Direct-Photon Production from SPS to RHIC Energies

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for the PHENIX collaboration

Why Direct Photons? (I)

- Direct Photons
  - Pragmatic Definition: Photons not coming from hadron decays
  - Difficult measurement: Large Background from
    - $\pi^0 \rightarrow \gamma + \gamma$
    - $\eta \rightarrow \gamma + \gamma$
- p+p:
  - Late 1970's: Direct Photons suggested presence of pointlike charged objects within hadrons
  - Test of QCD
  - Focus now on constraining gluon distribution functions
    - Quark-Gluon Compton scattering contributes at leading order (LO)
    - This is in contrast to Deep Inelastic Scattering and Drell-Yan where gluon is involved only at NLO

Why Direct Photons? (II)

- Nucleus+Nucleus collisions
  - Photons don't interact with the fireball and carry information about early stage of the A+A collision
  - QGP potentially detectable via thermal photon radiation
  - Thermal photons dominantly from early hot QGP phase:
    $\rightarrow$ initial temperature
  - Direct Photons at high p_T
    - Allow test of N_{coll} scaling for hard processes
    - Important for interpretation of high p_T hadron suppression at RHIC

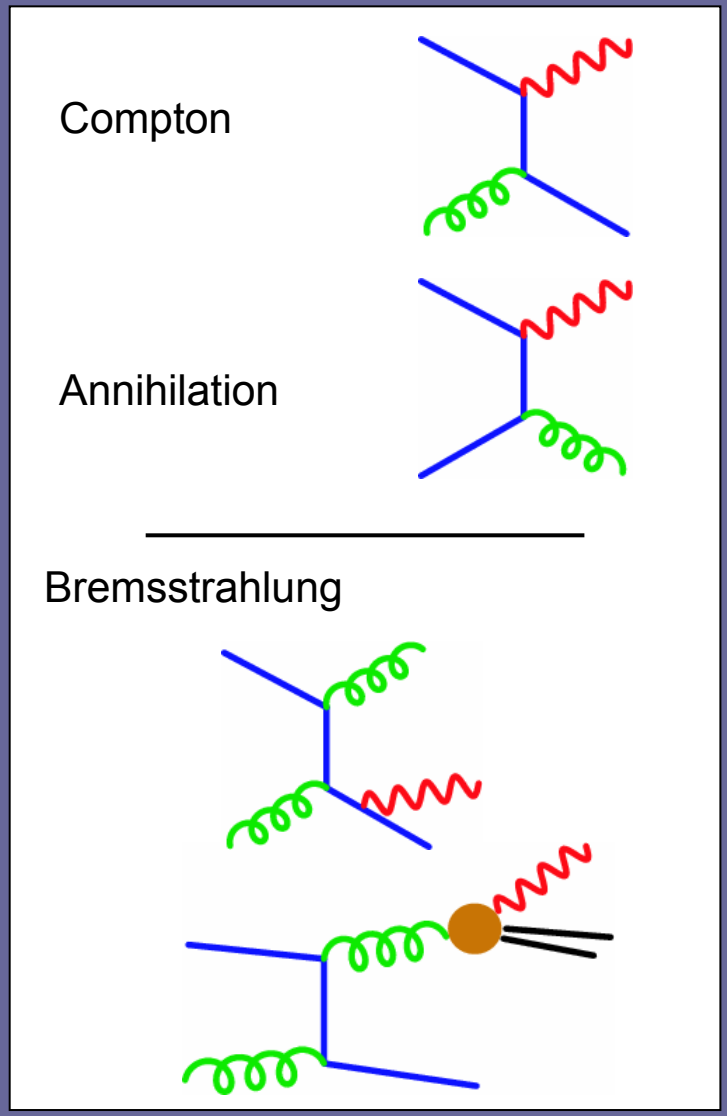
Klaus Reygers, Hard Probes 2004

Direct Photon Production in p+p: Hard Scattering

- Processes in perturbative QCD
  - Compton: $q + g \rightarrow \gamma + q$
  - Annihilation: $q + \bar{q} \rightarrow \gamma + g$
  - Bremsstrahlung

LO, NLO

- Typically 20-30% uncertainty in pQCD calculations related to choice of scales



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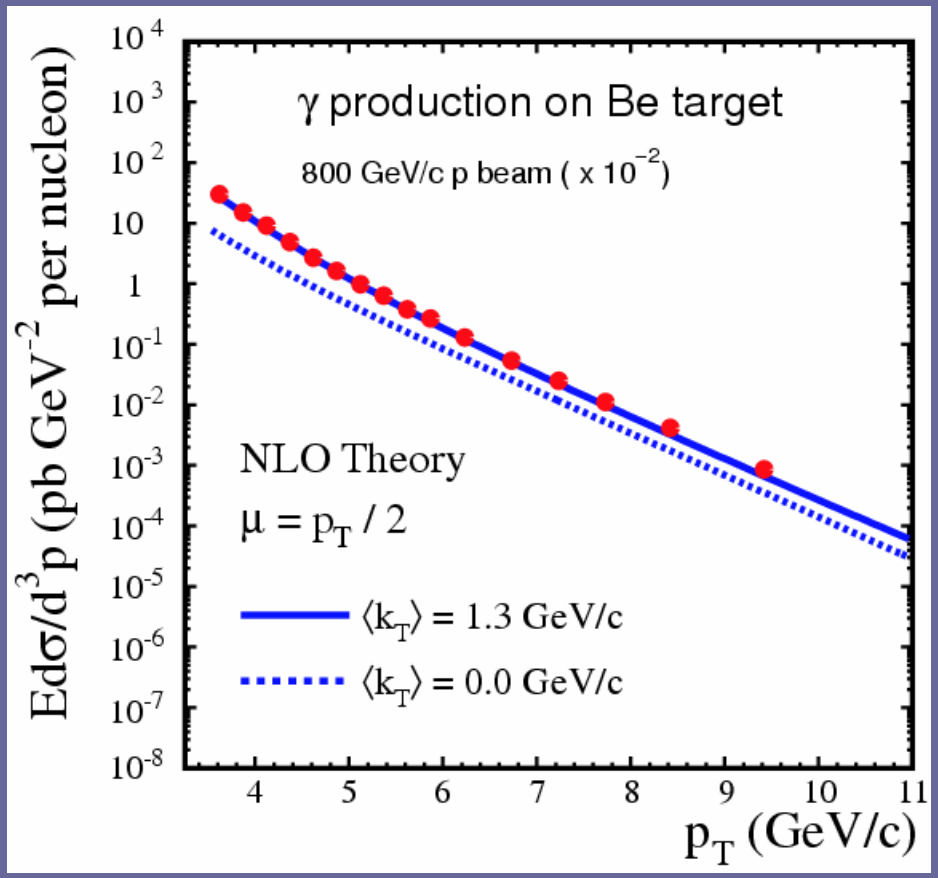
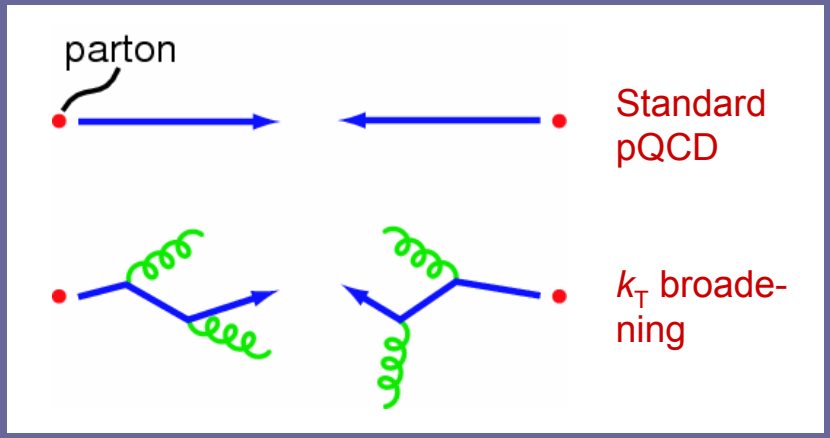
Evidence for k_T Broadening



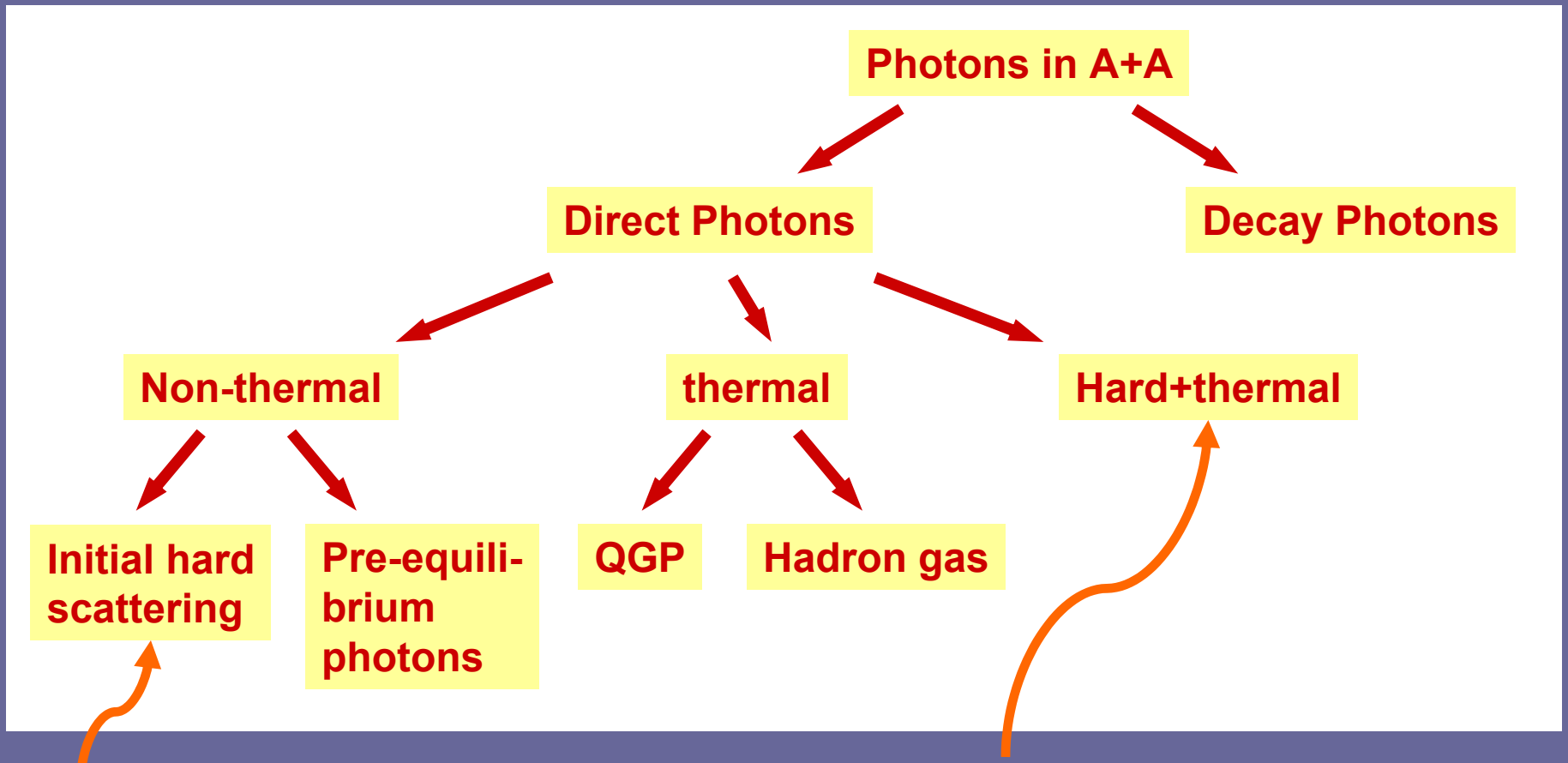
E706, hep-ex/0407011

- Systematic pattern of deviation between NLO pQCD and data
  - Data above pQCD
  - Especially at low $\sqrt{s}$
- Possible explanation: k_T broadening (which can be produced by multiple soft-gluon emission)



Klaus Reygers, Hard Probes 2004

Photon Sources in A+A



pQCD or
prompt photons

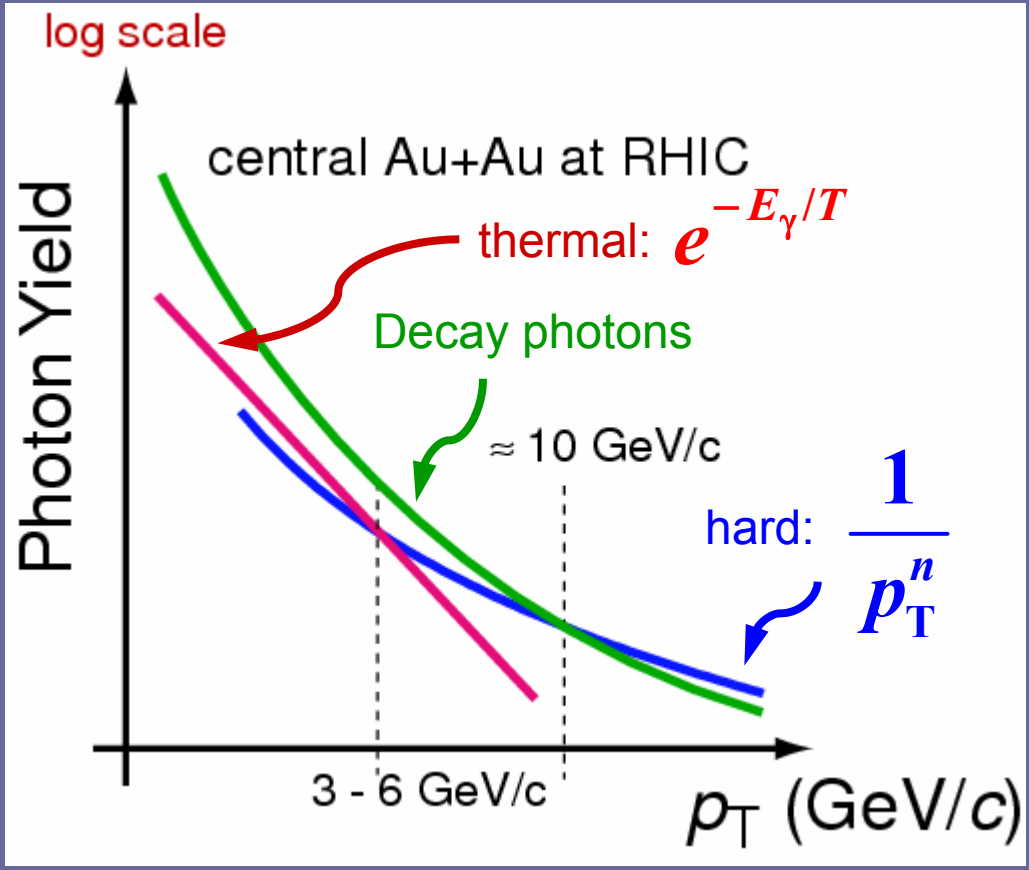
Interaction of hard parton with QGP

1) $q_{hard} + \bar{q}_{QGP} \rightarrow \gamma + g$ and $q_{hard} + g_{QGP} \rightarrow \gamma + q$

2) Medium induced photon bremsstrahlung

Klaus Reygers, Hard Probes 2004

Schematic Photon Spectrum in A+A



- Advantage in central A+A at RHIC:
  Decay photon background strongly reduced due to to π^0 suppression

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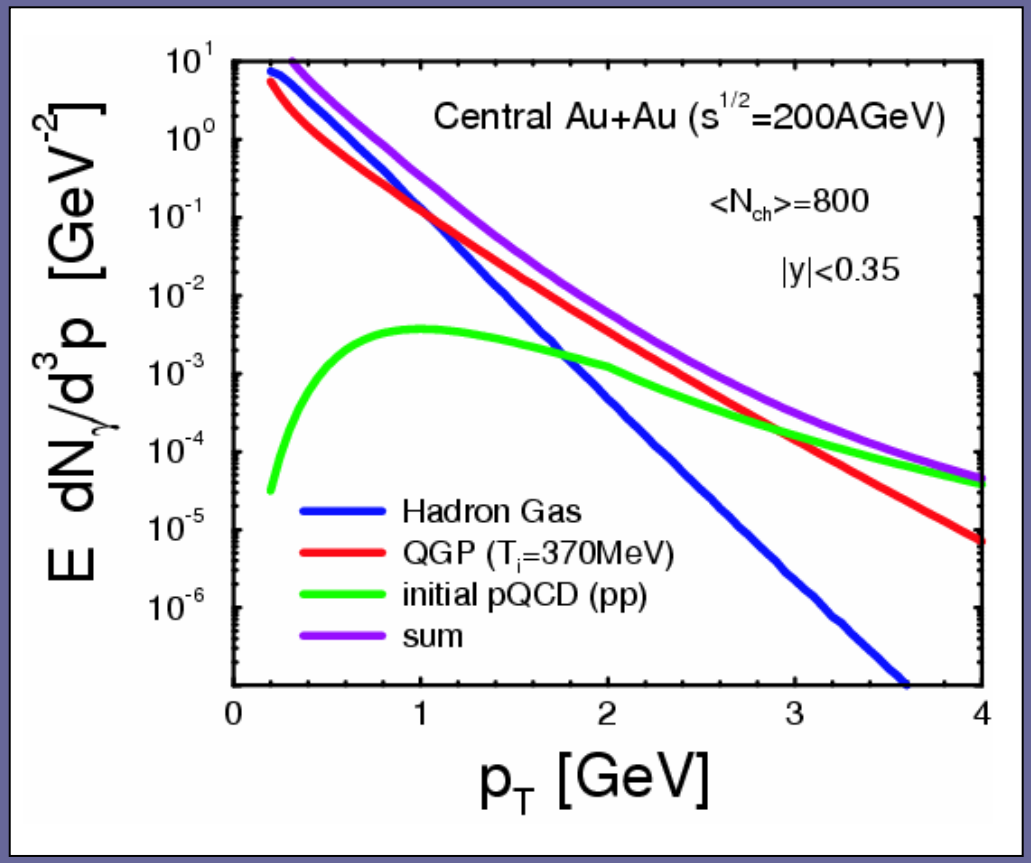
Realistic Calculation



Turbide, Rapp, Gale, Phys. Rev. C 69 (014902), 2004

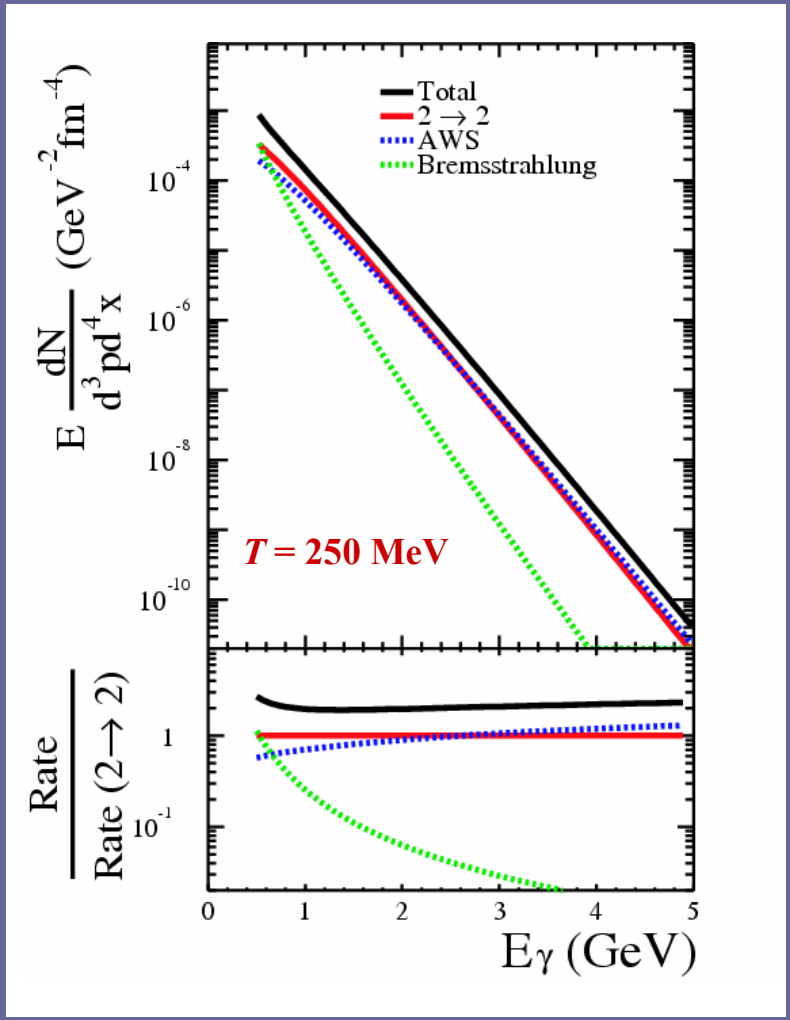
- Window for thermal photons from QGP in this calculation: p_T = 1 - 3 GeV/c

Thermal Photons as QGP Signature

- Conventional wisdom ca 1985:
  - QGP has lots of quarks flying around
  - QGP radiates more than HG at the same temperature **(false!)**
  - Lots of thermal radiation is evidence for QGP
- Current conventional wisdom:
  - QGP has more d.o.f. than HG and therefore lower temperature at the same energy density ε ($\varepsilon \sim g \cdot T^4$)
  - At the same energy density QGP radiates less than HG
  - Lack of radiation is evidence for QGP!

See talk by P. Stankus at CTEQ summer school 2004: http://www.cteq.org

Thermal Photon Rates in QGP



State-of-the-art result from Arnold, Moore, and Yaffe (including Landau-Pomeranchuk-Migdal destructive interference effect)

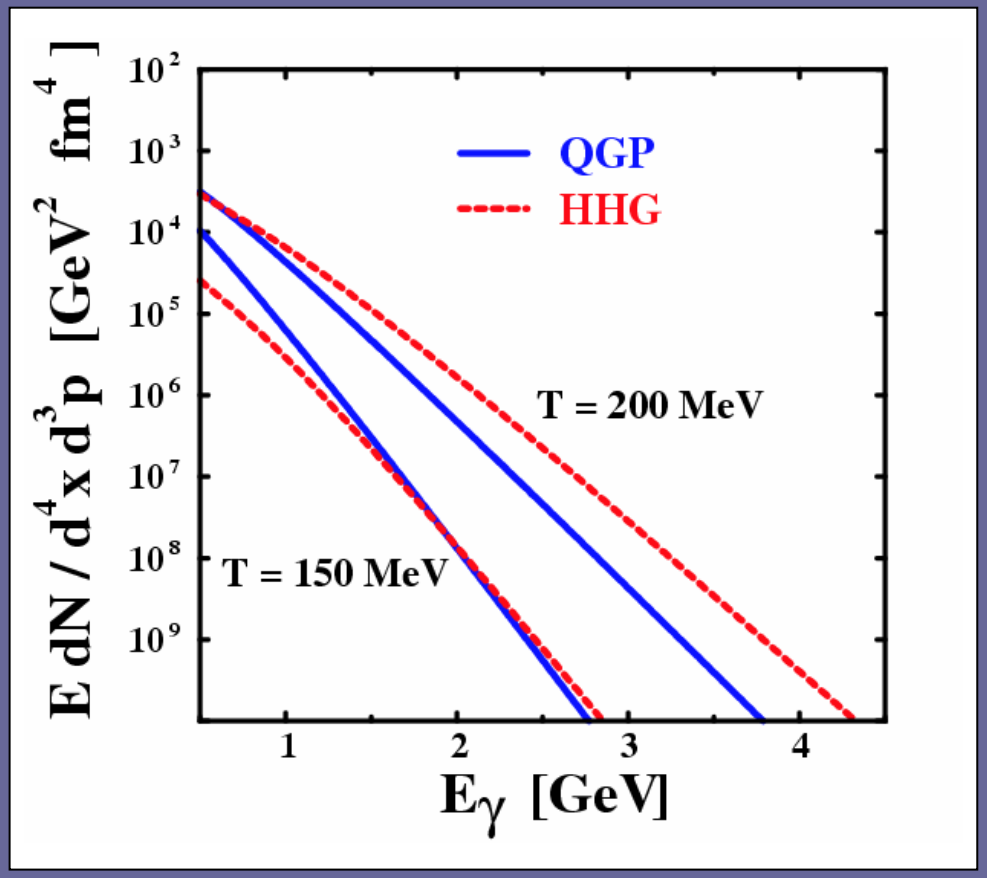
- Final thermal photon spectrum: QGP and HG photon rates convoluted with space-time evolution of the reaction
- Thermal photon rate in QGP
  - Hard-thermal-loop resummation
  - Effective in-medium Quark and Gluon propagators
  - Processes

$2 \to 2$
- Quark-Gluon-Compton scattering
- Quark-antiquark annihilation

- Annihilation with Scattering (AWS)
- Bremsstrahlung

Klaus Reygers, Hard Probes 2004

Photon Rates in HG and QGP



Steffen and Thoma, Phys. Lett. B 510, 98 (2001)

- Typical processes for direct photon production in hot hadron gas (HHG)
  - $\pi + \rho \rightarrow \pi + \gamma$
  - $\pi + N \rightarrow N + \gamma$
- Hadron gas at *T*=200 MeV radiates more than QGP at the same temperature

Measurement of Direct Photons

- Measure p_T spectrum of π^0 and η mesons with high accuracy
- Calculate number of decay photon per π^0
  - Usually with Monte-Carlo
  - m_T scaling for (η), η', ω, …
- Get clean inclusive photon sample
  - Charged background subtraction
- Finally:
  Subtract decay background from inclusive photon spectrum

Handy formula:

$$\frac{d\sigma}{dp_T} \propto 1/p_T^n$$

$$\Rightarrow \frac{\gamma_{\pi^0}^{decay}}{\pi^0} = \frac{2}{n-1} \approx 0.28 \text{ at RHIC}$$

$$"\gamma_{direct} = \gamma_{inclusive} - \gamma_{decay}"$$

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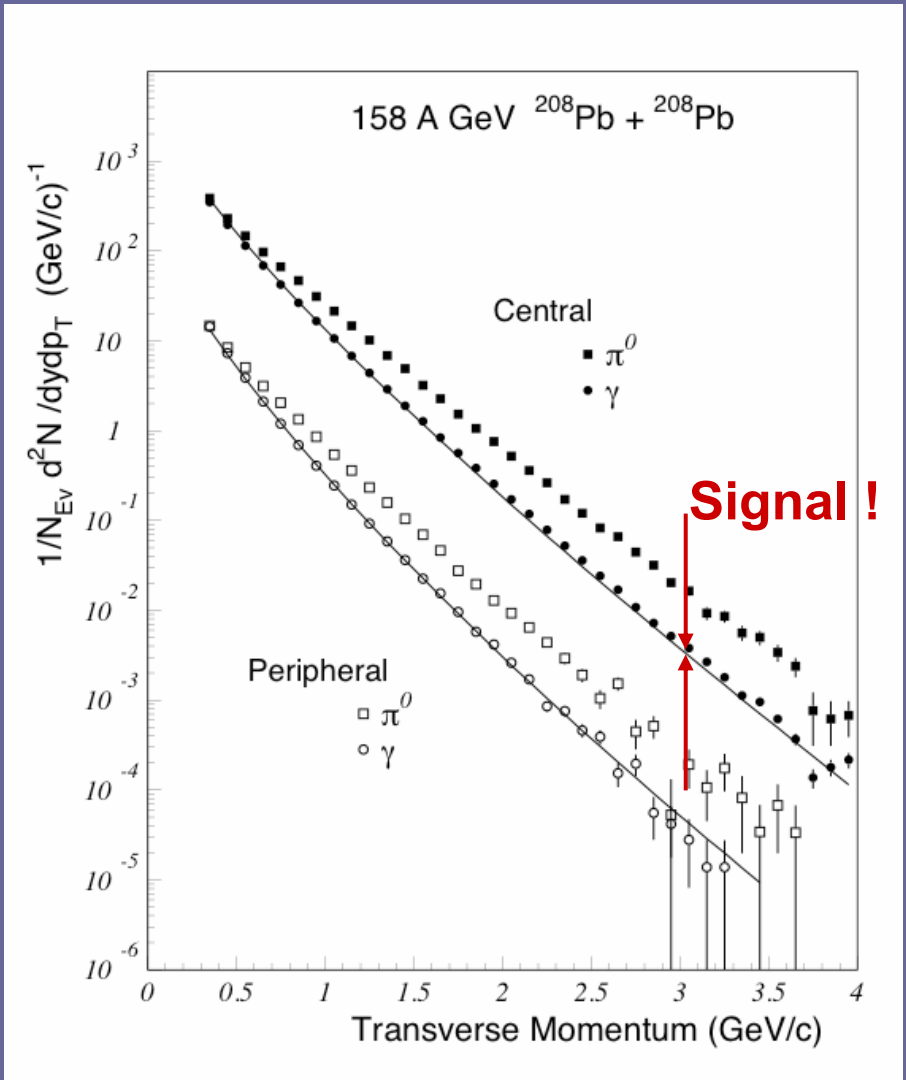
Why this is Difficult



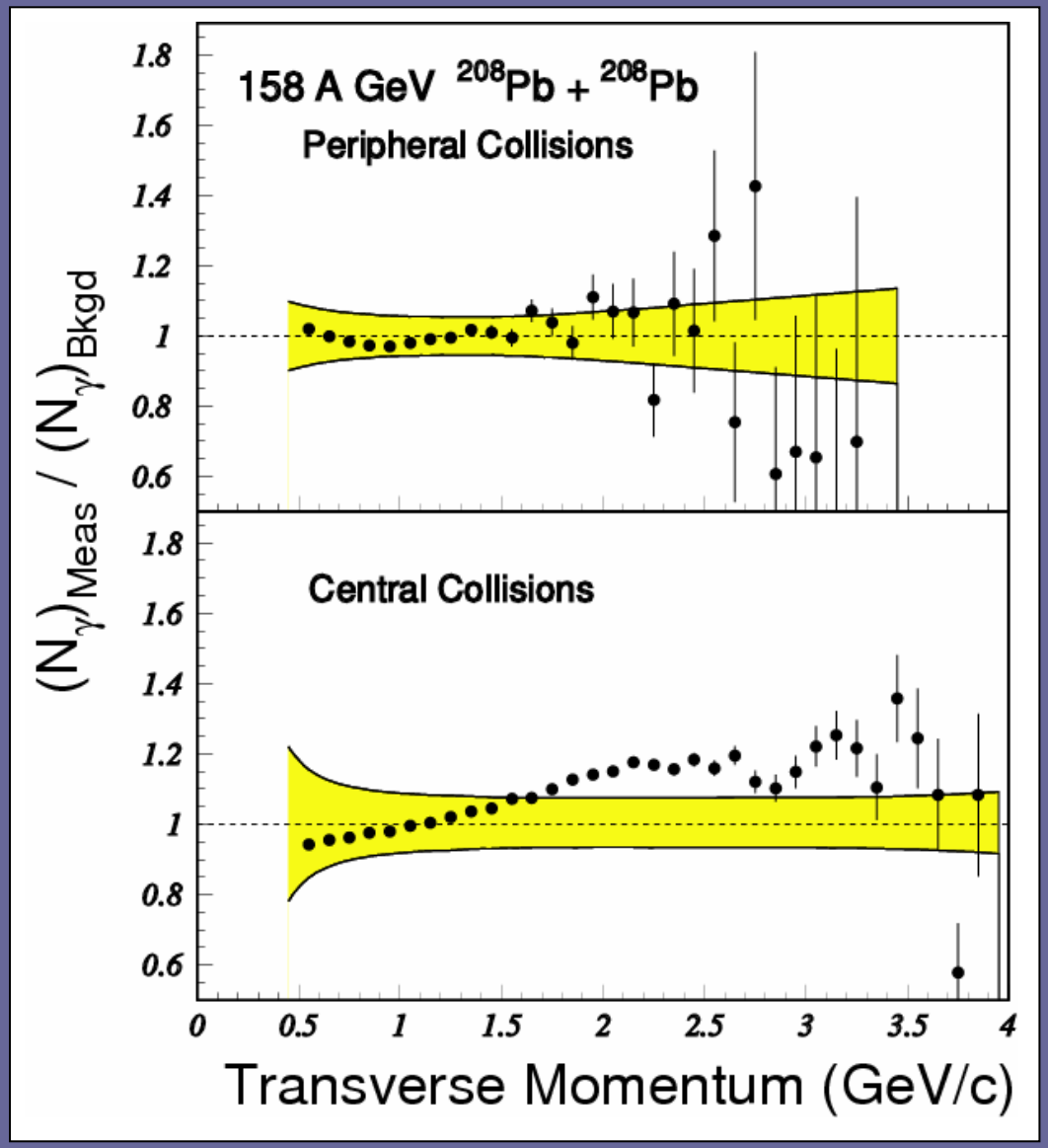
Systematic errors
(e.g. energy scale non-linearity)
partially cancel in this ratio

$$R = \frac{\gamma_{measured}}{\gamma_{decay}} = \frac{(\gamma/\pi^0)_{measured}}{(\gamma/\pi^0)_{decay}}$$

$$\gamma_{direct} = (1 - \frac{1}{R}) \cdot \gamma_{measured}$$

Klaus Reygers, Hard Probes 2004

WA98 Result



- 20% direct photon excess at high p_T in central Pb+Pb collisions at CERN SPS
- No signal within errors in peripheral collisions

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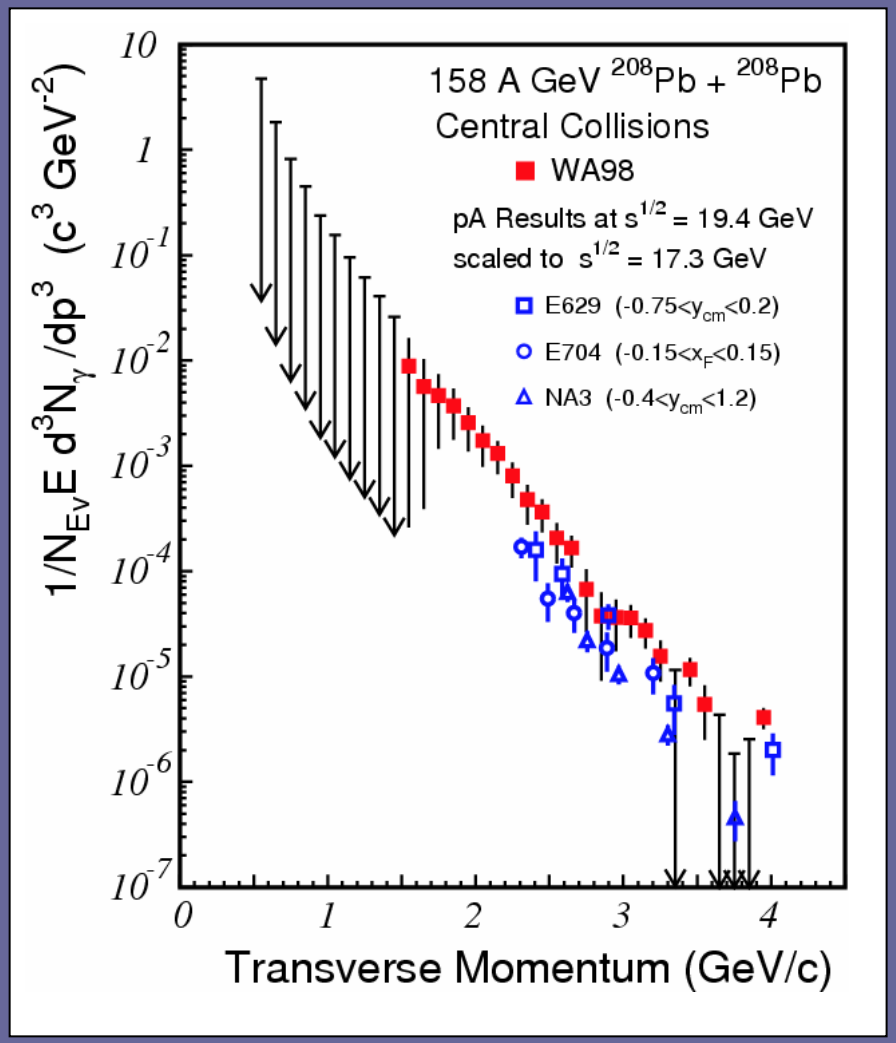
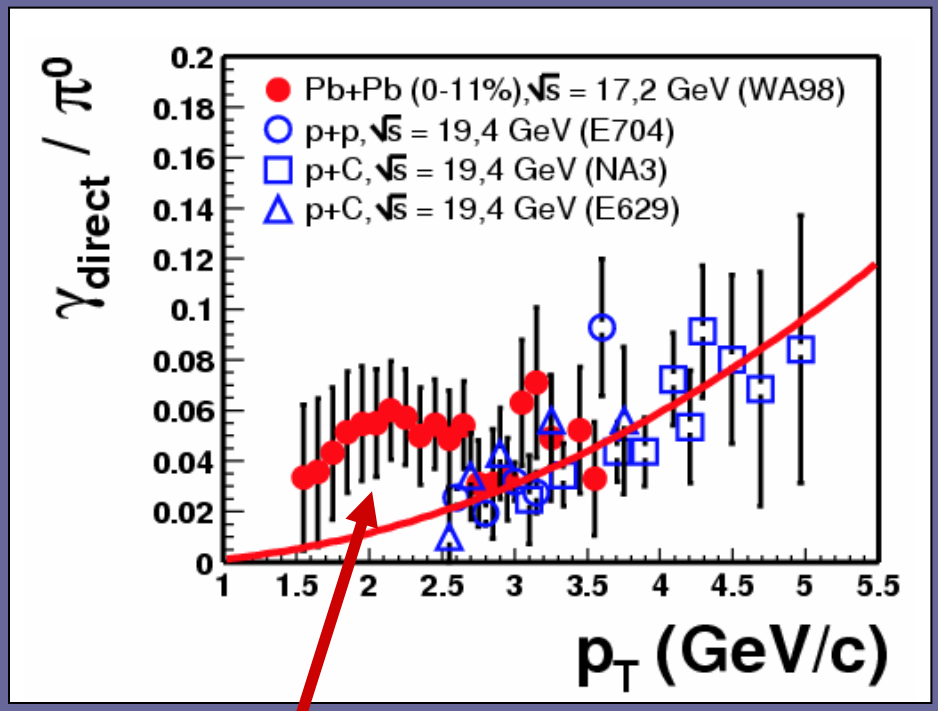
WA98 Direct Photon Spectrum





Thermal photon signal ?

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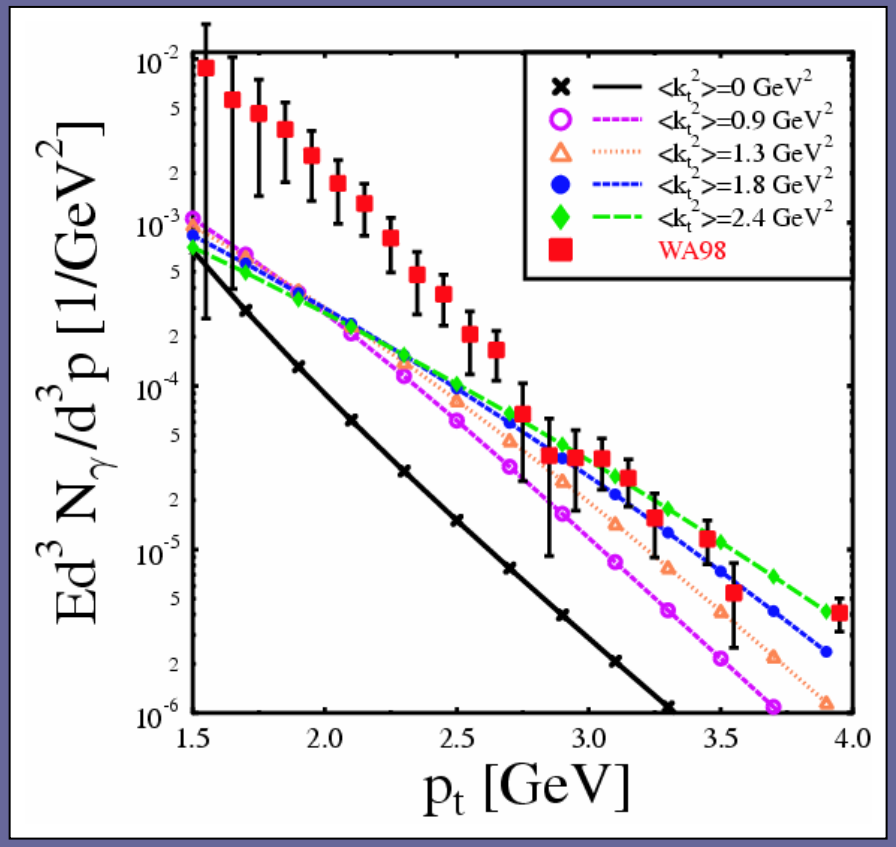
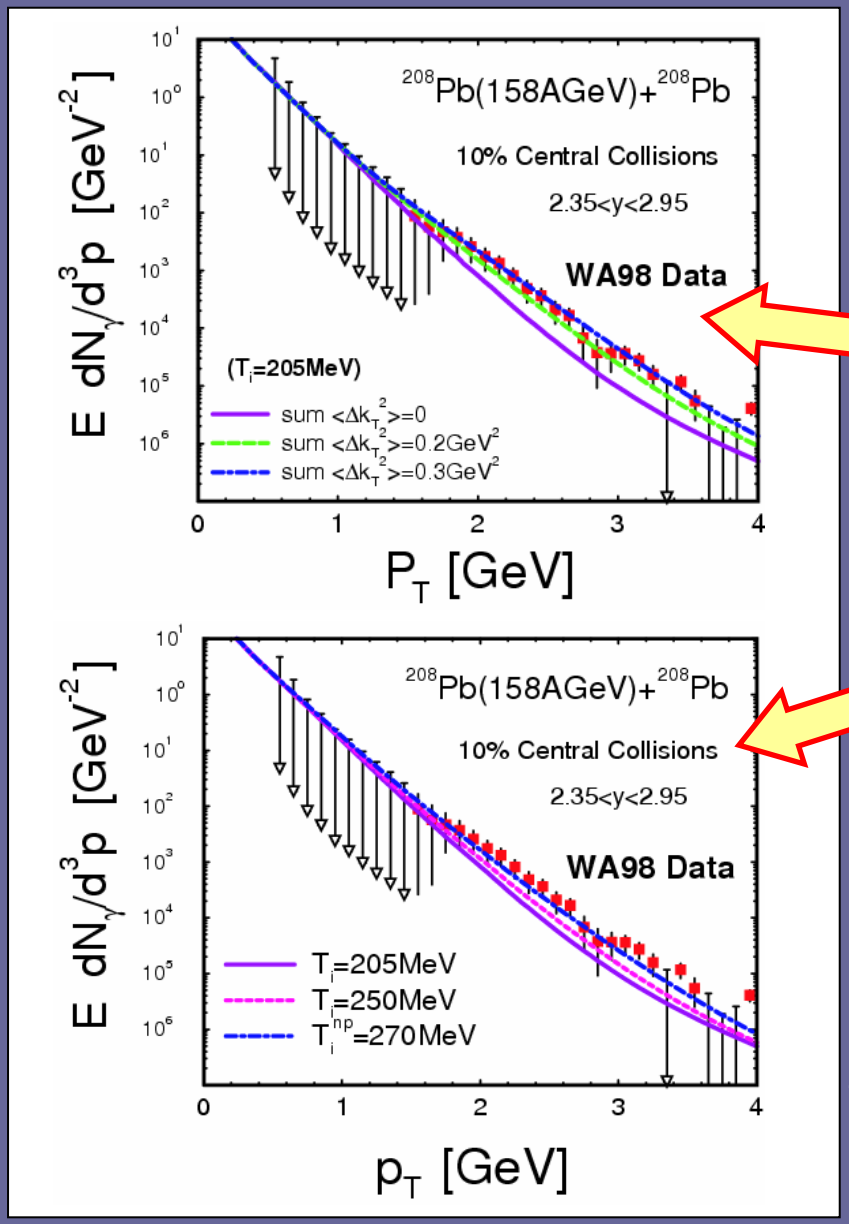
WA98 Interpretation I: pQCD with Nuclear k_T Broadening ?



Dumitru et al., Phys. Rev. C 64, 054909 (2001)

- High p_T part of the spectrum explained by pQCD + nuclear k_T broadening
  - p+p: $\langle k_T^2 \rangle \approx 1.4\ \mathrm{GeV}^2$
  - A+A: $\langle k_T^2 \rangle \approx 2.4\ \mathrm{GeV}^2$
- Intermediate p_T range cannot be explained regardless of amount of k_T

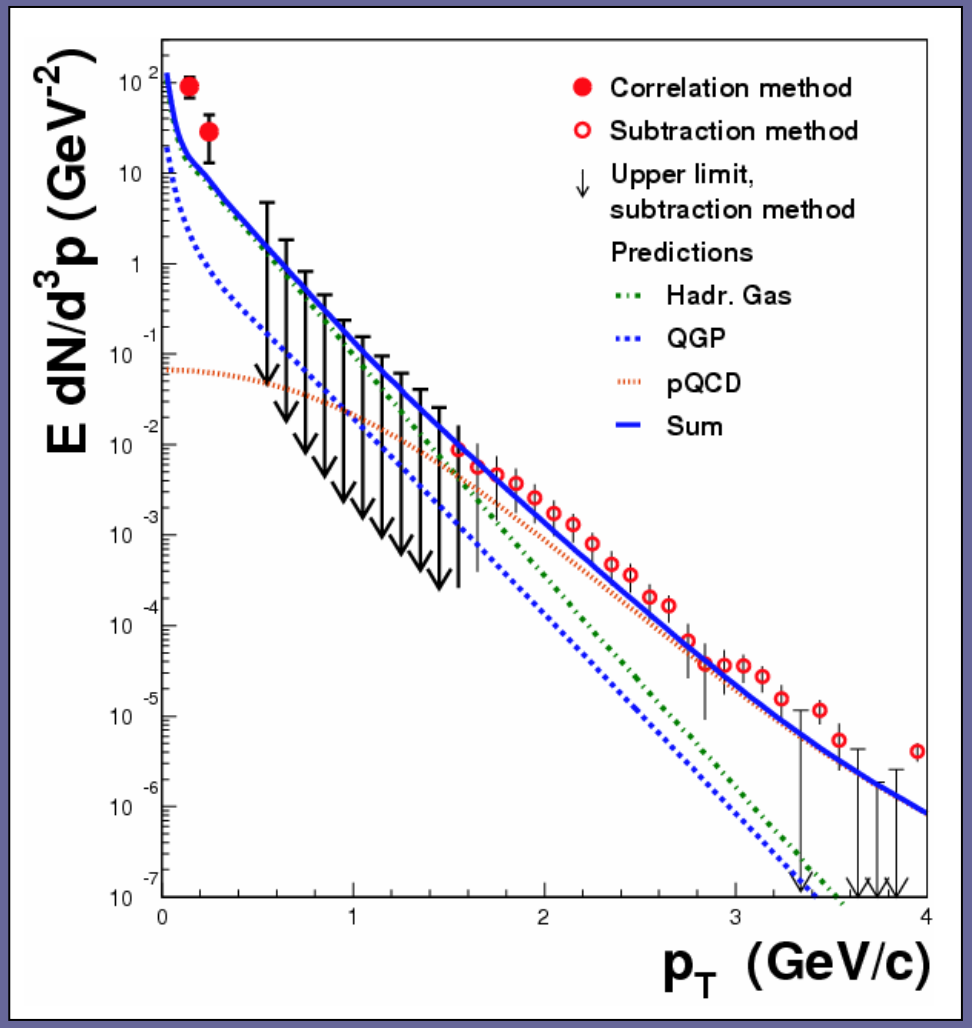
WA98 Interpretation II: T or k_T ?



- QGP + HG rates convoluted with simple fireball model plus pQCD hard photons
- Data described with initial temperature T_i=205 MeV + some nuclear k_T broadening (Cronin -effect)
- Data also described without k_T broadening but with high initial temperature (T_i=270 MeV)
- Other Models (see e.g. Huovinen et al., Nucl. Phys. A 650 (227) 1999) explain data without assuming QGP

Turbide, Rapp, Gale,
Phys. Rev. C 69 (014902), 2004

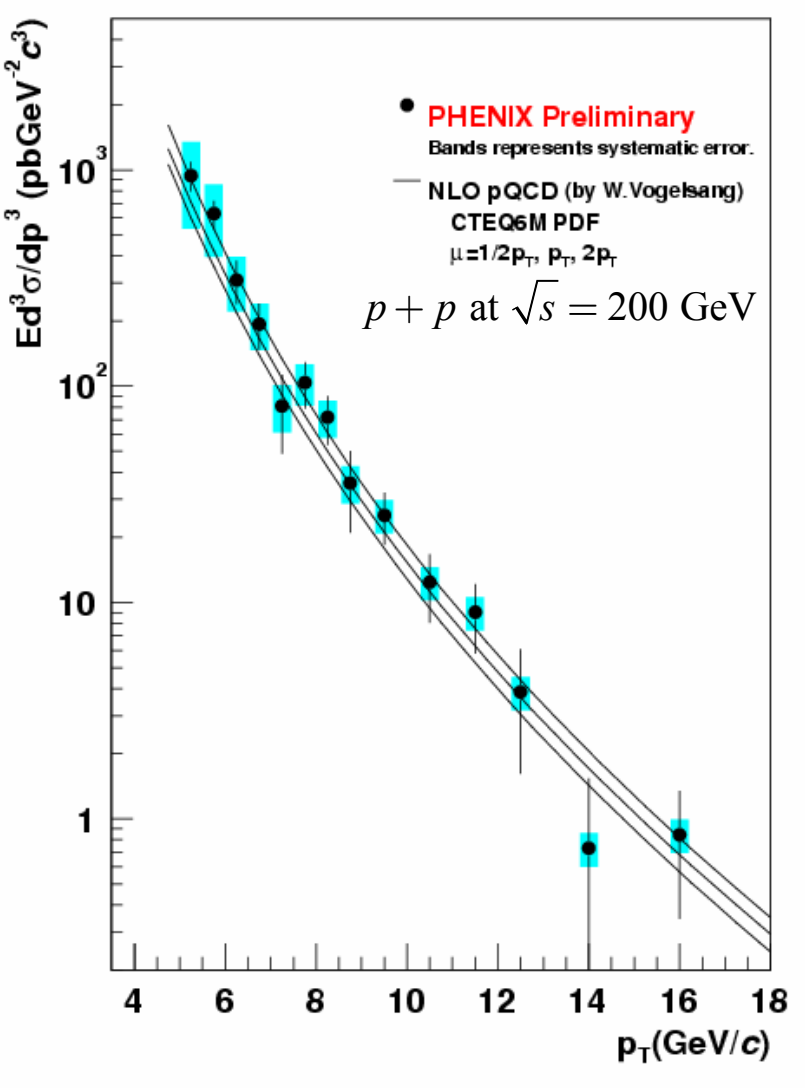
WA98: New low-p_T Points



- Two-photon correlations observed and attributed to Bose-Einstein correlations of direct photons
- Correlation strength used to extract direct photon signal at low p_T
- New points not described by current models

WA98, Phys. Rev. Lett. 93 (022301), 2004

Direct Photons at RHIC: p+p



- Data show good agreement with NLO pQCD calculation
- Important baseline for interpretation of Au+Au results

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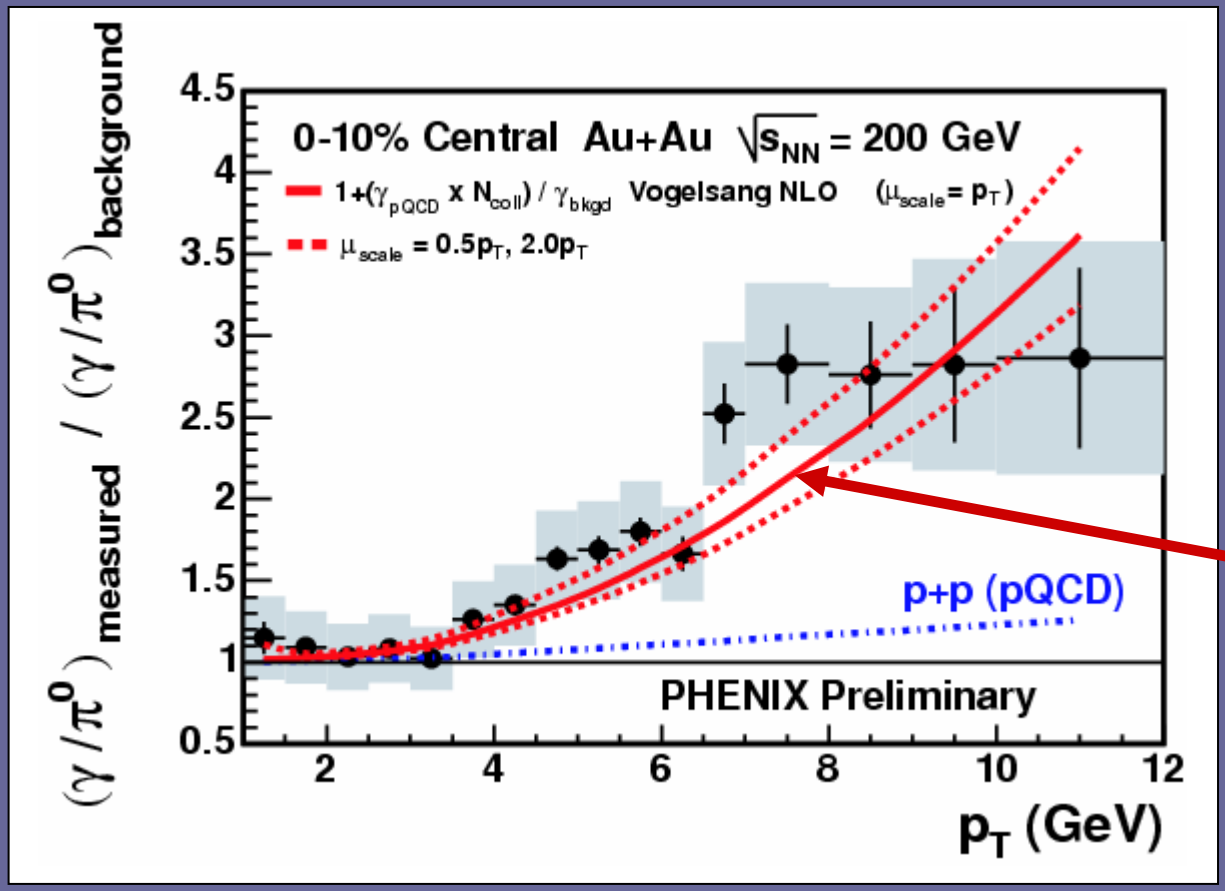
Direct Photons at RHIC: Au+Au



Expectation for N_{coll} scaling of direct photons

- Strong direct photon signal in central Au+Au
- Direct Photons at high p_T follow N_{coll} scaling
- Errors currently too large for statement about thermal photon signal

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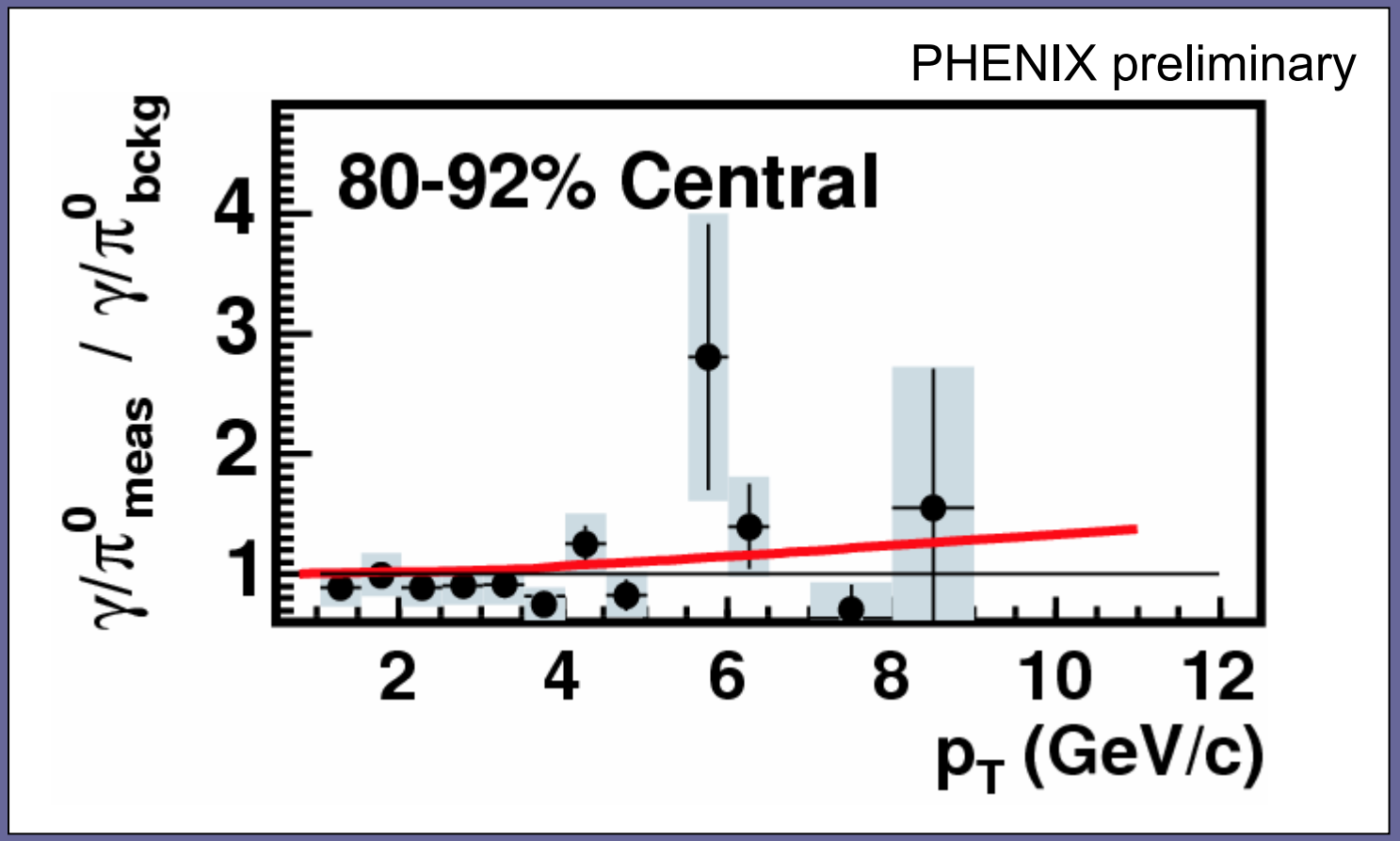
Centrality Dependence



- N_{coll} scaling holds for all centrality classes (within errors)

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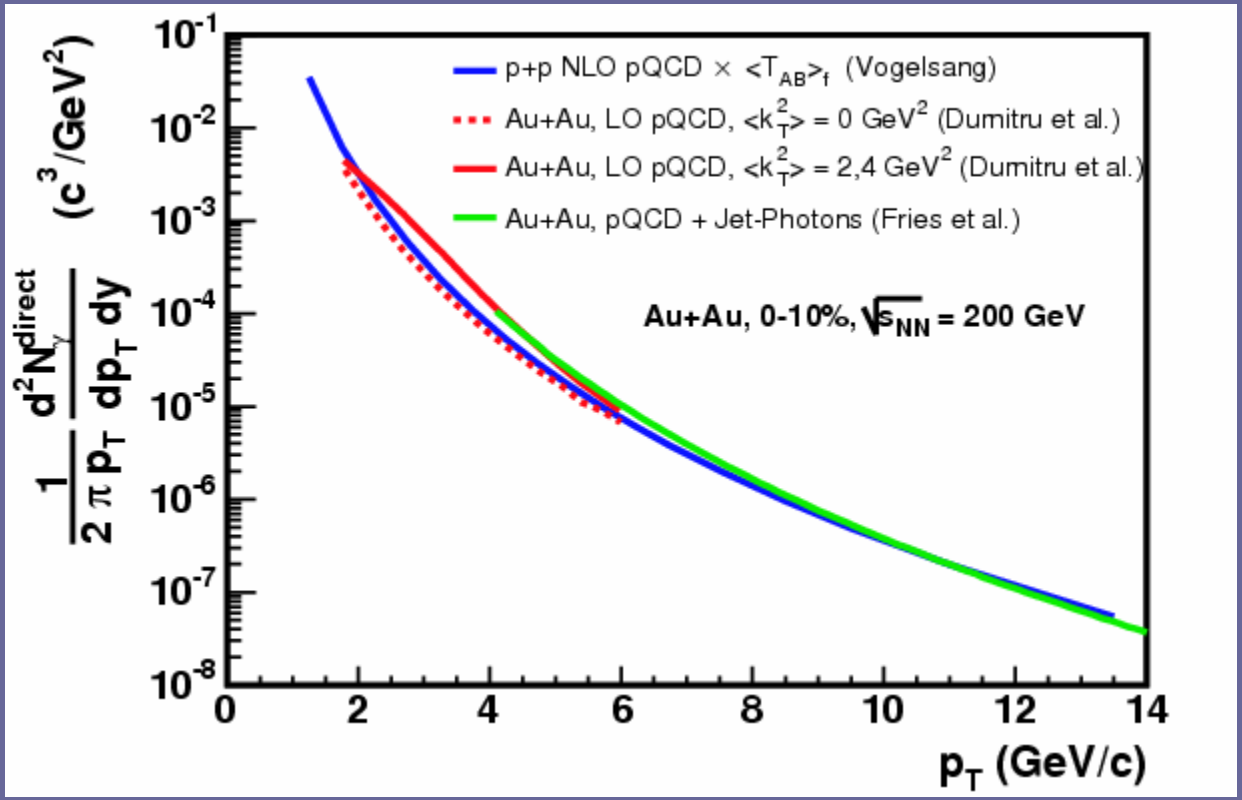
Beyond simple N_{coll} Scaling: k_T Effects and Photons from Quark-Jets



- Effect of k_T strongest where thermal QGP photons are expected
- Interaction of fast quarks with QGP significant photon source for p_T < 6 GeV/c (Jet-Photons: $q_{hard} + \bar{q}_{QGP} \rightarrow \gamma + g$ and $q_{hard} + g_{QGP} \rightarrow \gamma + q$)

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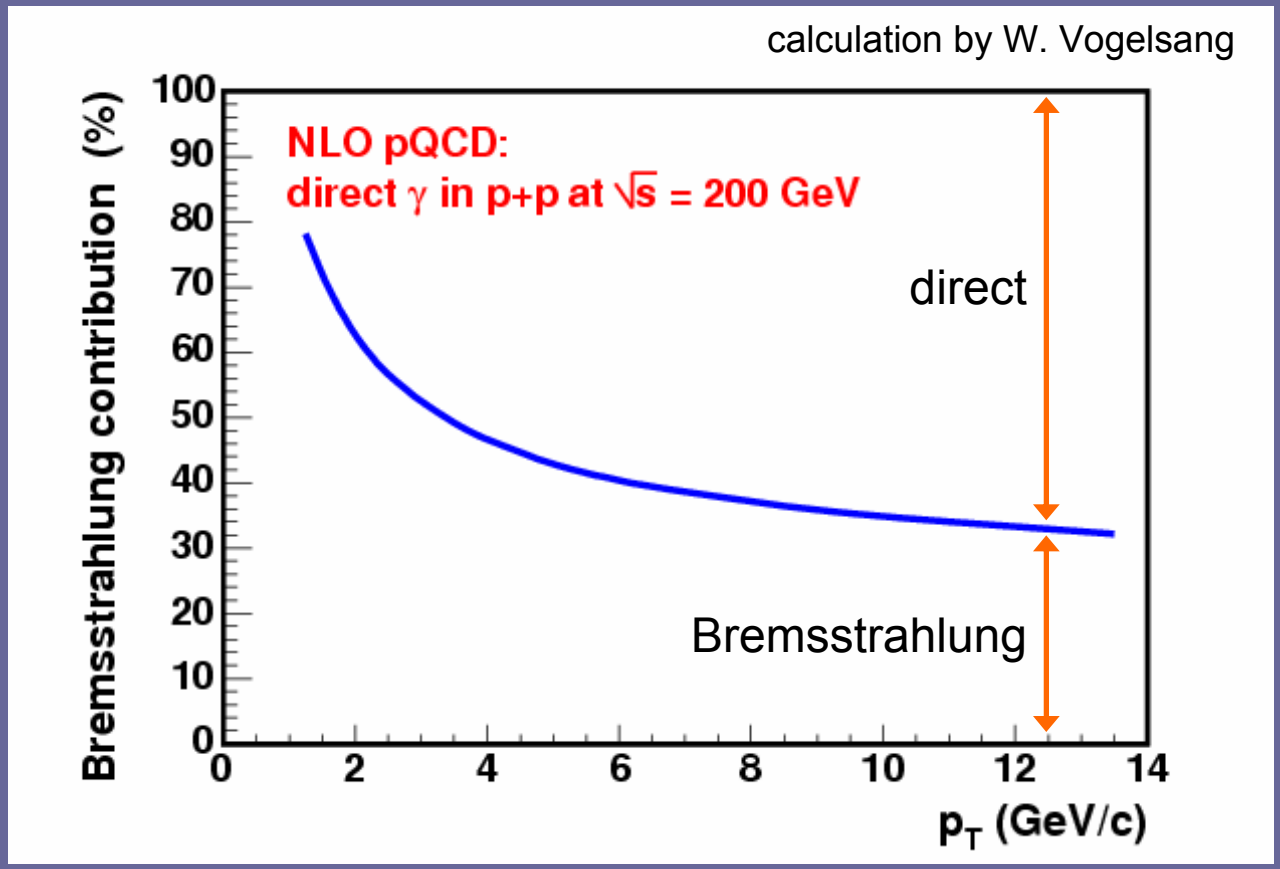
What about Photon Bremsstrahlung in A+A ?



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

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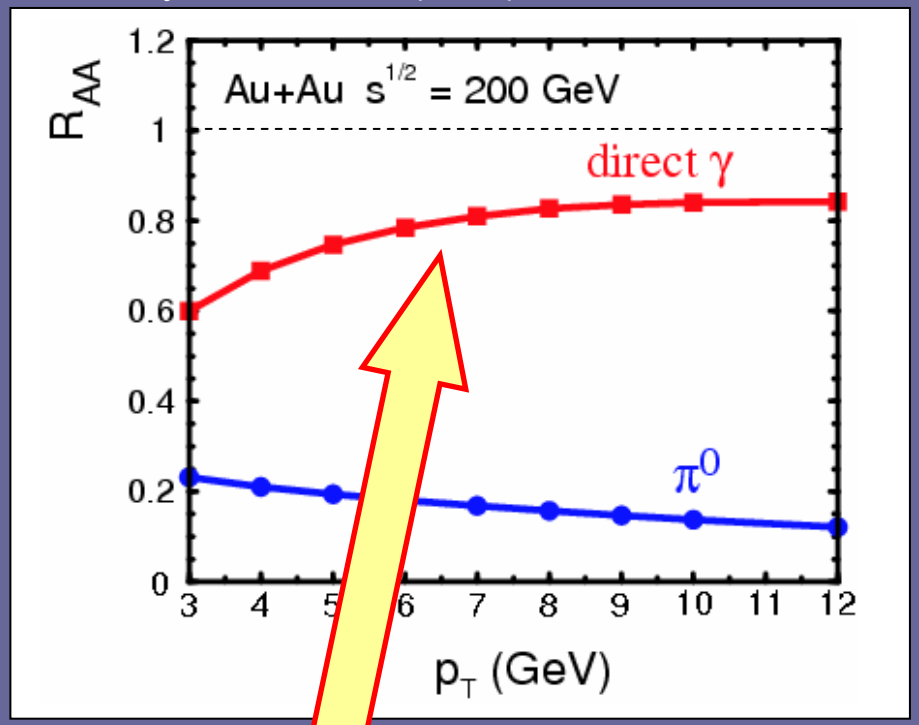
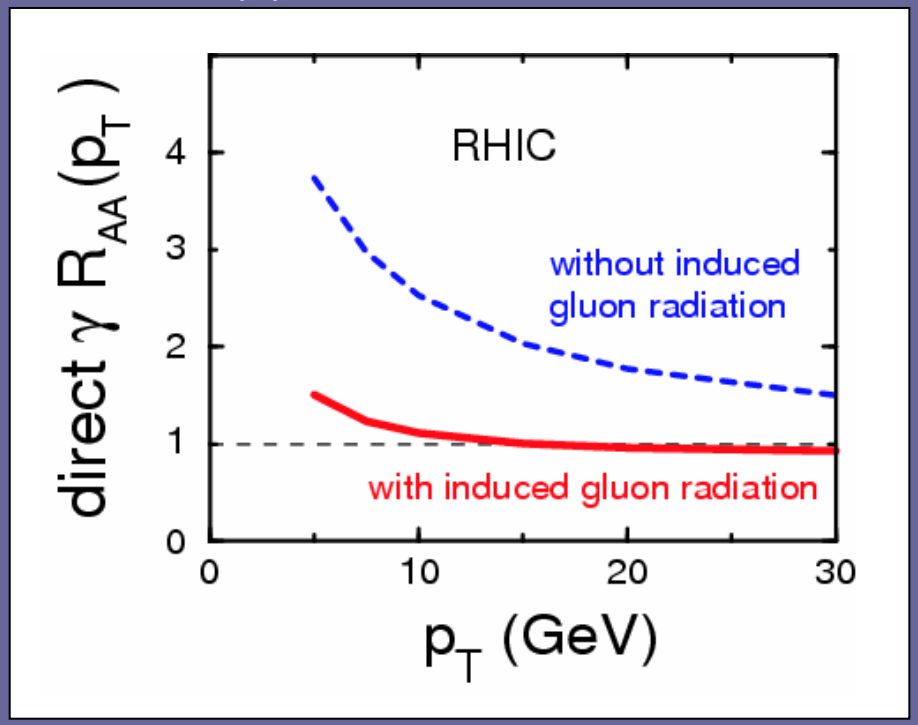
Modification of Bremsstrahlung Contribution in A+A

Jeon, Jalilian-Marian, Sarcevic,
Nucl. Phys. A 715, 795 (2003)



Zakharov, hep-ph/0405101



- Quark energy loss in QGP reduces bremsstrahlung contribution in A+A
- However, this is compensated by induced photon bremsstrahlung in QGP (according to Zakharov)
- Net result: direct photon $R_{AA} \geq 1$ at high p_T

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Model-independent Representation of π^0 Suppression

- Standard representation relies on assumption about scaling of hard scattering processes in A+A:

$$R_{AA}^{\pi^0} = \frac{\mathrm{d}^2N/\mathrm{d}p_T\mathrm{d}y\big|_{A+A}}{\langle N_{\mathrm{coll}}\rangle/\sigma_{\mathrm{inel}}^{\mathrm{pp}} \times \mathrm{d}^2\sigma/\mathrm{d}p_T\mathrm{d}y\big|_{p+p}}$$

- PHENIX result on high p_T direct photon production confirms this assumption
- However, it seems natural to avoid model assumptions and to use high p_T direct photons as a direct measure of the number of hard scatterings in A+A

- Define:

$$G_{AA} = \frac{(\gamma_{\mathrm{direct}} / \pi^0)_{\mathrm{p+p}}}{(\gamma_{\mathrm{direct}} / \pi^0)_{\mathrm{A+A}}}$$

- If direct photons exactly follow N_{coll} scaling then

$$G_{AA} = R_{AA}^{\pi^0}$$

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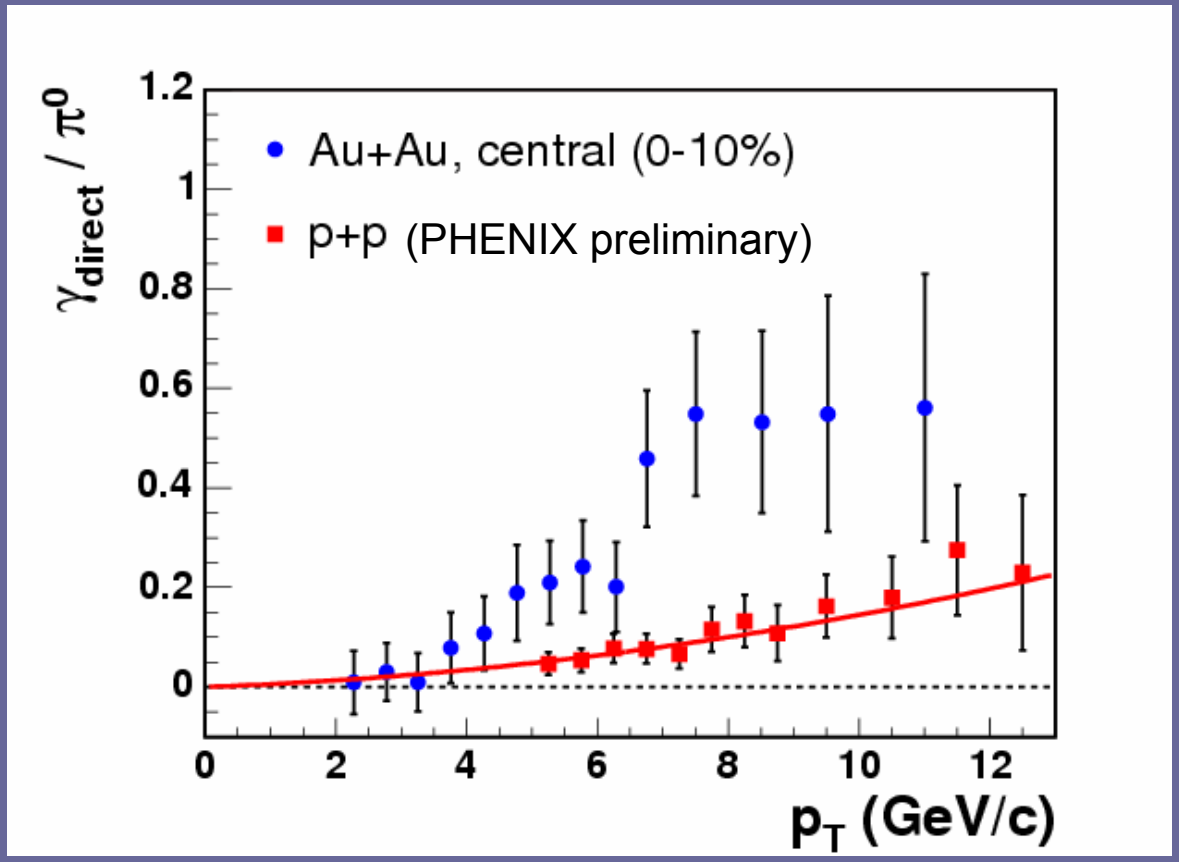
γ_{direct} / π^0



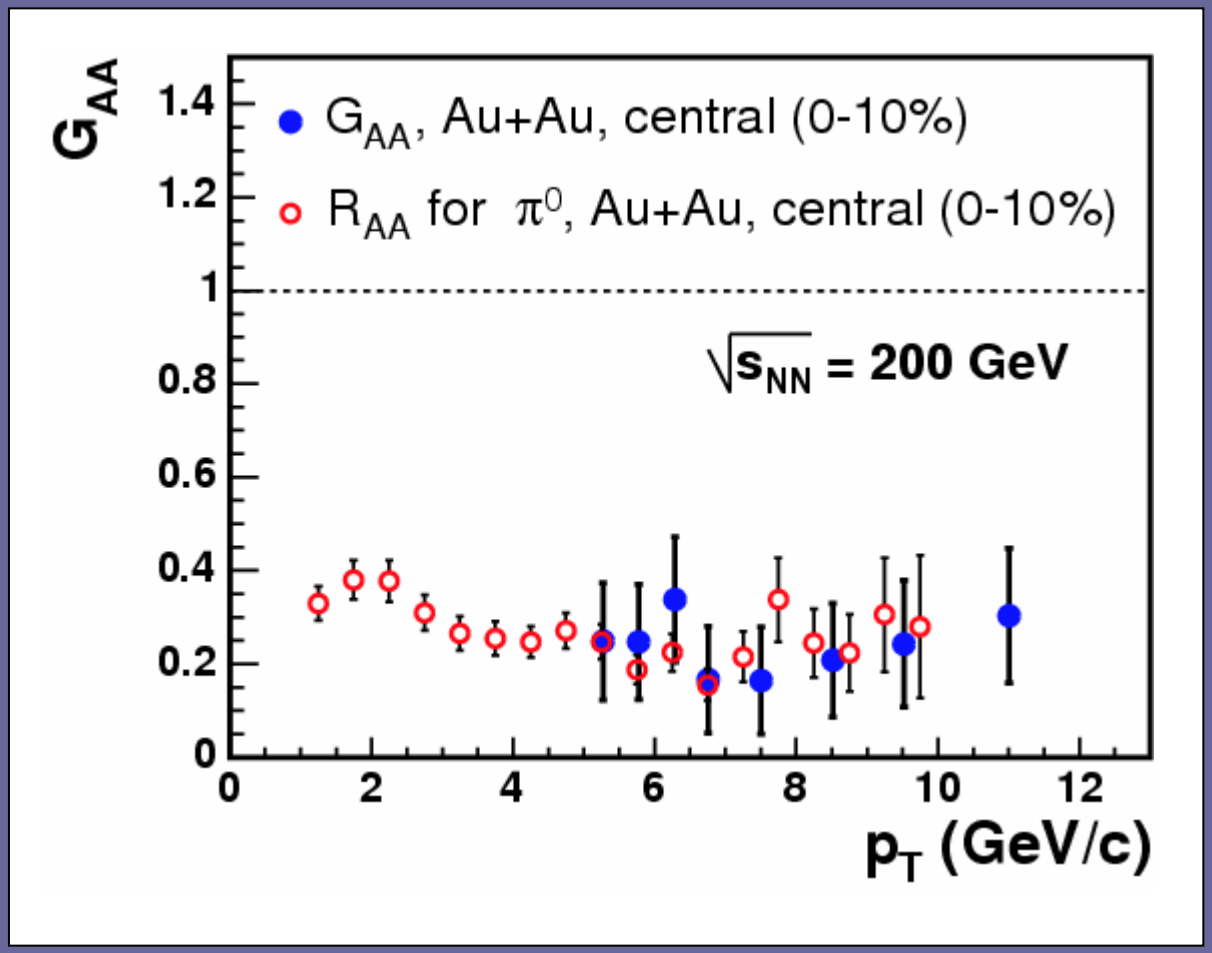
Blue points are another representation of the PHENIX preliminary double ratio:

$$\left(\frac{(\gamma / \pi^0)_{measured}}{(\gamma / \pi^0)_{decay}} - 1 \right) \times 0.3$$

$(\gamma/\pi^0)_{decay}$ above p_T = 3 GeV/*c*

Klaus Reygers, Hard Probes 2004

G_{AA} in central Au+Au at RHIC



- G_{AA} agrees well with the standard R_{AA} representation of the neutral pion suppression

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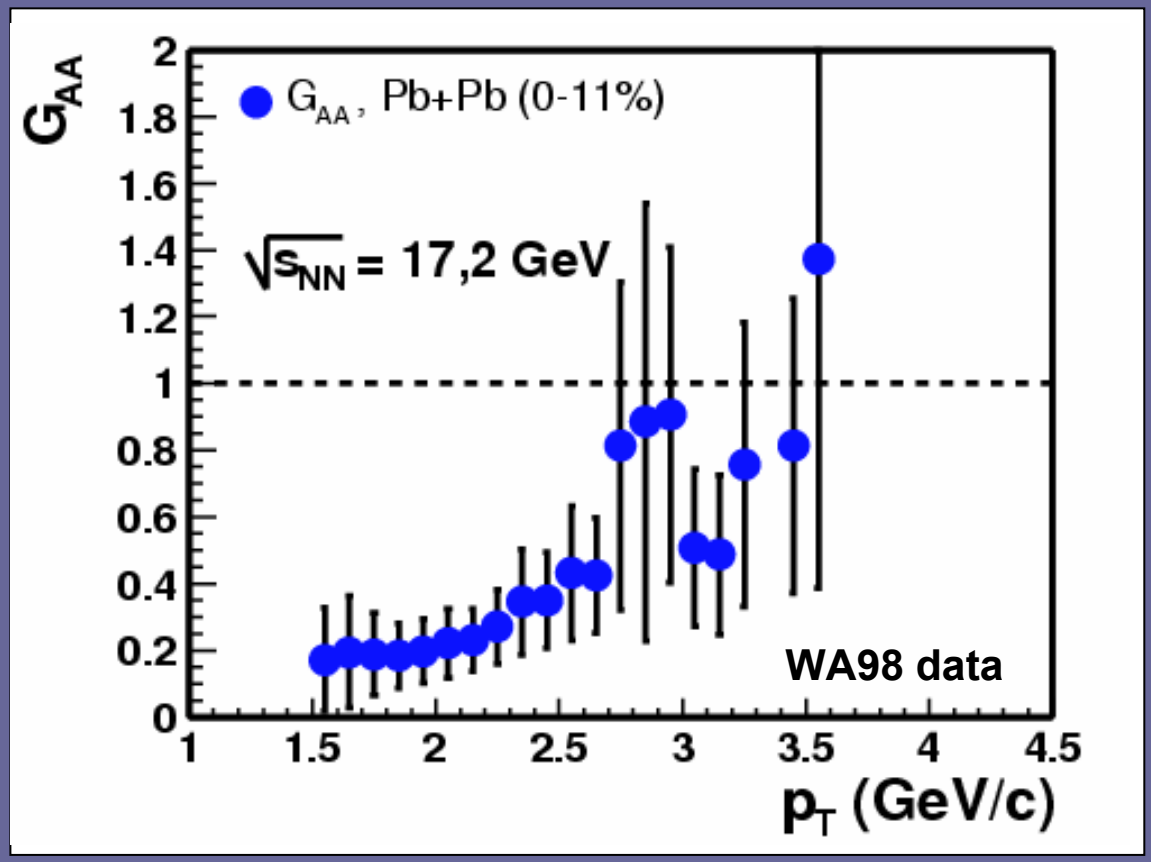
G_{AA} at CERN SPS



- G_{AA} consistent with 1 at high p_T (p_T >3 GeV/c)
- Moderate π^0 suppression also consistent with data

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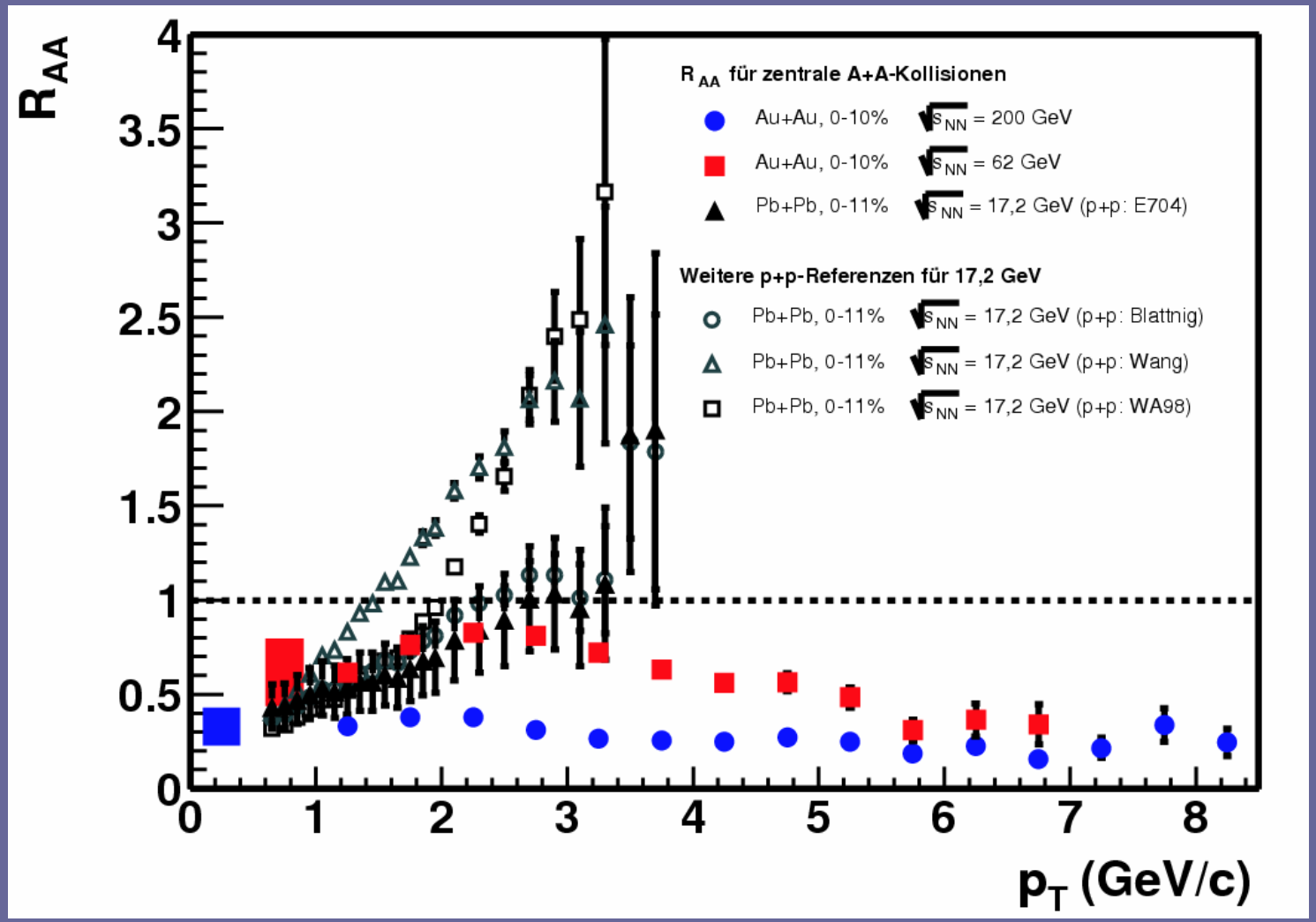
Summary

- Pb+Pb at CERN SPS:
  Direct photon signal consistent with QGP scenario, however, models without QGP are also able to explain the data

- Au+Au at RHIC:
  Direct photon signal observed at high p_T confirms N_{coll} scaling for hard processes and supports explanation of pion suppression as final state effect

Backup Slides

R_{AA} for Different Energies



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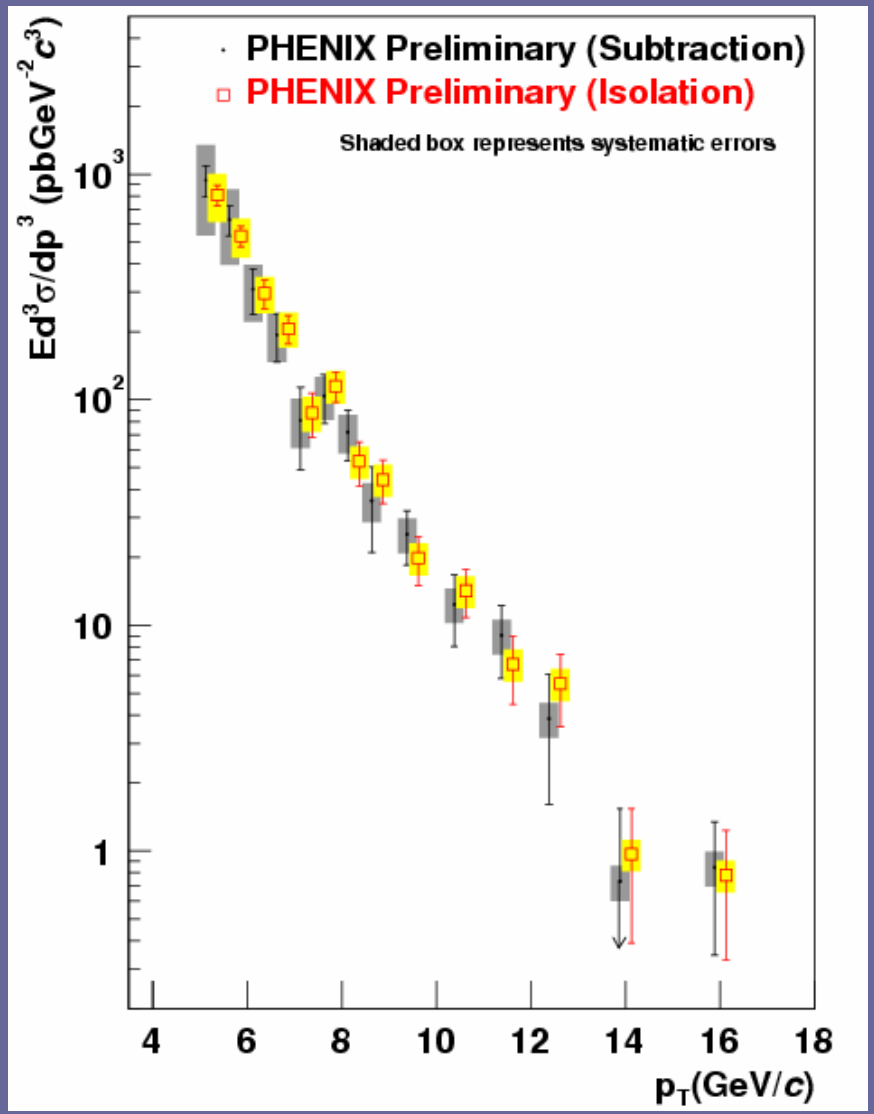
p+p Direct Photons: With and Without Isolation Cut

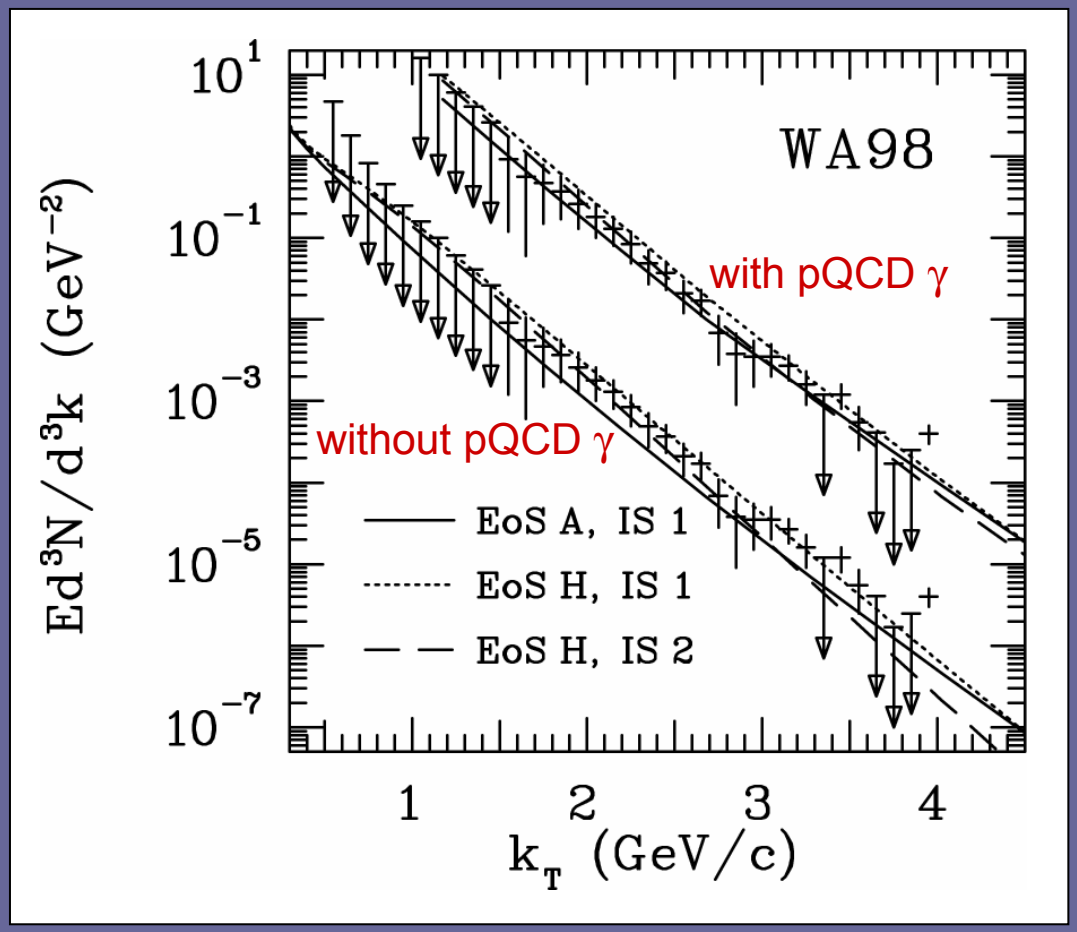


- No correction for direct photon loss due to isolation cut
- Nevertheless, no difference between cross section with and without isolation cut

Klaus Reygers, Hard Probes 2004

WA98 Interpretation: QGP or HG ?

Huovinen et al., Nucl. Phys. A 650 (227) 1999



- Hydro-calculations with different initial conditions
- EoS A:
  - QGP+HG (T_c = 165 MeV)
  - T_i = 255 MeV
- EoS H:
  - HG
  - T_i = 234 MeV