Direct Photons --
The Beautiful Glow that teaches us about the Quark--Gluon Plasma

Thomas K Hemmick

Personal Remarks

- I have lead a ~~fortunate~~ BLESSED life.
  - PhD – University of Rochester 1988.
    - Null search thesis…~30 years required for 10X better.
    - CHANGE FIELD!
    - RHI: "So new that they don't know anything either."
  - Yale University (postdoc on E814) 1989.
  - Stony Brook Faculty Position Opens (1990).
    - me: PERFECT job…too bad that I am too young.
    - PBM: "Where is your application?"
  - Dec 1990 – Spring 1995
    - Stony Brook Relativistic Heavy Ion Group: PBM, JS, TKH

Continuing Ed:

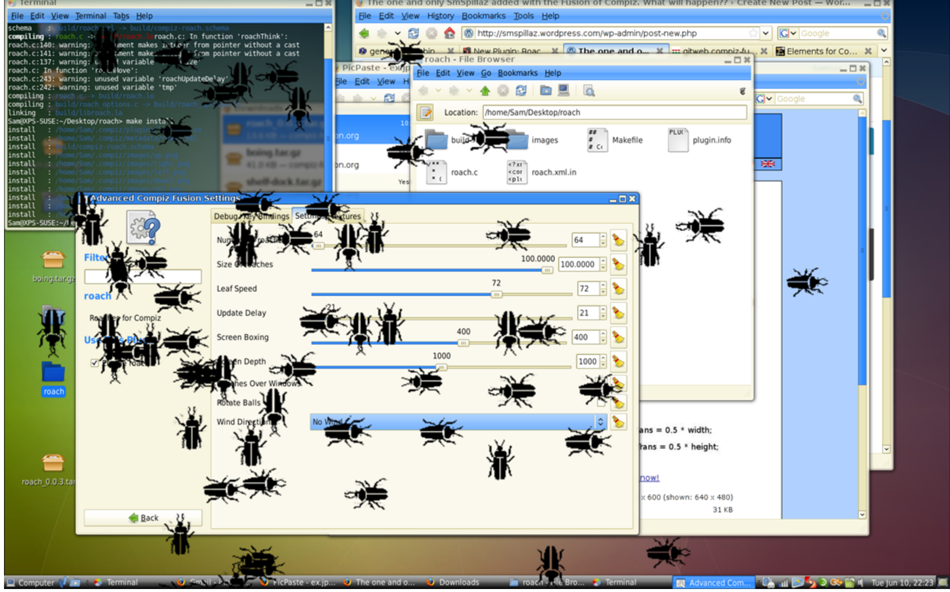
- During the job interview!
  - Let's talk about the vision for RHIC measurements.
  - Prescient: Today's topic is exactly the same.
- Landmark Publications:
  - Braun-Munzinger, Stachel, Wessels, and Xu
  - The birth of HADRO-CHEMISTRY.
  - Reinvention (Fourier-based) of Flow Measurements.
  - ($\Delta^{++} \rightarrow p\pi^{+}$ ($T_{freezeout}=138\downarrow-18\uparrow+23$ MeV @ AGS)).
- J. Stachel QM1988
  - Already leading figure in thermal modeling "Stopping and Energy Flow is Relativistic Nucleus-Nucleus Collisions."

Has Johanna always been a world leading "Thermal Phenomonologist"?

More than that! Johanna has always been a "Thermal Phenomon"!

Johanna Stories

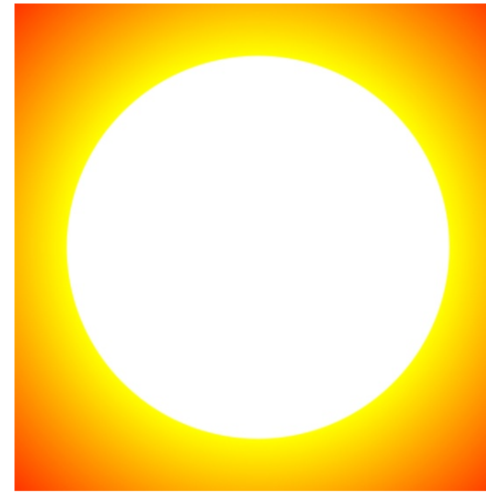
- X Terminal Security.
- Glühwein surprise.
- Slow Dancing.
- The Trip Home.



Thank you, Johanna

Remote Temperature Sensing

Red Hot



White Hot

- Hot Objects produce thermal spectrum of EM radiation.
- Red clothes are NOT red hot, reflected light is not thermal.

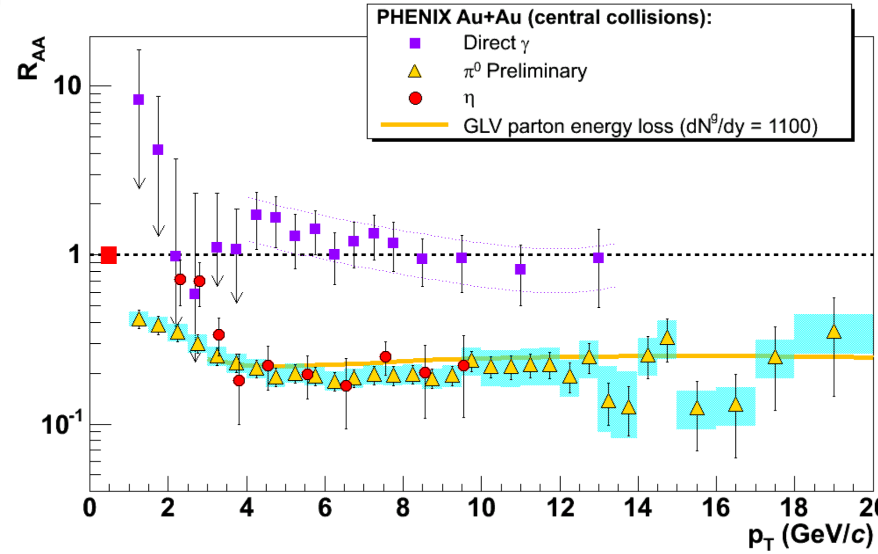
Not Red Hot!

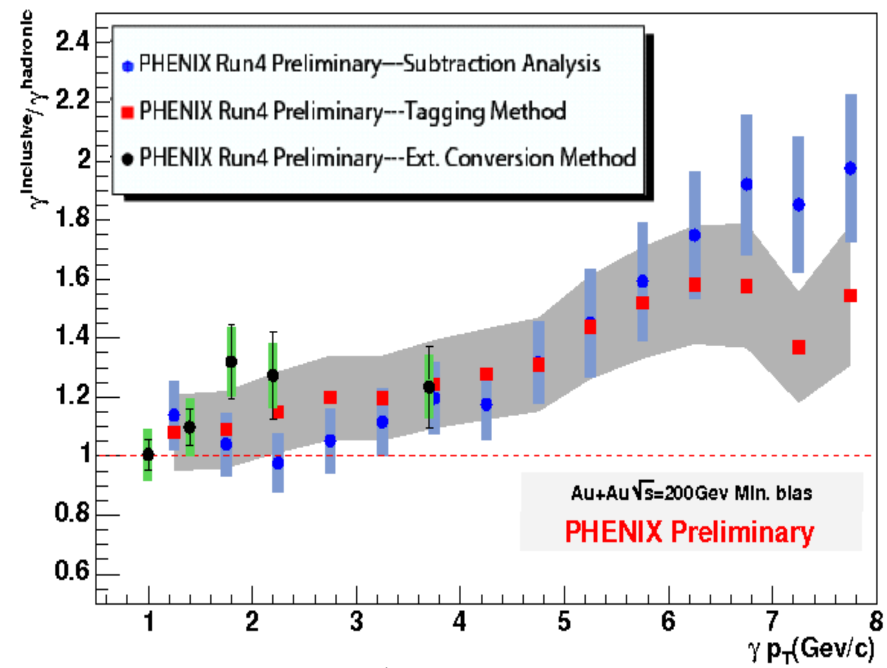
Photon measurements must distinguish thermal radiation from other sources: HADRONS!!!

Non-Thermal Real Photon Sources

- $\gamma^{inclusive}/\gamma^{hadronic}$ (1st plot) exceeds 1 at high p_T indicating presence of non-hadronic photons.
- R_{AA} equals 1 for these same p_T indicating that high p_T yields are similar to pp: initial state hard scattering.
- Measurement difficult at low p_T w/ real photons.

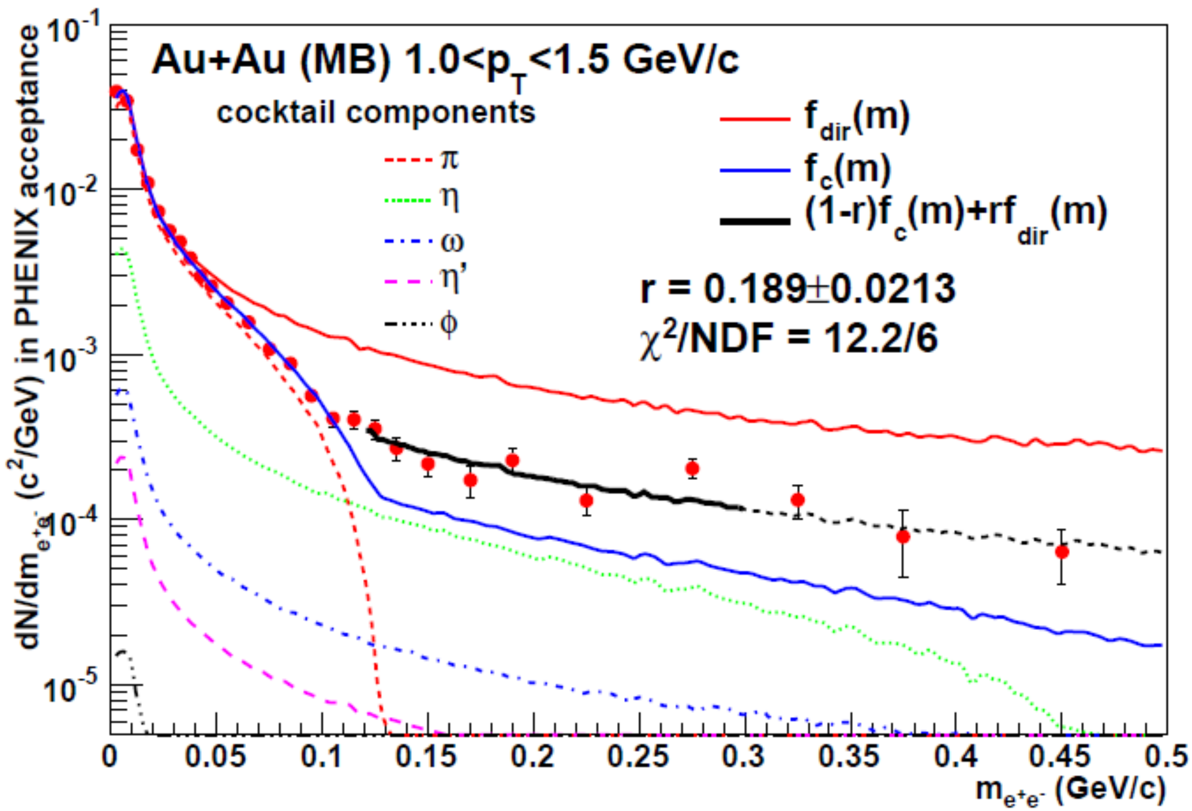
$$R_{AA}(p_T) \equiv \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$





Using Virtual Photons to Minimize Background:

- Example: one pT bin for Au+Au collisions



$$\frac{d^2N_{ee}}{dm_{ee}dp_T} = \frac{2\alpha}{3\pi}\frac{1}{m_{ee}}L(m_{ee})S(m_{ee},p_T)\frac{dN_\gamma}{dp_T},$$

$$L(m_{ee}) = \sqrt{1-\frac{4m_e^2}{m_{ee}^2}}\left(1+\frac{2m_e^2}{m_{ee}^2}\right).$$

$$S_{\rm KW}(M) = |F_P(M^2)|^2\left(1-\frac{M^2}{m_P^2}\right)^3$$

Yield truncated at parent mass

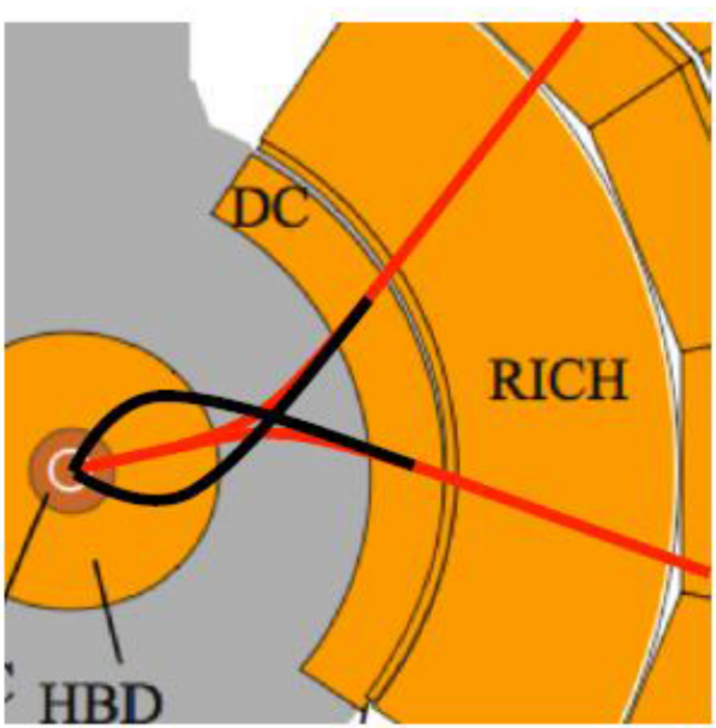
$f_c(m_{ee})$ and $f_{dir}(m_{ee})$ normalized to data for $m_{ee} < 30\,MeV$

Direct γ* yield fitted in range 120 to 300 MeV
Insensitive to π^0 yield

Using Real Photons via Conversion

PHENIX is special because DC has to assume track origin (vertex)
The way we handle this: "Alternate Tracking Model"

- → calculate momenta of e^+ e^- assuming they come from a/ vertex b/ HBD backplane
- → calculate invariant mass of e^+e^- pairs with both
- → for true photons, true momenta $M_{inv} \sim 0$, otherwise $M_{inv} > 0$



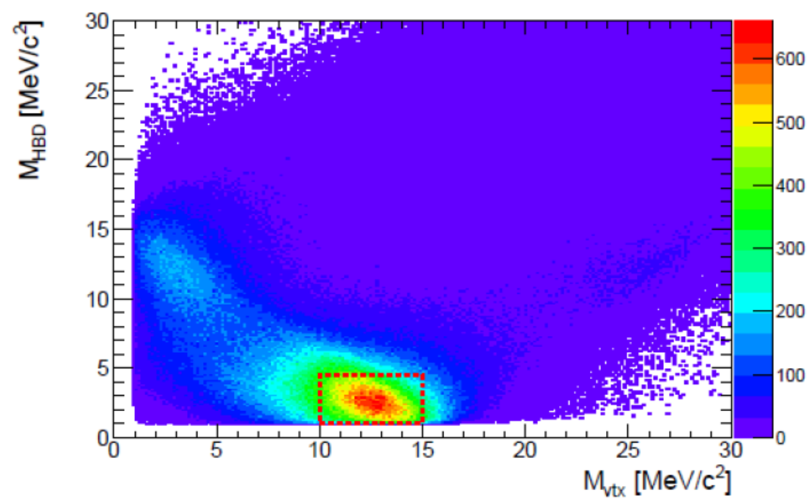
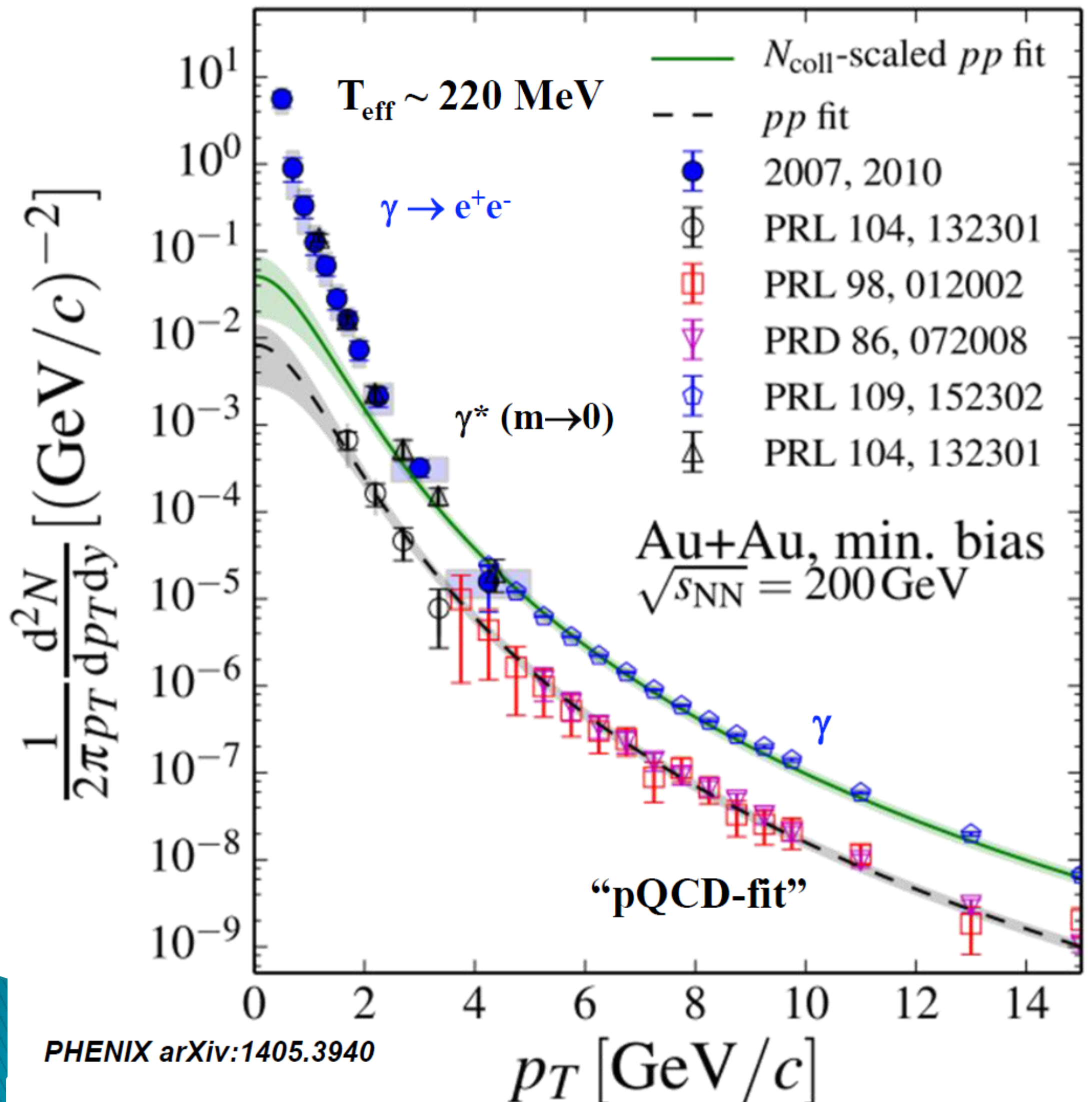


FIG. 2. A view of the cut space used for the conversion photon identification. The mass as calculated under the standard reconstruction algorithm (vtx) is plotted on the horizontal axis, while the mass as calculated under the alternate track model (HBD) is plotted on the vertical axis. The red dotted box indicates the region used to identify photon conversions.

All PHENIX Results Combined



PHENIX arXiv:1405.3940

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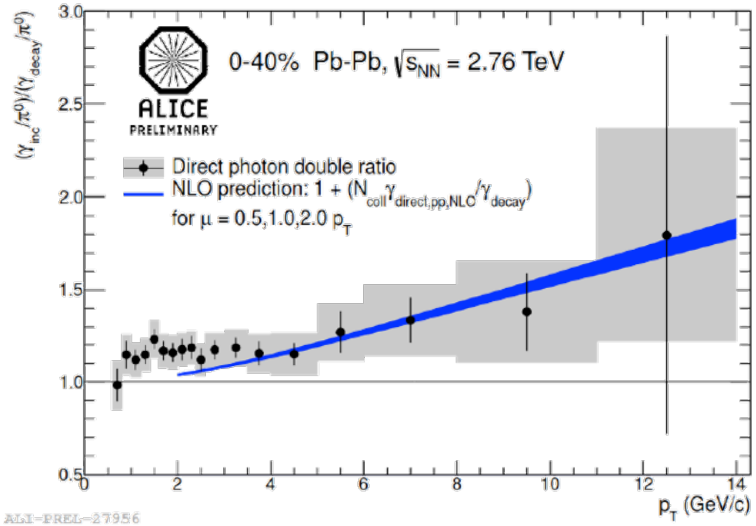
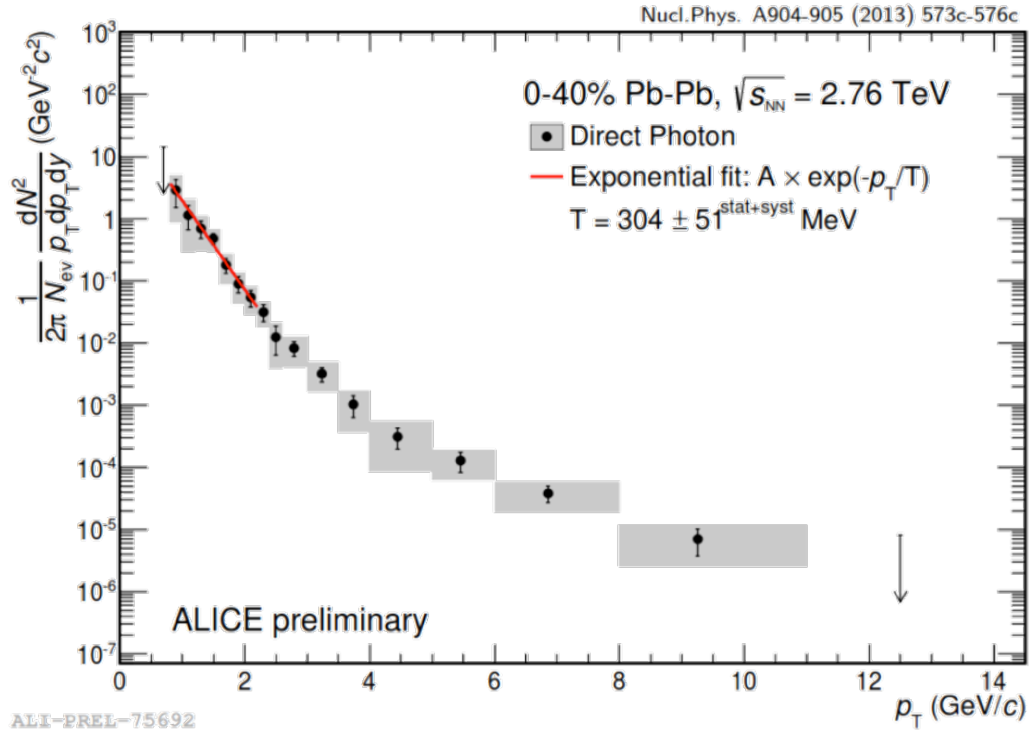
- **Direct photon yield well established**
  - pp consistent with pQCD
  - AuAu follows N_{coll} scaled pp above 4 GeV
  - Significant excess below 3 GeV in AuAu
  - Excess has nearly exponential shape

thermal photons:
T_{ini} > 240 MeV > T_C

large photon yield!

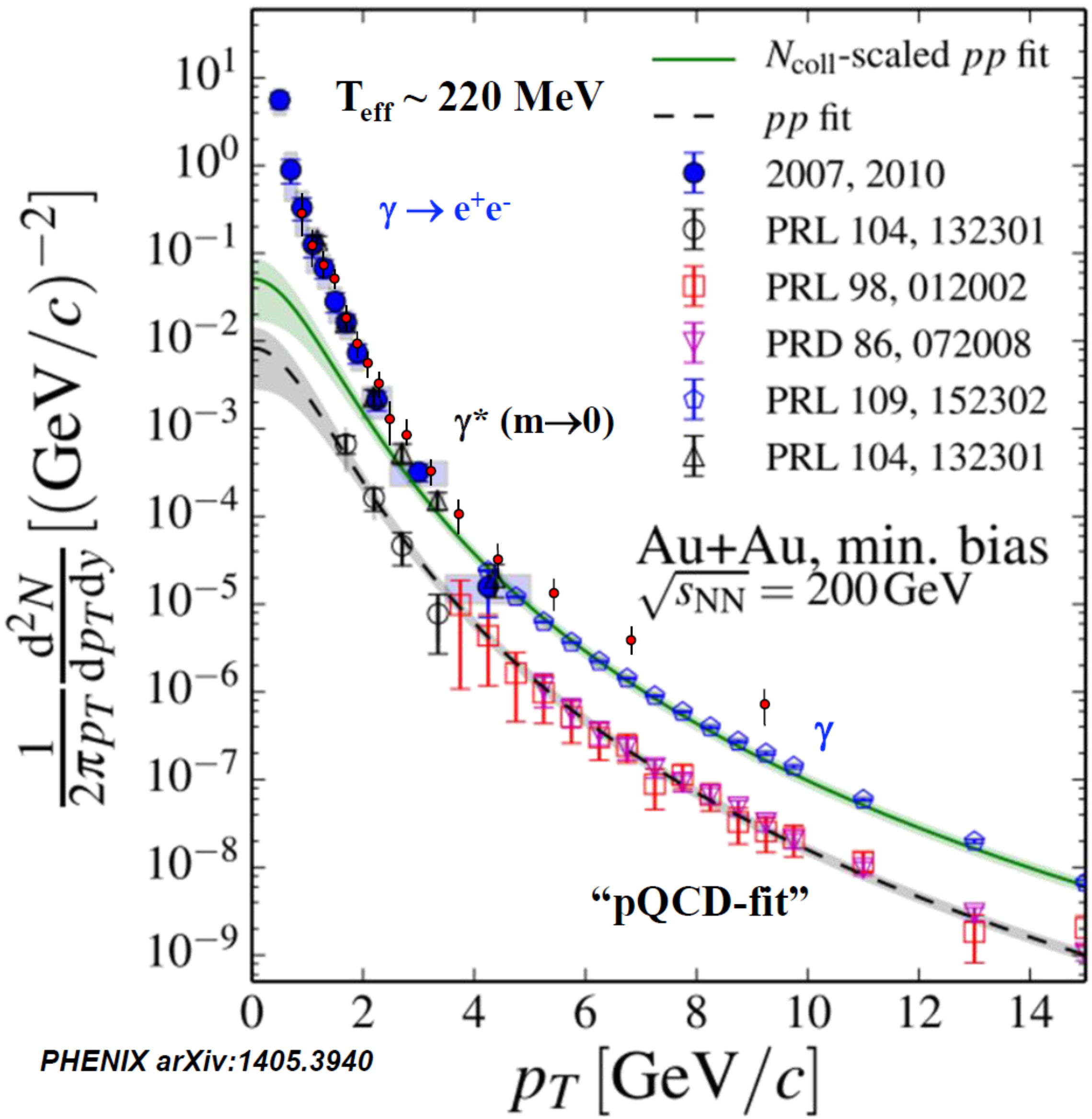
ALICE Results Spectacular





- **Direct photon yield observed by ALICE at LHC**
  - **PbPb follows N_{coll} scaled NLO calculations above 4 GeV**
  - **20 ± 10% excess below 3 GeV with in AuAu**
  - **Excess has nearly exp. shape with inv. slope T_{eff} ~ 300 MeV**

PHENIX and ALICE



PHENIX arXiv:1405.3940

ALICE preliminary $\gamma \rightarrow ee$
Nucl.Phys. A904-905 (2013) 573

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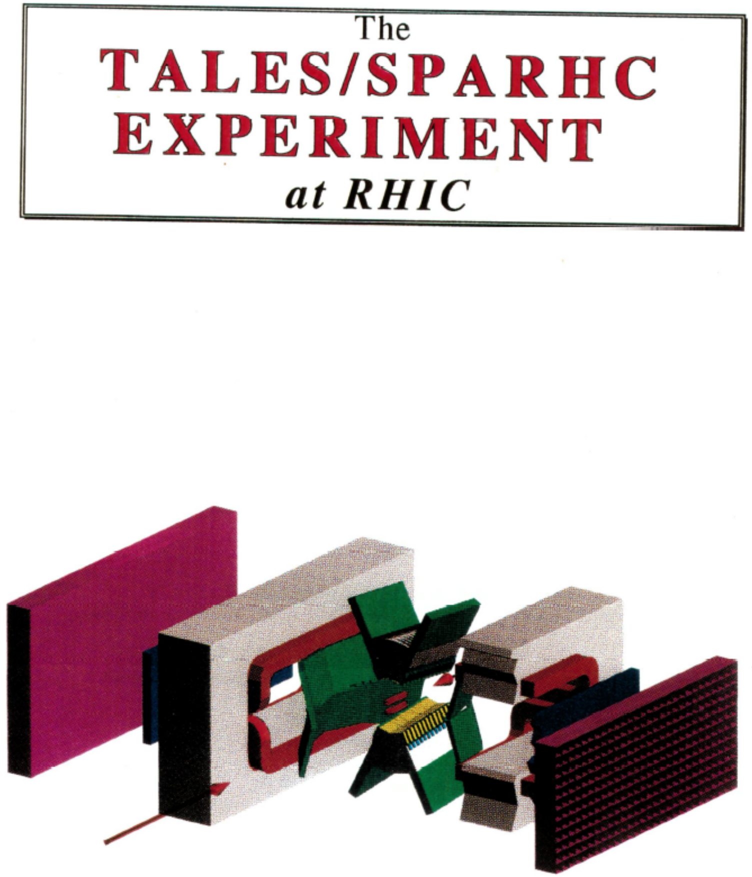
One more plot…



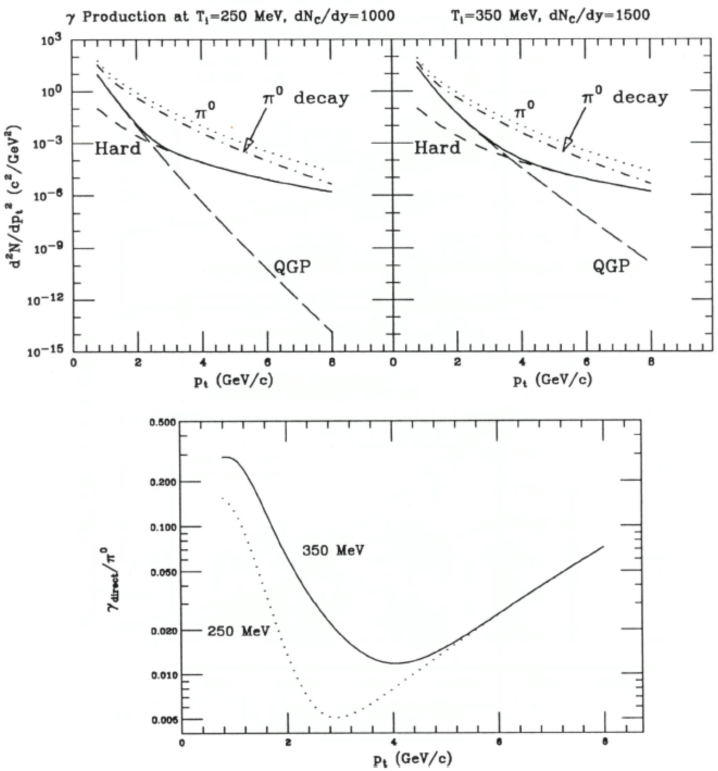


Figure 1: Expected photon p_t spectra for central Au+Au collisions and γ/π ratio.

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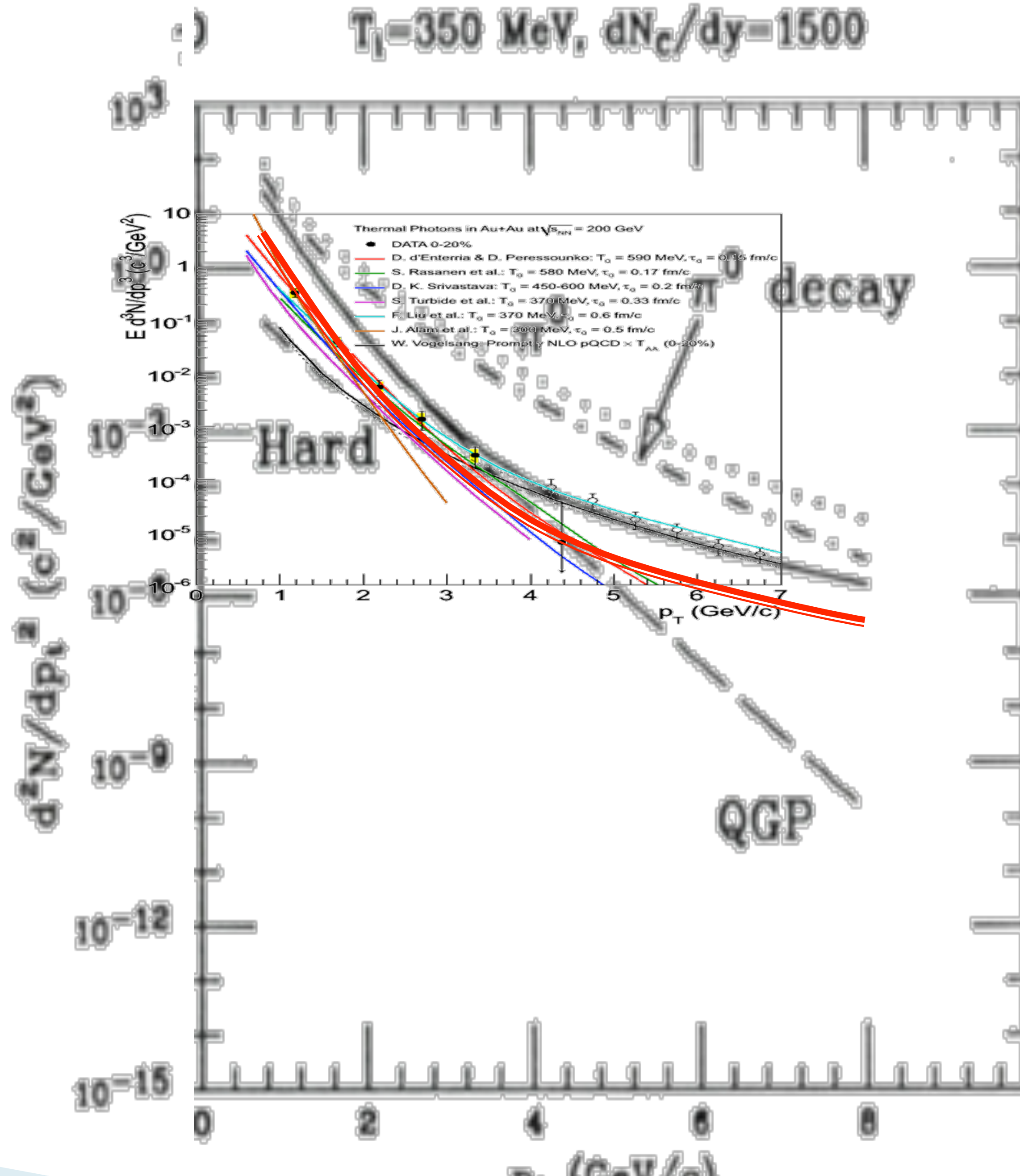
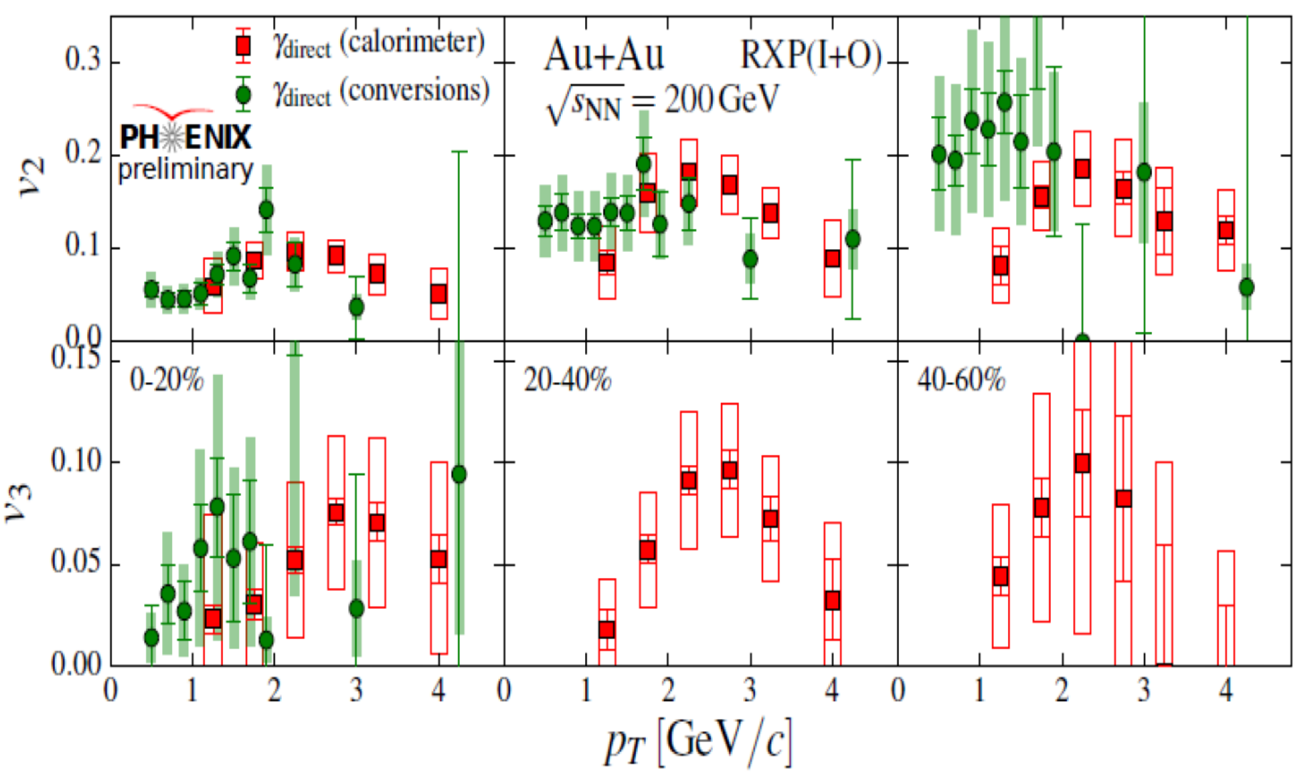
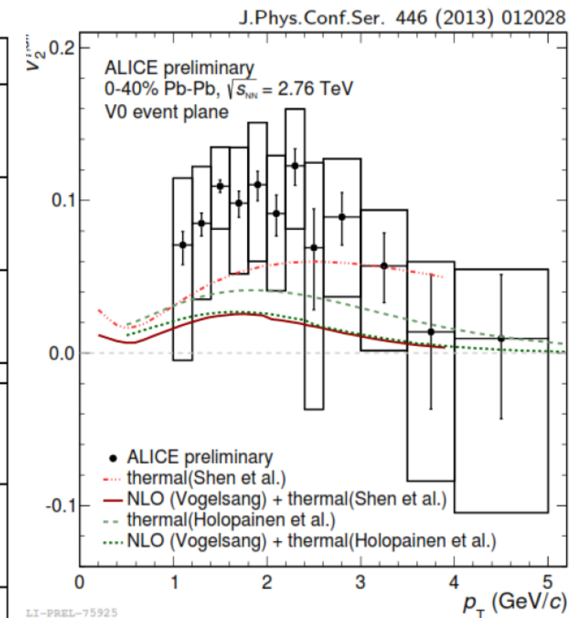
Works?

- Adjustments:
  - "π" from d^2N/dp_T^2 vs $E\, d^3N/dp^3$
  - π adjusted by eye
- dy=1 assumed.
- QGP yield runs <u>right through </u>the data!



Direct Gamma Puzzle!





- High yield should be hot/early times.
- Large flow should be late/cool times.

Many Models, no firm resolution…

Semi-QGP

1409.4778
(Gale, Jeon, Paquet, Pisarski, …)

Anisotropy from magnetic field

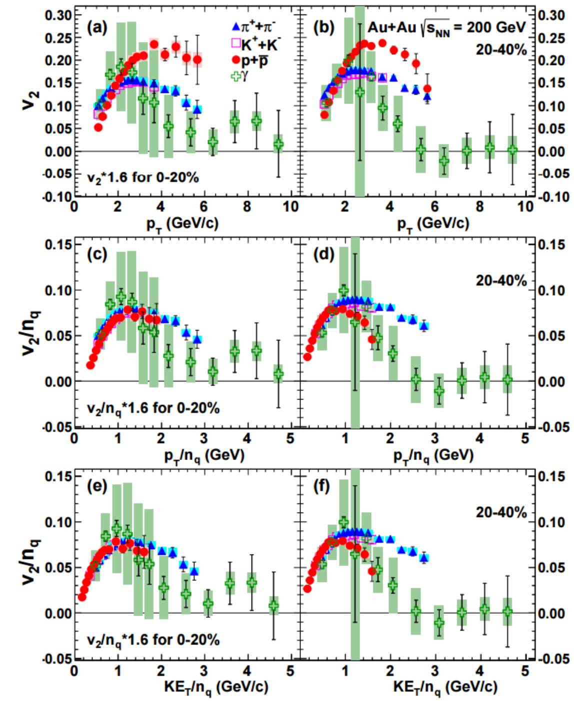
1308.6568

Same Blast Wave (BW) fit applied to phot

Photon observables are estimated as a massless

Direct photon flow – play with t

Hadronization Flash



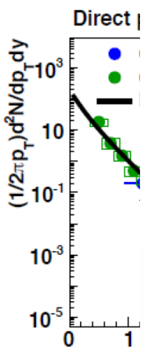
"…the strong … in the semi… elliptical flo… generated i…

Essentially: … T_c to $2T_c$ b… turns on (a…

If you look cl… but at the … total yield

Note: this is t… currently or… predicts no… The horizonta… roughly to …

The plot show… photon v_2 (… if ALL photo… magnetic o… magnetic fi…

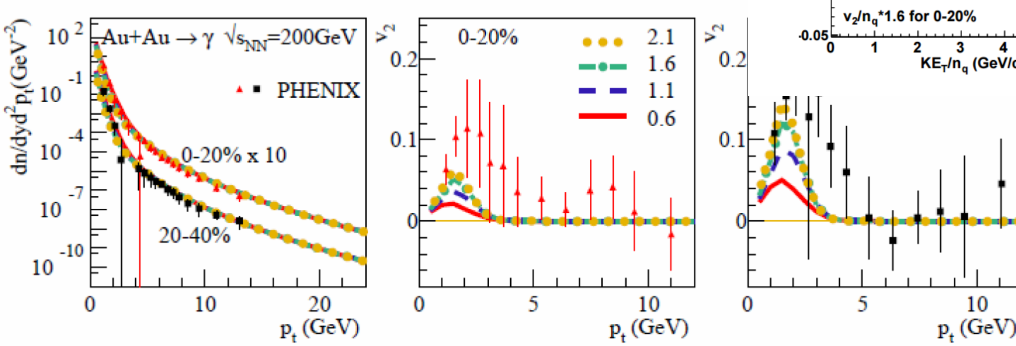


With a more … averaged n… contributior… up to a fact…

Photon … The v_n c… (Decay …

The slop… than 24… It is due…

F.-M. Liu
Early hydro initial time, QGP forms considerably later
(0.6 f/c vs QGP formation times up to 2.1 f/c)
→ early emission (no flow part) was overestimated



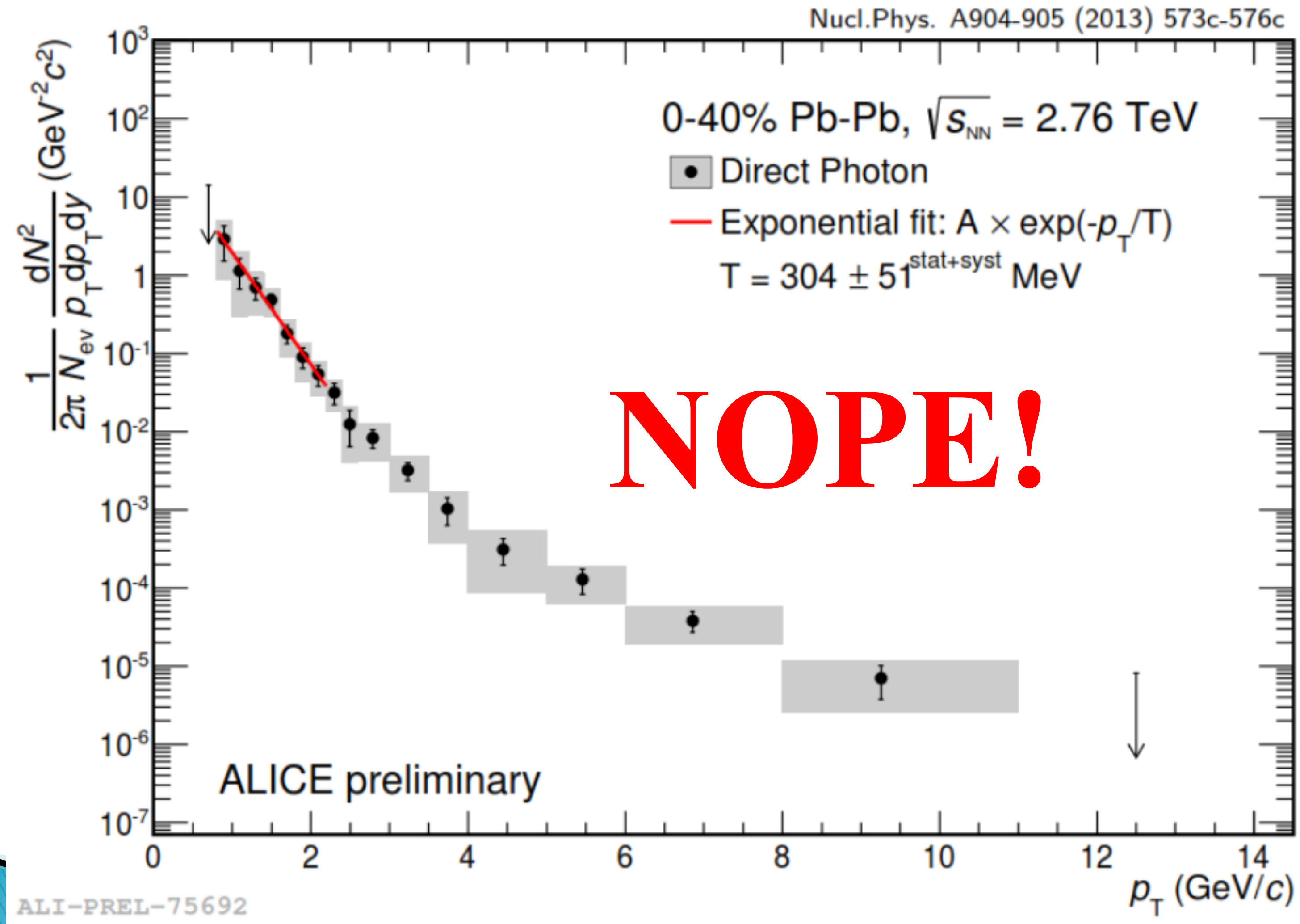
Q: what is the emission between τ_{hydro} and τ_{QGP}? Apparently unanswered
(looks a bit like a "**fiat**" type theory so far → fine for the trees
but where's the forest?)

Much More to Learn!

- Direct photon yields do not disappoint!
- Fascinating look into the full evolution.
- Puzzling yield/flow result.
- Much more to learn.

- Finish with a question and an answer:

Is this that Beautiful Glow that teaches us about the Quark-Gluon Plasma?

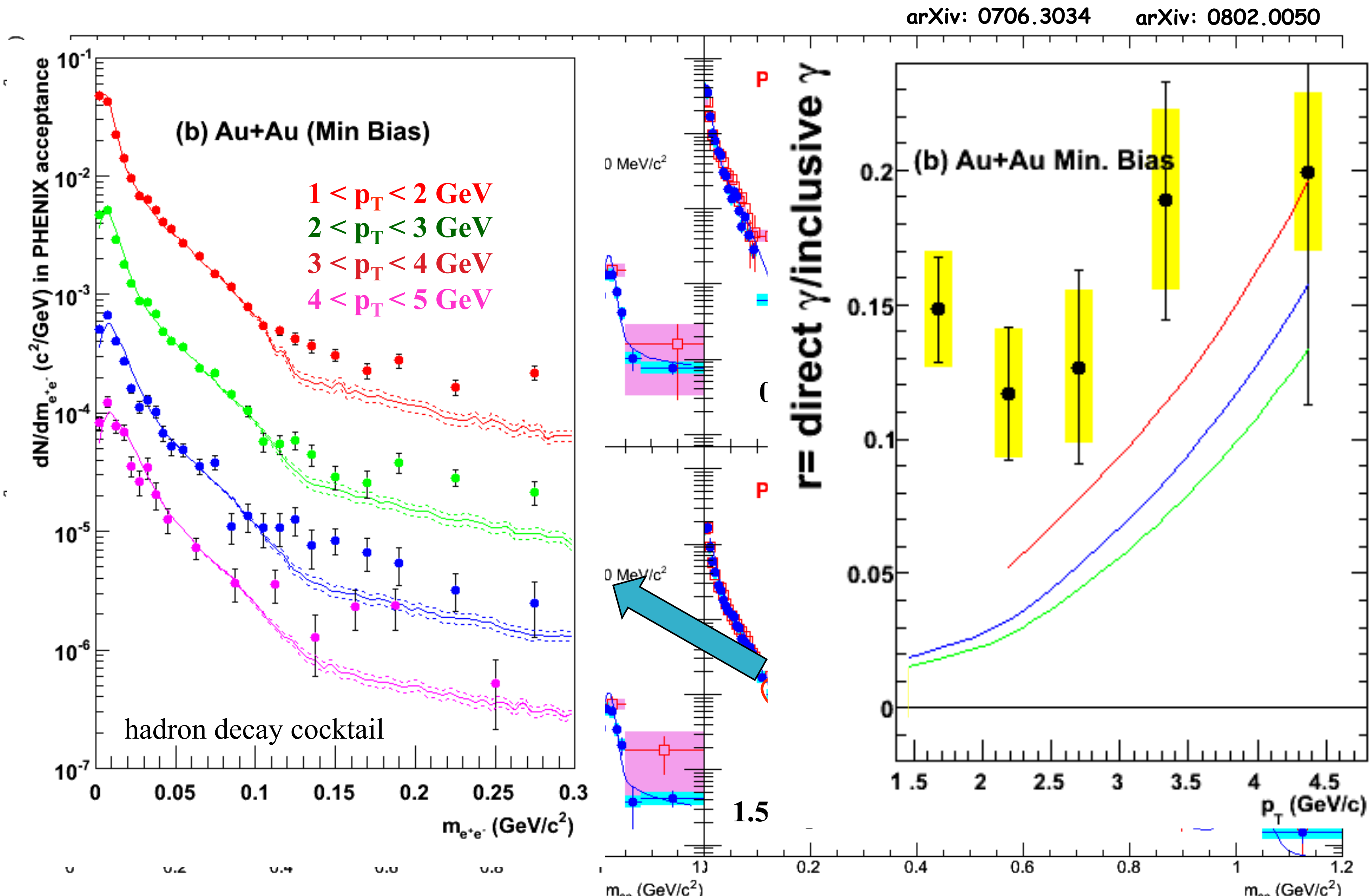


<u>THIS</u> is the Beautiful Glow that Teaches Us about the Quark-Gluon Plasma

Happy Birthday, Johanna!

Backups…

Dilepton Excess at High p_T – Small Mass



Significant direct photon excess beyond pQCD in Au+Au

Interpretation as Direct Photon

Relation between real and virtual photons:

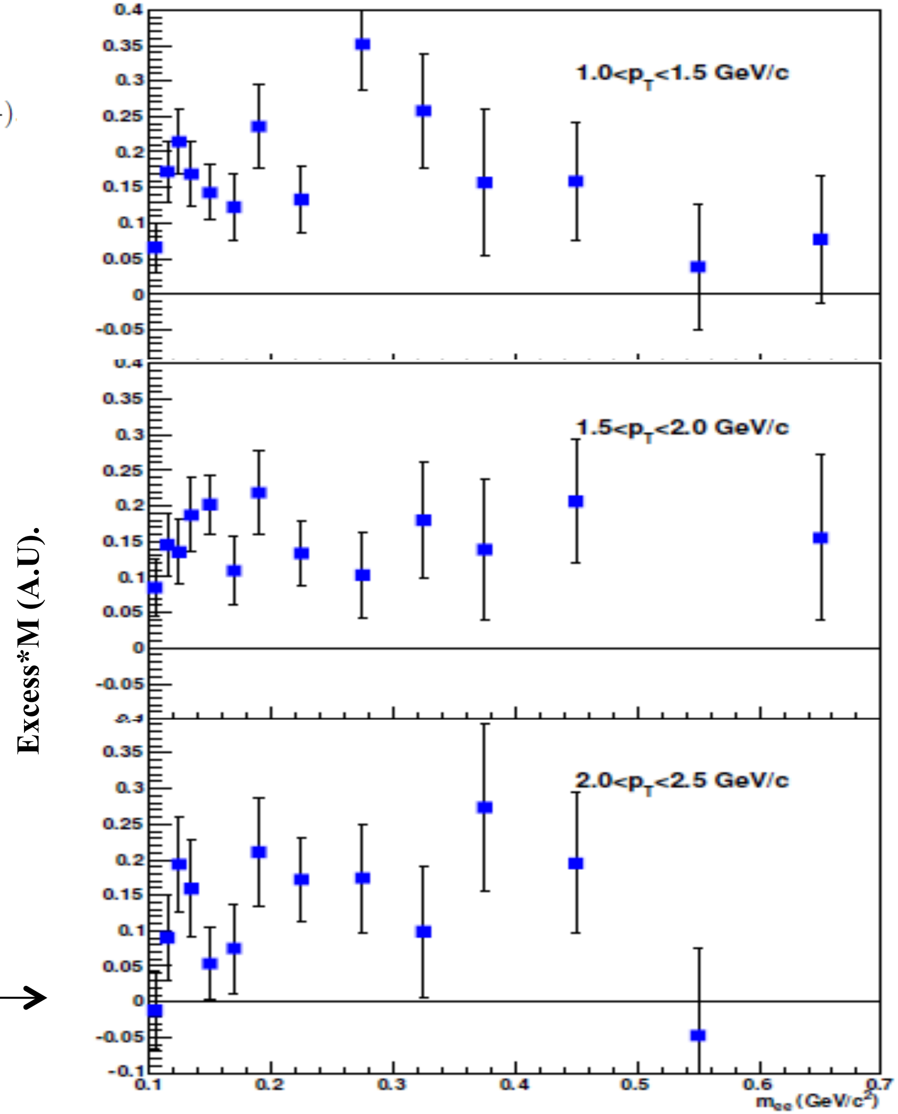
$$L(M) = \sqrt{1 - \frac{4m_l^2}{M^2}}\left(1 + \frac{2m_l^2}{M^2}\right)$$

$$\frac{d\sigma_{ee}}{dM^2 dp_T^2 dy} \cong \frac{\alpha}{3\pi}\frac{1}{M^2}L(M)\frac{d\sigma_\gamma}{dp_T^2 dy}$$

Extrapolate real γ yield from dileptons:

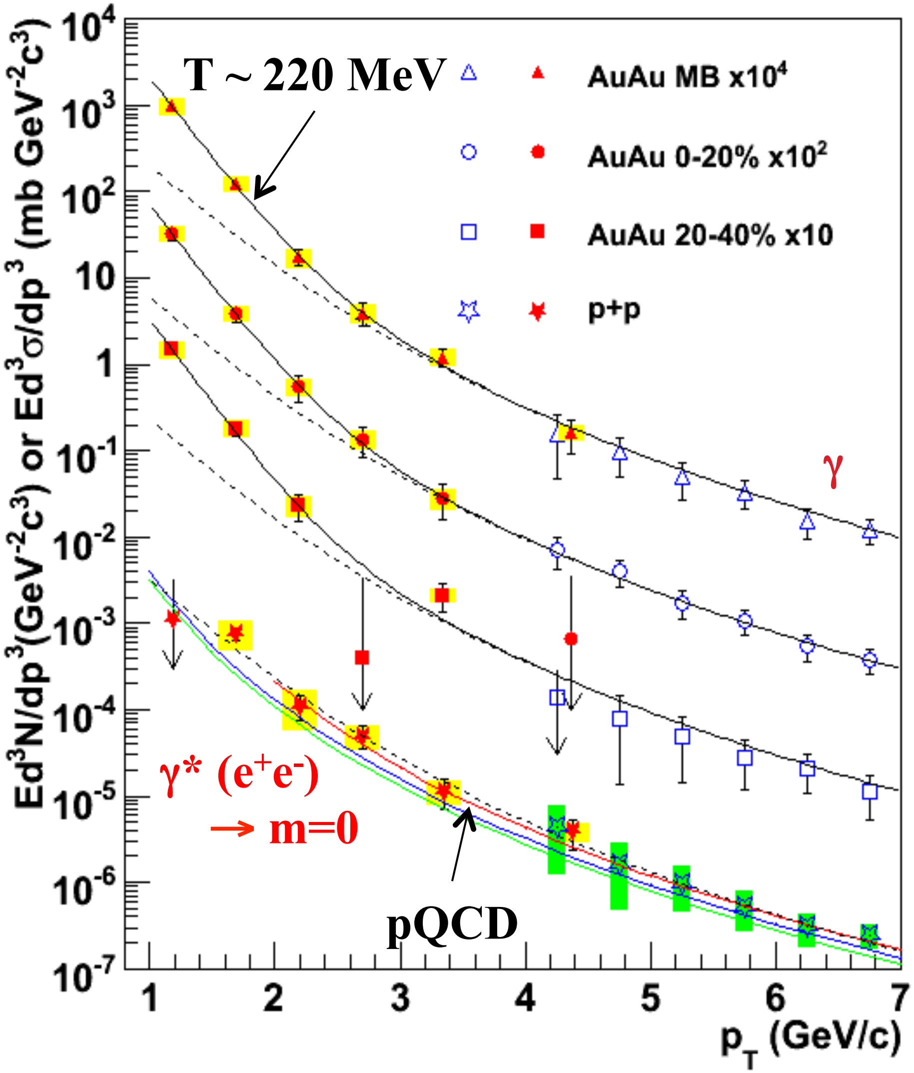
$$M \times \frac{dN_{ee}}{dM} \rightarrow \frac{dN_\gamma}{dM} \quad \text{for} \quad M \rightarrow 0$$

Virtual Photon excess
At small mass and high p_T
Can be interpreted as
real photon excess



no change in shape
can be extrapolated
to M=0

First Measurement of Thermal Radiation at RHIC



Direct photons from real photons:

- Measure inclusive photons
- Subtract π^0 and η decay photons at S/B < 1:10 for p_T<3 GeV

Direct photons from virtual photons:

- Measure e^+e^- pairs at $m_\pi < m << p_T$
- Subtract η decays at S/B ~ 1:1
- Extrapolate to mass 0

First thermal photon measurement: T_{ini} > 220 MeV > T_C

Interpretation as Direct Photon

Relation between real and virtual photons:

$$\frac{d\sigma_{ee}}{dM^2 dp_T^2 dy} \cong \frac{\alpha}{3\pi}\frac{1}{M^2}L(M)\frac{d\sigma_\gamma}{dp_T^2 dy}$$

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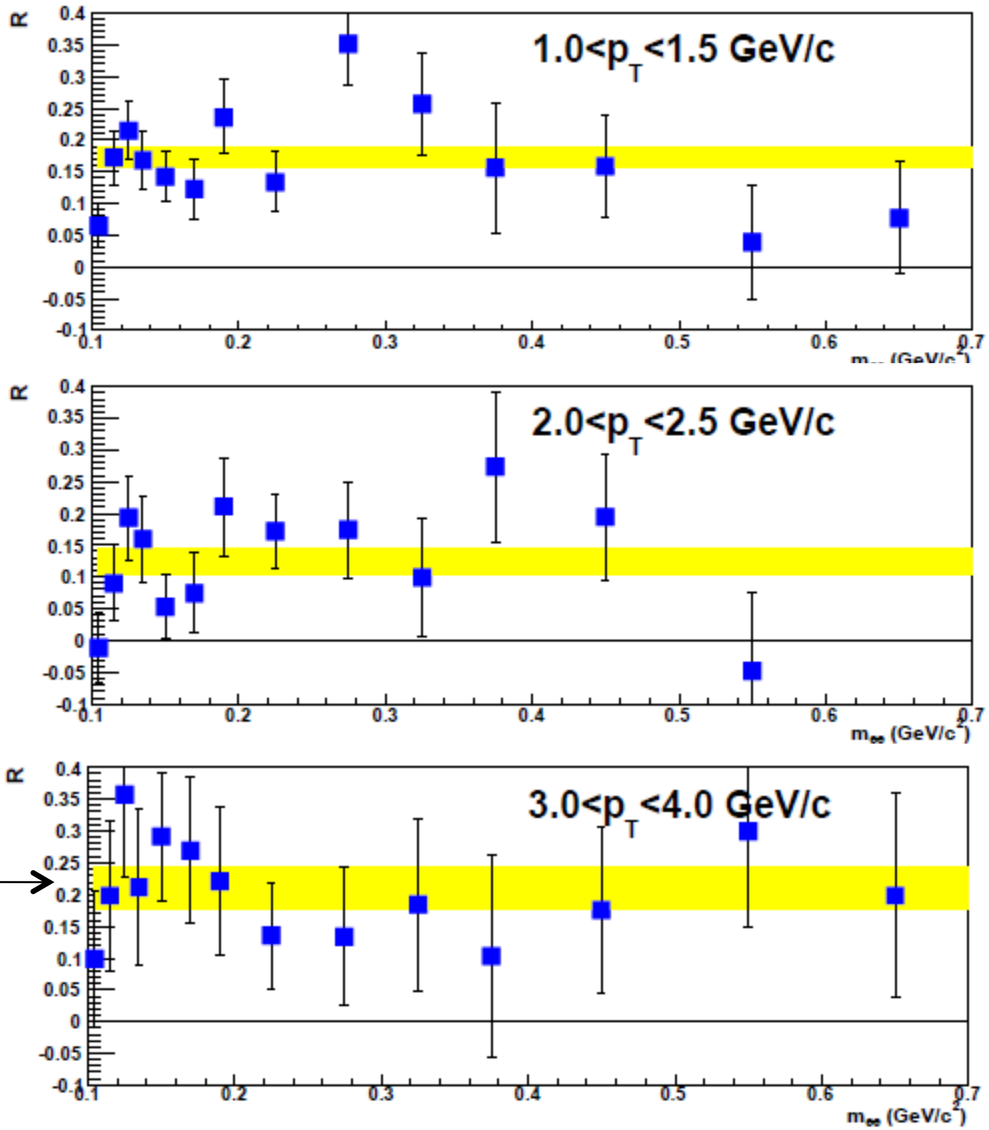


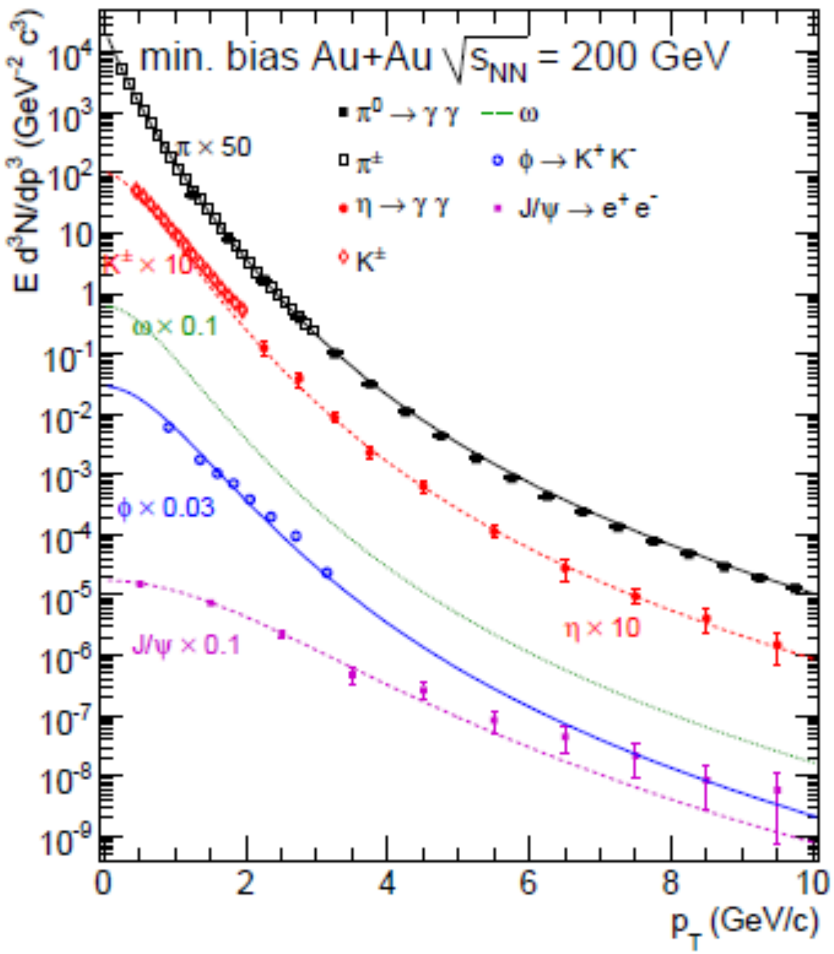
Estimate of Expected Sources

- Hadron decays:
  - Fit π^0 and $\pi^\pm$ data p+p or Au+Au

$$E\frac{d^3\sigma}{d^3p} = \frac{A}{\left(\exp(-ap_T - bp_T^2) + p_T/p_0\right)^n}$$

  - For other mesons $\eta, \omega, \rho, \phi, J/\psi$ etc. replace $p_T \rightarrow m_T$ and fit normalization to existing data where available

Hadron data follows "m_T scaling"



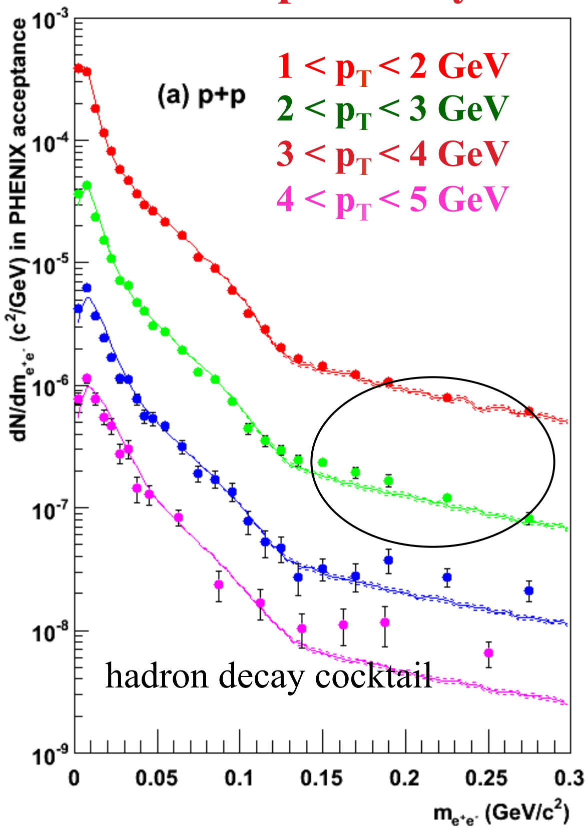
- Heavy flavor production:
  - $\sigma_c = N_{coll}$ x 567±57±193μb from single electron measurement

Predict cocktail of known pair sources

Direct (pQCD) Radiation

- **Measuring direct photons via virtual photons:**
  - any process that radiates γ will also radiate γ*
  - for $m << p_T$ γ* is "almost real"
  - extrapolate γ* → e+e− yield to m = 0 → direct γ yield
  - $m > m_\pi$ removes 90% of hadron decay background
  - S/B improves by factor 10: 10% direct γ → 100% direct γ*

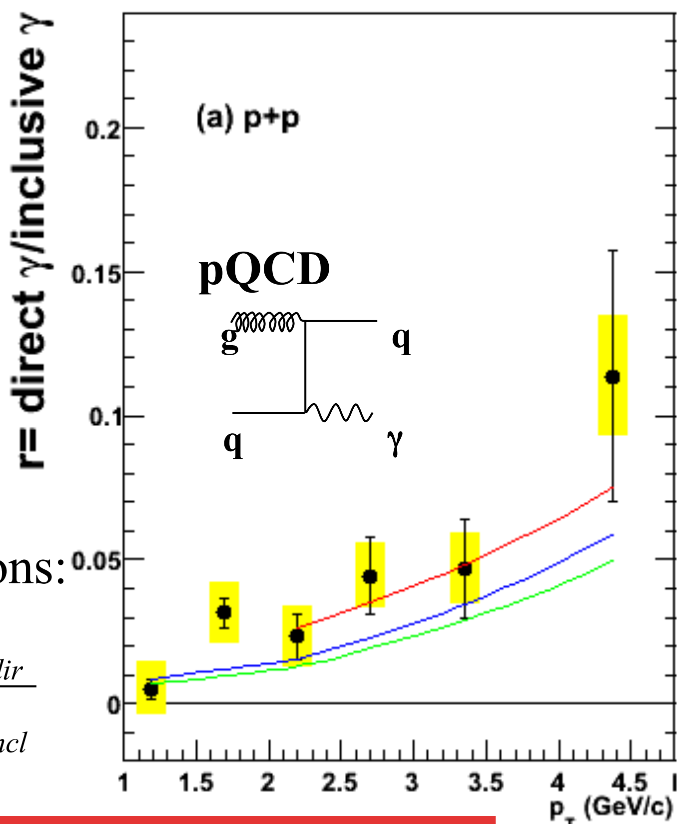
arXiv:0804.4168



access above cocktail

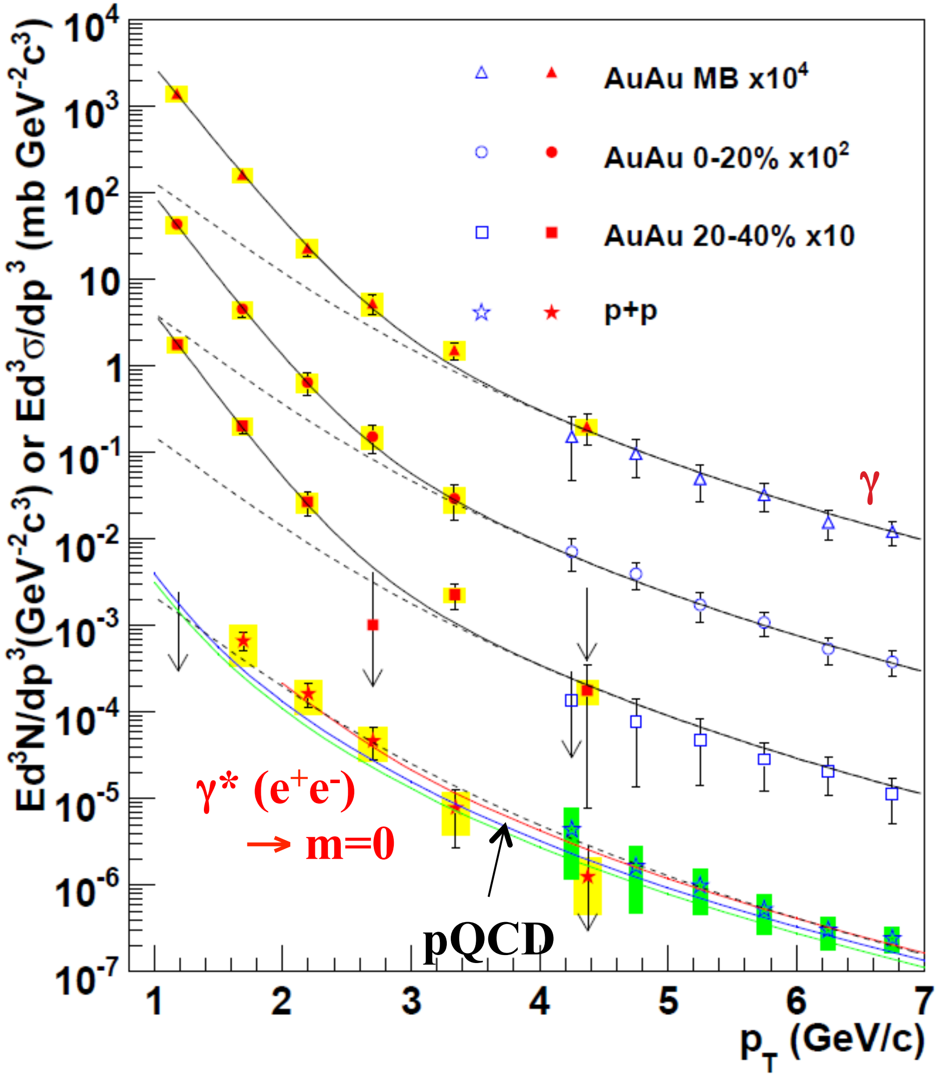
fraction or direct photons:

$$r = \frac{\gamma^*_{dir}}{\gamma^*_{incl}} = \frac{\gamma_{dir}}{\gamma_{incl}}$$



Small excess for $m << p_T$ consistent with pQCD direct photons

Thermal Radiation at RHIC



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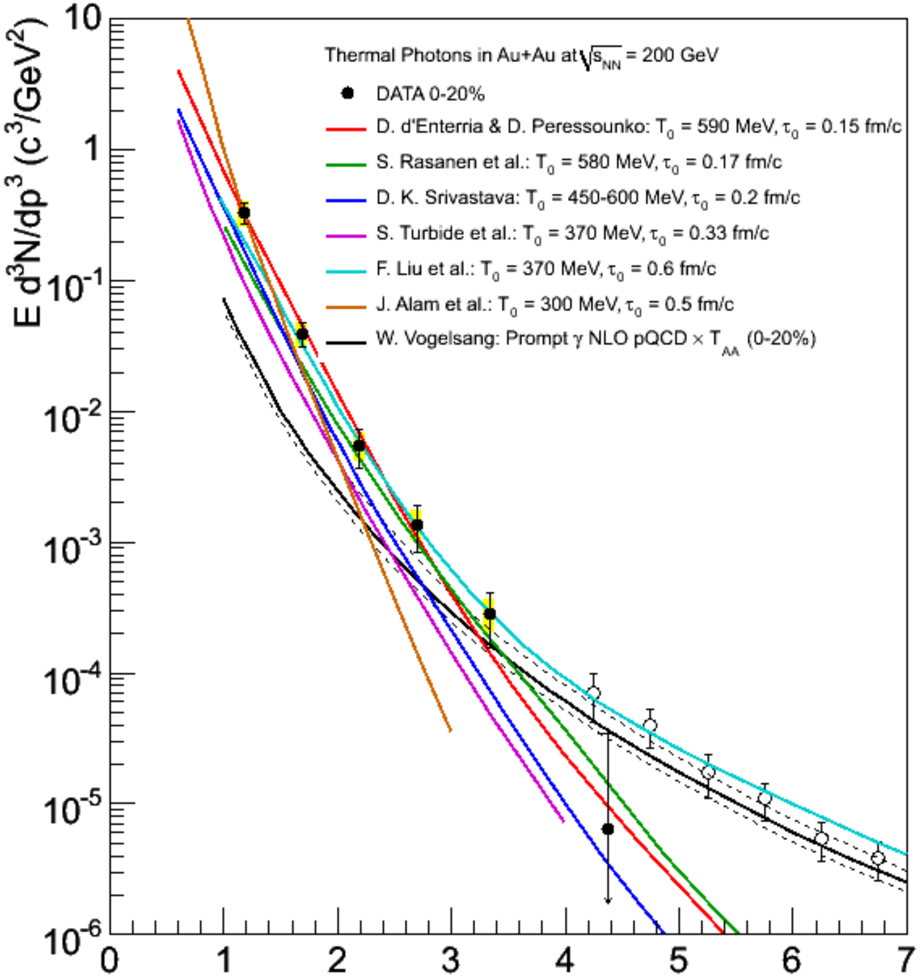
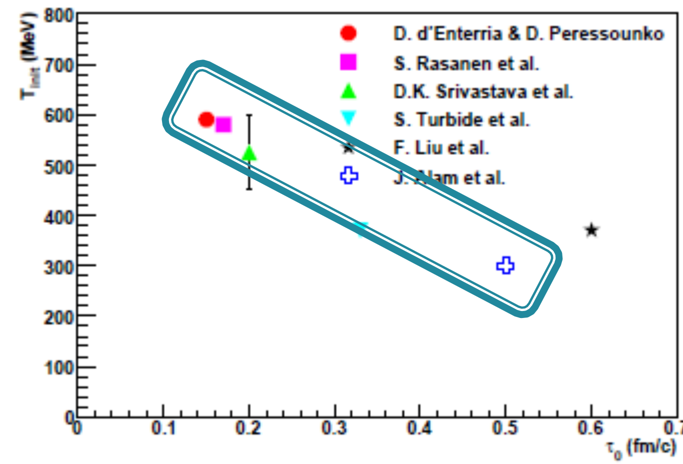
  - Extrapolate to mass 0

First thermal photon measurement in RHI Collisions!

Calculation of Thermal Photons



D.d'Enterria, D.Peressounko, Eur.Phys.J.C 46 (2006)



T_{ini} = 300 to 600 MeV
τ_0 = 0.15 to 0.5 fm/c

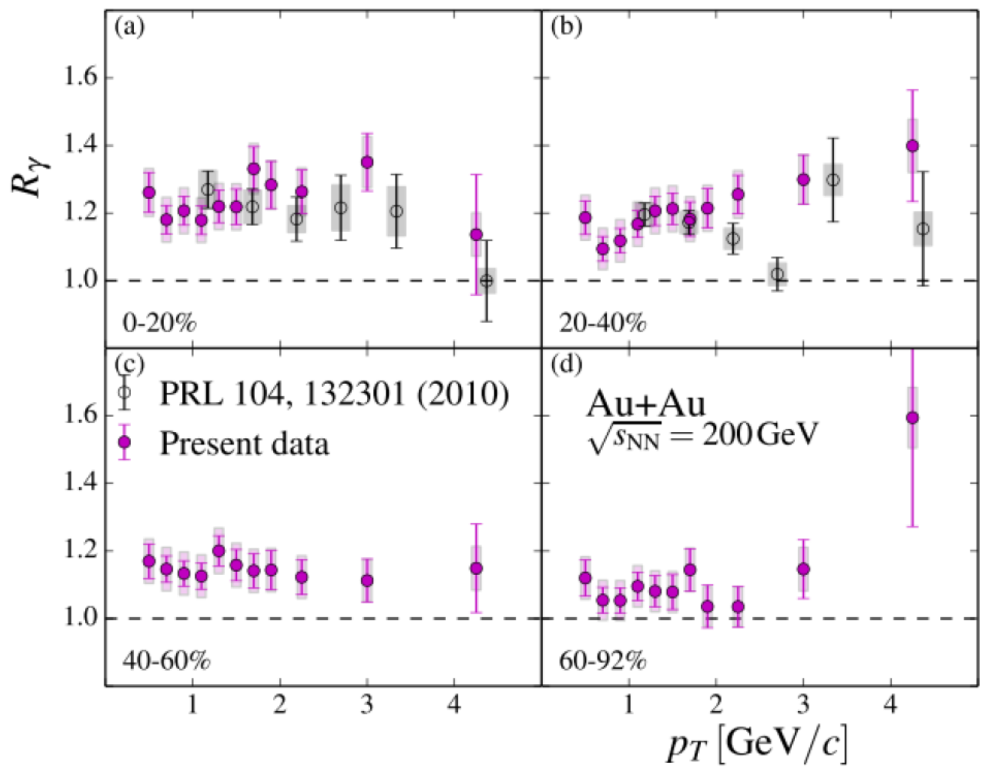
- Initial temperatures and times from theoretical model fits to data:
  - 0.15 fm/c, 590 MeV (d'Enterria et al.)
  - 0.2 fm/c, 450–660 MeV (Srivastava et al.)
  - 0.5 fm/c, 300 MeV (Alam et al.)
  - 0.17 fm/c, 580 MeV (Rasanen et al.)
  - 0.33 fm/c, 370 MeV (Turbide et al.

Real Photons Match Virtual

note: $1 - r_\gamma = \frac{1}{R_\gamma}$

$$R_\gamma = \frac{N_\gamma^{incl}}{N_\gamma^{hadr}} = \frac{\langle \varepsilon f \rangle \times \left(\frac{Y_\gamma^{incl}}{Y_\gamma^{\pi^0 tag}} \right)^{Data}}{\left(\frac{N_\gamma^{hadr}}{N_\gamma^{\pi^0}} \right)^{MC}}$$

PHENIX arXiv:1405.3940



- **Double ratio tagging method**
  - Clean photon sample with photon conversion
  - Explicit cancelation of systematic uncertainties
  - Combined result from 2 analyses
- **Direct photons**
  - Well established in AuAu at RHIC
  - Real and virtual photons consistent
  - Full centrality dependence

Almost 20% direct photons in central Au+Au!
Approx. independent of p_T from 0.4 to 4 GeV