High-p_T Suppression in Small Systems

Coleridge Faraday

Supervised by A/Prof. W. A. Horowitz

Based on CF, A. Grindrod, and W. A. Horowitz arXiv:2305.13182

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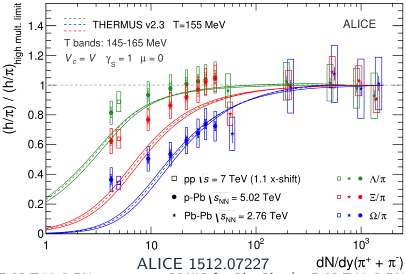
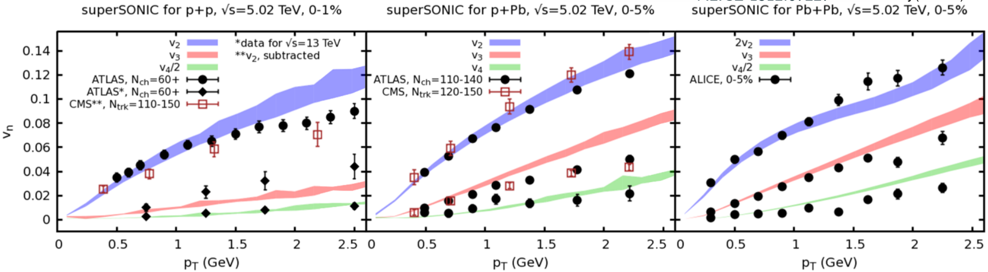
QGP Formation in Small Systems?

QGP signs in $p + A$ and high multiplicity $p + p$ collisions:

- Elliptic flow
- Quarkonium suppression
- Strangeness enhancement



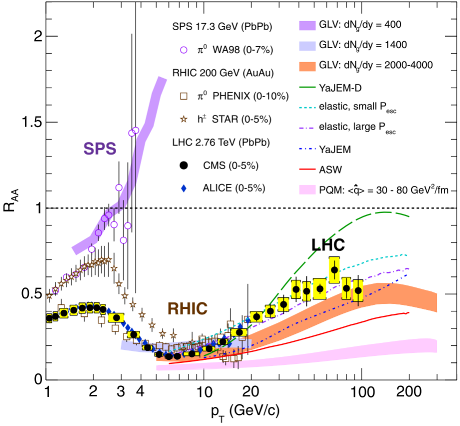
ALICE 1512.07227



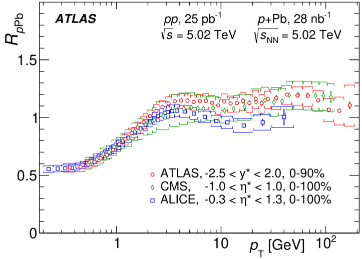
Weller et al. 2017, 1701.07145

Nuclear modification in Small Systems

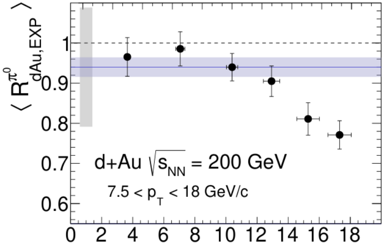
- Qualitative **success of pQCD** models in $A + A$



CMS 1202.2554



ATLAS 2211.15257



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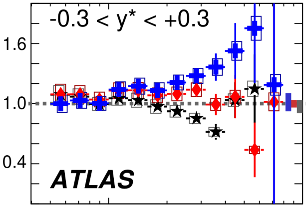


ATLAS 1412.4092

- Is there **nontrivial final state nuclear modification** in $p + A$?
- Theoretical control needed

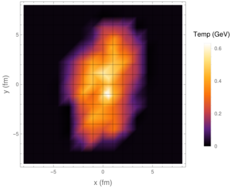
Making Energy Loss Predictions

Collision geometry → Static "bricks" with L_{eff} & T_{eff}

IP-Glasma → Collision geometry

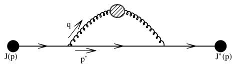
Debye screened scatt. centers → Static "bricks"

IP-Glasma



Schenke et al. 2005.14682

Making Energy Loss Predictions



Elastic E-loss

$P_{\text{el.}}(\epsilon) \sim$ Gaussian

Braaten & Thoma PRD 44 R2625

$$\frac{\Delta E}{E} \sim \alpha_s^2 T^2 L \log ET/m_g$$

Collision geometry

Static "bricks" with L_{eff} & T_{eff}

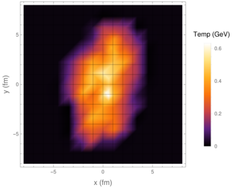
Total E-loss

$P_{\text{tot}}(\epsilon) = P_{\text{rad}}(\epsilon) \otimes P_{\text{el.}}(\epsilon)$

Radiative E-loss

$P_{\text{rad.}}(\epsilon) \sim$ Poissonian

IP-Glasma

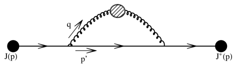


Debye screened scatt. centers

DGLV nucl-th/0310076

Schenke et al. 2005.14682

Making Energy Loss Predictions



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Collision geometry

Static "bricks" with L_{eff} & T_{eff}

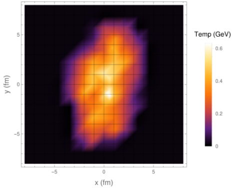
Total E-loss
$P_{\text{tot}}(\epsilon) = P_{\text{rad}}(\epsilon) \otimes P_{\text{el.}}(\epsilon)$

Partonic R_{AA} / R_{pA}
$\simeq \int \mathrm{d}x (1-x)^{n(p_T)} P_{\text{tot}}(x)$

Leading hadron R_{AA} / R_{pA}

Radiative E-loss
$P_{\text{rad.}}(\epsilon) \sim$ Poissonian

IP-Glasma



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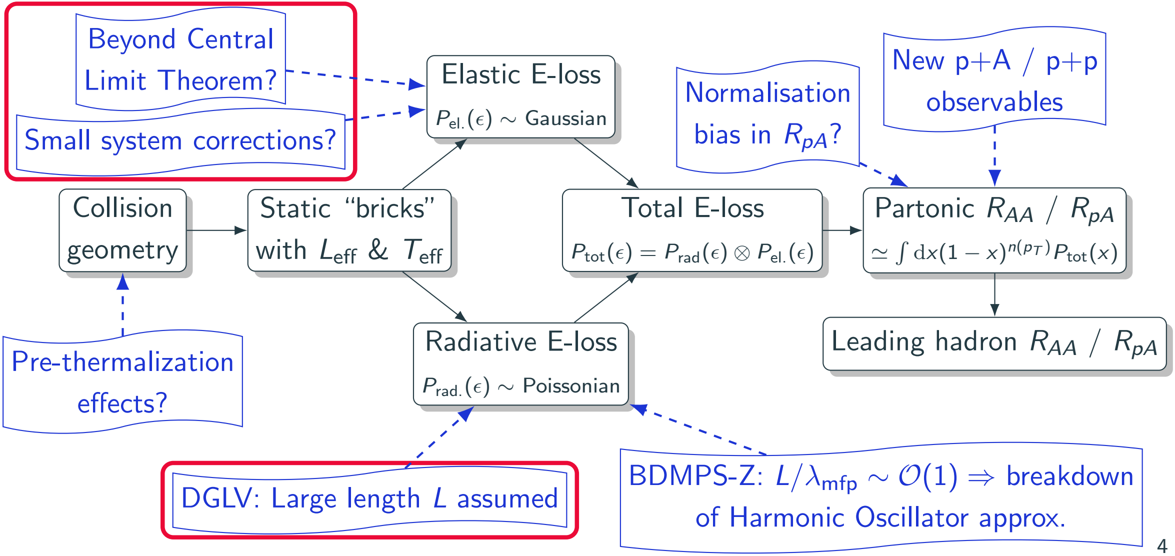
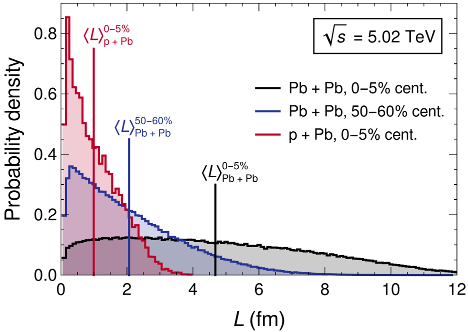
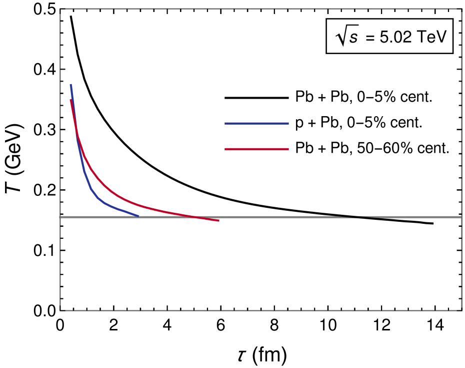
Making Energy Loss Predictions



What does QGP formation in p + A look like?





- L dist. is peaked with $\langle L \rangle_{p+\mathrm{Pb}} \sim 1$ fm cf. $\langle L \rangle_{\mathrm{Pb+Pb}} \sim 5$ fm
- Average L in central $p + A$ similar to in peripheral $A + A$
- Lifetime of central $p + A$ similar to peripheral $A + A$

Short Path Length (SPL) Corr. to Rad. E-loss

- SPL corr. from missed poles $\sim e^{-\mu L}$ Kolbe & Horowitz 1509.06122

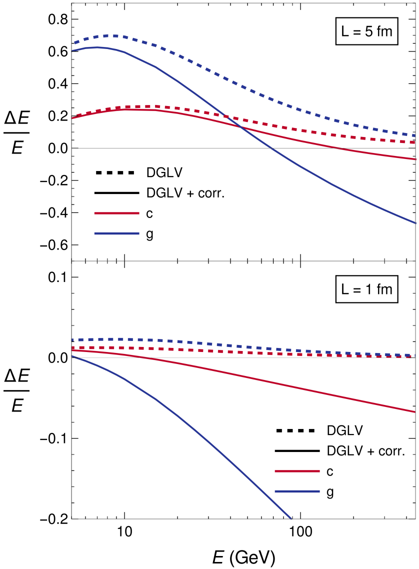
$$x\frac{\mathrm{d}N}{\mathrm{d}x} = \frac{C_R \alpha_s L}{\pi \lambda_g} \int \frac{\mathrm{d}^2\mathbf{q}_1}{\pi} \frac{\mu^2}{\left(\mu^2 + \mathbf{q}_1^2\right)^2} \int \frac{\mathrm{d}^2\mathbf{k}}{\pi} \int \mathrm{d}\Delta z \, \bar{\rho}(\Delta z) \tag{1}$$

$$\times \left[-\frac{2\left\{1 - \cos\left[\left(\omega_1 + \tilde{\omega}_m\right)\Delta z\right]\right\}}{\left(\mathbf{k} - \mathbf{q}_1\right)^2 + \chi} \left[\frac{\left(\mathbf{k} - \mathbf{q}_1\right) \cdot \mathbf{k}}{\mathbf{k}^2 + \chi} - \frac{\left(\mathbf{k} - \mathbf{q}_1\right)^2}{\left(\mathbf{k} - \mathbf{q}_1\right)^2 + \chi} \right] \right.$$
$$+ \frac{1}{2} e^{-\mu_1 \Delta z} \left(\left(\frac{\mathbf{k}}{\mathbf{k}^2 + \chi} \right)^2 \left(1 - \frac{2C_R}{C_A} \right) \left\{ 1 - \cos\left[\left(\omega_0 + \tilde{\omega}_m\right)\Delta z\right] \right\} \right.$$
$$\left.\left. + \frac{\mathbf{k} \cdot \left(\mathbf{k} - \mathbf{q}_1\right)}{\left(\mathbf{k}^2 + \chi\right)\left(\left(\mathbf{k} - \mathbf{q}_1\right)^2 + \chi\right)} \left\{ \cos\left[\left(\omega_0 + \tilde{\omega}_m\right)\Delta z\right] - \cos\left[\left(\omega_0 - \omega_1\right)\Delta z\right] \right\} \right) \right] \tag{2}$$

dGLV corr. ⟶

- Breaking of **color triviality**
  $\Rightarrow$ increased corr. for gluons
- Possibility of **energy gain**
- Nonzero correction for **all path lengths**

Implementation of SPL corr.



Asymptotically:

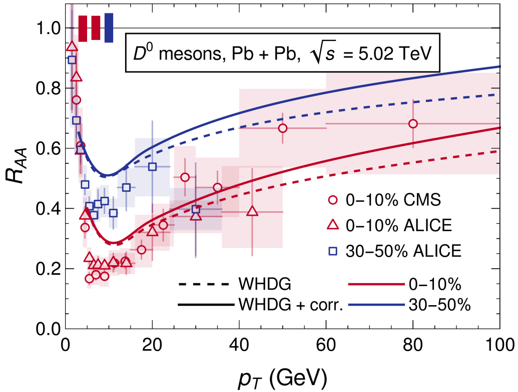
$$\frac{\Delta E_{\mathrm{DGLV}}}{E} \sim C_R\, L^2\, \frac{\log E/\mu}{E}. \tag{3}$$

$$\frac{\Delta E_{\mathrm{SPL}}}{E} \sim -C_R \left(\frac{C_R}{C_A}\right) L\, \log(EL) \tag{4}$$

We see that the SPL correction is

- Nonzero even for $L = 5\ \mathrm{fm}$
- Exceedingly large for gluons
- Dominates at high E
- Leads to energy gain at high E

Heavy flavour A+A



Pb + Pb suppression

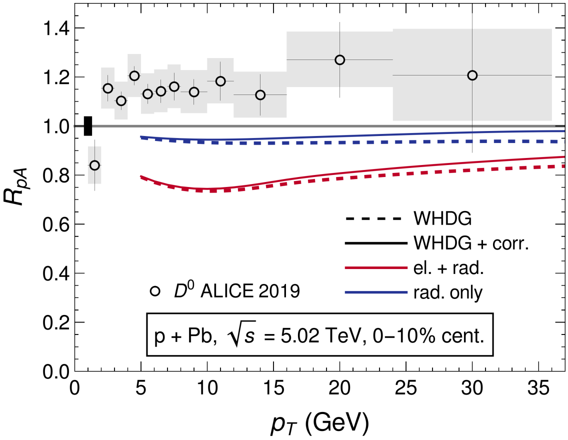
CF, Grindrod, Horowitz 2305.13182

Data: CMS 1708.04962 + ALICE 1804.09083

- Heavy flavour $A + A$ is a good testing ground, as SPL correction is expected to be small
- Correction nonzero since all path lengths are integrated over
- Model parameters could be fit to data; e.g. α_s, τ_0 , $\mathrm{d}N^g/\mathrm{d}y$

Heavy flavour p+A

- Is SPL corr. important for $p + A$?
- Shocking predicted suppression?
  - $\rightarrow$ Only $\mathcal{O}(1)$ scatter in $p + A$
  - $\rightarrow$ Central Limit Theorem (CLT) in el. E-loss breakdown $\Rightarrow$ small system elastic corr. needed

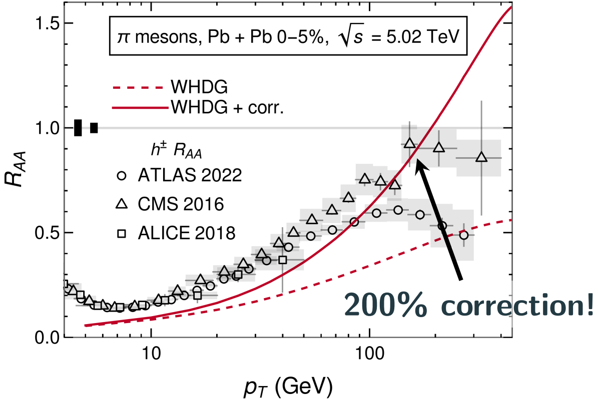


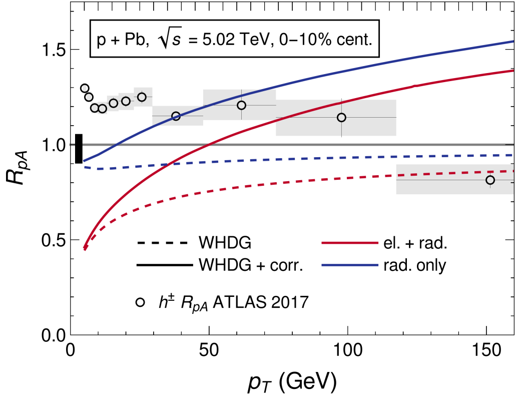
p + Pb suppression

CF, Grindrod, Horowitz 2305.13182

Data: ALICE 1906.03425

Light flavour predictions





- Corrected R_{AA} consistent with data for $p_T \sim \mathcal{O}(10\text{–}100)$ GeV
- 200% "correction" at high-p_T!

- Potentially contributing to $R_{pA}^{h^\pm} > 1$?
- Large suppression, inconsistent with data, for $\mathcal{O}(5\text{–}50)$ GeV pions

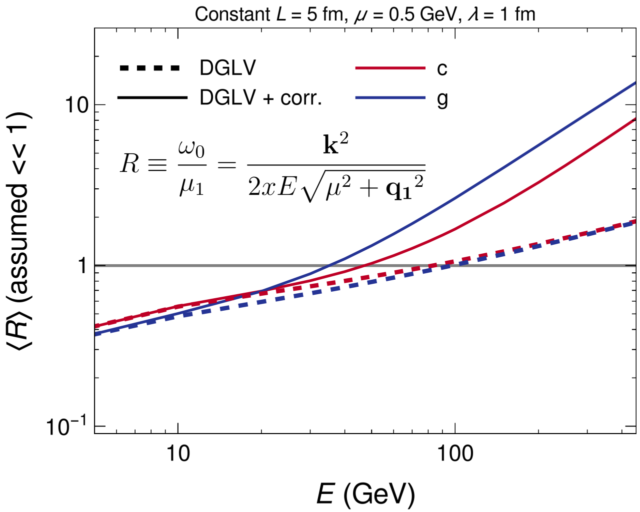
How physical are these results?
Is anything breaking?

Investigating the Model

- (Most) assumptions take form $R \ll 1$
  - $\rightarrow$ **Soft**: $x \ll 1$
  - $\rightarrow$ **Collinear**: $k^- / k^+ \ll 1$
  - $\rightarrow$ **Large pathlength**: $1/\Delta z \, \mu \ll 1$
  - $\rightarrow$ **Large Formation Time**: $\mathbf{k}^2 / 2x \, E \, \mu_1 \ll 1$
- Are assumptions valid where energy loss is greatest?
- Introduce energy loss weighted average

$$\text{Is } \langle R \rangle \equiv \frac{\int \mathrm{d}\{X_i\} \; R(\{X_i\}) \; \left| \frac{\mathrm{d}E}{\mathrm{d}\{X_i\}} \right|}{\int \mathrm{d}\{X_i\} \; \left| \frac{\mathrm{d}E}{\mathrm{d}\{X_i\}} \right|} \ll 1?$$

Consistency of Large Formation Time Assumption



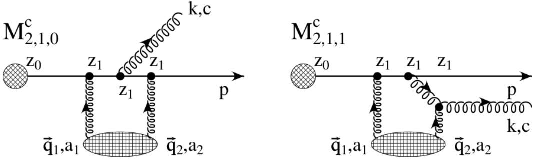
Disaster!

- Large Formation Time assumption **violated** for $E \gtrsim 20$ GeV
- Violated for **both** DGLV and DGLV + SPL corr.

E-weighted expectation of **large path length** assumption

Large Formation Time Assumption: Who cares?

- DGLV **neglects entire class of diagrams** based on large formation time assumption
  $\rightarrow$ and used heavily in simplification of matrix elements

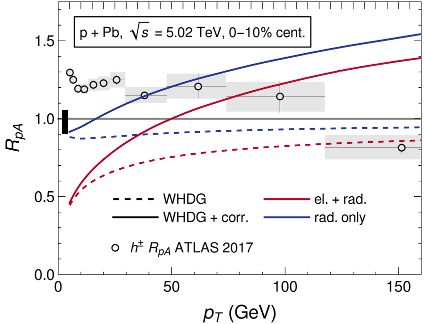


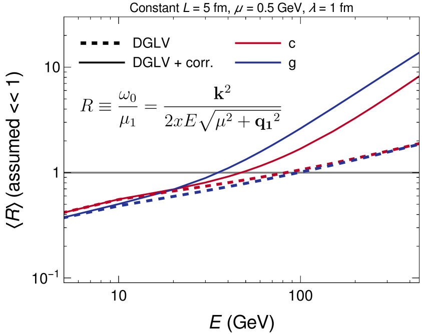
$$\sim \frac{\mathbf{k}_\perp^2 + m_g^2 + x^2 M^2}{2\omega} \frac{1}{\mu_1} \rightarrow 0$$

- SPL corr. **neglects 16/18 new corr. terms** based based on large formation time assumption
- Currently **impossible** to estimate the magnitude of corrections resulting from relaxing the large formation time assumption
- Calculation is **completely uncontrolled for** $p_T \gtrsim 30$ GeV

Summary

- First implementation of SPL corr. in energy loss model
- **Elastic short pathlength corr.** needed for quantitative $p + A$ predictions
- Final state radiation (potentially) affects **enhancement** in $p + A$?





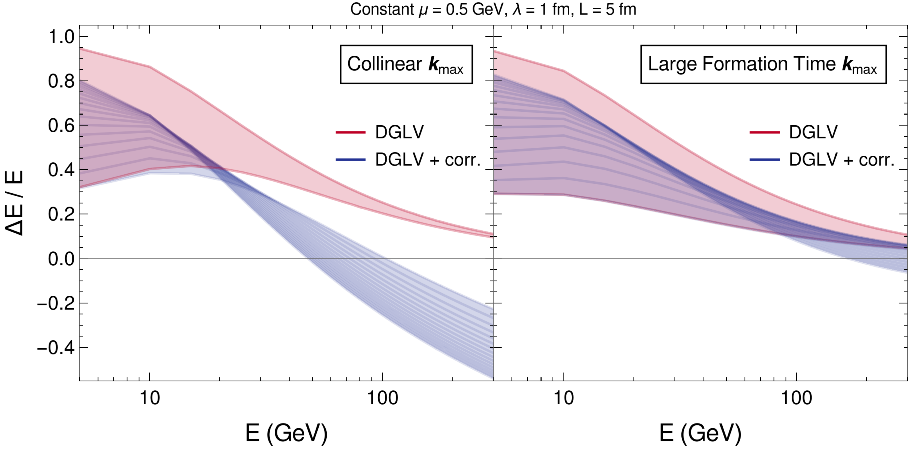
- Large formation time assumption **violated** at high-p_T for DGLV $\Rightarrow$ **short formation time corr. required**

  → Unknown impact in other similar frameworks like Higher Twist and BDMPS-Z?

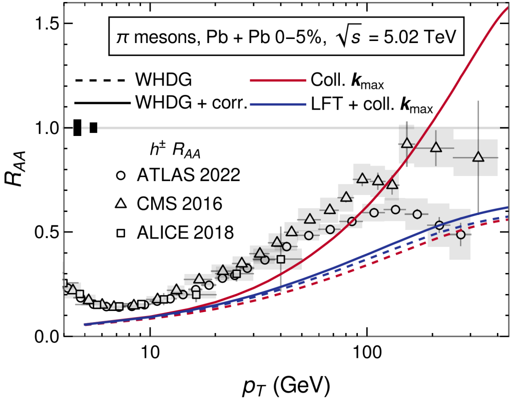
Bonus Slides

LFT Cutoff

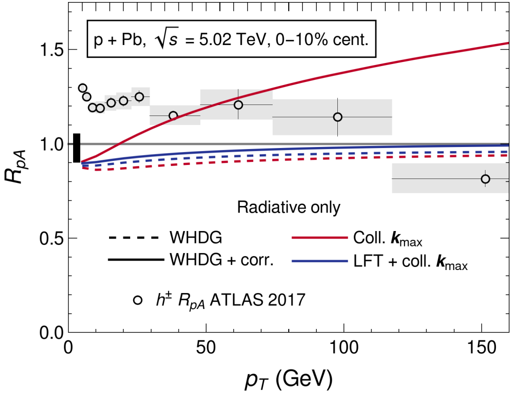
- Collinearity can be enforced via $|\mathbf{k}_\perp|_{\text{max}} = 2xE(1-x)$
- Similarly, collinearity + LFT $\Rightarrow |\mathbf{k}_\perp|_{\text{max}} = \text{Min}[2xE(1-x), \sqrt{2xE\mu_1}]$.



Predictions with LFT cutoff



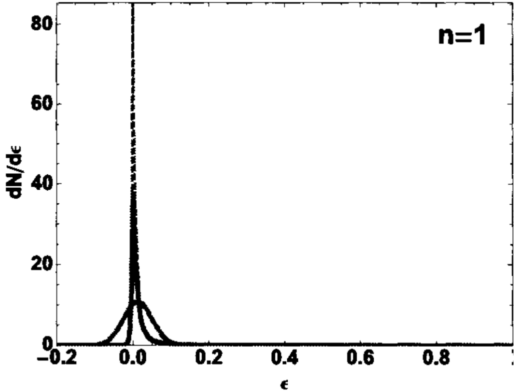
$A + A$

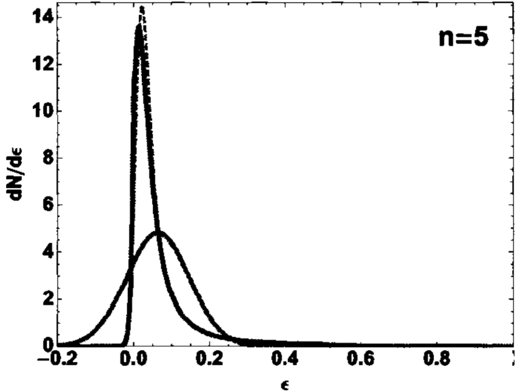


$p + A$

Size of correction dramatically **reduced**!

Elastic E-loss: Central limit theorem





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