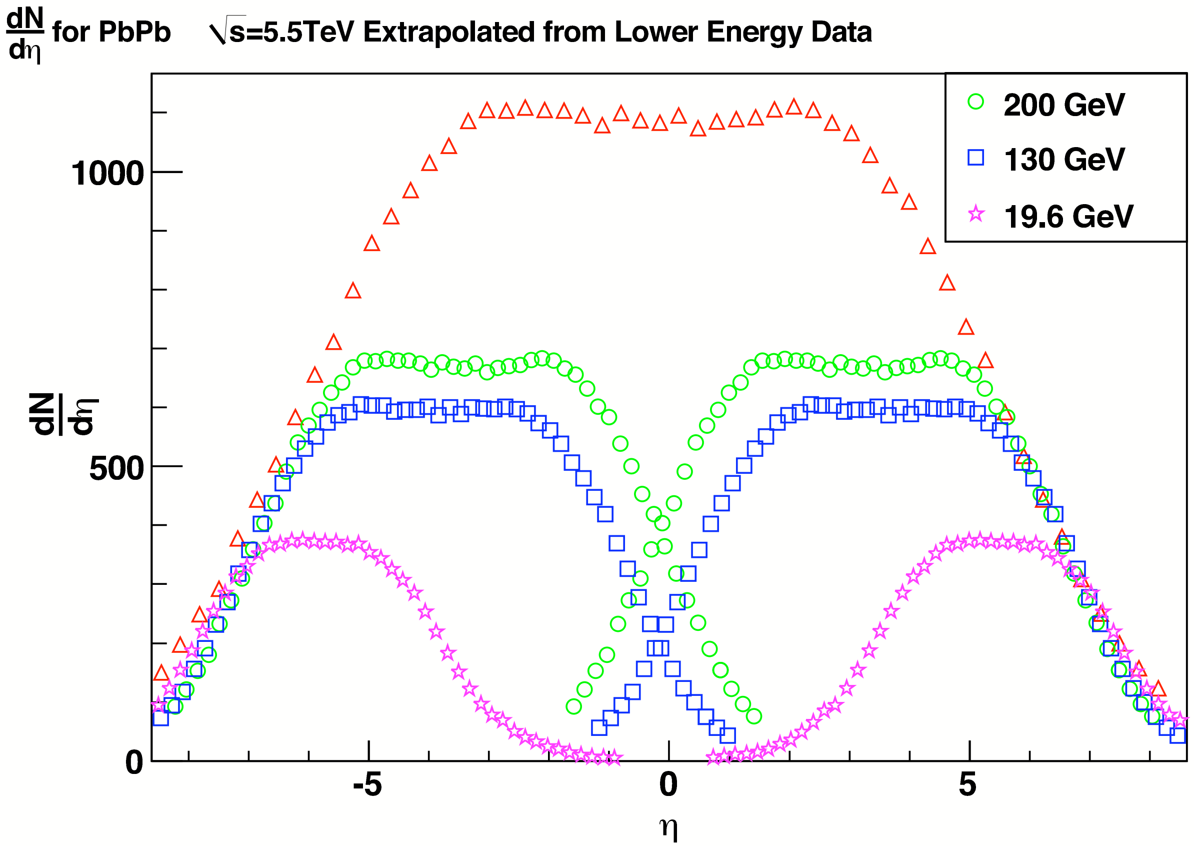
Bjorken expansion



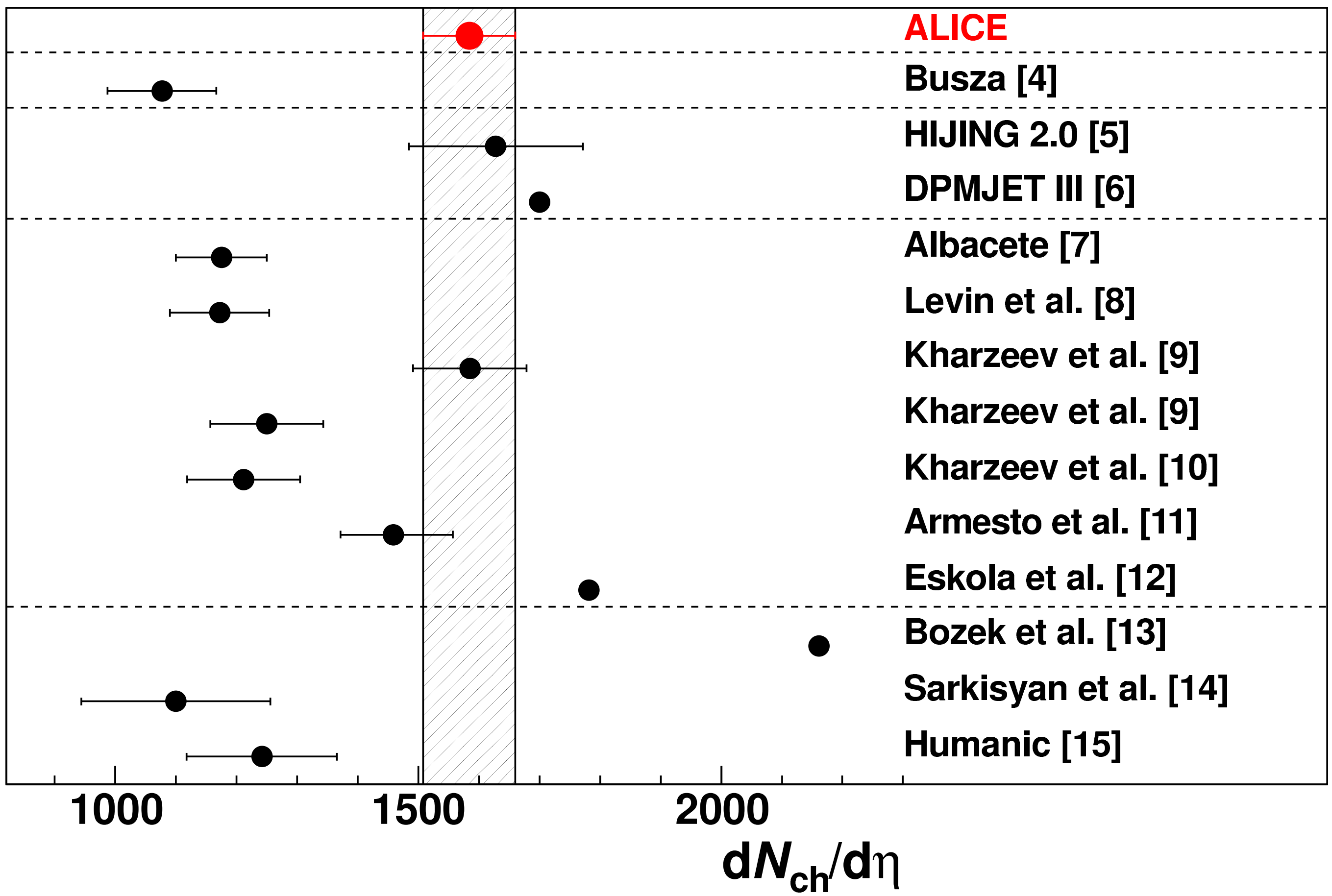
LHC: Pb+Pb $\sqrt{s_{NN}} = 2.76$ TeV



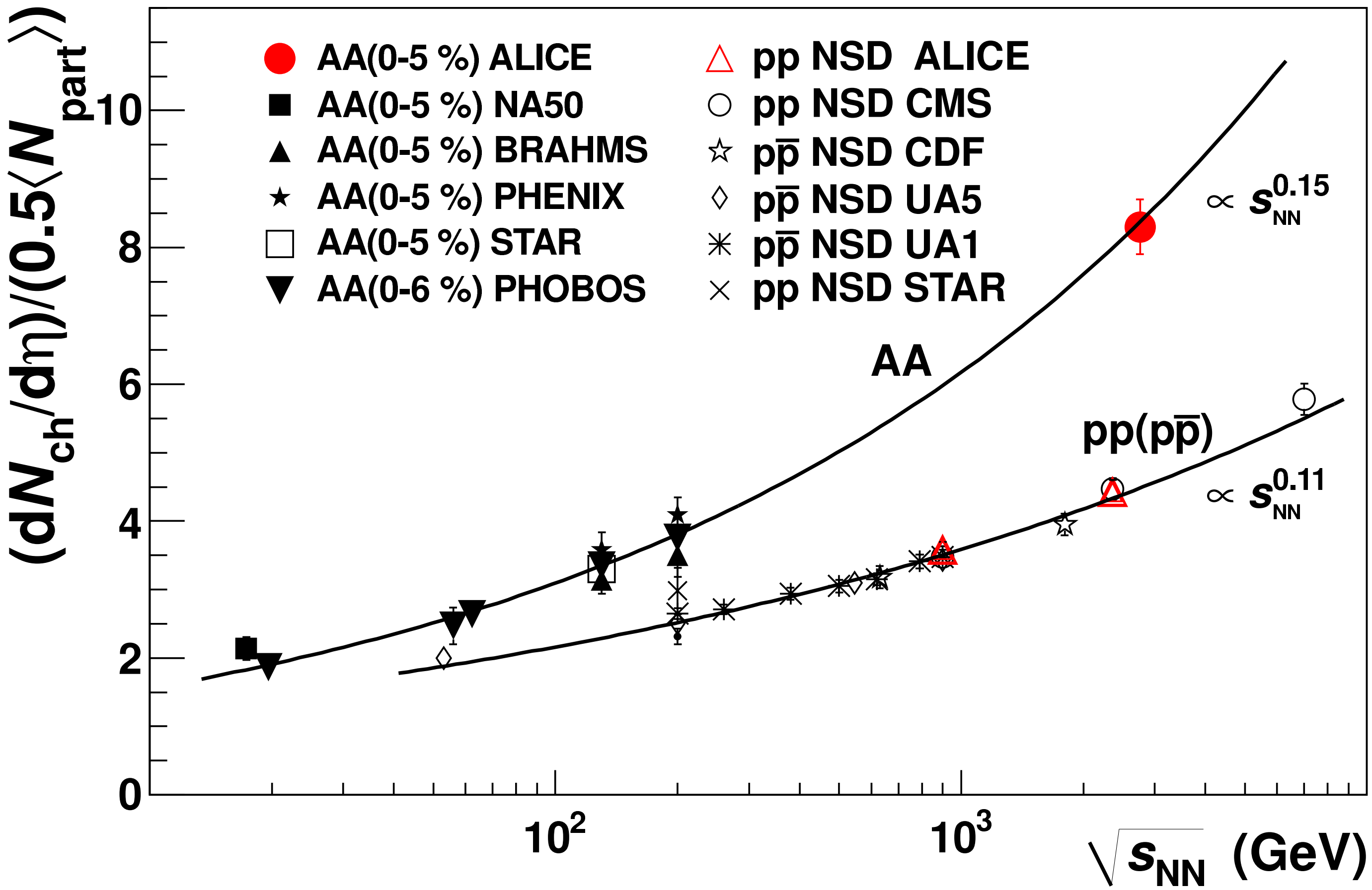
Predictions: Limiting fragmentation



Result vs Predictions: mini-jets, color glass, . . .



Alice results: Scaling with energy



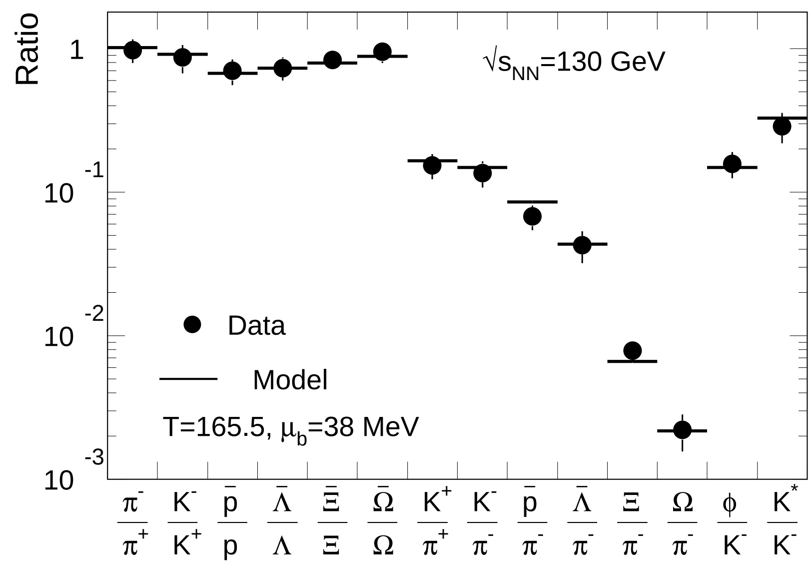
What does it mean?

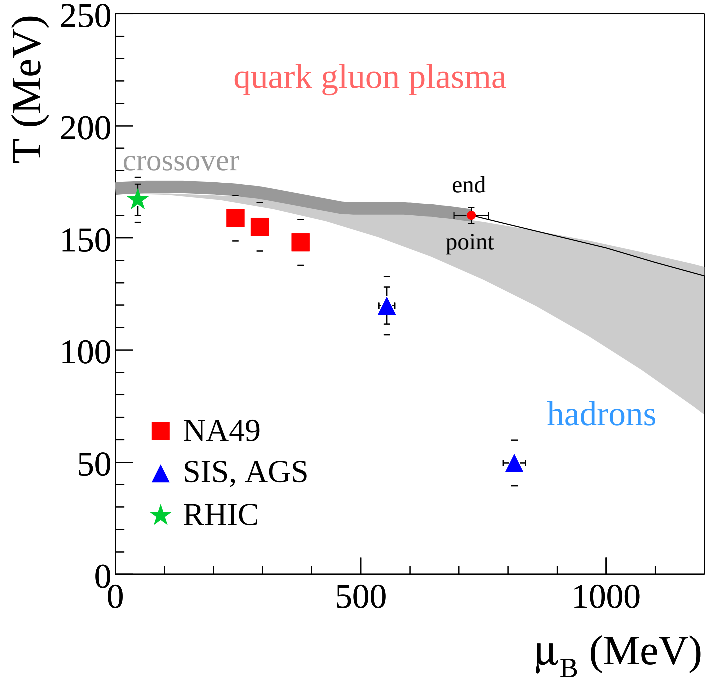
Factor 2.2 in multiplicity: factor 2.85 in energy density, factor 1.3 in temperature (at fixed τ_0)

AA $\neq$ pp: extra multiplicity per participant pair.

Simple saturation works better than improved saturation.

Chemical equilibrium at freezeout

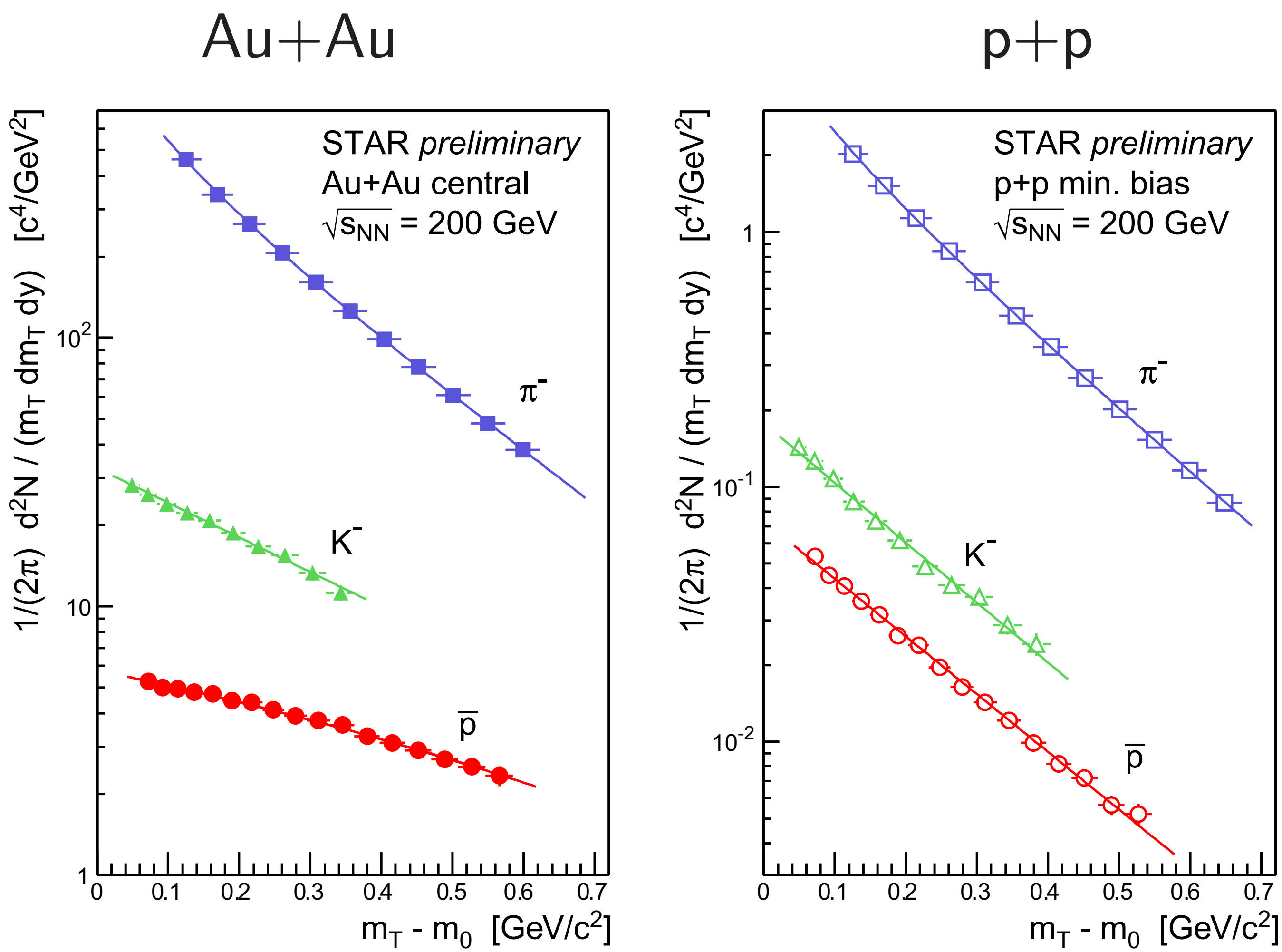




Andronic et al. (2006)

Collective behavior: Radial flow

Radial expansion leads to blue-shifted spectra in Au+Au



$v_T \sim 0.6c!$

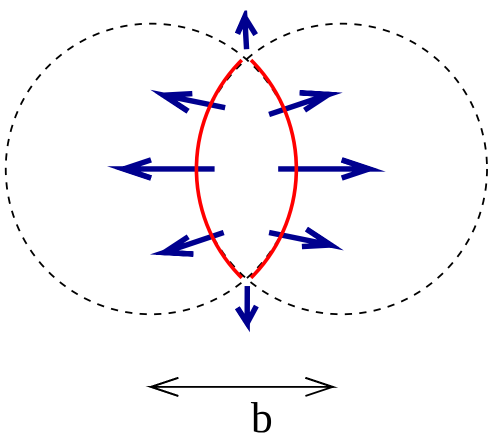
$m_T = \sqrt{p_T^2 + m^2}$

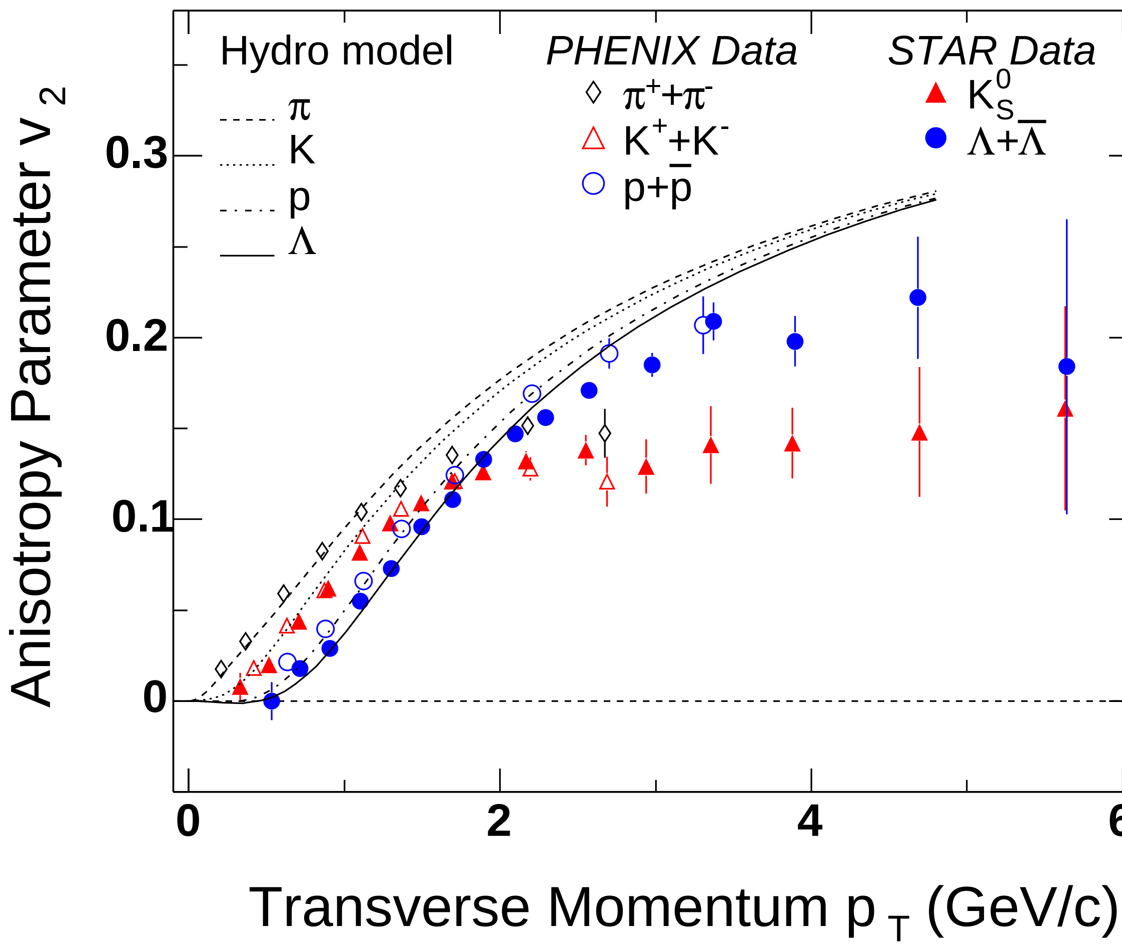
Collective behavior: Elliptic flow

Hydrodynamic expansion converts

coordinate space anisotropy

to momentum space anisotropy

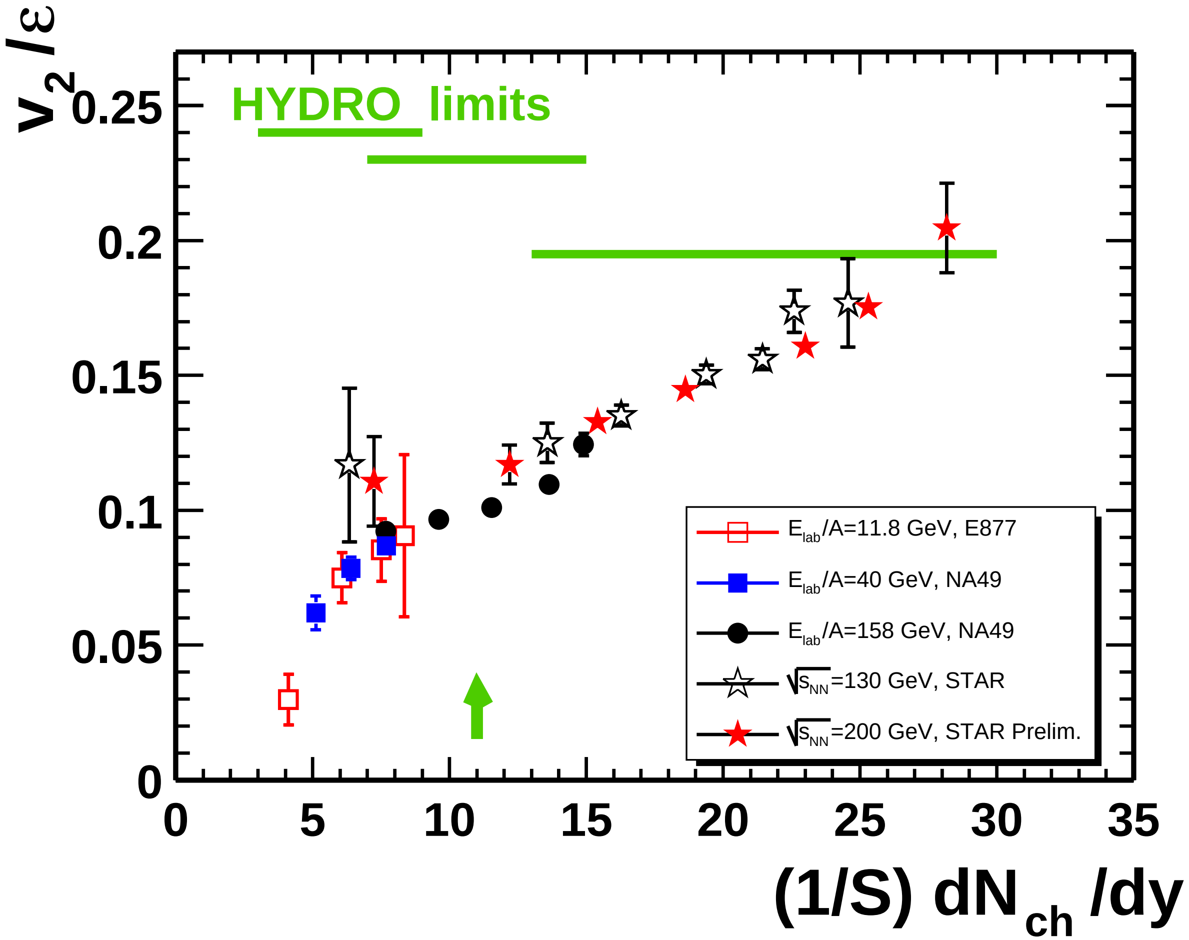




source: U. Heinz (2005)

$$p_0 \left.\frac{dN}{d^3p}\right|_{p_z=0} = v_0(p_\perp)\,(1 + 2v_2(p_\perp)\cos(2\phi) + \ldots)$$

Elliptic flow II: Multiplicity scaling



source: U. Heinz (2005)

Viscous Corrections

Longitudinal expansion: Bj expansion solves Navier-Stokes equation

entropy equation $$\frac{1}{s}\frac{ds}{d\tau} = -\frac{1}{\tau}\left(1 - \frac{\frac{4}{3}\eta + \zeta}{sT\tau}\right)$$

Viscous corrections small if $\frac{4}{3}\frac{\eta}{s} + \frac{\zeta}{s} \ll (T\tau)$

early	$T\tau \sim \tau^{2/3}$	$\eta/s \sim const$	$\eta/s < \tau_0 T_0$
late	$T\tau \sim const$	$\eta \sim T/\sigma$	$\tau^2/\sigma < 1$

Hydro valid for $\tau \in [\tau_0, \tau_{fr}]$

Viscous corrections to T_{ij} (radial expansion)

$$T_{zz} = P - \frac{4}{3}\frac{\eta}{\tau} \qquad T_{xx} = T_{yy} = P + \frac{2}{3}\frac{\eta}{\tau}$$

increases radial flow (central collision)

decreases elliptic flow (peripheral collision)

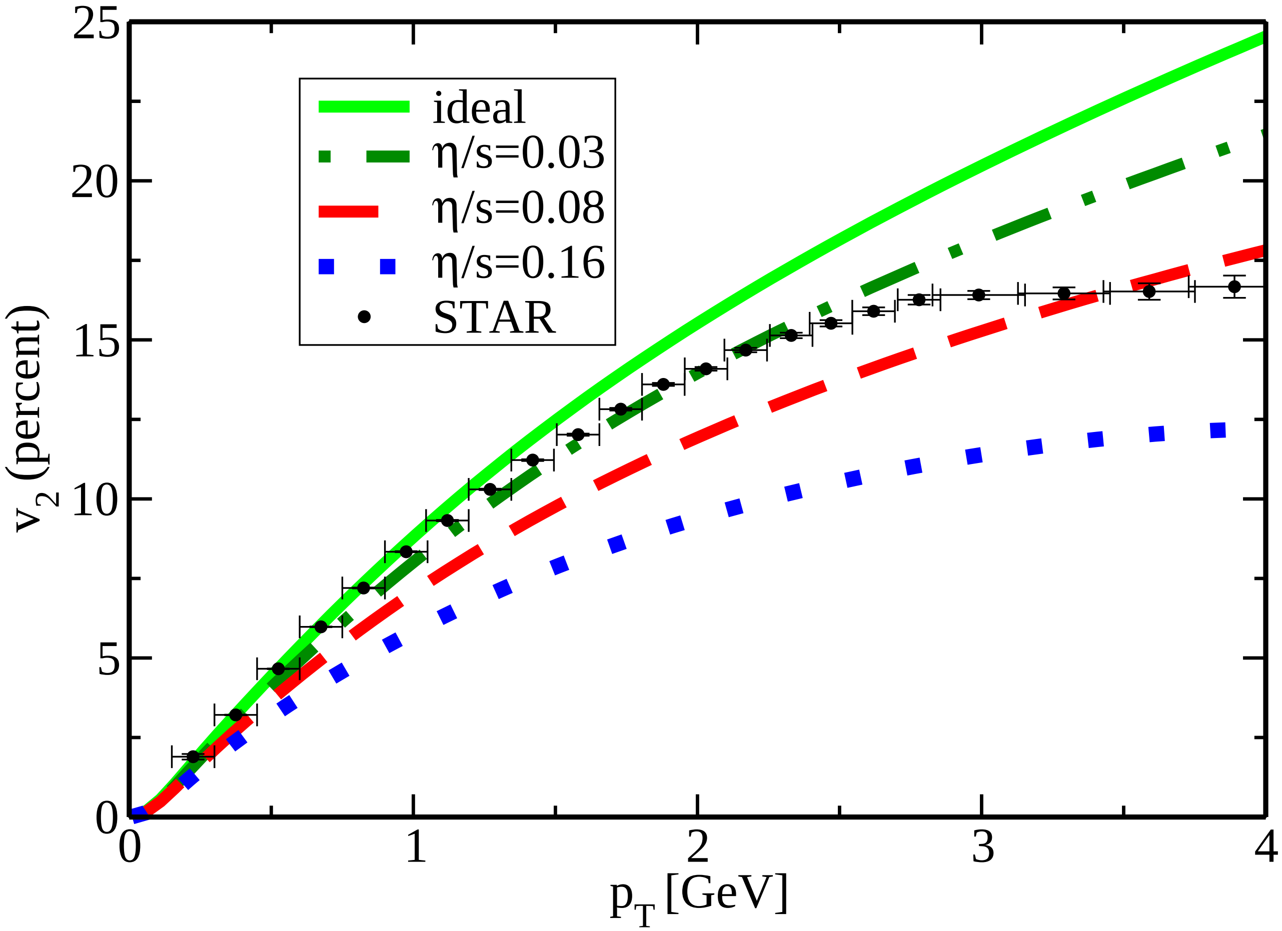
Modification of distribution function

$$\delta f = \frac{3}{8}\frac{\Gamma_s}{T^2} f_0(1+f_0) p_\alpha p_\beta \nabla^{\langle\alpha} u^{\beta\rangle}$$

Correction to spectrum grows with $p_\perp^2$

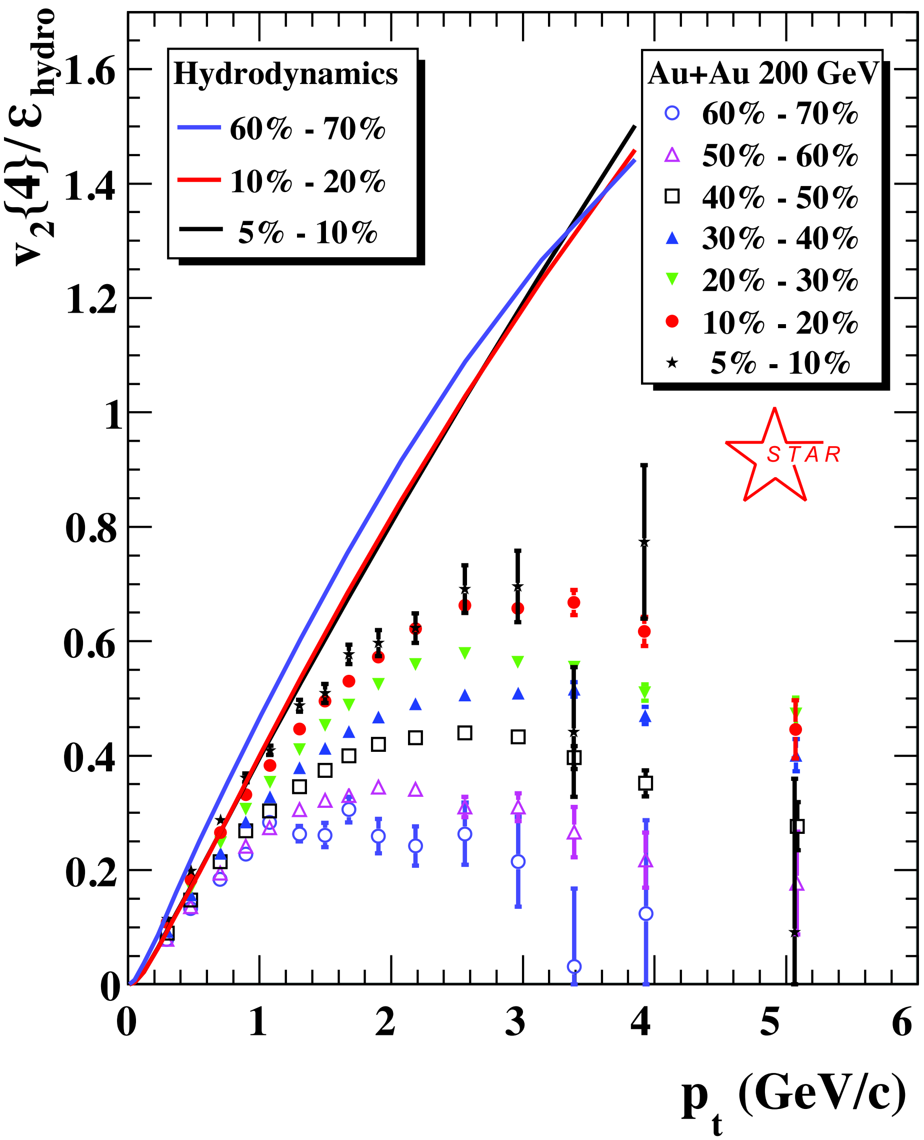
$$\frac{\delta(dN)}{dN_0} = \frac{\Gamma_s}{4\tau_f}\left(\frac{p_\perp}{T}\right)^2$$

Elliptic flow III: Viscous effects



Romatschke (2007), Teaney (2003)

Elliptic flow IV: Systematic trends



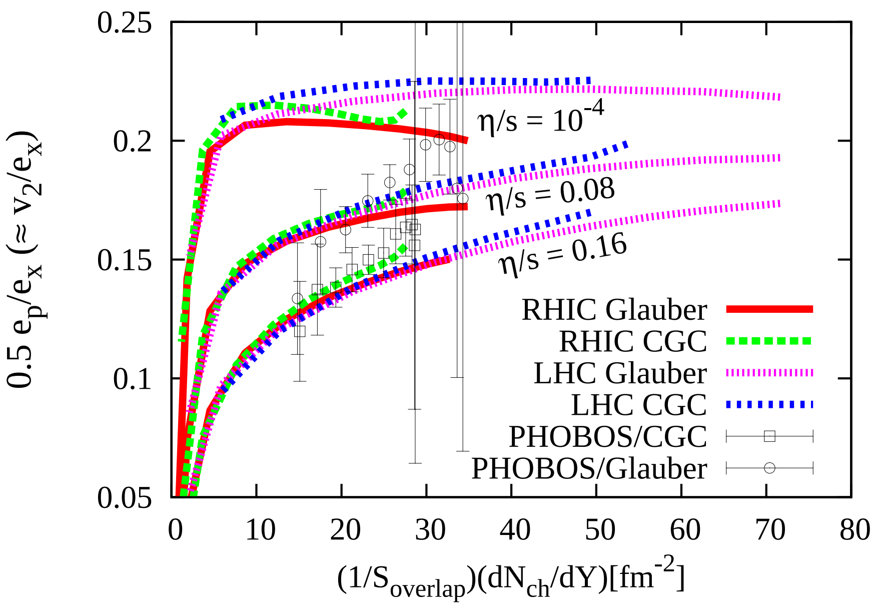
source: R. Snellings (STAR)

Deviation from ideal hydro

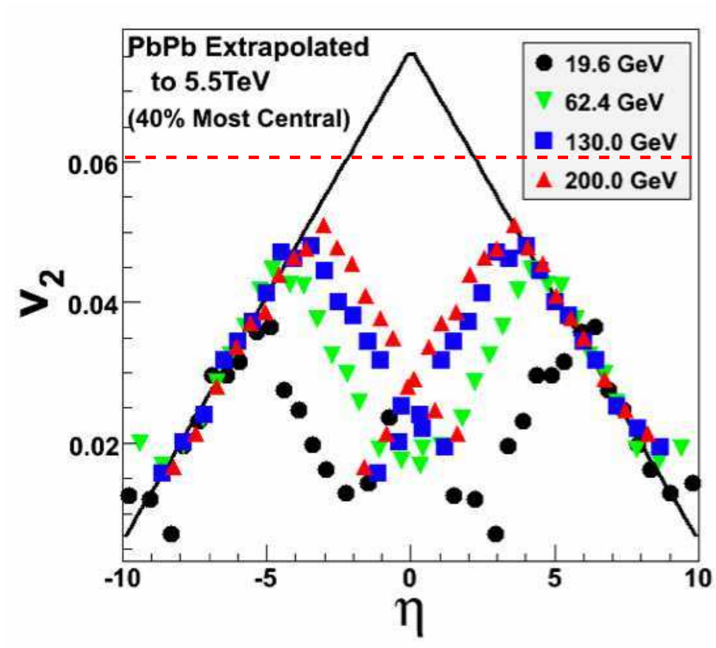
increases for more peripheral events

increases with $p_\perp$

Elliptic flow V: Predictions for LHC



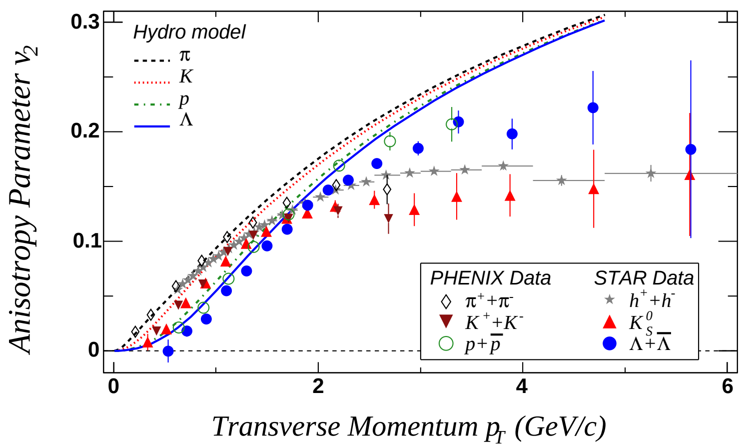
Romatschke, Luzum (2009)

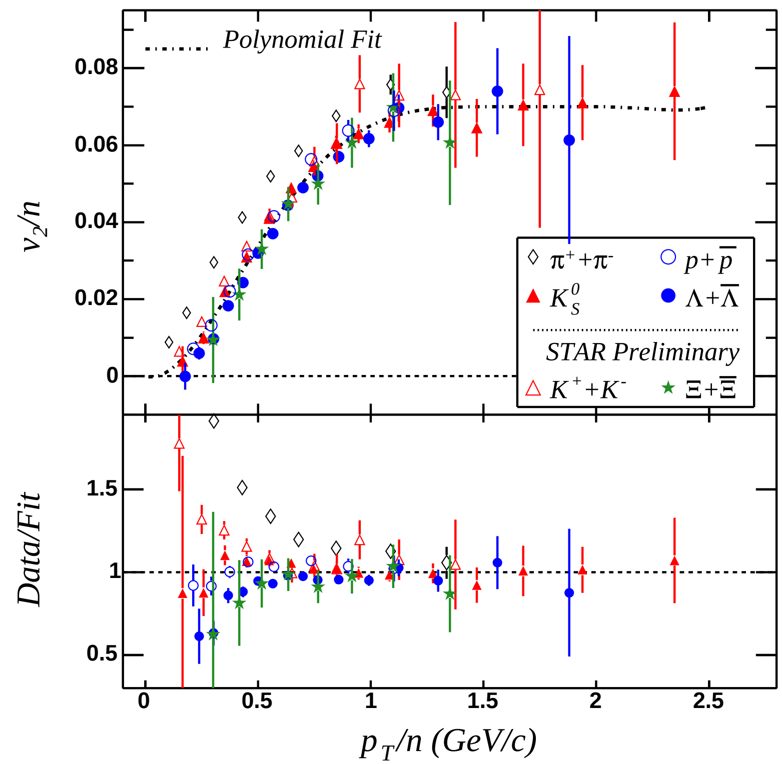


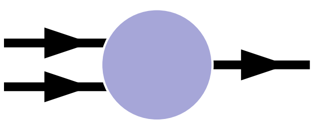
Busza (QM 2009)

Elliptic flow VI: Recombination

“quark number” scaling of elliptic flow

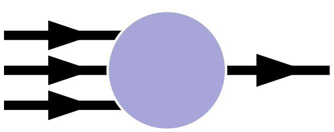






(q$\bar{q}$) (mes)

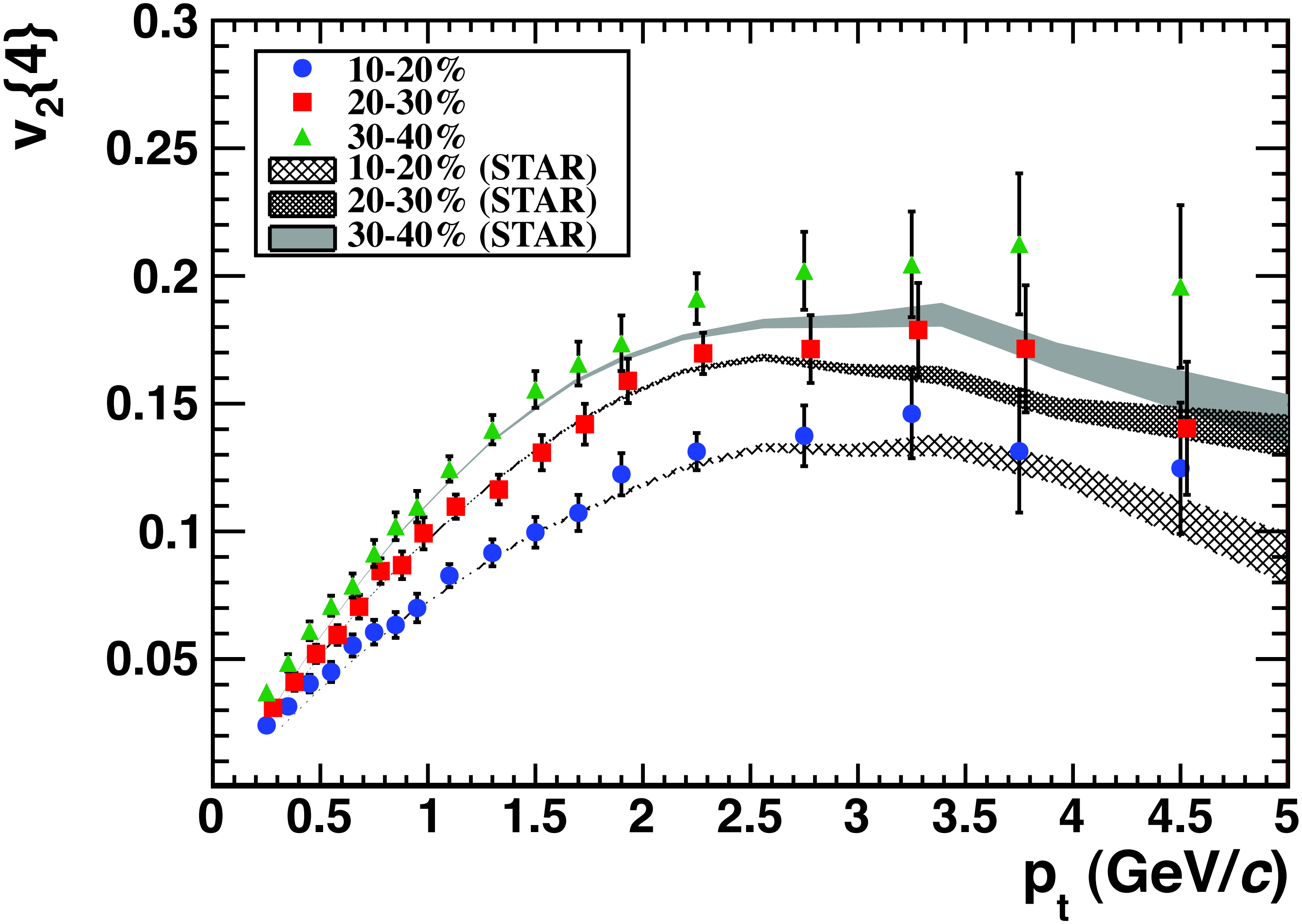
$$p_\perp^{mes} = 2 p_\perp^{qu}$$



(qqq) (bar)

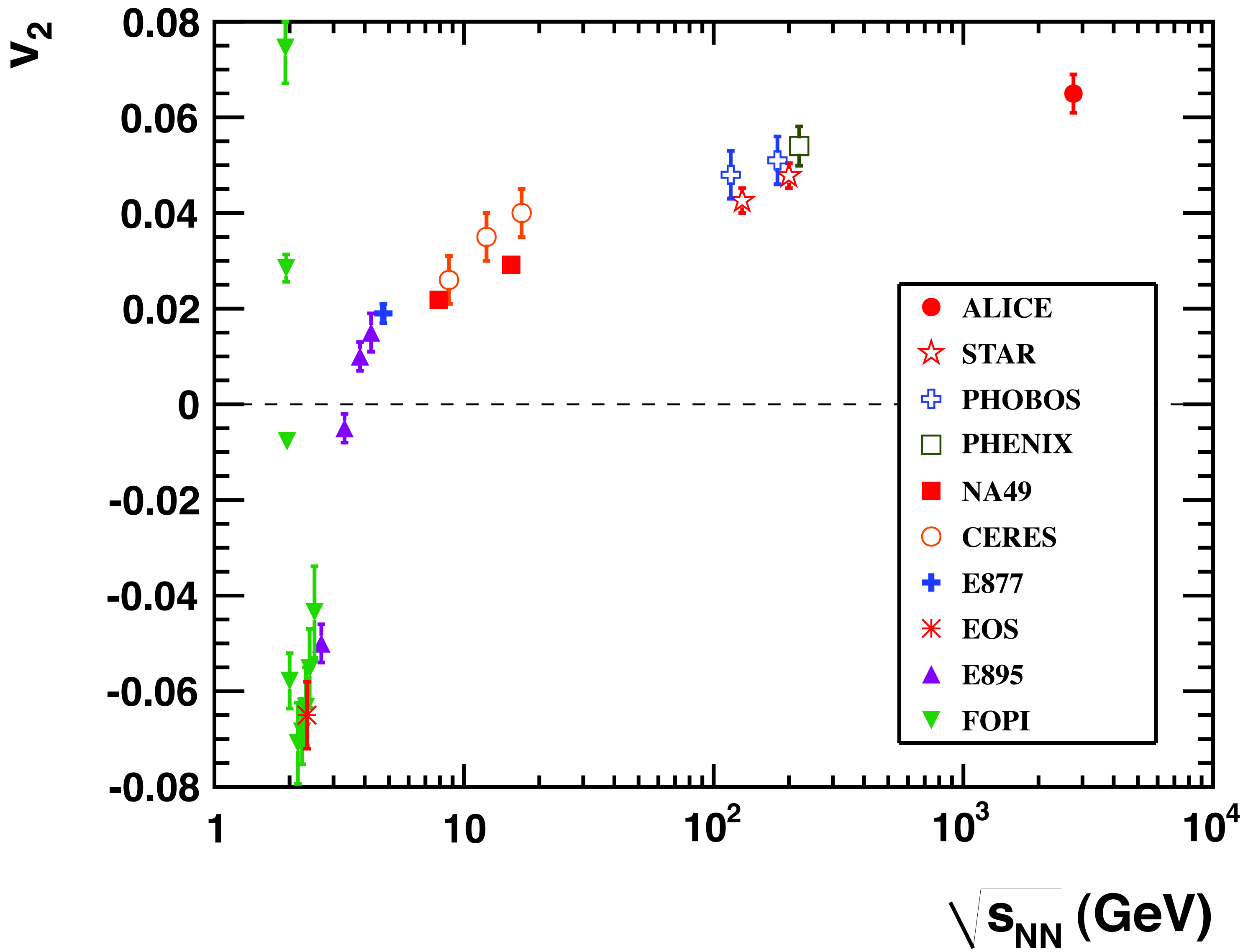
$$p_\perp^{bar} = 3 p_\perp^{qu}$$

Alice flow



$v_2\{4\}$
0.3
0.25
0.2
0.15
0.1
0.05
10-20%
20-30%
30-40%
10-20% (STAR)
20-30% (STAR)
30-40% (STAR)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
p_t (GeV/c)

Flow excitation function



What does it mean?

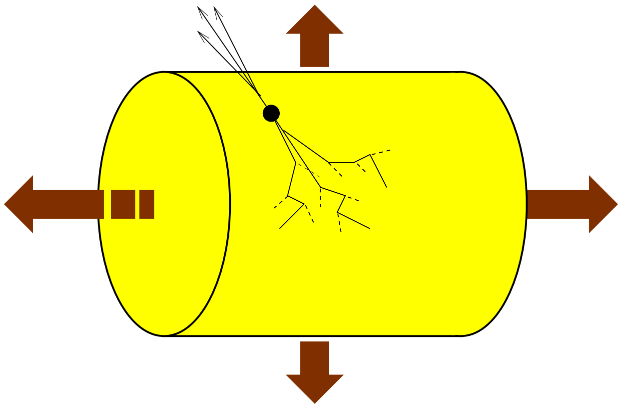
Hydro rules! RHIC data not an accident.

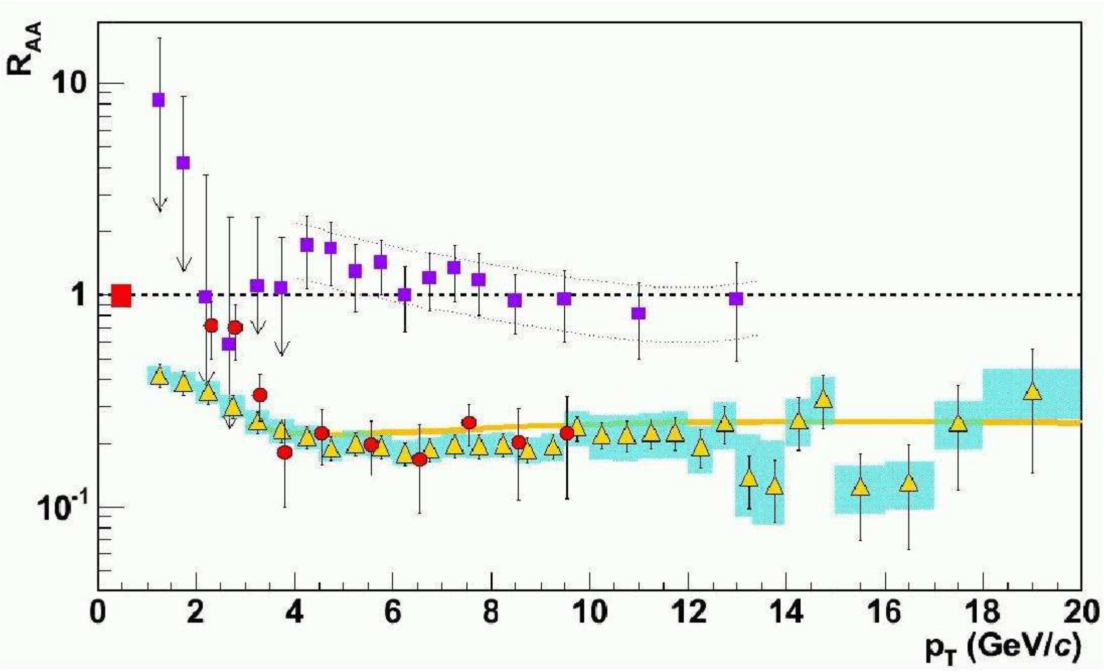
Differential v_2 exactly equal to RHIC (!?)

Integrated v_2 somewhat high: mean p_T increase? acceptance?

Jet quenching

$$R_{AA} = \frac{n_{AA}}{N_{coll} n_{pp}}$$

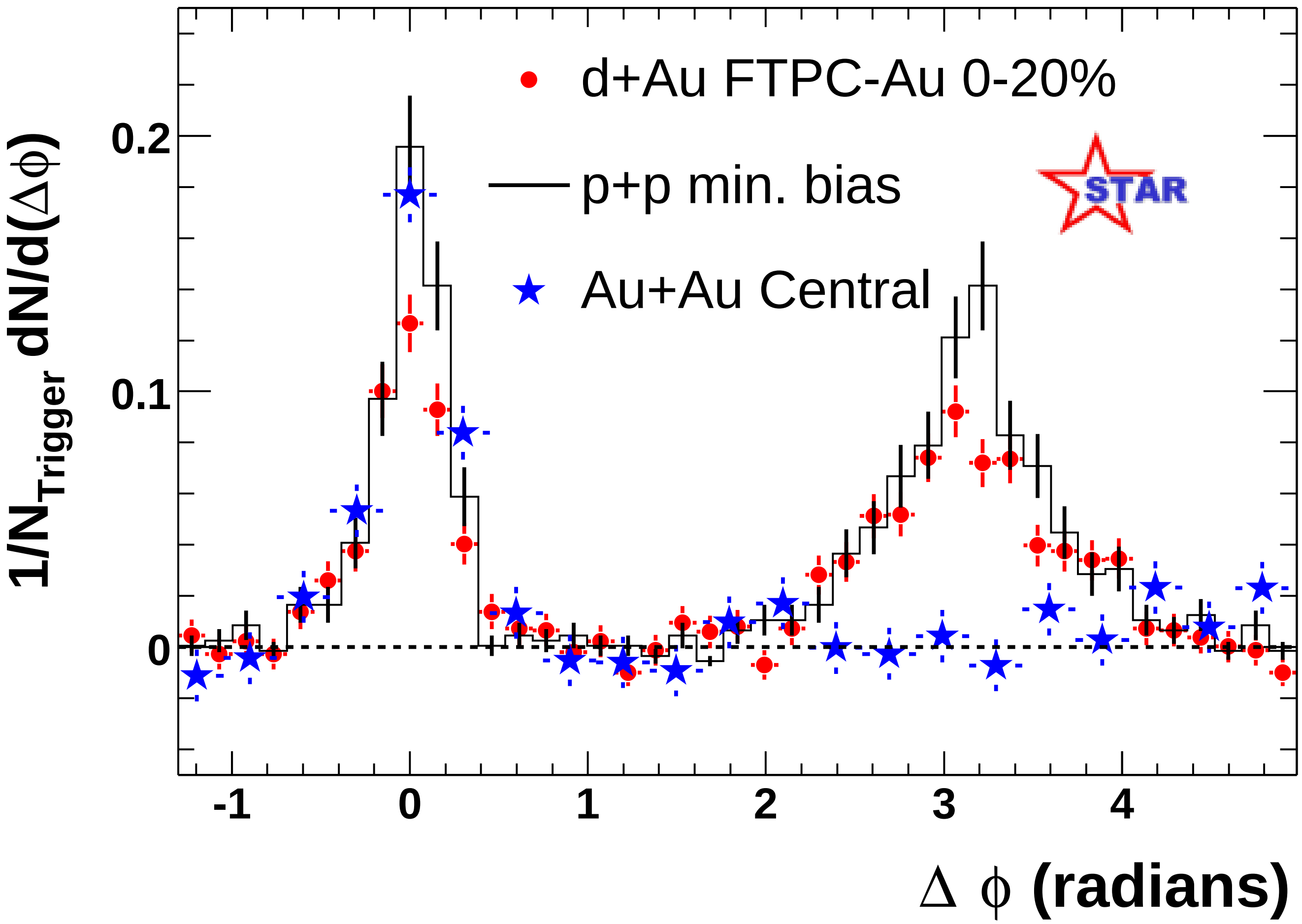




source: Akiba [Phenix] (2006)

Jet quenching II

Disappearance of away-side jet



source: Star White Paper (2005)

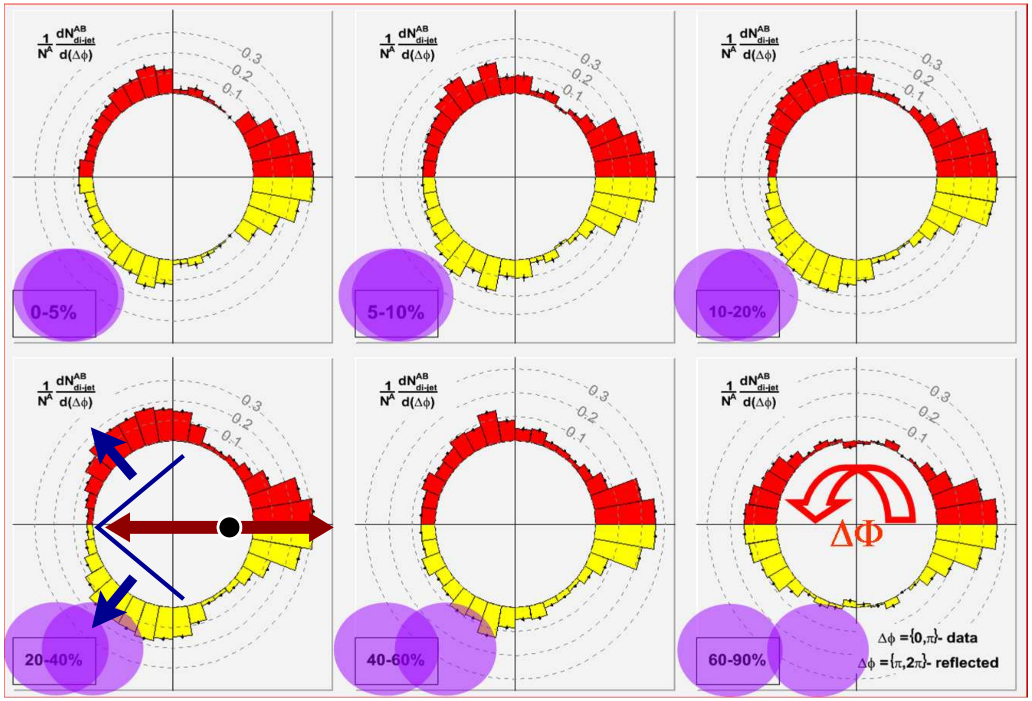
Jet quenching III: The Mach cone

azimuthal multiplicity $dN/d\phi$

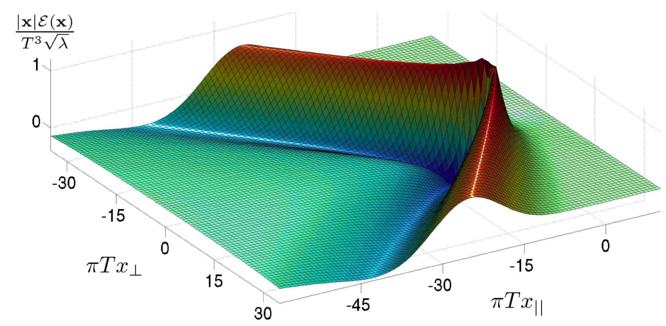
(high energy trigger particle at $\phi = 0$)

wake of a fast quark

in $\mathcal{N} = 4$ plasma



source: Phenix (PRL, 2006), W. Zajc (2007)

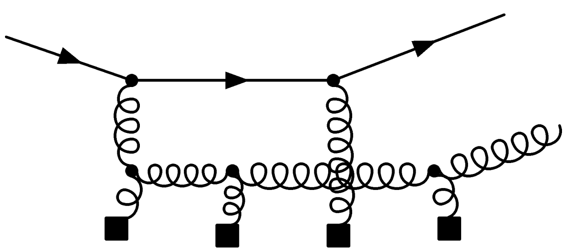


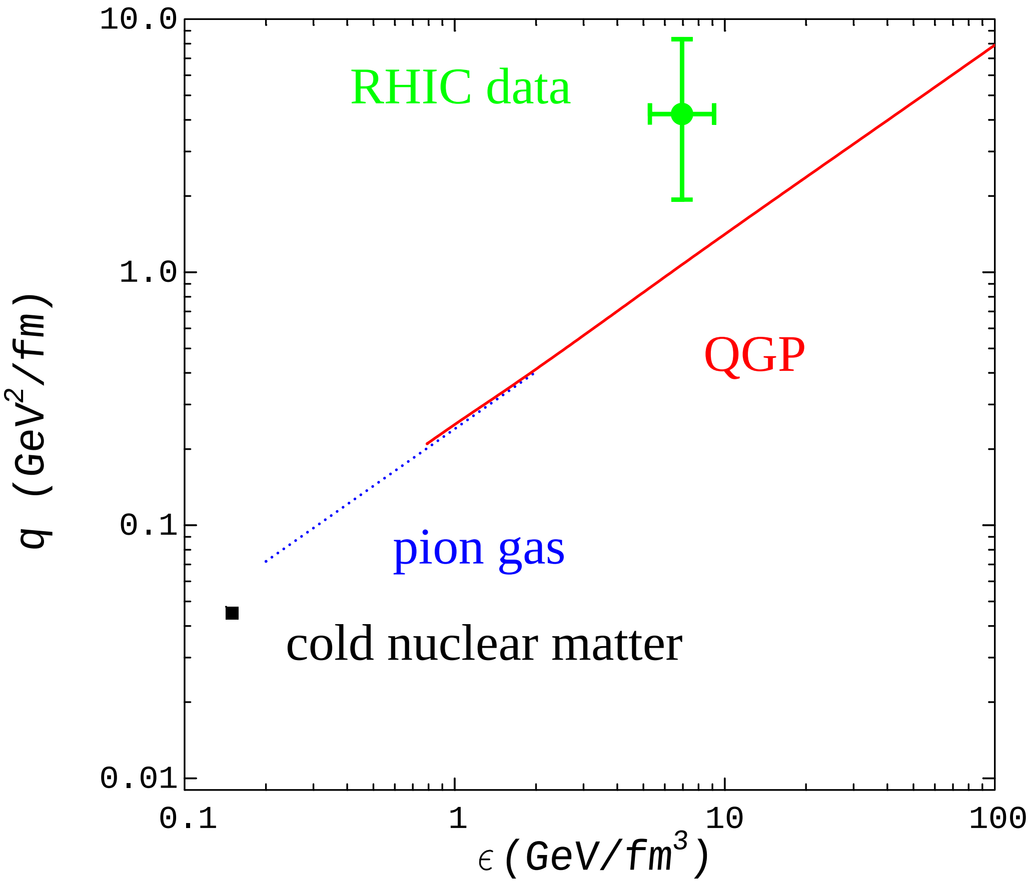
Chesler and Yaffe (2007)

Jet quenching: Theory

energy loss governed by

$$\hat{q} = \rho \int q_\perp^2 \, dq_\perp^2 \; \frac{d\sigma}{dq_\perp^2}$$



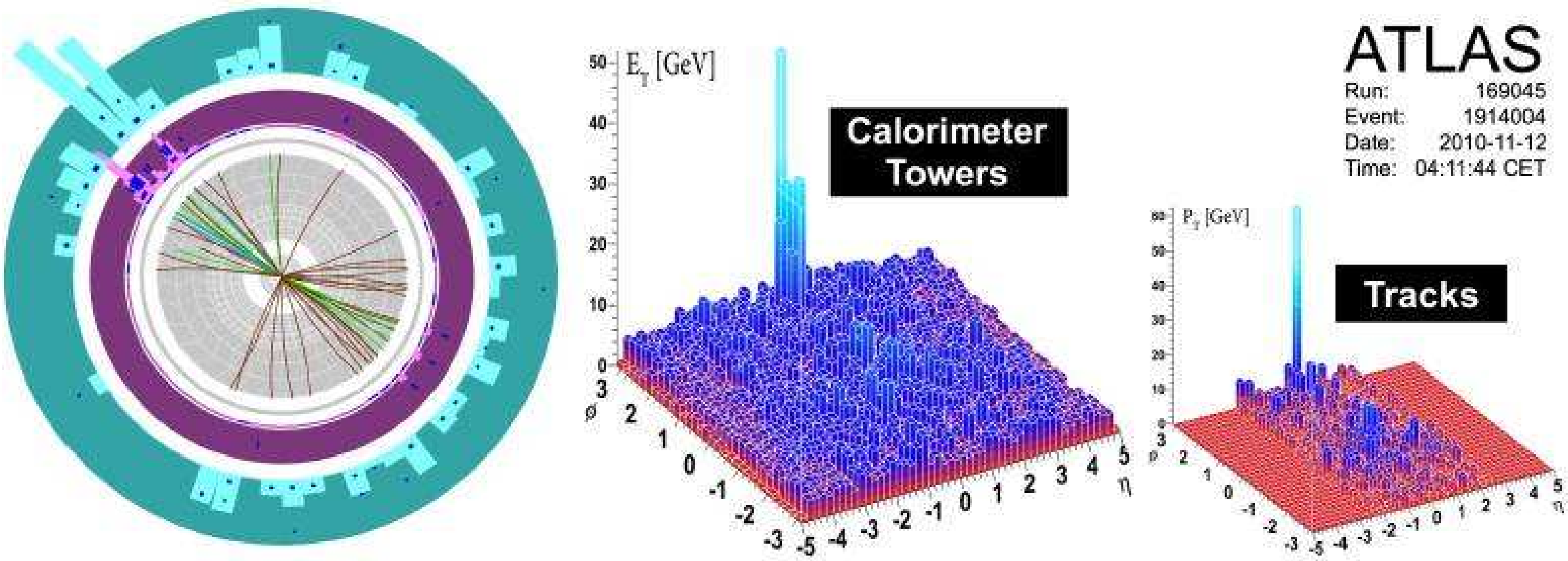


larger than pQCD predicts? relation to η? ($\hat{q} \sim 1/\eta$?)

also: large energy loss of heavy quarks

source: R. Baier (2004)

ATLAS mono-jet



Event display of a highly asymmetric dijet event, with one jet with $E_T > 100$ GeV and no evident recoiling jet, and with high energy calorimeter cell deposits distributed over a wide azimuthal region. Only tracks with $p_T > 2.6$ GeV.

What does it mean?

Jets can be identified in AA environment.

$E_T > 100$ GeV jet is stopped!

Proof of principle, detailed analysis needed.