Parton Energy Loss - Soft Colour Interaction Model and General Properties

a Monte Carlo Model for Jet Quenching

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Outline

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Rapidity Gaps and the Soft Colour Interaction Model

Soft Colour Interactions and Jet Quenching
- Introduction
- SCI Jet Quenching Model
- Results
- Summary

General Properties of Partonic Energy Loss
- Introduction
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Conclusions

Soft Colour Interactions in Diffractive DIS

- diffraction defined "phenomenologically" from final state

→ no specific mechanism

- photon-parton interaction takes place inside the proton
- more soft interactions going on below perturbative cutoff

⇒ hard scattered parton should interact with proton remnant

⇒ Soft Colour Interaction Model (SCI)

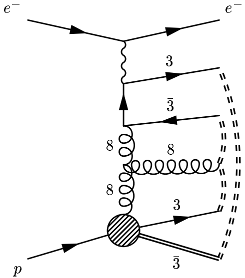
The SCI Model

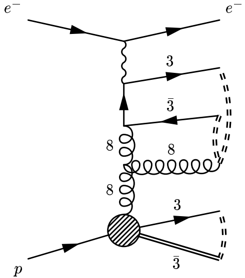
Edin, Ingelman, Rathsman, Phys. Lett. **B366** (1996) 371

soft colour interactions among partons:

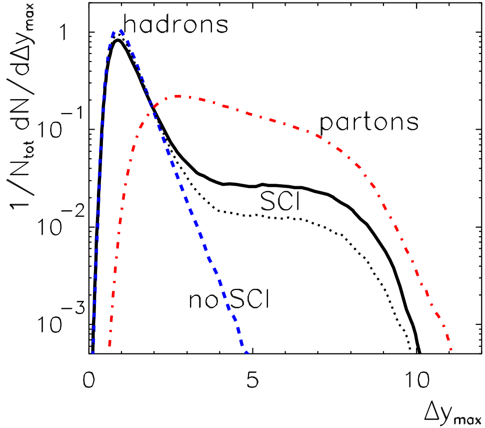
- interactions take place after the perturbative interaction and before hadronisation
- colour-anticolour (gluon) exchange between parton pairs
- changes colour topology → can create rapidity gaps
- describes all final states – diffractive and non-diffractive
- small momentum transfer does not change dynamics
- only parameter: interaction probability $P = 0.5$ (determined from HERA data)
- implemented in PYTHIA, LEPTO and AROMA

An Example



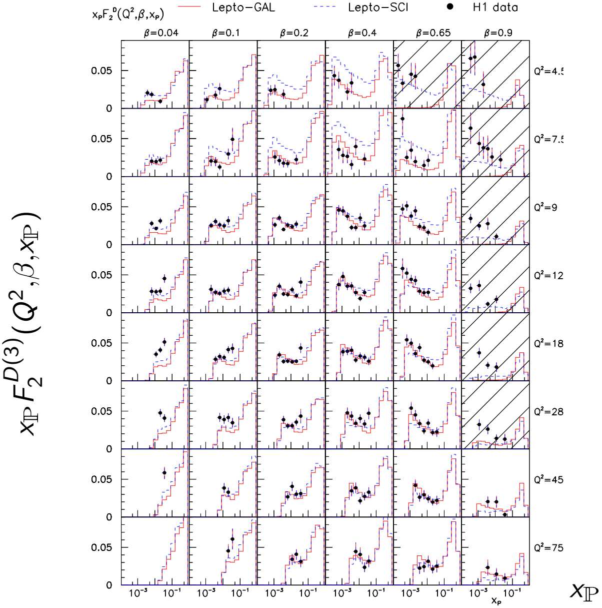


Results



plateau in Δy_{max} characteristic for diffraction

Diffraction at HERA



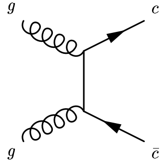
Diffraction at the TEVATRON

$$R_{\text{hard}} = \frac{1}{\sigma^{\text{tot}}_{\text{hard}}} \int_{x_{F\,\text{min}}}^{1} dx_F \, \frac{d\sigma_{\text{hard}}}{dx_F}$$

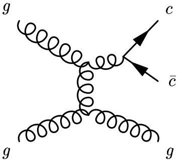
R_{hard} [%]	Exp.	observed	SCI
dijets	CDF	0.75 ± 0.10	0.7
W	CDF	1.15 ± 0.55	1.2
W	DØ	$1.08\,^{+0.21}_{-0.19}$	1.2
$b\bar{b}$	CDF	0.62 ± 0.25	0.7
Z	DØ	$1.44\,^{+0.62}_{-0.54}$	1.0
J/ψ	CDF	1.45 ± 0.25	1.4

← predictions

SCI can turn colour octet $c\bar{c}$ into colour singlet → J/ψ



(a)



(b)

Conclusions

The SCI model yields a satisfactory description of

- rapidity gaps in DIS
- leading protons/neutrons in DIS
- diffractive jets, W, Z, $b\bar{b}$, J/ψ at TEVATRON
- high-$p_\perp$ J/ψ, ψ', Υ at TEVATRON
- J/ψ, ψ' in fixed target πA and pA

$\Rightarrow$ not bad for a simple (one-parameter) model

The SCI model has recently received a firmer theoretical basis in terms of rescattering in QCD.

Brodsky, Enberg, Hoyer, Ingelman, Phys. Rev. **71** (2005) 074020

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Introduction

Basic idea

soft colour interactions with background important in *pp* collisions ⇒ should occur also in a QGP
much more interactions → even small momentum transfer may be important → jet quenching?

Application

comparison to RHIC data

People involved

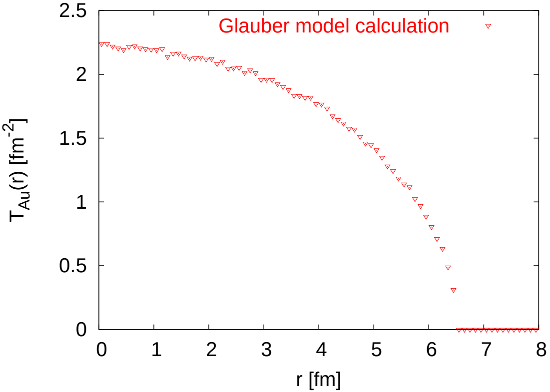
Uppsala	Heidelberg
G. Ingelman	J. Stachel
J. Rathsman	K. Zapp

The SCI Jet Quenching Model: QGP

- geometry: sharp shere potential + Glauber model
- energy density:
  $\epsilon(x,y) \propto T_{\mathrm{Au}}(x - b/2, y) \cdot T_{\mathrm{Au}}(x + b/2, y)$
- hard scattering: PYTHIA6.2 + distribution in transverse plain according to $\langle N_{\mathrm{coll}}(b) \rangle$
- EOS: ideal gluon gas
  $\rightarrow n = \frac{g}{\pi^2}\zeta(3)T^3$ and $\langle E_g \rangle = \frac{\epsilon_g}{n_g} \simeq 2.7\, T$
- evolution: Bjorken-like model with longitudinal expansion
  - $\epsilon(\tau) \propto \tau^{-4/3}$
  - $T(\tau) \propto \tau^{-1/3}$ until $T < T_c$ (=critical temperature)
  - $n(\tau) \propto \tau^{-1}$

Nuclear Thickness Function

$$T_{\mathrm{Au}}(r) = \int\limits_{-\infty}^{\infty} \mathrm{d}z\, n_{\mathrm{Au}}(\sqrt{r^2 + z^2}) \qquad n_{\mathrm{Au}} : \text{nuclear density}$$



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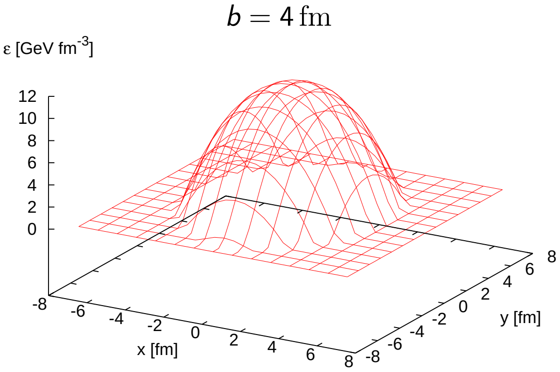
Energy Density Distribution at $\tau = 1\,\mathrm{fm/c}$



normalisation: require that mean energy density at $\tau = 1\,\mathrm{fm}$ is ϵ_0 for 0% centrality

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The SCI Jet Quenching Model: Parton - QGP Interactions

soft colour interactions with (small) momentum transfer

- treated as elastic scattering
- successive scatterings assumed to be independent
- momentum transfer t Gaussian distributed
- interaction probability is 0.5 for quarks and 0.75 for gluons

in practice:

- iterative procedure
- follow parton along its track
- update τ, T, $\langle E_g \rangle$, ... in each step
- interact with each QGP gluon closer than R_{scr} with probability p
- stop when parton leaves QGP or $T < T_c$

The SCI Jet Quenching Model: What else?

Cronin effect:

- $\sigma^2_{k_\perp}(x,y,b) = \sigma^2_{k_\perp,0}(x,y,b) + \alpha(\langle N^{(\mathrm{i})}_{\mathrm{scatt}}(x,y,b)\rangle - 1)$
- Wang, Phys. Rev. **C61** (2001) 064910
  Zhang, Fai, Papp, Barnafoldi, Levai, Phys. Rev. **C65** (2002) 034903

hadronisation:

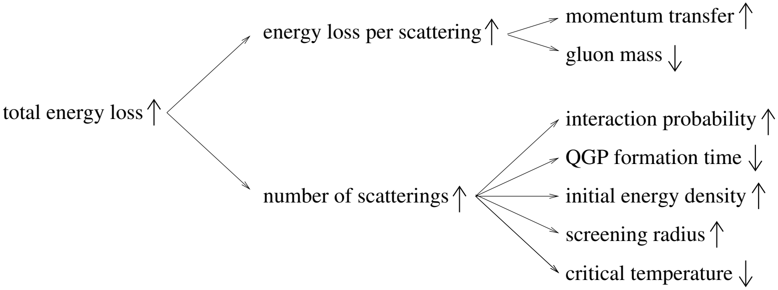
- cannot expect hadronisation to proceed as in vacuum
- but how?!
- colour connection to proton remnant is destroyed

⇒ use independent fragmentation for the time beeing

Model Parameters

QGP formation time	τ_i	0.2 fm
initial energy density $\epsilon(\tau = 1\,\mathrm{fm})$	ϵ_0	$5.5\,\mathrm{GeV\,fm^{-3}}$
critical temperature	T_c	0.175 GeV
gluon mass	m_g	0.2 GeV
interaction probability	p	0.5
screening radius	R_{scr}	0.3 fm
width of t - distribution	σ_t	$0.5\,\mathrm{GeV}^2$
Cronin parameter	α	$0.25\,\mathrm{GeV}^2$

Dependencies



total energy loss ↑

energy loss per scattering ↑

momentum transfer ↑

gluon mass ↓

number of scatterings ↑

interaction probability ↑

QGP formation time ↓

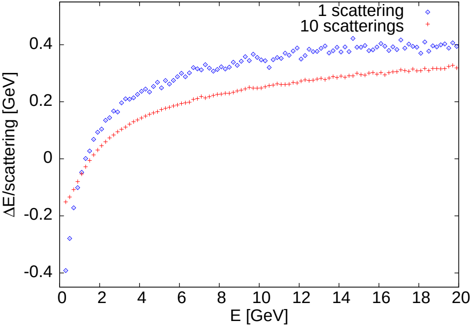
initial energy density ↑

screening radius ↑

critical temperature ↓

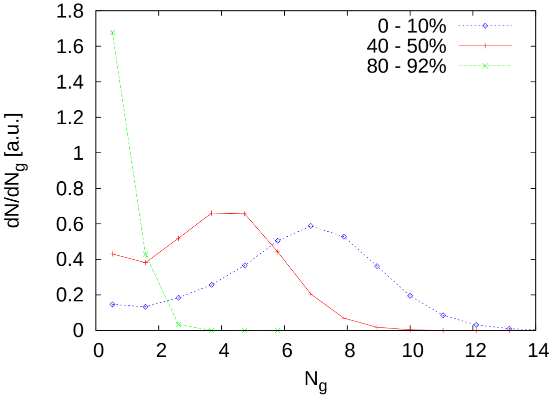
Energy Dependence of ΔE

energy loss of light quarks



- energy loss most efficient for partons with intermediate $p_\perp$

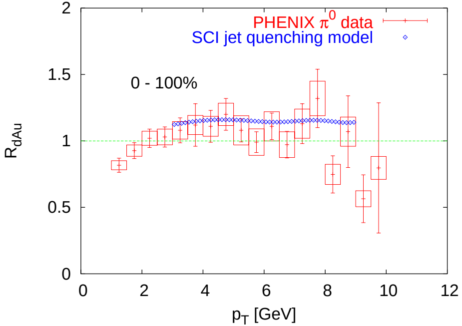
Number of Gluons Encountered by a Parton



centrality: percent of total geometric cross section, i.e. $\sigma_{\text{geo}}/\sigma_{\text{geo}}^{(\text{tot})} = 80 - 92\%$ ect.

Cronin Effect: d+Au

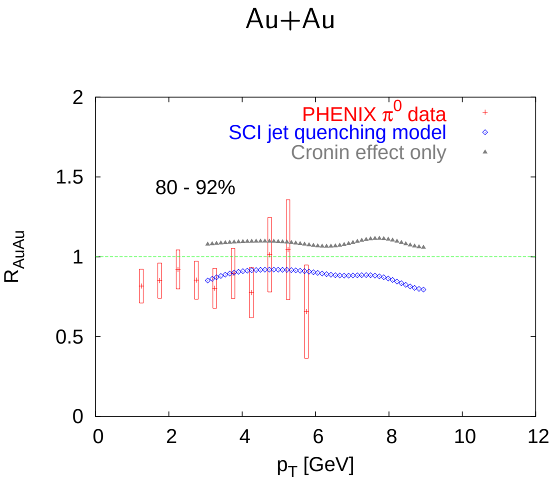
$$R_{\mathrm{AB}}(p_\perp,\eta) = \left(\frac{1}{N_{\mathrm{evt}}}\frac{\mathrm{d}^2N^{\mathrm{AB}}}{\mathrm{d}p_\perp\mathrm{d}\eta}\right)\cdot\left(\frac{\langle N_{\mathrm{coll}}\rangle}{\sigma_{\mathrm{inel}}^{\mathrm{pp}}}\frac{\mathrm{d}^2\sigma^{\mathrm{pp}}}{\mathrm{d}p_\perp\mathrm{d}\eta}\right)^{-1}$$



okay but relatively weak dependence on Cronin parameter

Adler *et al.*, PHENIX Collaboration, PRL **91** (2003) 072303

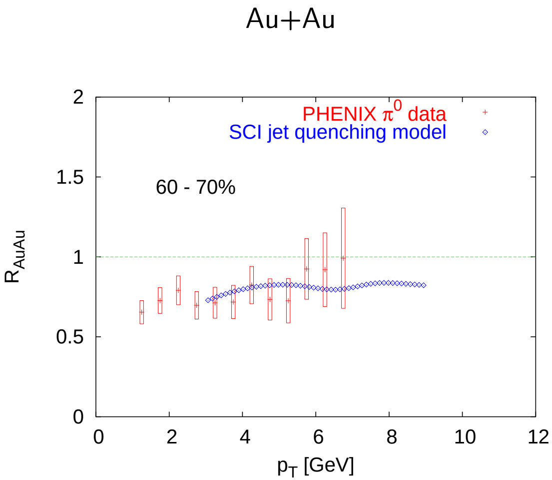
Nuclear Modification Factor



For 80-92% centrality we describe the data . . .

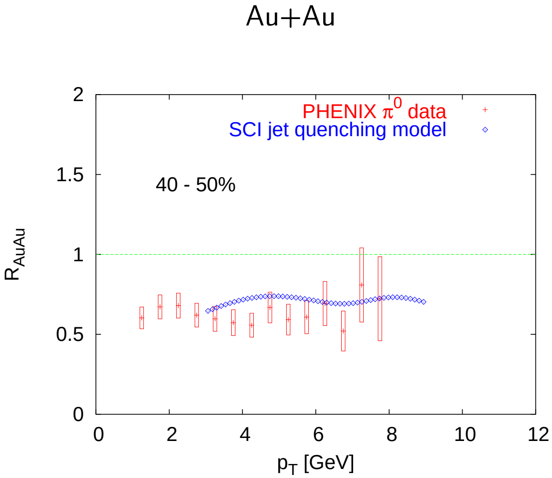
Adler *et al.*, PHENIX Collaboration, PRL **91** (2003) 072301

Nuclear Modification Factor



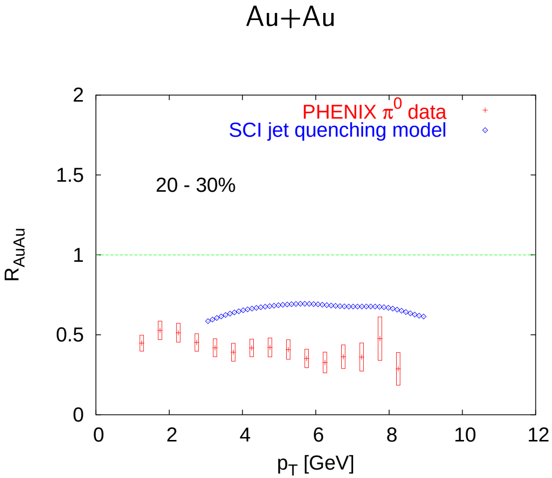
. . . 60-70% is still okay . . .

Nuclear Modification Factor



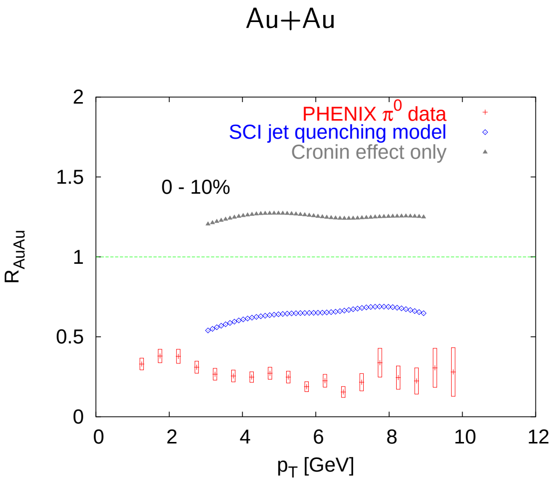
. . . there is a small deviation in 40-50% . . .

Nuclear Modification Factor



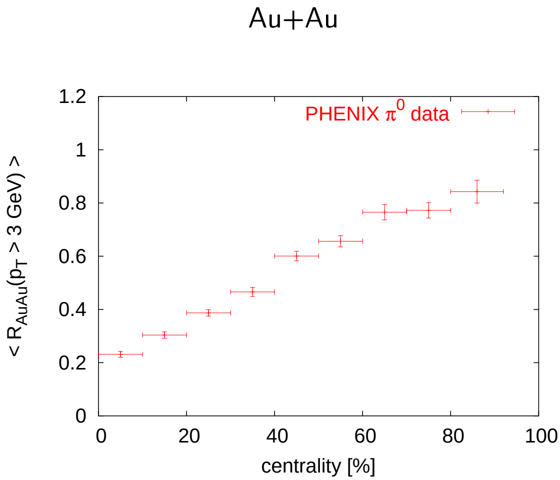
. . . in 20-30% the model clearly falls behind . . .

Nuclear Modification Factor



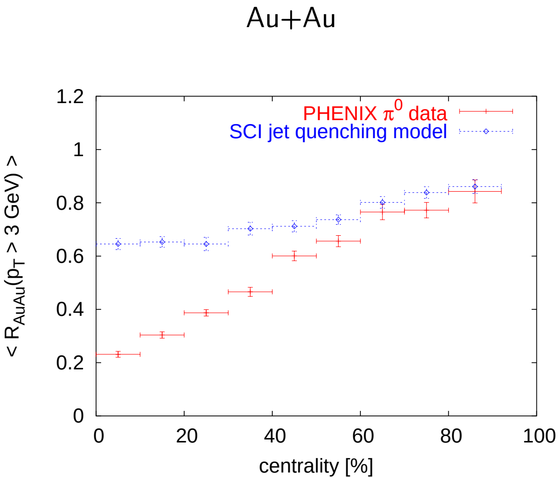
. . . and ends up at 50% of the observed effect in 0-10%.

Centrality Dependence: Data

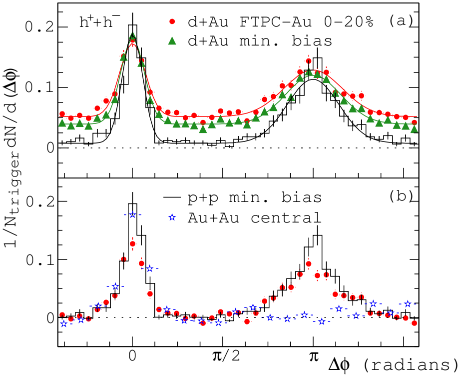


Adler *et al.*, PHENIX Collaboration, PRL **91** (2003) 072301

Centrality Dependence: Model



2-Particle Azimuthal Correlation: Data

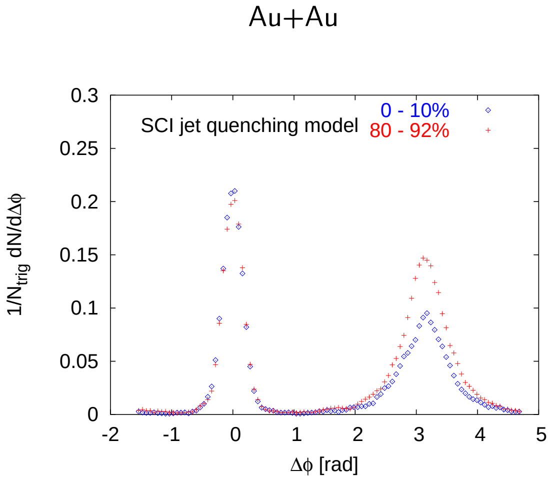


trigger particles: $4\,\mathrm{GeV} < p_\perp < 6\,\mathrm{GeV}$

associated particles: $2\,\mathrm{GeV} < p_\perp < p_\perp(\mathrm{trig})$

Adams *et al.*, STAR Collaboration, PRL **91** (2003) 072304

2-Particle Azimuthal Correlation: Model



We see a suppression but no disappearance of the away-side jet.

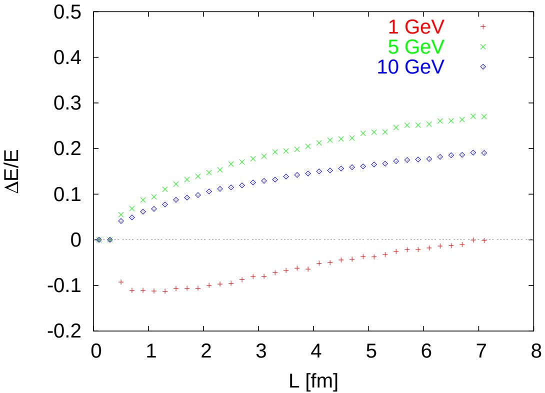
What is Going on here?

strong suppression of away-side peak requires asymmetric events

- hard scatterings occur preferentially near the centre → typically small path length differences (no surface emission)
- $n \propto \tau^{-1}$ → most scatterings at early times
- QGP lifetime limits available path length differences in central collisions
- QGP gluon energy $\propto \tau^{-1/3}$ → more energy loss per scattering at later times
- ME: 50% $q + g \rightarrow q + g$ processes → quarks and gluosn behave differently → asymmetry due to different parton species
- hadronisation not treated properly

Path Length Dependence of ΔE

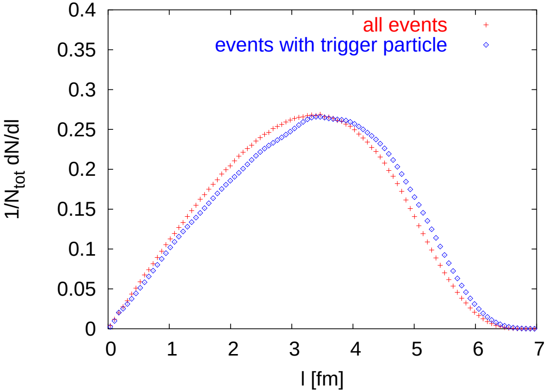
specific energy loss of light quarks emitted from centre of QGP with $\theta = \pi/4$



- gets flatter with increasing $L \longrightarrow$ early times more important
- quarks with low energy are thermalised

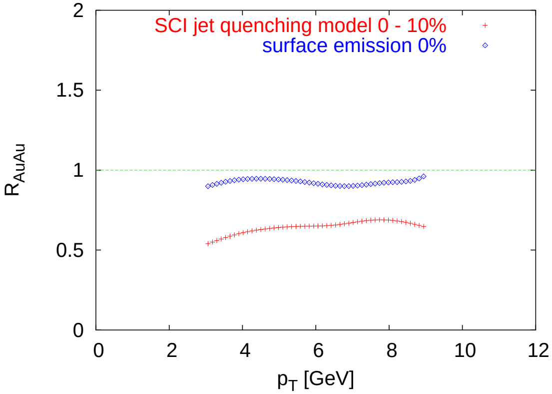
Surface Emission?

distance of hard scattering points from centre ($0 - 10\%$)



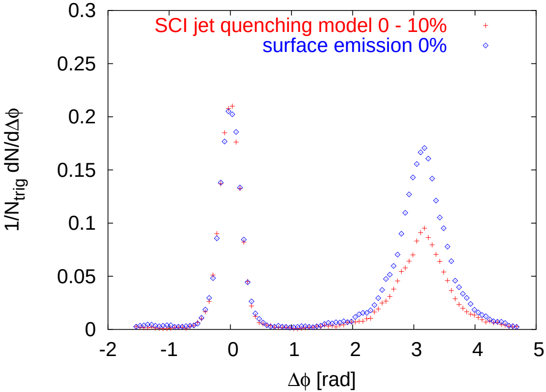
- No surface emission in the SCI jet quenching model!
- origin of partons that produce trigger particles well inside the fireball

SCI Jet Quenching Model with Enforced Surface Emission



- much smaller effect

SCI Jet Quenching Model with Enforced Surface Emission

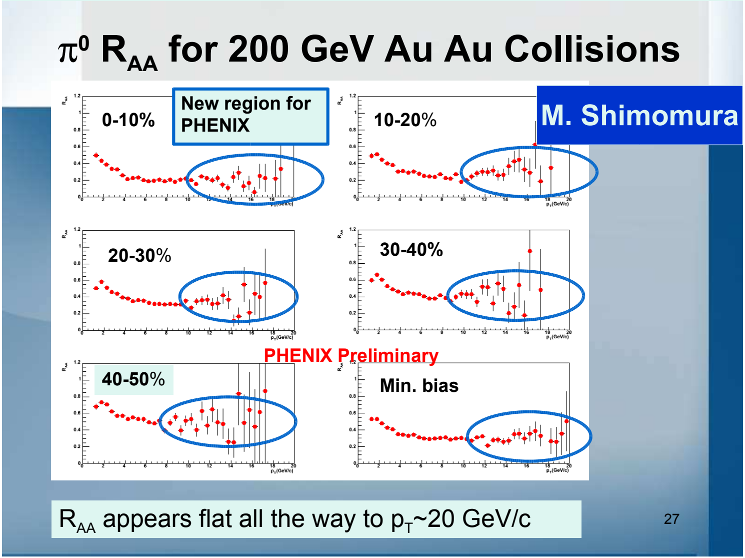


- same thing here

Why is this so Inefficient?

- mean path length relatively small for geometrical reasons
- QGP life time limits path lengths
- even inward moving parton never reaches dense parts of QGP
    - it starts at small densities near the surface
    - as it moves in the density drops like τ^{-1}
    - before it reaches the centre the QGP hadronises

Victoria Greene at Quark Matter 2005



π^0 R_{AA} for 200 GeV Au Au Collisions

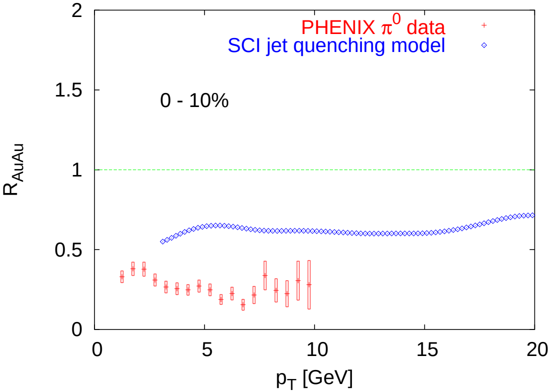
New region for PHENIX

M. Shimomura

PHENIX Preliminary

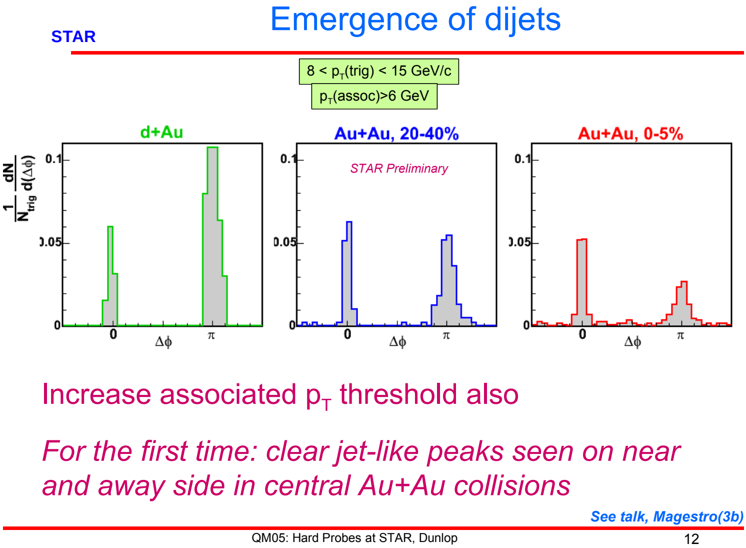
R_{AA} appears flat all the way to p_T~20 GeV/c

SCI Jet Quenching Model at Higher $p_\perp$



- R_{AuAu} stays flat (possibly moderate increase at $p_\perp > 17\,\mathrm{GeV}$)
- in agreement with newest PHENIX results

James Dunlop at Quark Matter 2005



STAR

Emergence of dijets

$8 < p_T(\mathrm{trig}) < 15$ GeV/c

$p_T(\mathrm{assoc}) > 6$ GeV

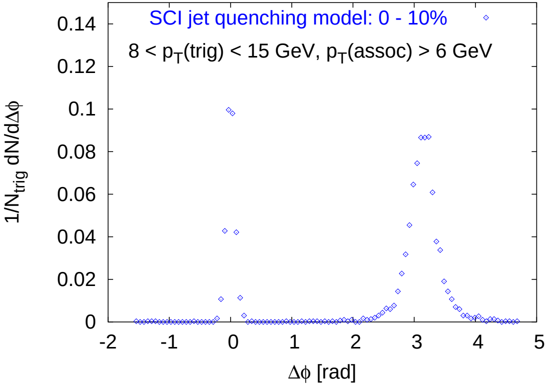
Increase associated p_T threshold also

For the first time: clear jet-like peaks seen on near and away side in central Au+Au collisions

See talk, Magestro(3b)

QM05: Hard Probes at STAR, Dunlop 12

SCI Jet Quenching Model at Higher $p_\perp$



- away-side peaks reappears at high $p_\perp$
- in agreement with newest STAR and PHENIX results

Summary I

Main Features of the Model

- QGP:
    - ideal gluon gas
    - Bjorken-like longitudinal expansion
- includes full geometry and space-time evolution
- simple model for Cronin effect included
- soft colour interactions of hard partons in QGP lead to significant energy loss

Remark

SCI Jet Quenching model cannot be complete → induced gluon radiation etc. missing

Summary II

What we have

- 50% of R_{AuAu} in central collisions
- $p_\perp$ - dependence of R_{AuAu} is okay also at higher $p_\perp$
- centrality dependence is different from data
- small effect on azimuthal correlation (mostly understood)
- away-side jet grows again at higher $p_\perp$ as observed in data

What needs to be done

- hadronisation

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Introduction

Question

What can we learn about the general properties of partonic energy loss without having a detailed model?

Are there clear indications for/against coherent gluon bremsstrahlung?

Approach

- take the SCI jet quenching model and replace the energy loss
- energy loss:
  - subtract certain amount of energy, no deflection
    $\Delta E \propto \text{const}, E, \sqrt{E}$
    $\Delta E \propto N_g, N_g^2 \quad ; \quad N_g = A_\perp \int n(\tau) \mathrm{d}\tau$
  - magnitude of ΔE is a free parameter
  - gluons lose more energy than quarks (factor 2)

Overview over Versions of the Toymodel

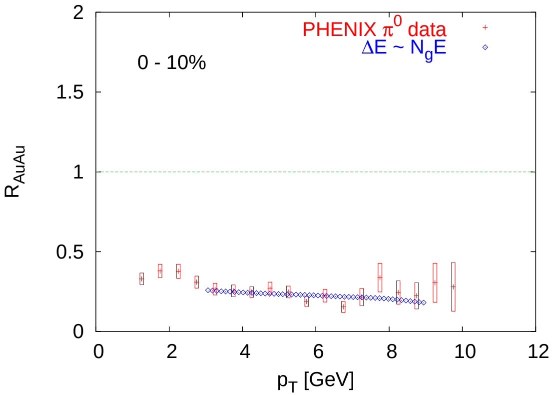
Dependencies		Constant
"path length"	energy	
N_g	E	$0.070\,\mathrm{GeV}$
N_g^2	E	$0.018\,\mathrm{GeV}$
N_g	$\sqrt{E}$	$0.300\,\mathrm{GeV}$
N_g^2	$\sqrt{E}$	$0.020\,\mathrm{GeV}$
N_g	const.	$0.425\,\mathrm{GeV}$
N_g^2	const.	$0.200\,\mathrm{GeV}$

energies are in units of 1 GeV

Attention!

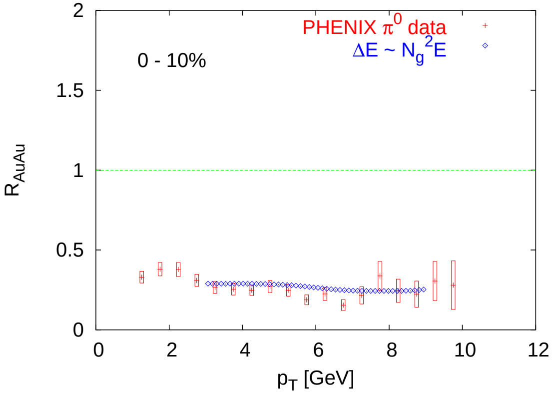
There is a hidden assumption, namely that there is no hard radiation in the jet cone, i.e. no radiation that survives the passage of the QGP!

Nuclear Modification Factor: $\Delta E \propto N_g E$



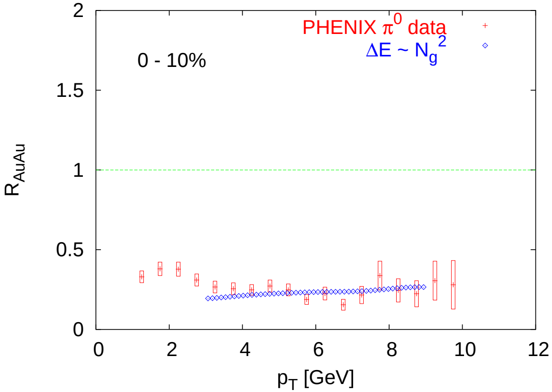
- fits quite well

Nuclear Modification Factor: $\Delta E \propto N_g^2 E$



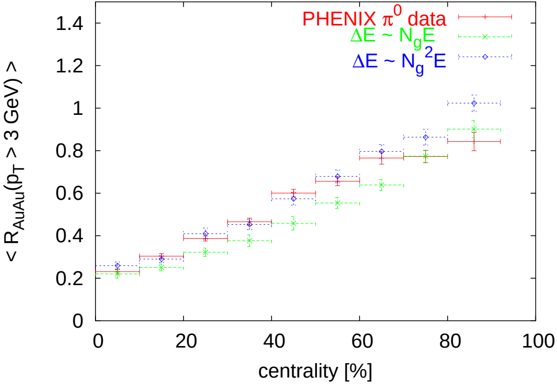
- practically the same

Nuclear Modification Factor: $\Delta E \propto N_g^2$



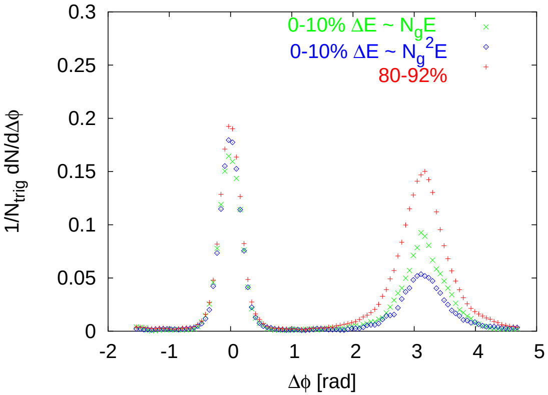
- also very similar

Centrality Dependence: $\Delta E \propto E$



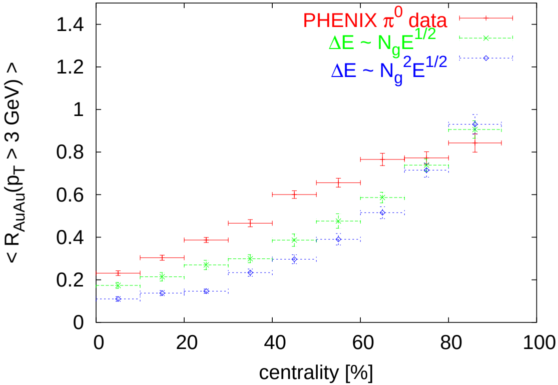
- not bad although slightly curved
- $\Delta E \propto N_g^2 \cdot E$ better than $\Delta E \propto N_g \cdot E$

Azimuthal Correlation: $\Delta E \propto E$



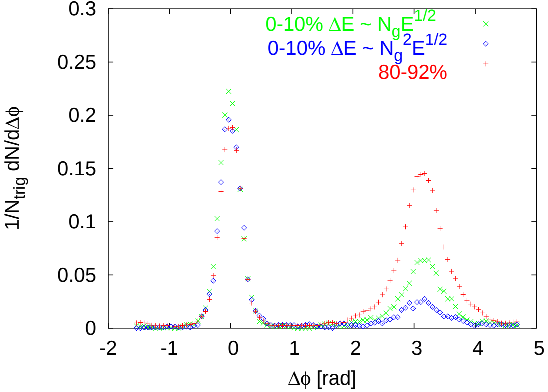
- clear suppression but not enough
- $\Delta E \propto N_g^2 \cdot E$ again somewhat better than $\Delta E \propto N_g \cdot E$

Centrality Dependence: $\Delta E \propto \sqrt{E}$



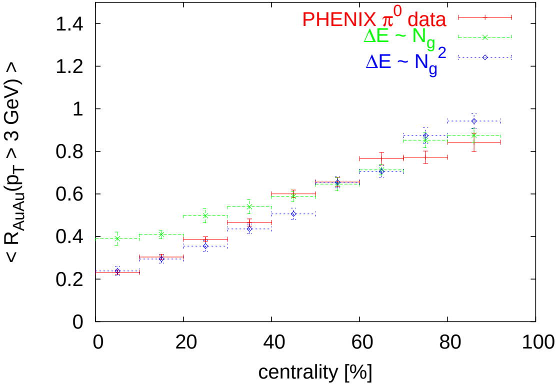
- wrong shape (parabolic)

Azimuthal Correlation: $\Delta E \propto \sqrt{E}$



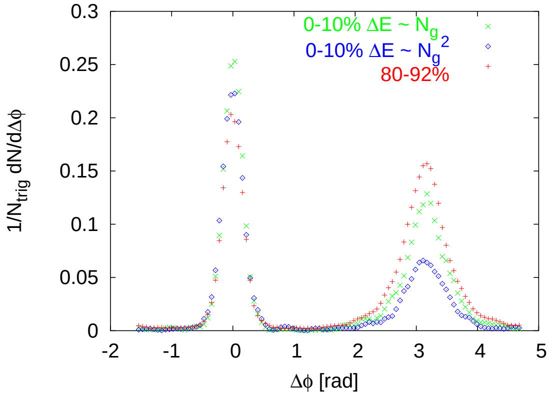
- even somewhat better than before

Centrality Dependence: ΔE indep. of E



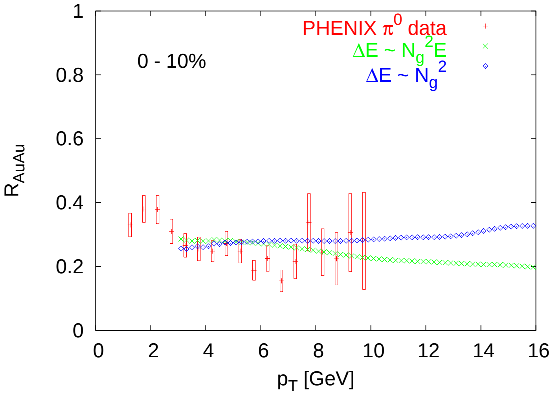
- not bad
- $\Delta E \propto N_g^2$ better than $\Delta E \propto N_g$

Azimuthal Correlation: ΔE independent of E



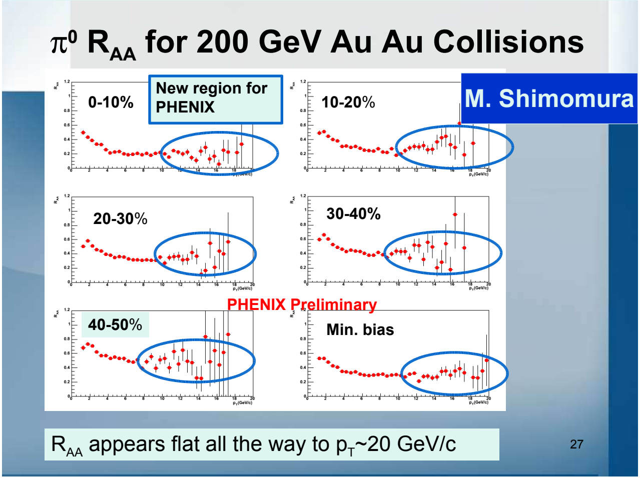
- not convincing: effect too small
- $\Delta E \propto N_g^2$ again better than $\Delta E \propto N_g$

Can $\Delta E \propto E$ and $\Delta E \propto \text{const}$ be distinguished?



- need more data at higher $p_\perp$

Once More: Victoria Greene at QM05

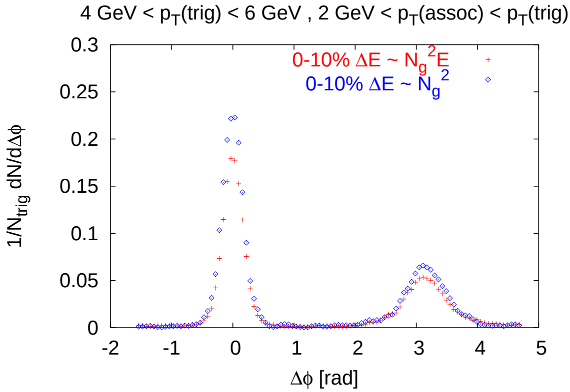


π^0 R_{AA} for 200 GeV Au Au Collisions

R_{AA} appears flat all the way to p_T~20 GeV/c

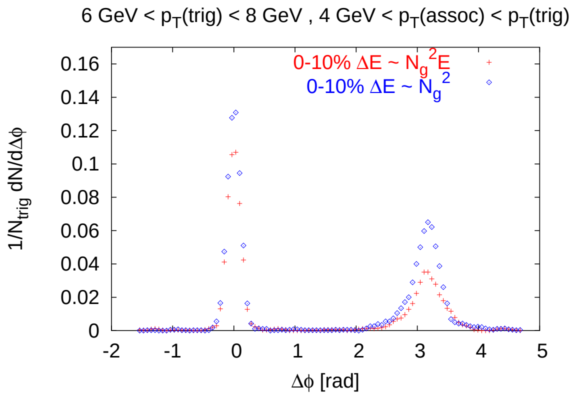
- $\Delta E \propto N_g^2$ favoured

Can $\Delta E \propto E$ and $\Delta E \propto$ const be distinguished?



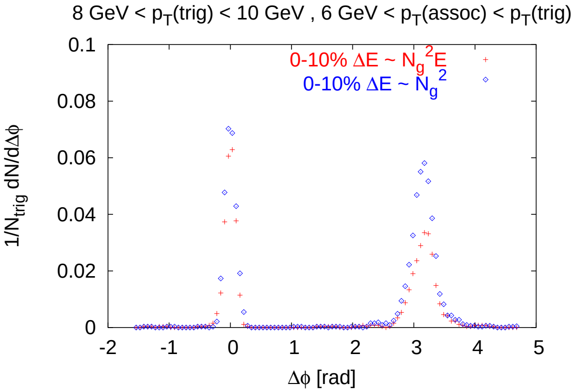
- not a big difference here

Can $\Delta E \propto E$ and $\Delta E \propto$ const be distinguished?



- somewhat bigger difference here . . .

Can $\Delta E \propto E$ and $\Delta E \propto$ const be distinguished?



- … and here
- reappearance of the away-side jet

Summary

- R_{AuAu} nearly the same in all configurations
- $\Delta E \propto \sqrt{E}$ gives the wrong centrality dependence
- $\Delta E \propto E$ and $\Delta E \propto$ const very similar
- $\Delta E \propto N_g^2$ looks slightly better than $\Delta E \propto N_g$
- partly good description of centrality dependence
- all fail to describe disappearance of away-side jet
- centrality dependence of R_{AuAu} sensitive to energy dependence of energy loss mechanism
- available path lengths limited by the geometry and not by QGP lifetime

Outline

Conclusions

- (soft) scattering can contribute signifcantly to parton energy loss
- SCI jet quenching in its present form is not complete and cannot describe all data
- the $\Delta E \propto N_g^2$ scenario does a somewhat better job than $\Delta E \propto N_g$
  $\rightarrow$ sign for coherence?
- toymodels fail to describe the disappearance of the away-side jet
  $\rightarrow$ redistribution of energy in the jet cone and/or effects of modified fragmentation?
- reappearance of the jet at higher $p_\perp$ seems to come about naturally