Photon Production in Heavy Ion Collisions

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@

RHIC & AGS Annual Users' Meeting

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Overview

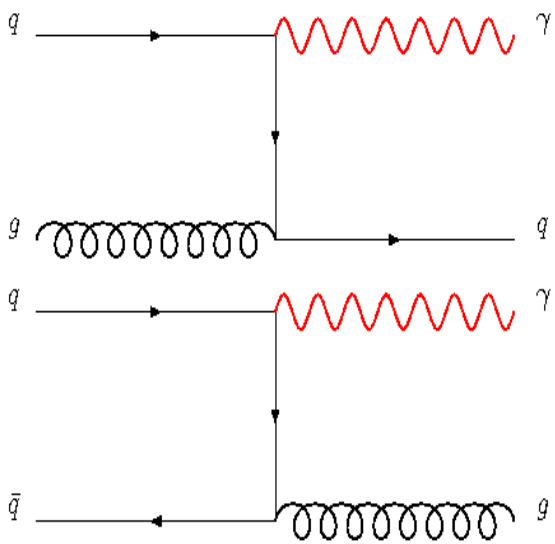
- Why photons?
- Initial hard direct photons
- Thermal photons
  - Hadronic and partonic emission
- Photons related to jet energy loss
  - Jet bremsstrahlung, conversion and fragmentation
- Tagging jets with photons

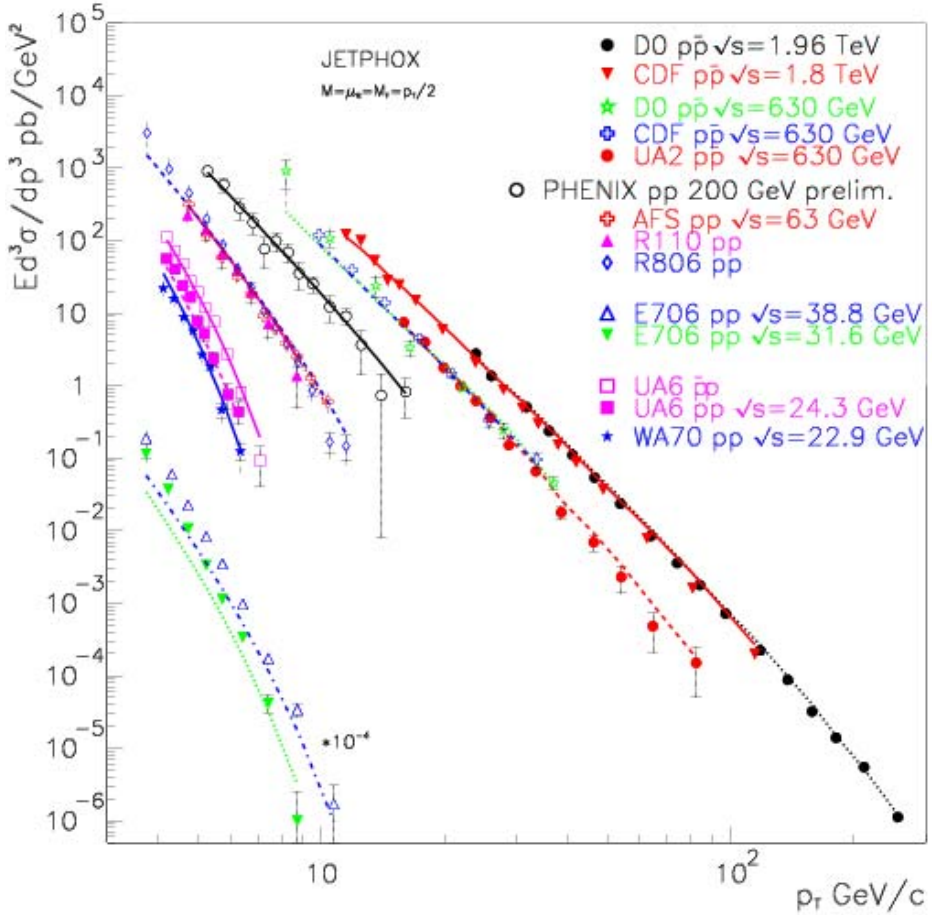
Photons

- **Interact only electro-magnetically $\alpha_{EM} \ll \alpha_s$**
  - **Small production rate**
  - **Large mean free path, leave the interaction zone untouched**
- **Have the potential to probe the highly excited matter**
  - **Low p_T photons: carry information about early QGP**
  - **High p_T photons: important for understanding jet quenching**
- **Emitted throughout the entire history**
  - **Need a thorough understanding of signals as well as the background**
- **From rate to spectra: integrate over space-time evolution of the system**
  - **Need a reliable evolution model of the fireball: hydrodynamics**

Initial hard direct photons

- **Produced from early collisions of partons from two nuclei**



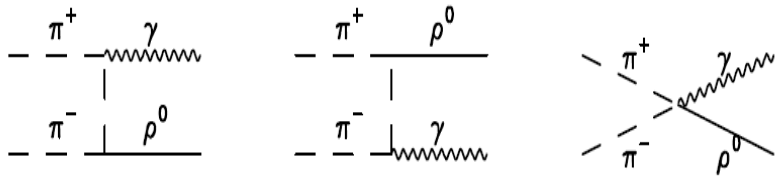


- **Data in p+p collisions well described by NLO calculations**

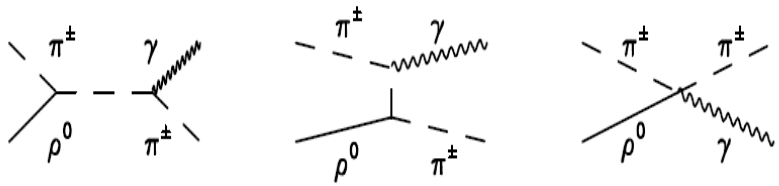
- Aurenche, Fontannaz,Guillet, Pilon and Werlen, PRD, 2006
- See also Gordon, Vogelsang, PRD, 1993; 1994

Photon emission from HG

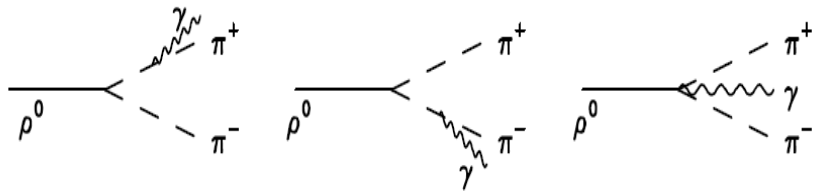
- **A thermal ensemble of hadrons produced in HIC**



- **Use effective / phenomenological Lagrangians**



- **Calculate the differential photon emission rates in kinetic theory**



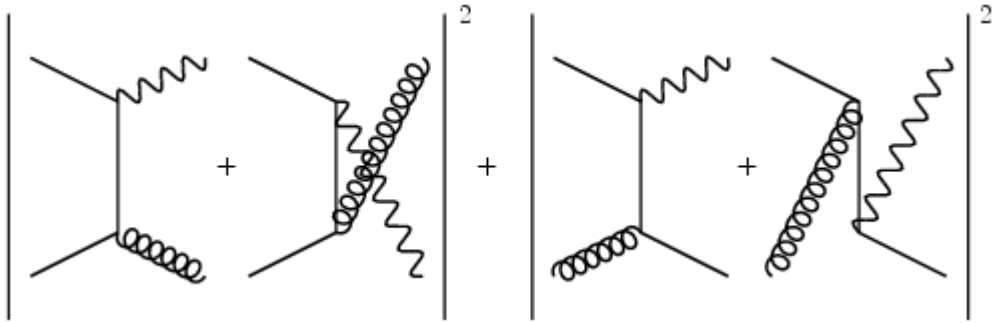
- **Strange mesons, baryons**

- Kapusta, Lichard and Seibert, PRD, 1991; Song, PRC, 1993; Rapp, PRC, 1999; Steffen, PLB, 2001; Srivastava, Sinha, PRC, 2001, Renk, PRC, 2003; Turbide, Rapp, Gale, PRC, 2004

……

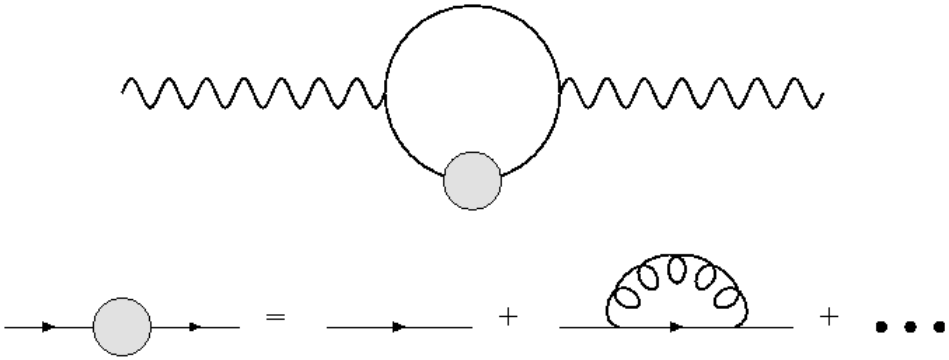
Photons from thermal QGP

- **pQCD calculation at leading order, infrared singularity for soft momentum transfer**



- McLerran and Toimela, PRD, 1985
- Kajantie, Kapusta, McLerran and Mekjian, PRD, 1986

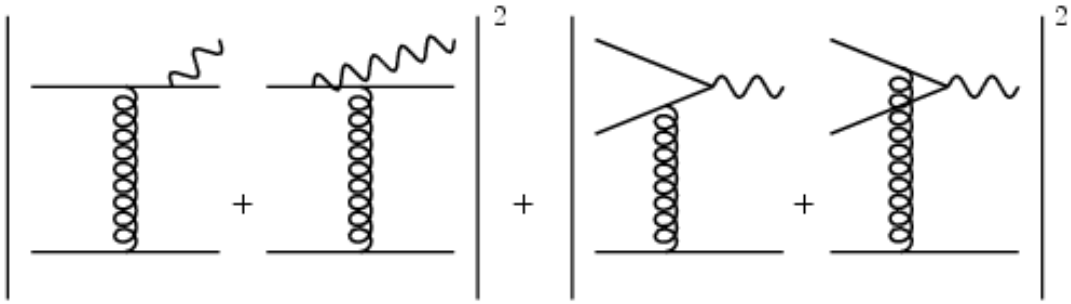
- **Divergence circumvented by Hard Thermal Loop (HTL) resummation**



- Braaten and Pisarski, NPB, 1990
- Kapusta, Lichard and Seibert, PRD 1991; 1993

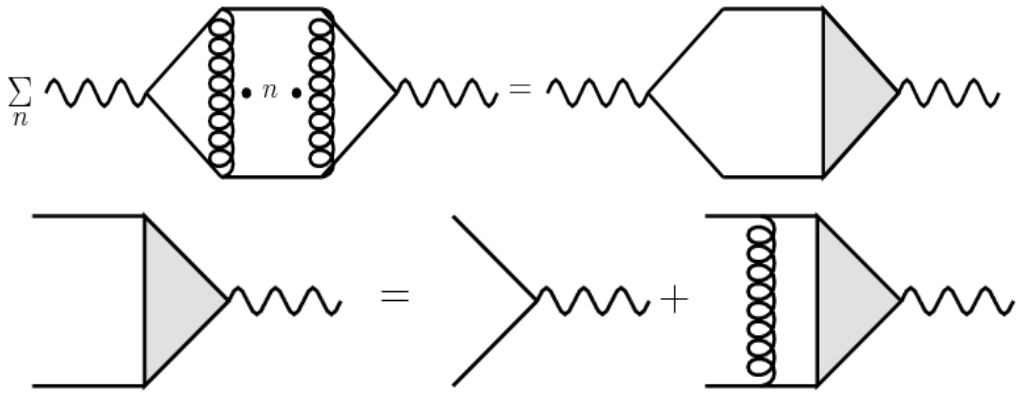
Photons from thermal QGP

- **Collinear enhancement makes 2→3 processes leading order as well**



- Aurenche, Gelis, Kobes and Zaraket, PRD, 1998

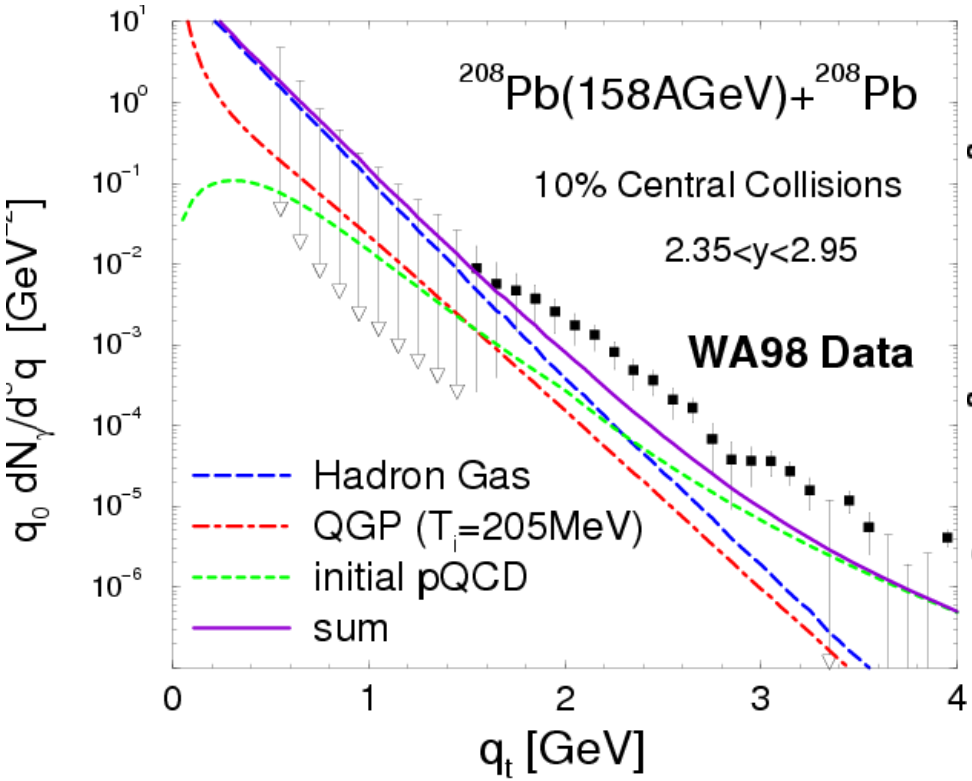
- **Complete leading order photon emission rate by AMY (LPM effect incorporated)**



- AMY(Arnold, Moore and Yaffe), JHEP, 2001; 2001; 2002.

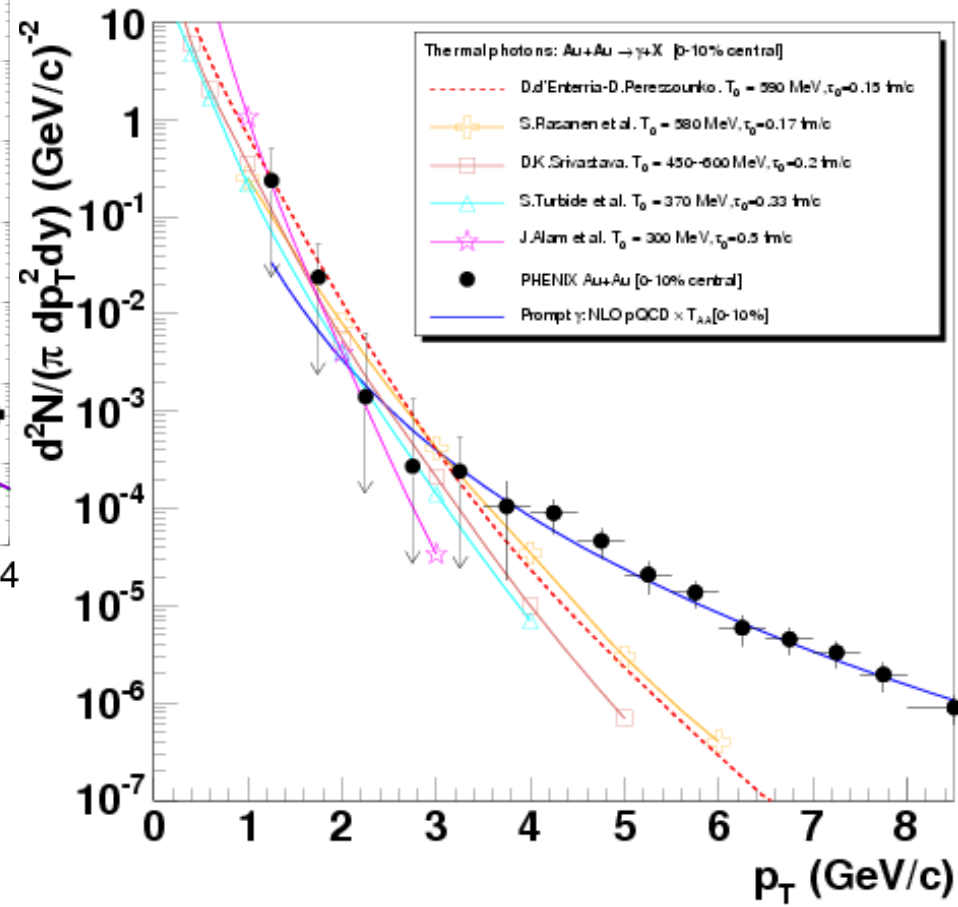
- **Can be expressed as a solution of a linear integral Eq.**

Photons so far



- Turbide, Rapp, Gale, PRC, 2004

- **Low p_T dominated by thermal sources**



- **Large p_T dominated by initial hard scatterings**

- d'Enterria, Peressounko, EPJC, 2006

More photon sources!

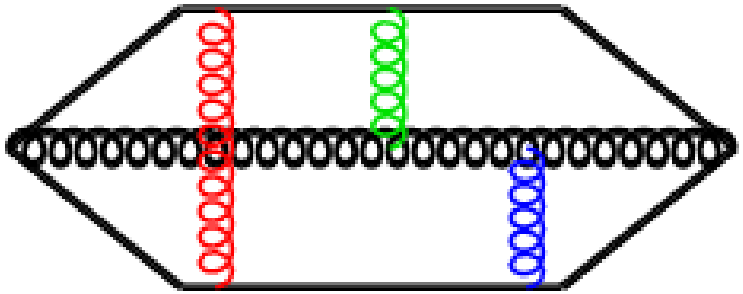
- **Sources that are not purely thermal, nor purely hard**

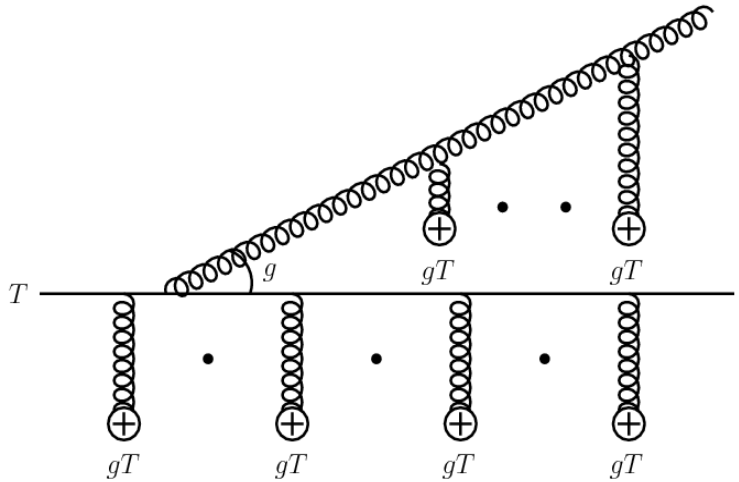
- **How is photon emission connected to jet energy loss?**
  - **Photons produced directly from final state interaction between jets and medium**
  - **Jets that fragment into photons in vacuum already lost energy during traversing medium**

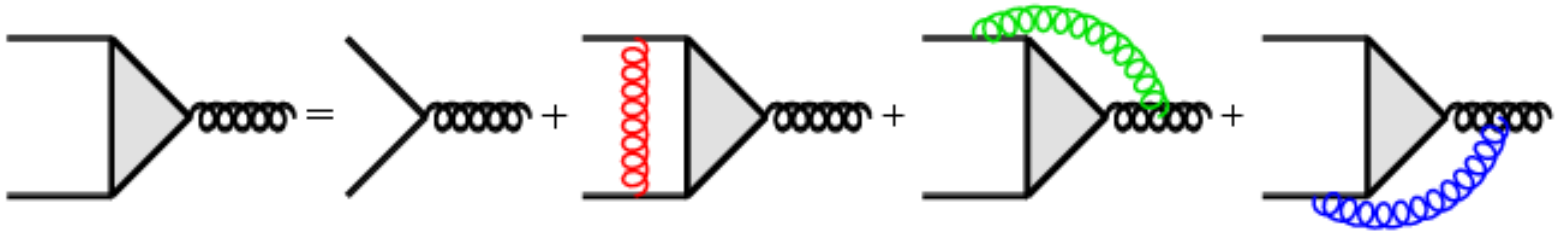
- **Photon production cannot be treated separately**
  - **Need to understand the energy loss of jet in the medium**
  - **Another constraint on jet energy loss models!**

Connecting jet Eloss & EM signal

- **Continue to work in finite temperature field theory**
- **AMY formalism** (Arnold, Moore and Yaffe, JHEP, 2001; 2001; 2002.)
  - **The induced collinear emission of both gluons and photons are treated together**
  - **Complete leading order result**







Evolution of parton distributions

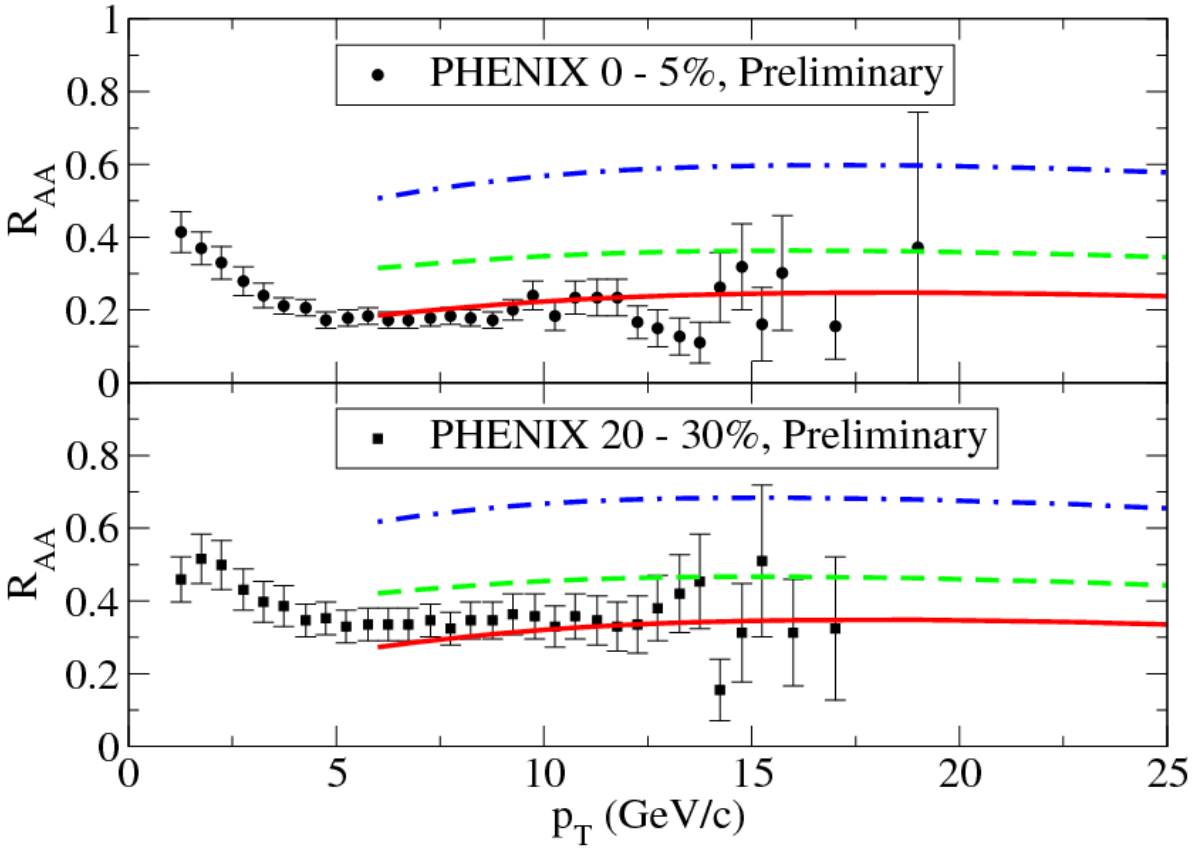
$$\frac{dP_q(p)}{dt} = \int_k P_q(p+k)\frac{d\Gamma^q_{qg}(p+k,k)}{dkdt} - P_q(p)\frac{d\Gamma^q_{qg}(p,k)}{dkdt} + 2P_g(p+k)\frac{d\Gamma^g_{q\bar{q}}(p+k,k)}{dkdt}$$

$$\frac{dP_g(p)}{dt} = \int_k P_q(p+k)\frac{d\Gamma^q_{qg}(p+k,p)}{dkdt} + P_g(p+k)\frac{d\Gamma^g_{gg}(p+k,k)}{dkdt} - P_g(p)\left(\frac{d\Gamma^g_{q\bar{q}}(p,k)}{dkdt} + \frac{d\Gamma^g_{gg}(p,k)}{dkdt}\Theta(2k-p)\right)$$

- **Evolve entire parton distribution**
- **Include a complete set of parton splitting processes**
- **Include gluon absorption and quark-anti-quark annihilation**
- **Keep track of subsequent evolutions of daughters**
- **Collisional Eloss also incorporated**

- Qin, Ruppert, Gale, Jeon, Moore and Mustafa, PRL, 2008
- Qin, Ruppert, Turbide, Gale, Nonaka and Bass, PRC, 2007
- Turbide, Gale, Jeon and Moore, PRC, 2005

R_{AA} @ RHIC



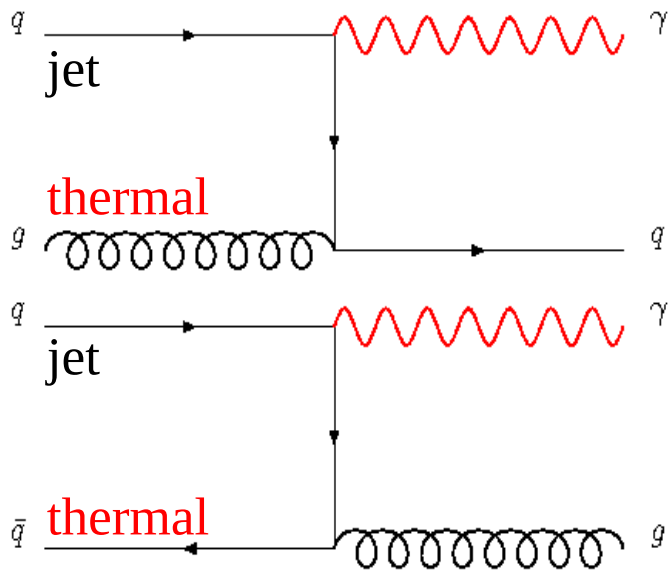
Red: tot. Green: rad. Blue: coll.

- **Jet-medium interaction: AMY (rad. + coll.)**
- **Initial jet spectra: pQCD**
- **Initial collision geometry: Glauber model**
- **Medium evolution: 3D hydrodynamics**

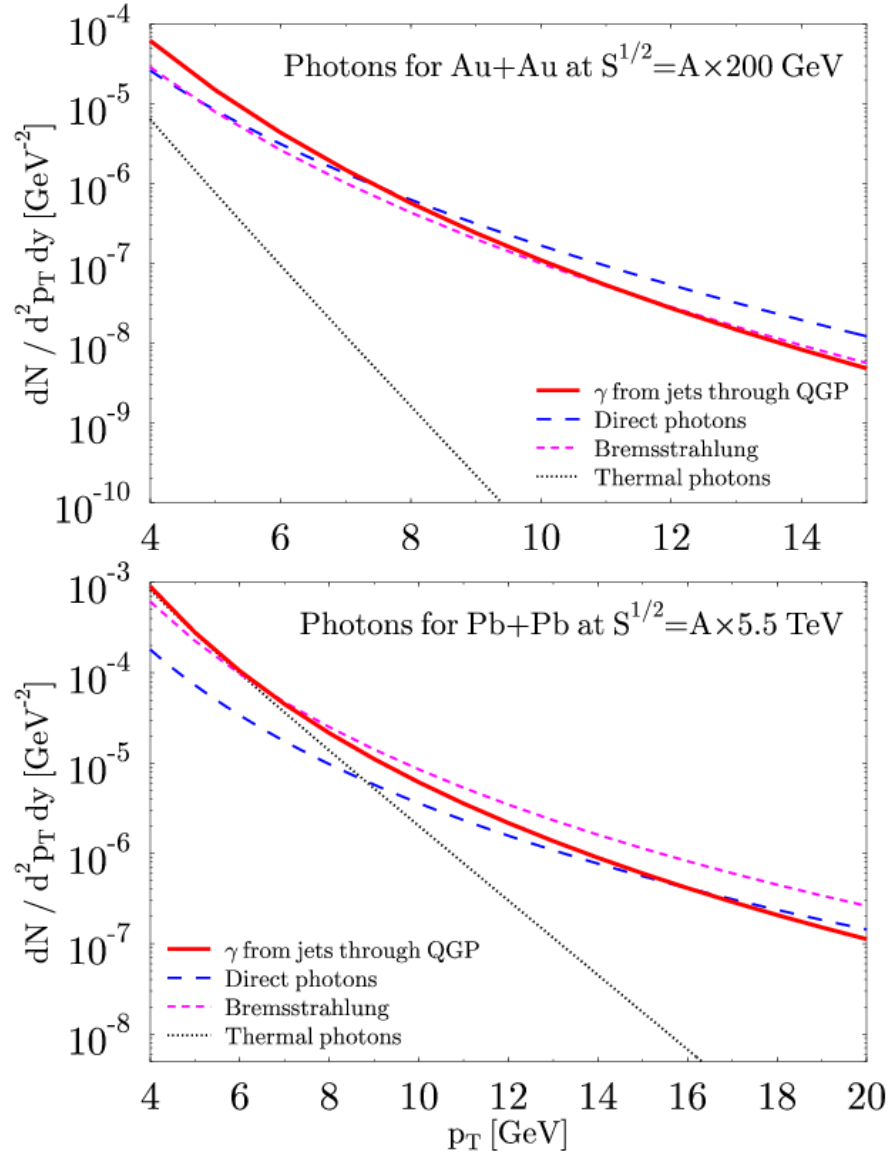
- Qin, Ruppert, Gale, Jeon, Moore and Mustafa, PRL, 2008

Photons converted from jets

- **The first check of jet-conversion photons**



- **Jet energy loss not yet included (Eloss before jet conversion!)**



- Fries, Muller, Srivastava, PRL, 2003

Include jet Eloss related photons

- **Photons from direct jet-medium interaction**

$$\frac{dP_\gamma^{\rm JM}(E,t)}{dt} = \int d\omega P_{q\bar{q}}(E+\omega,t)\frac{d\Gamma_{q\to\gamma}^{\rm JM}(E+\omega,\omega)}{d\omega dt}.$$

$$d\Gamma_{q\to\gamma}^{\rm JM}/d\omega dt = d\Gamma_{q\to\gamma}^{\rm brem}/d\omega dt + d\Gamma_{q\to\gamma}^{\rm conv}/d\omega dt.$$

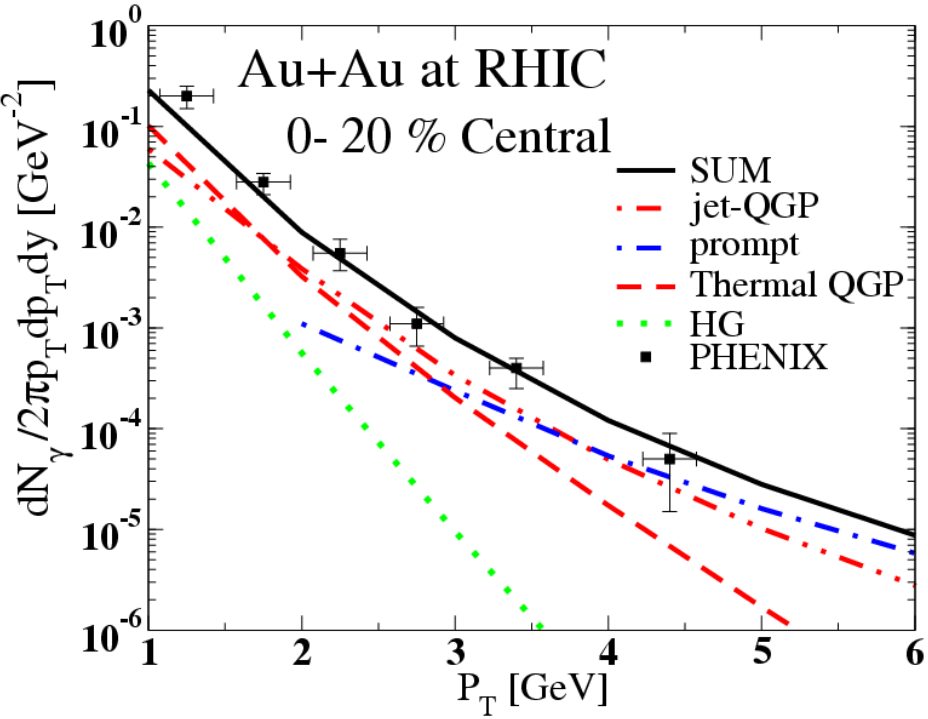
  - **Bremsstrahlung: emission rates from AMY**
  - **Jet-photon conversion: from local photon production rate**

$$\frac{d\Gamma_{q\to\gamma}^{\rm conv}(E,\omega)}{d\omega dt} = \sum_f \left(\frac{e_f}{e}\right)^2 \frac{2\pi\alpha_e\alpha_s T^2}{3E}\left(\frac{1}{2}\ln\frac{ET}{m_q^2} + C_{2\to 2}(E/T)\right)\delta(\omega).$$

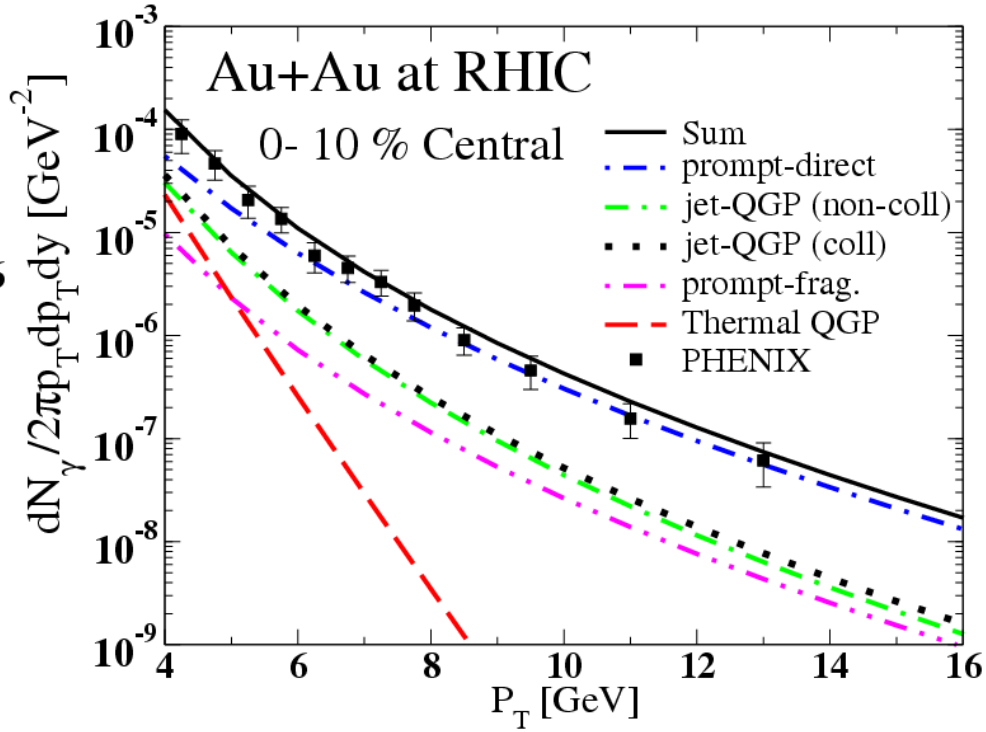
- **Photons from fragmenting jets after traversing medium**
  - **Initial jets (pQCD) + Jet Eloss (AMY) + Photon FF**

- Qin, Ruppert, Gale, Jeon, Moore, EPJC, 2008; in prep.
- Also Turbide, Gale, Frodermann, Heinz, PRC, 2008

Photons @ RHIC



- **Same hydrodynamical model**
- **No additional parameter in photon calculation**



- Turbide, Gale, Frodermann, Heinz, PRC, 2008
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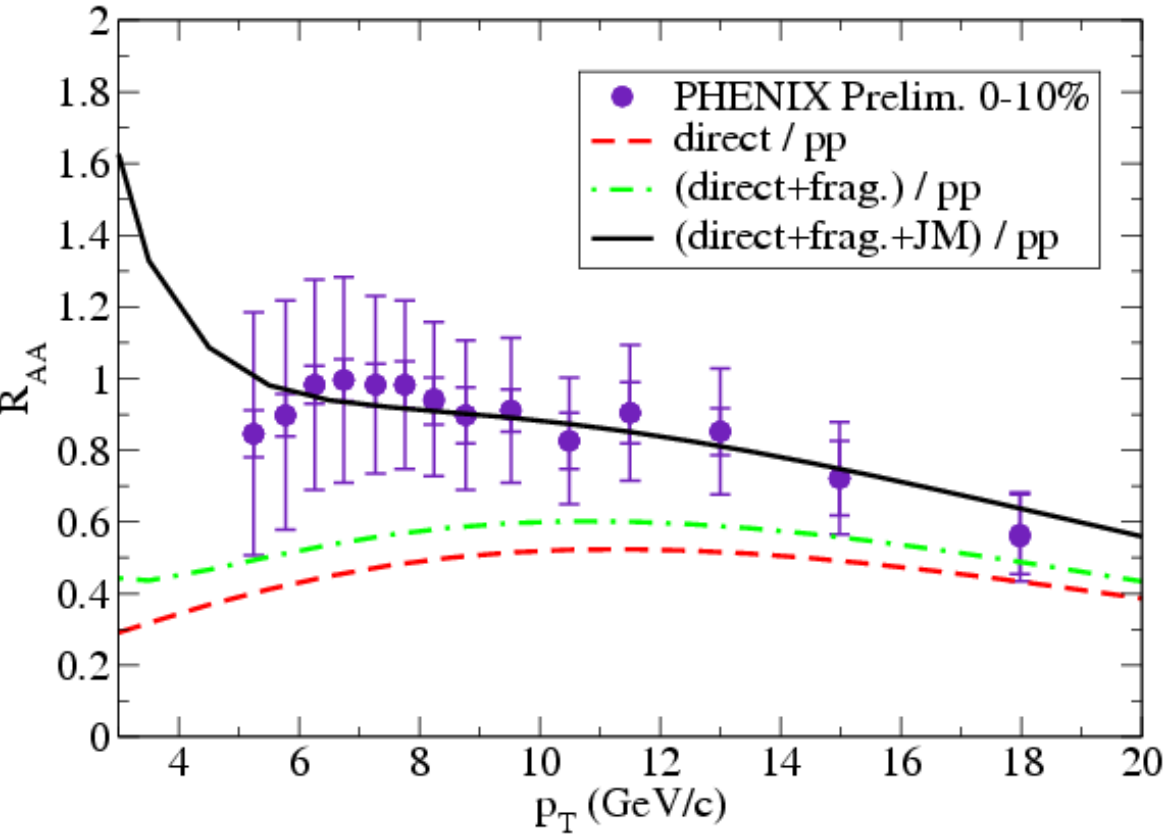
Photon R_{AA} @ RHIC

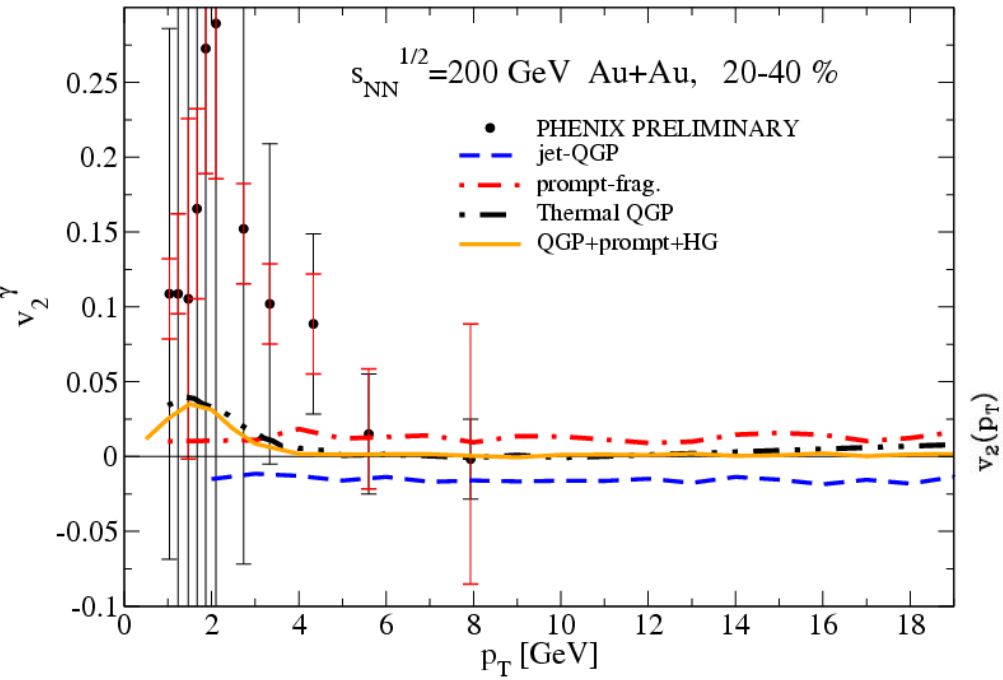


- **Low p_T dominated by thermal sources**
- **High p_T dominated by hard photons, isospin and initial nuclear effect**
- **Important contribution from Jet-medium photons**

- Qin, Ruppert, Gale, Jeon, Moore, EPJC, 2008; in prep.
- Turbide, Gale, Frodermann, Heinz, PRC, 2008
- See also: Arleo, JHEP, 2006; Vitev, Zhang, PLB, 2008, Liu, Hirano, Werner, Zhu, PRC, 2009

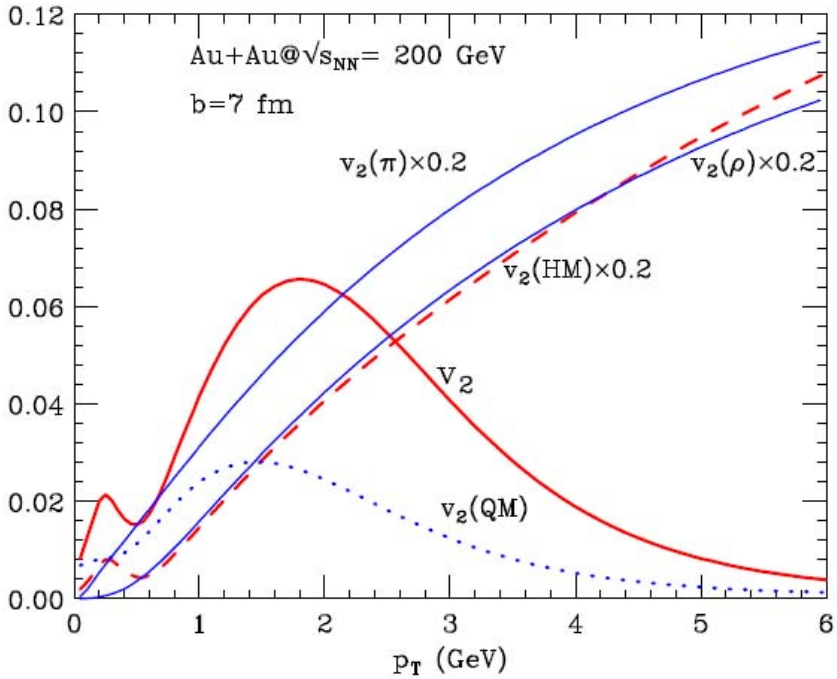
Photon v_2 @ RHIC

- **Negative contribution to v_2 from jet-medium photons**
  (Turbide, Gale, Fries, PRL, 2006)



- Turbide, Gale, Frodermann, Heinz, PRC, 2008
- **Isolation cuts might restore such sensitivity**

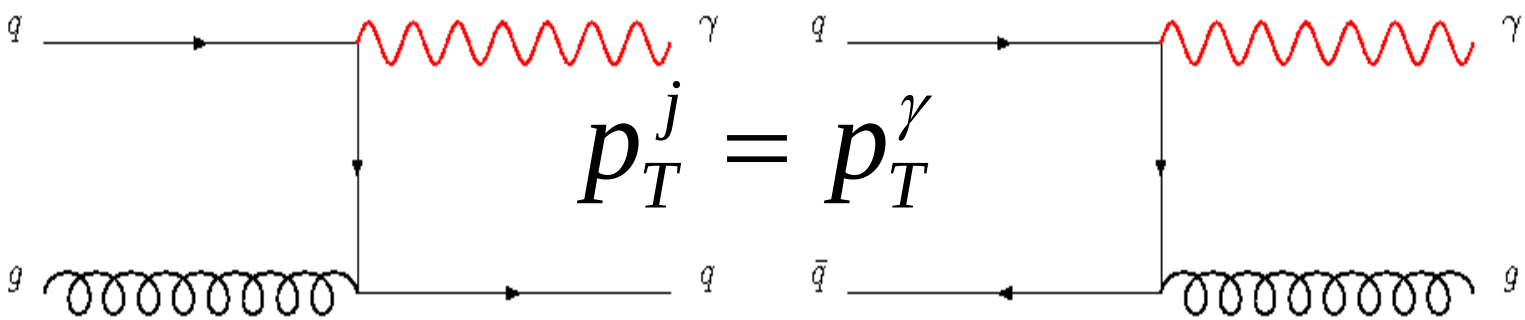
- **Thermal photon v_2 displays a transition from a behavior of hadronic matter to partonic matter**



- Charterjee, Frodermann, Heinz, Srivastava, PRL, 2006

Tagging jets with photons

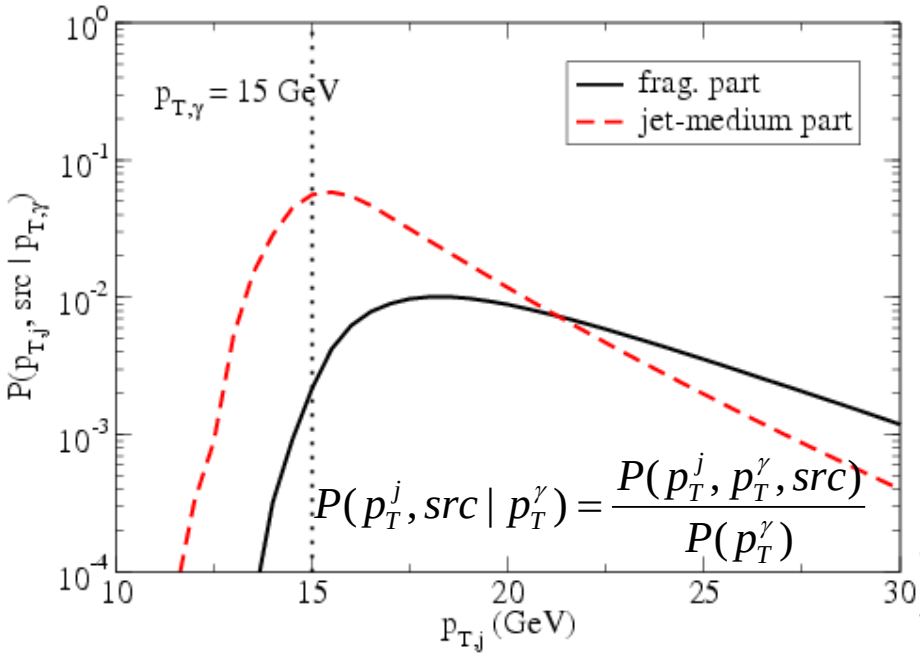
- **High p_T photons are dominated by early hard collisions**
- **At LO, the exact correlation between photon and recoiling parton allows us to directly measure the medium-modified FF** (Wang, Huang, Sarcevic, PRL,1996)



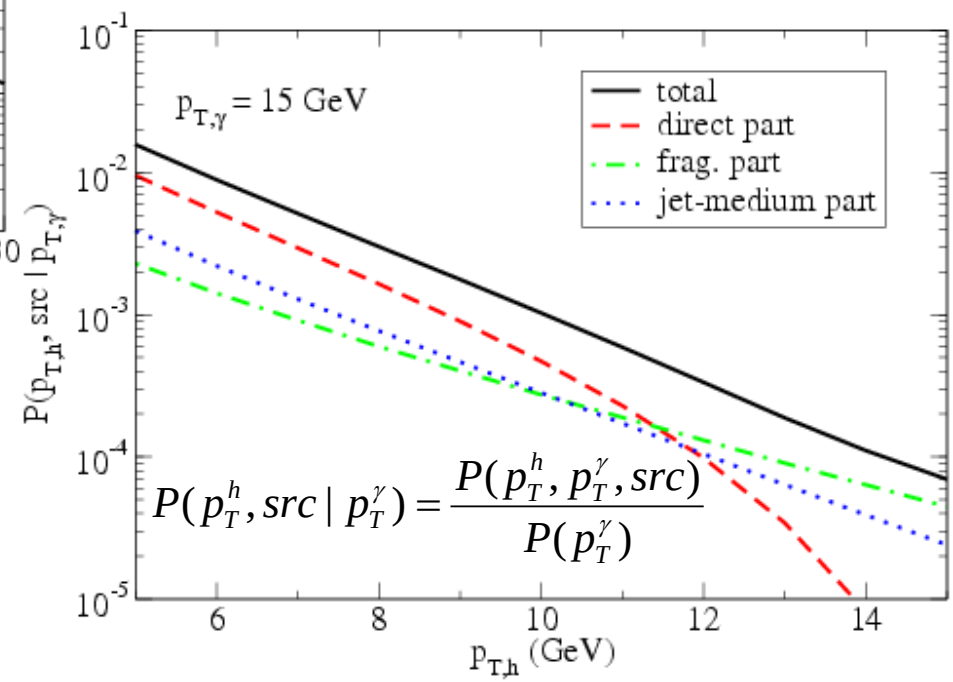
$$p_T^j = p_T^\gamma$$

- **A clean probe of jet E-loss?**
- **Additional photon sources modify the profiles of the photon-triggered jets!**

γ-triggered jets @ RHIC



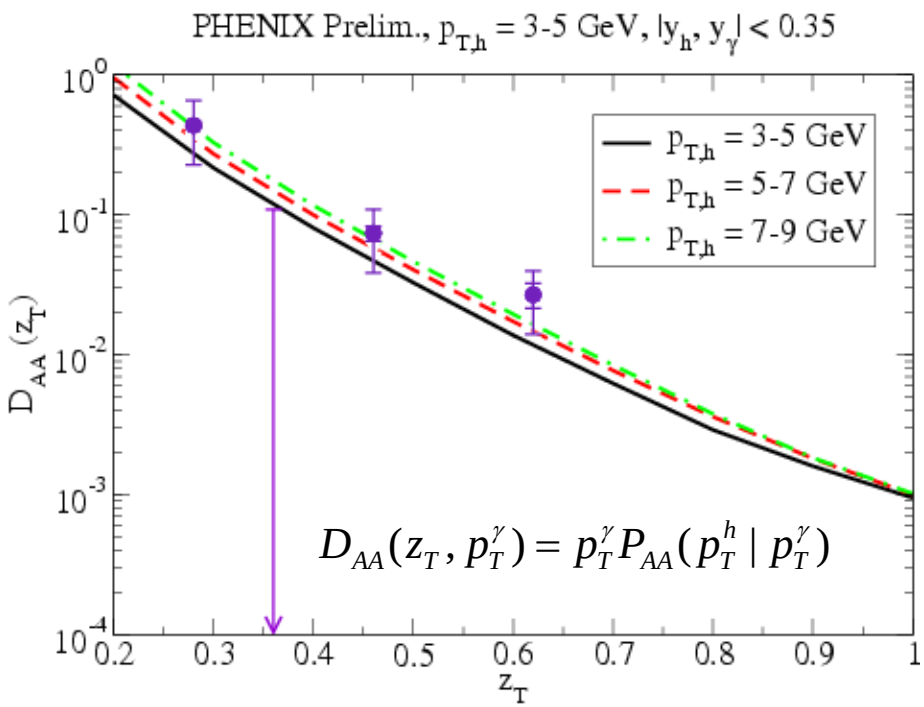
- **Large fraction of hadrons at high p_T come from jets tagged by jet-medium photons and frag. photons**

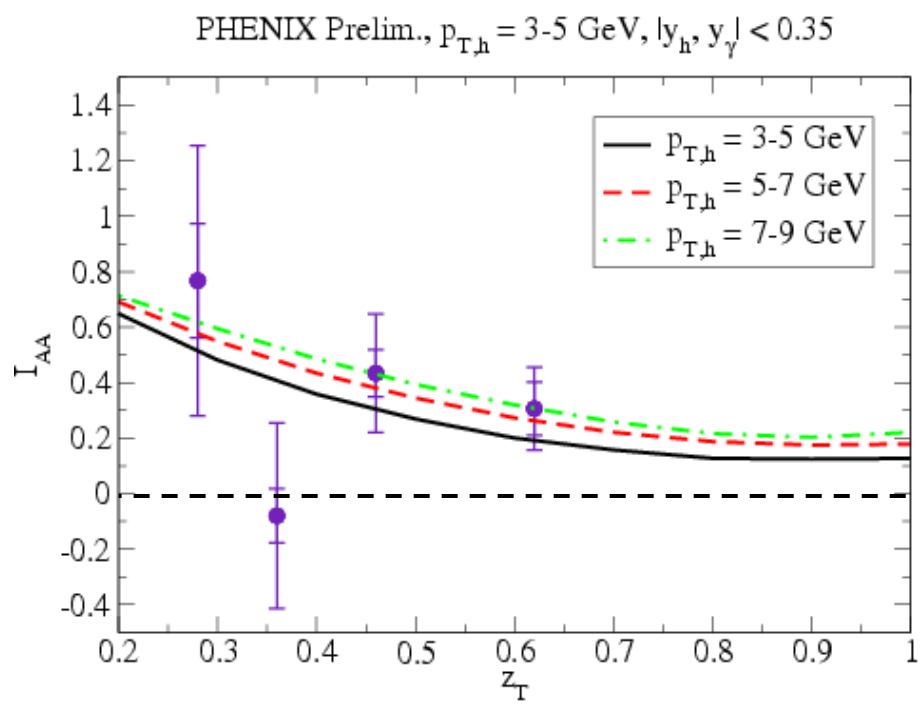


- **The initial jets at production time tend to have more energy than the triggered photon**

- Qin, Ruppert, Gale, Jeon, Moore, EPJC 2008

γ-h correlations @ RHIC



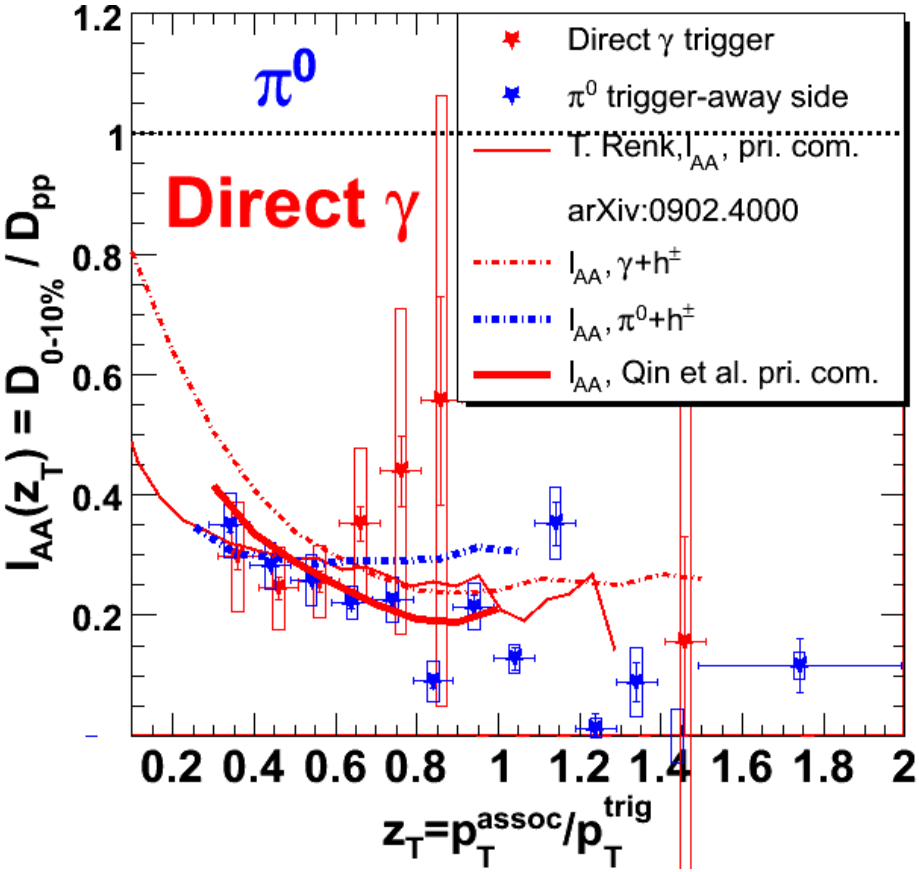


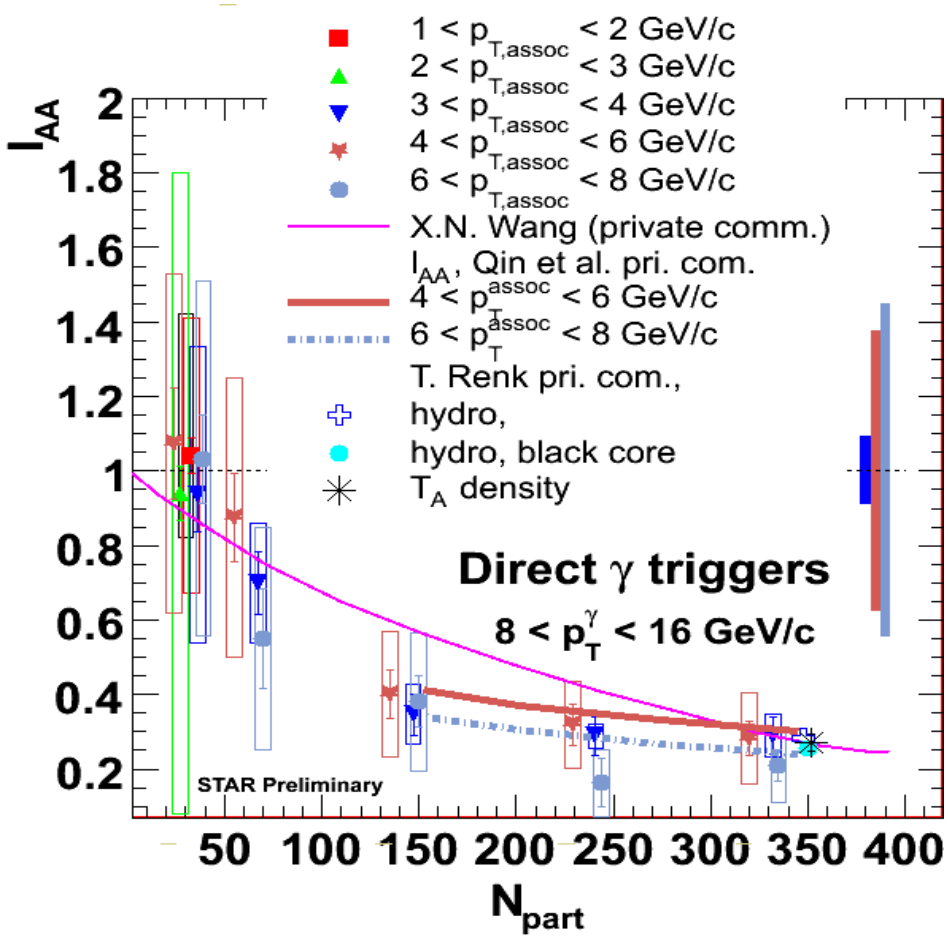
- **All hard photon sources included**
- **Both radiative and collisional jet Eloss**
- **Same hydrodynamical model**
- **A flattened I_{AA} is predicted at high z_T due to jet Eloss related photons**

$$I_{AA} = \frac{P_{AA}(p_T^h \mid p_T^\gamma)}{P_{pp}(p_T^h \mid p_T^\gamma)} = \frac{D_{AA}(z_T, p_T^\gamma)}{D_{pp}(z_T, p_T^\gamma)}$$

- Qin, Ruppert, Gale, Jeon, Moore, in prep.
- Data points: PHENIX, 2009

γ-h correlations @ RHIC





- **Correlation measurements has good discriminative power**

- From A. Hamed's talk in QM2009

Summary on photons

- Remarkable success in both theory and experiment
- Rates and medium evolution models more quantitative
- Various direct photon sources well understood
- Connection to jet energy loss
- Additional resolution provided by tagging jets with photons
- A very significant tool at RHIC
- Much brighter at the LHC (up to 100GeV)