Particle Suppression in AA and p/dA Collisions Including Short Path Length Corrections

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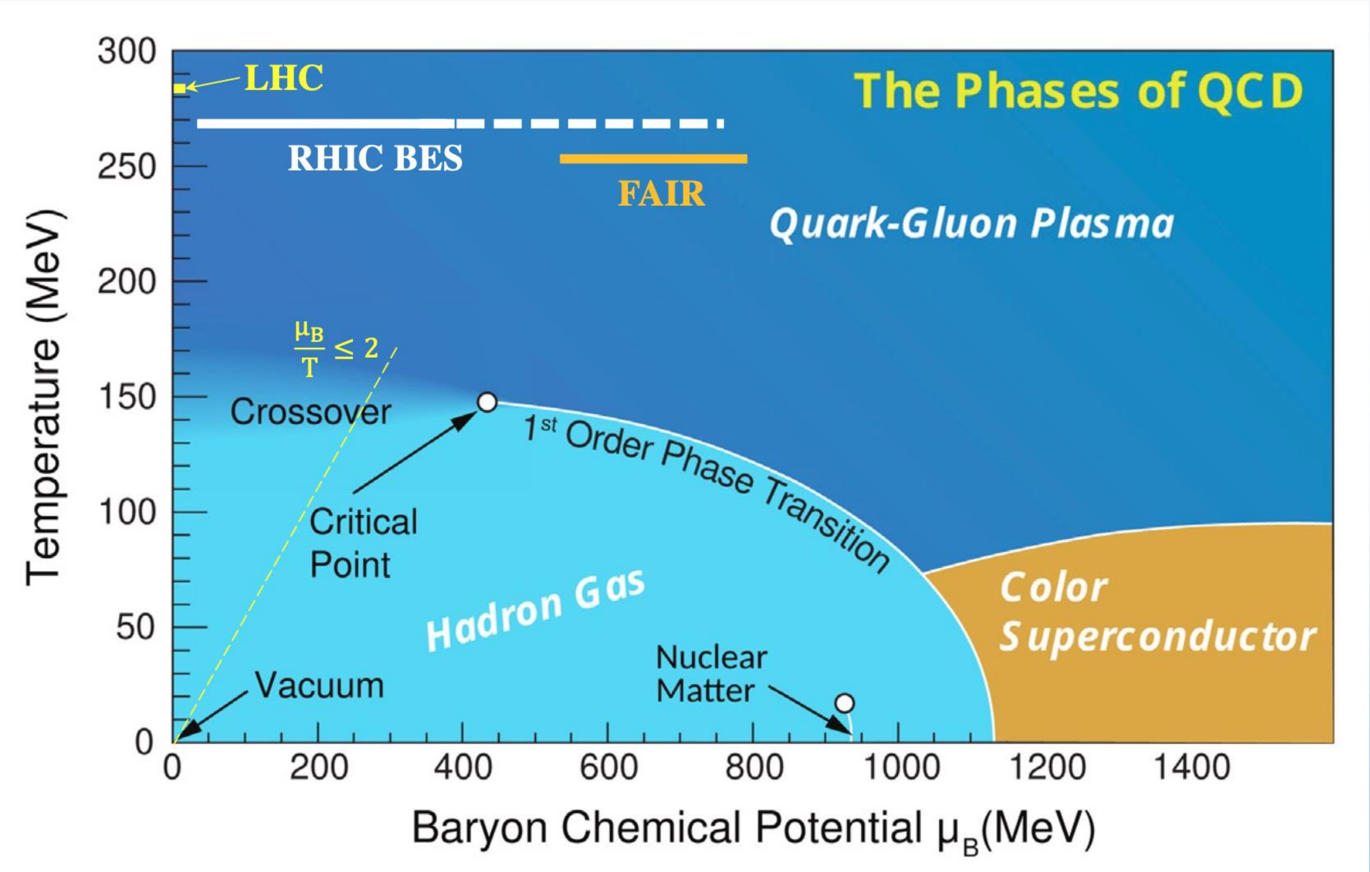
June 13, 2024

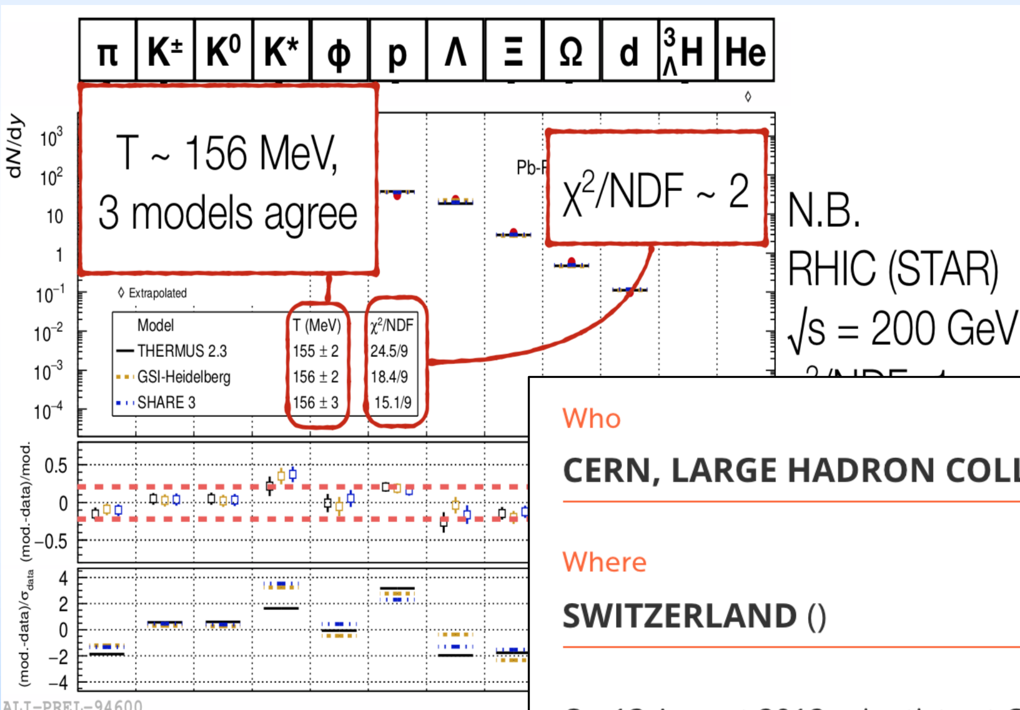
What Are We Studying?

- The emergent, many-body properties of the strong force (i.e. nuclear matter)



New State of Matter Found in AA:

- Species abundancies => hottest temperatures ever measured



J Cleymans, HEPP2018

Who

CERN, LARGE HADRON COLLIDER

What

5X10^12 DEGREE(S) KELVIN

Where

SWITZERLAND ()

When

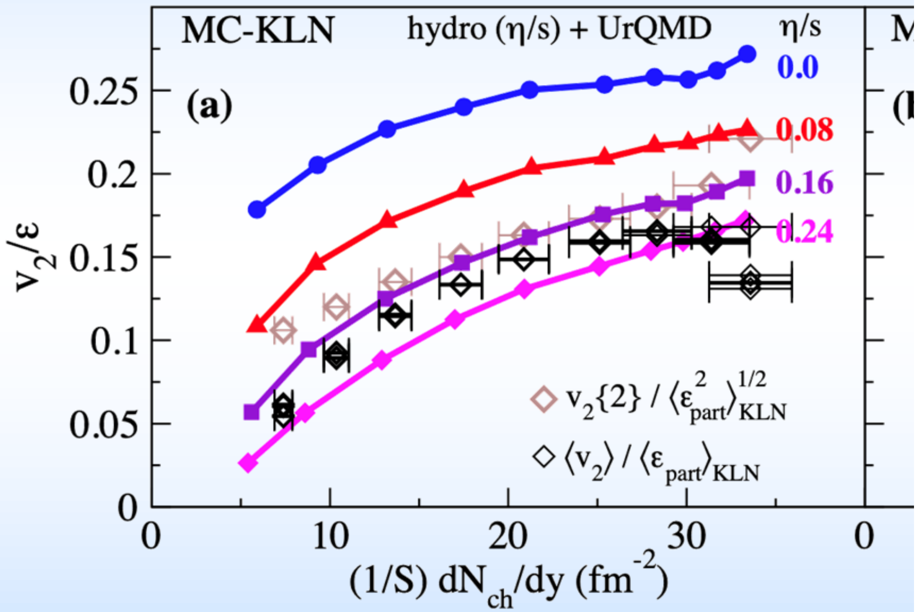
13 AUGUST 2012

On 13 August 2012 scientists at CERN's Large Hadron Collider, Geneva, Switzerland, announced that they had achieved temperatures of over 5 trillion K and perhaps as high as 5.5 trillion K. The team had been using the ALICE experiment to smash together lead ions at 99% of the speed of light to create a quark gluon plasma – an exotic state of matter believed to have filled the universe just after the Big Bang.

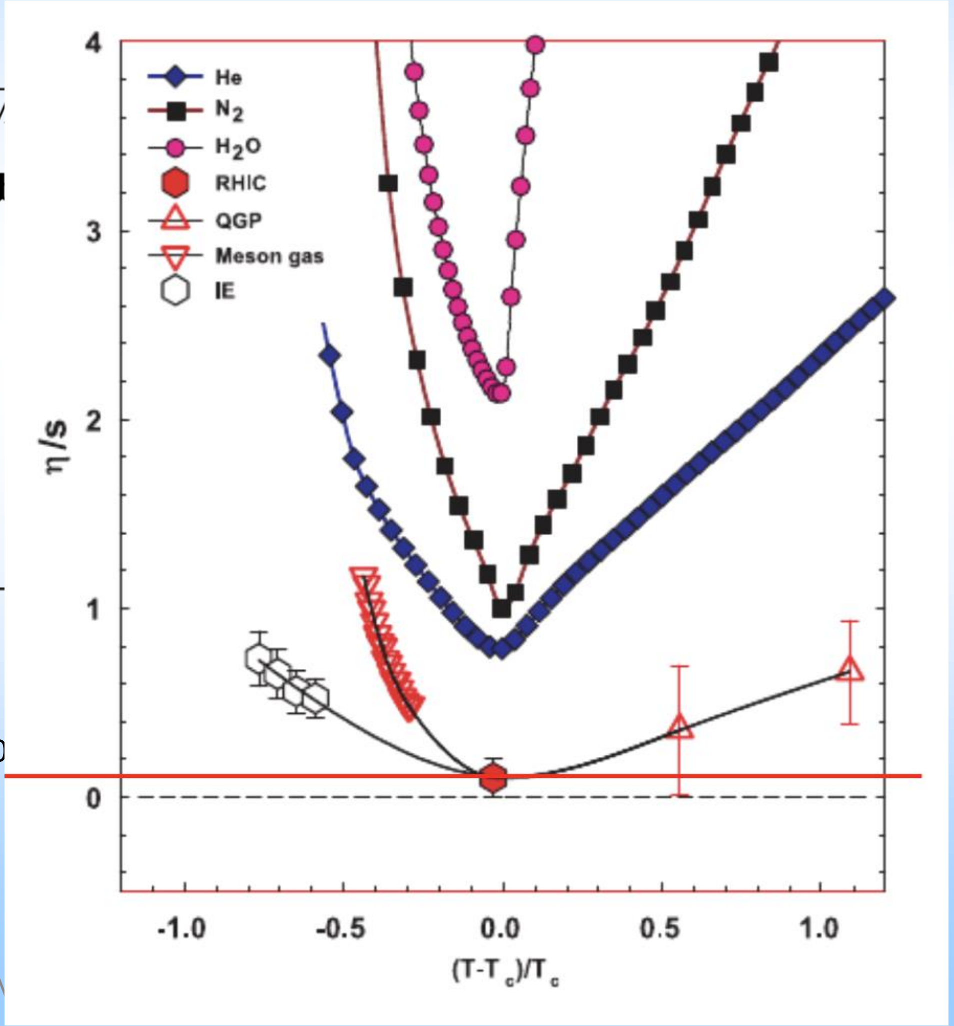
http://www.guinnessworldrecords.com/world-records/highest-man-made-temperature

New State of Matter Found in AA:

- Particle correlations => hydrodynamic flow of perfect fluid

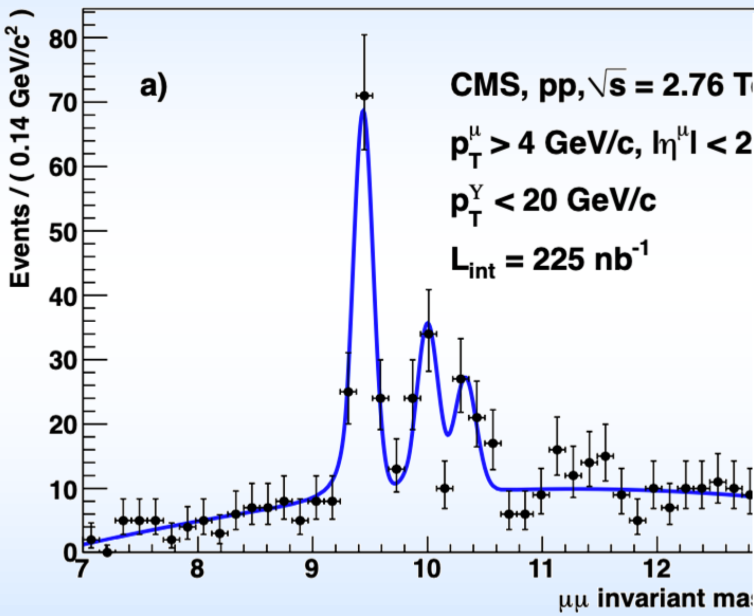


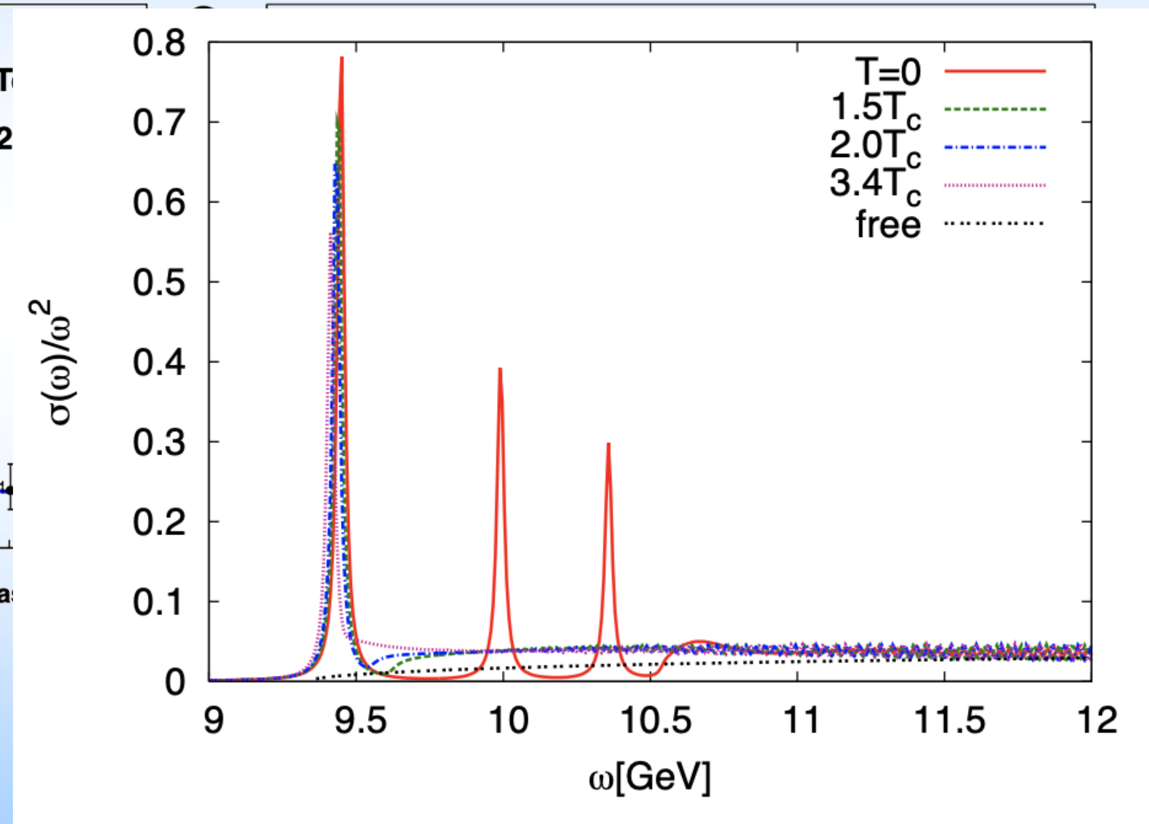
Song et al, PRL106 (20



New State of Matter in AA:

- Quarkonia melting => deconfined plasma

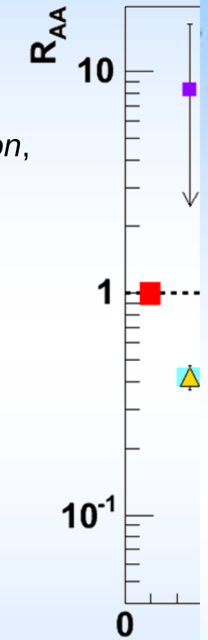




Mócsy and Petreczky, PRL99 (2007)

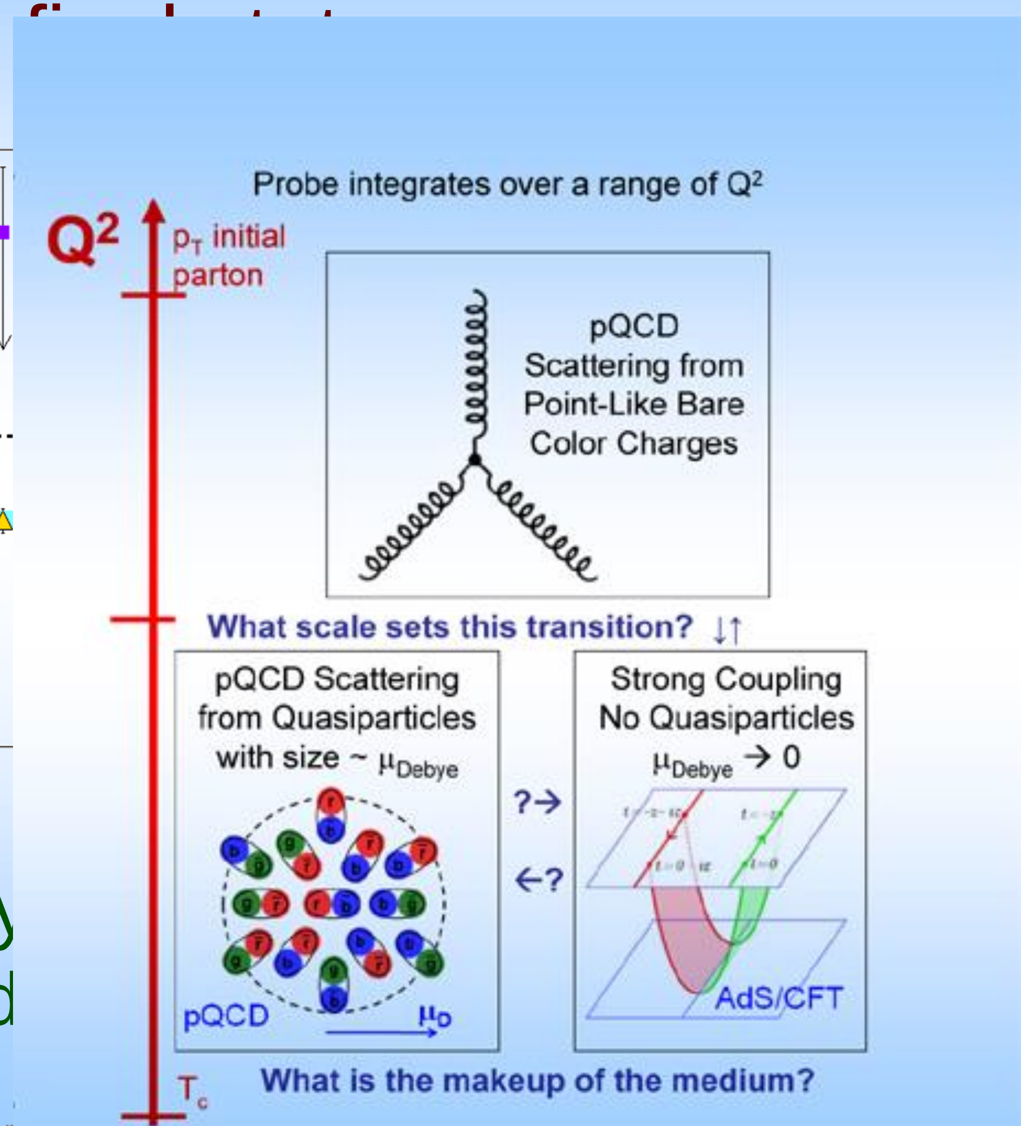
New State of Matter in AA:

- Particle suppression: fi... loss to medium



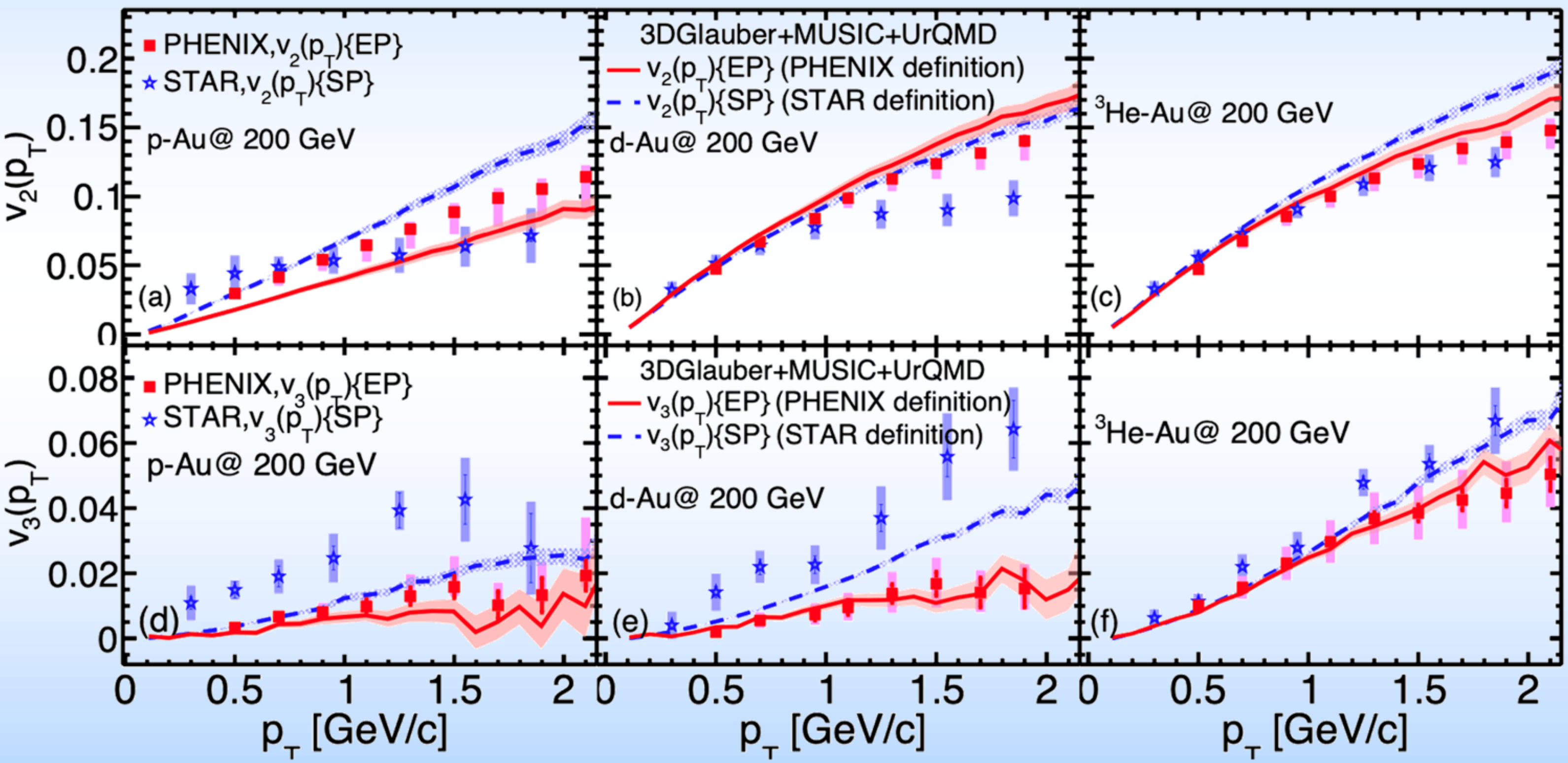
Y. Akiba *for the PHENIX collaboration*, hep-ex/0510008

- – Consistency: $R_{AA}(\eta)\sim R_{AA}(\pi)$
- – Null Control: $R_{AA}(\gamma)\sim 1$
- – GLV Prediction: Theory fixed L~5 fm and dN_g/d



New State of Matter in Small Systems?

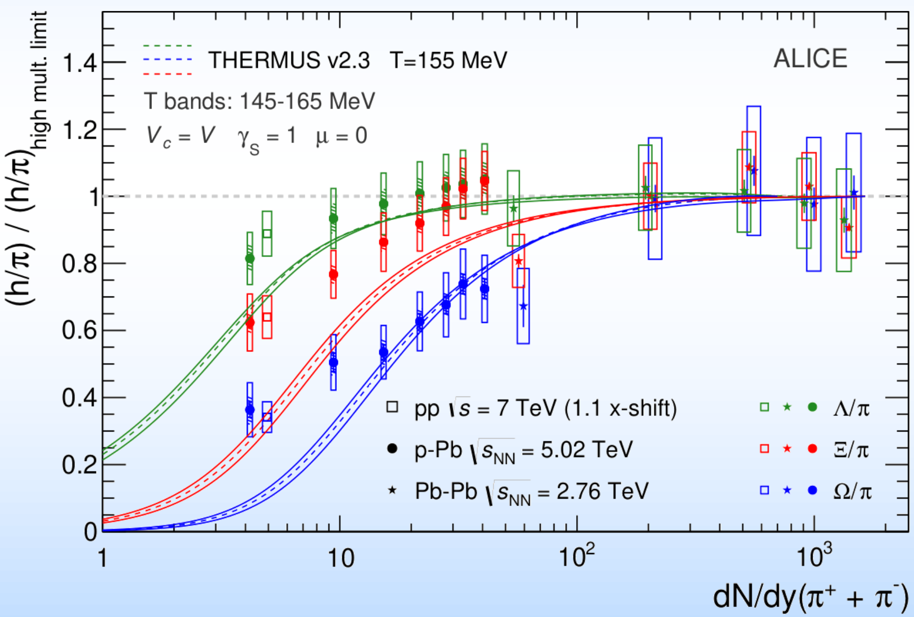
- Flow observed



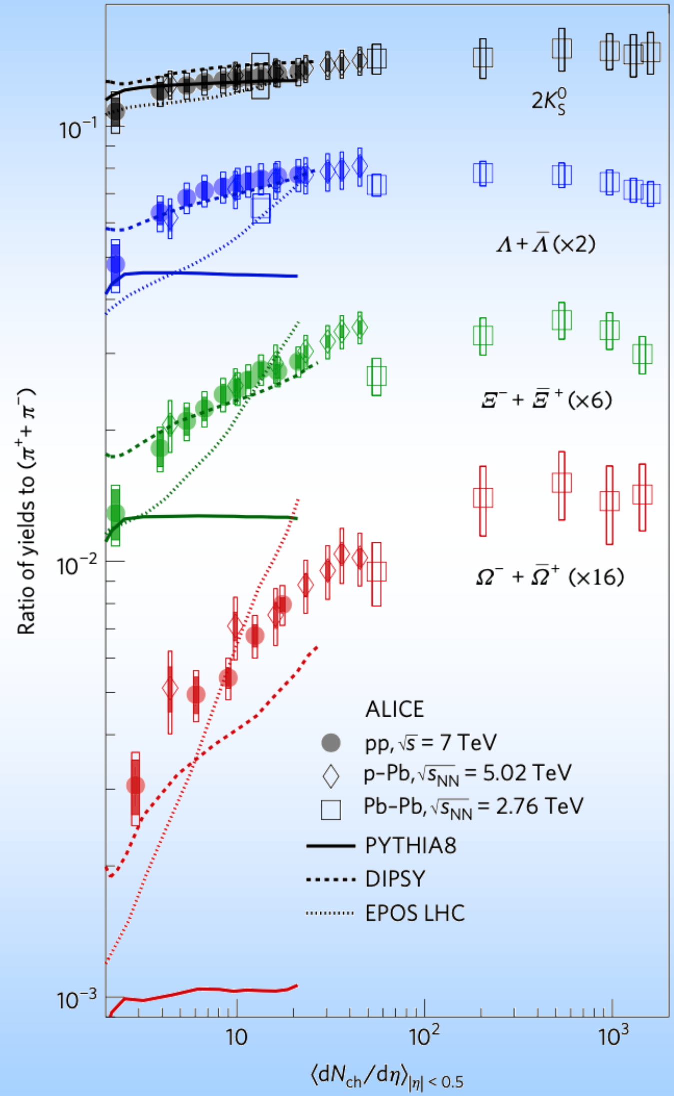
Zhao et al, PRC107 (2023) and Schenke SQM2024

New State of Matter in Small Systems?

- Strangeness enhanced



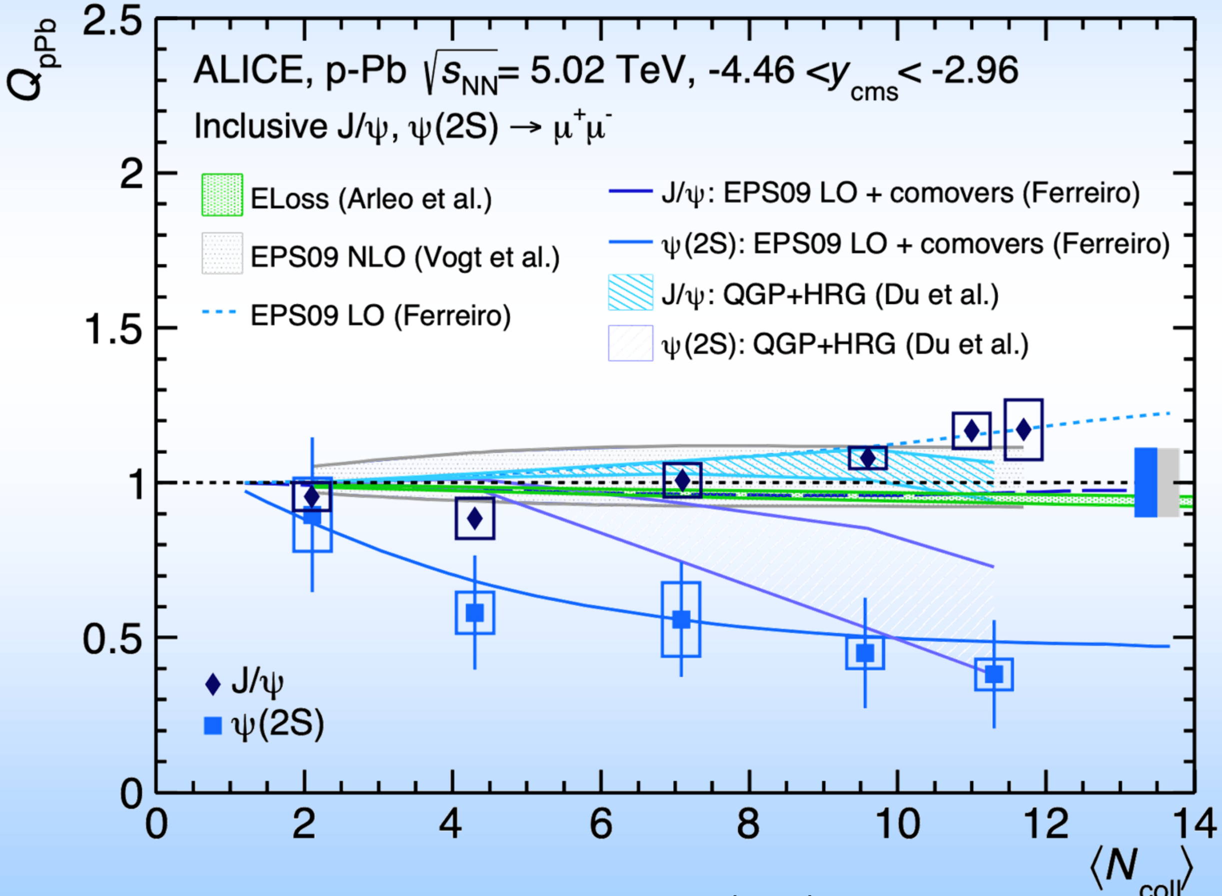
ALICE, PLB 758 (2016) 389-401



ALICE, Nature Physics (2017)

New State of Matter in Small Systems?

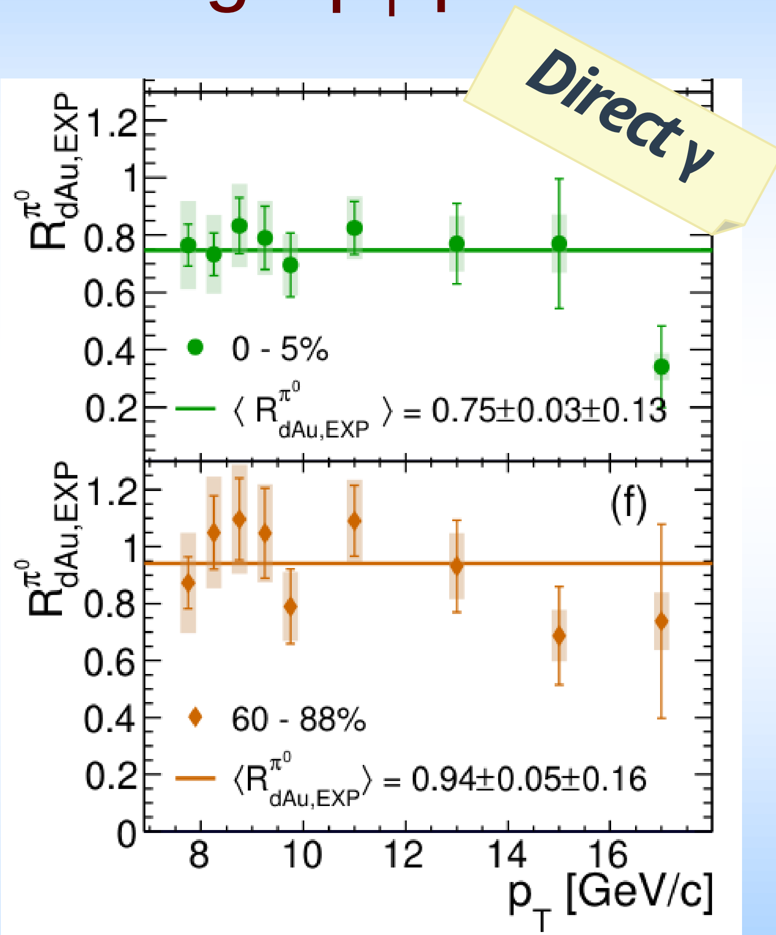
- Quarkonium suppression



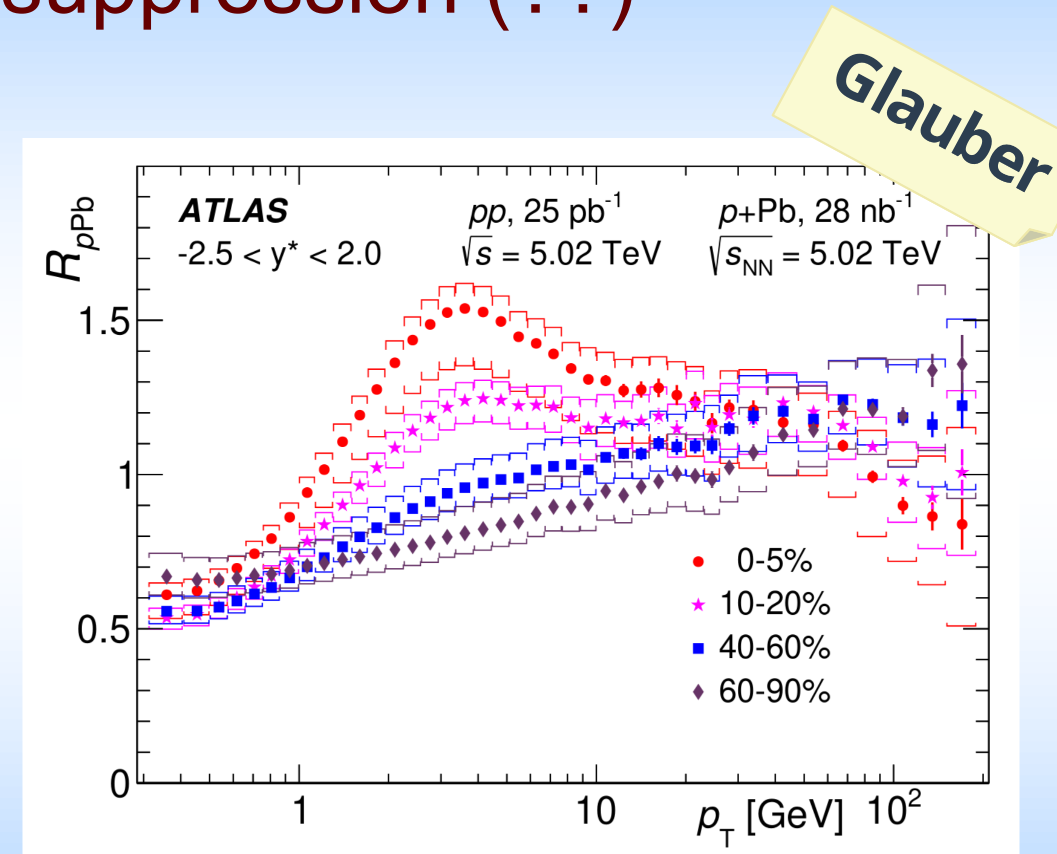
ALICE, JHEP 06 (2016)

New State of Matter in Small Systems?

- High-p_T particle…suppression (??)



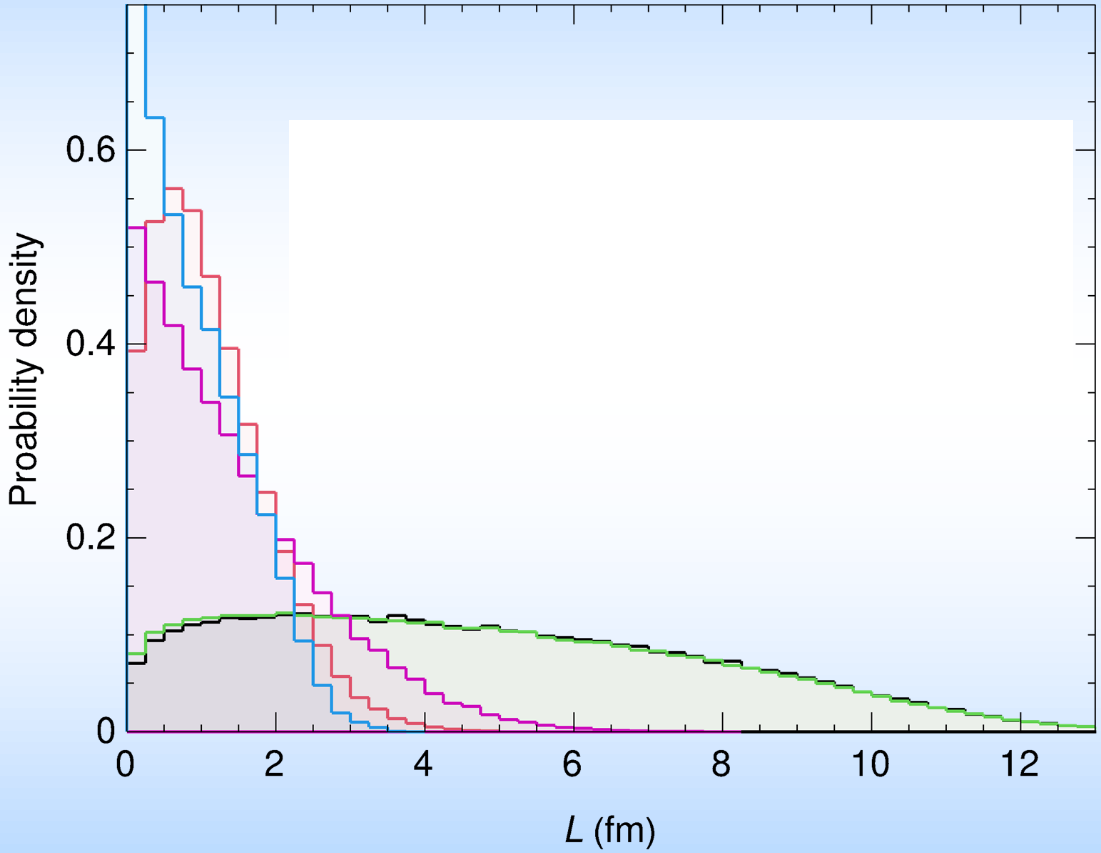
PHENIX, arXiv:2303.12899



ATLAS, JHEP 07 (2023) 074

Energy Loss in Small Systems

- Is there any? Isn't medium tiny?



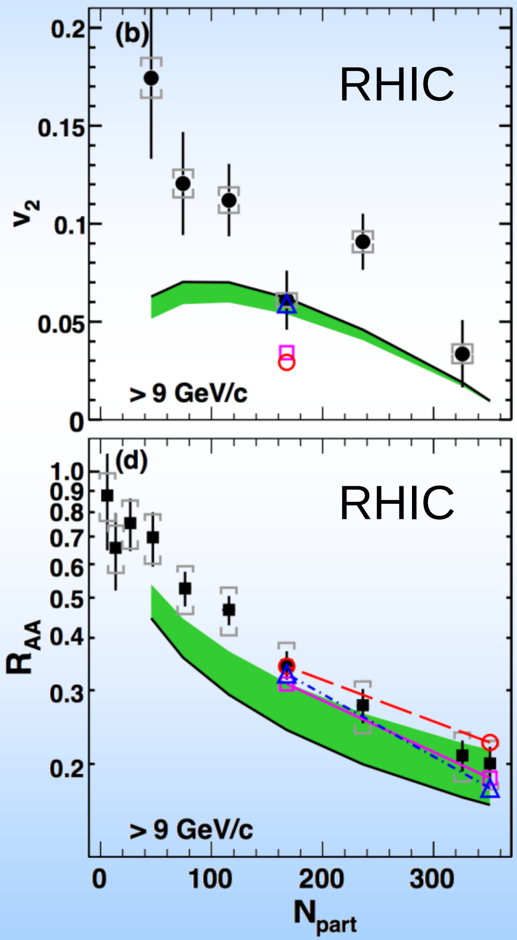
Cole Faraday

Faraday and WAH, in prep

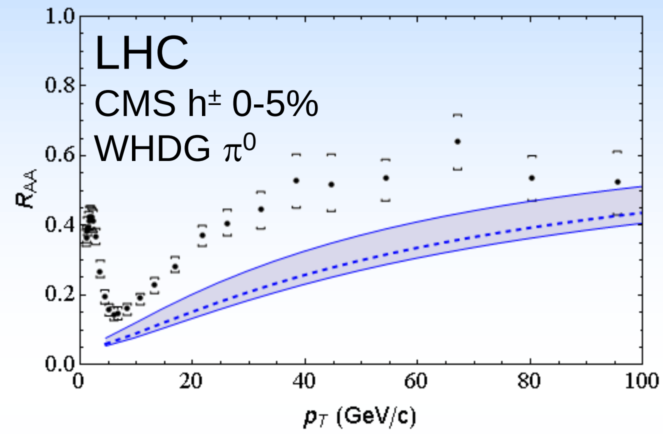
  - Small systems have non-trivial paths through them, similar to peripheral AA

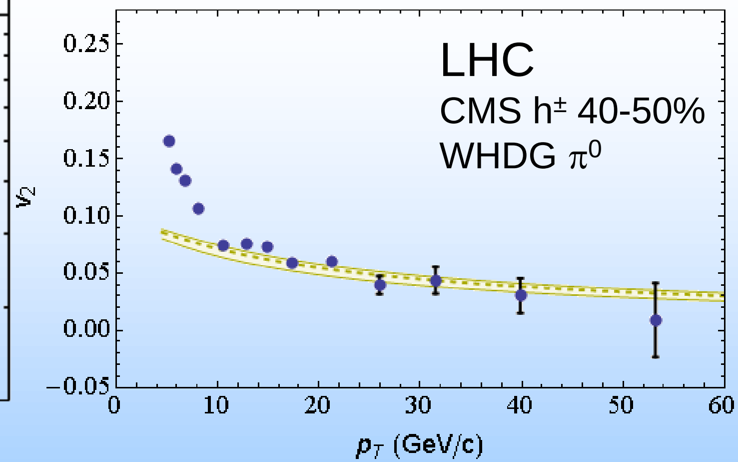
Energy Loss Mod's in Small Systems?

- Start with WHDG Rad + El + geom in AA

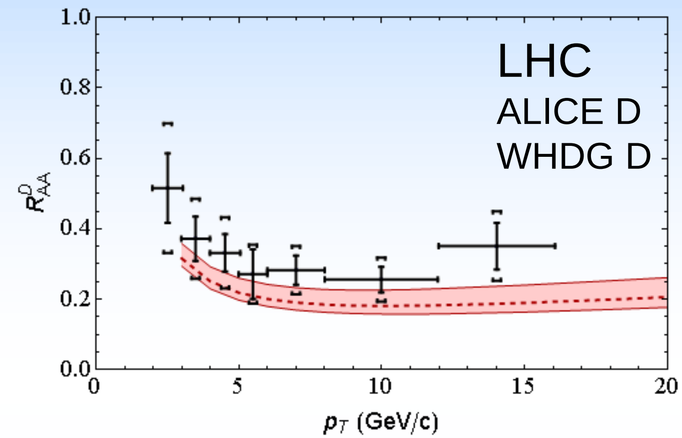


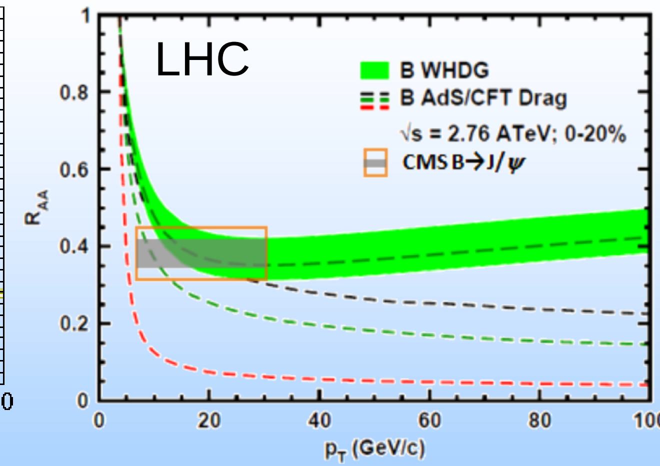
PHENIX PRL105 (2010)





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

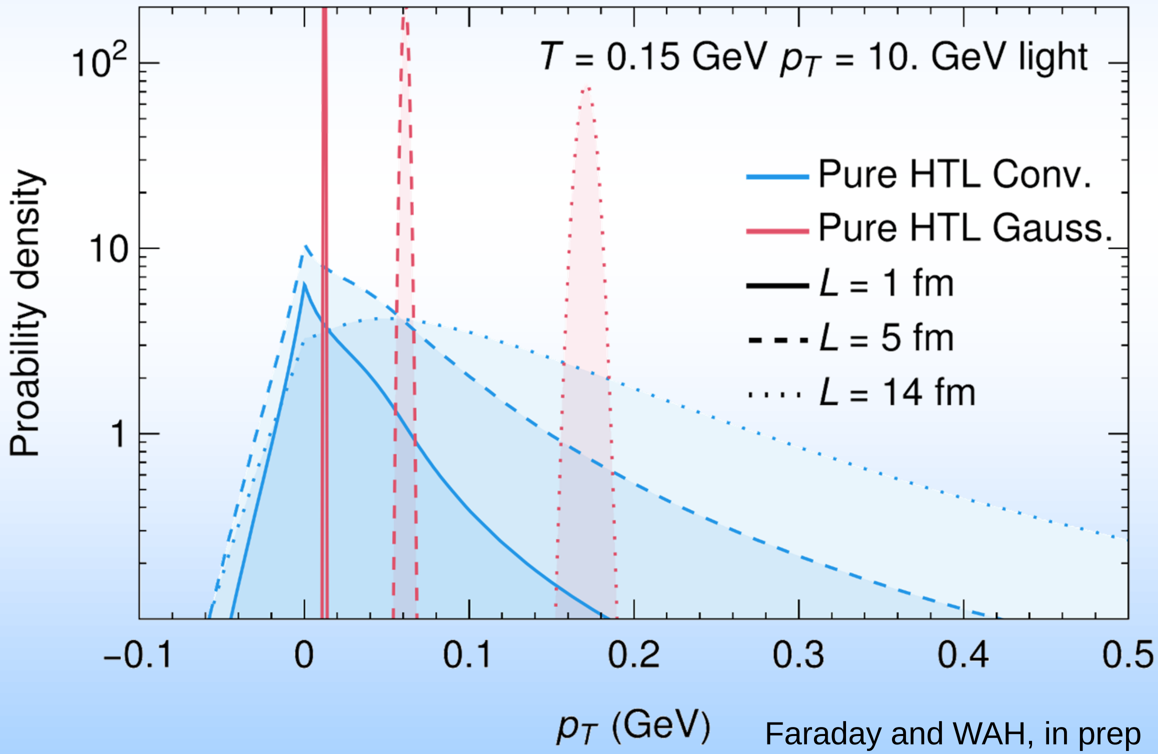




ALICE, JHEP1209 (2012) 112
CMS, JHEP 1205 (2012) 063

Changes Needed:

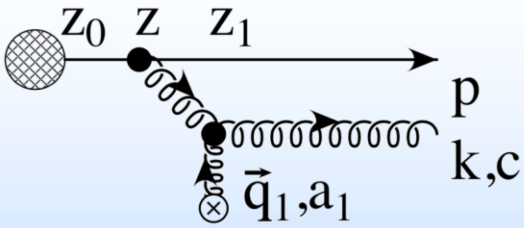
- Realistic fluctuations in elastic energy loss
  - Gaussian/F-D Thm => Poisson



Faraday and WAH, in prep

Changes Needed:

- Small system corrections to rad e-loss
  - DGLV ordering of scales $1/\mu_{\text{Debye}} \ll \lambda_{\text{mfp}} \ll \tau_{\text{form}} \ll L_{\text{pathlength}}$ doesn't necessarily hold
  - Rederive, including previously neglected contributions



$$\text{Res}(-i\mu_1) \approx \frac{4\pi\alpha_s\, e^{-\mu_1(z_1-z_0)}}{(-2i\mu_1)E^+k^+(-i\mu_1)^2}$$

Isobel Kolbé

Kolbé and WAH, PRC100 (2019)

Rad Correction:

- Short path length (SPL) correction:

$$x\frac{\mathrm{d}N}{\mathrm{d}x} = \frac{C_R\alpha_s L}{\pi\lambda_g}\int\frac{\mathrm{d}^2\mathbf{q}_1}{\pi}\frac{\mu^2}{\left(\mu^2+\mathbf{q}_1^2\right)^2}\int\frac{\mathrm{d}^2\mathbf{k}}{\pi}\int \mathrm{d}\Delta z\,\bar{\rho}(\Delta z)$$

$$\times\left[-\frac{2\left\{1-\cos\left[\left(\omega_1+\tilde{\omega}_m\right)\Delta z\right]\right\}}{\left(\mathbf{k}-\mathbf{q}_1\right)^2+\chi}\left[\frac{\left(\mathbf{k}-\mathbf{q}_1\right)\cdot\mathbf{k}}{\mathbf{k}^2+\chi}-\frac{\left(\mathbf{k}-\mathbf{q}_1\right)^2}{\left(\mathbf{k}-\mathbf{q}_1\right)^2+\chi}\right]\right.$$

(DGLV)

$$+\frac{1}{2}e^{-\mu_1\Delta z}\left(\left(\frac{\mathbf{k}}{\mathbf{k}^2+\chi}\right)^2\left(1-\frac{2C_R}{C_A}\right)\left\{1-\cos\left[\left(\omega_0+\tilde{\omega}_m\right)\Delta z\right]\right\}\right.$$

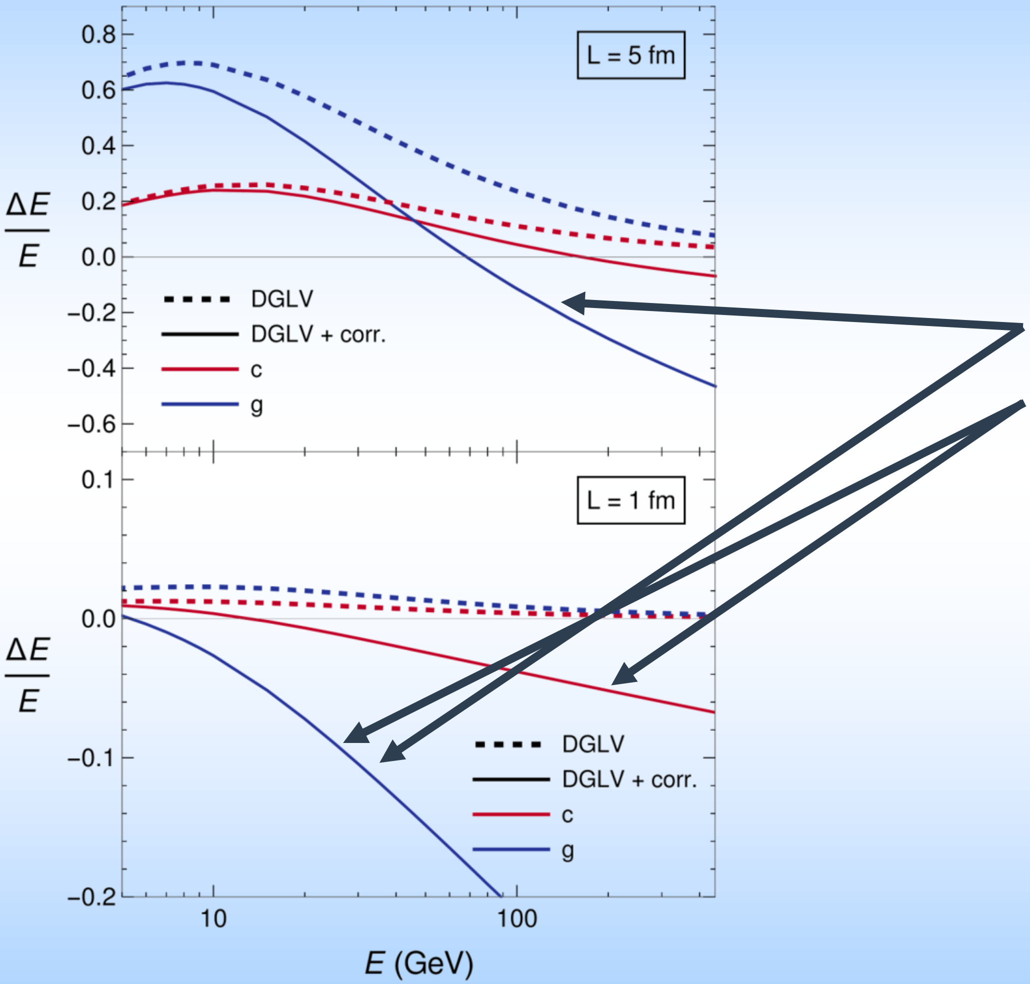
$$\left.\left.+\frac{\mathbf{k}\cdot\left(\mathbf{k}-\mathbf{q}_1\right)}{\left(\mathbf{k}^2+\chi\right)\left(\left(\mathbf{k}-\mathbf{q}_1\right)^2+\chi\right)}\left\{\cos\left[\left(\omega_0+\tilde{\omega}_m\right)\Delta z\right]-\cos\left[\left(\omega_0-\omega_1\right)\Delta z\right]\right\}\right)\right]$$

(SPL)

Kolbé and WAH, PRC100 (2019)

  - => 0 as m => 0, Δz => 0
  - breaks color triviality

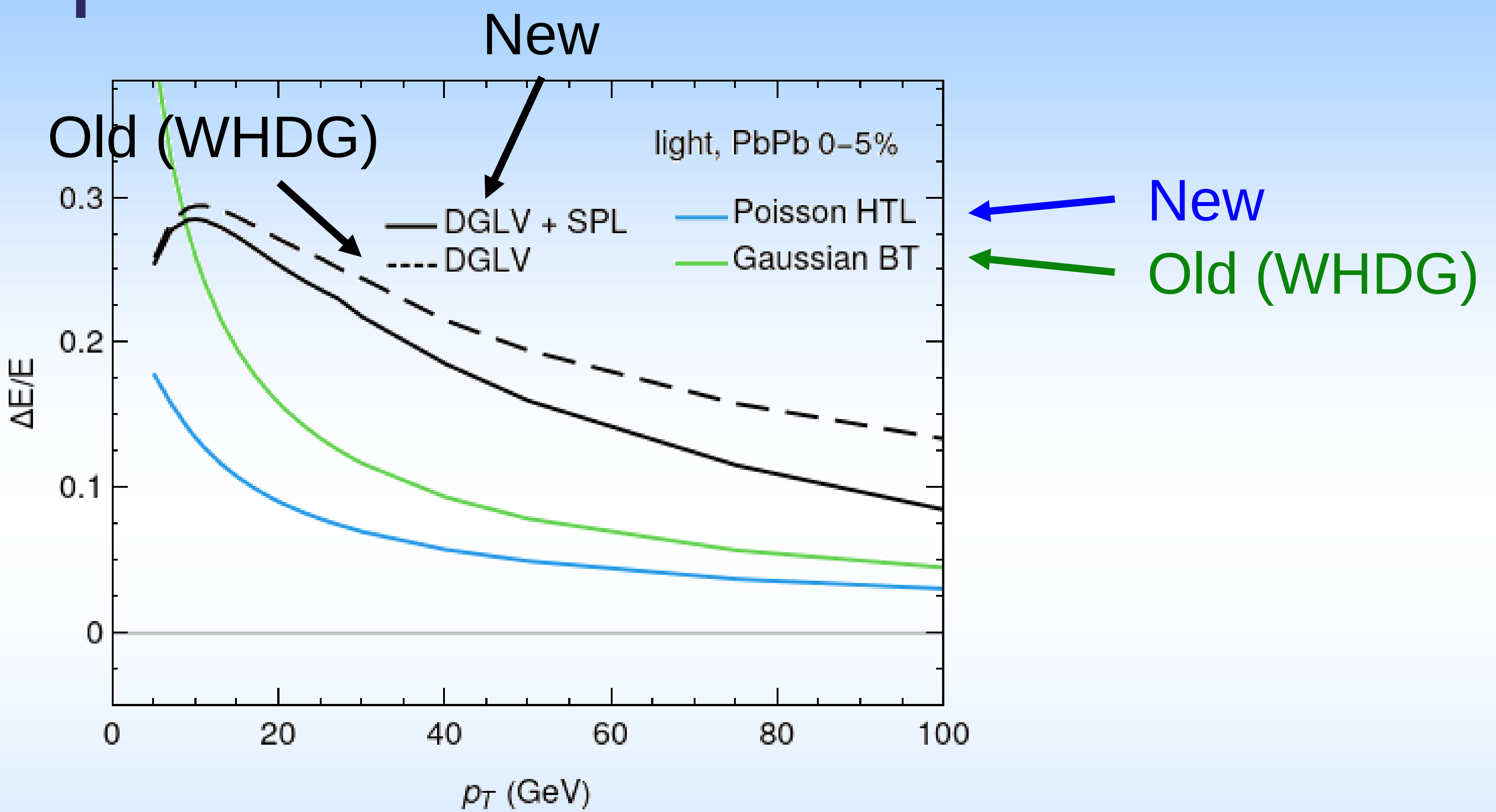
Rad Correction:



We see the SPL correction:

- Smaller as a function of *L*
- Much larger for gluons cf quarks
- Can lead to **negative** energy loss
- Larger as a function of E

Comparison of E-Loss Channels

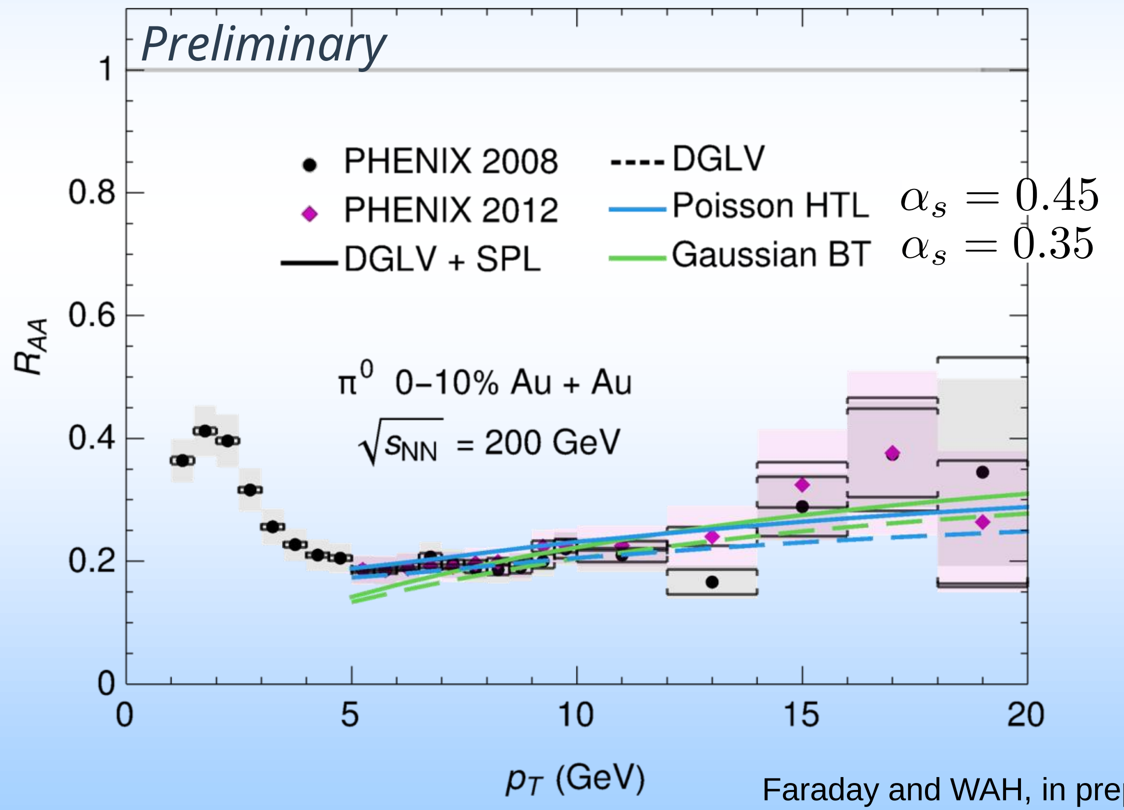


Faraday and Horowitz, in prep

- Change to full HTL propagators and Poisson reduces elastic loss significantly cf WHDG
- SPL => destructive interference => reduced e-loss

Compare to Data: AuAu

- Brand new (last week!) *preliminary* results
- Chi-by-eye from AuAu to fix α_s

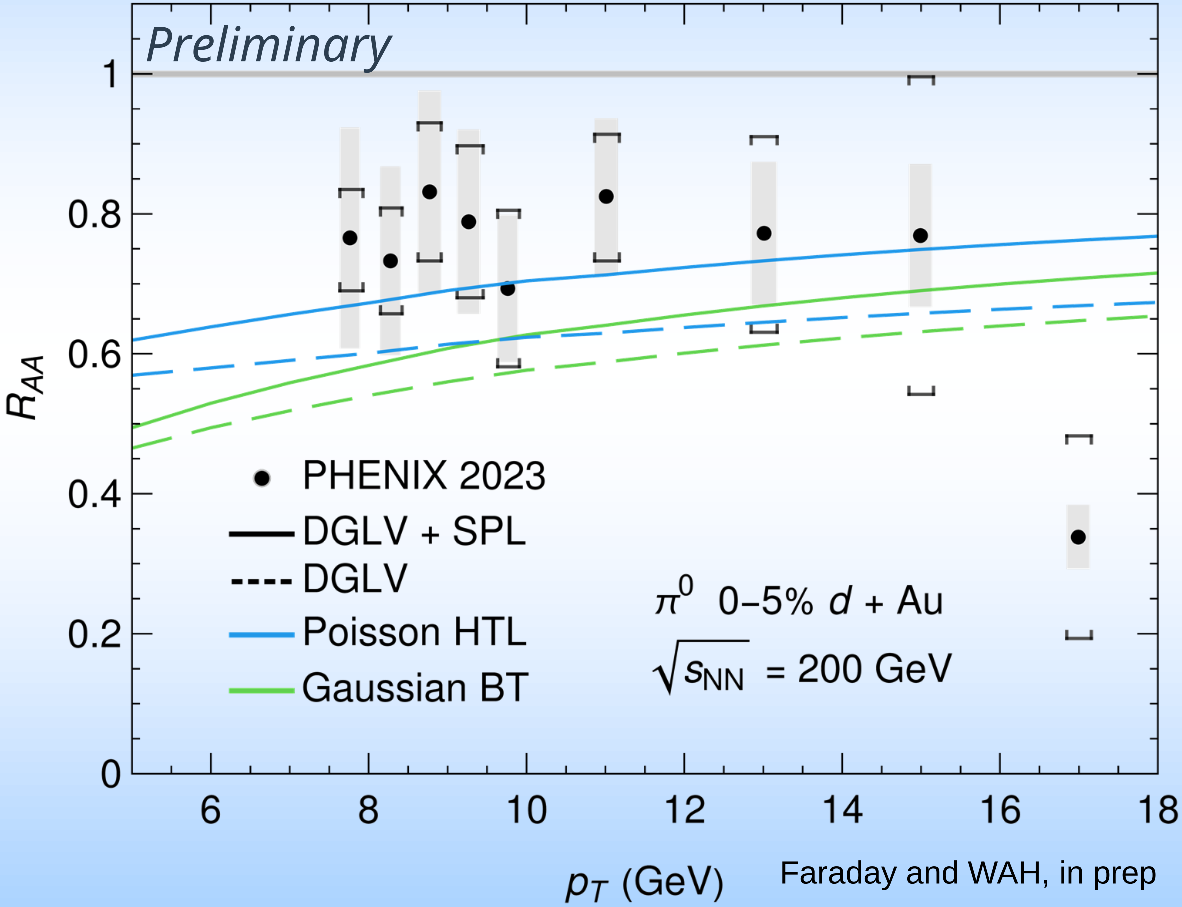


Cole Faraday

Faraday and WAH, in prep

Compare to Data: dA

- Theory predicts suppression in dA@RHIC

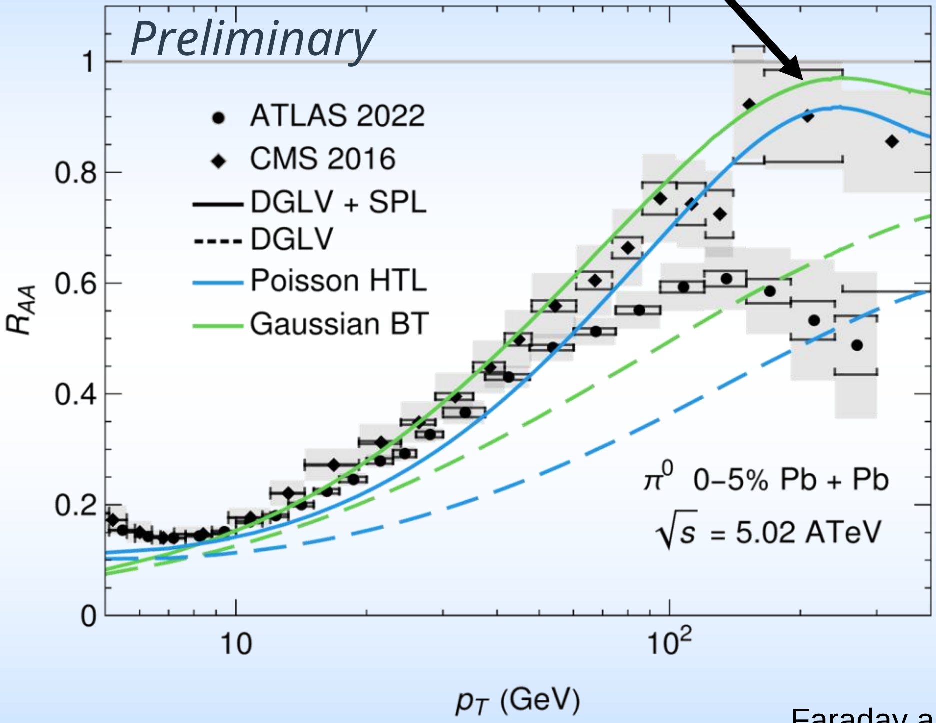


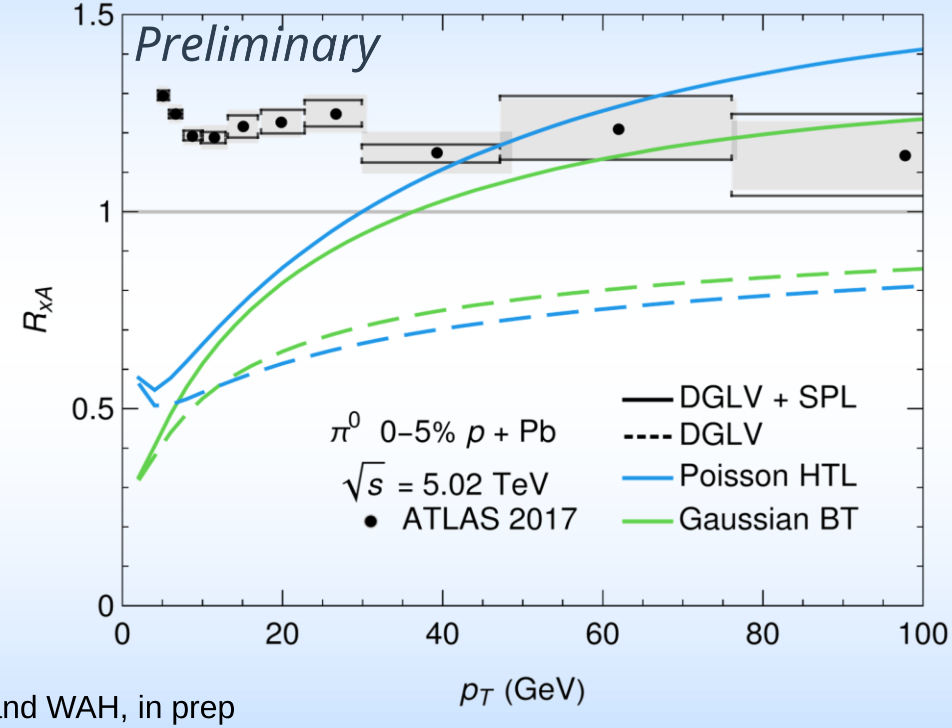
Faraday and WAH, in prep

  – Shockingly good agreement w data

Compare to Data: LHC π

SPL color triviality breaking

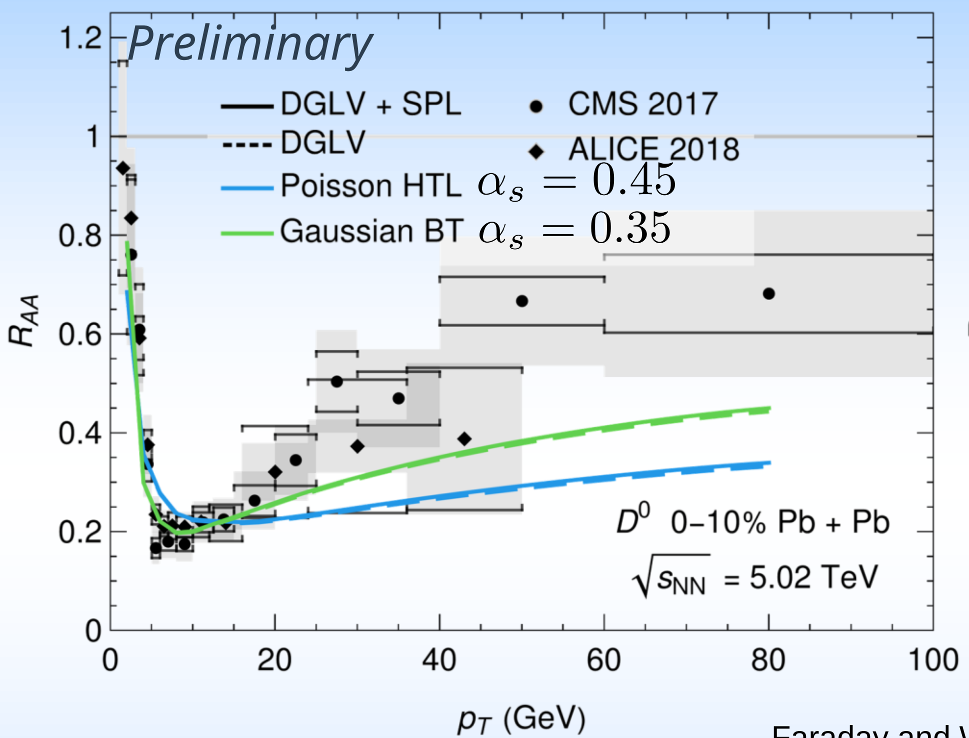


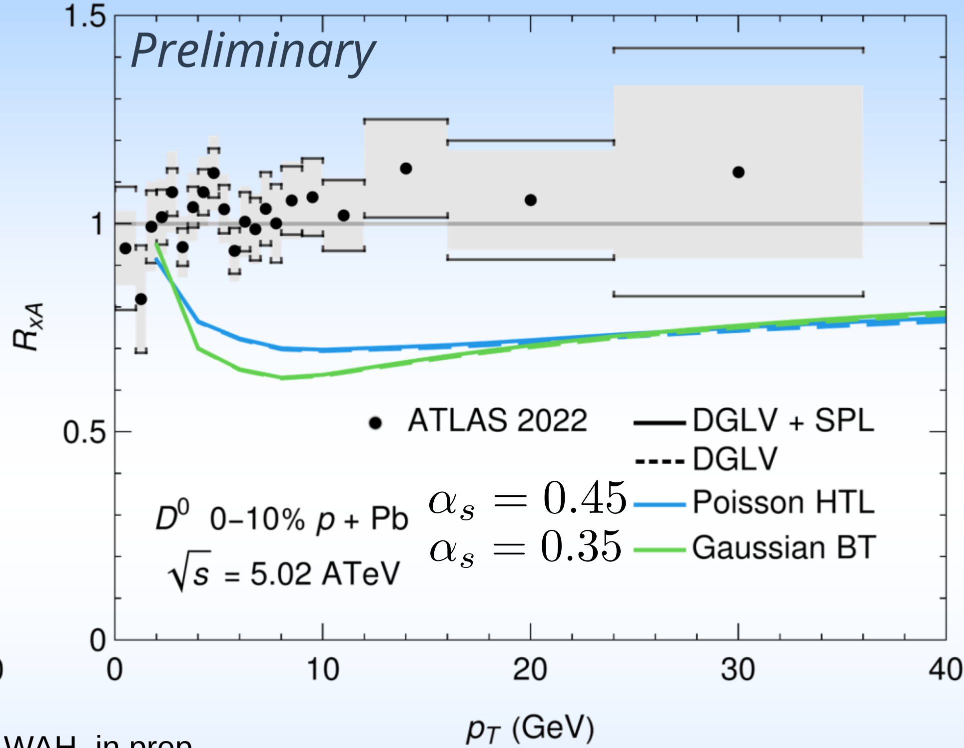


Faraday and WAH, in prep

– Results too good to be true?

Compare to Data: LHC D





Faraday and WAH, in prep

– HF predictions oversuppressed

- SPL small correction for quarks

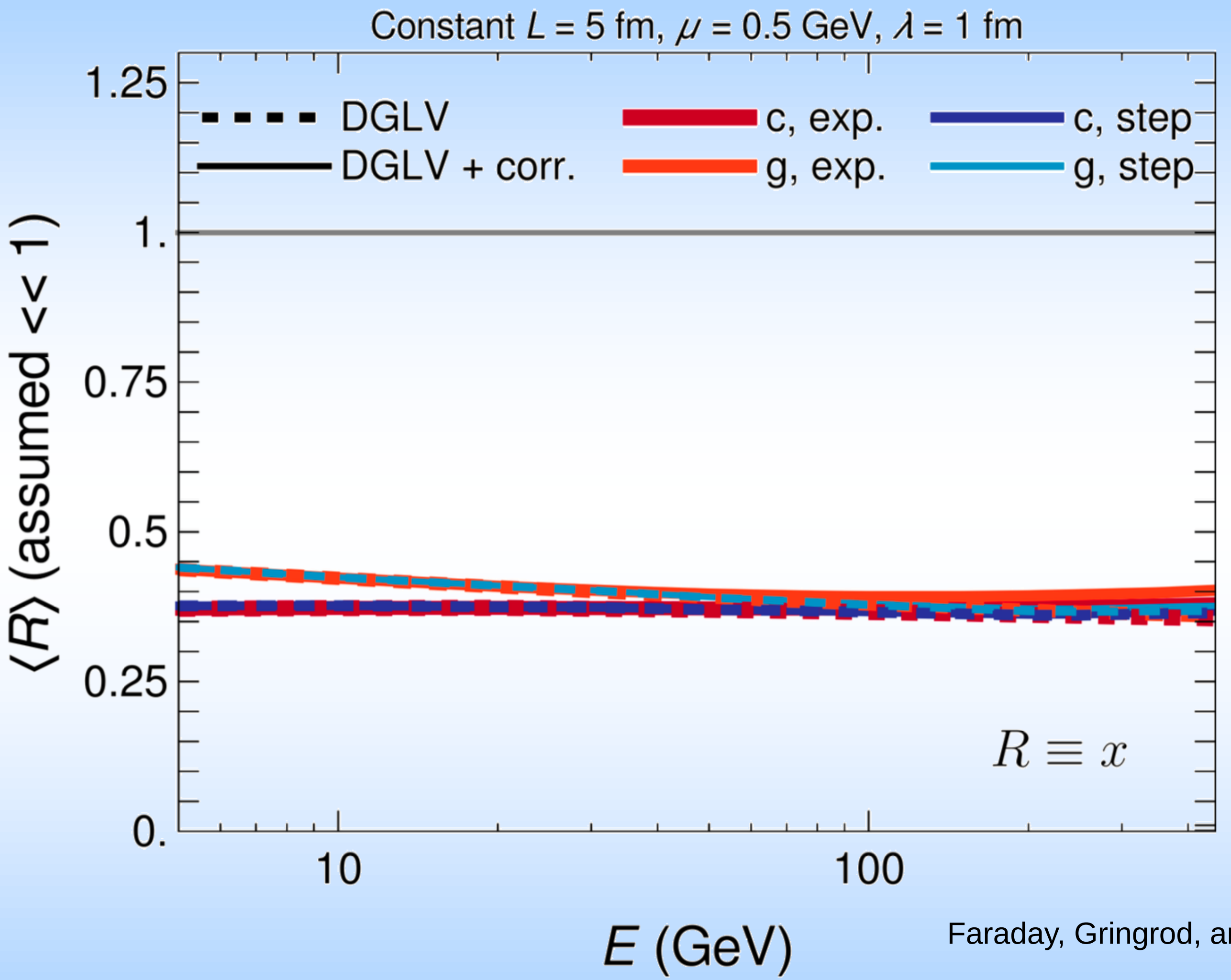
Is Model Self-Consistent?

- E-loss derivations make assumptions
  - Is E-loss model consistent with assumptions?
- Assumptions take form R << 1
  - Soft: R = x << 1
  - Collinear: R = k^-/k^+ << 1
  - Large Pathlength: R = $1/\Delta z\, m$ << 1
  - Large Formation Time: R = $k^2/2xE\mu_1$ << 1
- Introduce E-loss weighted R:

$$\langle R \rangle \equiv \frac{\int \mathrm{d}\{X_i\}\ R(\{X_i\}) \left|\frac{\mathrm{d}E}{\mathrm{d}\{X_i\}}\right|}{\int \mathrm{d}\{X_i\} \left|\frac{\mathrm{d}E}{\mathrm{d}\{X_i\}}\right|}$$

  - Are the assumptions violated in regions of importance for E-loss?

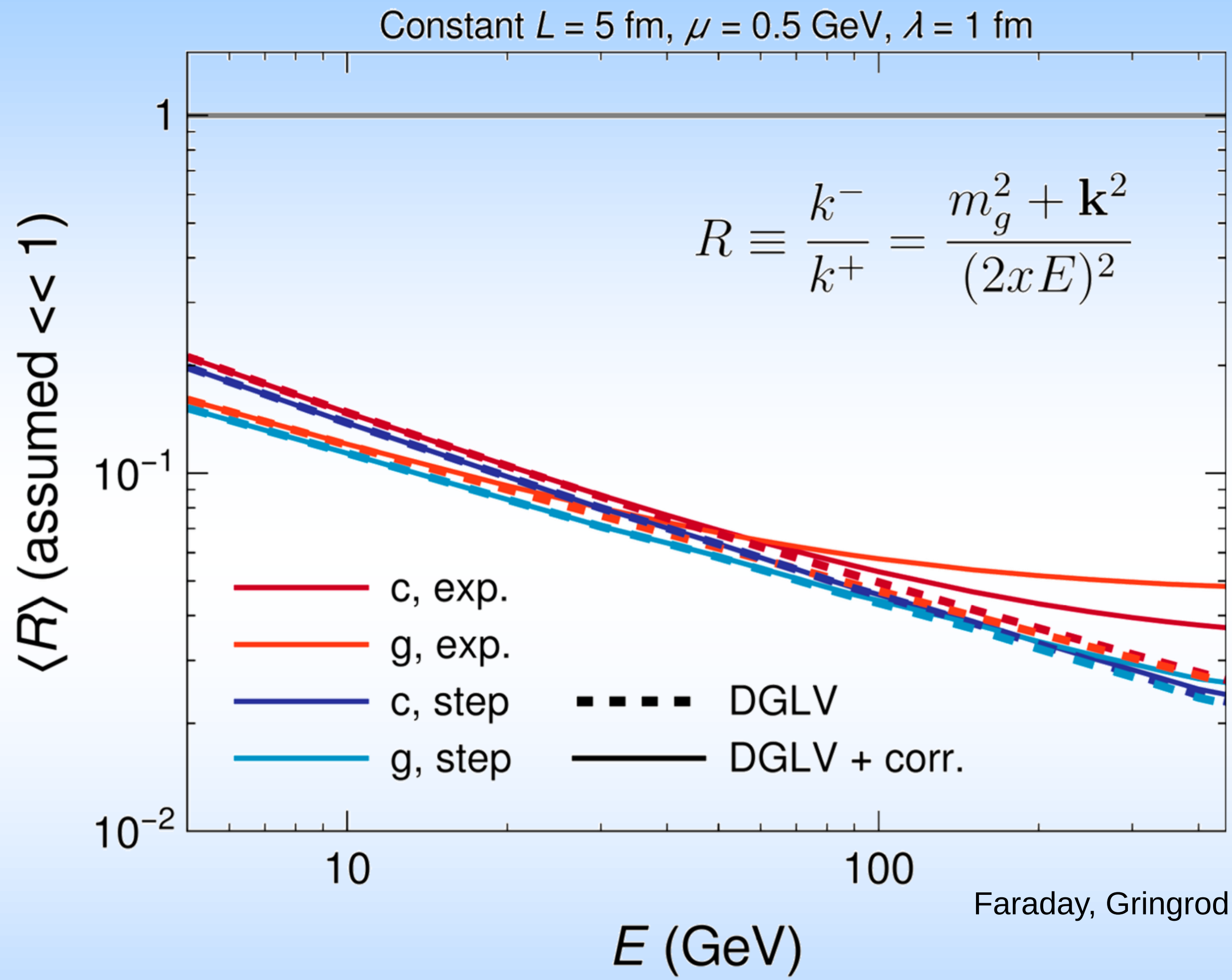
Check of Soft Approximation



Faraday, Gringrod, and WAH, EPJC83 (2023)

- Consistent for all models, energies, partons

Check of Collinear Assumption

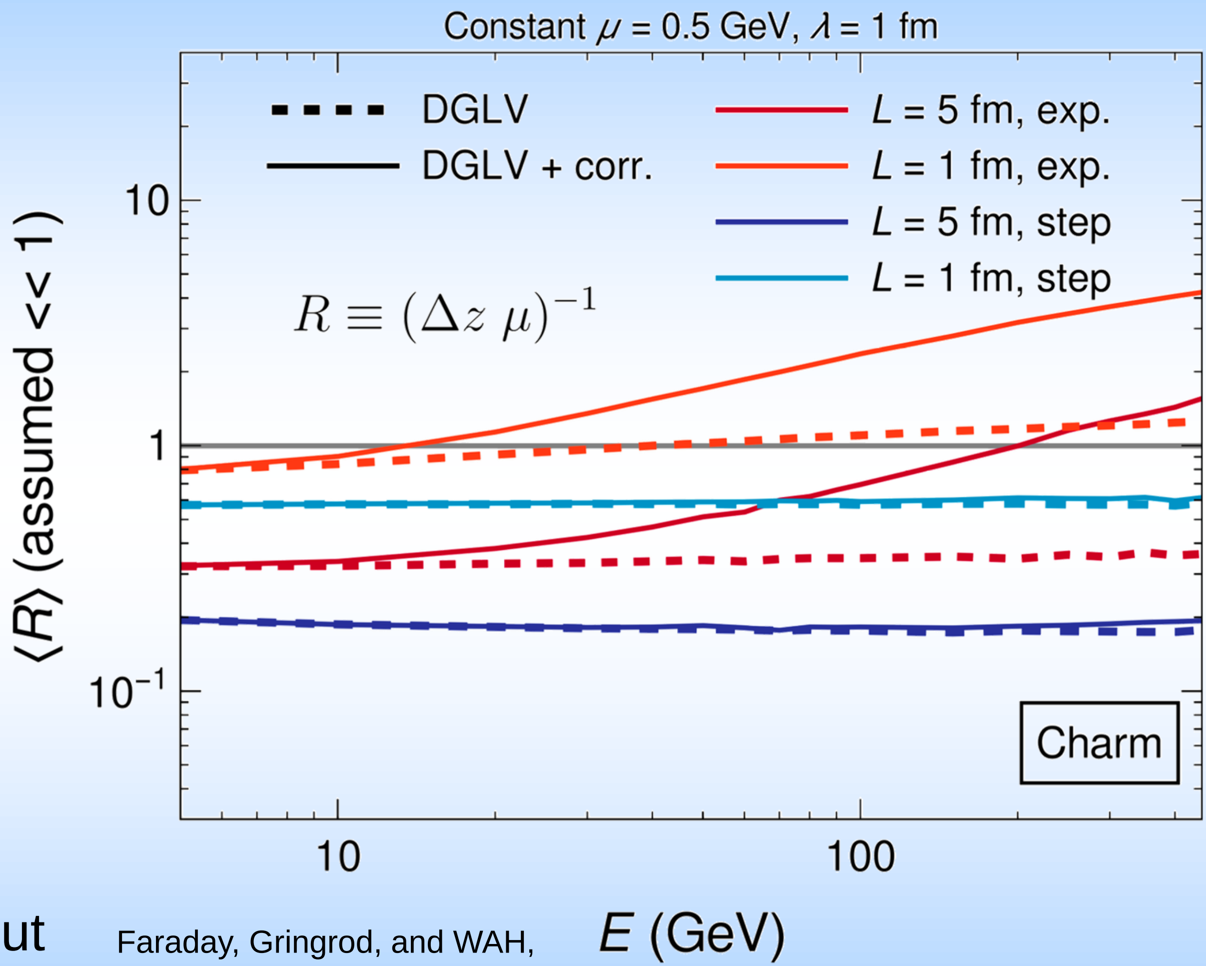


Faraday, Gringrod, and WAH, EPJC83 (2023)

- Consistent for all models, energies, partons
  - NB: enforced in part by phase space restrictions

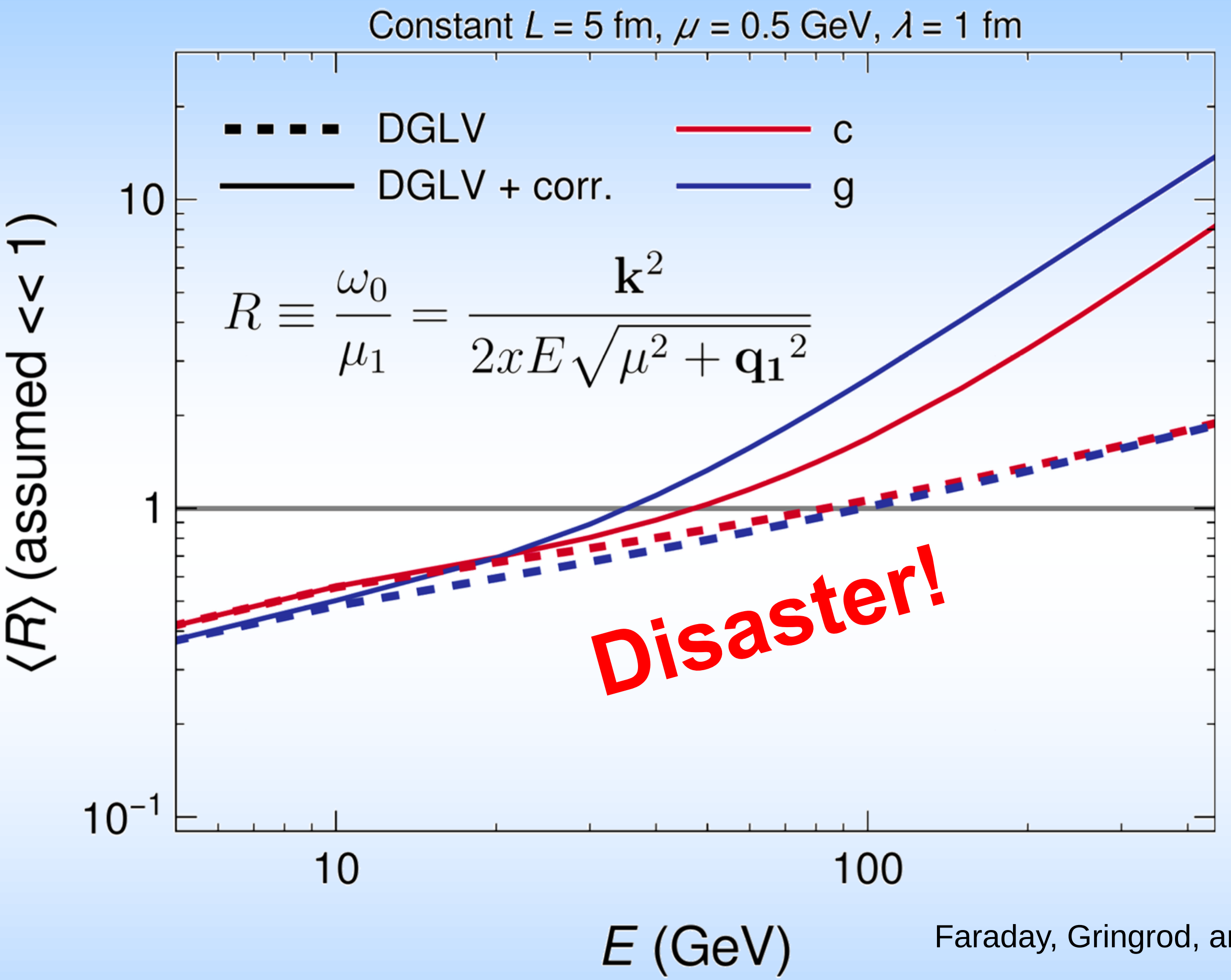
Check of Large Pathlength Assumption

- Large path length assumption depends sensitively on the distribution assumed for scattering centers
- $R_{DGLV} < 1$ self-consistently for L = 5 fm
- Once the correction is included, R > 1, even for L = 5 fm (at high enough energies).
  - R < 1 is a necessary but not sufficient condition for self-consistency



Faraday, Gringrod, and WAH, EPJC83 (2023)

Check of Large Formation Time Approx

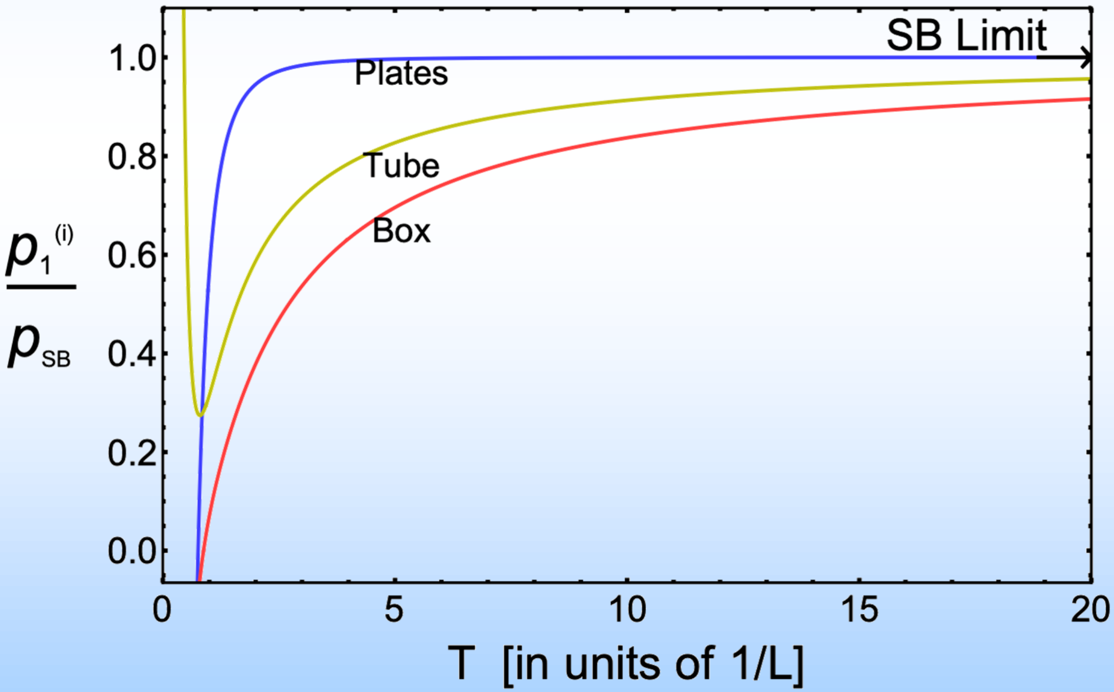


Faraday, Gringrod, and WAH, EPJC83 (2023)

- DGLV+SPL ***and*** DGLV violate LFT, at modest E (!!)
  - Insensitive to distribution of scattering centers and path length

Small Systems Modification to Hydro?

- Estimates show potentially significant corrections to thermodynamic quantities
  - Free, massless scalar field theory:

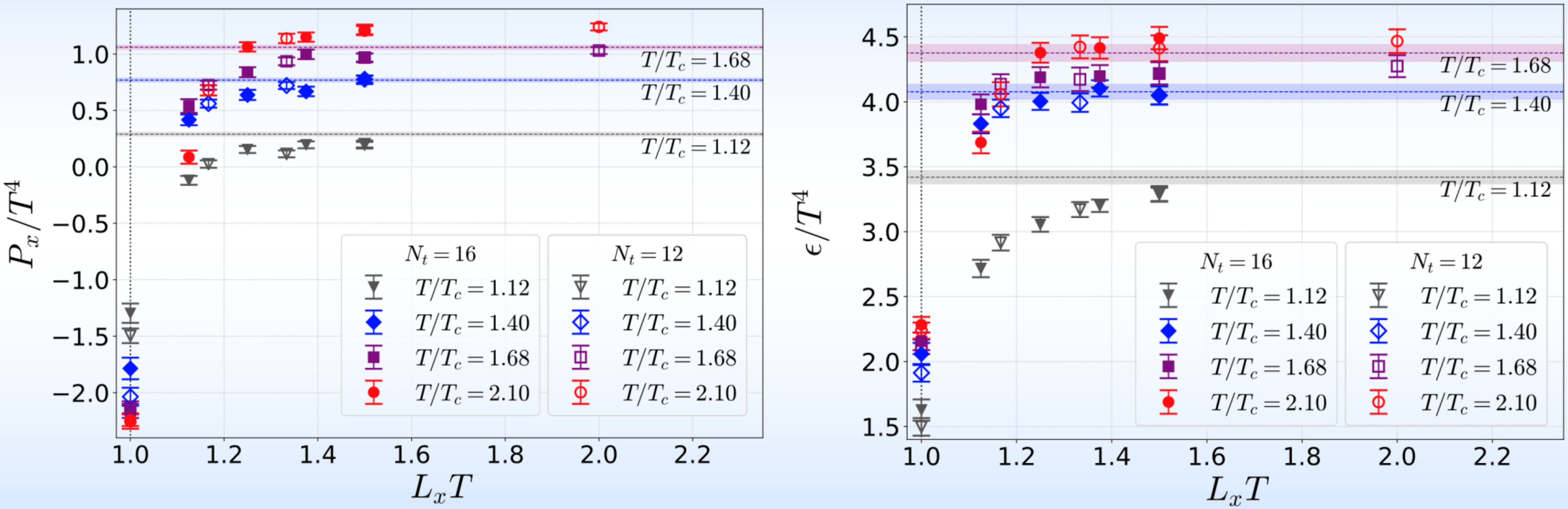


~10% effect at 400 MeV for ~1 fm system

Mogliacci, Kolbé, and WAH, PRD102 (2020)

FS Effects in Quenched QCD

- Thermodynamic quantities on anisotropic lattice with periodic boundary conditions



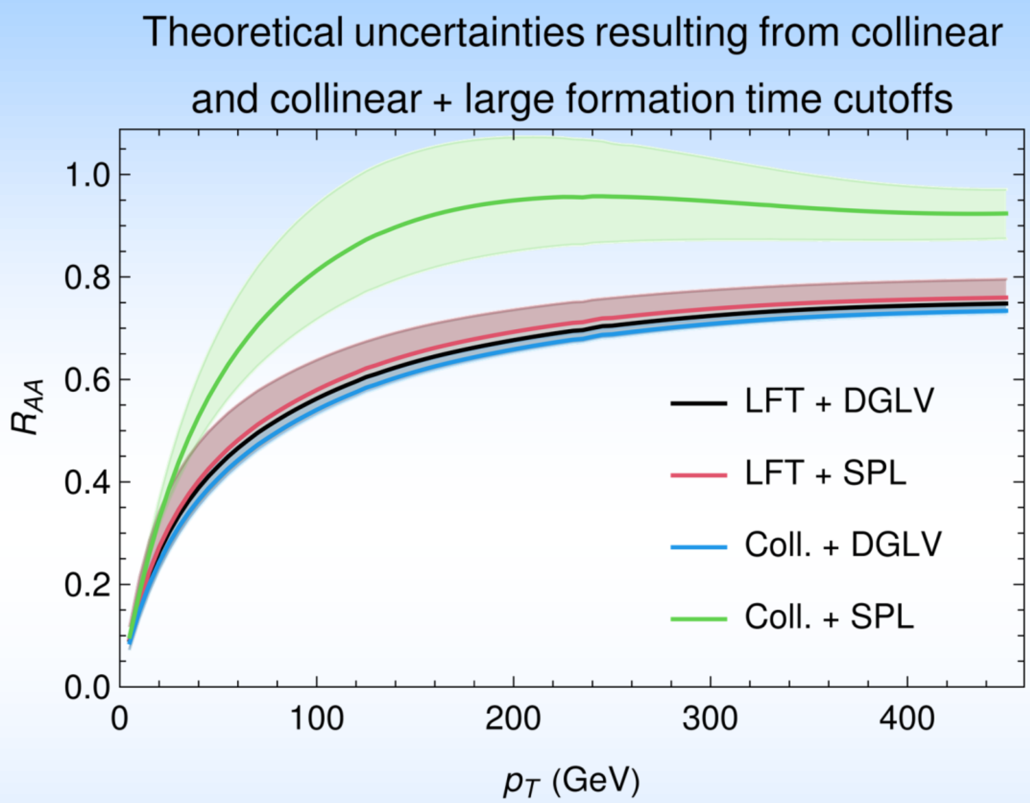
Kitazawa, Mogliacci, Kolbé, and WAH, PRD99 (2019)

  - Reduction of p, e with T*L qualitatively similar to free, massless scalar theory

Conclusions

- Small systems the frontier in many-body QCD
  - When do QGP signatures turn off?
    - Correlations seen in pp, γ^*A, inter-jet
    - Jet suppression in, e.g., high-multiplicity pp?
  - Measured N_{coll} (cf Glauber) determination in xA *critical*
    - Theory: significant suppression, consistent w RHIC data
  - Heavy flavor is a crucial consistency check
- Small systems derivations + models needed from theory
  - 1/L corrections can be large in e-loss and stat mech!
  - CAVEAT! E-loss formalisms require significant effort, need for overarching formalism and clear o-by-o exp'n

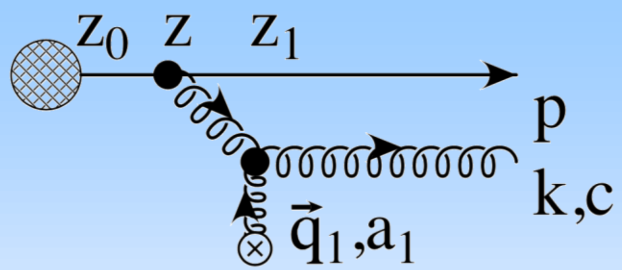
Sensitivity to LFT in SPL



Faraday and Horowitz, in prep

– Cutting out momentum space in integrals that violates the long formation time approximation significantly reduces the size of the short path length correction (cf black and red)

– Very important to re-compute SPL with LFT approximation relaxed



Neglected Poles

$$M_{1,0,1} = \int \frac{d^4 q_1}{(2\pi)^4}\, iJ(p+k-q_1)e^{i(p+k-q_1)x_0}\, \Lambda_1(p,k,q_1)V(q_1)e^{iq_1 x_1} \times$$
$$\times\, i\Delta_M(p+k-q_1)(-i)\Delta_{m_g}(k-q_1)$$

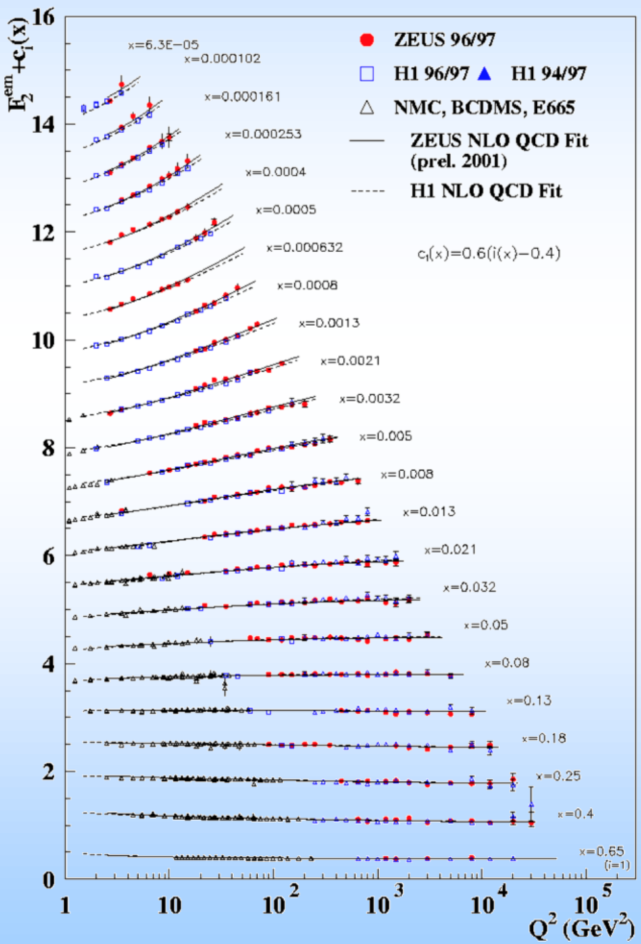
$$\mathrm{Res}(\bar{q}_1) \approx -v(-\omega_0-\tilde{\omega}_m, \mathbf{q}_1)\frac{e^{i(\omega_0+\tilde{\omega}_m)(z_1-z_0)}}{E^+k^+(\omega_1+\tilde{\omega}_m)}$$

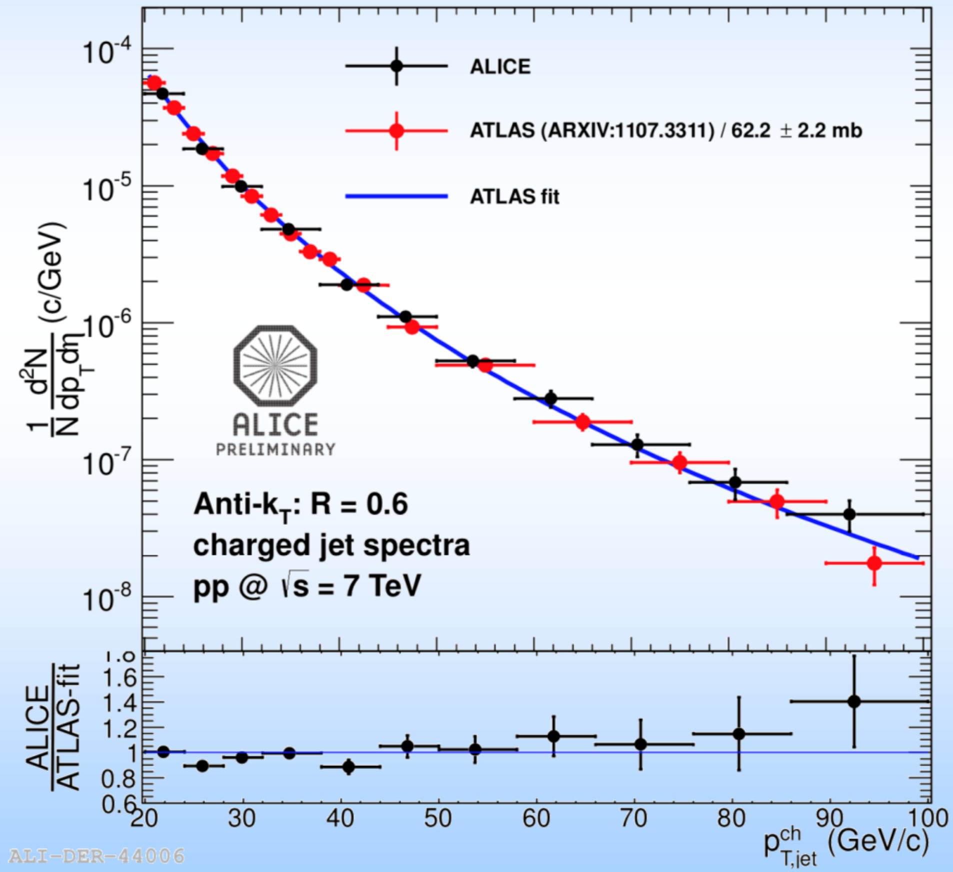
$$\mathrm{Res}(\bar{q}_2) \approx v(\omega_1-\omega_0, \mathbf{q}_1)\frac{e^{i(\omega_0-\omega_1)(z_1-z_0)}}{E^+k^+(\omega_1+\tilde{\omega}_m)}$$

$$\mathrm{Res}(-i\mu_1) \approx \frac{4\pi\alpha_s\, e^{-\mu_1(z_1-z_0)}}{(-2i\mu_1)E^+k^+(-i\mu_1)^2}$$

Much of QCD Particle Physics Understood

- e+p Collisions
- p+p Collisions





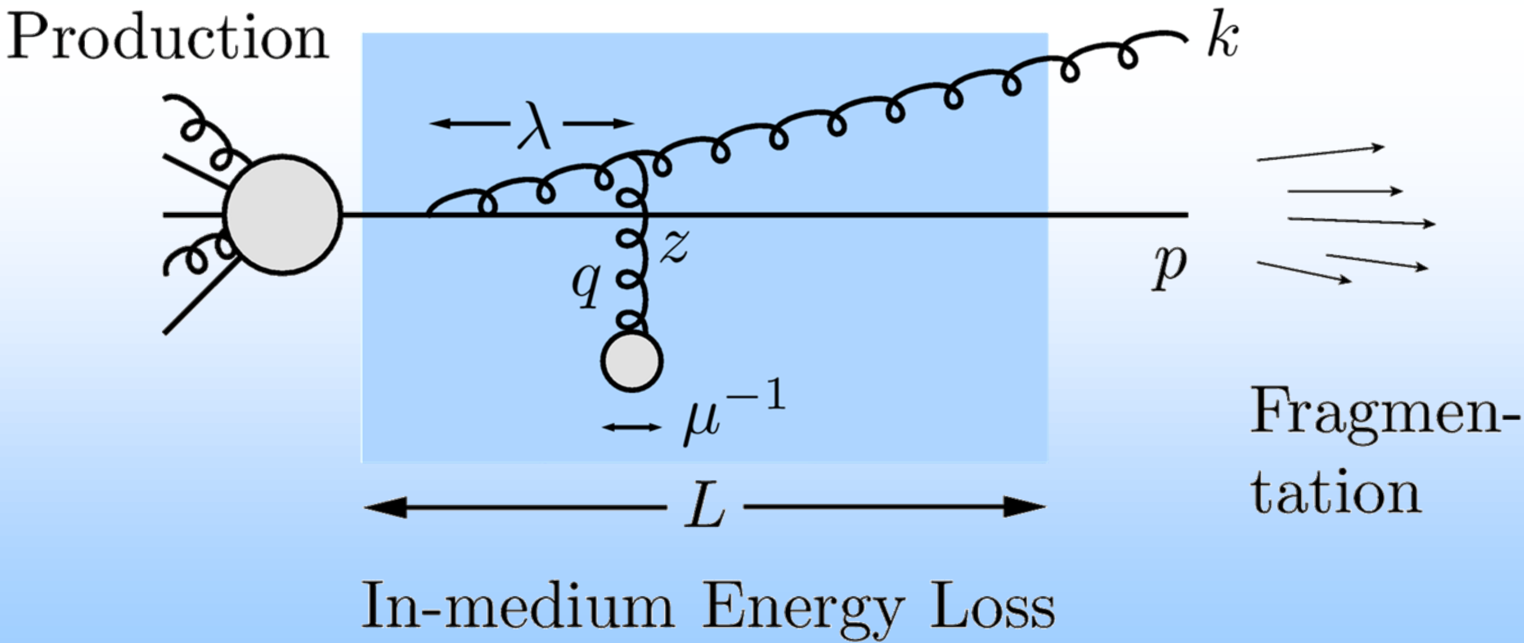
Why Energy Loss?

World’s Most Powerful Femtoscope:

Most direct probe of DOF of QGP

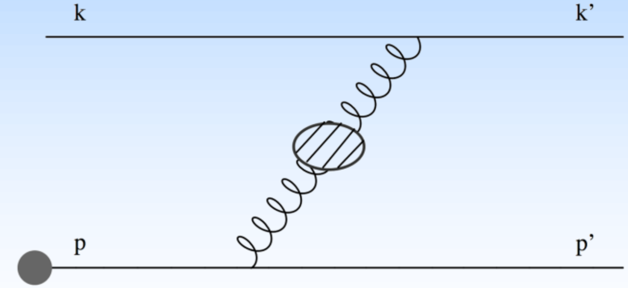
pQCD Picture

AdS/CFT Picture



Types of Energy Loss

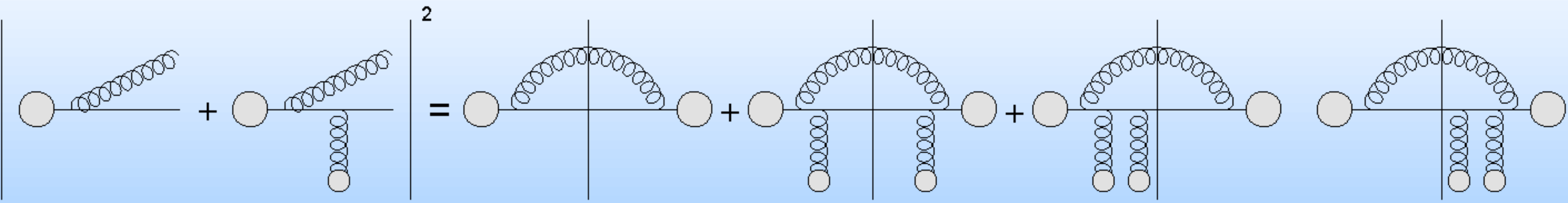
- Two types of E-loss
  - Collisional (elastic) 2➞2



Djordjevic, PRC74 (2006)

- Bjorken, FERMILAB-PUB-82-059-THY
- Braaten and Thoma, PRD44:2625–2630, 1991
- Djordjevic, Phys.Rev. C74 (2006) 064907
- Adil et al., Phys.Rev. C75 (2007) 044906

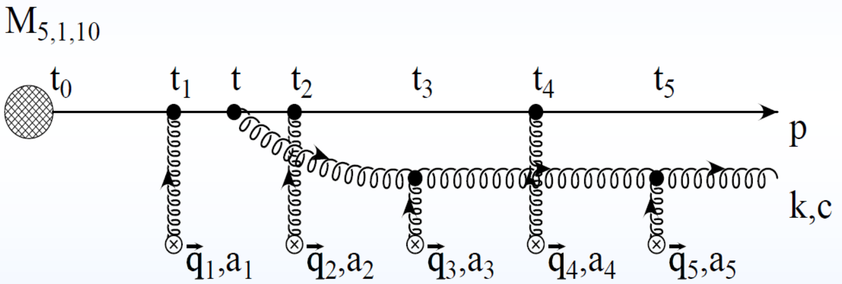
  - Radiative (inelastic) 2➞3
    - Scales => ~few scatterings, mult. coh. em. => LPM
    - Must include interference with production radiation



- Majumder and van Leeuwen, PPNPA66 (2011), and refs therein

pQCD Rad Picture

- Bremsstrahlung Radiation
  - Weakly-coupled plasma
    - Medium organizes into Debye-screened centers
  - $T \sim 250$ MeV, $g(2\pi T) \sim 2$
    - $\mu \sim gT \sim 0.5$ GeV
    - $\lambda_{mfp} \sim 1/g^2T \sim 1$ fm
    - $R_{Au} \sim 6$ fm
  - $1/\mu << \lambda_{mfp} << \tau_{form} << L$
    - mult. coh. em.



Gyulassy, Levai, and Vitev, NPB571 (2000)

- LPM

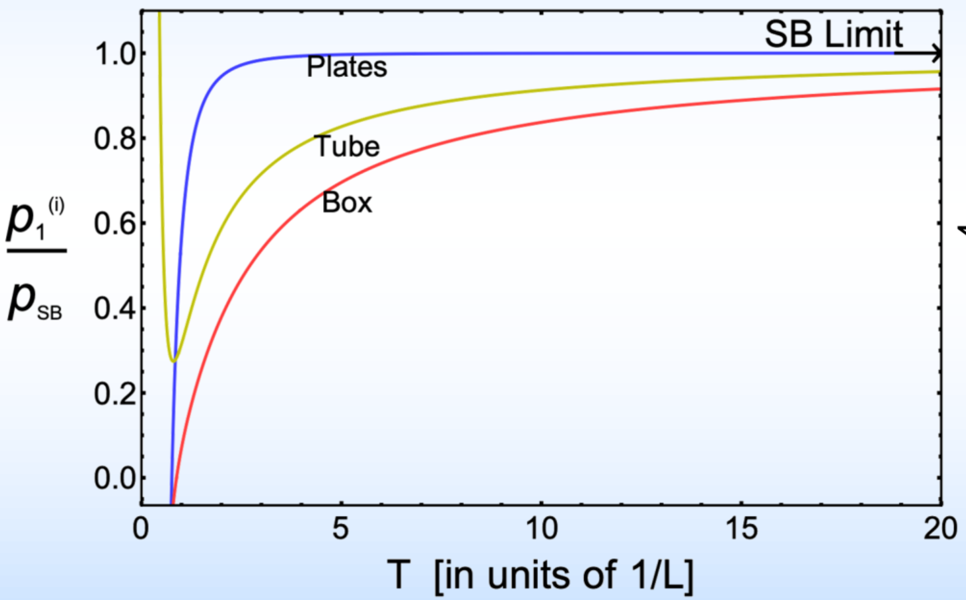
  $dp_T/dt \sim -LT^3 \log(p_T/M_q)$

- Bethe-Heitler

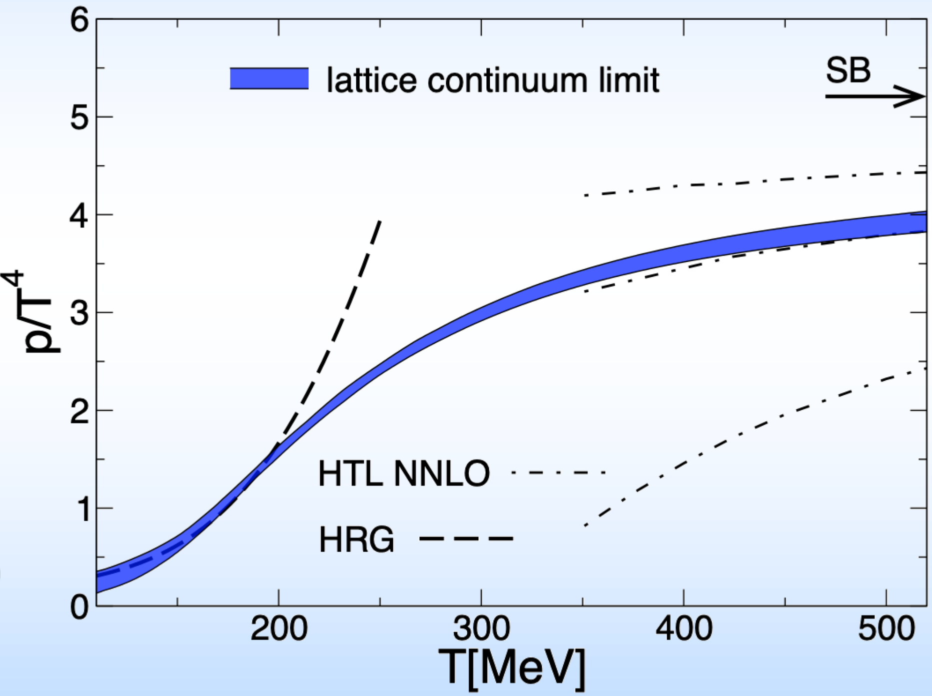
  $dp_T/dt \sim -(T^3/M_q^2)\, p_T$

Does Finite Size Affect Thermodyn.?

- Provocative qualitative T dependence:



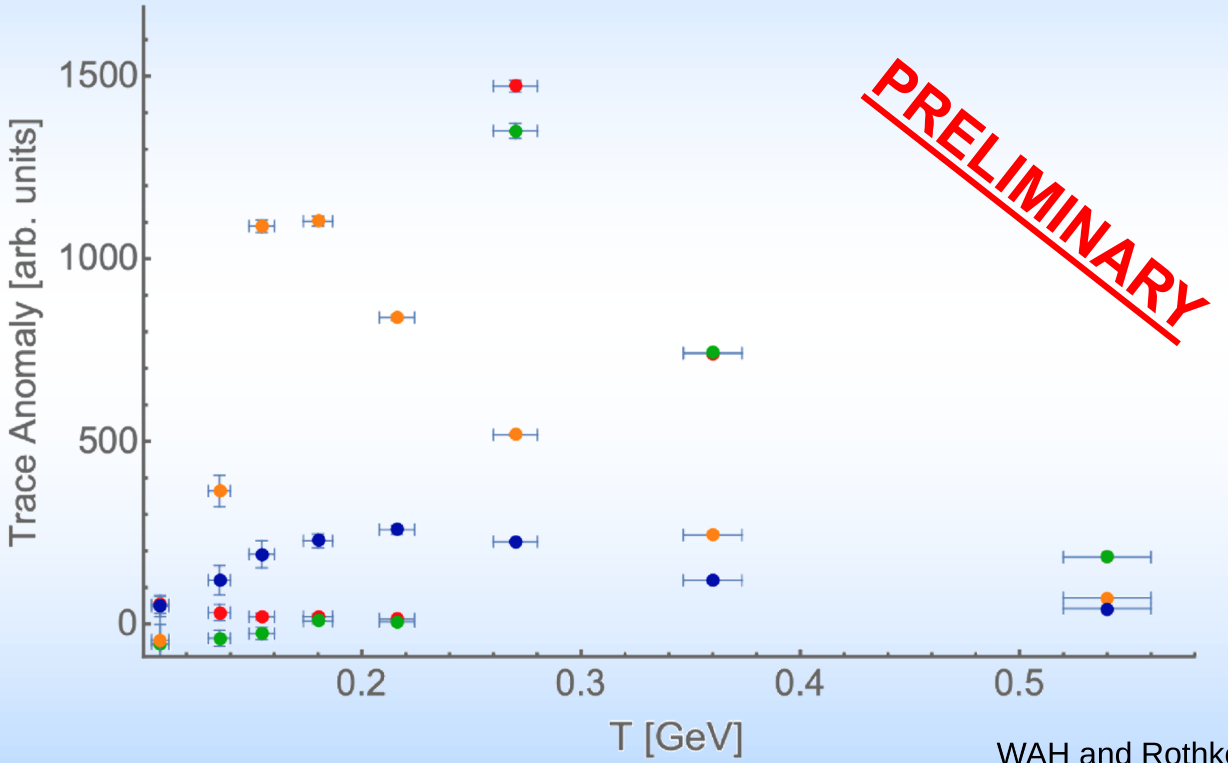
Mogliacci, Kolbé, and WAH, PRD102 (2020)



Borsanyi et al., PLB730 (2014)

What about Trace Anomaly Δ?

- Δ => c_s => η/s
- From lattice QCD:



Blessed Ngwenya

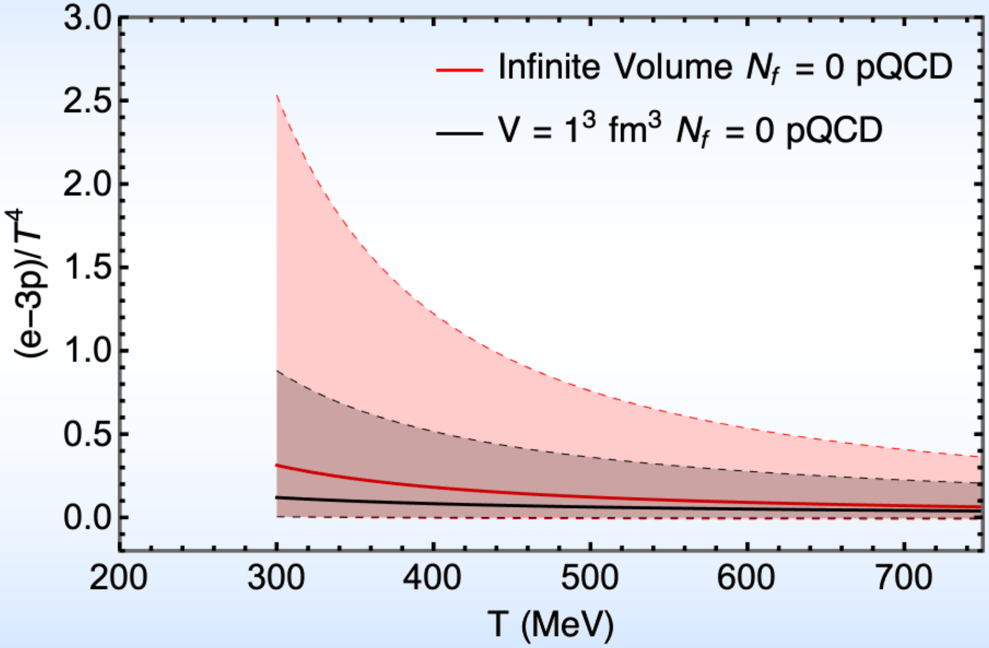
Quenched QCD
Periodic BCs

WAH and Rothkopf,
SciPost Phys.Proc. 10 (2022) 025

  – Decreasing system size:
    - decreases Δ
    - washes out phase transition

Analytic Results for Δ

- $\Delta = 0$ for massless, free ϕ^4
  - Even when in a box!
- $\Delta = 0$ for HTL QCD
  - Even to g^5!
- Δ != 0 *only* when coupling runs
- Estimate: use HTL QCD with lattice scalar running coupling
  - λ decreases and Δ *significantly* decreases from F.S.



WAH and Rothkopf, SciPost Phys.Proc. 10 (2022) 025