With Jet Quenching Towards the Quark Gluon Plasma

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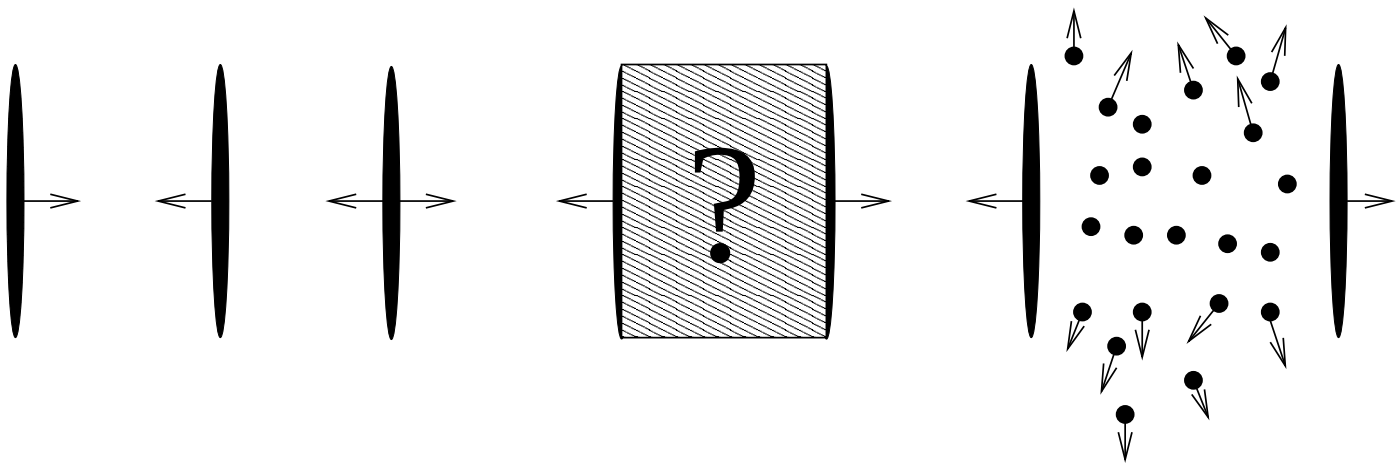
Part I

Introduction to QGP Search with Heavy Ions

Introduction

- QGP: state of deconfined quarks and gluons and restored chiral symmetry
- lQCD: QGP formation at high energy densities ($\epsilon_c \simeq 1\,\mathrm{GeV\,fm}^{-3}$)
- no unambiguous prediction for order of phase transition yet
- heavy ion collisions only possibility to create QGP in lab
- accelerators: AGS ($\sim$ 5A GeV), SPS ($\sim$ 20A GeV) and RHIC (100A GeV), i.e. at RHIC for first time hard probes available
- estimated energy density at RHIC $5\,\mathrm{GeV\,fm}^{-3}$

Heavy Ion Collisions



nothing
happening

overlap
hard scatterings

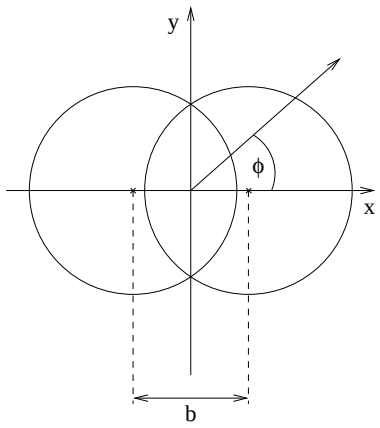
QGP?
hadron gas?

hadronisation
freeze-out

Heavy Ion Physics: Glauber Models

- idea: treat AA collisions as incoherent superposition of nucleon-nucleon collisions
- calculate mean number of binary nucleon-nucleon collisions $\langle N_{coll} \rangle(b)$ and mean number of participants (nucleons that took part in at least one interaction) $\langle N_{part} \rangle(b)$
- hard processes scale with $\langle N_{coll} \rangle(b)$
- soft processes scale with $\langle N_{part} \rangle(b)$
- in most central AA collisions $\langle N_{coll} \rangle(0) \propto A^{3/4}$ and $\langle N_{part} \rangle(0) \propto A$

Heavy Ion Physics: Azimuthal Asymmetry



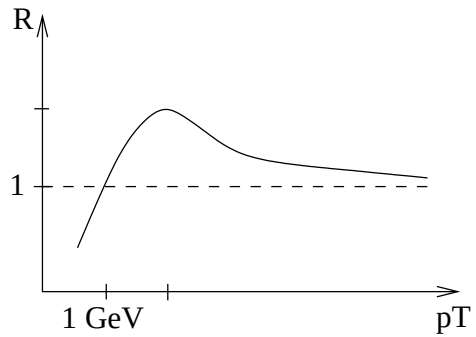
almond like shape of overlap region causes asymmetric particle emission

$$E\frac{\mathrm{d}^3N}{\mathrm{d}^3p} = \frac{1}{2\pi}\frac{\mathrm{d}^2N}{p_\perp \mathrm{d}p_\perp \mathrm{d}y}\left[1 + \sum_{n=1}^{\infty} 2v_n \cos(n\phi)\right]$$

Heavy Ion Physics: Cronin Effect

high-$p_\perp$ hadron production enhanced in pA collisions

$$R_{AB}(p_\perp) = \frac{B}{A}\frac{\mathrm{d}\sigma^{pA}/\mathrm{d}p_\perp}{\mathrm{d}\sigma^{pB}/\mathrm{d}p_\perp}$$



- can be explained by multiple scattering of the proton $\Rightarrow$ primordial transverse momentum $k_\perp$
- one possible model (includes also $k_\perp$ built up in parton showers):

$$\langle k_\perp^2 \rangle_A(Q^2) = \langle k_\perp^2 \rangle_N(Q^2) + \delta^2(Q^2)(\langle N_{\mathrm{coll}} \rangle(b) - 1)$$

Observables at AGS/SPS

- Strangeness Enhancement:
  - strangeness production suppressed in pp due to higher s quark mass
  - in QGP strangeness saturation due to $s\bar{s}$ pair production
  - expect enhanced strange particle yields with enhancement increasing with strangeness content
- Charmonium Suppression:
  - colour screening in QGP prevents $c\bar{c}$ pairs from binding
  - charmonium suppression already in pA due to interactions with spectators
  - expect anomalous charmonium suppression in case of QGP formation

AGS/SPS Results

- Strangeness Enhancement:
  - clear strangeness enhancement with expected hierarchy observed
  - evidence for QGP formation but still practical and conceptual problems
- Charmonium Suppression:
  - anomalous J/ψ suppression in central PbPb collisions at SPS, other data consistent with absorption in nuclear environment
  - signal for QGP but theoretical debate far from settled

$\Rightarrow$ no unambiguous proof for QGP formation

Jet Quenching (1)

- partons from hard scattering may have to traverse the QGP
- QGP dense and colour charged $\rightarrow$ expect strong interactions of parton with plasma
- parton has much higher energy $\rightarrow$ looses energy $\rightarrow$ softer jet
- fewer particles with high $p_\perp$ produced
- energy loss depends on path length in QGP, i.e. the geometry of the event
- parton may get stuck $\rightarrow$ no jet produced

Jet Quenching (2)

- if hard scattering near surface one parton may escape unharmed but the other one gets stuck
- leads to events with one nice jet
- models for jet quenching: gluon bremsstrahlung and hadronic rescattering

$\Rightarrow$ two signatures of jet quenching:

- high-$p_\perp$ hadron suppression
- suppression of the second jet

RHIC Results – High-$p_\perp$ Hadron Suppression

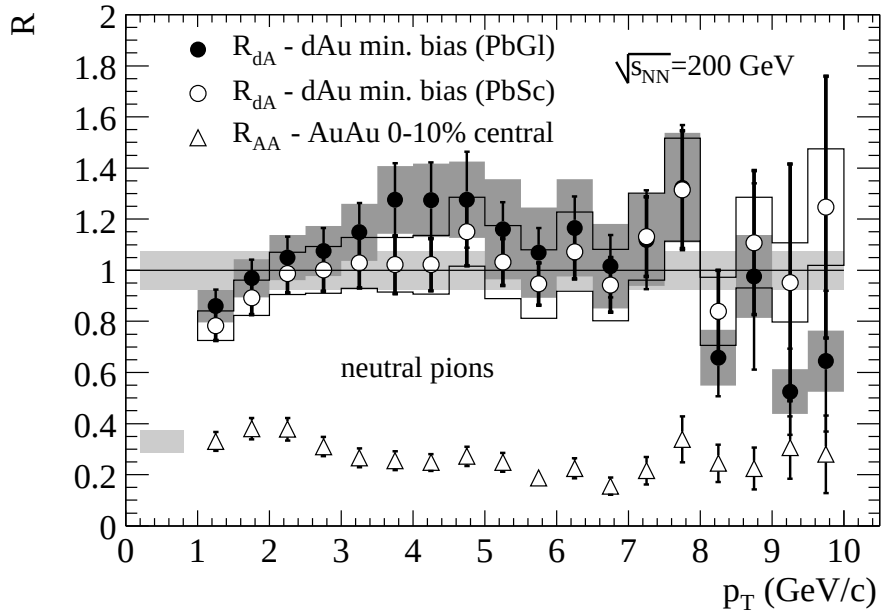
nuclear modification factor:

$$R_{\mathrm{AB}}(p_\perp, \eta) = \left(\frac{1}{N_{\mathrm{evt}}} \frac{\mathrm{d}^2 N^{\mathrm{AB}}}{\mathrm{d}p_\perp \mathrm{d}\eta} \right) \cdot \left(\frac{\langle N_{\mathrm{coll}} \rangle}{\sigma_{\mathrm{inel}}^{\mathrm{pp}}} \frac{\mathrm{d}^2 \sigma^{\mathrm{pp}}}{\mathrm{d}p_\perp \mathrm{d}\eta} \right)^{-1}$$

- clear suppression of high-$p_\perp$ hadrons in AuAu
- suppression increases with centrality
- no suppression dAu

RHIC Results – High-$p_\perp$ Hadron Suppression

PHENIX data



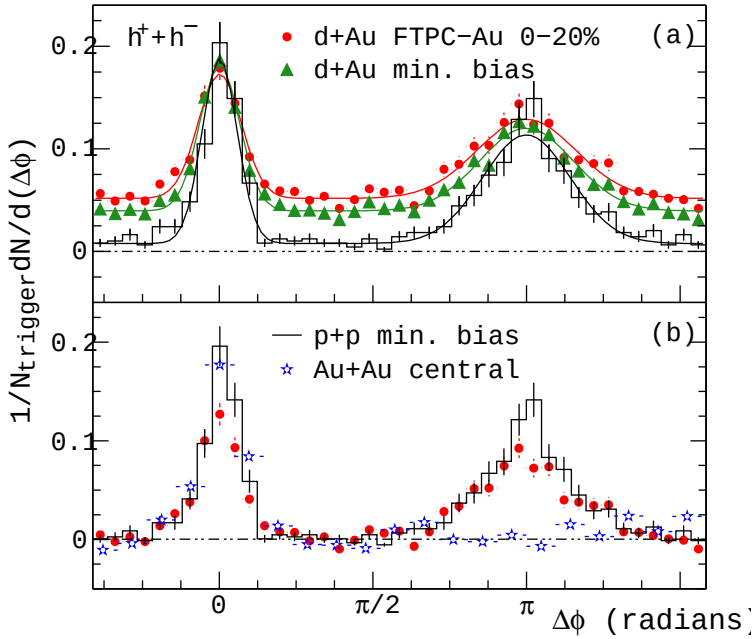
RHIC Results – Jet Disappearance

azimuthal correlation function: $D(\Delta\phi) = \frac{1}{N_{\mathrm{trig}}} \frac{\mathrm{d}N}{\mathrm{d}(\Delta\phi)}$

- trigger particle defined by $4 \leq p_\perp \leq 6\,\mathrm{GeV}$
- for each trigger particle look at all other particles with $2\,\mathrm{GeV} \leq p_\perp \leq p_\perp(\mathrm{trig})$ in the event
- disappearance of away-side jet in central AuAu collisions
- suppression increases with centrality
- only very weak suppression in dAu

RHIC Results – Jet Disappearance

STAR data



Part II

Our Activity

Reminder: Soft Colour Interactions

- interactions do not cease below pQCD cut-off (large coupling)
- SCI model in ep and $\bar{p}p$: partons interact with background field via soft gluon exchange $\longrightarrow$ change in string topology
- in practice: each parton can interact with each parton of the remnant
- assumption: change in dynamics negligible
- interaction probability only free parameter
- good description of large variety of data

Our Model: Basic Ideas

Why not soft colour interactions in a QGP?

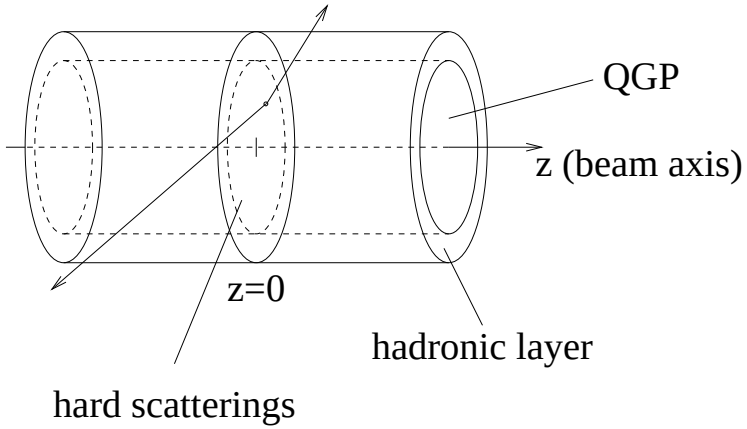
$\longrightarrow$ now many interactions per parton

$\longrightarrow$ take momentum transfer into account

$\longrightarrow$ energy loss

$\longrightarrow$ jet quenching?

Our Model: Geometry

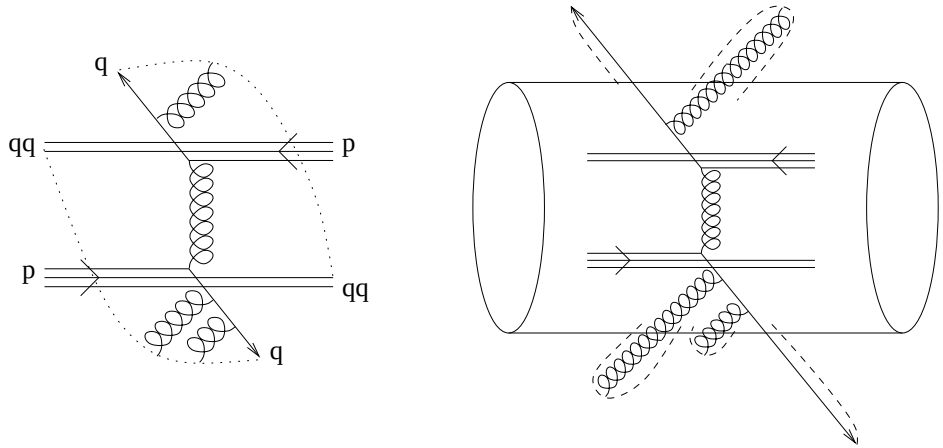


- constructed for most central collisions ($b = 0$)
- constant energy density in QGP
- (hard) interaction points in $z = 0$ plane

Our Model: Soft Interactions

- QGP consists of gluons
- each parton interacts with each gluon on its way with probability P_{int}
- interactions of partons with QGP: elastic scattering
- Gaussian t-distribution
- scattering angle: $\cos\theta_{cm} = \frac{t}{2(E_p^2 - m_p^2)} + 1$

Our Model: String Topology



- partons are no longer connected to the remnants but to the QGP

Our Model: Procedure

- choose hard interaction point (distribution flat in $\mathrm{d}r\,\mathrm{d}\cos\vartheta\,\mathrm{d}\varphi$)
- Cronin effect – set primordial $k_\perp$: $\langle k_\perp^2\rangle_{\mathrm{Au}} = 1\,\mathrm{GeV}^2 + d(\langle N_{\mathrm{coll}}\rangle(b) - 1)$
- generate pp collision
- for each parton calculate path length in plasma $\Rightarrow$ number of gluons
- simulate soft scatterings
- set string topology and hadronise

Our Model: Parameters

QGP	gluon energy	$\sigma_g = 0.1\,\mathrm{GeV}$
		$\mu_g = 0.1\,\mathrm{GeV}$
	gluon mass	$m_g = 0.5\,\mathrm{GeV}$
	radius	$R_{\mathrm{QGP}} = 5\,\mathrm{fm}$
	longitudinal extension	$z_{\mathrm{QGP}} = 10\,\mathrm{fm}$
	gluon density	$n_g = 80\,\mathrm{fm}^{-1} \leftrightarrow 15\,\mathrm{fm}^{-3}$
SI	int. probability	$P_{\mathrm{int}} = 0.5$
	t distribution	$\sigma_t = -0.1\,\mathrm{GeV}^2$
		$\mu_t = 0$
Cronin effect	$k_\perp$ broadening	$d = 0.3\,\mathrm{GeV}^2$

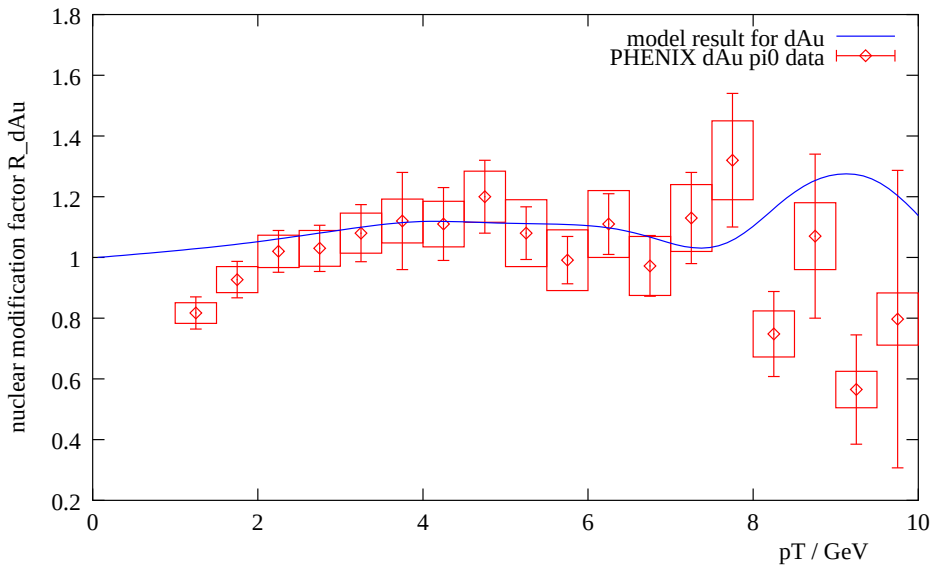
Limitations of the Model

- $p_\perp > 3\,\mathrm{GeV}$ required in pp collision
- plasma is not hadronised
- no underlying events

$\Rightarrow$ soft physics not treated properly

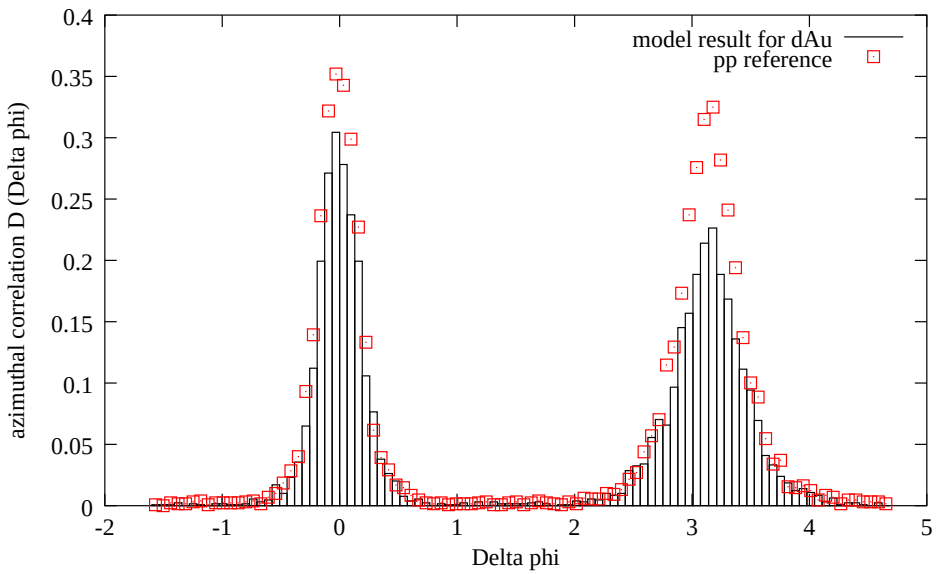
$\Rightarrow$ model only valid for $p_\perp > 3 - 4\,\mathrm{GeV}$

Results: dAu – Nuclear Modification Factor



good agreement for $3 < p_\perp < 7\,\mathrm{GeV}$ where the model is valid and the statistical error (not shown here) is reasonably small

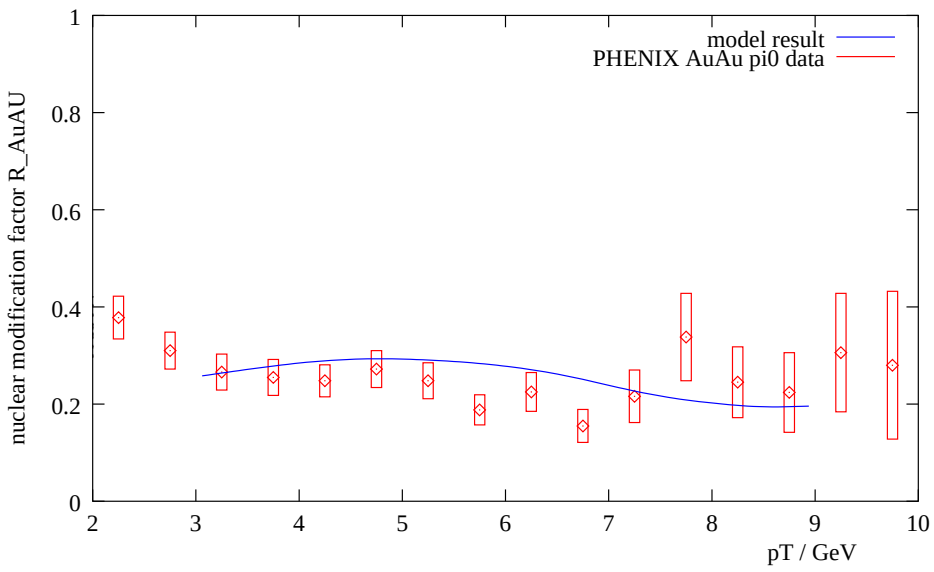
Results: dAu – Azimuthal Correlation



looks good

Results: AuAu – Nuclear Modification Factor

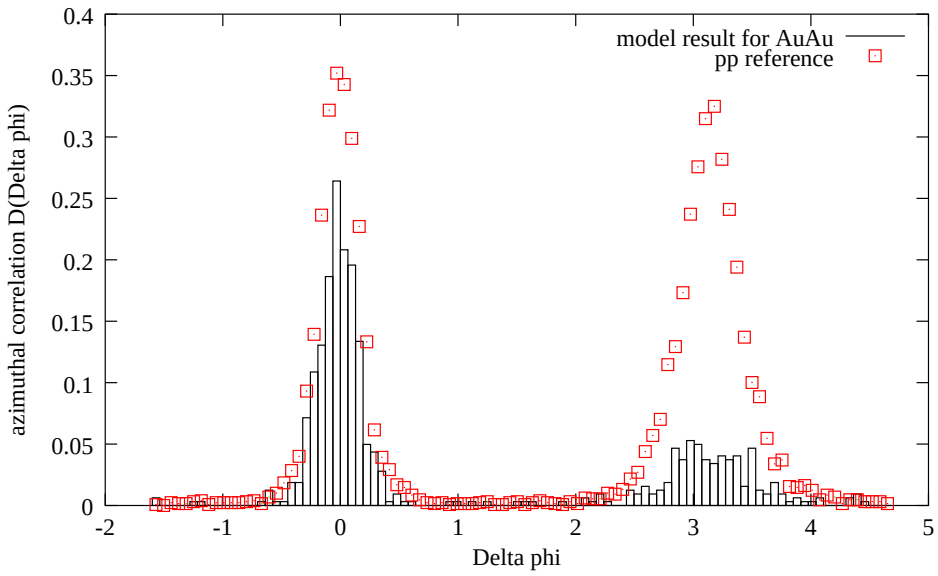
high-$p_\perp$ hadron suppression



not perfect but satisfactory

Results: AuAu – Azimuthal Correlation

disappearance of the away-side jet



qualitatively the same effect as in data

Conclusions

- good agreement with data for high-$p_\perp$ particle suppression (R_{dAu} and R_{AuAu})
- "systematic" uncertainties in azimuthal correlation ($D(\Delta\phi)$) but reasonable description of data

$\Rightarrow$ Soft Colour Interactions have to be taken into account when dealing with jet quenching

- results consistent with assumption of QGP formation, but no proof
- maybe combination of soft colour interactions with gluon bremsstrahlung a more realistic model

Have we seen the QGP?

- AGS: probably not
- SPS: maybe – there is some evidence but it cannot be unambiguously established
- RHIC: probably yes – clear jet quenching (and other effects) is observed but the positive proof is still missing