Minijet production and semihard parton rescatterings in heavy-ion collisions

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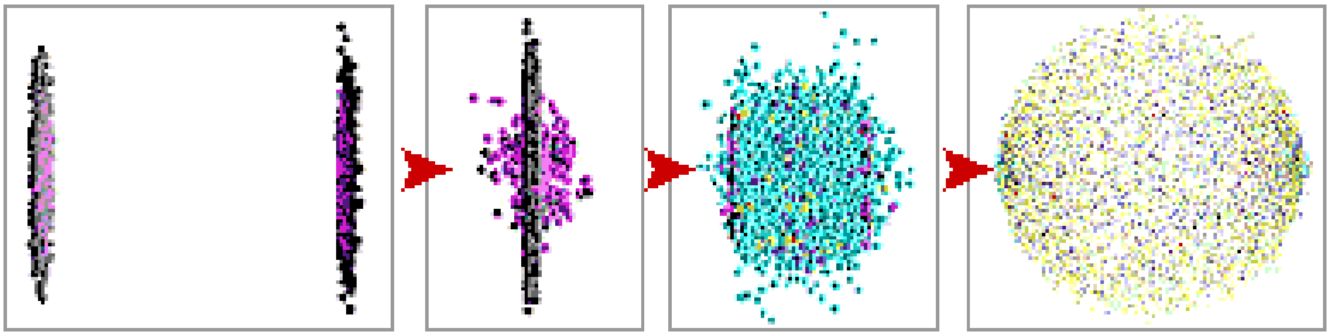
SUMMARY

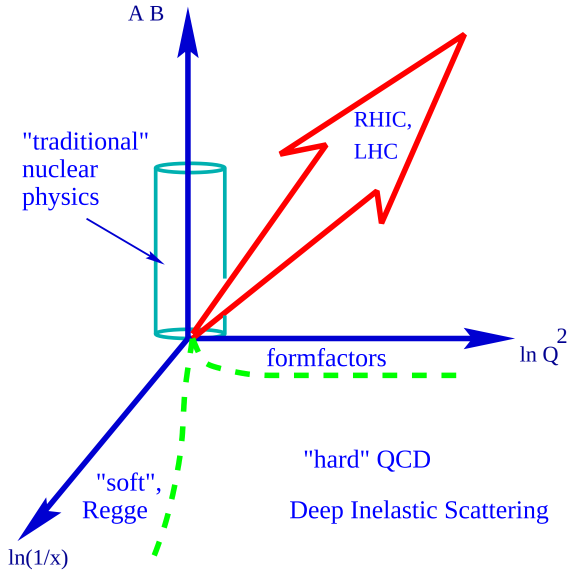
- Introduction
  - Heavy-ion collisions and the QGP
  - Global observables
- Saturation in the parton production
  - Semihard parton rescatterings
  - Saturation criterion
  - Charged particle multiplicities
- Non-flow two-particle correlation
  - Elliptic flow vs. azimuthal correlations
  - Correlated pion yield w.r.t. centrality
- Conclusions and perspectives

Heavy-ion collisions at high energy

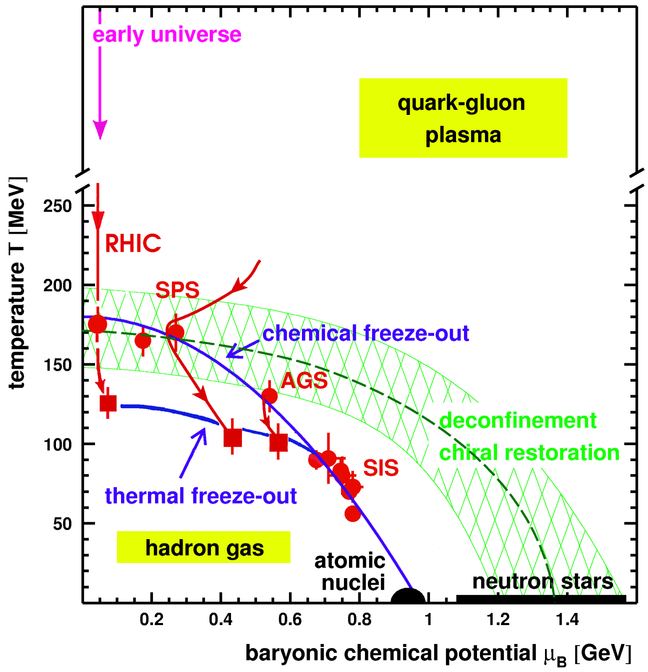


Au-Au at $\sqrt{s} = 200$ GeV

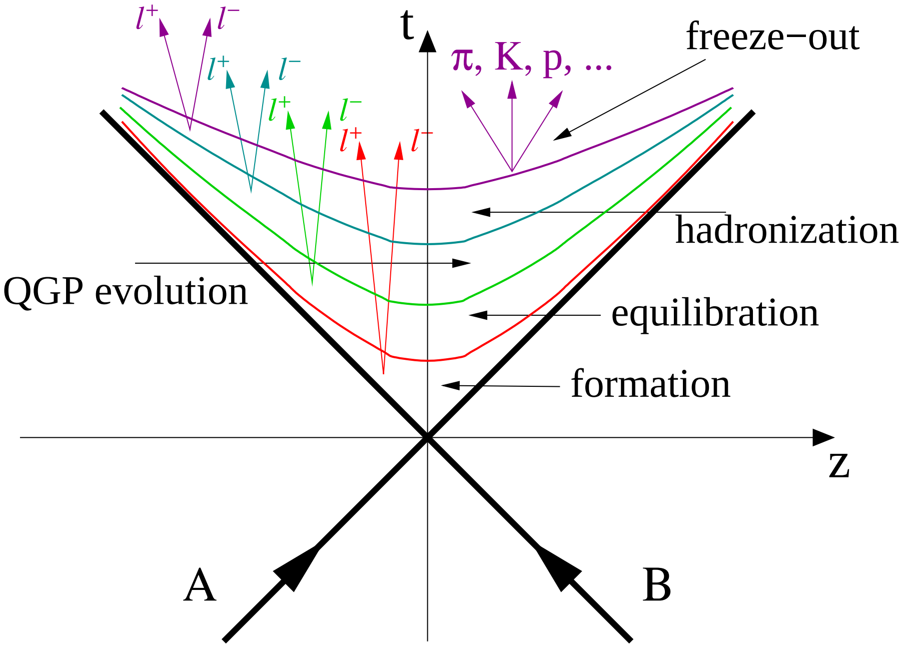
- New regimes of QCD
  - small Bjorken x
  - large typical momentum transfer $\overline{Q}$
  - partonic d.o.f.
  - nonlinear dynamics



- Quark-Gluon Plasma?
  - matter created at $\left\{ \begin{array}{l} \text{high density} \\ \text{high temperature} \end{array} \right.$
  - temperature drops with expansion
  - fast thermalization (?) $\Rightarrow$ QGP



Space-time evolution



Reconstructed from many late stage observables

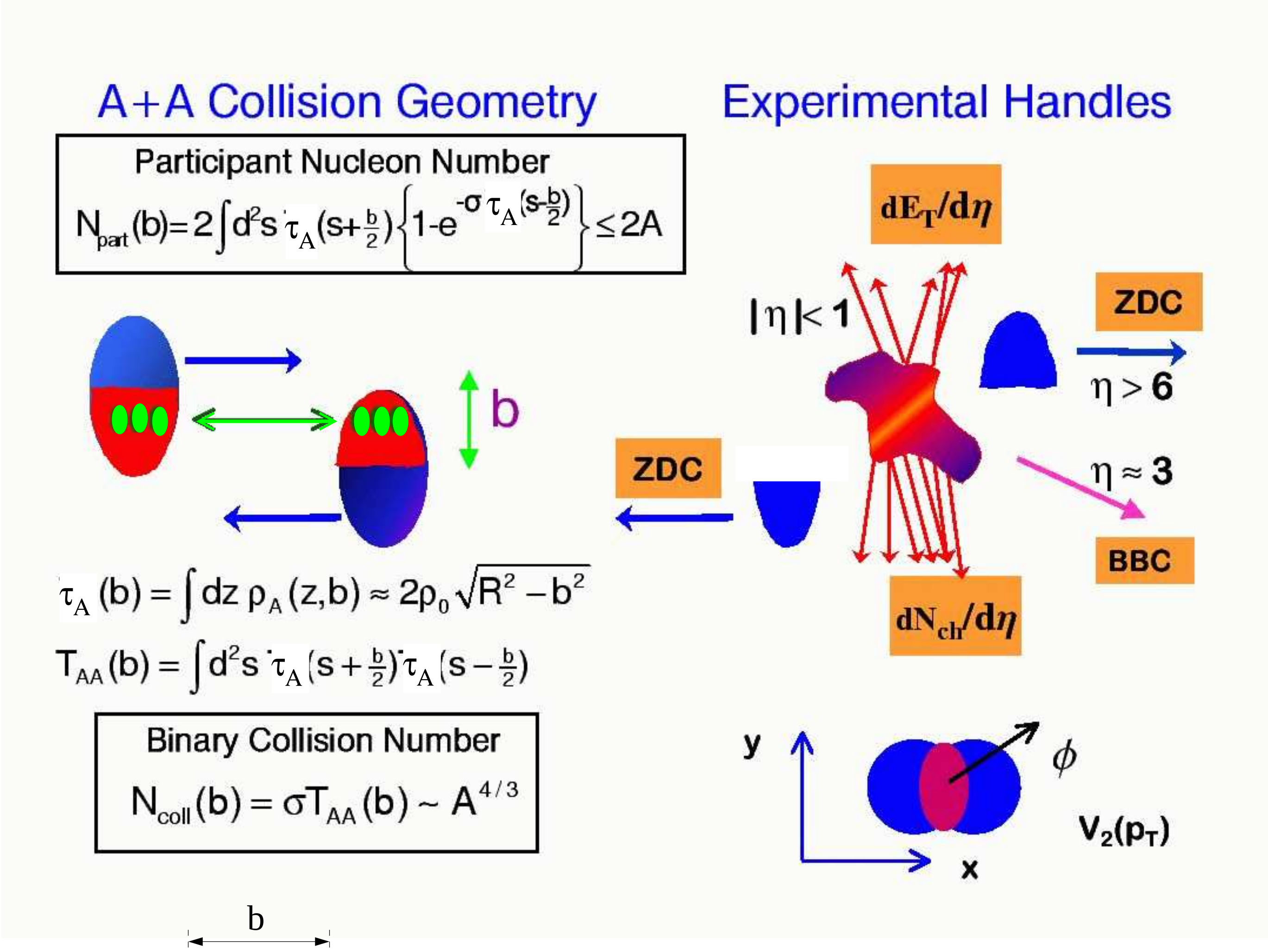
hadrons at freeze-out:
- global observables ($\boxed{N^{ch}}$, $flow$, $\boxed{\text{azimuthal correlations}}$ ...)
- hard probes (J/ψ, jet quench., high-p_T, ...)
- soft probes (low-p_T, interferometry, ...)

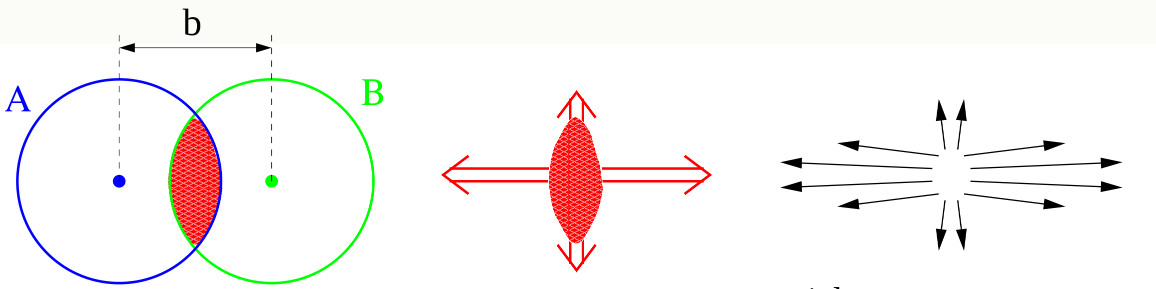
leptons, γ, ...:
- very weakly interacting
- the whole evolution is scanned

Our focus

- $\boxed{\text{Initial conditions of the minijet } (\equiv \text{ parton}) \text{ “plasma”}}$
- $\boxed{\text{From pQCD}}$ and semiclassical methods

Global observables





non−central collisions

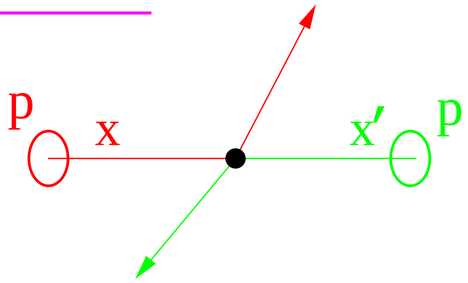
pressure gradients

particle transverse momenta
azimuthal anisotropy

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

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

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

where: p_0 = parton transverse momentum cutoff

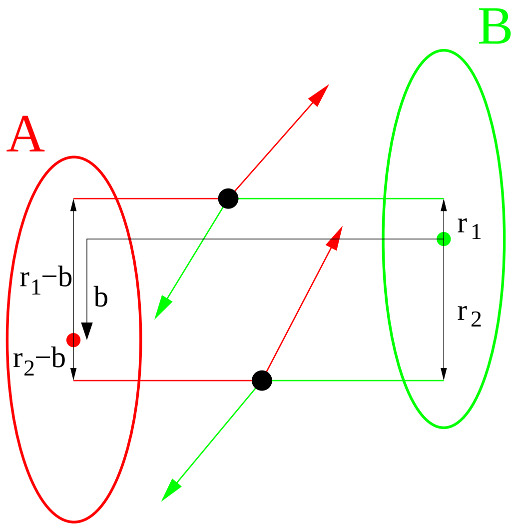
- At low enough p_0 we have $\sigma_J > \sigma_{inel}$

$\Longrightarrow$ 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:



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

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

$$\boxed{N_{jet} = 2N_{collisions}}$$

- 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

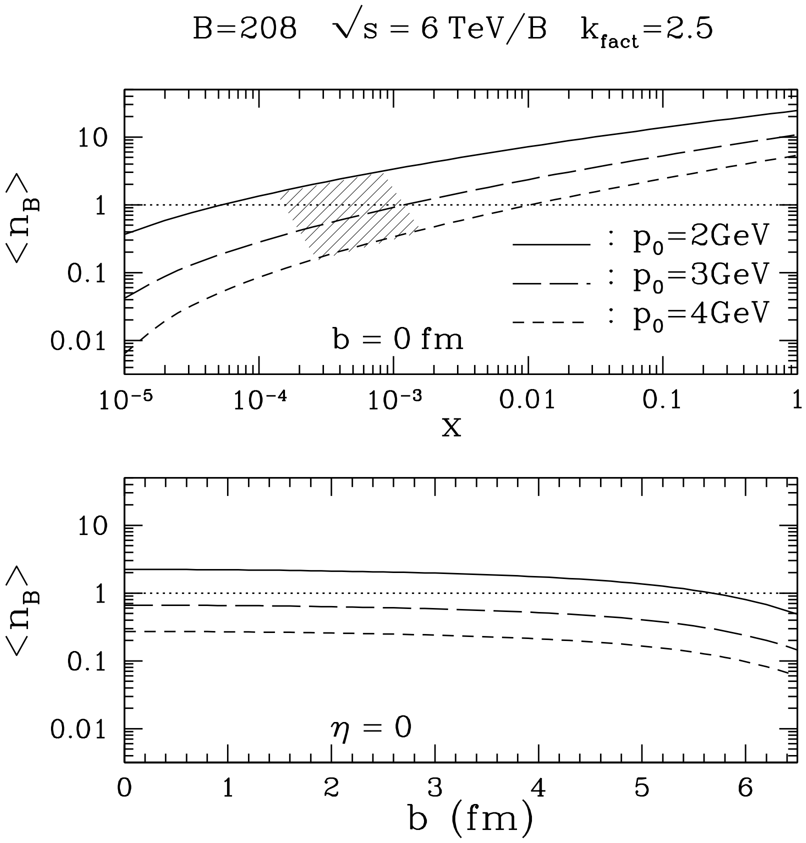
$\Gamma_A(x,r) = G(x)\tau_A(r)$ = nuclear PDF

- 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

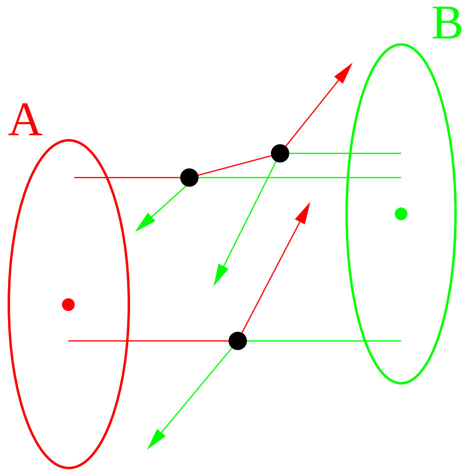
Calucci, Treleani, PRD41(90)3367, PRD44(91)2746

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

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

Assumptions:

- QCD factorization
- independent scatterings



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

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

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

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

$$\frac{dN_{jet}}{dx}(b) \longrightarrow \begin{cases} 2\int \Gamma_A \sigma_H \Gamma_B = \dfrac{dN^{eik}_{jet}}{dx}(b) & \dfrac{p_0}{\sqrt{s}} \to 1 \\ \underbrace{\int \Gamma_A + \int \Gamma_B}_{\text{"black-disc limit"}} \stackrel{def.}{=} \dfrac{dN_{lim}}{dx}(b) & \dfrac{p_0}{\sqrt{s}} \to 0 \end{cases}$$

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

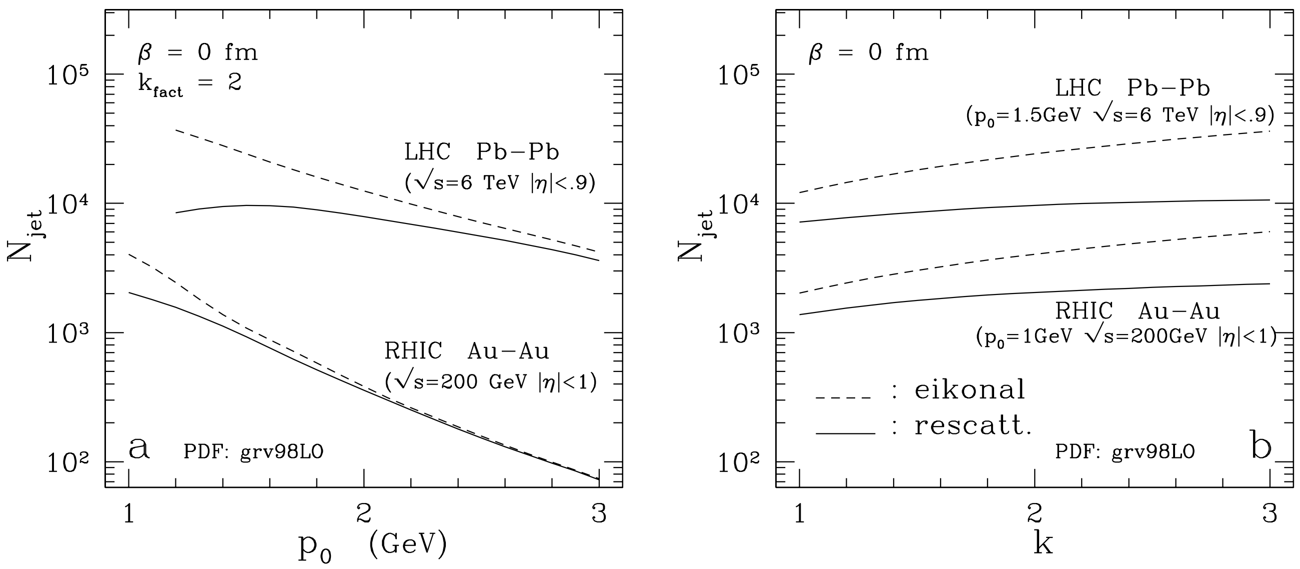
Initial conditions

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

Number of minijets:

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

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)

Saturation cutoff

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

Let's exploit the black-disc limit

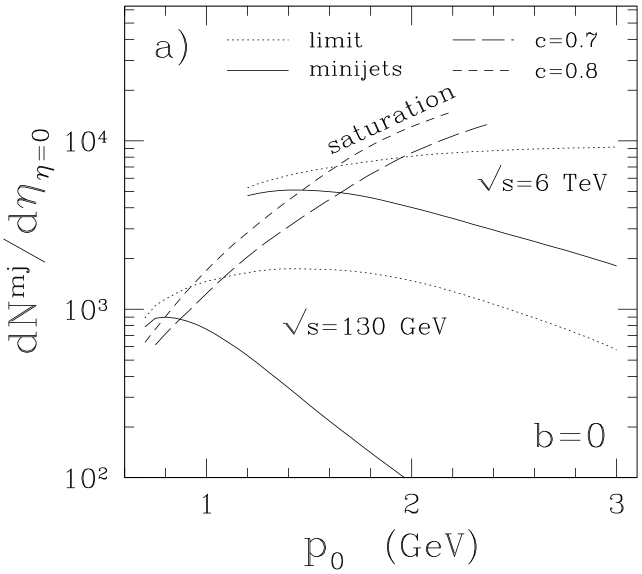
$$\frac{dN_{jet}}{dx}(b) \xrightarrow[p_0 \to 0]{} \frac{dN_{lim}}{dx}(b)$$

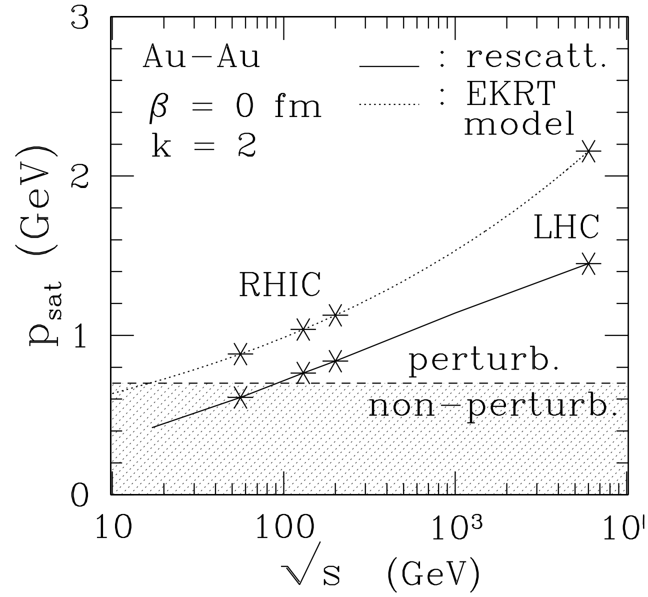
Def. Saturation cutoff:

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

Def. Saturated initial conditions:

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





- 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

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

- 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

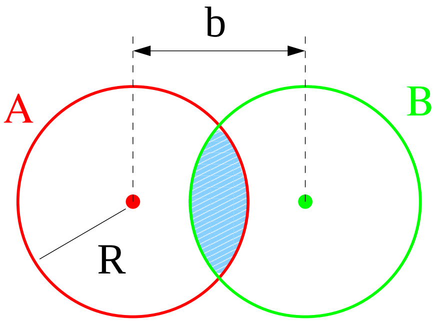
Two-component model (soft + semihard)

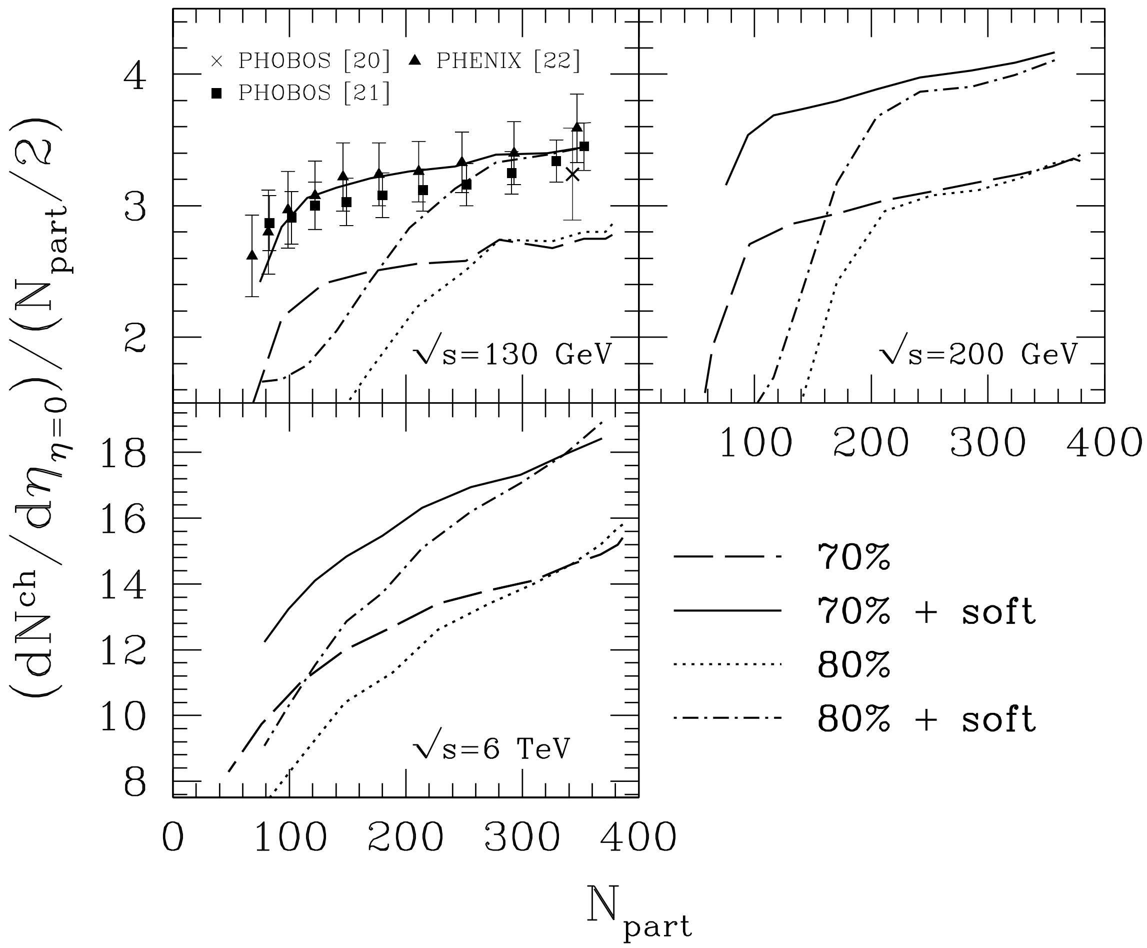
$$\boxed{\frac{2}{N_{part}(b)}\frac{dN^{ch}}{d\eta}(b) = x(\sqrt{s})\ n_{pp}(\sqrt{s}) + \frac{2}{N_{part}(b)}\frac{3}{5}\frac{dN^{sat}_{jet}}{d\eta}(b)}$$

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.



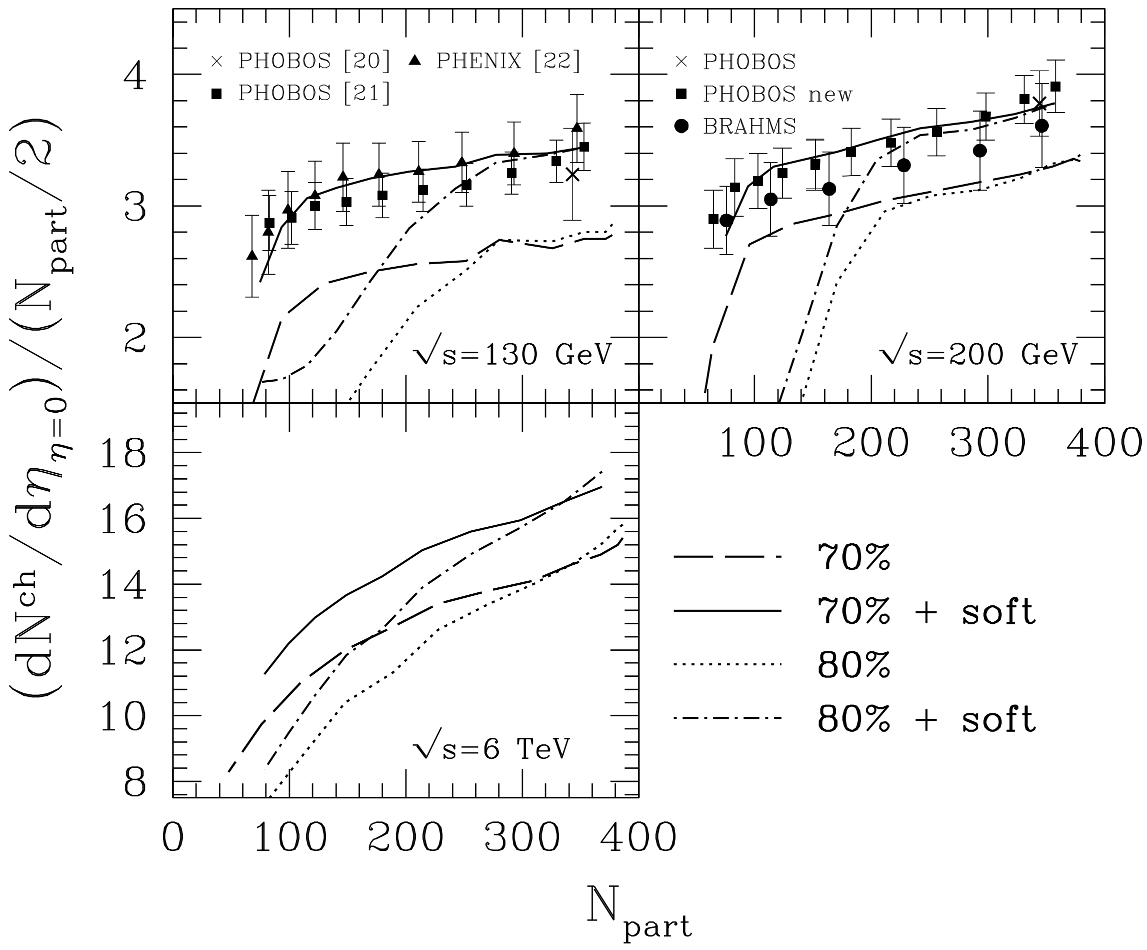


- Lower curves: semihard part only
- Upper curves at 130 GeV: soft fitted to most central point
- Upper curves at 200 GeV and 6 TeV: upper bound extrapolated from 130 GeV

Prediction vs. data

New data @ 200 GeV:

- PHOBOS (Aug'01, Jan'02)
- BRAHMS (Dec'01)

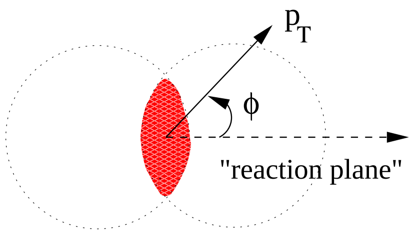


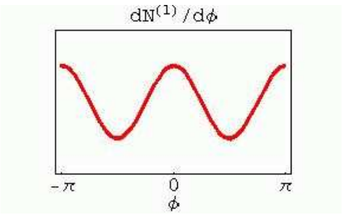
- Lower curves: semihard part only
- Upper curves at $\sqrt{s} = 130$ GeV and $\sqrt{s} = 200$: soft part fitted to most central point

Two-particle correlations

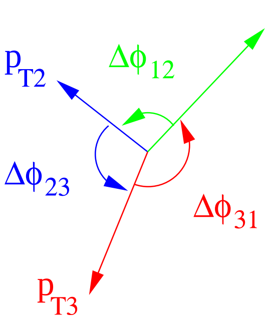
Elliptic flow and azimuthal distributions

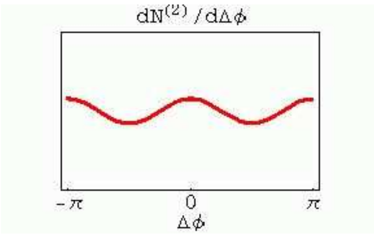
- Single particle: $$\frac{dN^{(1)}}{d\phi} = C\,[1 + 2\,v_2 \cos(2\phi) + \ldots]$$





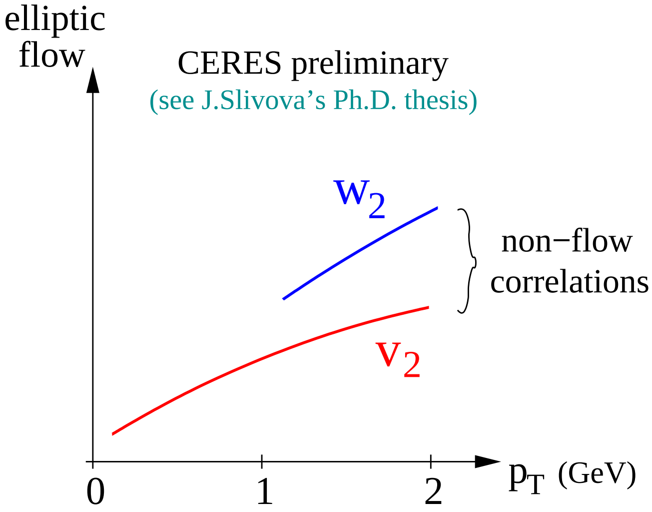
- Two-particle: $$\frac{dN^{(2)}}{d\Delta\phi} = D\,\left[1 + 2\,w_2^2 \cos(2\Delta\phi) + \ldots\right]$$





without other effects $\boxed{w_2 = v_2}$

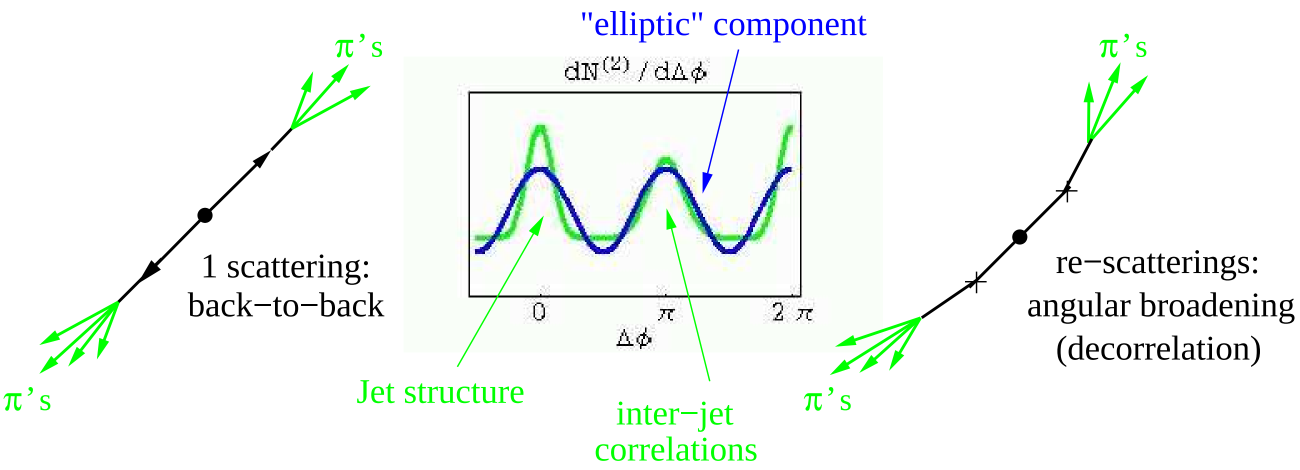
Non flow correlations



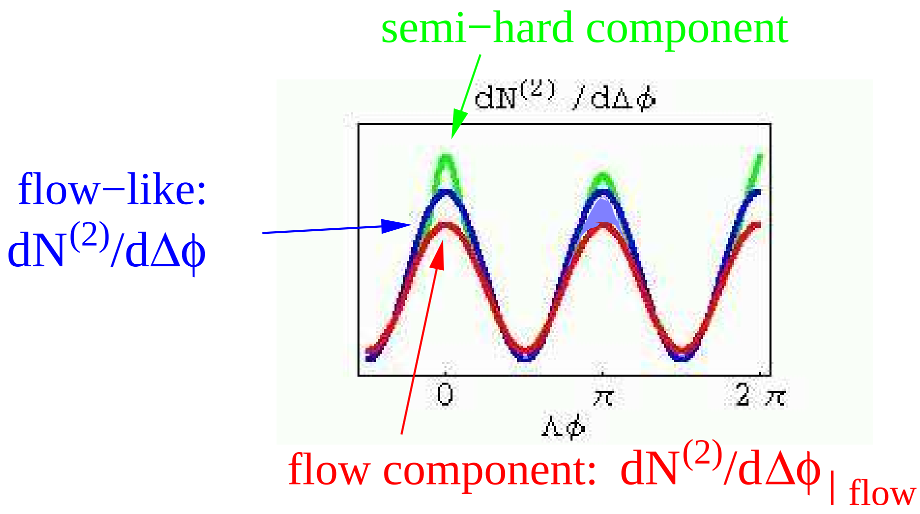
Preliminary evidence also from STAR and PHENIX - smaller effect

A.H.Tan hep-ph/0108029; J.Rak

Two-particle “semi-hard” correlations



Combining flow and non-flow:

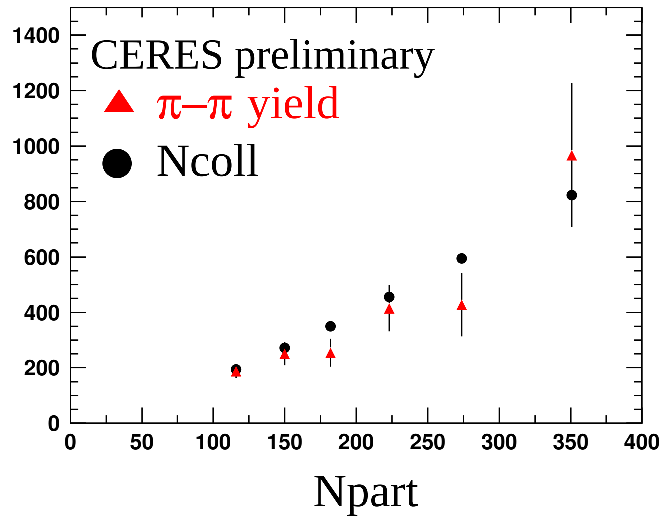


Correlated pion yield

The area between the two curves around $\Delta\phi = \pi$ gives the average number of correlated minijet pairs:

$$\Delta^{\pi\pi}(b) = \int_{\Delta\phi=\frac{\pi}{2}}^{\Delta\phi=\frac{3}{2}\pi} d\Delta\phi \left[\frac{dN^{(2)}}{d\Delta\phi} - \left.\frac{dN^{(2)}}{d\Delta\phi}\right|_{\text{flow}} \right]$$

Experimentally:



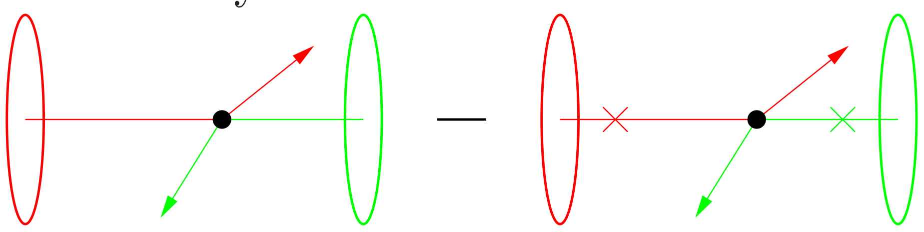
In our multiple semihard scattering model:

$$\underbrace{\Delta N^{JJ}(b)}_{\text{jet yield}} = \overbrace{2\int d^2r\, dx_1\, dx_2\, \Gamma_A(x_1, b-r)\sigma_H(x_1x_2)\Gamma_B(x_2, r)}^{\equiv \Delta N^{JJ}_{1\,\mathrm{scatt.}}(b)}$$

$$\underbrace{- 2\int d^2r\, dx_1\, dx_2\, \frac{dN^A_{jet}}{dx_1}(b, r)\sigma_H(x_1x_2)\frac{dN^B_{jet}}{dx_2}(r)}_{\text{decorrelation term}}$$

where $\frac{dN^A_{jet}}{dx}(b, r) = \Gamma_A(x, r-b)[1 - \exp(-\int dx'\Gamma_B(x', r)\sigma_H(xx'))]$.

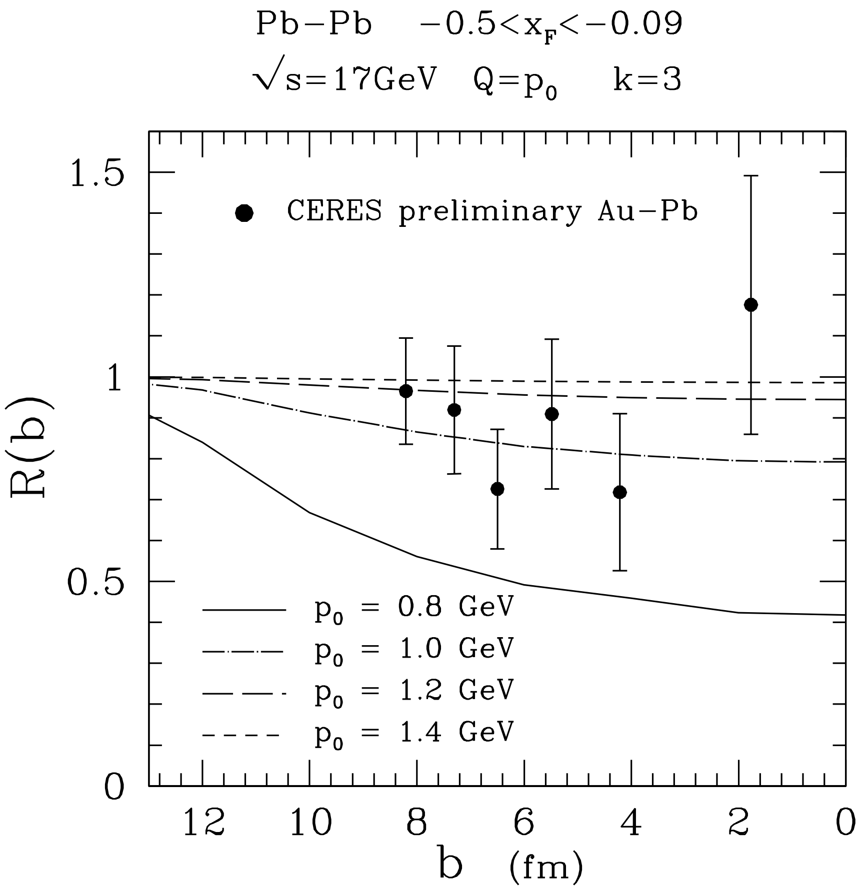
Diagrammatically:



Two limits: $\Delta N^{JJ} \longrightarrow \begin{cases} \Delta N^{JJ}_{1\,\mathrm{scatt.}} & \frac{p_{cut}}{\sqrt{s}} \longrightarrow 1 \\ 0 & \frac{p_{cut}}{\sqrt{s}} \longrightarrow 0 \end{cases}$

Most theoretical errors cancel in the ratio

$$R(b) = \frac{\Delta N^{JJ}(b)}{\Delta N^{JJ}_{1\,\mathrm{scatt.}}(b)}$$



NOTE: • data are for $\pi\pi$ pairs with $p_T \geq 1.2$ GeV

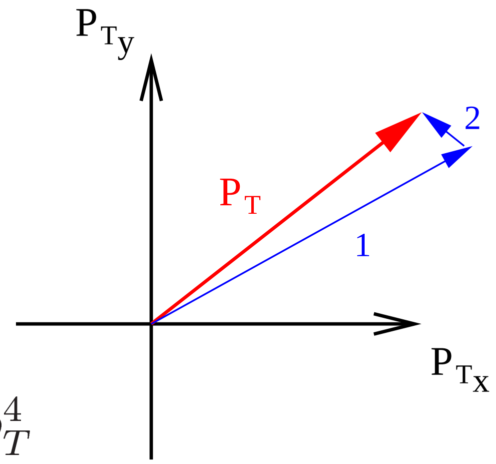
• hadronization effects partly cancel in the ratio

• p_T-cuts may be introduced in the computation

The model with $p_0 \sim 1$ GeV
seems able to reproduce the data

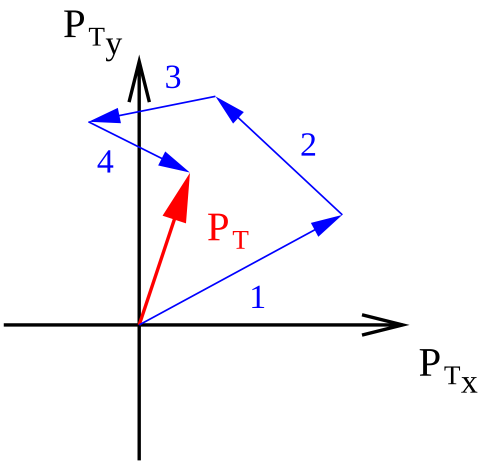
Picture of the interaction

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 $\sqrt{s}$
- **Semihard two-particle (de)correlation**
  - promising results compared to CERES data

What else?

- Differential dN^J/d^2p_t, $dN^{JJ}/d^2p_1\, d^2p_2$
  - Cronin effect A.A., D.Treleani, PRD64(2001)116004
  - p_T cuts for N^{ch} and ΔN^{JJ}
  - $\langle cos(2\Delta\phi)\rangle \rightsquigarrow$ non-flow v_2
- Inclusion of energy losses (collisional and radiative)