Energy Loss in the Context of the p/d-A Non-Null Control

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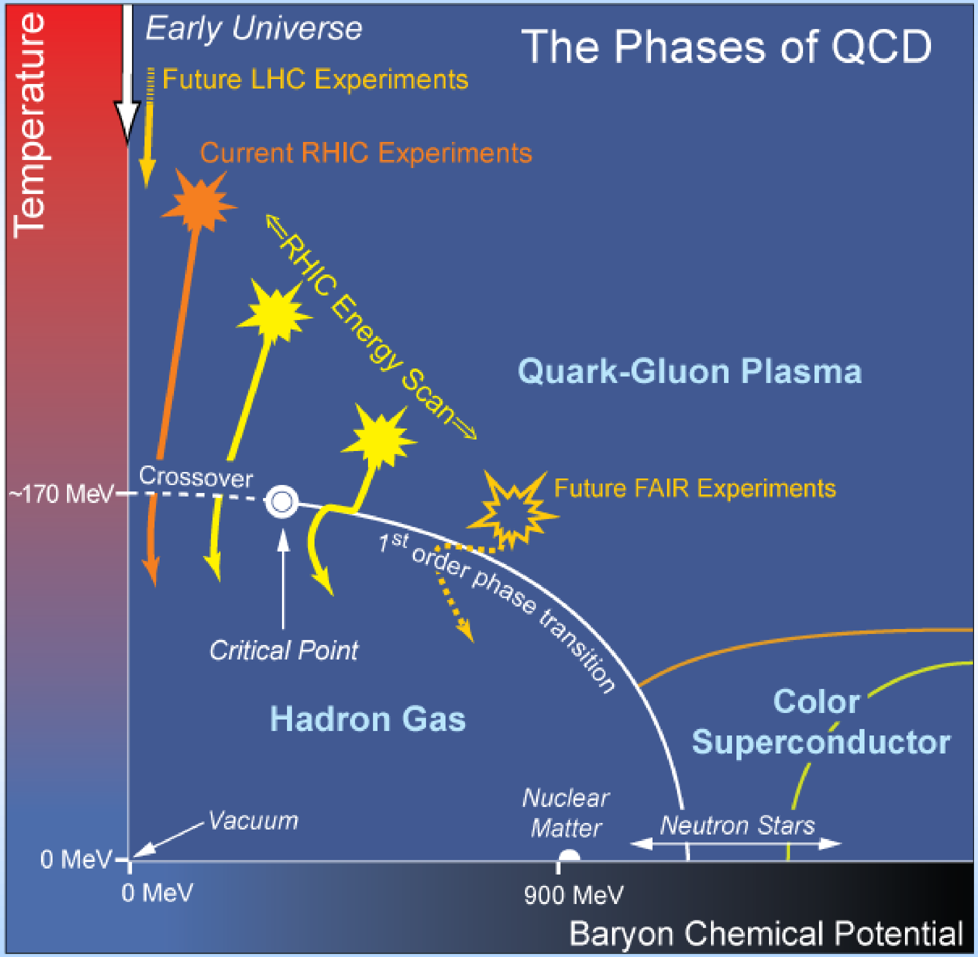
National Research Foundation

What Are We Interested In?

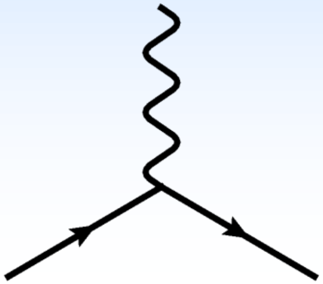
- Discover emergent, many-body physics of QGP through consistent theoretical description of experimental data



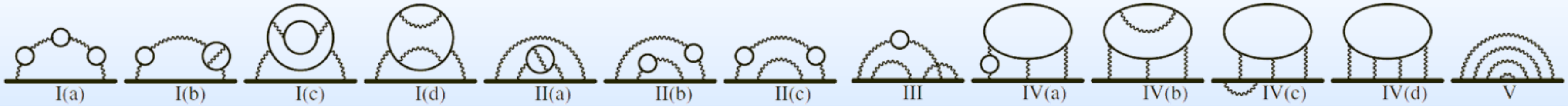
Long Range Plan, 2008

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)

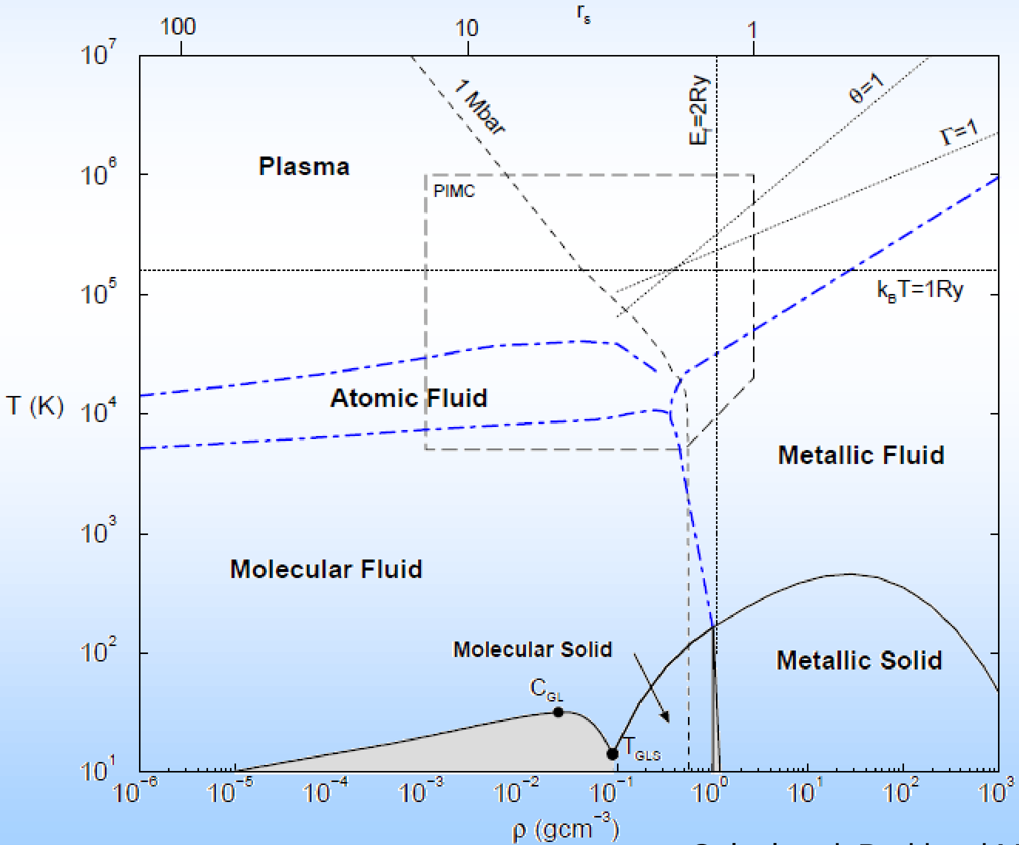
$$g/2 = 1.001\,159\,652\,180\,73(28) \quad [0.28 \text{ ppt}]$$

Hanneke, Fogwell, and Gabrielse, PRL100 (2008)

E&M Many Body Physics

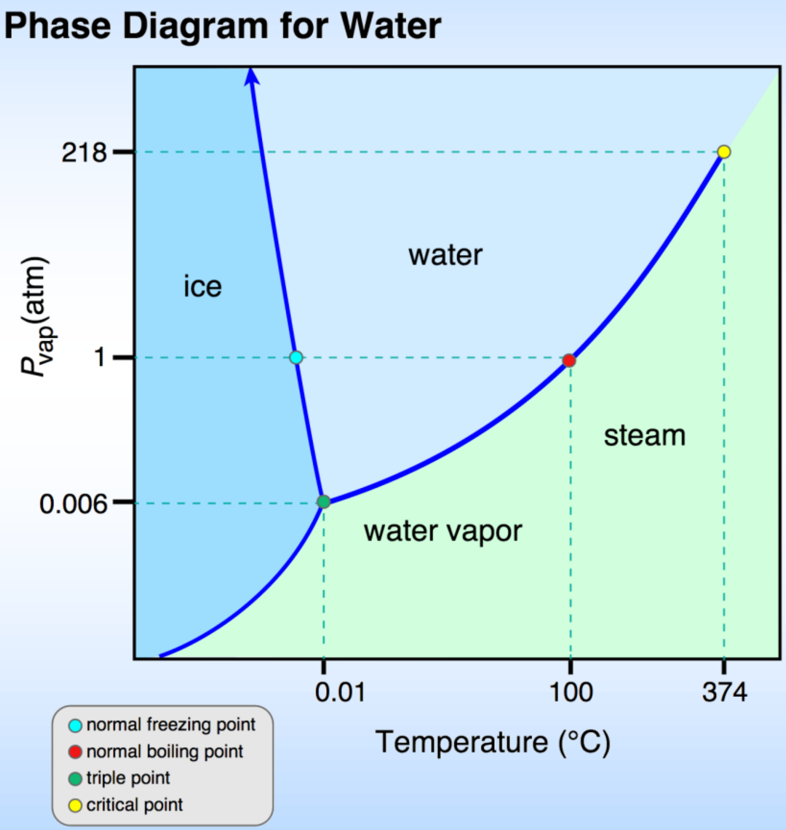
- Many body physics less well understood

Hydrogen Phase Diagram

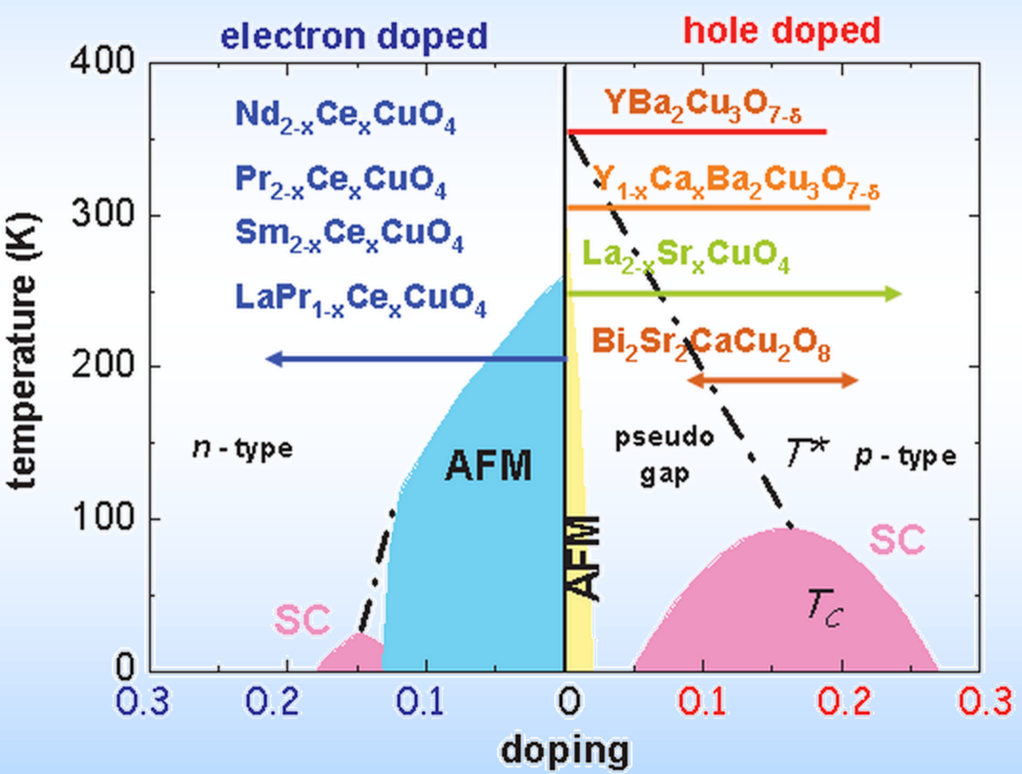


Calculated, Burkhard Militzer, 2000

E&M Many Body Physics (cont'd)



High T_c Superconductors

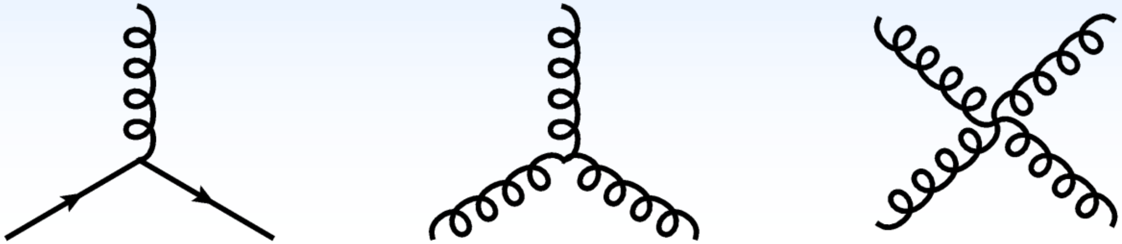


http://ch302.cm.utexas.edu/svg302/phase-diagram-water.svg

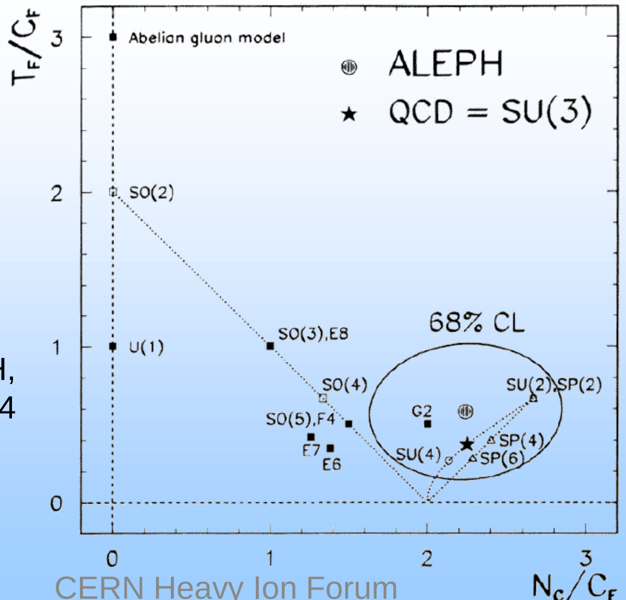
http://for538.wmi.badw-muenchen.de//projects/P4_crystal_growth/index.htm

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:



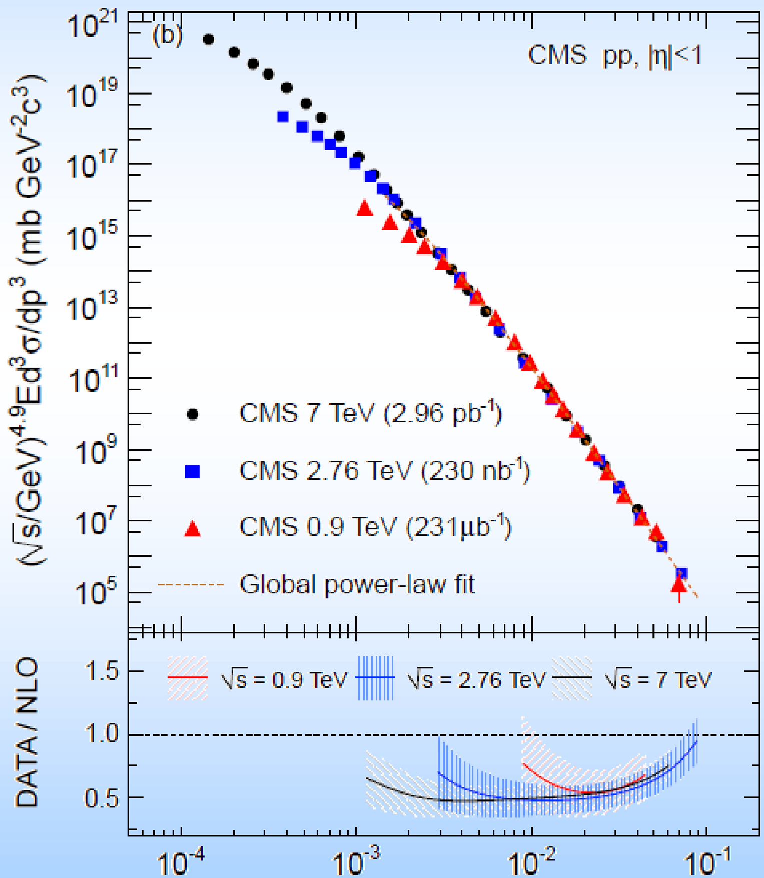
- Qualitative agreement w/ data



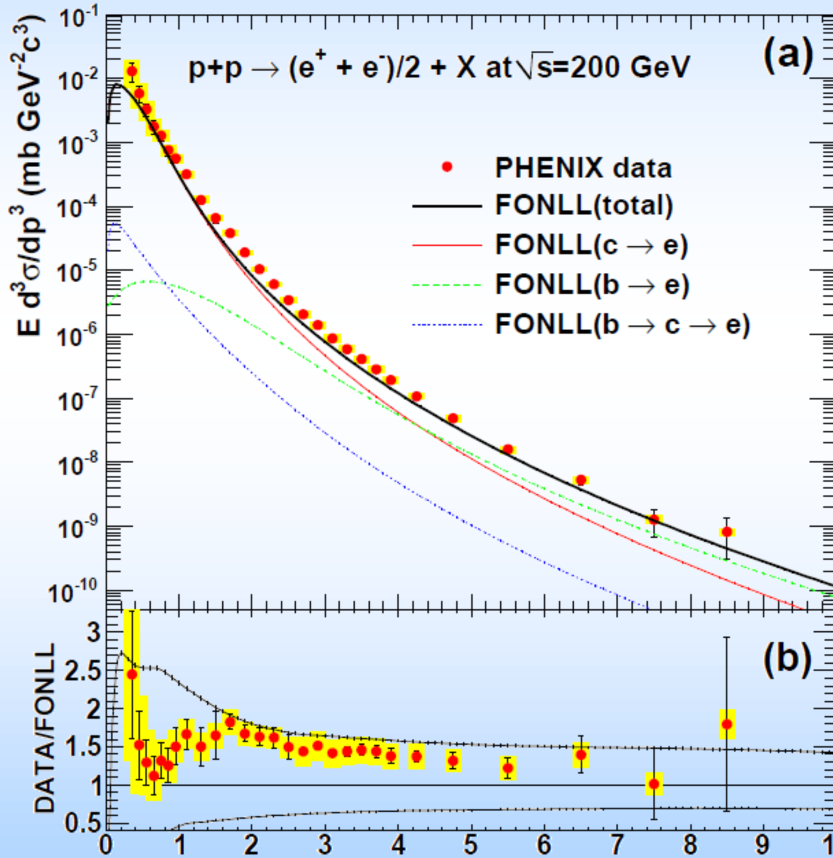
ALEPH, PLB284 (1992)

Quantitative QCD Particle Physics

- NLO pQCD in pp System ~ factor of 2

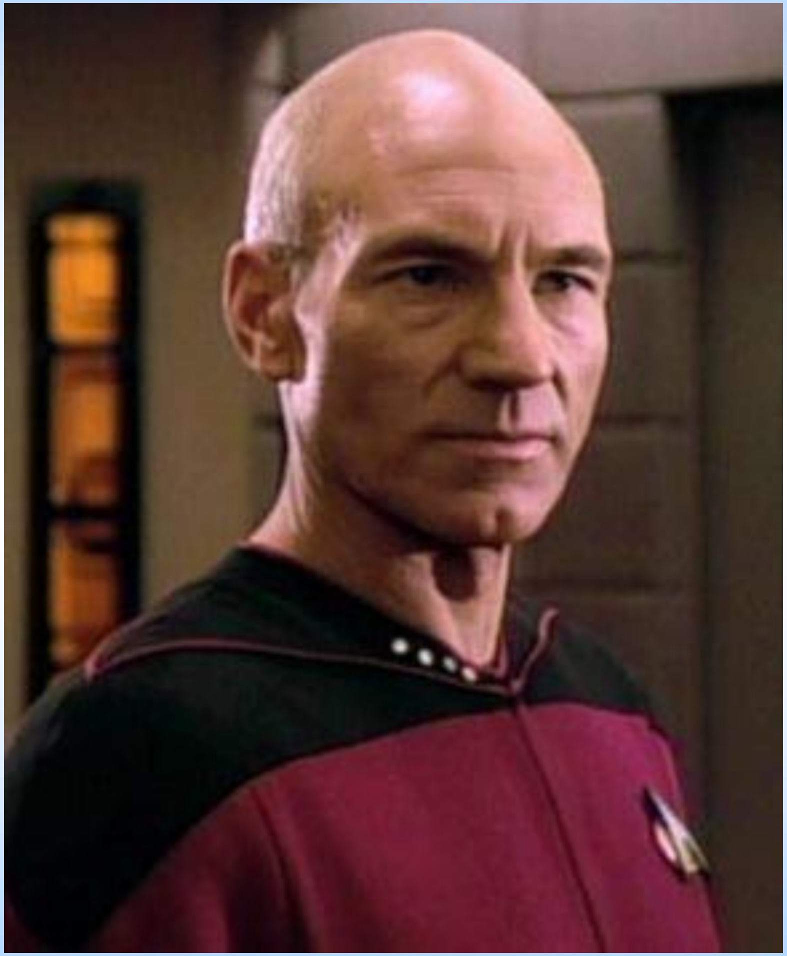


CMS, EurPhysJC72 (2012)



PHENIX, PRC84 (2011)

And so we boldly go…



(Thank you Google Image Search)

Hang on to your seats!

Worth Reviewing Some History

- ***Expect the Unexpected***
  - Before RHIC turned on

RHIC

Flow

- **Radial:**
  - Will (continue to) be a very large effect
  - Essential component to understanding spectra at RHIC.
- **Directed:**
  - Already small at SPS
  - Almost irrelevant at RHIC
- **Elliptic:**
  - Zero for truly central events (at any energy)
  - Is it
    - A necessary evil for understanding events with non-zero impact parameter?

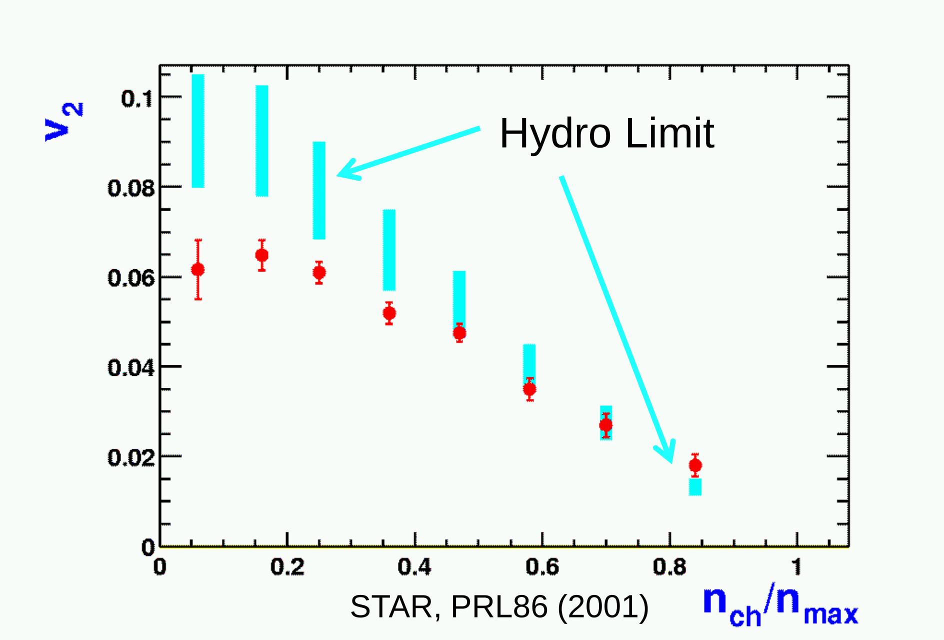
    Or
    - An essential tool to our understanding of EoS+(time evolution) of (non-isotropic) initial conditions?
  - My *prejudice:*
    Effects of elliptic flow will be small at RHIC

09-Jan-98 W.A. Zajc

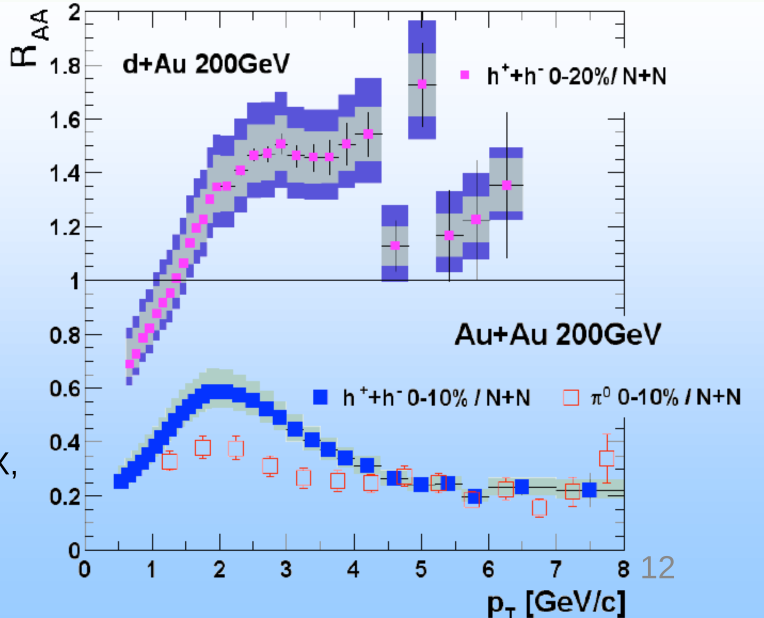
B Zajc, RHIC Winter Workshop at LBL (1998)

RHIC (Pre-)History

- Modesty to RHIC goals prior to turn on
  - “Create new form of matter”: QGP
- Early RHIC results
  - Nearly ideal hydro flow
    - Constituent quark scaling
  - Factor of 5 suppression at high-p_T
    - Null control $R_{dA} \sim 1$ and (later) γ R_{AA} => final state effect



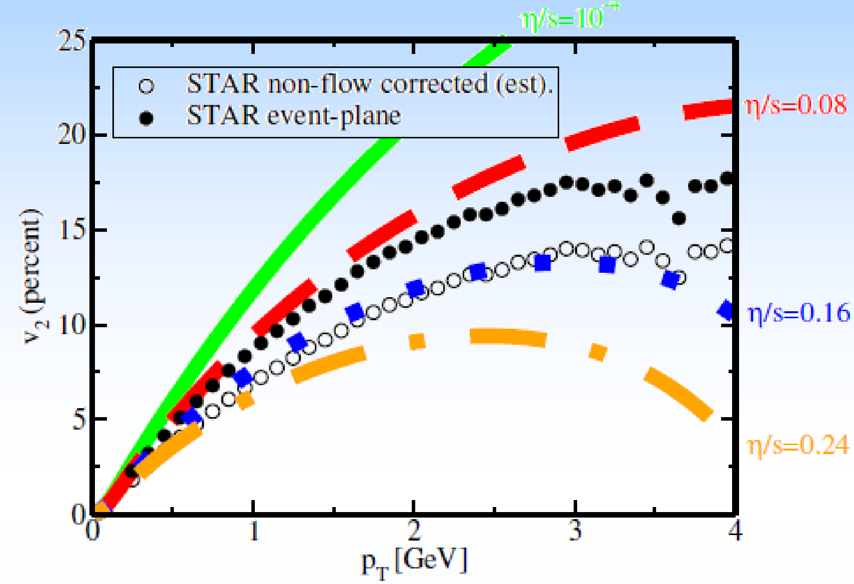
STAR, PRL86 (2001)



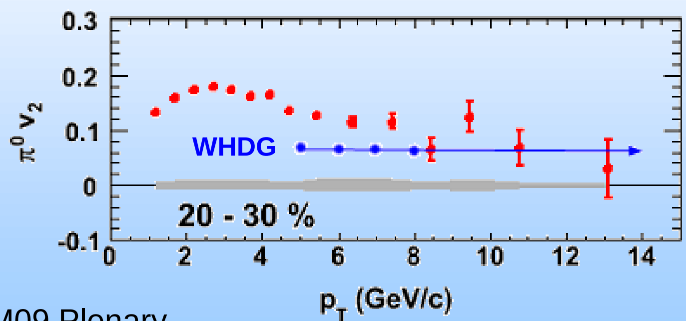
Johnson, for PHENIX, CAARI04

RHIC Continues

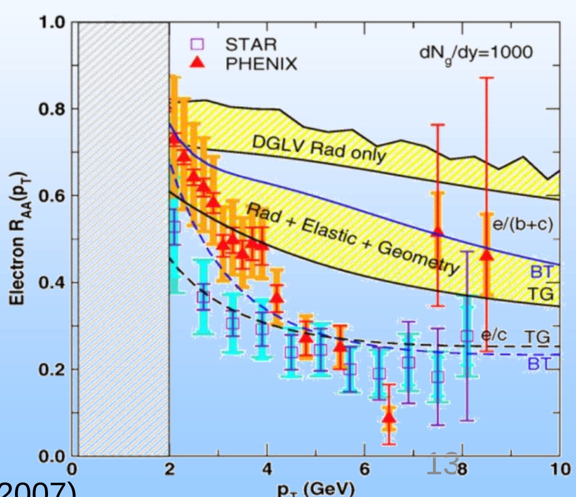
- After several years of RHIC running
  - Created “strongly-coupled fluid”: sQGP
    - Based on flow analysis, small extracted η/s
  - pQCD E-loss picture doesn’t quite hang together
    - v_2 too large
    - NPE R_{AA} too small



Luzum and Romatschke, Phys.Rev.C78:034915,2008



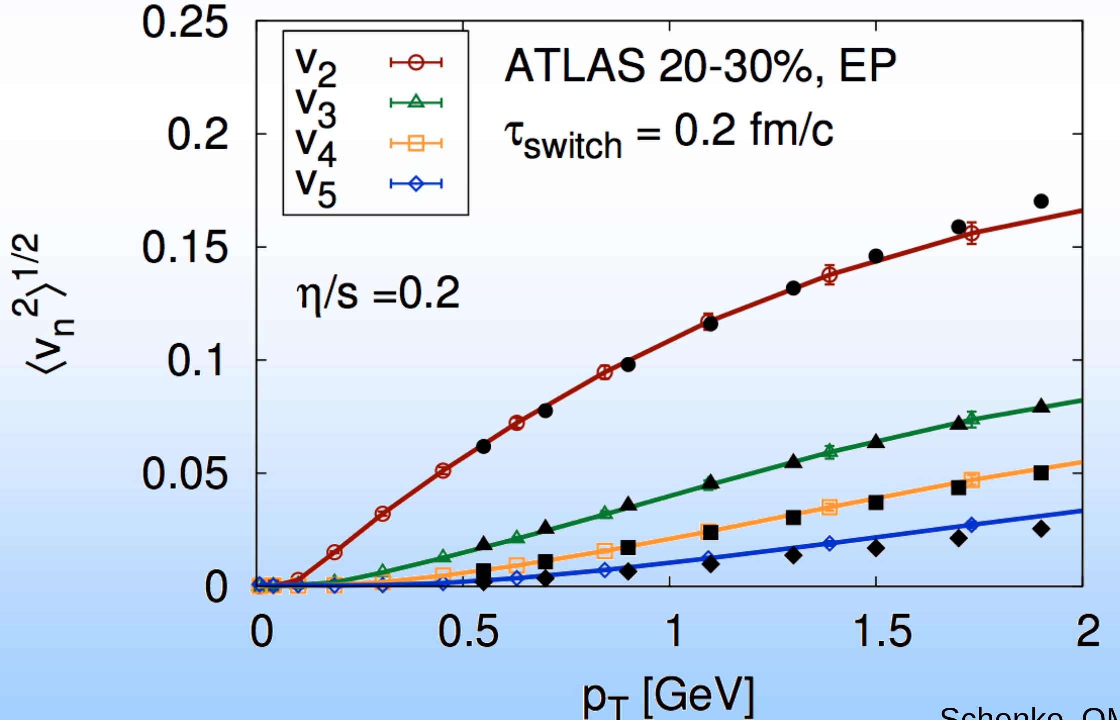
C. Vale, QM09 Plenary (analysis by R. Wei)



WHDG, NPA784 (2007)

LHC Turns On

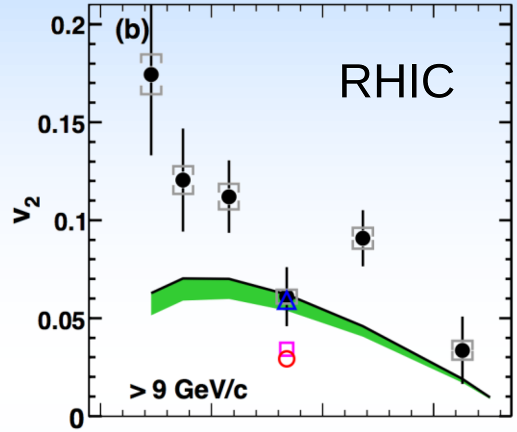
- Hydro story still consistent
  - v_n well described by nearly perfect fluid + fluctuating IS

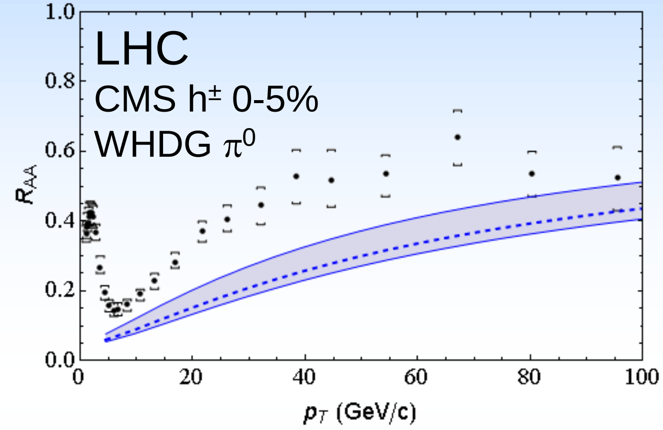


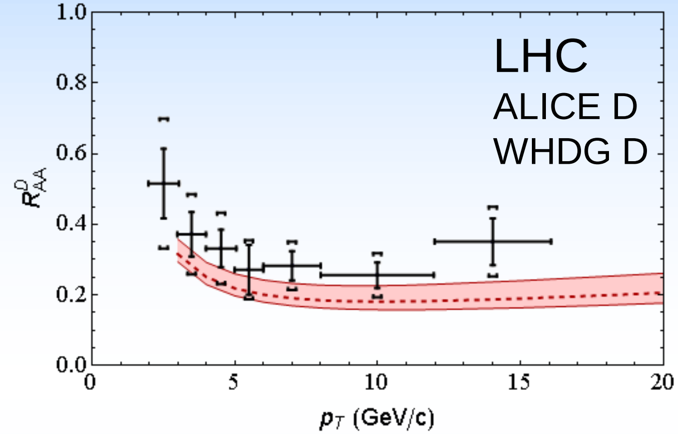
Schenke, QM2012

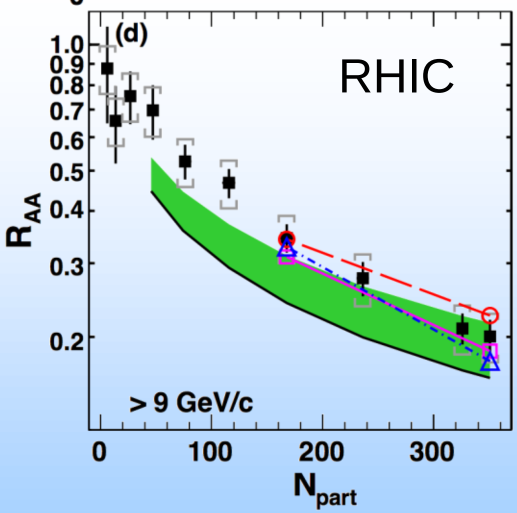
LHC is Hard

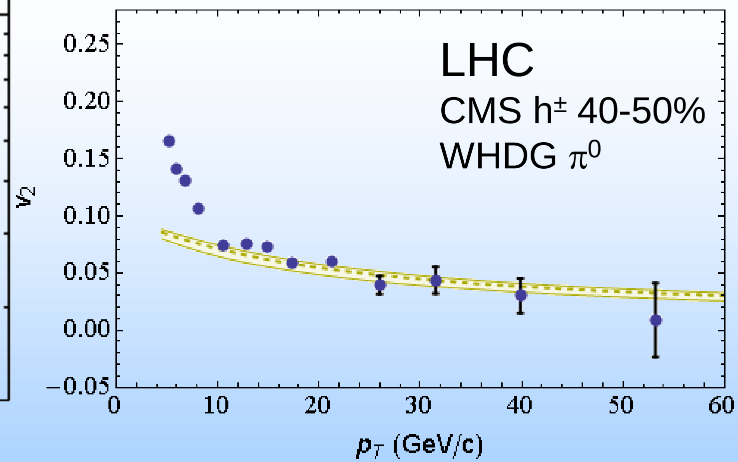
- pQCD E-loss makes more sense
  - Constrained by RHIC, LO pQCD predictions strikingly similar to LHC data

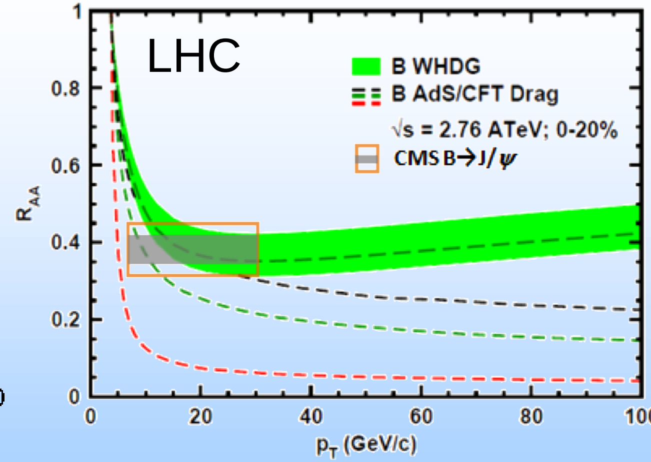












PHENIX PRL105 (2010)

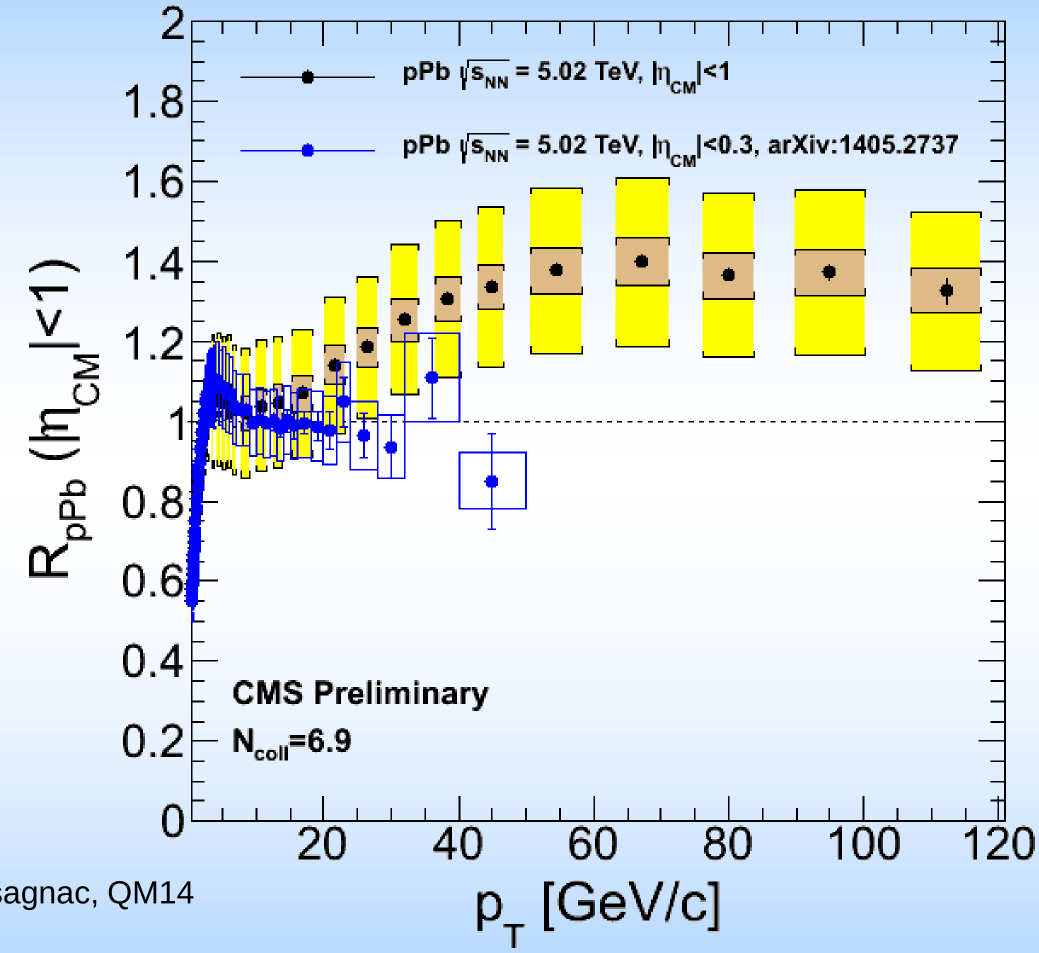
CMS, Eur.Phys.J. C72 (2012)
CMS, PRL109 (2012)

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

Prior to p + A

- Inconsistency btwn strong-coupling picture of hydro & weak-coupling picture of pQCD
  - Perhaps large Q^2 => pQCD at high-p_T
- Expect p + A to show:
  - Hydro turning off
  - $R_{pA} = 1$

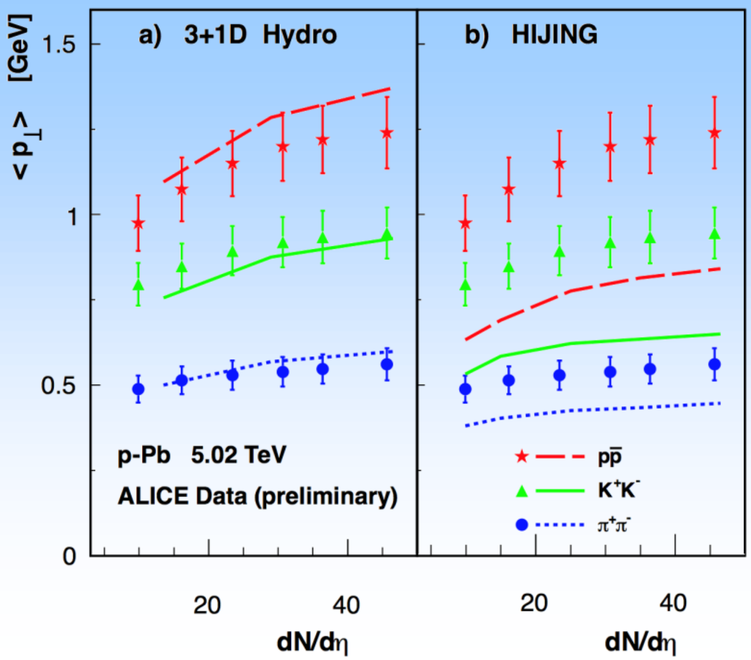
The Disaster in Pictures

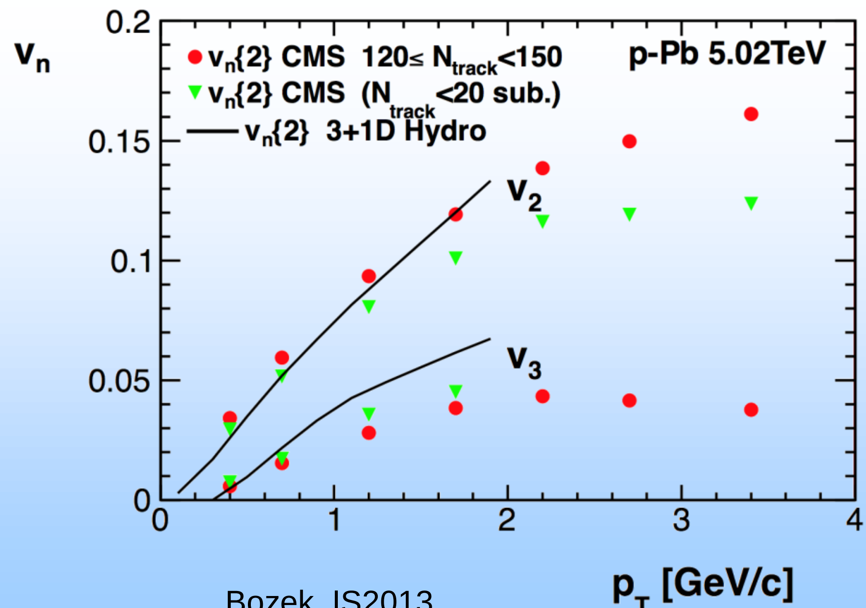


De Cassagnac, QM14

- ATLAS sees same enhancement as CMS

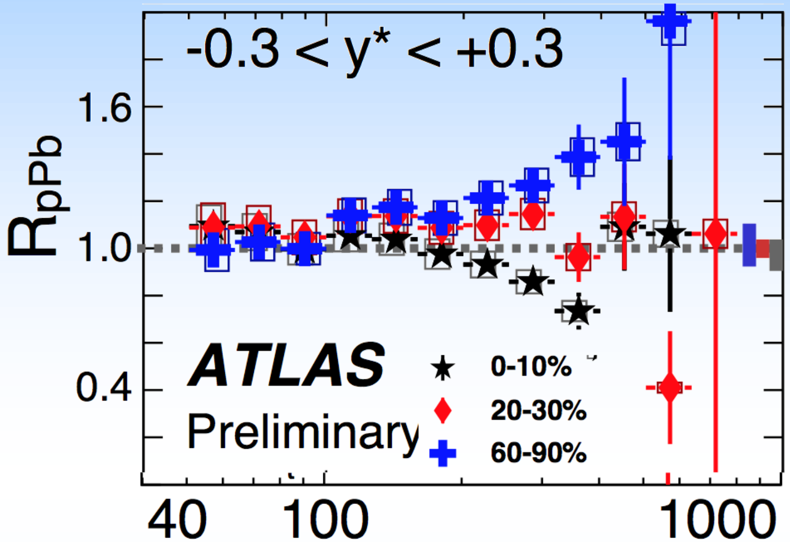
It’s a Tsunami

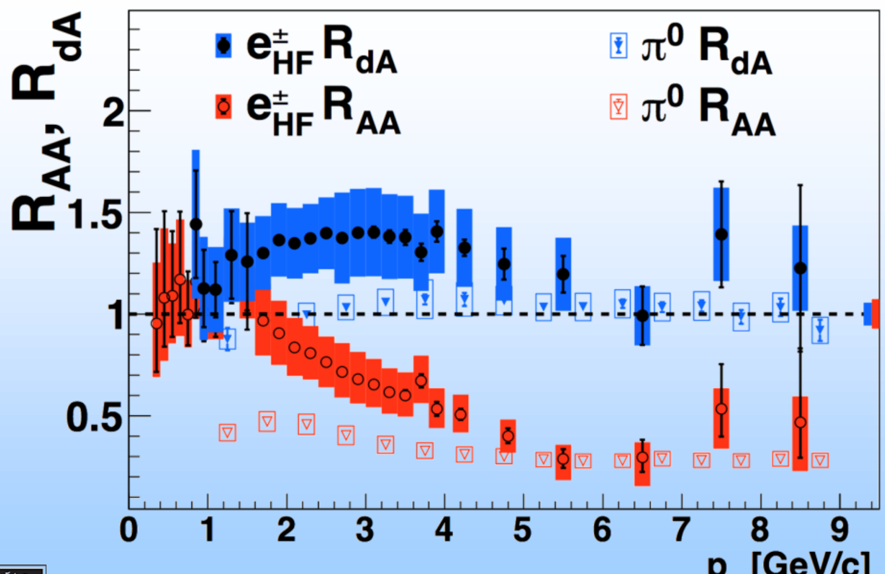




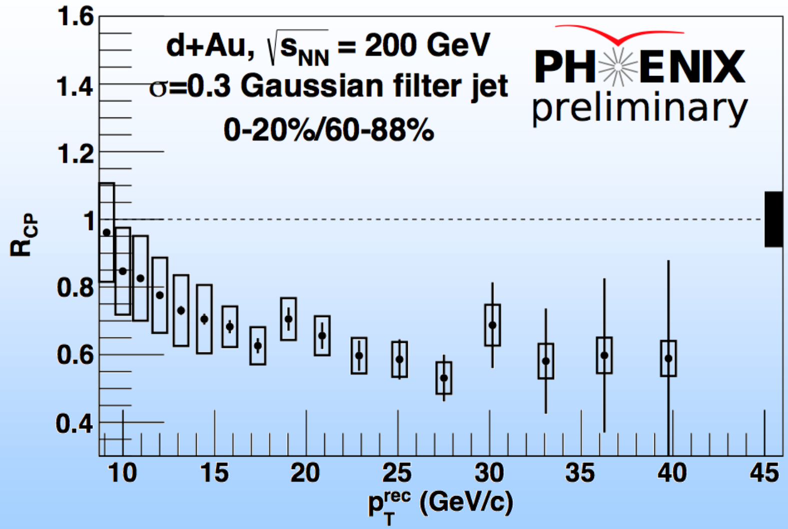
Bozek, IS2013,
arXiv:1401.2367

Even the Strong Come to Destroy



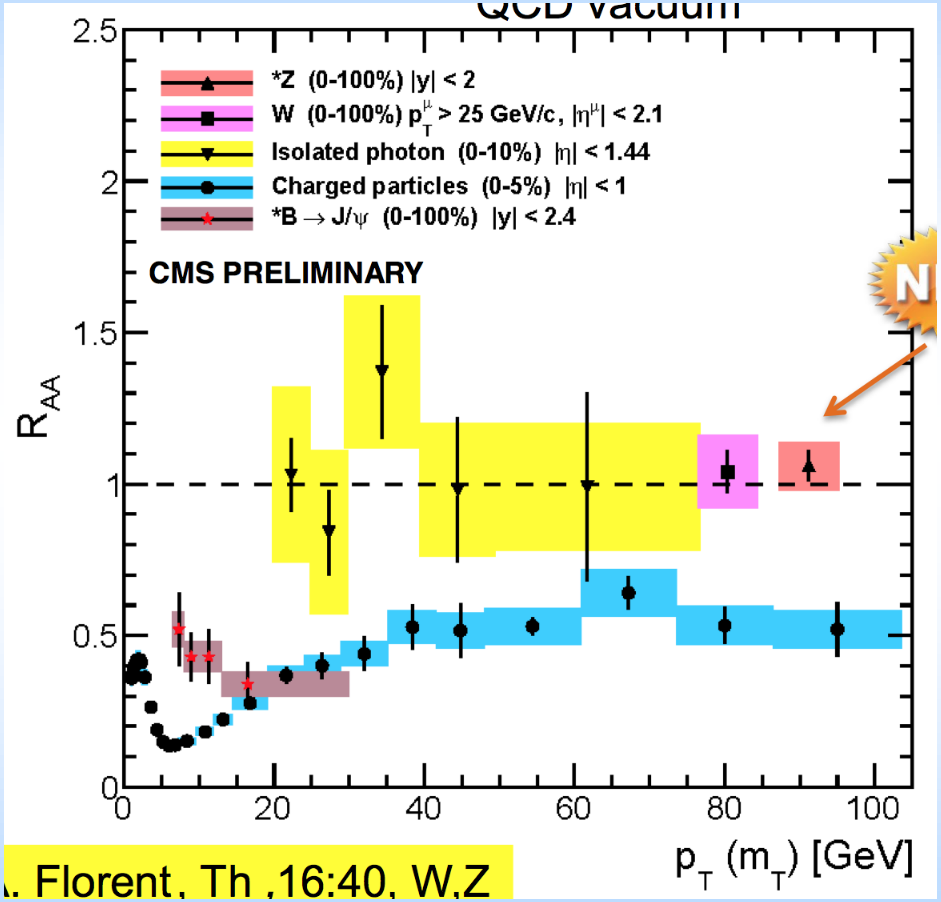


PHENIX, PRL109 (2012)



A Sickles, QM14

Option 1: Ignore

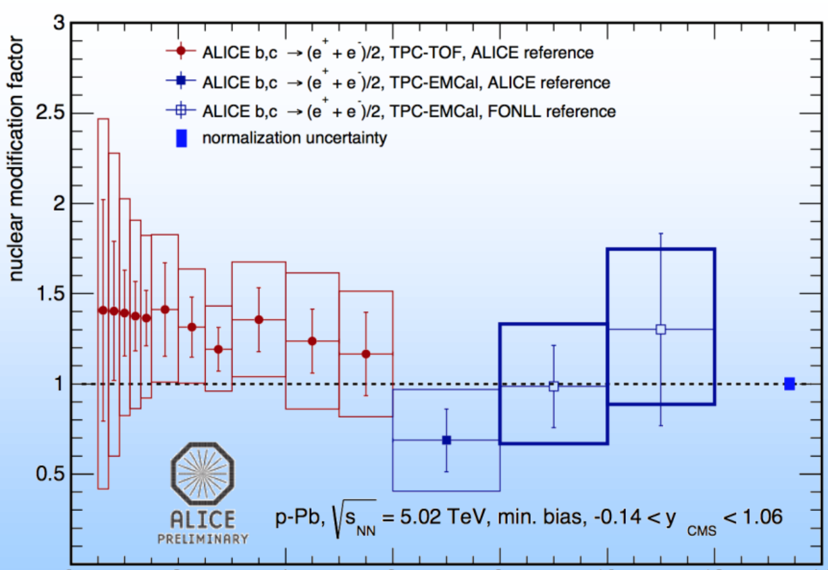


Velkovska, CMS Overview, HP13

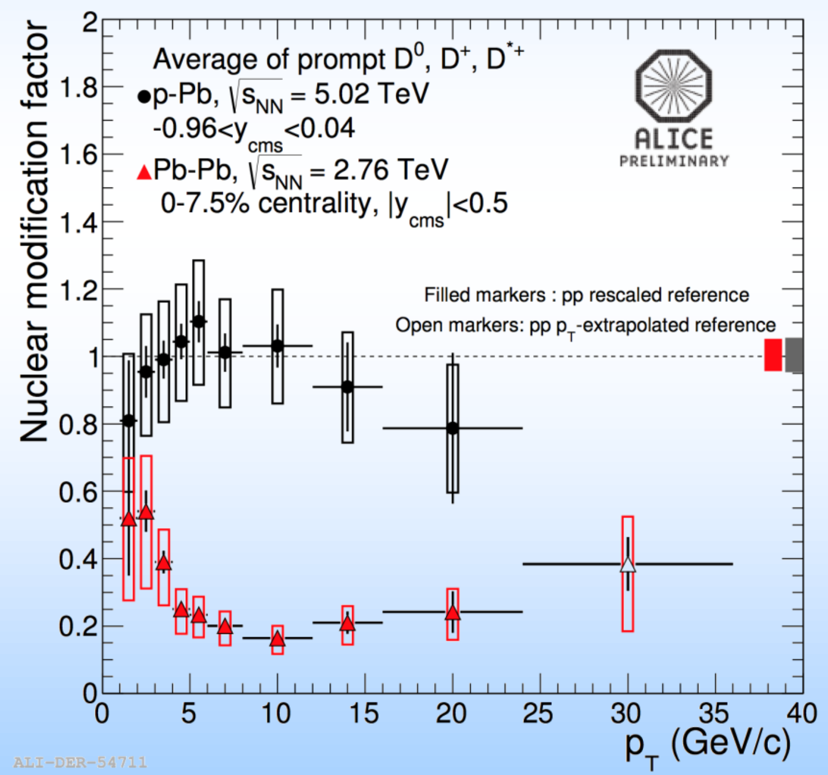
- Are $R_{p/dA}$ mysteries due to:
  - "Trivial" experimental issue (e.g. lack of baseline)?
    - Maybe for $h^{\pm}$:
      - Jet R_{pA} unmodified
      - Expect IS^2 in AA, but EW R_{AA} ~ 1 >> 0.5

Continue to Ignore

- Are $R_{p/dA}$ mysteries due to:
  - (Trivial) Bias?
    - Maybe jet $R_{pA}(N_{ch})$
  - What about HF?
    - No STAR data yet
    - ALICE: not clear; FF?



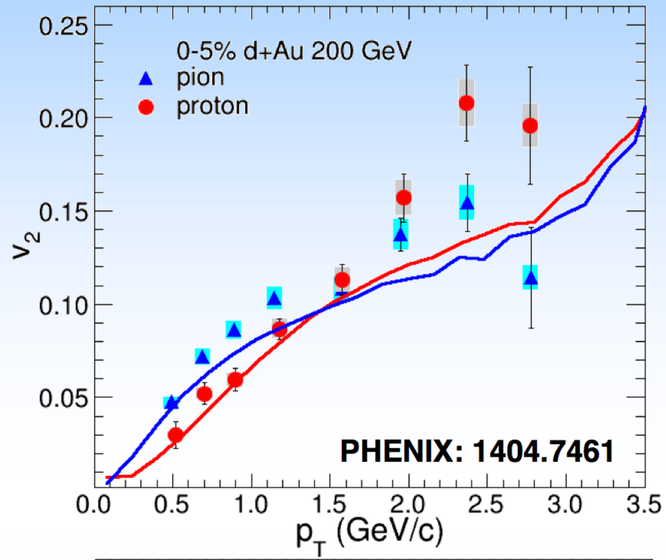
Pereira de Oliveira Filho for ALICE, HP2013, arXiv:1404.3983

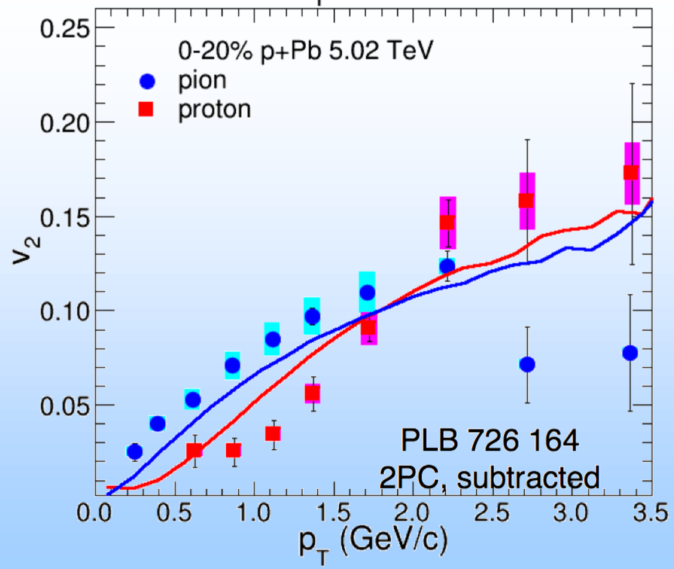


Wilkinson for ALICE, 9th High-p_T at LHC Workshop, arXiv:1402.3124

We Must Face Reality

- Too much to ignore?
- Are $R_{p/dA}$ mysteries due to:
  - – Large, currently uncontrolled, IS effects?
- What about hydro?
  - – Are 0-20% p + A collisions really large enough for hydro to work?
    - How big is the system?
      - – Big enough for energy loss? High-p_T measurements?
- Must understand p + A before making A + A claims
  - – Or p+p…





A Sickles, QM14

The Pivot

- Aim was to convince us that p + A => strong coupling
  - I'm not entirely persuaded
- If I were to bet:
  - $h^{\pm}$ R_{pA} will go away
  - Jet R_{pA} explained by bias induced by mult.
  - e^{-} $R_{p/dA}$ harder: IS? FF not well understood?

Two Common Theoretical Descriptions

- Weak Coupling
  - Assume $\alpha_s << 1$
  - Use pQCD
  - Appears:
    - consistent with high-p_T obs
      - Simultaneous description of: R_{AA}, v_2, light & heavy flavors, RHIC & LHC
    - inconsistent with low-p_T obs
      - Rapid thermalization, η/s

- Strong Coupling
  - Assume $\lambda >> 1$
    - $\lambda = (g^2 N_c)^{1/2}$
  - Use AdS/CFT
  - Appears:
    - consistent with low-p_T obs
      - Rapid thermalization, η/s
    - inconsistent with high-p_T obs
      - Simultaneous description of: R_{AA}, v_2, light & heavy flavors, RHIC & LHC

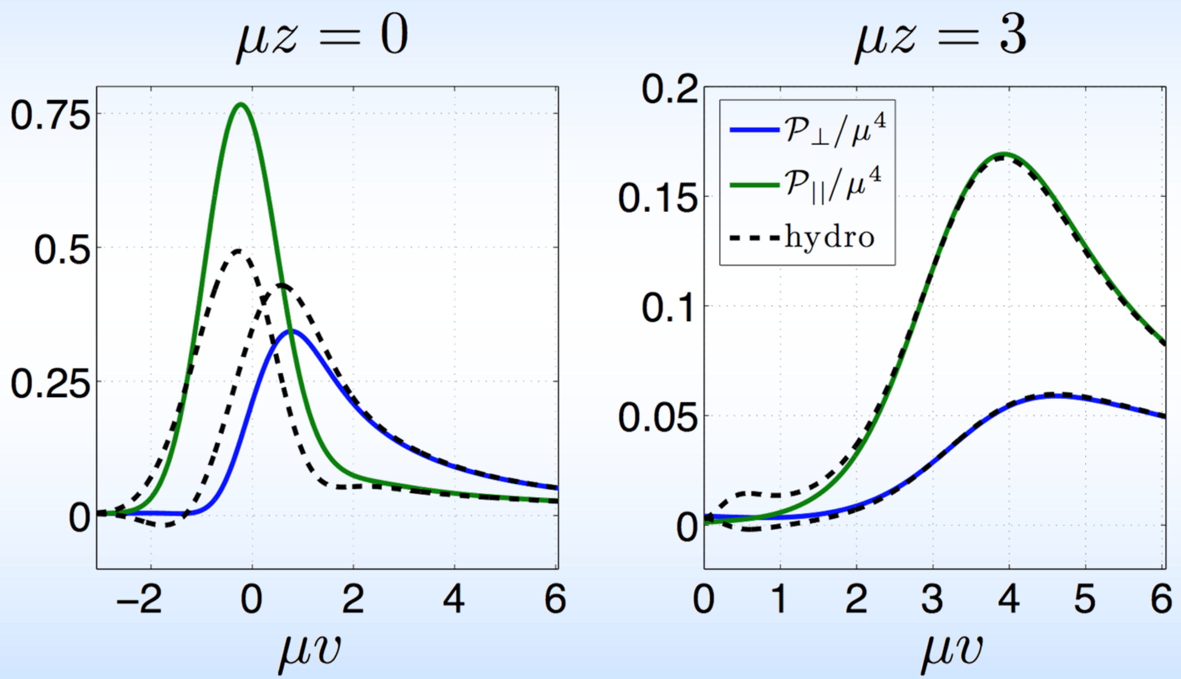
Look for picture of QGP properties consistent with ***all*** data

Towards Consistency

- Two alternatives. Seek:
  - Novel weak-coupling physics for low-p_T
  - New strong-coupling physics for high-p_T
- Today follow the latter
  - More correct description for light flavors
  - Include higher order effects for heavy flavors
- NB: higher orders necessary for a quantitatively consistent pQCD explanation of high-p_T

Reminder of AdS Successes I

- Rapid Thermalization



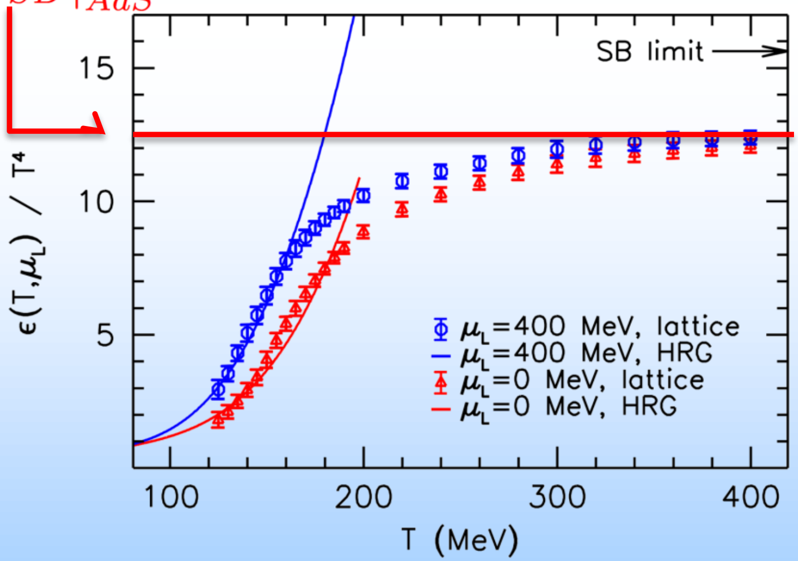
Chesler and Yaffe, PRL106 (2011)

– τ_{therm} ~ 0.35 fm

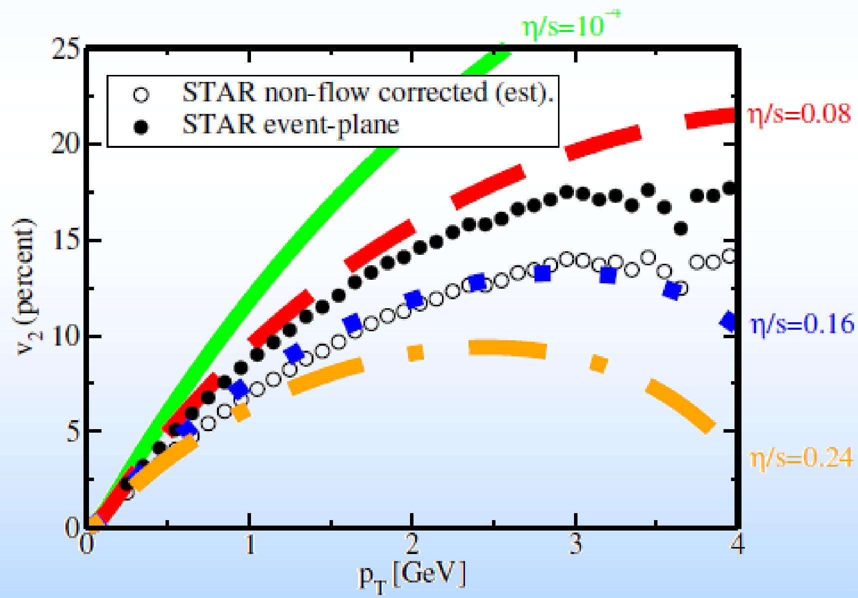
Reminder of AdS Successes II

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

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



Wuppertal, arXiv:1204.6710



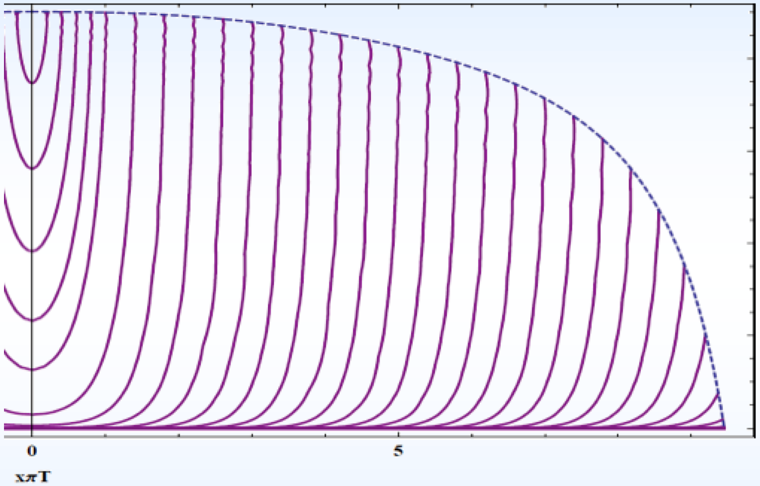
Luzum and Romatschke, PC78 (2008)

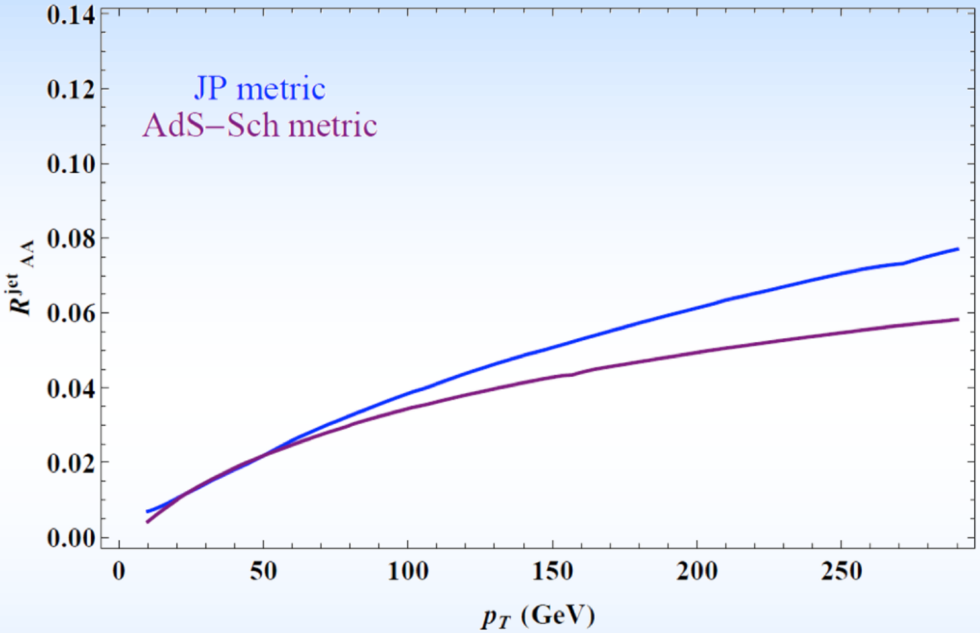
Why AdS at High-p_T?

- Perturbatively, 3 couplings for rad E-loss
  - Not known at which scale(s) couplings run
- $T_{QGP} \sim \Lambda_{QCD} \Rightarrow g(2\pi T) \sim 2$
  - 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

“Simple” LO AdS for Light High-p_T

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





R Morad and WAH, *in prep*

- Thermalization time very short
  - R_{AA} currently from v. naïve geom model
- In AdS setup, probe & gluon cloud indistinguishable from medium
  - Only makes sense to compare to ***jets***, not single particles

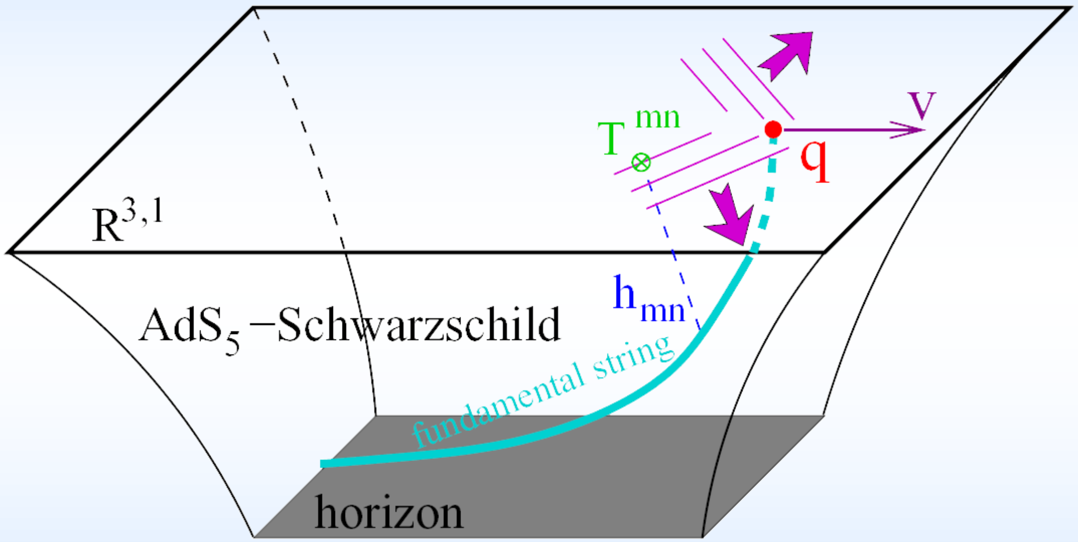
"Simple" LO AdS for Heavy High-p_T

- 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

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

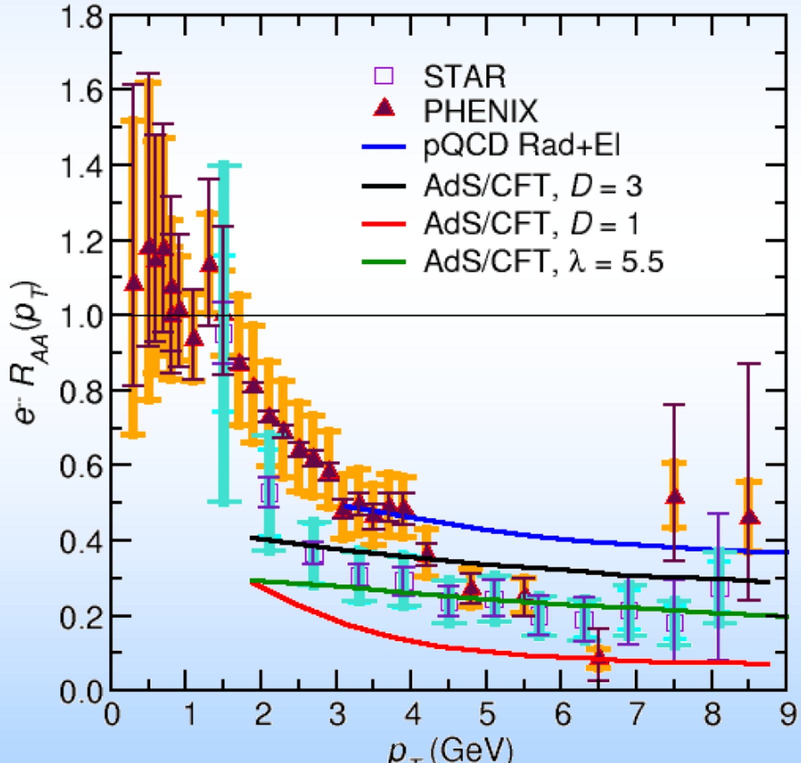
Very different from usual pQCD and LPM

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

AdS HQ Compared to Data

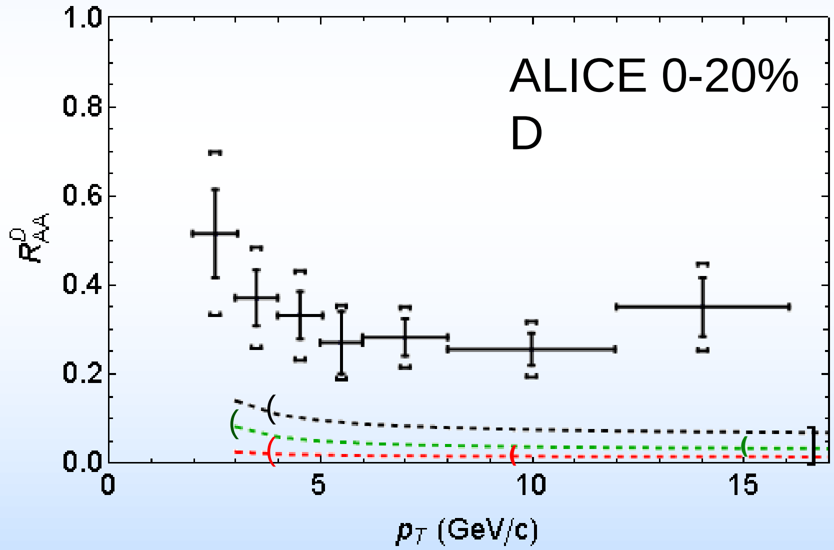
- Constrained by RHIC, oversuppresses LHC

RHIC



WAH, PhD Thesis, arXiv:1011.4316

LHC



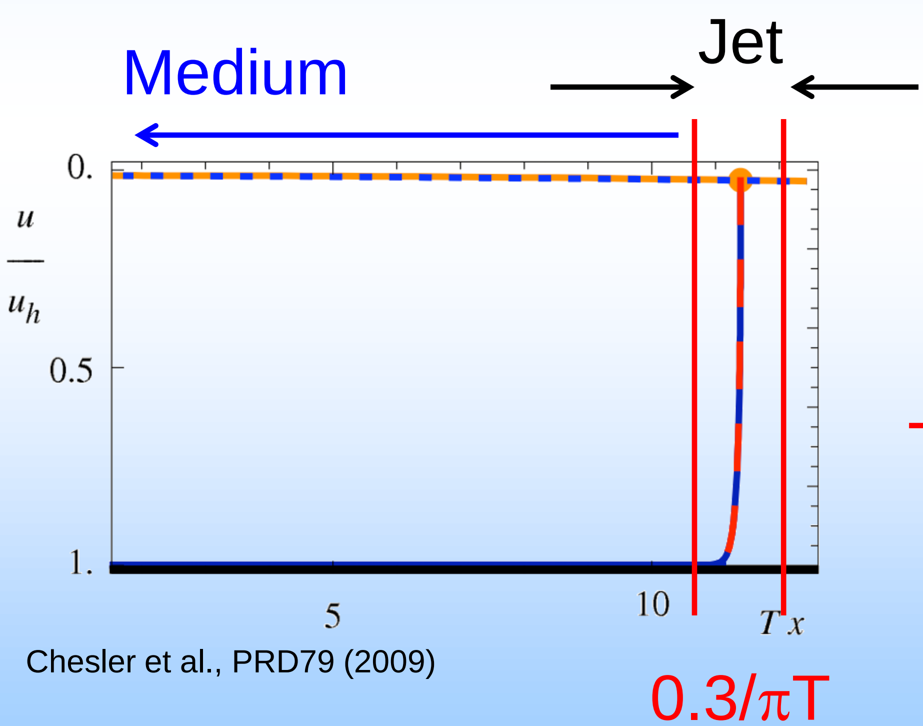
WAH, PANIC11 (arXiv:1108.5876)
ALICE, JHEP 1209 (2012)

Missing Physics?

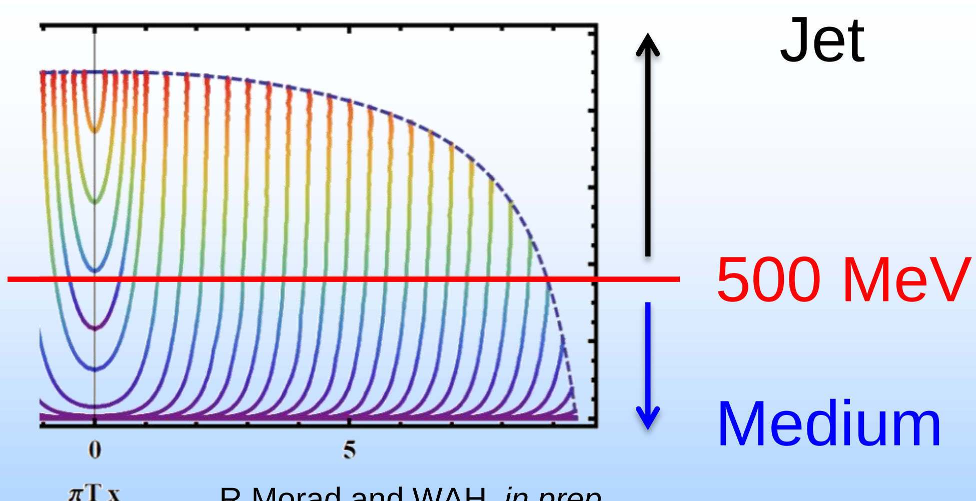
- Lights:
  - Is jet prescription correct?
    - See R Morad poster
  - Are IC reasonable?
    - See B Meiring poster
- Heavies:
  - Within limits of calculation?
  - Higher order corrections?

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



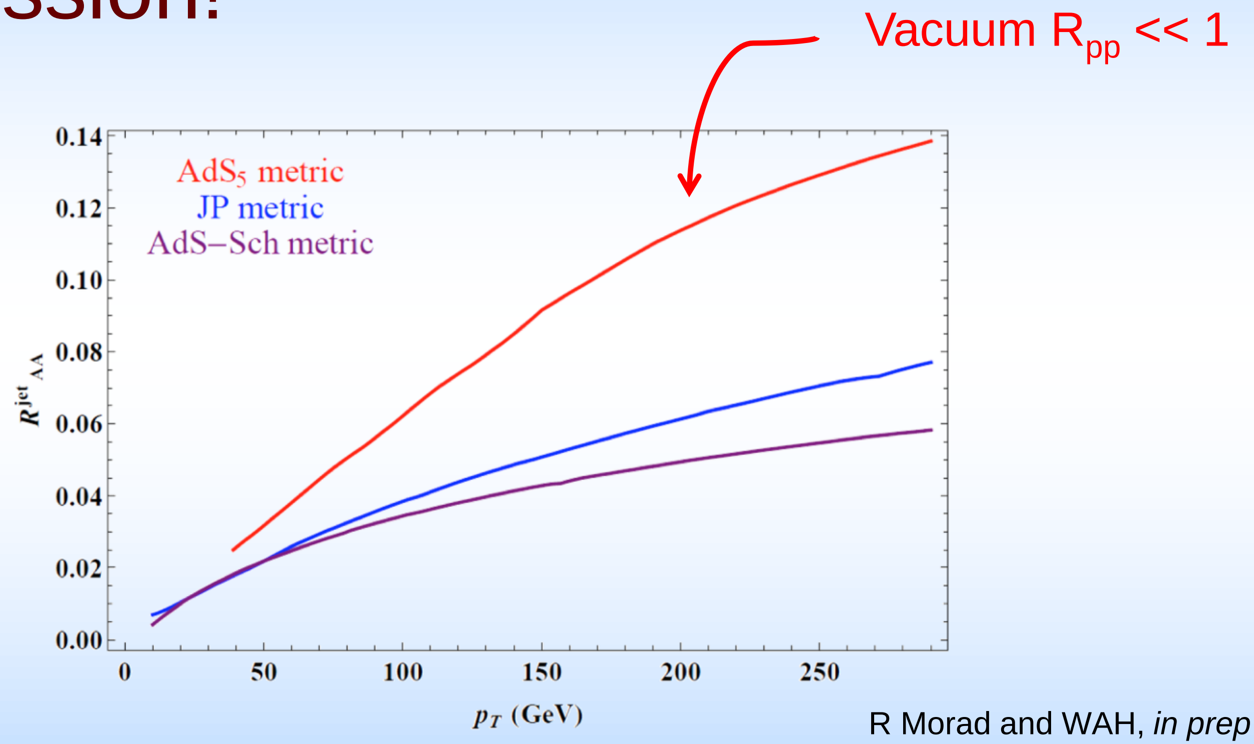
Chesler et al., PRD79 (2009)



R Morad and WAH, *in prep*

AdS: No-nucleus Suppression

- Original proposed IC => anomalous vacuum suppression!

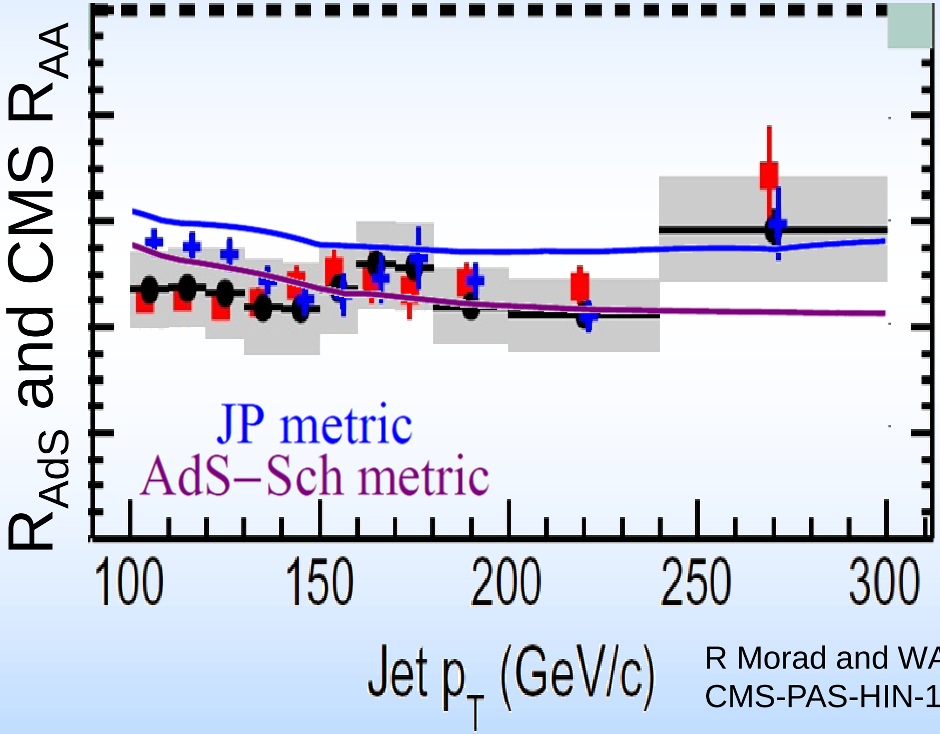


R Morad and WAH, *in prep*

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

AdS: Tantalizing Renormalization

- Can we capture diff. btwn. naïve AdS pp & AA?
  - Define renormalized R_{AdS} = "R_{AA} / R_{pp}"; cf CMS

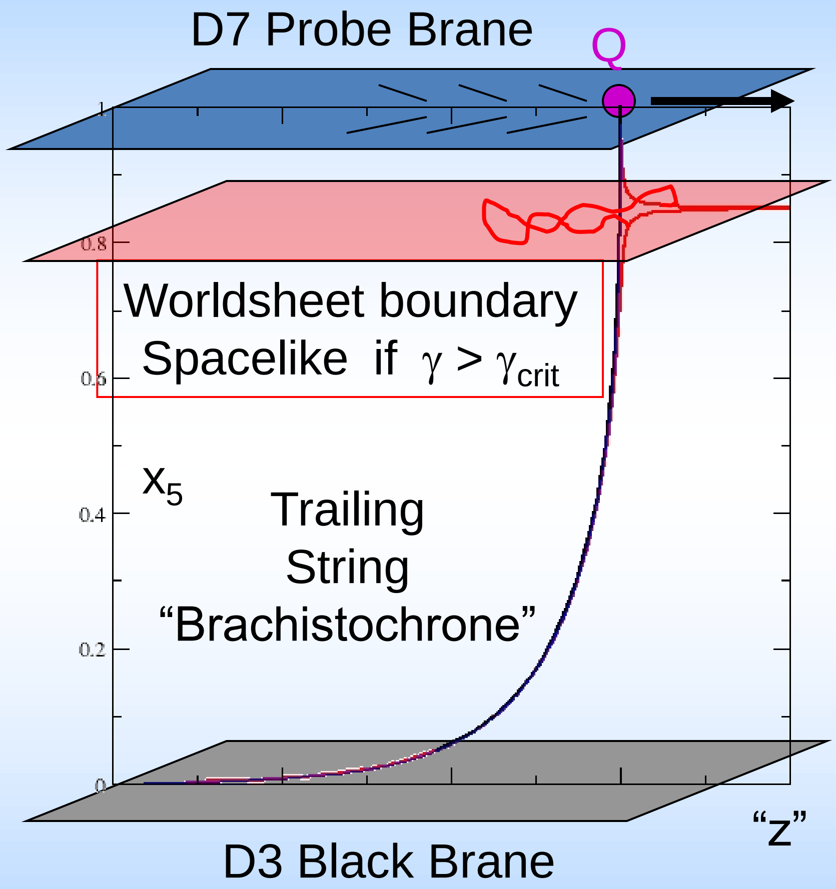


R Morad and WAH, *in prep*
CMS-PAS-HIN-12-004

  - Current/future work: hybrid model
    - use pQCD until τ_0, then evolve using AdS

Limits on Heavy Flavor AdS Setup

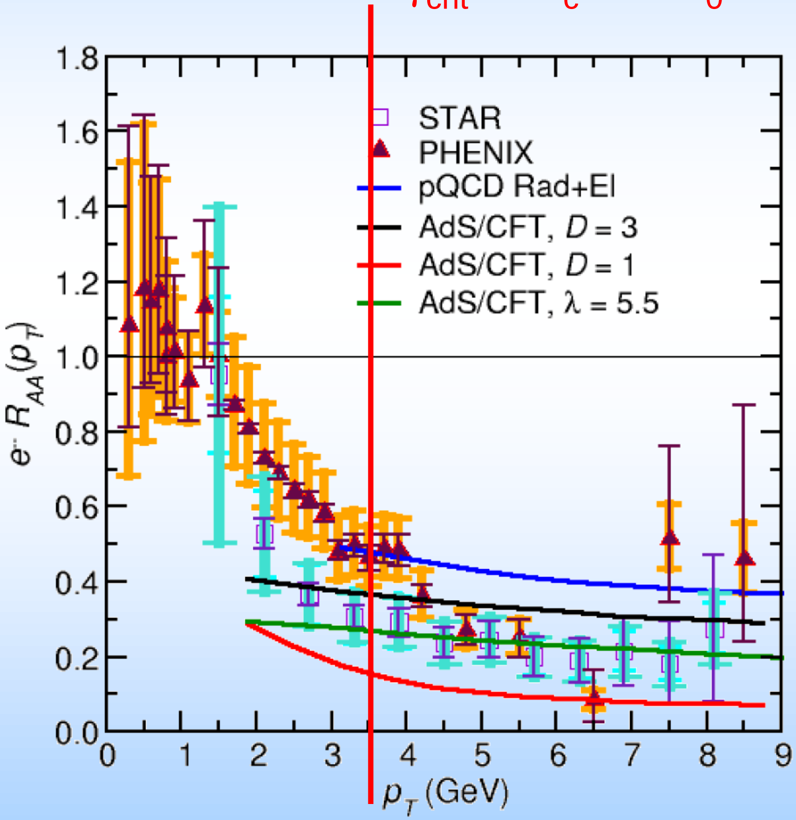
- For LO AdS:
  - Space-like quark endpoint
    - $\gamma_{crit} = (1 + 2M_q/\lambda^{1/2}\, T)^2$
      $\sim 4M_q^2/(\lambda T^2)$
  - Mom. Loss Fluctuations
    - $\gamma_{crit} = M_q^2/(4T^2)$
- Speed limit from fluct parametrically larger, but numerically smaller



HQ p_T Limits

RHIC

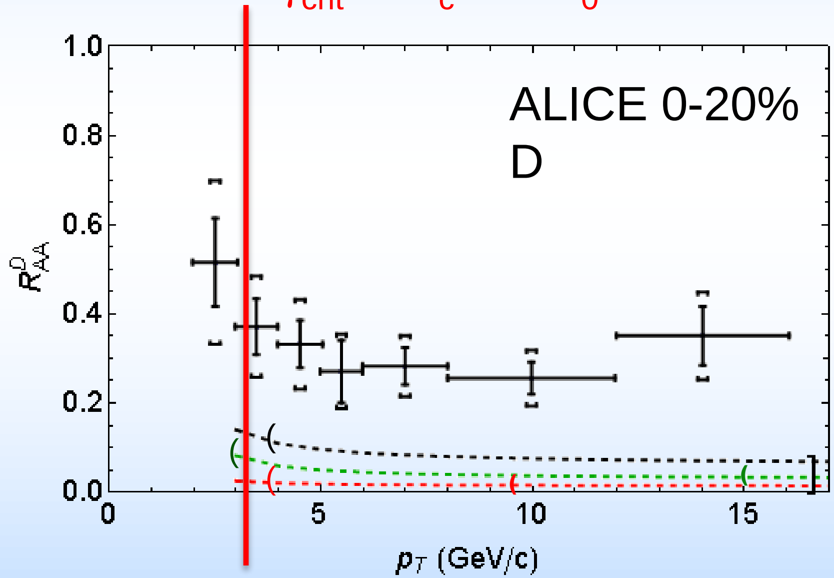
$\gamma_{crit} = M_c^2 / 4\ T_0^2 \sim 3 – 4$ GeV/c



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

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

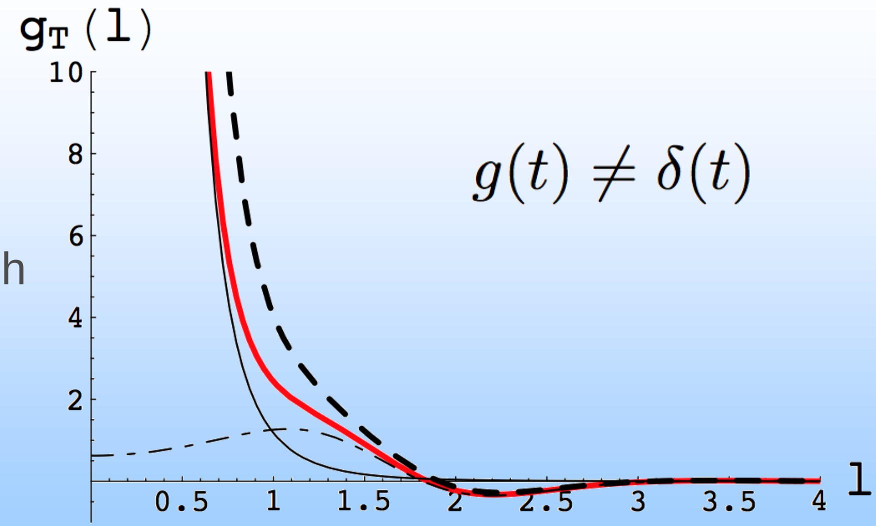
$$\langle F_i^L(t_1) F_j^L(t_2)\rangle = \kappa_L\, \hat{p}_i \hat{p}_j\, g(t_1 - t_2)$$

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

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

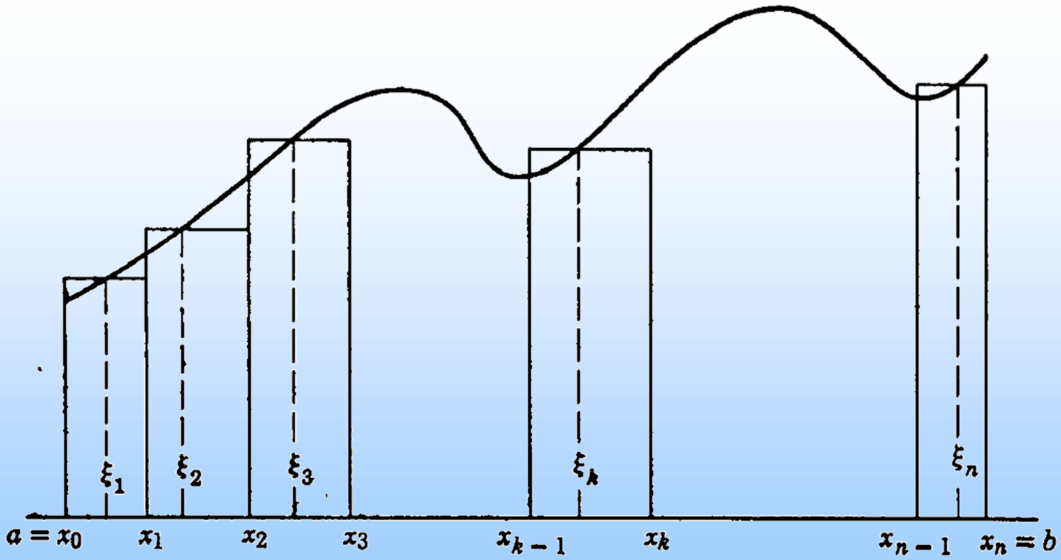
Gubser, NPB790 (2008)

- Obeys Einstein's relations *only* at v = 0 ($\kappa_{FD} = \pi T^3 \gamma (g^2 N_c)^{1/2}$)
- 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



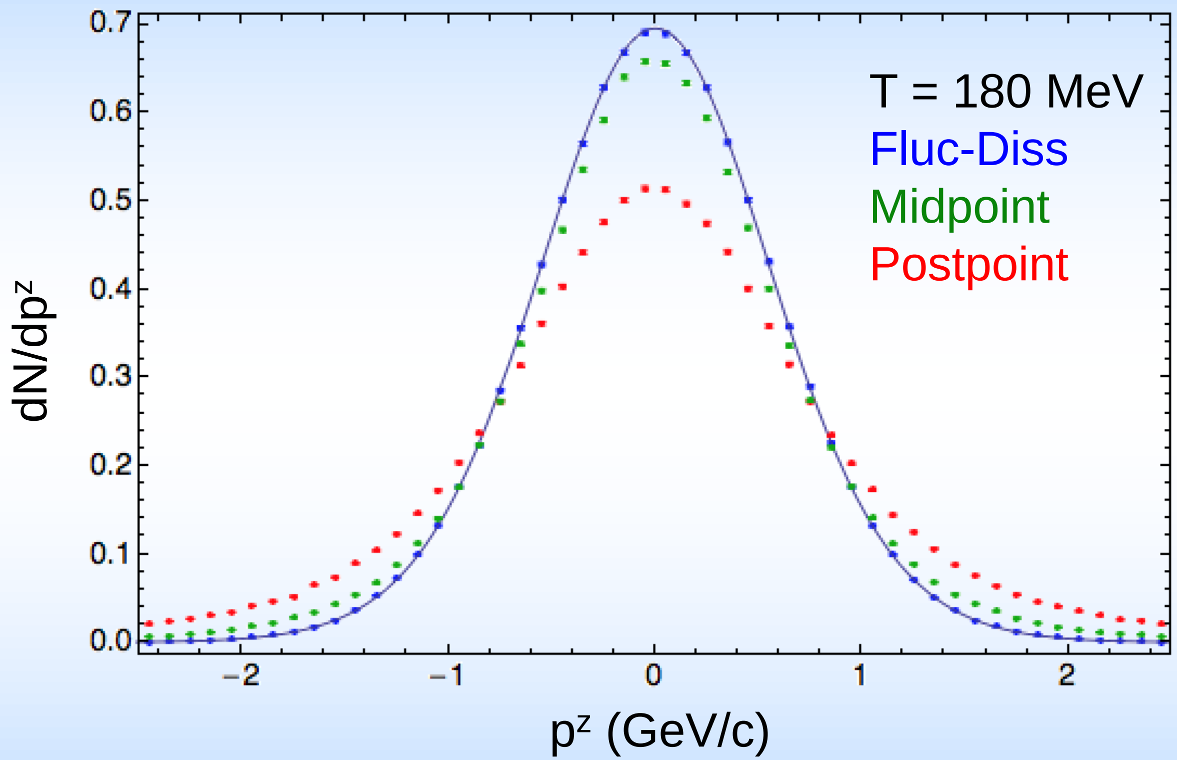
Discretizing Langevin

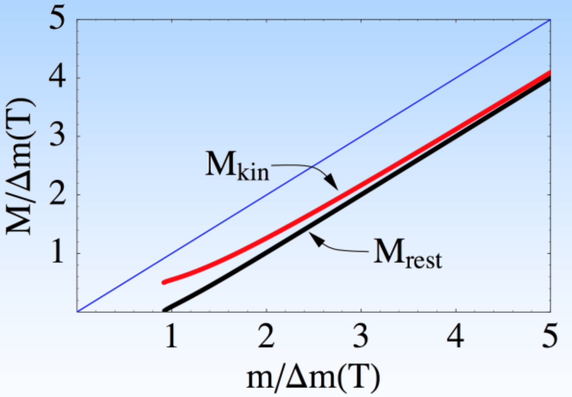
- Discretizing Riemann Calculus trivial
  - Sum converges regardless of bin widths and x* in bin as n increases
- Ambiguity in Ito Calculus
  - Results depend on discretization procedure



Discretization Ambiguity and Einstein

- Ex: momentum space distribution of c





Herzog et al., JHEP 0607 (2006)

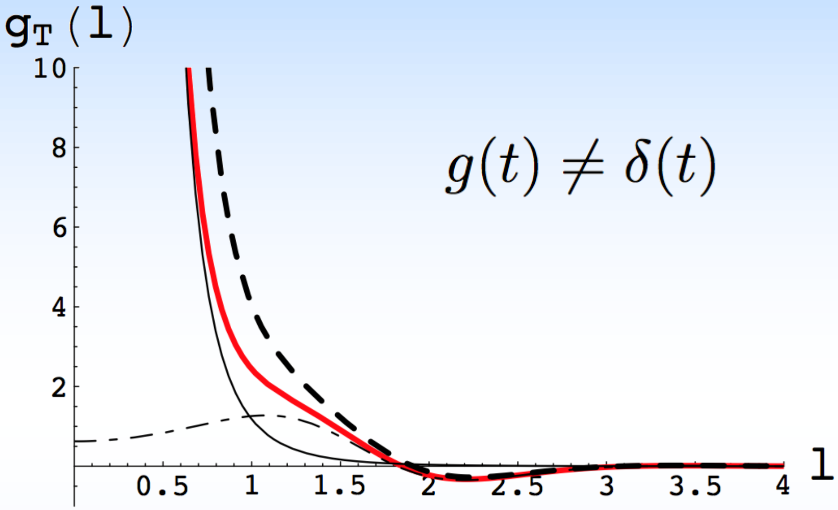
WAH, *in prep*

- AdS fluctuations very diff from fluc-diss, which lead to relativistic thermal (Jüttner) distribution
- Huge diff btwn pre-point (not shown), mid-point, and post-point
- AdS fluctuation derivation ignored changes to dispersion rel'n

Resolving the Ambiguity

- Saved by colored noise:

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



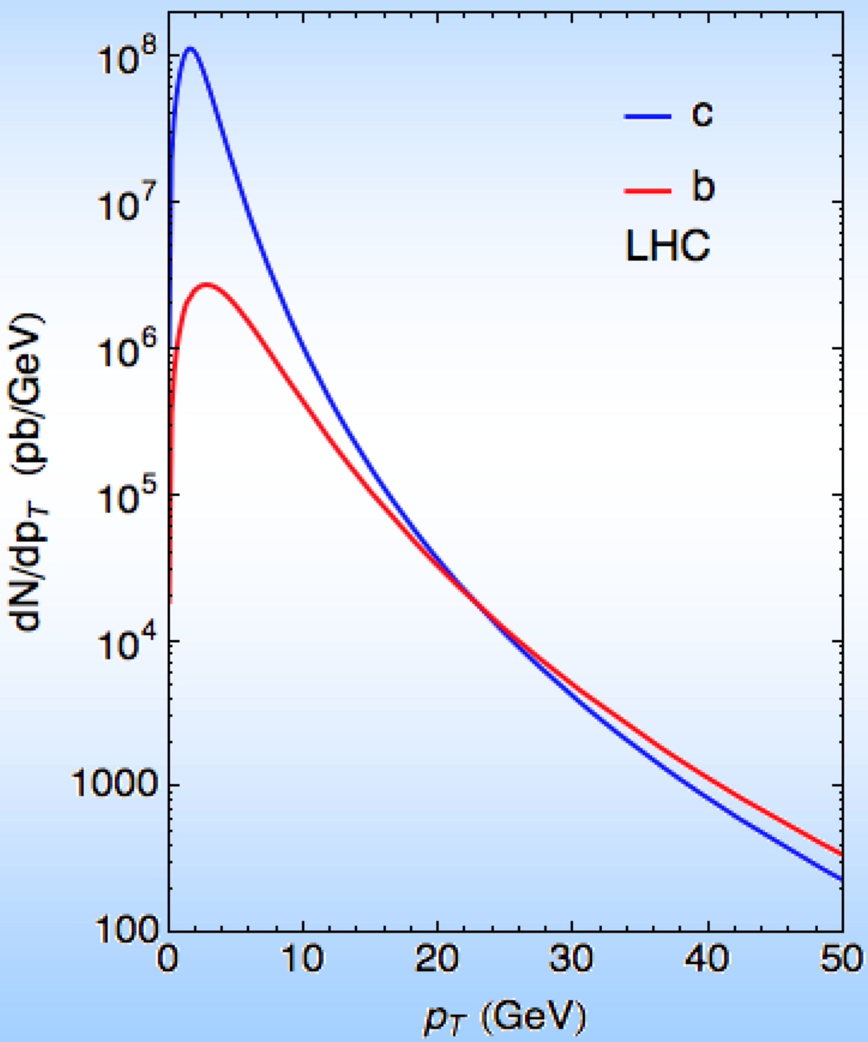
Gubser, NPB790 (2008)

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

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

Model Calculations

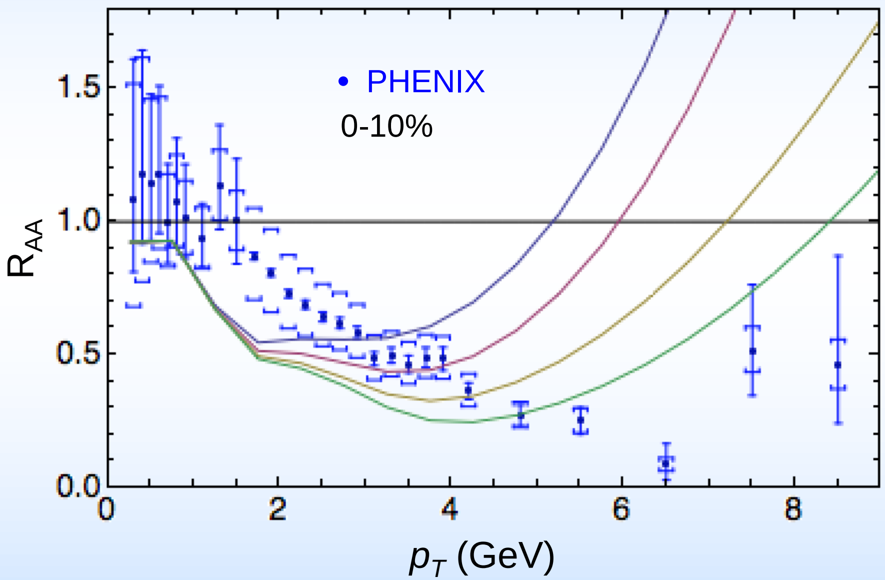
- Input FONLL c, b production spectra
  - Rapid dropoff in p_T
- Discretized Langevin through VISHNU
  - 2+1D viscous hydro
- FFs to B, D, e
- ***<u>VERY PRELIMINARY</u>***
  - Results converged just last week



Compare to RHIC

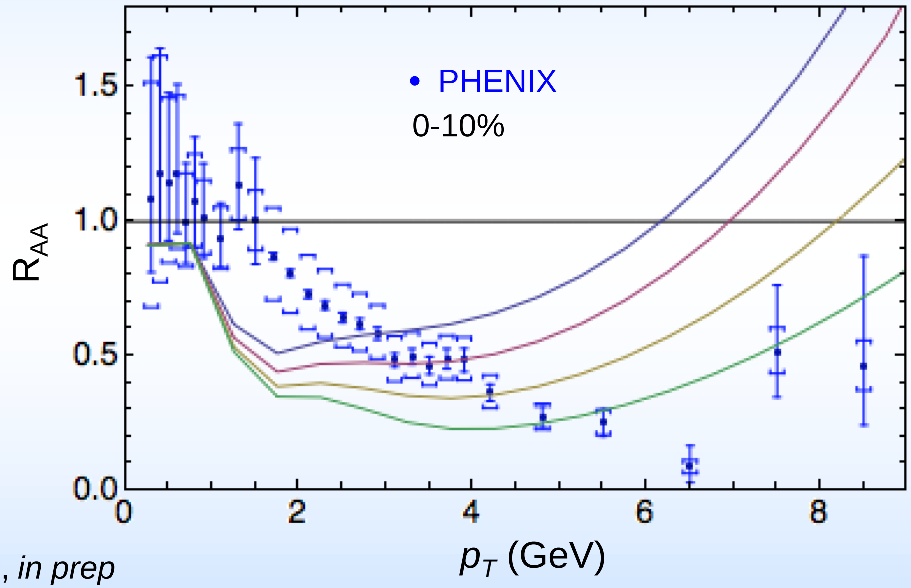
- $T_{SYM} = T_{QCD}$

$\alpha_s = 0.3$



- $T_{SYM} = T_{QCD}/3^{1/4}$
  - Adjust for #DOF

$\lambda = 5.5$



WAH, *in prep*

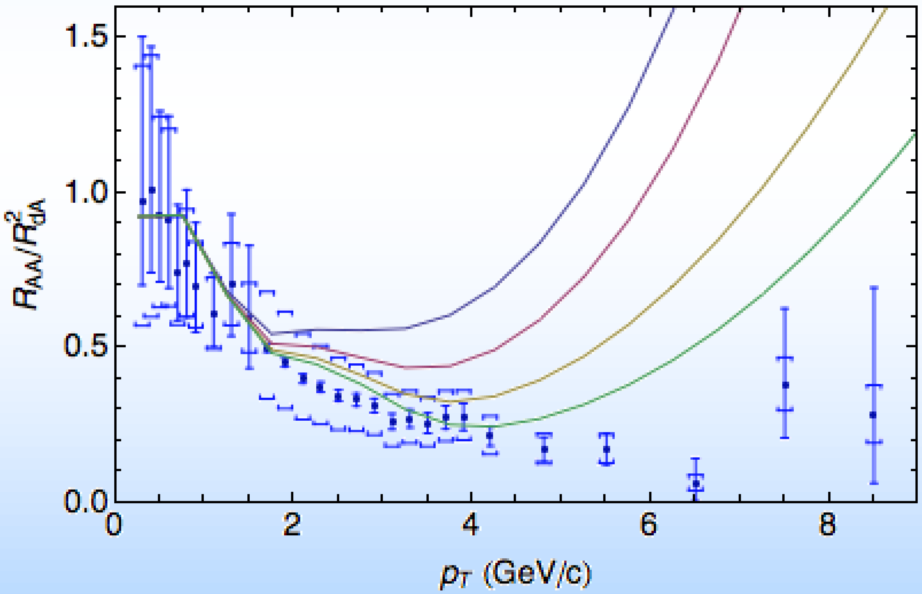
Data: PHENIX, PRL98 (2007)

- Steeply falling spectrum + fluc => huge growth in p_T in R_{AA} from c
- Speed limit => p_{max} ~ 6 GeV

BUT: e^- R_{dA} is Enhanced

- Perhaps IS effect: divide by R_{dA}^2
  - $T_{SYM} = T_{QCD}$
  - $T_{SYM} = T_{QCD}/3^{1/4}$
    - Adjust for #DOF

$\alpha_s = 0.3$



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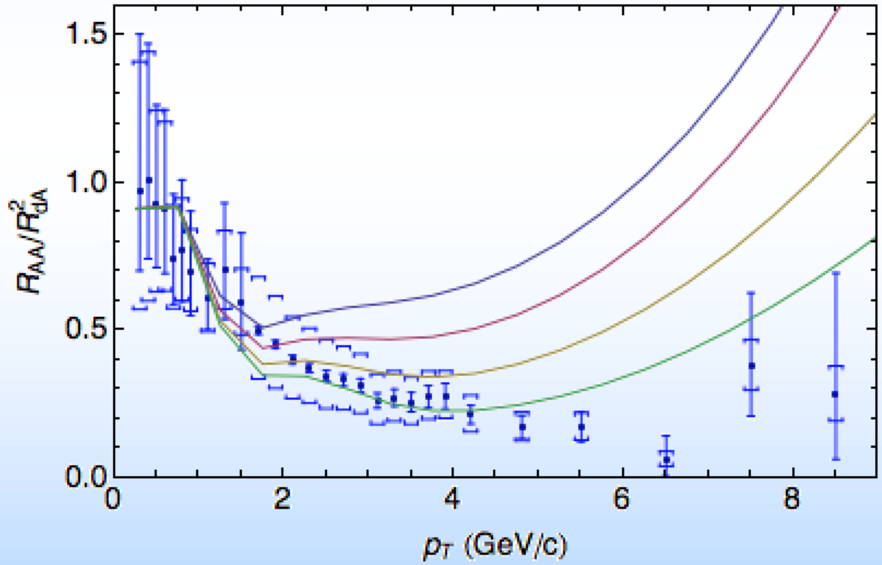
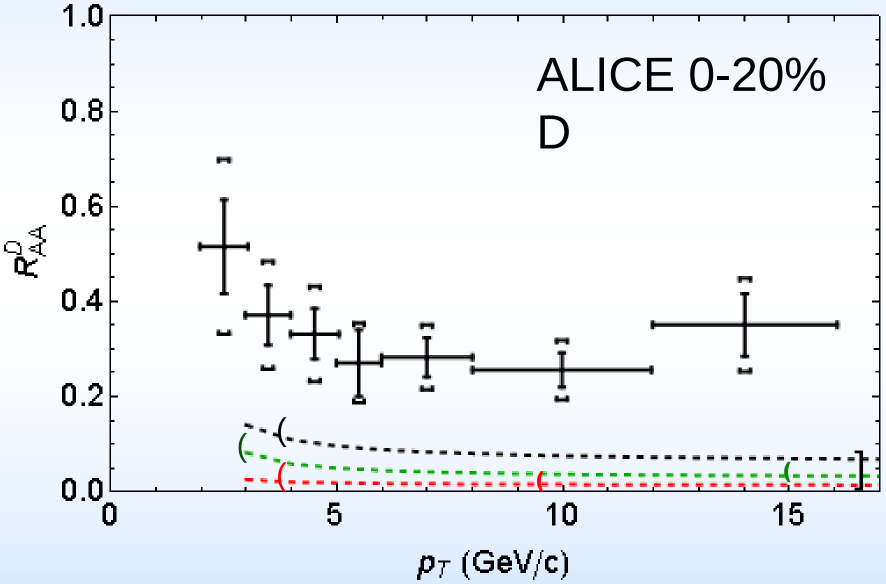


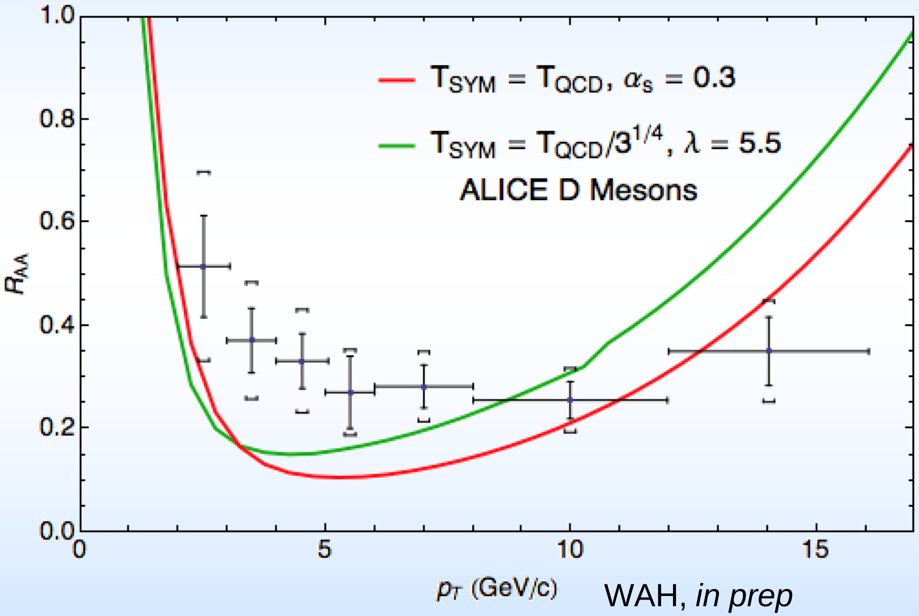
- Multiple curves from varying λ by powers of 2

LHC D Mesons 0-20%

- Recall drag only



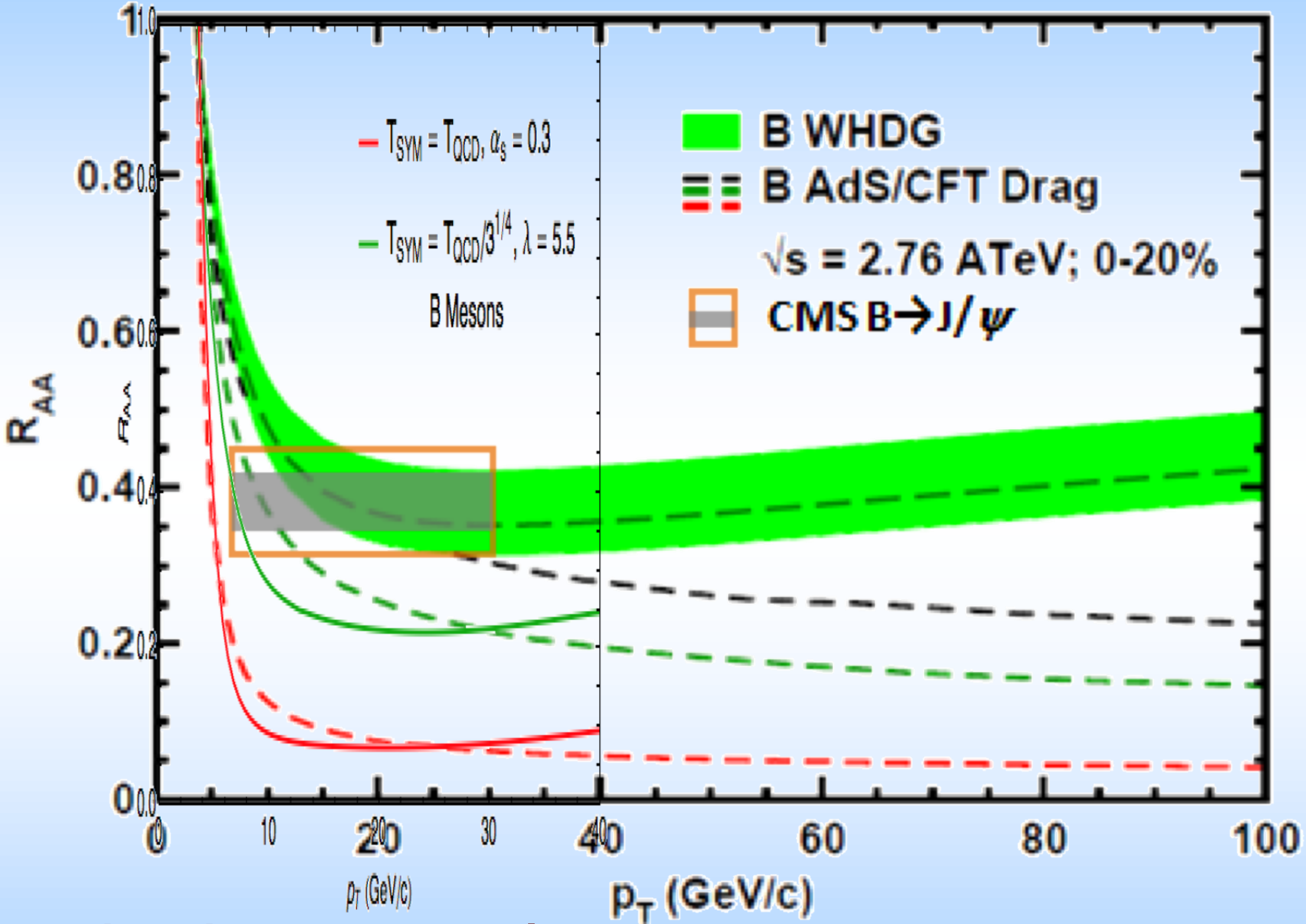
- With fluctuations



WAH, *in prep*

- Slightly different from QM (corrected trivial error)
- Again, huge inc. in R_{AA} as p_T inc.
- Expect speed limit corrections p_T ~ 10 – 15 GeV

LHC B Mesons Largely Unaffected

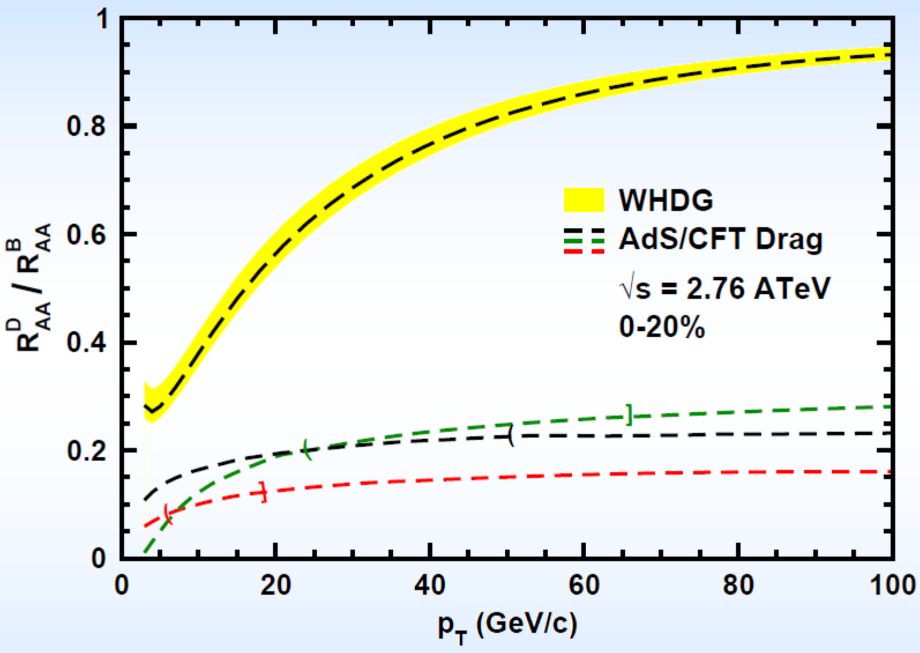


- Dashed: Drag Only
- Solid: With Fluctuations

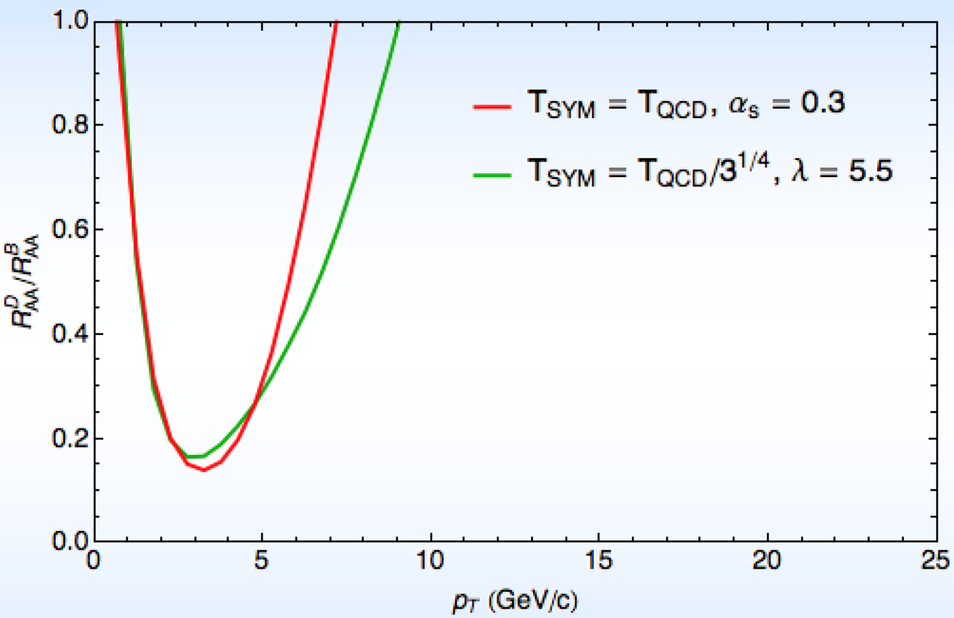
WAH, *in prep*

What Happens to D / B Ratio?

- Previously



- With fluctuations



WAH, *in prep*

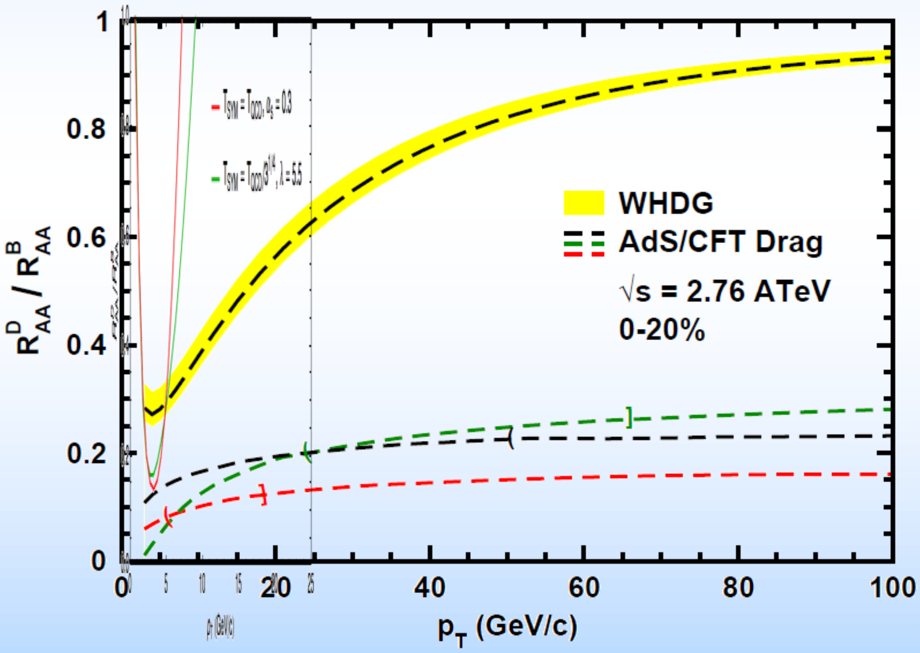
- Fluctuations ~$\gamma^{5/2}$ lead to *incredibly* rapid rise in D / B ratio

Conclusions

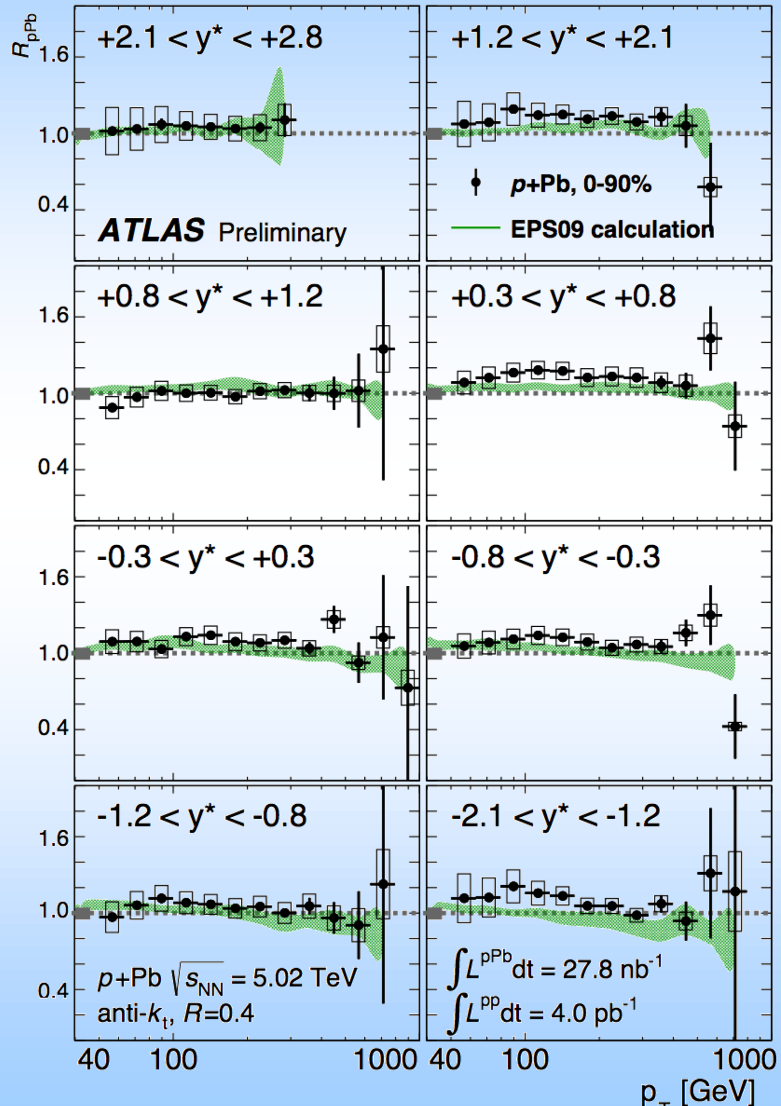
- Want consistent picture of QGP, but Expect the Unexpected
  - Shocking p/d + A results over past year(s)
  - Requires resolution (likely from precision data)
- Naïve LO AdS receives large corrections
  - Light flavor setup needs improvement
    - Suggestive early results
  - HF Fluctuations very important
    - Significant reduction in HF suppression
      - Effect appears to be too small at low pT and too large at p_T near speed limit for quantitative comparison
    - Likely also affects wide-angle scattering
- Future AdS work
  - Include colored noise
  - Improve light flavor IC
  - Transition HF to light flavor at speed limit
  - Still better HF/LF setup, a la Ficnar?

What Happens to D / B Ratio?

- Previously

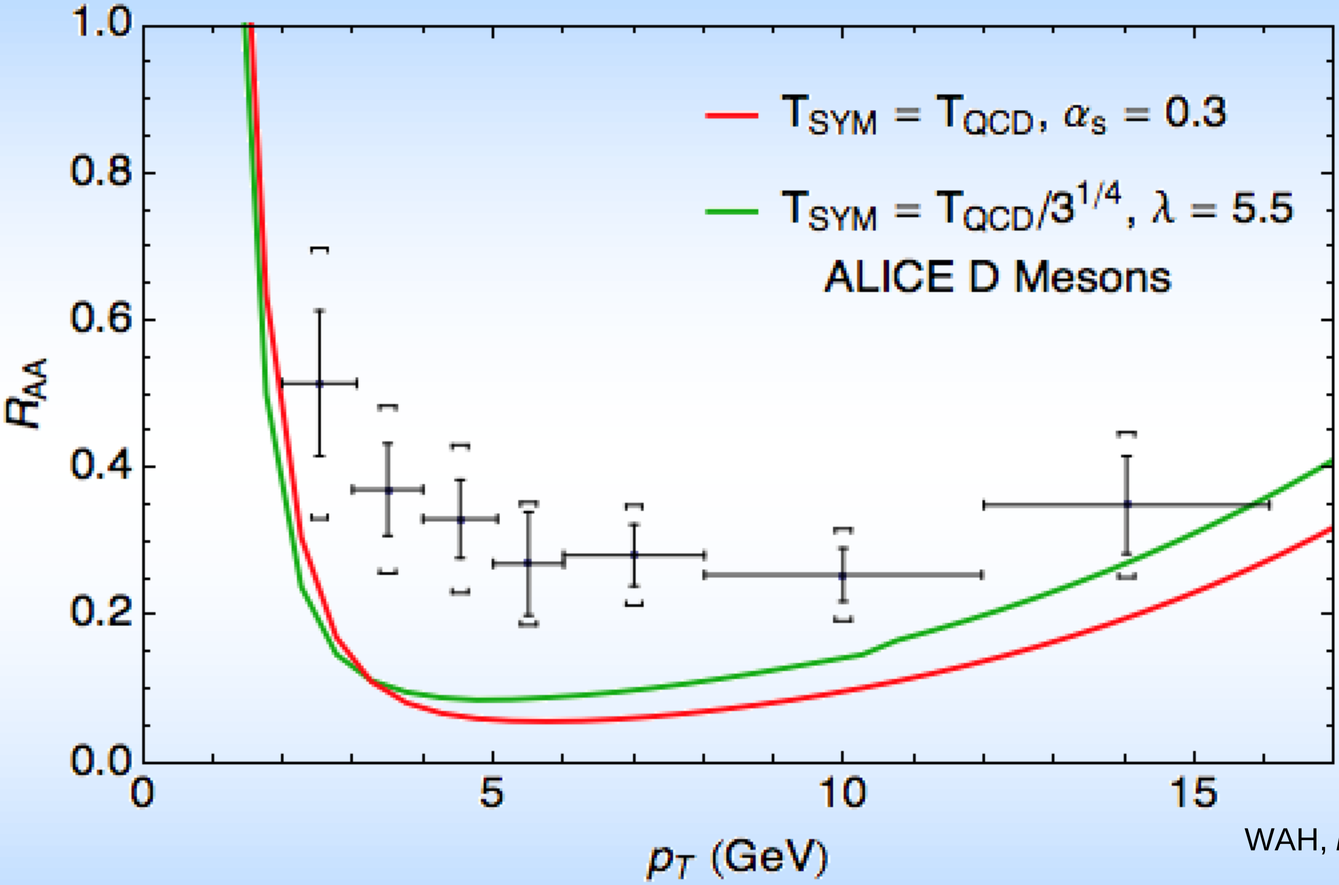


Jet R_{pA}



B Cole for ATLAS, QM14

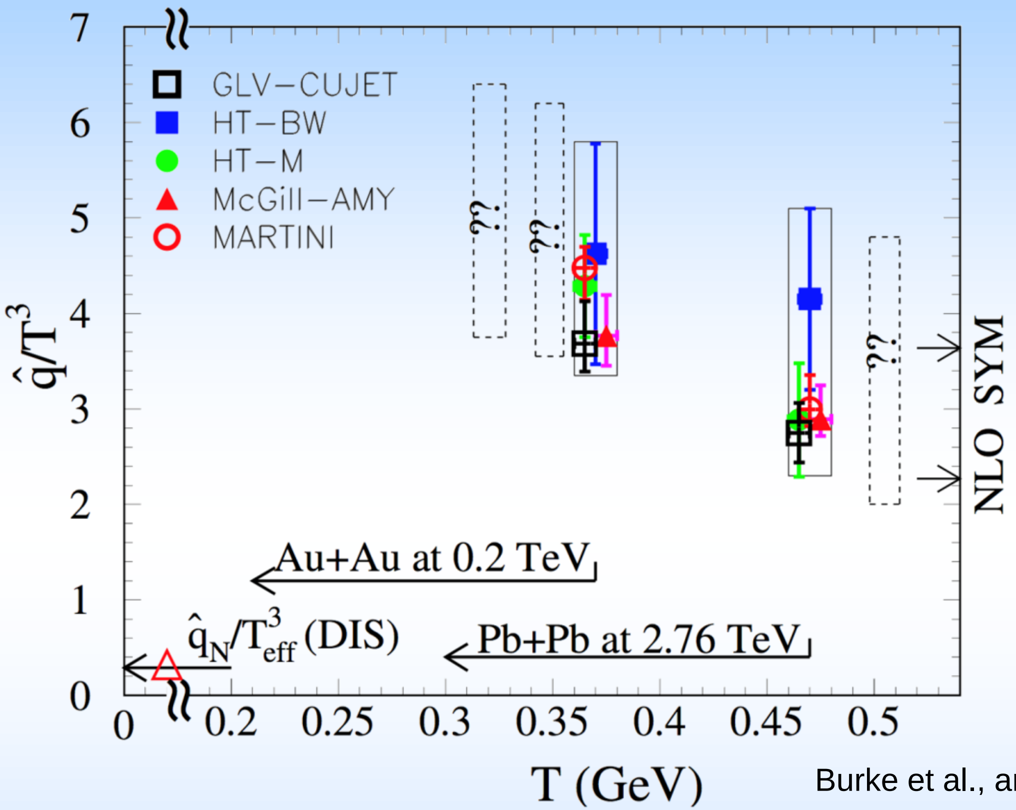
LHC D Mesons 0-20% (Old Result)



WAH, *in prep*

- Again, huge inc. in R_{AA} as p_T inc.
- Expect speed limit corrections p_T ~ 10 – 15 GeV

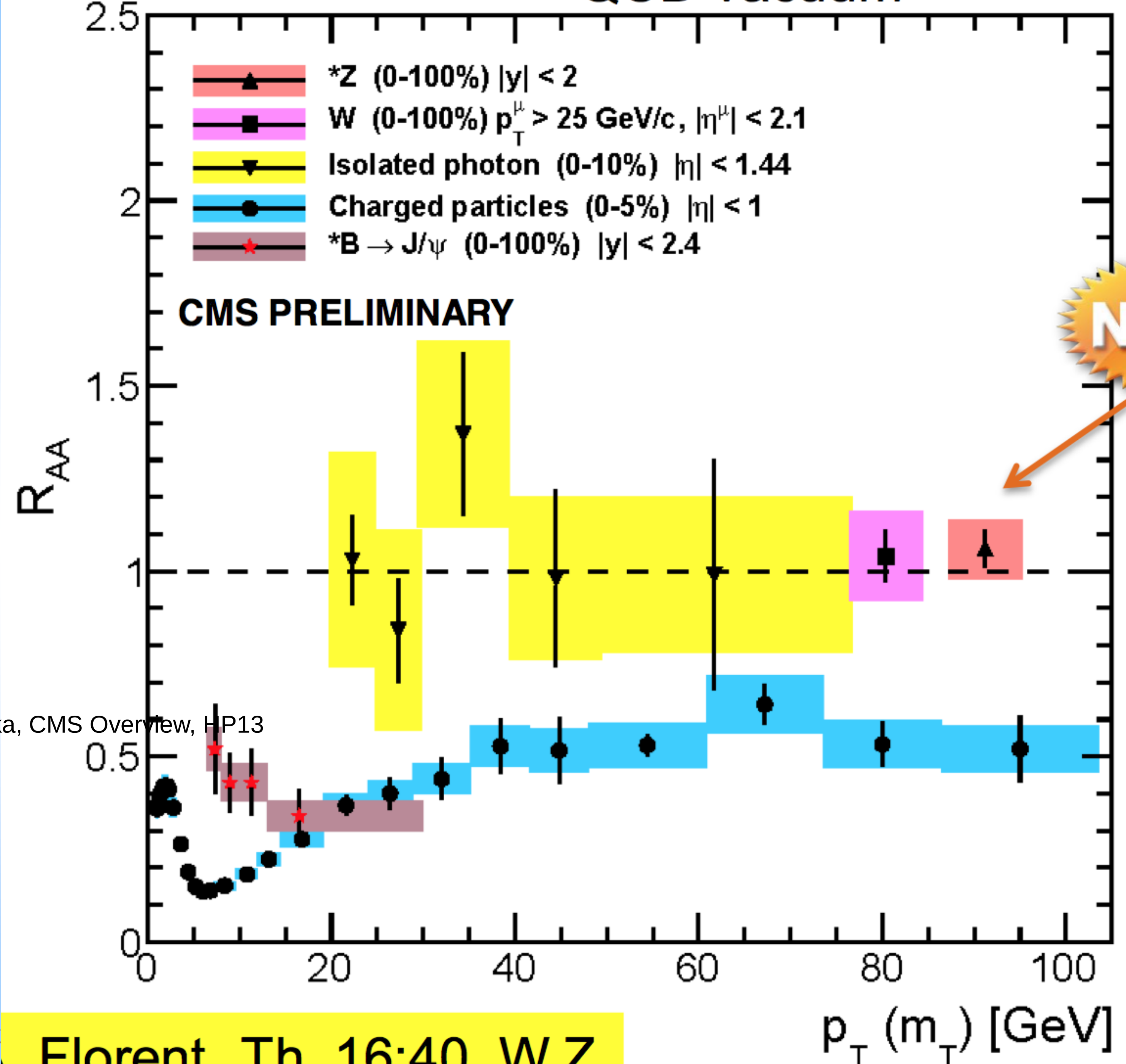
Recent JET Collab Results



Burke et al., arXiv:1312.5003

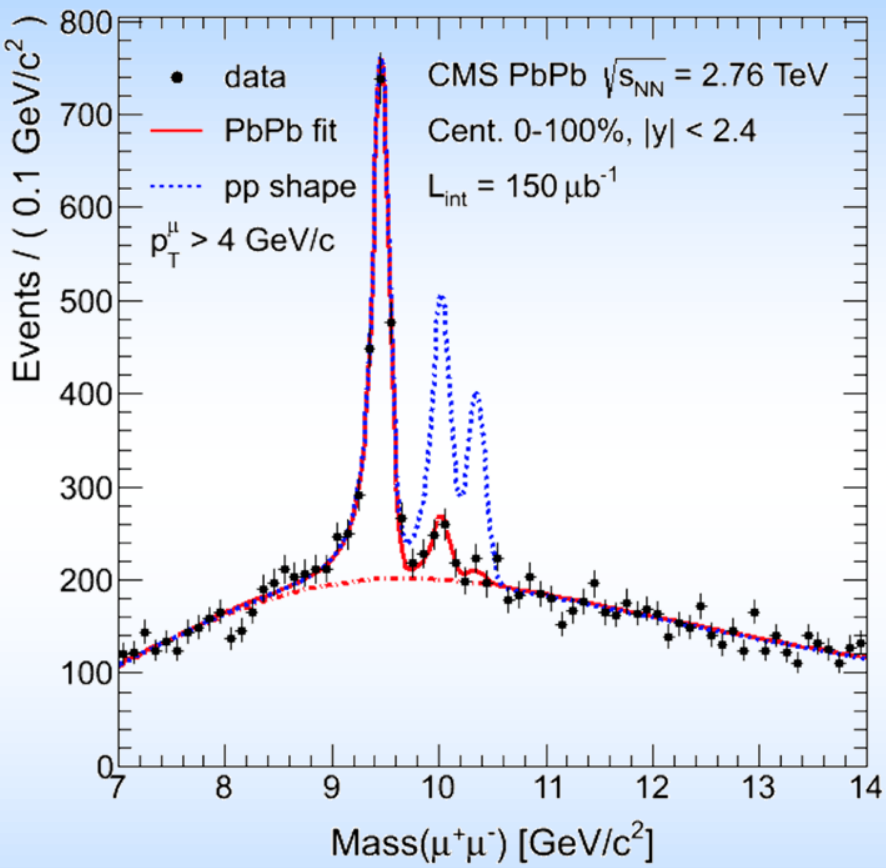
"…we summarize our current results and indicate needed future work by the JET collaboration toward a quantitative mapping of the jet transport parameter qhat over a wider range of jet energy and highest T…"

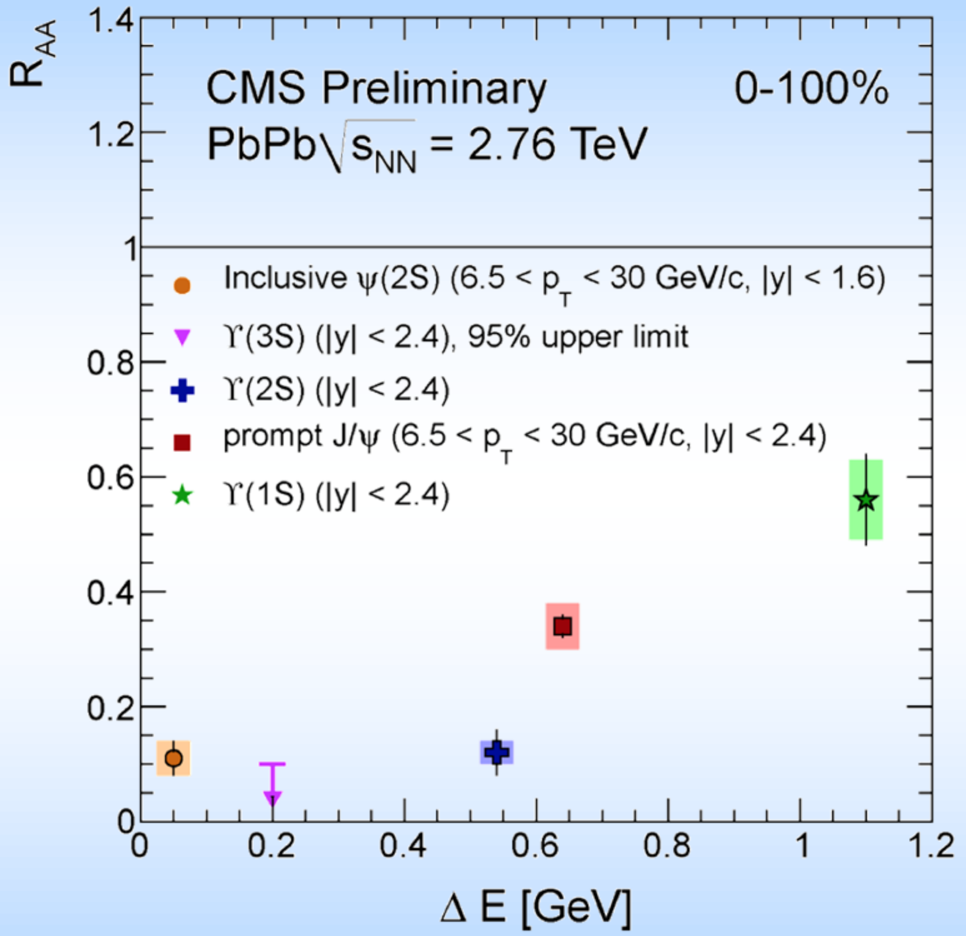
QCD vacuum



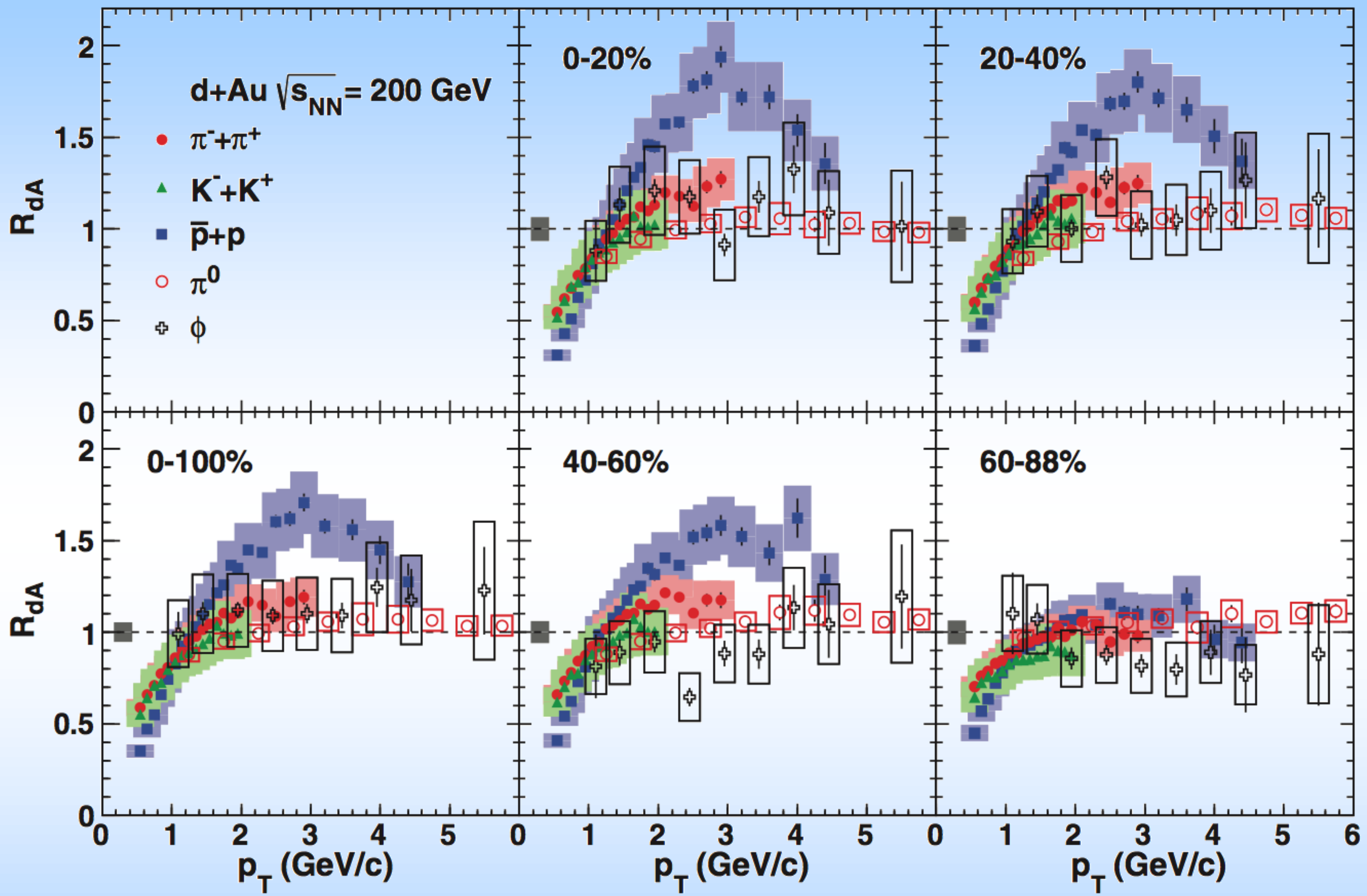
Velkovska, CMS Overview, HP13

. Florent, Th ,16:40, W,Z

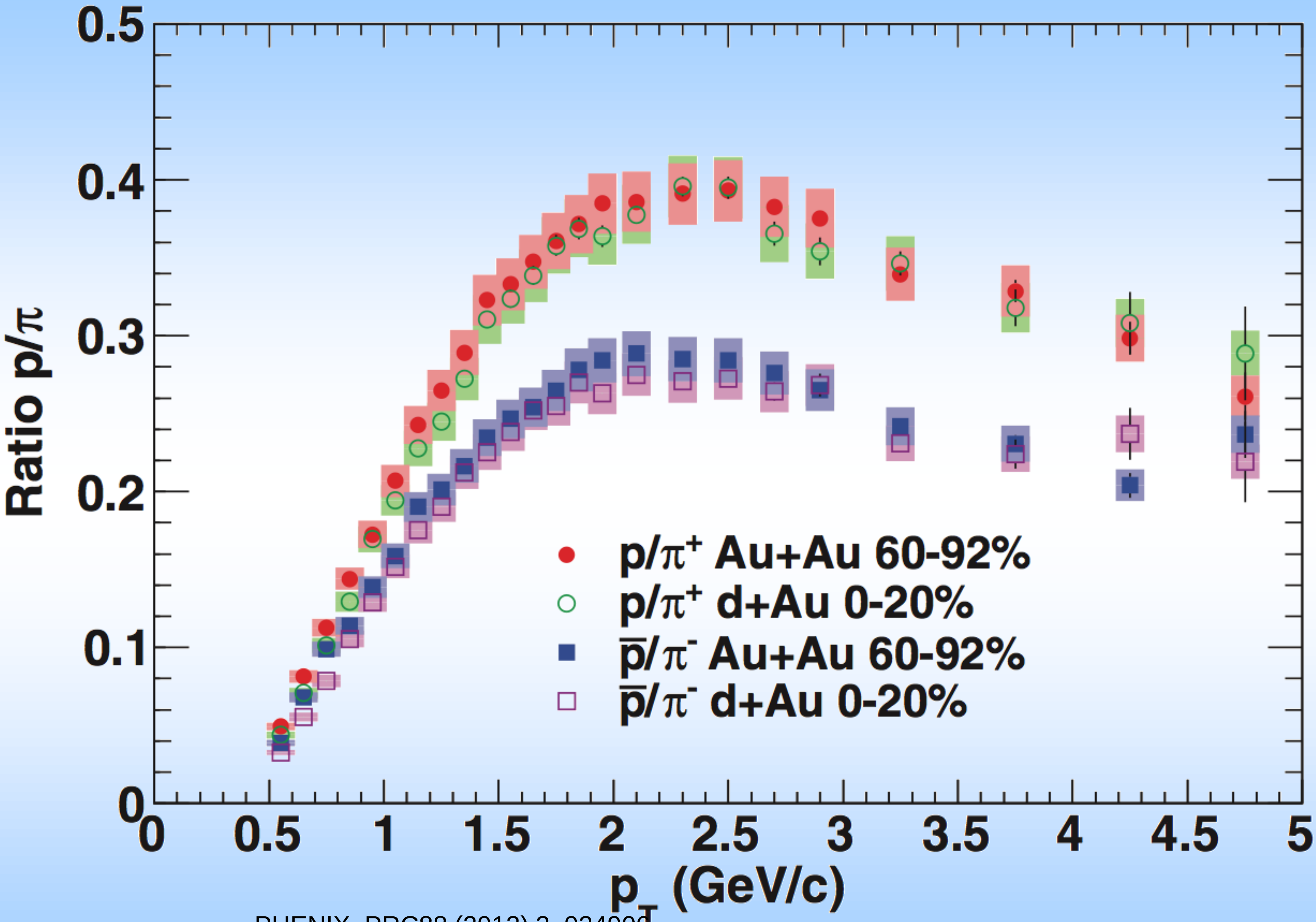




Velkovska, HP2013



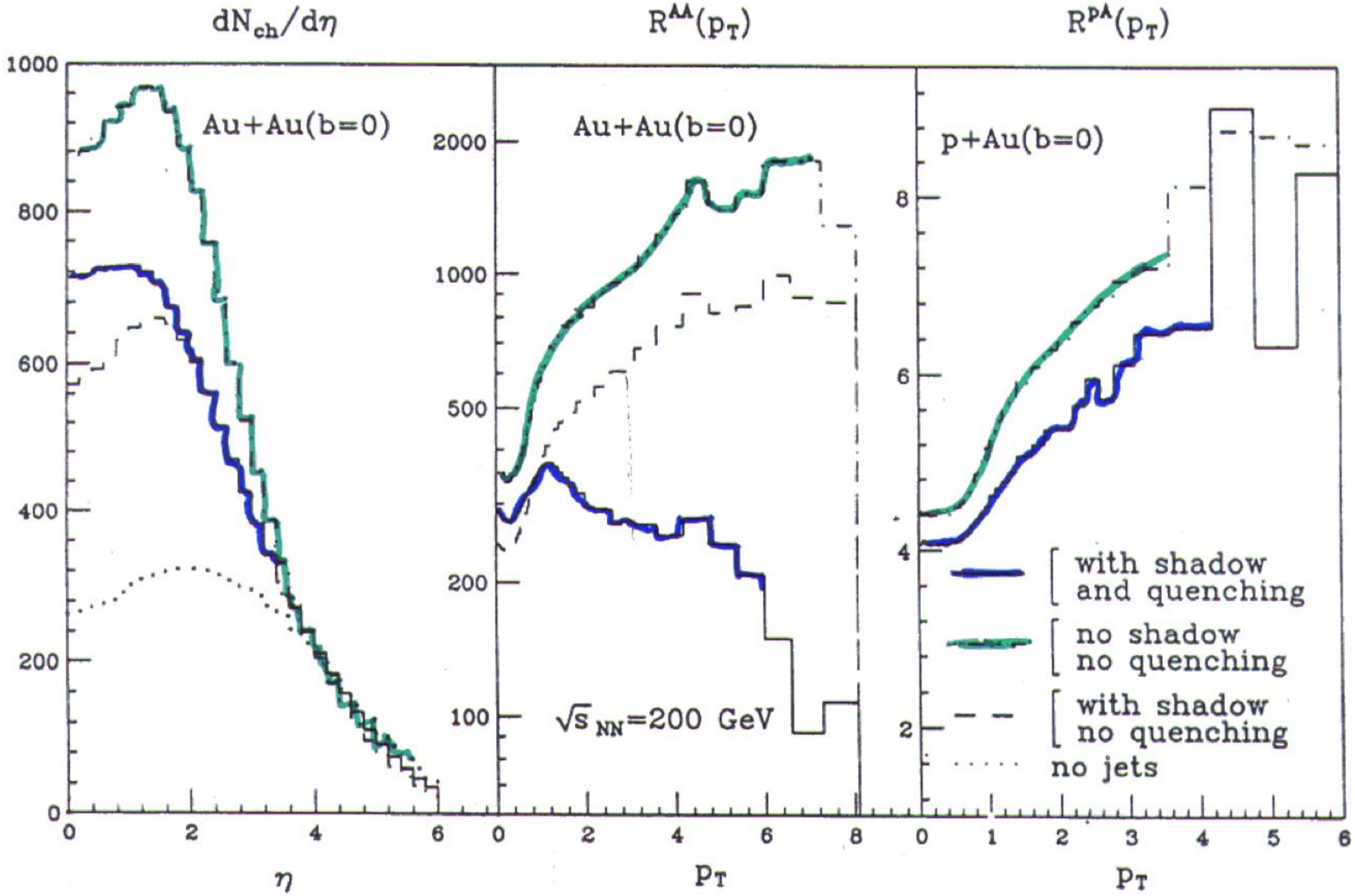
PHENIX, PRC88 (2013) 2, 024906



PHENIX, PRC88 (2013) 2, 024906

The Picture that started it all...

CAN WE UNDERSTAND INTERACTION OF A PARTON IN MEDIA?.....

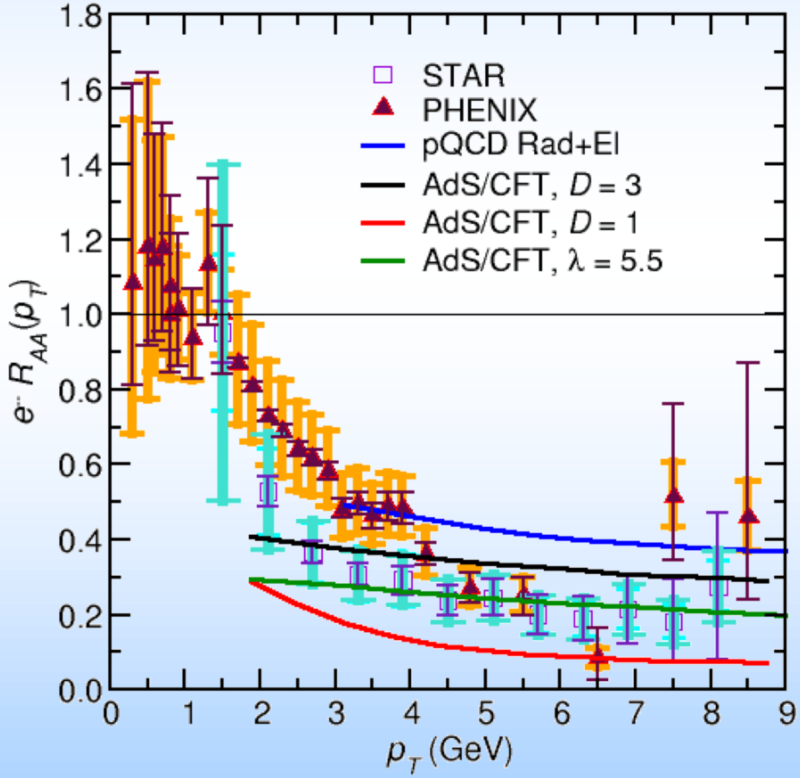


XN Wang
M Gyulassy
PRL 68 (1992) 1480

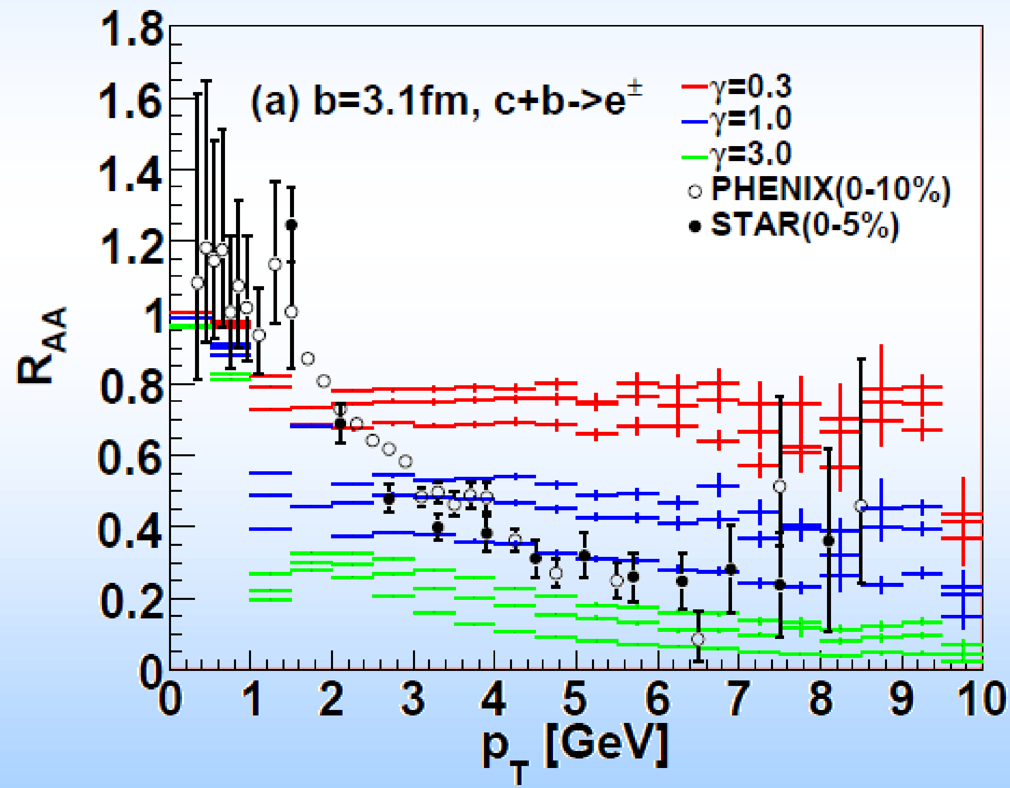
B Zajc, RHIC Winter Workshop at LBL (1998)

AdS and HQ

- String drag: qualitative agreement at RHIC



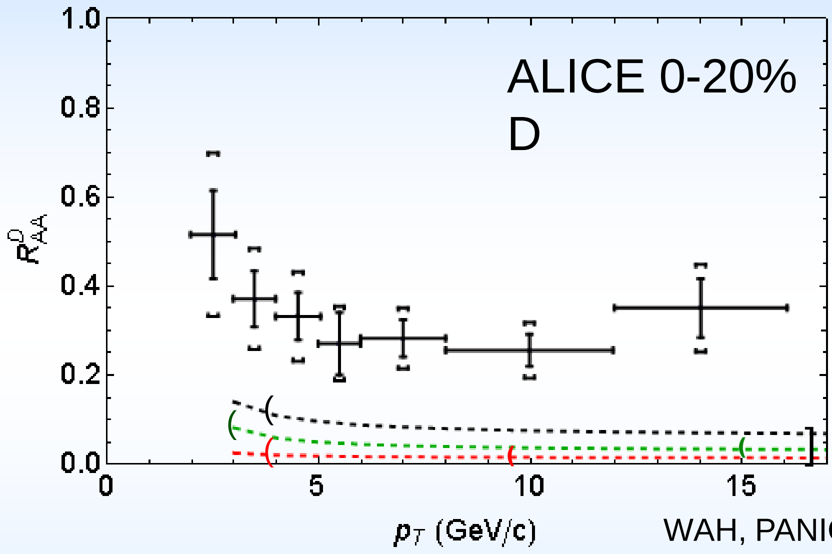
WAH, PhD Thesis, arXiv:1011.4316



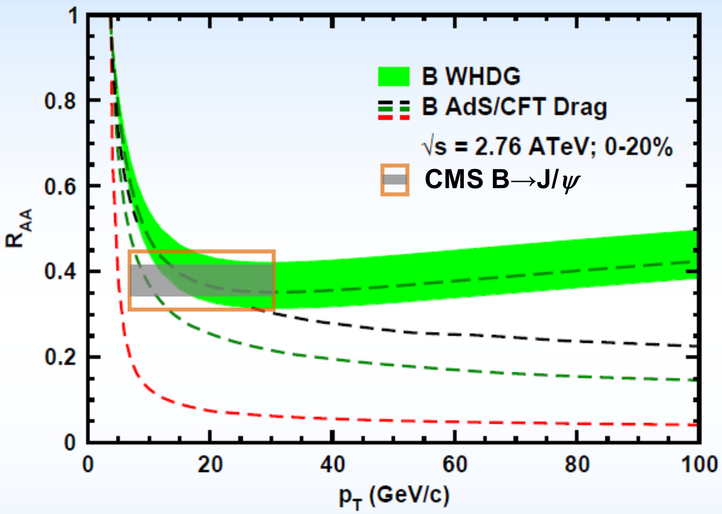
Akamatsu, Hatsuda, and Hirano, PRC79, 2009

AdS and HQ at LHC

- D Predictions



- B Predictions

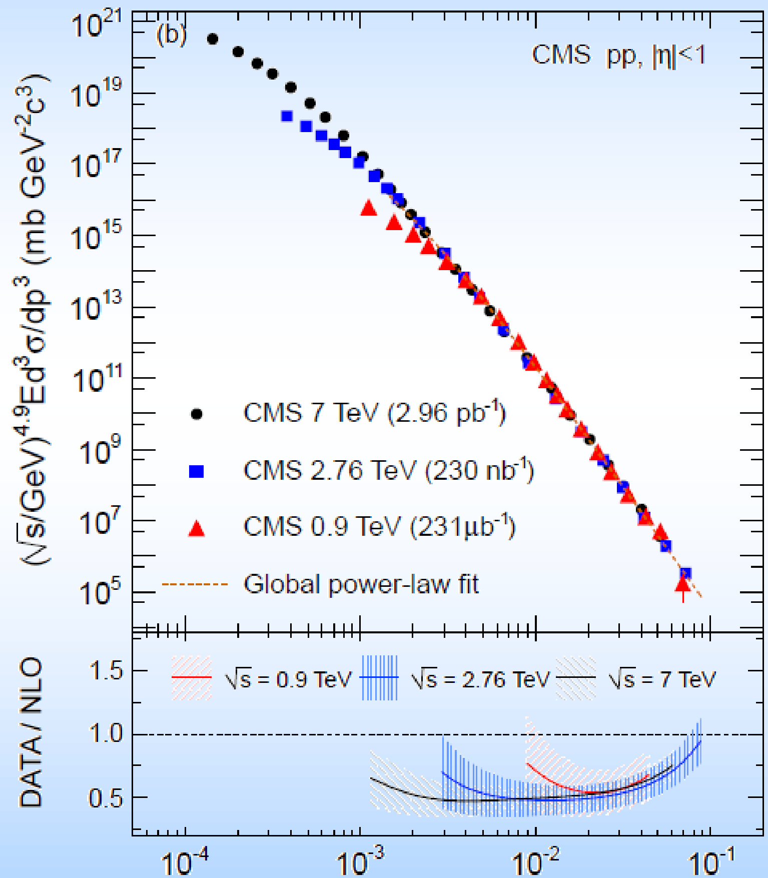


WAH, PANIC11 (arXiv:1108.5876)
ALICE, arXiv:1203.2160
CMS, JHEP 1205 (2012) 063

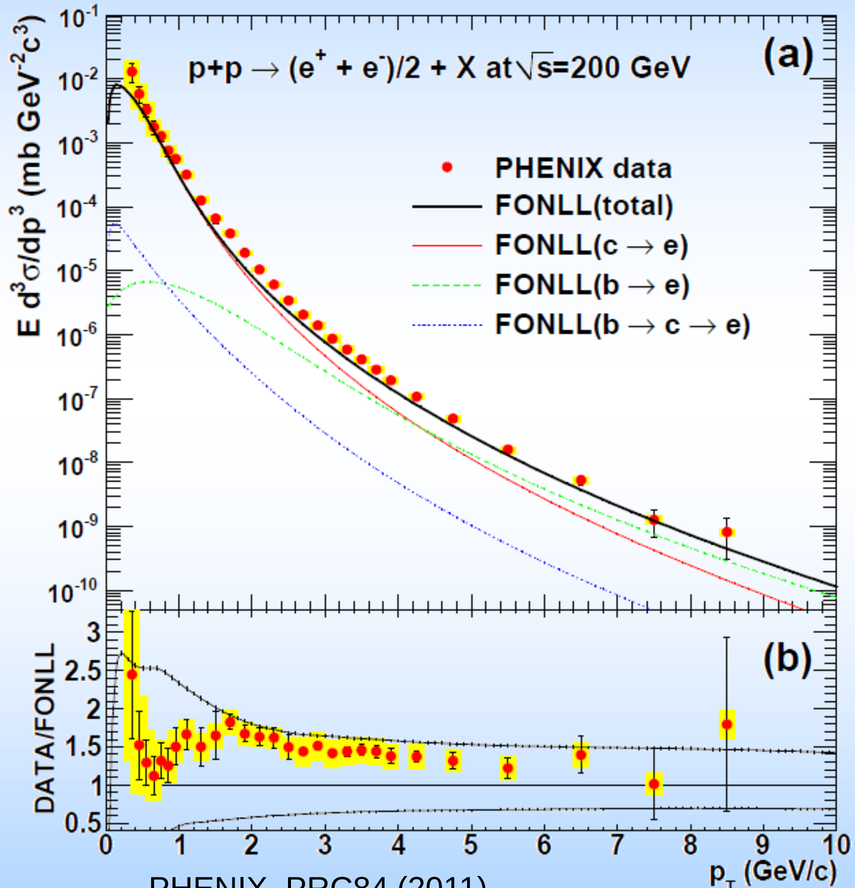
- AdS HQ Drag appears to oversuppress D
- Roughly correct description of current B→J/ψ

Set Scale for Expectations

- NLO pQCD in pp System ~ factor of 2



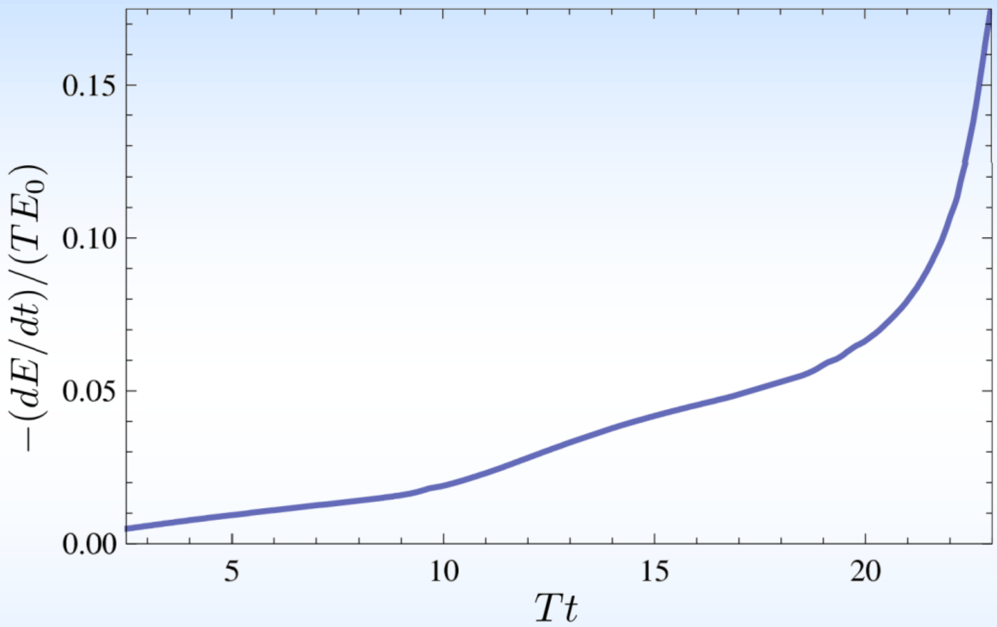
CMS, EurPhysJC72 (2012)

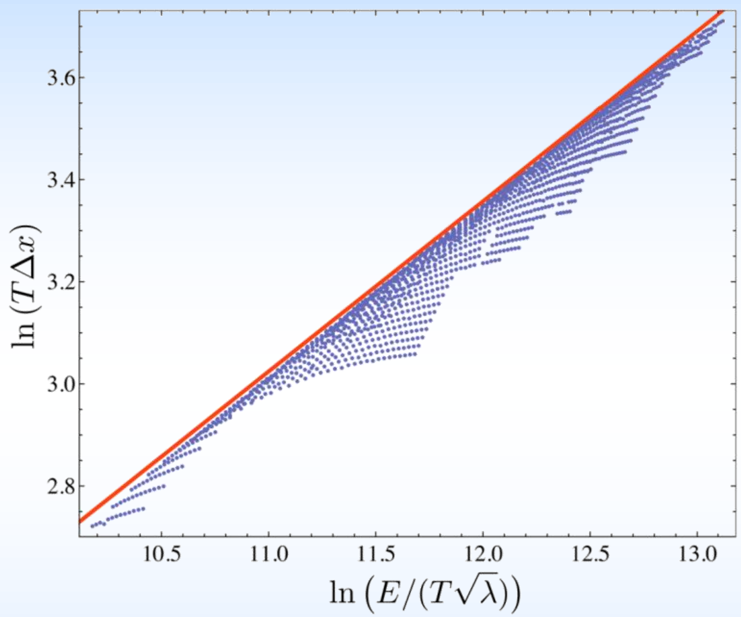


PHENIX, PRC84 (2011)

“Fragmentation functions may need to be revisited”

Claim of Generic Bragg Peak

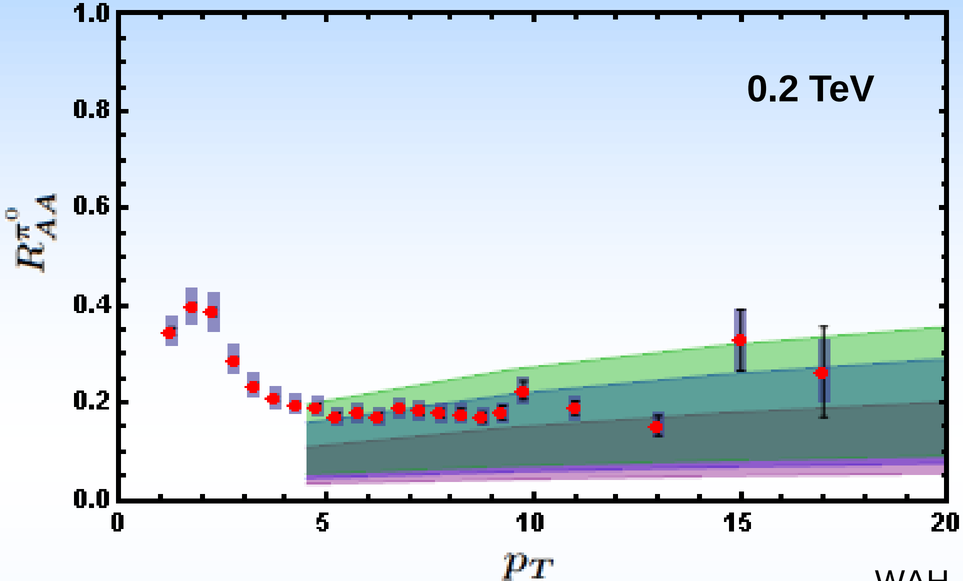


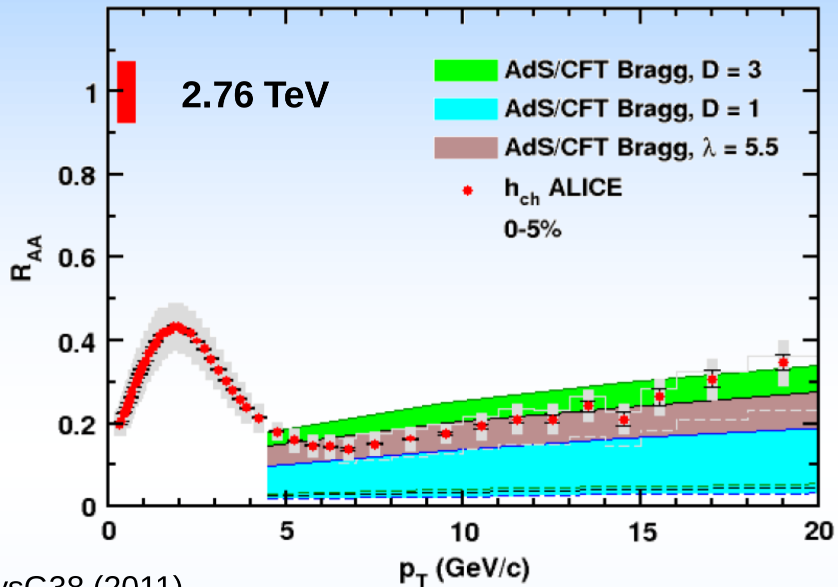


Chesler et al., PRD79 (2009)

– $\Delta x_{max} \sim (E/\lambda^{1/2}T)^{1/3}/T$
  - Different power from usual $\Delta E \sim L^2$ from pQCD

Simple Bragg Model vs. Data



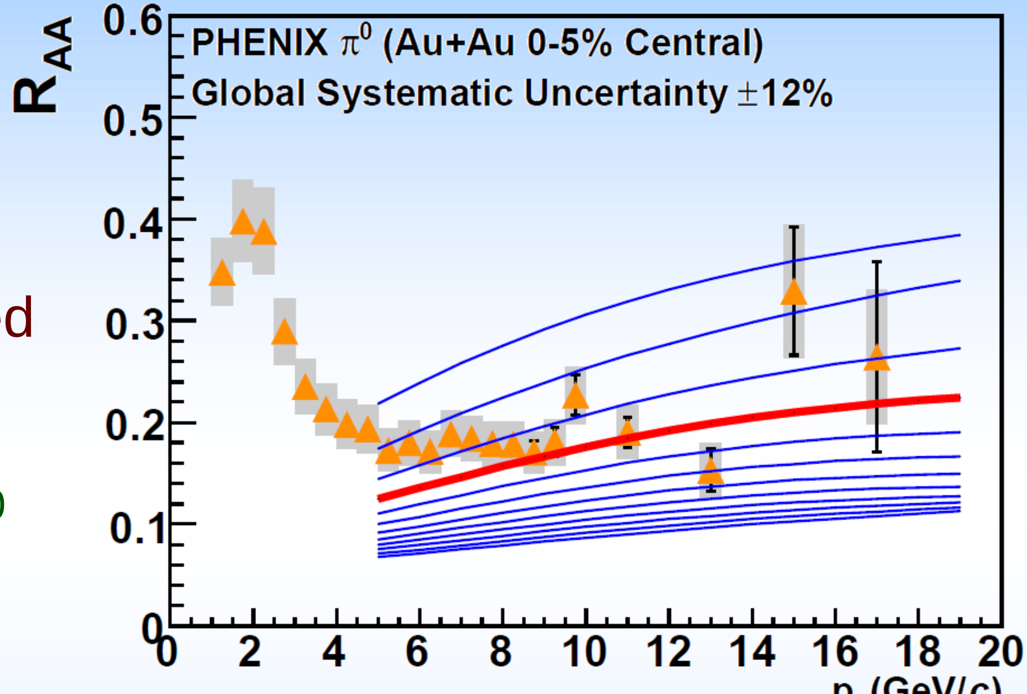


WAH, JPhysG38 (2011)

- P(escape) = θ(L-L_{therm})
- Huge uncertainties
- Systematic oversuppression?
  - Warrants further study

Compare to pQCD at RHIC & LHC

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

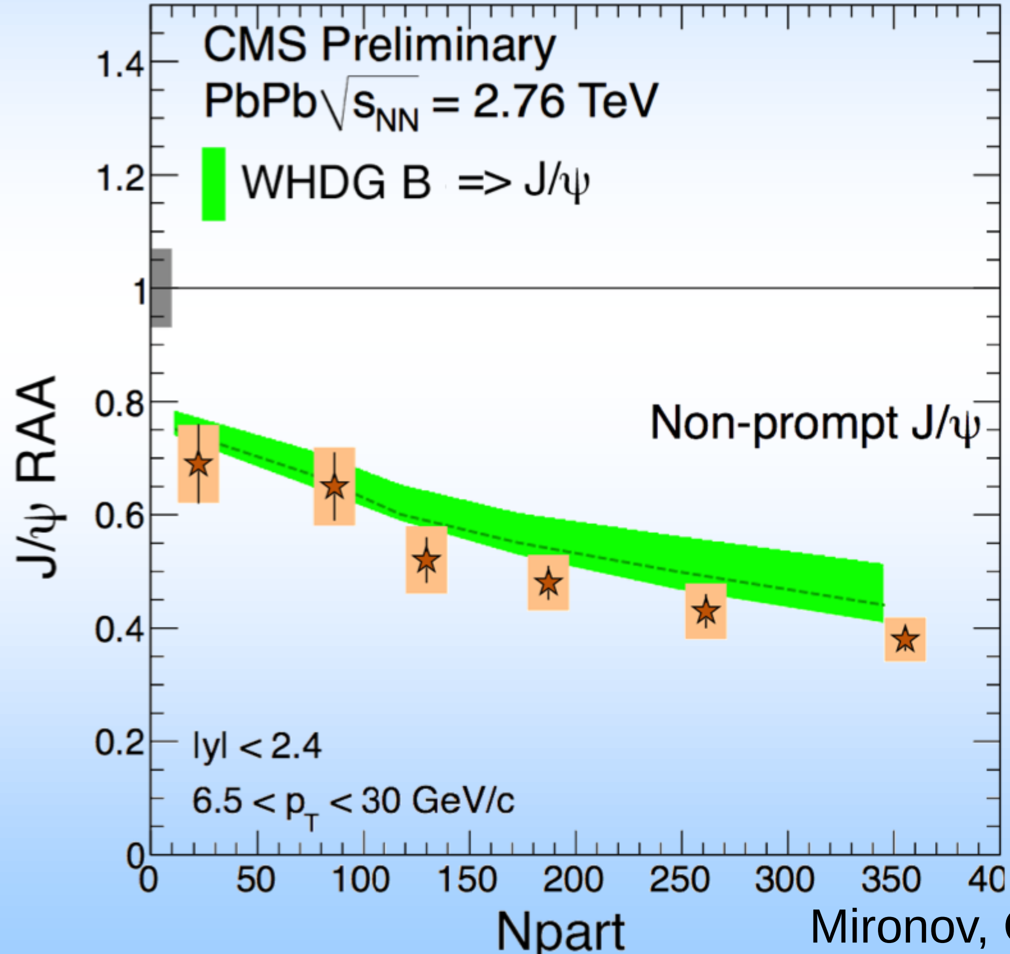


PHENIX, PRC77 (2008)

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

New WHDG J/ψ Comparison to CMS

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



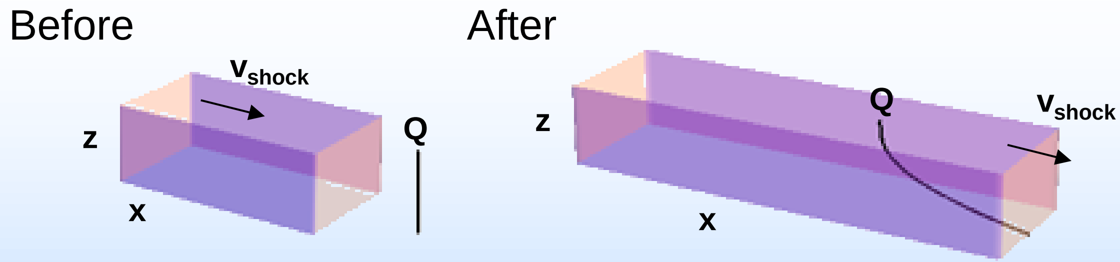
Mironov, QM2012
NPA 904-905 (2013)

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

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

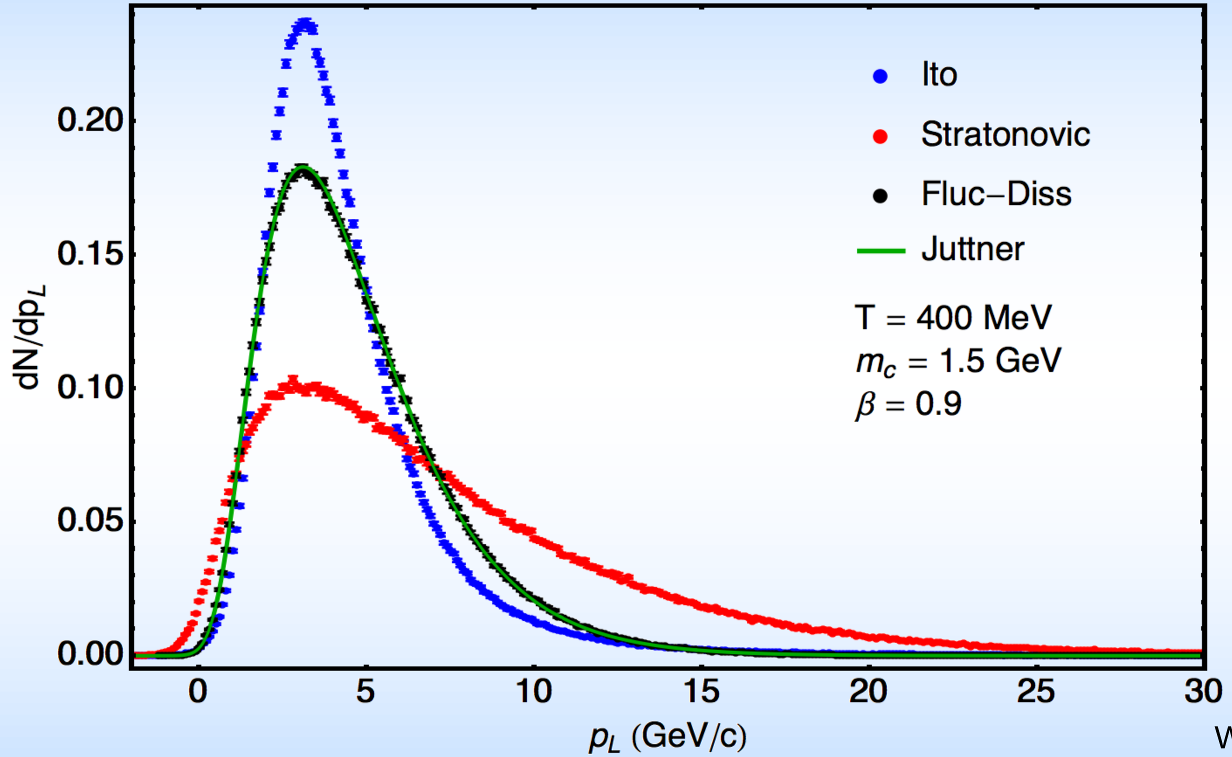


WAH and Kovchegov, PLB680 (2009)

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

Discretization Ambiguity and Einstein

- Ex: momentum space distribution of charm



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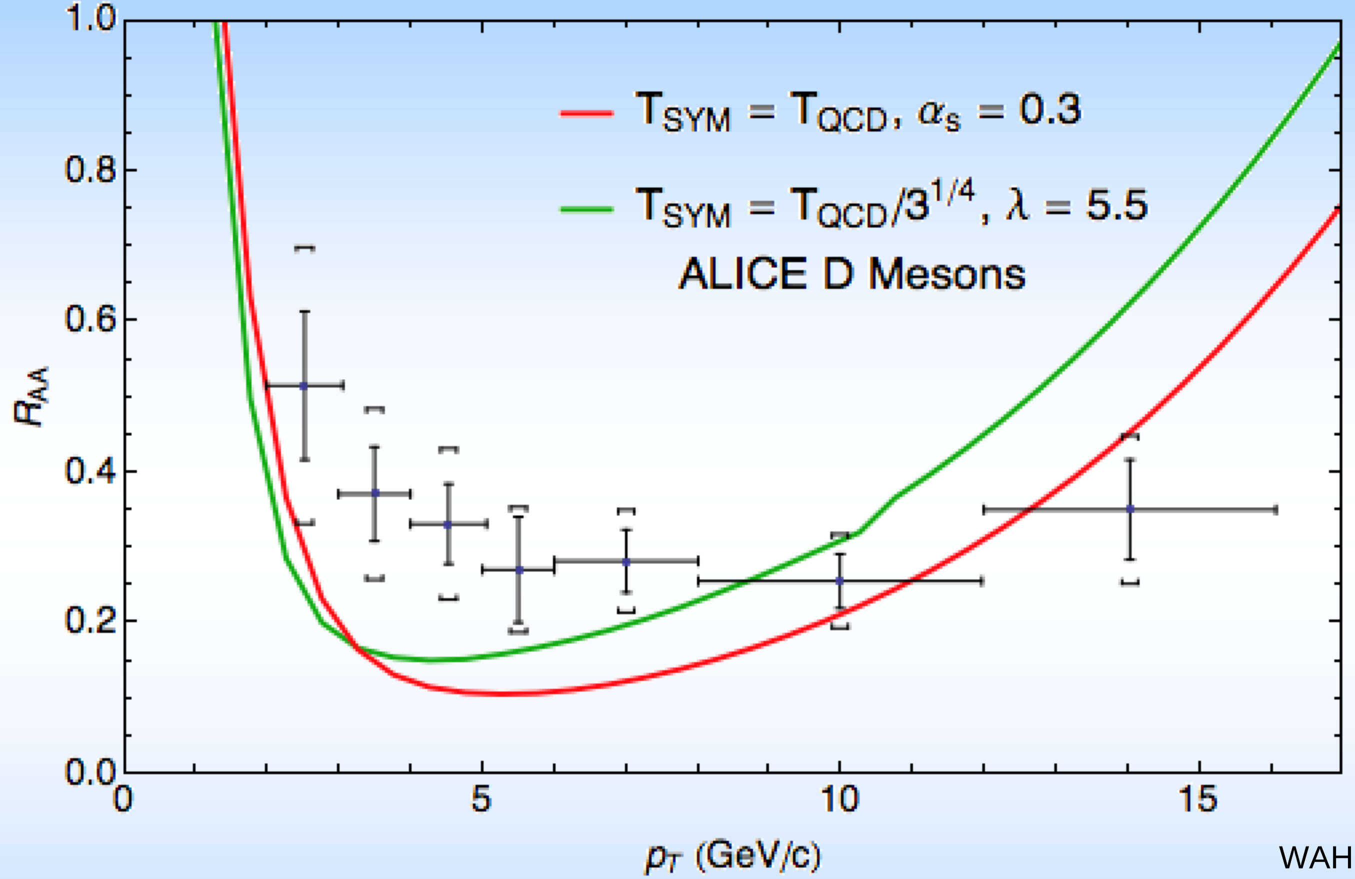

WAH, *in prep*

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