Where should we look for hard parton scatterings in flow measurements?

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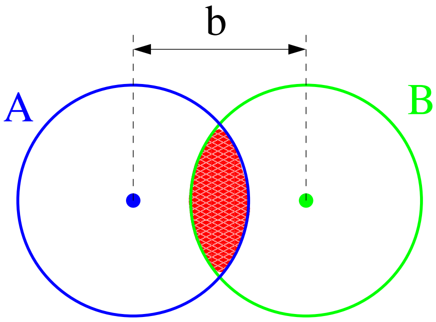
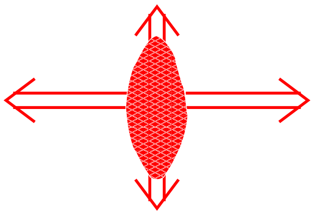
SUMMARY

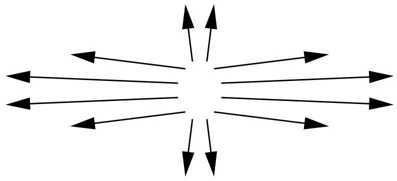
- Introduction
  - Flow and non-flow correlations
  - Semihard processes (qualitative)
- Minijet (parton) production
  - Semihard parton rescatterings
  - Inclusive minijet production
- Non-flow two-particle correlations
  - Elliptic flow vs. azimuthal correlations
  - Two-minijet production and correlations
  - "Broadening of π-peak" at CERES
  - "Disappearance of back-to-back jet" at STAR
- Answer and conclusions

Introduction

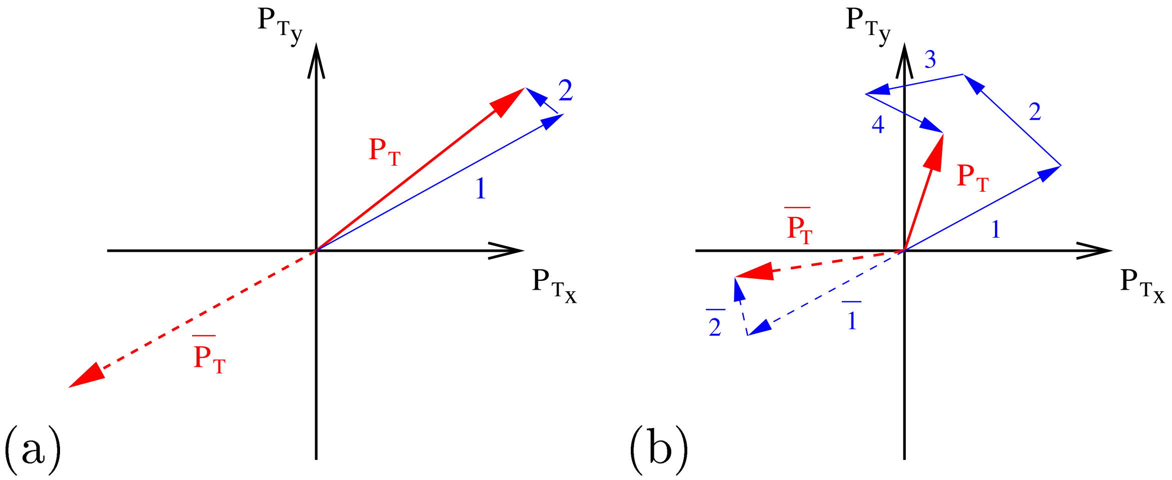


non–central collisions


pressure gradients


particle transverse momenta
azimuthal anisotropy

- Elliptic flow in non-central heavy-ion collisions induces two-particle (2P) azimuthal correlations
- CERES and STAR $\Longrightarrow$ also “non-flow” 2P correlations
- Natural candidate: minijet production
  - (a) Parton-parton scattering $\Rightarrow$ back-to-back correl.
  - (b) Parton rescatterings $\Rightarrow$ broadening of peak at 180^O in 2-particle azimuthal dist’s (seen at CERES)

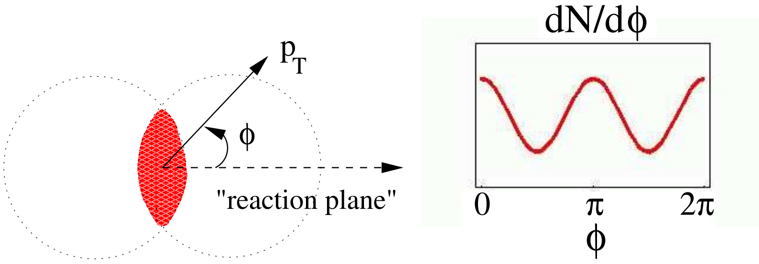


- Why smaller effect on v_2 at RHIC than at CERES?
- What the effect of “jet-quenching”?

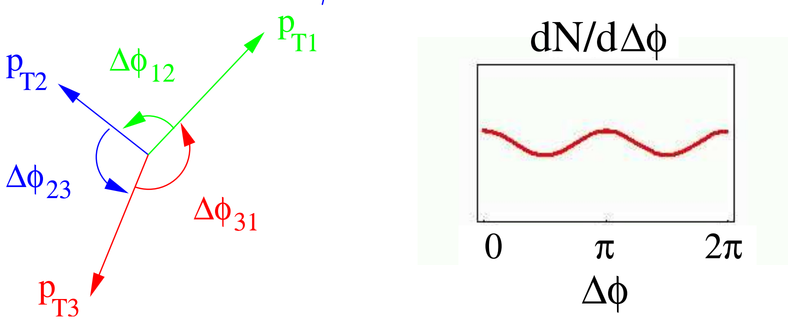
Two-particle correlations

Elliptic flow and azimuthal distributions

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



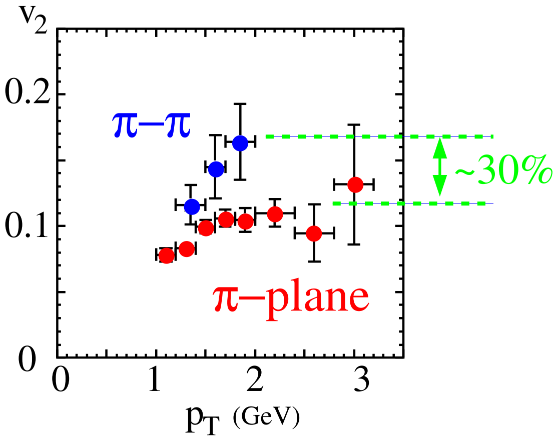
- Two-particle: $$\frac{dN^{(2)}}{d\Delta\phi} = D\left[1 + 2\, w_2^2 \cos(2\Delta\phi) + \ldots\right]$$



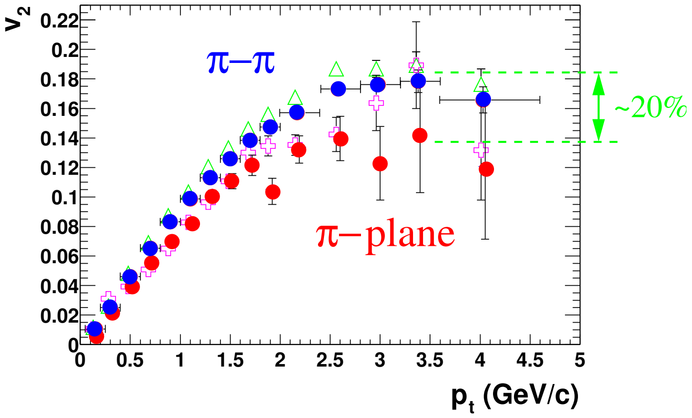
without other effects $\boxed{w_2 = v_2}$

Non flow correlations

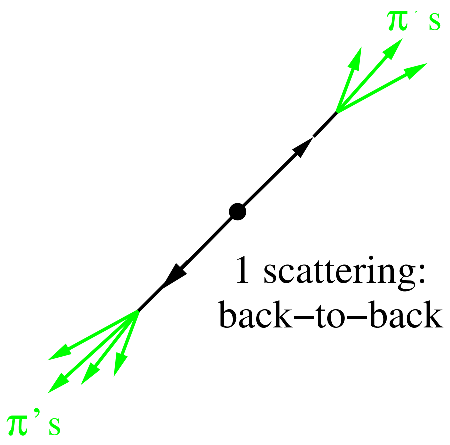
CERES prelim. J.Slivova's talk

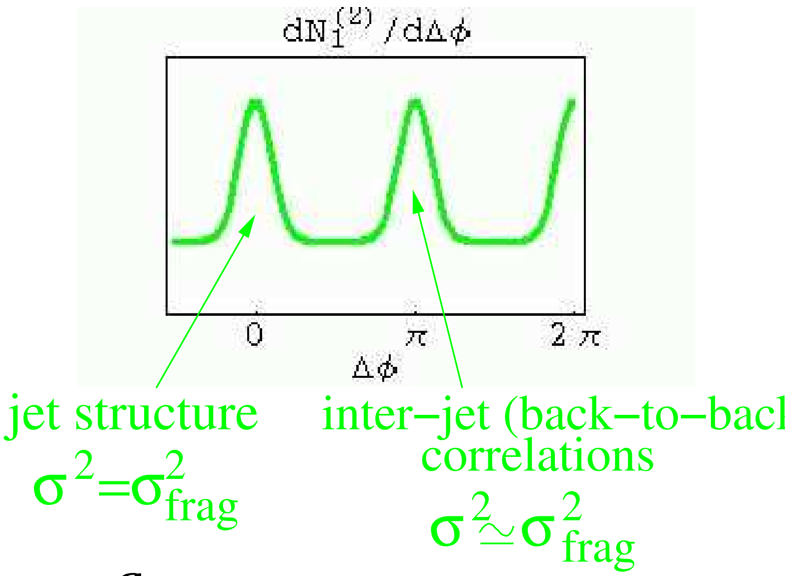


STAR Adler et al. nucl-ex/0206001

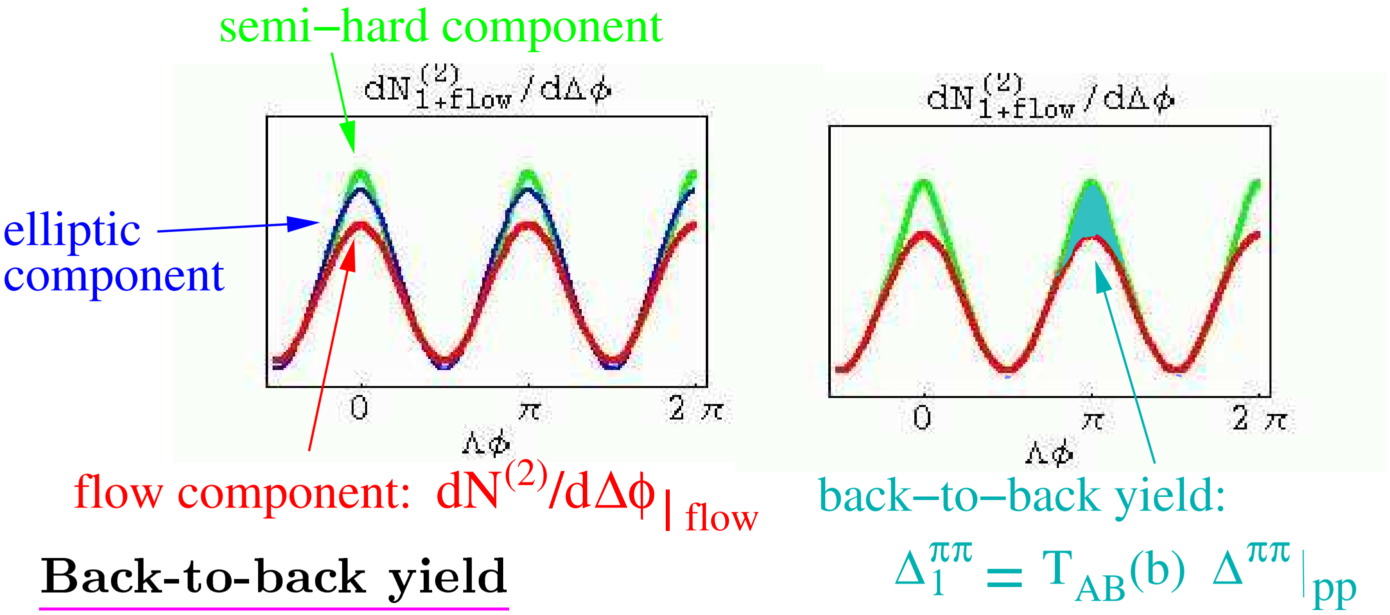


“Semihard” correlations: 1 scattering





Combining flow and non-flow:

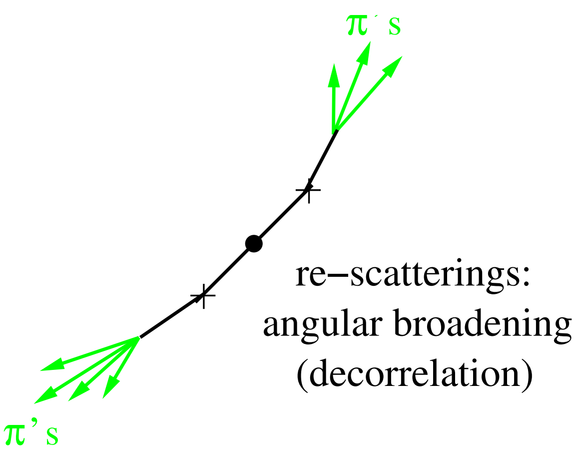


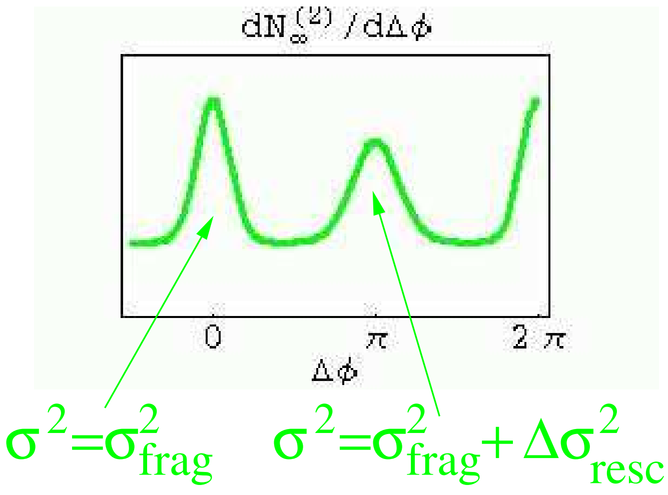
Back-to-back yield

The area between the two curves around $\Delta\phi = \pi$ gives the average number of π pairs correlated by semihard parton interactions:

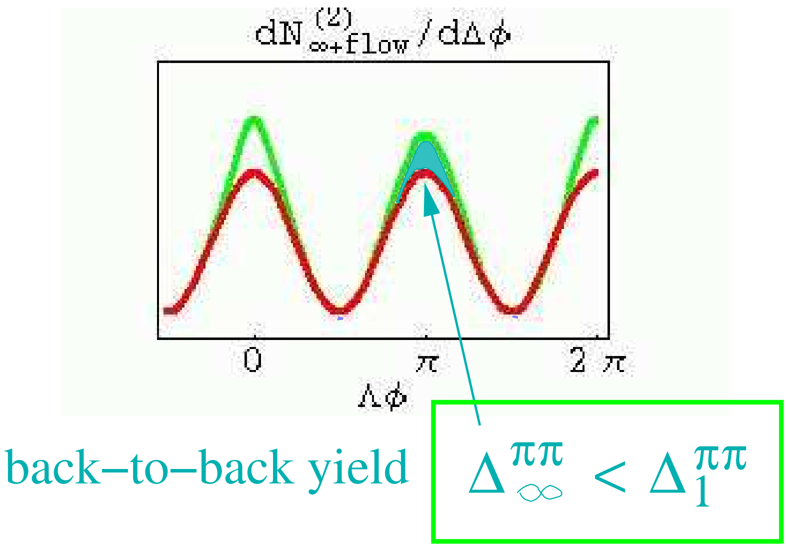
$$\Delta^{\pi\pi}(b) = \int_{\Delta\phi=\frac{\pi}{2}}^{\Delta\phi=\frac{3}{2}\pi} d\Delta\phi \left[\frac{dN^{(2)}}{d\Delta\phi} - \left.\frac{dN^{(2)}}{d\Delta\phi}\right|_{flow} \right]$$

“Semihard” correlations: rescatterings



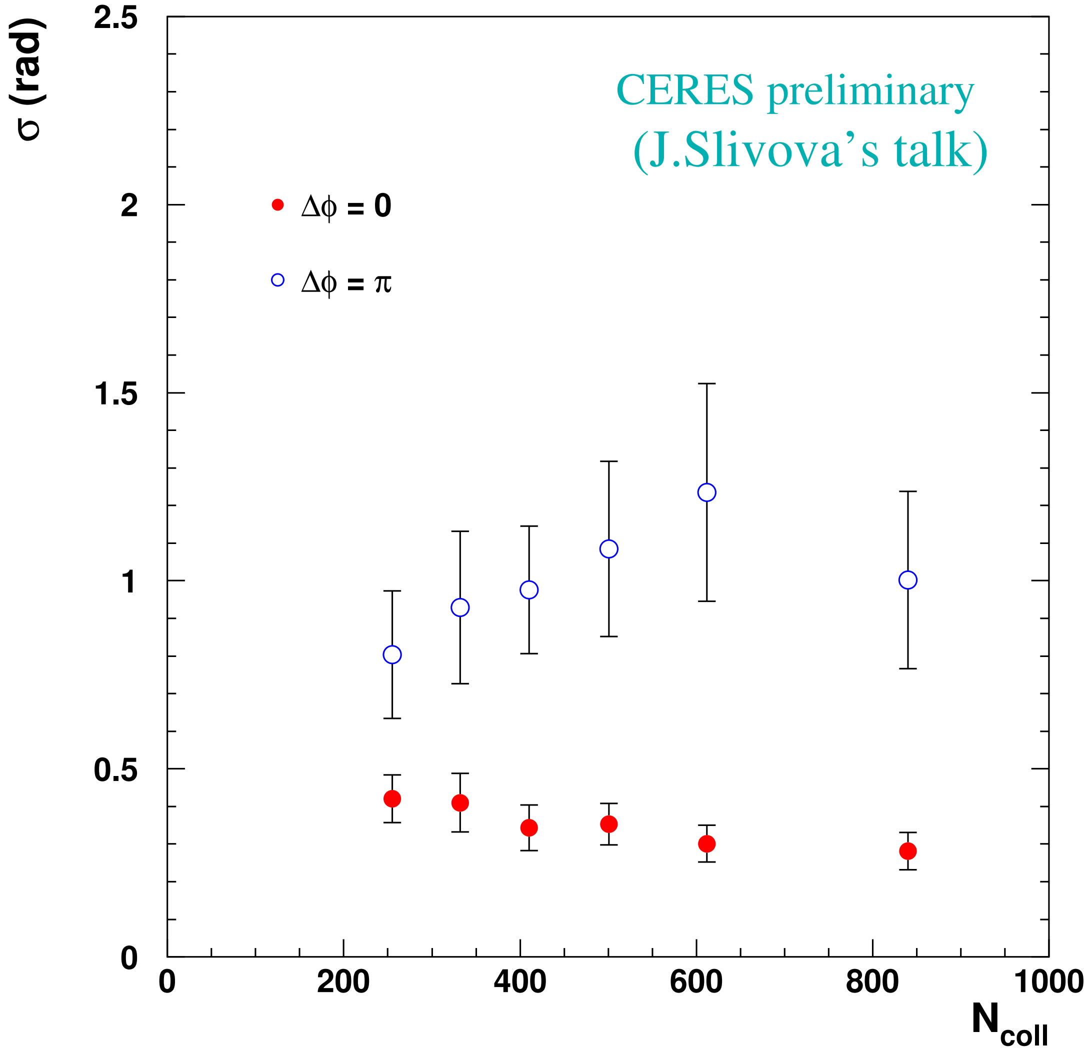


Combining flow and non-flow:



Parton rescatterings
broaden the peak at $\Delta\phi = \pi$
and reduce the back-to-back yield

Peak widths at $\Delta\phi = 0$ and $\Delta\phi = \pi$



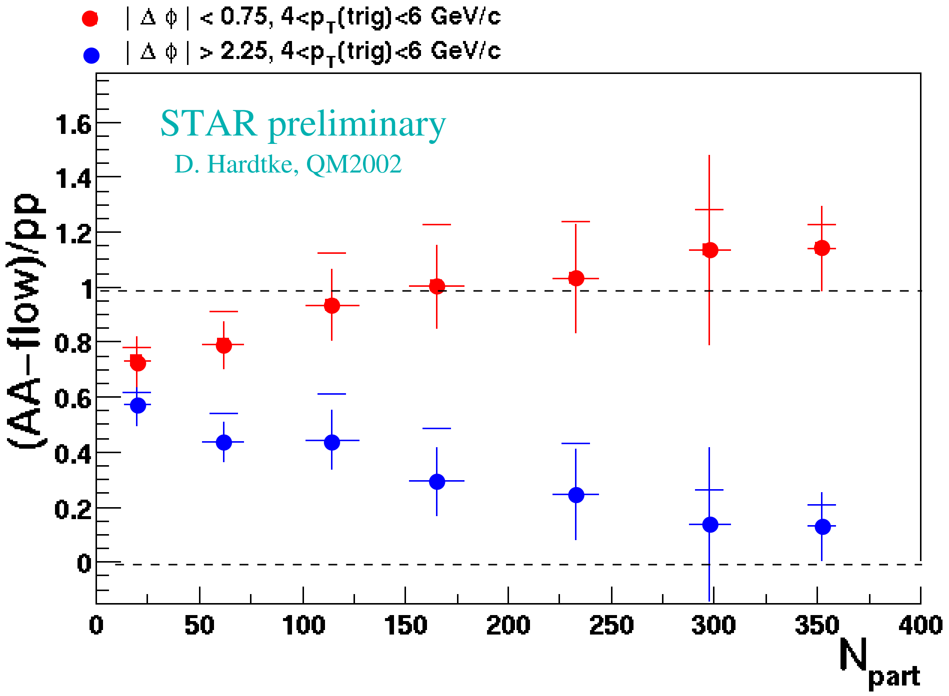
- Peak at $\Delta\phi = \pi$ broader than at $\Delta\phi = 0$
- The broadening seems to increase with centrality

Both effects support the rescattering picture

Suppression of b-t-b particles

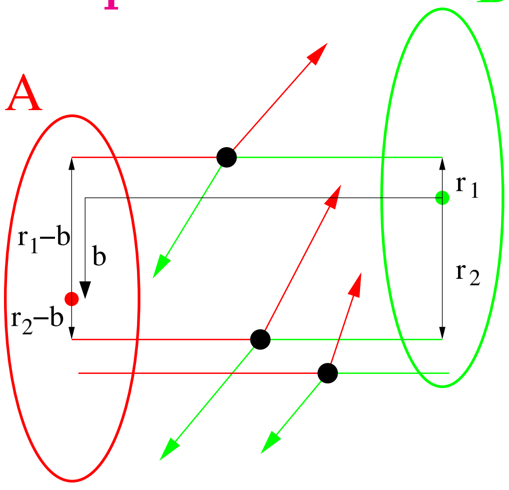
Observable: The ratio of the "back-to-back yield" at $\Delta\phi = \pi$ to the scaled pp data:

$$\frac{\Delta^{\pi\pi}(b)}{T_{AB}(b)\Delta^{\pi\pi}\big|_{pp}} \equiv \frac{AA - \text{flow}}{pp}$$



- Back-to-back particles are suppressed in peripheral collisions and "disappear" in central collisions.
- Same effect expected with semihard parton rescatterings

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 $p_0 \to 0$

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

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

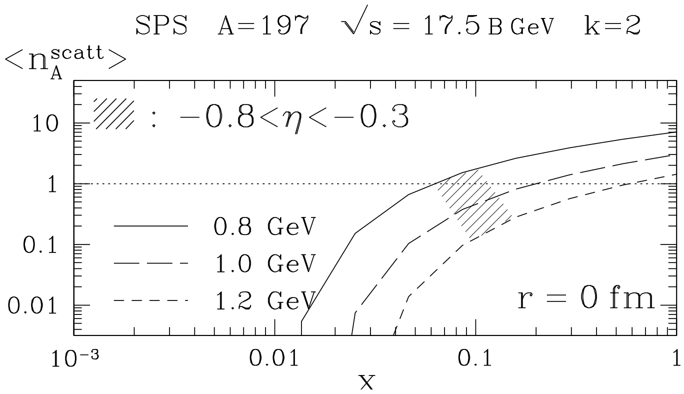
$\Longrightarrow$ some dynamics is missing

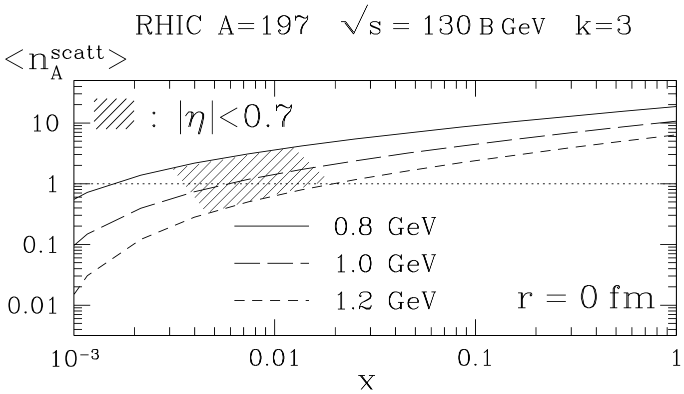
Average number of minijets

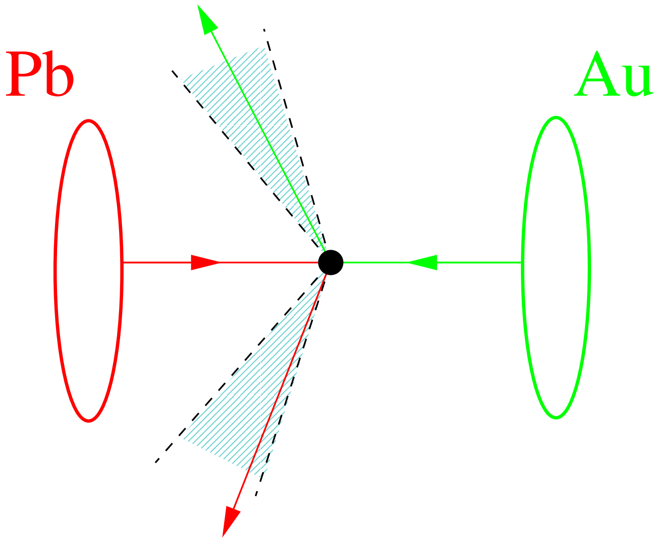
$$N_{jet}^{eik}(b) = 2\int d^2r\,dx\,\underbrace{G(x)\tau_A(b-r)}_{\text{proj. parton flux}}\underbrace{\int dx'\,\sigma_H(xx')\,G(x')\tau_B(r)}_{\text{average no. of scatterings}}$$

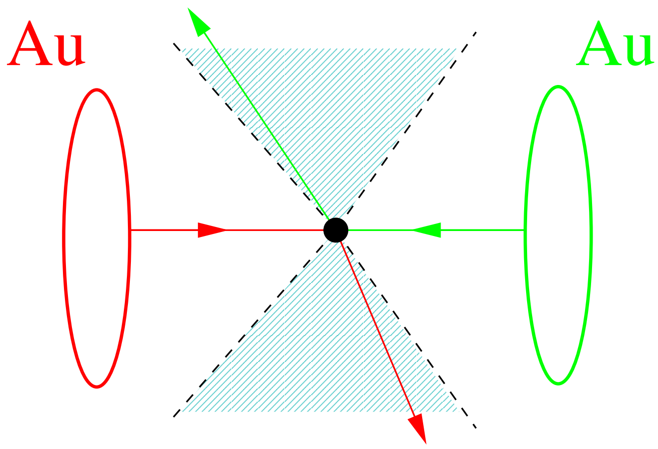
Number of scatterings of one incoming parton

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









WE NEED TO INCLUDE THE RESCATTERINGS

Semihard interactions: rescatterings

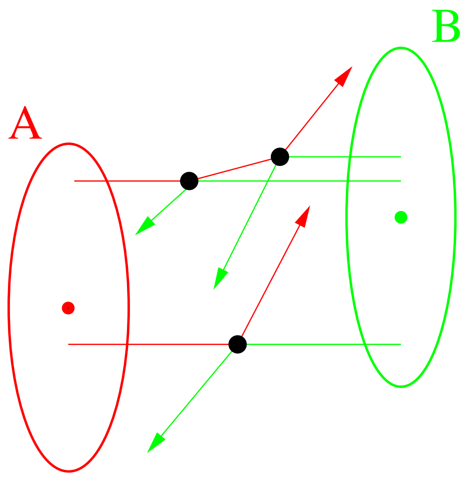
Calucci, Treleani, PRD41(90)3367, PRD44(91)2746

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



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

Multiparton distributions:

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

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:

$$\sigma_{mj} = \sum_{n,m=1}^{\infty} \int D^n_A \, P_{nm} \, D^m_B$$

Average number of minijets

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

Expansion in the no. of scatterings

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

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

Two remarkable limits

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

"black-disc limit"

Remarks

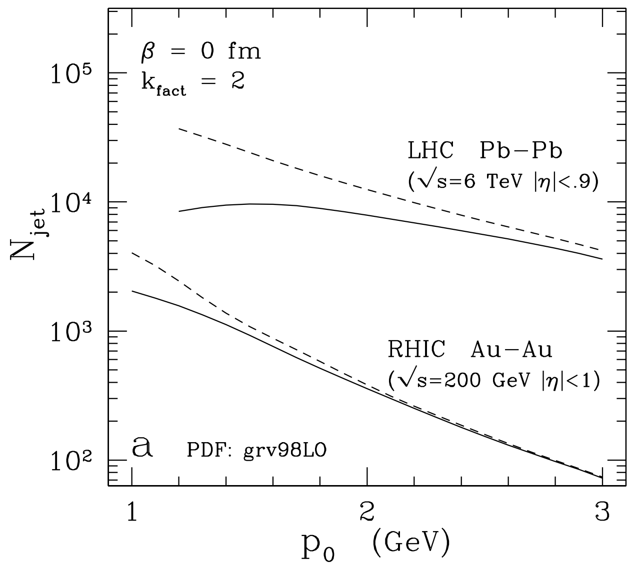
- finite limit at low cutoff:
  "Elastic semihard collisions cannot free more partons than those inside the incoming nucleus"
- at high cutoff disconnected collisions dominate

Minijet multiplicity

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 on p_0
- Minijet multiplicity is suppressed

Initial conditions: with $p_0 = 1\text{GeV}$ at RHIC
and $p_0 = 2\text{GeV}$ at LHC

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

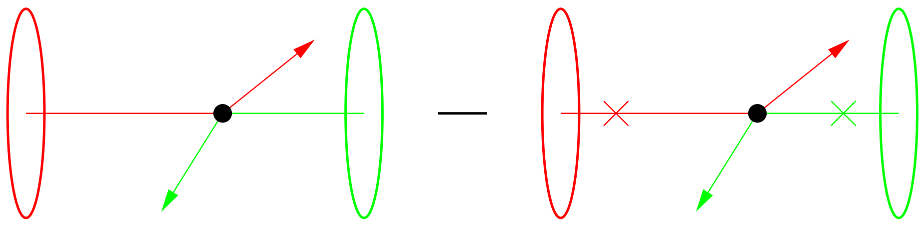
Back-to-back yield

In our multiple semihard scattering model:

$$\underbrace{\Delta N^{JJ}_{\infty}(b)}_{\text{jet yield}} = \overbrace{2\int d^2r\, dx_1\, dx_2\; G(x_1)\, \tau_A(b-r)\, \sigma_H(x_1x_2)\, G(x_2)\, \tau_B(r)}^{\equiv\, \Delta N_1^{JJ}(b)}$$
$$- \underbrace{2\int d^2r\, dx_1\, dx_2\; \frac{dN^A_{jet}}{dx_1}(b,r)\, \sigma_H(x_1x_2)\, \frac{dN^B_{jet}}{dx_2}(r)}_{\text{decorrelation term}}$$

where $\frac{dN^A_{jet}}{dx}(b,r) = G(x)\, \tau_A(b-r)\big[1 - \exp(-\int dx' G(x')\, \tau_B(r) \sigma_H(xx'))\big]$

Diagrammatically:



Two remarkable limits

$$\Delta N^{JJ}(b) \longrightarrow \begin{cases} \Delta N_1^{JJ}(b) = T_{AB}(b) \Delta^{\pi\pi}\big|_{pp} & \frac{p_0}{\sqrt{s}} \longrightarrow 1 \\ 0 & \frac{p_0}{\sqrt{s}} \longrightarrow 0 \end{cases}$$

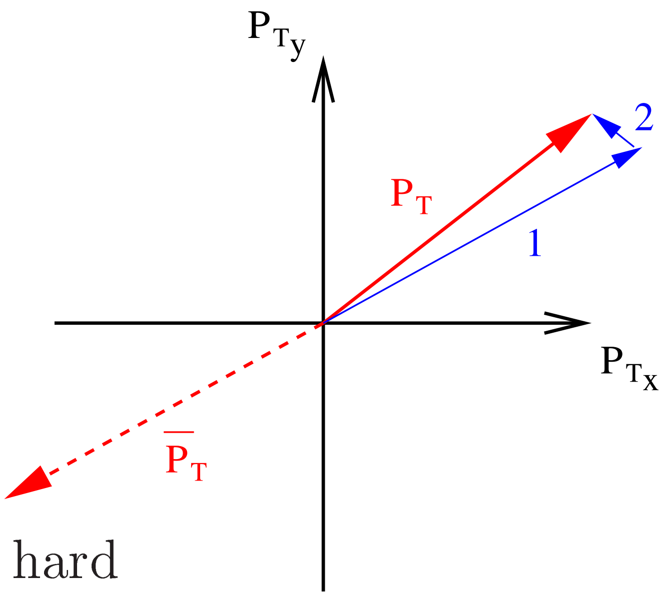
Double differential distribution also computable:

$$\frac{dN^{JJ}_{\infty}(b)}{dp_1\, dp_2\, d\Delta\phi}$$

Picture of the interaction

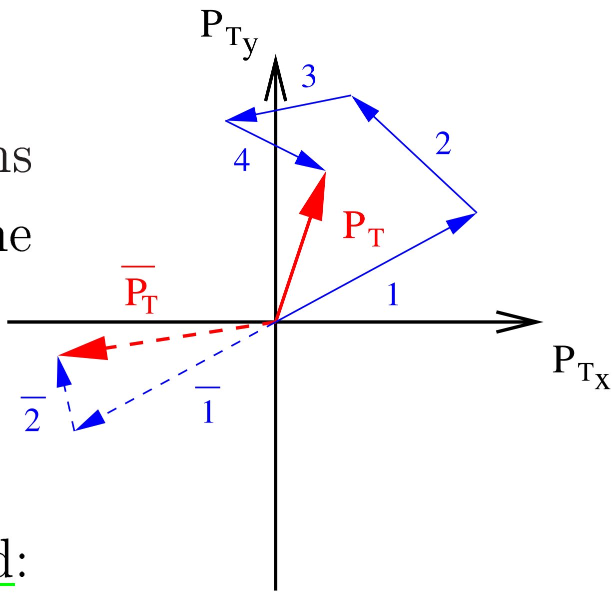
(fixed $\sqrt{s}$)

Small 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

Large b (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

p_T

low $\sqrt{s}$

high $\sqrt{s}$

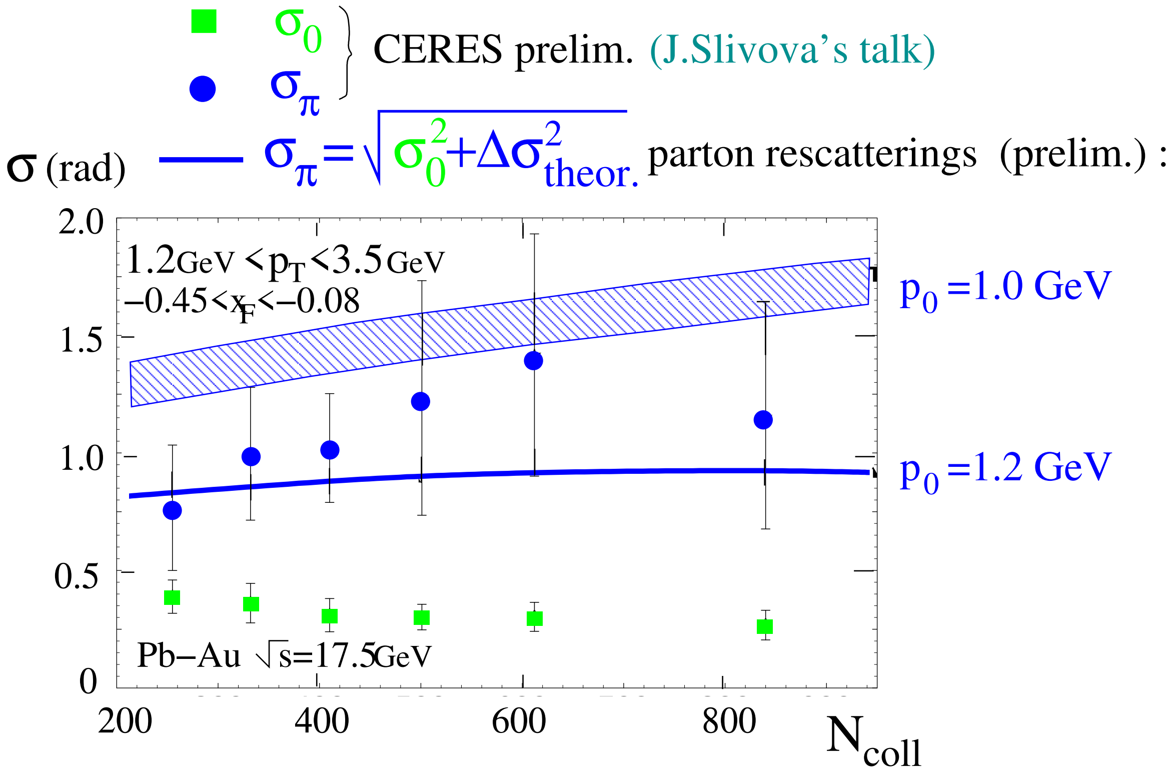
Broadening of peak at $\Delta\phi = \pi$

Accardi, Pirner, Treleani - in progress

$$\boxed{\Delta\sigma^2_{\text{theor.}} = \frac{\langle \sin^2(\Delta\phi - \pi)\rangle}{\langle 1 \rangle} \underset{\substack{\Delta\phi - \pi \\ \text{small}}}{\approx} \frac{\langle (\Delta\phi - \pi)^2 \rangle}{\langle 1 \rangle}}$$

where $\langle \mathcal{F}(\Delta\phi)\rangle = \int dp_1\, dp_2\, d\Delta\phi\, \mathcal{F}(\Delta\phi) \frac{dN^{JJ}_{\infty}}{dp_1\, dp_2\, d\Delta\phi} \otimes D_1^{\pi\pm} \otimes D_2^{\pi\pm}$

NOTE: $\Delta\phi - \pi \sim 1 \Longrightarrow$ corrections applied to compare with data. This introduces some theoretical errors, see plot.



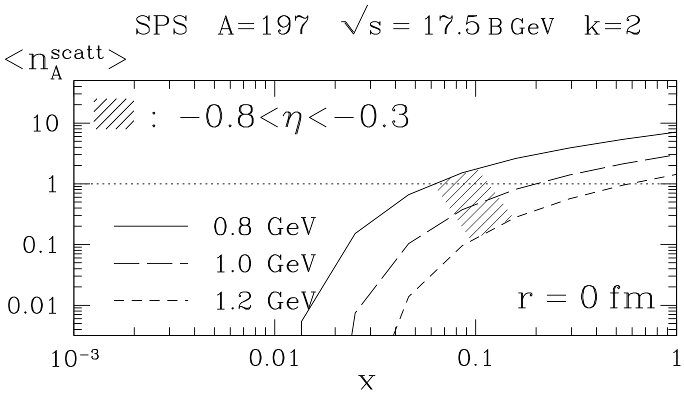
- Peak at $\Delta\phi = \pi$ broader than at $\Delta\phi = 0$
- The broadening seem to increase with centrality

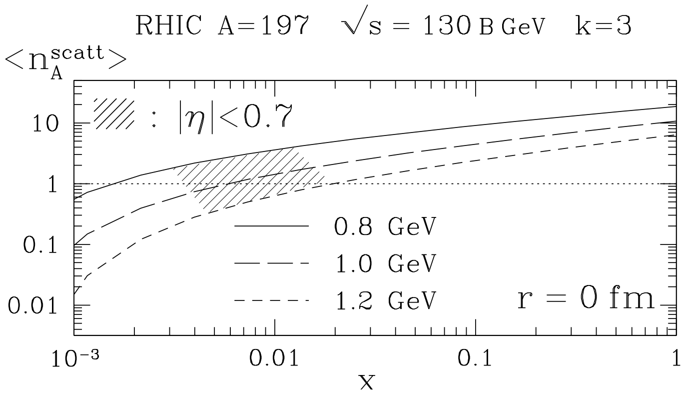
Both effects support the rescattering picture

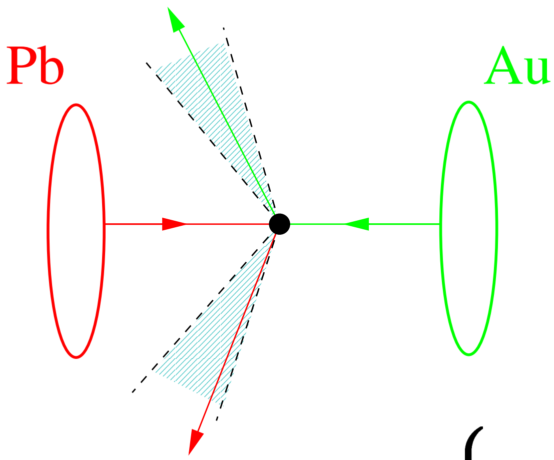
From SPS to RHIC

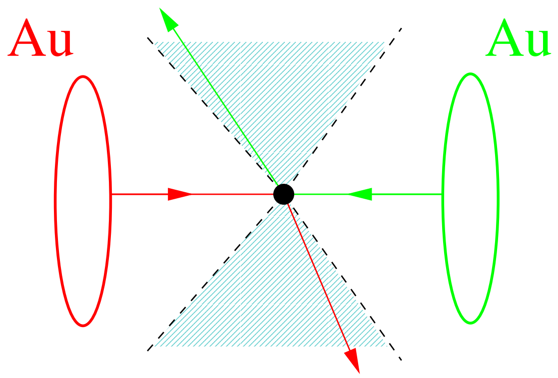
- Effects of rescatterings governed by the
  average no. of scatterings of one incoming parton:

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





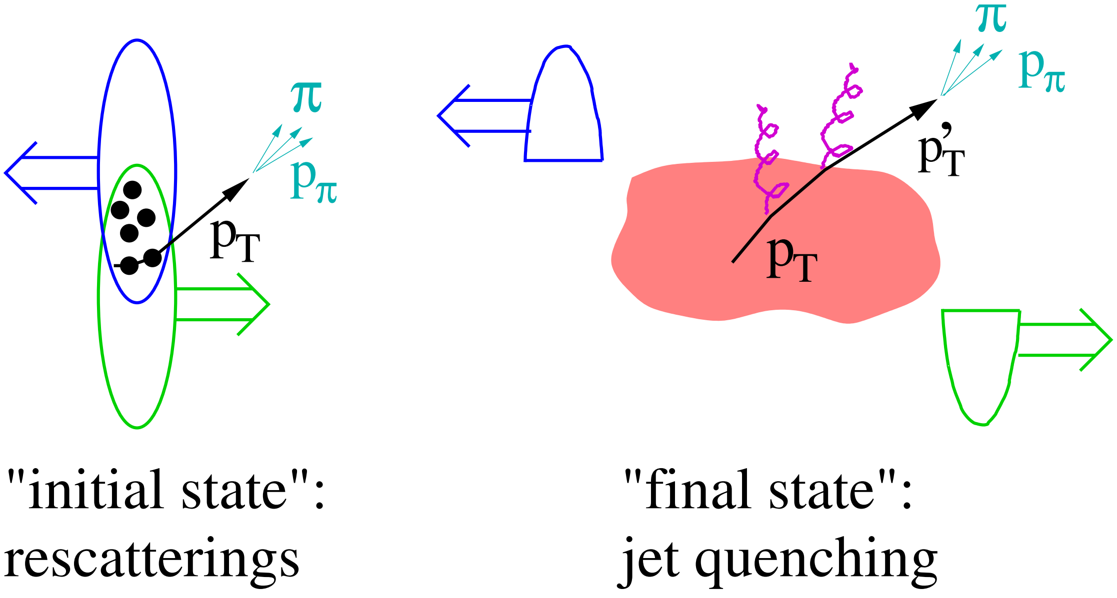




$$\langle n_A^{scat}(x,b)\rangle \begin{cases} \text{increases with } \sqrt{s} \\ \text{decreases as } p_T^{\rm jet} \text{ increases} \end{cases}$$

- At RHIC, in absence of other effects (e.g., jet quenching)
  $\Longrightarrow$ Semihard correlations at larger p_T than at SPS
  $\Longrightarrow$ Larger π-peak broadening than at SPS

Rescatterings vs. quenching



In presence of quenching, and fixing the pion transverse momentum p_T^π, the jet must exit the initial state rescattering with a higher transverse momentum p_T:

$$p_T|_{\text{quench.}} > p_T|_{\text{no quench.}}$$

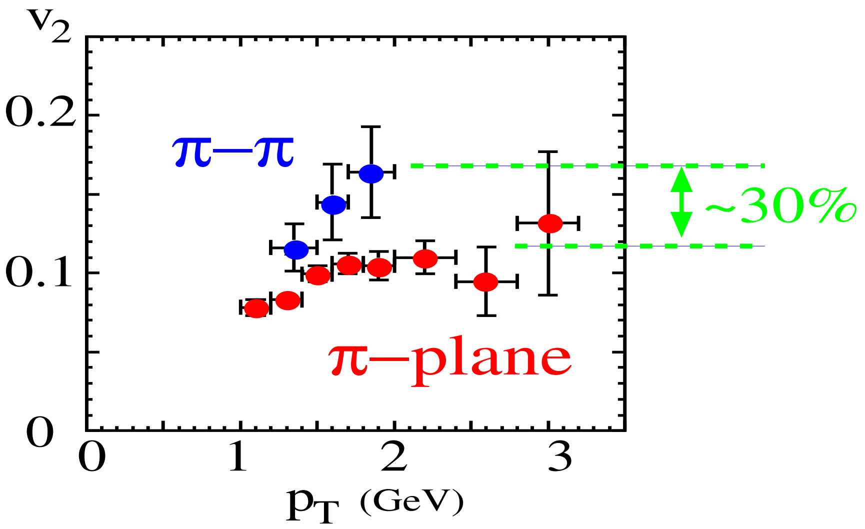
$\Longrightarrow$ Less rescatterings than without quenching
$\Longrightarrow$ Some correlations at low p_T may survive
$\Longrightarrow$ Extra broadening due to gluon radiation

Jet-quenching delays the disappearance
of correlations at high-$\sqrt{s}$

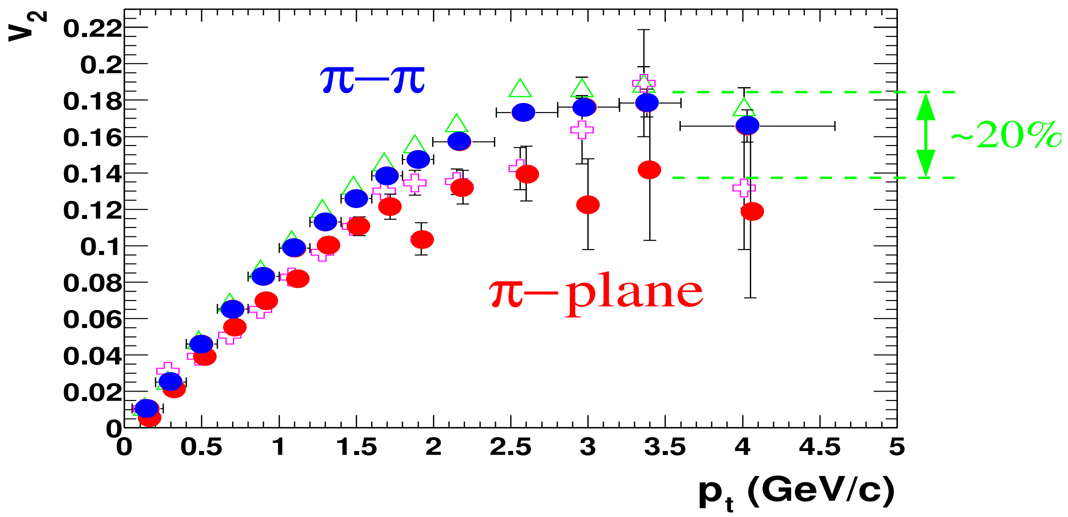
The interplay of rescatterings and jet-quenching
must be carefully studied.

Elliptic flow vs. energy

CERES preliminary data J.Slivova's talk



STAR data (min. bias) Adler et al., nucle-ex/0206001

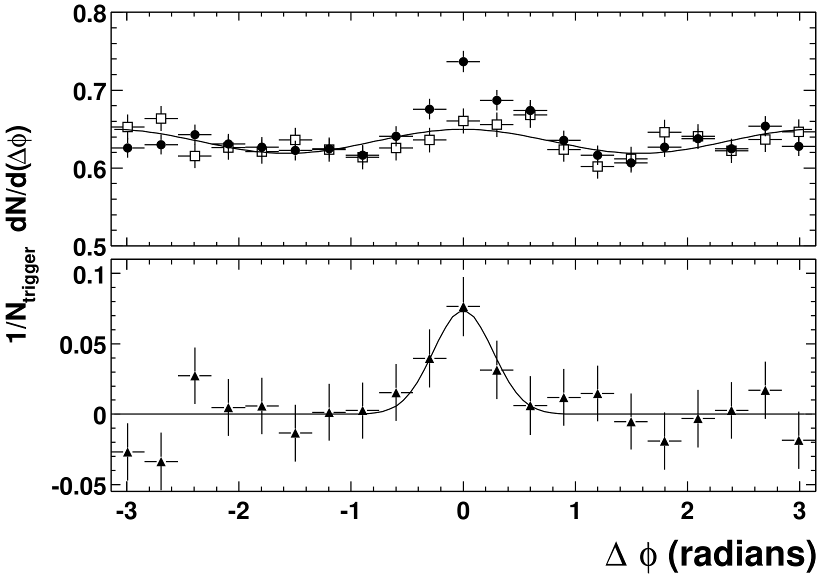


- Non-flow correlations appear at larger p_T at RHIC

  $\Longrightarrow$ as expected from semi-hard rescatterings

Evidence for minijets at STAR

Adler et al., nucle-ex/0206006



● : $|\eta_2 - \eta_1| < 0.5$

○ : $|\eta_2 - \eta_1| > 0.5$

△ = ● − ○

Gaussian fit:

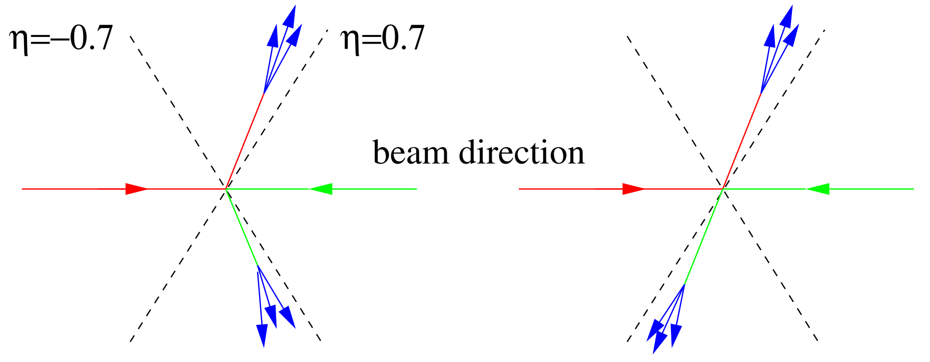
$\sigma = 0.27 \pm 0.09$ rad

$$\left.\begin{array}{lcl} \text{trigger particle} & : & 4 < p_T < 6 \\ \text{2nd particle} & : & 2 < p_T < 6 \end{array}\right\} |\eta| < 0.7$$

Remarks:

– In ●, hadrons from the same minijet are included (but also part of back-to-back minijet)

– In ○, hadrons from the same minijet are excluded (but the remaining back-to-back minijet are included)



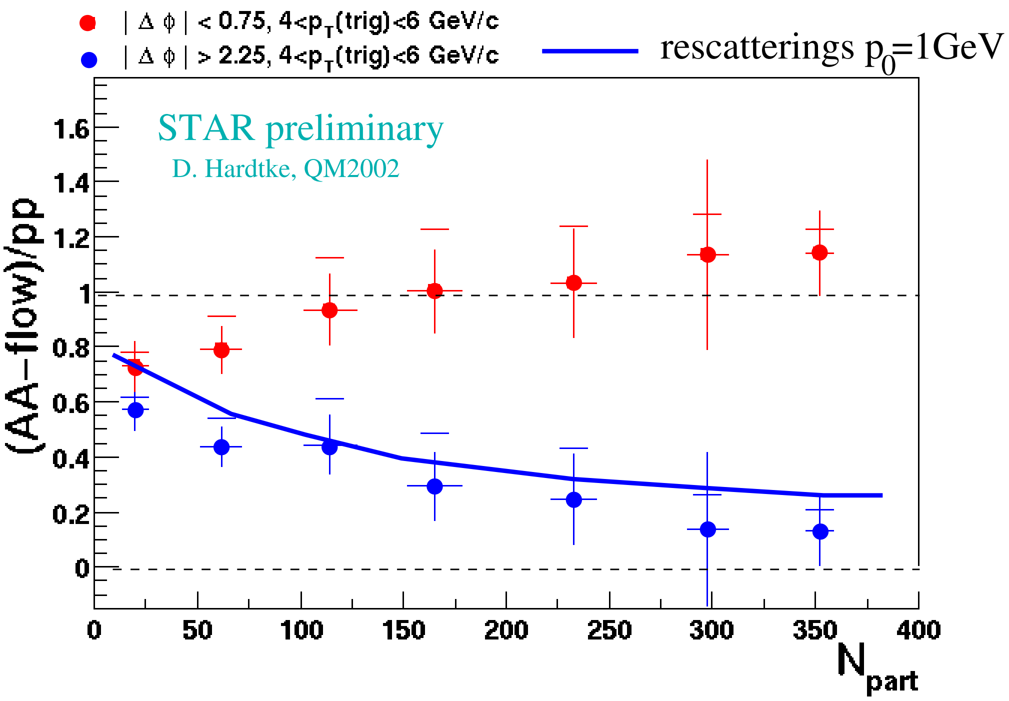
$x_1 \neq x_2 \quad |\eta_2 - \eta_1| < 0.5 \qquad x_1 = x_2 \quad |\eta_2 - \eta_1| > 0.5$

⇒ Back-to-back minijets almost cancel out in this observable

Back-to-back yield at STAR

Ratio of yield at π to scaled pp data:

$$R(b) = \frac{\Delta N_\infty^{JJ}(b)}{\Delta N_1^{JJ}(b)} \quad \text{vs.} \quad R_{\rm exp}(b) = \frac{\Delta N^{\pi\pi}(b)}{\Delta N^{\pi\pi}|_{pp} \times N_{\rm coll}(b)}$$



NOTE: • hadronization and p_T cuts not included in this computation (tempus fugit...)

• hadronization effects partly cancel in the ratio

$\Longrightarrow$ Rescatterings have good chances to account for the observed effect

COMING SOON: p_T-cuts and hadronization

CONCLUSIONS

- **Non-flow 2P correlations** observed:
  – 30% effect at CERES (p_T =1-2 GeV), 20% at STAR ((p_T =2-3 GeV)
- **Semihard parton rescatterings**
  - explain qualitatively why STAR < CERES
  - account for broadening of π-peak at CERES
  - have good chances for suppression of b-t-b yield at STAR
- **Where should we look?**
  - Centrality *OK*
  - p_T systematics
    CERES: $p_T \gtrsim$1 Gev, STAR $p_T \gtrsim$2 GeV
  - η systematics
- **Competing mechanisms** (e.g. "surface emission")
  $\Longrightarrow$ pA or dA collisions!
  (no "QGP" is formed - clean process)

Non-flow correlations vs. centrality

STAR data Adler et al., nucle-ex/0206001