Energy Loss in Small Quark Gluon Plasmas

Coleridge Faraday

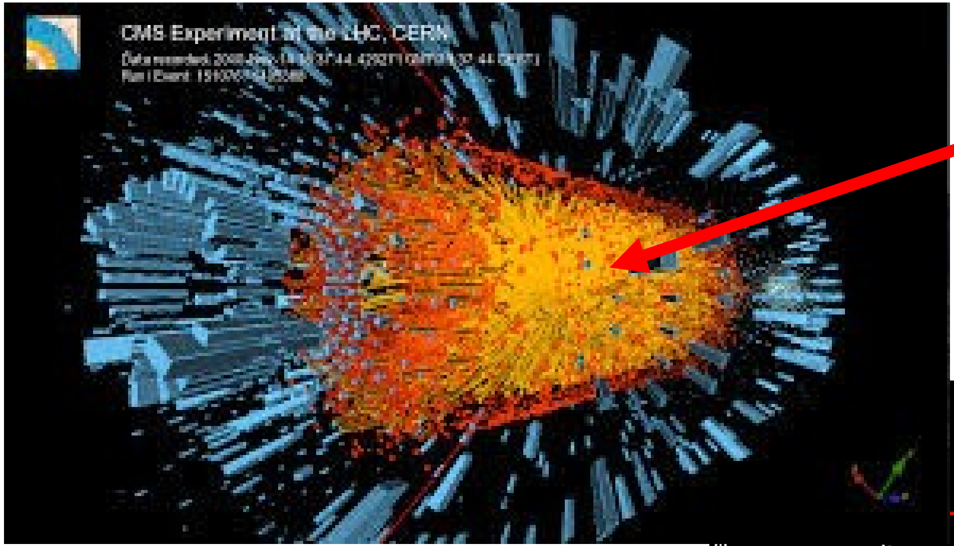
University of Cape Town, South Africa

68th Annual Conference of the South African Institute of Physics 2024

Based on CF, A. Grindrod, W. A. Horowitz arXiv:2305.13182;
CF, W. A. Horowitz in prep.

frdcol002@myuct.ac.za

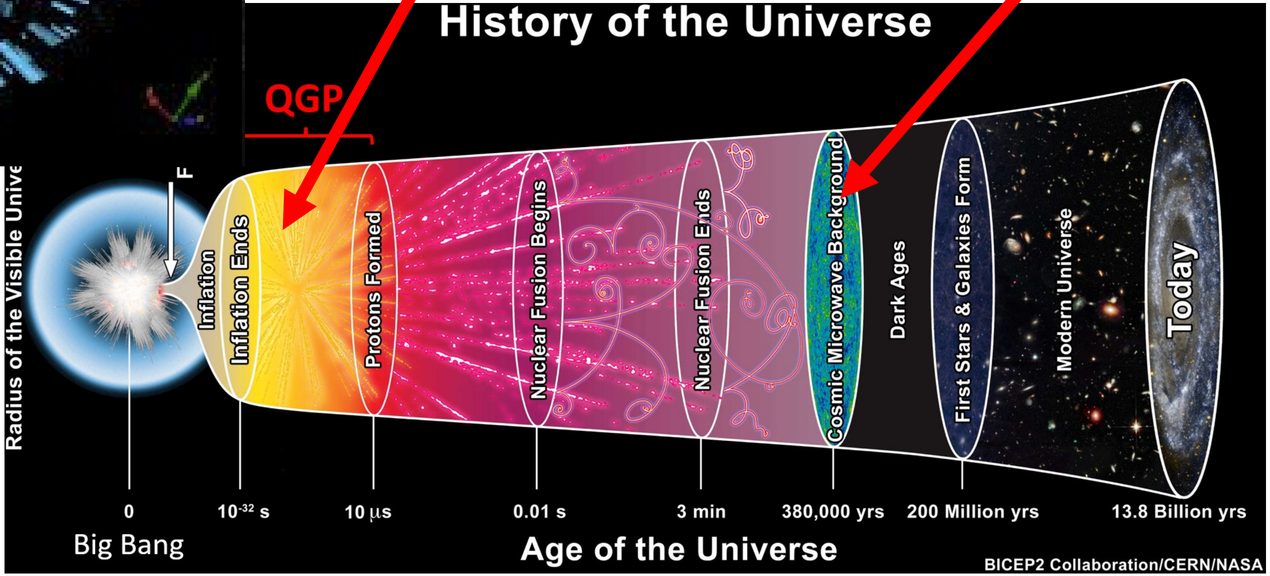
The Early Universe and Heavy-Ions



Quark Gluon Plasma?

CMB from telescopes

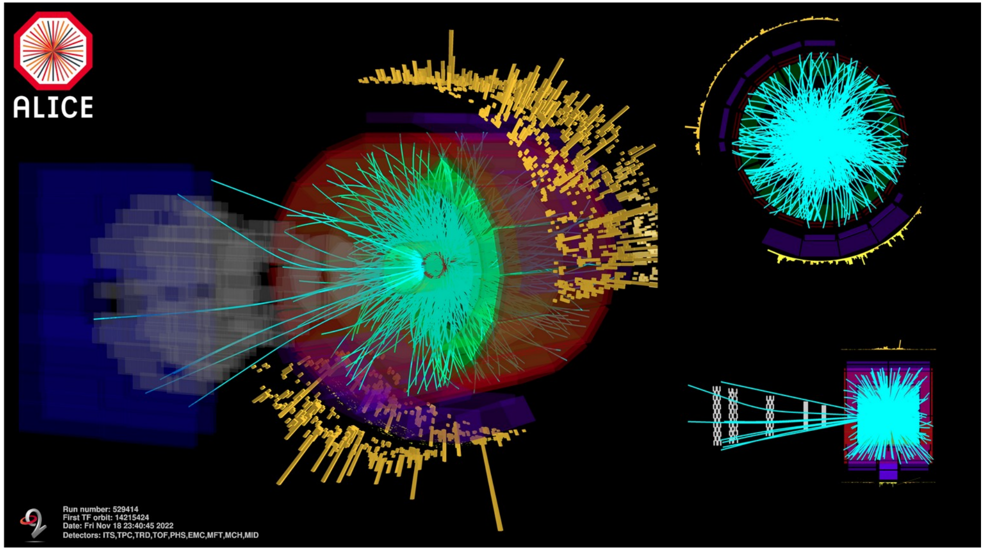
Heavy-ion collisions
at LHC and RHIC



Measuring the Quark Gluon Plasma

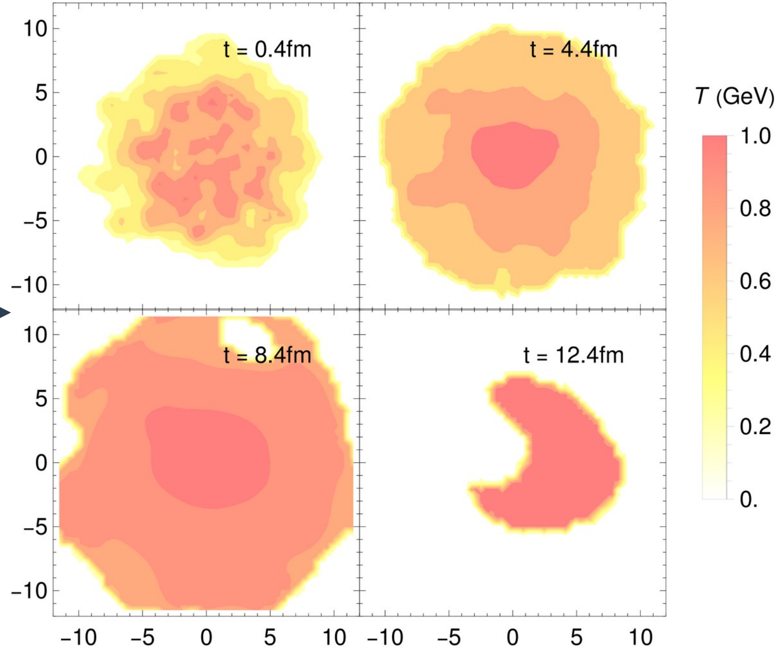
QGP in heavy-ion collisions lasts for only $\simeq 10^{-23}\,\mathrm{s}$! → difficult to probe

Experiment



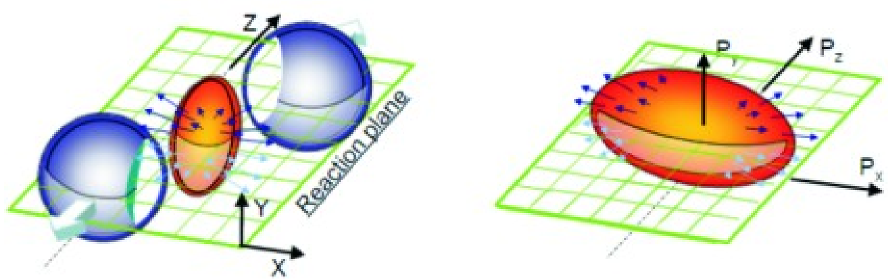
?

Theory



Angular Correlations

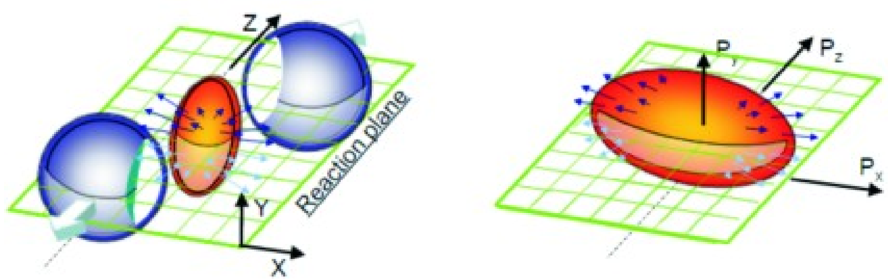
Aggarwal, Elliptic Flow in Relativistic Heavy-Ion Collisions

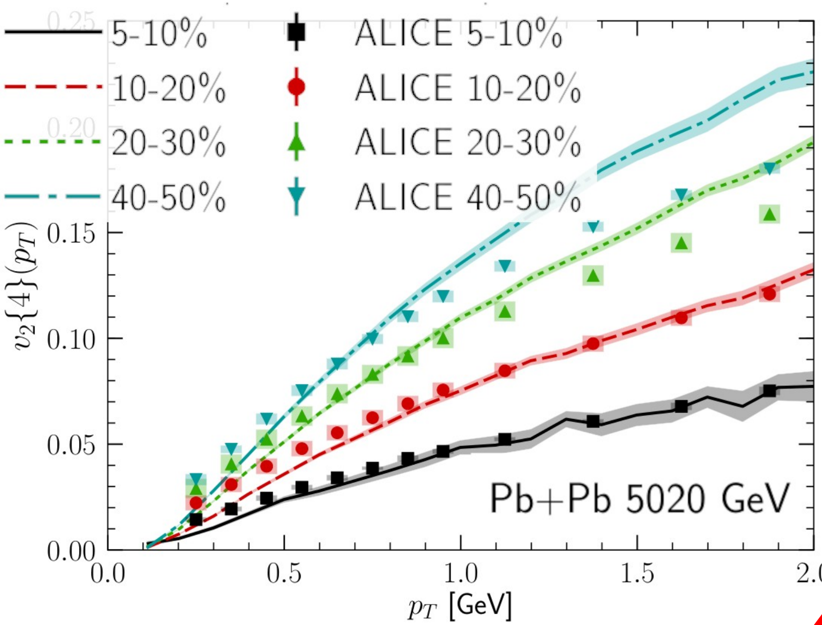


- Initial spatial anisotropy → final momentum anisotropy
- Quantified through angular correlations in final state particles

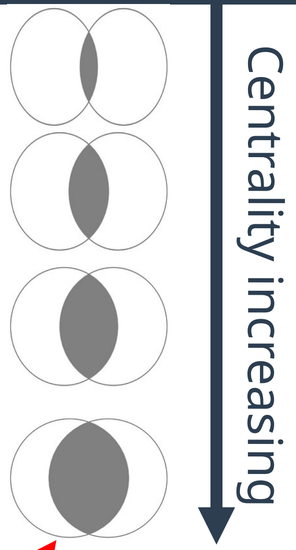
Angular Correlations

Aggarwal, Elliptic Flow in Relativistic Heavy-Ion Collisions





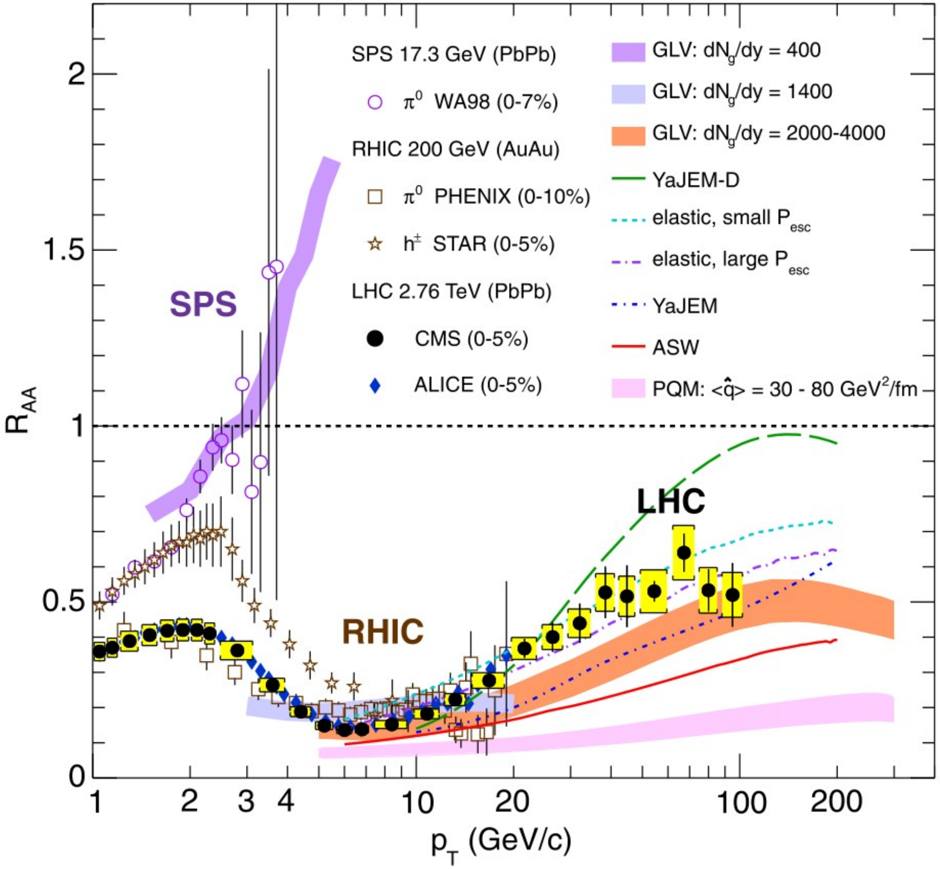
Schenke et al., Phys. Rev. C 102 (2020) 044905



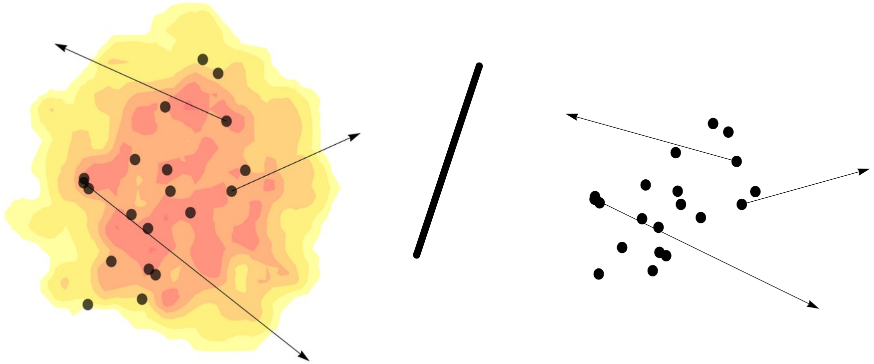
- Initial spatial anisotropy → final momentum anisotropy
- Quantified through angular correlations in final state particles

Elliptical overlap region → angular anisotropy!

Nuclear Modification Factor



$$R_{AA}(p_T) = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

$=$ 

Quantifies how much **energy is lost** in the medium

How do we *know* a medium is forming?

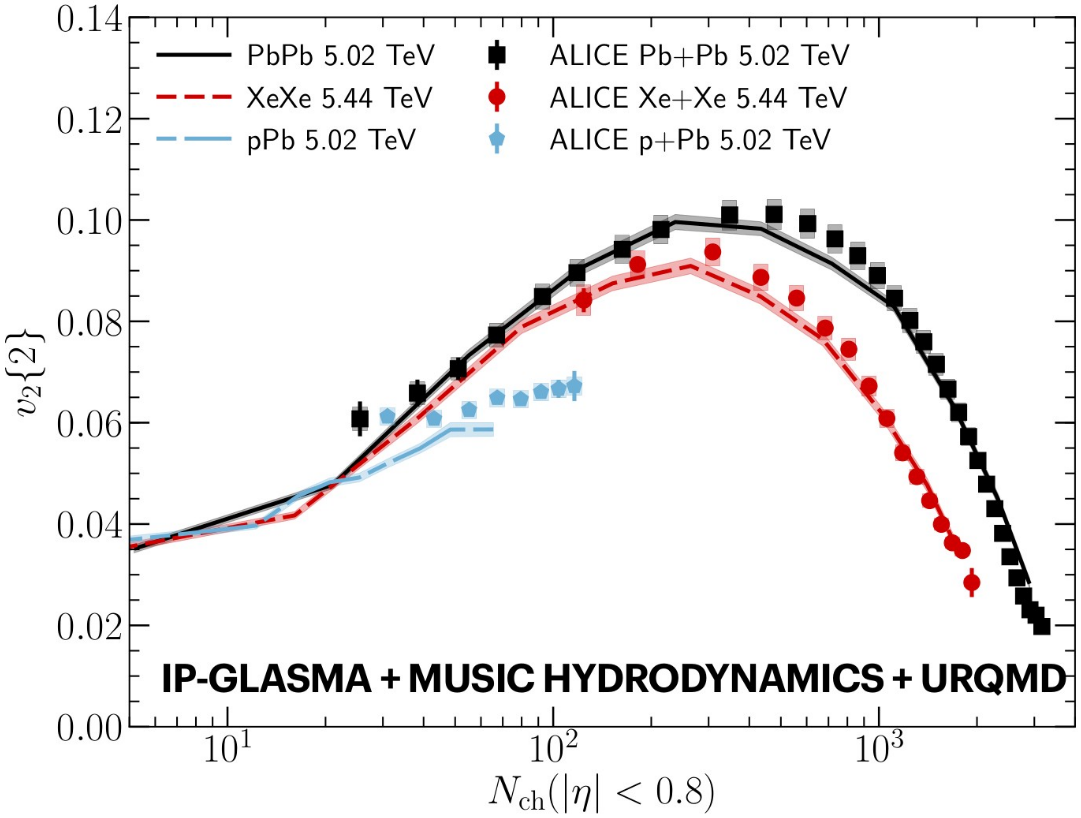
Natural question: can the experimental evidence be explained **without a medium**?

→ Look at $p + p$ and p + Pb collisions as a baseline

QGP in small systems?

Signatures of **QGP formation** in high multiplicity pp, $p\,/\,d\,/\,^3\mathrm{He}+A$!

+ other signatures including quarkonium suppression and strangeness enhancement



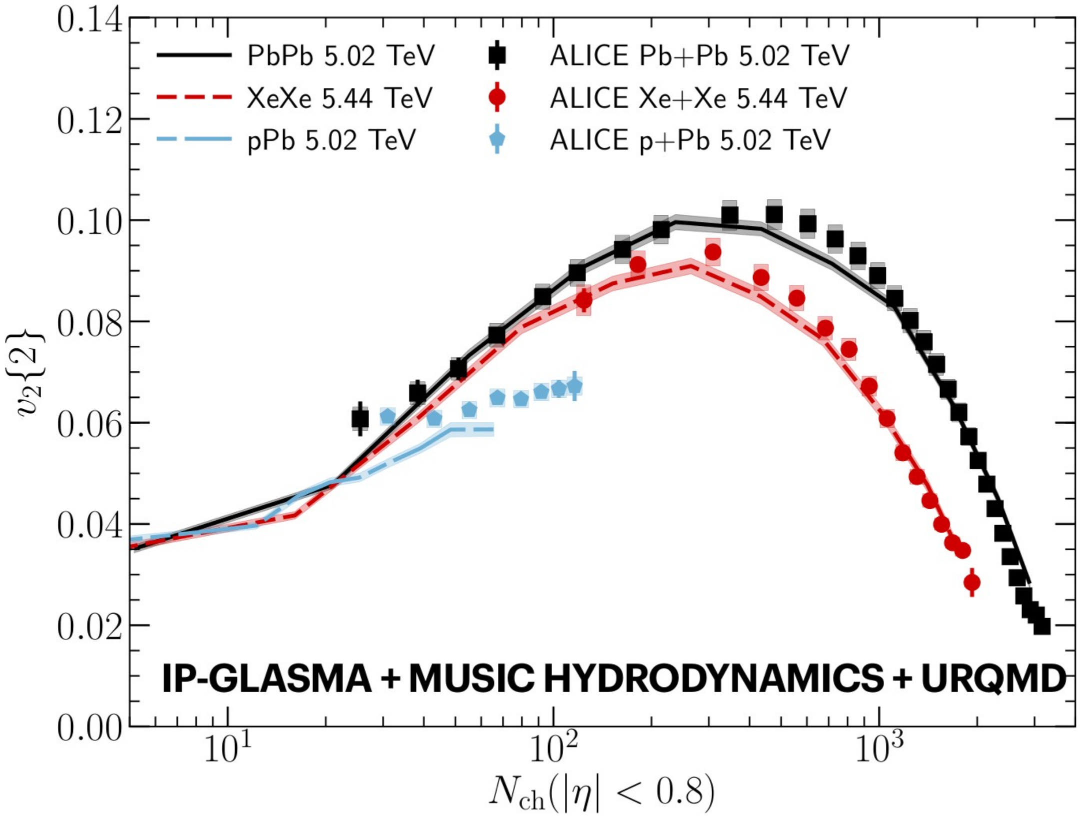
B. Schenke, C. Shen, P. Tribedy, Phys.Rev.C 102 (2020) 044905
ALICE Collaboration, Phys.Rev.Lett. 123 (2019) 142301

QGP in small systems?

Signatures of **QGP formation** in high multiplicity pp, $p\,/\,d\,/\,{}^3\mathrm{He} + A$!

+ other signatures including quarkonium suppression and strangeness enhancement

How about the Nuclear modification factor or R_{pA}?

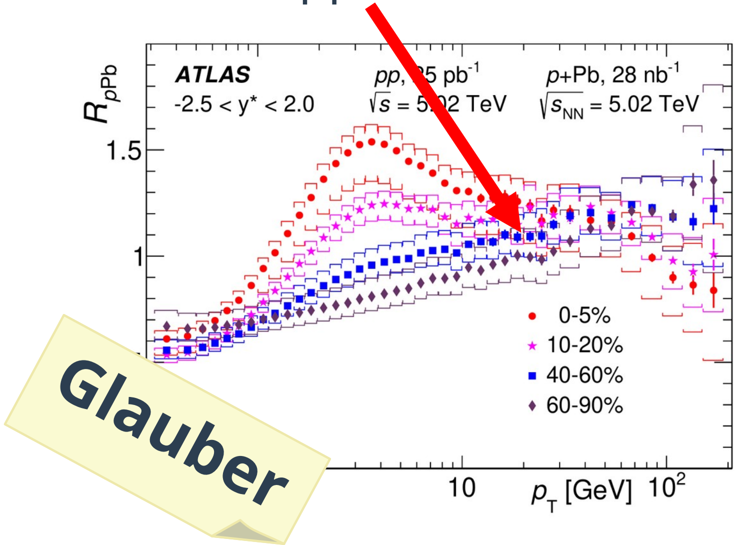


B. Schenke, C. Shen, P. Tribedy, Phys.Rev.C 102 (2020) 044905
ALICE Collaboration, Phys.Rev.Lett. 123 (2019) 142301

Nuclear Modification in Small Systems

Small system suppression pattern not as clear

No suppression!

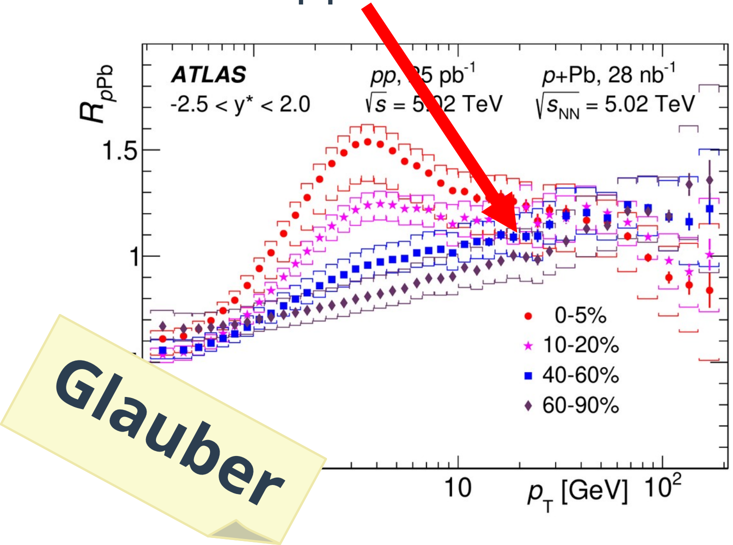


ATLAS, JHEP 07 (2023) 074

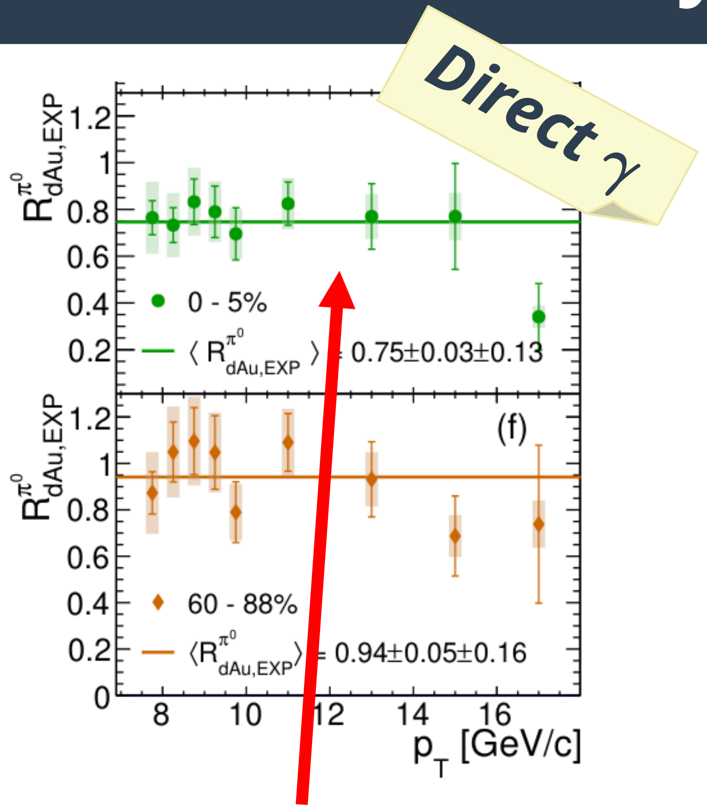
Nuclear Modification in Small Systems

Small system suppression pattern not as clear

No suppression!



ATLAS, JHEP 07 (2023) 074



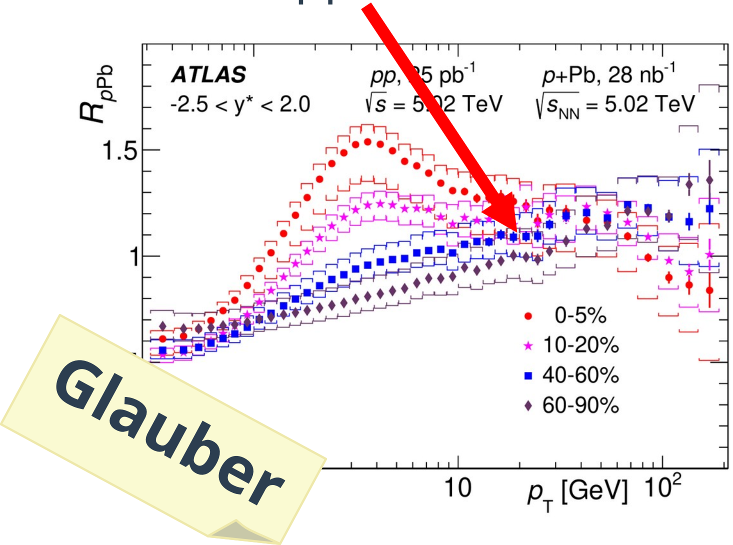
Suppression ~0.75!

PHENIX, arXiv:2303.12899 (2023)

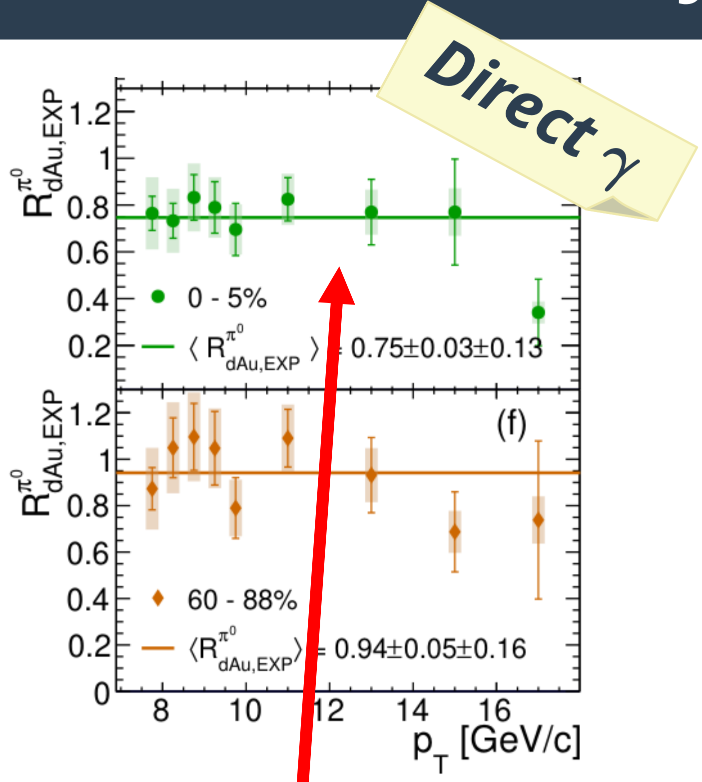
Nuclear Modification in Small Systems

Small system suppression pattern not as clear

No suppression!



ATLAS, JHEP 07 (2023) 074



Suppression ~0.75!

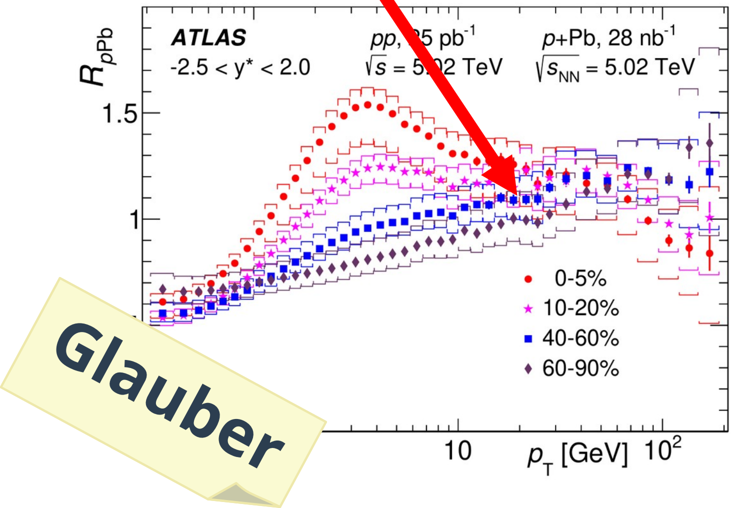
PHENIX, arXiv:2303.12899 (2023)

- Apparent tension between RHIC and LHC suppression results?
- R_{pA} is difficult to measure due to centrality bias

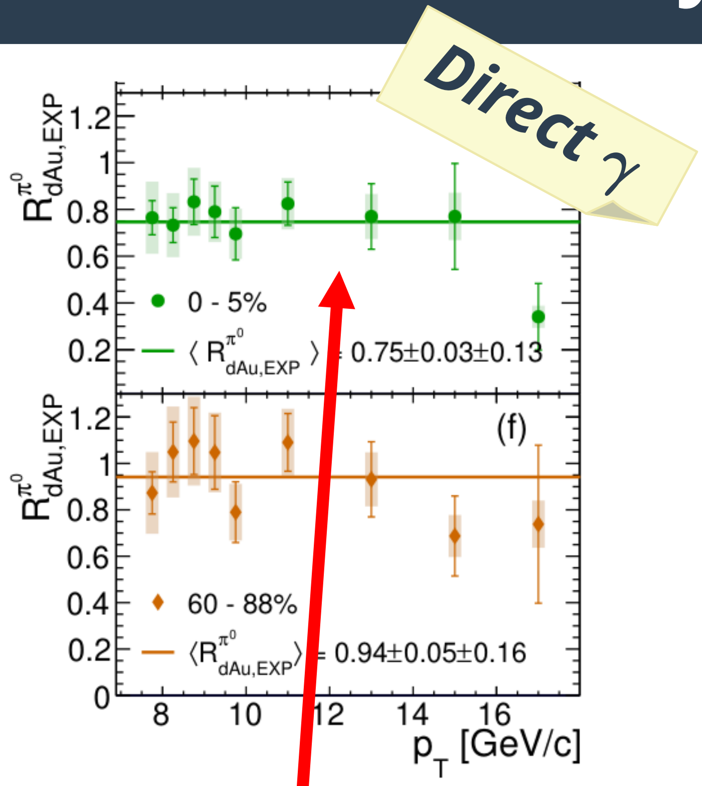
Nuclear Modification in Small Systems

Small system suppression pattern not as clear

No suppression!



ATLAS, JHEP 07 (2023) 074



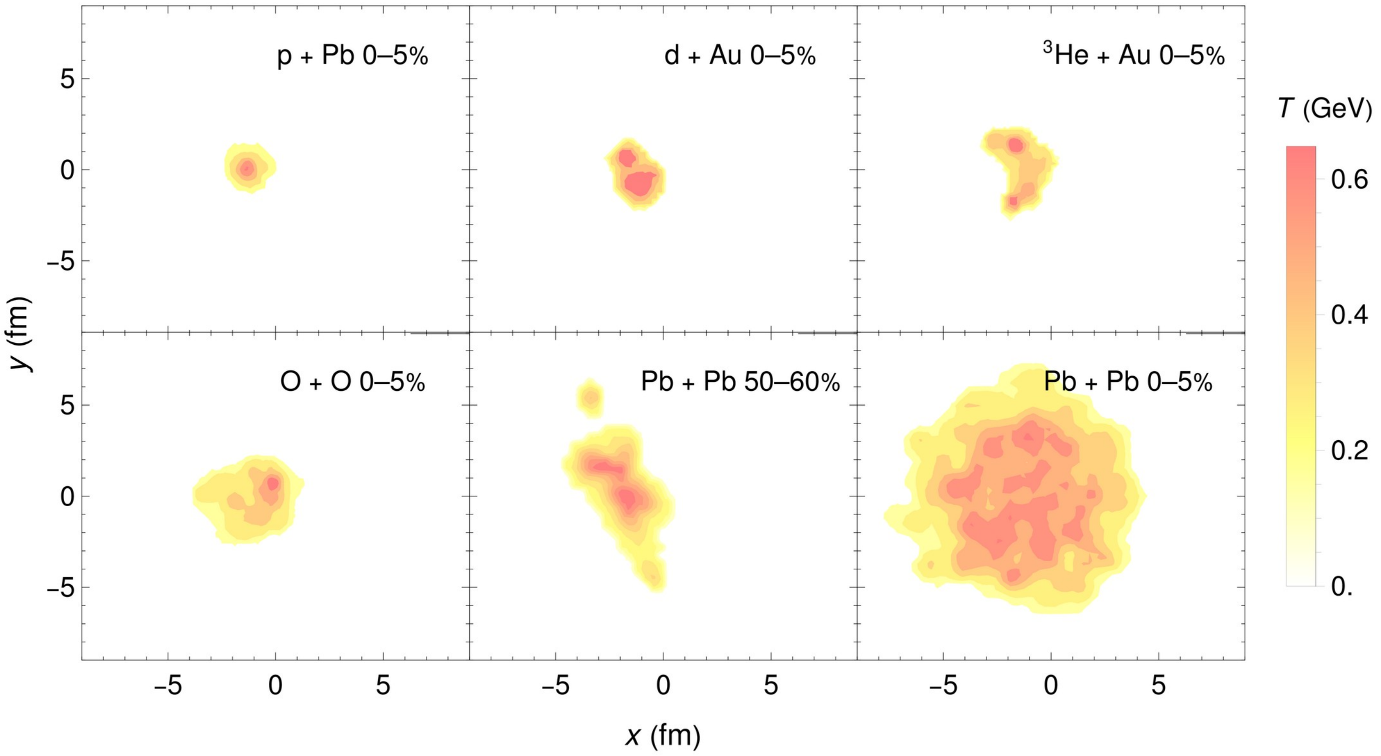
Suppression ~0.75!

PHENIX, arXiv:2303.12899 (2023)

- Apparent tension between RHIC and LHC suppression results?
- R_{pA} is difficult to measure due to centrality bias

→ **Theoretical input needed**

What do Small QGP's Look Like?



B. Schenke, C. Shen, P. Tribedy, Phys.Rev.C 102 (2020) 044905 (adapted)

According to hydrodynamic models:

- p+Pb much smaller than Pb+Pb, but with similarly large temperatures
- p+Pb has comparable length scales to peripheral PbPb collisions

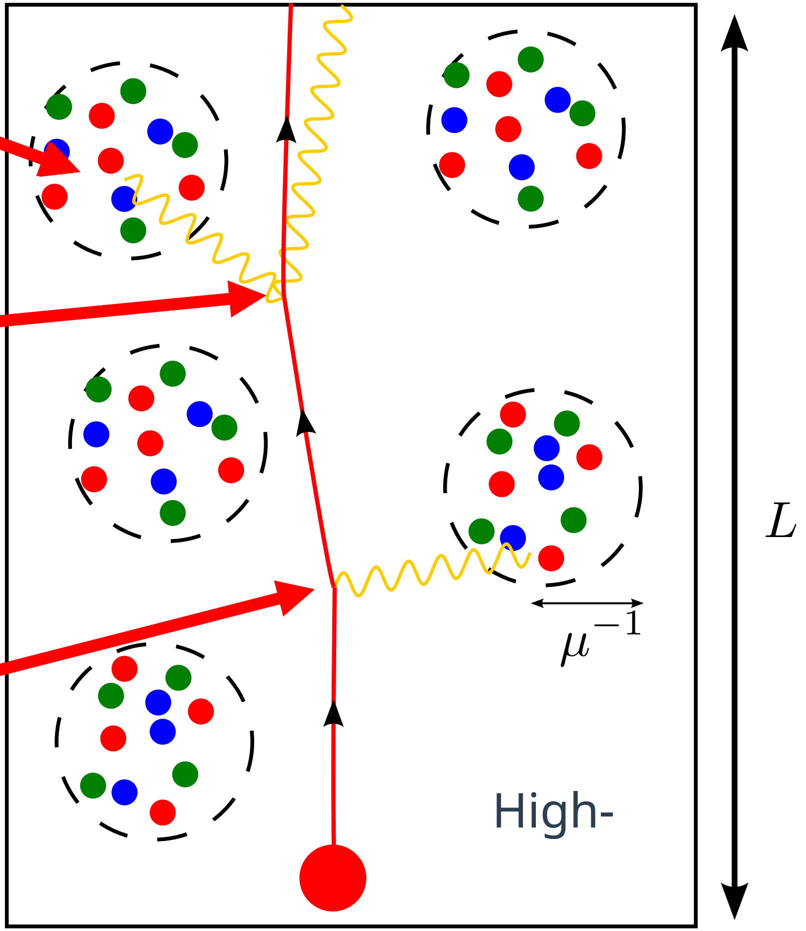
Energy Loss Model

- Model QGP using hydrodynamics
- Energy loss is *radiative* and *elastic*

Scattering Centre

Radiative Energy Loss

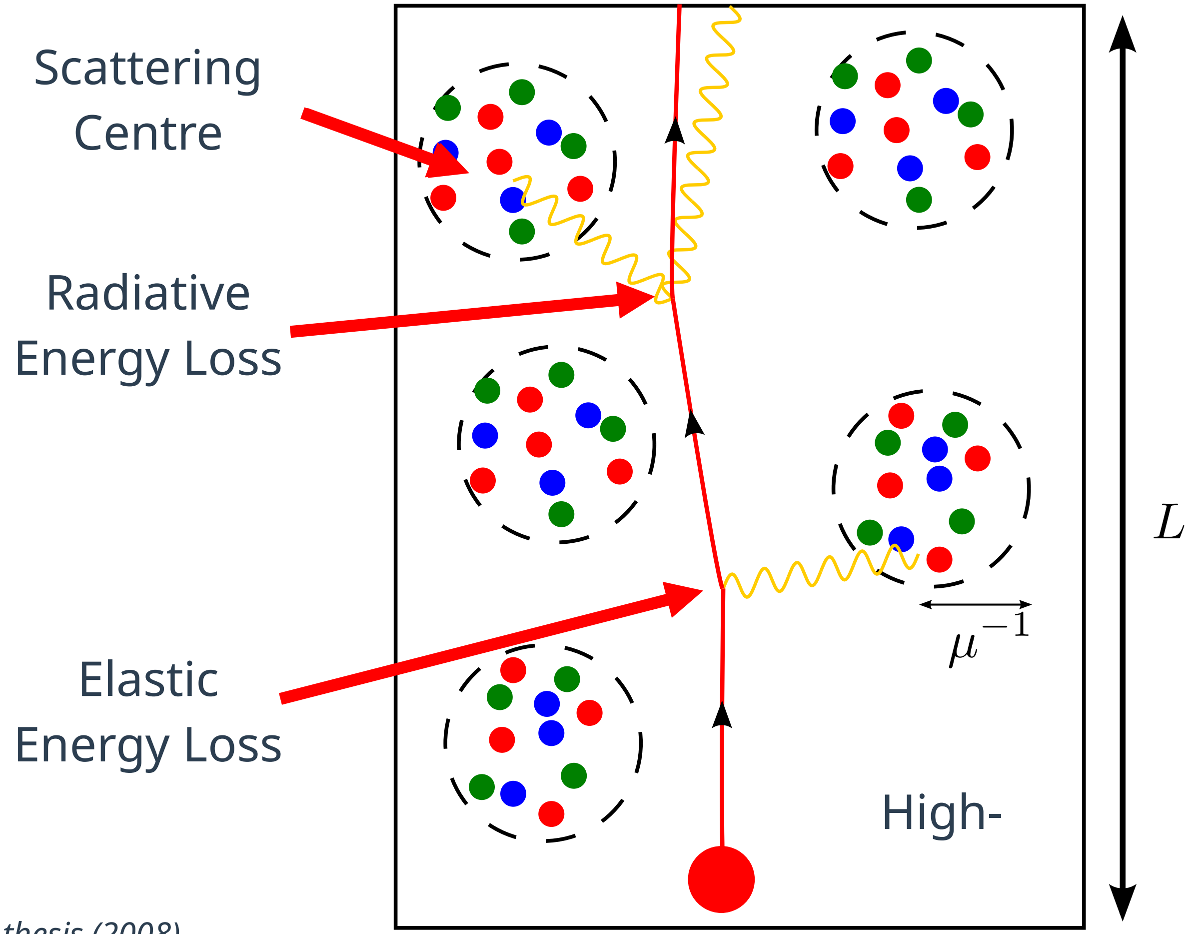
Elastic Energy Loss



Wicks, PhD thesis (2008)

Energy Loss Model

- Model QGP using hydrodynamics
- Energy loss is *radiative* and *elastic*



Wicks, PhD thesis (2008)

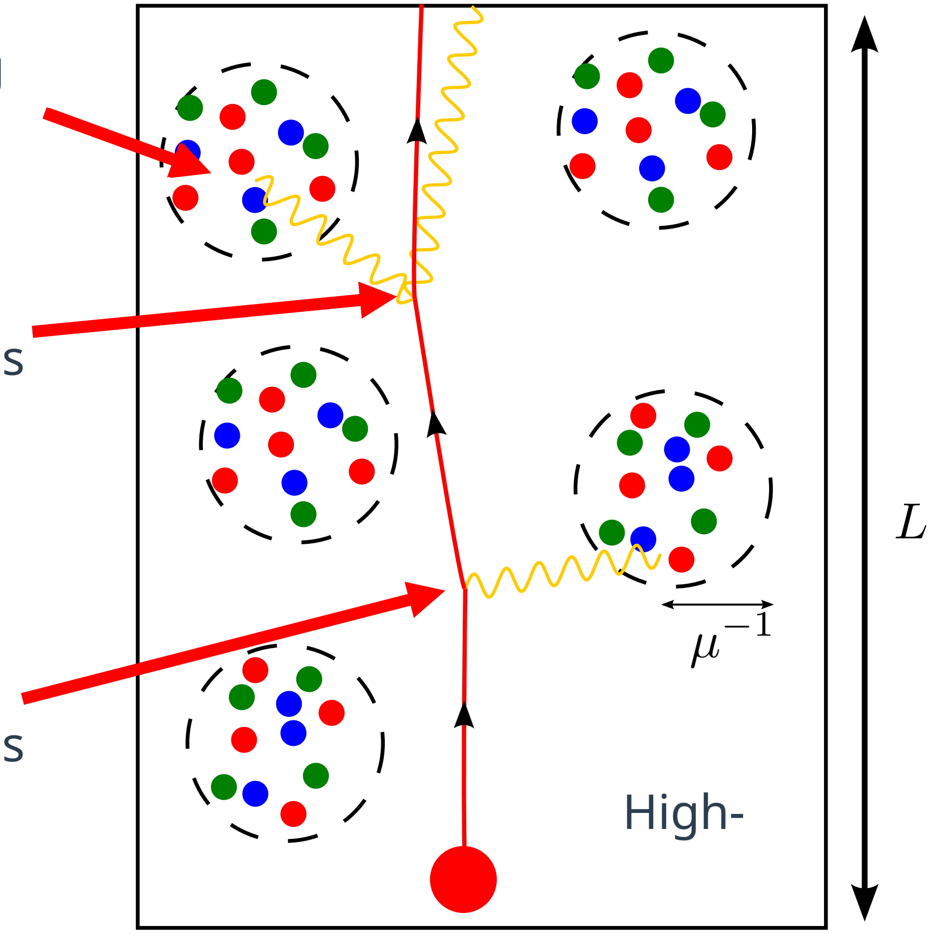
Energy Loss Model

- Model QGP using hydrodynamics
- Energy loss is *radiative* and *elastic*

Scattering Centre

Radiative Energy Loss

Elastic Energy Loss



Wicks, PhD thesis (2008)

Energy Loss Model

- Model QGP using hydrodynamics
- Energy loss is *radiative* and *elastic*

Scattering Centre

Radiative Energy Loss

Short path length correction: Neglected $e^{-\mu L}$ terms

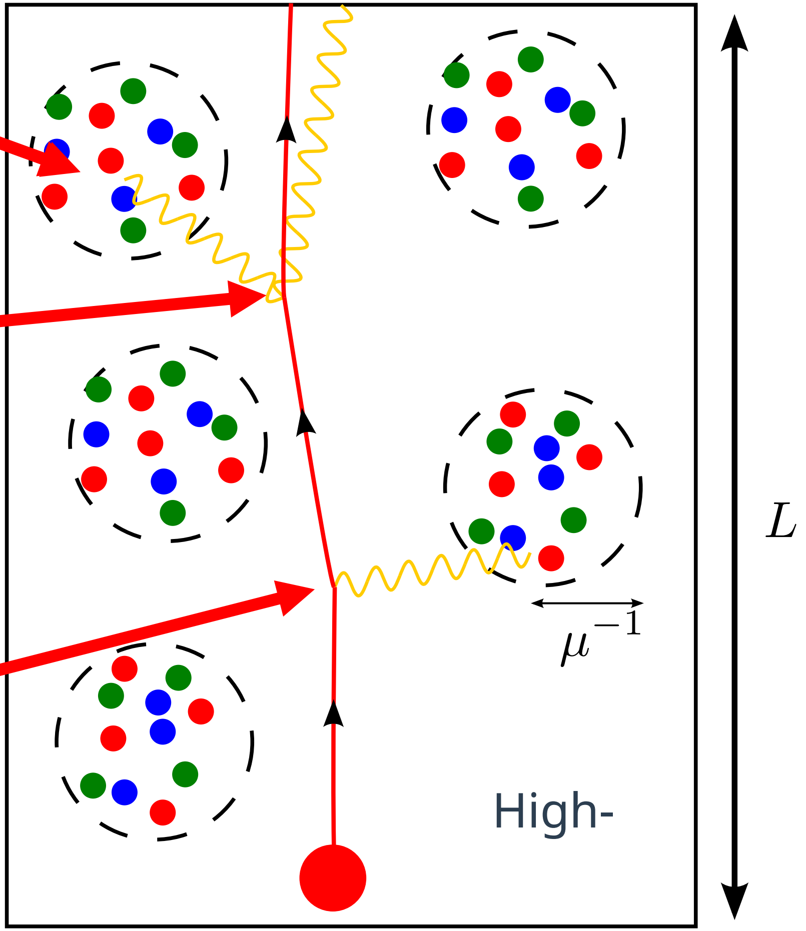
Kolbe & Horowitz, PRC 100 (2019) 024913

Theoretical challenges!

Elastic Energy Loss

Central limit theorem $L \gg \lambda$ applied

Wicks, PhD thesis (2008)



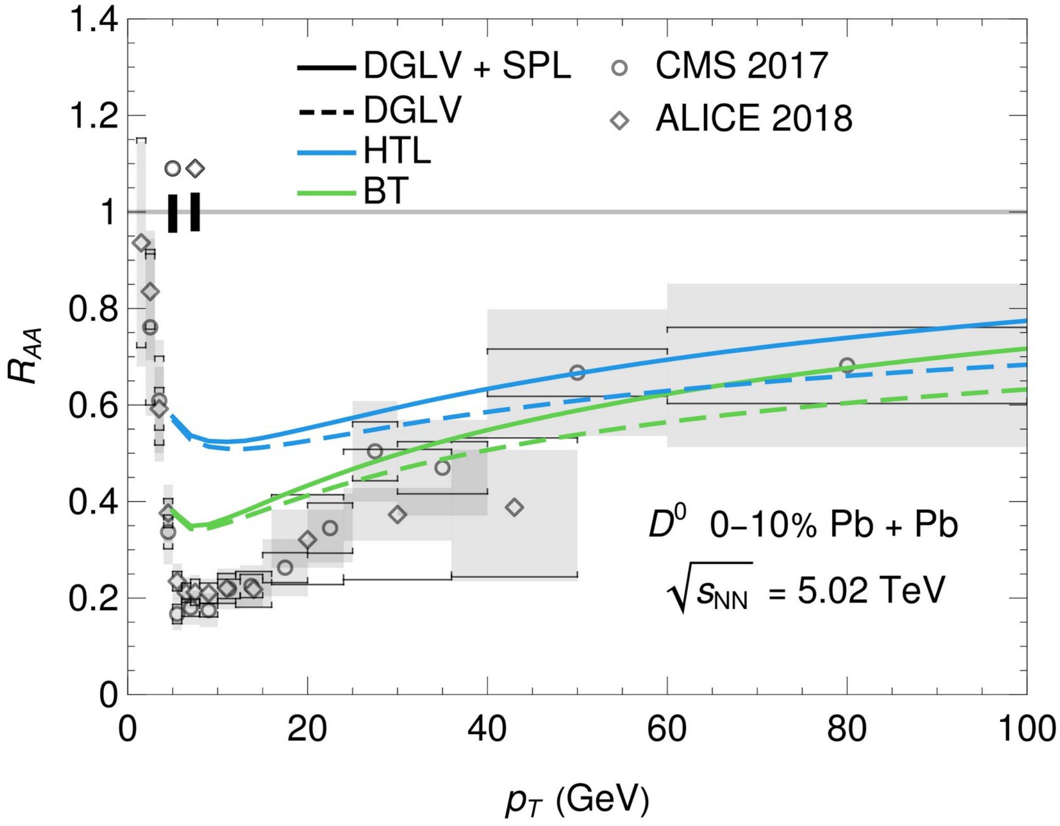
Elastic Energy Loss

Uncertainty in the elastic energy loss
relating to applying HTL vs Gaussian propagators

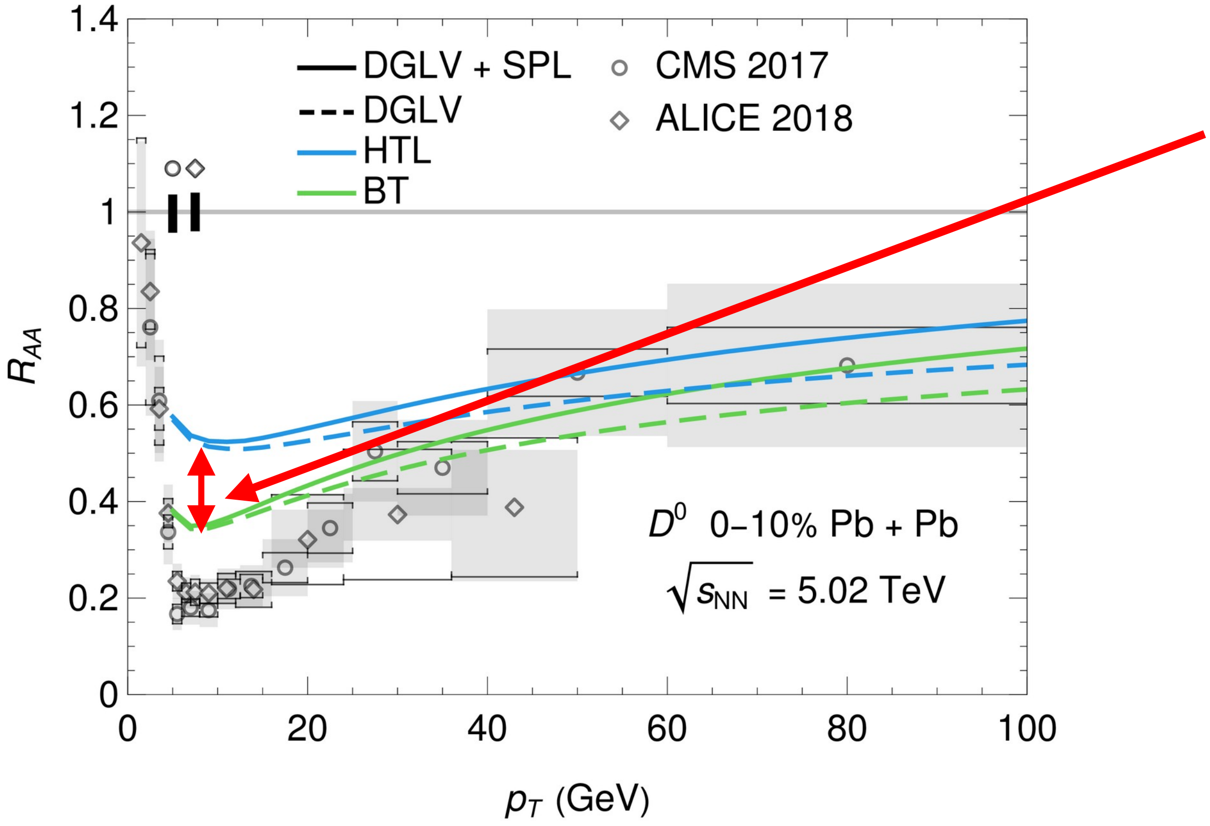
We compare two extremes to capture this uncertainty:

1. **BT** – combination of vacuum and HTL propagators
   Braaten and Thoma, Phys. Rev. D 44 (1991) R2625
2. **HTL** – HTL only propagators
   Wicks, PhD thesis (2008)

Heavy Flavour Suppression in PbPb

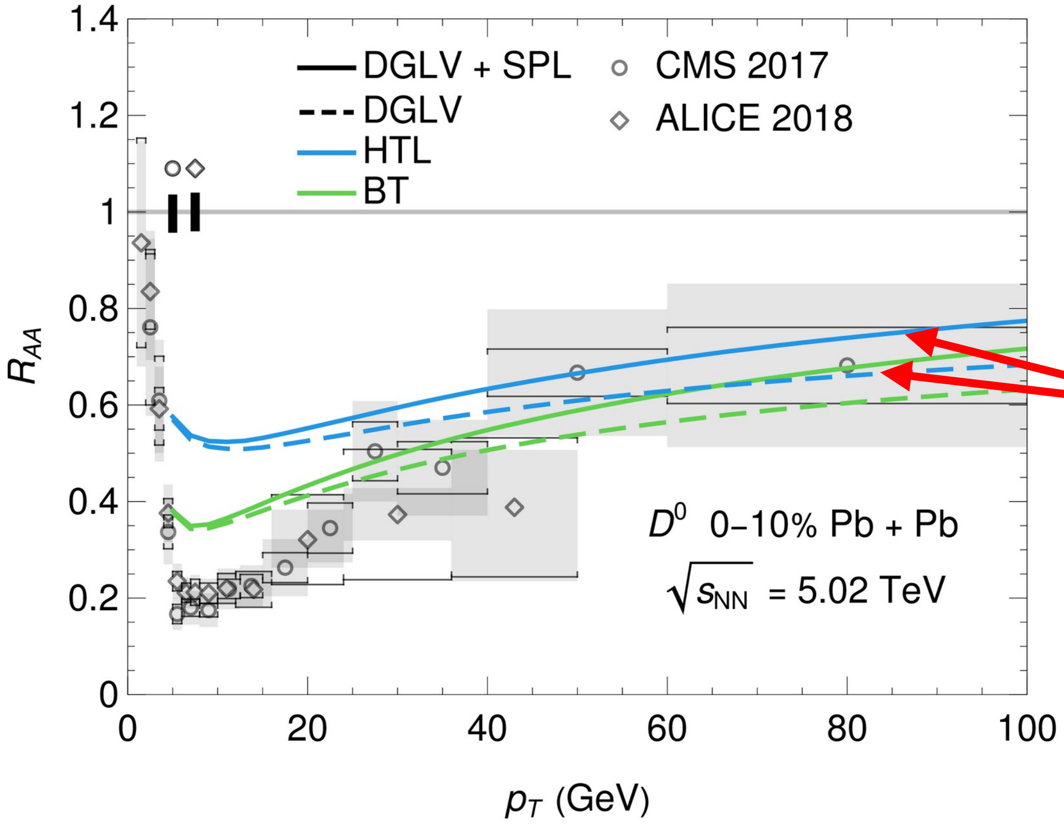


Heavy Flavour Suppression in PbPb



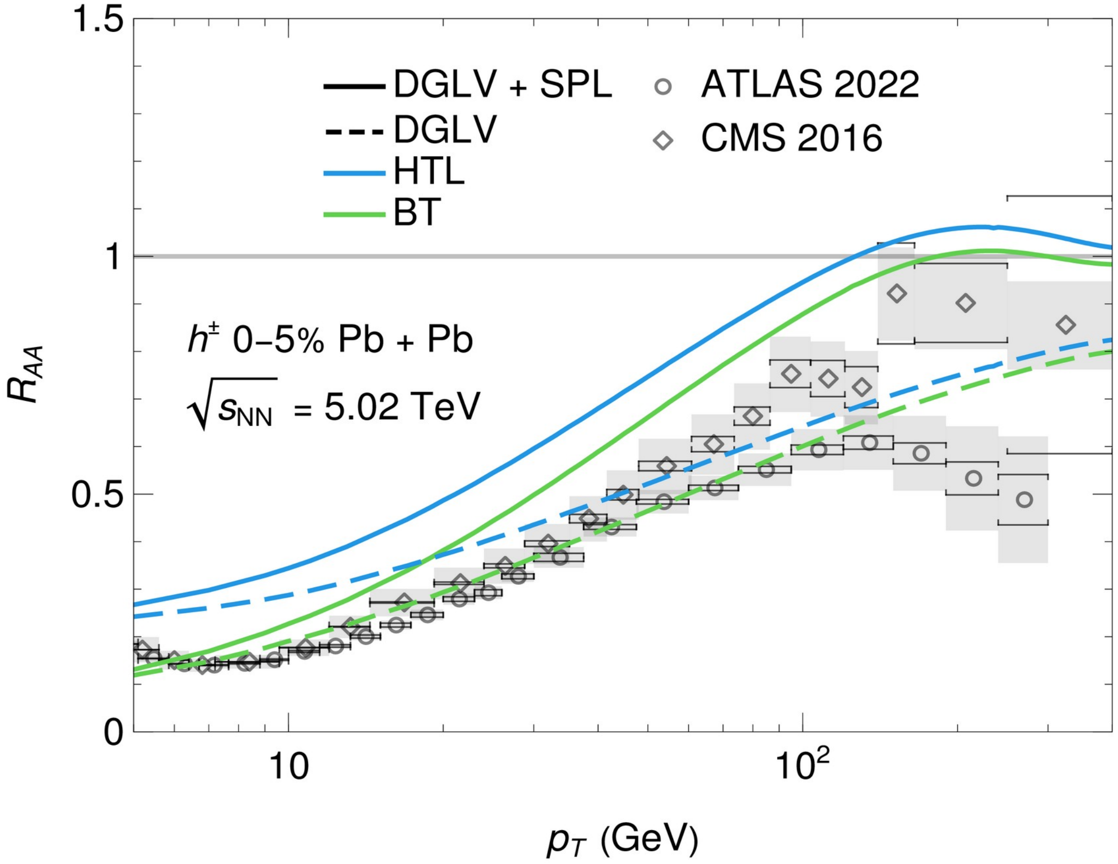
- Low pt is **sensitive to choice of elastic energy loss** (blue vs green)

Heavy Flavour Suppression in PbPb



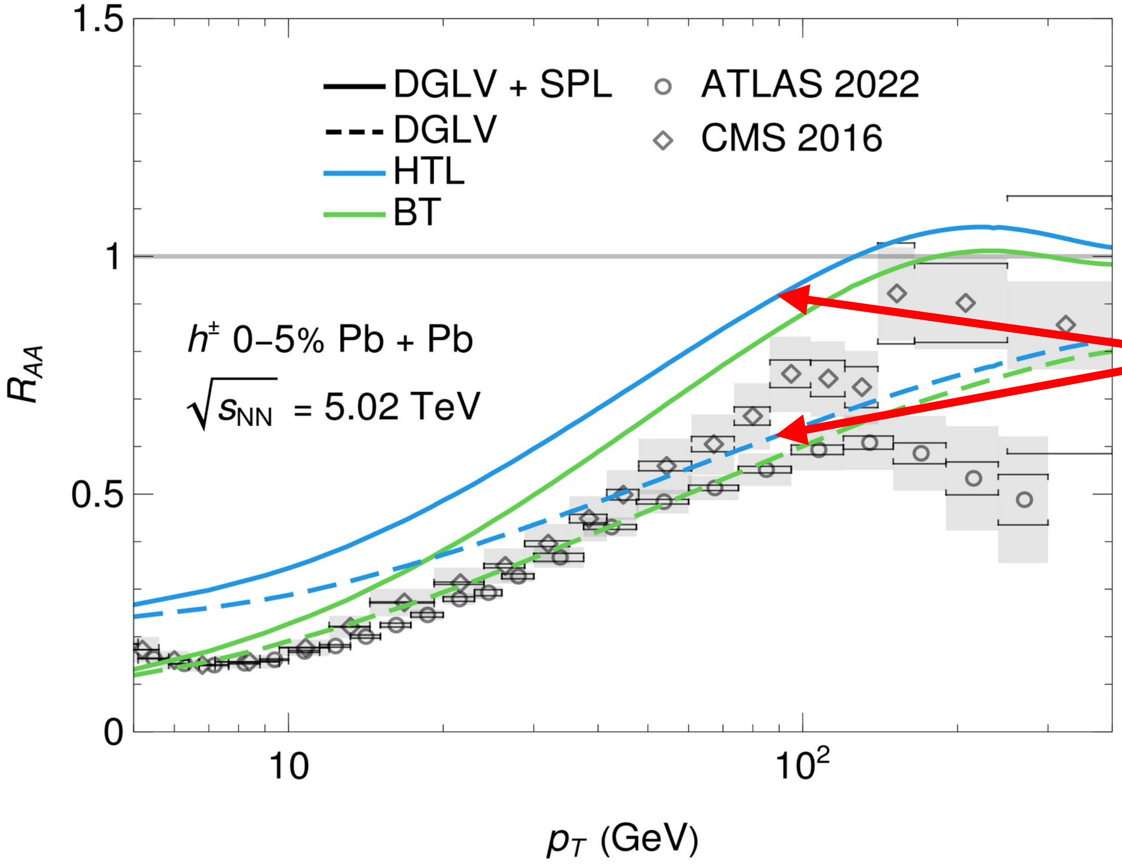
- Low pt is **sensitive to choice of elastic energy loss** (blue vs green)
- Short path length correction to radiative E-loss is small (solid vs dashed)

Light Flavour Suppression in PbPb



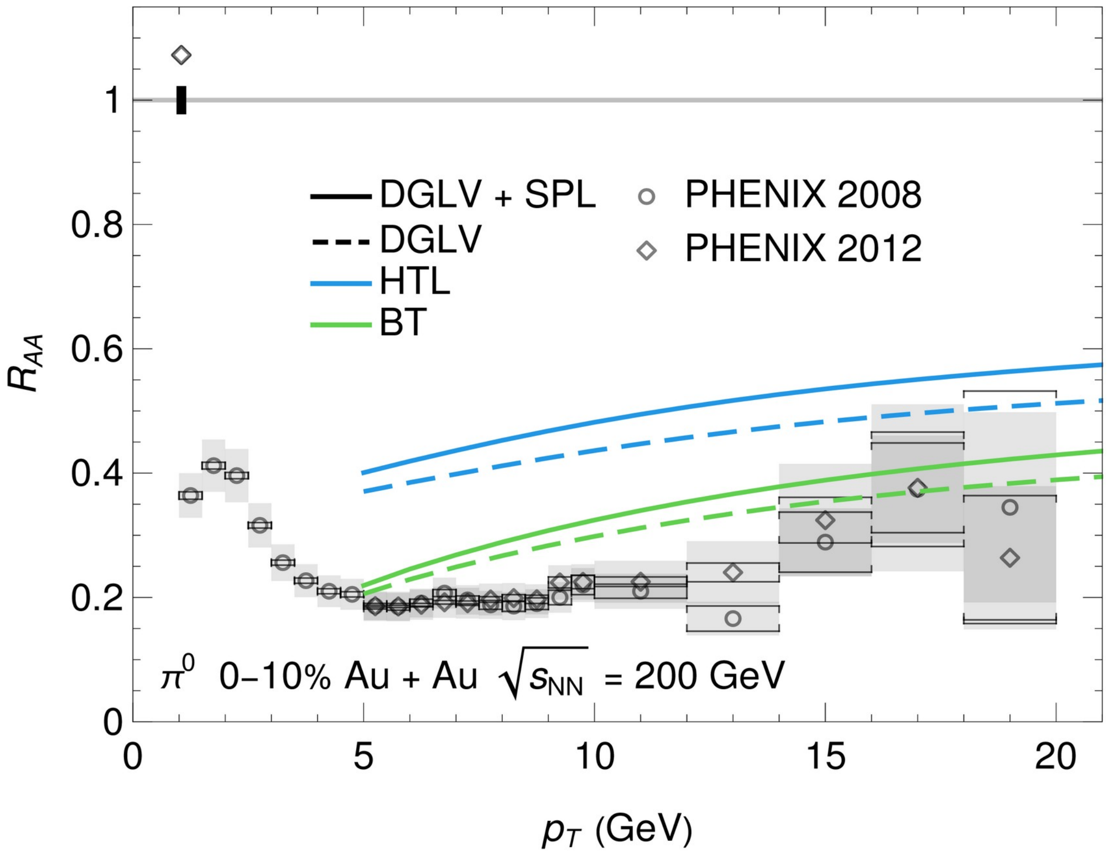
- Low-mid pt results sensitive to choice of elastic E-loss kernel

Light Flavour Suppression in PbPb



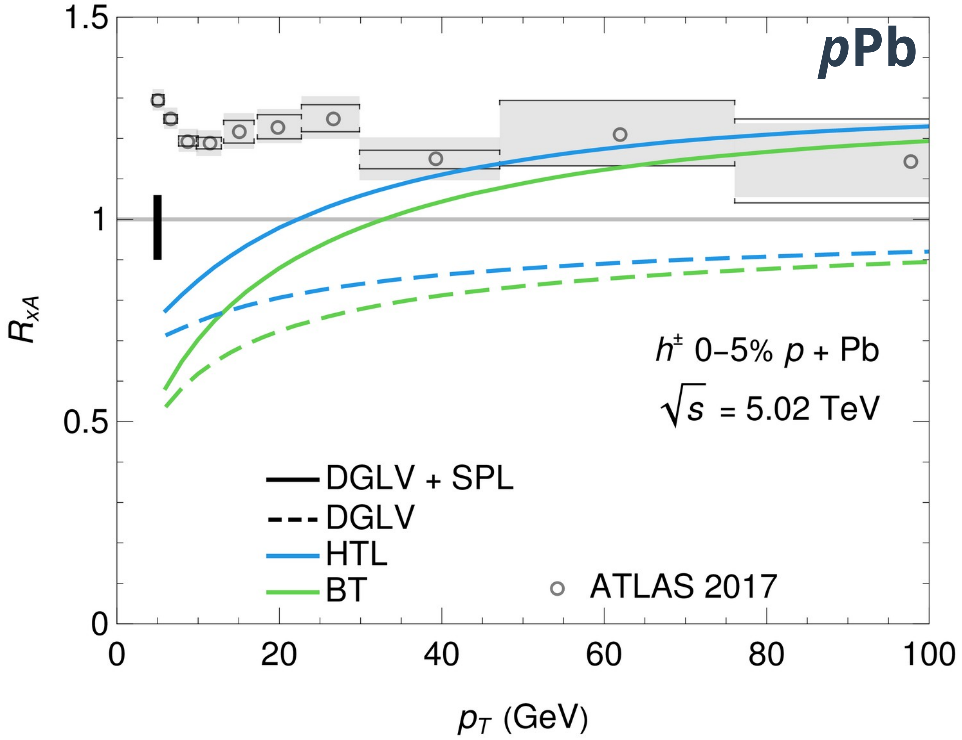
- Low-mid pt results sensitive to choice of elastic E-loss kernel
- **Short path length corr. is extremely large** due to large contribution for gluons compared to quarks
- SPL grows in quickly in p_T leading to fast rise in R_{AA}

Light Flavour Suppression in AuAu

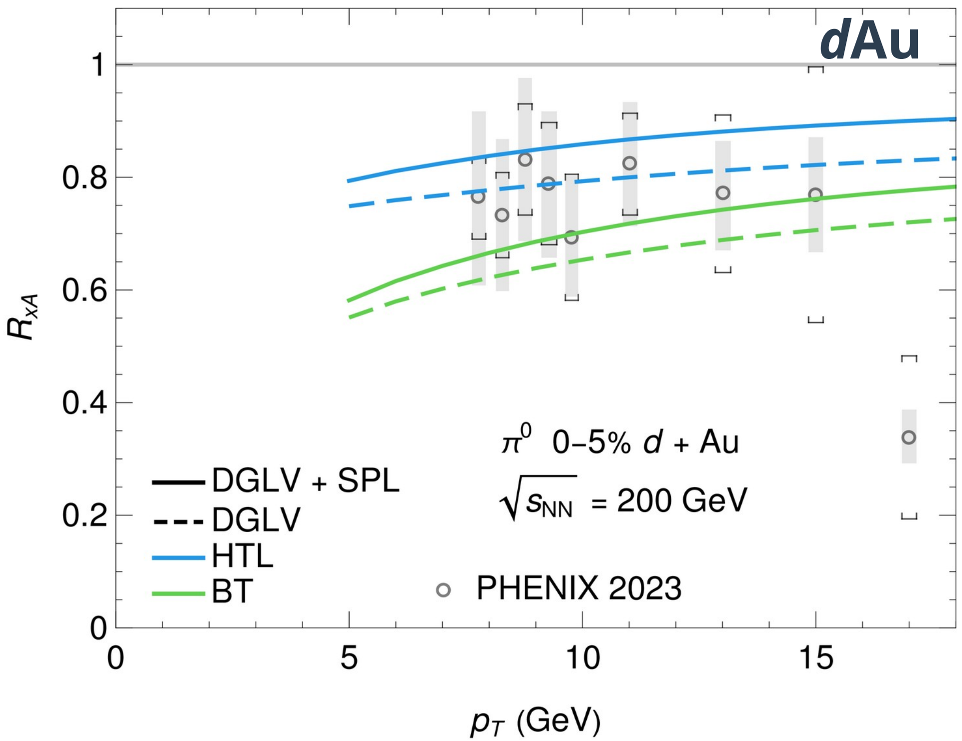


- More sensitive to elastic energy loss uncertainty than PbPb, ~100% effect!
- SPL correction is quite small, since it grows in p_T

Light Flavour Suppression in *p*Pb and *d*Au



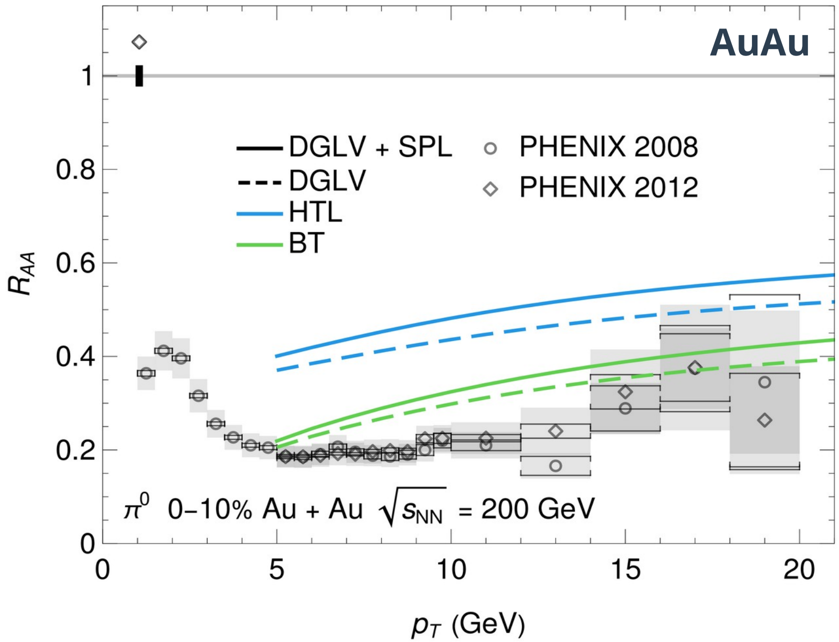
High p_T R_{AA} qualitatively consistent with SPL result, but low p_T dramatically inconsistent

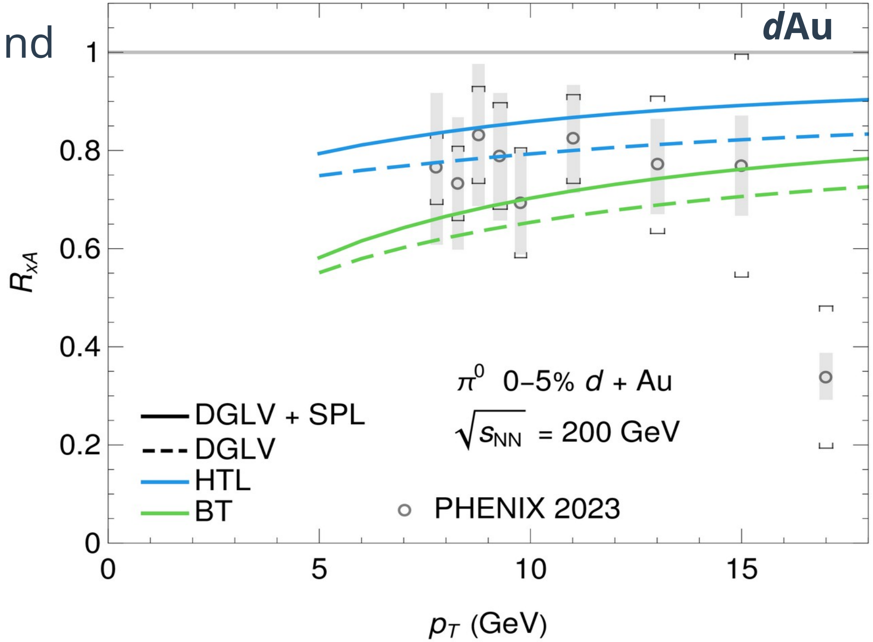


Models qualitatively consistent with data in *d*Au

Summary

- **Simultaneous suppression predictions** in *both* small and large systems, **qualitatively consistent with data**





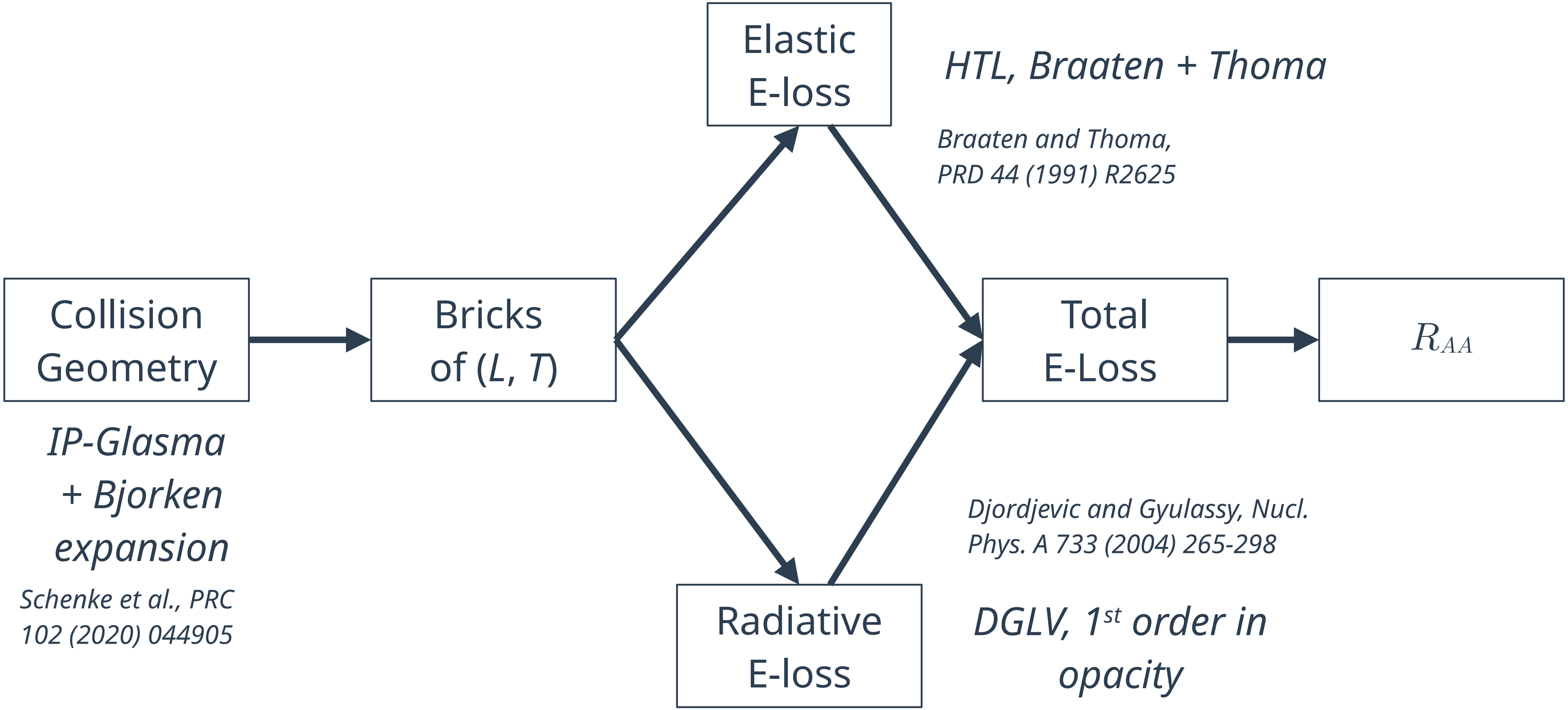
- **Small systems** are almost **entirely elastic energy loss**
  $\Rightarrow$ System size scan in R_{AA} could disentangle radiation vs elastic energy loss mechanisms

Future work:

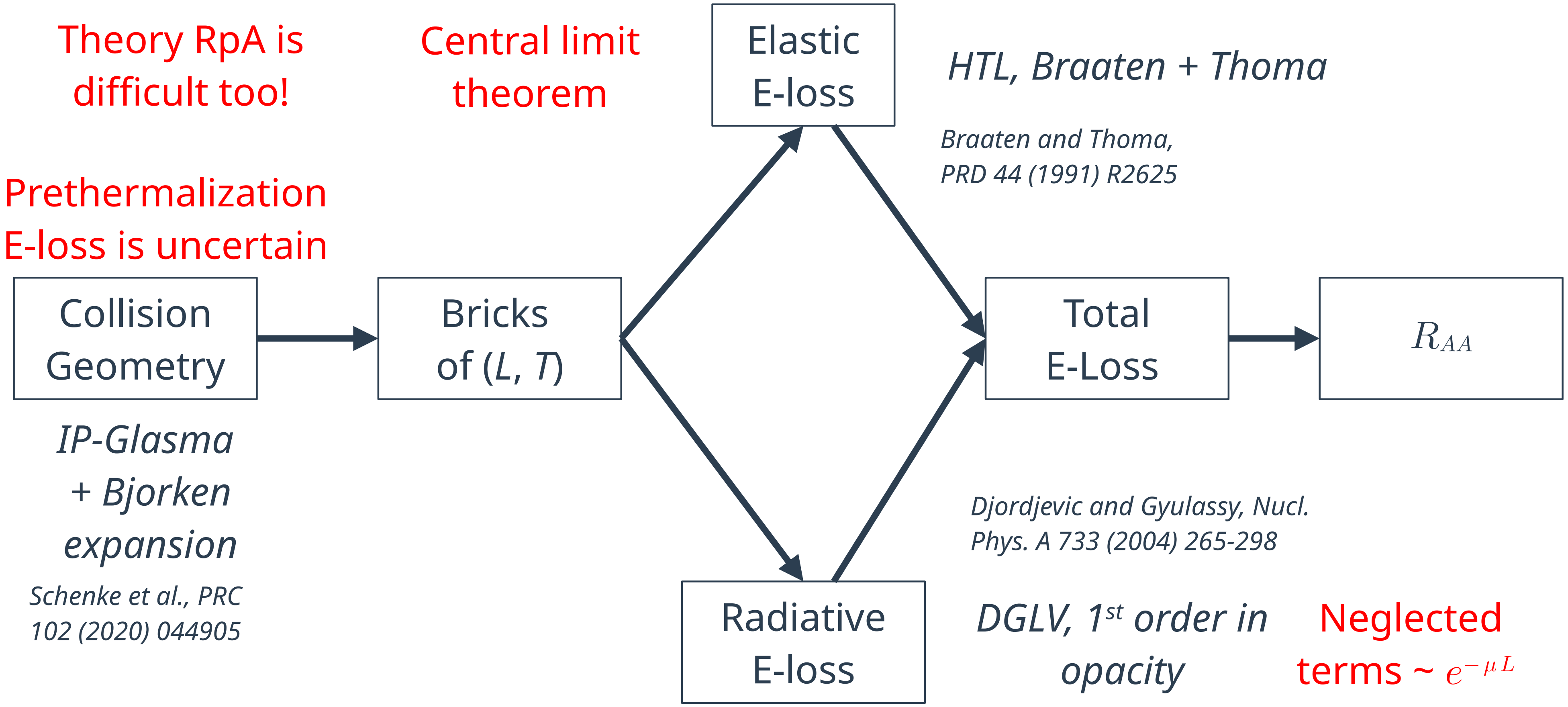
- System size scan with global fitted α_s
- HTL vs vacuum propagators
- Detailed uncertainty analysis

Bonus Slides

Energy Loss Models in Small Systems



Energy Loss Models in Small Systems



Energy Loss Models in Small Systems

Theory RpA is difficult too!

Central limit theorem

Prethermalization E-loss is uncertain

Collision Geometry → Bricks of (L, T) → Elastic E-loss / Radiative E-loss → Total E-Loss → R_{AA}

IP-Glasma + Bjorken expansion

Schenke et al., PRC 102 (2020) 044905

HTL, Braaten + Thoma

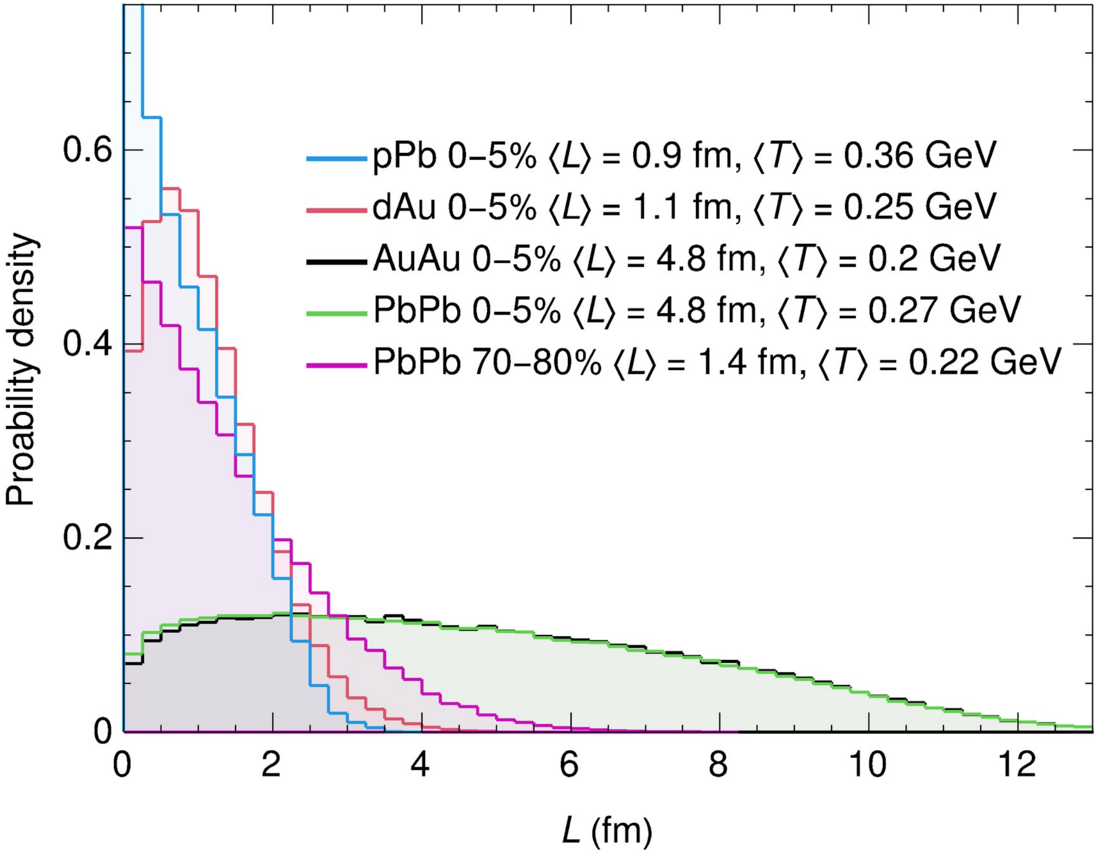
Braaten and Thoma, PRD 44 (1991) R2625

Djordjevic and Gyulassy, Nucl. Phys. A 733 (2004) 265-298

DGLV, 1st order in opacity

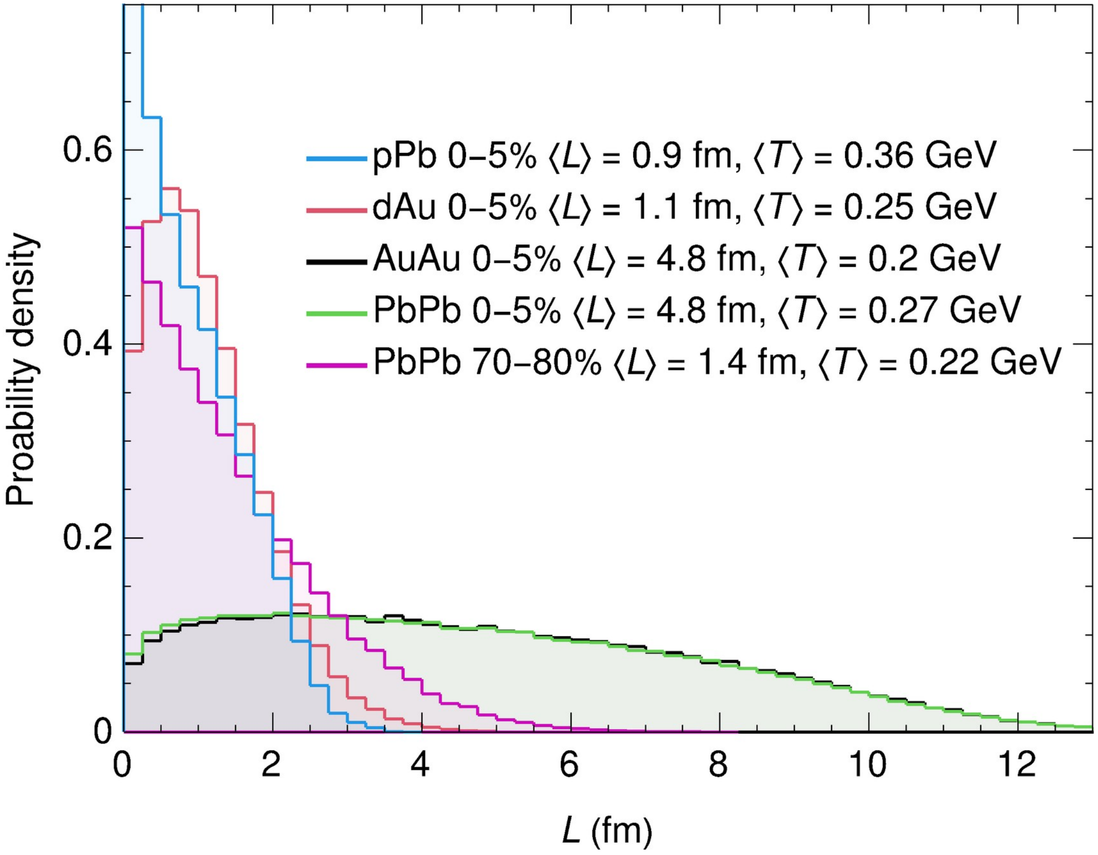
Neglected terms ~ $e^{-\mu L}$

What do Small QGP's Look Like?



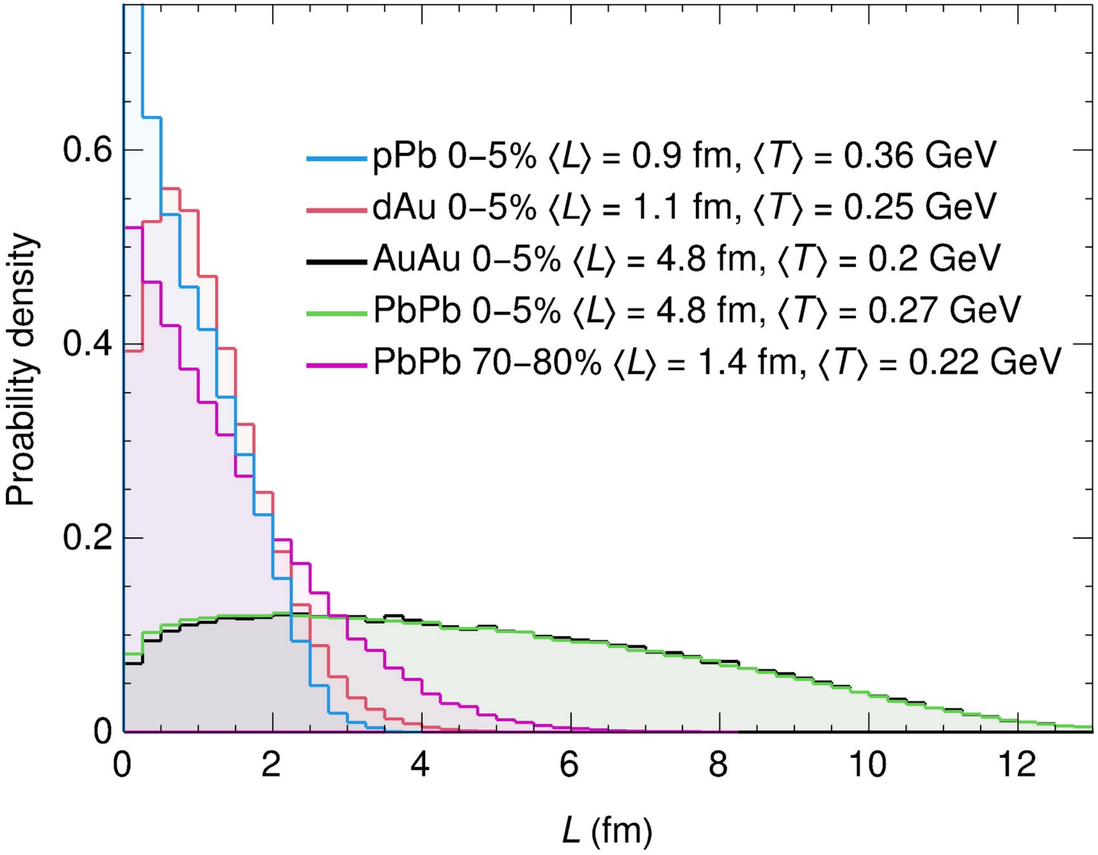
- Small system ⟨L⟩ ~ 1 fm comparable to peripheral AA

What do Small QGP's Look Like?



- Small system ⟨L⟩ ~ 1 fm comparable to peripheral AA
- Small systems have L/λ ~ 1
  - Central limit theorem inapplicable (elastic)
  - Multiple soft scatter approaches inapplicable

What do Small QGP's Look Like?



- Small system ⟨L⟩ ~ 1 fm comparable to peripheral AA

- Small systems have L/λ ~ 1
  - Central limit theorem inapplicable (elastic)
  - Multiple soft scatter approaches inapplicable
- Large systems have L/λ ~ 5
  - Central limit theorem still dubious?

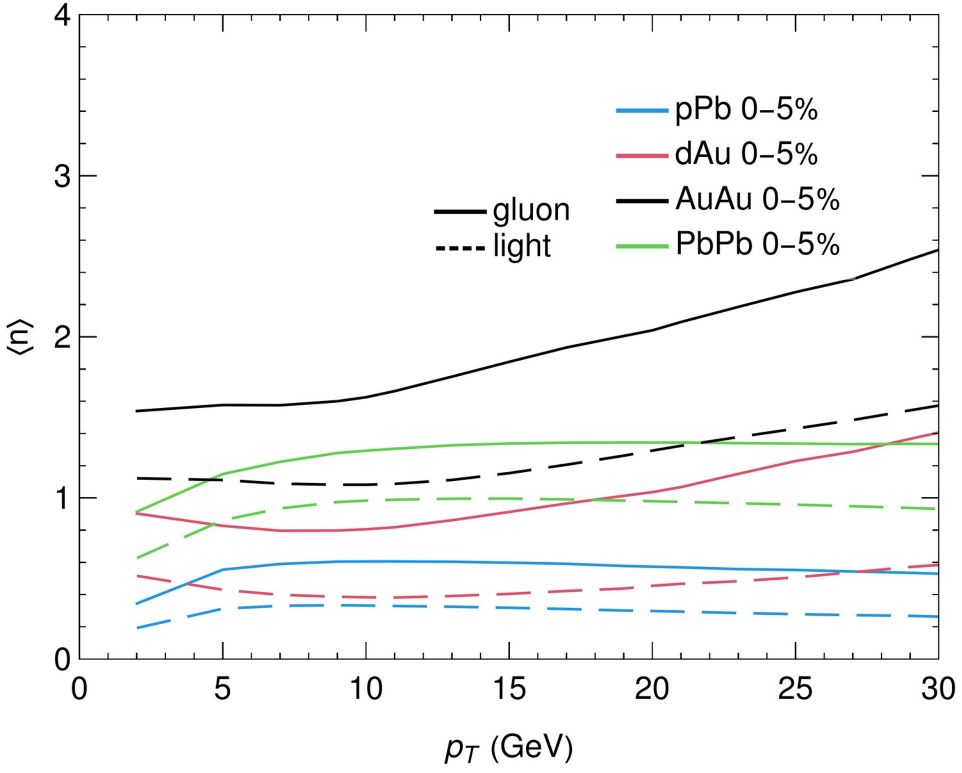
Why is Gaussian ~ Poisson?

Consider *moment expansion* of RAA

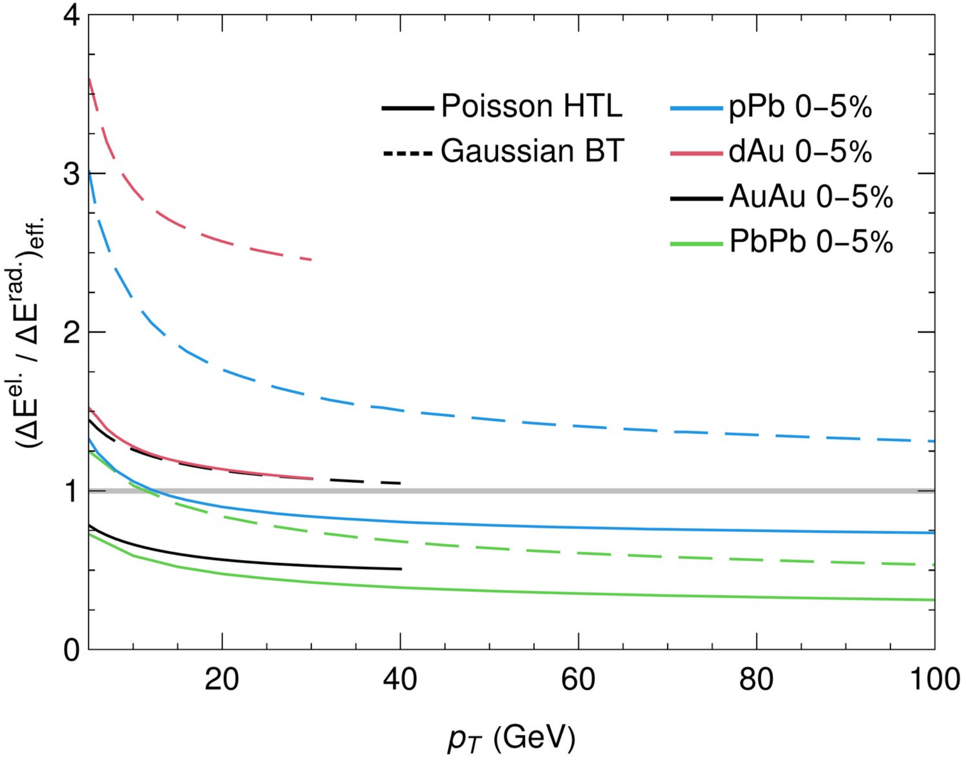
$$R_{AA}(p_T) = \sum_n c_n(p_T) \int d\epsilon \; P_{\text{tot.}}(\epsilon | p_T)$$
$$= \sum_n c_n(p_T) \, \langle \epsilon^n(p_T) \rangle_{\text{tot.}}$$

$$\langle n \rangle \equiv \frac{\sum_n n \; |c_n \langle \epsilon^n \rangle|}{\sum_n |c_n \langle \epsilon^n \rangle|}$$

Small <n> => Gaussian RAA ~ Poisson RAA since zeroth and first moments are identical



Elastic vs Radiative E-Loss Importance

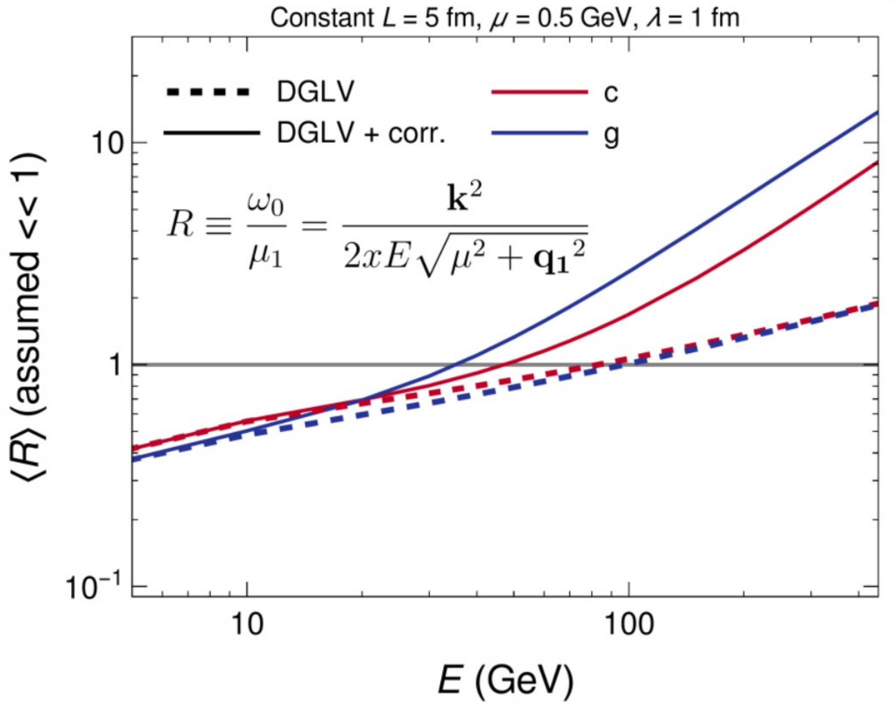


Elastic $\Delta E / E \simeq \alpha^2 T^2 \log(ET)/E$

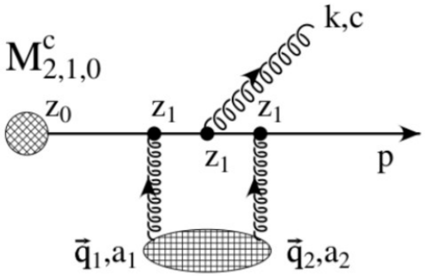
Radiative $\Delta E / E \simeq \alpha_s^3 L^2 T \log E / E$

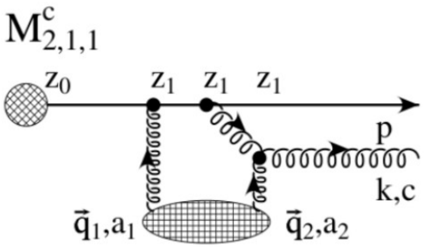
- Strong dependence on elastic E-loss used
- Small systems elastic is **~1-3x** more important than radiative

Large Formation Time Assumption



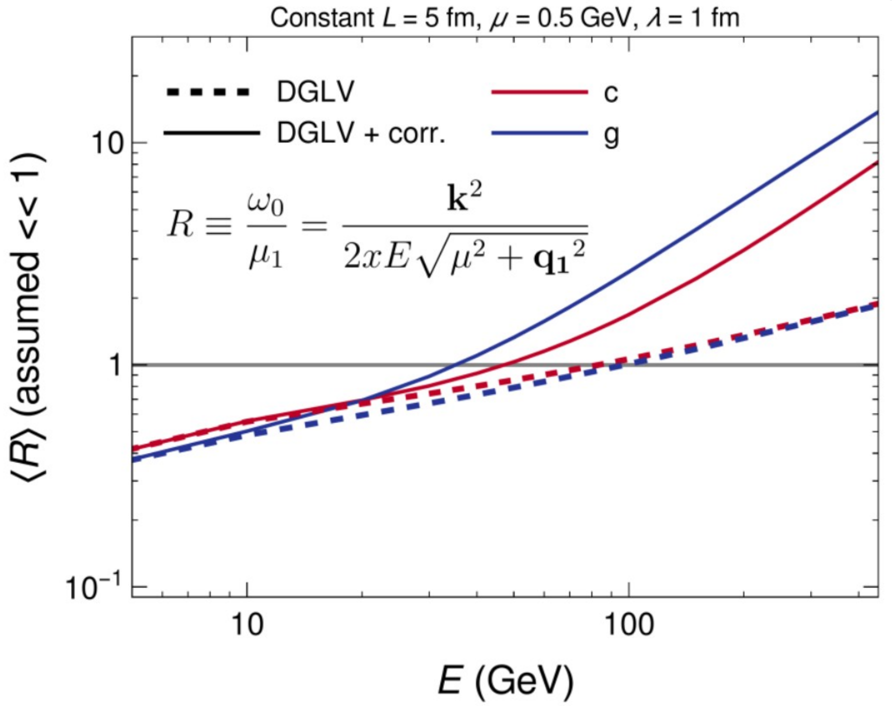
- **Large contributions** to SPL corr. at high energies from regions of phase space **not allowed** according to Large Formation Time assumption
- Also impacts DGLV



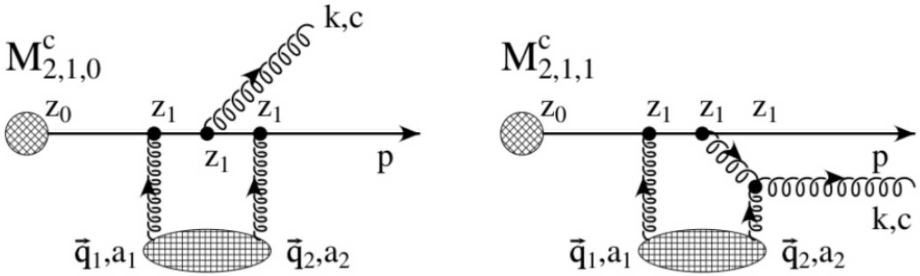


$$\sim \frac{\mathbf{k}_\perp^2 + m_g^2 + x^2 M^2}{2\omega} \frac{1}{\mu_1} \to 0$$

Large Formation Time Assumption

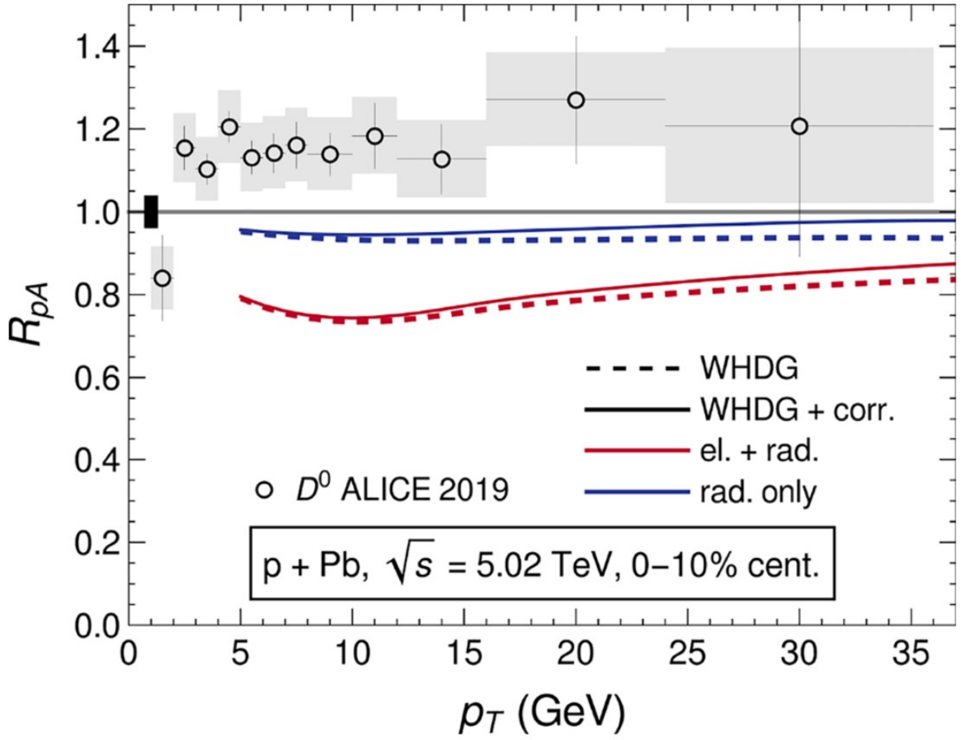


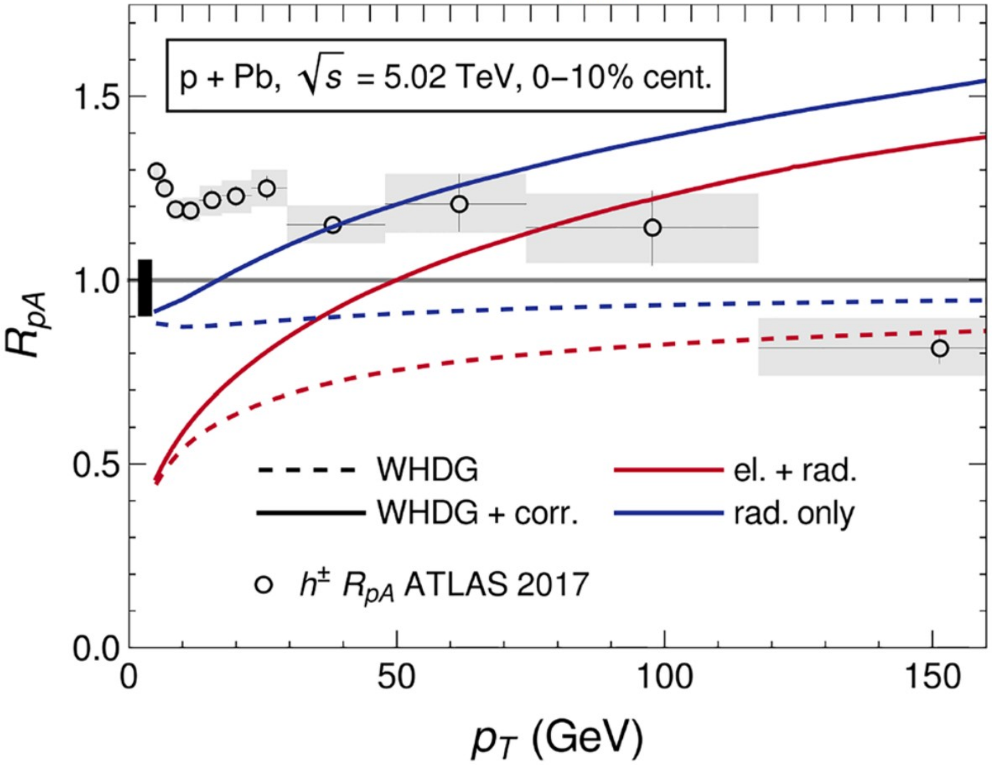
- **Large contributions** to SPL corr. at high energies from regions of phase space **not allowed** according to Large Formation Time assumption
- Also impacts DGLV
- Future work should include a full rederivation of DGLV with LFT assumption relaxed
- Can implement a phenomenological cut in the phase space as well to limit assumption-violating contributions



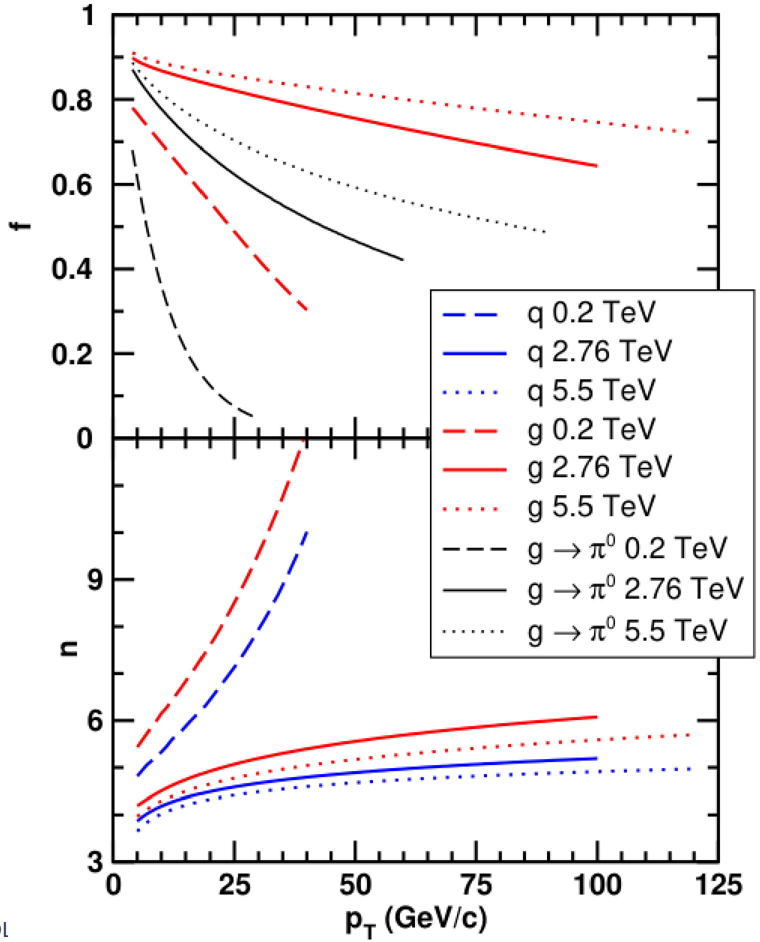
$$\sim \frac{\mathbf{k}_\perp^2 + m_g^2 + x^2 M^2}{2\omega} \frac{1}{\mu_1} \to 0$$

Turning Off Elastic E-Loss





Gluon to Light Quark Crossover



COL

Short pathlength (SPL) Corr. to DGLV

$$x\frac{\mathrm{d}N}{\mathrm{d}x} = \frac{C_R\alpha_s L}{\pi\lambda_g}\int\frac{\mathrm{d}^2\mathbf{q}_1}{\pi}\frac{\mu^2}{\left(\mu^2+\mathbf{q}_1^2\right)^2}\int\frac{\mathrm{d}^2\mathbf{k}}{\pi}\int\mathrm{d}\Delta z\,\bar{\rho}(\Delta z) \qquad (1)$$

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

DGLV 1st order in opacity

Djordjevic and Gyulassy, Nucl. Phys. A 733 (2004) 265-298

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

SPL corr.

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

Kolbe & Horowitz, PRC 100 (2019) 024913

Short pathlength (SPL) Corr. to DGLV

$$x\frac{\mathrm{d}N}{\mathrm{d}x} = \frac{C_R\alpha_s L}{\pi\lambda_g}\int\frac{\mathrm{d}^2\mathbf{q}_1}{\pi}\frac{\mu^2}{\left(\mu^2+\mathbf{q}_1^2\right)^2}\int\frac{\mathrm{d}^2\mathbf{k}}{\pi}\int\mathrm{d}\Delta z\,\bar{\rho}(\Delta z) \qquad (1)$$

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

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

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

DGLV 1st order in opacity

Djordjevic and Gyulassy, Nucl. Phys. A 733 (2004) 265-298

Suppressed for large *L*

SPL corr.

Kolbe & Horowitz, PRC 100 (2019) 024913

Short pathlength (SPL) Corr. to DGLV

$$x\frac{\mathrm{d}N}{\mathrm{d}x} = \frac{C_R \alpha_s L}{\pi \lambda_g} \int \frac{\mathrm{d}^2\mathbf{q}_1}{\pi} \frac{\mu^2}{(\mu^2 + \mathbf{q}_1^2)^2} \int \frac{\mathrm{d}^2\mathbf{k}}{\pi} \int \mathrm{d}\Delta z\, \bar{\rho}(\Delta z) \qquad (1)$$

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

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

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

DGLV 1st order in opacity

Djordjevic and Gyulassy, Nucl. Phys. A 733 (2004) 265-298

SPL corr.

Kolbe & Horowitz, PRC 100 (2019) 024913

Suppressed for large *L*

Breaking of **colour triviality**

→ we'll see this can lead to excessively large corr. for gluons!

Central Limit Theorem in Elastic E-loss

How important is **central limit theorem** in the elastic energy loss?

We compare:

1) HTL result with **Poisson** distribution (*Poisson HTL)*

$$P(\epsilon|E) = \sum_{n=0}^{\infty} P_n(\epsilon|E)$$

$$P_{n+1}(\epsilon) = \frac{1}{n+1} \int \mathrm{d}x_n \, \frac{\mathrm{d}N^g}{\mathrm{d}x} \, P_n(\epsilon - x_n)$$

2) HTL result with **Gaussian** distribution *(Gaussian HTL)*

$$P(\epsilon|E) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\left(\frac{\epsilon - \Delta E/E}{\sqrt{2}\sigma}\right)^2\right)$$

$$\sigma = \frac{2}{E^2} \int \mathrm{d}z \frac{\mathrm{d}E}{\mathrm{d}z} T(z)$$

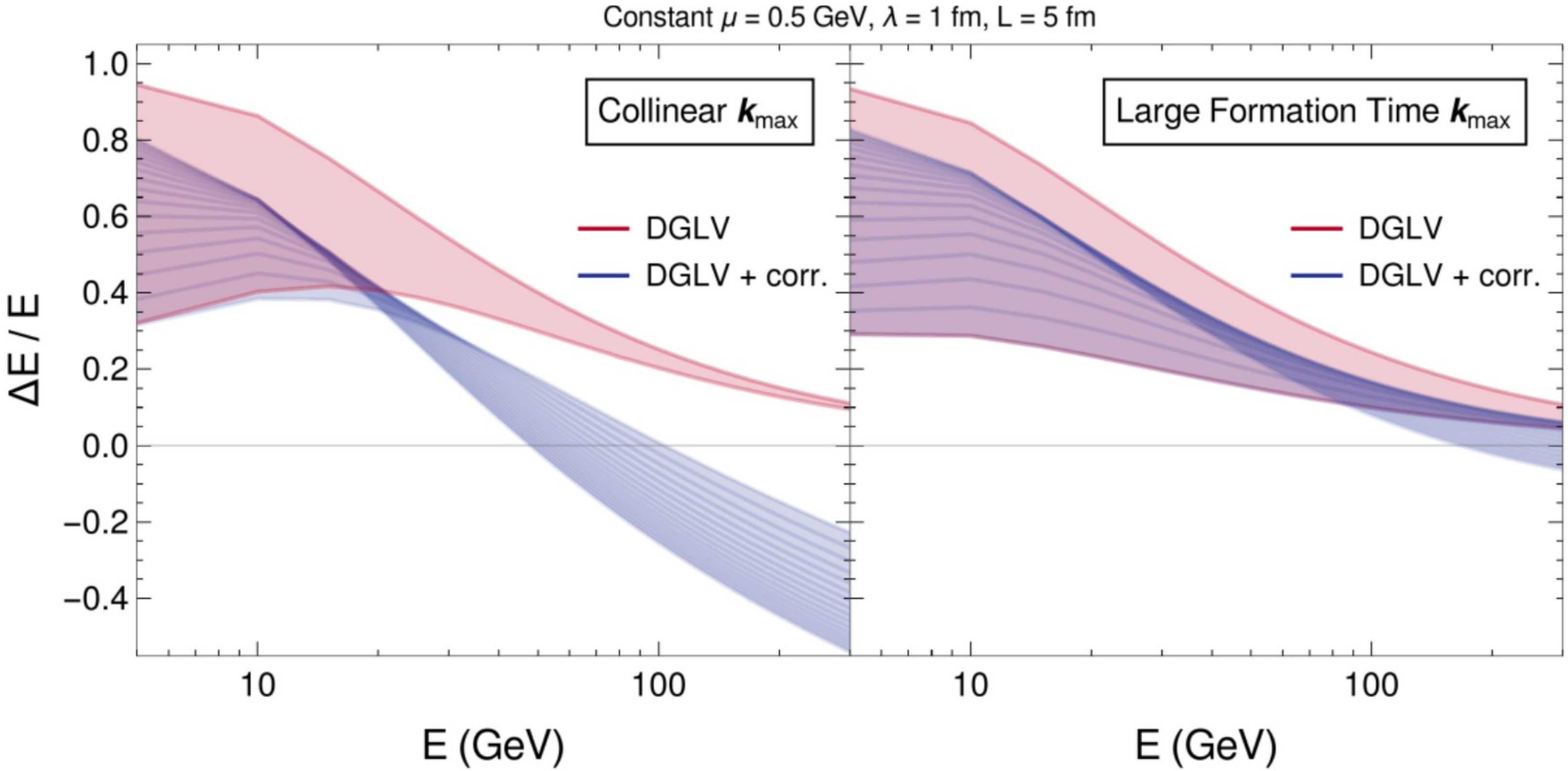
(Fluctuation Dissipation Thrm)

HTL vs Vacuum propagators

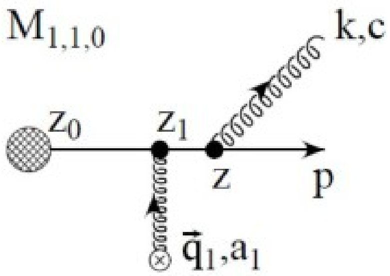
- HTL expands in momentum transfer: $q\,/\,T \simeq g_s$
- For large momentum transfer, vacuum propagators should be the correct theory
- The way in which you cross between the two, changes the longitudinal and transverse components
- Makes a large difference in energy loss

Controlling the LFT approximation

- Collinearity can be enforced via $|\mathbf{k}_\perp|_{\max} = 2xE(1-x)$
- Similarly, collinearity + LFT $\Rightarrow |\mathbf{k}_\perp|_{\max} = \mathrm{Min}[2xE(1-x), \sqrt{2xE\mu_1}]$.



Example contribution to SPL corr.



$$\mathscr{M}_{1,0,0} = \int \frac{d^4 q_1}{(2\pi)^4} iJ(p+k-q_1)e^{i(p+k-q_1)x_0}(ig_s)\epsilon_\alpha(2p-2q+k)^\alpha \times$$
$$\times\, i\Delta_M(p-q_1+k)i\Delta_M(p-q_1)(2p-q_1)^0 V(q1)e^{iq_1x_1}T_{a_1}a_1c$$
$$\approx J(p+k)e^{i(p+k)x_0}(-ig_s a_1 c T_{a_1})2E\int \frac{d^2\mathbf{q}_1}{(2\pi)^2}e^{-\mathbf{q}_1\cdot\mathbf{b}_1}I_1,$$

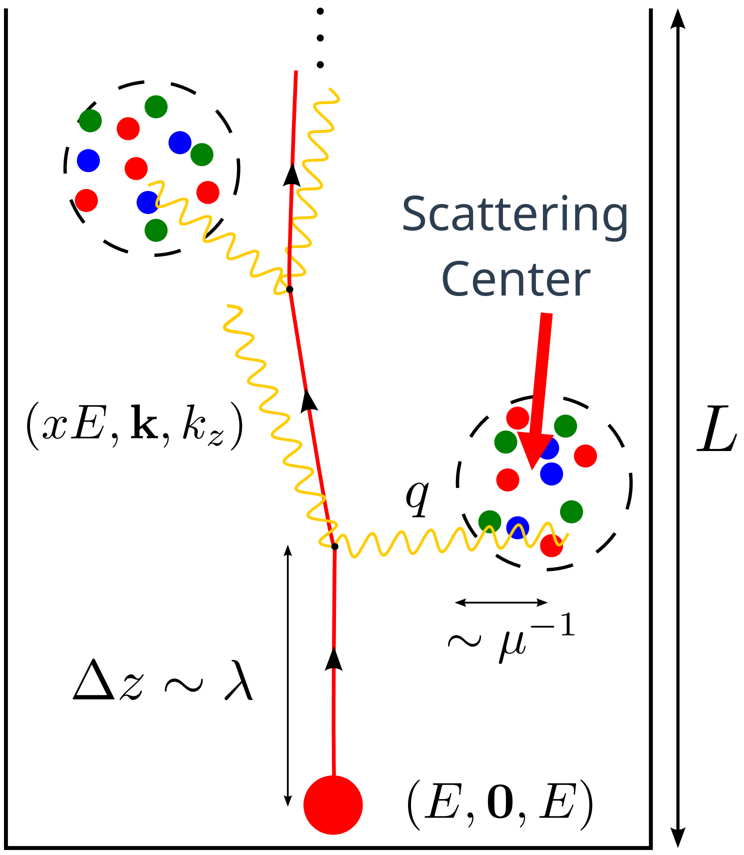
$$I_1(p,k,\mathbf{q}_1,z_1-z_0) = \int \frac{dq_1^z}{2\pi}\frac{\epsilon_\alpha(2p-2q+k)^\alpha}{(p-q_1+k)^2-M^2+i\epsilon}\times$$
$$\times \frac{1}{(p-q_1)^2-M^2+i\epsilon}v(\vec{\mathbf{q}}_1)e^{-iq_1^z(z_1-z_0)}$$

Pole at $q_1^{z(3)} = -i\mu_1$

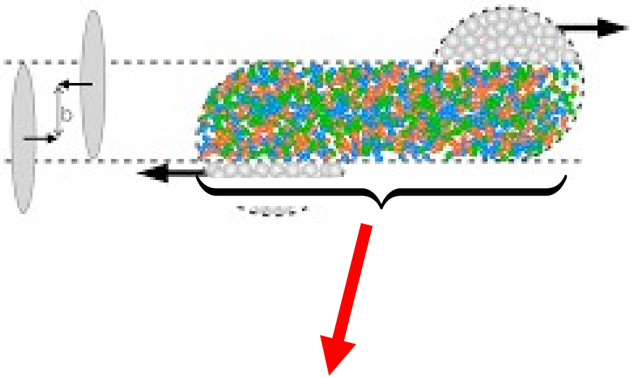
Short pathlength (SPL) Corr. to DGLV

- Standard radiative energy loss (DGLV) assumes $L \gg \mu^{-1}$
- *Short path length correction* adds back in neglected terms $\sim e^{-\mu L}$

  Kolbe & Horowitz, PRC 100 (2019) 024913



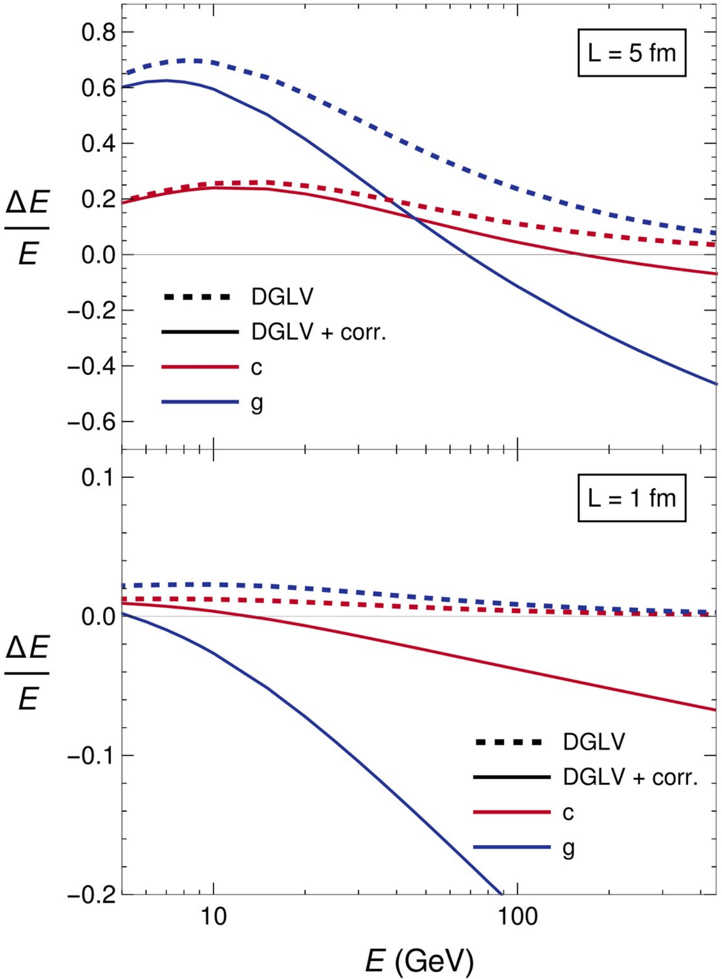
What is the Quark Gluon Plasma?



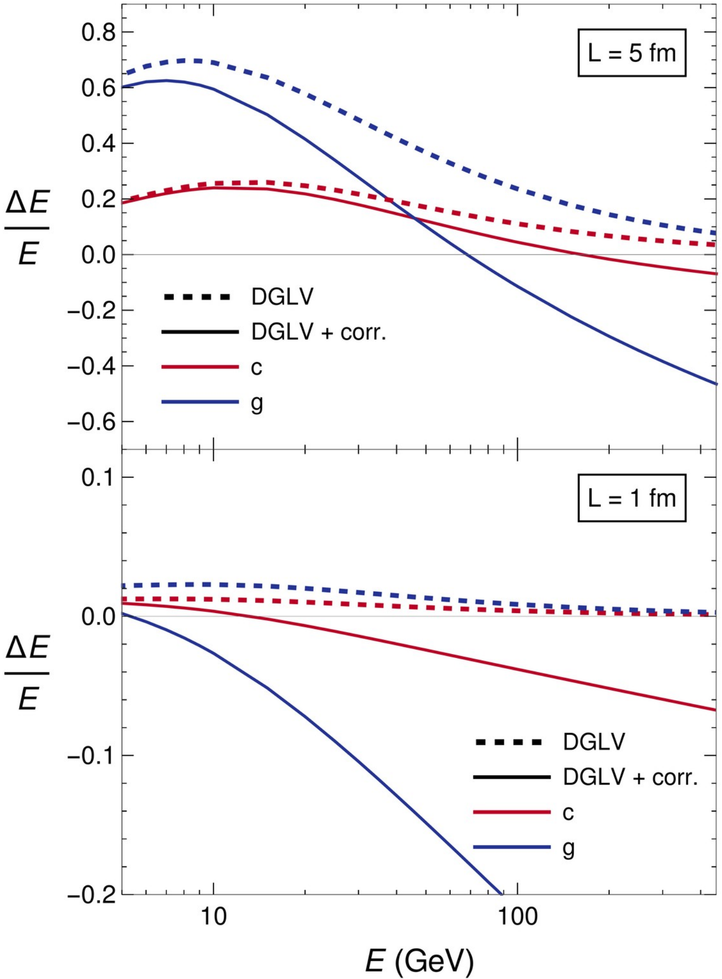
- State of the universe only **microseconds after the Big Bang!**
- Melted down protons and neutrons
- **Near perfect fluid** created in heavy-ion collisions at RHIC and the LHC
- Test **QCD** - core component of the standard model

→ **How do we *know* QGP is formed in heavy-ion collisions?**

Numerics of the Short Pathlength Corr.

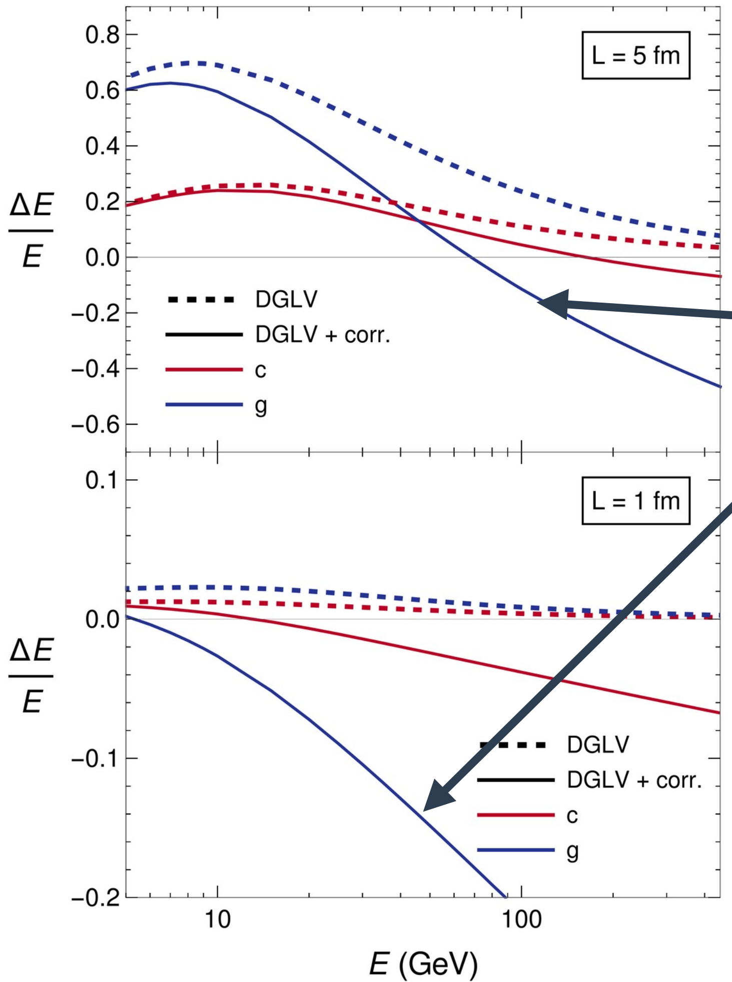


Numerics of the Short Pathlength Corr.



We see the SPL correction:

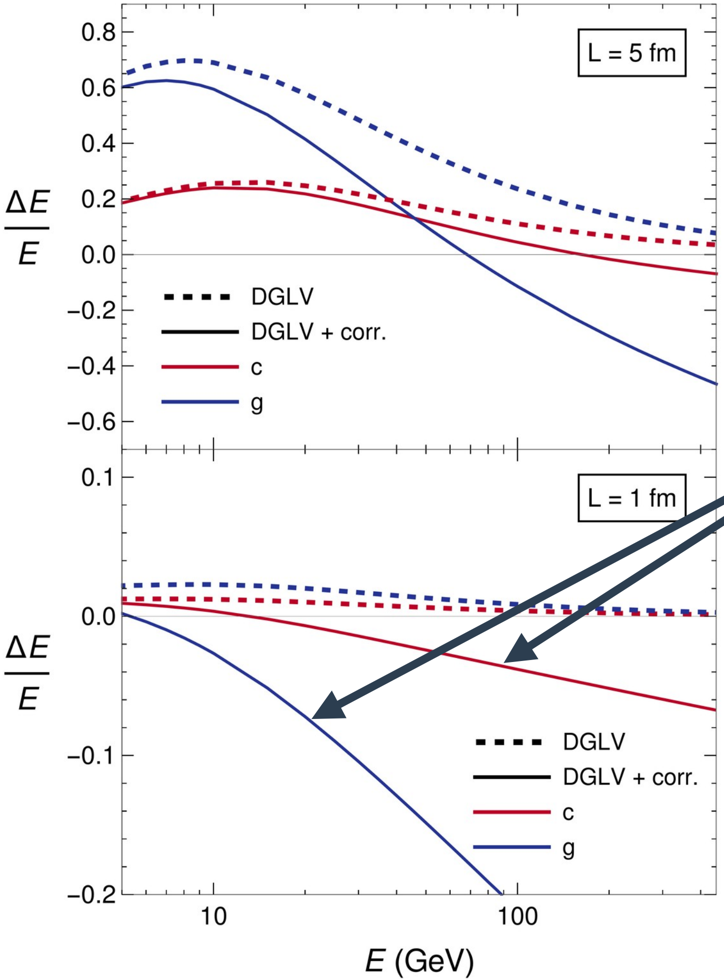
Numerics of the Short Pathlength Corr.



We see the SPL correction:

- Decreases as a function of *L*

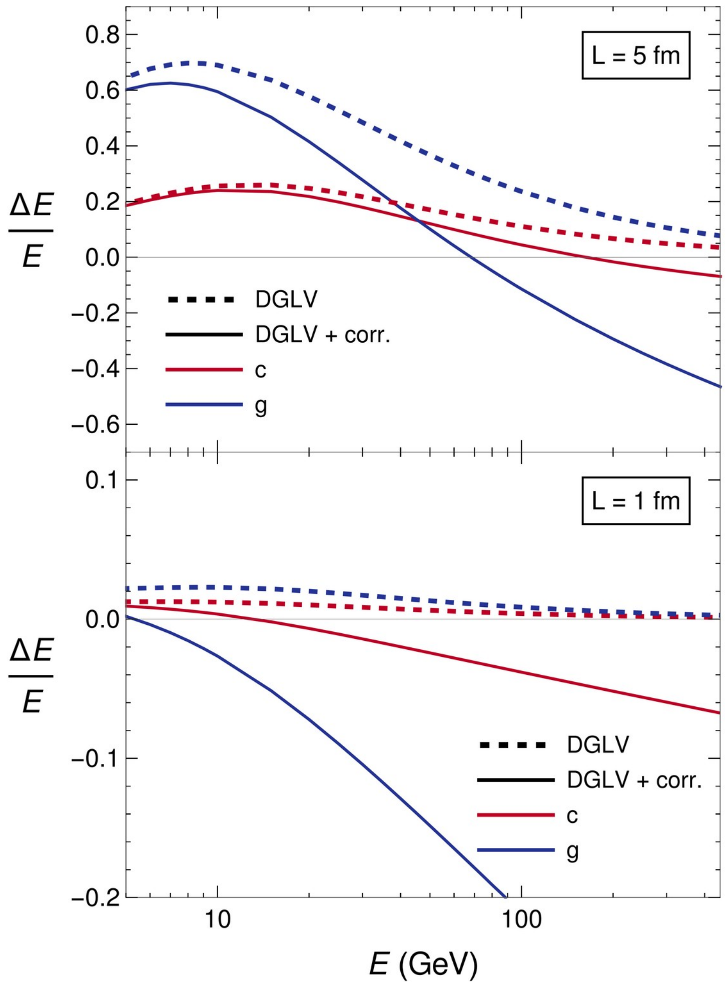
Numerics of the Short Pathlength Corr.



We see the SPL correction:

- Decreases as a function of L
- much larger for gluons cf quarks

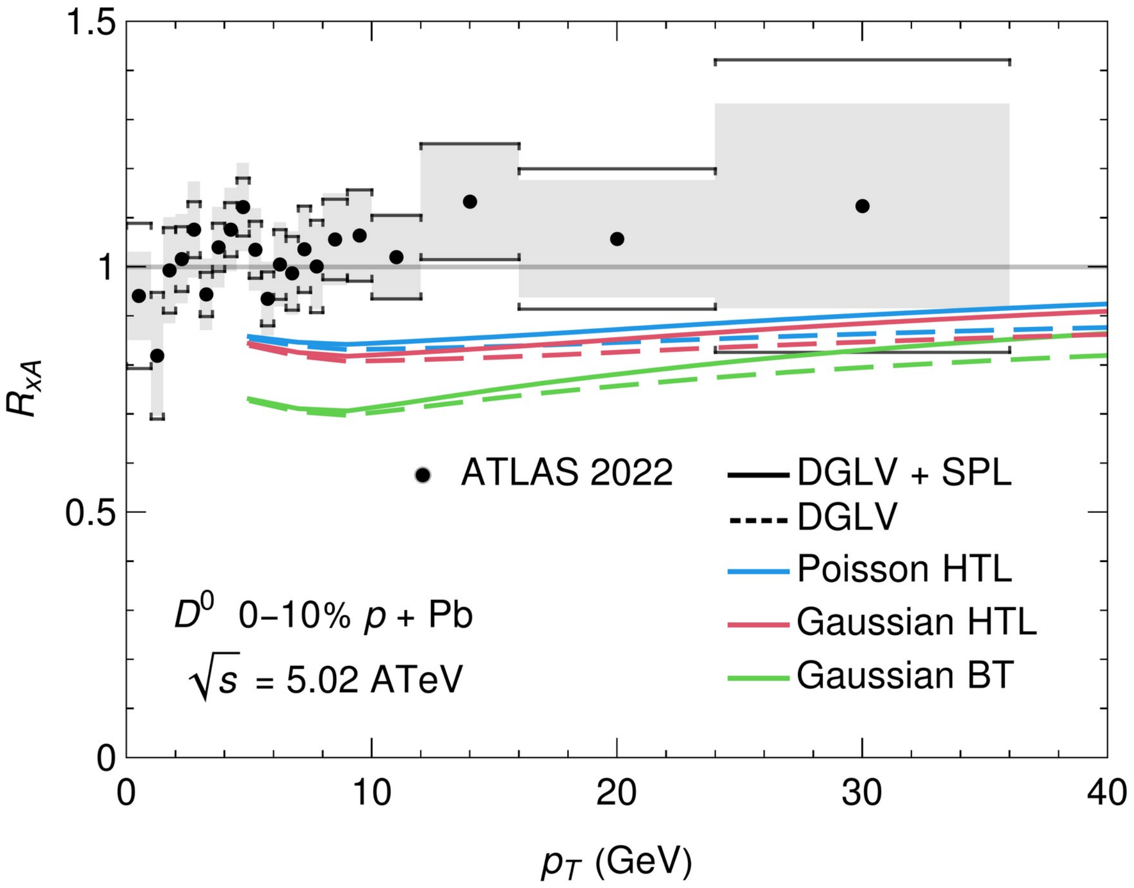
Numerics of the Short Pathlength Corr.



We see the SPL correction:

- Decreases as a function of L
- much larger for gluons cf quarks
- Can lead to **negative** energy loss
- Grows as a function of E

Heavy Flavour Suppression in pPb



- Gaussian R_{AA} ~ Poisson R_{AA}; Surprising since CLT should not be valid
- Extremely sensitive to elastic energy loss model (x2 suppression)

Preliminary results!

We want to understand:

- Do different **elastic/radiative energy loss models** → different signatures in energy loss?
- Can one simultaneously describe suppression (or lack thereof) in **small and large systems**?

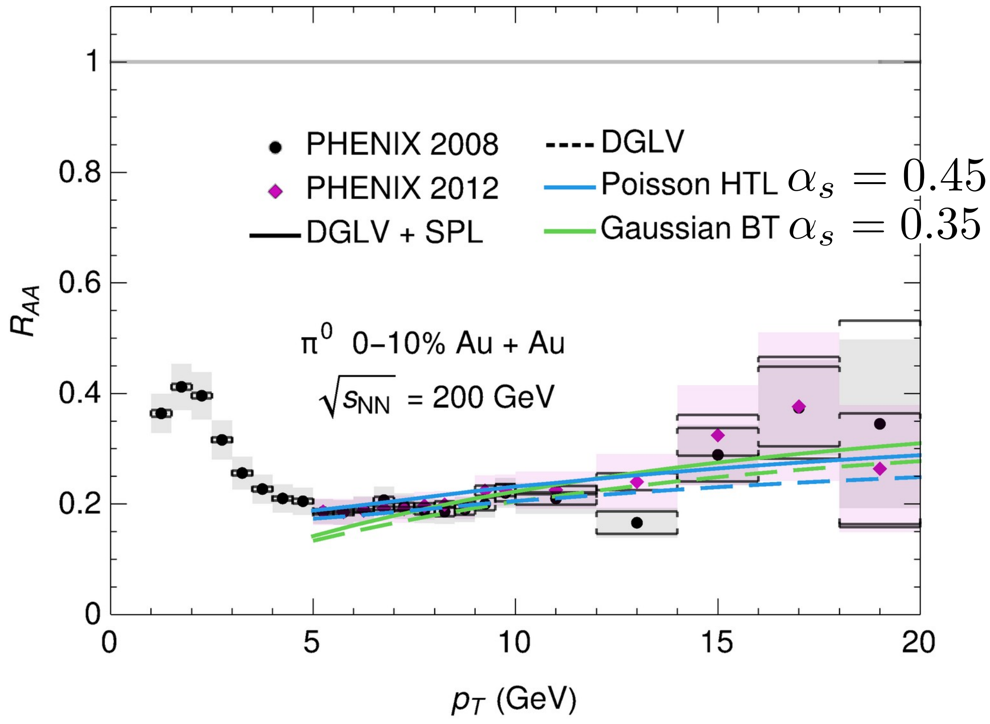
Preliminary results!

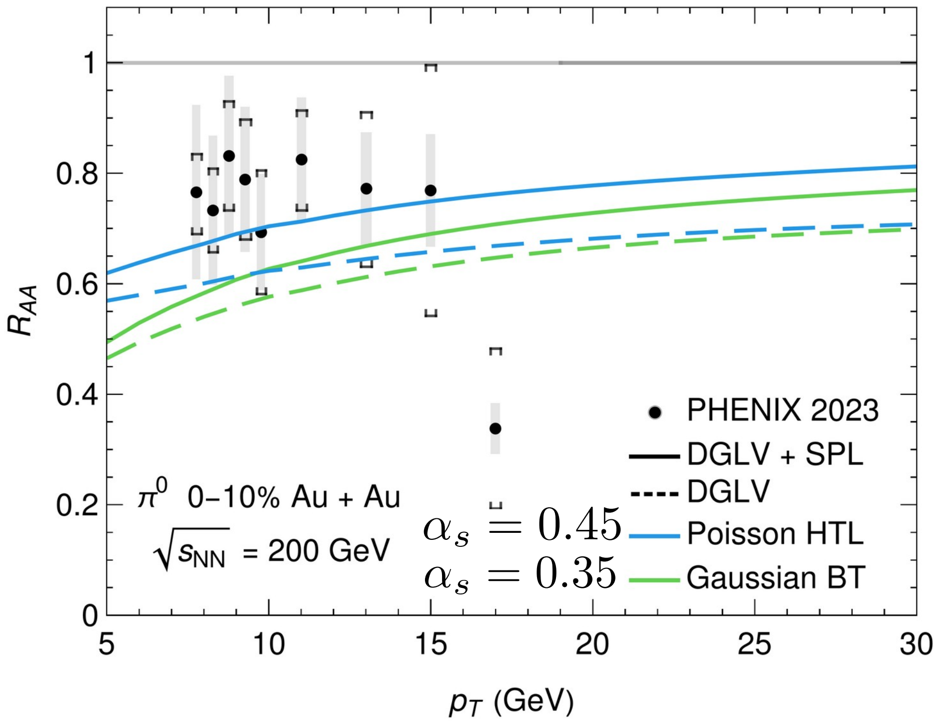
We want to understand:

- Do different **elastic/radiative energy loss models** → different signatures in energy loss?
- Can one simultaneously describe suppression (or lack thereof) in **small and large systems**?

→ Fit α_s on a per model basis

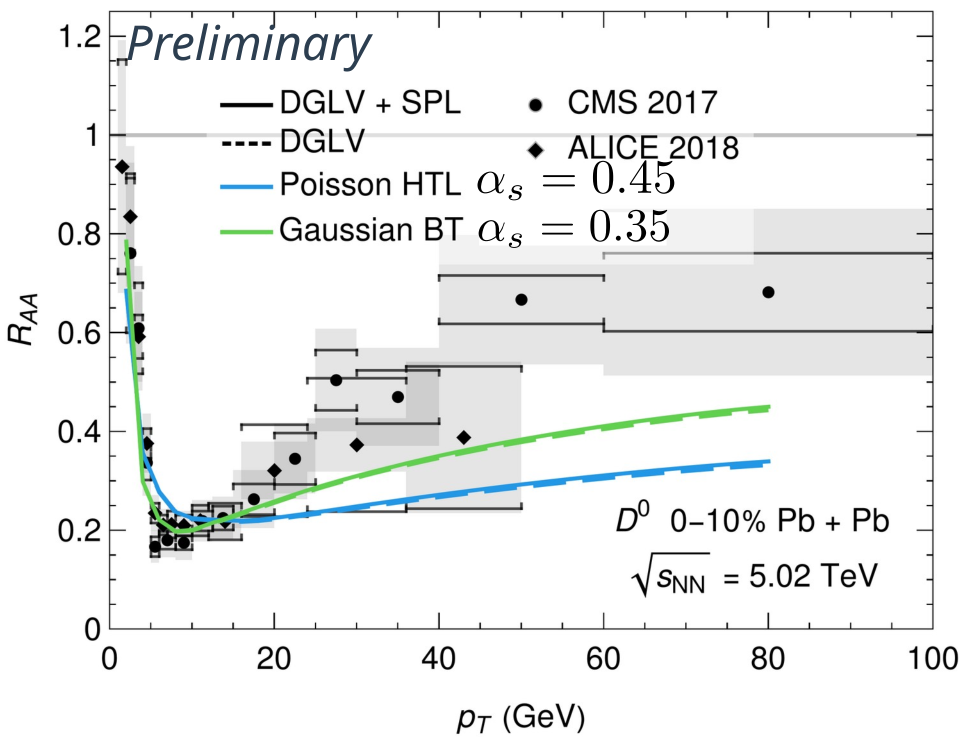
Global α-Fitted Results at RHIC

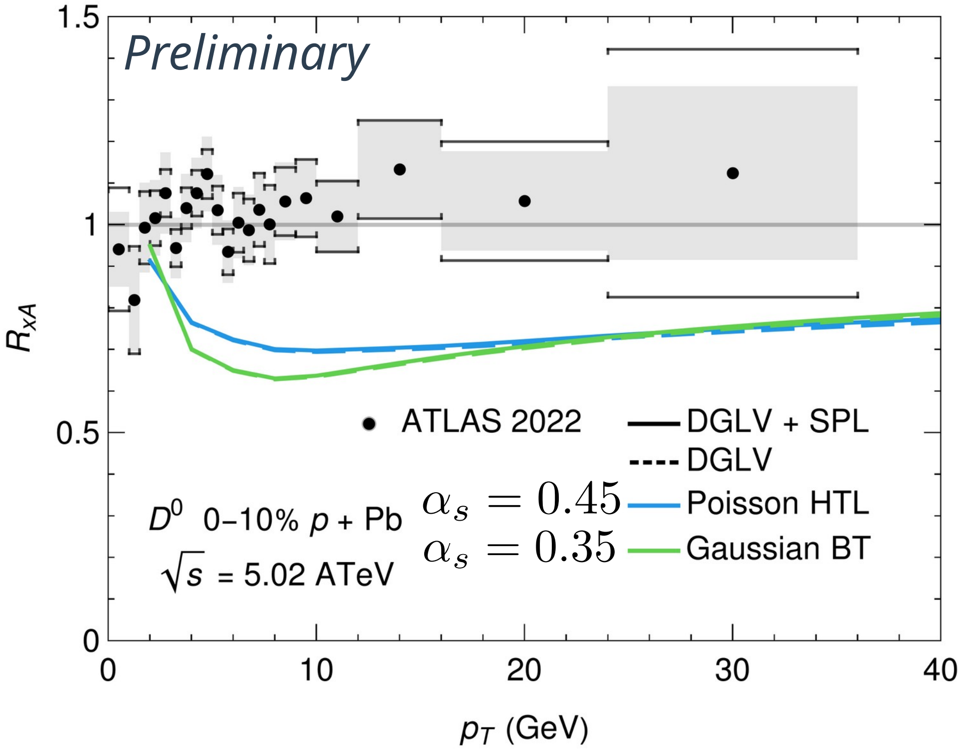




- Very different α_s required for different models
- All models can fit both small and large systems, but HTL closer to data

Global α-Fitted Results at the LHC (heavy)

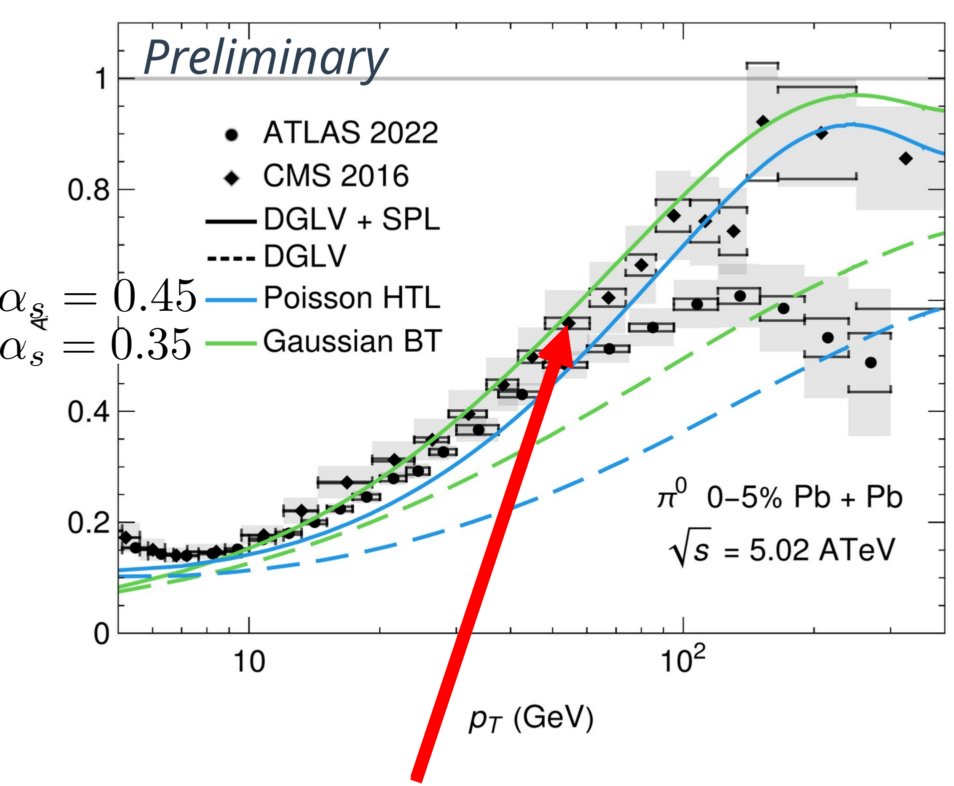


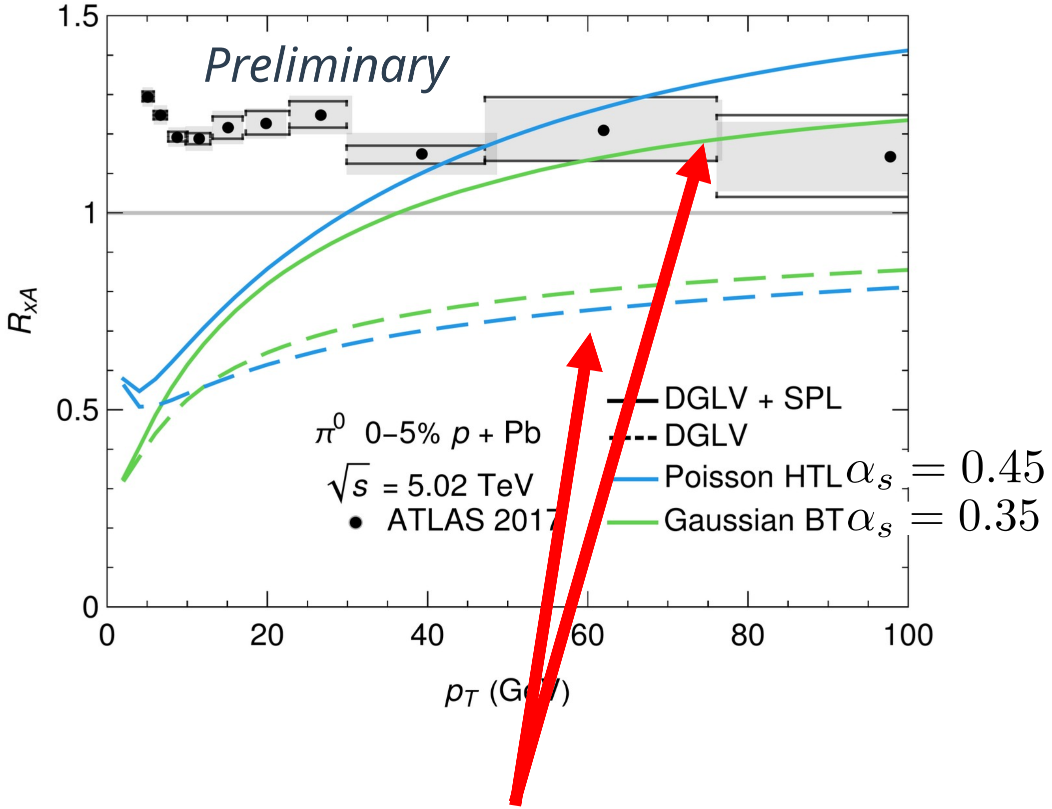


- All data over suppressed, especially small systems

Heavy flavour RAA is especially sensitive to elastic energy loss choice

Global α-Fitted Results at the LHC (light)

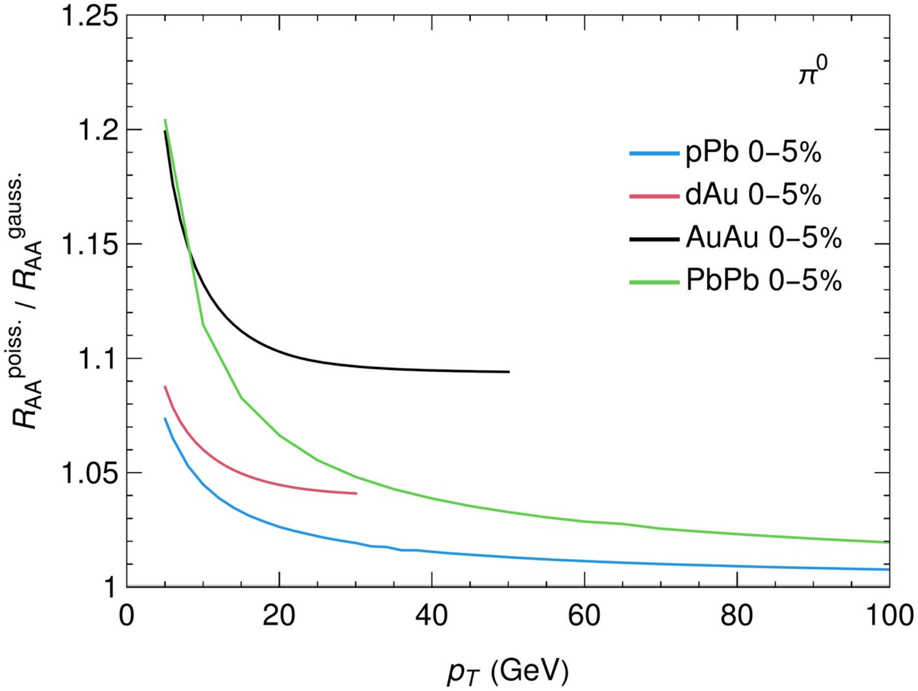




Too good to be true? No space for running coupling effects

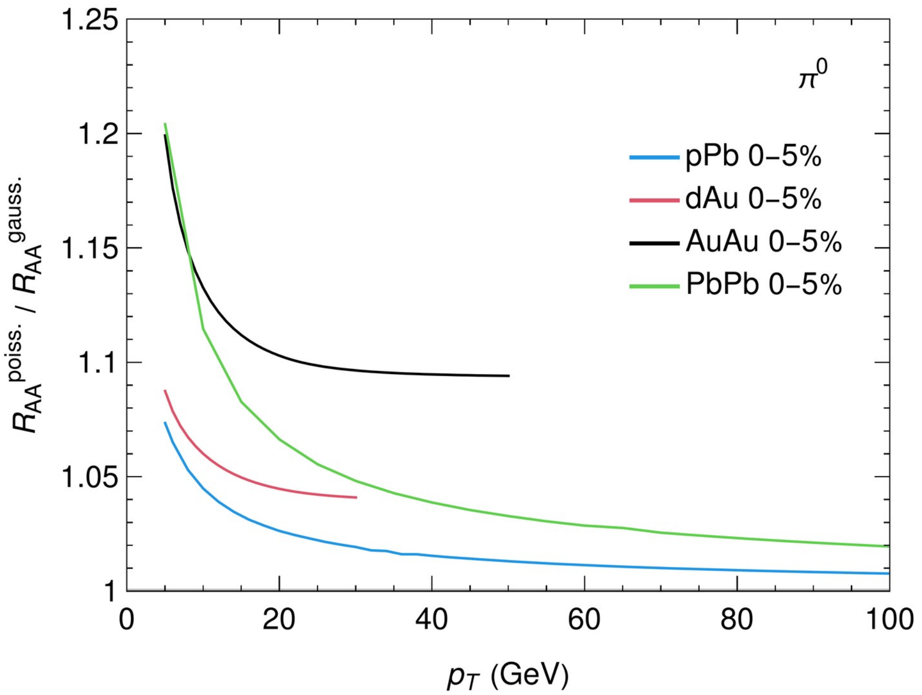
Over-suppressed in *p*Pb with DGLV, qualitative agreement at high pt with SPL

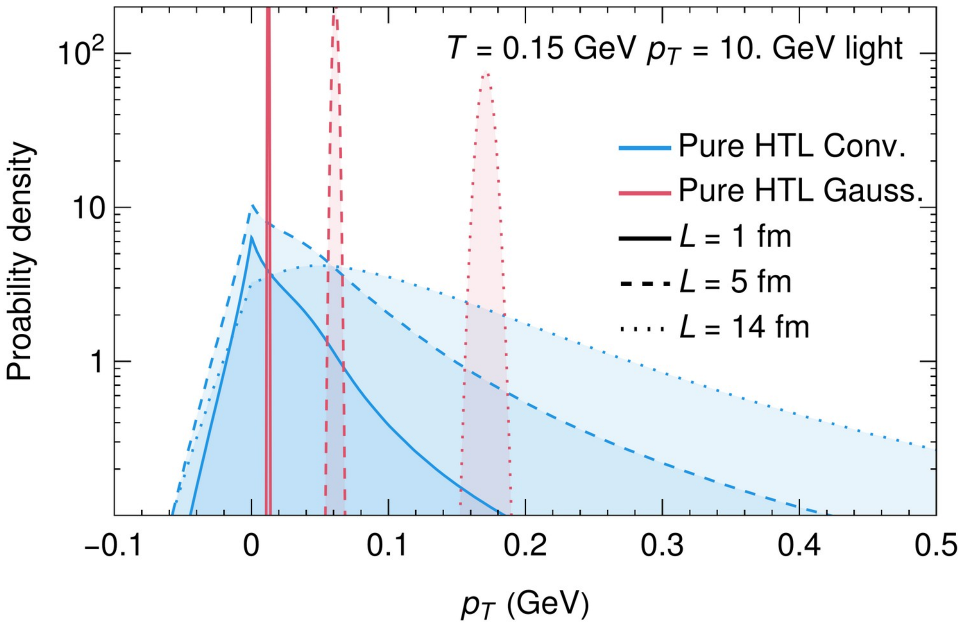
Gaussian ~ Poisson?



- Opposite ordering than expected according to CLT?
- Strong

Gaussian ~ Poisson?

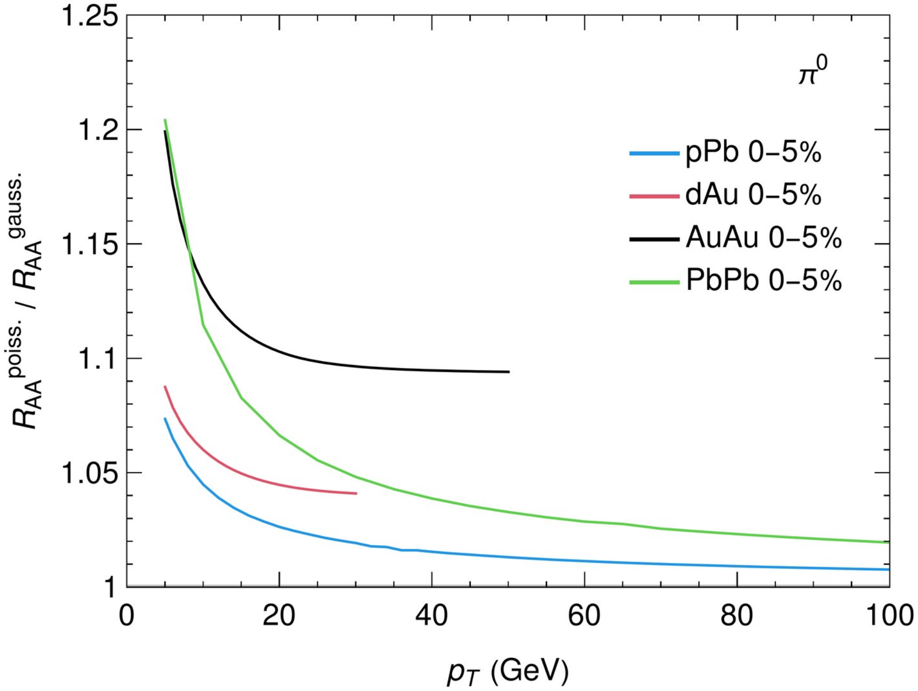


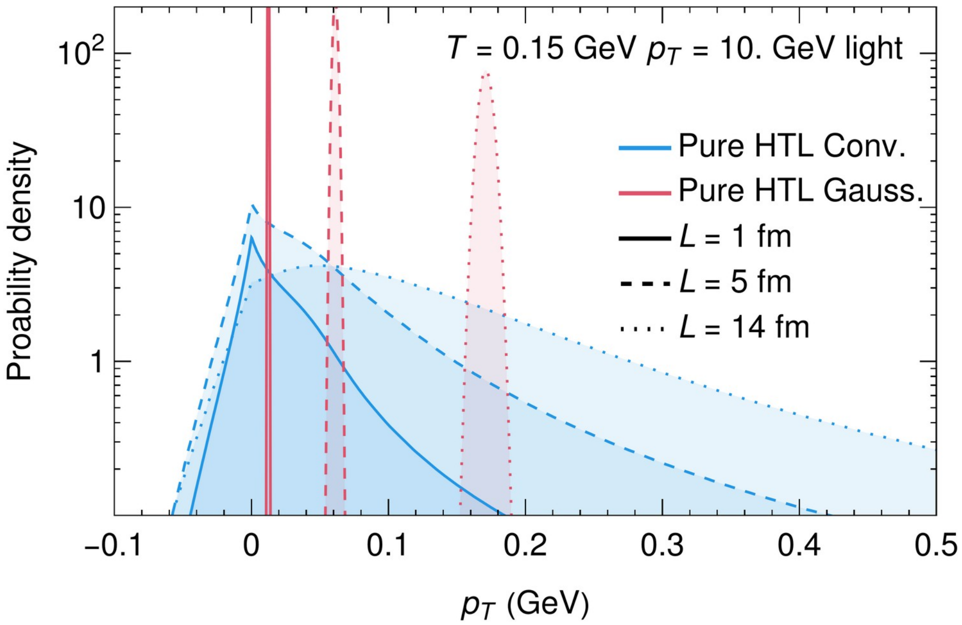


- Opposite ordering than expected according to CLT?
- Strong

Gaussian distribution not a good fit for **either** small or large systems

Gaussian ~ Poisson?





- Opposite ordering than expected according to CLT?
- Strong

Gaussian distribution not a good fit for **either** small or large systems

→ ***Why* is Gaussian R_{AA} ~ Poisson**

Why is Gaussian ~ Poisson?

One can show that:

1) In small systems: small energy loss $\Rightarrow R_{AA}$ depends mostly on **average energy loss**

$$R_{AA}(p_T) = \sum_n c_n(p_T) \int d\epsilon \epsilon^n P_{\text{tot.}}(\epsilon \mid p_T)$$
$$= \sum_n c_n(p_T) \langle \epsilon^n (p_T) \rangle_{\text{tot.}}$$

2) In large systems: elastic energy loss small fraction compared to radiative energy loss