

Shock Treatment: Heavy Quark Drag in Novel AdS Geometries

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Heavy Quark Physics in Nucleus-Nucleus Collisions, UCLA

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Motivation

- Why study AdS E-loss models?
 - Many calculations vastly simpler
 - Complicated in unusual ways
 - Data difficult to reconcile with pQCD
 - See, e.g., Ivan Vitev's talk for alternative
 - pQCD quasiparticle picture leads to dominant $q \sim \mu \sim .5 \text{ GeV}$ mom. transfers
- Use data to learn about E-loss mechanism, plasma properties
 - Domains of applicability crucial for understanding

Strong Coupling Calculation

- The supergravity double conjecture:

$$\text{QCD} \Leftrightarrow \text{SYM} \Leftrightarrow \text{IIB}$$

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

AdS/CFT Energy Loss Models

- Langevin Diffusion

- Collisional energy loss for heavy quarks
- Restricted to low p_T
- pQCD vs. AdS/CFT computation of D , the diffusion coefficient

Moore and Teaney, Phys.Rev.C71:064904,2005

Casalderrey-Solana and Teaney, Phys.Rev.D74:085012,2006; JHEP 0704:039,2007

- ASW/LRW model

- Radiative energy loss model for all parton species
- pQCD vs. AdS/CFT computation of $\hat{q}$
- Debate over its predicted magnitude

See Hong Liu's talk

BDMPs, Nucl.Phys.B484:265-282,1997

Armesto, Salgado, and Wiedemann, Phys. Rev. D69 (2004) 114003

Liu, Ragagopal, Wiedemann, PRL 97:182301,2006; JHEP 0703:066,2007

- Heavy Quark Drag calculation

- Embed string representing HQ into AdS geometry
- Includes all E-loss modes
- Previously: thermalized QGP plasma, temp. T , $\gamma_{\text{crit}} < \sim M/T$

Gubser, Phys.Rev.D74:126005,2006

Herzog, Karch, Kovtun, Kozcaz, Yaffe, JHEP 0607:013,2006

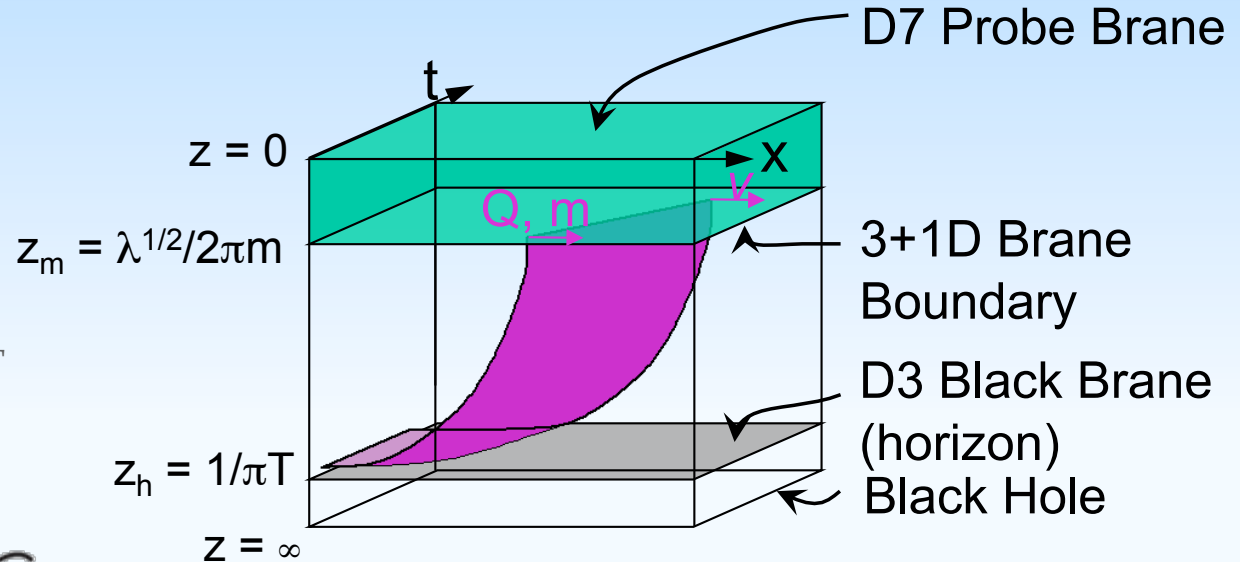
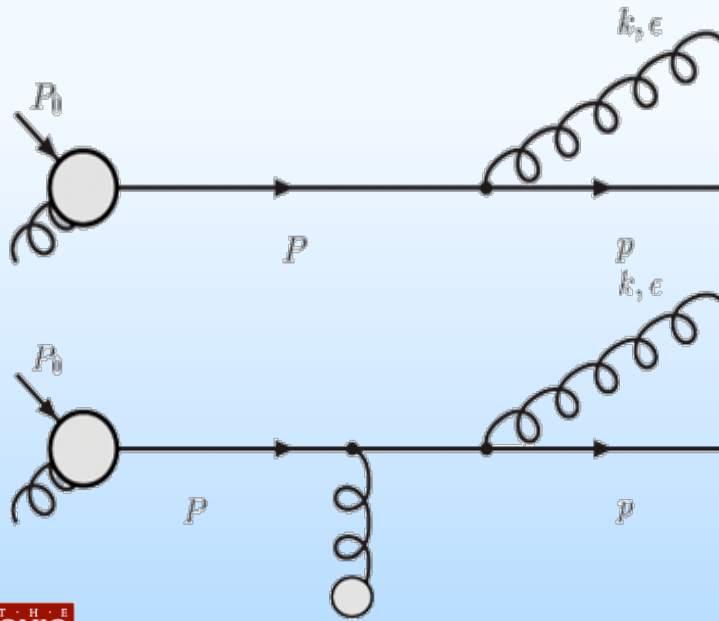
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Energy Loss Comparison

– AdS/CFT Drag:

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



– Similar to Bethe-Heitler

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

– Very different from LPM

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

R_{AA} Approximation

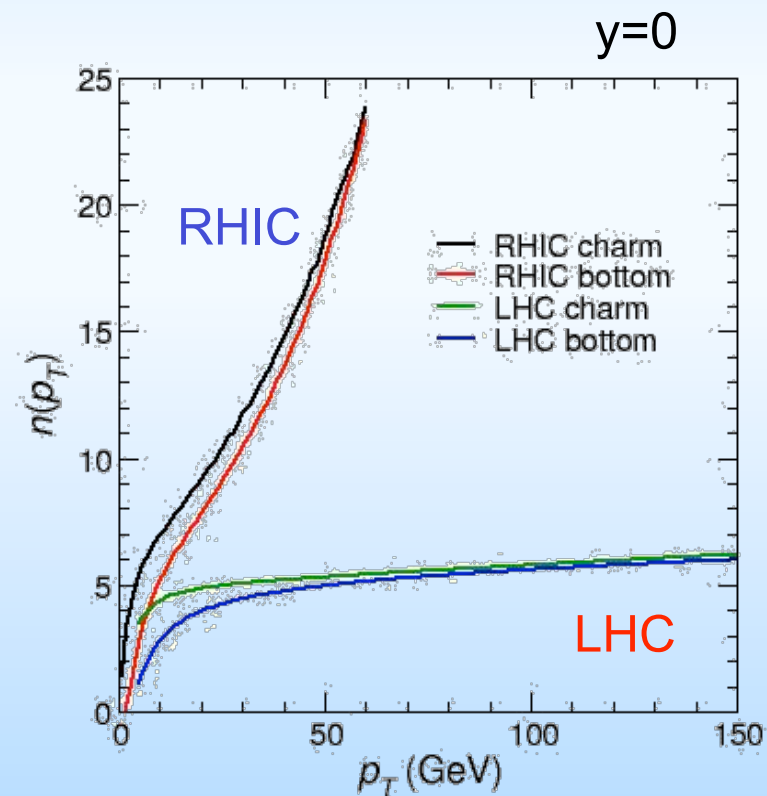
- Above a few GeV, quark production spectrum is approximately power law:

- $dN/dp_T \sim 1/p_T^{(n+1)}$, where $n(p_T)$ has some momentum dependence

- We can approximate $R_{AA}(p_T)$:

- $R_{AA} \sim (1-\varepsilon(p_T))^{n(p_T)}$,

where $p_f = (1-\varepsilon)p_i$ (i.e. $\varepsilon = 1-p_f/p_i$)



Looking for a Robust, Detectable Signal

- Use LHC's large p_T reach and identification of c and b to distinguish between pQCD, AdS/CFT

- Asymptotic pQCD momentum loss:

$$\varepsilon_{\text{rad}} \sim \alpha_s \hat{q} L^2 \log(p_T/M_q)/p_T$$

- String theory drag momentum loss:

$$\varepsilon_{\text{ST}} \sim 1 - \text{Exp}(-\mu L), \quad \mu = \pi\lambda^{1/2} T^2/2M_q$$

S. Gubser, Phys.Rev.D74:126005 (2006); C. Herzog *et al.* JHEP 0607:013,2006

- Independent of p_T and strongly dependent on M_q !
- T^2 dependence in exponent makes for a *very* sensitive probe

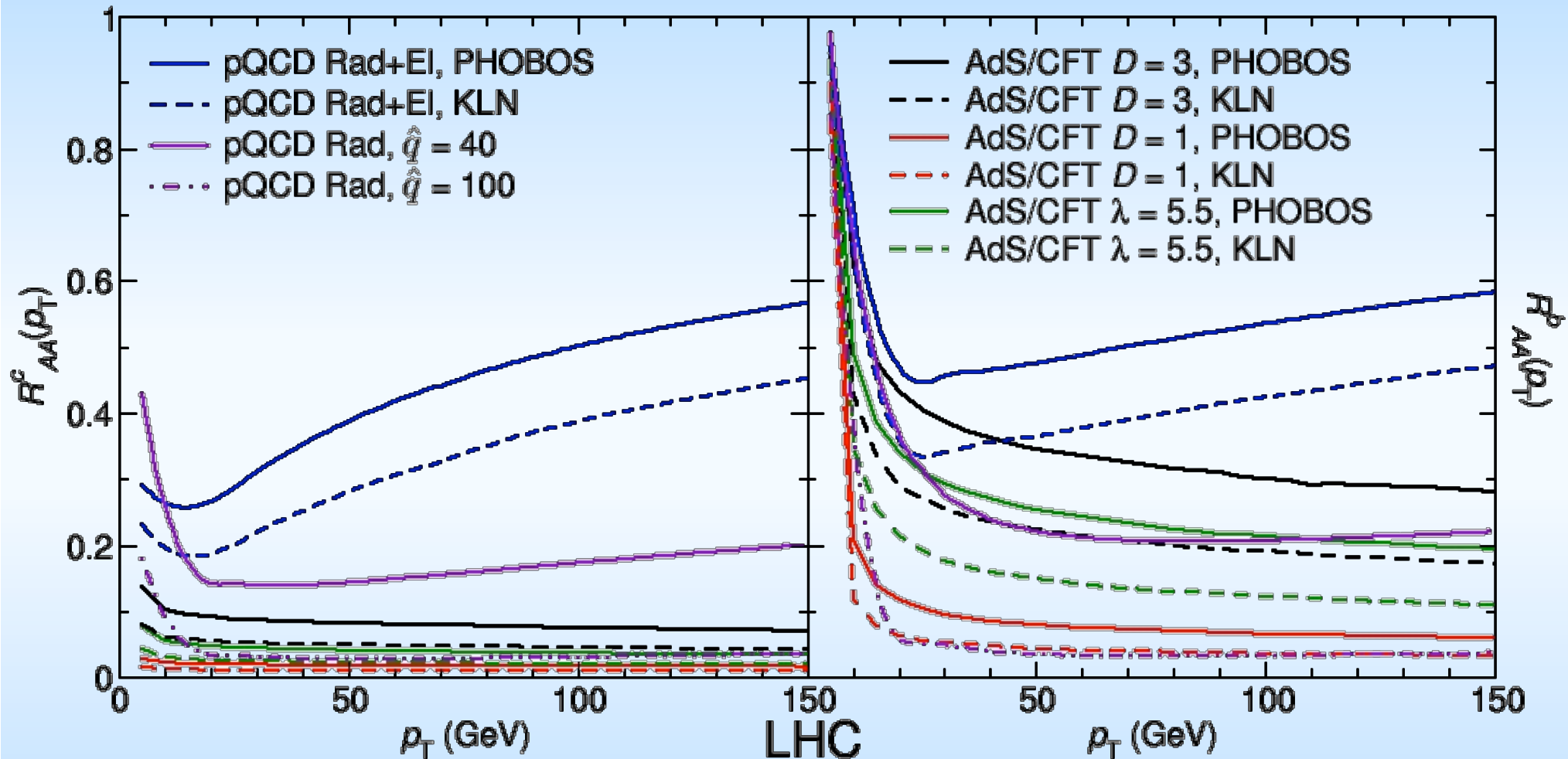
- Expect: $\varepsilon_{\text{pQCD}} \rightarrow 0$ vs. ε_{AdS} indep of p_T !!

- $dR_{\text{AA}}(p_T)/dp_T > 0 \Rightarrow \text{pQCD}; dR_{\text{AA}}(p_T)/dp_T < 0 \Rightarrow \text{ST}$

Model Inputs

- AdS/CFT Drag: nontrivial mapping of QCD to SYM
 - “Obvious”: $\alpha_s = \alpha_{\text{SYM}} = \text{const.}$, $T_{\text{SYM}} = T_{\text{QCD}}$
 - D $2\pi T = 3$ inspired: $\alpha_s = .05$
 - pQCD/Hydro inspired: $\alpha_s = .3$ (D $2\pi T \sim 1$)
 - “Alternative”: $\lambda = 5.5$, $T_{\text{SYM}} = T_{\text{QCD}}/3^{1/4}$
 - Start loss at thermalization time τ_0 ; end loss at T_c
- WHDG convolved radiative and elastic energy loss
 - $\alpha_s = .3$
- WHDG radiative energy loss (similar to ASW)
 - $\hat{q} = 40, 100$
- Use realistic, diffuse medium with Bjorken expansion
 - PHOBOS ($dN_g/dy = 1750$); KLN model of CGC ($dN_g/dy = 2900$)

LHC c, b R_{AA} p_T Dependence



- Single parton production is not sufficient to describe the data

- Use of a realistic geometry to study the Bjorken expansion allows saturation below .2

WH and M. Gyulassy,
Phys. Lett. B 666, 320 (2008)



An Enhanced Signal

- 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

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

- Ratio starts below 1, asymptotically approaches 1.

Approach is slower for higher quenching

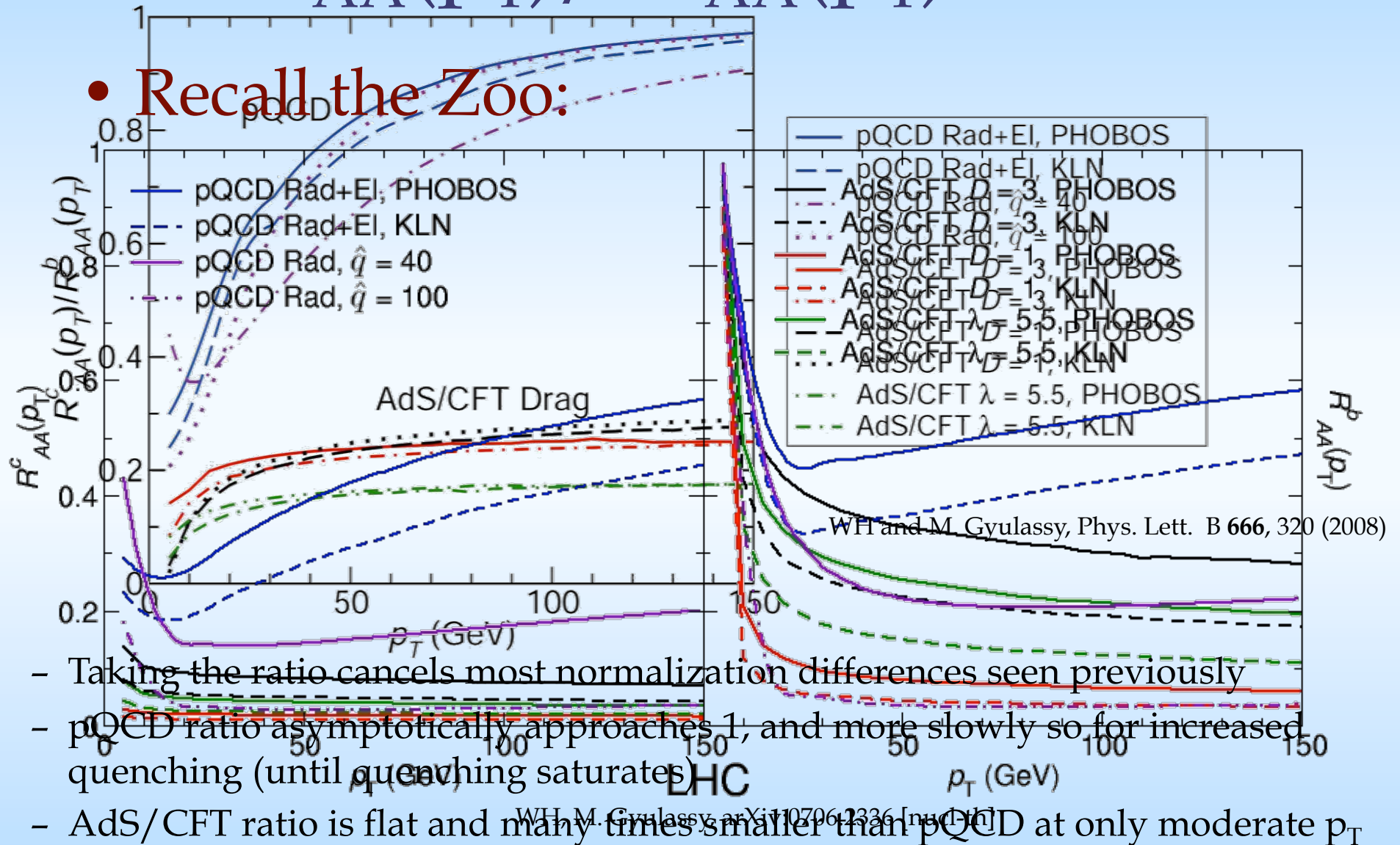
- ST: drag independent of p_T , inversely proportional to mass. Simple analytic approx. of uniform medium gives

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

- Ratio starts below 1; independent of p_T

LHC $R_{AA}^c(p_T)/R_{AA}^b(p_T)$ Prediction

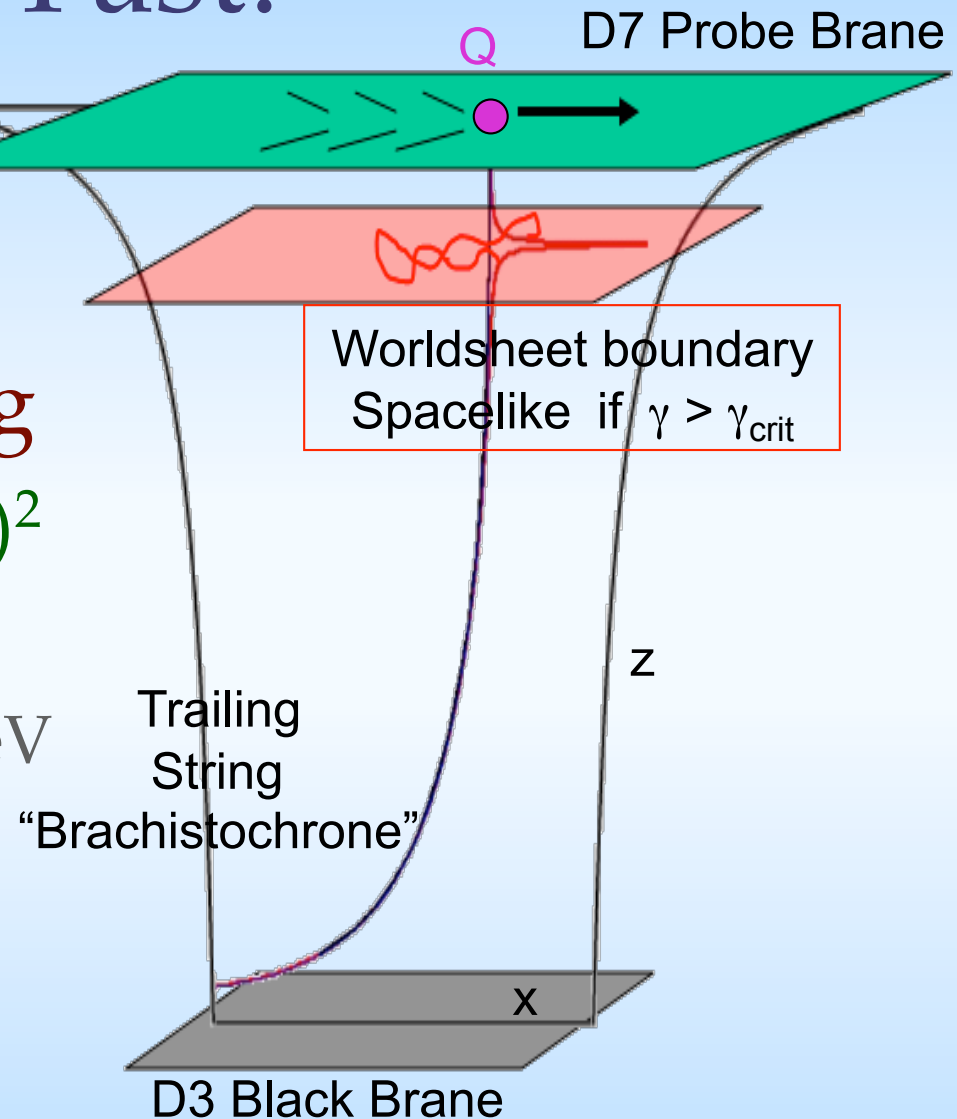
Recall the Zoo:



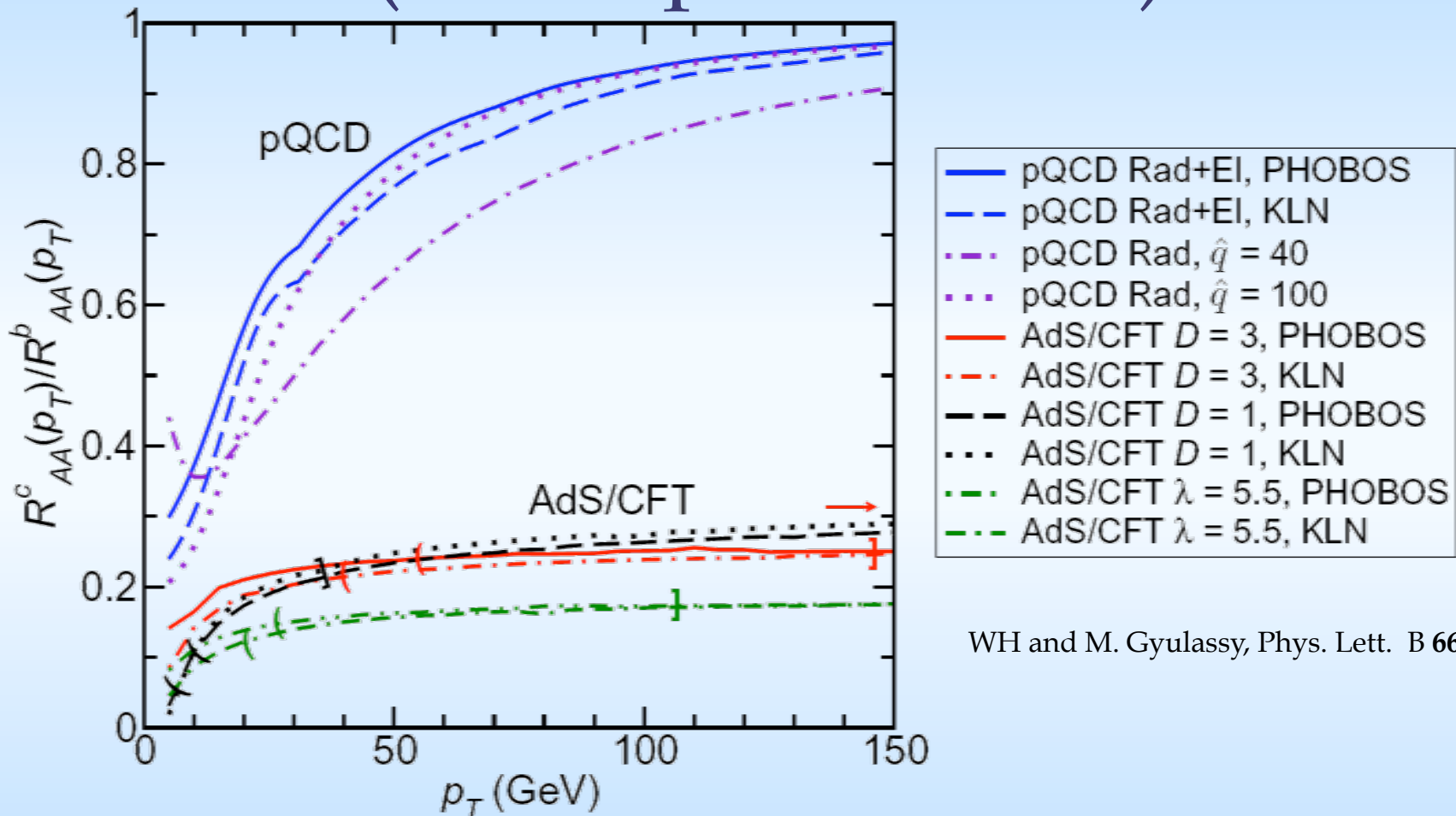
- Taking the ratio cancels most normalization differences seen previously
- pQCD ratio asymptotically approaches 1, and more slowly so for increased quenching (until quenching saturates)
- AdS/CFT ratio is flat and many times smaller than pQCD at only moderate p_T

Not So Fast!

- Speed limit estimate for applicability of AdS drag
 - $\gamma < \gamma_{\text{crit}} = (1 + 2M_q/\lambda^{1/2}T)^2 \sim 4M_q^2/(\lambda T^2)$
 - Limited by $M_{\text{charm}} \sim 1.2 \text{ GeV}$
- Similar to $\text{BH} \rightarrow \text{LPM}$
 - $\gamma_{\text{crit}} \sim M_q/(\lambda T)$
- No single T for QGP



LHC $R_{AA}^c(p_T)/R_{AA}^b(p_T)$ Prediction (with speed limits)



WH and M. Gyulassy, Phys. Lett. B **666**, 320 (2008)

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

Derivation of BH Speed Limit I

- Constant HQ velocity
 - Assume const. v kept by $F \cdot v$

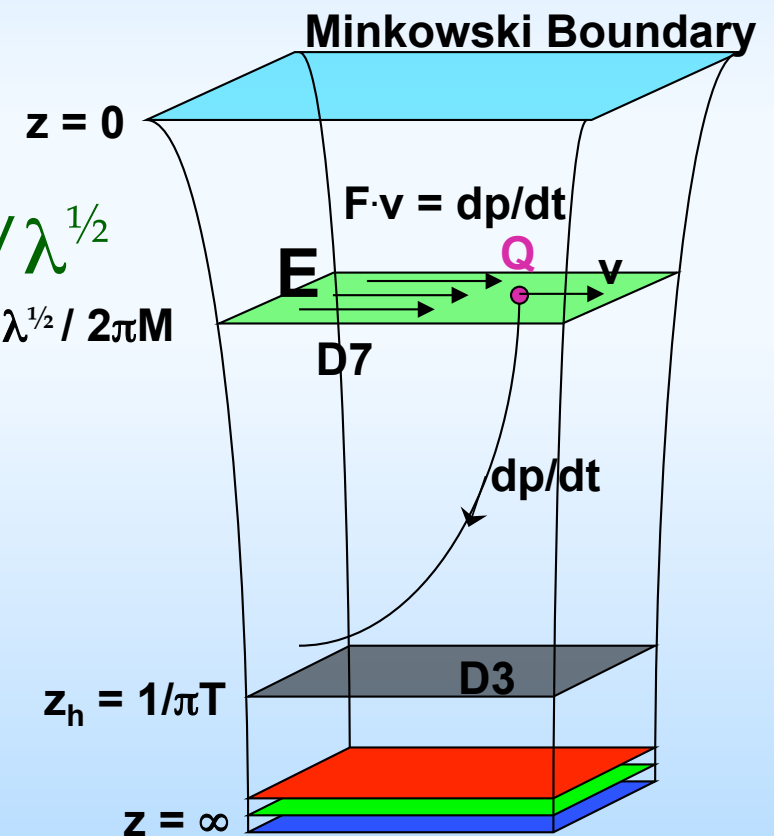
$$S_{BI} \sim \sqrt{1 - \left(2\pi\alpha' E \frac{R^2}{r^2}\right)^2}$$

- Critical field strength $E_c = M^2/\lambda^{1/2}$
 - $E > E_c$: Schwinger pair prod. $z_M = \lambda^{1/2} / 2\pi M$
 - Limits $\gamma < \gamma_c \sim T^2/\lambda M^2$

J. Casalderrey-Solana and D. Teaney, JHEP 0704, 039 (2007)

- Alleviated by allowing var. v
 - Drag similar to const. v

Herzog, Karch, Kovtun, Kozcaz, Yaffe, JHEP 0607:013 (2006)



Derivation of BH Speed Limit II

- Local speed of light

- BH Metric => varies with depth z

- $v(z)^2 < 1 - (z/z_h)^4$

- HQ located at $z_M = \lambda^{1/2}/2\pi M$

- Limits $\gamma < \gamma_c \sim T^2/\lambda M^2$

- Same limit as from const. v

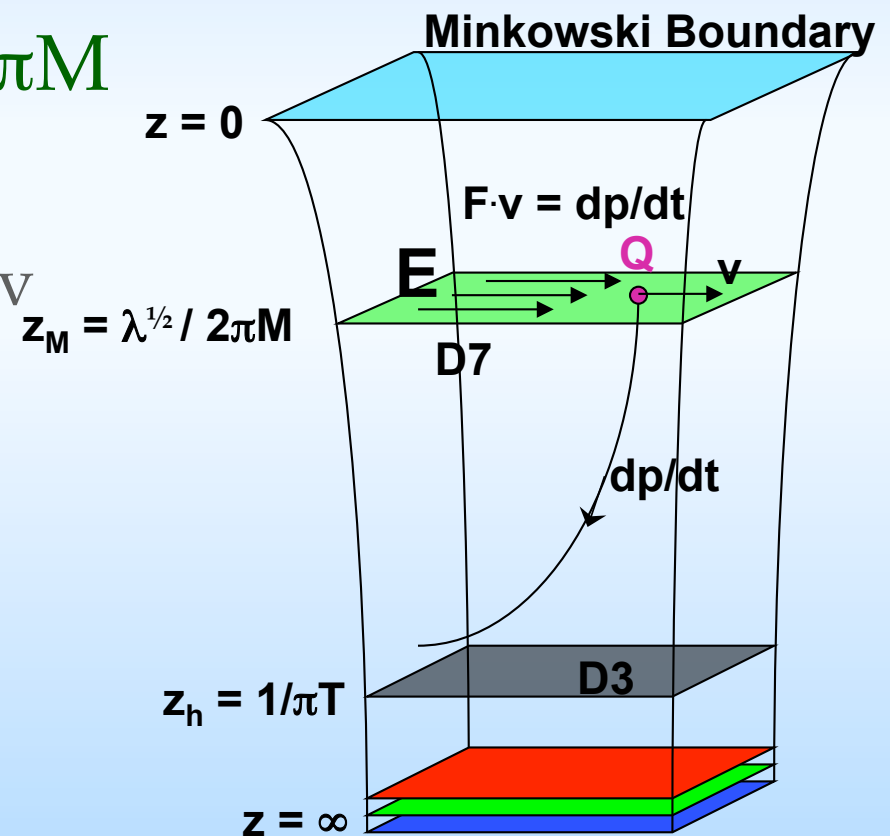
S. S. Gubser, Nucl. Phys. B 790, 175 (2008)

- Mass a strange beast

- $M_{\text{therm}} < M_{\text{rest}}$

- $M_{\text{rest}} \neq M_{\text{kin}}$

- Note that $M \gg T$



Universality and Applicability

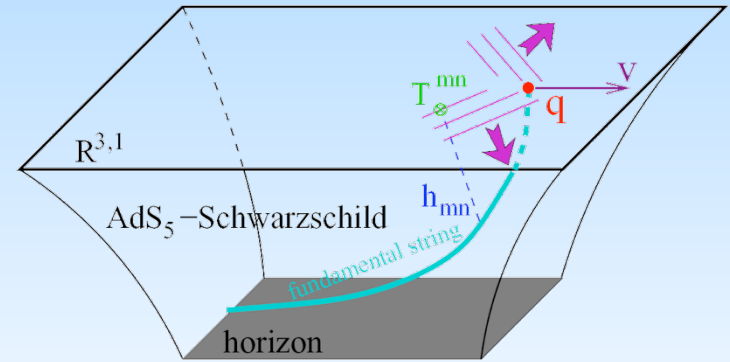
- How universal are drag results?
 - Examine different theories
 - Investigate alternate geometries
- When does the calculation break down?
 - Depends on the geometry used

New Geometries

Constant T Thermal Black Brane

$$ds^2 = \frac{L^2}{z^2} [-h(z)dt^2 + d\vec{x}^2 + h^{-1}(z)dz^2]$$

$$h(z) = 1 - z^4/z_h^4$$



J Friess, et al., PRD75:106003, 2007

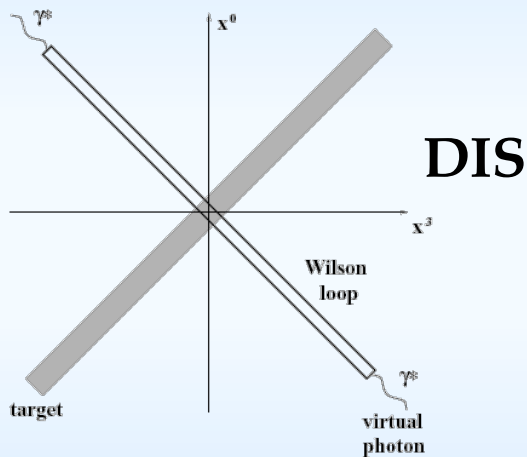
Shock Geometries

Nucleus as Shock

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

Embedded String in Shock

$$ds^2 = \frac{L^2}{z^2} [-(1 - \mu z^4)dt^2 - 2dtdx + (1 + \mu z^4)dx^2 + dx_{\perp}^2 + dz^2]$$

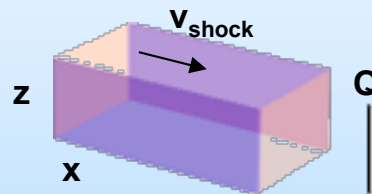


Albacete, Kovchegov, Taliotis,
JHEP 0807, 074 (2008)

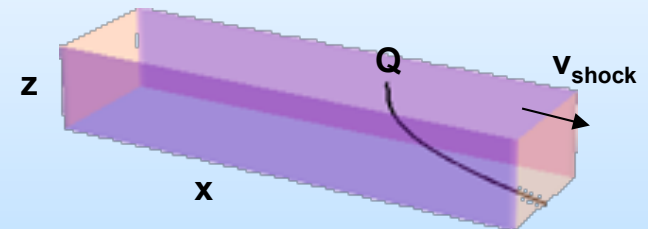
Bjorken-Expanding Medium

$$ds^2 = \frac{L^2}{z^2} \left[-\frac{(1 - z^4/\tau^{4/3})^2}{1 + z^4/\tau^{4/3}} d\tau^2 + \left(1 + z^4/\tau^{4/3}\right) (\tau^2 dy^2 + dx_{\perp}^2) + dz^2 \right]$$

Before



After



Shocking Motivation

- Consider string embedded in shock geometry
- Warm-up for full Bjorken metric

R. A. Janik and R. B. Peschanski, Phys. Rev. D **73**, 045013 (2006)



- No local speed of light limit!
 - Metric yields
$$-1 < (\mu z^4 - 1) / (\mu z^4 + 1) < v < 1$$
 - In principle, applicable to *all* quark masses for *all* momenta

Method of Attack

- Parameterize string worldsheet
 - $X^\mu(\tau, \sigma)$
- Plug into Nambu-Goto action

$$S_{NG} = -\frac{1}{2\pi\alpha'} \int d\sigma d\tau \sqrt{-\det g_{ab}}, \quad g_{ab} = G_{\mu\nu} \partial_a X^\mu \partial_b X^\nu$$

- Varying S_{NG} yields EOM for X^μ
- Canonical momentum flow (in τ, σ)

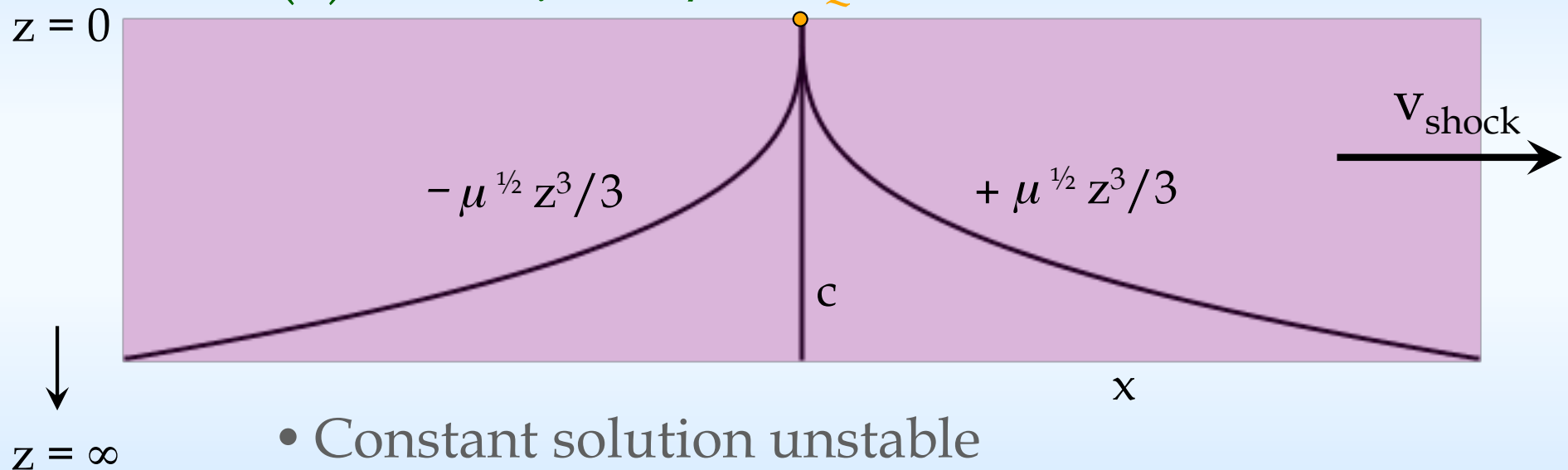
$$\pi_\mu^a = -\frac{\sqrt{-g}}{2\pi\alpha'} G_{\mu\nu} \partial^a X^\nu$$

Shock Geometry Results

- Three t-ind solutions (static gauge):

$$X^\mu = (t, x(z), 0, z)$$

$$- x(z) = c, \pm \mu^{1/2} z^3/3$$



- Constant solution unstable
- Negative x solution unphysical
- Sim. to $x \sim z^3/3$, $z \ll 1$, for const. T BH geom.

HQ Drag in the Shock

- $dp/dt = \pi^1_x = -\mu^{1/2} \lambda^{1/2} / 2\pi$
- Relate μ to nuclear properties
 - Coef. of $dx^{-2} = 2\pi^2 / N_c^2 T_{--}$
 - $T_{--} = (\text{boosted den. of scatterers}) \times (\text{mom.})$
 - $T_{--} = (\Lambda^3 p^+ / \Lambda) \times (p^+)$
 - Λ is typical mom. scale, $\Lambda \sim 1/r_0 \sim Q_s$
 - p^+ : mom. of shock as seen by HQ
 - $Mp^+ = \Lambda p$
- $dp/dt = -\lambda^{1/2} \Lambda^2 p / 2\pi M$
 - Recall for BH $dp/dt = -\pi \lambda^{1/2} T^2 p / 2M$
 - Shock gives *exactly* the same as BH for $\Lambda = \pi T$

Conclusions and Outlook

- Use exp. to test E-loss mechanism
- Applicability and universality crucial
 - Both investigated in shock geom.
- Shock geometry reproduces BH momentum loss
 - Unrestricted in momentum reach
- Future work
 - Time-dependent shock treatment
 - AdS E-loss in Bj expanding medium

Backup Slides



1/22/08

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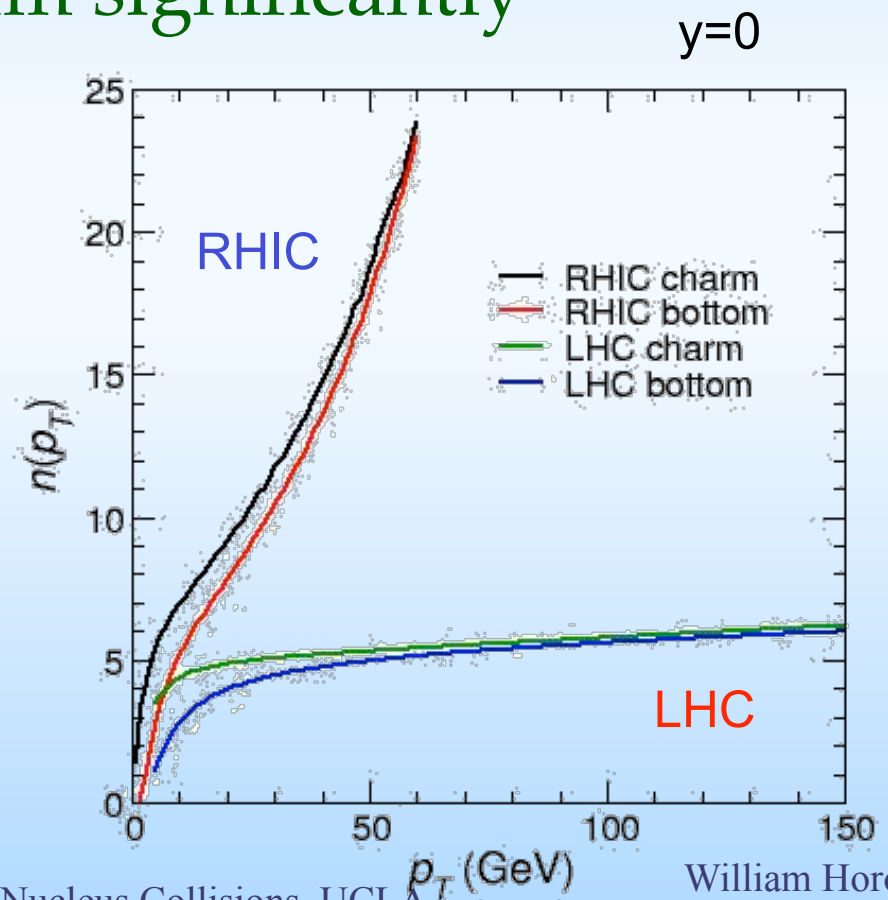
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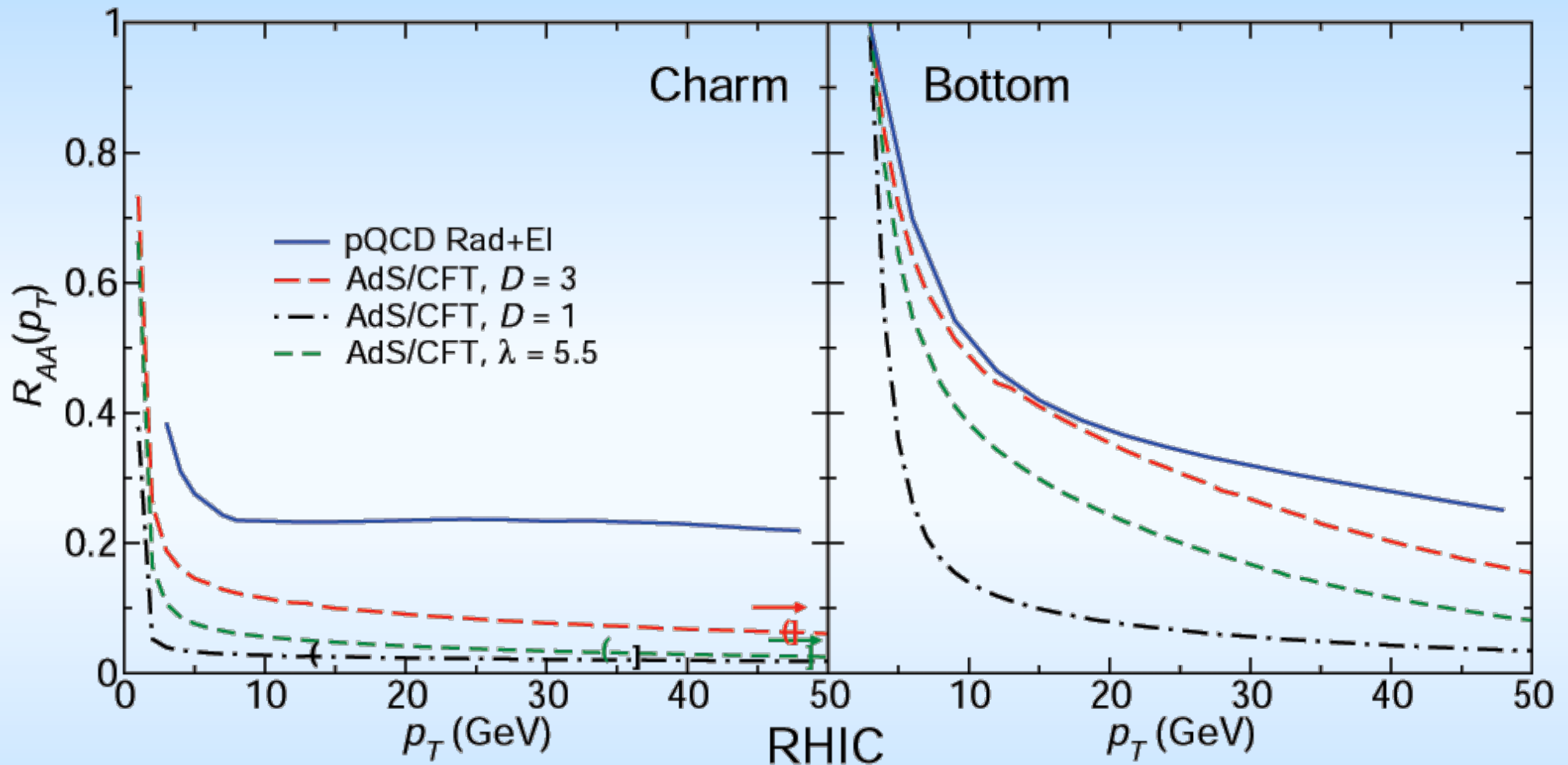
Measurement at RHIC

- Future detector upgrades will allow for identified c and b quark measurements
- RHIC production spectrum significantly harder than LHC

- $n_c \neq n_b \neq \text{const.}$
- NOT slowly varying
 - No longer expect $p\text{QCD } dR_{AA}/dp_T > 0$
- Large n requires corrections to naïve $R^{cb} \sim M_c/M_b$



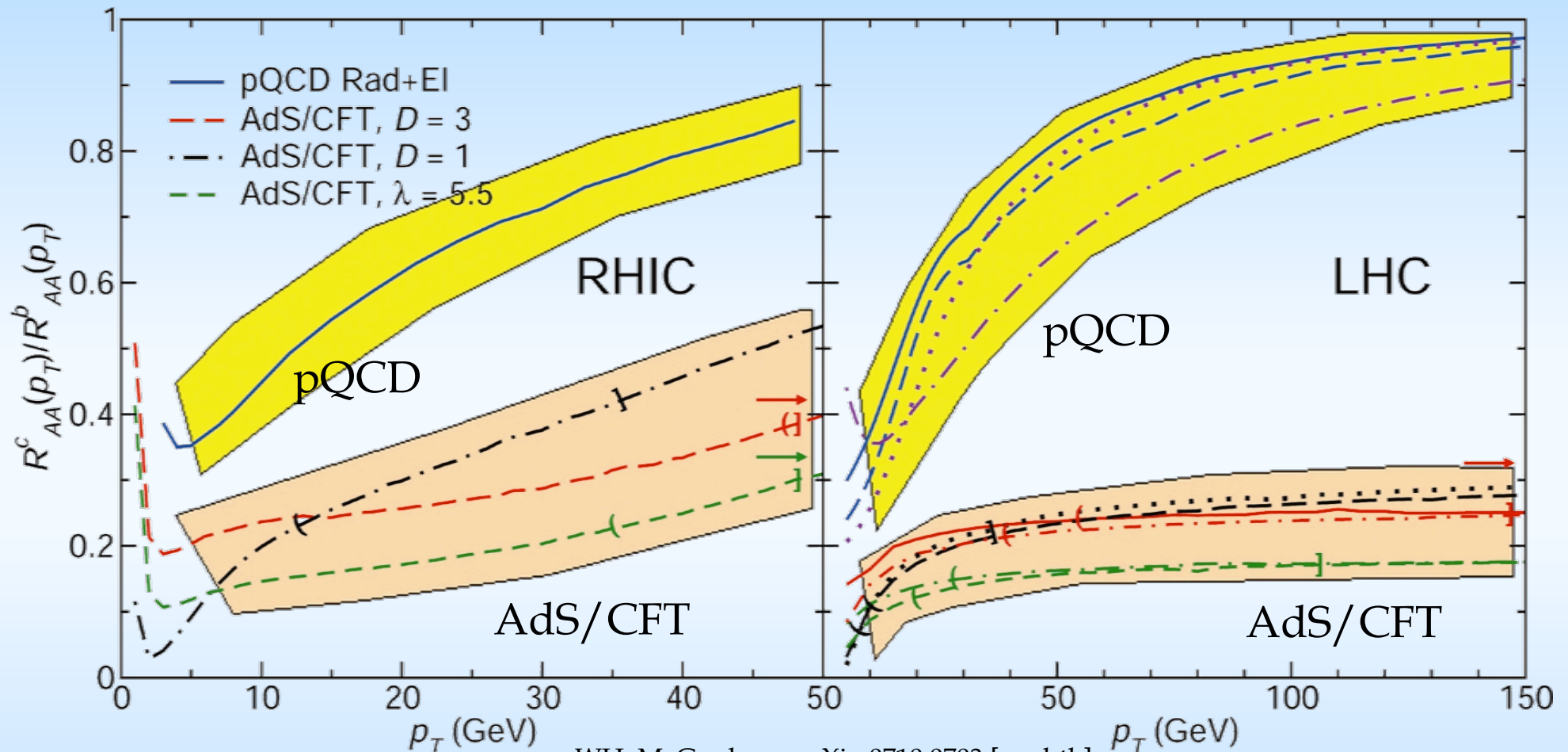
RHIC c, b R_{AA} p_T Dependence



WH, M. Gyulassy, arXiv:0710.0703 [nucl-th]

- Large increase in $n(p_T)$ overcomes reduction in E-loss and makes pQCD $dR_{AA}/dp_T < 0$, as well

RHIC R^{cb} Ratio



WH, M. Gyulassy, arXiv:0710.0703 [nucl-th]

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