Intrinsic k_T
in LO, NLO pQCD calculations
in the collinear approach
in pp, pA and AA collisions

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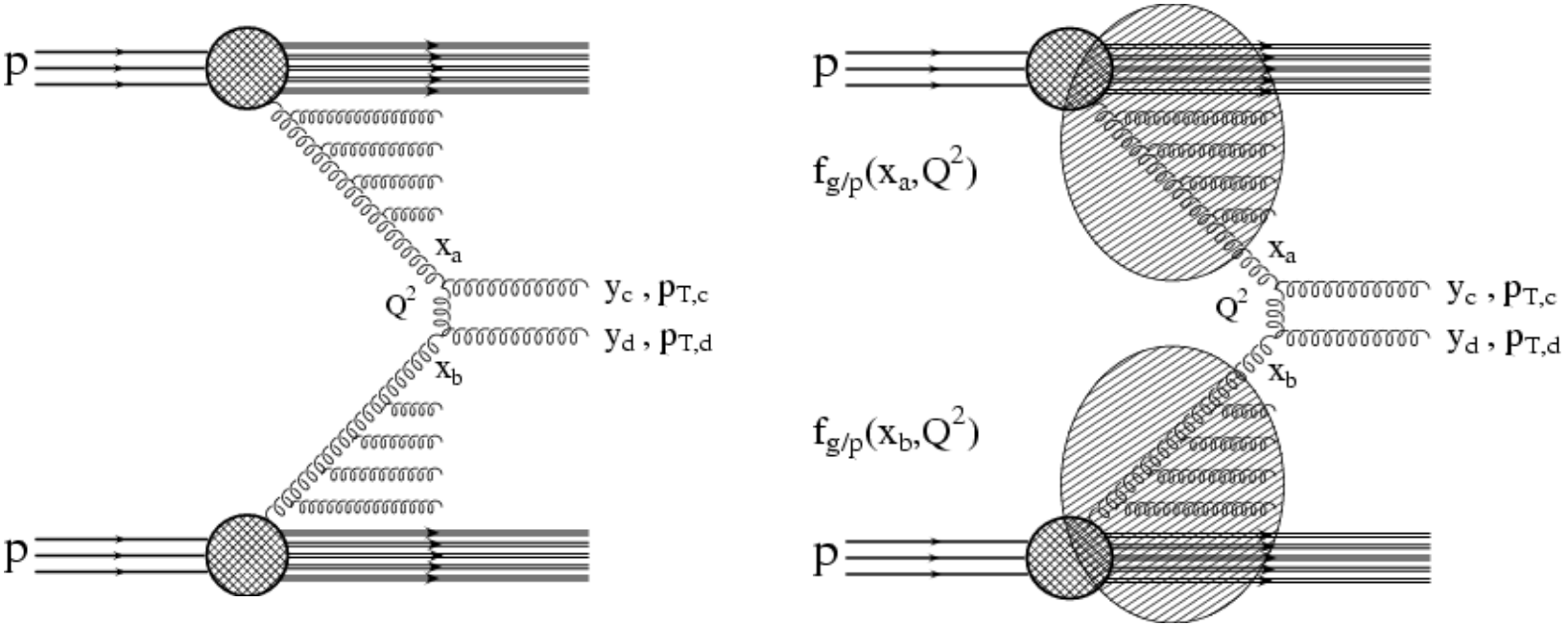
Budapest - Kent Collaboration

LUND Small-x Meeting, DESY Hamburg
7 May 2004

Explanation for the most boring title of the LUND Small-x Meeting – 1

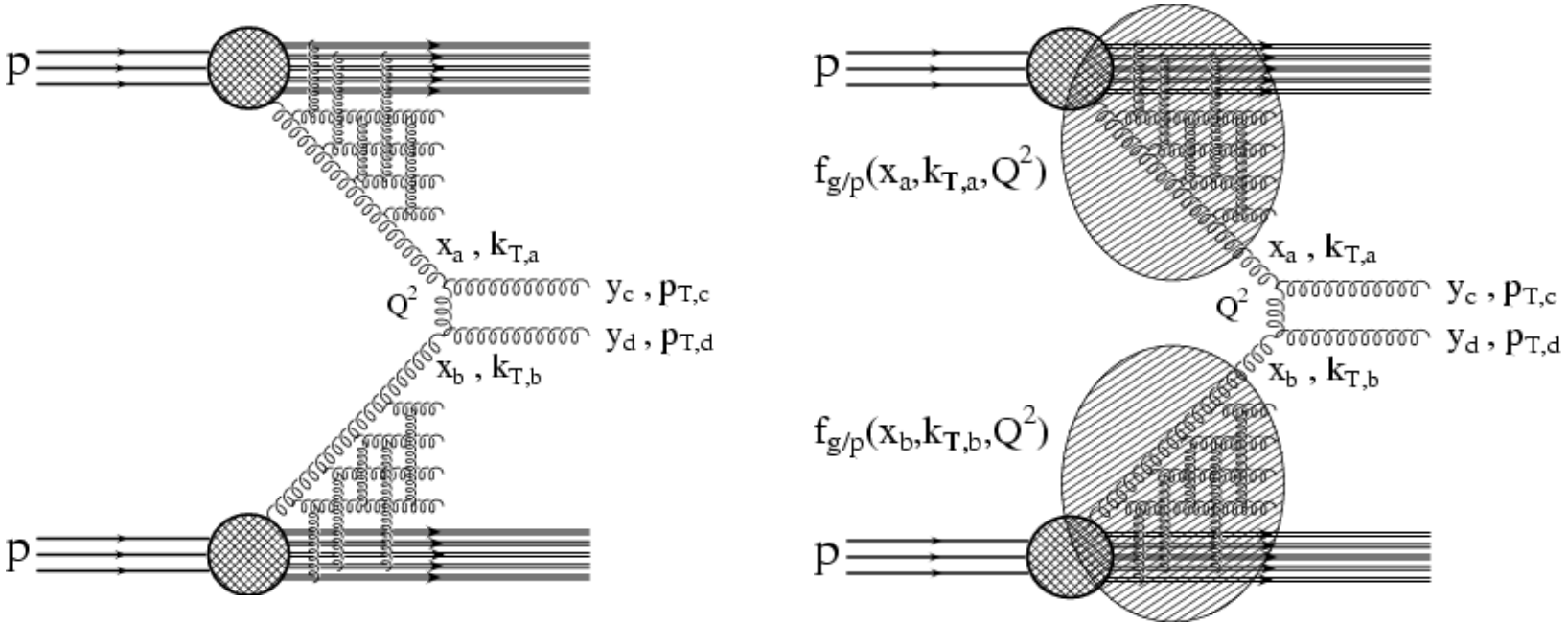
p + p collisions at CERN SPS, FERMILAB, RHIC, LHC energies



Collinear approximation + pQCD cross sections

Explanation for the most boring title of the LUND Small-x Meeting – 2

p + p collisions at CERN SPS, FERMILAB, RHIC, LHC energies

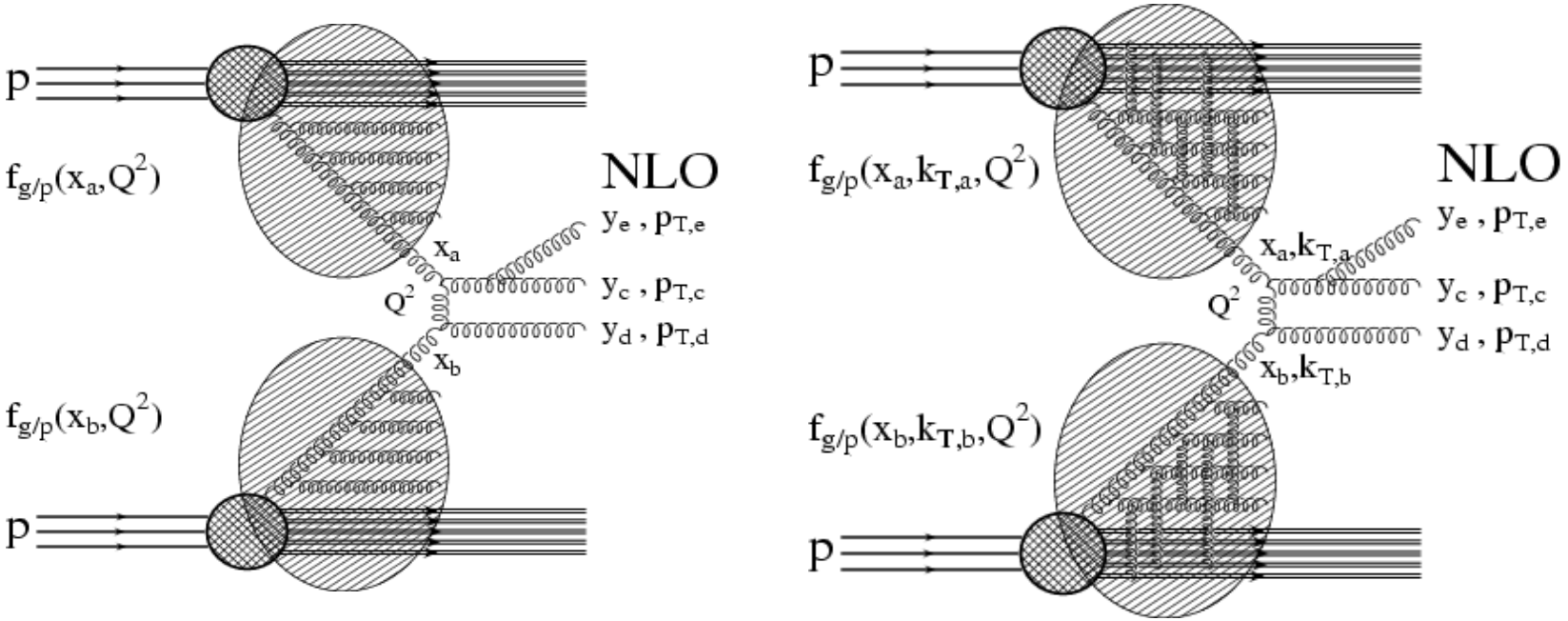


Collinear approximation + pQCD cross sections

+ interaction among the initial partons ➳ intrinsic k_T

Explanation for the most boring title of the LUND Small-x Meeting - 3

p + p collisions at CERN SPS, FERMILAB, RHIC, LHC energies

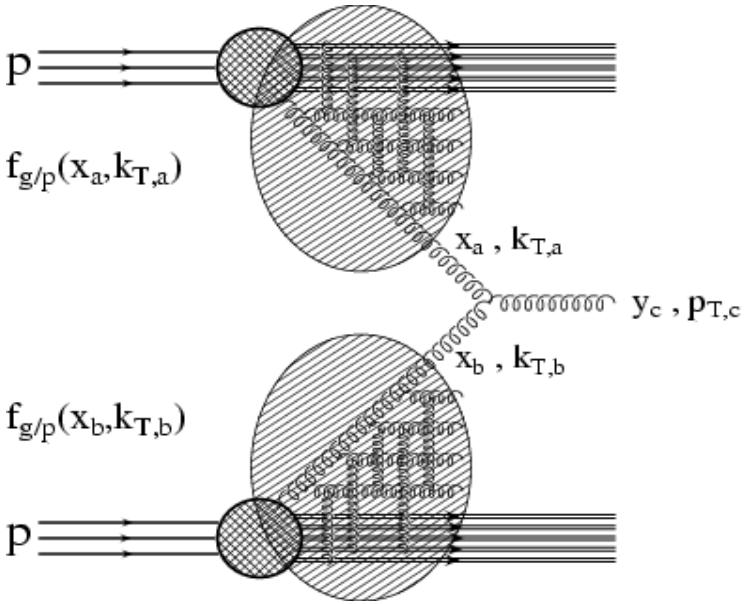


Collinear approximation + pQCD cross sections (NLO)

+ interaction among the initial partons ➳ intrinsic k_T

Explanation for the most boring title of the LUND Small-x Meeting - 4

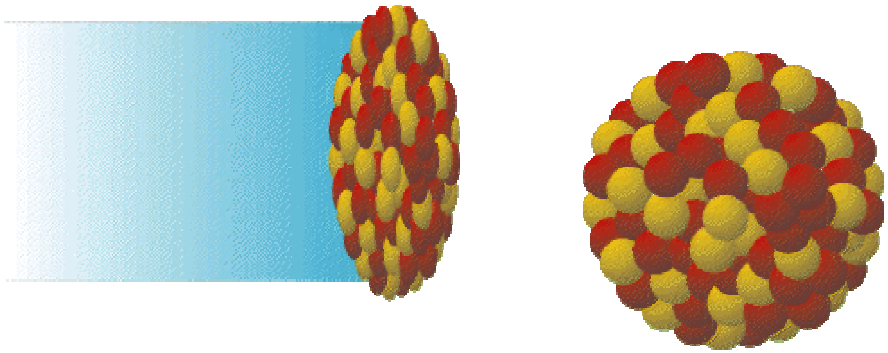
p + p collisions at CERN SPS, FERMILAB, RHIC, LHC energies



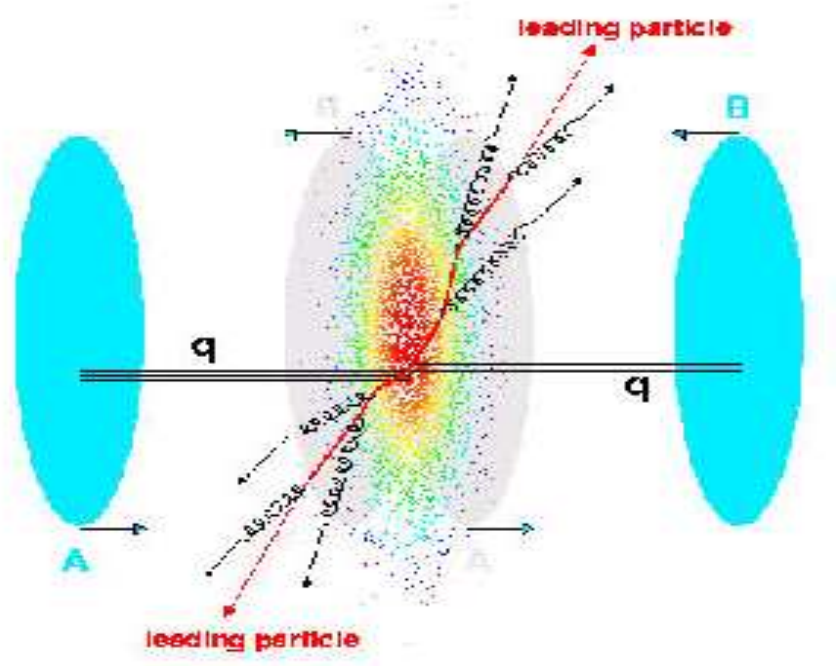
k_T factorization + pQCD cross sections (LO, NLO)

+ BFKL evolution ↣ NO intrinsic k_T !!!

Relativistic heavy ion collisions ($\sqrt{s}$=20-200 AGeV)



Collision of two extended objects consist of protons and neutrons.



Release of
subnuclear
degrees of freedom

↓

Quarks and gluons
with high energies ← Jets

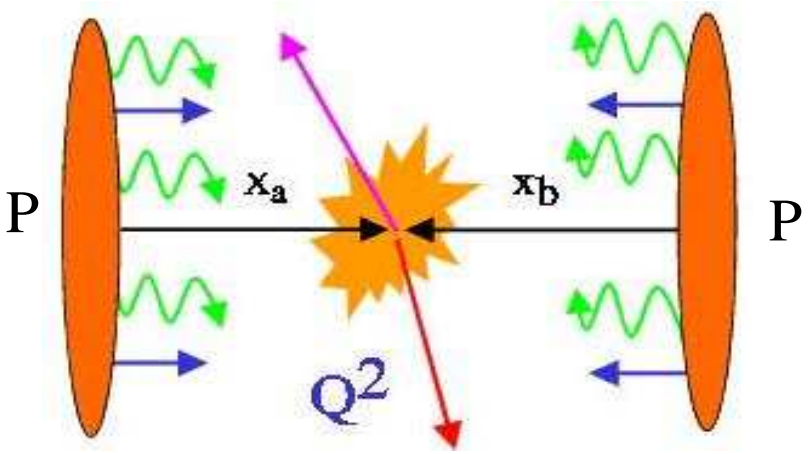
↓

Production
Propagation
Hadronization
in dense matter

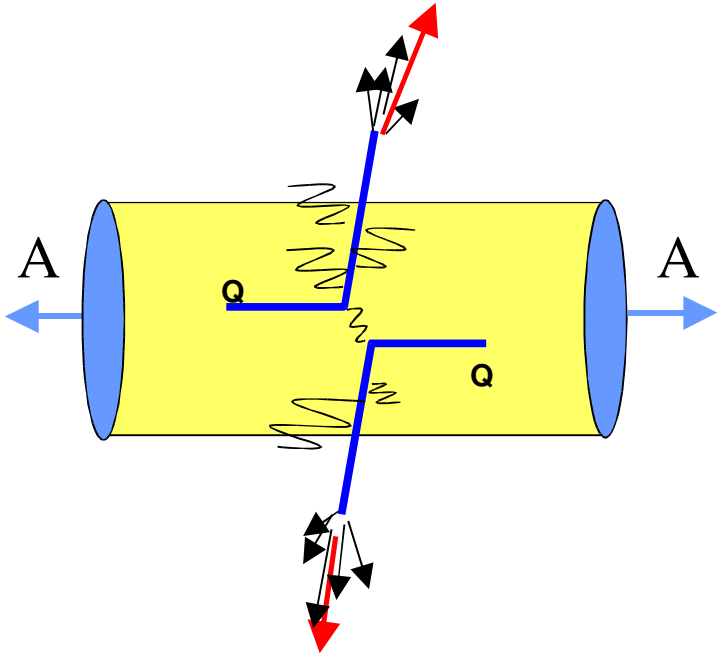
Testing the produced hot dense matter ➔ **Testing QCD**

Finding QGP !

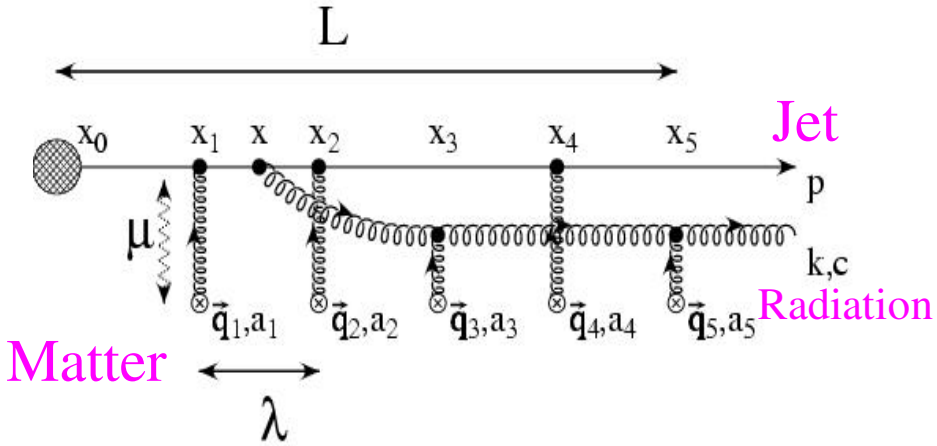
Jets in pp and in AA collisions:



Jet production in pp collision
(in vacuum):
↣ pQCD description

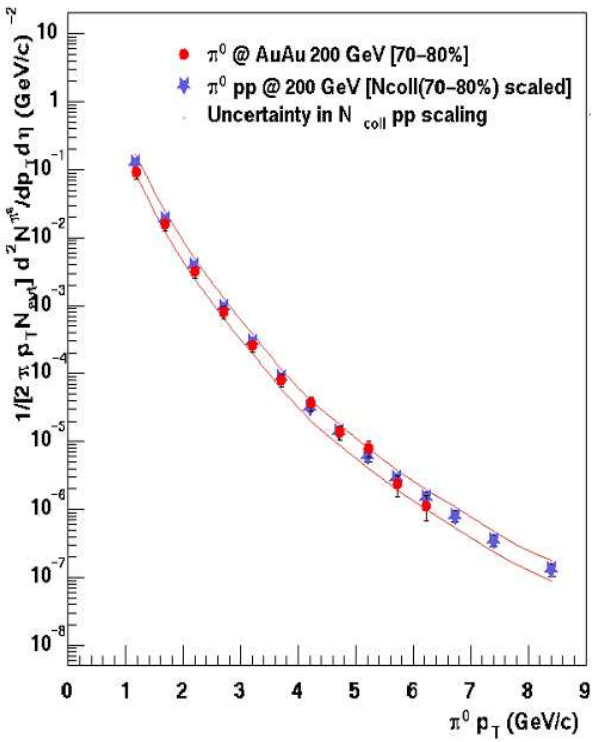


Jet production in AA collision:
(in hot dense matter)
↣ modified PQCD description
JET-TOMOGRAPHY



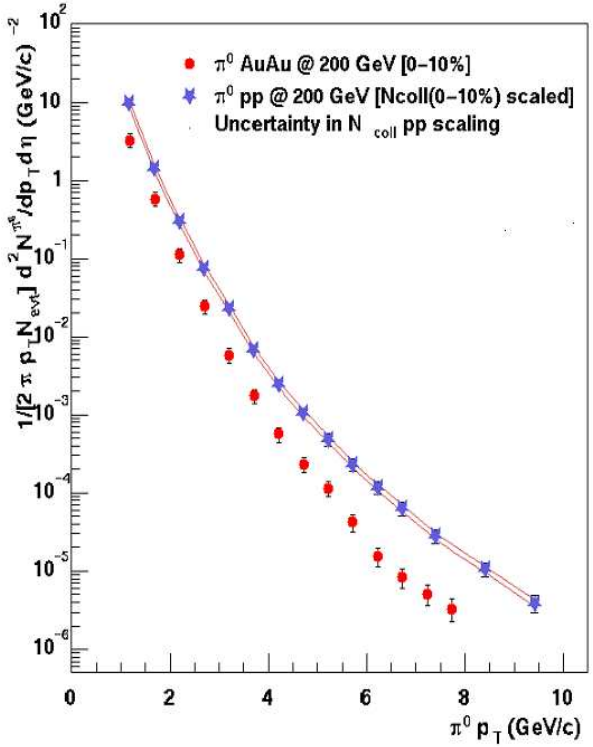
Exciting results from RHIC at √s = 130 and 200 A GeV -- π^0

PHENIX Coll., D. d'Enterria, hep-ex/0209051, QM02 Conf.



Peripheral coll. N(bin)=12.3±4

binary scaling is working



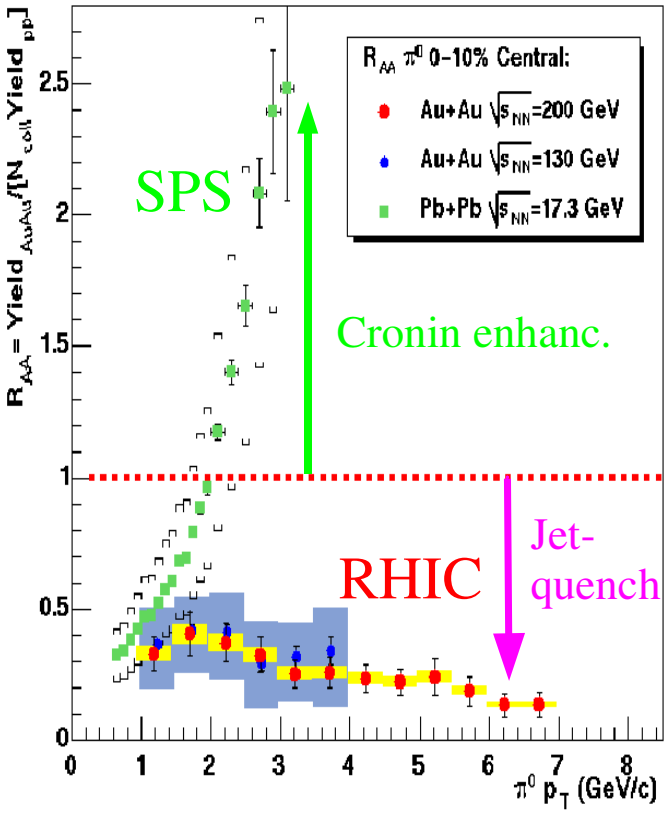
Central coll. N(bin)=975±94

binary scaling is violated

Nuclear modification factor:

$$R_{AA}(p_T) = \frac{(dN/dp_T)_{AA}}{\langle N_{bin} \rangle (dN/dp_T)_{pp}}$$

PRL 88, 022301 (2002)



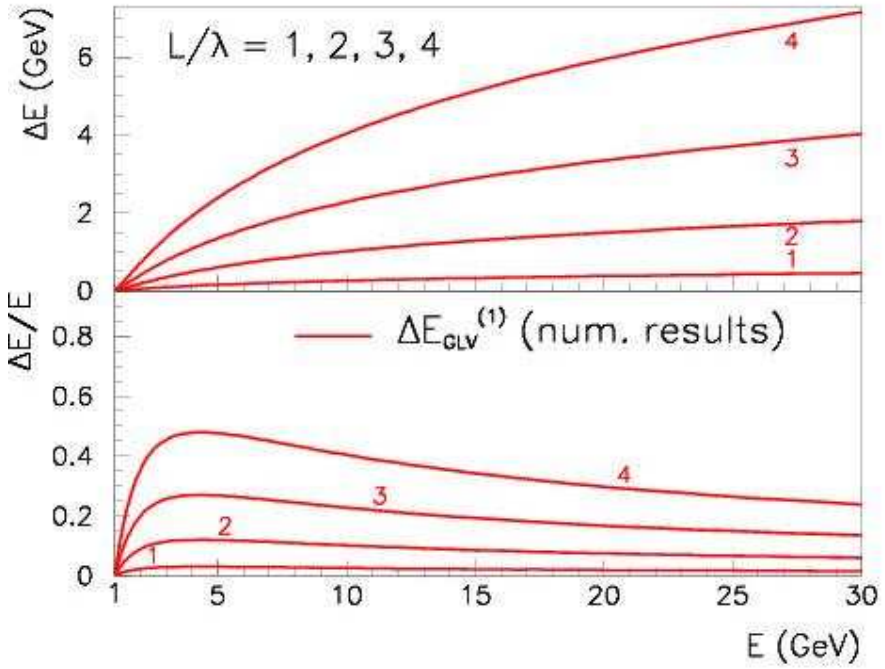
$p_T > 6-8\,GeV : Hard\ physics - pQCD$

$1.5\,GeV < p_T < 6\,GeV : Soft - hard\ overlap\ ???$

'Jet-quenching' : induced jet energy loss --- in thin colored matter

M. Gyulassy, P. Levai, I. Vitev,
PRL85,5535(2000), NPB594,371(2001)

GLV: time-ordered pQCD (Feyman diagrams)
+ OPACITY expansion (N = 1,2,3, ...)
+ kinematical cuts



$$\Delta E_{GLV} \approx \frac{C_R \alpha_s}{N(E)} \frac{L^2 \mu^2}{\lambda_g} \log \frac{E}{\mu}$$

E-dependent ΔE energy loss

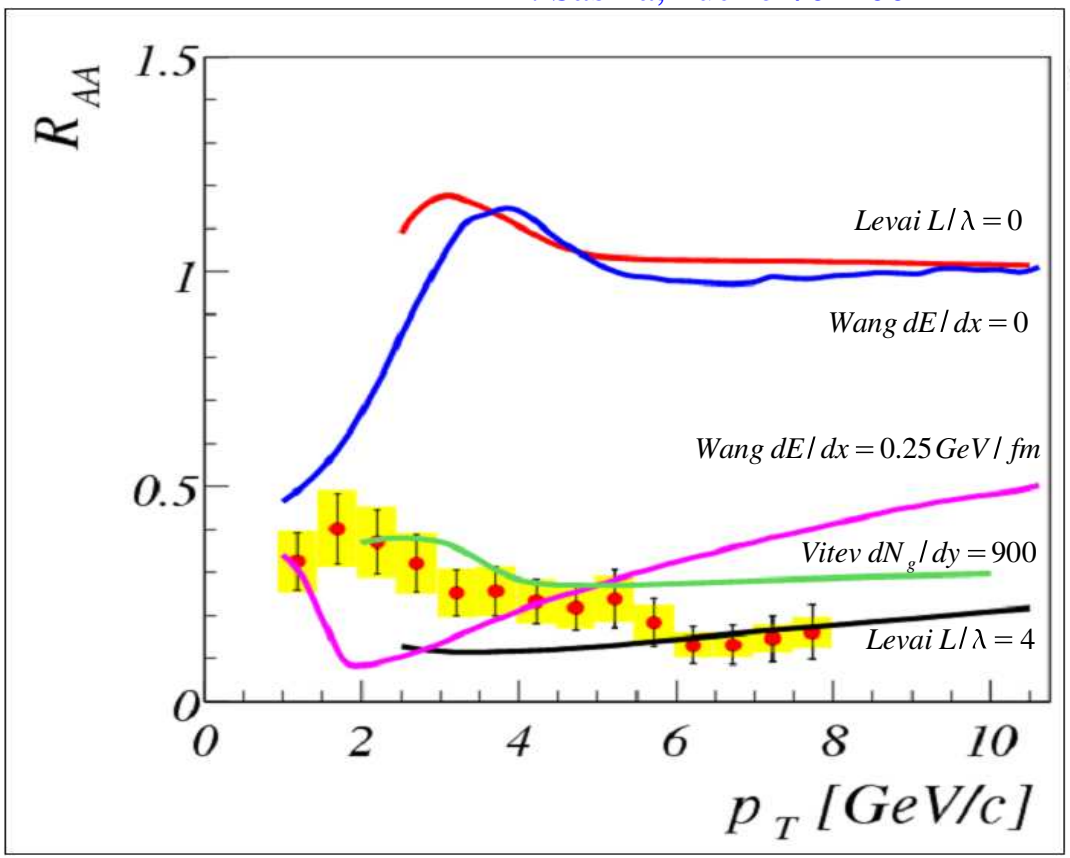
E-independent ΔE/E
in the window
3 < E < 10-15 GeV

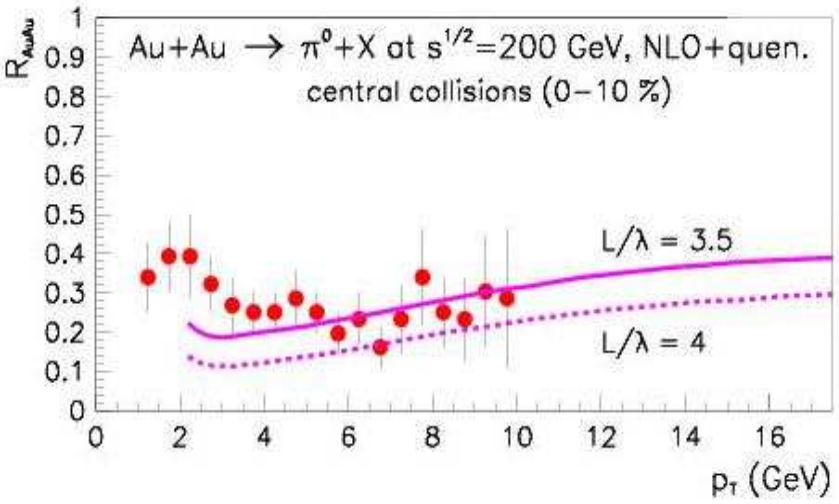
Hard physics: pion production in AA collision at high-p_T

Perturbative QCD calculations in NLO for heavy ion collisions:
geometrical overlap + shadowing, multiscattring, jet-quenching, ...

$$E_\pi \frac{d\sigma^{AB}}{d^3 p_\pi} = \int d^2b\, d^2r \;\; t_A(\vec{r})\, t_B(|\vec{b}-\vec{r}|) \;\; E_\pi \frac{d\sigma^{pp}}{d^3 p_\pi} \otimes S(...) \otimes M(...) \otimes Q(...)$$

Data: PHENIX Coll., D. d'Enterria, hep-ex/0209051
M. Saskia, nucl-ex/0210021





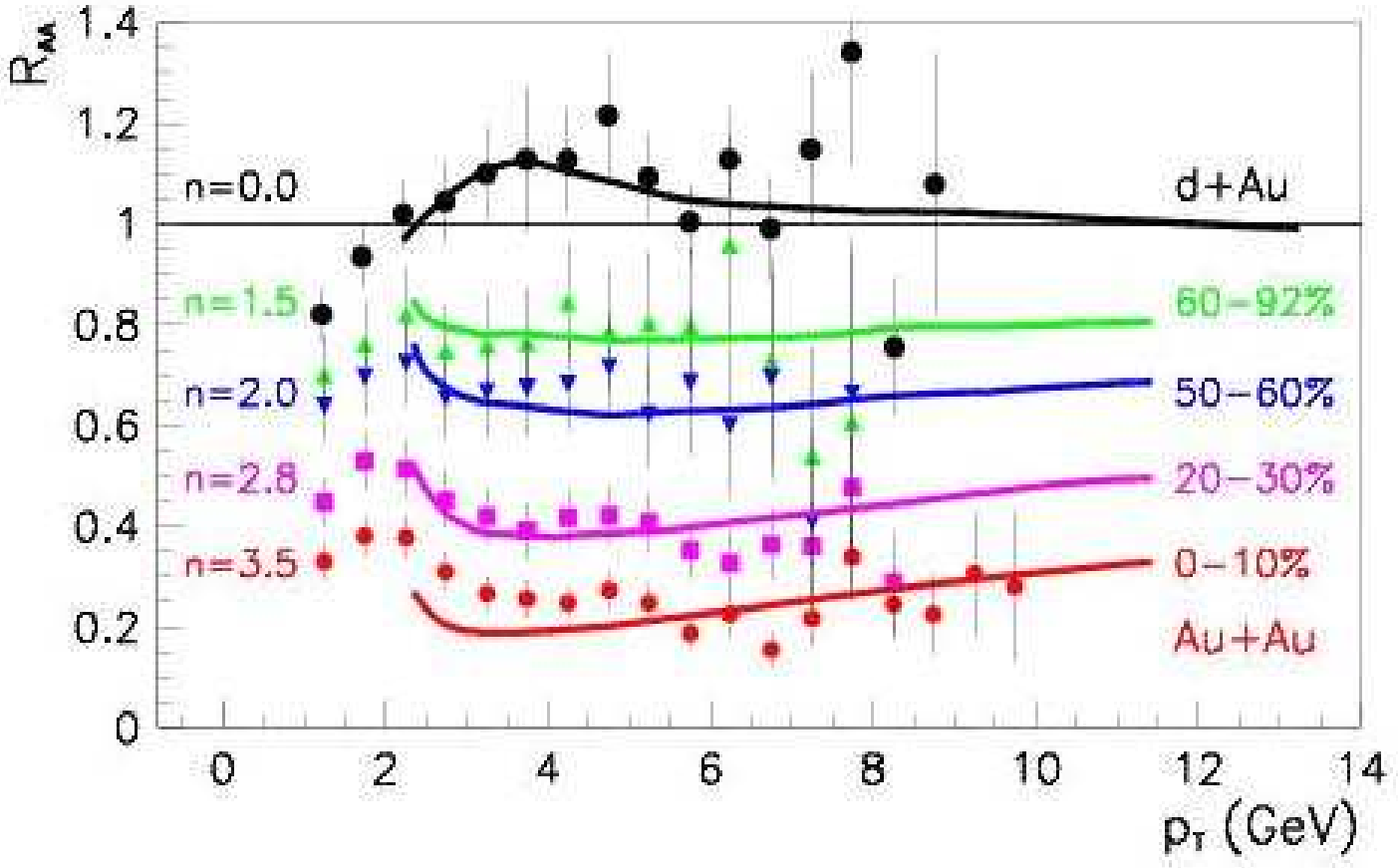
$$R_AuAu = \frac{Theory\ (with\ Cr+Sh+Quen)}{Theory\ (wo\ Cr,\ Sh,\ Quen)}$$

p_T > 2.5 GeV ***L/λ = 3.5 ± 0.25***
p_T < 2.5 GeV ***Soft contribution !!***
What is this ?

Hard physics: pion production in AA collision at high- p_T

Perturbative QCD calculations in NLO for heavy ion collisions:
geometrical overlap + shadowing, multiscattring, jet-quenching, ...

$$E_\pi \frac{d\sigma^{AB}}{d^3 p_\pi} = \int d^2b\, d^2r \;\; t_A(\vec{r})\, t_B(|\vec{b}-\vec{r}|) \;\; E_\pi \frac{d\sigma^{pp}}{d^3 p_\pi} \otimes S(...) \otimes M(...) \otimes Q(...)$$



d+Au

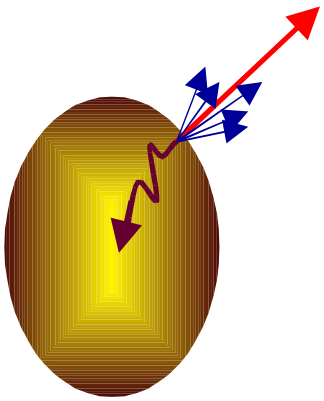
Au+Au

What do we expect from the experiments ?

Large energy jets suffer certain energy loss,
the number of high-pT particle is decreasing (suppression).
↣ suppression in the one-particle spectra !

OK !

Jets close to the surface can leave the hot matter,
but their counterpair can not pass the hot interior,
these jets loose most of their energy and disappear as jets.
↣ back-to-back correlation disappears !



Two-particle tomography

What is the density distribution of the interior of the hot zone.
[X-ray tomography]

Hard physics: two-particle correlation spectra at high-p_T

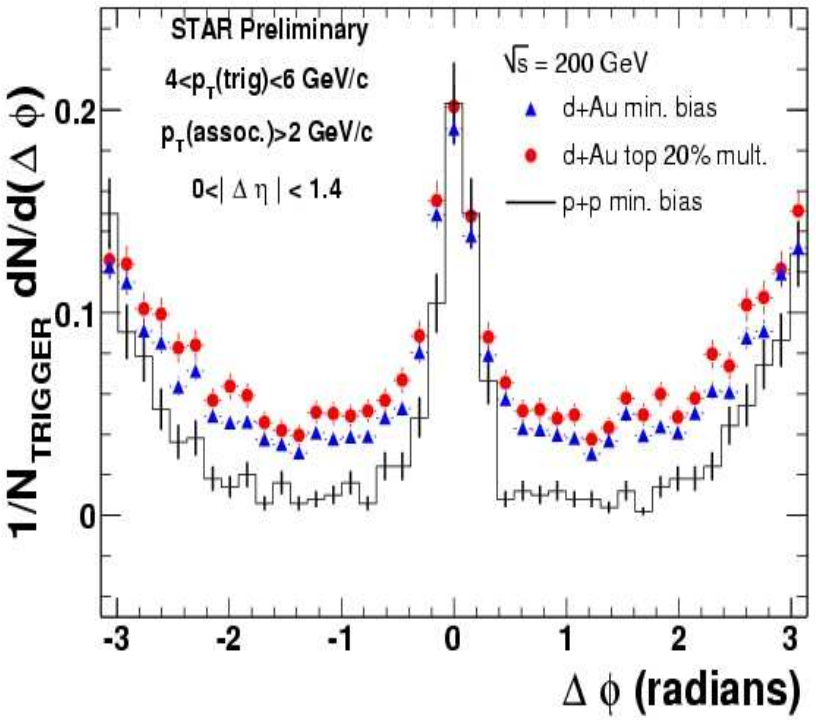
Perturbative QCD calculation of di-hadron, di-jet correlation can be performed:

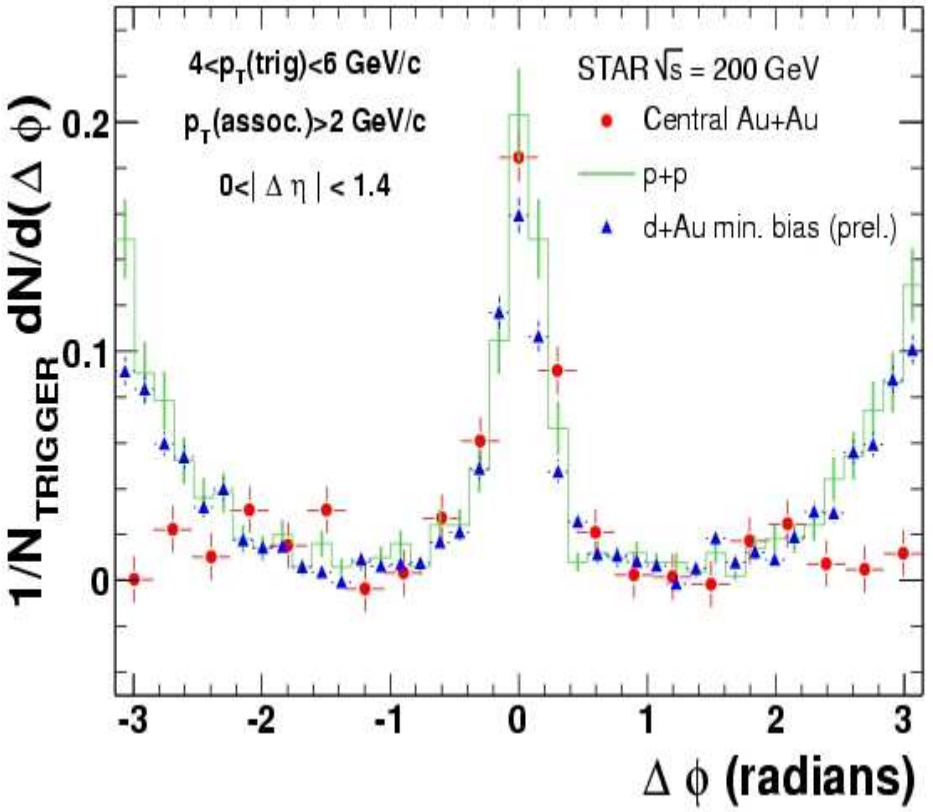
pp: scales and intrinsic-kT must be surveyed

pA: multiscattering & shadowing

AA: geometrical overlap + shadowing, multiscattring + jet-quenching, ...

Data: STAR Coll., D. Hardtke



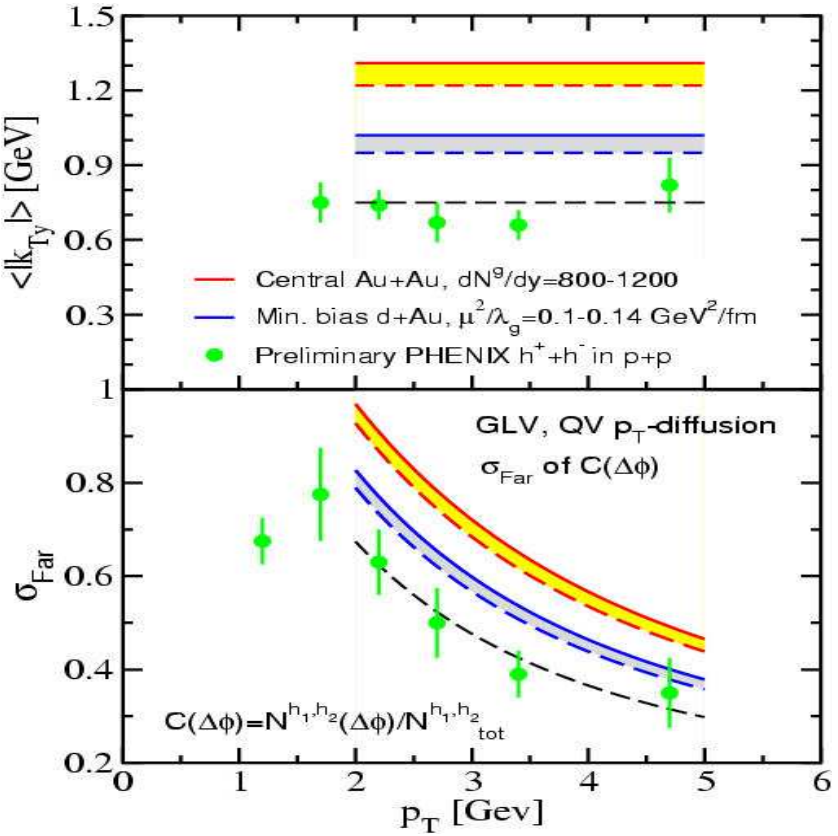


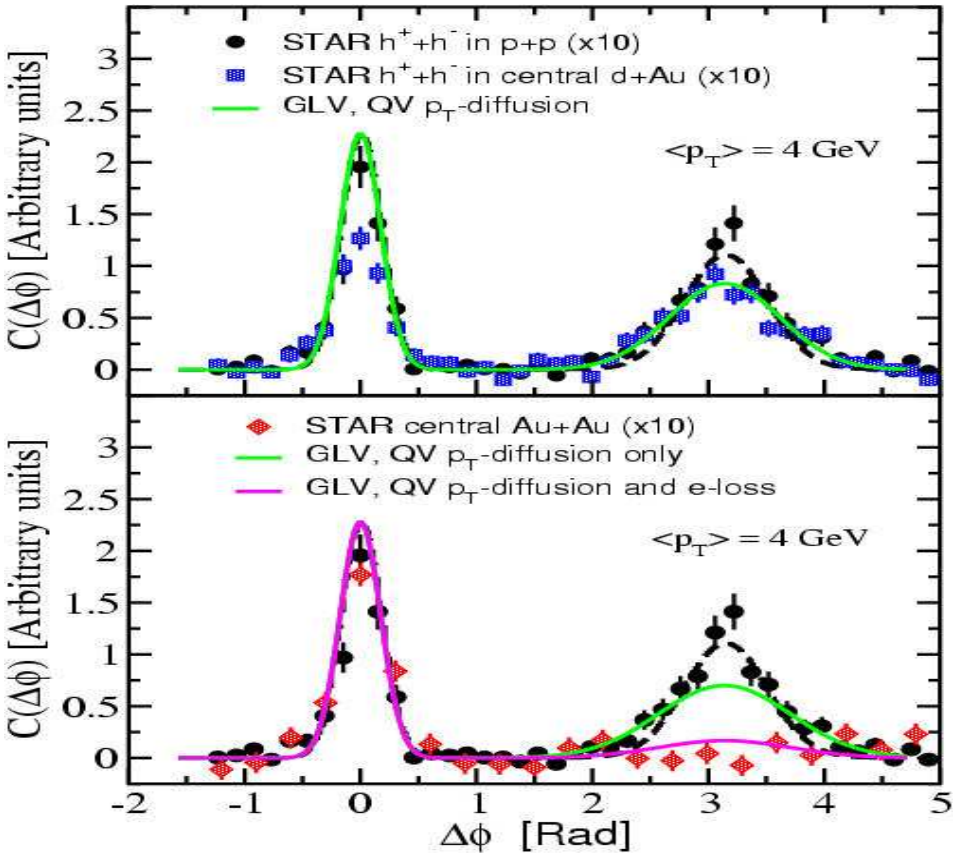
Can we reproduce nuclear broadening in dAu collision (b-dependence, etc.)

Can we determine final state interactions from the suppression of the away-correlation?

Hard physics: two-particle correlation spectra at high-p_T

Perturbative QCD calculation of di-hadron, di-jet correlation in LO:
J.W. Qiu, I. Vitev, nucl-th/0306039, nucl-th/0309094.





Need more quantitative work in LO, NLO.

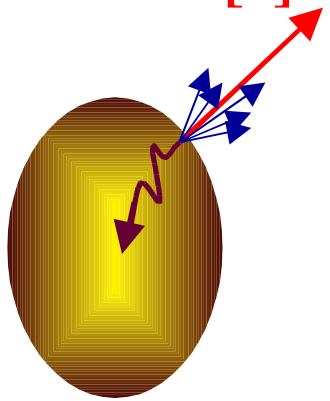
Our calculations are based on

$2 \rightarrowtail 2$ processes at parton level
collinear factorization
Cross sections, PDFs, FFs in LO, NLO

pp: If high-pT is OK, then something missing at low-pT !!!
$\rightarrowtail$ intrinsic -kT (our bet here)
$\rightarrowtail$ other pQCD component dominant at low-pT ?
$\rightarrowtail$ other non-pQCD component ?

pA: extra multiscattering of the incoming proton (Cronin) [?]
extra nuclear shadowing inside A [?]

AA: more multiscattering
nuclear shadowing in both A
high parton density $\rightarrowtail$ extra processes
$\rightarrowtail\rightarrowtail$ e.g. parton coalescence at low-pT



Hard physics: pion production in pp collision at high-p_T

Perturbative QCD calculations in NLO for p+p ➡ π + X process:

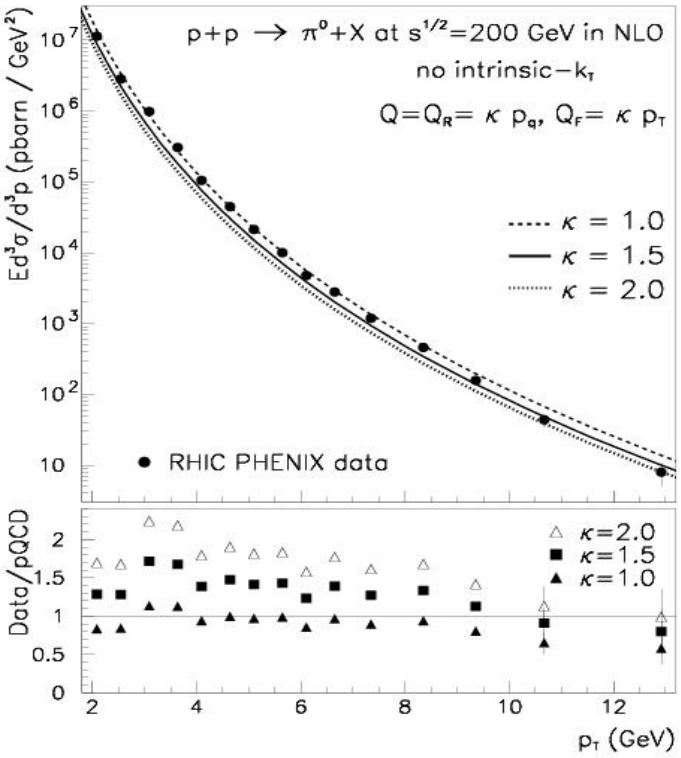
(M. Aversa et al. NPB327,105; P. Chiappetta et al. NPB412,3; P. Aurenche et al. NPB399,34; ...)

$$E_\pi \frac{d\sigma^{pp}}{d^3 p_\pi} = \int J\, dv\, dw\, dz_c\;\; f_{a/p}\;\; f_{b/p}\;\; [\frac{d\sigma^{BORN}}{dv}\delta(1-w) + \frac{\alpha_s}{\pi} K_{ab,c}]\;\; \frac{D_c^\pi(z_c)}{\pi z_c^2}$$

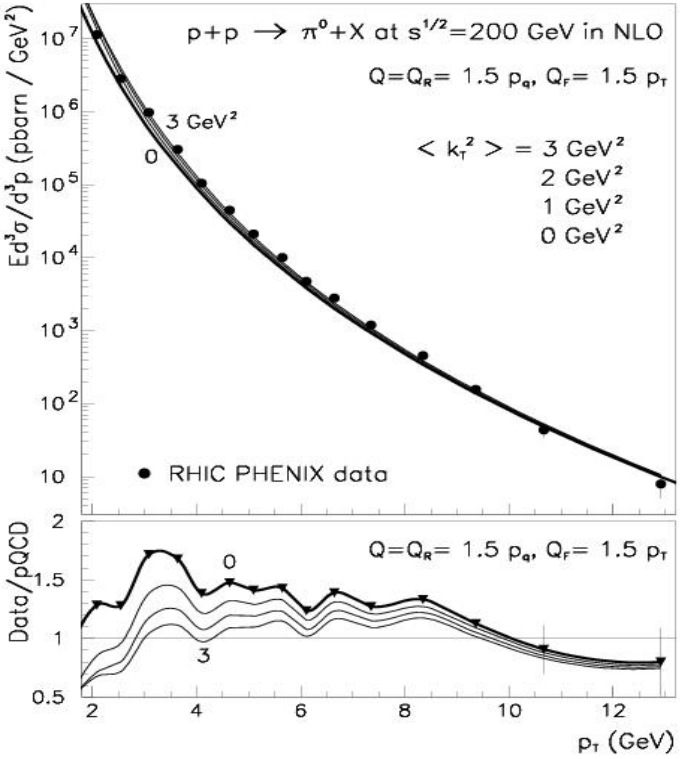
Data: PHENIX Coll., H. Torii, nucl-ex/0210005

G. Papp et al. (Budapest) (hep-ph/0212249)

Without intrinsic - k_T



with intrinsic - k_T



Hard physics: pion production in pp collision at high- p_T

What is this intrinsic - kT ? Does it exist ?

(A. L. S. Angelis, Phys. Lett. B97 (1980) 163. **If you can measure it, then it must exist !!**

Volume 97B, number 1 PHYSICS LETTERS 17 November 1980

ISR: p-p collision at √s=31,45,63 GeV

A MEASUREMENT OF THE TRANSVERSE MOMENTA OF PARTONS, AND OF JET FRAGMENTATION AS A FUNCTION OF $\sqrt{s}$ IN p–p COLLISIONS

CERN–Columbia–Oxford–Rockefeller (CCOR) Collaboration

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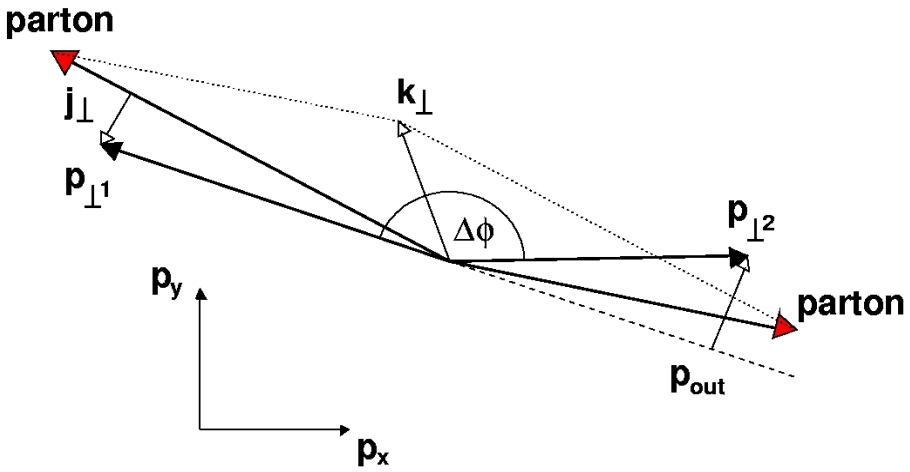
Received 11 August 1980
Revised manuscript received 2 September 1980

A large solid-angle apparatus consisting of a superconducting solenoid magnet, cylindrical drift chambers and two arrays of lead-glass counters was used to examine particles associated with a high transverse momentum trigger in p–p collisions with three $\sqrt{s}$ values at the CERN ISR. The trigger was given by energy deposition in lead-glass arrays centred at 90°. The trigger transverse momentum range covered was $3 < p_{T\,\mathrm{trig}} < 11$ GeV/c. Results are given for p_{out} for both individual charged particles, and also for the sum of charged particle momenta in the hemisphere opposite to the trigger. Mean values are then deduced for the parton transverse momentum k_T, and for the jet fragmentation momentum j_T.

Hard physics: pion production in pp collision at high-p_T

Intrinsic - k_T from jet-jet correlation :



$\langle |j_\perp| \rangle$ = **the mean transverse momentum of the hadron with respect to the jet axes in the plain perpendicular to the beam axes**

$\langle |k_\perp| \rangle$ = **the mean effective transverse momentum of the two colliding partons in the plain perp. To the beam axes (+ final state interaction in pA,AA)**

Jan Rak (PHENIX) CIPANP'03
in p+p at 200 GeV

$$\langle |j_\perp| \rangle = \frac{1}{\sqrt{\pi}} \sqrt{\langle j_\perp^2 \rangle} = p_\perp \sin \frac{\sigma_{Near}}{\sqrt{\pi}}$$

$$\langle |k_\perp| \rangle = \frac{1}{\sqrt{\pi}} \sqrt{\langle k_\perp^2 \rangle} = p_\perp \cos \frac{\sigma_{Near}}{\sqrt{\pi}} \sqrt{\frac{1}{2} \tan^2\left(\sqrt{\frac{2}{\pi}}\sigma_{Far}\right) - \tan^2\left(\frac{\sigma_{Near}}{\sqrt{\pi}}\right)}$$

Hard physics: pion production in pp collision at high-p_T

How large is this intrinsic kT ?

(A. L. S. Angelis, Phys. Lett. B97 (1980) 163.

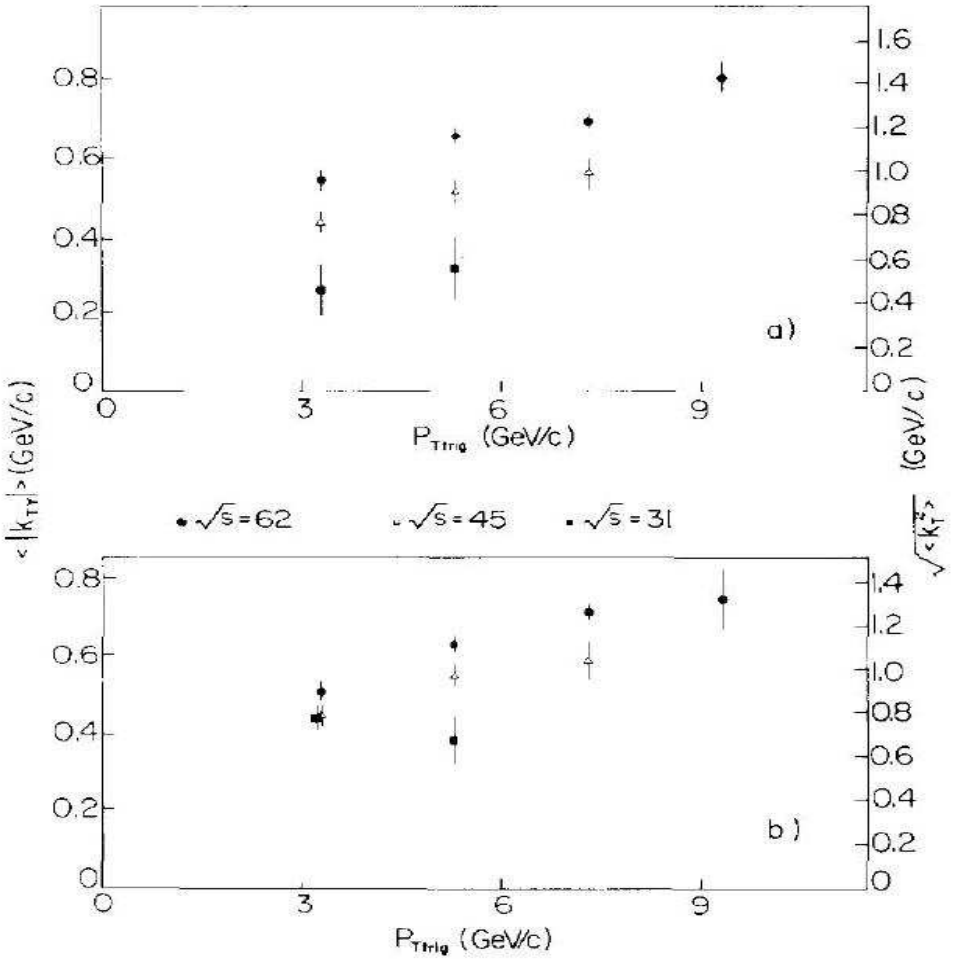


Fig. 4. (a) $\langle |k_{Ty}| \rangle$ and $(\langle k_T^2 \rangle)^{1/2}$ as a function of p_{Ttrig} for three different $\sqrt{s}$ values, obtained from single-particle correlations. (b) The same for multiple-particle correlations.

$$\langle k_T^2 \rangle \approx 1 - 2.5\, GeV^2$$

- at $\sqrt{s} = 63$ GeV in pp

It may increase
with energy !

What about small pT ?
Where does jetiness
start ?

Hard physics: pion production in pp collision at high- p_T

Perturbative QCD calculations in NLO for p+p ➡ π + X process with finite - k_T

G. Papp, P. Levai, G.G. Barnaföldi, G. Fai, hep-ph/0212249

$$E_\pi \frac{d\sigma^{pp}}{d^3 p_\pi} = \frac{1}{S} \sum_{a\,b\,c} \int_{VW/z_c}^{1-(1-V)/z_c} \frac{dv}{v(1-v)} \int_{VW/vz_c}^{1} \frac{dw}{w} \int^{1} dz_c$$

$$\int d^2\boldsymbol{k}_{Ta} \int d^2\boldsymbol{k}_{Tb}\; f_{a/p}(x_a, \boldsymbol{k}_{Ta}, Q^2)\; f_{b/p}(x_b, \boldsymbol{k}_{Tb}, Q^2)$$

$$\left[\frac{d\sigma^{BORN}}{dv}\delta(1-w) + \frac{\alpha_s(Q_R)}{\pi} K_{ab,c}(s, v, w, Q, Q_R, Q_F)\right] \frac{D_c^\pi(z_c)}{\pi z_c^2}$$

An approximation for the unintegrated parton distribution functions (PDFs) :

$$f_{a/p}(x_a, \boldsymbol{k}_{Ta}, Q^2) = f_{a/p}(x_a, Q^2) \quad g(\boldsymbol{k}_{Ta})$$

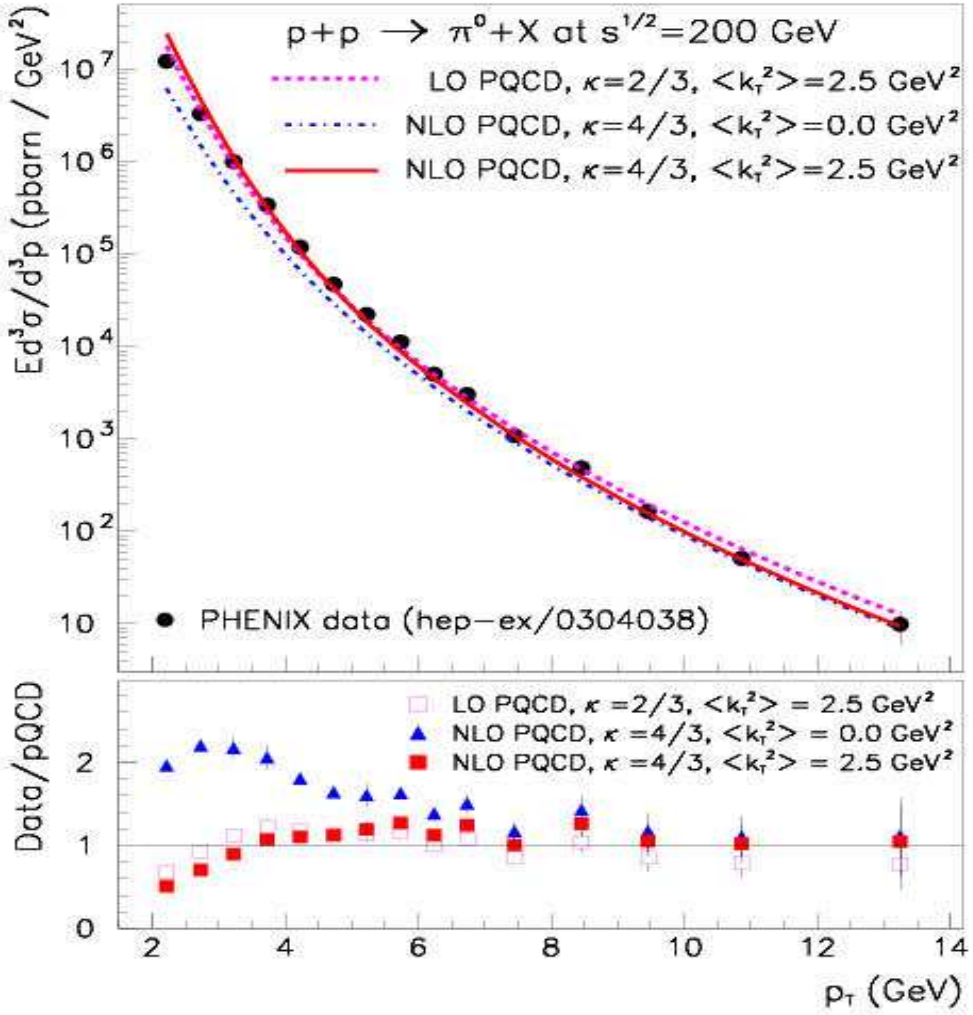
Where we use gaussian

$$g(\boldsymbol{k}_{Ta}) = \frac{1}{\pi \langle k_T^2 \rangle} e^{-k_T^2/\langle k_T^2 \rangle}$$

The width of the gaussian distribution for intrinsic-kT

Hard physics: pion production in pp collision at high- p_T

Perturbative QCD calculations in LO and NLO for pp --- including intrinsic- kT



LO:

$$Q = \kappa\, p_T / z_c, \quad Q_F = \kappa\, p_T$$

NLO:

$$Q = Q_R = \kappa\, p_T / z_c, \quad Q_F = \kappa\, p_T$$

All descriptions are approx.
good enough at 2 GeV < pT < 5 GeV.

Which κ should be used ?

P.L, G. Papp, G.G. Barnaföldi, G. Fai
(nucl-th/0306019)

Hard physics: pion production in dAu collision at high- p_T

Perturbative QCD calculations in LO and NLO for pp + CRONIN + SHADOWING:

CRONIN (nuclear multiscattering):

$$E_\pi \frac{d\sigma^{dAu}}{d^3p_\pi} = \int d^2\boldsymbol{b}\ d^2\boldsymbol{r}\ t_d(\boldsymbol{r}) t_{Au}(|\boldsymbol{b}-\boldsymbol{r}|)\ E_\pi \frac{d\sigma^{pp}(\langle k_T^2\rangle_{pAu}, \langle k_T^2\rangle_{pd})}{d^3p_\pi}$$

Where the k_T broadening in dAu :

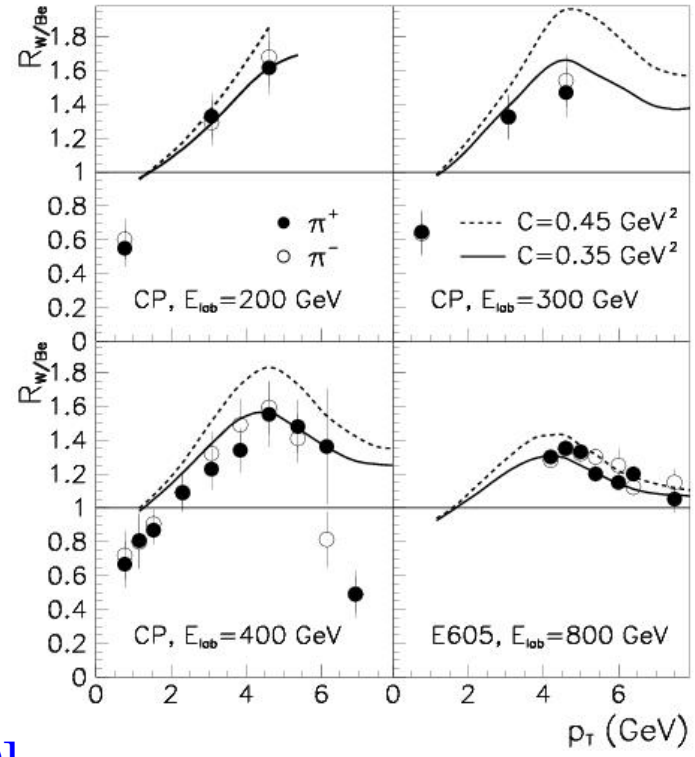
$$\langle k_T^2\rangle_{pAu} = \langle k_T^2\rangle_{pp} + C\ \ h_{pAu}(b)$$

- with the effective broading per collision

$$C = 0.4 \pm 0.05\, GeV^2$$

$$\langle k_T^2\rangle_{pp} = 2.2 - 2.4\, GeV^2$$

Fixed on FERMILAB data
[Antresyan et al, PRD19,764 (1979)]

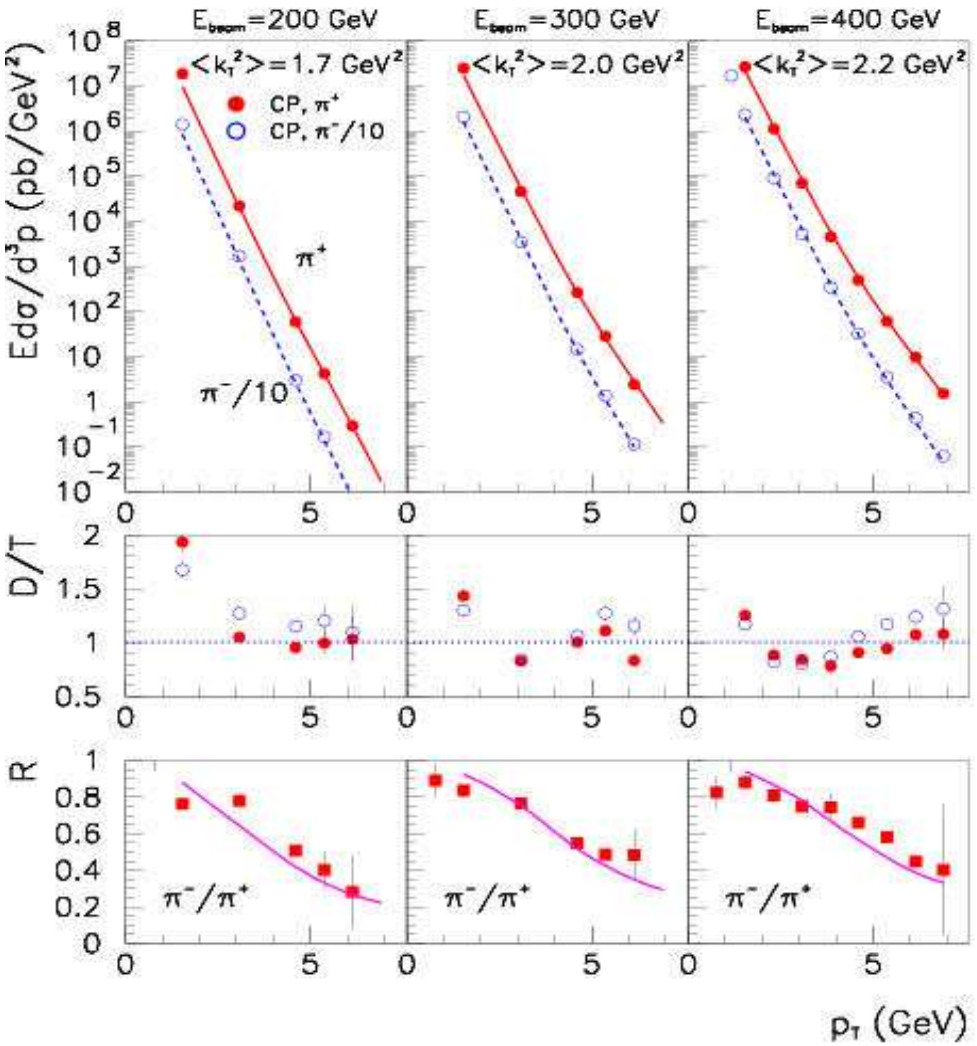


LO: Zhang, Fai, Papp, Barnafoldi, Levai, PRC65, 034903 (2002)

Hard physics: pion production in pp collision at high-p_T

Perturbative QCD calculations in LO for pp --- including intrinsic- kT

FERMILAB data: fix target p + p, Be, Ti, W at Elab = 200, 300, 400, 800 GeV



LO:

$$Q = \kappa\, p_T / z_c, \quad Q_F = \kappa\, p_T$$

LO approximation is approx. good enough at 2 GeV < pT < 5 GeV.

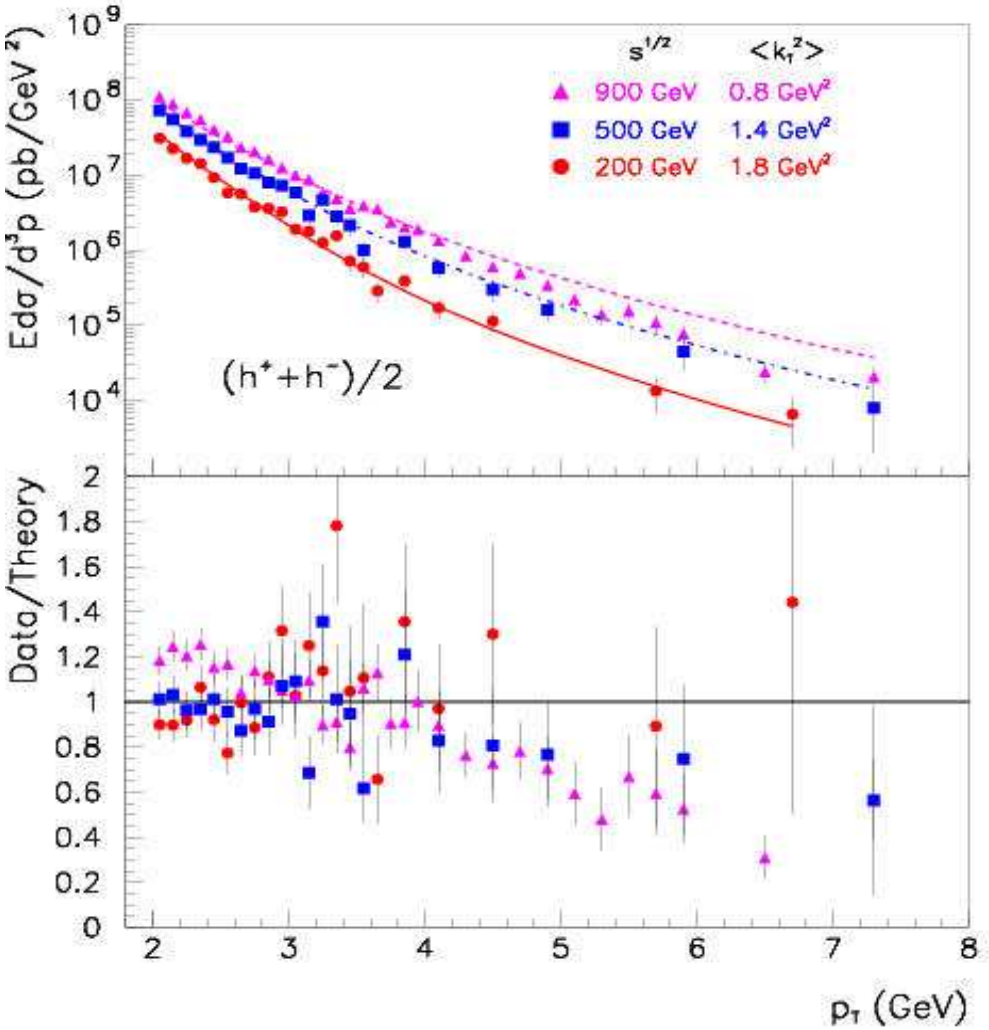
κ **= 1**

Y. Zhang, G. Fai, G. Papp, G.G. Barnafoldi, P.L., PRC65 (2002) 034903.

Hard physics: pion production in pp collision at high-p_T

Perturbative QCD calculations in LO for pp --- including intrinsic- kT

FERMILAB data: p + anti-p at s^1/2 = 200, 500, 900 GeV



LO:

$$Q = \kappa\, p_T / z_c, \quad Q_F = \kappa\, p_T$$

LO approximation is very good at 2 GeV < pT < 5 GeV.

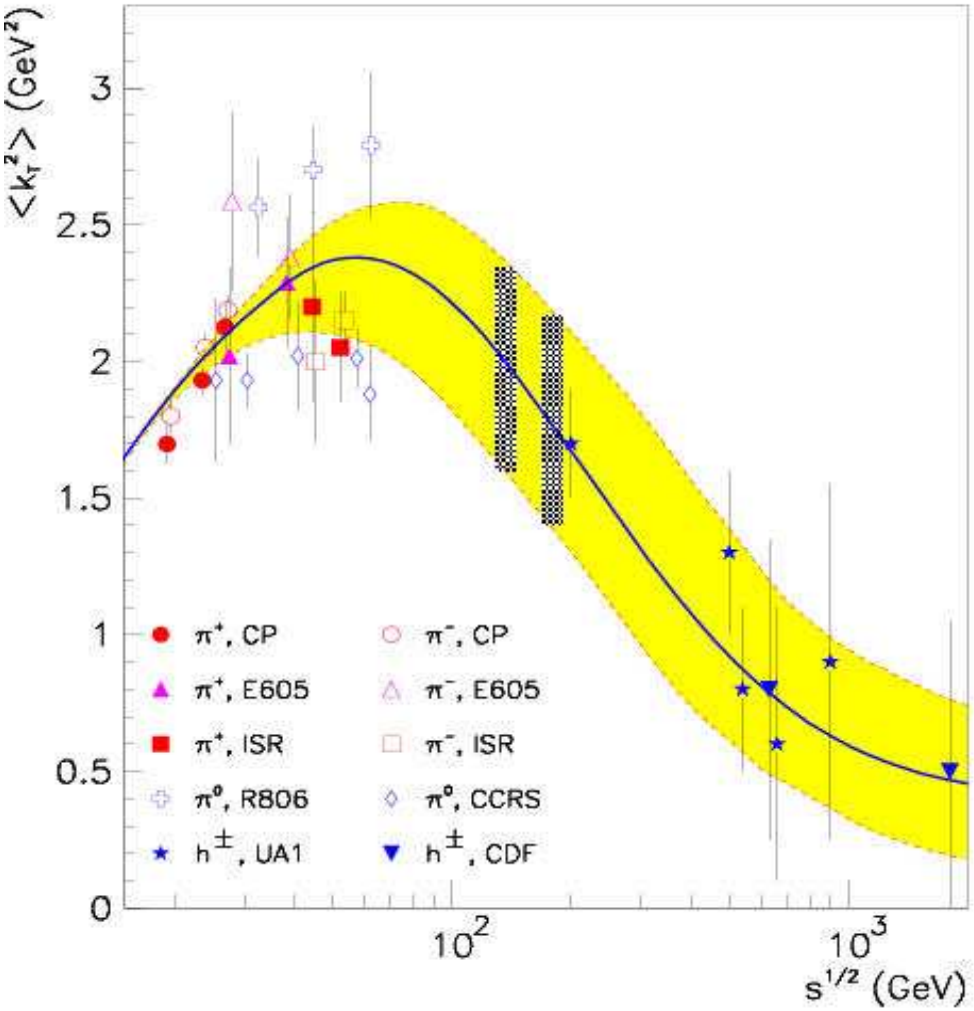
κ **= 1**

Y. Zhang, G. Fai, G. Papp, G.G. Barnafoldi, P.L., PRC65 (2002) 034903.

Hard physics: pion production in pp collision at high-p_T

Perturbative QCD calculations in LO for pp --- including intrinsic- kT

s^1/2 = 15 - 1800 GeV



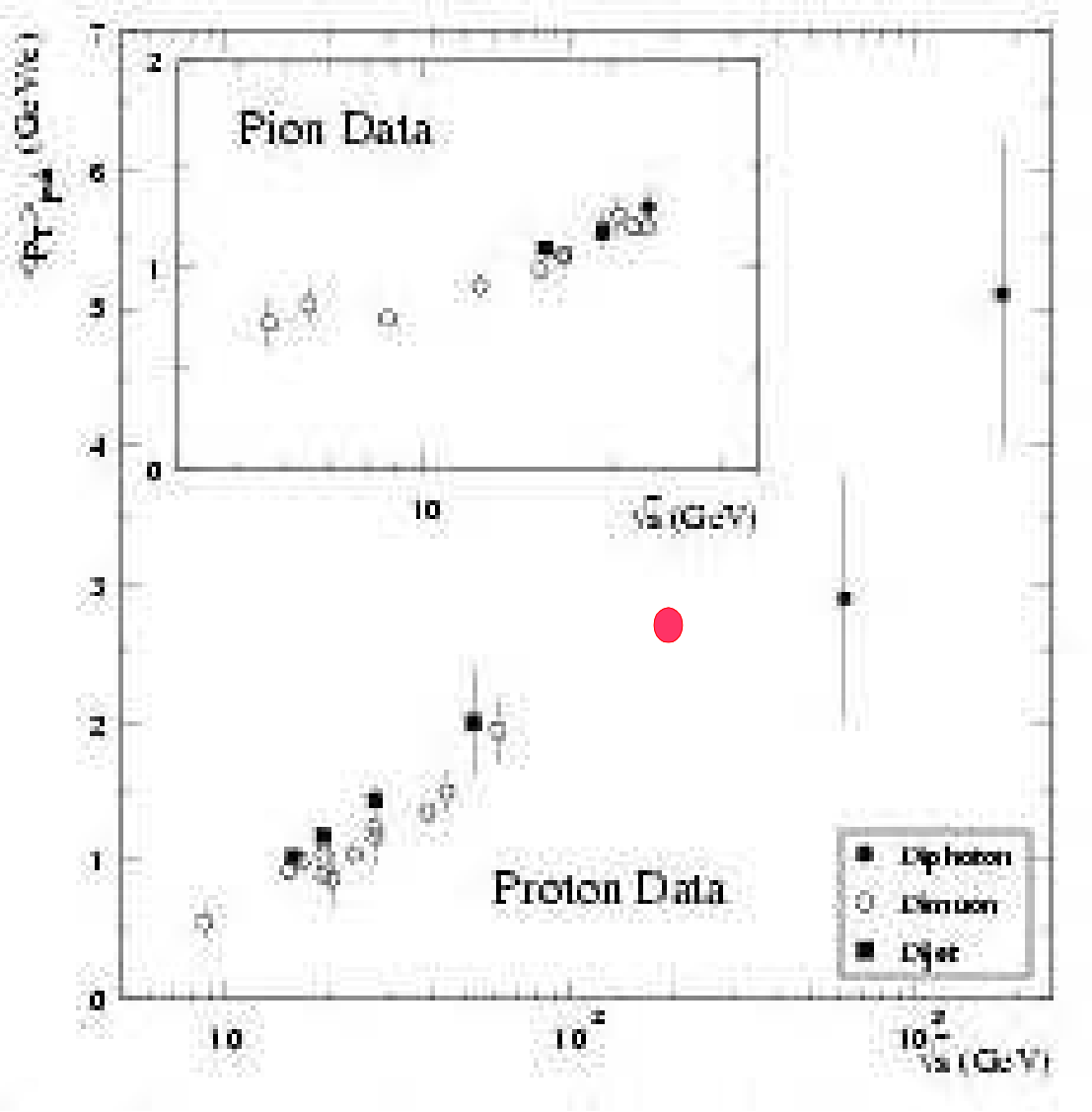
LO:

$$Q = \kappa\, p_T / z_c, \quad Q_F = \kappa\, p_T$$

Why do we need
large intrinsic-kT at low s^1/2
small intrinsic-kT at large s^1/2 ??

Y. Zhang, G. Fai, G. Papp,
G.G. Barnafoldi, P.L.,
PRC65 (2002) 034903.

Dihadron correlation (Fig . Zielinski, hep-ph/9811278)



RHIC value (200 GeV):

<|k_Tx|> = 950 MeV

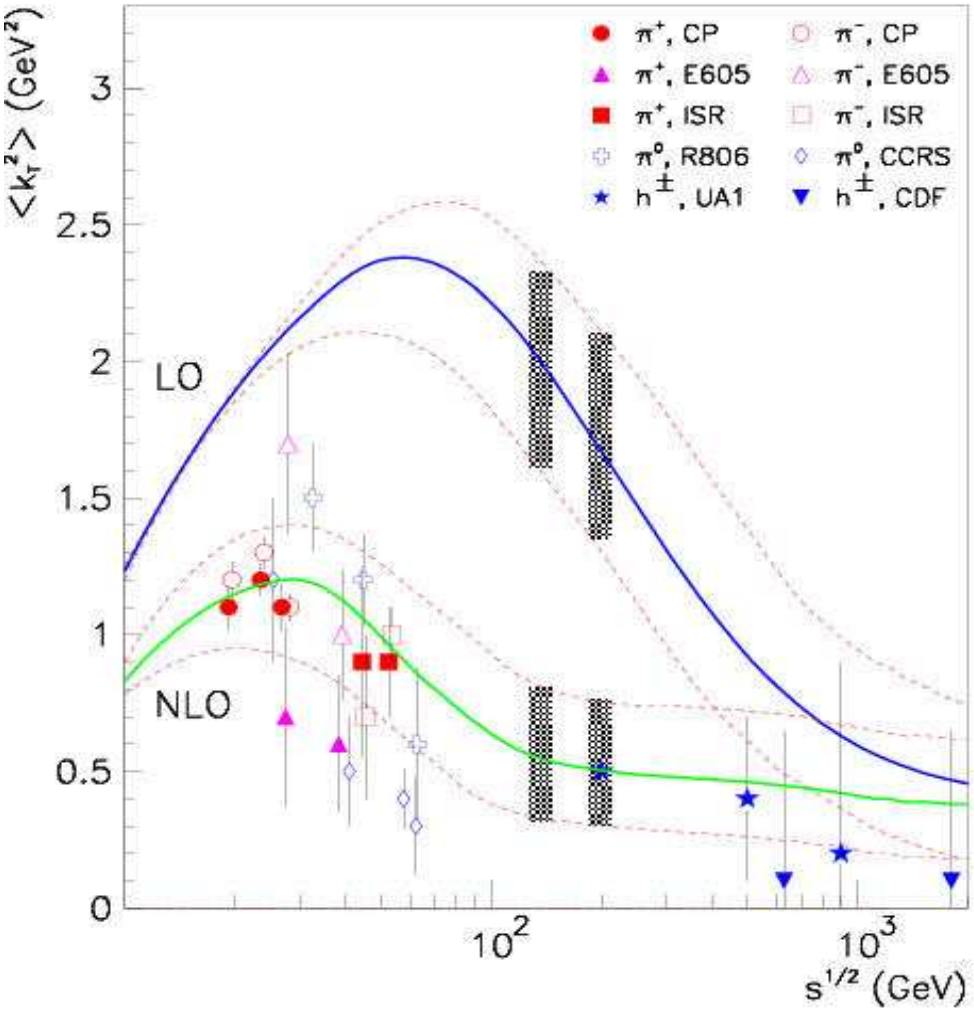
<p_Tpair> = 2.8 GeV

<k_T^2> = 2.3 GeV^2

Hard physics: pion production in pp collision at high- p_T

Perturbative QCD calculations in LO and NLO for pp --- including intrinsic- kT

s^1/2 = 15 - 1800 GeV



LO and NLO:

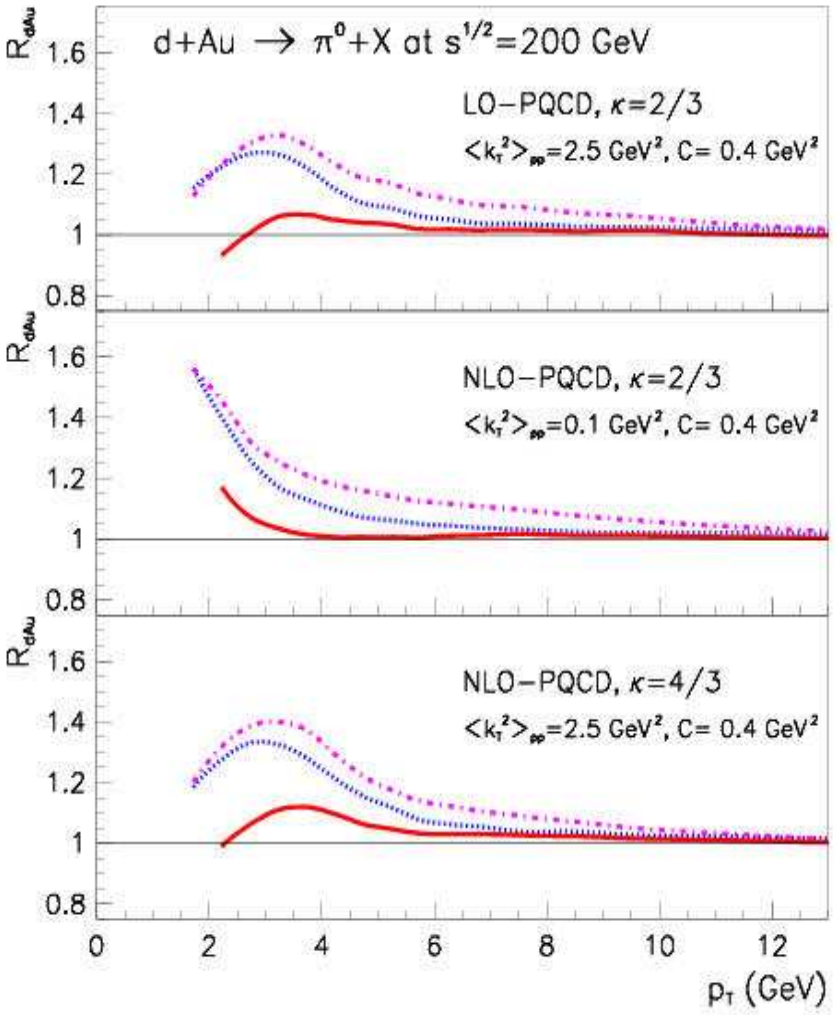
$$Q = \kappa\, p_T / z_c, \quad Q_F = \kappa\, p_T$$

Why do we need
large intrinsic-kT at low s^1/2
small intrinsic-kT at large s^1/2 ??

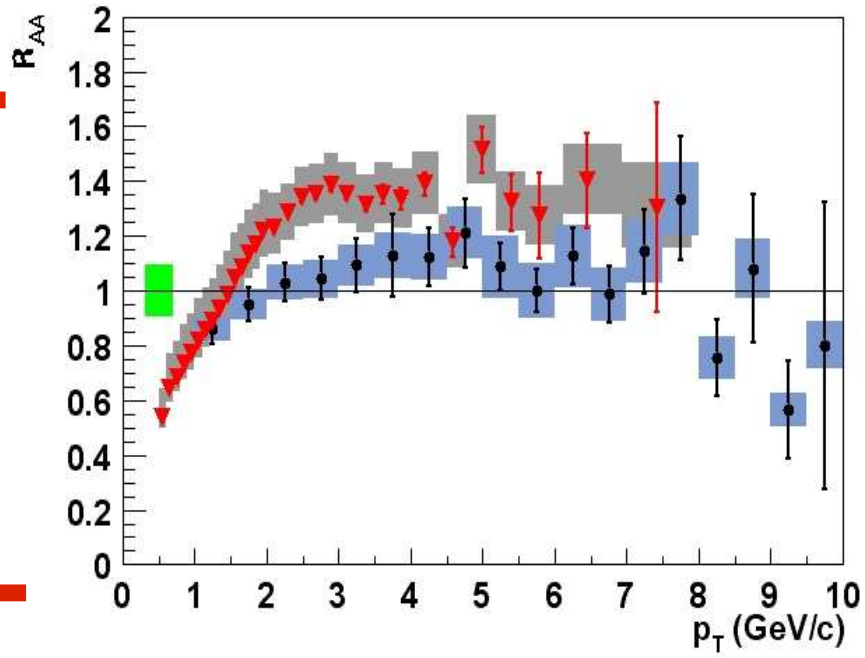
G.G. Barnafoldi, P.L., ...
Heavy Ion Phys. 18 (2003) 79.
(nucl-th/0206006)

Hard physics: pion production in dAu collision at high- p_T

Perturbative QCD calculations in NLO for pp + CRONIN + SHADOWING (LI & XNW):
+ SHADOWING (EKS)



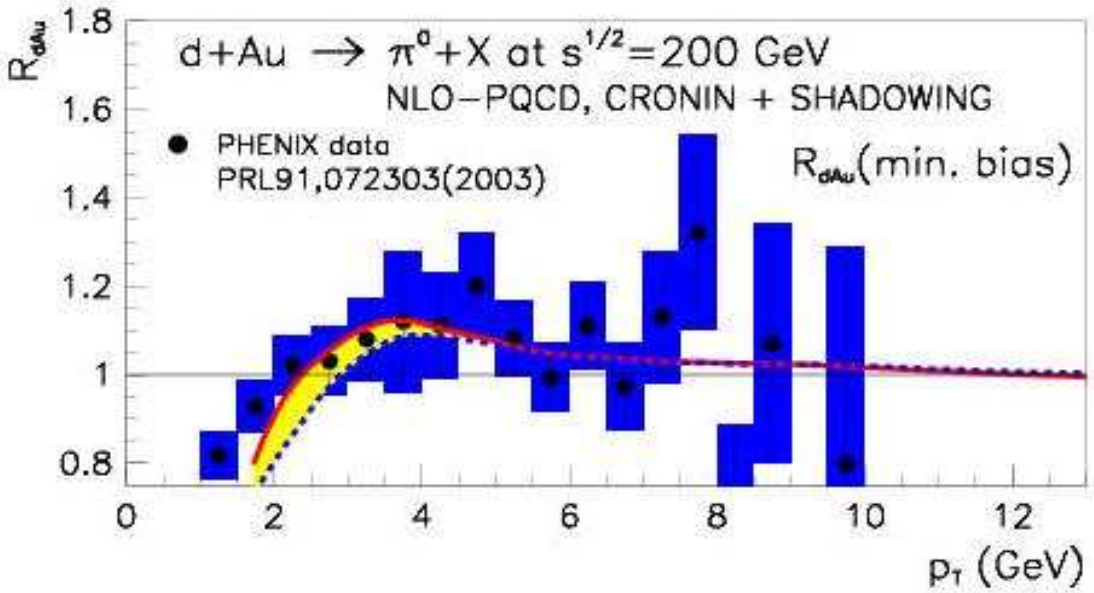
Data: PHENIX Coll., at AGS User Meeting'03



D+Au results can decide between good p+p parametrizations !!!!

Hard physics: pion production in dAu collision at high- p_T

Perturbative QCD calculations in NLO for pp + CRONIN + SHADOWING (LI & XNW):



- compared to data from PHENIX on neutral pion

AGS-RHIC User Meeting May 2003

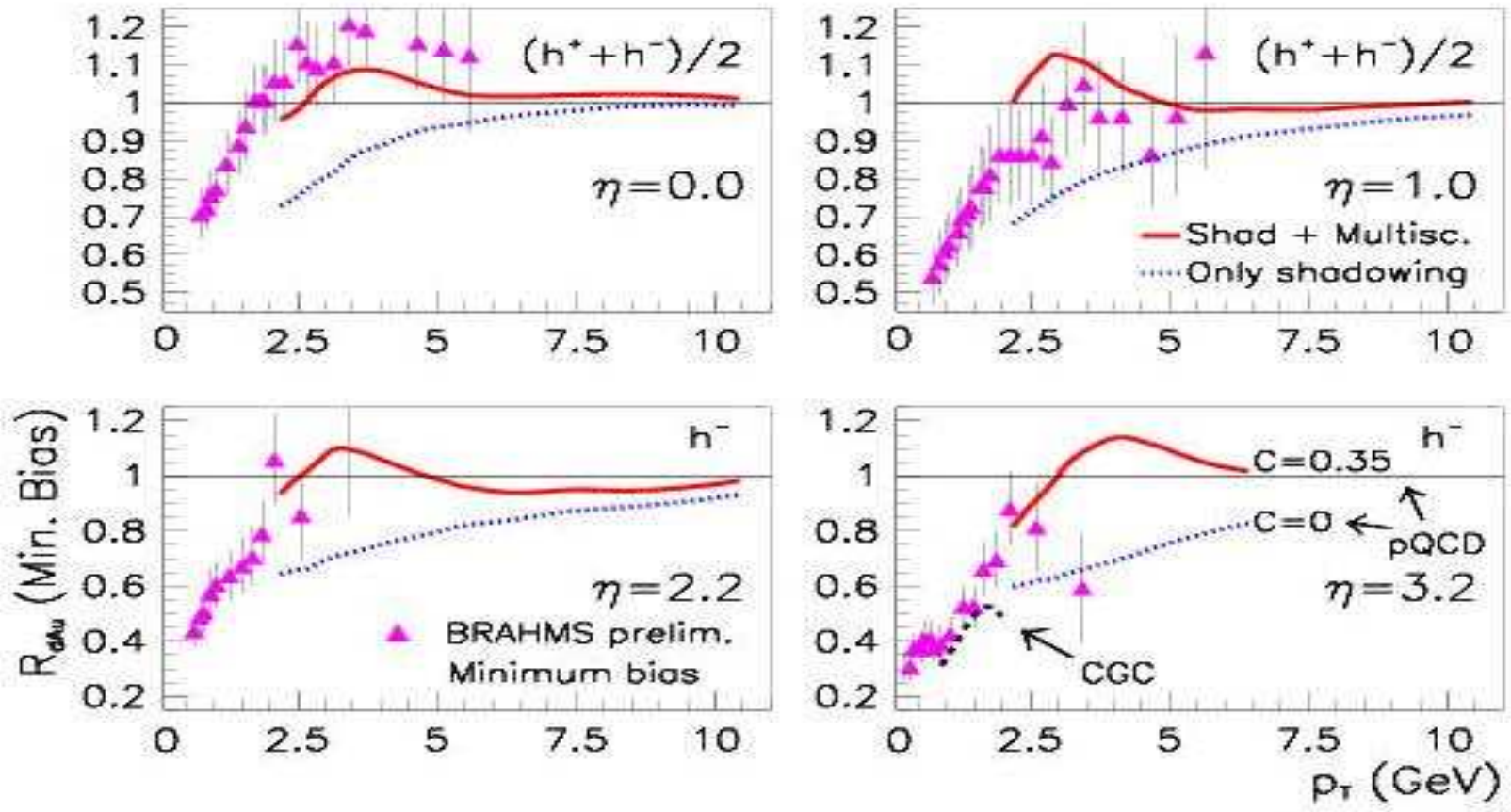
↣ *18 June 2003*

The same multiscattering strength was used as at 27.4 GeV (Antreasyan data)
---- the multiscattering is assumed to be energy independent (C=0.4 GeV^2)

At y=0 there is no room for extra suppression (no CGC) !
What about y=3 ? Let us see on QM04 in January.

Hard physics: pion production in dAu collision at high- p_T

Perturbative QCD calculations in NLO for pp + CRONIN + SHADOWING (LI & XNW):



G.G. Barnafoldi, P.L, ... , (nucl-th/0404012) QM04 Talk , J. Phys. G.

At η= 0 - 3 standard pQCD seems to be all right at pT > 2 GeV !
CGC may play role at pT < 2 GeV

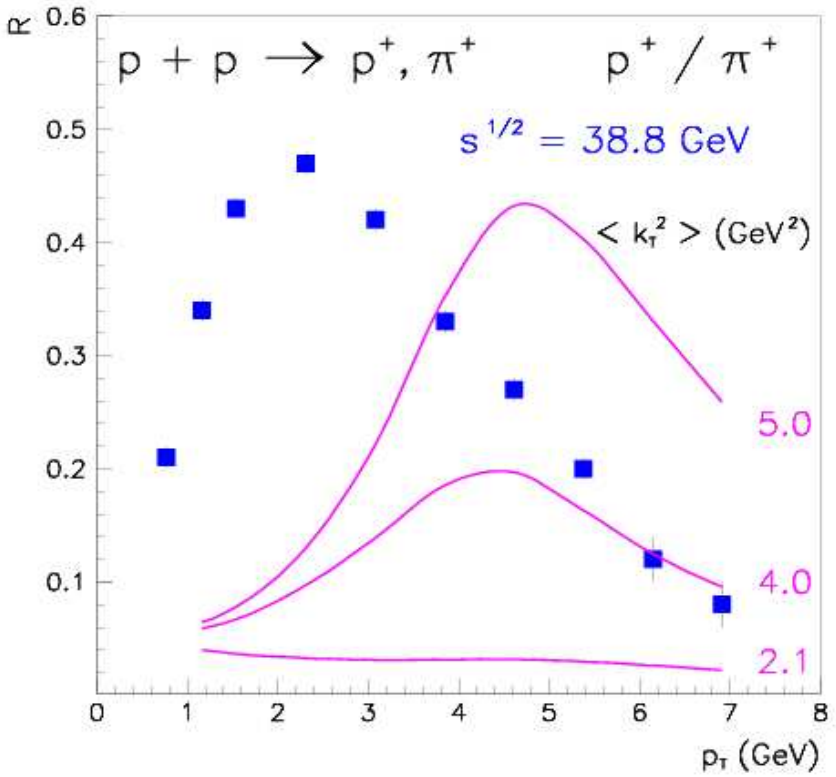
Problems: at pT < 5 GeV

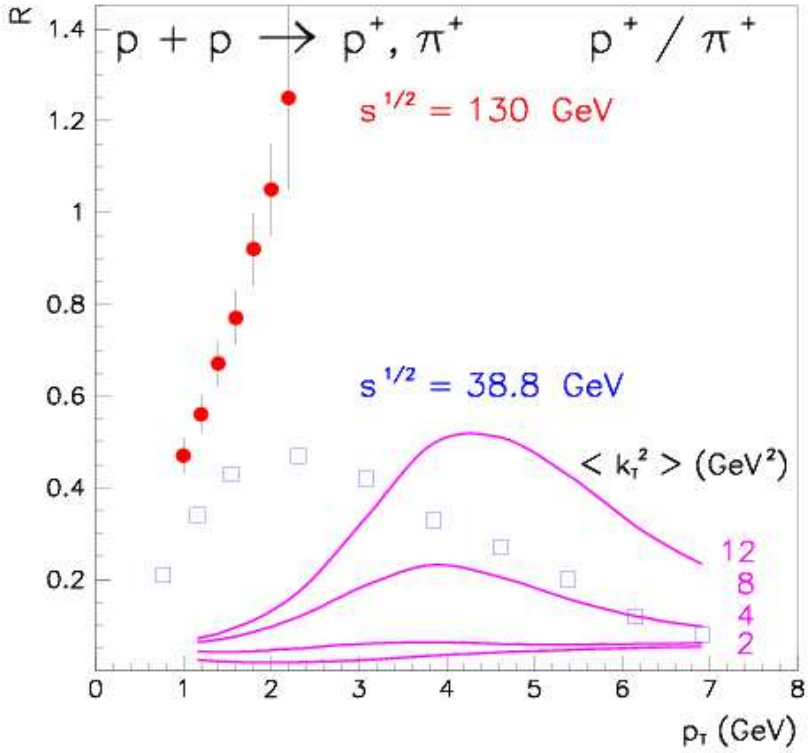
--- kaon production
--- proton, antiproton production
--- ratios
--- ....

--- jet-jet correlations
--- meson-meson correlations
--- baryon-baryon correlations
--- ...

Problems: at pT < 5 GeV

--- proton, antiproton production





FERMILAB data on p+/ π+ **early RHIC data on p+/ π+**

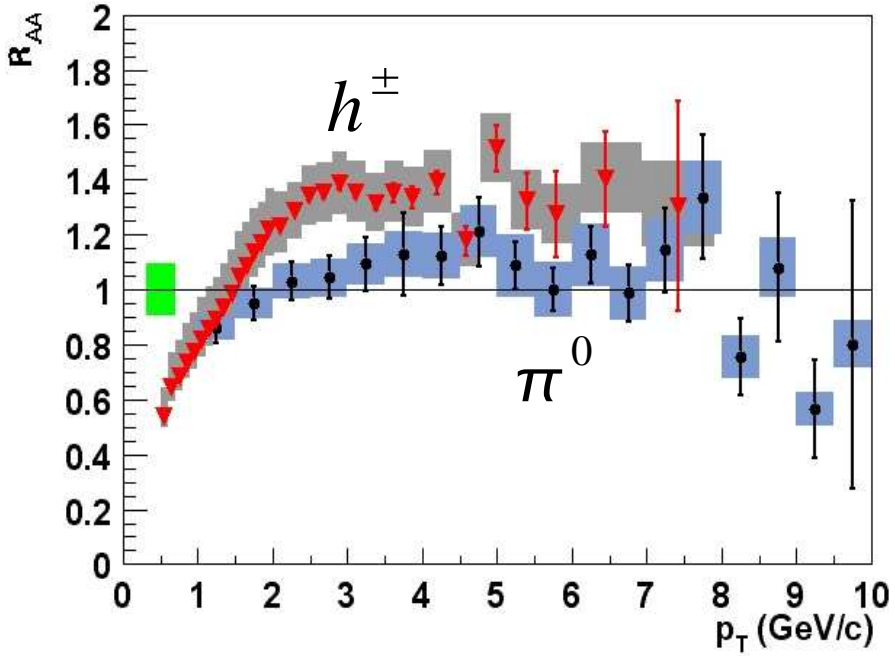
vs. pQCD calculations with intrinsic-k_T

Exciting results from RHIC in dAu at 200 AGeV -- R_{dAu}

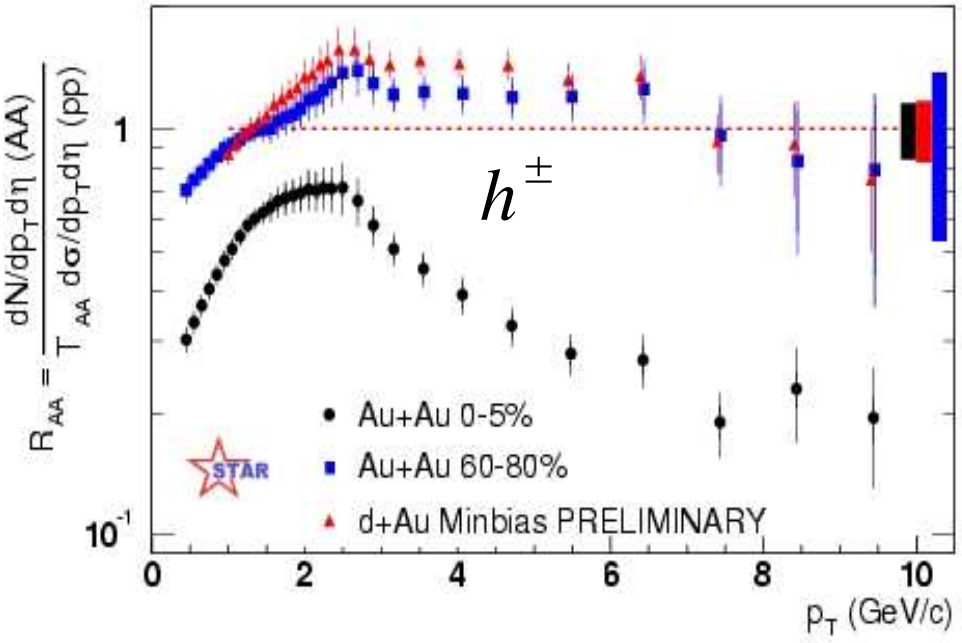
Nuclear modification factor :

$$R_{dAu} = \frac{E_\pi d\sigma_\pi^{dAu}/d^3p}{N_{bin} * E_\pi d\sigma_\pi^{pp}/d^3p} = \frac{E_\pi d\sigma_\pi^{dAu}(\textbf{YES nuclear effect})/d^3p}{E_\pi d\sigma_\pi^{dAu}(\textbf{NO nuclear effects})/d^3p}$$

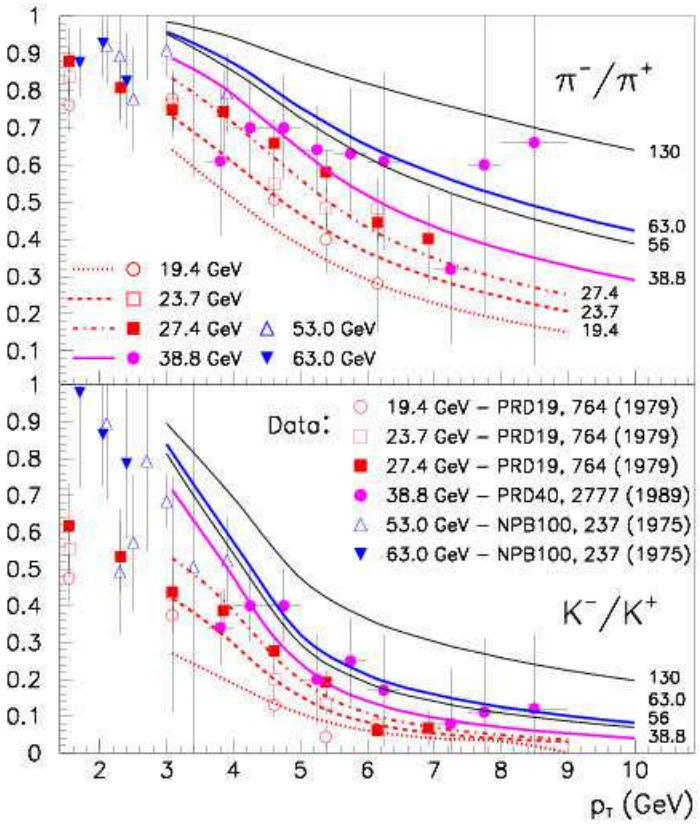
PHENIX data at 200 GeV



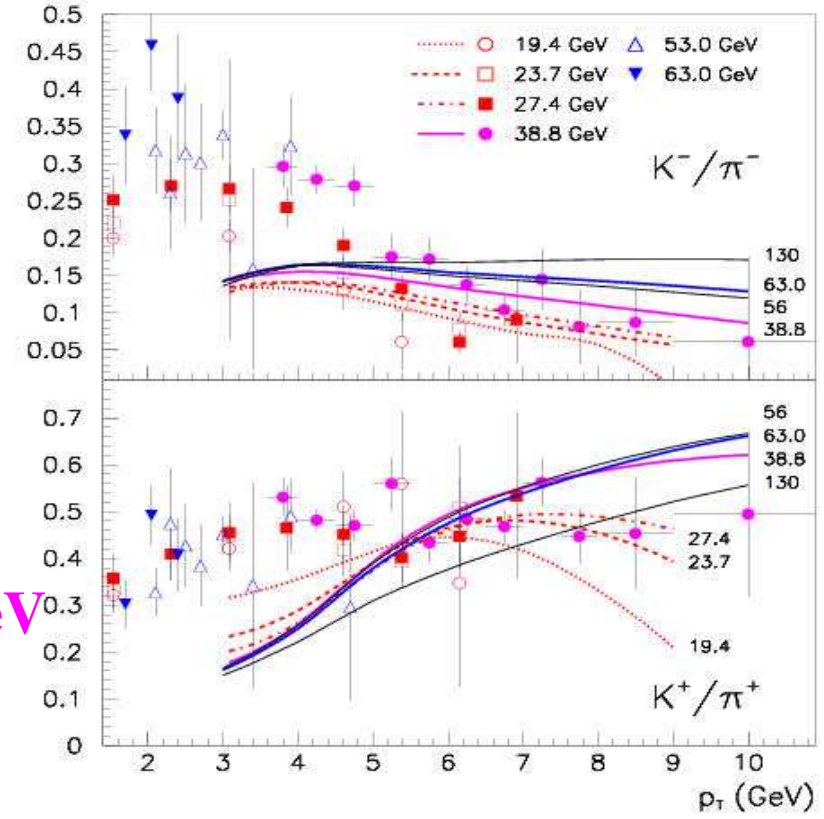
STAR data at 200 GeV



Problems with kaons, protons, antiprotons.



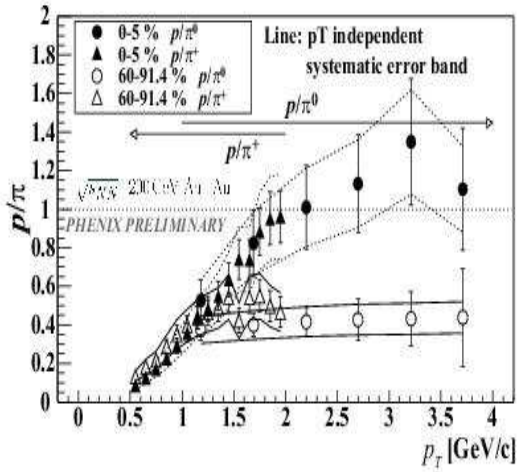
Ratios π-/π+ and K-/K+ can be reproduced quite precisely

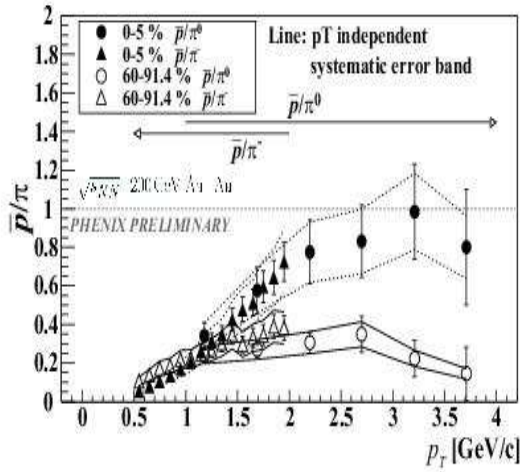


But K- /π- , K+ /π+ ratios were not reproduced under 5 GeV

Exciting results from RHIC at √s = 130 and 200 A GeV -- p/π^+ , $\bar{p}/\pi^-$

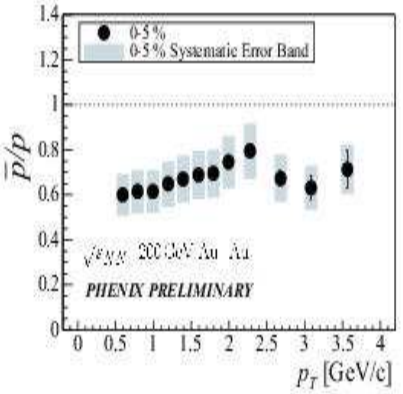
PHENIX Coll., T. Sakaguchi, nucl-ex/0209030, QM02 Conf.

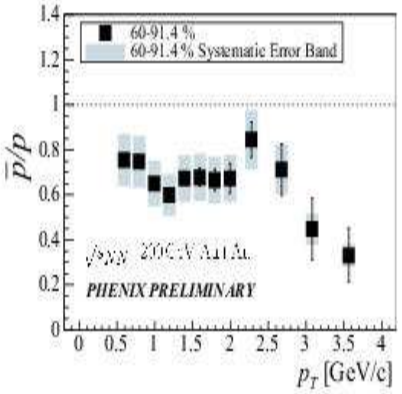


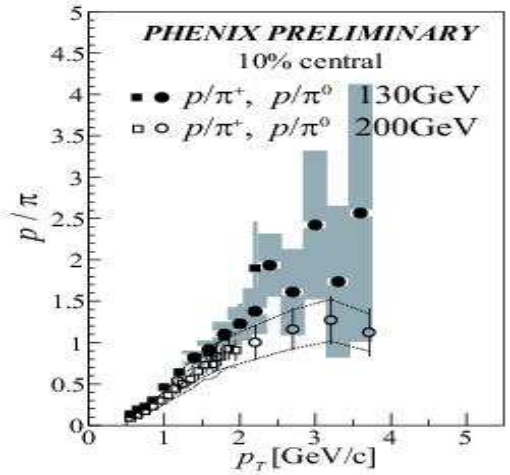


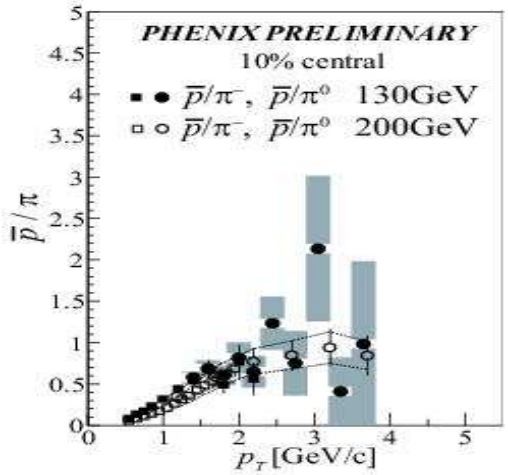
$$N(\bar{p}\ ) > N(\pi^-)!!!$$

Anomalous antiproton (proton) production ??









What is the pQCD result?

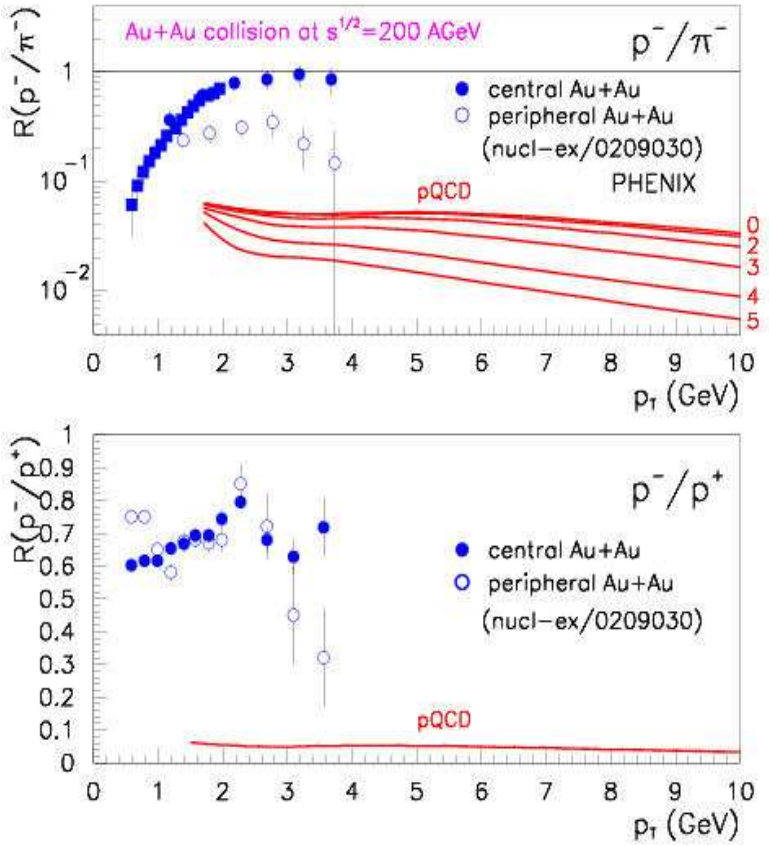
What is the effect of jet-quenching ?

Where is the soft-hard limit ?

Hard physics: proton and antiproton production in AA collision

Perturbative QCD calculations in NLO for heavy ion collisions:
geometrical overlap + shadowing, multiscattring, jet-quenching, ...

$$E_p \frac{d\sigma^{AB}}{d^3 p_p} = \int d^2b\, d^2r \;\; t_A(\vec{r})\, t_B(|\vec{b}-\vec{r}|) \;\; E_p \frac{d\sigma^{pp}}{d^3 p_p} \otimes S(...) \otimes M(...) \otimes Q(...)$$



Data: PHENIX Coll., T. Sakaguchi, nucl-ex/0209030

$$p_T < 4\,GeV$$

PQCD underpredicts data by a factor of 10 !!
- **-- even for peripheral collisions**
- **-- quenching makes it worst for central coll.**
- **-- may agree for p_T > 6 GeV or higher**
  (see previous slide for pions)

Problem has already appeared in pp collision:
X. Zhang, G. Fai, P. Levai, PRL89,272301(2002)

New production mechanism at intermediate p_T!?
1.5 GeV < p_T < 6 GeV

How to enhance baryon (antibaryon) production relative to meson's?

Basic question in HIJING and RQMD and other transport codes.
Answers:

a, String melting → Color ropes (diquark-antidiquark production is enhanced)
but at RHIC we expect deconfined state in the central rapidity

b, Junction physics: junction-antijunction pair decays into B-antiB pair
useful mechanism for baryon stopping into mid-rapidity
D. Kharzeev, M. Gyulassy, I. Vitev, ...

→ **c, Coalescence from constituent quarks and antiquarks:**
N(B) = C * N(Q) * N(Q) * N(Q)
N(M) = C' * N(Q) * N($\bar{Q}$) **It works well (ALCOR, MICOR,...)**
J. Zimanyi, T.S. Biro, P. Csizmadia, P. Levai, ...
A. Bialas, J. Pisut, R. C. Hwa, C.B. Yang, ...

d, PQCD with relatively enhanced intrinsic k_T
too much phenomenology
X. Zhang, G. Fai, P. Levai, ...

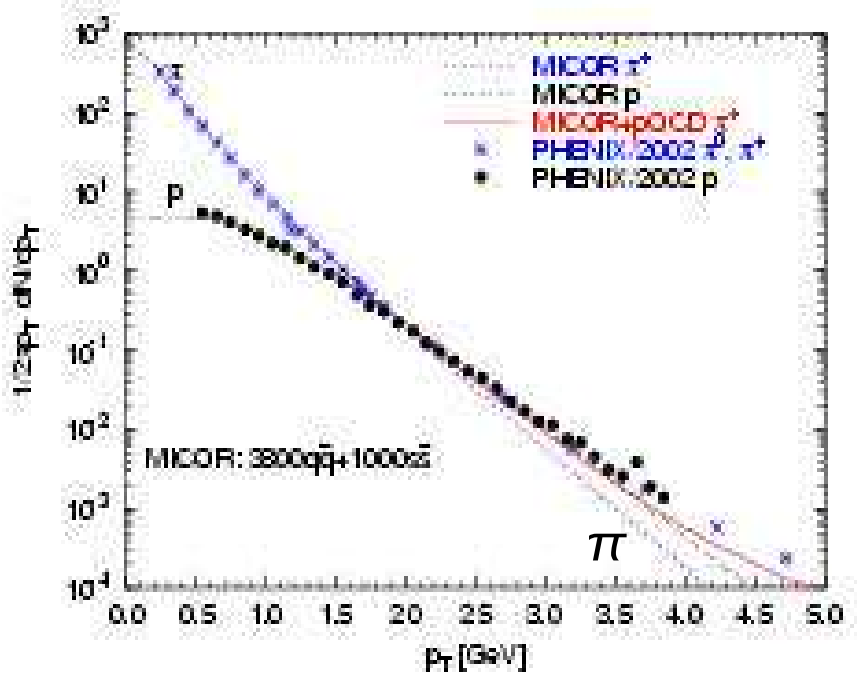
e, PQCD with modified fragmentation function (D_h/c)
.....

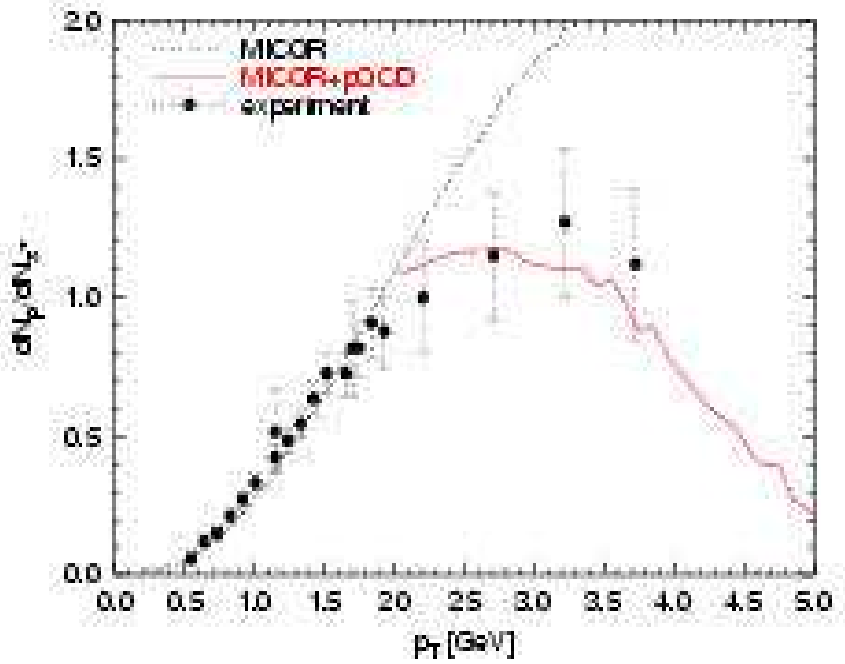
Quark coalescence at high p_T: MICOR + pQCD model

e.g. . proton/pion ratio P. Csizmadia, P.L. '03

MICOR model : quark-coalescence (0 < p_T < 4-5 GeV)

+ pert. QCD : + independent jet-fragment. (2 < p_T < 10-20 GeV)





MICOR: pion yield is decreasing faster than proton yield with increasing p_T

pQCD: FF pion yield is comparable with coal. yield, FF proton yield is negligible

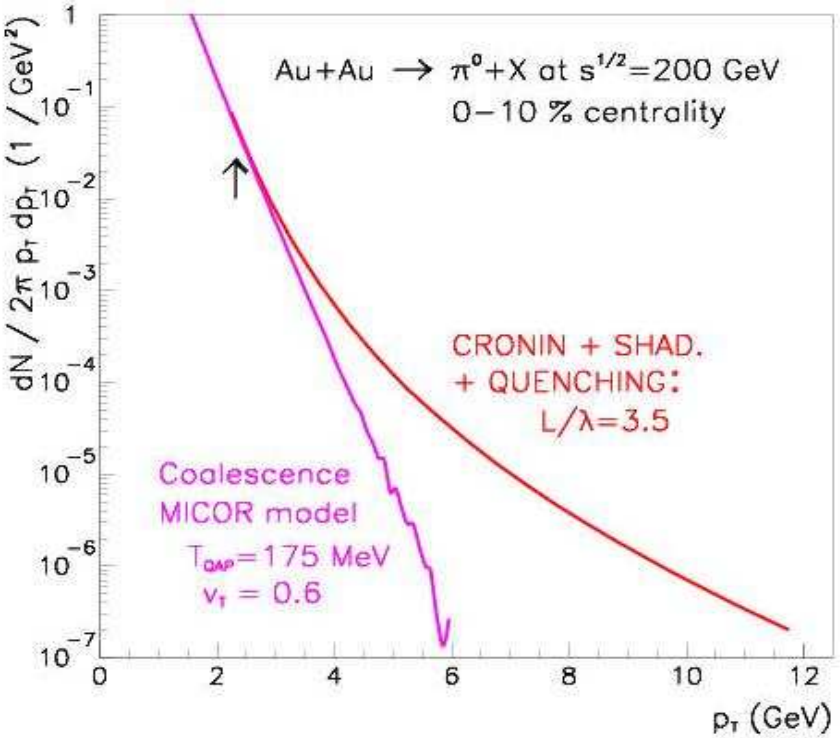
superposition: special structure in proton/pion ratio

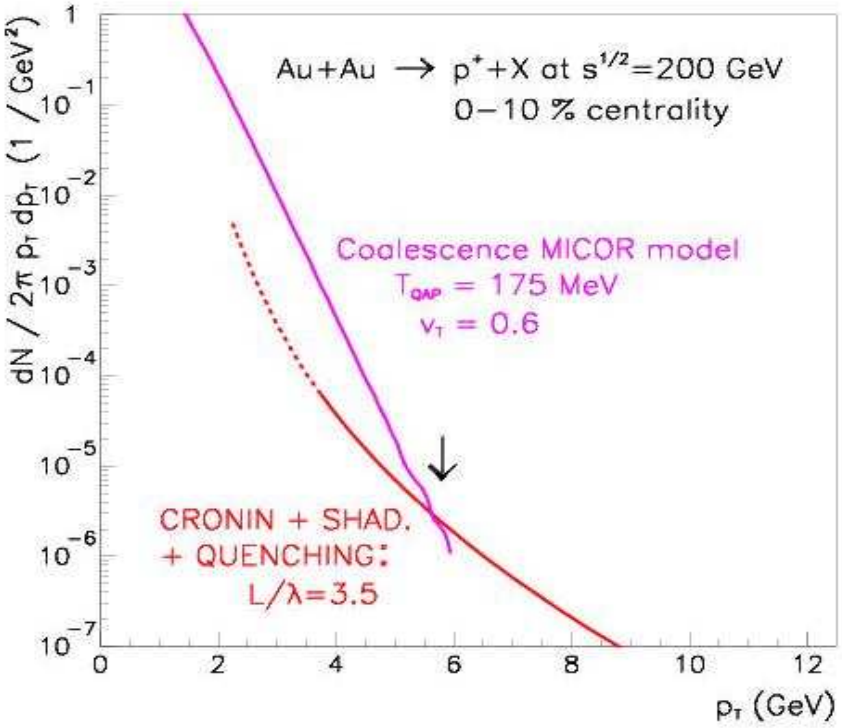
Quark coalescence at high p_T: MICOR + pQCD model

e.g. . proton and pion production P. Csizmadia, P.L. '03

MICOR model : quark-coalescence (0 < p_T < 4-5 GeV)

+ pert. QCD : + independent jet-fragment. (2 < p_T < 10-20 GeV)





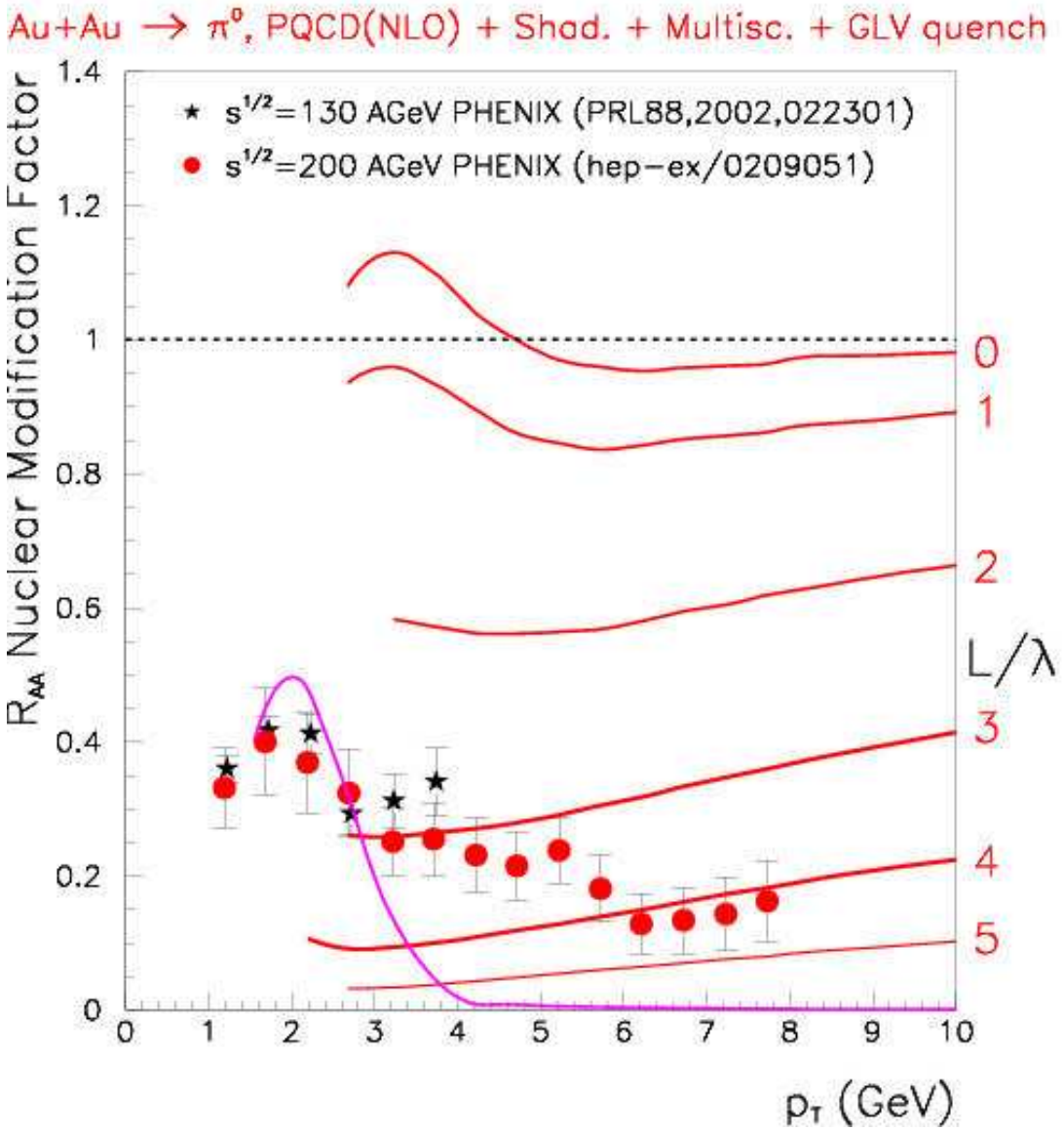
Pions are produced from jets for p_T > 2 GeV !!!!!

Protons are produced from jet ONLY after p_T > 5.5 GeV !!!!

SOLUTION for PROBLEM-III !

Jettiness and quark coalescence can exist together !

Parton colescence: R_AA nuclear modification factor



Intermediate (coalescence) region:

Location of the drop in
the R_AA factor:
(similarly to the ratios)

- ☞ end of the intermediate region
- ☞ information about the partonic thermal bath (T, flow)
- ☞ shape analysis (details)
- ☞ Δ_p momentum window in the coalescence process (crucial parameter)

Question:
directly produced pions ?
Or directly produced resonances will decay into pions ?
Answer: MICOR model
P. Csizmadia, P. L.

SUMMARY:

Questions, questions, questions, ...

Does parton coalescence exist ?

Or this contribution is coming from another channel, which looks like colaescence ? Gluon-fusion ? Small-x feature ? (CGC)

What about pA ?

What about pp ? $0 < p_T < 5$ GeV

Collinear factorization and/or k_T factorization ?

$2 \rightarrowtail 2$ and/or $2 \rightarrowtail 1$ processes ? ..... QGP ? Or something else ? RHIC. LHC, ...

See you in the Quark Matter 2005 Conference in Budapest !

1 - 6 August 2005, BUDAPEST, HUNGARY

http://qm2005.kfki.hu