QFTHEP2010
14.09.2010

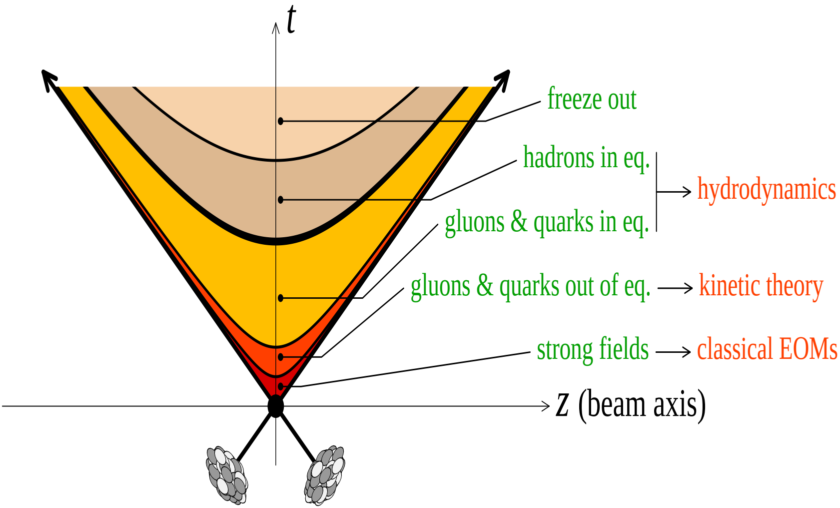
Dense strongly interacting matter: Lessons from RHIC and expectations for LHC

A. Leonidov

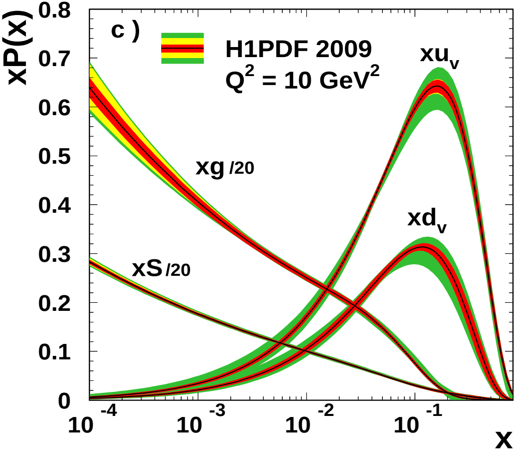
P.N. Lebedev Physical Institute

Main results at RHIC

- Multiplicities much lower than pre-RHIC predictions indicating strong coherence in particle production mechanisms.
- Observed elliptic flow is in agreement with hydrodynamics of (almost) ideal liquid indicating creation of dense strongly coupled matter
- New structures in the near-side (ridge) and away-side (Cherenkov/Mach cones) angular correlations
- Significant reduction in the yield of particles with large transverse momentum (jet quenching)

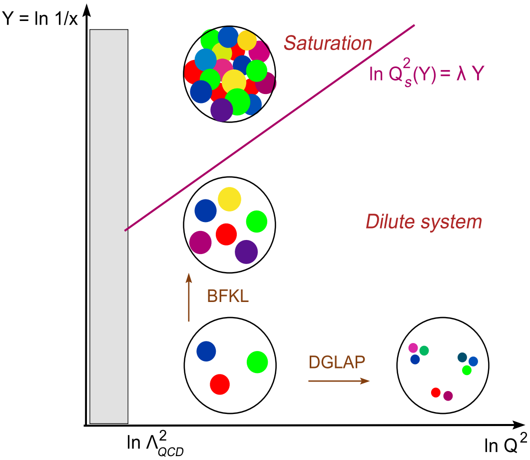

t
freeze out
hadrons in eq.
hydrodynamics
gluons & quarks in eq.
gluons & quarks out of eq.
kinetic theory
strong fields
classical EOMs
z (beam axis)

Basis of coherence in particle production: growth of gluon density at small Bjorken x at fixed Q^2:



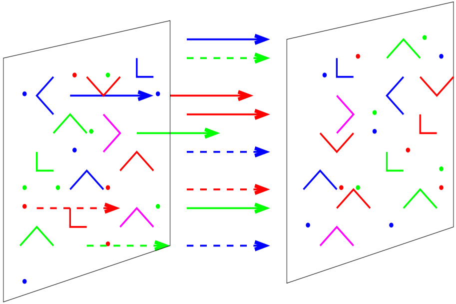
$$x = \frac{k^+}{P^+}$$

"Phase diagram" in the x - Q^2 plane:



$$x = \frac{k^+}{P^+} \qquad \delta S_\perp \sim \frac{1}{Q^2}$$

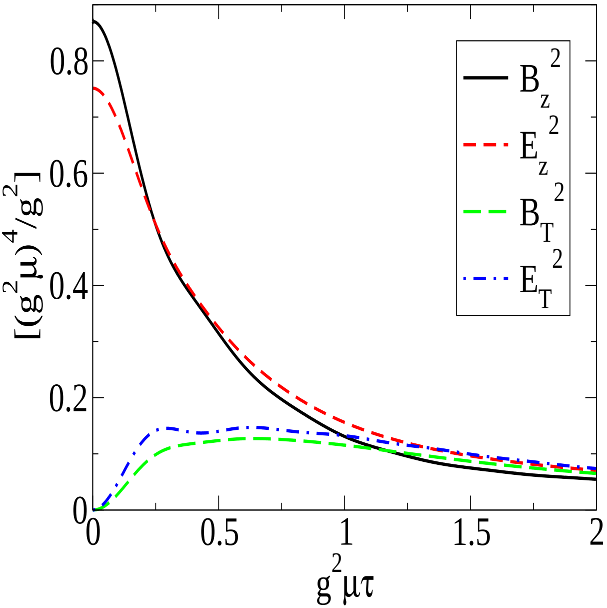
Immediately after collisions there form longitudinal chromoelectric and chromomagnetic fields - glasma :



$$E^z = ig\left[A^i_{(1)}, A^i_{(2)}\right]$$

$$B^z = ig\epsilon^{ij}\left[A^i_{(1)}, A^j_{(2)}\right]$$

Temporal evolution of longitudinal and transverse fields:



Initial multiplicity and energy density

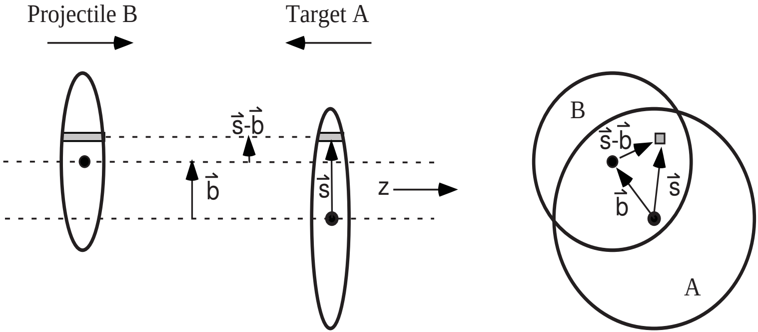
- $$\frac{dN}{d\eta}|_{\eta=0} = c_N \frac{\pi R_A^2 Q_S^2}{\alpha_s}$$
- $$\frac{dE_\perp}{d\eta}|_{\eta=0} = c_E \frac{\pi R_A^2 Q_S^3}{\alpha_s}$$

$$\mathrm{HERA} \Rightarrow Q_S^2 \simeq 1.2\,\mathrm{GeV} \Rightarrow \frac{dN}{d\eta}|_{\eta=0} \simeq 1100$$

Instabilities of the boost-invariant solution

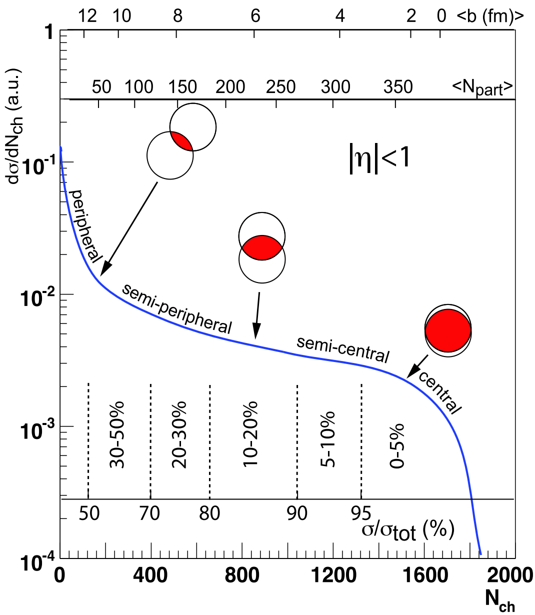
- Rapidity-dependent configurations generate explisively growing transverse fields
$$|E_\perp|, |B_\perp| \sim \mathrm{e}^{\sqrt{Q_s \tau}}$$
- New mechanism of energy losses
- Turbulent isotropisation?
- Quantum corrections to the glasma picture: GLV - BK - JIMWLK equations

Glauber geometry

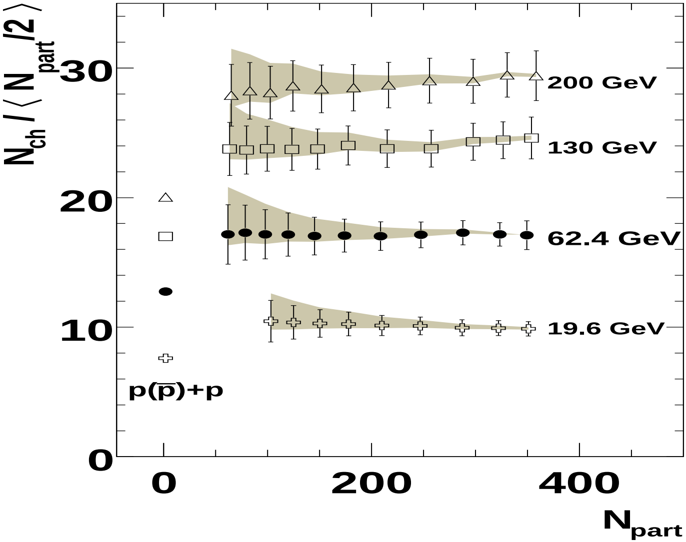


a) Side View b) Beam-line View

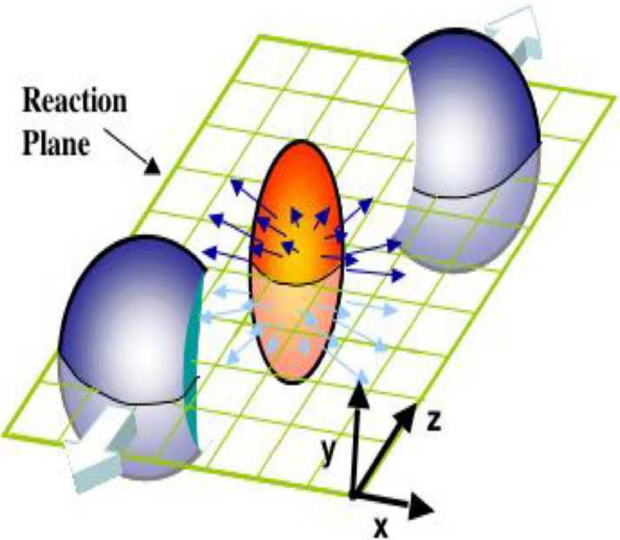
Classification in centrality



Scaling in N_{part}



Elliptic flow



Elliptic flow: some definitions

- Directed and elliptic flow v_1 and v_2

$$\frac{N}{dp_\perp^2\, dy d(\phi - \Psi)} = \frac{dN}{dp_\perp^2\, dy}\left[1 + 2v_1 \cos(\phi - \Psi) + 2v_2 \cos(2(\phi - \Psi)) + \cdots\right]$$

Ψ : a reaction plane angle

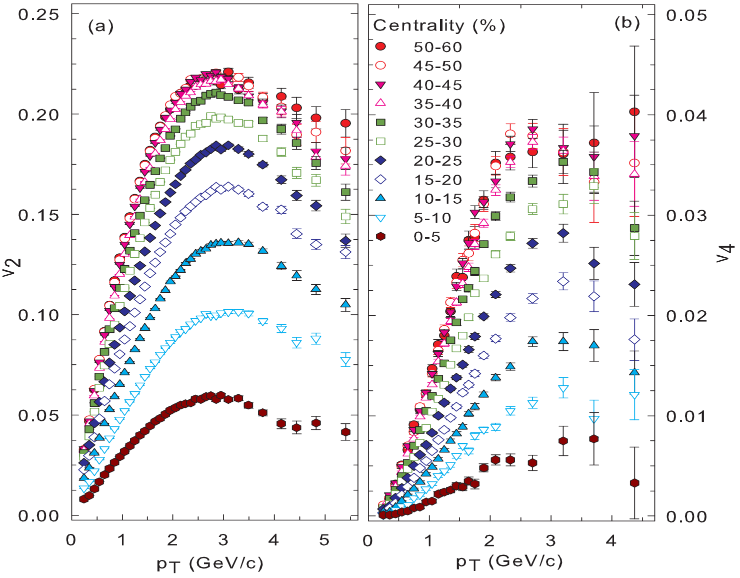
- Spatial anisotropy ϵ_x and elliptic flow

$$\epsilon_x = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}; \qquad v_2 \sim \epsilon_x \frac{1}{S_{\mathrm{overlap}}} \left.\frac{dN}{dy}\right|_{y=0}$$

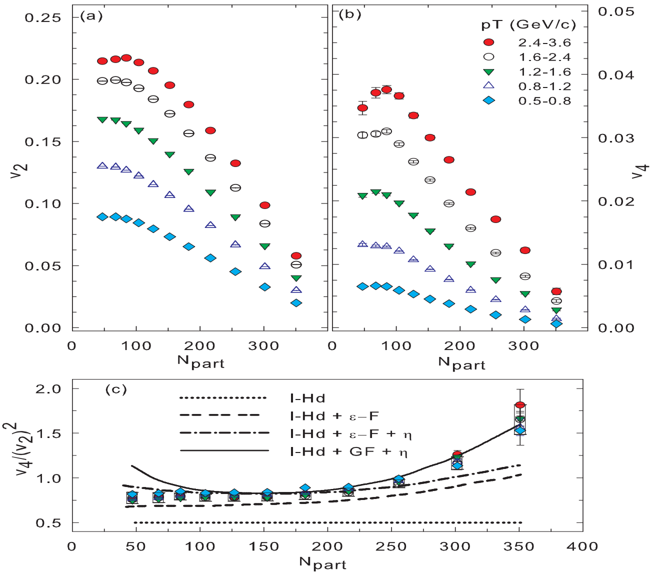
- Momentum anisotropy ϵ_p

$$\epsilon_x = \frac{T_{xx} - T_{yy}\rangle}{\langle T_{xx} + T_{yy}\rangle}; \qquad v_2 \sim \epsilon_p/2$$

Elliptic flow: experimental data



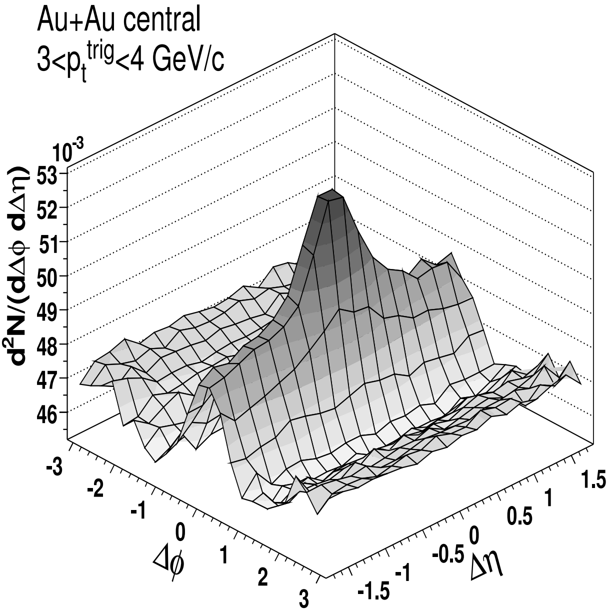
Elliptic flow: experimental data



Elliptic flow: theory

- Measured elliptic flow at small transverse momenta agrees with predictions of hydrodynamics of almost ideal (low viscosity) liquid
- Quantitative description requires full three-dimensional viscous hydro taking into account fluctuations of initial conditions
- Exciting theoretical developments: physics of sQGP as conformal relativistic hydrodynamics, etc.
- Exciting perspectives for theoretical development: turbulence in sQGP

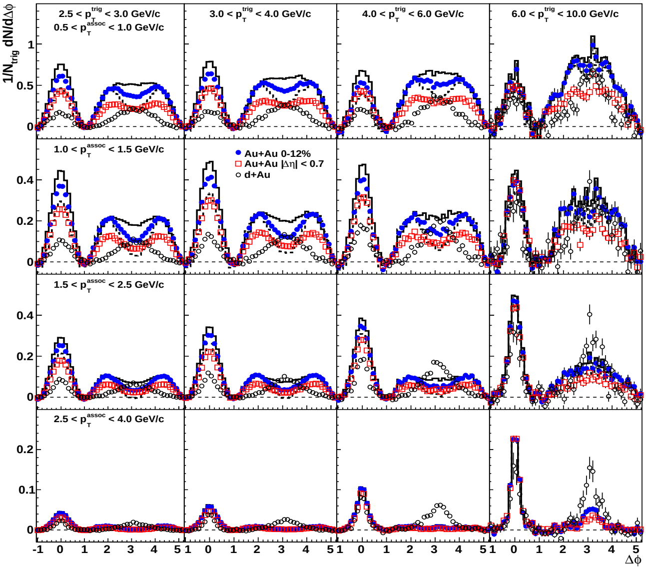
Two-particle correlations: Ridge



Two-particle correlations: Ridge

- Experimental situation is not very clear
- Theoretical explanations are not precise and not convicing

Experimental data on two-particle azimuthal correlations

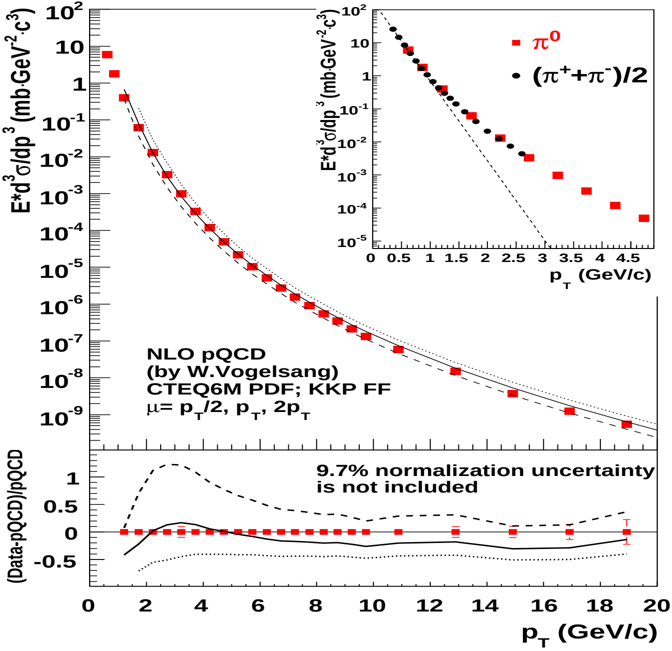


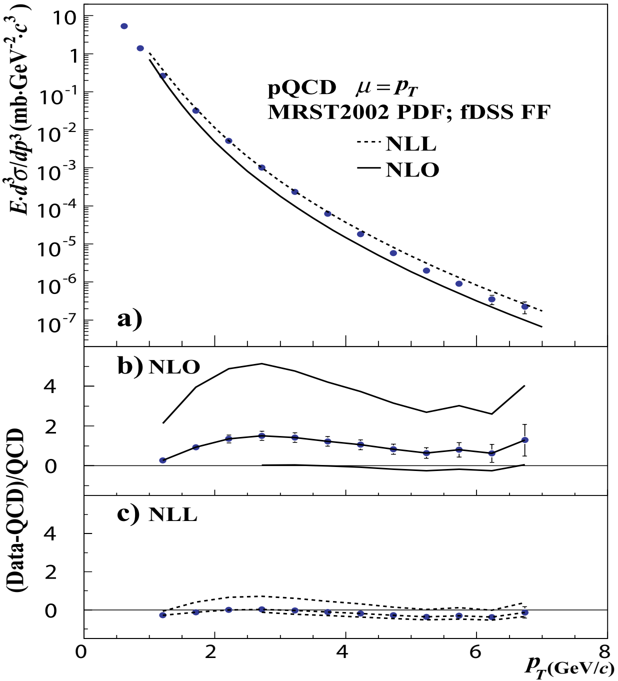
Theory of two-particle azimuthal correlations

- Two possible explanations: Cherenkov gluons and Mach cones
- Description in terms of Cherenkov gluons possible. Its validity depends on the validity of quasiparticle approach to sQGP.
- Description in terms of Mach cones possible for special initial conditions. Difficult to get transverse momentum dependence of the away-side structure.

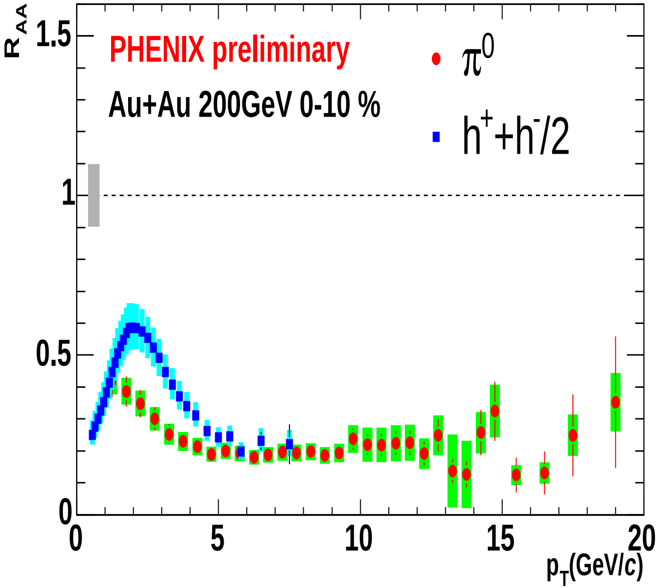
Jet quenching

$$R_{AB}^{h}\left(p_{\perp}, y \middle| \text{centrality}\right) = \frac{\frac{dN^{AB\rightarrow h}}{dp_{\perp}\,dy}}{\langle N_{\text{coll}}^{AB}(centrality)\rangle \frac{dN^{pp\rightarrow h}}{dp_{\perp}\,dy}}$$

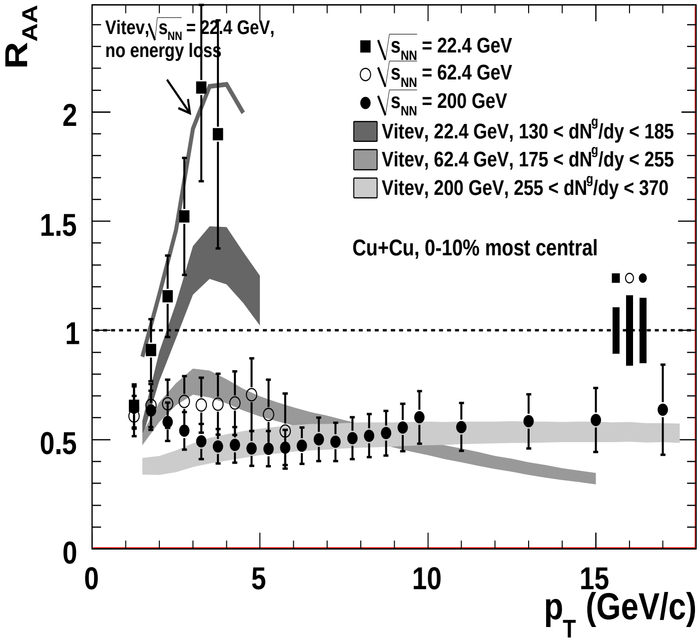

E*d³σ/dp³ (mb·GeV⁻²·c³)
NLO pQCD
(by W.Vogelsang)
CTEQ6M PDF; KKP FF
μ= p_T/2, p_T, 2p_T
π⁰
(π⁺+π⁻)/2
p_T (GeV/c)
(Data-pQCD)/pQCD
9.7% normalization uncertainty
is not included
p_T (GeV/c)



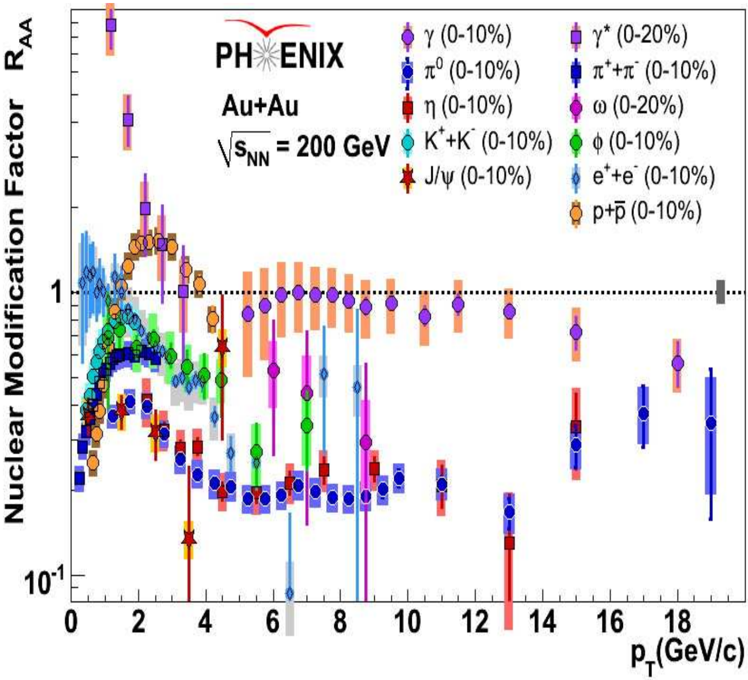
$E \cdot d^3\sigma/dp^3$(mb·GeV^{-2}·c^3)
pQCD $\mu = p_T$
MRST2002 PDF; fDSS FF
NLL
NLO
a)
b) NLO
c) NLL
(Data-QCD)/QCD
p_T(GeV/c)
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
4
2
0
0
2
4
6
8



R_AA
1.5
1
0.5
0
0
5
10
15
20
p_T(GeV/c)
PHENIX preliminary
Au+Au 200GeV 0-10 %
π^0
h^+ + h^-/2



R_{AA}
Vitev, $\sqrt{s_{NN}}$ = 22.4 GeV,
no energy loss
$\sqrt{s_{NN}}$ = 22.4 GeV
$\sqrt{s_{NN}}$ = 62.4 GeV
$\sqrt{s_{NN}}$ = 200 GeV
Vitev, 22.4 GeV, 130 < dN^g/dy < 185
Vitev, 62.4 GeV, 175 < dN^g/dy < 255
Vitev, 200 GeV, 255 < dN^g/dy < 370
Cu+Cu, 0-10% most central
0
0.5
1
1.5
2
0
5
10
15
p_T (GeV/c)

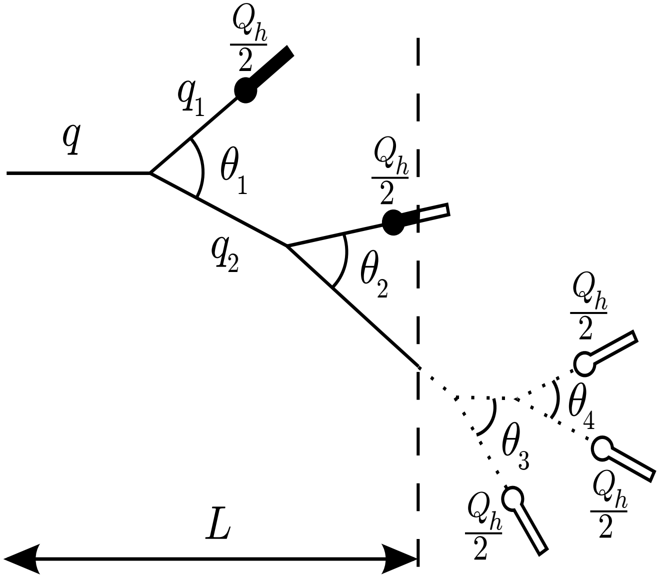


PHENIX
Au+Au
$\sqrt{s_{NN}}$ = 200 GeV
γ (0-10%)
γ* (0-20%)
π⁰ (0-10%)
π⁺+π⁻ (0-10%)
η (0-10%)
ω (0-20%)
K⁺+K⁻ (0-10%)
φ (0-10%)
J/ψ (0-10%)
e⁺+e⁻ (0-10%)
p+p̄ (0-10%)
Nuclear Modification Factor R_AA
1
10⁻¹
0
2
4
6
8
10
12
14
16
18
p_T (GeV/c)

Jet quenching: theory

- Quenching of heavy quarks not understood
- Charmonium quenching not understood
- Models with calculation energy loss still not too realistic
- Expected progress: accurate treatment of coherence length
- Expected progress: Energy loss in ADS/CFT. Drastic prediction: limiting value for the energy loss.

In-medium QCD cascade



In-medium QCD cascade: models

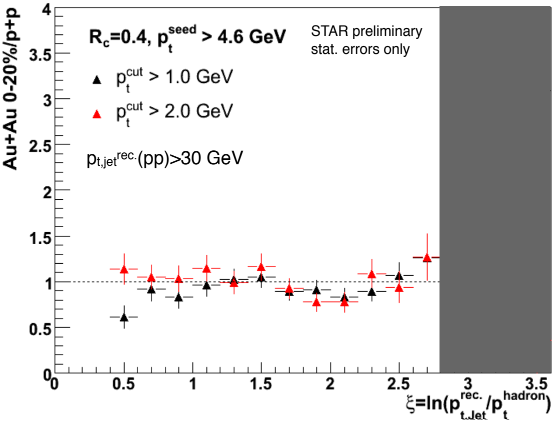
- Two types of QCD cascades:
  - Cascade driven by degradation of virtuality (DGLAP)
  - Cascade driven by medium-induced particle production (similar to electromagnetic showers in matter)

- Rigorous description combining both effects is currently not available. Medium effects are taken into account by phenomenological "deformations" of one of the two basic alternatives

- Most studies "deform" the DGLAP evolution.

EXPERIMENTAL RESULTS ON JET STRUCTURE AT RHIC

Ratio of fragmentation functions in AA and pp collisions

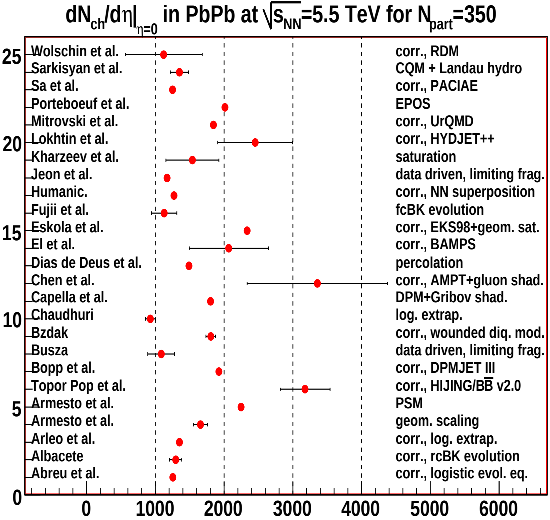


Current conclusions on the experimental situation:

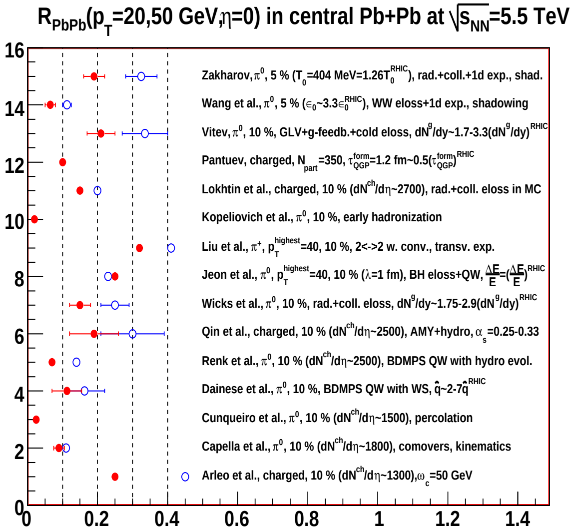
- Observed fragmentation functions in AA collisions are the same as in pp ones.
- Natural explanation: jet finding procedures bias the ensemble in such a way that only jets coming from the surface of the hot fireball are detected.
- Prospects of improving the situation unclear.

Predictions for

LHC: multiplicity



Predictions for LHC : R_{AA}



Predictions for LHC : conservative expectations

- Coherence effects in multiparticle production stronger than at RHIC
- Elliptic flow less or similar than at RHIC
- Jet quenching similar at intermediate transverse momenta, weaker at large
- In general: more intense and longer living sQGP, similar hadronization
- We'll learn some of it by the end of 2010. First heavy ion run at LHC: November 2010

Unique window of opportunities for QCD-based research of multiparticle production!

- Heavy ion collision became big science:
- Astonishingly diverse and accurate experimental data
- Possibility of testing deepest aspects of high-energy high-density QCD through using most advanced methods from QFT, gravity and string theory