Effect of Hadronic Matter on Parton Energy Loss

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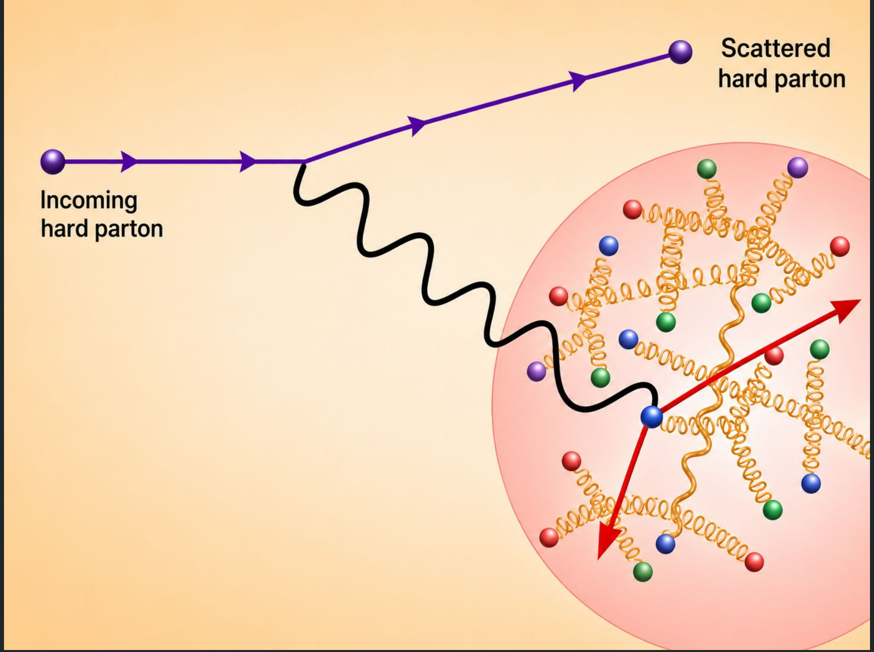
Outline

- Partonic interactions in Hadronic phase
- Nuclear initial-state effects
- Simulation setup
- Results
- Outlook and Summary

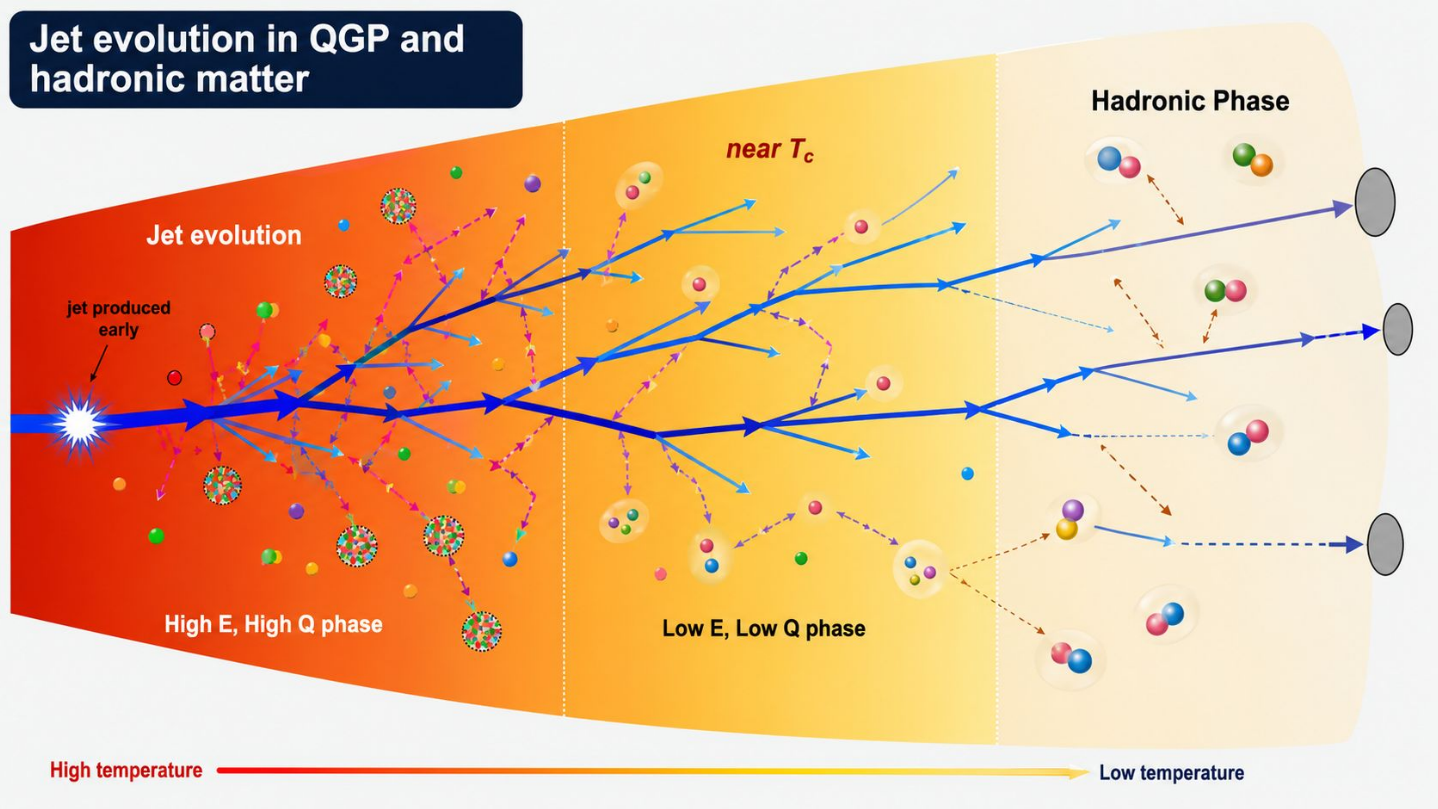
Can hard partons lose energy in hadronic matter?

Should energy loss stop at critical temperature ?

How does this affect $\mathbf{R_{AA}}$, $\mathbf{v_2}$, and **substructure** ?



Can hard partons lose energy in hadronic matter?



Can hard partons lose energy in hadronic matter?

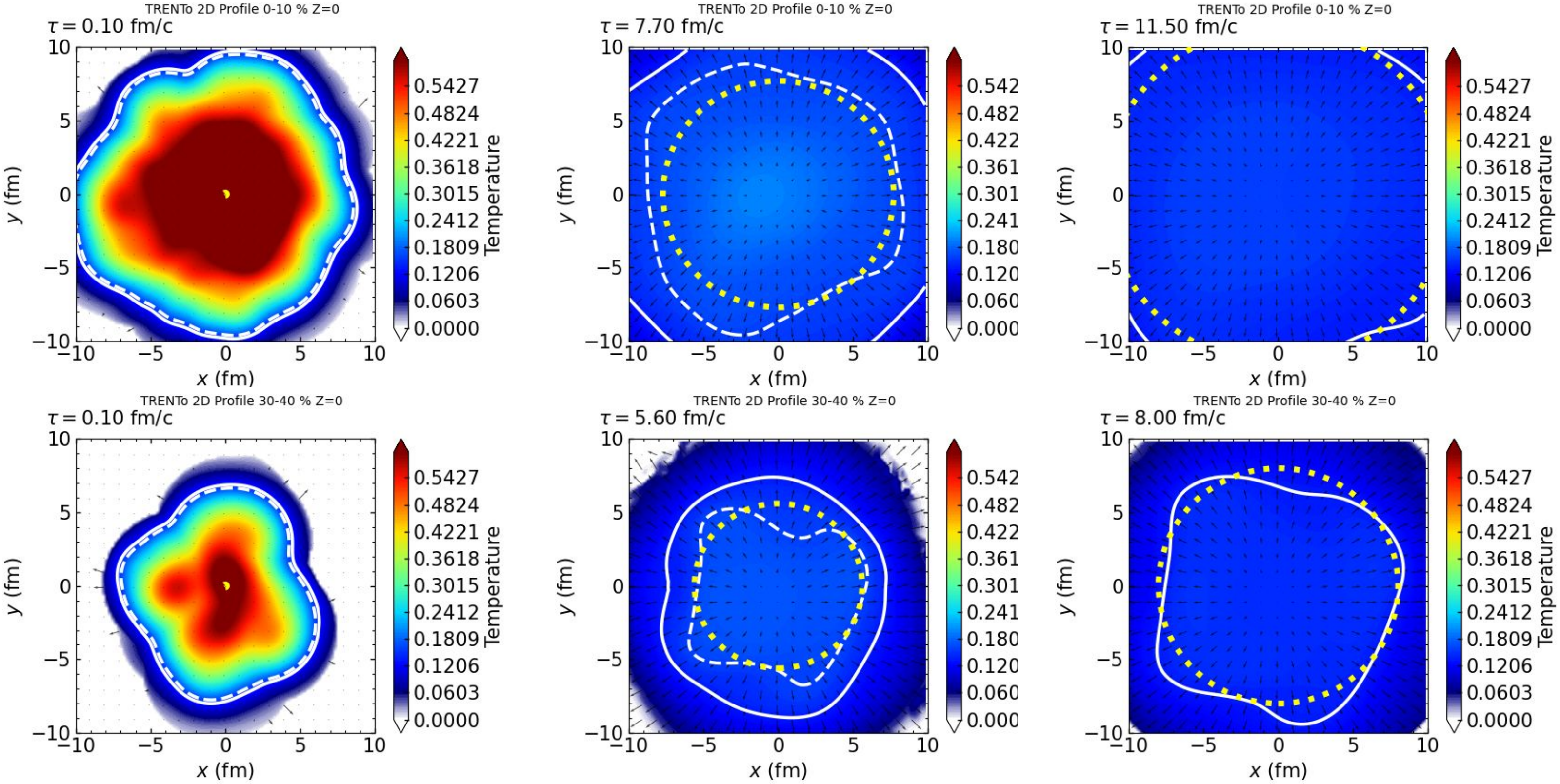
0-10%

T=135 MeV

T=160 MeV

Parton

30-40%



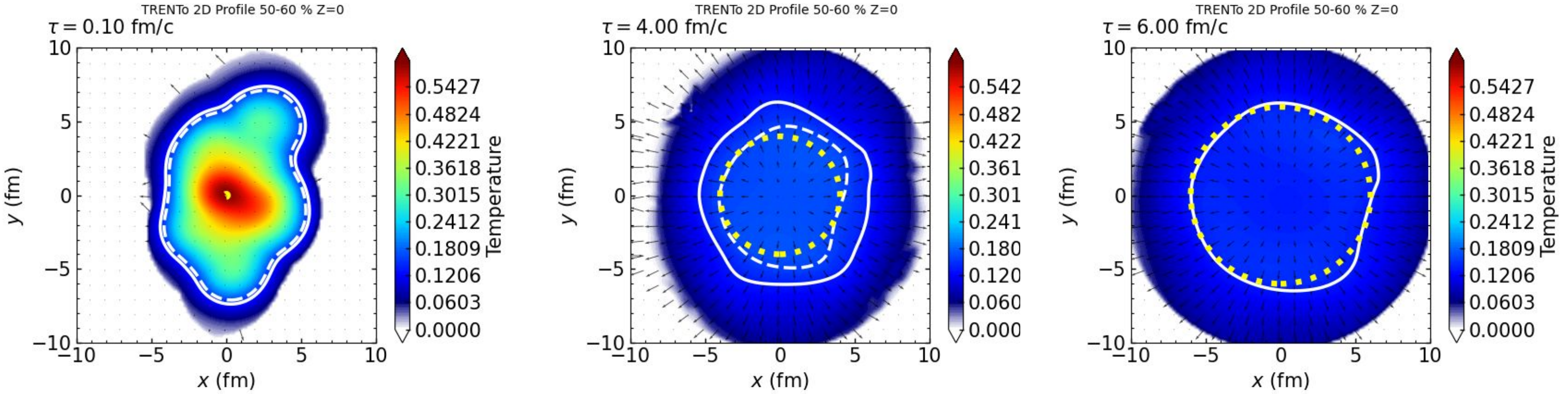
Can hard partons lose energy in hadronic matter?

50-60%

T=135 MeV —

T=160 MeV - - -

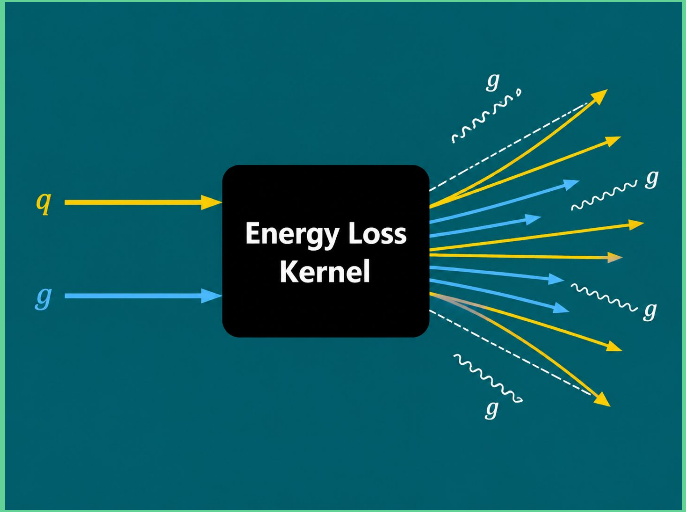
Parton ■ ■ ■



$$F = \frac{t(T = 135MeV) - t(T = 160MeV)}{t(T > 160MeV)}$$

$$F_{0-10\%} < F_{30-40\%} < F_{50-60\%}$$

How do we model the energy loss in Hadronic phase?

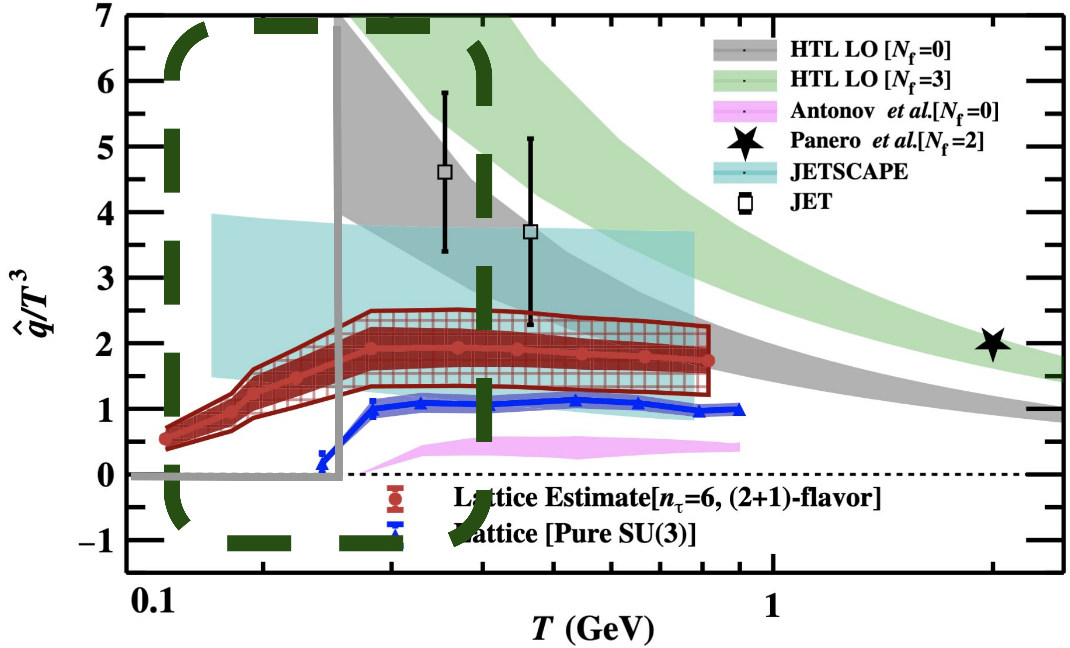


Jet Transport Coefficient

Medium scale governed by the transport coefficient

$$\hat{q} = \frac{1}{N_{event}} \sum_i^{N_{event}} \frac{(k_\perp^i)^2}{L}$$

HTL effective theory is valid in the weak coupling regime.



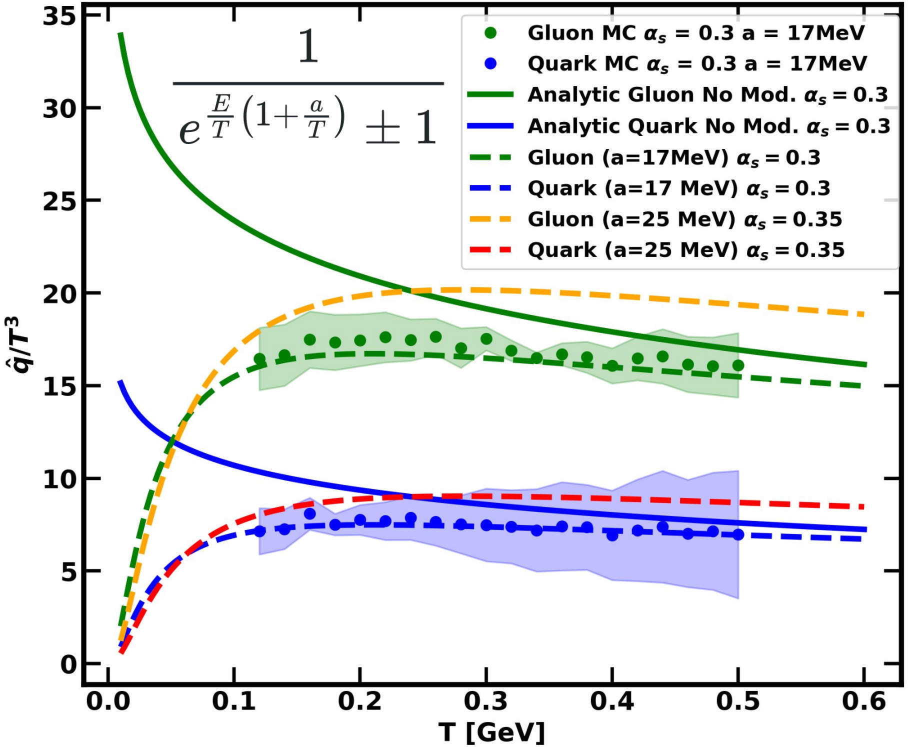
[Kumar, A., ,Majumder, A., and Weber, J. (2022). *PRD*, 106(3), 034505.]

Introduce a modified kernel distribution

- As T →T_c, effective color degrees of freedom decrease.
- Suppressed thermal phase-space density of scattering quasiparticles.

$$n_R(E,T) = \frac{d_s d_N}{\exp\left[\frac{E}{T}F(T)\right] \pm 1}$$

$$F(T) = 1 + \sum_{n=1}^{N} \left(\frac{a_n}{T}\right)^n$$



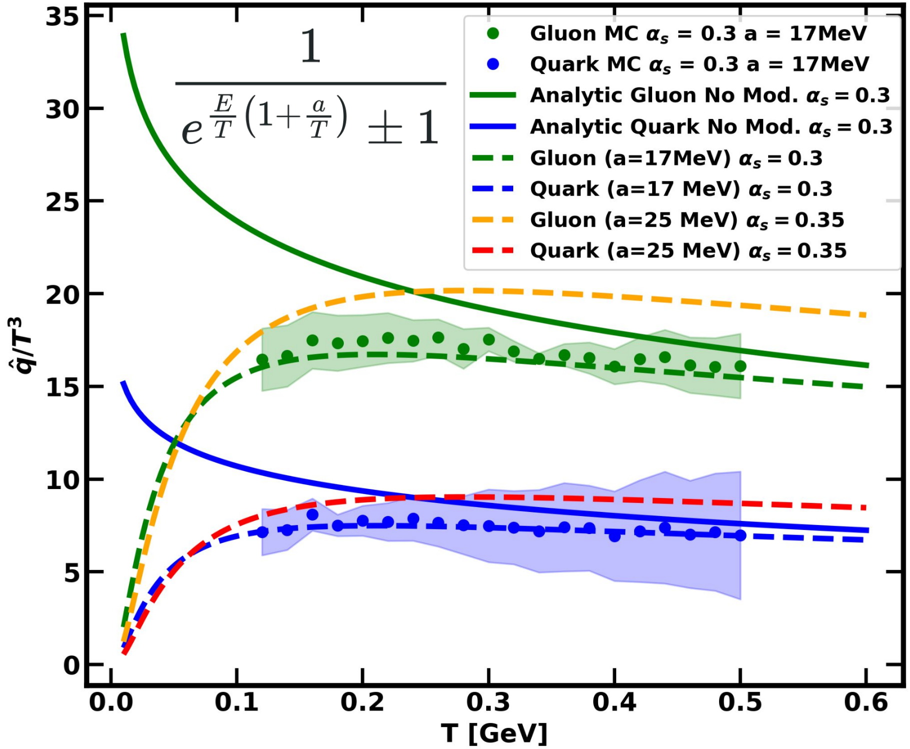
Introduce a modified kernel distribution

$$n_R(E,T) = \frac{d_s d_N}{\exp\left[\frac{E}{T}F(T)\right] \pm 1}$$

$$F(T) = 1 + \sum_{n=1}^{N}\left(\frac{a_n}{T}\right)^n = 1 + \Delta F(T)$$

Interpretations of ΔF(T) :

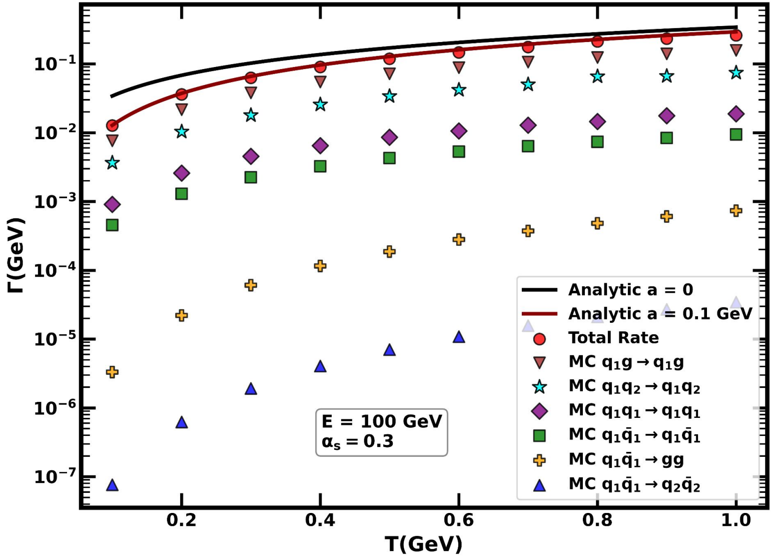
- Change in dispersion relation
- Fugacity

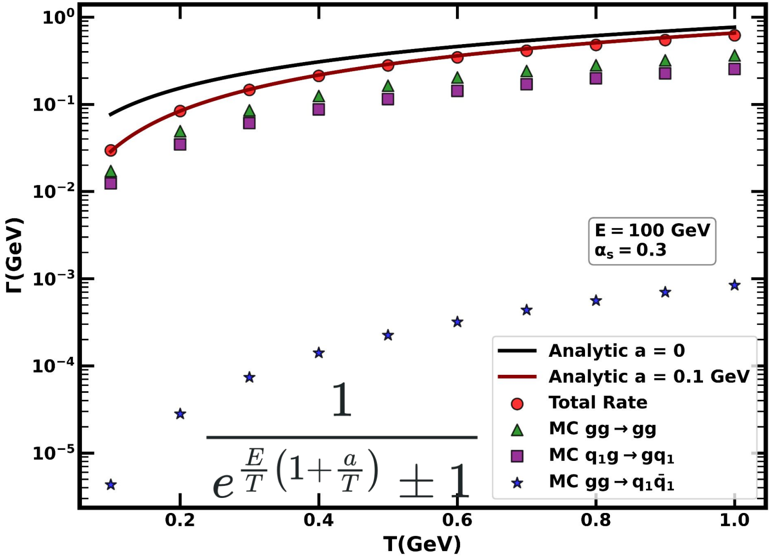


Introduce a modified kernel distribution

$$\Gamma = n \int_0^{s/4} dq_\perp^2 \frac{d\sigma_{el}}{dq_\perp^2}$$

$$\Gamma \to \Gamma_{\text{default}} / F(T)$$





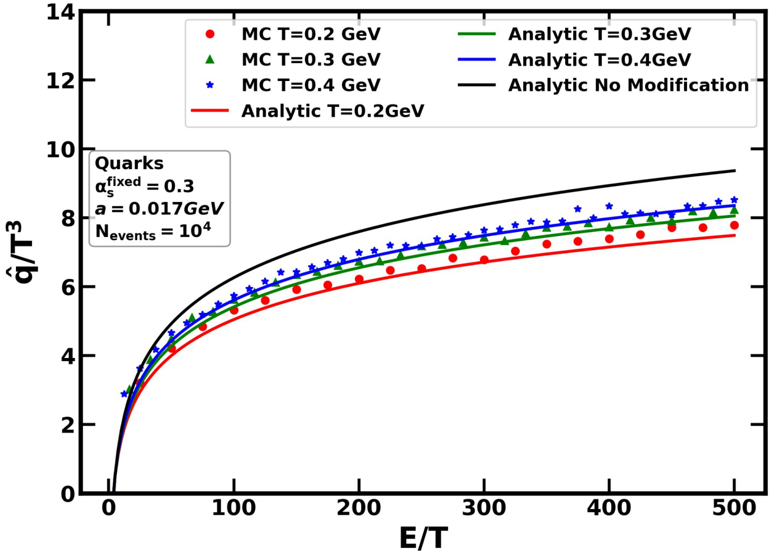
$$\frac{1}{e^{\frac{E}{T}\left(1+\frac{a}{T}\right)} \pm 1}$$

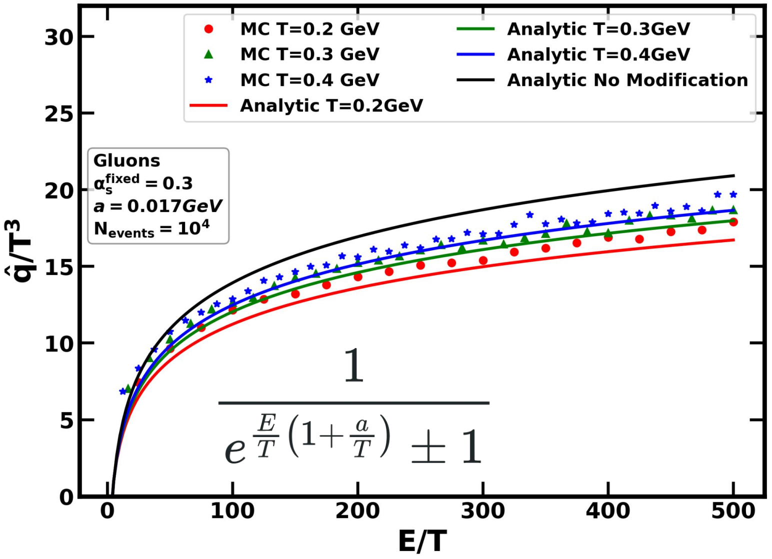
Pow 1
Truc.

Introduce a modified kernel distribution

$$\hat{q} \approx \frac{C_a}{F(T)^3} 42 \frac{\zeta(3)}{\pi} \alpha_s^2 T^3 \ln\left(\frac{s^*}{4F(T)m^2_{D,\text{mod.}}}\right)$$

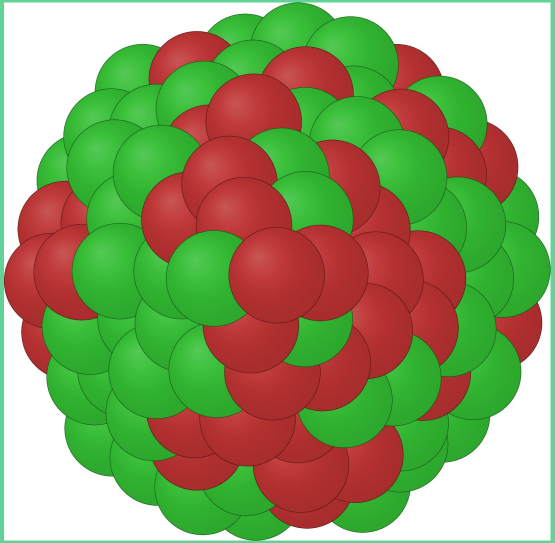
$$m^2_{D_{mod.}} = \frac{g^2T^2}{3}\left(N_c + \frac{N_f}{2}\right)\frac{1}{F(T)^2}$$





$$\frac{1}{e^{\frac{E}{T}\left(1+\frac{a}{T}\right)} \pm 1}$$

Nuclear Initial State Effects



Initial hard production: from PDF to nPDF

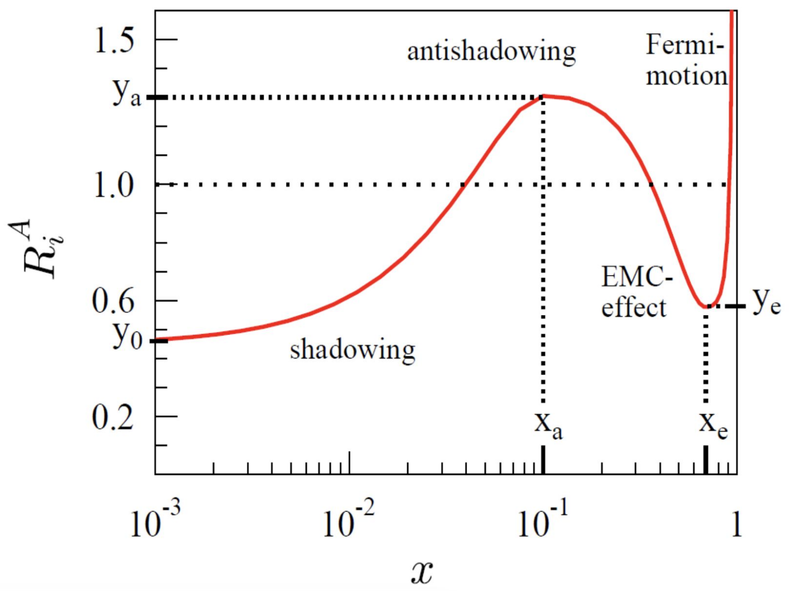
$$d\sigma_{pp\to h/j} \approx f_i^p(x_1,Q^2) f_j^p(x_2,Q^2) \otimes \hat{\sigma_{ij}} \otimes D$$

Then,

$$f_i^A(x,Q^2) = R_i^A(x,Q^2) f_i^p(x,Q^2)$$

proton PDF: $f_i^p(x,Q^2)$

Nuclear PDF: $R_i^A(x,Q^2) \times f_i^p(x,Q^2)$



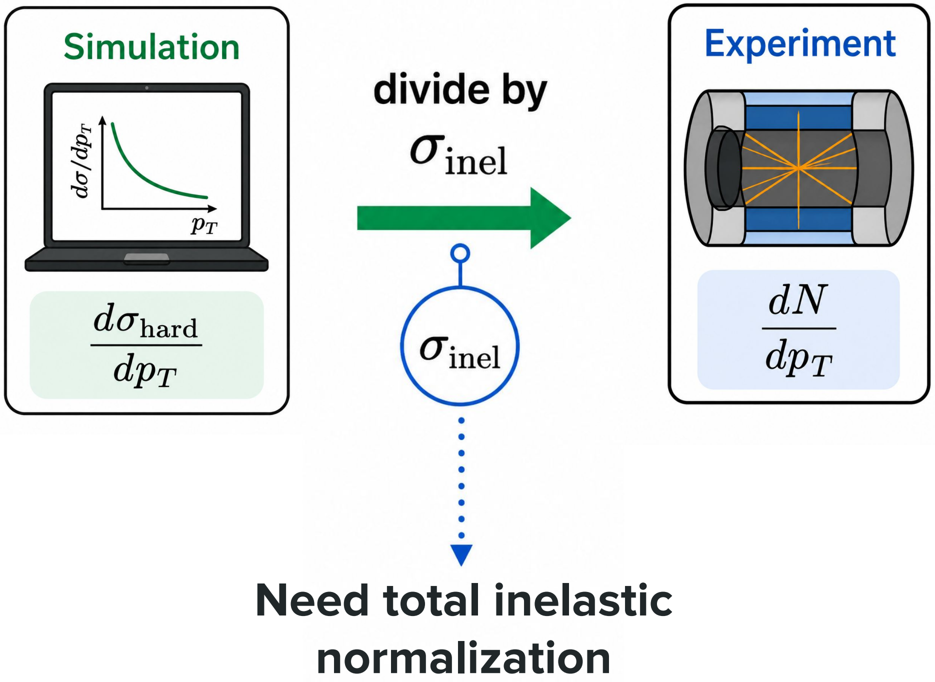
Nuclear Effects : Computing Inelastic Cross-Section

Why do we need $\sigma^{NN}_{\text{inel.}}$?

- Simulation gives: $d\sigma_{\text{hard}}/dp_T$
- Experiments report: dN/dp_T
- Need inelastic normalization :

$$\frac{dN}{dp_T} \sim \frac{1}{\sigma_{\text{inel}}} \frac{d\sigma_{\text{hard}}}{dp_T}$$

- In pp, $\sigma^{pp}_{\text{inel}}$ is known.
- With nPDF effects: effective $\sigma^{NN}_{\text{inel.}}$ is not directly known.



Simulation

$$\frac{d\sigma_{\text{hard}}}{dp_T}$$

divide by σ_{inel}

σ_{inel}

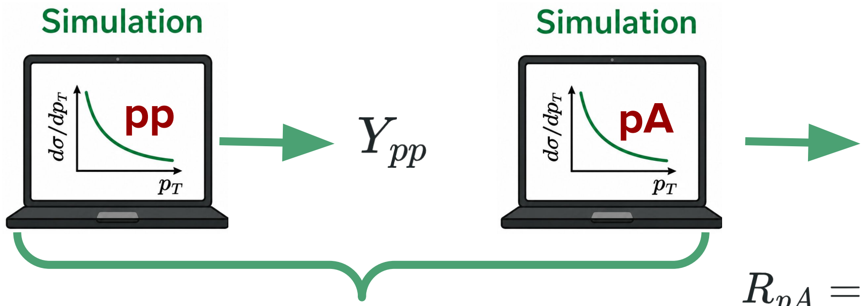
Experiment

$$\frac{dN}{dp_T}$$

Need total inelastic normalization

Nuclear Effects : Leveraging on pA

- pA has minimal final state energy loss.



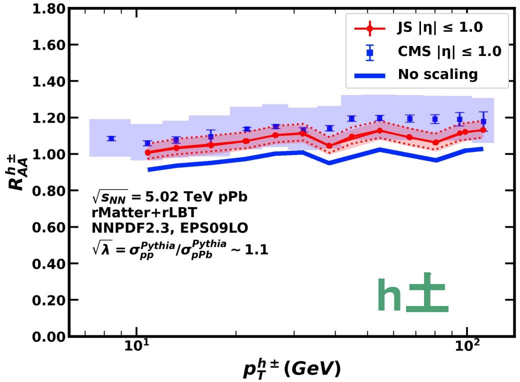
$$Y_{pp}$$

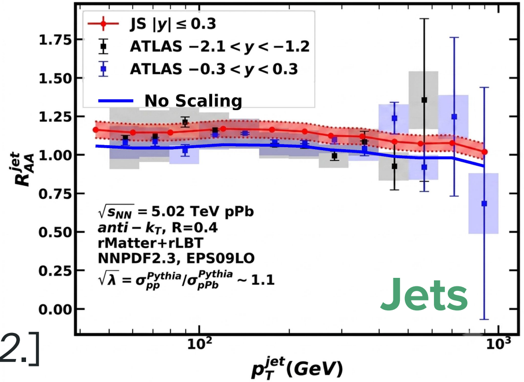
$$\frac{\sqrt{\lambda}}{\sigma^{pp}_{inel.}} \frac{d\sigma_{hard}}{dp_T}$$

$$R_{pA} = \sqrt{\lambda} \frac{d\sigma^{hard}/dp_T|_{pA}}{d\sigma^{hard}/dp_T|_{pp}}$$

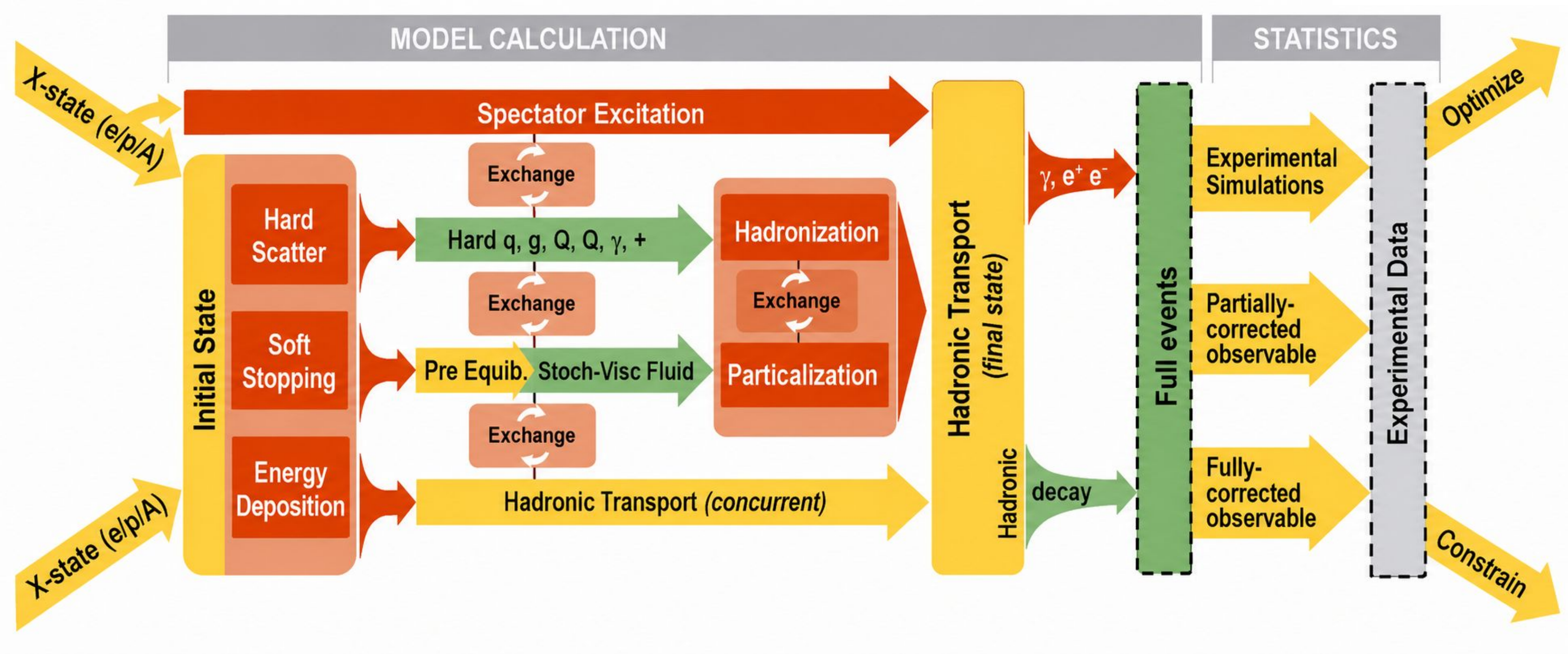
- Fit $\sqrt{\lambda}$ to pA hadron and jet data.
- We found $\sqrt{\lambda} \approx \sigma^{pp}_{\text{Hard}}/\sigma^{eff.pp}_{\text{Hard}}$
- $R_{AA} \approx \lambda \frac{d\sigma^{hard}/dp_T|_{AA}}{d\sigma^{hard}/dp_T|_{pp}}$

[arxiv:2512.23692.]

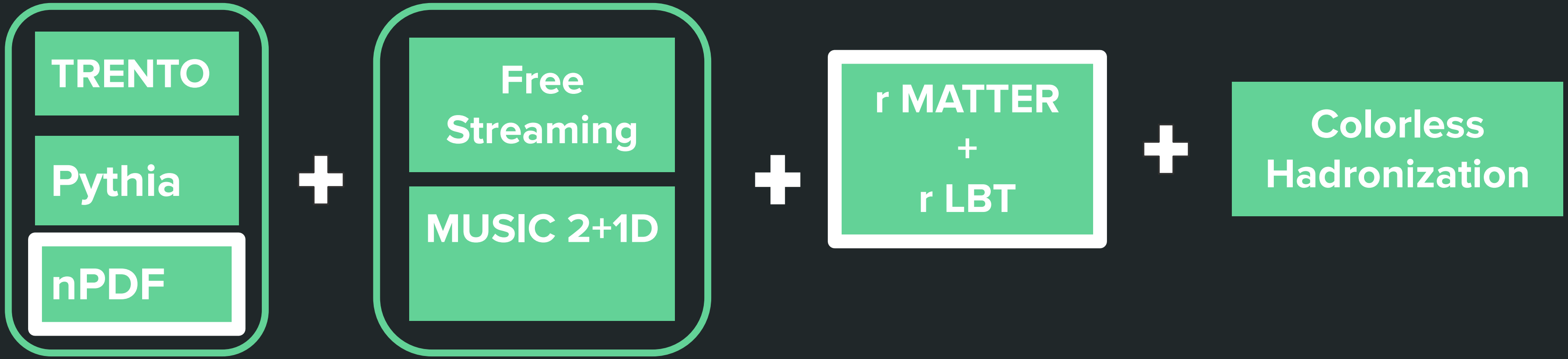




Simulation Setup:



Simulation Setup:



TRENTO

Pythia

nPDF

+

Free Streaming

MUSIC 2+1D

+

r MATTER
+
r LBT

+

Colorless Hadronization

Most hard parameters match the previous JS publication, with only a few exceptions. [PRC 107, 034911 (2023)]

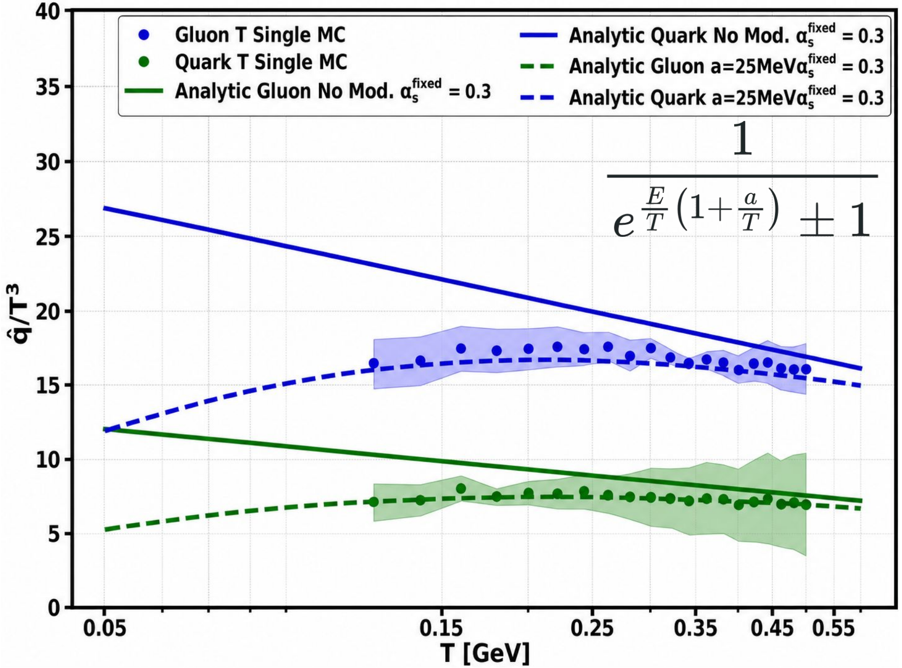
Simulation Setup : New Parameter Set

- Minimal truncation of modified distribution

$$f(E,T) = \frac{1}{exp(E/T(1+a/T)) \pm 1},$$

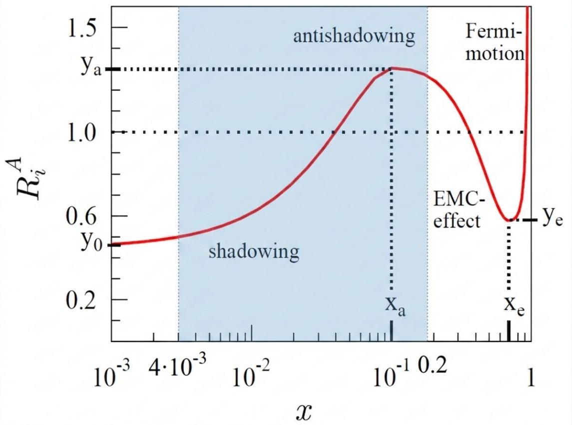
$$a = 25\mathrm{MeV}$$

- Reduces $\hat{q}$ near/below T_c, so need a larger α_s^{fix}.



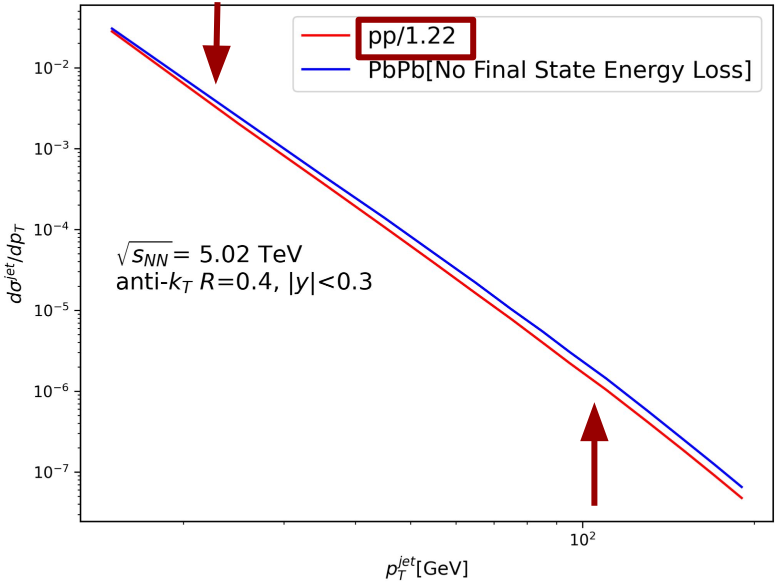
Simulation Setup : New Parameter Set

- At mid-rapidity $x \sim 2p_T/\sqrt{s_{NN}}$



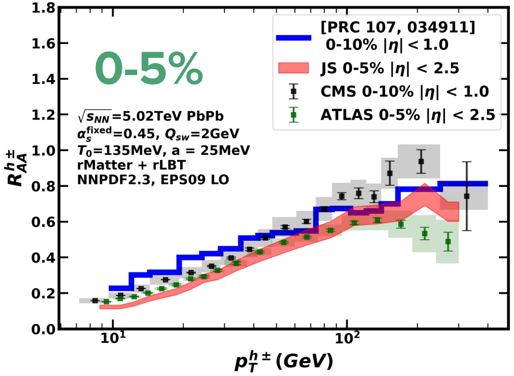
- Shadowing modifies spectrum slope

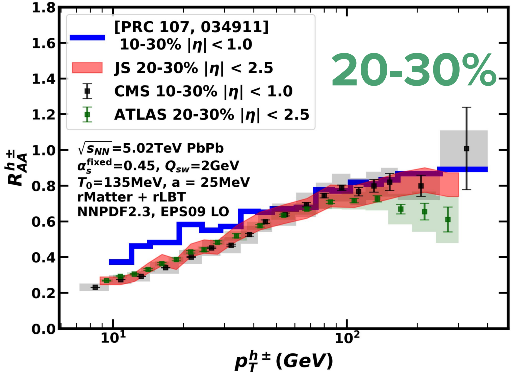
$$\frac{d\sigma}{dp_T} \propto p_T^{-m}, \qquad R_{AA} \sim \left(\frac{p_T}{\Delta p_T + p_T}\right)^m$$

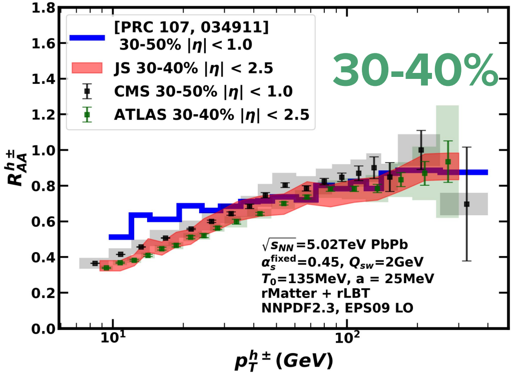


- λ scaling raises the R_{AA}.
- $\alpha_s^{\text{fix}}, \ 0.3 \rightarrow 0.45$

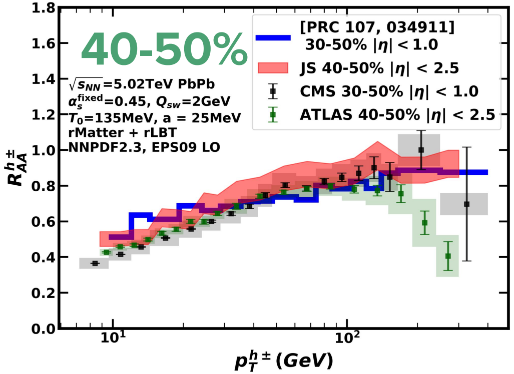
Results: Nuclear Modification (h±)

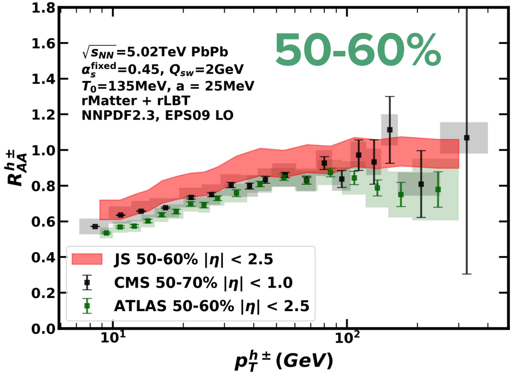






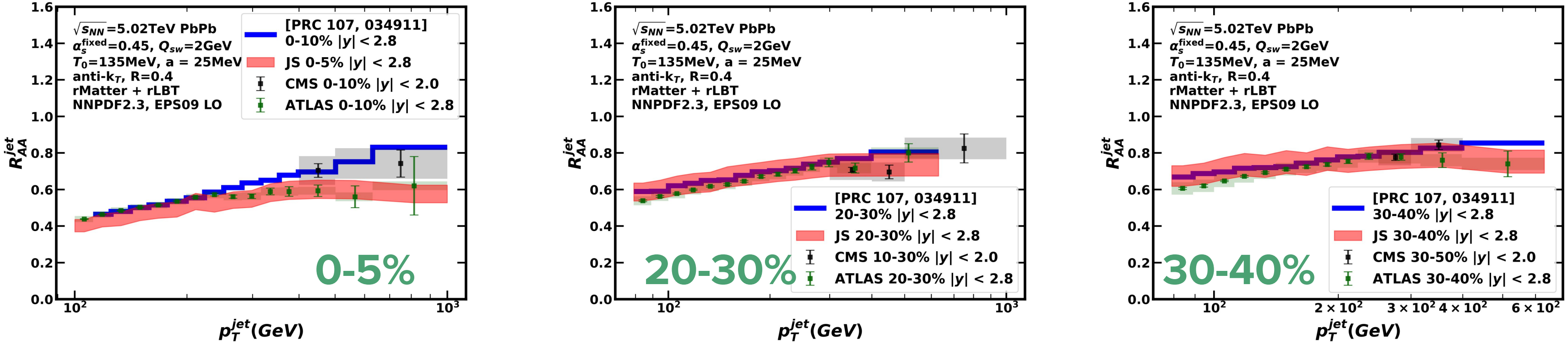
$$\frac{1}{e^{\frac{E}{T}\left(1+\frac{a}{T}\right)} \pm 1}$$



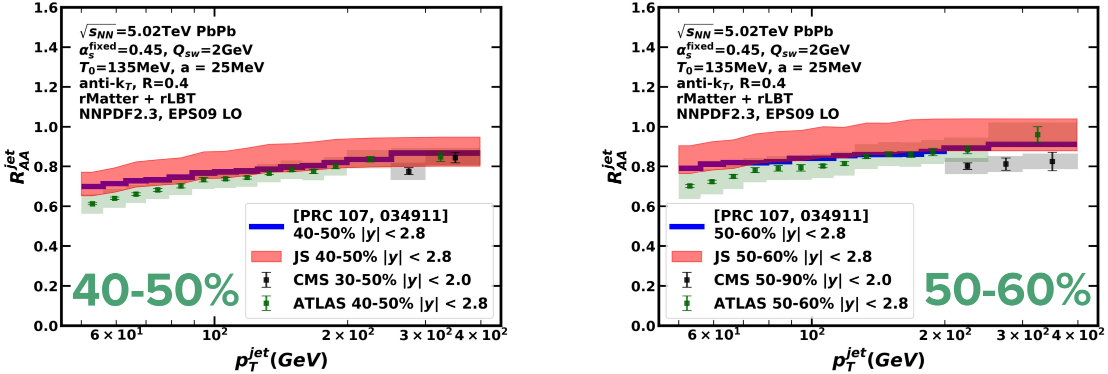


[arxiv:2512.23692.]

Results: Nuclear Modification (Jets)

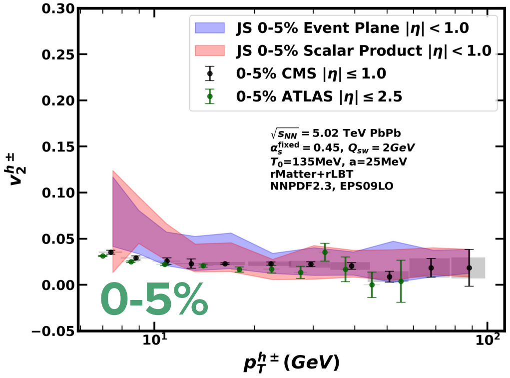


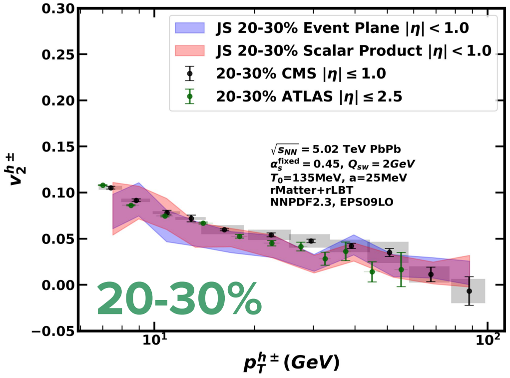
$$\frac{1}{e^{\frac{E}{T}\left(1+\frac{a}{T}\right)}\pm 1}$$

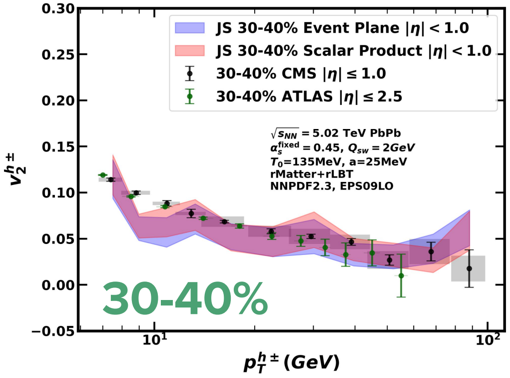


[*arxiv:2512.23692.*]

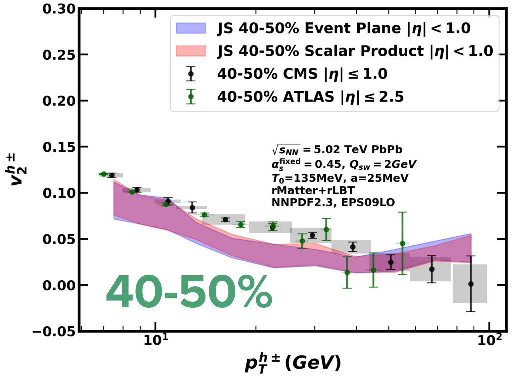
Results: Azimuthal Anisotropy (h±)

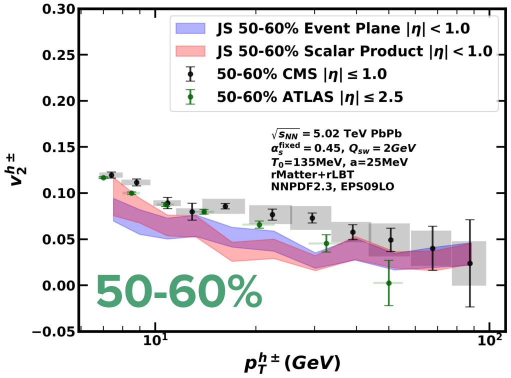






$$\frac{1}{e^{\frac{E}{T}\left(1+\frac{a}{T}\right)}\pm 1}$$





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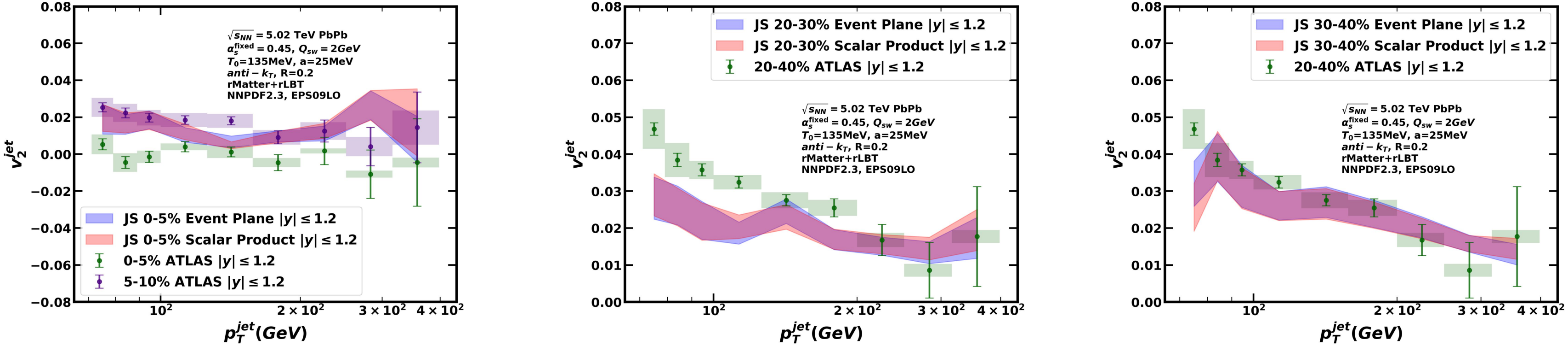
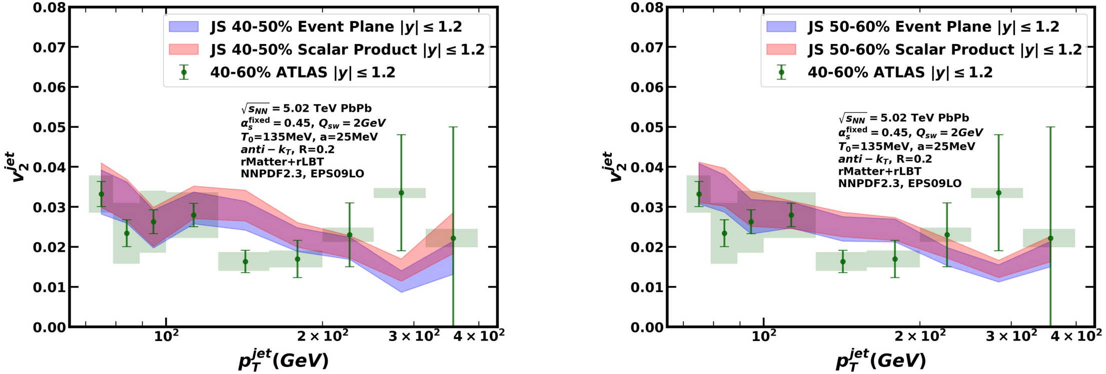
Results: Azimuthal Anisotropy (Jets)

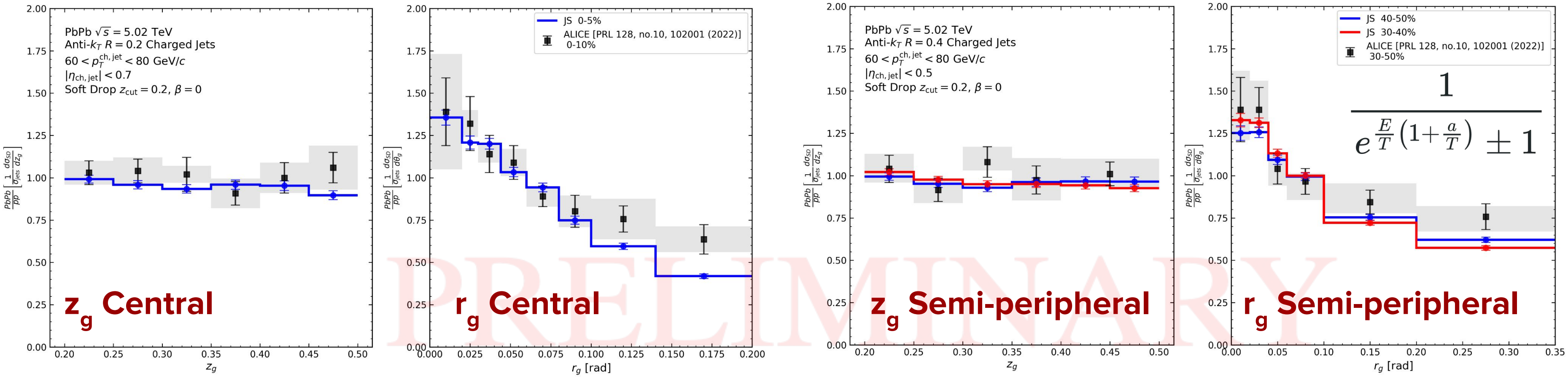


$$\frac{1}{e^{\frac{E}{T}\left(1+\frac{a}{T}\right)} \pm 1}$$

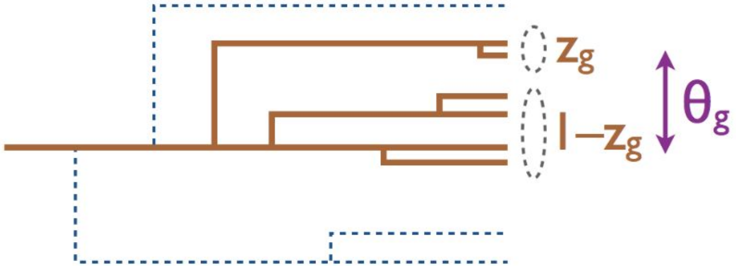


[*arxiv:2512.23692.*]

Results: Jet Substructure



$$\text{Soft Drop Condition :}\quad \overset{z_g}{\boxed{\frac{min(p_{T,1},p_{T,2})}{p_{T,1}+p_{T,2}}}} > z_{cut}\left(\frac{\overset{r_g}{\boxed{\Delta R_{12}}}}{R}\right)^{\beta}$$

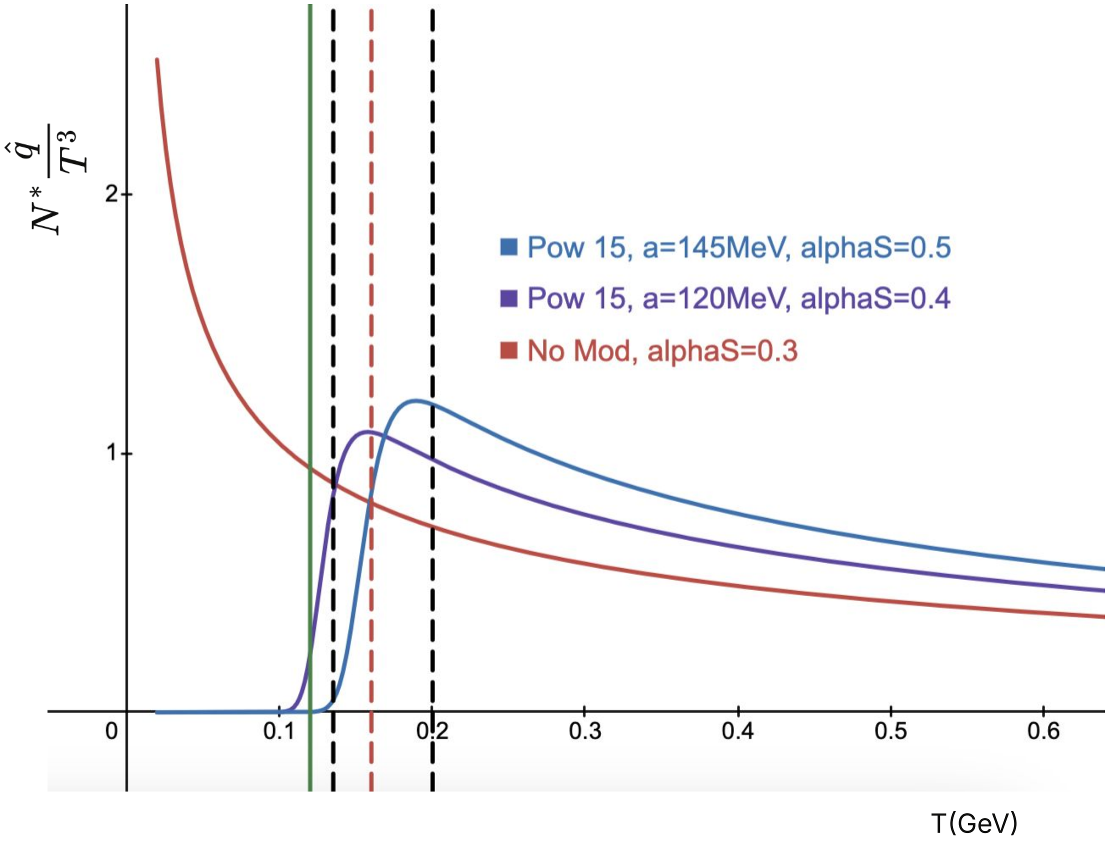


Summary and Outlook

- Modified Kernel to extend the transport coefficients at low T.
- Incorporation of partonic interactions in the hadronic phase.
- Initial-state effects drive the v_2 trend; extended path length improves agreement.
- Framework tested against R_{AA}, v_2, z_g, r_g.
- Apply to small systems.
- Constrain the fugacity factor.
- Bayesian extraction for higher-order F(T).

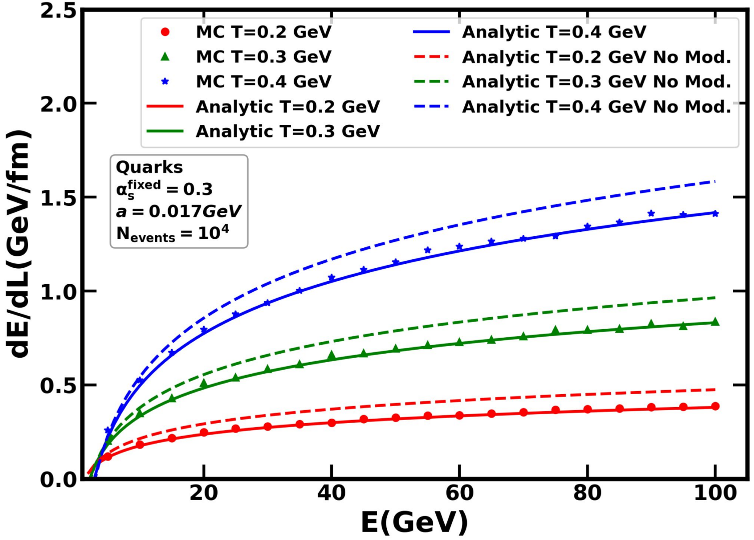
Backup

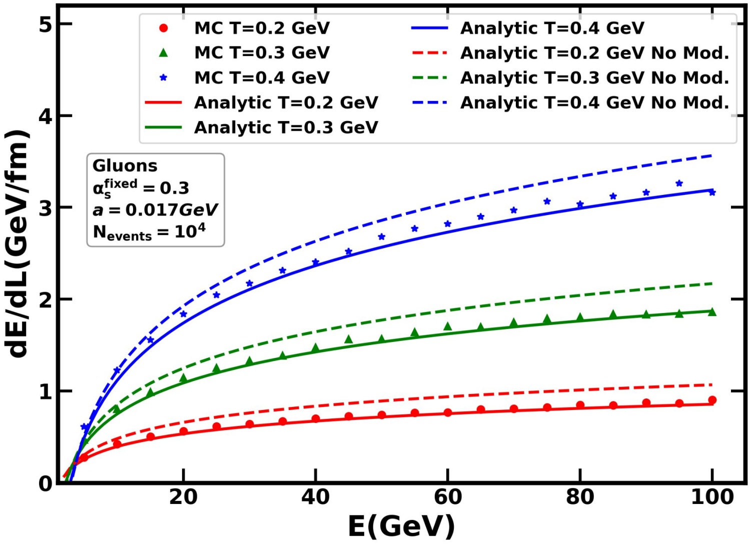
Jet Transport Coeff. vs T



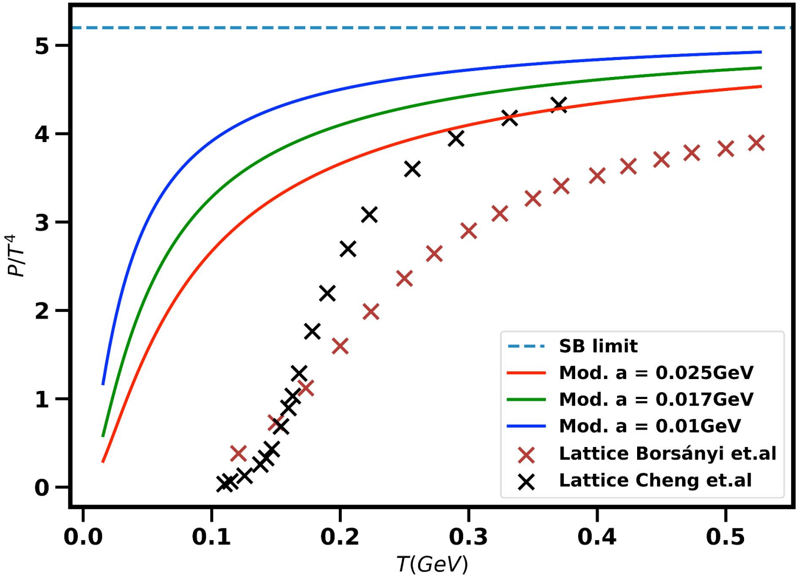
Introduce a modified kernel distribution

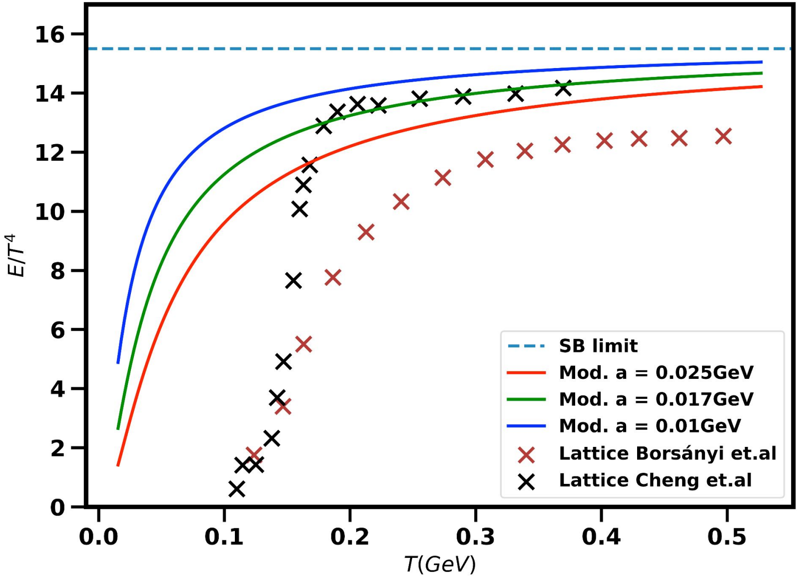
$$\frac{dE^a_{\mathrm{el}}}{d\lambda} \approx \frac{C_a}{F(T)^3}\frac{3\pi}{2}\alpha_s^2 T^2 \ln\left(\frac{s*}{4F(T)m^2_{D_{mod.}}}\right) \quad m^2_{D_{mod.}} = \frac{g^2T^2}{3}\left(N_c + \frac{N_f}{2}\right)\frac{1}{F(T)^2}$$





EOS - Fugacity Picture

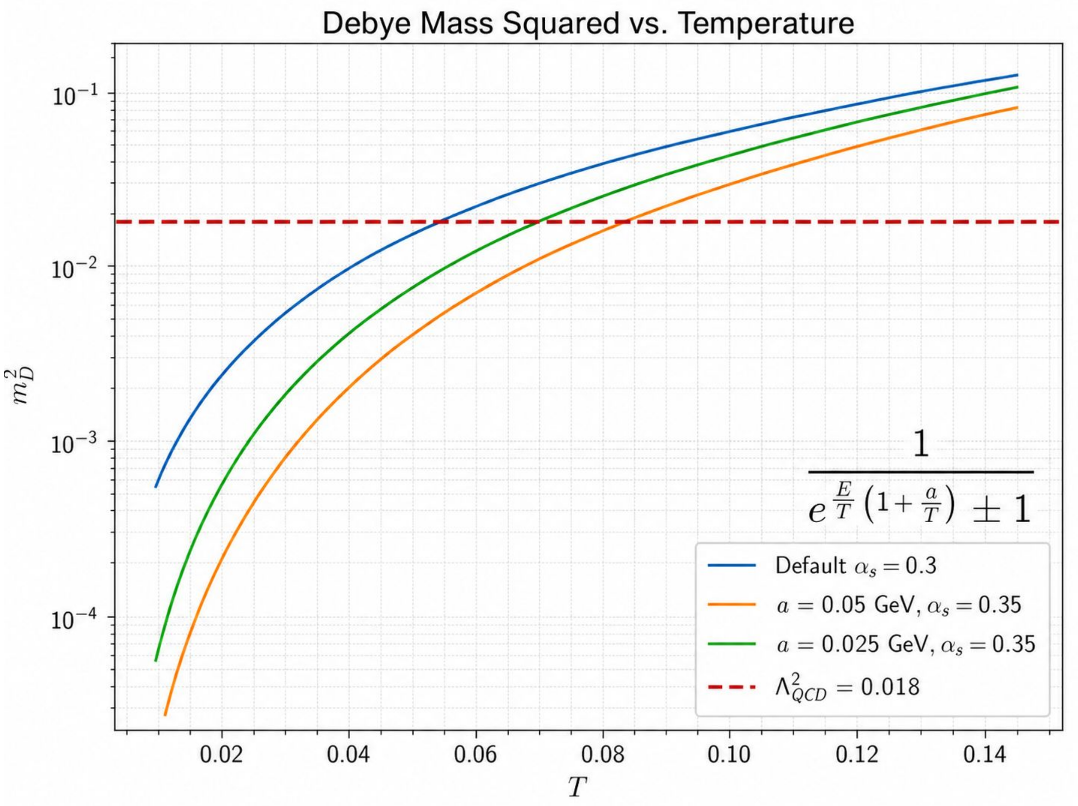




$$\tilde{n}^{q,g}(\vec{p},T) = \frac{1}{z_{q,g}^{-1}(T)\, e^{E_p/T} \pm 1}$$

$$z_{q,g}(T) = exp(-aE_p/T^2)$$

Screening Mass

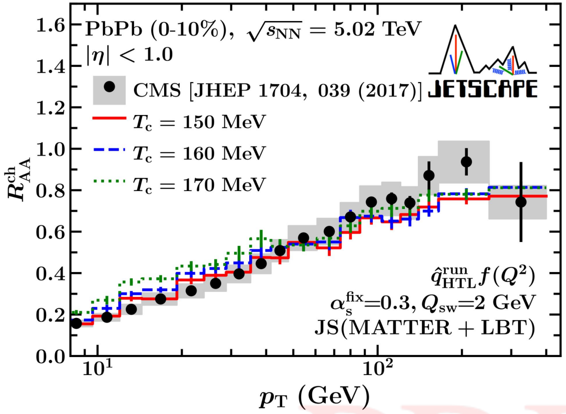


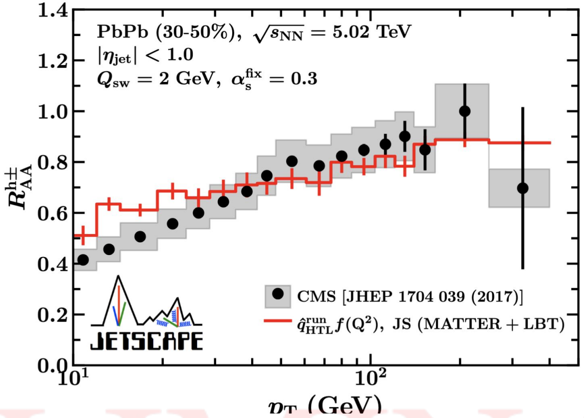
Debye Mass Squared vs. Temperature

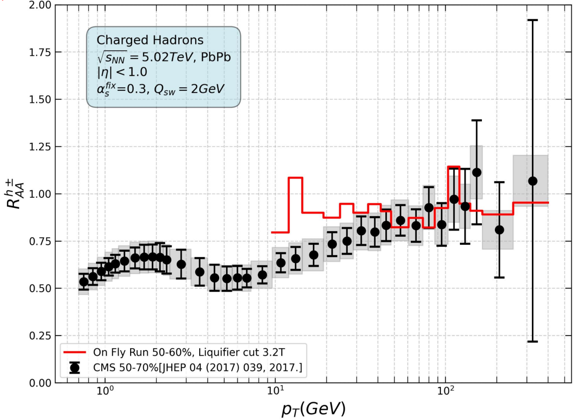
$$\frac{1}{e^{\frac{E}{T}\left(1+\frac{a}{T}\right)} \pm 1}$$

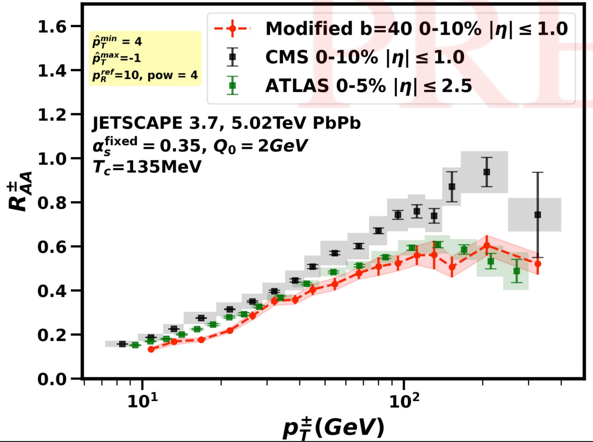
No Nuclear Effects (h±)

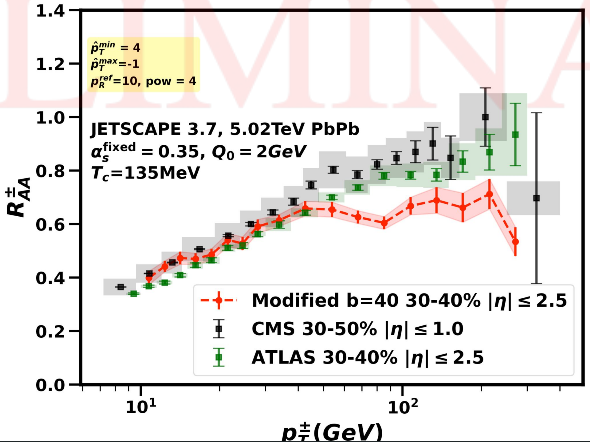
[Kumar, A., et al. (2023) *Phys. Rev. C*, *107*(3), 034911]

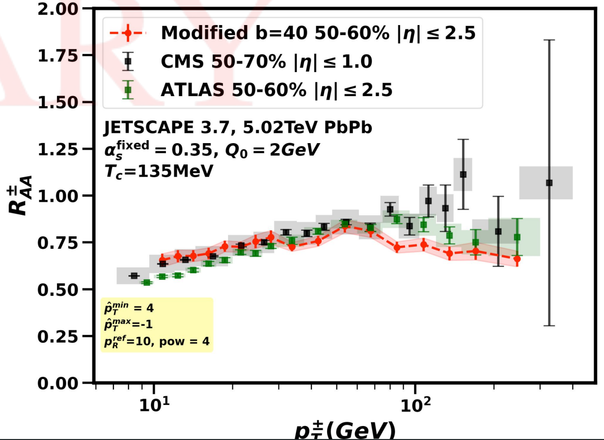






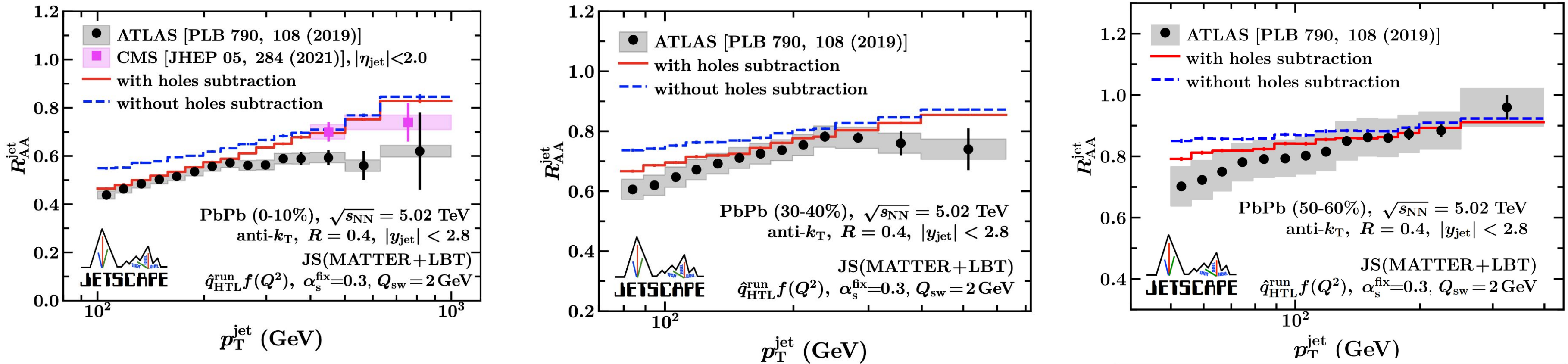


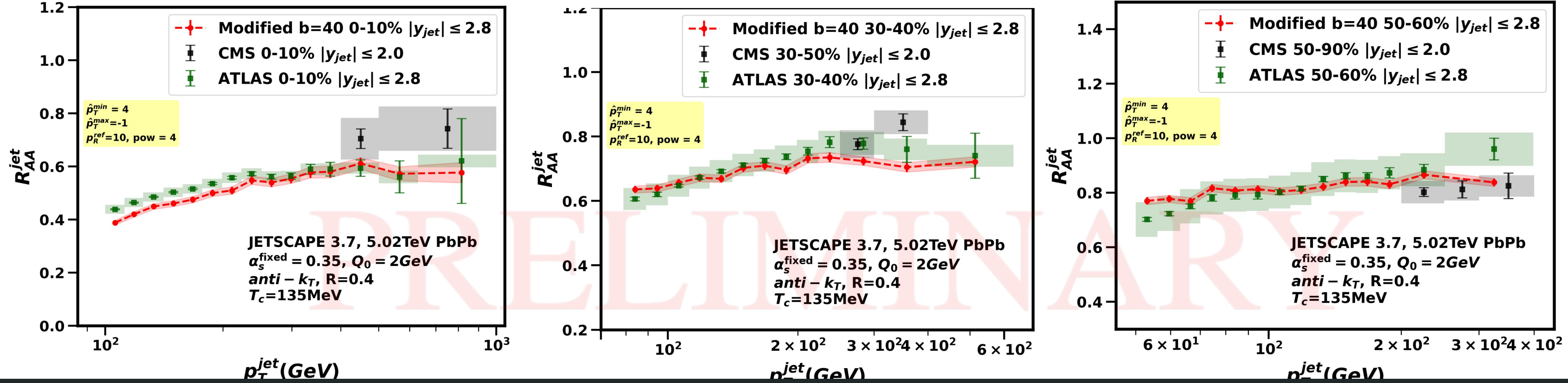




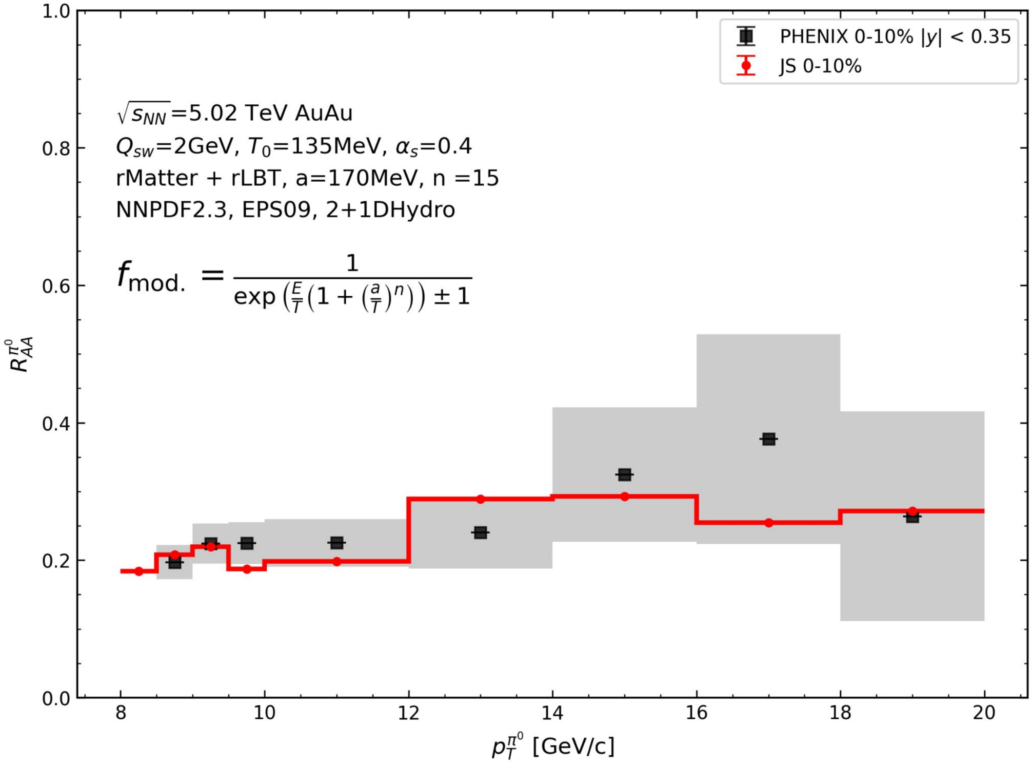
No Nuclear Effect (Jet)

[Kumar, A., et al. (2023) *Phys. Rev. C*, *107*(3), 034911]

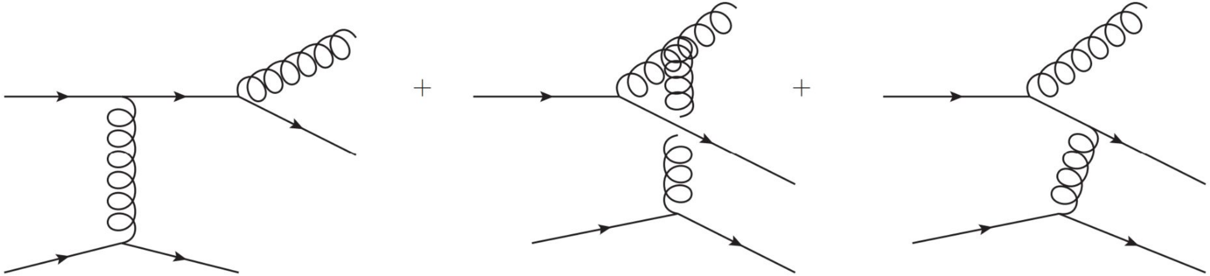




AuAu 200 GeV 0-10%



Evolution Equations



- Medium-induced gluon radiation:

$$\langle N_g^a \rangle = \Delta t \int dx dk_\perp^2 \frac{dN_g^a}{dx dk_\perp^2 dt}$$

- The gluon radiation spectrum from Higher-Twist

$$\frac{dN_g^a}{dx dk_\perp^2 dt} = \frac{2\alpha_s C_A \hat{q}_a P_a(x) k_\perp^4}{\pi(k_\perp^2 + x^2 m^2)^4} \sin^2\left(\frac{t - t_i}{2\tau_f}\right)$$

$$\tau_f = \frac{2Ex(1-x)}{k_\perp^2 + x^2 M^2}$$

- Multiple gluon radiation during each time step is allowed:

$$P(n) = \frac{\langle N_g \rangle^n}{n!} e^{-\langle N_g \rangle}$$

- Probability of gluon radiation

$$P_{inel} = 1 - e^{-\langle N_g \rangle}$$

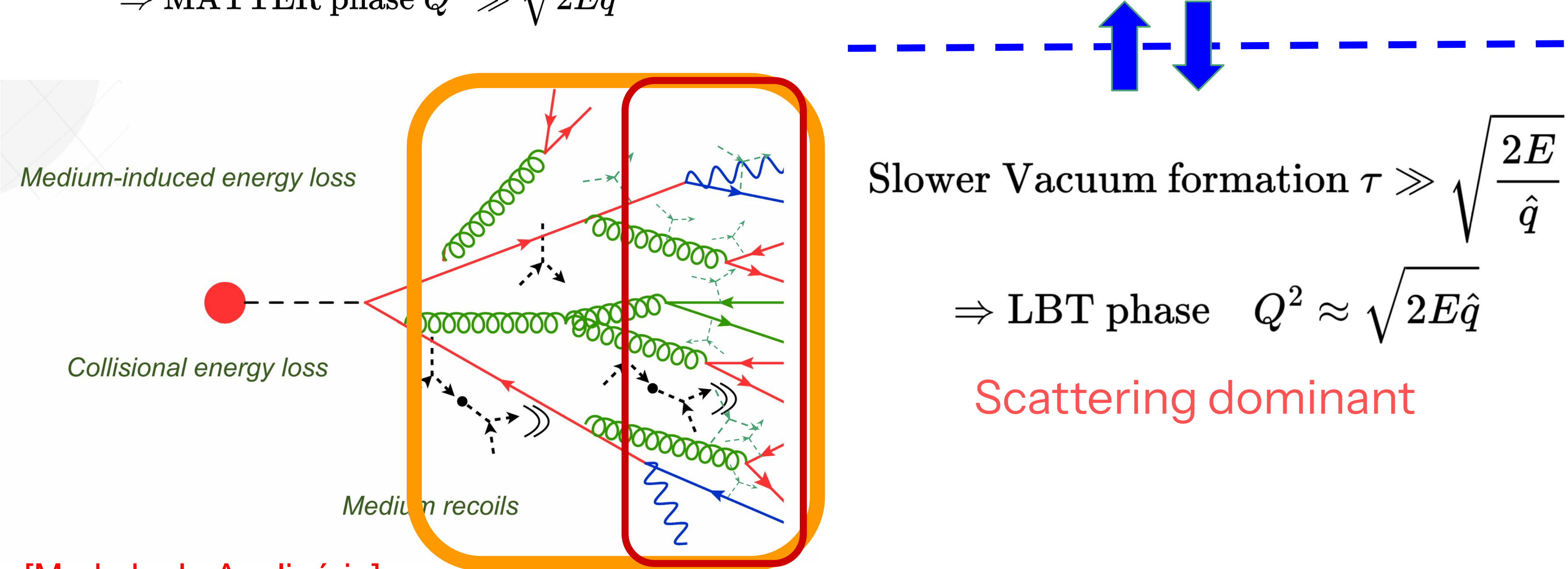
$$\boxed{\begin{gathered} p^\mu d_\mu f_a(x,p) = EC_{inel+el} \\ P_{\text{tot}}^a = P_{\text{el}}^a(1 - P_{\text{inel}}^a) + P_{\text{inel}}^a \end{gathered}}$$

Jet transport coefficient

$$\text{Faster Vacuum formation } \tau \ll \sqrt{\frac{2E}{\hat{q}}}$$

$$\Rightarrow \text{MATTER phase } Q^2 \gg \sqrt{2E\hat{q}}$$

Splitting dominated



$$\text{Slower Vacuum formation } \tau \gg \sqrt{\frac{2E}{\hat{q}}}$$

$$\Rightarrow \text{LBT phase} \quad Q^2 \approx \sqrt{2E\hat{q}}$$

Scattering dominant

[Made by L. Apolinário]

Evolution Equations

$$p_1^\mu \partial_\mu f_a(p_1) = -\int \frac{d^3p_2}{2E_2(2\pi)^3}\int \frac{d^3p_3}{2E_3(2\pi)^3}\int \frac{d^3p_4}{2E_4(2\pi)^3}\sum_{b(c,d)}\frac{g_b}{2}\Big[\underbrace{\boxed{f_a(p_1)f_b(p_2)}}_{\text{Loss}}-\overbrace{\boxed{f_c(p_3)f_d(p_4)}}^{\text{Gain}}\Big]$$

$$\times\,|M_{ab\to cd}|^2(2\pi)^4\delta^4(p_1+p_2-p_3-p_4). \tag{3.5}$$

Considering the scattering particle in a spatially homogeneous system

$$\Gamma_a = \frac{1}{f_a}\frac{\partial f_a}{\partial t} = \frac{C^{\text{loss}}(f_a, f_b)}{f_a(p_1)E_1},$$

Scattering Rate

$$\Gamma_{ab\to cd} = \frac{1}{E_1}\int \frac{d^3p_2}{(2\pi)^3 2E_2}\int \frac{d^3p_3}{(2\pi)^3 2E_3}\int \frac{d^3p_4}{(2\pi)^3 2E_4}\frac{g_b}{2}f_b(p_2)|\mathcal{M}_{ab\to cd}|^2$$

$$S_2(s,t,u)(2\pi)^4\delta^4(p_1+p_2-p_3-p_4)$$

Evolution Equations

$$\text{Screening Mass} = g^2 N_C \int \frac{d^3p}{(2\pi)^3} \frac{f(p)}{p}$$

$$\frac{d\sigma_{ab}}{q_\perp^2} \sim C_{ab} \frac{2\pi\alpha_s^2}{q_\perp^4} \text{ Small Angle Limit}$$

$$< f(q_\perp) >= \frac{1}{\sigma_{el}} \int_{\mu_D^2}^{s/4} dq_\perp^2 \frac{d\sigma_{ab}}{dq_\perp^2} f(q_\perp)$$

$$\Gamma = n_a \int_{\mu_D^2}^{s/4} dq_\perp^2 \frac{d\sigma_{ab}}{dq_\perp^2}$$

$$f_{eq}^g = \frac{z_g \exp(-\beta p)}{\Big(1 - z_g \exp(-\beta p)\Big)},$$

$$f_{eq}^q = \frac{z_q \exp(-\beta p)}{\Big(1 + z_q \exp(-\beta p)\Big)},$$

$$\ln(Z_g) = -\nu_g V \int \frac{d^3p}{8\pi^3} \ln(1 - z_g \exp(-\beta p))$$

$$\ln(Z_q) = \nu_q V \int \frac{d^3p}{8\pi^3} \ln(1 + z_q \exp(-\beta p))$$