QCD and JETS

an introduction

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Quantum Chromodynamics (QCD) is *the* theory of strong interactions

fundamental degrees of freedom: colored quarks and gluons are well established even though they cannot be directly observed as free particles, but only in color neutral bound states (confinement) and as jets - due to asymptotic freedom property of the QCD running coupling constant, $\alpha_s(Q^2)$, which decreases at short distances/high energies:

$$\lim_{Q^2 \to \infty} \alpha_s(Q^2) = 0$$

[D. J. Gross and F. Wilczek; H. D. Politzer (1973)]

QCD - as part of the Standard Model - is a mature subject $---->$ predictive power:

nuclear physics at ultra-relativistic energies offers unique tools to study QCD in a new domain

outline

- large $p_\perp$ physics:
  jets and high $p_\perp$ hadrons
- gluon radiation and heavy ion collisions (HIC)

  initial (Cronin enhancement) versus
  final state interaction (radiative energy loss -
  suppression/depletion of large $p_\perp$ hadrons)

references - books and reviews

1. T. Muta, *Foundations of Quantum Chromodynamics*,
   Lecture Notes in Physics – Vol. 57 (World Scientific, Singapore, 1997)
2. R.K. Ellis, W.J. Stirling and B.R. Webber, *QCD and Collider Physics*
   (Cambridge Univ. Press, Cambridge, 1996)
3. R. D. Field, *Applications of Perturbative QCD*
   (Addison-Wesley Pub. Comp., 1989)
4. J.-P. Blaizot and E. Iancu, eds., *QCD Perspectives on Hot and Dense Matter*
   (Kluwer Academic Publ., 2002)
5. Proceedings QM2004, Oakland, USA,
   Journal of Physics G: Nuclear and Particle Physics, Vol. 30, Number 8, August 2004

references, cont.

6. L. Accardi et al., CERN Yellow Report on *Hard Probes in Heavy Ion Collisions at the LHC: Jet Physics* (hep-ph/0212148)
7. A. Kovner and U. A. Wiedemann, in *Quark Gluon Plasma 3*, eds. R. C. Hwa and X.-N. Wang (World Scientific, Singapore, 2004)
8. recent experimental reviews:
   BRAHMS (nucl-ex/0410020); PHENIX (nucl-ex/0410003);
   PHOBOS (nucl-ex/0410022); STAR (nucl-ex/041...)

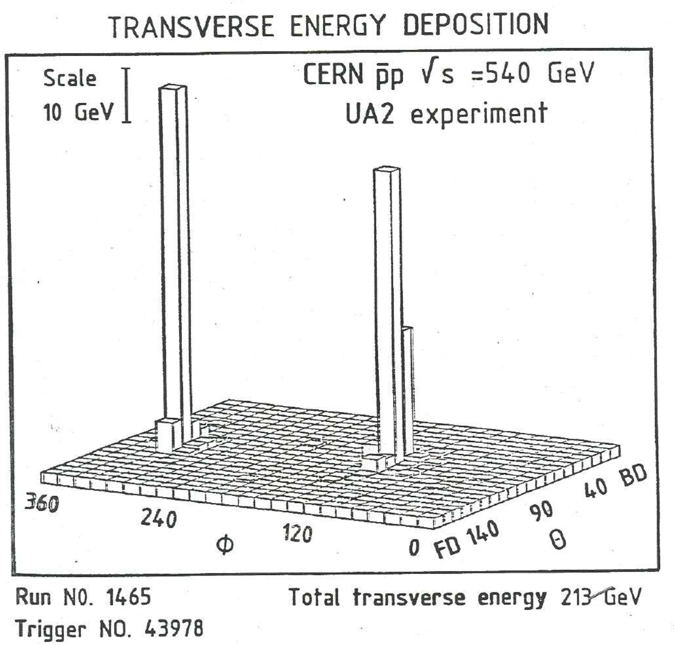
   also: www.bnl.gov/RHIC/
9. recent theoretical reviews:
   P. Jacobs and X.-N. Wang (hep-ph/0405125);
   M. Gyulassy and L. McLerran (nucl-th/0405013);
   E. V. Shuryak (hep-ph/0405066);

   J.-P. Blaizot and F. Gelis (hep-ph/0405305)
10. and extensive references therein

jets in hadron - hadron collisions

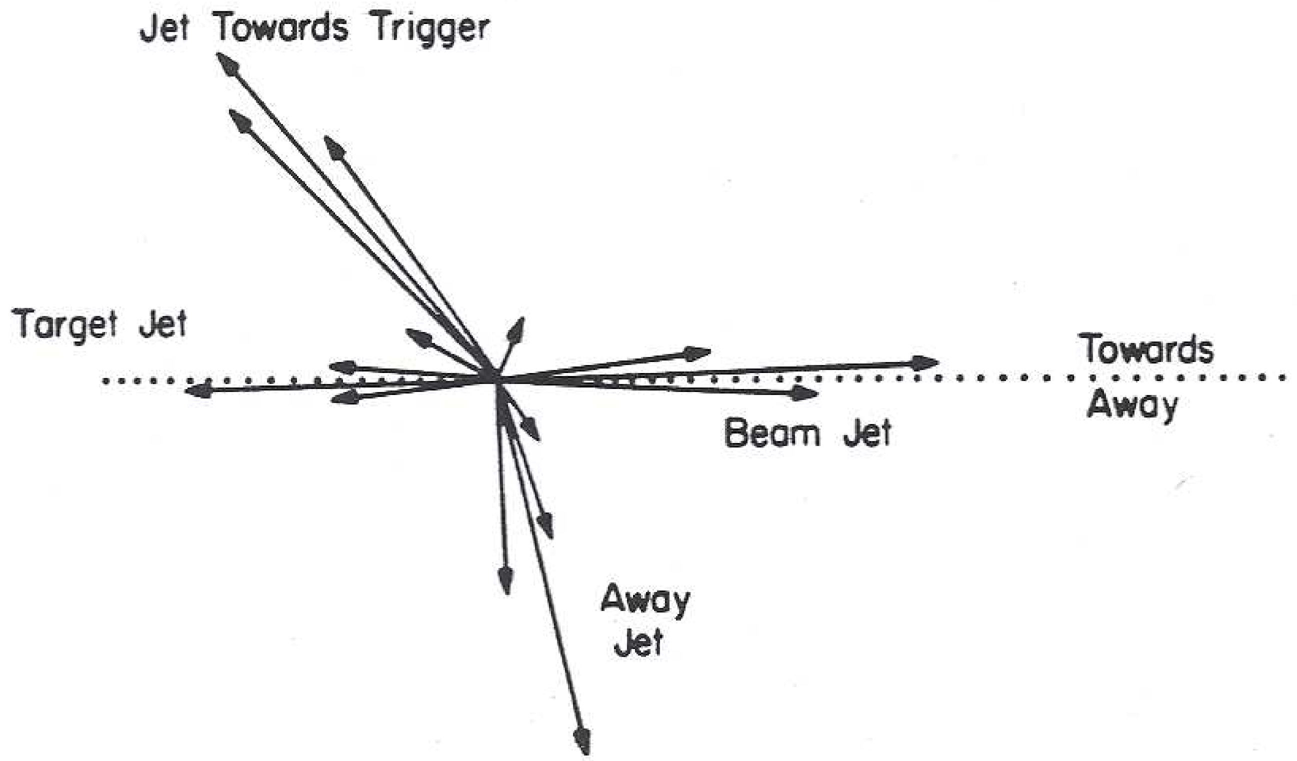
jets are NOT single particles (like photons, ..)

jets are sets of hadrons moving rapidly in nearly the same direction, following the nominal paths of the original quarks/gluons (common “soft” radiation creates new particles, but does not disrupt the flow of energy, the probability is small for emitting a quark or gluon that drastically alters the flow of momentum)



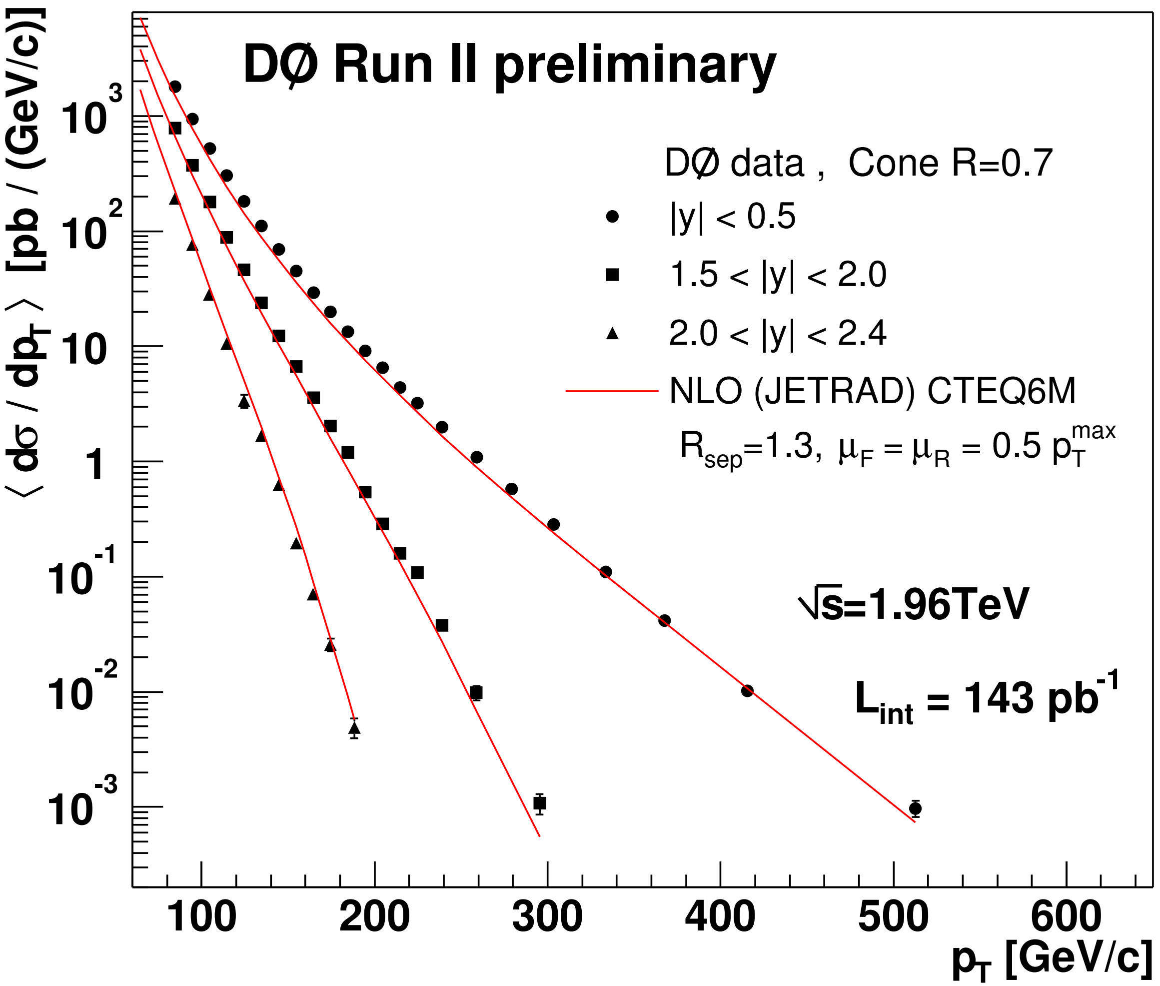
Lego towers (note: $\frac{3-jet}{2-jet} = O(\alpha_s)$)

illustration



inclusive large $p_\perp$ jets

(from R. D. Field)



jet cross section as measured by the D0 experiment, in three rapidity bins

factorization

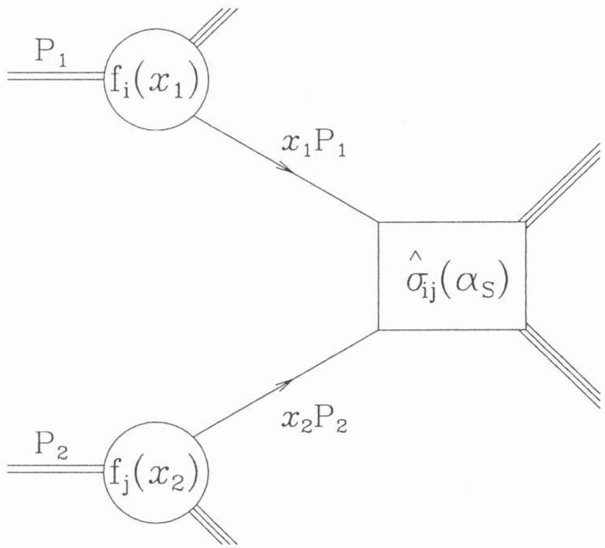


Fig. 7.1. The parton model description of a hard scattering process.

$f(x, \mu^2)$.. quark or gluon QCD distributions, σ_{ij}.. parton scattering cross section

$$\sigma(P_1, P_2) = \sum_{ij} \int dx_1 dx_2 f_1(x_1, \mu^2) f_2(x_2, \mu^2)\, \sigma_{ij}(x_1, x_2, \alpha_s(\mu^2), Q^2/\mu^2)$$

(from R. K. Ellis et al.)

diagrams for $2-2$ parton processes

7 Hadroproduction of jets and photons

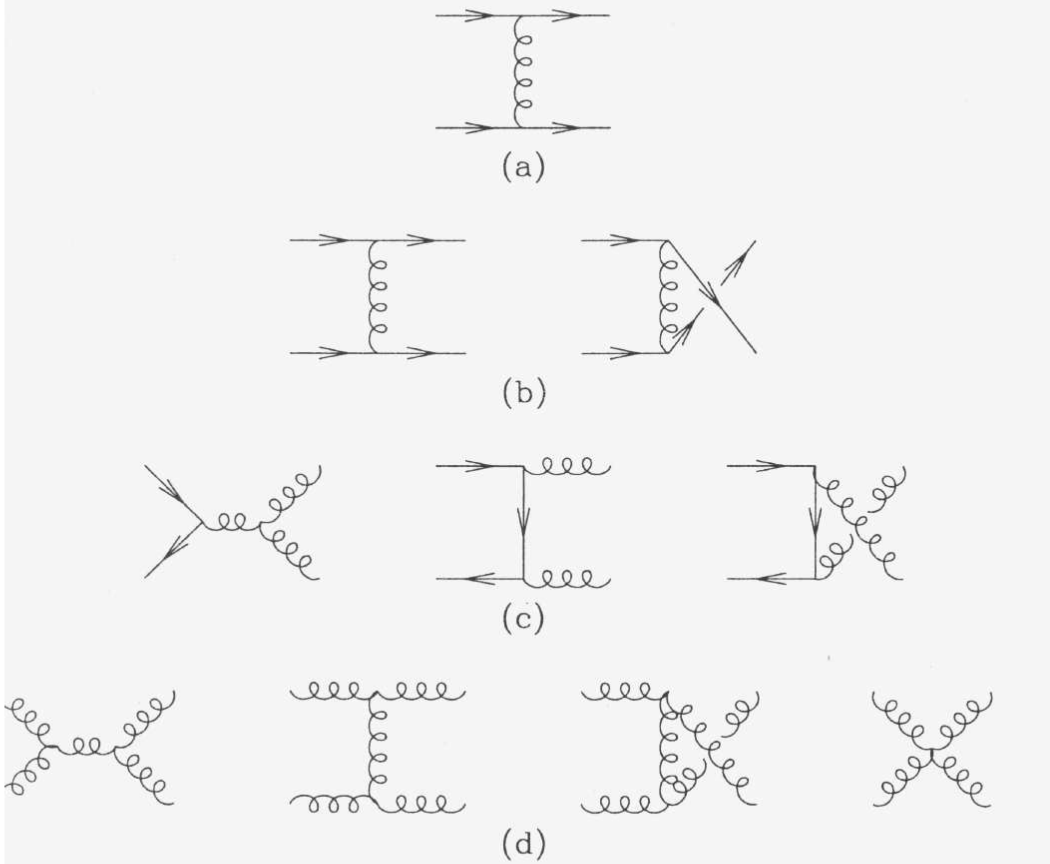
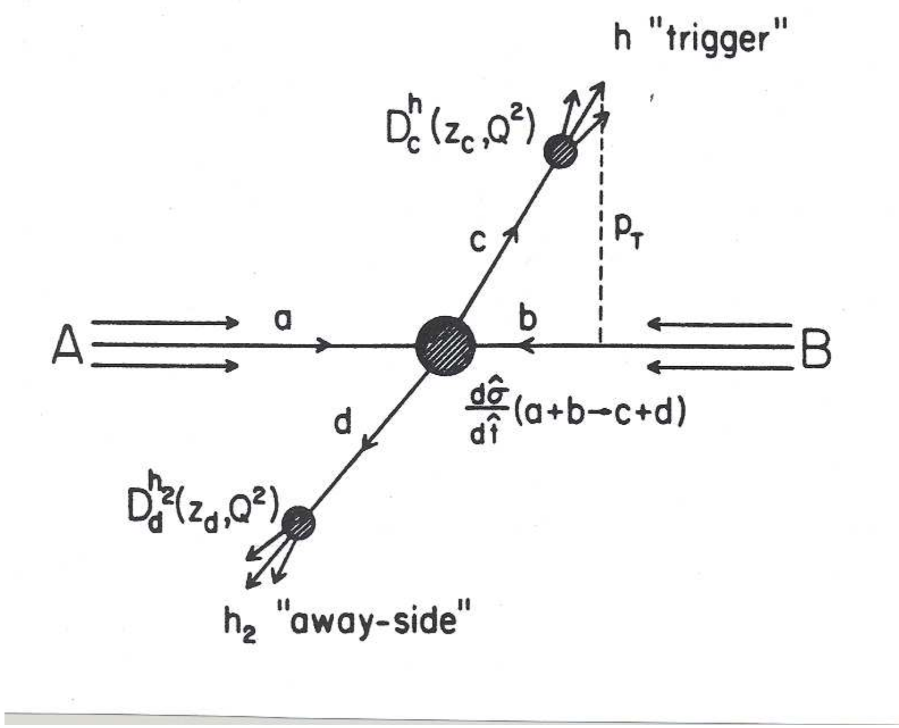


Fig. 7.6. Diagrams for jet production.

(from R. K. Ellis et al.)

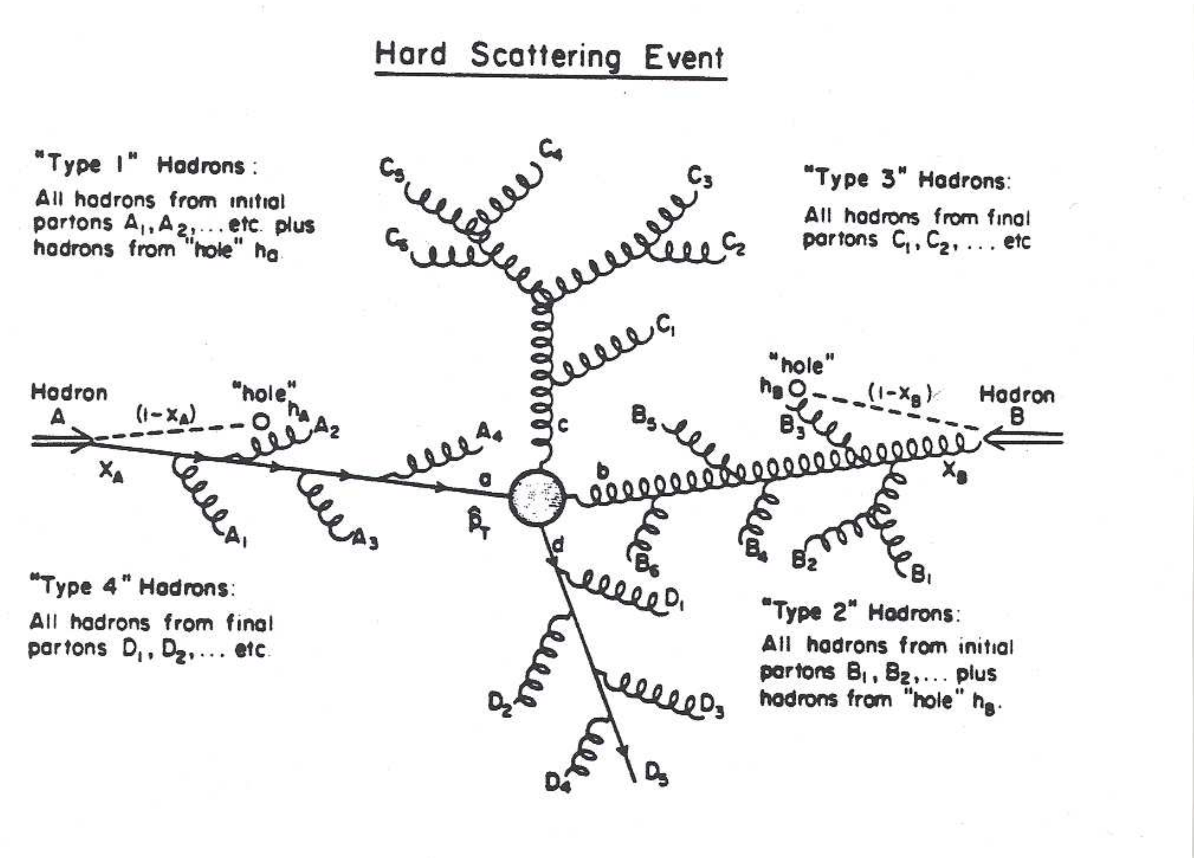
illustration, cont.



inclusive large $p_\perp$ hadron production process resulting from $2-2$ hard parton subprocess and parton $-->$ hadron fragmentation $D(z,Q^2)$

history: hard scattering in p-p collisions discovered at CERN-ISR in 1972

scaling violation



(from R. D. Field)

scaling properties

parton model - dimensional argument

$$E\frac{d\sigma}{d^3p} = \frac{1}{p_\perp^4}\, F(x_\perp = \frac{2p_\perp}{\sqrt{s}}, y) = \frac{1}{(\sqrt{s})^n}\, \tilde{F}(x_\perp, y)$$

"scaling violation" due to $\alpha_s(Q^2)$, $f(x, Q^2)$ and $D(z, Q^2)$

$$n = 4 \;\Rightarrow\; n_{eff} = n(x_\perp, y, \sqrt{s})$$

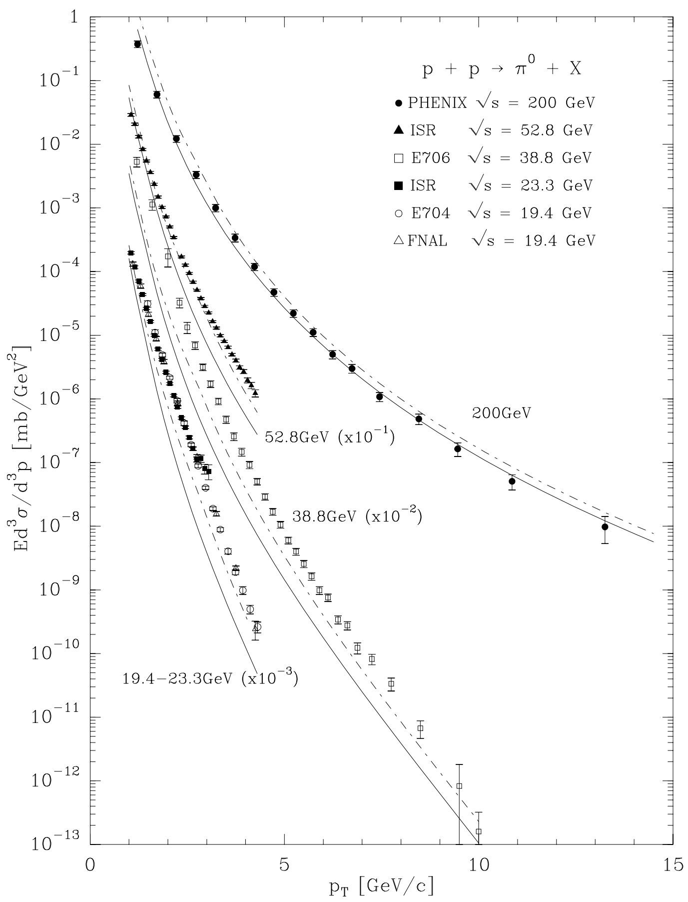
spectra: reasonably well parametrized by power-law form

$$E\frac{d\sigma}{d^3p} = A \cdot (1 + p_\perp/p_0)^{-n}$$

effective power n

system	$\sqrt{s}$ (GeV)	A (mb GeV$^{-2}c^3$)	p_0 (GeV/c)	n
$p + p \to h^{\pm}$	130	330	1.72	12.40
$p + \bar{p} \to h^{\pm}$ (NSD, UA1)	200	286	1.80	12.14
$p + p \to h^{\pm}$ (NSD, STAR)	200	286	1.43	10.35
$p + p \to \pi^0$ (inel., PHENIX)	200	386	1.22	9.99

(from D. d'Enterria)



invariant cross-sections as a function of $p_\perp$

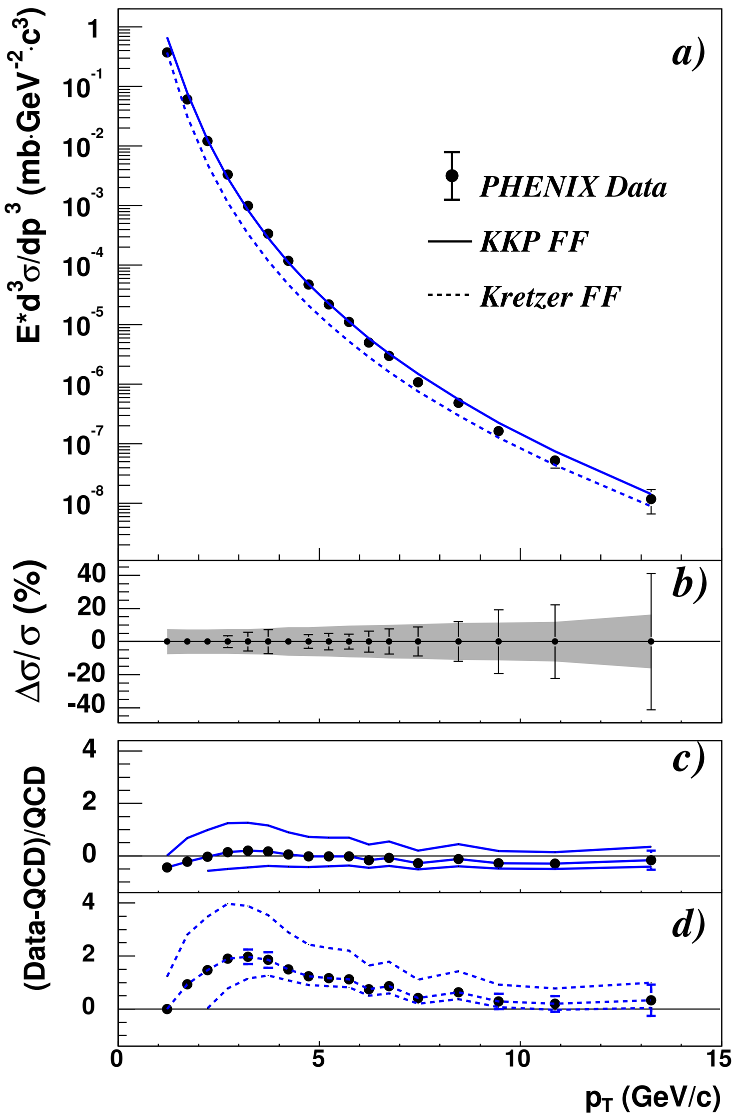
measured at midrapidity $y = 0$ in $p + p$ collisions

(compared to NLO pQCD calculations at different $\sqrt{s}$)

significant increase with energy at fixed $p_\perp$

(exploring small $x_\perp$, i.e. small x in distribution functions)

NLO pQCD



high $p_\perp$ cross section successfully compared with NLO pQCD

angular distribution

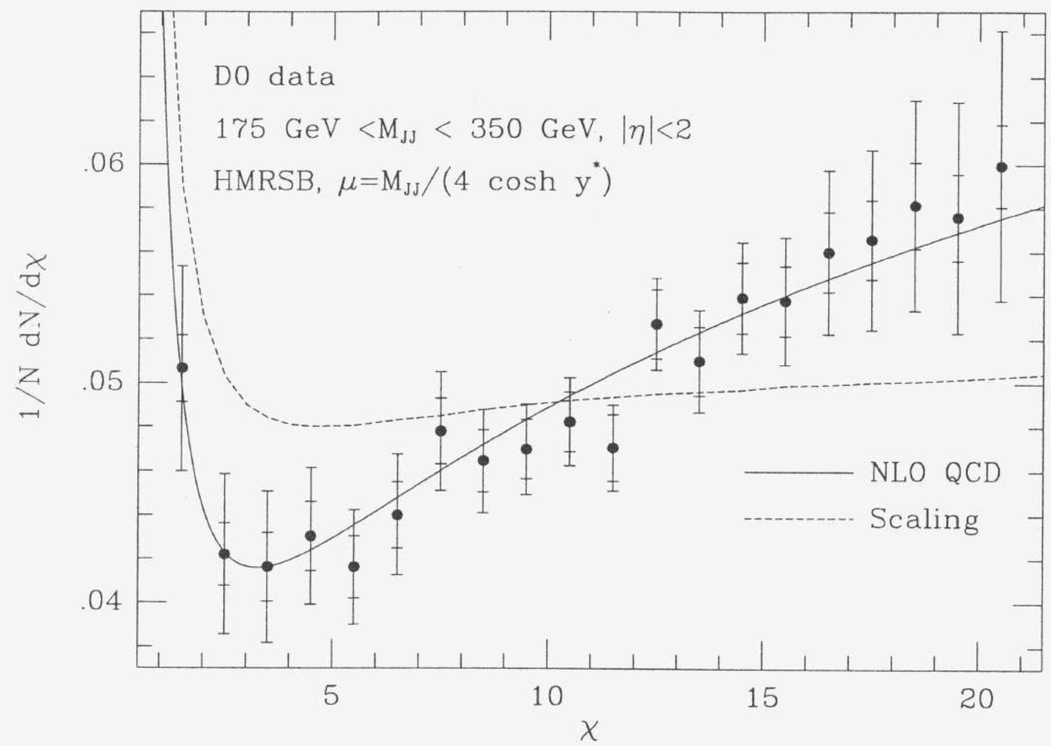


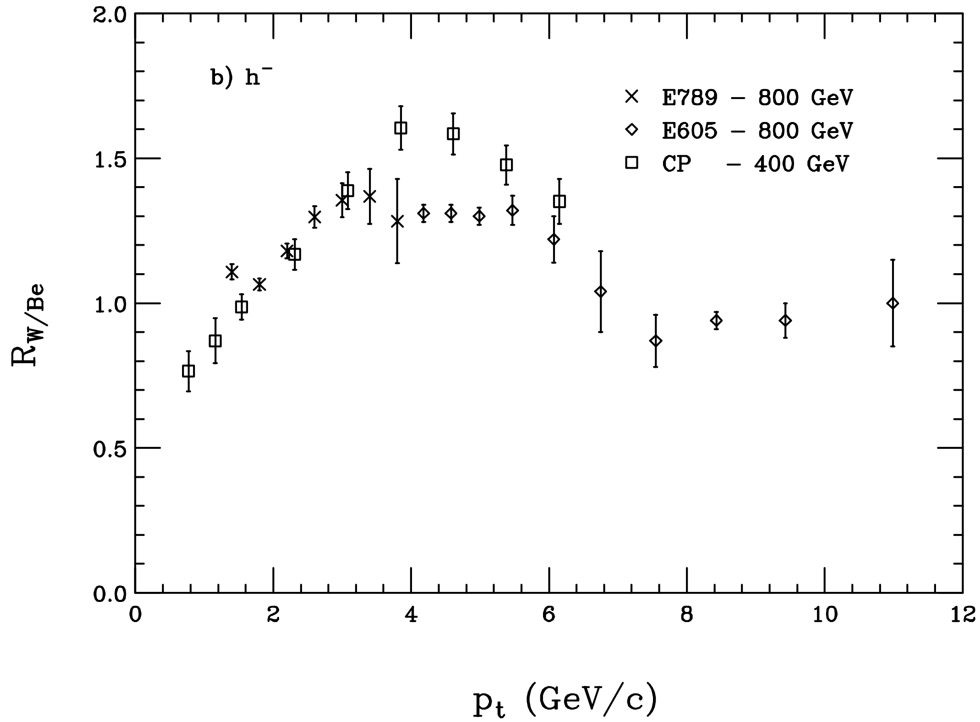
Fig. 7.9. Distribution of χ from the D0 collaboration [14] compared with QCD predictions [15].

for small CMS angle θ^* : vectorboson= gluon exchange

$$\chi = \frac{1+\cos\theta^*}{1-\cos\theta^*}, \quad \theta^* \to 0 \Rightarrow \chi \to \infty$$

Rutherford: $\frac{d\sigma}{d\chi} \sim const$

nuclear effects



Cronin effect at fixed target energies:
enhancement of particle production at intermediate $p_\perp$ in pA vs. (scaled by A) pp collisions

here: ratio of the point-like scaled cross sections in pW and pBe collisions vs. $p_\perp$

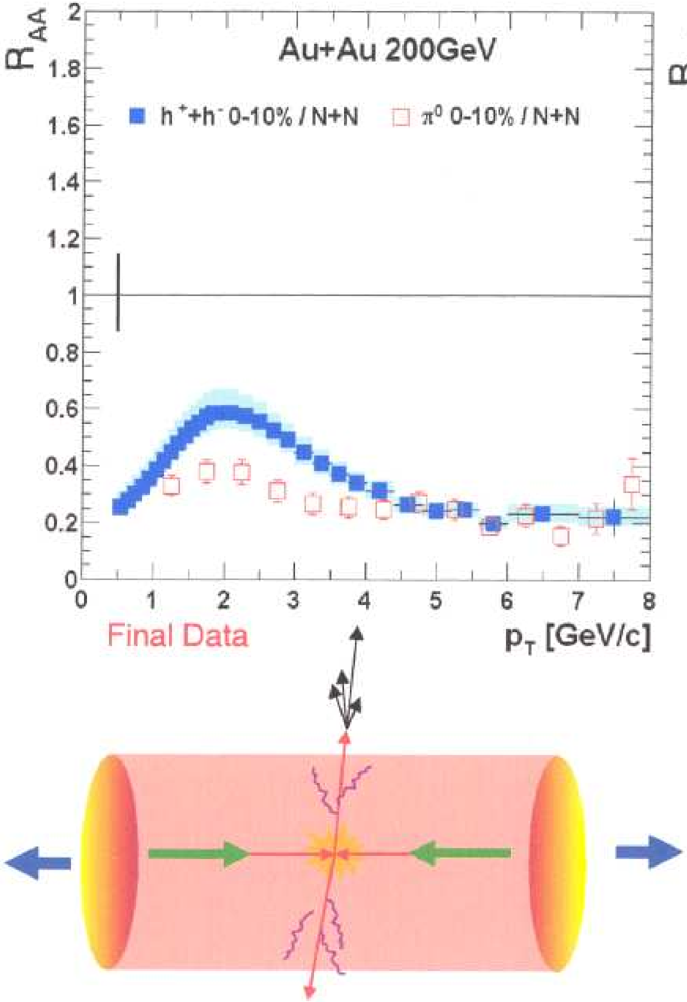
(from C. N. Brown et al.)

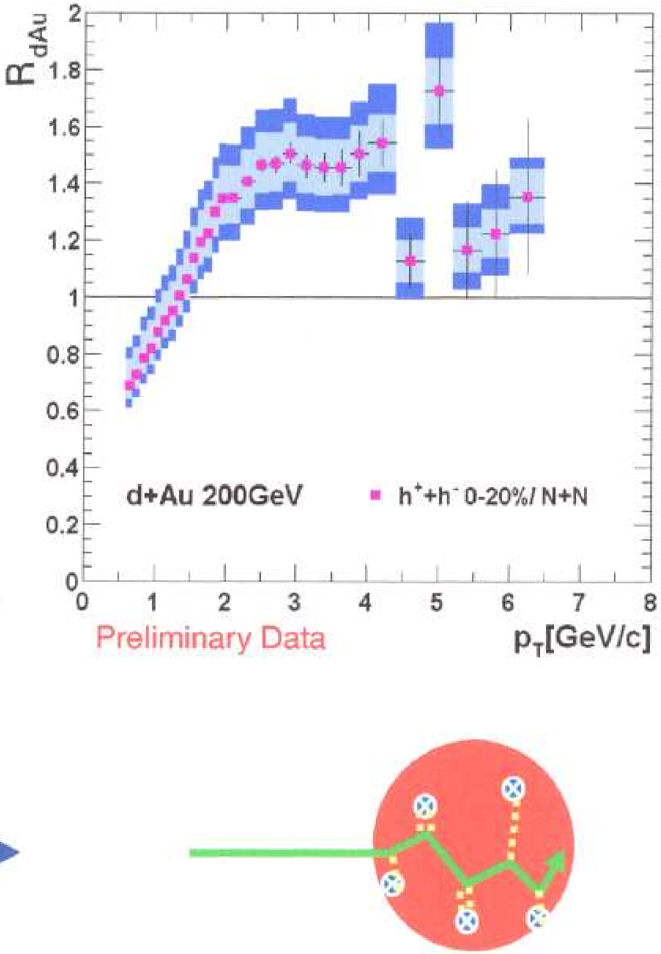
- energy of individual partons is sufficiently high for jets to be produced and detected
- high $p_\perp$ hadrons at midrapidity: suppression in gold-gold collisions
  NONE in deuteron-gold
- back-to-back jets and "out of plane" jets in $Au - Au$ collisions:
  striking evidence for suppression, e.g. one jet observed perpendicular to the reaction plane, NONE is observed in the opposite direction (completely absorbed in the medium)!
- NO similar suppression of back-to-back jet correlations observed in deuteron-gold collisions at midrapidity

Centrality Dependence: Au+Au vs. d+Au

June 03: At midrapidity, high-pt suppression is final state effect

- Final state suppression
- Initial state enhancement





(from U. A. Wiedemann)

nuclear modification factor

QCD factorization: inclusive A+B cross-sections for hard processes scales as

$$E\, d\sigma^{hard}_{AB\to h}/d^3p = A \cdot B \cdot E\, d\sigma^{hard}_{pp\to h}/d^3p$$

for impact parameter b - nuclear overlap integral $T_{AB}(b)$

$$E\, dN^{hard}_{AB\to h}/d^3p\,(b) = \langle A \cdot B \cdot T_{AB}(b)\rangle \cdot E\, d\sigma^{hard}_{pp\to h}/d^3p,$$

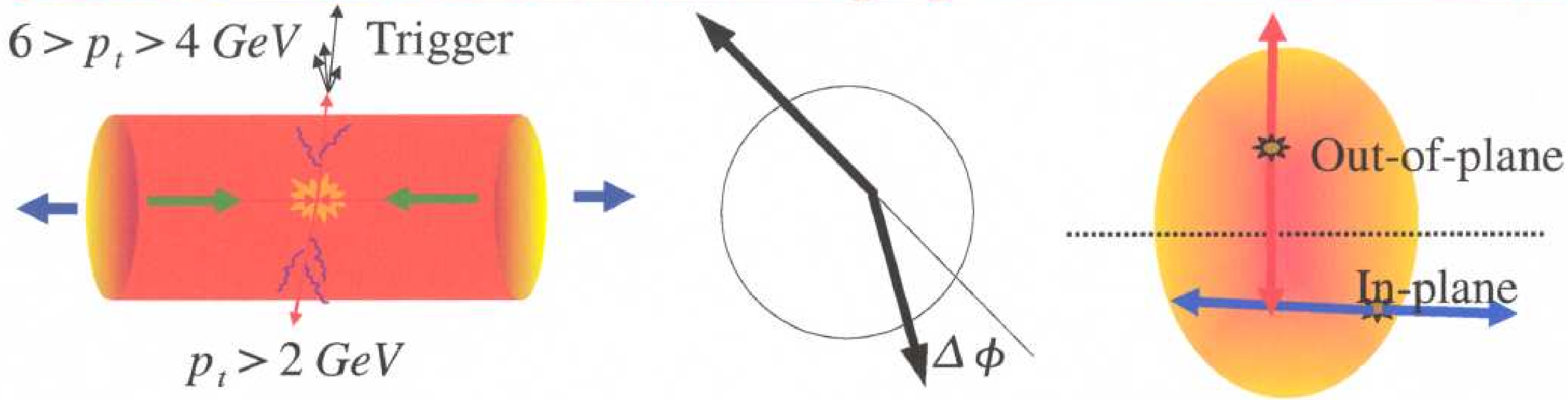
in terms of invariant yields ("N_{coll} scaling") $\langle N_{coll}(b)\rangle = \sigma_{pp}\, \langle A \cdot B \cdot T_{AB}(b)\rangle \propto A^{4/3}$:

$$E\, dN^{hard}_{AB\to h}/d^3p\,(b) = \langle N_{coll}(b)\rangle \cdot E\, dN^{hard}_{pp\to h}/d^3p$$

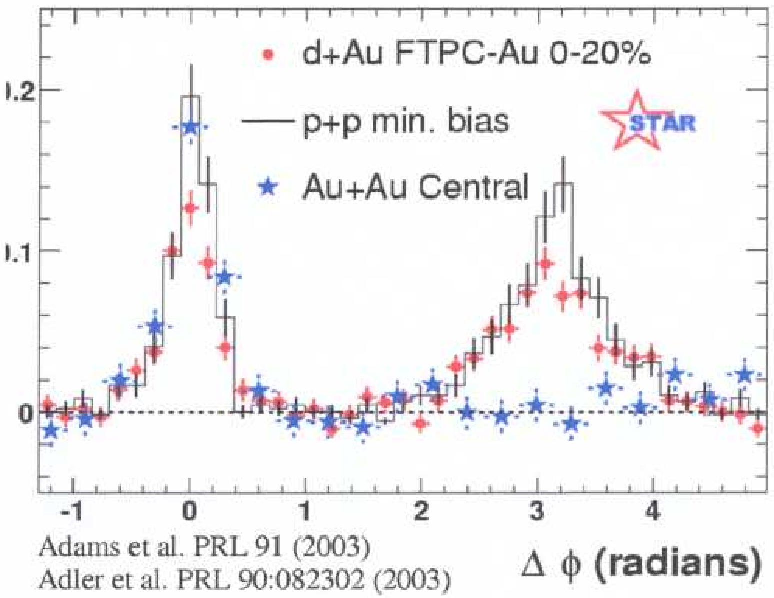
nuclear modification factor:

$$R_{AB}(p_T, y; b) \;=\; \frac{\text{" QCD medium"}}{\text{"QCD vacuum"}} \;=\; \frac{d^2N_{AB}/dydp_T}{\langle A \cdot B \cdot T_{AB}(b)\rangle\;\times\; d^2\sigma_{pp}/dydp_T}$$

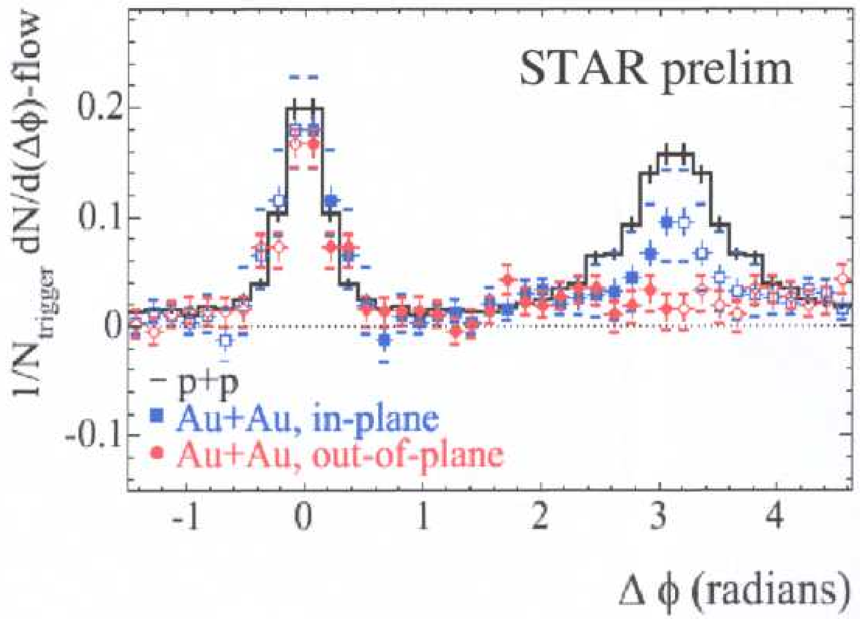
Back-to-Back Correlations: p+p vs. d+Au vs Au-Au



QM'02: dependence on centrality ; QM'04 dependence on orientation w.r.t. plane



Adams et al. PRL 91 (2003)
Adler et al. PRL 90:082302 (2003)



(from U. A. Wiedemann)

gluon radiation

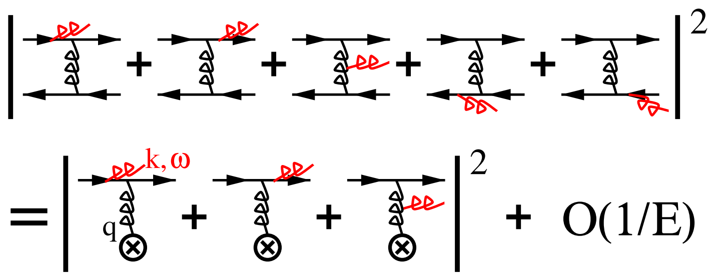
- initial state ($p_\perp$ broadening)
-final state (energy loss/jet quenching)

gluon emission

well-known Gunion-Bertsch radiation cross section in the high energy limit for gluon radiation in quark-quark (gluon-gluon, gluon-quark) scattering

$$k^0 \frac{d\sigma^{\rm GB}}{d^3k} = \frac{N_c\,\alpha_s}{\pi^2}\,\frac{1}{k_\perp^2} \int d^2q_\perp\, \frac{\alpha_s}{q_\perp^2}\, \frac{\alpha_s}{(\vec{k}_\perp - \vec{q}_\perp)^2}$$

($k_\perp$ – factorisation)



(from A. Kovner and U. A. Wiedemann)

produced number of gluons:

$$N^{GB}_{\rm prod}(\vec{k}) = \omega \frac{dI^{GB}}{d\omega d^2k_\perp} \propto \alpha_s \int d^2q_\perp \left[\frac{1}{\sigma}\frac{d\sigma}{d^2q_\perp}\right] \frac{q_\perp^2}{k_\perp^2\,(\vec{k}_\perp - \vec{q}_\perp)^2} \propto \frac{\alpha_s \mu^2}{k_\perp^4}$$

multiple scattering in hadron-nucleus collision

$p_\perp (k_\perp)$ broadening on path z - average (characteristic) width

$$< k_\perp^2(z) > \quad = \quad \frac{Q_s^2}{L}\, z = \hat{q} z$$

$$= (\rho \int d^2k_\perp\, k_\perp^2 \, \frac{d\sigma}{d^2k_\perp})\, z \quad = \quad (\rho\sigma\mu^2)\, z = (\frac{\mu^2}{\lambda})\, z$$

i.e. random walk - transport coefficient: $\hat{q}$

μ... screening mass, $\lambda = 1/\rho\sigma$.... mean free path

from Gaussian:

$$< k_\perp^2(z) > \simeq \int d^2k_\perp\, k_\perp^2 \, \frac{1}{\pi z (Q_s^2/L)} \exp\left[- \frac{k_\perp^2}{z(Q_s^2/L)} \right]$$

with saturation scale:

$$Q_s^2/L \simeq \frac{4\pi^2 \alpha_s N_c}{N_c^2 - 1}\, (\rho\, xG(x, Q_s^2))$$

ρ.. nuclear density, $xG = xG_{\mathrm{nucleon}}$ gluon in the nucleon

survival probability

consider: probability distribution $f(z, \vec{k}_\perp)$ for the gluon (at longitudinal coordinate z and with transverse momentum $\vec{k}_\perp$) passing through a nucleus

master equation ("- loss + gain"):

$$\frac{\partial f(z, \vec{k}_\perp)}{\partial z} = -\frac{1}{\lambda} \int d^2 k'_\perp V(\vec{k}_\perp - \vec{k}_\perp{}') f(z, \vec{k}_\perp) + \frac{1}{\lambda} \int d^2 k'_\perp V(\vec{k}_\perp{}' - \vec{k}_\perp) f(z, \vec{k}'_\perp)$$

$$= -\frac{1}{\lambda} f(z, \vec{k}_\perp) + \frac{1}{\lambda} \int d^2 k'_\perp V(\vec{k}_\perp{}') f(z, \vec{k}_\perp - \vec{k}'_\perp)$$

initial condition:

$$f(0, \vec{k}_\perp) = \delta(\vec{k}_\perp)$$

e.g. gluon-quark (medium) scattering potential:

$$V(\vec{k}_\perp) = \frac{1}{\sigma} \frac{d\sigma}{d^2 k_\perp} = \frac{\mu^2}{\pi (k_\perp^2 + \mu^2)^2}, \quad \sigma \simeq \frac{2\pi \alpha_s^2}{\mu^2}$$

[from BDMS]

Fourier transform

transverse coordinate $\vec{x}_\perp$:

$$\tilde{f}(z,\vec{x}_\perp) = \int d^2k_\perp e^{-i\vec{k}_\perp\cdot\vec{x}_\perp} f(z,\vec{k}_\perp)$$

$$\Rightarrow \frac{\partial \tilde{f}(z,\vec{x}_\perp)}{\partial z} = -\frac{1}{\lambda}\underbrace{[1-\widetilde{V}(\vec{x}_\perp)]}\,\tilde{f}(z,\vec{x}_\perp)$$

$$\text{Gaussian} \Rightarrow \tilde{f}(z,\vec{x}_\perp) = \exp\left[-\frac{z}{L}\,\vec{x}_\perp^{\,2}\,Q_s^2/4\right]$$

$$\text{momentum space}: \Rightarrow f(z,\vec{k}_\perp) = \frac{1}{\pi z(Q_s^2/L)}\exp\left[-\frac{k_\perp^2}{z(Q_s^2/L)}\right]$$

$$\frac{Q_s^2}{L} = \frac{4[1-\widetilde{V}(\vec{x}_\perp)]/\lambda}{x_\perp^2} \underset{\vec{x}_\perp\to 0}{\simeq} \rho\sigma\mu^2\ln\frac{Q^2}{\mu^2} \approx \frac{\alpha_s}{N_c}\,\rho x G(x,1/x_\perp^2)$$

Kovchegov - Mueller model

produced gluon number spectrum

multiple scatterings (i.e. gluon exchange potential $V(\vec{q}_\perp) \to$ Gaussian for $z = L$):

$$N_{\rm prod}(\vec{k}) \propto \alpha_s \int \frac{d^2 q_\perp}{Q_s^2} \exp\left[-\frac{q_\perp^2}{Q_s^2}\right] \frac{q_\perp^2}{k_\perp^2 (\vec{k}_\perp - \vec{q}_\perp)^2}$$

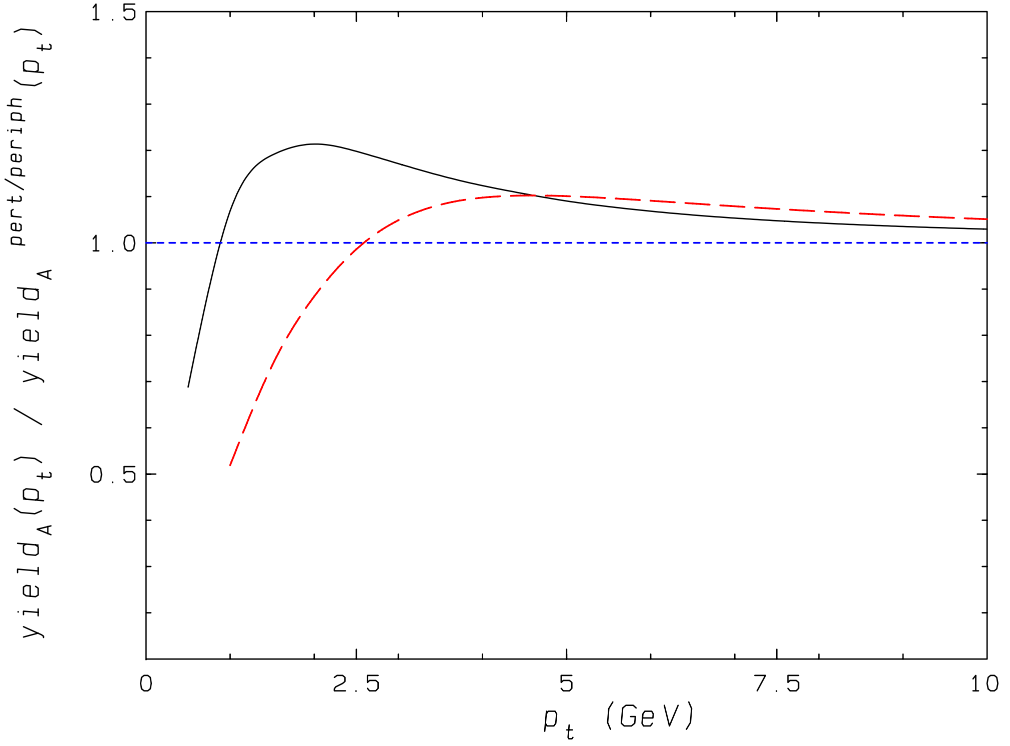
relation to dipole model formalism by Fourier transform

$$\propto \alpha_s \int d^2 x_\perp \, d^2 y_\perp \, e^{i\vec{k}_\perp \cdot (\vec{x}_\perp - \vec{y}_\perp)} \frac{\vec{x}_\perp \cdot \vec{y}_\perp}{x_\perp^2 \, y_\perp^2}$$

$$\times \left(1 + e^{-(\vec{x}_\perp - \vec{y}_\perp)^2 \frac{Q_s^2}{4}} - e^{-x_\perp^2 \frac{Q_s^2}{4}} - e^{-y_\perp^2 \frac{Q_s^2}{4}}\right)$$

$$\text{with} : \frac{\vec{k}_\perp}{k_\perp^2} = \frac{-i}{2\pi} \int d^2 x_\perp \, e^{i\vec{k}_\perp \cdot \vec{x}_\perp} \frac{\vec{x}_\perp}{x_\perp^2}$$

Cronin effect



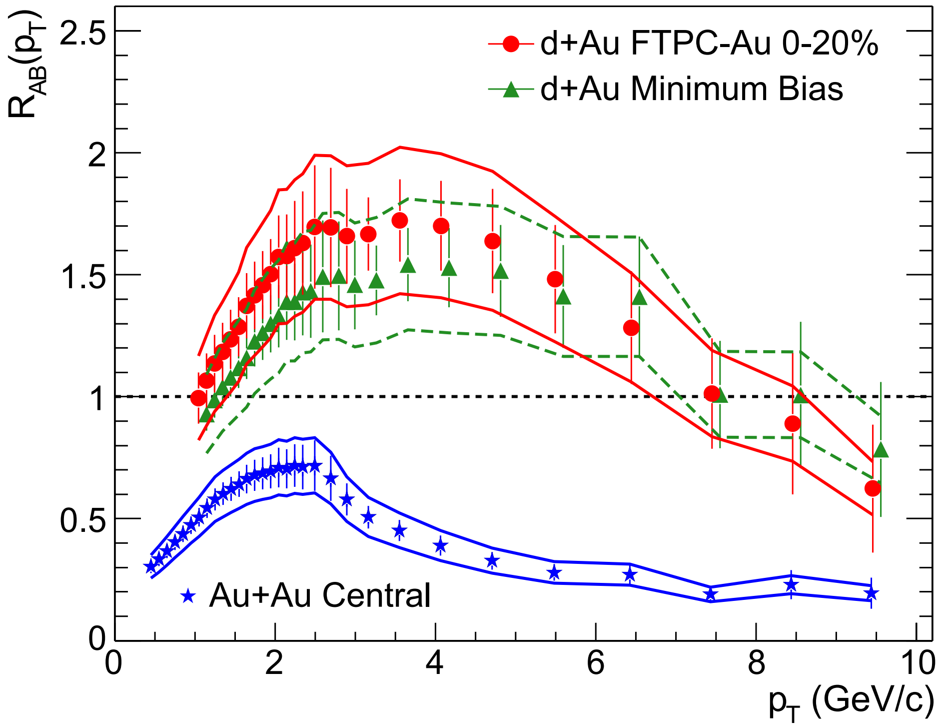
Cronin effect in p_t dependence of gluon production yields for p-A collisions

Solid curve for the McLerran - Venugopalan gluon distribution in the k_t factorized cross section;

dashed: Kovchegov - Mueller model, ($Q_s^2 \simeq 2\ \mathrm{GeV}^2$)

(from R. Baier, A. Kovner and U.A. Wiedemann)

RHIC data



STAR Collaboration: $R_{AB}(p_T)$ for minimum bias and central d+Au collisions (“Cronin effect”), and central Au+Au collisions (“suppression”). The bands show the normalization uncertainties.

energetic gluon / quark jets

produced in hard collisions at very early times in A - A collisions,
when propagating through partonic matter
- suffer

- elastic scattering [J. D. Bjorken (1982)]:
  elastic ("ionization") loss in medium of energy density ϵ
  QGP: $-\frac{dE}{dz} \sim \alpha_s \sqrt{\epsilon} <$ string tension ~ 1 GeV/fm

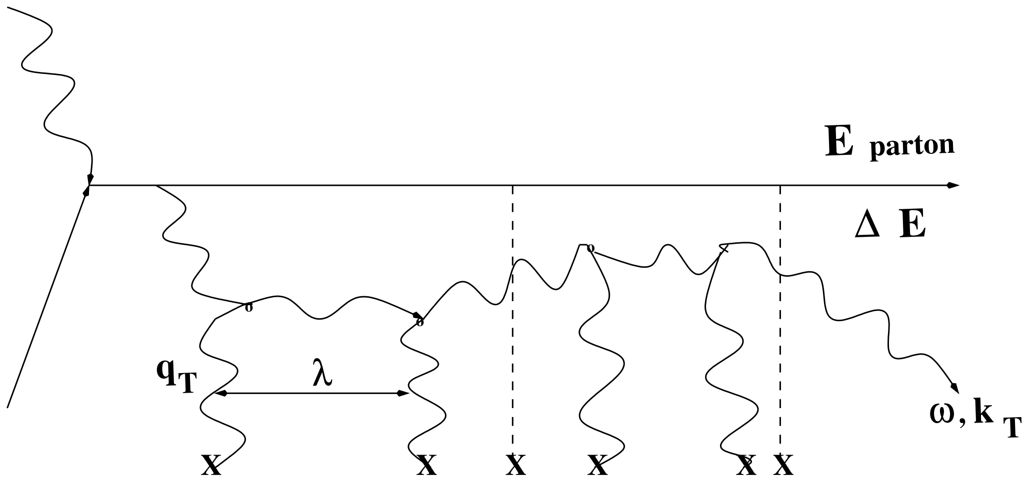
- inelastic multiple scatterings [M. Gyulassy and X.-N. Wang (1994)] $\Rightarrow$ gluon radiation
  $\Longrightarrow$

high momentum jet and leading hadron spectra are
suppressed / depleted / quenched / becoming extinct

indeed significant jet quenching observed at RHIC energies

ZIG-ZAG gluon in (large) finite size L medium

$E_{\rm parton} \to \infty$, loss ΔE



typical gluon radiation diagram with dominant gluon multiple scatterings

mean free path $\lambda > \frac{1}{\mu}$ range of screened gluon interaction

from BDMPS (1995), B. G. Zakharov, U. A. Wiedemann, ...

reviews: R. Baier, D. Schiff and B. G. Zakharov (2002)

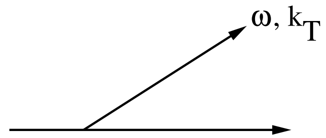
A. Kovner and U. A. Wiedemann (2004); M. Gyulassy and X.-N. Wang (2004)

time scales

formation time and coherence length

t_{form} : on-shell quark and gluon well separated

$E >> \omega >> k_\perp,\ E \to \infty$



$$t_{form} \sim \frac{E}{\sqrt{p\cdot k}}\frac{1}{\sqrt{p\cdot k}} \sim \frac{2\omega}{k_\perp^2}$$

multiple interactions: - group of scattering centers acts as ONE source of radiation

- defines t_{coh}

$$t_{form} \equiv \underline{t_{coh}} \simeq \frac{\omega}{\langle k_\perp^2\rangle|_{t_{coh}}} \simeq \frac{\omega}{\mu^2 t_{coh}/\lambda}$$

random walk:

$$\langle k_\perp^2\rangle|_{t_{coh}} \simeq N_{coh}\mu^2 \simeq \frac{t_{coh}}{\lambda}\,\mu^2 \implies t_{coh} \simeq \sqrt{\frac{\lambda\omega}{\mu^2}}$$

$N_{coh} =$ number of coherent scatterings

$\hat{=}$ scattering centers which participate coherently in the gluon emission with energy ω

- nonabelian properties of gluons
- average energy loss from (soft) gluon radiation:

$$\Delta E = \int^{\omega_c} \frac{\omega dI}{d\omega} d\omega \simeq \alpha_s \, \omega_c, \;\; \omega_c = \frac{1}{2}\hat{q}L^2$$

- transport coefficient:

$$\hat{q} \simeq \mu^2/\lambda \simeq \rho \int d^2q_\perp q_\perp^2 d\sigma/d^2q_\perp$$

ρ ... density of medium, σ ... gluon-medium (nucleus, partons) interaction

- random walk due to multiple scatterings: accumulated $k_\perp^2 \simeq N_{coh}\mu^2$
- number of coherent scatterings: $N_{coh} \simeq t_{coh}/\lambda \simeq \sqrt{\omega/\mu^2\lambda} >> 1$
- coherence/formation time: $t_{coh} \simeq \omega/k_\perp^2 \simeq \sqrt{\omega\lambda/\mu^2} \simeq \sqrt{\omega/\hat{q}}$

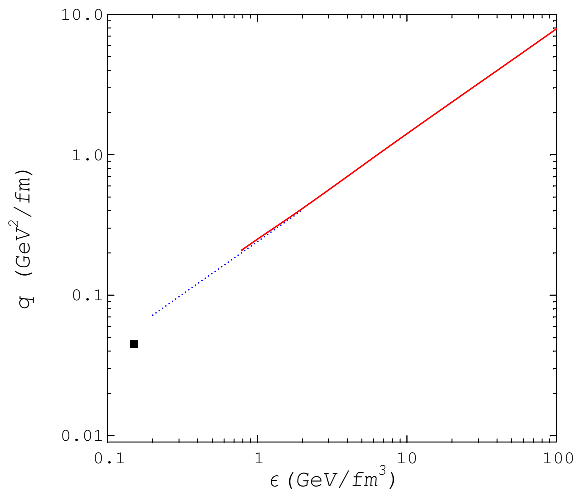
- soft spectrum: $\frac{\omega dI}{d\omega dz} \simeq \frac{1}{t_{coh}} \frac{\omega dI^{GB}}{d\omega} \simeq \frac{\alpha_s}{t_{coh}} \simeq \alpha_s \sqrt{\hat{q}/\omega}$

medium dependence of transport coefficient $\hat{q}$

equilibrated media:

nuclear matter - (massless) pion gas - (ideal) QGP

QGP : density $\rho(T) \sim T^3 \sim$ energy density $\epsilon^{\frac{3}{4}}$



how to "see" a **phase transition** at $\epsilon \simeq O\ (1\text{Gev/fm}^3)$?

expect instead: "smooth" increase of $\hat{q}$ with increasing energy density of the medium, and

$$\hat{q}|_{\text{hot}} >> \hat{q}|_{\text{nuclear matter}}$$

energy loss is increasing with energy density of the medium

how to "measure" energy loss $\Delta E(L)$?

inclusive large $p_\perp$ hadrons in $A-A$ collisions: shift of leading particle/pion

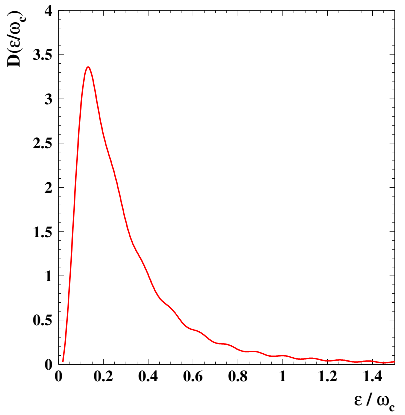
$\Rightarrow$ additional suppression of real gluon emission by trigger bias

due to steeply falling (parton) spectrum: $\frac{d\sigma^{\text{vacuum}}(p_\perp)}{dp_\perp^2} \propto \frac{1}{p_\perp^n}$ at RHIC $n \sim 12$

probability $D(\epsilon)$ that radiated gluons carry away the energy ϵ,

assume independent emission of soft primary gluons:

$D(\epsilon)$ peaks at small gluon energies $\epsilon < \omega_c = \frac{\hat{q}}{2} L^2$



[from F. Arleo]

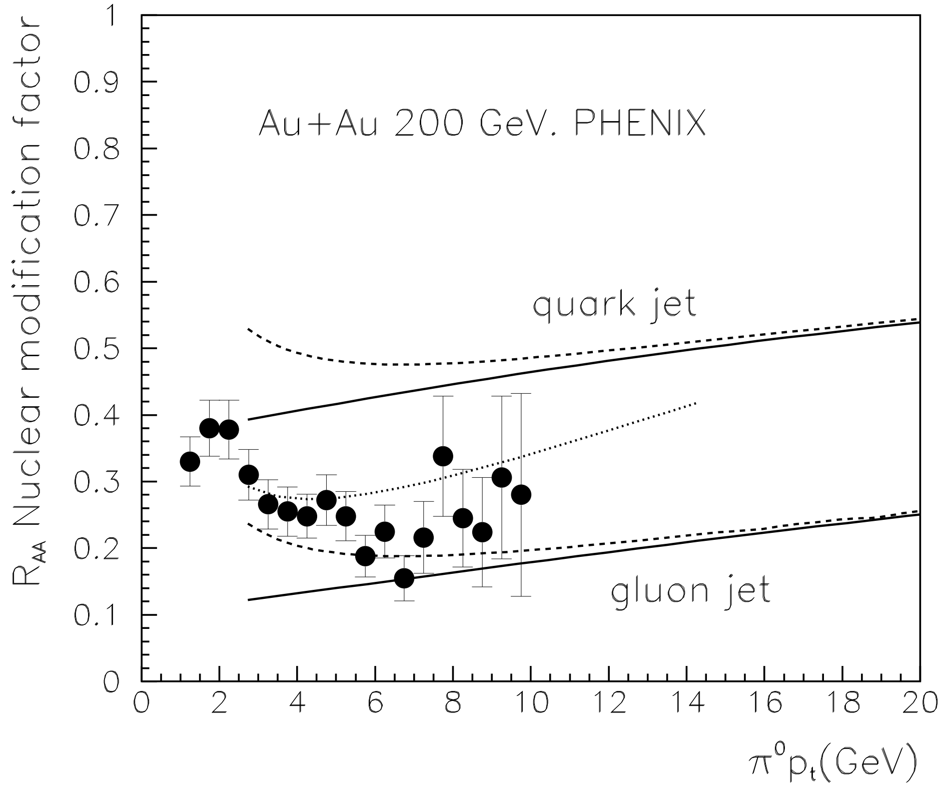
convolution with the production cross section:

$$\frac{d\sigma^{\text{medium}}(p_\perp)}{dp_\perp^2} \simeq \int d\epsilon\, D(\epsilon)\, \frac{d\sigma^{\text{vacuum}}(p_\perp+\epsilon)}{dp_\perp^2} \simeq \frac{d\sigma^{\text{vacuum}}(p_\perp+S(p_\perp))}{dp_\perp^2}$$

$S(p_\perp) <$ average loss ΔE !

(from BDMS)

comparison with data

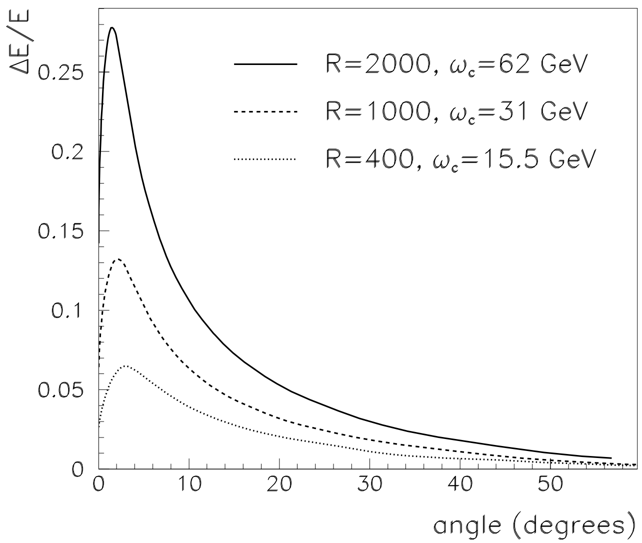


nuclear modification factor for π^0-production compared to model calculations involving parton energy loss (dashed lines take into account finite energy cuts)

dotted line: fractional contribution from quarks and gluons to final pions

(from C. A. Salgado and U. A. Wiedemann)

jets - radiation cone



average energy loss radiated outside a cone of angle θ for a quark jet with $E = 100$ GeV

typical gluon emission angle:

$$\theta^2 \simeq 1/\hat{q}L^3 (\simeq 1/R)$$

from $\omega \simeq \omega_c \simeq \hat{q}L^2, k_\perp^2 \simeq \hat{q}L$ and $\theta \simeq k_\perp/\omega$

(from U. A. Wiedemann, BDMS)

What have we learned from jets and large $p_\perp$ hadrons as hard probes about QCD matter ?

- **pQCD describes production of jets and large $p_\perp$ hadrons** via quarks and gluons
- **Genuine pQCD phenomenon:**

  gluon radiation and gluon multiple scatterings
- **Energy loss of high energy partons is dominated by gluon radiation and rescattering**
- **Importance of trigger bias in - quenched/depleted - large $p_\perp$ hadron spectra**
- **Medium modified jet shapes**
- **Large $p_\perp$ hadron data for nucleon-nucleus and nucleus-nucleus collisions**

  BNL RHIC: BRAHMS, PHENIX, PHOBOS and STAR Collaborations
- **Formation of dense partonic matter**

  which (expanding) QCD medium is probed by final state interactions of partons ?

more to learn during the following days of the conference