Direct Photons in Relativistic Heavy Ion Collisions

T.C. Awes, ORNL

Workshop on QCD, Confinement, and Heavy Ion Reactions
Tucson, AZ, October 29, 2003

"The virtue of γs (and π^0's)"

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,…**

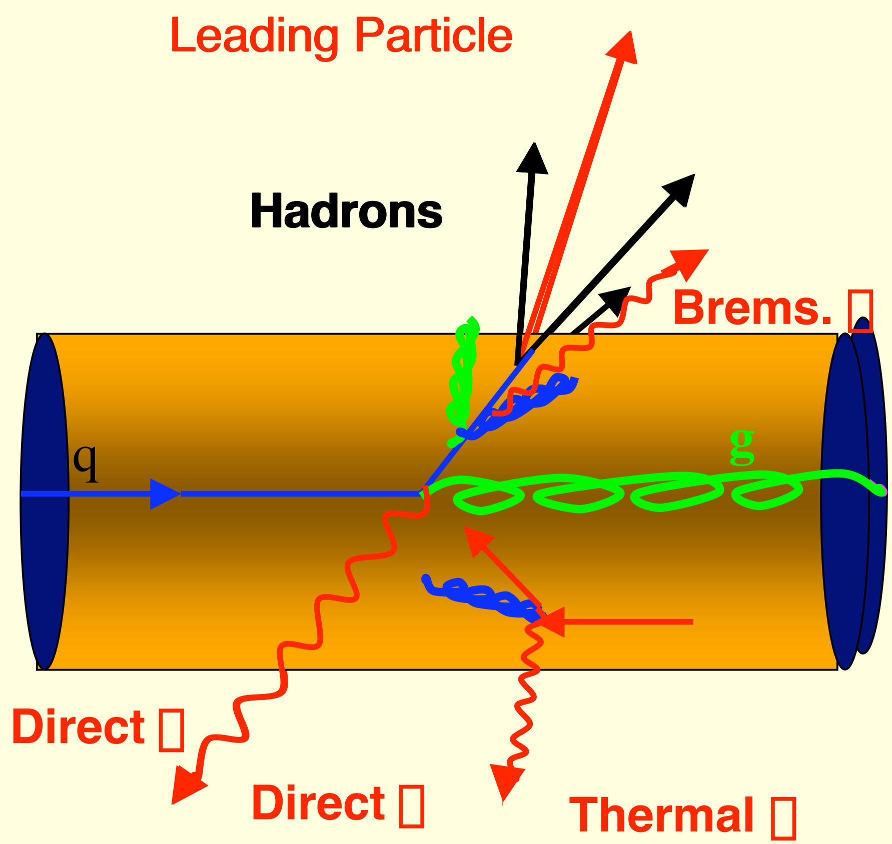
π^0's produced in the final state: Rescattering (low p_T), Absorption, k_T Broadening, Jet/Parton Energy Loss ,…

Experimental virtues (calorimeter measurement):

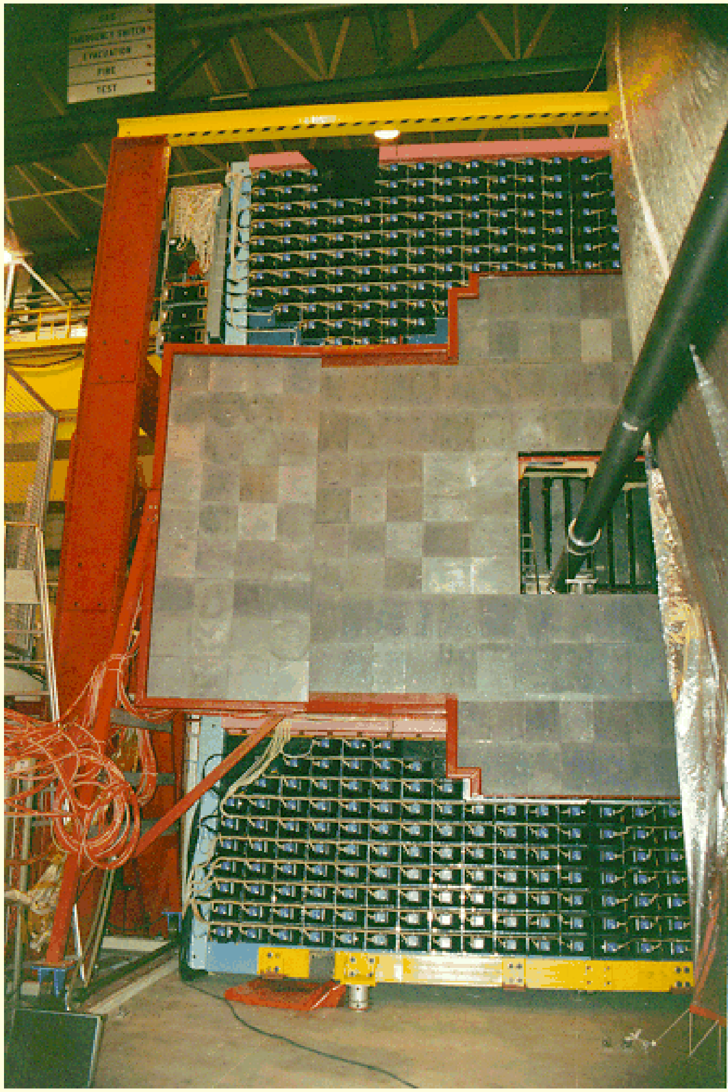
- **Measure γ and π^0 in same detector**
- **Identified particles to very high p_T**
- **π^0's abundantly produced**
- **π^0 mass provides calibration check**

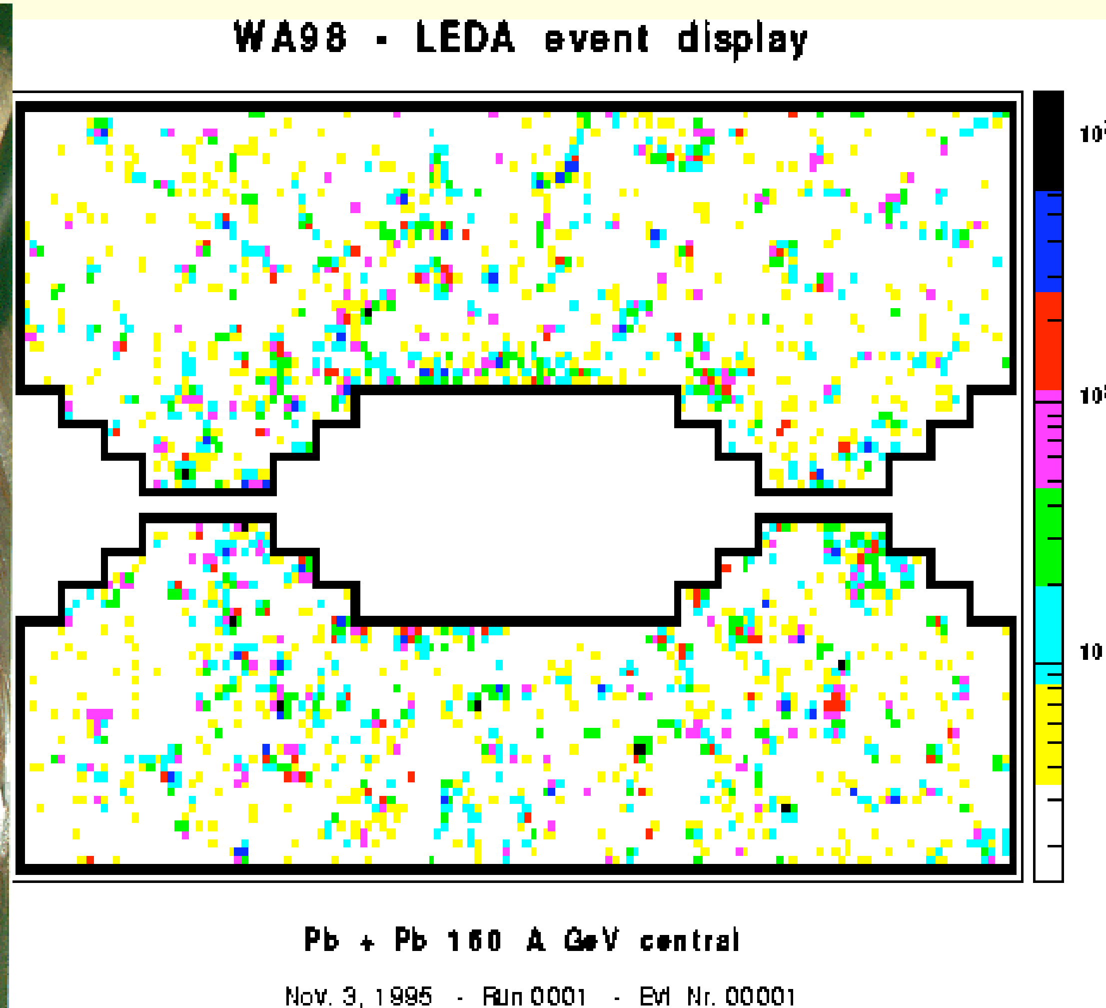
Direct Photon Production

- High p_T direct γ produced in hard q-g Compton-like scatterings. Sensitive to PDFs, (especially gluon).
- In the HI case, γ from initial hard scattering 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.

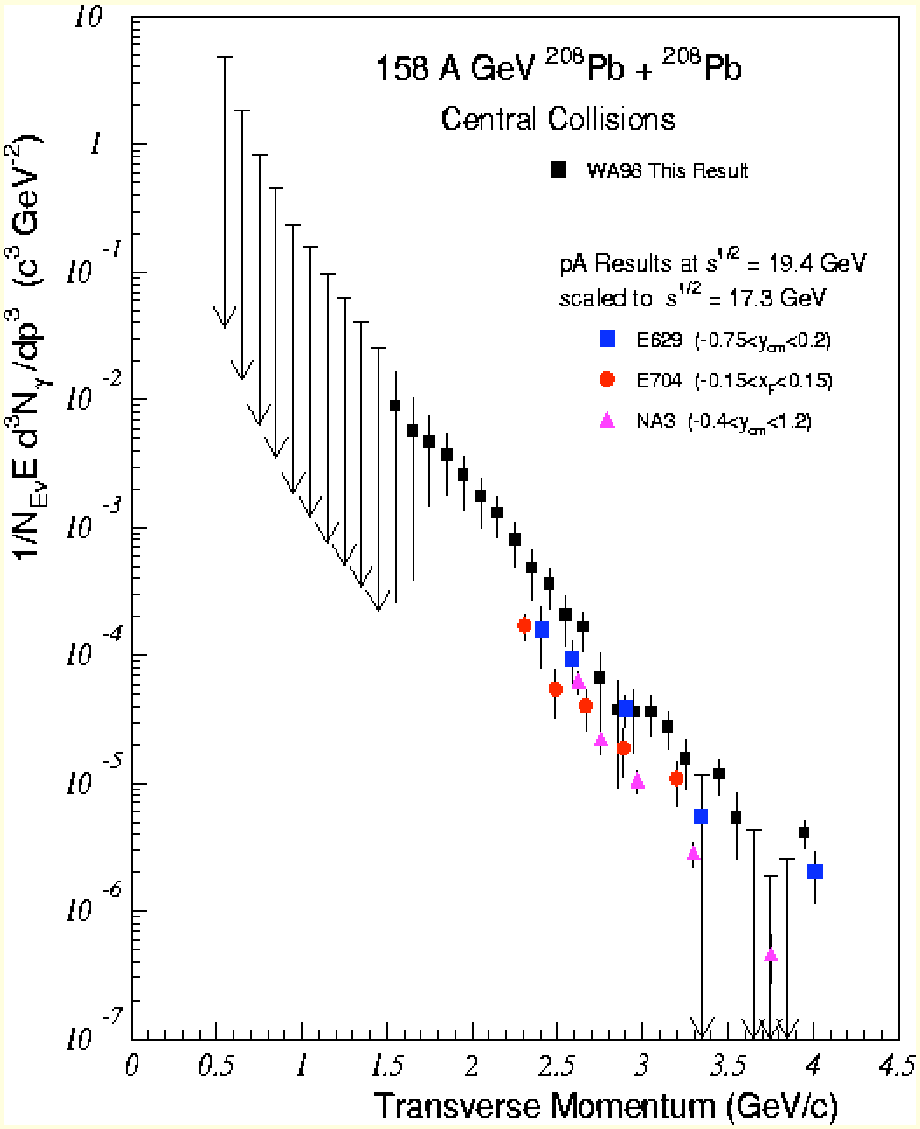


π^0 and η in WA98 at SPS: Pb+Pb 158AGeV





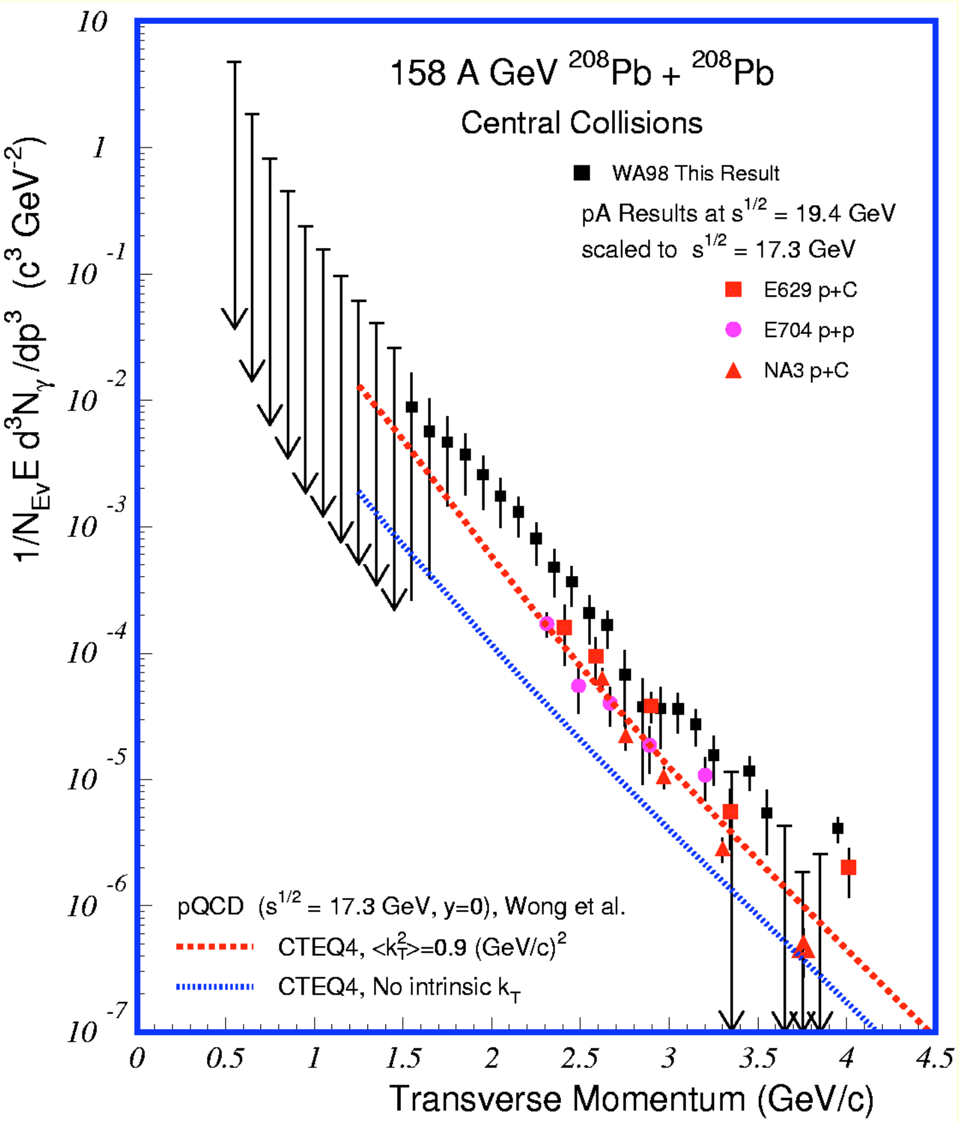
Central Pb+Pb Direct □ p_T Spectrum



- Compare to proton-induced prompt □results:
  - Assume hard process - scale with the number of binary collisions (=660 for central).
  - Assume invariant yield has form $f(x_T)/s^2$ where $x_T=2p_T/s^{1/2}$ for $s^{1/2}$-scaling.
- Factor ~2 variation in p-induced results.
- For Pb+Pb, similar □ spectral shape, but factor ~2-3 enhanced yield.

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

Direct Comparison to pQCD Calculation



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

- NLO pQCD calculations factor of 2-5 below $s^{1/2}$ =19.4 GeV p-induced prompt 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 spectrum shape for Pb case, but factor ~2-3 enhanced yield.

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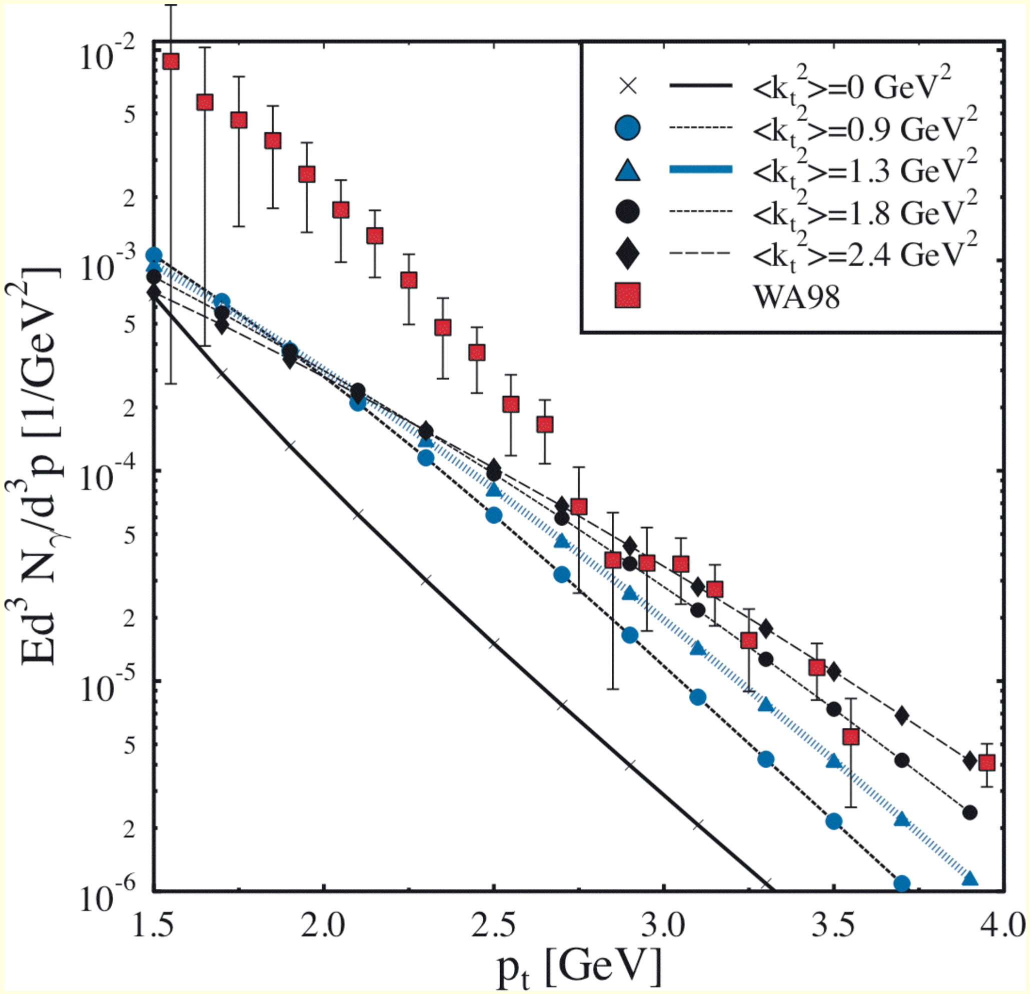
Photons - k_T Broadening



Dumitru et al., PRC64 054909.

- pQCD-calculations
  - * Fit intrinsic k_T in pp (E704) ($Q^2 = (2p_T)^2$)

  $< k_T^2 > \sim 1.3 - 1.5$ GeV^2

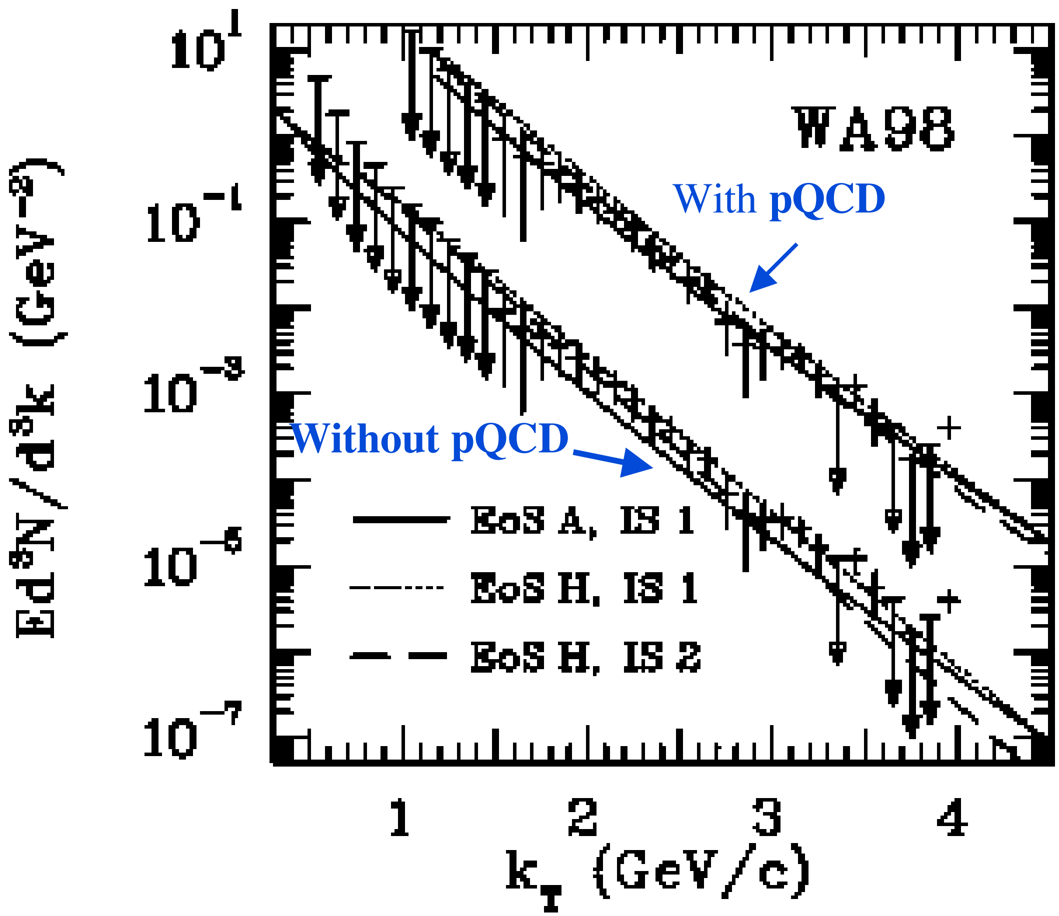
- k_T - broadening in Pb+Pb

  □$k_T^2 \sim 1$ GeV^2

  - * Magnitude "consistent" with expectations from pA

- Conclusion: Excess could be due to k_T- broadening...

Direct : Comparison to Hydro Model Calculations



P.Houvinen, et al., PLB 535(2002)109.

Full Hydro can describe ^{0} and with EOS with or without QGP

- **But need high initial temperature, well above T_C.**

Situation at SPS is unclear: Many sources of theoretical uncertainty:

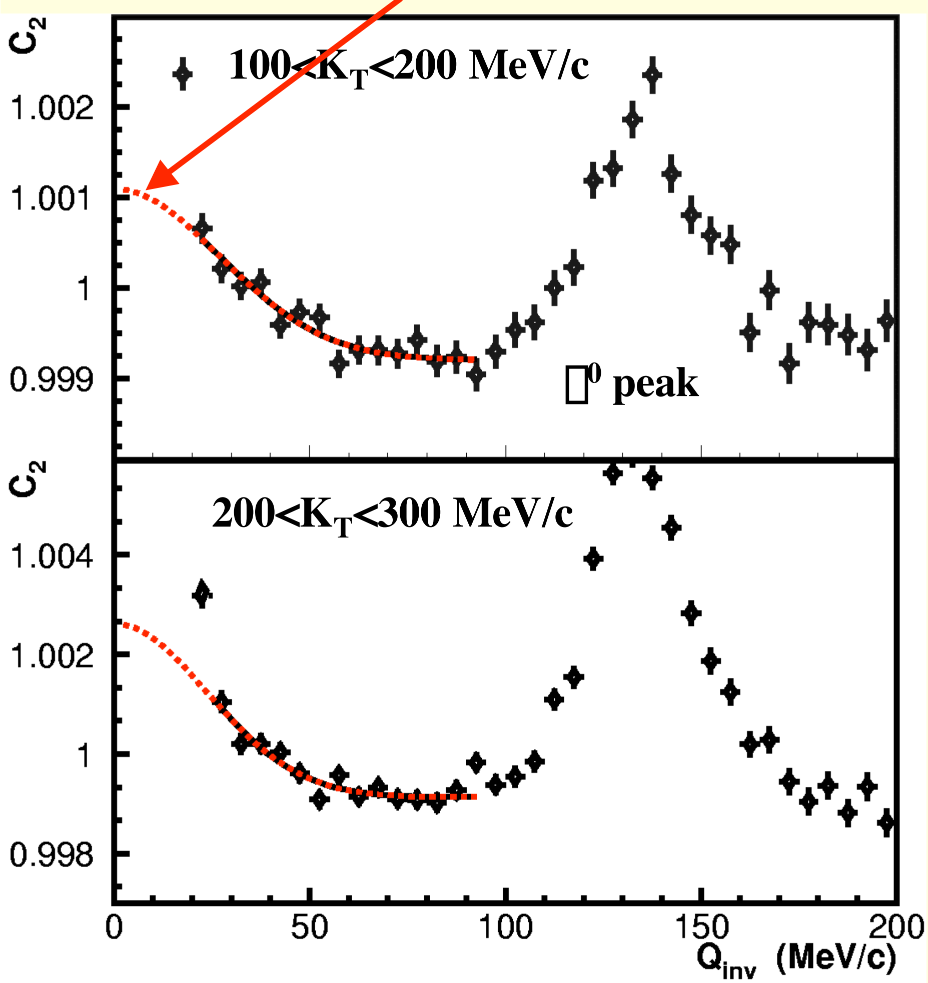
- intrinsic k_T, $k_{}$ broadening
- preequilibrium
- QM rates: (under control!)
- HM rates: in-medium masses
- Hydro evolution: flow

Need further experimental constraints:

- Hadron spectra
- dileptons (CERES,NA50)
- pA results (WA98)
- Results from RHIC

Direct γ Yield via γγ HBT Correlations: Pb+Pb@SPS

$C_2 = A[1 + \lambda \exp(-Q^2_{inv} R^2_{inv})]$



Pure BE effect - no Coulomb, no FSI

2λ = fraction of γ pairs which are Direct (2 polarizations)

Direct γ = $\sqrt{2\lambda}$ × Total γ

Only possible at low K_T since $Q_{inv} \sim K_T \times \Delta L$

For close shower separation ΔL background sources from:

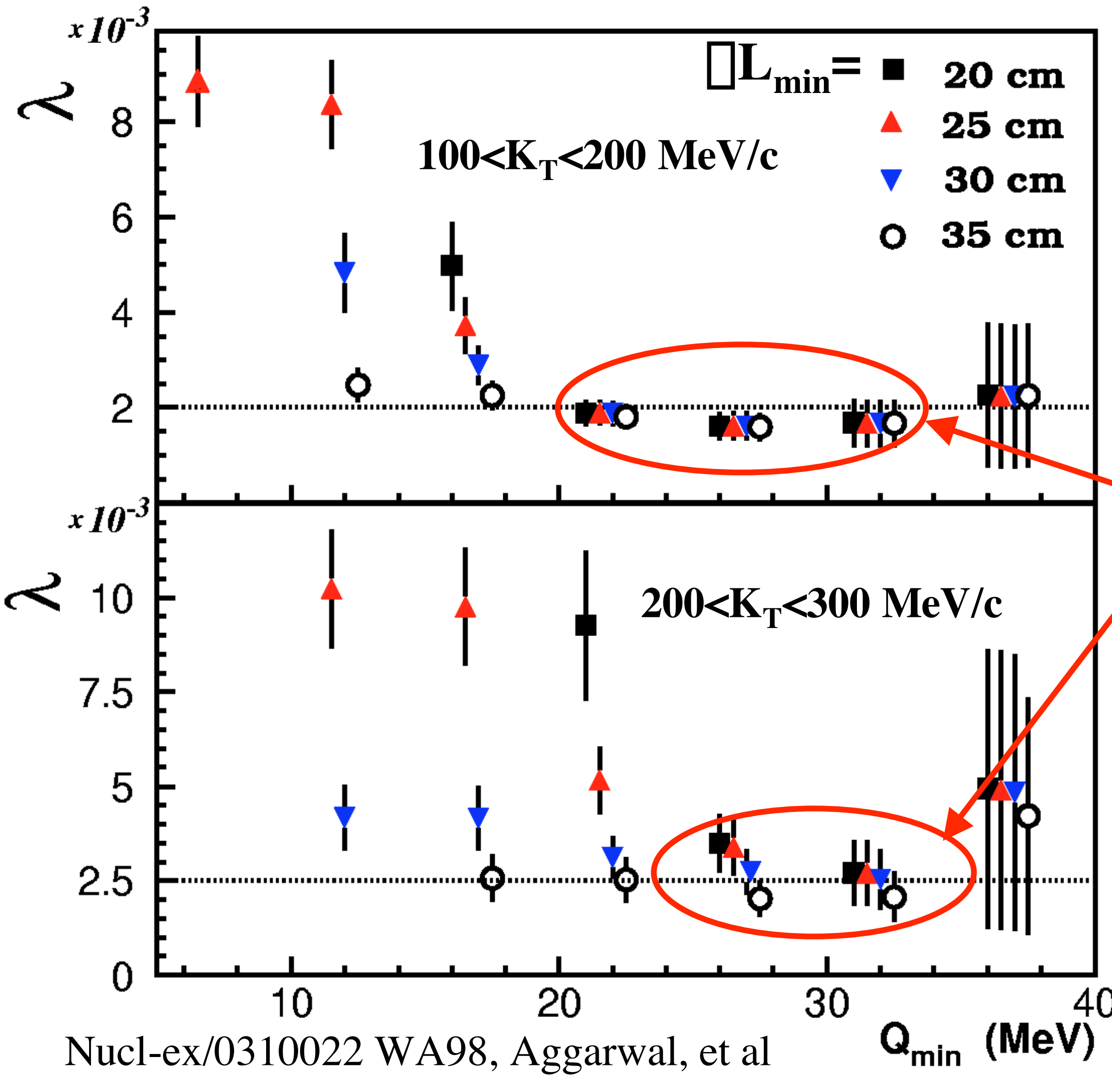
- **False splitting of showers**
- **Photon conversions**

Must make min distance cut ΔL_{min}

$K_T = |\vec{p}_1 + \vec{p}_2| / 2$

Nucl-ex/0310022 WA98, Aggarwal, et al
Analysis: D.Peressounko

□L$_{min}$ Dependence of □□ □Correlation Strength □



Nucl-ex/0310022 WA98, Aggarwal, et al

Since $Q_{inv} \sim K_T$ x □L$_{min}$ a cut on □L$_{min}$ has similar effect as restricting the fit to region above Q_{min}.

Stable fit results with □L$_{min}$ > 35cm cut or by restricting Q_{inv} fit region.
Similar result for $R_{inv.}$

Implies region free of background and detector effects.

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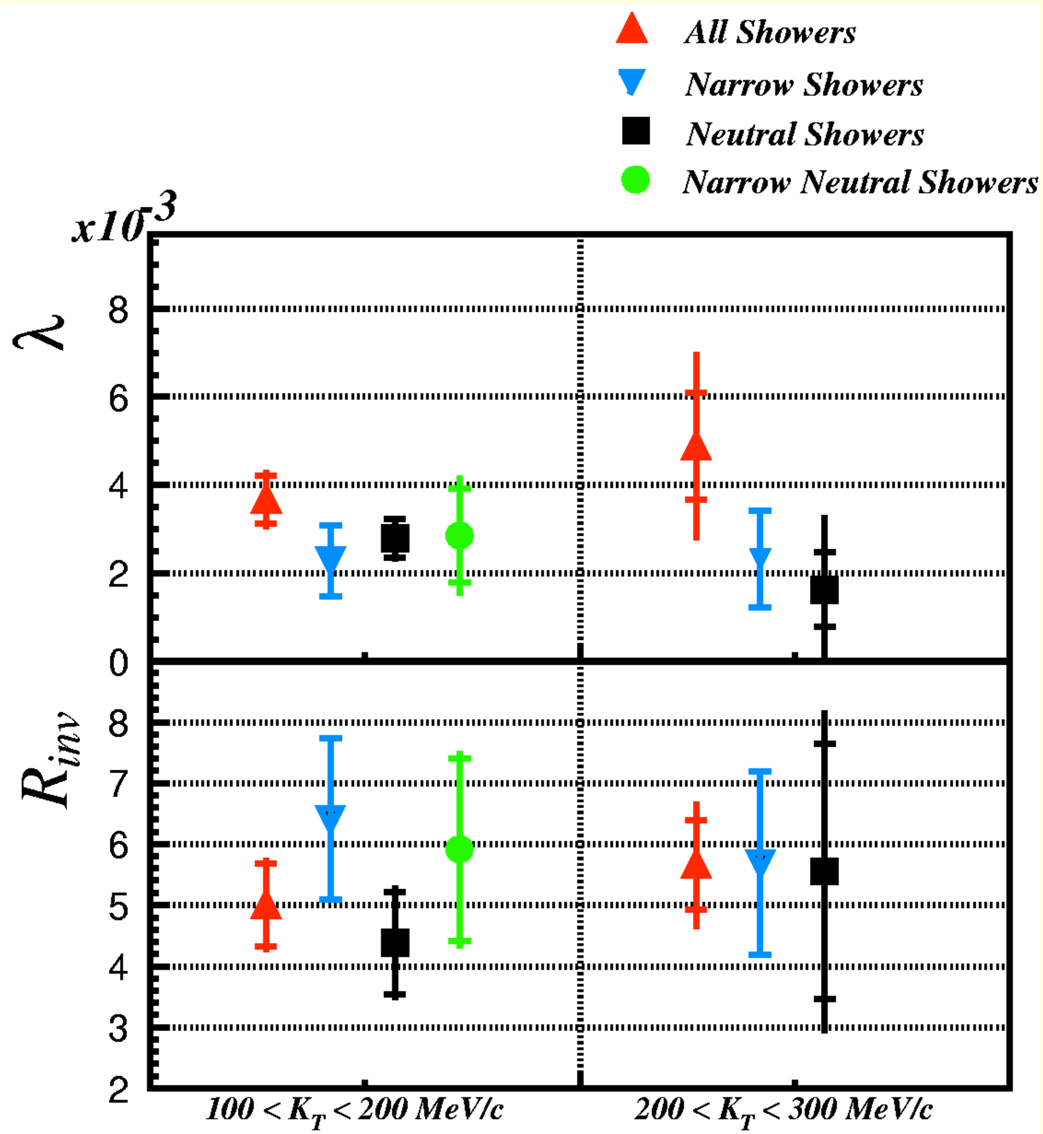
Dependence of HBT Parameters on PID



- Vary shower identification criteria to vary non- background fraction:
  - 37% and 22% charged bkgd for 2 K_T bins with All showers
  - 16% and 4% with Narrow showers
  - <2% with no CPV
- If correlation due to background, it should be strongly affected by PID cuts.
- Observe no dependence on PID cuts which indicates a true correlation.
- R_{inv} ~ 5-6 fm
- Compare $R_{inv}(\pi^-)$=6.6-7.1 fm

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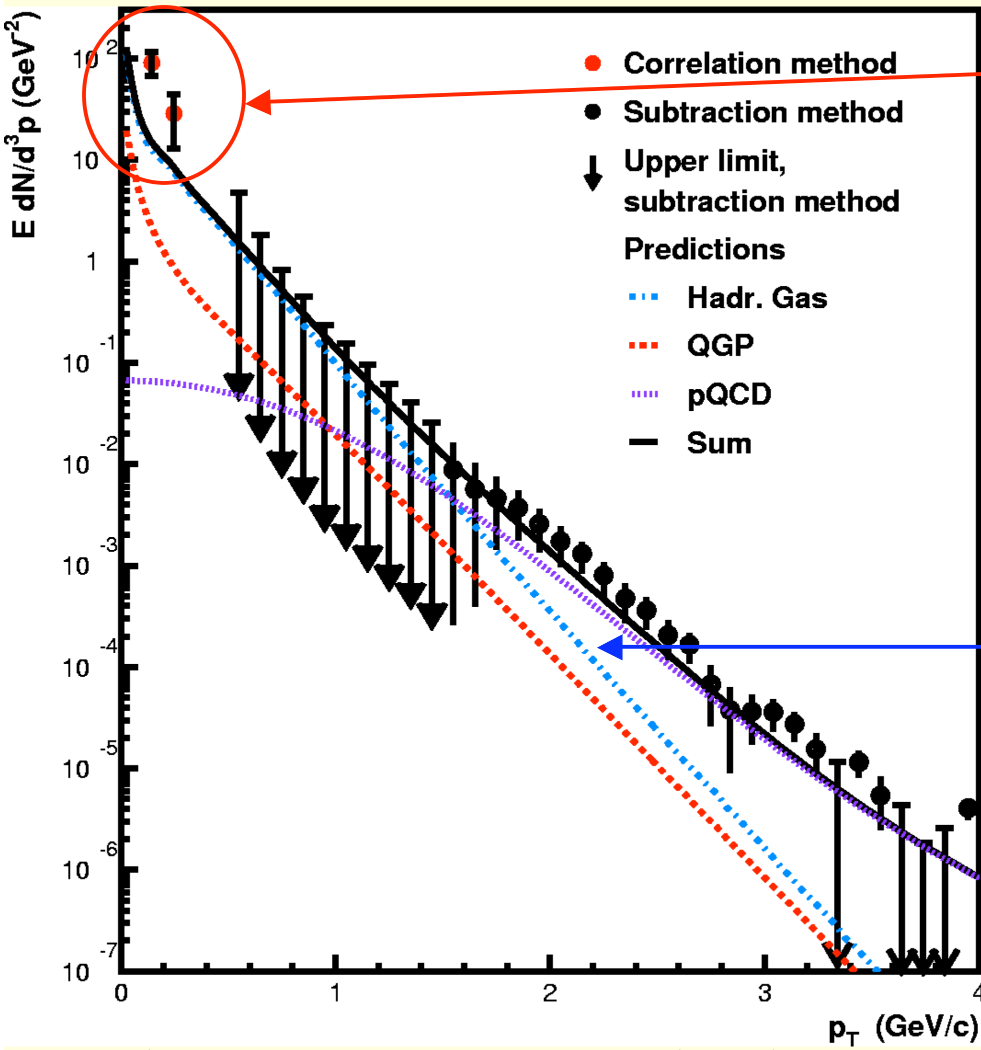
Direct □Yield via □□□HBT Correlations



Nucl-ex/0310022 WA98, Aggarwal, et al

Two new low p_T direct □points from □ of □□□correlation.

Fireball model predictions:
Turbide, Rapp, Gale hep-ph/0308085.
Latest in Hadronic rates, pQCD + k_T broadening, T_i=205 MeV, T_c=175MeV

Low p_T region dominated by Hadron Gas phase, but underpredicts measurements.

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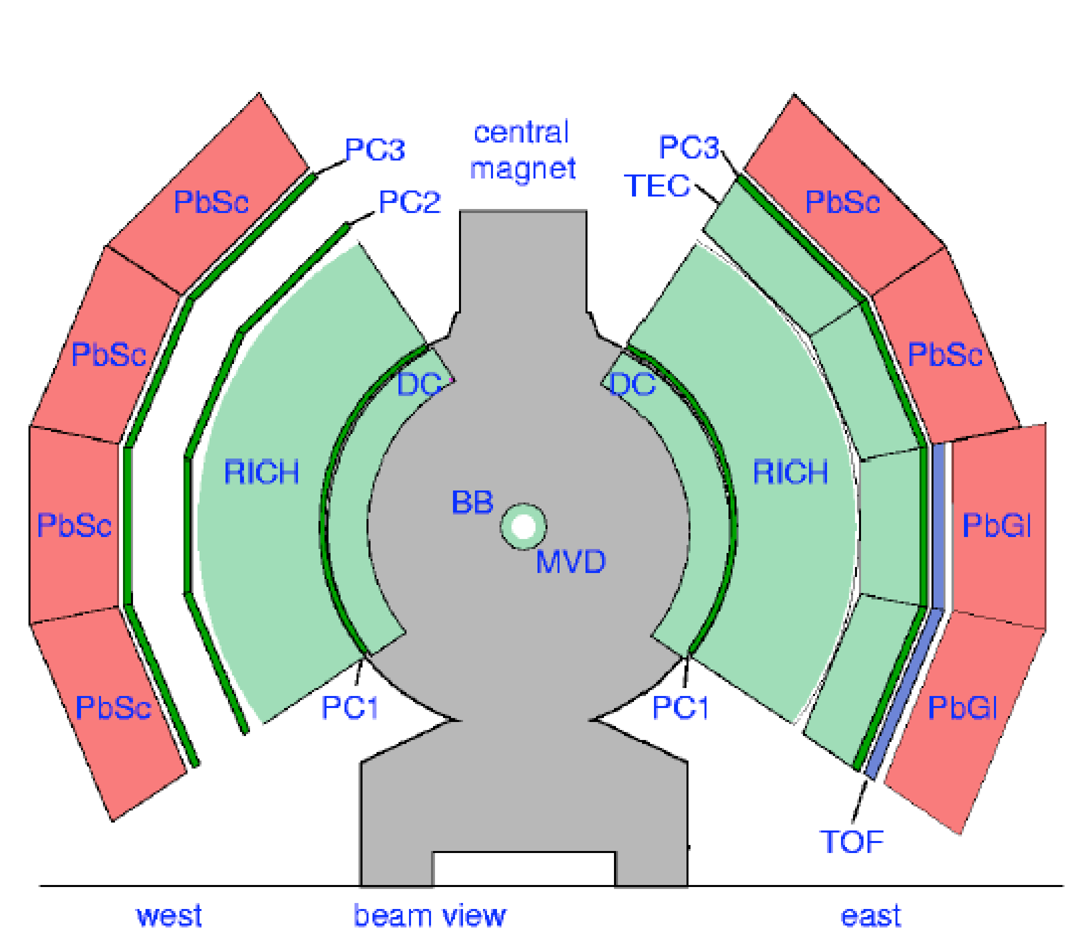
PHENIX Electromagnetic Calorimeter



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

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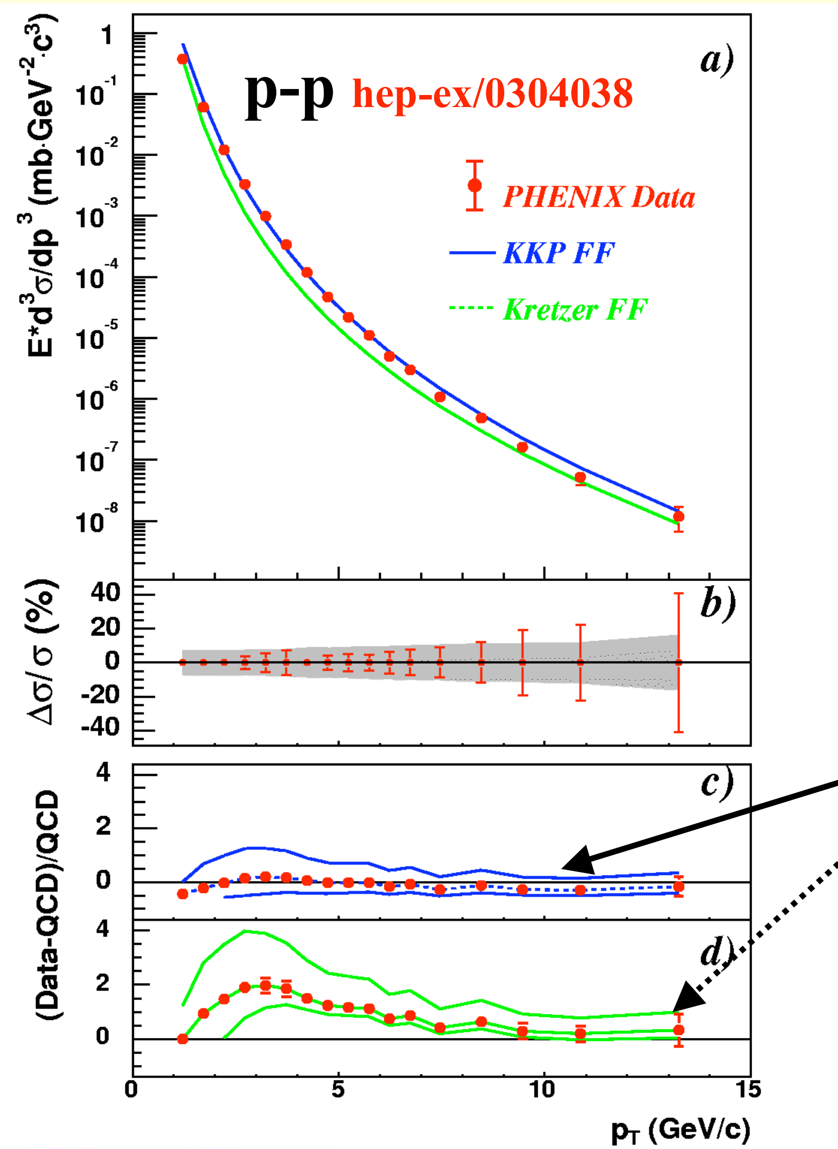
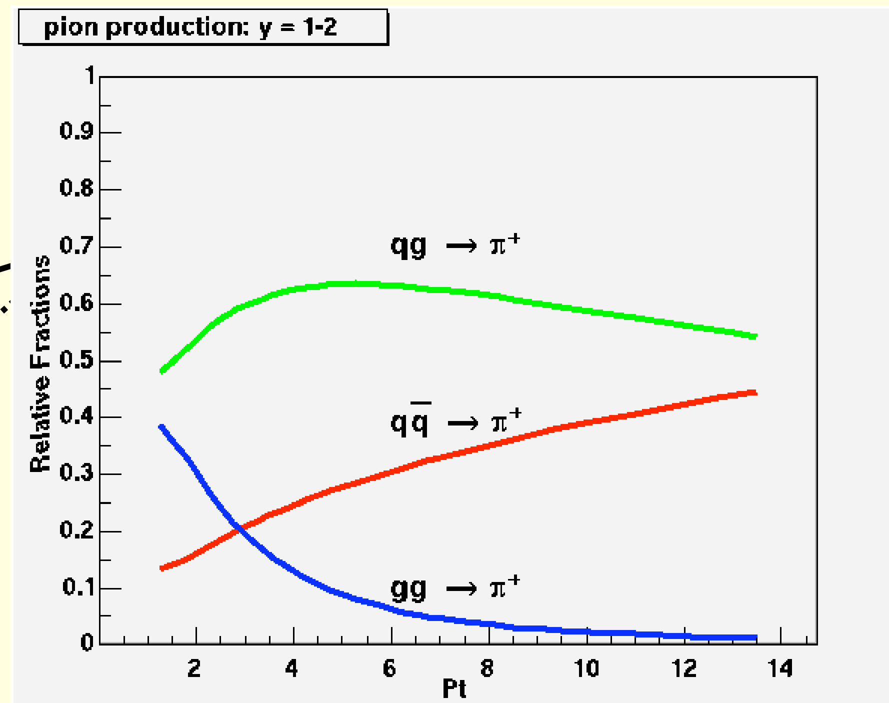
High-P_T π^0 spectra in p+p collisions at 200 GeV/c



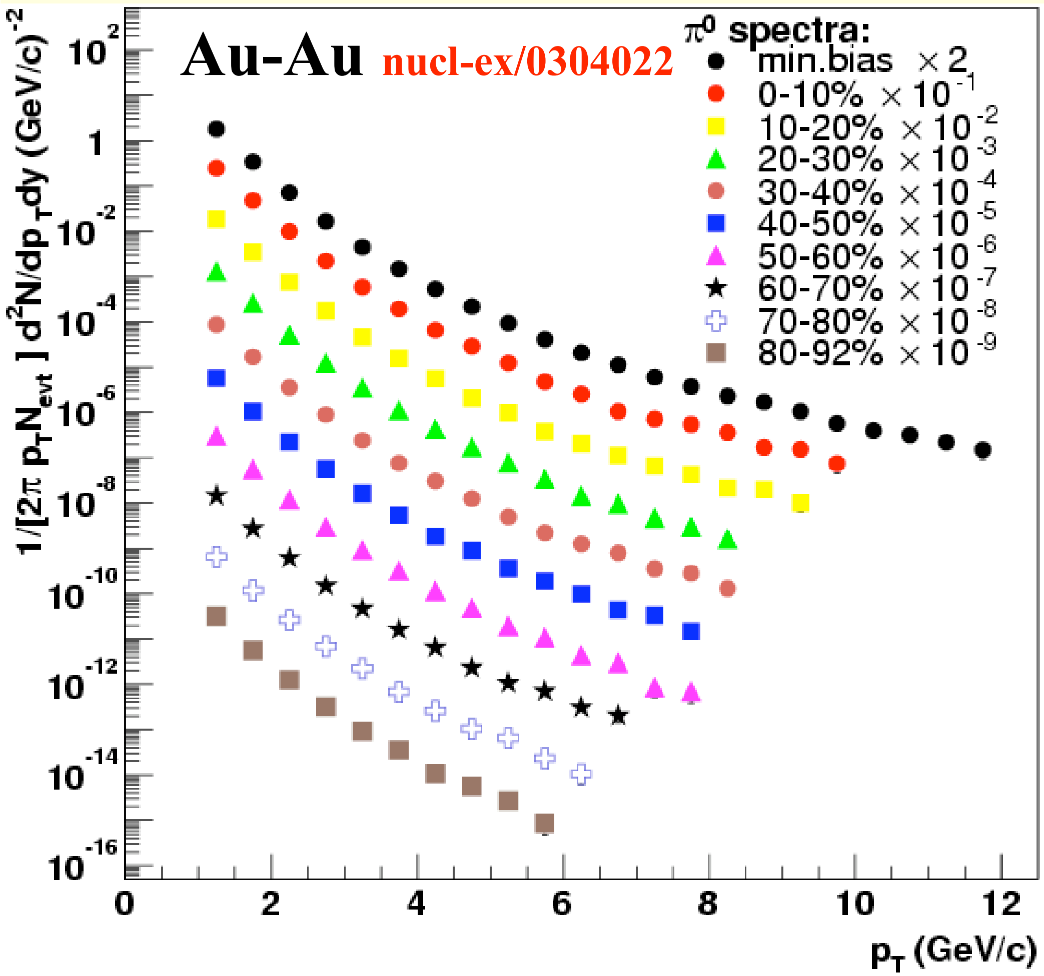
Spectra for π^0 out to 12 GeV/c compared to NLO pQCD predictions. **No intrinsic k_T necessary.**

pQCD works very well!

Good news for Direct γ measurement!

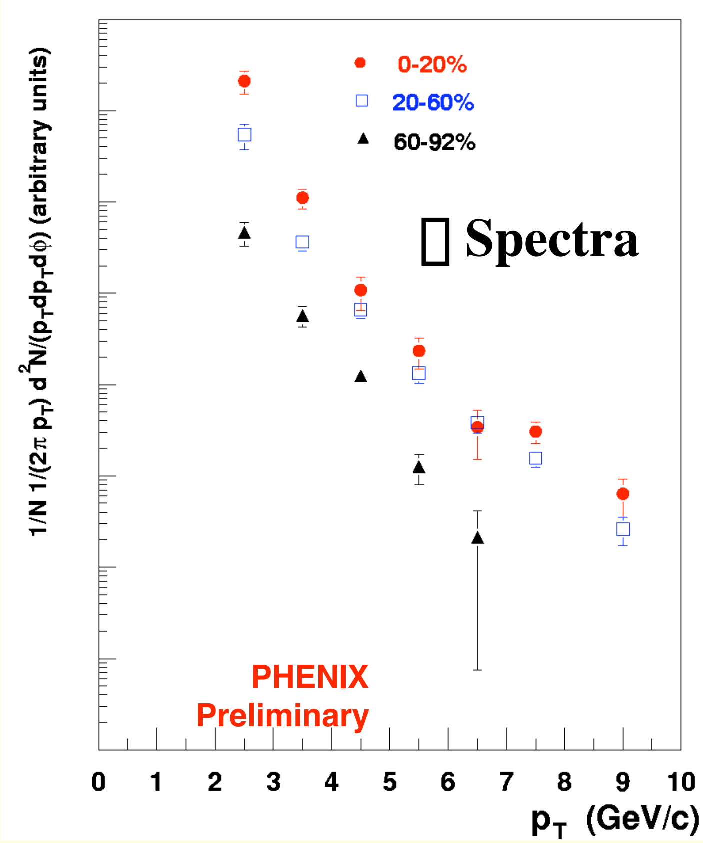


RHIC: Direct γ in √s=200 GeV/c Au+Au collisions



Measure π^0 and γ distributions-

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



S.Mioduszewski, CG-011, Friday AM

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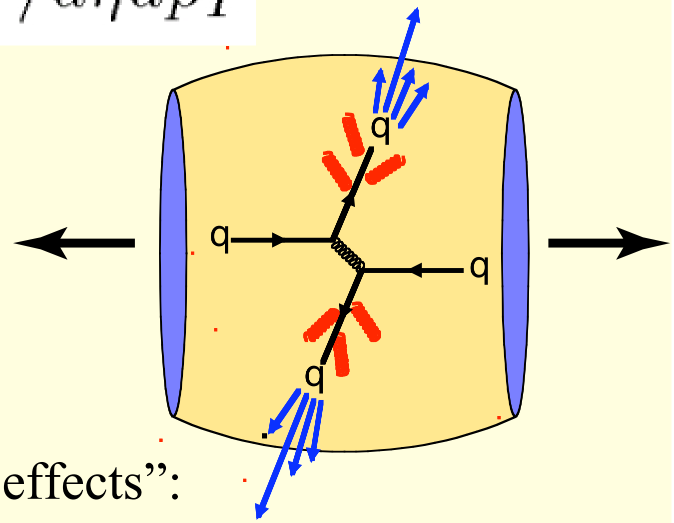
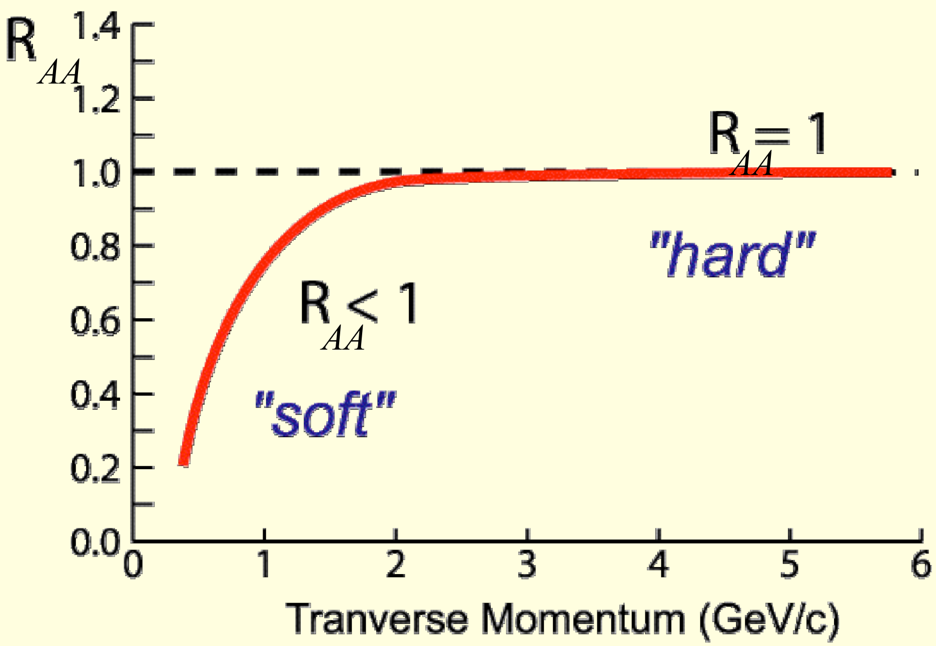
High p_T Suppression: The Nuclear Modification Factor R_{AA}

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
- $R_{AA} > 1$ due to k_T broadening (Cronin)

Suppression:

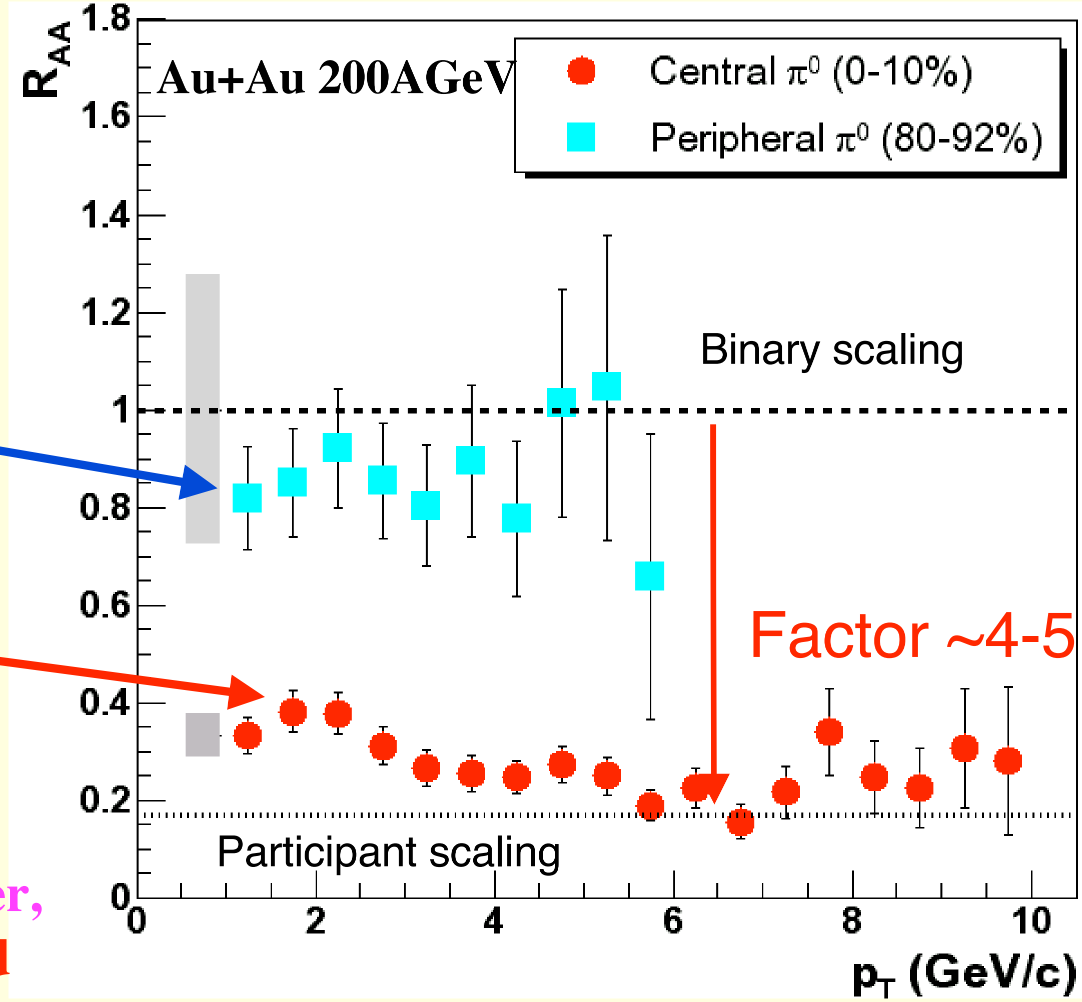
$R_{AA} < 1$ at high-p_T

R_{AuAu} : High P_T π^0 Suppression to at least 10 GeV/c

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

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

Large suppression in central Au+Au: Jet Quenching, or Gluon Saturation?



Implies γ decay background suppressed in central Au+Au.

-> Direct γ measurement easier, unless direct γ also suppressed due to gluon saturation…

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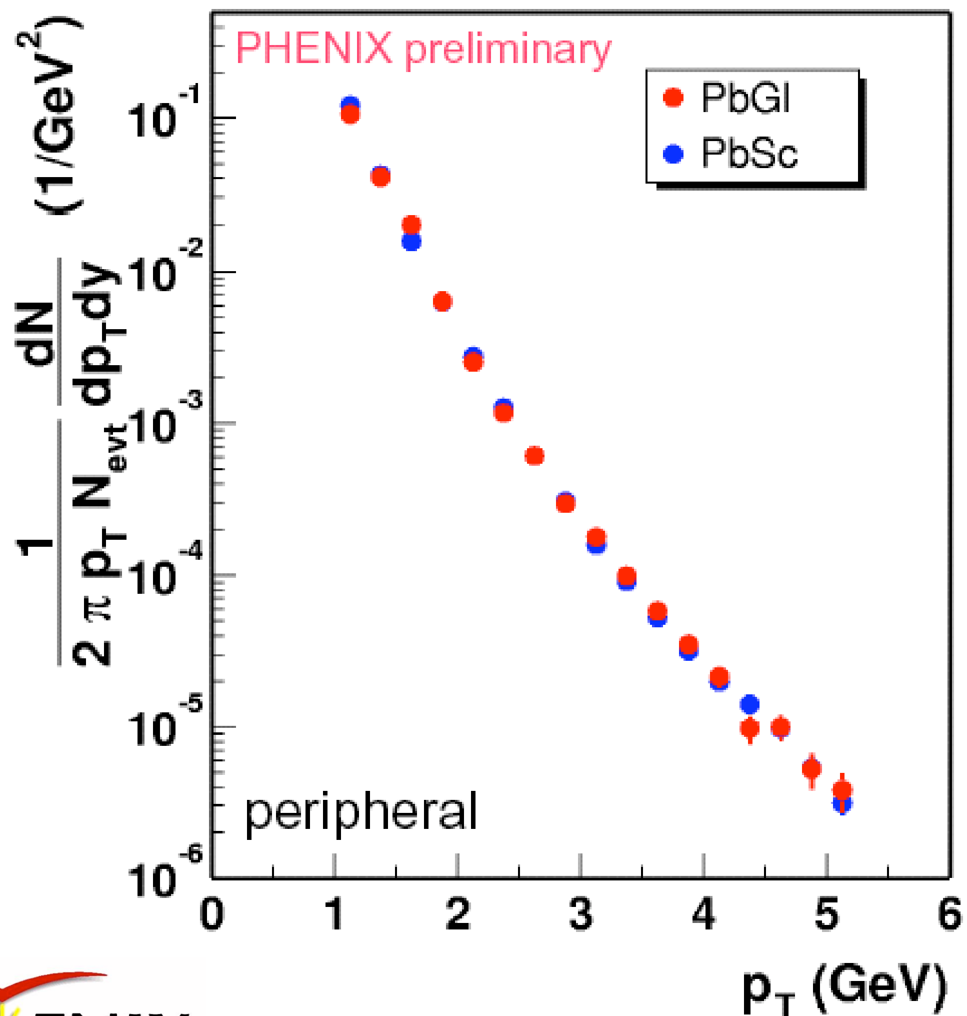
PRL 91 (2003) 072301

Inclusive γ : Peripheral Au+Au @ $\sqrt{s}$=200 GeV/c



PbGl and PbSc consistent

Compare with inclusive γ spectrum calculated via Monte Carlo with measured π^0 cross section as input…

Note: Results presented here are PHENIX Preliminary as of QM'02 - no new result…
See J.Frantz, CG-002, Friday AM

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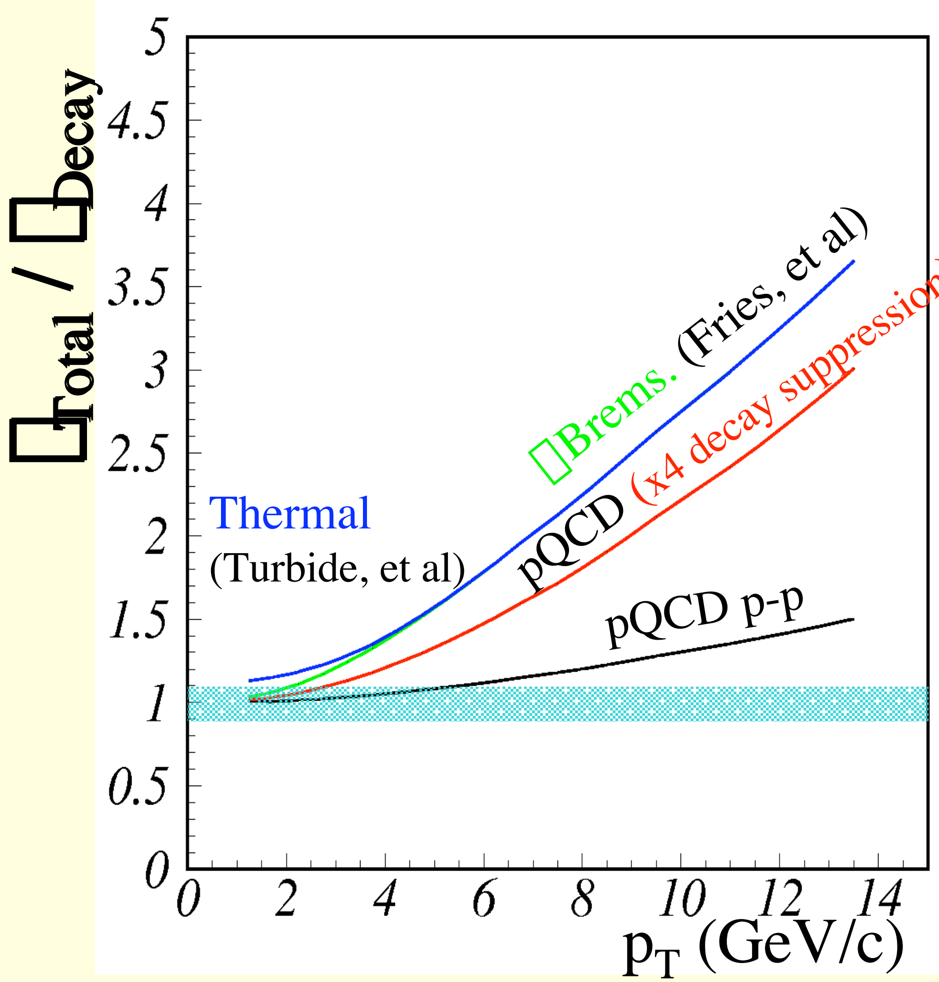
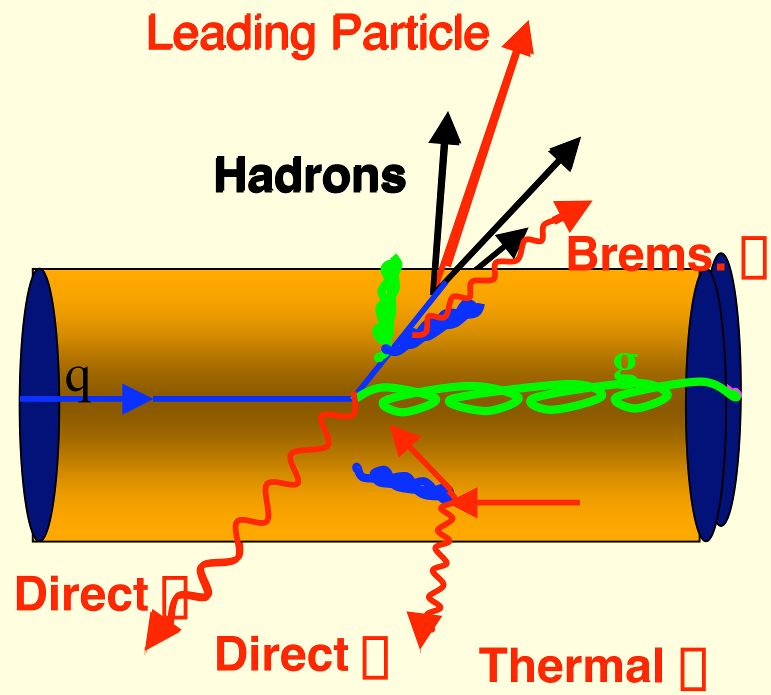
Direct Photon Expectations at RHIC





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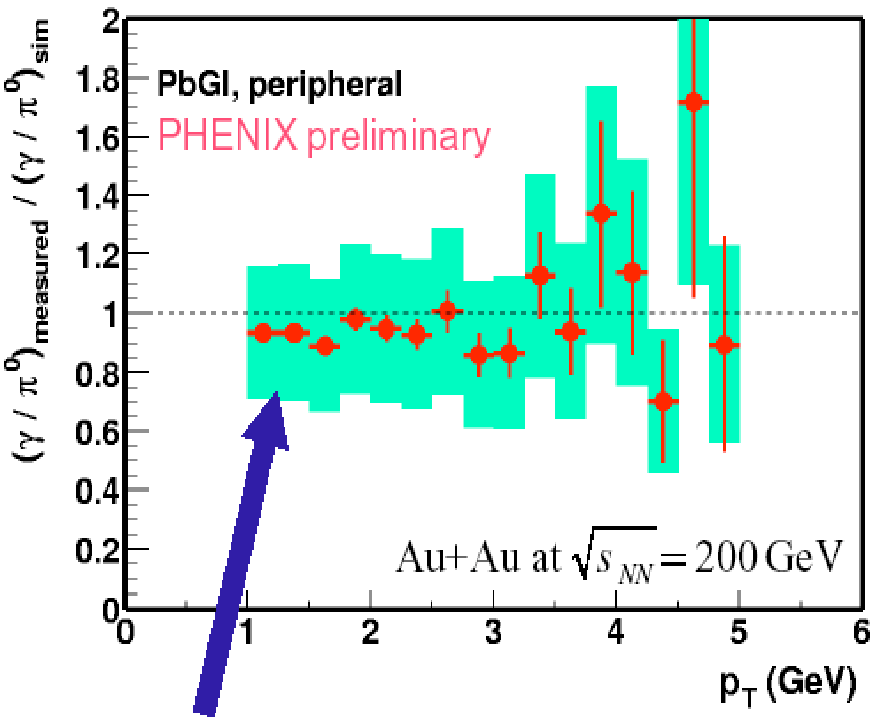
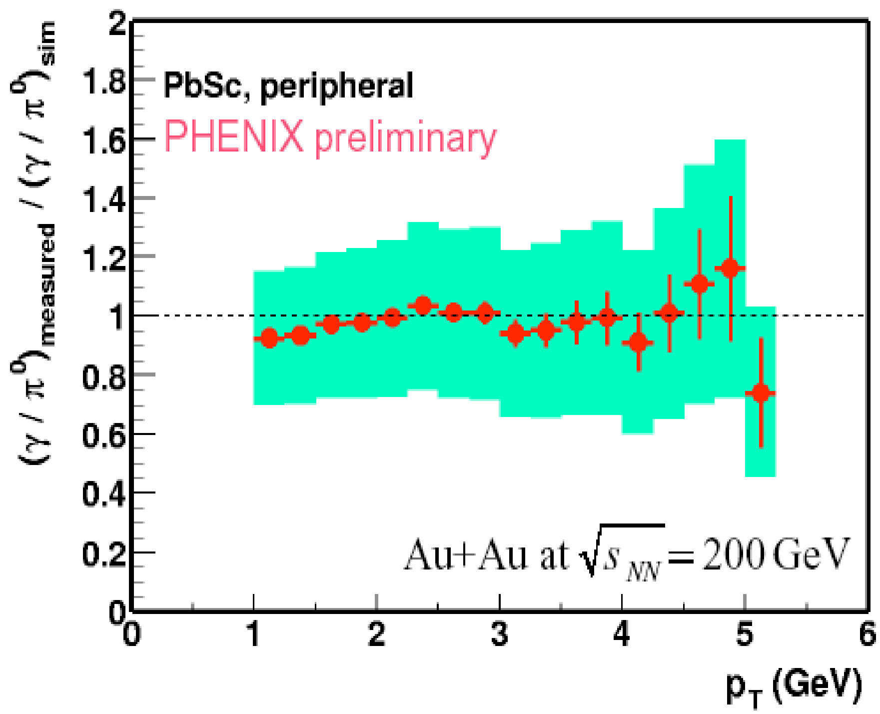
(γ/π^0)measured / (γ/π^0)simulated : Peripheral

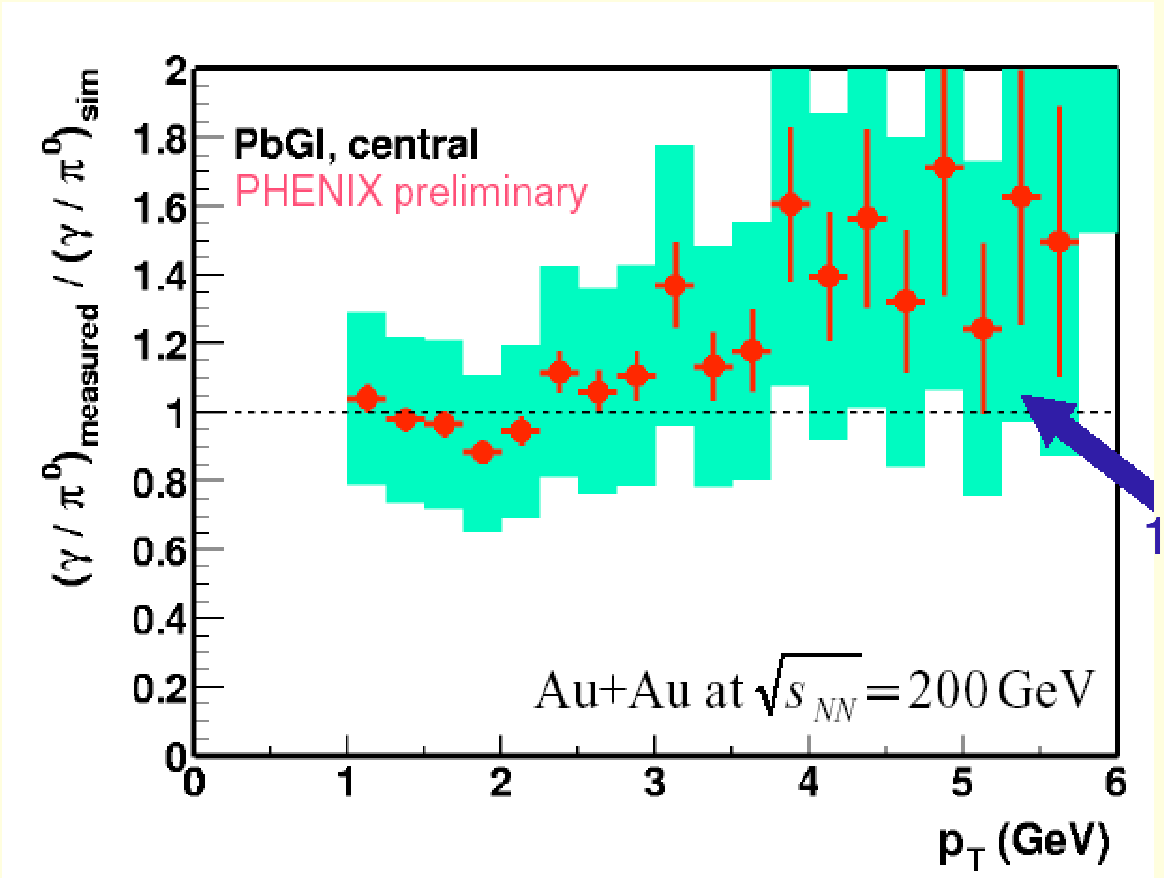
PbGl and PbSc consistent with no γ excess in peripheral





Boxes: 1σ systematic error

(/0)measured / (/0)simulated : Central

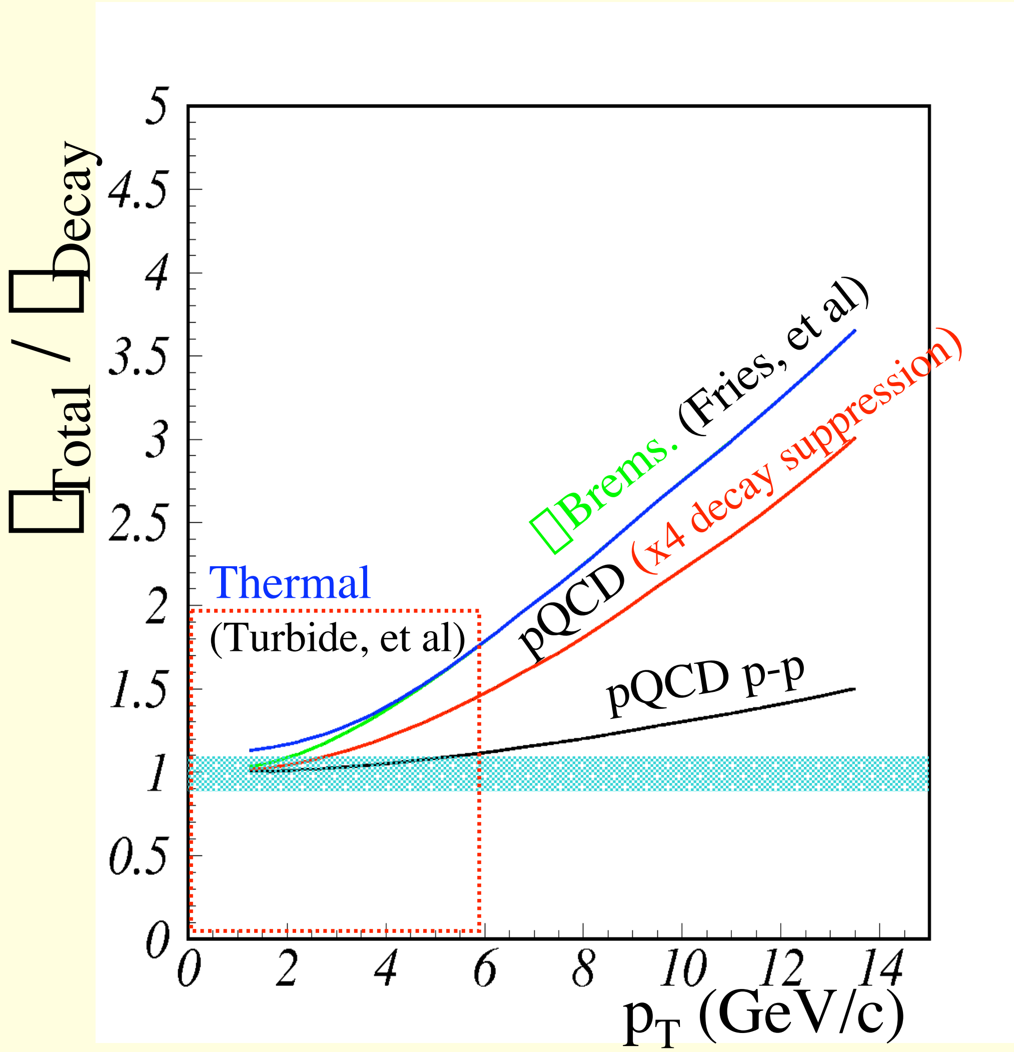


1 systematic errors

No photon excess seen within errors

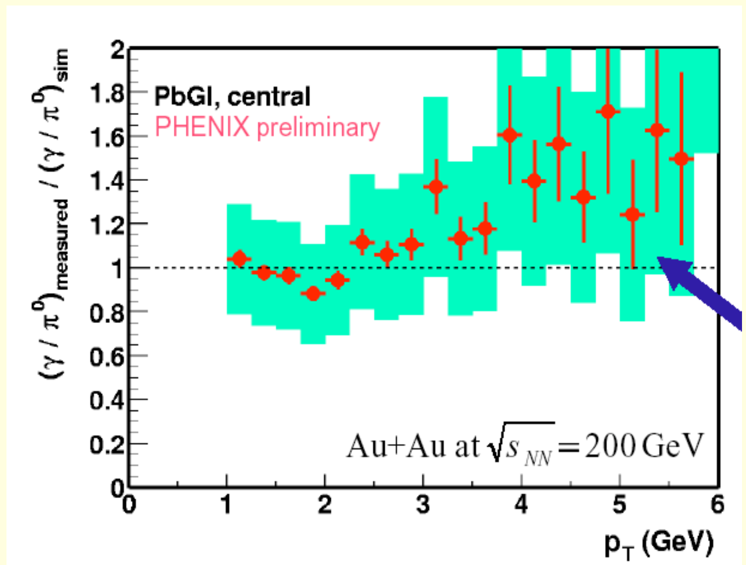
Working on better understanding of systematics

pQCD Direct predictions for RHIC



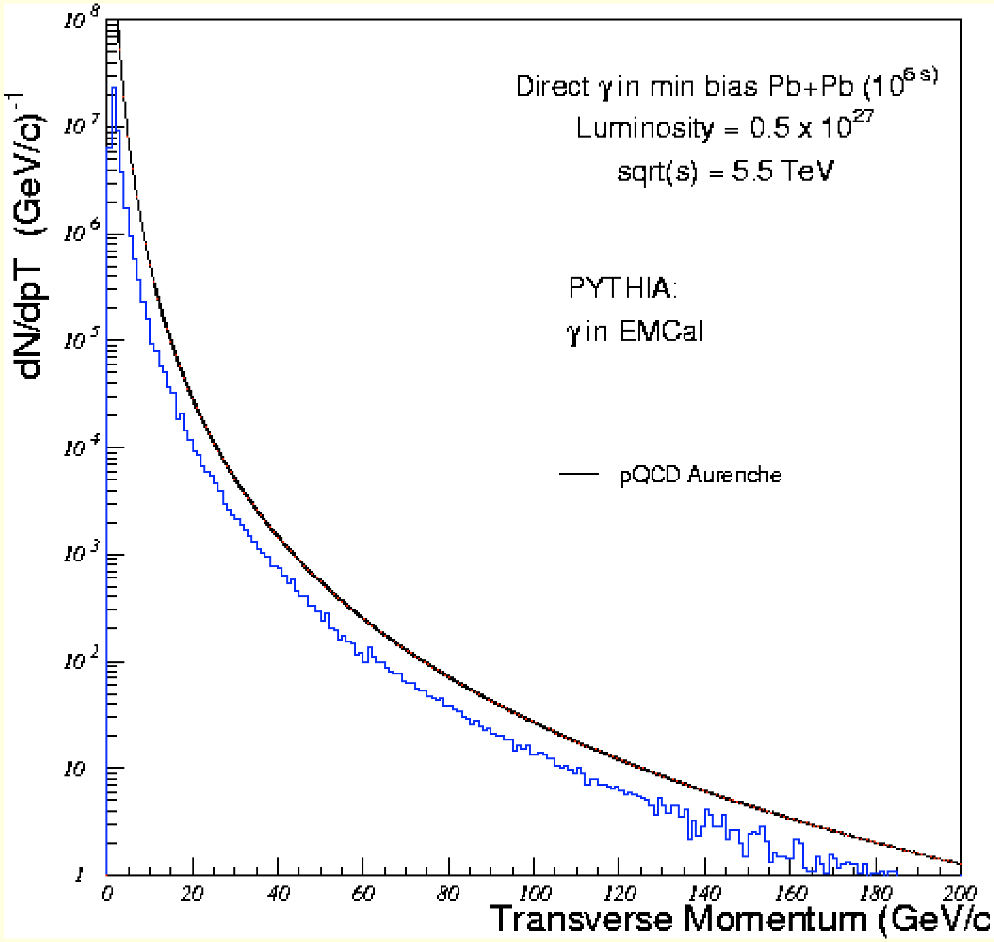
Plotted here as /Decay
(as with data)

Expect to see large direct signal, unless also suppressed (CGC)!



Direct γ, π^0 at LHC

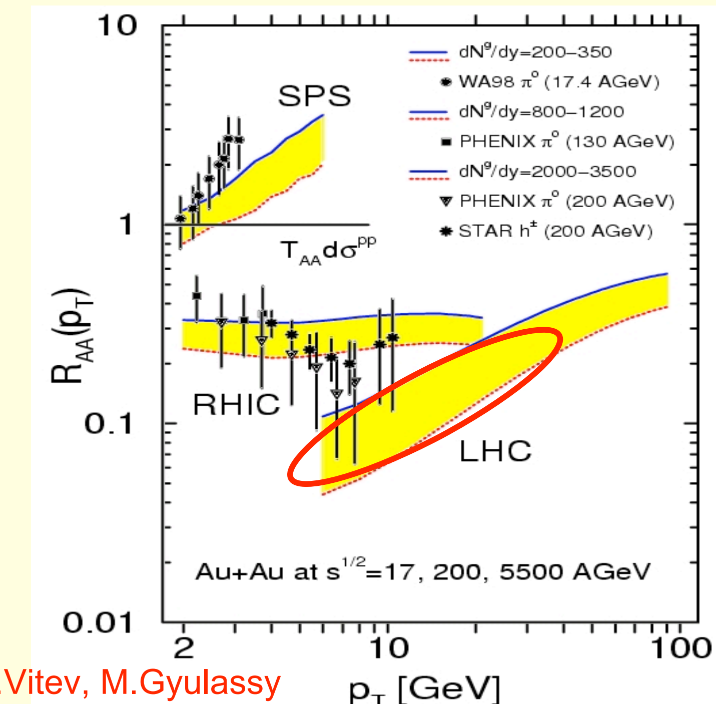
Direct γ(= γ+jet) in ALICE EMCal in one Pb+Pb LHC run.



Large direct γ rates to ~100 GeV/c,

Large π^0 suppression expected.

Direct γ measurement will provide a powerful probe at LHC.



I.Vitev, M.Gyulassy
PRL 89 252301 (2002)

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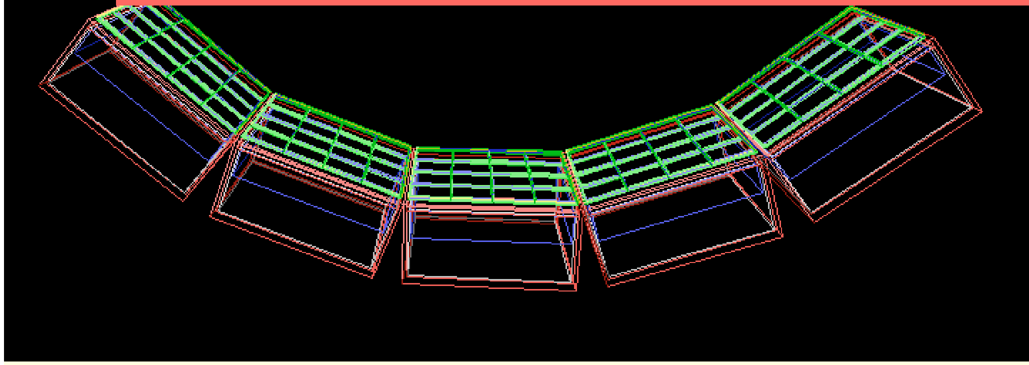
LHC: Electromagnetic Calorimeters in ALICE: PHOS

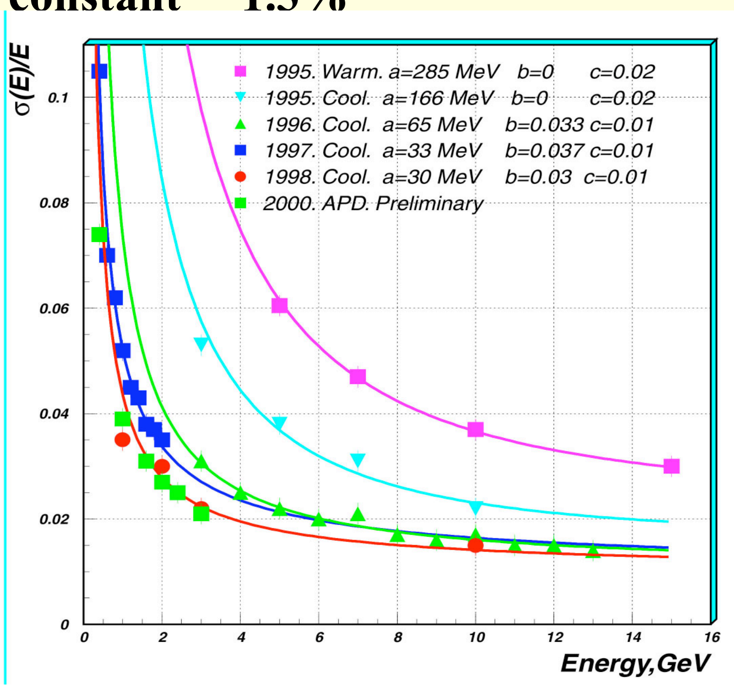


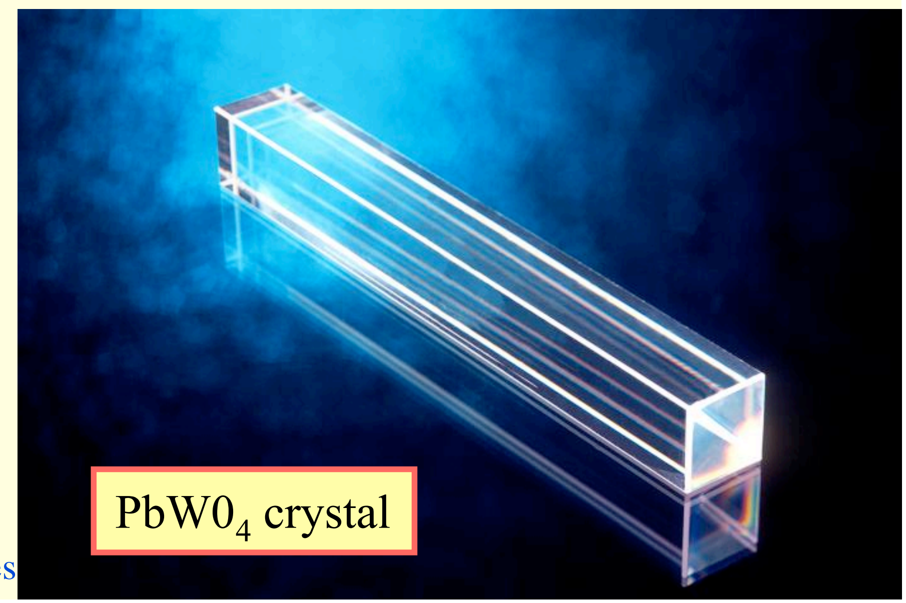
□/□^{0} separation and identification up to ~100 GeV/c

- **high granularity**
  - * 2.2x2.2 cm^2 @ 5m
  - * ~ 18 k channels, ~ 8 m^2
  - * cooled to -25^{o}C

$PbW0_4$: Very dense: $X_0 < 0.9$ cm
Good energy resolution (after 6 years R&D):

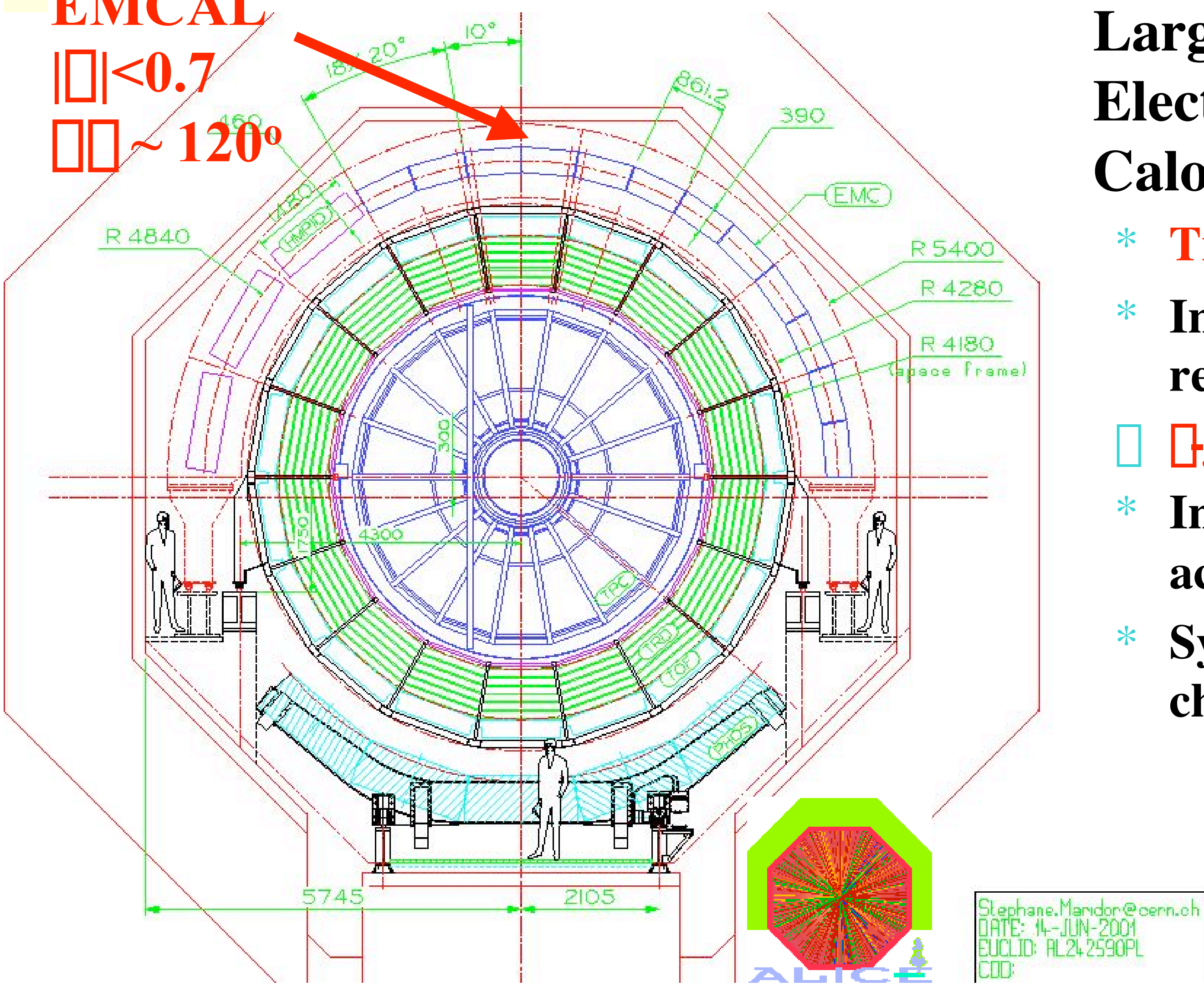
stochastic 2.7%/$E^{1/2}$
noise 2.5%/E
constant 1.3%





Electromagnetic Calorimeters in ALICE: EMCal

Proposed EMCAL
$|\eta|<0.7$
$\Delta\phi \sim 120^o$



US Proposal to build a Large area Electromagnetic Calorimeter

- **Trigger on γ, π^0, and jets**
- **Improve jet energy resolution**
- **γ-jet coincidences**
- **Increased γ, π^0 acceptance**
- **Systematic error cross check**

Summary and Conclusions

• **Direct γ signal observed at SPS in Pb+Pb collisions possibly explained by EOS with QGP, but also consistent with HG. Many ambiguities - poor pQCD description, intrinsic k_T effects, etc. Situation will be clearer at RHIC.**

• **The strong suppression of hadron production (factor of ~4-5) observed in central Au+Au collisions at RHIC should make the direct photon measurement that much easier, unless hadron suppression is due to initial state Gluon Saturation.**

• **If the π^0 suppression is due to parton energy loss, then the direct γ measurement at RHIC and LHC should be as easy as falling off a log!**

Great promise for direct γ for future QGP diagnostics.

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Brazil University of São Paulo, São Paulo

China Academia Sinica, Taipei, Taiwan
China Institute of Atomic Energy, Beijing
Peking University, Beijing

France LPC, University de Clermont-Ferrand, Clermont-Ferrand
Dapnia, CEA Saclay, Gif-sur-Yvette
IPN-Orsay, Universite Paris Sud, CNRS-IN2P3, Orsay
LLR, Ecole Polytechnique, CNRS-IN2P3, Palaiseau
SUBATECH, Ecole des Mines de Nantes, CNRS-IN2P3, Univ. Nantes

Germany University of Münster, Münster

Hungary Central Research Institute for Physics (KFKI), Budapest
Debrecen University, Debrecen
Eötvös Loránd University (ELTE), Budapest

India Banaras Hindu University, Banaras
Bhabha Atomic Research Centre, Bombay

Israel Weizmann Institute, Rehovot

Japan Center for Nuclear Study, University of Tokyo, Tokyo
Hiroshima University, Higashi-Hiroshima
KEK, Institute for High Energy Physics, Tsukuba
Kyoto University, Kyoto
Nagasaki Institute of Applied Science, Nagasaki
RIKEN, Institute for Physical and Chemical Research, Wako
RIKEN-BNL Research Center, Upton, NY
University of Tokyo, Bunkyo-ku, Tokyo
Tokyo Institute of Technology, Tokyo
University of Tsukuba, Tsukuba
Waseda University, Tokyo

S. Korea Cyclotron Application Laboratory, KAERI, Seoul
Kangnung National University, Kangnung
Korea University, Seoul
Myong Ji University, Yongin City
System Electronics Laboratory, Seoul Nat. University, Seoul
Yonsei University, Seoul

Russia Institute of High Energy Physics, Protovino
Joint Institute for Nuclear Research, Dubna
Kurchatov Institute, Moscow
PNPI, St. Petersburg Nuclear Physics Institute, St. Petersburg
St. Petersburg State Technical University, St. Petersburg

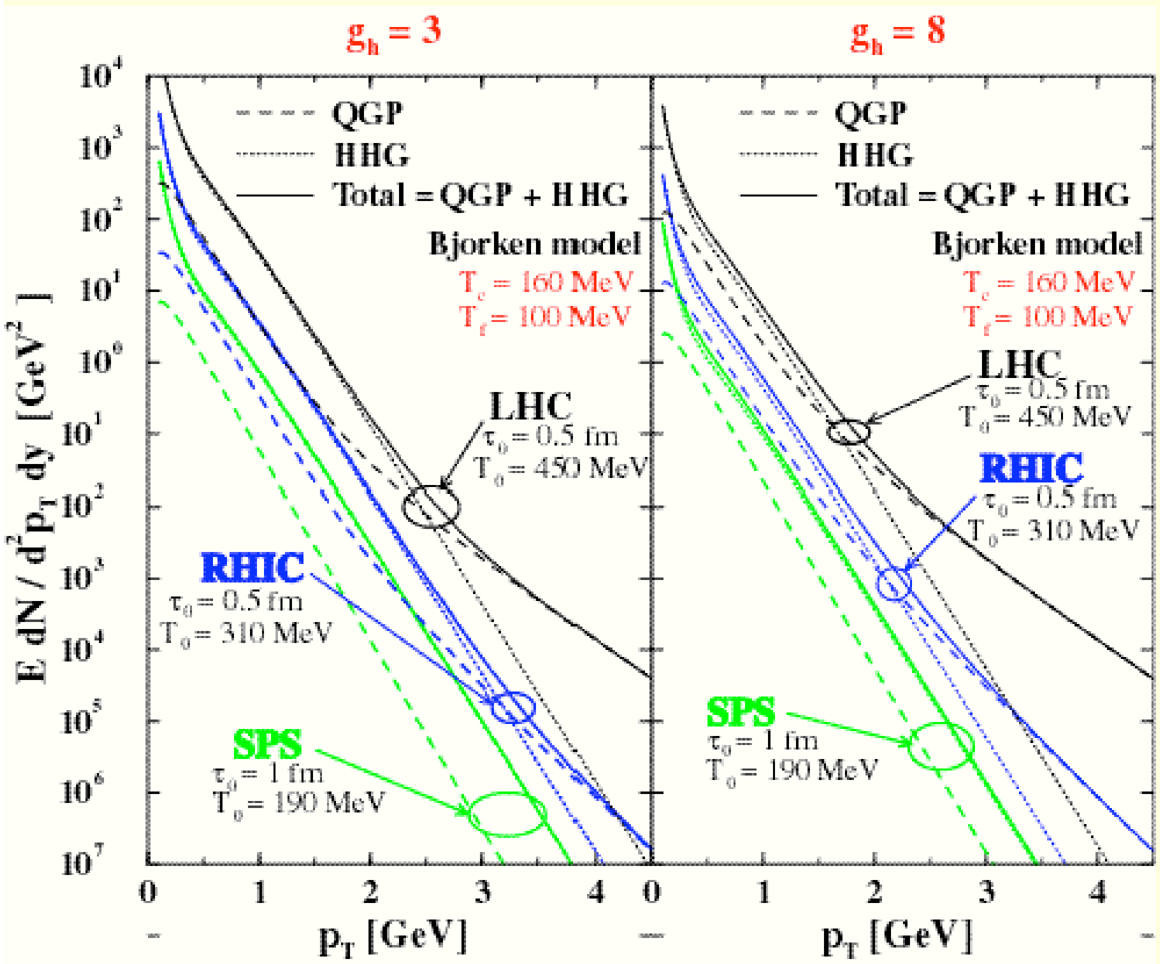
Sweden Lund University, Lund

12 Countries; 57 Institutions; 460 Participants

USA Abilene Christian University, Abilene, TX
Brookhaven National Laboratory, Upton, NY
University of California - Riverside, Riverside, CA
University of Colorado, Boulder, CO
Columbia University, Nevis Laboratories, Irvington, NY
Florida State University, Tallahassee, FL
Georgia State University, Atlanta, GA
University of Illinois Urbana Champaign, IL
Iowa State University and Ames Laboratory, Ames, IA
Los Alamos National Laboratory, Los Alamos, NM
Lawrence Livermore National Laboratory, Livermore, CA
University of New Mexico, Albuquerque, NM
New Mexico State University, Las Cruces, NM
Dept. of Chemistry, Stony Brook Univ., Stony Brook, NY
Dept. Phys. and Astronomy, Stony Brook Univ., Stony Brook, NY
Oak Ridge National Laboratory, Oak Ridge, TN
University of Tennessee, Knoxville, TN
Vanderbilt University, Nashville, TN

BACKUP SLIDES

Direct γ: Expectations for RHIC & LHC

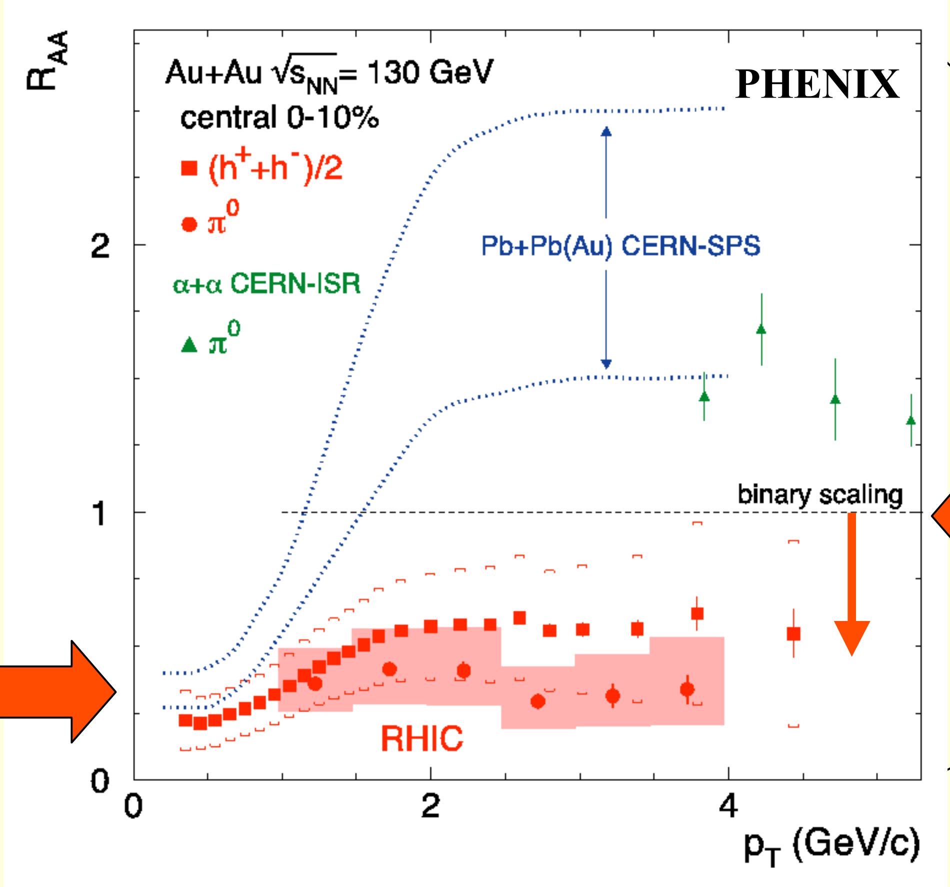


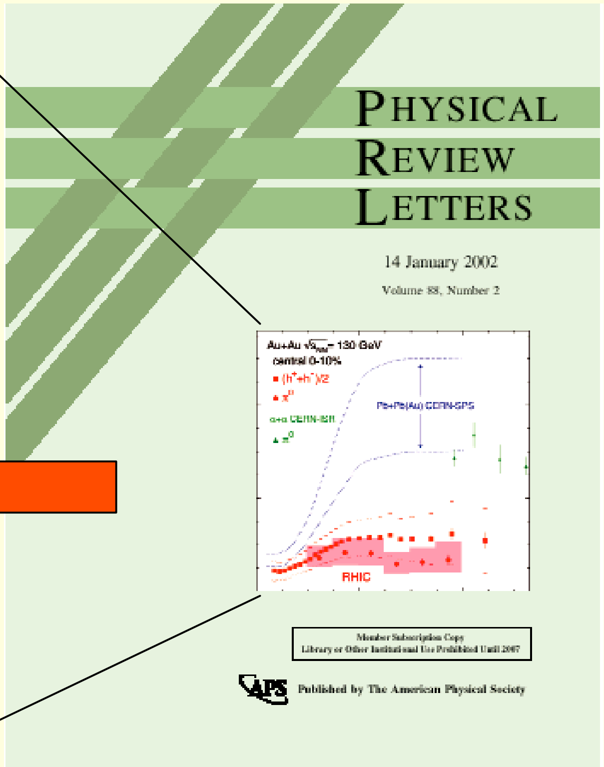
Steffan & Thoma PLB 510 (2001) 98.

- At RHIC & LHC the QM contribution dominates for p_T>2-3 GeV/c
- π^0 "suppression" = decay suppression
  - Increases Direct/Decay
- For PHENIX:

  $s^{1/2}$ =200 GeV:
  - Two times WA98 central sample in PHENIX MinBias
  - High p_T trigger events another x2 increase
  - Harder p_T spectra

RHIC Headline News…





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

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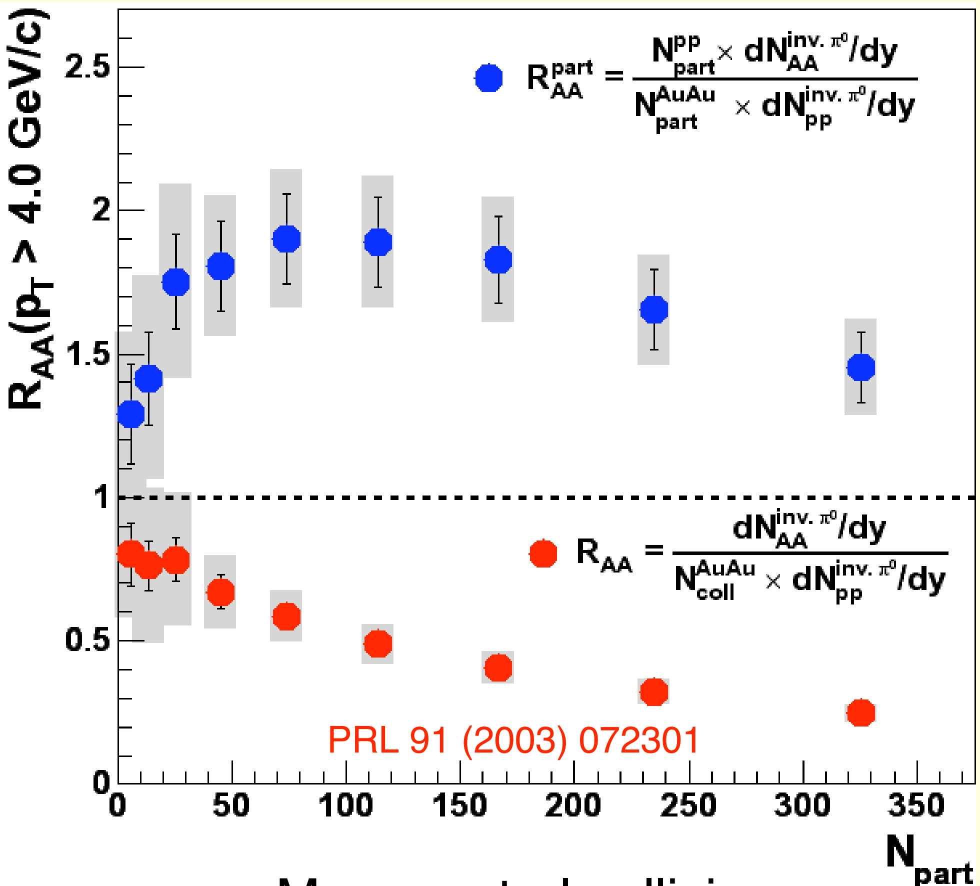
Centrality Dependence of R_{AA}

The suppression increases smoothly with centrality

- approximate N_{part} scaling.

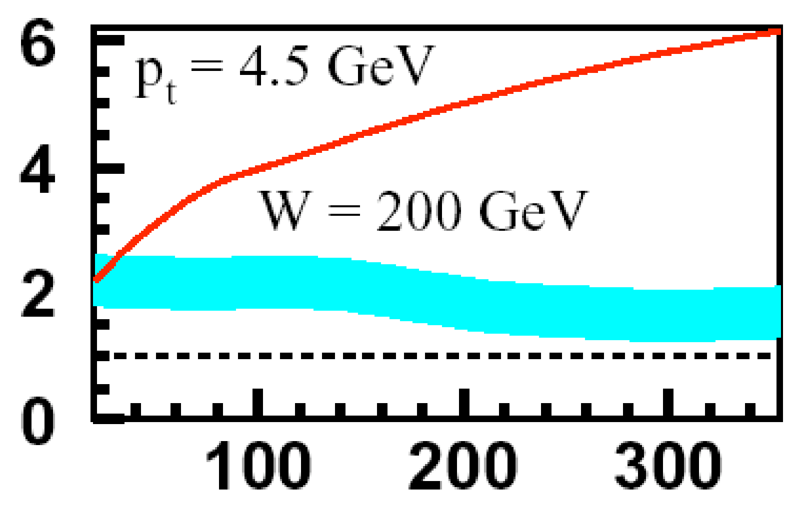


More central collisions

Centrality dependence similar to predictions of Color Glass Condensate (AKA Gluon Saturation)

-Suggests Initial state effect!?!

-Need p+Au (d+Au)



D.Kharzeev, E.Levin, L.McLerran
hep-ph/0210332

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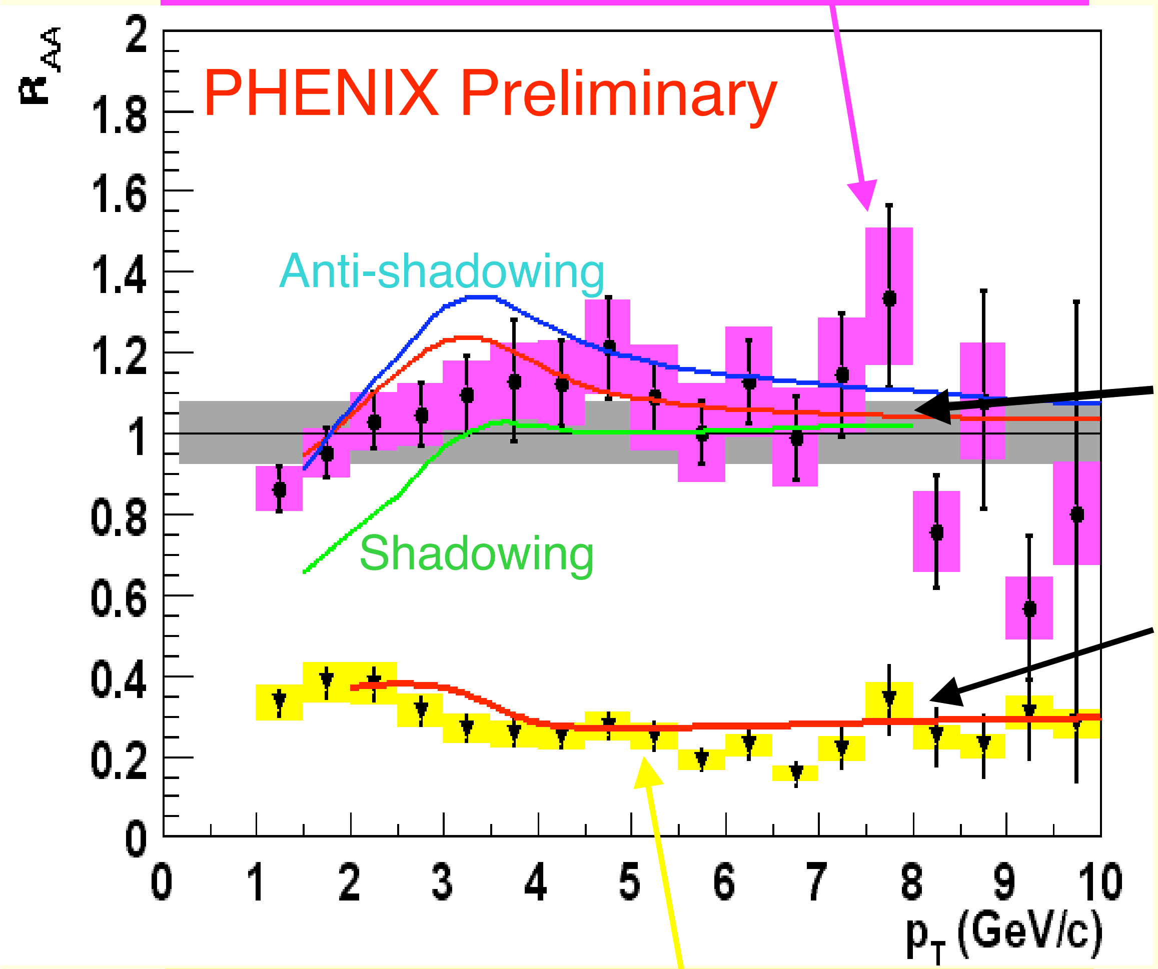
Data vs Theory : □^{0}

□^{0} d+Au (minbias) 200 GeV



□^{0} Au+Au (0-5%) 200 GeV

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

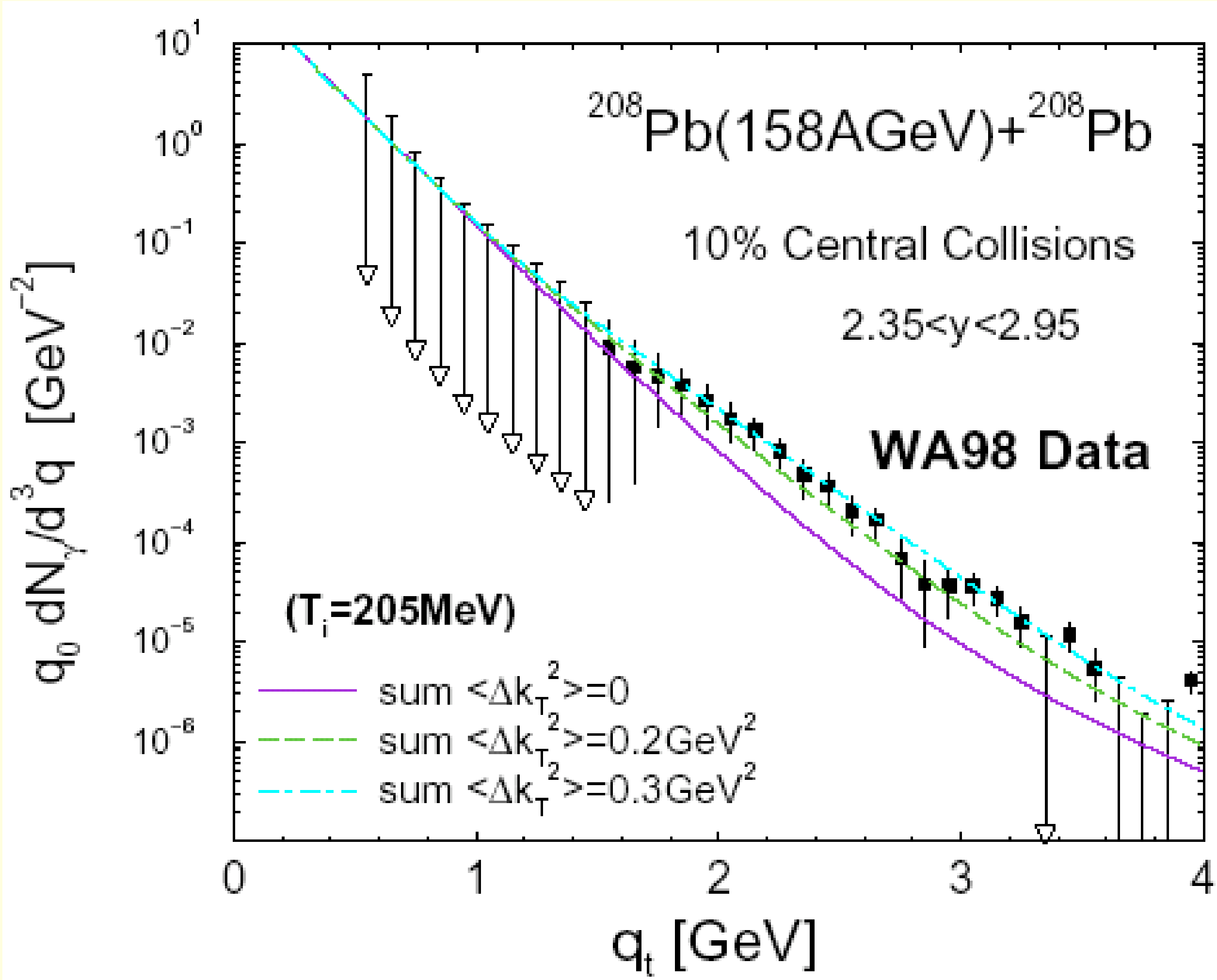
Can dAu and AuAu central dependence also be explained?

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

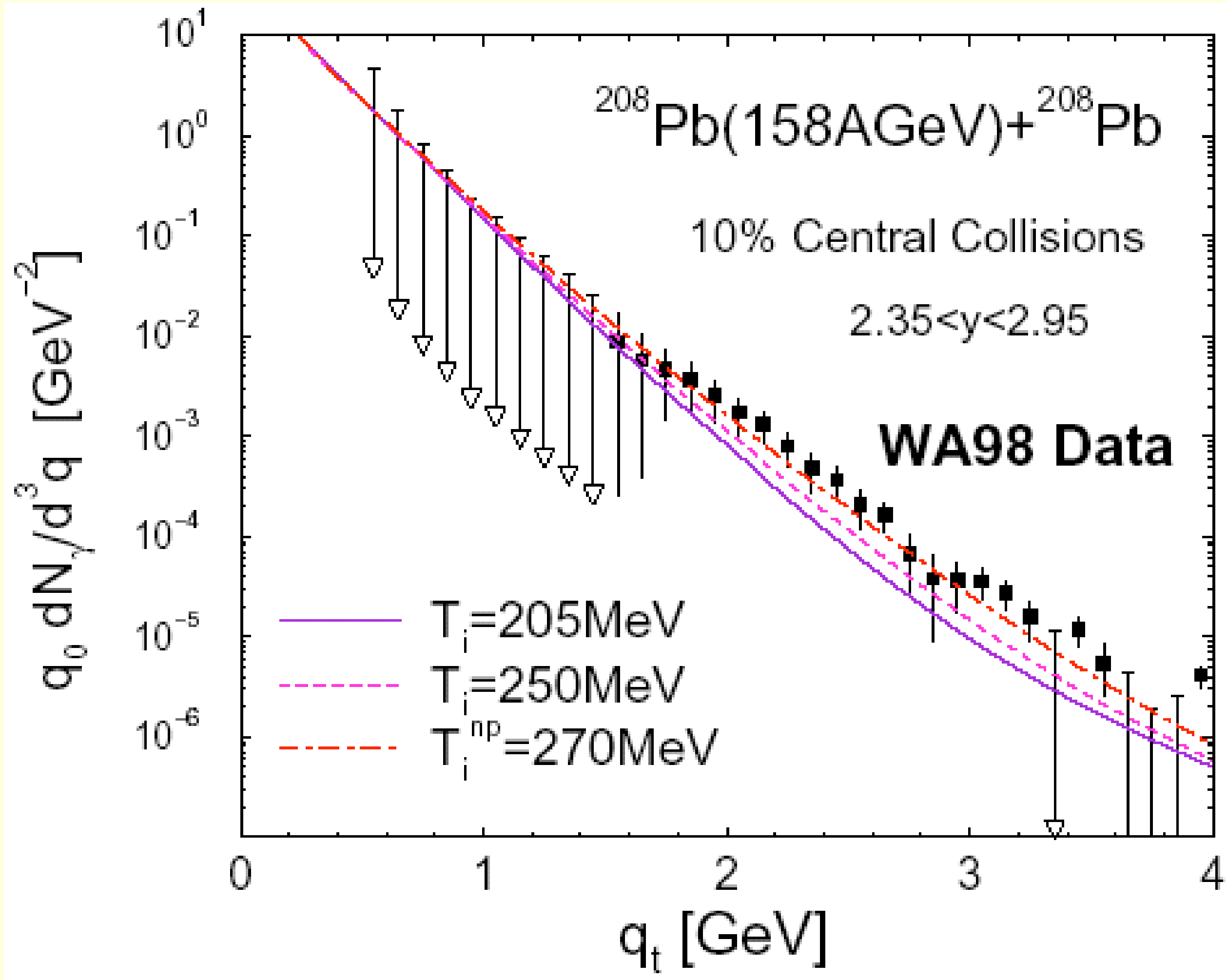
Au+Au: I. Vitev and M. Gyulassy, hep-ph/0208108, to appear in Nucl. Phys. A; M. Gyulassy, P. Levai and I. Vitev, Nucl. Phys. B 594, p. 371 (2001).

T.C.Awes

PHENIX



^{208}Pb(158AGeV)+^{208}Pb
10% Central Collisions
2.35<y<2.95
WA98 Data
(T$_i$=205MeV)
sum <Δk$_T^2$>=0
sum <Δk$_T^2$>=0.2GeV^2
sum <Δk$_T^2$>=0.3GeV^2
$q_0\, dN_\gamma/d^3q$ [GeV^{-2}]
q_t [GeV]



^{208}Pb(158AGeV)+^{208}Pb
10% Central Collisions
2.35<y<2.95
WA98 Data
T_i=205MeV
T_i=250MeV
T_i^{np}=270MeV
$q_0\, dN_\gamma/d^3q$ [GeV^{-2}]
q_t [GeV]

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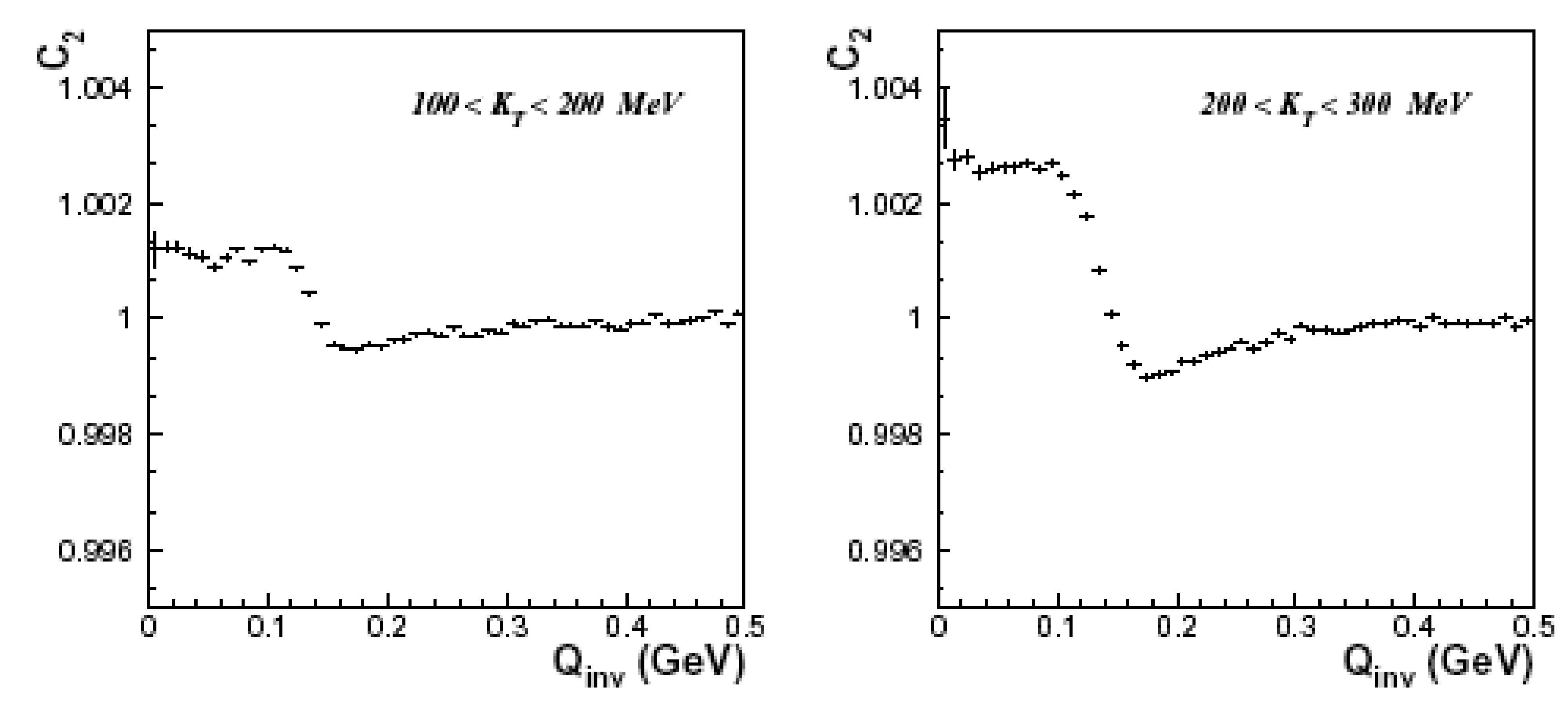

C2
1.004
1.002
1
0.998
0.996
100 < K_T < 200 MeV
0
0.1
0.2
0.3
0.4
0.5
Q_inv (GeV)
C2
200 < K_T < 300 MeV
Q_inv (GeV)

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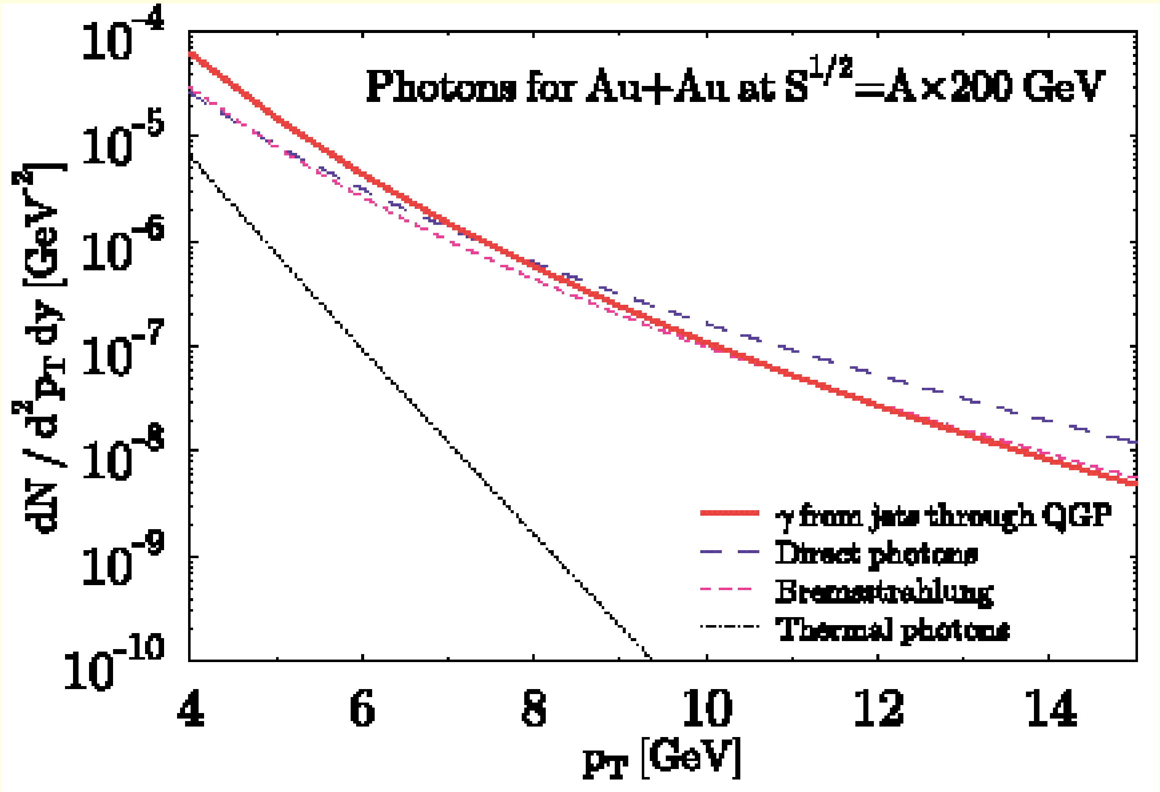

Photons for Au+Au at S^1/2=A×200 GeV
γ from jets through QGP
Direct photons
Bremsstrahlung
Thermal photons
dN / d²pT dy [GeV⁻²]
pT [GeV]
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
4
6
8
10
12
14

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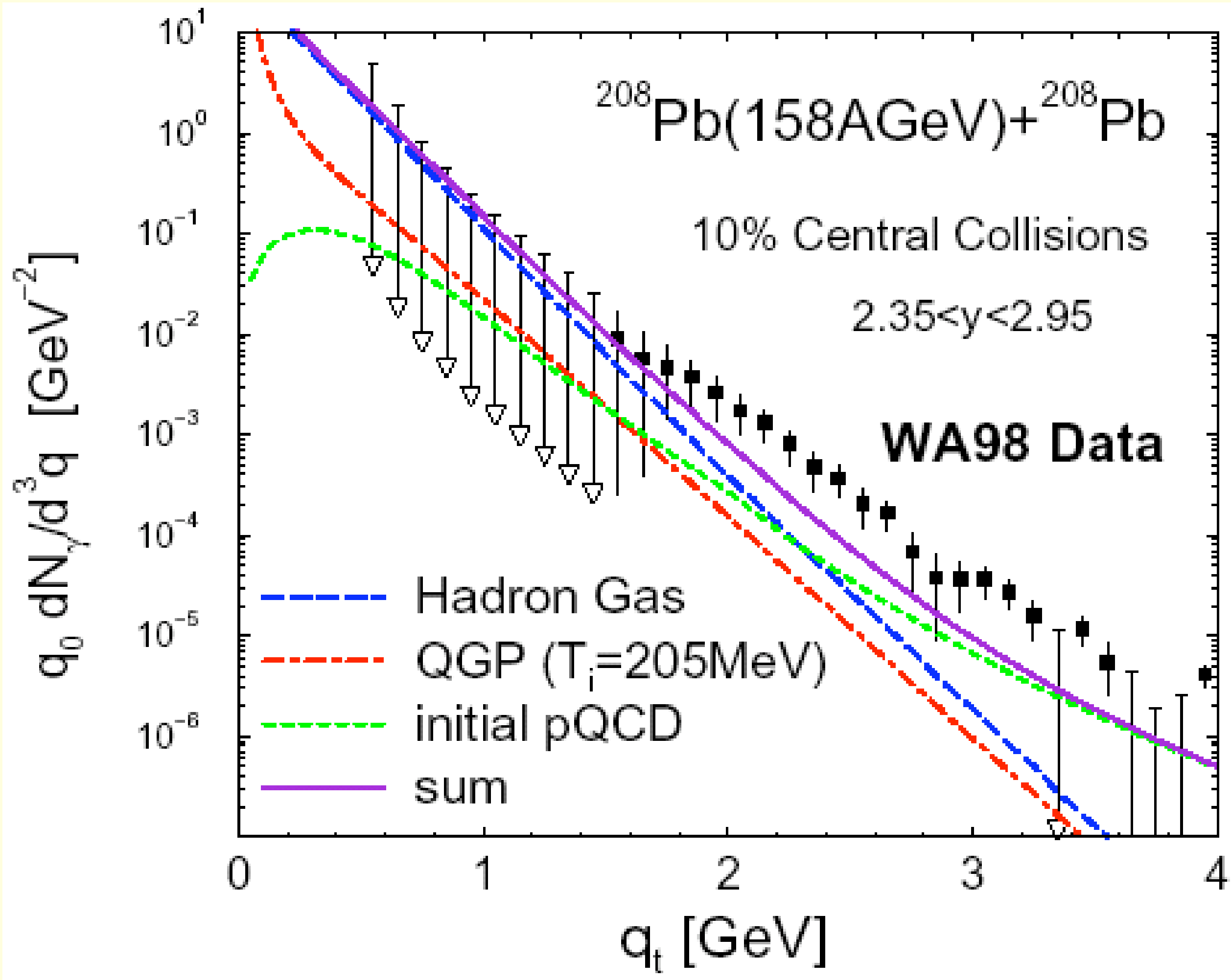

208Pb(158AGeV)+208Pb
10% Central Collisions
2.35<y<2.95
WA98 Data
Hadron Gas
QGP (Ti=205MeV)
initial pQCD
sum
q0 dNγ/d3q [GeV-2]
qt [GeV]

T.C.Awes

Quenching of Hard Scattered Partons

- **Hard parton scatterings in nucleon-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"**
- **Reference case: d+Au**
  No produced medium.