Heavy Flavour Energy Loss in Small and Large Systems

Coleridge Faraday

University of Cape Town, South Africa

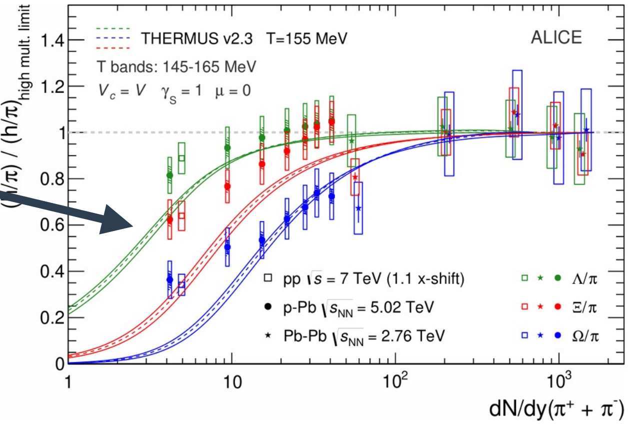
Strangeness in Quark Matter - 4th of June 2024

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

QGP Formation in Small Systems?

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

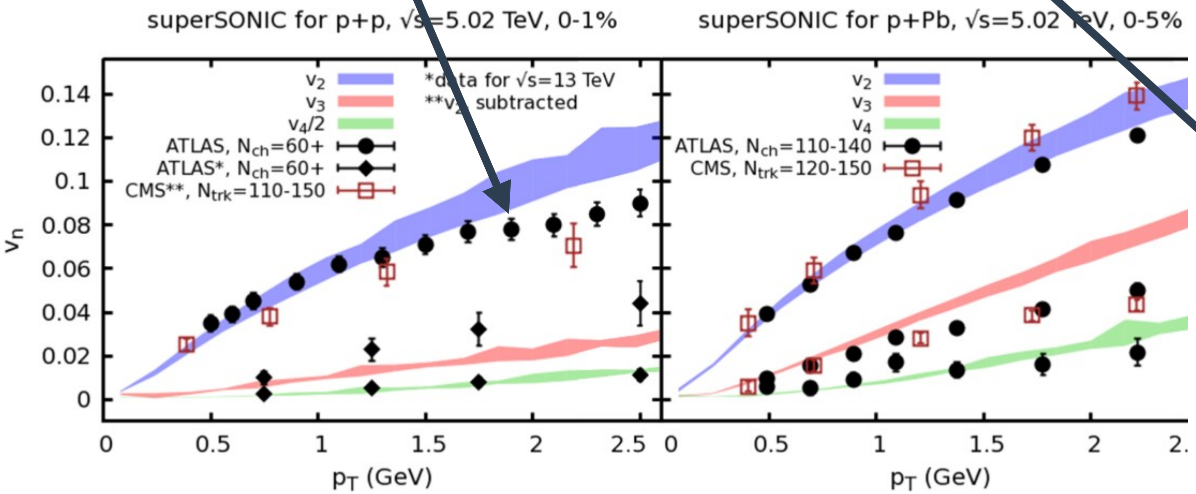
Strangeness enhancement



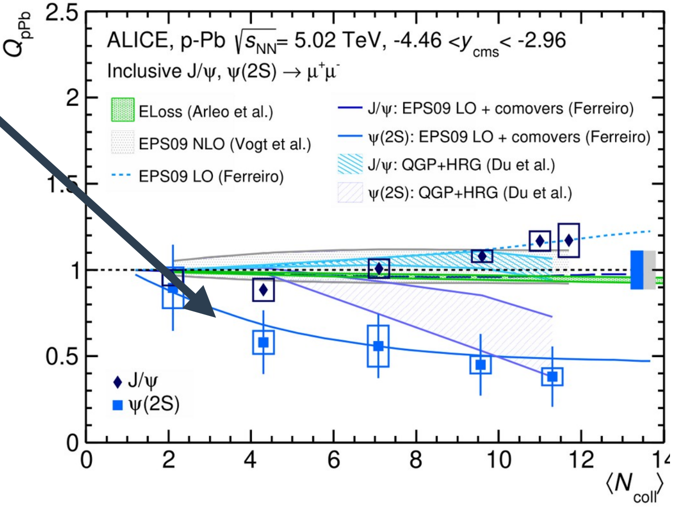
ALICE, PLB 758 (2016) 389-401

Elliptic flow

Quarkonium suppression

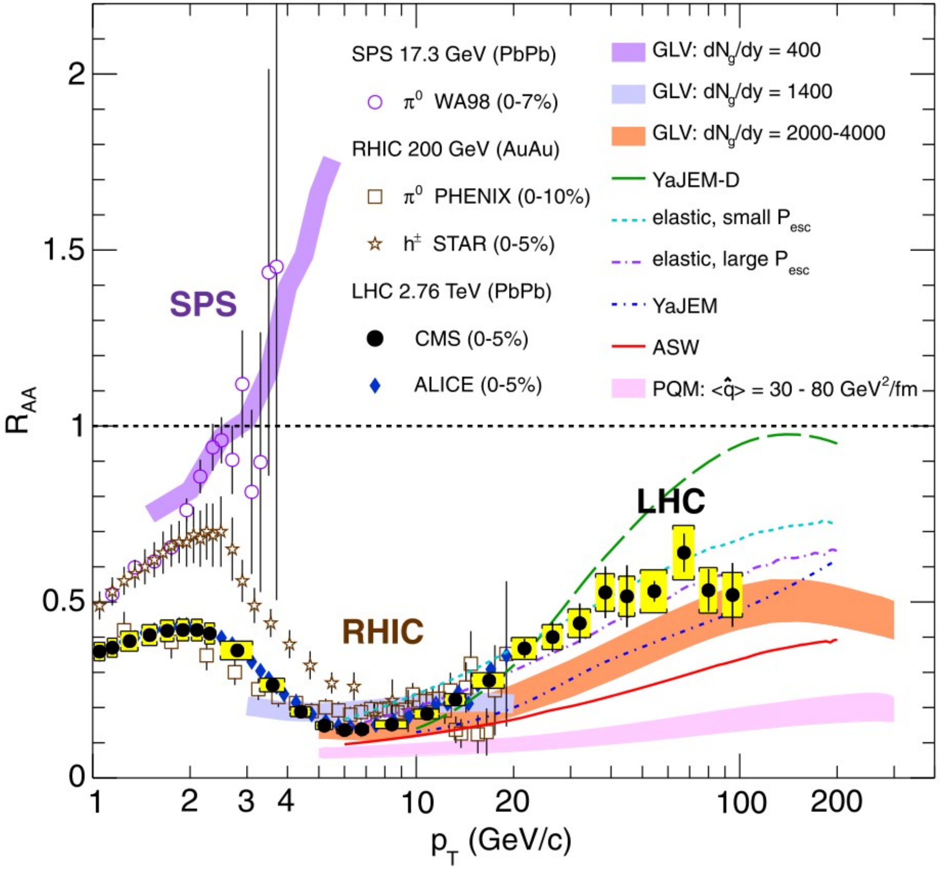


Weller et al., PLB 774 (2017) 351-356



ALICE, JHEP 06 (2016) 050

Nuclear Modification Factor



Qualitative success of pQCD energy loss models in large systems

$$R^h_{AB}(p_T) \equiv \frac{\mathrm{d}N^{AB\to h}/\mathrm{d}p_T}{\langle N_{\mathrm{coll}}\rangle \mathrm{d}N^{pp\to h}/\mathrm{d}p_T}$$

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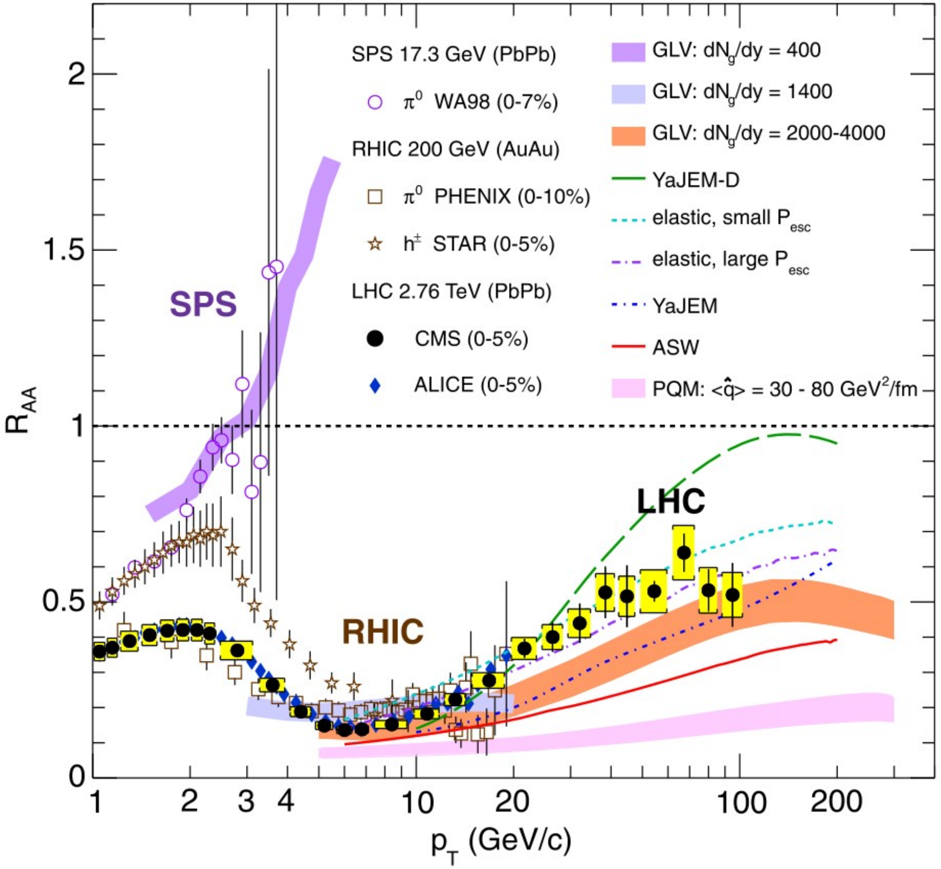

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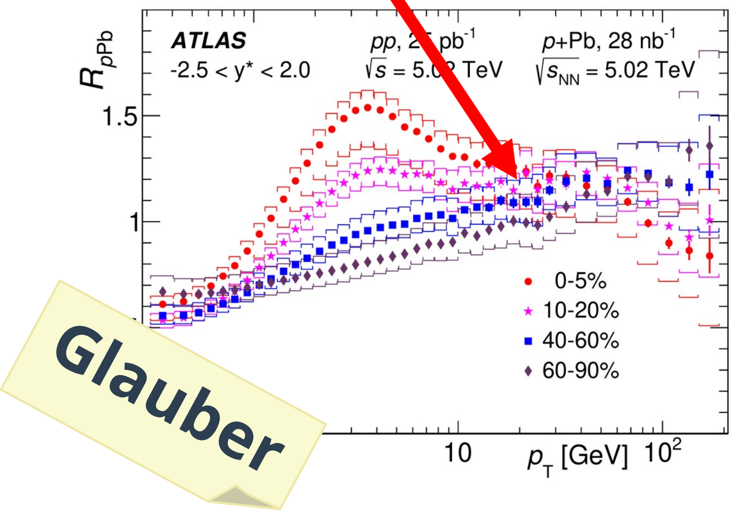
If QGP forms in small systems, then we should *also* see suppression?

Nuclear Modification in Small Systems

Small system suppression pattern not as clear

No suppression!



ATLAS, JHEP 07 (2023) 074

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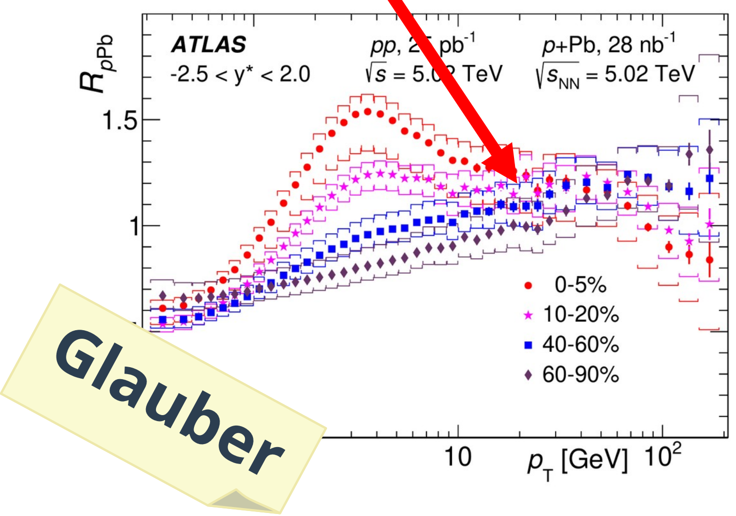

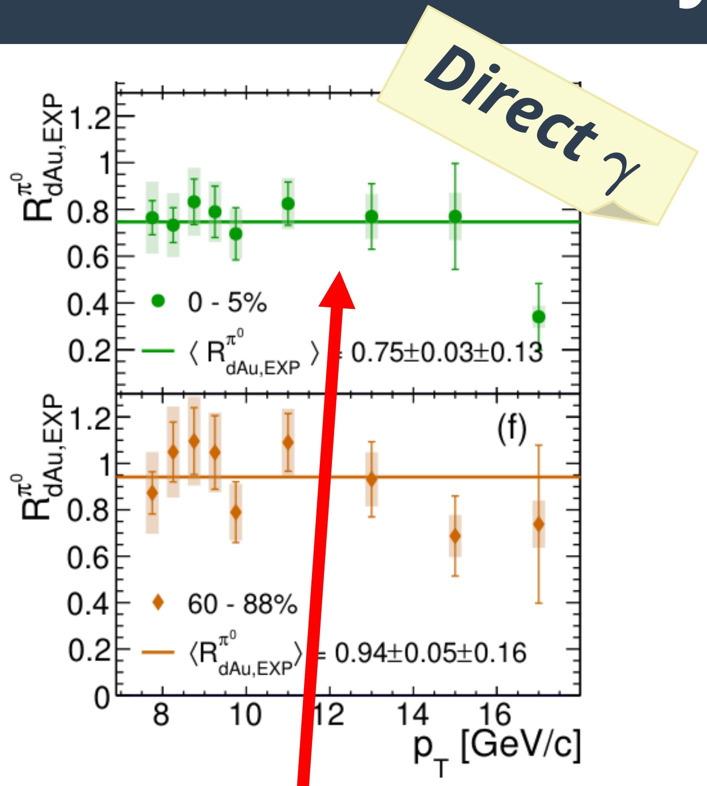

Suppression ~0.75!

ATLAS, JHEP 07 (2023) 074

PHENIX, arXiv:2303.12899 (2023)

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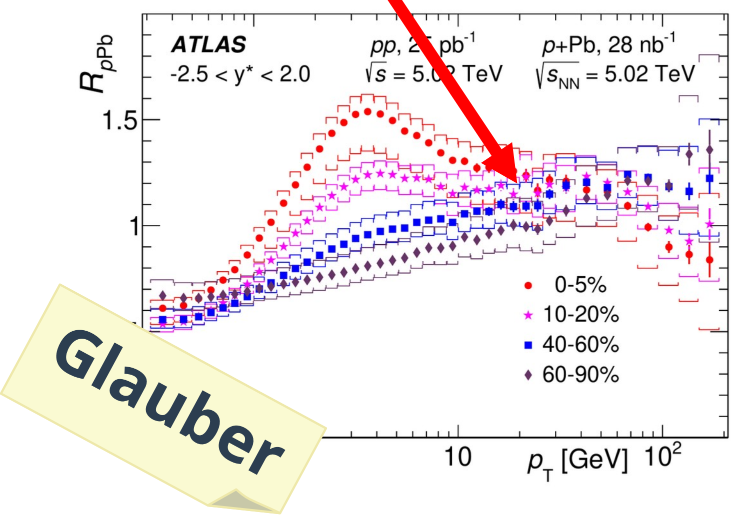
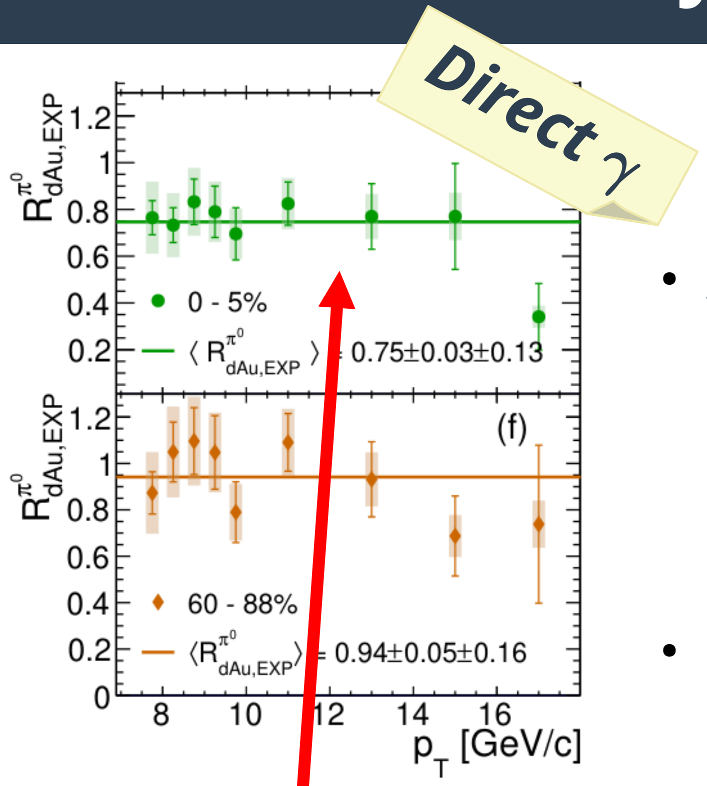


ATLAS, JHEP 07 (2023) 074



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

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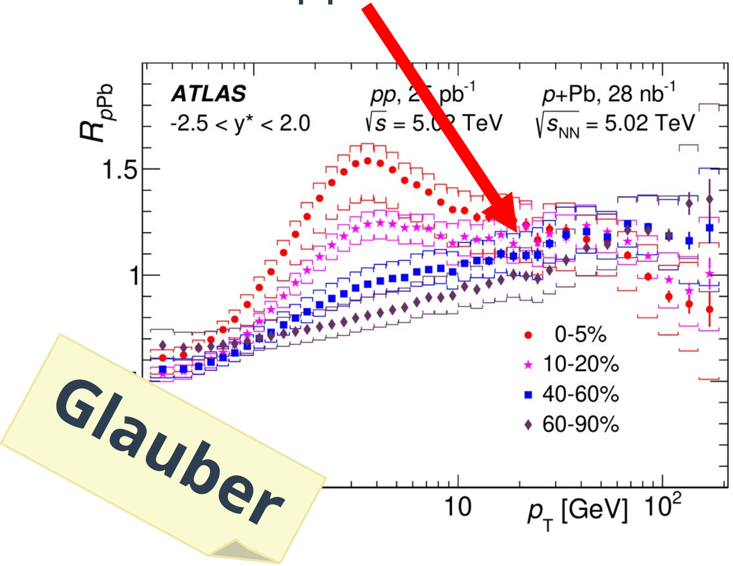

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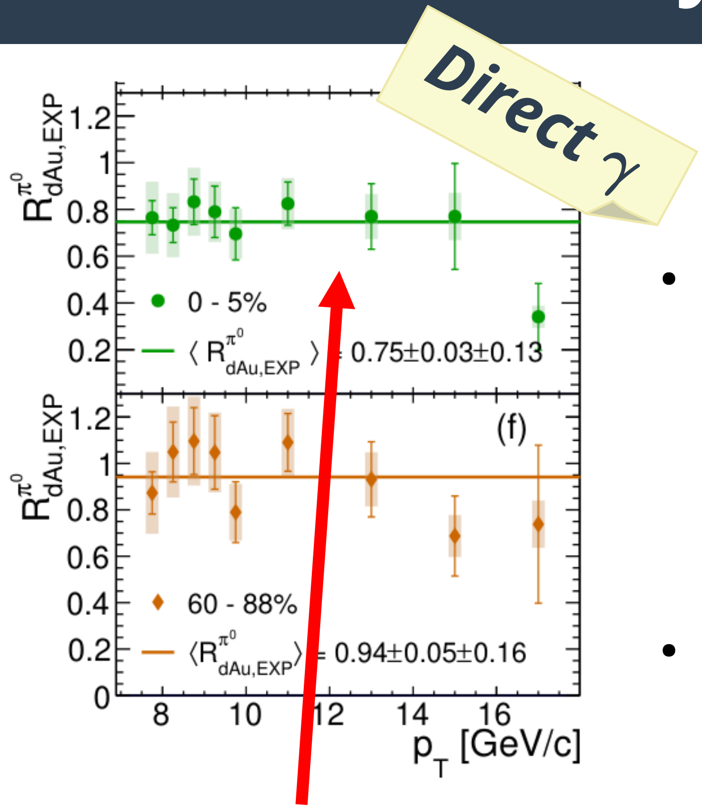

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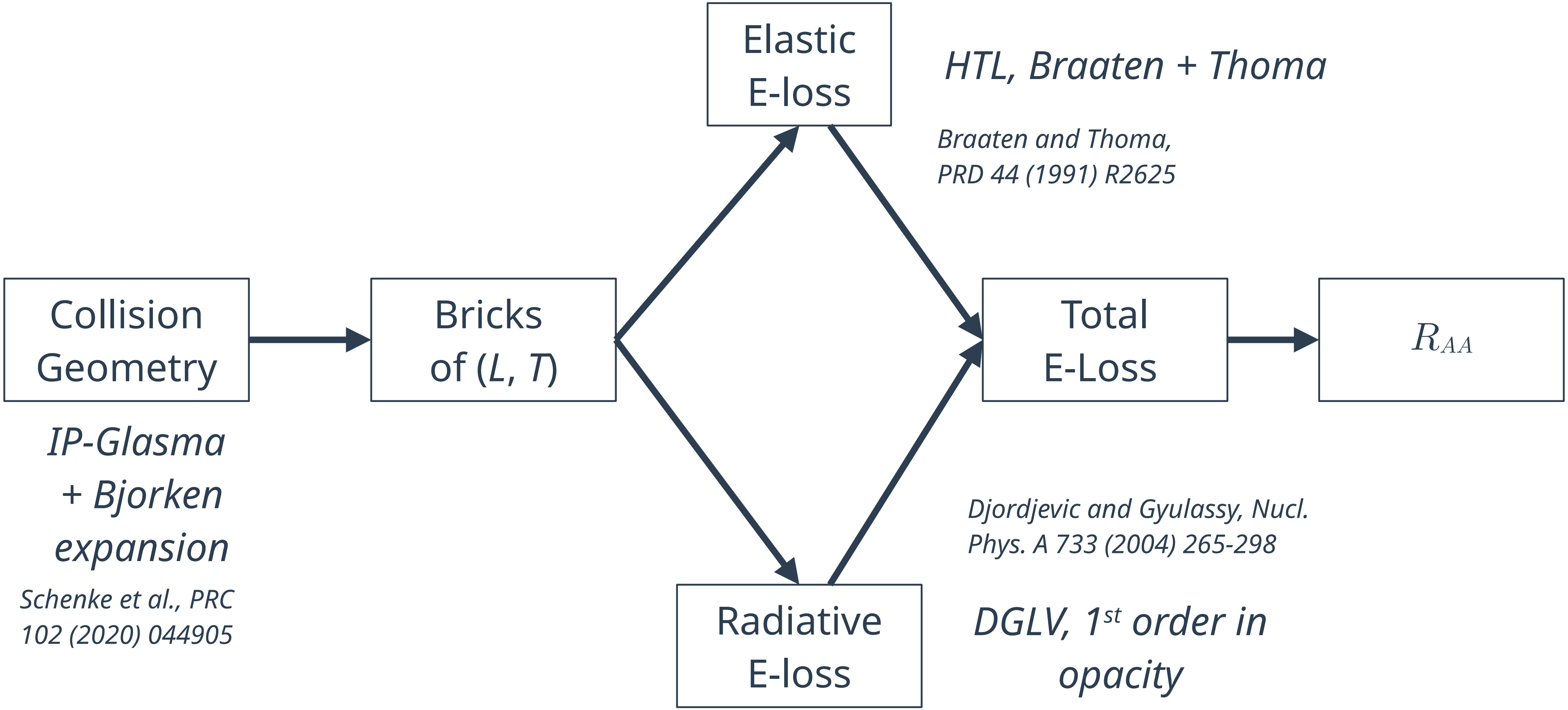
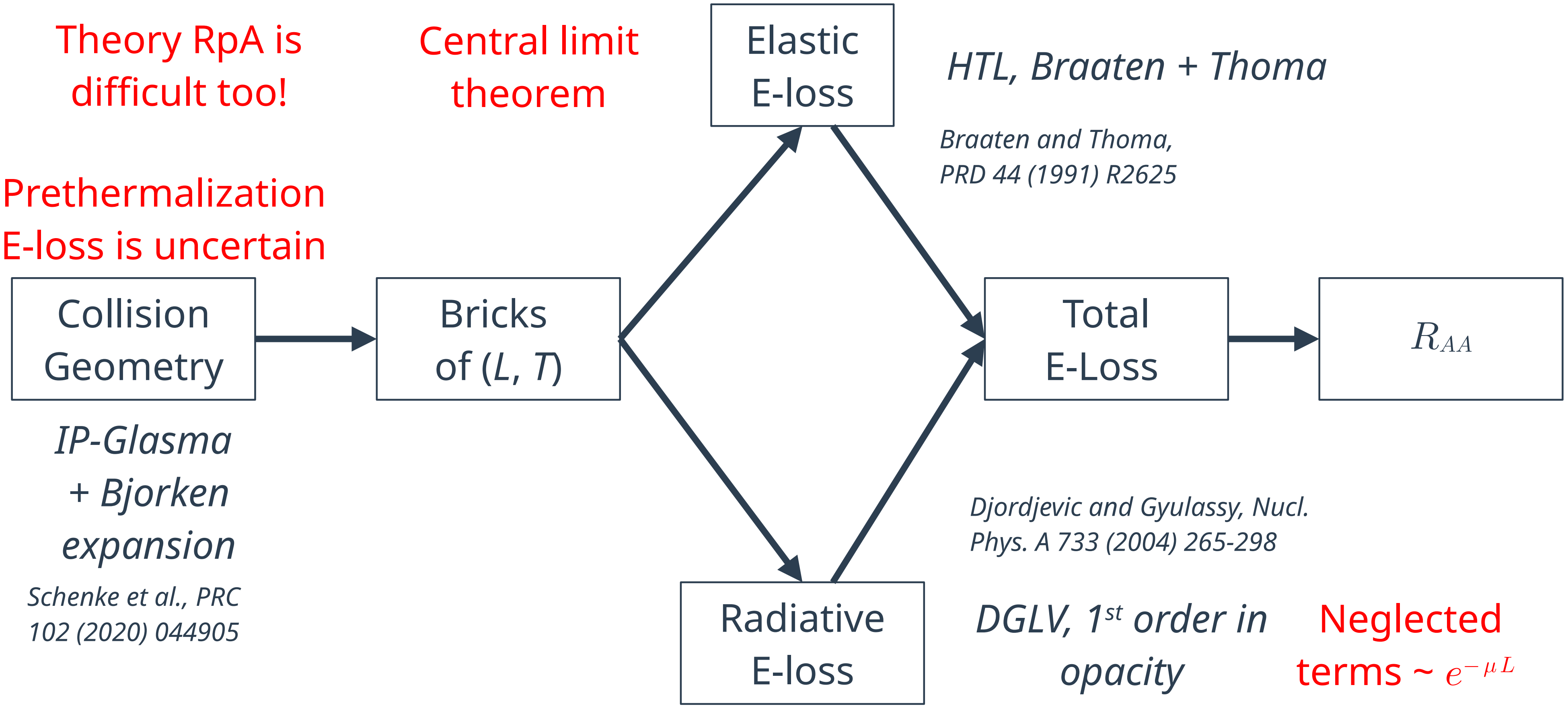
→ **Theoretical input needed**

Energy Loss Models in Small Systems



Energy Loss Models in Small Systems



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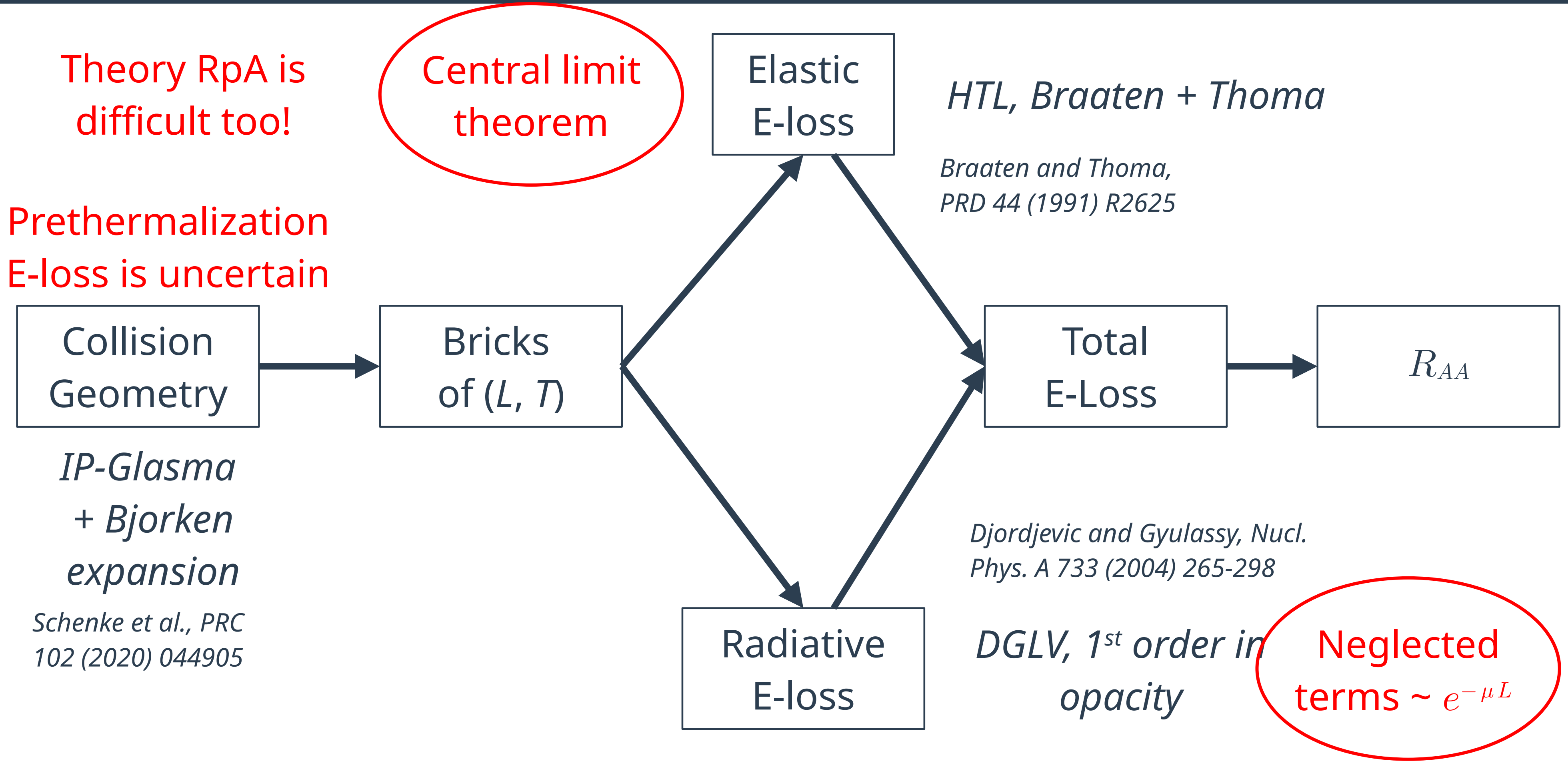
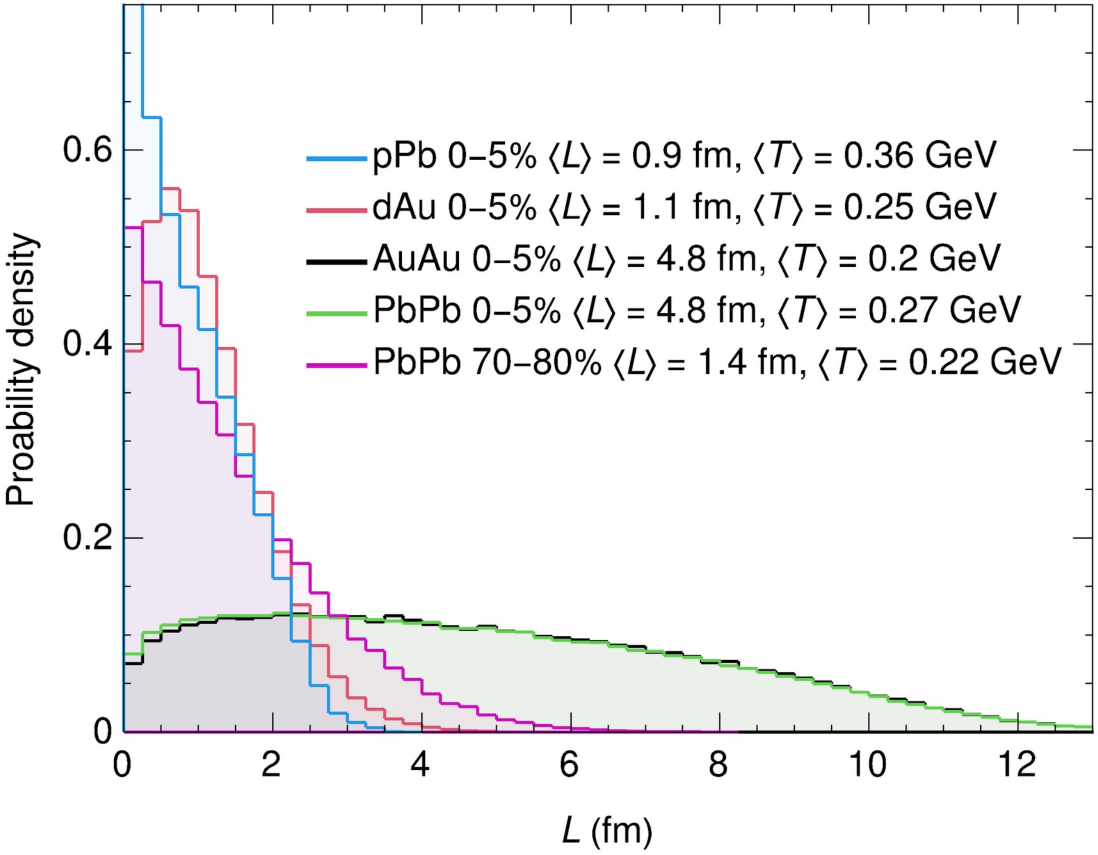


What do Small QGP's Look Like?



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

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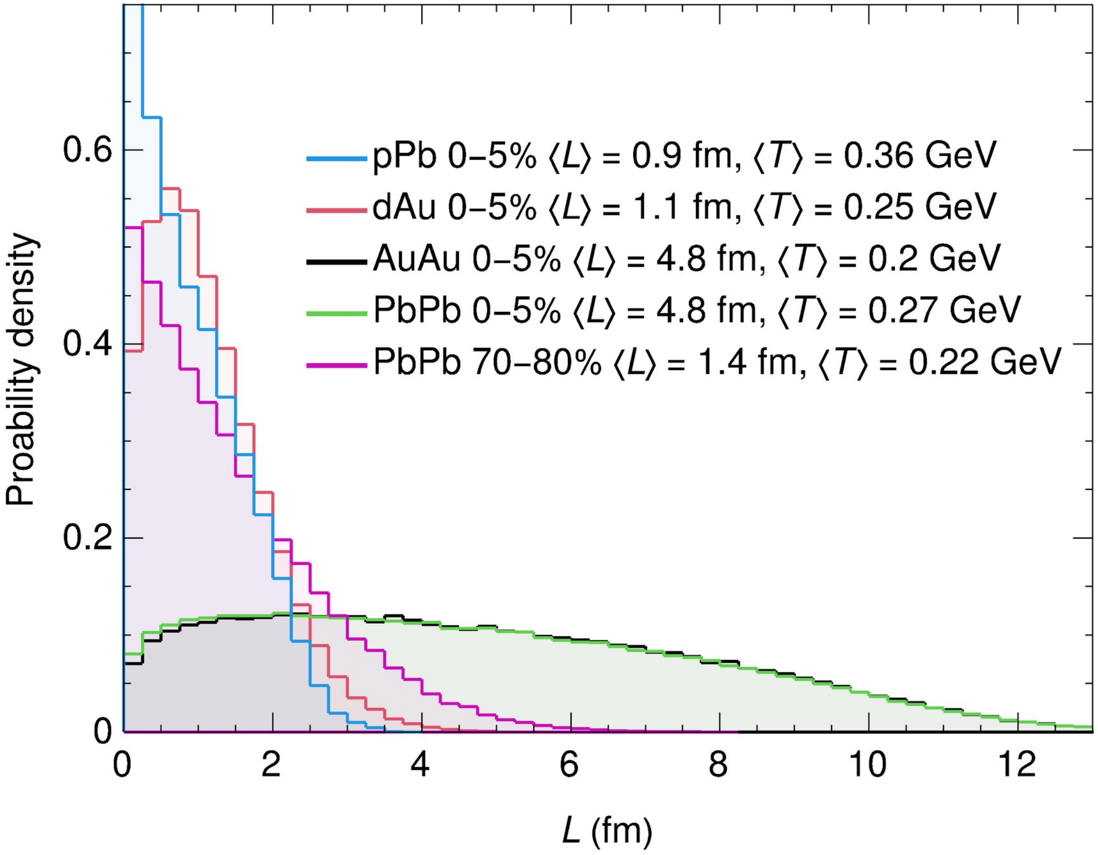

- Small system ⟨L⟩ ~ 1 fm comparable to peripheral AA

- Small systems have L/λ ~ 1
  - ➔ Central limit theorem inapplicable (elastic)
  - ➔ Multiple soft scatter approaches inapplicable

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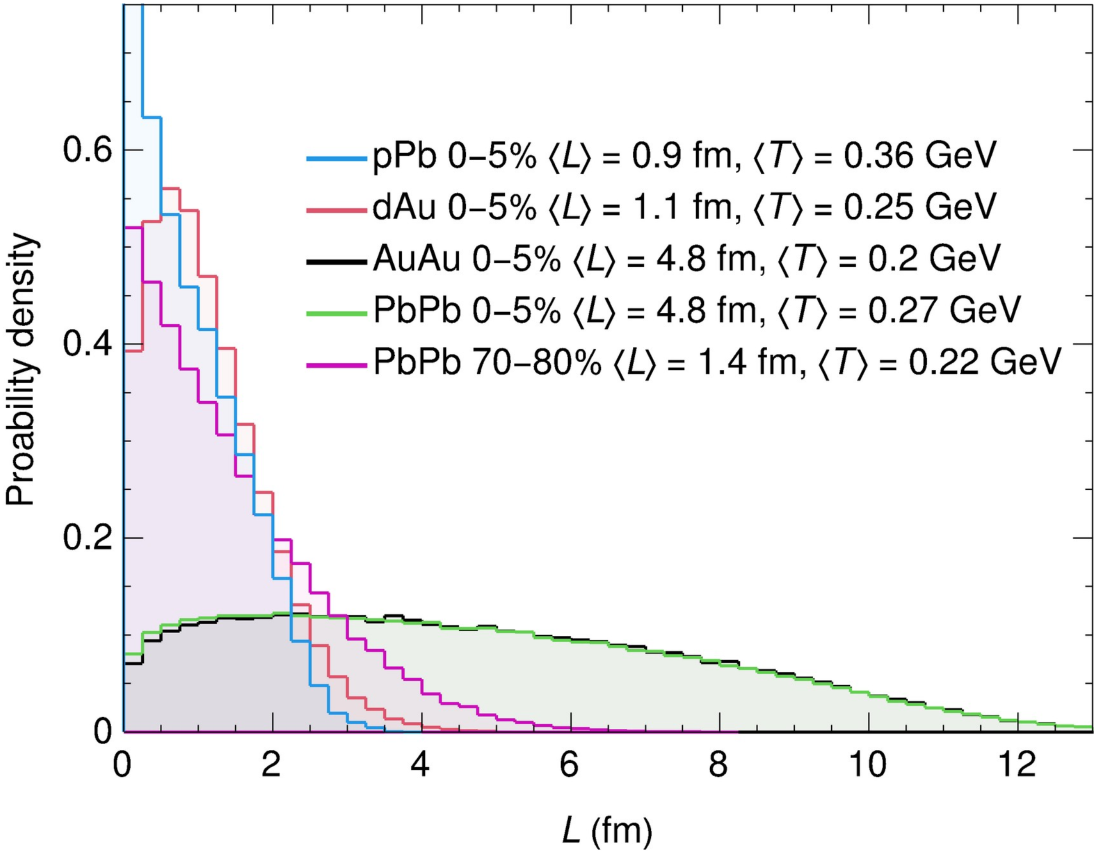
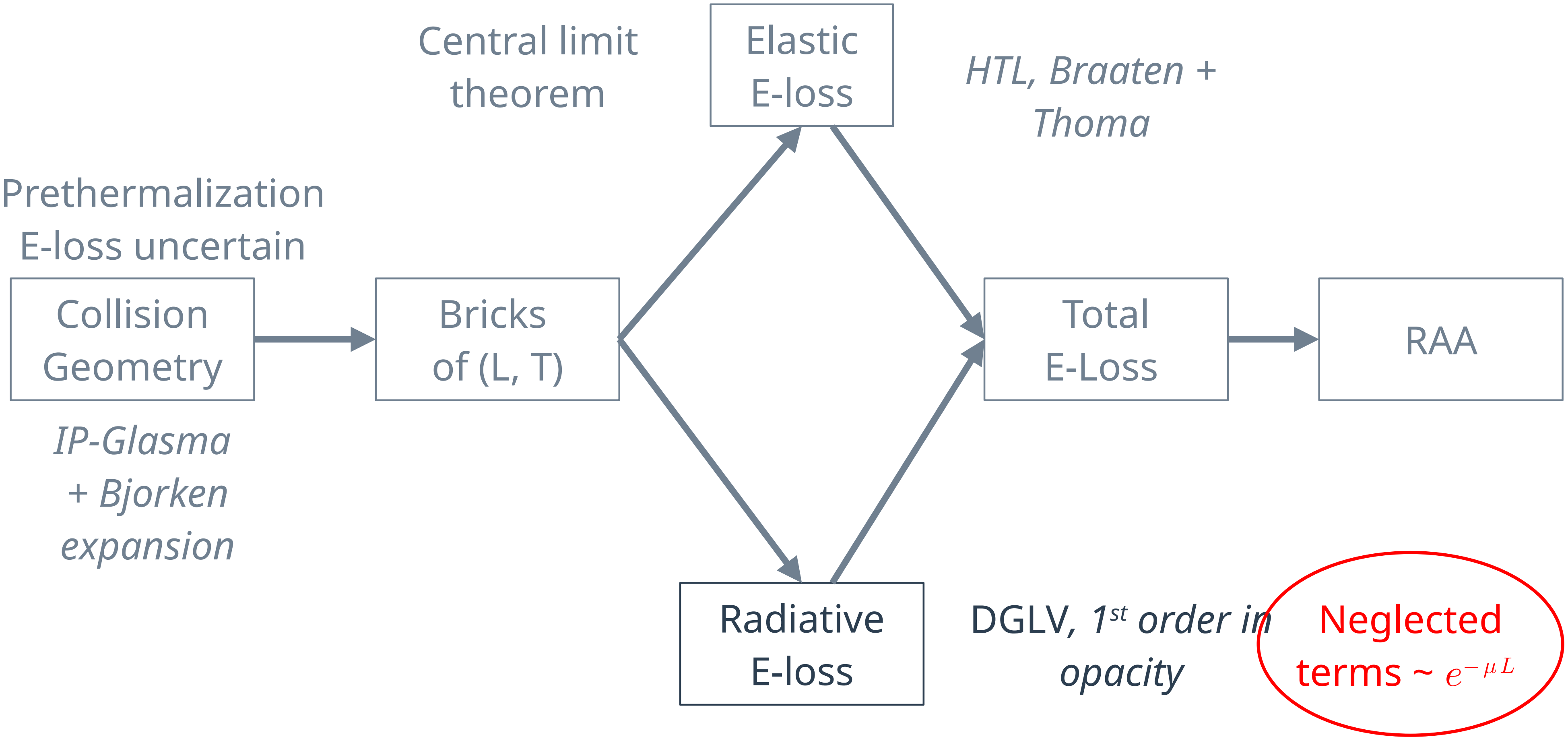


- Small system ⟨L⟩ ~ 1 fm comparable to peripheral AA

- Small systems have $L/\lambda \sim 1$
  - Central limit theorem inapplicable (elastic)
  - Multiple soft scatter approaches inapplicable
- Large systems have $L/\lambda \sim 5$
  - Central limit theorem still dubious?

Energy Loss Models in Small Systems



Short pathlength (SPL) Corr. to DGLV

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

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

DGLV 1st order in opacity

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

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

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

SPL corr.

Kolbe & Horowitz, PRC 100 (2019) 024913

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

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DGLV 1st order in opacity

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

Suppressed for large *L*

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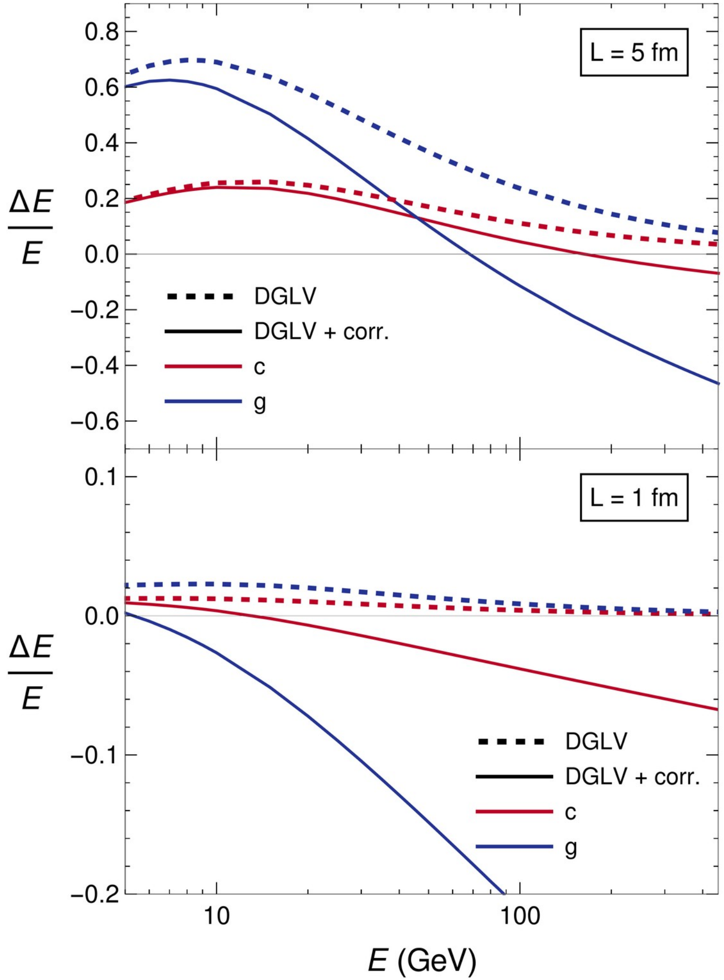
Suppressed for large *L*

Breaking of **colour triviality**

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

Numerics of the Short Pathlength Corr.



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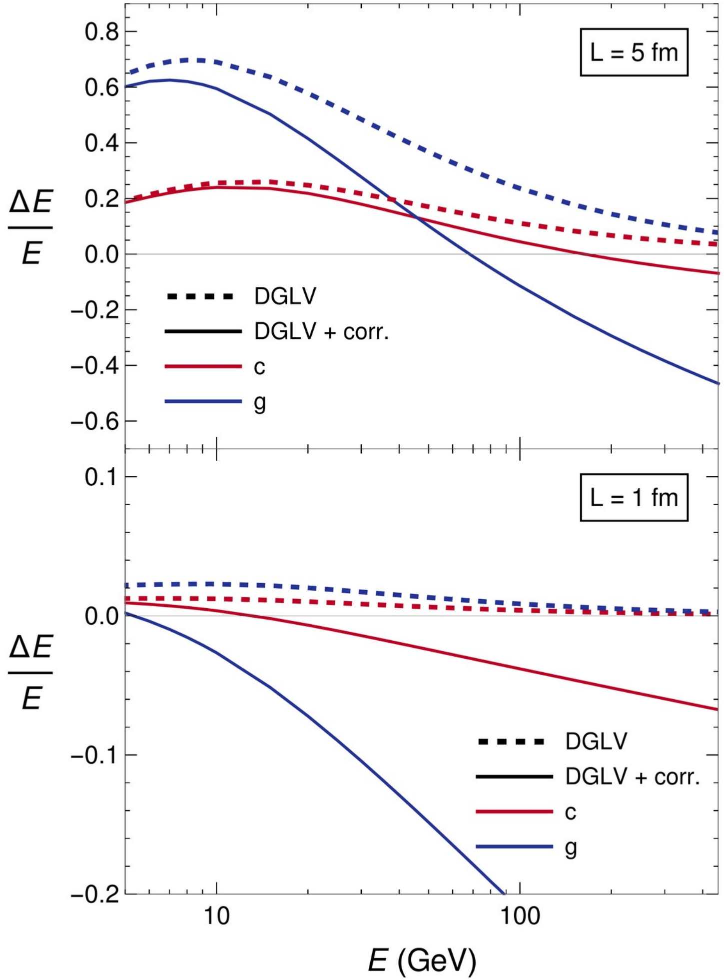
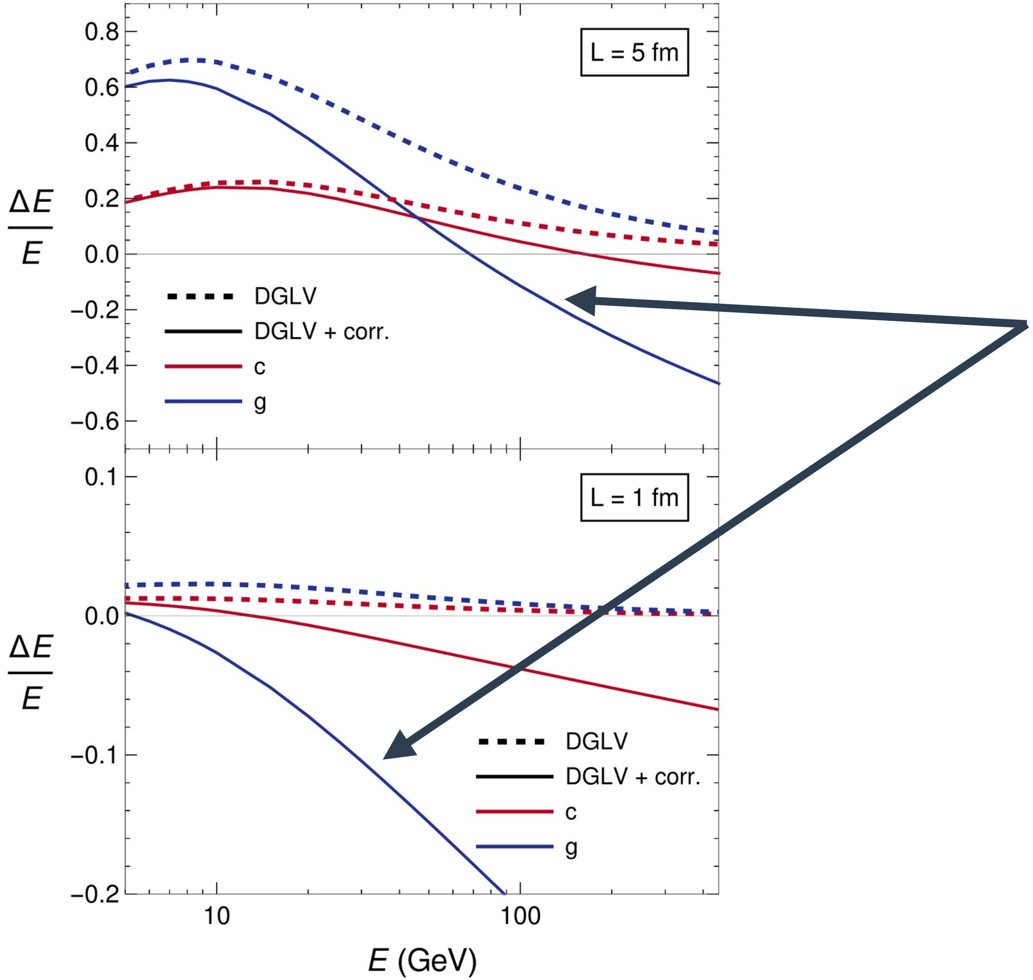


We see the SPL correction:

Numerics of the Short Pathlength Corr.



We see the SPL correction:

- Decreases as a function of *L*

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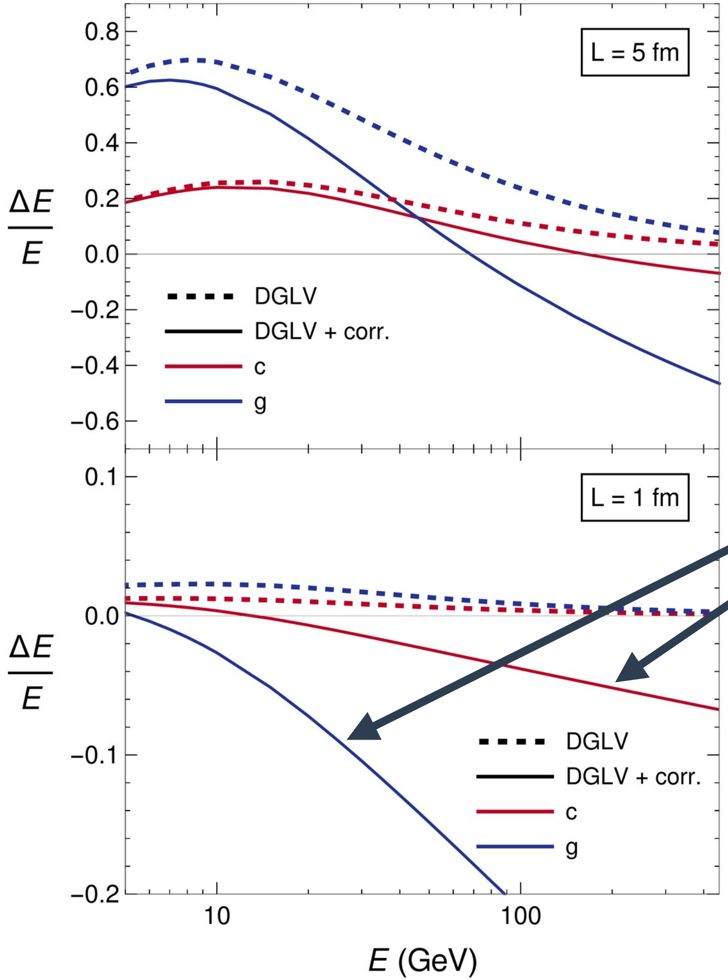

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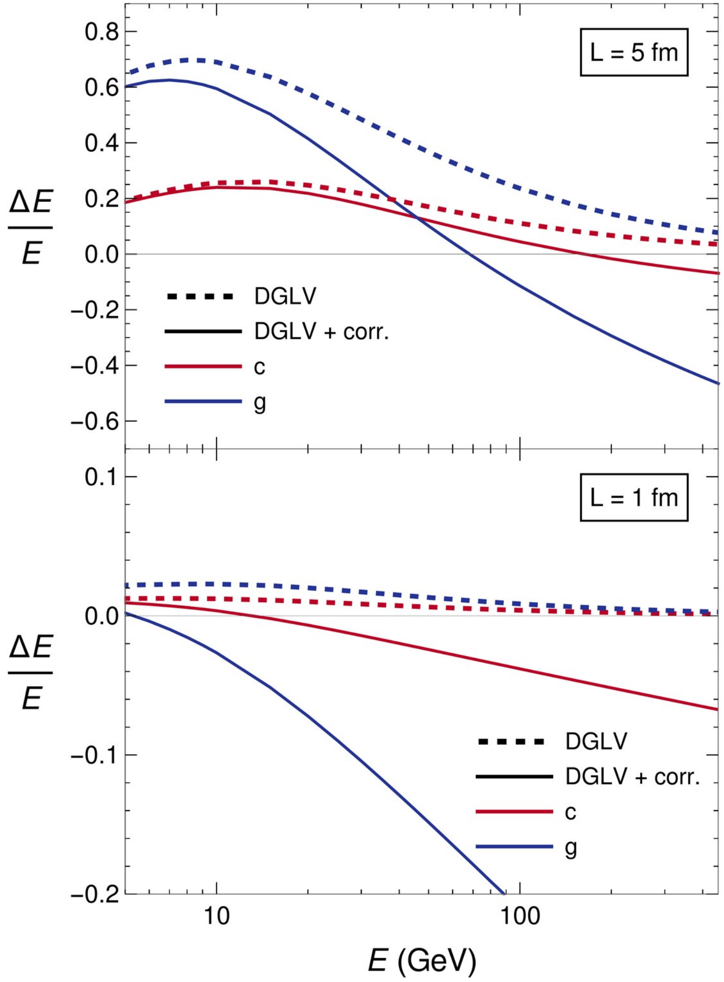
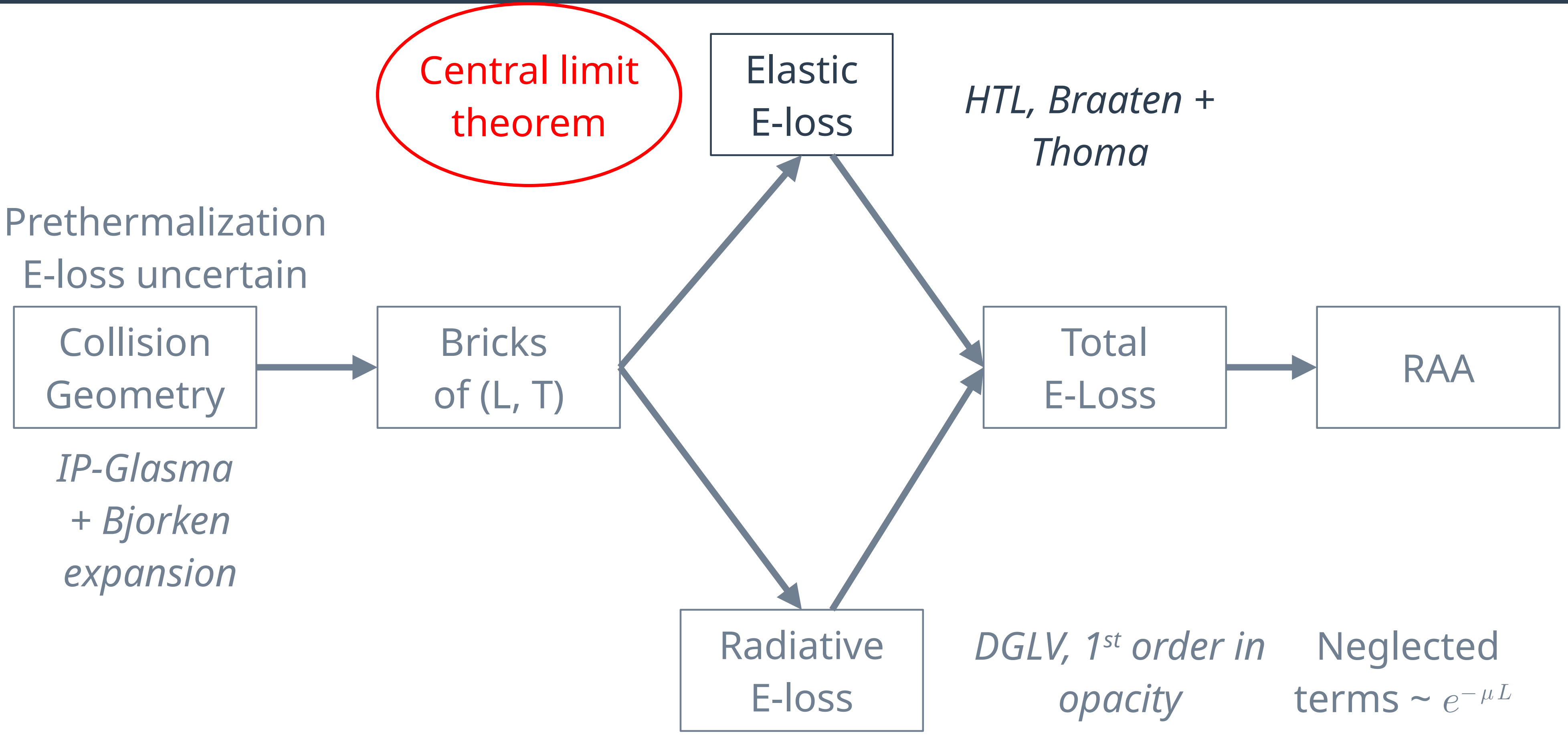


We see the SPL correction:

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

Energy Loss Models in Small Systems



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)*

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

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

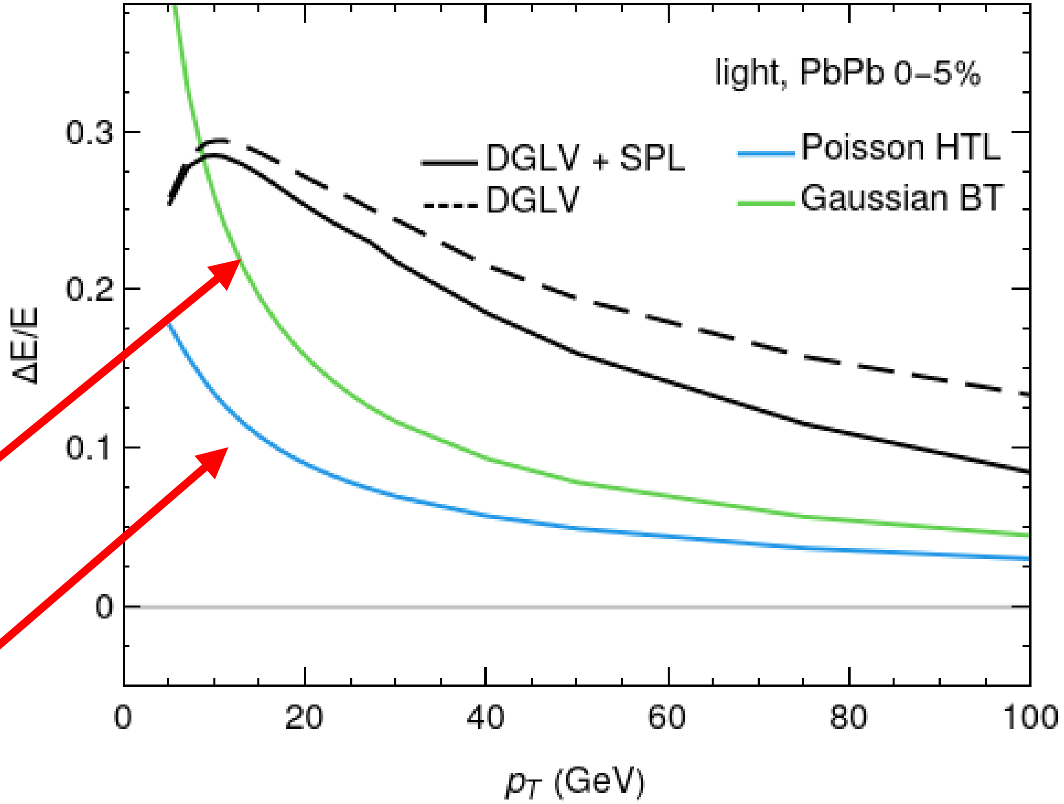
(Fluctuation Dissipation Thrm)

Elastic Energy Loss

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

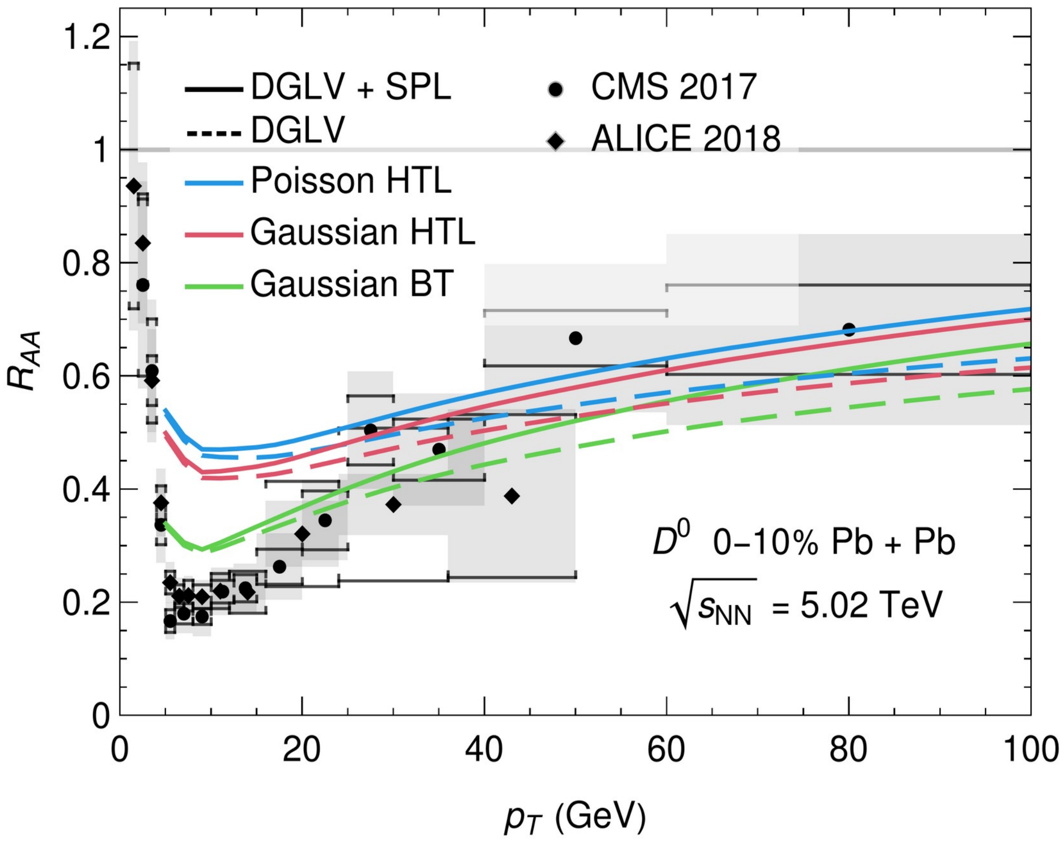
We compare two extremes to capture this uncertainty:

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



Generically in HIC radiative E-loss > elastic E-loss

Heavy Flavour Suppression in PbPb



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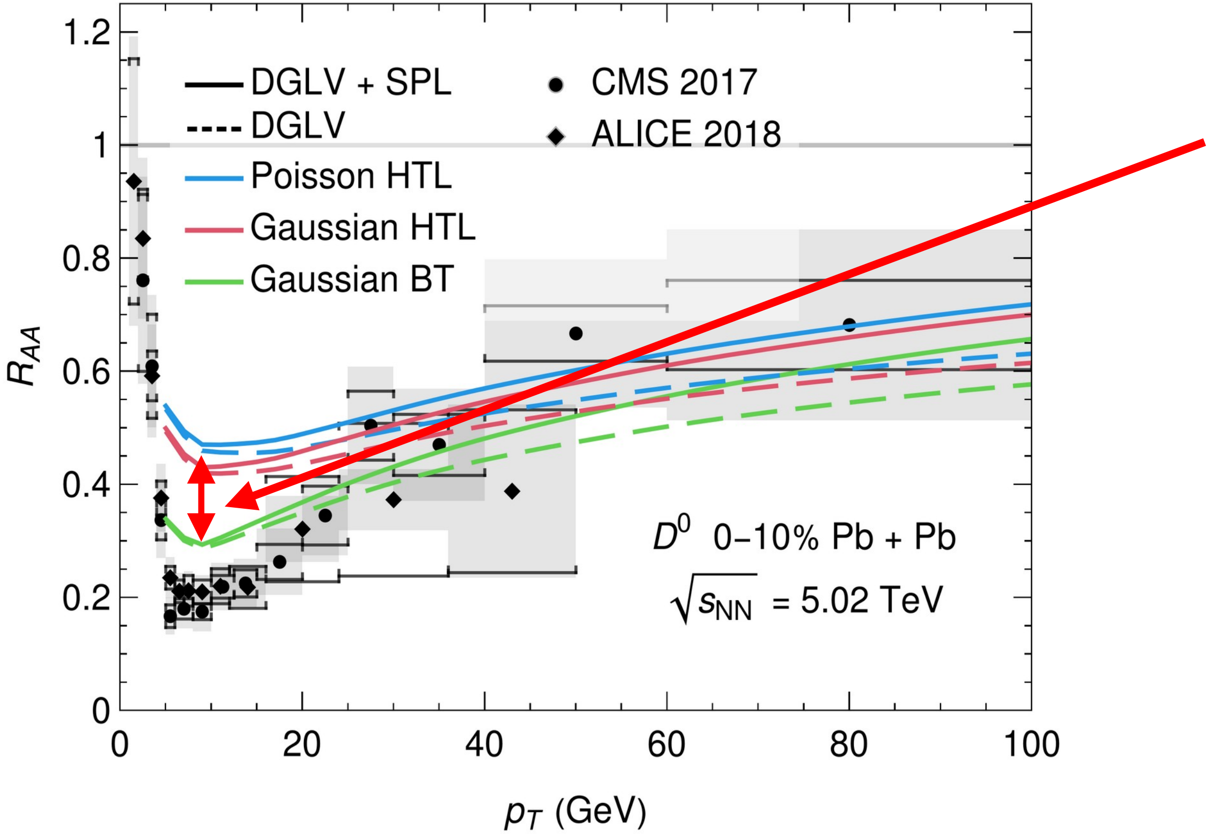

- Low pt is **sensitive to choice of elastic energy loss** (HTL vs vacuum propagators)

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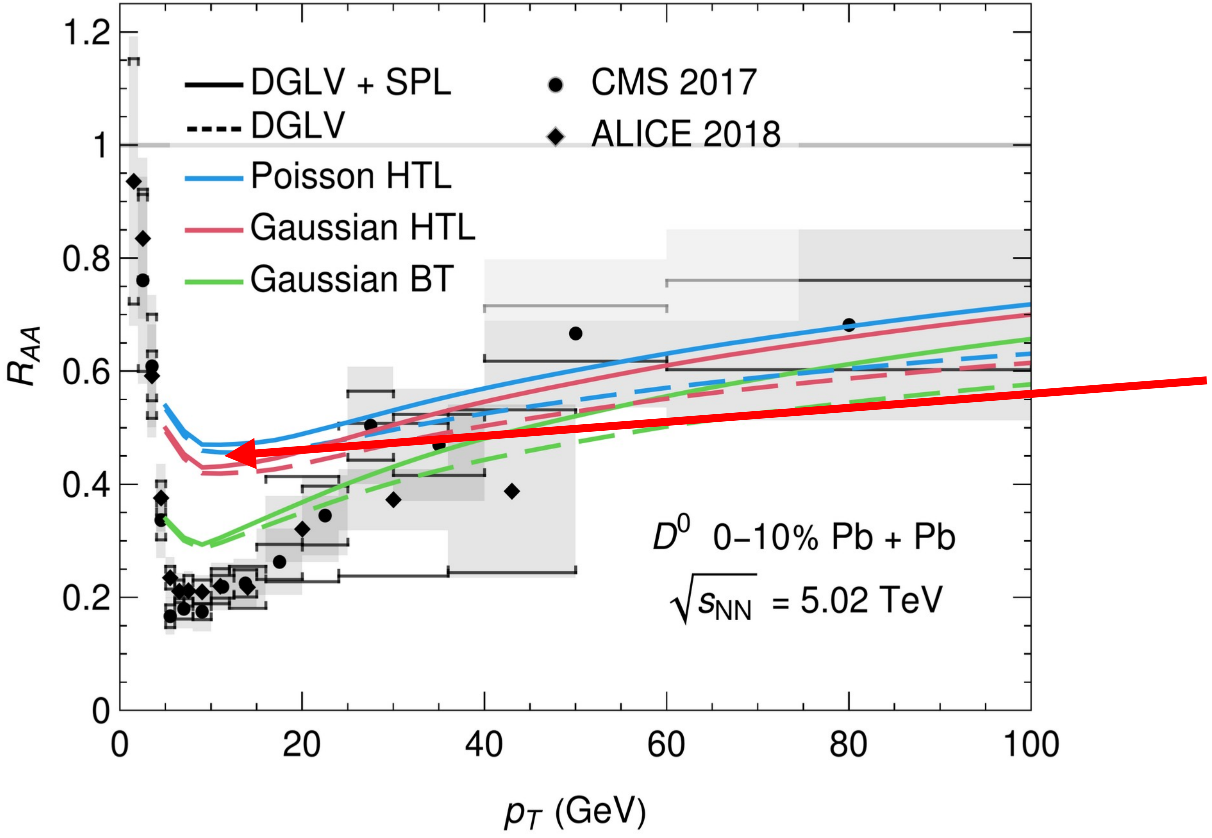

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- **Gaussian approximation ~ full Poisson result** for all pt (blue vs red)

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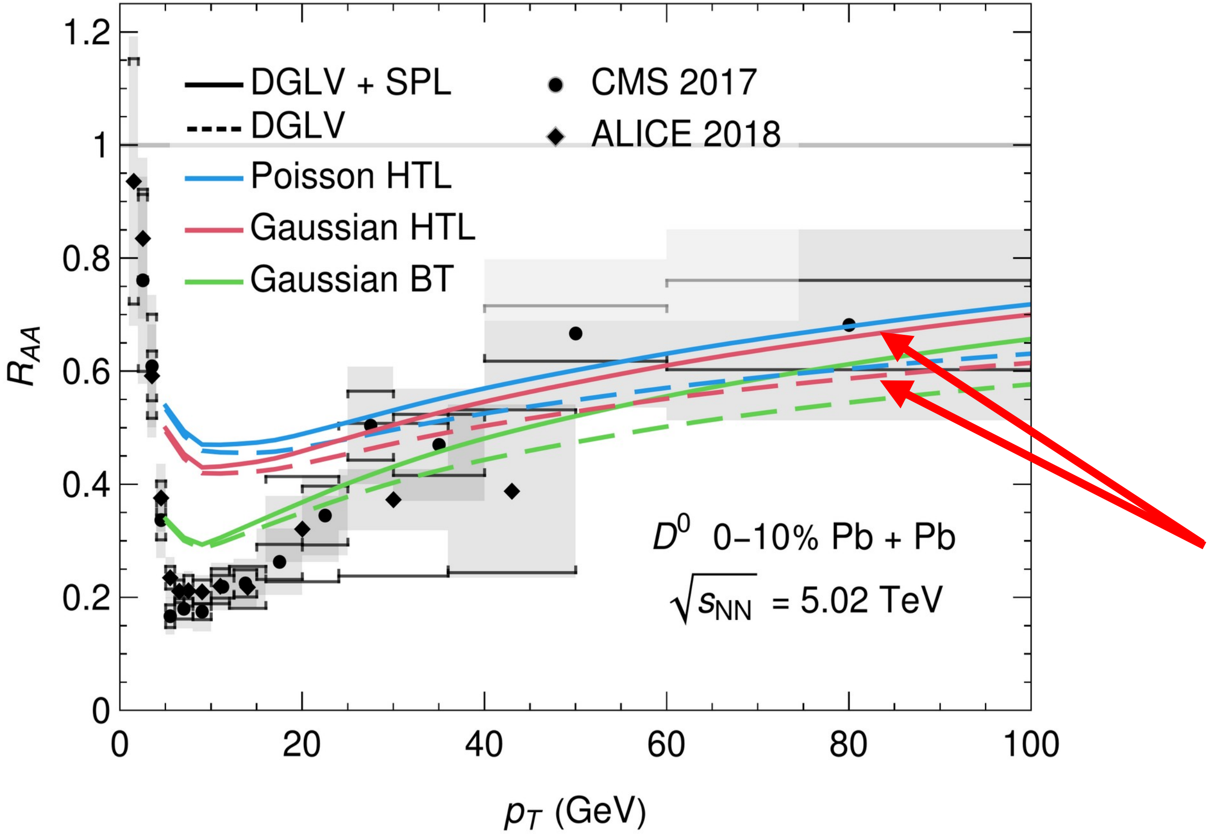
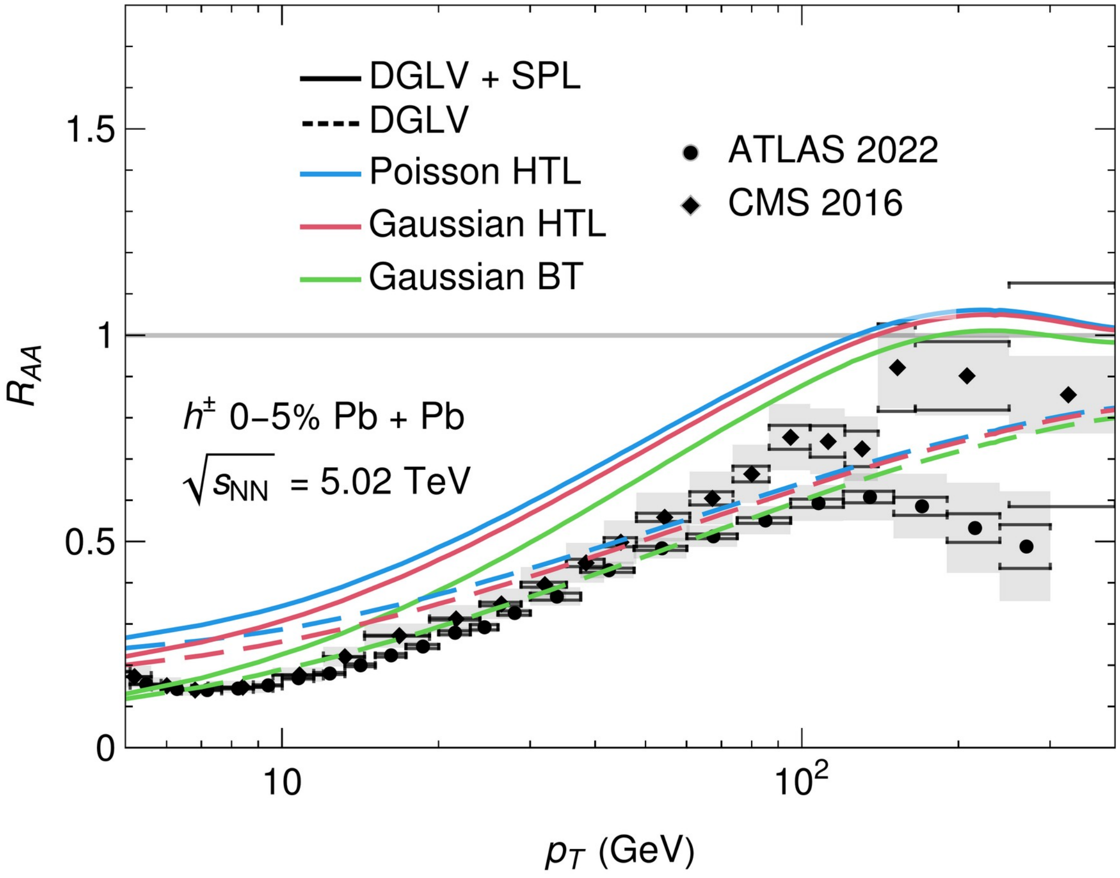


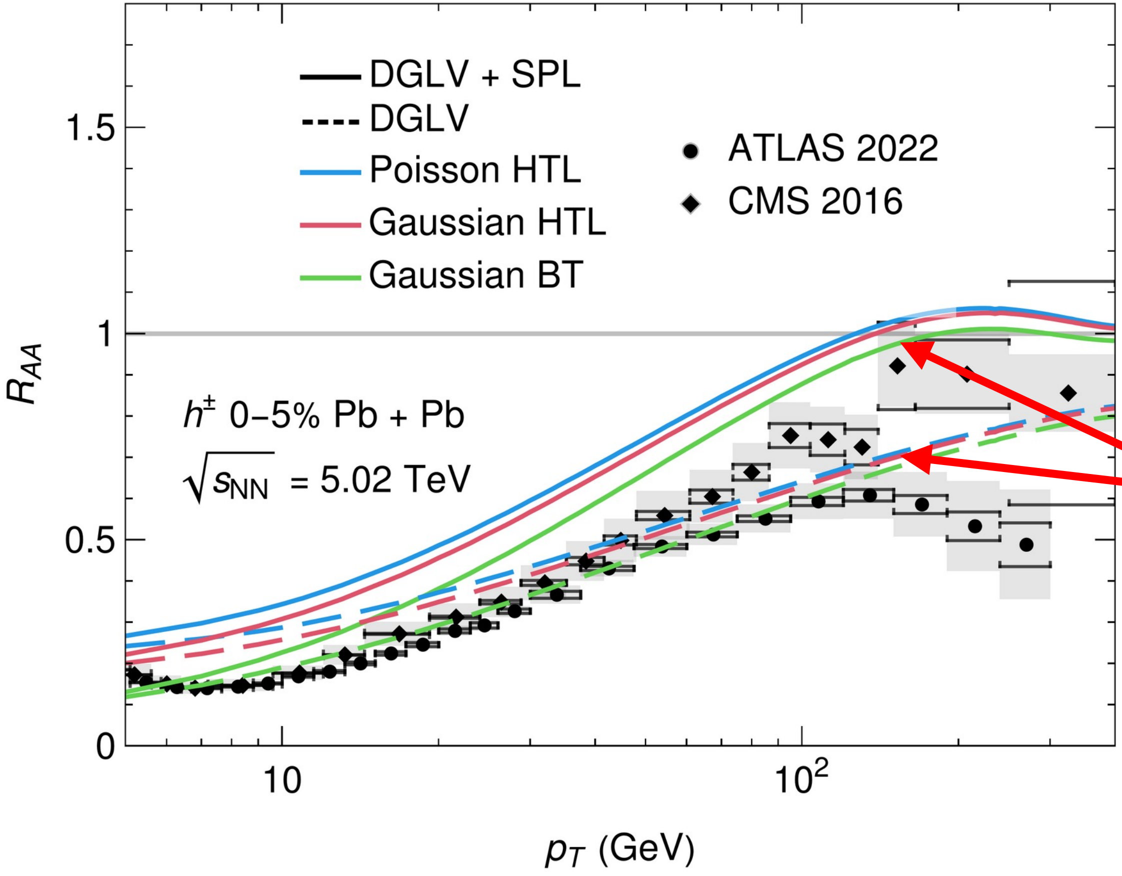
- Low pt is **sensitive to choice of elastic energy loss** (HTL vs vacuum propagators)
- **Gaussian approximation ~ full Poisson result** for all pt (blue vs red)
- Short pathlength correction to radiative E-loss is small

Light Flavour Suppression in PbPb



- Gaussian ~ Poisson for all pt
- Low-mid pt results sensitive to choice of elastic E-loss kernel

Light Flavour Suppression in PbPb



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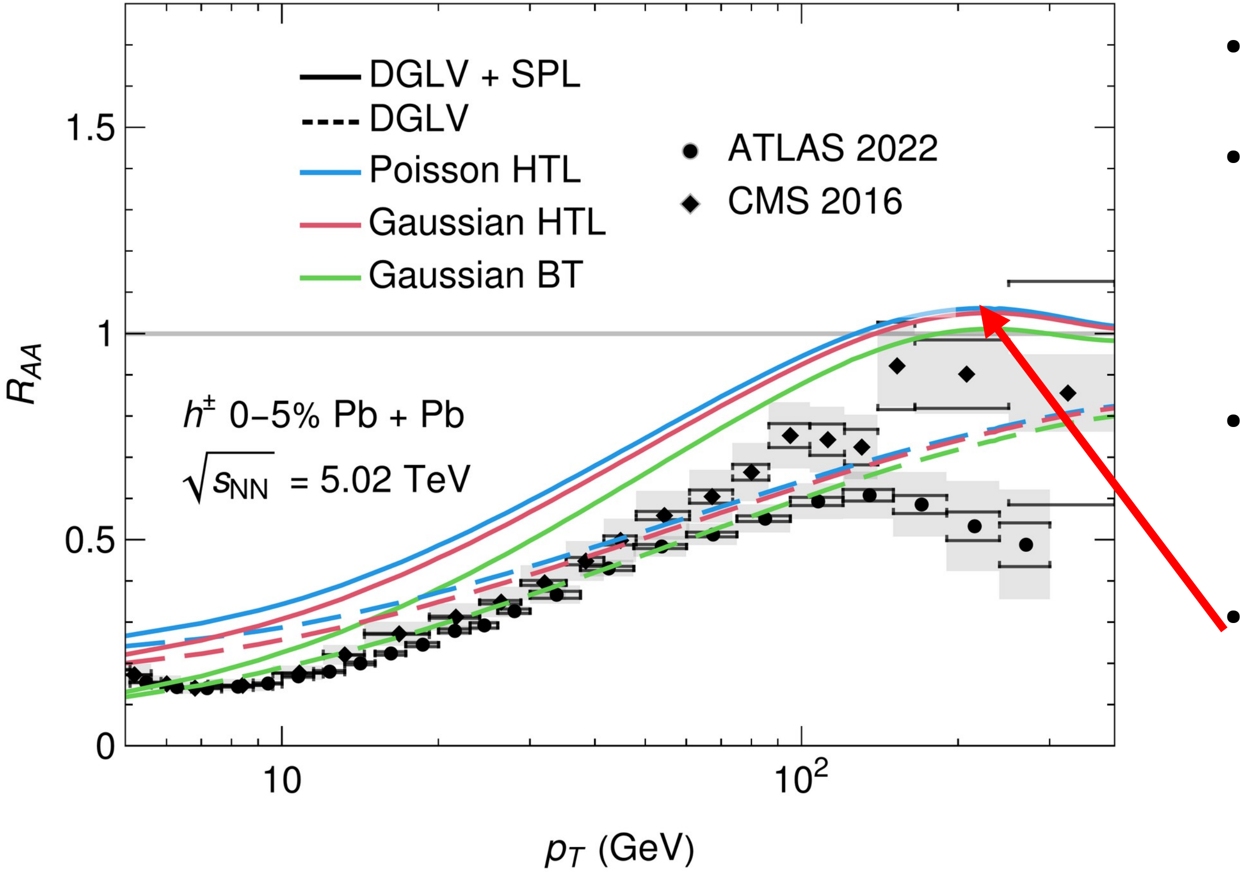
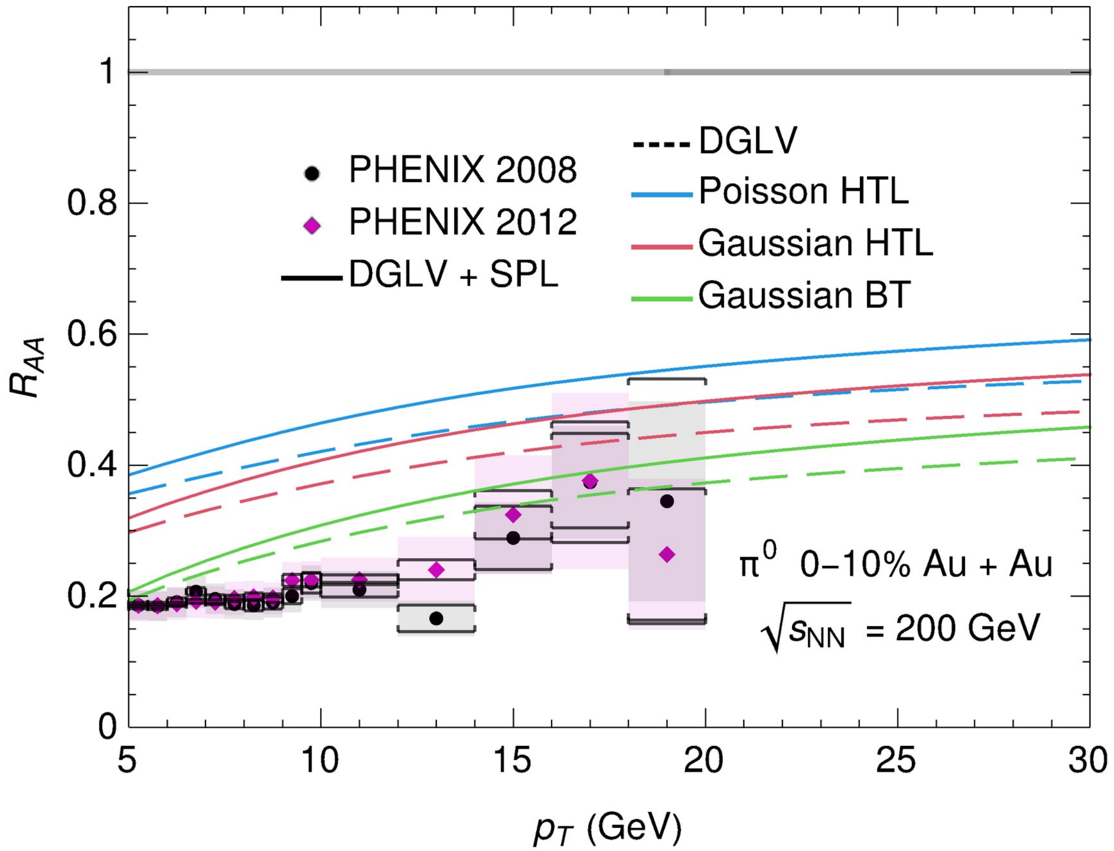


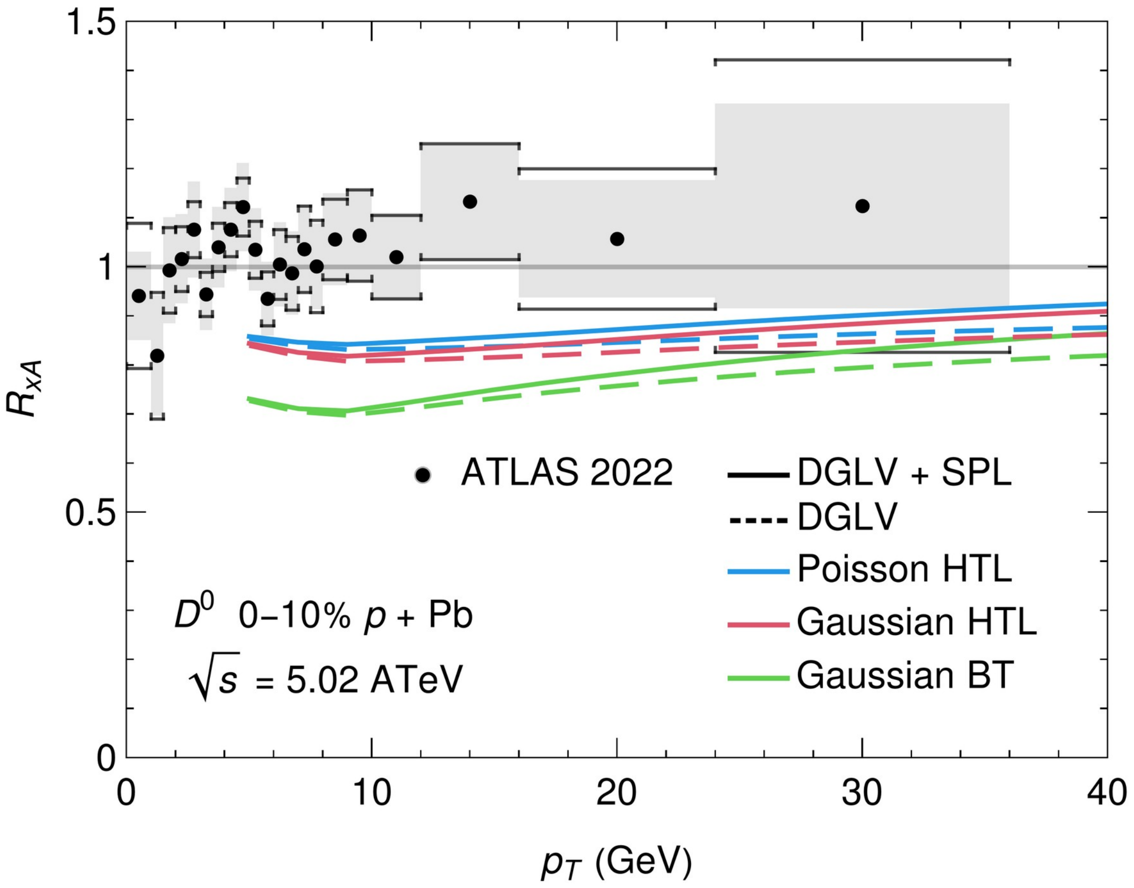
- Gaussian ~ Poisson for all pt
- Low-mid pt results sensitive to choice of elastic E-loss kernel
- SPL corr. has a large effect, which may contribute to fast pion RAA rise in p_T
- Turnover can be understood as crossover from gluons to light quark dominated spectra

Light Flavour Suppression in AuAu



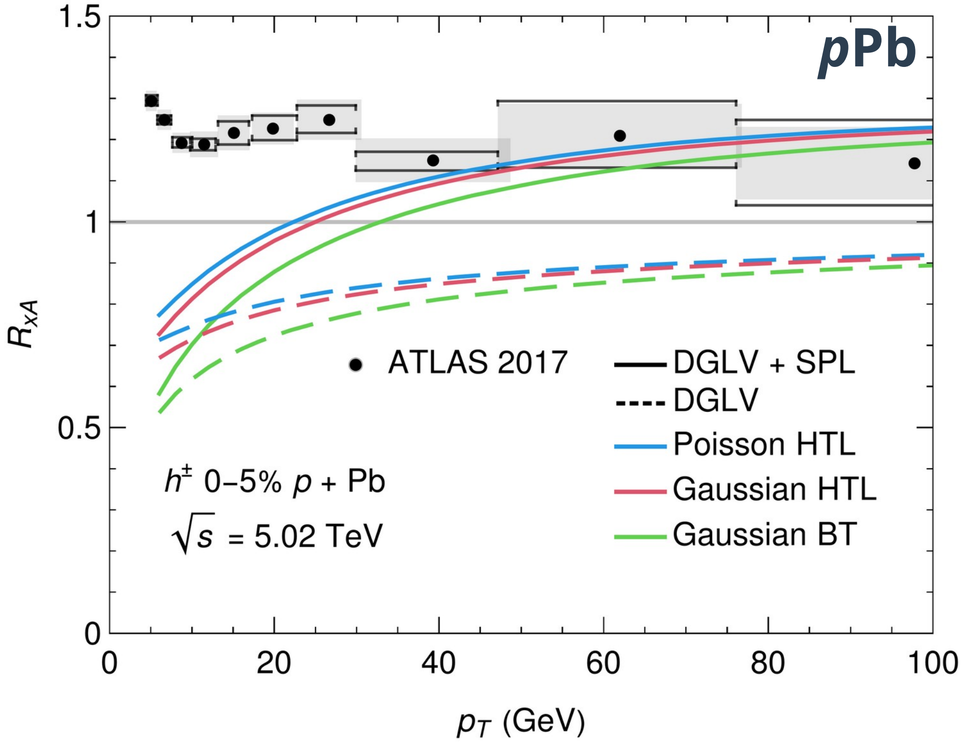
- More sensitive to HTL vs BT elastic energy loss than PbPb, ~100% effect!
- Poisson vs Gaussian is $\mathcal{O}(10\text{-}25\%)$ effect size

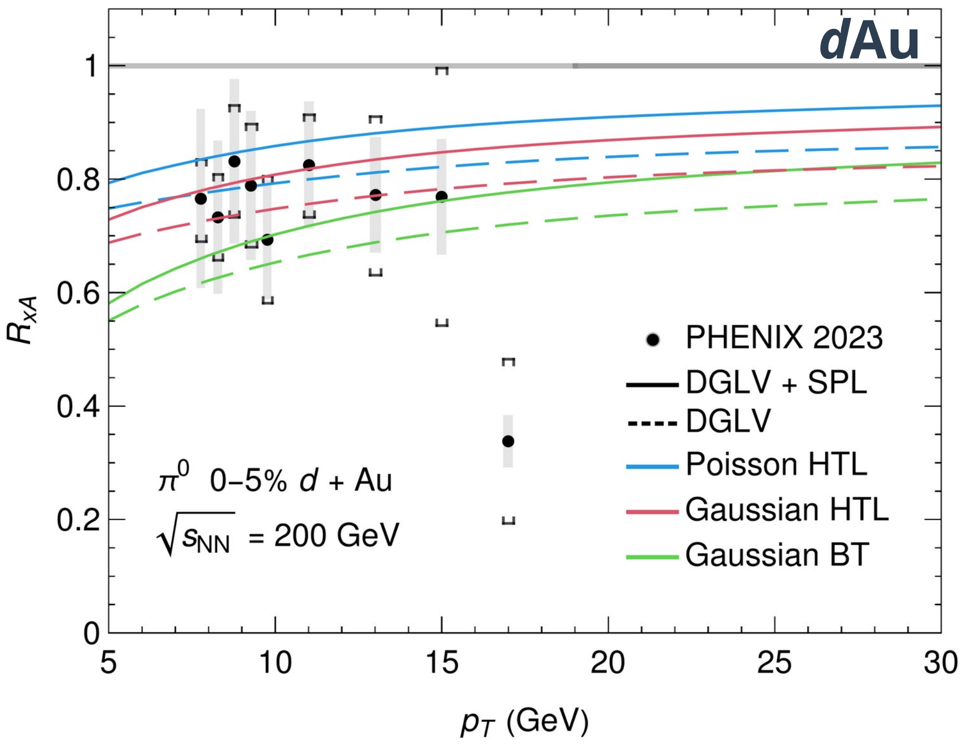
Heavy Flavour Suppression in pPb



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

Light Flavour Suppression in pPb and dAu

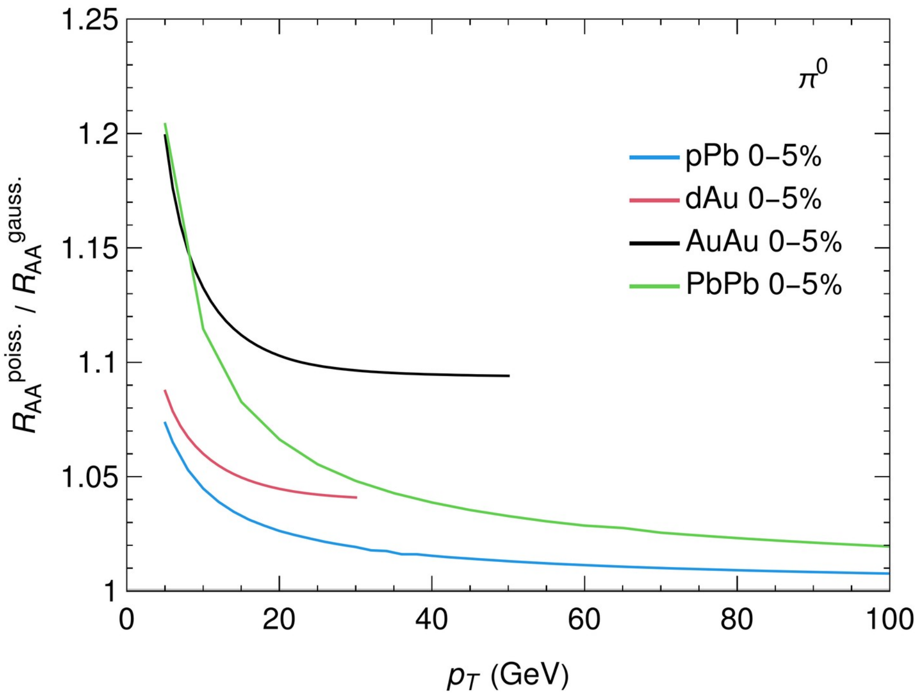




High p_T R_{AA} qualitatively consistent with SPL result, but low p_T dramatically inconsistent

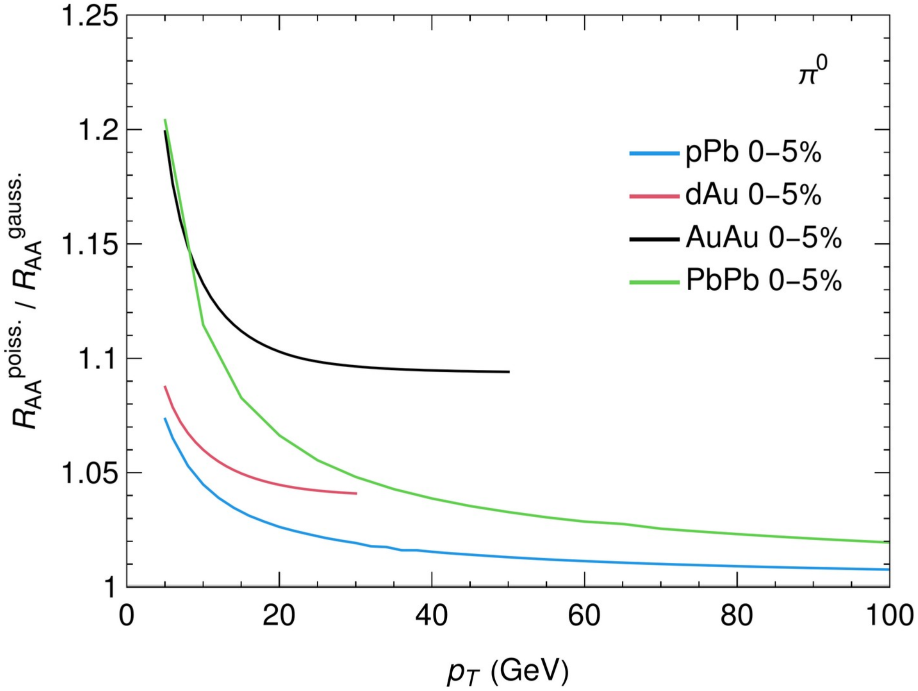
Models qualitatively consistent with data in *d*Au

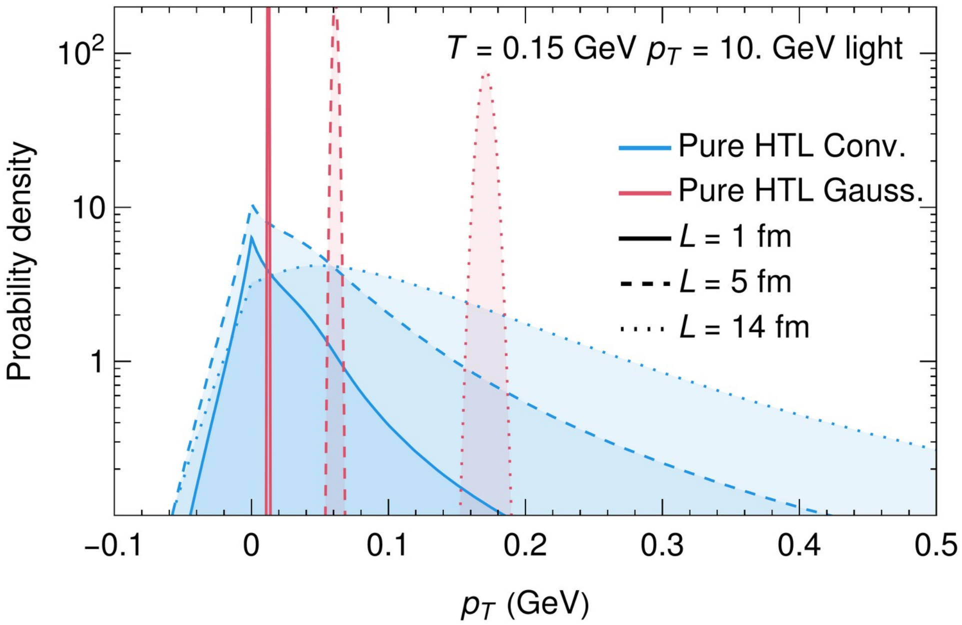
Gaussian ~ Poisson?



- Opposite ordering than expected according to CLT?
- Strong

Gaussian ~ Poisson?





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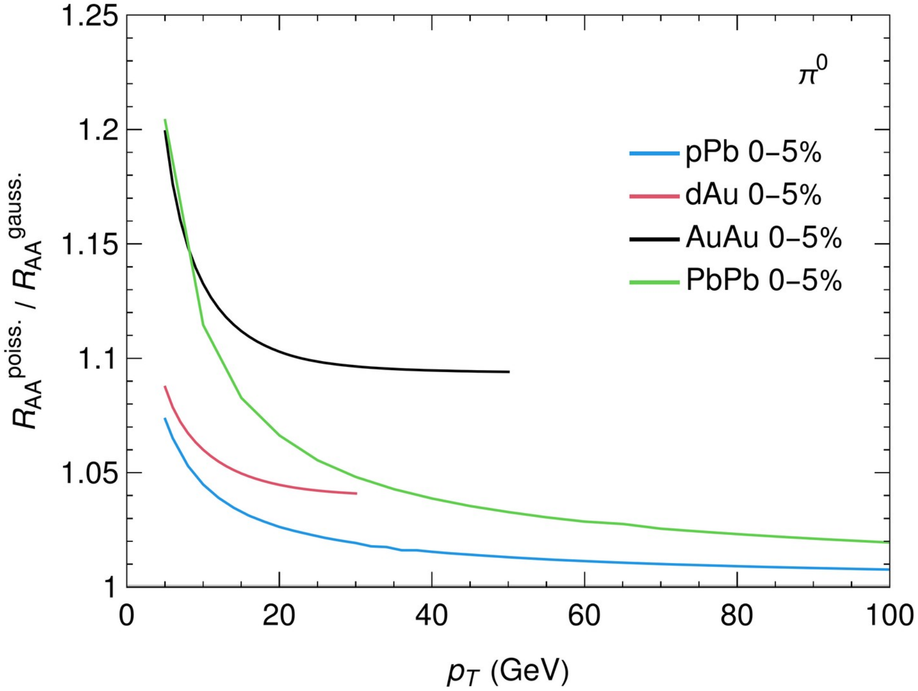
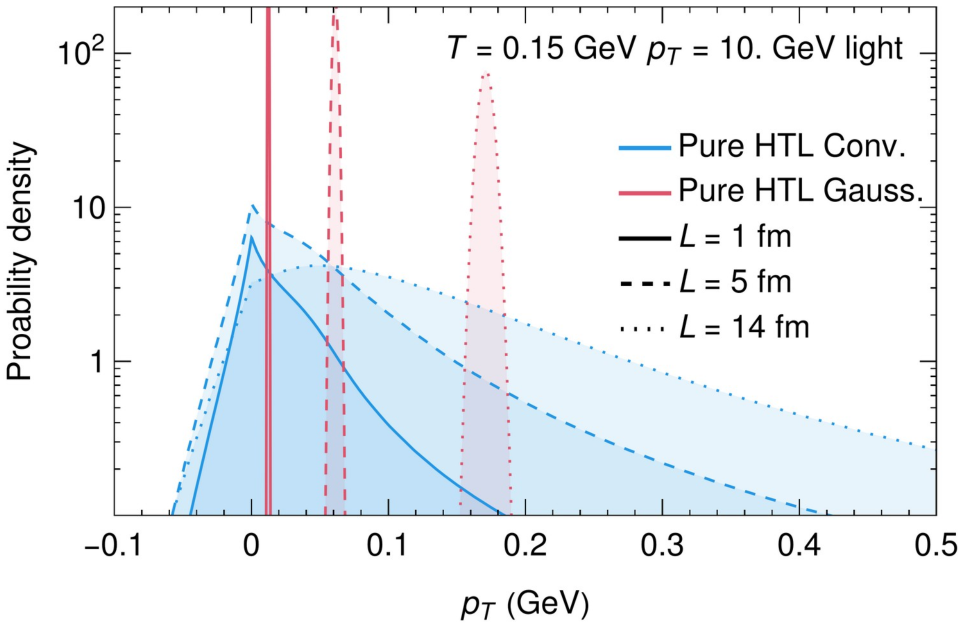
Gaussian distribution not a good fit for **either** small or large systems

Gaussian ~ Poisson?





- Opposite ordering than expected according to CLT?
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Gaussian distribution not a good fit for **either** small or large systems

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

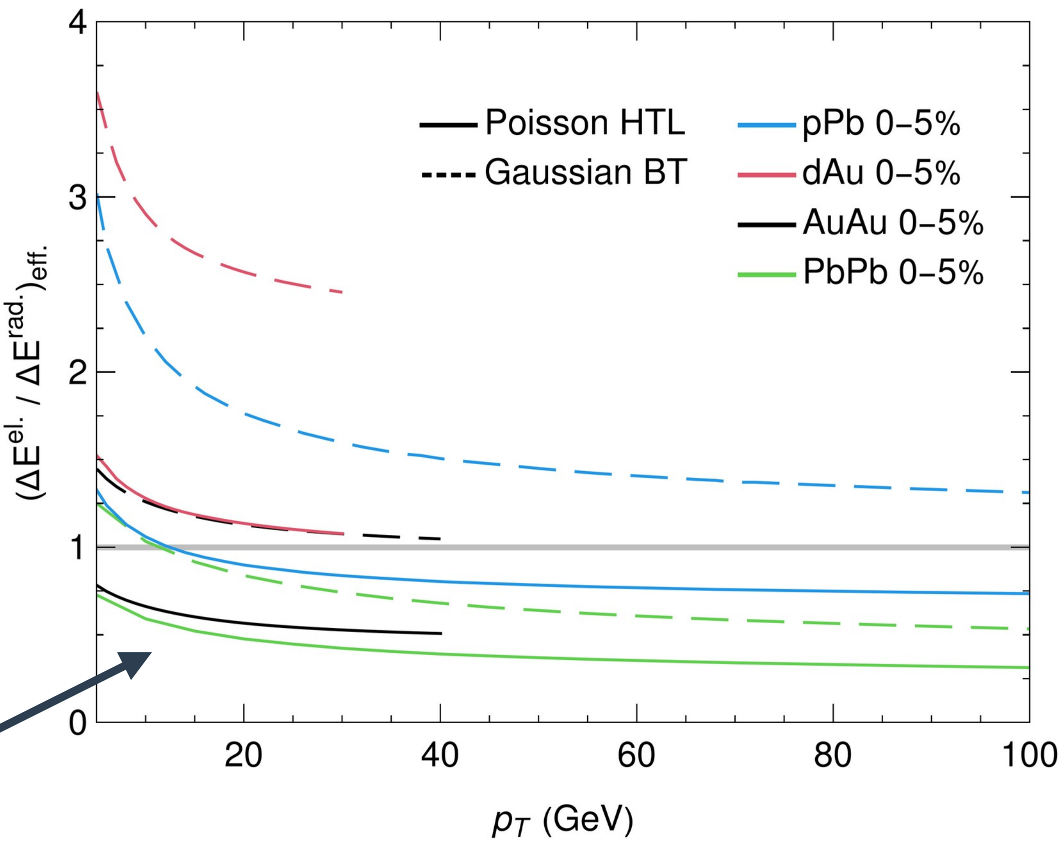
Why is Gaussian ~ Poisson?

One can show that:

1) In small systems: small energy loss
⇒ 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



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!

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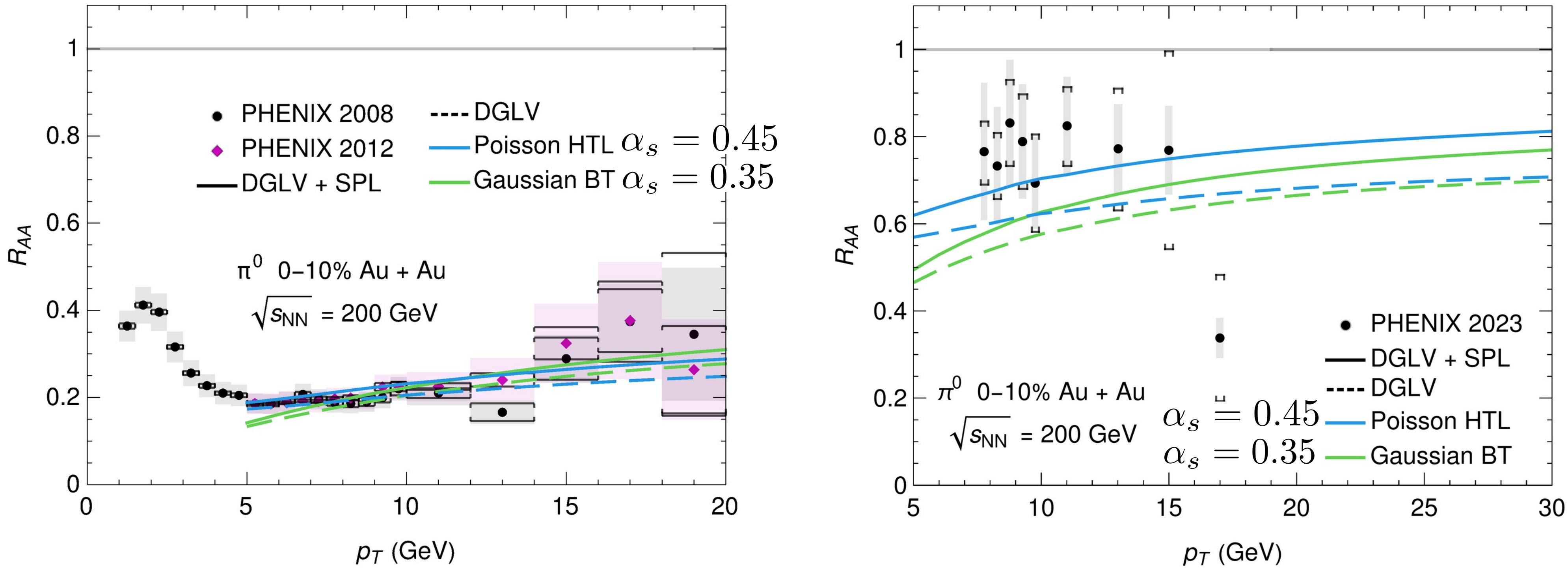
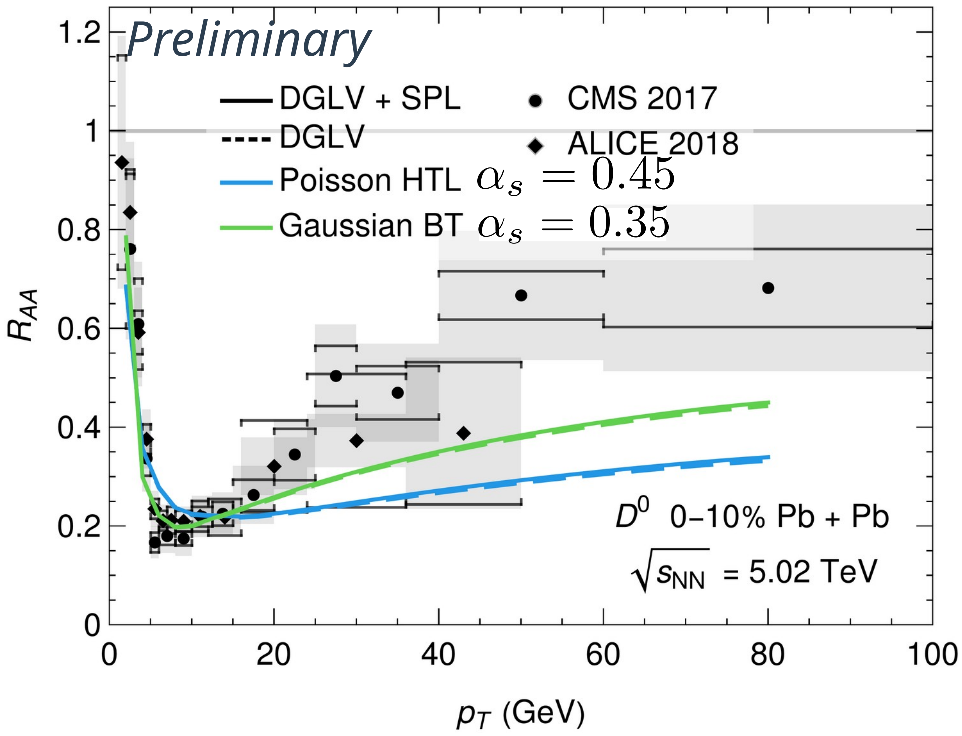
→ Fit α_s on a per model basis

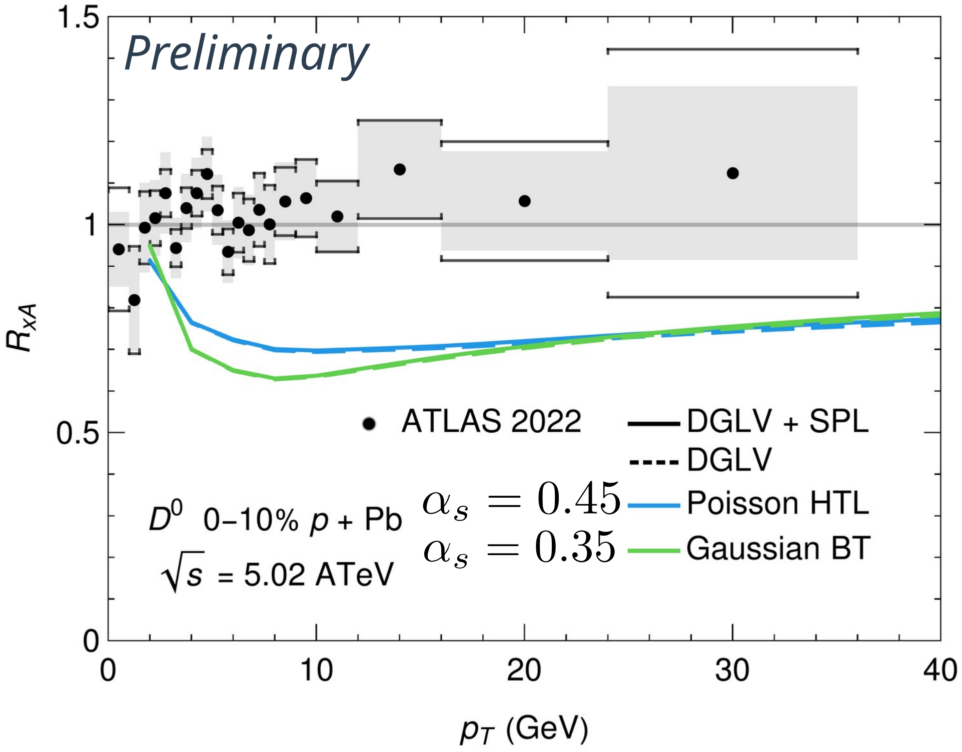
Global α-Fitted Results at RHIC



- 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)

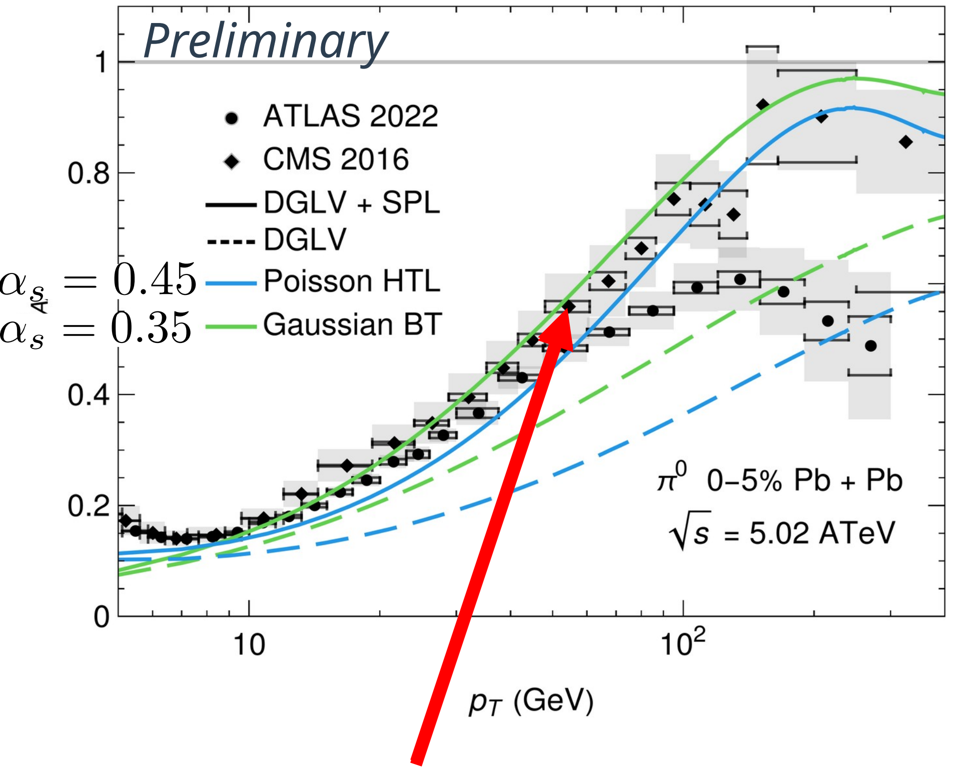


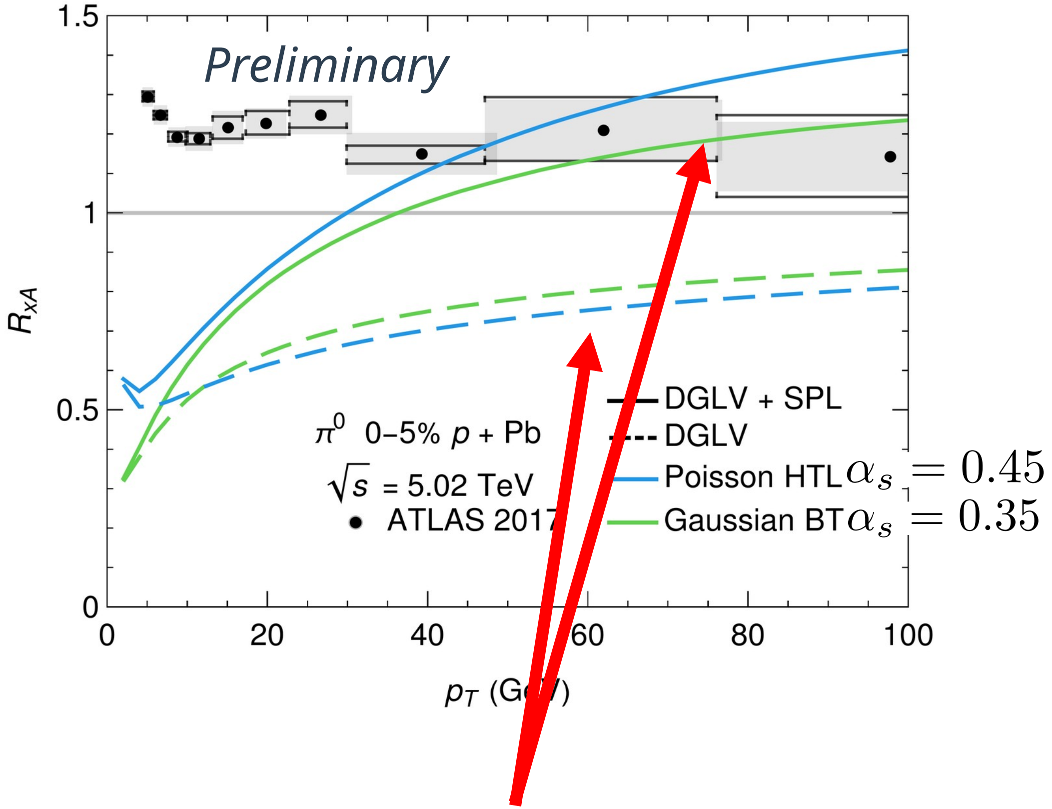


- All data over suppressed, especially small systems

Heavy flavour RAA is especially sensitive to elastic energy loss choice

Global α-Fitted Results at the LHC (light)



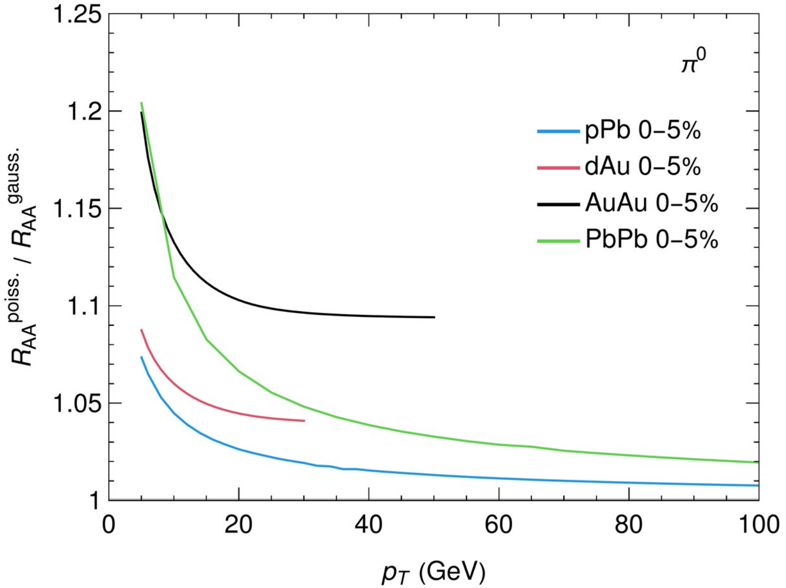


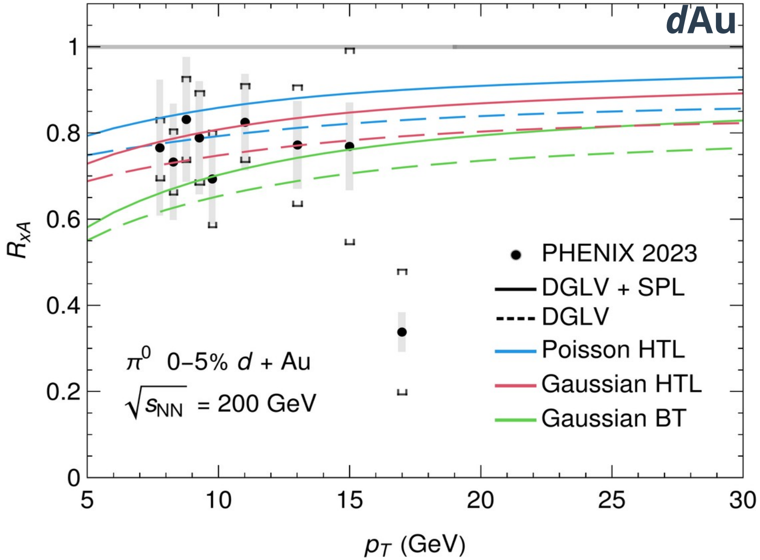
Too good to be true? No space for running coupling effects

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

Summary

- R_{AA} largely **independent of distribution** used for **elastic energy loss**
  ⇒ More sensitive at low $\sqrt{s}$, low p_T and large systems





- **Small systems** are almost **entirely elastic energy loss**
  ⇒ System size scan in R_{AA} could disentangle radiation vs elastic energy loss mechanisms
- Model is qualitatively consistent with data in both *d*Au and AuAu

Future work:

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

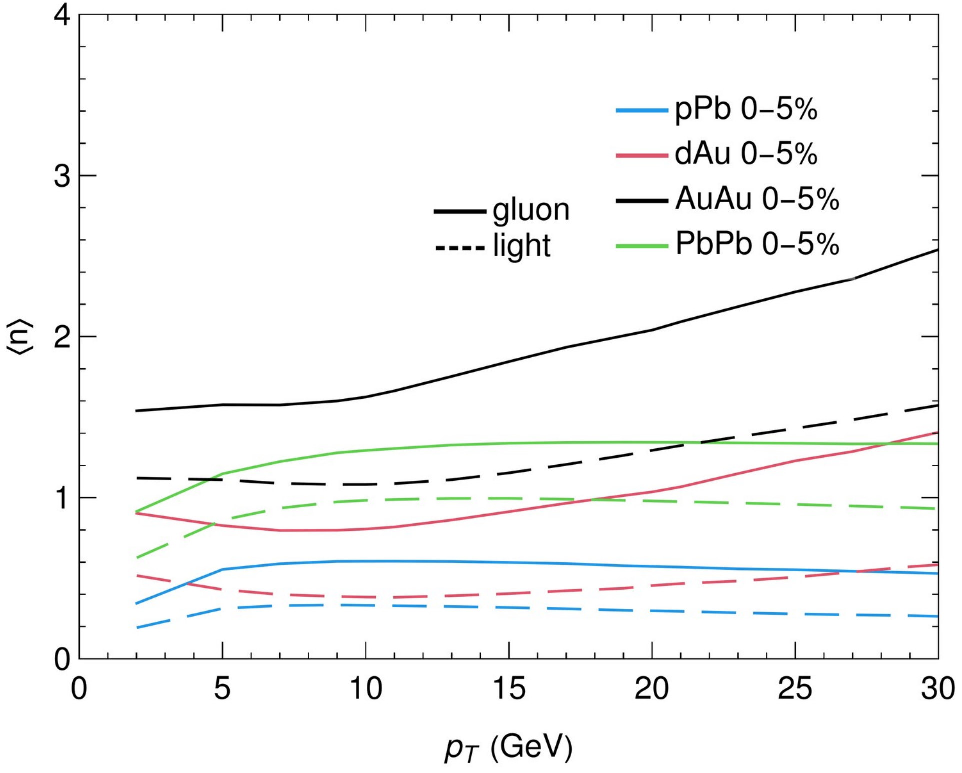
Bonus Slides

Why is Gaussian ~ Poisson?

Consider *moment expansion* of RAA

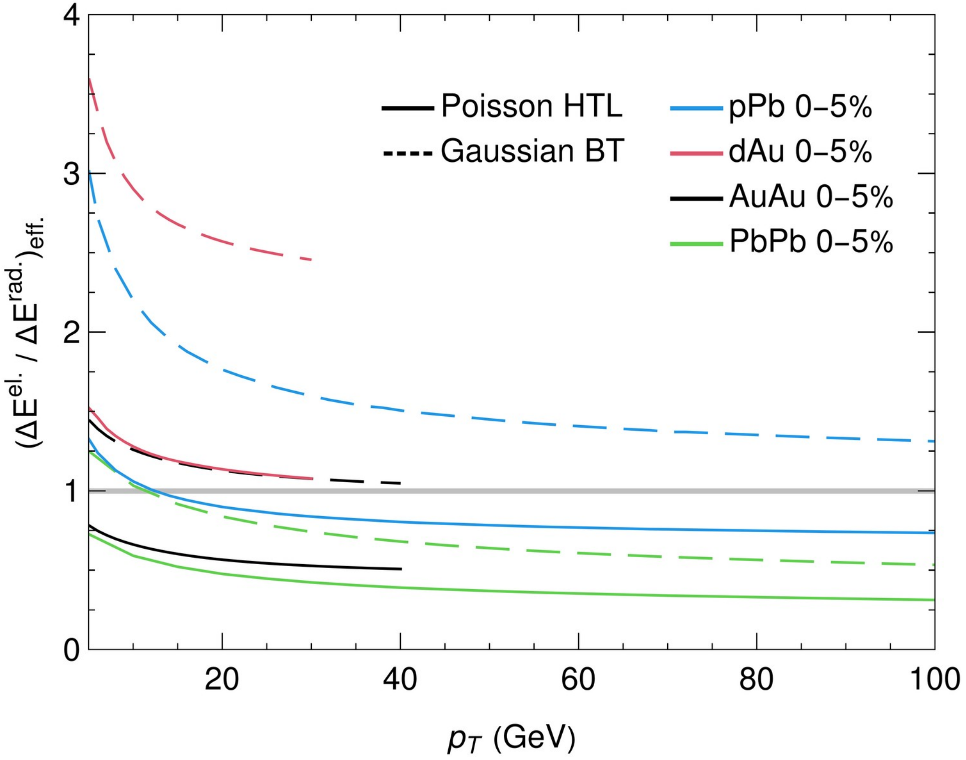
$$R_{AA}(p_T) = \sum_n c_n(p_T) \int d\epsilon\, P_{\text{tot.}}(\epsilon|p_T) = \sum_n c_n(p_T) \langle \epsilon^n(p_T) \rangle_{\text{tot.}}$$

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



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

Elastic vs Radiative E-Loss Importance

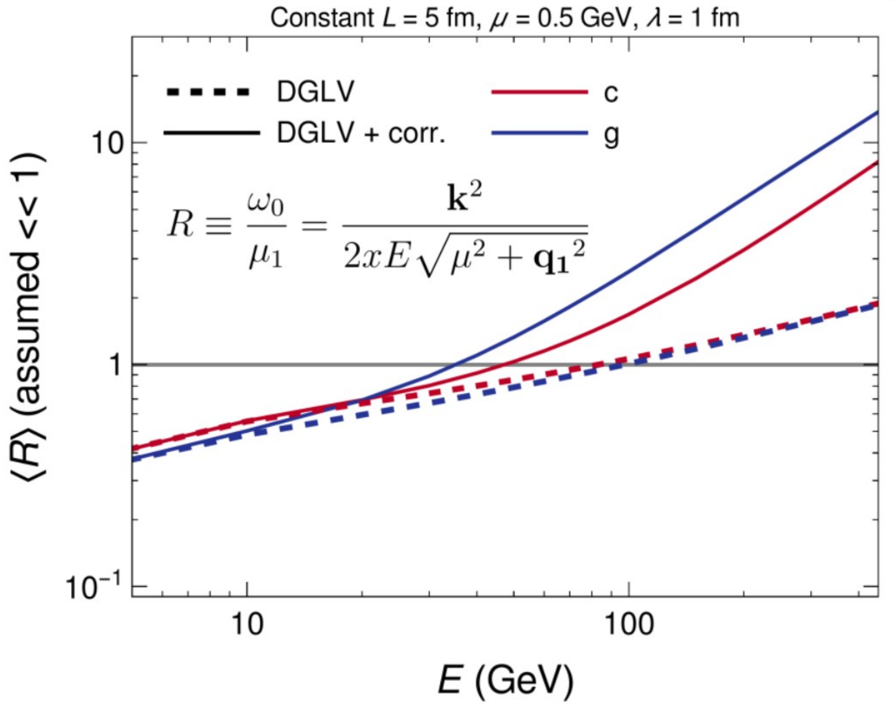


Elastic $\Delta E / E \simeq \alpha^2 T^2 \log(ET)/E$

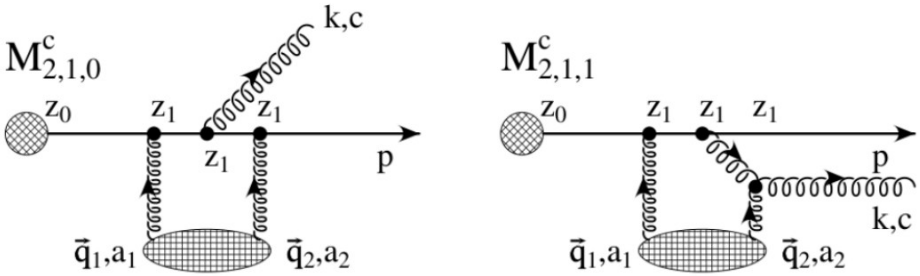
Radiative $\Delta E / E \simeq \alpha_s^3 L^2 T \log E / E$

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

Large Formation Time Assumption

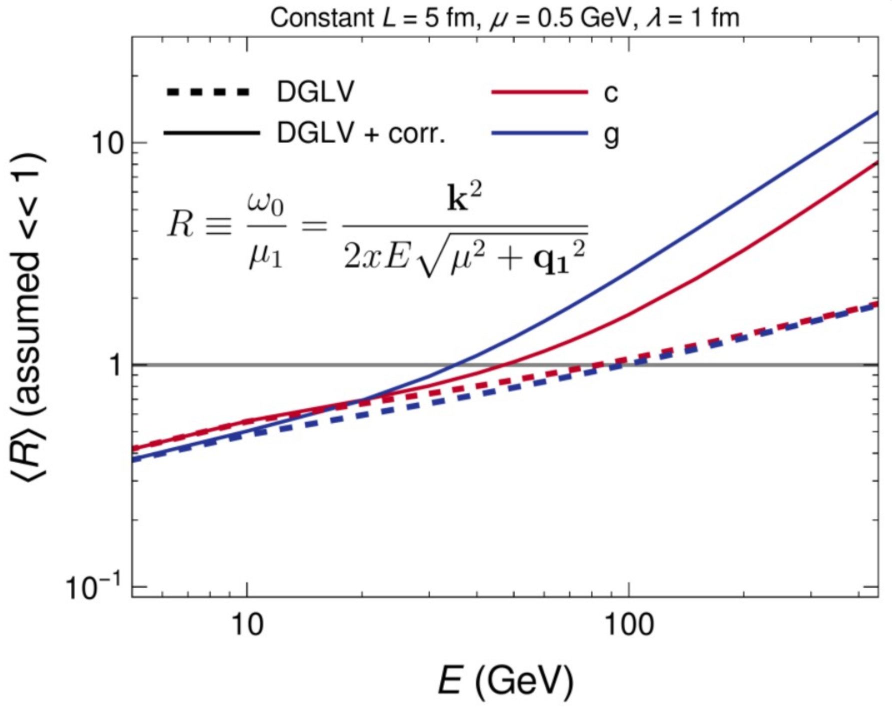


- **Large contributions** to SPL corr. at high energies from regions of phase space **not allowed** according to Large Formation Time assumption
- Also impacts DGLV

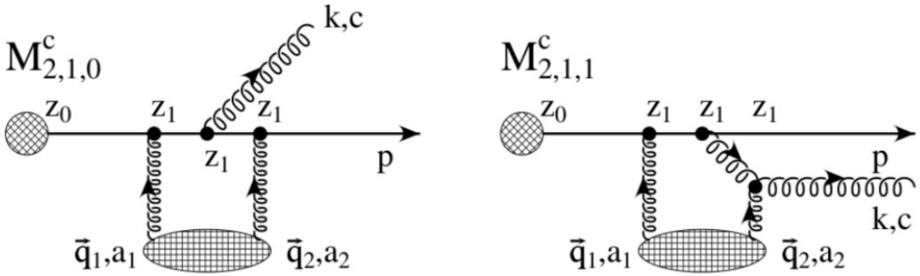


$$\sim \frac{\mathbf{k}_\perp^2 + m_g^2 + x^2 M^2}{2\omega} \frac{1}{\mu_1} \to 0$$

Large Formation Time Assumption

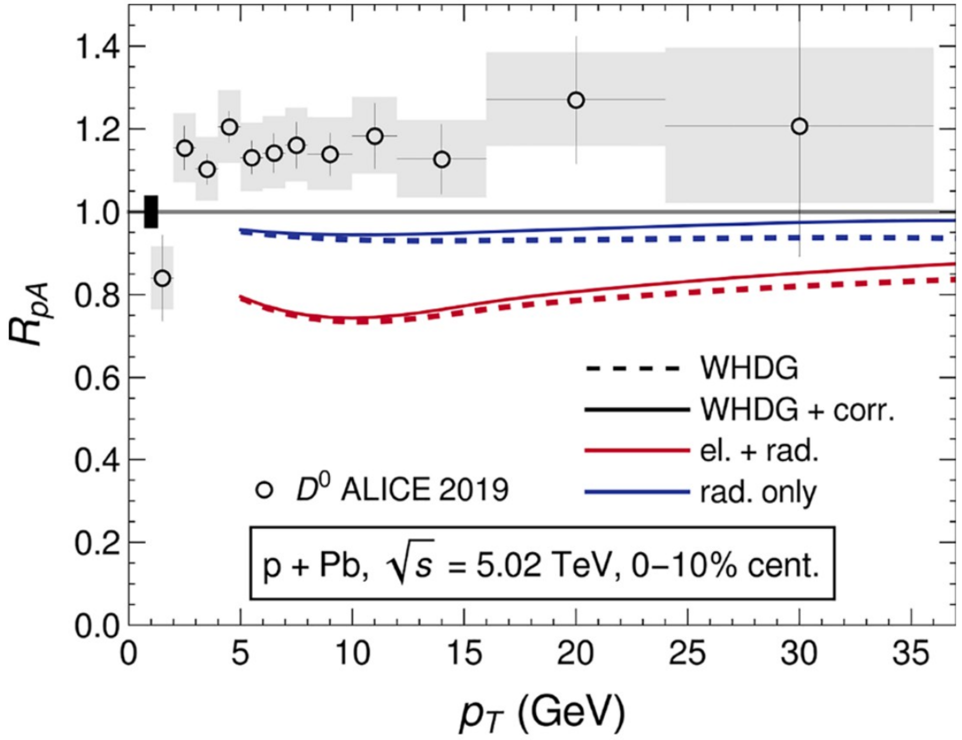


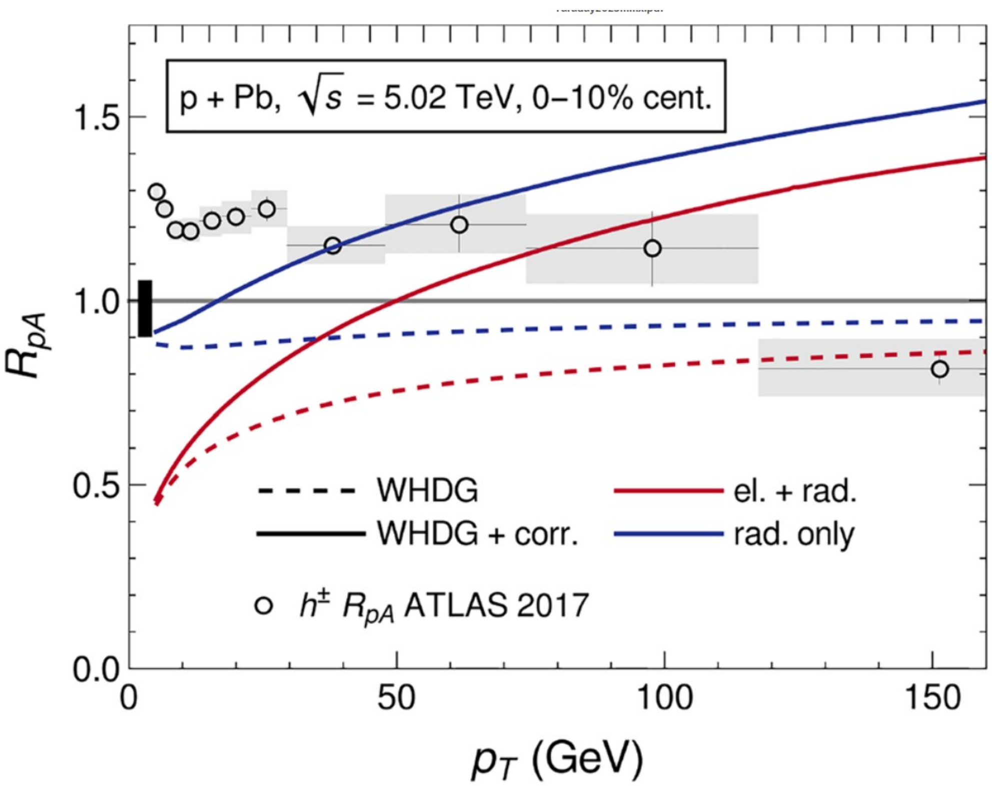
- **Large contributions** to SPL corr. at high energies from regions of phase space **not allowed** according to Large Formation Time assumption
- Also impacts DGLV
- Future work should include a full rederivation of DGLV with LFT assumption relaxed
- Can implement a phenomenological cut in the phase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



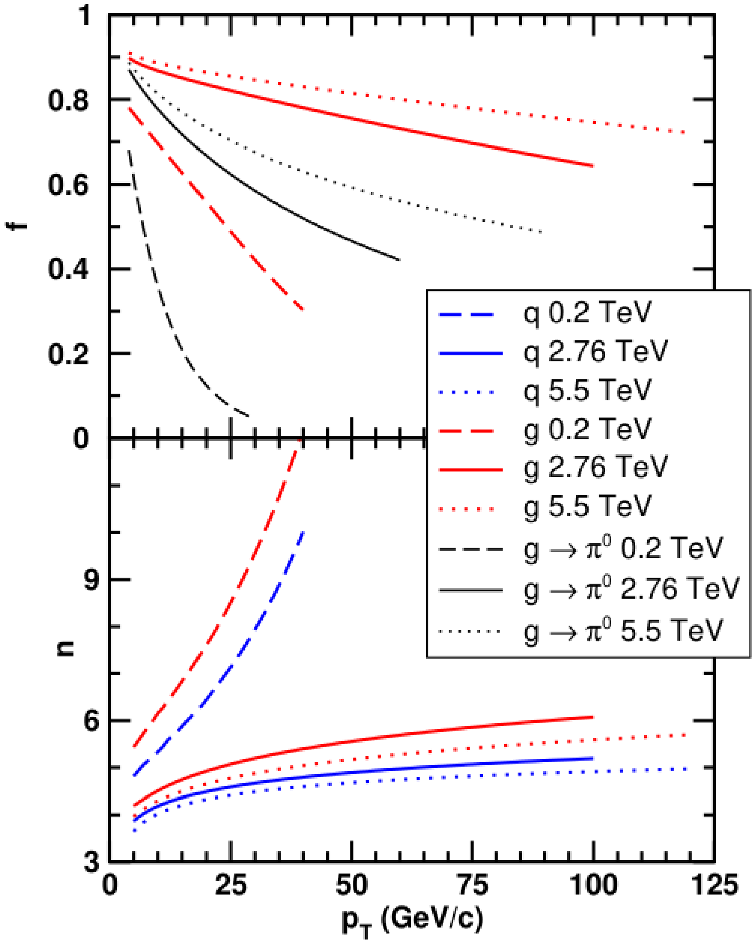
$$\sim \frac{\mathbf{k}_\perp^2 + m_g^2 + x^2 M^2}{2\omega} \frac{1}{\mu_1} \to 0$$

Turning Off Elastic E-Loss





Gluon to Light Quark Crossover

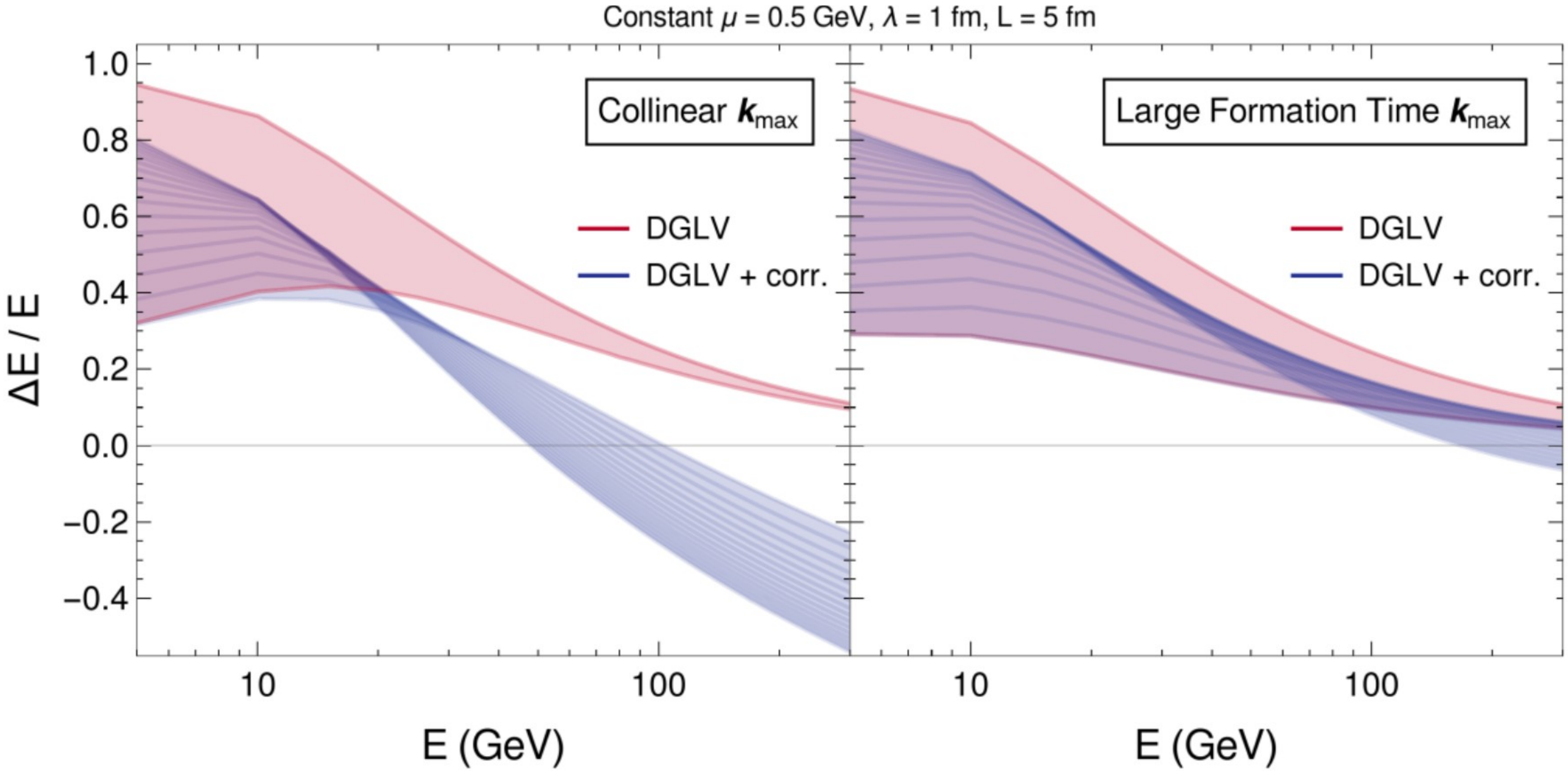


HTL vs Vacuum propagators

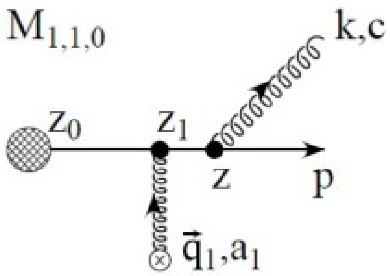
- HTL expands in momentum transfer: $q/T \simeq g_s$
- For large momentum transfer, vacuum propagators should be the correct theory
- The way in which you cross between the two, changes the longitudinal and transverse components
- Makes a large difference in energy loss

Controlling the LFT approximation

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



Example contribution to SPL corr.



$$
\begin{aligned}
\mathscr{M}_{1,0,0} = & \int \frac{d^4 q_1}{(2\pi)^4} iJ(p+k-q_1) e^{i(p+k-q_1)x_0} (ig_s)\epsilon_\alpha (2p-2q+k)^\alpha \times \\
& \times i\Delta_M(p-q_1+k) i\Delta_M(p-q_1)(2p-q_1)^0 V(q1) e^{iq_1 x_1} T_{a_1} a_1 c \\
\approx & J(p+k) e^{i(p+k)x_0} (-ig_s a_1 c T_{a_1}) 2E \int \frac{d^2\mathbf{q}_1}{(2\pi)^2} e^{-\mathbf{q}_1\cdot\mathbf{b}_1} I_1,
\end{aligned}
$$

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

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