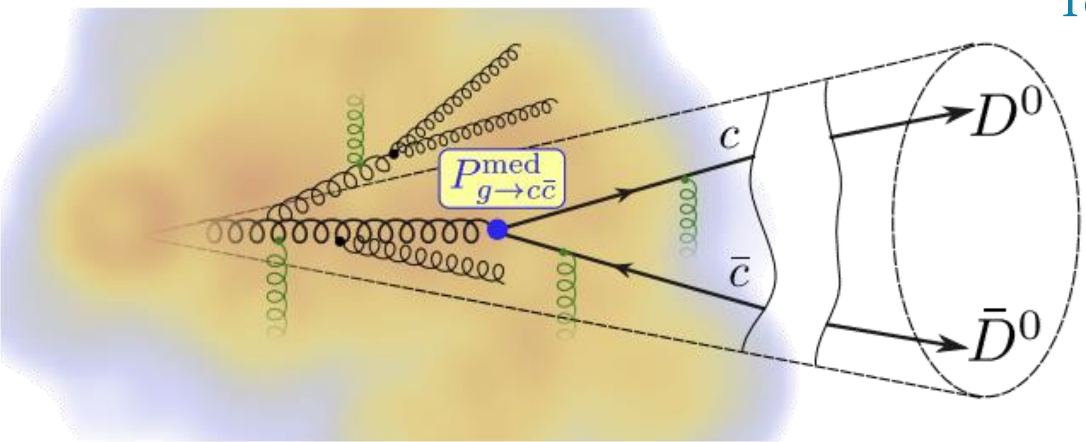
Probing parton formation times with $g \to c\bar{c}$ splitting

Towards a spatio-temporal view of a parton shower

Together with Jasmine Brewer, Aleksas Mazeliauskas, Maximilian Attems, Gian Michele Innocenti, Sohyun Park and Urs Wiedemann

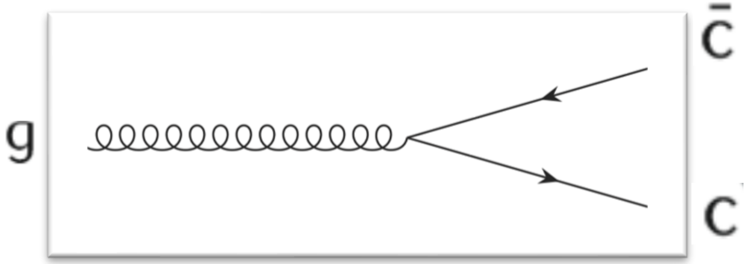
Based on 2203.11241 (JHEP), 2209.13600 and to appear



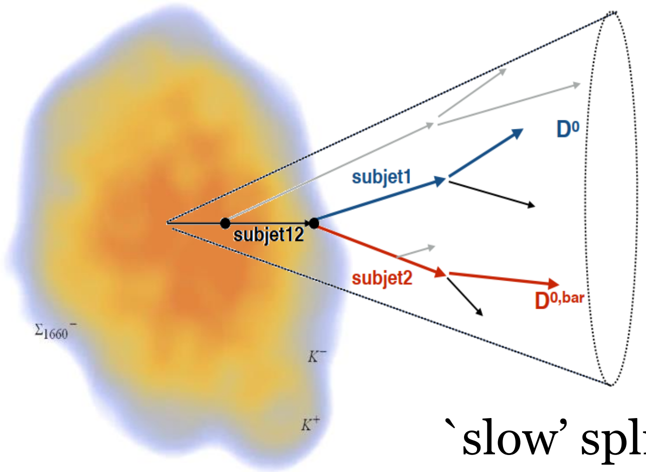
Wilke van der Schee

Quark Matter 2023, Houston
September 2023

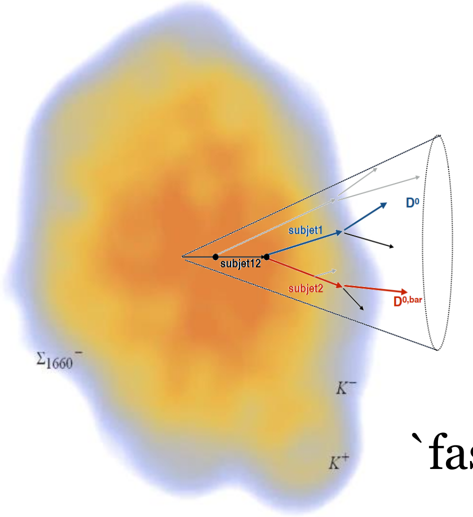
Gluon to c-cbar splitting



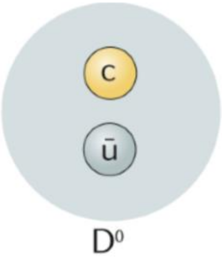
Illuminating the *spatio-temporal structure* of parton showers



\`slow' splitting



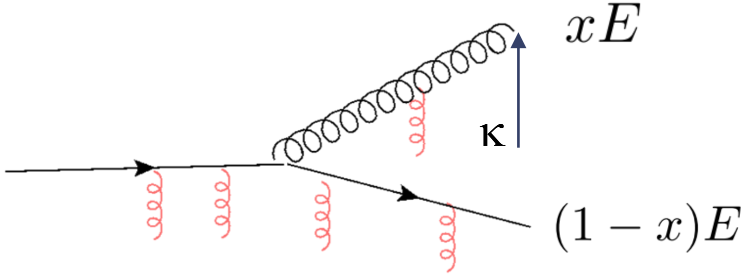
\`fast' splitting



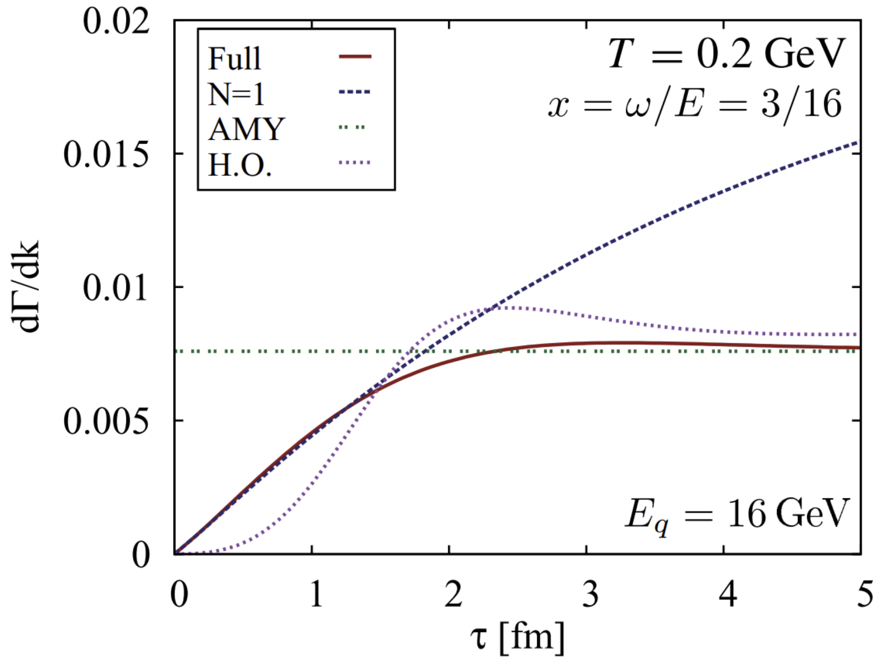
Does the gluon split within the medium (~8 femtometer)?

- Vacuum: usual momentum-space picture
- The QGP can provide a \`measurement', much like observations in the two-split experiment

Pathlength dependent radiation rate



Rate of gluons radiating fraction *x* from a quark

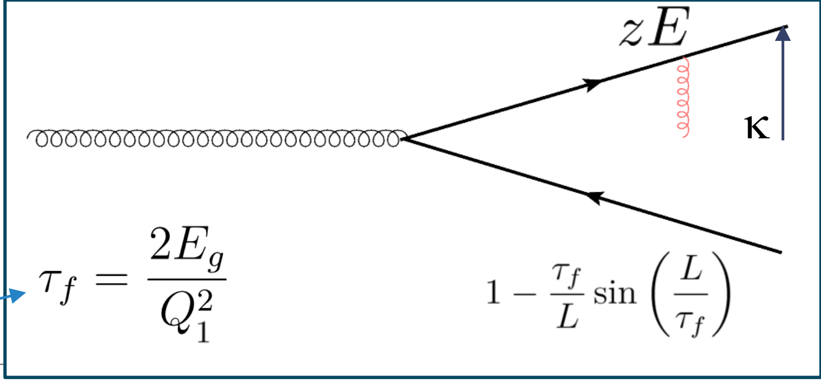


BDMPS-Z *formation time* in three approximations:

- AMY: infinite medium, no formation time
- N = 1: single scattering, accurate at early times
- H.O.: good approximation at late time

Simon Caron-Huot and Charles Gale, Finite-size effects on the radiative energy loss of a fast parton in hot and dense strongly interacting matter (2010)

N = 1 approximation (GLV)



Full form
$g \to c\bar{c}$

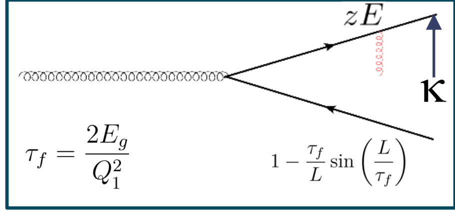
$$\left(\frac{1}{Q^2}P_{g\to c\bar{c}}\right)^{\text{med}}_{N=1} = \frac{1}{2}n_0\,L\int\frac{d\mathbf{q}}{(2\pi)^2}|a_3(\mathbf{q},z)|^2\left(1-\frac{\tau_f}{L}\sin\left(\frac{L}{\tau_f}\right)\right)$$
$$\times\left[\left(\frac{1}{Q^2}P_{g\to c\bar{c}}\right)^{\text{vac}}_{\boldsymbol{\kappa}\to\boldsymbol{\kappa}+\mathbf{q}} - \left(\frac{1}{Q^2}P_{g\to c\bar{c}}\right)^{\text{vac}}\right.$$
$$\left.+\left(\frac{1}{Q_1^2}-\frac{1}{Q^2}\right)^2\frac{m_c^2}{2z(1-z)}+\left(\frac{(\boldsymbol{\kappa}+\mathbf{q})}{Q_1^2}-\frac{\boldsymbol{\kappa}}{Q^2}\right)^2\frac{z^2+(1-z)^2}{2z(1-z)}\right]$$

Scatterings + interference term

Shifting of momentum (broadening)

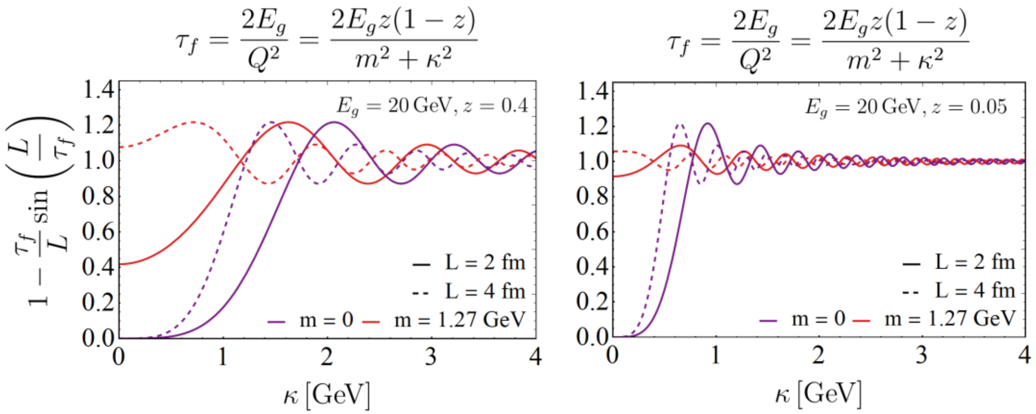
Enhanced production

- $n_0\,L$: number of scattering centres encountered
- $|a_3(\mathbf{q},z)|$ cross section for scattering with medium parton with momentum **q**
- $\left(\frac{1}{Q^2}P_{g\to c\bar{c}}\right)^{\text{vac}}_{\boldsymbol{\kappa}\to\boldsymbol{\kappa}+\mathbf{q}}$: vacuum splitting function, but with transverse momentum broadened by **q**
- Q (Q_1): virtuality of parent gluon after (before) medium interactions



The interference term

z = 0.4 z = 0.05



Looks somewhat deceptively simple:

$$\frac{1}{2} n_0\, L \int \frac{d\mathbf{q}}{(2\pi)^2} |a_3(\mathbf{q}, z)|^2 \left(1 - \frac{\tau_f}{L}\sin\left(\frac{L}{\tau_f}\right)\right)$$

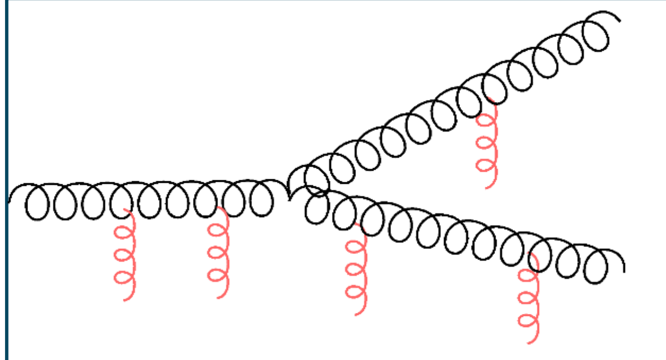
$$\tau_f = \frac{2E_g}{Q^2} = \frac{2E_g z(1-z)}{m^2+\kappa^2}$$

- Proportional to density, length
- No scatterings before the (vacuum-like) splitting

- Charm mass is essential: cuts of low **q** limit
- Larger effect for democratic splittings (z = 1/2)

$$\omega \frac{d(I_g - I_{vac})}{d\omega} = \frac{\alpha}{\pi} x P_{s\to g}(x) \log\left|\cos\left(L\sqrt{\frac{C_A(1-x)+x^2C_s}{2ix(1-x)E}\hat{q}}\right)\right| \qquad x = \omega/E$$

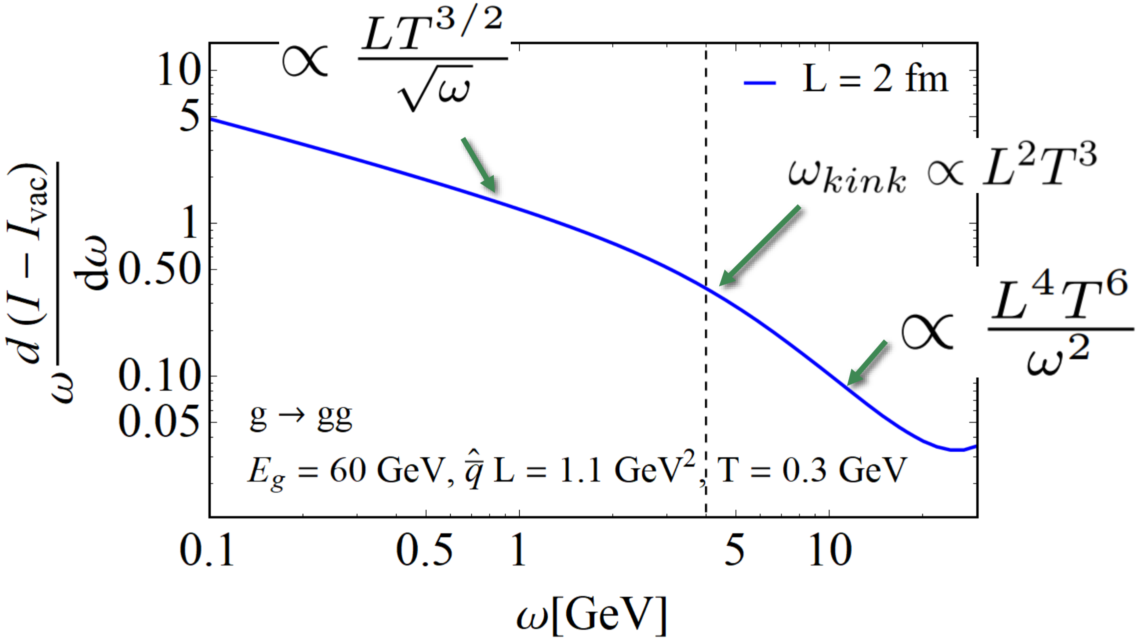
$$P_{g\to gg}(x) = C_A \frac{1+x^4+(1-x)^4}{x(1-x)}$$



$$|a(\boldsymbol{q})|^2 \propto \frac{1}{(\frac{1}{2}A^2+\boldsymbol{q}^2)^2} \to e^{-\boldsymbol{q}^2/A^2}$$

Multiple soft scatterings

Can be solved analytically for arbitrary # gluons:



$$x = z$$
$$\omega = k$$

- Non-trivial length dependence: $\int d\omega\omega \frac{d(I_g - I_{vac})}{d\omega} \sim L^2T^3$ (both regimes) $(\omega_{kink} \ll E)$
- Can easily be generalised to evolving mediums
- Important caveat: approximation does not work well for small lengths…

R. Baier, Yu.L. Dokshitzer, A.H. Mueller, D. Schiff, Medium-induced radiative energy loss; equivalence between the BDMPS and Zakharov formalisms (1998)
Peter Arnold, Simple Formula for High-Energy Gluon Bremsstrahlung in a Finite, Expanding Medium (2008)

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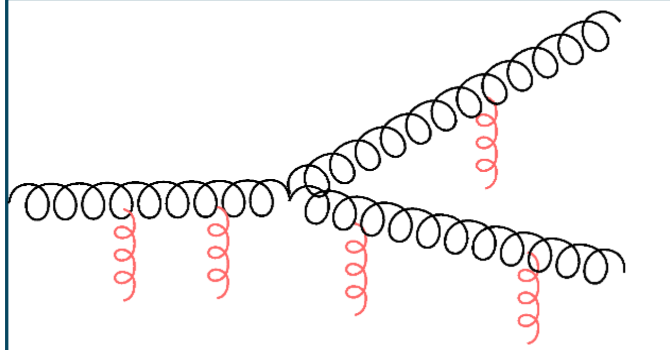

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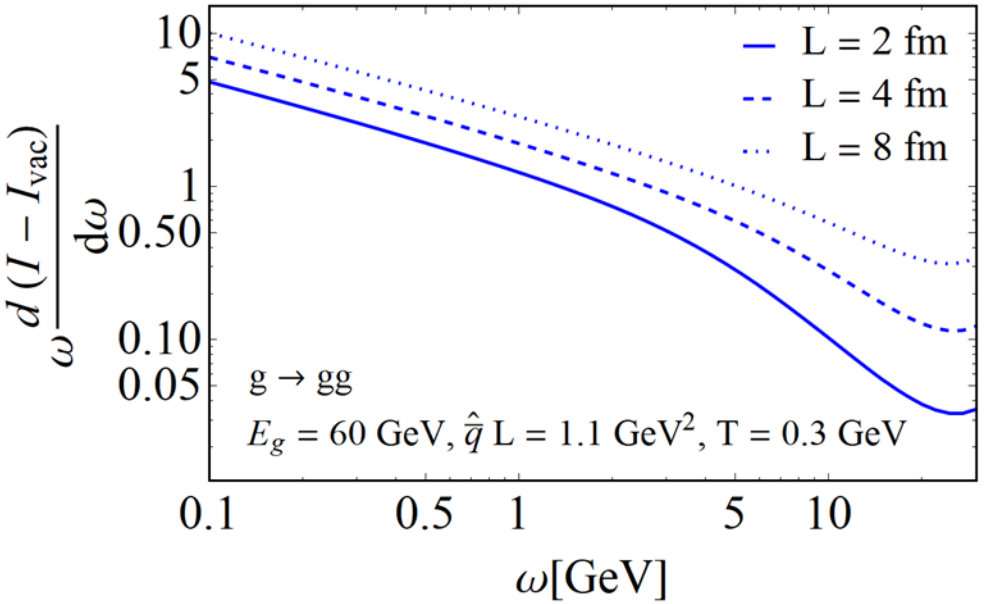

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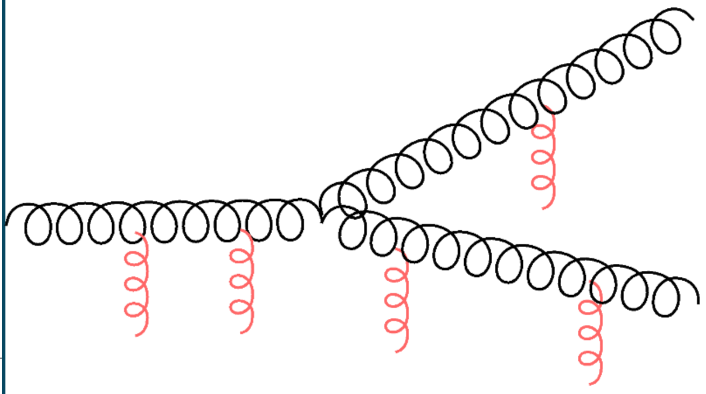
$$\omega \frac{d(I_{q\bar{q}} - I_{vac})}{d\omega} = \frac{\alpha}{\pi} x P_{g\to q\bar{q}}(x) \log\left|\cos\left(L\sqrt{\frac{(C_F - x(1-x)C_A}{2ix(1-x)E}\hat{q}}\right)\right| \qquad x = \omega/E$$

$$P_{g\to c\bar{c}}(x) = t_F(x^2 + (1-x)^2) + m_c^2/Q^2 \approx 1/2$$

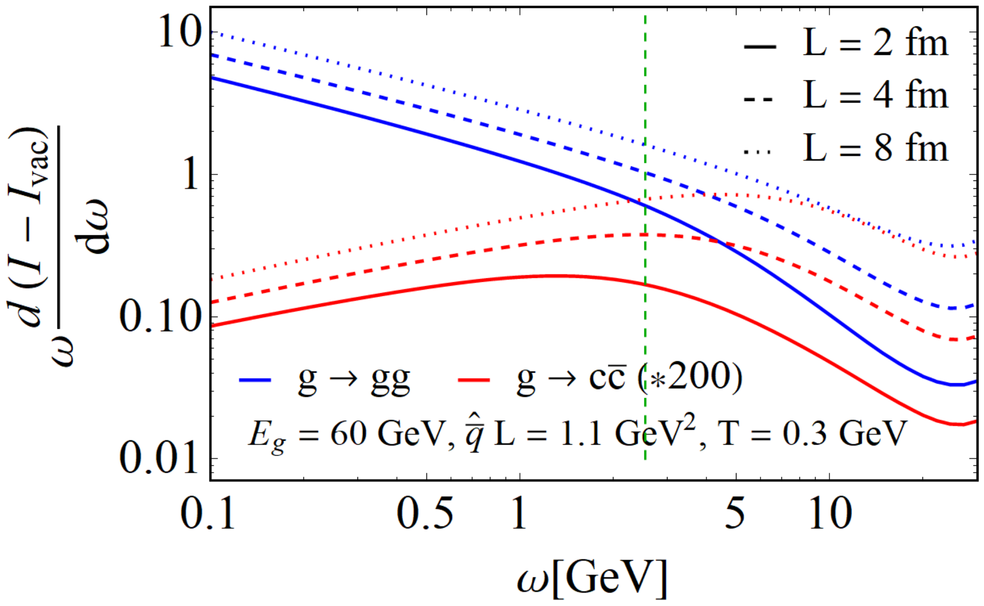


$$|a(\boldsymbol{q})|^2 \propto \frac{1}{(\frac{1}{2}A^2 + \boldsymbol{q}^2)^2} \to e^{-\boldsymbol{q}^2/A^2}$$

Multiple soft scatterings

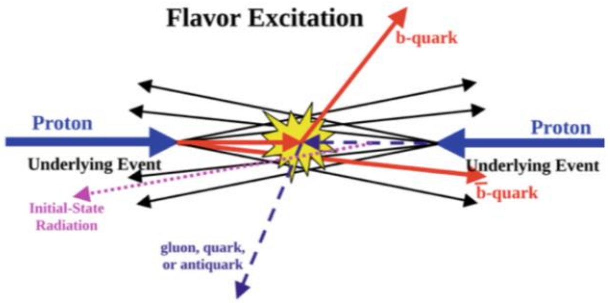
Generalised to quark-antiquark pairs:

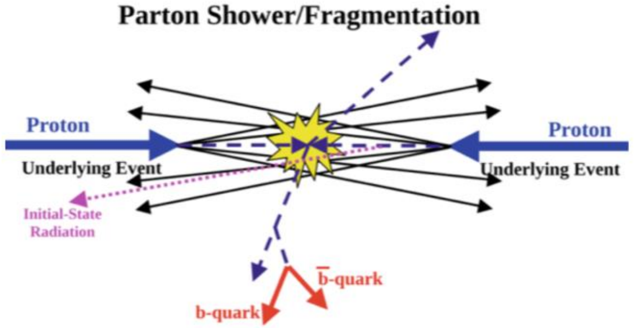
m_c

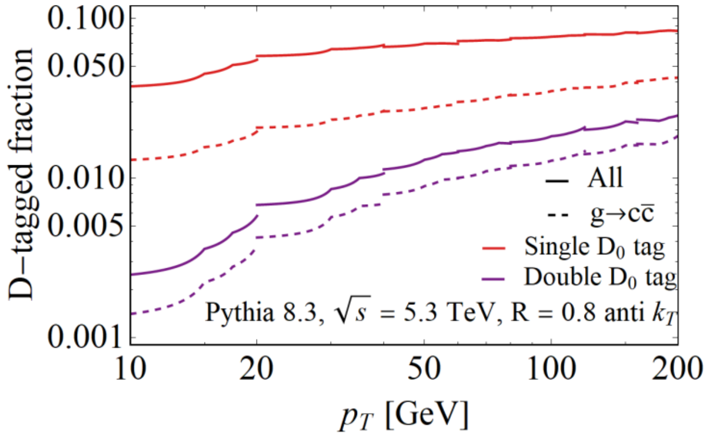


- No IR-divergence, stronger length dependence
- Lower cut off in IR at twice the charm mass (green line)

Some D meson basics



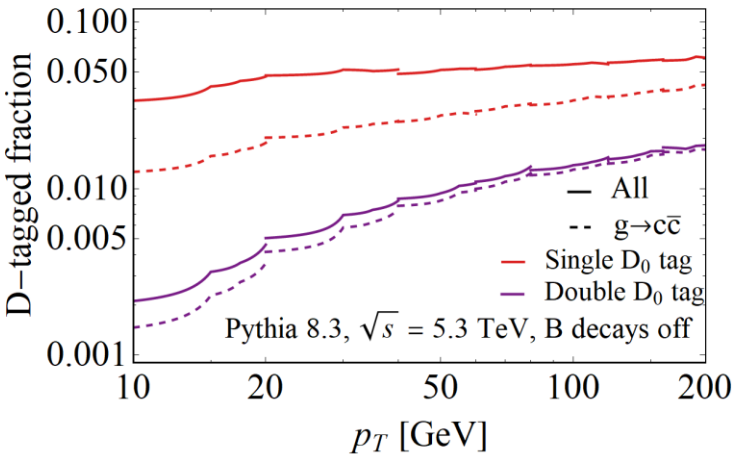




Charm and D meson production

- ~Few percent: Hard scattering
- ~1/4: B-meson decays
  - Can in principle be removed as background
- ~1/3: Flavour excitation / initial state radiation
- ~1/2: Gluon splitting
  - Can identify gluon splitting by doubly-tagged D meson jets:

Turn off B decays:



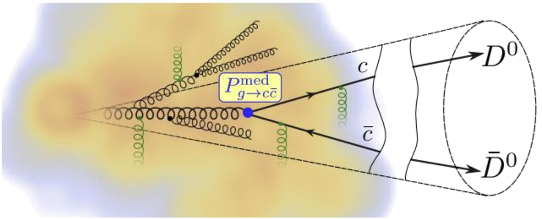
How to identify the charms experimentally?

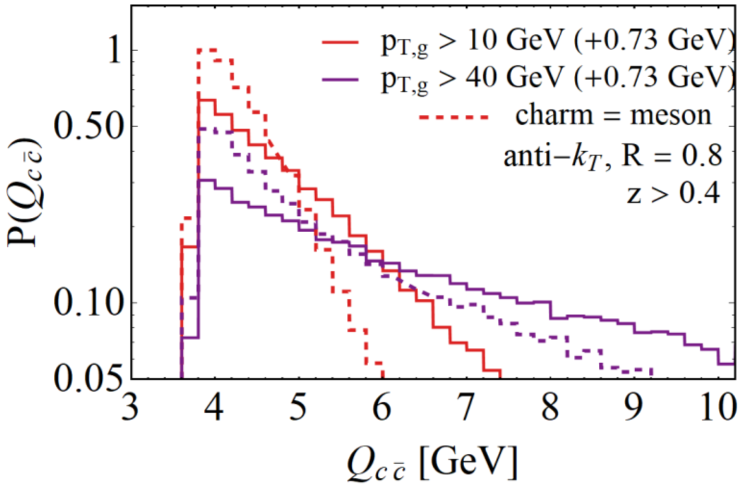
Charms decay to D-mesons: focus on D_0 for relatively clean decay channel

Ideally we need:

- Energy of the gluon, angular distance charm-anticharm, ratio energies charm/anticharm
  - Equivalently: E, Q and z

First obvious strategy: identify D-mesons with charms:





Shift virtuality by difference charm/D mass

Underestimates virtuality significantly

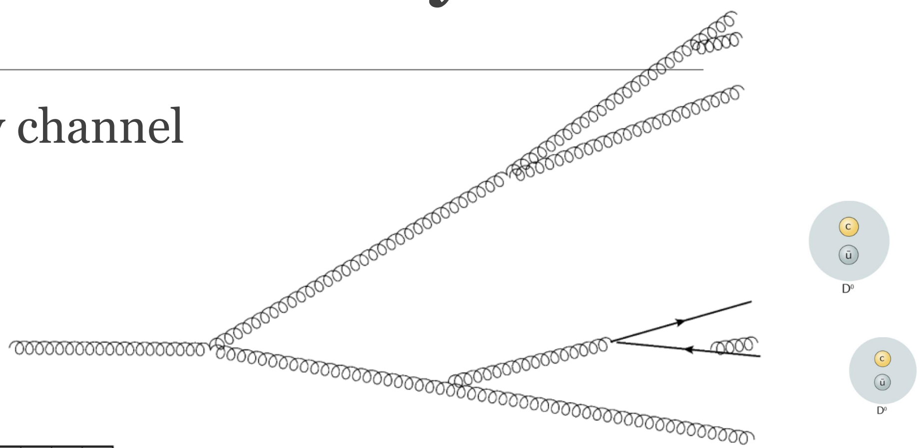
→ c branches into more particles than D

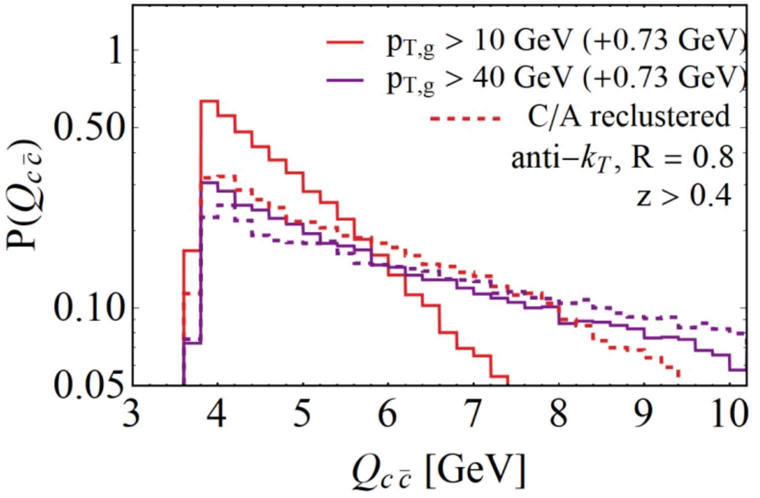
How to identify the charms experimentally?

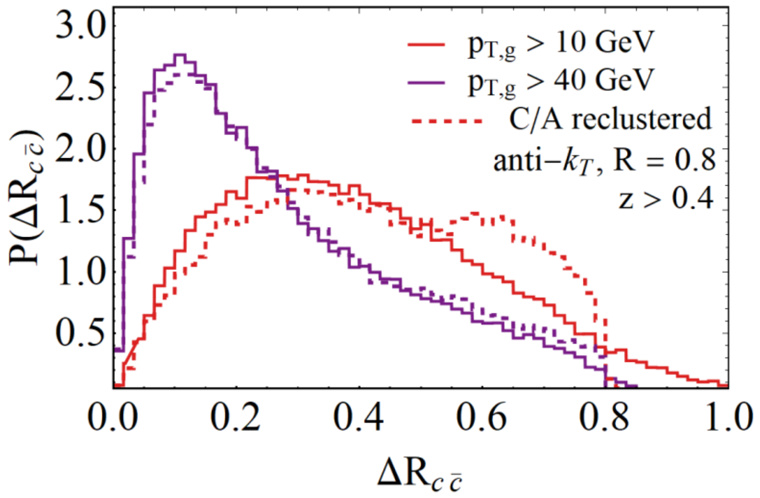
Charms decay to D-mesons: focus on D_0 for relatively clean decay channel

Second relatively obvious strategy:

- Find subjets with C/A reclustering until two subjets have one D meson
- No grooming necessary (but worry about IRC safety?)







Works much better at high p_T

Relatively good angle

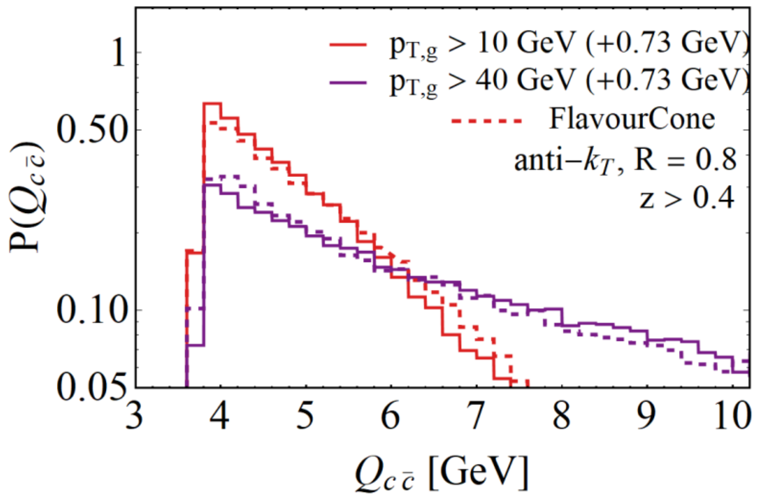
Gluon splitting and modified FlavourCone

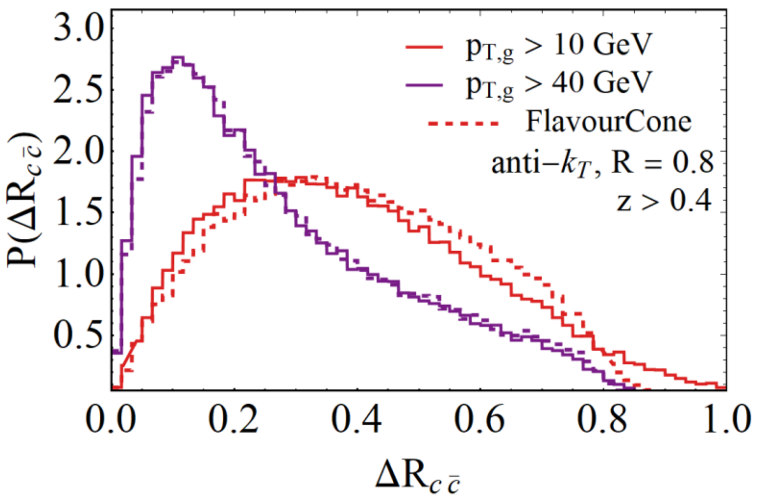
FlavourCone is a simple algorithm:

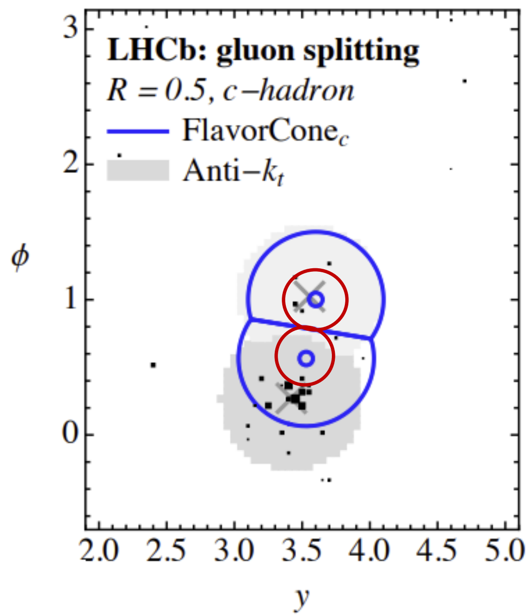
- Flavoured hadrons provide seeds
- Particles are clustered to closest seed within distance R

Turns out small modification needed:

- Take radius R to be half-distance between the D mesons







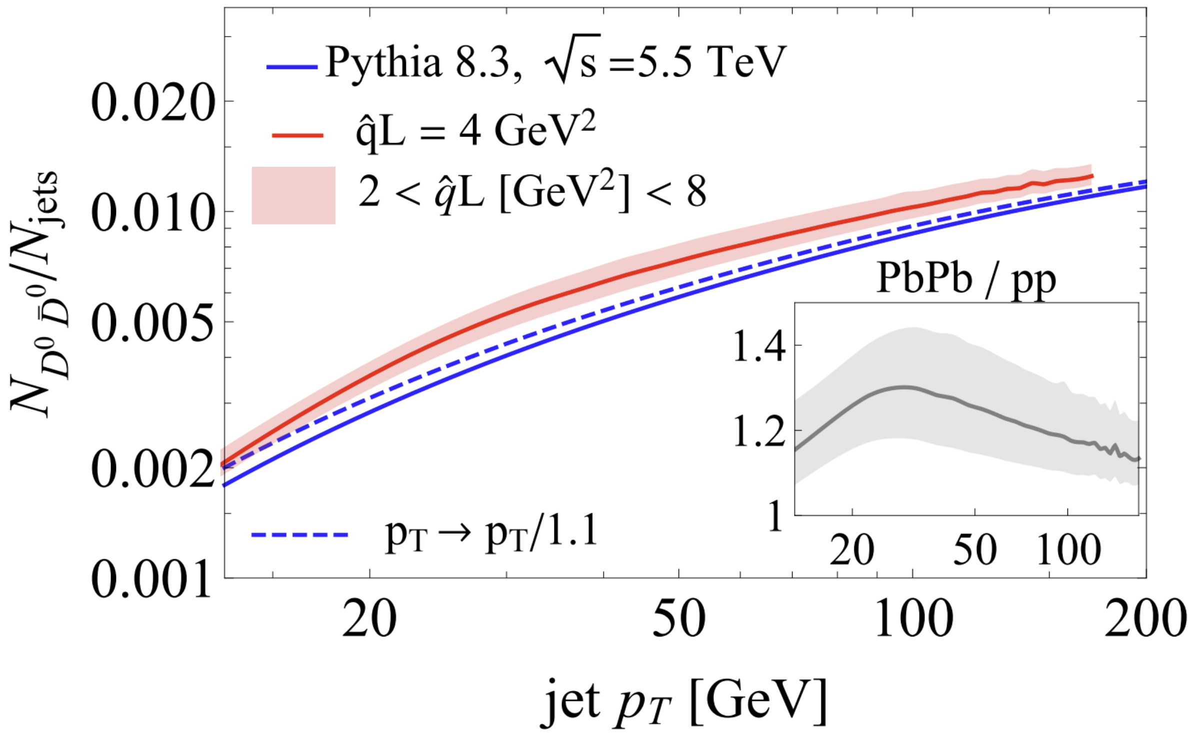
Two subtleties: works less well at small z (see back-up), harder to find estimate for gluon energy

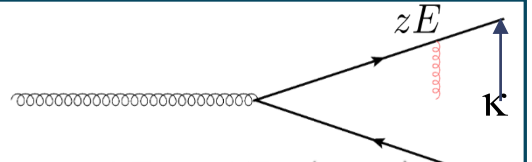
Medium modification: total integrated enhancement

A reweighting prescription for medium modification:

$$w_{event} = 1 + \frac{P_{med}}{P_{vac}}$$

Enhancement decreases towards high p_T





$$\tau_f = \frac{2E_g}{Q^2} = \frac{2E_g z(1-z)}{m^2+\kappa^2}$$

Medium modifications for Q

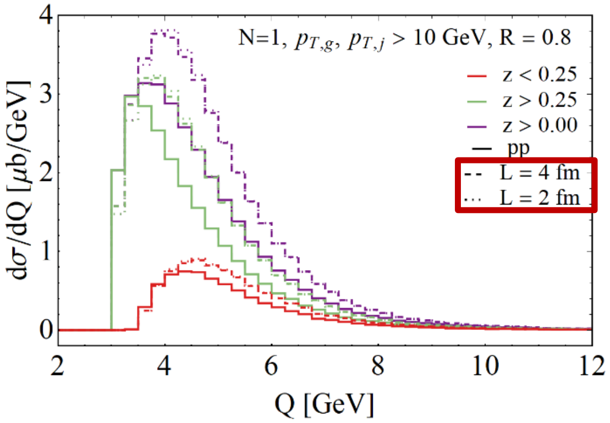
A reweighting prescription for medium modification:

$$w_{event} = 1 + \frac{P_{med}}{P_{vac}}$$

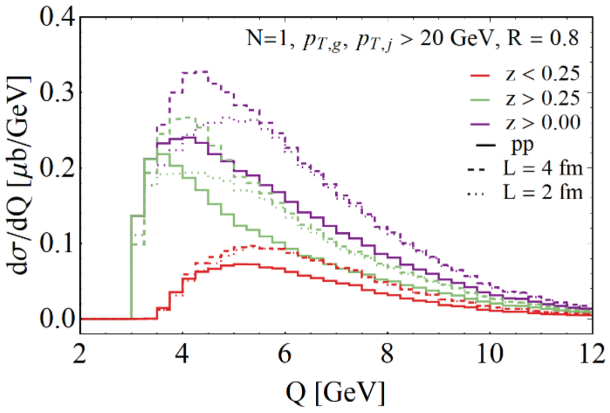
Virtuality distribution at fixed $\hat{q}L$:

- Enhanced and broadened (shift to higher Q)
- Strong length dependence for large E, small Q and high z (~long formation time)
- Optimal energy ~20-40 GeV for length dependence

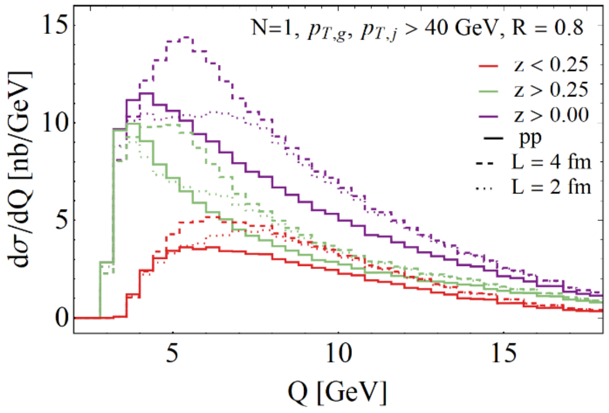
E_g > 10 GeV



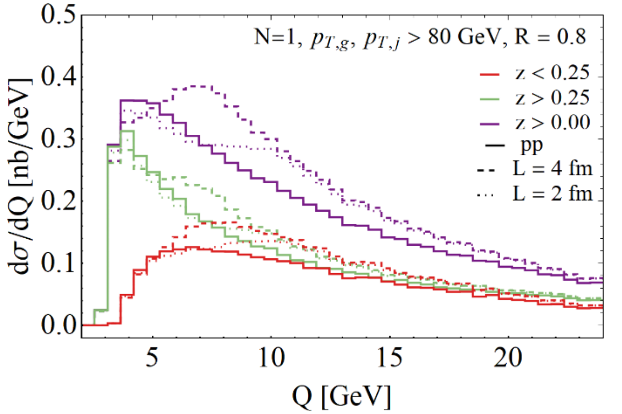
E_g > 20 GeV



E_g > 40 GeV



E_g > 80 GeV



Outlook

Gluon to ccbar as a probe into the spacetime structure of the parton shower

- Reviewed formation time in parton showers
  - Should be significantly less medium modification for small path lengths (keeping $\hat{q}L$ fixed)
- How to identify a charm?
  - Tried three approaches; remarkable success with modified FlavourCone
- A reweighting prescription for medium modifications
  - Enhancement and broadening that sensitively depend on the path length

Ccbar in a jet unique observable: direct access to a splitting with interesting QGP modification

- 20 to 40 GeV optimal range to see length dependence

The ideal playground for the formation time will be PbPb + OO collisions (vary L, fix $\hat{q}L$)

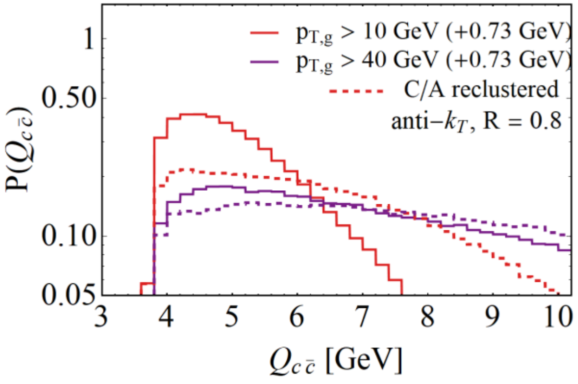
Many things to improve for realistic modelling

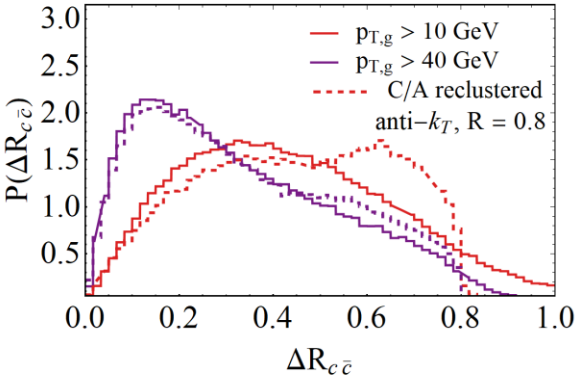
1. Realistically evolving medium (hydrodynamics)
2. Full medium modified parton shower with formation time
3. Smoking gun signal for the formation time?

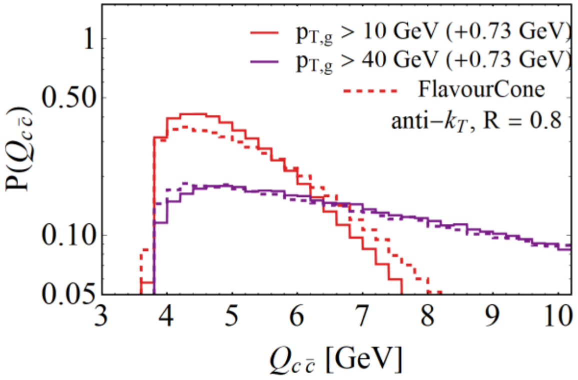
Back-up

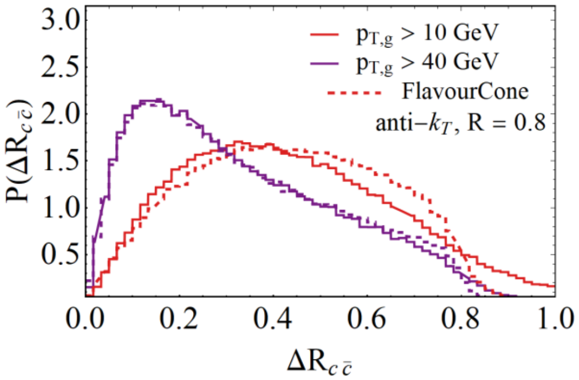
Inclusive gluon splitting with C/A and FlavourCone

More difficult to estimate splittings with *small z* (e.g. high virtuality) (less relevant for formation time)







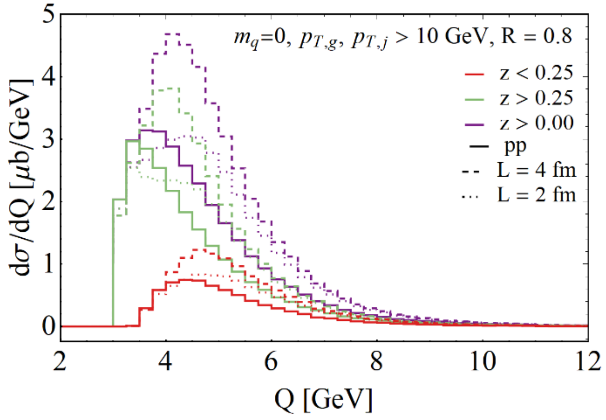


Importance of charm mass

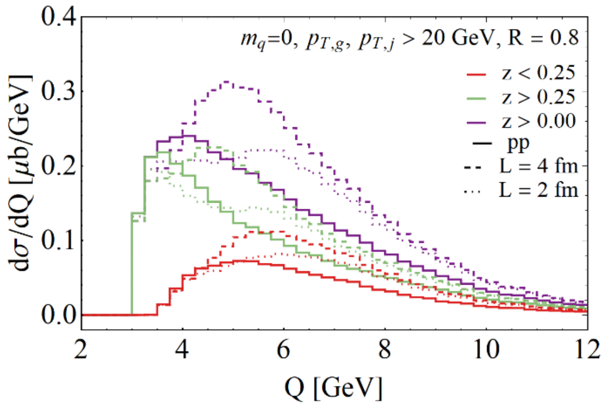
Toy computation; take N=1 medium splitting function, but with *m = 0*.

Much larger effects, and larger length dependence (formation time longer)

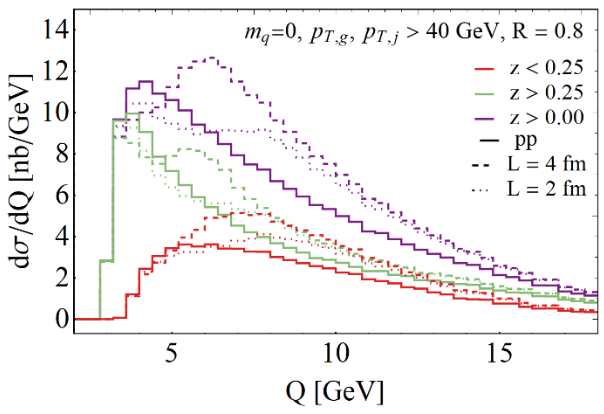
$E_g > 10$ GeV



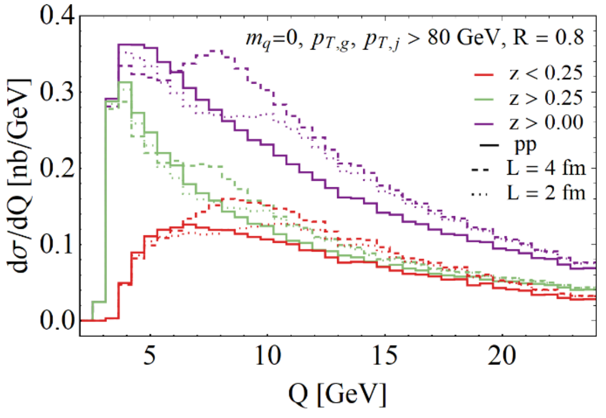
$E_g > 20$ GeV



$E_g > 40$ GeV



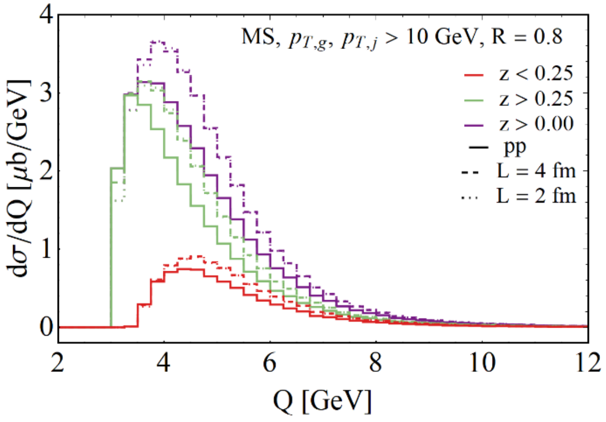
$E_g > 80$ GeV



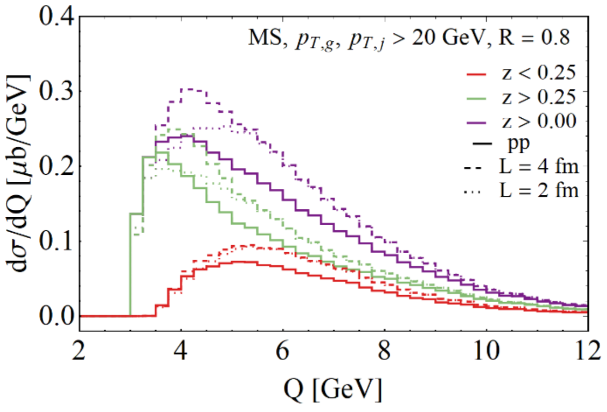
Medium modifications

Similar results in multiple soft/harmonic oscillator approximation:

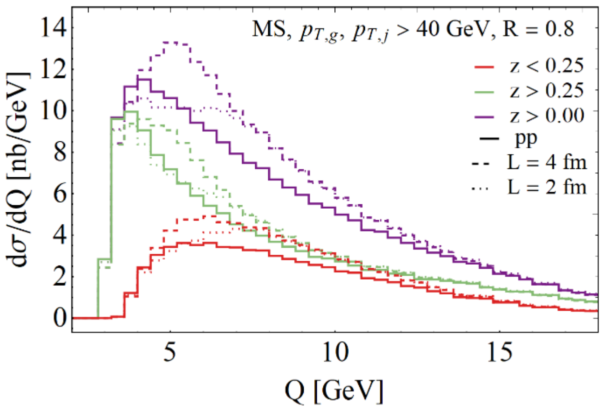
$E_g > 10$ GeV



$E_g > 20$ GeV



$E_g > 40$ GeV



$E_g > 80$ GeV