# NLO Heavy Quark Energy Loss in Strongly-Coupled Quark-Gluon Plasmas

W. A. Horowitz

University of Cape Town

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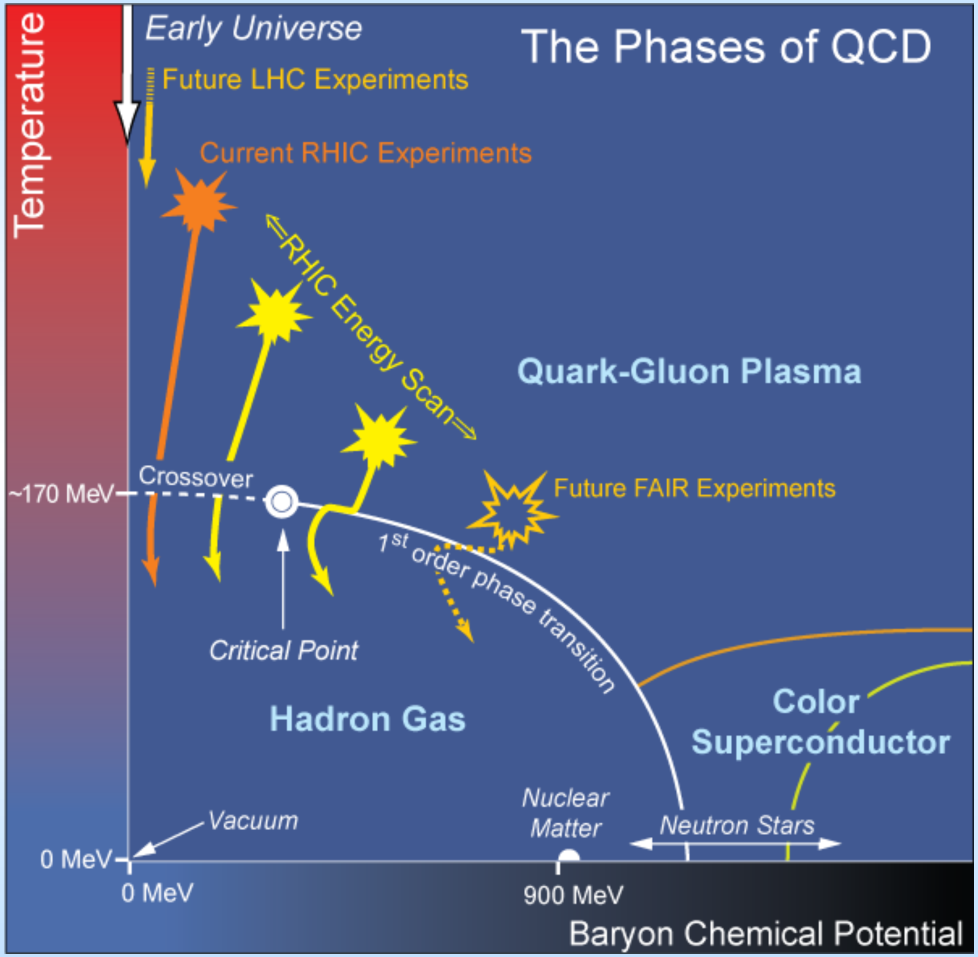
With many thanks to Ulrich Heinz, Ben Meiring, Razieh Morad, Chun Shen, and Derek Teaney

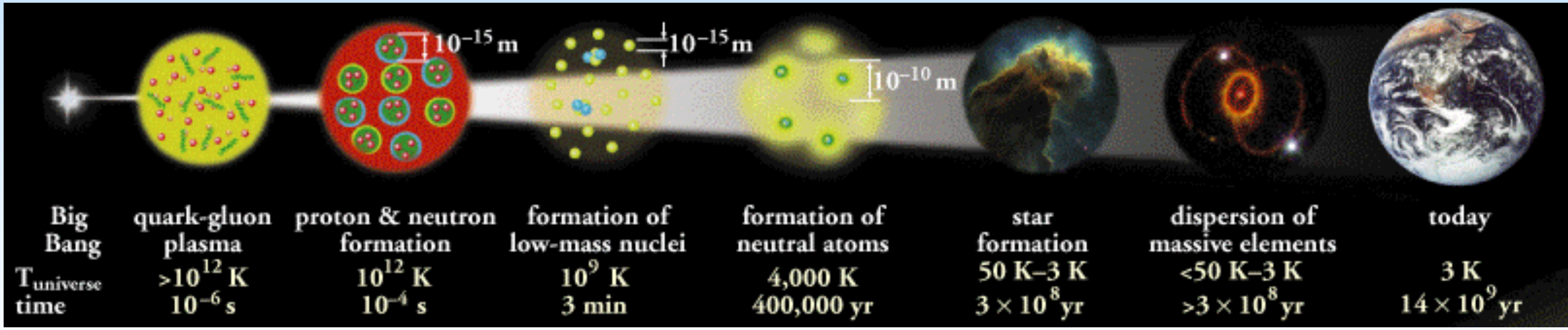
# What Are We Interested In?

- Discover emergent, many-body physics of QGP through consistent theoretical description of experimental data



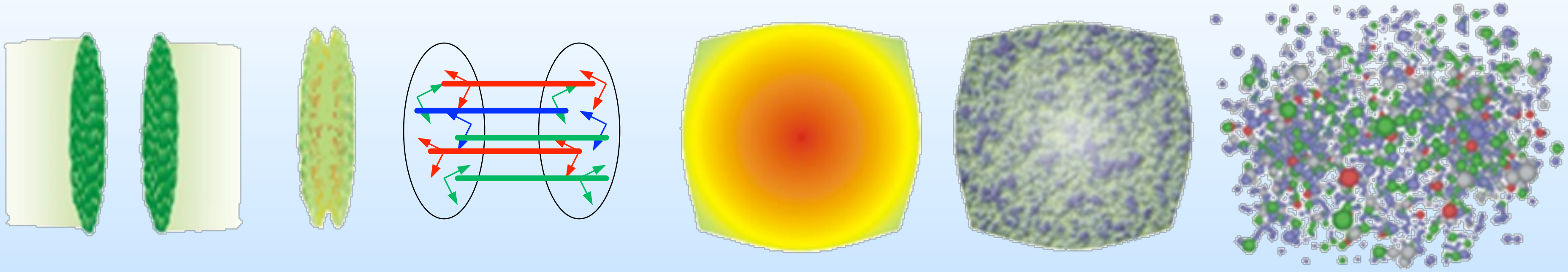

Long Range Plan, 2008

# Big Bang vs. Little Bang




ALICE Collaboration

t = - ∞ | t = 0 | t = 1 fm/c | t = 3 fm/c | t = 4 fm/c | t = + ∞



Initial State | Initial Overlap | Thermalization | QGP | Hadronization | Hadron Gas

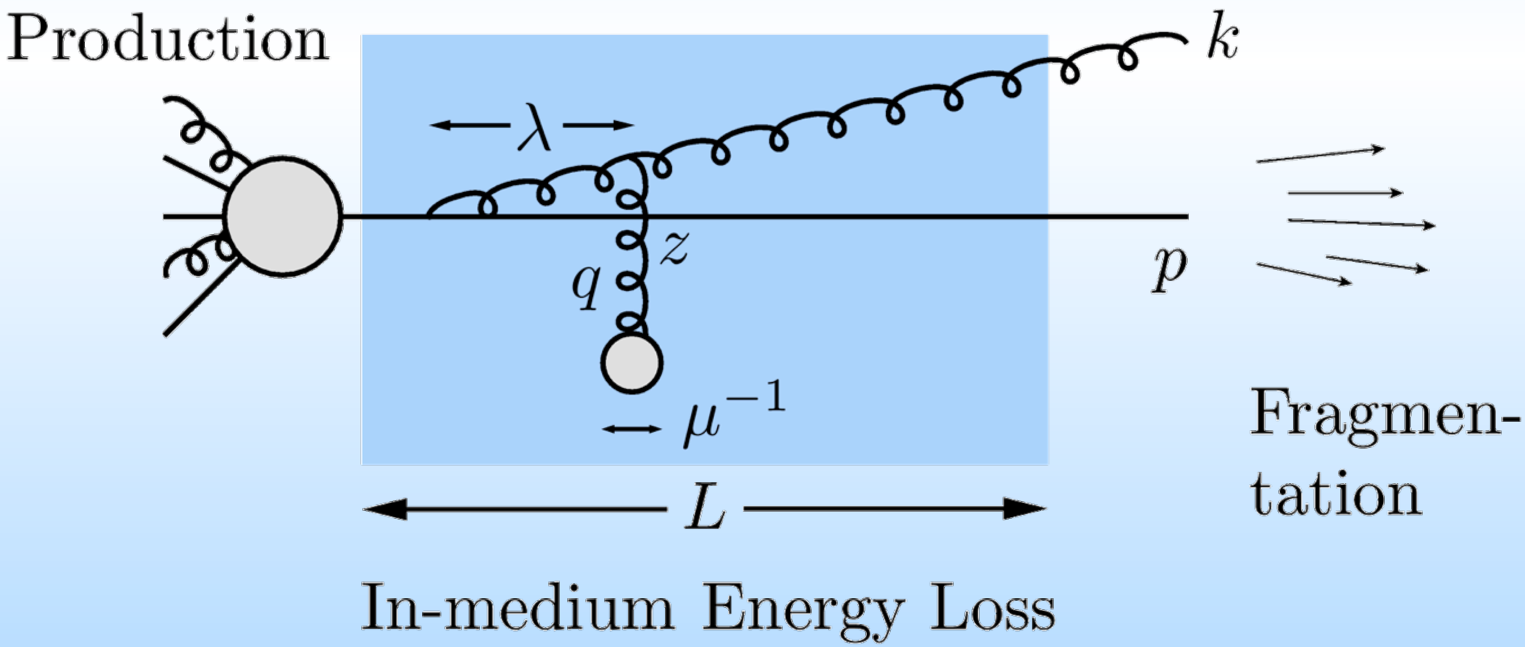
# Learning about QCD

- Use heavy ion collisions as testbed
  - $T_{QGP}$ ~ 1 trillion degrees, 10,000 times hotter than center of Sun
  - Macroscopic collision energies:
    - RHIC ~ two mosquitoes colliding mid-air
- Various observables
  - Two large classes (non-exhaustive):
    - Low-$p_T$ and High-$p_T$
- Low-$p_T$: see, e.g., Ulrich Heinz's excellent overview of th. & exp. collective effects

# High-$p_T$ Observables

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

pQCD Picture
AdS/CFT Picture



# Tools for Studying QCD

- Lattice
  - Requires imaginary time correlators
    - Difficult to compute quantities such as viscosity
- pQCD
  - Requires large momentum scale
- AdS/CFT
  - Requires Maldacena conjecture, theory with a dual

# Gross Oversimplification of LO QGP Phenomenology

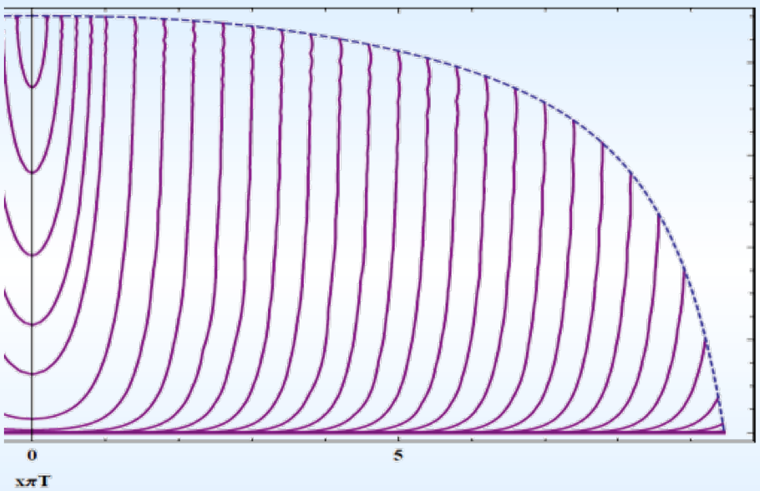
| | pQCD | AdS/CFT |
|---|---|---|
| low-$p_T$/ collective | Novel/better weak-coupling physics? | Rapid thermalization<br>$\eta/s$ |
| high-$p_T$/ energy loss | Suppression<br>$v_2$<br>Light & heavy flavors<br>RHIC & LHC | Novel/better strong-coupling physics? |

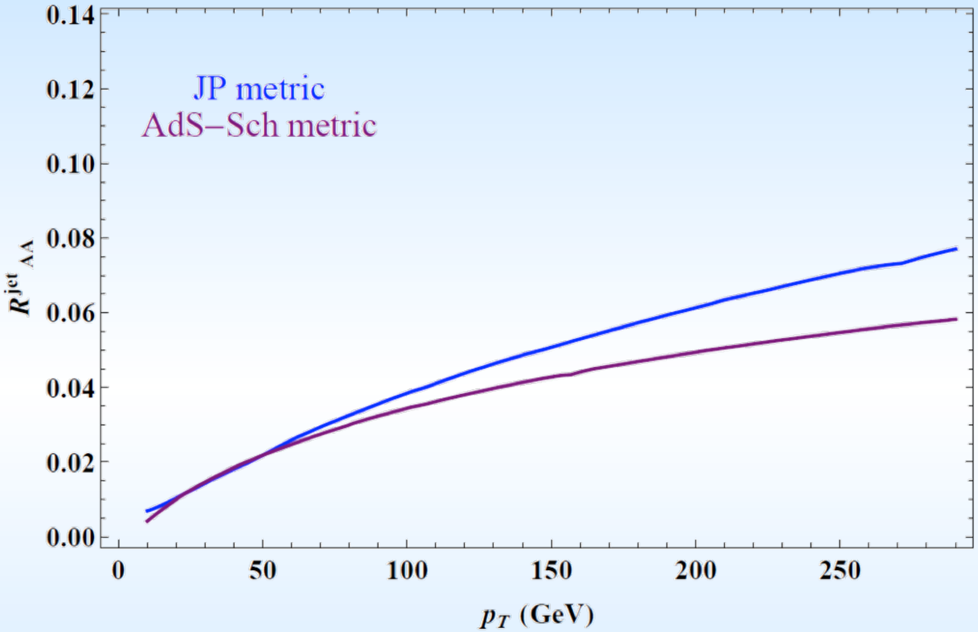
# Why AdS at High-$p_T$?

- Perturbatively, 3 couplings for rad E-loss
  - Not known at which scale(s) couplings run
- $T_{QGP} \sim \Lambda_{QCD}$ => $g(2\pi T) \sim 2$
  - Always "small" scale in problem
  - Perhaps low-$Q^2$ plasma physics dominates over high-$Q^2$ in E-loss physics?
    - Factorization not proven in AA
- Work here assumes all couplings strong
  - Cf, e.g., Casalderrey-Solana et al. for alternative

# ***Failure*** of Naïve LO AdS: Light High-$p_T$

- Assume *all* couplings large
  - Jet E-loss for lights




R Morad and WAH, JHEP 11 (2014) 017

- Thermalization time very short
- In AdS setup, probe & gluon cloud indistinguishable from medium
  - Only makes sense to compare to ***jets***, not single particles

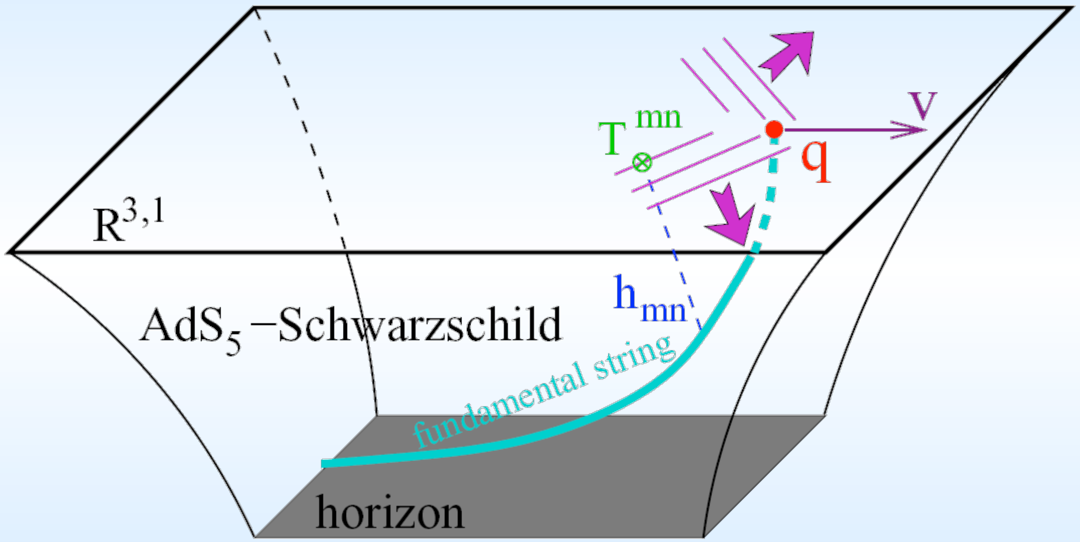
# LO AdS for Heavy High-$p_T$

- Assume all couplings large

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

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

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




J Friess, et al., PRD75 (2007)

Similar to Bethe-Heitler

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

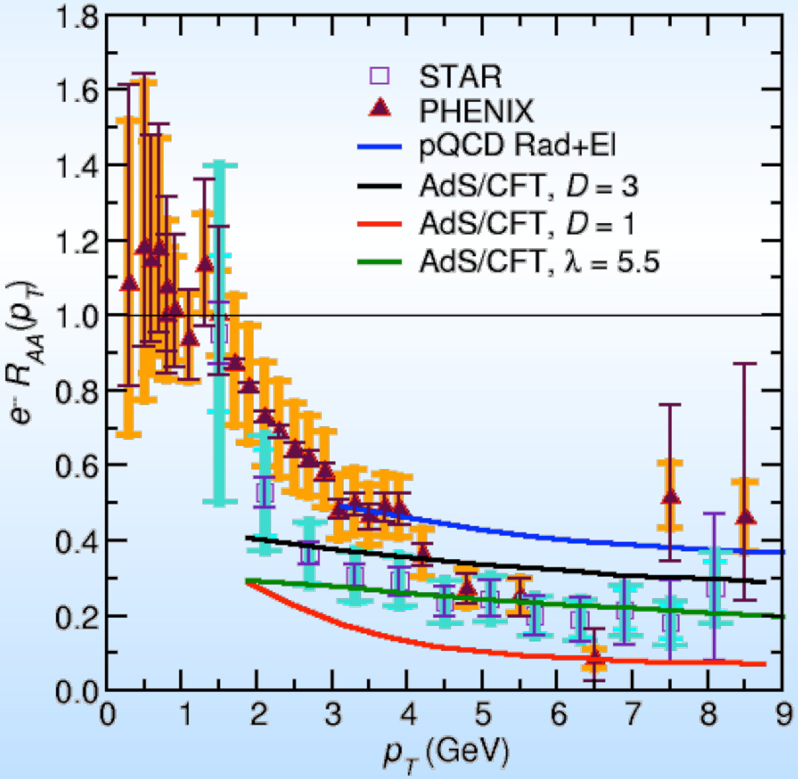
Very different from usual pQCD and LPM

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

# *Failure* of LO AdS for Heavy High-$p_T$

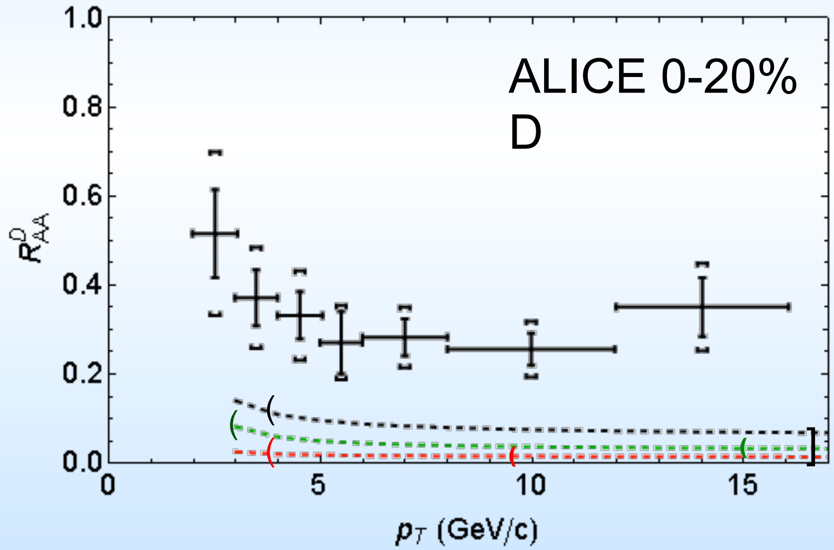
- Constrained by RHIC, oversuppresses LHC

RHIC




WAH, PhD Thesis, arXiv:1011.4316

LHC



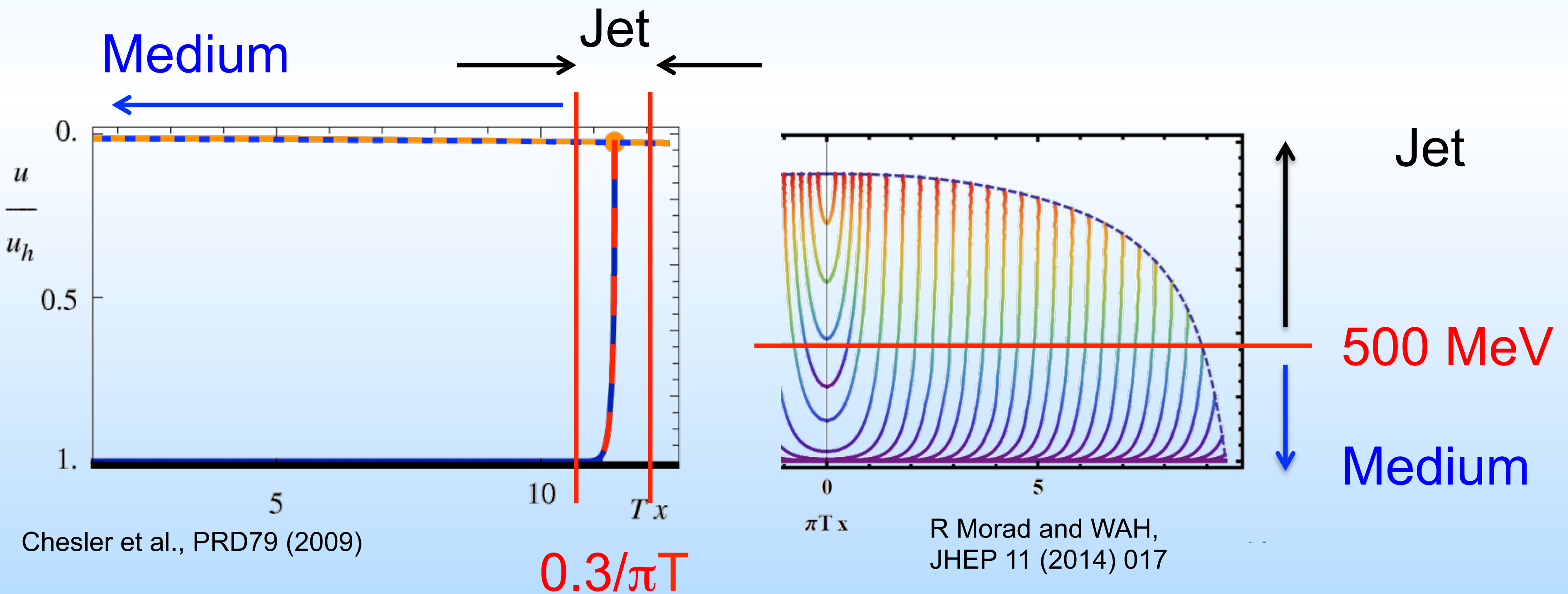

WAH, PANIC11 (arXiv:1108.5876)
ALICE, JHEP 1209 (2012)

# Missing Physics?

- Lights:
  - Better jet prescription
  - Renormalized $R_{AA}$
    - Razieh Morad, Wed 3:30pm
  - Improved IC
    - Ben Meiring, Thurs 2:30pm
- Heavies:
  - Within limits of calculation?
  - Higher order corrections?

# Improved AdS Jet Prescription?

- All approximations to a full $T^{\mu\nu}$ calc.
- Original jet defined by spatial proximity
- New suggestion: separation by E scale



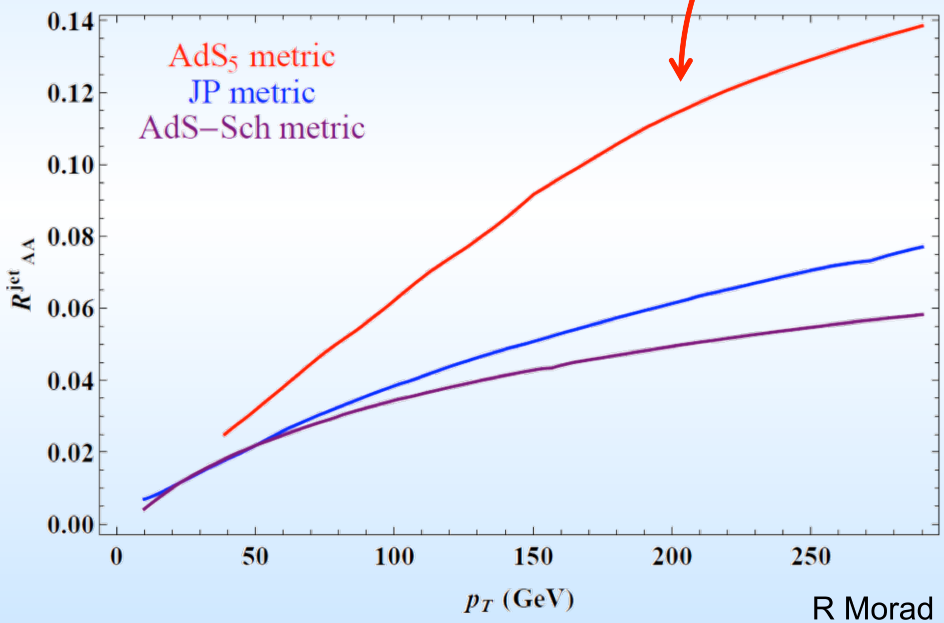

Chesler et al., PRD79 (2009)

R Morad and WAH, JHEP 11 (2014) 017

# AdS: No-nucleus Suppression

- Original proposed IC => anomalous vacuum suppression!

Vacuum $R_{pp} << 1$



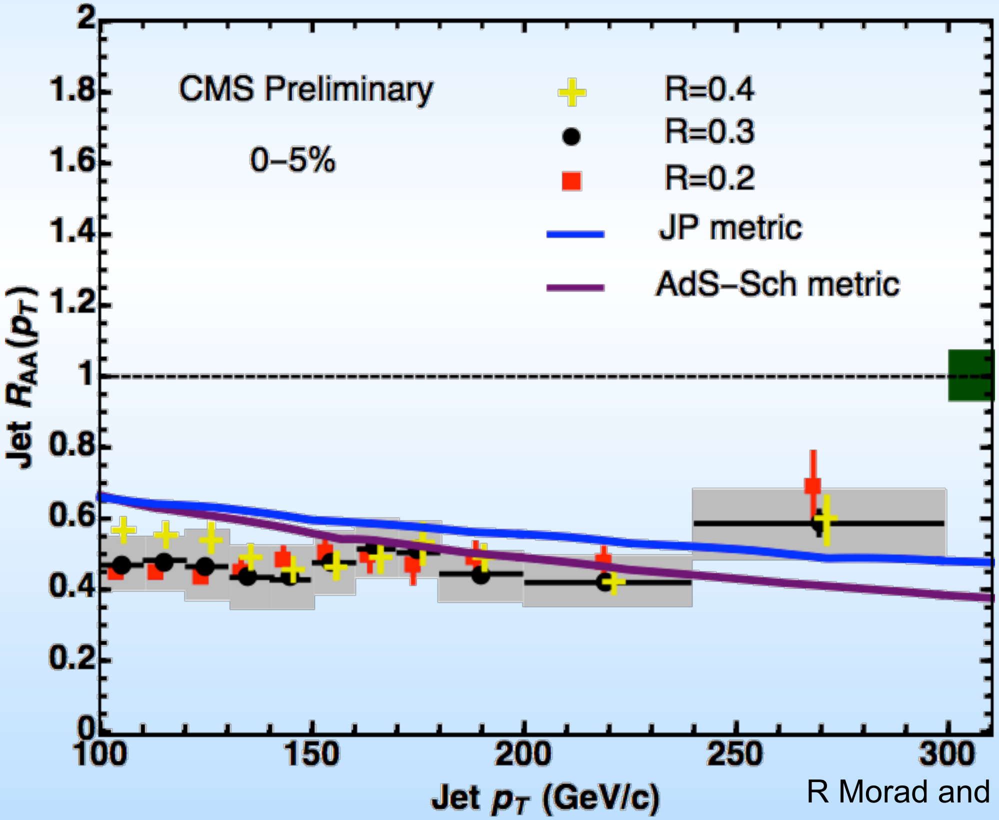

R Morad and WAH, JHEP 11 (2014) 017

– Suggests oversuppression artifact of string IC
  - See B Meiring parallel for work to more realistic IC

# AdS: Exciting Renormalization

– Can we capture diff. btwn. naïve AdS pp & AA?

- Define renormalized $R_{AdS}$ = "$R_{AA}$ / $R_{pp}$"; cf CMS
  - Use reasonable $\lambda = 12$ <=> $\alpha_s = 0.3$: **no fitting**



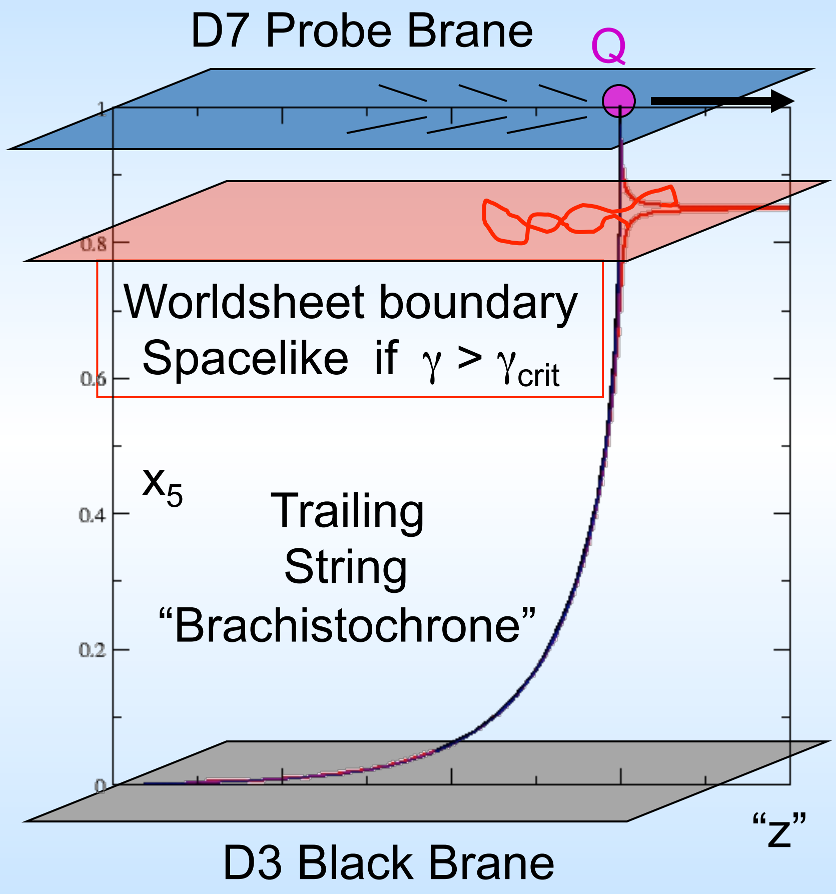

Very first, fully strongly coupled jet $R_{AA}$ calculation

R Morad and WAH, JHEP 11 (2014) 017

- Similar results for renorm. via $\Delta E_{renorm} = \Delta E_{AA} - \Delta E_{pp}$

# Limits on Heavy Flavor AdS Setup

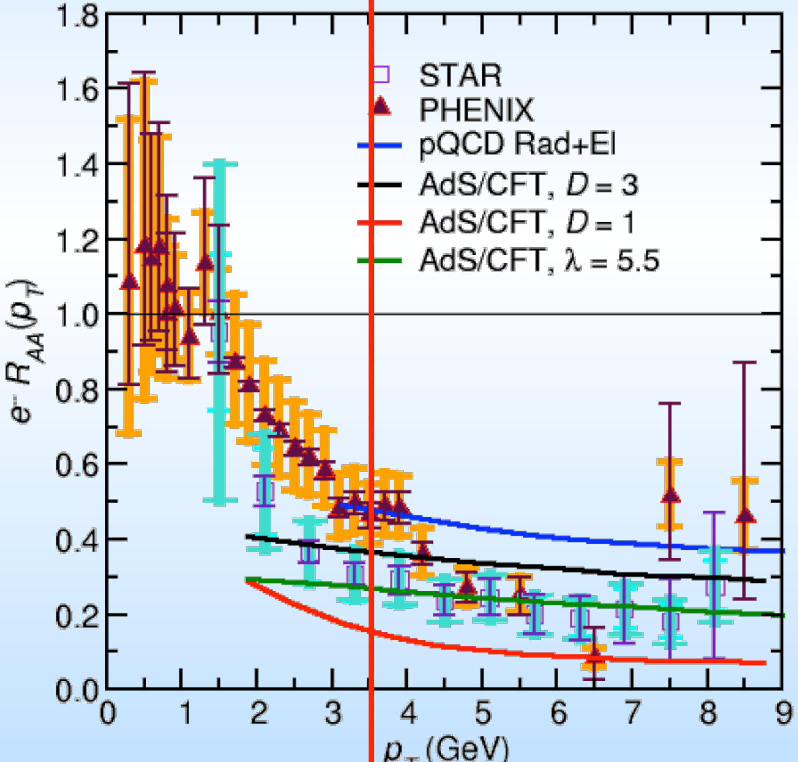
- For LO AdS:
  - Space-like quark endpoint
    - $\gamma_{crit} = (1 + 2M_q/\lambda^{1/2}\, T)^2$
      $\sim 4M_q^2/(\lambda T^2)$
  - Mom. Loss Fluctuations
    - $\gamma_{crit} = M_q^2/(4T^2)$
- Speed limit from fluct parametrically larger, but numerically smaller



# HQ $p_T$ Limits

RHIC

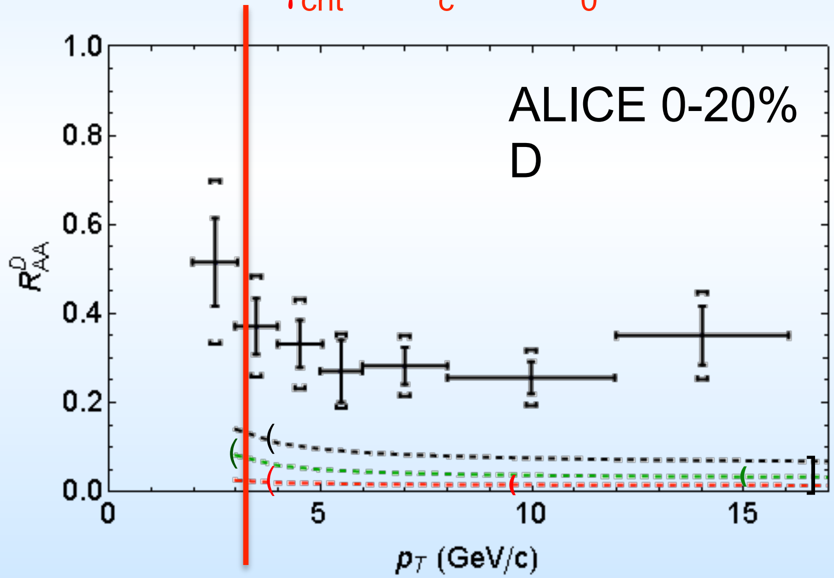
$\gamma_{crit} = M_c^2 / 4\ T_0^2 \sim 3 – 4$ GeV/c




WAH, PhD Thesis, arXiv:1011.4316

LHC

$\gamma_{crit} = M_c^2 / 4\ T_0^2 \sim 3 – 4$ GeV/c




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

# Including Fluctuations in AdS HF

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

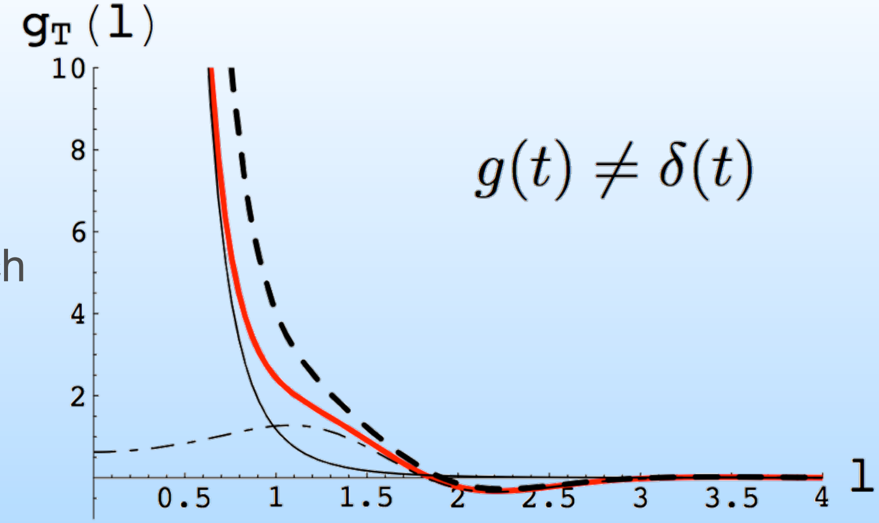
$$\langle F_i^L(t_1) F_j^L(t_2)\rangle = \kappa_L\, \hat{p}_i \hat{p}_j\, g(t_1 - t_2)$$

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

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

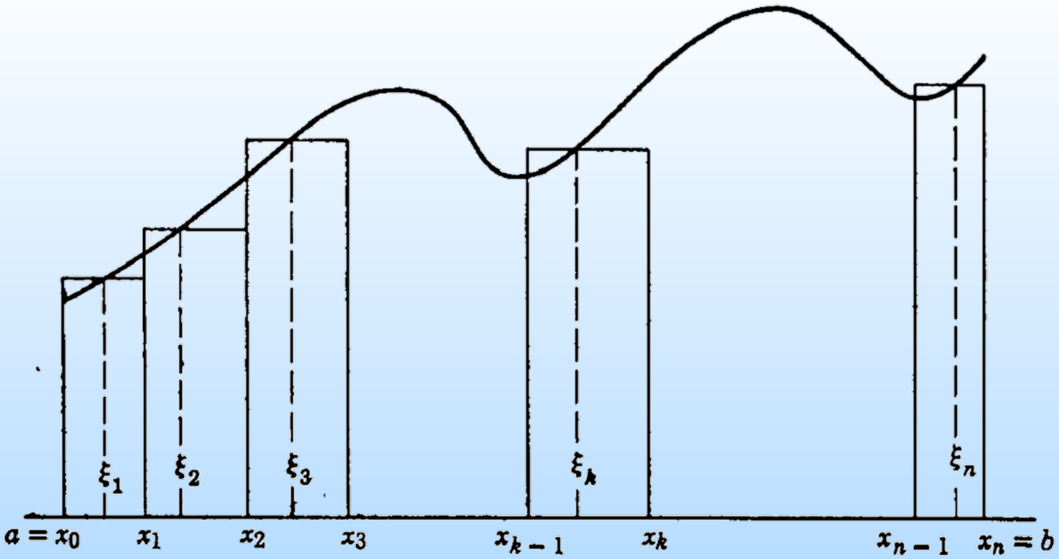
Gubser, NPB790 (2008)

- Obeys Einstein's relations *only* at v = 0
- 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



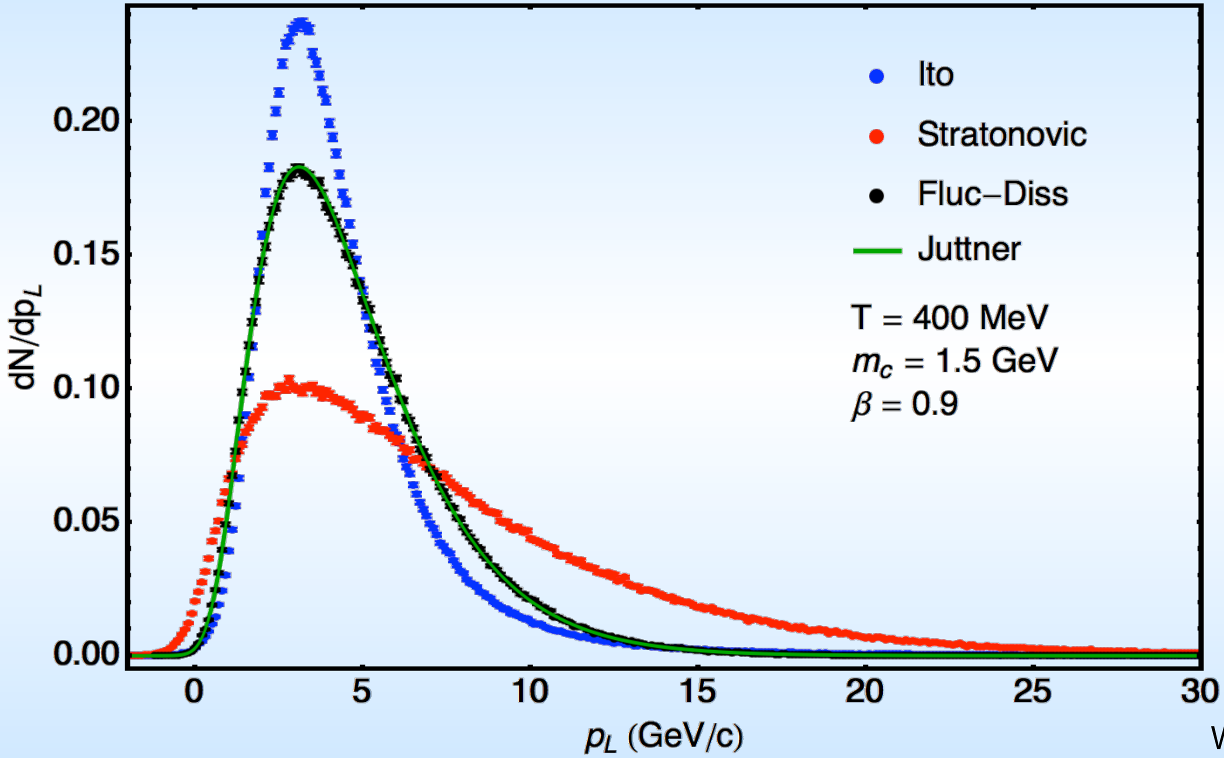
# Discretizing Langevin

- Discretizing Riemann Calculus trivial
  - Sum converges regardless of bin widths and x* in bin as n increases
- Ambiguity in Ito Calculus
  - Results depend on discretization procedure



# Discretization Ambiguity and Einstein

- Ex: momentum space distribution of charm




WAH, *in prep*

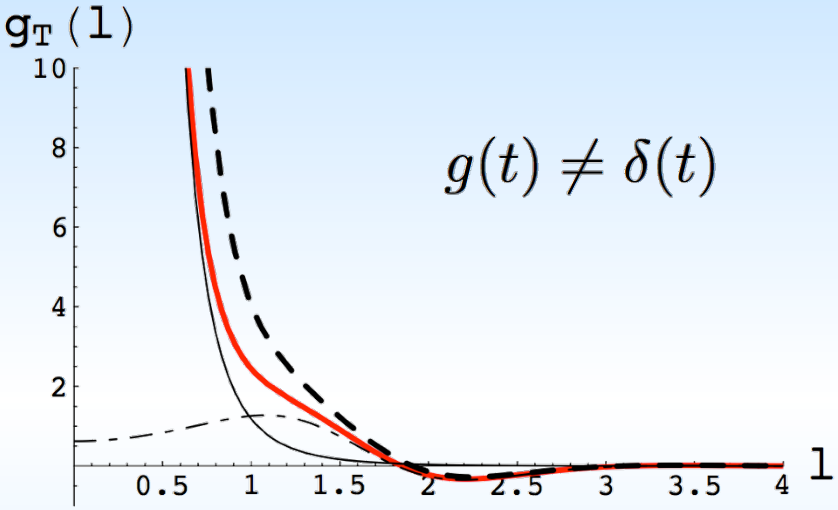
- AdS fluctuations very diff from fluc-diss, which lead to relativistic thermal (Jüttner) distribution
- Huge diff btwn pre-point and mid-point

# Resolving the Ambiguity

- Saved by colored noise:

$$\frac{dp_i}{dt} = -\eta_D + F_i^L + F_i^T$$
$$\langle F_i^L(t_1)F_j^L(t_2)\rangle = \kappa_L\,\hat{p}_i\hat{p}_j\,g(t_1-t_2)$$
$$\langle F_i^T(t_1)F_j^T(t_2)\rangle = \kappa_T\,(\delta_{ij}-\hat{p}_i\hat{p}_j)\,g(t_1-t_2)$$

Gubser, NPB790 (2008)




  – $t_{corr}\mu \sim \frac{1}{2}\sqrt{g^2 N_c}\sqrt{\gamma}\frac{T}{M_q} < 1$ for $\gamma < \gamma_{speed\ limit}$

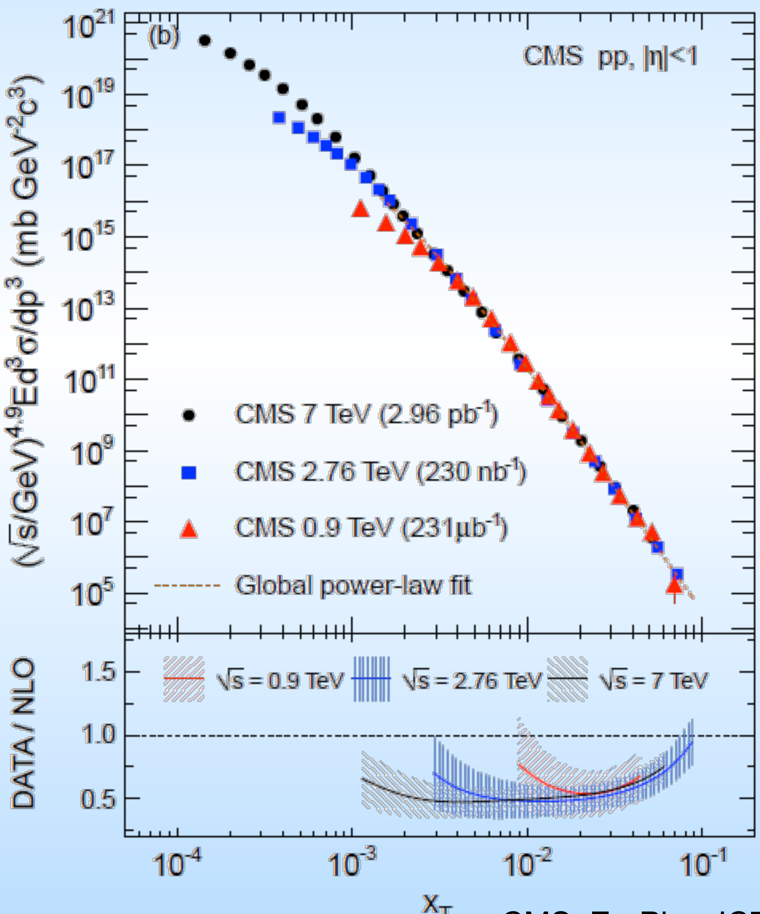
- Wong-Zakai Theorem:
  – As autocorrelation => 0, Langevin => Stratonovich

# Model Calculations

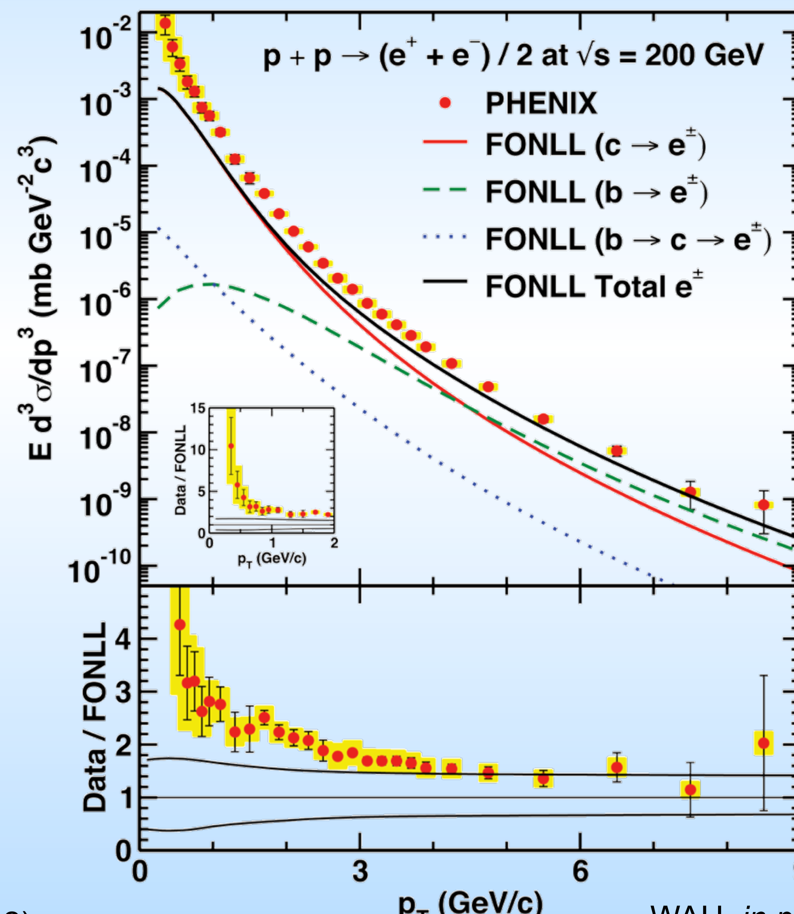
- Input FONLL c, b production spectra
- Discretized Langevin through VISHNU
  - 2+1D viscous hydro
- FONLL FFs to B, D, e
- Uncertainty in map from QCD to N = 4 SYM
  - Explore systematics with two reasonable assumptions
    - $\alpha_s = 0.3$, $T_{SYM} = T_{QCD}$
    - $\lambda = 5.5$, $T_{SYM} = T_{QCD}/3^{1/4}$

# p+p Baseline

- Precision QCD is difficult

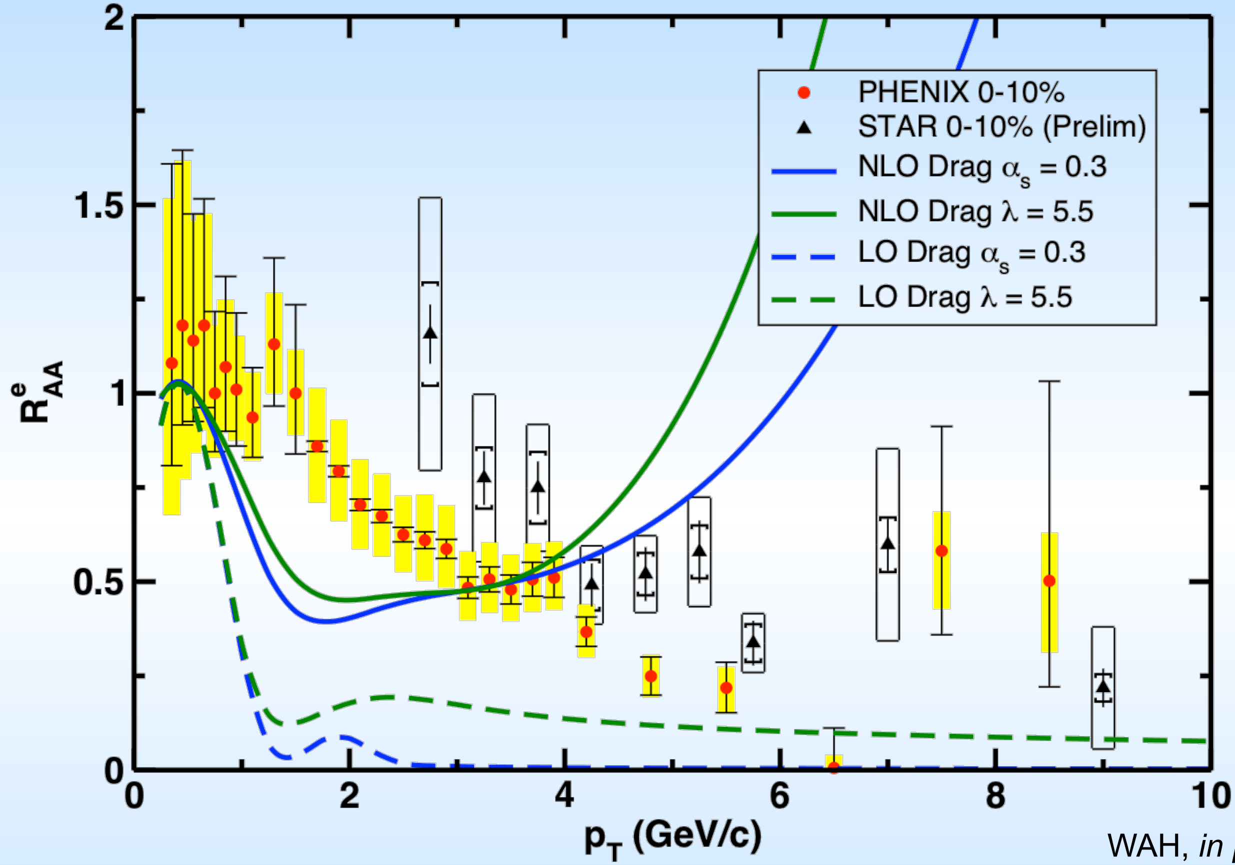



CMS, EurPhysJC72 (2012)




WAH, *in prep*

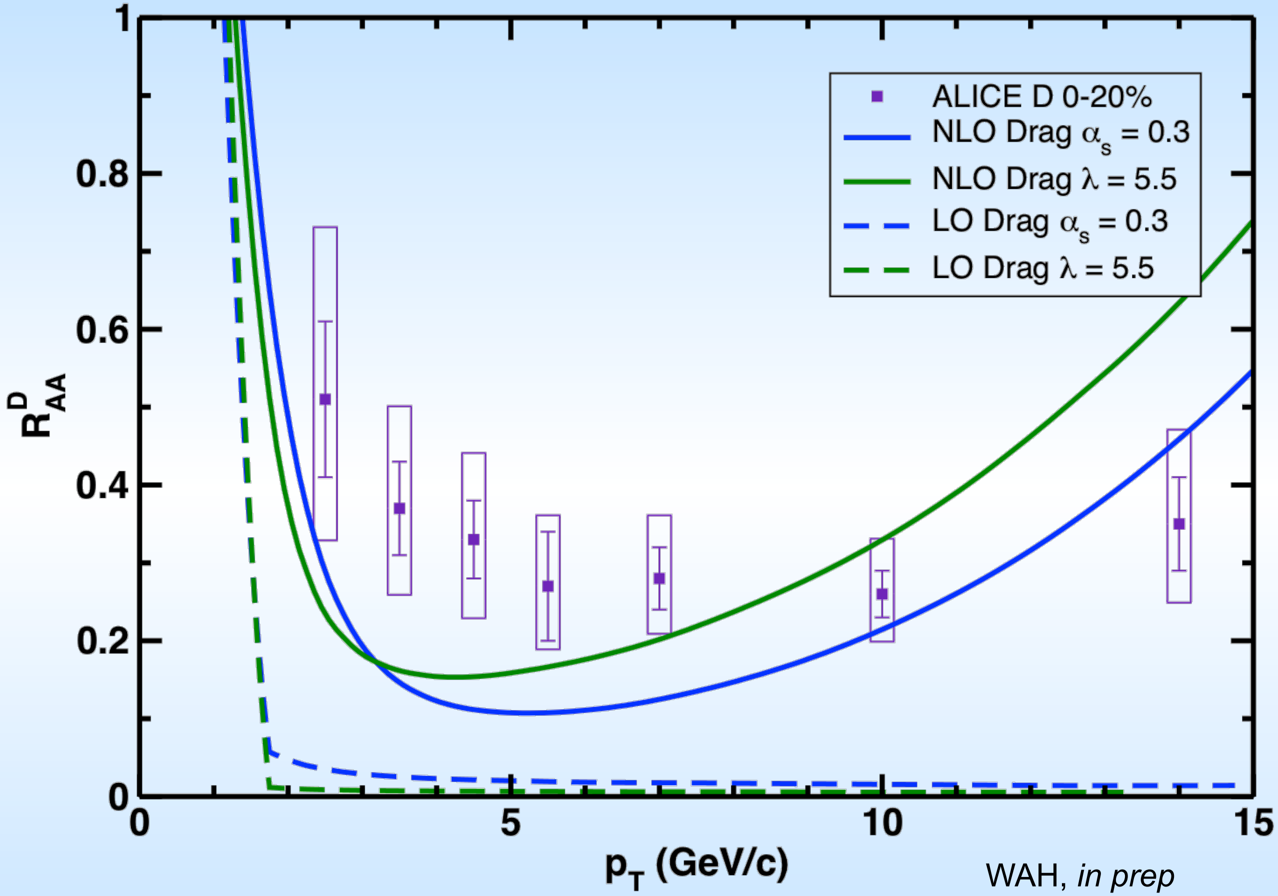
# Compare to RHIC HF Electrons




WAH, *in prep*

- Agreement in sweet spot $p_T \sim 3 – 4$ 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.

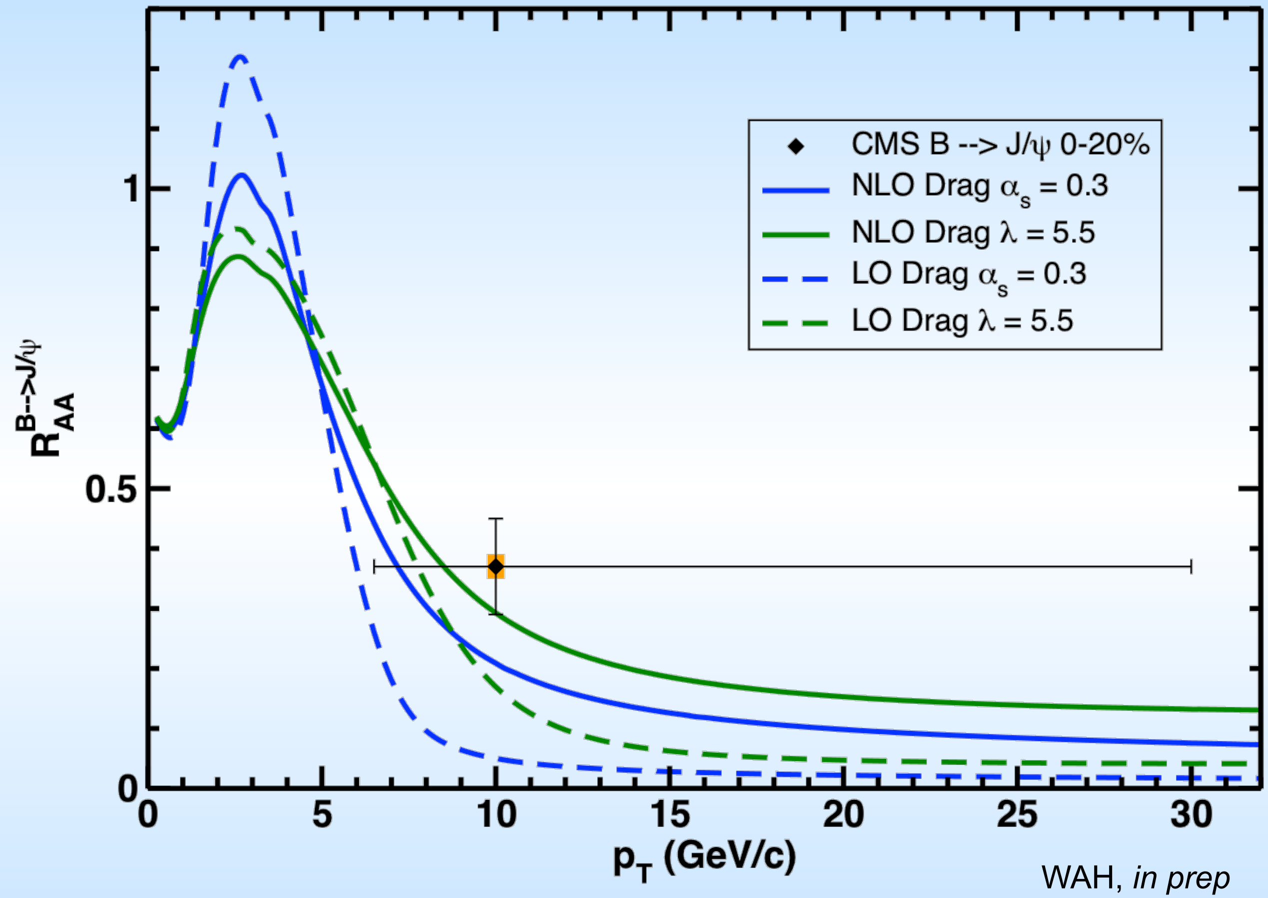
# Compare to LHC D Mesons




WAH, *in prep*

- Inclusion of fluctuations yields results qualitatively similar to D suppression

# Compare to LHC B => J/$\psi$



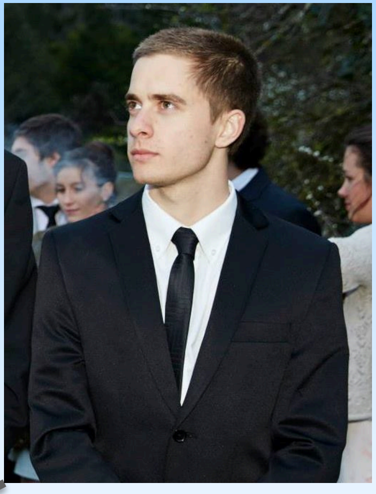

WAH, *in prep*

- B suppression also in qualitative agreement

# Conclusions

- Exciting times in QGP physics
- Very first, all strong-coupling jet $R_{AA}$
  - No parameter fitting
  - Consistent with preliminary CMS data
- Very first correct inclusion of fluctuations in HQ E-loss
  - No parameter fitting
  - Qualitatively consistent with RHIC, LHC data
- Prospect of consistent, strong-coupling picture of QGP from low- to high-$p_T$

# Future Outlook



Robert Moerman

Isobel Kolbe

## Future Outlook:

- AdS:
  - Find more appropriate light quark setup, IC (Morad, Meiring)
    - Match $T^{\mu\nu}$ from pQCD and AdS/CFT
  - Derive & include HQ E-loss corrections (Robert Moerman)
    - Colored noise, allow quark to slow
- pQCD:
  - E-loss in p+A (Daniel Adamiak, Isobel Kolbe)
    - New spectra, E-loss formulae
  - Multigluon approximation: MHV (Andri Rasoanaivo)
  - Derive & include NLO corrections, esp. running coupling (Garry Kemp)

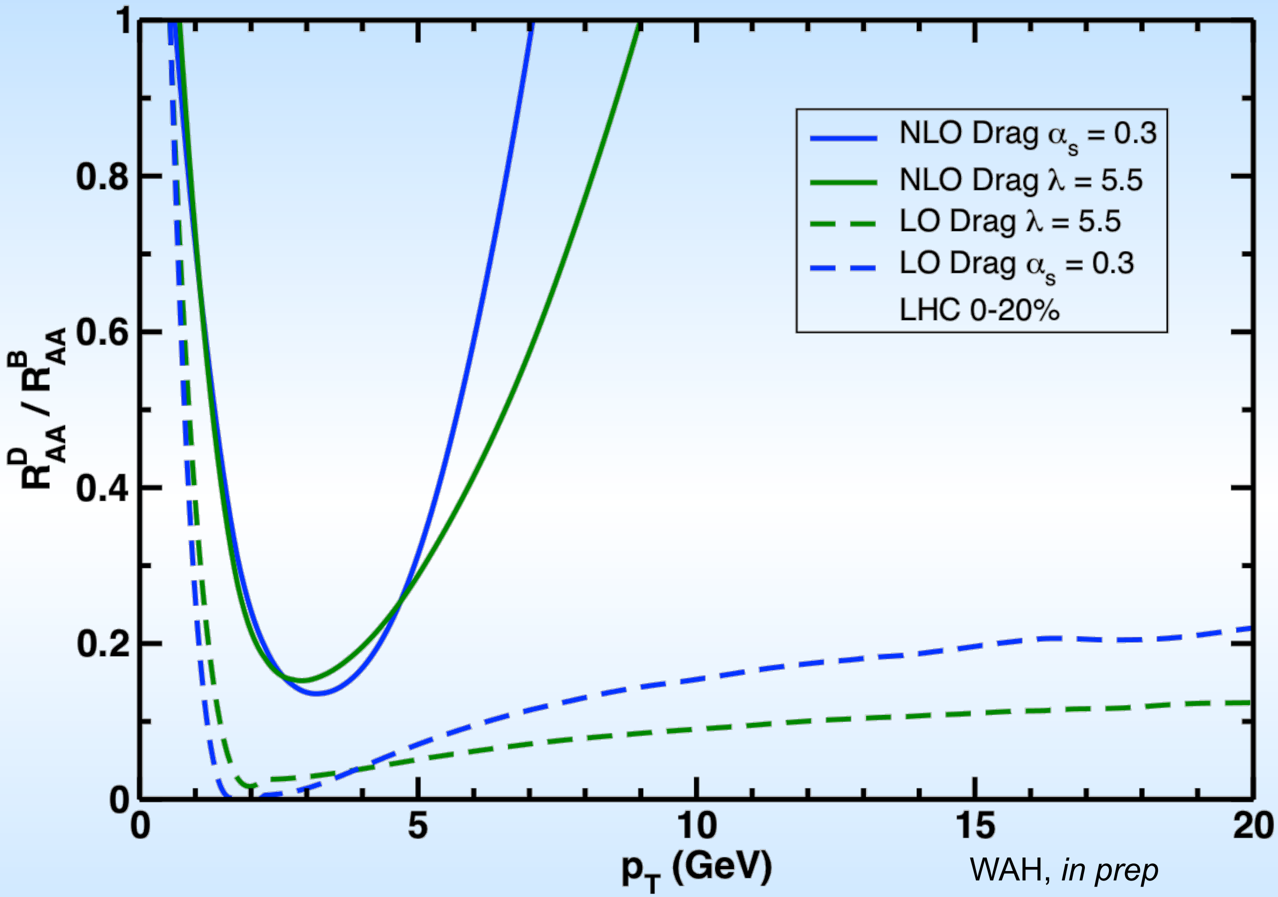
Daniel Adamiak

Garry Kemp

Andri Rasoanaivo

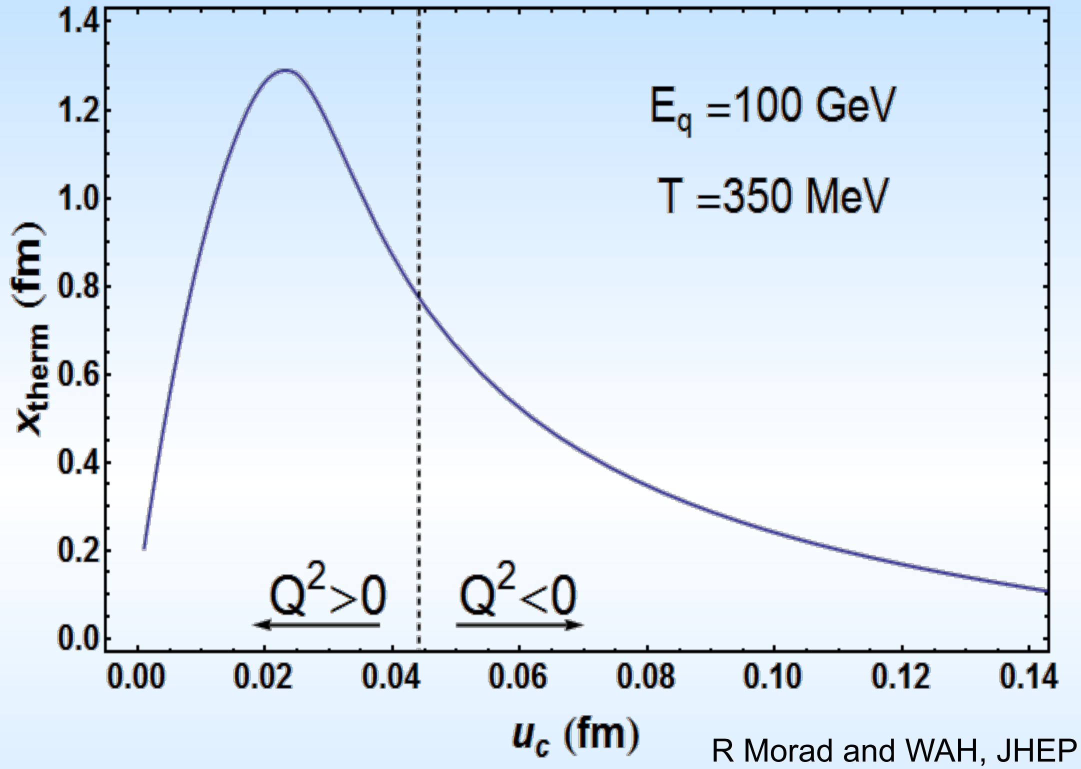
# Bonus Material

# D to B Ratio




- Fluctuations ruin flat, $p_T$-ind prediction of double ratio from LO AdS/CFT drag

# AdS Jet Suppression Sensitivity

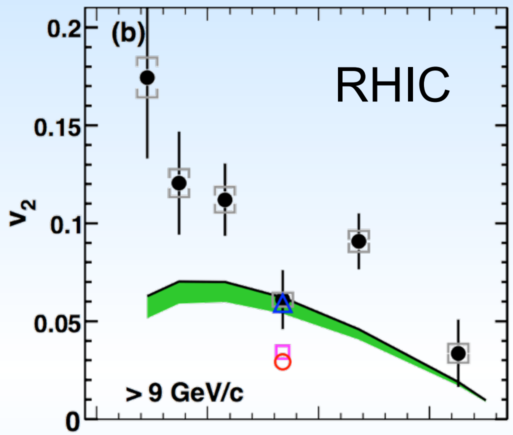


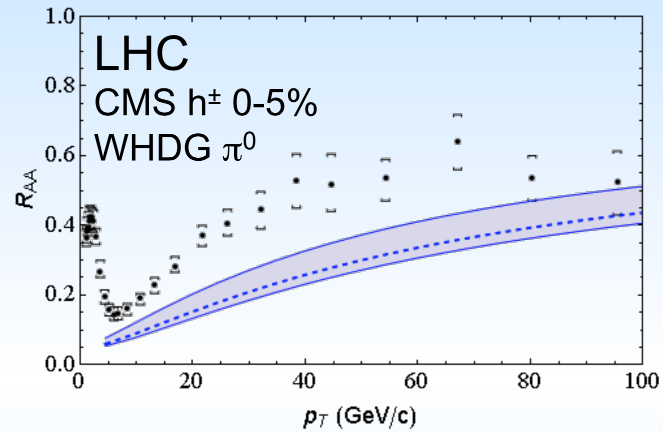

R Morad and WAH, JHEP 11 (2014) 017

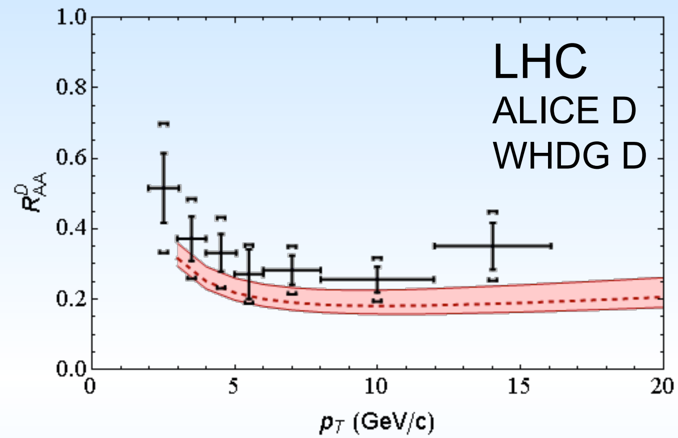
- Stopping distance of light quark extremely sensitive to IC, e.g. virtuality
  - Doubly infinite dimensional space of IC mostly unexplored

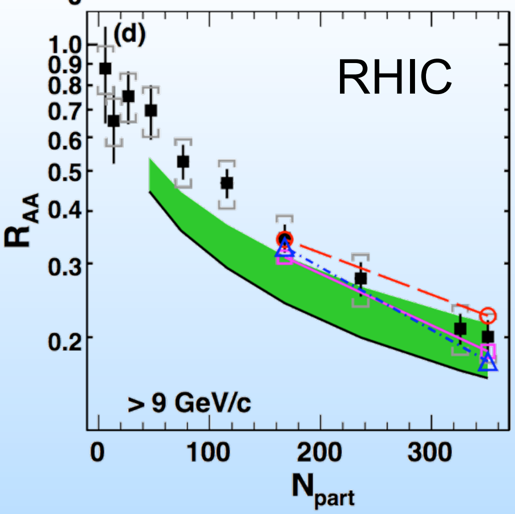
# LHC is Hard

- pQCD E-loss makes more sense
  - Constrained by RHIC, LO pQCD predictions strikingly similar to LHC data

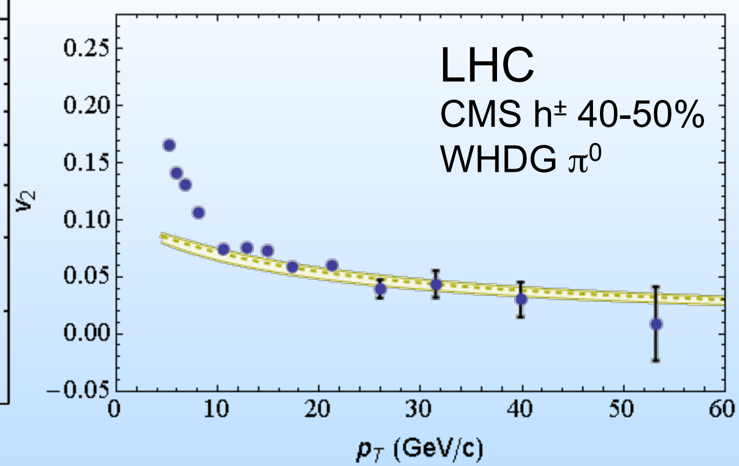


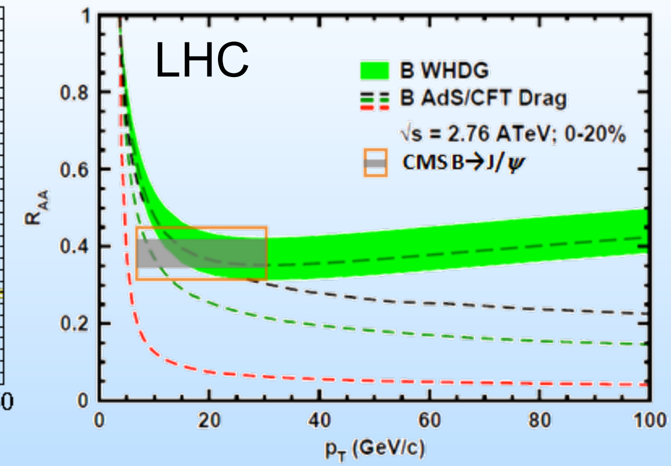




PHENIX PRL105 (2010)



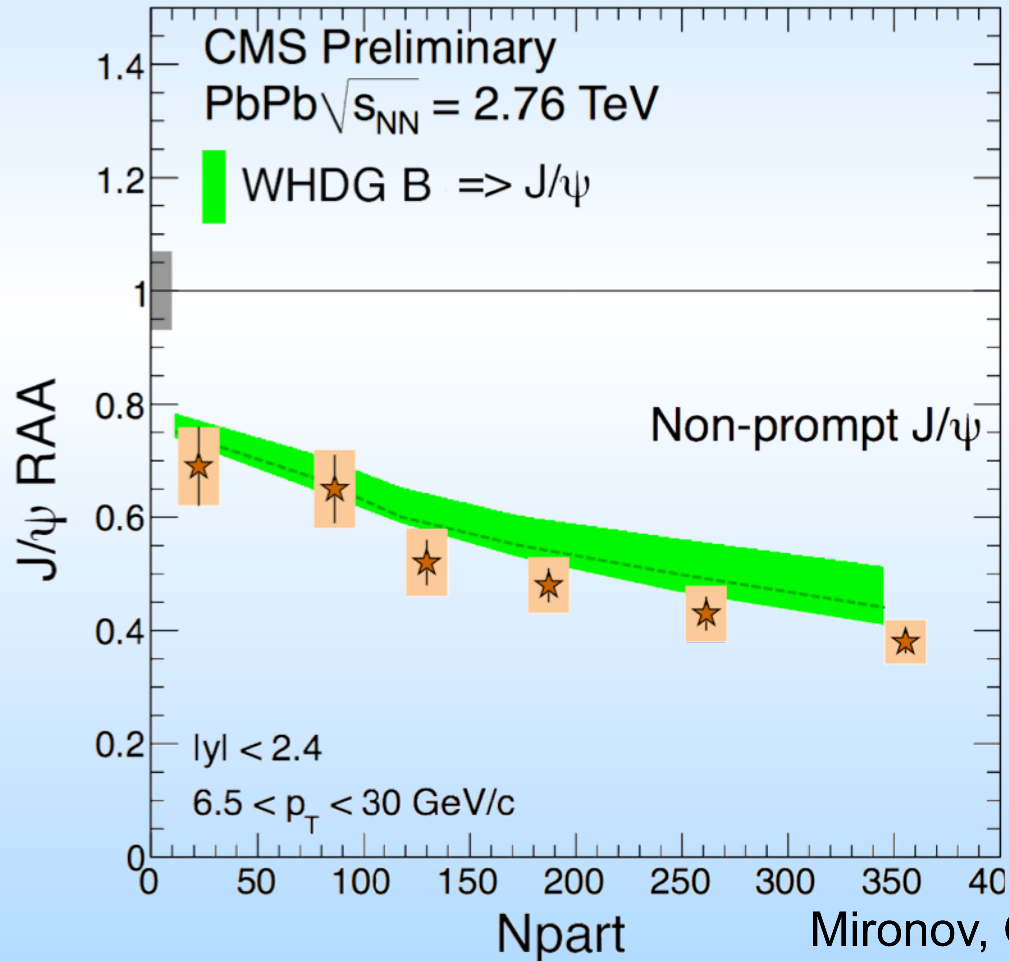

CMS, Eur.Phys.J. C72 (2012)
CMS, PRL109 (2012)




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

# New WHDG J/$\psi$ Comparison to CMS

- WHDG B + B => J/$\psi$ decay
  - Thanks to Andrea Dainese and Zaida Conesa Del Valle




Mironov, QM2012
NPA 904-905 (2013)

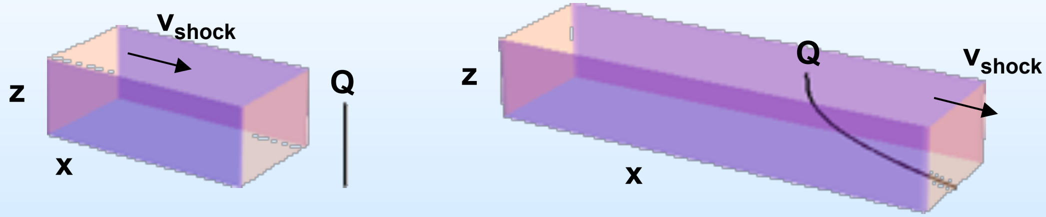
# Strongly Coupled HF and p+A

- Measure open HF in p+A
  - Midrapidity: test production
  - 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

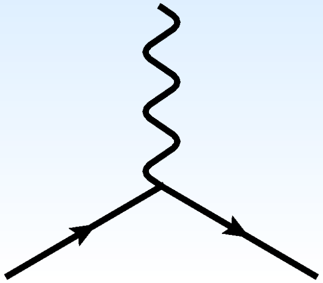



WAH and Kovchegov, PLB680 (2009)

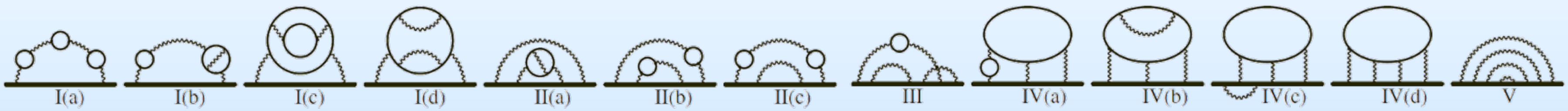
$$\frac{dp'}{dt'} = -\frac{\sqrt{\lambda}}{2\pi}\frac{\Lambda^2}{M_q}p'$$

# E&M Particle Physics Well Understood

- Lagrangian known: $\mathcal{L}_{EM} = \bar{\psi}\left(i\not{D} - m\right)\psi - \frac{1}{4}F^2$
- QED Vertex:



- Ex. of Precision QED: g - 2




Gabrielse et al., PRL97 (2006)

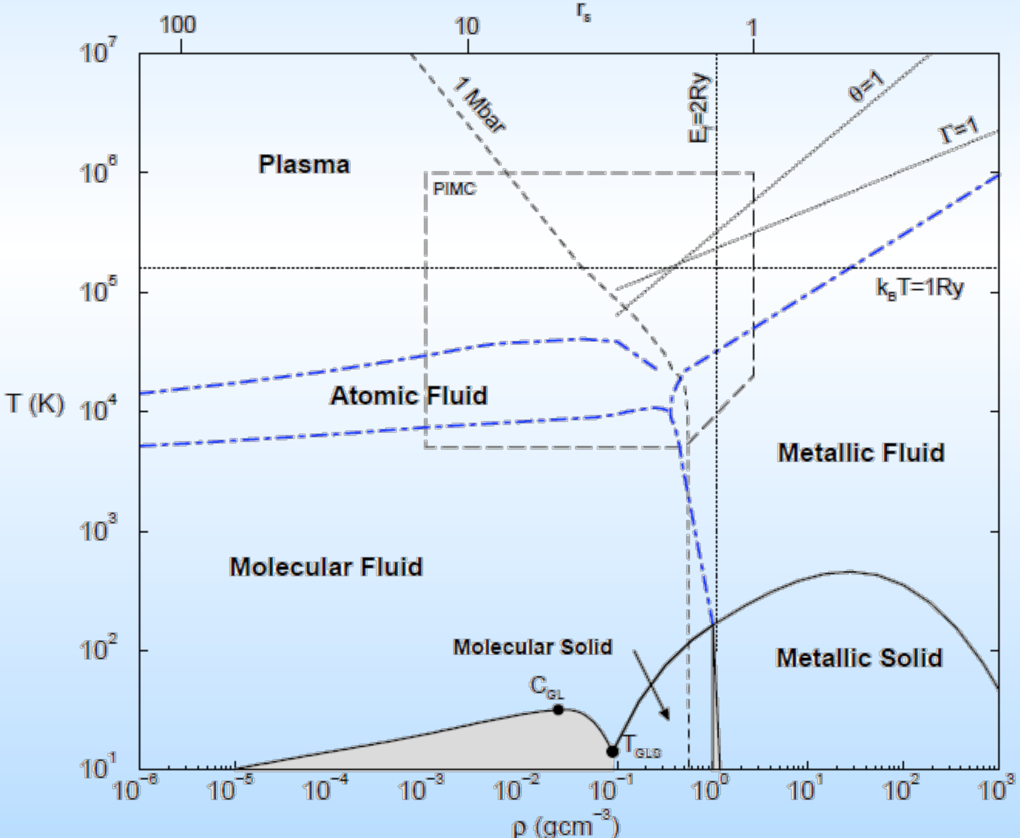
$$g/2 = 1.001\,159\,652\,180\,73(28) \quad [0.28\ \text{ppt}]$$

Hanneke, Fogwell, and Gabrielse, PRL100 (2008)

# E&M Many Body Physics

- Many body physics less well understood

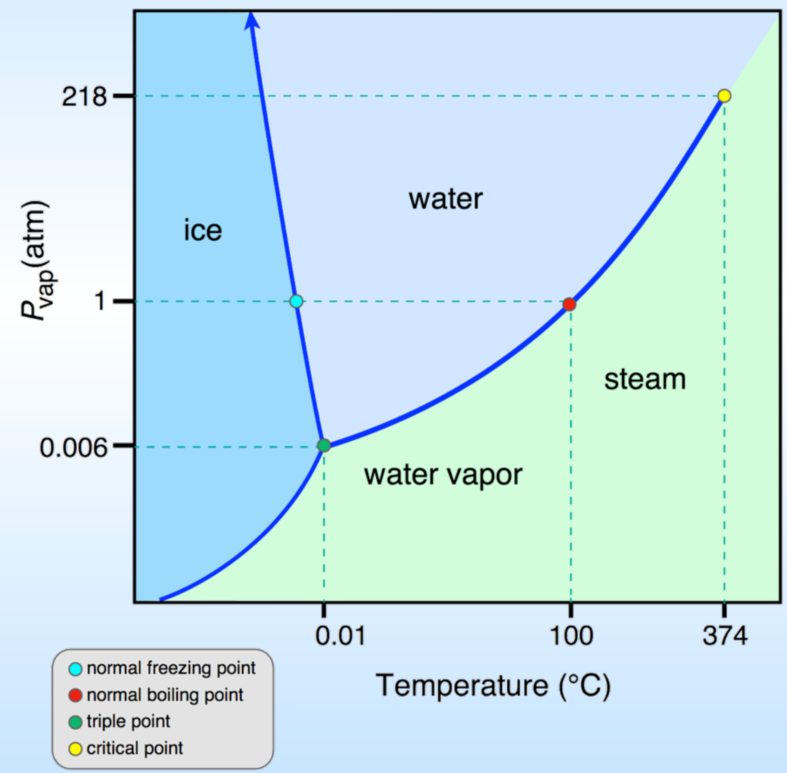
Hydrogen Phase Diagram




Calculated, Burkhard Militzer, 2000

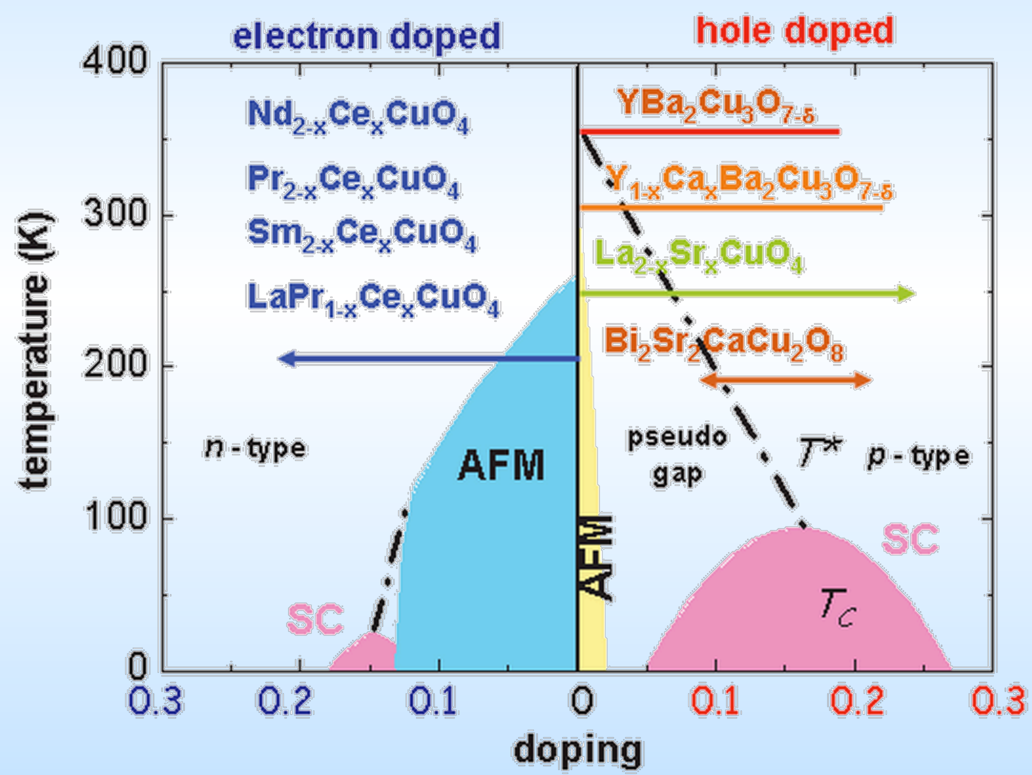
# E&M Many Body Physics (cont'd)

Phase Diagram for Water




http://ch302.cm.utexas.edu/svg302/phase-diagram-water.svg

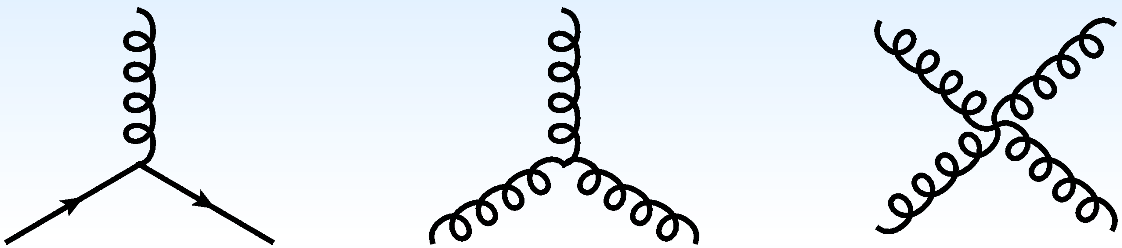
## High $T_c$ Superconductors




http://for538.wmi.badw-muenchen.de//projects/P4_crystal_growth/index.htm

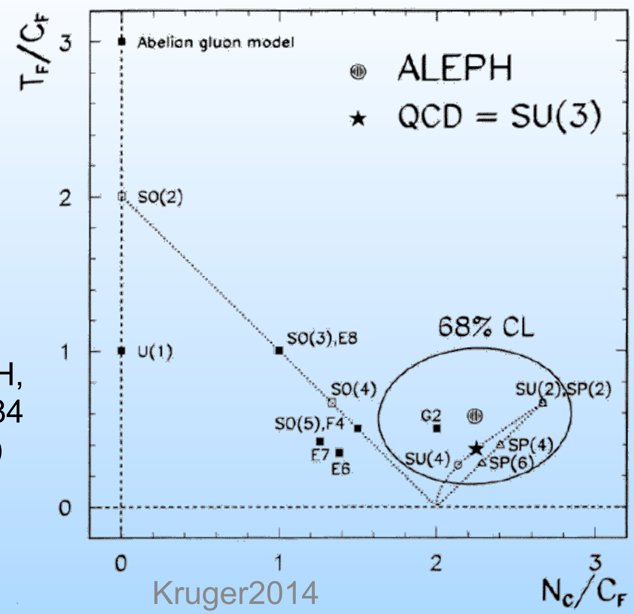
# QCD Particle Physics

- Lagr. known: $$\mathcal{L}_{QCD} = \sum_j \bar{\psi}_j \left(i \not{D} - m_j\right) \psi_j - \frac{1}{4} (F^a)^2$$
- QCD Vertices:



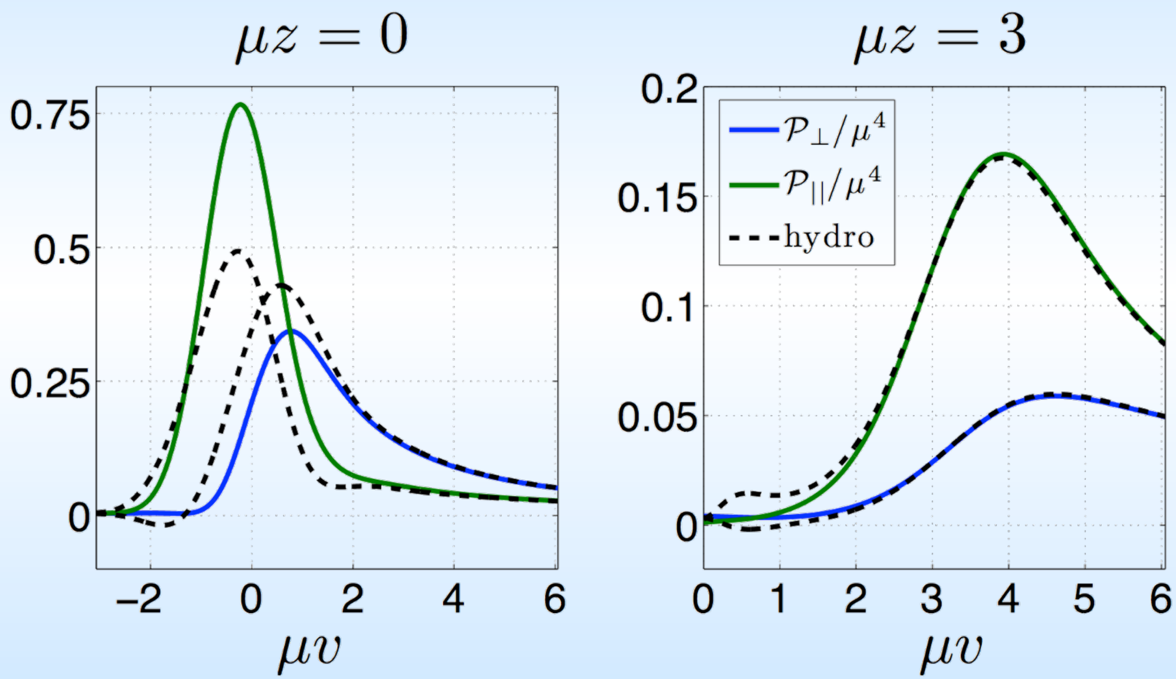
- Quantitative agreement w/ data

ALEPH, PLB284 (1992)



# Reminder of AdS Successes I

- Rapid Thermalization



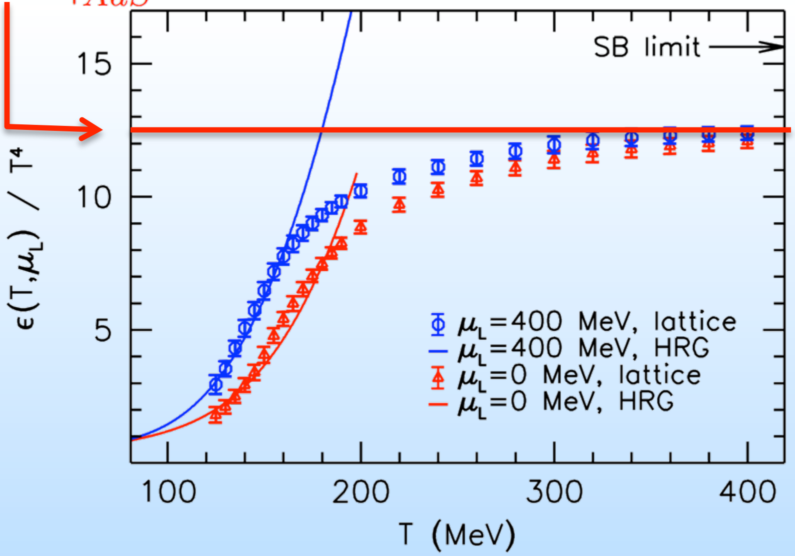

Chesler and Yaffe, PRL106 (2011)

– $\tau_{therm}$ ~ 0.35 fm

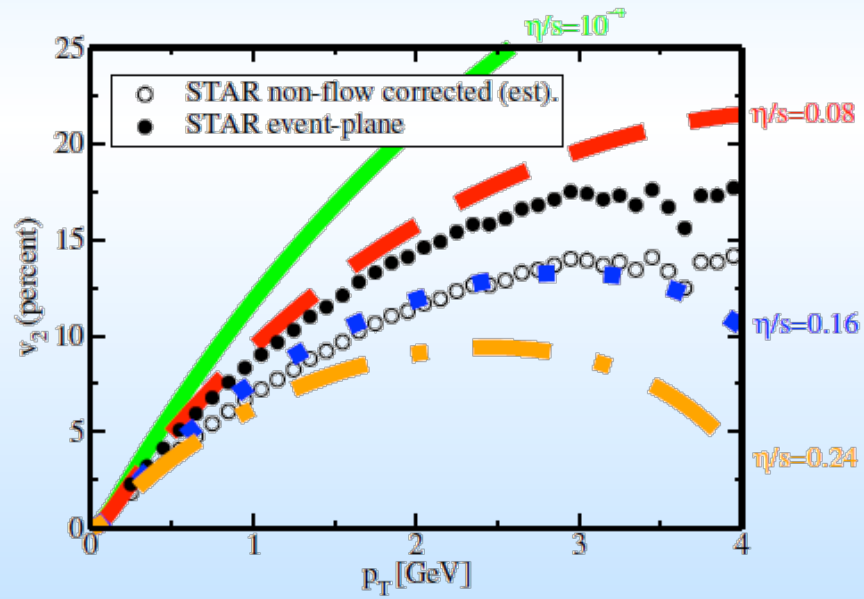
# Reminder of AdS Successes II

- Bulk Properties
  - Leading order results reproduce well:
    - Energy density, entropy, shear viscosity

$$\frac{\epsilon}{\epsilon_{SB}}\bigg|_{AdS} = \frac{3}{4} + \frac{1.69}{\lambda^{3/2}} + \dots$$




Wuppertal, arXiv:1204.6710




Luzum and Romatschke, PC78 (2008)