Gamma-jet correlations

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@

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BROOKHAVEN NATIONAL LABORATORY

Outline

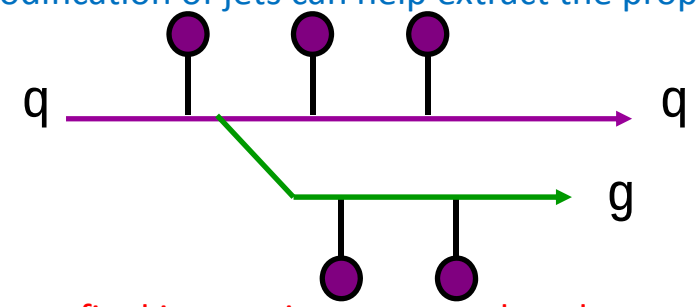
- Why gamma-jet?
- Jet energy loss
- Photon production
- Jet-photon correlations
- Summary

Probing medium with jets and photons

- **A strongly coupled, super hot and dense matter has been formed in high energy nuclear collisions.**

- Jets and photons are valuable probes: weak coupling, perturbative treatment applicable, well controlled in reference pp collisions

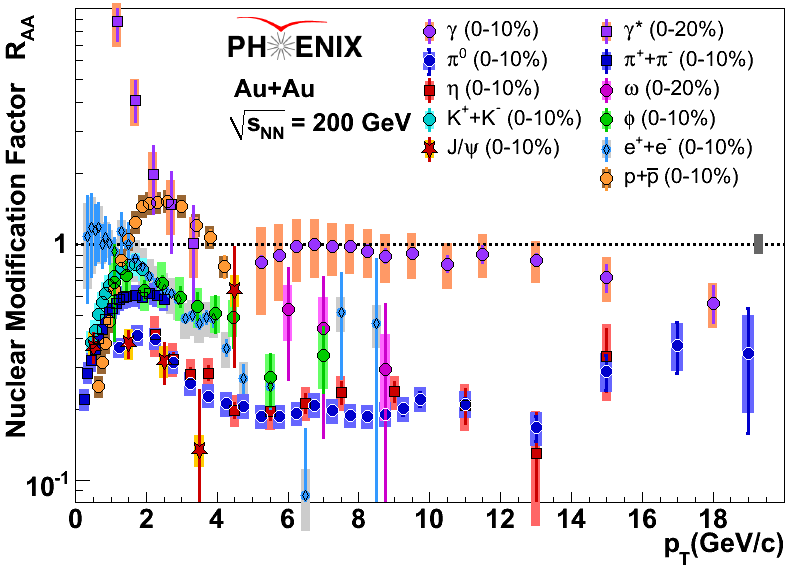
- High energy jets:
  - Interact with the medium and lose energy by induced radiation and elastic collisions
  - Studying medium modification of jets can help extract the properties of the dense medium

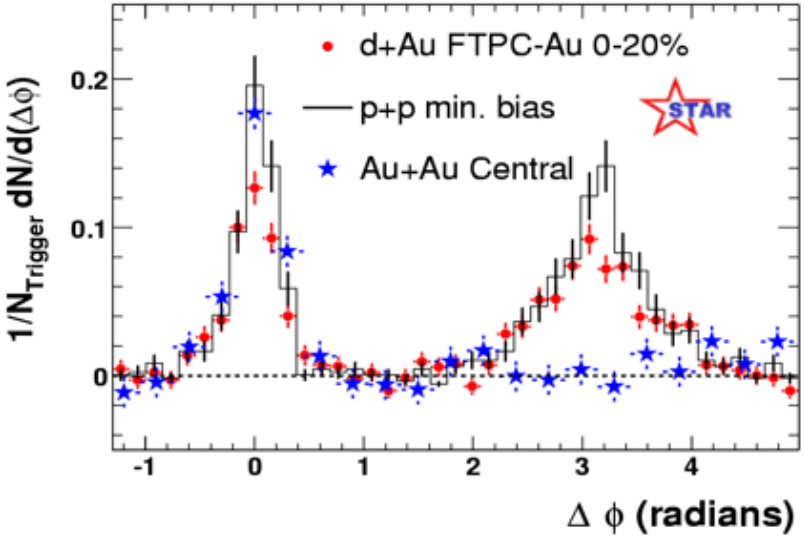


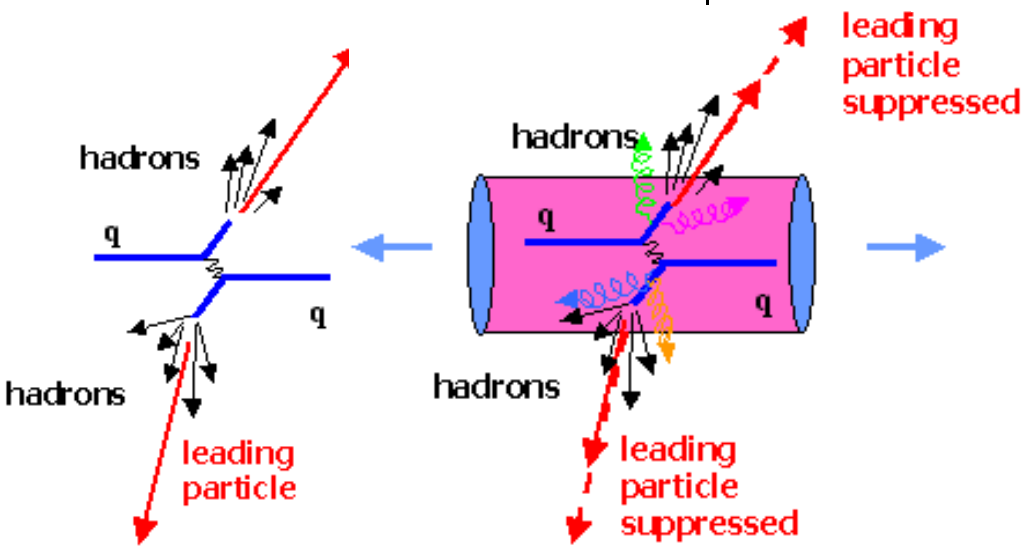
- Photons:
  - Long mean free path, no final interaction once produced
  - Carry directly the information of the medium at the time and place they are produced

$$\omega \frac{d^3R}{d^3k} = -\frac{g^{\mu\nu}}{(2\pi)^3} \mathrm{Im}\Pi^R_{\mu\nu}(k) \frac{1}{e^{\beta\omega}-1}$$

Remarkable results from RHIC





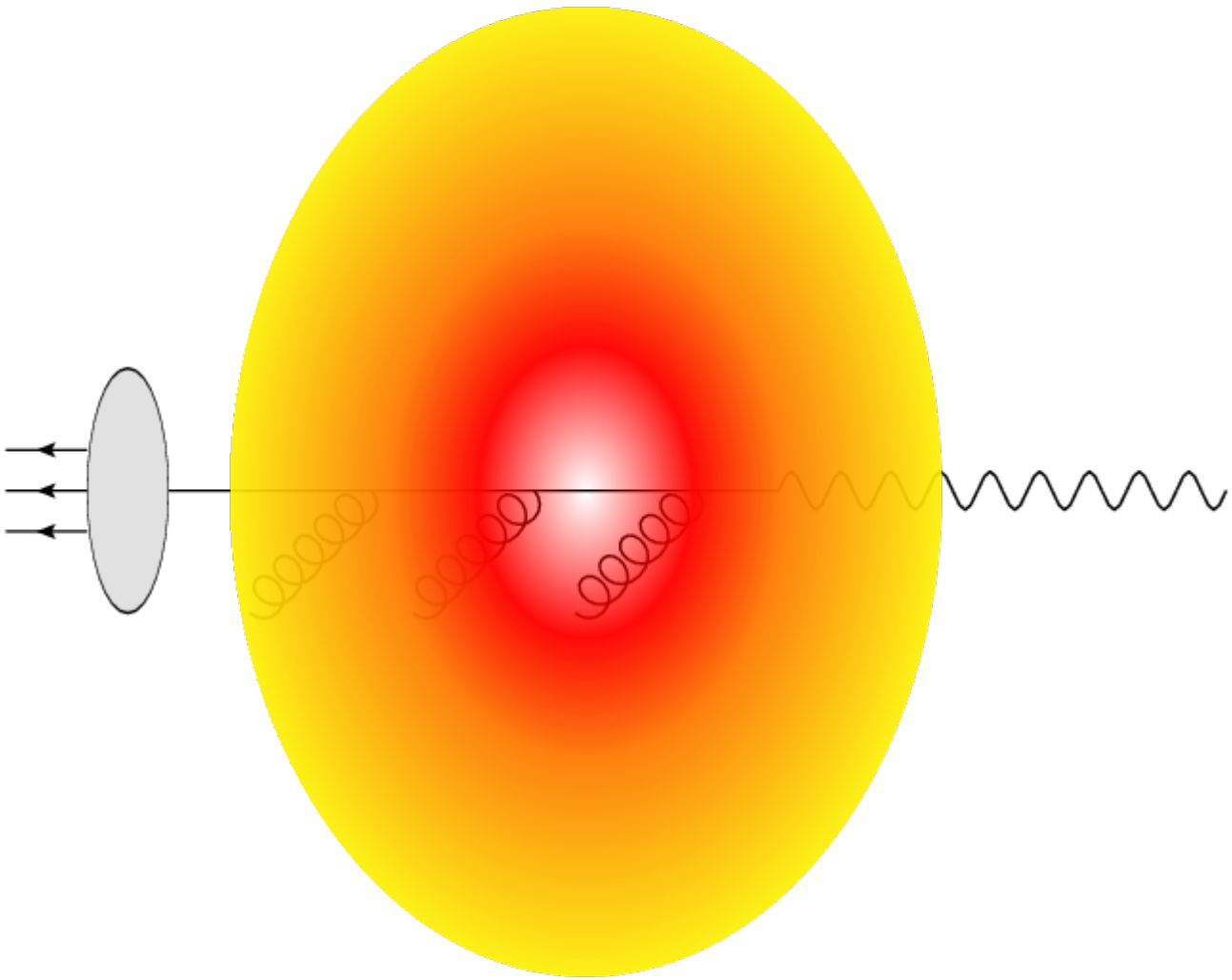


Evidence for partons energy loss due to interaction with hot and dense medium:

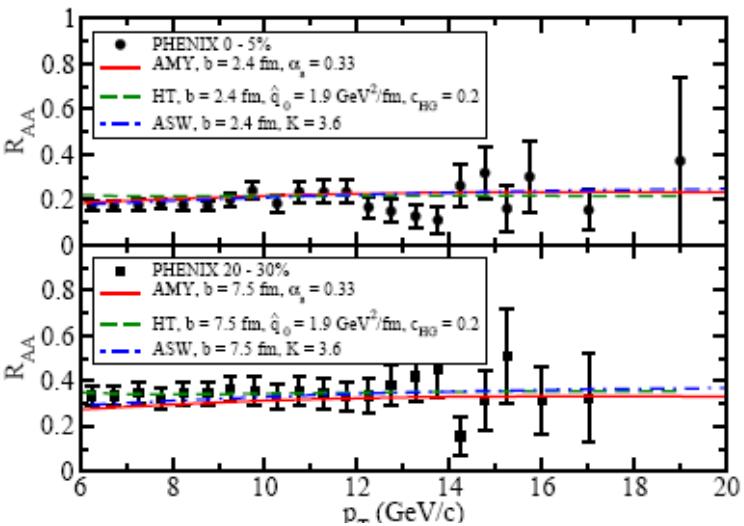
- Hadrons are suppressed in Au+Au, while photons are not

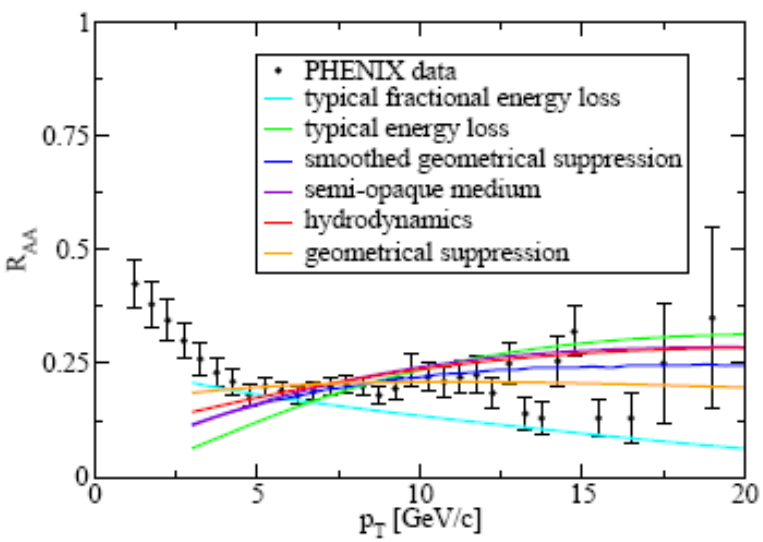
- No suppression for d+Au

Why gamma-jet correlations?



Limitations of R_{AA}





Single particle R_{AA} doesn't work: flat!!!

- Models with various underlying physics can describe the flat data

- Average over different production points (path lengths)

-A convolution of parton production and parton fragmentation

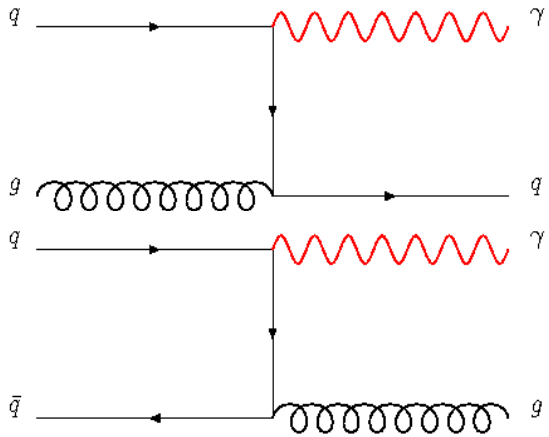
- The suppression of hadron with certain p_T involves partons with various p_T

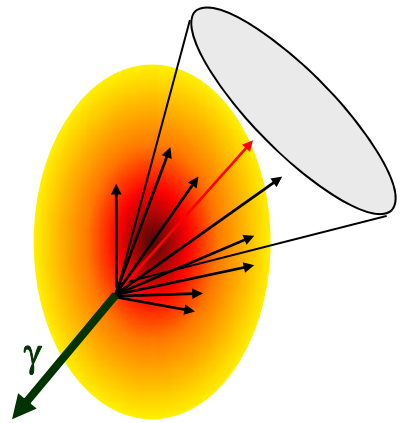
- need more differential observables to resolve the differences

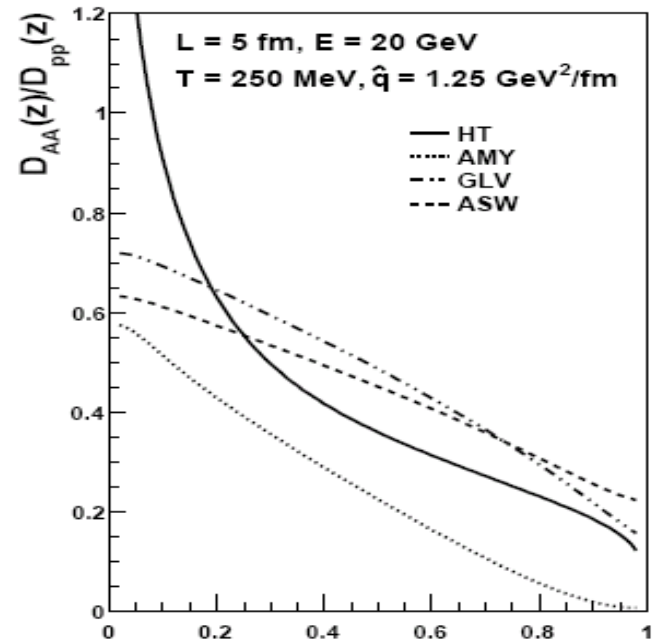
- To get medium modified FF => Ideal to fix parton p_T!

Bass, Gale, Majumder, Nonaka, GYQ, Renk, Ruppert, PRC, 2009
Renk, PRC, 2006

Gamma-jet tomography

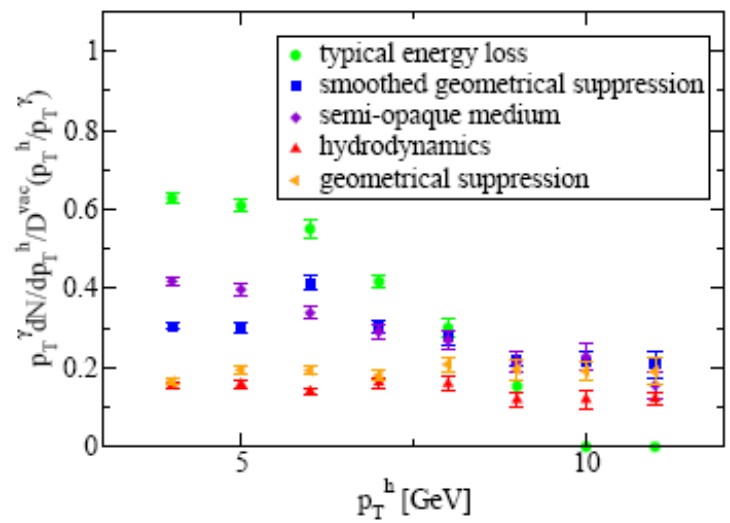






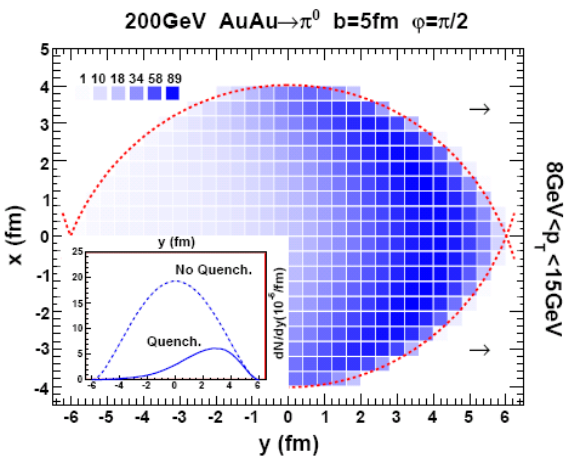
"Golden" channels dominate hard photon production: q+g->q+gamma, g+qbar->g+gamma

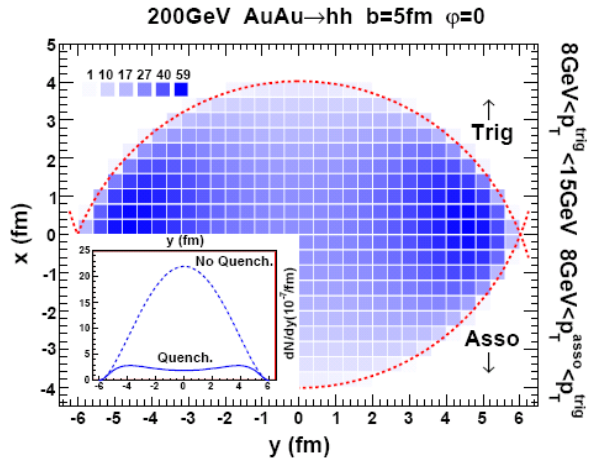
- Parton p_T determined by the trigger photon @ LO
- Medium-modified FF directly measured
- Potential to distinguish different E-loss models

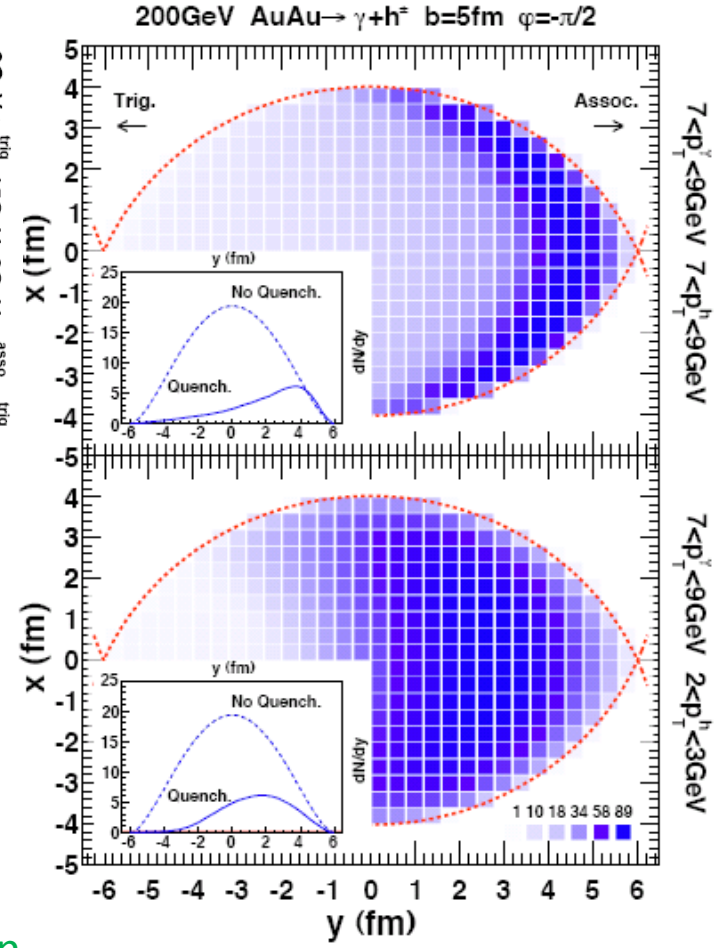


Wang, Zhang, Sarcevic, RRL, 2006
Renk, PRC, 2006
Majuder, Van Leeuwen, arXiv:1002.2206

Gamma-jet tomography







All three are averaged over different production points (need sensitivity to initial medium density)

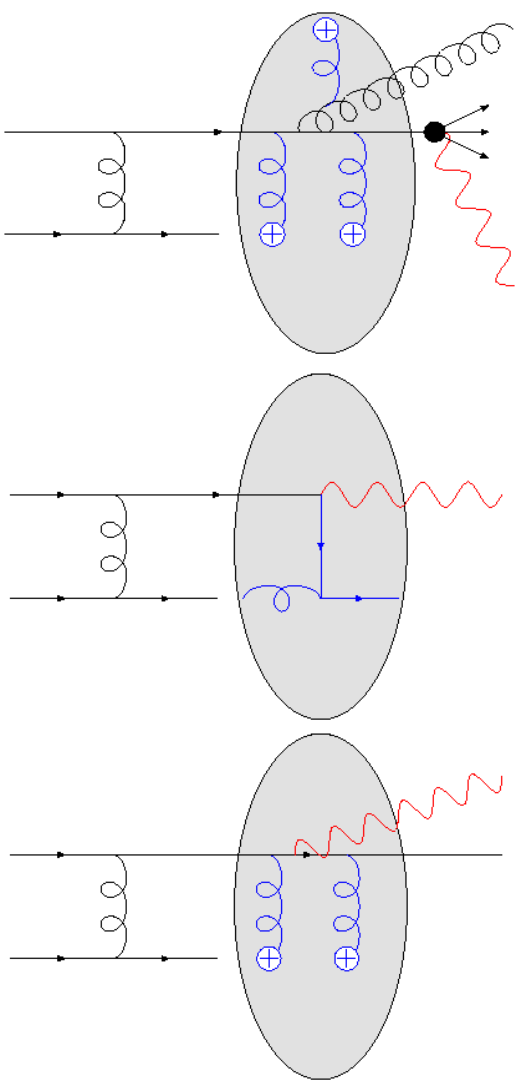
- Single hadron biased by surface emission, not good

- Di-hadron biased by tangential emission, a little better

- Gamma-hadron: high z_T dominated by surface emission, small z_T more evolved with volume emission, good

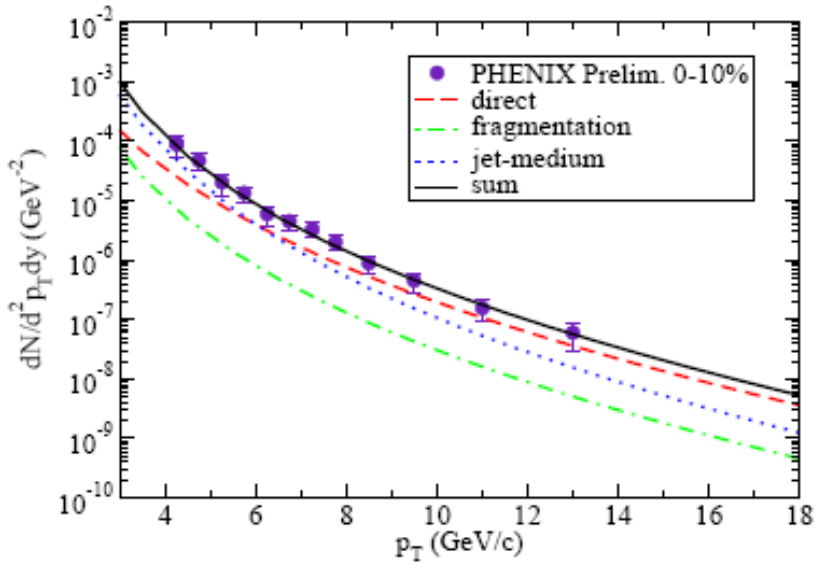
Zhang, Owens, Wang, Wang, PRL, 2008; 2009

What is more?



Except "golden" channels, photons can be produced during and after the passage of jets in the medium:

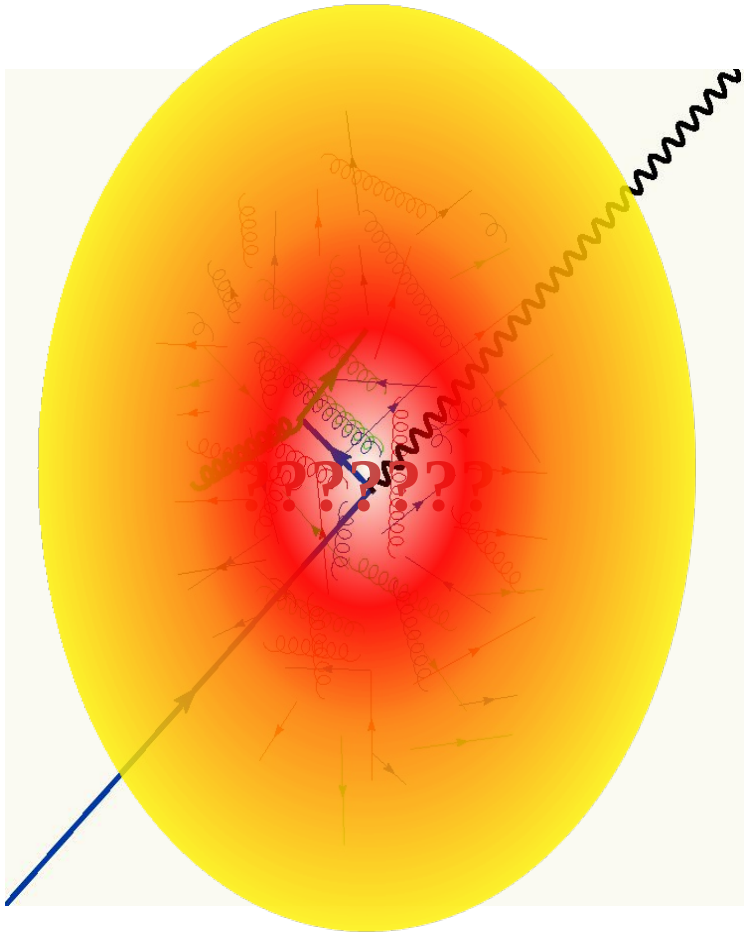
- jet-fragmentation photons
- jet-photon conversion
- induced photon radiation



GYQ, Ruppert, Gale, Jeon, Moore, PRC, 2009

Jet-initiated photon sources will change the shape of gamma-tagged jets (see later)

What needed for gamma-jet study?



- How jets are produced and interact with medium

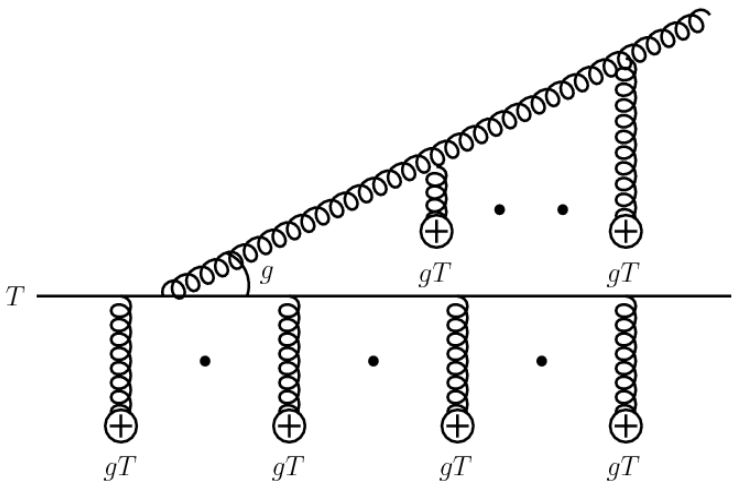
- How the fireball evolves in space-time?

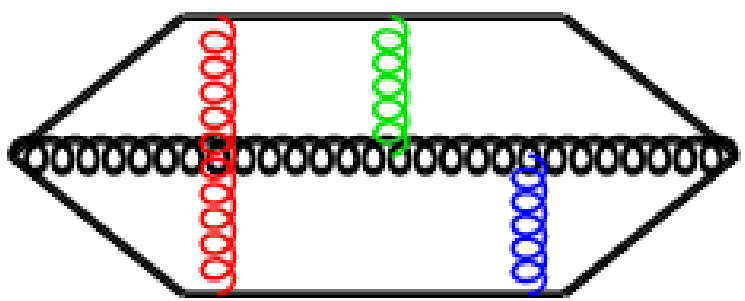
- How photons are produced (during the history of the fireball evolution)?

- Some photons are initiated by jets: photon production is another signature of jet energy loss

- Need a theory that can treat both jet E-loss and photon production together consistently

Connecting jet E-loss with EM



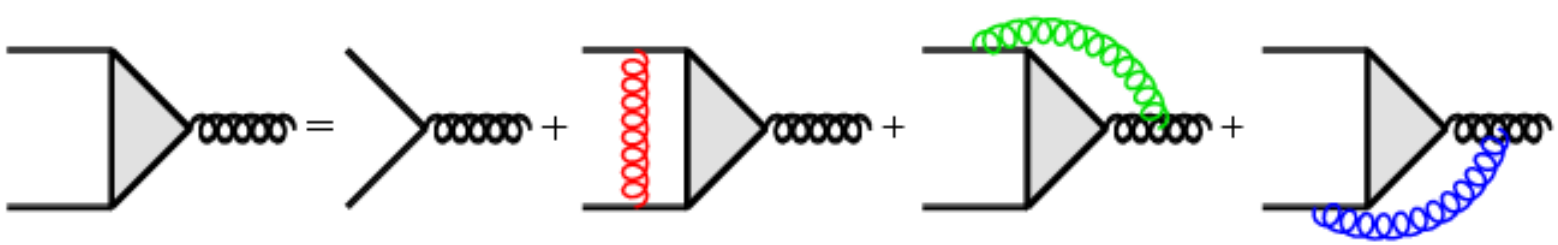


Finite temperature field theory: Complete leading order result!

- AMY formalism: The induced emissions of photons and gluons are treated together consistently

- Including elastic energy loss of jets and jet-photon conversion

AMY (Arnold, Moore, Yaffe), JHEP, 2001; 2001; 2002
GYQ, Ruppert, Gale, Jeon, Moore, Mustafa, PRL, 2008.
GYQ, Ruppert, Gale, Jeon, Moore , PRC, 2009



General idea of jet E-loss calculation

- Hadron production factorized into three pieces:

$$\sigma_{\text{hadron}} \sim \sigma_{\text{parton}} \otimes \text{parton evolution in medium} \otimes D_{\text{vacuum}}$$

- Medium modiffied FF defined as

$$\tilde{D}_{h/j}(z) = \sum_{j'} \int dp_{j'} \frac{z'}{z} P(p_{j'}|p_j) D_{h/j'}(z')$$

- Evolve jets in a set of coupled evolution equations

$$\frac{dP_j(E,t)}{dt} = \sum_{ab} \int d\omega \left[P_a(E+\omega,t) \frac{d\Gamma_{a\to j}(E+\omega,\omega)}{d\omega dt} - P_j(E,t) \frac{d\Gamma_{j\to b}(E,\omega)}{d\omega dt} \right]$$

- Partonic rates (dependent on medium properties) calculated from finite temperature field theory

- Medium information T(x), u(x) taken from hydrodynamic simulation

Evolution of parton distributions

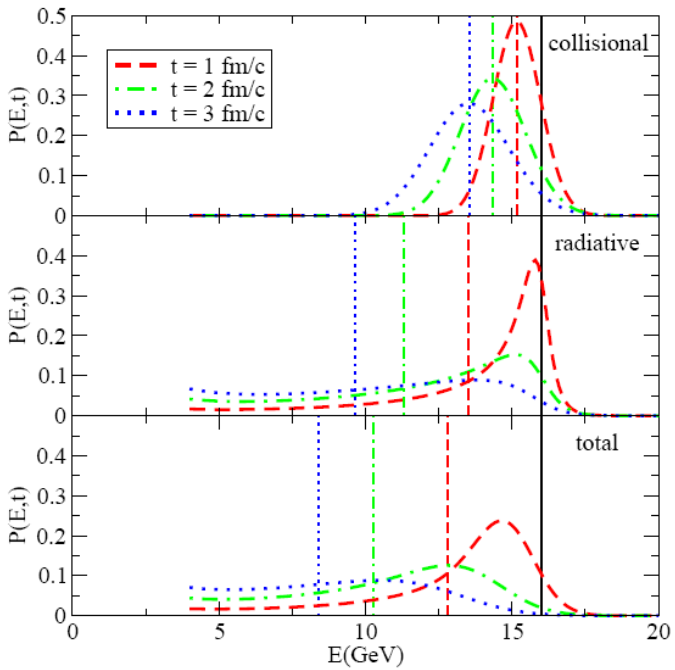
$$\frac{dP_q(p)}{dt} = \int_k P_q(p+k)\frac{d\Gamma^q_{qg}(p+k,k)}{dkdt} - P_q(p)\frac{d\Gamma^q_{qg}(p,k)}{dkdt} + 2P_g(p+k)\frac{d\Gamma^g_{q\bar{q}}(p+k,k)}{dkdt}$$

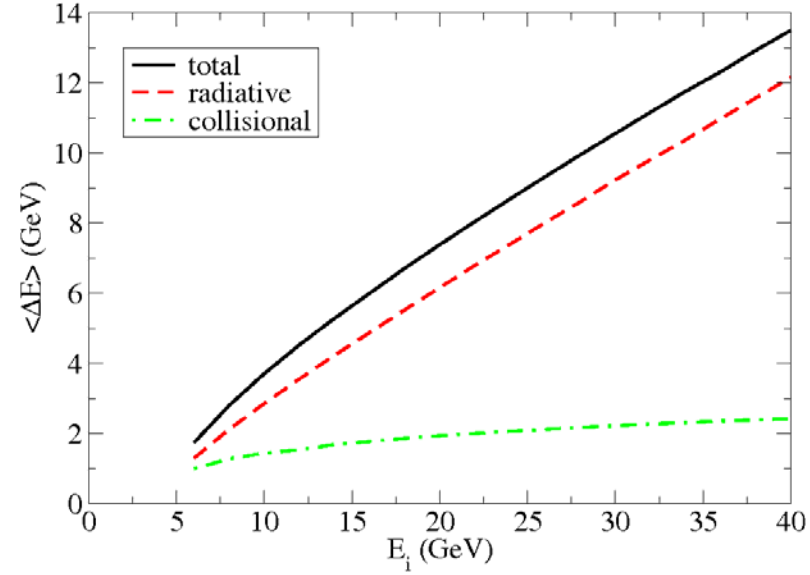
$$\frac{dP_g(p)}{dt} = \int_k P_q(p+k)\frac{d\Gamma^q_{qg}(p+k,p)}{dkdt} + P_g(p+k)\frac{d\Gamma^g_{gg}(p+k,k)}{dkdt} - P_g(p)\left(\frac{d\Gamma^g_{q\bar{q}}(p,k)}{dkdt} + \frac{d\Gamma^g_{gg}(p,k)}{dkdt}\Theta(2k-p)\right)$$

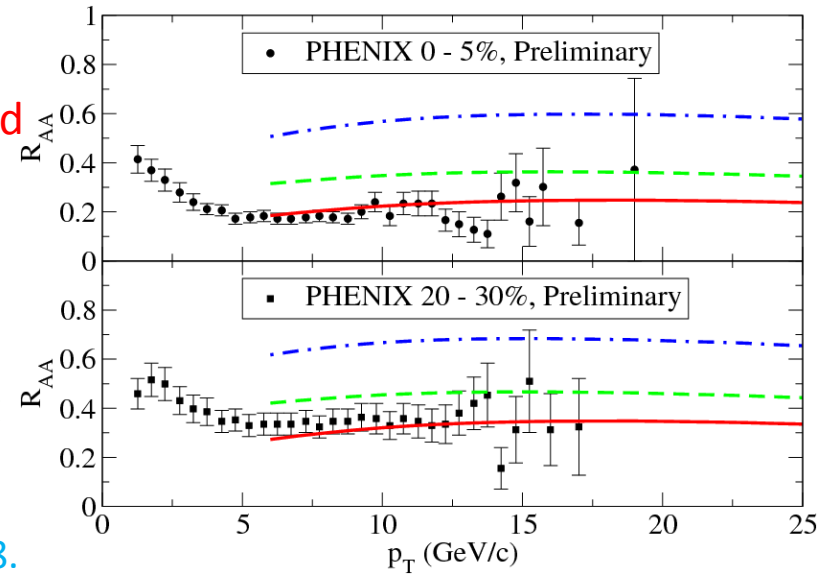
- Evolve entire parton distributions
- Include complete parton split processes
- Include gluon absorption and quark-antiquark annihilation
- Keep track of produced daughters
- Elastic E-loss included as well

GYQ, Ruppert, Gale, Jeon, Moore and Mustafa, PRL, 2008
GYQ, Ruppert, Gale, Jeon, Moore , PRC, 2009
GYQ, Ruppert, Turbide, Gale, Nonaka, Bass, PRC 2007
Turbide, Gale, Jeon, and Moore, PRC, 2005. Jeon, Moore, PRC, 2005

Jet energy loss







-Different evolution patterns from radiative and collisional energy loss

- Average E-loss dominated by radiations

- Contribution from elastic collisions to R_{AA} not negligible

GYQ, Ruppert, Gale, Jeon, Moore, Mustafa, PRL, 2008.

Compute various photons

- Hard direct photons from early collisions: pQCD calculation with proper initial isospin and shadowing effect

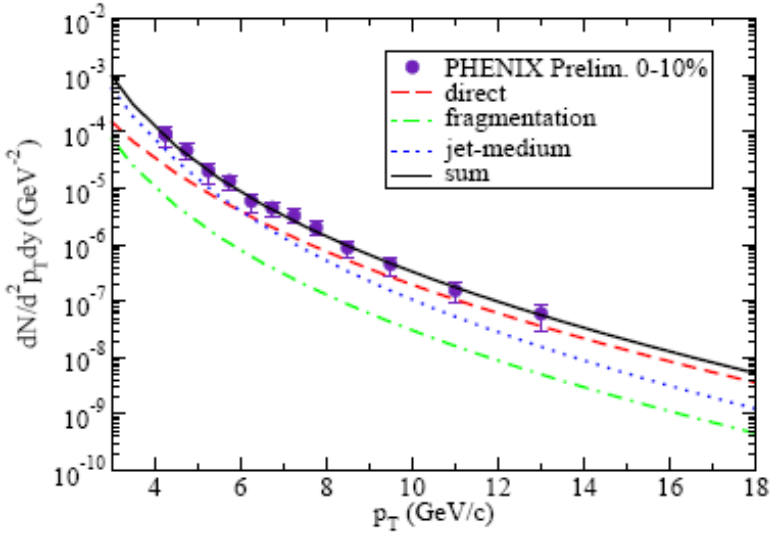
- Fragmentation photons from surviving jets after the passage of medium: Jet E-loss model + photon FF

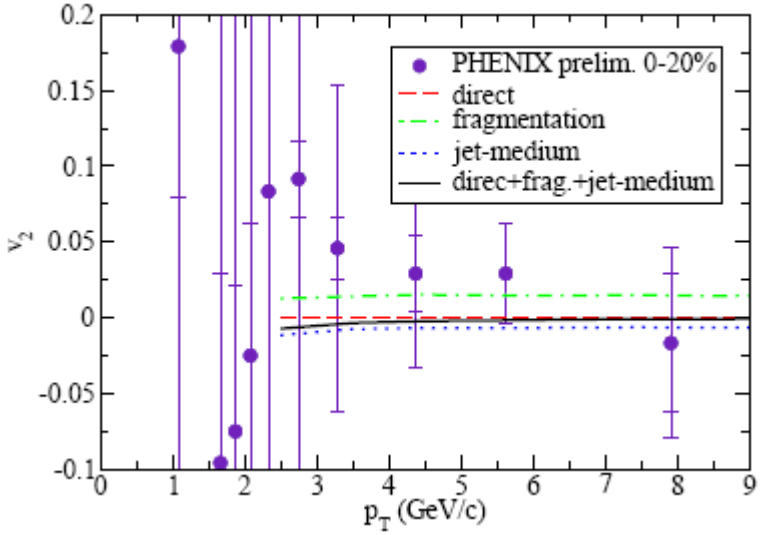
- Jet-medium photons: produced from jets simultaneously with jet evolution

$$\frac{dP_{\gamma}^{\mathrm{jet-plasma}}(E,t)}{dt} = \int d\omega P_{q\bar{q}}(E+\omega,t)\left(\frac{d\Gamma_{q\to\gamma}^{\mathrm{brem}}(E+\omega,\omega)}{d\omega dt} + \frac{d\Gamma_{q\to\gamma}^{\mathrm{conv}}(E+\omega,\omega)}{d\omega dt}\right).$$

  – Photon bremsstrahlung rate and jet-photon conversion rate are obtained from thermal field theory

Photons @ RHIC





Different sources, different characteristic spectra

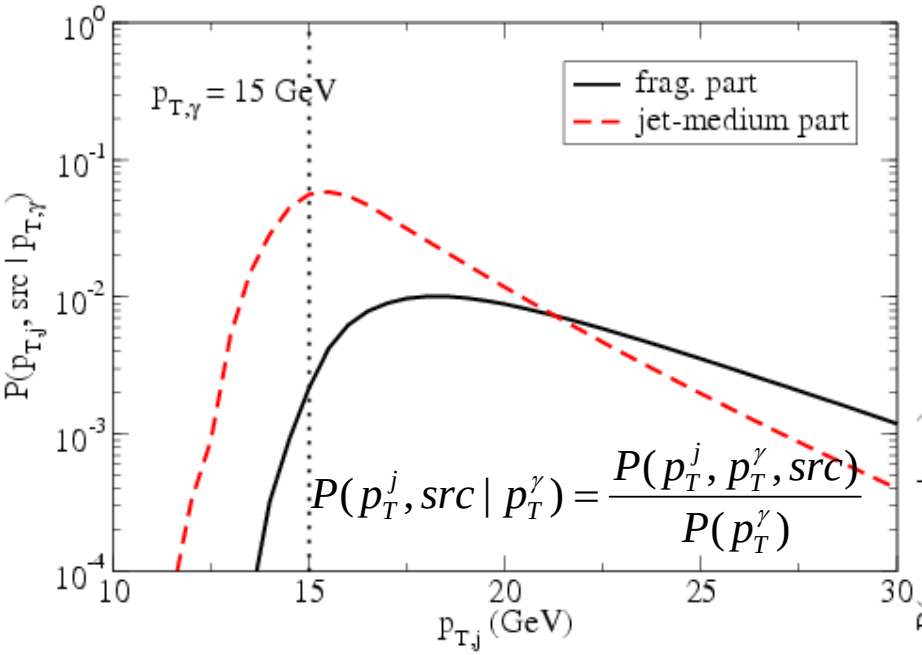
- High p_T dominated by initial hard direct photons
- Important contribution from jet-medium photons at intermediate p_T
- Thermal photons not included, dominated at low p_T

- Negative v_2 from jet-medium photons is compensated by fragmentation photons

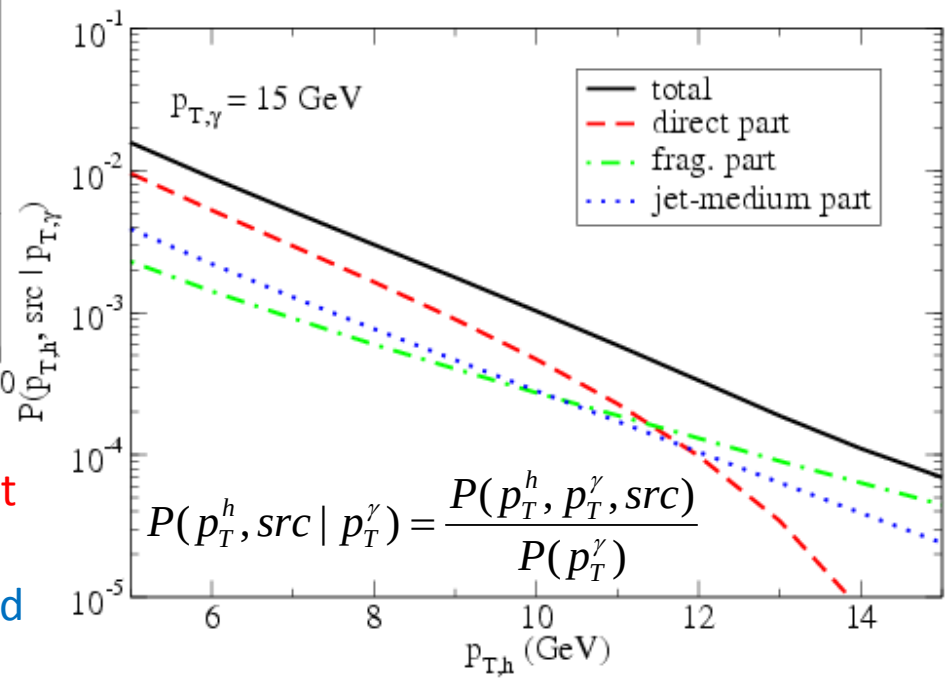
- Isolation of fragmentation photons and centrality cuts are helpful to see the signal of negative v_2

GYQ, Ruppert, Gale, Jeon, Moore, PRC, 2009

Tagging jets with different photons



A large fraction of hadrons at high $p_T(z_T)$ come from jets tagged by jet-medium photons and fragmentation photons

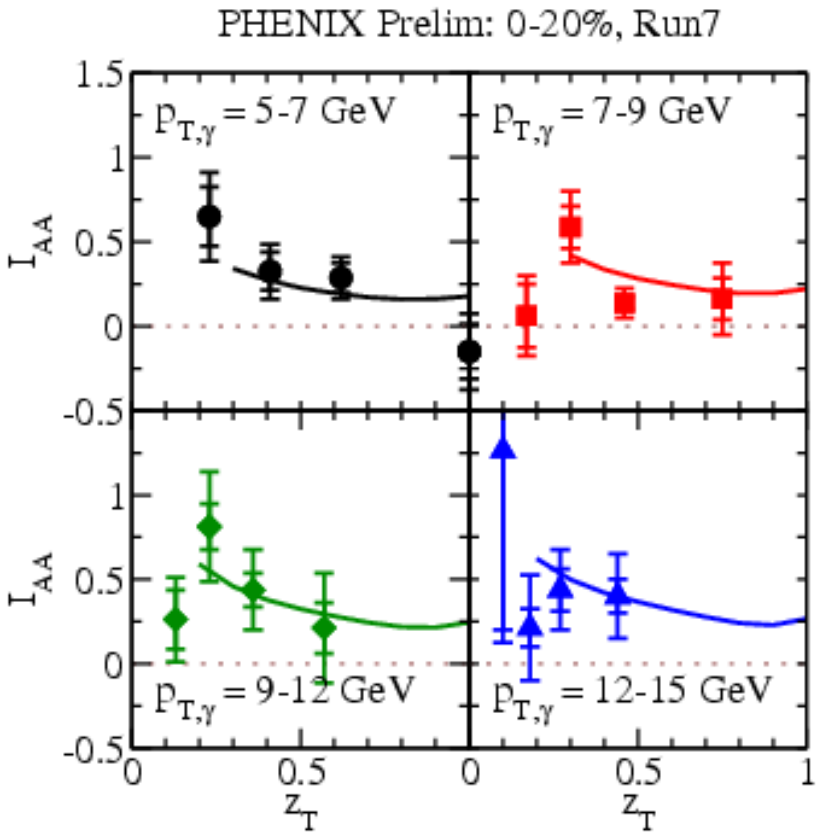


- Different photon-tagged jets have different shapes
- The associated jets at production time tend to have more p_T than the triggered photon

Note NLO for initial hard photon production would change the kinematics

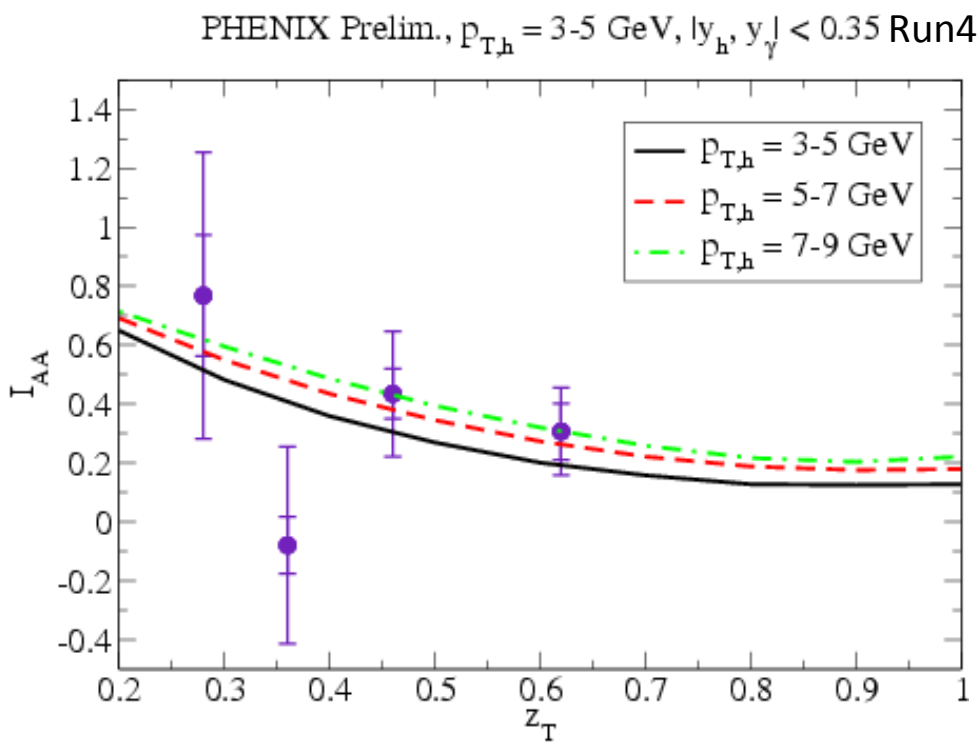
GYQ, Ruppert, Gale, Jeon, Moore, EPJC, 2008

Gamma-h compared to data



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

- Flattening for high z_T due to the inclusion of jet-medium photons and jet-fragmentation photons
- No strong dependence on triggered and associated p_T



GYQ, Ruppert, Gale, Jeon, Moore, PRC, 2009

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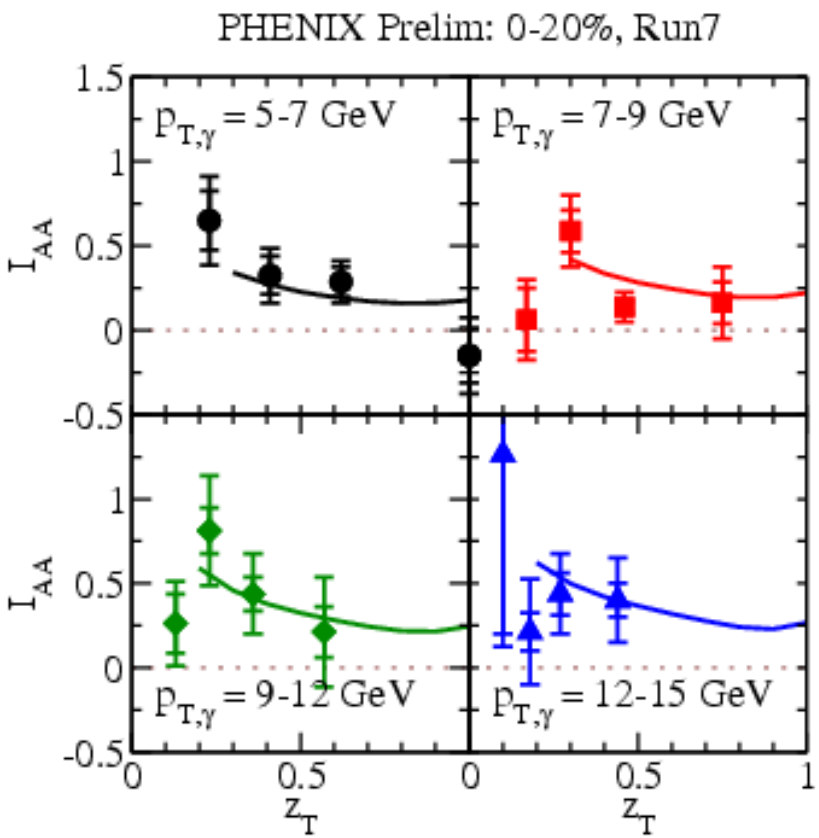

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GYQ, Ruppert, Gale, Jeon, Moore, PRC, 2009

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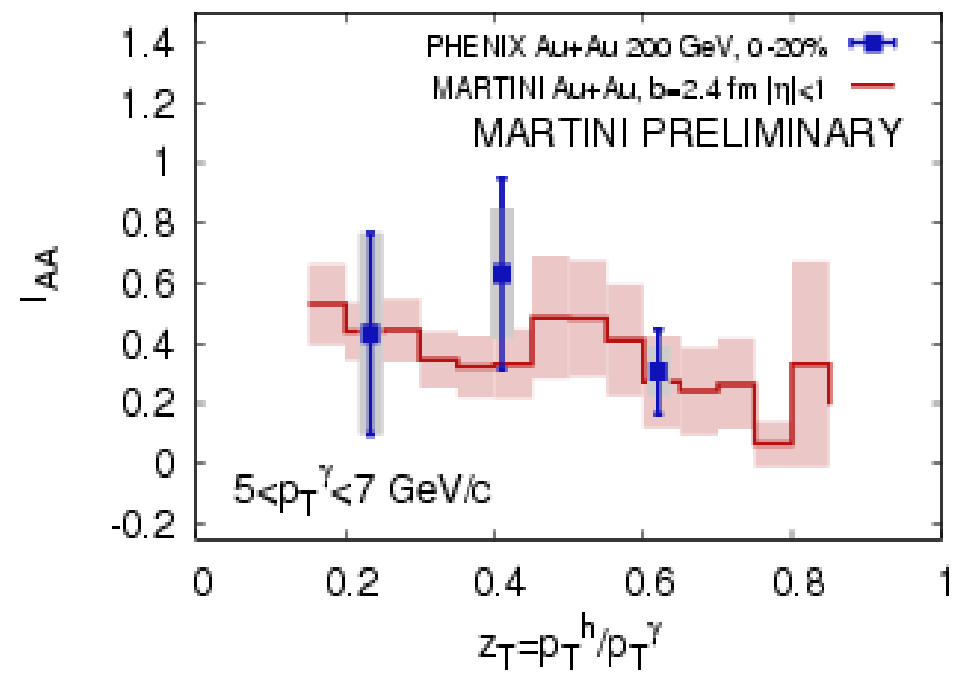
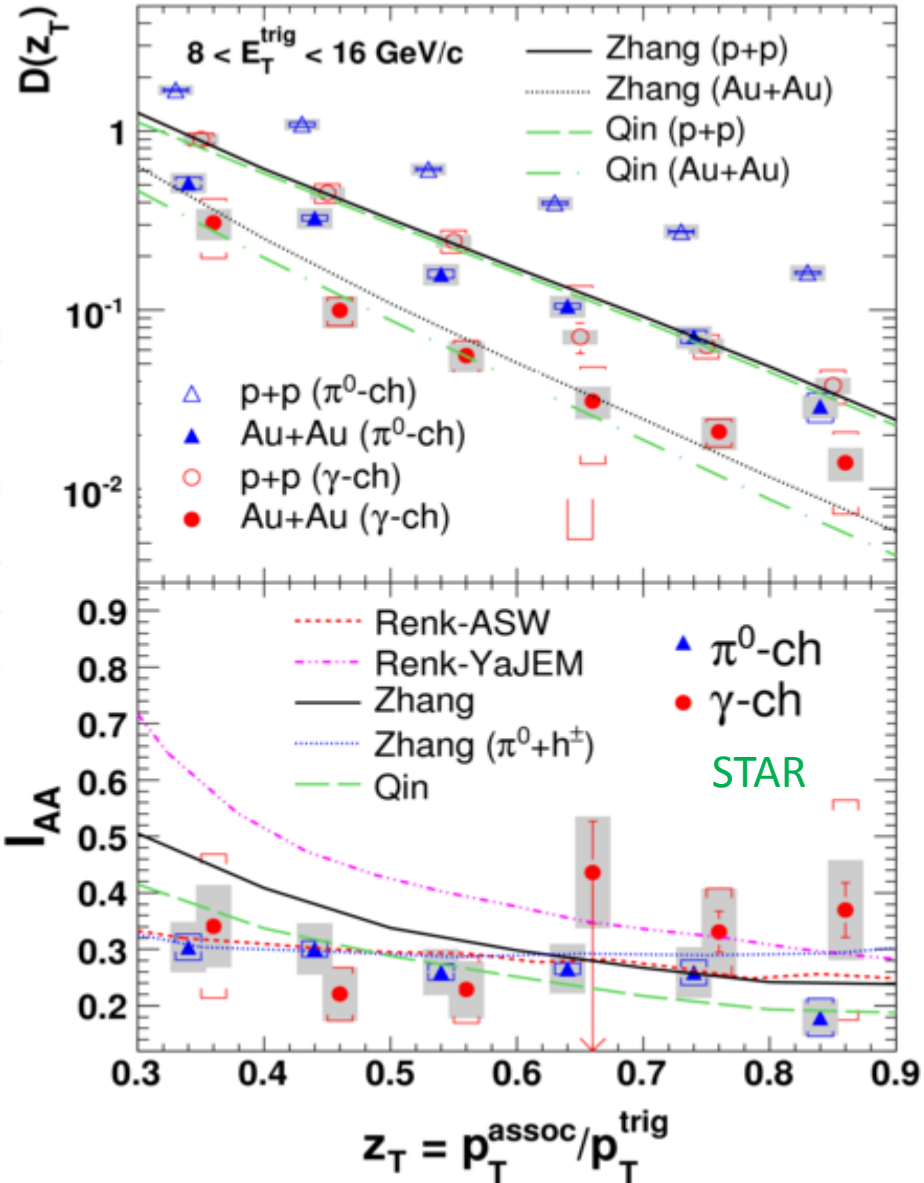
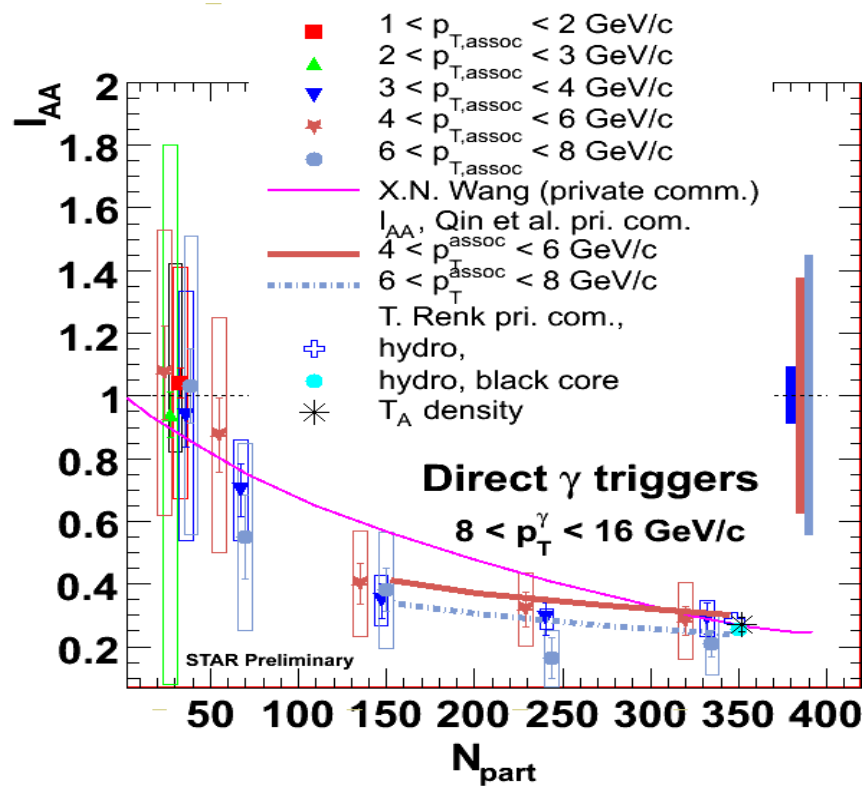


Schenke, priv. comm.

Gamma-h status @ RHIC





Sizable difference from models esp. low z_T:

- surface emission
- parton shower
- q/g effect
- intrinsic k_T
- …

Summary

- So far so good
  - Consistent treatment of EM and jet E-loss
  - Predictions consistent with current data
  - More discriminative power than single inclusive R_{AA}
  - Complications in gamma-jet study

- But a lot remains to be explored
  - Need to kill models
  - More differential observables
  - Viscosity
  - Consistent NLO calculation for jet production, jet E-loss and photon production, including both initial and final effects
  - LHC is a spectacular place for gamma-jet study