DIS 2005 XIII International Workshop on Deep Inelastic Scattering

π^0, η, and Direct γ, Production in p+p and Au+Au collisions

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For the PHENIX collaboration

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U.S.A.

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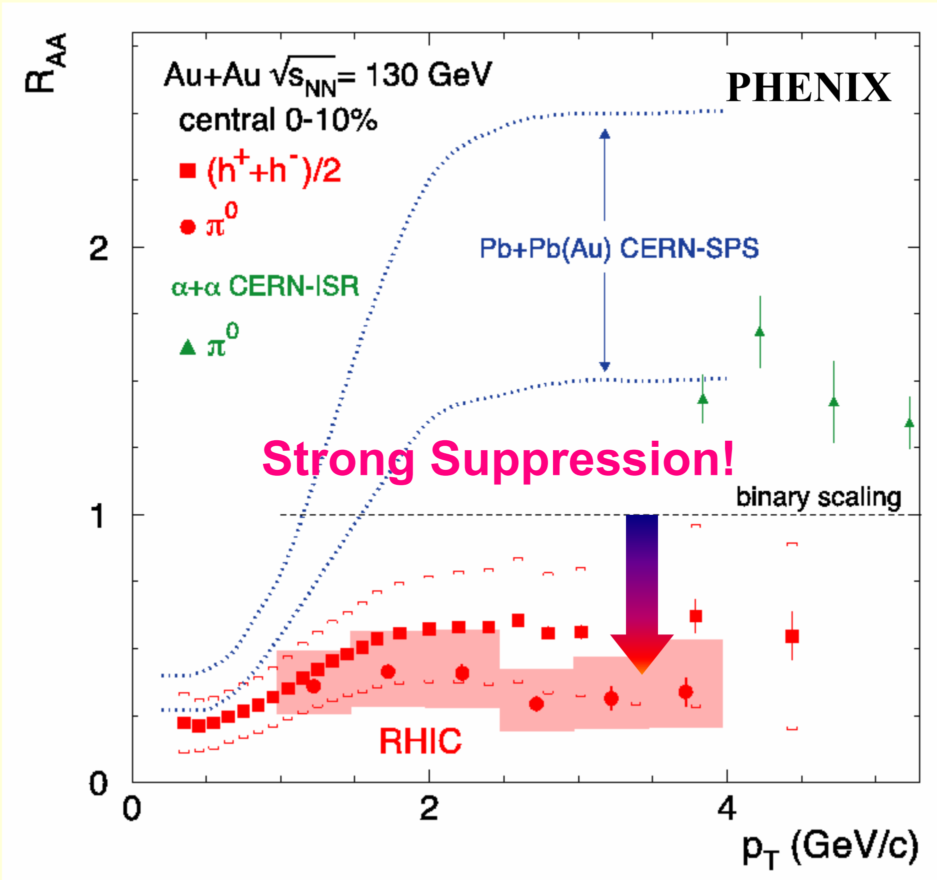
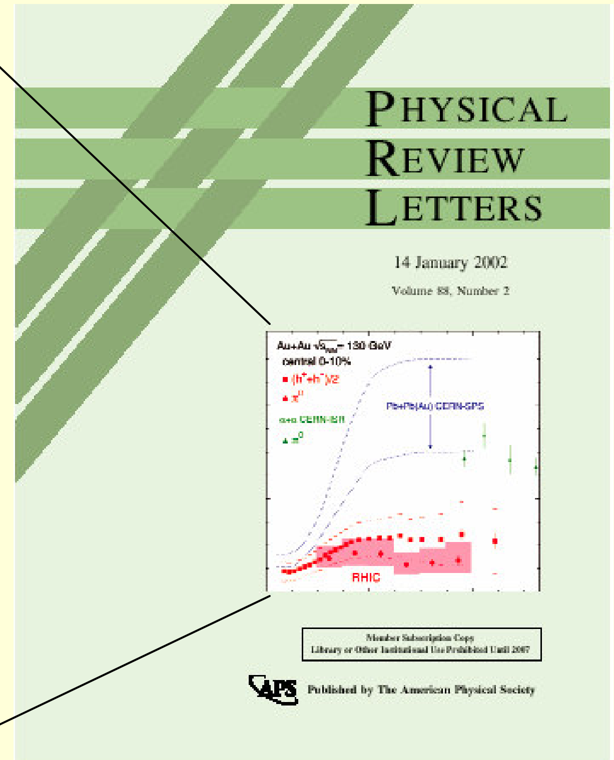
RHIC Headline News… January 2002





PHENIX PRL 88, 022301 (2002)

Large (x5!) suppression of high p_T hadron yield: Huge 'Nuclear effect'

"Jet Quenching"? == Quark Gluon Plasma?

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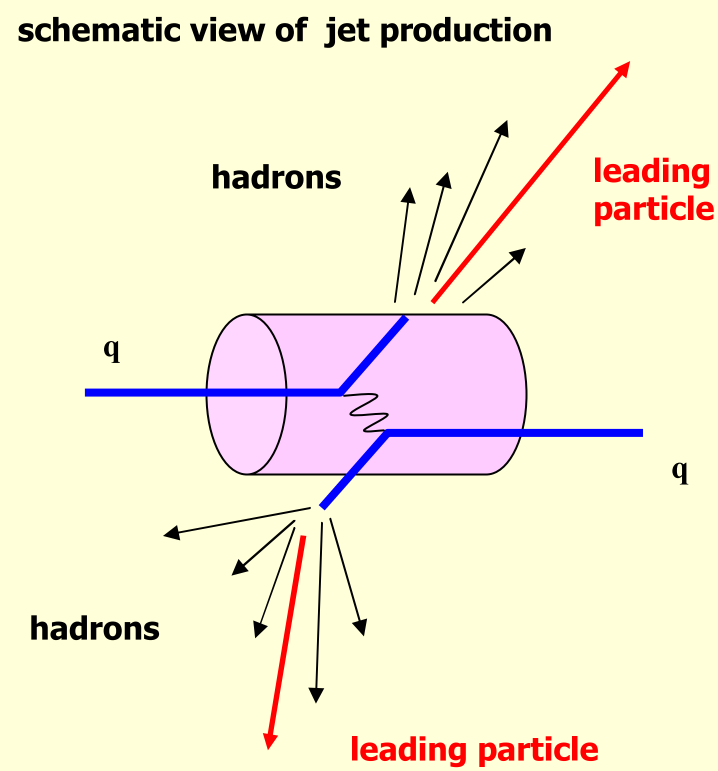
Quenching of Hard Scattered Partons

- **Hard parton scatterings in nucleon collisions produce jets of particles.**
- **In the presence of a dense strongly interacting medium, the scattered partons will suffer soft interactions losing energy (dE/dx~GeV/fm).**
- **"Jet Quenching"**



"The virtue of π^0 and γ Measurements"

To determine if we have produced deconfined QGP we must separately distinguish initial state effects from final state effects.

Once produced, γ's do not interact -> sensitive to: (yield goes ↓ ↑)

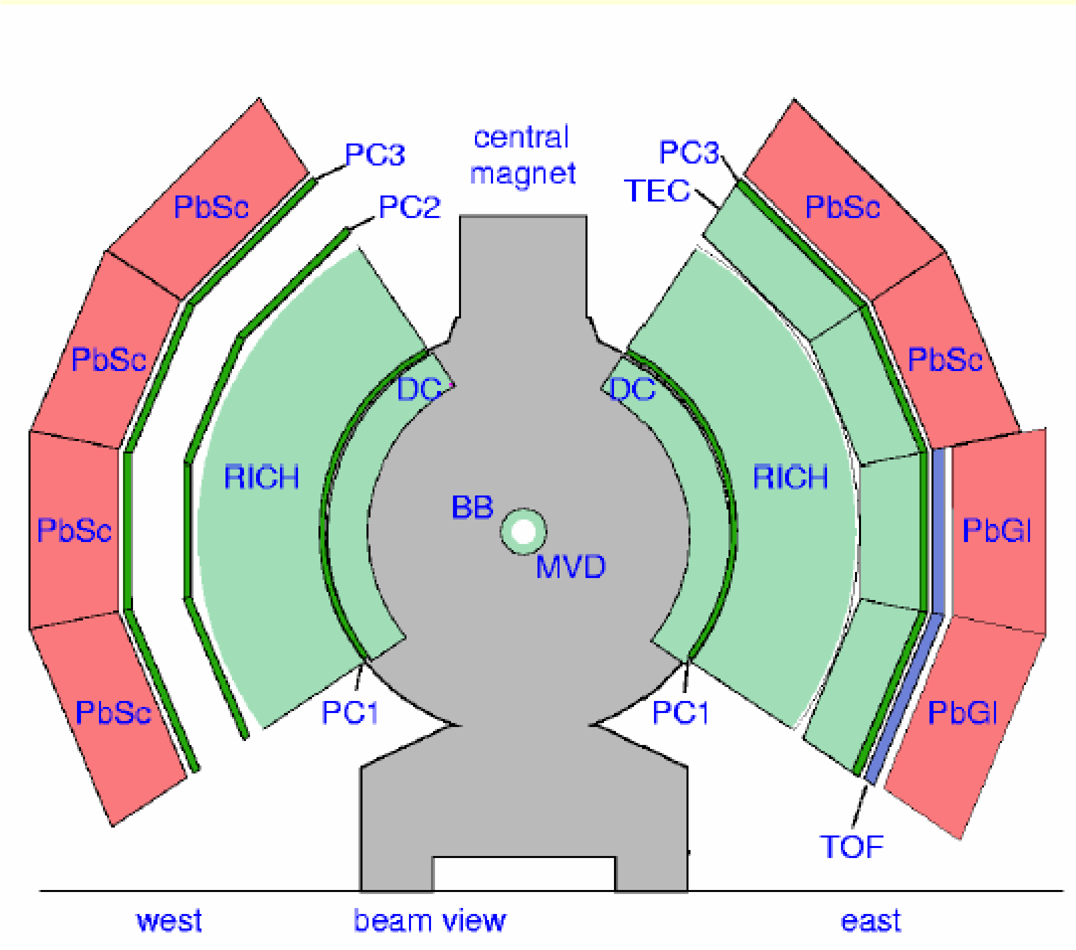
- **initial parton distributions: Intrinsic k_T, k_T Broadening, Shadowing, Anti-shadowing, Saturation, …**
- **final state parton/hadron rescatterings: Thermal, Jet/Parton Radiation or fragmentation after Eloss,…**

π^0's will suffer additional final state effects: Rescattering (low p_T), Absorption, k_T Broadening, <u>Jet/Parton Energy Loss</u> ,…

Experimental virtues (calorimeter measurement):

- Measure γ and π^0 in same detector
- Identified particles to very high p_T
- π^0's abundantly produced
- π^0 mass provides calibration check

PHENIX Electromagnetic Calorimeter



PbSc

• Highly segmented lead **scintillator** sampling Calorimeter

• Module size: 5.5 cm x 5.5 cm x 37 cm

PbGl

•Highly segmented lead glass **Cherenkov** Calorimeter

• Module size: 4 cm x 4 cm x 40 cm

Two Technologies - very important for systematic error understanding!

Differences:

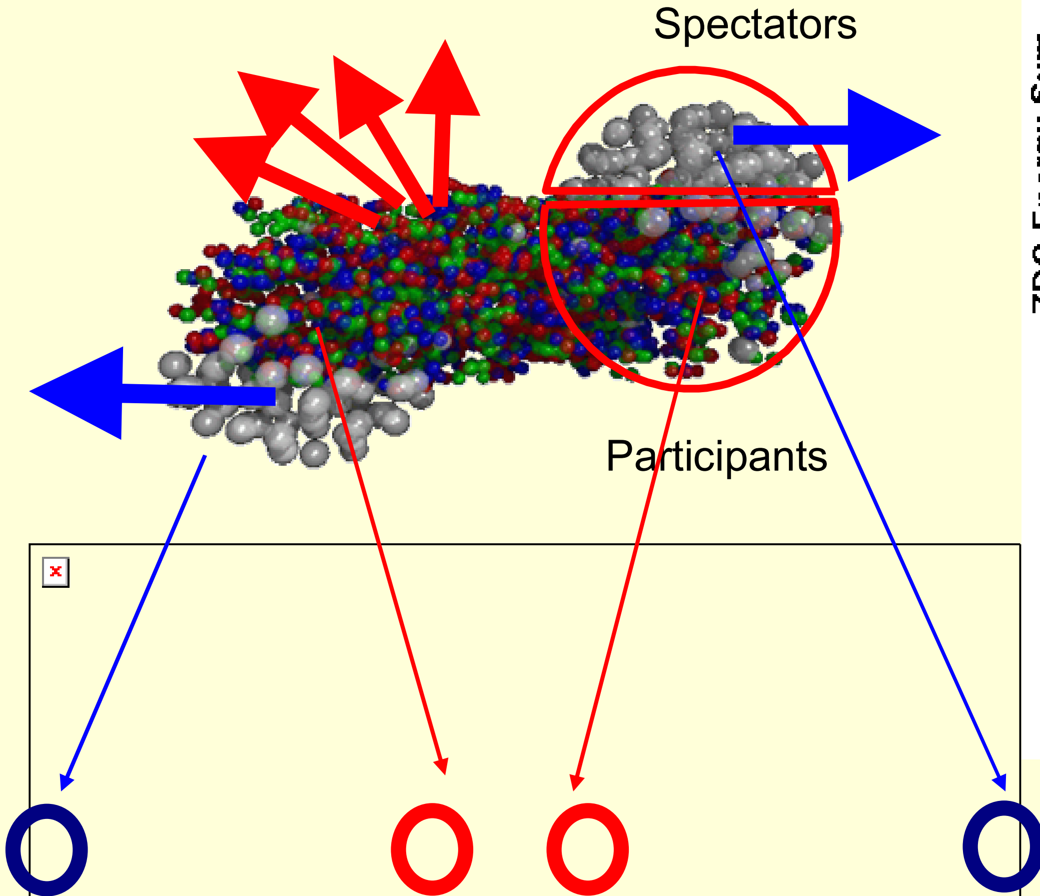
• Different response to hadrons

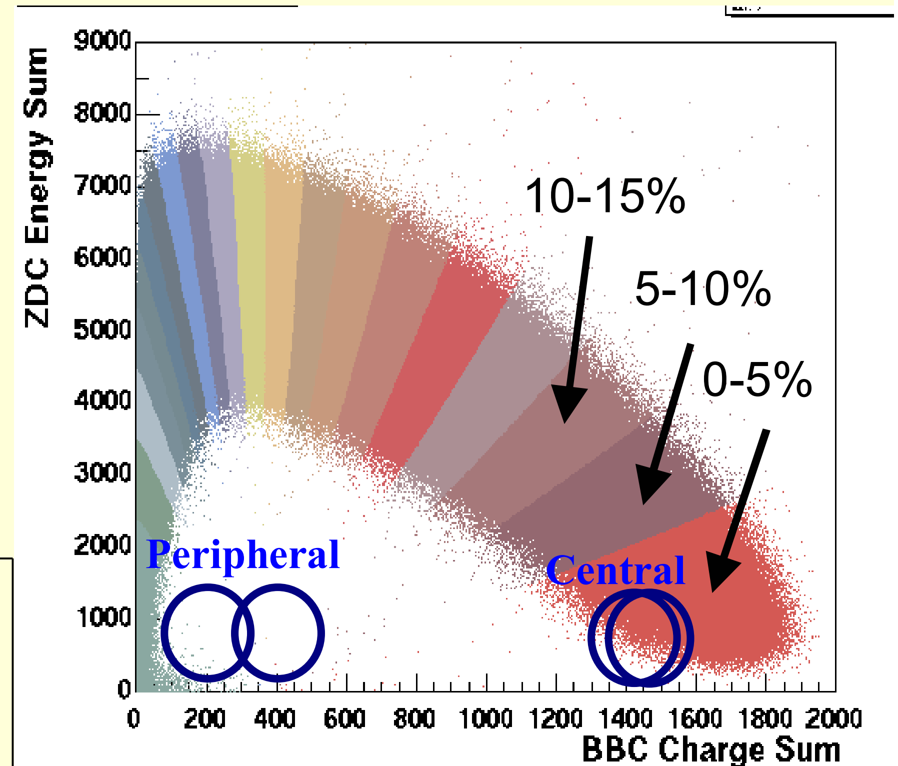
• Different corrections to get linear energy response

• Different shower overlap corrections

• p+p Measurements in same detector

Collision Geometry Matters!





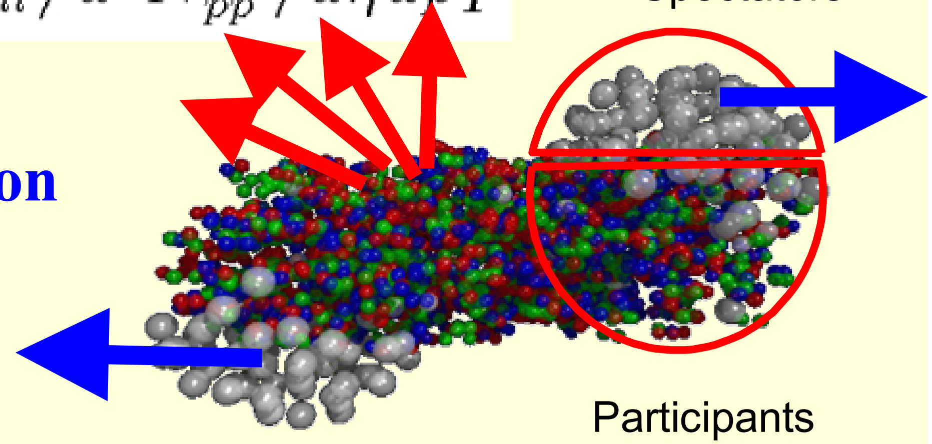
- Centrality selection : Sum of Beam-Beam Counter (**BBC**, $|\eta|=3\sim4$) and energy of Zero-degree calorimeter (**ZDC**)
- Extracted N_{coll} and N_{part} based on Glauber model.

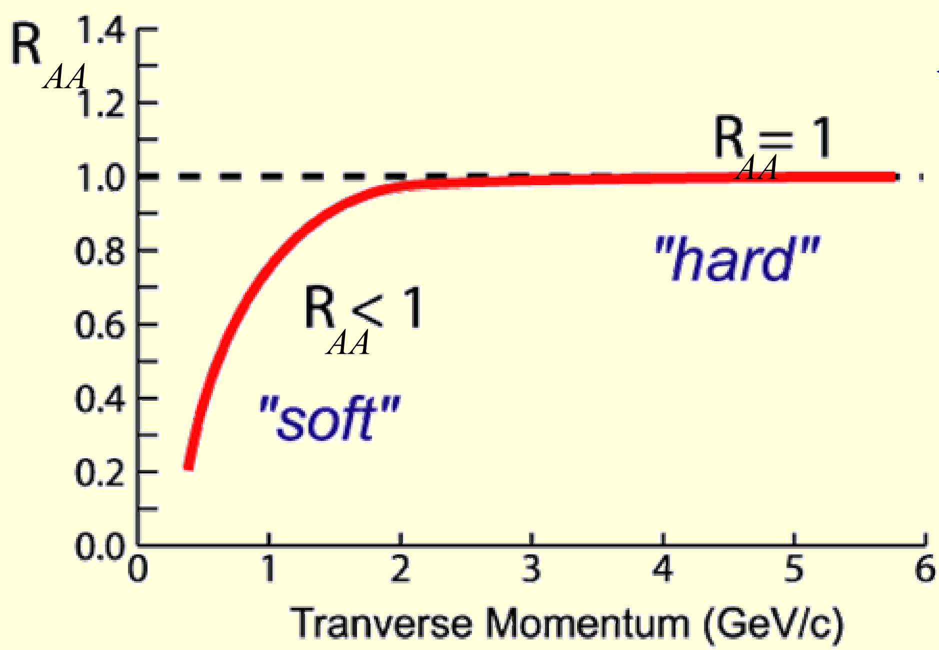
Nuclear Effects?: The Nuclear Modification Factor R_{AA}

Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{d^2N_{AA}/d\eta dp_T}{\langle N_{coll}\rangle d^2N_{pp}/d\eta dp_T}$$

Compare A+A to p+p cross section





"Nominal effects":

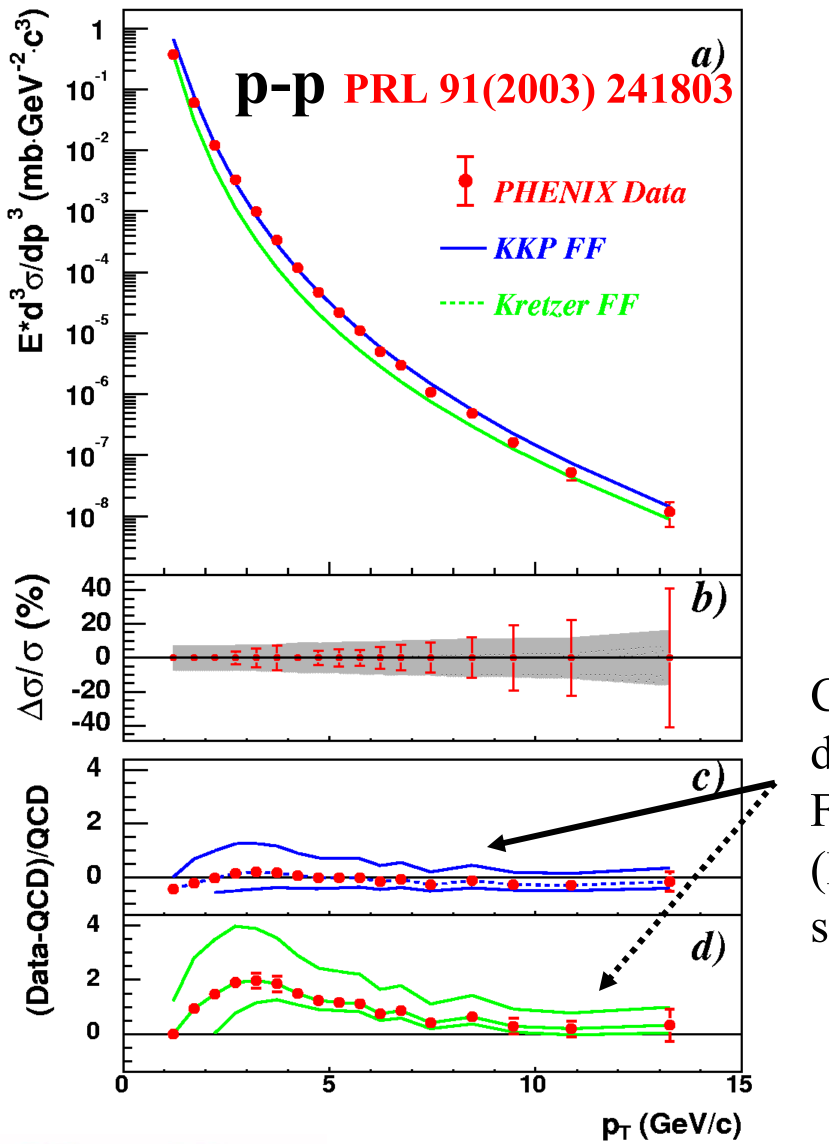
$R_{AA} < 1$ in regime of soft physics

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

Suppression: $R_{AA} < 1$ at high-p_T

k_T broadening (Cronin): $R_{AA} > 1$

High-P_T π^0 spectra in p+p collisions at 200 GeV/c

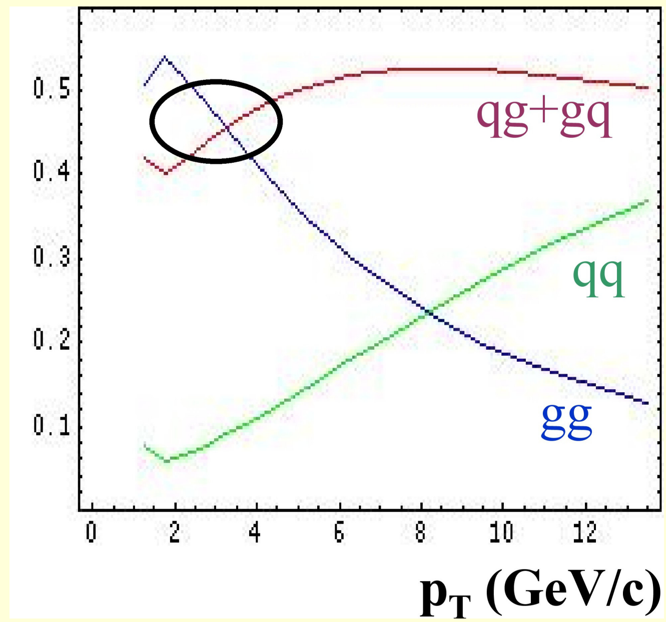


Spectra for π^0 out to 12 GeV/c compared to NLO pQCD predictions
(by W.Vogelsang)

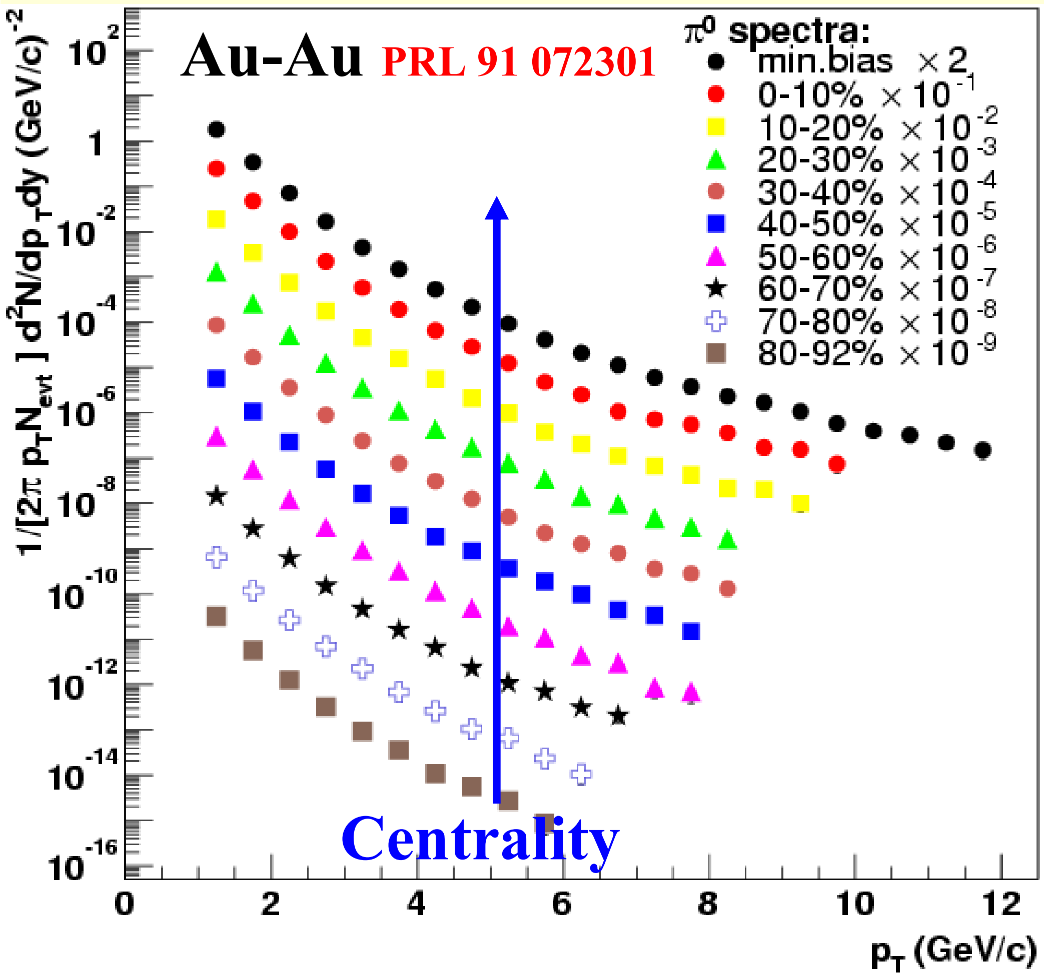
pQCD works very well!

Large contribution from gluon fragmentation.

Calculations with different (gluon) FF's
(Regions indicate scale uncertainty)

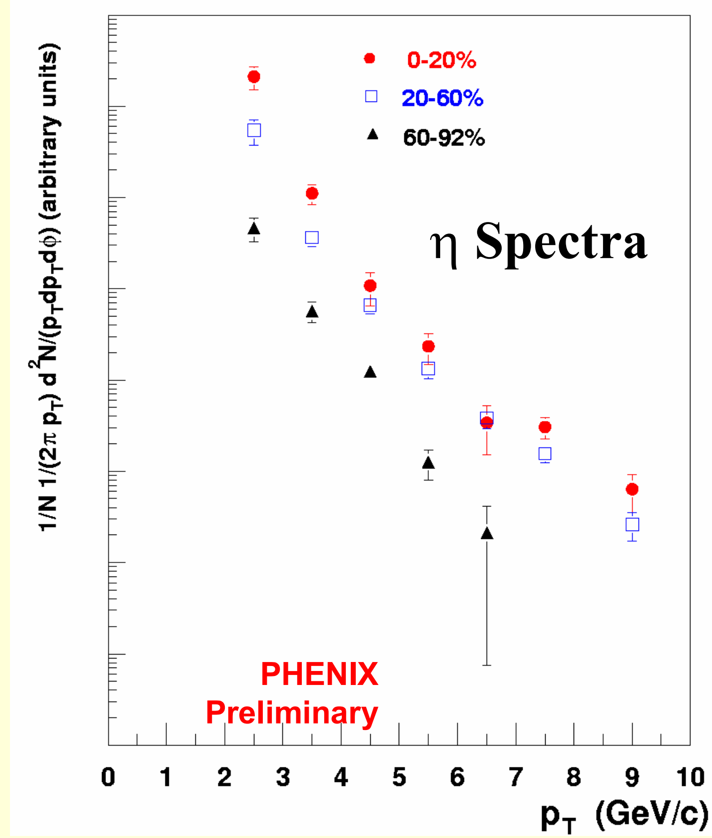


RHIC: π^0 and η - On the way to Measuring Direct γ in $\sqrt{s}$=200 GeV/c Au+Au collisions



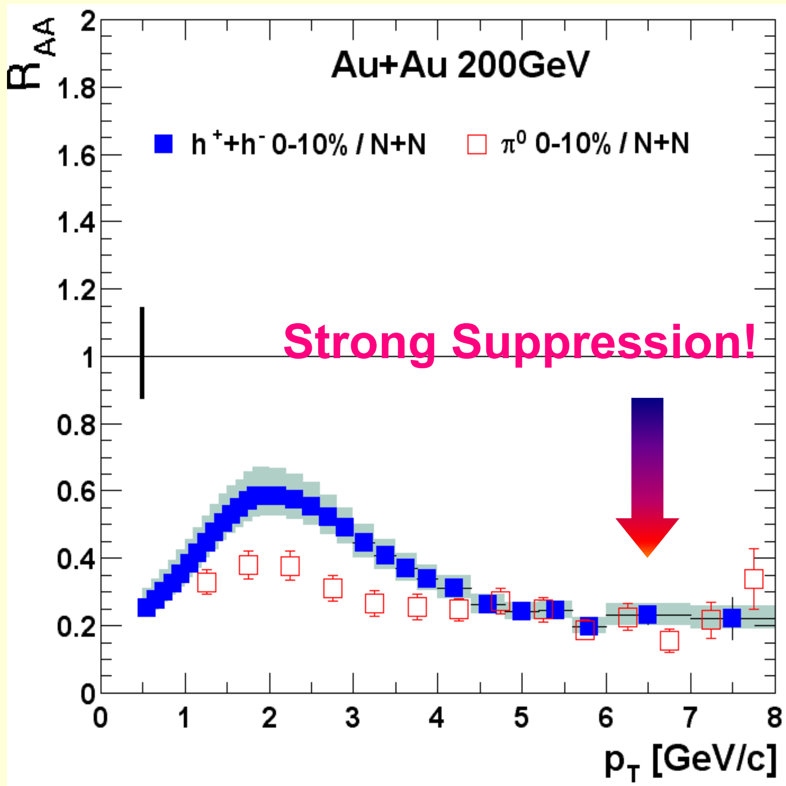
Measure π^0 and η distributions-

- Input to MC to predict decay γ
- Compare measured γ to decay γ to extract direct γ yield



Centrality Dependence R_{AA} for π^0 and charged hadron

$$R_{AA} = \frac{Yield_{AuAu} / \langle N_{binary} \rangle_{AuAu}}{Yield_{pp}}$$



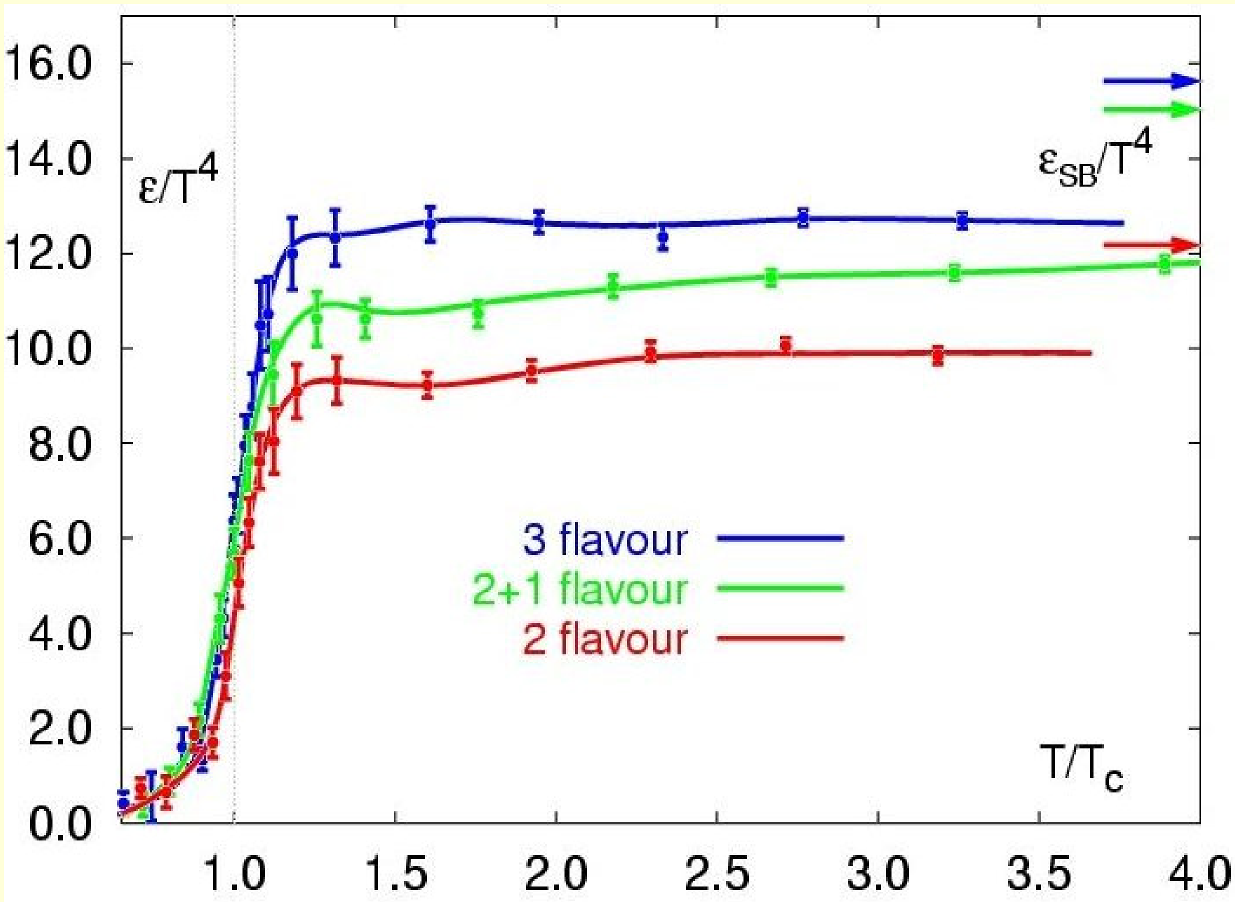
PHENIX AuAu 200 GeV
π^0 data: PRL 91 (2003) 072301.
charged hadron: PRC 69 (2004) 034909.

Suppression increases with increasing nuclear overlap volume.
Increasing density and pathlength.

- Large suppression implies large energy loss, implies high gluon densities $dN_g/dy \sim 1000$
- Implies large energy density (as well as e.g. E_T measurements) $\varepsilon > 5$ GeV/fm^3 well above critical energy density $\varepsilon_{crit} \sim 1$ GeV/fm^3

(Difference between π^0 and charged hadrons due to contributions from protons and kaons)

Deconfinement and High-Energy Nuclear Collisions



170 MeV

Lattice QCD predicts a sharp rise in the number of degrees of freedom (naively thought of as hadrons to quarks and gluons), the deconfinement phase transition.

Ideally, a combination of energy density and temperature measurements (thermal γ radiation) could map out the transition.

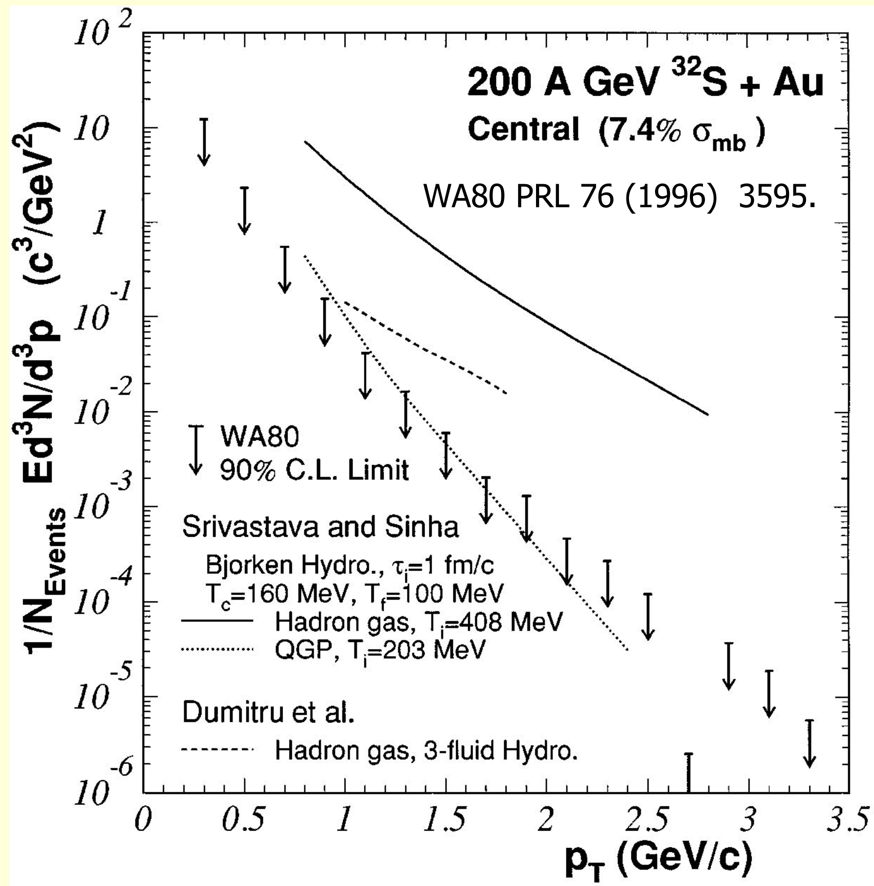
Early γ Expectations and First HI Results

- Initial Expectations (pre-experiment):
  - * Chiral symmetry restored, quark masses ~0
  - * Lots of q+g scatterings
  - * QM rates greater than HM (false)

Expect lots of Thermal γ Radiation as a signature of Quark Gluon Plasma!

- No γ excess observed in S+Au @SPS
  - * If thermalized, result implies "low" initial Temperature.
  - * Given large initial energy density, result implies large # d.o.f. As in a QGP!

Lack of Thermal γ is a signature of QGP!



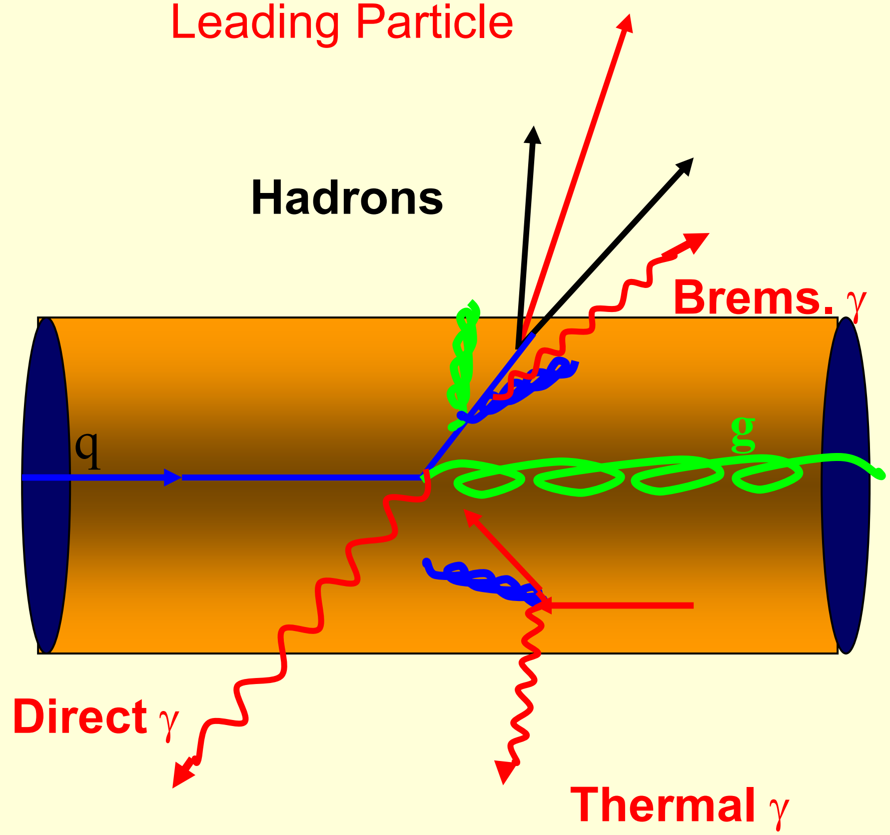
But a π+ρ hadron gas is too naïve - Must consider d.o.f. of full hadron mass spectrum…Hagedorn Bootstrap spectrum… But is 5-10 hadrons/fm^3 physical?

Further Illumination with Direct Photons

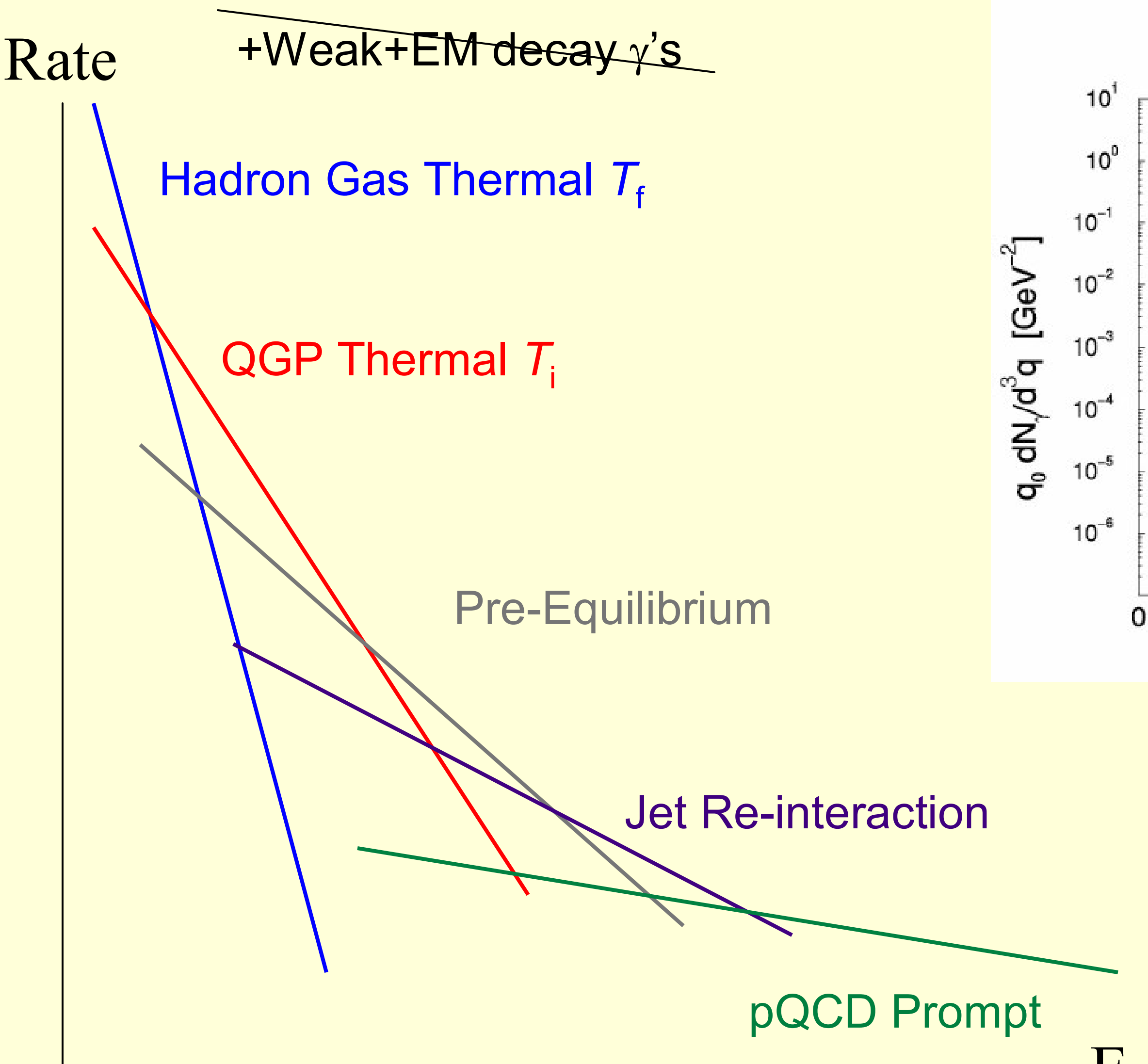
- High p_T direct γ produced in hard q-g Compton-like scatterings. Sensitive to PDFs, (especially gluons).

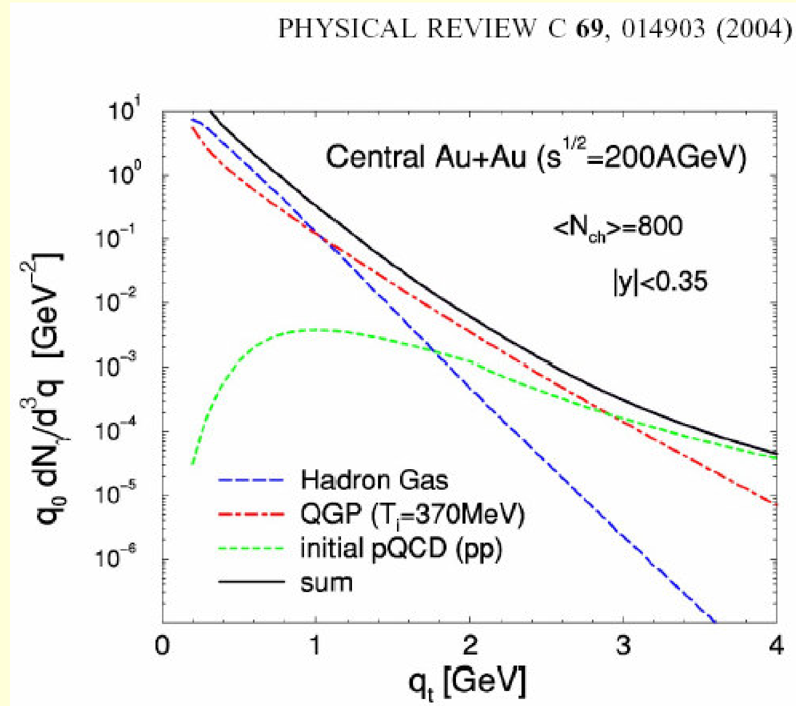
- In the HI case, γ from initial hard scattering escape. Can be used to tag recoiling jet to study jet energy loss ("Jet Quenching"), which may produce additional Brems. γ's.

- Additional thermal γ's produced in scatterings in QGP or hadronic phase of collision.
- If "Gluon Saturation" occurs, initial γ (and π^0) will be suppressed.
- With parton Eloss, the fragmentation contribution could also be suppressed.



Photons: Continum Spectrum with Many Sources

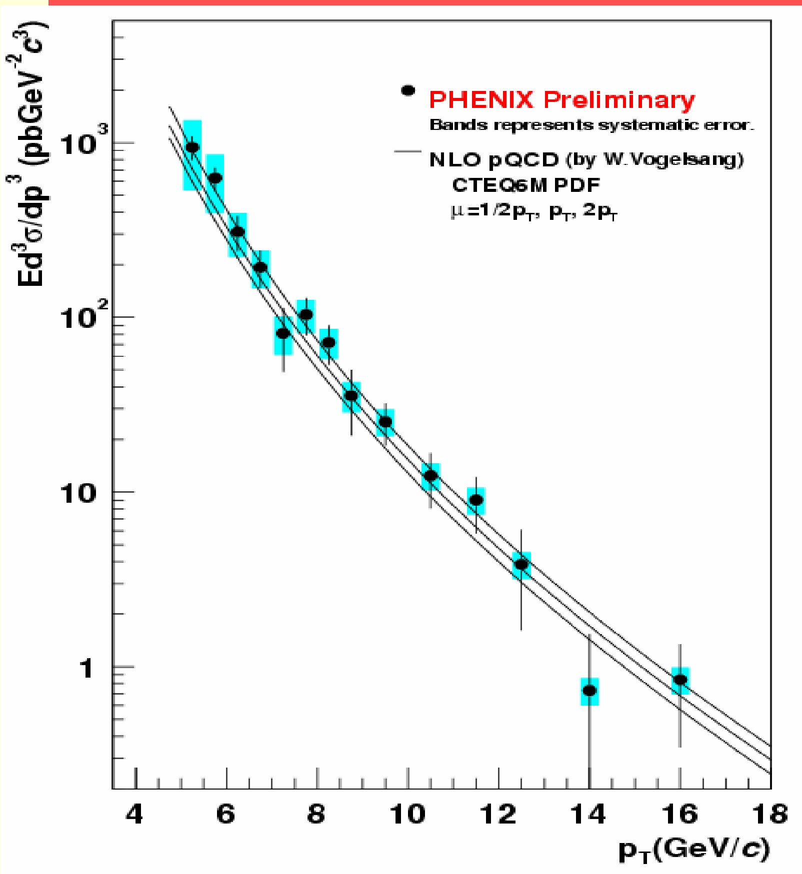


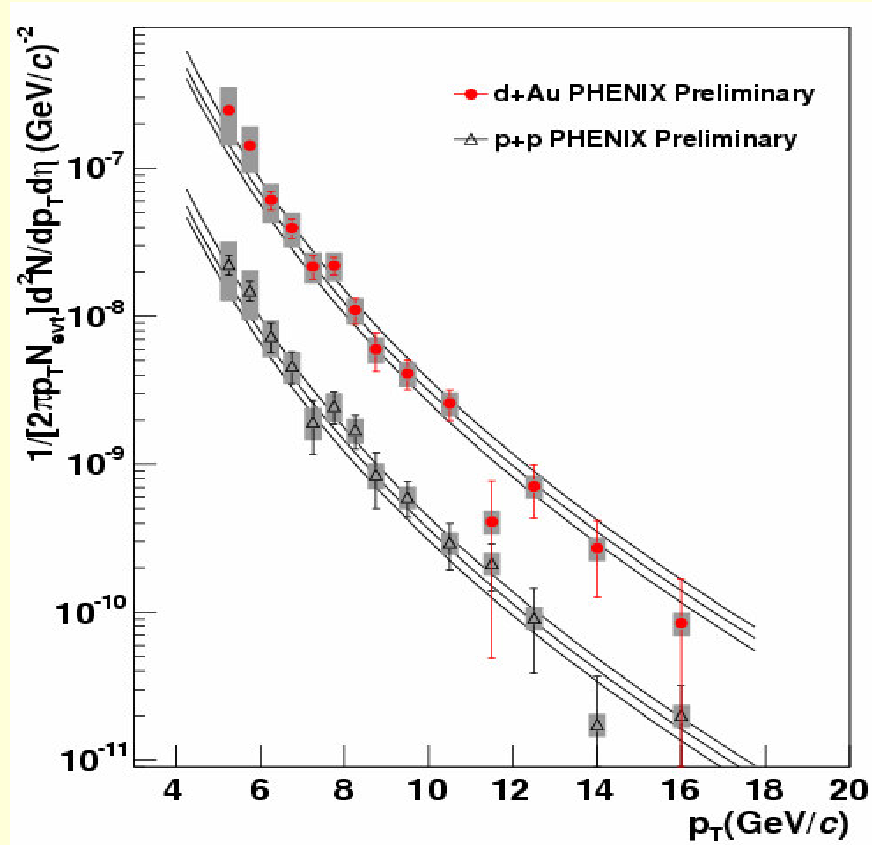


Turbide, Rapp, Gale

Final-state photons are the sum of emissions from the entire history of a nuclear collision.

High-p_T γ in p+p (d+Au) Collisions at 200 GeV/c

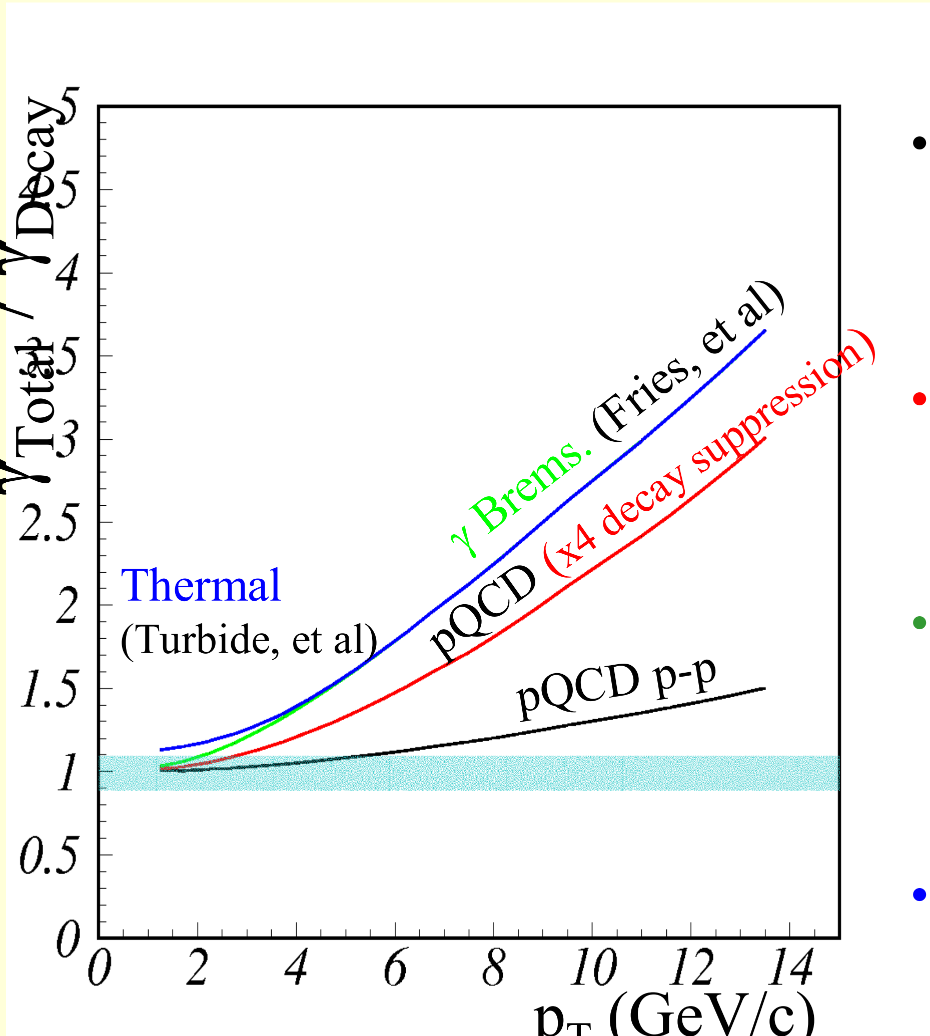




As observed for π^0 production, the preliminary direct photon measurement in p+p agrees with NLO pQCD calculations. The preliminary d+Au γ yield also agrees with <Ncoll> -scaled NLO pQCD calculation.

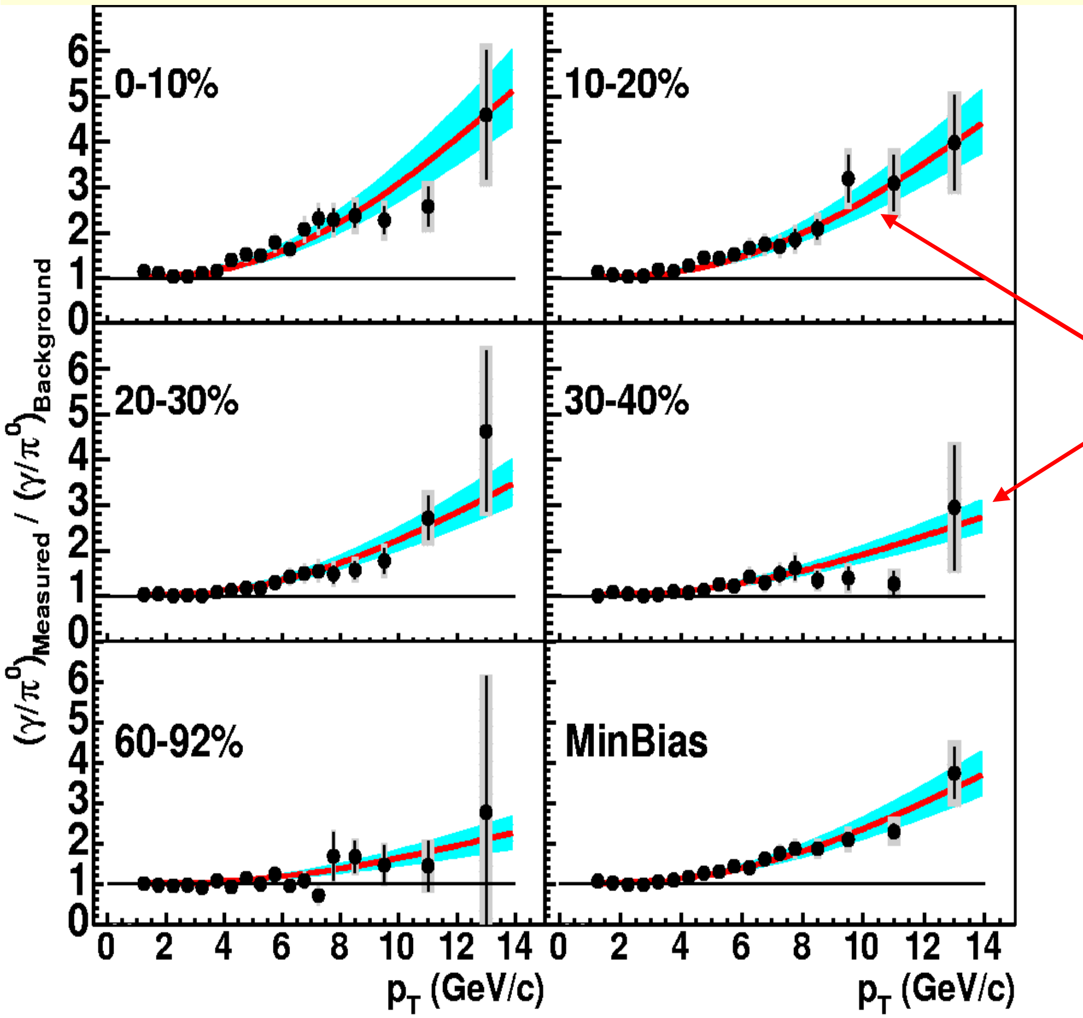
Baseline for comparison with Au+Au γ results.

Au+Au Direct Photon Expectations at RHIC



- pQCD γ from initial hard scattering is small relative to decay γ from pQCD π^0 prediction.
- But π^0 suppressed by ~4-5 in Central Au+Au due to parton energy loss - Decay γ suppressed by ~4-5.
- Additional γ radiation by Bremsstrahlung due to parton Eloss (or less γ from fragmenting partons after Eloss)?
- Low p_T γ from thermal radiation.

First RHIC Au+Au Direct Photon Results



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$$\left(\frac{\gamma^{Inclusive} / \pi^0}{\gamma^{Decay} / \pi^0} \right) \approx \frac{\gamma^{Decay} + \gamma^{Direct}}{\gamma^{Decay}}$$

$$1 + (\gamma^{pQCD} / \gamma^{Decay})$$

- Direct γ excess consistent with NLO pQCD p+p predictions, scaled by the number of binary collisions.
- Suppression of high-p_T π^0 in nuclear collisions at RHIC greatly increases $\gamma^{Direct}/\gamma^{Decay}$, making direct photons much easier to measure!
- Fragmentation?, Bremsstrahlung?, Thermal?

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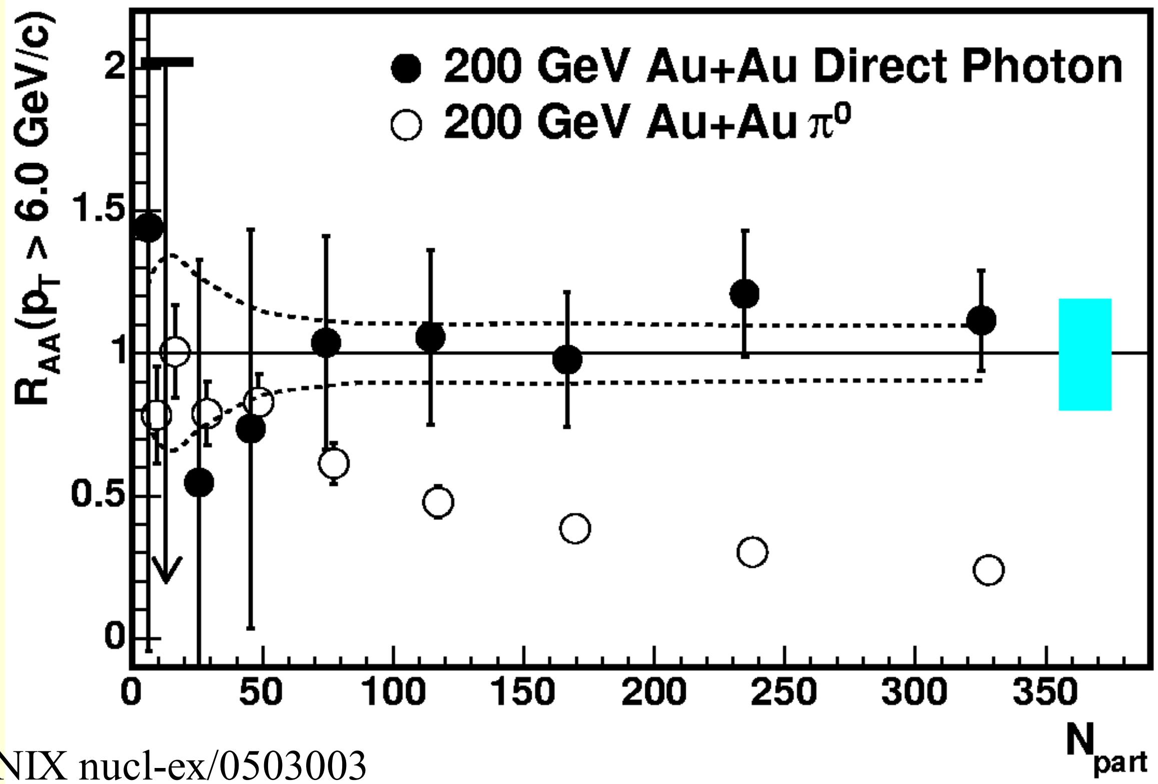
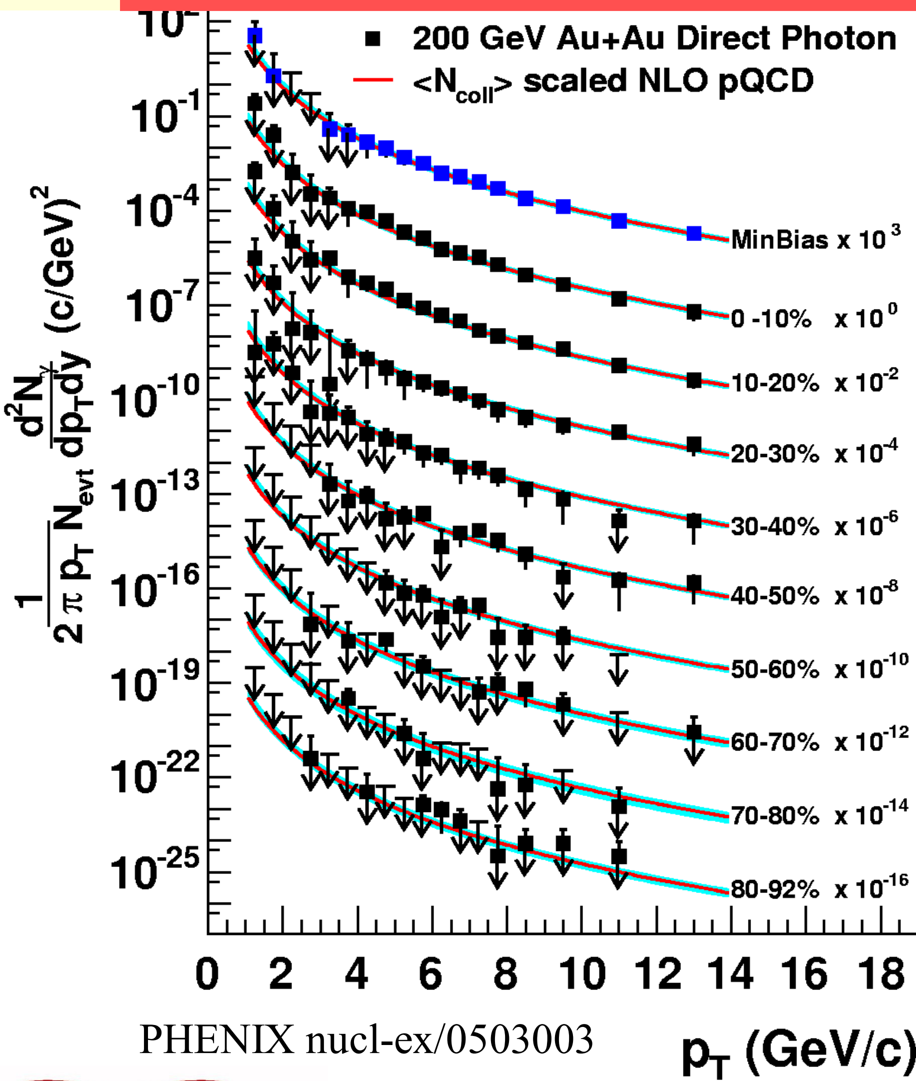
Centrality Dependence of High p_T Direct Photons



PHENIX nucl-ex/0503003

- Trend of γ yield with centrality (impact parameter) follows expected binary collision scaling behavior (=constant) and agrees with pQCD (=1).
- **Direct γ are not suppressed - strong evidence that hadron suppression is due to final state, i.e. parton energy loss.**

Centrality Dependence of Direct Photons



PHENIX nucl-ex/0503003

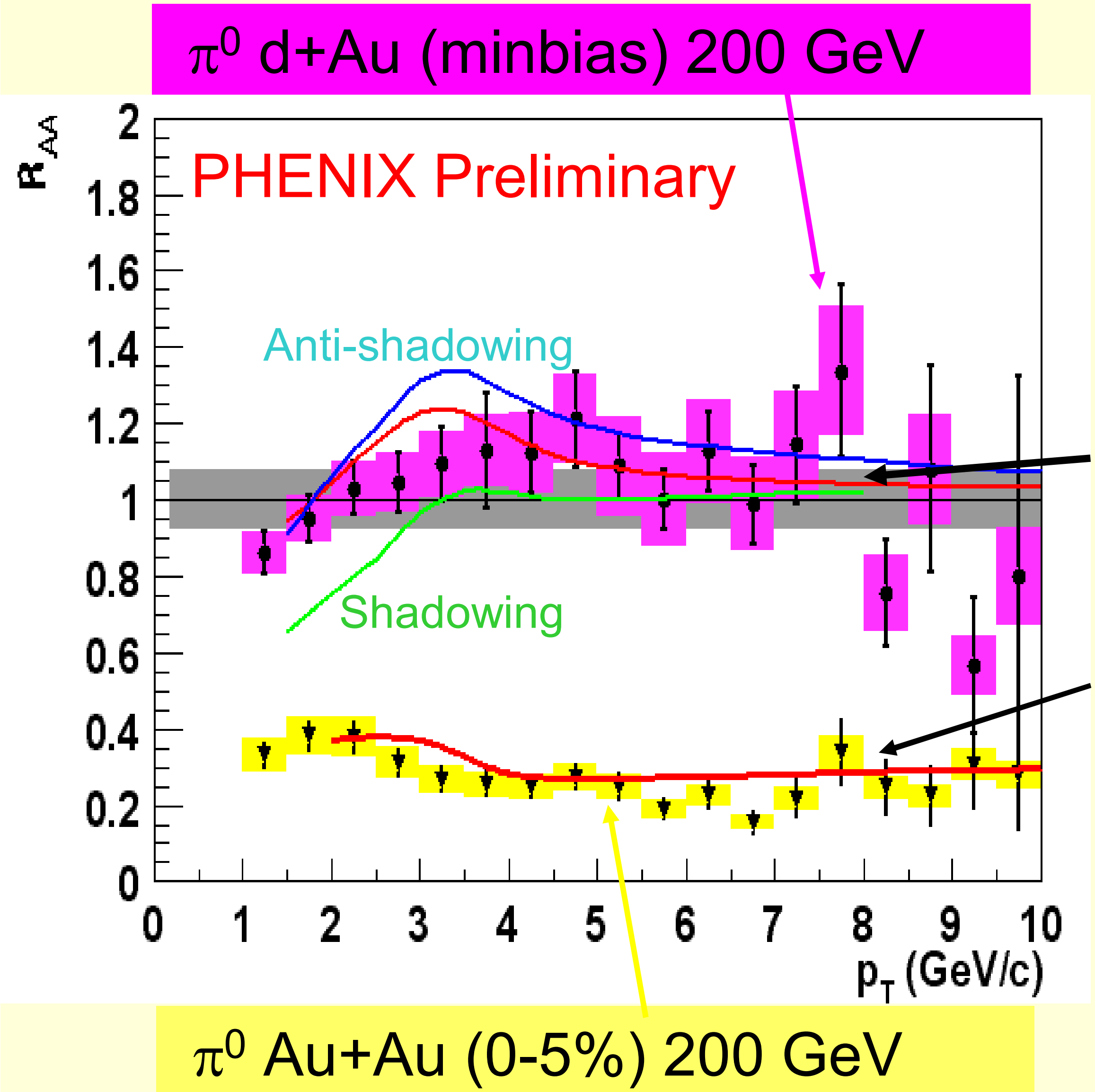
- Within errors $\langle N_{coll} \rangle$ scaled NLO pQCD describes γ yield even to low p_T
- Need to improve errors on p+p and Au+Au measurements to search for deviations from pQCD as evidence for other contributions, e.g. thermal γ

Summary and future plans

- NLO pQCD predictions provide good description of γ and π^0 production in p+p at sqrt(s)=200GeV
- π^0 production is strongly suppressed in Au+Au - "jet quenching"
- Direct γ in Au+Au is consistent with pQCD prediction.
  - Strong confirmation that hadron suppression is due to parton energy loss in dense produced matter (QGP) rather than modification of PDFs (gluon saturation).
  - But >30% of direct γ from parton fragmentation - Suppressed with parton energy loss? But enhanced γ bremsstrahlung during parton energy loss?
  - k_T broadening (Cronin effect)? Thermal γ's?
- Future Improvements:
  - Larger data sets for Au+Au (~x20) and p+p (~x15)
  - Greater use of tracking (electrons from conversions), convertor runs
  - γ-jet studies for quantitative study of parton energy loss

BACKUP SLIDES

Data vs Theory : π^0



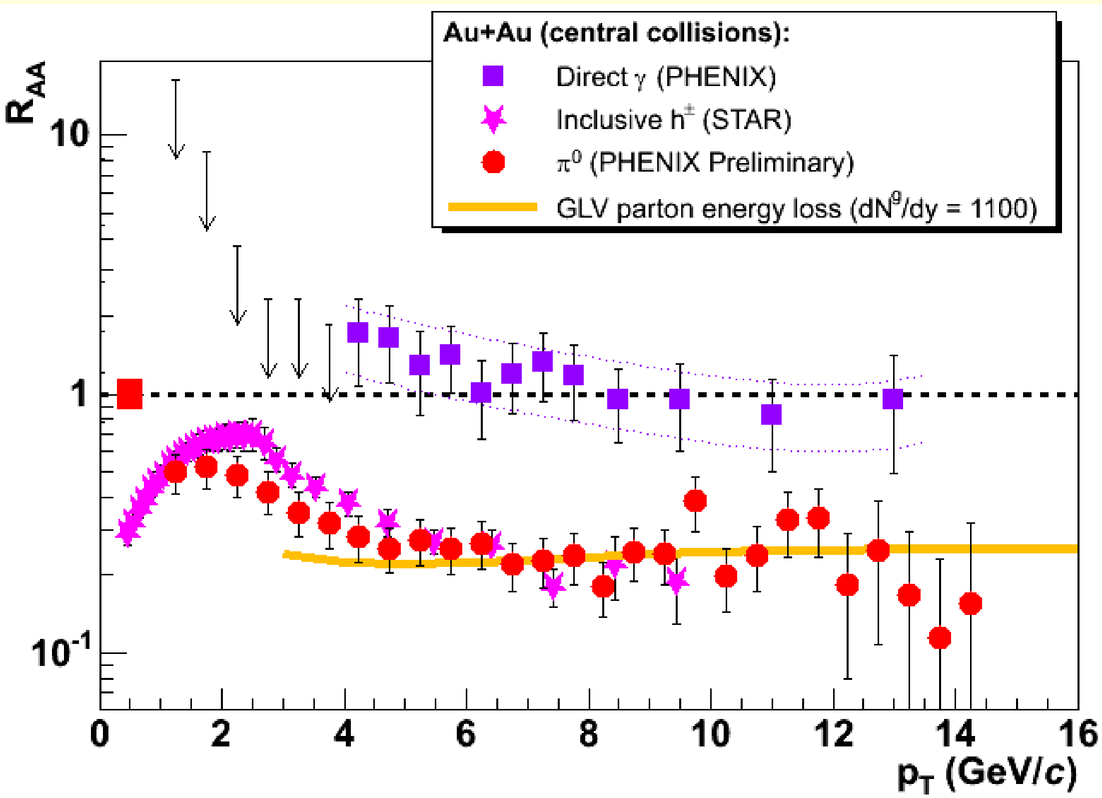
Energy loss + Shadowing + Cronin = flat R_{AA} Explains both AuAu and dAu

Can dAu and AuAu central dependence also be explained?

d+Au: I. Vitev, nucl-th/0302002 and private communication.

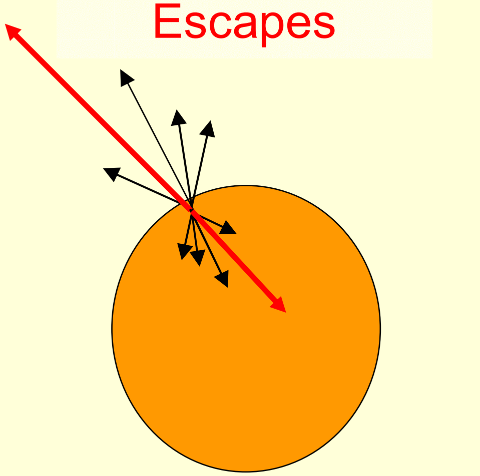
Au+Au: I. Vitev and M. Gyulassy, hep-ph/0208108, to appear in Nucl. Phys. A; M. Gyulassy, P. Levai and I. Vitev, Nucl. Phys. B 594, p. 371 (2001).

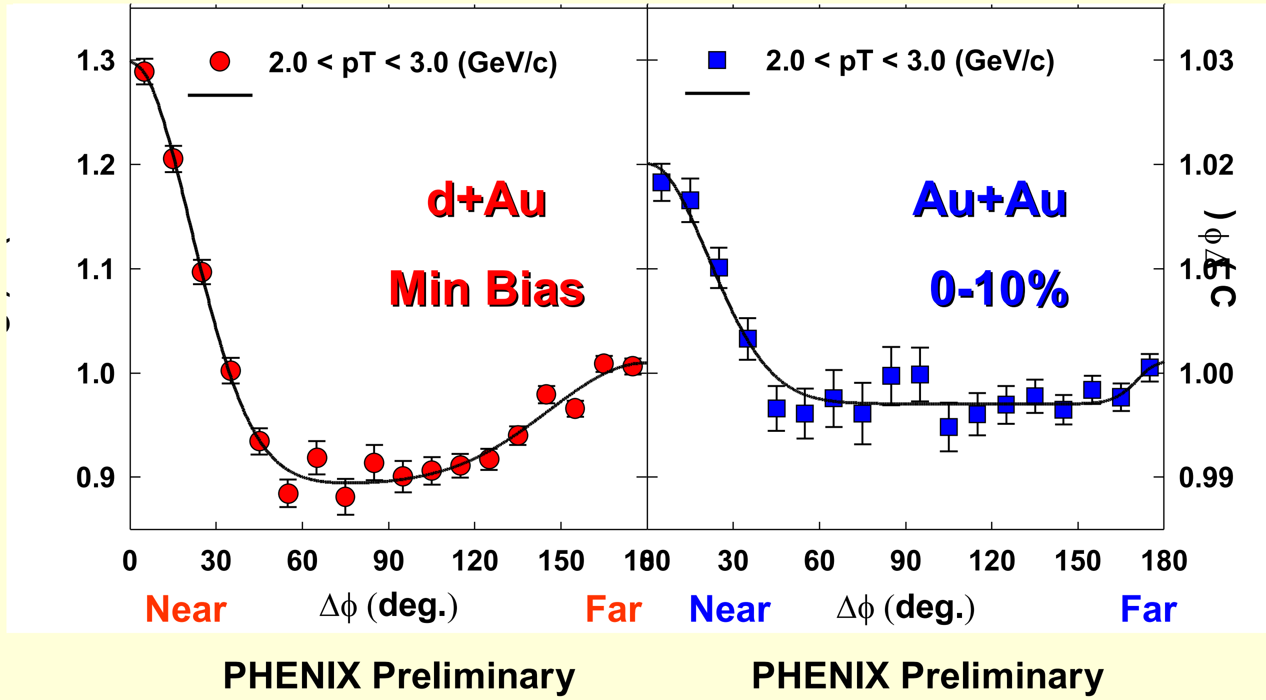
A Closer Look at p_T Dependence of Direct Photons and π^0 Production for Central Au+Au



- High p_T γ yield consistent with binary scaled pQCD in contrast to factor of 5 suppression of π^0 & hadron yields.
- **Direct γ are not suppressed - strong evidence that hadron suppression is due to final state, i.e. parton energy loss.**
- Errors don't preclude a thermal γ contribution at low p_T

The "Away-Side" Jet: 2-Particle Correlations





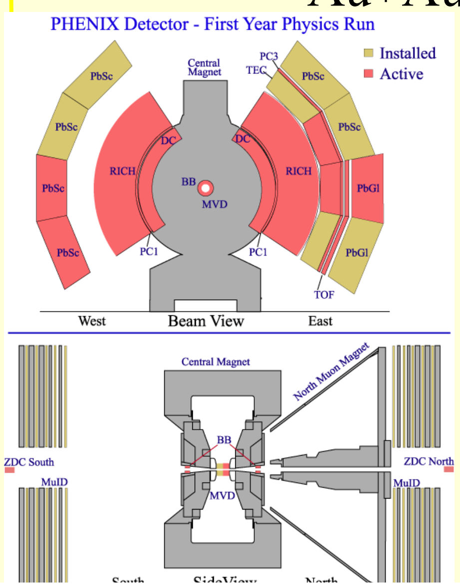
Parton exiting on the periphery of the collision zone should survive while partner parton propagating through the collision zone is more likely to be absorbed.

- Peripheral Au+Au similar to d+Au
- Central Au+Au shows distinct reduction in far side correlation.
- **Away-side Jet is suppressed in Central Au+Au - Further indication of suppression by produced medium.**

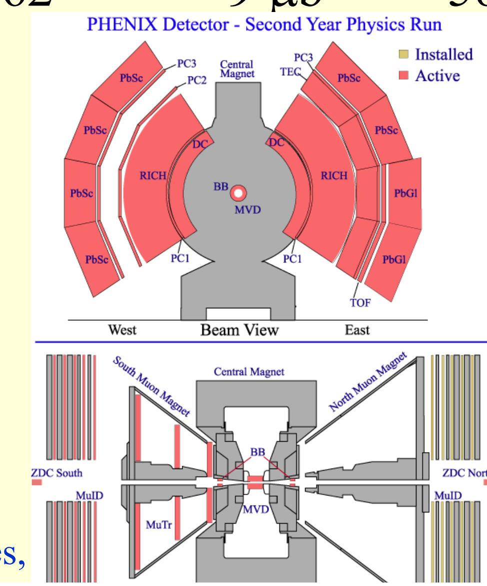
Run-1 to Run-4 Capsule History

Run	Year	Species	$s^{1/2}$ [GeV]	∫Ldt	N_{tot}	p-p Equivalent	Data Size
01	2000	Au+Au	130	1 μb^{-1}	10M	0.04 pb^{-1}	3 TB
02	2001/2002	Au+Au	200	24 μb^{-1}	170M	1.0 pb^{-1}	10 TB
		p+p	200	0.15 pb^{-1}	3.7G	0.15 pb^{-1}	20 TB
03	2002/2003	d+Au	200	2.74 nb^{-1}	5.5G	1.1 pb^{-1}	46 TB
		p+p	200	0.35 pb^{-1}	6.6G	0.35 pb^{-1}	35 TB
04	2003/2004	Au+Au	200	241 μb^{-1}	1.5G	10.0 pb^{-1}	270 TB
		Au+Au	62	9 μb^{-1}	58M	0.36 pb^{-1}	10 TB

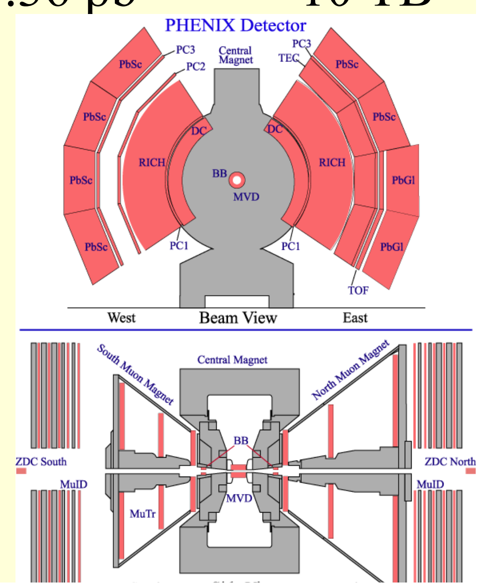
Run-1



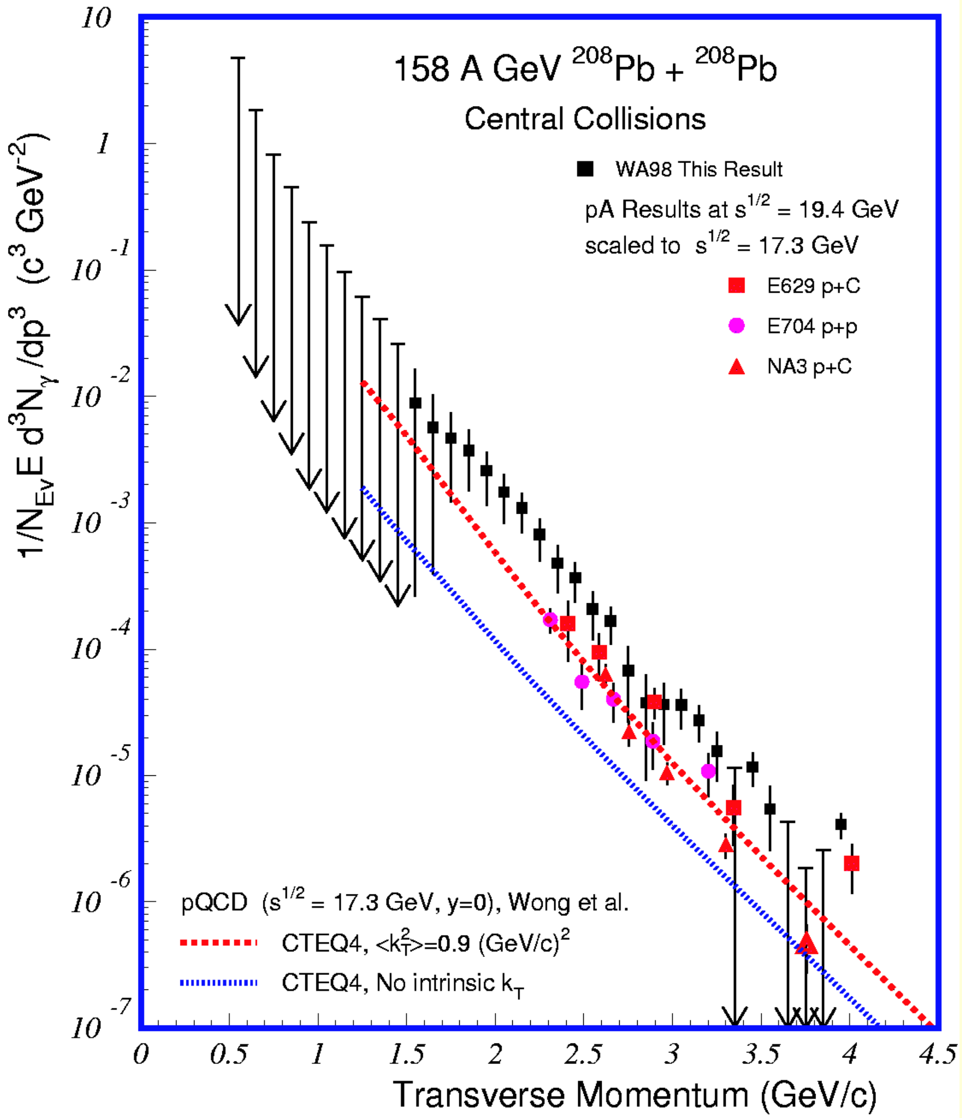
Run-2



Run-3



Direct γ: Comparison to pQCD Calculation



- NLO pQCD calculations factor of 2-5 below $s^{1/2}$ =19.4 GeV p-induced prompt γ results.
- But p-induced can be reproduced by effective NLO (K-factor introduced) if intrinsic k_T is included.
- Same calculation at $s^{1/2}$=17.3 GeV reproduces p-induced result scaled to $s^{1/2}$ =17.3 GeV
- Similar γ spectrum shape for Pb case, but factor ~2-3 enhanced yield.

WA98 nucl-ex/0006007, PRL 85 (2000) 3595.