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Calculations of heavy meson production at the EIC

IInd, Yellow Report Workshop, May 20-22, 2020
Virtual meeting, Pavia, IT

Los Alamos
NATIONAL LABORATORY
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Outline of the talk

- Motivation
- NLO calculations of heavy mesons in e+p
- Evaluation of meson production in e+A
- Underlying formalism
- Results on nuclear modification. NLO effects
- Summary

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

Work primarily done by Z. Liu and H. Li

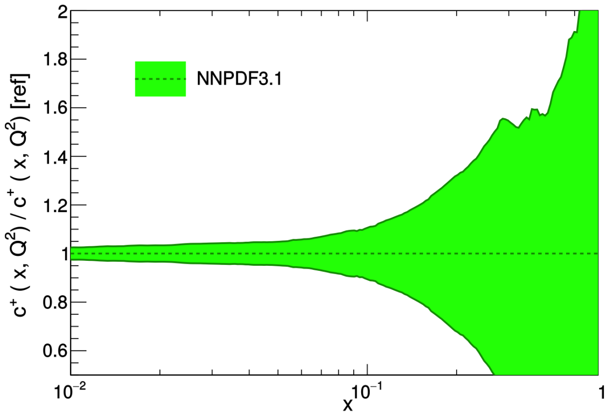
TMD Collaboration

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

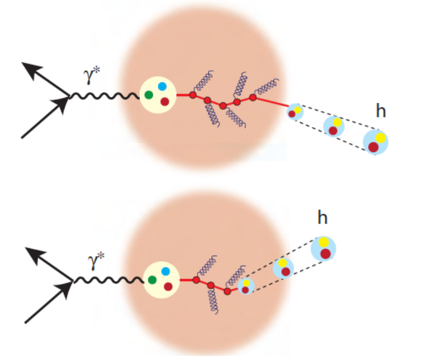
Motivation

Multiple uses of heavy flavor

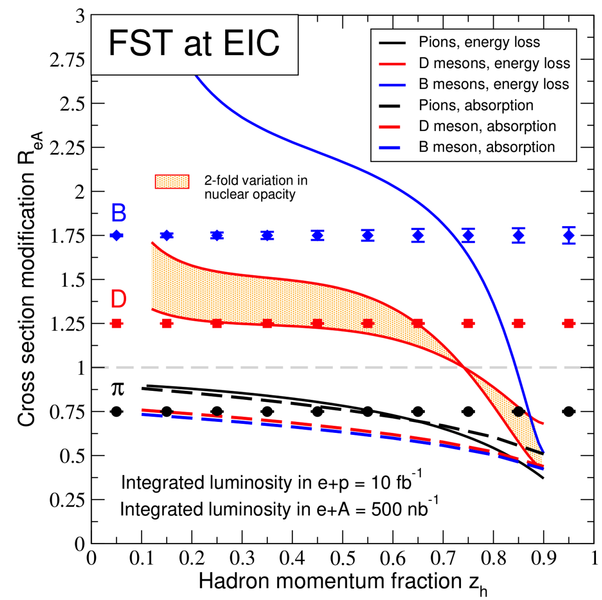
- Constrain gluon and c/b distributions. Look for intrinsic charm



R. Ball et al. (2016)



- Constrain the transport properties of cold nuclear matter
- Shed light on the picture of hadronization, differentiate between energy loss and hadron absorption
- Go beyond energy loss phenomenology at the EIC

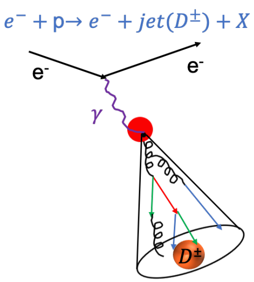


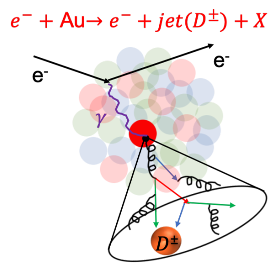
X. Li et al. (2020)

Evaluation in e+p

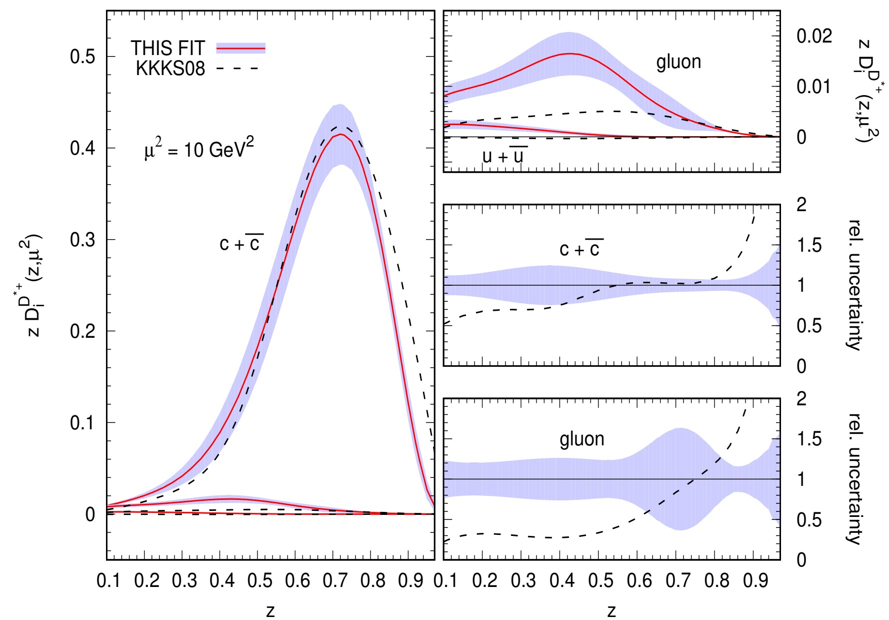
Cross sections in DIS

$$E_h \frac{d^3\sigma^{\ell N\to hX}}{d^3P_h} = \frac{1}{S}\sum_{i,f}\int_0^1 \frac{dx}{x}\int_0^1 \frac{dz}{z^2}\, f^{i/N}(x,\mu)\,\boxed{D^{h/f}(z,\mu)}\,\hat{\sigma}^{i\to f}(s,t,u,\mu)$$





- Parton distribution functions – CT10
- Fragmentation functions for light partons HKNS
- Fragmentation functions for heavy flavor – see below
- Hard part up to NLO. Analytic approach



T. Kneech et al. (2008)

D. Anderle et al. (2017)

P. Hinderer et al. (2015)

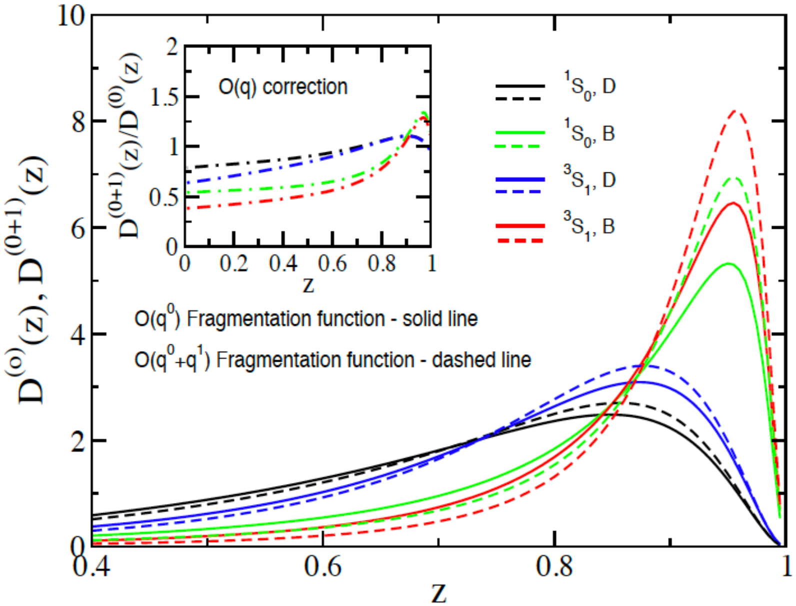
The gluon contribution at EIC is small

Perturbative calculations of fragmentation

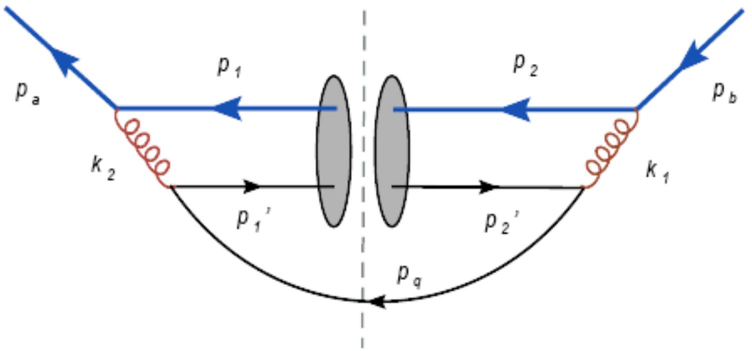
Heavy quarks introduce a mass scale that allows the fragmentation function shape to be computed perturbatively.

Chang et al. (1992)

Braaten et al. (1995)



R. Sharma et al. (2009)

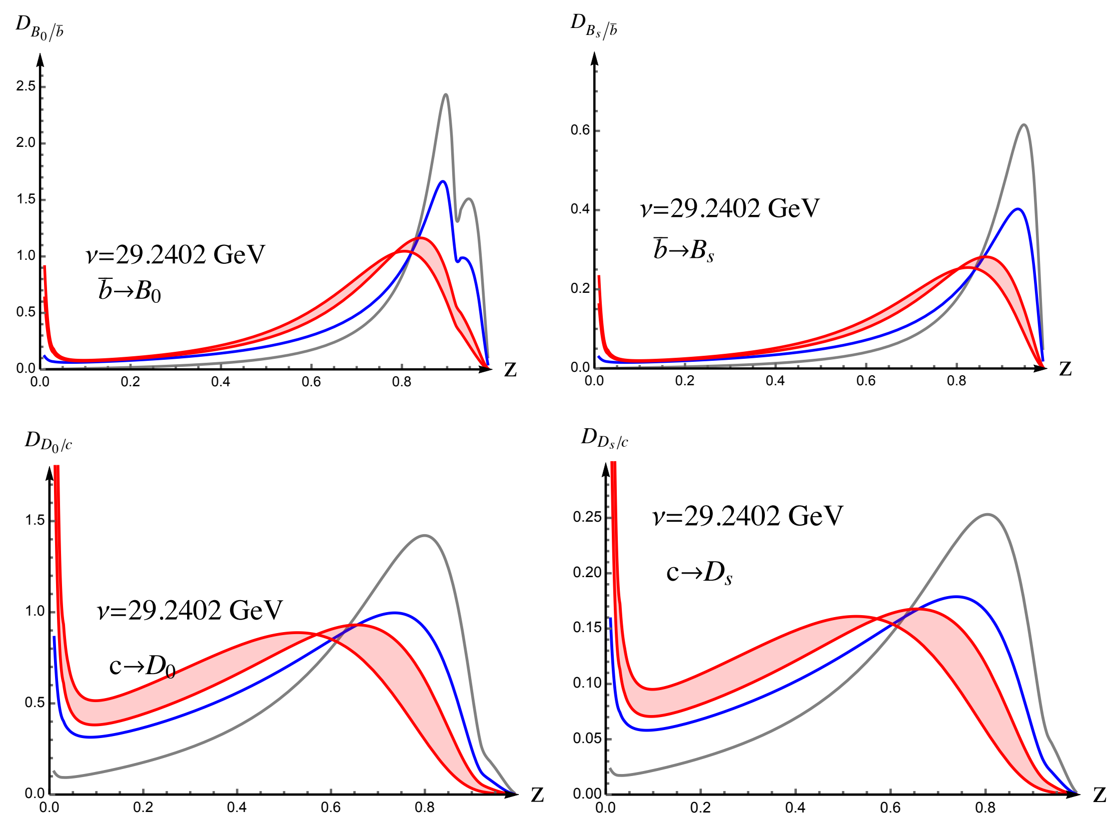


Pseudoscalar, vector, tensor channels – these contribute to the various D and B meson states

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

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

Standard vacuum DGLAP evolution – standard tools

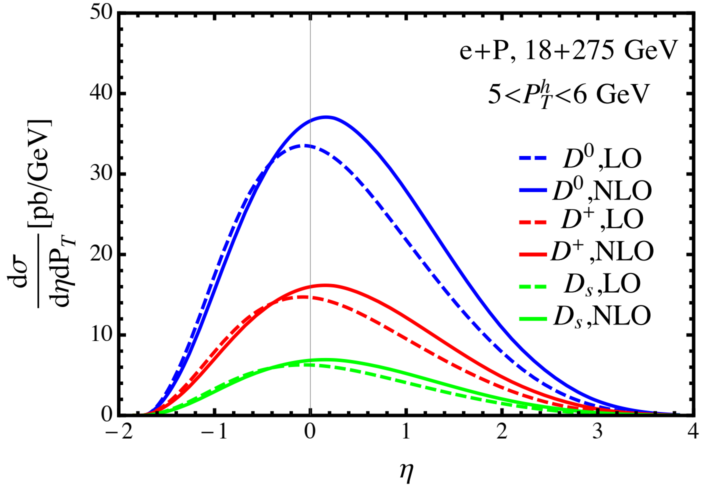
Boundary condition

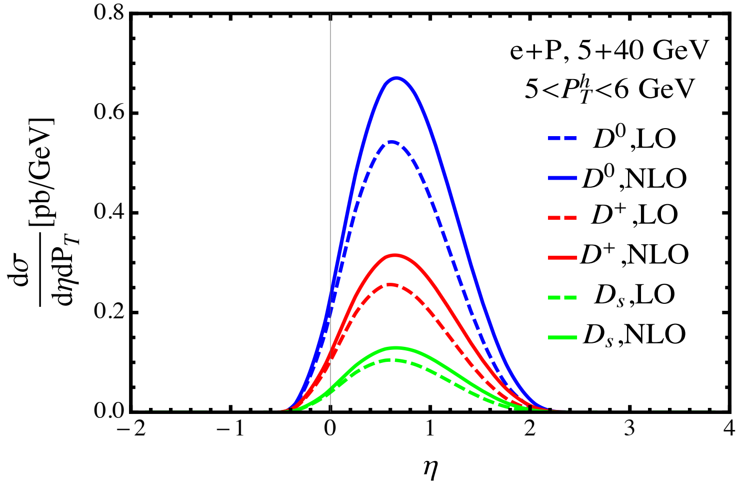
Vacuum evolution

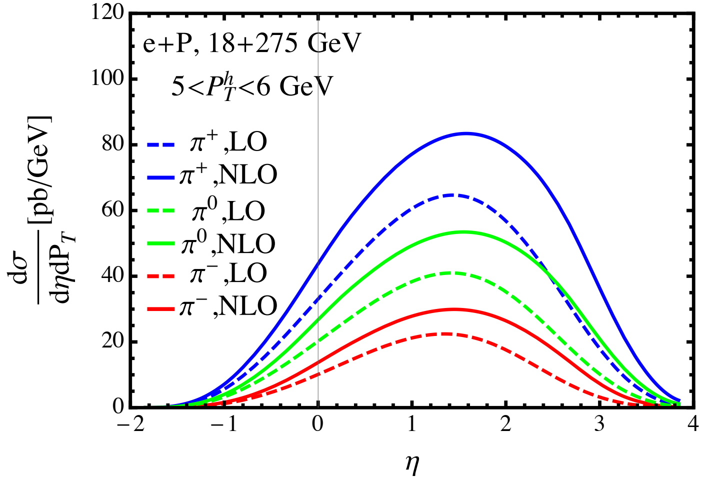
Medium evolution

Kinematic maps

Note, results are preliminary, Evaluated using over all Q² range







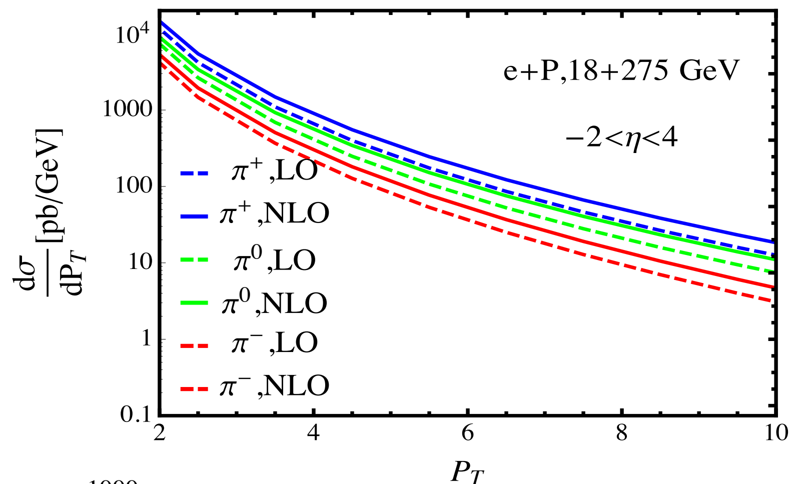
Uncertainties on the order of 20%

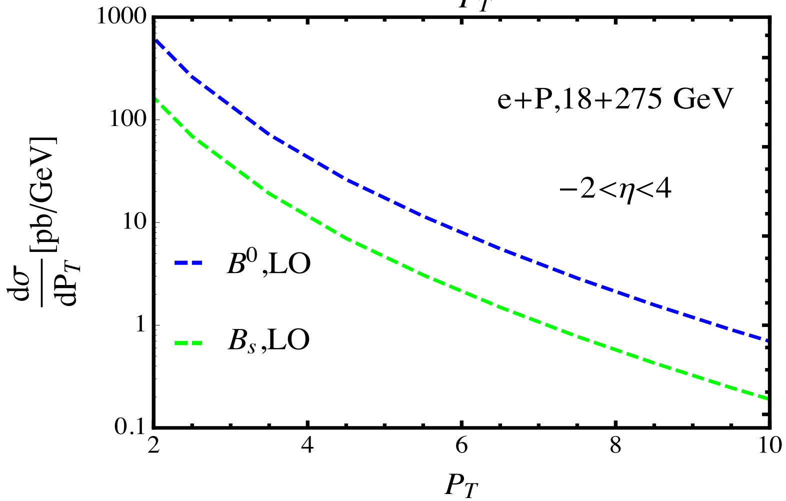
Rough estimate of charm baryons ~ 10% of the mesons

Generally production is at more forward rapidities. Most pronounced for pions. Differences are attributed to parton distributions

Kinematic maps

We found that the NLO results for B mesons are not stable. For B we use LO





	5+40 GeV			10+100 GeV			18+275 GeV		
p_T^h [GeV]	[2 ,3]	[5 ,6]	[10 ,11]	[2 ,3]	[5 ,6]	[10 ,11]	[2 ,3]	[5 ,6]	[10 ,11]
π^+	1.4×10^7	136123	61	3.2×10^7	989140	26624	5.4×10^7	2.4×10^6	145501
π^0	8.0×10^6	72980	31	2.0×10^7	578330	14523	3.4×10^7	1.5×10^6	86560
π^-	3.3×10^6	16572	4	1.0×10^7	232546	3734	1.9×10^7	768976	36313
D^0	1.9×10^6	8490	1	9.0×10^6	173922	2432	2.4×10^7	924804	37115
D^+	854390	4057	1	3.9×10^6	78303	1145	1.0×10^7	406404	16632
D_s	360778	1646	0	1.7×10^6	32940	469	4.4×10^6	173427	7015
B^0	39712	647	0	566160	16915	346	2.6×10^6	115150	5376
B_s	10717	181	0	151256	4592	98	692331	30905	1472

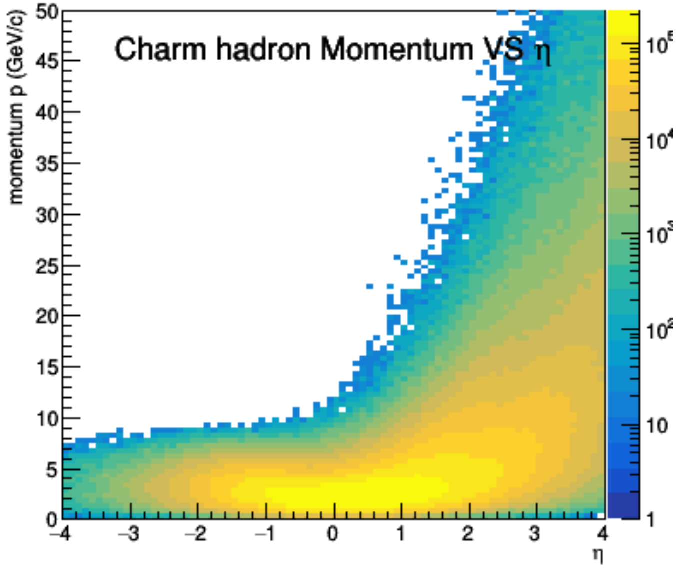
TABLE I: Event number of hadron production at the EIC at selected p_T bins of hadron with luminosity 10 fb^{-1} at different collision energy. The event number of B^+ is totally the same as B^0.

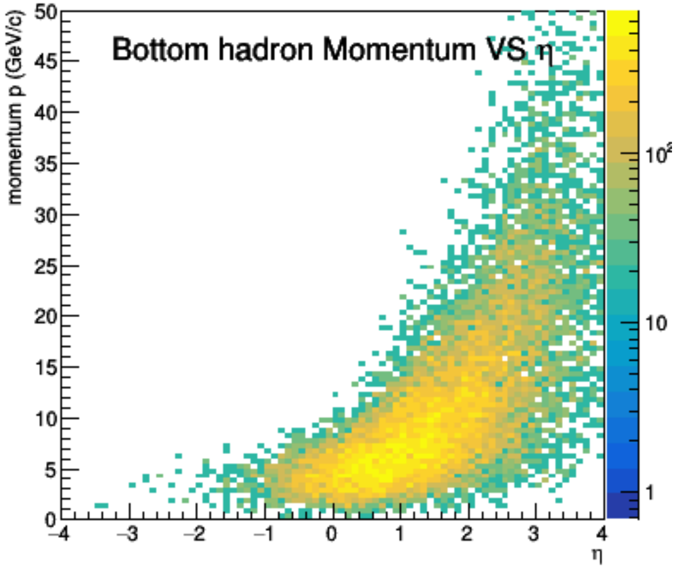
There is sizable number of D mesons, less B mesons.

In the low p_T bin for heavy flavor we should take results with a grain of salt

Complements running PYTHIA simulations

10 GeV electron + 100 GeV proton with integrated luminosity at 10 fb^{-1}.
Minimum Q^2 = 10 $(GeV)^2$





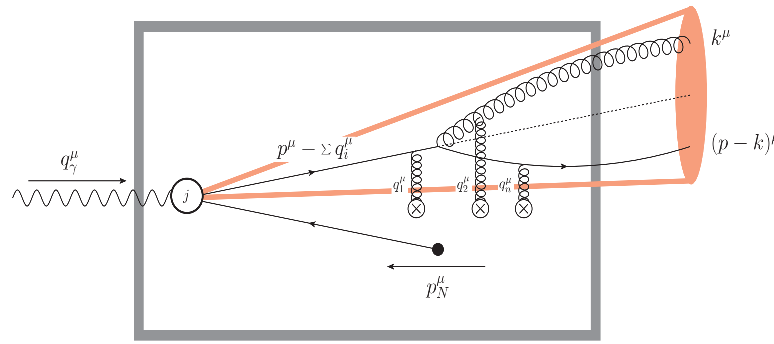
Integrated in eta (-2, 4). Gets most of the statistics

Order of magnitude consistent with simulations

Simulation X. Li

In–medium splitting functions in the LCWF formalism

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

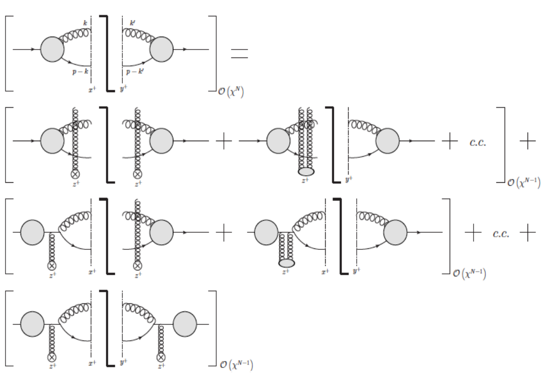


Supplement 2-body phase space

M. Sievert et al . (2019)

$$\Delta E^-(\underline{\kappa}) = -\frac{\kappa_T^2 + \nu^2 m^2}{2x(1-x)p^+}$$

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

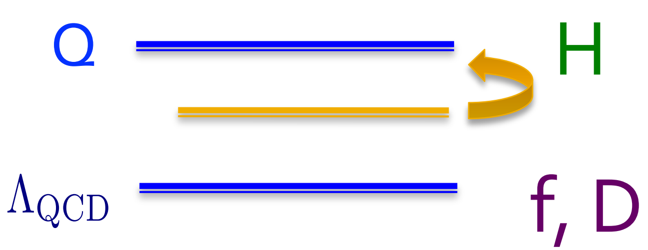


- Iterative approach to deriving the splitting functions. Separate contributions from interactions before and after the splitting

$$\begin{bmatrix} f_{F/F}^{(N)}(\underline{k}, \underline{k}', \underline{p};\, x^+, y^+) \\ f_{I/F}^{(N)}(\underline{k}', \underline{p};\, x^+, y^+) \\ f_{F/I}^{(N)}(\underline{k}, \underline{p};\, x^+, y^+) \\ f_{I/I}^{(N)}(\underline{p};\, x^+, y^+) \end{bmatrix} = \int_{x_0^+}^{\min[x^+, y^+, R^+]} \frac{dz^+}{\lambda^+} \int \frac{d^2q}{\sigma_{el}} \frac{d\sigma^{el}}{d^2q} \begin{bmatrix} \mathcal{K}_1 & \mathcal{K}_2 & \mathcal{K}_3 & \mathcal{K}_4 \\ 0 & \mathcal{K}_5 & 0 & \mathcal{K}_6 \\ 0 & 0 & \mathcal{K}_7 & \mathcal{K}_8 \\ 0 & 0 & 0 & \mathcal{K}_9 \end{bmatrix} \begin{bmatrix} f_{F/F}^{(N-1)}(\underline{k}, \underline{k}', \underline{p};\, x^+, y^+) \\ f_{I/F}^{(N-1)}(\underline{k}', \underline{p};\, x^+, y^+) \\ f_{F/I}^{(N-1)}(\underline{k}, \underline{p};\, x^+, y^+) \\ f_{I/I}^{(N-1)}(\underline{p};\, x^+, y^+) \end{bmatrix}$$

Modification of light hadrons

- The equations for the in-medium splitting functions can be solved analytically and we evaluate the result numerically

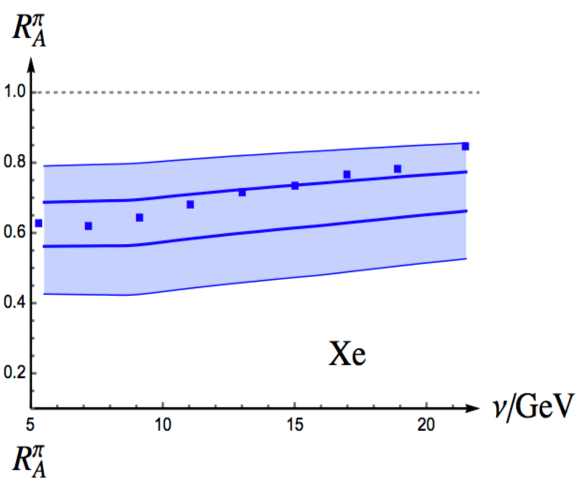


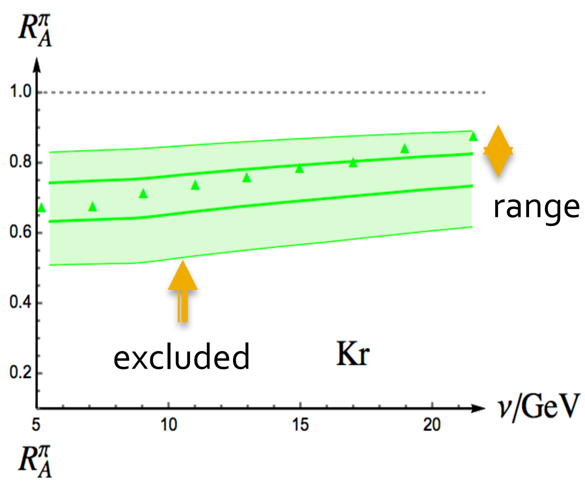
$$\frac{\mathrm{d}D_q(z,Q)}{\mathrm{d}\ln Q} = \frac{\alpha_s(Q^2)}{\pi}\int_z^1 \frac{\mathrm{d}z'}{z'}\left\{P_{q\to qg}(z',Q)D_q\left(\frac{z}{z'},Q\right) + P_{q\to gq}(z',Q)D_g\left(\frac{z}{z'},Q\right)\right\},$$

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

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

We choose to put the medium effect in the evolution and let the hard part be

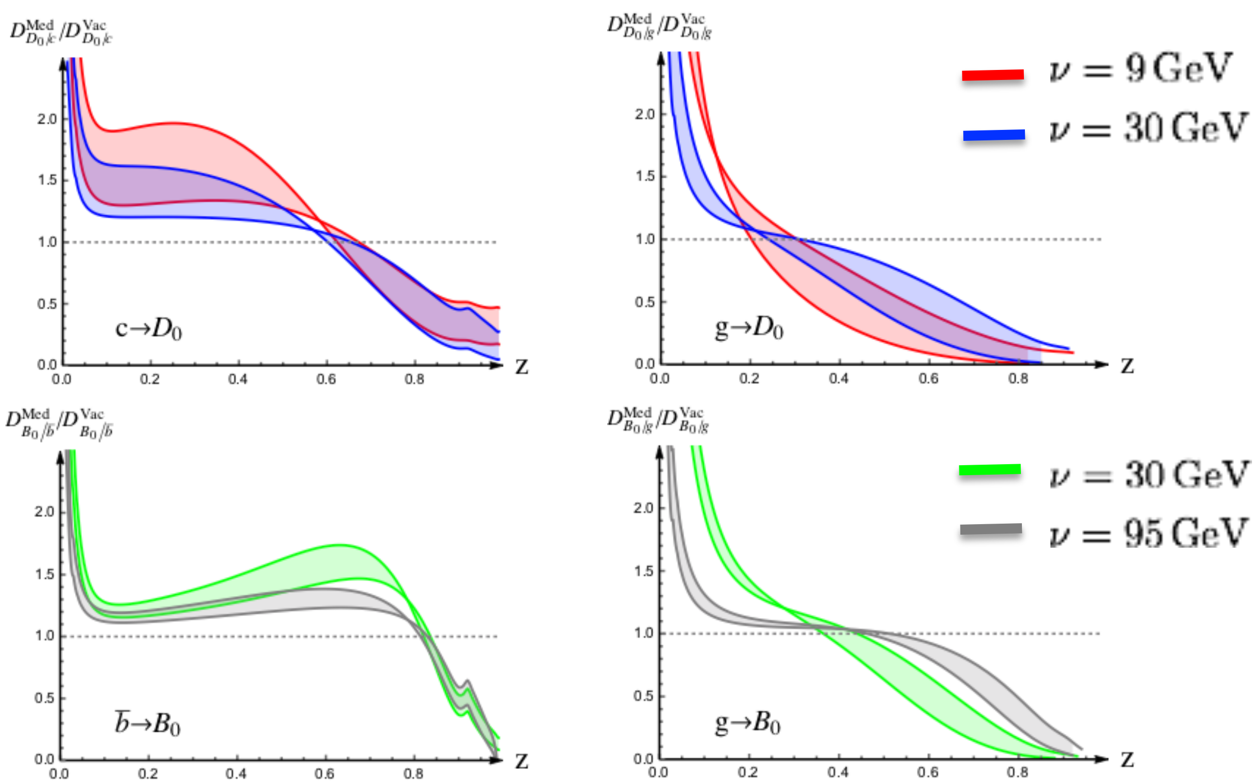




- We constrain a range of transport properties to explore from HERMES

In-medium evolution of fragmentation functions

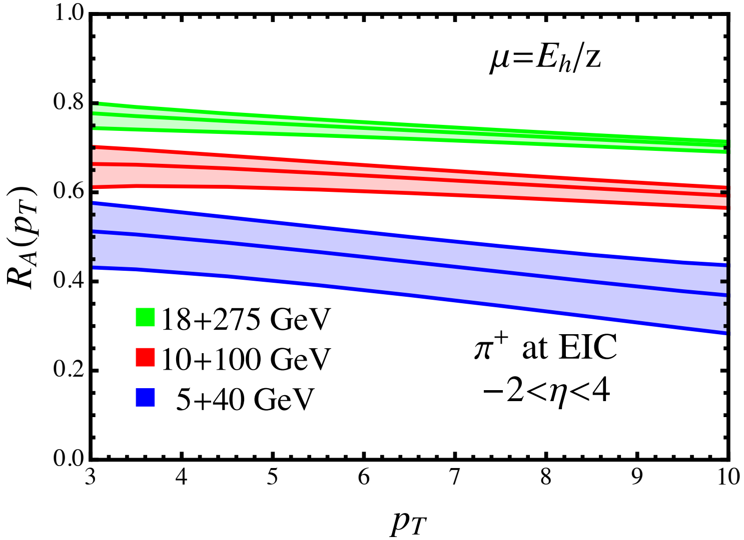
- The modification of heavy flavor channels is very different than for light channels

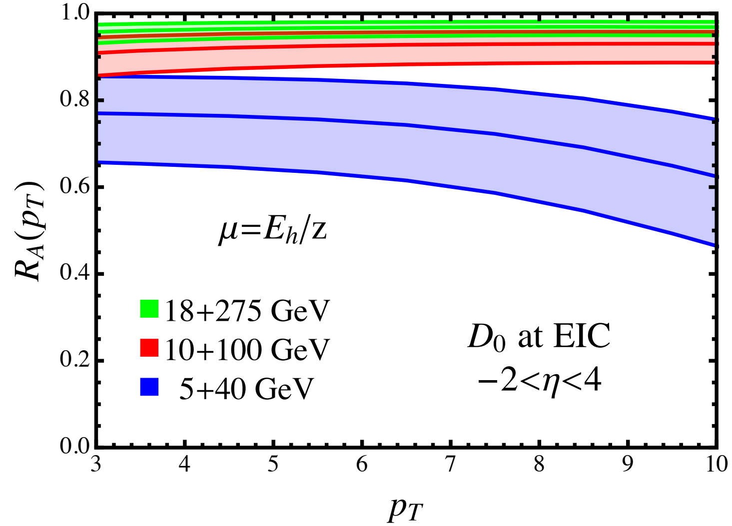


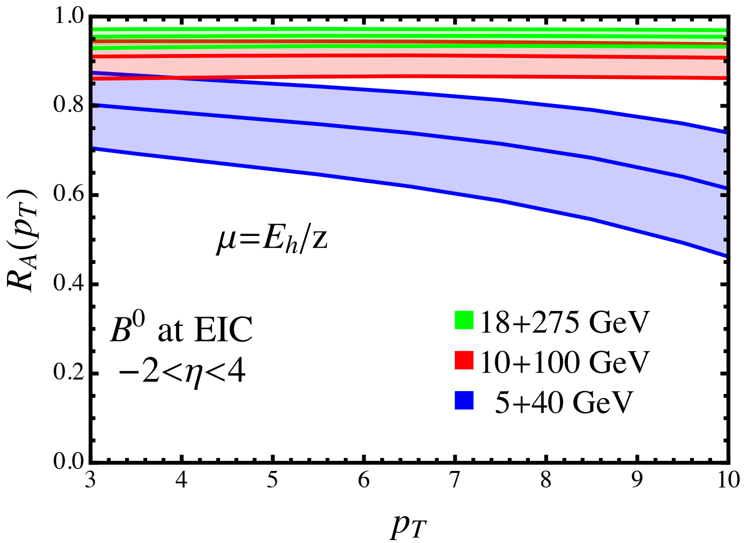
- Very characteristic enhancement at small and moderate values of z. Transition from. Suppression to enhancement is much steeper for B mesons
- Gluon fragmentation pattern different (minimal contrib.)

Ratio of in-medium evolution to vacuum-evolved FFs

Modification of heavy mesons – first vs p_T



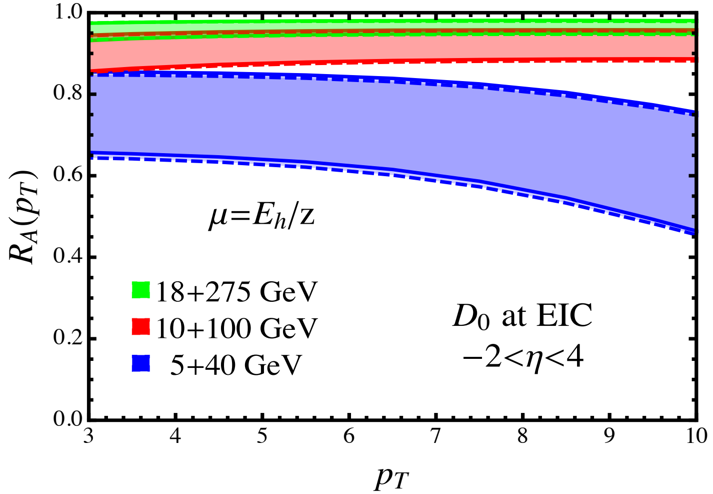


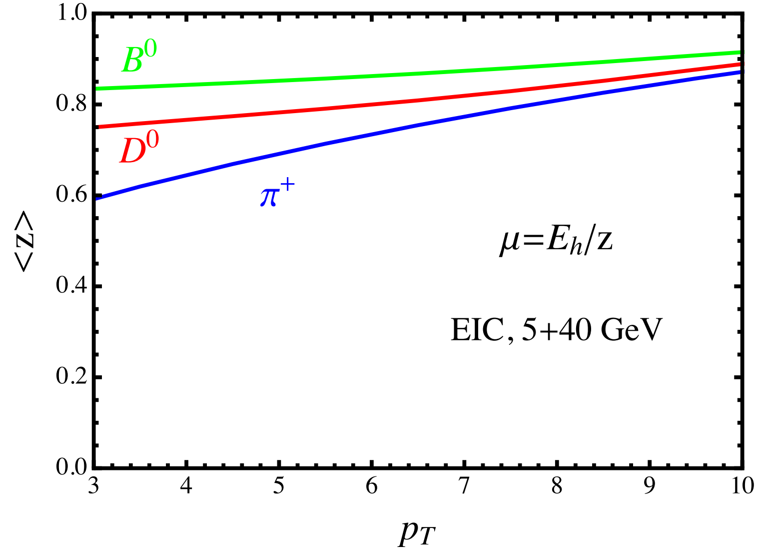


- Observe suppression. Suppression can be as large as a factor of 2
- Suppression is different for different CM energies. Lower CM energies are clearly better for the e-loss/hadronization studies
- The differences between pi, D, B are due to production and not mass

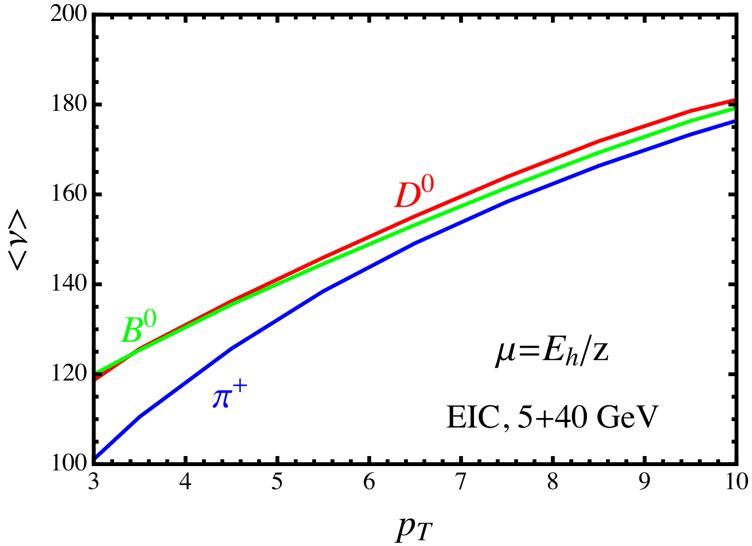
Understanding the modification patterns

NLO does not affect the nuclear modification (because gluon contribution remains small)



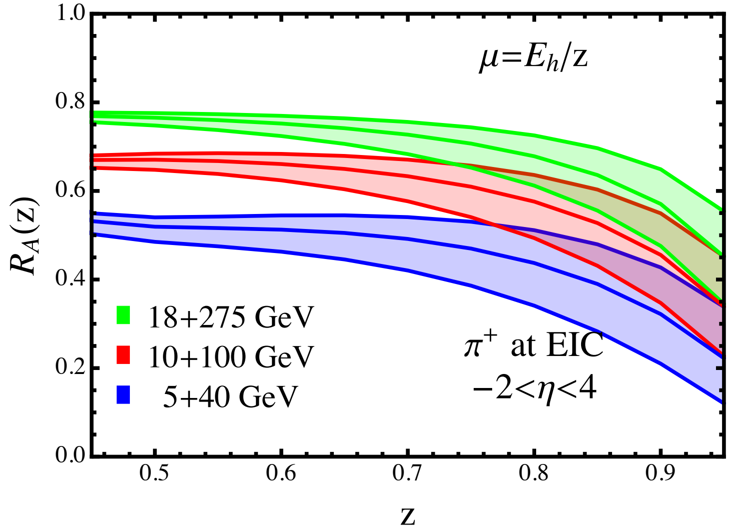


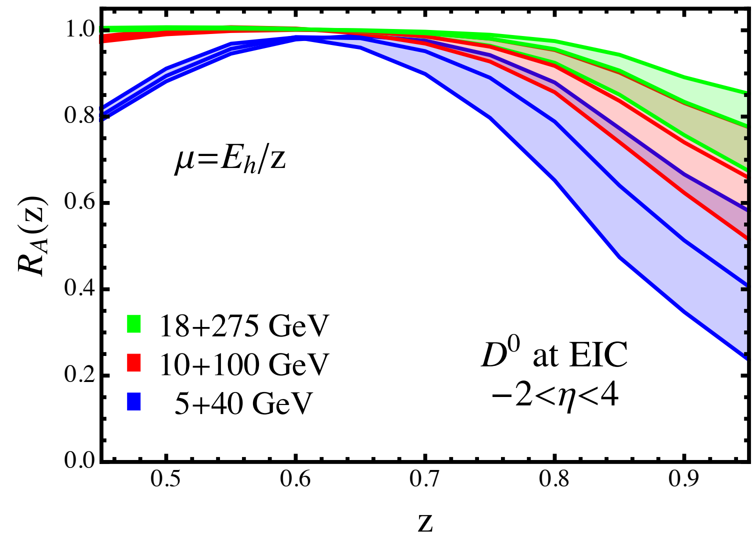
- Evaluated average z, fragmentation fraction. Large and in the suppression region
- Note that the parton energies in the rest frame of the nucleus ν are large. Mass differences are small to negligible

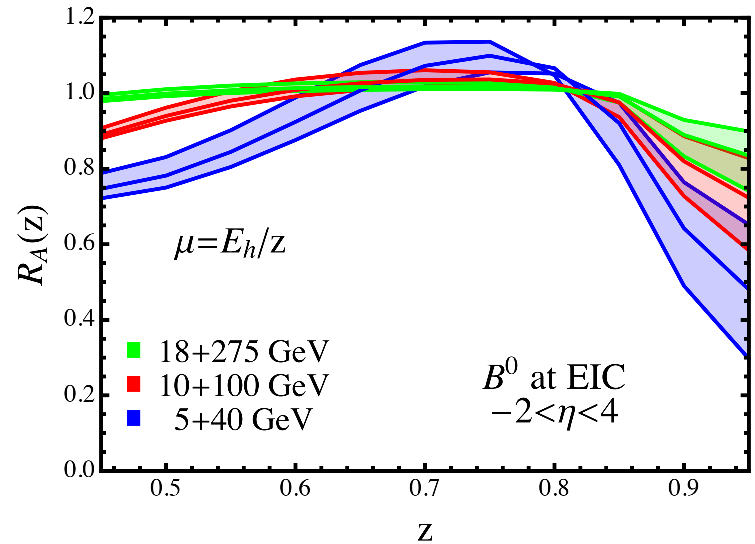


Presenting the modification vs z

The differences are much more pronounced between light and heavy hadrons







- There results highlight the suppression of light hadrons and transmission to enhancement to heavy
- Working to understand aspects of the behavior at smaller z. Very large rapidity interval?

Conclusions

- Open heavy flavor heavy flavor production at the EIC can constrain gluon and heavy quark distributions, pin down the transport properties of cold nuclear matter, and shed light on the process of hadronization
- We developed an NLO code to evaluate light and heavy favor production at the EIC. Works well fore D mesons. Kinematic maps produced for e+p to complement MC simulations indicate adequate projected statistics
- Obtained in-medium splitting functions (and energy loss in the soft gluon limit) in cold nuclear matter. Calculated the medium evolution of light/heavy fragmentation functions. Studied the distribution of a variety of observables
- Found that small CM energies are best suited to study the physics of energy loss & hadronization. Modifications are large and measurable. Identified the most sensitive observables to this physics