Direct Photons in p+p,p+A, and A+A Collisions

T.C. Awes, Oak Ridge National Laboratory

Topics:

- **Results from p+p, p+A (k_T effects)**
- **Results from A+A (thermal)**
- **Other methods (virtual γ, γ–γ HBT, γ flow)**
- **Jets in ALICE (γ+jet)**

"The virtue of π^0 and γ Measurements"

To properly deduce the properties of the produced QCD matter we must separately distinguish initial state effects from final state effects.

γ's sensitive only to production processes, do not interact, sensitive to:

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

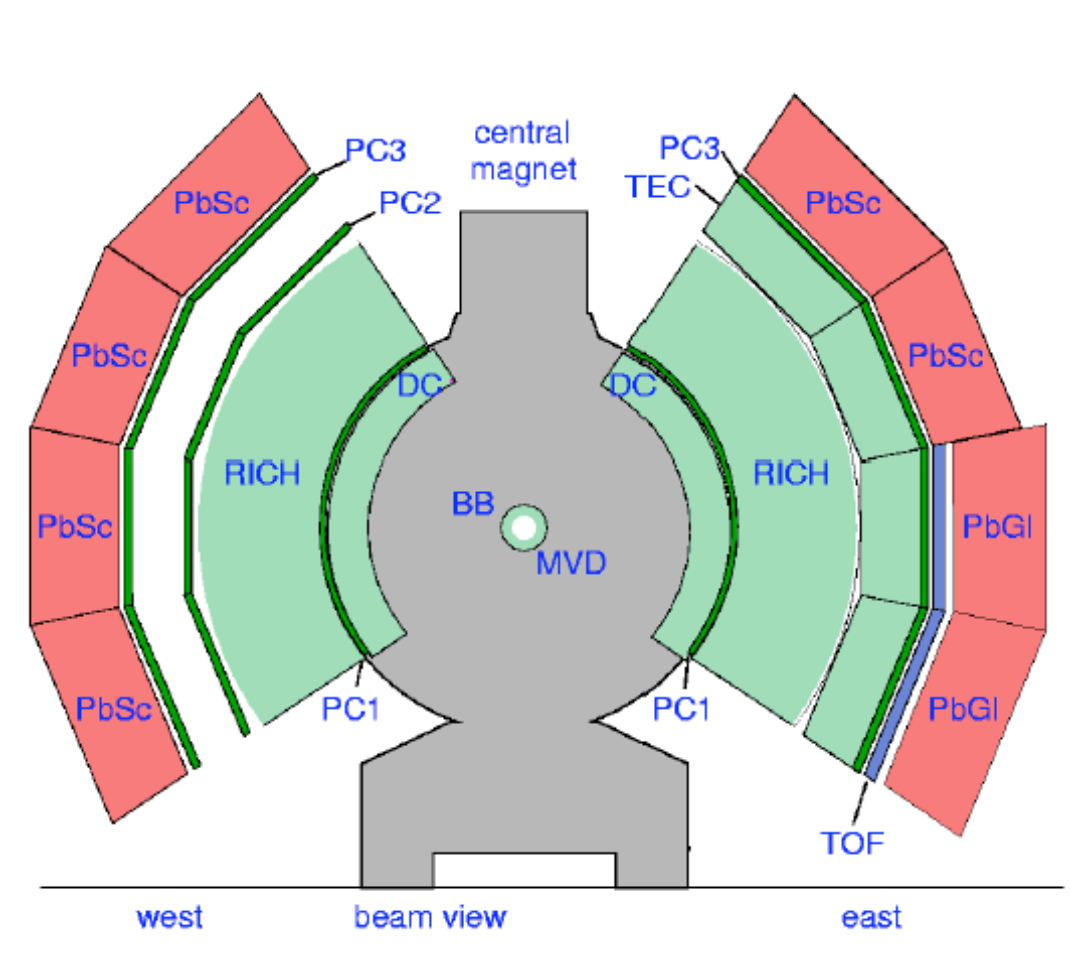
π^0's produced in final state (fragmentation or recombination):

- **initial parton distributions: as for γ**
- **large final state effects: 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

PHENIX Electromagnetic Calorimeter



PbSc

- Highly segmented lead **scintillator** sampling Calorimeter
- Module size: 5.5 cm x 5.5 cm x 37 cm

PbGl

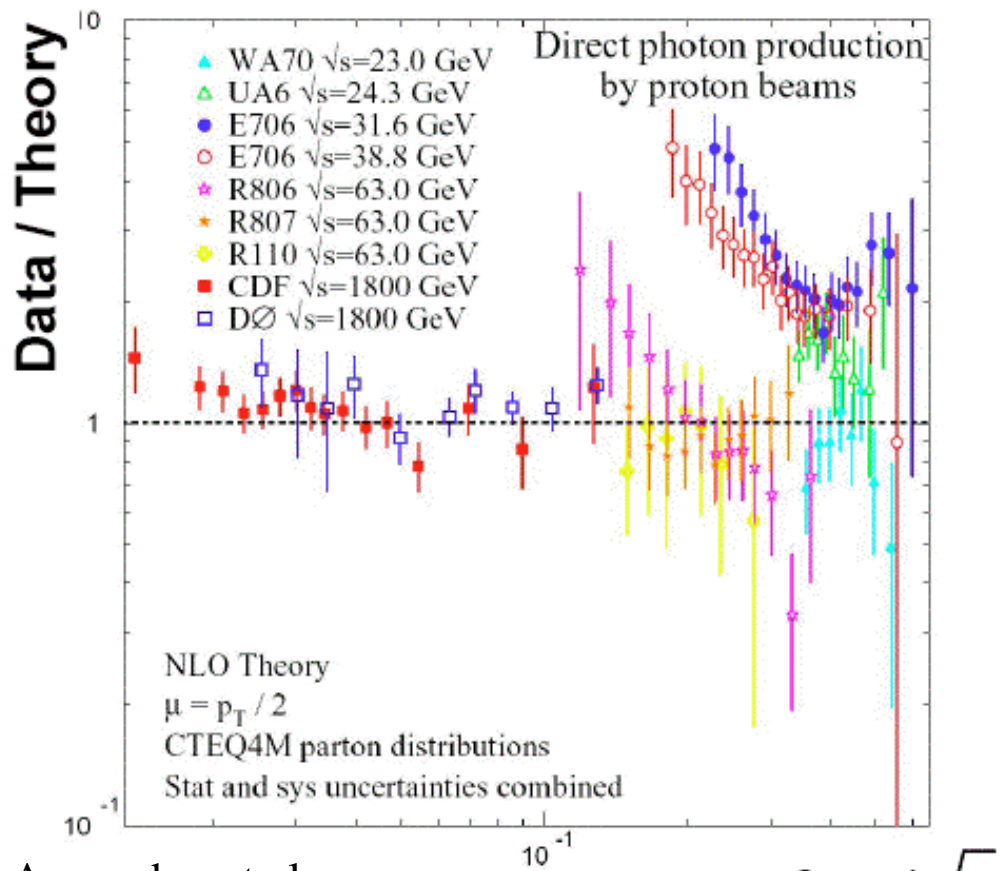
- Highly segmented lead glass **Cherenkov** Calorimeter
- Module size: 4 cm x 4 cm x 40 cm

Two Technologies - very important for systematic error understanding!

Differences:

- Different response to hadrons
- Different corrections to get linear energy response
- Different shower overlap corrections

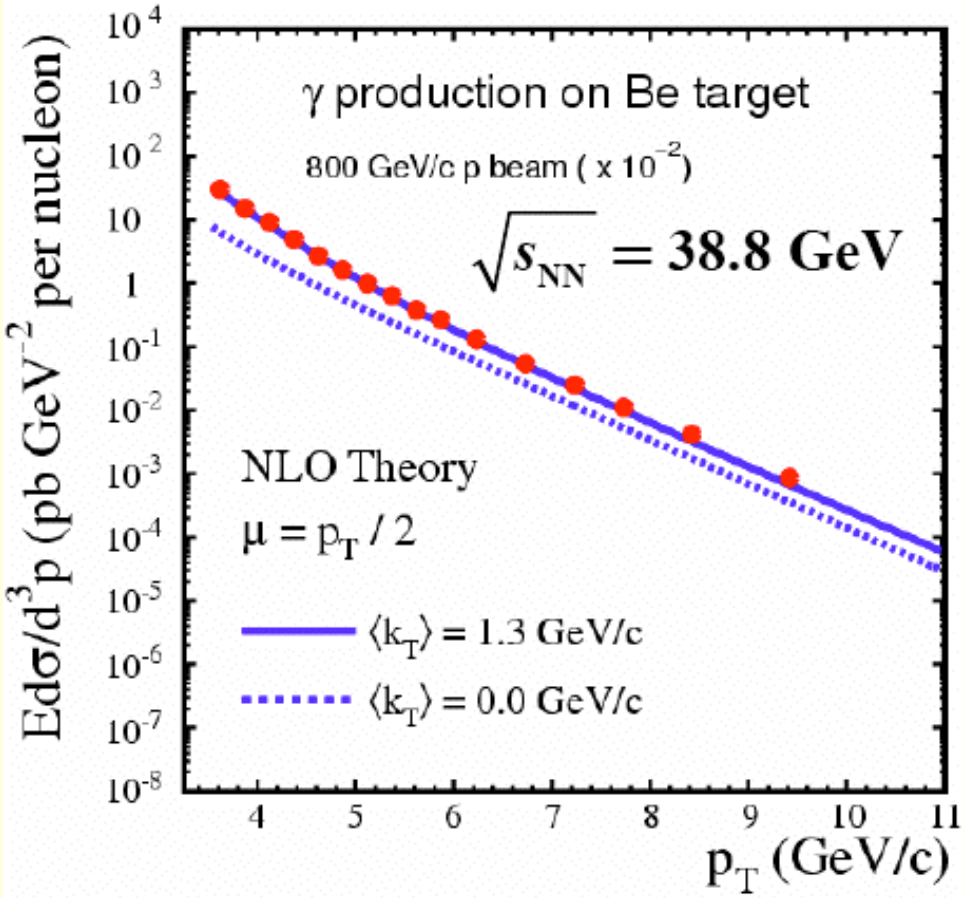
Direct Photons Summary: proton beams



Aurenche, et al.
hep-ph/0005226

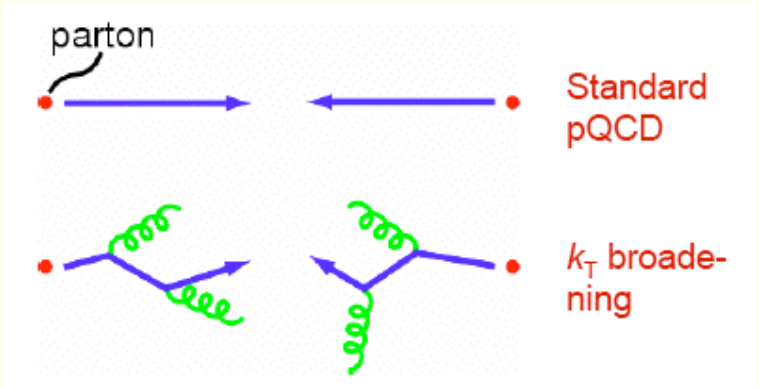
- Direct photon production can provide important information on gluon PDFs since gluons enter in lowest order diagram - gluon Compton (q+g-> q+γ).
- NLO works well at large sqrt(s) but not at low sqrt(s).
- Is there a systematic pattern?
- Data consistent? (experimental problem), or due to other effect such as "intrinsic k_T"

Evidence for K_T Broadening

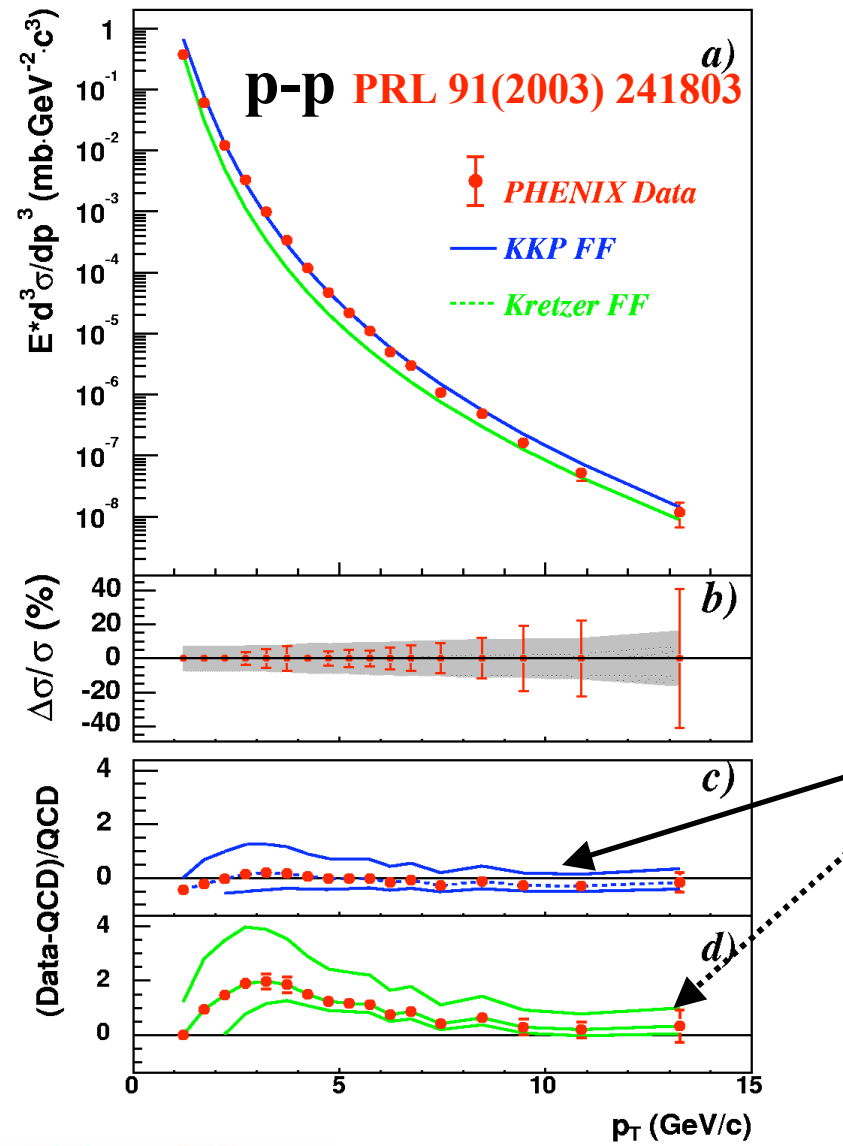


E706 PRD70 (2004) 092009

- Data from E706 fixed target experiment at FNAL cannot be explained by NLO predictions.
- The data can be described by the introduction of additional "k_T broadening" with $\langle k_T \rangle = 1.3$ GeV/c

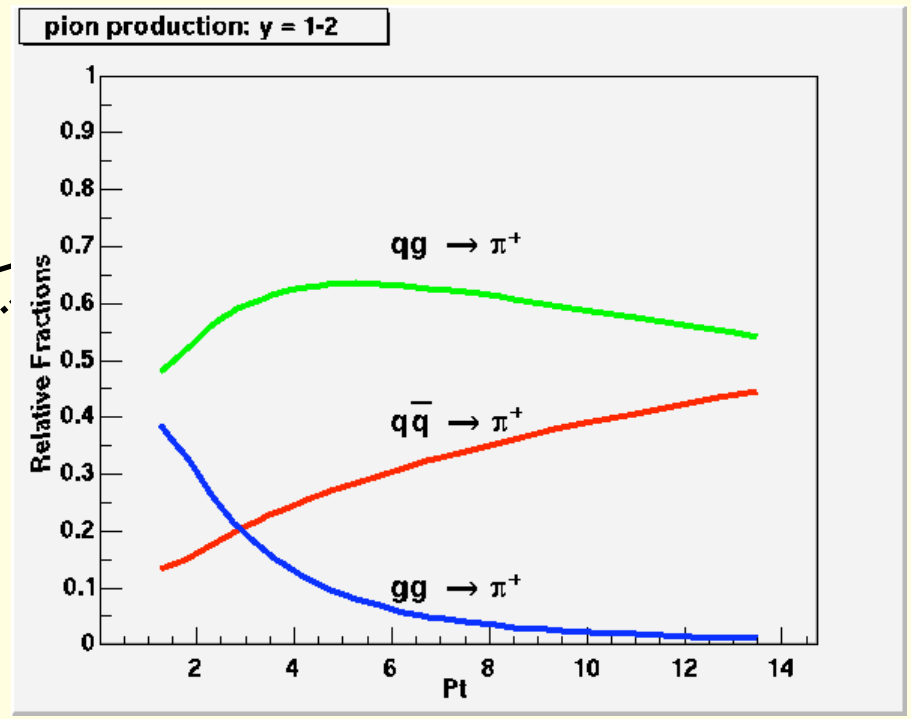


High-P_T π^0 spectra in p+p collisions at 200 GeV/c



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

pQCD works very well!



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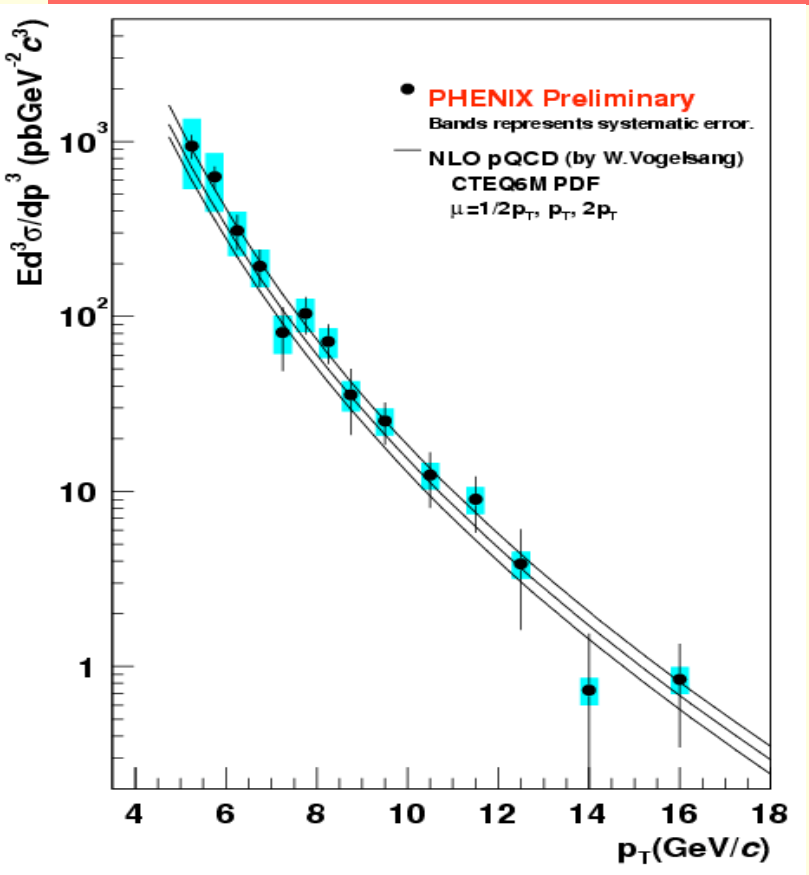
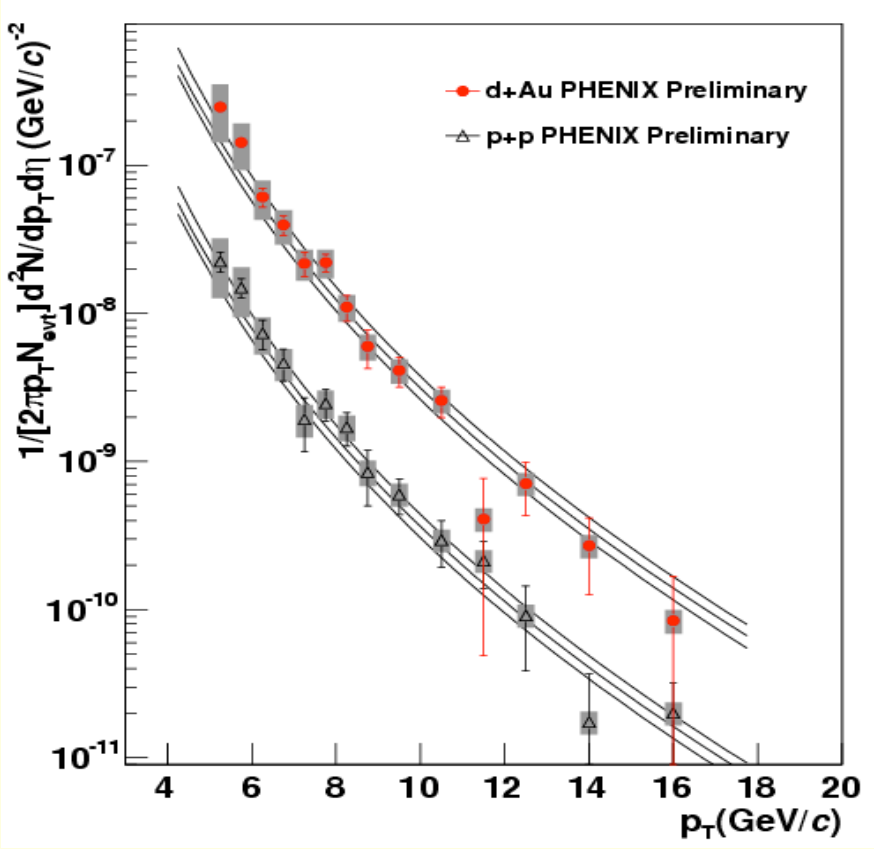
High-p_T γ in p+p (d+Au) Collisions at 200 GeV/c

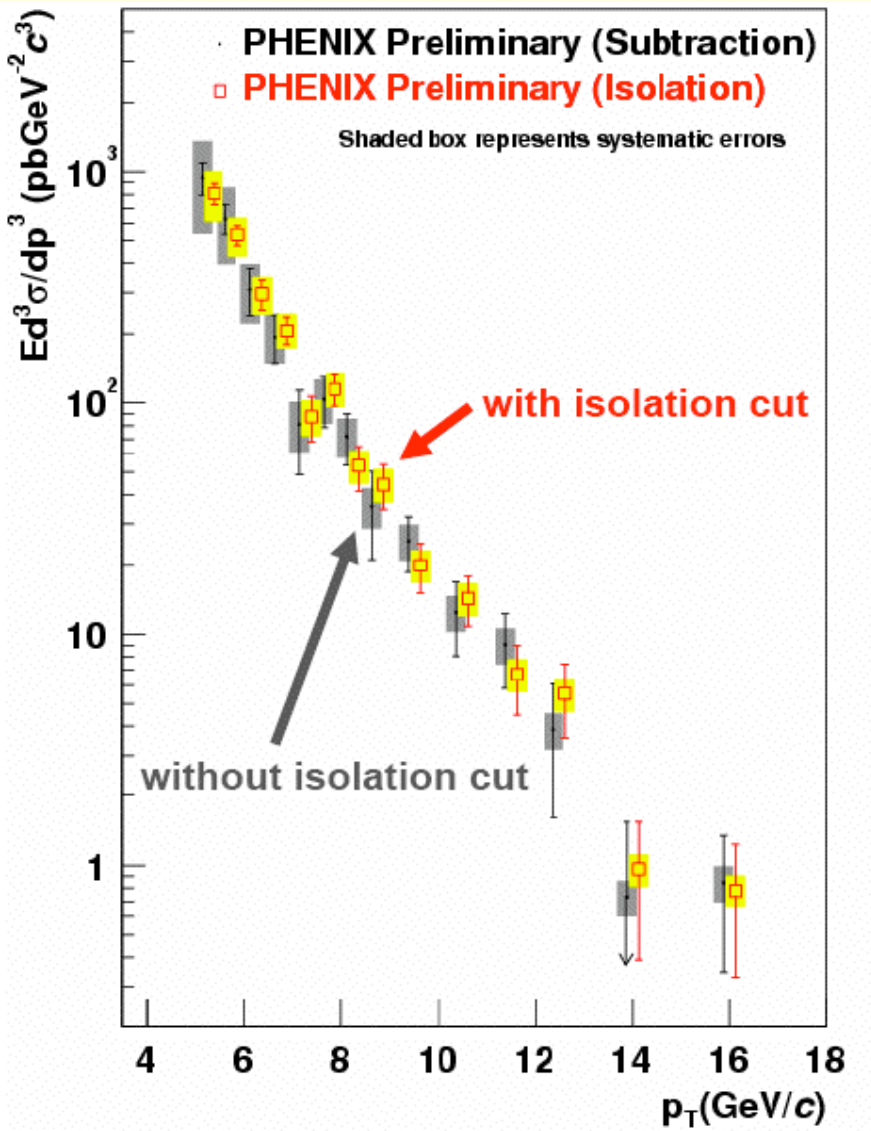




As observed for π^0 production, the preliminary direct photon measurement in p+p agrees with NLO pQCD calculations. The preliminary d+Au γ yield also agrees with $\langle N_{coll} \rangle$ -scaled NLO pQCD calculation.

Baseline for comparison with Au+Au γ results.

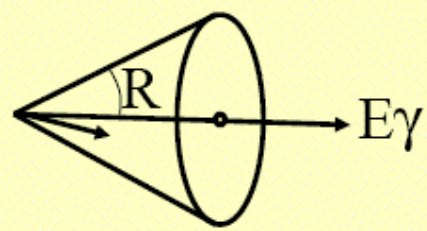
Isolating Fragmentation Component



- Remove contribution of γ produced from parton fragmentation by an isolation cut requiring no nearby activity (R<0.5).
- Problem: PHENIX acceptance is too small (Δϕ=90,|Δη|=.35)- no attempt to correct for cut efficiency.
- No significant difference (different analysis group).

$$R := \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

$$E_{sum}(R < 0.5) < E_\gamma \times 0.1$$



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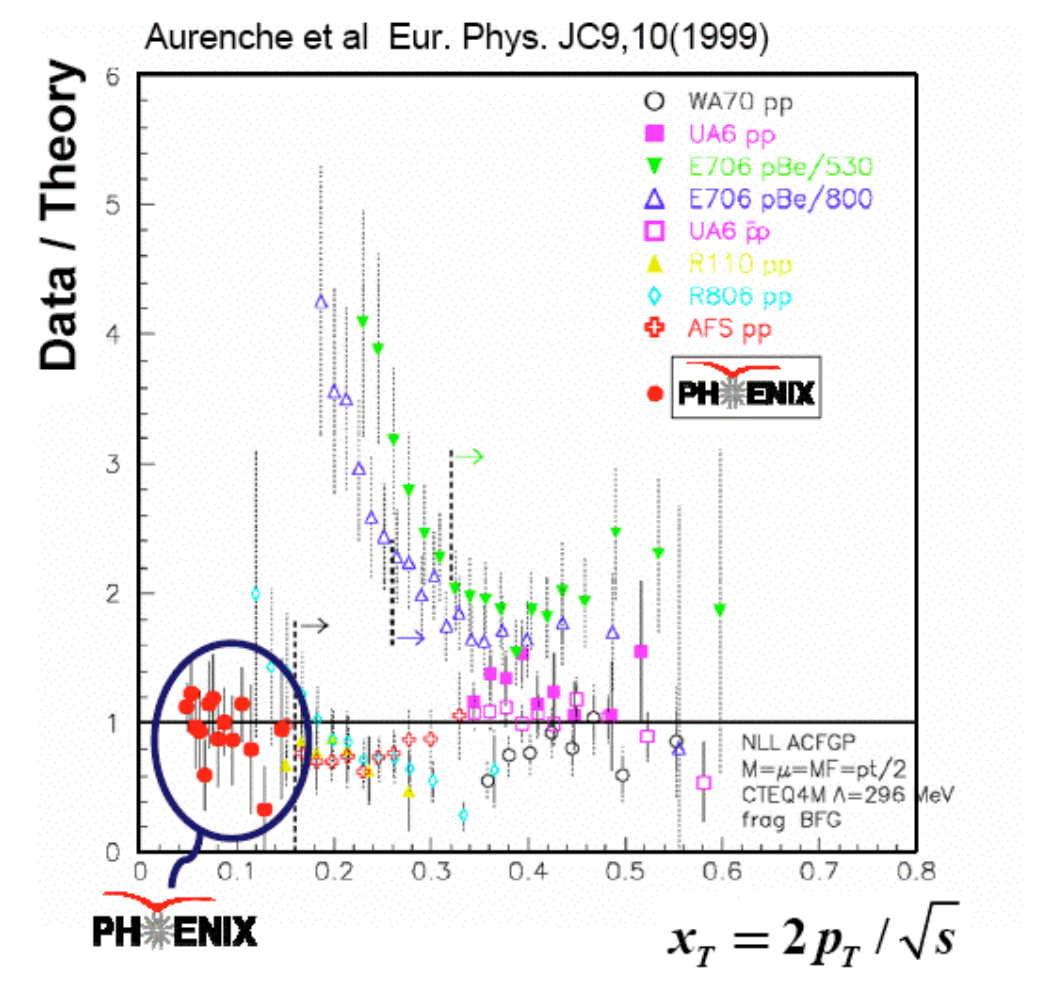
Direct Photon Summary: proton beams



- PHENIX data provide lowest x_T photon results to date (x_T<0.1)
- NLO works well without "intrinsic k_T".
- k_T effects appear to be important only at low sqrt(s).
- RHIC plans to run p+p at sqrt(s)=63 GeV as part of Run 6 and possibly at 20 GeV in the near future.

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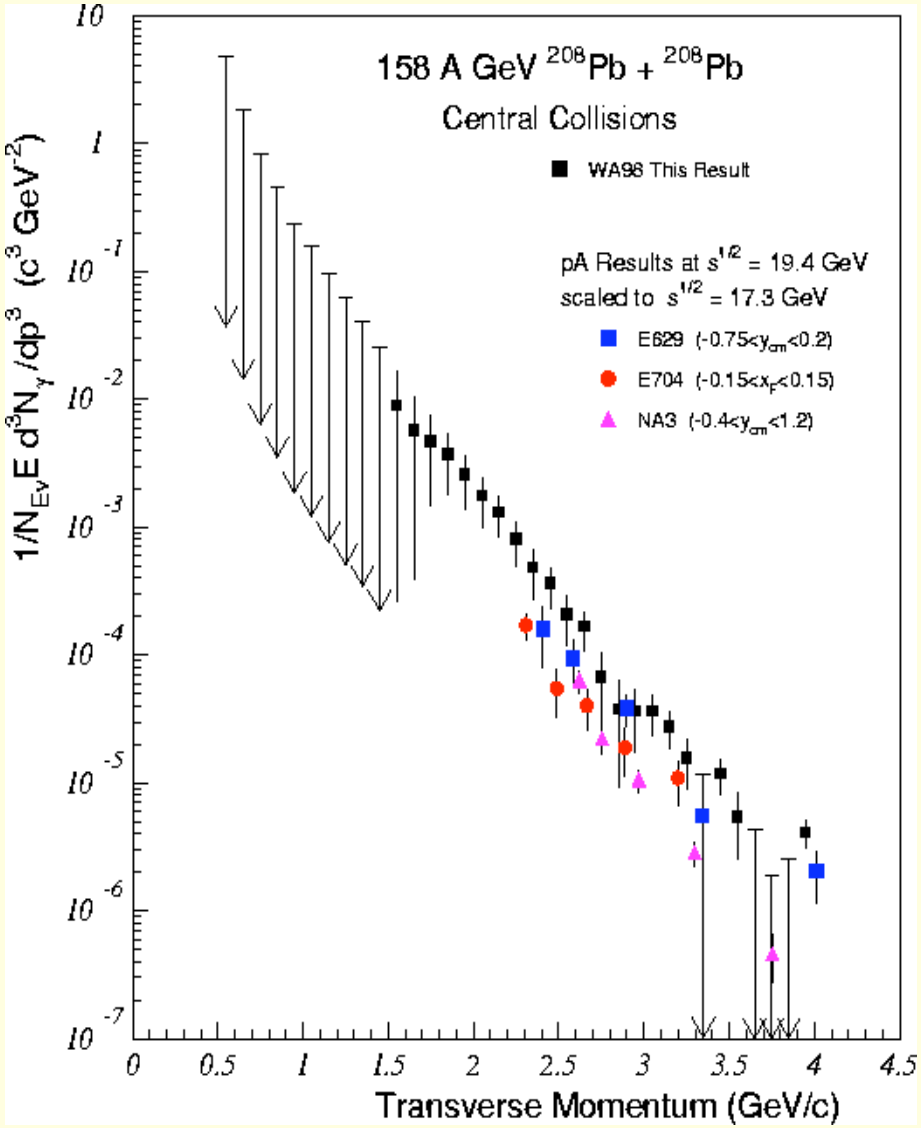
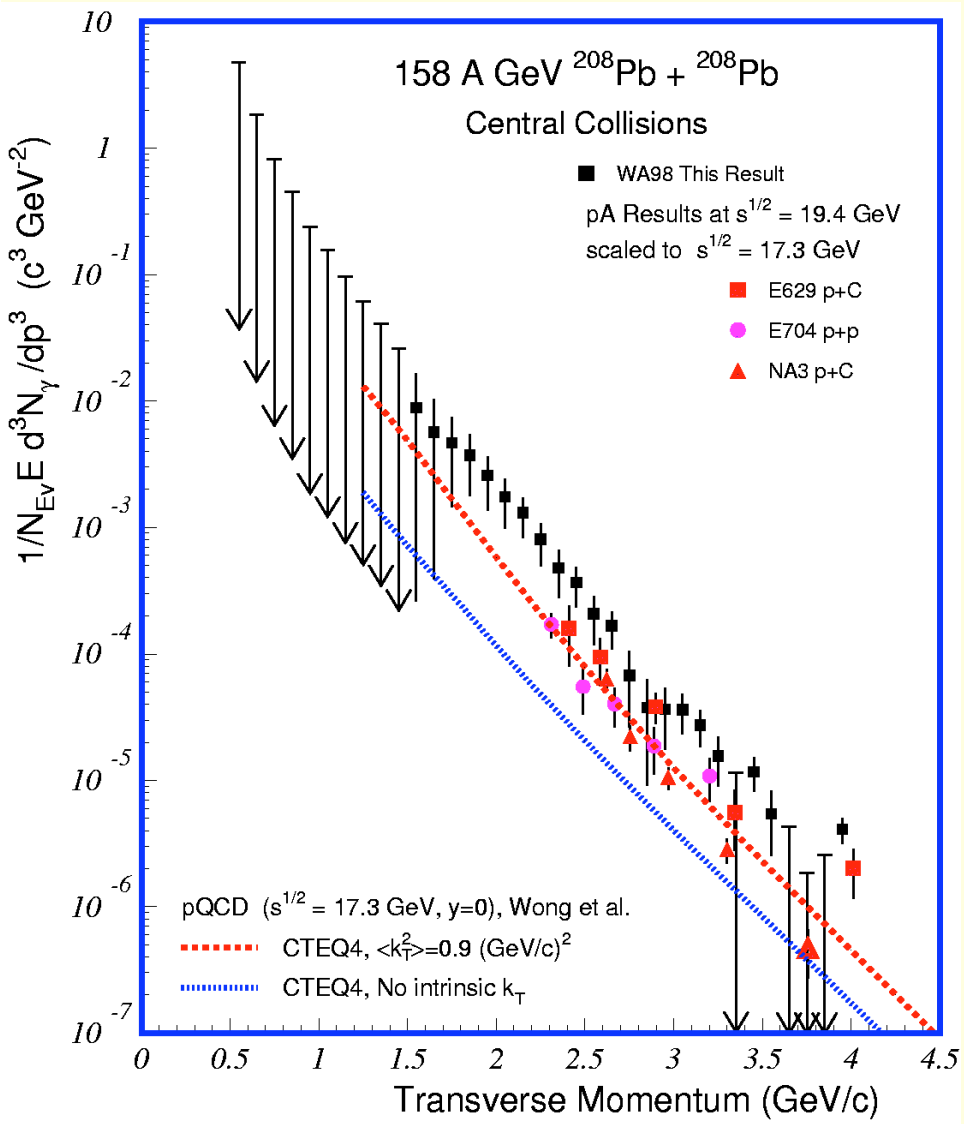
Lower sqrt(s): Central Pb+Pb Direct γ



- Compare to proton-induced prompt γ 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 γ spectral shape, but factor ~2-3 enhanced yield.

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

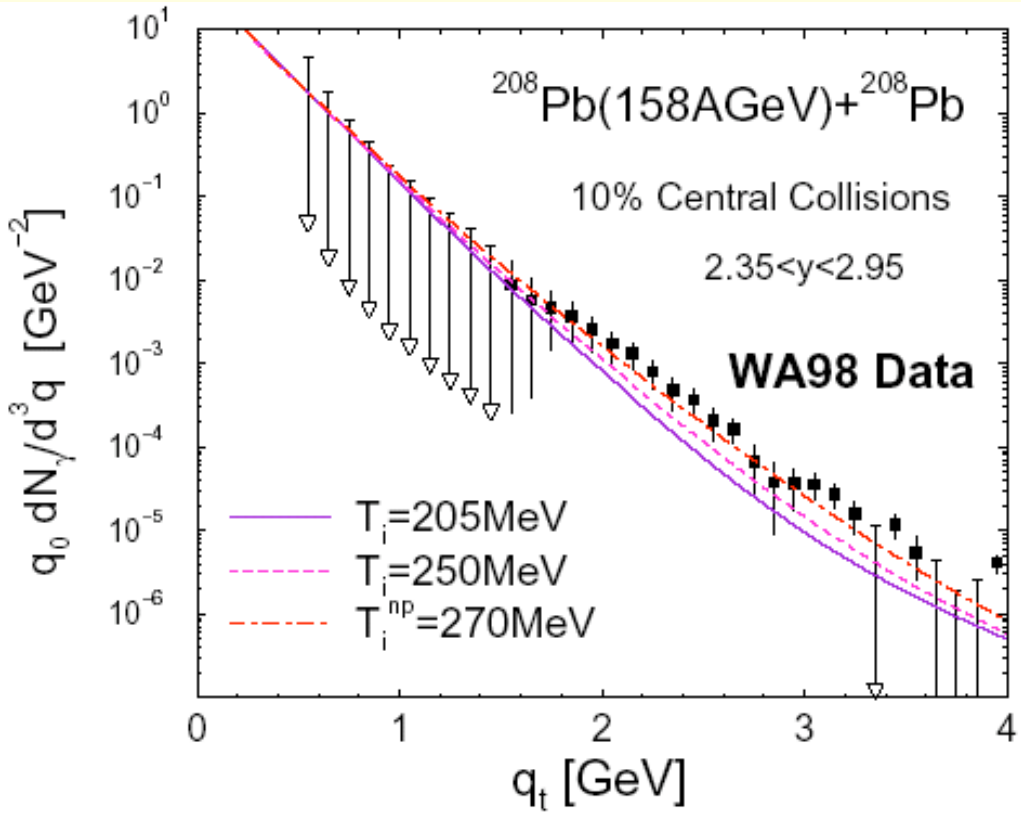
Direct γ: Comparison to pQCD Calculation



- NLO pQCD calculations factor of 2-5 below $s^{1/2}$ =19.4 GeV p-induced prompt γ results (not shown in previous systematics).
- 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.

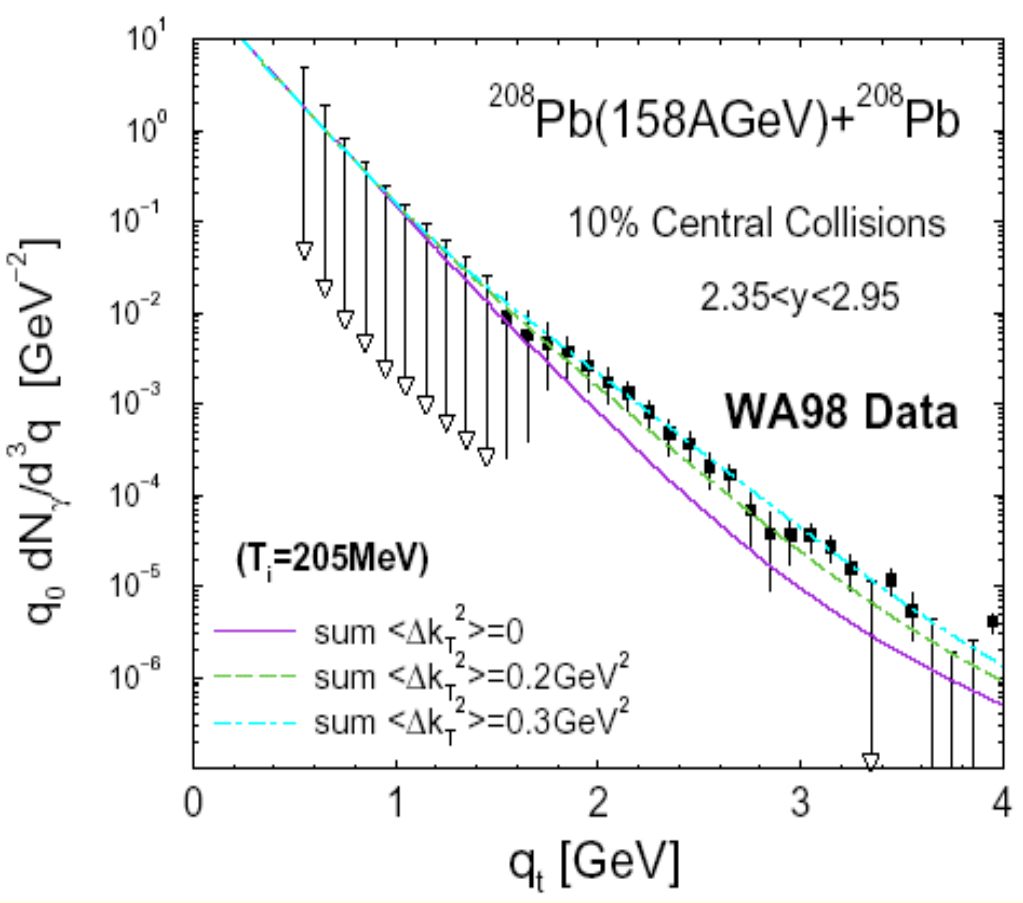
Photons - Initial Temperature



- pQCD (with k_T to fit p+p) plus Fireball thermal contributions with T_0=205MeV (τ_0=1fm/c) underpredicts observed excess.
- Better agreement assuming T_0=250MeV (τ_0=0.5fm/c).
- Better still taking into account d.o.f. reduced by 20% as according to lattice. T_0=270MeV (τ_0=0.5fm/c).

Turbide et al., PRC69(2004)014903.

Photons - k_T Broadening

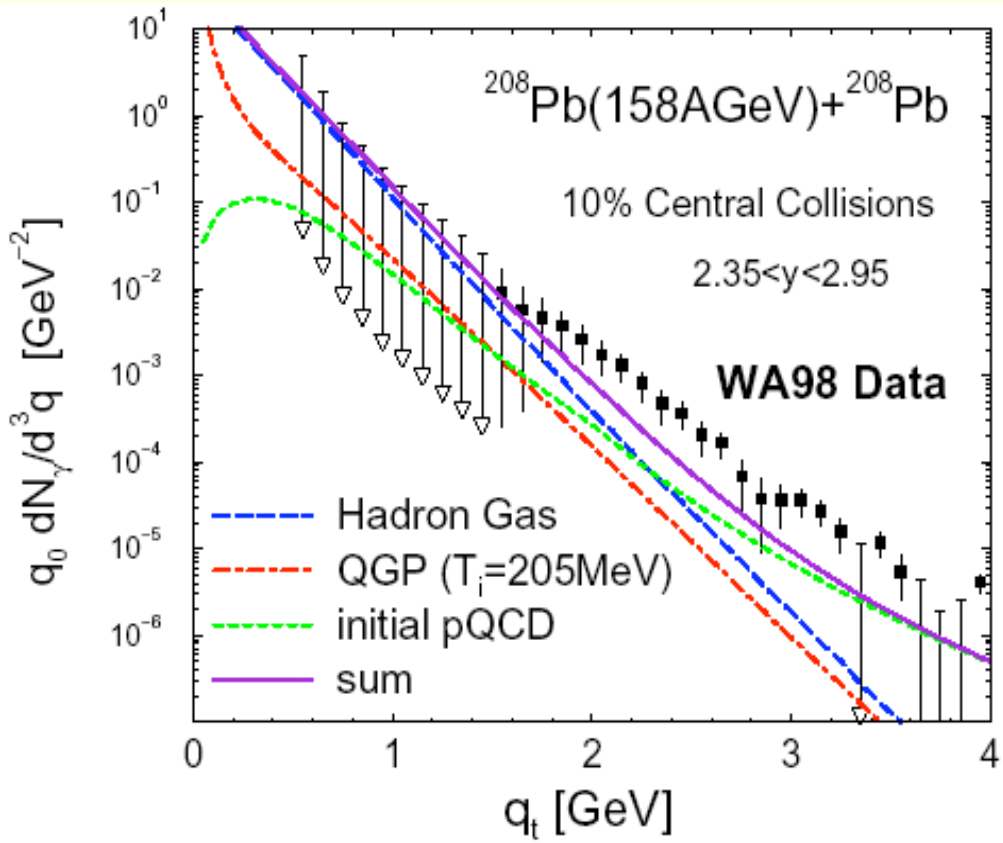


Turbide et al., PRC69(2004)014903.

- pQCD-calculations
  - * Fit intrinsic k_T in pp (E704)
- k_T - broadening in Pb+Pb

  $\Delta k_T^2 \sim 0.3\ GeV^2$
  - * Magnitude "consistent" with expectations from pA
- Conclusion: Large part of excess could be due to k_T-broadening...

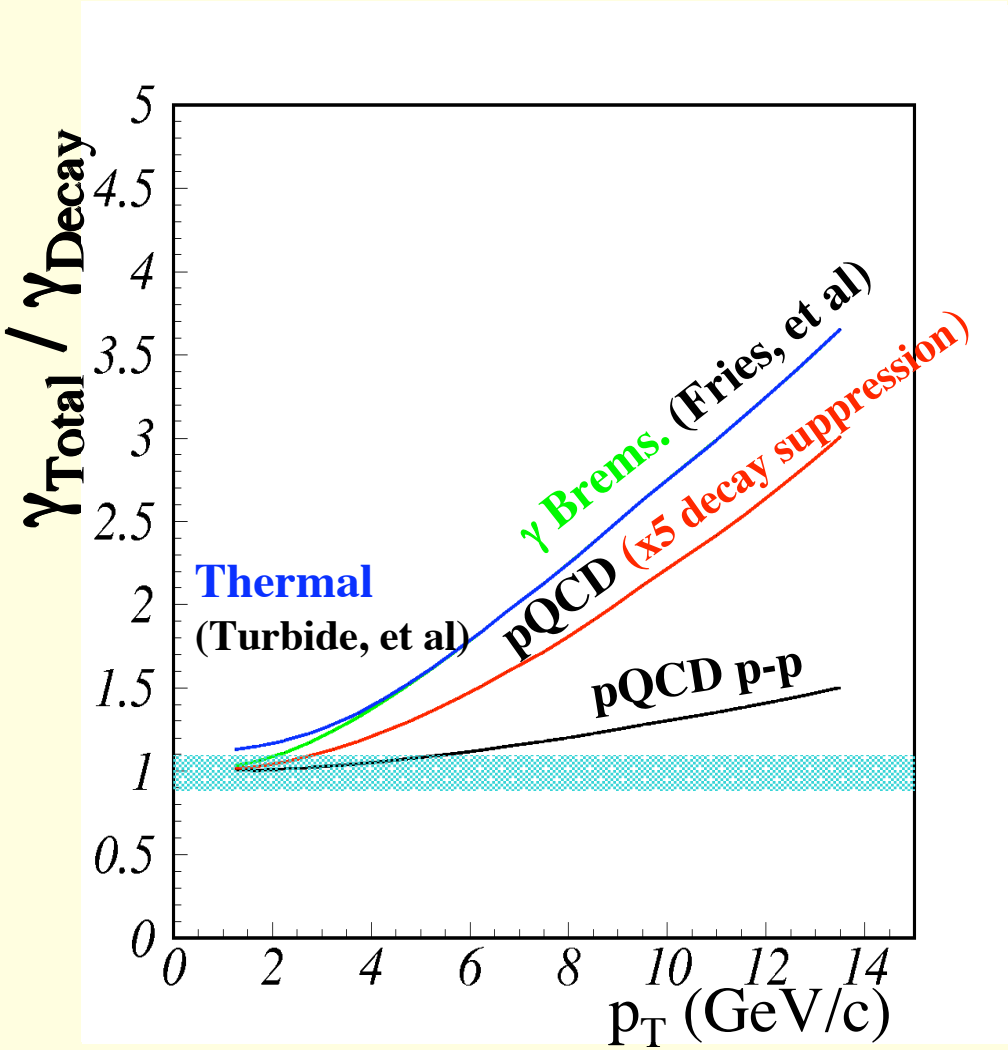
Direct γ Conclusions at SPS Energy

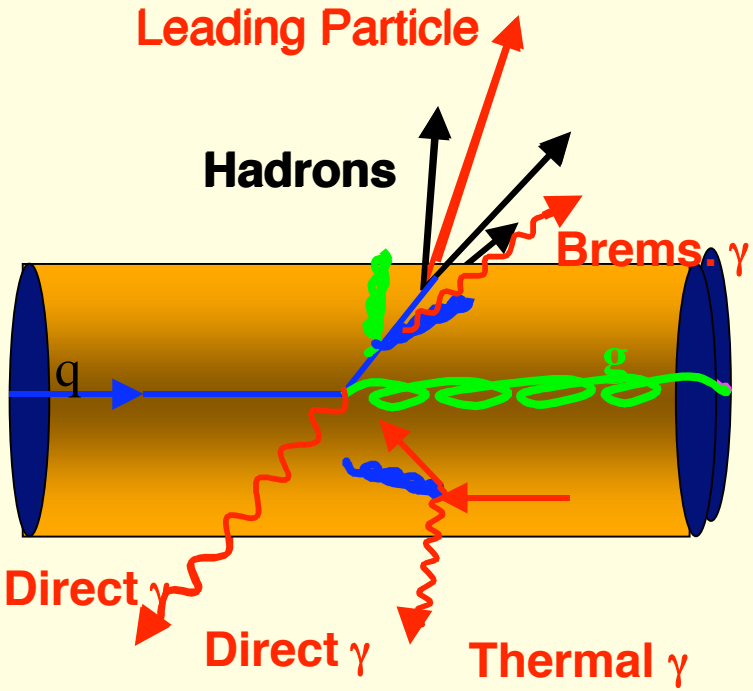


Turbide et al., PRC69(2004)014903.

- **Full Hydro can describe π^0 and γ 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_T broadening
  - preequilibrium
  - QM γ rates: (under control!)
  - HM γ rates: in-medium masses
  - Hydro evolution: flow
- **Need further experimental constraints:**
  - Hadron spectra
  - dileptons (CERES,NA50)
  - pA results (WA98)
  - Results from RHIC

Direct Photon Expectations at RHIC





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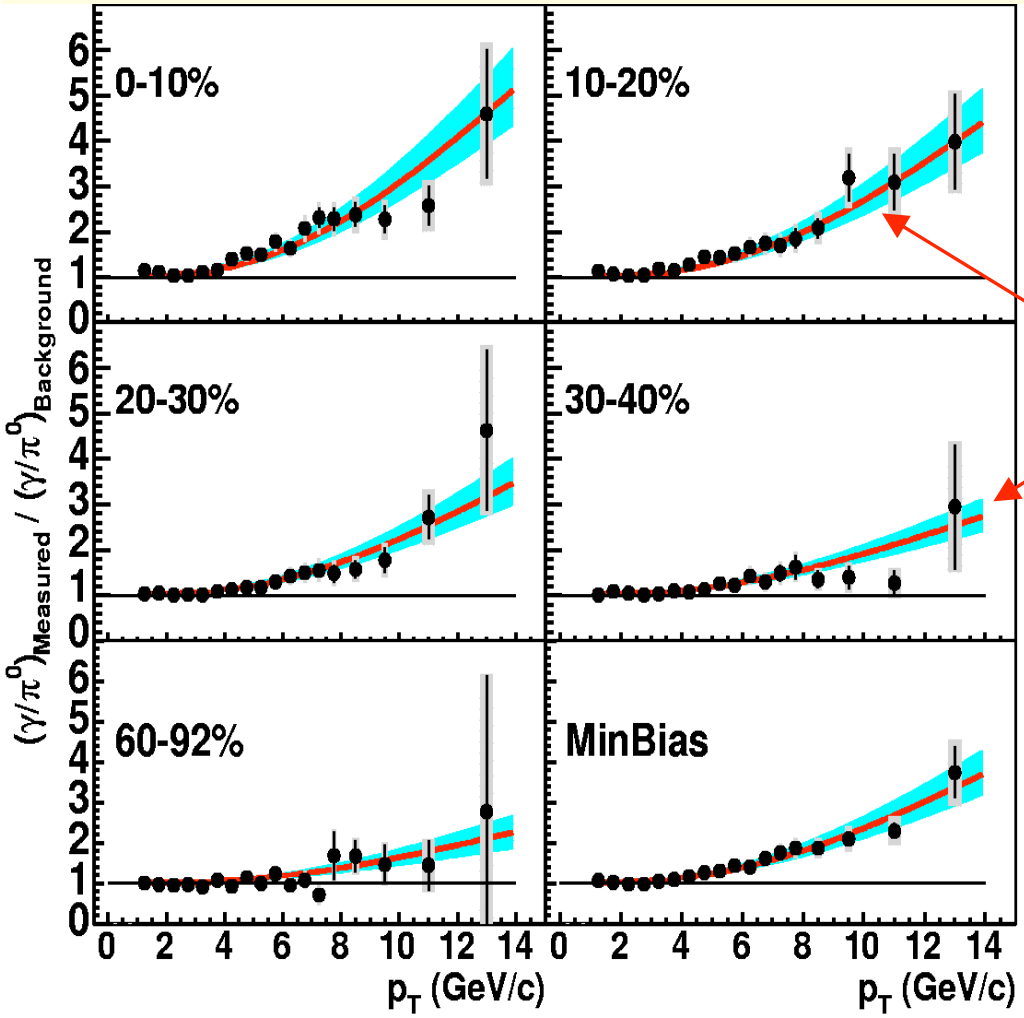
First RHIC Au+Au Direct Photon Results



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

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

- 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 $\gamma^{\text{Direct}}/\gamma^{\text{Decay}}$, making direct photons much easier to measure!
- Fragmentation?, Bremsstrahlung?, Thermal?

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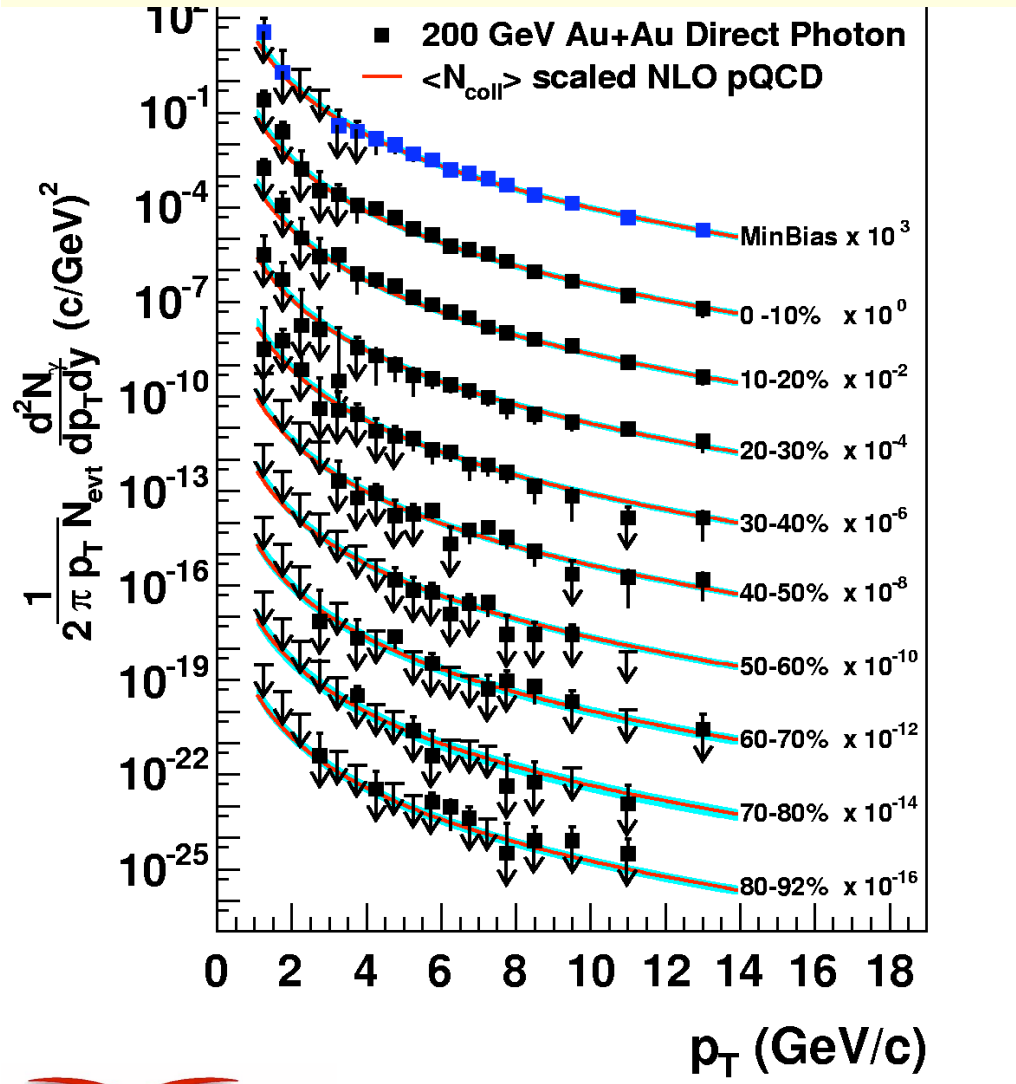
PHENIX PRL 94, 232301 (2005)

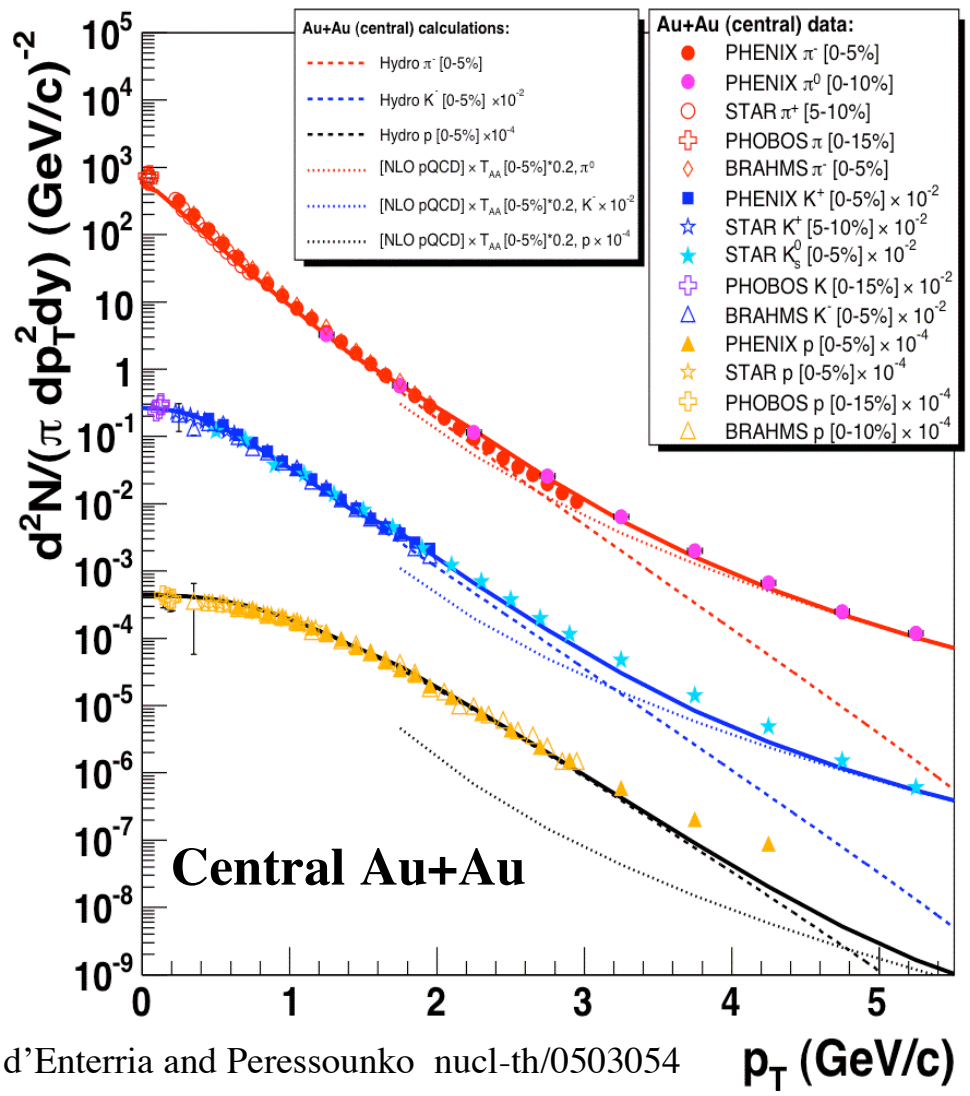
Centrality Dependence of Direct Photons



- 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

PHENIX PRL 94, 232301 (2005)

Thermal Photon Expectations?



d'Enterria and Peressounko nucl-th/0503054

- Use recent Hydrodynamical Model calculation to compare measured γ yields to thermal γ prediction.
- Good description of π, K, p production

Parameters:

$\tau_0 = 0.15$ fm/c (Effectively inlcudes PreEquil.)

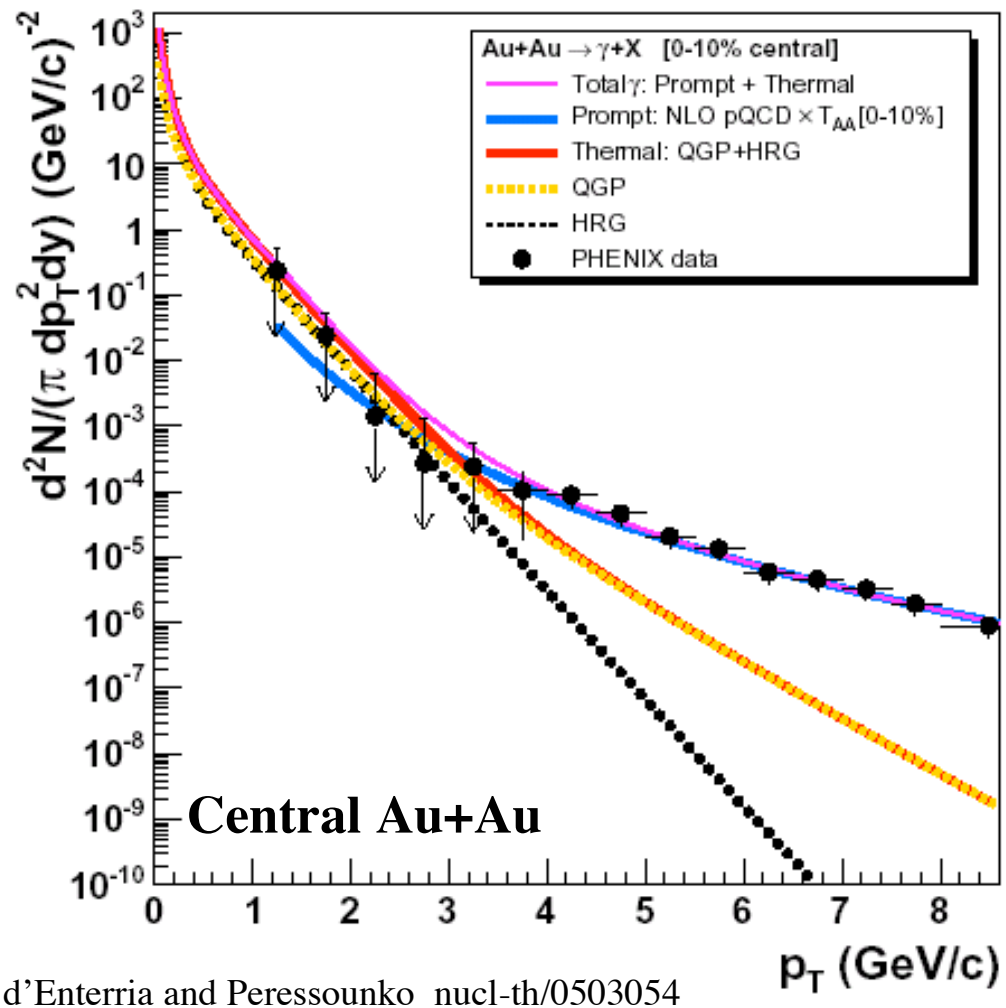
$\varepsilon_0 = 220$ GeV/fm^3 ($< \varepsilon_0 >$=72 GeV/fm^3)

$T_0 = 596$ MeV ($<T_0>$=378 MeV)

$T_{critcal} = 165$ MeV

$T_{fo} = 120$ MeV

Thermal Photon Expectations?



d'Enterria and Peressounko nucl-th/0503054

- Hydrodynamical predictions for thermal γ (HRG + QGP) plus prompt NLO pQCD prediction yields.
- Measured γ yield is consistent with NLO pQCD prediction with or without thermal contribution…it will be difficult to extract thermal γ.
- Confirms large number of degrees of freedom, as in QGP
- NLO pQCD works too well!? Fragmentation γ contributions are large (~50% at 3 GeV/c, 35% at 10 GeV/c). Should be suppressed, but additional quark bremstrahlung compensates?

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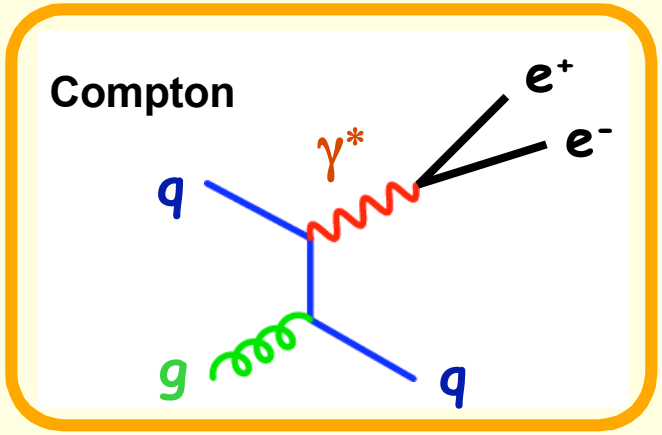
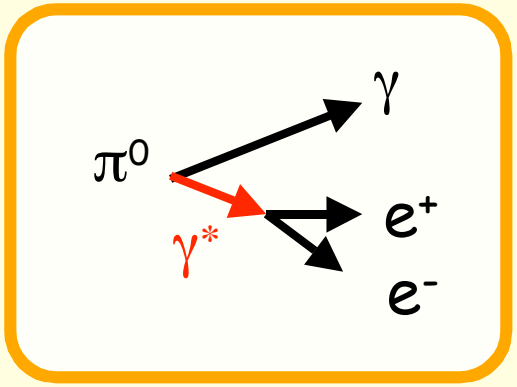
A New Approach: Measure Thermal Virtual Photons



Use lepton pairs to measure virtual γ

Any source of real γ's emits virtual γ's, mostly with very low mass.
(But, converse is not true!)



Background from Dalitz decay

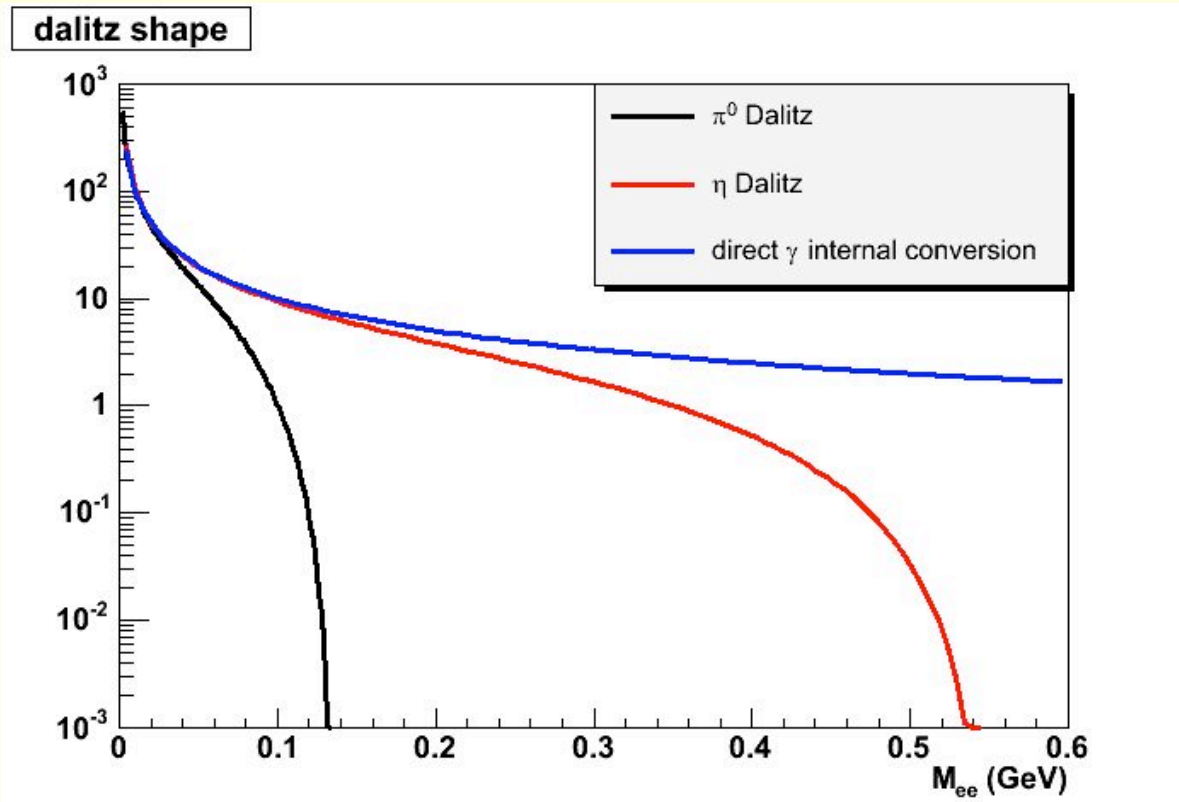
PHENIX features:

- **Low conversion rate**
- **Excellent mass resolution**
- **High statistics in Run2004**

Inv. Mass Distribution of e+e- Dalitz Pairs

$$\frac{1}{N_\gamma}\frac{dN_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi}\sqrt{1-\frac{4m_e^2}{m_{ee}^2}}\left(1+\frac{2m_e^2}{m_{ee}^2}\right)\frac{1}{m_{ee}}\left|F(m_{ee}^2)\right|^2\left(1-\frac{m_{ee}^2}{M^2}\right)^3$$

Kroll-Wada Formula

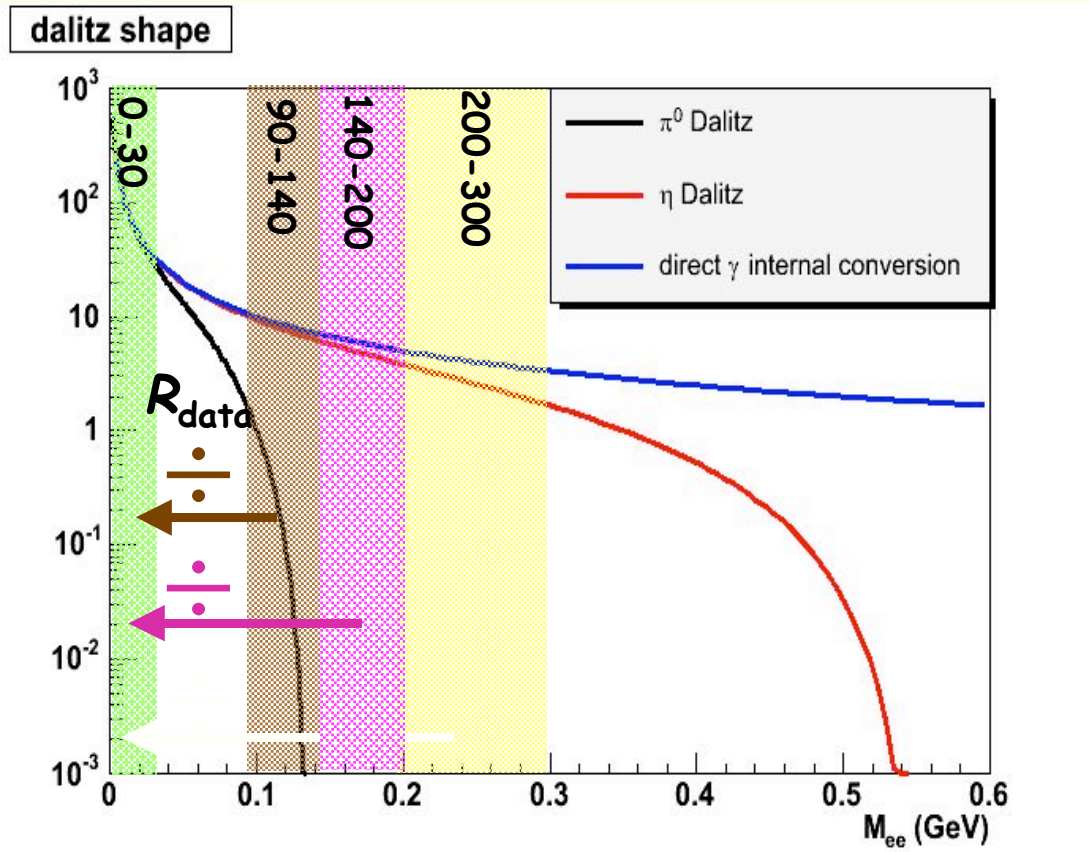


Form factor (π^0,η)= 1 at low mass for high p_T internal conversion γ

Phase space factor = 1 at low mass for high p_T internal conversion γ

Shape of low mass region is process independent.

Inv. Mass Distribution of Dalitz Pairs

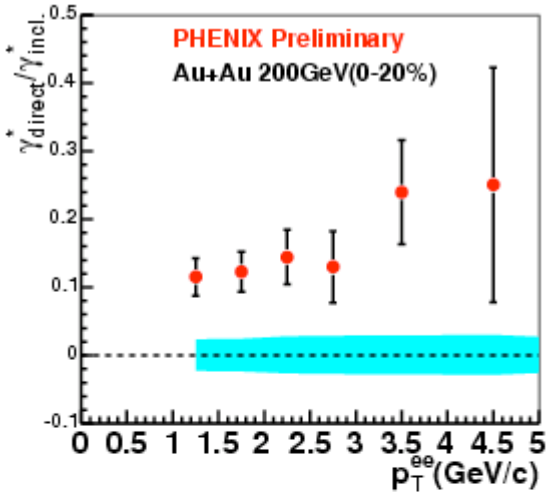


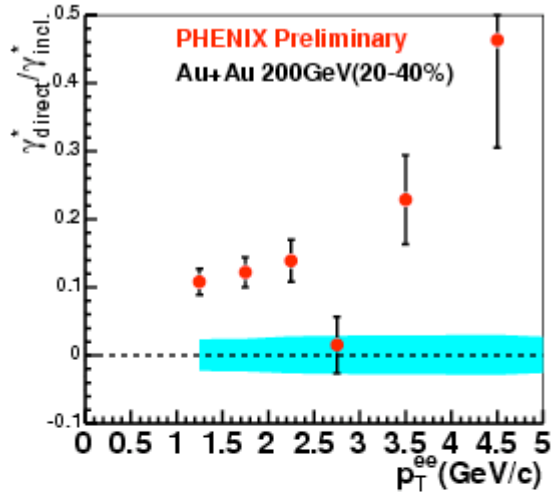
- Analyze yield ratios R in different M_{ee} mass bins
- Ratios of M_{ee} yields can be calculated from formula for π and η Dalitz. Use Monte Carlo for all Bkgd γ
- Note π^0 background is essentially removed in high mass bins. Remove π^0 background at cost of α_e in yield. A possible advantage if systematic error dominated.

$$\frac{N^{0-30}_{\gamma^*_{Direct}}}{N^{0-30}_{\gamma^*_{All}}} = \frac{R_{Data} - R_{Bkgd}}{R_{Direct} - R_{Bkgd}} \cong \frac{N_{\gamma^*_{Direct}}}{N_{\gamma^*_{All}}} \cong \frac{N_{\gamma_{Direct}}}{N_{\gamma_{All}}}$$

$\gamma^*_{direct} / \gamma^*_{inclusive}$

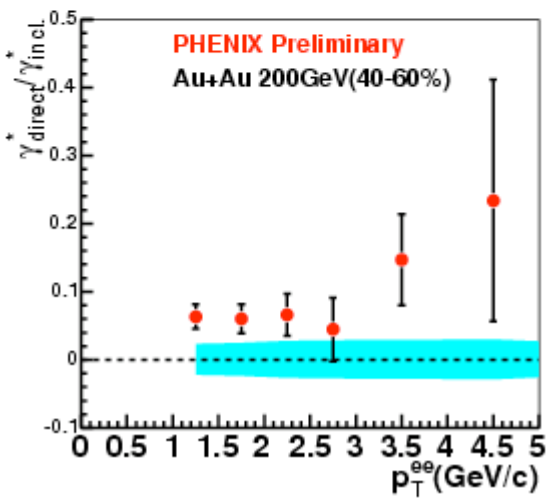
0-20%

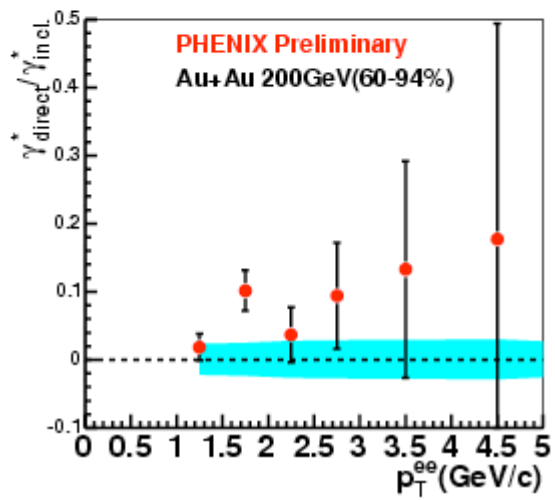




20-40%

40-60%





60-94%

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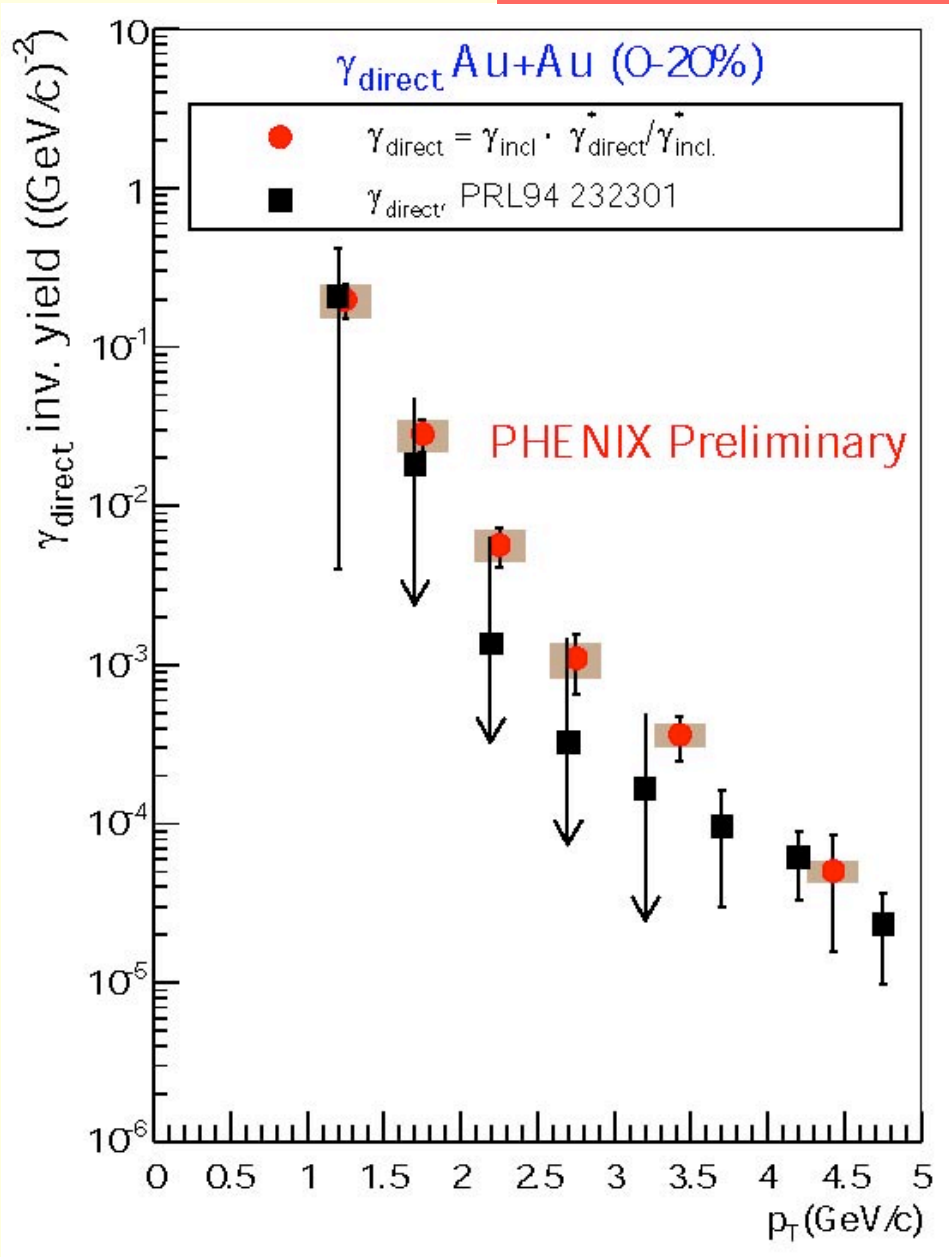
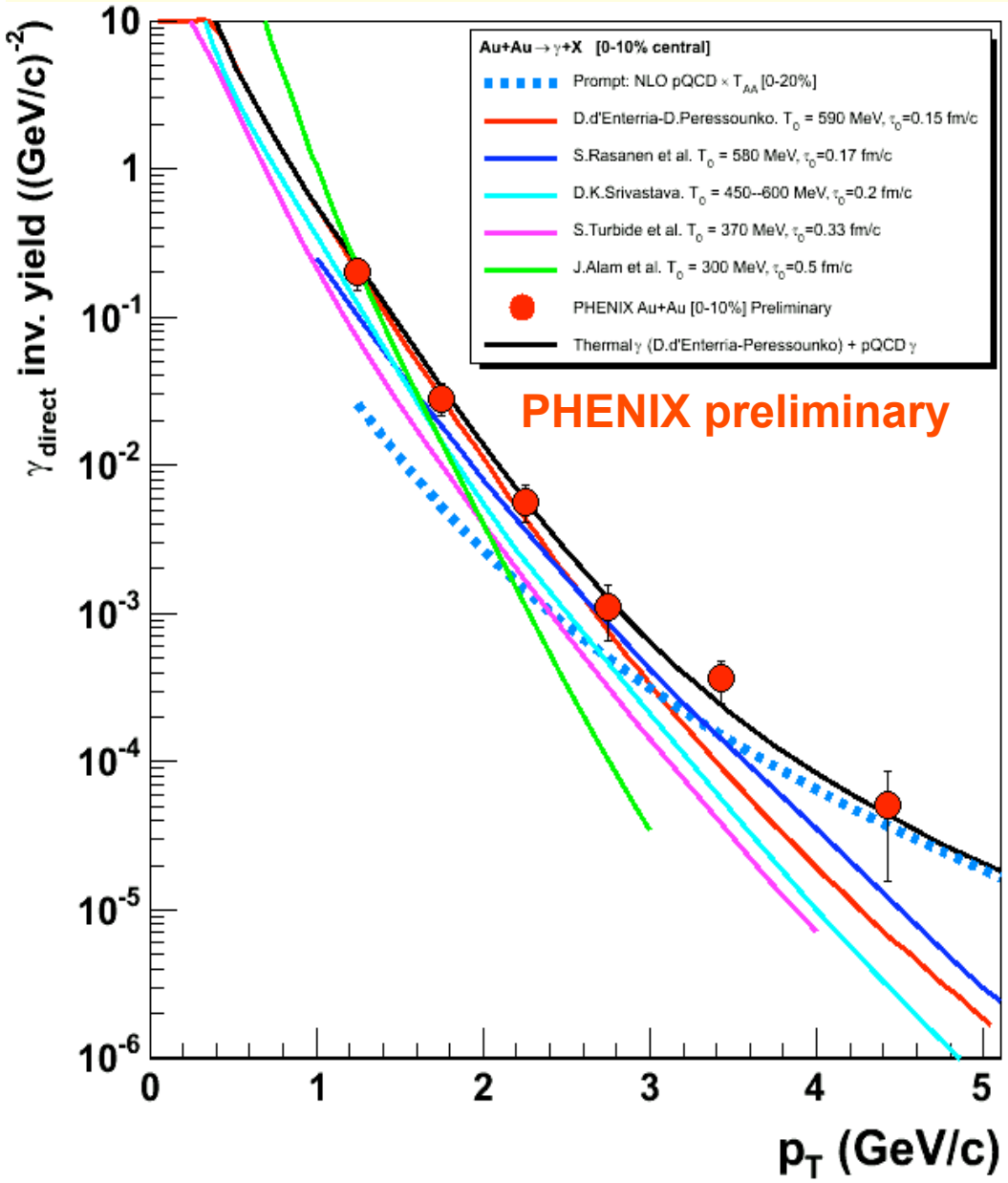
Extracting the Yield



$$\gamma_{direct} = \gamma_{incl.}(\gamma^*_{direct} / \gamma^*_{incl.})$$

Run2 data:
Phys. Rev. Lett. 94, 232301 (2005)

Thermal Photons: Model Comparisons

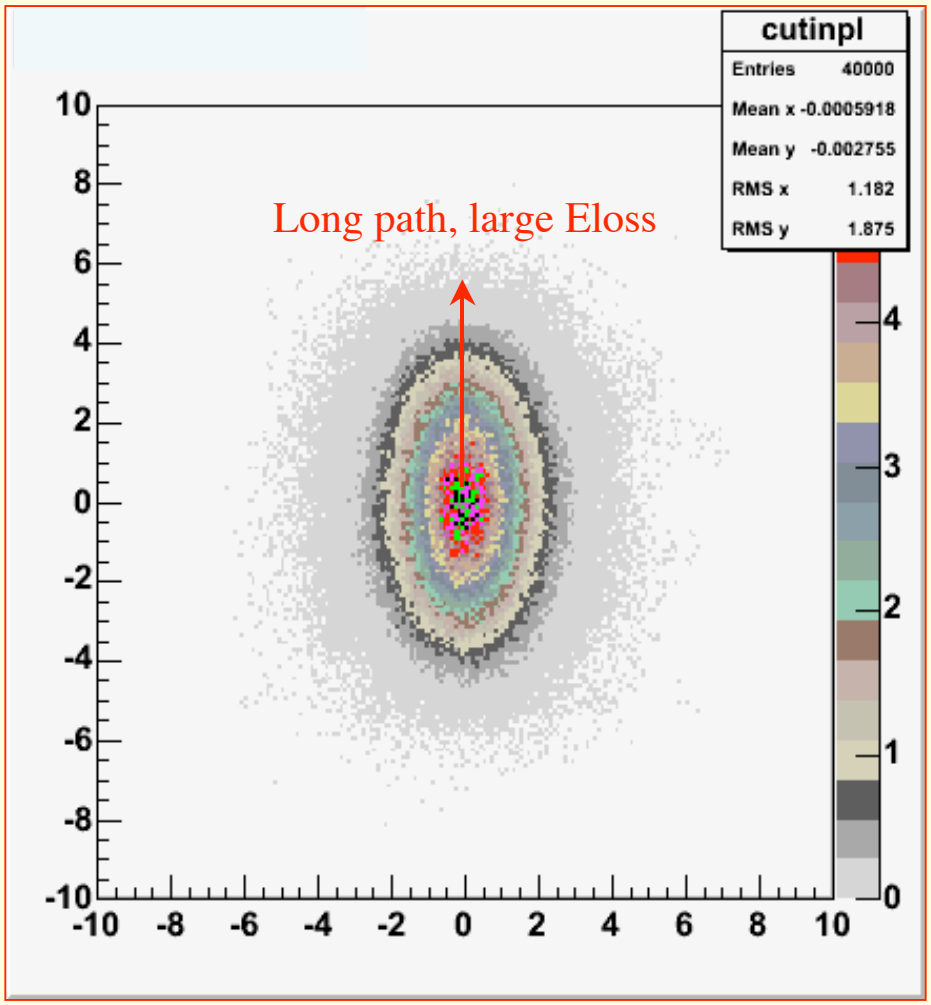


- Preliminary result from higher statistics Run4 data set using virtual photon measurement.
- Can deduce that the photon yield is consistent with various predictions with
  $T_0^{max} \sim$ 500-600 MeV
  $T_0^{ave} \sim$ 300-400 MeV

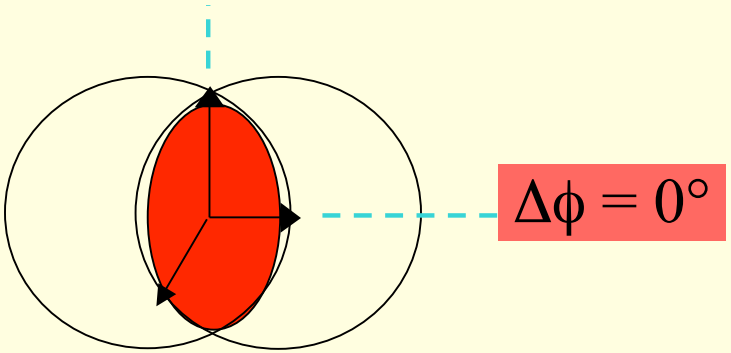
Future γ studies in PHENIX

- Thermal region:
  * Improve errors (~x15 statistics from Run 4)
  * Other techniques - γ–γ HBT, conversions
  * 62 GeV Au+Au, better signal/background? (Run 4 ~ Run 2)
- Measure Fragmentation contribution in p+p:
  * Improve p+p measurement (~x15 statistics from Run 5)
  * Perform direct γ analysis with/without isolation cuts
- Measure direct γ vs Reaction Plane in A+A:
  * q+g Compton isotropic, Thermal flows, Fragmentation enhanced or suppressed with pathlength?
- Measure γ+jet :
  * The γ measures p_T of the recoiling parton - measure modified recoil Fragmentation Function to extract parton energy loss directly.

Investigate γ, π^0 yields vs Reaction Plane (Pathlength)

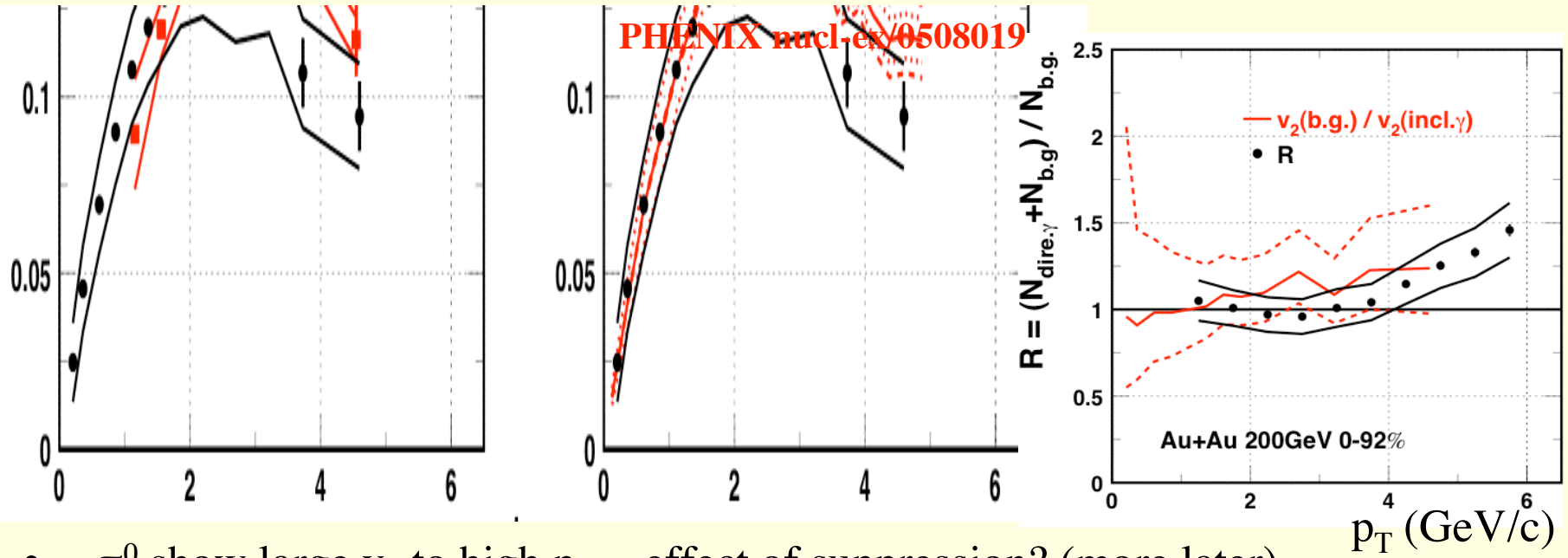


$\Delta\phi = 90°$



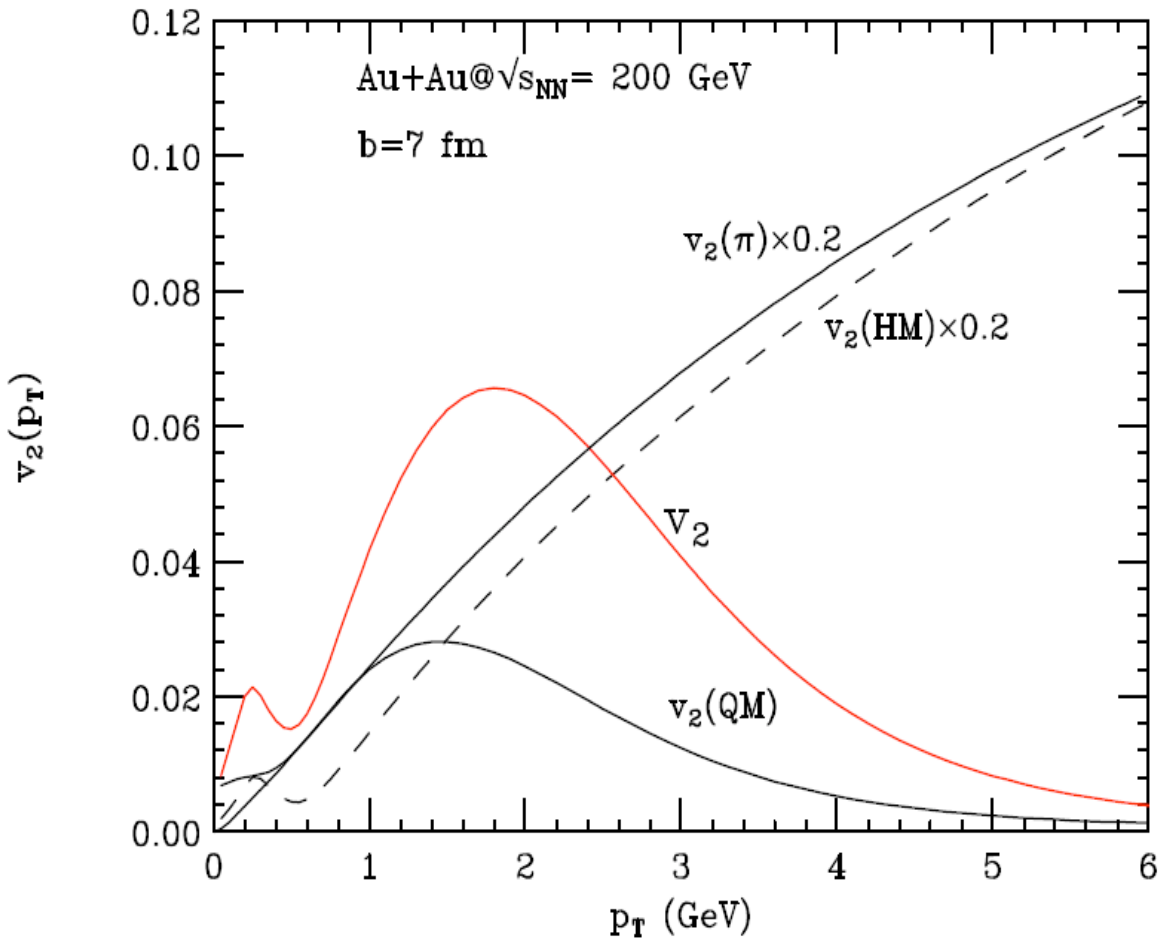
- Measure Reaction Plane using BBCs
- Measure Yields vs. orientation w.r.t. RP $\Delta\phi$
- Expect largest E-loss or suppression at $\Delta\phi = 90$ in " long" direction
- Interplay between flow (v_2) and Supression? Both give expectation of in-plane enhancement.

π^0 and inclusive γ v_2 analysis



- π^0 show large v_2 to high p_T - effect of suppression? (more later)
- Inclusive γ show similar large v_2
- Use π^0 measurement as input to MC to predict decay γ v_2 - if no direct γ signal, or v_2(direct γ) = v_2(bgd γ), then should have v_2(bgd γ) = v_2(incl γ)
- Use Direct γ measurement $R=\gamma^{Total}/\gamma^{Decay}$ then
  - $v_2(\text{direct } \gamma) = (R*v_2(\text{incl } \gamma) - v_2(\text{bgd } \gamma)) / (R-1)$
- Or, assume v_2(direct γ) = 0 to extract R. Gives agreement with measurement of R=0 in this p_T range. (Proof of principle at this point)

Elliptic flow of thermal γ

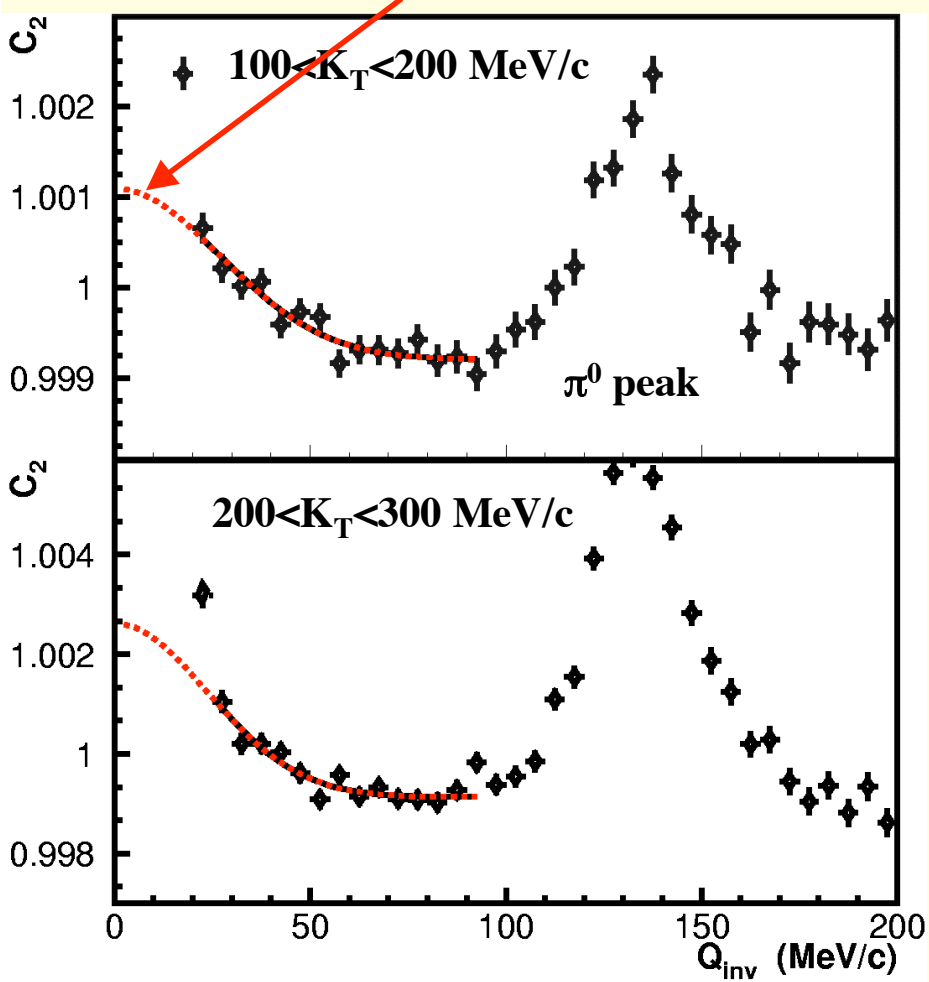


Chatterjee et al, nucl-th/0511079

- P_T dependence of v_2 for HM and QM very different. QM γ v_2 different shape than HM γ v_2 , which is similar to π^0 v_2.
- Measurement of direct γ v_2 signal might be clean way to extract QM information - initial T and lifetime.

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

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



PRL93(2004)022301 WA98, Aggarwal, et al
Analysis: D.Peressounko

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:

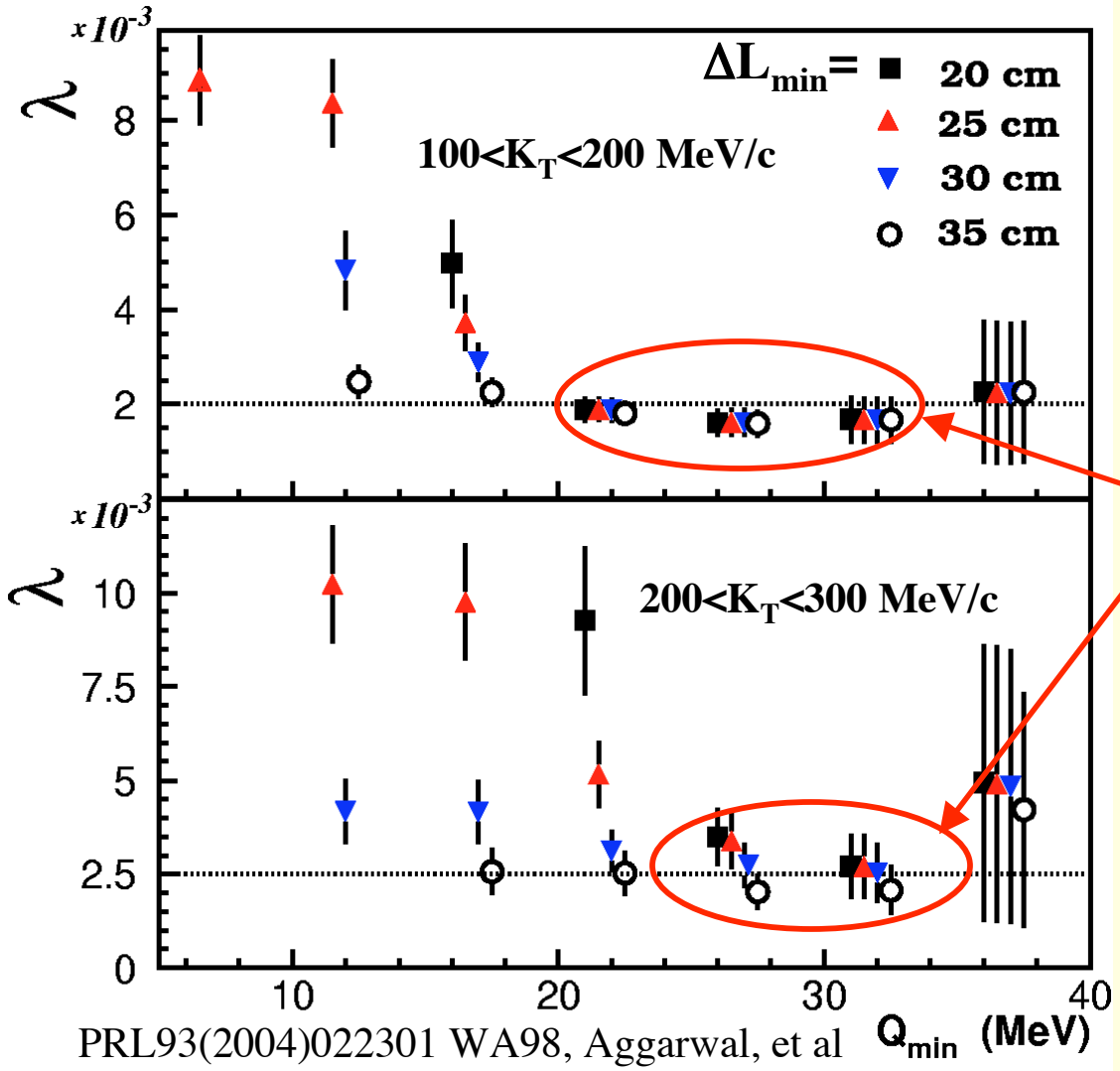
> False splitting of showers

> Photon conversions

Must make min distance cut ΔL_{min}

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

ΔL_{min} Dependence of $\gamma-\gamma$ Correlation Strength λ



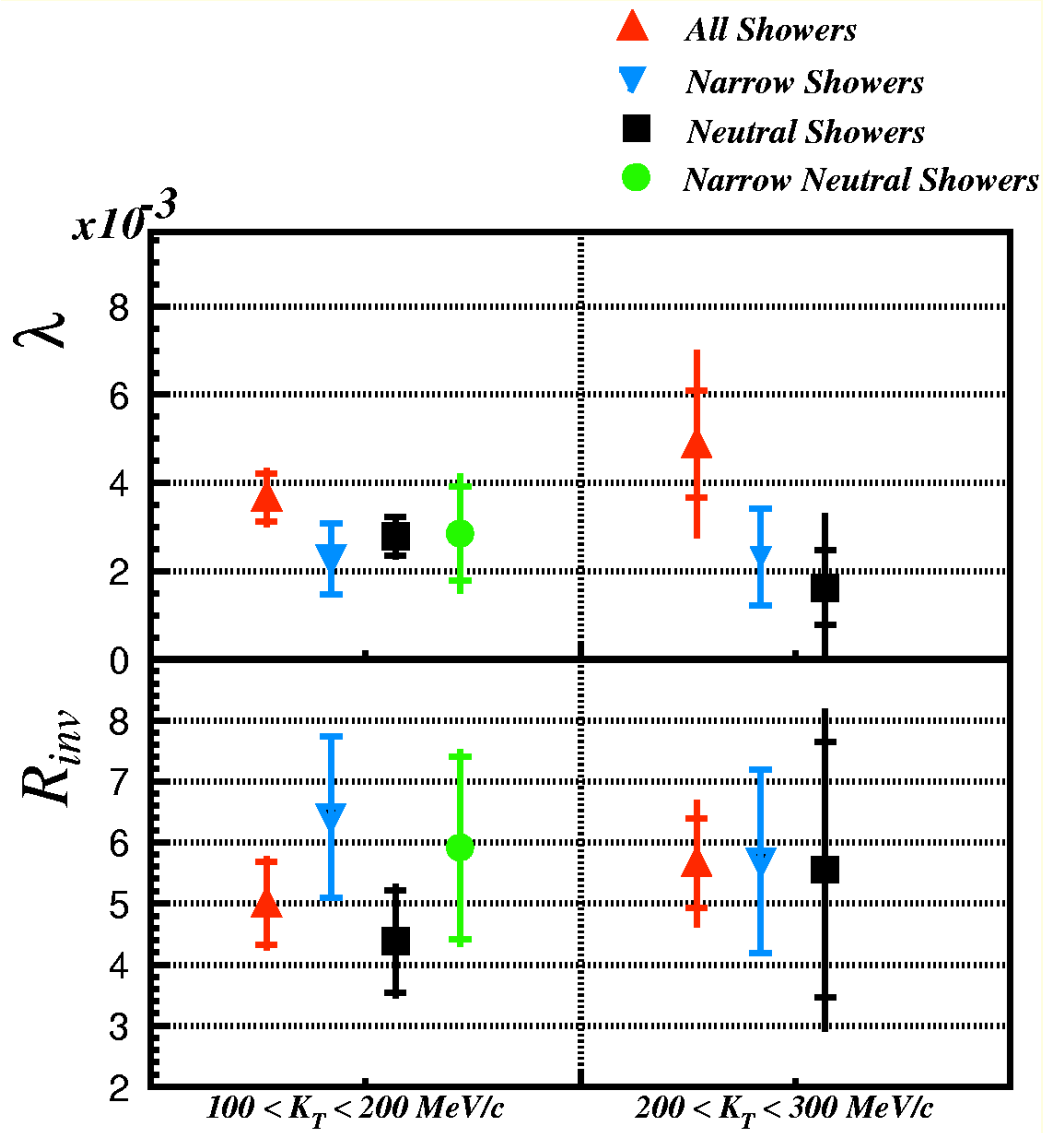
PRL93(2004)022301 WA98, Aggarwal, et al

Since $Q_{inv} \sim K_T \times \Delta L_{min}$ a cut on ΔL_{min} has similar effect as restricting the fit to region above Q_{min}.

Stable fit results with $\Delta L_{min} > 35$cm cut or by restricting Q_{inv} fit region.
Similar result for $R_{inv.}$

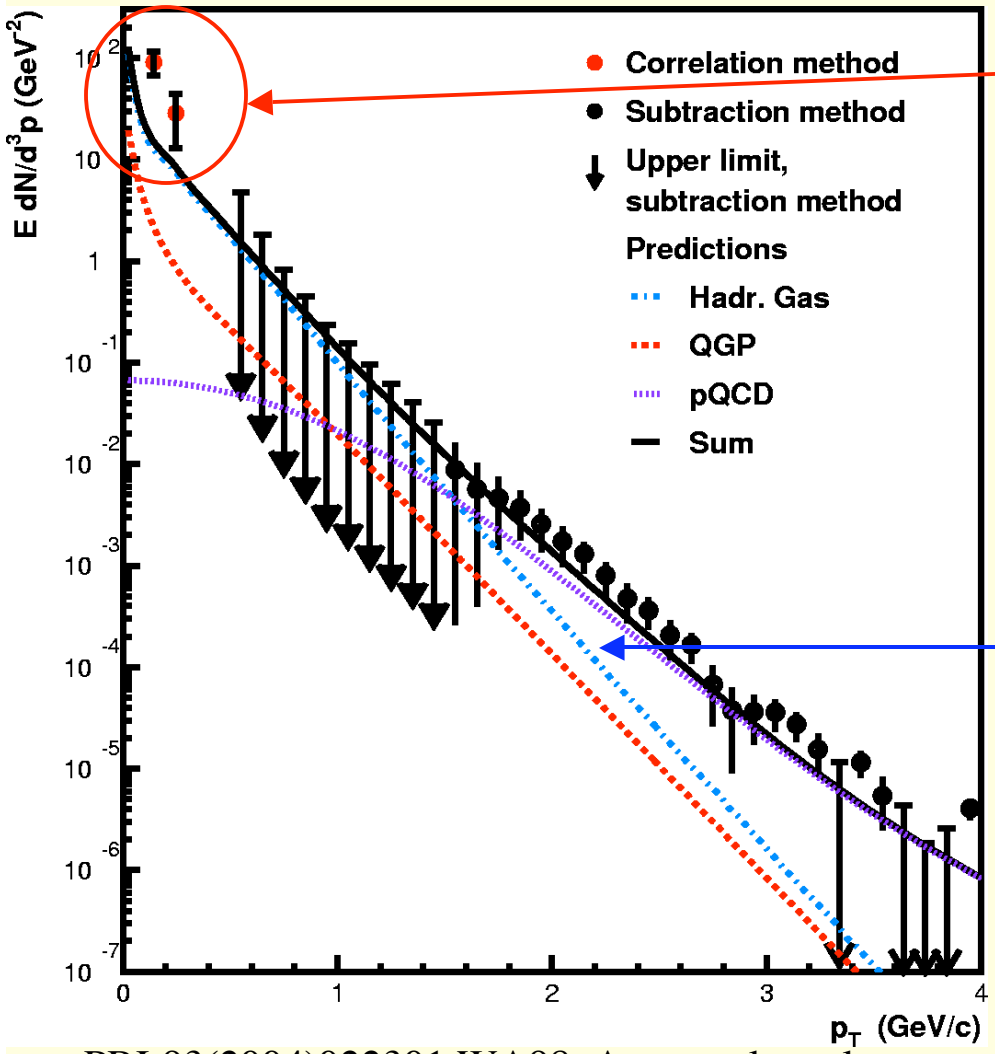
Implies region free of background and detector effects.

Dependence of γ–γ HBT Parameters on γ PID



- Vary γ shower identification criteria to vary non-γ 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 γ–γ correlation.
- **R_{inv} ~ 5-6 fm**
- **Compare $R_{inv}(\pi^-)$=6.6-7.1 fm**

Direct γ Yield via γ–γ HBT Correlations



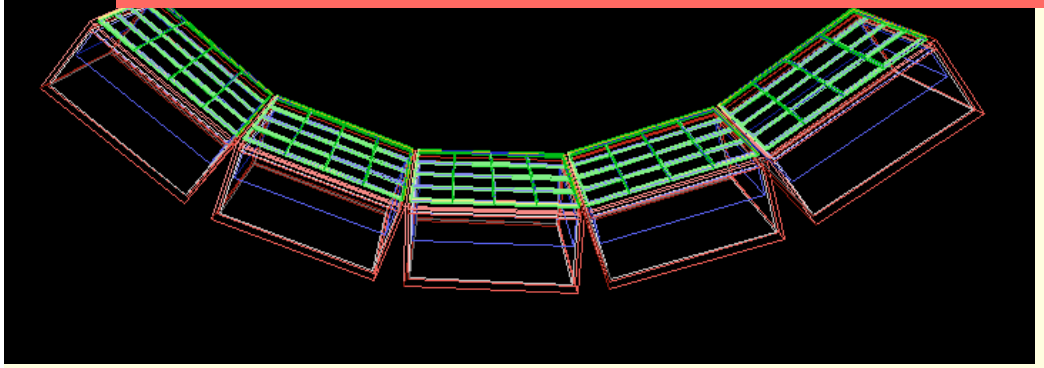
Two new low p_T direct γ points from λ of γ–γ correlation.

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.

PRL93(2004)022301 WA98, Aggarwal, et al

LHC: Electromagnetic Calorimeters in ALICE: PHOS

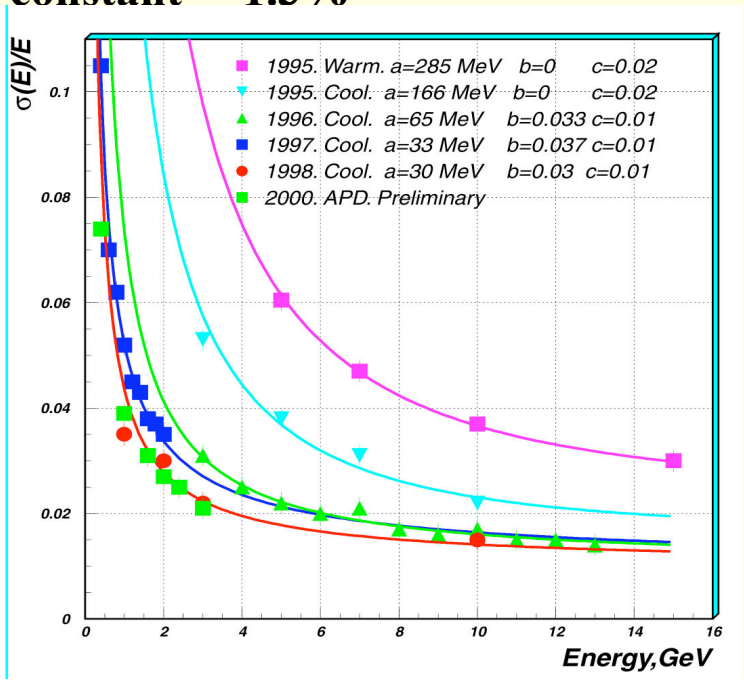


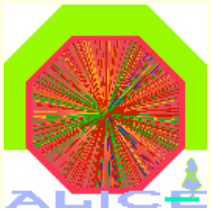
γ/π^0 separation and identification up to ~100 GeV/c

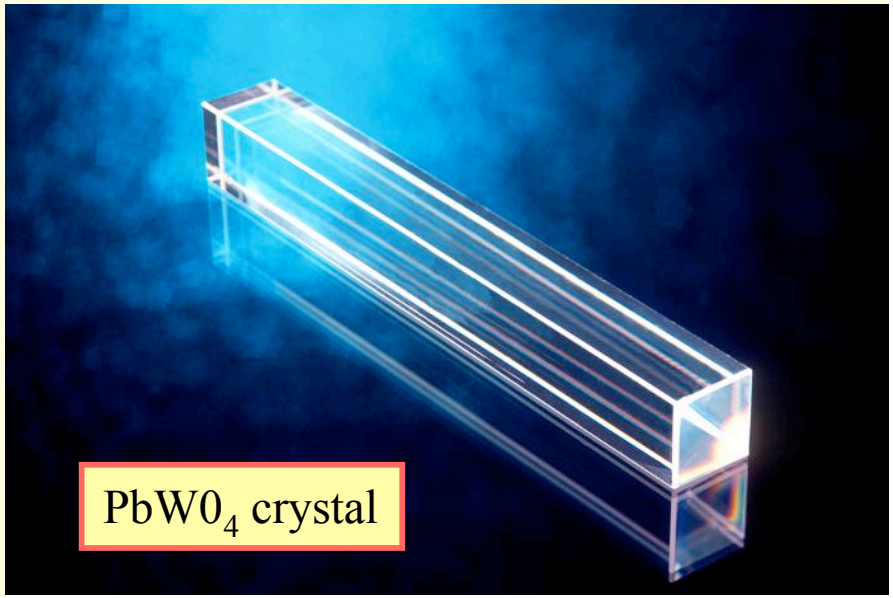
- **high granularity**
  - **2.2x2.2 cm² @ 5m**
  - **~ 18 k channels, ~ 8 m²**
  - **cooled to -25°C**

$PbW0_4$: 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%**

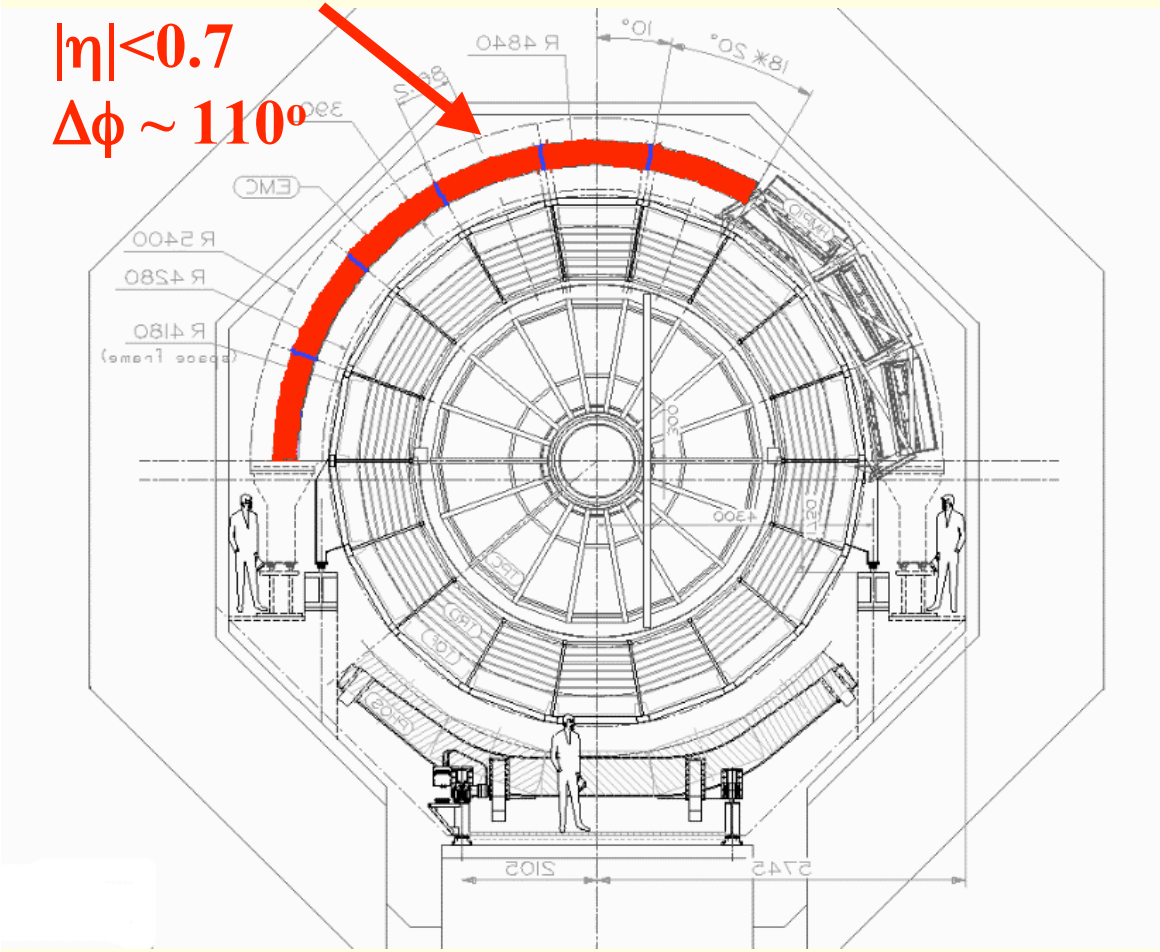






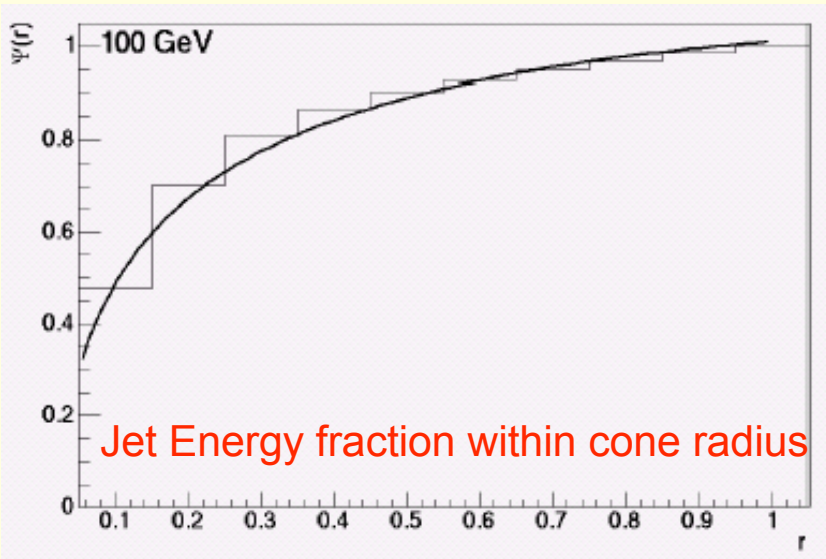
Electromagnetic Calorimeters in ALICE: EMCal

Proposed EMCAL
$|\eta|<0.7$
$\Delta\phi \sim 110^o$



- **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**

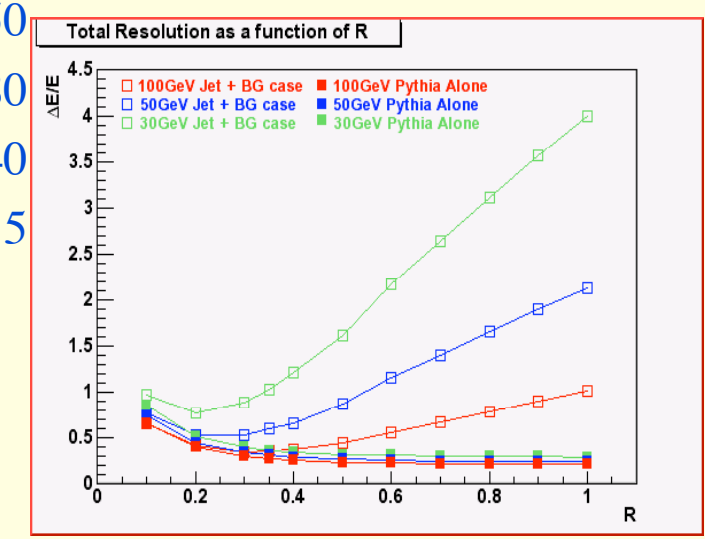
ALICE EMCal is large enough for jet measurements



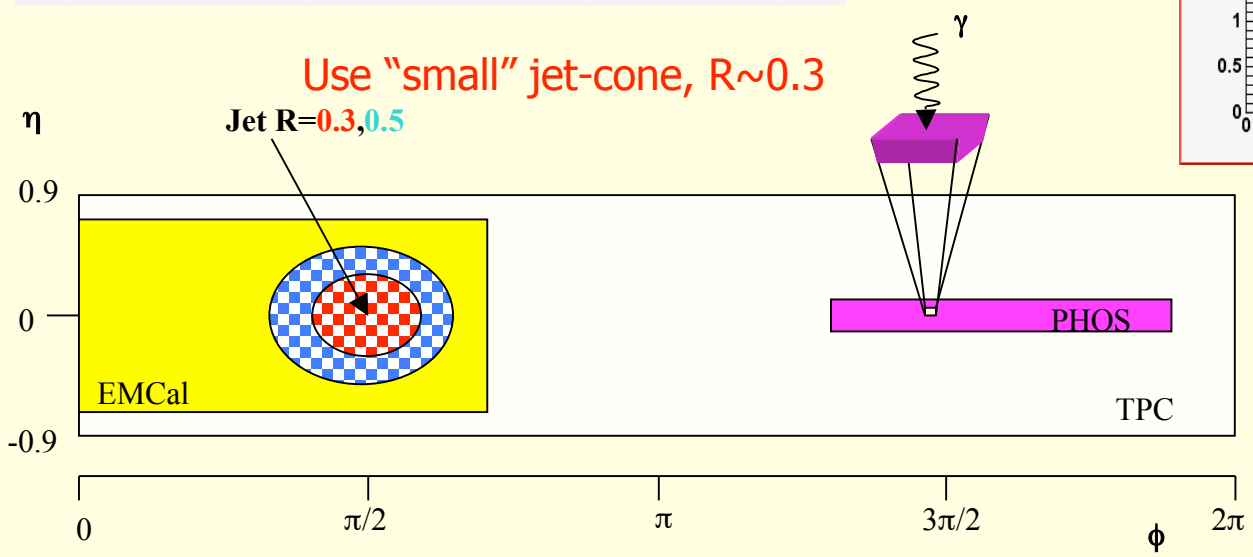
PROBLEM: Underlying event

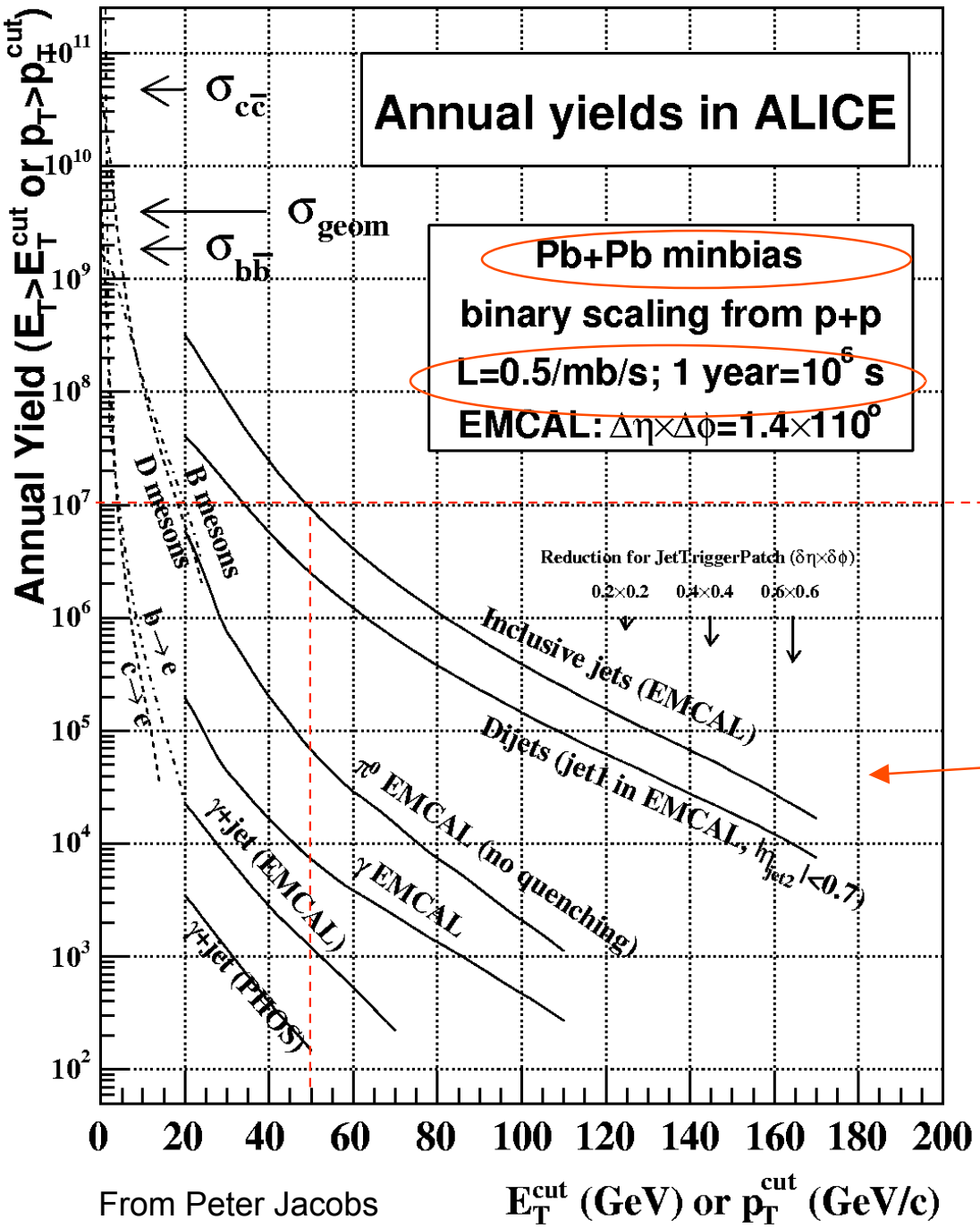
non-jet energy:

Radius	Cone Energy (GeV)
0.7	750
0.5	380
0.3	140
0.1	15



Use "small" jet-cone, R~0.3





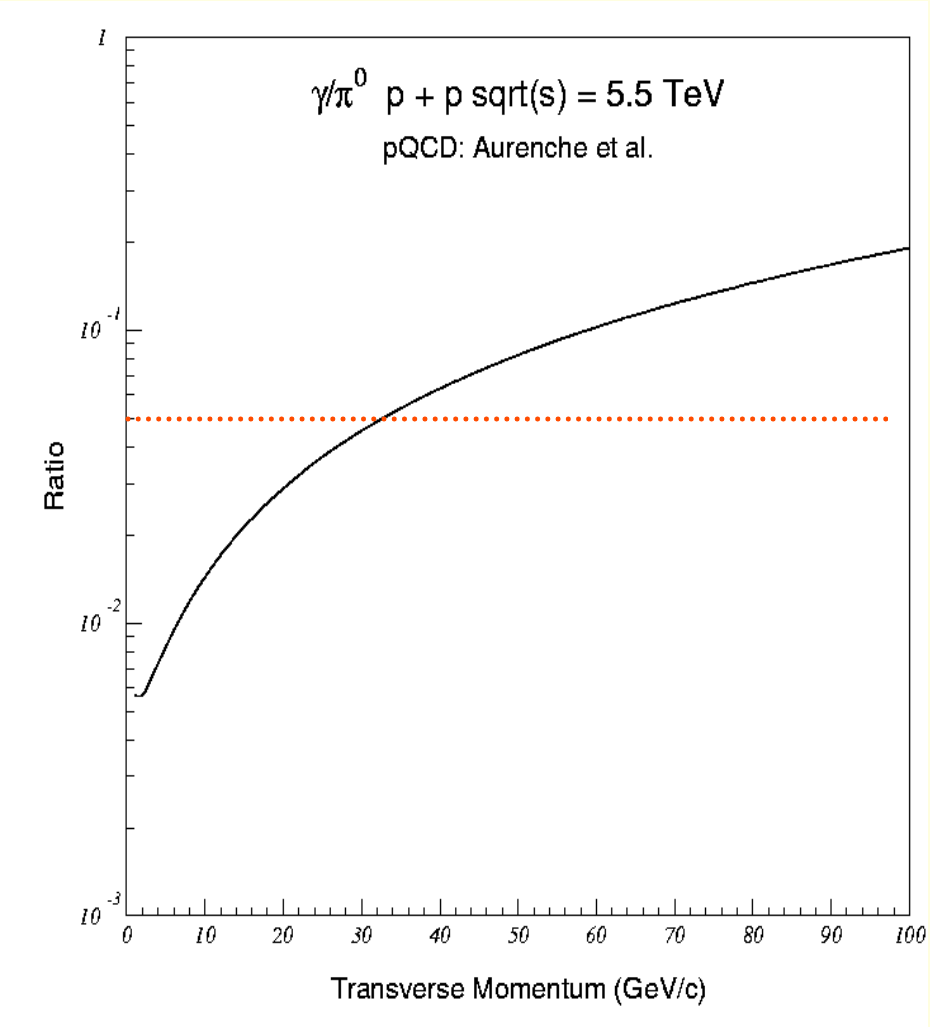
From Peter Jacobs

Extend RHIC measurements to much higher p_T

Inclusive jets
10 Hz @ 50 GeV

few x 10^4/year for E_T>150 GeV

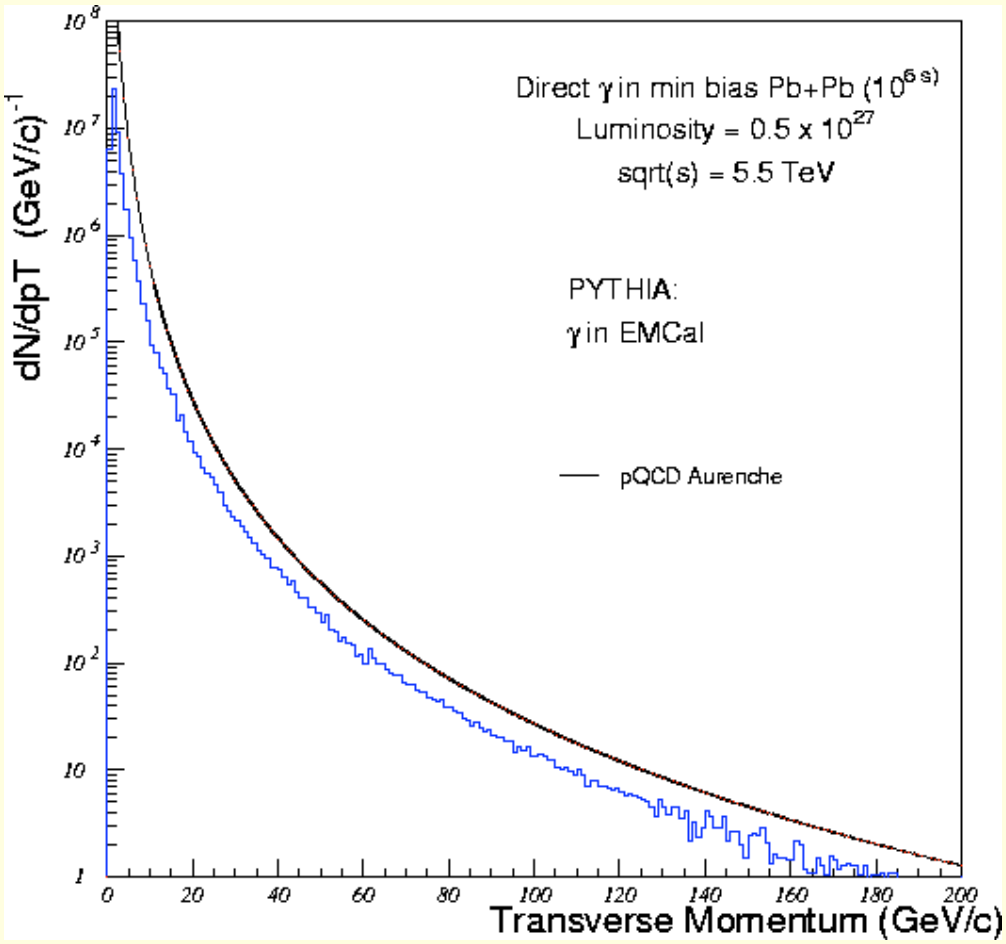
Direct γ/π^0 Ratio at LHC (NLO predictions)



- Ratio γ/π^0 provides figure of merit for direct gamma measurement:
  - $\gamma/\pi^0 \sim 10\%$ **easy**
    $\sim$ 3-5% limit
- ∀ π^0 suppression by factor of ~5-10 (jet quenching) would allow direct photon measurement down to a few GeV/c
- Expectations for π^0 suppression at high p_T at LHC?

Direct γ, π^0 at LHC

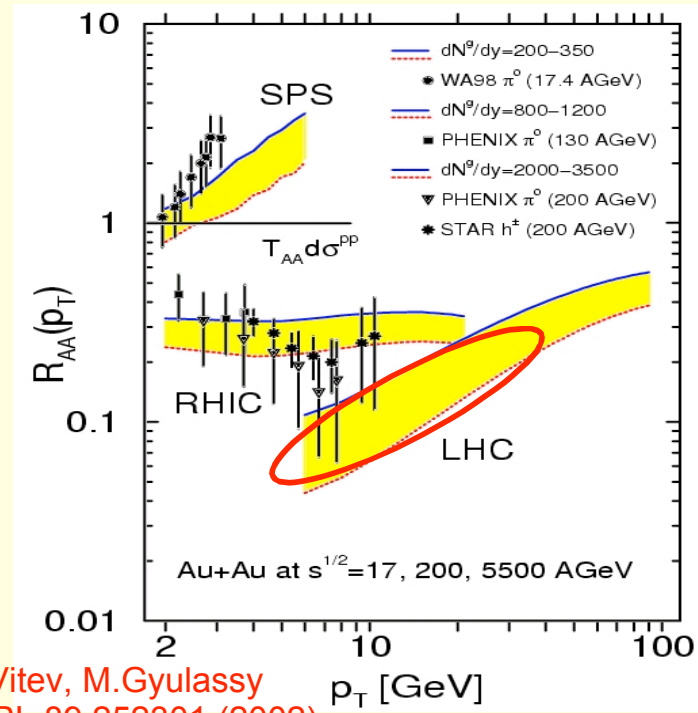
Direct γ (= γ+jet) in ALICE EMCal in one Pb+Pb LHC run.



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)

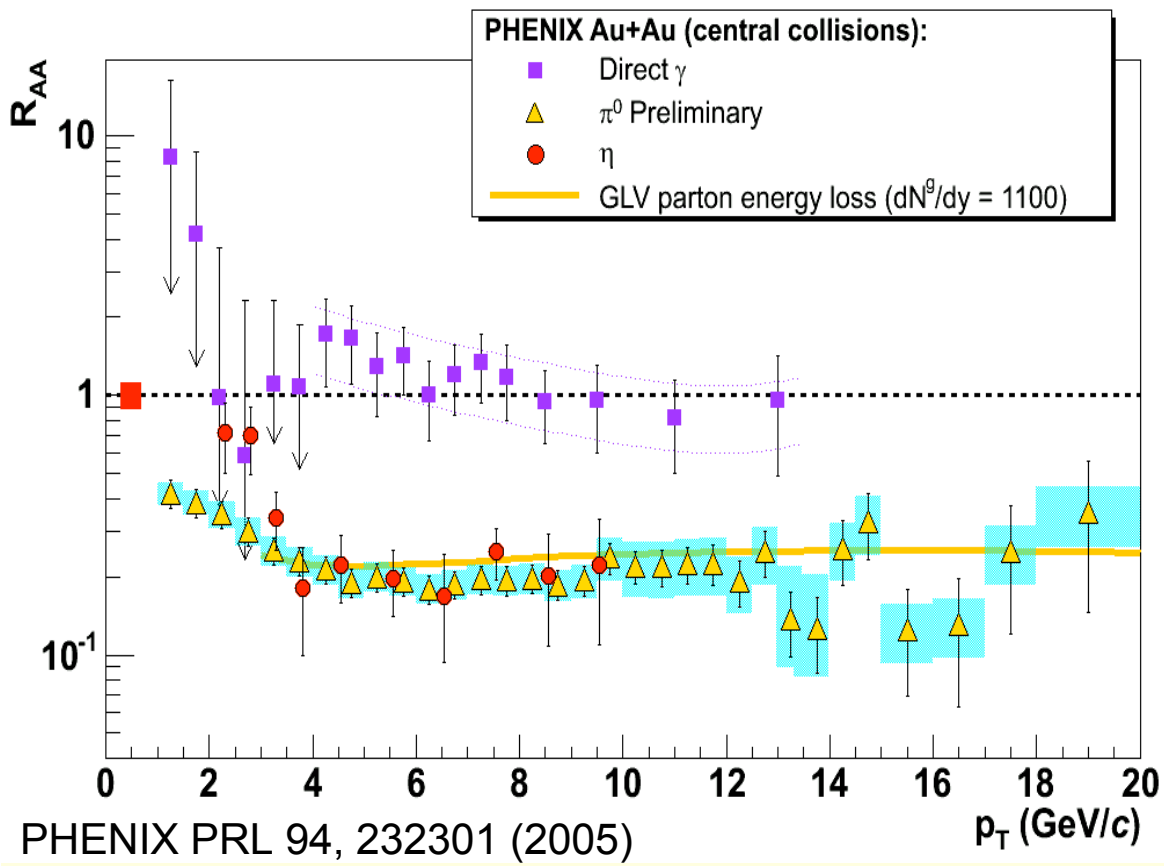
Summary and Conclusions

- **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.**
- **Direct γ production in p+p at RHIC well described by NLO pQCD.**
- **The strong suppression of hadron production (factor of ~4-5) observed in central Au+Au collisions at RHIC reduces decay backgrounds to make the direct photon measurement much easier.**
- **Direct γ production at high p_T in Au+Au at RHIC well described by NLO pQCD. Hadron suppression due to final state effect.**
- **Direct γ production at low p_T in Au+Au at RHIC consistent with Thermal contribution with T_0 as high as ~600MeV.**
- **Many other γ measurements to come:**
  - **γ flow**
  - **γ–γ HBT**
  - **γ+jet**

Great promise for direct γ for future QGP diagnostics.

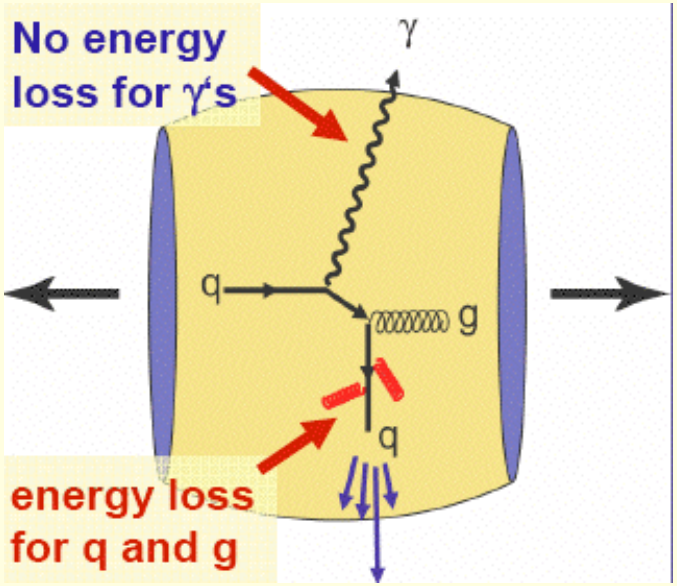
BACKUP SLIDES

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



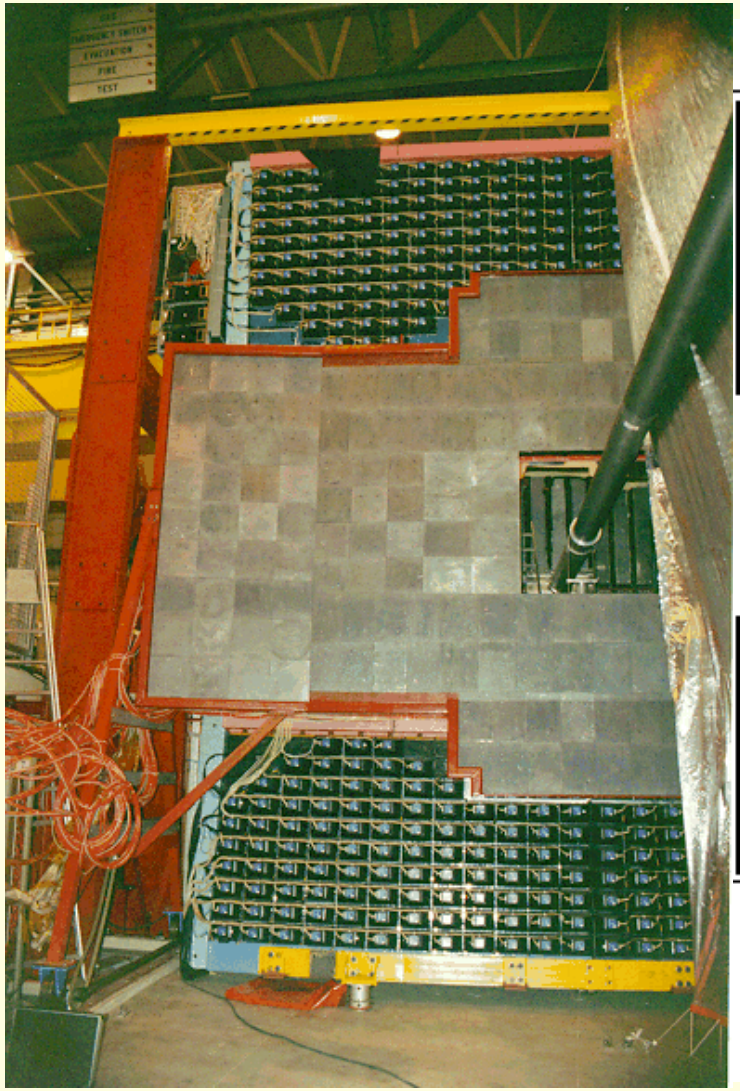
PHENIX PRL 94, 232301 (2005)

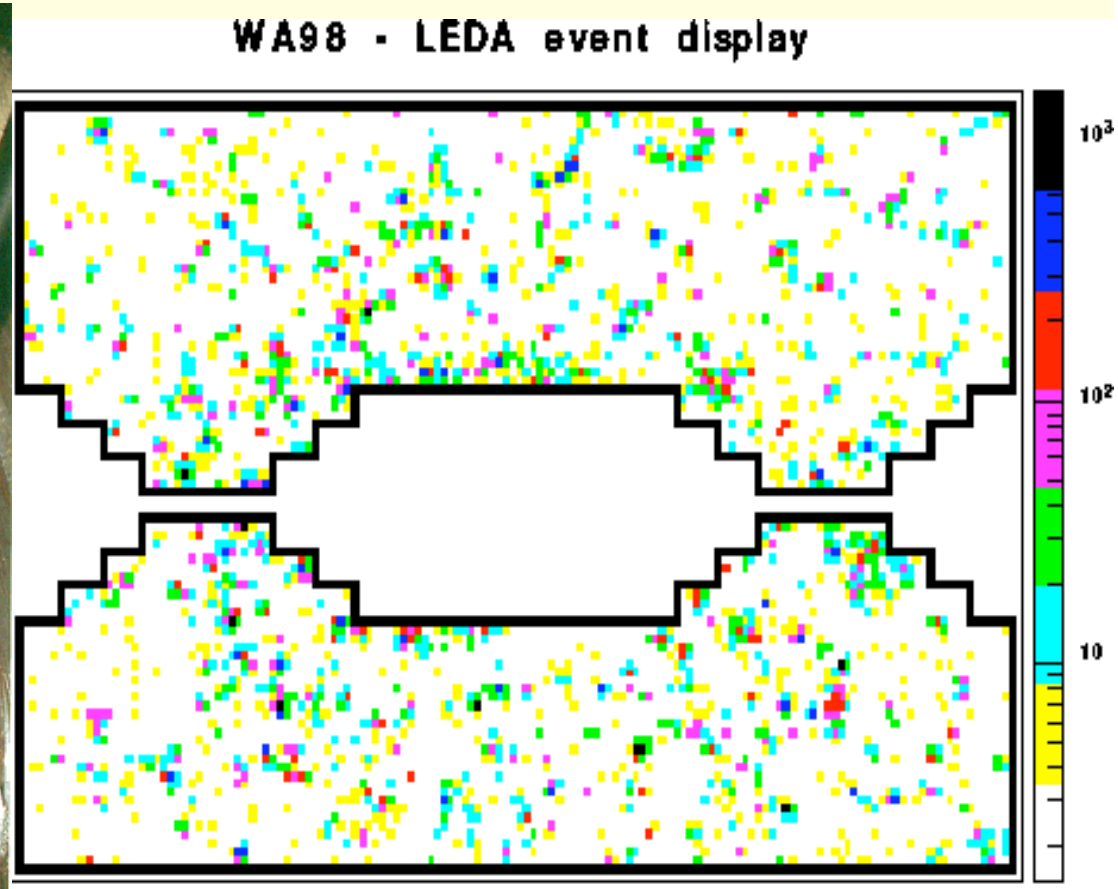
- High p_T γ yield consistent with binary scaled pQCD in contrast to factor of 5 suppression of π^0 & η yields.



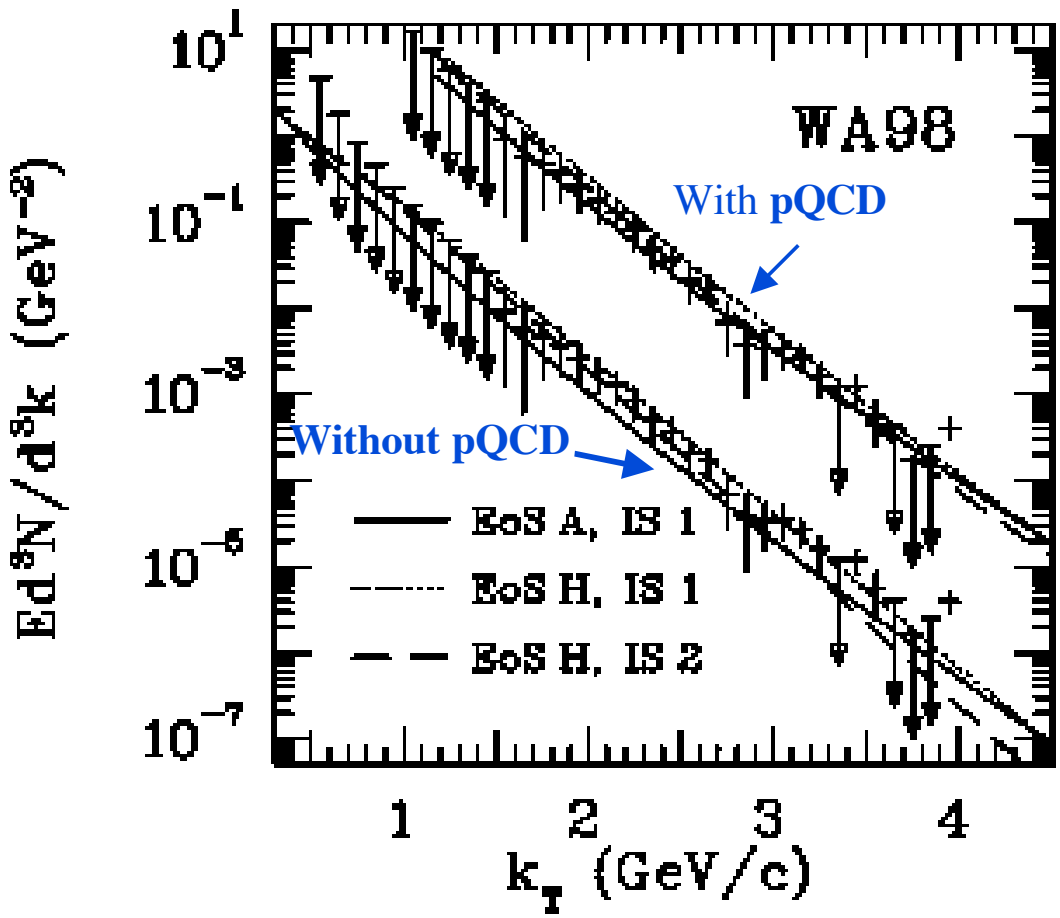
- **Direct γ are not suppressed - strong evidence that hadron suppression is due to final state, i.e. parton energy loss.**

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





Direct γ: Comparison to Hydro Model Calculations



Full Hydro can describe π^0 and γ 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:**

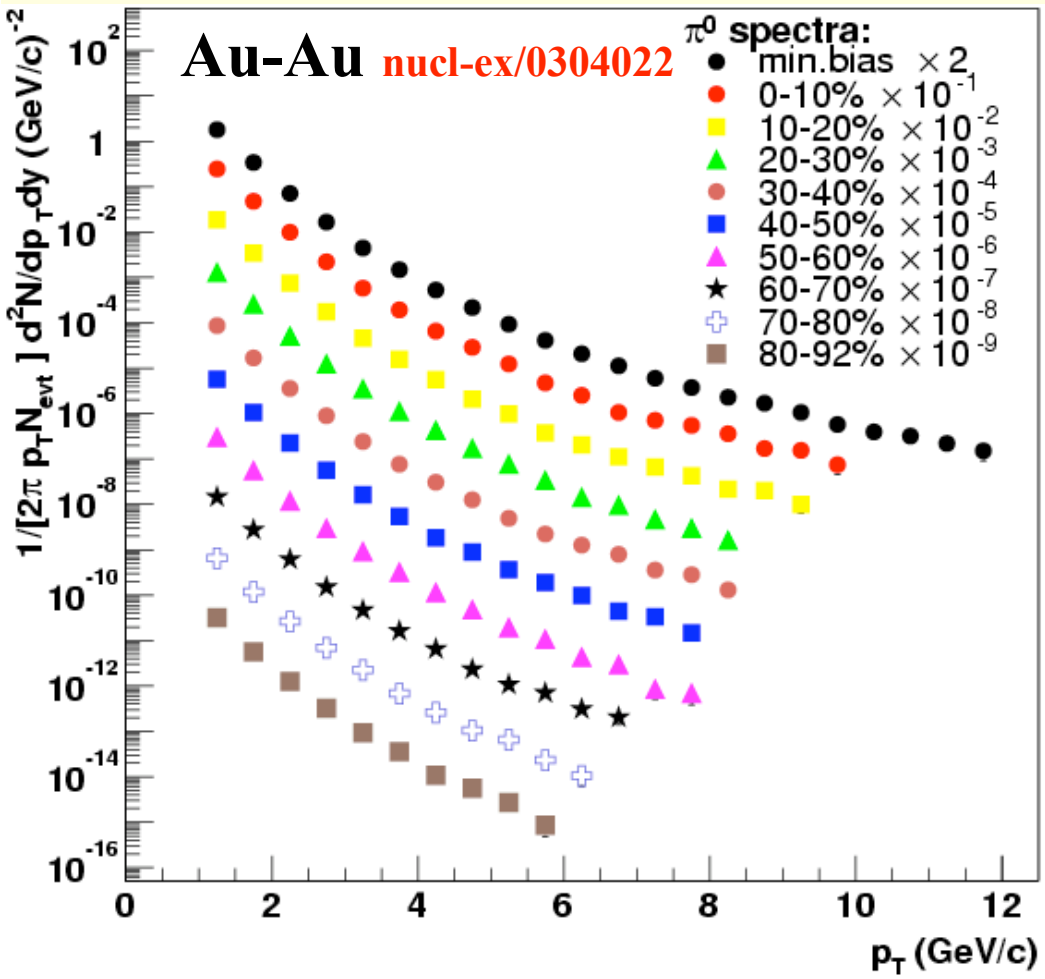
- intrinsic k_T, k_T broadening
- preequilibrium
- QM γ rates: (under control!)
- HM γ rates: in-medium masses
- Hydro evolution: flow

Need further experimental constraints:

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

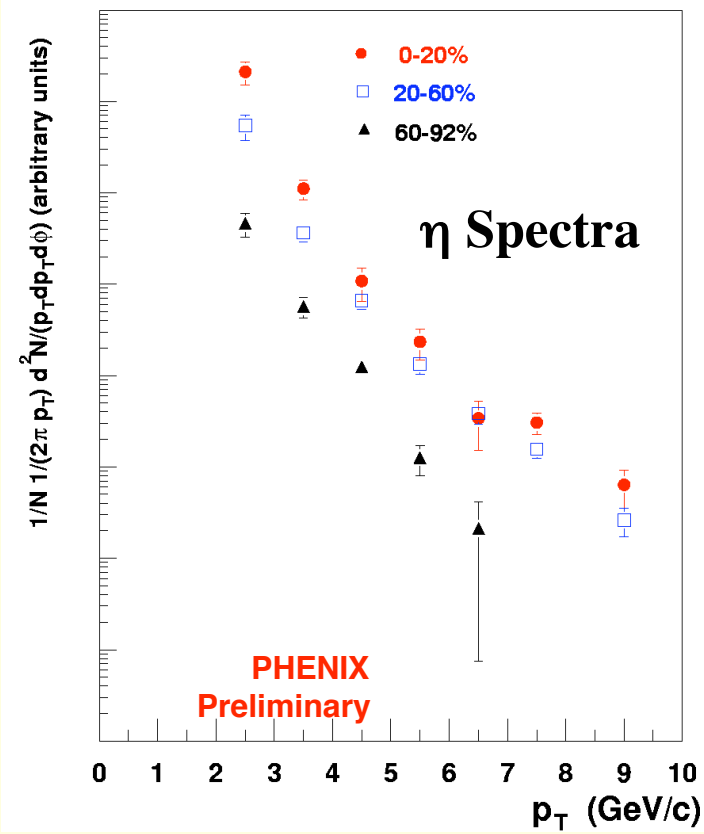
P.Houvinen, et al., PLB 535(2002)109.

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



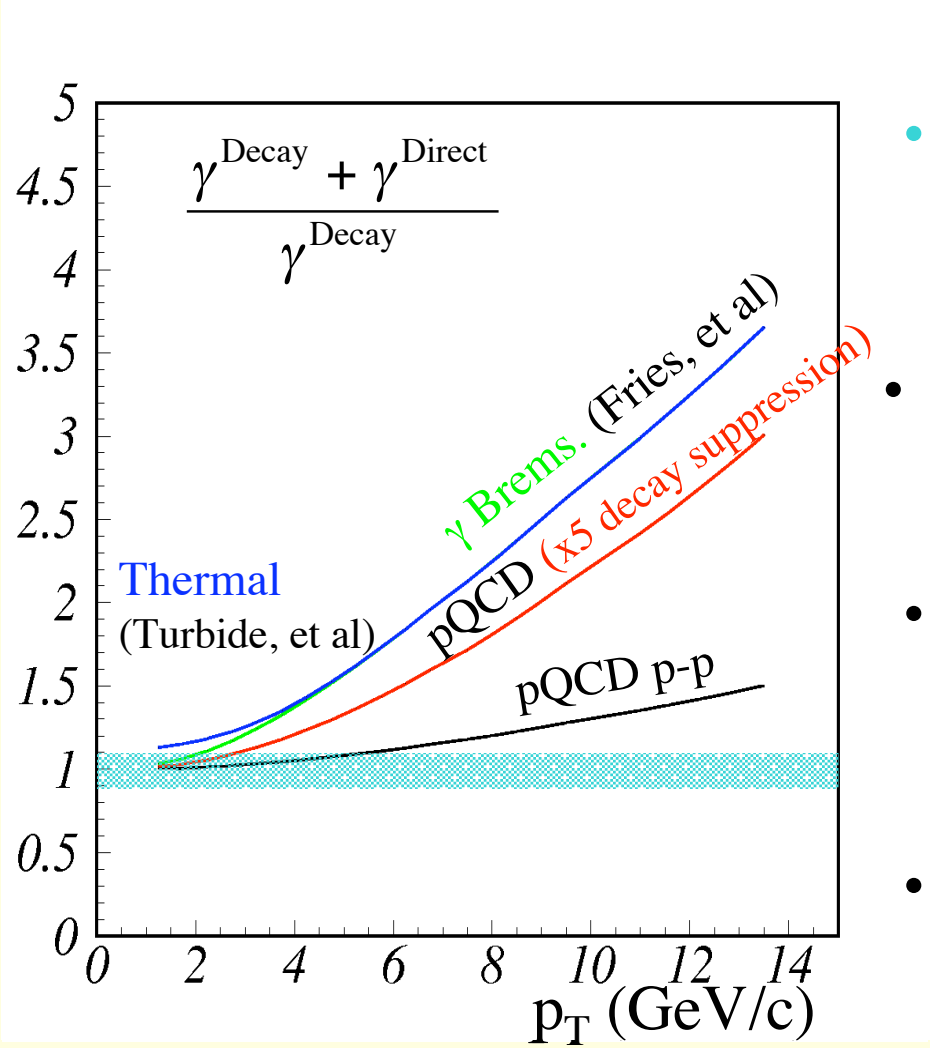
Measure π^0 and η distributions-

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



S.Mioduszewski, CG-011, Friday AM

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 ~5 in Central Au+Au -> Decay γ suppressed by ~5. If by E-loss, direct γ not suppressed
- Additional γ radiation by Bremsstrahlung due to parton Eloss (or less γ from fragmenting partons after Eloss)?
- Low p_T γ from thermal radiation.

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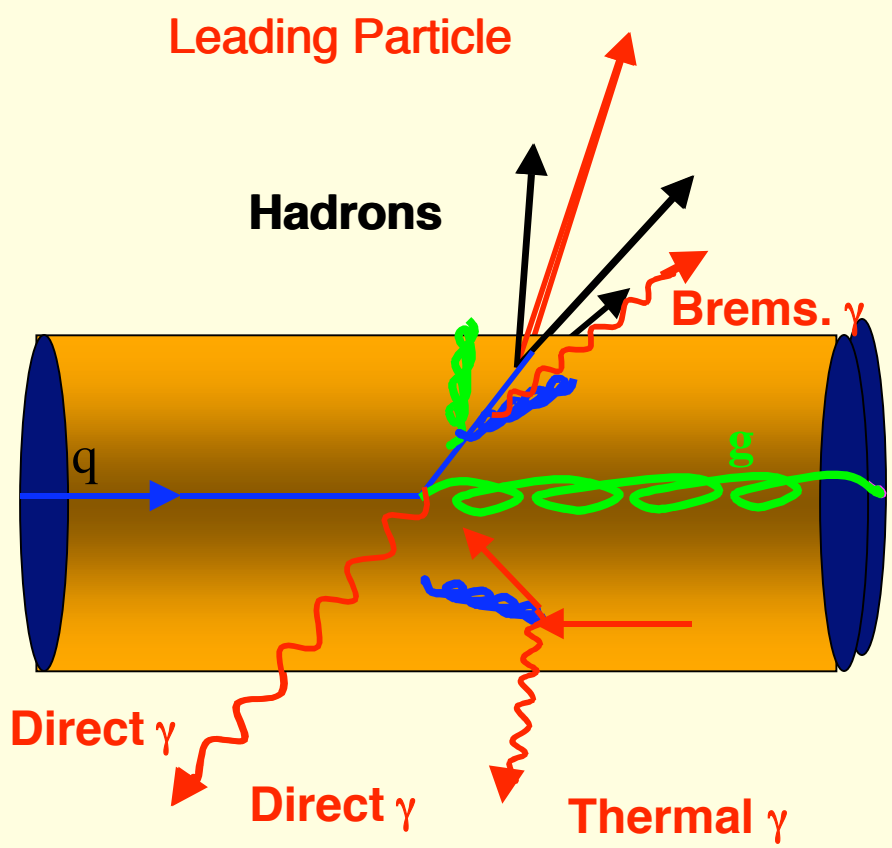
Direct Photon Production

- 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.



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