Applied High Energy Physics---
The use of hard-scattering to diagnose the final state of Au+Au collisions at RHIC

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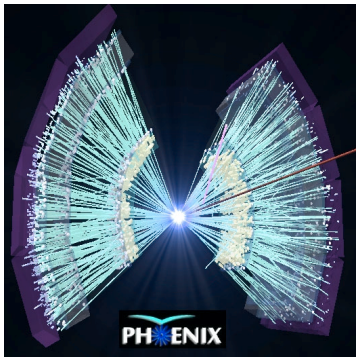


National Society of Black Physicists
Washington, DC, February 21, 2004

Bjorken Scaling in Deeply Inelastic Scattering and the Parton Model---1968

♡ The discovery that the DIS structure function

$$F_2(Q^2, \nu) = F_2(\frac{Q^2}{\nu}) \qquad (1)$$

"SCALED" i.e just depended on the ratio

$$x = \frac{Q^2}{2M\nu} \qquad (2)$$

independently of Q^2 $(\sim 1/r^2)$

♡ as originally suggested by **Bjorken** Phys. Rev. **179**, 1547 (1969)

♡ Led to the concept of a proton composed of point-like **partons**. Phys. Rev. **185**, 1975 (1969)

□ The probability for a parton to carry a fraction x of the proton's momentum is measured by $F_2(x)$

$$\nu = \frac{Q^2}{2Mx}$$

BBK 1971

S.M.Berman, J.D.Bjorken and J.B.Kogut, Phys. Rev. **D4**, 3388 (1971)

- BBK calculated for p+p collisions, the inclusive reaction

$$A+B \rightarrow C + X$$ when particle C has $p_T \gg 1$ GeV/c

  - The charged partons of DIS **must scatter electromagnetically** *"which may be viewed as a* **lower bound** *on the real cross section at large p_T."*

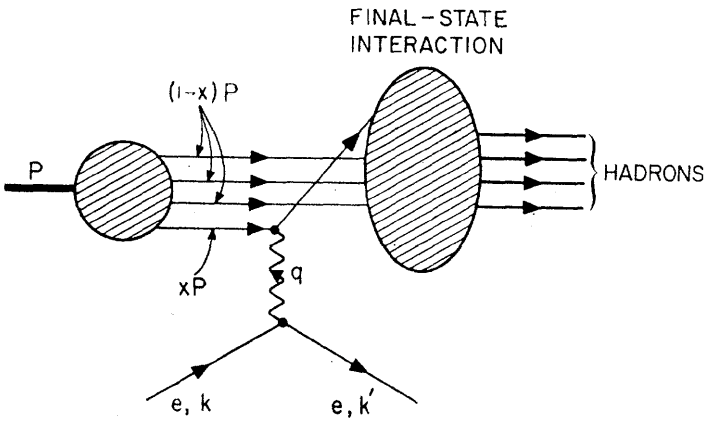
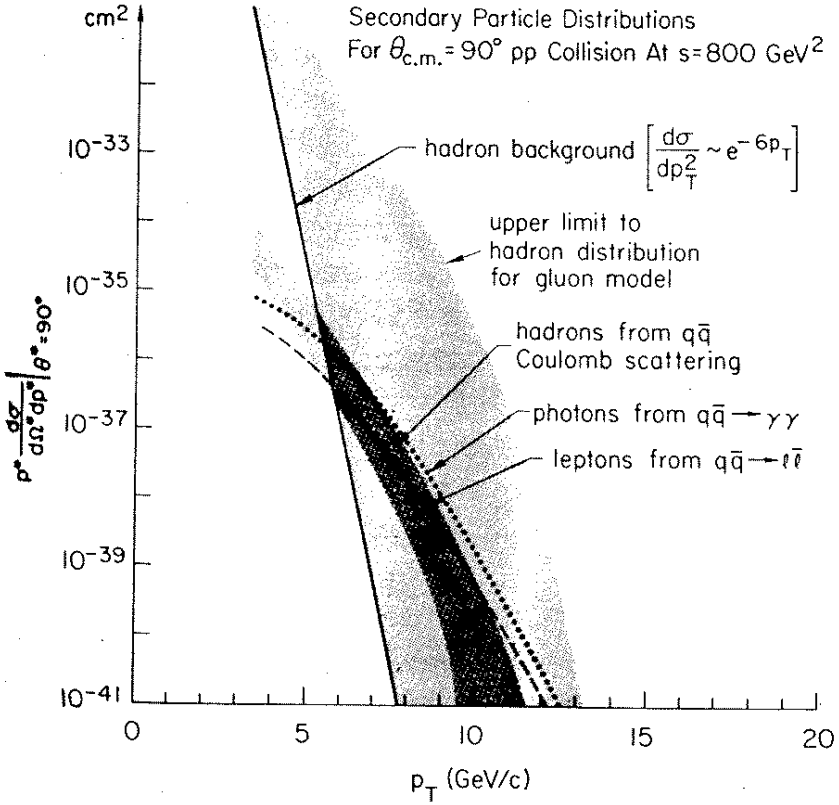


FIG. 1. Kinematics of lepton-nucleon scattering in the parton model.



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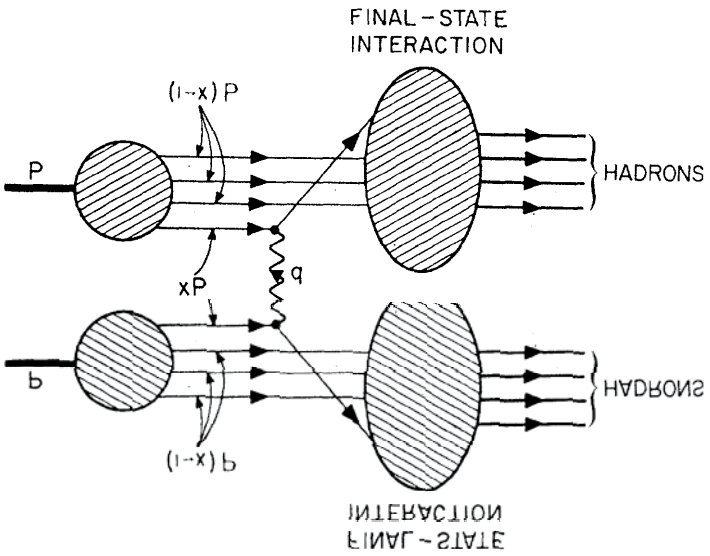
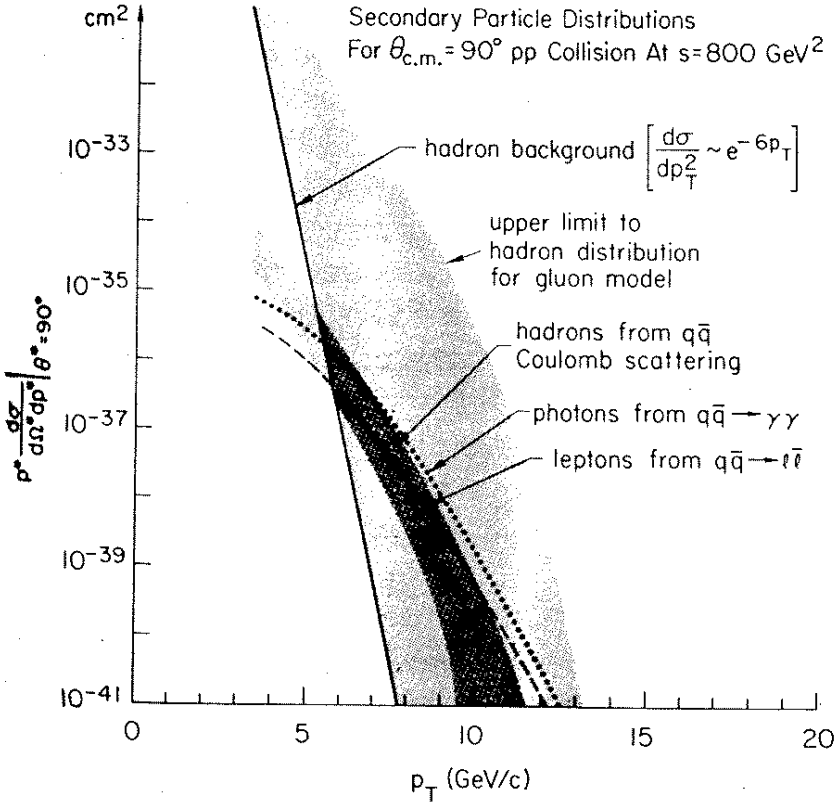
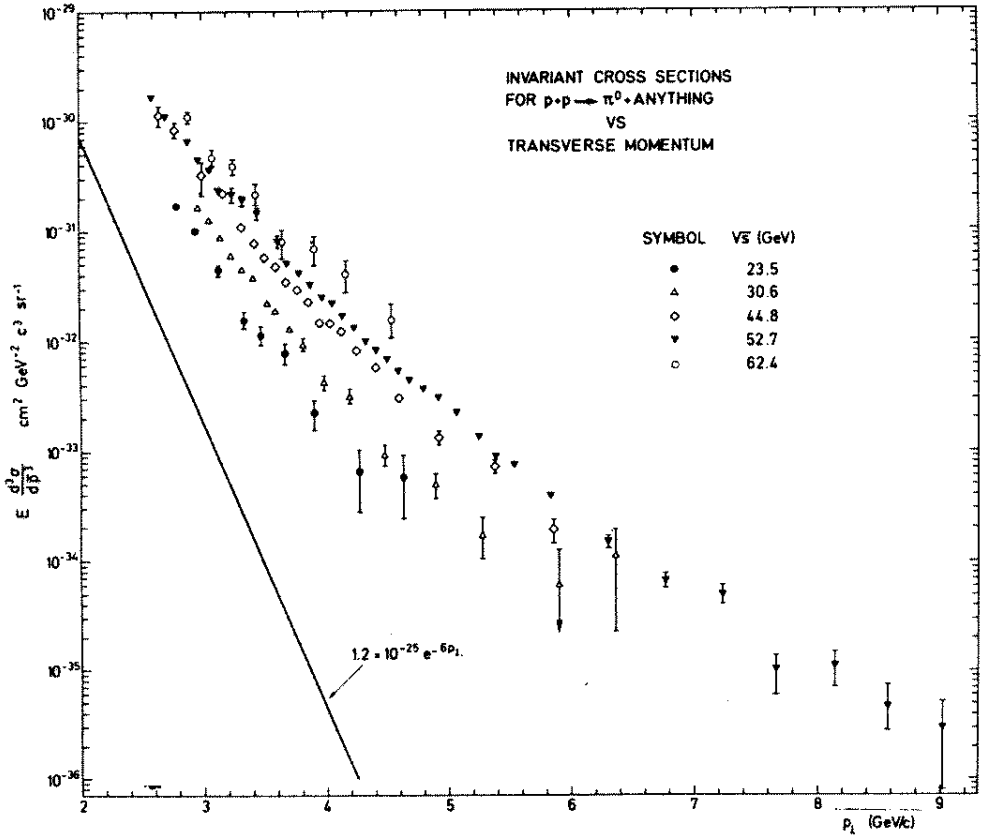




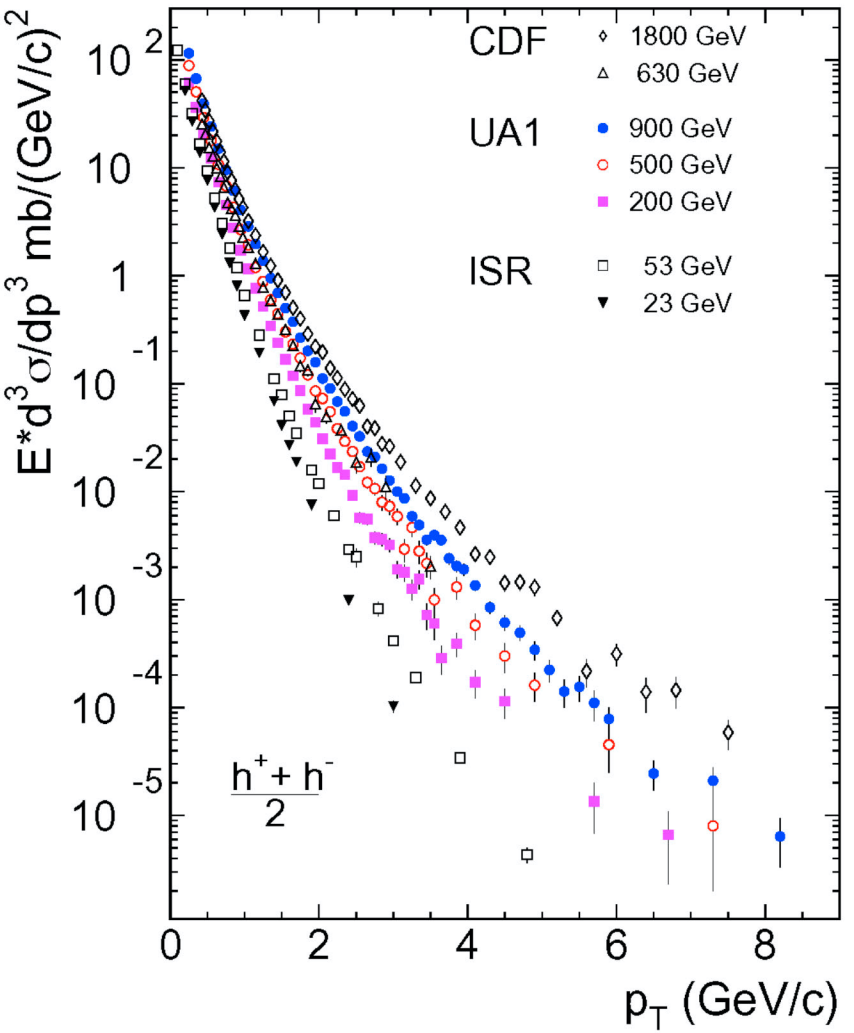
CCR at the CERN-ISR
Discovery of high p_T production in p-p

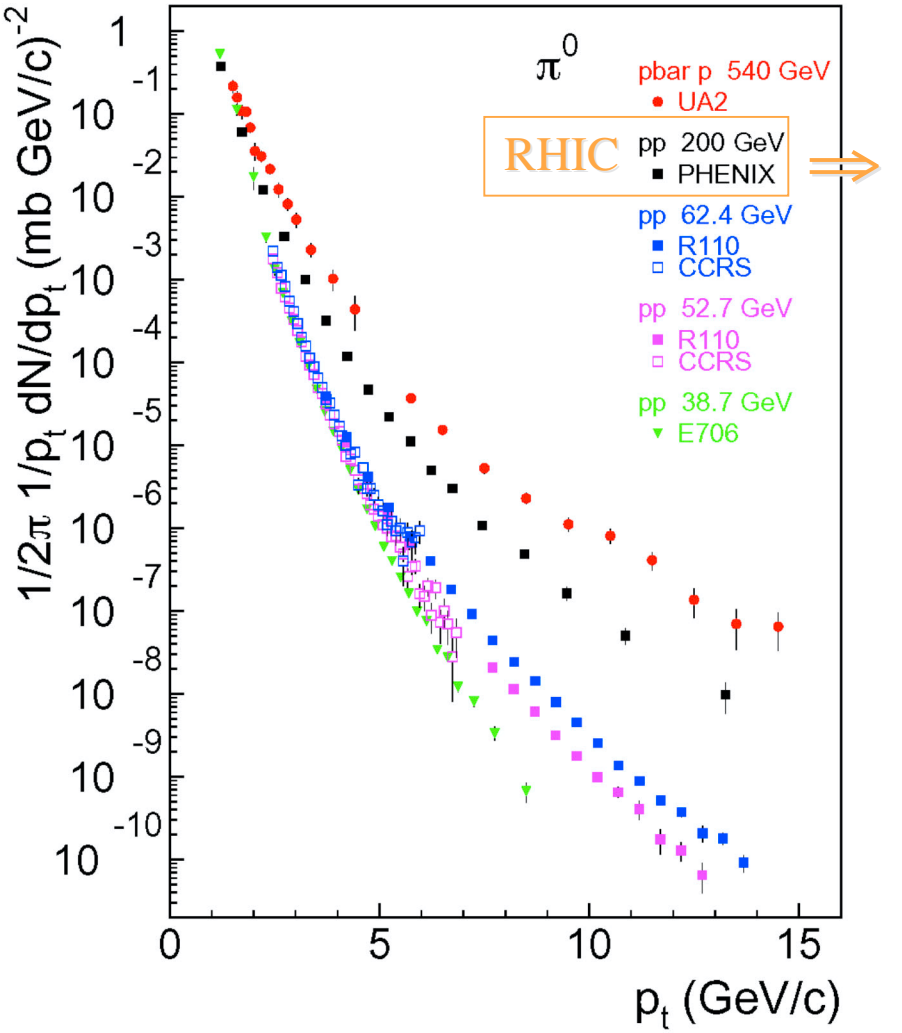


F.W. Busser, *et al.*,
CERN, Columbia, Rockefeller Collaboration
Phys. Lett. **46B**, 471 (1973)

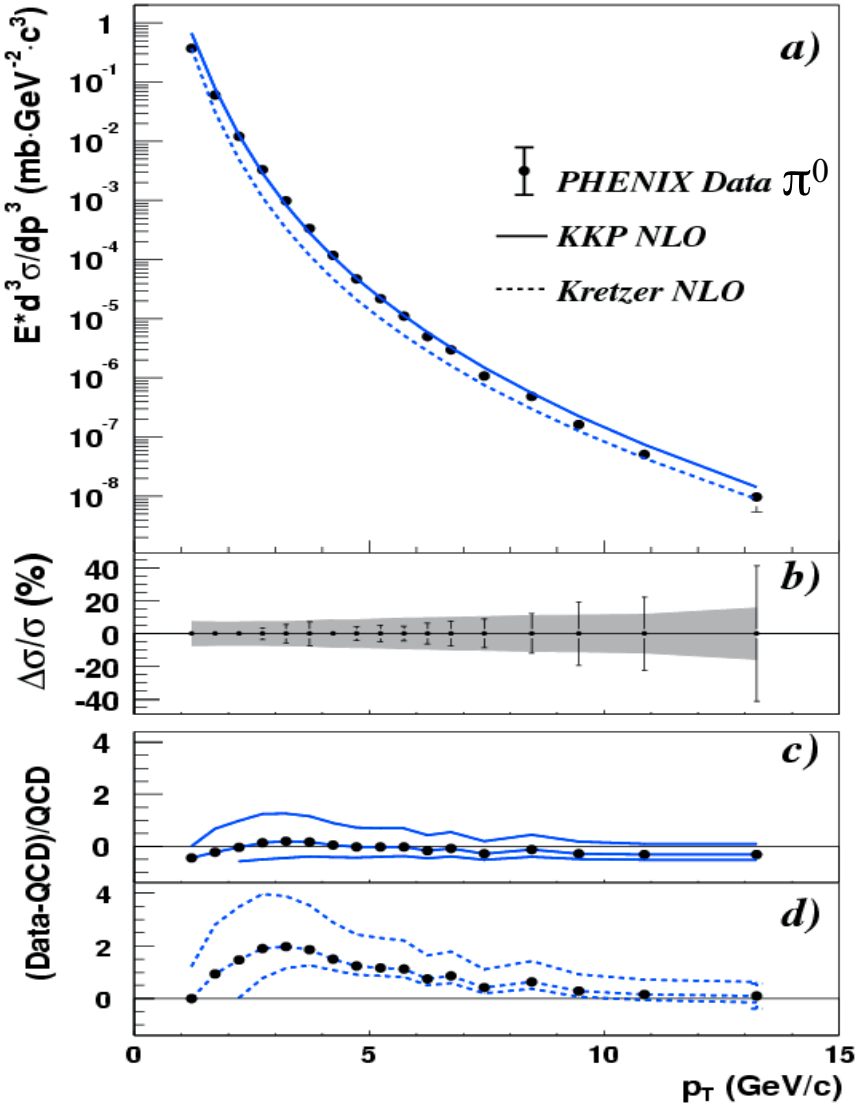
- e^{-6p_T} breaks to a power law at high p_T with characteristic √s dependence
- Large rate indicates that partons interact strongly (>> EM) with other.
- This and other experiments prove that high p_T particles are the result of hard-scattering of the constituents of the protons as described by QCD (1975-83)

Subsequent inclusive single hadron high p_T spectra in p-p collisions all show the same effect ⇒





RHIC pp spectra √s=200 GeV nicely illustrate hard scattering phenomenology



- Good agreement with NLO pQCD
  - ✓ this is no surprise for `old timers' (like me) since as I just explained, single particle inclusive spectra were what proved QCD in the late 1970's before jets.
- **Reference for A+A and p+A spectra**
  - ✓ π^0 measurement in same experiment allows us the study of nuclear effect with less systematic uncertainties.

PHENIX (p+p) hep-ex/0304038

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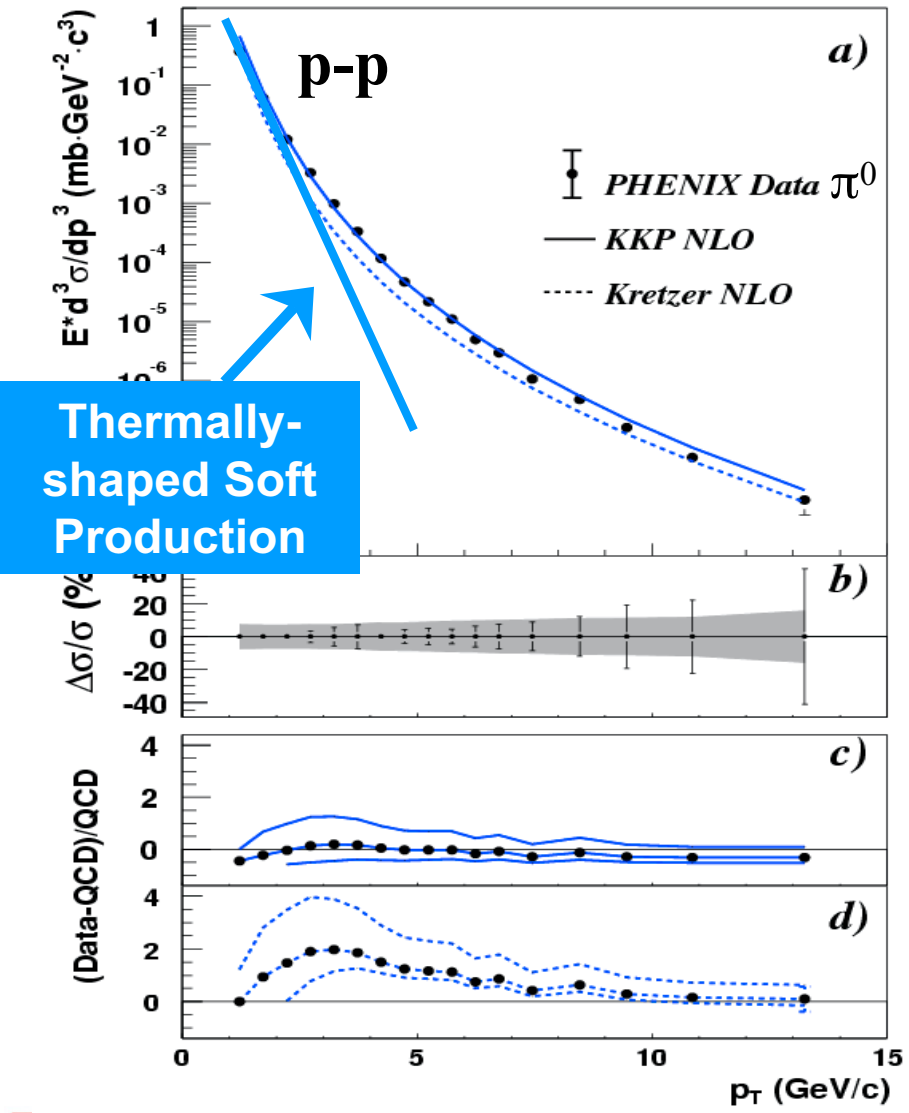

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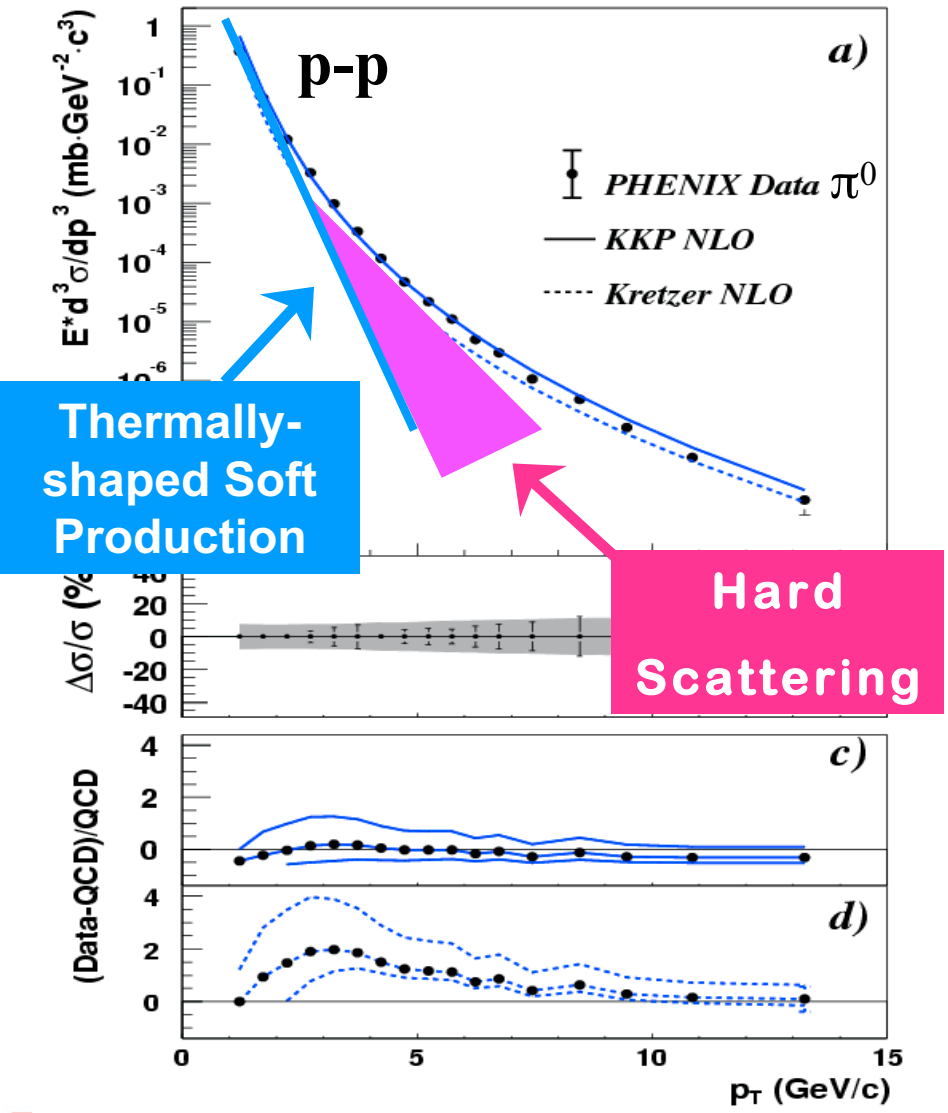

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μ-A DIS at AGS (1973)--Hard-Scattering is pointlike

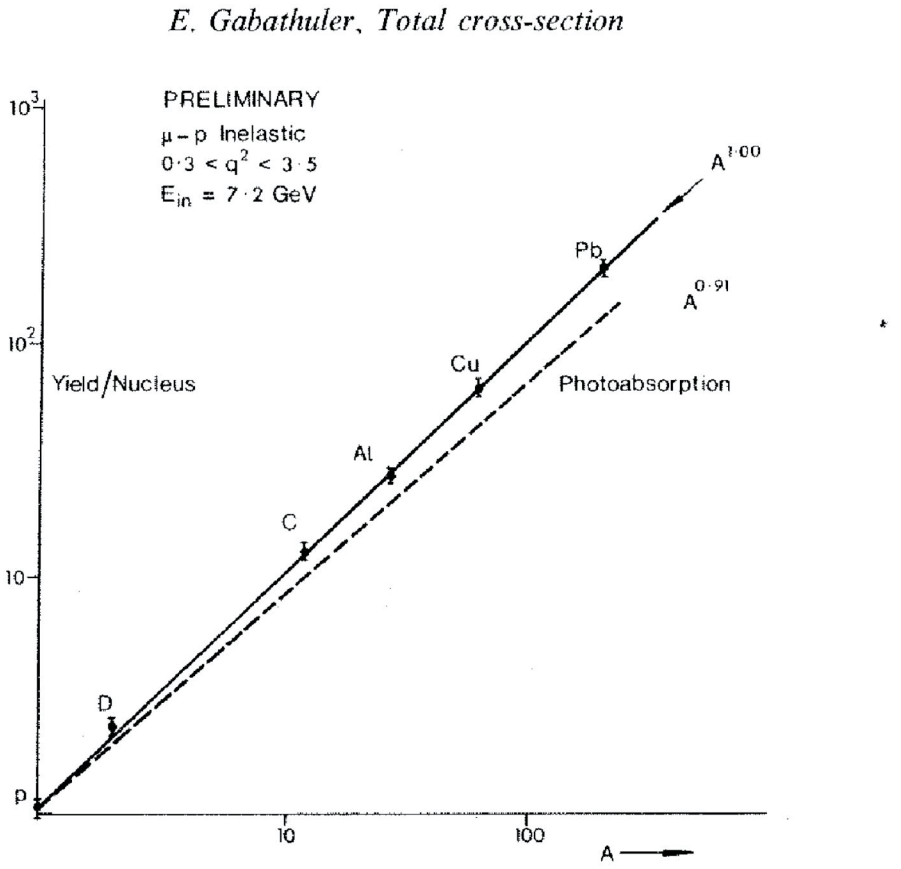
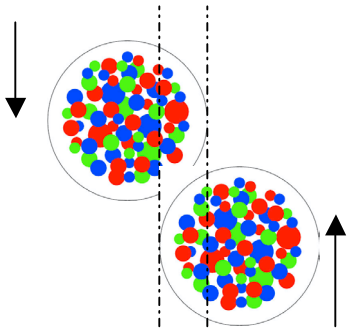


Fig. 14. The A dependence of the inelastic muon cross-section as presented by Tannenbaum (see discussion).

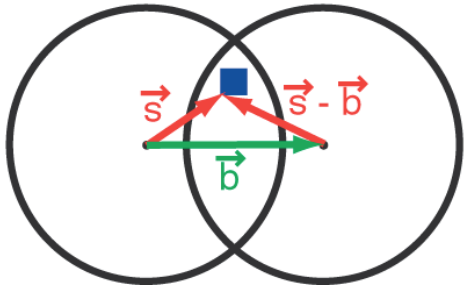
AGS $\mu - A$ scattering data, from E. Gabathuler's talk, [Proc. 6th Int. Symposium on Electron and Photon Interactions at High Energies, Bonn (1973)].

- ♡ DIS is pointlike $A^{1.00}$ even at modest q^2—no shadowing.
- ♡ Photoproduction is shadowed—$A^{0.91}$

High p_T in A+B collisions---T_{AB} Scaling



looking down



view along beam axis

- For point-like processes, the cross section in p+A or A+B collisions compared to p-p is simply proportional to the relative number of pointlike encounters

  - ✓ A for p+A, AB for A+B for the total rate

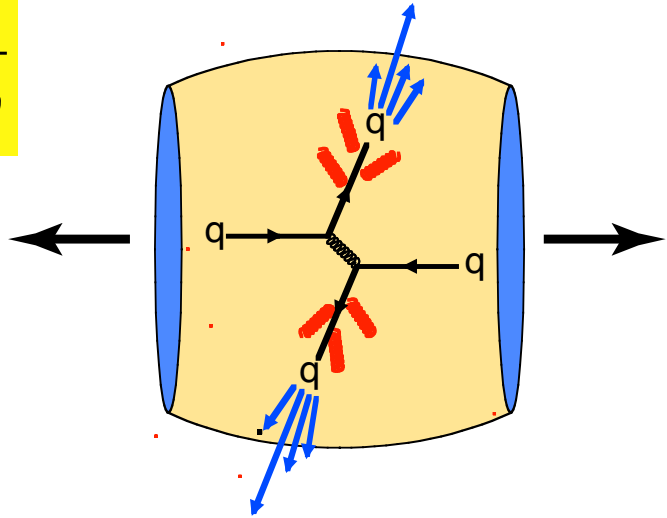
  - ✓ T_{AB} the overlap integral of the nuclear profile functions, as a function of impact parameter b

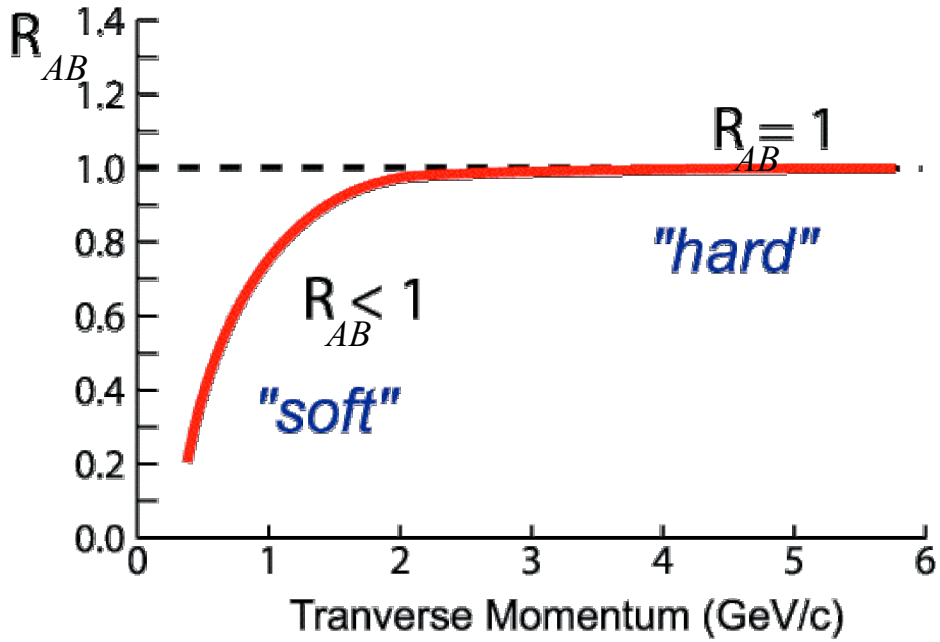
The Nuclear Modification Factor R_{AB} is the ratio of pointlike scaling of an A+B measurement to p-p

Nuclear Modification Factor:

$$R_{AB}(p_T) = \frac{d^2N^{AB}/dp_T d\eta}{T_{AB} d^2\sigma^{pp}/dp_T d\eta}$$

Compare A+B to p-p cross sections





"Nominal effects":

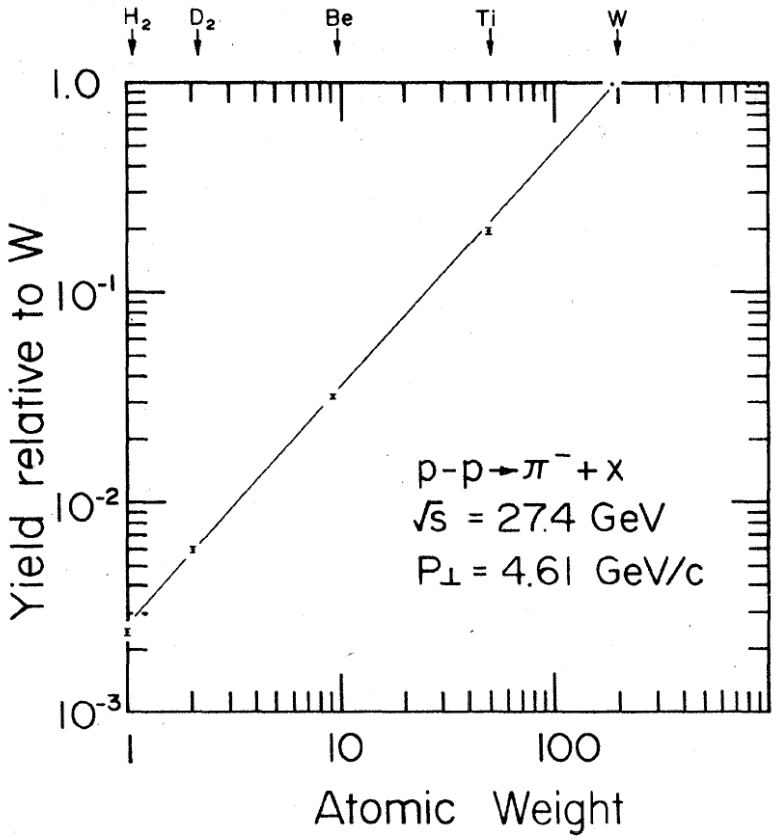
$R_{AB} < 1$ in regime of soft physics

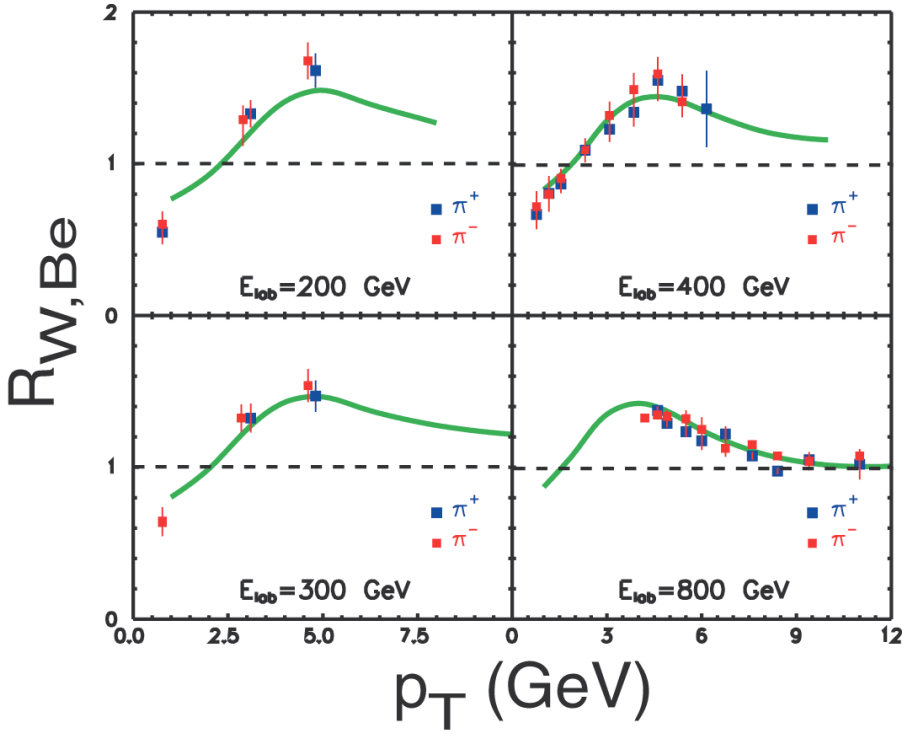
$R_{AB} = 1$ at high-p_T where hard scattering dominates

What really Happens for p+A: $R_A > 1$!

The anomalous nuclear enhancement a.k.a. the Cronin effect--
due to multiple scattering of initial nucleons (or constituents)

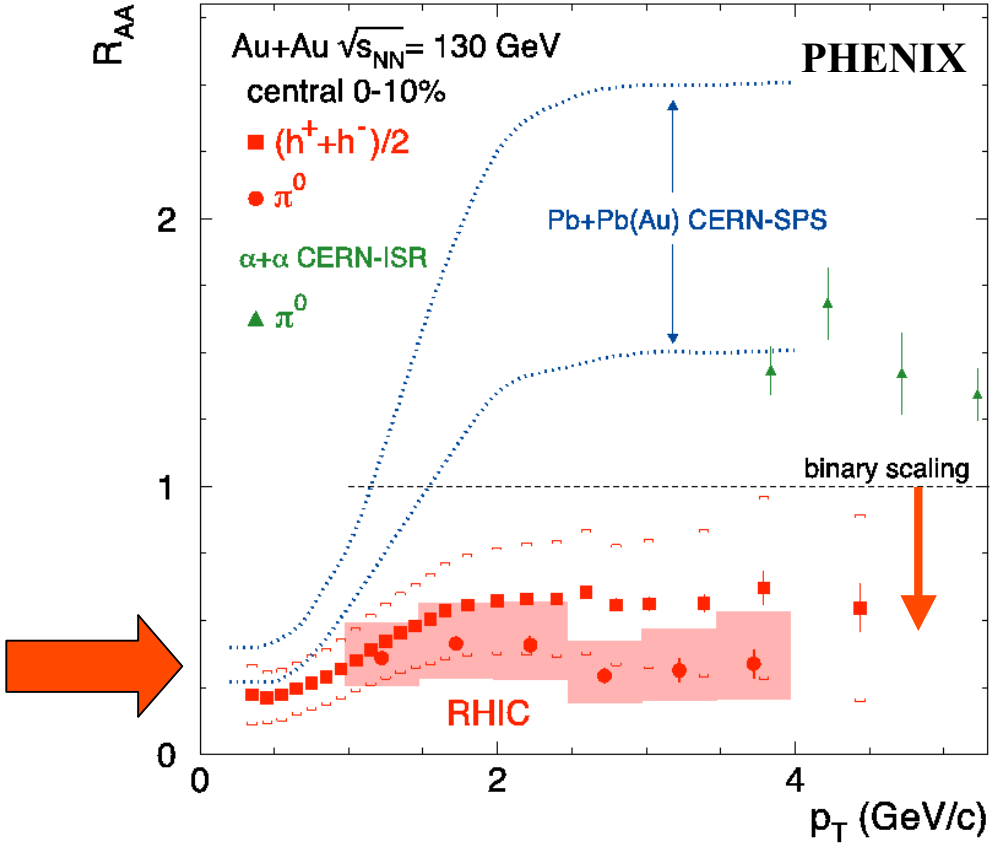
- Known since 1975 that yields increase as A^{α}, $\alpha > 1$





- J.W. Cronin et al., Phys. Rev. **D11**, 3105 (1975)
- D. Antreasyan et al., Phys. Rev. **D19**, 764 (1979)

For Au+Au at RHIC: Completely different! Headline News… First results $\sqrt{s_{NN}}$=130 GeV

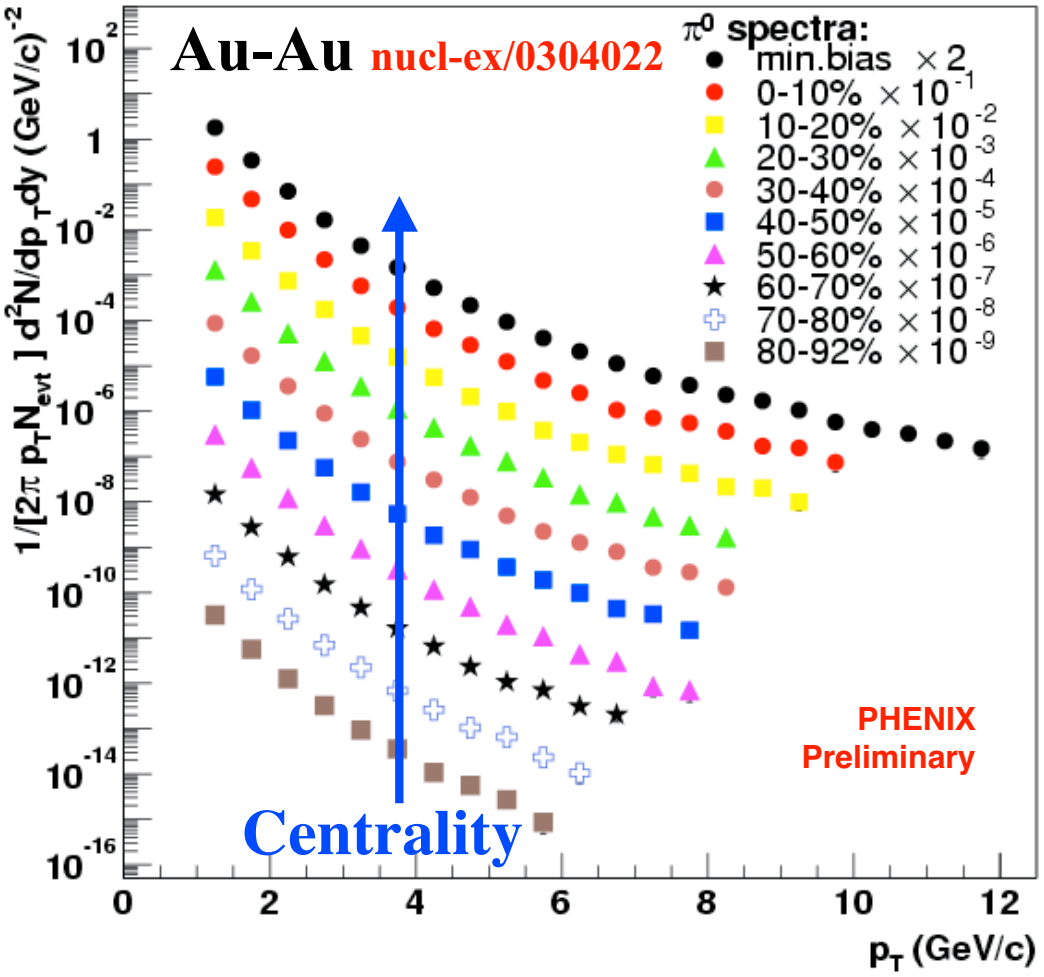


PHENIX PRL 88, 022301 (2002)

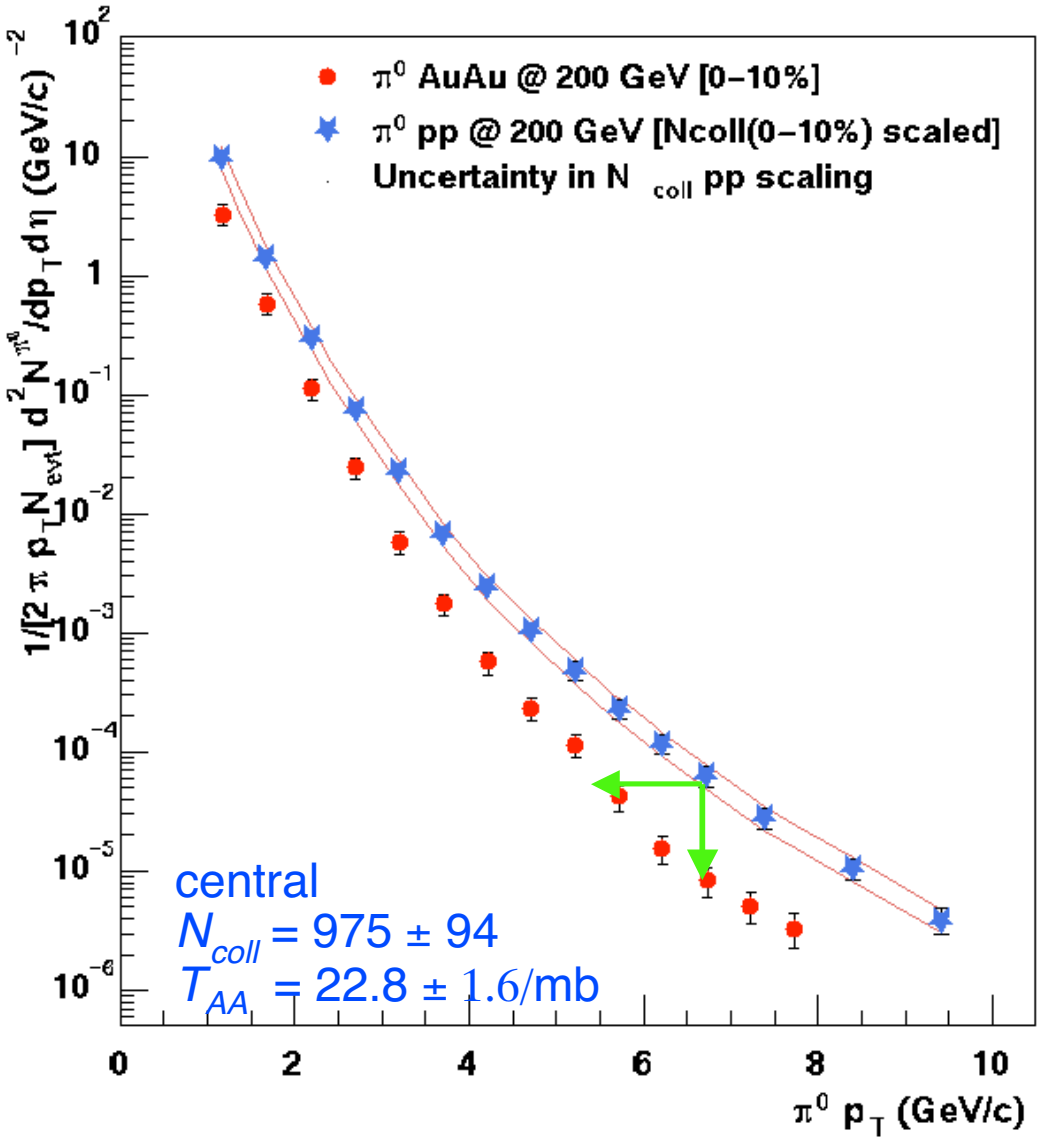
First observation of *large* suppression of high p_T hadron yields

"Jet Quenching''? == Quark Gluon Plasma?

RHIC Run 2-- $\sqrt{s_{NN}}$=200 GeV Au+Au collisions: Extend to higher p_T + p-p reference measurement



Central Spectrum is suppressed---is this due to a shift caused by energy loss

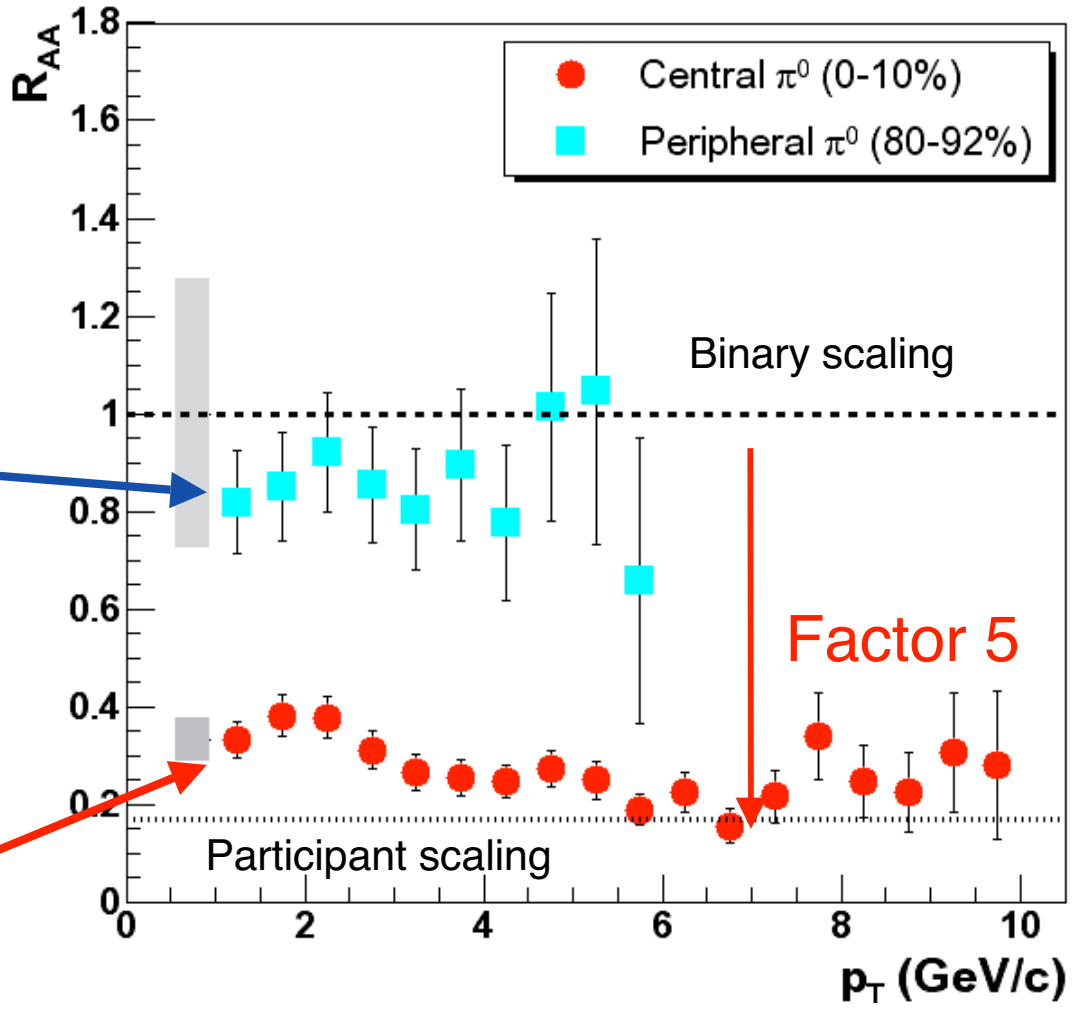


R_{AA} : High P_T Suppression to at least 10 GeV/c

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

Peripheral AuAu - consistent with N_{coll} scaling (large systematic error)

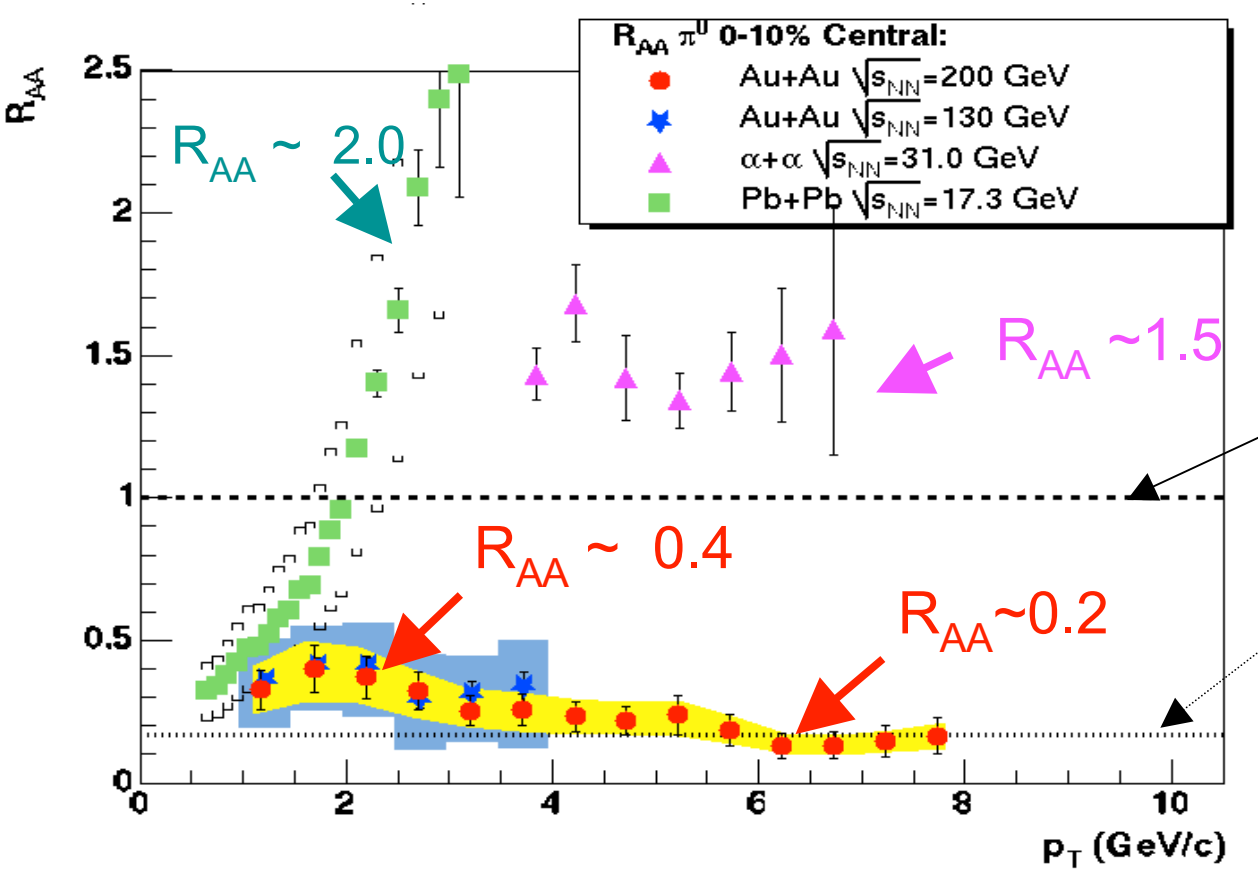
Large suppression in central AuAu - close to participant scaling at high P_T



PRL 91 (2003) 072301

Nuclear modification factor: $\sqrt{s_{NN}}$ dependence for A+B collisions

CERN: Pb+Pb ($\sqrt{s_{NN}}$ ~ 17 GeV), α+α ($\sqrt{s_{NN}}$ ~31 GeV): **all previous msmts B+A**-Cronin enhancement



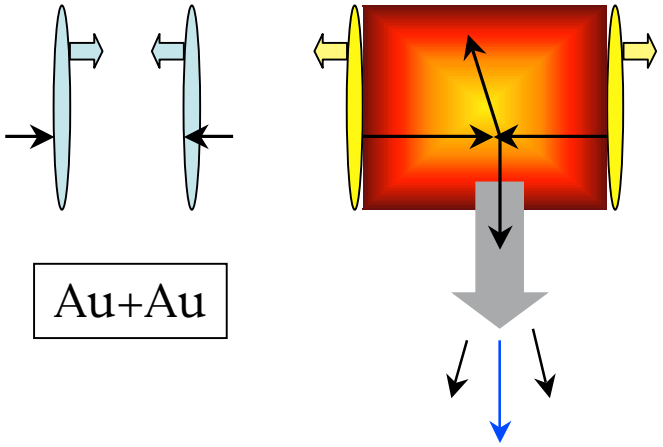
$N_{collision}$ scaling

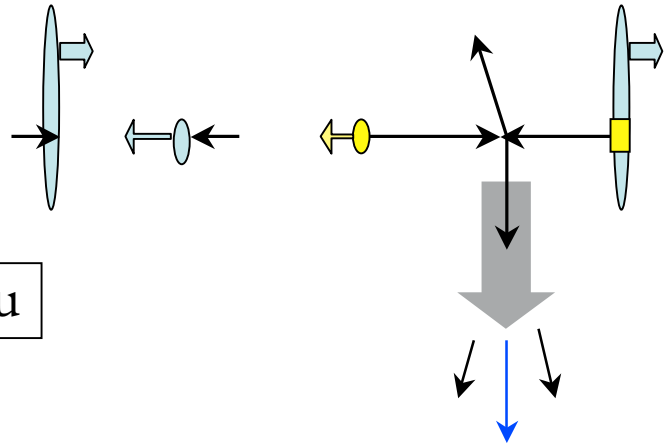
N_{part} scaling

A.L.S.Angelis PLB 185, 213 (1987)
WA98, EPJ C 23, 225 (2002)
PHENIX, PRL 88 022301 (2002)
D.d'E. PHENIX Preliminary QM2002

RHIC Au+Au $\sqrt{s_{NN}}$=130 and 200 GeV HUGE SUPPRESSION---Major Discovery 2001-2

d+Au: Control Experiment to prove the Au+Au discovery





= hot and dense medium

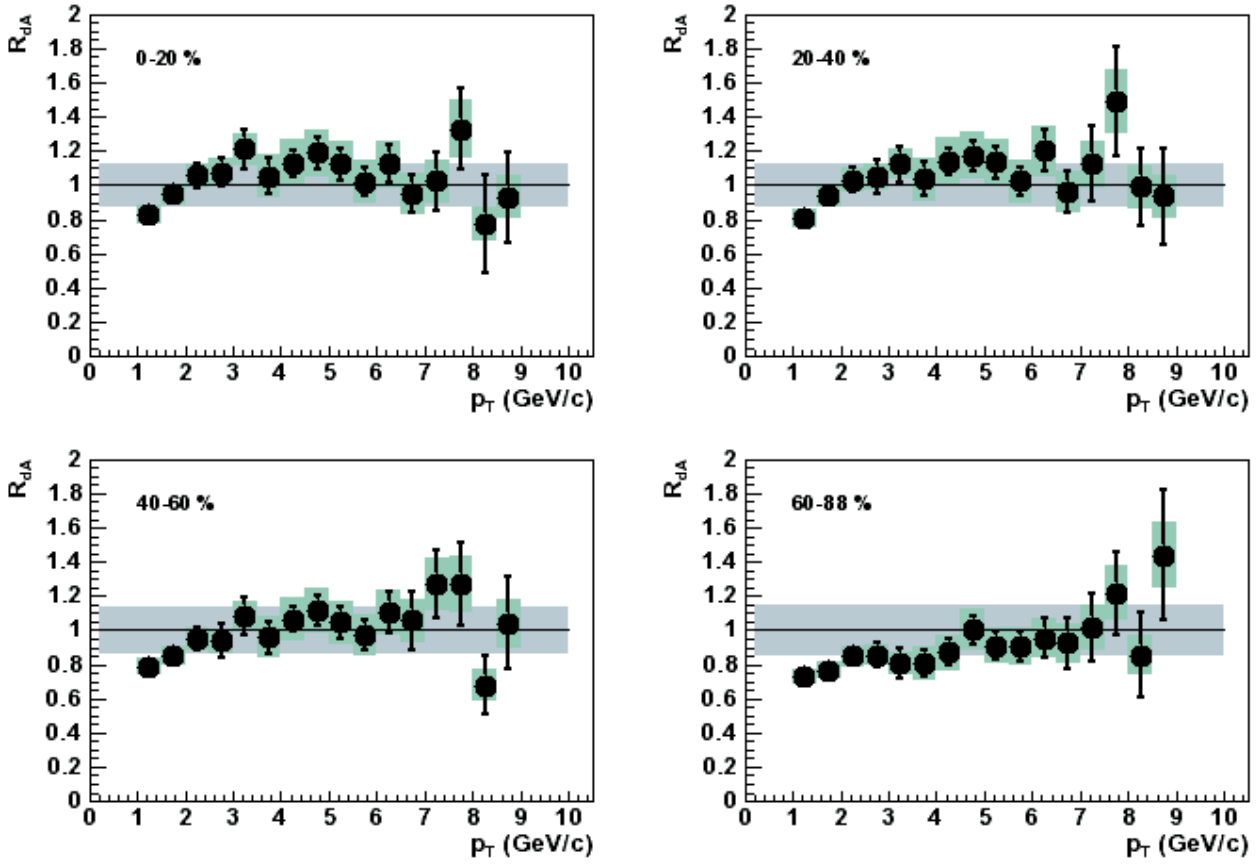
Initial + Final State Effects

= cold medium

Initial State Effects Only

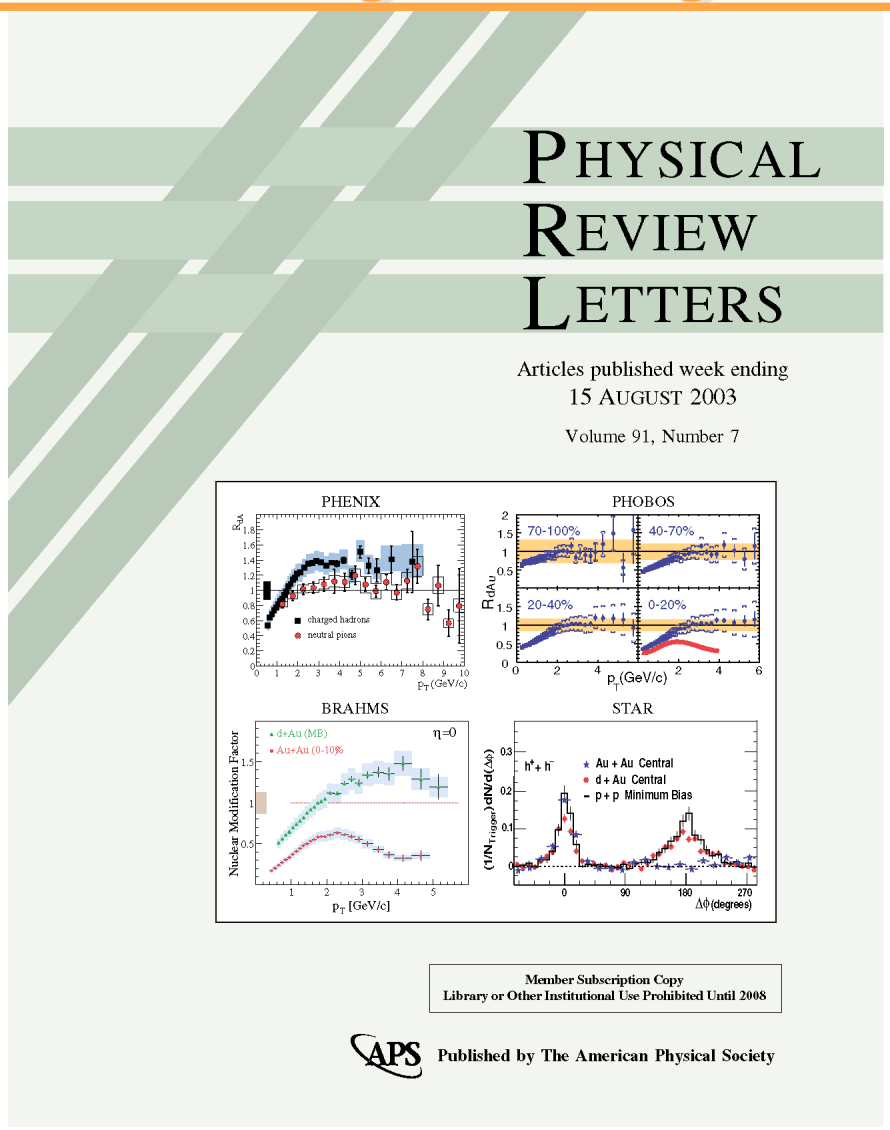
- The "Color Glass Condensate" model predicts the suppression in **both Au+Au and d+Au** (due to the initial state effect).
- **The d+Au experiment tells us that the observed hadron suppression at high p_T central Au+A is a final state effect.**
- This diagram also explains why we can't measure jets directly in Au+Au central collisions: all nucleons participate so charged multiplicity is ~200 times larger than a p-p collision→ 300 GeV in standard jet cone.

Cronin effect observed in d+Au at RHIC $\sqrt{s_{NN}}$=200 GeV



PHENIX preliminary π^0 d+Au vs centrality for DNP2003

This leads to our second PRL cover, our first being the original Au+Au discovery



Conclusions

- Suppression of high p_T π^0 compared to point-like scaling of hard-scattering processes at mid-rapidity in $\sqrt{s_{NN}}$=200 GeV Au+Au collisions at RHIC is unique. All previous measurements in p+A and A+A at lower $\sqrt{s_{NN}}$ have shown an enhancement known as the "Cronin effect"

- The uniqueness of the Au+Au suppression is further emphasized by the fact that there is no suppressionin d+Au collisions at RHIC.

- This indicates that the suppression is due to interaction with the medium produced in the final state of Au+Au collisions at RHIC.

- Such an effect has been predicted in QCD, for a sufficiently hot, dense, and colorful medium, due to the interaction of the outgoing partons with the medium ⇒ a calibrated probe of medium.

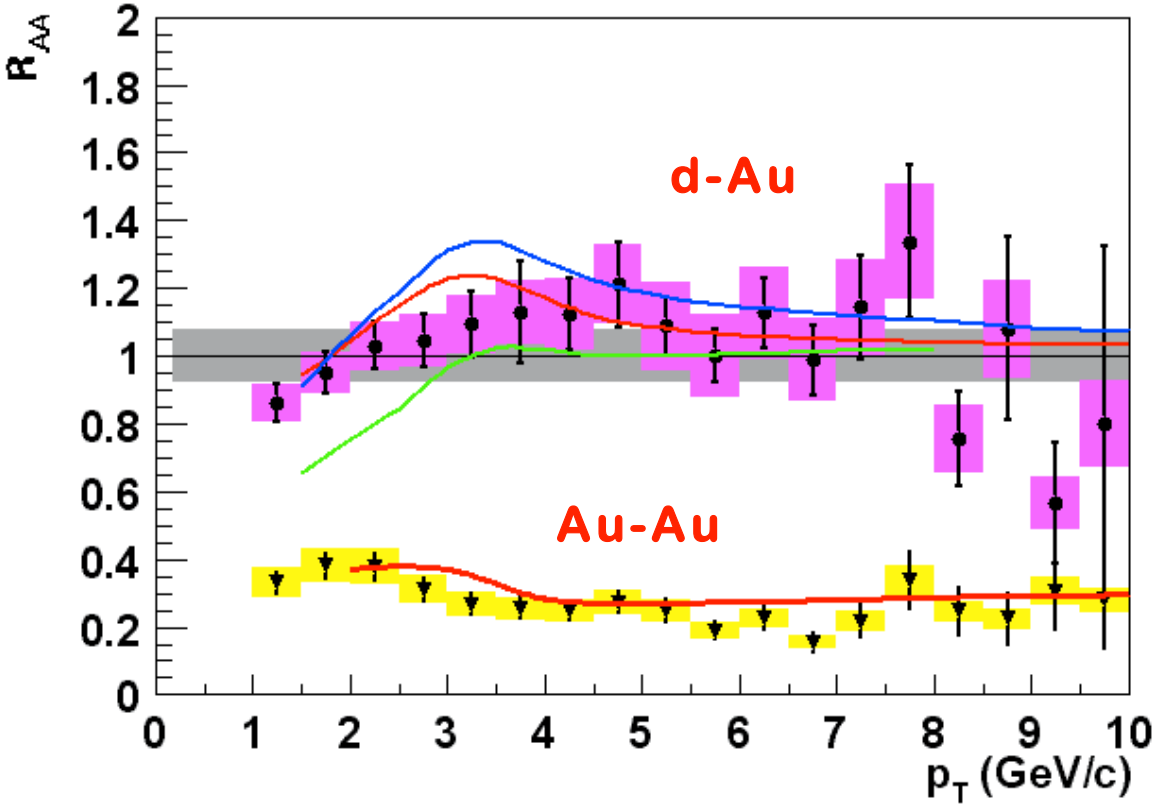
Theoretical Understanding?

Both

- ✓ Au-Au suppression **(I. Vitev and M. Gyulassy, hep-ph/0208108)**
- ✓ d-Au enhancement **(I. Vitev, nucl-th/0302002)**

understood in an approach that combines multiple scattering with absorption in *a dense partonic medium* See nucl-th/0302077 for a review.

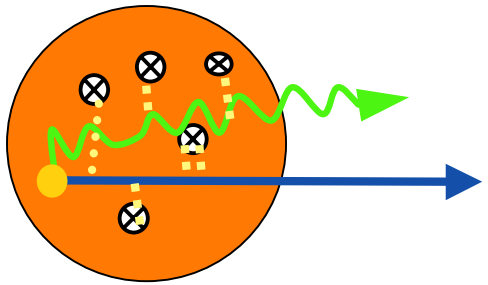
➡ Our high p_T probes have been calibrated and are now being used to explore the precise properties of the medium



Suppression: Final State Effect?

- **Hadronic absorption of fragments:**
  - ✓ Gallmeister, et al. PRC67,044905(2003)
  - ✓ Fragments formed inside hadronic medium
- **Parton recombination (up to moderate p_T)**
  - ✓ Fries, Muller, Nonaka, Bass nucl-th/0301078
  - ✓ Lin & Ko, PRL89,202302(2002)
- **Energy loss of partons in dense matter**
  - ✓ Gyulassy, Wang, Vitev, Baier, Wiedemann…

  See nucl-th/0302077 for a review.



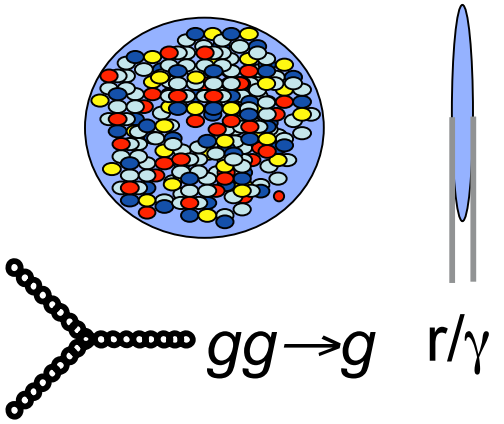
Alternative: Initial Effects

- **Gluon Saturation**
  - ✓ **(color glass condensate: CGC)**

Wave function of low x gluons overlap; the self-coupling gluons fuse, saturating the density of gluons in the initial state.

(gets N_{ch} right!)

hep-ph/0212316; D. Kharzeev, E. Levin, M. Nardi



D.Kharzeev et al., PLB 561 (2003) 93

- **Multiple elastic scatterings**

(Cronin effect)

Wang, Kopeliovich, Levai, Accardi

- **Nuclear shadowing**