Initial conditions at RHIC and LHC from semihard parton rescatterings

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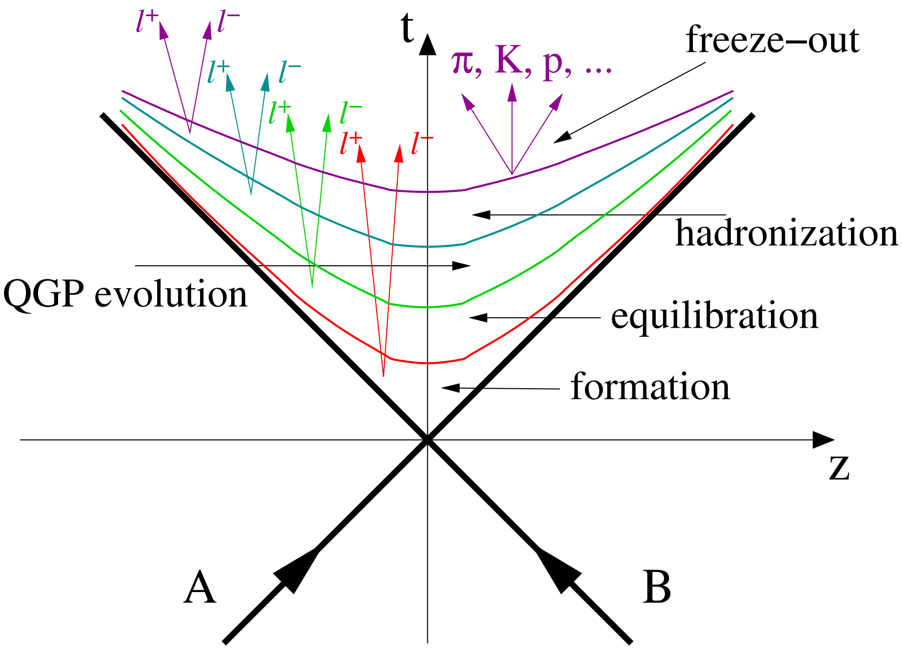
OVERVIEW

- MINIJET PRODUCTION IN pA AND AA
  - Semihard parton rescatterings
  - Inclusive minijet production
- (ANOTHER) SATURATION MODEL
  - "Saturation of minijet production"
  - Initial conditions & charged multiplicity
- COMPARISON WITH OTHER SATURATION MODELS
- SUMMARY AND CONCLUSIONS

Space-time evolution of "QGP"



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, ...)

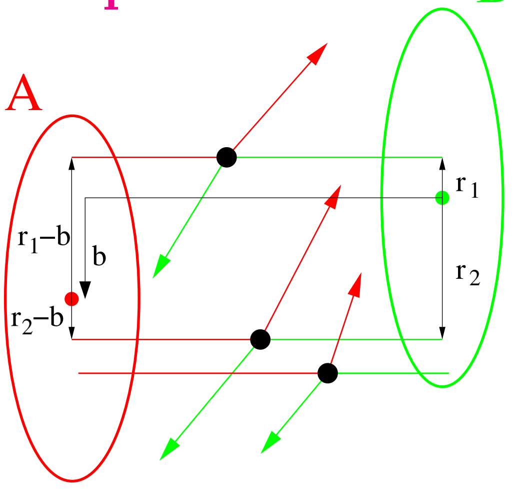
leptons, γ, ...
- very weakly interacting
- the whole evolution is scanned

Our focus

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

Semihard interactions - standard picture

- Nucleus–nucleus cross-section by eikonalizing *pp* cross-section
- It includes only *disconnected collisions* between partons:



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

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

where: $\sigma_J = \int dx\, dx'\, G(x)\, \sigma_H(xx')\, G(x') \propto 1/p_0^n$

x, x' = parton fractional momenta

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

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

p_0 = IR regulator

$T_{AB}(b) = \int \tau_A(b-r)\, \tau_B(r)\, d^2r$ = nuclear overlap

$\tau_A(r)$ = nuclear thickness function

- Minijet cross-section is unitarized: $\sigma_{mj} \underset{p_0 \to 0}{\longrightarrow} \pi(R_A + R_B)^2$
- BUT energy conservation is violated: E_T diverges as $p_0 \to 0$

$$N_{jet}^{eik}(b) = 2\sigma_J T_{AB}(b) \propto 1/p_0^2$$

$$E_{T\,jet}^{\,eik}(b) \approx p_0 N_{jet}^{eik} \propto 1/p_0$$

$\Longrightarrow$ some dynamics is missing

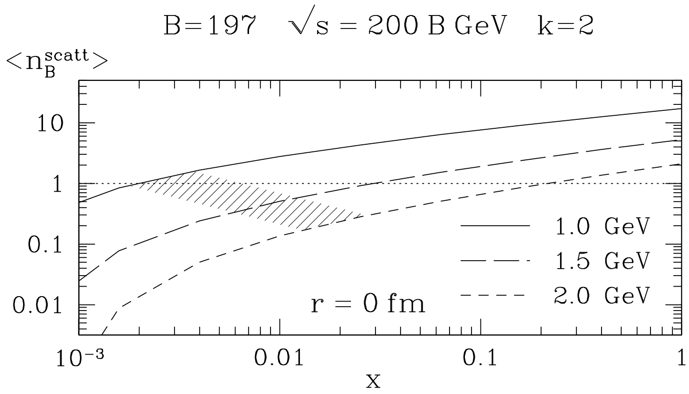
Average number of minijets

$$N_{jet}^{eik}(b) = 2\int d^2r dx \underbrace{G(x)\tau_A(b-r)}_{\text{proj. parton flux}} \underbrace{\int dx'\,\sigma_H(xx')\,G(x')\tau_B(r)}_{\text{average no. of scatterings}}$$

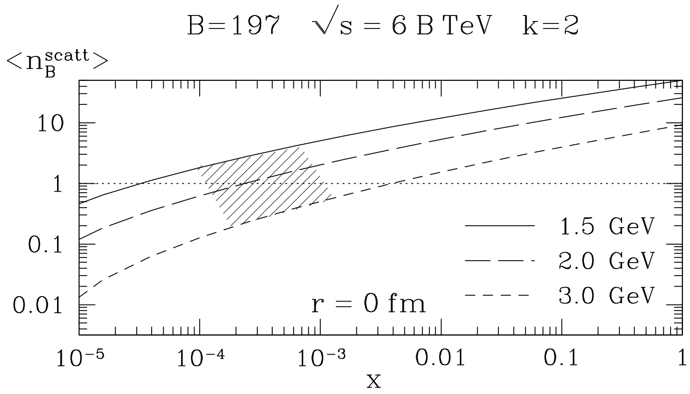
Number of scatterings of one incoming parton

$$\langle n_A^{scat}(x,b)\rangle = \int dx'\,\sigma_H(xx')\,G(x';Q=p_0)\,\tau_B(b)$$

RHIC



LHC



When $\langle n_A^{scat}\rangle \gtrsim 1$ the single-scattering approx. breaks down

This happens • at RHIC for $p_0 \lesssim 1Gev$

• at LHC for $p_0 \lesssim 2Gev$

i.e., where the bulk of minijet production is expected

$$\boxed{\text{WE NEED TO INCLUDE THE RESCATTERINGS}}$$

Semihard interactions: rescatterings

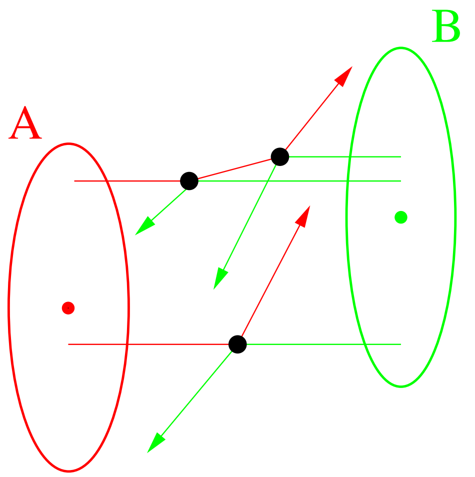
Calucci, Treleani, PRD41(90)3367, PRD44(91)2746

Def. minijet = parton with at <u>at least</u>
1 semi-hard scattering

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

Assumptions:

- QCD generalized factorization
- independent scatterings



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

Multiparton distributions:

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

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

$$\frac{dN^A_{jet}}{dx}(b) = \int d^2r \, \overbrace{G(x)\tau_A(b-r)}^{\text{density of projectiles}} \underbrace{\left(1 - e^{-\overbrace{\int dx' \sigma_H(xx')G(x')\tau_B(r)}^{\langle n_B^{\text{scat}}\rangle \text{ or ``target opacity''} \omega_B}}\right)}_{\text{prob. of at least 1 scatt.}}$$

Expansion in the no. of scatterings

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

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

Two remarkable limits

$$\frac{dN_{jet}}{dx}(b) \longrightarrow \begin{cases} 2\int G\,\tau_A\,\sigma_H\,G\,\tau_B = \dfrac{dN^{eik}_{jet}}{dx}(b) & \dfrac{p_0}{\sqrt{s}} \to 1 \\ \int G\,\tau_A + \int G\,\tau_B \overset{def.}{=} \dfrac{dN_{lim}}{dx}(b) & \dfrac{p_0}{\sqrt{s}} \to 0 \end{cases}$$

"black-disc limit"

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

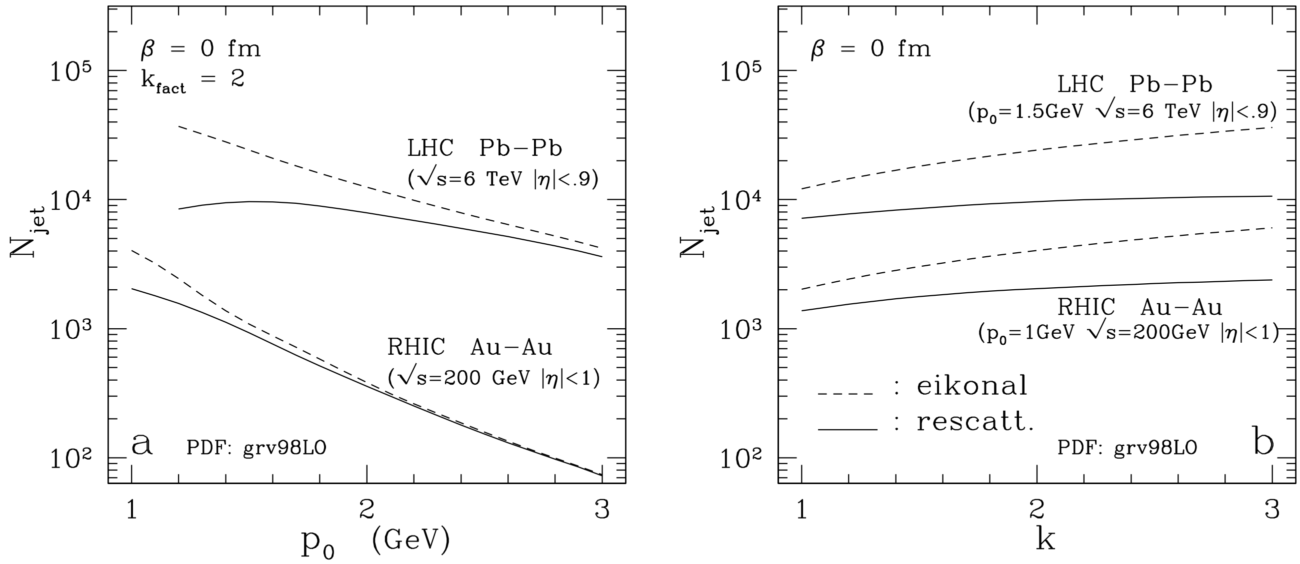
Initial conditions

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

$$N_{jet}(b) = \int d^2r\,dx\,G(x)\tau_A(b-r)\left(1 - e^{-\int dx'\sigma_H(xx')G(x')\tau_B(r)}\right)$$

$$+A \leftrightarrow B$$

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

Choosing typically $p_0 = 1\text{GeV}$ at RHIC
$p_0 = 2\text{GeV}$ at LHC

$$\boxed{\left.\frac{dN}{dy}\right|_{y=0} \approx \ 1000\ (\text{RHIC}),\ 5000\ (\text{LHC})}$$

Average minijet energy

$$E_{jet}(b) = \int d^2r dx \left(x \frac{\sqrt{s}}{2} \right) G(x) \tau_A(b-r) \left(1 - e^{-\int dx' \sigma_H(xx') G(x') \tau_B(x',r)} \right) + A \leftrightarrow B$$

Performing the integral over d^2r we have an upper limit for the minijet total energy:

$$E_{jet}(b) \lesssim N_{part}(b) \frac{\sqrt{s}}{2} \int dx \, xG(x) = N_{part}(b) \frac{\sqrt{s}}{2}$$

Energy conservation has been implemented
(consequence of the unitarization)

Saturation cutoff

A.A., Phys.Rev.C 64 (2001) 064905

Let's exploit the black-disc limit

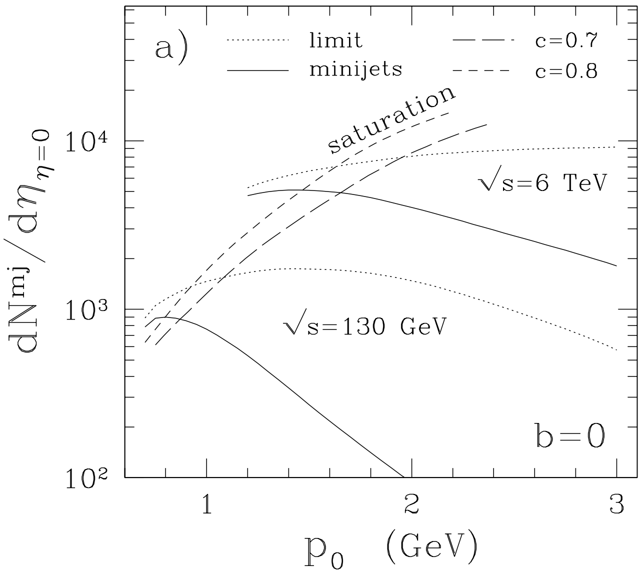
$$\frac{dN_{jet}}{dx}(b) \underset{p_0 \to 0}{\longrightarrow} \frac{dN_{lim}}{dx}(b)$$

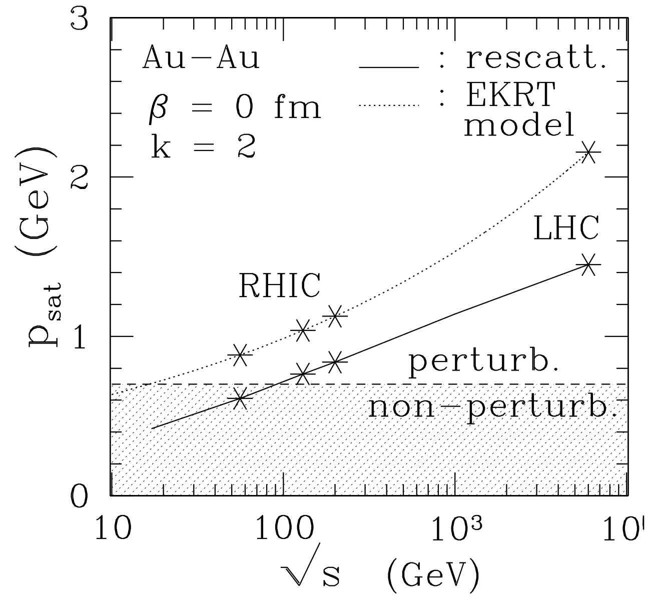
Def. Saturation cutoff:

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

Def. Saturated initial conditions:

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





- 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

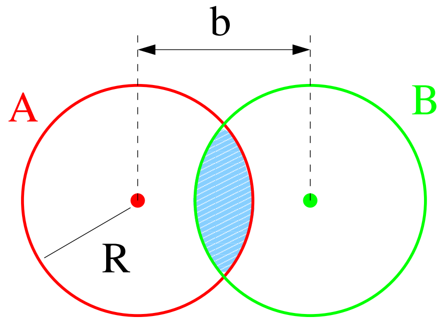
Two-component model (soft + semihard)

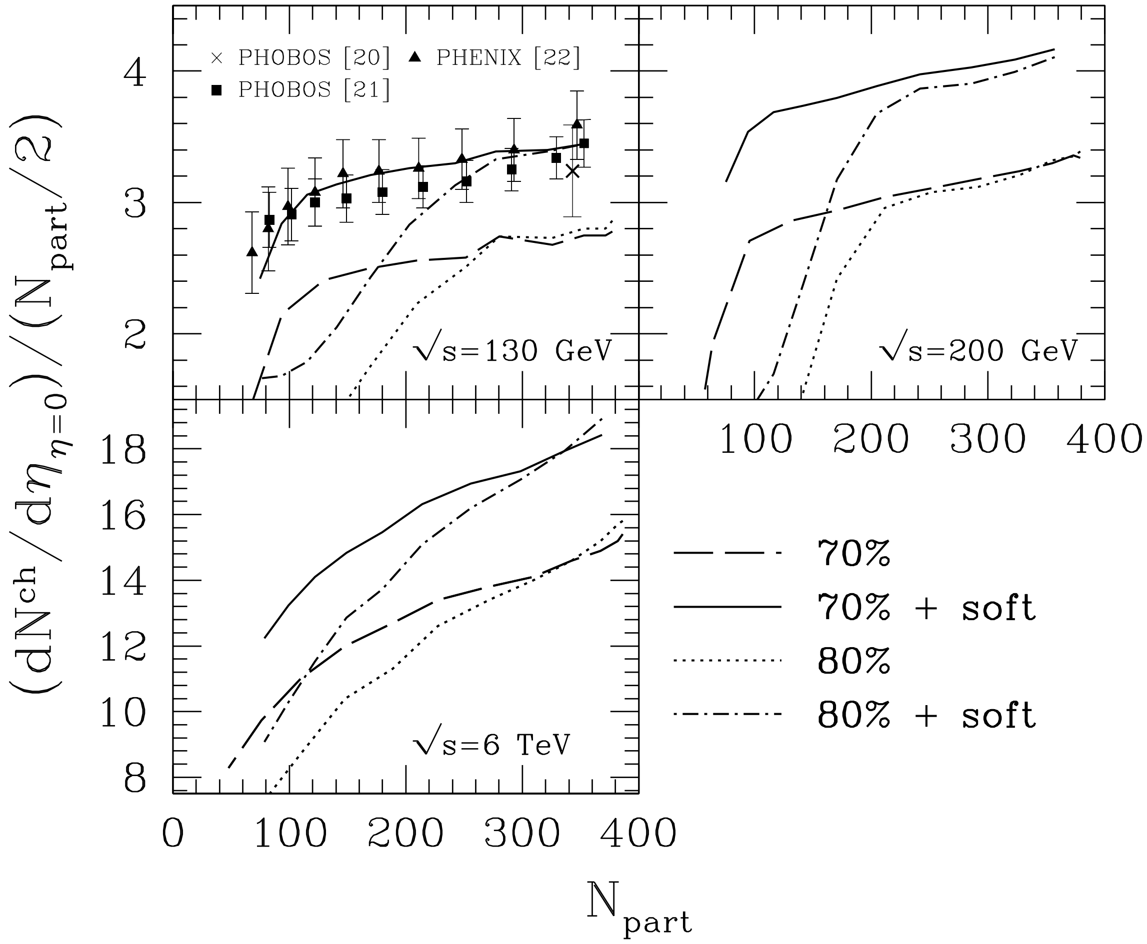
$$\boxed{\frac{2}{N_{part}(b)}\frac{dN^{ch}}{d\eta}(b) = 2\,x(\sqrt{s})\;n_{pp}(\sqrt{s}) + \frac{2}{N_{part}(b)}\frac{3}{5}\frac{dN^{sat}_{jet}}{d\eta}(b)}$$

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.

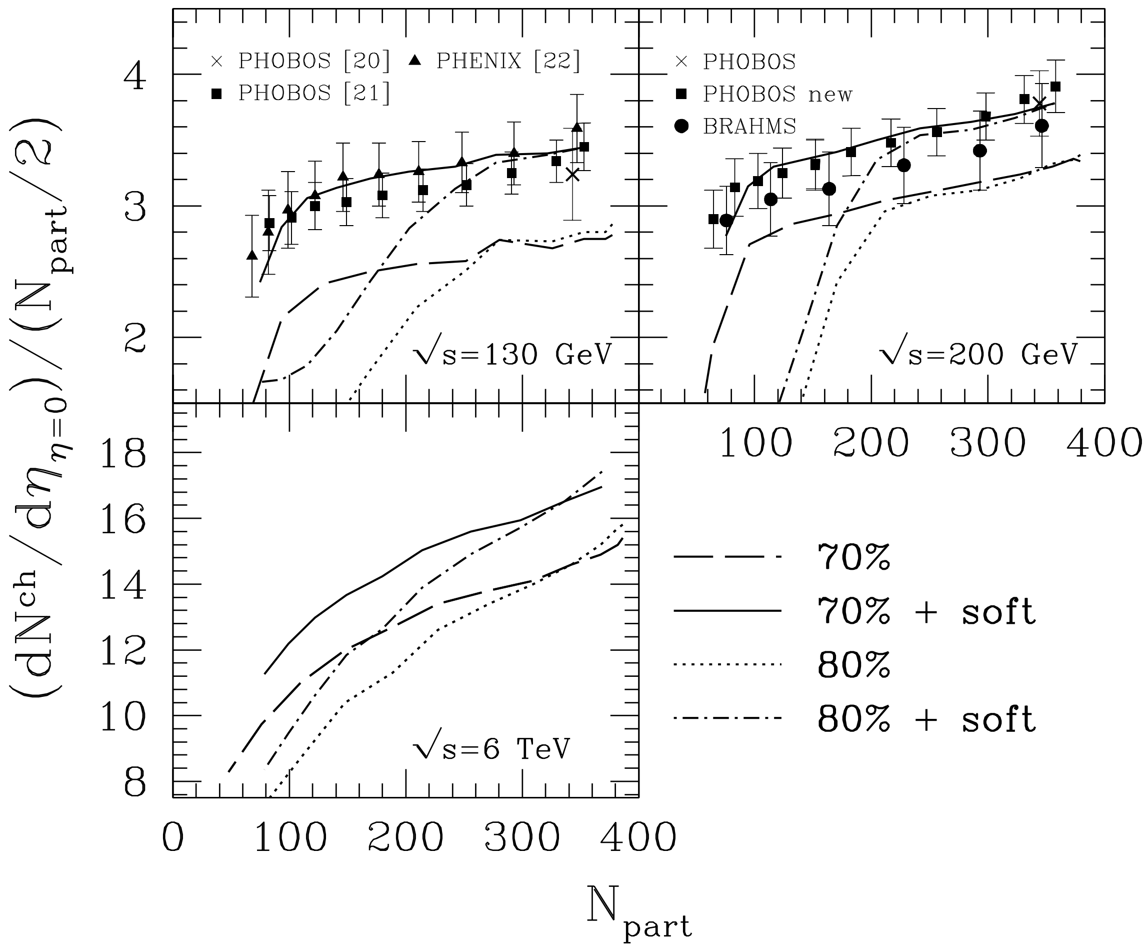




- Lower curves: semihard part only
- Upper curves at 130 GeV: soft fitted to most central point
- Upper curves at 200 GeV and 6 TeV are an upper bound extrapolated from 130 GeV

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

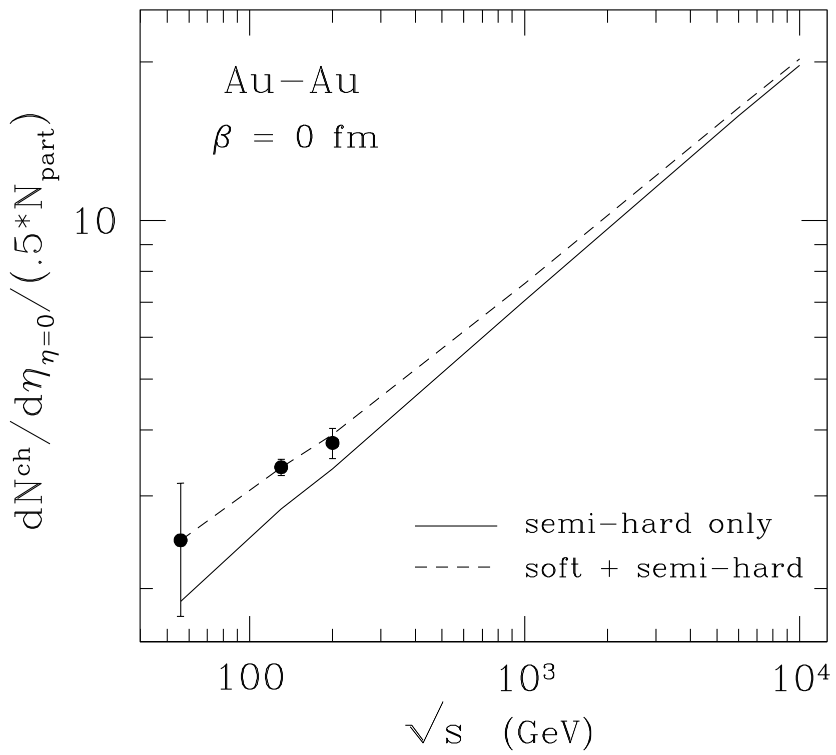
Energy dependence

- Semihard production increases 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:

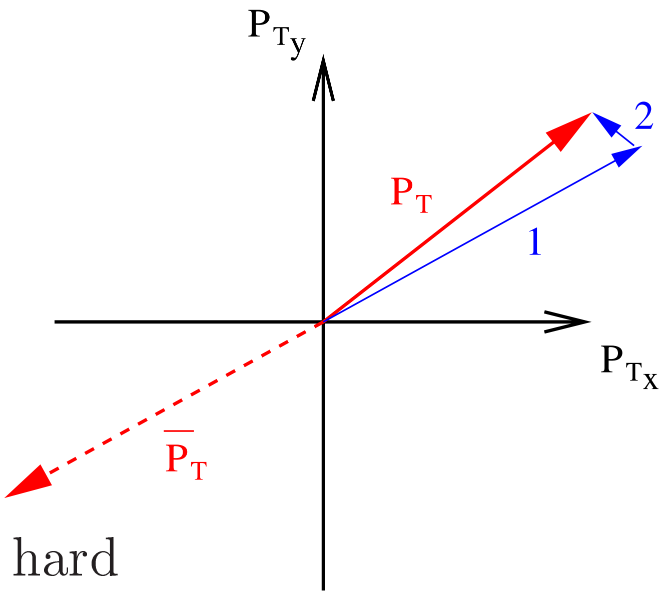


at RHIC 80-85% semihard
at LHC 95% semihard

Picture of the interaction

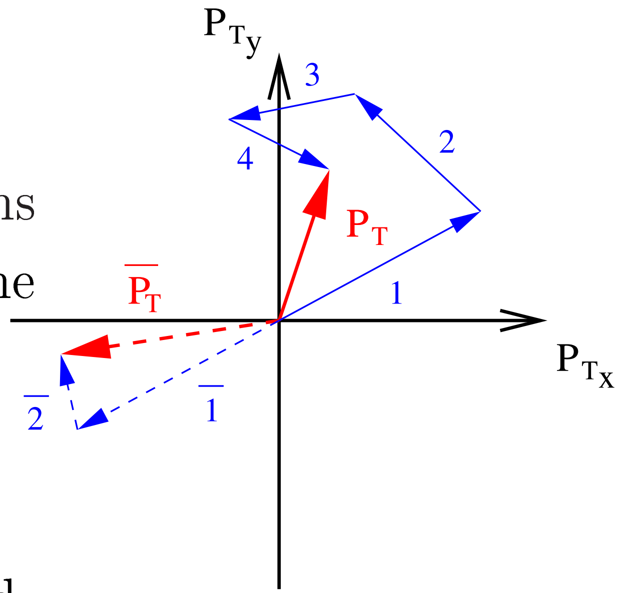
(fixed $\sqrt{s}$)

Large b (high $\mathbf{p}_T$)



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

Small b (low $\mathbf{p}_T$)



- Onset of black-disc limit
- 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

$\cancel{p_T}$

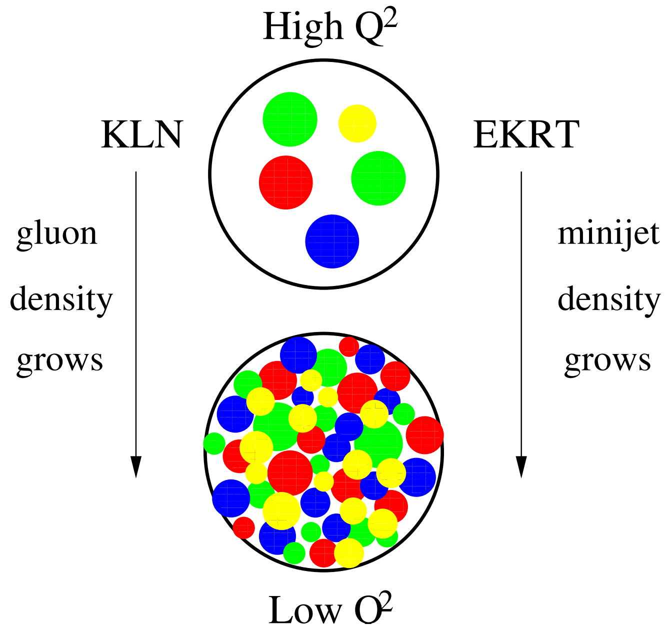
$\cancel{\textbf{low } \sqrt{s}}$

$\cancel{\textbf{high } \sqrt{s}}$

Other saturation models

KLN model: initial state saturation of nuclear parton densities.

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



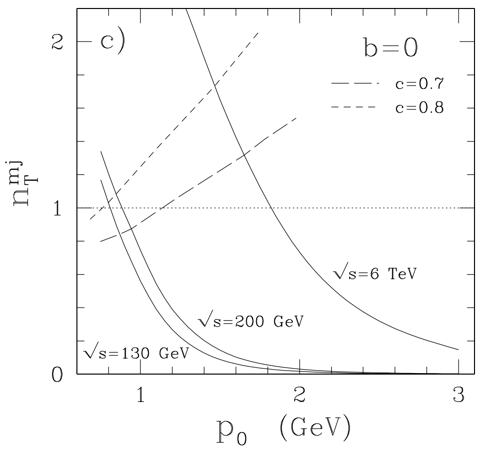
Where does the "minijet production saturation" stand?

initial state saturation	——	m.j. production saturation	——	final state saturation
modify G(x)		upper limit on N_{jet} from unitarization		produced mj limited by fusion processes

- Use modified PDF in rescattering formulae
- Average occupation no. in tr. plane:

$$n_T^{mj} = N_{jet}^{sat}/(\pi R_A^2)$$

At LHC $n_T^{mj} > 1$: final state int's are possible.



Answer 1 (naïve):

The "production saturation" mechanism is complementary to initial and final state saturation mechanisms.

EKRT saturation and transverse area

Global saturation

- The saturation cutoff $p_{sat} = p_{sat}(b)$ is the solution of

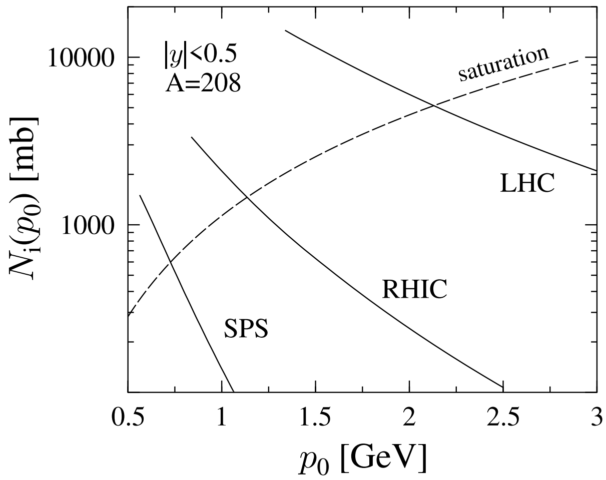
$$N_{jet}(p_0, b) \times a_T(p_0) = \mathcal{A}_T(b)$$

where: $a_T \approx \pi/p_0$ = minijet transverse area
$\mathcal{A}_T(b)$ = transverse overlap area of nuclei

- In the Eikonal approximation

$$T_{AA}(b)\,\sigma_{pQCD}(p_0) \times \frac{\pi}{p_0^2} = \mathcal{A}_T(b) \Longrightarrow p_{sat}(b)$$

where $T_{AA}(b) = \int d^2r\, \tau_A(b-r)\tau_A(r)$.



- The saturated minijet multiplicity is then

$$N_{jet}^{sat}(b) = N_{jet}\big(p_0 = p_{sat}, b\big)$$

Local saturation

- $p_{sat} = p_{sat}(b,r)$ is defined locally in the transverse plane as the solution of

$$\frac{dN_{jet}}{d^2r}(p_0, b, r) \times a_T(p_0) = 1$$

- In the Eikonal approximation

$$\tau_A(b-r)\tau_A(r)\,\sigma_{pQCD}(p_0) = \frac{p_0^2}{\pi} \Longrightarrow p_{sat}(b,r)$$

- The saturated minijet multiplicity is obtained by integration over the transverse area:

EKRT: Transverse area such that $p_{sat} \geq p_{min} = 0.5$ GeV

$$N_{jet}^{sat}(b) = \frac{1}{\pi}\int d^2r\, p_{sat}^2(b,r)\,\theta(p_{sat} - p_{min})$$

very sensitive to p_{min}

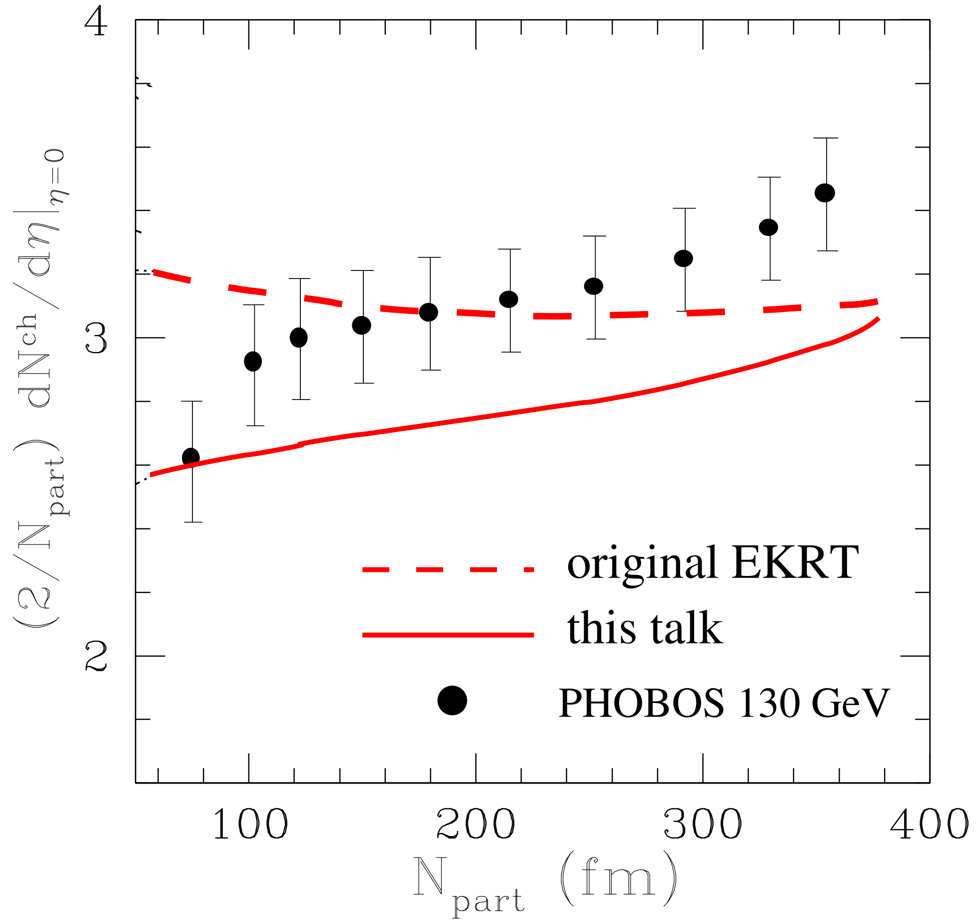
THIS TALK: d^2r weighted by Glauber model

$$N_{jet}^{sat}(b) = \frac{1}{\pi}\int d^2r\, p_{sat}^2(b,r)\,\underbrace{\left(1 - e^{-\sigma_{pp}\tau_A(b-r)}\right)\left(1 - e^{-\sigma_{pp}\tau_A(r)}\right)}_{\text{probability of at least 1 pp collision}}$$

no free parameter

Original and modified local EKRT saturation

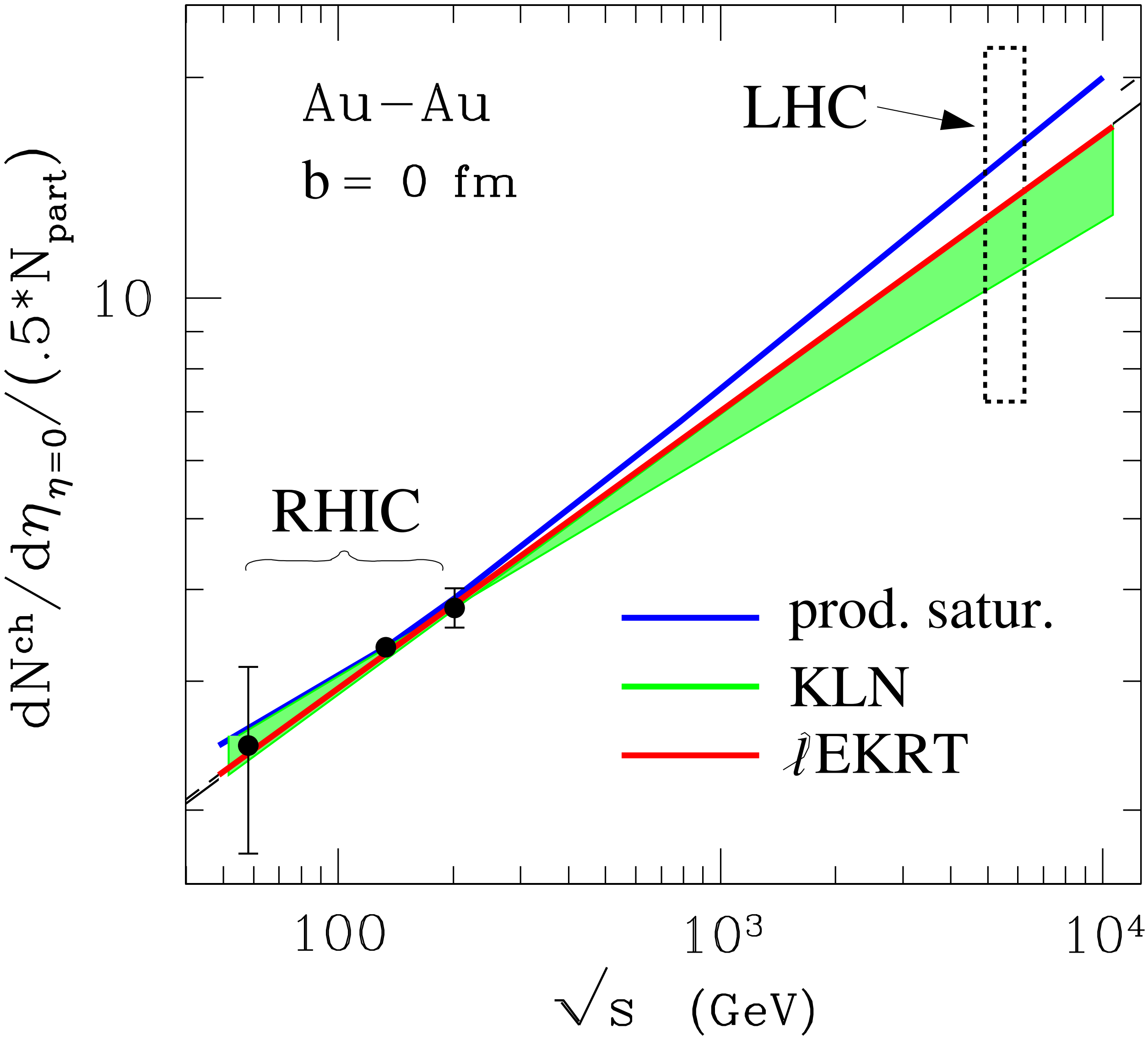
$$\frac{dN^{ch}}{d\eta}(b) = 0.9\ \frac{2}{3}\ \frac{dN^{sat}_{jet}}{d\eta}(b)$$



- Missing soft contribution?
- Fine tuning of a coefficient in the sat'n condition?

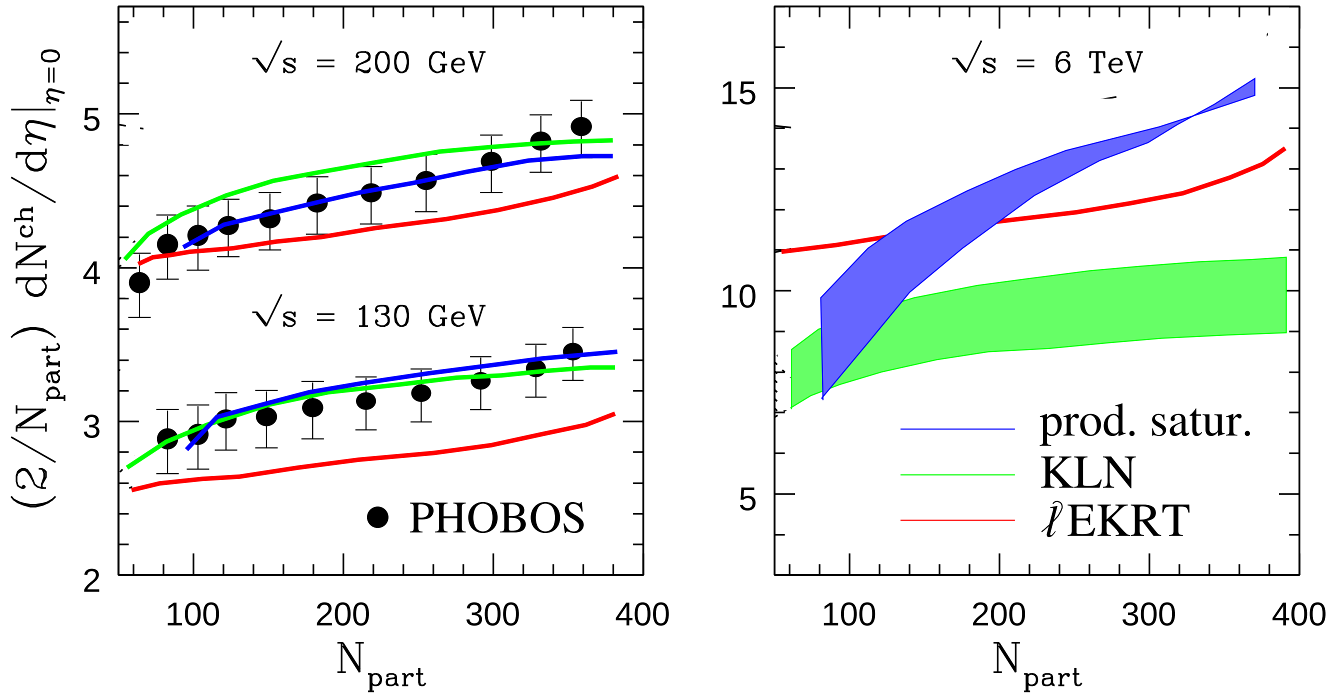
$\rightsquigarrow$ let's look the data at 130 GeV and 200 GeV

Energy dependence



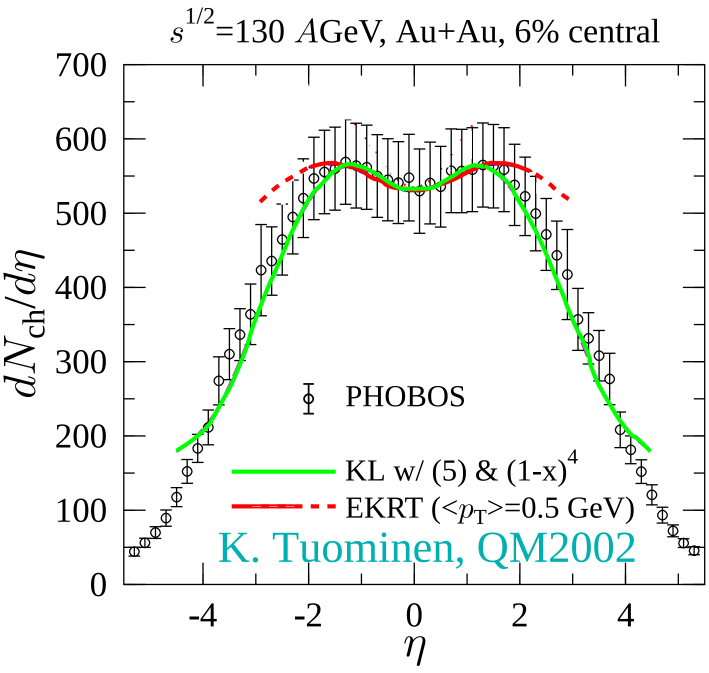
Extrapolation of models to LHC energy gives similar results

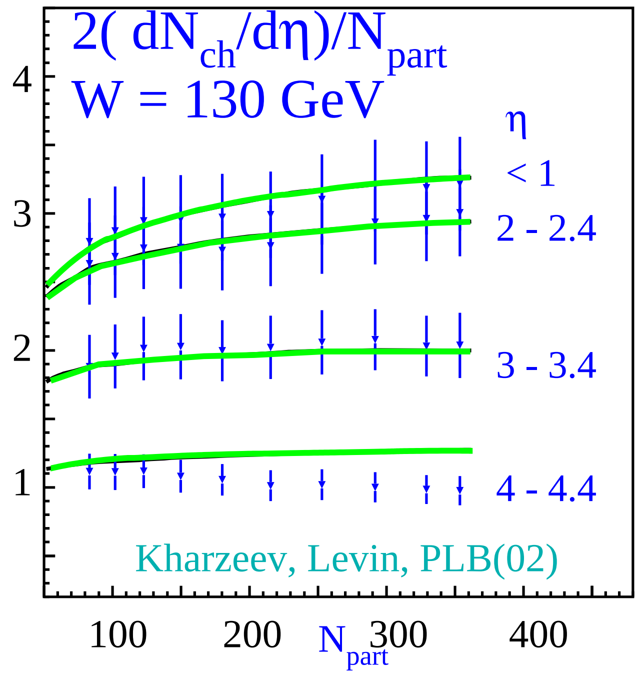
Centrality dependence



- the ℓEKRT model always underestimates the data:
  – missing soft physics?
- RHIC allows only a partial discrimination of models
- LHC might allow to decide.

Pseudorapidity dependence

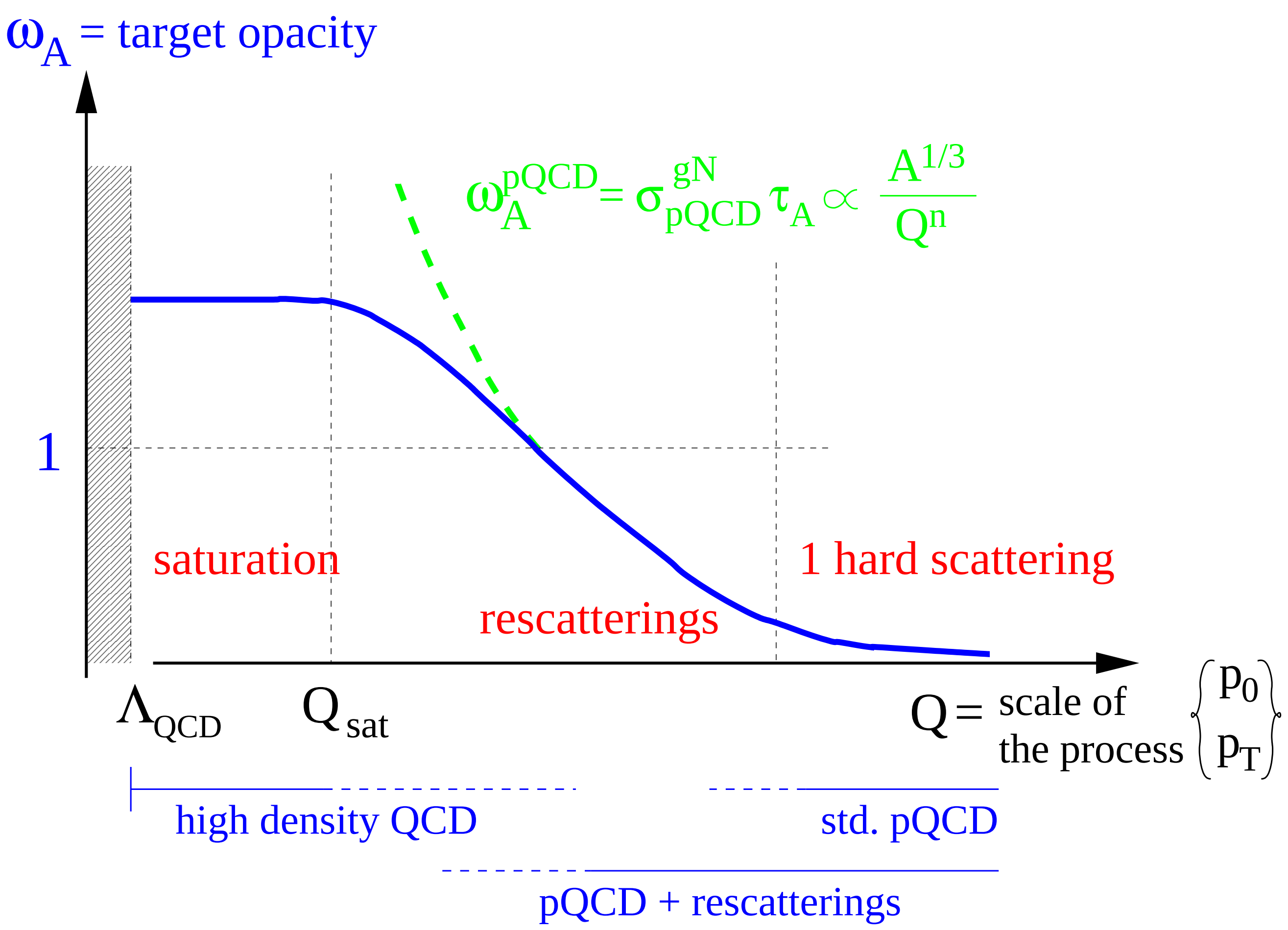




- Good test of the underlying dynamics
- EKRT limited in η due to violation of energy conservation
- Semi-hard rescatterings conserve energy

  $\Longrightarrow$ ideally suited for this observable ... work in progress!

Summary



Answer 2: Semihard rescatterings allow to study the onset of the black disc limit by pQCD computations

- Identify observables (almost) insensitive on ω_A
  $\Longrightarrow$ computable with pQCD+rescatterings
  [e.g., N^{ch}, N^{jet}, E_T^{jet}]
- Identify observables with sensitivity to ω_A
  $\Longrightarrow$ compare low-Q and high-Q approaches in the overlap region of validity
  $\Longrightarrow$ Do they match? If not, why?
  [e.g., Cronin effect in dA]

CONCLUSIONS

- **Semihard parton rescatterings**
  - Unitarize perturbative gluon-nucleus cross-section
    - $\rightsquigarrow$ energy conservation
    - $\rightsquigarrow$ small sensitivity of N_{jet} on p_0 and k-factor
  - Onset of black-disc limit by pQCD methods

- **Saturation of minijet production**
  - break-up of N_{coll} scaling for semihard processes
  - testable in b and η dependence of N^{ch}

    (possibly needs LHC data)

- **Further important observables**
  - Cronin effect on hadron p_t spectra (dA at RHIC)
  - Non-flow two-particle correlations

    (CERES and STAR data)