Improving Strong and Weak Coupling Energy Loss

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May 12, 2017

WAH, Phys.Rev. D91 (2015) [arXiv:1501.04693]
Isobel Kolbé and WAH, arXiv:1511.09313
R. W. Moerman and WAH, arXiv:1605.09285
Abdullah Khalil and WAH, arXiv:1701.00763

In collaboration with Nadia Barnard, Robert Hambrock, Abdullah Khalil, Isobel Kolbé, Robert Moerman, and Andri Rasoanaivo,

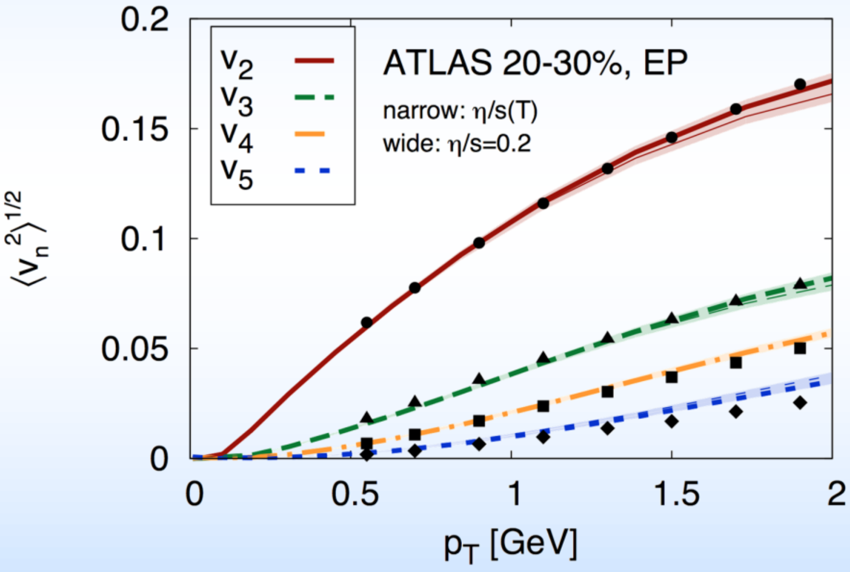
National Research Foundation

NRF

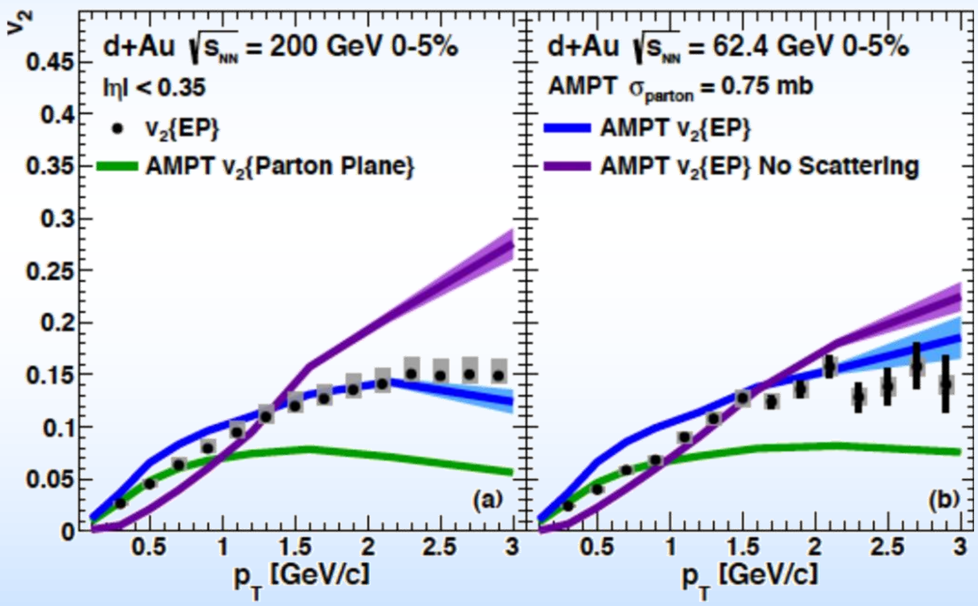
CERN

Low-p_T Obs: Strong or Weak?

- Hydro: Strong
- AMPT: Weak



Gale et al., PRL110 (2013)

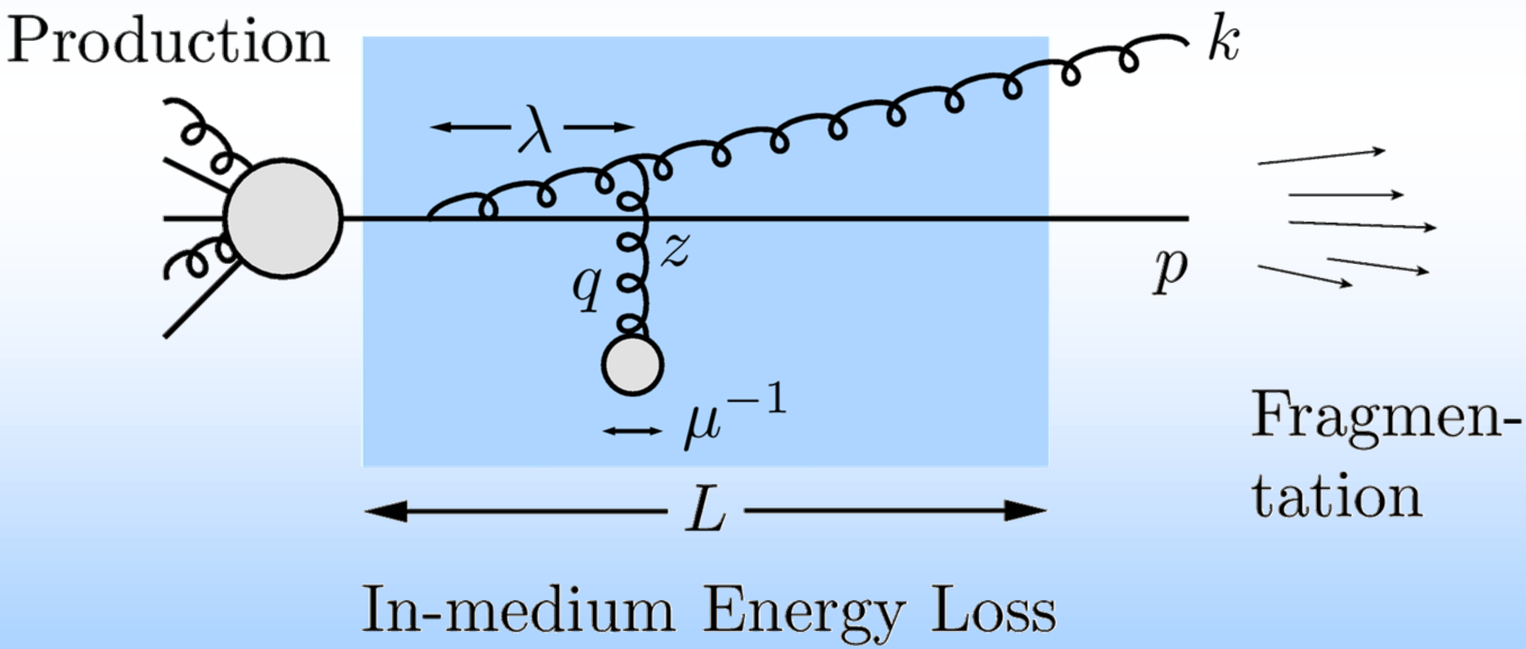


AMPT (from Zajc QM17)

Use High-p_T Femtoscope to Differentiate

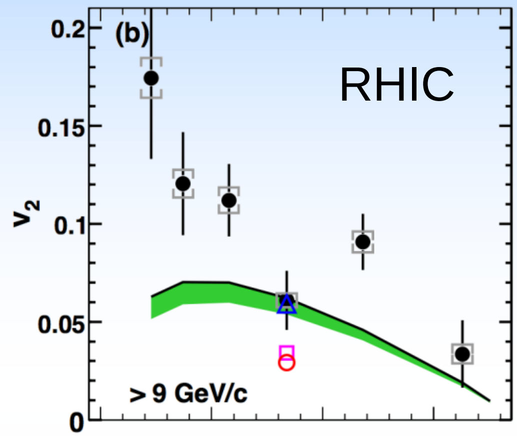
Most direct probe of DOF of QGP

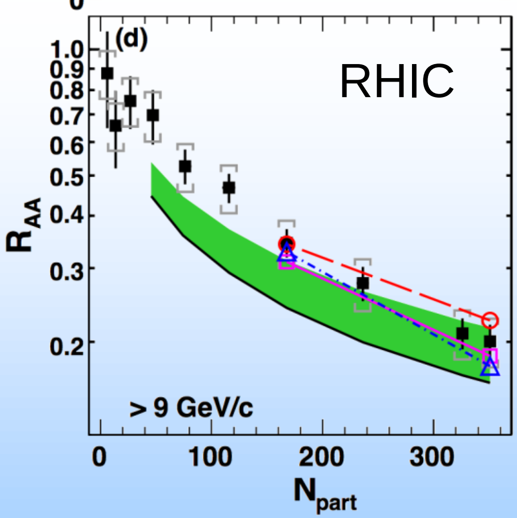
AdS/CFT Picture
pQCD Picture



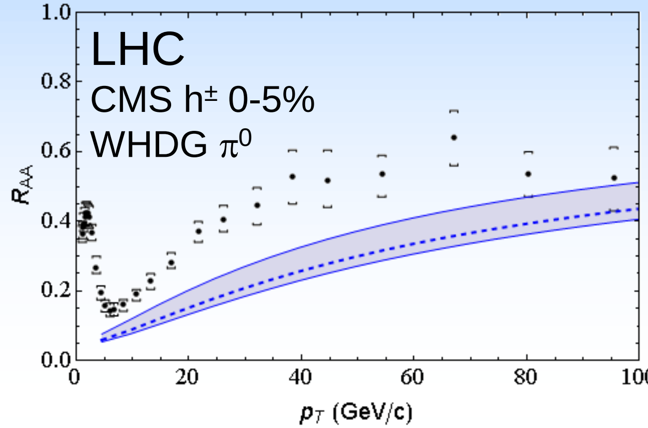
pQCD E-loss Describes RHIC/LHC

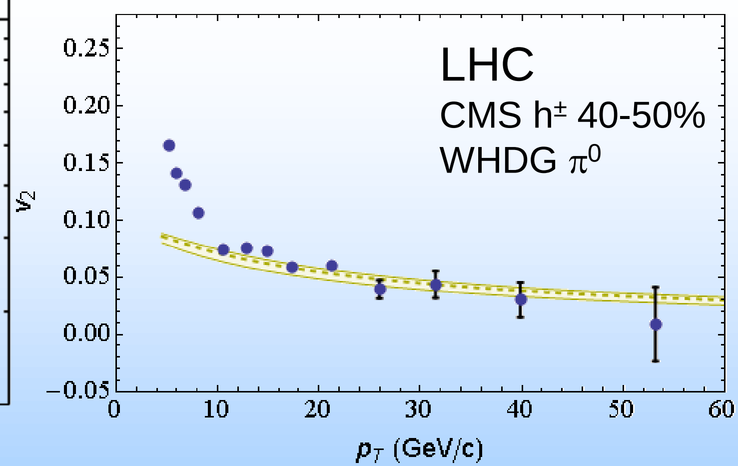
– Constrained by RHIC, LO pQCD predictions strikingly similar to LHC data



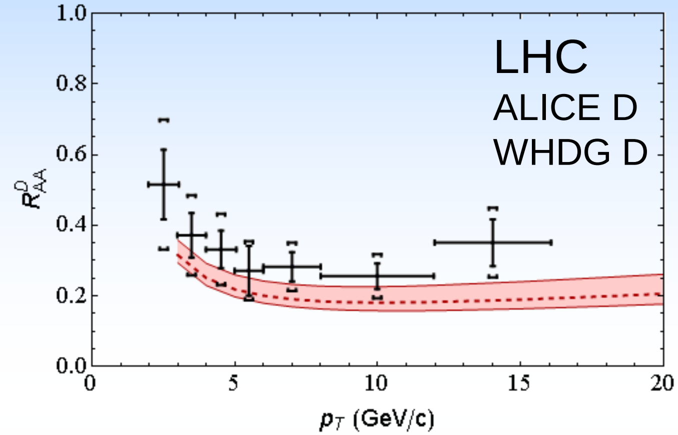


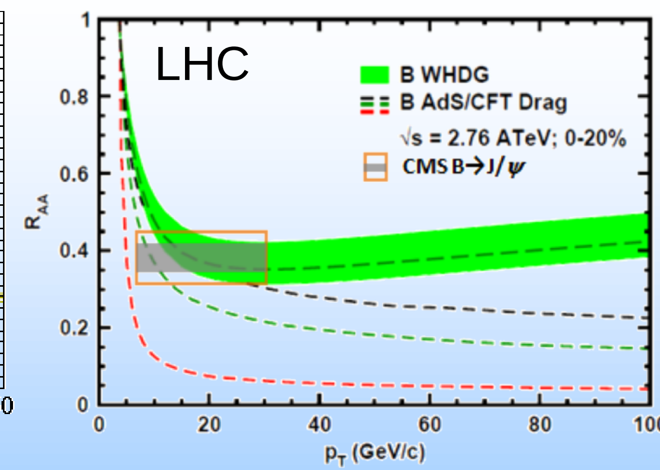
PHENIX PRL105 (2010)





CMS, Eur.Phys.J. C72 (2012)
CMS, PRL109 (2012)

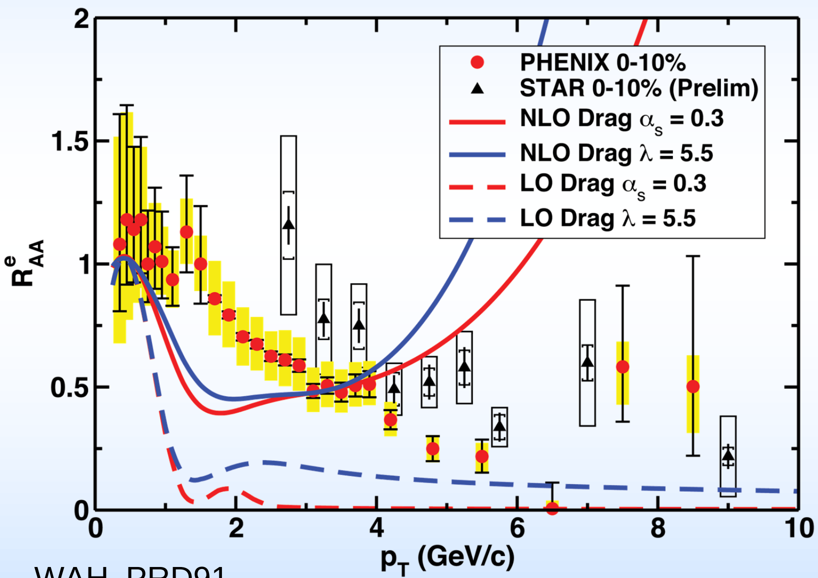




ALICE, JHEP1209 (2012) 112
CMS, JHEP 1205 (2012) 063

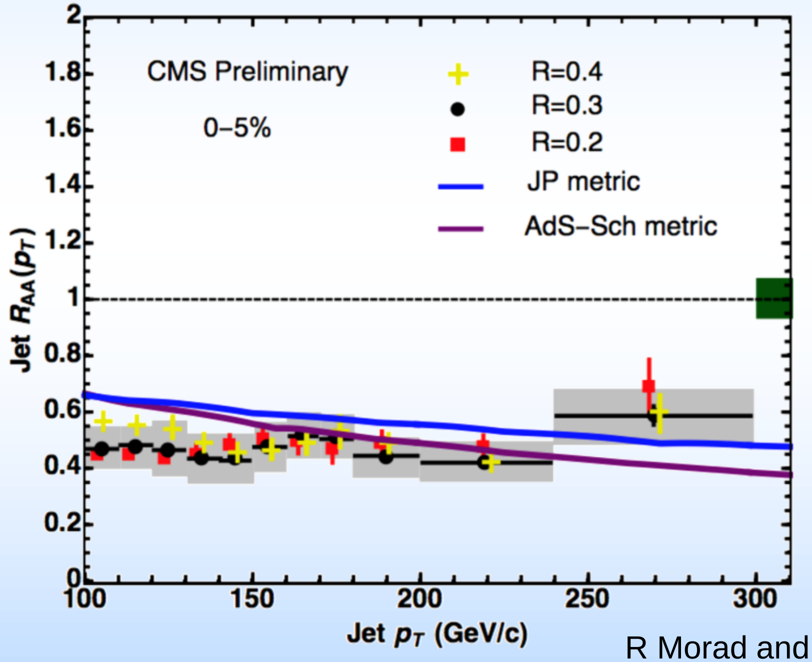
AdS/CFT Describes RHIC/LHC

- RHIC HF e-



WAH, PRD91 [1501.04693]

- LHC Jets



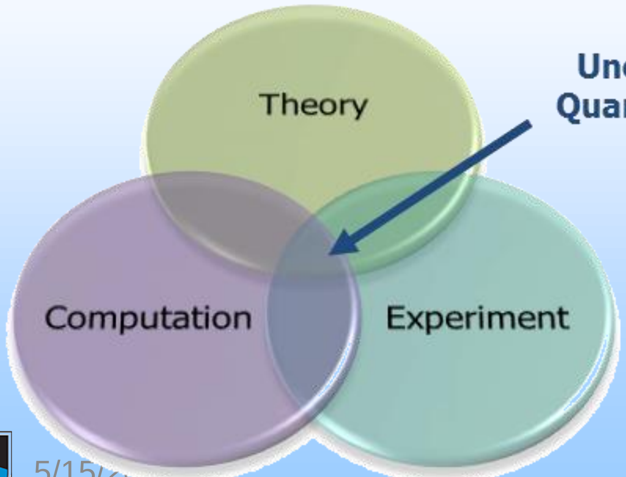
R Morad and WAH, JHEP11(2014)017

One Approach

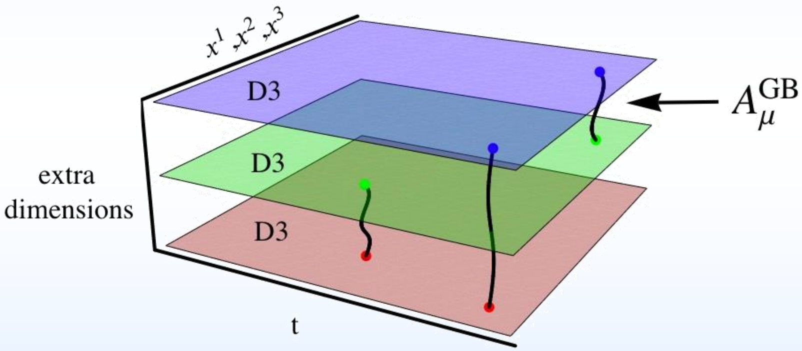
- Error bars are infinite
- F€¢$ it, let's all become bankers

Another Approach

- Seek for both pQCD and AdS/CFT to
  - reduce theoretical uncertainties
  - extend regime of applicability
  - find differentiating observables

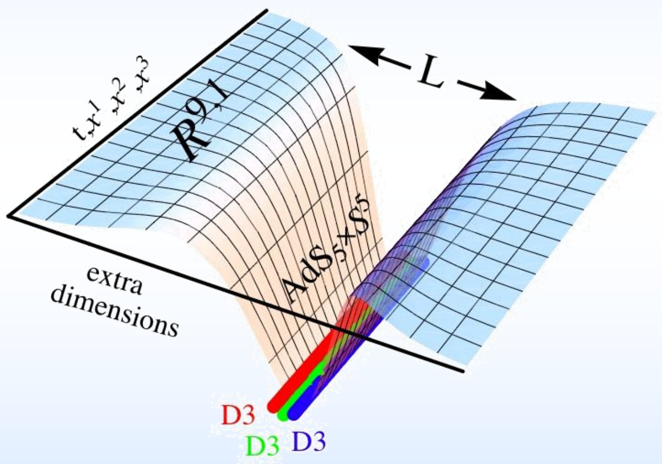


Start with AdS/CFT



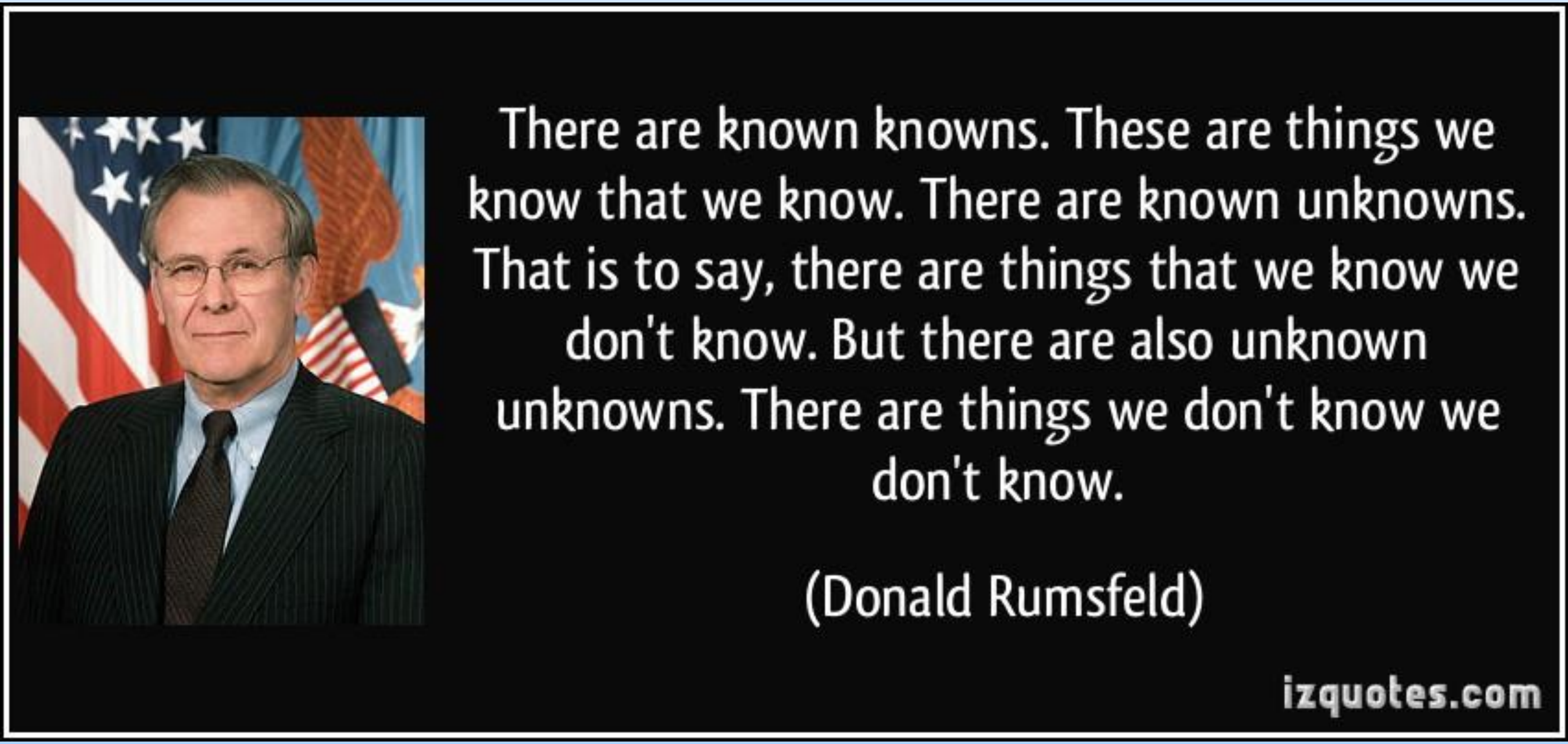
weak coupling

<=>



strong coupling

From When We Had Sensible, Rational US Leadership…



Rummy Says We Have Some

- Known knowns:
  - LO energy loss for an infinitely massive dragged, time invariant string in static background N = 4 SYM; some generalizations of N = 4
  - …
- Known unknowns:
  - Correct dual for light flavor/jets
  - Unforced heavy quarks
  - Momentum fluctuations
  - Connection to QCD
  - …
- Unknown unknowns: ???

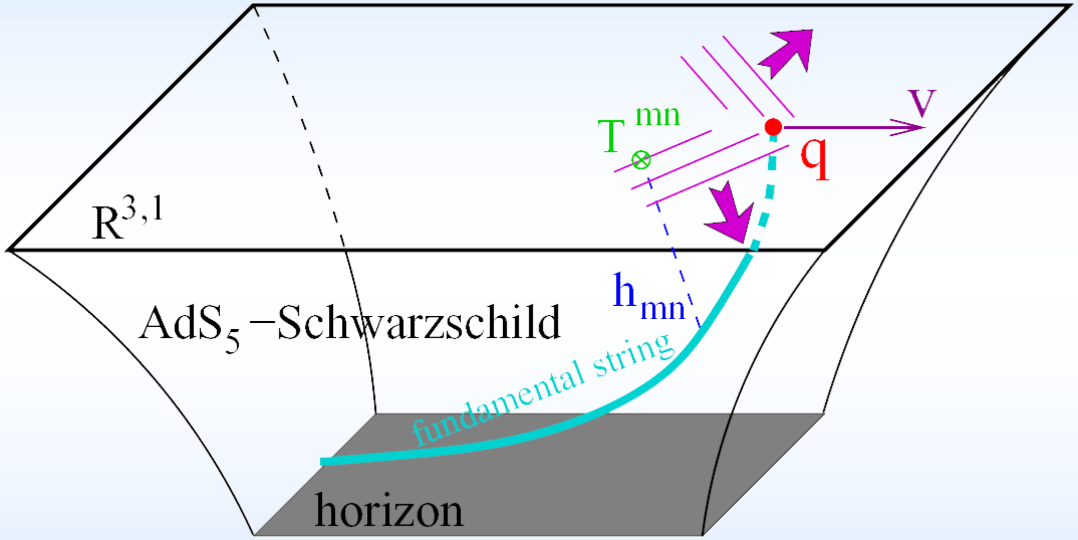
LO AdS for Heavy Quark E-Loss

- Result is a drag:

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

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

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



J Friess, et al., PRD75 (2007)

Similar to Bethe-Heitler

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

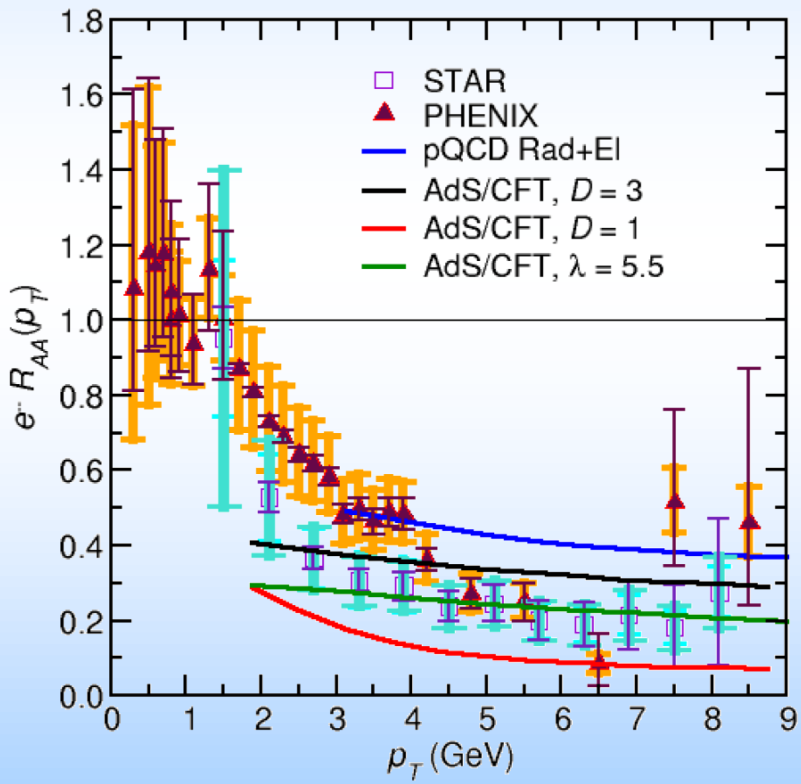
Very different from usual pQCD and LPM

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

Failure of LO AdS for Heavy High-p_T

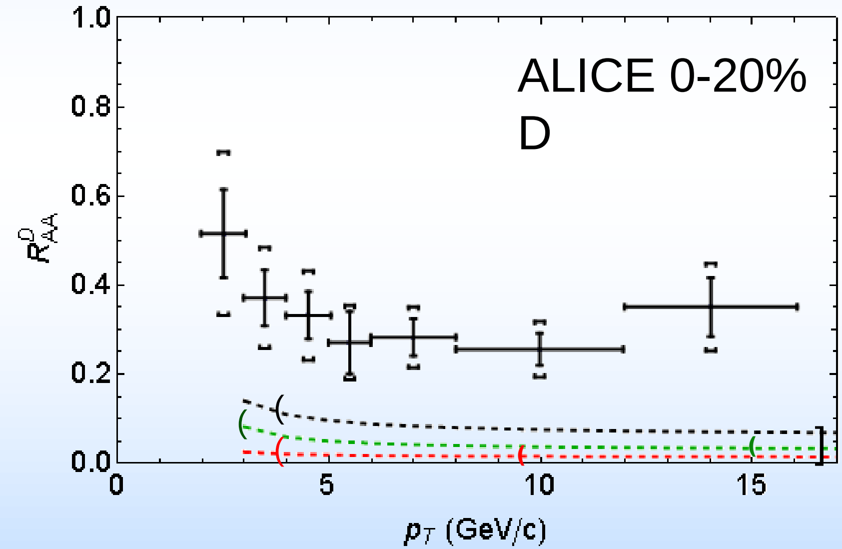
- Constrained by RHIC, oversuppress LHC

RHIC



WAH, PhD Thesis, arXiv:1011.4316

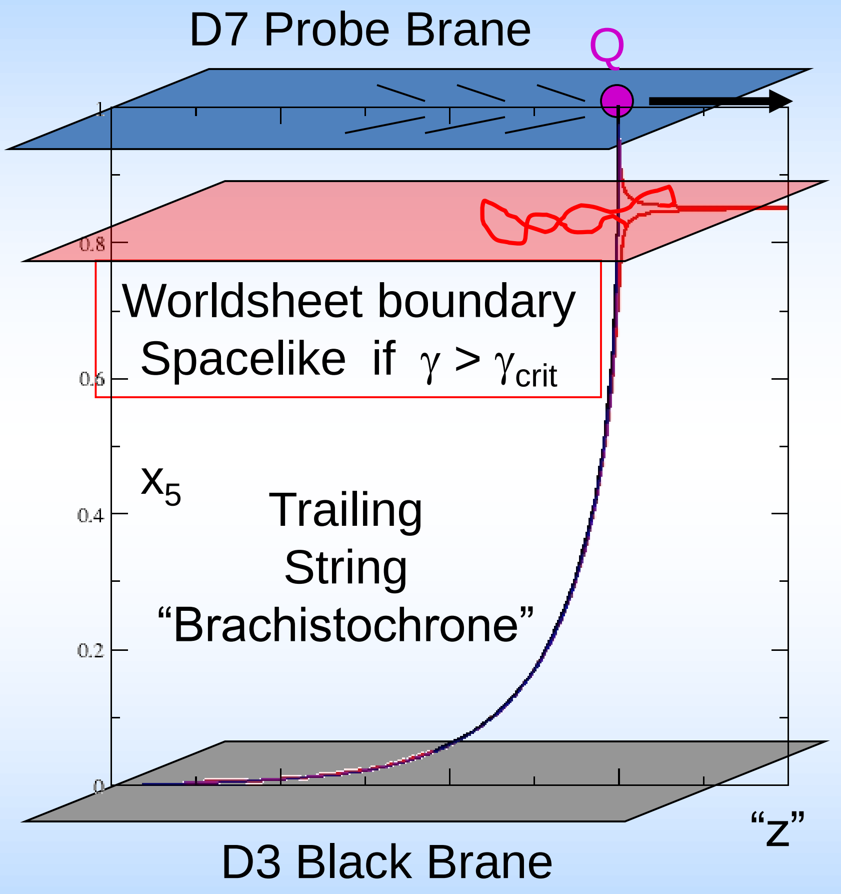
LHC



WAH, PANIC11 (arXiv:1108.5876)
ALICE, JHEP 1209 (2012)

Limits on Heavy Flavor AdS Setup

- For LO AdS:
  - Space-like quark endpoint
    - $\gamma_{crit} = (1 + 2M_q/\lambda^{1/2}\,T)^2 \sim 4M_q^2/(\lambda T^2)$
    - Equiv. due to Schwinger
  - Mom. Loss Fluctuations
    - $\gamma_{crit} = M_q^2/(4T^2)$
- Speed limit from fluct parametrically larger, but numerically smaller



Fluctuations a la Gubser/Teaney

$$\frac{dp_i}{dt} = -\eta_D + F_i^L + F_i^T$$

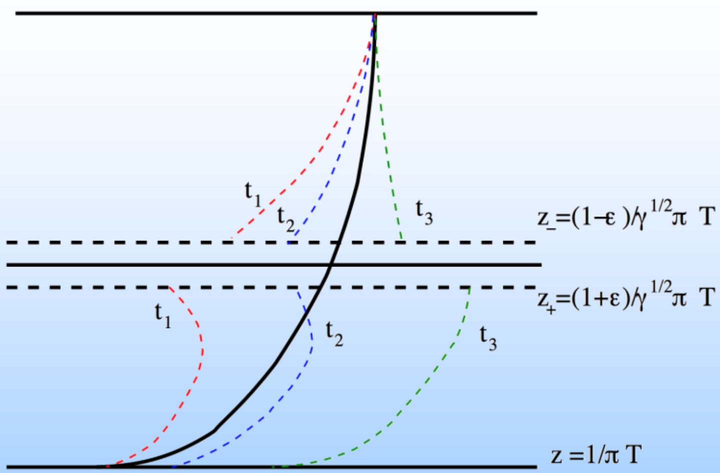
$$\langle F_i^L(t_1) F_j^L(t_2) \rangle = \kappa_L \, \hat{p}_i \hat{p}_j \, g(t_1 - t_2)$$

$$\langle F_i^T(t_1) F_j^T(t_2) \rangle = \kappa_T \, (\delta_{ij} - \hat{p}_i \hat{p}_j) \, g(t_1 - t_2)$$

$$\kappa_T = \pi \sqrt{g^2 N_c} T^3 \sqrt{\gamma}; \qquad \kappa_L = \pi \sqrt{g^2 N_c} T^3 \gamma^{5/2}$$

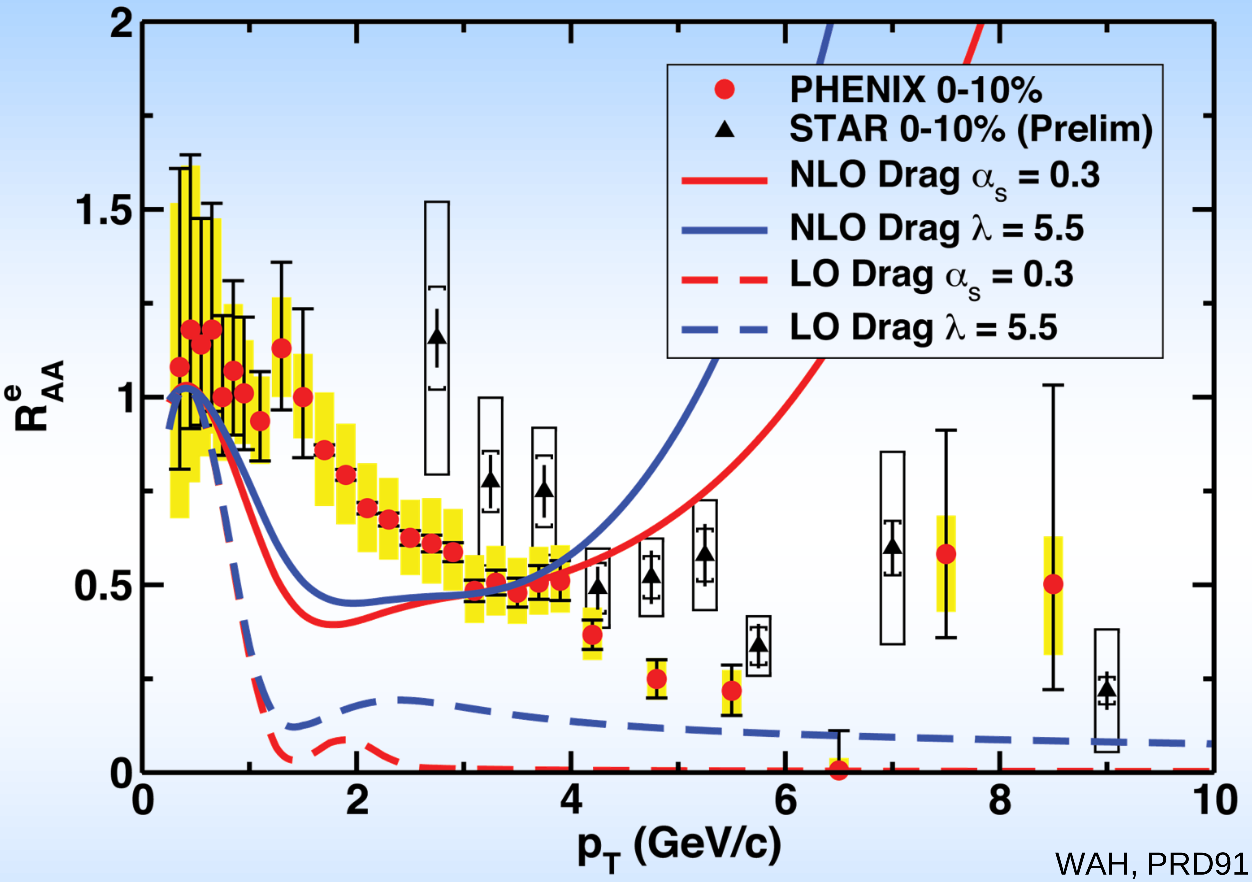
- Obeys Einstein's relations *only* at v = 0. Thermal in origin?
- Multiplicative Langevin problem!
  - Results depend on time within timestep kicks are evaluated
    - Ito, Stratonovich, Hänggi-Klimontovich
- Non-Markovian:
  - Colored (not white) noise
    - Momentum kicks have a memory

Gubser, NPB790 (2008)



Teaney and Casalderrey-Solana, JHEP 0912 (2009) 066

Compare to RHIC HF Electrons

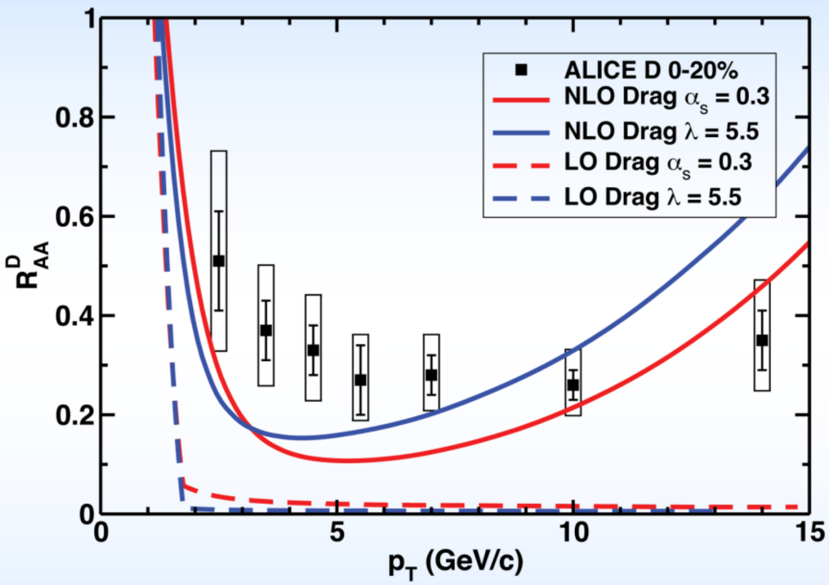


WAH, PRD91 [1501.04693]

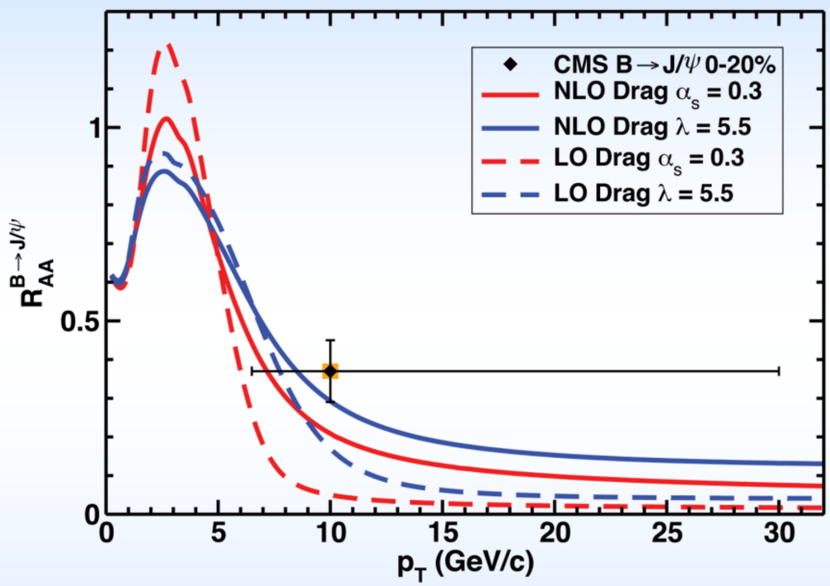
- Agreement in sweet spot p_T ~ 3 – 4 GeV/c
  - Below 3 GeV production unreliable
  - Above 4 GeV theory corrections necessary (col. noise, non-const p)
- NB: VISHNU medium hotter than from previous calc => larger LO supp.

Compare to LHC: R_{AA}

- D Mesons



- B Mesons

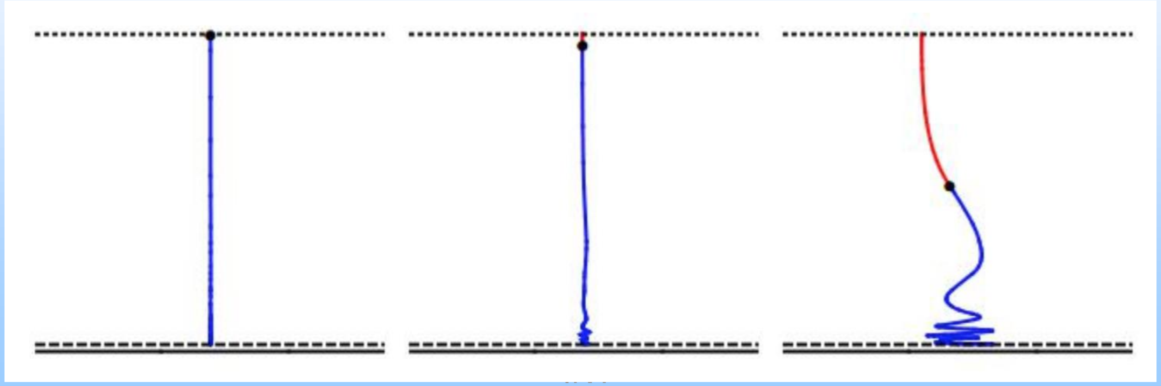


WAH, PRD91 [1501.04693]

- Predictions qualitatively similar to data
  - D harder than e; m_B => valid to higher p_T

Extending Fluctuating E-Loss

- What happens when dragging string picture breaks down at high-p_T?
  - Equivalently, how do fluctuations affect light flavor?
- Extremely difficult problem
  - Solve simpler initial v = 0 in AdS_3
    - Compute mean distance squared travelled by the endpoint as it falls

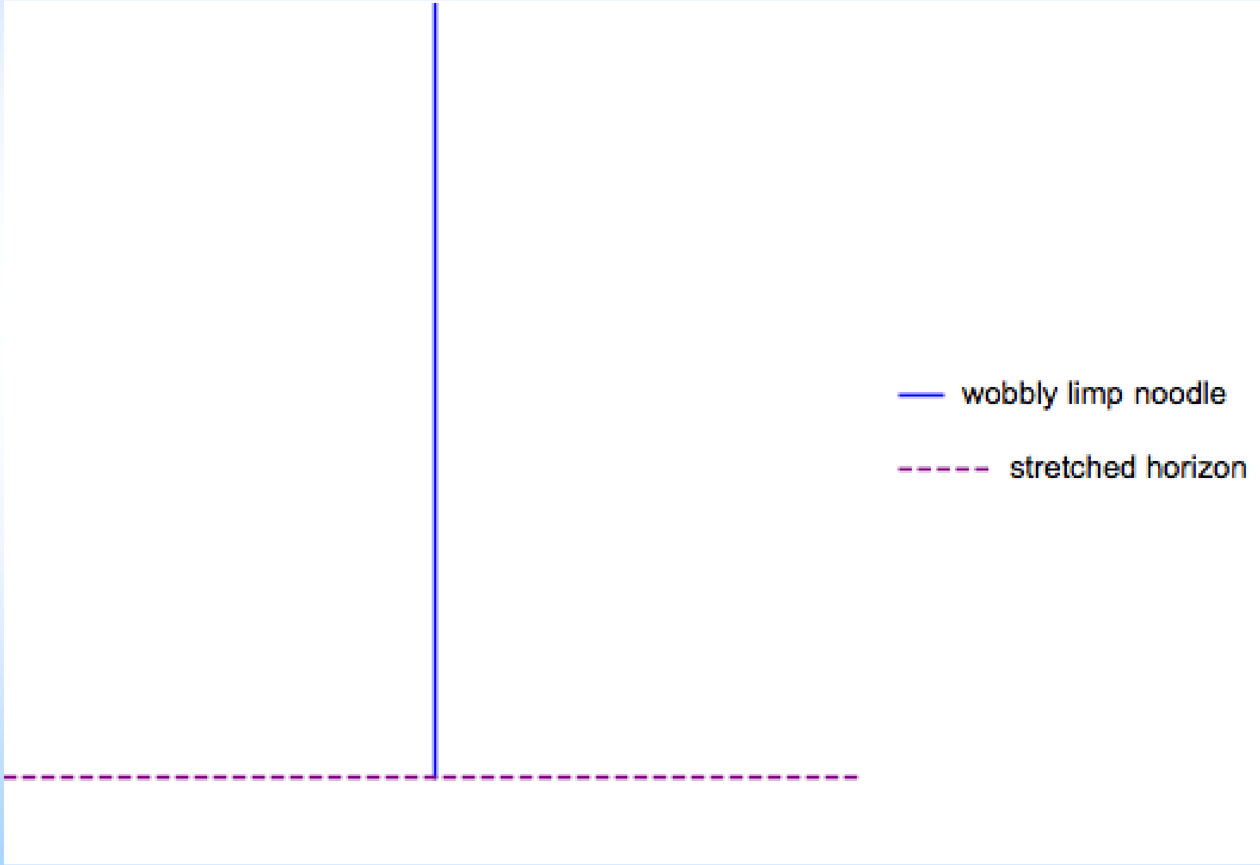


Outline of Solution:

- Derive classical solution
- Quantize perp dir's of motion given classical sol'n
- Populate quanta according to Bose statistics (semi-classical approx.)
- Compute correlators
  - For details, see slides at end or arXiv:1605.09285

Non-equilibrium Thermodynamics

- Extend to massless sol'n:



Analytic Brownian Motion

- Average distance squared travelled as a fcn of time *t*

$$s^2(t;a) := \langle : (\hat{X}_{\mathrm{End}}(t;a) - \hat{X}_{\mathrm{End}}(0;a))^2 : \rangle$$

$$= \frac{\beta^2}{4\pi^2\sqrt{\lambda}} \int_0^\infty \frac{d\omega}{\omega} \frac{1}{e^{\beta\omega} - 1} \left| f_\omega(\sigma_f - at) - f_\omega(\sigma_f) e^{i\omega t} \right|^2$$

  - *a* is the speed at which the endpoint falls
    - Allows interpolation btwn known HQ and new light quark results
    - Will also allow for qhat(t)

Relate $D(a,d)$ to qhat(t)

- At late times $t \gg \beta$, $s^2 = 2\,D(a,d)\,t$, with

$$D(a,d) := \frac{(d-1)^2\beta}{8\pi\sqrt{\lambda}}\left(1-\frac{a}{2}\right)$$

- Conjecture connection to moving setup:

$$\hat{q} = \frac{\langle p_T^2\rangle}{\lambda_{mfp}} = \frac{2\kappa_T}{v} = \frac{4T^2}{vD} = \frac{32\pi\sqrt{\lambda}T^3}{(d-1)^2(1-a/2)v}$$

- Time dependence in $a(t)$ and $v(t)$
  - Rate that endpoint falls in "5th" dimension

Heavy Quark qhat

- For heavy quarks *a* = 0

$$\hat{q}_{MH} = \frac{2\pi\sqrt{\lambda}T^3}{v}$$

<= This work

$$\hat{q}_{Gubser} = \frac{2\pi\sqrt{\lambda}T^3}{v}\sqrt{\gamma}$$

<= Gubser, NPB790 (2008)

  - MH result behaves sensibly as v => 1
  - No speed limit

Light Quark qhat

- For light quarks

$$\hat{q}_{MH} = \frac{2\pi}{(1-a/2)v}\sqrt{\lambda}T^3 \simeq 2\pi\sqrt{\lambda}T^3$$

<= This work, $t = 0$

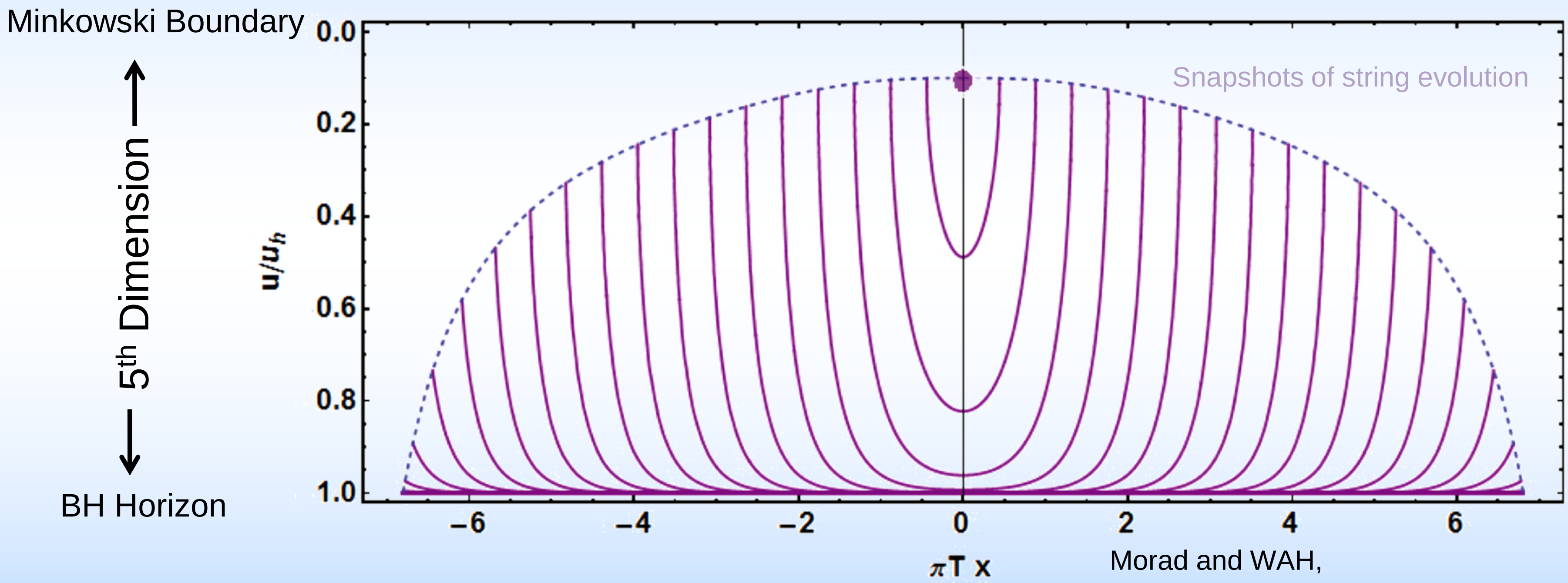
$$\hat{q}_{LRW} = \frac{\pi^{3/2}\Gamma(3/4)}{\Gamma(5/4)}\sqrt{\lambda}T^3 \simeq 7.5\sqrt{\lambda}T^3$$

<= Liu, Rajagopal, Wiedemann, PRL97 (2006) 182301

  – Similar results to LRW; completely different method

Relate $D(a, d = 5)$ to qhat(t)

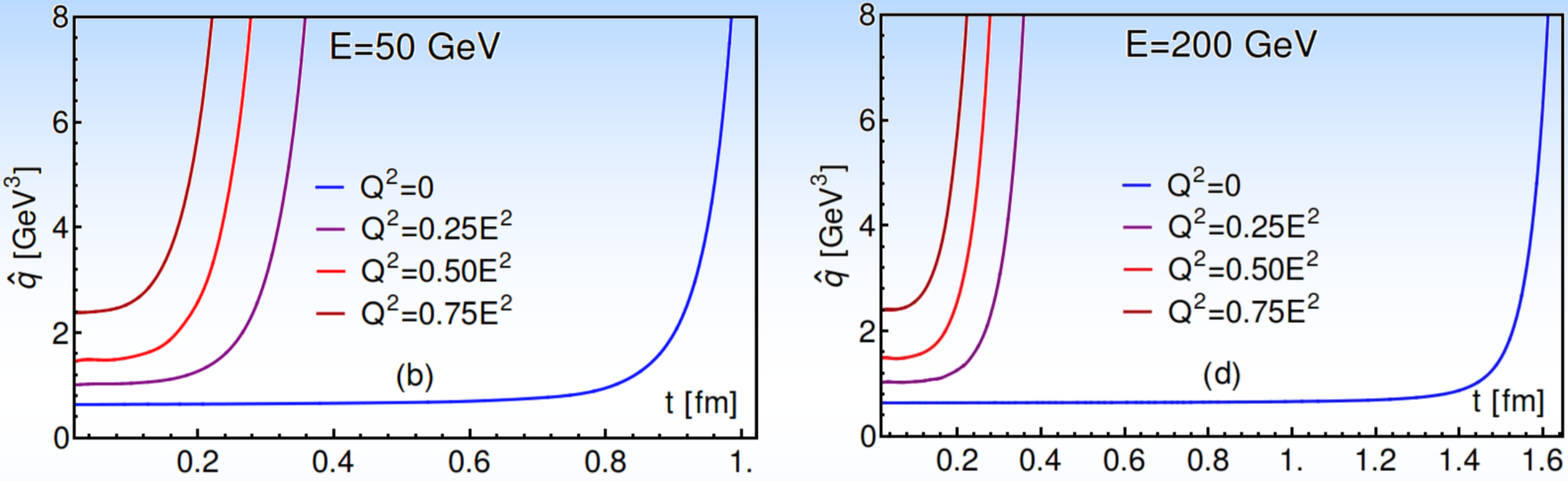
- We have numerical solutions for leading order falling strings in AdS_5



Morad and WAH,
JHEP 1411 (2014) 017 [1409.7545]

– Our numerical sol'n gives us the rate at which the endpoint is falling, the *a* in the previous!!

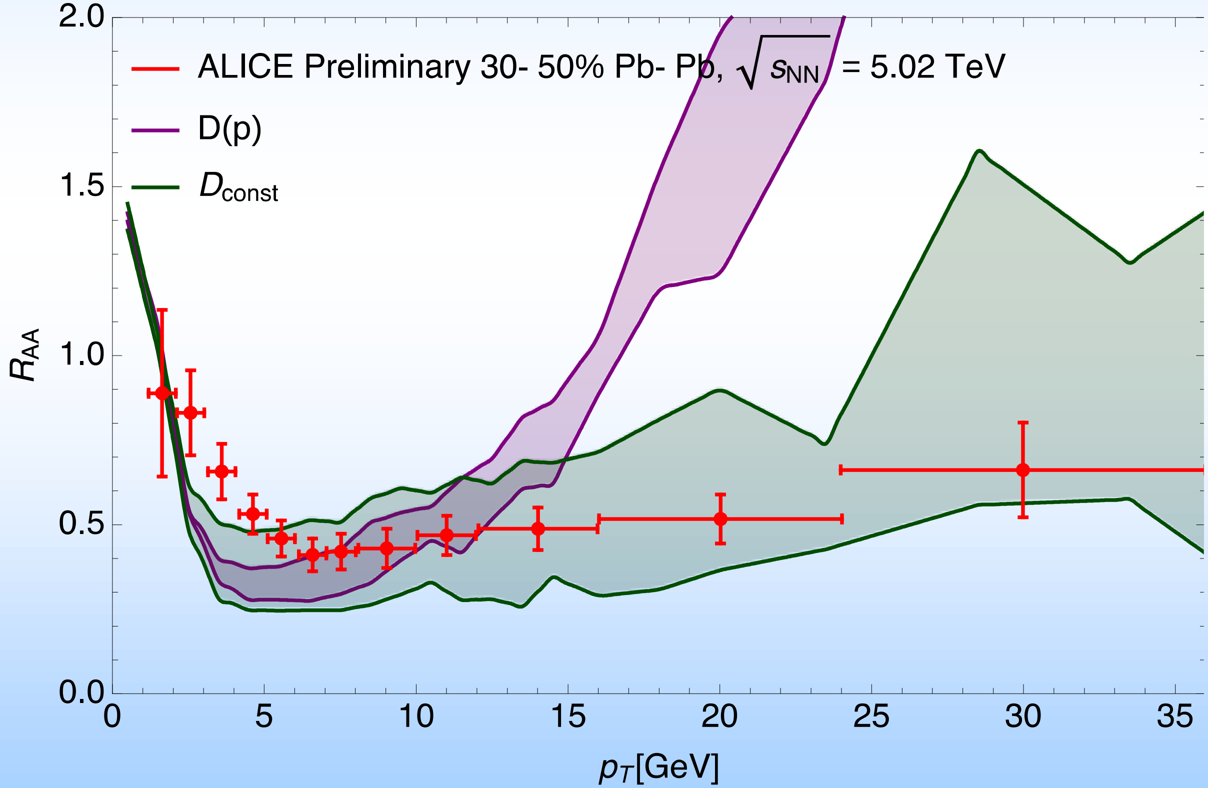
t Dependent qhat



- qhat(t = 0) ~ 3 – 10 GeV^2/fm, then increases
  - T = 350 MeV
- qhat(t=>∞) => ∞ trivially as v => 0

Apply New D = const to HF

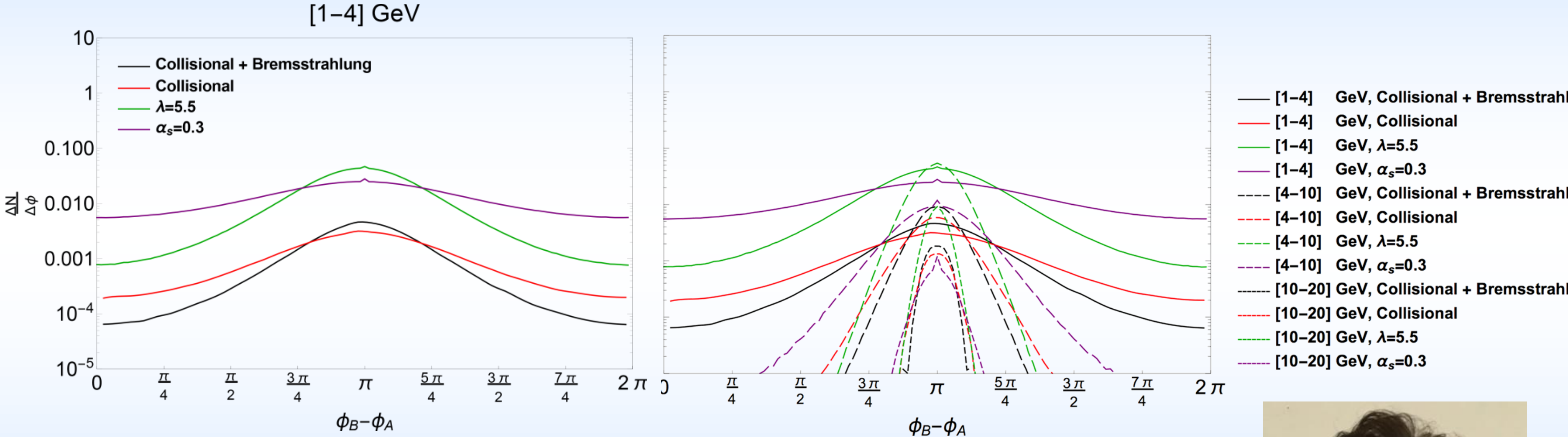
- Take $D = 2/\pi T\lambda^{1/2}$ as fundamental
  - Longitudinal fluc & drag by fluc-diss



R Hambrock and WAH, *in prep*

AdS vs pQCD HF Correlations

- Attempt to differentiate between pQCD and AdS with correlations

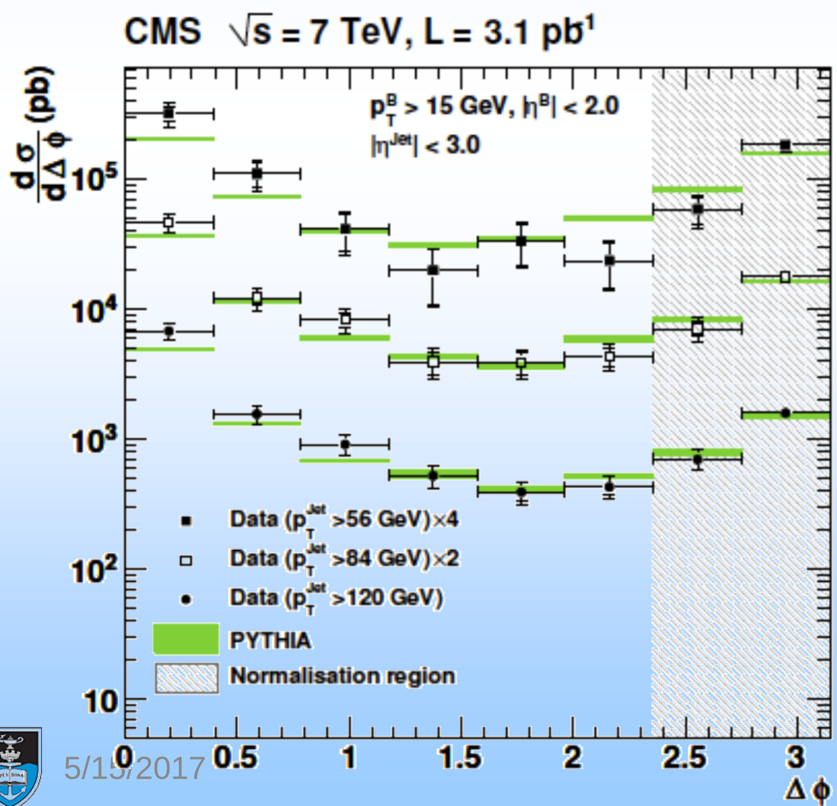


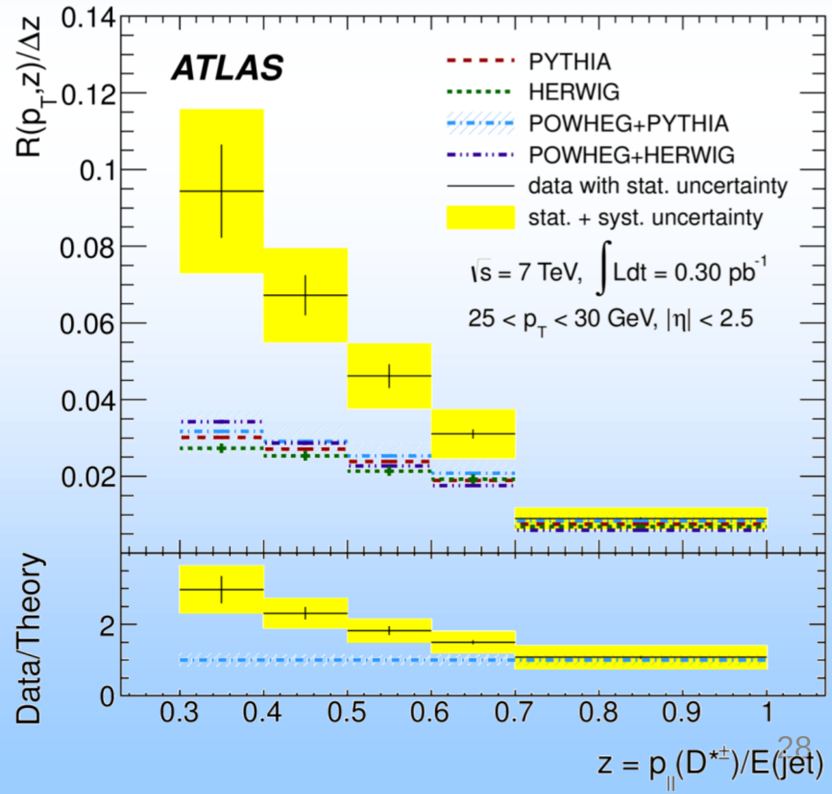
R Hambrock and WAH, *in prep*
pQCD from Narhgang et al., PRC90 (2014)

- – Difficult to differentiate with dN/dΔϕ
- – Factor 10 difference in $dN/d\Delta p_T$

Plea for HF pp

- Require good theoretical control over pp baseline
  - No exclusive NLO + NLL calculation exists
  - New tools: need importance sampling
- Not much pp HF correlations to compare to

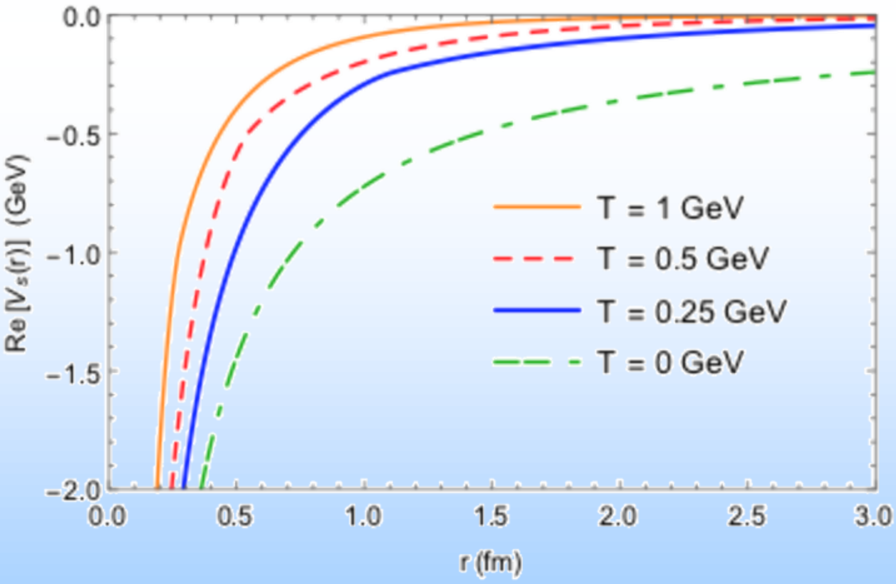


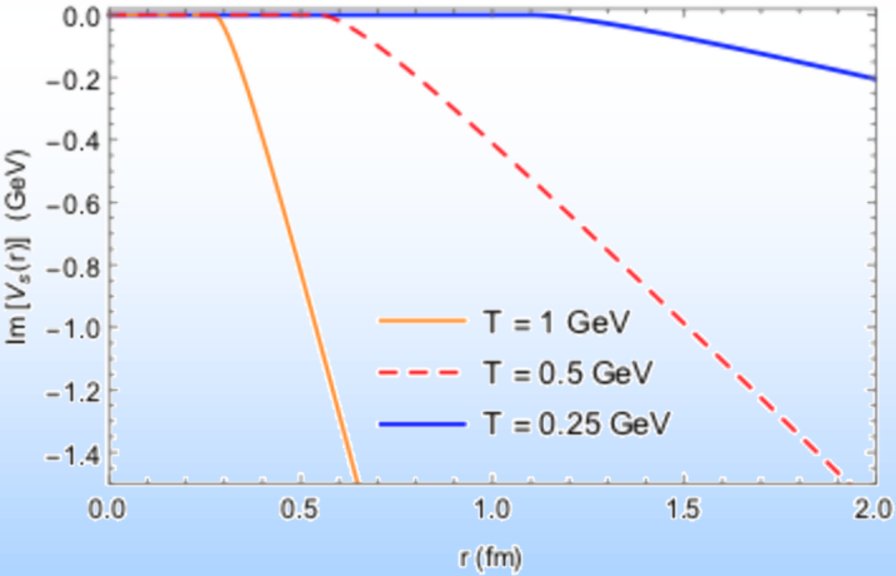


Apply AdS/CFT to Quarkonia

Nadia Barnard

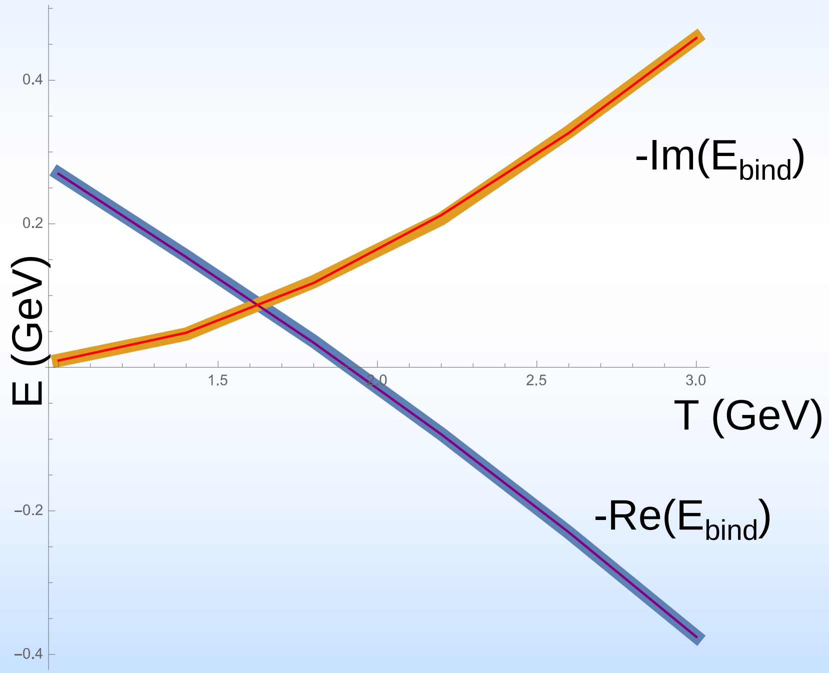
- Inspired originally by LRW $L \sim (1\text{-}v)^{1/4}$
- Use Albacete, Kovchegov, Talioltis V(r)
  - No v dependence (yet)





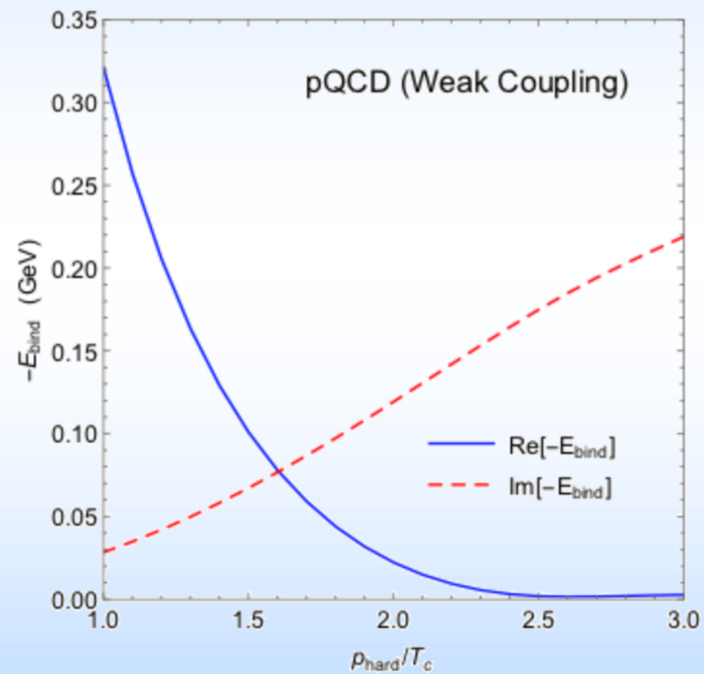
From Binding Energy to R_{AA}

- Binding Energy

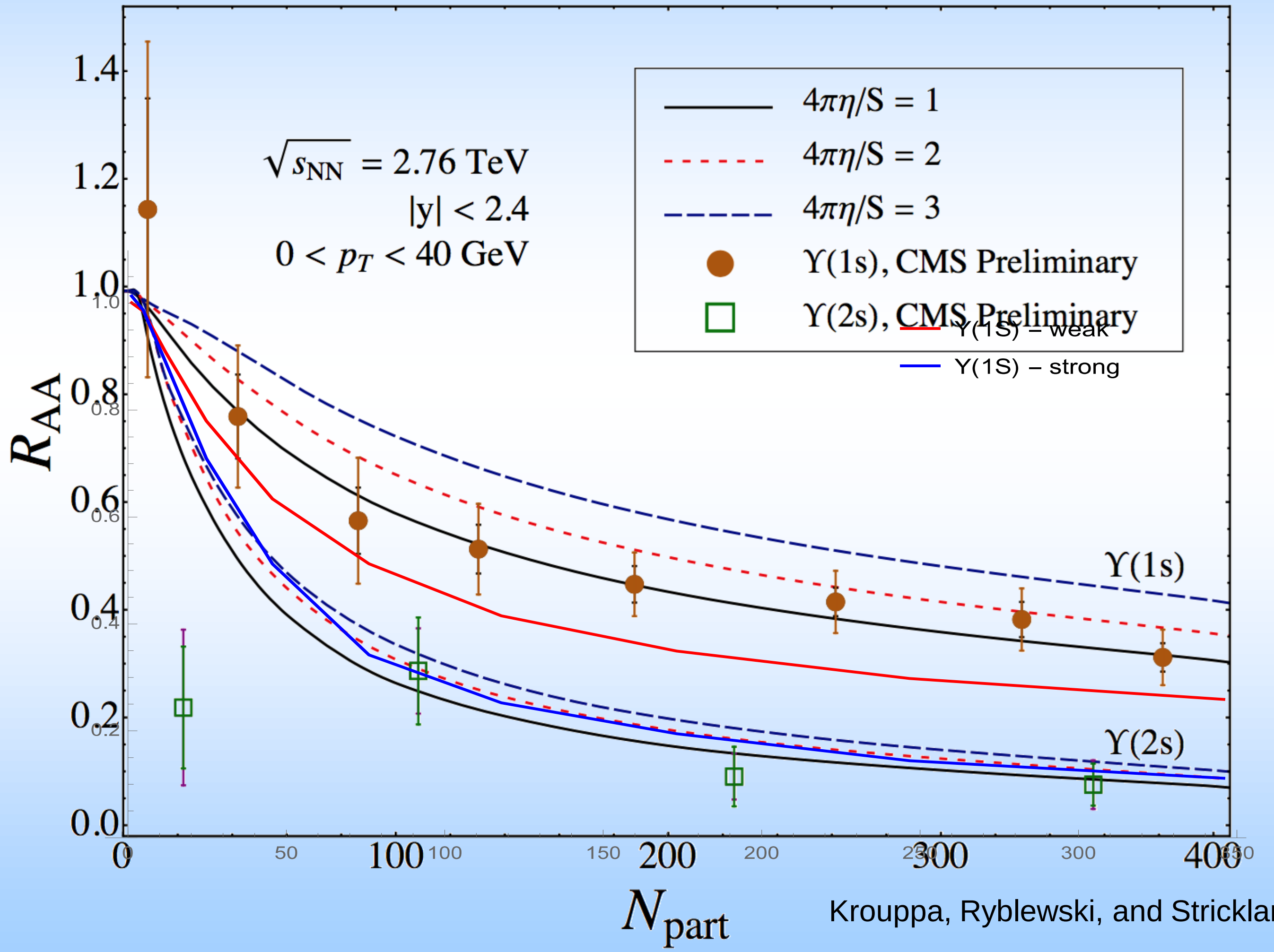


N Barnard and WAH, *in prep*

- Cf pQCD Binding E

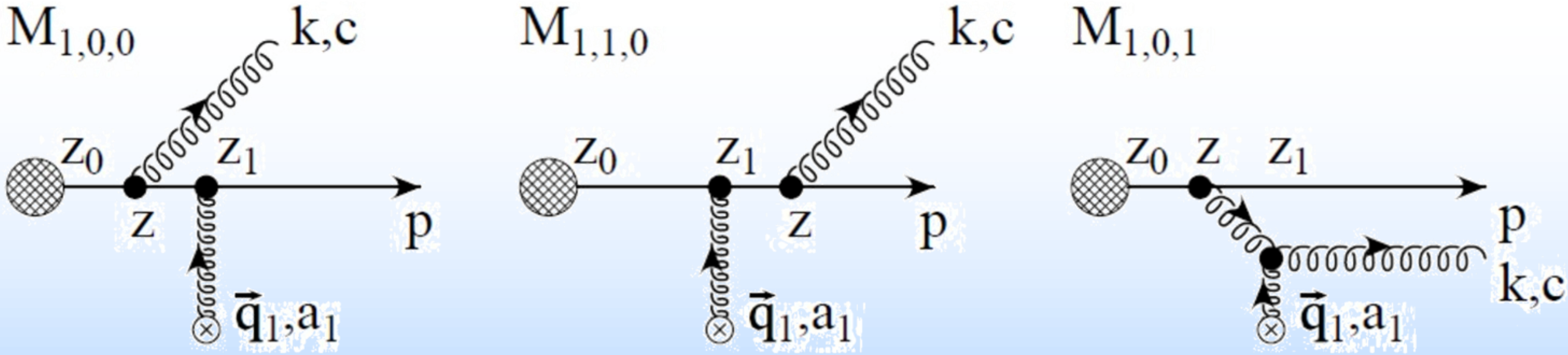


Compare to Data



Krouppa, Ryblewski, and Strickland, PRC92 (2015)

pQCD

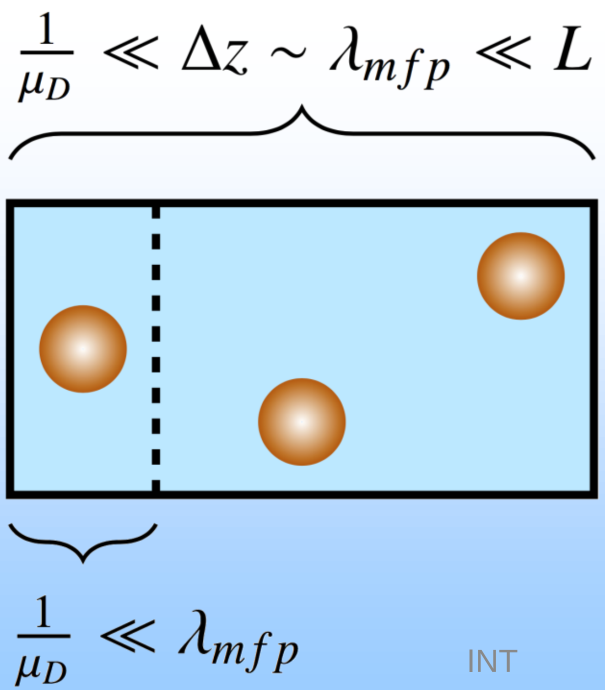


Rummy Says We Have Some

- Known knowns:
  - LO, all orders in opacity radiative energy loss off static scattering centers
  - Small system correction to LO and LO in opacity
  - …
- Known unknowns:
  - Wide angle radiation
  - Multiple gluon emission
  - NLO, running coupling
  - Early time evolution
  - …
- Unknown unknowns: ???

pQCD E-Loss in pA

- Take seriously potential E-loss in small systems
  - ***ALL*** current E-loss models *assume* large system size
- Wish to apply DGLV
  - DGLV assumes ordering of scales



Summed, Squared Result

$$\Delta E^{(1)}_{ind} = \frac{C_R \alpha_s L E}{\pi\lambda} \int \frac{d^2\mathbf{q}_1}{\pi} \frac{\mu^2}{(\mu^2+\mathbf{q}_1^2)^2} \frac{d^2\mathbf{k}}{4\pi} \int d\Delta z \bar{\rho}(\Delta z) \times$$

$$\times \Bigg[-2 \frac{(\mathbf{k}-\mathbf{q}_1)}{(\mathbf{k}-\mathbf{q}_1)^2 + M^2 x^2 + m_g^2} \times \left(1 - \cos\left\{(\omega_1 + \tilde{\omega}_m)\Delta z\right\}\right)$$

$$\times \left(\frac{\mathbf{k}}{m_g^2 + \mathbf{k}^2 + x^2 M^2} - \frac{(\mathbf{k}-\mathbf{q}_1)}{(\mathbf{k}-\mathbf{q}_1)^2 + M^2 x^2 + m_g^2} \right)$$

$$+ \frac{1}{2} e^{-\mu\Delta z)} \Bigg\{ \left(\frac{\mathbf{k}}{m_g^2 + \mathbf{k}^2 + x^2 M^2} \right)^2 \times$$

$$\times \left(1 - \frac{2C_R}{C_A}\right) \left(1 - \cos\{(\omega_0 - \tilde{\omega}_m)\Delta z\}\right)$$

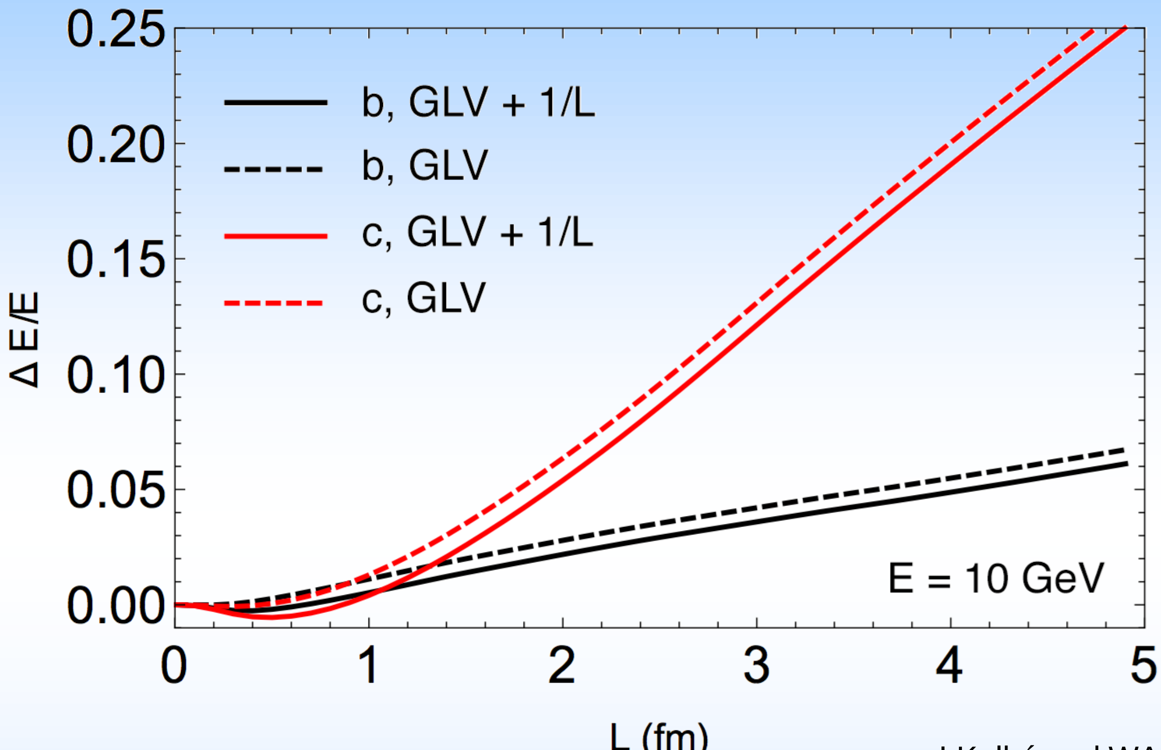
$$+ \frac{\mathbf{k}}{m_g^2 + \mathbf{k}^2 + x^2 M^2} \cdot \frac{(\mathbf{k}-\mathbf{q}_1)}{(\mathbf{k}-\mathbf{q}_1)^2 + M^2 x^2 + m_g^2} \times$$

$$\times \left(\cos\{(\omega_0 - \tilde{\omega}_m)\Delta z\} - \cos\{(\omega_0 - \omega_1)\Delta z\} \right) \Bigg\} \Bigg]$$

DGLV

"Small L" Modification

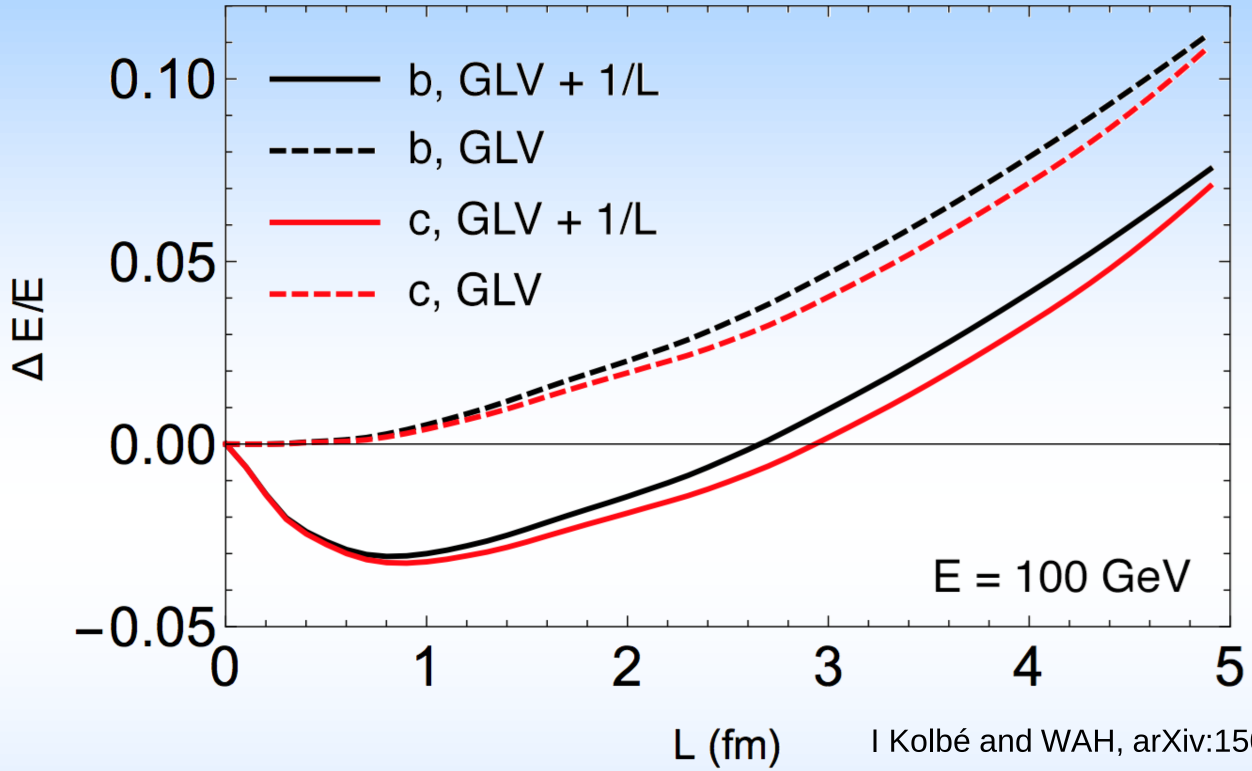
Numerics of the Correction



I Kolbé and WAH, arXiv:1509.06122

- Surprise 1: Correction leads to *reduction* in E-loss
  - LPM suppression of 0th order production radiation
- Surprise 2: Affects *all* pathlengths L
  - Due to integrating over all distances to scattering Δz in [0,L]

Correction at High-p_T

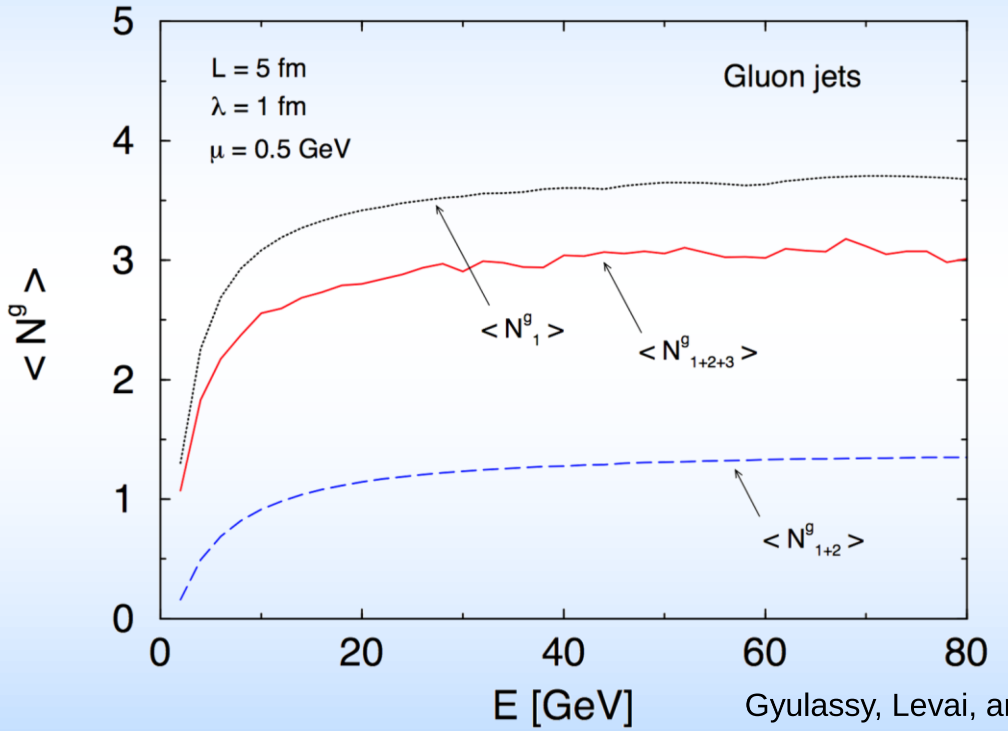


I Kolbé and WAH, arXiv:1509.06122

- Surprise 3: Correction *grows* with p_T
  - GLV ~ $L^2\mu^2 \log E/\mu$
  - "1/L" ~ $-LE \log E/\mu$

Towards Quantitative pQCD E-Loss: Poisson Multigluon Emission?

- GLV => $N_g^{emitted} \sim 3$

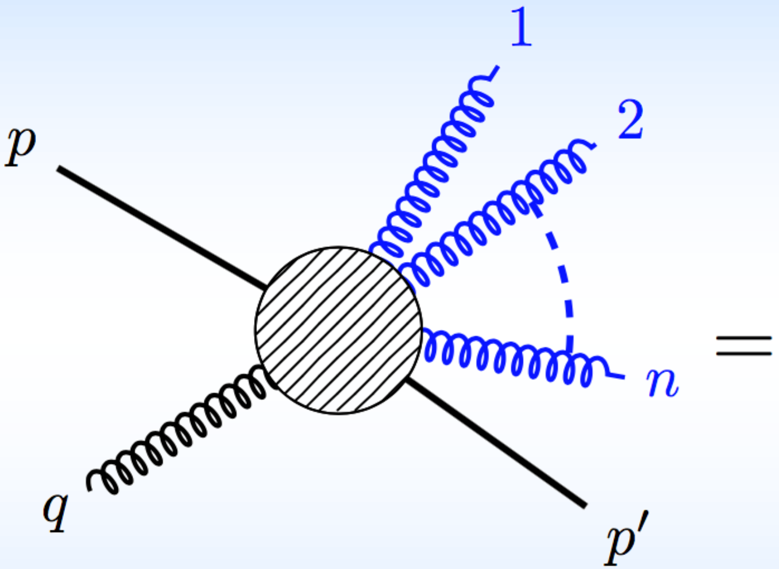


Gyulassy, Levai, and Vitev, PLB538 (2002)

  – Assume multi-g emission follows Poisson
    - Reasonable approx based on QED

Multigluon Emission in QCD

- Use MHV Techniques
  - PhD project for Andri Rasoanaivo



$$g^{n-1}\frac{\langle pq\rangle^3\langle qp'\rangle}{\langle pp'\rangle\langle p'q\rangle\langle q1\rangle\langle 12\rangle\cdots\langle np\rangle}$$

Deviations from Poisson

- 2 gluon emission

$$|J_2(k_1,k_2)|^2 = \frac{1}{4}[3 + F(k_1,k_2)] \times \prod_{i=1}^{2} |J_1(k_i)|^2$$

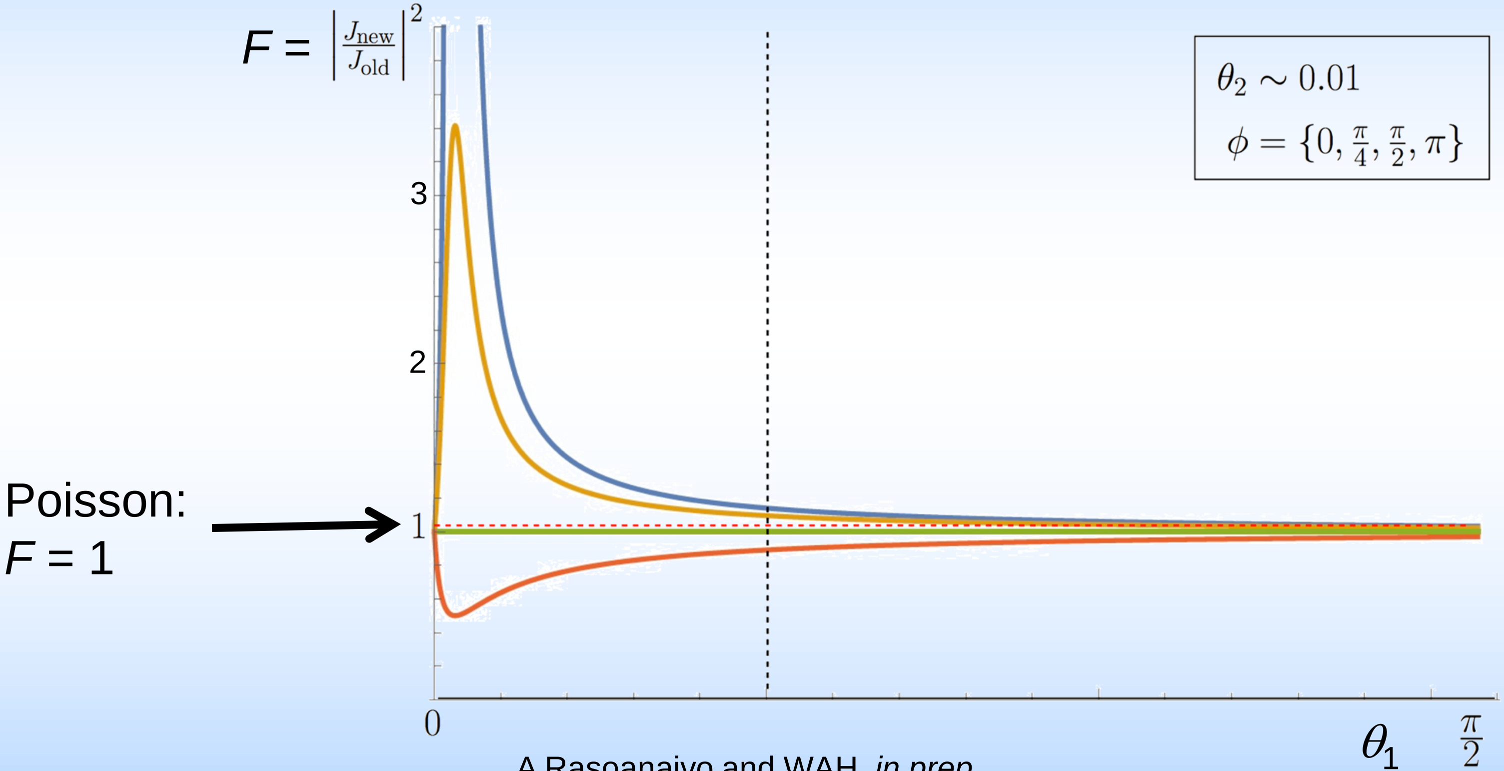
- For gluons in the same plane

$$F(\theta_1,\theta_2) = \frac{1-\cos\theta_1\cos\theta_2}{1-\cos(\theta_1-\theta_2)}$$

  – Poisson for strong angular ordering $\theta_2 << \theta_1$

Non-Poisson Corrections

$$|J_2(k_1,k_2)|^2 = \frac{1}{4}[3+F(k_1,k_2)] \times \prod_{i=1}^{2} |J_1(k_i)|^2$$

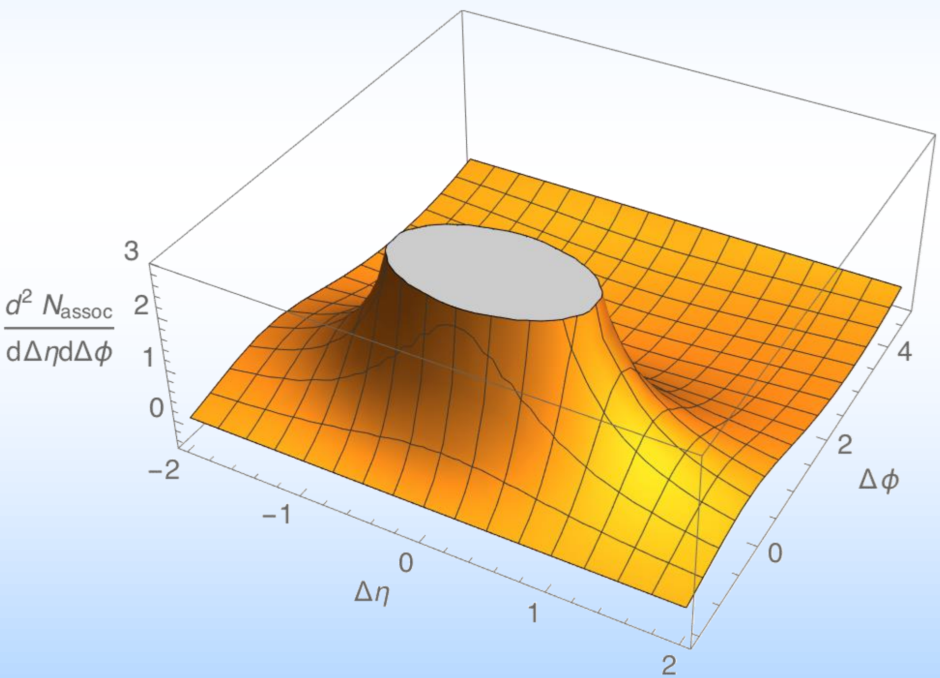


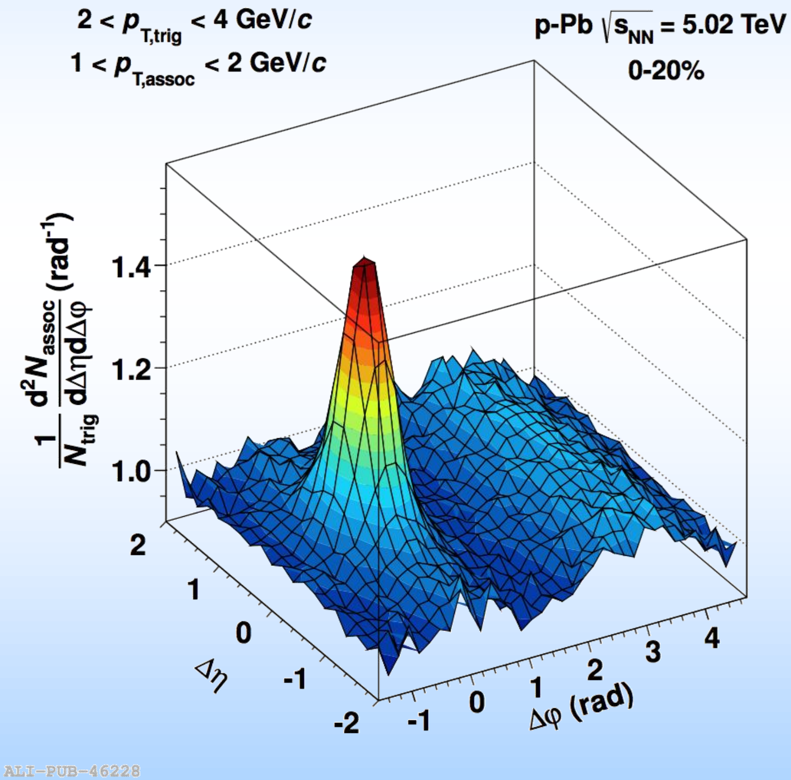
A Rasoanaivo and WAH, *in prep*

- For general angle, potentially *large* corrections

Correlations

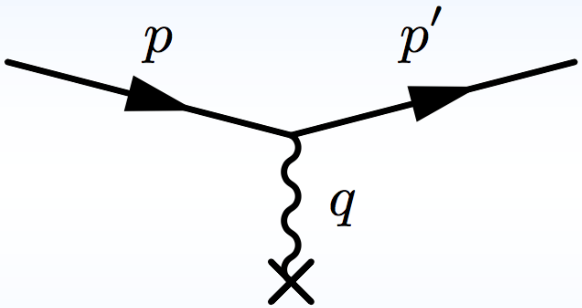
- Multiple gluon emission naturally yields suggestive correlations





Towards NLO Energy Loss

- Start with simpler problem:
  - Rutherford scattering in QED

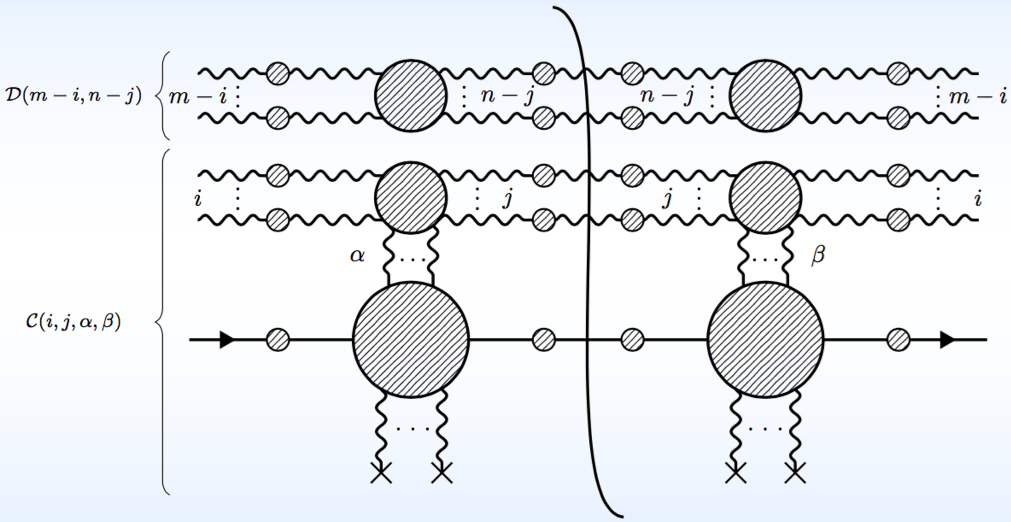


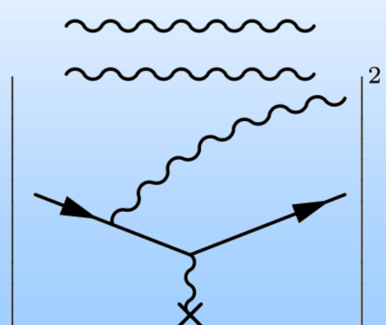
Abdullah Khalil

  - Similar to GW interaction
- What is NLO QED Rutherford?
  - 50 year old, fundamental open problem
  - For solution details, see arXiv:1701.00763

Infinite Number of Soft Diagrams

- Must carefully rearrange formally divergent series to obtain finite, sensible result





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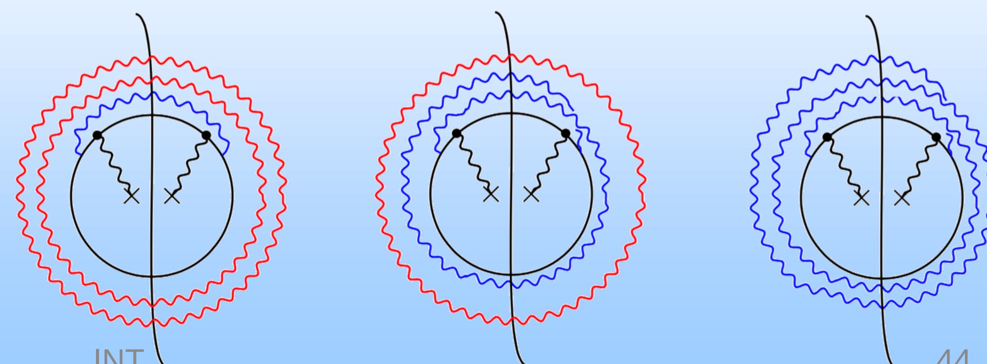

Final Result

- First ever complete to O(1) NLO Rutherford x-scn

$$\left(\frac{d\sigma}{d\Omega}\right)_{\texttt{NLO}} = \left(\frac{d\sigma}{d\Omega}\right)_{\texttt{0}} \Bigg\{ 1 + \frac{\alpha}{\pi}\Bigg[\log\left(\frac{Q^2}{\delta^2 E^2}\right)\left(\log\left(\frac{E^2}{\Delta^2}\right) + \frac{3}{2}\right) + \frac{2}{3}\log\left(\frac{Q^2}{\mu^2_{\overline{\mathrm{MS}}}}\right) - \pi^2\left(\frac{1}{\left(\frac{2E}{Q}+1\right)} + \frac{1}{3}\right) + \frac{5}{36} + \mathcal{O}(m^2, \delta^2)\Bigg]\Bigg\}$$

  - δ: experimental angular resolution
  - Δ: experimental energy resolution
  - Non-trivial check: satisfies Callan-Symanzik

Conclusions

- Many areas of theoretical uncertainty, some addressed in this work
- AdS Heavy flavor:
  - Increased understanding of momentum fluctuations
    - Conjecture: HF diffusion coef. ind. of v
    - Smooth transition from heavy to light quarks in one picture
  - *Momentum correlations* as distinguishing observable
  - Need for more precise pp theory & exp for HF production
  - Brand new Υ $R_{AA}(N_{part})$
- pQCD:
  - Small system E-loss
  - Corrections for 2 gluon emission
    - Potential ridge component
    - Partial results for n gluon emission
  - First ever full NLO Rutherford, correct implementation of KLN theorem
- Future Work:
  - Continue improving theoretical understanding, implement results into energy loss models, and compare with data