High-$p_\perp$ charged particle azimuthal correlations at RHIC

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Focus of this talk

RHIC machine - new era of pQCD phenomena in heavy-ion physics
collinear factorization - high-p_T jets.

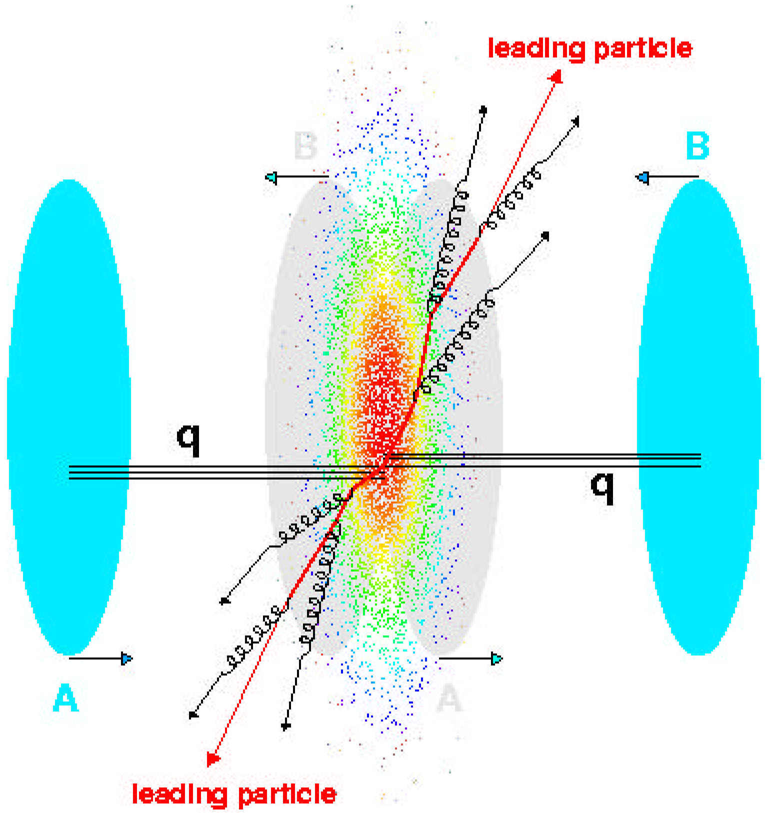
RHIC data - first two years of RHIC running brought many exciting results, two striking obsevations:

- high-p_T particle suppression
- exceedingly large and p_T independent azimuthal anisotropy

Although tremendous progress in theoretical understanding of observed phenomena has been made, the satisfactory picture is still missing.

Hard scattering in Heavy Ion collisions

schematic view of jet production



Jets:

- primarily from gluons at RHIC
- produced early (τ<1fm)
- sensitive to the QCD medium (dE/dx)

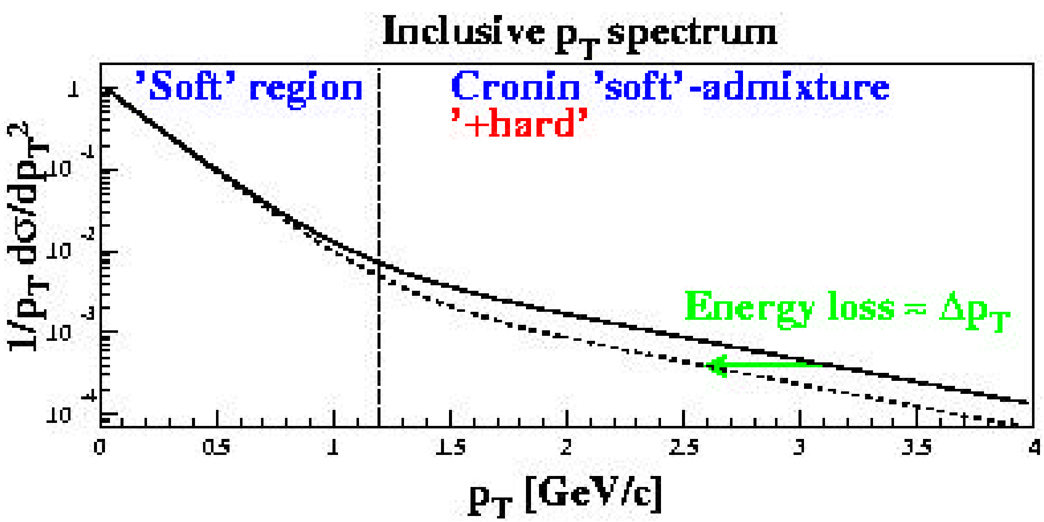
Observed via:

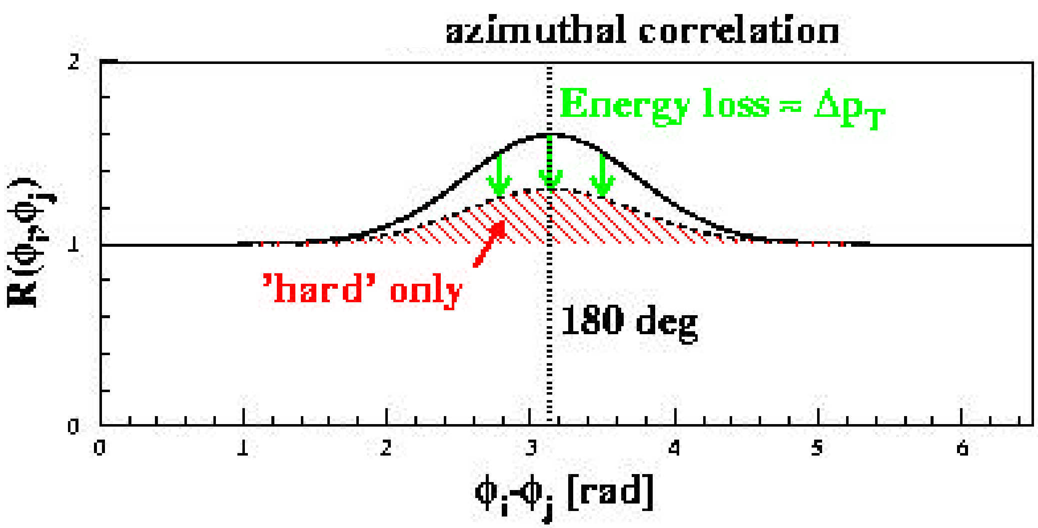
- fast leading particles or
- azimuthal correlations between them

Mechanisms of energy loss in vacuum (*pp)* is understood in terms of formation time and static chromoelectric field regeneration* . Any nuclear modification of this process could provide a hint of QGP formation.

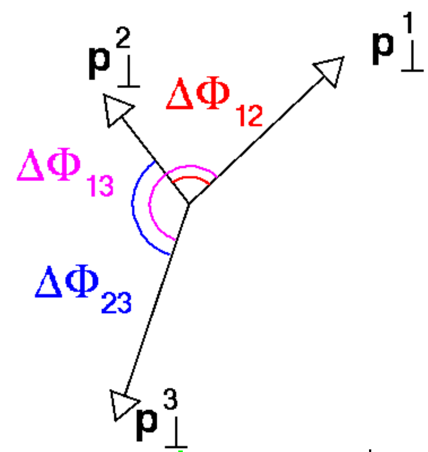
* *F.Niedermayer, Phys.Rev.D34:3494,1986.*

Hard scattering signals





Hard scattered partons fragment into two back-to-back jets in azimuth.

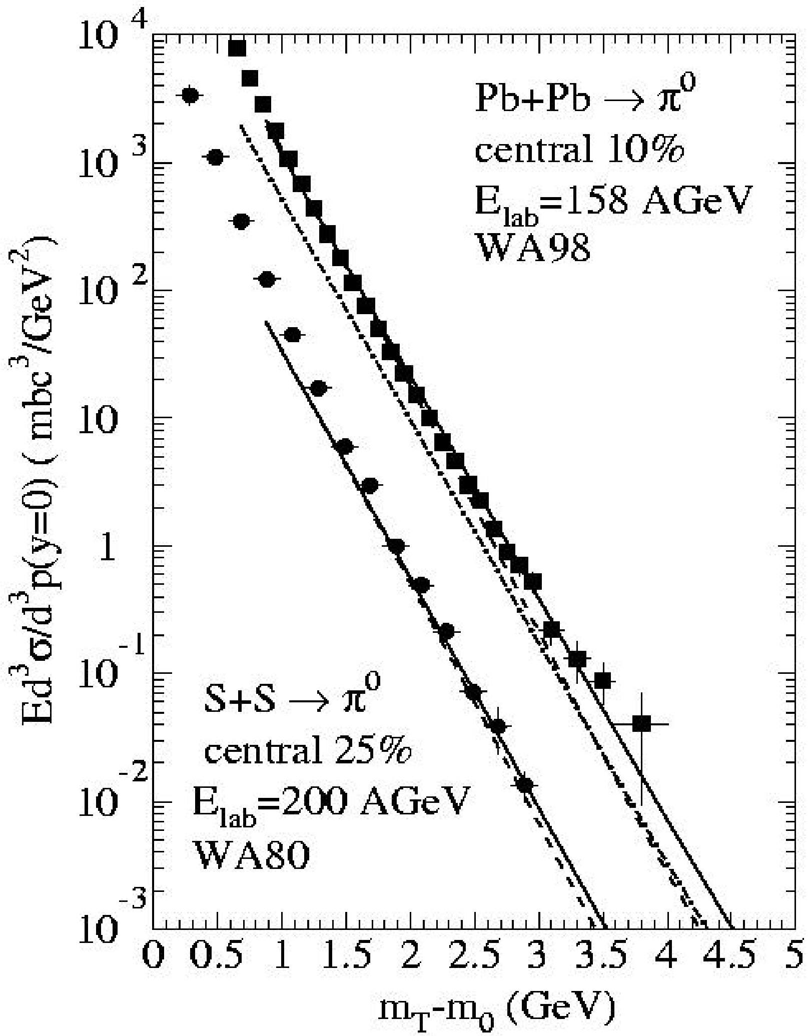


Partonic energy loss may*

- reduce the back-to-back peak
- modify the fragmentation function - near angle peak

* *X.N. Wang, Phys.Rev.Lett.81:(1998)2655*

pQCD phenomena in HI before RHIC era



The pQCD phenomena in AA collisions were observed already at lower energy (SPS Ös = 17 AGeV)

- J/Y suppression
- DY
- direct photons

Jet suppression proposed as a additional signature of QGP formation.

First attempt - first speaker of this session - WA98 data.

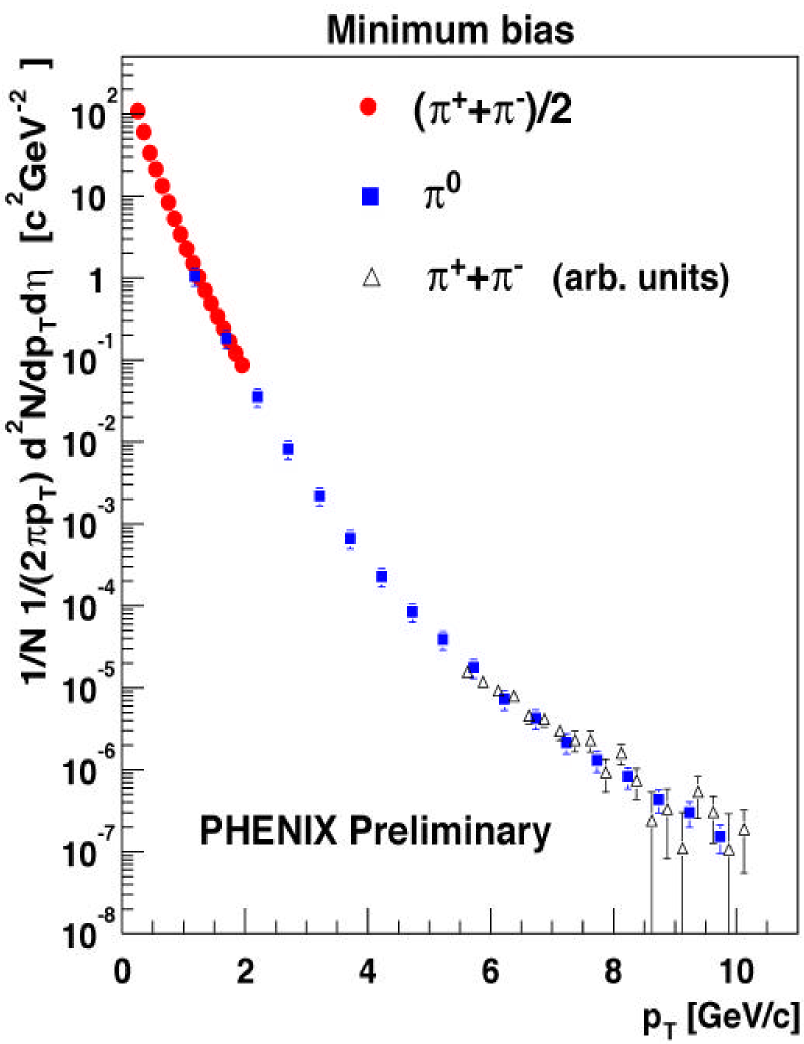
the dense matter. To verify that these spectra are from jet production and fragmentation rather than from hydrodynamic flow, one can measure the azimuthal particle correlation (selecting particles above a certain p_T) rela-

Where is the jet quenching in Pb+Pb ...

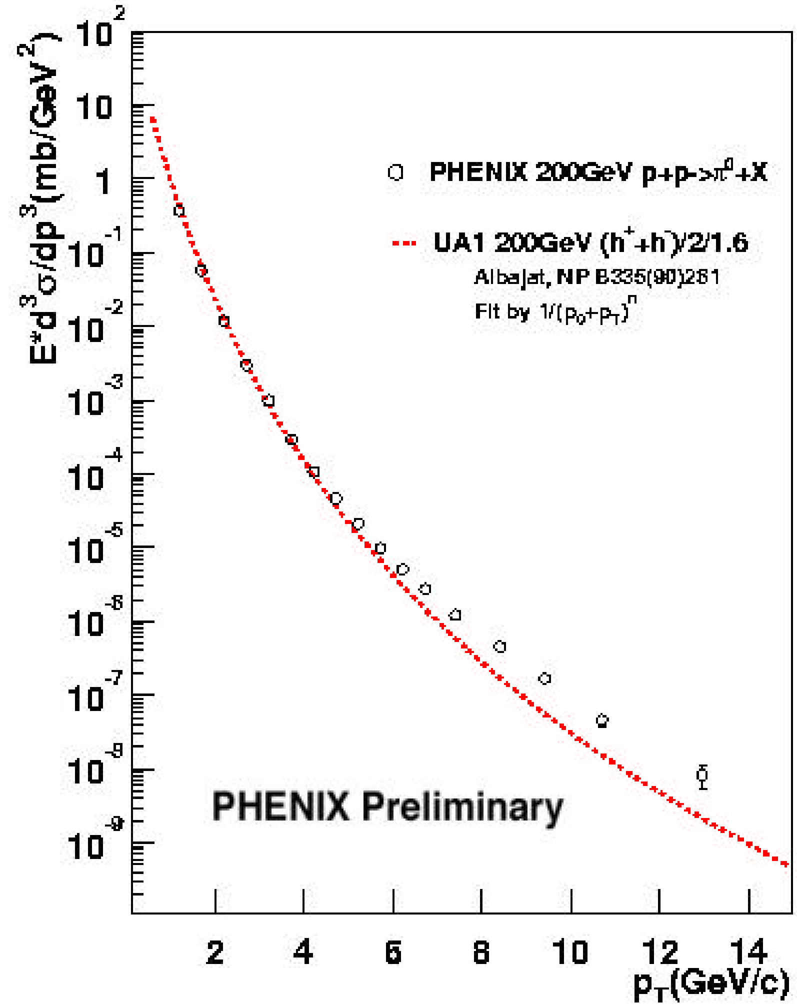
X.N. Wang, Phys.Rev.Lett.81:2655-2658,1998

PHENIX charged and neutral π^0

AuAu $\sqrt{s}$ = 200 GeV



pp $\sqrt{s}$ = 200 GeV π^0



PHENIX π^0 R_{AA}

- There is a massive suppression of high-pt yield, factor 2-5.
- Sets on around 2 GeV/c and then it is slightly decreasing with p_T.
- Unlike @SPS ($\sqrt{s}$ = 17 GeV) we do not observe the Cronin effect.
- Is this what we expected from partonic energy-loss ?

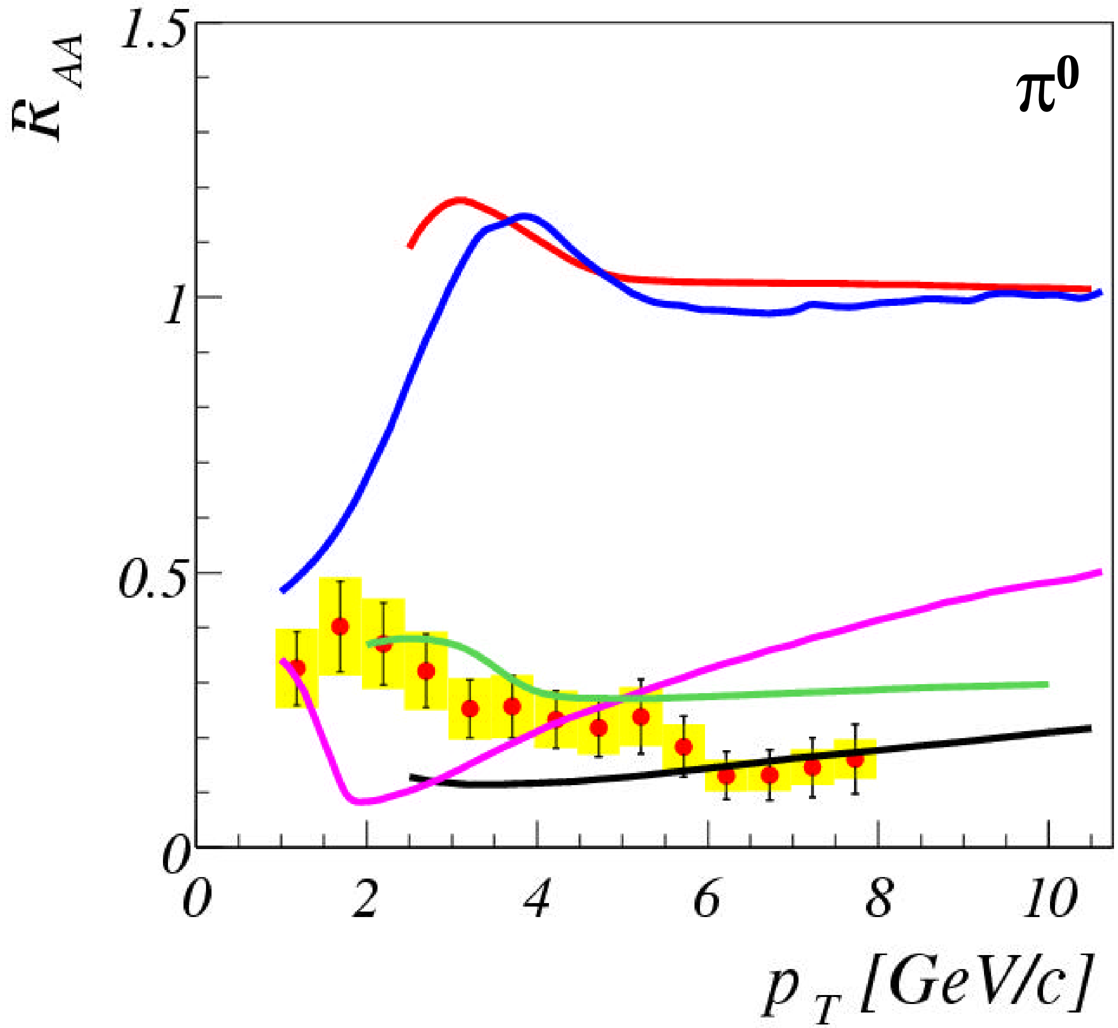
--- Wang dE/dx = 0

--- dE/dx =0.25 GeV/fm
X.N. Wang, Phys. Rev. C61, 064910 (2000).

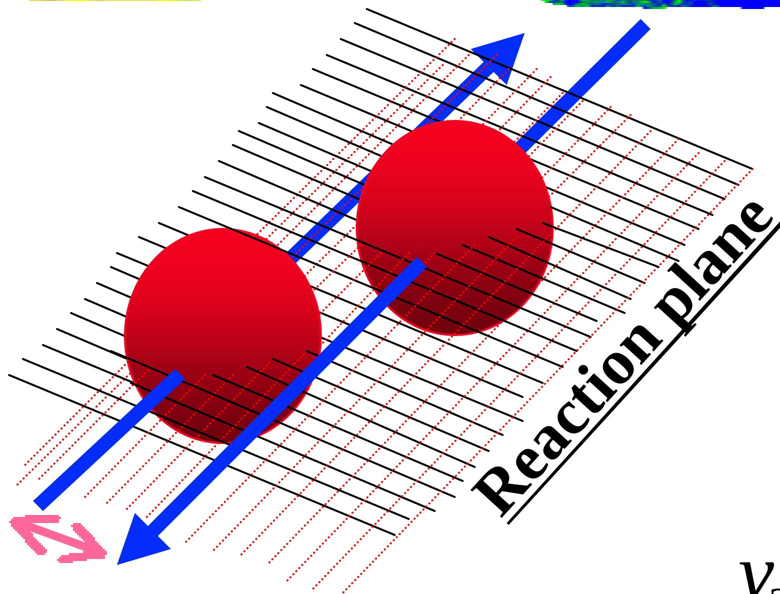
--- Levai L/λ = 0

--- L/λ = 4
Gyulassy, Levai, Vitev: P.Levai, Nuclear Physics A698 (2002) 631.

--- Vitev dNg/dy = 900
GLV, Nucl. Phys. B 594, p. 371 (2001) + work in preparation.



Azimuthal anisotropy

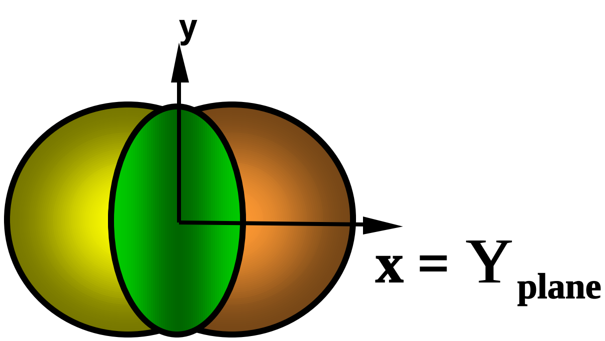


b : Impact parameter

$$e = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

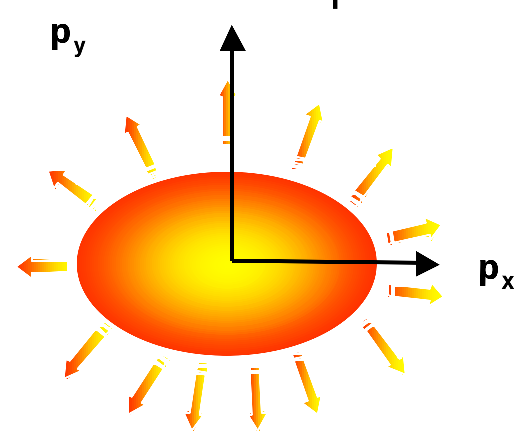
$$v_2 = \frac{\langle p_x{}^2 - p_y{}^2 \rangle}{\langle p_x{}^2 + p_y{}^2 \rangle}$$

Coordinate space

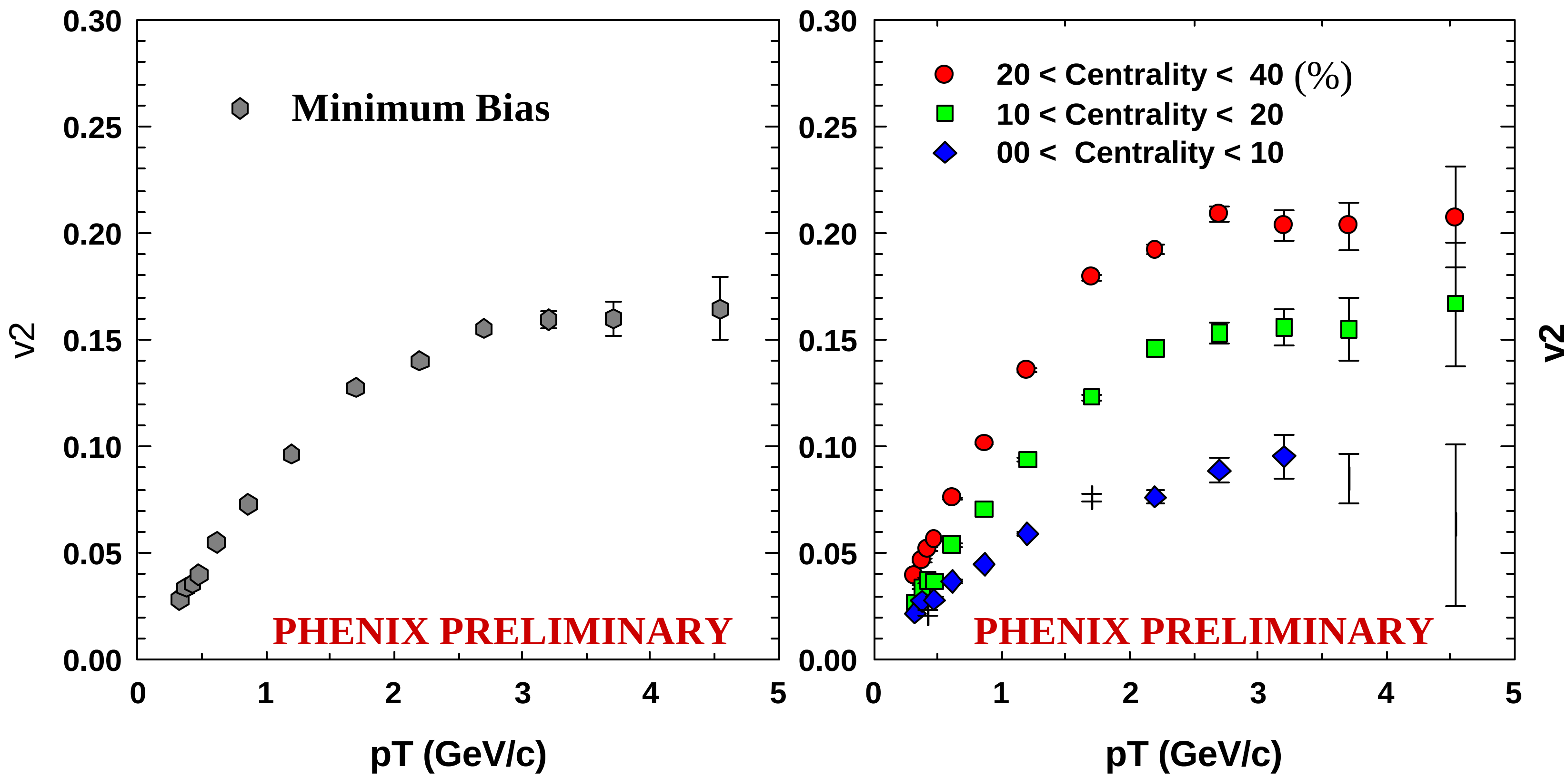


thermalization

momentum space

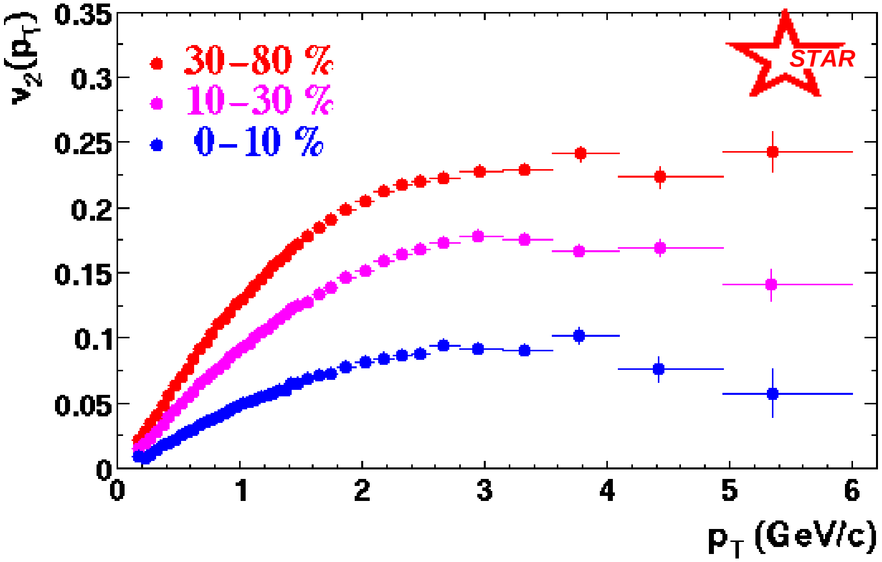


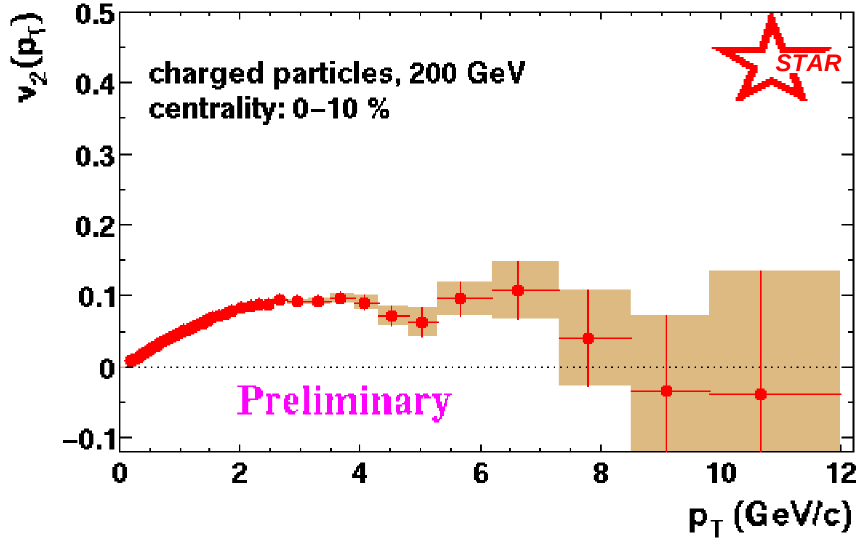
Differential v2

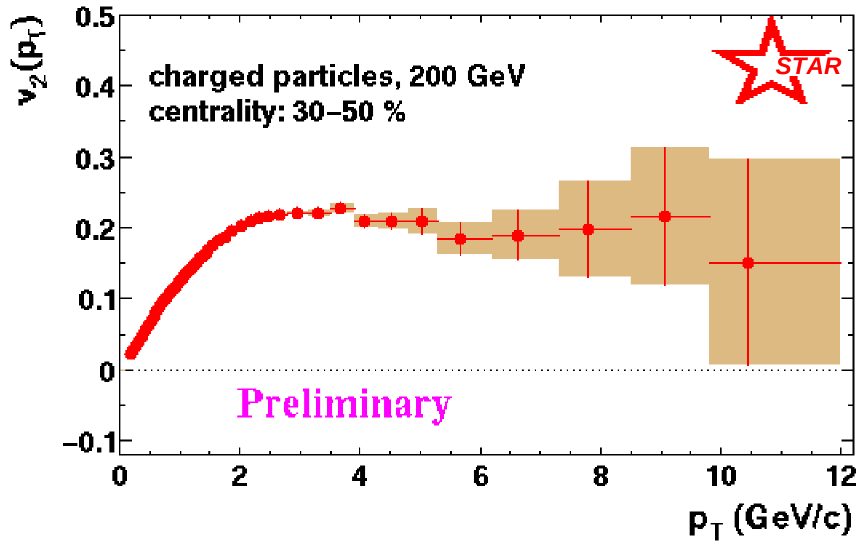


V2 Saturates at ~ 2.5 GeV/c; Similar Trend for all Centralities
V2 increases with Centrality

STAR Reaction Plane $v_2(p_T)$



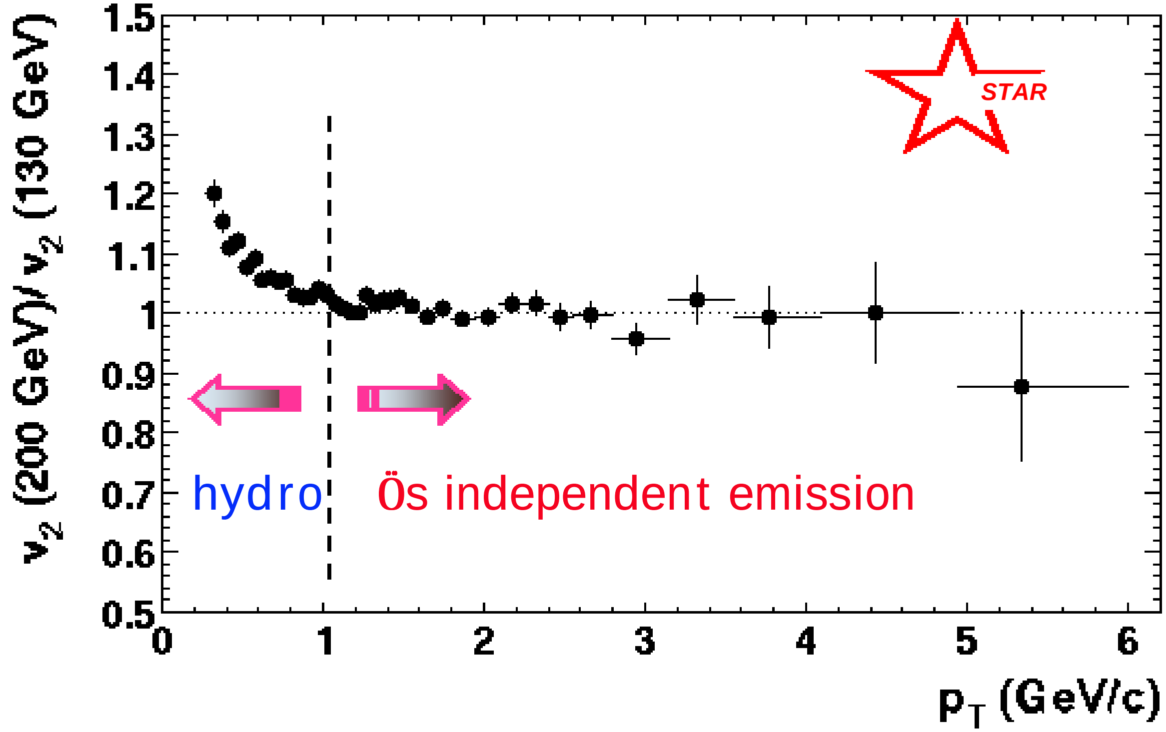




Excellent agreement between STAR and PHENIX

√s=200 AGeV versus √s=130 AGeV

- v_2(pt) saturates at p_T>2.5 GeV/c for all centralities at both beam energies
- for pt < 1GeV/c the conventional hydrodynamics seems to dominate
- for pt > 1GeV/c we observe Ös independent emission pattern

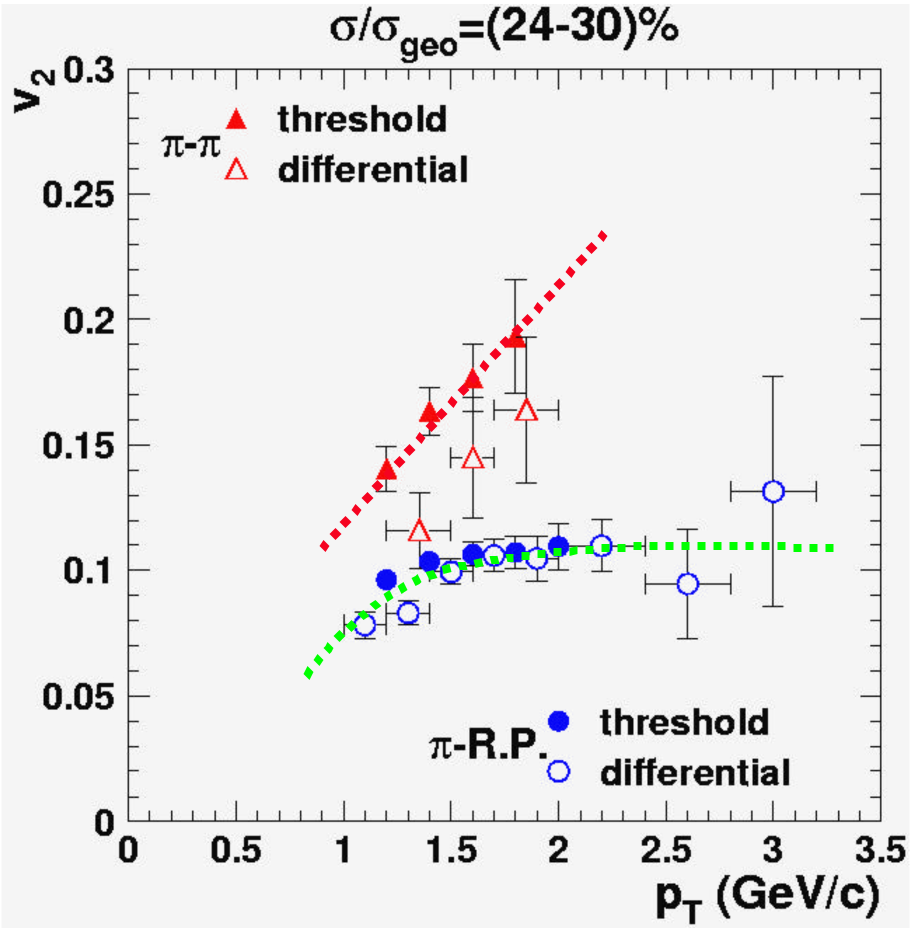


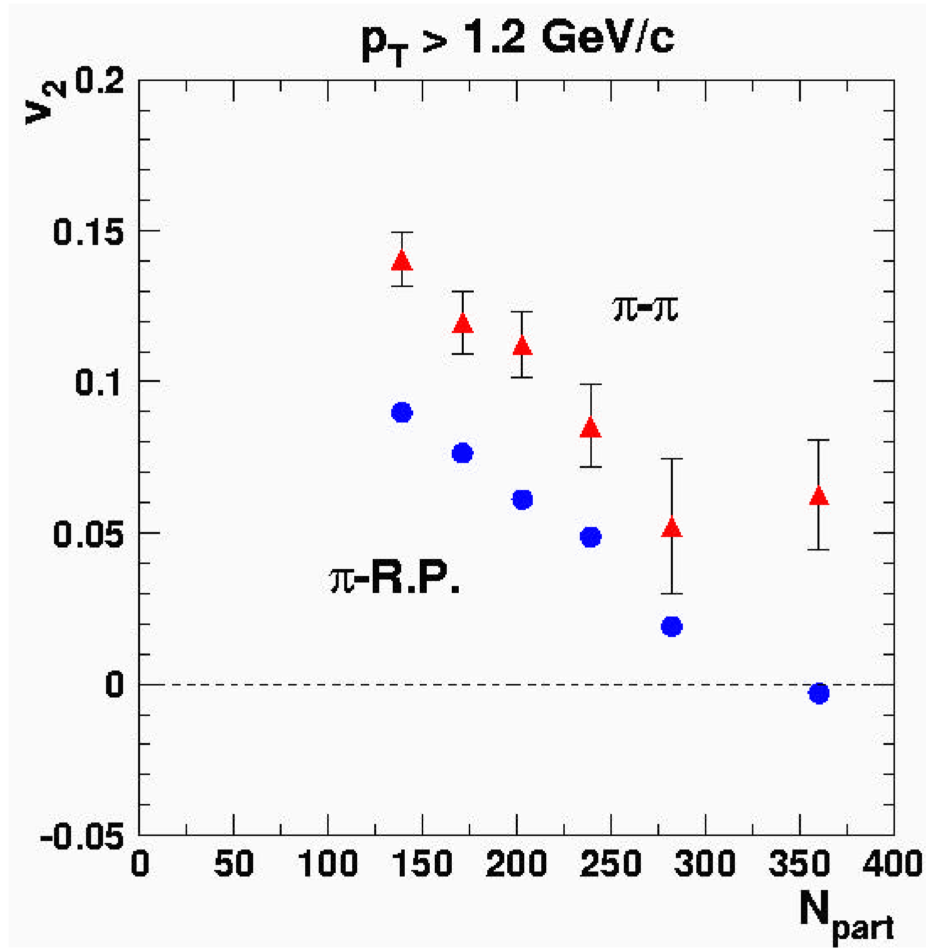
Any dynamical scenario would imply Ös and pt dependence.

There seems to be novel mechanism of high-pt particle production.

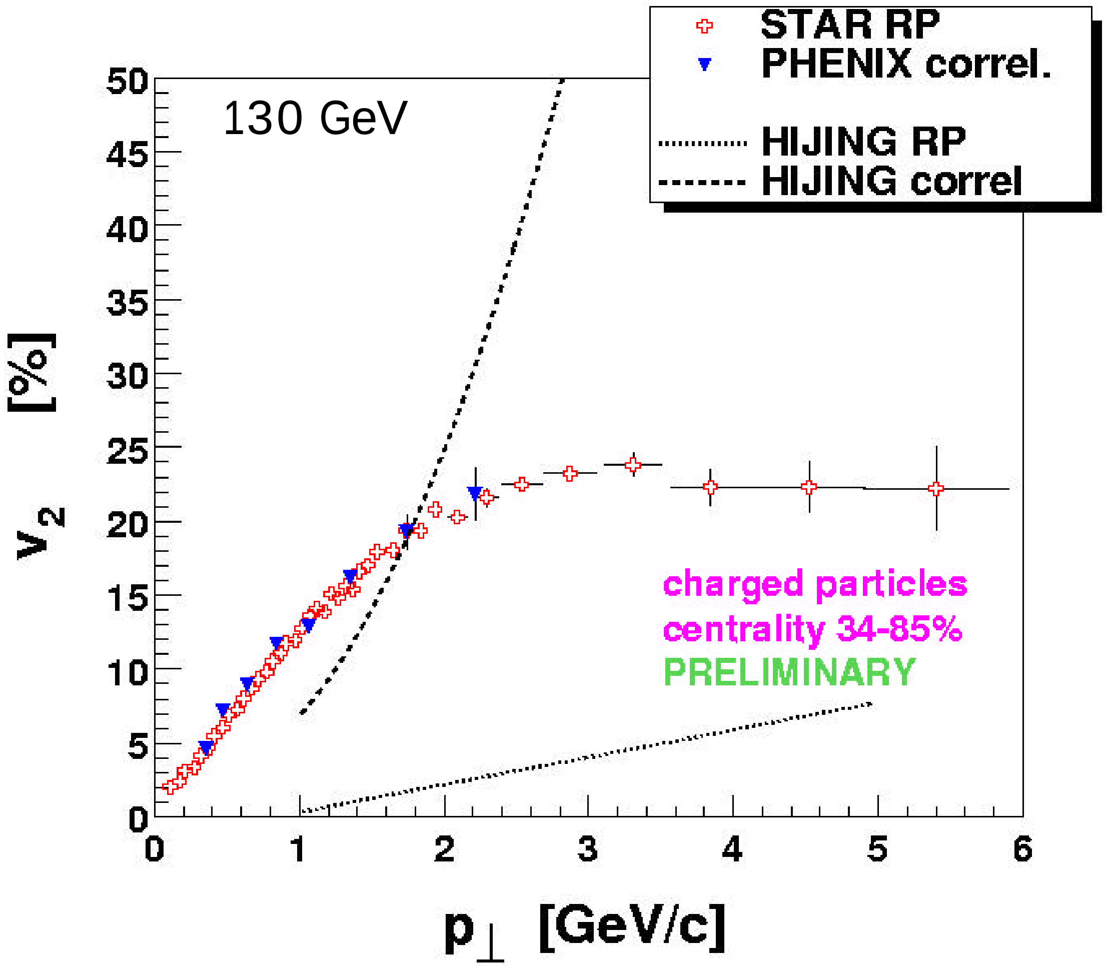
The hint might be seen already in high-pt yield suppression.

SPS CERES $\sqrt{s}$=17AGeV identified π^{+-}





$v_2(p_\perp)$ PHENIX vs. STAR



- PHENIX two particle correl.
  - Good agreement with RP
- HIJING **(dE/dz = 0 & 2 GeV/fm).**
  - RP v_2 is too small over the full range, but grows with $p_\perp$,
  - Correlation v_2 is large, (not seen in data).

(See E.V. Shuryak, nucl-th/0112042)

weaker jet correlations @RHIC than @SPS

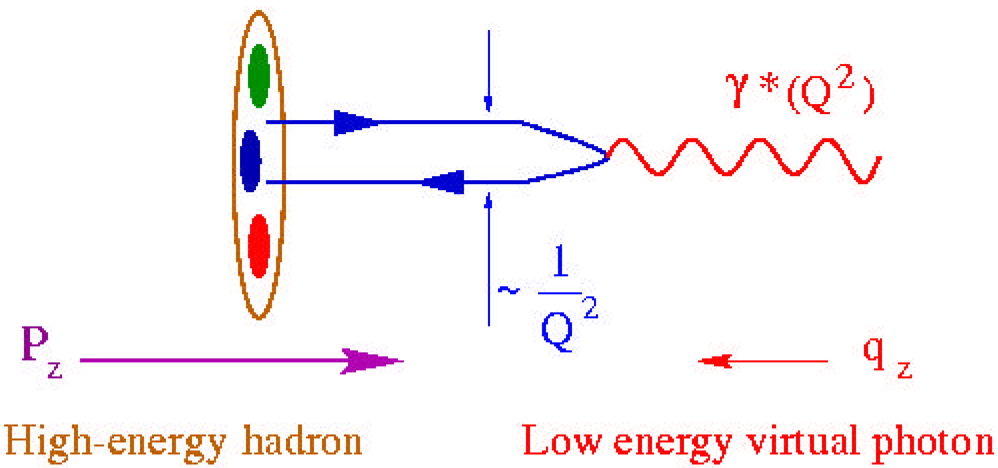
$\langle x_\wedge \rangle = 2 \langle p_\wedge \rangle /$Ös » 0.1 @SPS

» 0.01 @RHIC

Deep Inelastic Scattering

CGC: The matter made of small–x gluons in a very energetic hadron

- Deep Inelastic Scattering at high energy



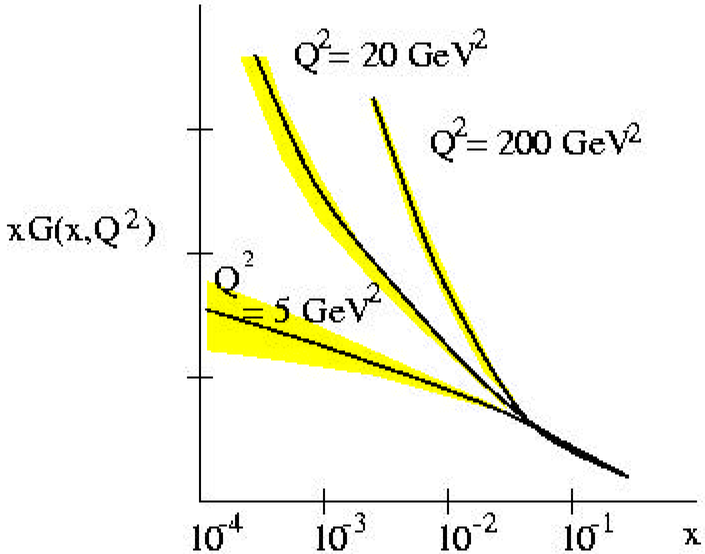
- The $q\,\bar{q}$ pair scatters off the low momentum, or small–x, gluons.

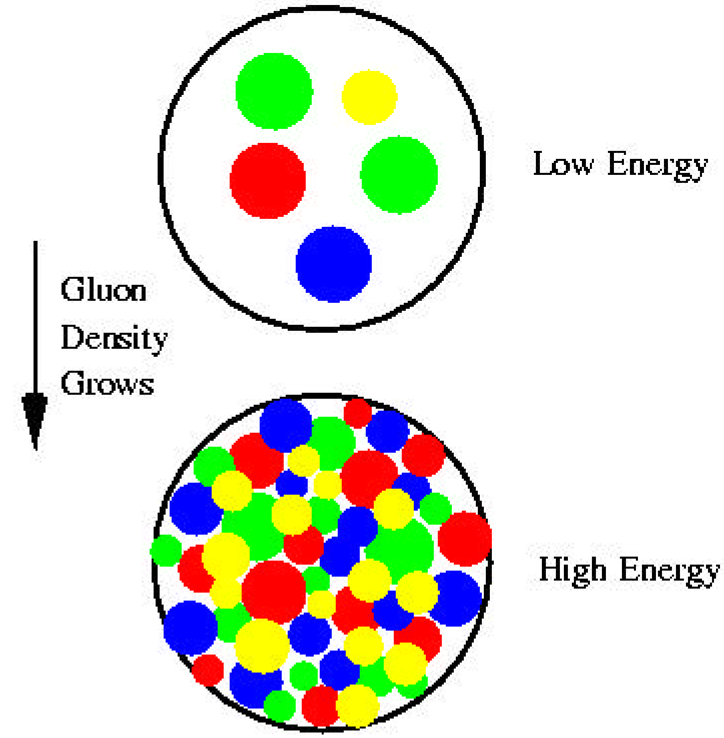
Saturation in AA

DIS

AA

The Gluon Density Grows at Small x



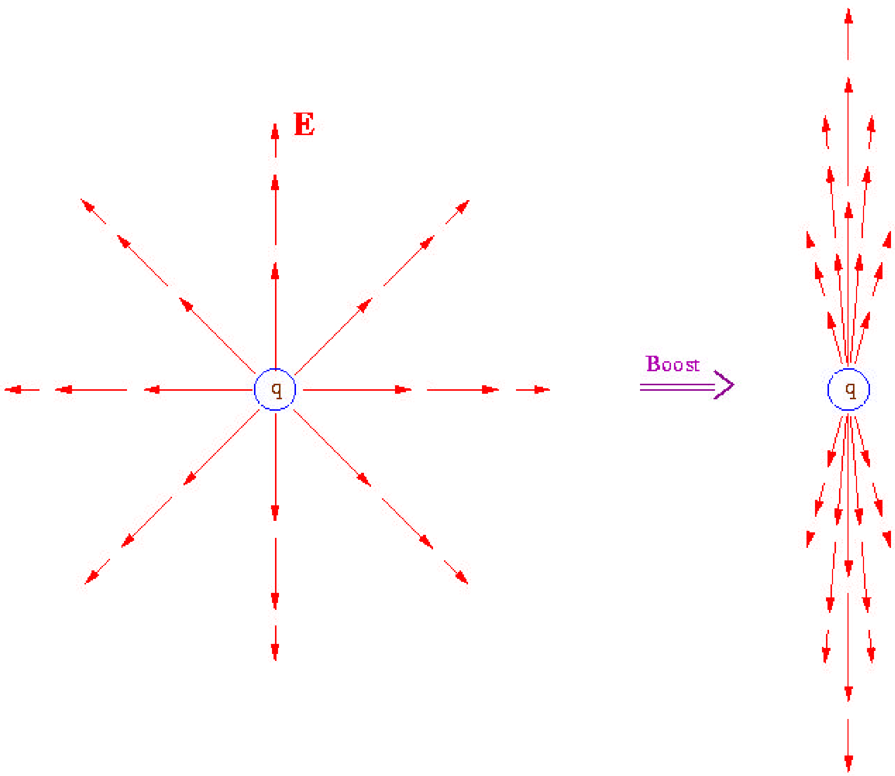


- Increase at fixed Q^2
- More rapid increase at larger Q^2

As long as $\mathbf{Q^2_S(x) << k^2_T}$ Linear evolution (BFKL)

When $\mathbf{Q^2_S(x) >> k^2_T}$ Saturation

2D colored field



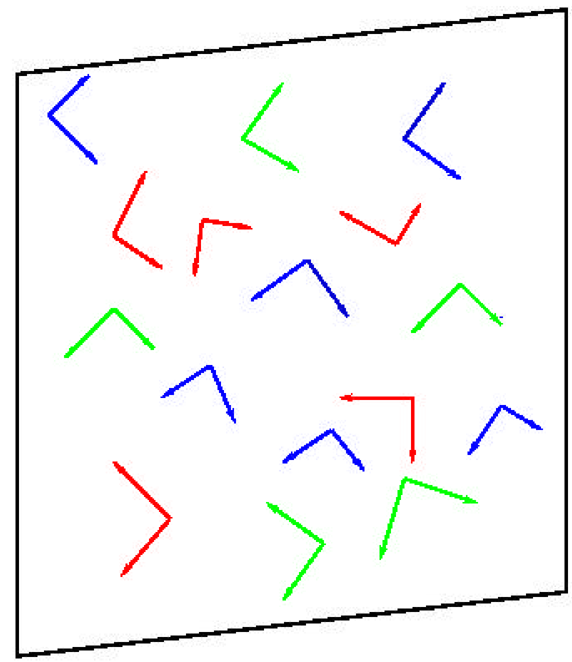
Boosted charge -> pancake

E = v x B

The Classical Solution

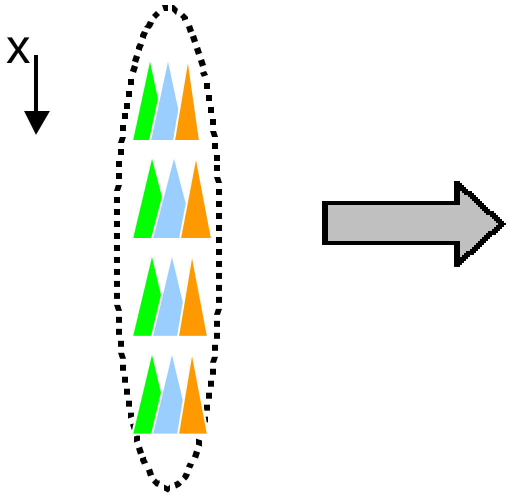
A non-Abelian Weiszäcker–Williams field

- $E_z = B_z = 0$
  $E_x = B_y; \quad E_y = -B_x \quad (\mathbf{E}_\perp \cdot \mathbf{B}_\perp = 0)$



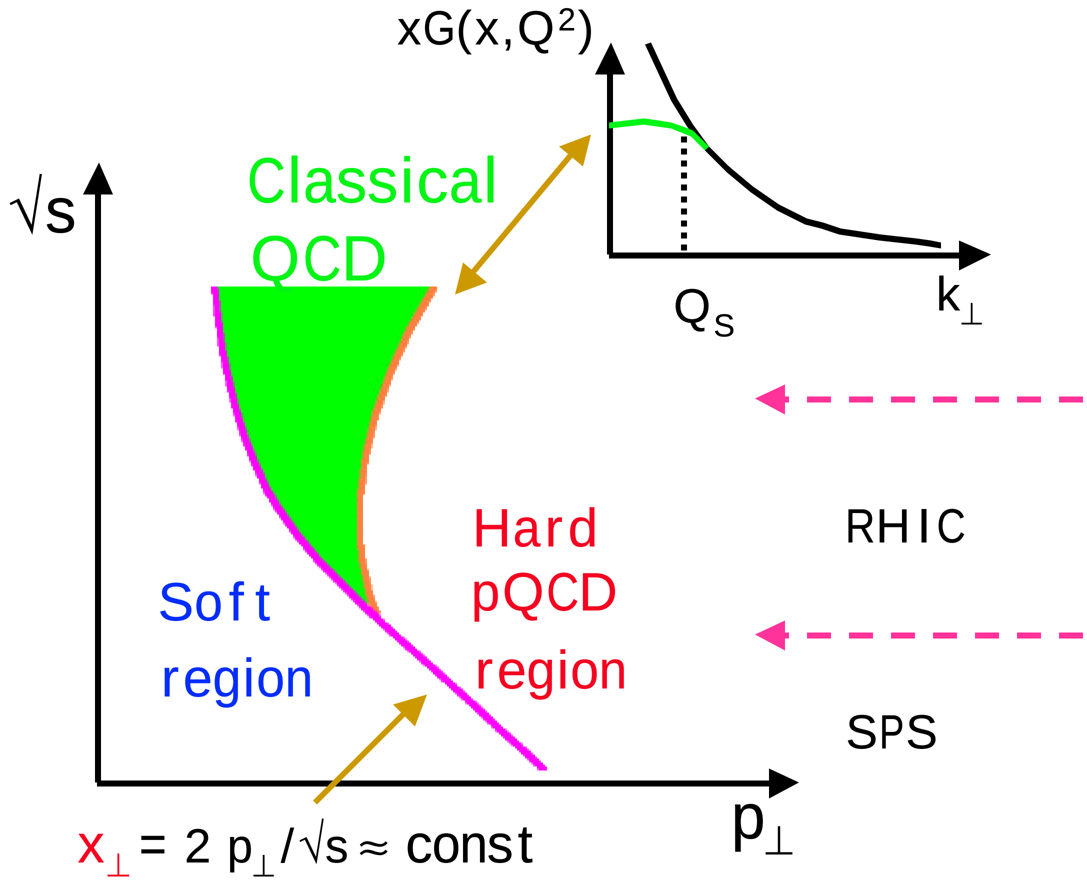
Gluon condensate at small X

See D. Kharzeev, E. Levin Nucl-th/0108006



At small Bjorken x partonic wave functions starts to overlap

- Saturation
- coherence
- multi-parton correlation breaks down



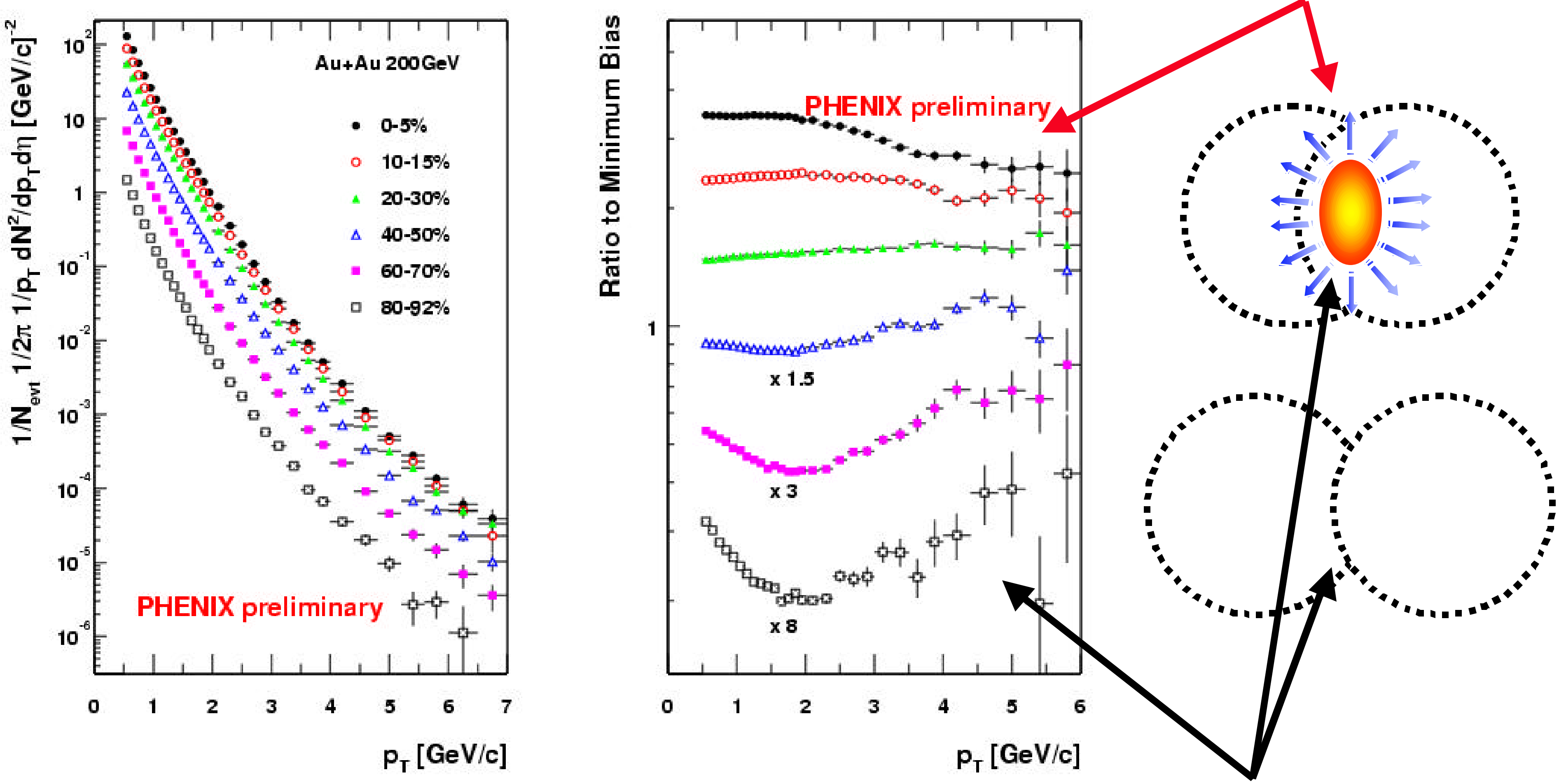
In Classical region the particle production mechanism is 2->1 unlike the pQCD 2->2. This implies:

Below $2^*Q_S \approx 2^*2$ GeV produced particles are not correlated.

CGC and suppression

Charged hadrons rations to minimum bias

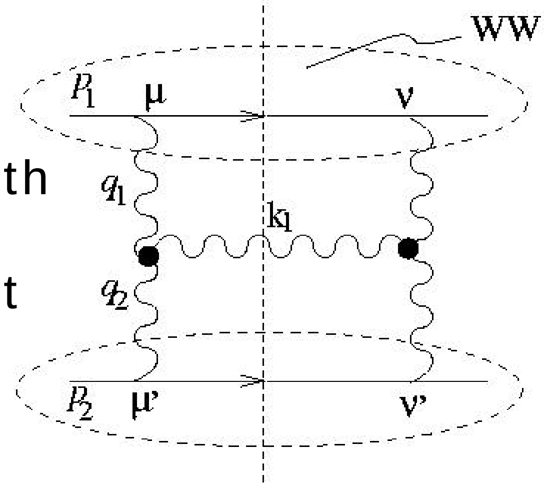
CGC field radiation ?

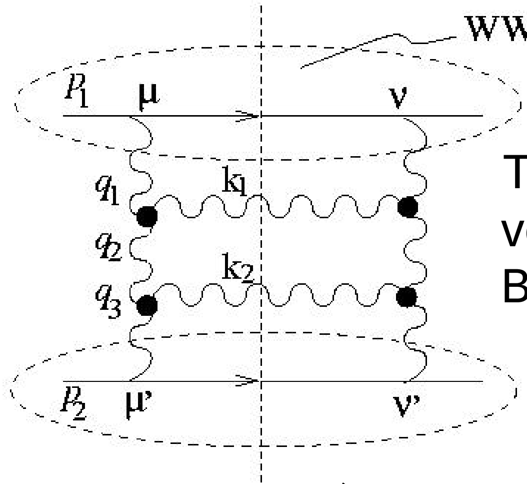


pQCD hard scattering - surface

$P_\perp$ and $\sqrt{s}$ independent $v_2(p_\perp)$

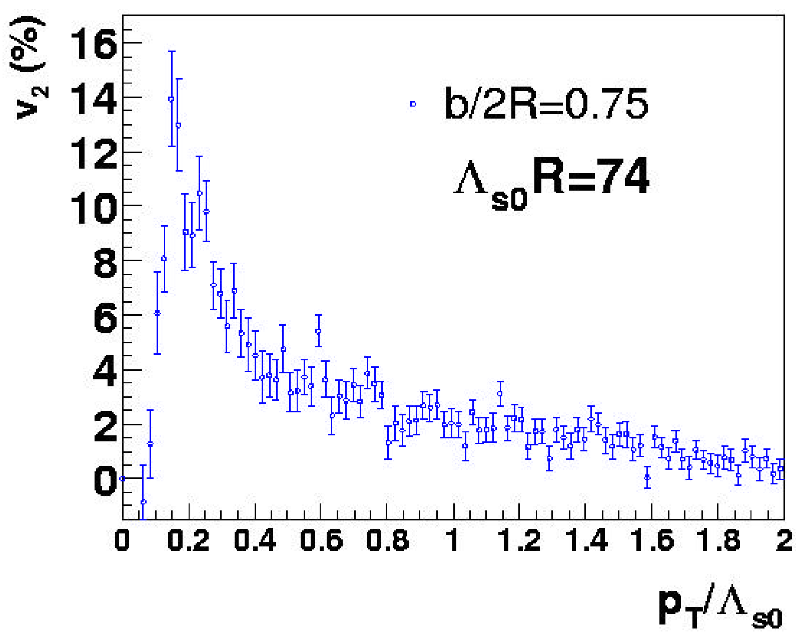
Classical CGC with mono-gluon jets doesn't get v2 at all.



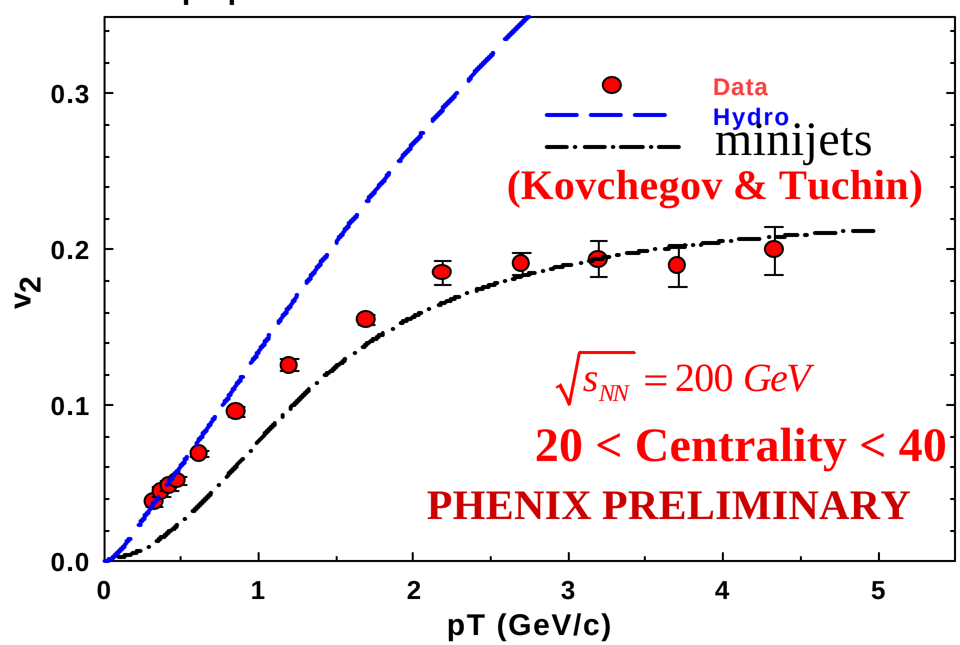


Two gluons Lipatov vertex looks OK, BUT…

hep-ph/0204361

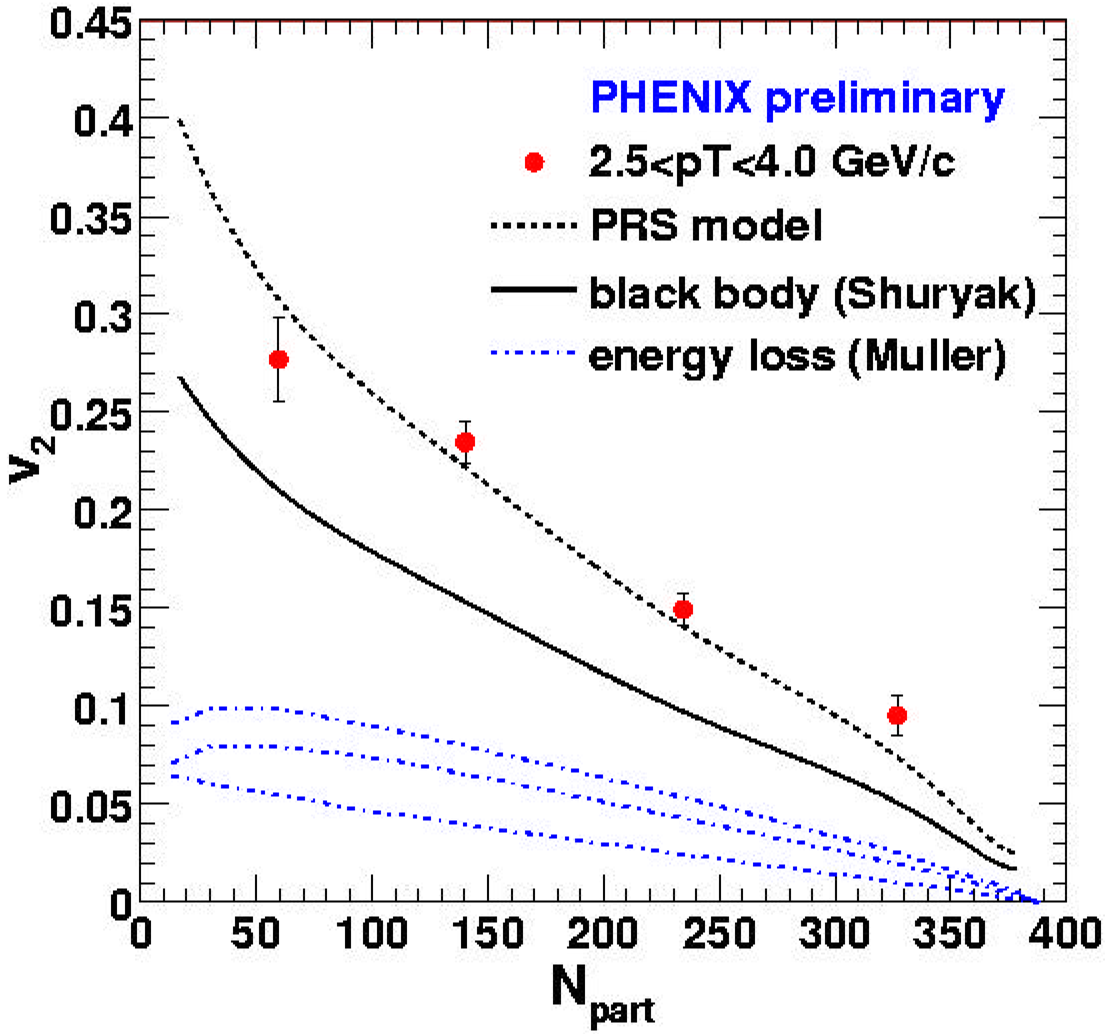


hep-ph/0203213

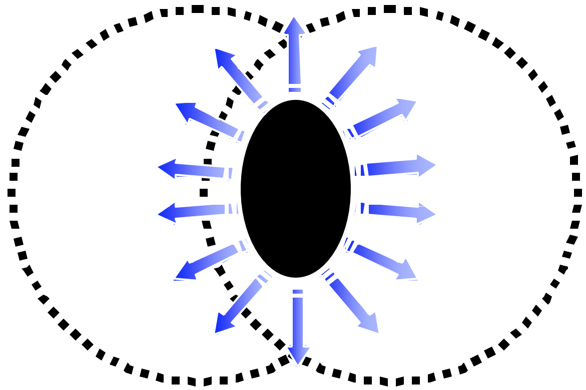


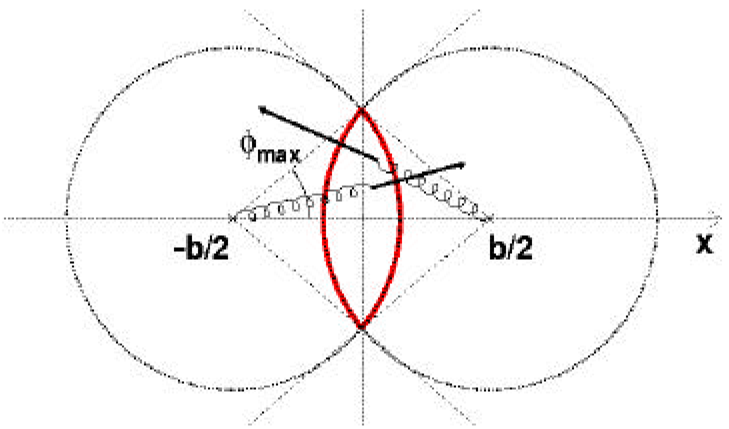
Geometrical upper limit exceeded ??

E.Shuryak Phys. Rev. C66 027902, 2002
B. Muller nucl-th/0208038



Black body radiation limit absolute quenching (surface emission)





Primordial radial streaming ??

Summary

- HI physics enters the pQCD regime, but not in the way we have (some of us) expected.

- First two years of RHIC running - unexpected experimental results in high-p_T sector, namely
  - huge high-p_T particles yield suppression
  - huge p_T -independent azimuthal anisotropy

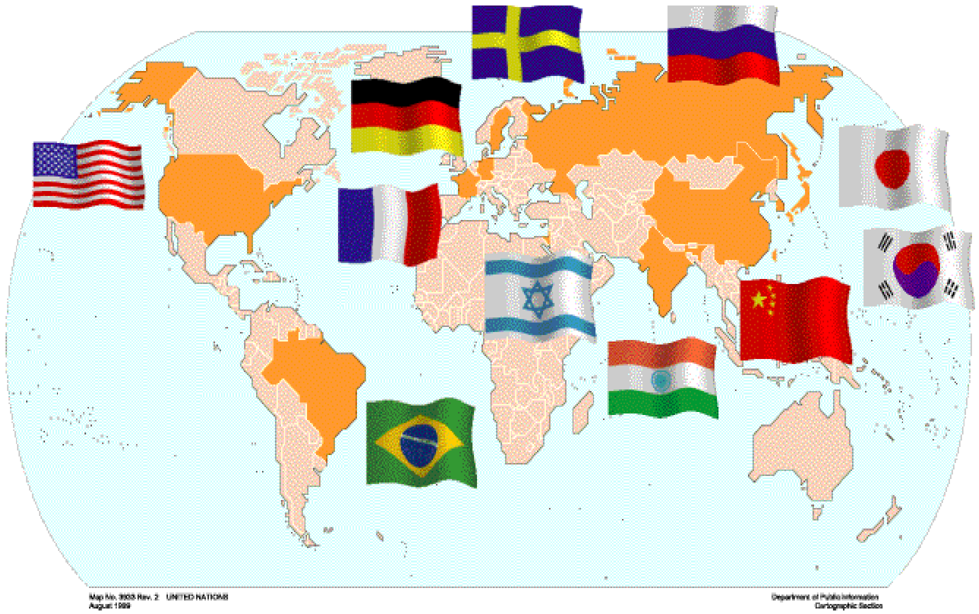
- Parton energy-loss effect proposed as a probe for quark-gluon-plasma formation doesn't give the good description of all observables - fails for v2.

- CGC models seems to be a reasonable alternative to the jet-quenching model. It might be able to describe both R_{AA} and v2, but it is still premature.

- The absolute value of v2 still resists to be understood in any scenario.

Back up slides

PHENIX



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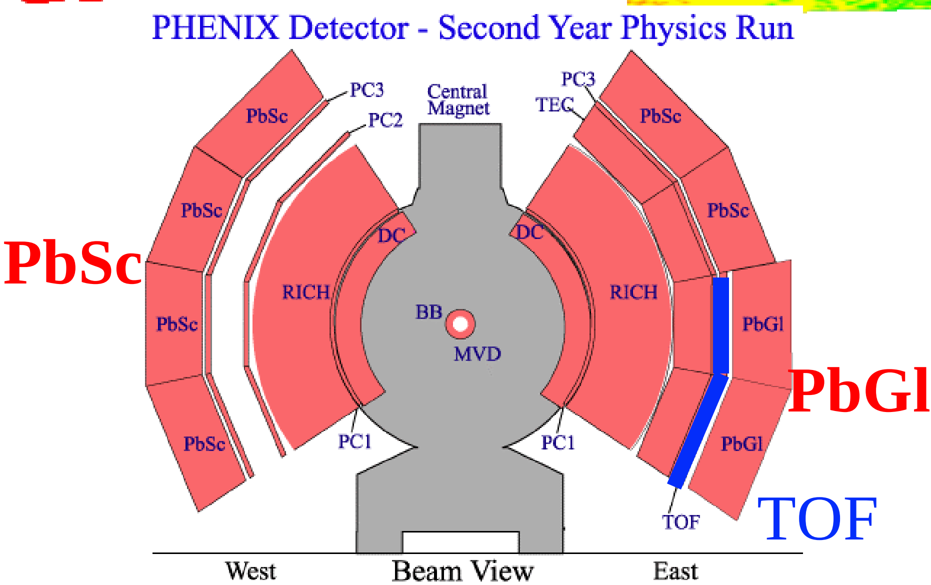
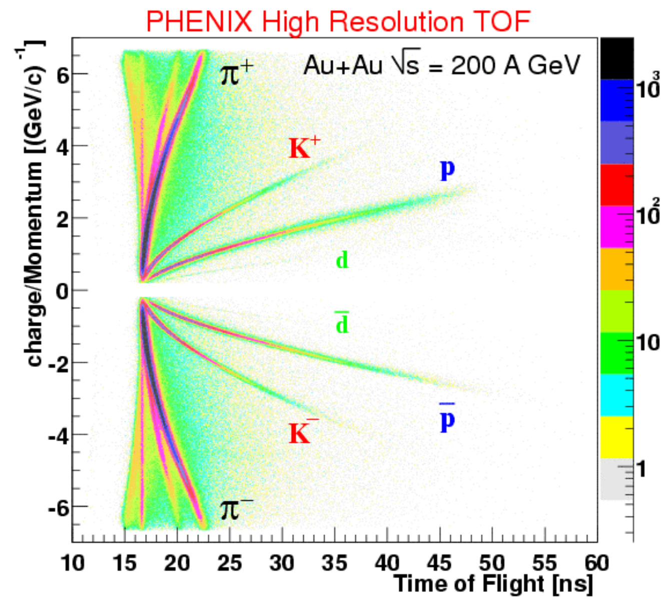
University of Tennessee (UT), Knoxville, TN 37996, USA
Vanderbilt University, Nashville, TN 37235, USA

PHENIX Central Arm



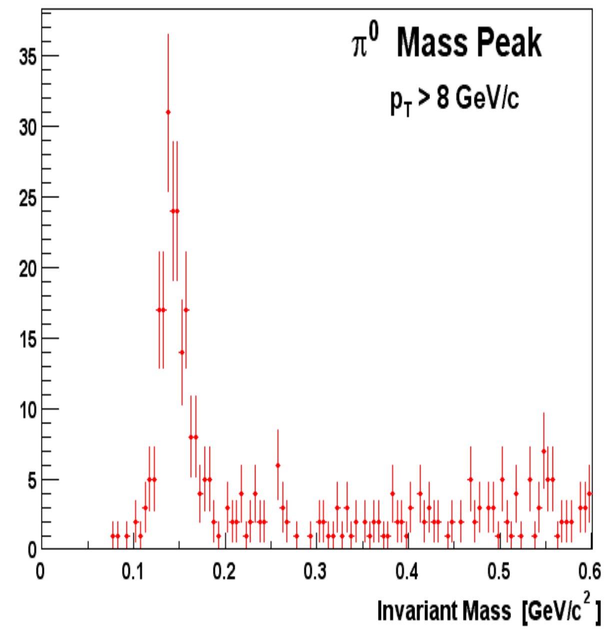


PID by high resolution TOF

- p, K < 2 GeV/c
- proton, anti-proton < 4 GeV/c
- Df = p/4

p0 measurement by EMCal

- 1<pt<10GeV/c
- 6 lead- scintillator (PbSc) sectors
- 2 lead- glass (PbGl) sectors
- |h|<0.38 at midrapidity, Df = p



Two-Particles Correlation Function

$$C(\Delta f) = \frac{N_{real}(\Delta f)}{N_{mixed\ events}(\Delta f)} \qquad \Delta f = f_i - f_j$$

Directed flow

Elliptic flow

Fourier decomposition:

$$C(\Delta f)_{flow} \propto (1 + 2\,v_1^{\,2}\cos(\Delta f) + 2\,v_2^{\,2}\cos(2\,\Delta f))$$

Correlation function

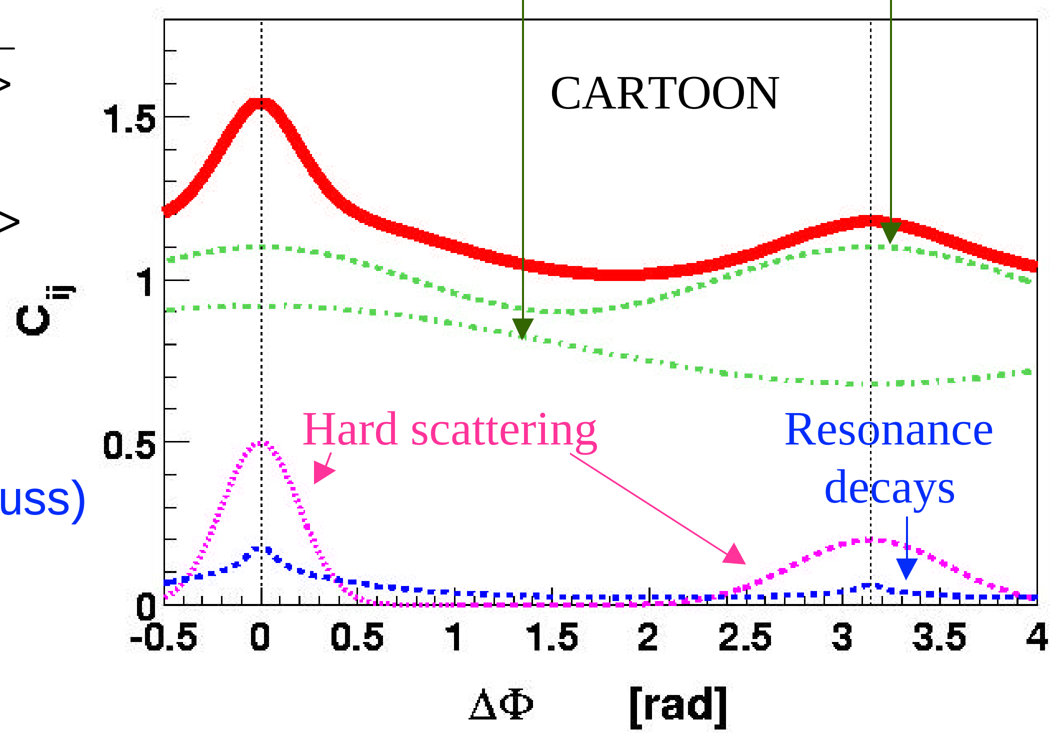
$$v_2 = \sqrt{< \cos(2(\Phi_i - \Phi_j)) >}$$

Reaction plane

$$v_2 = < \cos(2(\Phi_i - \Psi_{RP})) >$$

We observe a sum of

- Flow anisotropy (cos)
- Hard scattering peaks (gauss)
- Resonace decays



J.Y.Ollitrault, nucl-th/0004026

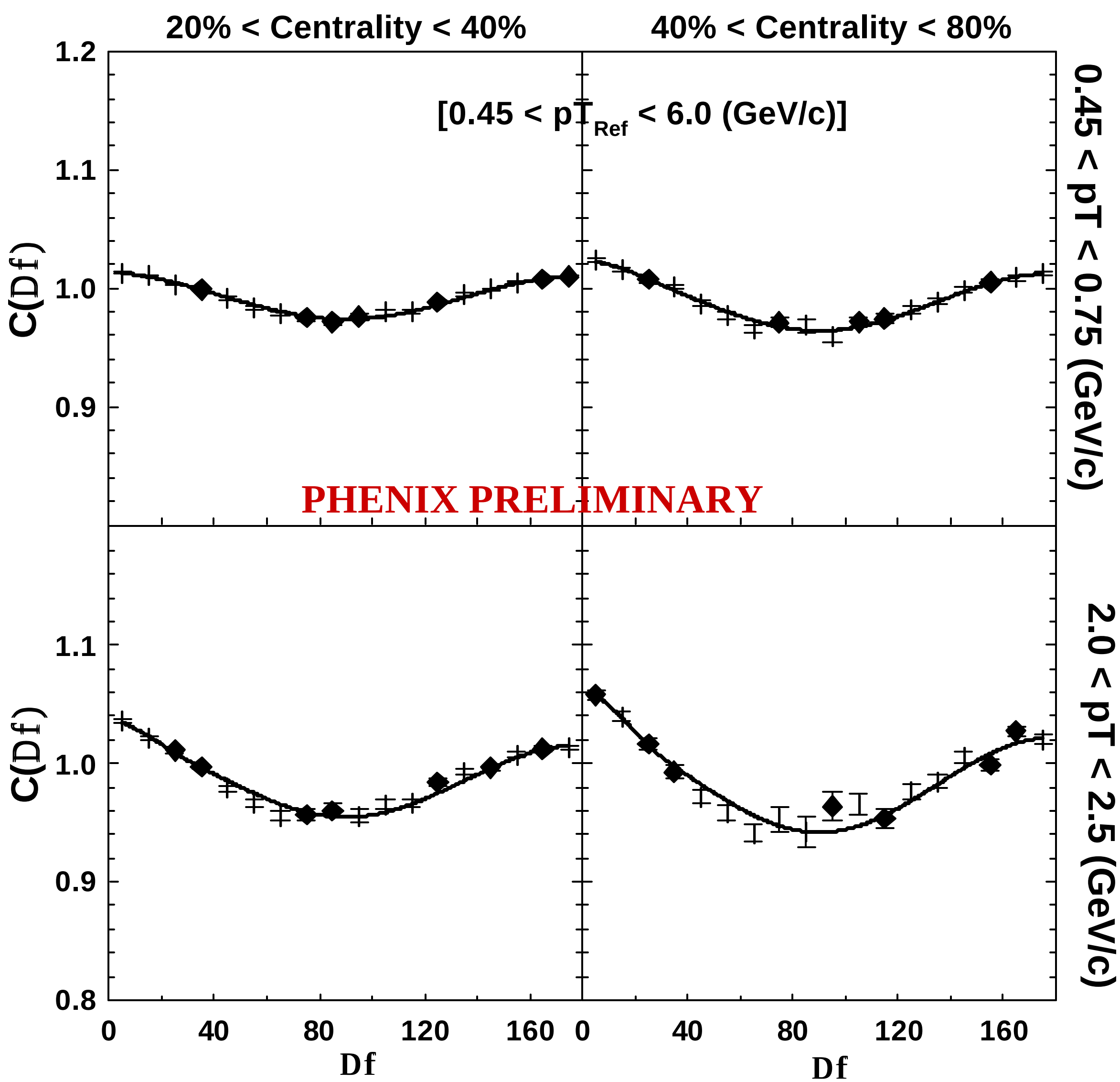
Low-pt correlation functions

$\sqrt{s_{NN}} = 200\ GeV$

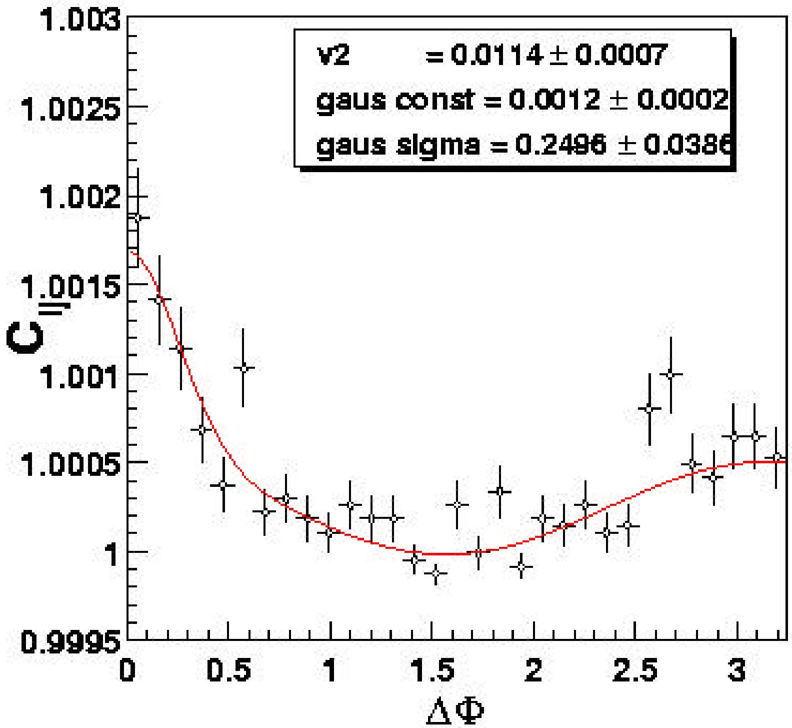
- Anisotropy increases with pt and Centrality
- Asymmetric Component seen especially at high pt

Important to test the response of the asymmetry to various Cuts

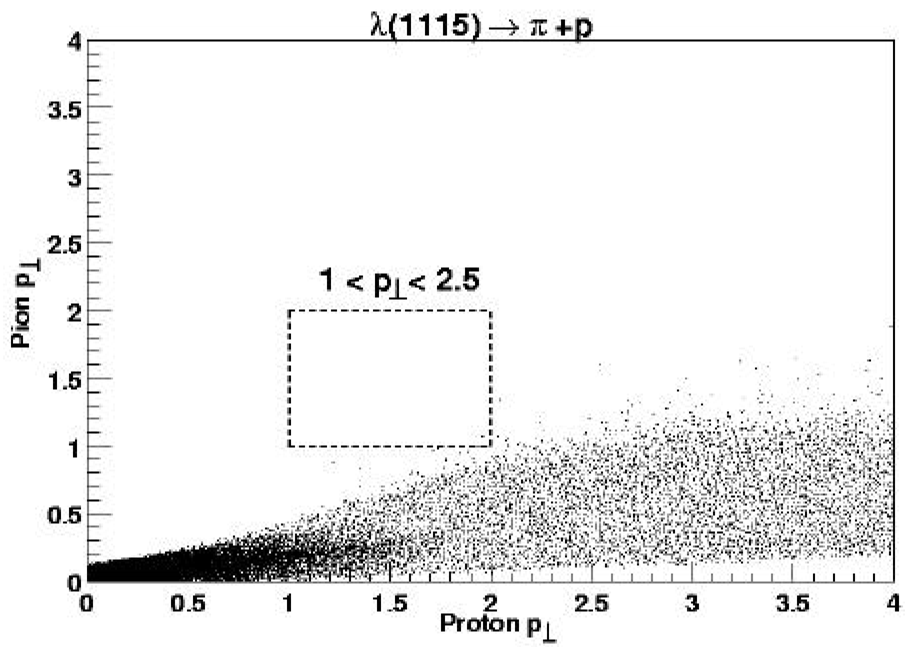
- **Jets**
- **v2 values**



Resonance decay – UrQMD simulations



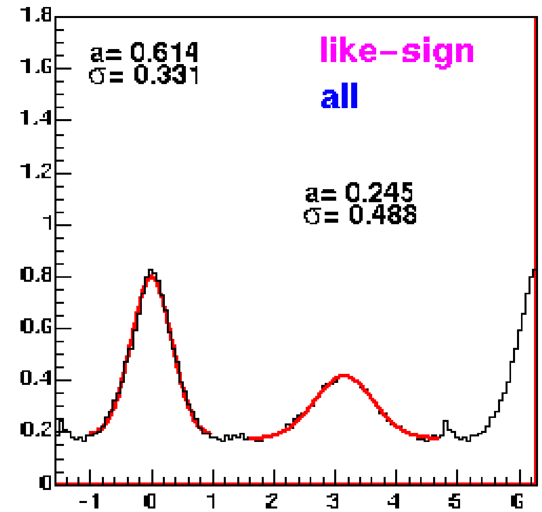
- Light resonance's :
  - contribute most to near-angle peak
  - V_2 is of order 1%.
- Weak decay:
  - Long lived particles (K_S^0 $c\tau$=2.7cm), decays in the mag. field and the daughters look like high-$p_\perp$ particles. Has been checked in GEANT.



- Baryon resonance's :
  - $p_\perp$-cut removes large fraction.

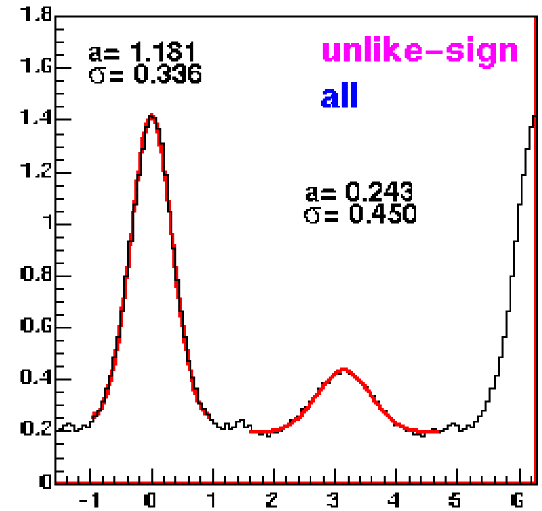
Charged hadrons in Pythia

PYTHIA p+p at $s^{1/2}$ = 130 GeV
1.0 < pt < 2.5 GeV/c, |η| < 0.35



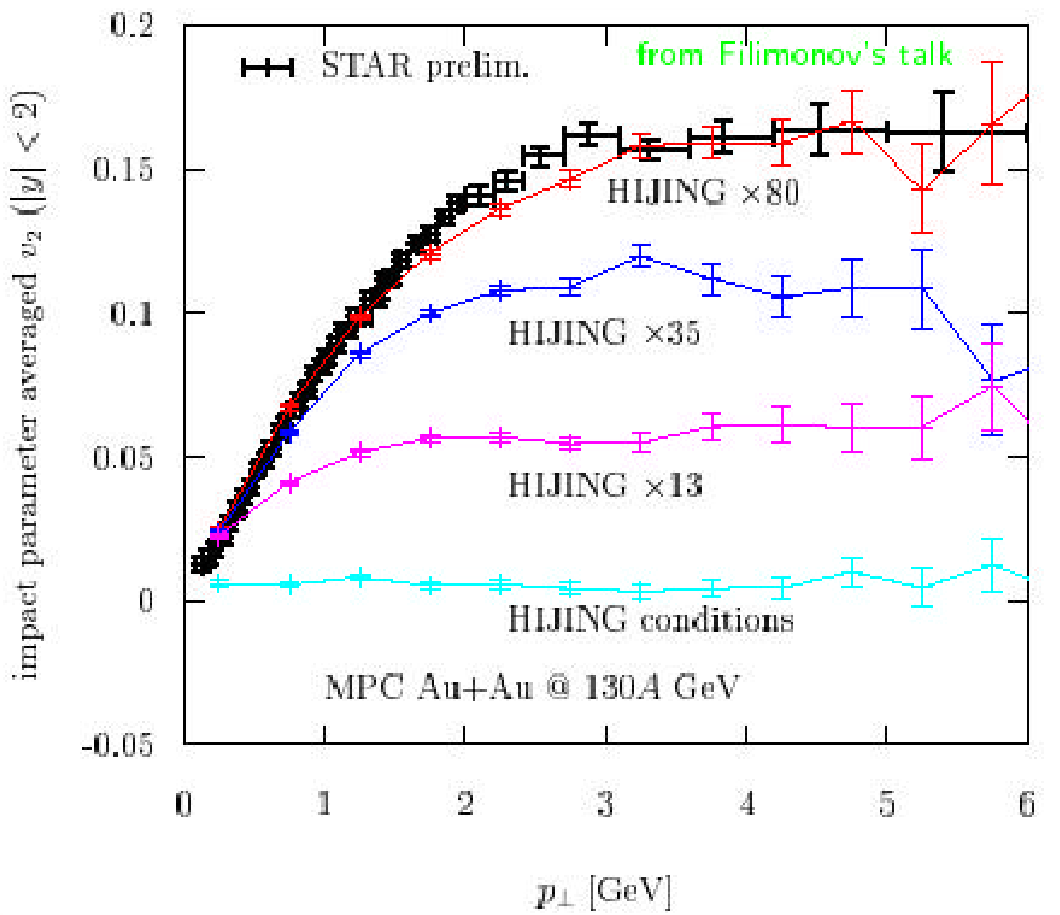
ΔΦ [rad]

- near-angle correlation stronger than back-to-back (opposite to what is observed for @SPS Calculations)
- near/far like-sign = 1.7 and unlike-sign = 3.6
- near-angle width of 0.35 rad = 20 deg
- far-angle width of 0.48 rad = 28 deg (near*√2)



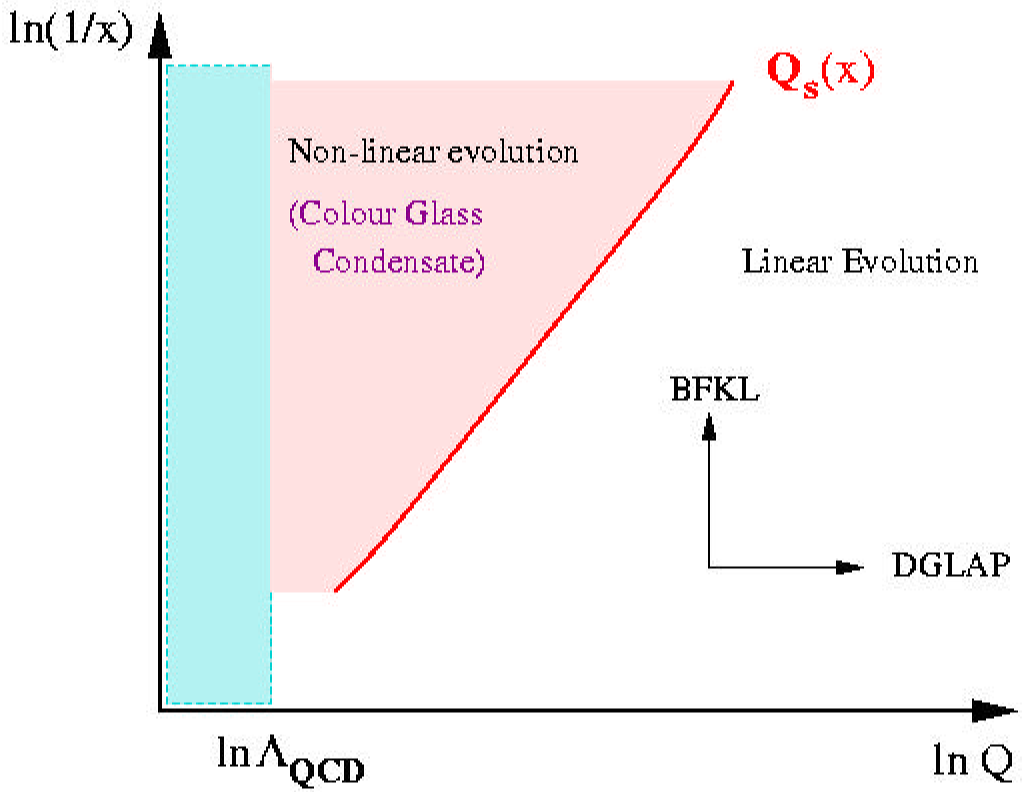
ΔΦ [rad]

HIJING and opacity

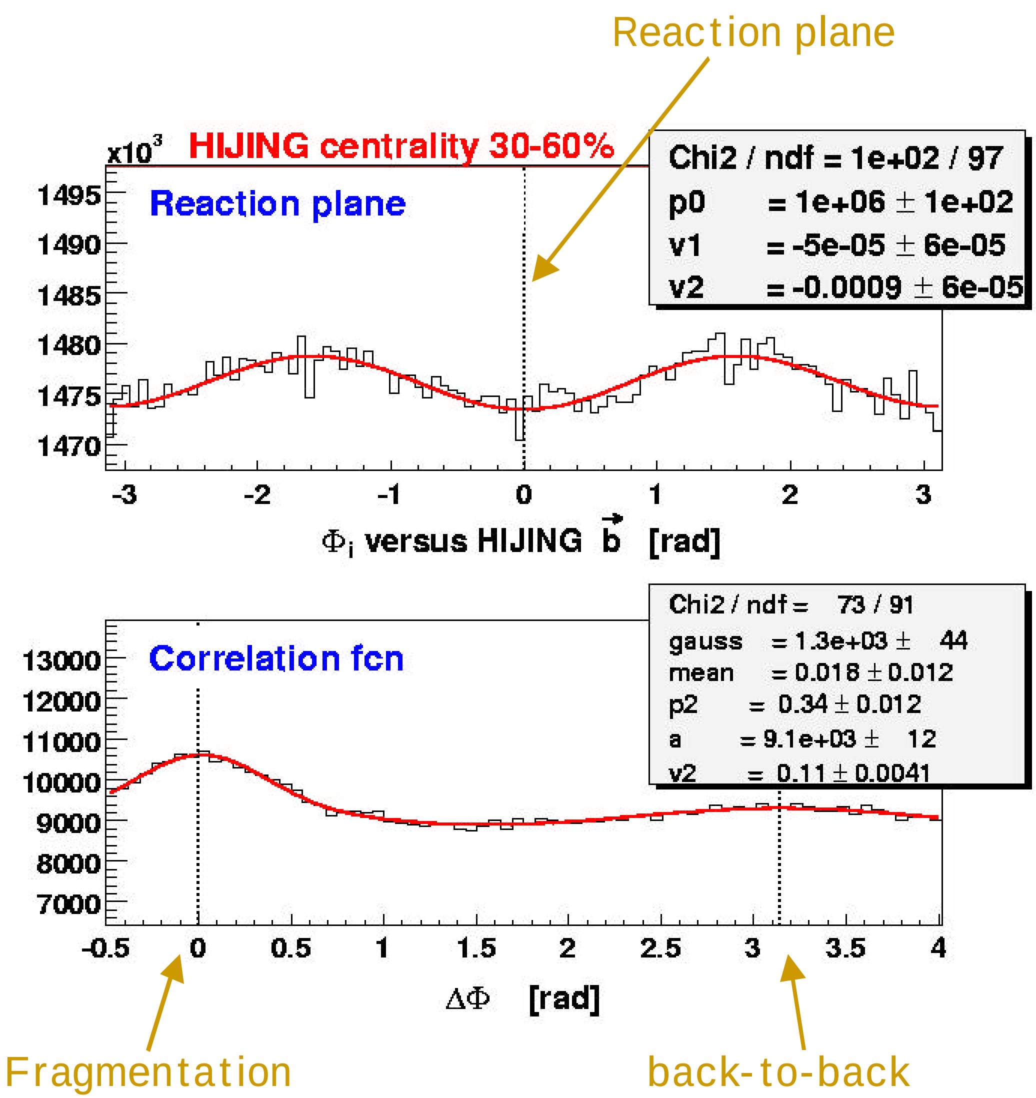


- 80xmore opaque gluon plasma @ RHIC then from pQCD (see D. Molnar nucl-th/0005051, nucl-th/0104073 or

http://nt3.phys.columbia.edu/people/molnar)


ln(1/x)
$Q_s(x)$
Non-linear evolution
(Colour Glass
Condensate)
Linear Evolution
BFKL
DGLAP
$\ln \Lambda_{QCD}$
ln Q

HIJING azimuthal anisotropy



HIJING (dE/dz = 0 GeV)

(pQCD jet production – no hydro)

- Reaction plane
  - $v_2 = \langle\cos(2\phi)\rangle$ is small and negative (out-of-plane)
  - More material induces more gluon emission
- Two particle correlations
  - $v_2 = \sqrt{\langle\cos(2\Delta\phi)\rangle}$ is large