

Direct-Photon Production in $\sqrt{s_{NN}} = 200 \text{ GeV Au+Au Collisions}$

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University of Münster
for the PHENIX collaboration**

Direct Photons in A+A collisions – Why?

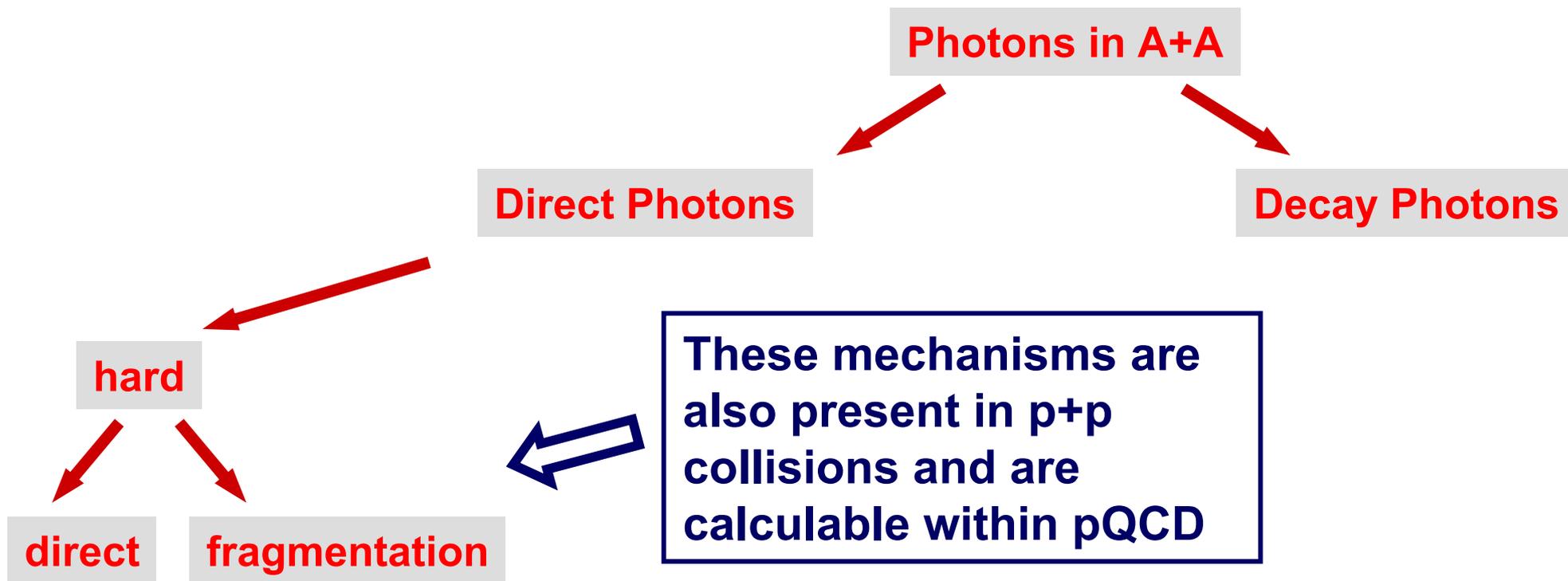
High p_T (> 6 GeV/c):

- High- p_T direct photons produced in initial hard parton-parton scatterings
- Photons leave the subsequently produced medium (quark-gluon plasma !?) unaltered
- Test hard scattering predictions
- Measure rate of hard processes

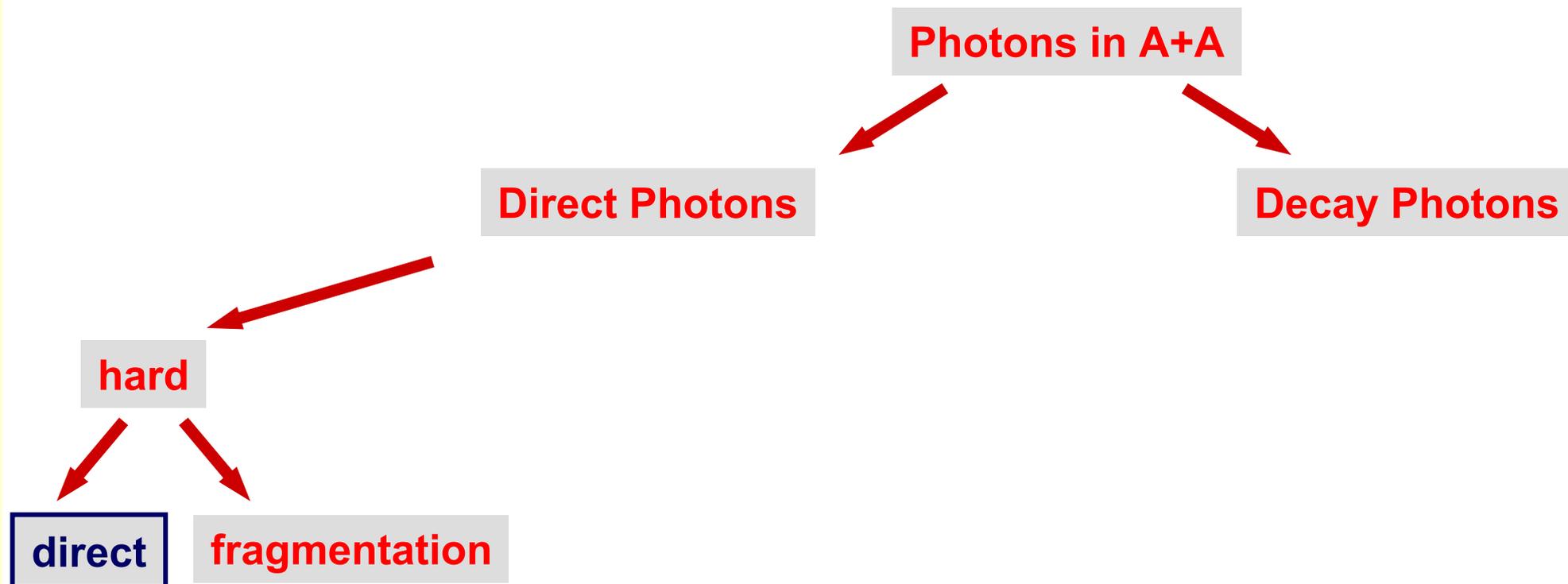
Low p_T :

- Low p_T thermal direct photons expected to reflect the initial temperature of the fireball
- Temperatures above T_c indicate quark-gluon plasma phase

Known and Presumed Photon Sources in A+A

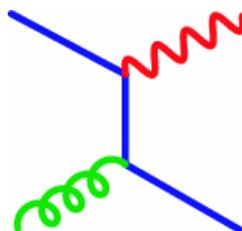


Known and Presumed Photon Sources in A+A

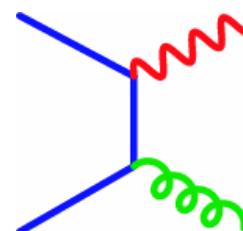


Hard direct photons:
direct component

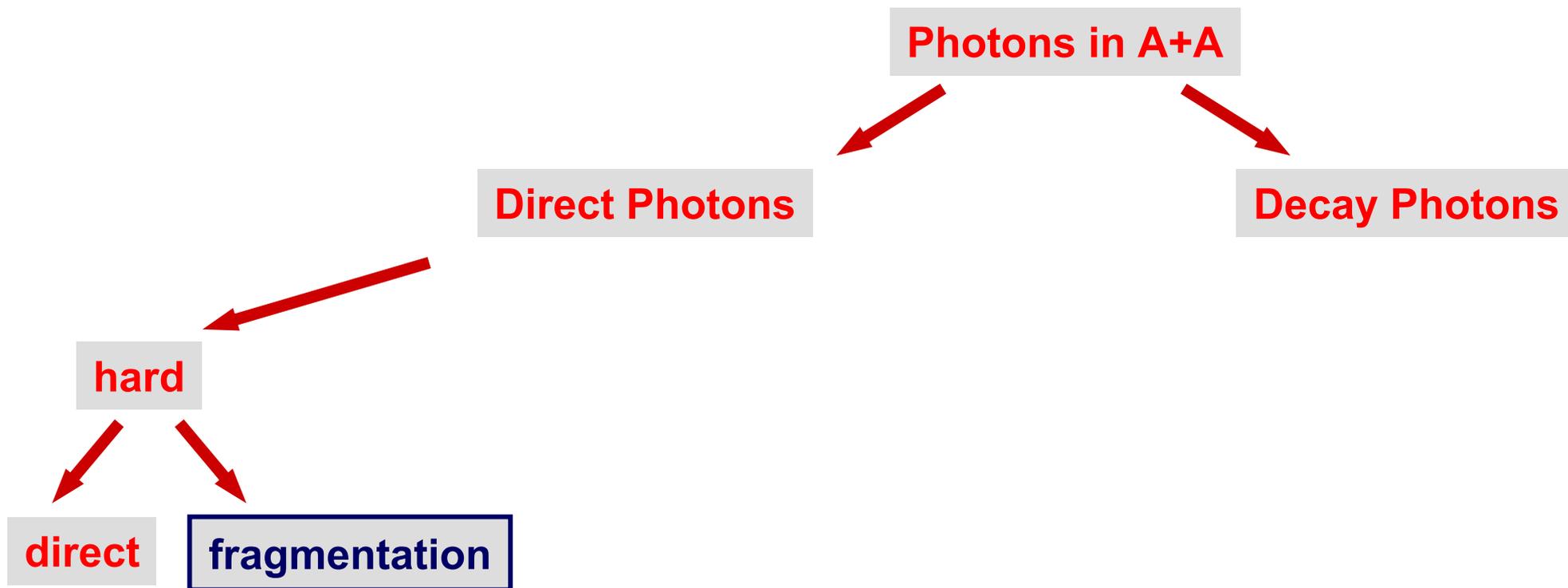
Compton
 $q + g \rightarrow \gamma + q$



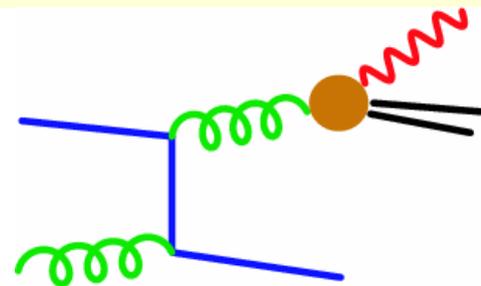
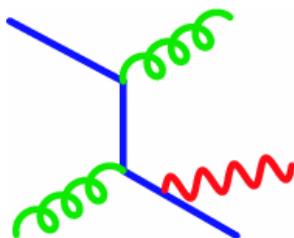
Annihilation
 $q + \bar{q} \rightarrow \gamma + g$



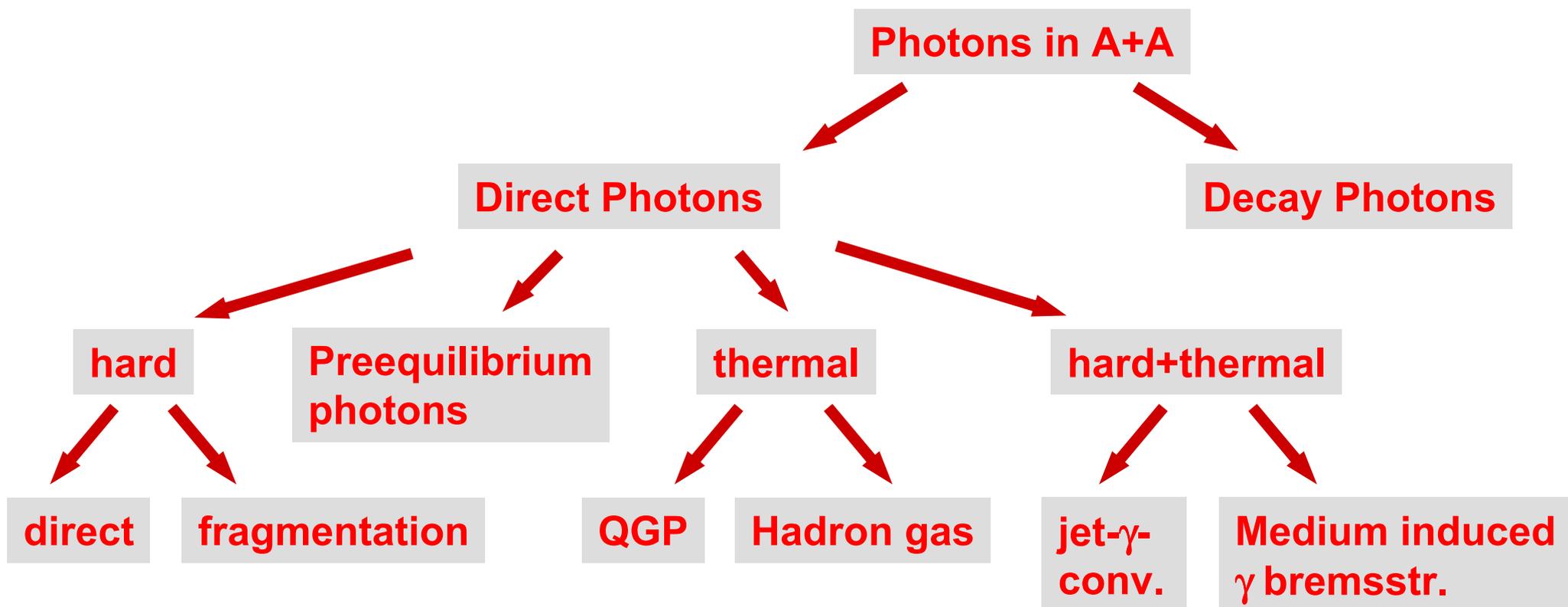
Known and Presumed Photon Sources in A+A



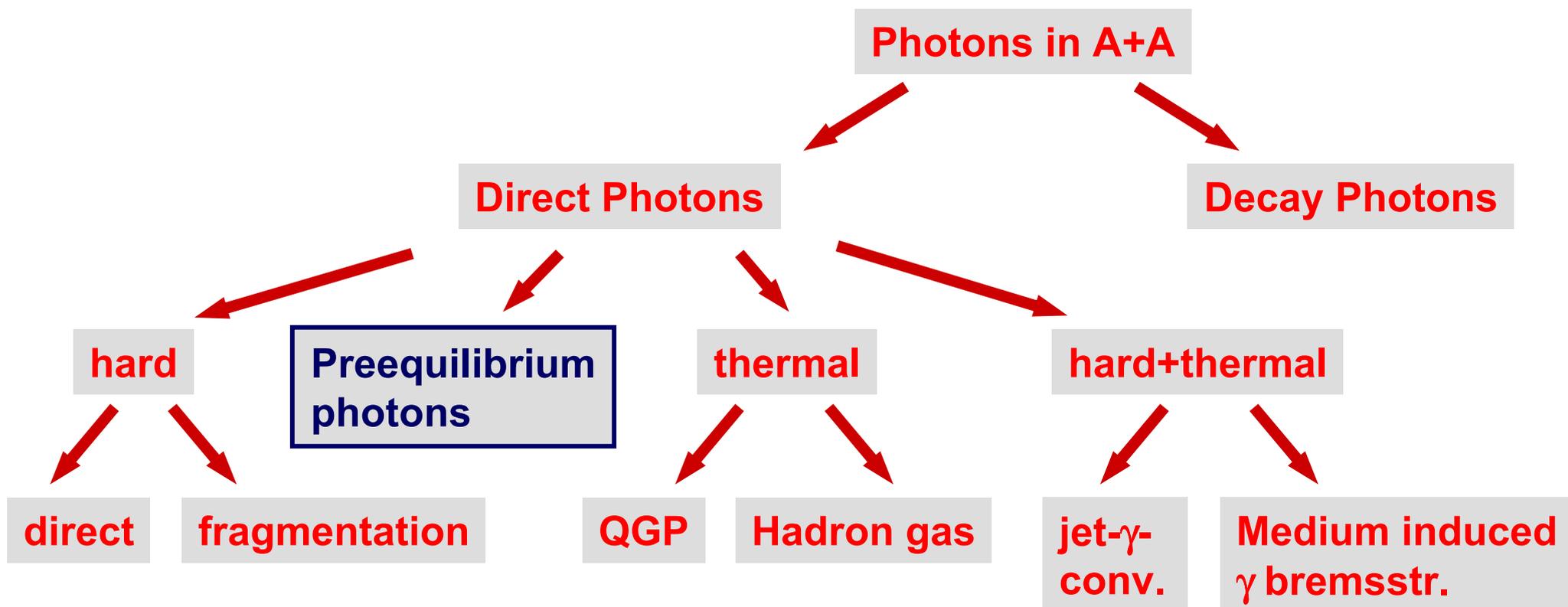
Hard direct photons:
bremsstrahlung /
fragmentation
component



Known and Presumed Photon Sources in A+A



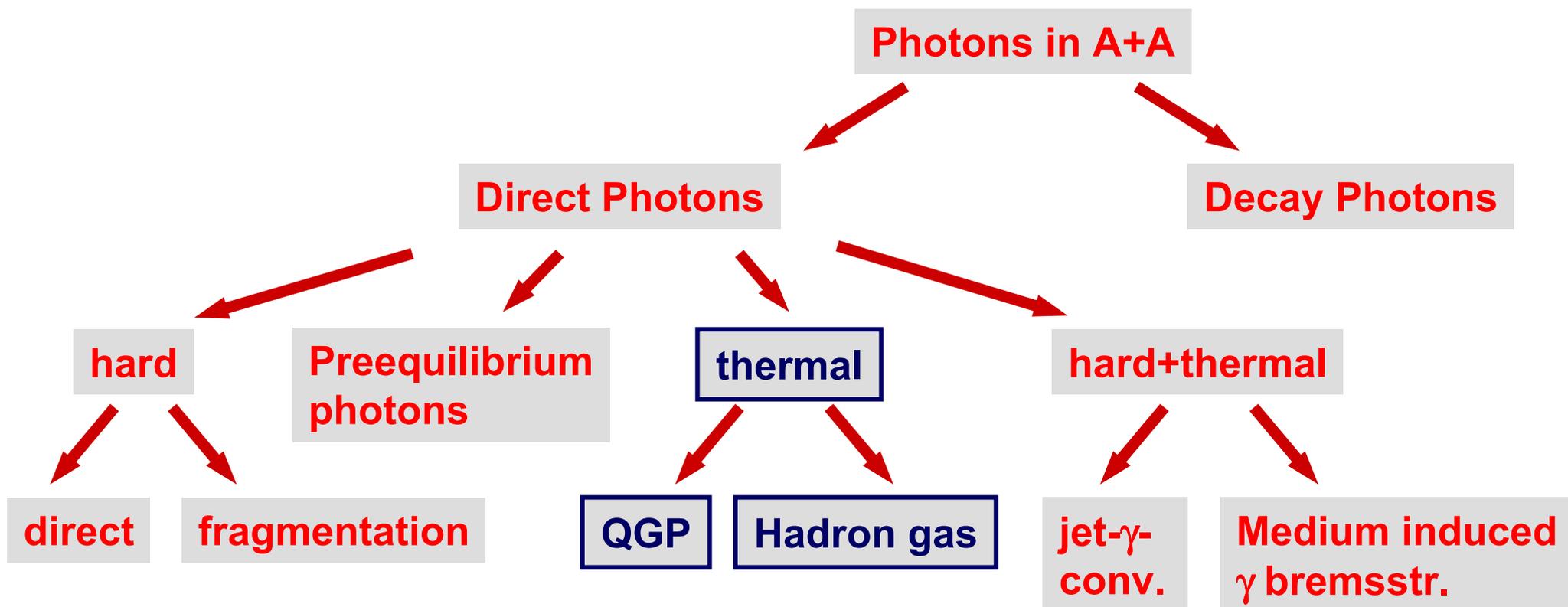
Known and Presumed Photon Sources in A+A



Preequilibrium photons

- Produced through rescattering of the primarily produced partons prior to thermalization
- Difficult to treat theoretically

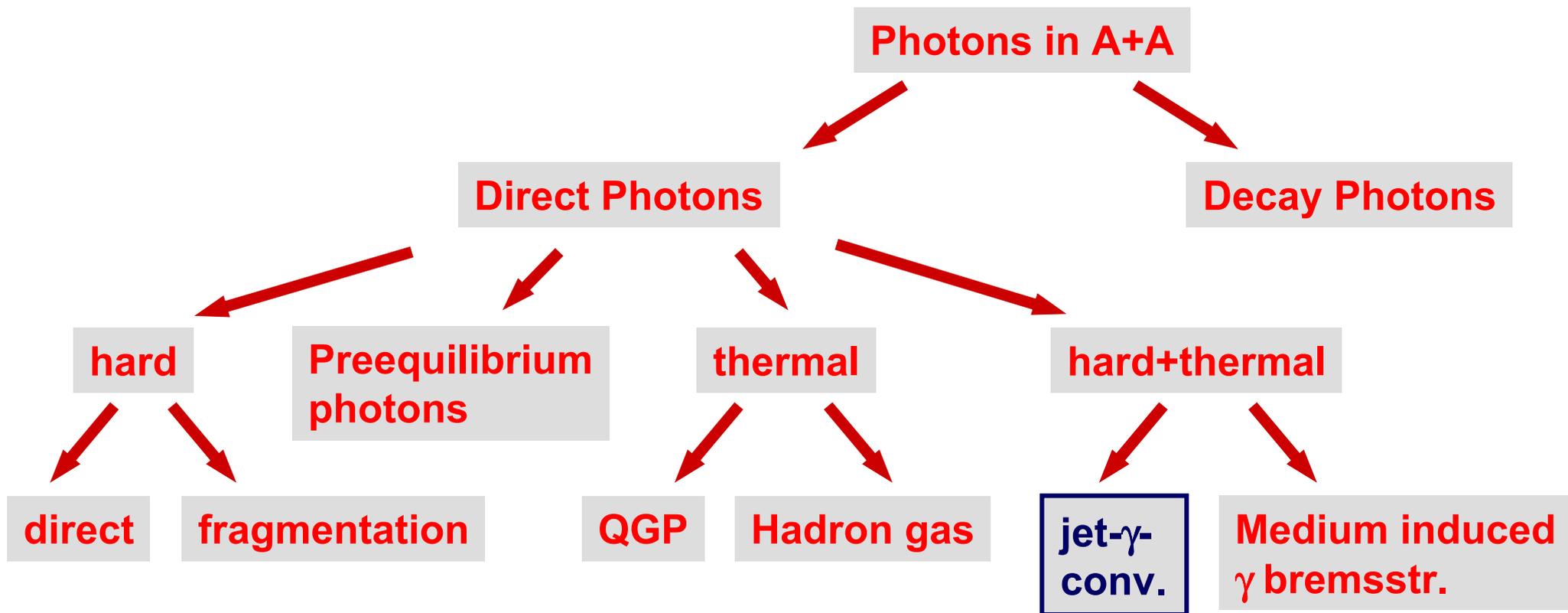
Known and Presumed Photon Sources in A+A



Thermal photons

- Reflect temperature of the system, produced over entire evolution
- Significant direct photon source only at low p_T

Known and Presumed Photon Sources in A+A



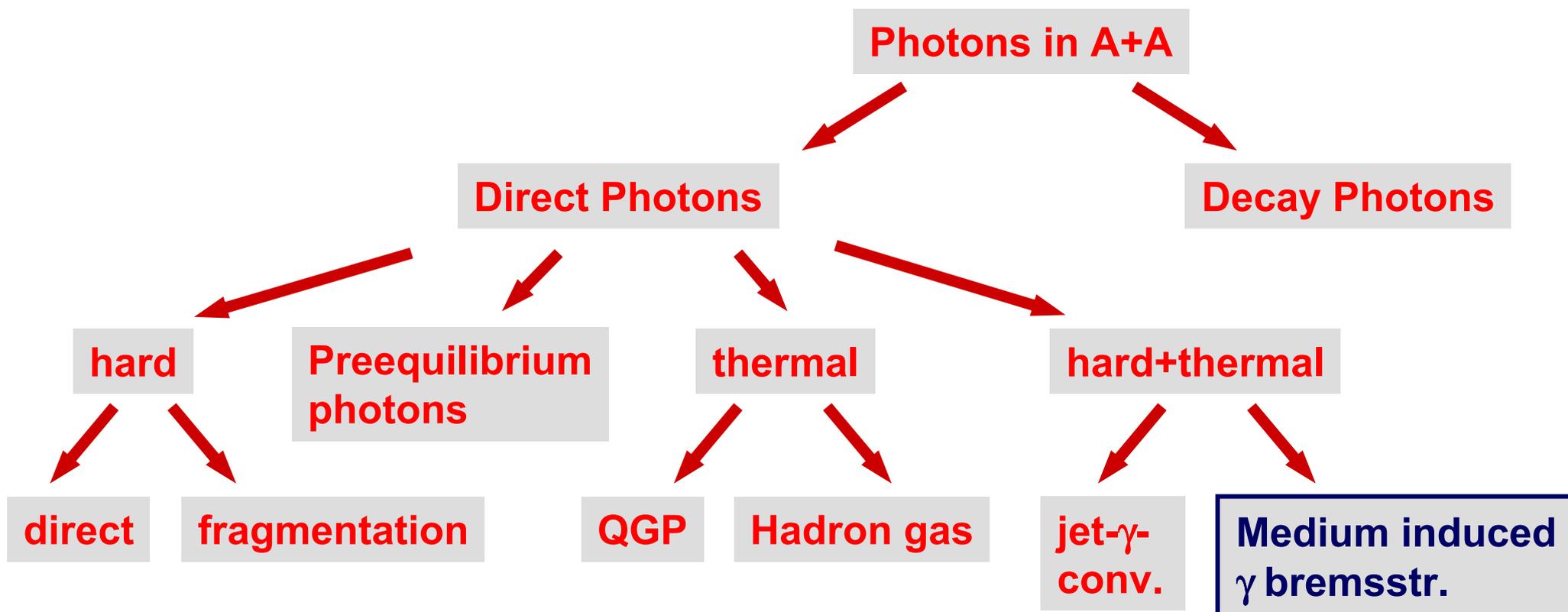
Hard+thermal: Jet-Photon- Conversion

Interaction of parton from hard scattering with soft parton

$$\sigma_{\text{jet-}\gamma\text{-conv}} \sim \delta^3(p_{\text{jet}} - p_{\gamma})$$



Known and Presumed Photon Sources in A+A

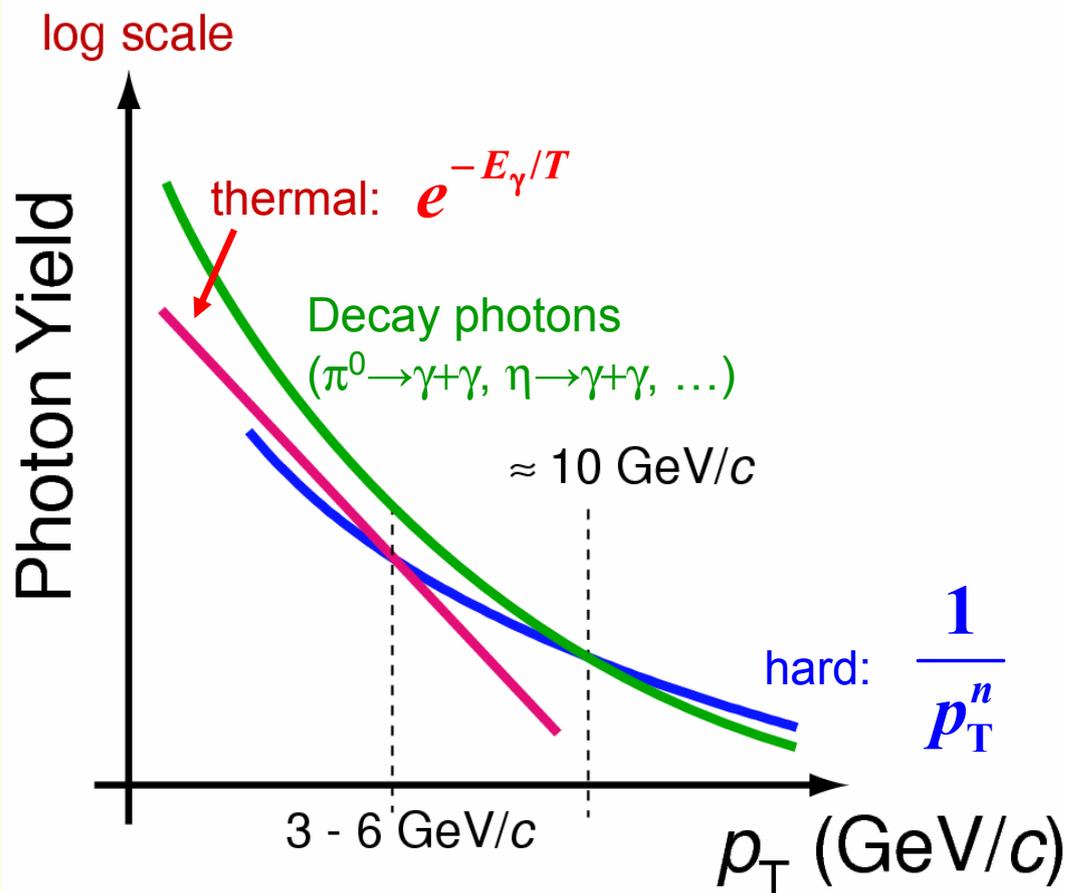


Medium induced photon bremsstrahlung

- Due to multiple scattering of quarks in the medium
- Different theoretical predictions, likely rather small contribution

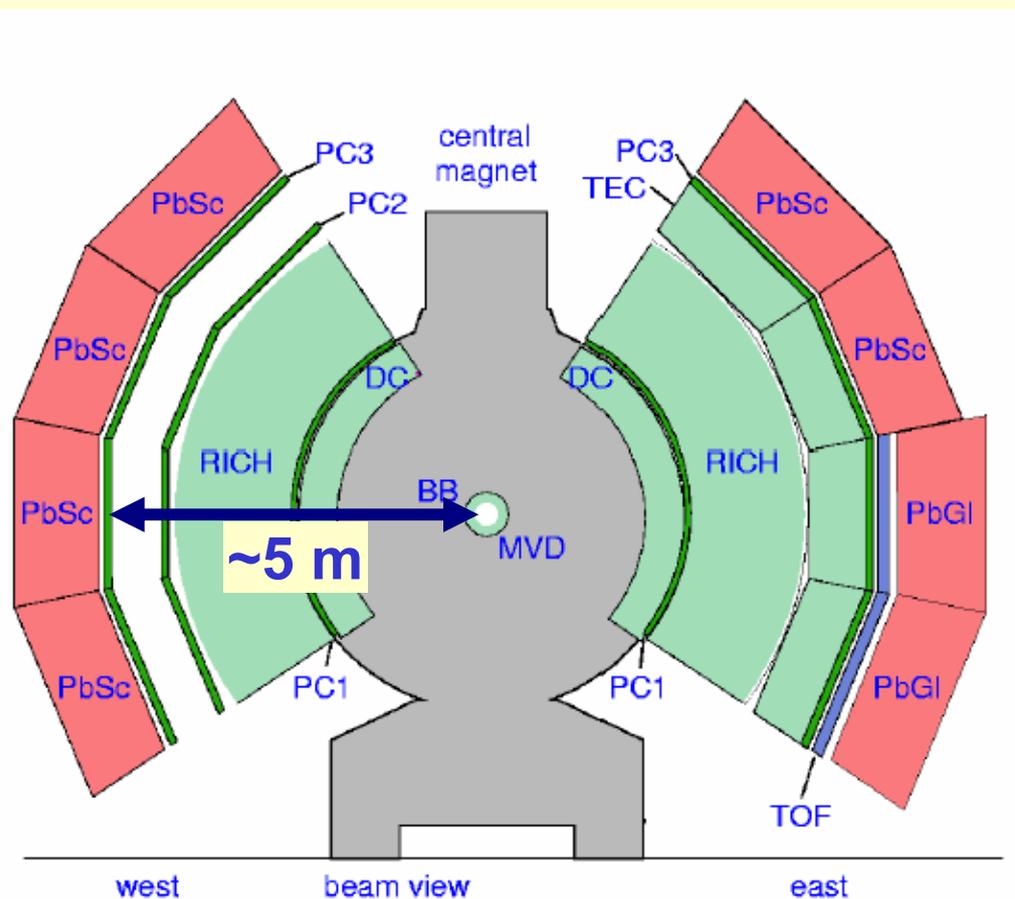
Schematic Photon Spectrum in A+A

Central Au+Au at RHIC



- Hard photons dominant direct photon source for $p_T > \sim 6 \text{ GeV}/c$
- Thermal photons expected to be significant contribution below $p_T \sim 3 \text{ GeV}/c$
- Jet-photon conversion might be significant contribution below $p_T \sim 6 \text{ GeV}/c$

PHENIX: Photon and Electron Detectors



Pseudorapidity coverage : $|\eta| < 0.35$

■ PbSc:

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

■ PbGl:

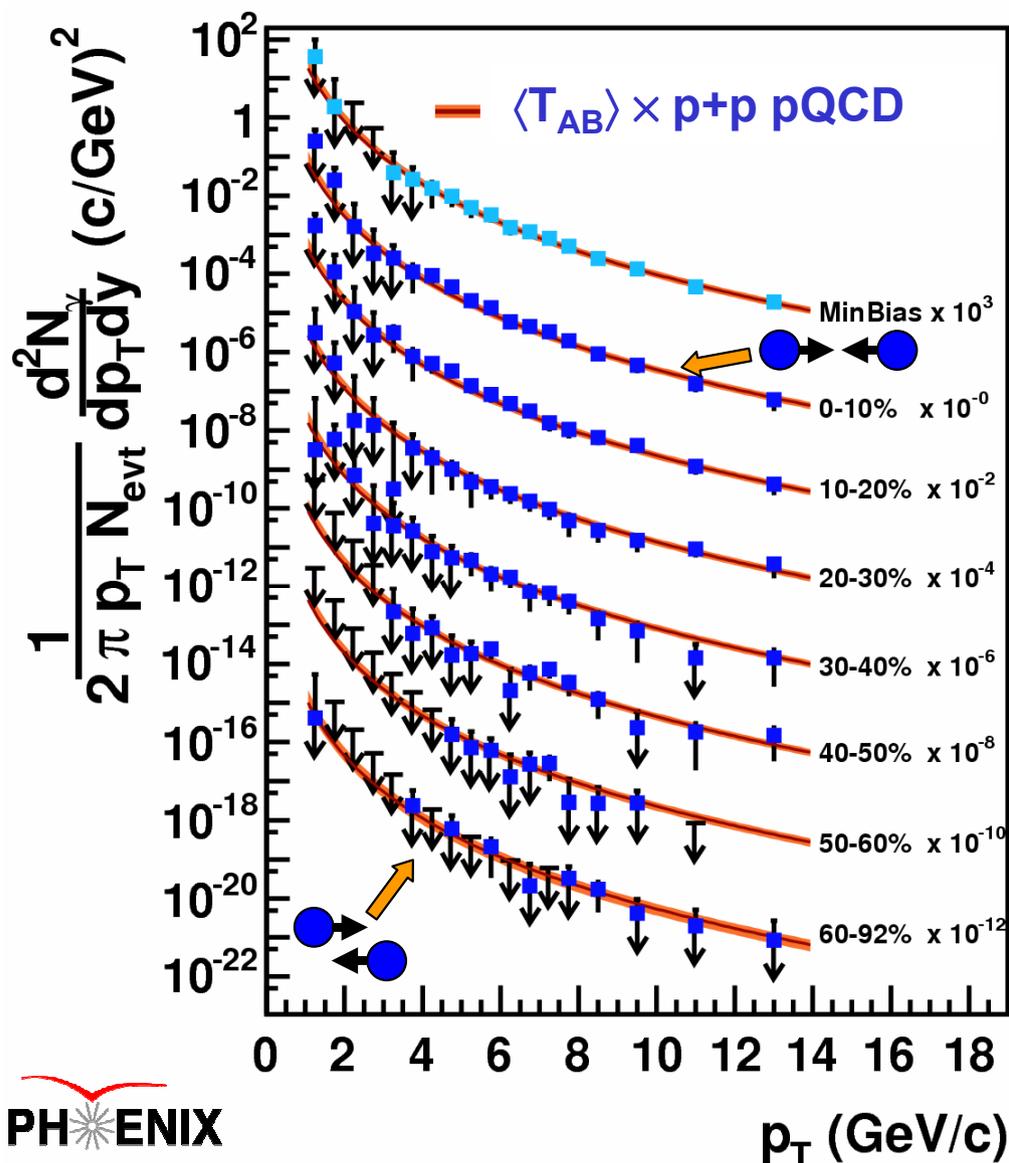
- ◆ Highly segmented lead glass **Cherenkov** calorimeter
- ◆ Module size:
4.0 cm x 4.0 cm x 40 cm

■ Ring Imaging Cherenkov Detector (RICH):

- ◆ Electron identification
- ◆ Insensitive to pions with
 $p < 4.6 \text{ GeV}/c$

Direct-Photon Spectra in Au+Au

Au+Au at $\sqrt{s_{NN}} = 200$ GeV (RHIC run 2)

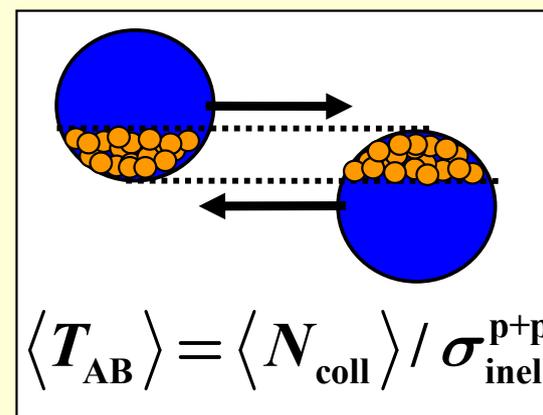


PHENIX

Phys.Rev.Lett.94:232301,2005

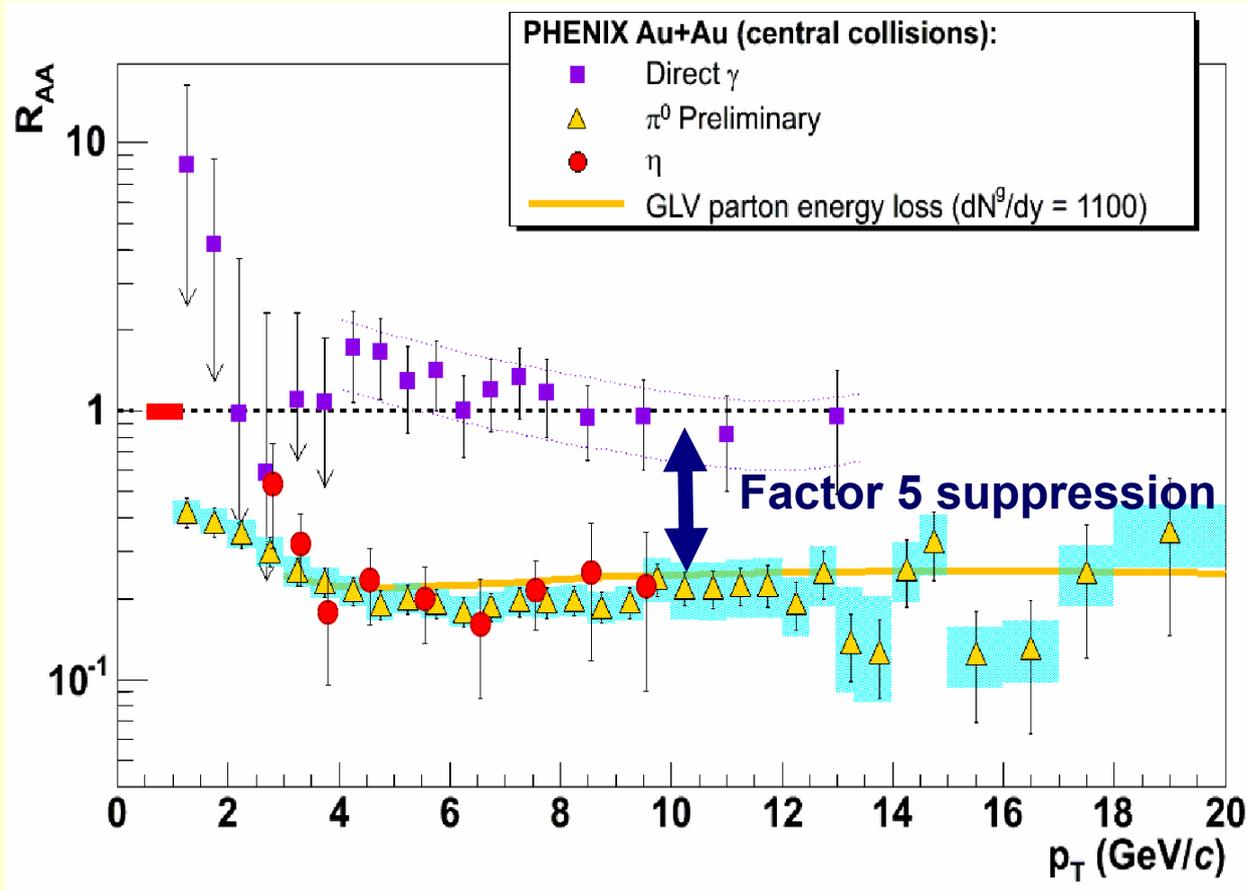
Nuclear overlap function $\langle T_{AB} \rangle$

- Measures increase of parton luminosity relative to p+p
- Calculated with a simple geometrical Glauber model

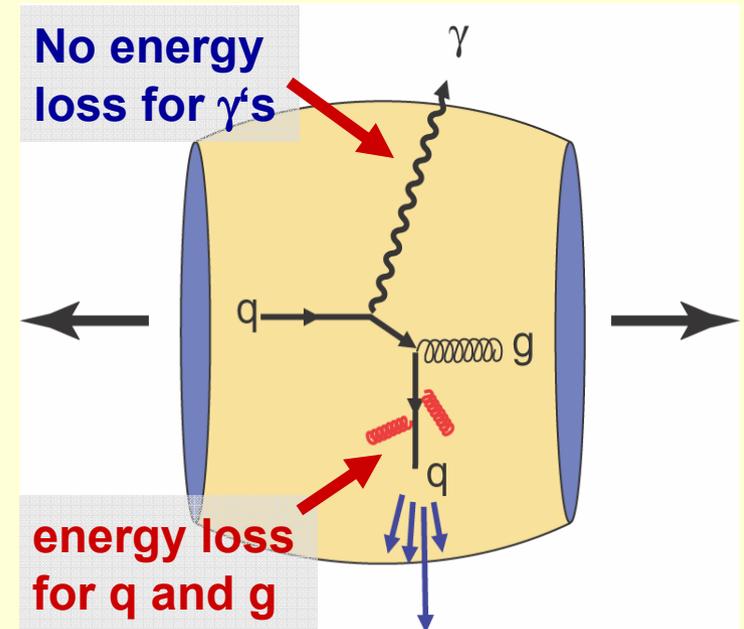


High- p_T direct photons
scale with $\langle T_{AB} \rangle$

Hadron Suppression: A Final State Effect!

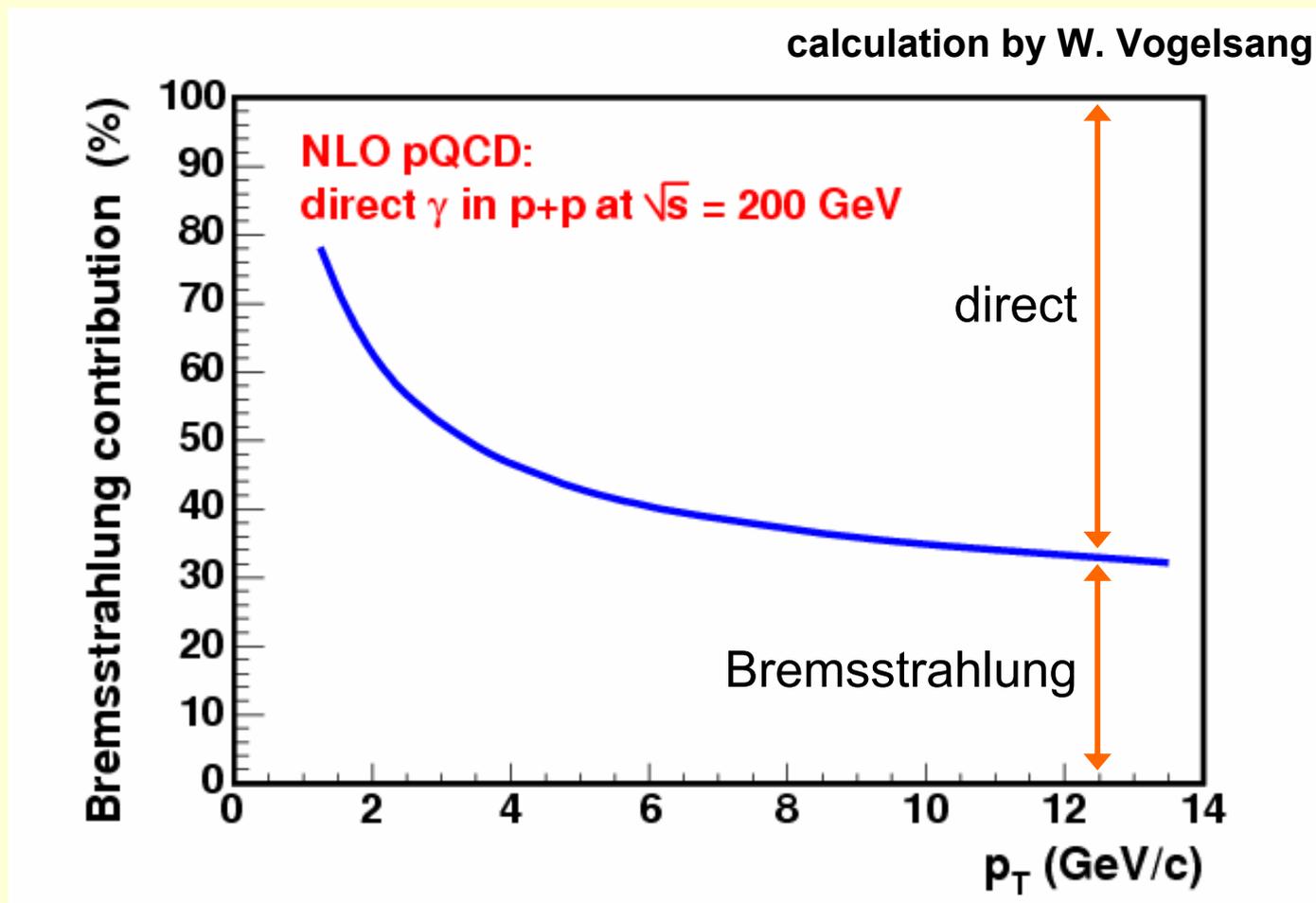


$$R_{AB} = \frac{dN / dp_T|_{A+B}}{\langle T_{AB} \rangle \times d\sigma / dp_T|_{p+p}}$$



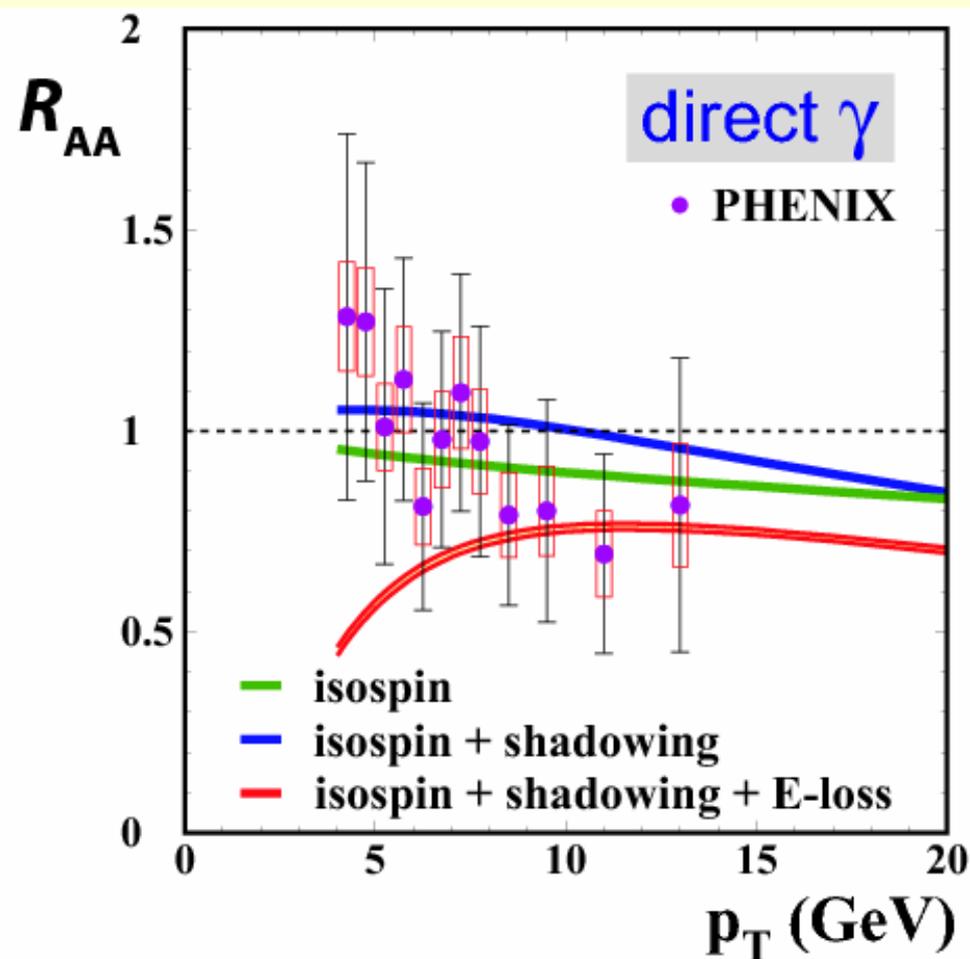
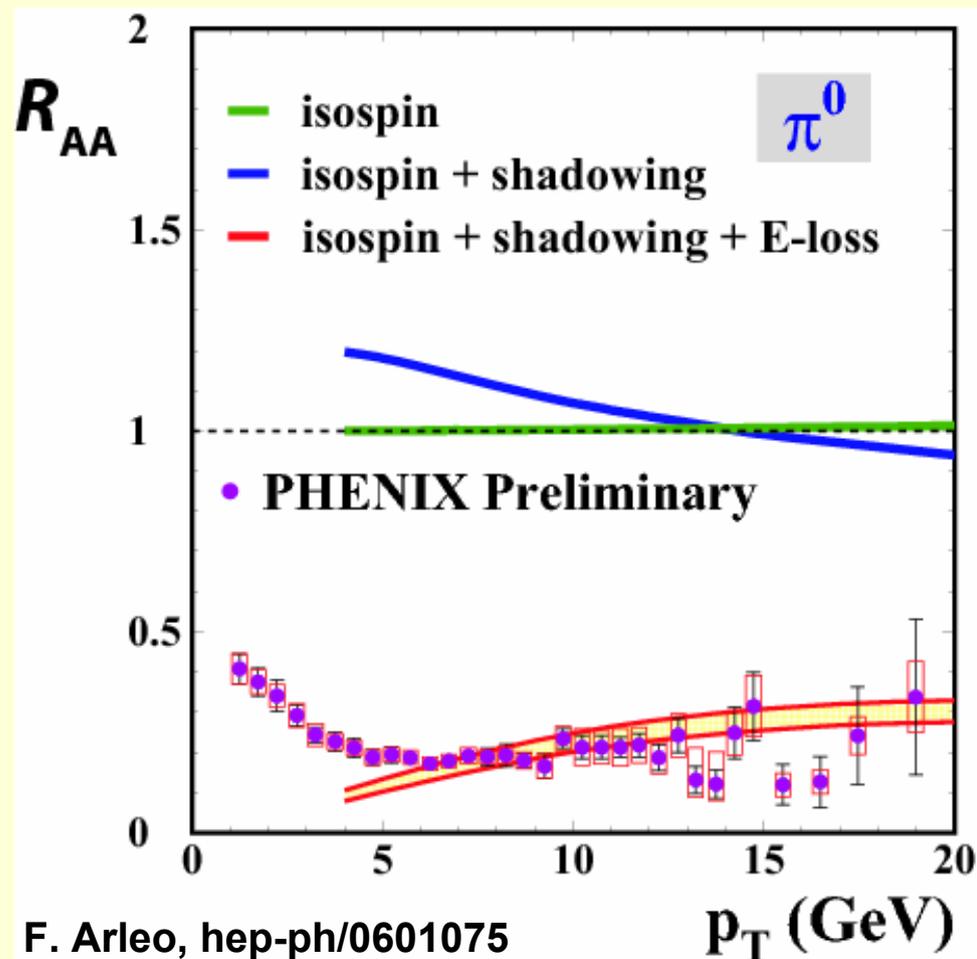
**Hadrons are suppressed whereas direct photons are not:
Evidence for parton energy loss (as expected in the QGP)**

Bremsstrahlung Component



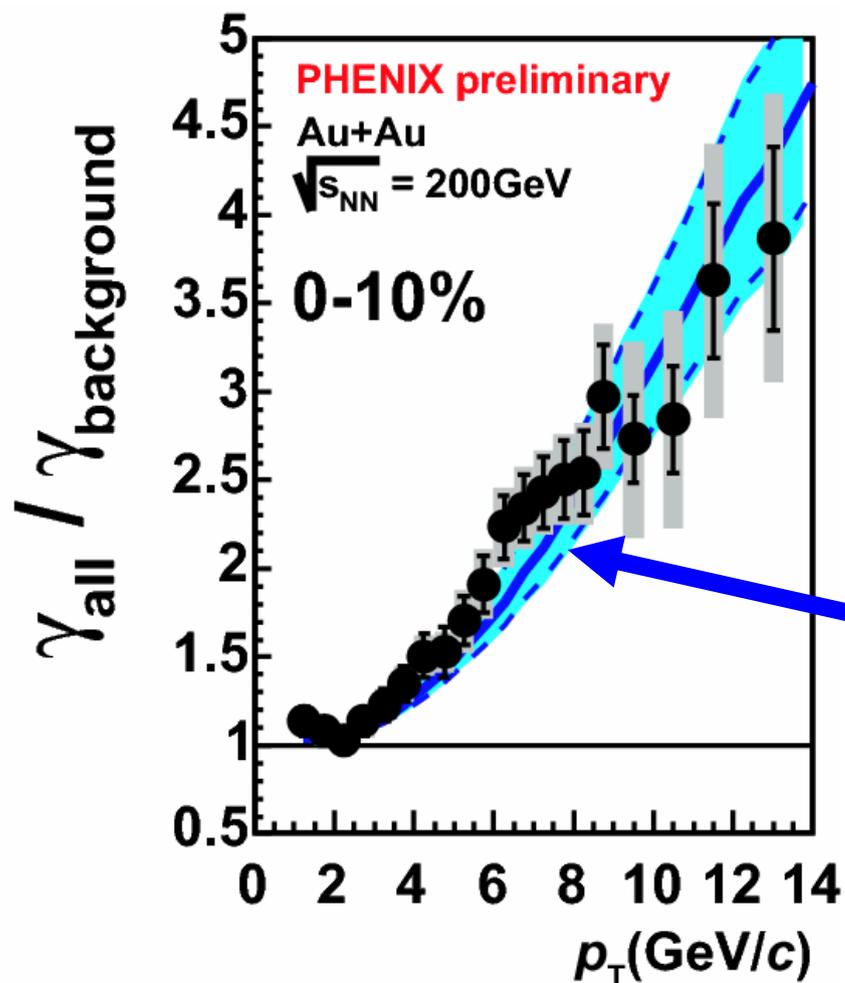
- Bremsstrahlung contribution large
- Modification of Bremsstrahlung contribution expected in A+A

Effect of Parton Energy Loss



- 20-30% reduction of direct photon R_{AA} expected due to parton energy loss
- Consistent with PHENIX data

New High-Statistics Data (Run 4)

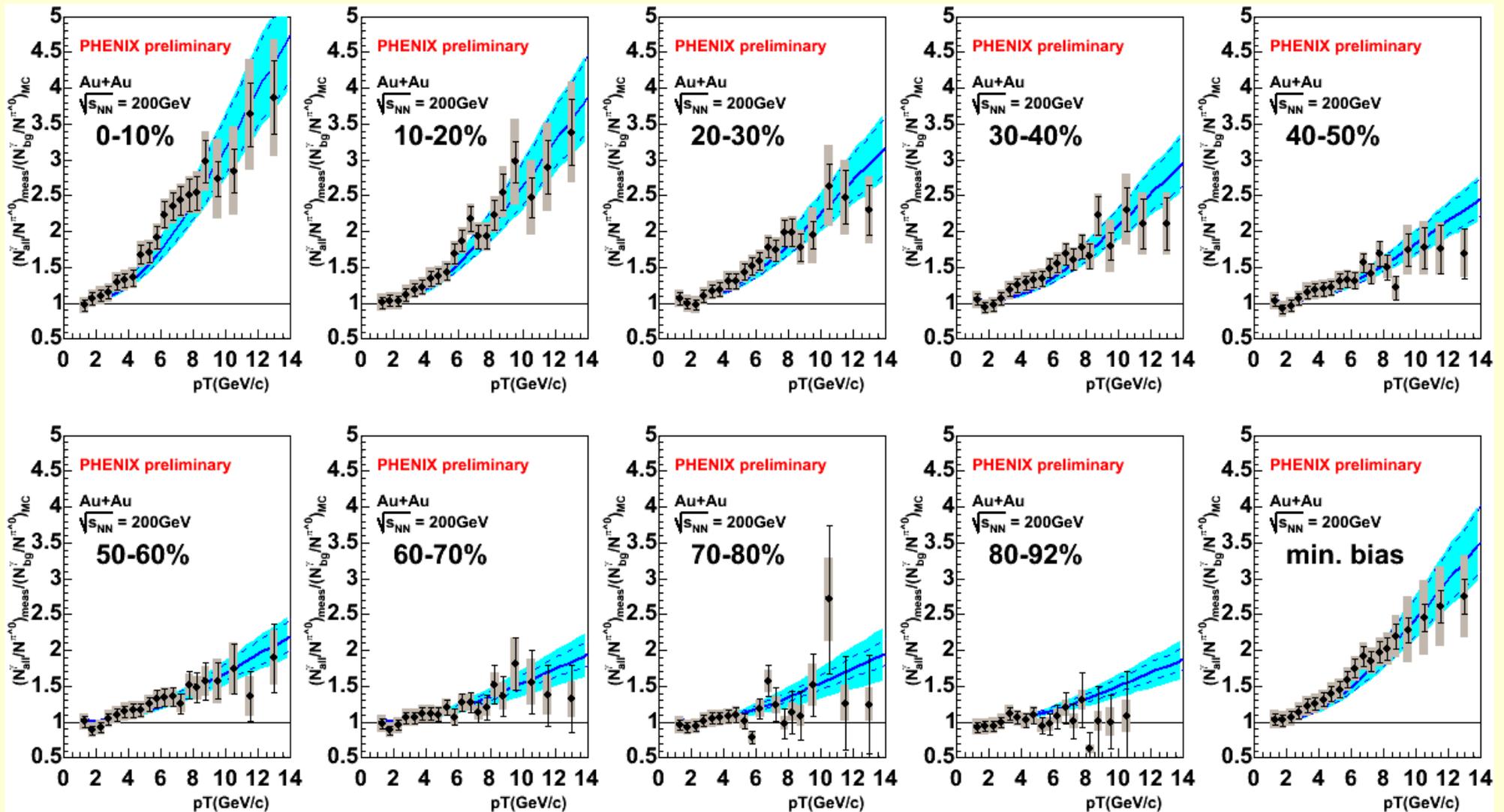


- Run 4: factor ~ 10 increase in statistics compared to run 2
- Direct-photon signal up to $p_T \sim 13 \text{ GeV}/c$, reduced statistical uncertainties
- Consistent with N_{coll} -scaled pQCD calculation

$$1 + \frac{N_{\text{coll}} \times \gamma_{\text{pQCD}}^{\text{p+p}}}{\gamma_{\text{background}}^{\text{Au+Au}}}$$

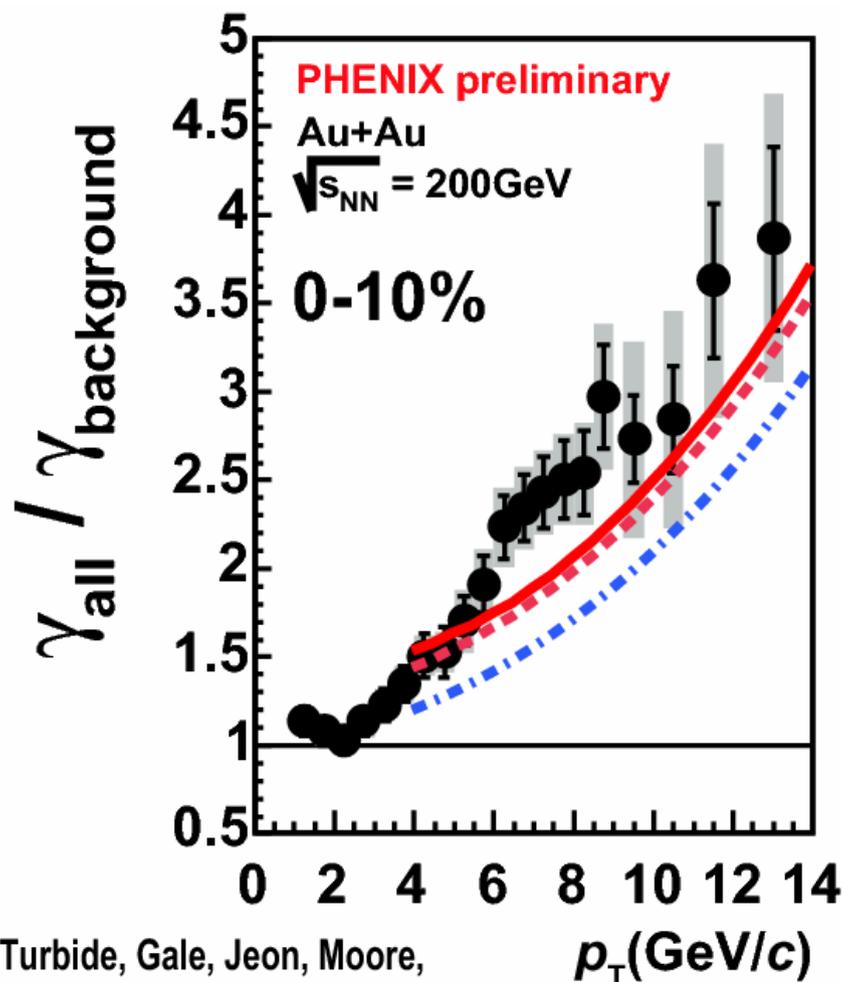
Calculated based on measured π^0 and η spectra

Centrality Dependence



No significant deviation from N_{coll} -scaled pQCD for all centralities

Direct Photons from Jet-Medium Interactions?



Turbide, Gale, Jeon, Moore,
 Phys. Rev. C 72, 014906, 2005

- Prompt + QGP, $T_i = 447$ MeV
- - - Prompt + QGP, $T_i = 370$ MeV
- · · Prompt, $T = 370$ MeV

- Model parameters (QGP evolution, parton energy loss) adjusted so as to describe the pion suppression
- Bremsstrahlung component reduced due to parton energy loss
- Direct photons:
 Better agreement with data if **jet-photon conversion** is added

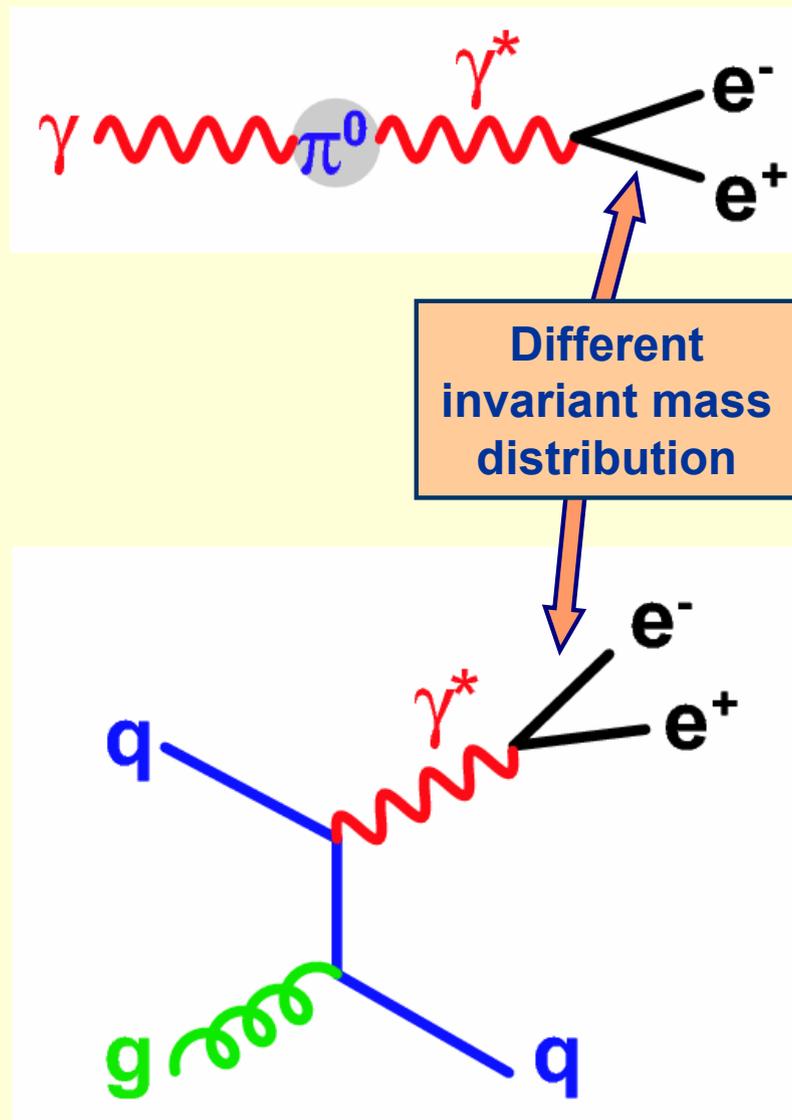
Jet-photon conversion:

$$q_{\text{hard}} + g_{\text{QGP}} \rightarrow \gamma + q$$

$$q_{\text{hard}} + \bar{q}_{\text{QGP}} \rightarrow \gamma + g$$

Direct Photons via Internal Conversion

- Any source of real photons emits virtual photons with small invariant mass
- The distribution of the virtual photon mass depends on the emitting source
- Phase space at higher inv. masses limited for virtual photons from hadron decays
- **Signal/background for virtual direct photons significantly improves with increasing mass**



Internal Conversion: Kroll-Wada Formula

Kroll-Wada formula:

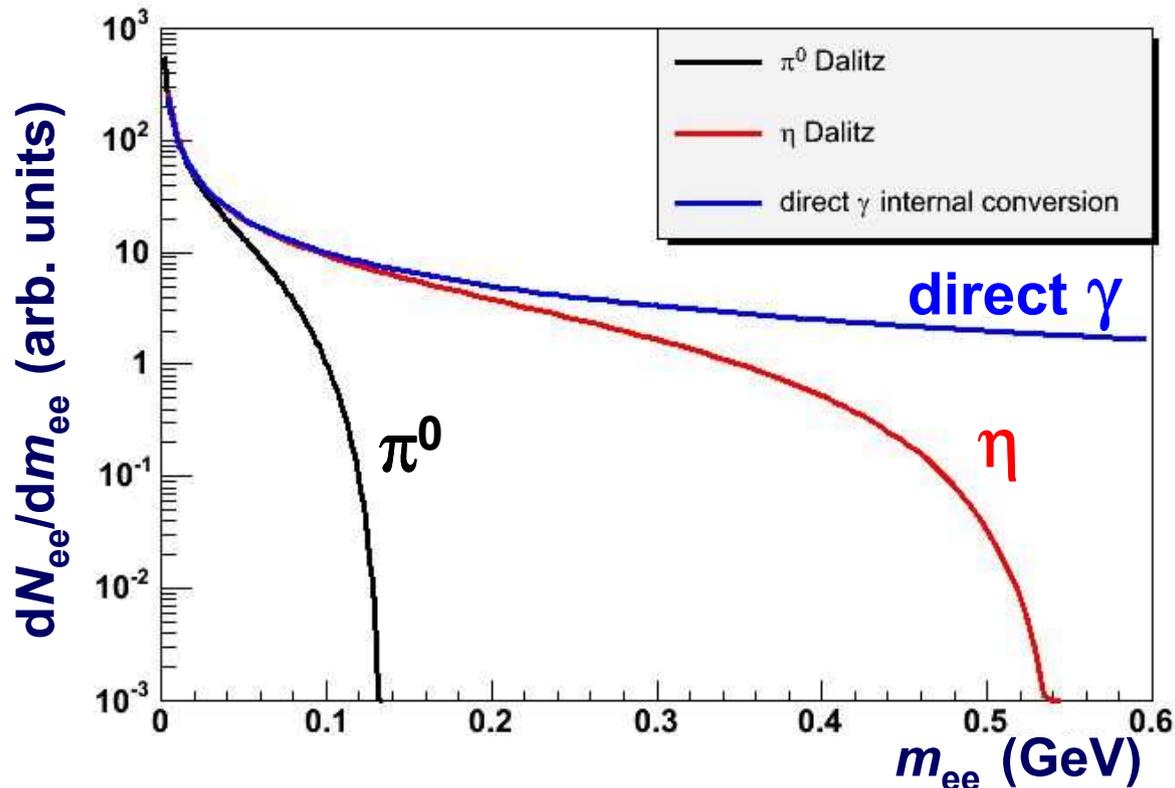
$$\frac{1}{N_\gamma} \frac{dN_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi} \sqrt{1 - \frac{4m_e^2}{m_{ee}^2}} \left(1 + \frac{2m_e^2}{m_{ee}^2}\right) \frac{1}{m_{ee}} \left(1 - \frac{m_{ee}^2}{M^2}\right)^3 |F(1 - \frac{m_{ee}^2}{M^2})|^2$$

Virtual photon
mass distribution

QED

phase
space

form
factor



Direct photon internal conversion:

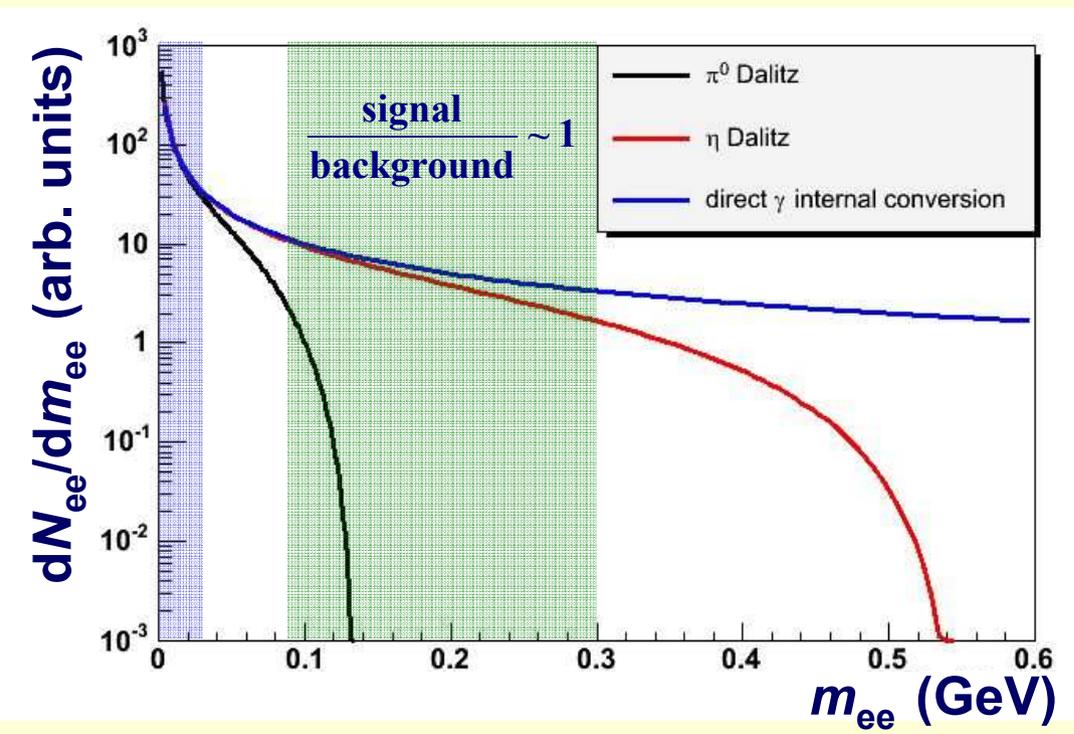
→ **Described by QED part alone**
(as long as $p_T \gg m_{ee}$)

π^0 and η Dalitz decay:

→ **QED part dominates for $m_{ee}/M \rightarrow 0$**
→ **meson mass limits m_{ee}**

Internal Conversion: Analysis Method

Measured quantity: $R_{\text{data}} = N_{ee}^B / N_{ee}^A$



Without direct photons:

$$R_{\text{data}} = R_{\text{hadron}}^{\text{Kroll-Wada}}$$

input: η/π^0 ratio

$R_{\text{data}} > R_{\text{hadron}}^{\text{Kroll-Wada}}$ translates into

fraction of virtual direct photons:

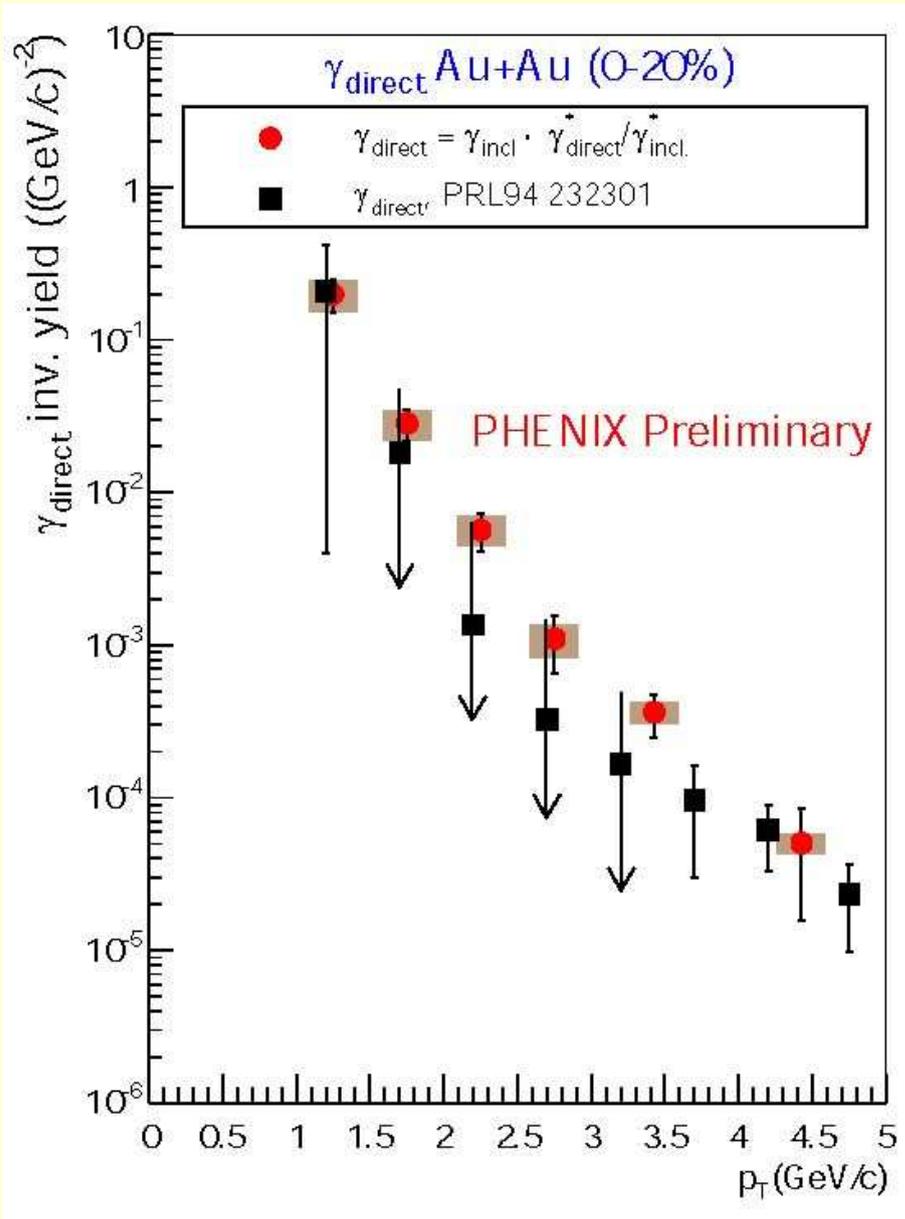
$$\frac{\gamma_{\text{direct}}^*}{\gamma_{\text{all}}^*} = \frac{R_{\text{data}} - R_{\text{hadron}}^{\text{Kroll-Wada}}}{R_{\text{direct } \gamma}^{\text{Kroll-Wada}} - R_{\text{hadron}}^{\text{Kroll-Wada}}}$$

Direct photon spectrum via inclusive photon spectrum from EMCAL:

$$\gamma_{\text{direct}} = \frac{\gamma_{\text{direct}}^*}{\gamma_{\text{all}}^*} \cdot \gamma_{\text{all}}$$

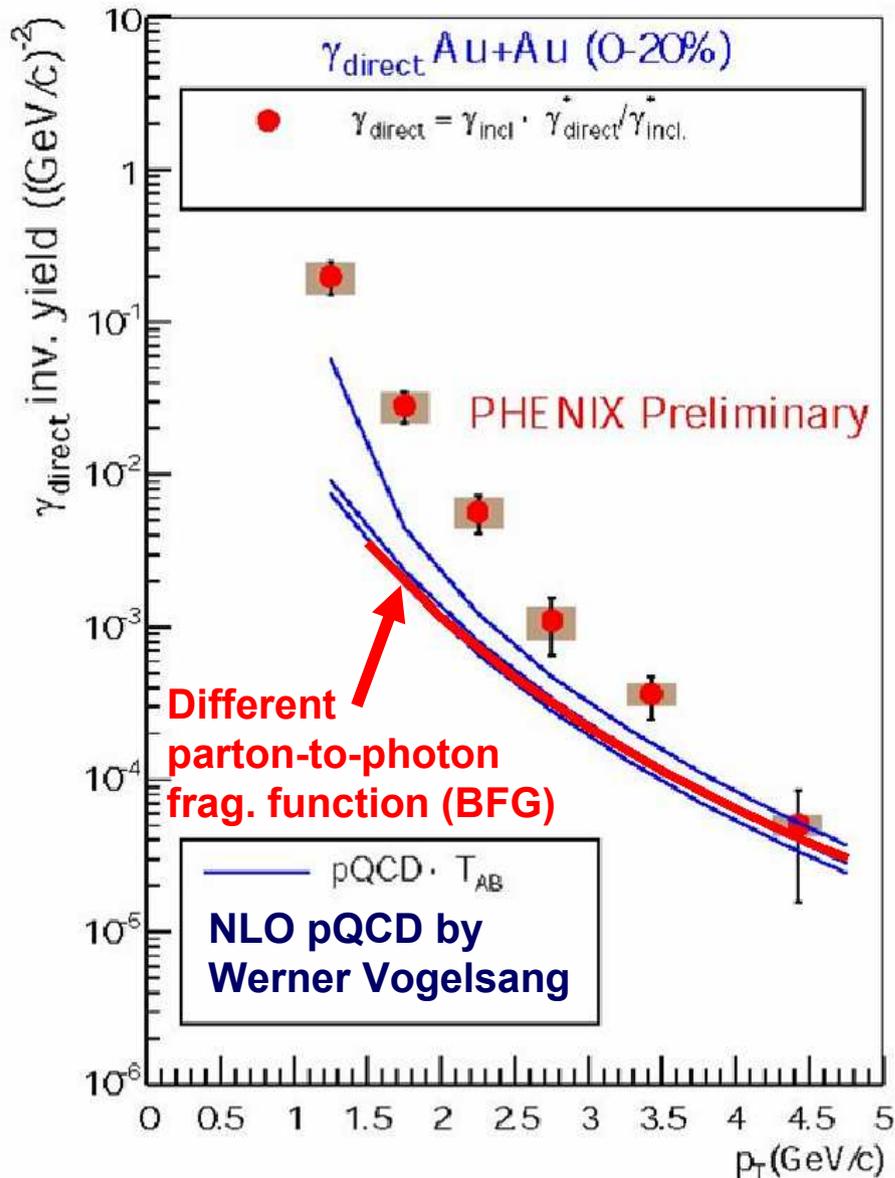
from EMCAL

Direct Photon Spectrum in Central Au+Au



- Direct photon spectrum for $1 < p_T < 4.5 \text{ GeV}$ via internal conversion
- Systematic errors
 - ◆ Small! (~25 %)
 - ◆ Dominated by uncertainty of η/π^0 ratio
- A breakthrough!
- Agreement with conventional method

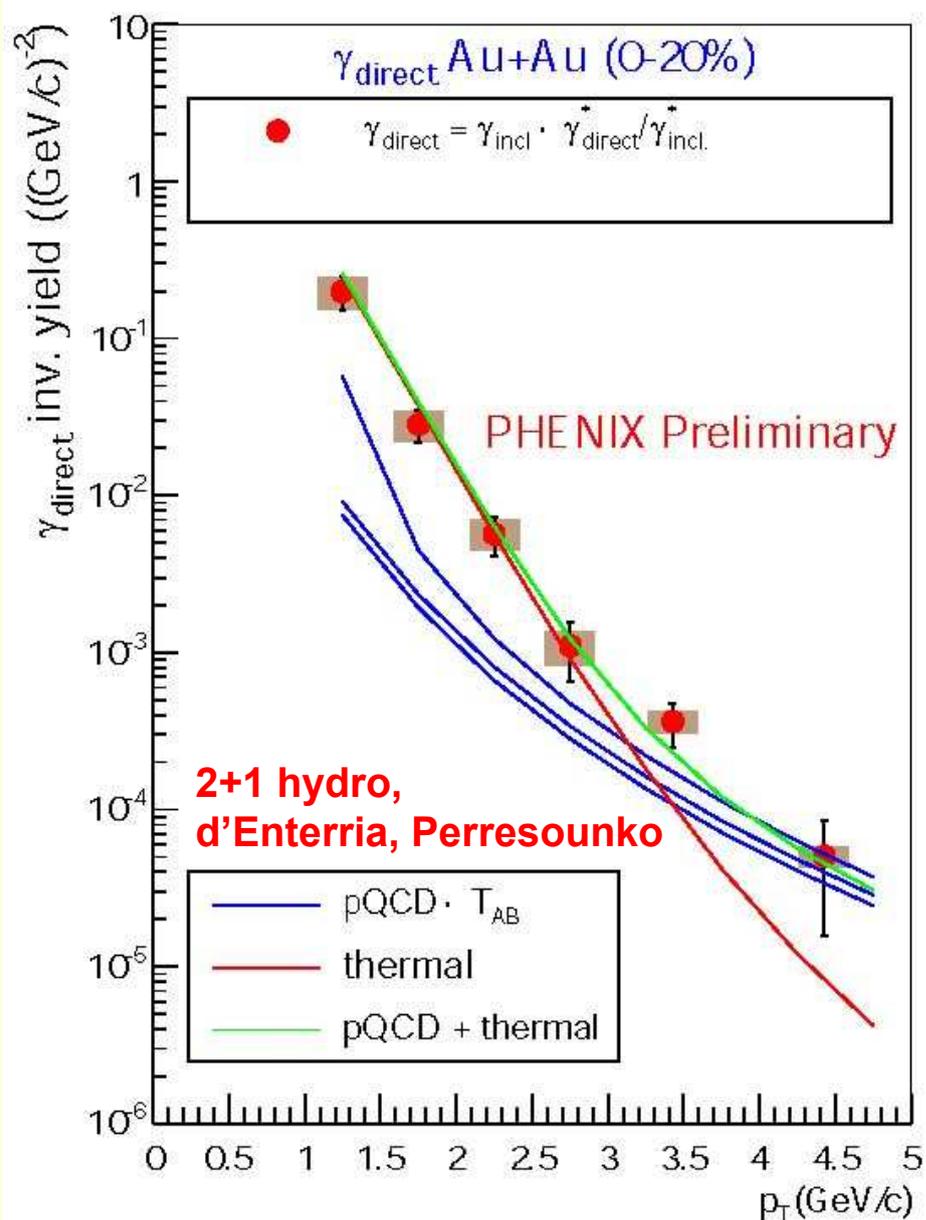
Comparison with Scaled pQCD



- Contribution of hard processes estimated with scaled pQCD
- pQCD uncertainties
 - ◆ Arbitrary scales
 - ◆ Parton distribution function
 - ◆ Parton-to-photon frag. function
- Scale uncertainties dominate
- Cold nuclear matter effects (“ k_T broadening”) likely to be negligible

Excess above pQCD possibly due to thermal photons

Comparison with Hydro-Models



- Hydro models: QGP and HG photon rates convolved with fireball evolution
- Data can be described with pQCD + hydro

	$T_{i,\text{max}}$ (MeV)	τ_i (fm/c)
Alam et al.	400	0.2
Chaudhuri	400	0.6
d'Enterria, Perresounko	570	0.15

Temperatures above critical temperature T_c for QGP transition

Conclusions

Direct Photons in $\sqrt{s_{NN}} = 200 \text{ GeV Au+Au}$

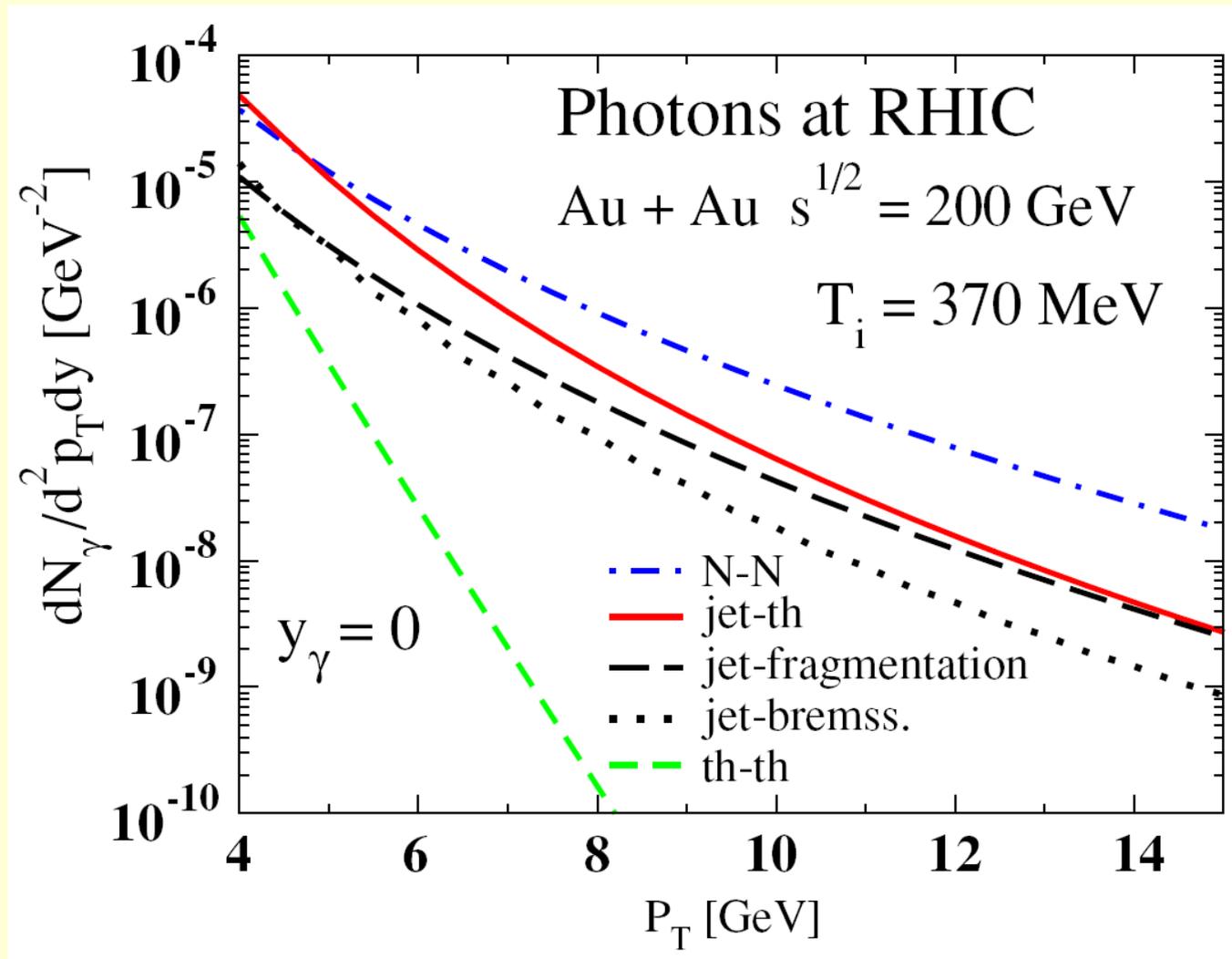
High $p_T (> 6 \text{ GeV}/c)$:

- Unlike pions high- p_T direct photons are not suppressed (i.e. they follow T_{AB} scaling)
- Thus, pion suppression is a final state effect, consistent with parton energy loss in a quark-gluon plasma

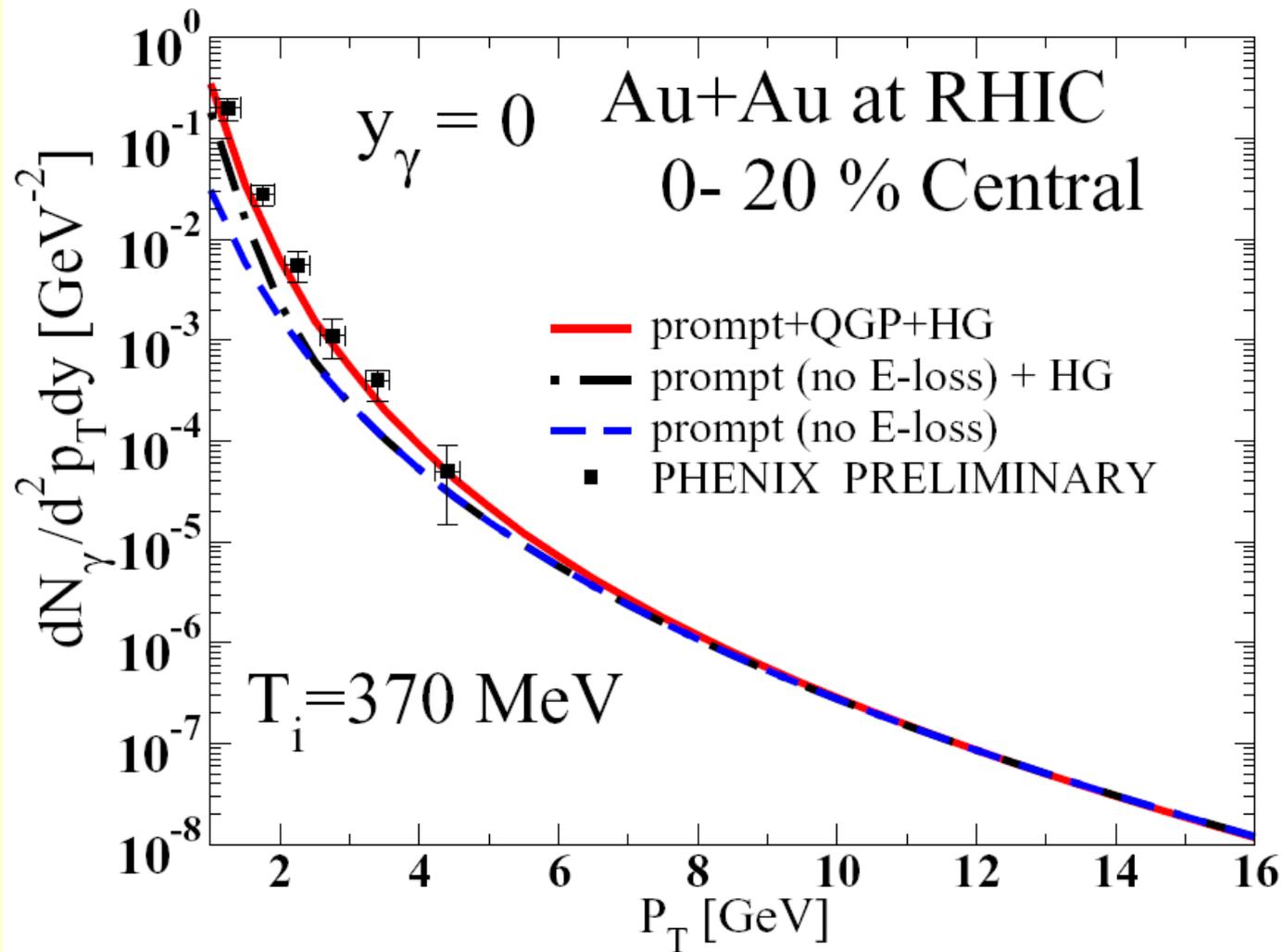
Low p_T :

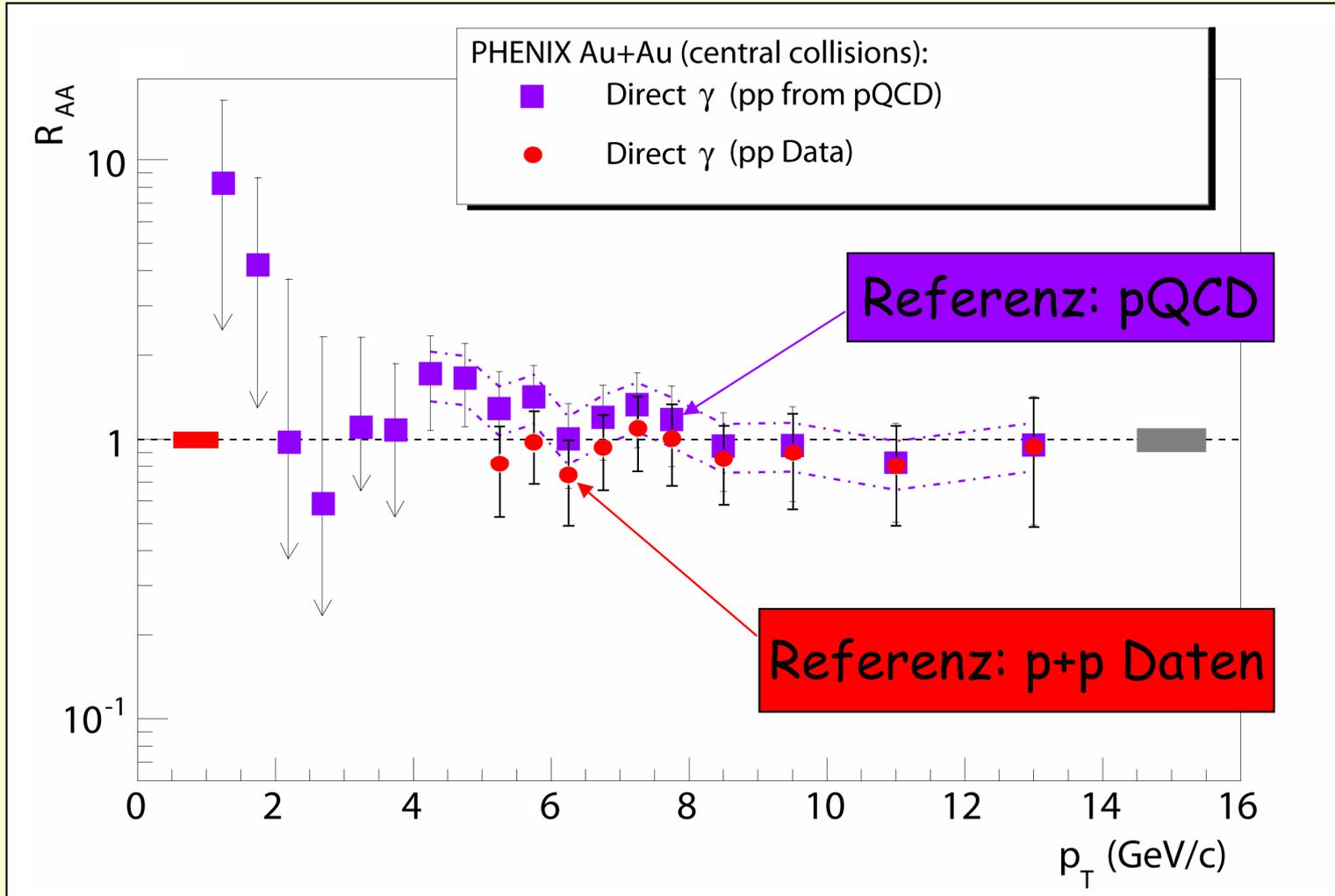
- Direct Photon measurement via internal conversion
- Excess above pQCD possibly due to thermal radiation
- Data only described with initial temperatures above T_c

Backup

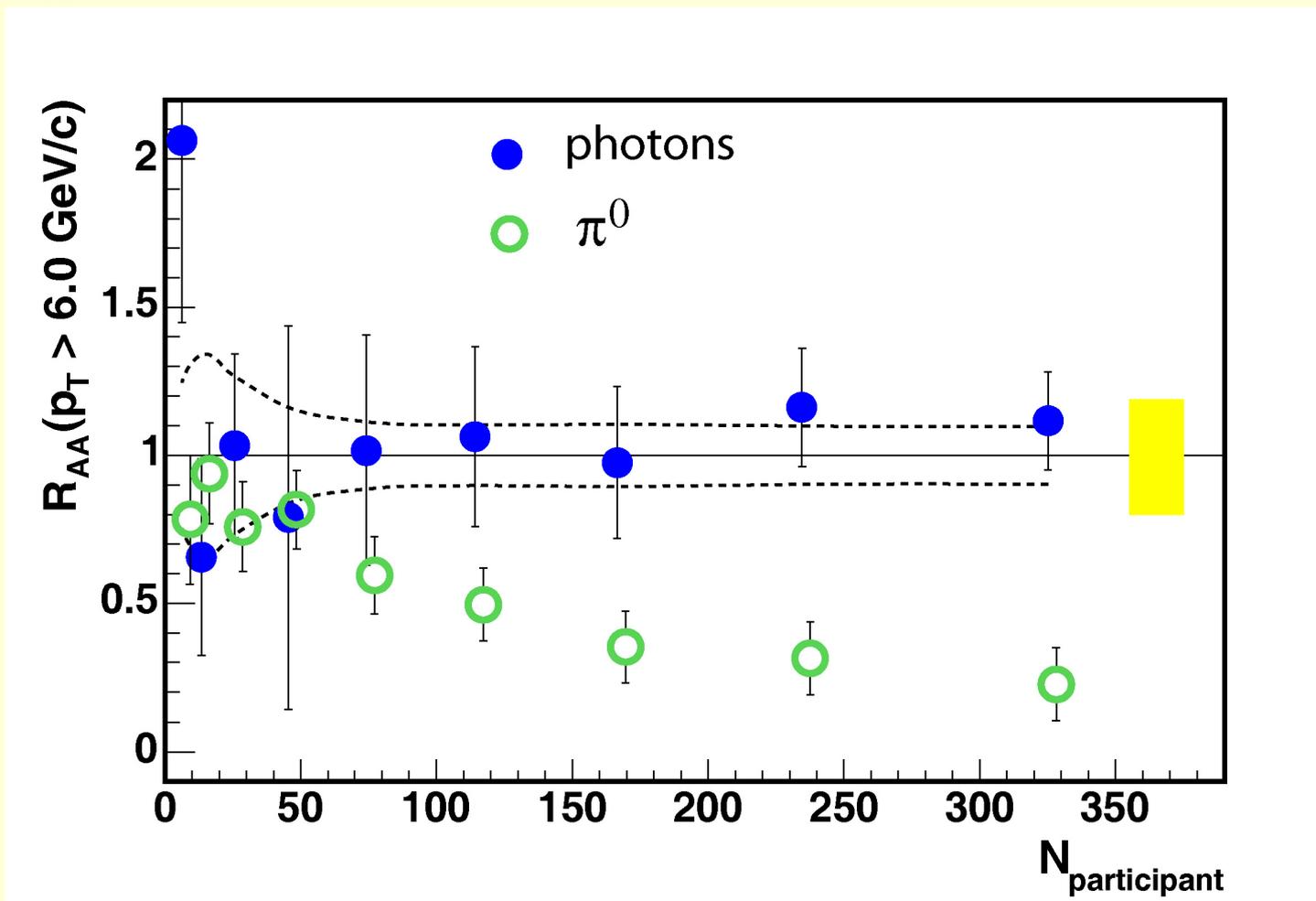


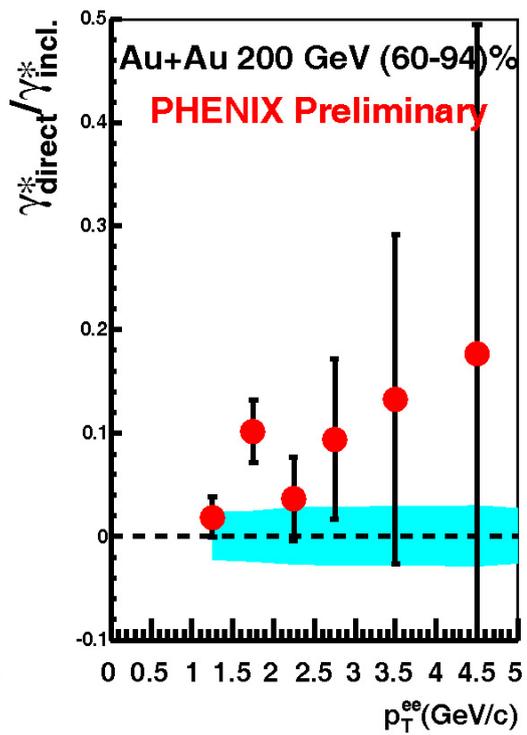
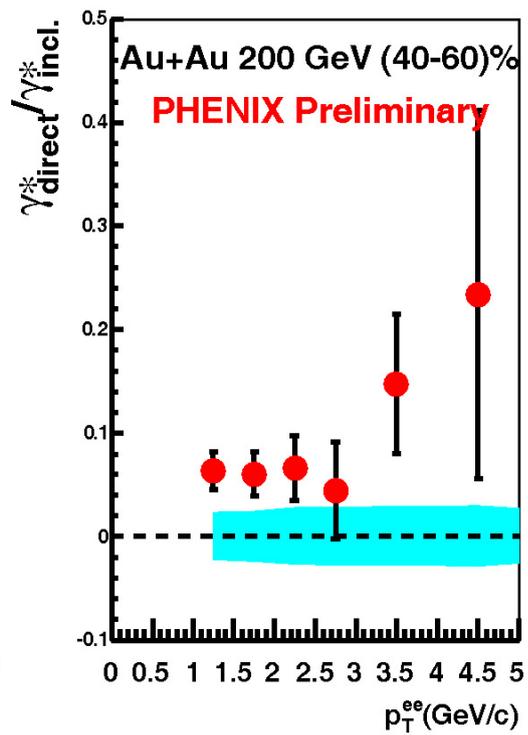
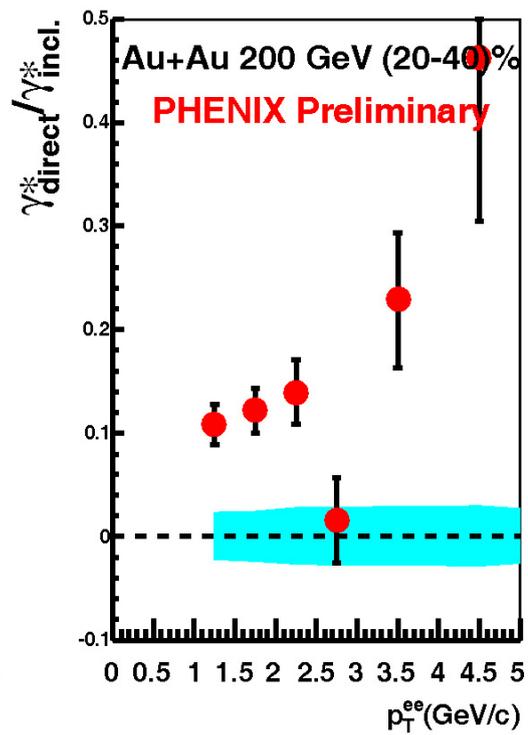
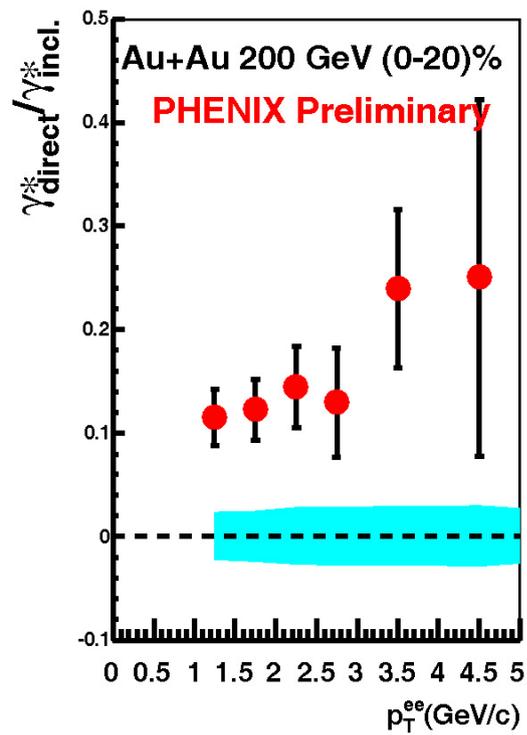
Turbide, Gale, Jeon, Moore,
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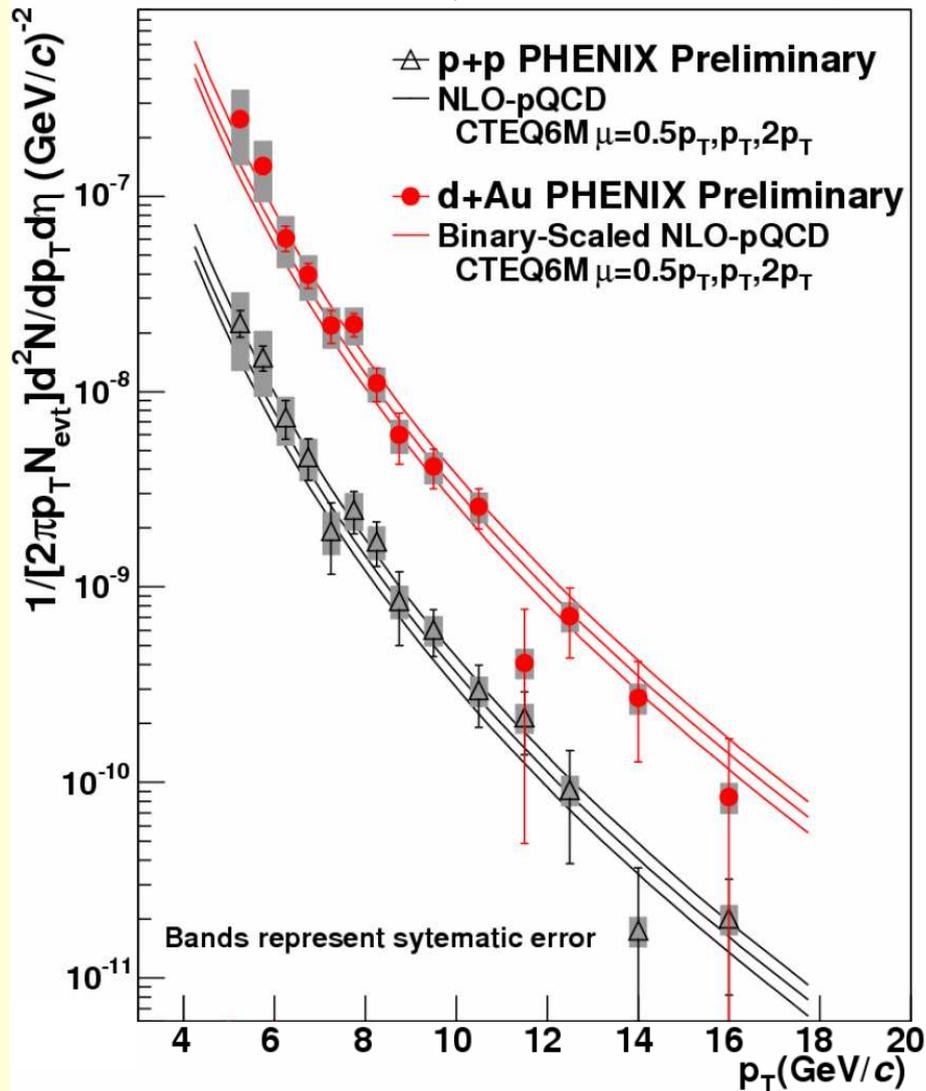


$$R_{AA} = \frac{dN_{AA}^{\pi^0} / dp_T}{\langle T_{AA} \rangle_f d\sigma_{NN}^{\pi^0} / dp_T}$$



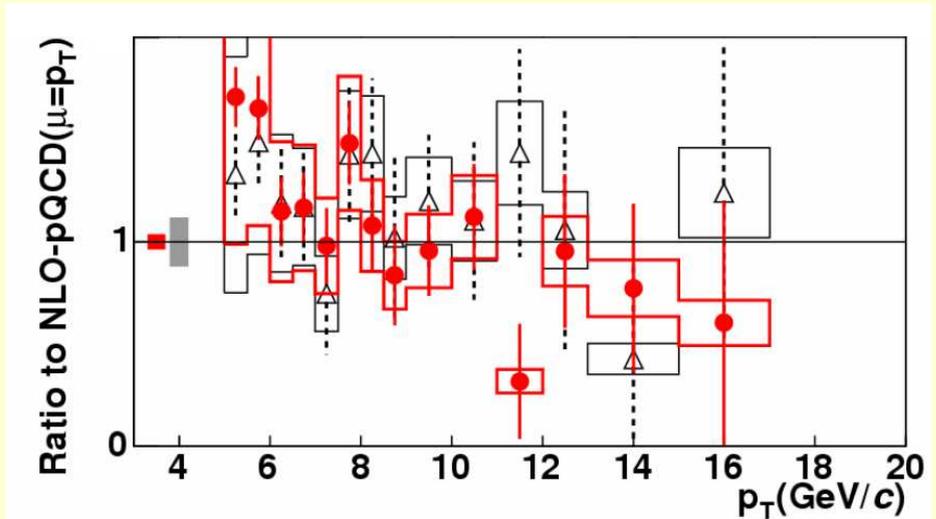


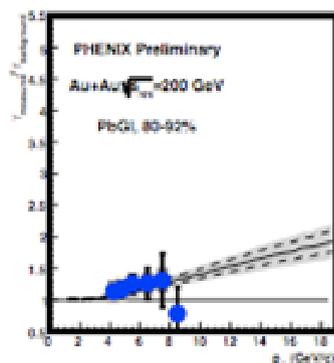
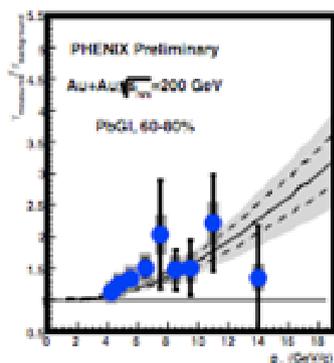
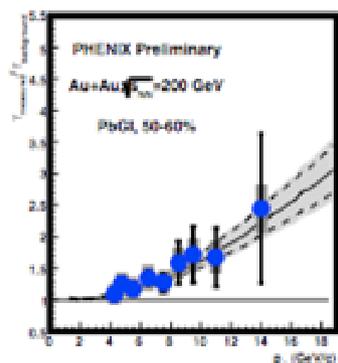
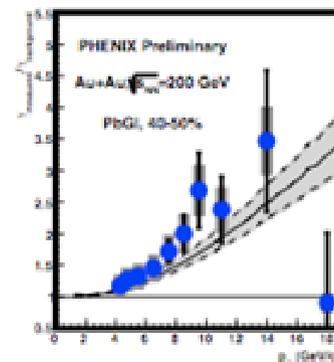
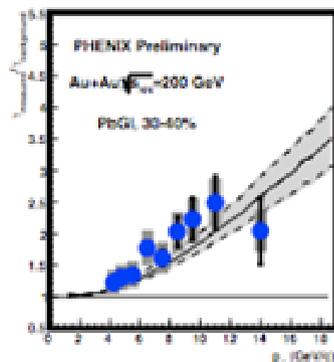
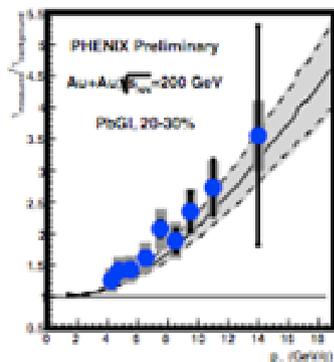
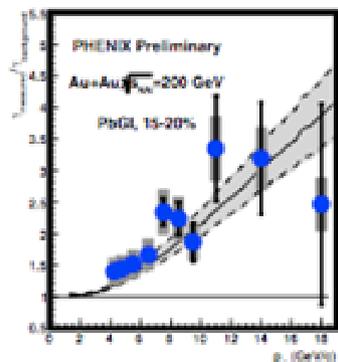
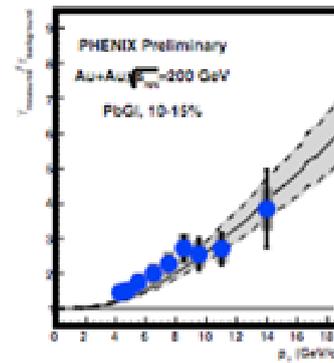
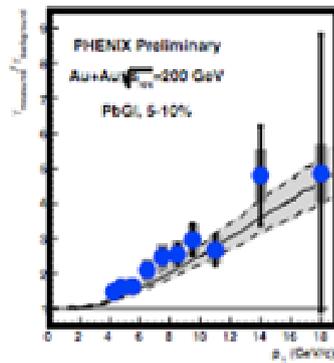
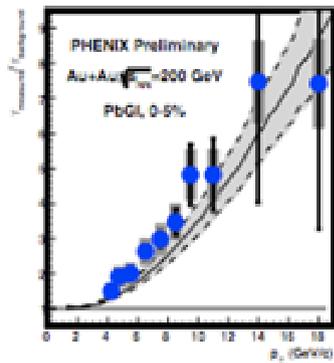
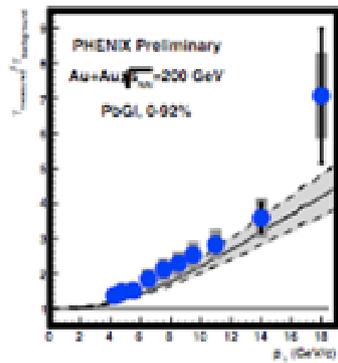
d+Au at $\sqrt{s} = 200$ GeV



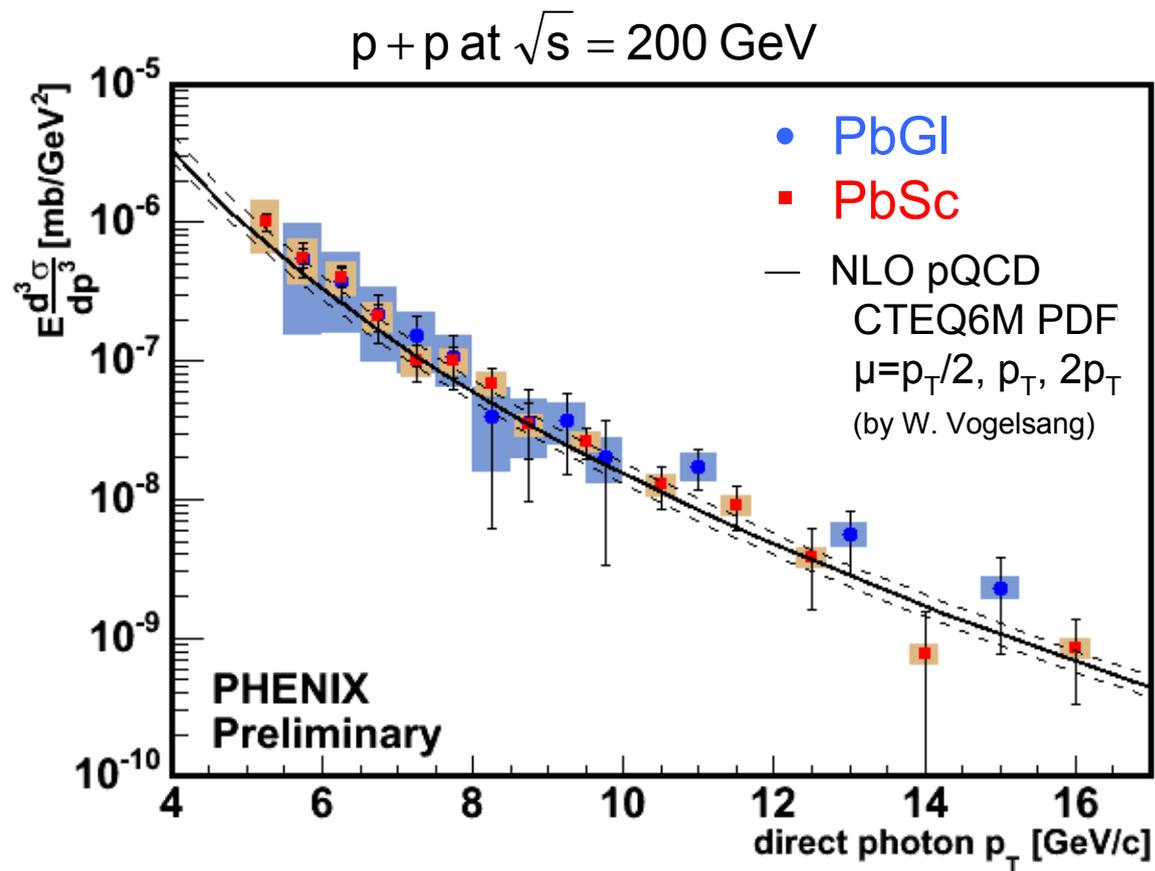
$$R_{AB} = \frac{dN/dp_T|_{A+B}}{\langle T_{AB} \rangle \times d\sigma/dp_T|_{p+p}}$$

$$\langle T_{AB} \rangle = \frac{\langle N_{coll} \rangle}{\sigma_{NN}}$$





Lines:
 $1 + N_{coll} \times N_{\gamma,pQCD}/N_{\gamma,bg}$
 (dashed lines: $\mu=2p_T$,
 $\mu=0.5p_T$; grey band
 includes error in N_{coll})



isolation cut

