Short pathlength corrections to energy loss in a quark gluon plasma

Based on arXiv:2305.13182

Coleridge Faraday

Supervised by A/Prof. W. A. Horowitz

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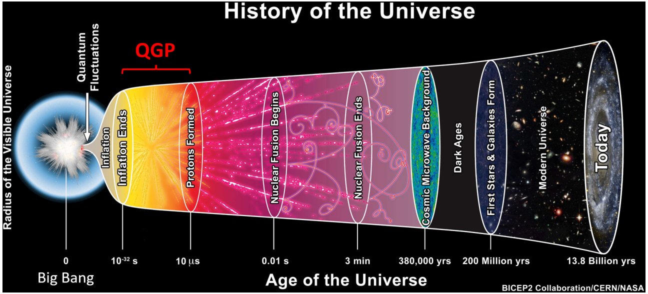
Role of QCD in understanding the universe

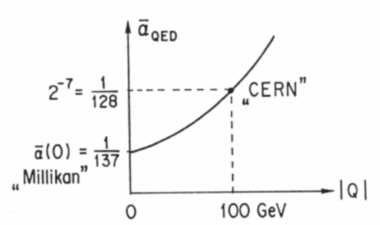
- First microseconds after the Big Bang?
- Physics of a trillion degrees?
- Neutrons stars?



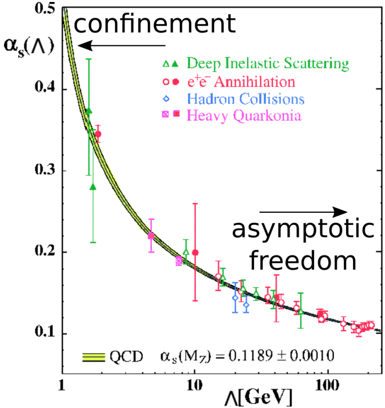
- *Quantum Chromodynamics* (QCD) describes quarks and gluons, which make up protons and neutrons

What makes QCD special?

- Coupling $\sim$ interaction strength
- Running coupling and perturbation theory
- Nonabelian gauge group



QED running coupling, perturbative at all scales of interest



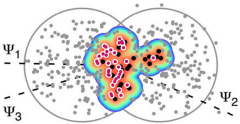
QCD running coupling, perturbative **only** at high energies

How to study QCD?

- Want to study *Quark Gluon Plasma* $\rightarrow$ high-energy heavy-ion collisions

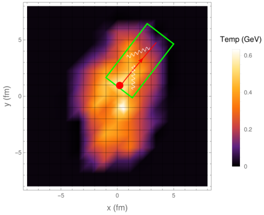
How to study QCD?

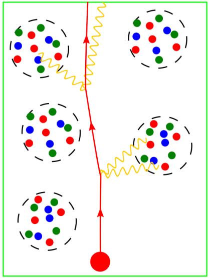
- Want to study *Quark Gluon Plasma* → high-energy heavy-ion collisions



Collision sets up geometry

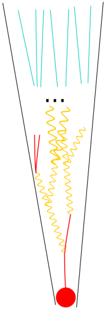
QGP evolves with hydro





Energy loss

Hadronisation and jet detection



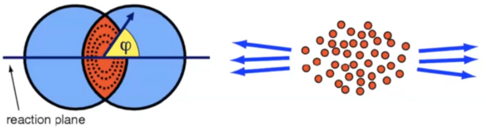
Hadrons

q, g

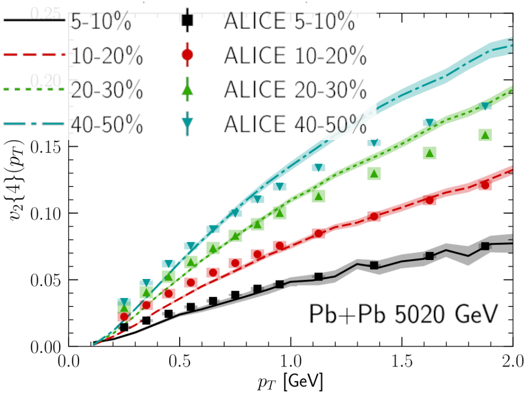
Evidence for QGP formation: Angular correlations

$$v_n \equiv \langle \cos [n(\phi - \Psi_n)] \rangle$$

- For peripheral collisions dominant v_2 due to *elliptic geometry*
- Well described by *hydrodynamic* models at low-p_T

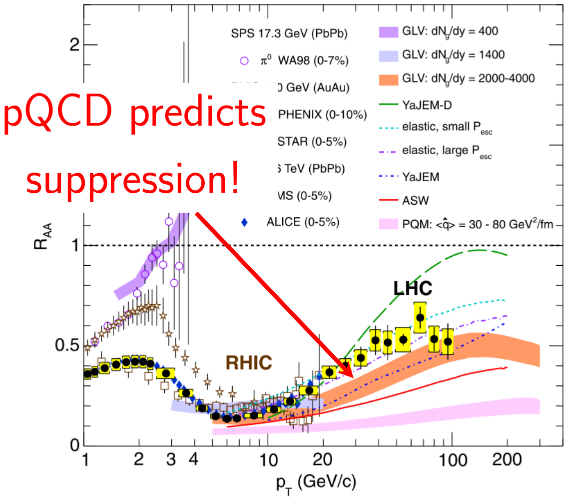


Spatial anisotropy → momentum anisotropy
(Source: CTMP talk by François Arleo)



2nd Fourier coefficient related to azimuthal anisotropy (sig. of *"Elliptic flow"*)
(Schenke et al. 2020, 2005.14682)

Evidence for QGP formation: Energy loss

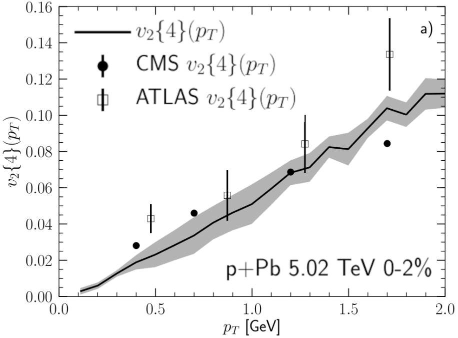


$$R^h_{AB} \equiv \frac{d\sigma^h_{AB}}{N_{\text{coll}}\, d\sigma^h_{pp}}$$

- N_{coll} from Glauber model, treating nucleons as independent
- Normalised s.t.
  - $R_{AB} < 1 \implies$ suppression
  - $R_{AB} = 1 \implies$ no final state effects
  - $R_{AB} > 1 \implies$ enhancement

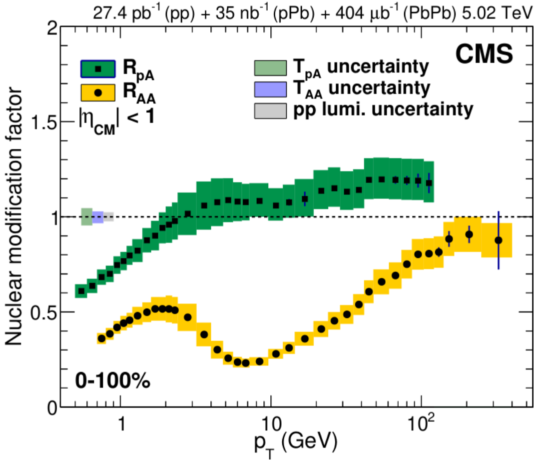
Solid evidence for QGP in $A + A$; $p + A$ as a null control?

QGP formation in small systems?

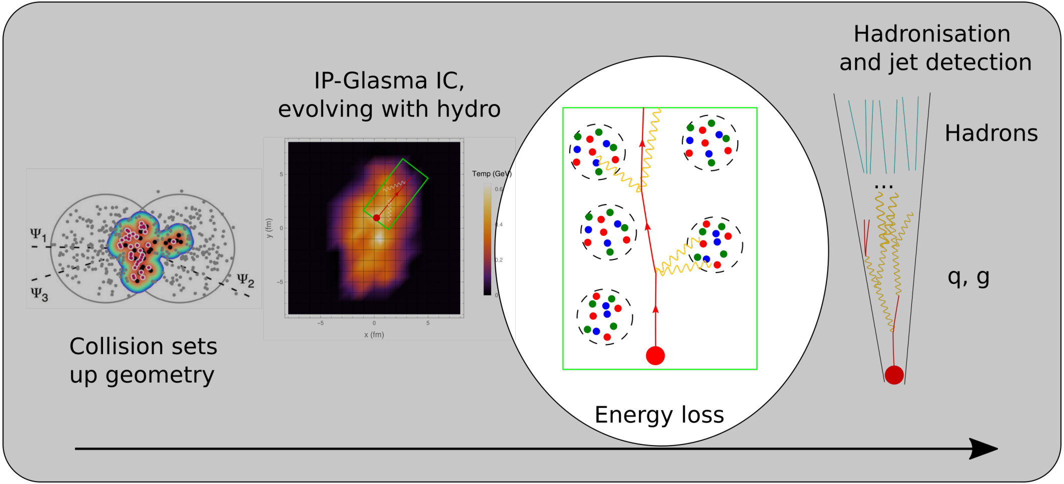


Elliptic flow in p+A?
(Schenke et al. 2020, 2005.14682)

+ other signs (quarkonium suppression, strangeness enhancement)

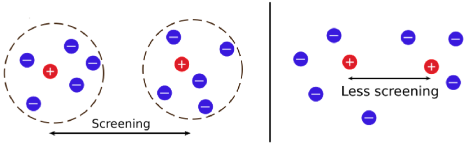


Final state enhancement in p+A?
(CMS 2017, 1611.01664)

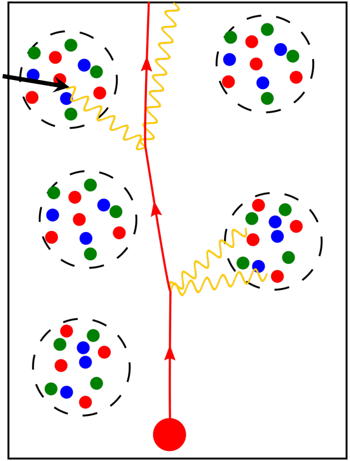

Collision sets up geometry
IP-Glasma IC, evolving with hydro
Temp (GeV)
x (fm)
y (fm)
Energy loss
Hadronisation and jet detection
Hadrons
q, g

Energy loss in QGP

- Energy loss via *elastic* and *radiative* interactions with scattering centers.
- *Radiative*: Assume few, hard scatters and expand in powers of *opacity* L/λ (DGLV)



(Gyulassy et al. 2001, nucl-th/0006010, Djordjevic et al. 2004, nucl-th/0310076, Braaten et al. 1991, 10.1103/PhysRevD.44.R2625)



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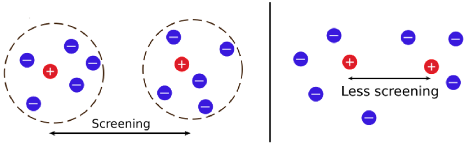

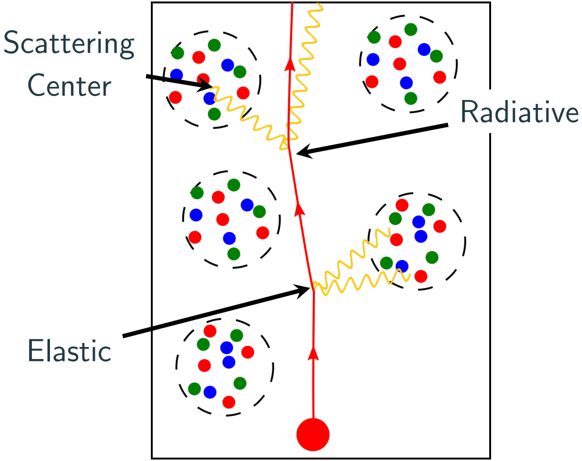

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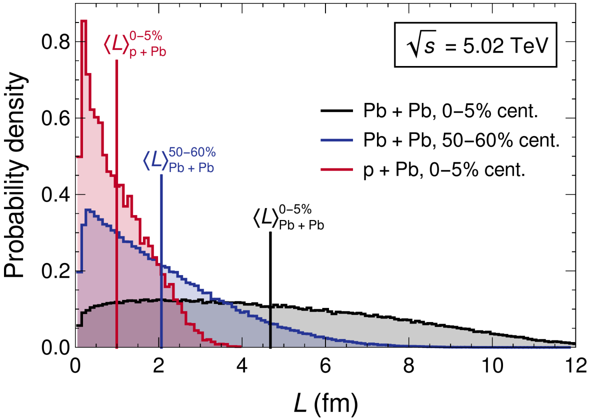
Applicability of conventional $A + A$ techniques for $p + A$?

Energy loss in small systems

- *Radiative*: Large pathlength assumption $L \gg \lambda$
- *Elastic*: Central limit theorem (large num. of scatters)
- Nonequilibrium effects $\tau < \tau_0$
- First principle derivations in finite systems



Distribution of path lengths weighted by binary collision density. For all collisions $\lambda \sim 1$ fm

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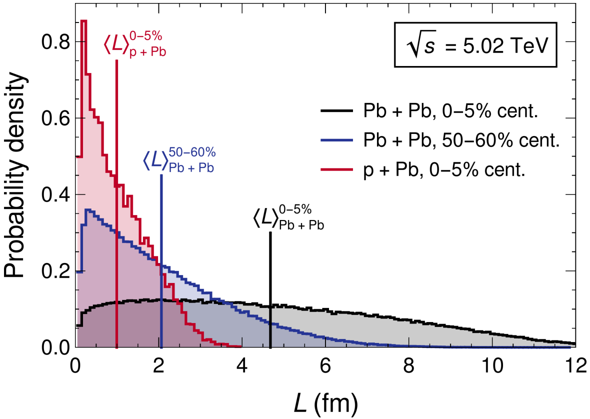
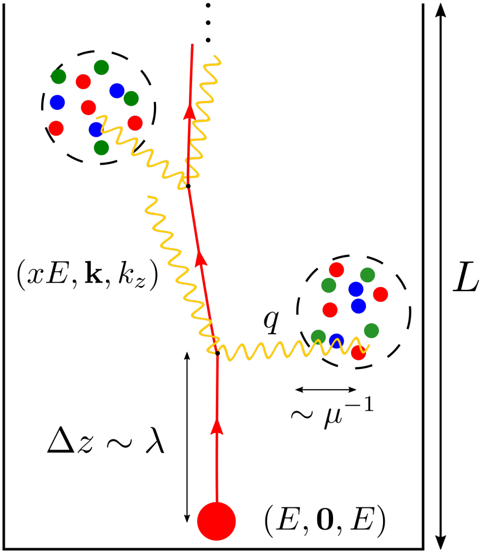


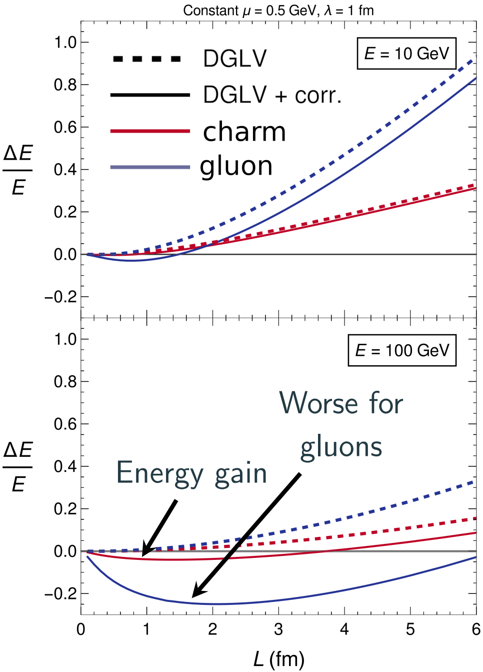
Distribution of path lengths weighted by binary collision density. For all collisions $\lambda \sim 1$ fm

Short path length corrections to radiative E-loss

Following arXiv:1511.09313 by Kolbé and Horowitz

- Weakening of assumptions: $1/\mu \ll \Delta z \sim \lambda \ll L \mapsto 1/\mu \ll \lambda$, *well separated assumption*
- Important for small systems





Correction results in:

- Breaking of *color triviality*
- Possibility of *energy gain*
- Nontrivial correction for *all path lengths*
- Correction grows *faster in E* than uncorrected result

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

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

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

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

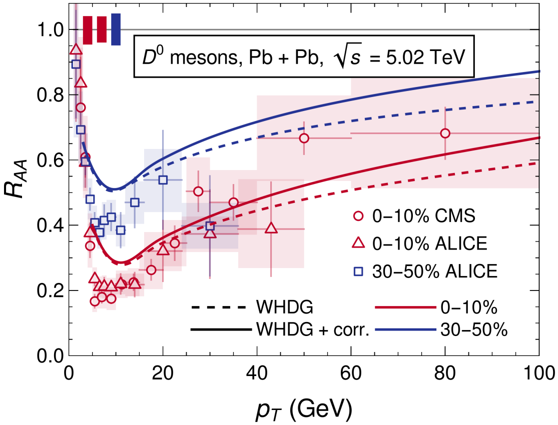
where $\omega \equiv x E^+/2,\ \omega_0 \equiv \mathbf{k}^2/2\omega,\ \omega_i \equiv (\mathbf{k} - \mathbf{q}_i)^2/2\omega,$

$\mu_i \equiv \sqrt{\mu^2 + \mathbf{q}_i^2}$, and $\tilde{\omega}_m \equiv (m_g^2 + M^2 x^2)/2\omega$

(Kolbé et al. 2015, 1511.09313, Djordjevic et al. 2004, nucl-th/0310076, Gyulassy et al. 2001, nucl-th/0006010)

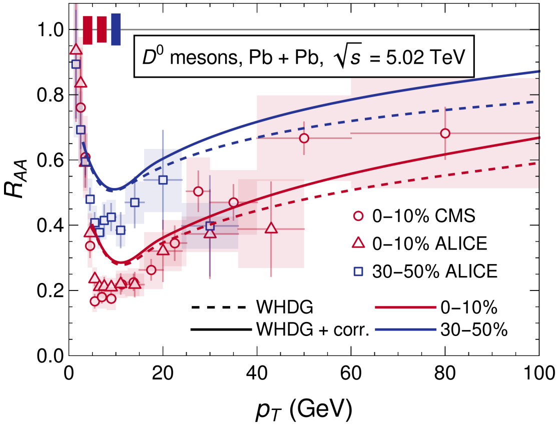
Predictions with the short path length correction

Heavy flavour predictions



$A + A$

Heavy flavour predictions



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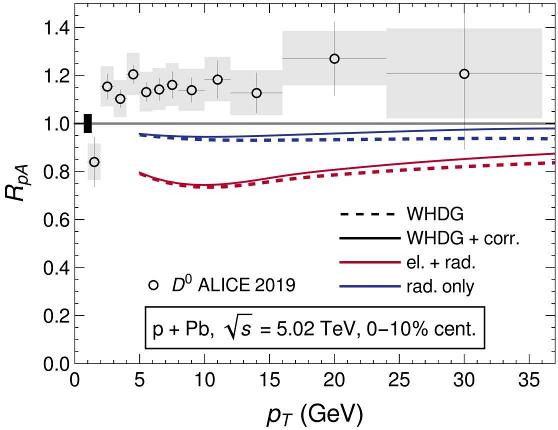
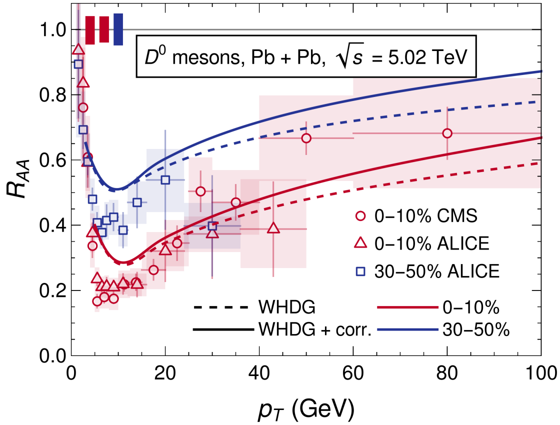
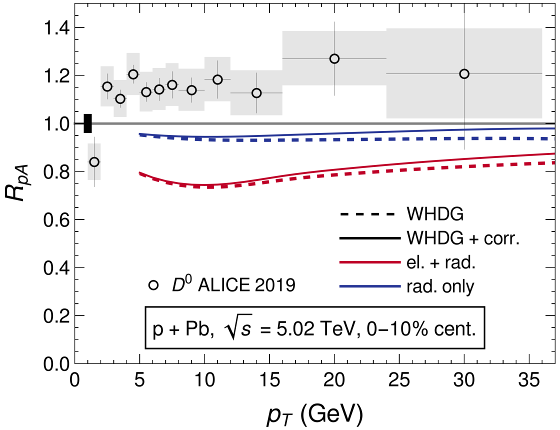


$p + A$

Heavy flavour predictions



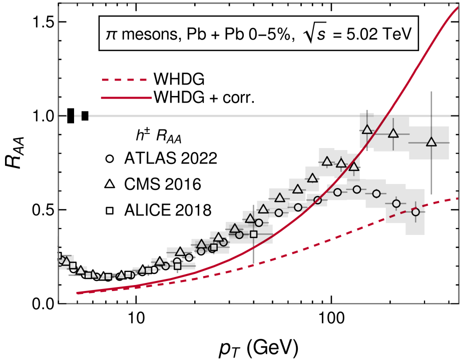
$A + A$



$p + A$

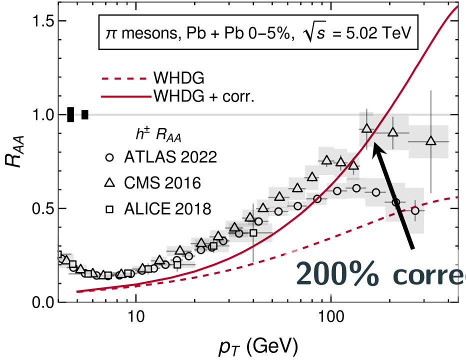
Excessive elastic E-loss in p+A $\implies$ Central limit thrm approx. *breakdown*

Light flavour predictions



$A + A$

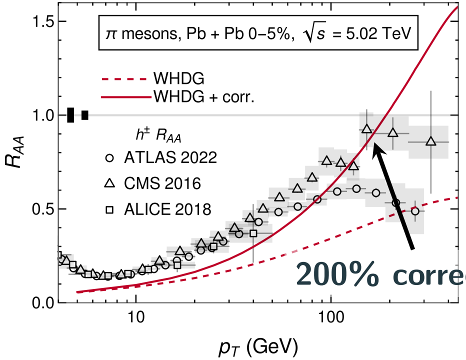
Light flavour predictions



200% correction!

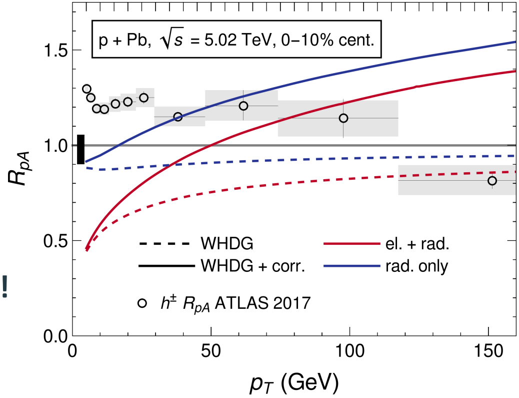
$A + A$

Light flavour predictions



200% correction!

$A + A$



$p + A$

What’s going wrong?
How physical are these results?

Breakdown of assumptions?

- Assumptions have the form $R \ll 1$ where $R = R(\mathbf{k}, \mathbf{q}, x, \Delta z)$
- Compute an *expectation value*:

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

and investigate whether $\langle R \rangle \ll 1$?. Note: $\mathrm{d}E = \int \mathrm{d}x\, xE\, \mathrm{d}N/\mathrm{d}x$

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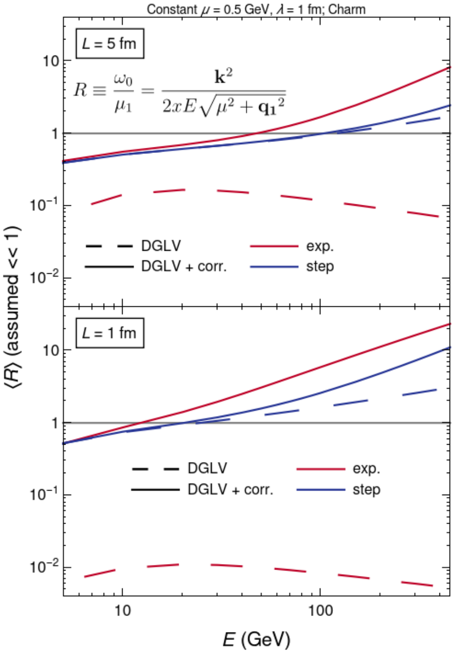
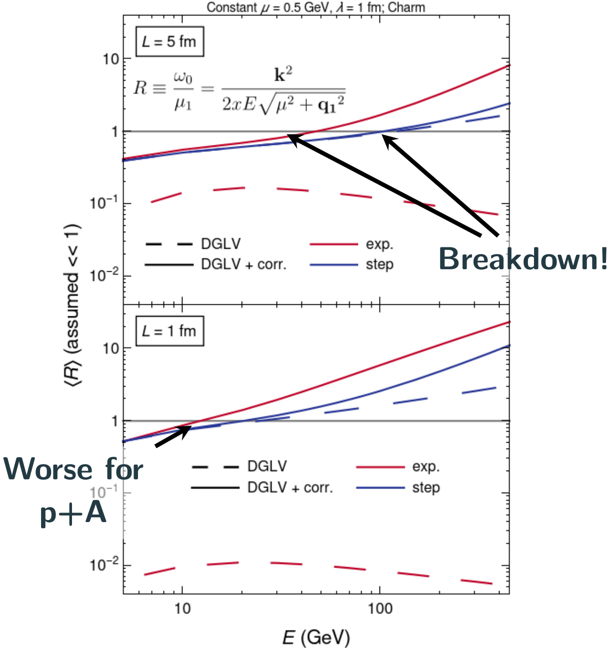
  and investigate whether $\langle R \rangle \ll 1$?. Note: $\mathrm{d}E = \int \mathrm{d}x\, xE\, \mathrm{d}N/\mathrm{d}x$
- Also; impact of scattering center distribution? For now:
  - Exponential: $\rho_{\mathrm{exp.}}(\Delta z) \equiv \frac{2}{L} \exp[-2\Delta z/L]$
  - Truncated step: $\rho_{\mathrm{step}}(\Delta z) \equiv (L - \tau_0)^{-1} \Theta(\Delta z - \tau_0) \Theta(L - \Delta z)$



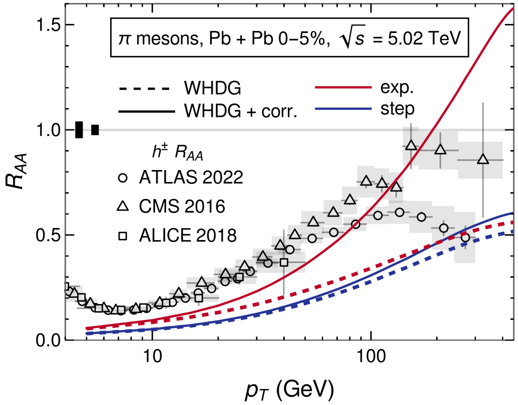
Plot of consistency of *large formation time* assumption: $\mu_1^{-1} \ll \omega_0^{-1}$.



Plot of consistency of *large formation time* assumption: $\mu_1^{-1} \ll \omega_0^{-1}$.

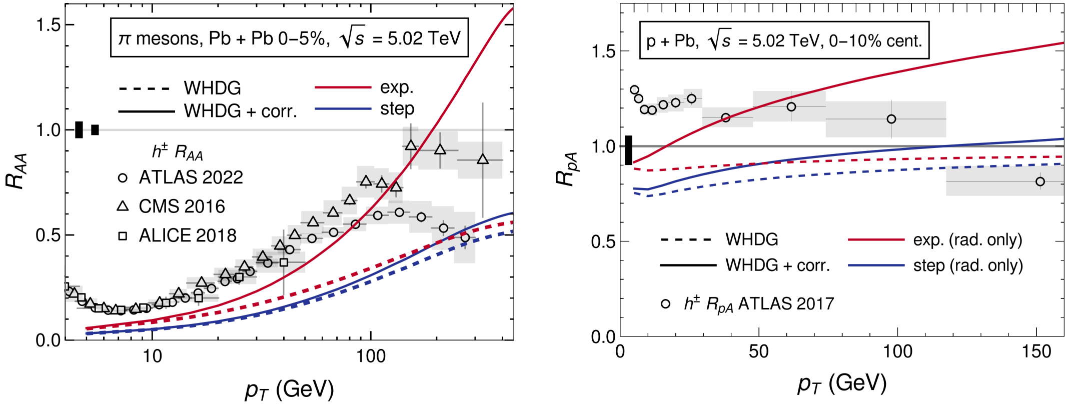
- Formation time $\tau = \omega_0^{-1} \sim \frac{2\omega}{\mathbf{k}^2}$
- Sensitivity of breakdown to *scattering distribution* $\rightarrow$ impact on R_{AA}?
- All other assumptions are satisfied self-consistently ✓

Recalculate R_{AA} with truncated step dist.



π mesons, Pb + Pb 0–5%, $\sqrt{s}$ = 5.02 TeV
WHDG
WHDG + corr.
exp.
step
$h^{\pm}$ R_{AA}
ATLAS 2022
CMS 2016
ALICE 2018
R_{AA}
p_T (GeV)
1.5
1.0
0.5
0.0
10
100

$A + A$



$A + A$ $p + A$

Size of correction dramatically *reduced*!

Conclusions / Outlook

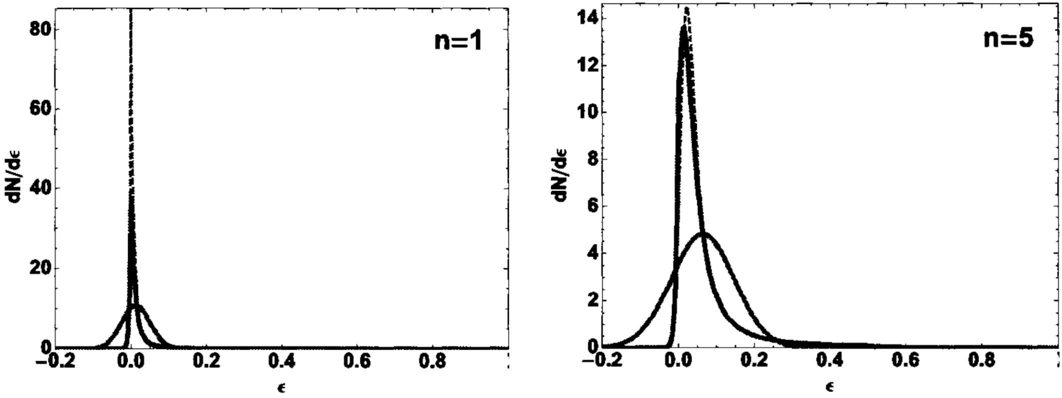
- *Elastic short pathlength corr.* needed for $p + A$
- *Short formation time corr.* to radiative E-loss
- Final state radiation (partially) responsible for *enhancement* in $p + A$?

  Or just normalisation / initial state effects?

Special thanks to my supervisor and SA-CERN.

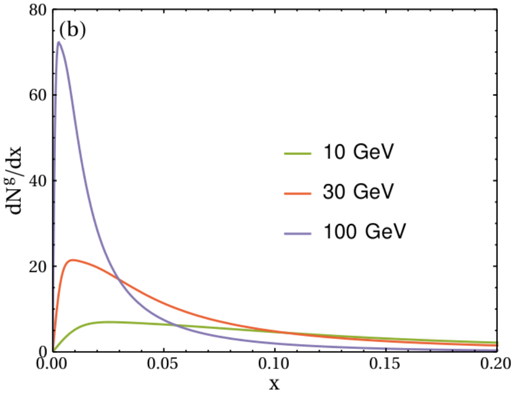
Thanks for listening!

Elastic E-loss: Central limit theorem

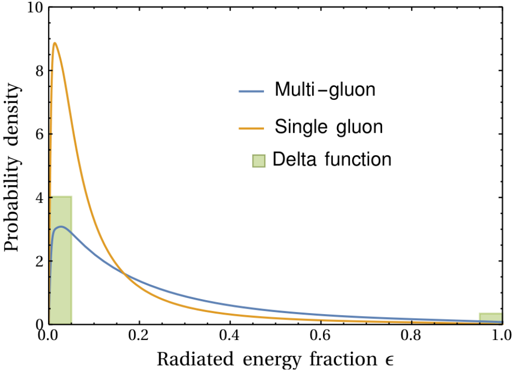


Fractional collisional elastic energy loss distribution where ε is the momentum fraction lost.
(Wicks 2008, PhD thesis)

Radiative emission kernel

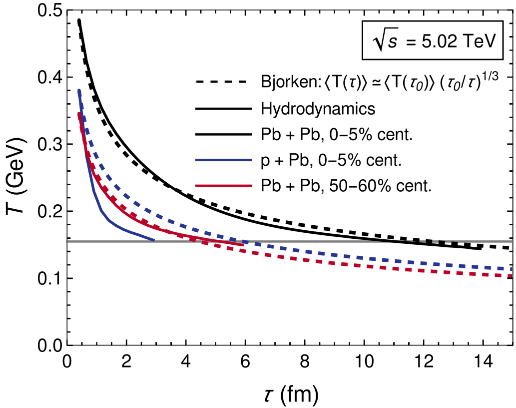


Single gluon emission kernel for Charm quarks at different energies



Single vs multiple gluon emission kernel for Charm quarks

Geometry



Temperature T of the plasma as a function of proper time τ.

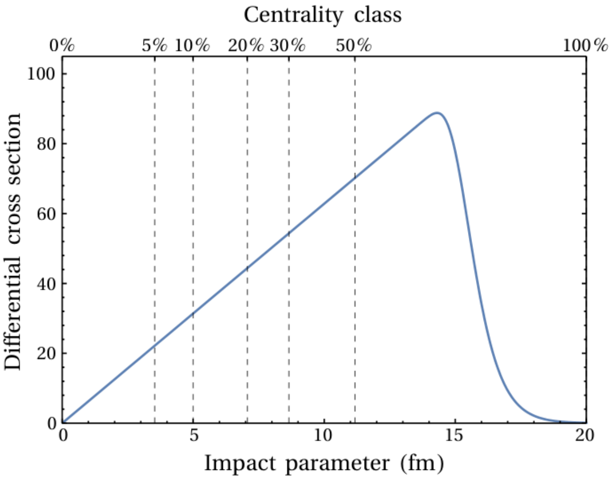
$$\langle T(\tau)\rangle \equiv \left(\frac{\int \mathrm{d}^2x\, T^6(\tau,\mathbf{x})}{\int \mathrm{d}^2x\, T^3(\tau,\mathbf{x})}\right)^{1/3} \qquad (1)$$

where

$$\rho_{\text{part}}(\tau,\mathbf{x}) = \frac{\zeta(3)}{\pi^2}(16+9n_f)\,T^3(\tau,\mathbf{x}), \qquad (2)$$

is the nucleon participant density.

Centrality explanation



Connecting centrality (experiment) and impact parameter (theory)

Making a prediction

- Interpret $\mathrm{d}N/\mathrm{d}x$ as a probability
- Total probability for E-loss is the convolution $P_{\text{tot}}(\epsilon) = \int \mathrm{d}x \ P_{\text{rad}}(x) P_{\text{el}}(\epsilon - x)$
- The R_{AA} is schematically

$$R_{AA} = \text{hadronization} \otimes \text{geometry} \otimes \underbrace{\int \mathrm{d}x \ P_{\text{tot}}(x)(1-x)^{n(p_T)}}_{\text{E-loss in brick}}, \qquad (3)$$

where $n(p_T)$ and hadronization are measured.

Accessing R_{AA} theoretically

Assume slowly-varying power law production spectrum:

$$\frac{dN^q_{\text{prod}}}{dp_i}(p_i) \propto \frac{1}{p_i^{n(p_i)}}, \tag{4}$$

leads to

$$R^q_{AA}(p_T) = \int \mathrm{d}\epsilon \, P_{\text{tot}}(\epsilon, p_T)\,(1-\epsilon)^{n(p_T)-1}. \tag{5}$$

Averaging over geometry:

$$\langle R^q_{AA}(p_T)\rangle_{\text{geom.}} = \int \mathrm{d}L_{\text{eff}}\,\rho(L_{\text{eff}}) \times \int \mathrm{d}\epsilon \, P_{\text{tot}}(\epsilon, \{p_T, L_{\text{eff}}, \langle T(\tau_0)\rangle\})\,(1-\epsilon)^{n(p_T)-1}. \tag{6}$$

Asymptotic energy loss

$$\frac{\Delta E_{\text{corr.}}}{E} = \frac{C_R \alpha_s}{2\pi} \frac{L}{\lambda_g} \left(-\frac{2C_R}{C_A}\right) \frac{\log\left(\frac{2EL}{2+\mu L}\right)}{2+\mu L}, \tag{7}$$

$$\frac{\Delta E_{\text{DGLV}}}{E} = \frac{C_R \alpha_s}{4} \frac{L^2 \mu^2}{\lambda_g} \frac{1}{E} \log \frac{E}{\mu}. \tag{8}$$

(Kolbé et al. 2019, 1511.09313; Gyulassy et al. 2001, nucl-th/0006010)