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In-Medium Branching Processes, their Features, and Applications to the EIC

CIPANP – 14th edition
29 August - 4 September 2022

Lake Buena Vista, FL

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Outline

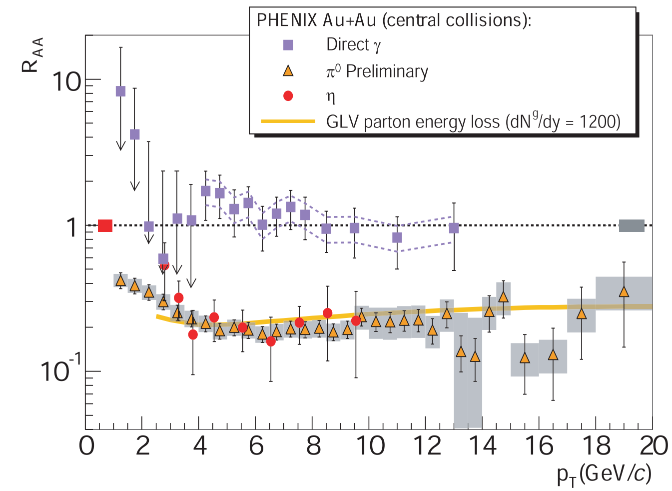
This work is supported by the TMD topical collaboration and the LANL LDRD program

- Introduction and motivation
- Why are vacuum and in-medium splitting functions different
- Calculation of all in-medium splitting functions / numerical evaluation and features
- Implementation in higher order and resumed calculations
- Existing approximate implementations in MC
- Conclusions

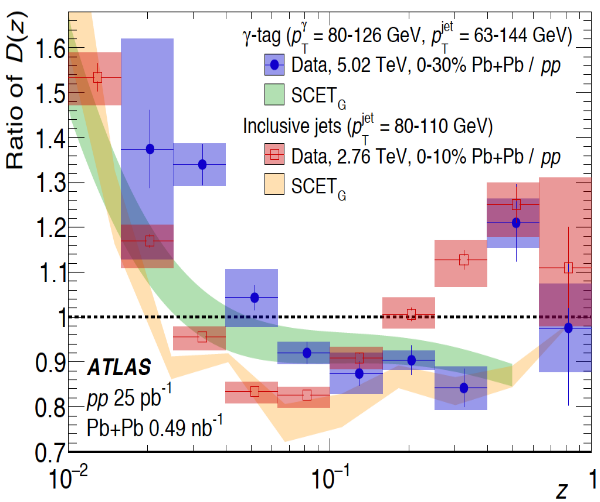
Introduction & Motivation

- In reactions with nuclei in-medium parton showers are the cornerstone of the physics of hard probes – high p_T hadrons, jets, heavy flavor
- The associated phenomena were dubbed jet quenching and established in a myriad of observables

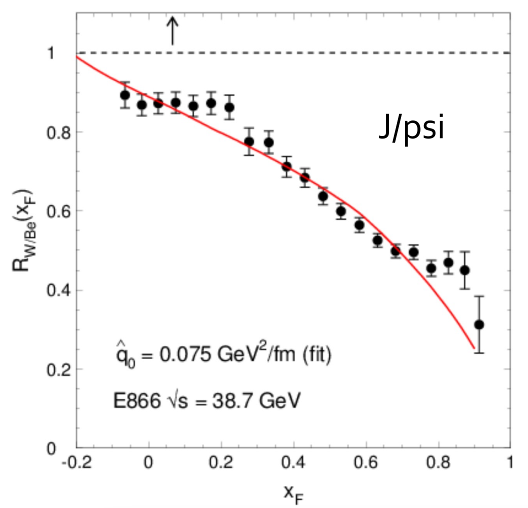
M. Gyulassy et al . (1992)



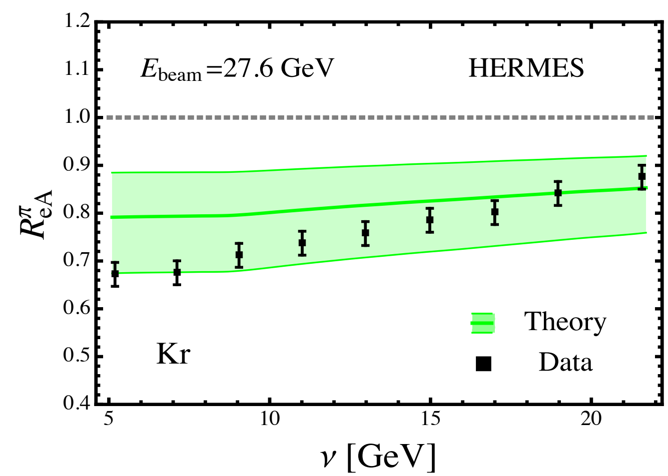
Inclusive hadron suppression, hadron correlations



Jet suppression, enhanced dijet asymmetries, jet substructure



Heavy flavor suppression, b jets, di-b jets, quarkonia



Also in cold nuclear matter

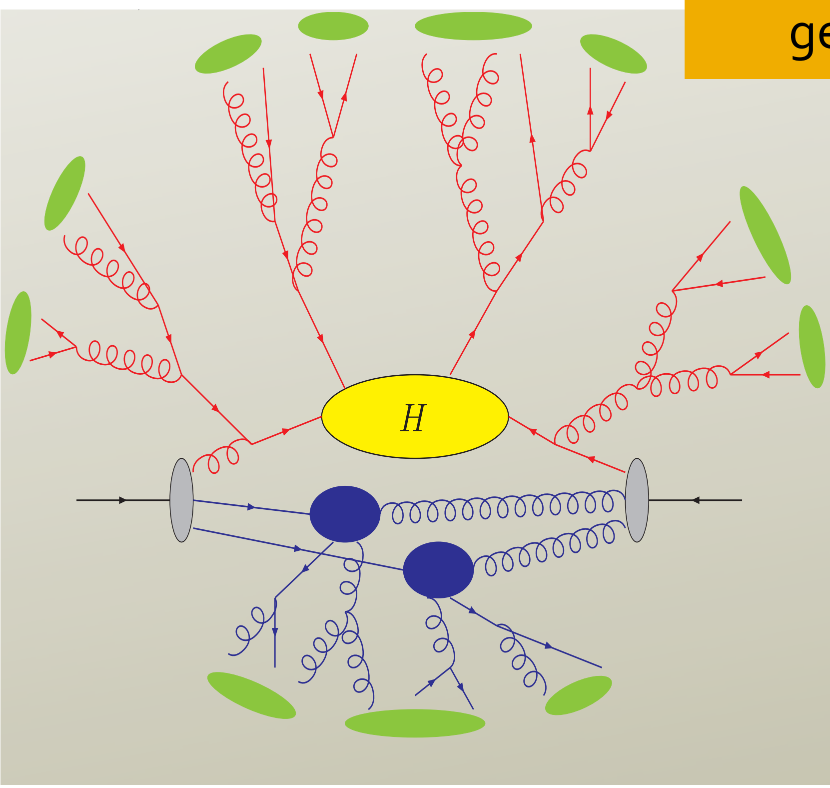
The splitting kernels

Gribov et al. (1972)

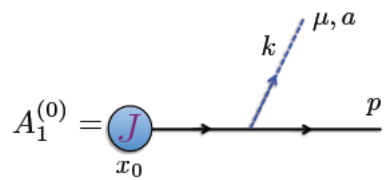
G. Altarelli et al. (1977)

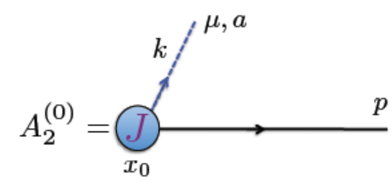
Y. Dokshitzer (1977)

- In general, knowledge of branching processes is necessary for higher order and resumed calculations
- Also essential ingredient for MC event generators



Bridge the gap between HEP and NP theory/phenomenology for hard processes





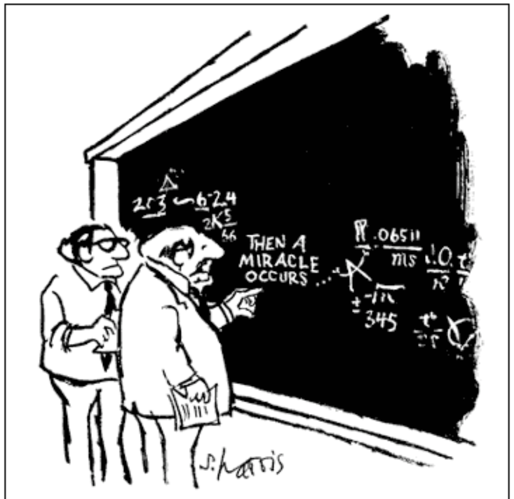
C. Bauer et al . (2001)

M. Beneke et al . (2002)

- In SCET splitting functions are related to beam (B) and jet (J) functions in SCET

$$\sigma = \mathrm{Tr}(HS) \otimes \prod_{i=1}^{n_B} B_i \otimes \prod_{j=1}^{N} J_j + \text{power corrections}$$

I. In-medium parton showers



"I think you should be more explicit here in step two."

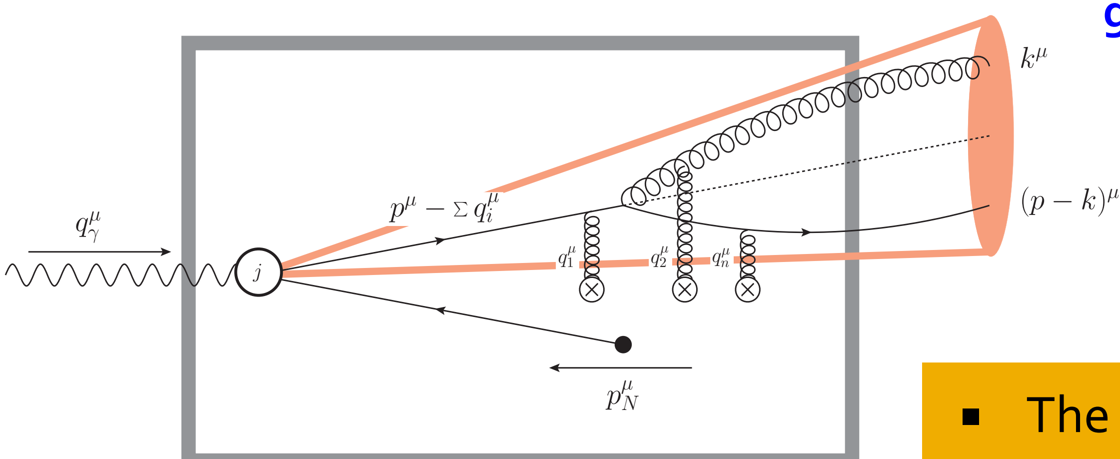
Theoretical framework

- The theoretical framework is completely general – it is applicable for both cold nuclear matter and the QGP.
- This is achieved by isolating the medium in transport parameters and universal gluon-mediated interactions

$$\mathcal{L}_{opac.} = \mathcal{L}_{QCD} + \mathcal{L}_{ext}^{qG} + \mathcal{L}_{ext}^{gG} + \mathcal{L}_{G.F.} + \cdots$$

$$v(q_T^2) \to \frac{-g_{eff}^2}{q_T^2 + \mu^2} \qquad \frac{d\sigma^{el}}{d^2q} = \frac{1}{(2\pi)^2}\frac{C_F}{2N_c}[v(q_T^2)]^2$$

In deep inelastic scattering (DIS) the lowest order processes involve prompt quark. Even at NLO the prompt gluon jet contribution is small



M. Sievert et al. (2018), (2019)

$$\frac{1}{p_N^-} \ll l_f^+ \sim \lambda^+ \sim L^+$$

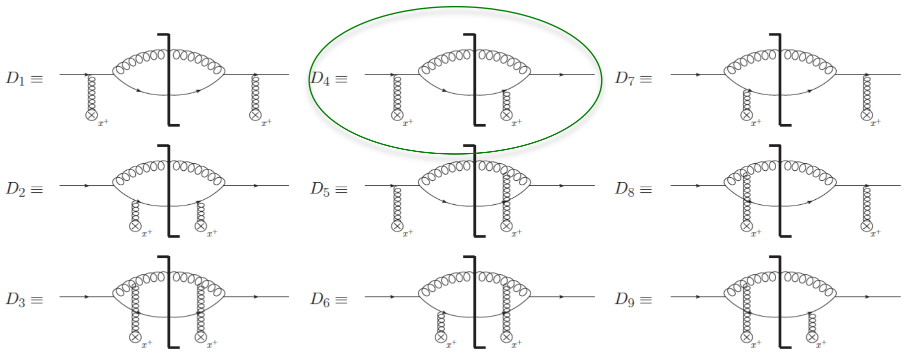
- The limit we are interested in

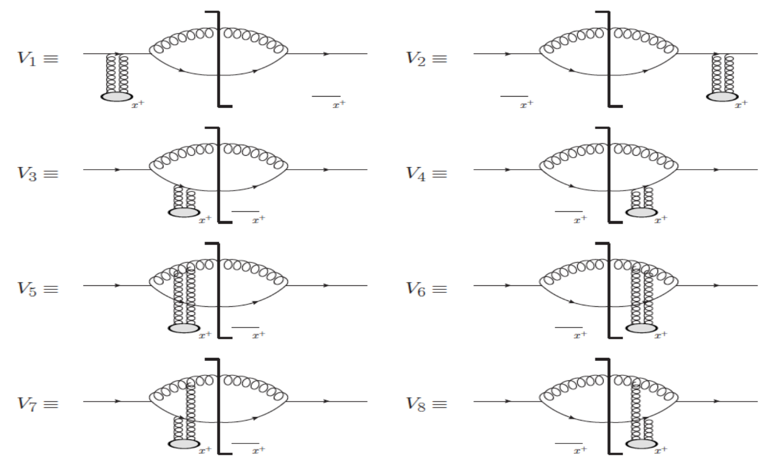
$$\mathcal{O}\left(\frac{\perp^2}{Q^2}\right)$$

Note that the leading subeikonal corrections have also been computed (not covered here)

A. Sadofyev et al. (2021)

Opacity expansion building blocks – direct and virtual terms





- Interaction in the amplitude and the conjugate amplitude (Direct). Two in the amplitude or the conjugate (Virtual)

Representative forward cut diagram. Propagators hide in wavefunction

$$D_4 = \left[\frac{-1}{2N_c C_F}\, e^{+i[\Delta E^-(\underline{k}-x\underline{p})-\Delta E^-(\underline{k}-x\underline{p}+x\underline{q})]z^+}\right] \psi(x,\underline{k}-x\underline{p}) \left[0 - e^{-i\Delta E^-(\underline{k}-x\underline{p})z^+}\right]$$
$$\times \left[e^{+i\Delta E^-(\underline{k}-x\underline{p}+x\underline{q})z^+} - e^{+i\Delta E^-(\underline{k}-x\underline{p}+x\underline{q})x_0^+}\right] \psi^*(x,\underline{k}-x\underline{p}+x\underline{q})\,,$$

$$p^- - k^- - (p-k)^- = \Delta E^-(\underline{k}-x\underline{p})$$

- Vitruallity changes enter the interference phases and are related to the propagators

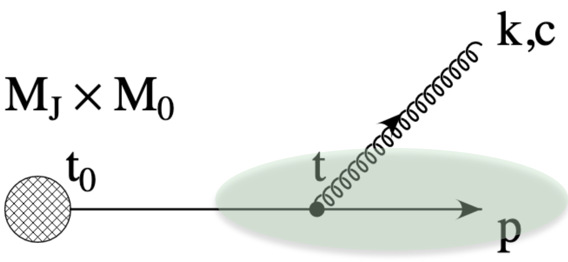
c.f.

G. Ovanesyan et al . (2012)

Z. Kang et al . (2016)

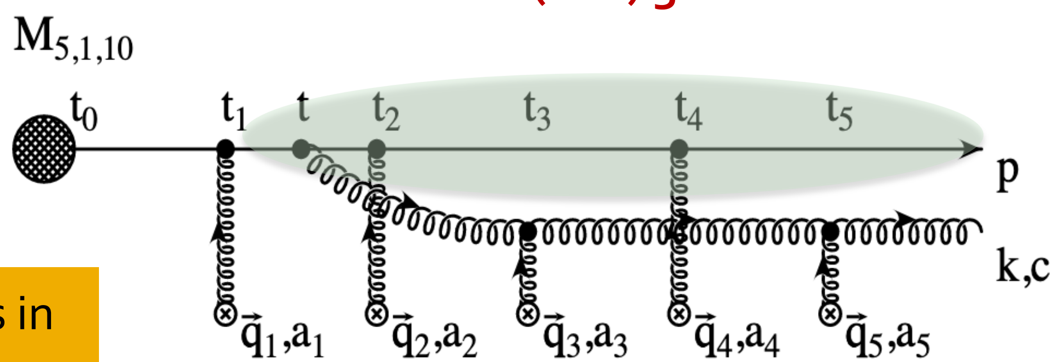
Non-local physics and coherence

Vacuum



Medium

Let's try to evaluate the formation time of the (soft) gluon at t



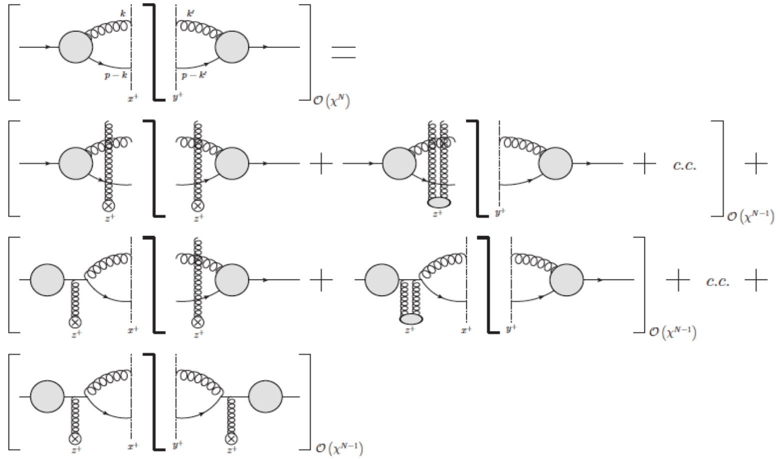
- Consider the formation times in the soft gluon emission limit

$$LPM \sim L/\tau_f \qquad \frac{1}{\Delta E} = \tau_{form} = \frac{2\omega}{k_\perp^{\;2}} \qquad \frac{1}{\Delta E} = \tau_{form} = \frac{2\omega}{(k-q_3-q_5)_\perp^{\;2}}$$

- In the case of a medium we cannot guess from its final distribution. In fact future interactions can in fact affect this formation time and how the system in turn will interact. (This is a quantum coherent effect.)
- This also shows right away the difficulty of implementing LPM parton showers in time-ordered MCs

Master equation – matrix form

- Color is not entangled, homogeneous structure and multiplicative factors that can be algebraically treated
- Finally, relative to the splitting vertex we classify the as
- Initial/Initial, Initial/Final, Final/Initial and Final/Final



Calculated: initial conditions, kernels, and wrote a Mathematica code to solve it

$$\frac{dN(tot.)}{dxd^2k_\perp} = \frac{dN(vac.)}{dxd^2k_\perp} + \frac{dN(med.)}{dxd^2k_\perp}$$

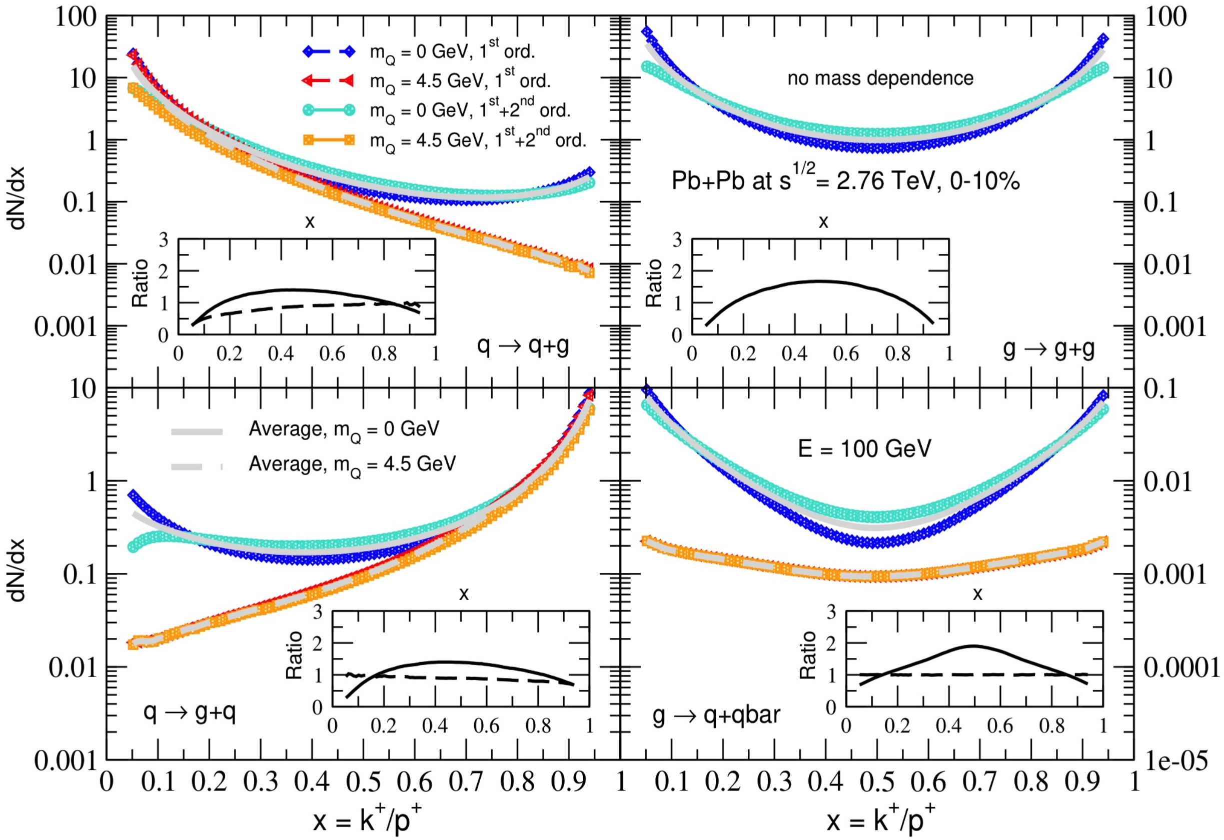
$$\left(\frac{dN^{\rm med}}{dxd^2\boldsymbol{k}_\perp}\right)_{Q\to Qg} = \frac{\alpha_s}{2\pi^2}C_F \int \frac{d\Delta z}{\lambda_g(z)} \int d^2\boldsymbol{q}_\perp \frac{1}{\sigma_{el}}\frac{d\sigma_{el}^{\rm med}}{d^2\boldsymbol{q}_\perp} \left\{ \left(\frac{1+(1-x)^2}{x}\right) \left[\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2} \right.\right.$$
$$\times \left(\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2} - \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}\cdot\left(2\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2} - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\right.$$
$$\left. -\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_3)\Delta z]) + \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\cdot\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}(1-\cos[(\Omega_2-\Omega_3)\Delta z])$$
$$+\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\cdot\left(\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2+\nu^2} - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\right)(1-\cos[\Omega_4\Delta z]) - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\cdot\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2+\nu^2}(1-\cos[\Omega_5\Delta z])$$
$$\left. +\frac{1}{N_c^2}\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\cdot\left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2} - \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z])\right]$$
$$\left. +x^3m^2\left[\frac{1}{\boldsymbol{B}_\perp^2+\nu^2}\cdot\left(\frac{1}{\boldsymbol{B}_\perp^2+\nu^2} - \frac{1}{\boldsymbol{C}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \ldots\right]\right\}$$

Done, of course, for all splitting functions

- Factorize from the hard part
- Gauge-invariant
- Depend on the properties of the medium
- Can be expressed as corrections to Altarelli-Parisi

Differential branching spectra

In-medium parton showers are softer than the ones in the vacuum. There is even more soft gluon emission – medium induced scaling violations, enhancement of soft branching



Effects of opacity

- Reduction of small-x and large-x probabilities (assymptotics modulated by thermal mass)
- Enhancement of democratic branching (x~0.5)

Jet substructure – splitting functions

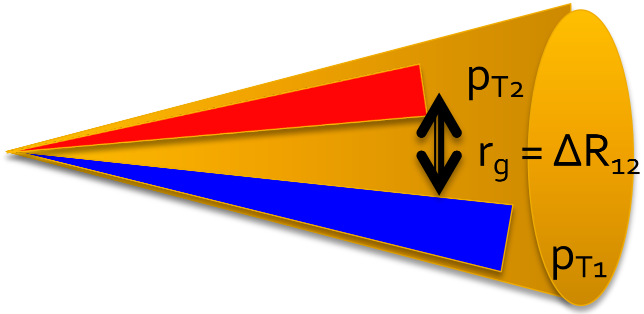
A. Larkoski et al. (2015)

In-medium splitting functions can be measured directly through observables

Soft dropped momentum sharing distributions

$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\rm cut} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

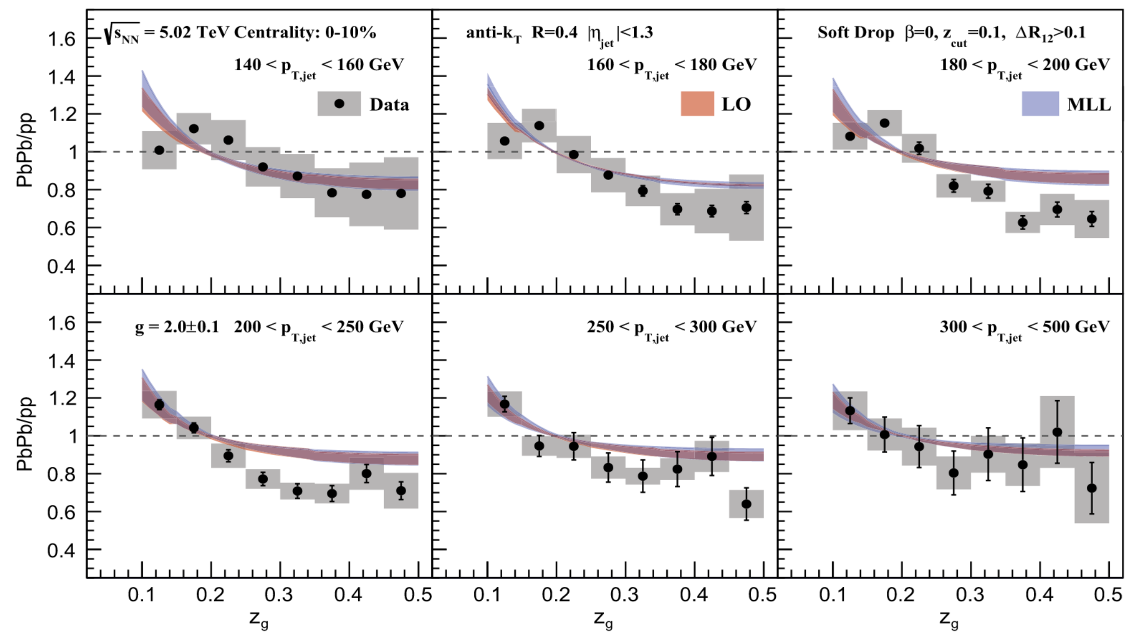
$$\frac{dN_j^{\rm vac,MLL}}{dz_g d\theta_g} = \sum_i \left(\frac{dN^{\rm vac}}{dz_g d\theta_g}\right)_{j\to i\bar{i}} \underbrace{\exp\left[-\int_{\theta_g}^{1} d\theta \int_{z_{\rm cut}}^{1/2} dz \sum_i \left(\frac{dN^{\rm vac}}{dz d\theta}\right)_{j\to i\bar{i}}\right]}_{\text{Sudakov Factor}}$$



Directly proportional to the splitting functions, + resummation for small angles

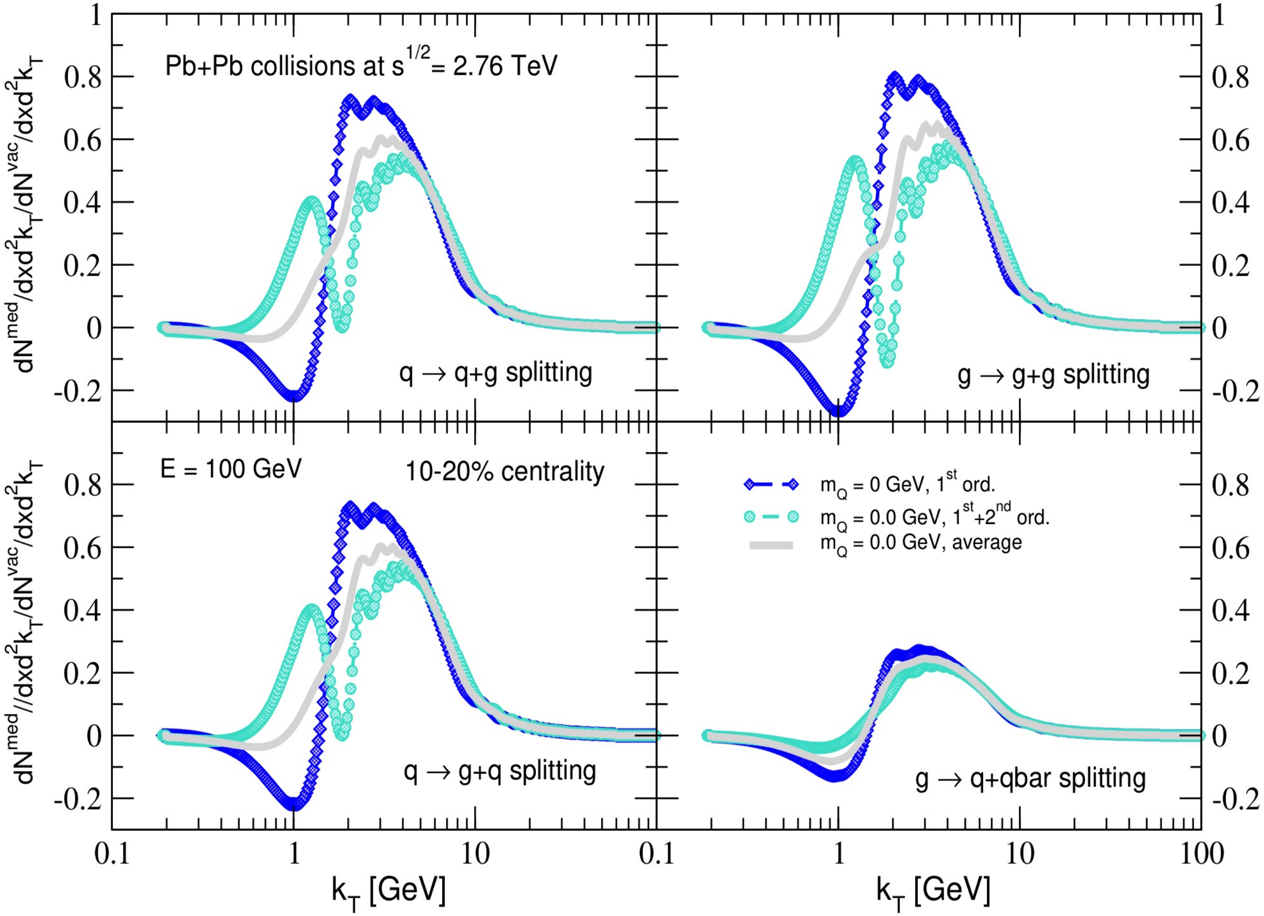
The softer in-medium branching is directly observed!

H. Li et al. (2018)



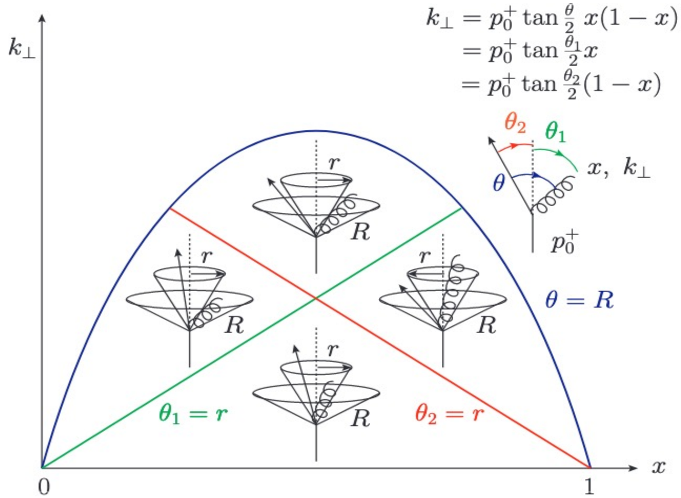
Differential branching spectra

In-medium parton showers are broader than the ones in the vacuum. There is even more large – angle gluon emission. The effect of heavy quark masses ("dead cone" effect) is also enhanced.



- Broder angular enhancement region
- Oscillating series – the average of 1^{st} and $1^{st+}2^{nd}$ order- candidate for pheno.

Jet substructure – jet shape



$$\Psi_\omega(r) = \frac{J_{\omega,E_r}(\mu)}{J_{\omega,E_R}(\mu)}$$

Expressed from jet functions, themselves computed from integrals of the splitting functions

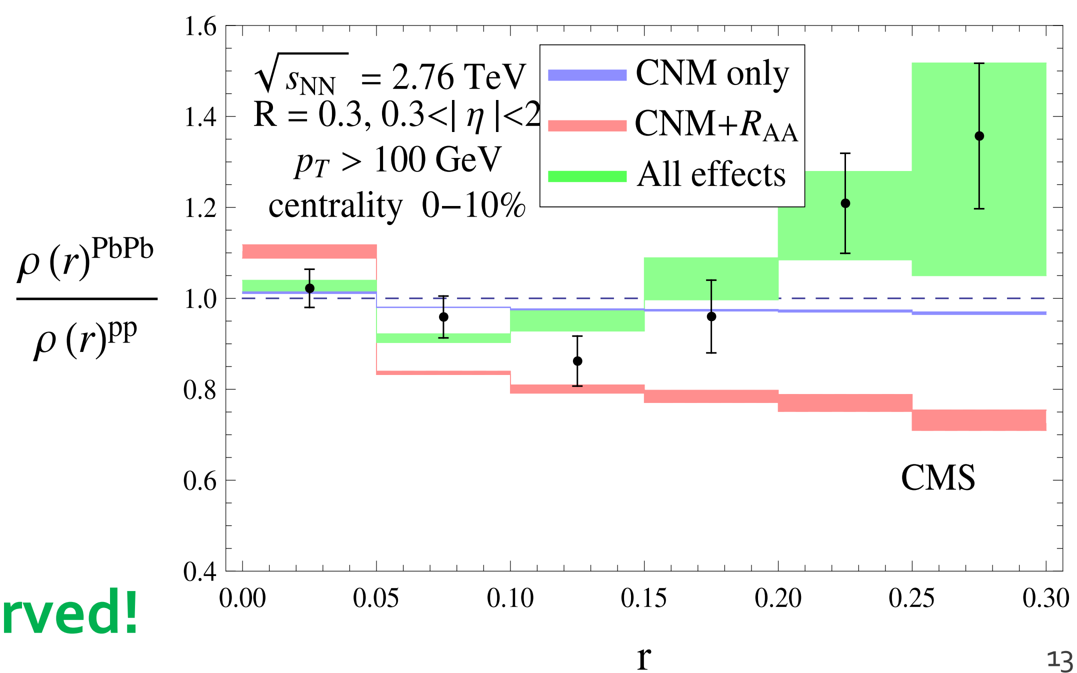
Integral jet shape

$$\Psi_J(r) = \frac{\sum_{i,\ d_{i\hat{n}}<r} E_T^i}{\sum_{i,\ d_{i\hat{n}}<R} E_T^i} .$$

Differential Jet shape

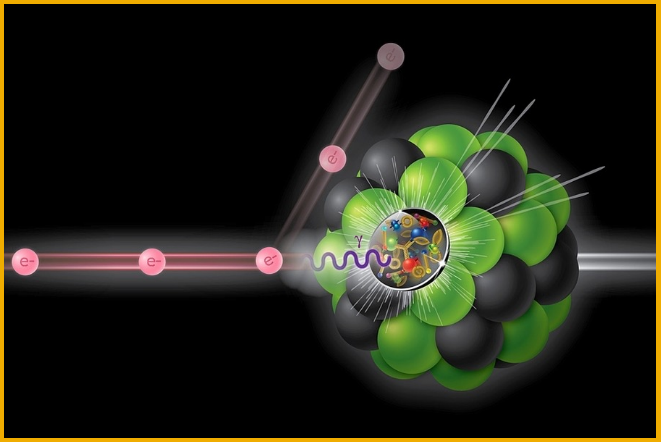
$$\frac{\Delta\Psi(r)}{\Delta r} = \frac{1}{N_J}\sum_{J=1}^{N_J} \frac{\Psi_J^{\text{track}}(r+\delta r/2) - \Psi_J^{\text{track}}(r-\delta r/2)}{\delta r}$$

Y. Chien et al. (2015)



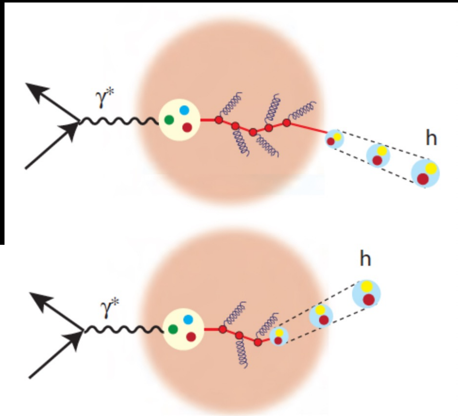
The broader in-medium branching is directly observed!

II. EIC examples



"I'm firmly convinced that behind every great man is a great computer."

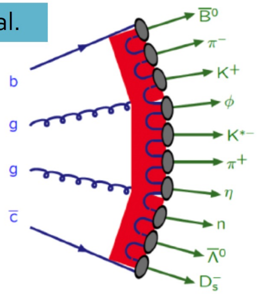
A little extra motivation - hadronization



Hadronization not well understood, independent fragmentation, MC implementations ...

String fragmentation

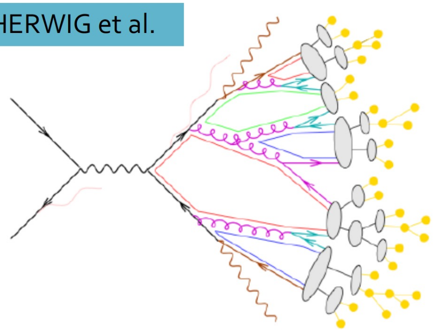
PYTHIA et al.



$$f(z) \propto \frac{1}{z}(1-z)^a \exp\left(-\frac{bm_\perp^2}{z}\right)$$

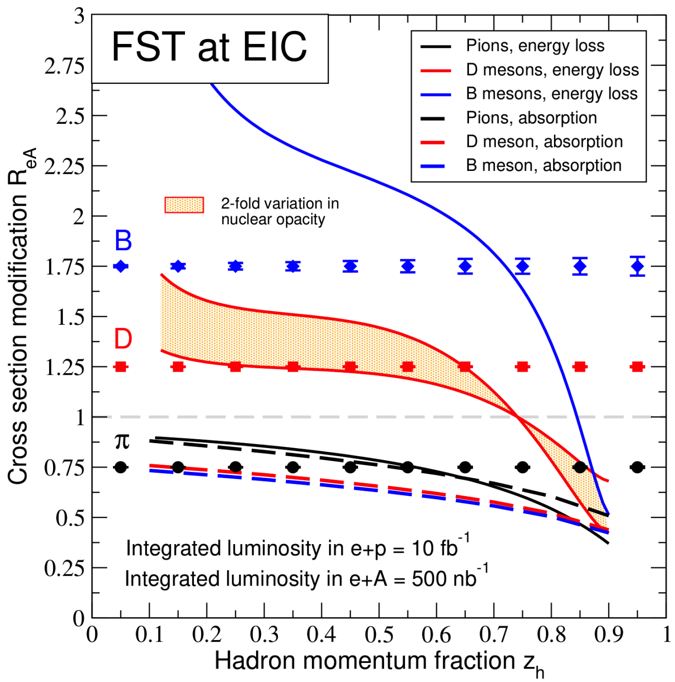
Cluster hadronization

HERWIG et al.



- Heavy mesons have very different fragmentation functions and formation times
  - Easy to discriminate between larger suppression for D/B mesons (in-medium hadronization) and strong small/intermediate z enhancement (E-loss)
  - Enhanced sensitivity to the transport properties of nuclei

X. Li *et al.* (2020)



Utility of heavy flavor measurements at the EIC in constraining hadronization physics and the transport properties of nuclear matter

I. Hadron production in eA

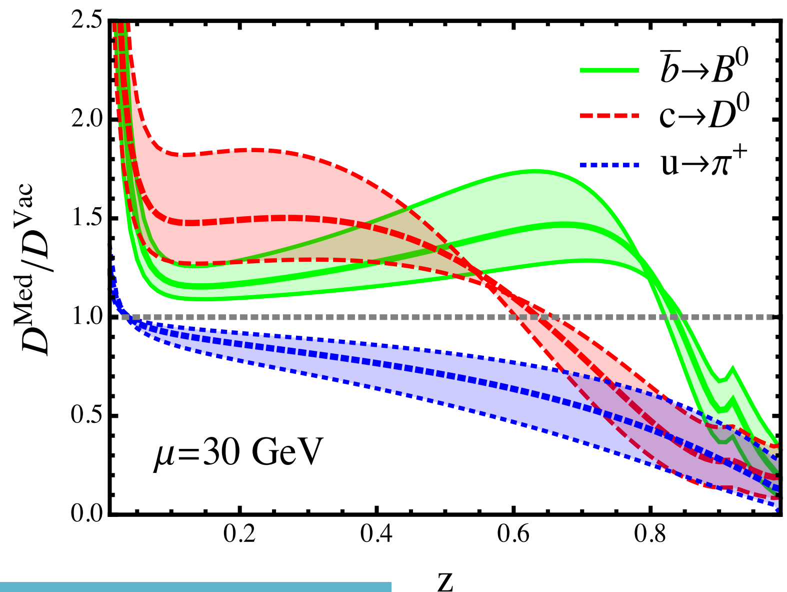
In-medium splitting functions provide correction to vacuum showers and correspondingly modification to DGLAP evolution for FFs

Integrate out the space-time information. All applications in momentum space

$$\frac{\mathrm{d}D_q(z,Q)}{\mathrm{d}\ln Q} = \frac{\alpha_s(Q^2)}{\pi}\int_z^1 \frac{\mathrm{d}z'}{z'}\left\{P_{q\to qg}(z',Q)D_q\left(\frac{z}{z'},Q\right) + P_{q\to gq}(z',Q)D_g\left(\frac{z}{z'},Q\right)\right\},$$

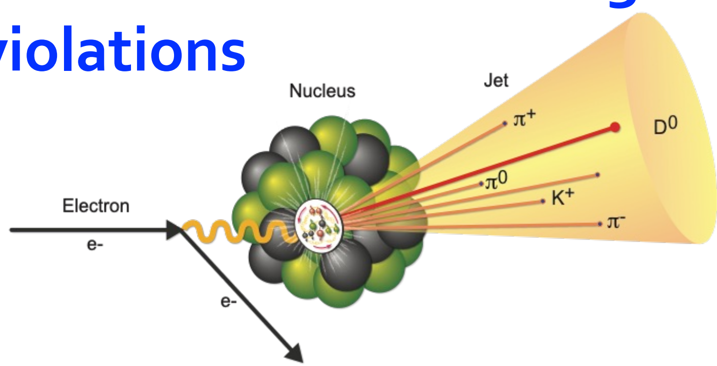
$$\frac{\mathrm{d}D_{\bar q}(z,Q)}{\mathrm{d}\ln Q} = \frac{\alpha_s(Q^2)}{\pi}\int_z^1 \frac{\mathrm{d}z'}{z'}\left\{P_{q\to qg}(z',Q)D_{\bar q}\left(\frac{z}{z'},Q\right) + P_{q\to gq}(z',Q)D_g\left(\frac{z}{z'},Q\right)\right\},$$

$$\frac{\mathrm{d}D_g(z,Q)}{\mathrm{d}\ln Q} = \frac{\alpha_s(Q^2)}{\pi}\int_z^1 \frac{\mathrm{d}z'}{z'}\Bigg\{P_{g\to gg}(z',Q)D_g\left(\frac{z}{z'},Q\right) + P_{g\to q\bar q}(z',Q)\left(D_q\left(\frac{z}{z'},Q\right) + f_{\bar q}\left(\frac{z}{z'},Q\right)\right)\Bigg\}.$$



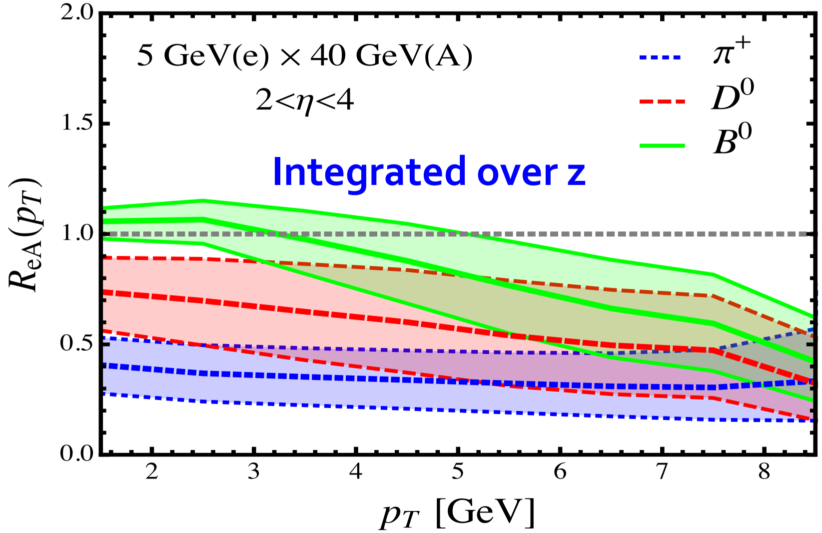
Z. Liu et al. (2020)

Medium induced scaling violations



- Always enhancement at small z but for pions (light hadrons) at very small values – mostly suppression
- Very pronounced differences between light and heavy flavor fragmentation

Light and heavy flavor suppression at the EIC

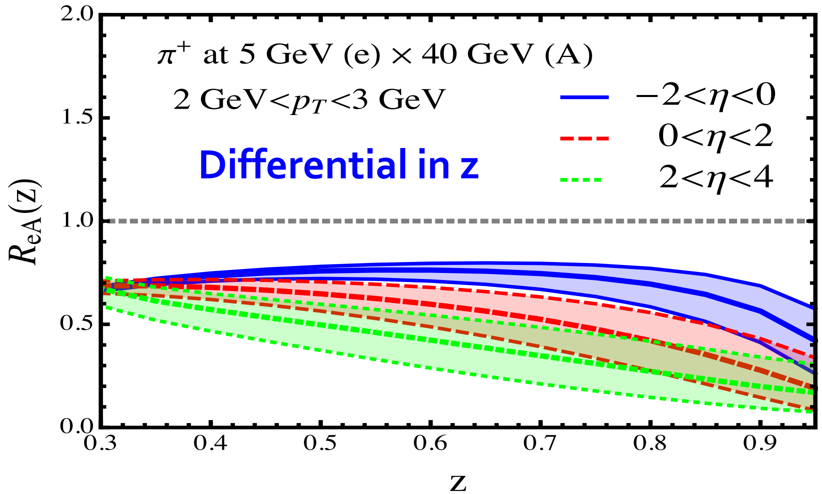


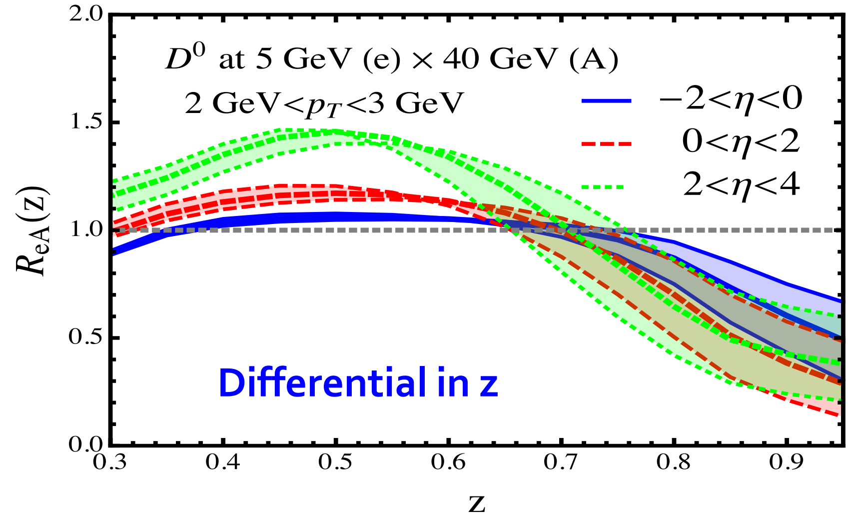
$$R^h_{eA}(p_T,\eta,z) = \frac{\left.\frac{N^h(p_T,\eta,z)}{N^{\text{inc}}(p_T,\eta)}\right|_{\text{e+Au}}}{\left.\frac{N^h(p_T,\eta,z)}{N^{\text{inc}}(p_T,\eta)}\right|_{\text{e+p}}}$$

Effects are the largest at forward rapidities (p/A going)

Light pions show the largest nuclear suppression at the EIC. However to differentiate models of hadronization heavy flavor mesons are necessary

Z. Liu et al . (2020)





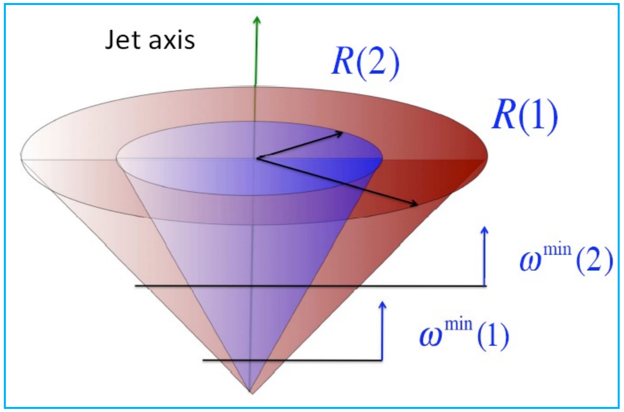
Clear new insights into hadronization from light+heavy flavor

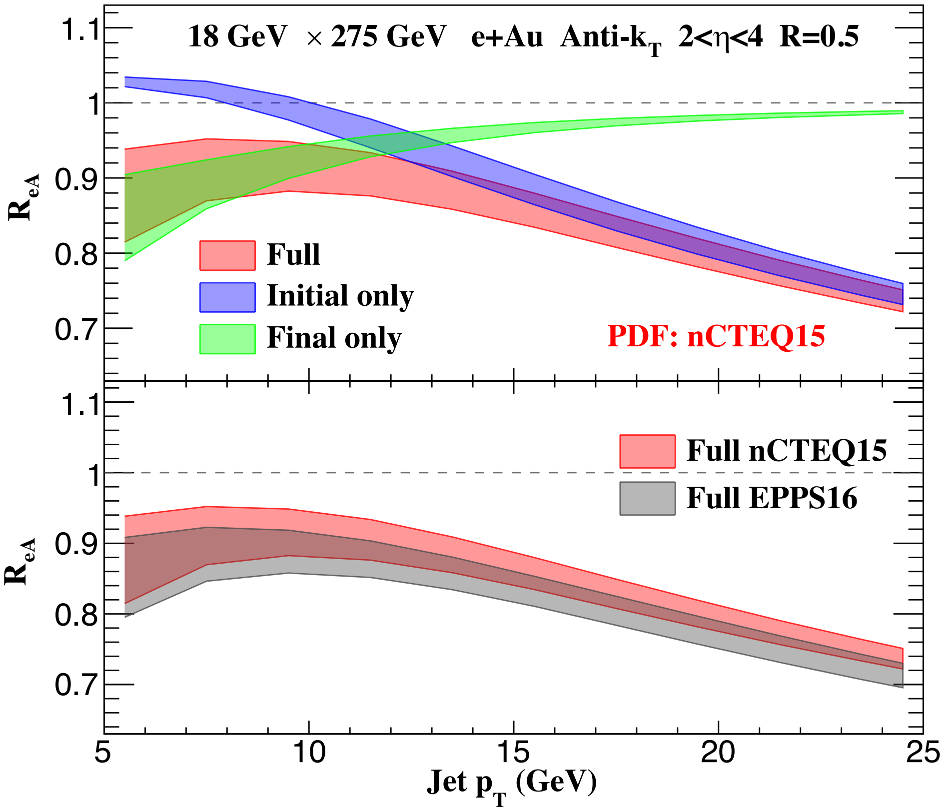
II. Jet results at the EIC

- The physics of reconstructed jet modification

H. Li et al. (2020)

$$R_{\mathrm{eA}}(R) = \frac{1}{A}\frac{\int_{\eta 1}^{\eta 2} d\sigma/d\eta dp_T\big|_{e+A}}{\int_{\eta 1}^{\eta 2} d\sigma/d\eta dp_T\big|_{e+p}}$$





Two types of nuclear effect play a role

- **Initial-state effects parametrized in nuclear parton distribution functions or nPDFs**
- **Final-state effects from the interaction of the jet and the nuclear medium – in-medium parton showers and jet energy loss**

- Net modification 20-30% even at the highest CM energy
- E-loss has larger role at lower p_T. The EMC effect at larger p_T

Separating initial-state from final-state effects at EIC

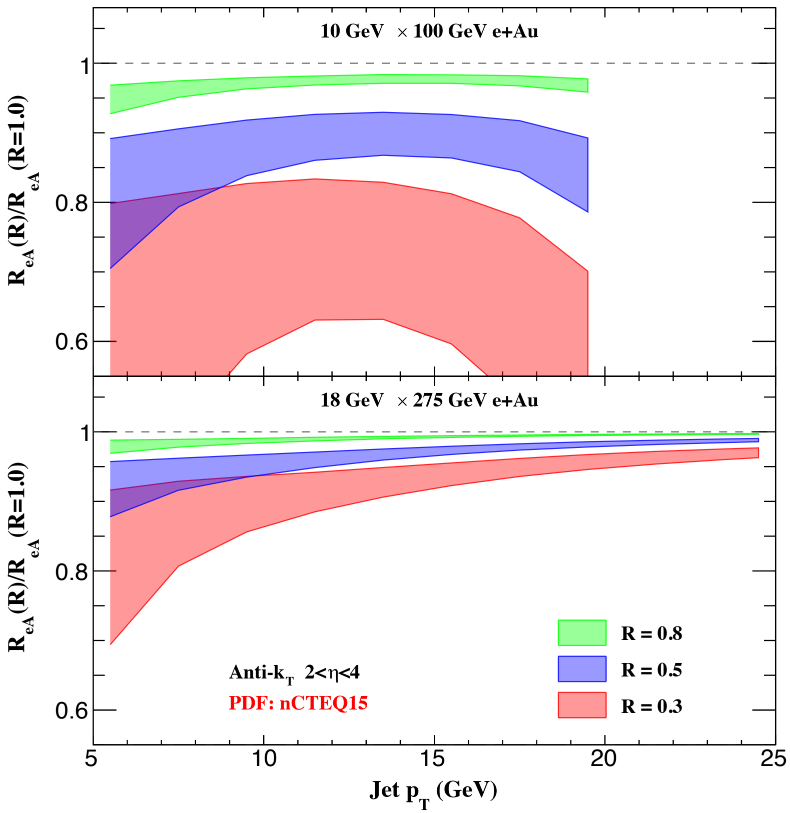
H. Li et al. (2020)

A key question – will benefit both nPDF extraction and understanding hadronization / nuclear matter transport properties - how to separate initial-state and final-state effects?

Define the ratio of modifications for 2 radii (it is a double ratio)

$$R_R = R_{eA}(R) / R_{eA}(R=1)$$

- Jet energy loss effects are larger at smaller center of mass energies (electron-nuclear beam combinations)
- Effects can be almost a factor of 2 for small radii. Remarkable as it approaches magnitudes observed in heavy ion collisions (QGP)



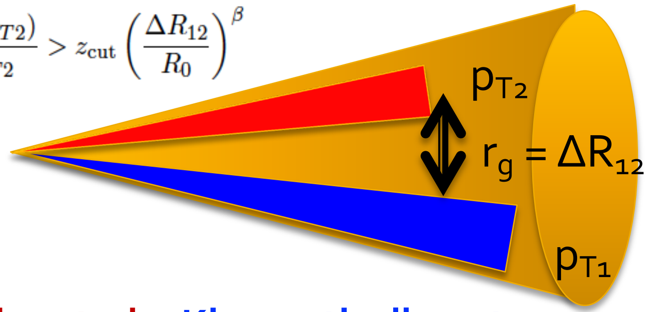
Initial-state effects are successfully eliminated

Can get detailed insights into shower structure in CNM

III. Heavy flavor jets substructure in DIS

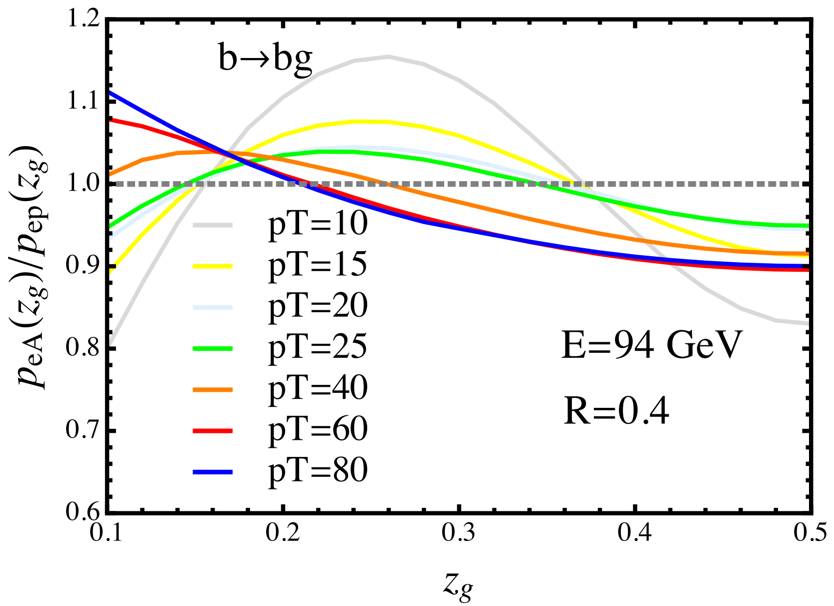
Z. Liu et al. (2021)

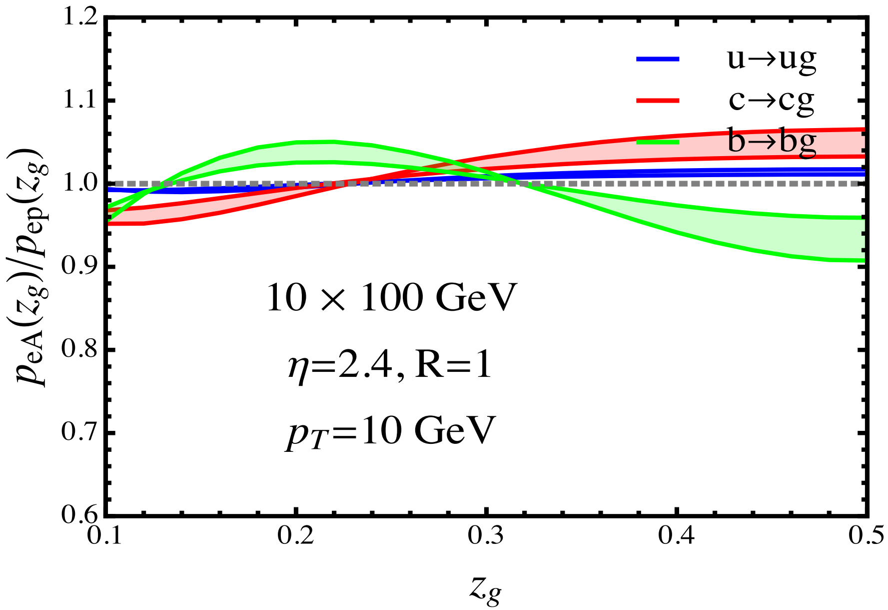
$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1}+p_{T2}} > z_{\rm cut}\left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$



- Modification of both c-jets and b-jets substructure in eA is relatively small
- It is dominated by limited phase space

Illustrative study: Kinematically not possible in DIS but illustrates very well the difference with HIC





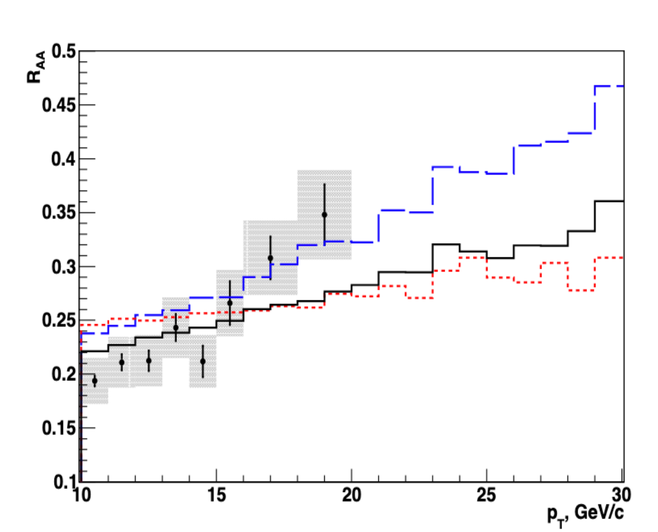
Effects of heavy quark mass - most pronounced in substructure

III. Comments on MC implementation

Disclaimer – selected results taken from literature

PYQUEN and JEWEL

I. Lokhtin et al. (2006)



PYQUEN

All PYTHIA based

Assumptions for angular gluon distribution

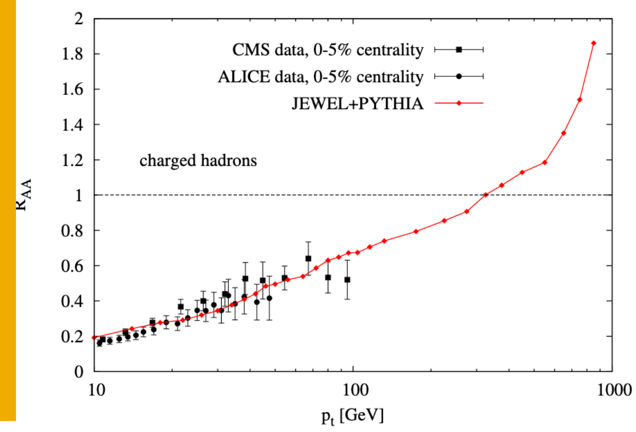
Gaussian $$\frac{dN^g}{d\theta} \propto \sin\theta \exp\left(-\frac{(\theta-\theta_0)^2}{2\theta_0^2}\right)$$

Wide $$\frac{dN^g}{d\theta} \propto 1/\theta$$

Extra wide $$\frac{dN^g}{d\theta} \propto 1/\sqrt{\theta}$$

- Collisional energy loss
- Soft gluon emission intensity

K. Zapp et al. (2008)



JEWEL

$$\sigma^{\text{elas}} = \int_0^{|t_{\max}|} d|t| \, \frac{\pi \alpha_s^2(|t|+\mu_D^2)}{s^2} C_R \, \frac{s^2+(s-|t|)^2}{(|t|+\mu_D^2)^2}$$

$$\hat{P}_{a\to bc}(z) \longrightarrow (1+f_{\text{med}})\,\hat{P}_{a\to bc}(z)$$

- Collisional energy loss implemented
- Radiative processes – just numerical enhancement of the vacuum shower
- Later version include Bertsch-Gunion radiation and formation time prescription to suppress radiation

Bertsch-Gunion

$$\frac{d\sigma^{(\text{GB})}}{d\mathbf{k}_\perp d\mathbf{q}_\perp} \propto \frac{\mathbf{q}_\perp^2}{\mathbf{k}_\perp^2(\mathbf{k}_\perp-\mathbf{q}_\perp)^2}$$

Challenged by more differential observables

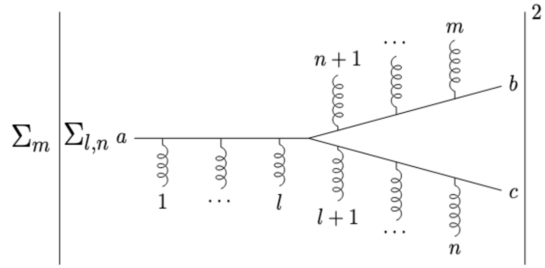
Other implementations

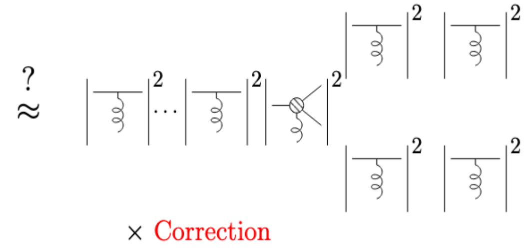
LIDO model

Not a general purpose model

W. Ke et al. (2018)

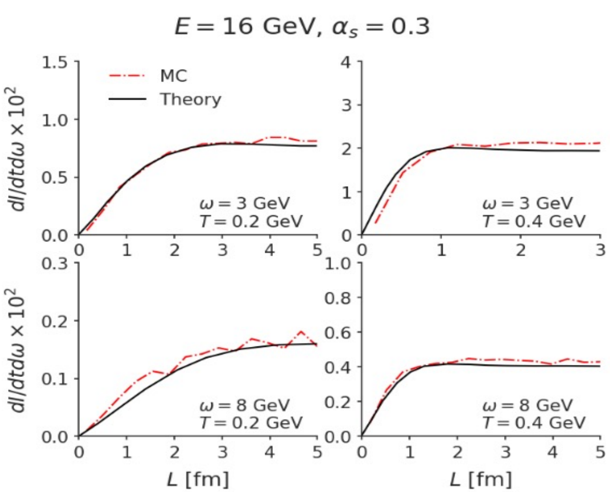
- The same idea of reducing the incoherent radiation
- Improvement in determining the suppression factor





Let $N = \tau_f/\lambda$. From analysis[1] of the AMY equation[2] for the single-gluon emission rate:

Semi-classical rate ($N < 1$)	Leading-ln N ($N \gg 1$)	NLL
$\frac{dR^{\rm incoh}}{d\omega}$	$\propto \frac{dR^{\rm incoh}}{d\omega}\frac{1}{N}$	$\propto \frac{dR^{\rm incoh}}{d\omega}\frac{1}{N'}$ improved N'



Can reproduce radiative spectrum in the large number of scatterings limit

JETSCAPE model, etc ..

Monte – Carlo time is not the real time, it is virtuality, transverse momentum, etc … variable

- **The challenge is to keep momentum and spacetime information (*and history*) for *all* partons**
- **Need two "passes" one in space-time and one in momentum**

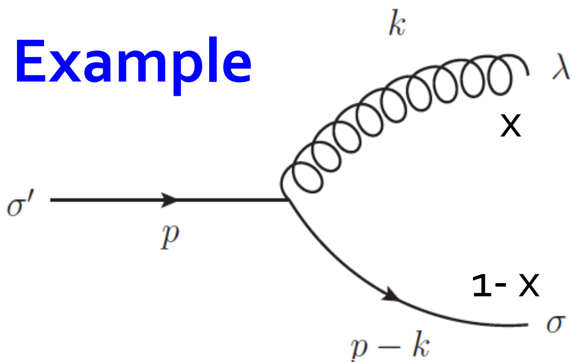
- Sample *simultaneously* vacuum and medium-induced branching processes

Conclusions

- In the past 30 years reactions with nuclei have produced spectacular results. The key to their interpretation is in-medium parton showers
- In-medium splitting functions have been derived using different methods. In-medium parton showers are softer and broader than the ones in the vacuum. This is now experimentally verified.
- In-medium splitting functions can be calculated and tabulated (integrating out the space-time information). Implemented in higher order and resumed calculations. Very significant effects on hadrons, jets and jet substructure at the EIC
- Monte Carlos that incorporate this physics properly do not exist. The problem is the coherent nature of the emission. Various approximations and prescriptions how to mimic LPM effect proposed. The detailed shower characteristics not included
- For serious implementation of in-medium showers in MC generators significant effort is needed / conceptually different from current efforts (LUTs combined with space-time integration and then momentum space)

Lightcone wave functions and parton branchings

Example



- The technique of lightcone wavefunctions

$$\psi(x,\underline{k}-x\underline{p}) \equiv \frac{1}{2p^+}\frac{1}{p^- - (p-k)^- - k^-}\overline{U}_\sigma(p-k)\left[-g\not{\epsilon}^*_\lambda(k)\right]U_{\sigma'}(p)$$
$$= \frac{gx(1-x)}{(k-xp)_T^2 + x^2m^2}\left\{\frac{2-x}{x\sqrt{1-x}}\left(\epsilon^*_\lambda\cdot(\underline{k}-x\underline{p})\right)\left[\mathbb{1}\right]_{\sigma\sigma'} + \frac{\lambda}{\sqrt{1-x}}\left(\epsilon^*_\lambda\cdot(\underline{k}-x\underline{p})\right)\left[\tau_3\right]_{\sigma\sigma'} + \frac{im\,x}{\sqrt{1-x}}\epsilon^*_\lambda\times\left[\underline{\tau_\perp}\right]_{\sigma\sigma'}\right\}.$$

$$\langle\psi(x,\underline{\kappa})\,\psi^*(x,\underline{\kappa}')\rangle \equiv \sum_{\lambda=\pm1}\frac{1}{2}\mathrm{tr}\left[\psi(x,\underline{\kappa})\,\psi^*(x,\underline{\kappa}')\right]$$
$$= \frac{8\pi\alpha_s\,(1-x)}{[\kappa_T^2+x^2m^2]\,[\kappa_T'^2+x^2m^2]}\left[(\underline{\kappa}\cdot\underline{\kappa}')\,\left[1+(1-x)^2\right]+x^4m^2\right]$$

Useful to express in Pauli matrixes

c.f.

G. Ovanesyan et al . (2012)

Z. Kang et al . (2016)

Branchings depending on the intrinsic momentum of the splitting $\underline{\kappa} = \underline{k - xp}.$

$$xp^+\frac{dN}{d^2k\,dx\,d^2p\,dp^+}\bigg|_{\mathcal{O}(\chi^0)} = \frac{\alpha_s C_F}{2\pi^2}\,\frac{(k-xp)_T^2\,\left[1+(1-x)^2\right]+x^4m^2}{[(k-xp)_T^2+x^2m^2]^2}\times\left(p^+\frac{dN_0}{d^2p\,dp^+}\right)$$

- Certain advantages – can provide in “one shot” both massive and massless splitting functions
- Have checked that results agree for massless and massive DGLAP

Full in medium splitting

- Full massless and massive in-medium splitting functions now available to first order in opacity

G. Ovanesyan et al . (2011)

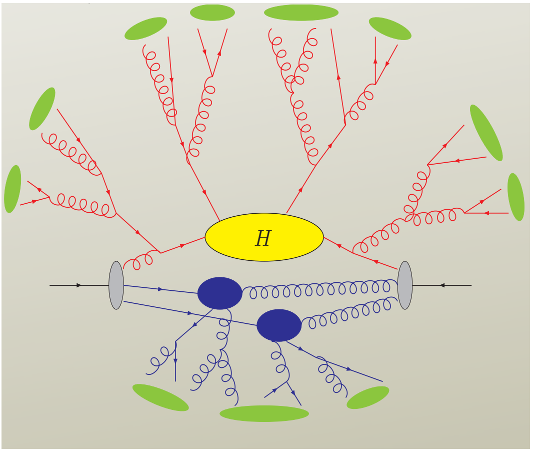
- SCET-based effective theories created to solve this problem

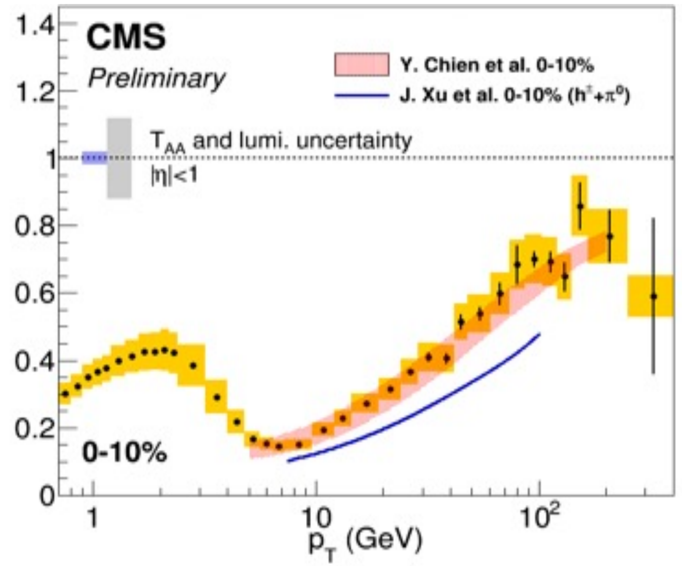
F. Ringer et al . (2016)

Representative example

$$
\begin{aligned}
\left(\frac{dN^{\rm med}}{dx\,d^2\mathbf{k}_\perp}\right)_{Q\to Qg} &= \frac{\alpha_s}{2\pi^2}C_F \int \frac{d\Delta z}{\lambda_g(z)} \int d^2\mathbf{q}_\perp \frac{1}{\sigma_{el}}\frac{d\sigma_{el}^{\rm med}}{d^2\mathbf{q}_\perp} \left\{ \left(\frac{1+(1-x)^2}{x}\right) \left[\frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2+\nu^2} \right.\right. \\
&\times \left(\frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2+\nu^2} - \frac{\mathbf{C}_\perp}{\mathbf{C}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \frac{\mathbf{C}_\perp}{\mathbf{C}_\perp^2+\nu^2}\cdot\left(2\frac{\mathbf{C}_\perp}{\mathbf{C}_\perp^2+\nu^2} - \frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2+\nu^2}\right. \\
&\left. - \frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_3)\Delta z]) + \frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2+\nu^2}\cdot\frac{\mathbf{C}_\perp}{\mathbf{C}_\perp^2+\nu^2}(1-\cos[(\Omega_2-\Omega_3)\Delta z]) \\
&+ \frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2+\nu^2}\cdot\left(\frac{\mathbf{D}_\perp}{\mathbf{D}_\perp^2+\nu^2} - \frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2+\nu^2}\right)(1-\cos[\Omega_4\Delta z]) - \frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2+\nu^2}\cdot\frac{\mathbf{D}_\perp}{\mathbf{D}_\perp^2+\nu^2}(1-\cos[\Omega_5\Delta z]) \\
&\left. + \frac{1}{N_c^2}\frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2+\nu^2}\cdot\left(\frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2+\nu^2} - \frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z]) \right] \\
&\left. + x^3 m^2 \left[\frac{1}{\mathbf{B}_\perp^2+\nu^2}\cdot\left(\frac{1}{\mathbf{B}_\perp^2+\nu^2} - \frac{1}{\mathbf{C}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \ldots\right]\right\}
\end{aligned}
$$

- For the first time we were able to do is higher order and resummed calculations





Z. Kang et al . (2015)

Parton branching to any order in opacity

- Treating color (one complication in QCD).

M. Sievert et al . (2018)

$$\mathcal{C}_1 = \frac{1}{N_c C_F} \mathrm{tr}[t^b t^b \, t^a M^a] = \mathcal{C}_0 \,,$$

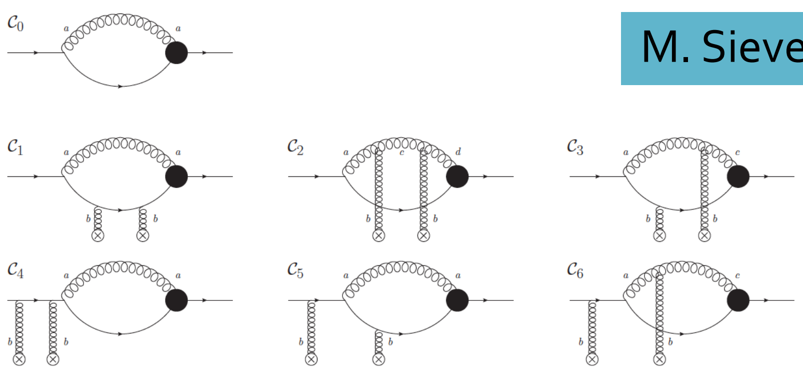
$$\mathcal{C}_2 = \frac{1}{N_c C_F} f^{acb} f^{cdb} \mathrm{tr}[t^a M^d] = -\frac{N_c}{C_F} \mathcal{C}_0 \,,$$

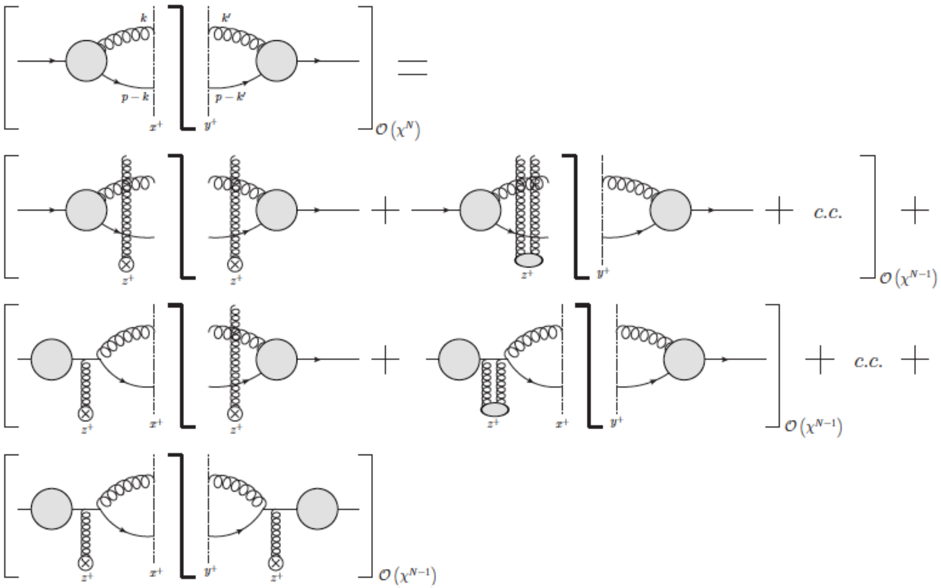
$$\mathcal{C}_3 = \frac{1}{N_c C_F} f^{acb} \mathrm{tr}[t^b t^a M^c] = \frac{i N_c}{2 C_F} \mathcal{C}_0 \,,$$

$$\mathcal{C}_4 = \frac{1}{N_c C_F} \mathrm{tr}[t^a \, t^b t^b M^a] = \mathcal{C}_0 \,,$$

$$\mathcal{C}_5 = \frac{1}{N_c C_F} \mathrm{tr}[t^b t^a t^b M^a] = \frac{-1}{2 N_c C_F} \mathcal{C}_0 \,,$$

$$\mathcal{C}_6 = \frac{1}{N_c C_F} f^{acb} \mathrm{tr}[t^a t^b M^c] = \frac{-i N_c}{2 C_F} \mathcal{C}_0 \,.$$

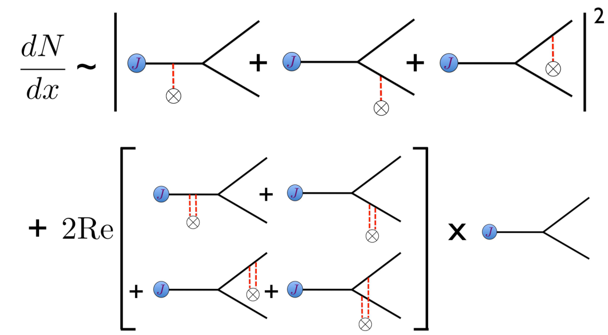




- Color is not entangled, homogeneous structure and multiplicative factors that can be algebraically treated
- Finally, relative to the splitting vertex we classify the as
- Initial/Initial, Initial/Final, Final/Initial and Final/Final

Generalizing the result to all in-medium splittings

- Note – all splittings have the same topology.
  Same - structure, interference phases, propagators
  Different - mass dependence, wavefunctions, color (which also affects transport coefficients)



$$\langle \psi(x,\underline{\kappa})\,\psi^*(x,\underline{\kappa}')\rangle = \frac{8\pi\alpha_s\, f(x)}{[\kappa_T^2+\nu^2m^2]\,[\kappa_T'^2+\nu^2m^2]}\left[g(x)\,(\underline{\kappa}\cdot\underline{\kappa}')+\nu^4m^2\right] \quad \Delta E^-(\underline{\kappa}) = -\frac{\kappa_T^2+\nu^2m^2}{2x(1-x)p^+}$$

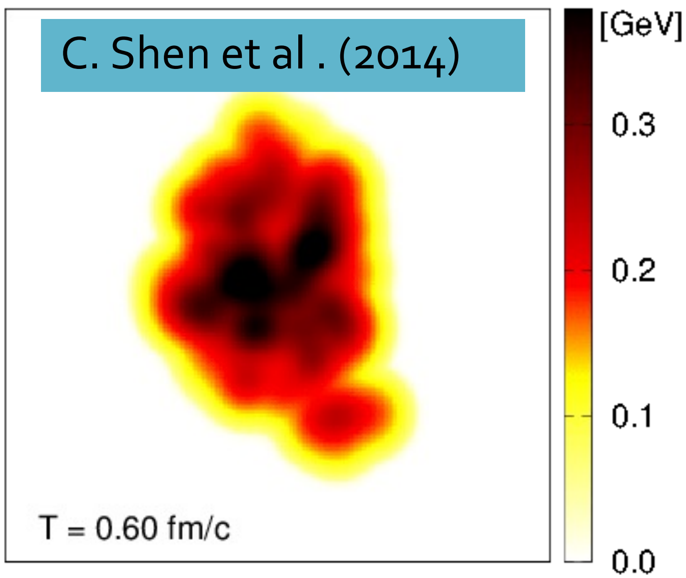
- Master table that gives all ingredients

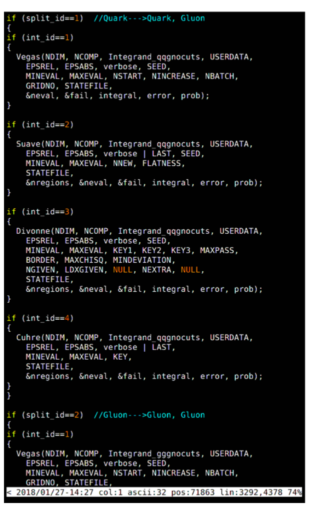
	d_1	d_2	d_3	d_4	d_5	d_6	v_1	v_2	v_3	v_4	λ_R^+	$\mathcal{C}_0$	ν	$f(x)$	$g(x)$
G/q	1	1	$\frac{N_c}{C_F}$	$\frac{-1}{2N_cC_F}$	$\frac{N_c}{2C_F}$	$\frac{-N_c}{2C_F}$	$-\frac{1}{2}$	$-\frac{1}{2}$	$\frac{-N_c}{2C_F}$	$\frac{N_c}{2C_F}$	λ_q^+	C_F	x	$1-x$	$1+(1-x)^2$
q/q	1	1	$\frac{N_c}{C_F}$	$\frac{-1}{2N_cC_F}$	$\frac{N_c}{2C_F}$	$\frac{-N_c}{2C_F}$	$-\frac{1}{2}$	$-\frac{1}{2}$	$\frac{-N_c}{2C_F}$	$\frac{N_c}{2C_F}$	λ_q^+	C_F	$1-x$	x	$1+x^2$
q/G	1	$\frac{C_F}{N_c}$	$\frac{C_F}{N_c}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2N_c^2}$	$-\frac{1}{2}$	$-\frac{C_F}{2N_c}$	$\frac{-N_c}{2C_F}$	$\frac{-1}{2N_c^2}$	λ_G^+	$\frac{1}{2}$	1	$x(1-x)$	$x^2+(1-x)^2$
G/G	1	1	1	$\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	$\frac{1}{2}$	λ_G^+	N_c	0	$1+x^4+(1-x)^4$	1

We have now solved the problem for all splitting functions

M. Sievert et al . (2019)

Improvements in physics & code





Refactoring

- Code is **restructured** (in C++) and shortened (**24K → 8K lines**). 20x speed improvement

Effective incorporation of simulated QGP medium

- Reduced overhead for calling QGP medium grid function. 2x speed improvement

Efficient on-node parallelization

- New parallelization shows much better scaling 10x speed improvement

Overall improvement:

18 days → 1 hour