Status and perspectives of jets and high-p_T physics

Peter Jacobs
CERN and Lawrence Berkeley National Laboratory

- Where does pQCD work at RHIC?
- What have we learned from inclusive hadron suppression?
- Where does jet behavior emerge in nuclear collisions?
- Can we see the interaction of the probe with the medium?
- Future

What I will not discuss

Time is limited and the subject is vast.

I will concentrate on jet physics ⇒ mainly at the highest available p_T at midrapidity

Among the important topics I will not discuss in any detail are:

- recombination
- Cronin effect
- forward physics

Fermi National Accelerator Laboratory

FERMILAB-Pub-82/59-THY
August, 1982

Energy Loss of Energetic Partons in Quark-Gluon Plasma: Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

J. D. BJORKEN
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P.O. Box 500, Batavia, Illinois 60510

Abstract

High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to ionization loss of charged particles in ordinary matter. The dE/dx is roughly proportional to the square of the plasma temperature. For

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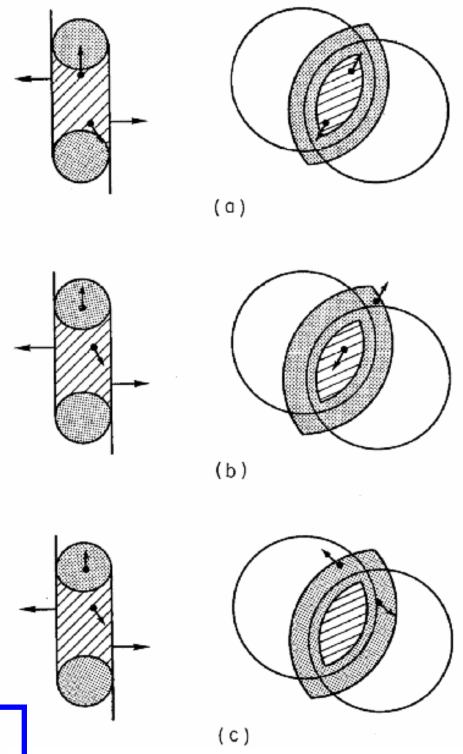
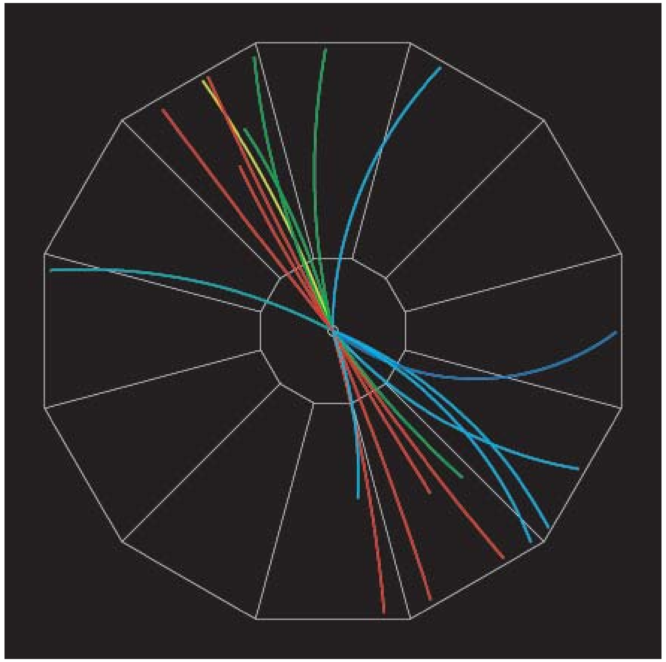


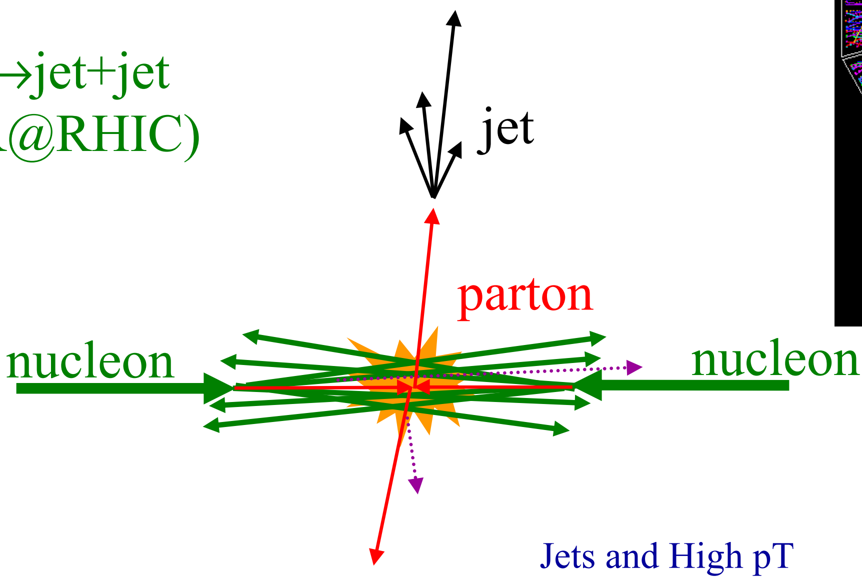
produced in its local environment. High energy hadron jet experiments should be analysed as function of associated multiplicity to search for this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.

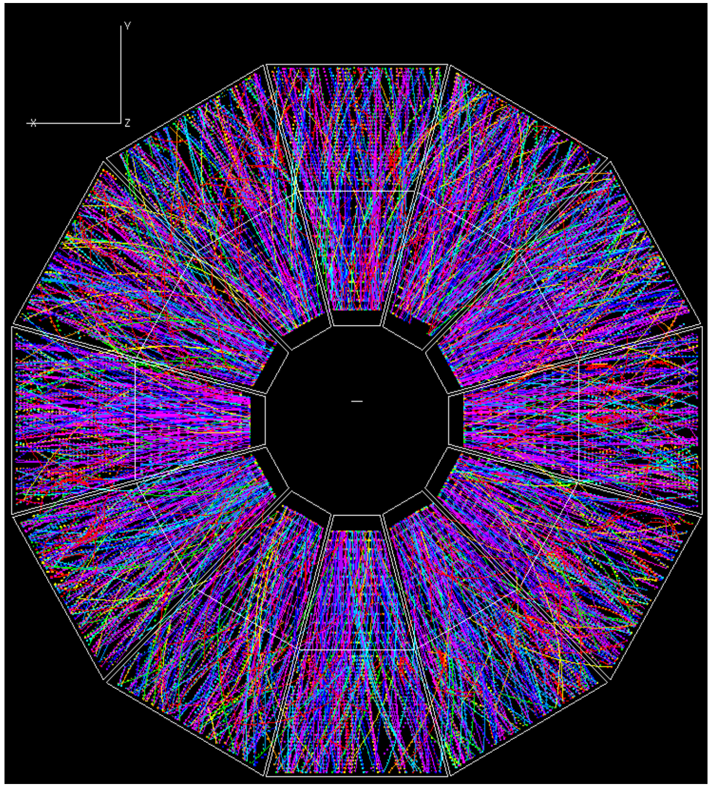
Jets in RHI Collisions

Find this……….in this



p+p →jet+jet
(STAR@RHIC)



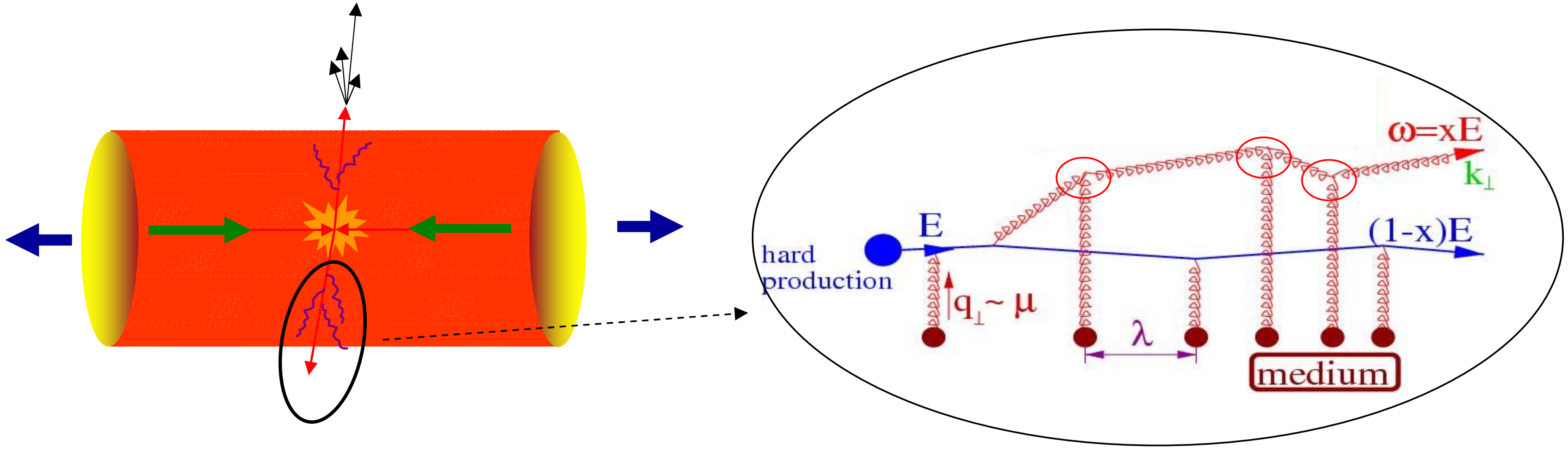


Au+Au →???
(STAR@RHIC)

Partonic energy loss in a colored medium

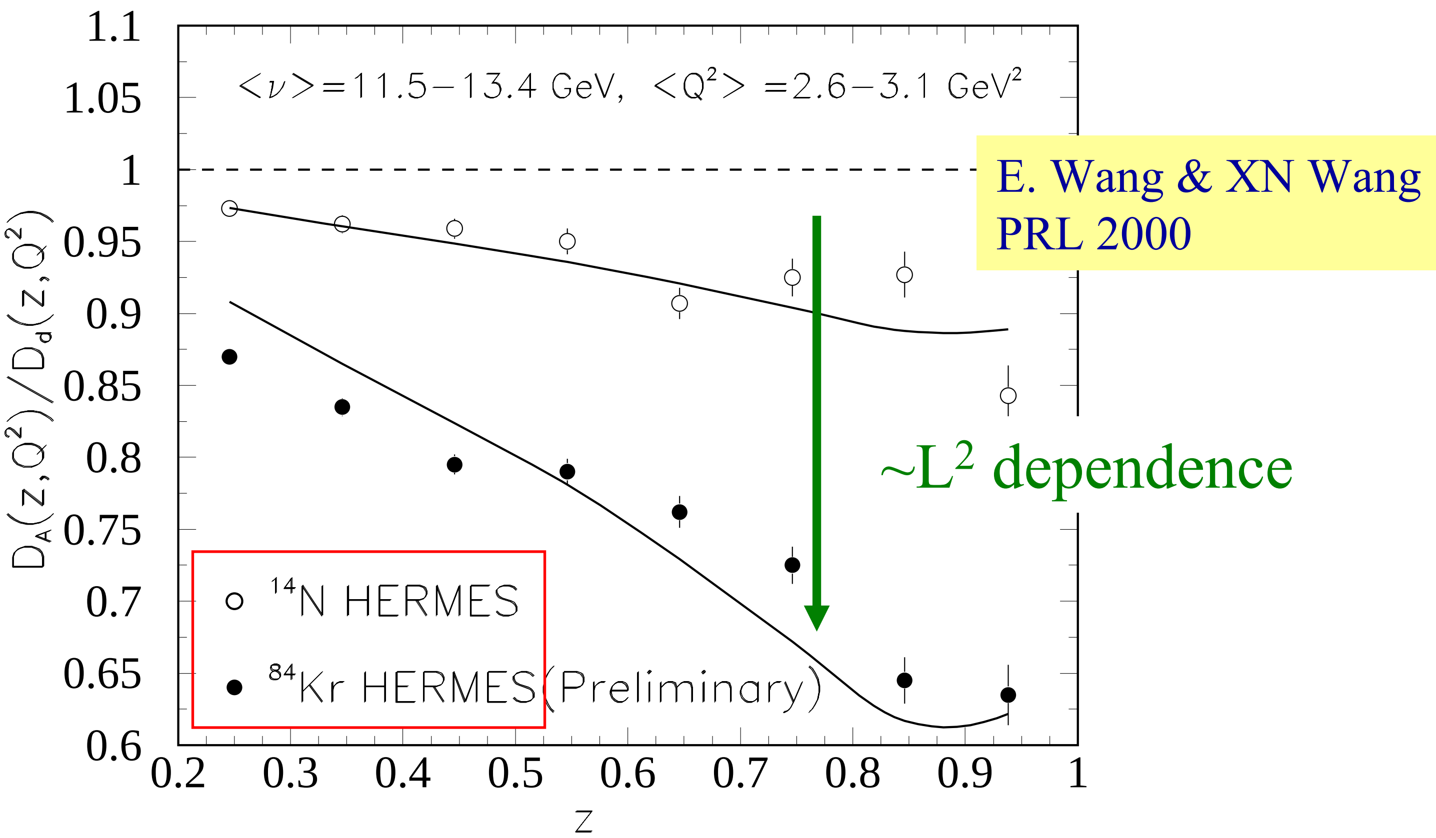
Bjorken, Gyulassy, Pluemer, Wang, Baier, Dokshitzer, Mueller, Pegne, Schiff, Levai, Vitev, Zhakarov, Wang, Salgado, Wiedemann,…

- Elastic scattering generated unmeasurably small effects
- But bremsstrahlung is more effective:



- Essential physics: radiated gluon decoheres due to multiple interactions with medium
- ΔE sensitive to color-charge density
- Unique non-abelian feature: system size dependence $\Delta E \sim L^2$

Modified fragmentation in cold matter



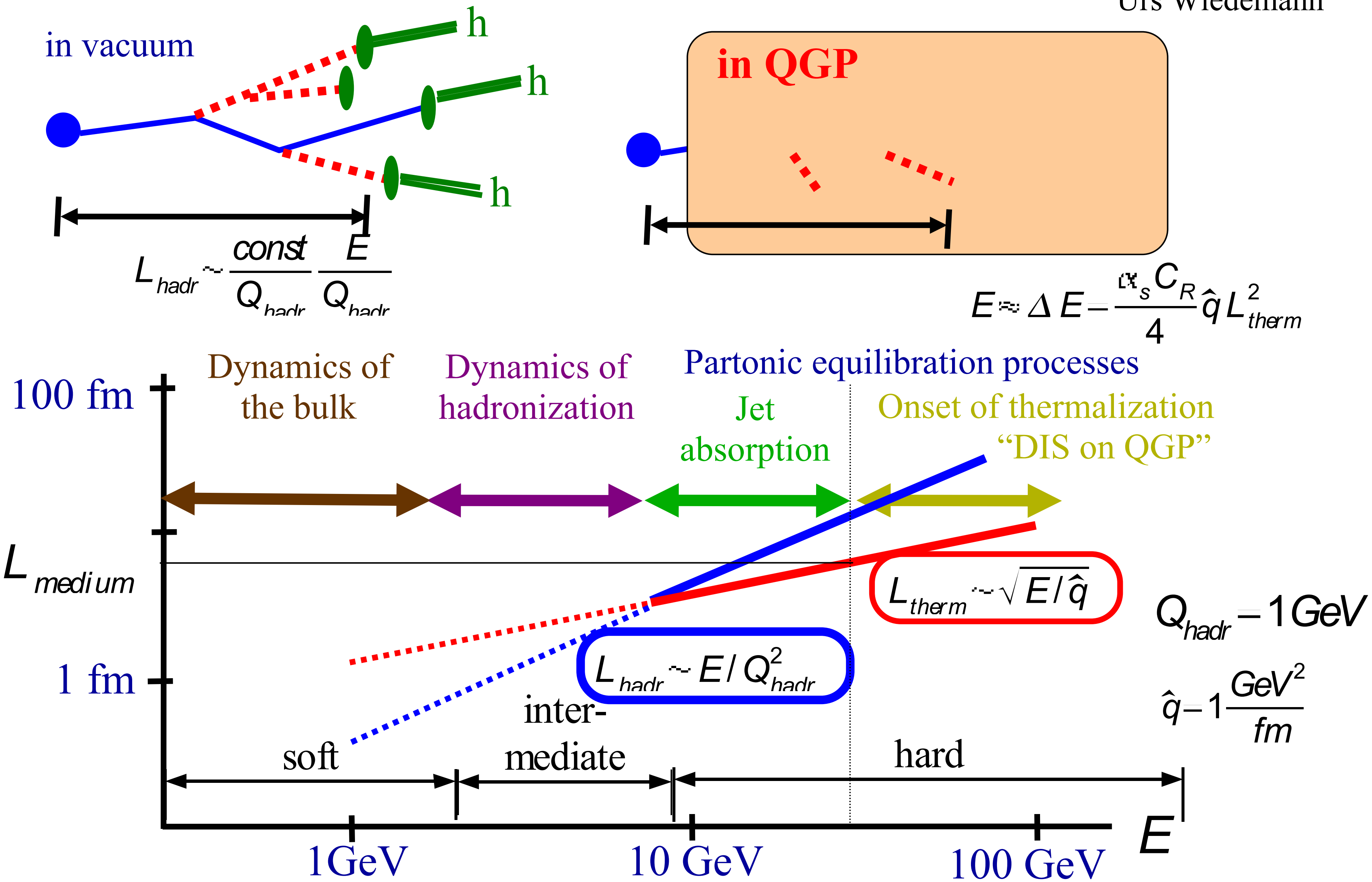
$$C\alpha_s^2 \approx 0.00065 \;\; \text{GeV}^2$$

in Au nuclei

$$\frac{dE}{dx} \approx 0.5 \text{ GeV/fm}$$

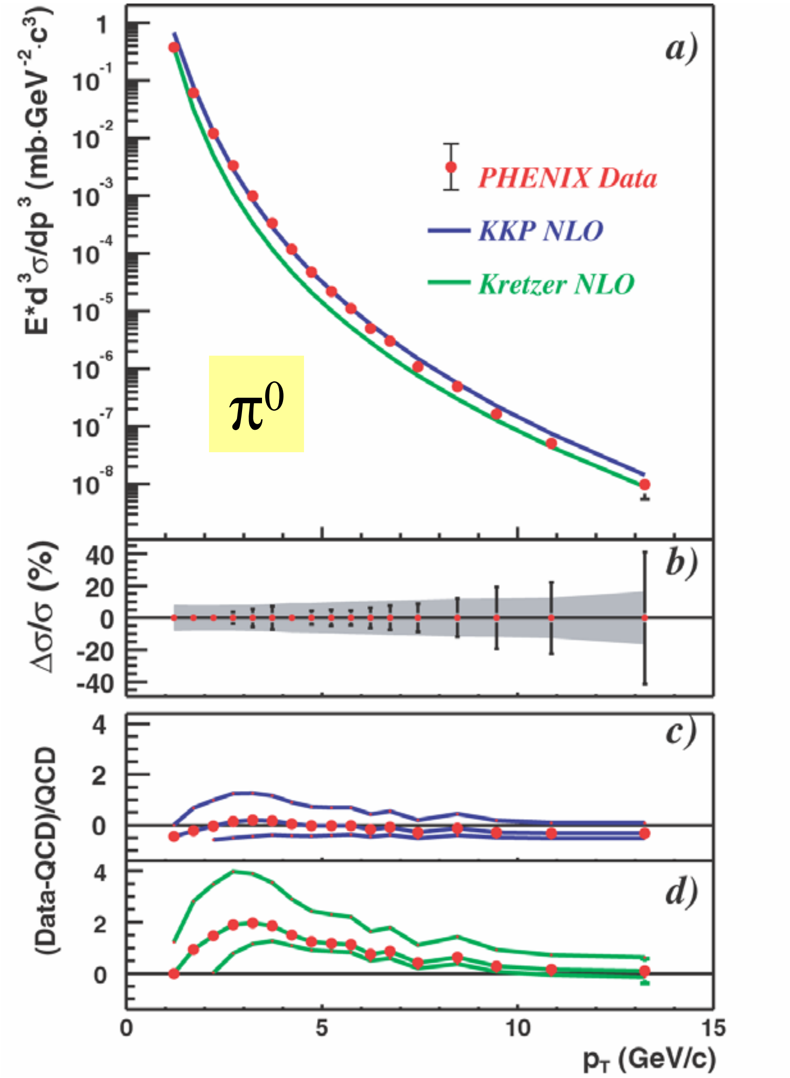
Hadronization versus Thermalization of Jets

Urs Wiedemann

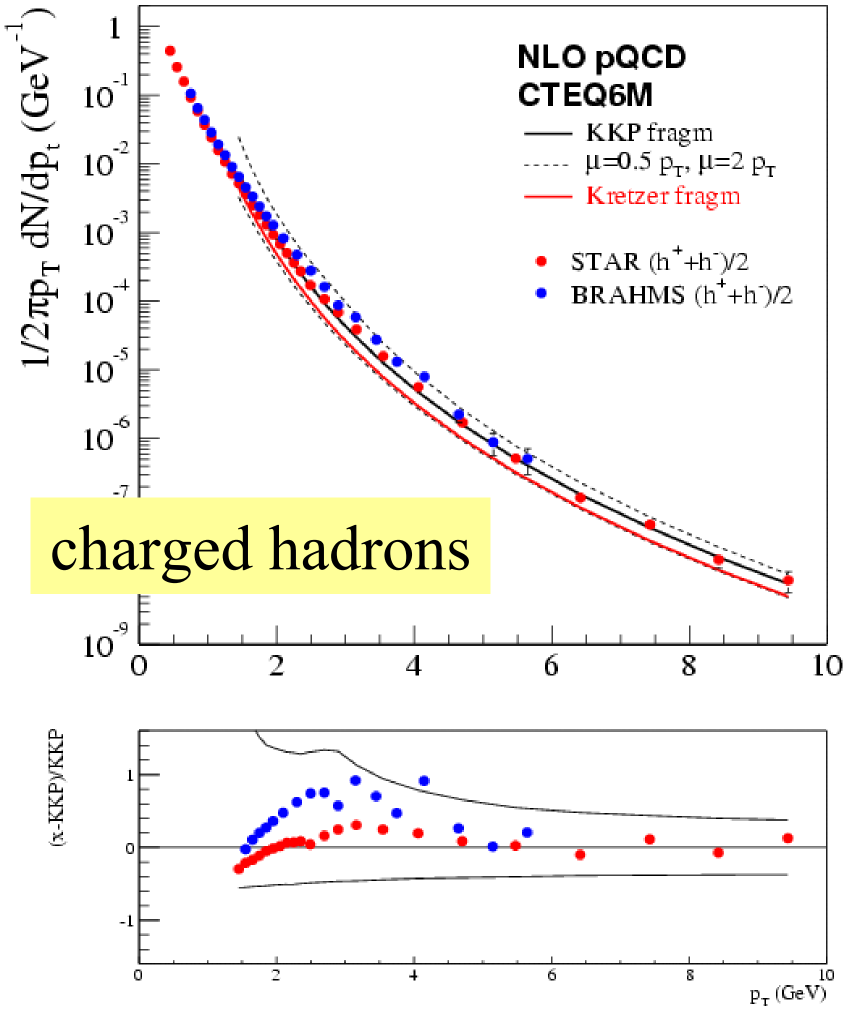


Intermediate p_T: expect unique interplay between probe and medium

p+p spectra vs NLO pQCD

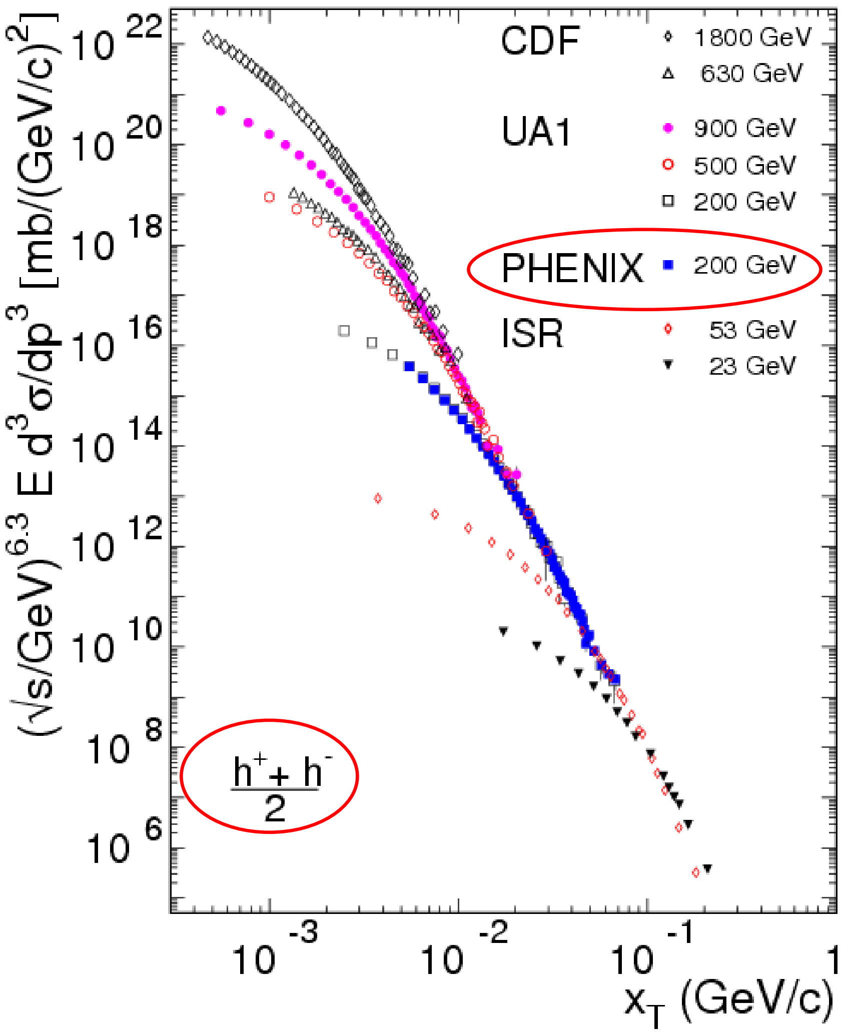


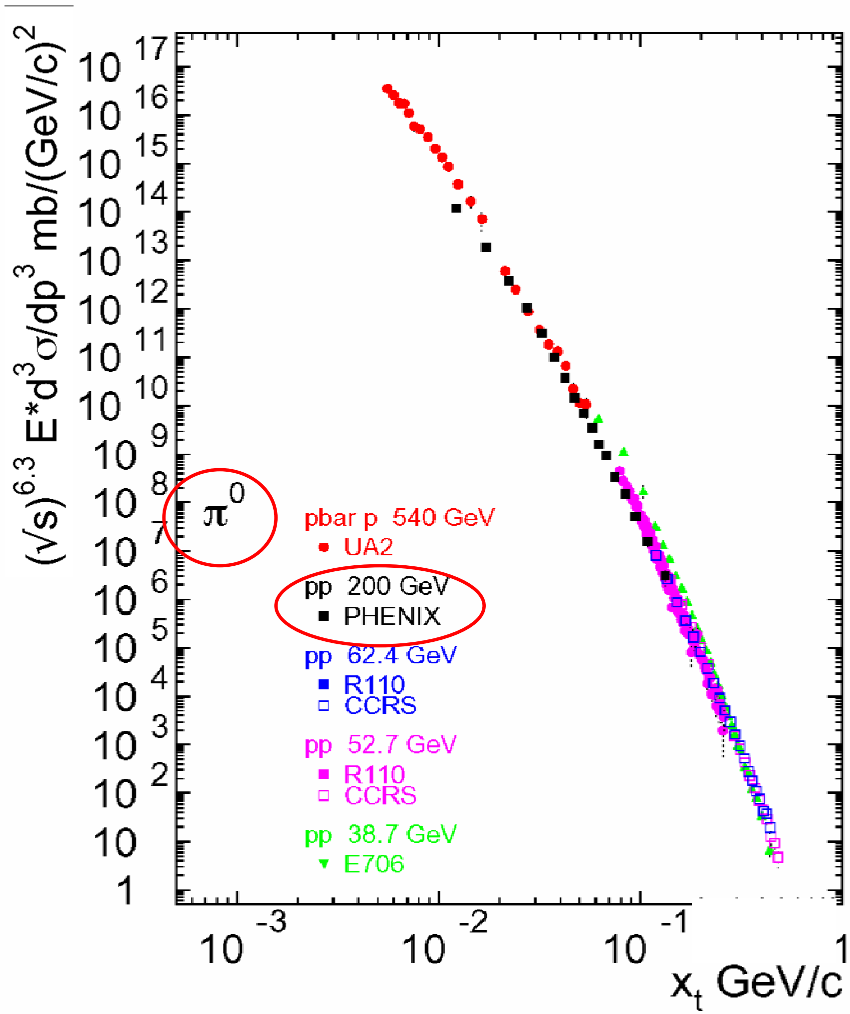
calculations: W. Vogelsang



Good agreement

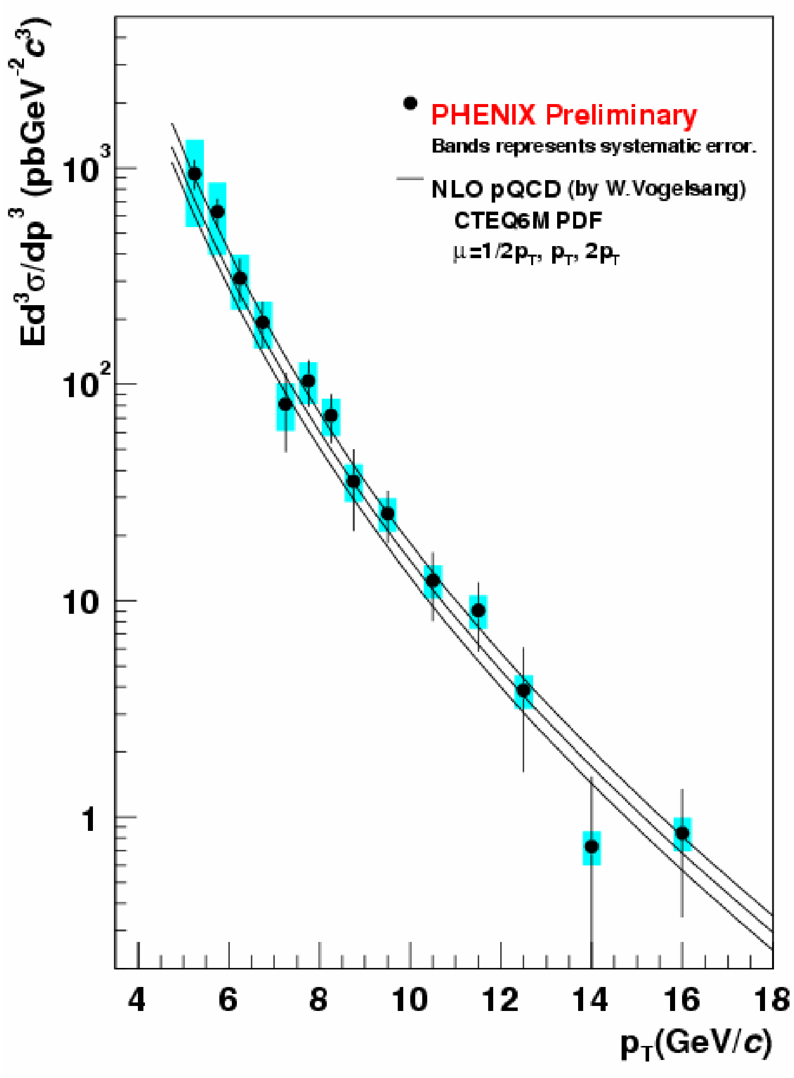
x_T scaling of p(bar)+p(bar) spectra

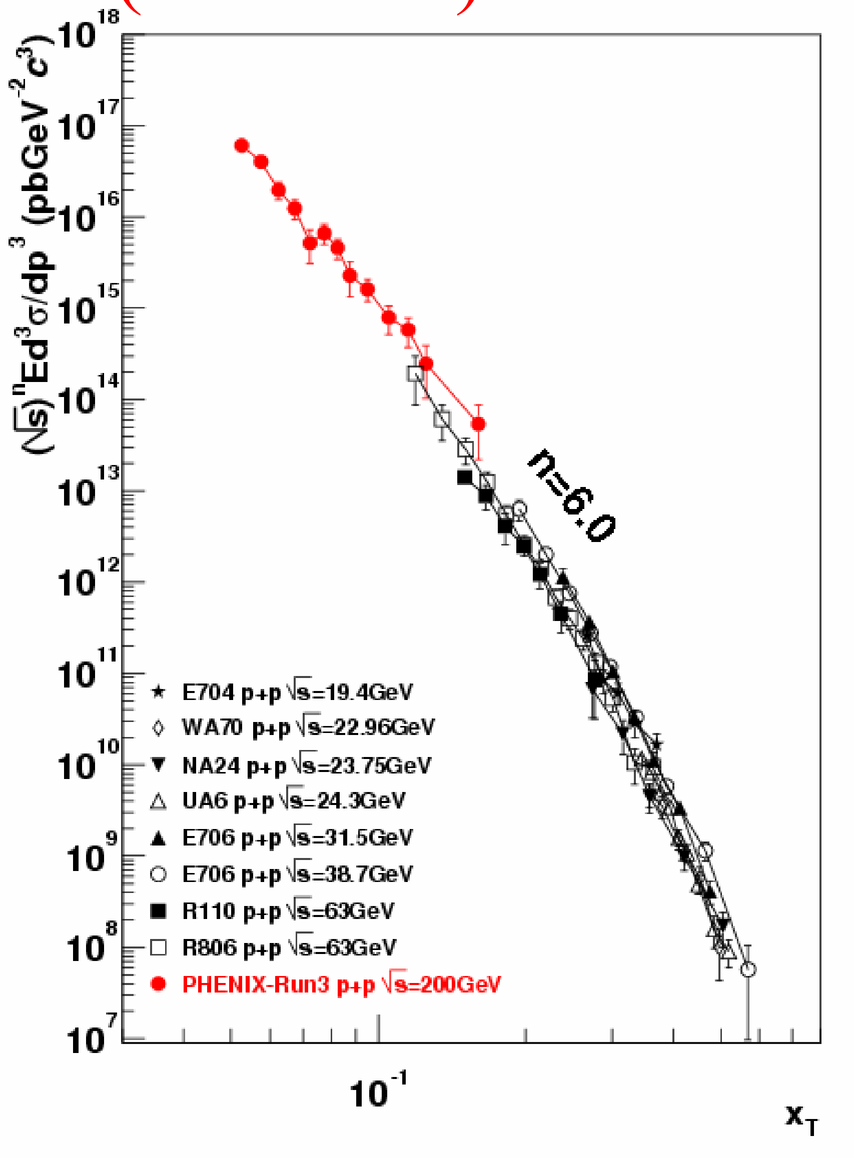




As expected for hard scattering

p+p direct photons (PHENIX)

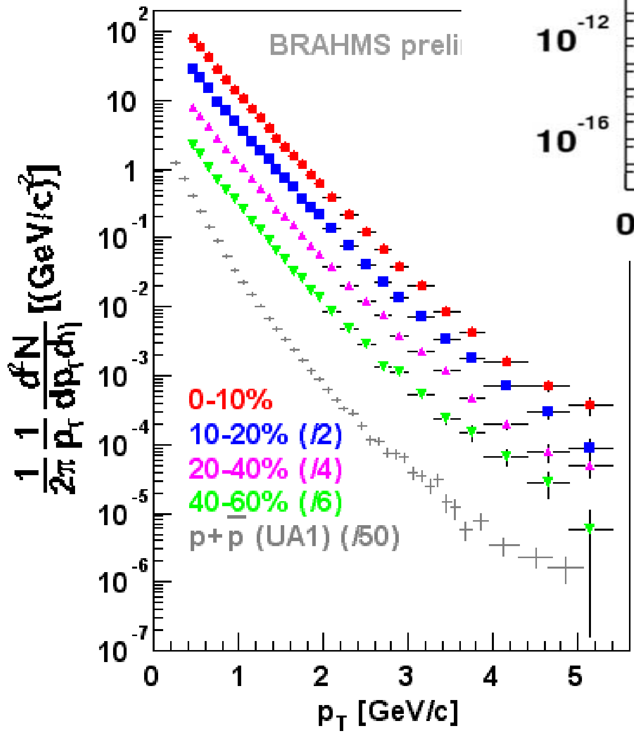


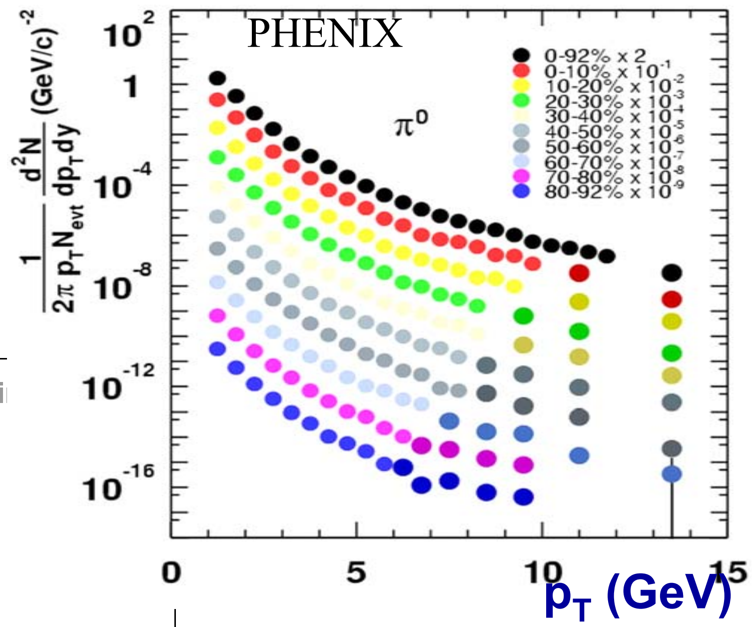


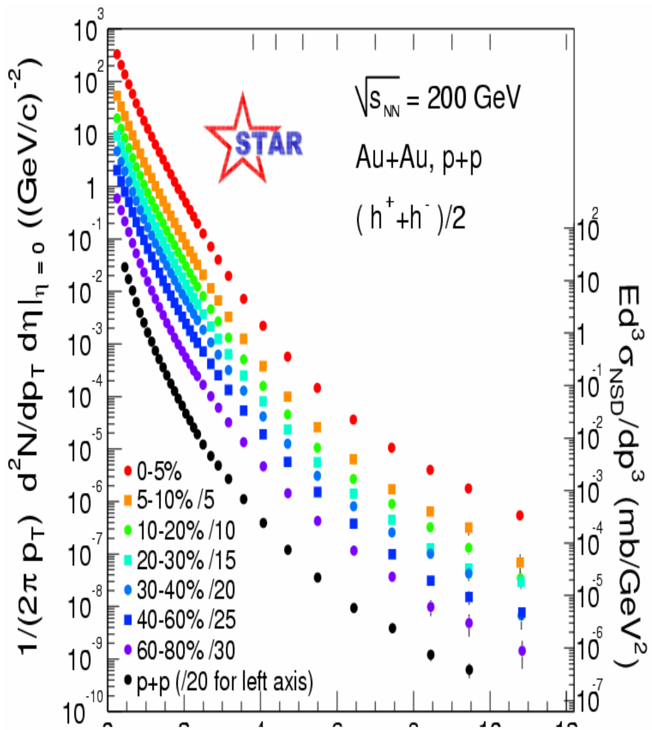
Also in good agreement:

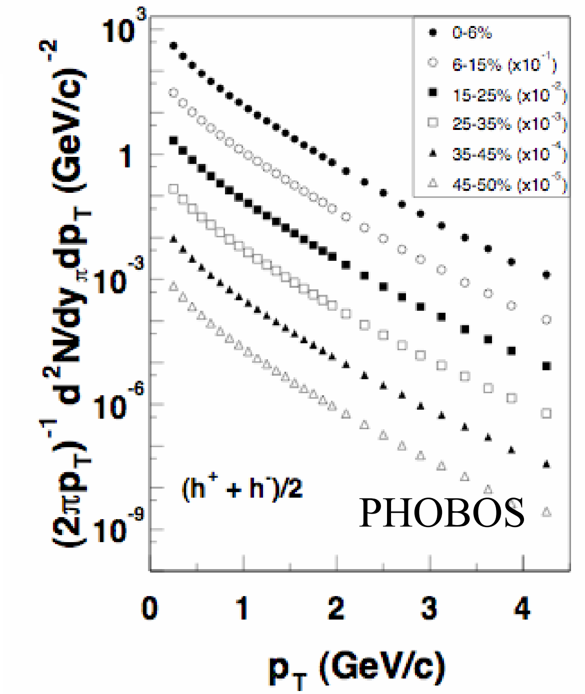
p+p baseline measurements and calculations are under control

Inclusive hadron suppression in Au+Au

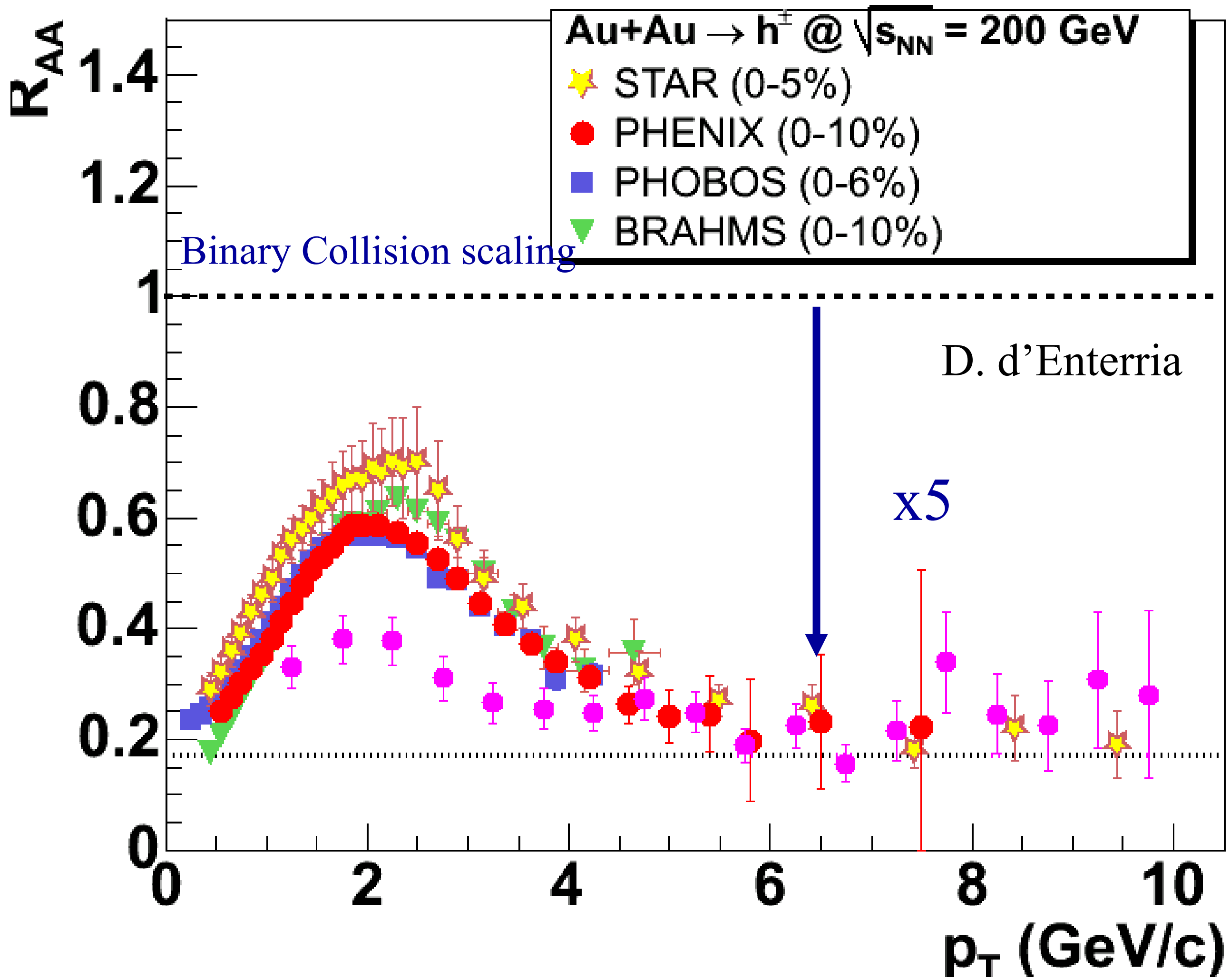






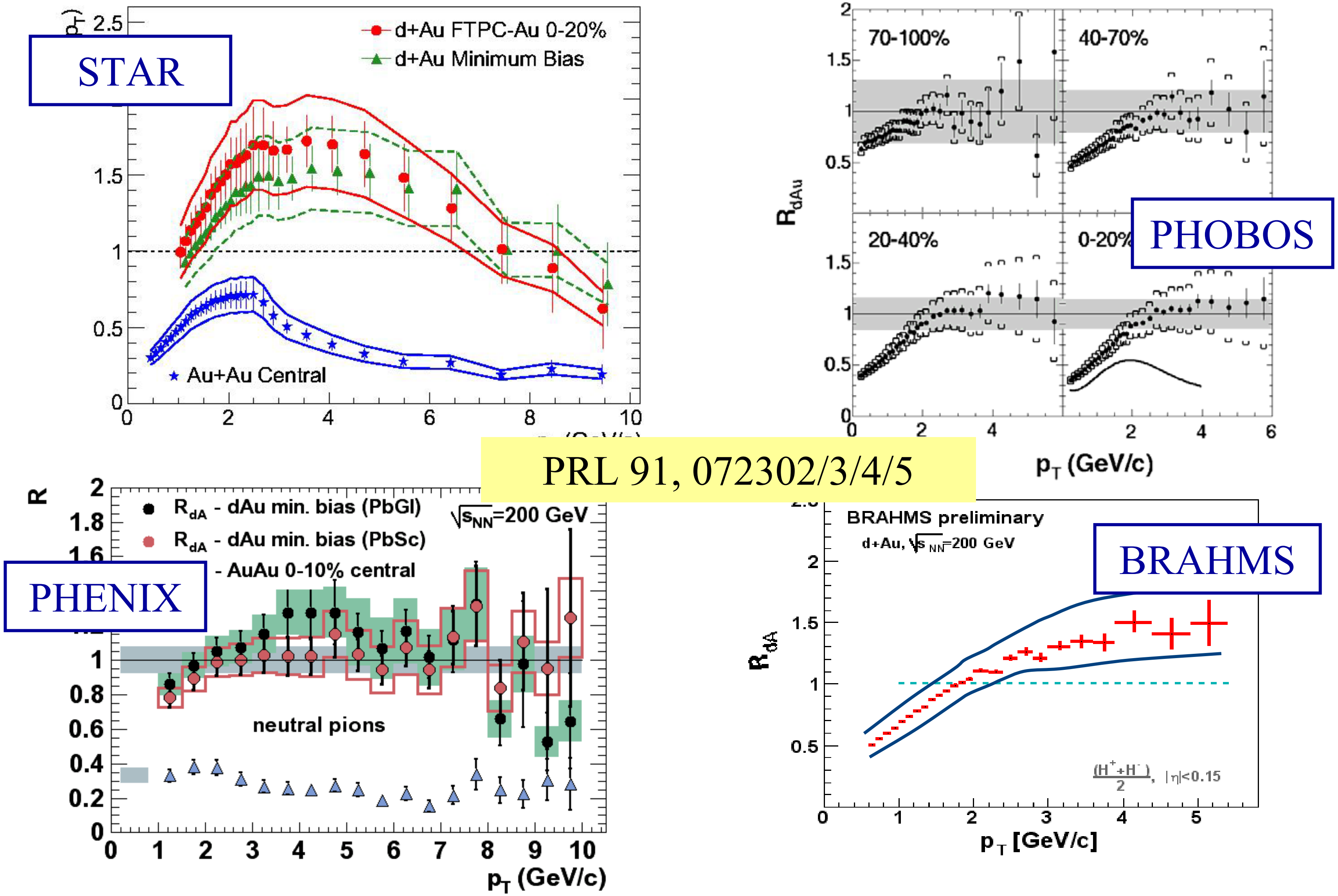


High p_T yields in central Au+Au are suppressed



Factor 5 suppression: huge effect!

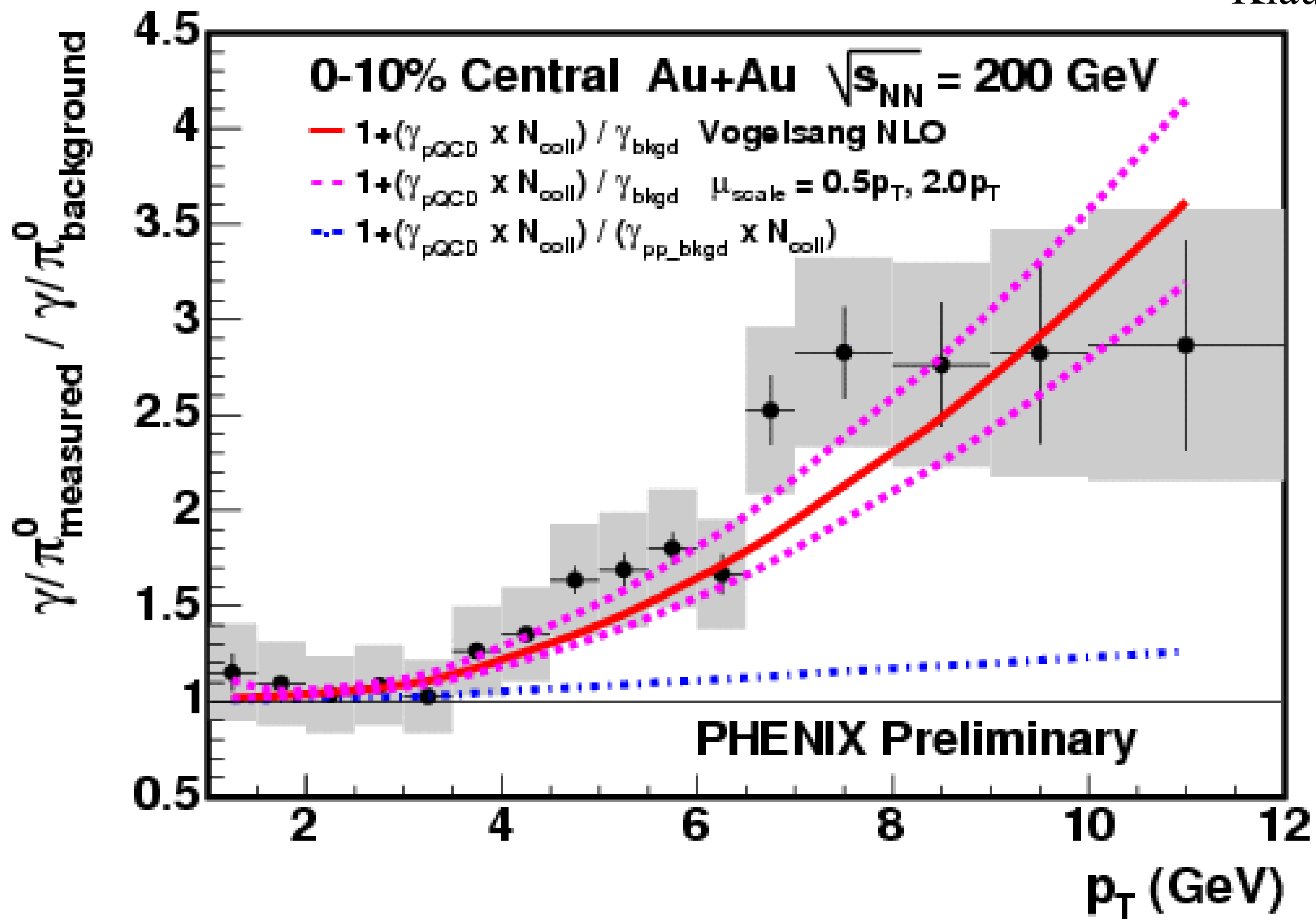
d+Au yields are not suppressed



Hadron suppression in central Au+Au is a final state effect

Cross check: direct photons in Au+Au

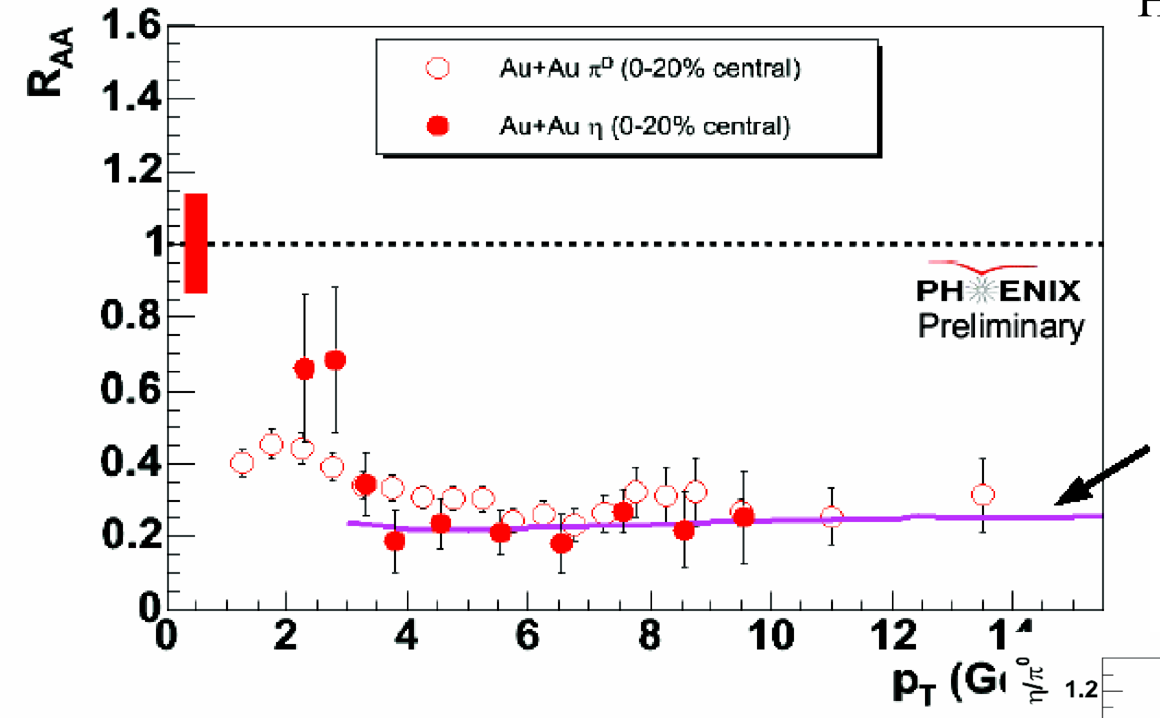
Klaus Reygers

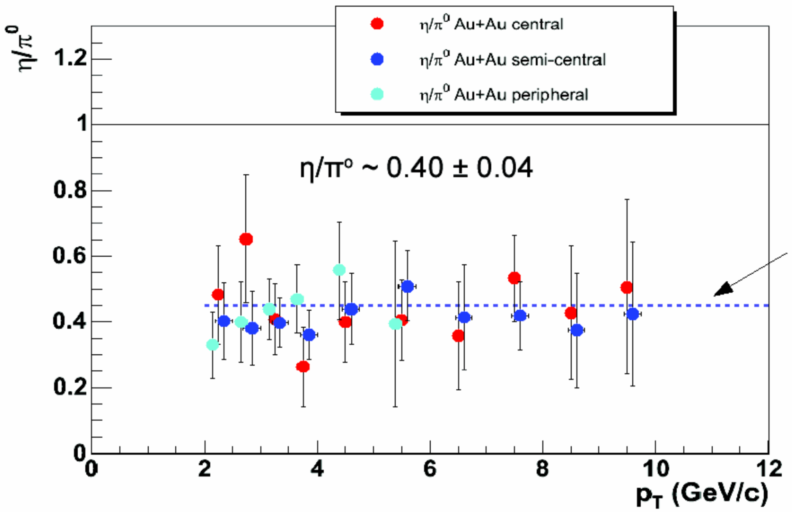


- Photons scale as binary collisions while π^0 are suppressed: consistent with energy loss picture
- but what does fragmentation component of photon yield do?

Another test: η production

Henner Buesching/PHENIX

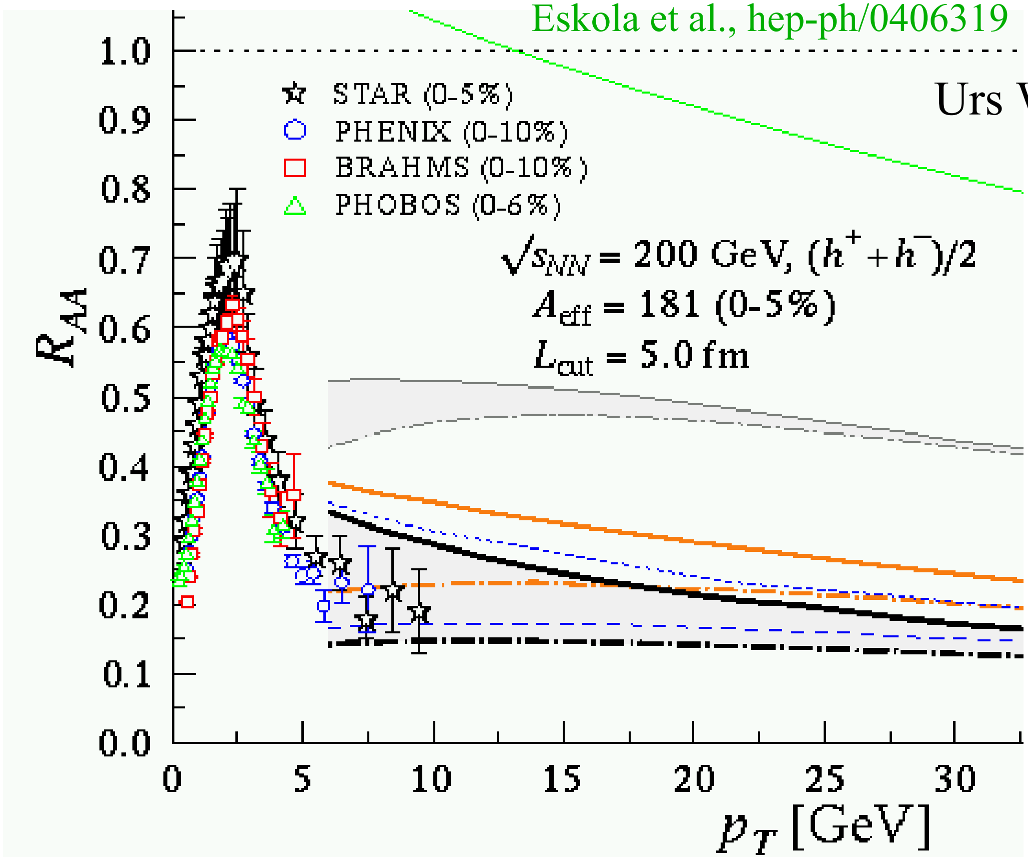




- η suppression follows π^0
- η/π^0 ~invariant with system
- fully consistent with partonic energy loss

What do we learn from the suppression?

Comparison to energy loss calculations: suppression requires initial density >~30 times cold nuclear matter density



Urs Wiedemann

$\hat{q} = 0\, GeV^2/fm$

$\hat{q} = 1\, GeV^2/fm$

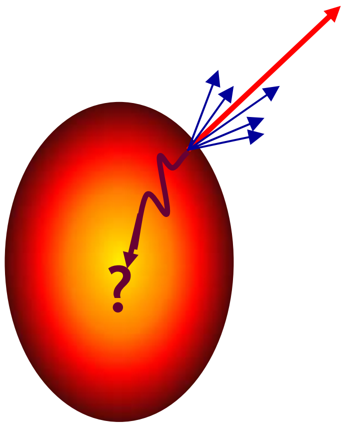
$\hat{q} = 5-15\, GeV^2/fm$

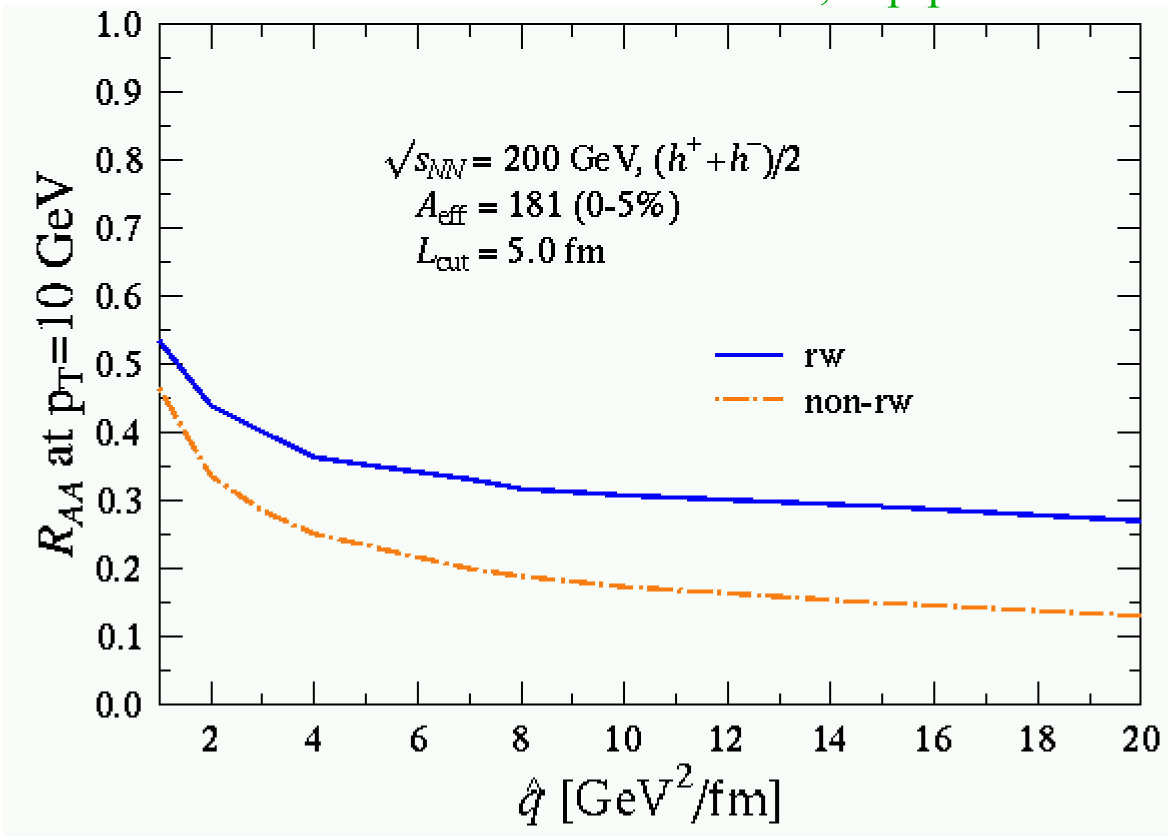
But suppression only supplies lower bound on density (see also Drees et al., Loizedes et al.)

Surface emission ("trigger bias")

Urs Wiedemann

Eskola et al., hep-ph/0406319

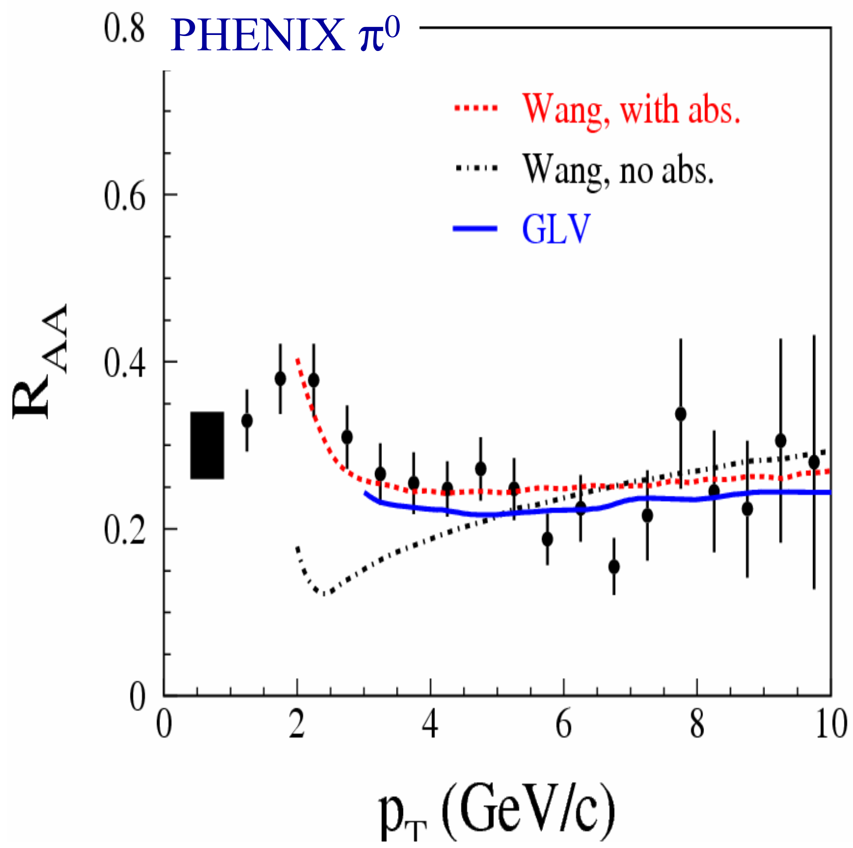


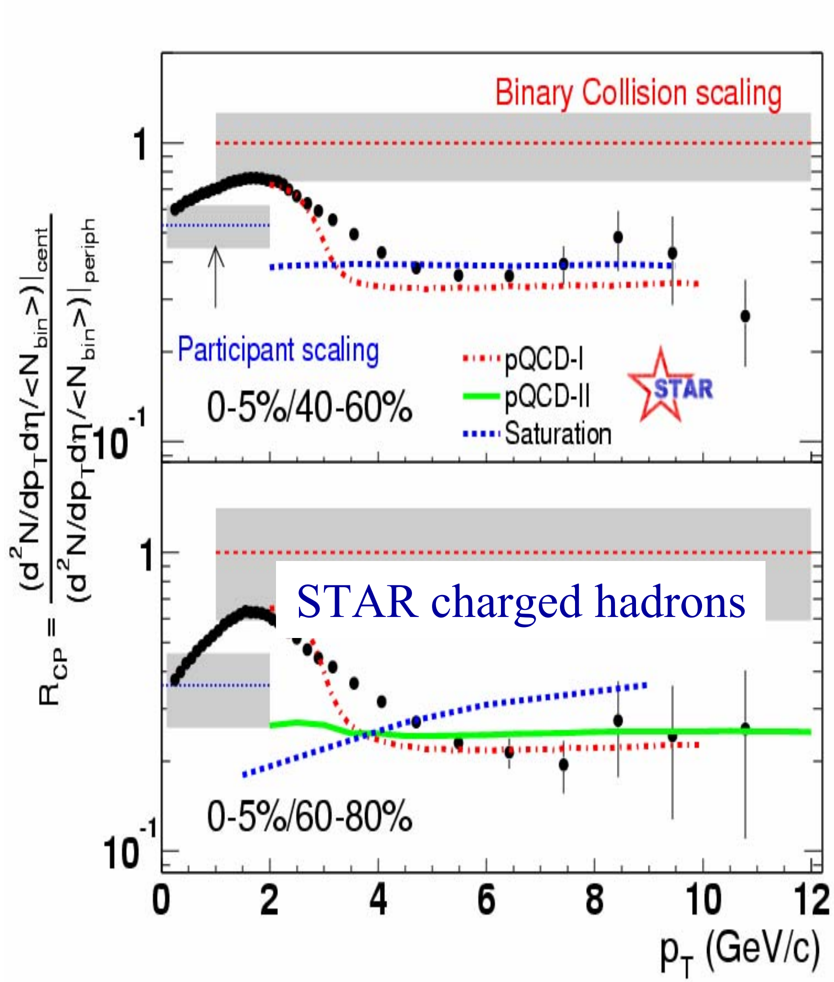


- Opaque core ⇒sensitivity only to minor variations in surface opacity
- R_{AA}~0.2-0.3 for broad range of qhat

R_{AA}: p_T (in-)dependence

Brian Cole, Urs Wiedemann





- Suppression level is a parameter (that's the measurement)
- p_T and centrality dependence are predictions of the theory
- so why is R_{AA} ~independent of p_T at high p_T?

R_{AA}: p_T (in-)dependence (II)

Bremsstrahlung energy loss $\Delta E \sim \log(E)$

Multiple explanations for $\sim p_T$-independence of R_{AA}:

• Gyulassy, Levai and Vitev: intricate interplay between energy loss, Cronin effect and shadowing

• Wang and Wang: feedback from medium at moderate E

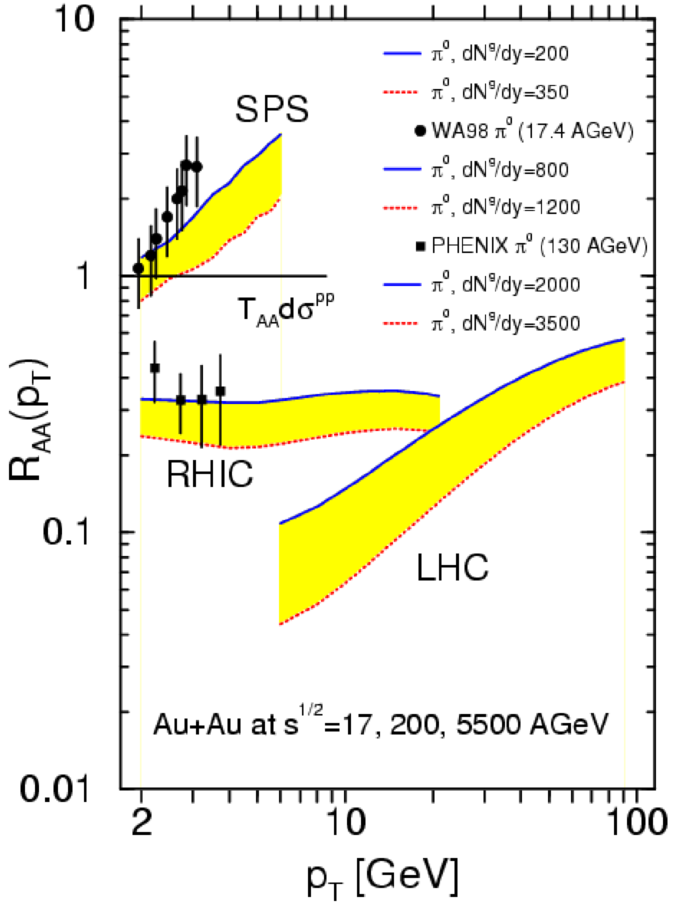
• Eskola, Honkanen, Salgado and Wiedemann: interplay between energy loss and p_T-dependence of underlying spectrum $\sim 1/p_T$^$n(p_T)$

More generally: how to disentagle the physics underlying the suppression? Vary initial conditions by varying sqrt(s)….

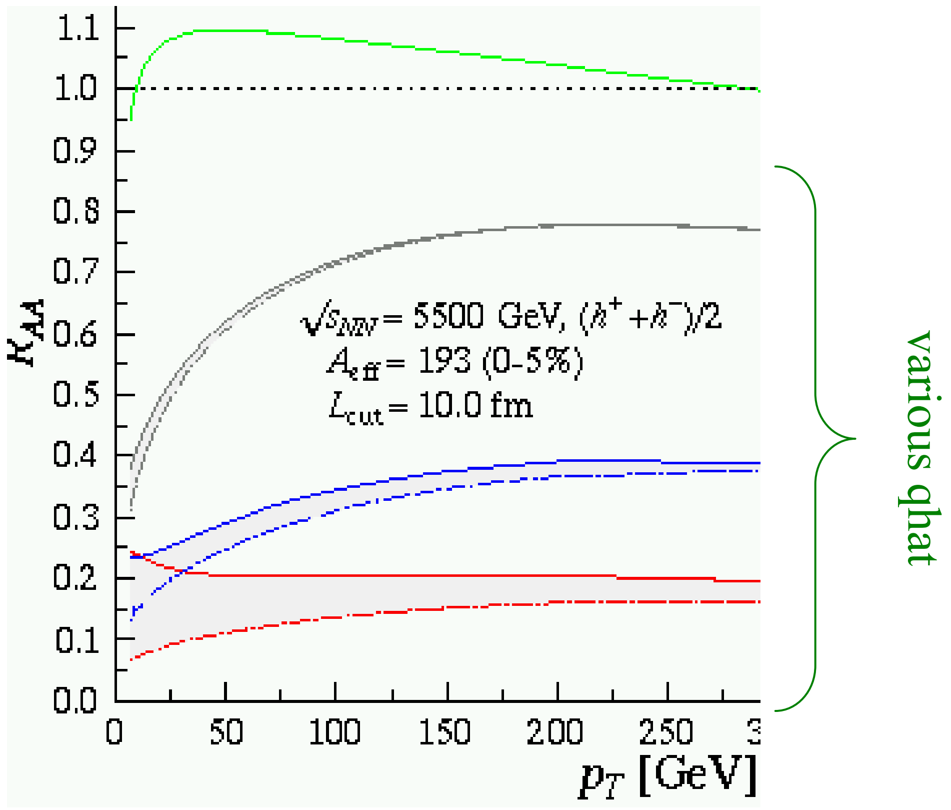
R_{AA}: p_T (in-)dependence (III)

Significant differences expected at the LHC

Vitev and Gyulassy

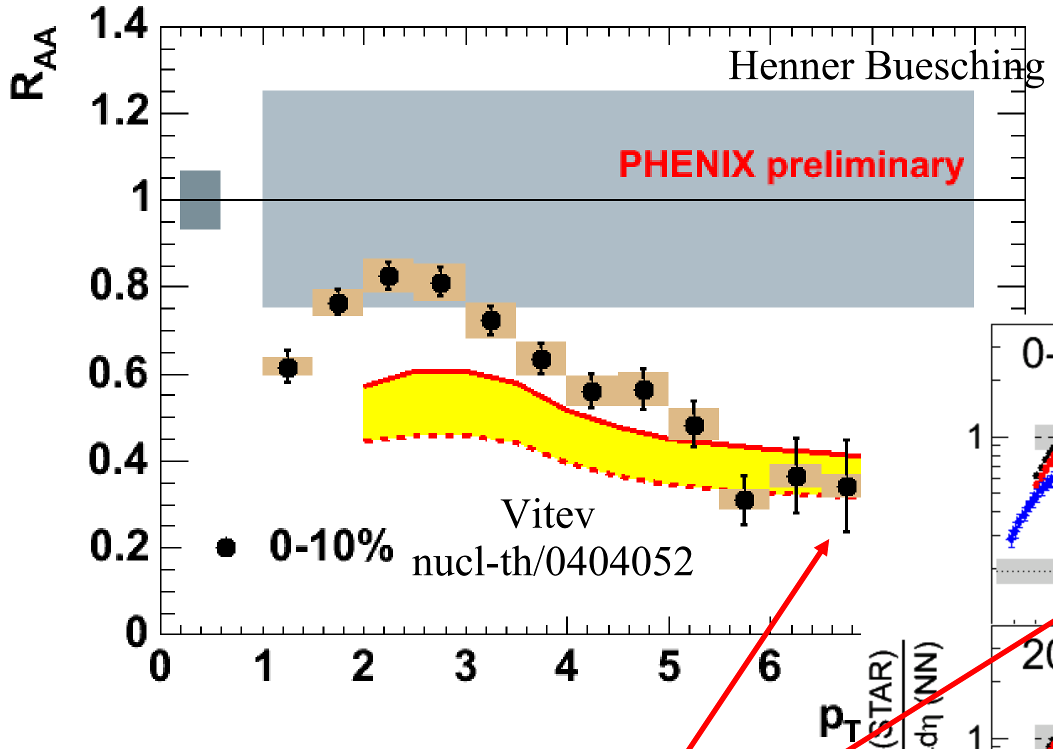


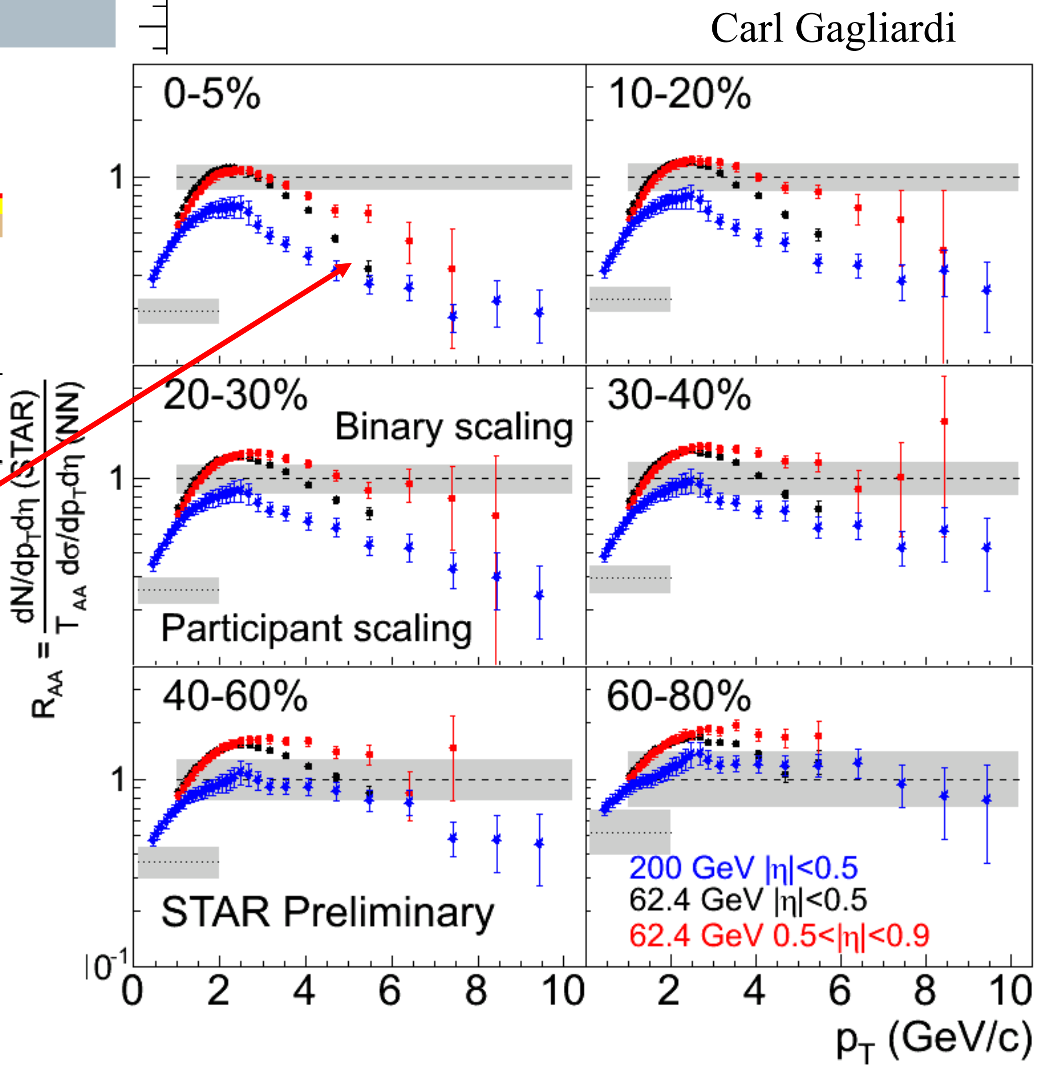
Eskola et al



But that's a long time from now…

R_{AA} for Au+Au at 62.4 GeV



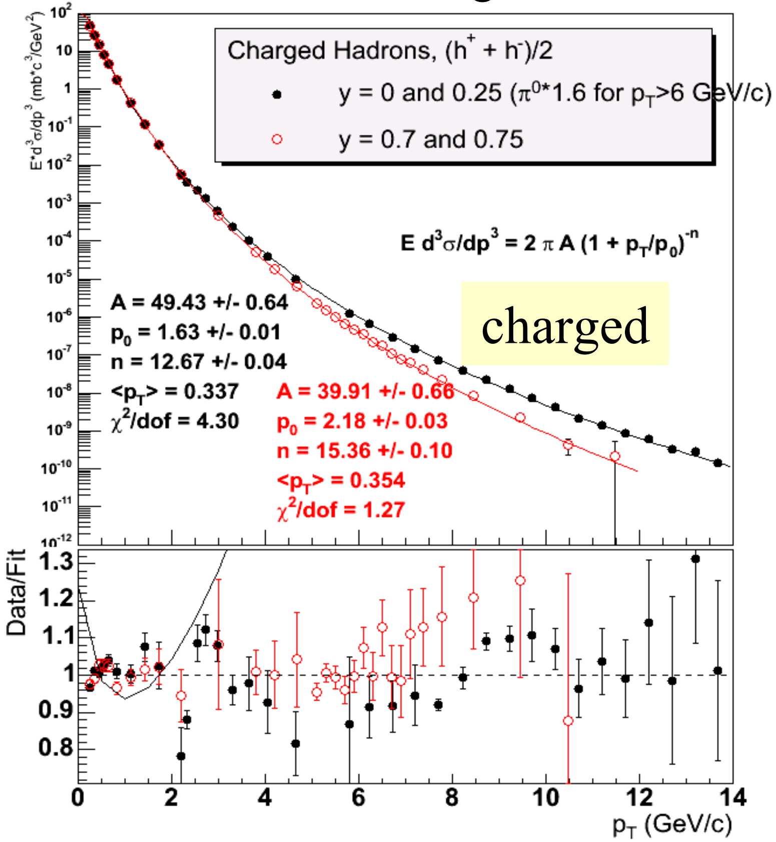


R_{AA} using p+p from ISR

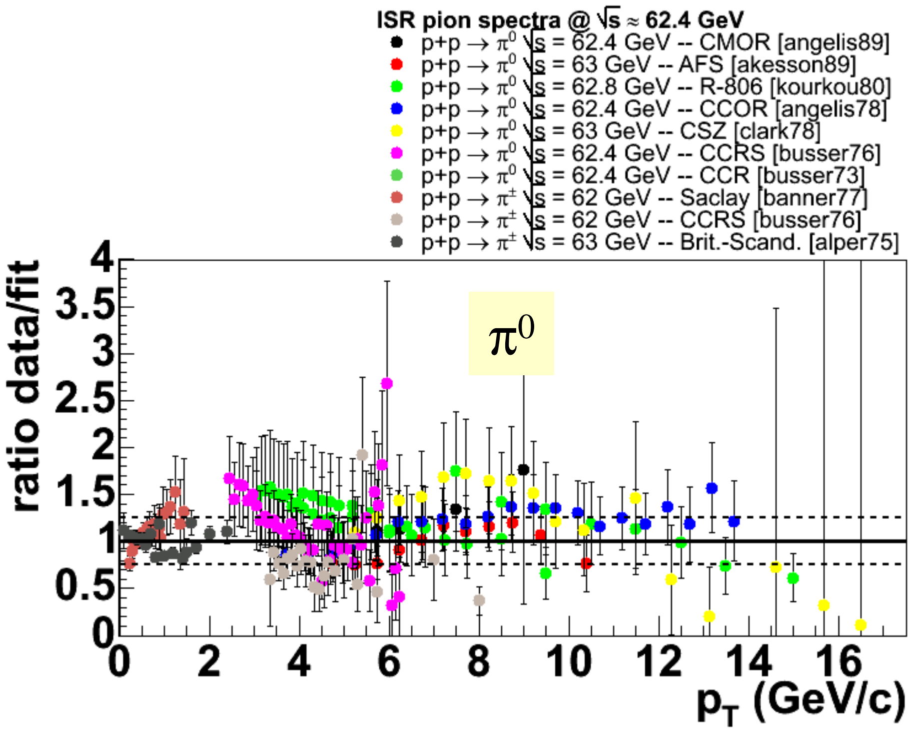
Significant suppression in central collisions at high p_T

The 62 GeV Reference Spectrum Problem

Carl Gagliardi



David d'Enterria

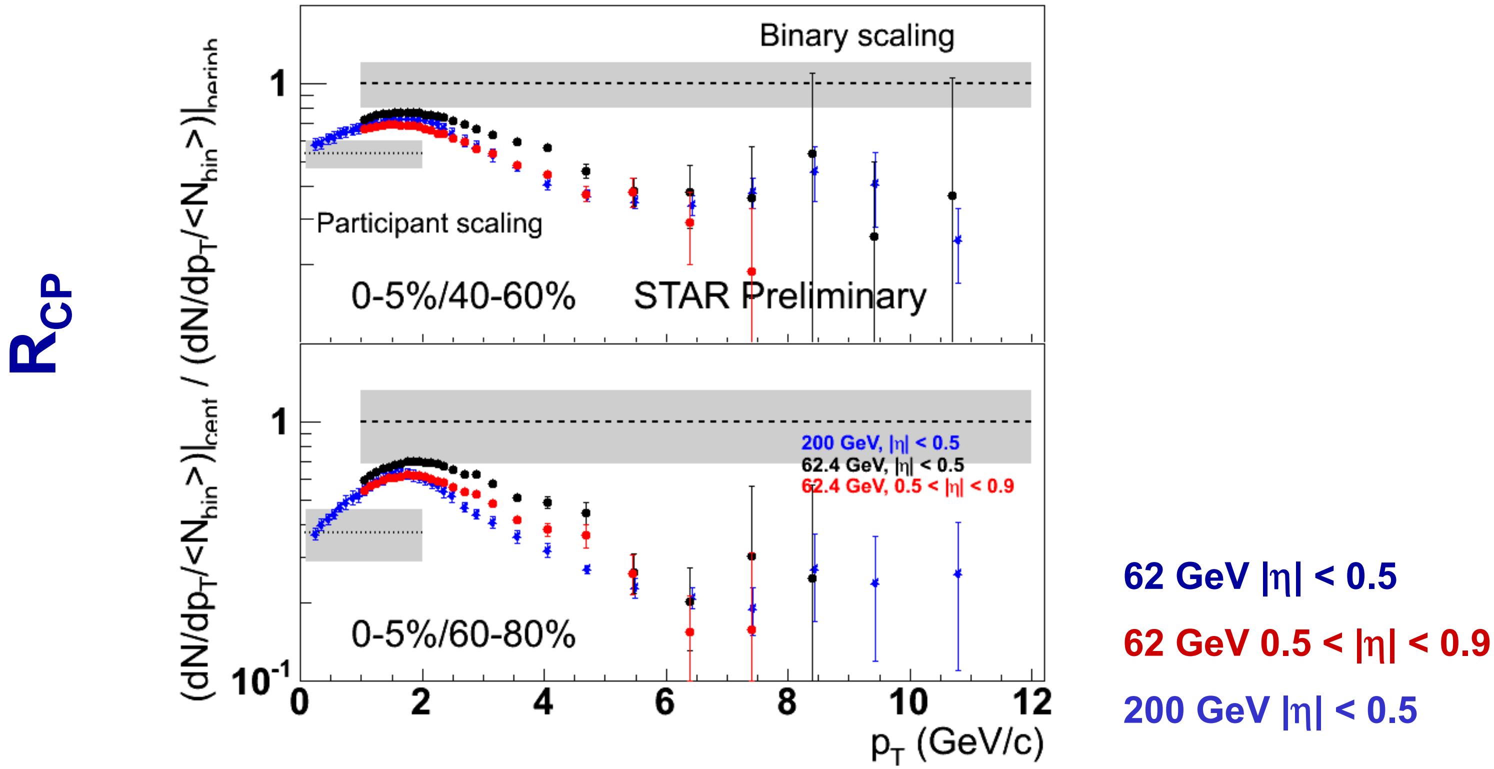


- Irreducible uncertainties in ISR data of order 30%
- need to measure at RHIC

R_{CP} for Au+Au at 62.4 GeV

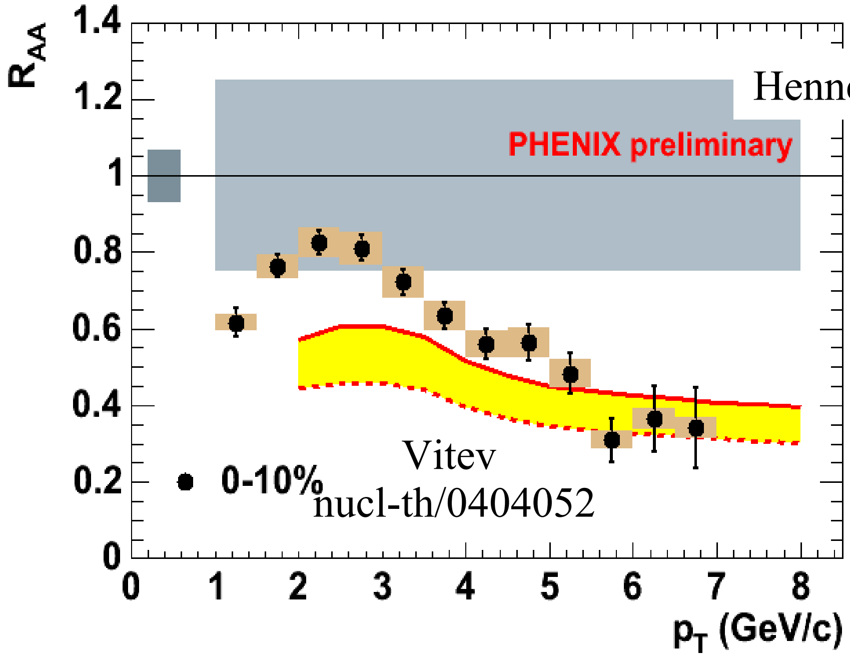
STAR

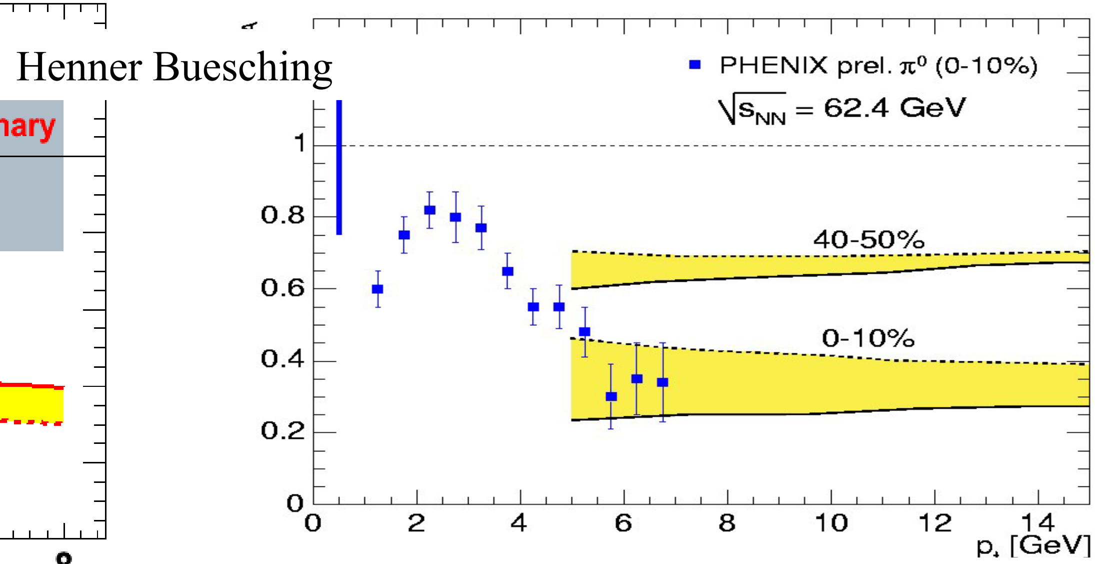
Carl Gagliardi

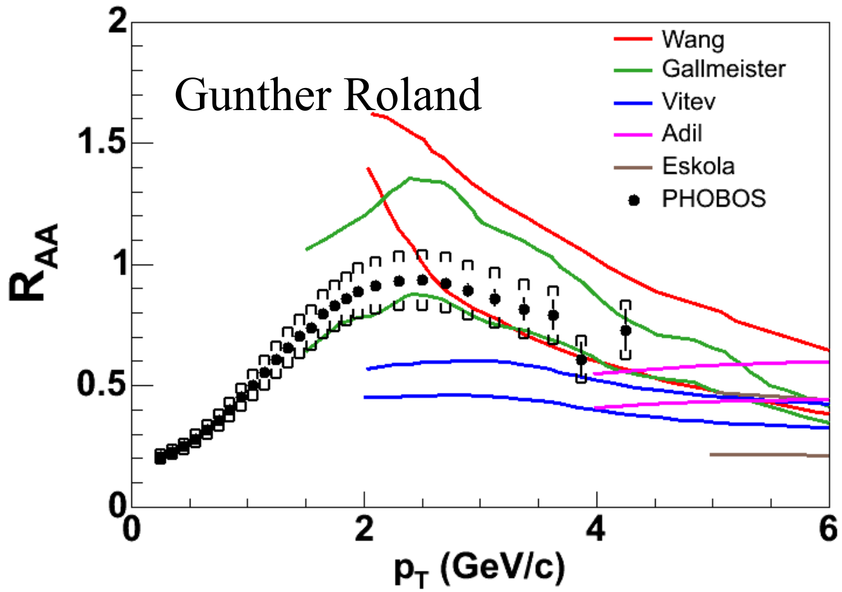


- 62 GeV: clear suppression at high p_T, similar in magnitude to 200 GeV
- but statistics insufficient for detailed studies beyond the “baryon enhancement” regime

R_{AA} @ 62 GeV: comparison to theory





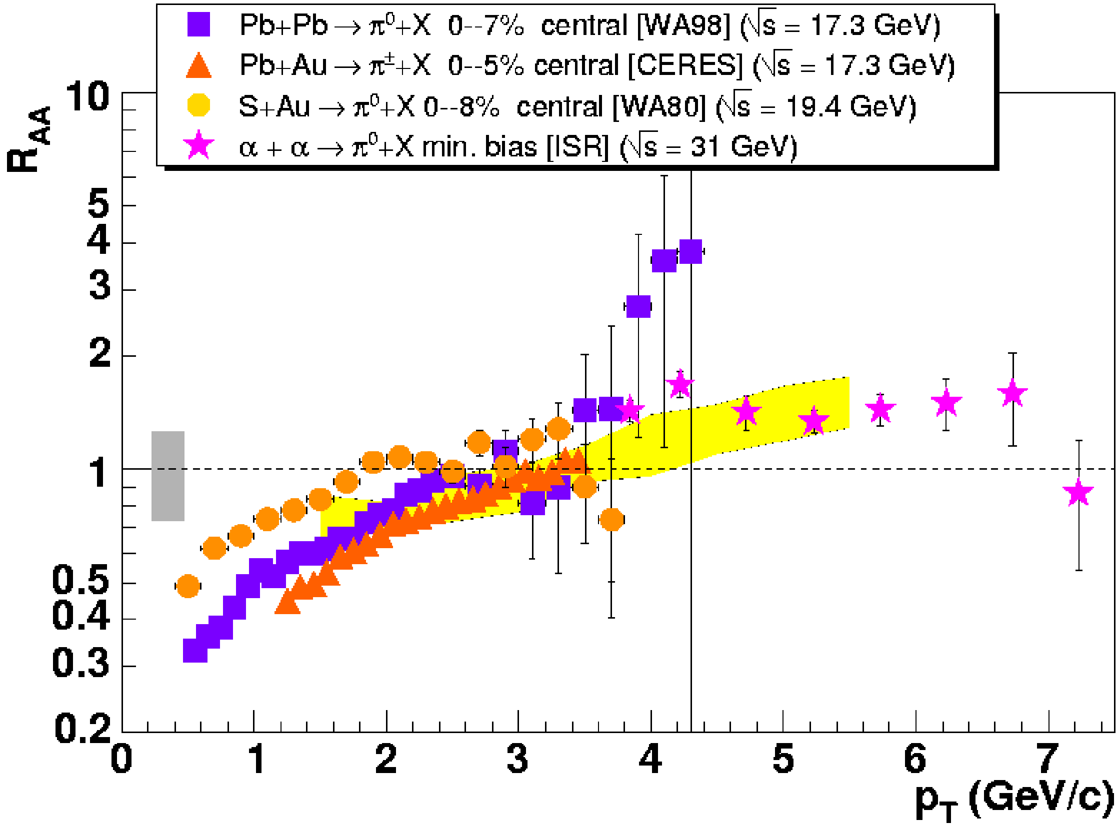


- Rough agreement with theoretical *predictions*

- R_{AA}~0.3 for dN_g/dy~800

High p_T at the SPS, revisited

David d'Enterria



- reassessment of p+p reference at 17.3 GeV
- $dN_g/dy \sim$ 400-600(Vitev nucl-th/0404052)
- more consistent with estimated $\varepsilon_{Bj} \sim 3$ GeV/fm^3

High p_T hadron suppression: summary

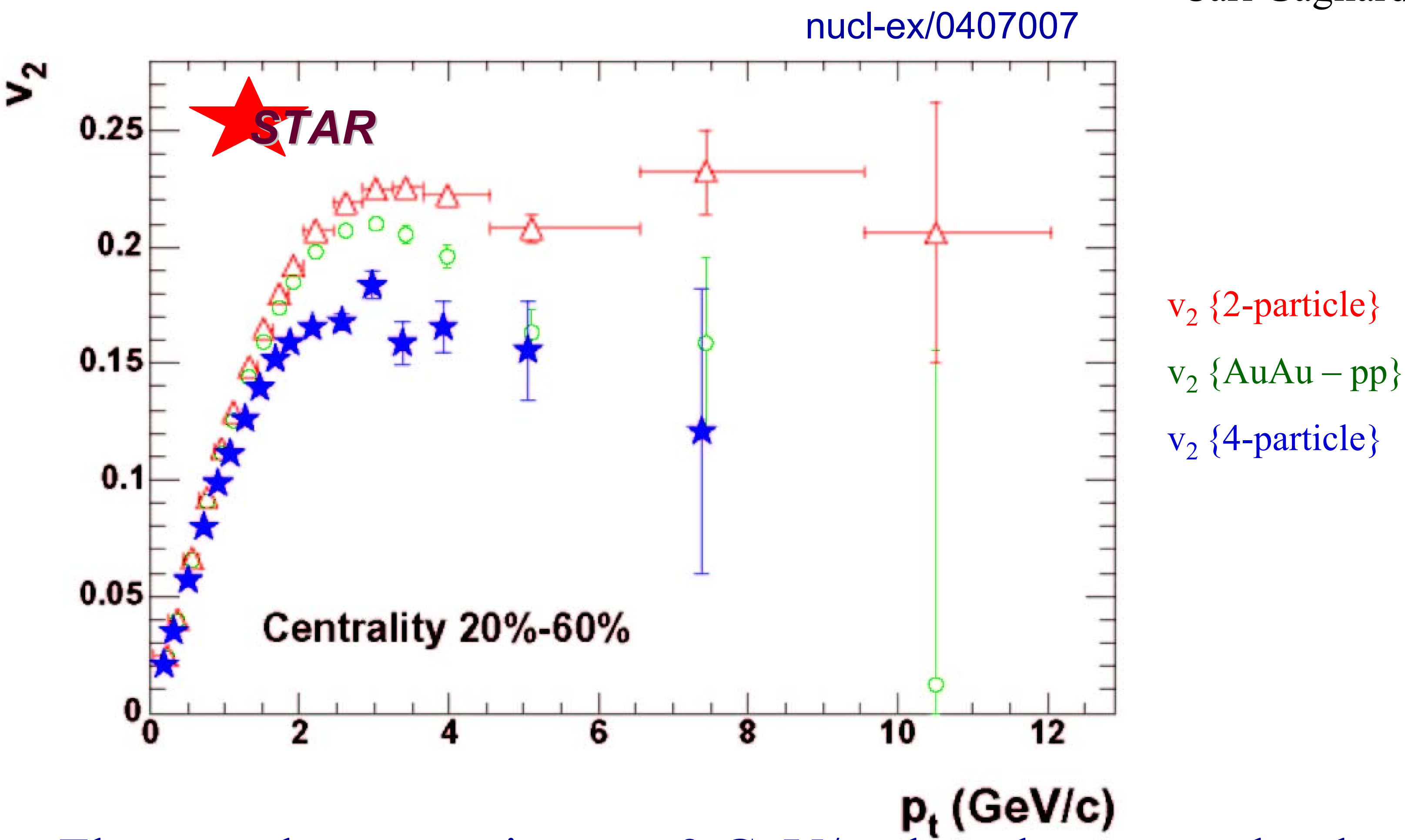
- Suppression is a large effect for all hadrons at high p_T
- Gross features described by energy loss models
- Supplies significant lower bound on initial color charge density
- Intrinsically limited as an observable, insensitive to density beyond a moderate limit

Current data insufficient to disentangle underlying mechanisms

Need: run V Cu+Cu, run IV analysis for 200 GeV, better p+p and Au+Au at 62 GeV, much better data at lower energies

Azimuthal anisotropy at high p_T

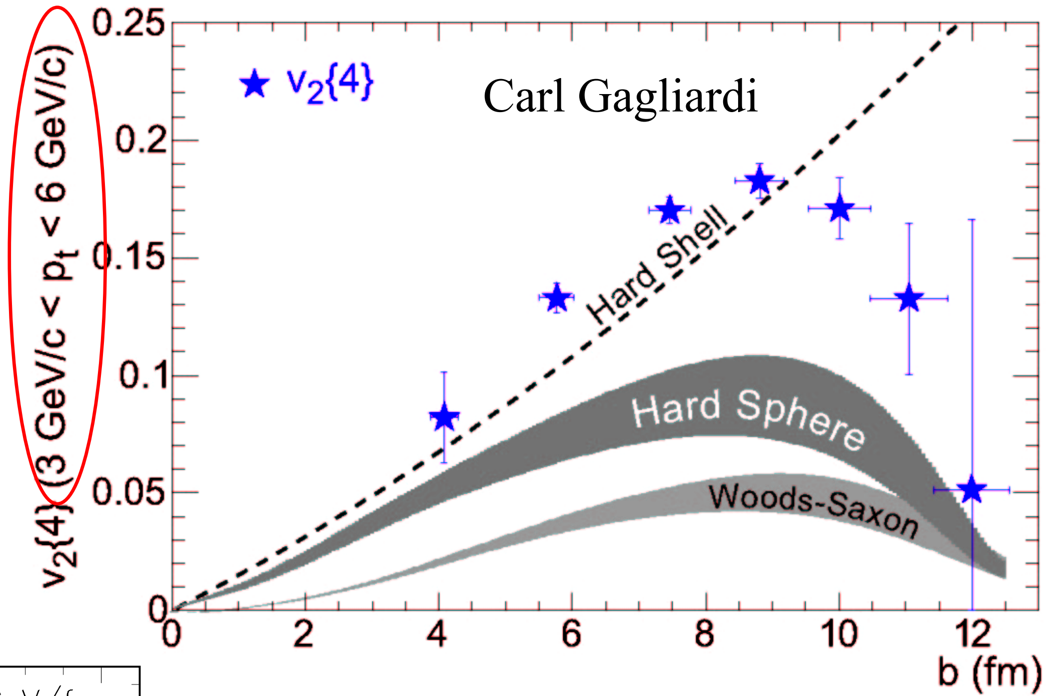
Carl Gagliardi

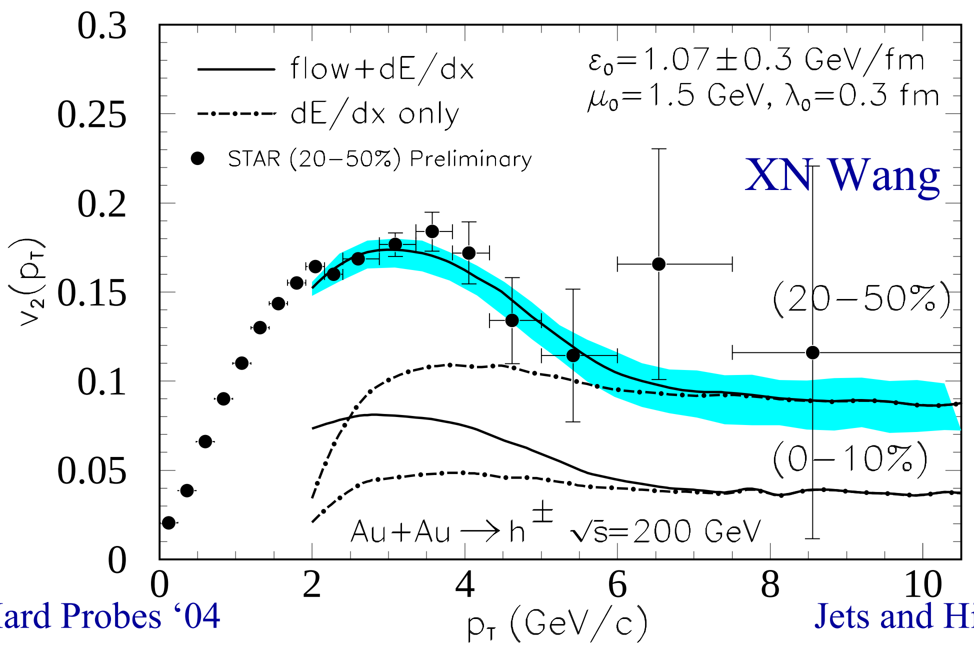


- Flow reaches a maximum ~3 GeV/c, then decreases slowly
- Non-zero real “flow” to ~8 GeV/c in mid-central collisions
- But uncertainties are large at p_T>5 GeV/c

v_2 vs. Geometry in 200 GeV Au+Au

- v_2 at high p_T exhausts all reasonable geometric limits (Shuryak)
- too large to be accounted for by energy loss consistent with other high p_T observations (Drees et al.)



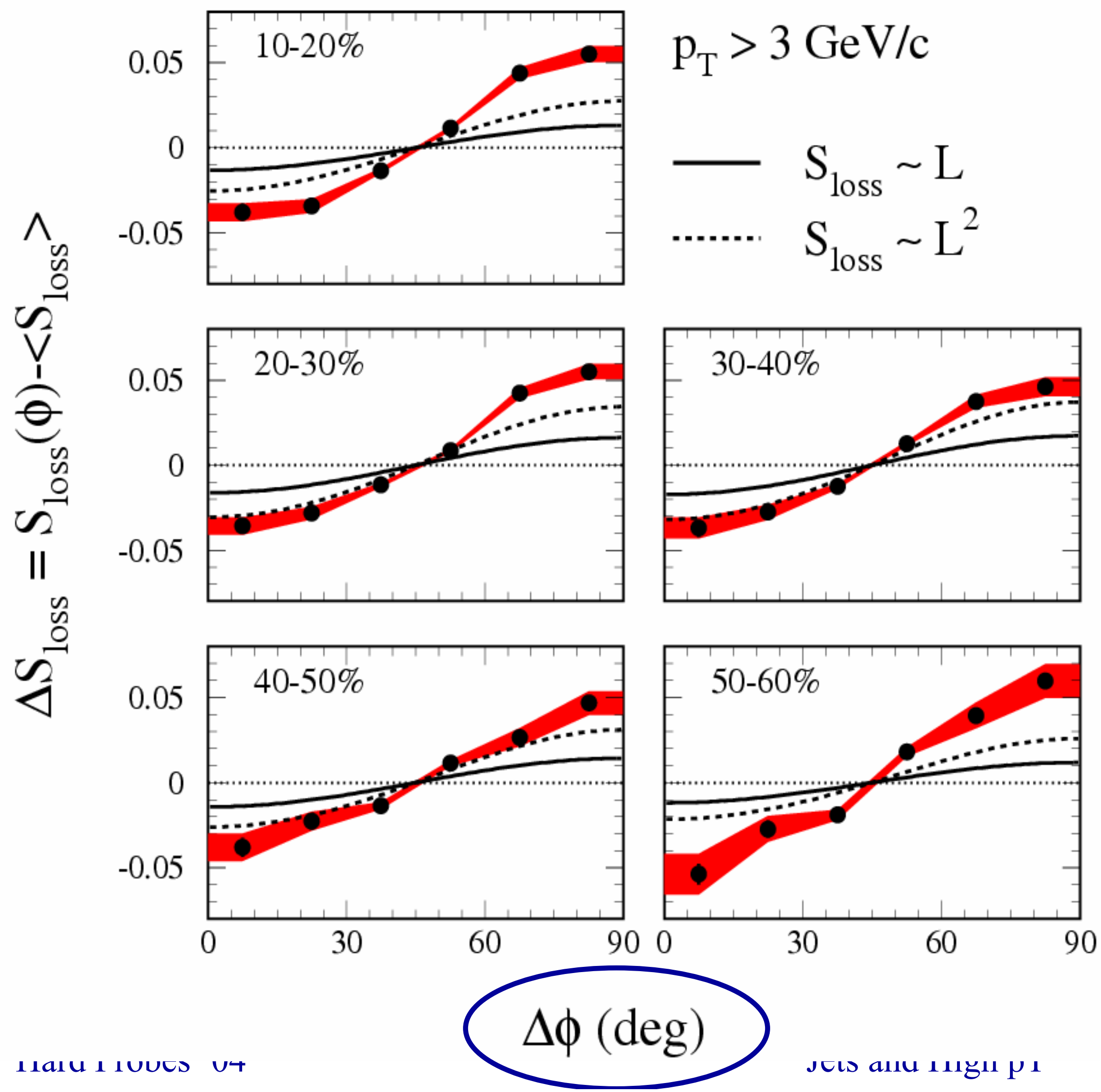


Maybe non-perturbative mechanisms at play at intermediate p_T?

Energy Loss vs Path Length

PHENIX preliminary

Brian Cole

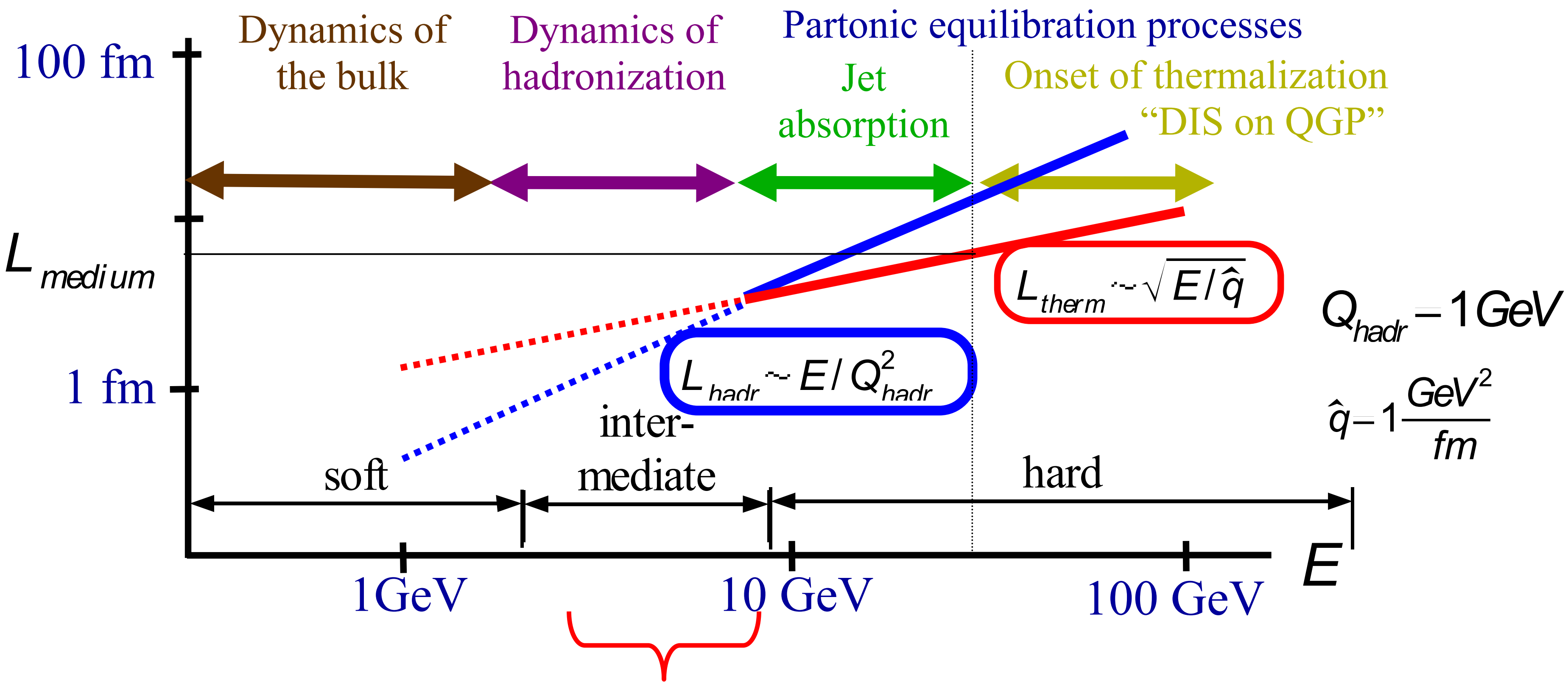


Perhaps not surprising that simple geometric approaches to ΔE extract very strong dependence on L

$\Rightarrow$ origin is same as unexpectedly large v_2

Where does jet behavior emerge?

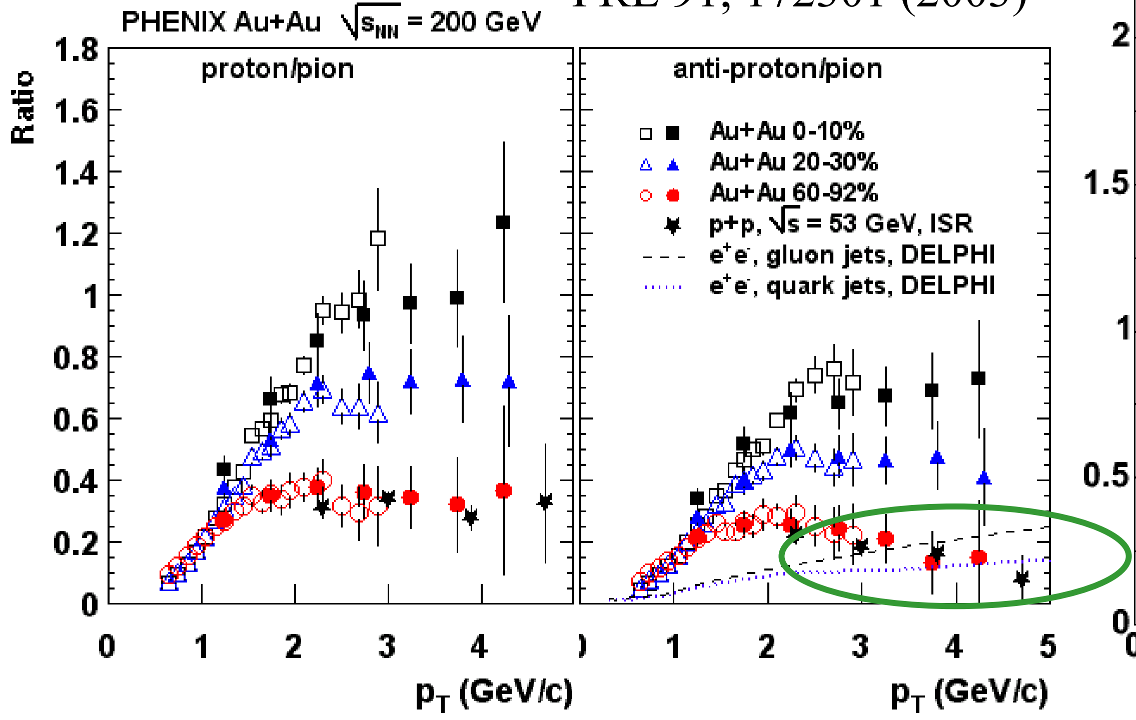
Urs Wiedemann

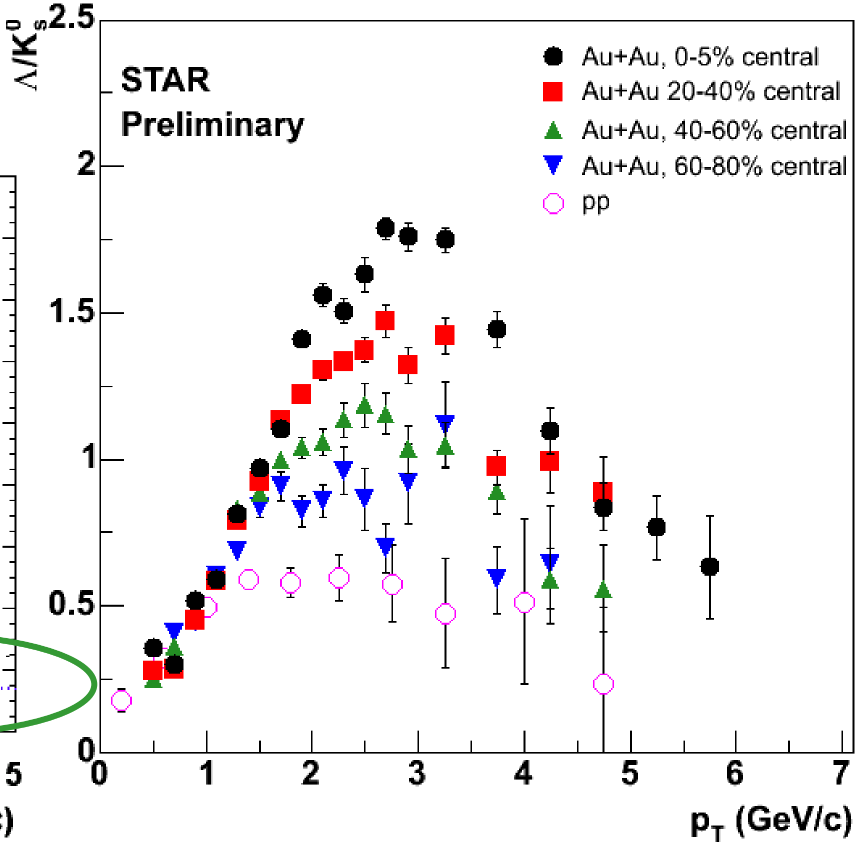


Look at intermediate p_T: evidence of interplay between soft processes and fragmentation?

Intermediate p_T: anomalous baryon production

PRL 91, 172301 (2003)

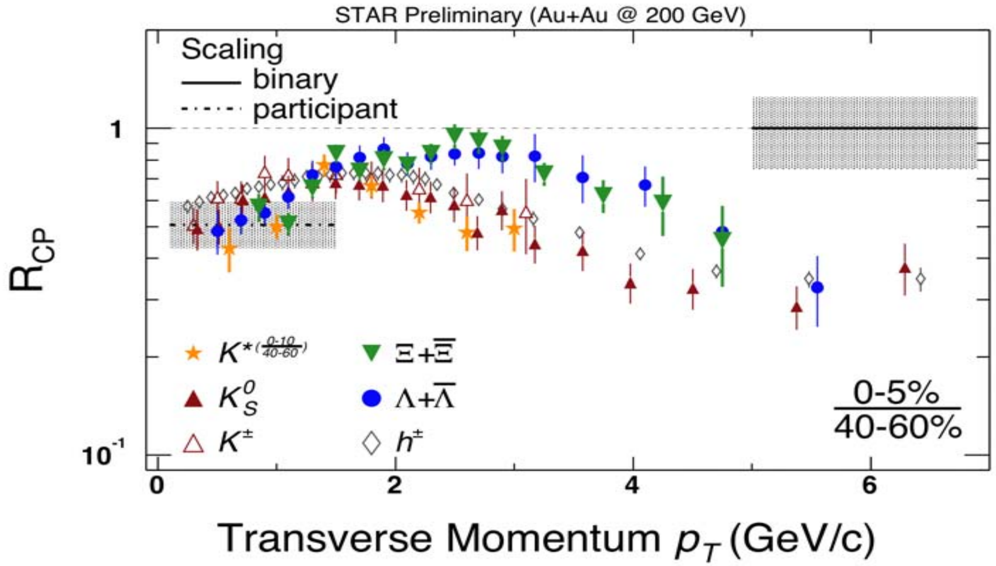




Central Au+Au: baryon/meson yields substantially in excess of expectations from jet fragmentation

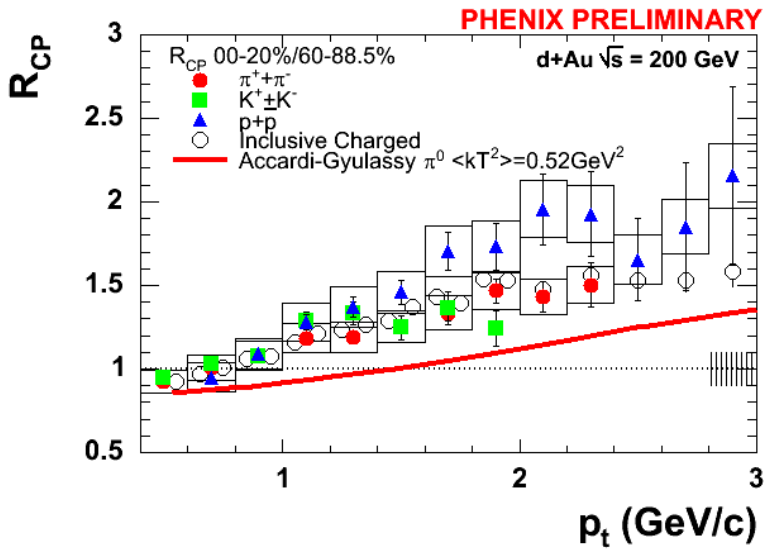
Initial state contribution? Check d+Au

Au+Au



d+Au

Barbara Jacak



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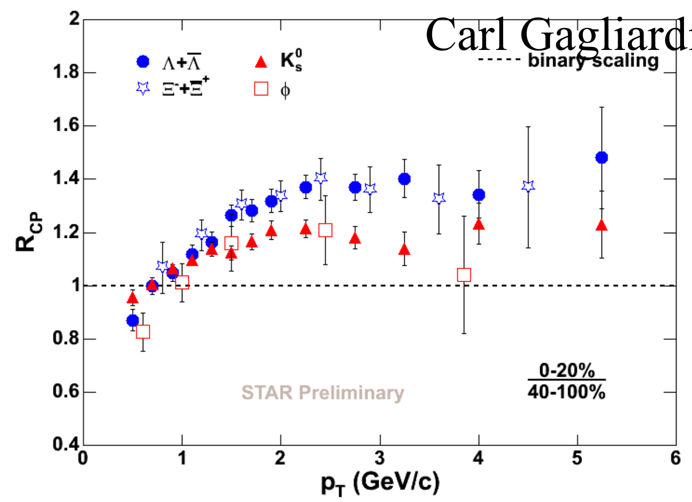


Baryon excess persists for d+Au but at much reduced magnitude

- Cronin effect?
- Recombination? (Rudi Hwa)

Formation time of fragmentation hadrons

Barbara's time scale estimates:

- Uncertainty principle:

  $\tau_f \sim$ 9-18 fm/c for pions; $R_h \sim$0.5-1 fm

  $\tau_f \sim$ 2.7 fm/c for baryons ($R_h \sim$1 fm)

- color singlet dipole formation:

  $\tau_f \sim 2E_h (1-z)/(k_T^2+m_h^2)$

  for z = 0.6-0.8 and $k_T \sim \Lambda_{QCD}$ (τ_f baryons) ~ 1-2 fm/c

R(Au nucleus) ~ 7 fm

→ Baryon formation is INside the medium!

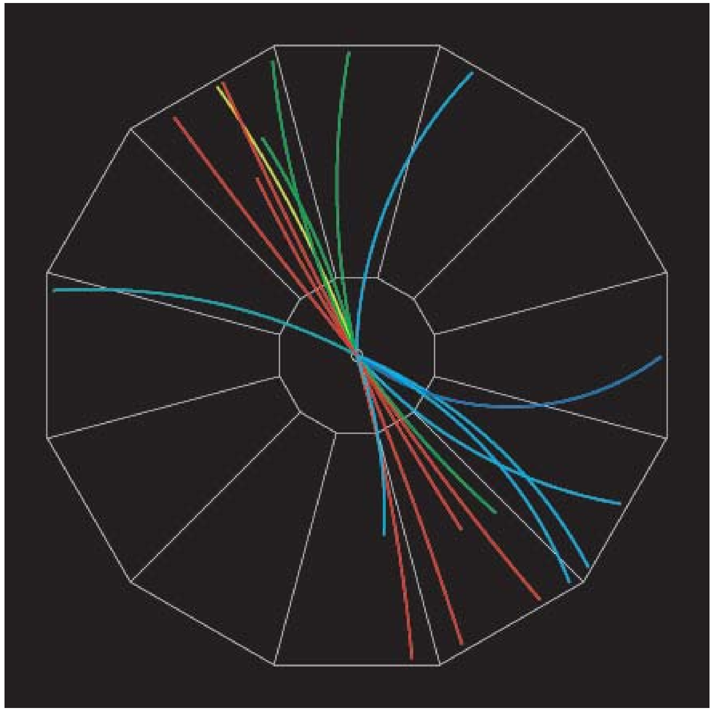
Jet energy loss interpretation:

Early hadronization ⇒ color charge is neutralized early

Strong L dependence of ΔE ⇒ substantially reduced suppression?

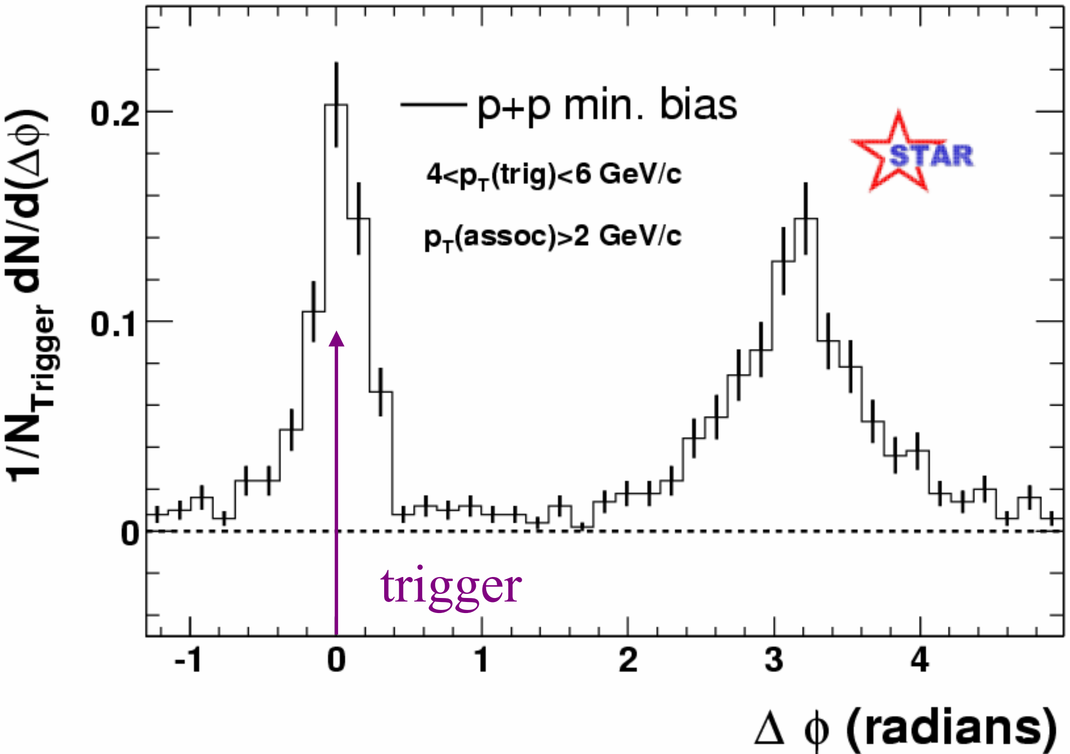
"Jets" via dihadron azimuthal distributions

p+p → dijet



- trigger: highest p_T track
- $\Delta\phi$ distribution: 2 GeV/c<p_T<$p_T^{trigger}$
- normalize to number of triggers

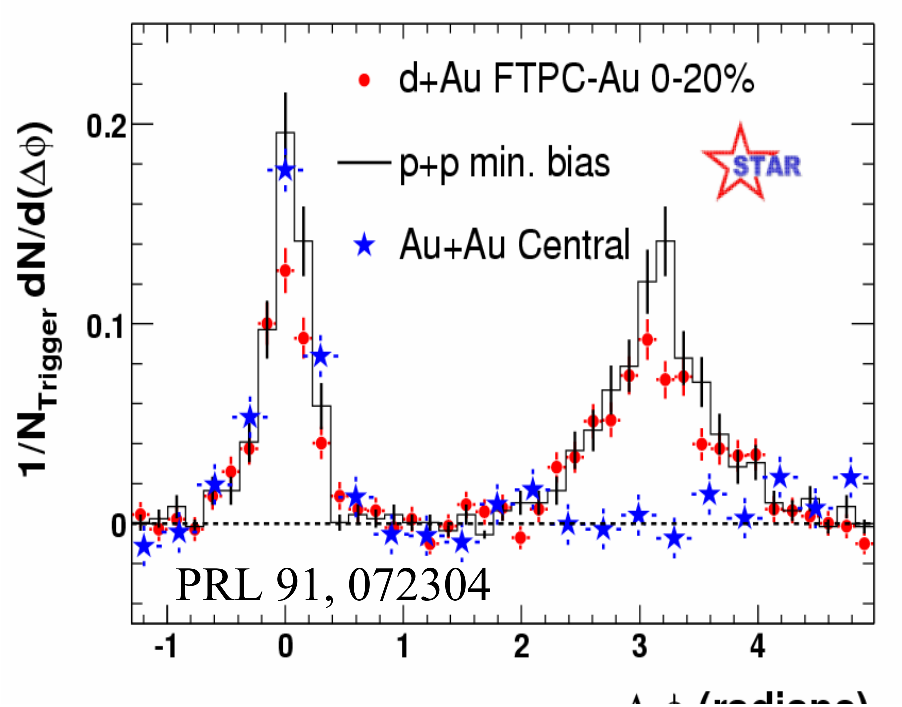
Phys Rev Lett 90, 082302

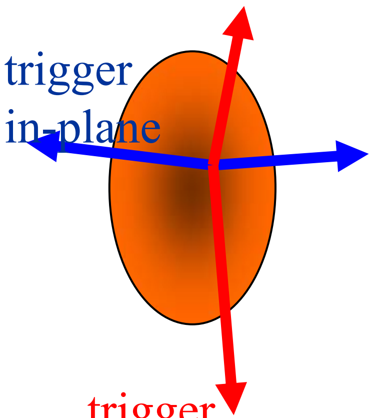


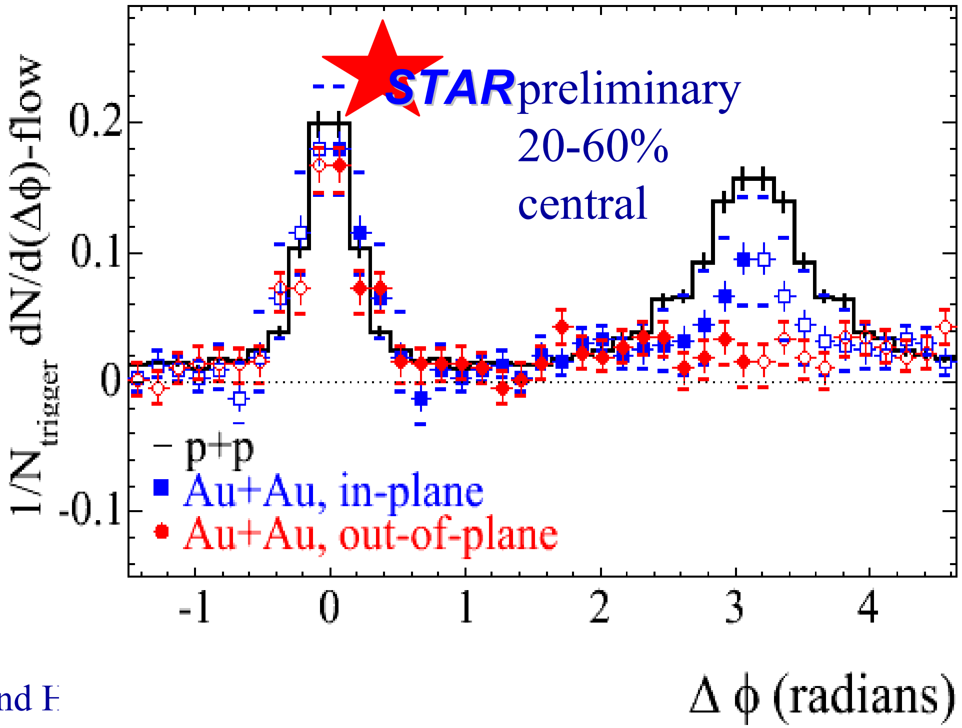
Dihadron correlations in $\Delta\phi$

Dan Magestro

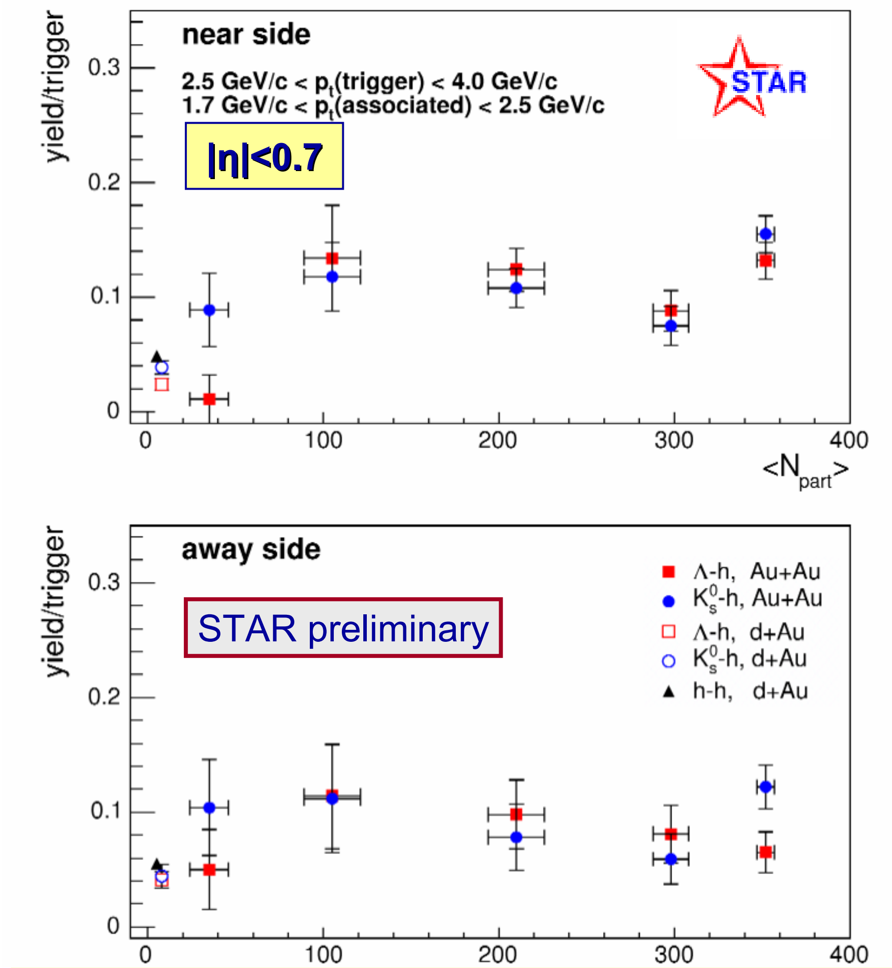
Striking final state effects

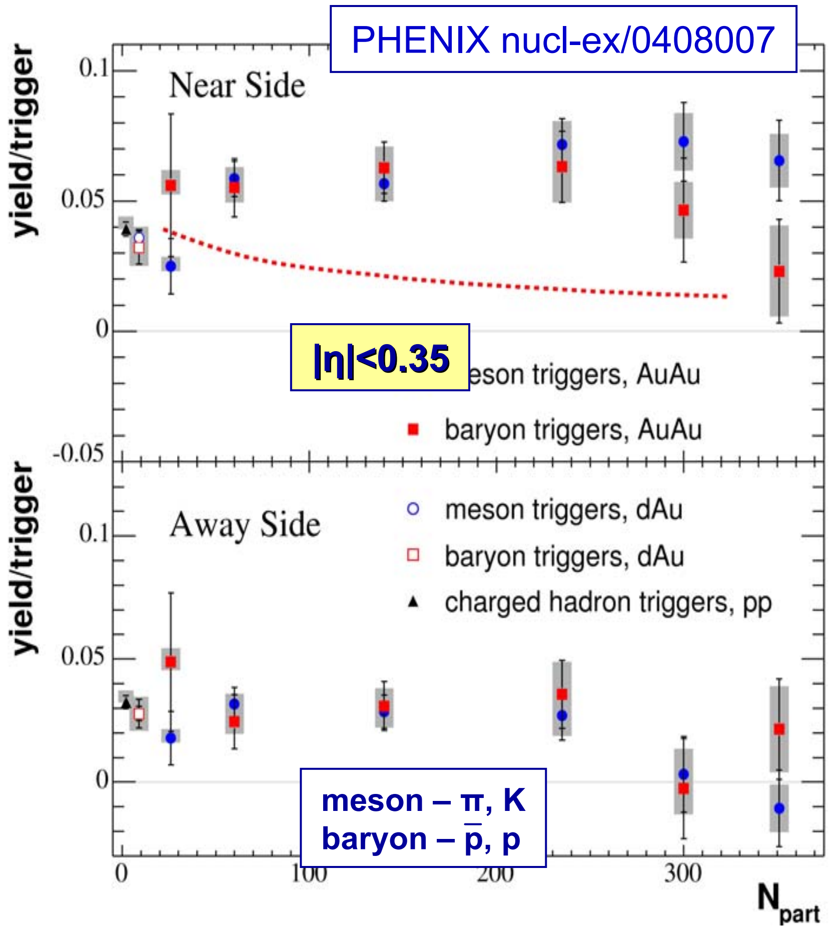






Meson vs baryon trigger: associated yields





- Associated yields similar everywhere for meson and baryon triggers (perhaps weak dilution for baryons in central collisions)
- Dominance of jet-like production but widely differing suppression for baryons and mesons???

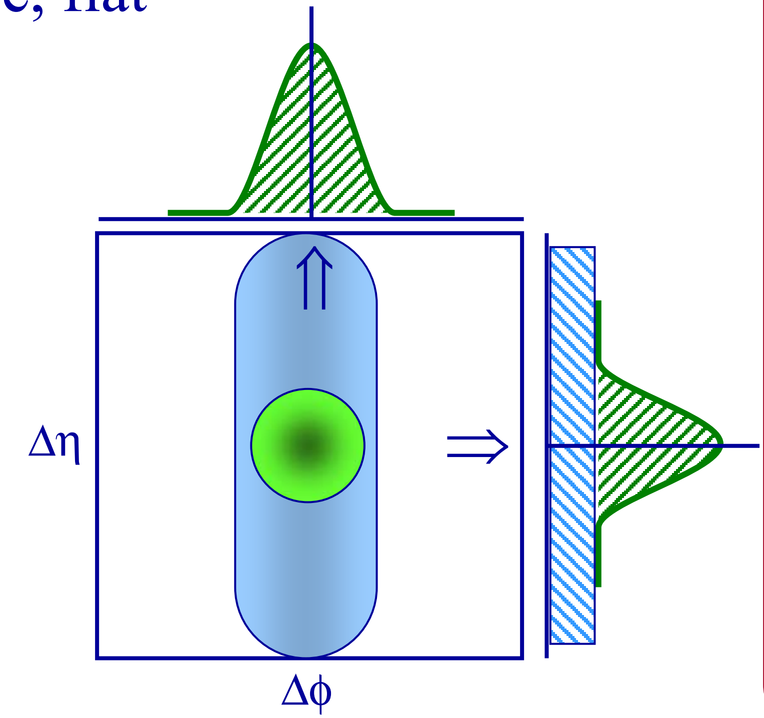
Look in detail at near-side correlations

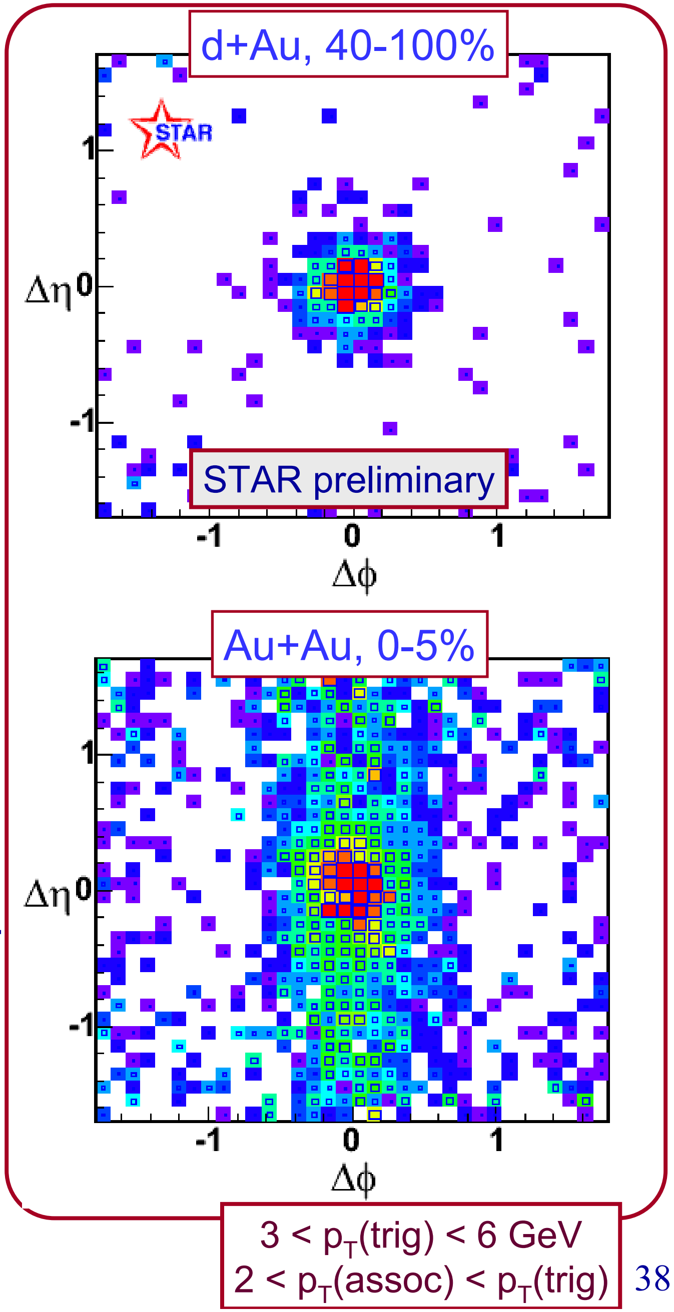
Dan Magestro

Near side: small $\Delta\phi$

Two components in $\Delta\eta$:

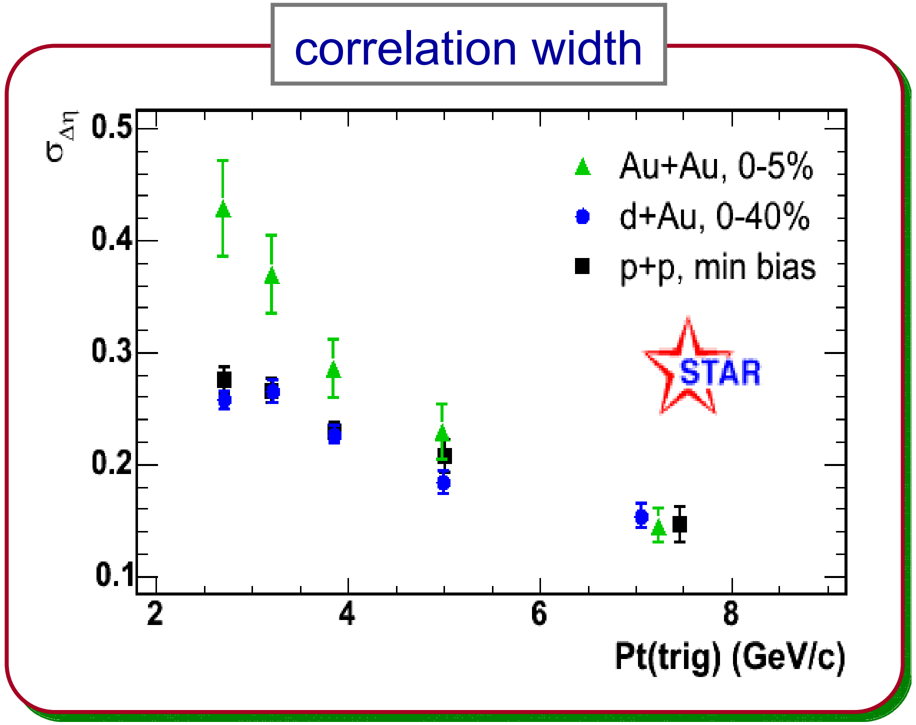
1. Short range, jet-like
2. Long range, flat

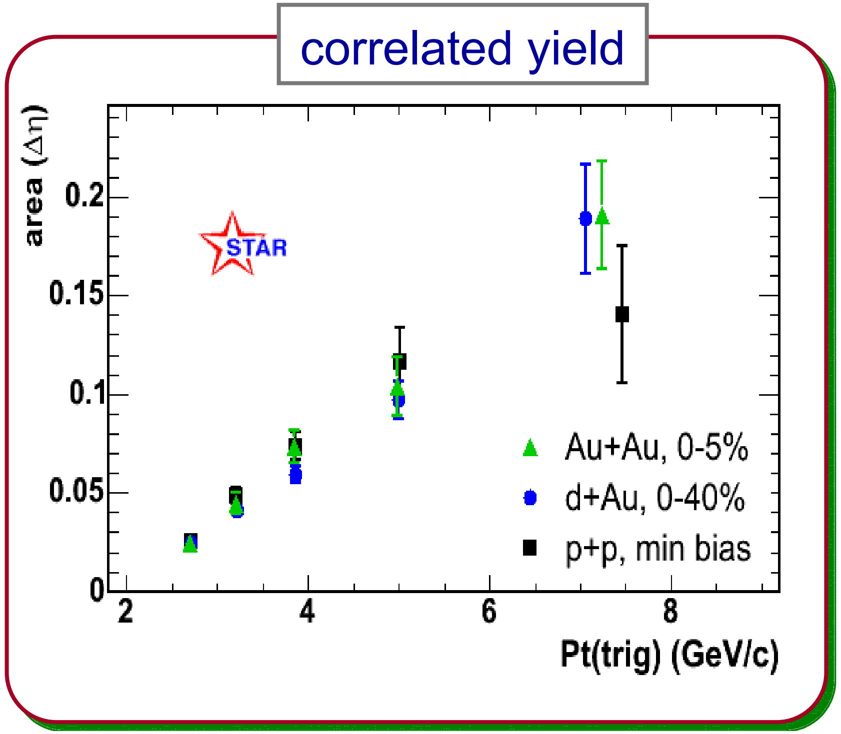




Jet-like Δη correlation: p_T systematics

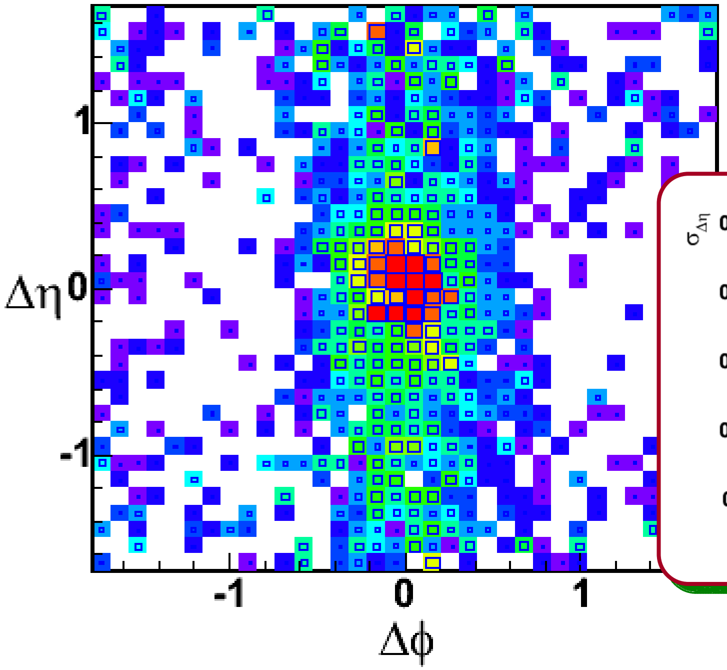
Dan Magestro

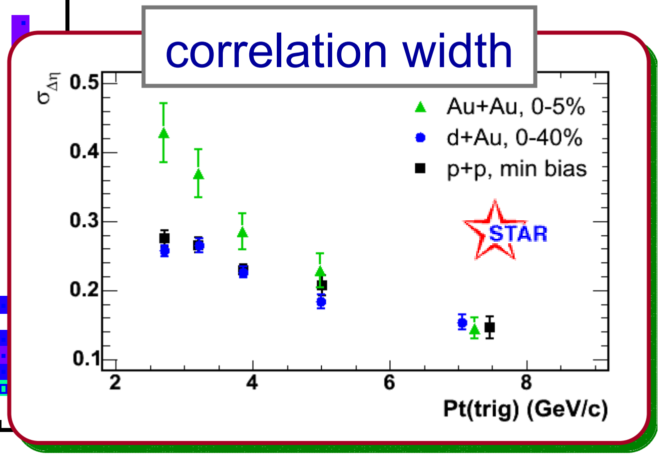


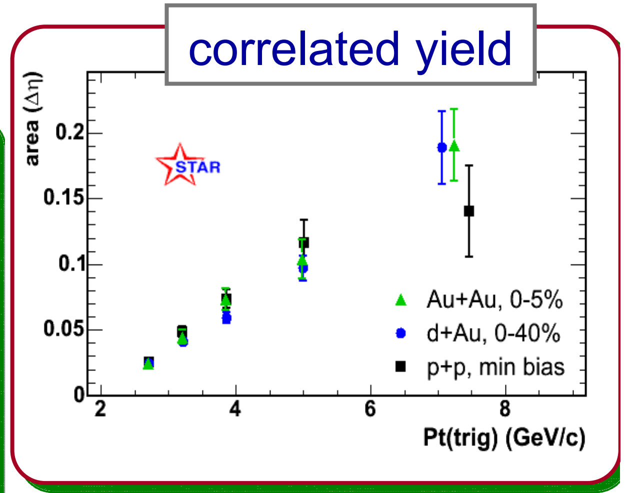


- Significant nuclear broadening at low p_T(trig), disappears with increasing p_T(trig)
- associated yields invariant with system

Δη correlations (cont'd)



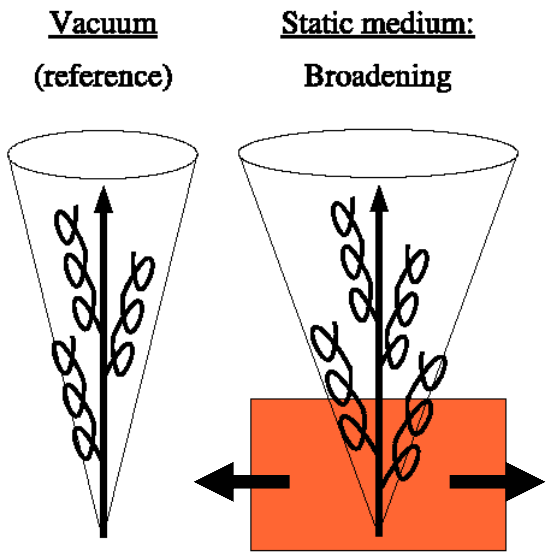




- Recombination effects? Coupling of radiation to flow medium?
- Long-range correlation: interplay of jet quenching and transverse radial flow?

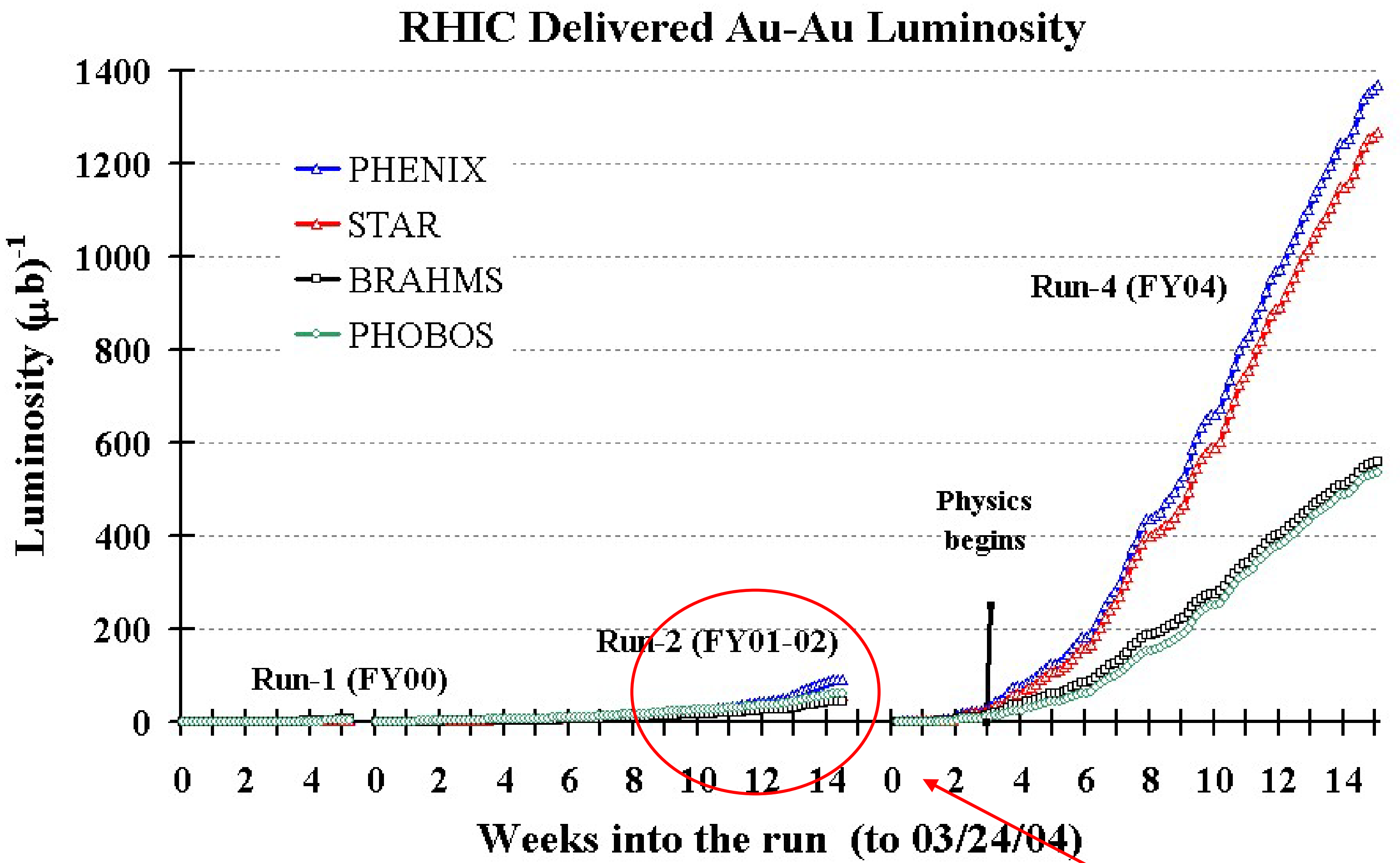
Voloshin, nucl-th/0312065

No simple, consistent picture emerges



Armesto et al.

RHIC is a hard probes machine



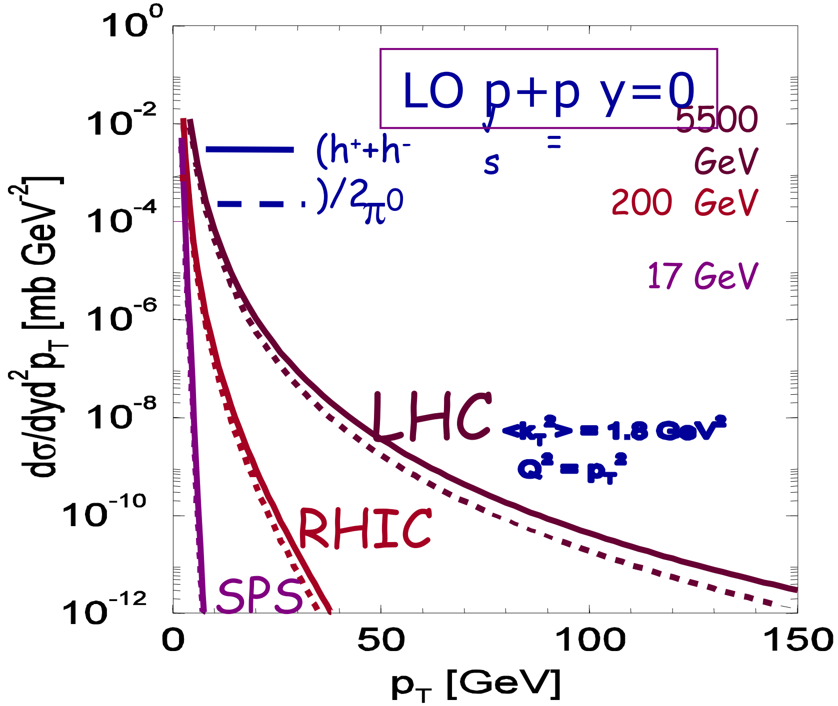
Most 200 GeV Au+Au results to date are from here

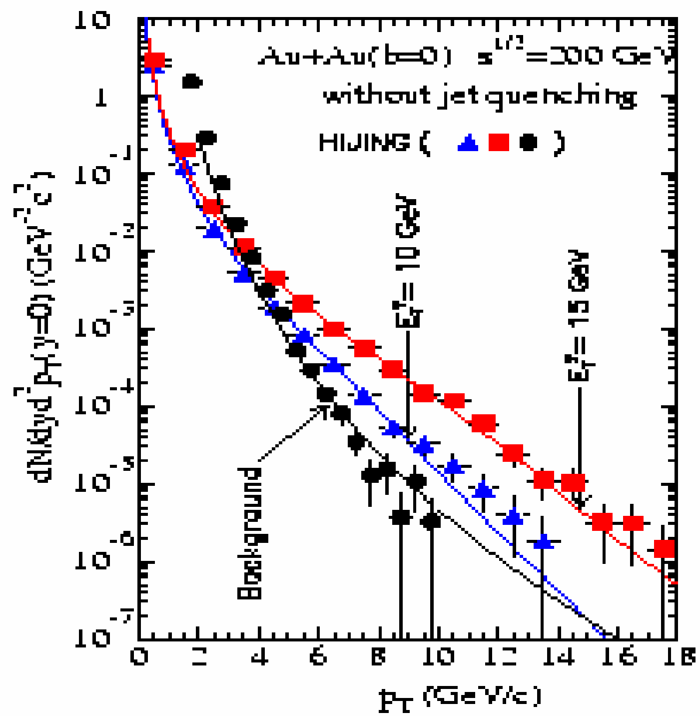
RHIC II and LHC

John Harris, Bolek Wyslouch

Increased luminosity (RHIC II) and increased energy (LHC):

Enormous increases in p_T reach, huge increases in statistics: qualitatively new probes of the fragmentation





Summary and Outlook

Partonic energy loss in nuclear collisions at RHIC is firmly established

- broadly consistent with pQCD-based energy loss models
- present measurements supply significant lower bound to initial color charge density

But it promises much more: detailed study of interplay between fragmentation and thermalization may supply new and unique probes of the dynamics

- This is hard, we are only at the beginning
- Intermediate p_T~5-10 GeV/c appears to provide a laboratory in which we can isolate the various physics