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SCET

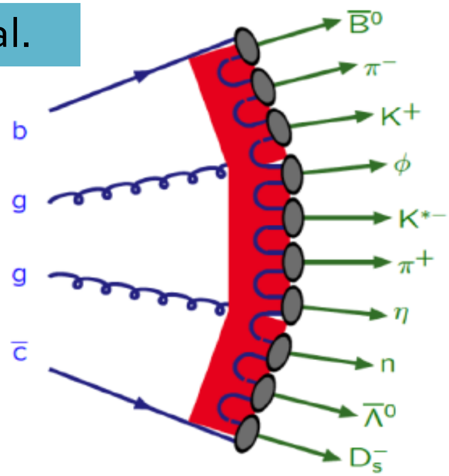
Heavy Flavor Transport in QCD Matter
ECT, Trento, Italy, Apr. 26 – 30, 2021*

Introduction

- Hadronization and SCET phenomenology for D and B mesons

String fragmentation

PYTHIA et al.

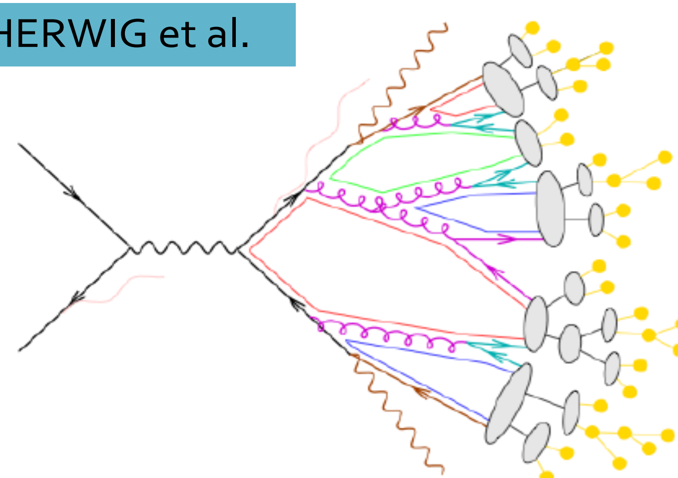


$$f(z) \propto \frac{1}{z}(1-z)^a \exp\left(-\frac{bm_\perp^2}{z}\right)$$

- This picture allows to derive the form of fragmentation functions (not as general) but comes from a model

Cluster hadronization

HERWIG et al.



program	PYTHIA	HERWIG
model	string	cluster
energy–momentum picture	powerful	simple
	predictive	unpredictive
parameters	few	many
flavour composition	messy	simple
	unpredictive	in-between
parameters	many	few

Perturbative calculations and fragmentation

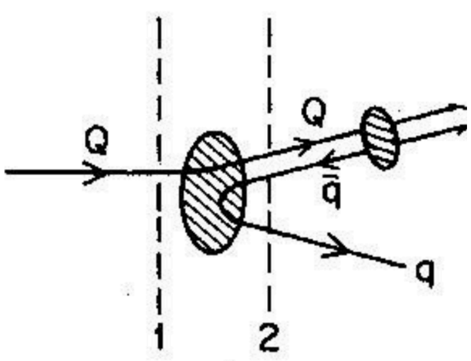
Perturbative calculations are based on the factorization approach

$$E_h \frac{d\sigma}{d^3p} \propto f_{a/A}(x_a, Q^2) \otimes f_{b/B}(x_b, Q^2) \otimes \frac{d\sigma^{ab\to cd}}{dt} \otimes D(z, Q^2)$$

$$D(z,Q^2) \to \int_0^1 P(\varepsilon) \frac{1}{1-\varepsilon} D\left(\frac{z}{1-\varepsilon}, Q^2\right)$$

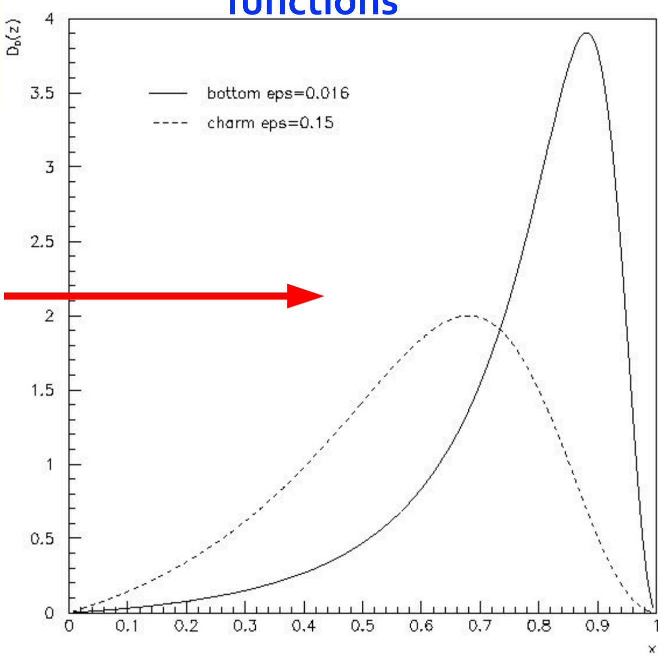
Fragmentation functions

C. Peterson et al. (1983)



$$f(z) \propto \frac{1}{z(1 - 1/z - \epsilon/(1-z))^2}$$

Based on energy transfer in the pictured process

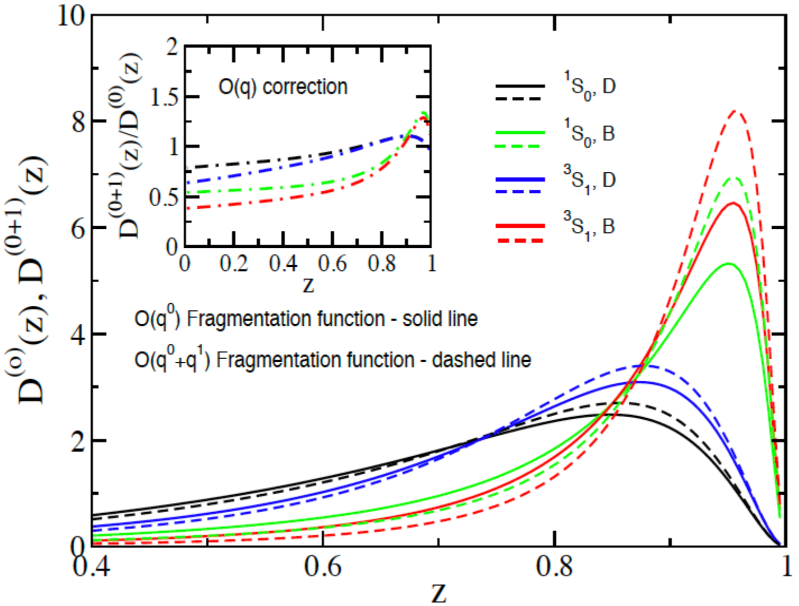


Perturbative calculations of fragmentation

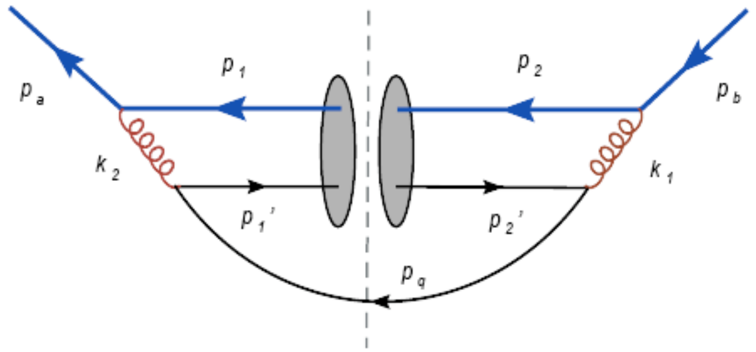
Heavy quarks introduce a mass scale that allows the fragmentation function shape to be computed perturbatively. HQET

Chang et al. (1992)

Braaten et al. (1995)



R. Sharma et al. (2009)



Pseudoscalar, vector, tensor channels – these contribute to the various D and B meson states

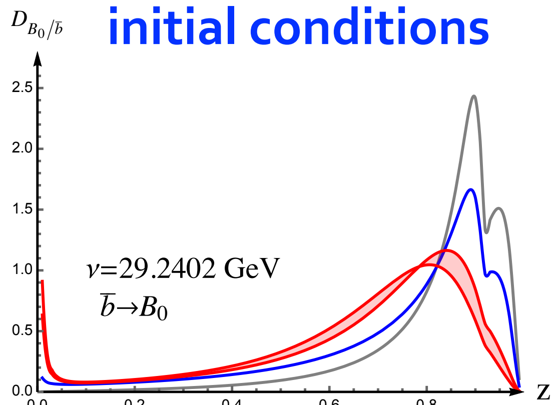
- Still depends on non-perturbative parameters $r = m_q/M_Q$, the square of the wavefunction in the origin. Fitted to data

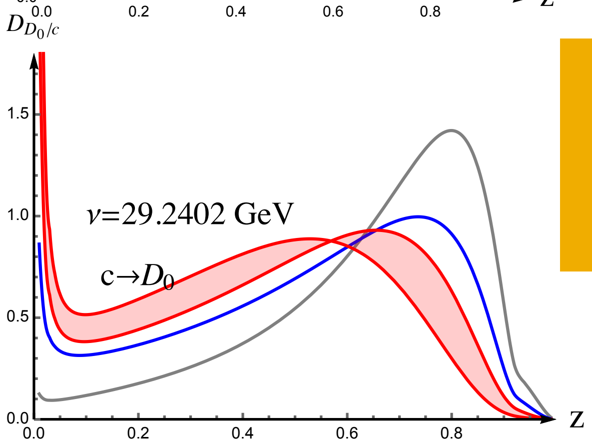
FONLL uses this parametrizations. Note that no evolution is used

Evolution to higher scales

The FF calculation is used for initial condition, which is further evolved to the scale of choice for the calculation

Feed down from higher excided states taken into account. Included in initial conditions





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

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

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

$$\left.+P_{g\to q\bar{q}}(z',Q)\left(D_q\left(\frac{z}{z'},Q\right) + f_{\bar{q}}\left(\frac{z}{z'},Q\right)\right)\right\}.$$

Standard vacuum DGLAP evolution – standard tools

Boundary condition
Vacuum evolution
Medium evolution

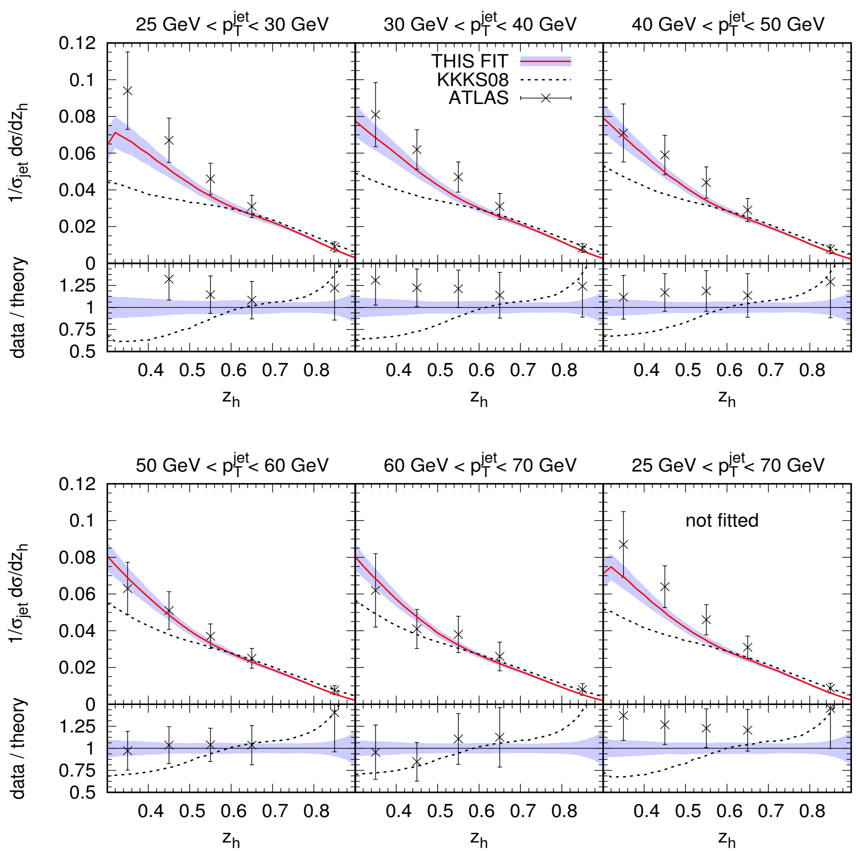
The important part is the that with NO gluon to heavy quark contribution in initial conditions it is GENERATED through evolution and mixing

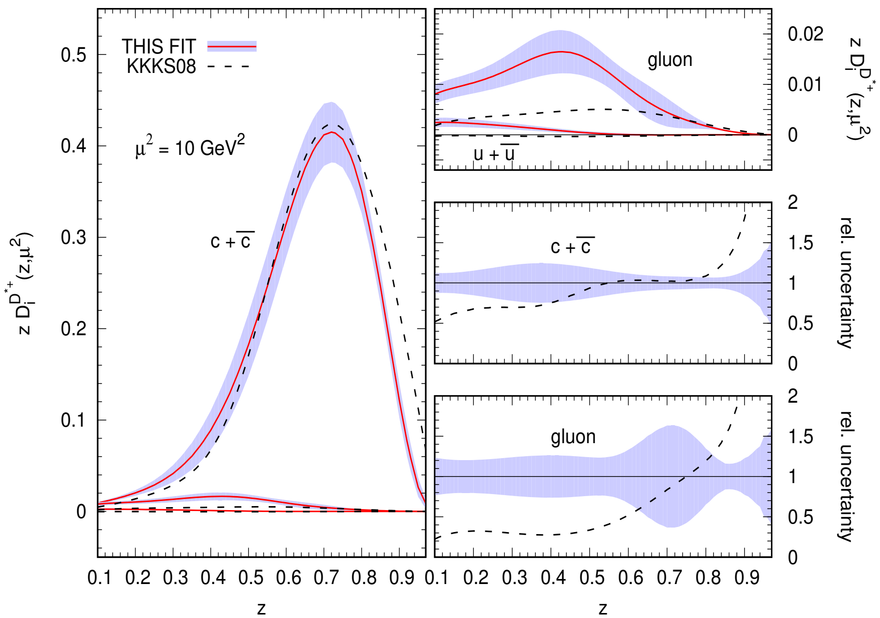
Full gluon fragmentation in open heavy flavor

$$\frac{d\sigma_{pp}^{H}}{dp_T d\eta} = \frac{2p_T}{s} \sum_{a,b,c} \int_{x_a^{\min}}^{1} \frac{dx_a}{x_a} f_a(x_a,\mu) \int_{x_b^{\min}}^{1} \frac{dx_b}{x_b} f_b(x_b,\mu) \times \int_{z_c^{\min}}^{1} \frac{dz_c}{z_c^2} \frac{d\hat{\sigma}_{ab}^{c}(\hat{s},\hat{p}_T,\hat{\eta},\mu)}{dvdz} D_c^H(z_c,\mu),$$

T. Kneech et al. (2008)

Started by Kniehl and Kneesch, treat all partons on the same footing





D. Anderle et al. (2017)

Charm production inside jets provides strong constraints in gluon fragmentation in D mesons

SCET phenomenology I

F. Ringer et al. (2017)

Application at LHC – strictly NLO. Uses full splitting functions

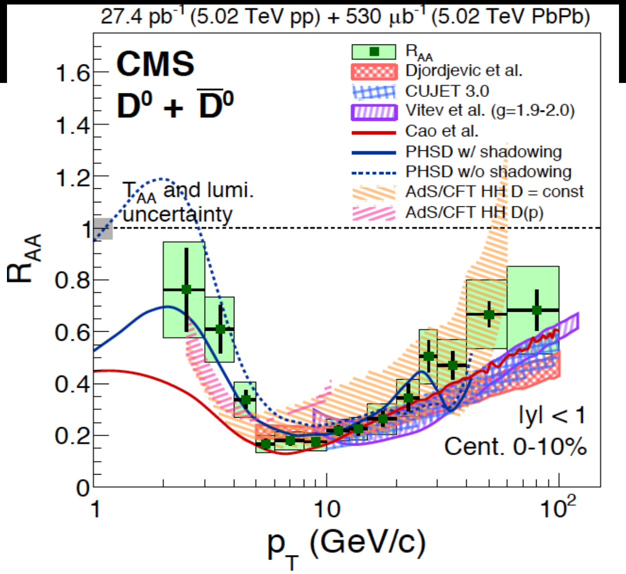
$$d\sigma^{H}_{\mathrm{PbPb}} = d\sigma^{H,\mathrm{NLO}}_{pp} + d\sigma^{H,\mathrm{med}}_{\mathrm{PbPb}}$$

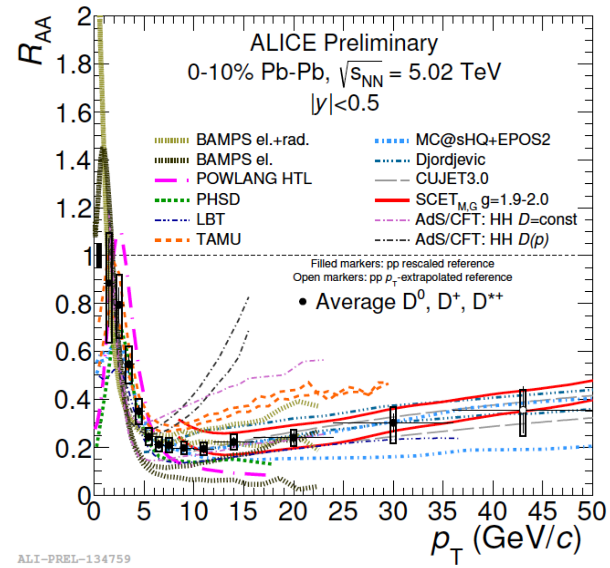
$$\sum_j \hat{\sigma}_i^{(0)} \otimes \mathcal{P}^{\mathrm{med}}_{i\to jk} \otimes D_j^H \equiv \hat{\sigma}_i^{(0)} \otimes D_i^{H,\mathrm{med}}$$

$$D_q^{H,\mathrm{med}}(z,\mu) = \int_z^1 \frac{dz'}{z'} D_q^H\left(\frac{z}{z'},\mu\right) \mathcal{P}^{\mathrm{med}}_{q\to qg}(z',\mu) - D_q^H(z,\mu)\int_0^1 dz' \mathcal{P}^{\mathrm{med}}_{q\to qg}(z',\mu) + \int_z^1 \frac{dz'}{z'} D_g^H\left(\frac{z}{z'},\mu\right) \mathcal{P}^{\mathrm{med}}_{q\to gq}(z',\mu)\,,$$

$$D_g^{H,\mathrm{med}}(z,\mu) = \int_z^1 \frac{dz'}{z'} D_g^H\left(\frac{z}{z'},\mu\right) \mathcal{P}^{\mathrm{med}}_{g\to gg}(z',\mu) - \frac{D_g^H(z,\mu)}{2}\int_0^1 dz' \Big[\mathcal{P}^{\mathrm{med}}_{g\to gg}(z',\mu) + 2N_f \mathcal{P}^{\mathrm{med}}_{g\to q\bar{q}}(z',\mu)\Big] + \int_z^1 \frac{dz'}{z'} \sum_{i=q,\bar{q}} D_i^H\left(\frac{z}{z'},\mu\right) \mathcal{P}^{\mathrm{med}}_{g\to q\bar{q}}(z',\mu)\,.$$

- Strictly fixed order – NLO, uses the first step in te DGLAP evolution
- Uses fragmentation of all partons. Gluon fragmentation to D mesons gives significant contribution



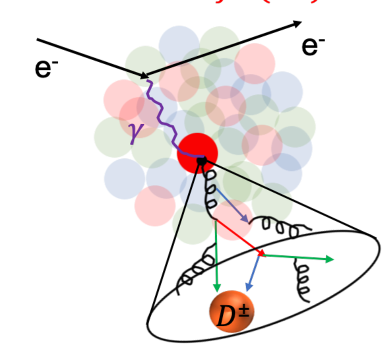


SCET phenomenology II

Z. Liu et al. (2020)

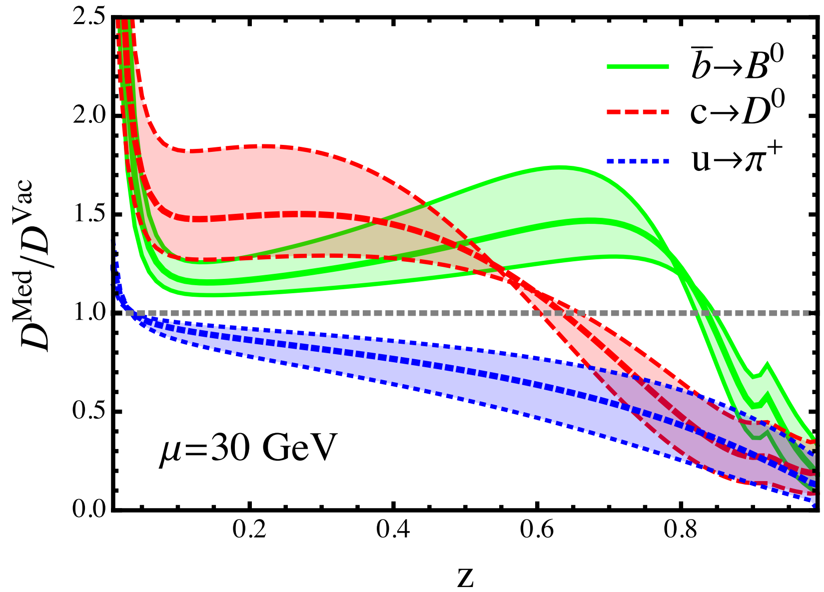
Application at EIC – Full in-medium DGLAP evolution. Uses full splitting functions

$e^- + \mathrm{Au} \rightarrow e^- + jet(D^{\pm}) + X$

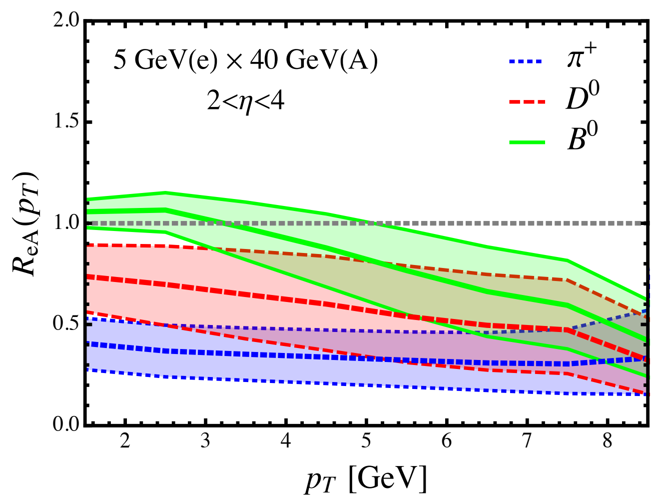


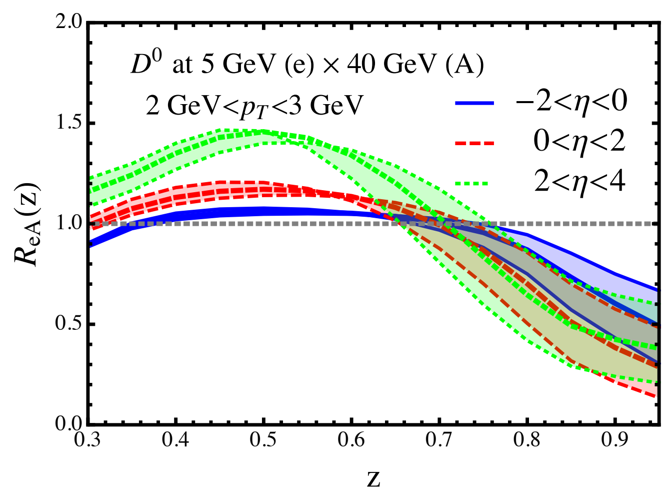
$$R^h_{eA}(p_T,\eta,z) = \frac{\left.\frac{N^h(p_T,\eta,z)}{N^{\mathrm{inc}}(p_T,\eta)}\right|_{\mathrm{e+Au}}}{\left.\frac{N^h(p_T,\eta,z)}{N^{\mathrm{inc}}(p_T,\eta)}\right|_{\mathrm{e+p}}}$$

Normalized by inclusive large radius jet production. To LO equivalent inclusive normalization

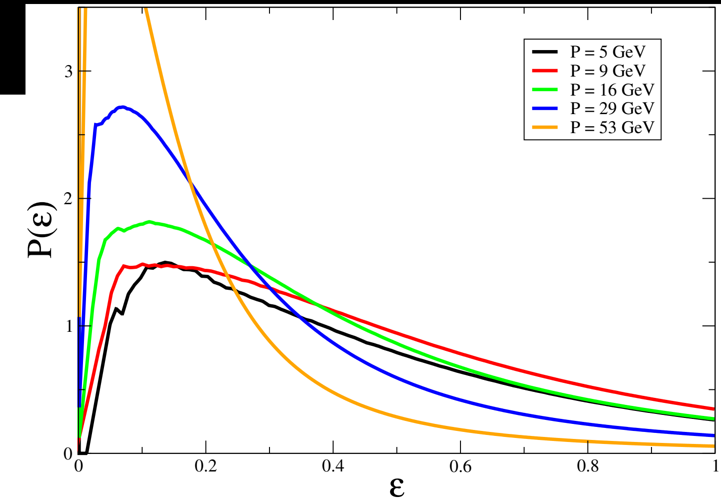


- The technique is developed. The example we have is cold nuclear matter and the EIC





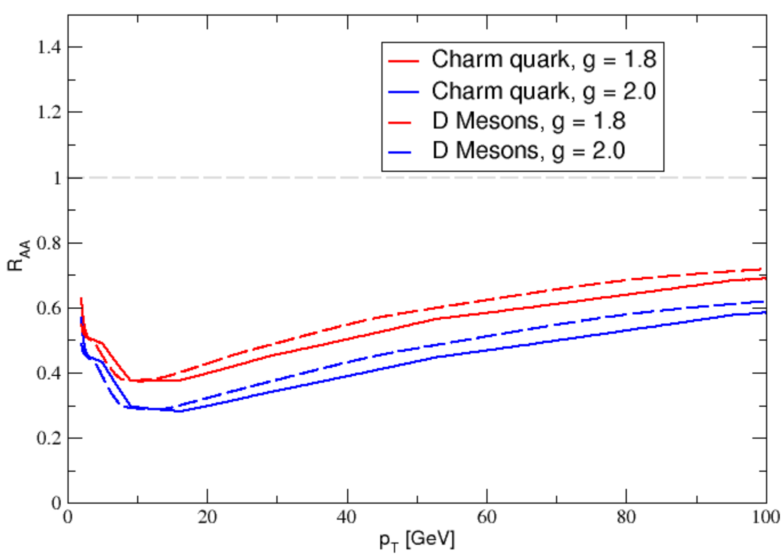
SCET phenomenology III a

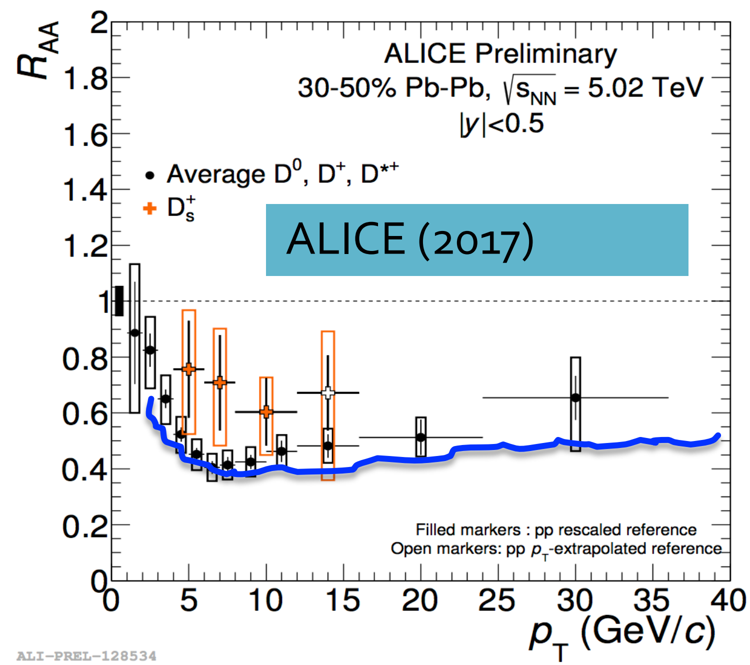


Application to homework – energy loss limit and LO cross sections

- There are two ways to implement energy loss
  - quench the partons
  - effective quenched fragmentation functions

$$\frac{1}{\langle N_{\rm coll.}\rangle}\frac{d\sigma^h_{med}}{dyd^2p_T} = \sum_c \int_{z_{\rm min}}^1 dz \int_0^1 d\epsilon\, P(\epsilon)\, \frac{d\sigma^c\left(\frac{p_T}{(1-\epsilon)z}\right)}{dyd^2p_{T_c}} \frac{1}{(1-\epsilon)^2 z^2} D_{h/c}(z)$$



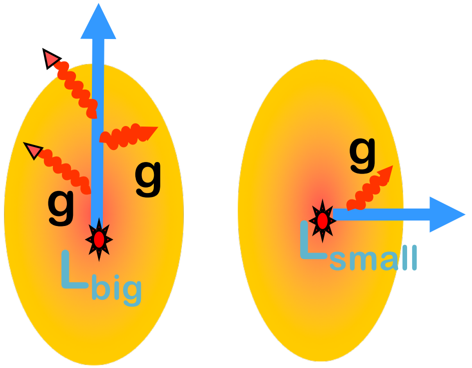


SCET phenomenology III b

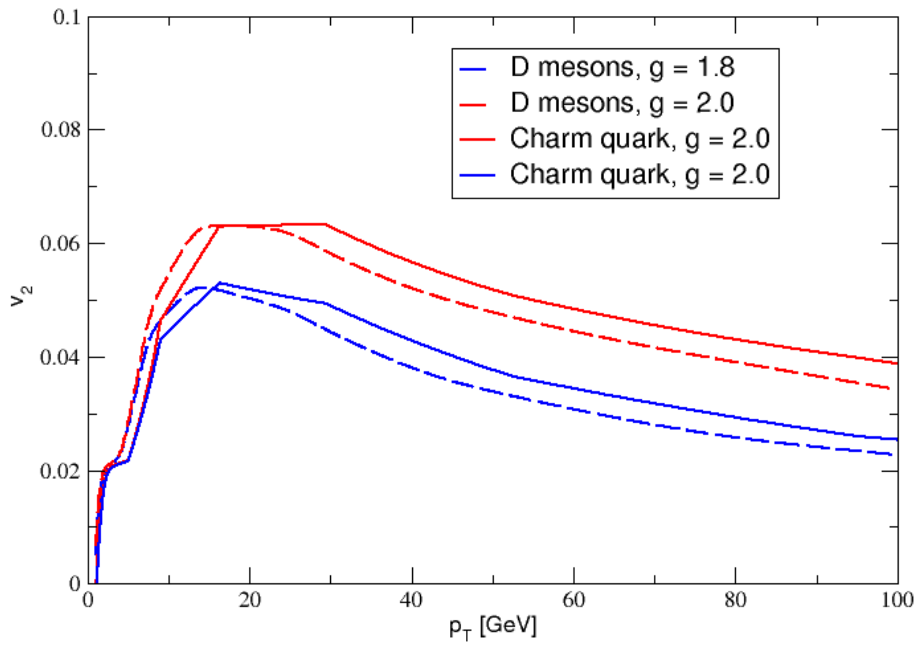
Application to homework – energy loss limit and LO cross sections

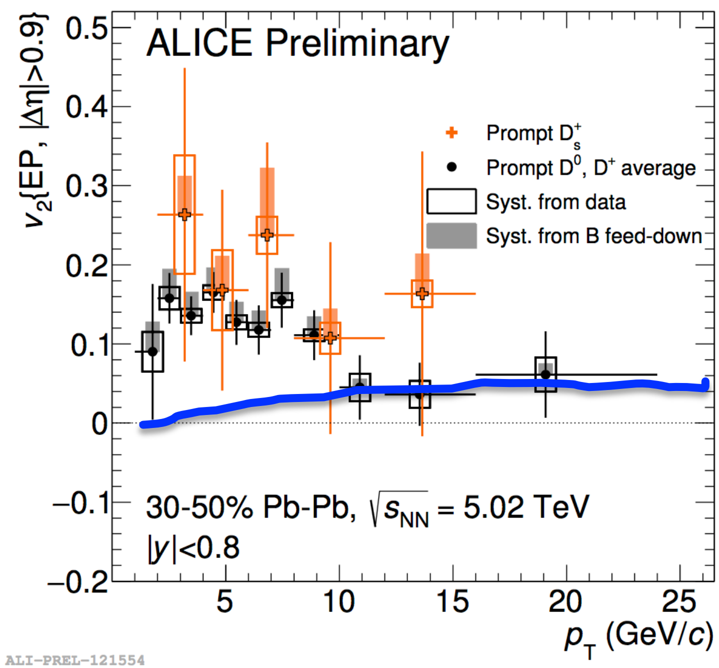
- Calculated from in-plane vs out-of-plane suppression

Azimuthal tomography



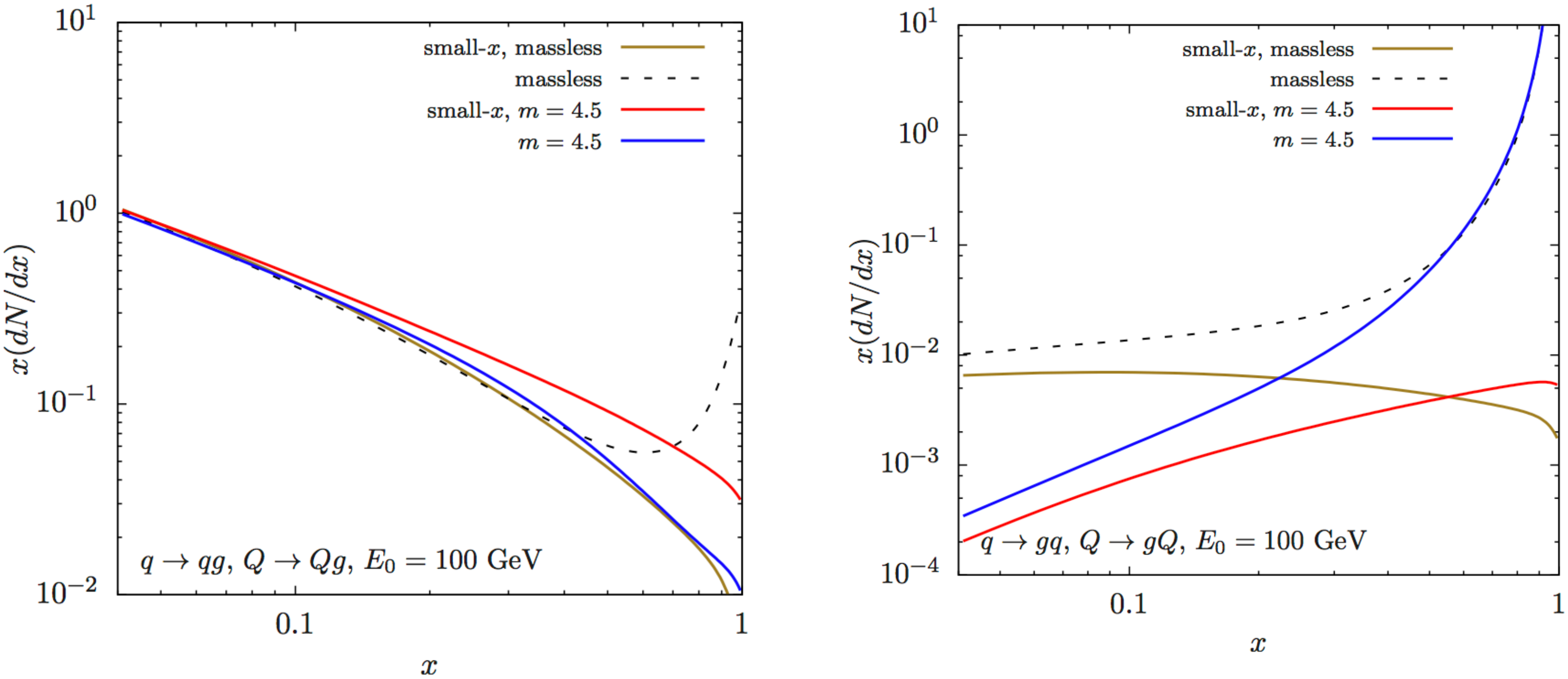
ALICE (2017)





Backup

You recall that SCET provides a full set of splitting functions as well as their energy loss limit



- The full splitting functions and the energy loss limit require different techgniqies to implement in cross section calculations