Energy Loss in the Hot QCD Brick I

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With many thanks to Brian Cole, Miklos Gyulassy, Yuri Kovchegov, and TECHQM Collab.

Outline

- High-p_T motivation
- Differences seen in parameters OK
- Collinear approximation leads to large systematic theoretical uncertainty
- Thermal gluon mass effects (surprisingly!) small
- Conclusions

Why Study High-p_T Particles?

- Learn about QGP medium
  - Measure suppression, use theory to invert
    - density profile and evolution
    - transport coefficients

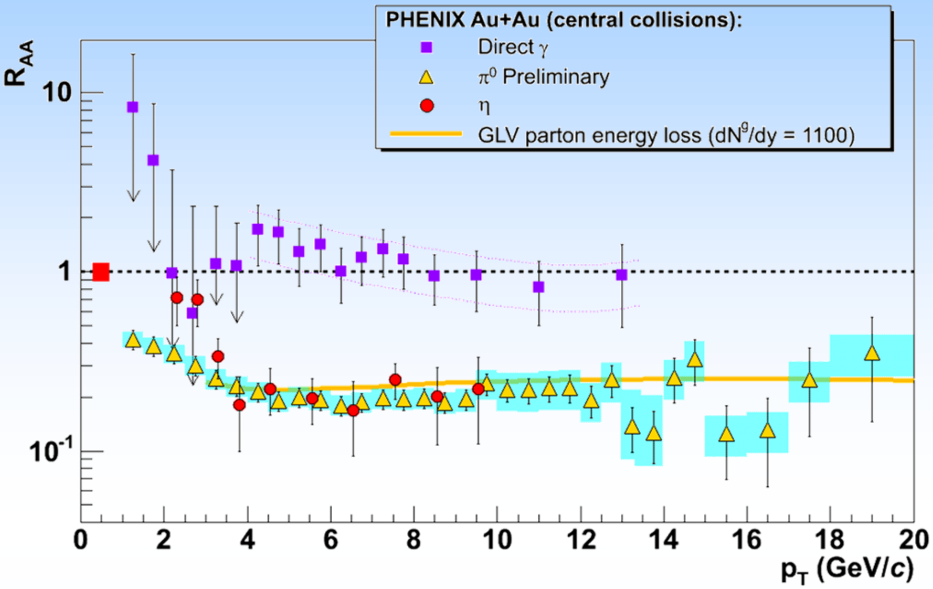
- Tomography in Medicine

SPECT-CT Scan uses internal γ photons and external X-rays

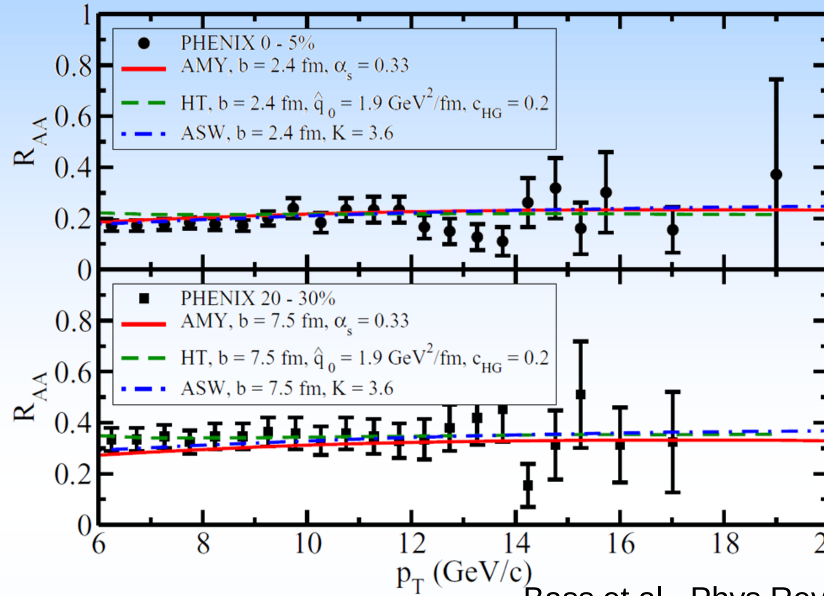
Acronyms, Acronyms

- Four major pQCD formalisms for Rad E-loss
  - Opacity expansion: GLV (DGLV), ASW-SH
  - Multiple soft scattering: BDMPS (ASW-MS)
  - Higher Twist: HT
  - Thermal field theory: AMY

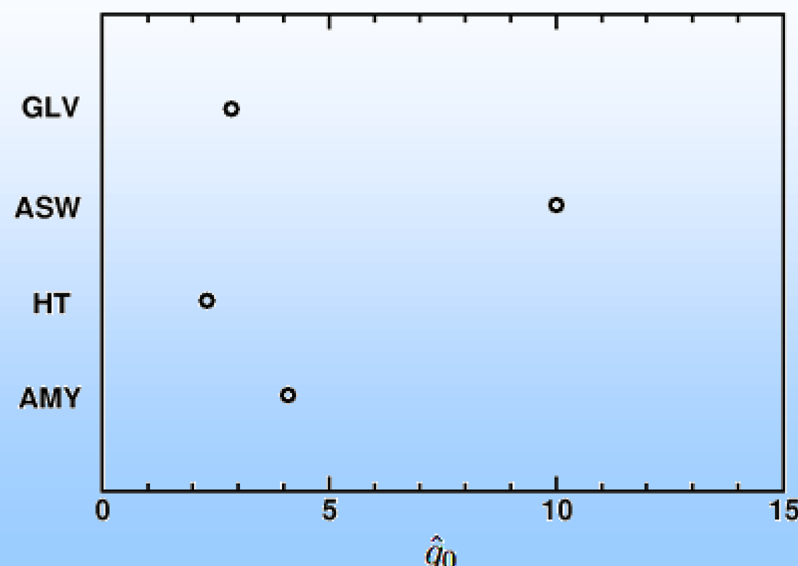
Different Formalisms, Different Results



Y. Akiba *for the PHENIX collaboration*, hep-ex/0510008



Bass et al., Phys.Rev.C79: 024901,2009



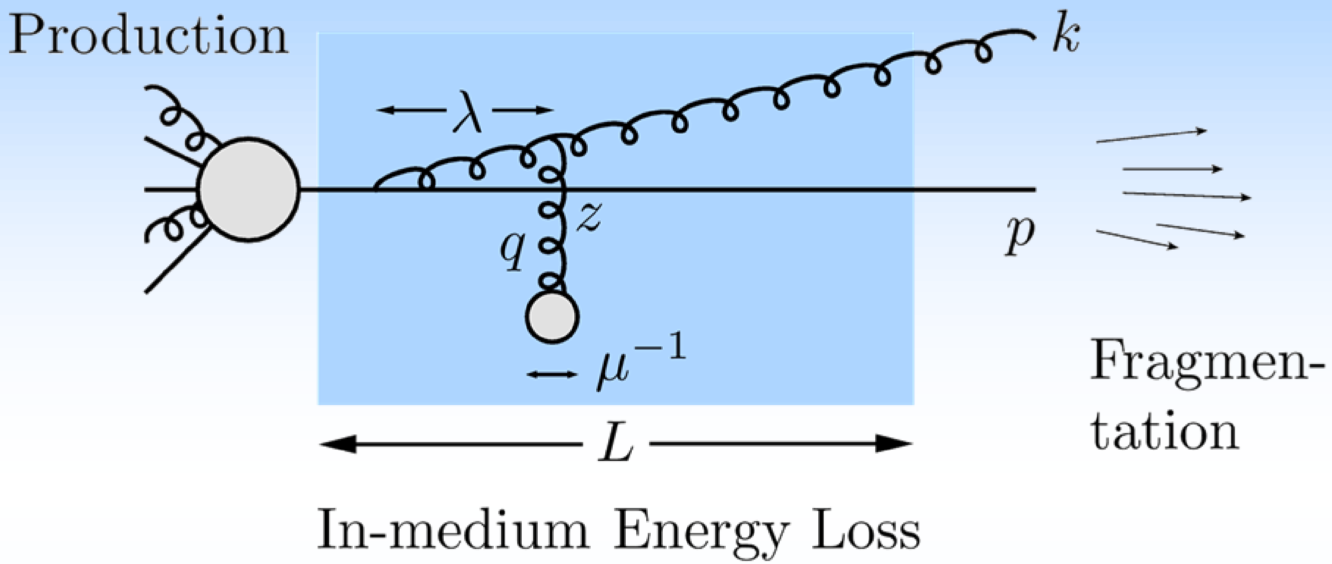
What to Do, What to Do?

- Expectation of theorists: settle on single value of extracted parameter
  - Within pQCD: very diff. assumptions about the relevant physics
    - *Shouldn't* expect a single density, qhat, etc. from different physics
  - Treat all theories as equal?
    - Ex: AdS/CFT
- Need experimental observables to determine the relevant physics
  - Use suppression to learn about QCD, QGP
  - Brick problem: see Marta's talk

Need for Theoretical Uncertainty

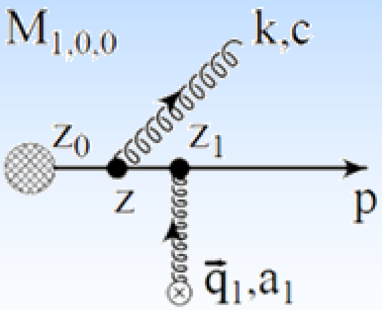
- Want to rigorously:
  - falsify theories
  - quantify medium
- Therefore need:
  - Precise observables
  - Precise theory
- Distinguish between systematic uncertainties:
  - between formalisms
    - Due to diff. physics assumptions
  - within formalisms
    - Due to simplifying approximations
- Focus specifically on opacity expansion
  - GLV; ASW-SH (never been compared with data)

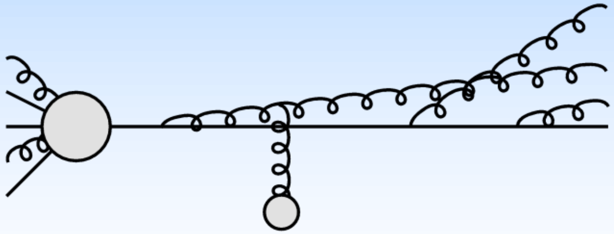
Energy Loss



- $R_{AA} \sim \int (1-\epsilon)^n P(\epsilon)\, d\epsilon$
  - $E_f = (1-\epsilon)E_i$
- Opacity expansions finds single inclusive gluon emission spectrum
  - $dN_g/dx dk_T dq_T$

Poisson Convolution





Gyulassy, Levai, and Vitev NPB594 (2001)

- Find P(ϵ) by convolving dN_g/dx
  - Approximates probabilistic multiple gluon emission
    - assume independent emissions

Opacity Expansion Calculation

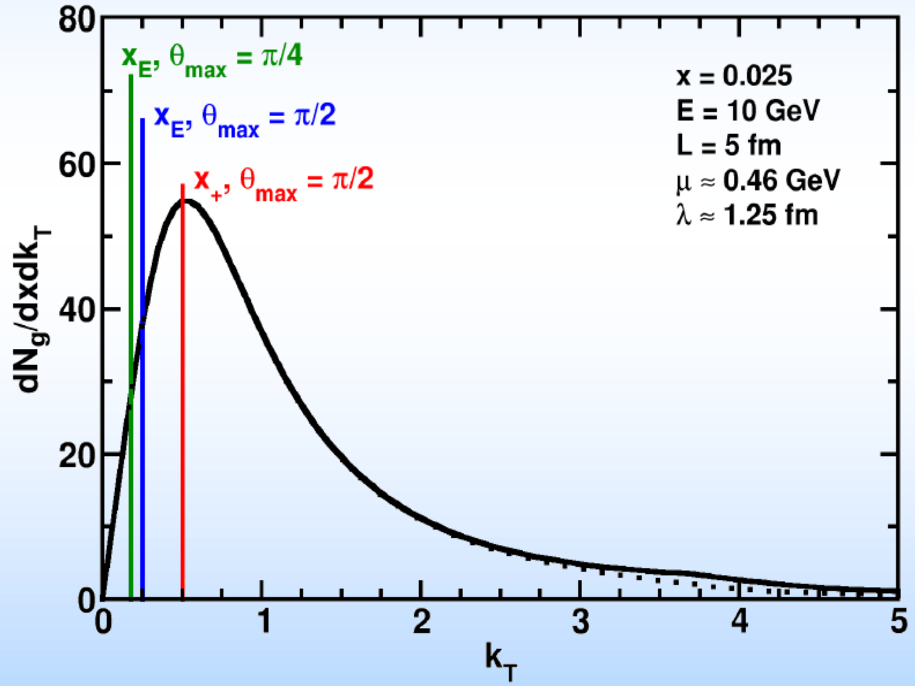
- Want to find dN_g/dx
  - Make approximations to simplify derivation
    - Small angle emission: $k_T << xE$
      - Note: ALL current formalisms use collinear approximation
  - Derived $dN_g/dxdk_T$ violates collinear approx

$$x\frac{dN_g}{dx} = \frac{C_R\alpha_s}{\pi}\frac{L}{\lambda}\int_0^{q^2_{\max}} \frac{2q^2\mu^2 dq^2}{\left(4xE\hbar c/L\right)^2 + \left(q^2+\beta^2\right)^2} \times \int_0^{k^2_{\max}} \frac{dk^2}{k^2+\beta^2}\frac{k^2\left(k^2-q^2+\mu^2\right) - \beta^2\left(k^2-q^2-\mu^2\right)}{\left((k-q)^2+\mu^2\right)^{3/2}\left((k+q)^2+\mu^2\right)^{3/2}} + \mathcal{O}\left(\left(k_T/xE\right)^2\right)$$

- Both IR and UV safe
- Enforce small angle emission through UV cutoff in k_T

Uncertainty from Collinear Approx

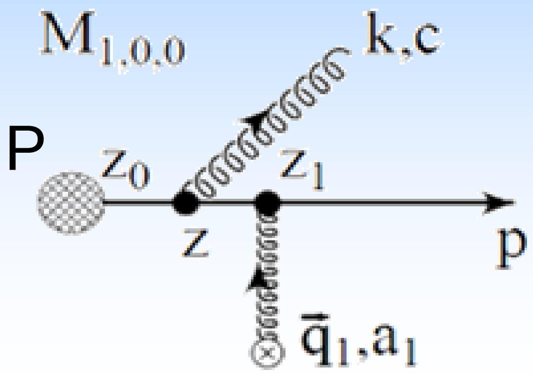
- Derived $dN_g/dxdk_T$ maximally violates collinear approximation
  - dN_g/dx depends sensitively on k_T cutoff
    - Despite UV safety
  - For effect on extracted prop., must understand x
    - Discovered through TECHQM Brick Problem



WAH and B Cole, arXiv:0910.1823

ASW-SH Definition of x

- ASW-SH: x_E
  - Minkowski coords



$$P = (E, E, 0)$$

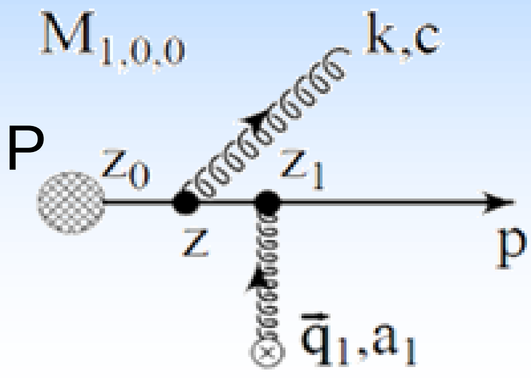
$$p = ((1 - x_E)E, \sqrt{((1 - x_E)E)^2 - (\mathbf{q}_\perp - \mathbf{k}_\perp)^2}, \mathbf{q}_\perp - \mathbf{k}_\perp)$$

$$k = (x_E E, \sqrt{(x_E E)^2 - \mathbf{k}_\perp^2}, \mathbf{k}_\perp)$$

- Always on-shell

GLV Definition of x

- GLV: x_+
  - Light-cone coords



$$P = (E, E, 0, 0) = [E^+, 0, 0]$$

$$k = [x_+ E^+, \frac{\mathbf{k}_\perp^2}{x_+ E^+}, \mathbf{k}_\perp]$$

$$p = [(1 - x_+)E^+, \frac{(\mathbf{q}_\perp - \mathbf{k}_\perp)^2}{(1 - x_+)E^+}, \mathbf{q}_\perp - \mathbf{k}_\perp]$$

- Always on-shell

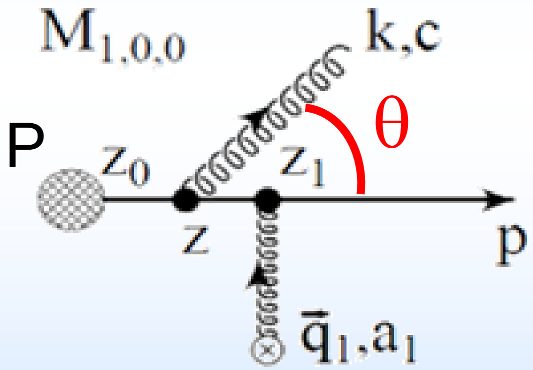
$$k = \left(\frac{1}{2} x_+ E^+ \left[1 + \left(\frac{\mathbf{k}_\perp}{x_+ E^+} \right)^2 \right], \frac{1}{2} x_+ E^+ \left[1 - \left(\frac{\mathbf{k}_\perp}{x_+ E^+} \right)^2 \right], \mathbf{k}_\perp \right)$$

Coordinate Transformations

$$x_+ = \frac{x_E}{2}\left(1+\sqrt{1-\left(\frac{\mathbf{k}_\perp}{x_E E}\right)^2}\right) \qquad x_E = x_+\left(1+\left(\frac{\mathbf{k}_\perp}{x_+ E^+}\right)^2\right)$$

– Same in the limit $k_T/xE \rightarrow 0$!

- UV cutoff given by restricting maximum angle of emission



$$k_{\max} = \begin{cases} x_+ E^+ \tan(\theta_{\max}/2), & x = x_+, \\ x_E E \sin(\theta_{\max}), & x = x_E. \end{cases}$$

– Previous comparisons with data took $\theta_{max}=\pi/2$

– Vary θ_{max} to estimate systematic theoretical uncertainty

Jacobians

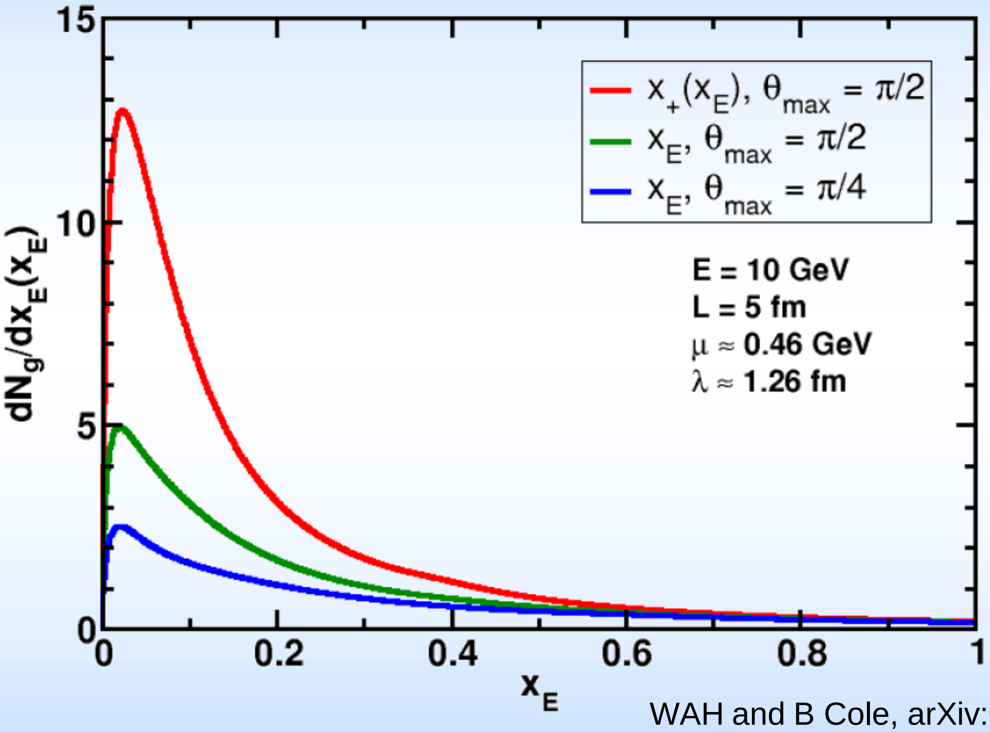
- ϵ is fraction of longitudinal momentum
  - Need dN_g/dx_E to find $P(\epsilon)$
  - A Jacobian is required for $x = x_+$ interpretation

$$\frac{dN_g^J}{dx_E}(x_E) \equiv \int^{x_E E \sin(\theta_{\max})} dk_T \frac{dx_+}{dx_E} \frac{dN_g}{dx_+ dk_T}(x_+(x_E)),$$

$$\frac{dx_+}{dx_E} = \frac{1}{2}\left[1 + \left(1 - \left(\frac{k_T}{x_E E}\right)^2\right)^{-1/2}\right].$$

Rad. Gluon Kin. Sensitivities

- UV



WAH and B Cole, arXiv:0910.1823

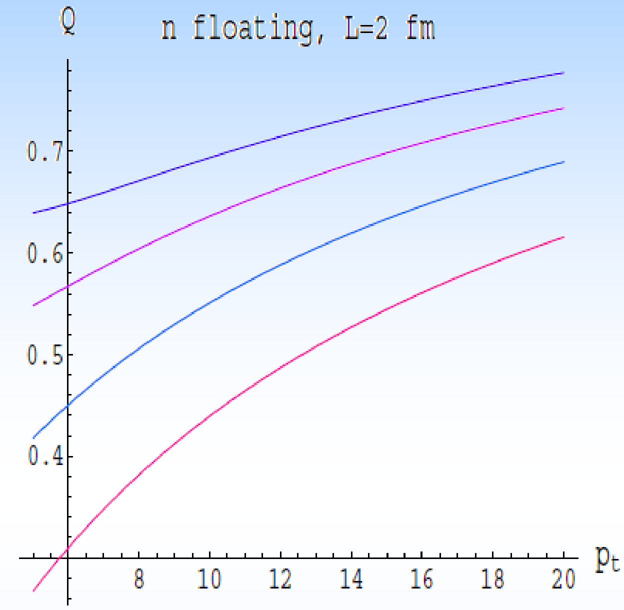
- What about IR?

Collinearity and Gluon Mass

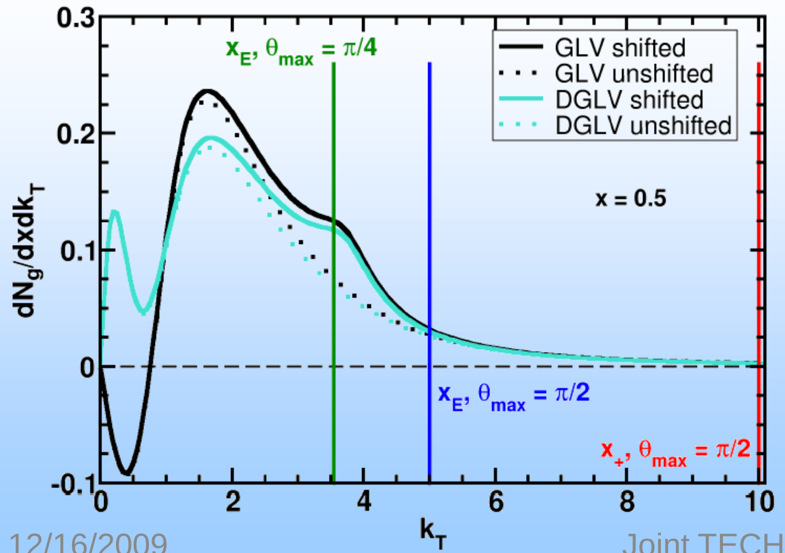
- Massless gluons:
  - – Large IR cutoff sensitivity
- Gluons with thermal mass

$$\tau_{\rm coh} = \frac{2xE}{q_T^2 + \beta^2}$$

m_g^2



BDMS, JHEP 0109 (2001)

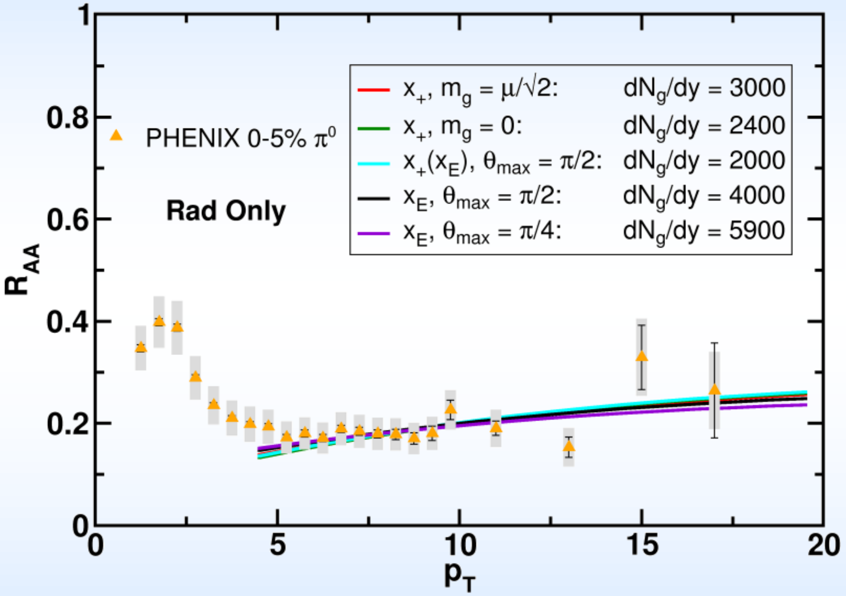


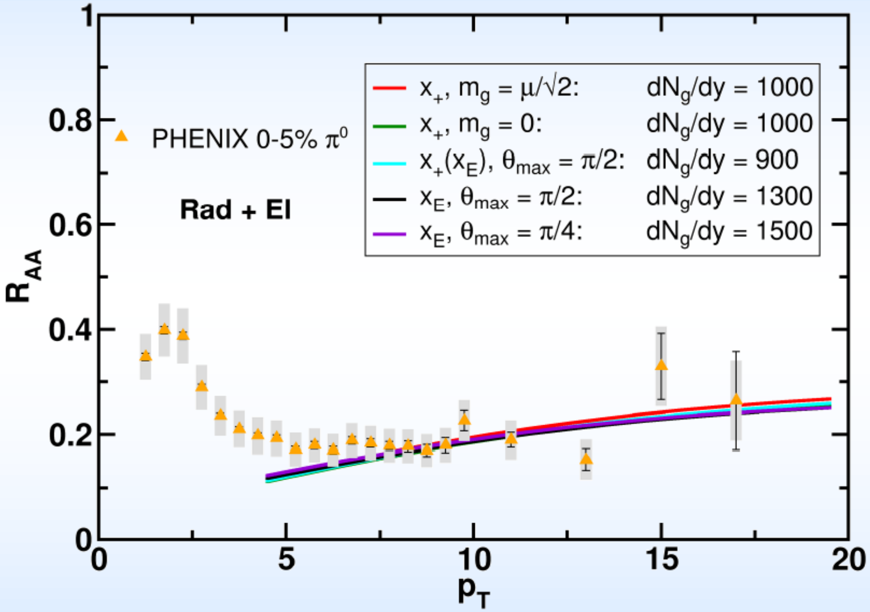
WAH and B Cole, arXiv:0910.1823

Larger x better respects $k_T << xE$

Results

- Quantitatively compare to PHENIX data



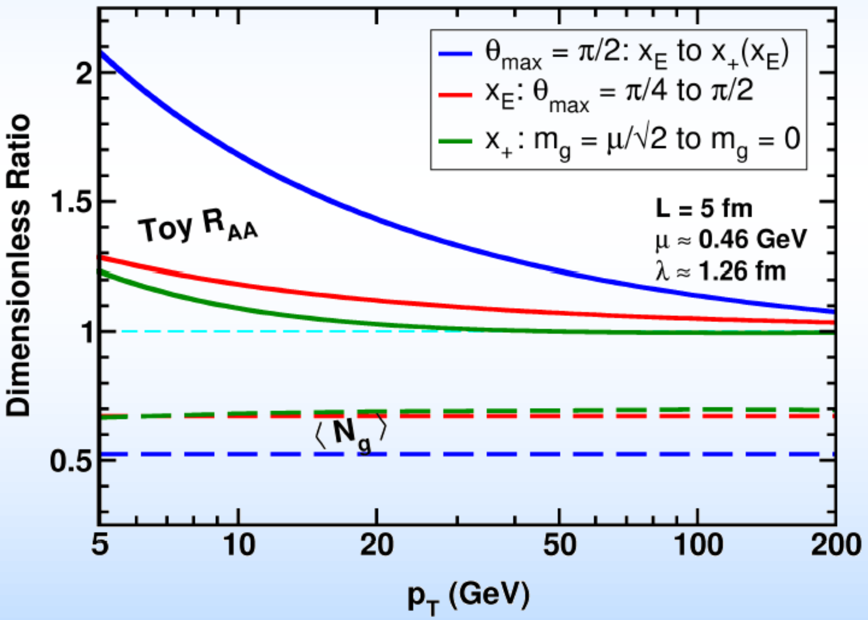


WAH and B Cole, arXiv:0910.1823

  - Assumed infinite Elastic precision

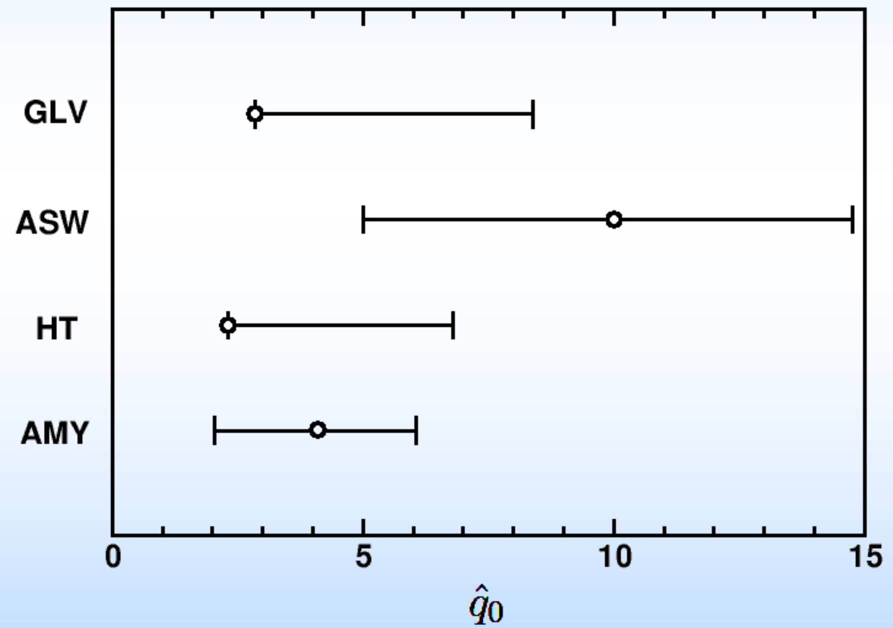
Parton Energy Dependence

- Dependence on parton energy



WAH and B Cole, arXiv:0910.1823

- Uncertainty on qhat



– Assume all formalisms equally affected

Conclusions

- Use different physics, expect different parameters
- $dN_g/dxdk_T$ drastically violates collinear approx.
  - Large angle radiation is important
    - Not under theoretical control
  - Leads to ~200% systematic theoretical uncertainty in extracted medium density at RHIC
  - Extracted parameters from pQCD formalisms likely consistent within uncertainty
- Thermal gluon mass effects small
- LHC
  - R_{AA} insensitive to collinear approx. at ultra-high-p_T
  - $\langle N_g \rangle$ uncertainty E-independent
    - Large cone jets not under theoretical control