Quenching and Tomography from RHIC to LHC

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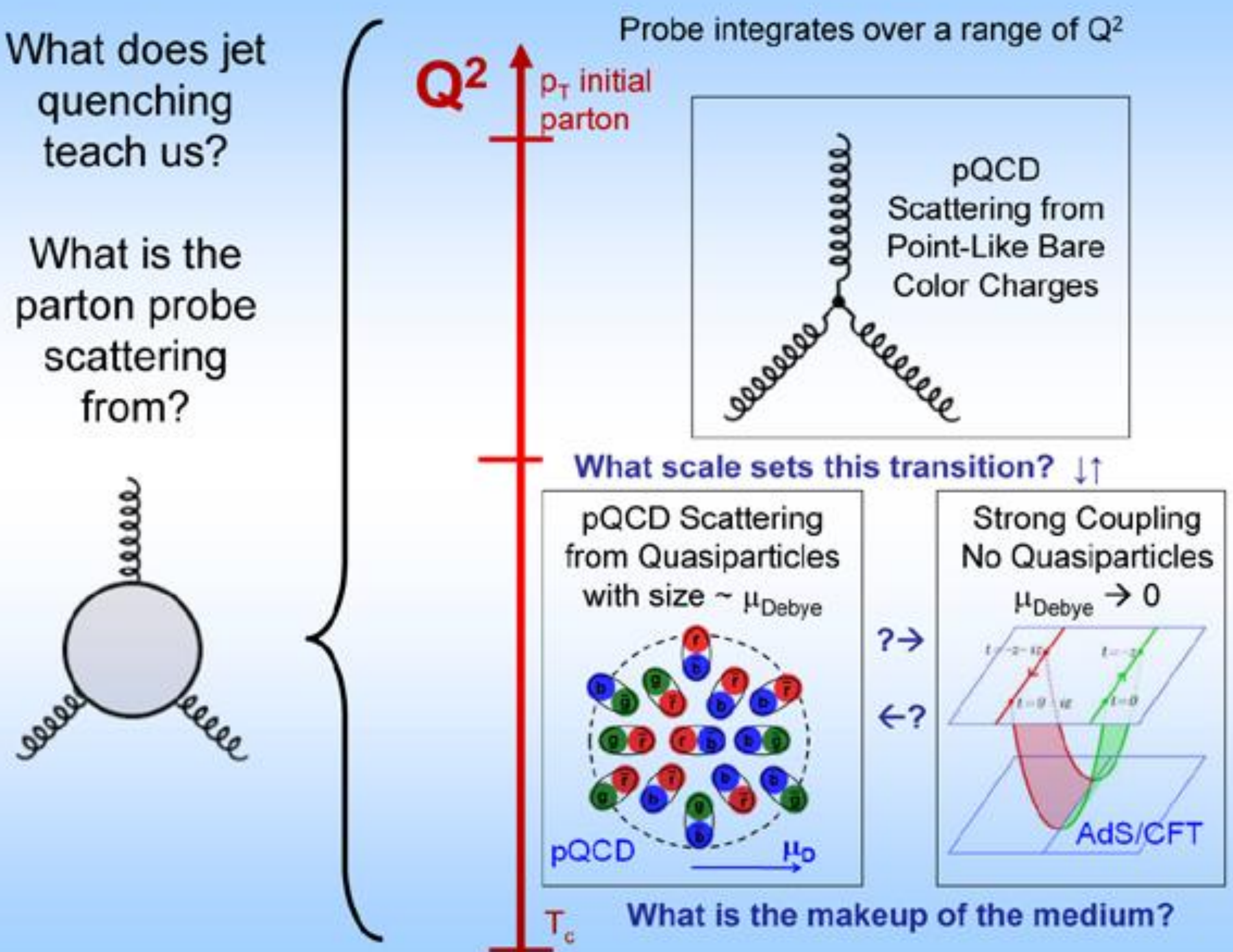
May 26, 2011

With many thanks to Alessandro Buzzatti, Brian Cole, Miklos Gyulassy, Jiangyong Jia, and Yuri Kovchegov

Motivation



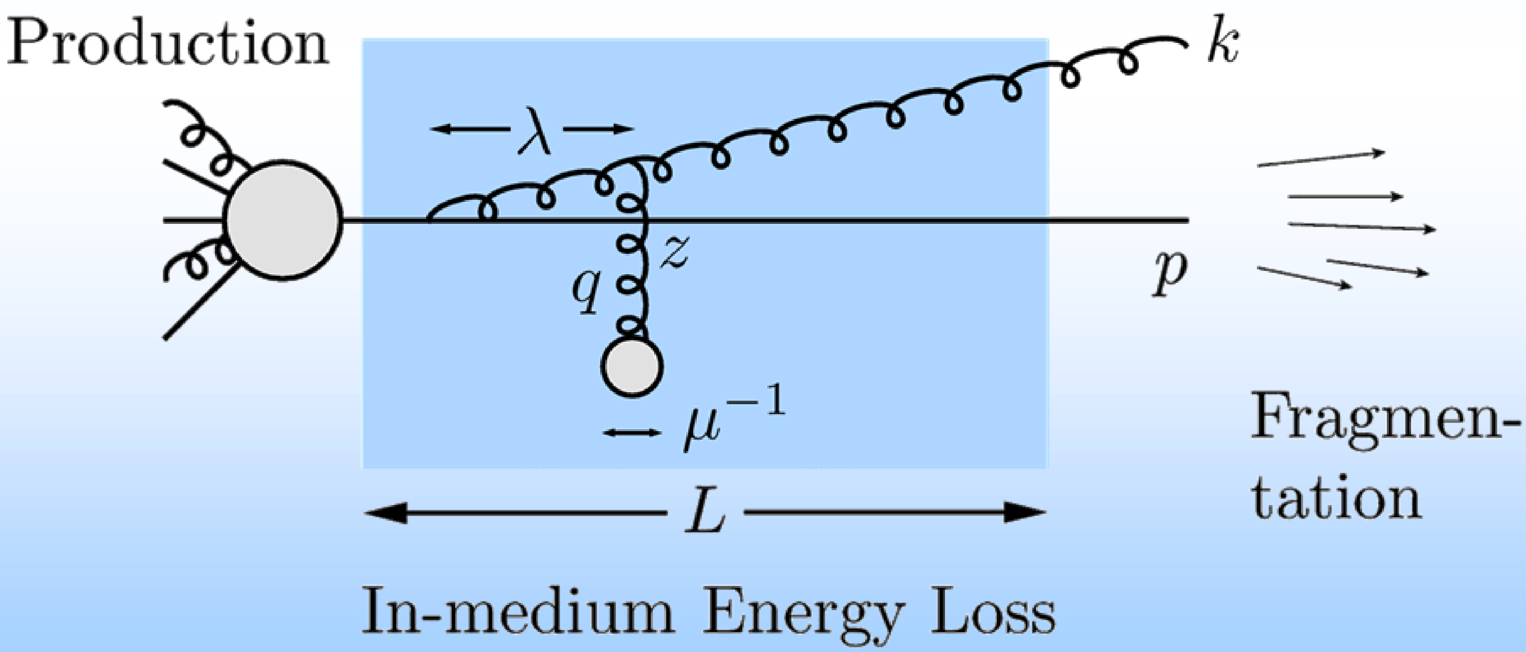
What does jet quenching teach us?
What is the parton probe scattering from?
Probe integrates over a range of Q²
Q²
p_T initial parton
pQCD Scattering from Point-Like Bare Color Charges
What scale sets this transition? ↓↑
pQCD Scattering from Quasiparticles with size ~ μ_Debye
Strong Coupling No Quasiparticles μ_Debye → 0
?→
←?
pQCD
μ_D
AdS/CFT
T_c
What is the makeup of the medium?

QGP Energy Loss

- Learn about E-loss mechanism
  - Most direct probe of DOF

pQCD Picture

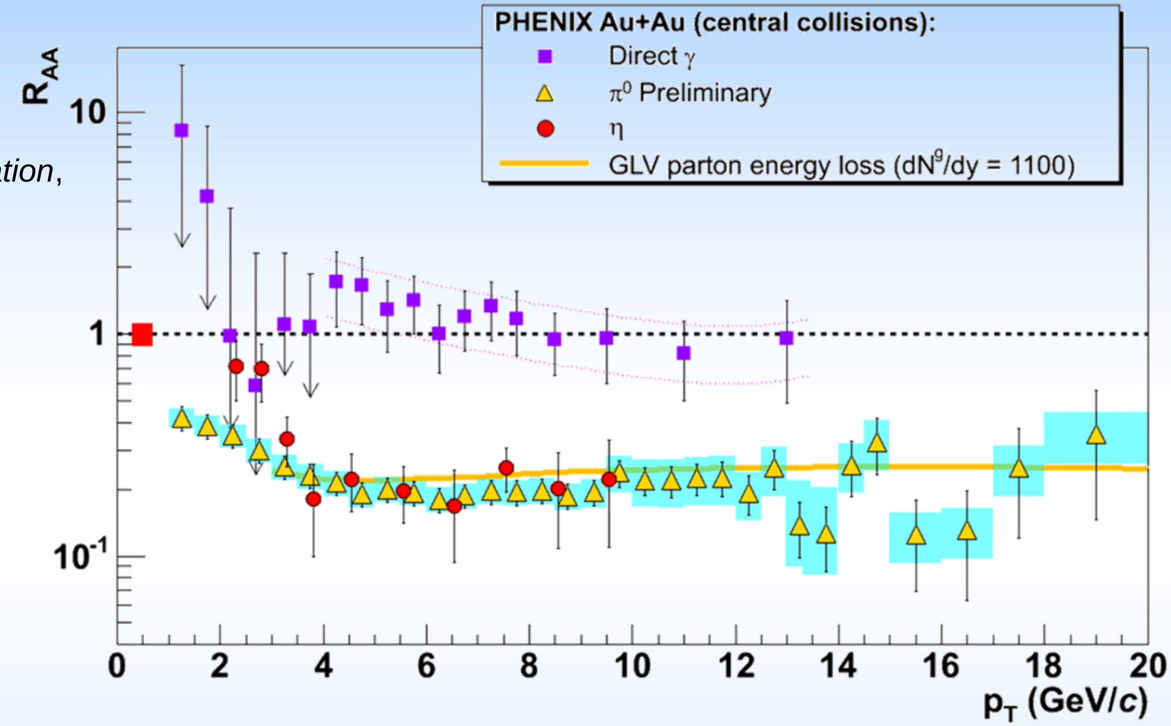
AdS/CFT Picture



pQCD Success at RHIC:

(circa 2005)

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



– Consistency: $R_{AA}(\eta)$~$R_{AA}(\pi)$

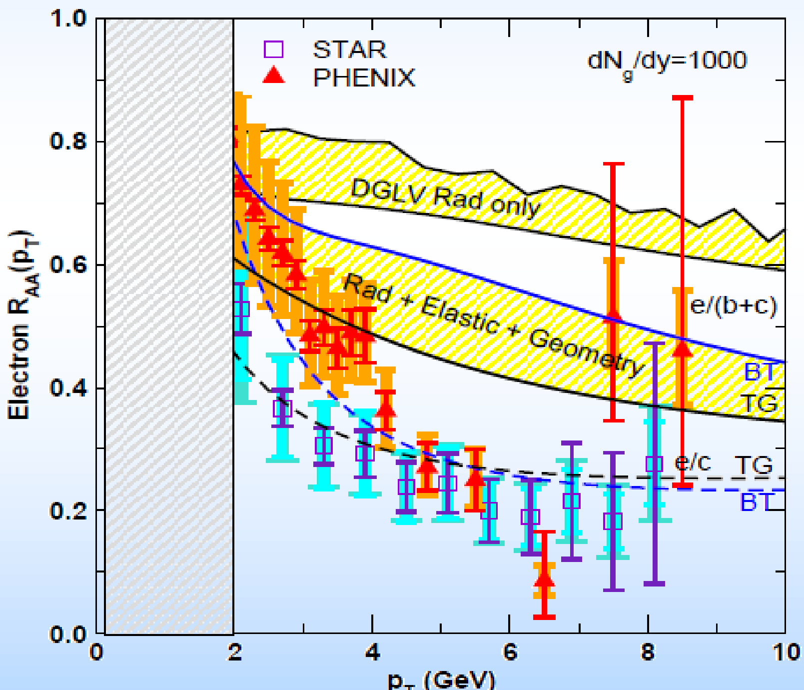
– Null Control: $R_{AA}(\gamma)$~1

– GLV Prediction: Theory~Data for reasonable fixed L~5 fm and dN_g/dy~dN_π/dy

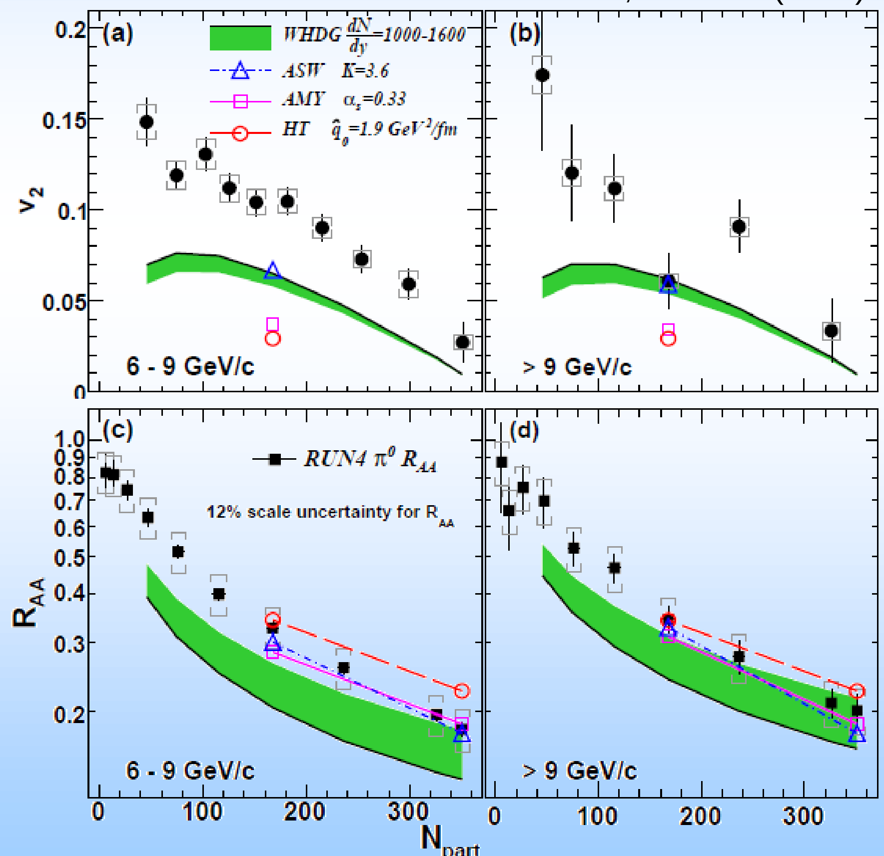
pQCD Suppression Picture Inadequate

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

PHENIX, PRL 105 (2010)



Wicks et al., NPA784, 2007

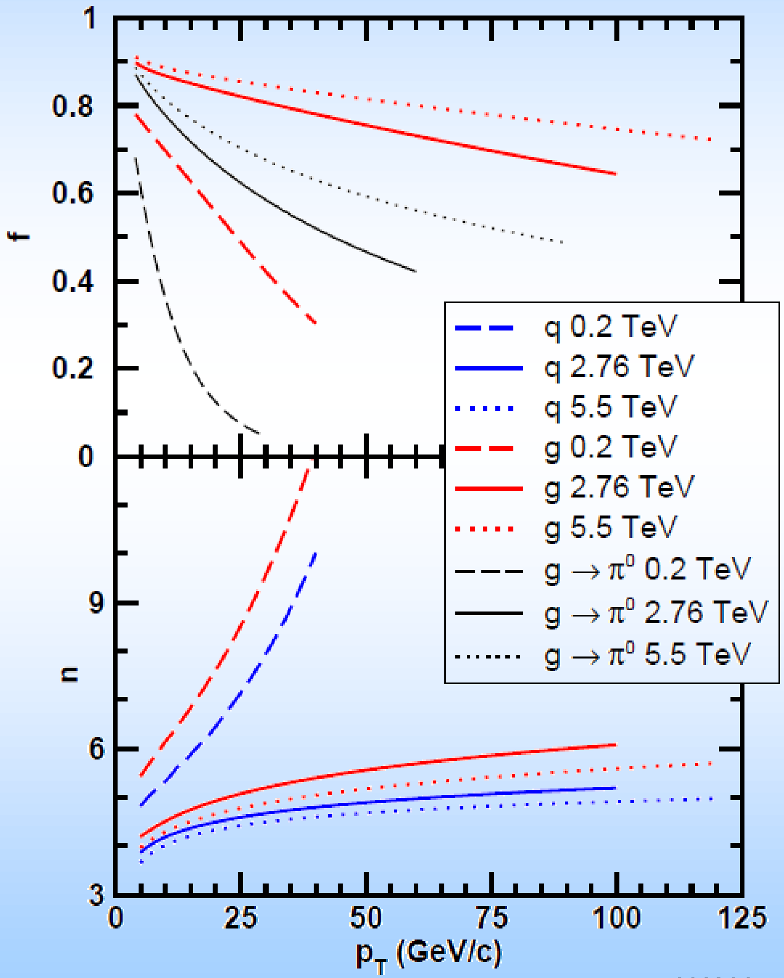


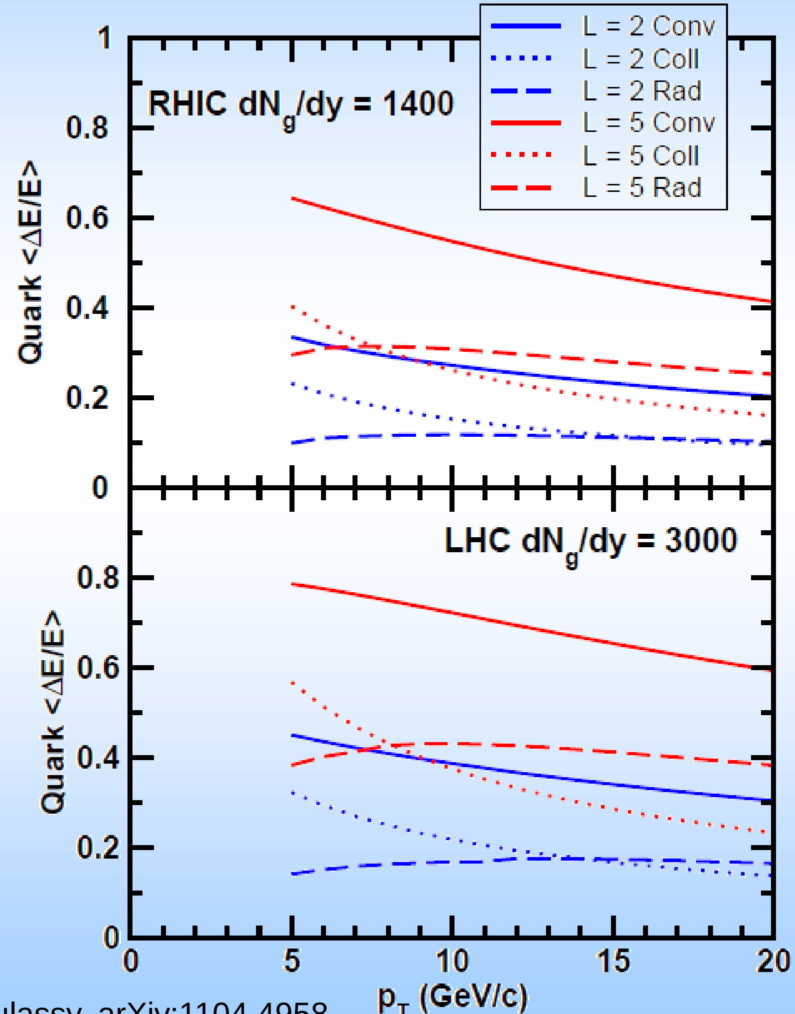
See also J Jia from QM09,
J Nagle QM09

Pert. at LHC energies?

LHC Context

- LHC is gluon machine
- Elastic ~ Radiative

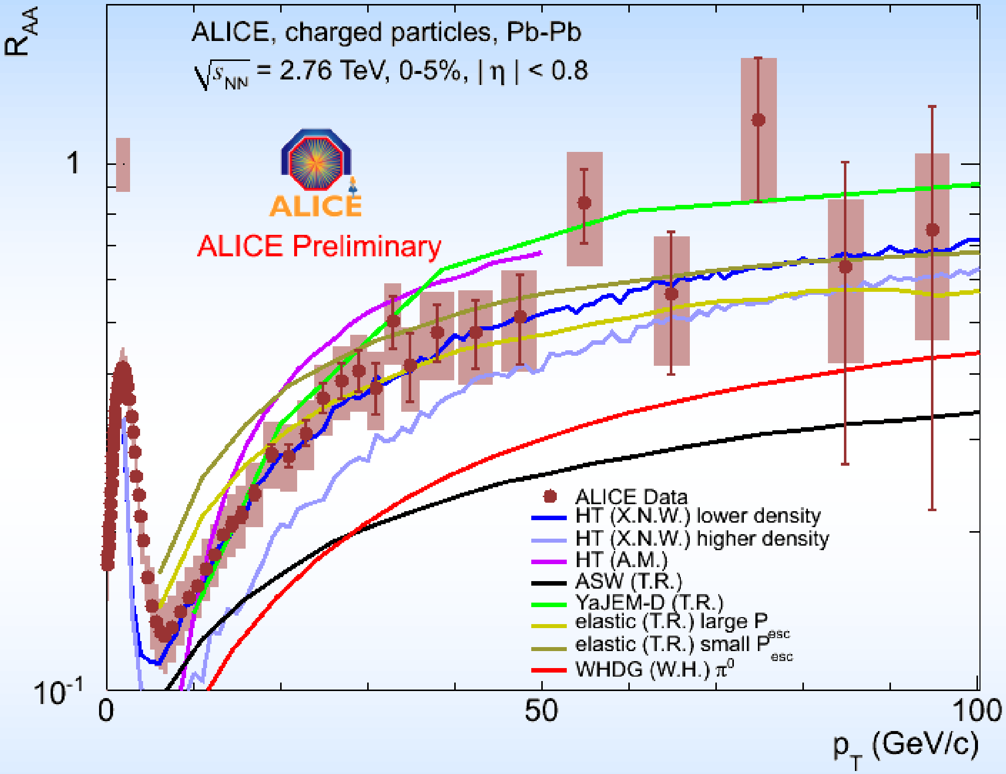




WAH and M Gyulassy, arXiv:1104.4958

- Flatter spectra

pQCD at LHC?



Appelshauser, ALICE, QM11

– $R_{AA} \sim (1-\varepsilon)^{n-1}$

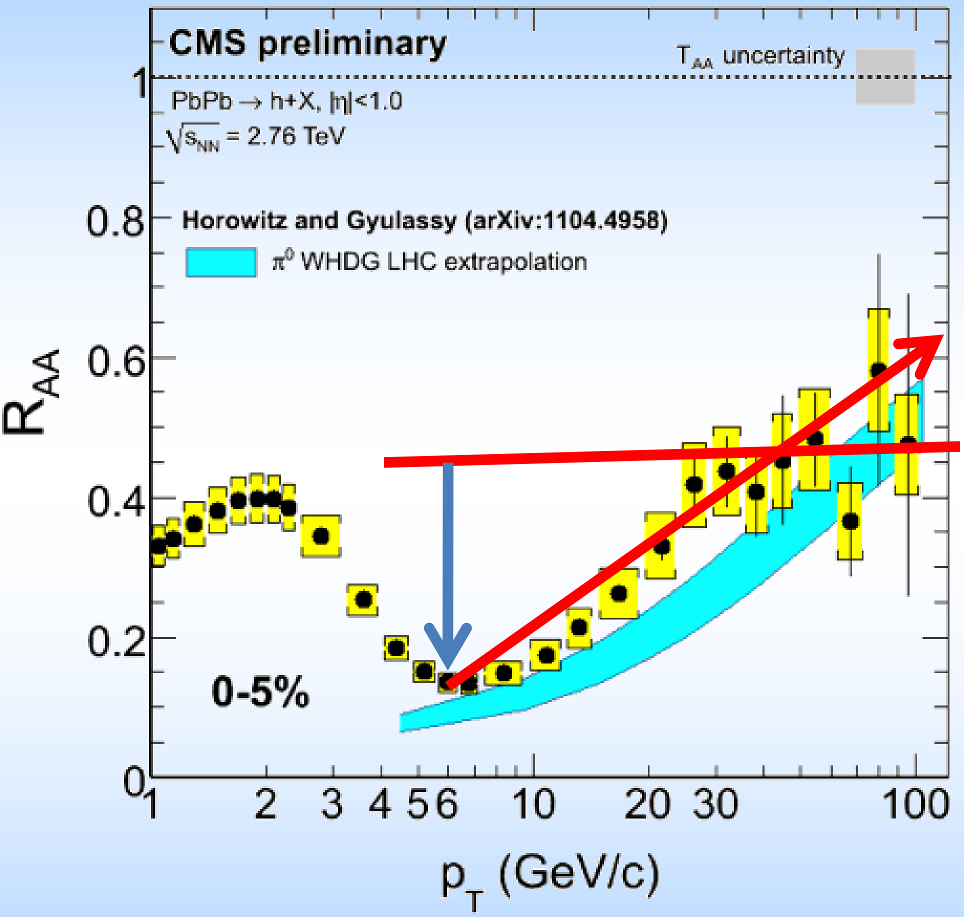
$\varepsilon = (E_i-E_f)/E_i$

– $\langle\varepsilon\rangle_{rad,\ pQCD} \sim \log(p_T)/p_T$

=> R_{AA} inc. with p_T

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

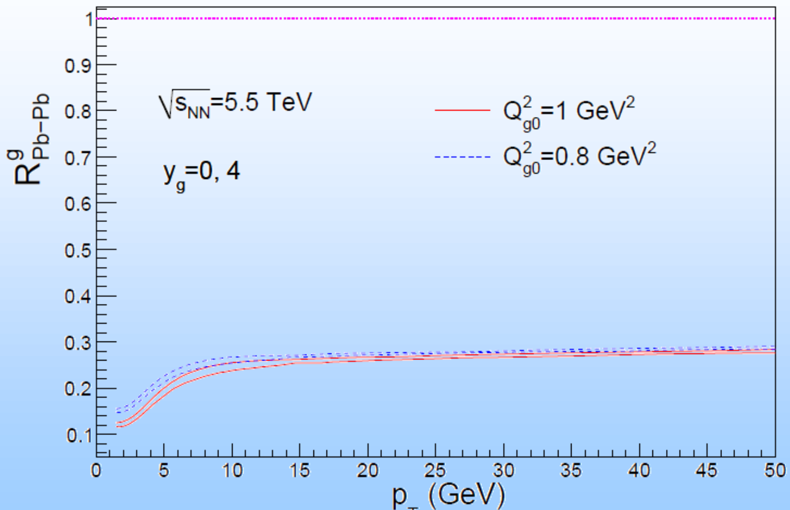
Rise in R_{AA} a Final State Effect?



Wenger, private communication

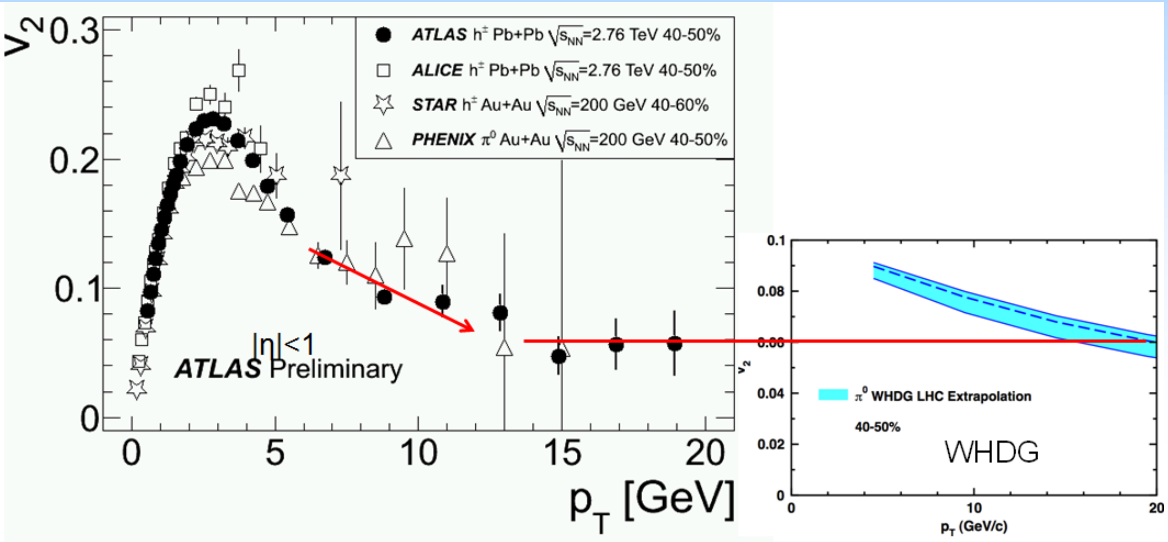
- Is rise really due to pQCD?
- Or other quench (flat?)

+ initial state CNM effects a la CGC?

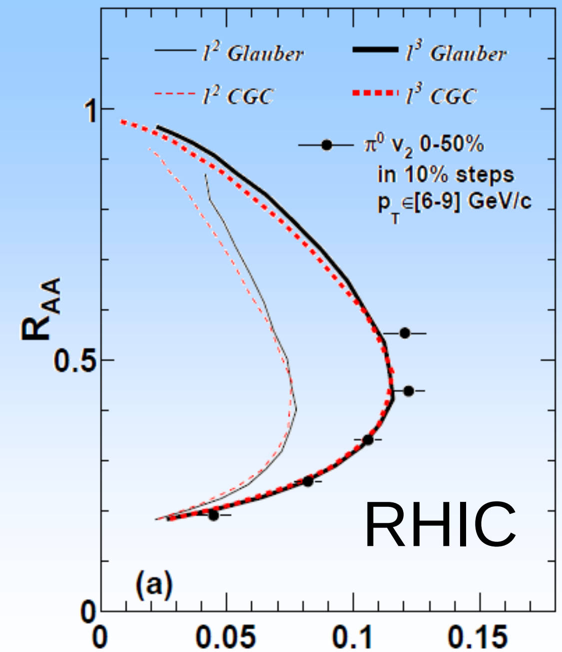


Albacete and Marquet, PLB687 (2010)

Mult. Obs. at LHC?

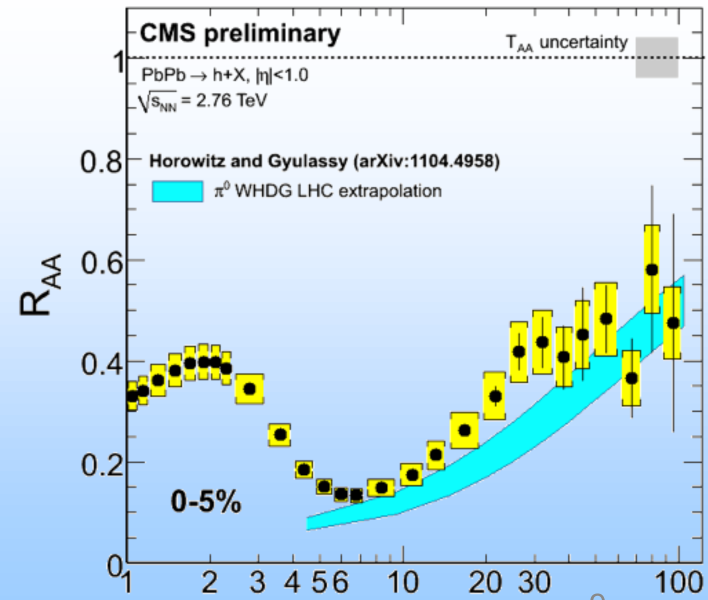


Jia, ATLAS, QM11



J Jia, WAH, J Liao, arXiv:1101.0290 v_2

- Are pQCD predictions of ***both*** R_{AA} & v_2 consistent with data? At 100 GeV/c?



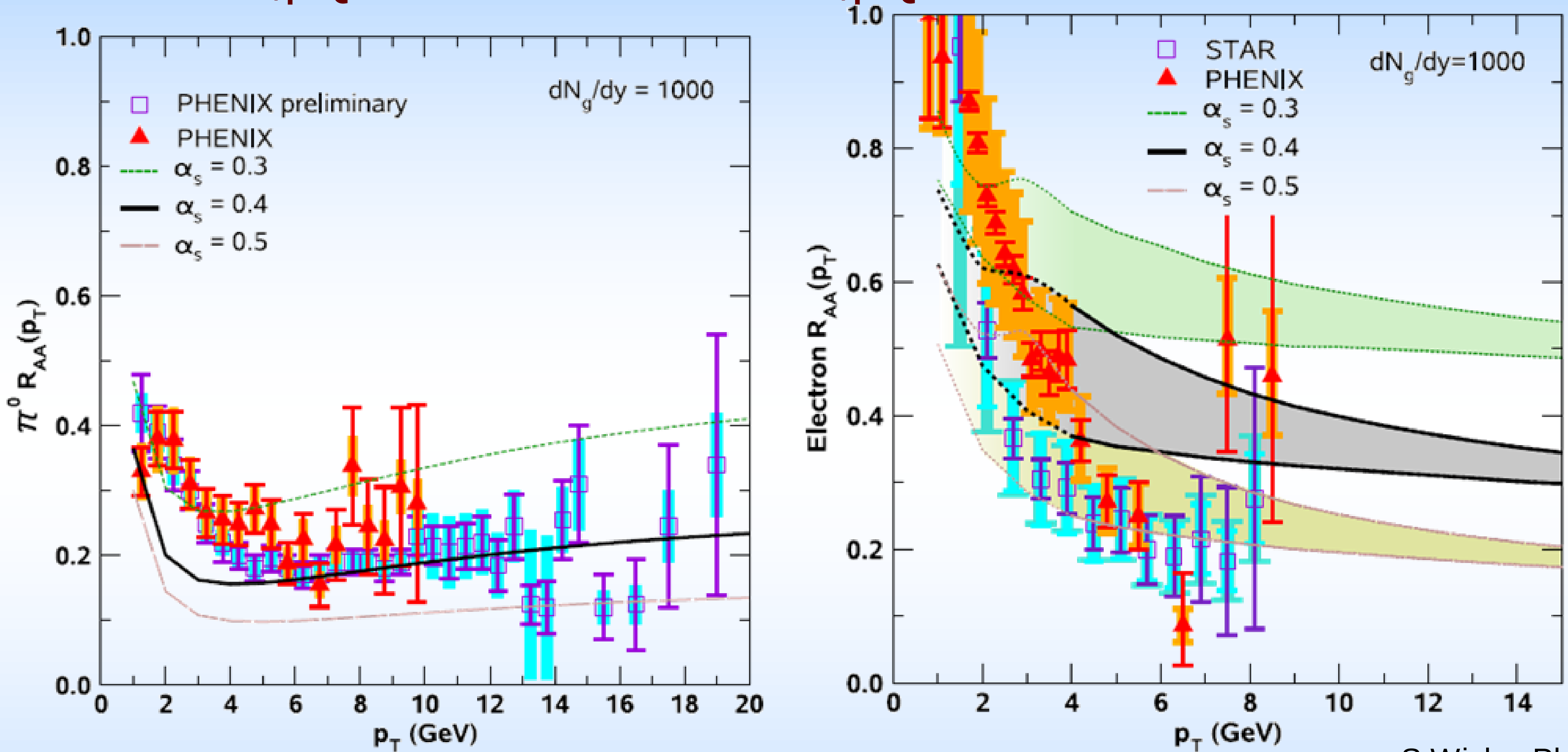
Wenger, private communication p_T (GeV/c)

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 poster)
    - dyn. vs. static centers (see Buzzatti poster)
    - hydro background (see Renk)
  - better treatment of
    - Coh. vs. decoh. multigluons (see Mehtar-Tani)
    - elastic E-loss
    - E-loss in confined matter

Varying α_s has ***huge*** effect

- $<\varepsilon>_{rad,pQCD} \sim \alpha_s^3$; $<\varepsilon>_{el,pQCD} \sim \alpha_s^2$

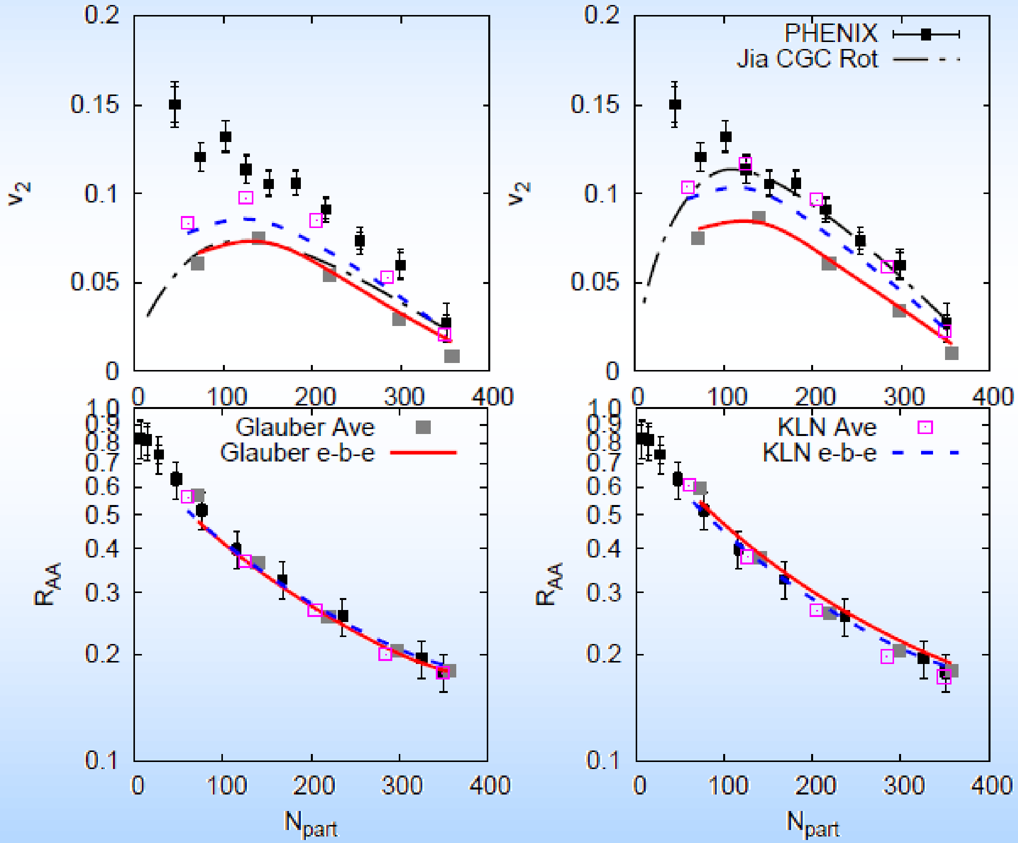


S Wicks, PhD Thesis

  – Role of running coupling, irreducible uncertainty from non-pert. physics?
  – Nontrivial changes from better elastic treatment

Quantifying Sensitivity to Geometry IC

- Effects of geom. on, e.g. v_2, might be quite large



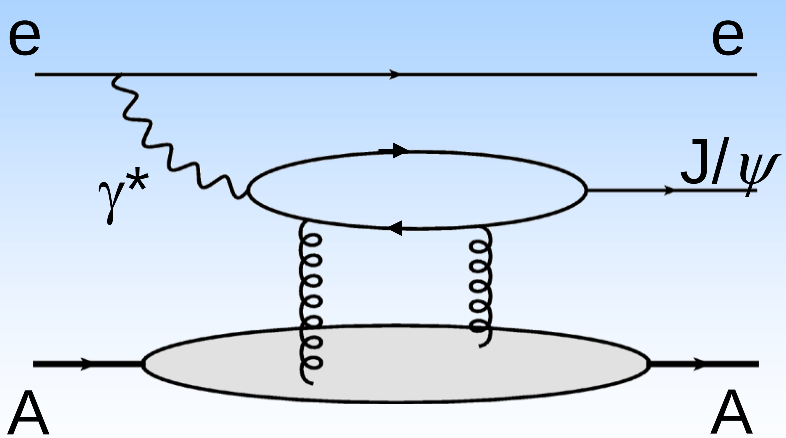
Betz, Gyulassy, and Torrieri, arXiv:1102.5416 [nucl-th]

- – KLN CGC vs. WS Glaub. and rotating RP
- – Effect not large enough for pQCD

Possibly truly extreme initial geometry?

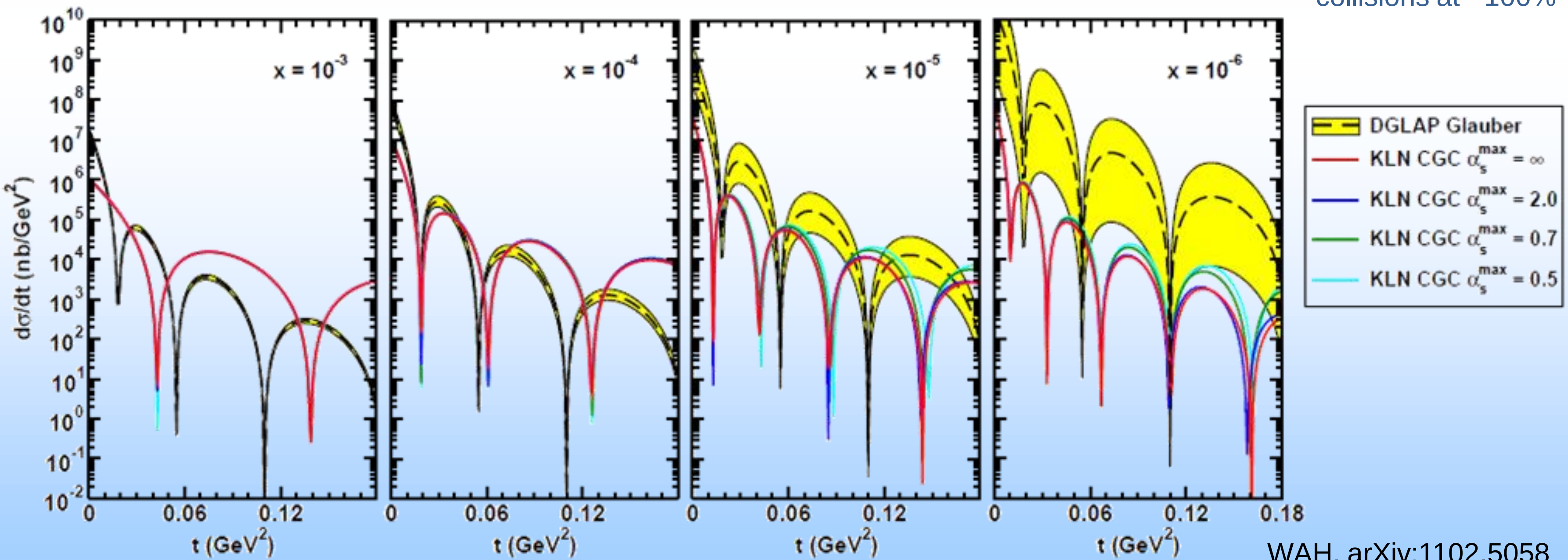
– See also Renk et al., PRC83 (2011)

Gluon Distribution of A at x ~ 10^{-3}



- Coherent vector meson production in e + A
  - 2 gluon exchange => mean & fluc.

Must reject incoherent collisions at ~100%

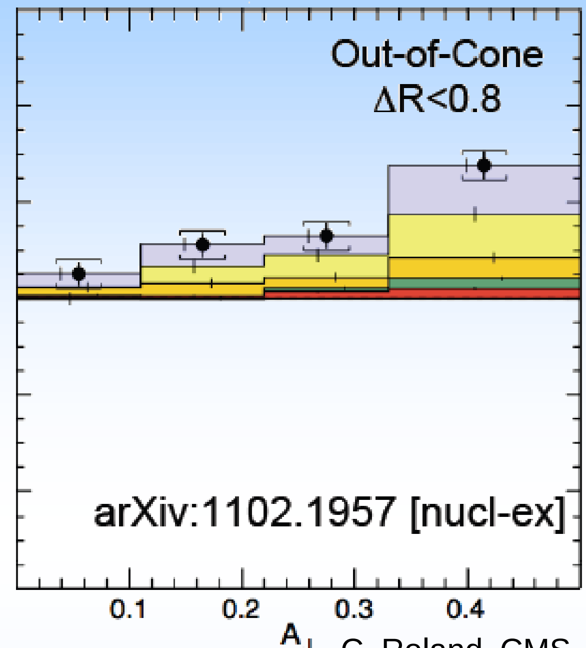


WAH, arXiv:1102.5058

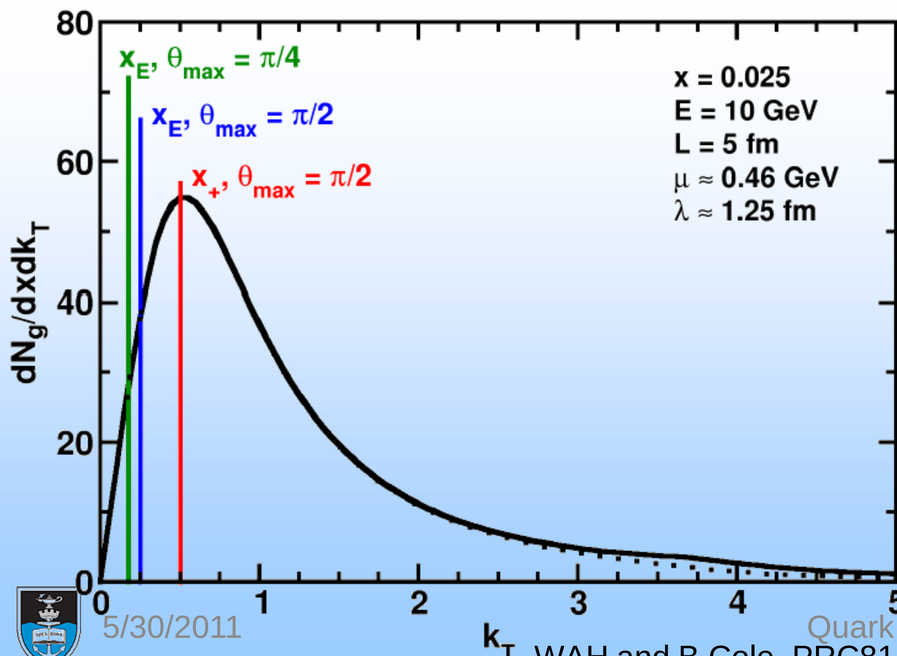
Also DVCS and Incoherent production; see talk by A Stasto

pQCD and Jet Measurements

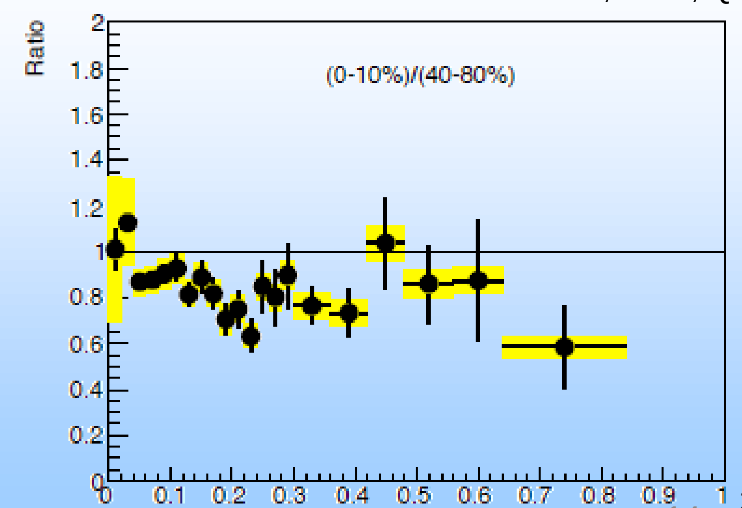
- Naively, pQCD =>
  $x_{typical}$, $\theta_{typical}$ ~ μ/E; μ ~ 0.5 GeV
- ***All*** current Eloss calculations assume small angle emission
  ($k_T << xE$)
- Collinear approximation is (maximally) violated; x_{typ} ~ μ/E
- pQCD not obviously inconsistent



C Roland, CMS, QM11



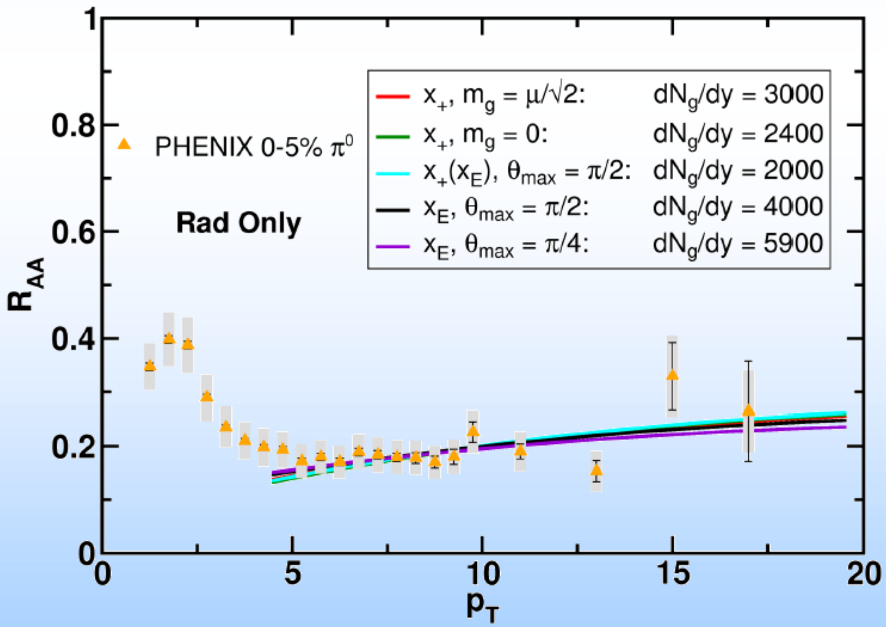
WAH and B Cole, PRC81, 2010

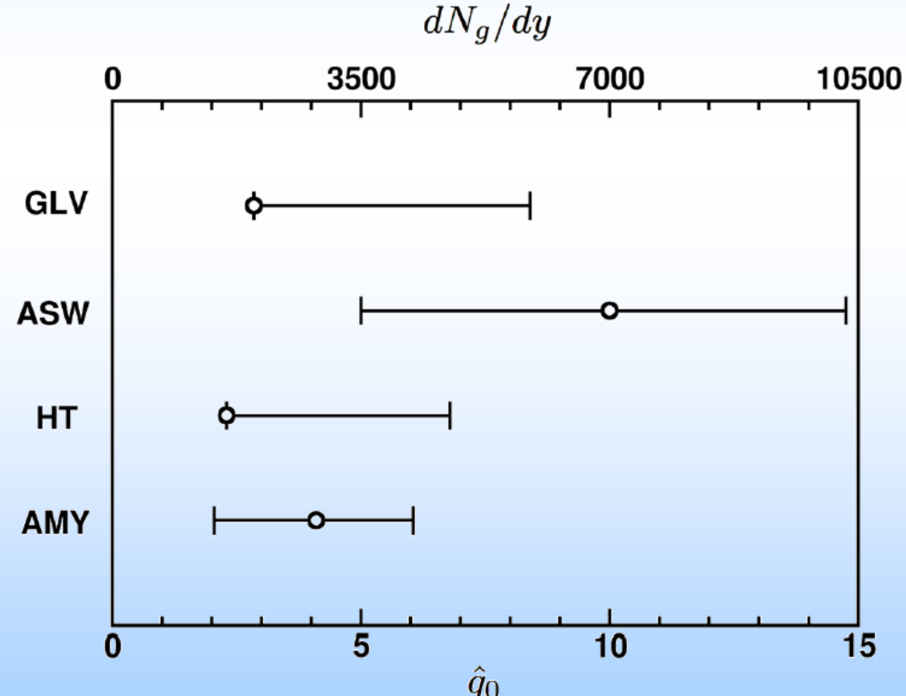


B Cole, ATLAS, QM11

Quantification of Collinear Uncertainty

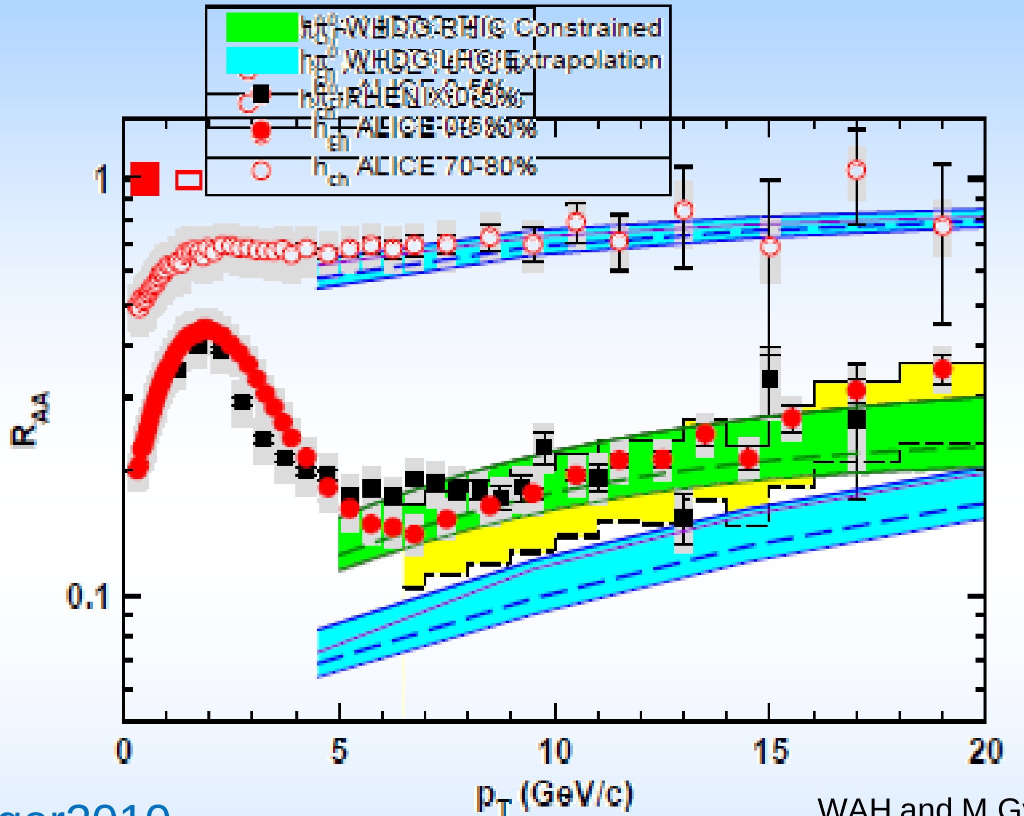
- Factor ~ 3 uncertainty in extracted medium density!
- "qhat" values from *different formalisms* **consistent** w/i unc.





WAH and B Cole, PRC81, 2010

WHDG π^0 R_{AA} at LHC: First Results



Data shown at Kruger2010

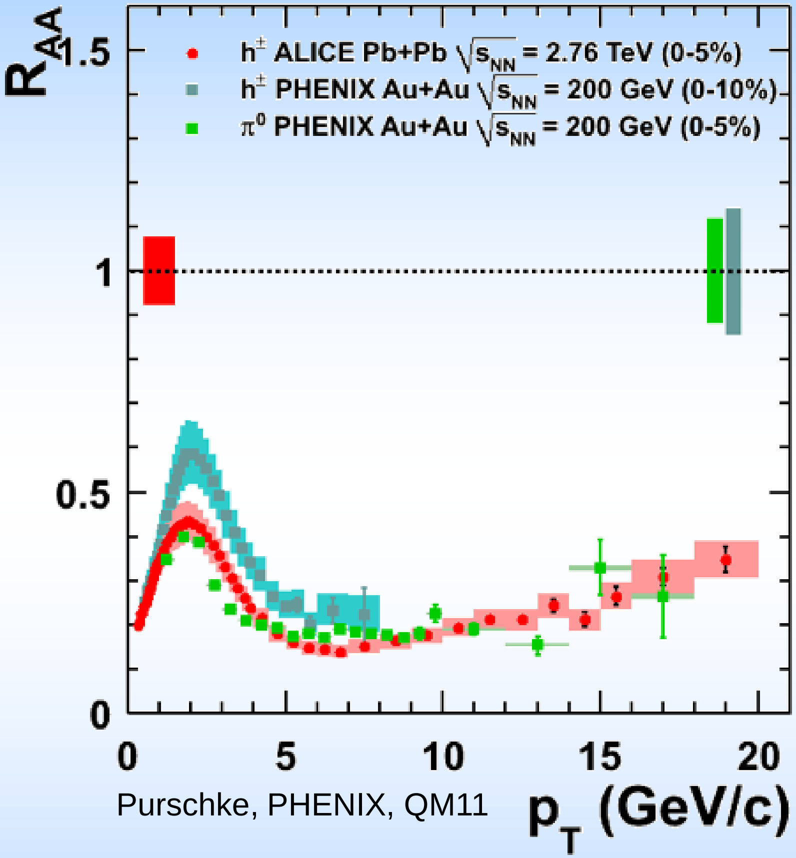
WAH and M Gyulassy, arXiv:1104.4958

- WHDG band from 1-σ RHIC dN_g/dy extraction
- Note that constrained predictions have small uncertainty from collinear approx

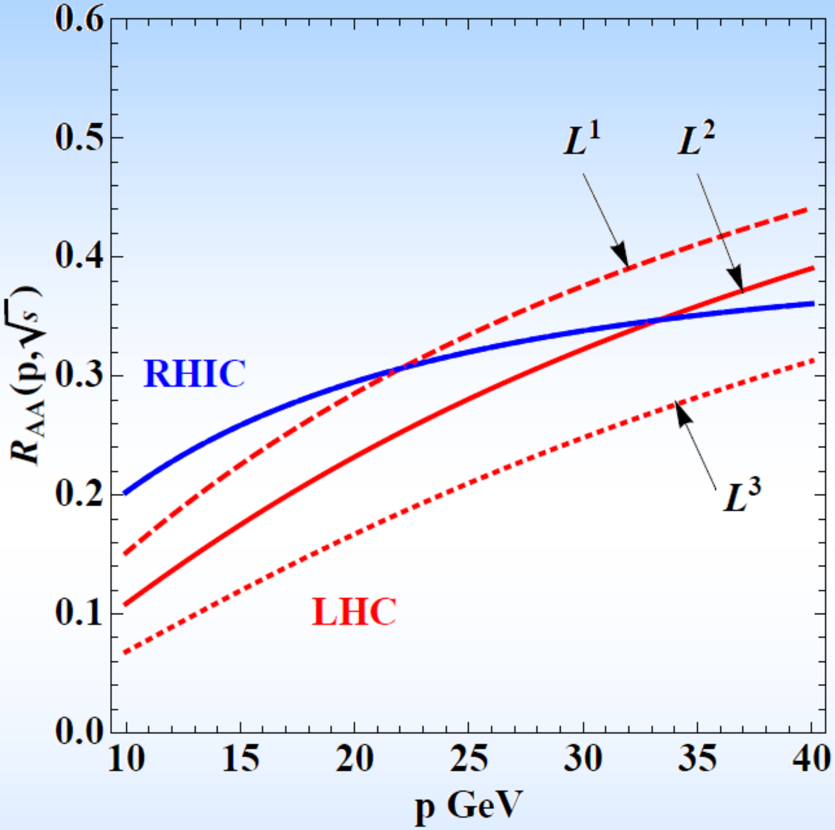
- Constrain WHDG at RHIC
- Make LHC predictions assuming $dN_g/dy \sim dN_{ch}/d\eta$

$\Rightarrow dN_g^{LHC}/dy = 2.4\, dN_g^{RHIC}/dy$

Suppression From RHIC to LHC



Purschke, PHENIX, QM11

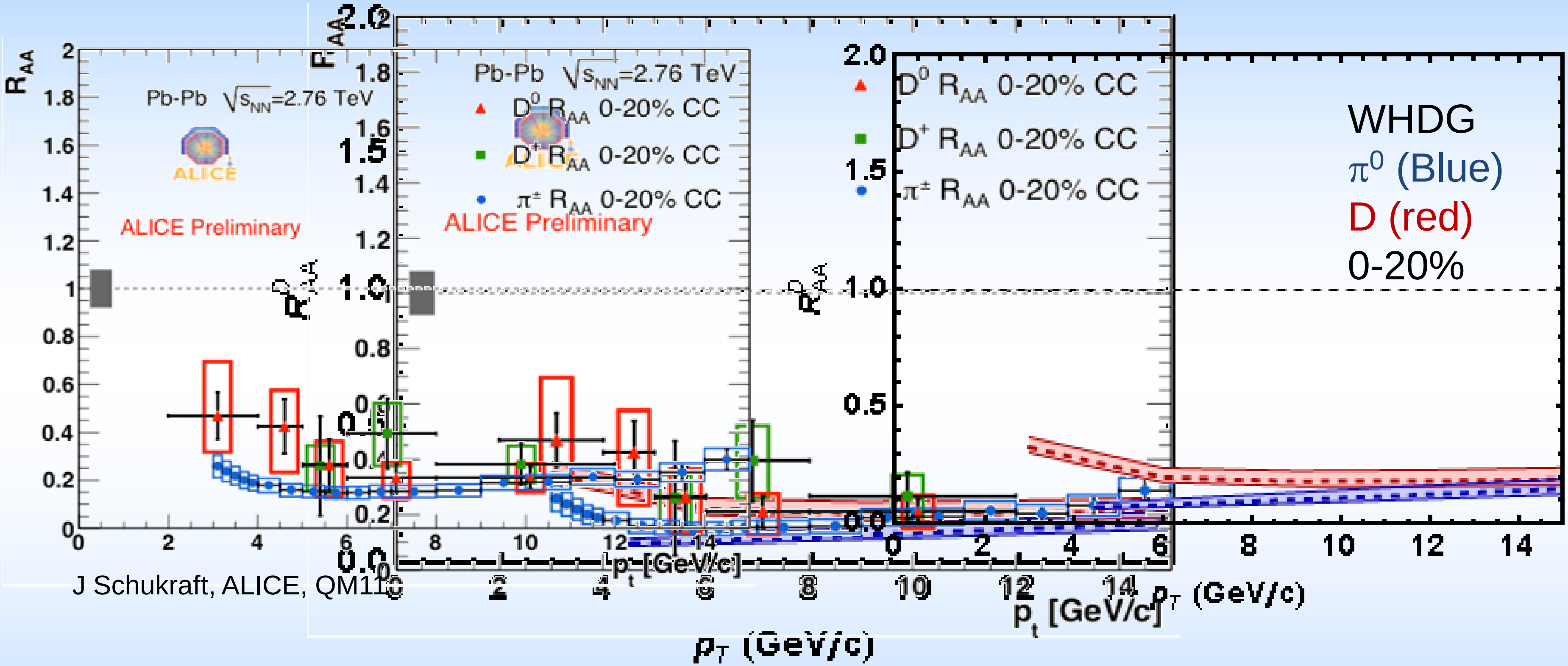


WAH and M Gyulassy, arXiv:1104.4958

- Non-suppression RHIC to LHC ***generically*** hard to understand from dE/dx ~ ρ^m Eloss
- Eloss insensitive to temperature?

WHDG D R_{AA} at LHC: First Results

- D Meson Predictions



J Schukraft, ALICE, QM11

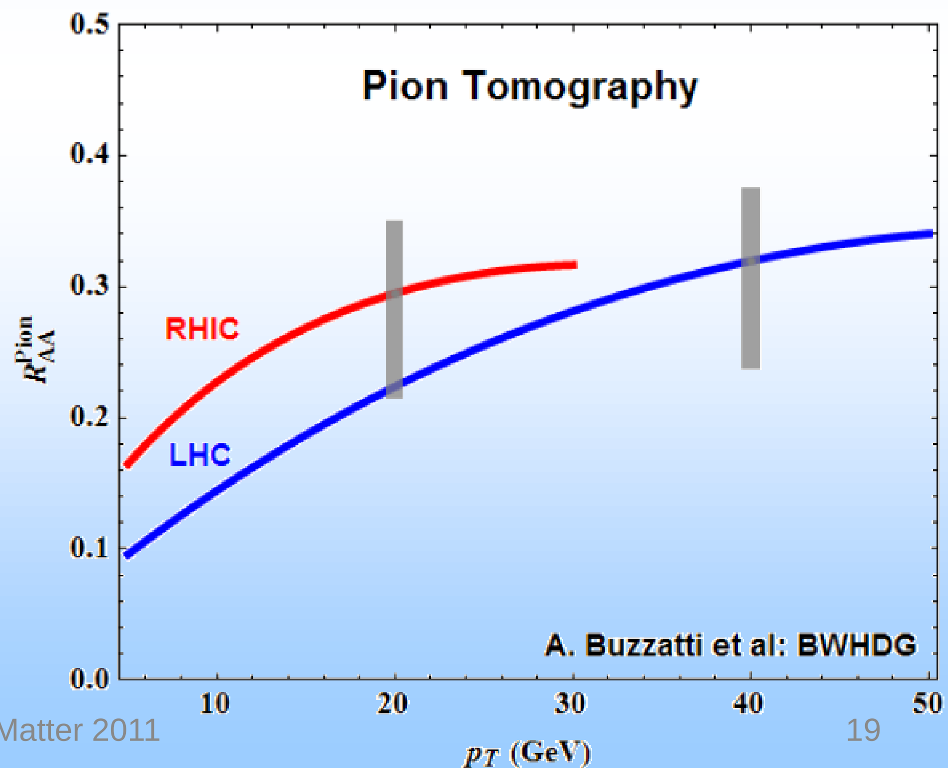
– R_{AA} requires: production, E-loss, FF
  - Does not immediately follow that $R^{\pi}_{AA} << R^{D}_{AA} << R^{B}_{AA}$

– See also A Dainese, ALICE, QM11; CMS B -> J/Ψ

Geometry, Early Time Investigation

- ***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
  - See A Buzzatti's QM poster

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

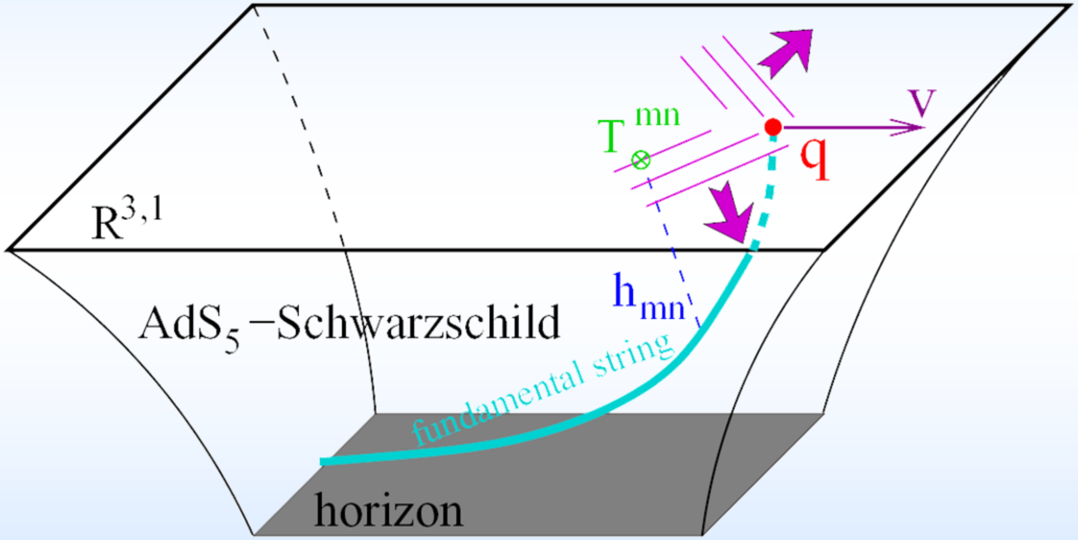


Jets in AdS/CFT

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

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

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



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

– Similar to Bethe-Heitler

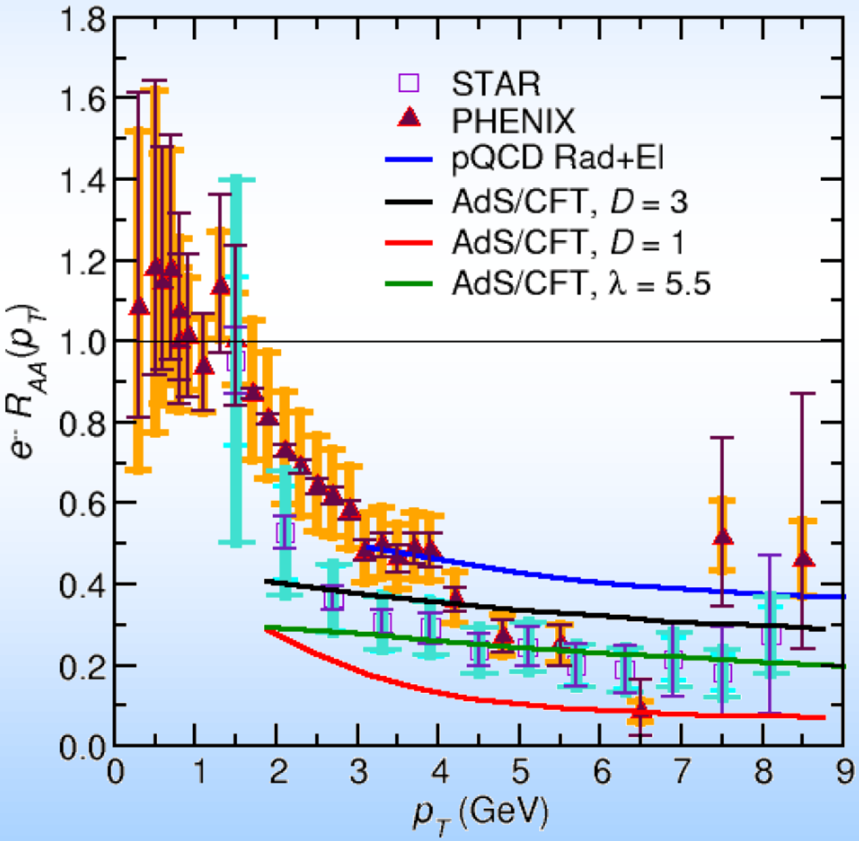
$dp_T/dt \sim -(T^3/M_q^2)\, p_T$

– Very different from usual pQCD and LPM

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

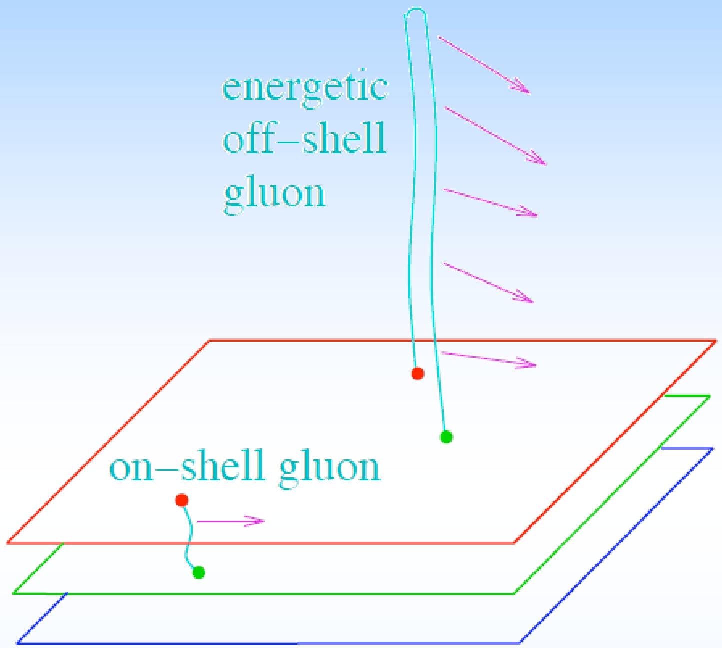
Compared to Data

- String drag: qualitative agreement



WAH, PhD Thesis

Light Quark and Gluon E-Loss



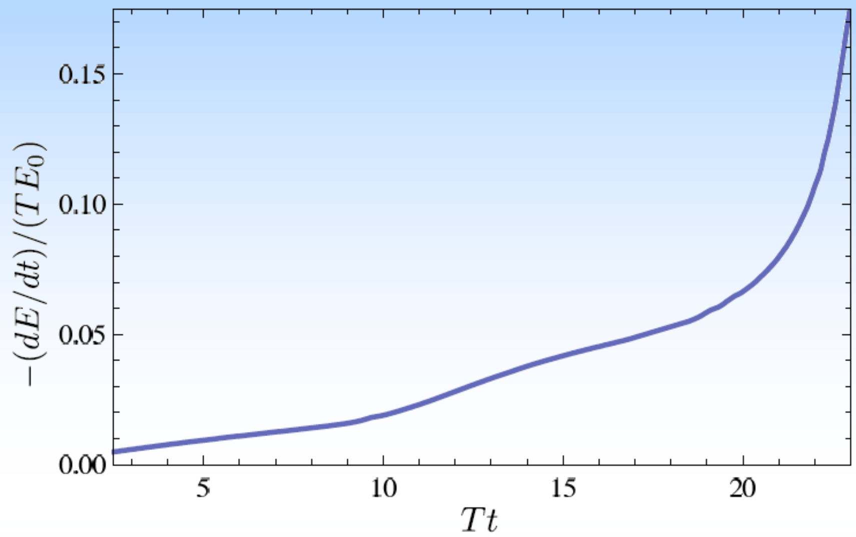
SS Gubser, QM08

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

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

Gubser et al., JHEP0810 (2008)
Chesler et al., PRD79 (2009)

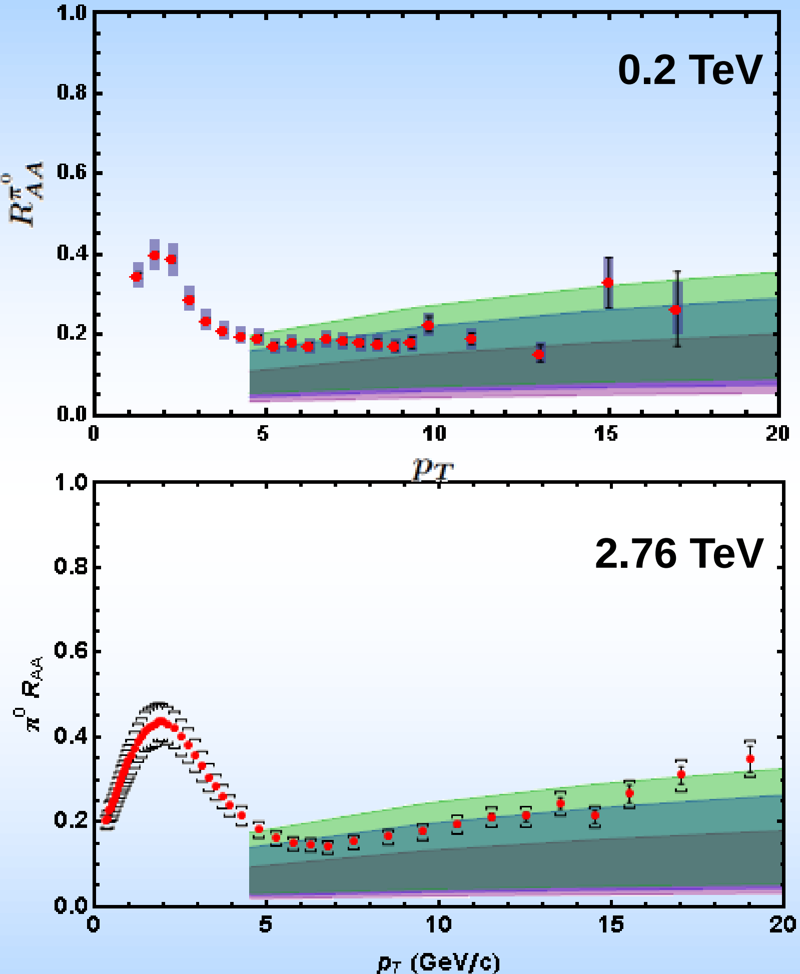
See also Marquet and Renk, PLB685 (2010), and Jia, WAH, and Liao, arXiv:1101.0290, for v_2



Chesler et al., PRD79 (2009)

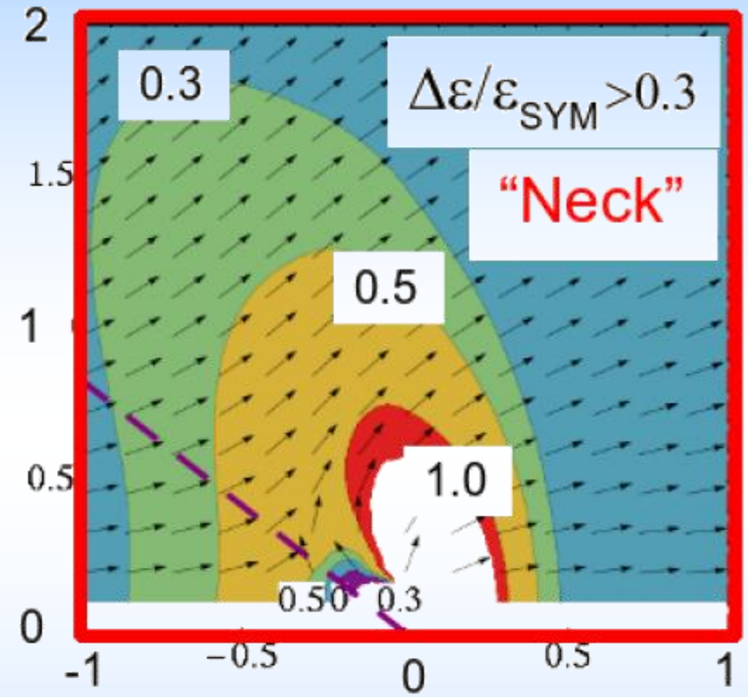
- Light quarks and gluons: generic Bragg peak
  - Leads to lack of T dependence?

AdS/CFT Energy Loss and Distribution



WAH, *in preparation*

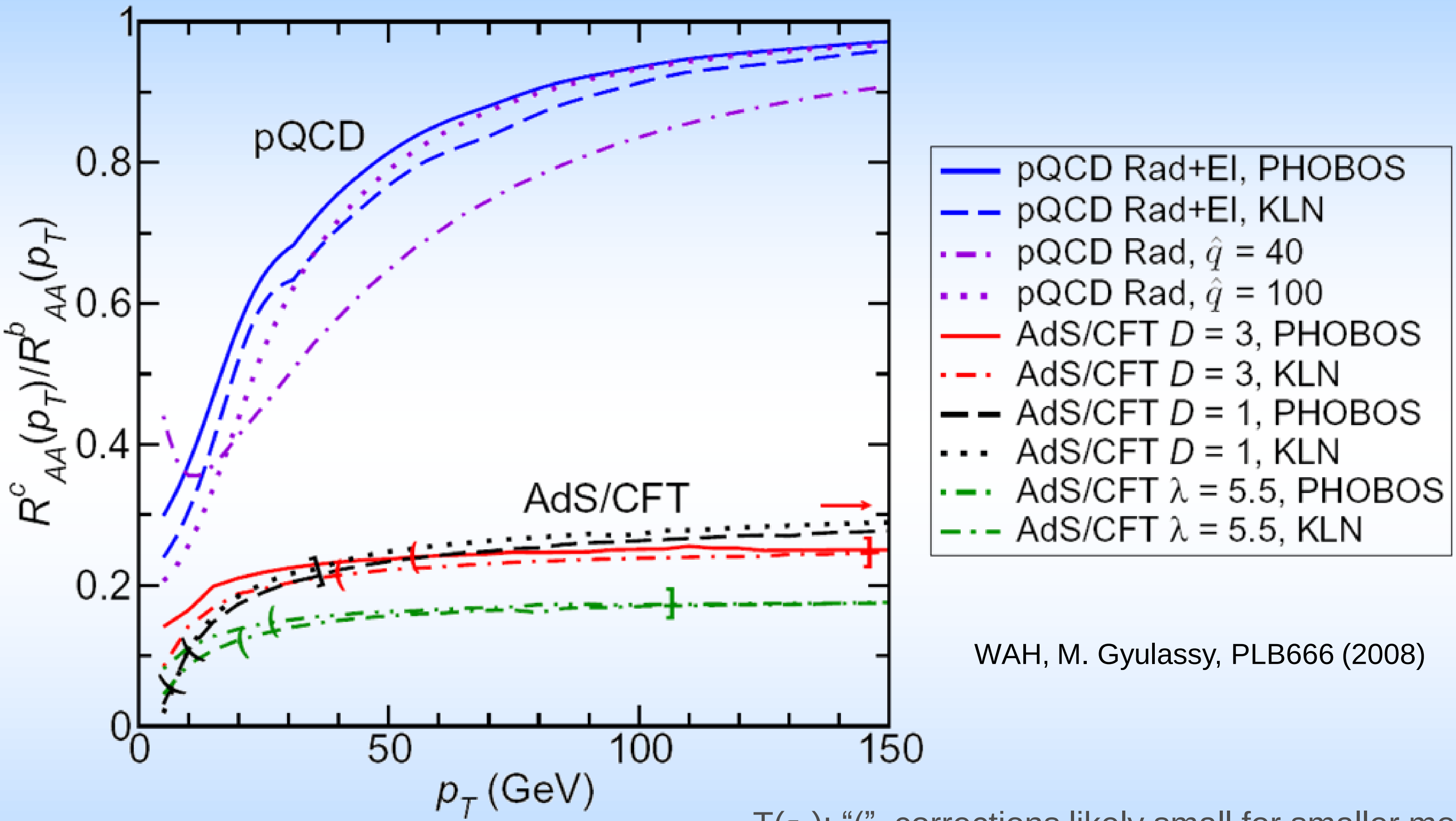
Simple Bragg peak model



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

- In AdS/CFT, heavy quarks: wide angle energy loss

LHC $R^c_{AA}(p_T)/R^b_{AA}(p_T)$ Prediction (with speed limits)



WAH, M. Gyulassy, PLB666 (2008)

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

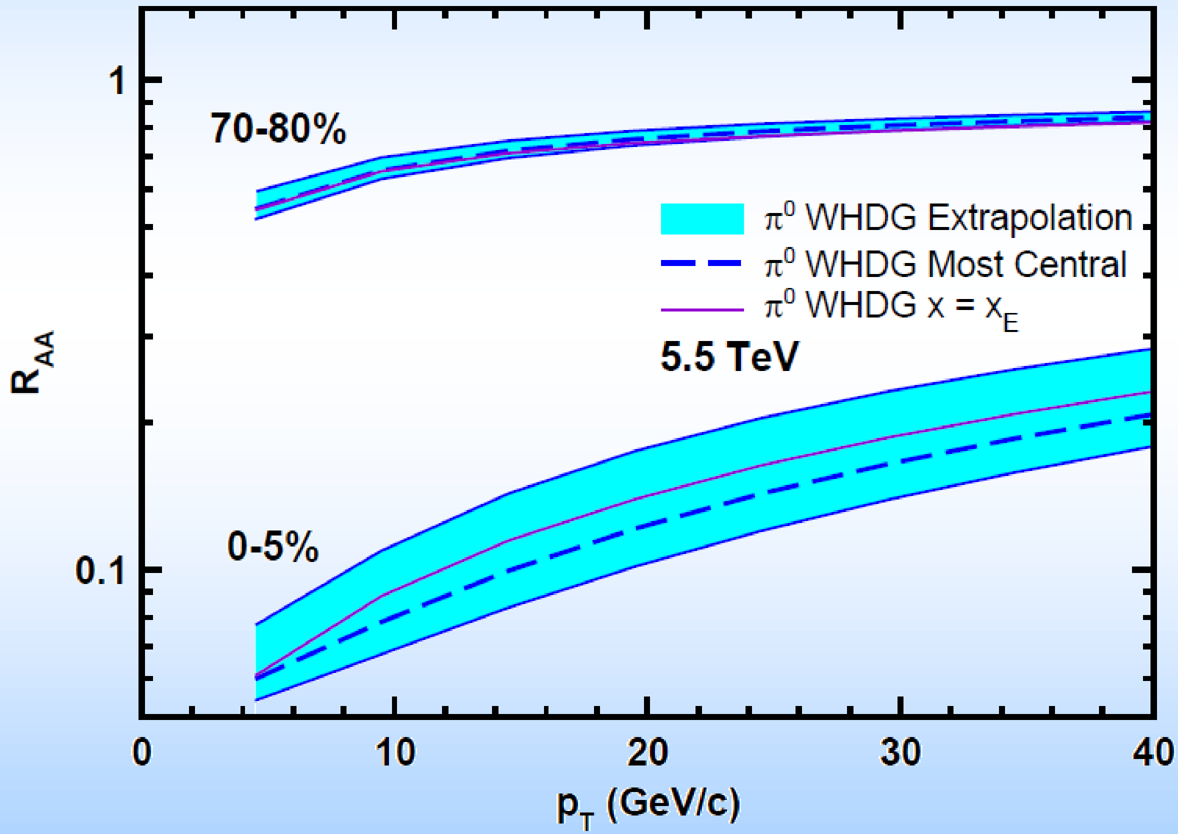
Qualitatively, corrections to AdS/CFT result will drive double ratio to unity

Conclusions: Questions

- Does rise in $R_{AA}(p_T)$ imply perturbative E-loss dominant at LHC?
  - To make a qualitative statement need:
    - Experimental control over production effects
    - Reduced exp. uncertainties at large (~100 GeV/c) p_T
    - Consistency check btwn pQCD and mult. observables at large (~100 GeV/c) p_T, esp. v_2
- Data suggests:
  - surprisingly little T, strong L dependencies
    - Generically difficult to understand in typical dE/dx picture (both pQCD and AdS/CFT)
    - E-loss in (currently) uncontrolled pre-thermalization dynamics?
    - Possibly signal of AdS/CFT Bragg peak physics
  - Soft particle energy loss at very wide angles
    - Not inconsistent with pQCD or AdS/CFT pictures
- WHDG zero parameter LHC predictions constrained by RHIC appear to:
  - (Possibly) systematically oversuppress light hadron R_{AA}
  - Describe light hadron v_2 at "intermediate" p_T ~ 20 GeV/c
  - Describe D meson suppression
    - **CAUTION**: many important effects not currently under th. control
- AdS Eloss: consistent with RHIC and LHC within large th. uncertainties
- Looking forward to exciting future distinguishing measurements, esp. heavy quark suppression separation

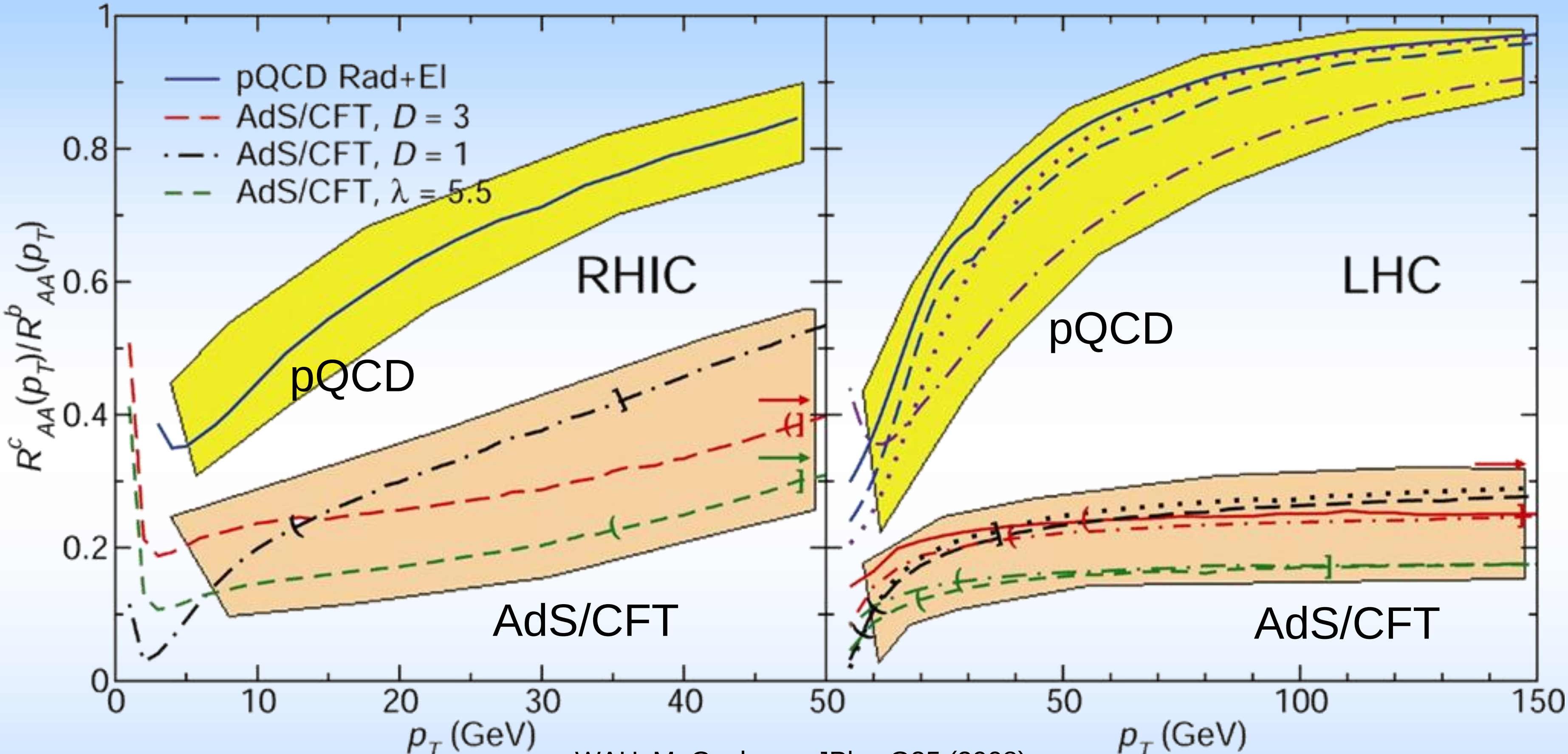
Top Energy Predictions

- For posterity:



WAH and M Gyulassy, *in preparation*

RHIC R^{cb} Ratio

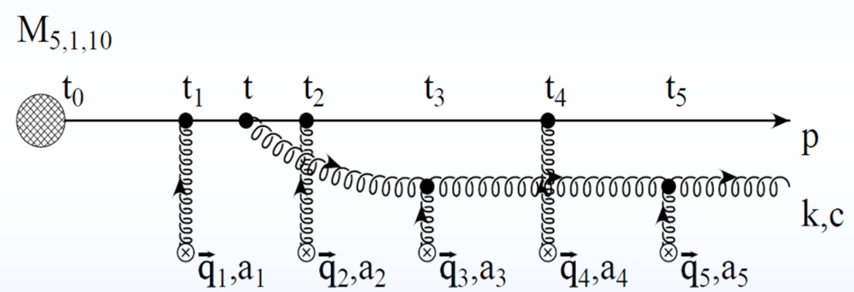


WAH, M. Gyulassy, JPhysG35 (2008)

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

pQCD Rad Picture

- Bremsstrahlung Radiation
  - Weakly-coupled plasma
    - Medium organizes into Debye-screened centers
  - T ~ 250 MeV, g ~ 2
    - μ ~ gT ~ 0.5 GeV
    - λ_{mfp} ~ $1/g^2T$ ~ 1 fm
    - R_{Au} ~ 6 fm
  - $1/\mu \ll \lambda_{mfp} \ll L$
    - mult. coh. em.



Gyulassy, Levai, and Vitev, NPB571 (200)

- LPM

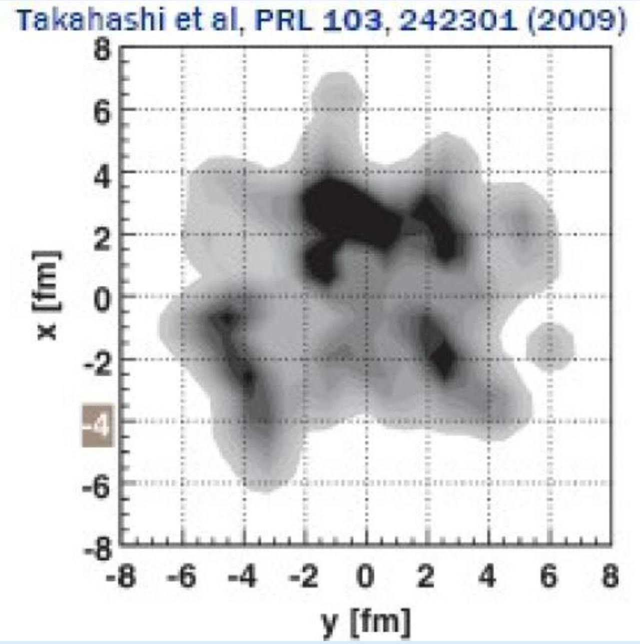
  $dp_T/dt \sim -LT^3 \log(p_T/M_q)$

- Bethe-Heitler

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

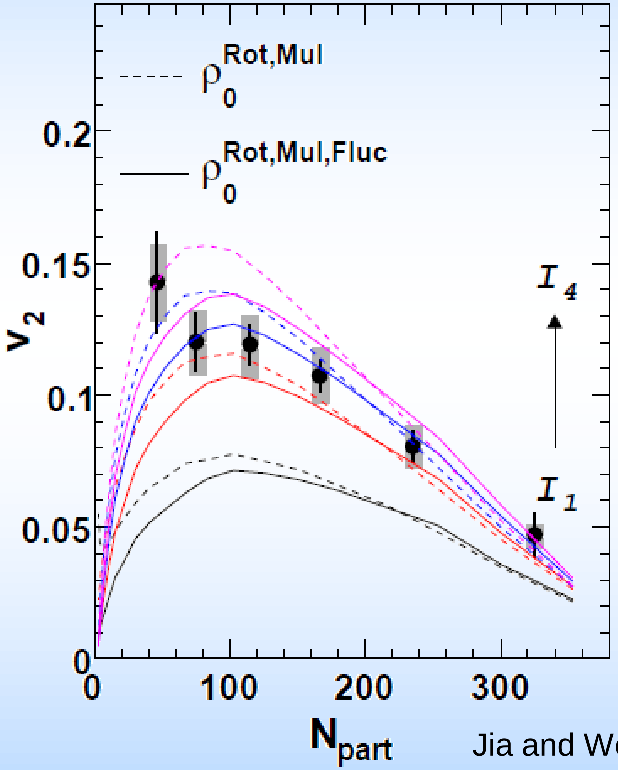
What About Fluctuations?

- Hot spots can be huge



  – NEXUS calculation for ***10% most central*** top RHIC energy event

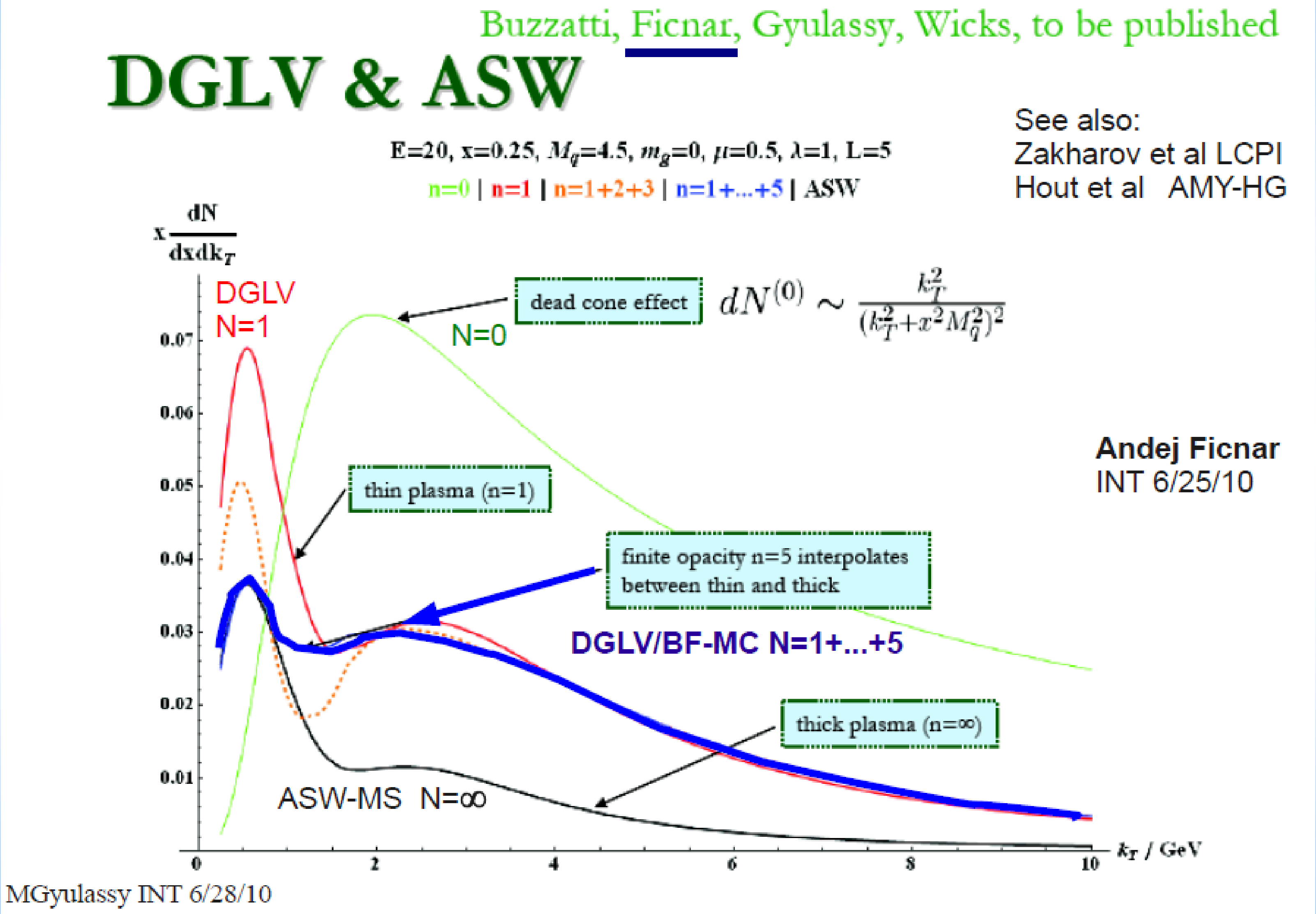
- For simple E-loss not a large effect



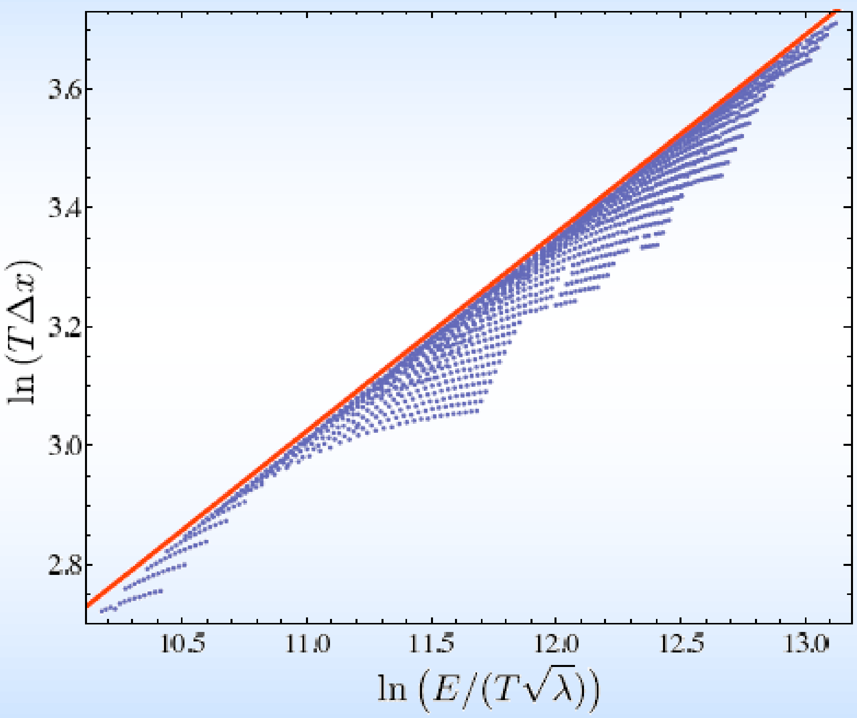
Jia and Wei, arXiv:1005.0645

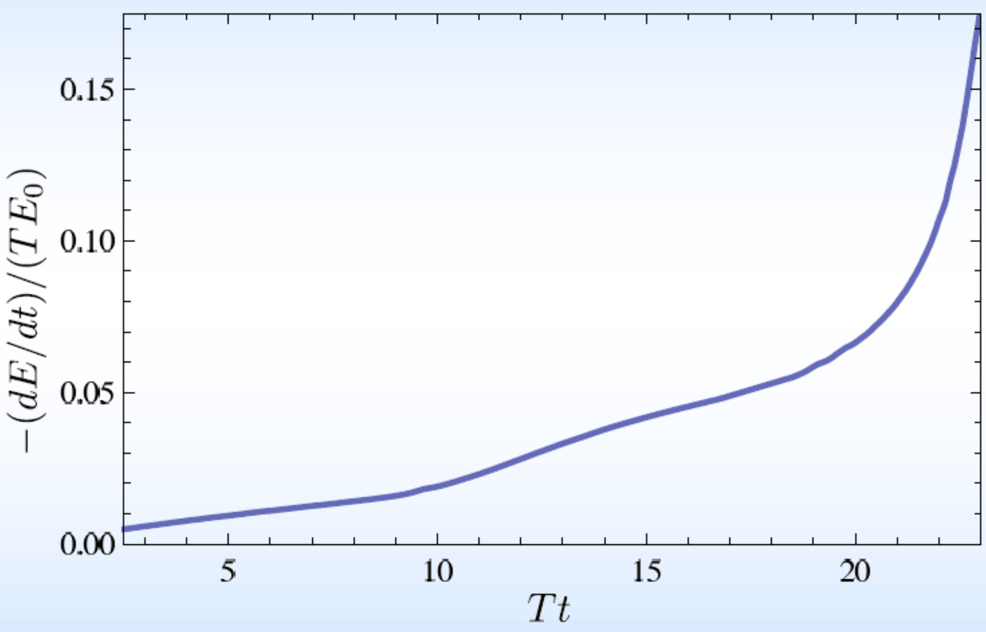
  – Important for fluc., opacity exp.?

Opacity Corrections

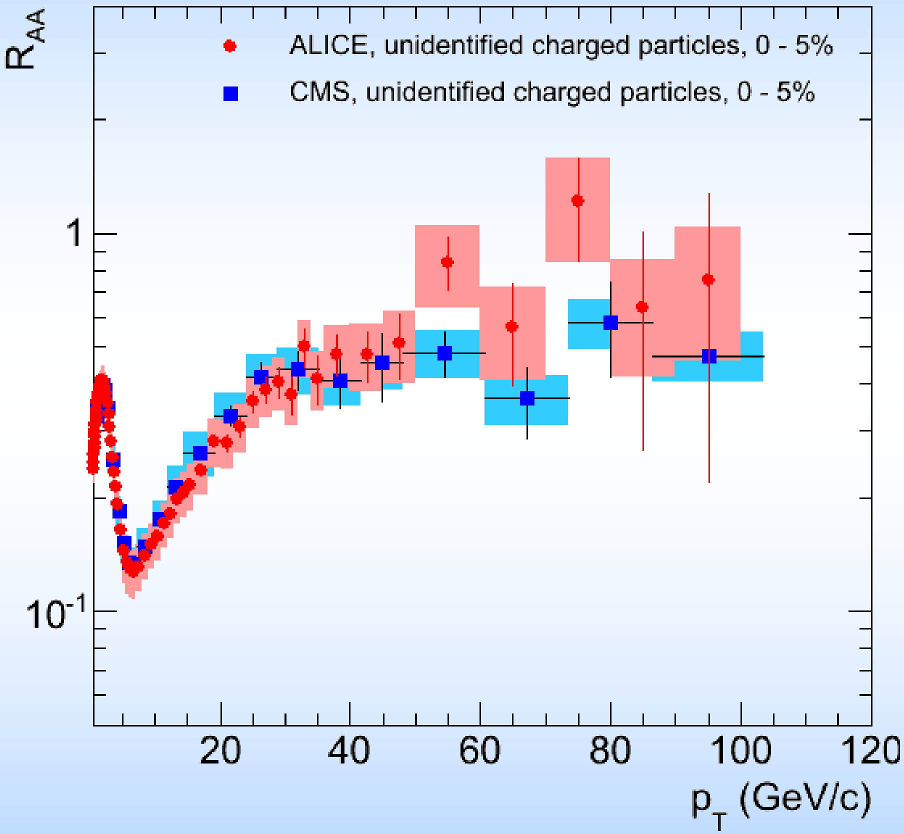


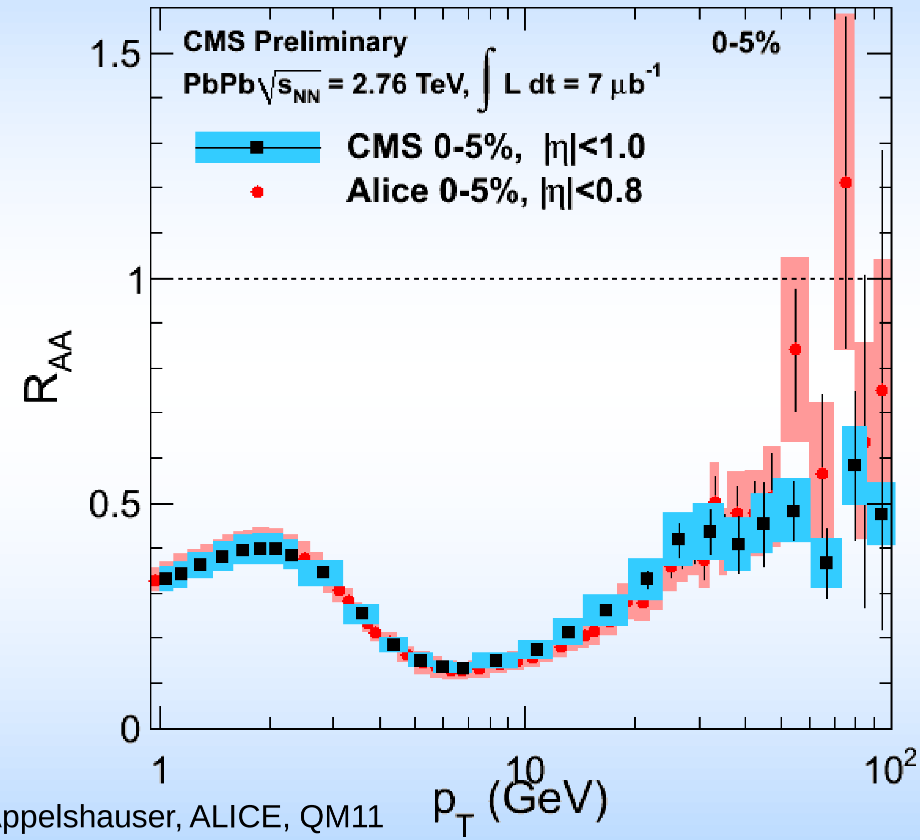
Likely important, but integration over many variables required for comparison to data





Chesler et al., PRD79 (2009)

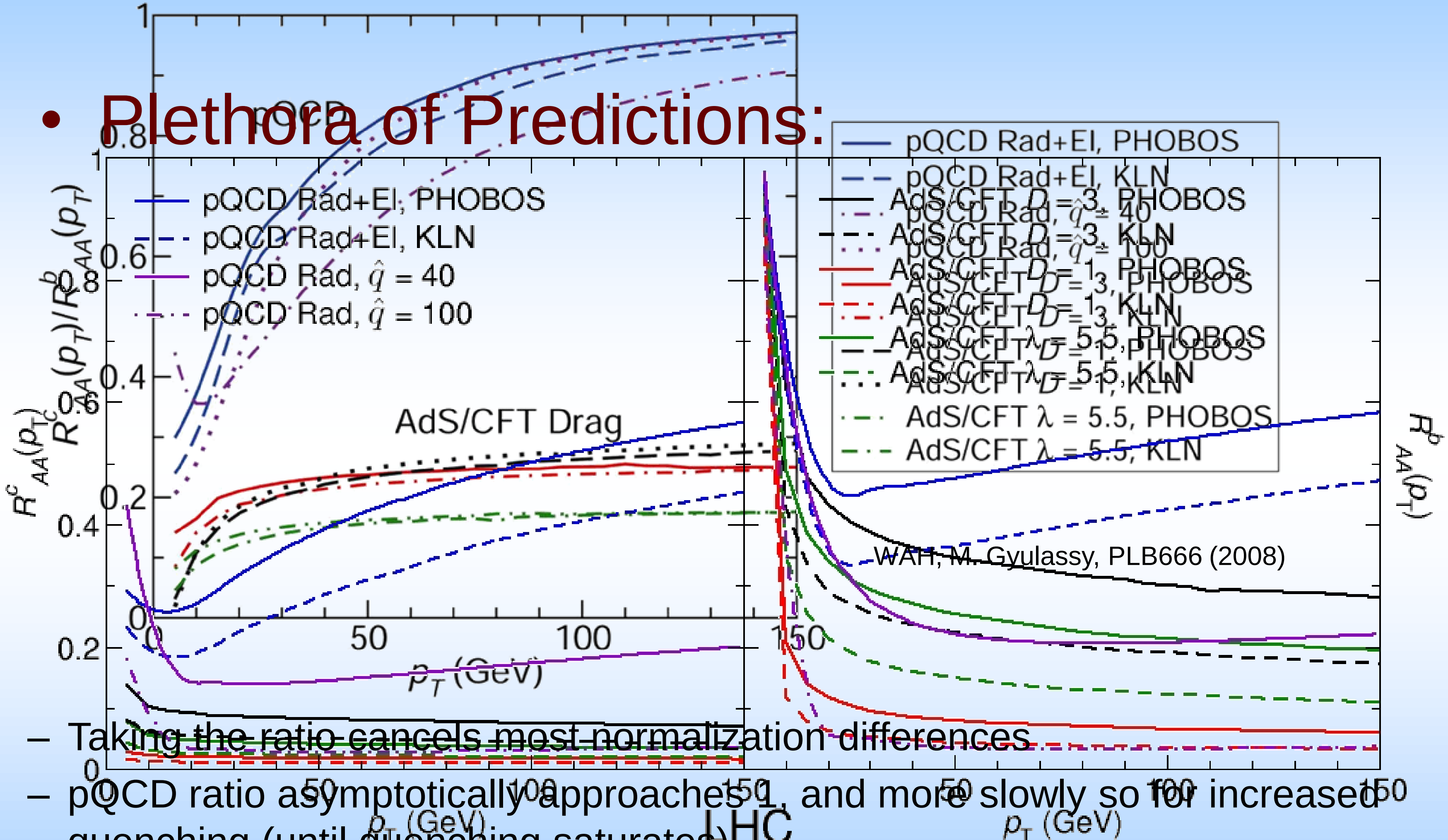




Appelshauser, ALICE, QM11

pQCD vs. AdS/CFT at LHC

- Plethora of Predictions:



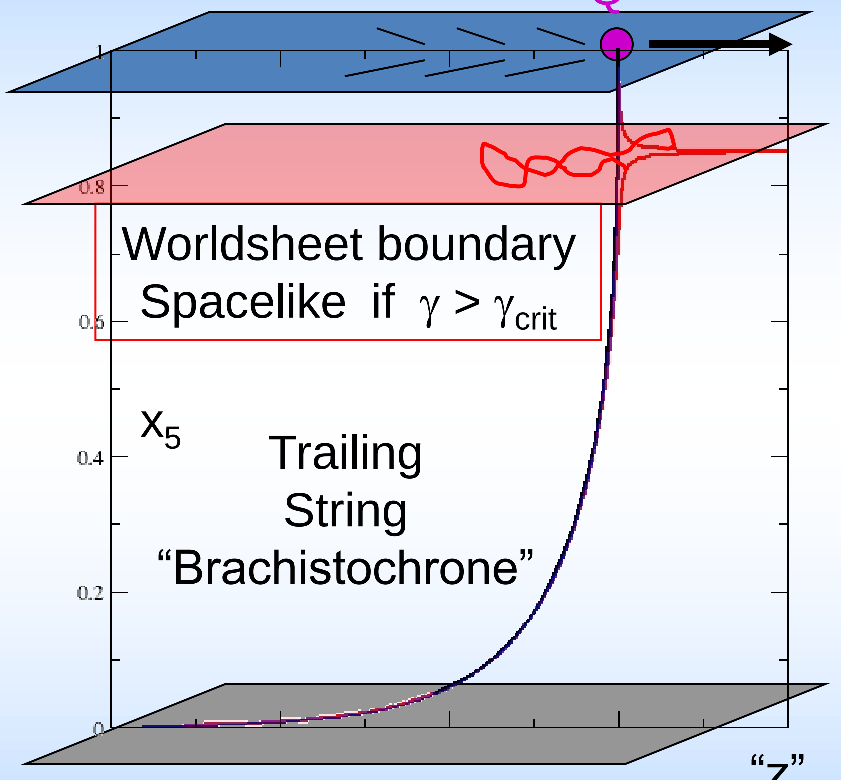
  - Taking the ratio cancels most normalization differences
  - pQCD ratio asymptotically approaches 1, and more slowly so for increased quenching (until quenching saturates)

WAH, M. Gyulassy, PLB666 (2008)

  - AdS/CFT ratio is flat and many times smaller than pQCD at only moderate p_T

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
    $T = T_c$: "]"

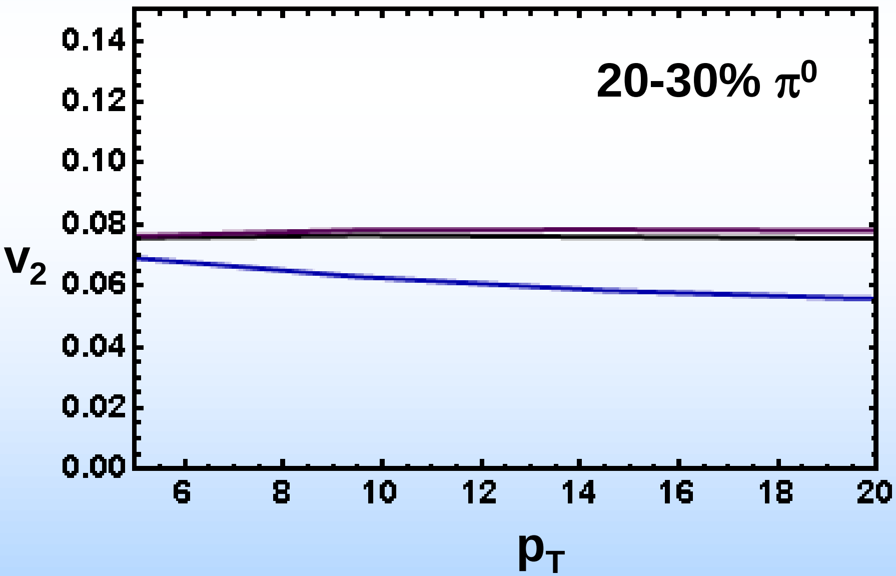


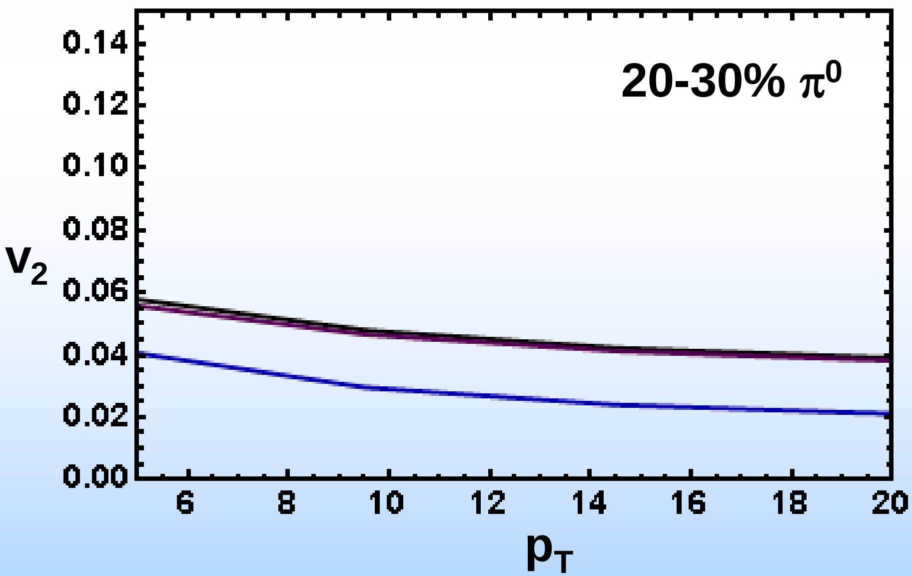
v_2: "Collinearly Safe"

- Fix dN_g/dy from R_{AA}, calculate v_2
  - Expect larger v_2 for smaller opening angle

($\tau_{coh} \sim 1/k_T^2$)

- Rad Only
- Rad + El





WAH, *in preparation*