Why I think the low p_T photons are thermal

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Workshop on Thermal
Photons and Dileptons
December 5-7, 2011
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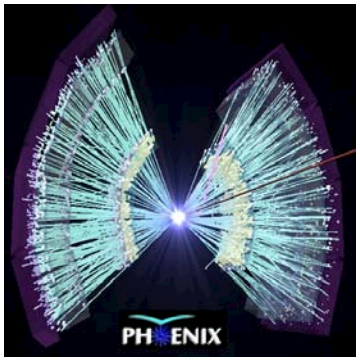


Hard and soft particle production

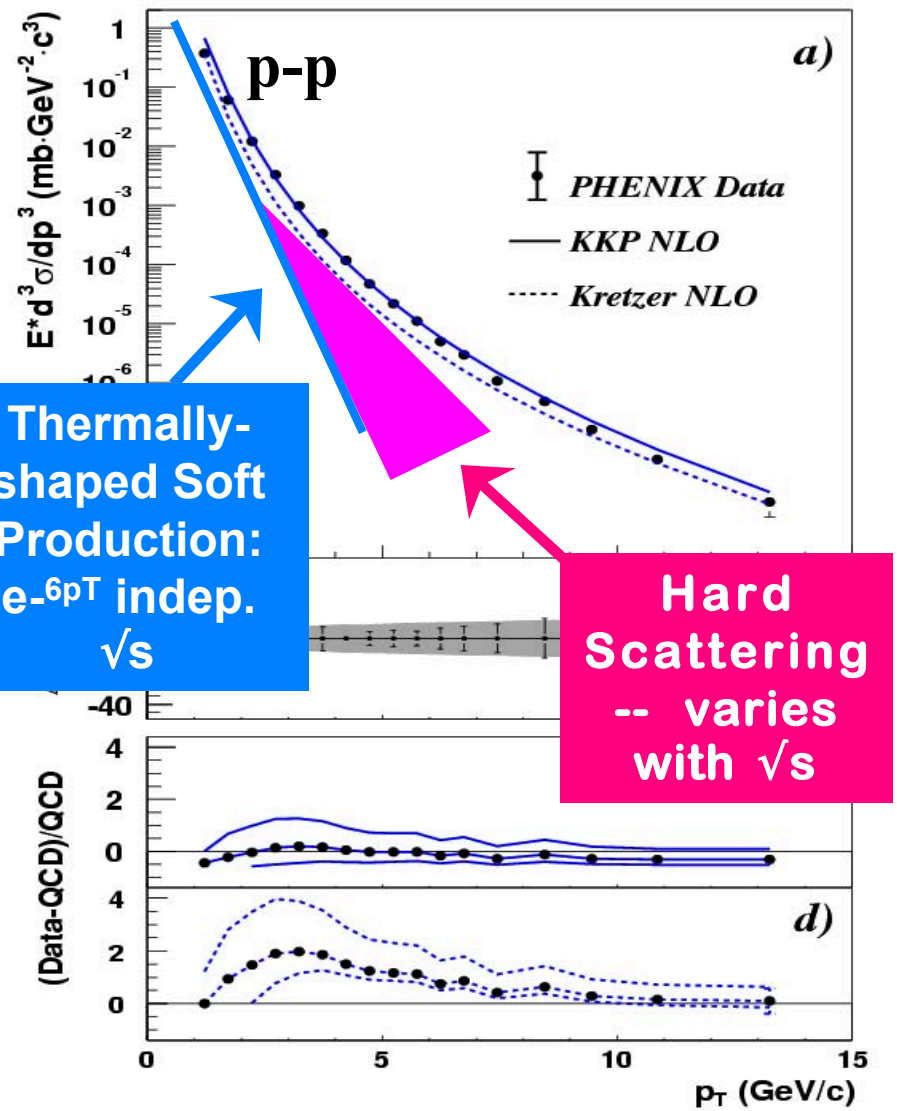
In p-p and A+A collisions most if not all hadrons are produced by both:

- **"soft" processes**, exponential as $p_T \rightarrow 0$ (with a characteristic inverse slope which is believed by many to represent the temperature T of the system) typically due to the stretching and breaking of color strings, or to diffraction dissociation.
- **"hard" processes**, with a characteristic power law for large $p_T > 2$ GeV/c, d<0.1fm due to scattering of quarks and gluons from the initial nucleons or nuclei with each other. The power law stays finite as $p_T \rightarrow 0$ by turning over and becoming relatively flat, i.e. not exponential.

π^0's in p+p $\sqrt{s}$=200 GeV: Data vs. pQCD

- Result from run2 published-a classic
  - ✓ PRL91 (2003) 241803
- New result from run5
  - ✓ preliminary
- Comparison of π^0 cross section
  - ✓ Next-to-leading order(NLO) pQCD
    - CTEQ6M + KKP or Kretzer
    - Matrix calculation by Aversa, et. al.
    - Renormalization and factorization sc are set to be equal and set to

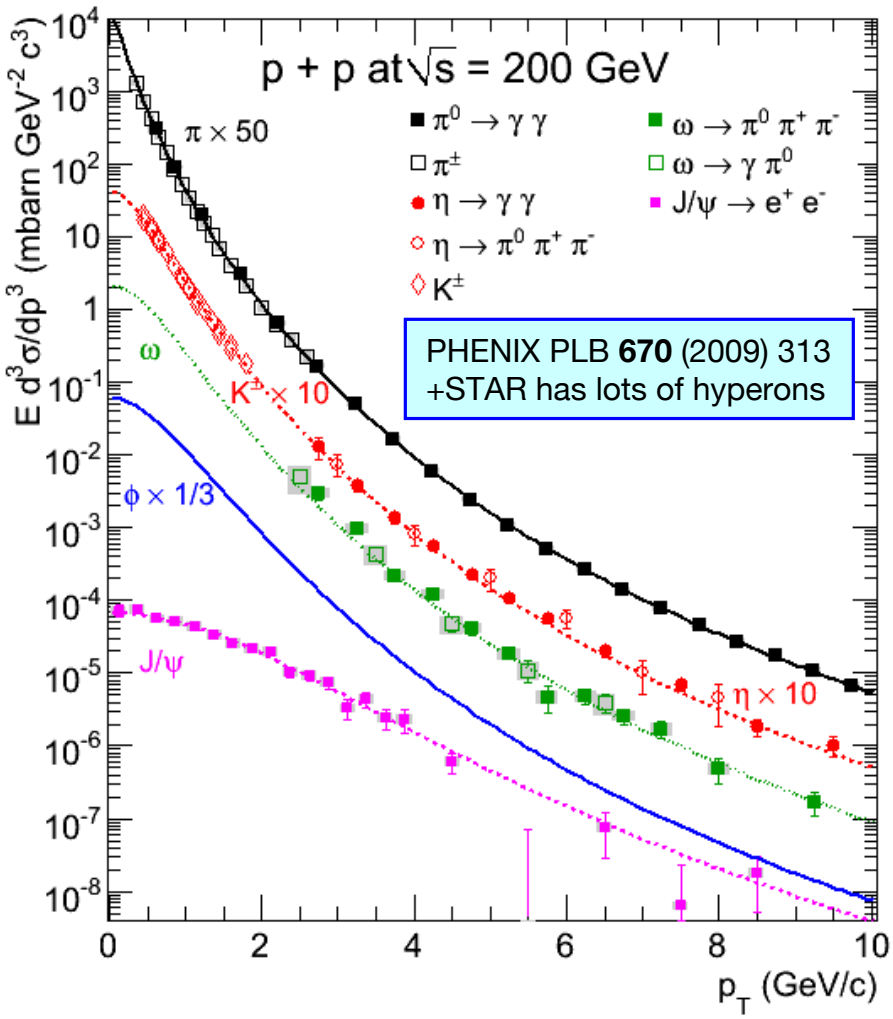
      $1/2p_T$, p_T, $2p_T$
    - Calculated by W.Vogelsang



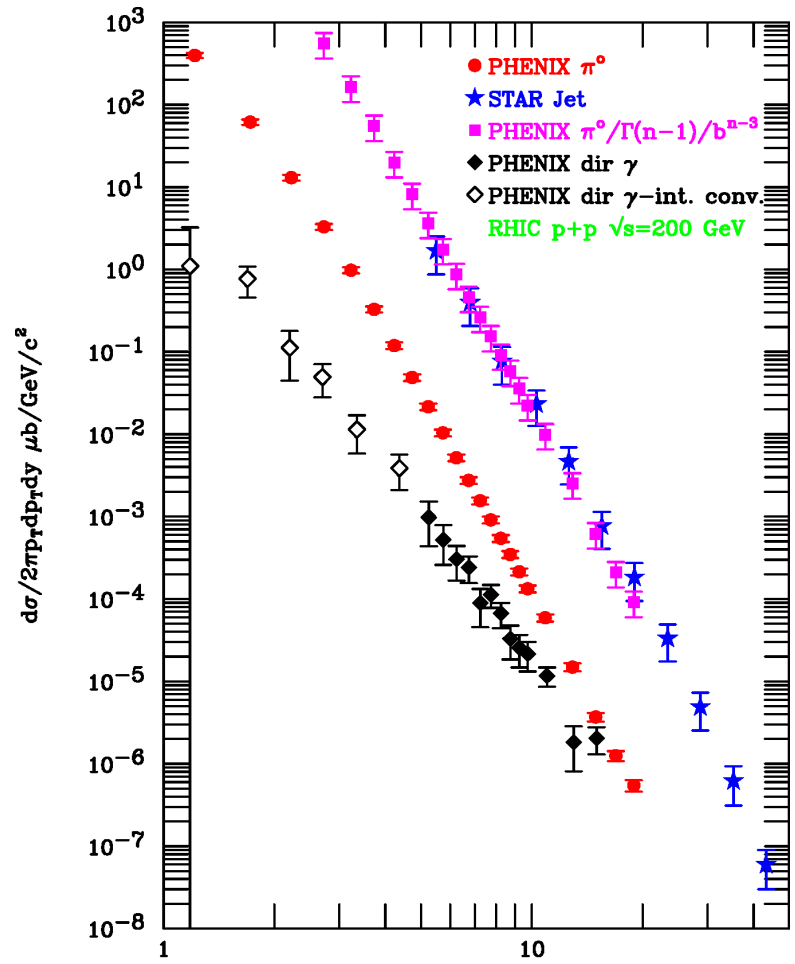
NLO-pQCD described very well down even to $p_T \sim 1$ GeV/c

Inclusive invariant π^0 spectrum is pure power law for $p_T \geq 3$ GeV/c n=8.1±0.1

pid measurements in p+p: mesons, γ, jet



PHENIX PLB **670** (2009) 313
+STAR has lots of hyperons



All hadrons are exponential as $p_T \rightarrow 0$

In Hard-scattering: direct-γ have notably smaller "n" than hadrons (π^0) and clearly flatten as $p_T \rightarrow 0$. There is no soft process in p-p collisions for direct-γ production

This is similar to another purely hard process Drell Yan

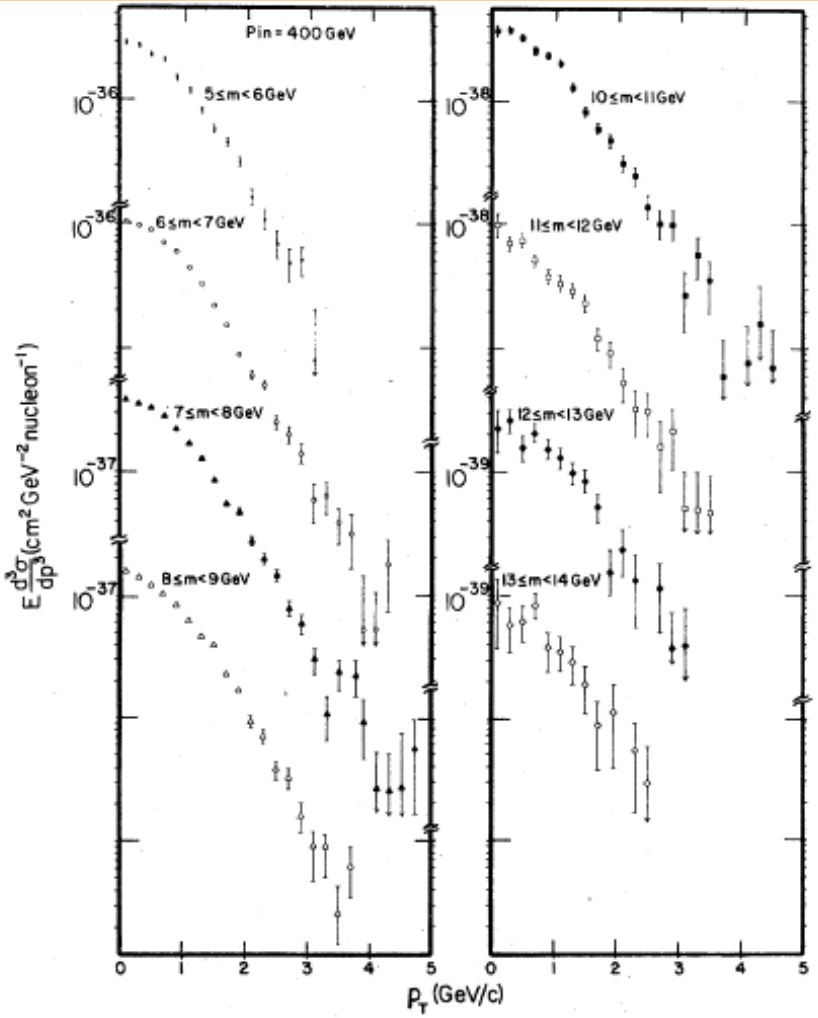
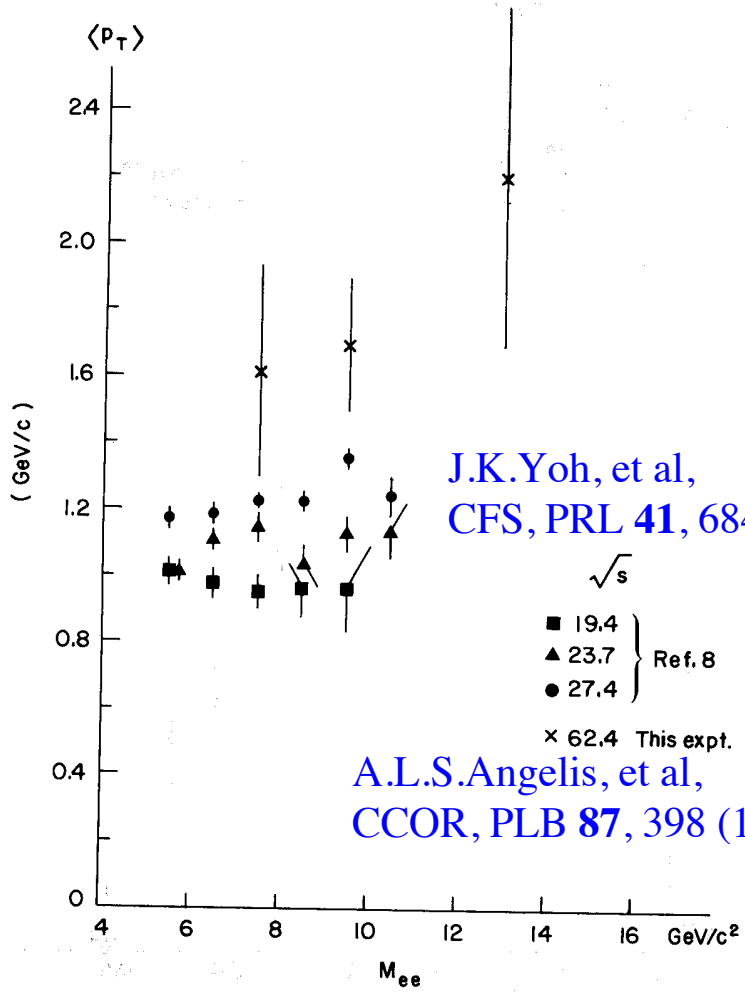


FIG. 12. Invariant yield of dimuons as a function of the transverse momentum p_T of the muon pair for 400 GeV incident protons.

A.S.Ito, et al, PRD23,604 (1981)



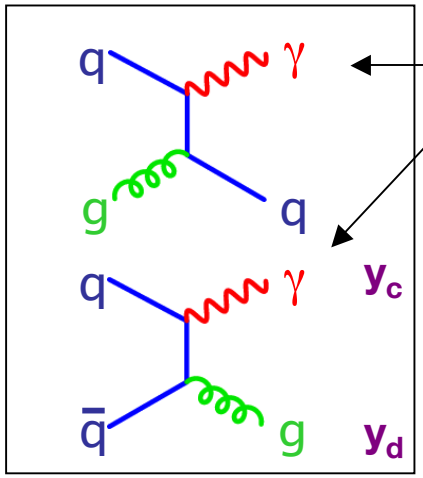
J.K.Yoh, et al, CFS, PRL **41**, 684 (1978)

A.L.S.Angelis, et al, CCOR, PLB **87**, 398 (1979)

Note: power-law at larger p_T turns "Gaussian" in shape as $p_T \rightarrow 0$ independent of mass

Direct photon production-simple theory hard experiment

See the classic paper of Fritzsch and Minkowski, PLB **69** (1977) 316-320



isolated photons

q is 8/1 u/d quark

Analytical formula for γ-jet cross section for a photon at p_T, y_c (and *parton* (jet) at p_T, y_d):

$$\frac{d^3\sigma}{dp_T^2\,dy_c\,dy_d} = x_1 f_g^A(x_1)\,F_{2B}(x_2,Q^2)\frac{\pi\alpha\alpha_s(Q^2)}{3\hat{s}^2}\left(\frac{1+\cos\theta^*}{2}+\frac{2}{1+\cos\theta^*}\right)$$
$$+\;F_{2A}(x_1,Q^2)\,x_2 f_g^B(x_2)\frac{\pi\alpha\alpha_s(Q^2)}{3\hat{s}^2}\left(\frac{1-\cos\theta^*}{2}+\frac{2}{1-\cos\theta^*}\right)$$

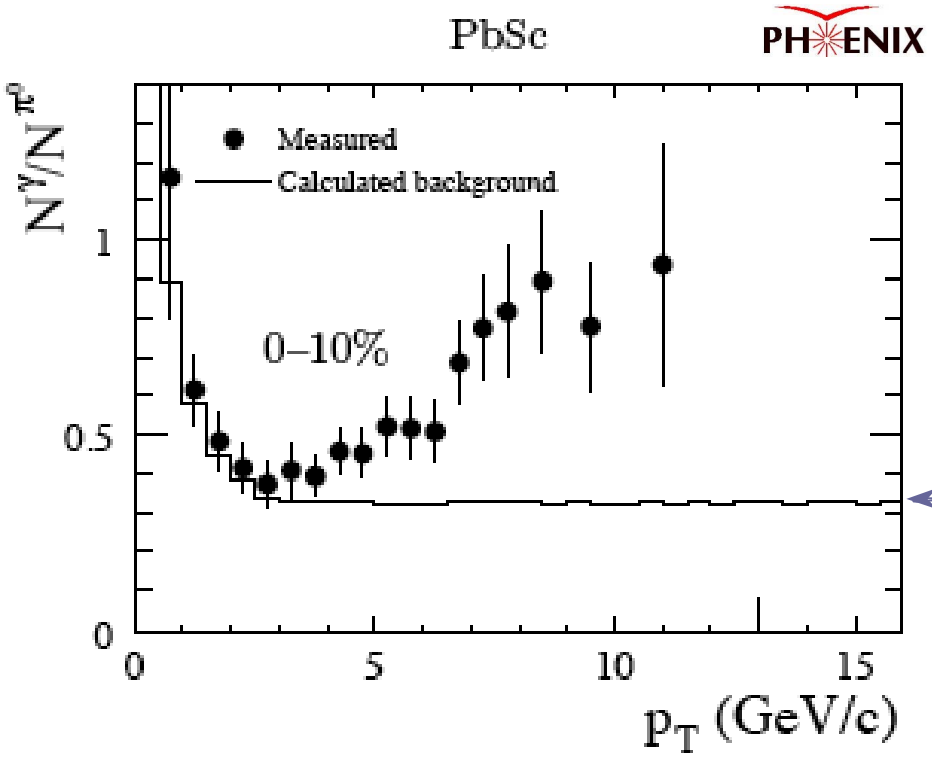
$$\cos\theta^* = \tanh\frac{(y_c-y_d)}{2}$$

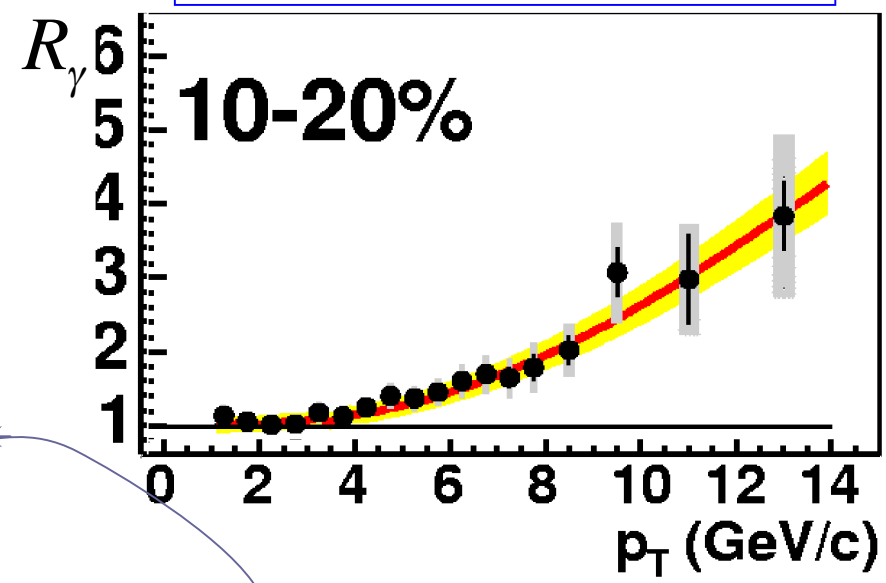
$$x_{1,2} = x_T\frac{e^{\pm y_c}+e^{\pm y_d}}{2}$$

f_g(x) and F_2(x) are g and q pdf's in nuclei A,B

Experimental problem is HUGE background from $\pi^0 \rightarrow \gamma\gamma$, $\eta \rightarrow \gamma\gamma$, etc. But this is less of a problem in Au+Au due to suppression of π^0

PHENIX PRL**94** (2005) 232301





$$R_\gamma = \frac{(\gamma/\pi^0)_{\text{Measured}}}{(\gamma/\pi^0)_{\text{Background}}} \approx \frac{\gamma_{\text{Measured}}}{\gamma_{\text{Background}}}$$

If $\frac{dn_{\pi^0}}{p_T dp_T} \propto p_T^{-n}$ then $\left.\frac{\gamma}{\pi^0}\right|_{\pi^0}(p_T) = 2/(n-1)$ x (1.19)=0.335

η/π^0=0.50

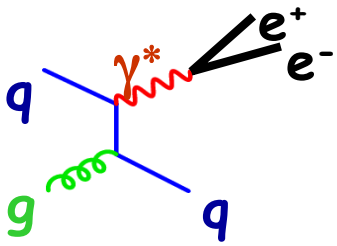
Since the the photons from $\pi^0 \rightarrow \gamma+\gamma$, $\eta \rightarrow \gamma+\gamma$ and similar decays are the principal background to direct photon production, the importance of a precise estimate of this background can not be overstated.

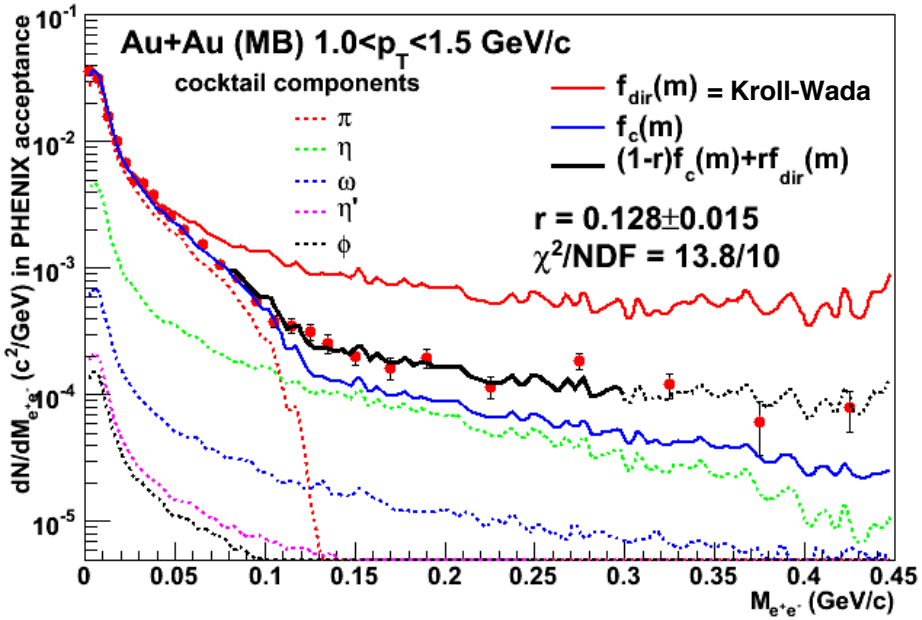
QM2005-direct γ in AuAu via internal conversion

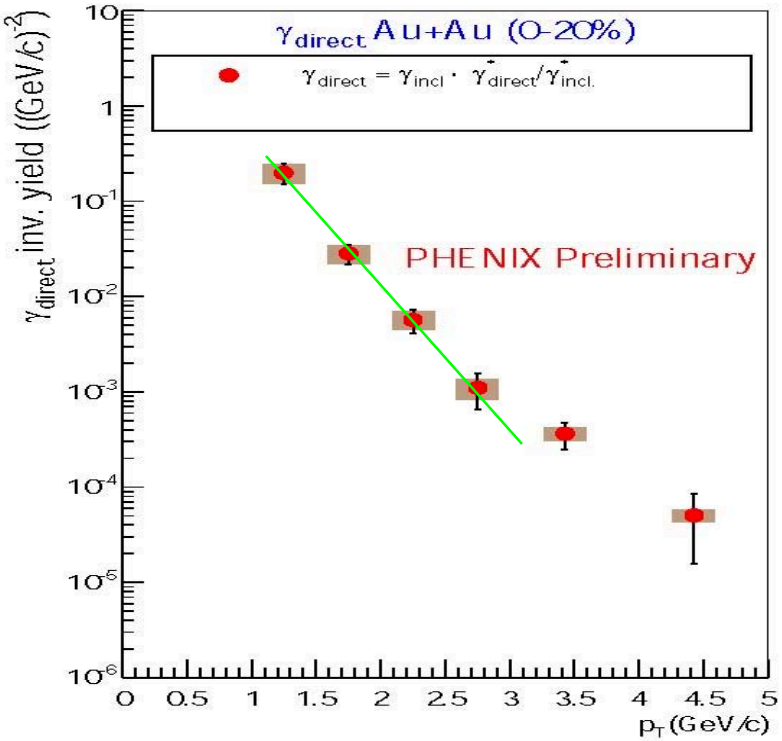
Kroll Wada PR**98**(1955) 1355

PHENIX NPA**774**(2006)403

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



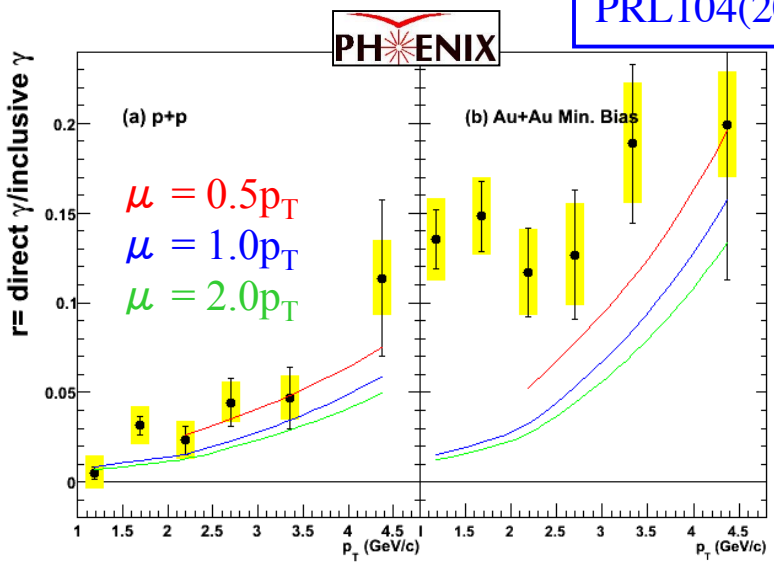


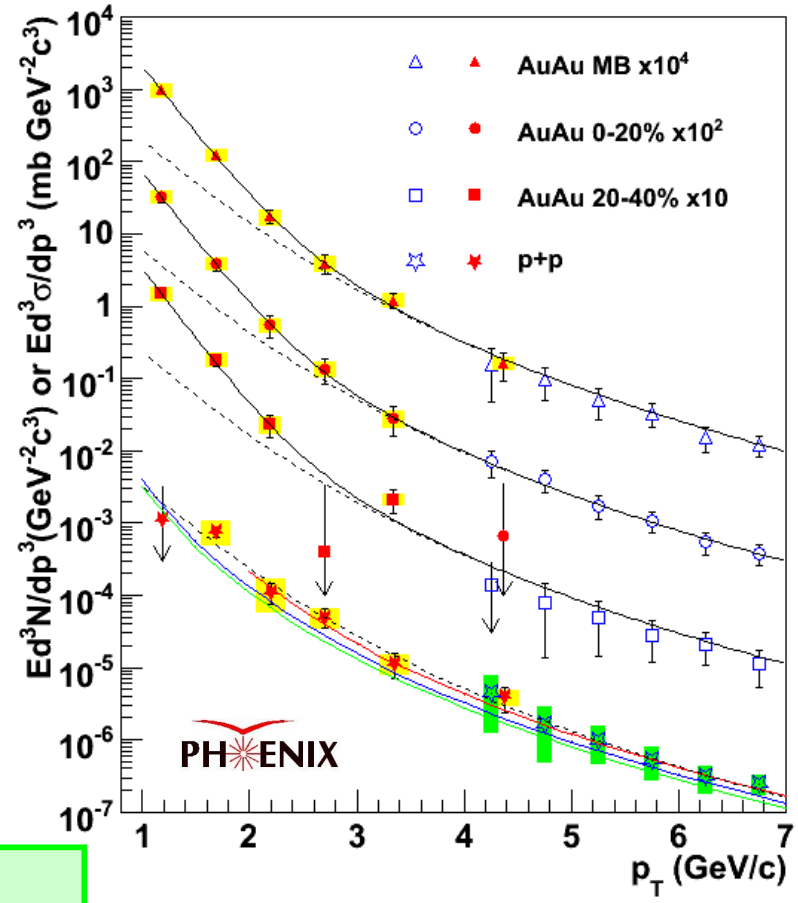


Eliminating the π^0 background by going to $0.2<m_{ee}<0.3$ GeV enables direct γ signal to be measured for $1<p_T<3$ GeV/c in Au+Au. It is exponential, does that mean it is thermal. We must see whether p-p direct γ turns over as $p_T \rightarrow 0$ as in Drell-Yan or exponential like for π^0

QM2008 direct γ in p-p via internal conversion

PRL104(2010)132301





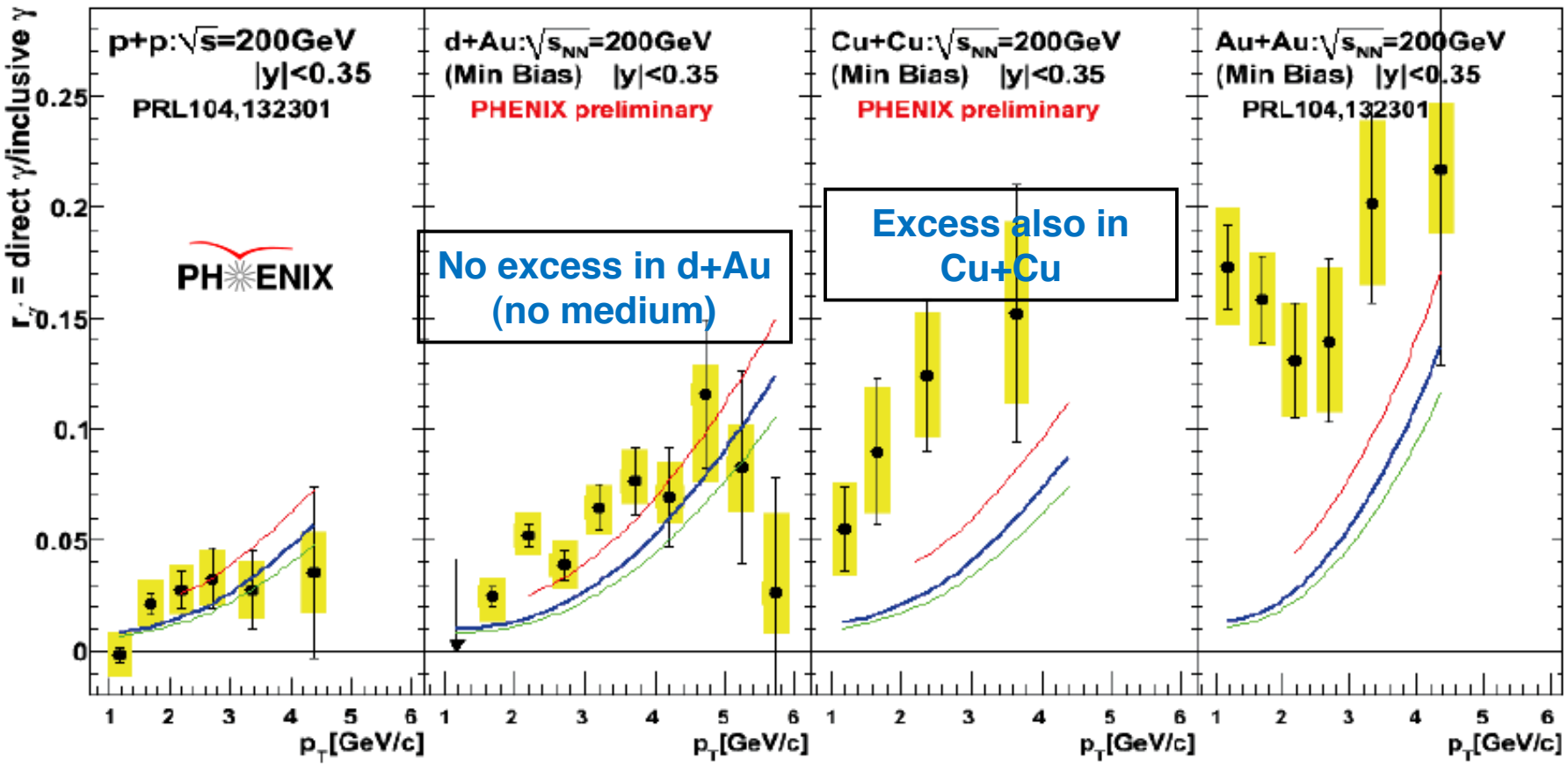
Lowest p_T direct γ ever measured in p-p (and Au+Au). Curves are pQCD extrapolated (W.Vogelsang)

This is a major discovery, p-p result turns over as $p_T \rightarrow 0$, follows the same function $B(1+p_T^2/b)^{-n}$ used in Drell Yan [Ito, et al, PRD23, 604 (1981)] .
Fit to Au+Au is $[A\, e^{-p_T/T} + \langle T_{AA} \rangle B_{pp}(1+p_T^2/b_{pp})^{-n_{pp}}]$.
Significance of exponential (thermal?) is > 3 σ

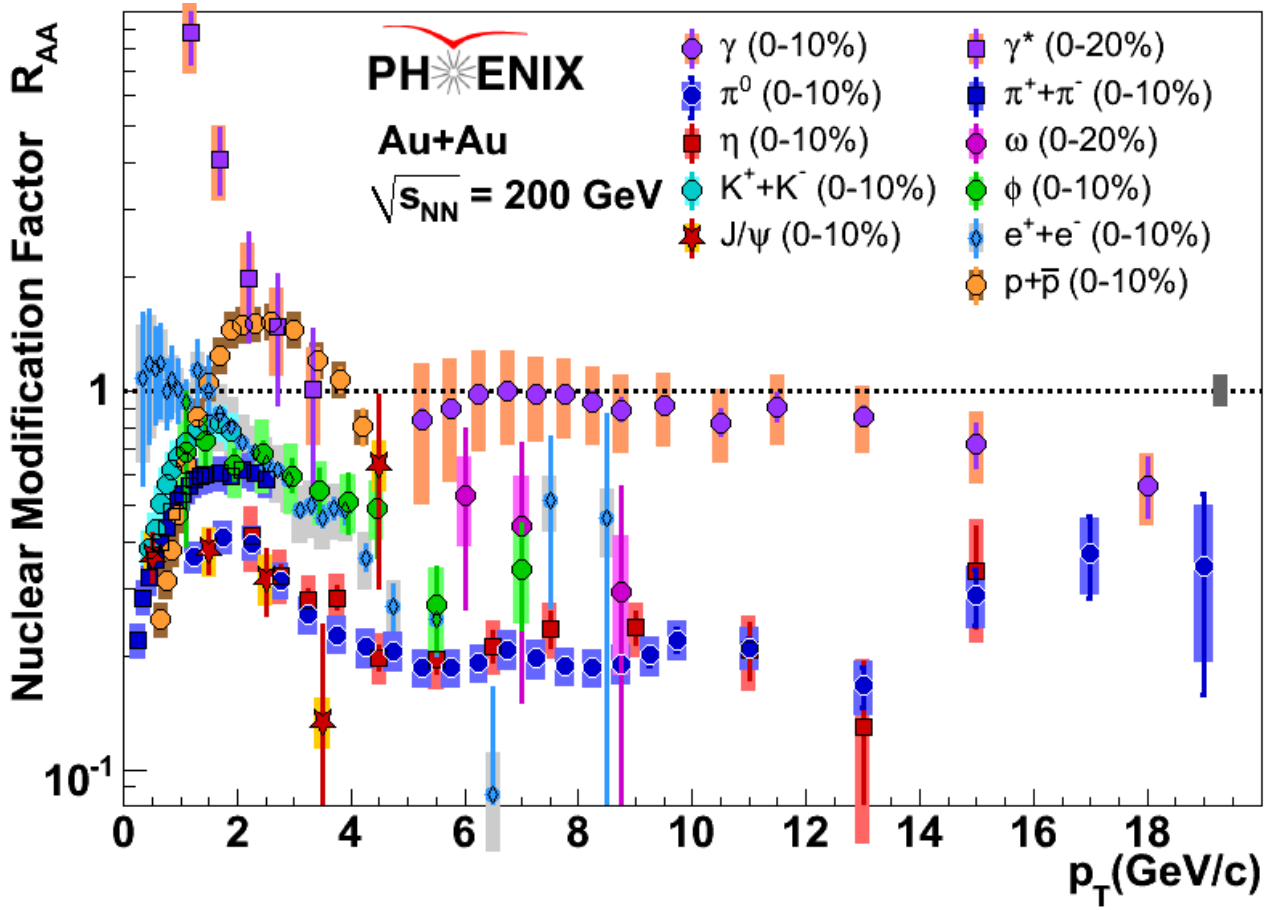
centrality	$dN/dy(p_T > 1\text{GeV}/c)$	T(MeV)
0-20%	$1.10 \pm 0.20 \pm 0.30$	$221 \pm 23 \pm 18$
20-40%	$0.52 \pm 0.08 \pm 0.14$	$215 \pm 20 \pm 15$
MB	$0.33 \pm 0.04 \pm 0.09$	$224 \pm 16 \pm 19$

Confirmation from *d*+Au and Cu+Cu-QM2011

- Fraction of direct photons compared to pQCD



Status of R_{AA} in AuAu at $\sqrt{s_{NN}}$=200 GeV QM09



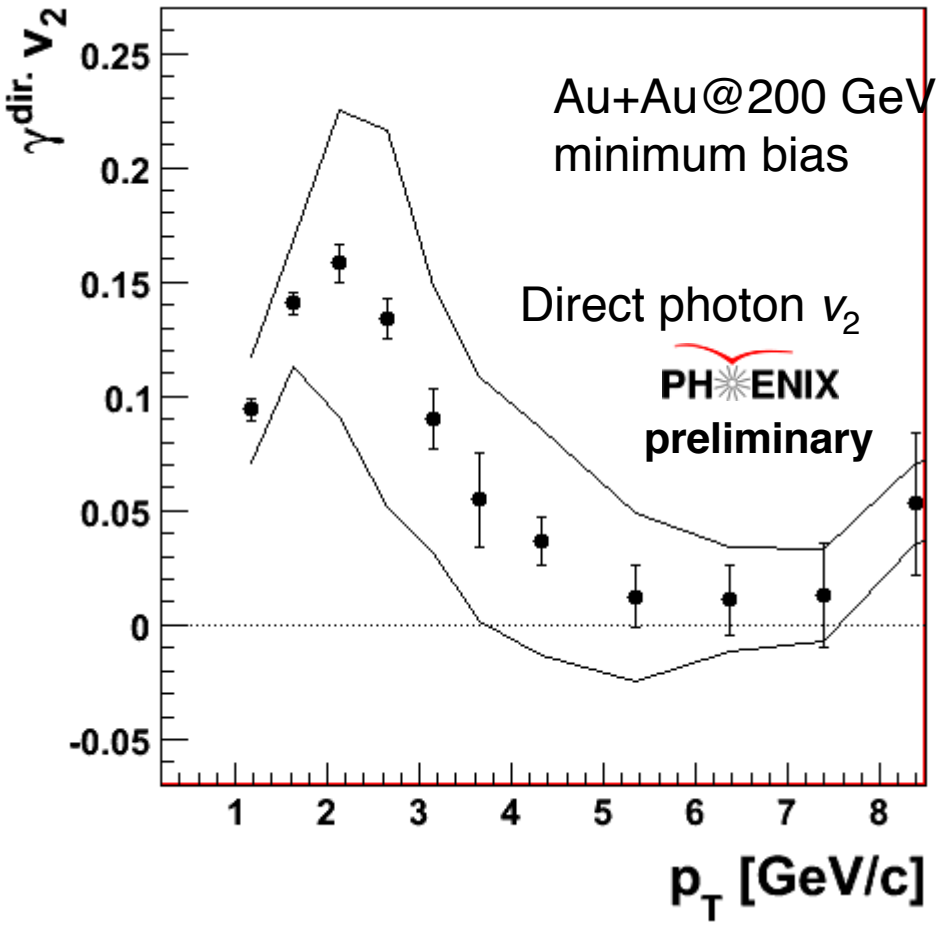
particle ID is crucial different particles behave differently

Exponential enhancement of direct-γ as $p_T \rightarrow 0$ is unique. No other particle is enhanced except in the region of the 'baryon anomaly'. This suggests new physics, *i.e.* thermal photons.

How to prove that exponential low p_T direct-γ in Au+Au are thermal?

- Since the time of Max Planck, thermal photons are "black body" radiation with an asymptotic exponential spectrum produced in/by a hot body or medium.
- This means that unlike the high p_T direct-γ produced in the initial hard-collision, which don't interact with the medium and hence do not exhibit "flow", the thermal photons produced in/by the medium should exhibit the properties of the medium, NOTABLY ANISOTROPIC FLOW.

Et Voilà : Direct Photon v_2



- direct photon v_2 large (~15 %) at p_T =2.5 GeV comparable to π^0
- $v_2 \rightarrow 0$ where hard photons dominate

PHENIX, QM2011

Q.E.D.

The low p_T photons are thermal.