Heavy Quark Production and Energy Loss

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August 14, 2012

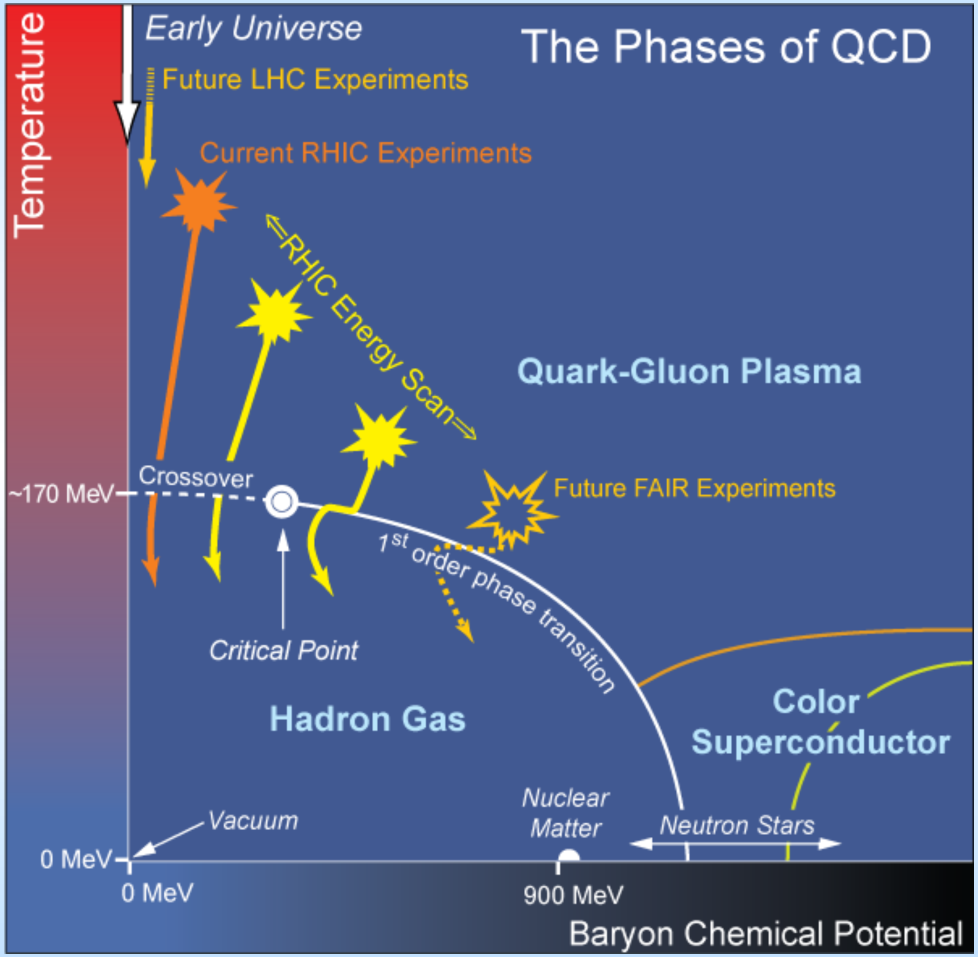
With many thanks to Razieh Morad, Miklos Gyulassy, and Yuri Kovchegov

National Research Foundation

SA-CERN

What Are We Interested In?

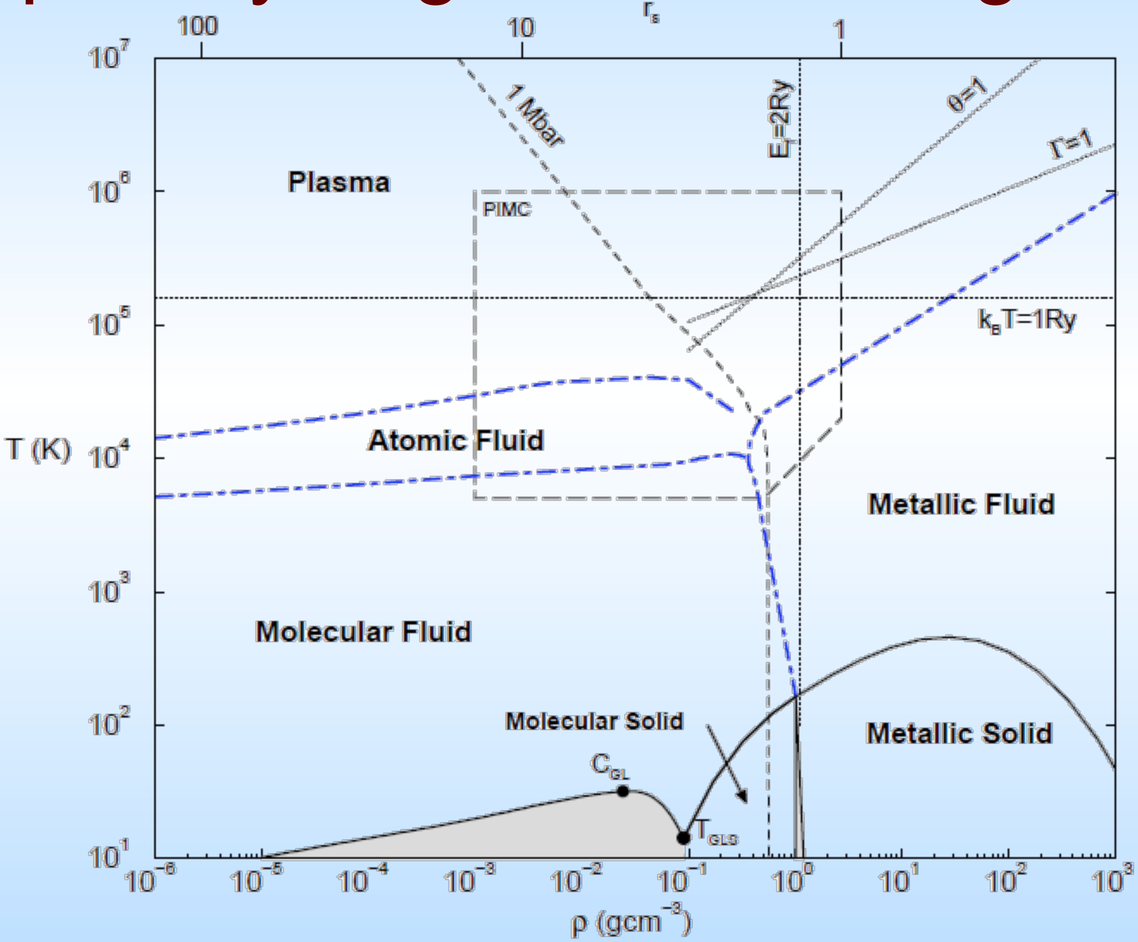
- Measure the properties of many-body strong force
- Test & understand theory of many-body non-Abelian fields



Long Range Plan, 2008

Compare to Easiest QED

- "Simple" Hydrogen Phase Diagram

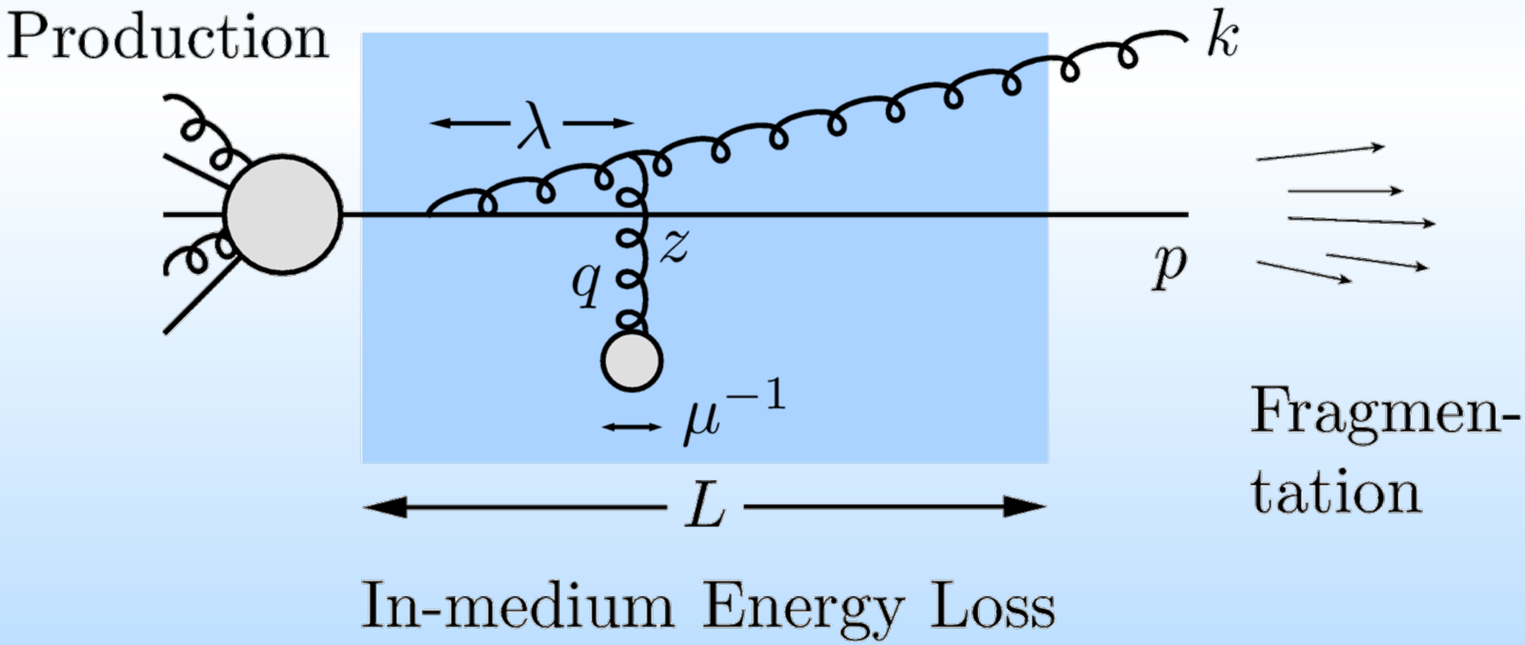


Calculated, Burkhard Militzer, Diploma Thesis, Berlin, 2000

Why Energy Loss?

Most direct probe of DOF of QGP

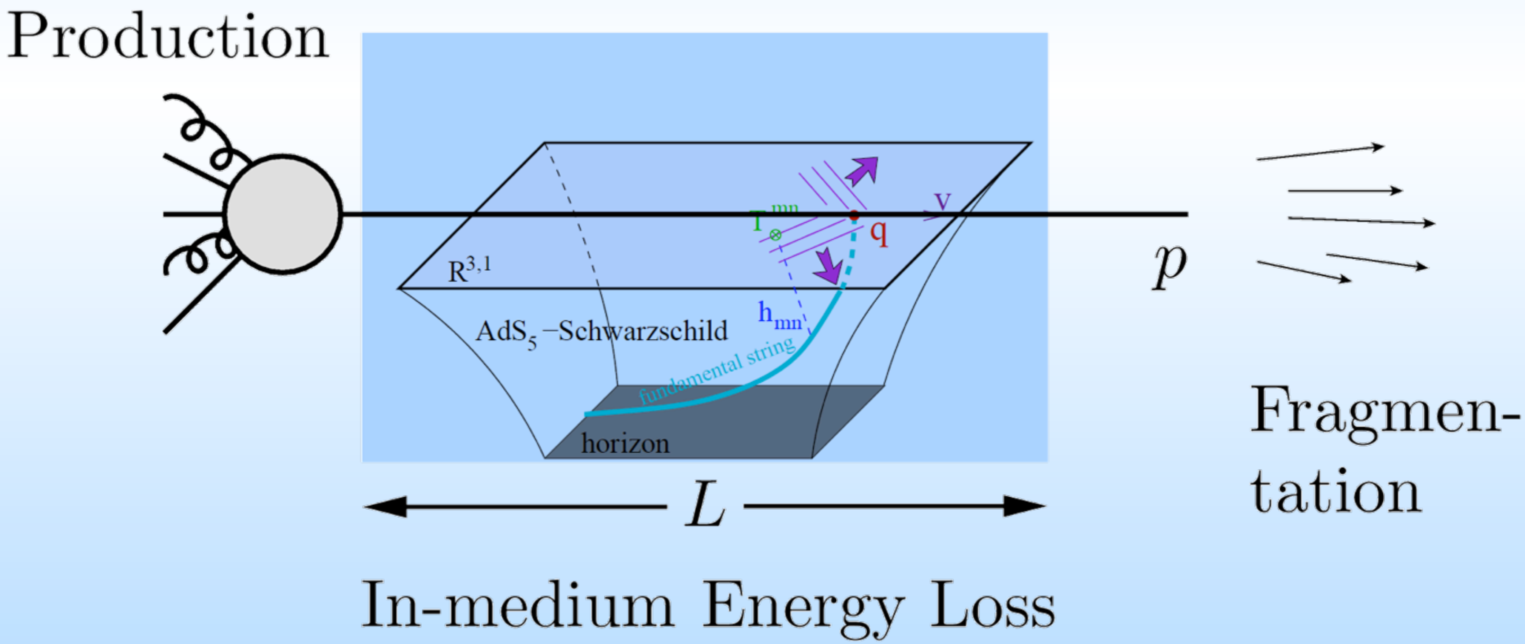
pQCD Picture



Why Energy Loss?

Most direct probe of DOF of QGP

AdS/CFT Picture

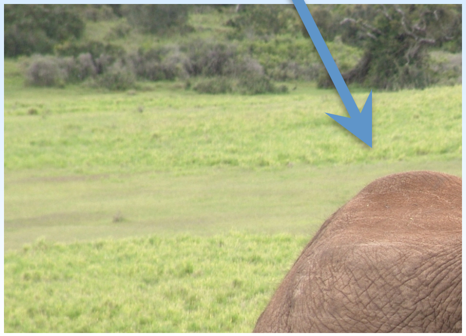


Heavy Quarks in Context

QGP

Heavy Quarks in Context

High p_T Light Hadrons



QGP

Heavy Quarks in Context

High p_T Light Hadrons

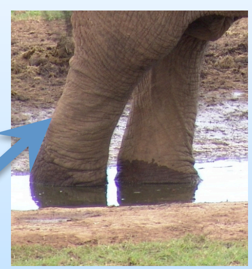
QGP

Quarkonia

Heavy Quarks in Context

High p_T Light Hadrons

QGP



Open Heavy Flavor

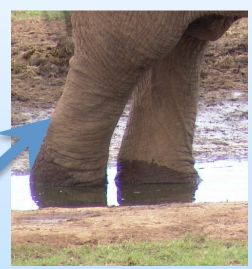
Quarkonia

Heavy Quarks in Context

High p_T Light Hadrons

EM Probes

QGP



Open Heavy Flavor

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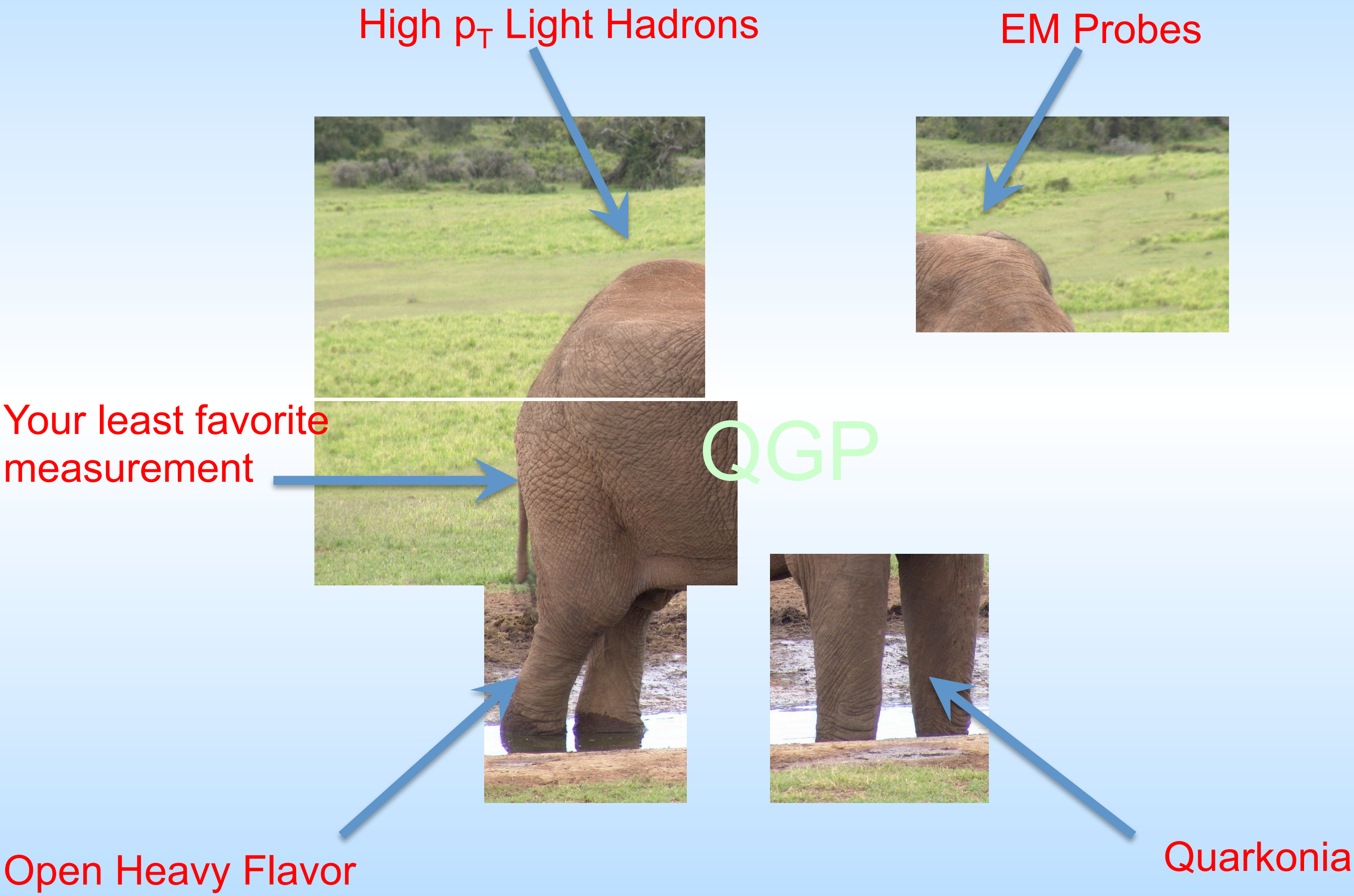
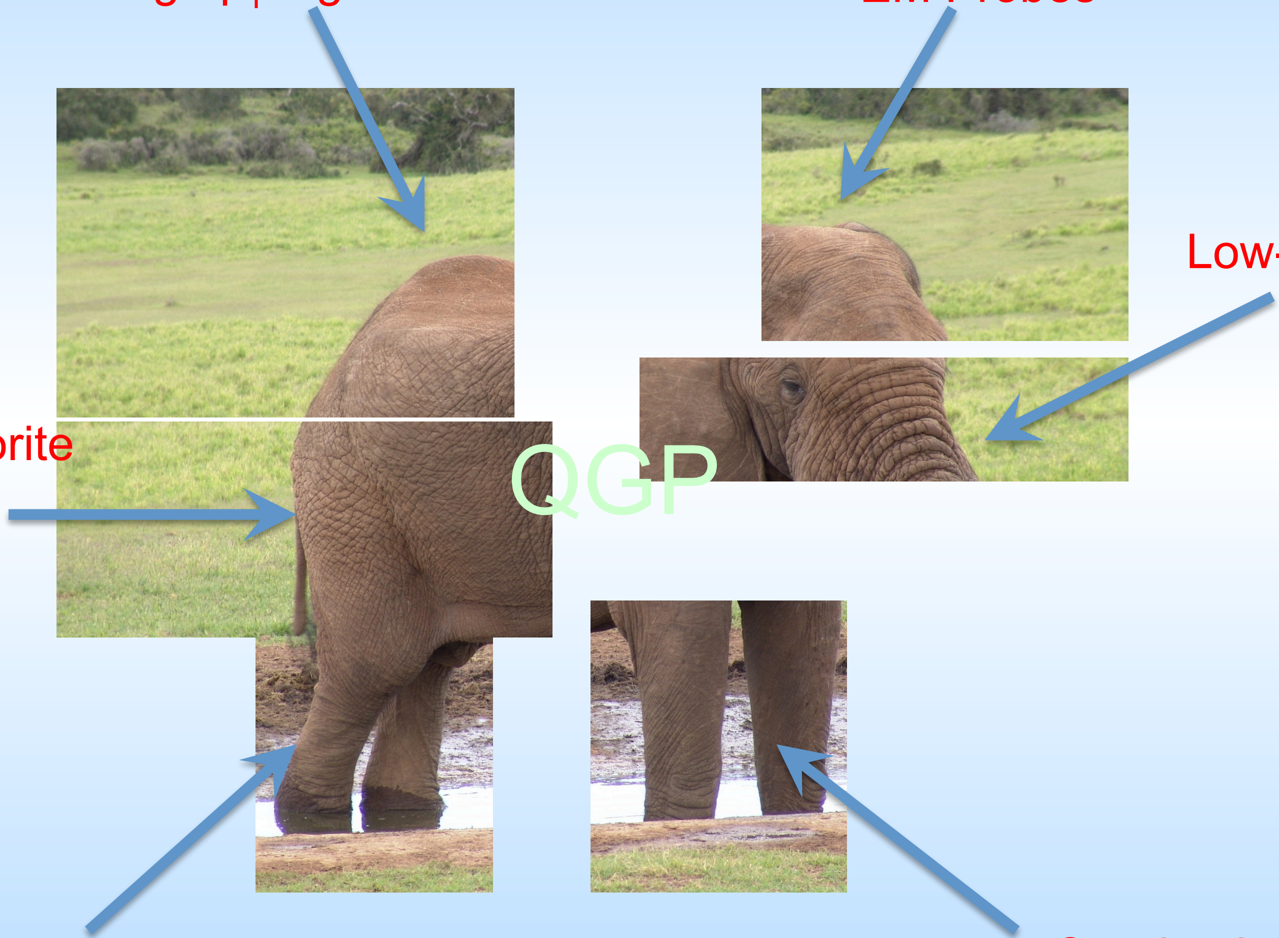
Heavy Quarks in Context



Heavy Quarks in Context



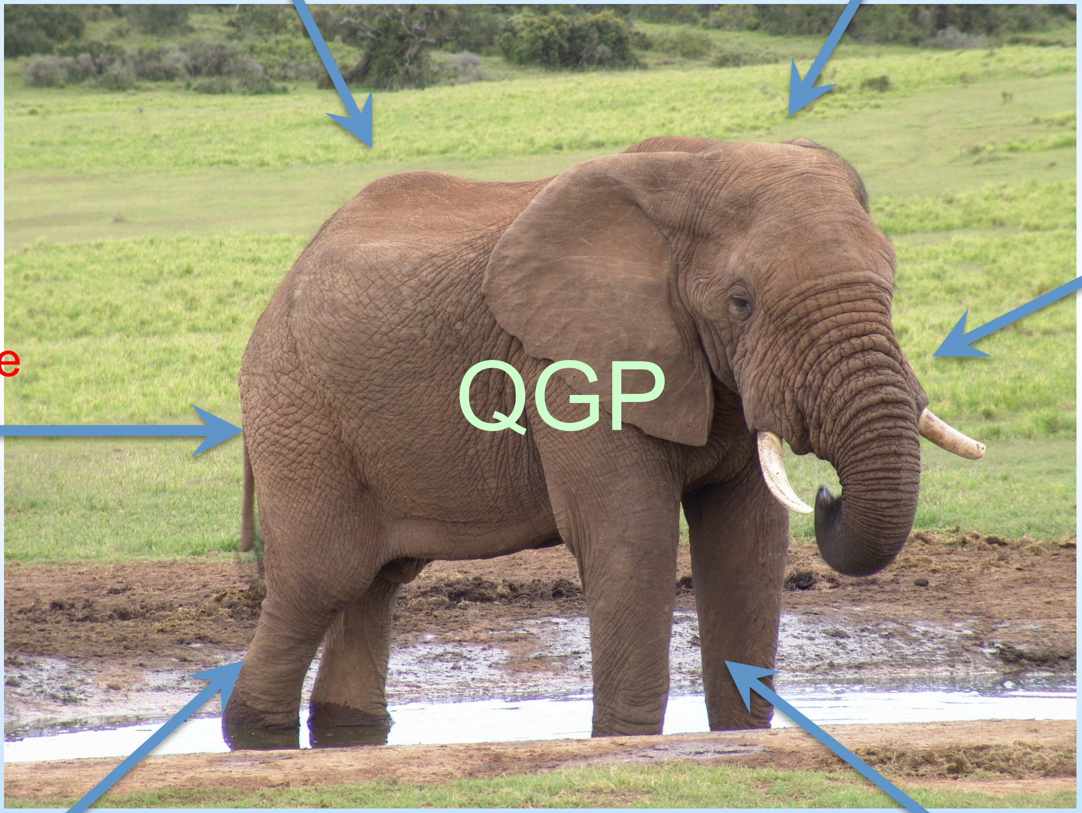
Heavy Quarks in Context

High p_T Light Hadrons

EM Probes

Low-p_T particles

Your least favorite measurement



Open Heavy Flavor

Quarkonia

Searching for this coherent, consistent picture

Why Heavy Quarks?

- E-loss picture assumes QGP properties => $P(\Delta p_T \mid p_T, L, T, M_Q, R)$
- Want to test $P(\Delta p_T)$
  - A+B, $\sqrt{s}$, centrality, M_h, …

Qualitative Expectations for HF

- Energy loss decreases with M_Q

  $\Rightarrow \Delta E_b < \Delta E_c < \Delta E_{u,d} < \Delta E_g$

  - For experts: not always true for pQCD

    (τ_{form} decreases with M_Q)

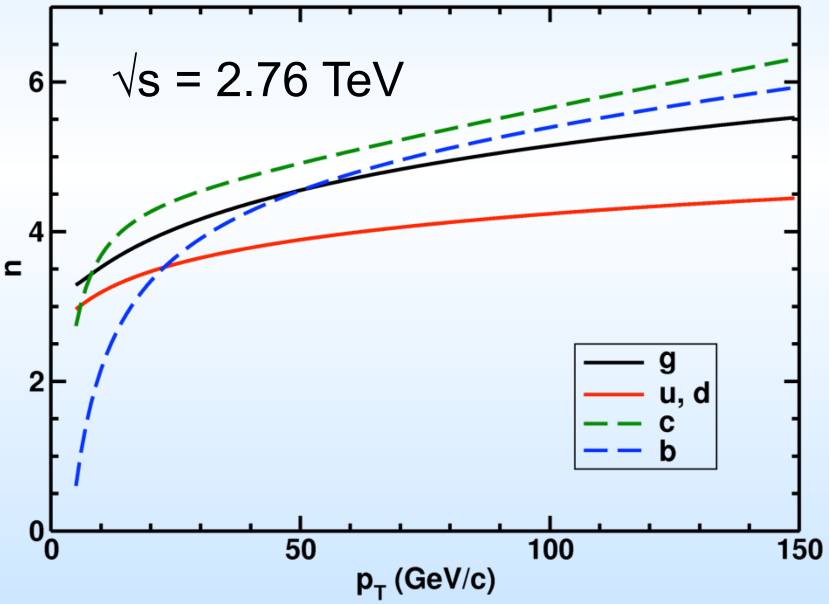
- DOES NOT IMPLY R_{AA} ORDERING
  - For approx. power law production and energy loss probability $P(\varepsilon)$, $\varepsilon = (E_i - E_f)/E_i$

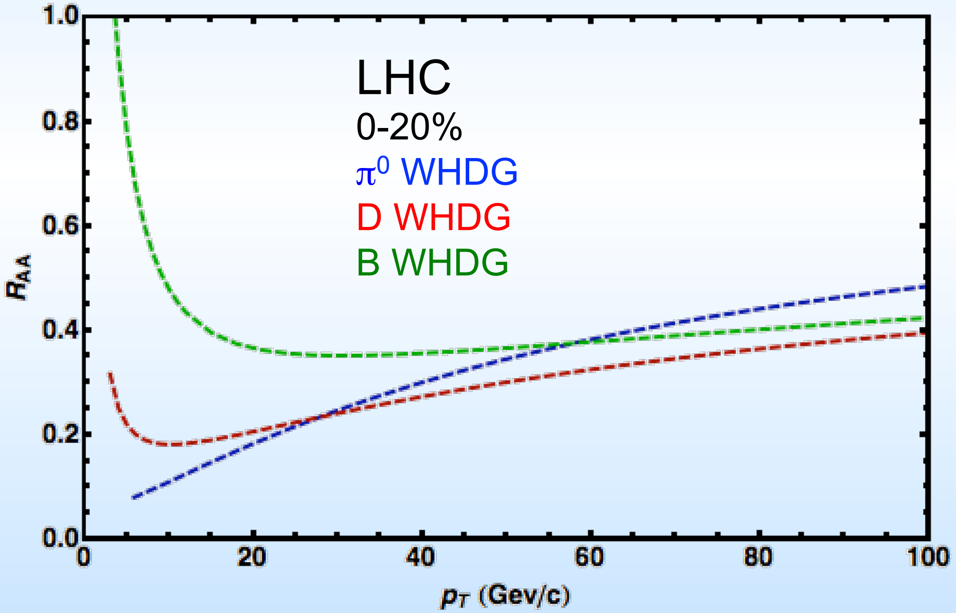
$$\frac{dN}{dp_T} \sim \frac{1}{p_T^{n+1}} \quad \Rightarrow \quad R_{AA} \approx \langle \int d\varepsilon (1-\varepsilon)^n P(\varepsilon) \rangle$$

  - Larger n => smaller R_{AA} for same energy loss

Importance of Production

- HQ production spectra softer than lights
  - => Nontrivial ordering of $R_{AA}(p_T)$

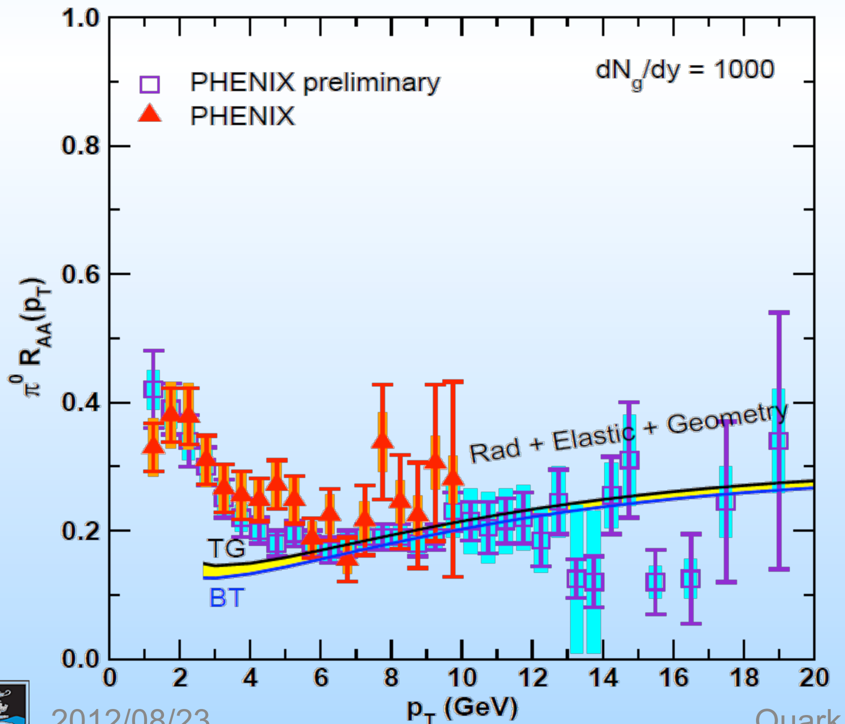


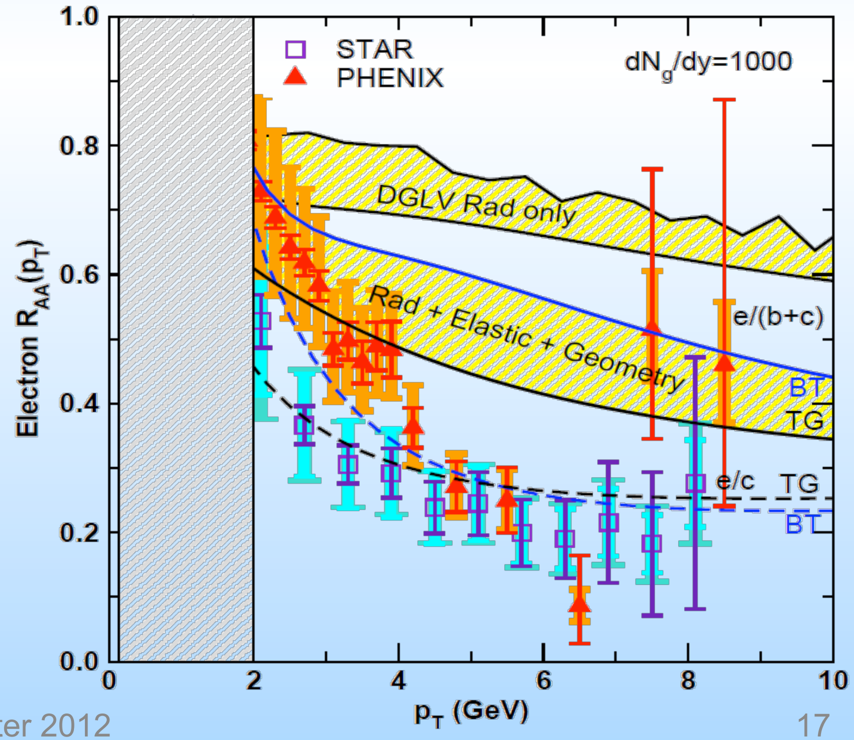


See also
Buzzatti, 5C (NB: High-p_T and Jets)

Lesson from RHIC

- Extremely difficult to consistently describe all observables
  - HF suppression places ***stringent constraint*** on possible E-loss mechanism





Wicks, WAH, Djordjevic, Gyulassy, NPA784 (2007)

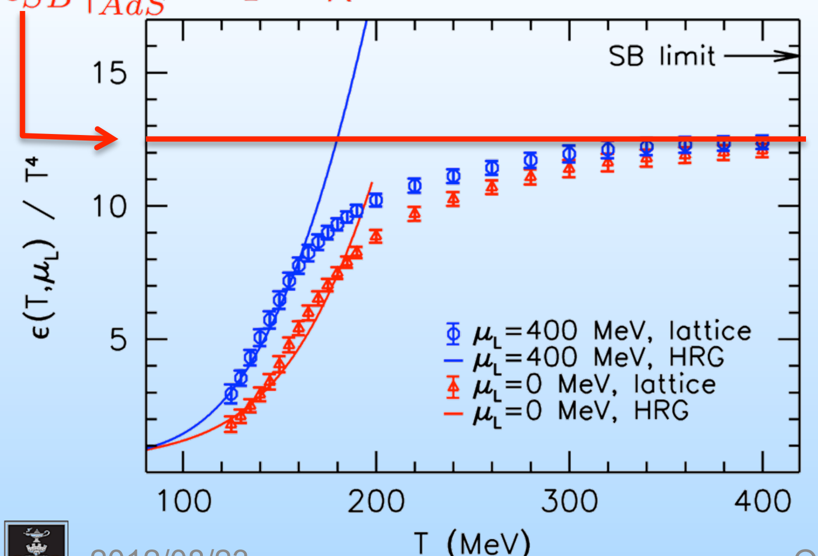
Demonstrating E-loss Value

- Compare E-loss observables to data with two very different assumptions of properties of QGP:
  - Strongly coupled medium coupling strongly to a high-p_T particle
  - Weakly coupled medium coupling weakly to a high-p_T particle

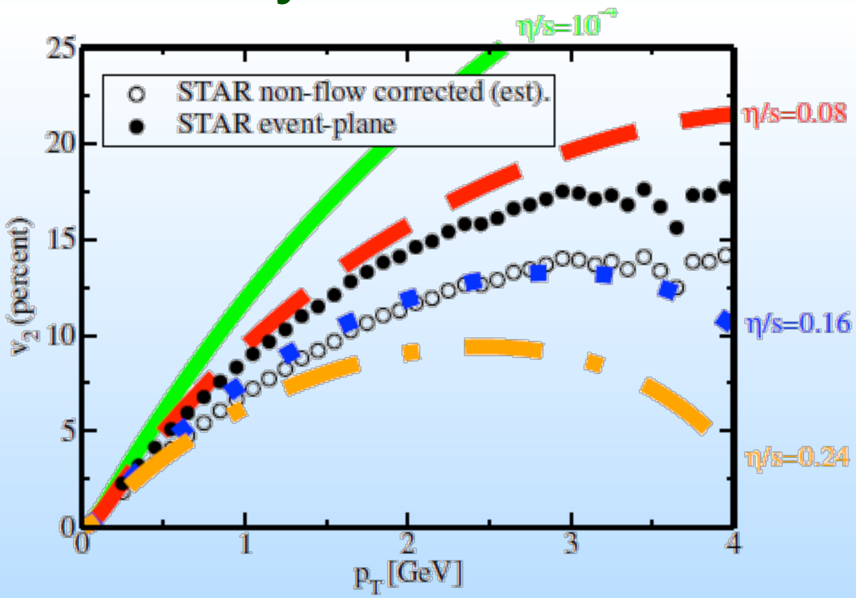
Let's Assume Strong Coupling

- Not crazy
  - – $T \sim 250$ MeV, $g(2\pi T) \sim 2$, $\lambda = g^2 N_c \sim 12 \gg 1$
    - Always small T scale
  - – $T \gtrsim T_c$, lattice deviates from Stefan-Boltzmann
  - – $\eta/s \sim 1/4\pi$ readily explained by AdS/CFT

$$\left.\frac{\epsilon}{\epsilon_{SB}}\right|_{AdS} = \frac{3}{4} + \frac{1.69}{\lambda^{3/2}} + \ldots$$



Wuppertal, arXiv:1204.6710



Luzum and Romatschke, PC78 (2008)

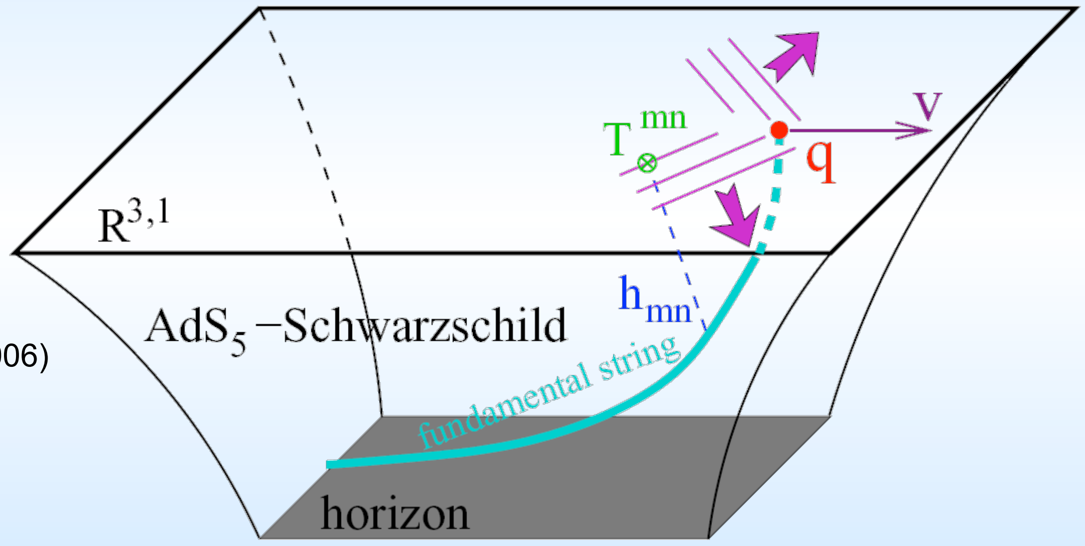
Heavy Quark E-Loss in AdS/CFT

- Model heavy quark jet energy loss by embedding string in AdS space

$dp_T/dt = - \mu\, p_T$

$\mu = \pi\lambda^{1/2}\, T^2/2M_q$

Herzog et al., JHEP 0607 (2006)
Gubser, PRD74 (2006)



J Friess, S Gubser, G Michalogiorgakis, S Pufu, Phys Rev **D75** (2007)

– Similar to Bethe-Heitler

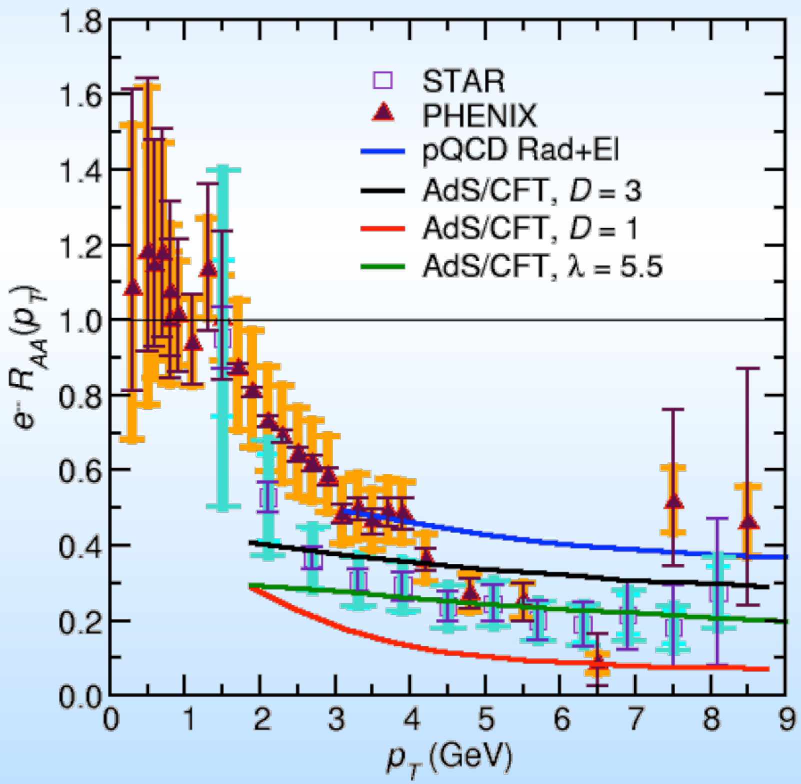
$dp_T/dt \sim -(T^3/M_q^2)\, p_T$

– Very different from usual pQCD and LPM

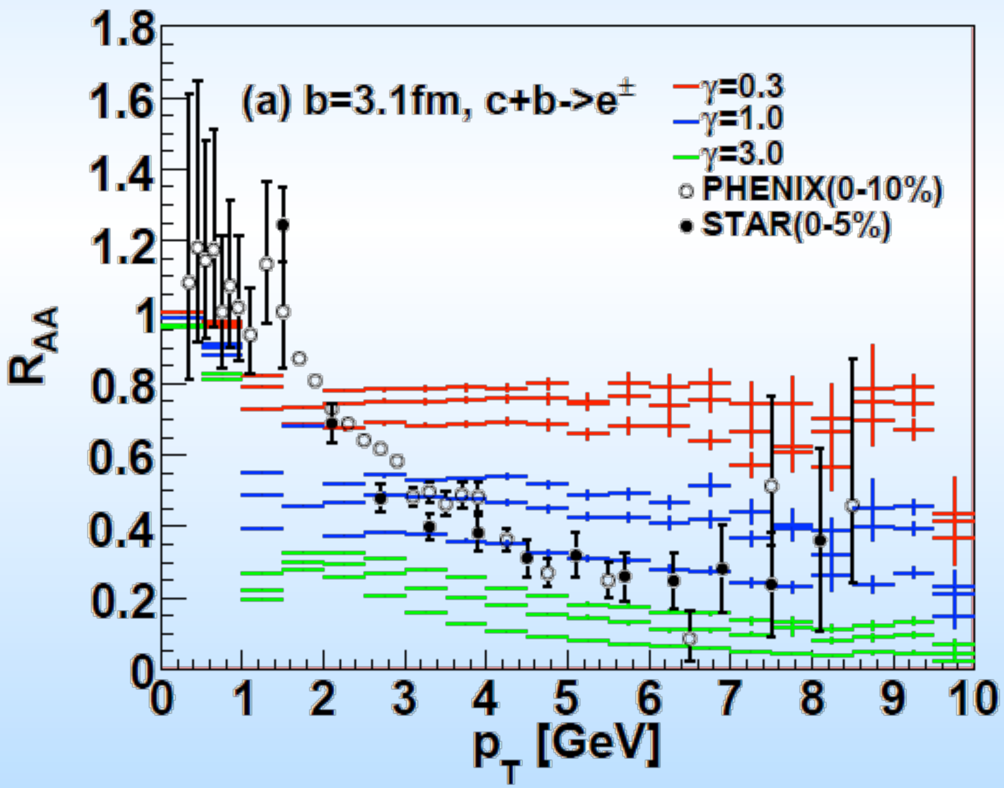
$dp_T/dt \sim -LT^3 \log(p_T/M_q)$

AdS/CFT and HQ

- String drag: qualitative agreement at RHIC



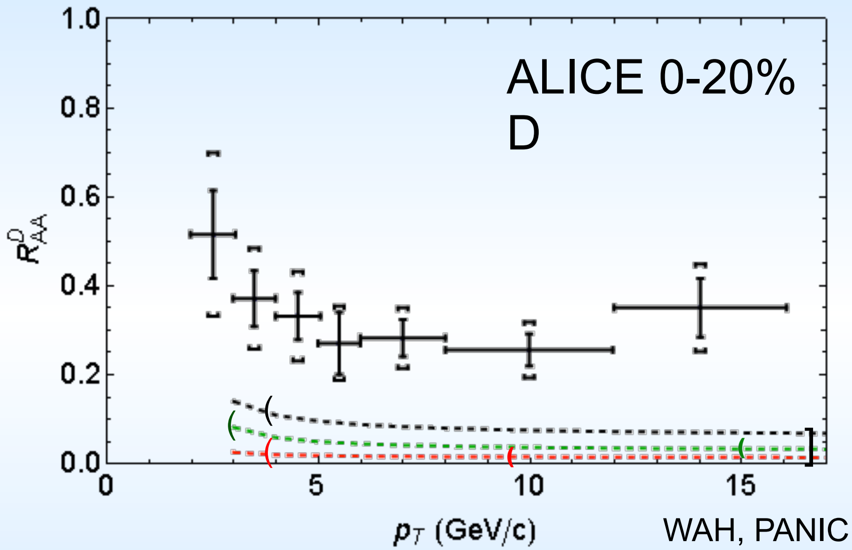
WAH, PhD Thesis, arXiv:1011.4316



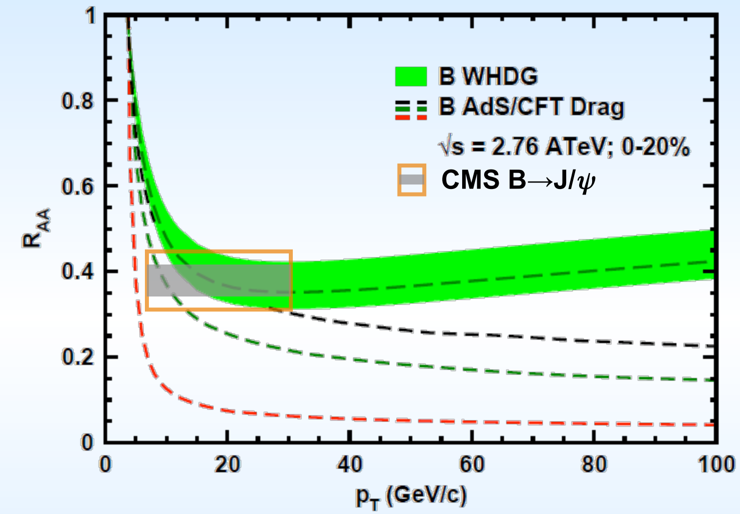
Akamatsu, Hatsuda, and Hirano, PRC79, 2009

AdS/CFT and HQ at LHC

- D Predictions



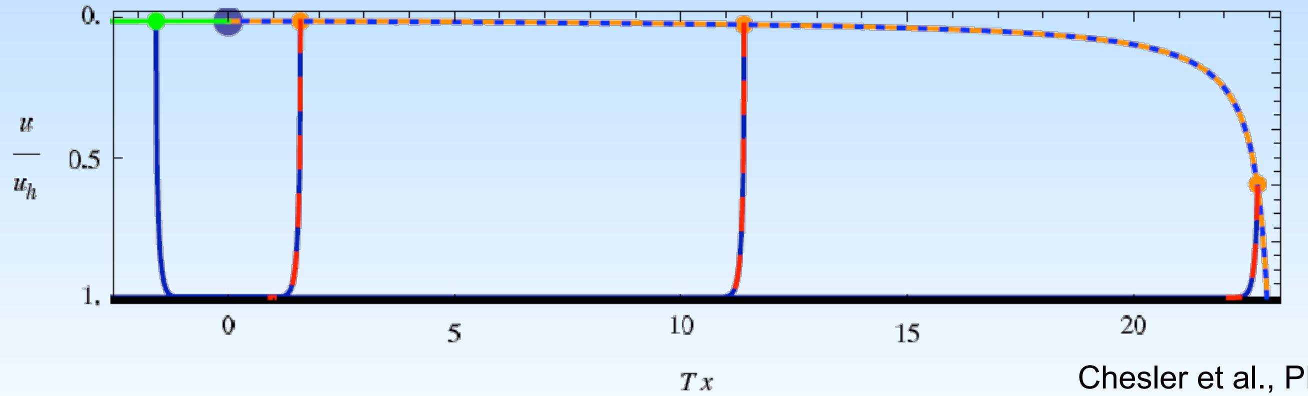
- B Predictions



WAH, PANIC11 (arXiv:1108.5876)
ALICE, arXiv:1203.2160
CMS, JHEP 1205 (2012) 063

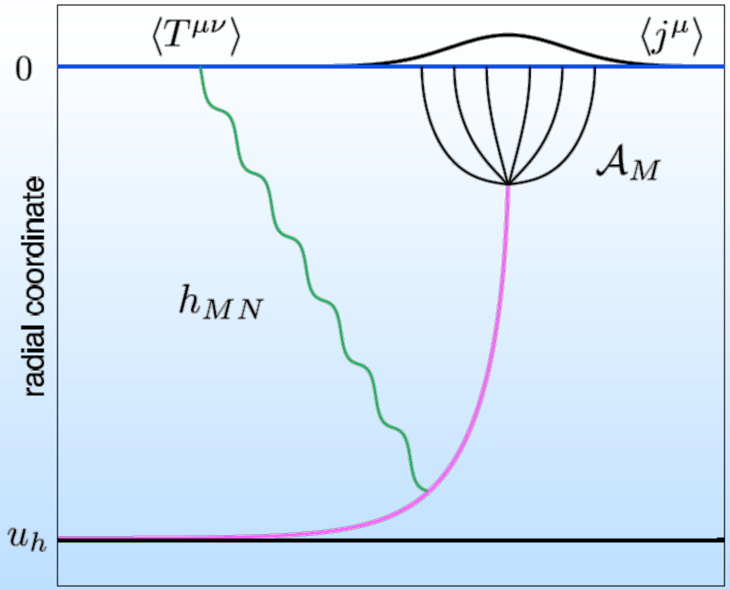
- AdS HQ Drag appears to oversuppress D
  - Long. fluctuations likely important, not included
- Roughly correct description of B→J/ψ

Light Quark E-Loss in AdS

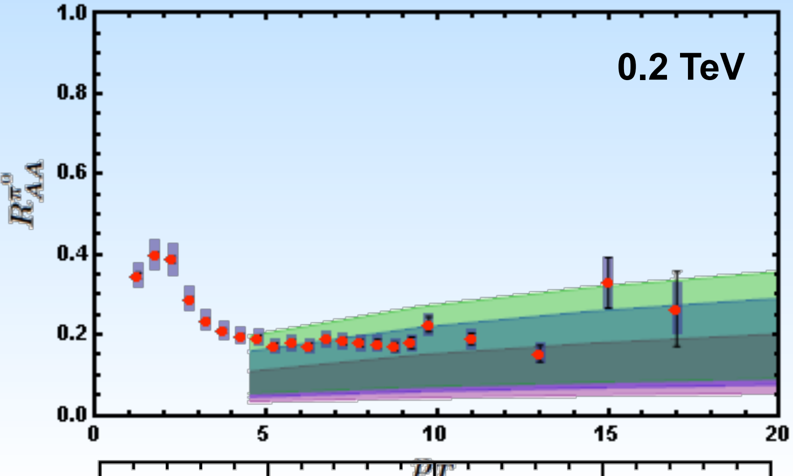


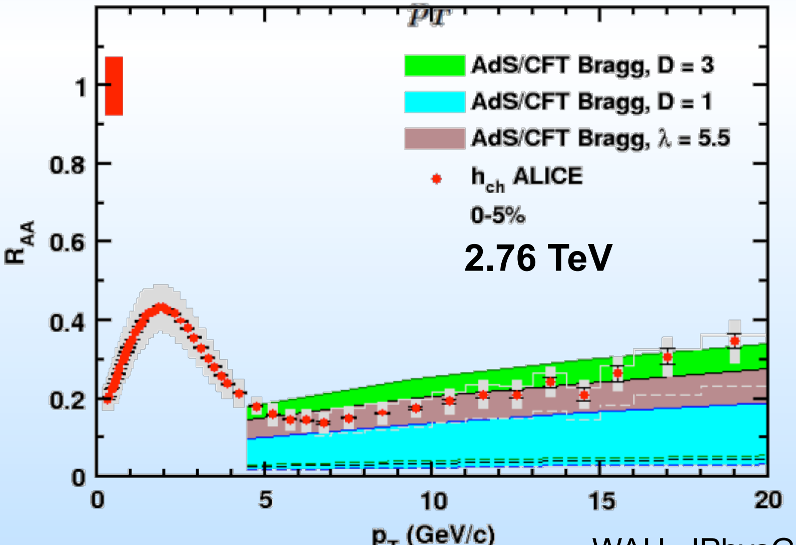
Chesler et al., PRD79 (2009)

- Complications:
  - string endpoints fall
    => painful numerics
  - relation to HI meas.
    - less obvious than HQ
- In principle, compute $T^{\mu\nu}$ from graviton emission
  - Extremely hard



AdS/CFT Light q E-Loss





WAH, JPhysG38 (2011)

Simple Bragg peak model

- Static thermal medium => very short therm. time
  - τ_{th} ~ 2.7 fm
    - AdS likely oversuppresses compared to data
- Examine T ~ $1/\tau^{1/3}$ geom
  - τ_{th} ~ 4.1 fm; Bragg peak disappears

R Morad

Strongly Coupled HF @QM

- More information/differing opinions
  - Chesler, "Gravitational collapse and holographic thermalization", 3D
  - Rajagopal, "Shining a Gluon Beam through Quark-Gluon Plasma", 5D
  - Ficnar, "Can falling strings in deformed AdS geometries account for the surprising transparency of the sQGP at LHC?", Poster

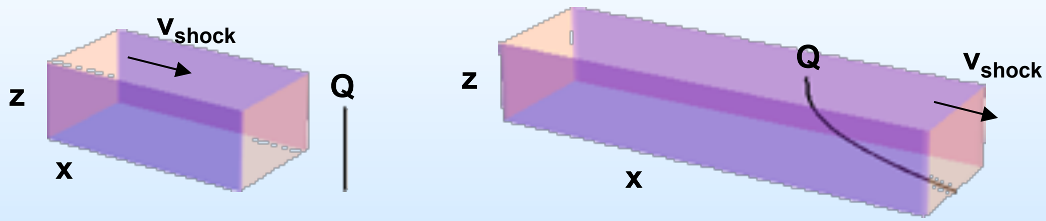
Strongly Coupled HF into the Future

- Measure open HF in p+A
  - Midrapidity: test production (Tuchin, 2D)
  - Forward: test CNM HF E-loss

Embedded String in Shock

$$ds^2 = \frac{L^2}{z^2}\left[-2dx^+dx^- + 2\,\mu\,z^4\,\theta(x^-)\,dx^{-2} + dx_\perp^2 + dz^2\right]$$

Before After

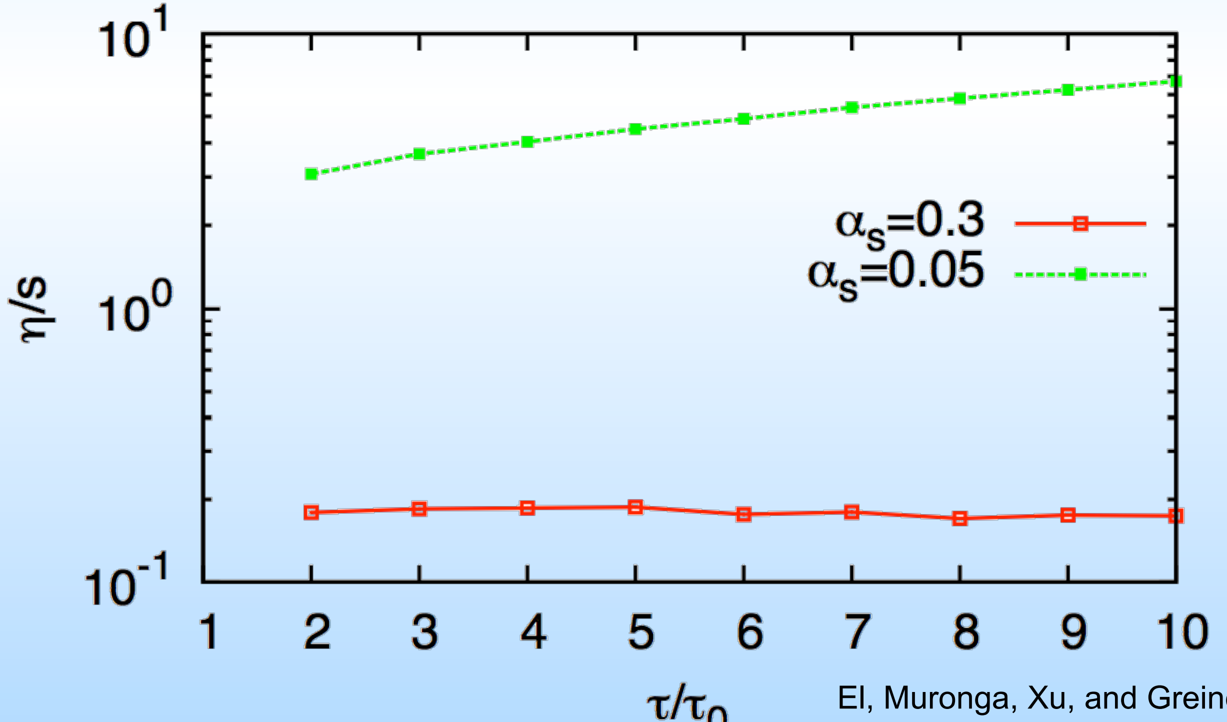


WAH and Kovchegov, PLB680 (2009)

$$\frac{dp'}{dt'} = -\frac{\sqrt{\lambda}}{2\pi}\frac{\Lambda^2}{M_q}p'$$

Let's Assume pQCD is the Best Approx

- Also not unreasonable
  - $\alpha_s(2\pi T) = 0.3$
    - Always large p_T scale
  - 2➞2 & 2➞3 pQCD MC suggests η/s ~ few/4π



El, Muronga, Xu, and Greiner, PRC79 (2009)

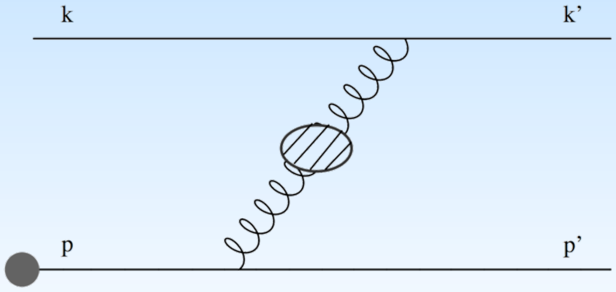
Let's Assume pQCD is the Way to Go

- Thermal Field Theory =>
  - Debye mass $\mu \sim gT$
  - Mean free path $\lambda_{mfp} \sim 1/g^2T$
- Entropy/Hydro => $T_{RHIC(LHC)} \sim 350\ (450)$ MeV
  - $\mu \sim gT \sim 0.7\ (0.8)$ GeV => $1/\mu \sim 0.3\ (0.2)$ fm
  - $\lambda^{gluon}_{mfp} \sim 1/g^2T \sim 0.8\ (0.7)$ fm
  - $R_{Au,Pb} \sim 6$ fm
- $1/\mu \ll \lambda_{mfp} \ll L$
  - Scattering off separated, well-defined quasiparticles
  - For HQ, order a few collisions, ~ 4

pQCD Continued

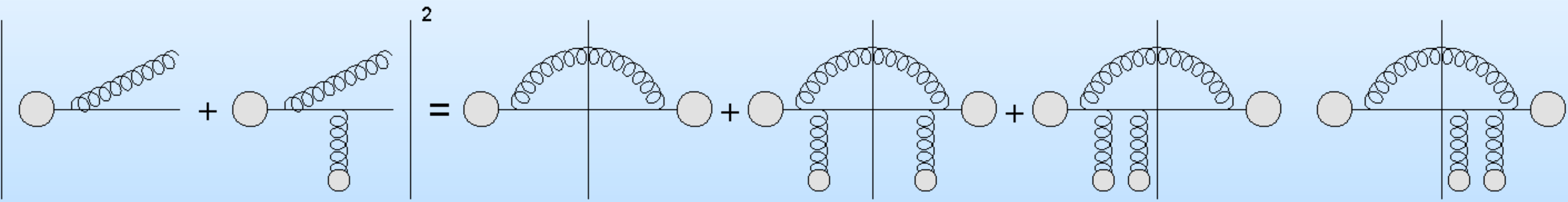
- Two types of E-loss
  - Collisional (elastic) 2→2

- Bjorken, FERMILAB-PUB-82-059-THY
- Braaten and Thoma, PRD44:2625–2630, 1991
- Djordjevic, Phys.Rev. C74 (2006) 064907
- Adil et al., Phys.Rev. C75 (2007) 044906



Djordjevic, PRC74 (2006)

  - Radiative (inelastic) 2→3
    - Scales => ~few scatterings, mult. coh. em. => LPM
    - Must include interference with production radiation



- Majumder and van Leeuwen, PPNPA66 (2011), and refs therein

Asymptotic Analytic pQCD

- Naively, $\Delta E_{el} << \Delta E_{rad}$ as $E \rightarrow \infty$

- Elastic E-loss:

$$dp_T/dt \sim -T^2 \log(p_T/M_Q)$$

- Radiative E-loss, in expected deep LPM regime:

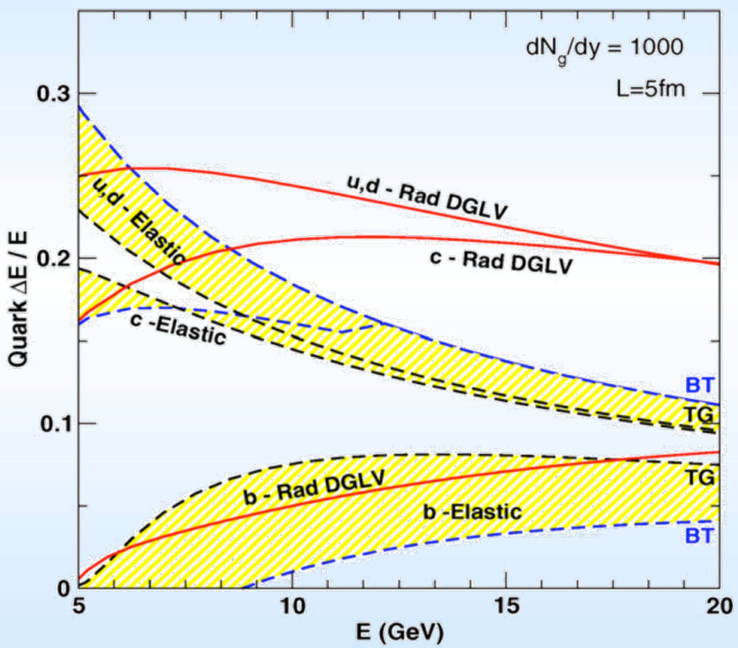
$$dp_T/dt \sim -L\, T^3 \log(p_T/M_Q)$$

  – Compare to Bethe-Heitler $dp_T/dt \sim -(T^3/M^2)p_T$

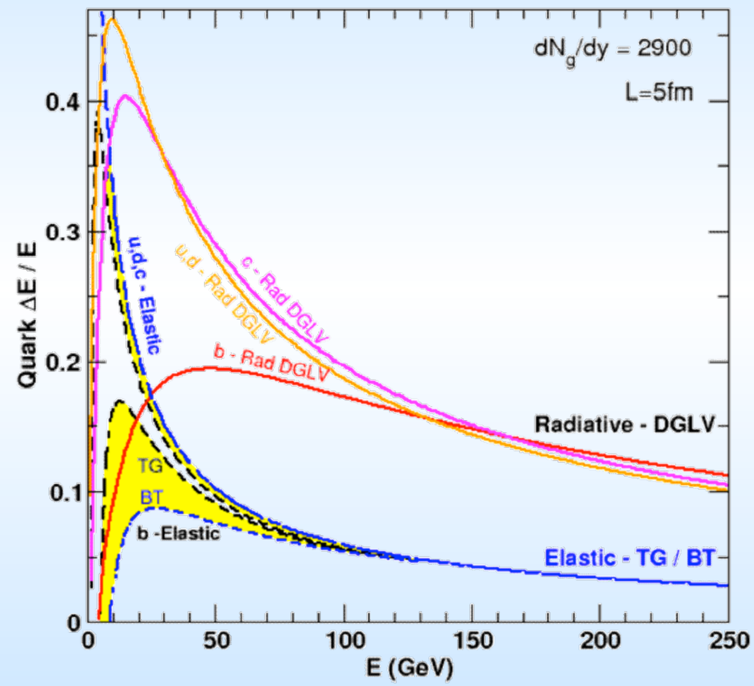
Results

- Naively, $\Delta E_{el} << \Delta E_{rad}$ as $E \rightarrow \infty$

RHIC



LHC

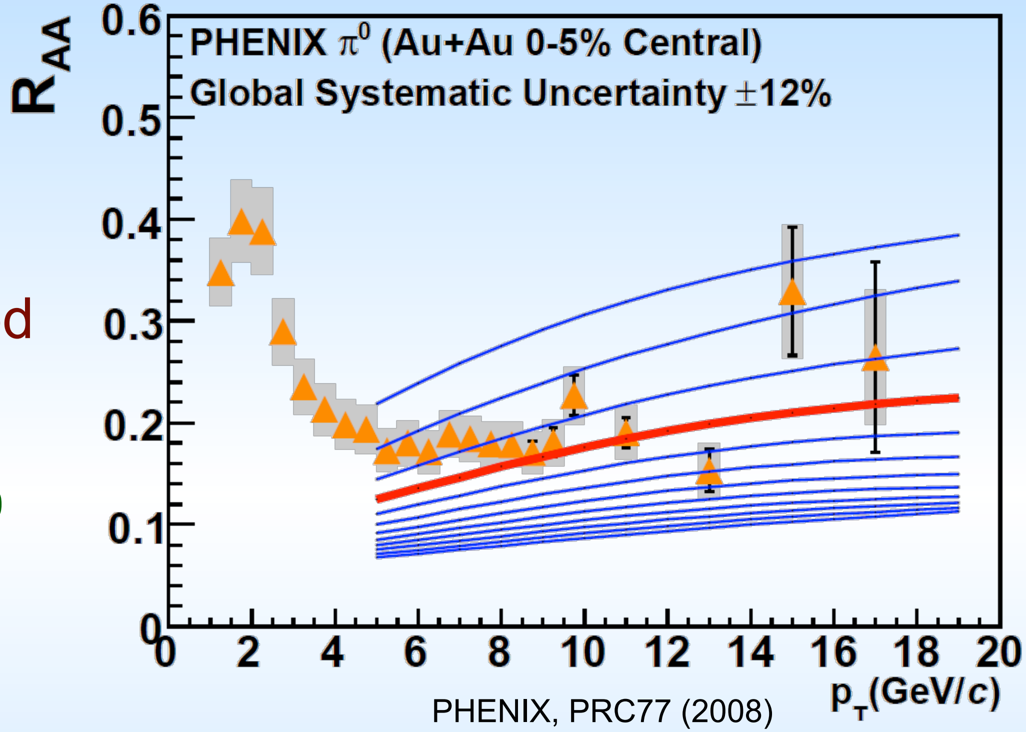


WAH, PhD Thesis, arXiv:1011.4316

Finite RHIC/LHC kinematics: both radiative and collisional energy loss processes are important for $p_T \sim 5$ GeV/c and higher

Compare to RHIC & LHC

- RHIC R_{AA}: not unreasonable ρ_{med}
  - – $dNg/dy = 1400^{+200}_{-375}$
  - – $\alpha_s = 0.3$, fixed

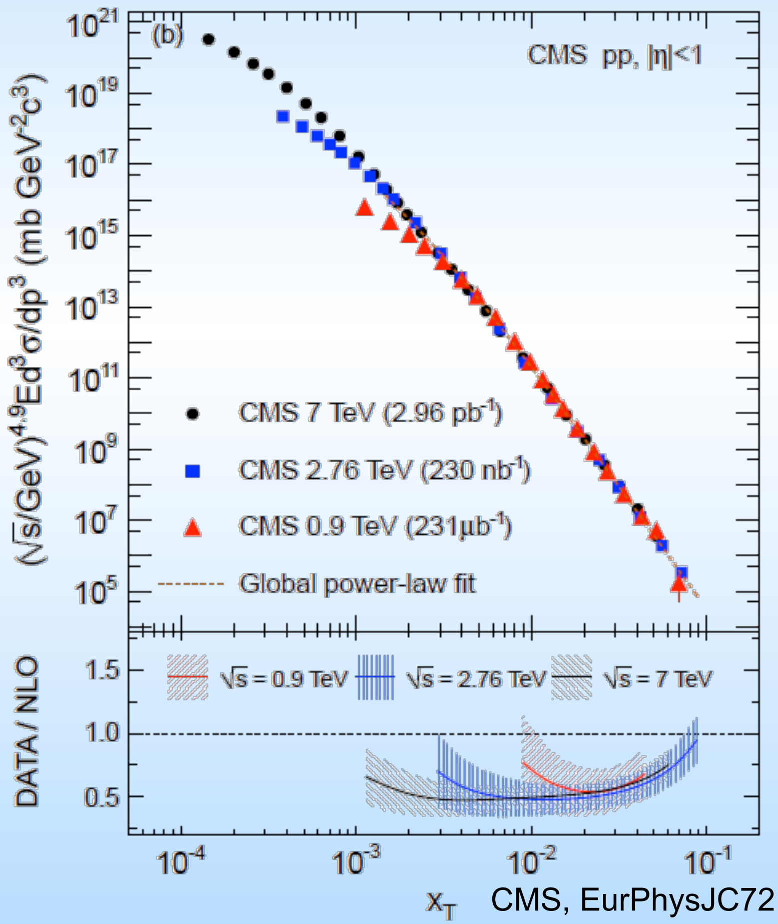


PHENIX, PRC77 (2008)

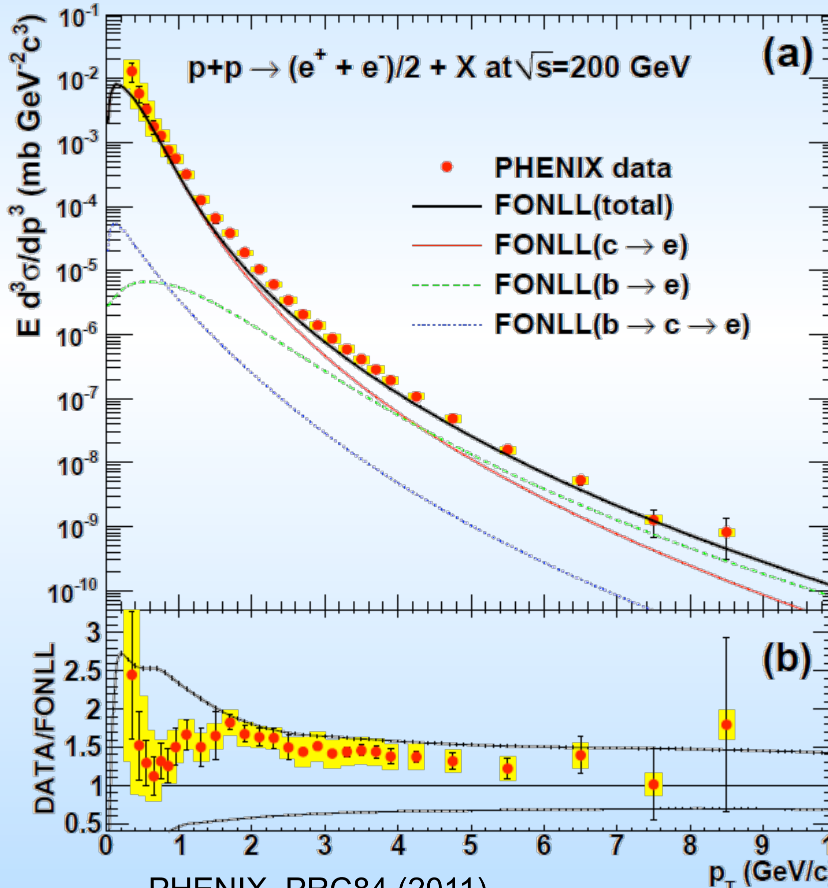
- For LHC predictions: change only $\rho_{med} \propto dN_{ch}/d\eta$

Set Scale for our Expectations

- NLO pQCD in pp System ~ factor of 2



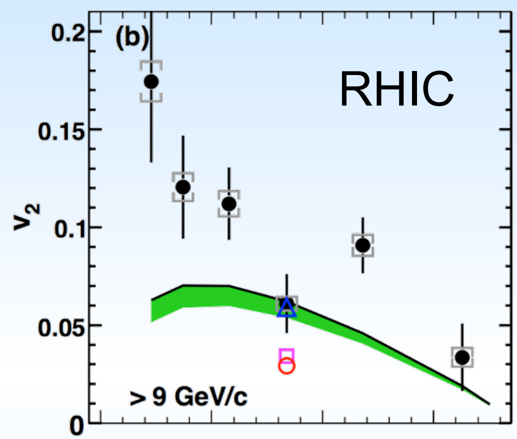
CMS, EurPhysJC72 (2012)

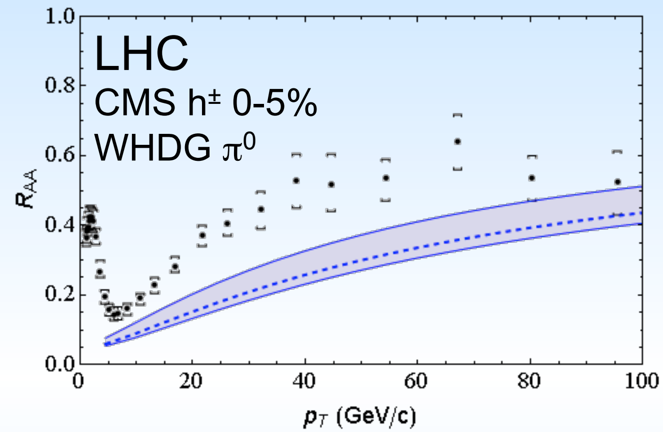


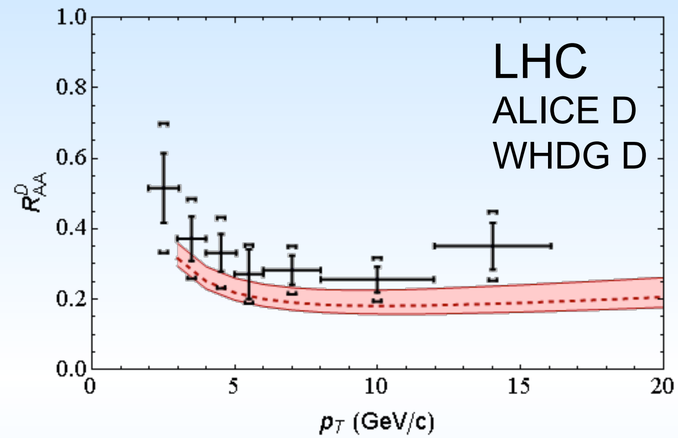
PHENIX, PRC84 (2011)

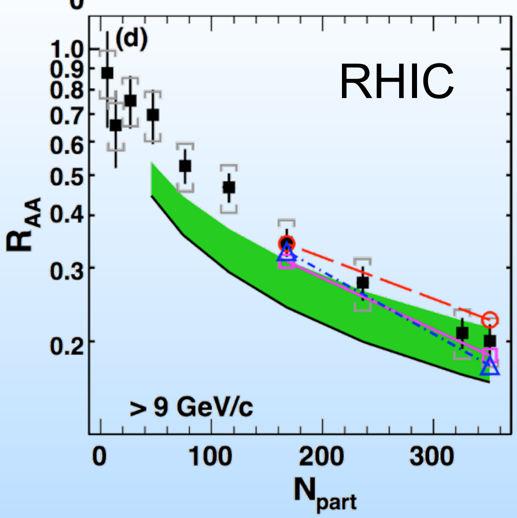
Global Qualitative Agreement

- LO pQCD E-loss correct to factor ~2

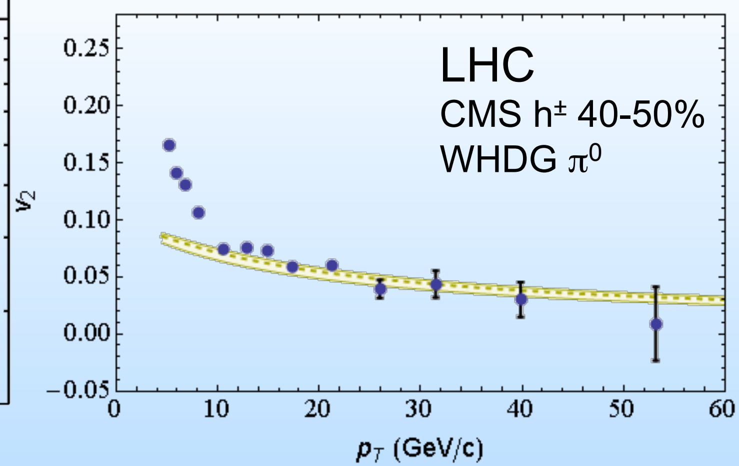




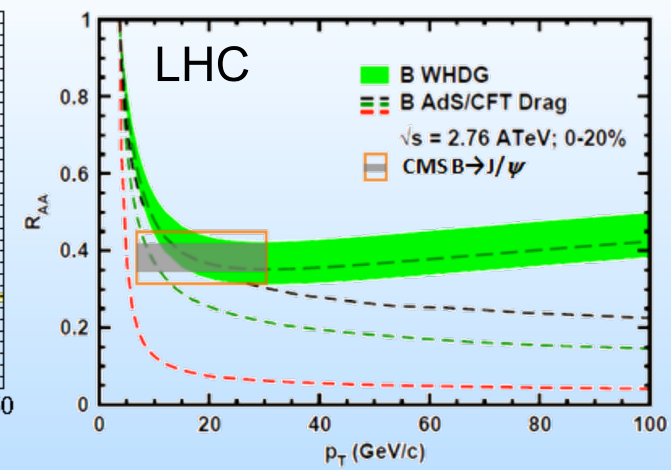




PHENIX PRL105 (2010)



CMS, Eur.Phys.J. C72 (2012)
CMS, arXiv:1204.1850

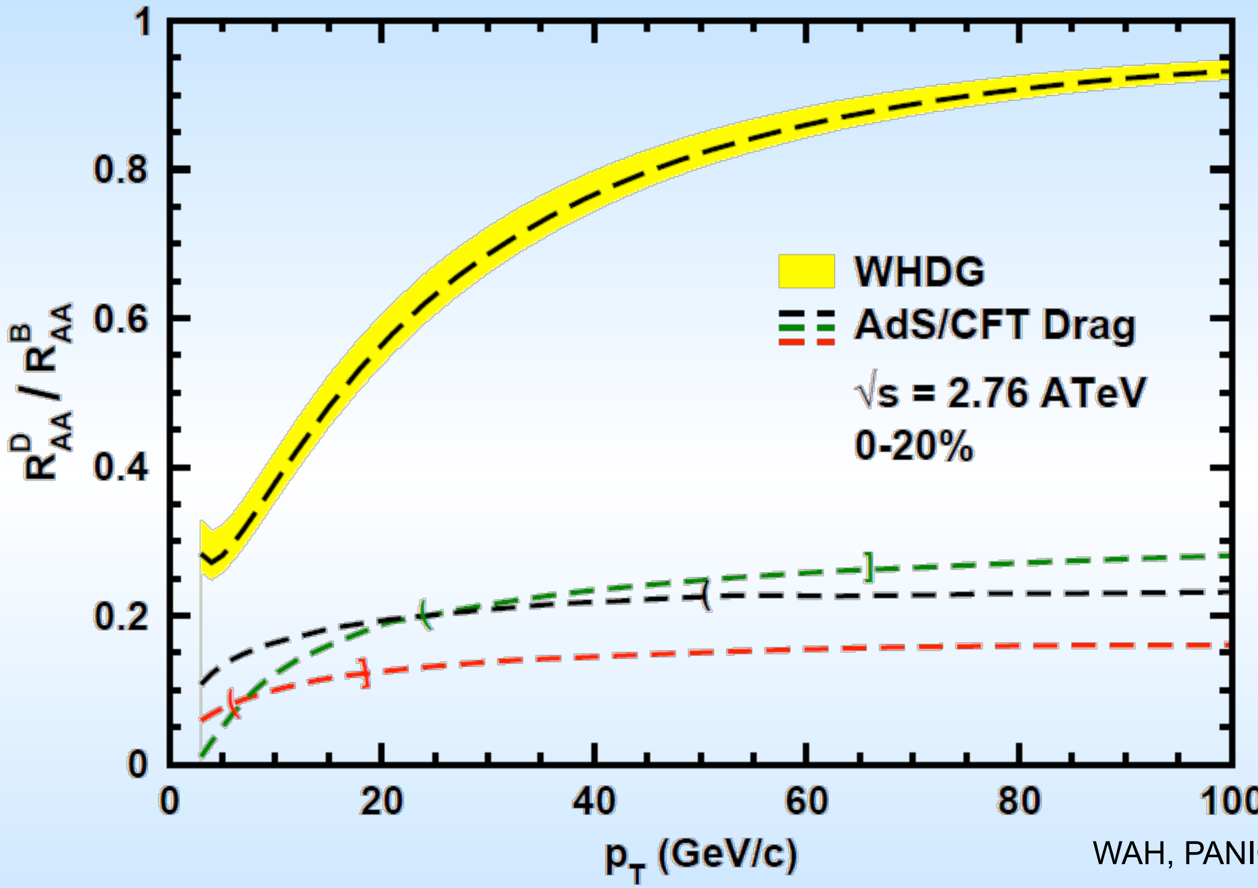


ALICE, arXiv:1203.2160
CMS, JHEP 1205 (2012) 063

Potential Improvements at QM

- MC, parton cascade: Uphoff, poster
- NLO ansatz, better modeling: Buzzatti, 5C
- Additional Channels
  - In-medium fragmentation: Sharma, 2D
  - Non-perturbative 2→2 x-scns: He, Poster
- Be careful with:
  - Uncontrolled (& esp. uncontrollable) physics
  - Radiative only or Elastic only
  - Lack of finite time effects: wrong L dependence
  - Approximating pQCD with Langevin: far from central limit theorem, wrong p_T dependence

Does pQCD or AdS Yield Correct Mass & Momentum Dependecies at LHC?



WAH, PANIC11 (arXiv:1108.5876)

– $T(\tau_0)$: "(", corrections likely small for smaller momenta
– T_c: "]", corrections likely large for higher momenta

Qualitatively, corrections to AdS/CFT result will drive double ratio to unity

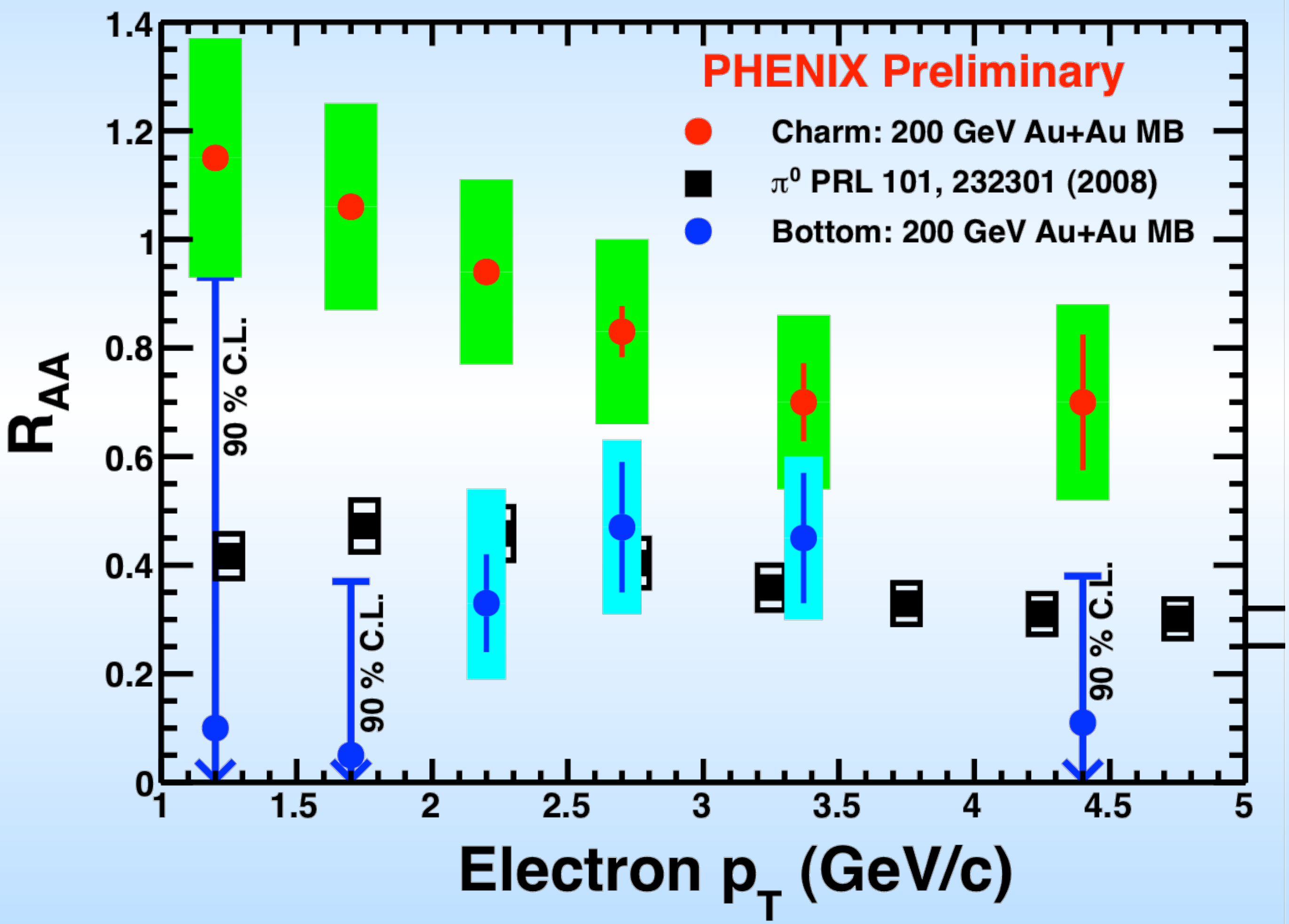
See also:
WAH, M. Gyulassy, PLB666 (2008)

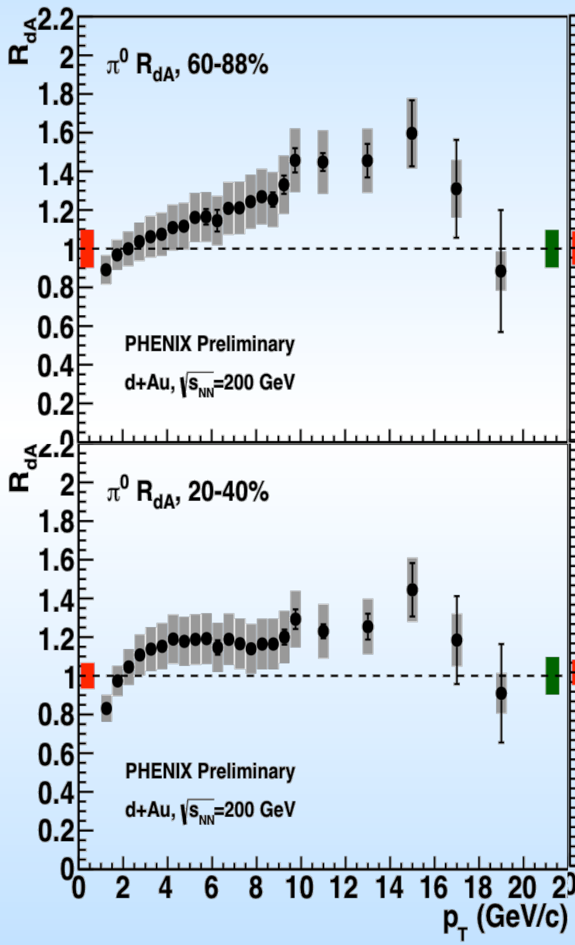
Take-away Messages

1. E-loss depends on p_T, L, T, M_Q
   1. M_Q dependence provides unique insight into E-loss, QGP properties
   2. Want to vary others, too: consistent, coherent picture
2. Multiple observables demand simultaneous description: ***hard***
   1. Difficult to describe data with AdS/CFT?
   2. LO pQCD gives reasonable qualitative description
      1. How do we understand sQGP(hydro) => wQGP(E-loss)
3. p+A is more than control experiment
4. HF E-loss physics exciting with much fascinating research ahead!

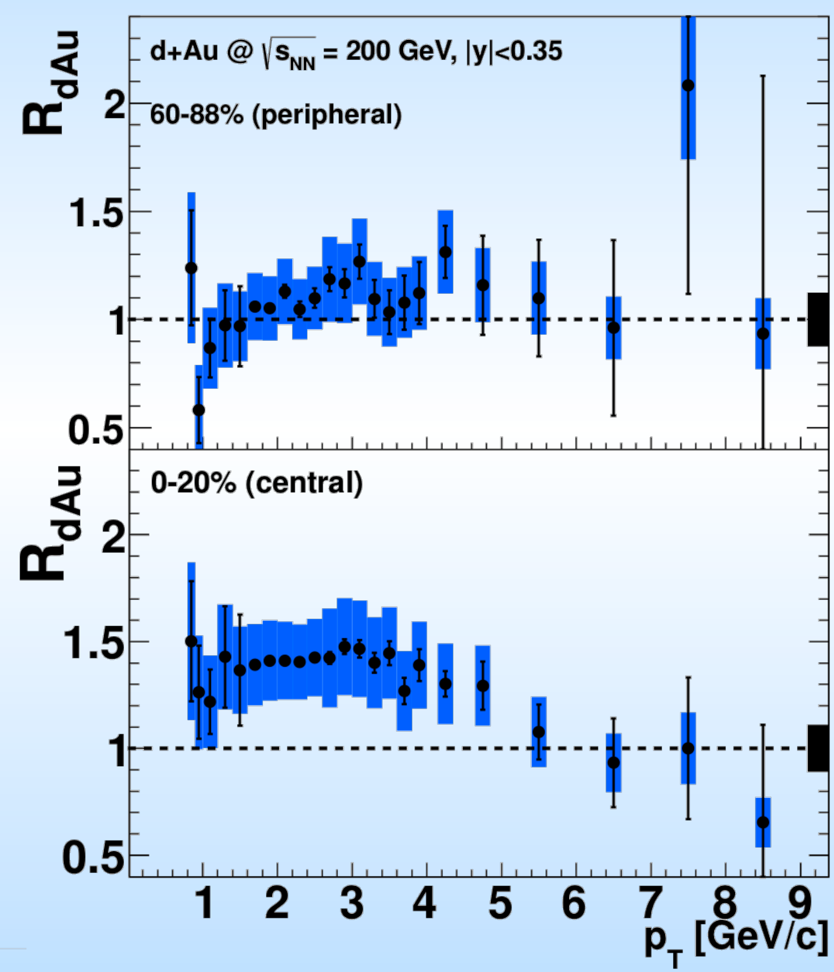
Rich and Vigorous HF E-loss Theory

- Talks:
  - Cao, "Heavy quark evolution and flow in hot and dense medium," 6A
  - Buzzatti, "A Running Coupling Explanation of the Surprisingly Transparency of the QGP at LHC," 5C
  - Gossiaux, "Heavy quark quenching from RHIC to LHC and the consequences of gluon damping," 7E
  - Rapp, "Comprehensive Analysis of In-Medium Quarkonia from SPS to LHC," 1D
  - Sharma, "High transverse momentum quarkonium production and dissociation in heavy ion collisions," 2D
- Posters:
  - Abir, "Soft gluon emission and energy loss of heavy flavors in relativistic heavy ion collisions"
  - Akamatsu, "Quantum Description of Impurities - Heavy Quarks and Quarkonia"
  - Begum, "Suppression of D-mesons production at relativistic heavy ion collisions"
  - Durham, "A detailed study of open heavy flavor production, enhancement, and suppression at RHIC"
  - Ficnar, "Can falling strings in deformed AdS geometries account for the surprising transparency of the sQGP at LHC?"
  - Levai, "Charm production in the early phase and the charm baryon-to-meson ratios at LHC energies"
  - Nahrgang, "Influence of a realistic medium description including fluctuations on heavy quark observables"
  - Petran, "Charm contribution to final hadron yield at LHC"
  - Uphoff, "Open heavy flavor and J/psi at RHIC and LHC within a transport model"
  - van Hees, "Heavy-quark diffusion at the LHC within a UrQMD-hydrodynamical hybrid model"
  - Vogel, "Influence of the medium evolution on heavy quark observables"
  - Vogel, "Heavy quark energy loss in p+p collisions at the LHC"

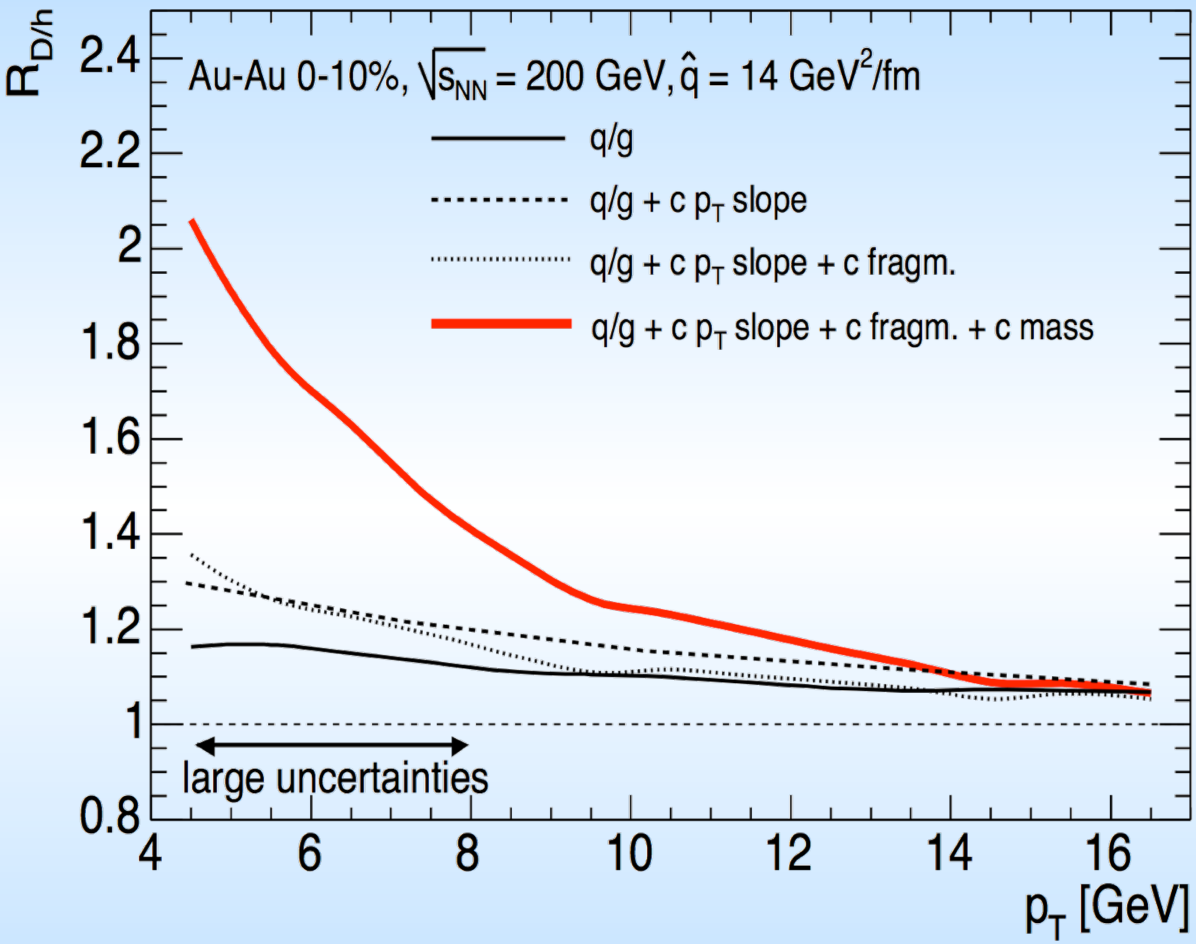

PHENIX Preliminary
Charm: 200 GeV Au+Au MB
π^0 PRL 101, 232301 (2008)
Bottom: 200 GeV Au+Au MB
90 % C.L.
90 % C.L.
90 % C.L.
R_{AA}
Electron p_T (GeV/c)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1
1.5
2
2.5
3
3.5
4
4.5
5



π^0 R_{dA}, 60-88%
π^0 R_{dA}, 40-60%
π^0 R_{dA}, 20-40%
π^0 R_{dA}, 0-20%
PHENIX Preliminary
d+Au, $\sqrt{s_{NN}}$=200 GeV
R_{dA}
p_T (GeV/c)



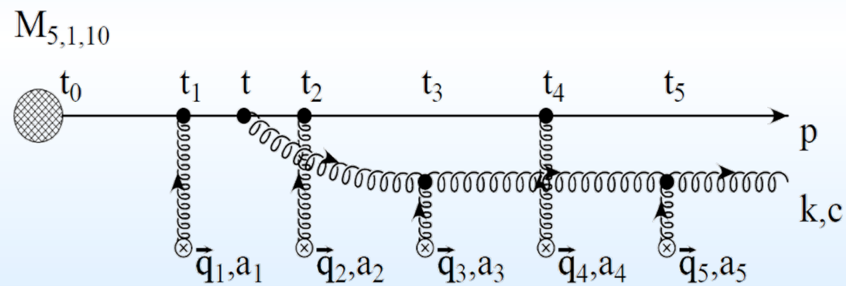
d+Au @ $\sqrt{s_{NN}}$ = 200 GeV, |y|<0.35
60-88% (peripheral)
0-20% (central)
R_{dAu}
p_T [GeV/c]



Armesto et al., NPA774 (2006)

pQCD Rad Picture

- Bremsstrahlung Radiation
  - Weakly-coupled plasma
    - Medium organizes into Debye-screened centers
  - T ~ 350 (450) MeV, g ~ 1.9 (1.8)
    - $\mu \sim gT \sim 0.7\ (0.8)$ GeV
    - $\lambda_{mfp} \sim 1/g^2T \sim 0.8\ (0.7)$ fm
    - $R_{Au,Pb} \sim 6$ fm
  - $1/\mu \ll \lambda_{mfp} \ll L$
    - multiple coherent emission



Gyulassy, Levai, and Vitev, NPB571 (2000)

- LPM

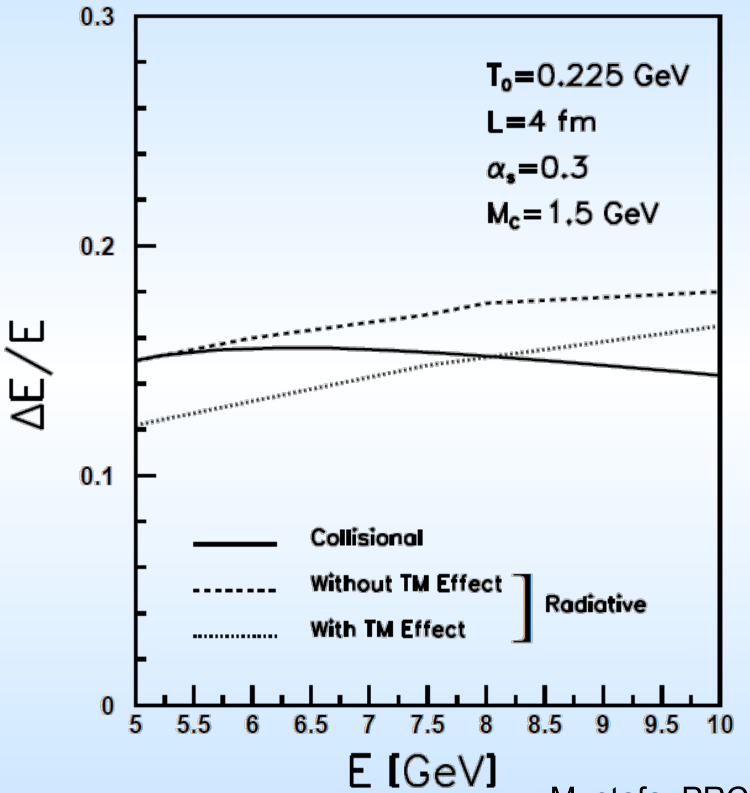
  $dp_T/dt \sim -LT^3 \log(p_T/M_q)$

- Bethe-Heitler

  $dp_T/dt \sim -(T^3/M_q^2)\ p_T$

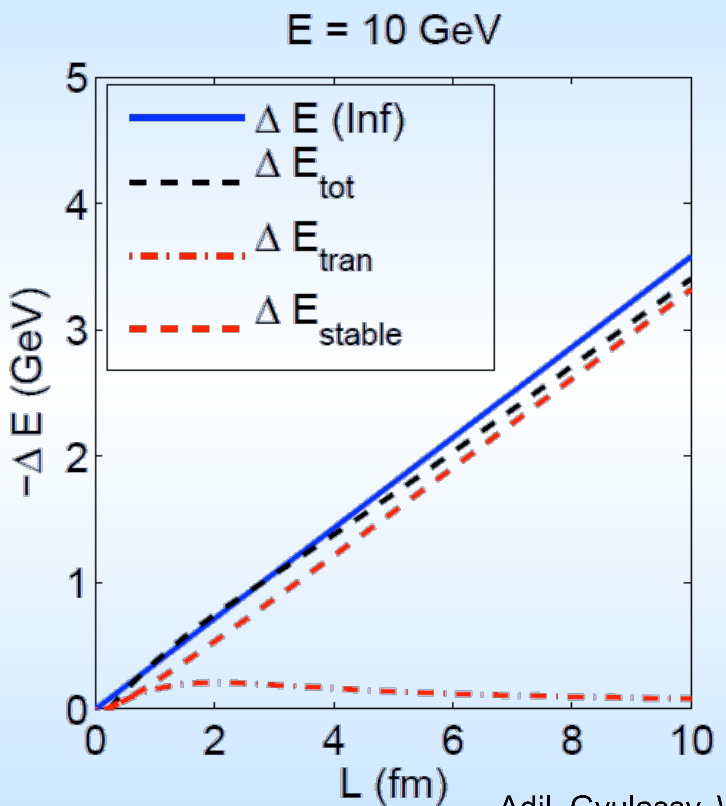
What About Elastic Loss?

- Appreciable!



Mustafa, PRC72 (2005)

- Finite time effects small



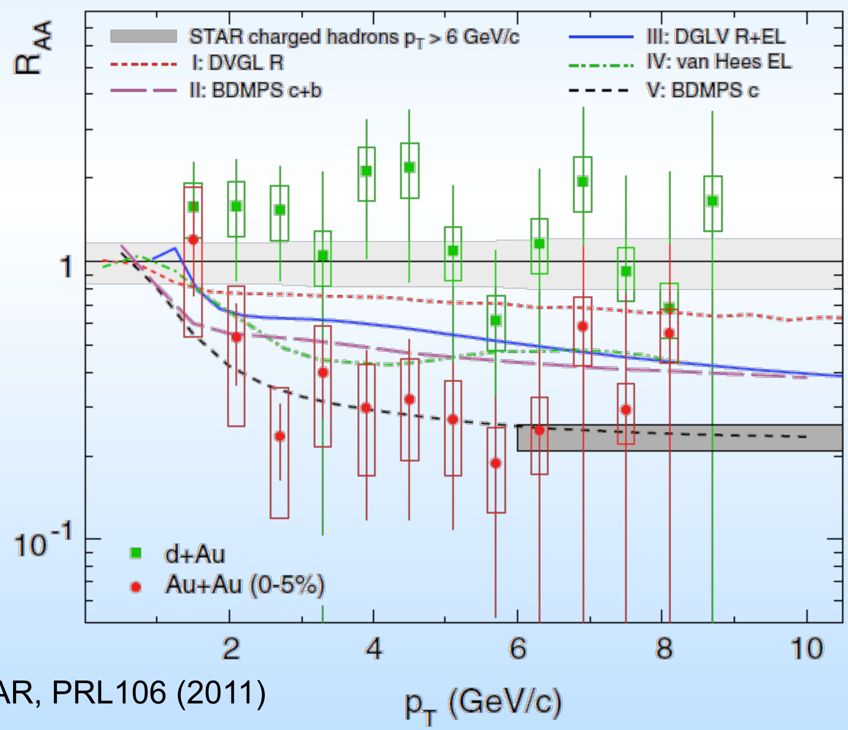
Adil, Gyulassy, WAH, Wicks, PRC75 (2007)

– For pQCD comparisons with data, use WHDG Rad+El +Geom model; formalism valid for g/lq & hq

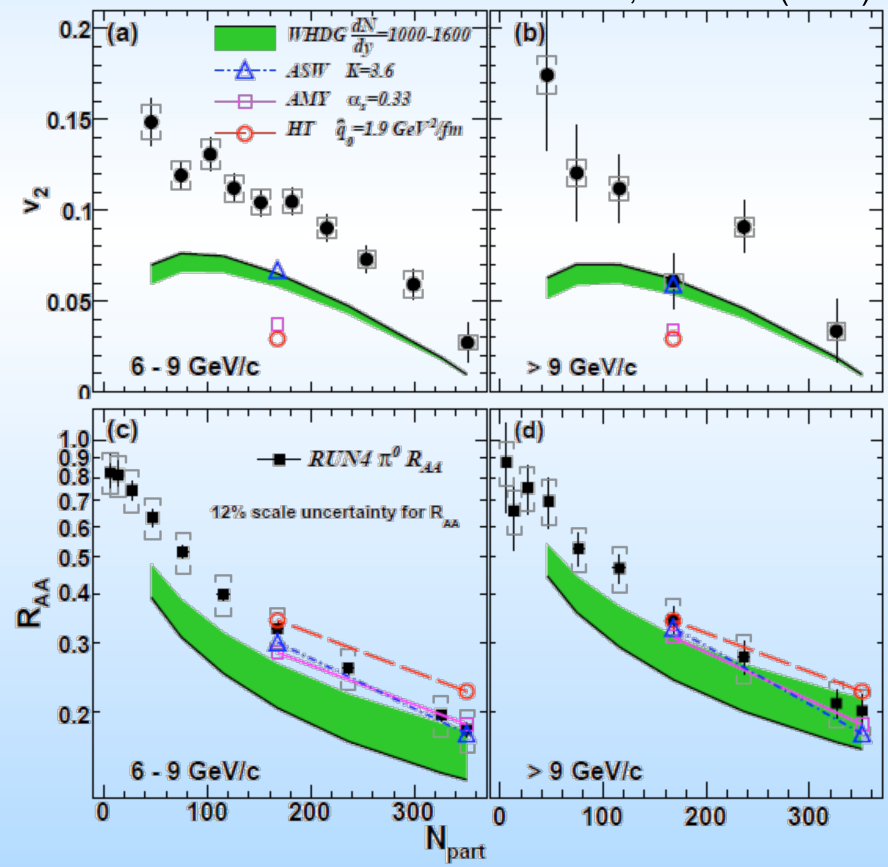
pQCD Not Quantitative at RHIC

- Lack of simultaneous description of multiple observables
  - even with inclusion of elastic loss

PHENIX, PRL 105 (2010)



STAR, PRL106 (2011)



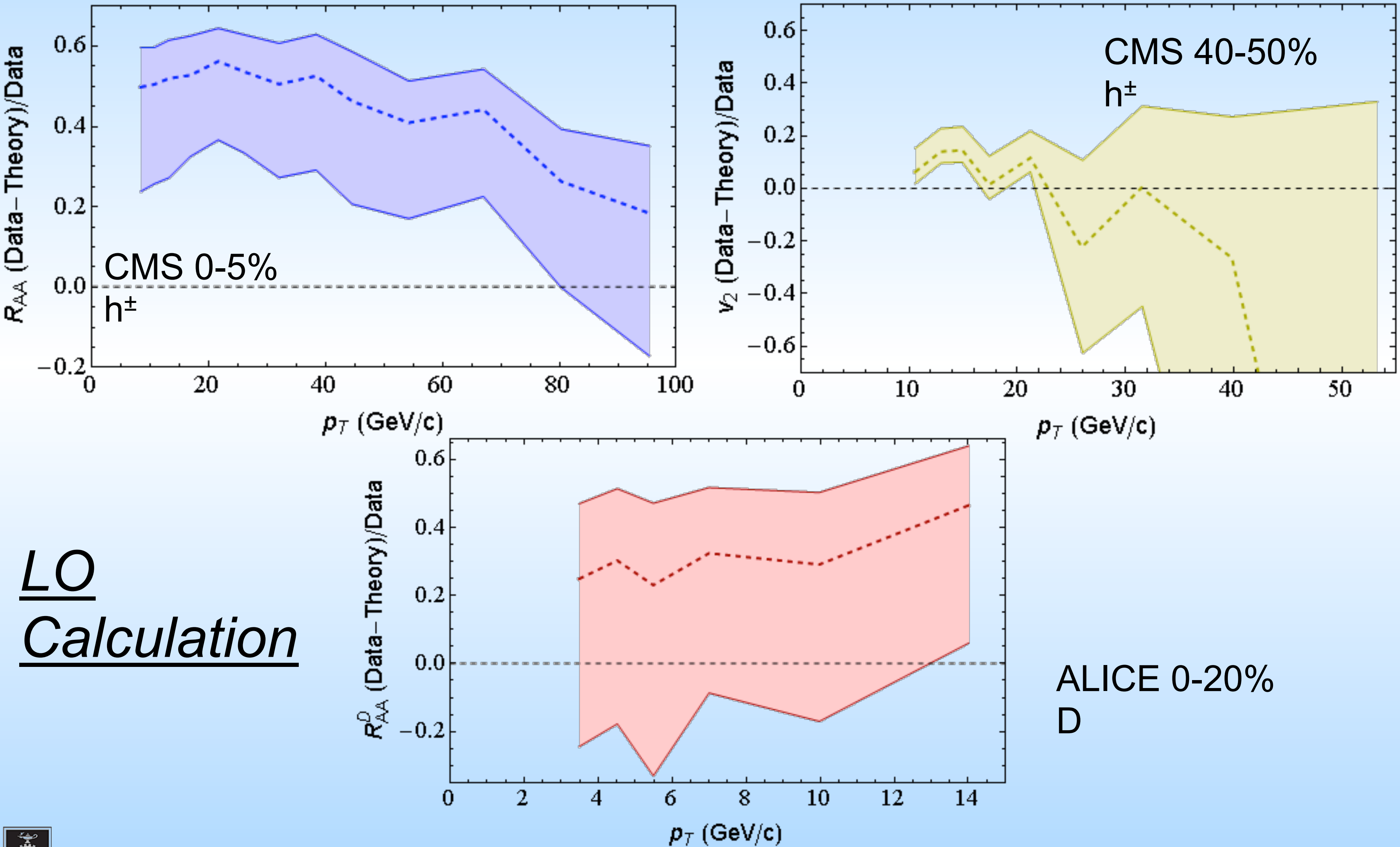
See also J Jia from QM09,
J Nagle QM09

LHC energies?

Quant. (Qual?) Conclusions Require...

- Further experimental results
- Theoretically, investigation of the effects of
  - higher orders in
    - α_s (***large***)
    - k_T/xE (***large***)
    - M_Q/E (large?)
    - opacity (large?)
  - geometry
    - uncertainty in IC (small)
    - coupling to flow (large?)
    - Eloss geom. approx. (?)
    - $\tau < \tau_0$ (***large***: see Buzzatti and Gyulassy)
    - dyn. vs. static centers (see Djordjevic)
    - hydro background (see Renk, Majumder)
  - better treatment of
    - Coh. vs. decoh. multigluons (see Mehtar-Tani)
    - elastic E-loss
    - E-loss in confined matter

(Data – pQCD)/Data



LO Calculation

ALICE 0-20%
D

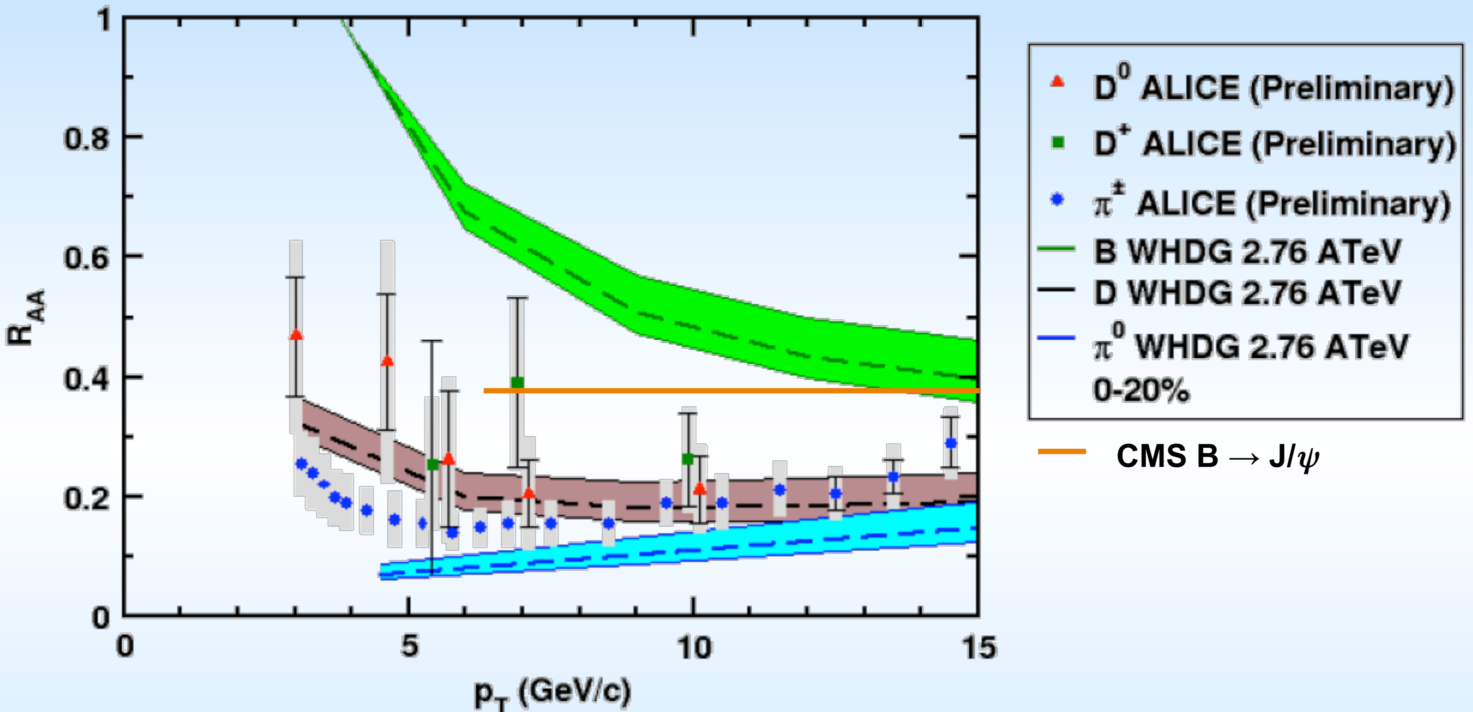
Strong Coupling Calculation

- The supergravity double conjecture:

  QCD ⇔ SYM ⇔ IIB

  - ***IF*** super Yang-Mills (SYM) is not too different from QCD, &
  - ***IF*** we believe Maldacena conjecture
  - Then a tool exists to calculate strongly-coupled QCD in SUGRA

And D, B (?) R_{AA} at LHC

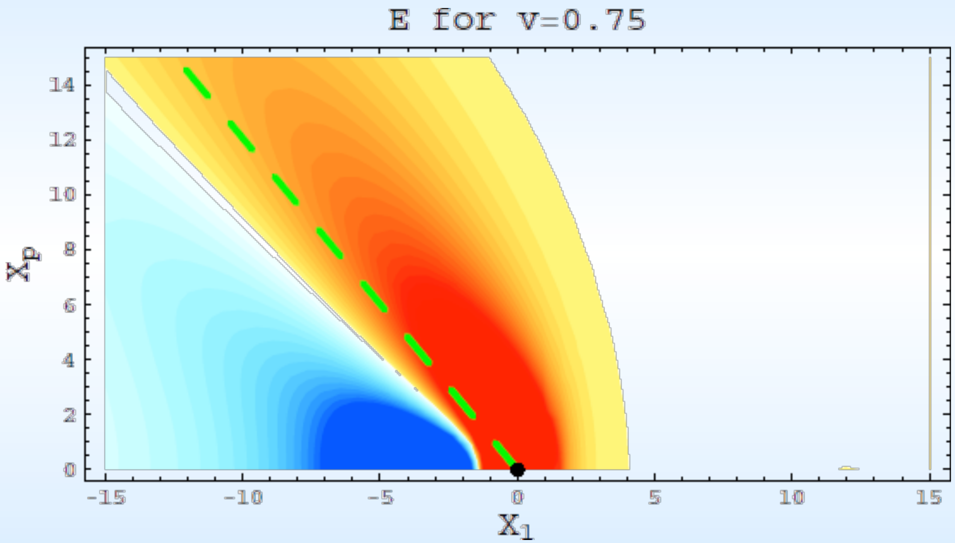


WAH and M Gyulassy, PANIC11 (arXiv:1107.2136)
ALICE, 1203.2160

- NB: R_{AA} requires production, E-loss, FF
  - Does not immediately follow that $R^{\pi}_{AA} << R^{D}_{AA} << R^{B}_{AA}$

Comparing to RHIC, LHC

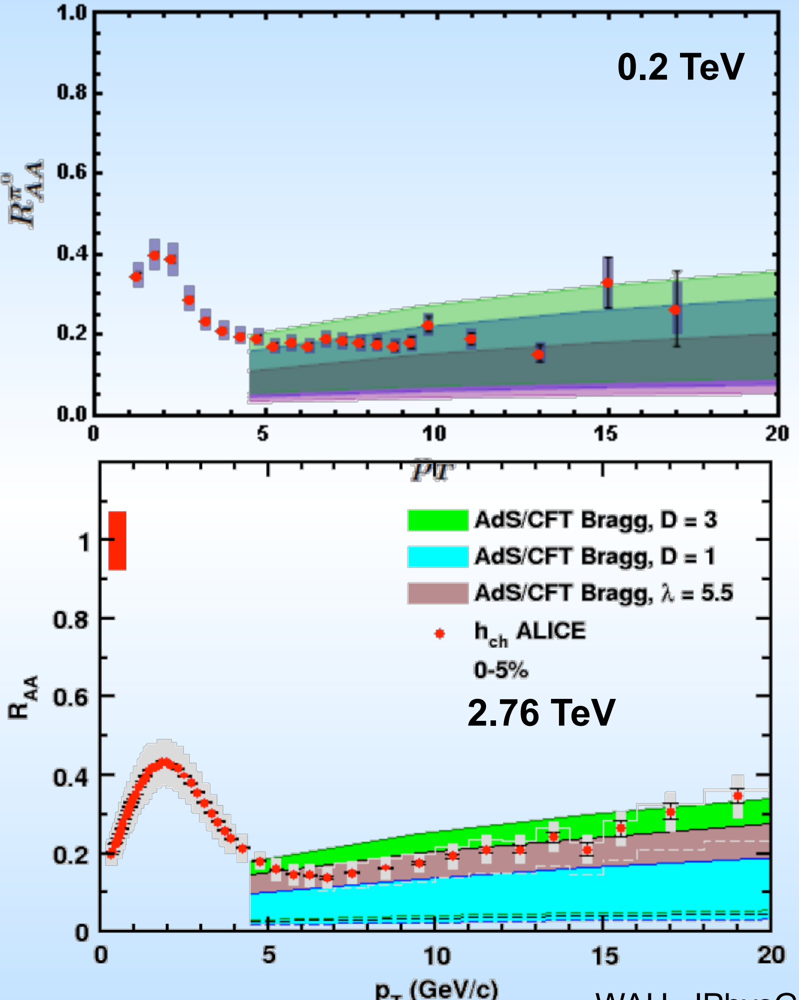
- In principle, can compute Tmn from graviton emission



Gubser, Pufu, Yarom, JHEP 0709 (2007)
See also Friess et al., PRD75 (2007)

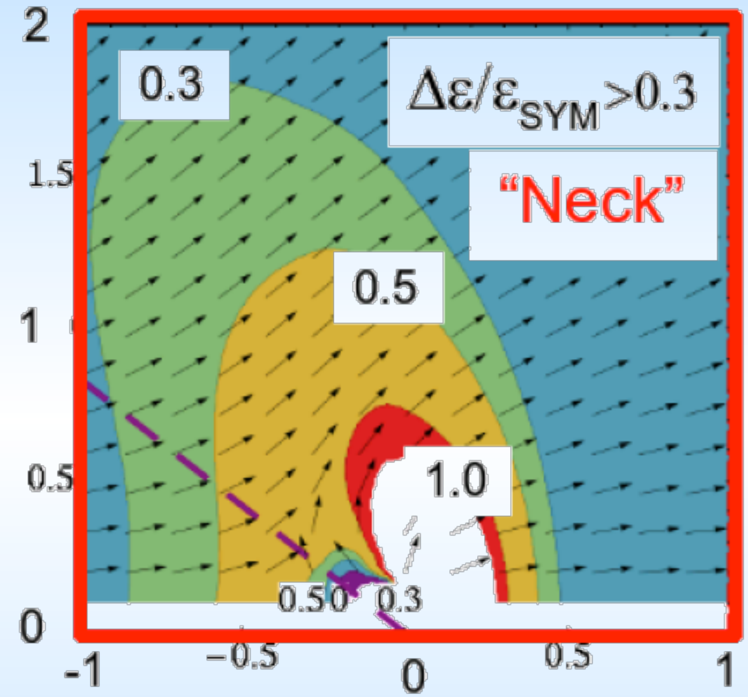
  - Extremely hard

AdS/CFT Light q E-Loss & Dist.



WAH, JPhysG38 (2011)

Simple Bragg peak model



Jo Noronha, M Gyulassy, and G Torrieri, PRL102 (2009)

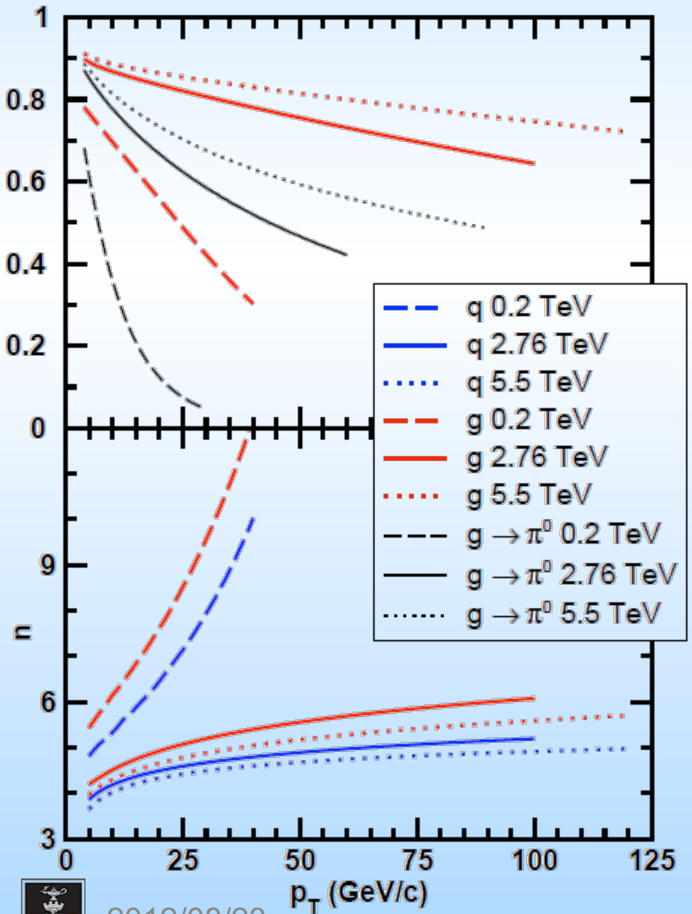
- Suggests wide angle energy loss

Energy Loss in QGP

- Claim: LHC predictions from rigorously RHIC constrained pQCD E-loss in qualitative/quantitative agreement with current data
  - Want to stress test the theory with as many experimental levers as possible
- Counter-claim: LHC predictions from AdS/CFT not falsified by current data
  - Want an obvious distinguishing measurement

Qualitative Expectations for LHC

– For approx. power law production and energy loss probability P(ε), $\varepsilon = (E_i - E_f)/E_i$



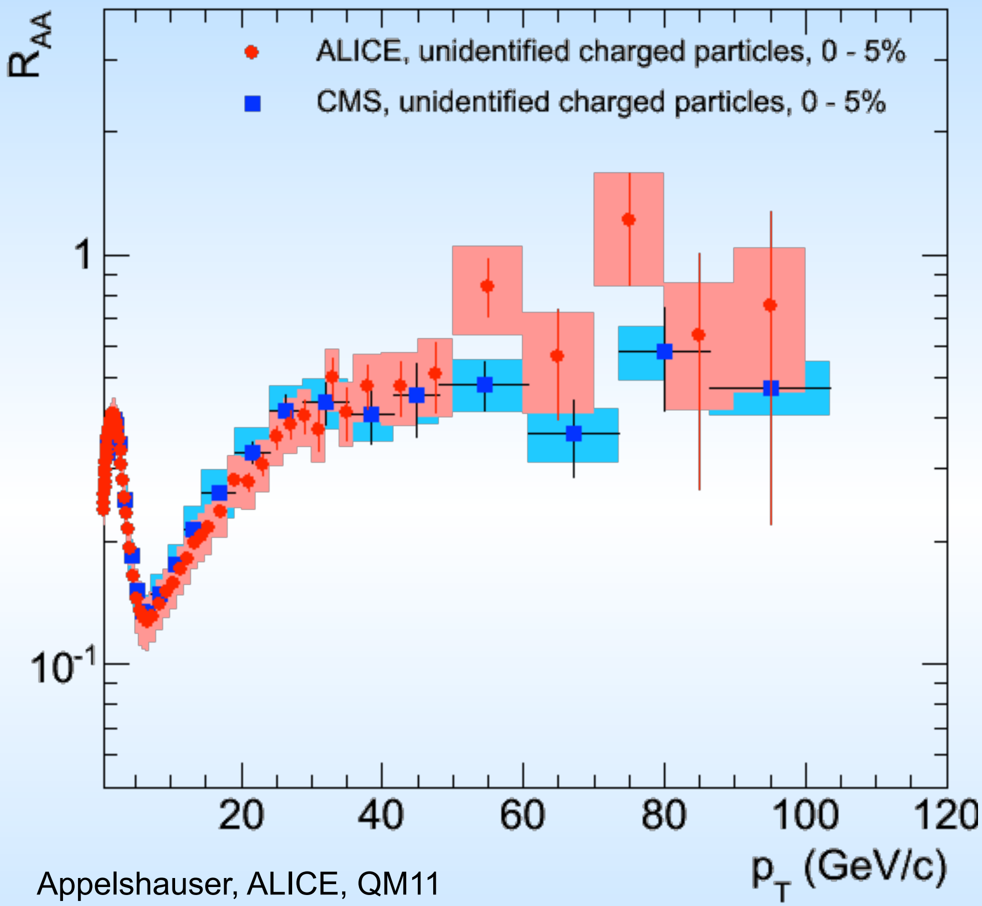
$$\frac{dN}{dp_T} \sim \frac{1}{p_T^{n+1}} \quad \Rightarrow \quad R_{AA} \approx \langle \int d\varepsilon (1-\varepsilon)^n P(\varepsilon) \rangle$$

– Asymptotically, pQCD => ΔE/E ~ log(E/μ)/E

- ~ flat $R_{AA}(p_T)$ at RHIC
- Rising $R_{AA}(p_T)$ at LHC

– NB: LHC is a glue machine

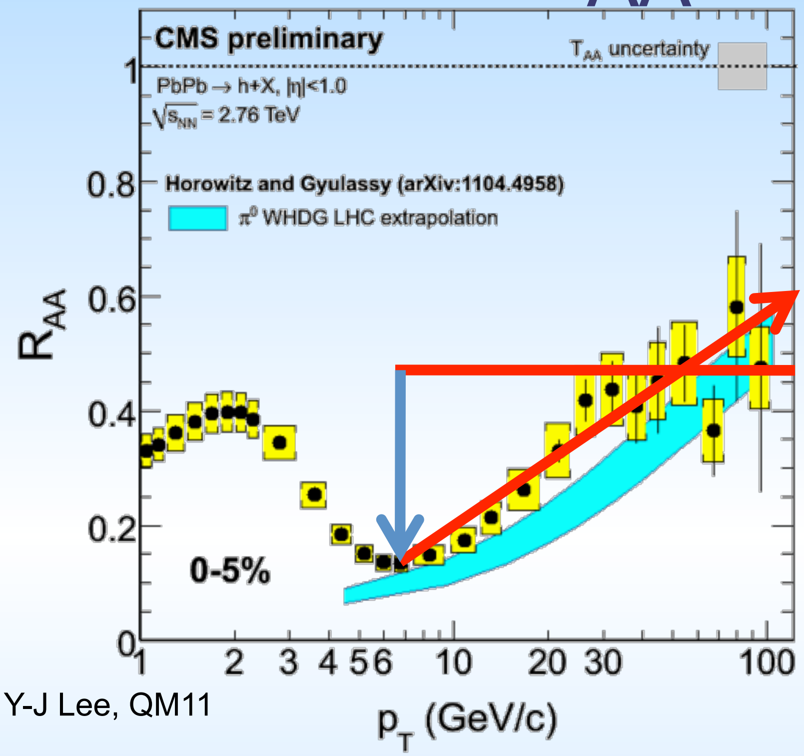
Qualitatively Perturbative at LHC



Appelshauser, ALICE, QM11

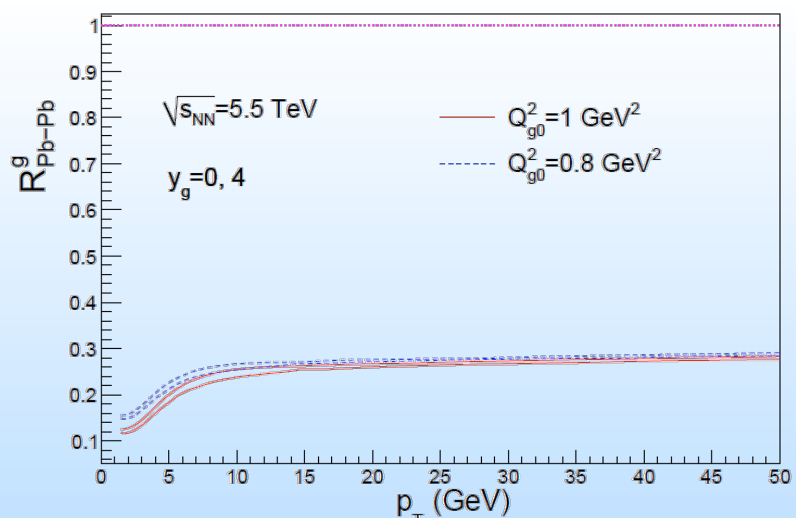
- p_T rise in data readily understood from generic perturbative physics!

Rise in R_{AA} a Final State Effect?

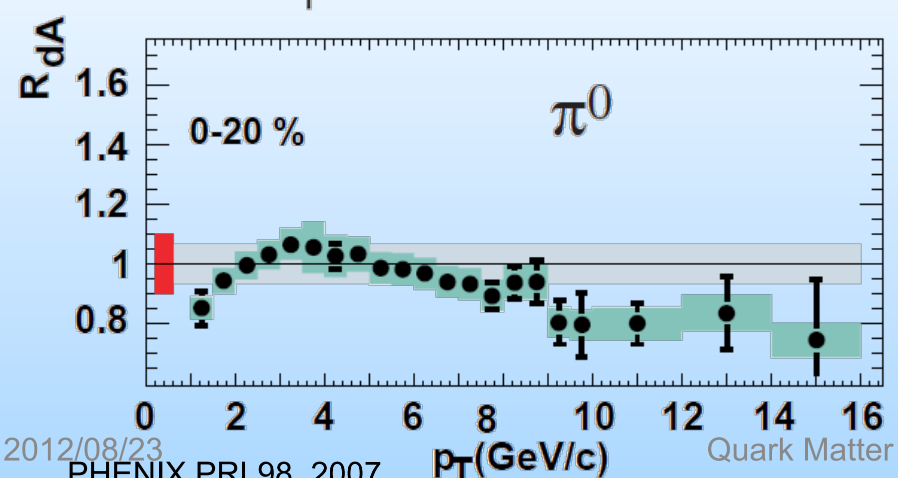


Y-J Lee, QM11

- Is rise really due to pQCD?
- Or other quench (flat?)
  - + initial state CNM effects a la CGC?



Albacete and Marquet, PLB687 (2010)



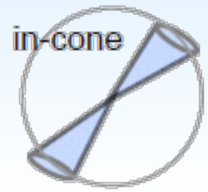
PHENIX PRL98, 2007

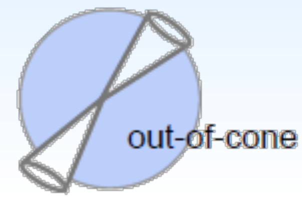
Require p + A and/or direct γ

pQCD and Jet Measurements

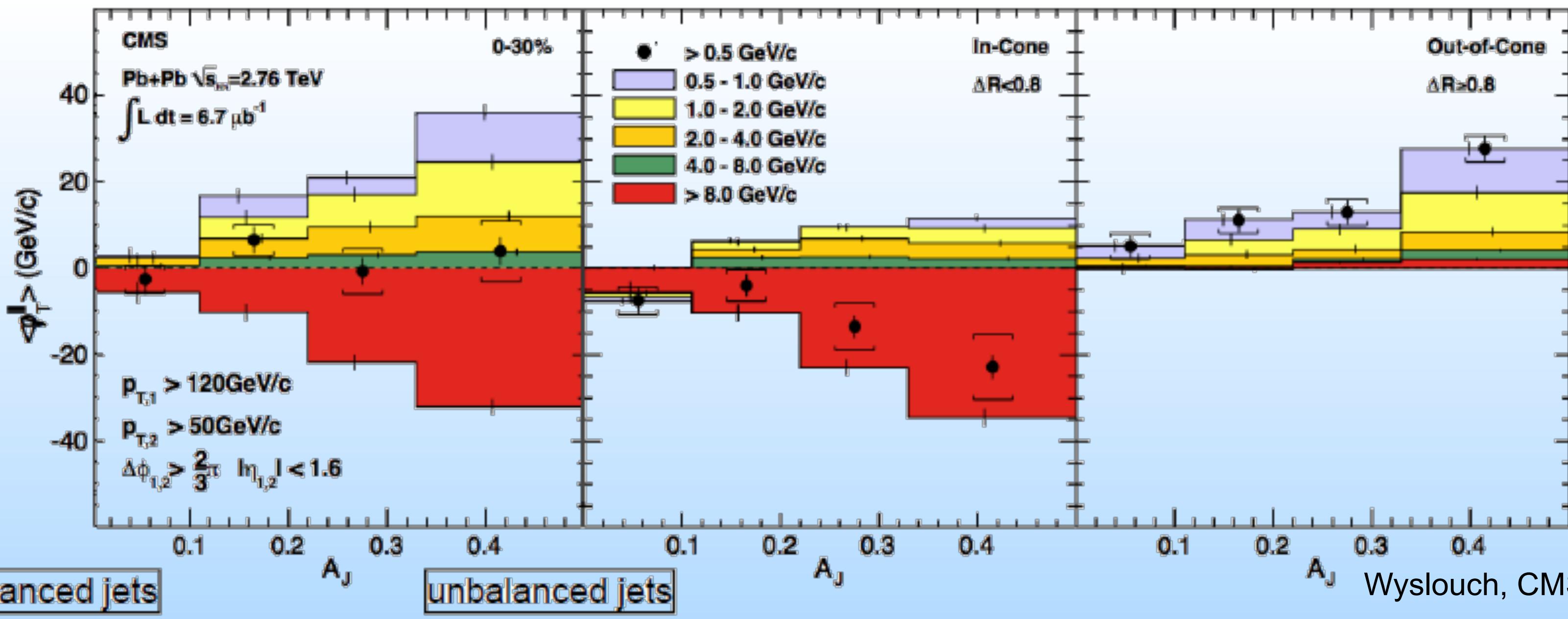
- CMS sees redistribution of lost energy at large angles
  - Naive pQCD expectation: collinear radiation

$$\not{p}_{\mathrm{T}}^{\parallel} = \sum_{\mathrm{Tracks}} -p_{\mathrm{T}}^{\mathrm{Track}} \cos\left(\phi_{\mathrm{Track}} - \phi_{\mathrm{Leading\ Jet}}\right)$$





0-30% Central PbPb



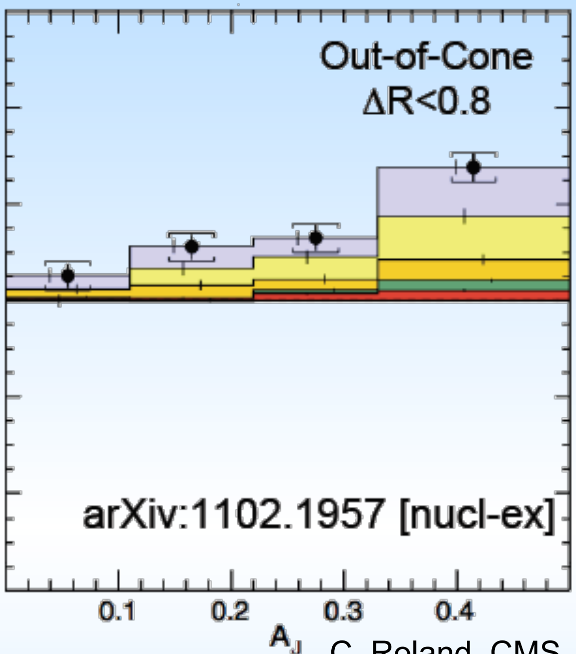
Wyslouch, CMS, QM11

pQCD and Wide Angle Radiation

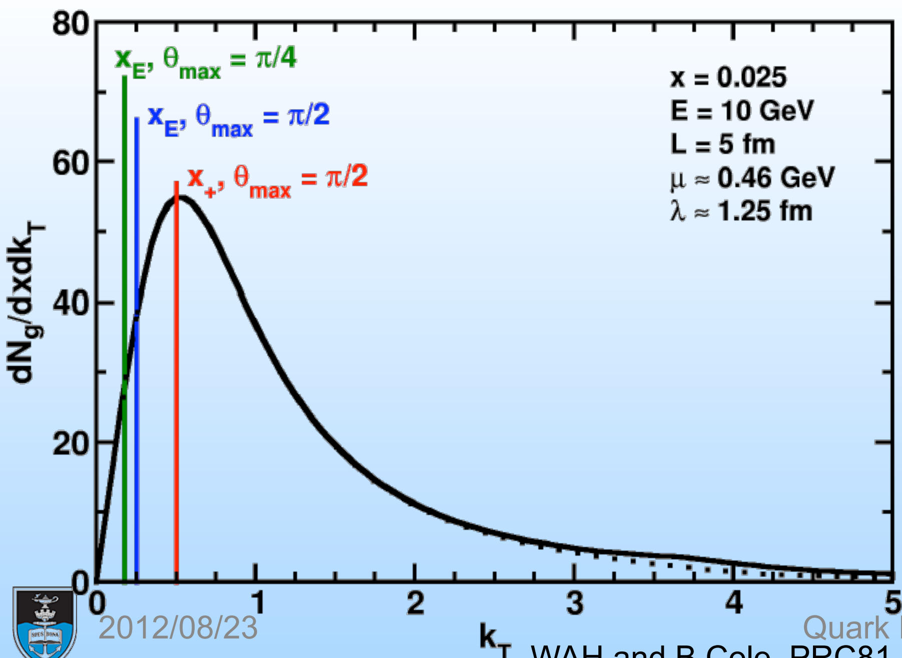
- Naively, pQCD =>

  $x_{typical}$, $\theta_{typical}$ ~ μ/E; μ ~ 0.5 GeV
- ***All*** current Eloss calculations assume small angle emission

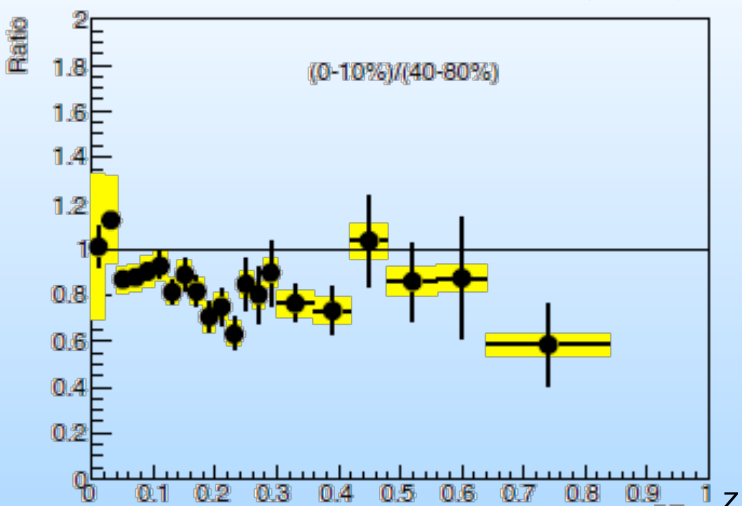
  (k_T << xE)
- Collinear approximation is (maximally) violated; x_{typ} ~ μ/E
- pQCD is not inconsistent with data



C Roland, CMS, QM11



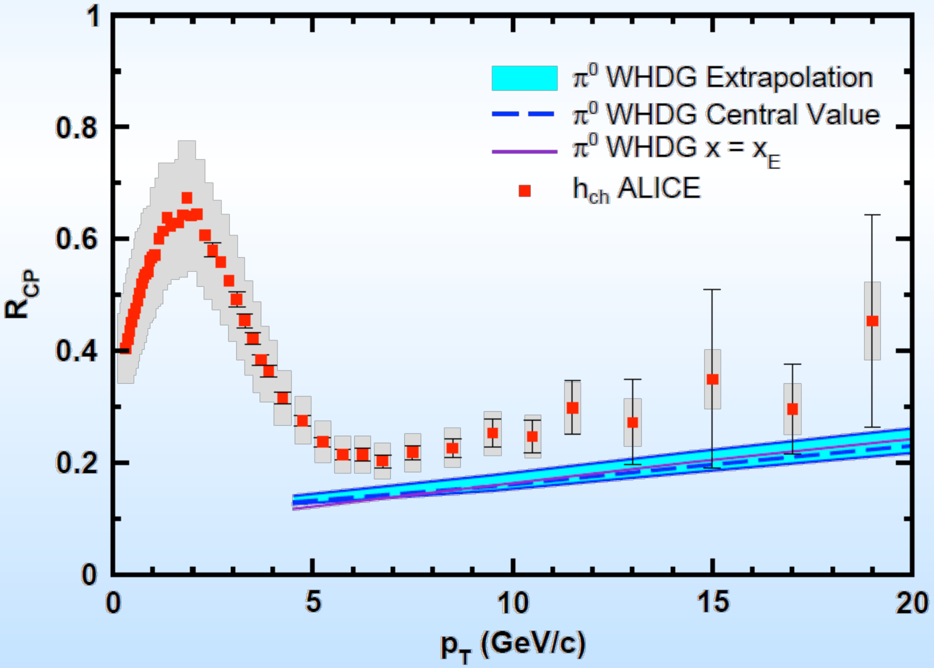
WAH and B Cole, PRC81, 2010



B Cole, ATLAS, QM11

WHDG Compared to R_{CP}

- Examine R_{CP}, ratio of central to peripheral R_{AA}
  - p + p uncertainty cancels
  - 0-5% R_{AA} to 70-80% R_{AA}
  - Validity of E-loss in very peripheral collisions?



WAH and M Gyulassy, NPA872 (2011)

Comparing AdS and pQCD

- But what about the interplay between mass and momentum?
  - Take ratio of *c* to *b* $R_{AA}(p_T)$
    - pQCD: Mass effects die out with increasing p_T

$$R^{cb}_{pQCD}(p_T) \sim 1 - \alpha_s\, n(p_T)\, L^2 \log(M_b/M_c)\, (\hat{q}/p_T)$$

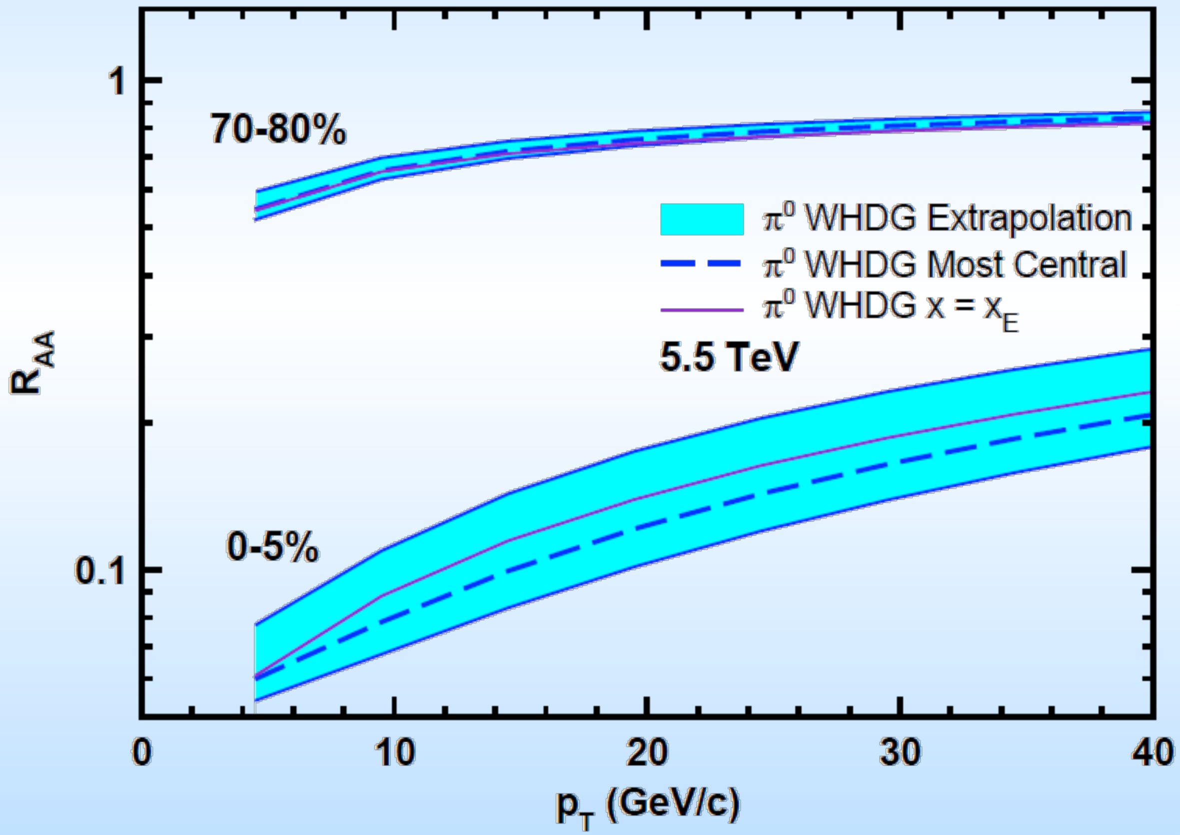
      - Ratio starts below 1, asymptotically approaches 1. Approach is slower for higher quenching
    - ST: drag independent of p_T, inversely proportional to mass. Simple analytic approx. of uniform medium gives

$$R^{cb}_{pQCD}(p_T) \sim n_b M_c / n_c M_b \sim M_c/M_b \sim .27$$

      - Ratio starts below 1; independent of p_T

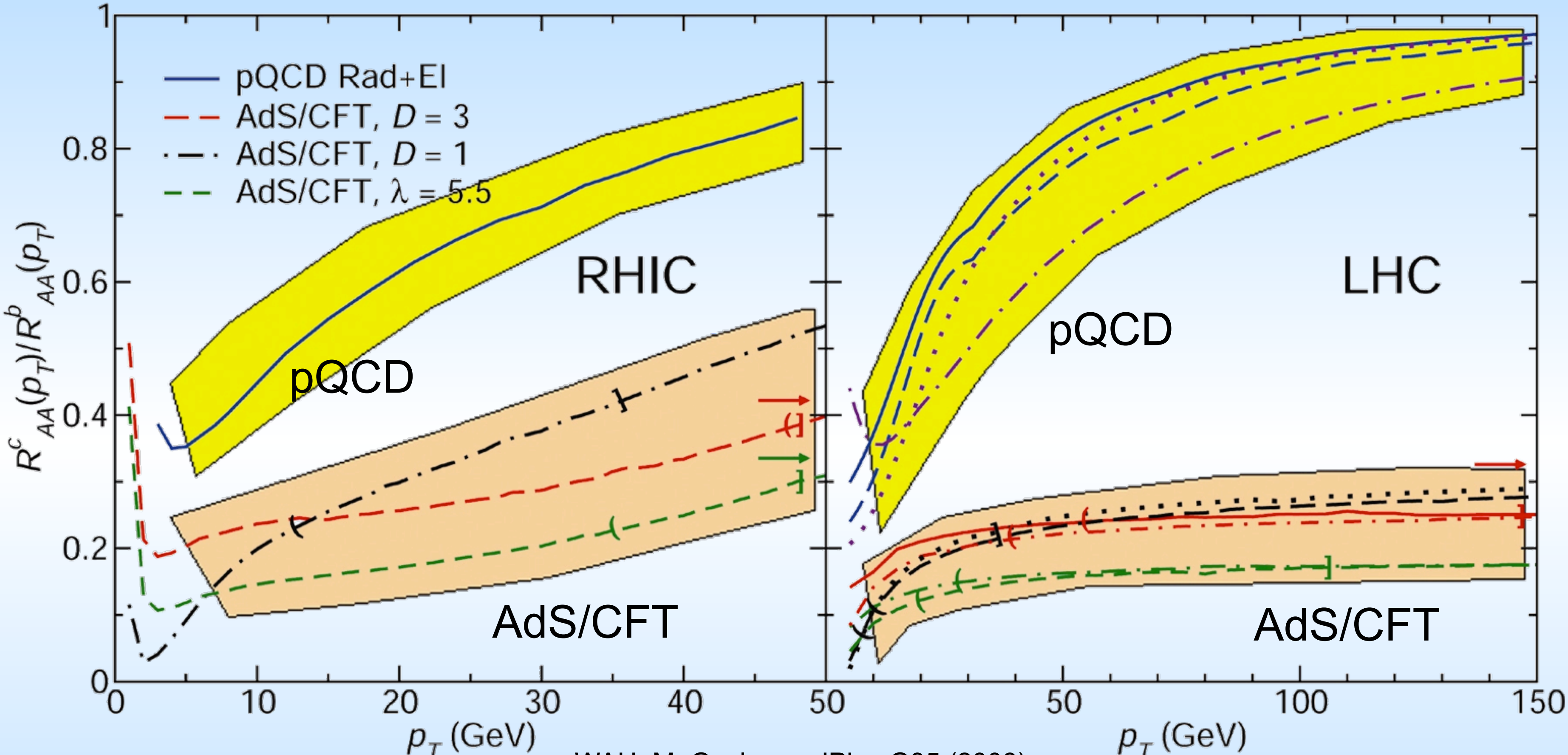
Top Energy Predictions

- For posterity:



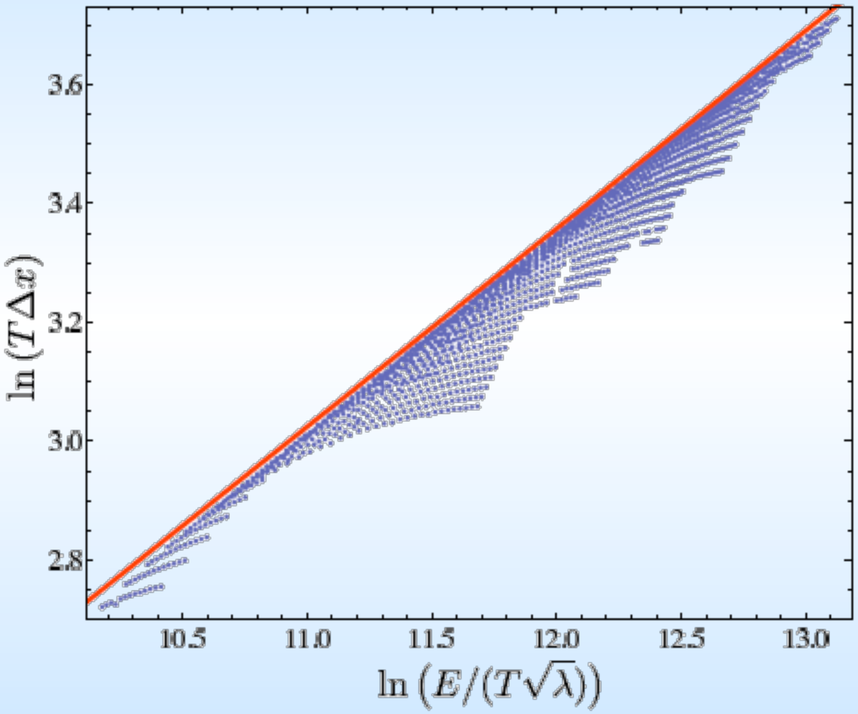
WAH and M Gyulassy, *in preparation*

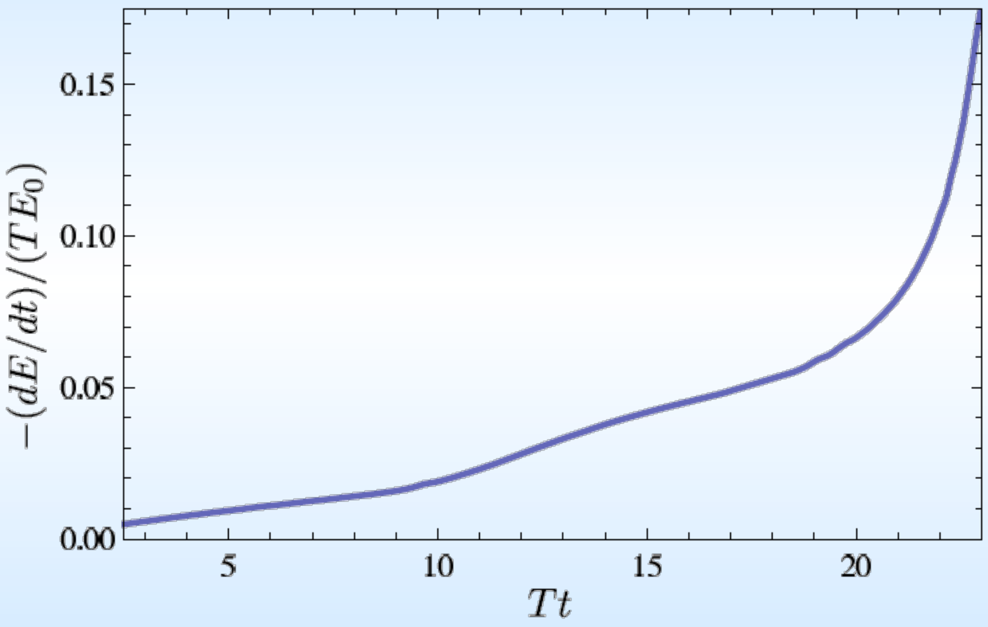
RHIC R^{cb} Ratio



WAH, M. Gyulassy, JPhysG35 (2008)

- Wider distribution of AdS/CFT curves due to large *n*: increased sensitivity to input parameters
- Advantage of RHIC: lower T => higher AdS speed limits



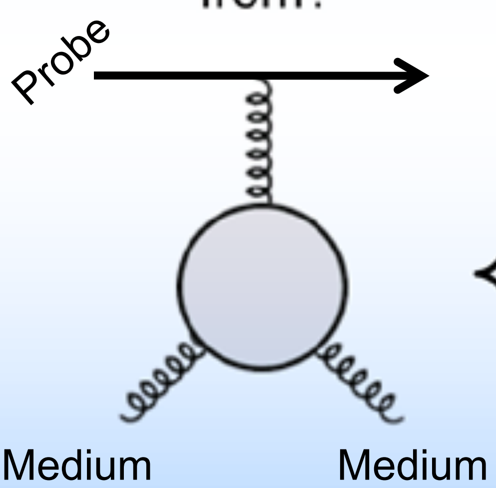


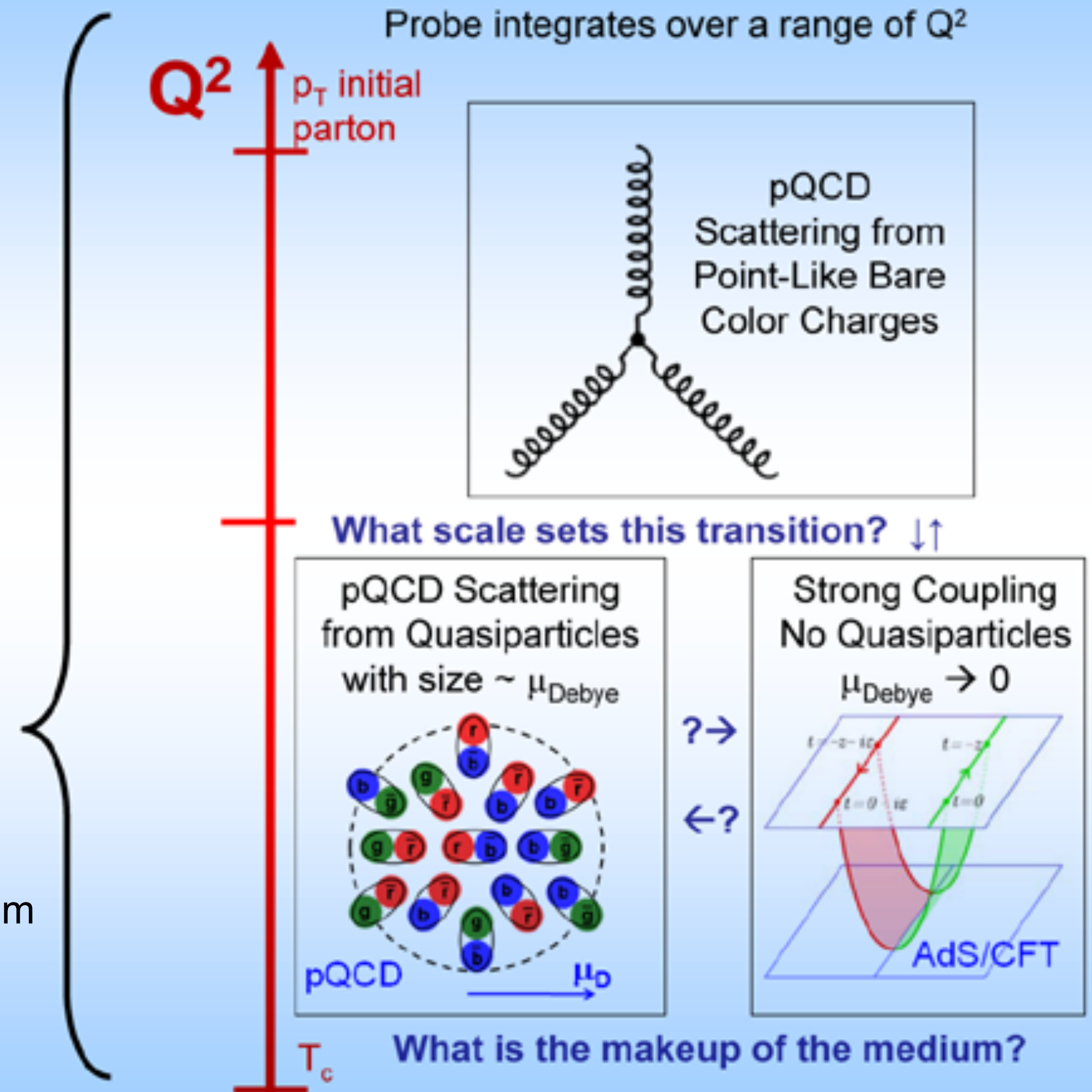
Chesler et al., PRD79 (2009)

Motivating High Momentum Probes

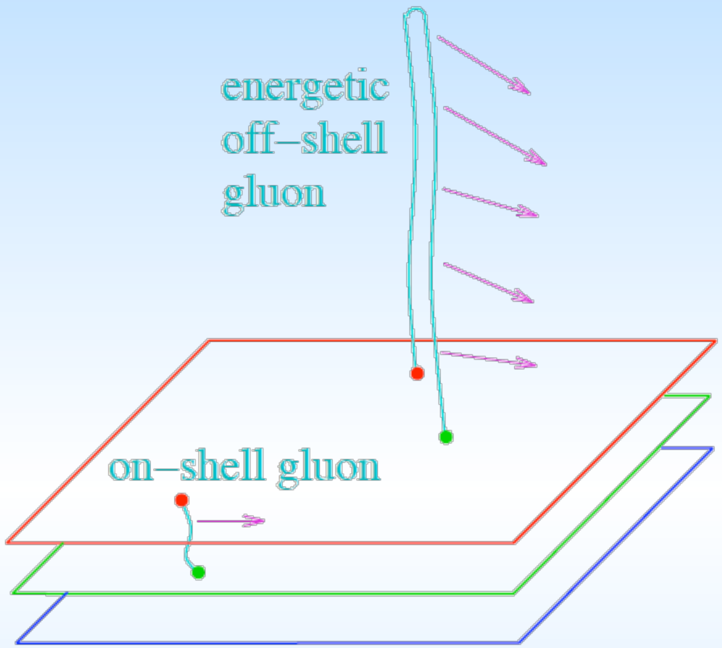
What does jet quenching teach us?

What is the parton probe scattering from?

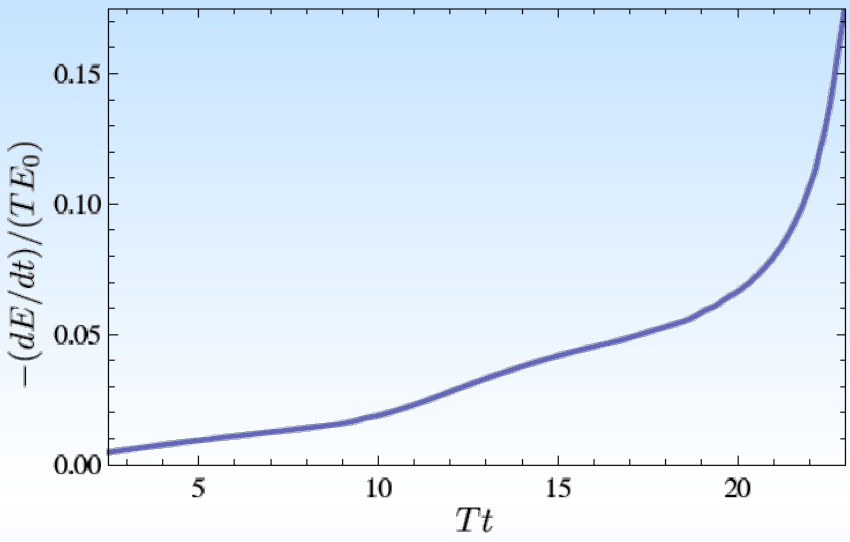




Light Quark and Gluon E-Loss



SS Gubser, QM08



Chesler et al., PRD79 (2009)

$\Delta L^{q}_{therm} \sim E^{1/3}$

$\Delta L^{q}_{therm} \sim (2E)^{1/3}$

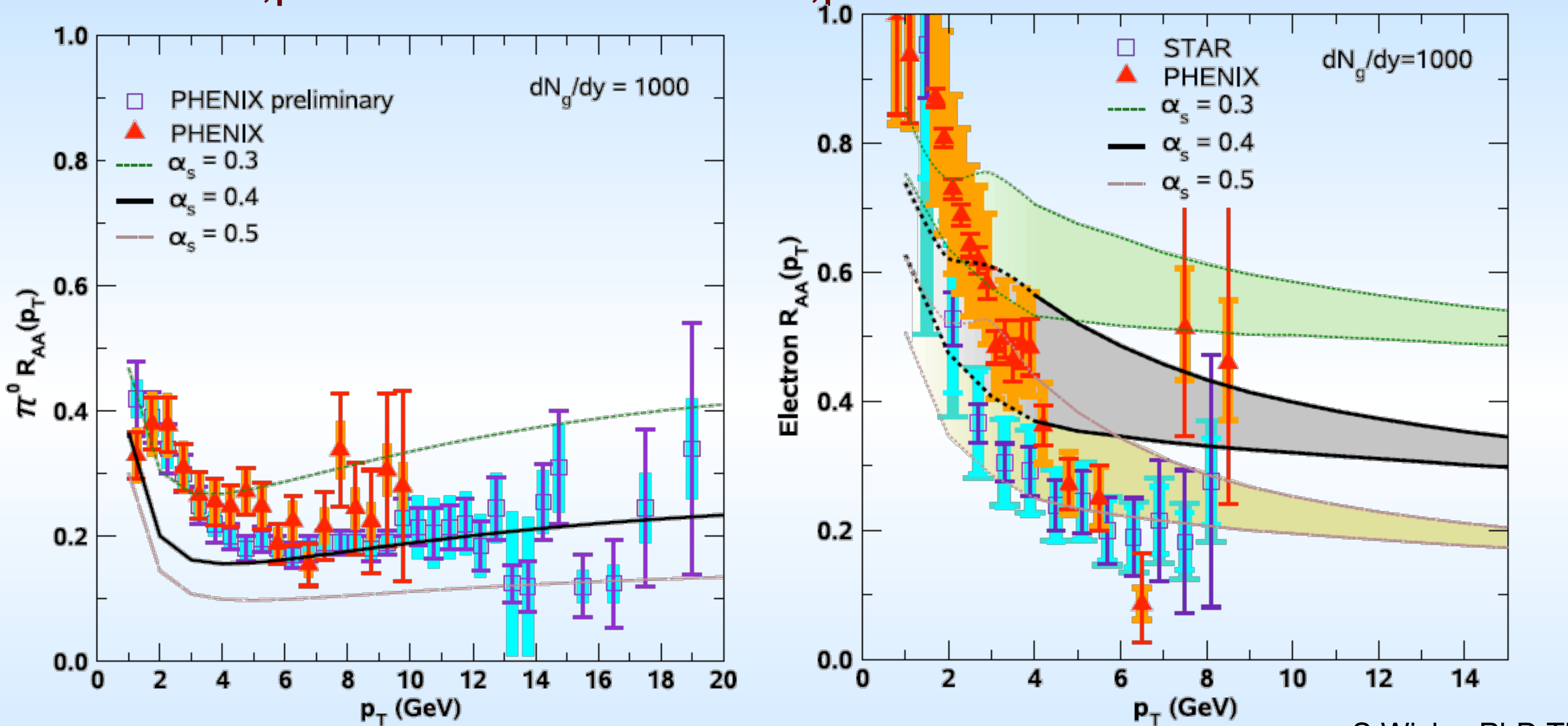
Gubser et al., JHEP0810 (2008)
Chesler et al., PRD79 (2009)
Arnold and Vaman, JHEP 1104 (2011)

- Light quarks and gluons: generic Bragg peak
  - Leads to lack of T dependence?

See also Marquet and Renk, PLB685 (2010), and Jia, WAH, and Liao, arXiv:1101.0290, for v_2

Varying α_s has ***huge*** effect

- $\langle\varepsilon\rangle_{rad,pQCD} \sim \alpha_s^3$; $\langle\varepsilon\rangle_{el,pQCD} \sim \alpha_s^2$



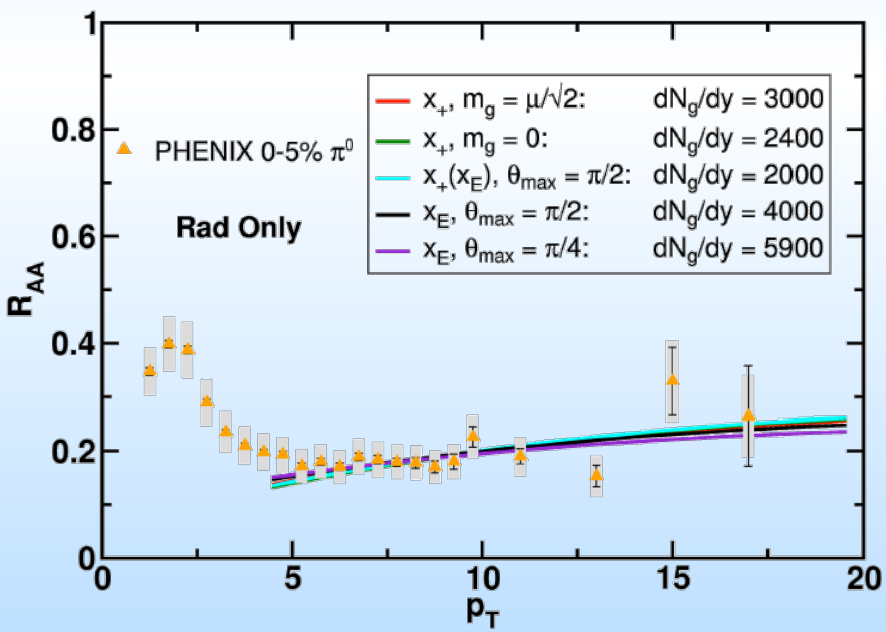
S Wicks, PhD Thesis

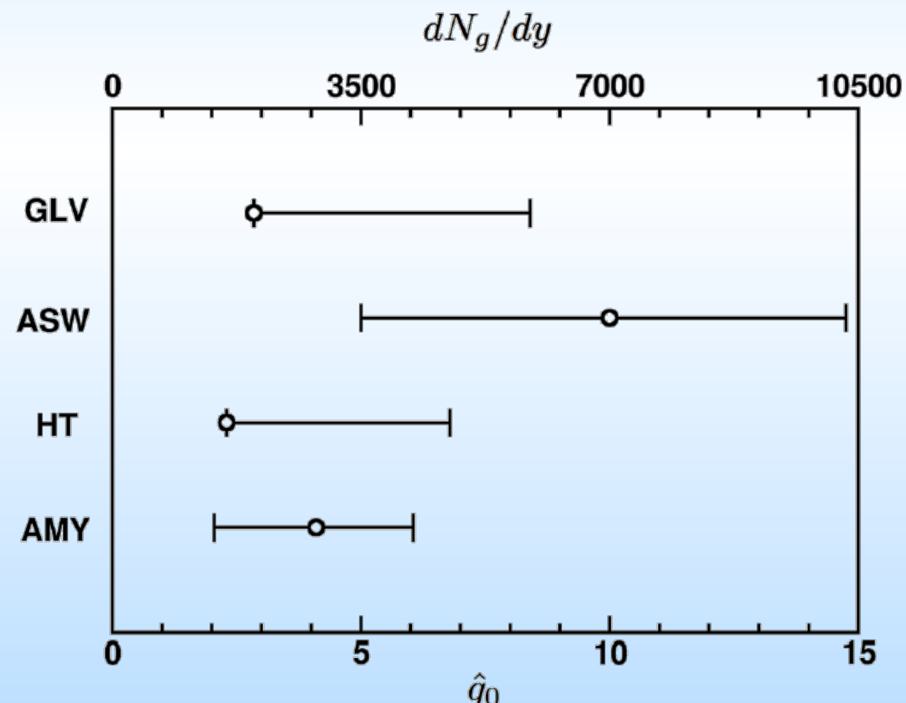
– Role of running coupling, irreducible uncertainty from non-pert. physics?

– Nontrivial changes from better elastic treatment

Quantification of Collinear Uncertainty

- Factor ~ 3 uncertainty in extracted medium density!
- "qhat" values from *different formalisms* **consistent** w/i unc.



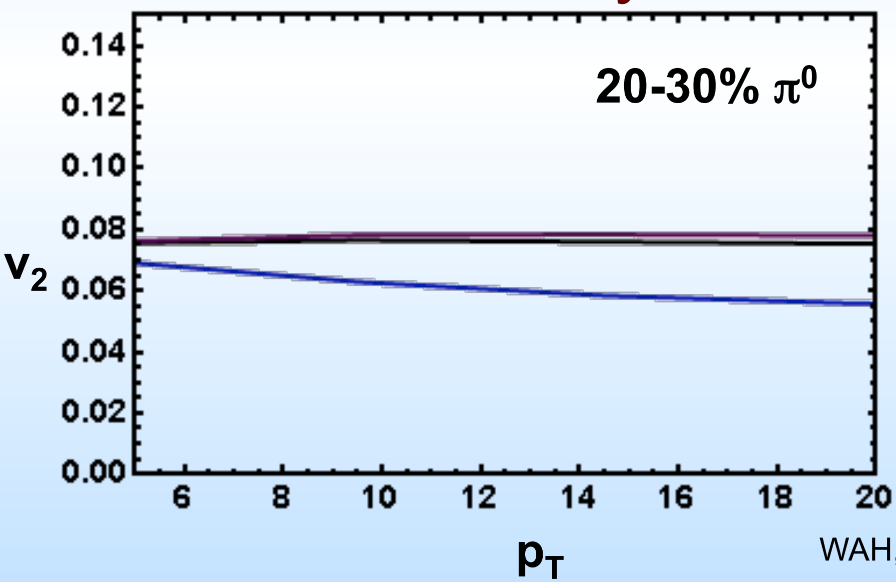


WAH and B Cole, PRC81, 2010

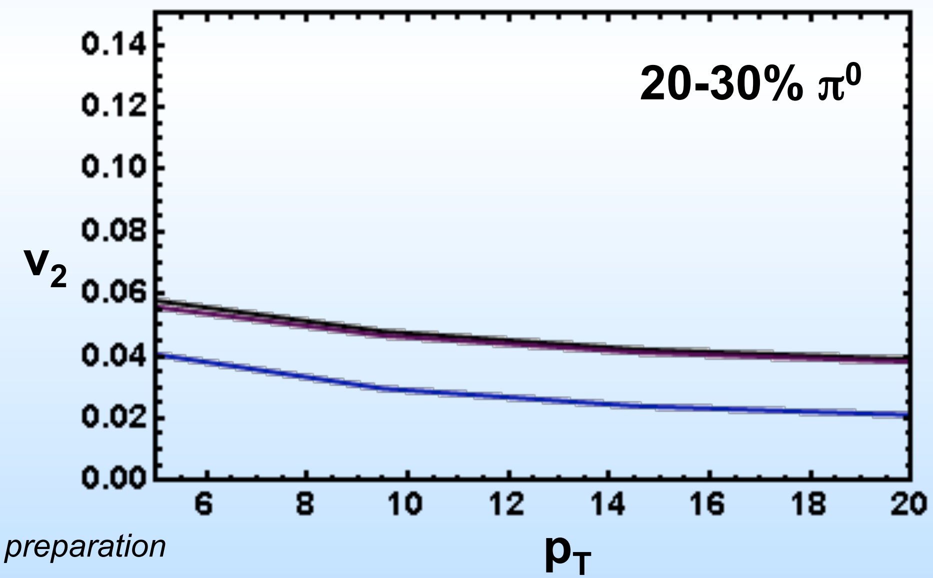
Coll. Approx. and Constrained v_2

- Fix dN_g/dy from R_{AA}, calculate v_2
  - Expect: larger v_2 for smaller opening angle
    - $\tau_{coh} = xE/k_T^2$ larger for smaller θ_{max}
      - more paths in deep LPM ($\Delta E \sim L^2$) region

- Rad Only



- Rad + El



WAH, *in preparation*

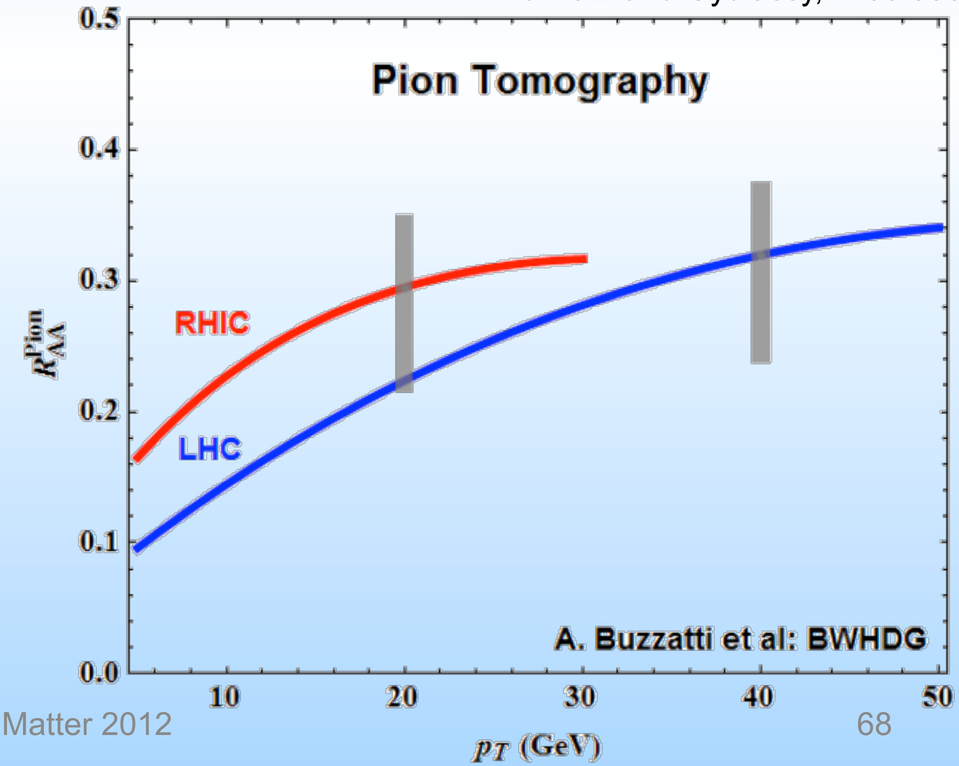
  - Not large sensitivity

Geometry, Early Time Investigation

$$\frac{dN_g}{dx_+}(x,\phi) = \frac{C_R\alpha_s}{\pi}\int d\tau \frac{d^2k}{\pi}\frac{d^2q}{\pi}\frac{1}{x_+}\frac{\frac{9}{2}\pi\alpha^2}{\boldsymbol{q}^2(\boldsymbol{q}^2+\mu^2(\tau))}$$
$$\times\frac{2(\boldsymbol{k}+\boldsymbol{q})}{(\boldsymbol{k}+\boldsymbol{q})^2+\chi(\tau)}\left(\frac{(\boldsymbol{k}+\boldsymbol{q})}{(\boldsymbol{k}+\boldsymbol{q})^2+\chi(\tau)}-\frac{\boldsymbol{k}}{\boldsymbol{k}^2+\chi(\tau)}\right)$$
$$\times\left(1-\cos\left(\frac{(\boldsymbol{k}+\boldsymbol{q})^2\chi(\tau)}{2x_+E}\tau\right)\right)\rho_{QGP}(\boldsymbol{x}+\boldsymbol{v}\tau,\tau)$$

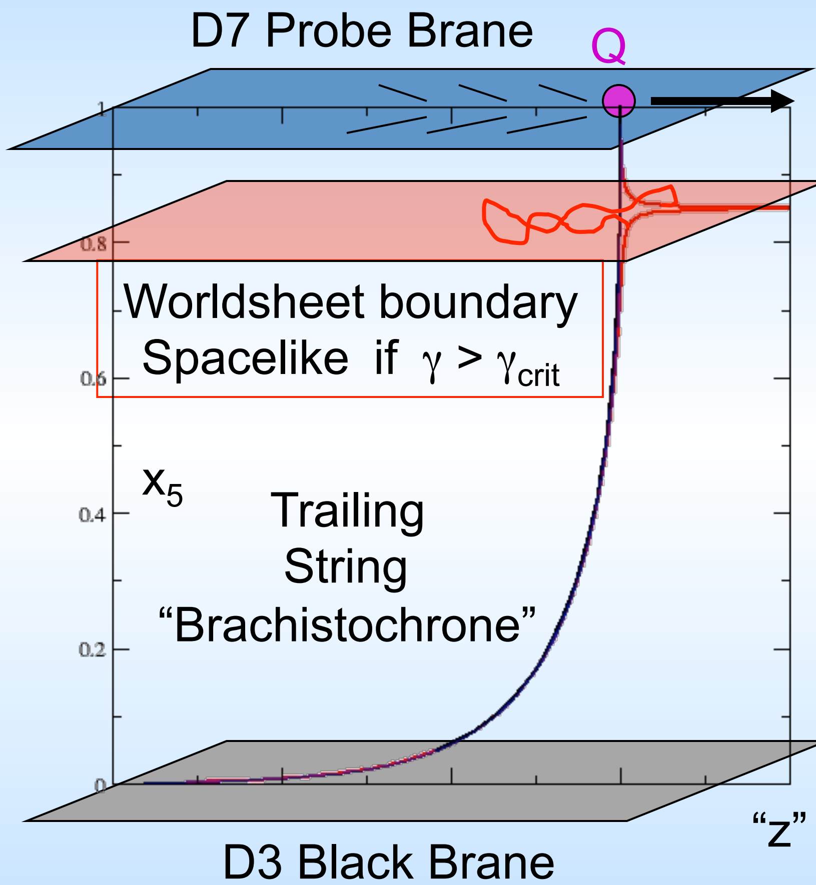
- ***Significant*** progress made
  - Full geometry integration, dynamical scattering centers
  - RHIC suppression with $dN_g/dy = 1000$
  - Large uncertainty due to unconstrained, non-equilibrium $\tau < \tau_0$ physics
  - Future work: higher orders in opacity

Buzzatti and Gyulassy, 1106.3061

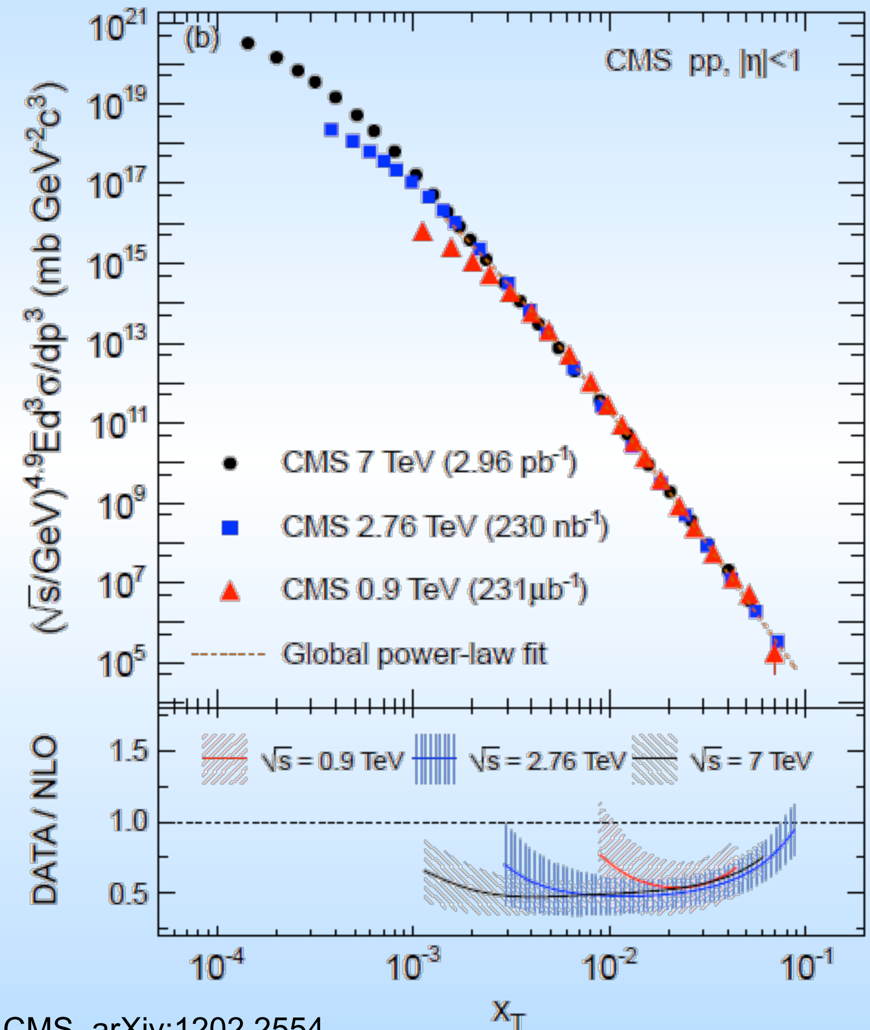


Not So Fast!

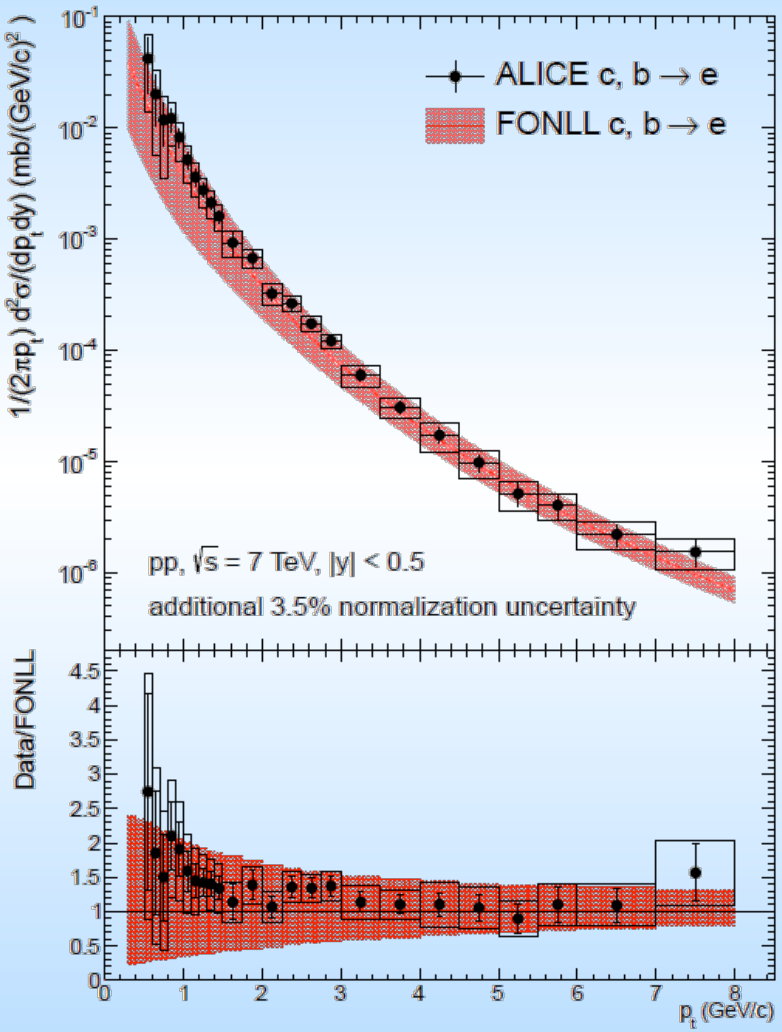
- Speed limit estimate for applicability of AdS drag
  - $\gamma < \gamma_{crit} = (1 + 2M_q/\lambda^{1/2}\, T)^2$
    $\sim 4M_q^2/(\lambda\, T^2)$
    - Limited by $M_{charm} \sim 1.2$ GeV
  - Similar to BH→LPM
    - $\gamma_{crit} \sim M_q/(\lambda T)$
- No Single T for QGP
  - smallest γ_{crit} for largest T
    $T = T(\tau_0, x=y=0)$: "("
  - largest γ_{crit} for smallest T
    $T = T_c$: "]"



pQCD pp Predictions vs. Data



CMS, arXiv:1202.2554



ALICE, arXiv:1205.5423