Summary of Jets and Heavy Flavor WG Activities

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EICUG Miami Meeting

07/16/2020

Outline

- ❑ Heavy Flavor
- ❑ Light-Flavor Jets
- ❑ Theoretical Developments

Too many results to detail fully here – apologies for any omitted material

Of course, any mistakes or misrepresentations are my own

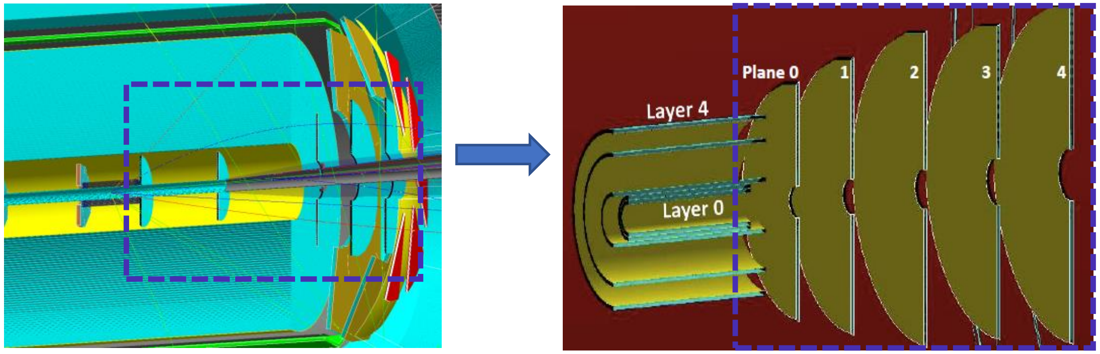
Detector simulation and implementation in physics simulation is ongoing

Los Alamos NATIONAL LABORATORY EST. 1943

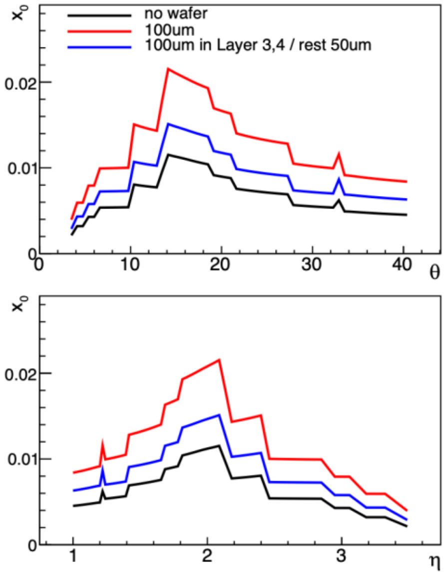
- Different geometries for the proposed forward silicon tracking detector (FST) has been implemented in the Fun4All simulation.
- Optimization underway.

FST geometry in GEANT4

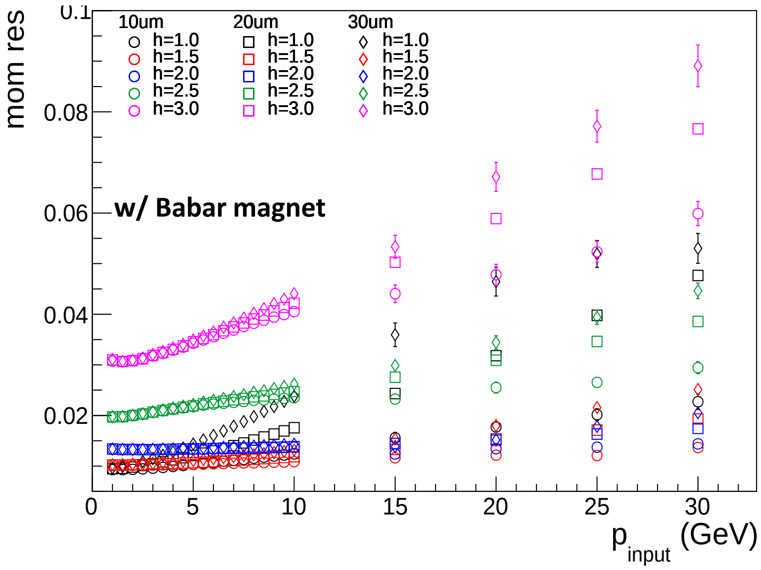
C.P. Wong, X. Li, A. Morreale



Material budget scan



Track momentum resolution

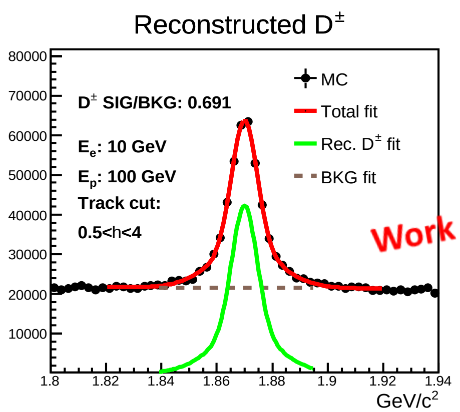


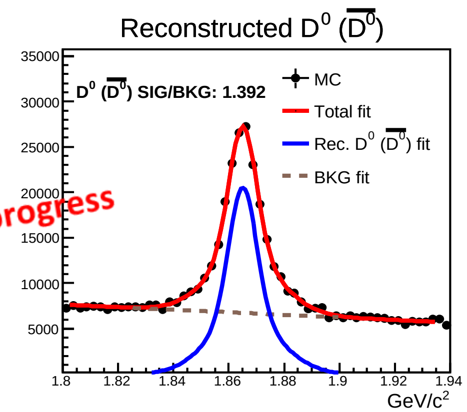
- The proposed FST material budgets and tracking performance have been evaluated.
- Physics simulation including the detector performance with different design and technology options is underway.

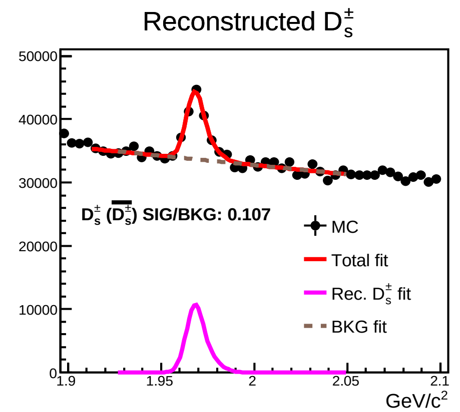
We will document the updated studies and summarize detector requirements.

Heavy Flavor hadron reconstruction demonstrated in PYTHIA simulation

- PYTHIA simulation for 10 GeV electron and 100 GeV proton collisions with integrated luminosity: 10 fb^{-1}.
- Reconstructed D-meson and B-meson mass distributions.
  - Primary vertex resolution: 20 μm.
  - Tracking performance implemented in the simulation.
  - 95% $K/\pi/p$ separation is implemented.
  - Track η: 0.5 to 4.

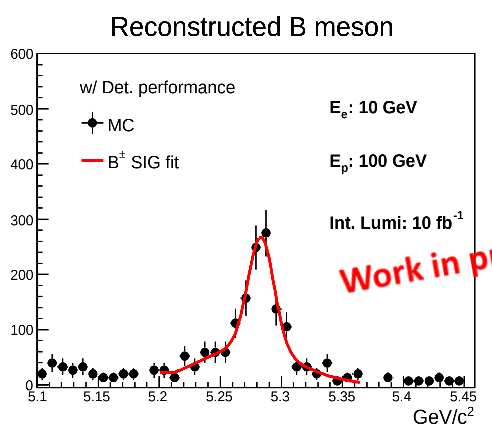


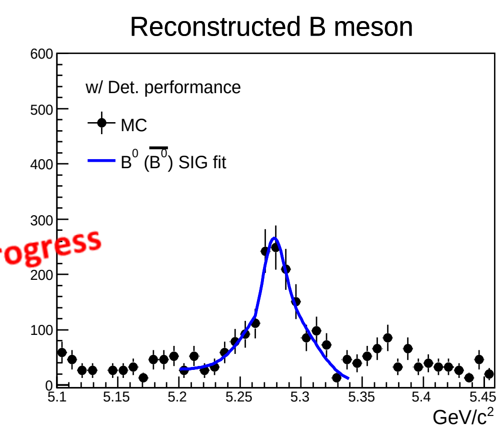




X. Li

Silicon vertex/tracking setting:
B=3T
Pixel pitch = 30 μm
Materials per layer: 0.4% X_0





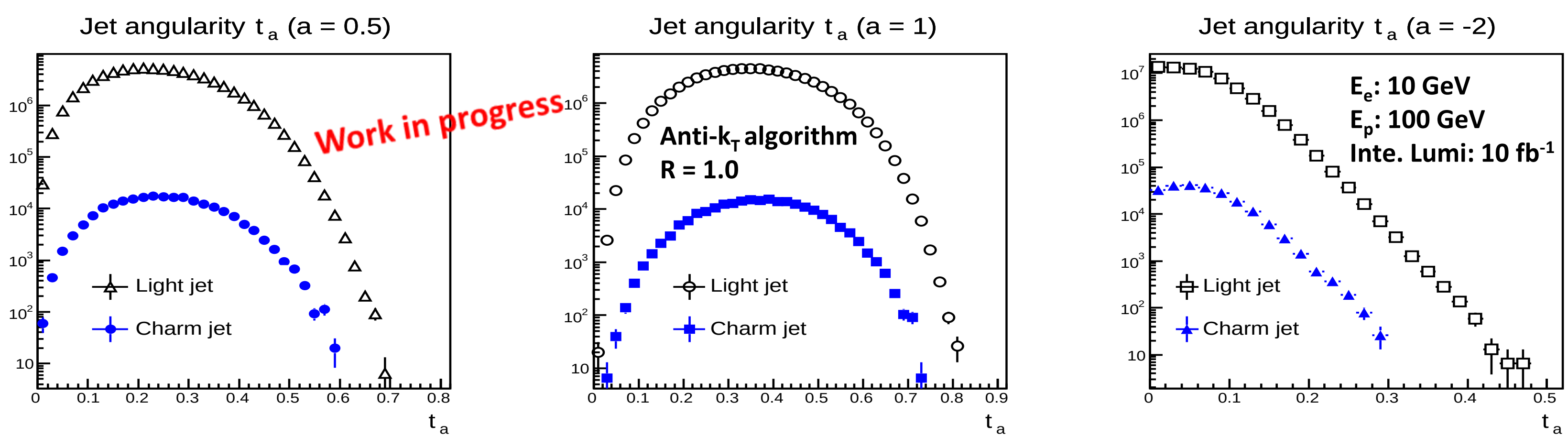
- Clear D-meson and B-meson signal can be determined with one of the initial silicon tracker designs.
- The projected R_{eA} for reconstructed Heavy flavor has been updated.

New heavy flavor observables under study

- Heavy flavor jet tagging and sub-structure under study.

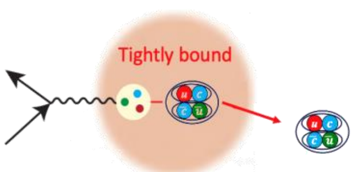
Jet angularity definition: $$\tau_a \equiv \tau_a^{pp} \equiv \frac{1}{p_T} \sum_{i \in J} p_T^i \left(\Delta \mathcal{R}_{iJ}\right)^{2-a}$$ JHEP 1804 (2018) 110

- Light-jet and charm-jet jet angularity comparison: **X. Li, C.P. Wong**

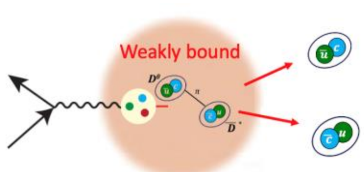


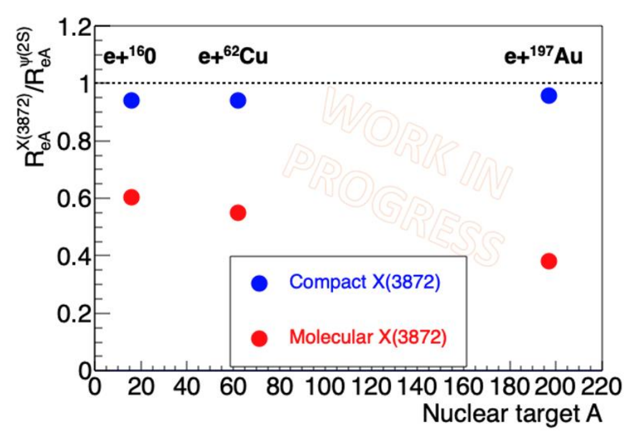
- New exotic state structure studies at the EIC. **M. Durham**

Penta-quark state?
PRD 71, 014028 (2005)
PLB 662 424 (2008)



D-meson molecule?
PLB 590 209 (2004)
PRD 77 014029 (2008)
PRD 100 0115029(R) (2019)





Relative modification of X(3872)/ $\psi(2S)$ projection at $\sqrt{s}$ = 63.2GeV

Arleo *et al.*, PRC, 61 054906 (2000)

LBNL Group:
Matthew Kelsey, Nu Xu, Sooraj Radhakrishnan, Xin Dong, Yuanjing Ji

BERKELEY LAB

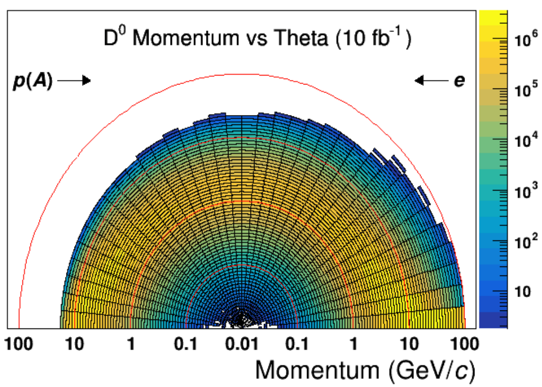
Representative Acceptance Plots

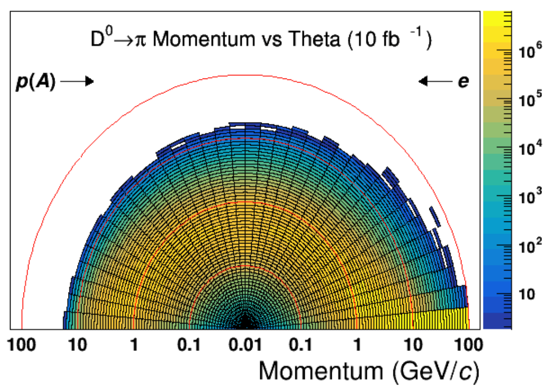
Gluon PDFs, charm F_2, nPDFs

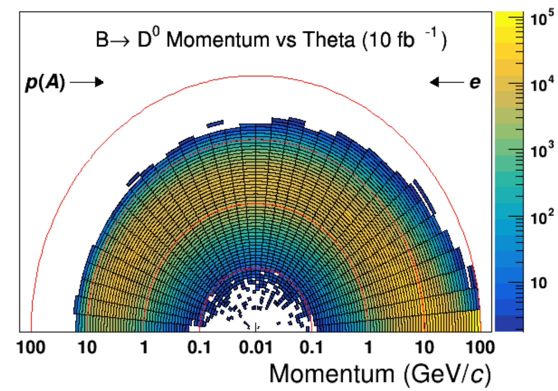
Heavy hadron pair production – gluon TMDs, Sievers, linearly polarized gluons

Cold nuclear medium effects in e-A collisions (e.g., Λ_c/D^0)

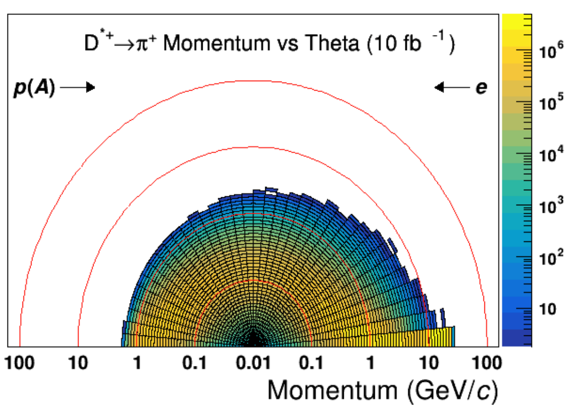
Similar for $D^0 \rightarrow K$

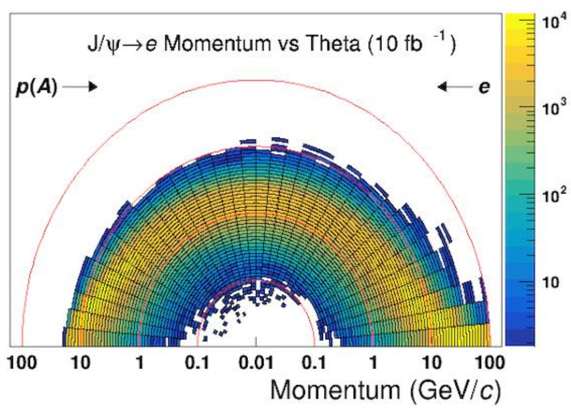


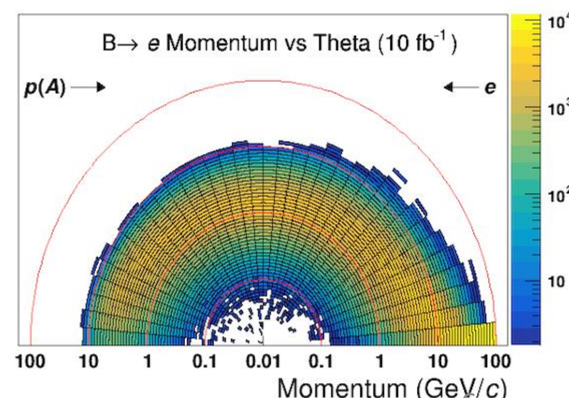




Similar for $J/\Psi \rightarrow \mu$

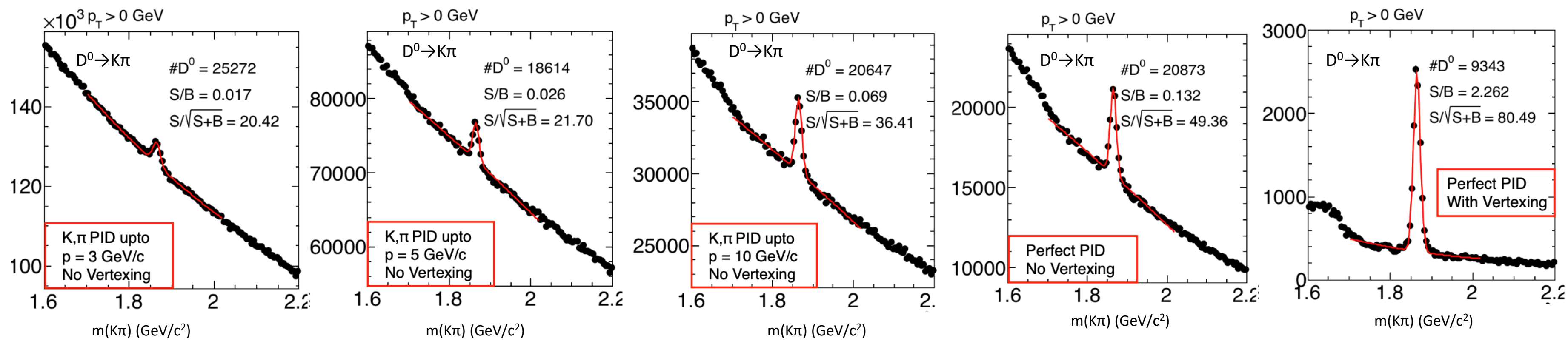






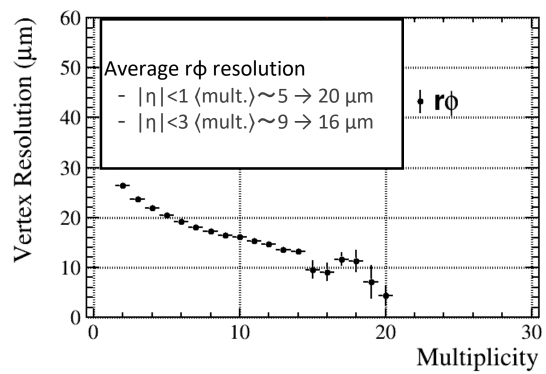
$D^0 \to K\pi$ Reconstruction

PYTHIA e+p 18+275 GeV, |η|<3, ~0.013 fb^{-1} All tracks momentum+position smearing with EIC detector matrix

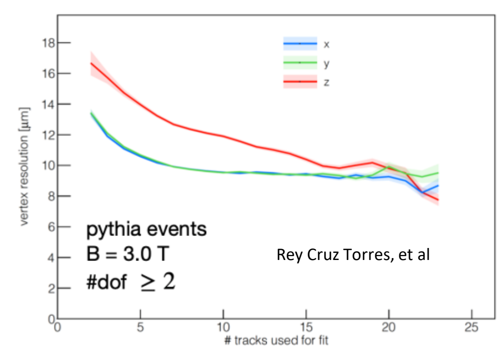


- PID up to +10 GeV/c greatly improves signal significance (x2.5)
- PV resolution studies in smeared PYTHIA sim.
  - Comparable to all-Si full GEANT+tracking studies in x-y plane

PYTHIA FastSim Simple PV Fitter



All-Si Full Simulation



- 2nd vertex reconstruction (rϕ plane) enabled by decent PV resolution
- Simple topo. Variables (rϕ plane): cos[θ(rϕ)] > 0.98; Decay length>40 μm; Kπ d_0(rϕ)<150 μm → Additional increase in significance

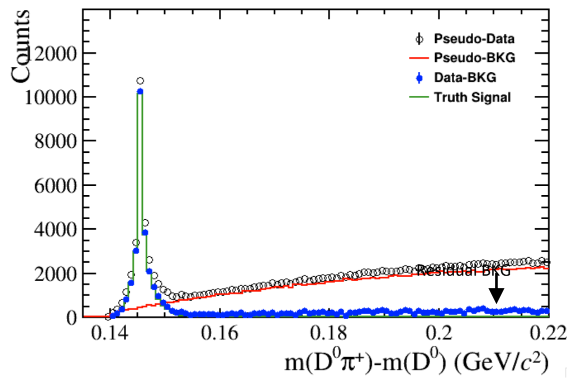
D*+ and Bottom Reconstruction

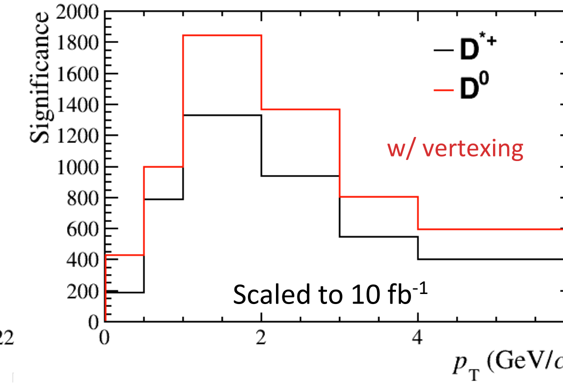
Reconstruction studies of $D^{*+} \rightarrow D^0\pi_{slow}$

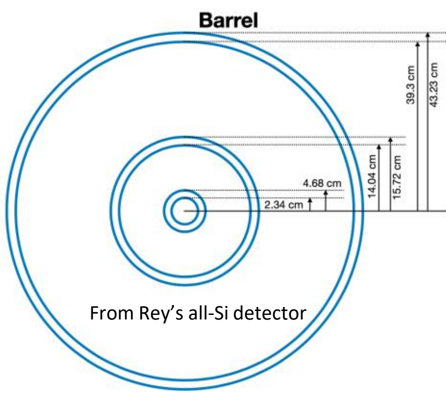
- Slow pion required to hit inner two Si layers ($\delta p/p \sim 10\%$)
- Reconstructed via $\Delta m = m(D^{*+}) - m(D^0)$

$D^0 \rightarrow K\pi$: pT>200 MeV/c, $|\eta|<3$, perfect PID, $|m(D^0_{PDG})|<30$ MeV

D^{*+} signal significance slightly under than D^0 with vertexing → Viable channel for charm studies







All three layers: Min. p_T = 200 MeV/c

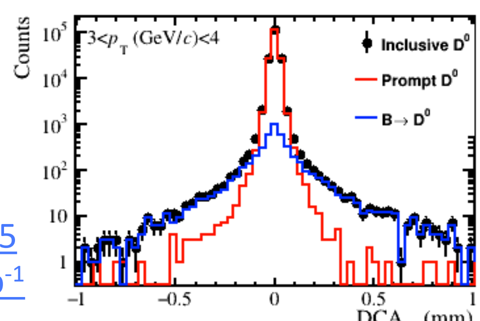
Two inner layers: Min. p_T = 70 MeV/c

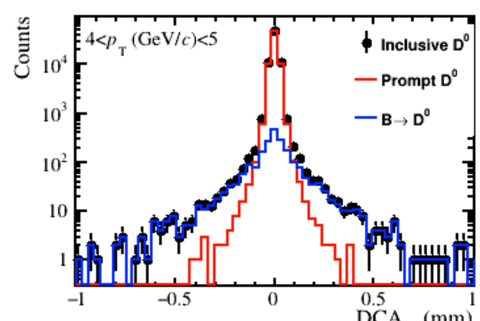
Bottom studies enabled by measurements of displaced charm hadrons (+leptons)

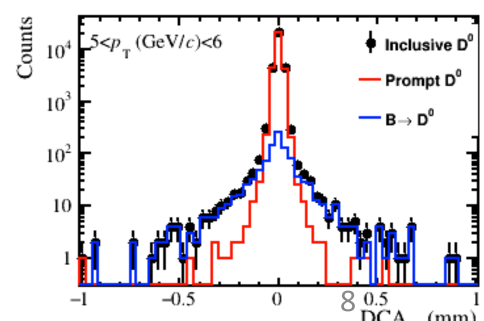
Including pointing resolution from detector matrix + PV resolution on previous slides → Good separation between prompt and non-prompt

<u>$B \rightarrow D^0$ (1.5M at 10 fb^{-1})</u>

PYTHIA e+p 18+275 GeV, $|\eta|<1$, ~5 fb^{-1}



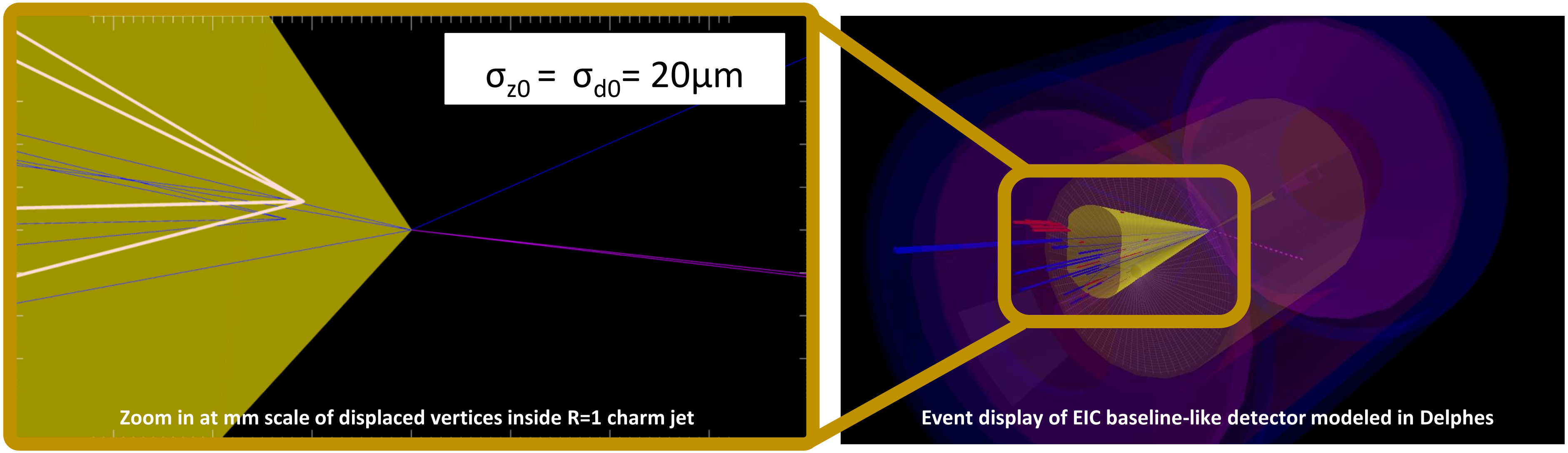




Charm-tagged jets as a probe of intrinsic strangeness

[Arratia, Burleson, Furletova, Hobbs, Nam, Olness, Sekula, Surrow]

arXiv:2006.12520



- Flavor-tag the charm jets (p_T^{jet}>5 GeV) using counting of signed high-impact-parameter (HIP) tracks (p_T^{trk}>0.75 GeV, $N_{trk} > 1$,
  IP3D significance>3.75 after optimization)
  - *Light jet efficiency of 10^{-5} maintained by (re-)optimization*

- Also explored PID-based tagging with K, e, μ
- Vertexing (Nam, Surrow) and jet substructure (Burleson, Sekula) tagging studies ongoing

(σ_{z0}, σ_{d0}) in μm	Average HIP-track-only charm tagging efficiency
(20,20)	12%
(100,20)	9.4%
(100,100)	8.0%

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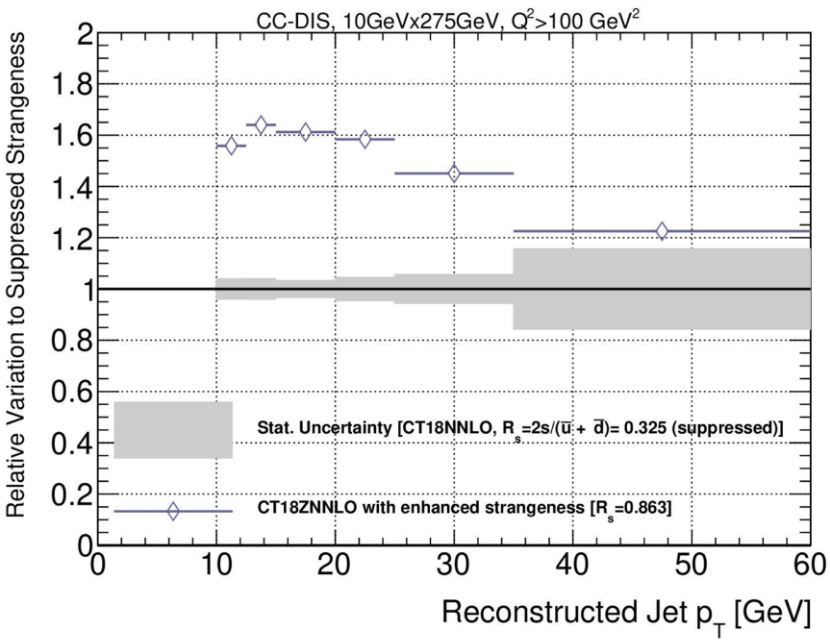
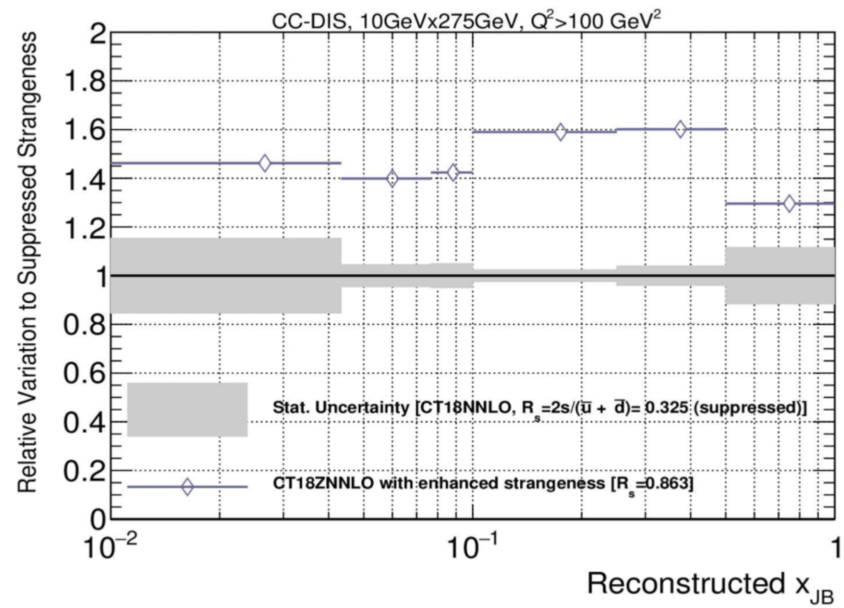




Compare statistical uncertainty (gray) on yield of HIP-tagged charm jets (suppressed strangeness) in $100 fb^{-1}$ (10x275) to the relative yield variation (diamonds) comparing suppressed and enhanced strangeness. The range is motivated by tension in CTEQ18 PDF fits to different data sets (fixed target, LHC, etc.)

We observe strong potential to better understand the existing tension using EIC data and specifically the CC DIS process. We believe that with further evolution of the tagging approach (enhance efficiency) this will be a crucial component in an eventual global strangeness analysis at EIC. The range of x with the highest sensitivity is currently poorly understood.

Heavy Flavor Summary

- Feasibility of measuring several heavy flavor channels ($D^{\pm}$, D^0, $D_s^{\pm}$, $B^{\pm}$, B^0, D^{*+}) under investigation

- Effects of vertex resolution, PID, detector layout, etc on heavy flavor reconstruction have been studied in detail

- Specific detector implementations (FST @ LANL and silicon tracker @ Berkeley) being studied using both full simulation and fast smearing

- Other methods of accessing heavy flavor such as looking at jet substructure and ‘high impact’ tracks within jets are also being pursued

1-Jettiness – L. Cunqueiro, P. Jacobs, H. Klest, S. Lee

https://arxiv.org/abs/1303.6952 - D. Kang et. al.

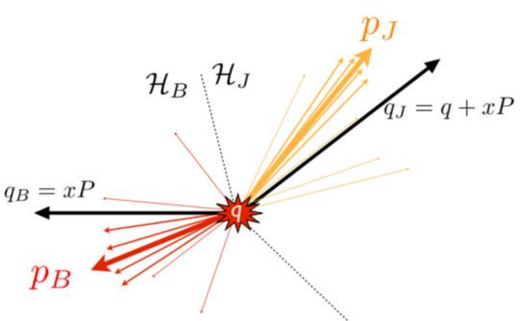
Global event shape; calculable with high theoretical precision (Chris Lee, Jets/HF WG meeting Apr. 6)
Similar experimental precision at EIC? Opportunity to measure running of α_s

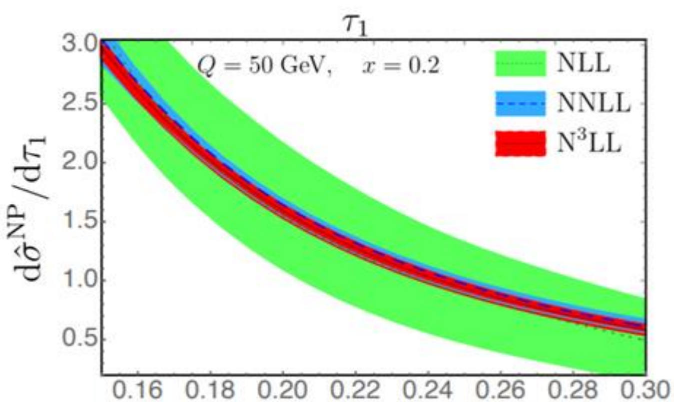
Experimental studies ongoing: uncertainties, detector requirements

PYTHIA, EICsmear

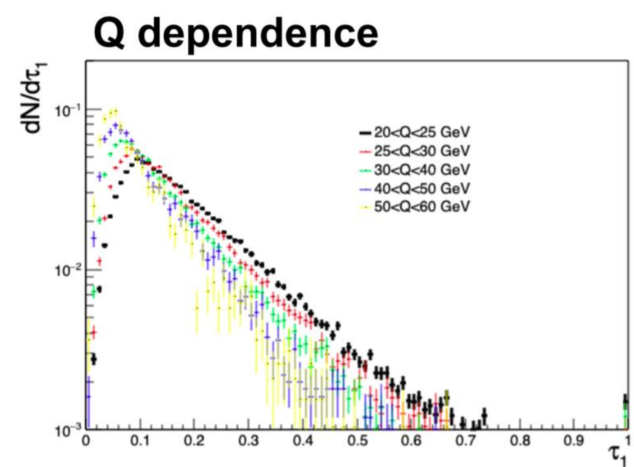
x-Q^2 resolution, statistical uncertainties, effects of cuts, comparison to HERA measurements

$$\tau_1 = \frac{2}{Q^2} \sum_{i \in X} \min\{q_B \cdot p_i, q_J \cdot p_i\}$$





Theory uncertainty at N^{3}LL to be published soon

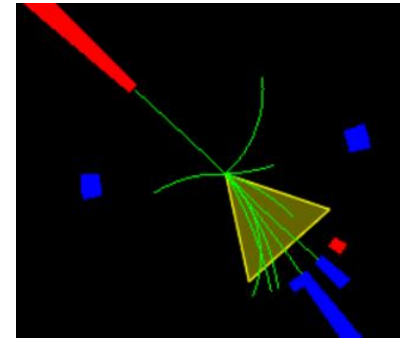


First look at τ_1 in the lab frame

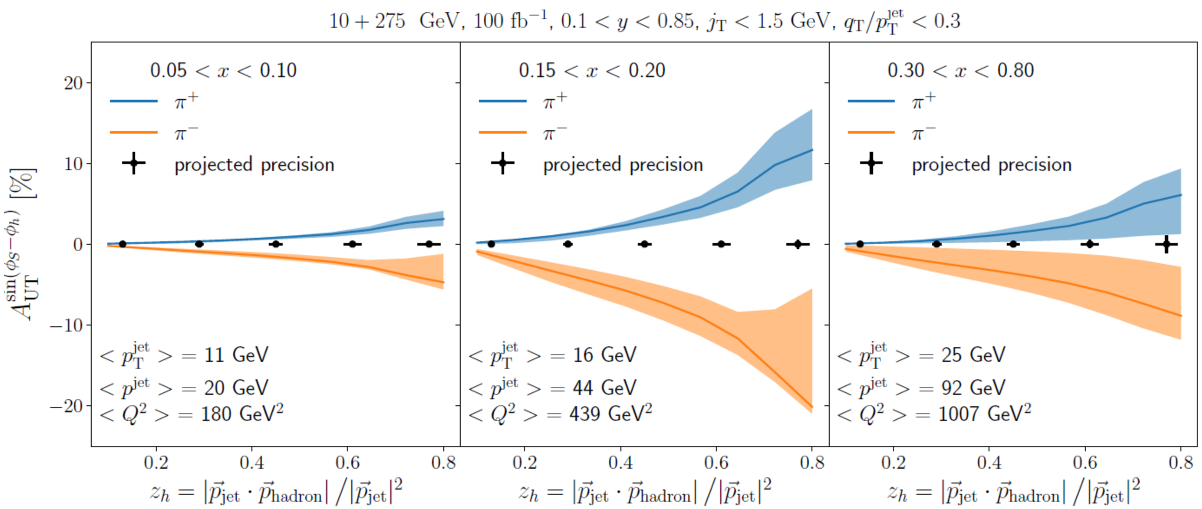
Jet-based measurements of Sivers and Collins asymmetries at the future Electron-Ion Collider

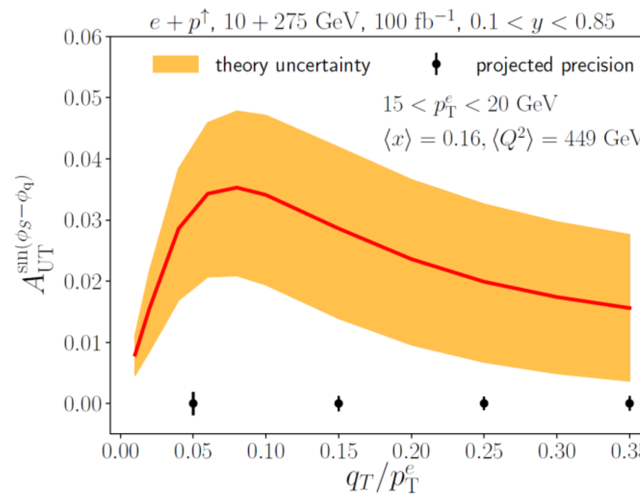
Miguel Arratia,[1,2,*] Zhong-Bo Kang,[3,4,5,†] Alexei Prokudin,[6,2,‡] and Felix Ringer[7,8,§]

Today on arXiv:2007.07281

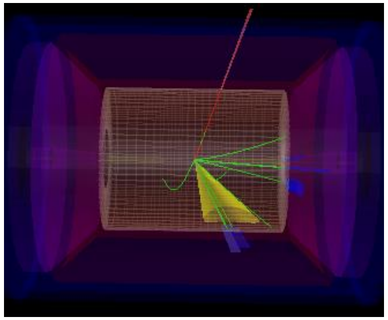


$$e + p(\vec{s}_T) \to e + (\text{jet}(\vec{q}_T)\, h(z_h, \vec{j}_T)) + X$$

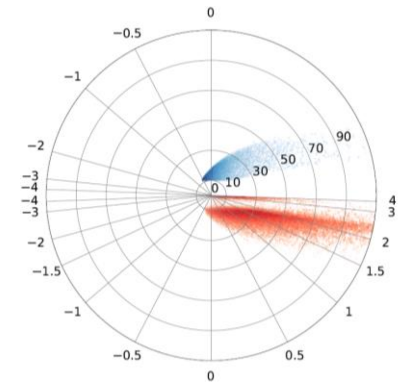




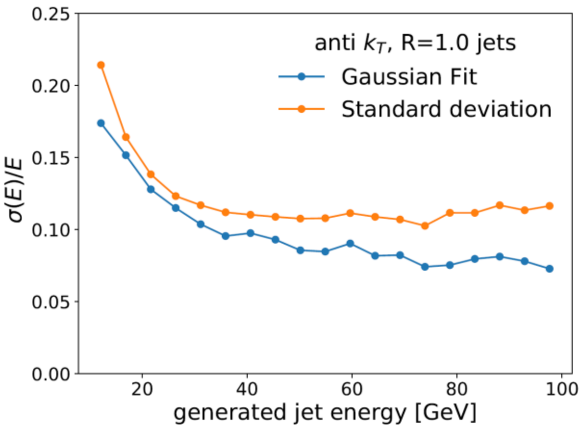
Performance estimates



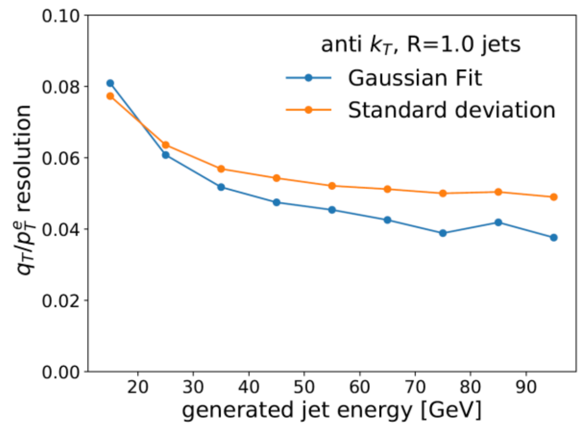
Collins requires jet-energy resolution, PID and momentum resolution
Sivers requires momentum-imbalance resolution



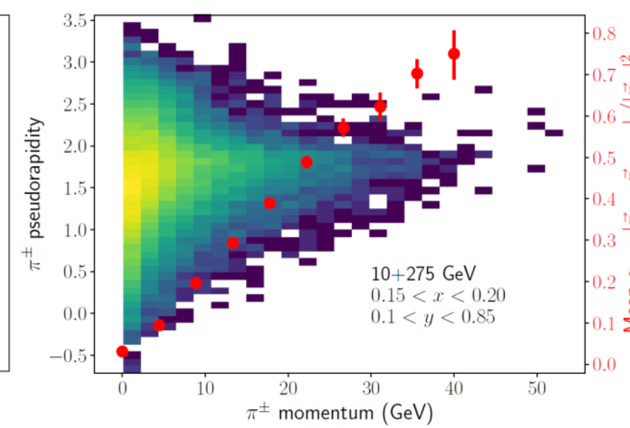
Jet-energy resolution



Momentum-imbalance



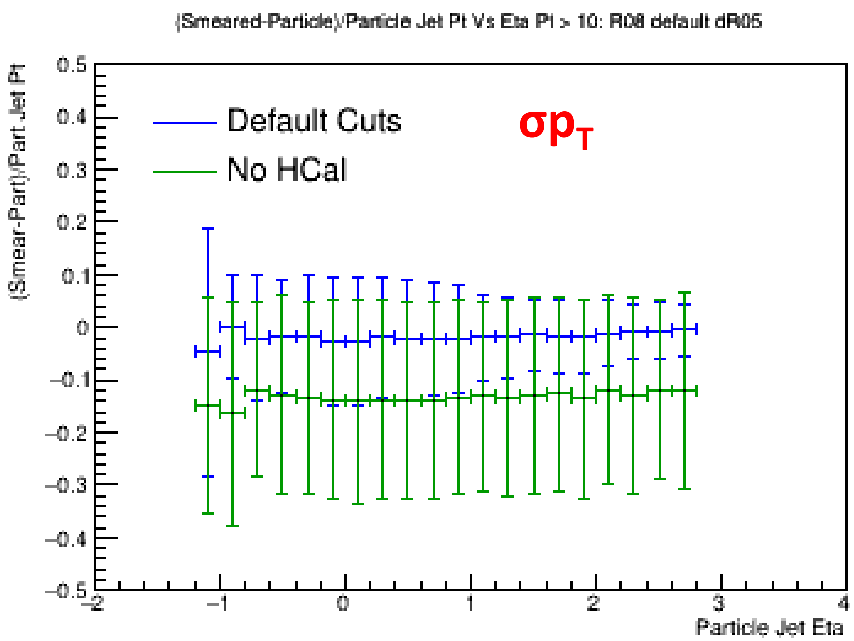
PID requirements



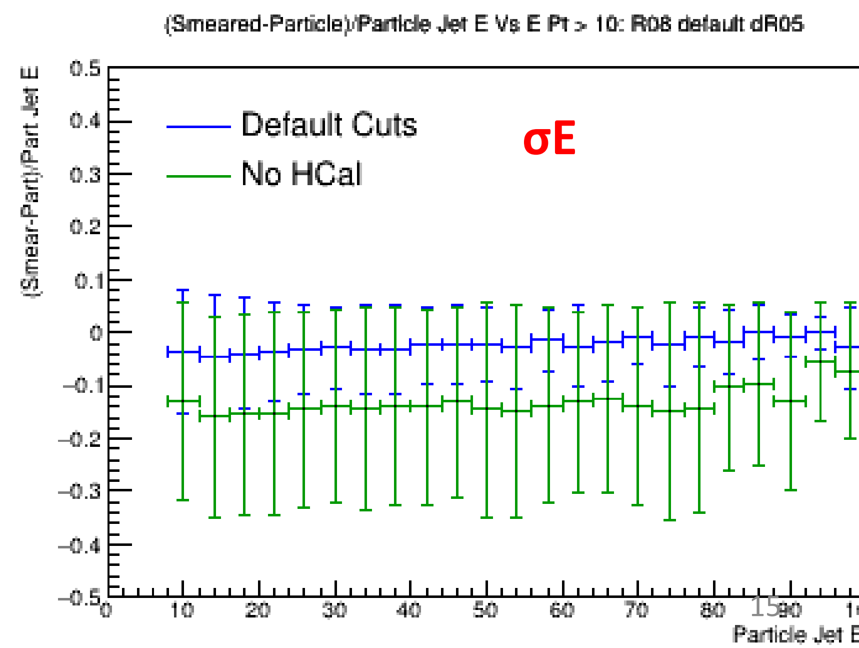
Baseline specs meet requirements; improved jet-energy resolution would improve zh and qT resolutions, enabling more-differential measurements (studies ongoing)

Photoproduction Jet Smearing and Angularity – B. Page

- Generate jets in photoproduction region ($10^{-5} < Q^2 < 1.0$) at top energy in PYTHIA6
- Find jets in lab frame using Anti-k_T and R = 0.8
- Study detector effects using eic-smear with the Handbook Detector v1.2 implementation



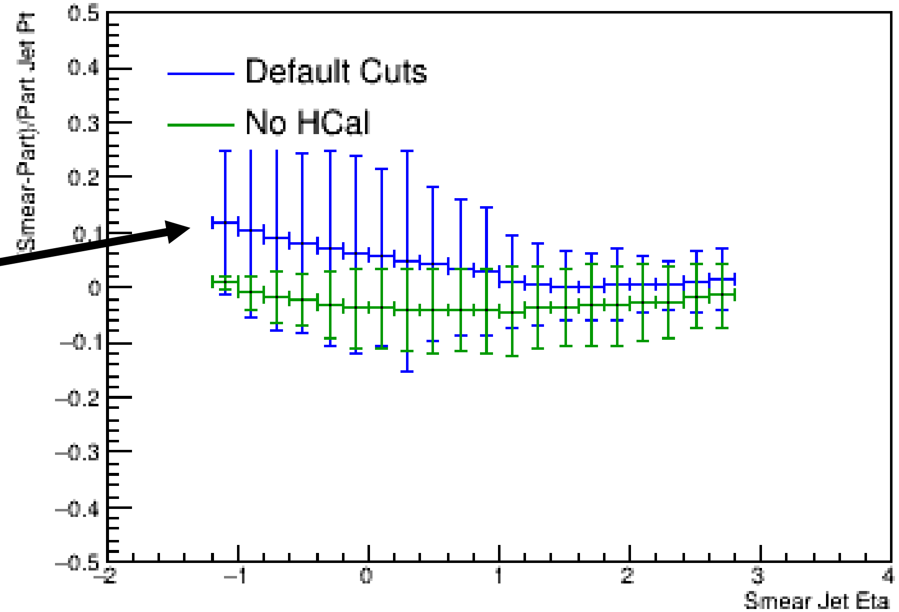
- Look at jet p_T / energy resolution
- Foreach particle level jet that passes criteria, select associated smeared jet and plot (Smear – Particle)/Particle p_T or energy

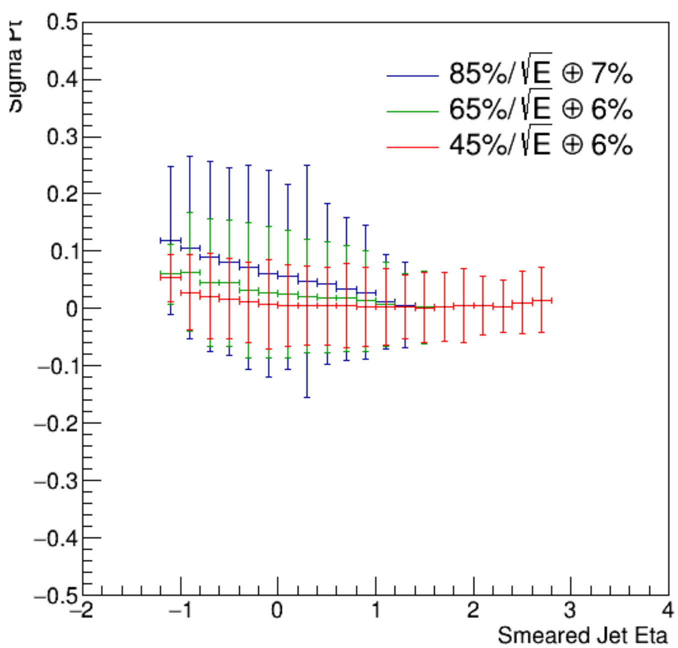


- Energy and p_T resolutions look reasonable
- ~10% resolution for Handbook (default) detector setup

Reconstruction Bias from Neutral Hadrons

- For each smeared jet with p_T > 10 GeV, select associated particle level jet: significant bias and degradation in resolution is seen at low eta and low p_T (low-x region) for default Handbook implementation
- Default detector preferentially selects jets containing neutral hadrons which smear to higher energies due to poor HCal resolution

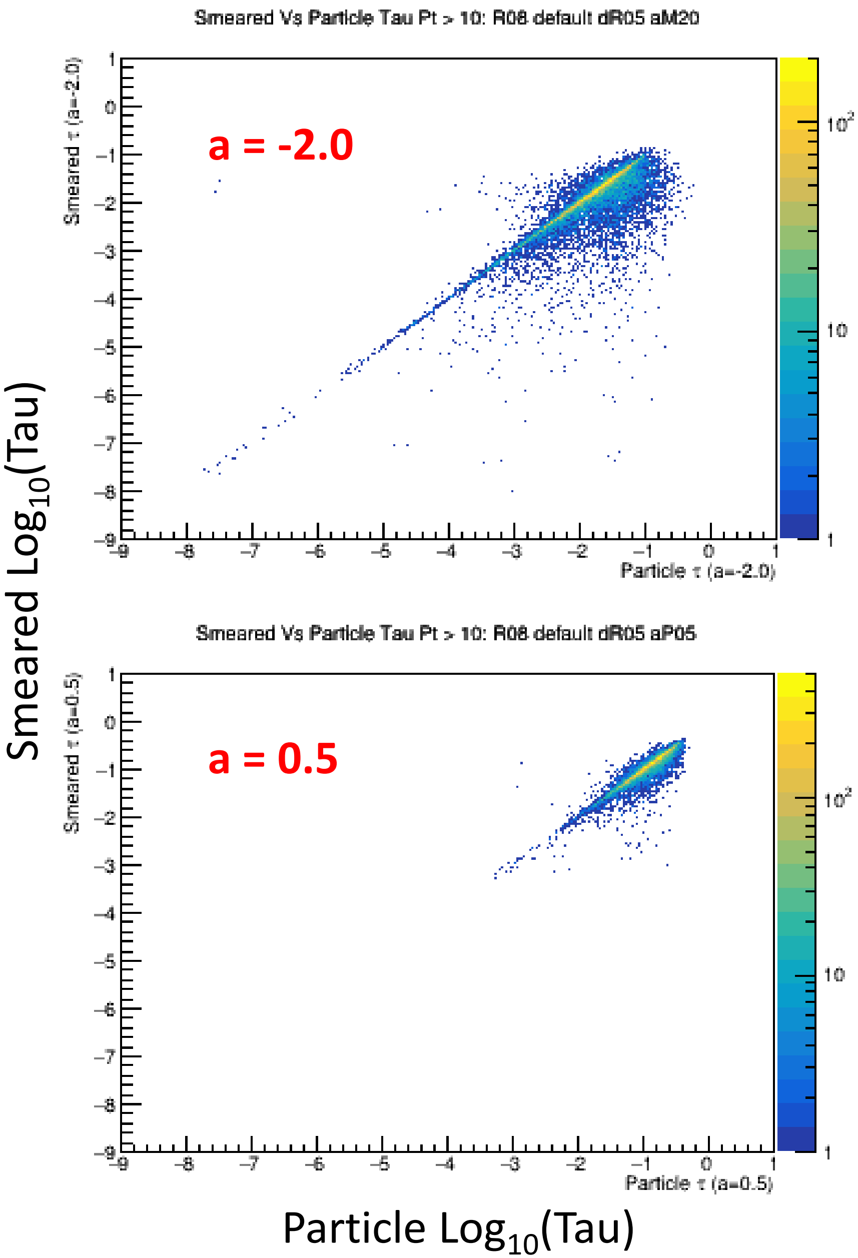




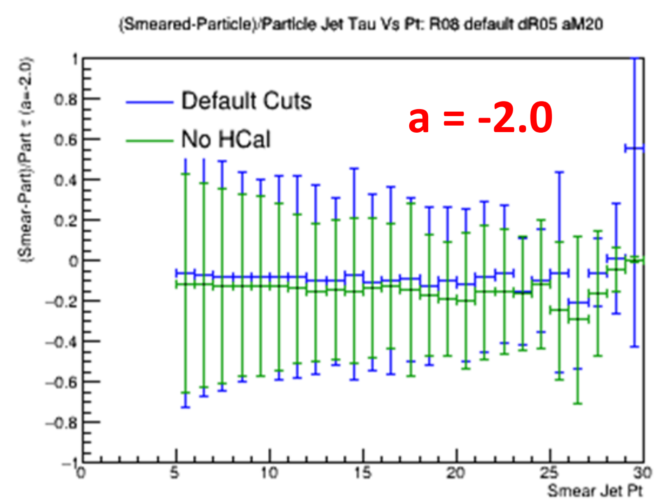
- Ignoring HCal information when reconstructing jets improves resolution but at the cost of severely reducing fraction of jets containing neutral hadron
- Increasing HCal resolution in barrel improves situation – need to see if these resolutions are feasible
- More studies needed to assess effect such biases will have on various observables

Angularity Smearing

$$\tau_a \equiv \frac{1}{p_T} \sum_{i \in J} p_T^i \left(\Delta R_{iJ}\right)^{2-a}$$

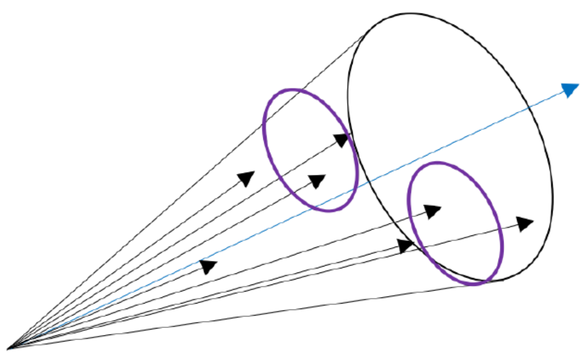


- Angularity sums over the p_T of each particle in the jet weighted by the distance of the particle from the jet thrust axis
- The ‘a’ parameter controls how heavily the distance is weighted
- Comparison of Smeared Vs Particle Log_{10}(Tau) shows relatively good correlation
- Larger ‘a’ values have less scatter than more negative ‘a’ values
- Bias from neutral hadrons does not seem as strong – but need further investigation



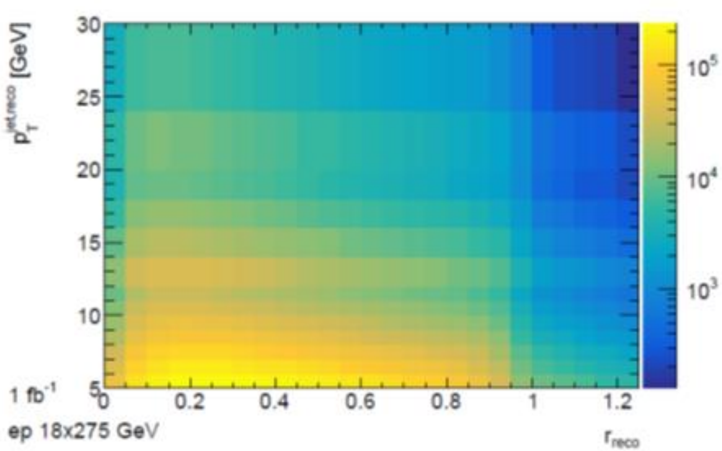
Groomed Jet Substructure – J. Osborn, D. Fitzgerald

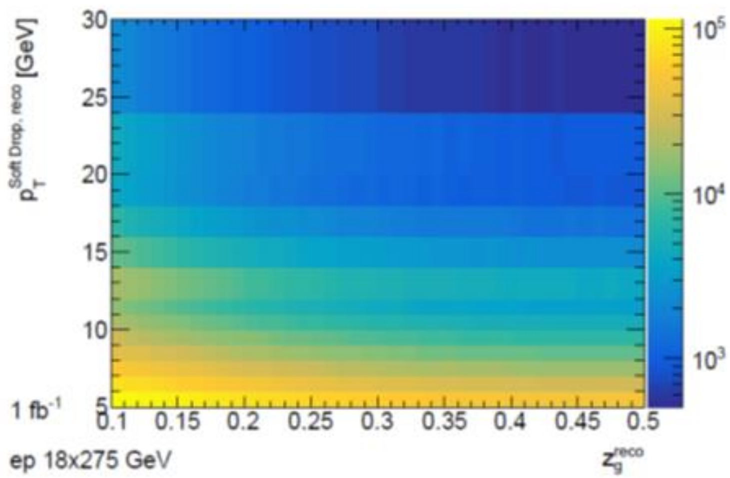
- Goal: assess feasibility of measuring standard and soft-dropped groomed jet substructure and also D jet tagging
- Generate events with Q2 > 9 GeV2 at top energy using PYTHIA6
- Smear with eic-smear with 'Handbook' detector configuration
- Soft drop parameters: z_{cut} = 0.1, β= 0



$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

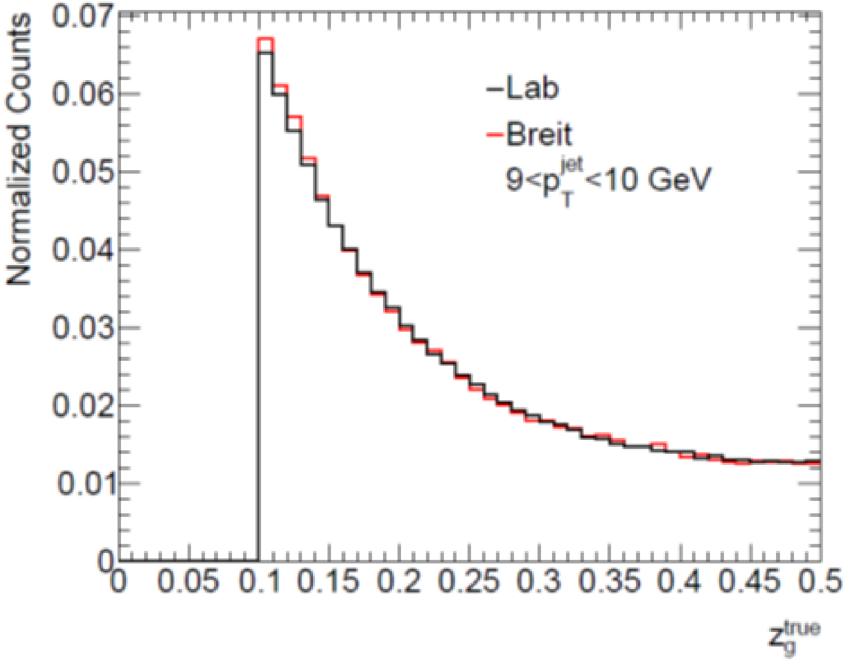
$$R_g = \Delta R(p_{T,1}, p_{T,2})$$





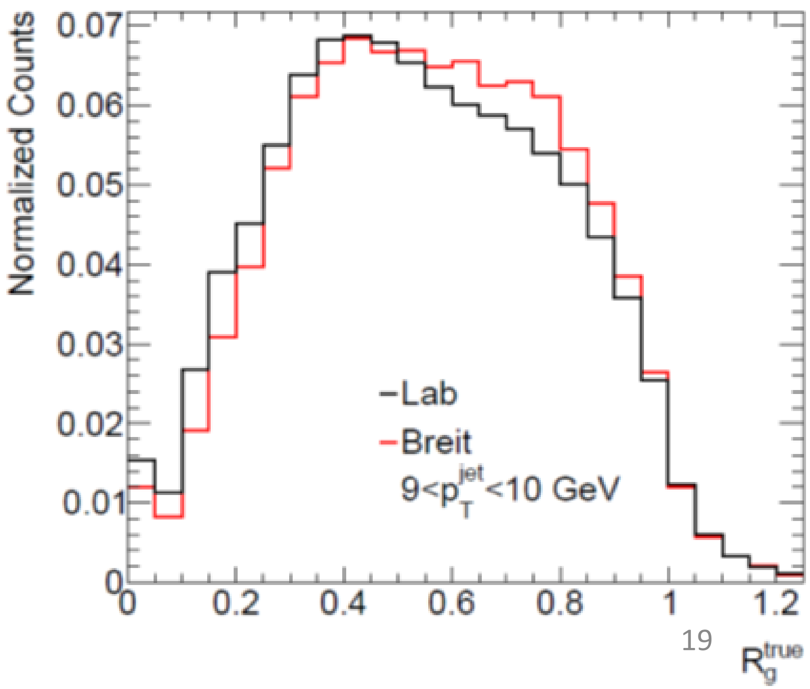
Statistics for 1 fb^{-1}

Groomed Observables: Lab Vs Breit Frame



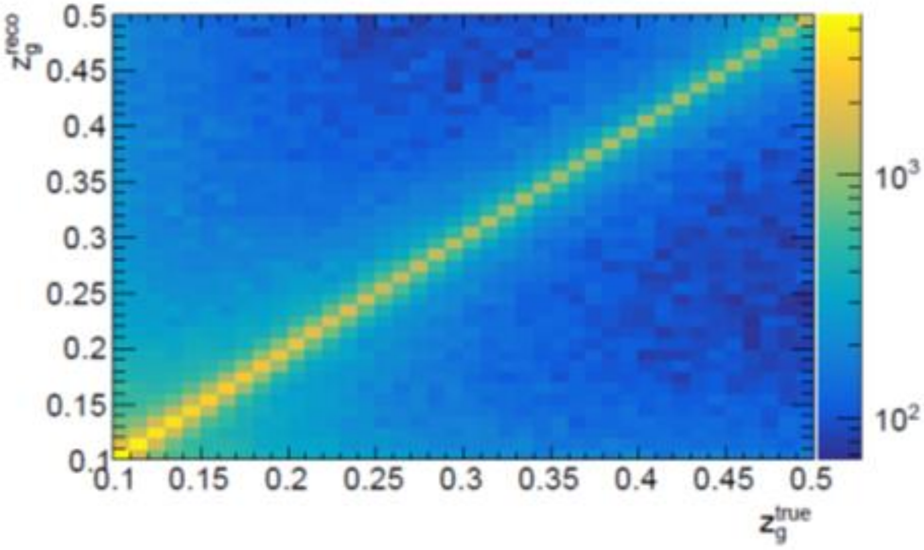
- Can groomed observables be used to separate quark and gluon initiated jets?
- High-p_T jets in lab frame dominated by LO DIS -> quark jets
- LO DIS highly suppressed in Breit frame leading to larger fraction of gluon jets in sample

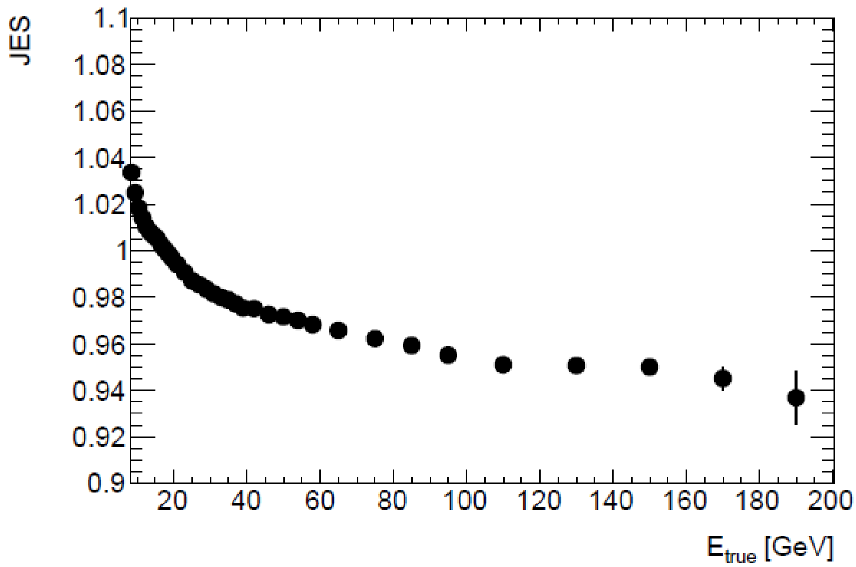
- Results shown at Particle Level
- Z_g shows little sensitivity, but a noticeable shift is seen in R_g

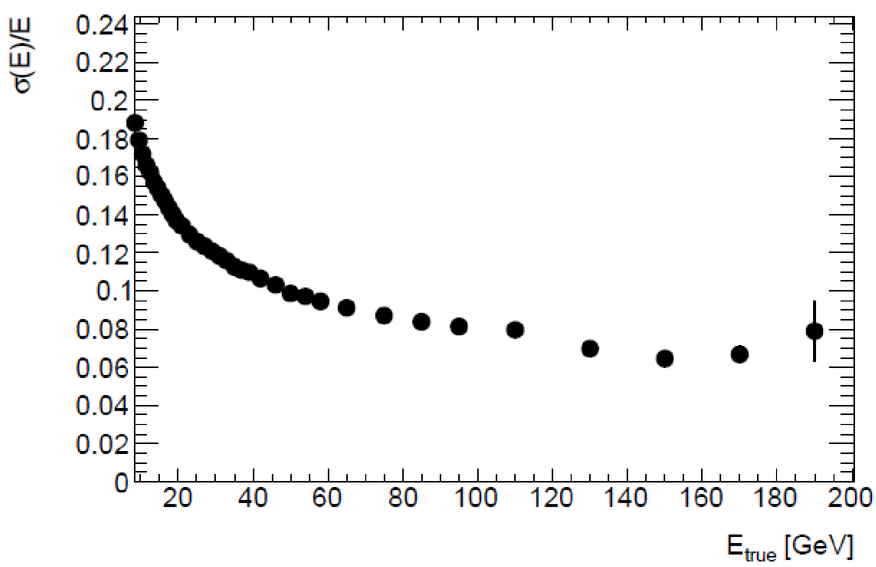


Resolutions

- Correlation between reconstructed and true Z_g shown on right
- Jet energy scale and jet energy resolution shown below – largely in line with what is seen in other analyses







Light – Flavor Jet Summary

- Extensive studies of jet smearing in both low and high Q^2 regimes have been carried out using both the DELPHES and eic-smear frameworks
- Overall, Handbook parameters found to be adequate for TMD and angularity studies, although reconstruction bias seen in certain kinematics due to poor HCal resolution
- First studies of detector effects on groomed jet substructure observables being carried out using eic-smear framework
- Work beginning on global event shapes which can provide constraints on strong coupling and hadronization effects
- Implementation of calorimeter position resolutions in smearing will be crucial for substructure and event shape studies

Linearly polarized gluon TMDs at the EIC

- Opportunity to study linearly polarized gluons at the EIC

The gluon correlator:

$$\Gamma_g^{\mu\nu[\mathcal{U},\mathcal{U}']}(x,k_T) \equiv \mathrm{F.T.}\langle P|\mathrm{Tr}_c\left[F^{+\nu}(0)\,\mathcal{U}_{[0,\xi]}\,F^{+\mu}(\xi)\,\mathcal{U}'_{[\xi,0]}\right]|P\rangle$$

For unpolarized protons:

$$\Gamma_U^{\mu\nu}(x,p_T) = \frac{x}{2}\left\{-g_T^{\mu\nu} f_1^g(x,p_T^2) + \left(\frac{p_T^\mu p_T^\nu}{M_p^2} + g_T^{\mu\nu}\frac{p_T^2}{2M_p^2}\right) h_1^{\perp\,g}(x,p_T^2)\right\}$$

unpolarized gluon TMD

linearly polarized gluon TMD

Gluons inside *unpolarized* protons can be polarized!

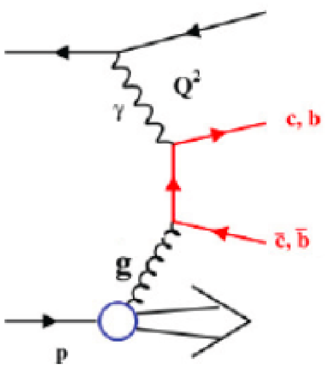
[Mulders, Rodrigues '01]

- Tough to probe at the LHC, although J/ψ, η production possible (also Higgs, but suppressed by $O(\alpha_s^2)$)

Daniel Boer

Linearly polarized gluon TMDs at the EIC

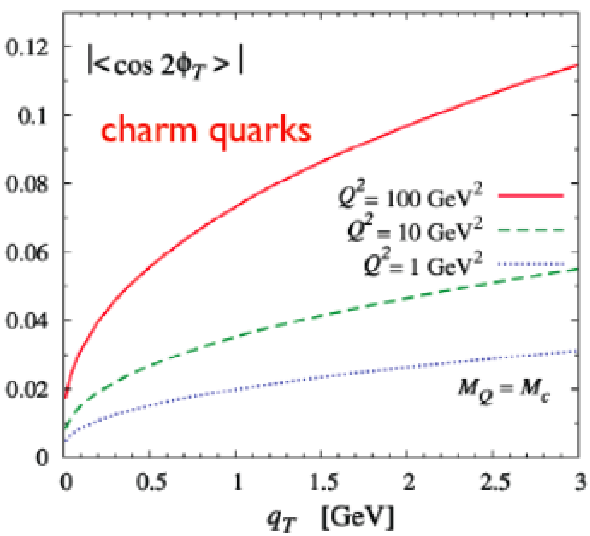
- Accessible through azimuthal asymmetries in open heavy flavor production

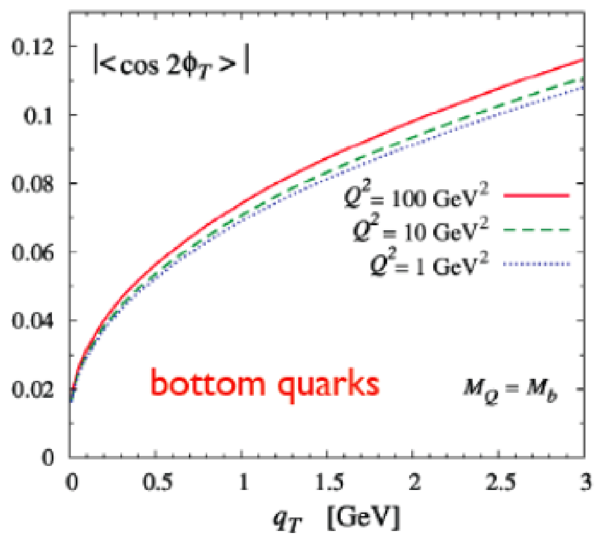


$$|\langle \cos 2\phi_T \rangle| = \left| \frac{\int d\phi_\perp d\phi_T \, \cos 2\phi_T \, d\sigma}{\int d\phi_\perp d\phi_T \, d\sigma} \right| = \frac{\boldsymbol{q}_T^2 \, |B_0^U|}{2 \, A_0^U} = \frac{\boldsymbol{q}_T^2}{2M^2} \frac{\left| h_1^{\perp g}(x, \boldsymbol{p}_T^2) \right|}{f_1^g(x, \boldsymbol{p}_T^2)} \frac{\left| \mathcal{B}_0^{eg \to eQ\overline{Q}} \right|}{\mathcal{A}_0^{eg \to eQ\overline{Q}}}$$

φ_T is the azimuthal angle of the heavy-quark pair w.r.t. the lepton

Asymmetry in φ_T proportional to linearly-polarized gluon TMD





Sizable asymmetries expected

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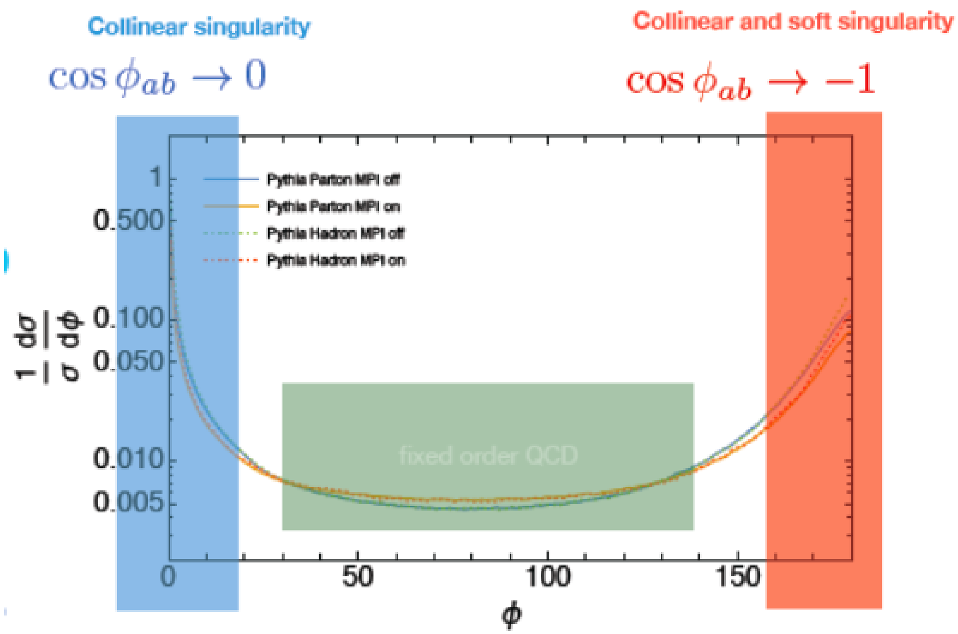
Transverse energy-energy correlators

- TEEC serve as a precision probe of QCD and potentially nucleon/nuclear structure

Transverse hadronic energy

$$\text{TEEC} = \sum_a \int d\sigma_{lp\to l+a+X} \frac{E_{T,a}}{\sum_i E_{T,i}} \delta\left(\cos\phi_{la} - \cos\phi\right)$$

Azimuthal angle between lepton and hadronic energy



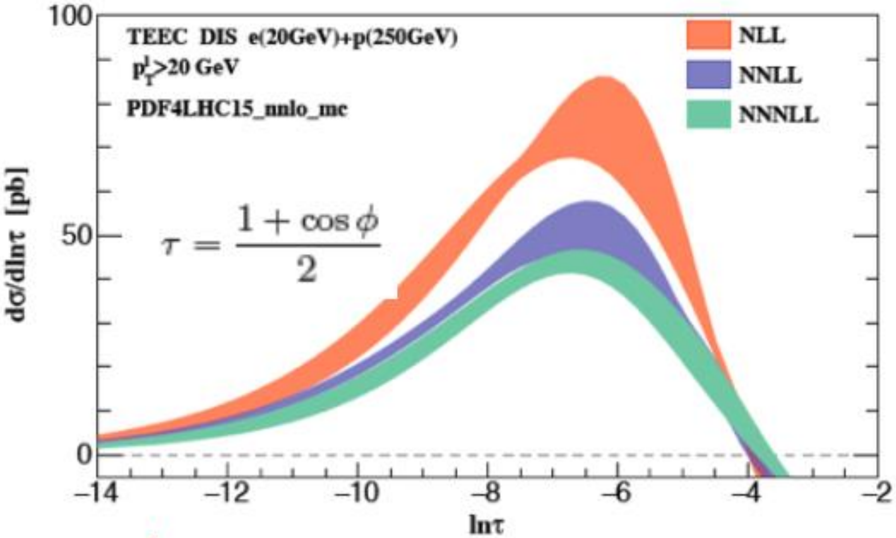
Can establish factorization theorem in back-to-back ($\varphi \to \pi$) limit:

$d\sigma/d\varphi \sim B \otimes H \otimes J \otimes S$

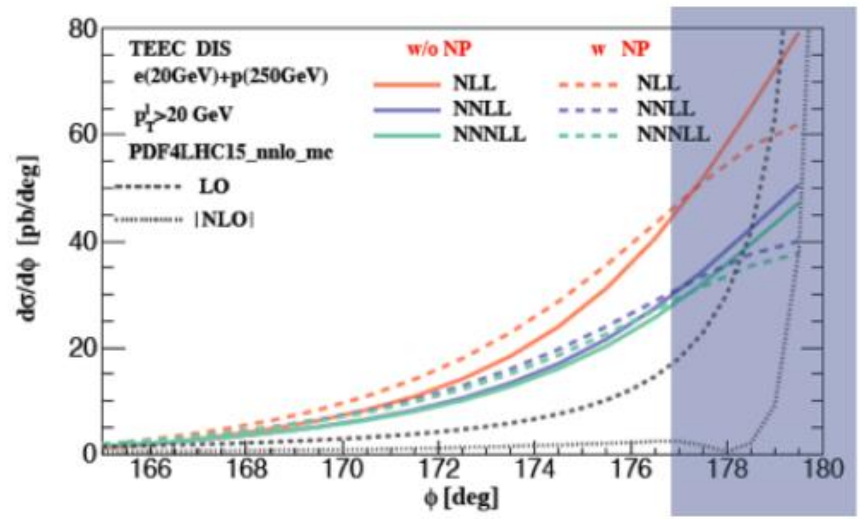
Haitao Li

Transverse energy-energy correlators

- Predictable to very high precision in the back-to-back region



← $\varphi \to \pi$

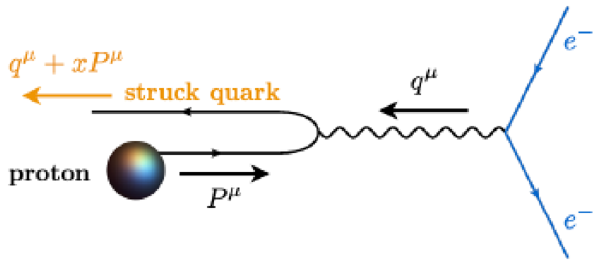


Large NP effects and nuclear corrections expected near $\varphi \sim \pi$

Asymmetric jet clustering in deep-inelastic scattering *arXiv: 2006.10751*

M. Arratia,[1,2,*] Y. Makris,[3,†] D. Neill,[4,‡] F. Ringer,[5,§] and N. Sato[6,¶]

Jet clustering in the Breit frame

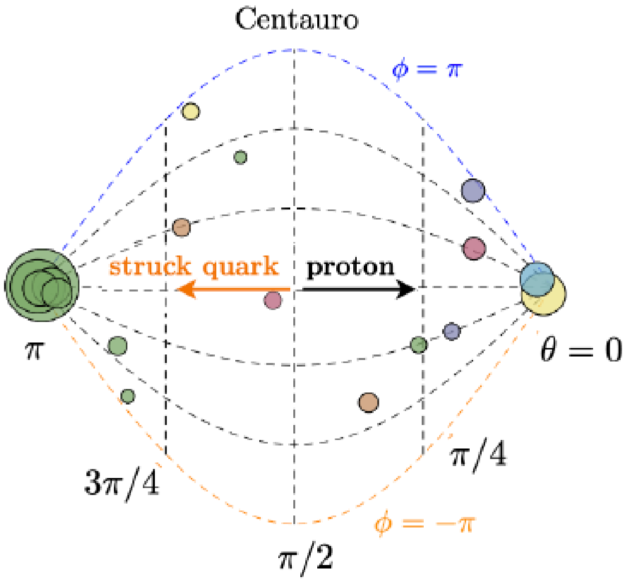


- Measure energy of jets

$$z_{\rm jet} = \frac{P \cdot p_{\rm jet}}{P \cdot q} \simeq \bar{n} \cdot p_{\rm jet}/Q = p^-_{\rm jet}/Q$$

- Ideally suited for TMD studies

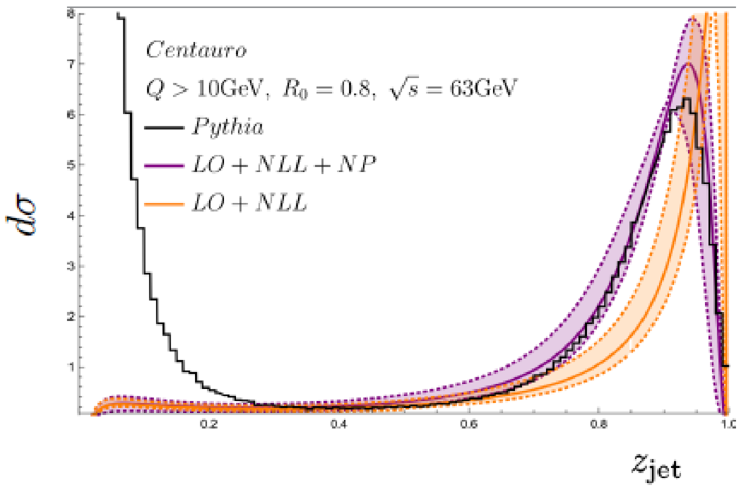
A new jet algorithm **"Centauro"** which captures the leading-order DIS jet



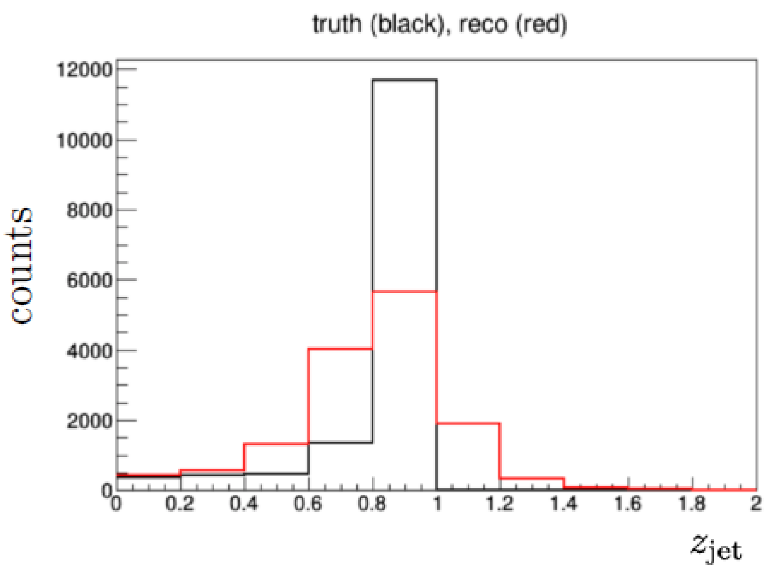
The necessary files and instruction on how to use Centauro within FastJet can be found on Github:

https://github.com/miguelignacio/CentauroJetAlgorithm

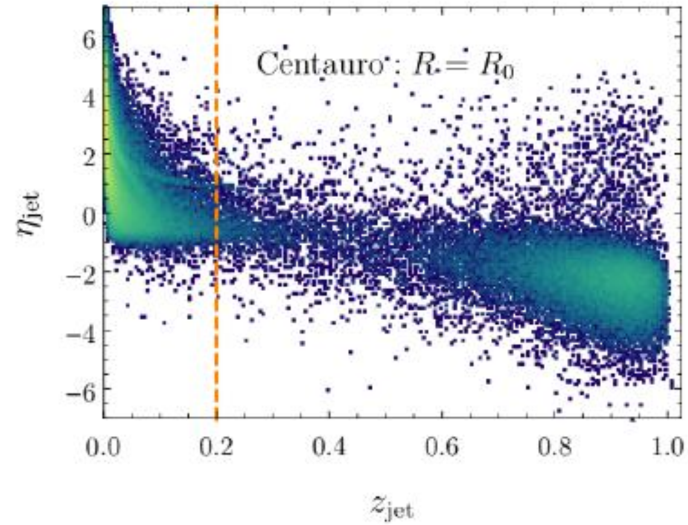
- The jet energy spectrum

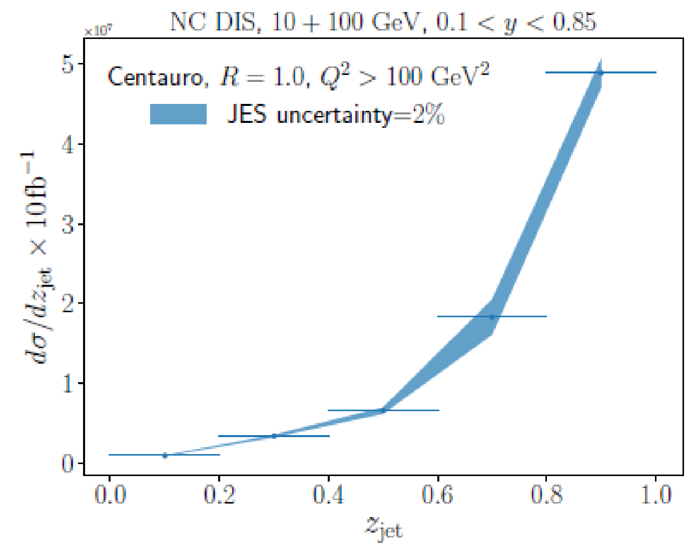


Good jet energy resolution needed



- Clean separation of current and target fragmentation





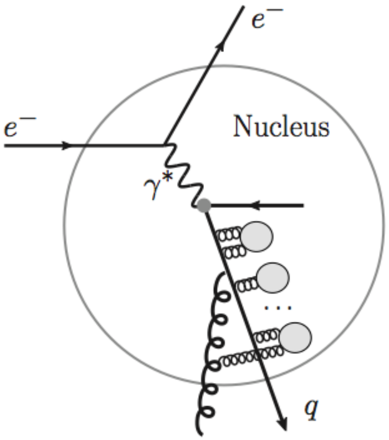
Heavy meson tomography of cold nuclear matter at the EIC

Zelong Liu

Los Alamos National Lab.

In collaboration with I. Vitev and H.T. Li

arXiv:2007.xxxxx



Overarching goal – understand the processes of energy loss and hadronization in cold nuclear matter at EIC; identify optimal observables and kinematics; develop a new theoretical framework for light and heavy flavor modification

$$E_h \frac{d^3\sigma^{\ell N \to hX}}{d^3 P_h} = \frac{1}{S} \sum_{i,f} \int_0^1 \frac{dx}{x} \int_0^1 \frac{dz}{z^2} f^{i/N}(x,\mu) \times D^{h/f}(z,\mu) \left[\hat{\sigma}^{i\to f} + f_{\rm ren}^{\gamma/\ell}\left(\frac{-t}{s+u},\mu\right) \hat{\sigma}^{\gamma i \to f} \right]$$

Developed NLO code for light and heavy meson production at the EIC

- Healthy number of mesons produced even at high p_T
- NLO K-factors about 2 (1.5-2.5 depending on kinematics)
- Allows for differential studies for hadronization and energy loss

		5 GeV×40 GeV		10 GeV×100 GeV		18 GeV×275 GeV	
p_T^h [GeV]		[2,3]	[5,6]	[2,3]	[5,6]	[2,3]	[5,6]
π^+	LO	5.3×10^6	24260	1.4×10^7	3.0×10^5	2.9×10^7	9.6×10^5
	NLO	1.1×10^7	69473	2.8×10^7	6.1×10^5	5.6×10^7	1.9×10^6
D^0	LO	1.4×10^6	3242	8.6×10^6	89952	3.1×10^7	6.6×10^5
	NLO	3.7×10^6	8536	2.1×10^7	2.1×10^5	7.2×10^7	1.5×10^6
B^0	LO	3.7×10^5	1171	2.4×10^6	28413	9.0×10^6	2.0×10^5
	NLO	1.1×10^6	3333	6.2×10^6	72329	2.1×10^7	4.7×10^5

Selected light and heavy meson yields for integrated luminosity 10 fb^{-1} integrated in rapidity range $-2 < \eta < 4$

Evolution of Fragmentation Functions

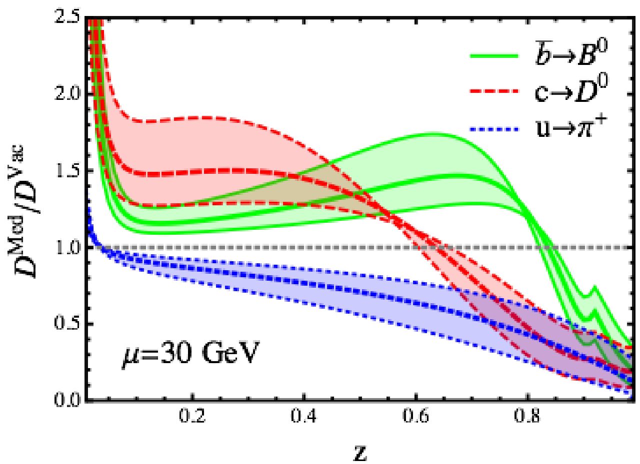
- Evolution based on standard DGLAP. For heavy flavor – perturbatively calculated initial conditions

$$\frac{\mathrm{d}D_{h/q}(z,Q)}{\mathrm{d}\ln Q} = \frac{\alpha_s(Q)}{\pi}\int_z^1 \frac{\mathrm{d}z'}{z'}\left[P^{\mathrm{full}}_{q\to qg}(z',Q;\beta)D_{h/q}\left(\frac{z}{z'},Q\right) + P^{\mathrm{full}}_{q\to gq}(z',Q;\beta)D_{h/g}\left(\frac{z}{z'},Q\right)\right]$$

- In-medium splitting functions are derived based on $\mathrm{SCET}_{(\mathrm{M})\mathrm{G}}$. Accounts for medium-induced shower contribution

$$P_i^{\mathrm{full}}(x,\boldsymbol{k}_\perp;\beta) = P_i^{\mathrm{vac}}(x) + P_i^{\mathrm{med}}(x,\boldsymbol{k}_\perp;\beta)$$

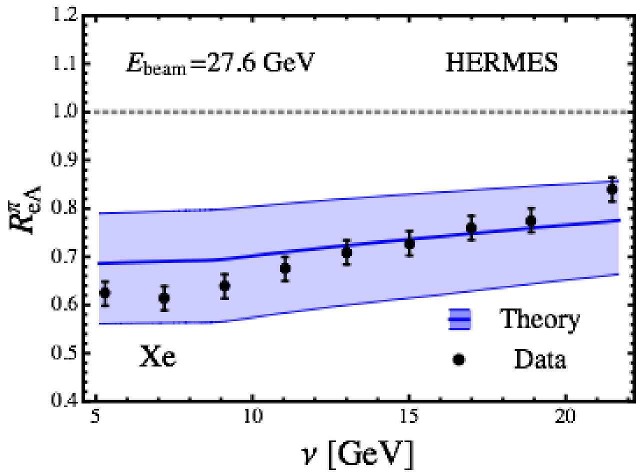
Suppression at large momentum fraction z. Significant enhancement at small z for heavy flavors

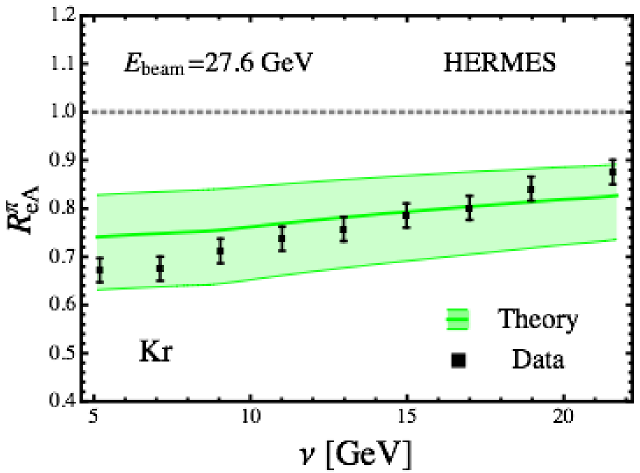


Modification of FFs relative to the vacuum for Au nucleus

Validation of phenomenology

Good description of HERMES data at low CM energies



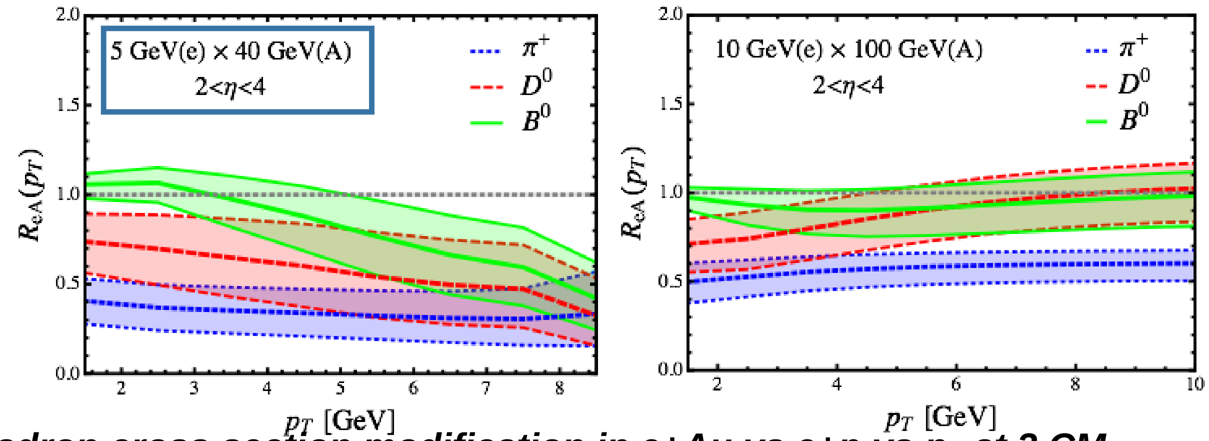


Comparison to fixed target HERMES measurement of pions from nuclear targets

Phenomenology at the EIC

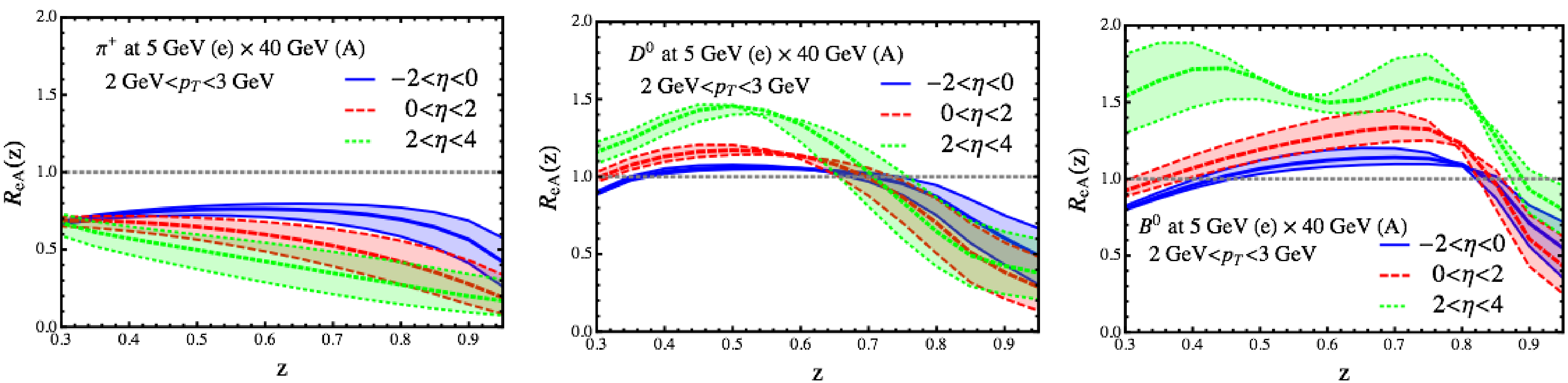
Cold Nuclear Matter effects are more significant in the forward rapidity region at lower energy collisions

Transvesre momentum distributions are not the optimal observable to study. Much of the heavy flavor physics is lost



Hadron cross section modification in e+Au vs e+p vs p_T at 2 CM energies

- **Best observable identified is the hadronization fraction z. To study energy loss the largest and most differentiation effects are at 5 GeV x 40 GeV and forward rapidity η>2**
- **Conversely at at backward rapidities and large CM energies effects expected to predominantly come form NPDFs, saturation**



Light and heavy hadron cross section modification vs fragmentation ftaction z in e+Au vs e+p vs p_T at 3 rapidity intervals

Theory Summary

- Over the course of the YR exercise, have had several interesting theoretical presentations outlining new opportunities for jet and HF observables

- Several new opportunities to explore: linearly polarized gluons using open HF, NP and CNM effects using event shapes, and fragmentation using a novel jet clustering algorithm

- There will not be time in YR exercise to fully explore the detector requirements for many of these proposals, but important to document for future study