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Semihard parton rescatterings in heavy-ion interactions at collider energies

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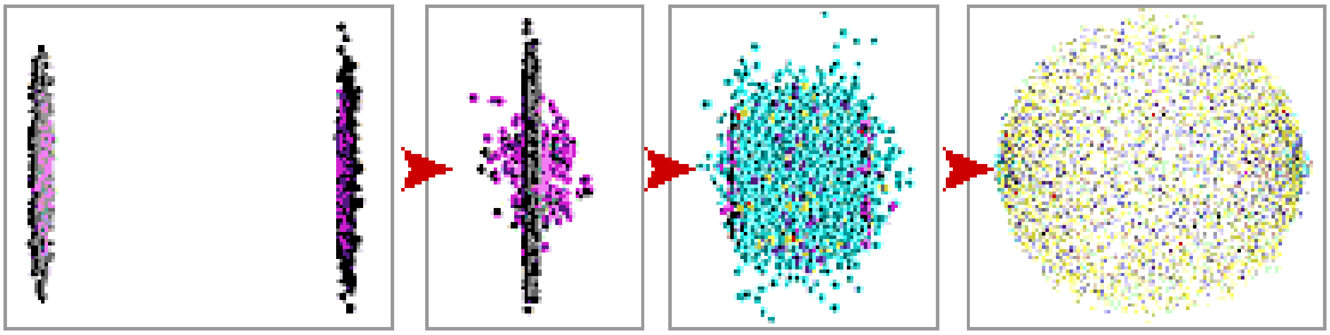
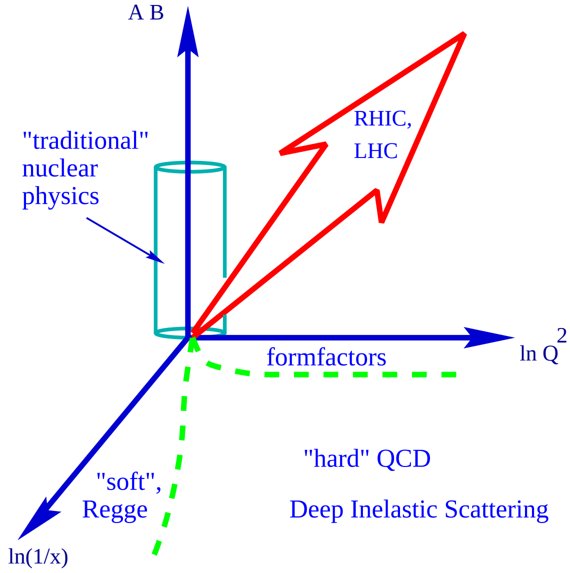
SUMMARY

- Introduction
  - Heavy-ion collisions
  - The Quark-Gluon Plasma
  - (Global) observables
- Initial conditions and saturation
  - Semihard parton rescatterings
  - Initial conditions
  - Saturation in the parton production
  - Charged particle multiplicities
- Minijet transverse spectrum
  - a closer look into parton dynamics
- Conclusions and perspectives

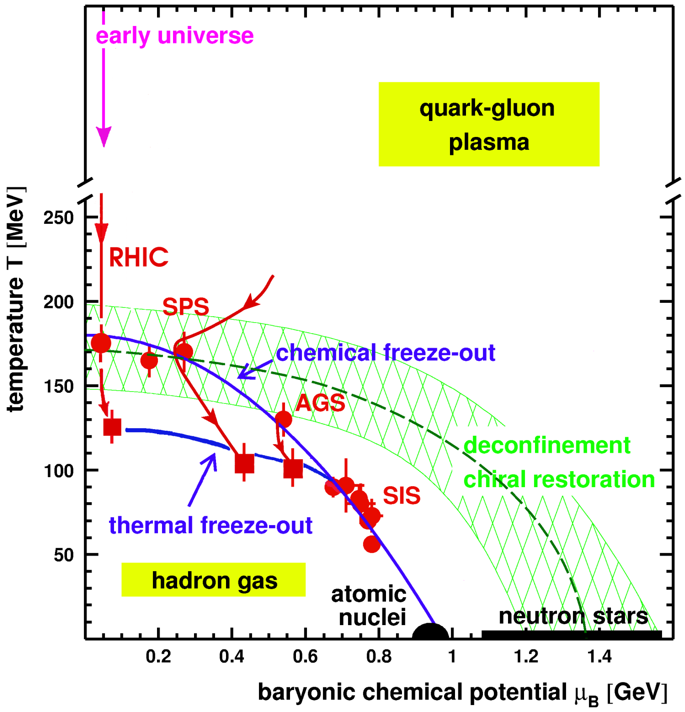
Heavy-ion collisions at high energy



Au-Au at $\sqrt{s} = 200$ GeV



- New regimes of QCD
  - small Bjorken x
  - large typical momentum transfer $\overline{Q}$
  - nonlinear dynamics
- Quark-Gluon Plasma?
  - matter created at $\begin{cases} \text{high density} \\ \text{high temperature} \end{cases}$
  - temperature drops with expansion
  - fast thermalization (?) $\Rightarrow$ QGP



Minijet plasma

Perturbative QCD may be used:

- large $\overline{Q} \Longleftrightarrow$ small coupling $\alpha_s(\overline{Q})$
  $\Longrightarrow$ partonic degrees of freedom

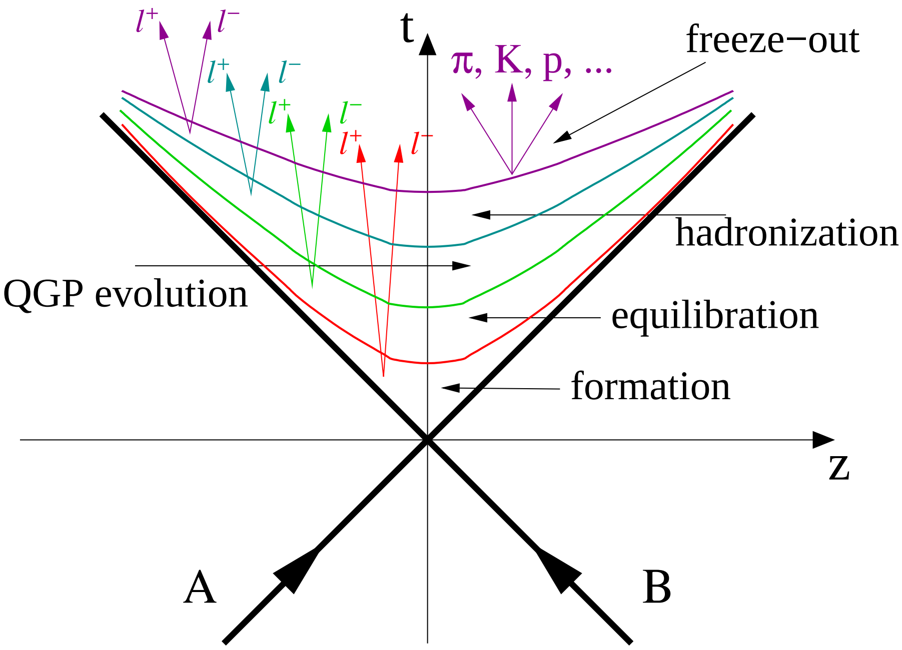
- Initial production of partons $\begin{cases} \text{high density} \\ \text{high temperature} \end{cases}$
  $\Longrightarrow$ "MINIJET PLASMA"

	SPS (CERN)	RHIC (Brookhaven)	LHC (CERN)
first coll.	'80s	2000	2006
nuclei	^{208}Pb–^{208}Pb	^{197}Au–^{197}Au	^{208}Pb–^{208}Pb
$\sqrt{s}$/A	17 GeV	200 GeV	6000 GeV
$\overline{Q}$	$<$ 1 GeV	$\sim$ 1 GeV	$\sim$ 2 GeV
minijet σ	$\sim$ 10%	$\sim$ 50%	$\sim$ 90%

SEMIHARD PROCESSES

DOMINATE AT HIGH ENERGY

Space-time evolution



Reconstructed from many late stage observables

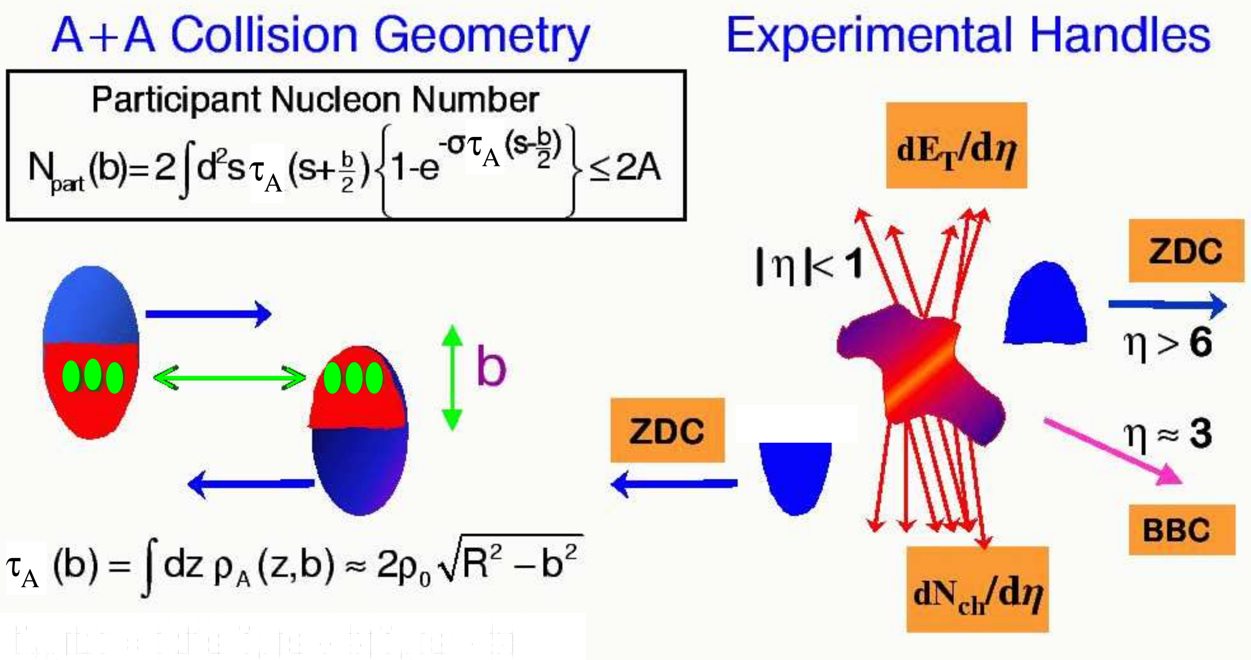
hadrons at freeze-out
- global observables ($\boxed{N^{ch}}$, E_T^{ch}, flow, ...)
- hard probes (J/ψ, jet quench., high-p_T, ...)
- soft probes (low-p_T, interferometry, ...)

leptons, γ, ...
- very weakly interacting
- the whole evolution is scanned

Our focus

- $\boxed{\text{Initial conditions of the minijet plasma}}$
- $\boxed{\text{From pQCD}}$ and semiclassical methods

Global observables



Control over the initial conditions:

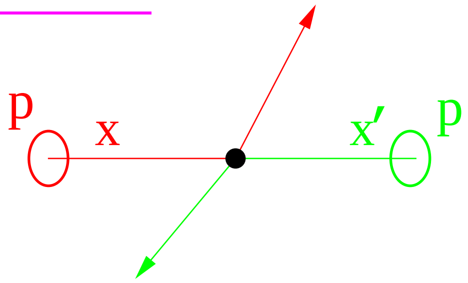
$$\boxed{N^{mj}} \xrightarrow[\text{entropy conserv.}]{\text{evolution}} \boxed{N^{ch}|_{semihard} = 0.9\,\frac{2}{3}\,N^{mj}}$$

$$\boxed{E_T^{mj}} \xrightarrow[\text{pdV work}]{\text{evolution}} E_T^{ch}|_{semihard} < 0.9\,\frac{2}{3}\,E_T^{mj}$$

Need of rescatterings

Proton–proton minijet cross-section

$$\sigma_J = \int dx\, dx'\, G(x)\, \sigma_H(xx')\, G(x')$$



where: x, x' = parton fractional momenta

$G(x)$ = Parton Distribution Function (PDF)

$\sigma_H(xx')$ = pQCD parton-parton cross-section

- Example: gluon-gluon scattering at high energy

$$\sigma_H(xx') = \int_{|p_T| \geq p_0} d^2 p_T \; \frac{9}{2} \alpha_S^2 \frac{1}{p_T^4}$$

$$\boxed{\sigma_H(xx') \propto 1/p_0^2}$$

where: p_0 = parton transverse momentum cutoff

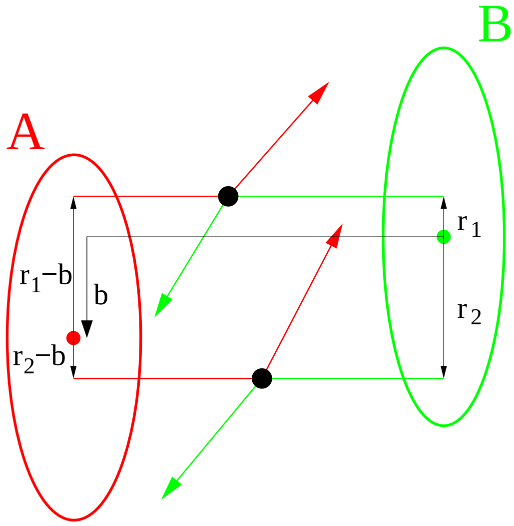
- At low enough p_0 we have $\sigma_J > \sigma_{inel}$

$\Longrightarrow$ violation of unitarity

σ_J is not an "infrared-safe observable"

Nucleus–nucleus minijet cross-section

Eikonalization unitarizes minijet cross-section, but describes only *disconnected collisions* between partons:



$$\sigma_{mj} = \int d^2b \left(1 - e^{-\sigma_J T_{AB}(b)}\right)$$

$$\sigma_{mj} \leq \pi (R_A + R_B)^2$$

- Average number of minijets

$$N_{jet}^{eik}(b) = 2N_{collisions} = 2\sigma_J T_{AB}(b)$$

$$= 2\int d^2r dx dx' \Gamma_A(x, b-r)\sigma_H(xx')\Gamma_B(x', r)$$

where: $T_{AB}(b) = \int \tau_A(b-r)\tau_B(r)\ d^2r$

$\tau_A(r)$ = nuclear thickness function

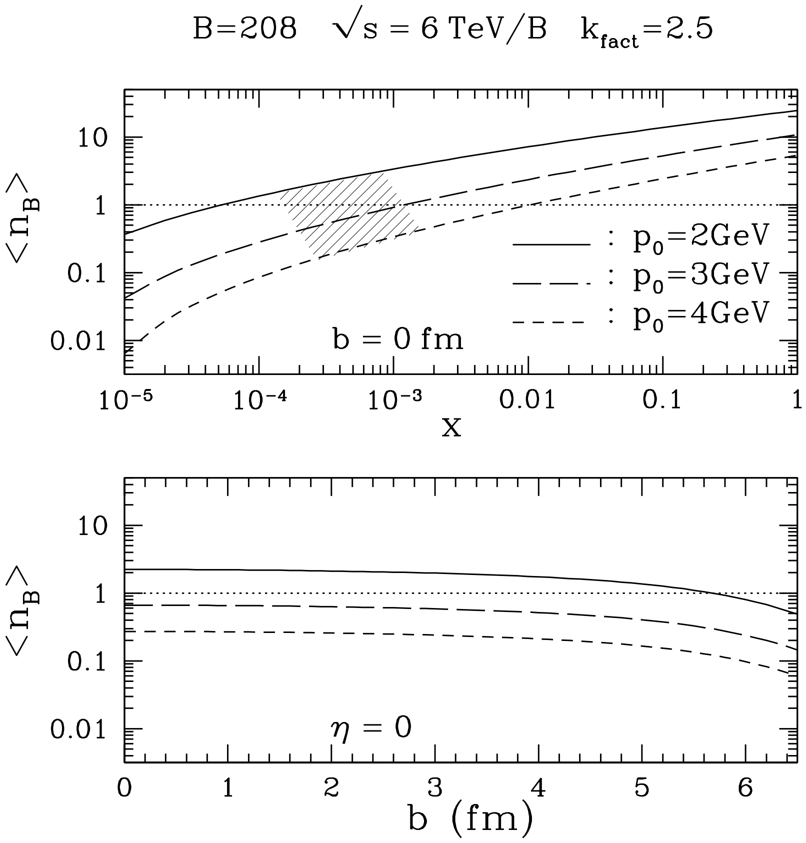
$\Gamma_A(x,r) = G(x)\tau_A(r)$ = nuclear PDF

- N_{jet}^{eik} diverges as $p_0 \longrightarrow \infty$:

$\Longrightarrow$ the infrared problem has come back in N_{jet}^{eik}

Number of scatterings per incoming parton

$$\langle n_B^{scat}(x,b)\rangle = \int dx' \sigma_H(xx')\Gamma_B(x',b)$$



At LHC & $p_0 = 2\ GeV$, for $|\eta| \leq 1$

$$\boxed{\langle n_B^{scat}\rangle = 2-3}$$

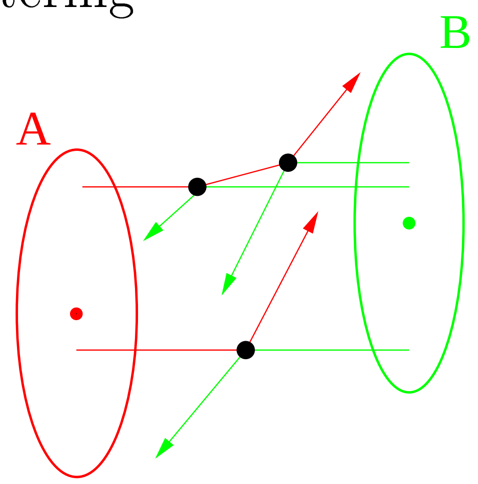
WE NEED TO INCLUDE
THE RESCATTERINGS

The model

Calucci, Treleani, PRD41(90)3367, PRD44(91)2746

Def. semi-hard scattering = $p_{exch} > p_0$

Def. minijet = parton with at at least 1 semi-hard scattering



$N_{jet} \leq 2N_{collisions}$

Assumptions:

- QCD factorization
- independent scatterings

Multiparton distributions:

$$D_A^n = \frac{1}{n!} \underbrace{\Gamma_A \ldots \Gamma_A}_{n \text{ times}} e^{-\int \Gamma_A}$$

Probability of at least 1 semi-hard interaction

$$P_{nm} = 1 - \prod_{i=1}^{n} \prod_{j=1}^{m} (1 - \hat{\sigma}_{ij})$$

where $\hat{\sigma}_{ij}(x_i x'_j, r_i - r'_j) = \sigma_H(x_i x'_j)\delta^{(2)}(r_i - r'_j)$ is the probability of a semi-hard parton-parton scattering

Minijet cross-section:

$$\sigma_{mj} = \sum_{n,m=1}^{\infty} \int D_A^n \, P_{nm} \, D_B^m$$

Average number of minijets

$$\frac{dN^A_{jet}}{dx}(b) = \int d^2r \, \overbrace{\Gamma_A(x, b-r)}^{\text{density of projectiles}} \underbrace{\left(1 - e^{-\int dx' \sigma_H(xx')\Gamma_B(x',r)}\right)}_{\text{prob. of at least 1 scatt.}}$$

Expansion in the no. of scatterings

$$\frac{dN^A_{jet}}{dx}(b) = \int d^2r`, \Gamma_A(x, b-r)$$

$$\times \sum_{n=1}^{\infty} \underbrace{\frac{1}{n!}\left[\int dx' \sigma_H(xx')\Gamma_B(x',r)\right]^n \overbrace{e^{-\int dx' \sigma_H(xx')\Gamma_B(x',r)}}^{\substack{\text{absorption factor} \\ \text{(prob. conservation)}}}}_{\text{PROBABILITY of } n \text{ scatterings}}$$

Two remarkable limits

$$\frac{dN_{jet}}{dx}(b) \longrightarrow \begin{cases} 2\int \Gamma_A \sigma_H \Gamma_B = \dfrac{dN^{eik}_{jet}}{dx}(b) & \dfrac{p_0}{\sqrt{s}} \to \infty \\ \underbrace{\int \Gamma_A + \int \Gamma_B}_{\text{“black-disc limit”}} \overset{def.}{=} \dfrac{dN_{lim}}{dx}(b) & \dfrac{p_0}{\sqrt{s}} \to 0 \end{cases}$$

Remarks

- finite limit at low cutoff:
  "Elastic semihard collisions cannot free more partons than those inside the incoming nucleus"
- at high cutoff disconnected collisions dominate

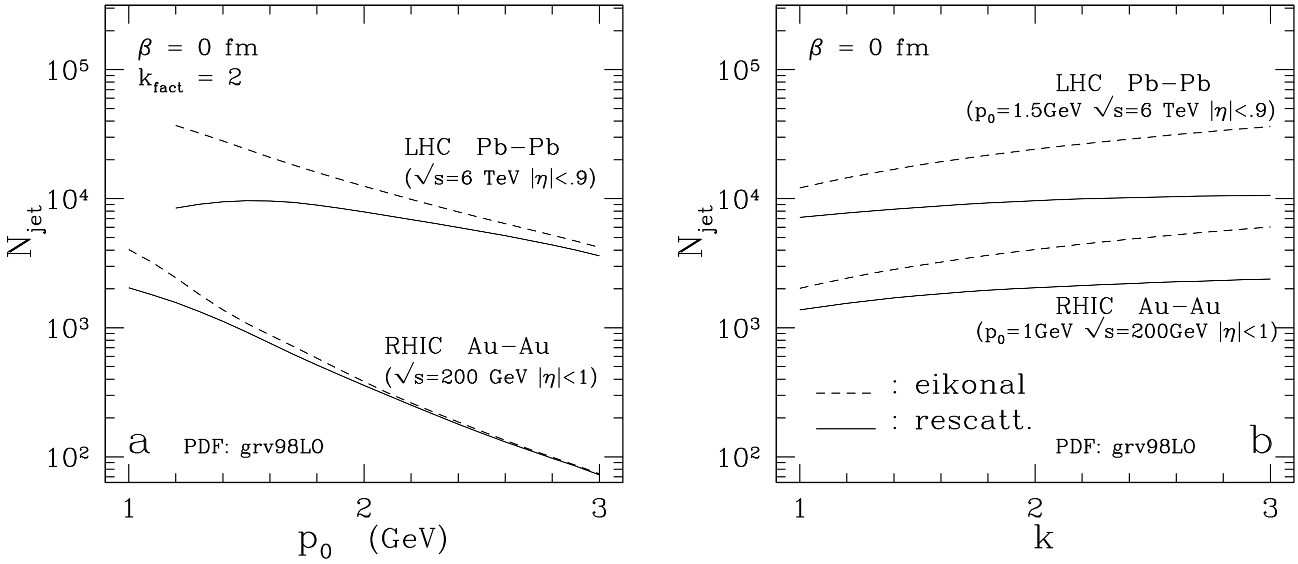
Initial conditions

A.A., D.Treleani, Phys.Rev.D 63(2001)116002

Number of minijets:

$$N_{jet}(b) = \int d^2r dx\, \Gamma_A(x, b-r) \left(1 - e^{-\int dx' \sigma_H(xx')\Gamma_B(x',r)}\right) + A \leftrightarrow B$$

NOTE: in all computations we set the scale $Q = p_0$.

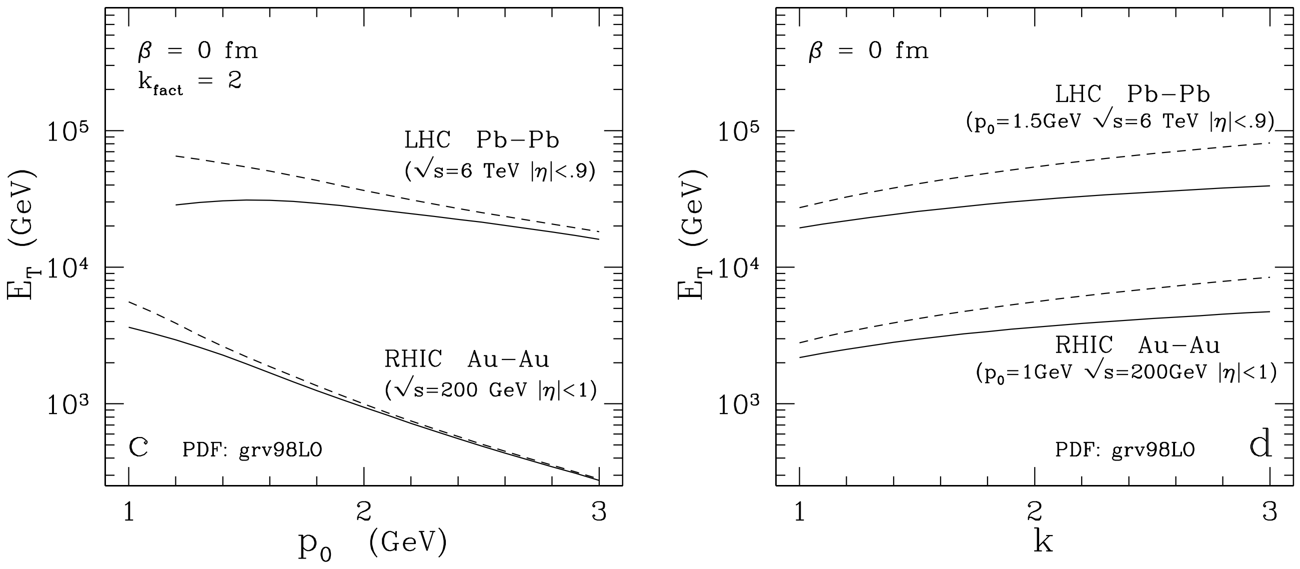


Rescatterings vs. single-scattering:

- Less sensitive to both p_0 and the k-factor
- Minijet multiplicity tends to saturate below 1 GeV (RHIC), 2 GeV (LHC)

Average transverse energy

$$E_T = \int \Gamma_A \int du \left(-\frac{\widetilde{\sigma}'(u)}{u} \right) \Gamma_B e^{-\int (\widetilde{\sigma}'(u) - \sigma_H)\Gamma_B} + A \leftrightarrow B$$



Same pattern as N_{jet}:

- Smoother in p_0 and k-factor
- E_T production tends to saturate at low cutoff

Initial conditions of the minijet plasma

At a time $\tau \simeq \frac{1}{p_0} \sim 0.2(0.1)$ fm at RHIC(LHC)

$$\left.\frac{dN}{dy}\right|_{y=0} \approx \ 1200 \text{ (RHIC)}, \ 5000 \text{ (LHC)}$$
$$\left.\frac{dE_T}{dy}\right|_{y=0} \approx \ 2\,\text{TeV (RHIC)}, 15\,\text{TeV (LHC)}$$

Saturation cutoff

A.A., hep-ph/0104060 & Phys.Rev.C 64(2001)064905

Let's exploit the black-disc limit

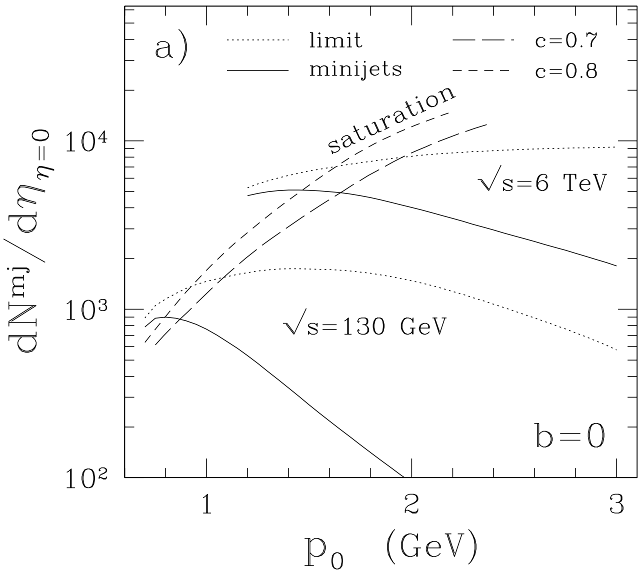
$$\frac{dN_{jet}}{dx}(b) \underset{p_0 \to 0}{\longrightarrow} \frac{dN_{lim}}{dx}(b)$$

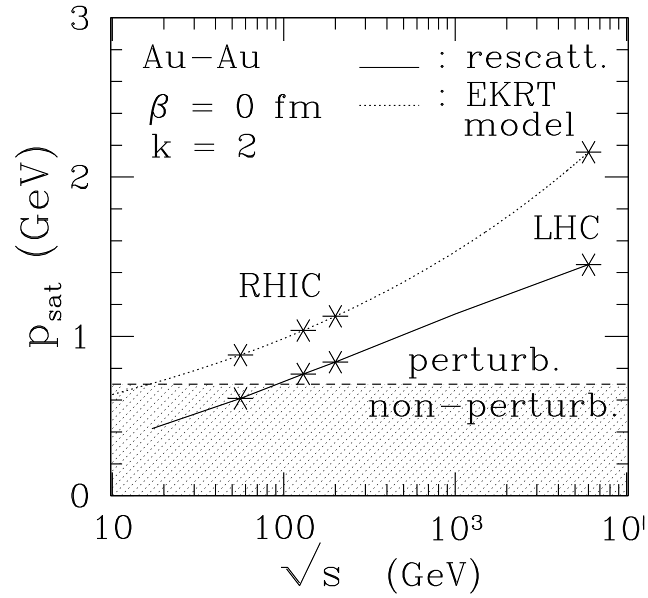
Def. Saturation cutoff:

$$N_{jet}(p_0 = p_{sat}) = 80\%\; N_{lim}(p_0 = p_{sat})$$

Def. Saturated initial conditions:

$$N^{sat}_{jet} = N_{jet}(p_{sat})$$





- If p_{sat} far enough from Λ_{QCD} we can trust these perturbative computations.
- The 80% is a parameter and replaces the choice of p_0. Results don't depend strongly on it.

Charged particle multiplicity

Semihard part: from our model + saturation

$$\left.\frac{dN^{ch}}{d\eta}\right|_{s.h.}(b) = 0.9\ \frac{2}{3}\ \frac{dN_{jet}^{sat}}{d\eta}(b)$$

- Isentropic expansion & d.o.f conversion $\rightsquigarrow$ 0.9
- Parton-hadron duality $\rightsquigarrow$ 2/3

Soft part (= non minijet-like):

from the wounded nucleon model

$$\left.\frac{dN^{ch}}{d\eta}\right|_{soft}(b) = x(\sqrt{s})\ n_{pp}(\sqrt{s})\ N_{part}(b)$$

$x(\sqrt{s})$ = relative weight of soft and hard

$n_{pp}(\sqrt{s})$ = ch. part. pseudorap. density in *pp* scattering

$N_{part}(b)$ = Number of participant nucleons

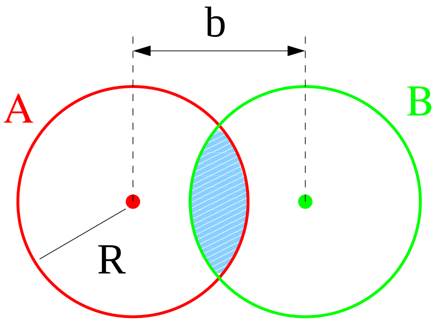
Two-component model (soft + semihard)

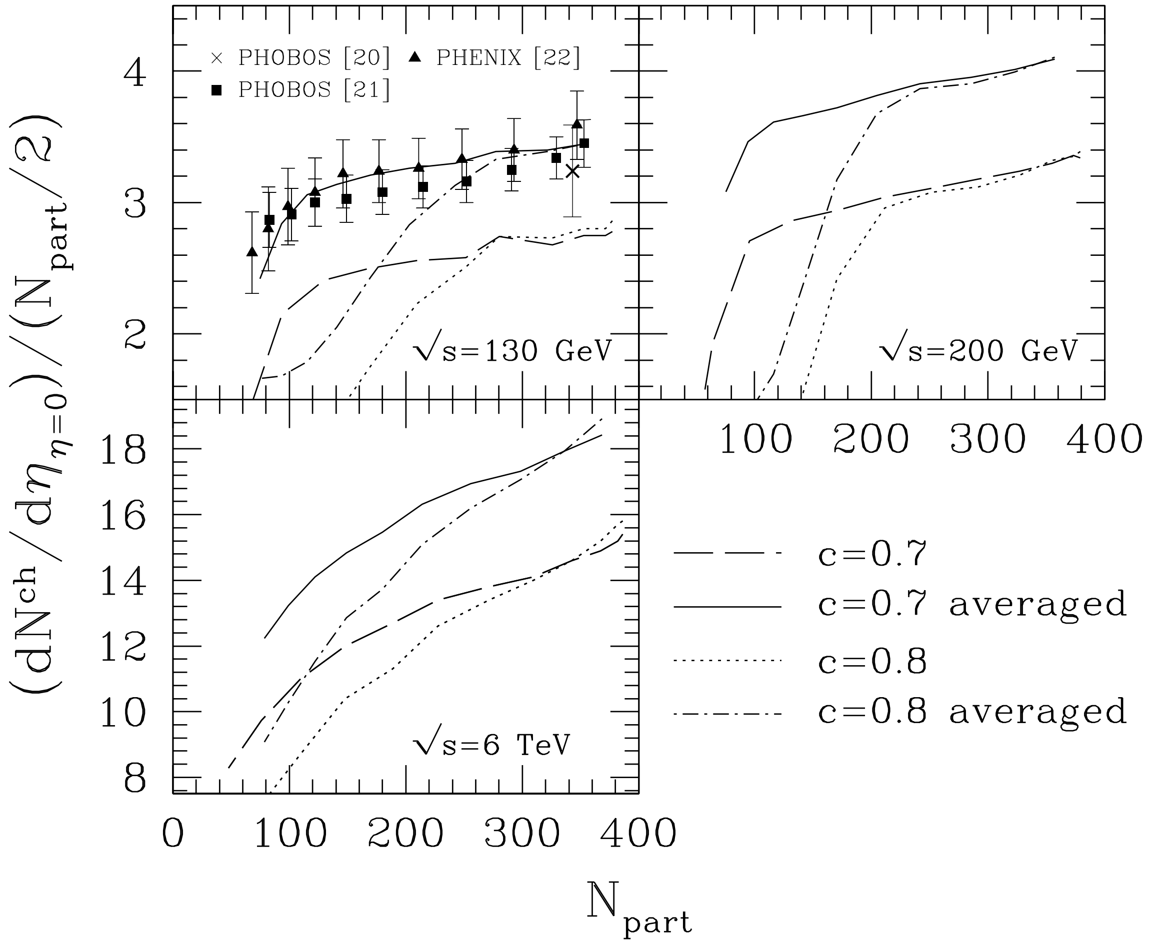
$$\boxed{\frac{2}{N_{part}(b)}\frac{dN^{ch}}{d\eta}(b) = x(\sqrt{s})\ n_{pp}(\sqrt{s}) + \frac{2}{N_{part}(b)}\frac{3}{5}\frac{dN_{jet}^{sat}}{d\eta}(b)}$$

Note: soft part independent of impact parameter

Centrality dependence

We enforce the geometry by defining the interaction transverse area with the help of the Glauber model for pA interactions.



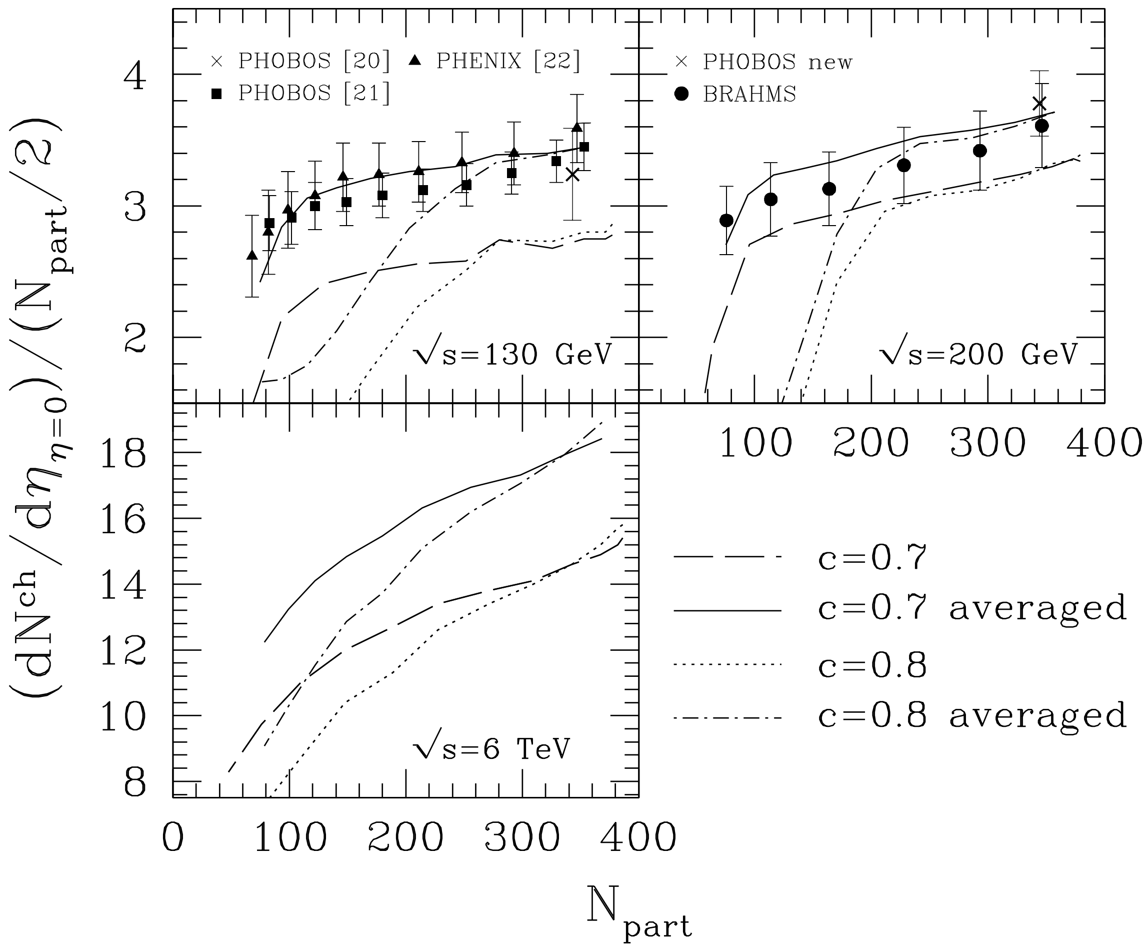


- Lower curves: semihard part only
- Upper curves at 130 GeV: soft fitted to most central point
- Upper curves at 200 GeV and 6 TeV:
  upper bound extrapolated from 130 GeV

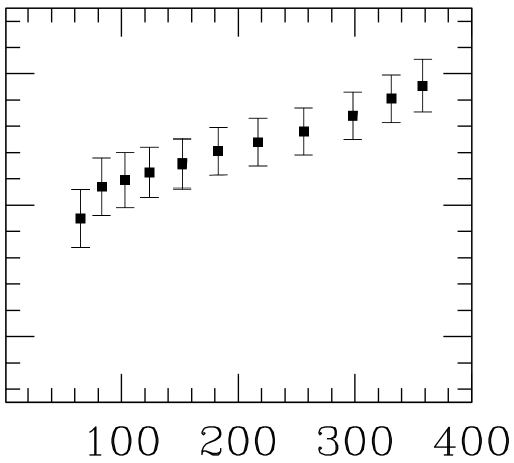
Prediction vs. data

New data @ 200 GeV from

- PHOBOS (Aug. 2001)
- BRAHMS (Dec. 2001)



- Lower curves: semihard part only
- Upper curves at $\sqrt{s} = 130$ GeV and $\sqrt{s} = 200$: soft part fitted to most central point


100
200
300
400

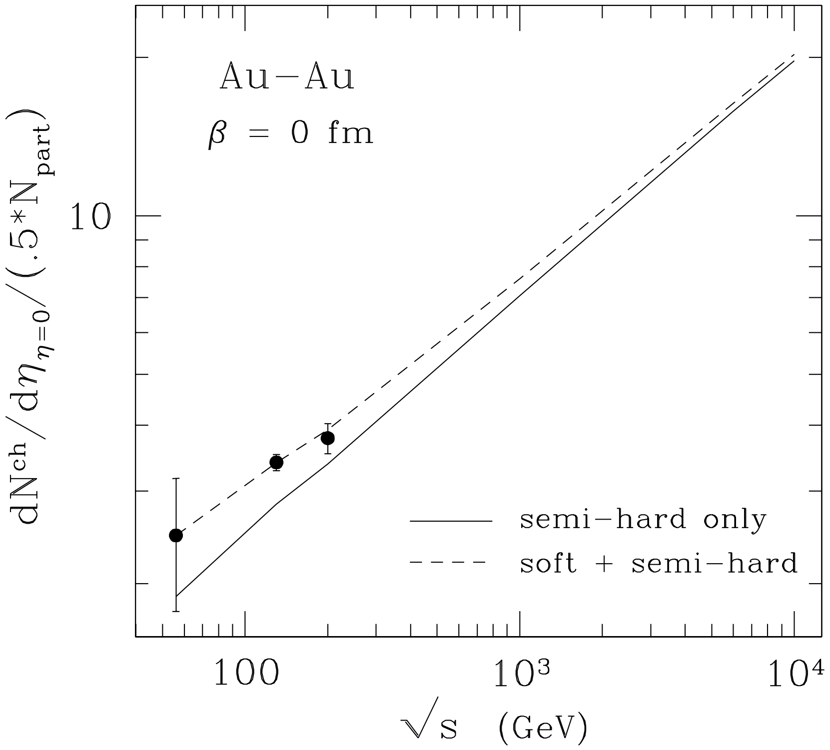
Energy dependence

- Semihard production increas at high $\sqrt{s}$
- Naive modeling of the fraction of semihard processes

$$\frac{dN^{ch}_{s.h.}}{d\eta}(s)\Big/\frac{dN^{ch}}{d\eta}(s) \;=\; 1 - a\frac{1}{(\sqrt{s})^b} \underset{\sqrt{s}\to\infty}{\longrightarrow} 1$$

By fitting RHIC data at $\sqrt{s} = 56, 130, 200$ GeV we obtain $a = 0.565$ and $b = 0.415$.

- Extrapolation at higher energies:



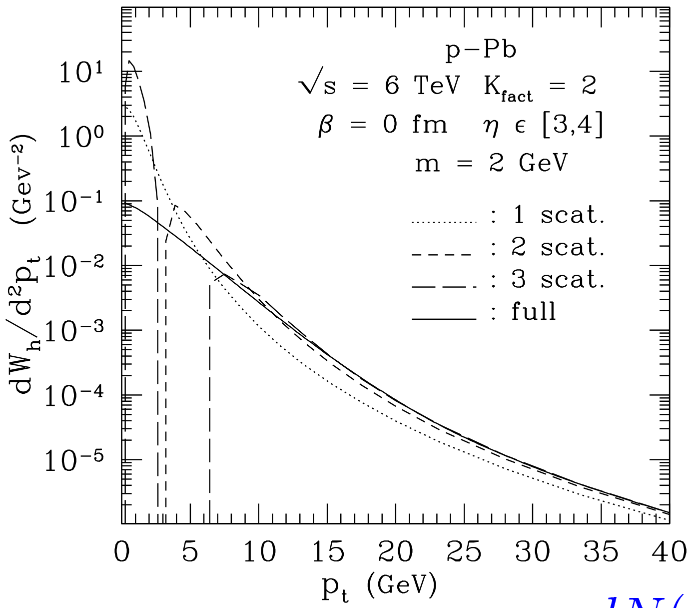
at RHIC 80-85% semihard
at LHC 95% semihard

Minijet p_T-spectrum

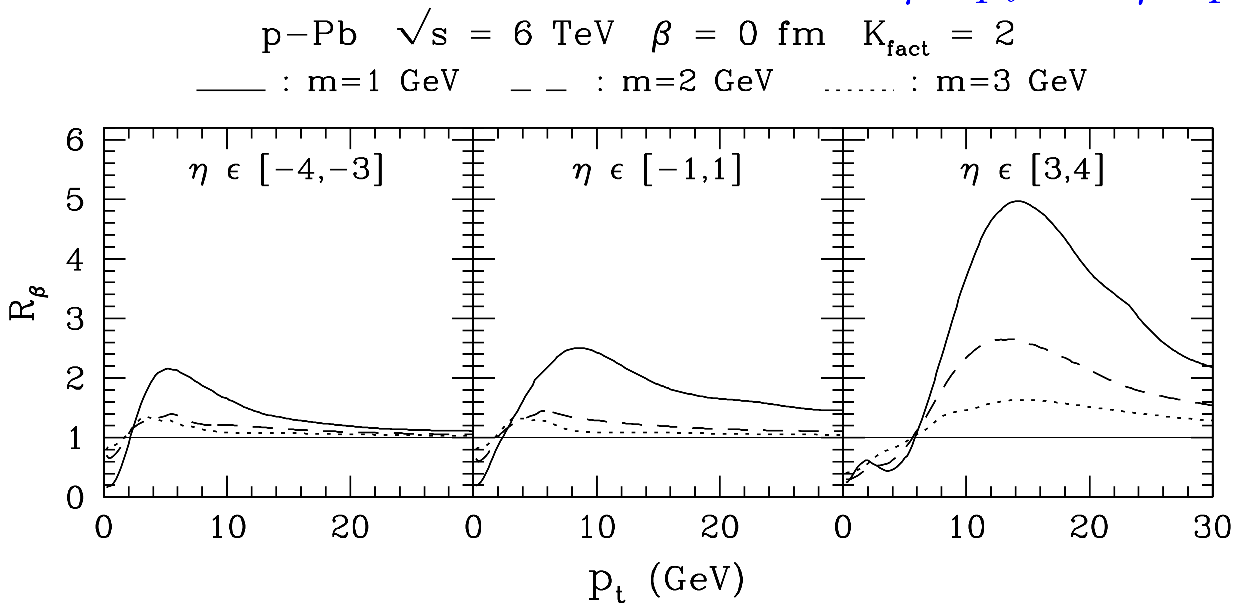
A.A., D.Treleani, Phys.Rev.D 64(2001)116004

Expansion in the no. of semihard scatterings

$$\boxed{\frac{dN(b)}{d\eta\, d^2p_t}} = \frac{dN^{(1)}(b)}{d\eta\, d^2p_t} + \frac{dN^{(2)}(b)}{d\eta\, d^2p_t} + \boxed{\frac{dN^{(3)}(b)}{d\eta\, d^2p_t}} + \dots$$

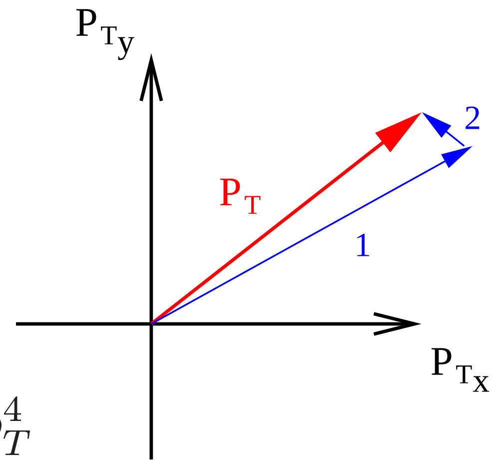


Cronin effect for minijets: $R_b = \frac{dN(b)}{d\eta\, d^2p_t} \Big/ \frac{dN^{(1)}(b)}{d\eta\, d^2p_t}$



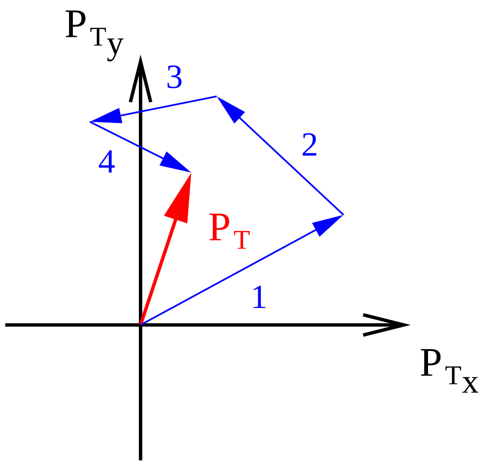
Picture of the interaction

High $\mathbf{p}_T$



- very few rescatterings: disconnected collisions dominate
- transverse spectrum $\propto 1/p_T^4$
- strong correlations due to hard back-to-back scatterings

Low $\mathbf{p}_T$



- a lot of rescatterings: partons do a random-like walk in the p_T plane
- Cronin effect (deformation of the p_T spectrum)
- more and more uncorrelated: they loose memory of their targets

CONCLUSIONS

Inclusion of the rescatterings in the interaction dynamics has many consequences:

- **Consistent use of pQCD** for global observables at low cutoff – next to non-perturbative region
- **Dynamical saturation criterion**
  - basically parameter free
  - o.k. with RHIC charged multiplicities
  - predictions at higher $\sqrt{s}$
- **Rich dynamics** testable also with
  - transverse spectrum & Cronin effect in pA collisions (necessary baseline for AA)
  - two particle correlations (applications are in progress)

PERSPECTIVES

On the theoretical side:

- "Running" scale Q and local saturation criterion
- Connection with "higher-twist" PDF's
- Gluon radiation beside elastic rescatterings.

On the phenomenological side:

- Test of model with $dN^{ch}/d\eta|_b$ and $N^{ch}(b)|_{\eta\neq 0}$
- Use N^{mj} and E_T^{mj} as initial conditions in hydrodynamic models
- Detailed study of Cronin effect for
  - minijets and hadrons in pA collisions
  - hadrons in AA collisions
- Minijet induced two-particle correlations (e.g., as a bckgr. in elliptic flow measure)

Are semi-hard scatterings enough?

i.e. is the perturbative N_{jet} a good estimate?

Would we able to compute $\sigma = \sigma_H + \sigma_S$,

$$N_{jet}^{true} = \int \Gamma_A \left(1 - e^{-\int (\sigma_H + \sigma_S)\Gamma_B}\right) =$$

$$= \int \Gamma_A \sum_{n=1}^{\infty} \underbrace{\frac{1}{n!} \left[(\sigma_H + \sigma_S)\Gamma_B\right]^n e^{-\int (\sigma_H + \sigma_S)\Gamma_B}}_{\text{PROBABILITY of } n \text{ scatterings}}$$

Define:

- N_{soft} = partons with just soft scatterings
- N_{jet} = partons with at least one semi-hard scattering (+ semihard and soft)

and play with the above probabilities according to the two definitions

Then one finds:

$$N_{soft} = \int \Gamma_A \quad \underbrace{e^{-\int \sigma_H \Gamma_B}}_{\text{no s.h. scatt.}} \quad \underbrace{\left(1 - e^{-\int \sigma_S \Gamma_B}\right)}_{\text{at least 1 soft scatt.}}$$

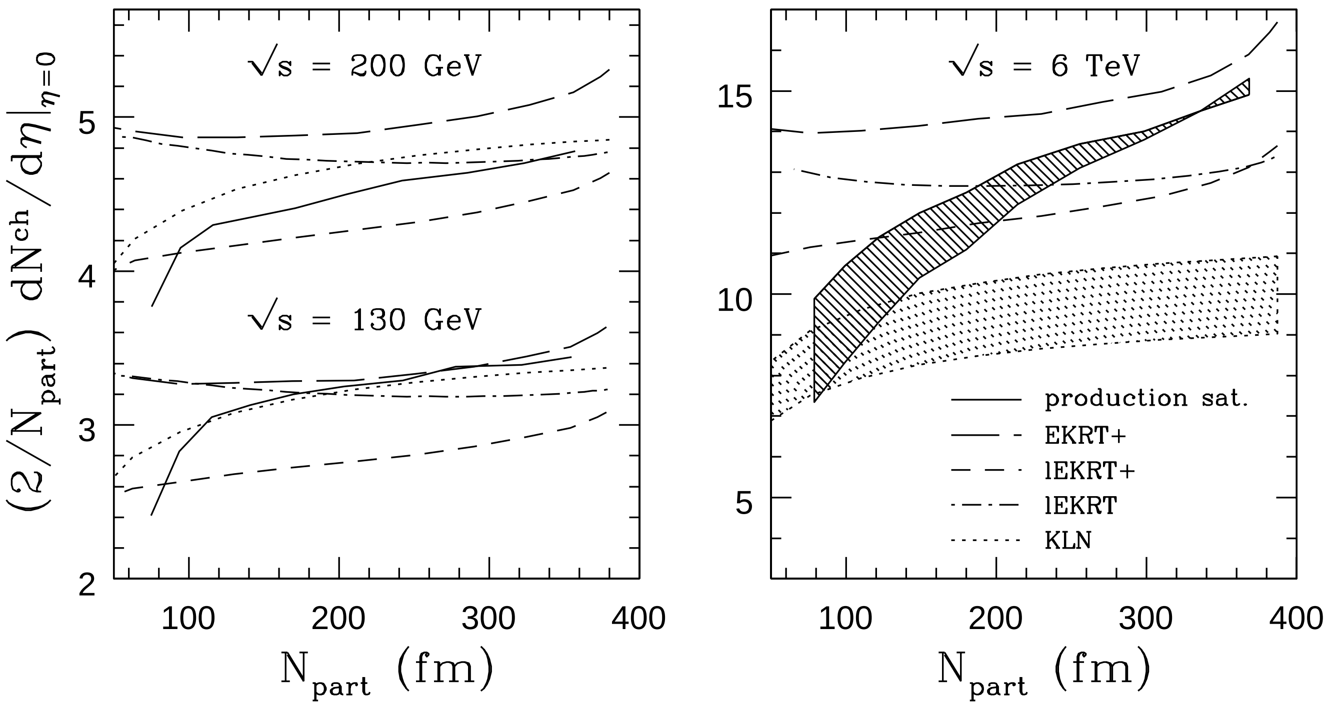
$$N_{jet} = \int \Gamma_A \quad \underbrace{\left(1 - e^{-\int \sigma_H \Gamma_B}\right)}_{\text{at least 1 s.h. scatt. (+ \underline{SOFT} !!)}}$$

- In this observable, 1 s.h. collision is sufficient to "shadow" completely the soft ones
  $\longrightarrow$ SELF-SHADOWING

- In our computation of total minijet multiplicity (and transverse energy)

we are missing only the jets that had just soft scatterings

Comparison with other models



EKRT model: final state geometric saturation of the transverse area.

KLN model: initial state saturation of nuclear parton densities.