Jets and Heavy Flavor Production at the EIC

Prabhakar Palni
IIT Mandi

International Workshop on Probing Hadron Structure at the EIC
5-9 February 2024, ICTS, Banglore

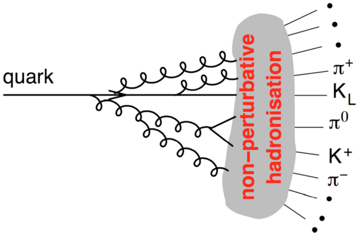
Indian Institute of Technology Mandi

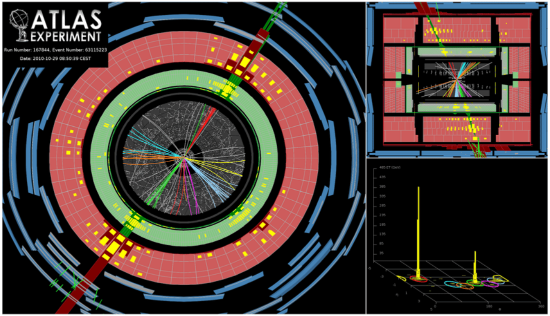
Jets are Important

- EIC physics and the relevant measurements listed in Yellow Report (Nucl. Phys. A, Vol 1026, 122447)

Topics \ Processes	Inclusive	Semi-Inclusive	Jets, Heavy Quarks	Exclusive	Diffractive, Forward Tagging
Global properties & parton structure	incl. SF	h, hh	jet, Q	excl. $Q\bar{Q}$	incl. diffraction, tagged DIS on D/He
Multidimensional Imaging		h	jet, di-jet, jet+h, Q, $Q\bar{Q}$	DVCS, DVMP, elast. scattering	
Nucleus	incl. SF	h, hh	jet, di-jet, Q, $Q\bar{Q}$	coh. VM, di-jet, h, hh, D/He FF	diffr. SF, incoh. VM, di-jet, h, hh, nucl. fragments
Hadronization		h, hh, jet+h	jet, Q, $Q\bar{Q}$		
Other fields	incl. SF with e^+, $\sigma^{tot}_{\gamma A}$	charged curr. DIS, $\sigma_{\gamma A \to hX}$		$\sigma^{elast}_{\gamma A}$	$\sigma^{diffr}_{\gamma A}$

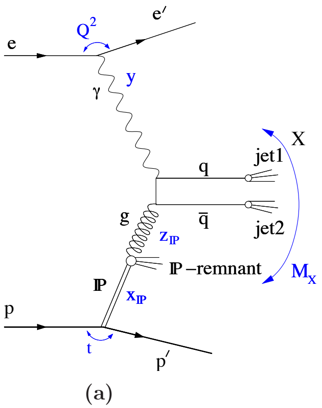
What are Jets?





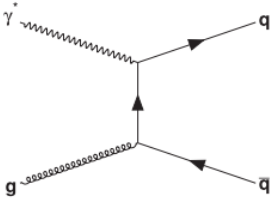
Important Sub-processes involving Jets

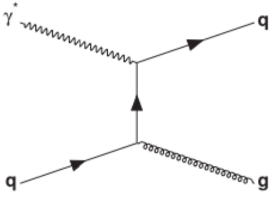
- Diffractive Dijets in Photoproduction



Direct ($x_\gamma \approx 1$) **Resolved ($x_\gamma < 1$)**

Important Sub-processes involving Jets

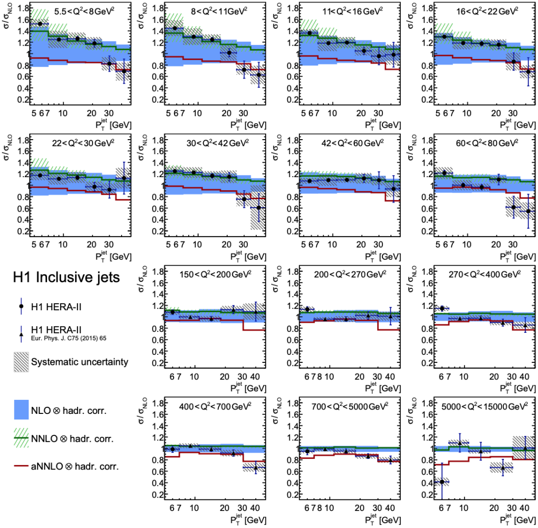




Photon Gluon Fusion (PGF) **QCD Compton Scattering (QCDC)**

Inclusive Jets Cross-section Measurements at HERA

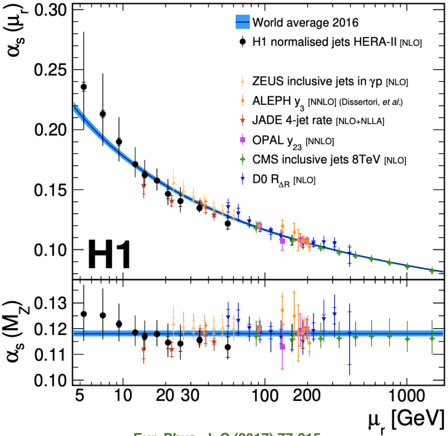
- Normalized inclusive jet cross-sections for different Q^2 intervals



Eur. Phys. J. C (2017) 77:215

Inclusive Jets Cross-section Measurements at HERA

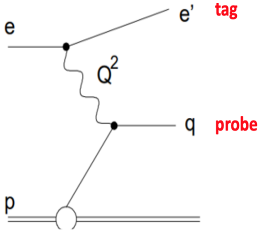
- Precision jet measurements can be used to constrains PDF parametrisations
- Extract strong coupling constant with better precision

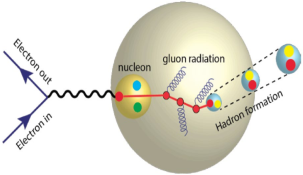


Eur. Phys. J. C (2017) 77:215

DIS Jets as a Precision Tool in e+A Collisions

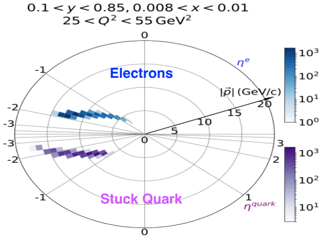
- DIS jets can be used as a precision tool in e+A collisions
- Tag and probe method
- Analyze propagation of quark through nucleus, its quark structure, and hadronization.
- Match jet to the stuck quark and measure it precisely, by separating beam remnant



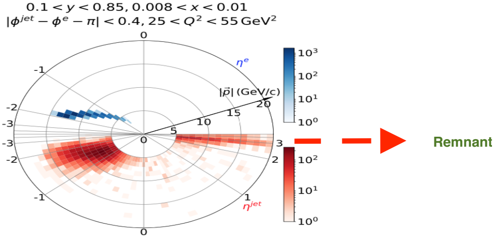


Phys. Rev. C 101, 065204 (2020)

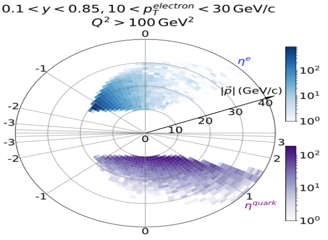
Separation of Struck Quark from Beam Remnant



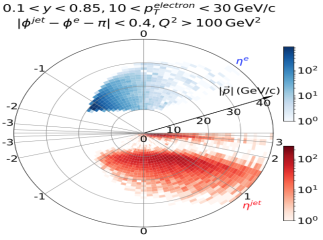
(a)



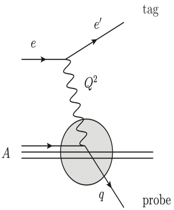
(b)



(d)



(e)

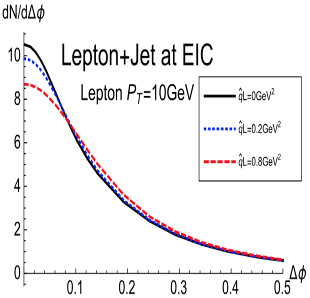


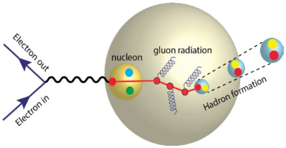
Phys. Rev. C 101, 065204 (2020)

Lepton+ Jet Azimuthal Correlation

Phys. Rev. Lett. 122 (19) (2019) 192003

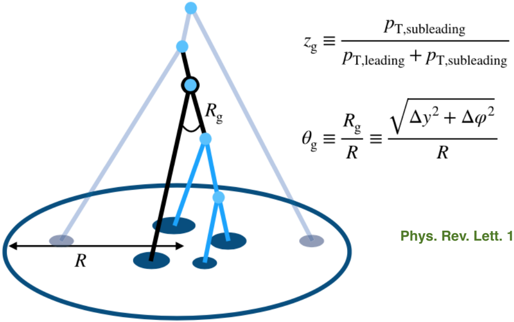
- p_T broadening effects can be used to explore cold nuclear effects in e+A
- Highly energetic jet experiences multiple interactions with the target nucleus which will generate p_T broadening
- $\hat{q}L \equiv$ transverse momentum gained by the quark through multiple interactions
- Clean channel to measure jet transport parameter & nuclear quark TMD PDF





Jet Substructure Measurement at the EIC

- Jet substructure observables offer novel and independent probes of nuclear effects at the future EIC
- Soft drop groomed jets can be used at the EIC
- Angularly ordered Cambridge-Aachen reclustering of jet constituents and subsequent soft drop grooming procedure

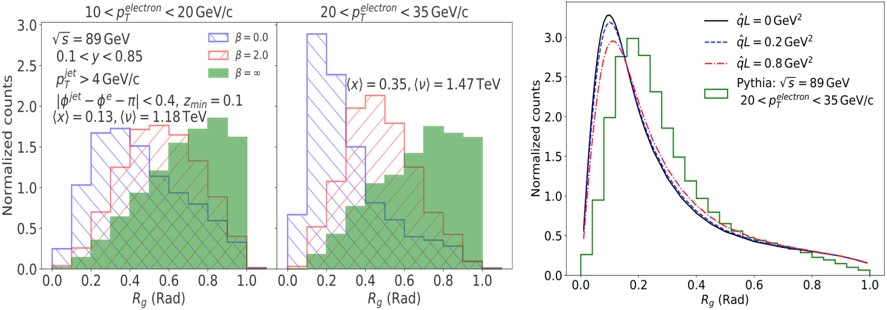


Phys. Rev. Lett. 128, 102001 (2022)

Grooming condition: $z > z_{cut}\theta^{\beta}$

Soft Drop Groomed Jets at the EIC

- Jet substructure measurement at the EIC
- Jet substructure observables offer novel and independent probes of nuclear effects at the future EIC



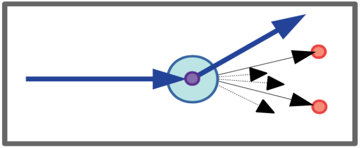
Phys. Rev. C 101, 065204 (2020)

Single and Double Spin Asymmetry

Cross Section

(Or Multiplicity)

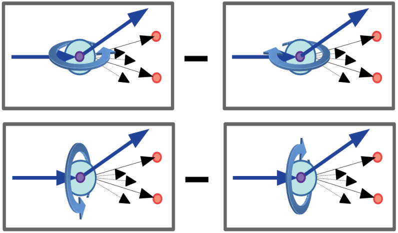
$$d\sigma$$



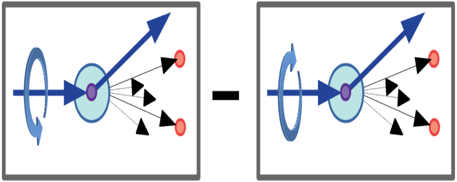
Target Spin Asymmetry

A_{UT}

A_{UL}



Beam Spin Asymmetry A_{LU}



Double Spin Asymmetries

$$A_{LL} = \frac{(d\sigma_{++} + d\sigma_{--}) - (d\sigma_{+-} + d\sigma_{-+})}{d\sigma}$$

Figures from Christopher Dilks Talk at DIS 2023

Transverse Momentum Dependent (TMD) PDFs

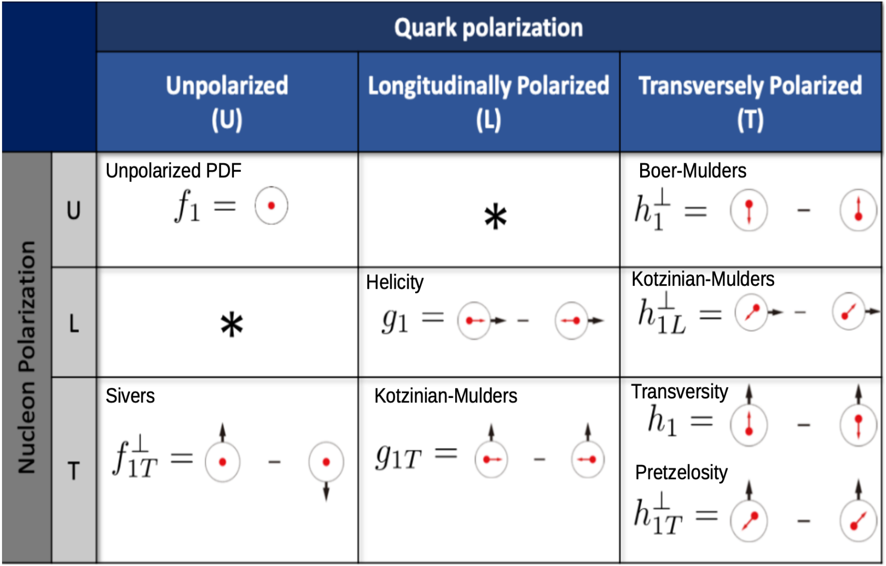
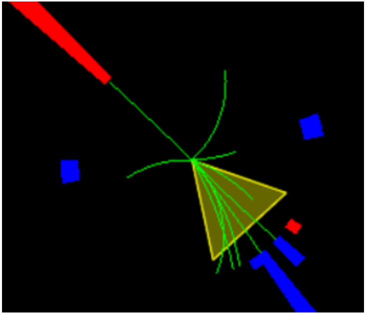
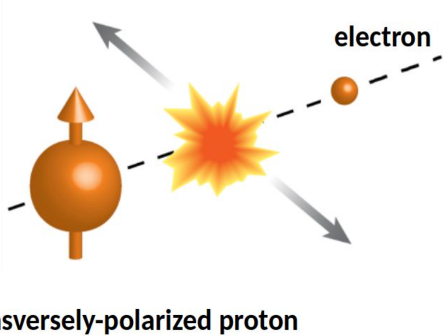


Figure from S.J. Brodsky, et al., Int.J.Mod.Phys.E 29 (2020) 08, 2030006

Projections for Electron-Jet Azimuthal Correlations

- Collisions of electrons with a transversely-polarized protons
- EIC detector implemented in Delphes

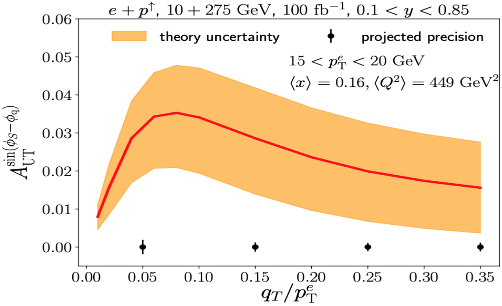




Nucl. Phys. A 1026 (2022) 122447

Projections for Electron-Jet Azimuthal Correlations

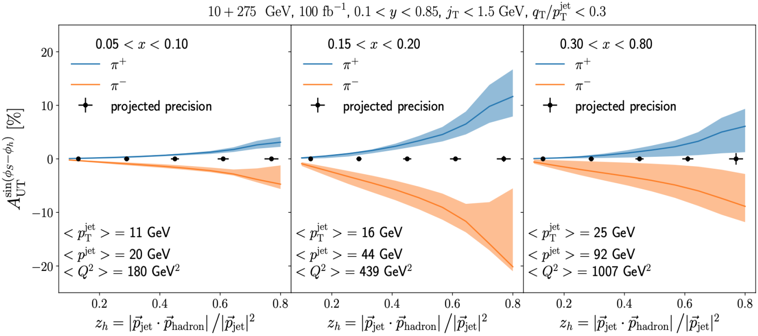
- Electron-jet azimuthal correlations are sensitive to Sivers asymmetry
- Projections of statistical uncertainties for an EIC measurement are shown in black error bars
- A small imbalance $q_T = |\vec{p_T}^{jet} + \vec{p_T}^{e^-}|$



Phys. Rev. D 102, 074015 (2020)

Projections for Hadron-in-Jet Collins asymmetry

- Distribution of hadrons inside the jet is sensitive to Collins asymmetry
- In particular, transverse momentum of hadrons w.r.t jet axis is sensitive to Collins asymmetry
- Projections for an EIC measurement are shown in black error bars

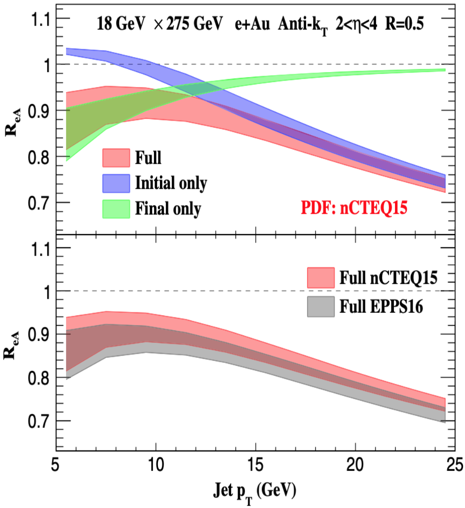


Phys. Rev. D 102, 074015 (2020)

Nuclear Matter Effects on Jet Production at EIC

- Modifications of the inclusive jet cross section in e + Au collisions
- First calculation of inclusive jet production in e+Au collisions at the EIC, which investigates the impact of initial and final state cold nuclear matter effects.

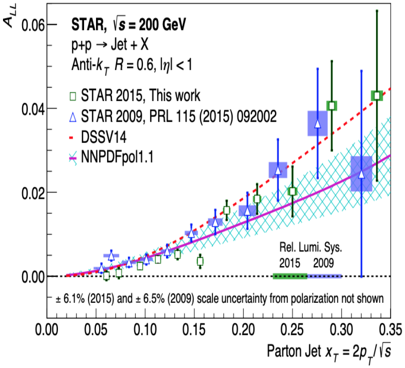
$$R_{eA} = \frac{1 \int_{\eta_1}^{\eta_2} d\sigma/d\eta dp_T|_{e+A}}{A \int_{\eta_1}^{\eta_2} d\sigma/d\eta dp_T|_{e+p}}$$



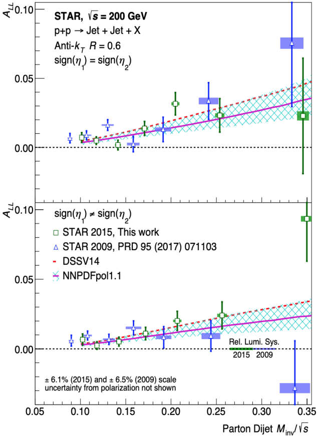
Phys. Rev. Lett. 126, 252001 (2021)

Gluon Spin Contribution to the Proton (STAR Results)

- Longitudinal double-spin asymmetry for inclusive jets



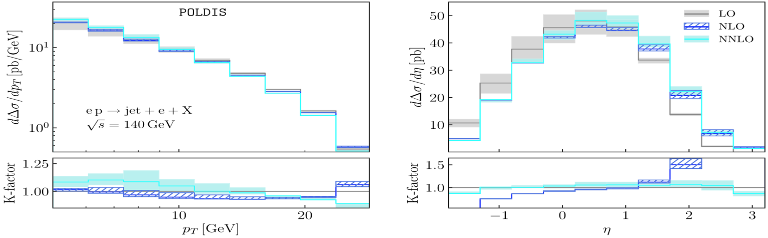
- Longitudinal double-spin asymmetry for dijets



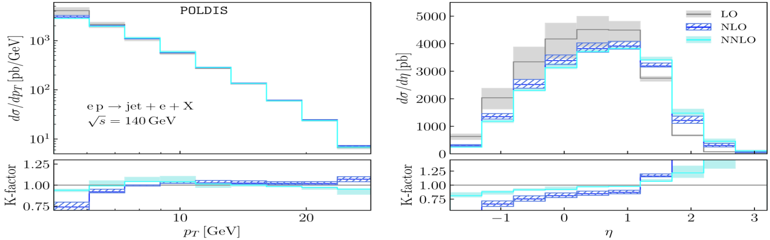
Phys. Rev. D 103, 091103 (2021)

Gluon Spin Contribution to the Proton (e+p Results)

- Single-jet p_T and η unpolarized distributions at LO, NLO, & NNLO



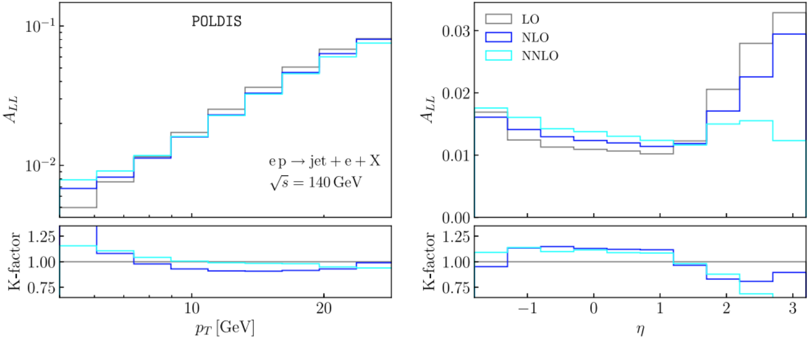
- Single-jet p_T and η polarized distributions at LO, NLO, & NNLO



Phys. Rev. Lett. 125, 082001 (2020)

Gluon Spin Contribution to the Proton (e+p Results)

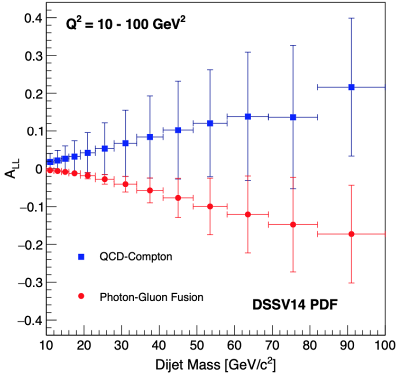
- Double spin asymmetries A_{LL} at LO, NLO, and NNLO at EIC
- Here, K-factor $= \frac{\sigma^{NNLO/NLO}}{\sigma^{LO}}$



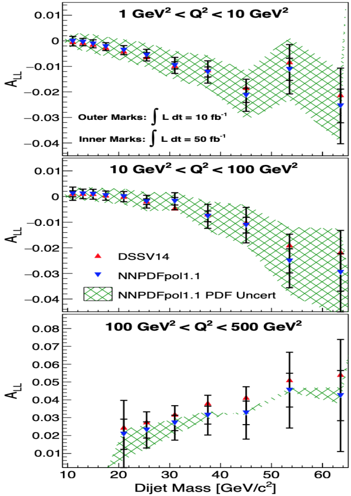
Phys. Rev. Lett. 125, 082001 (2020)

Gluon Spin Contribution to the Proton (ePIC)

- Dijet A_{LL} for QCDC and PGF sub-processes



- Dijet A_{LL} for the combined QCDC & PGF subprocesses

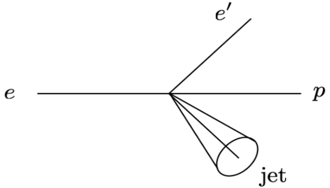


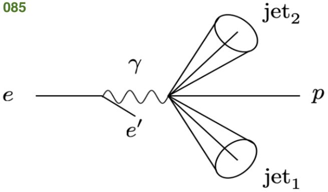
Phys. Rev. D 101, 072003 (2020)

Machine Learning Tools to Classify Jets for EIC

- Jet production processes at low-Q^2 and at high-Q^2 in electron-proton scattering
- Photon virtuality and inelasticity is in the range $25 < Q^2 < 1000$ GeV^2 and $0.1 < y < 0.85$

JHEP 03, (2023) 085

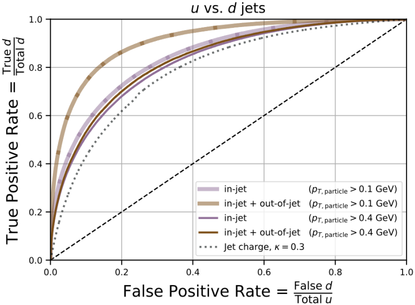


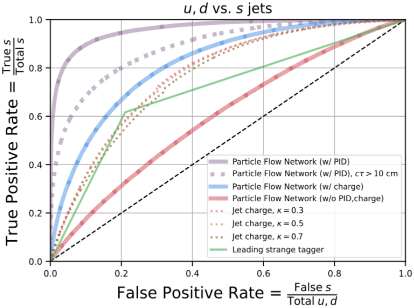


- Final state in high-Q^2 events: consists of the scattered electron and a single jet originating from different quark flavors
- Final state in low-Q^2: consists of the di-jet photoproduction events (including both the direct and resolved photon contributions)

Machine Learning Tools to Classify Jets for EIC

- Jet flavor identification



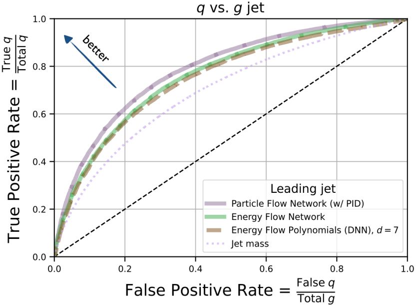


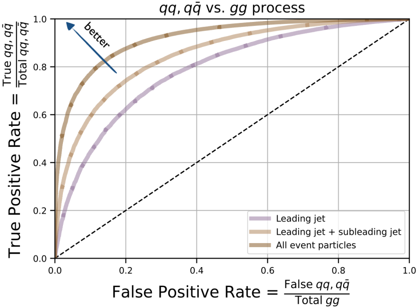
- Overall performance of u, d vs s tagging improves significantly when PID information is added

JHEP 03, (2023) 085

Machine Learning Tools to Classify Jets for EIC

- Quark vs. gluon jet tagging
- Classify hard process generating ($qq, q\bar{q}$ vs. gg) di-jets



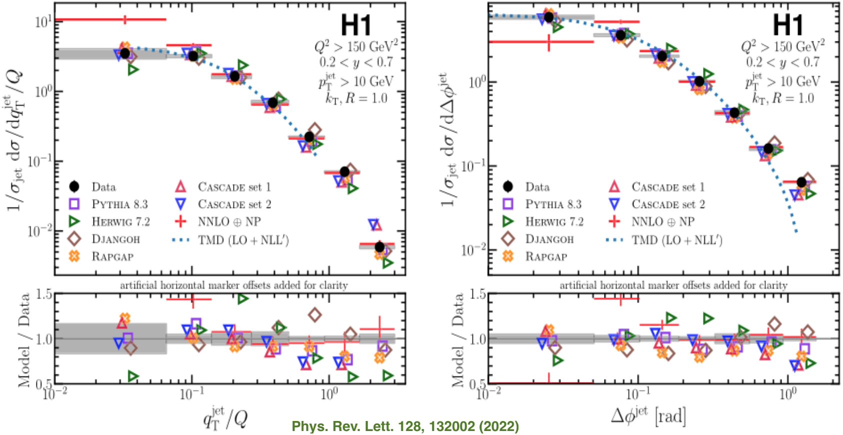


- This classification can be used to tag resolved photoproduction processes

JHEP 03, (2023) 085

Recent Machine Learning Based Results from H1

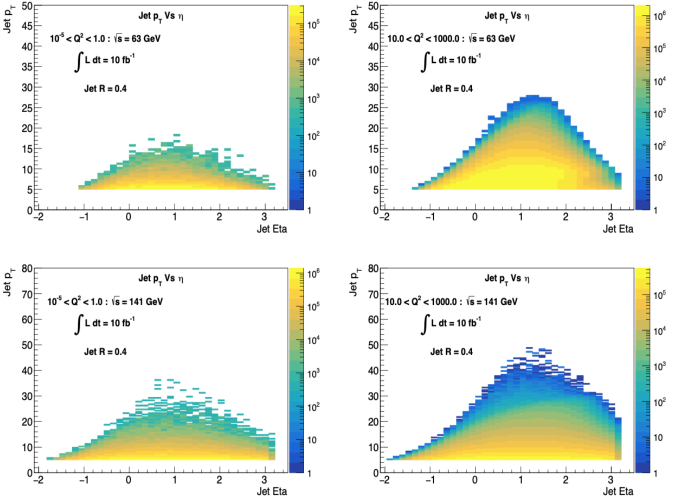
- First measurement of lepton-jet imbalance (q_T) at high Q^2
- q_T is sensitive to TMD PDFs and their evolution
- Provide a baseline for jet studies in DIS of polarized protons and nuclei at the EIC



Phys. Rev. Lett. 128, 132002 (2022)

The ePIC Detector Performance for Jets

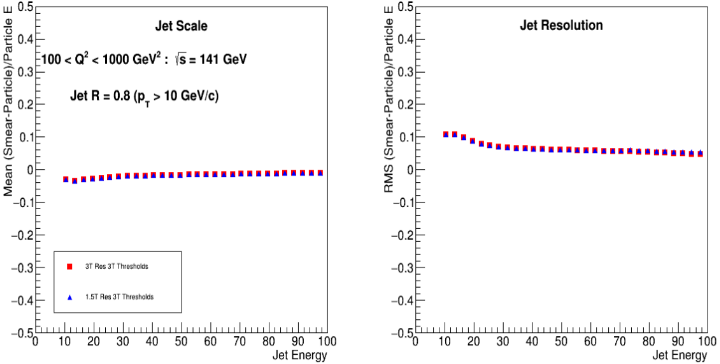
- Jet energy vs η measurements shown for two energies with detector smearing effects



Nucl. Phys. A 1026 (2022) 122447

The ePIC Detector Performance for Jets

- Jet energy scale and jet energy resolution studies shows sufficient resolution for measurements like lepton + jet Sivers Assymetry and dijets p_T imbalance etc.
- Resolution remains almost same for the 3T and 1.5T track momentum resolution parameter

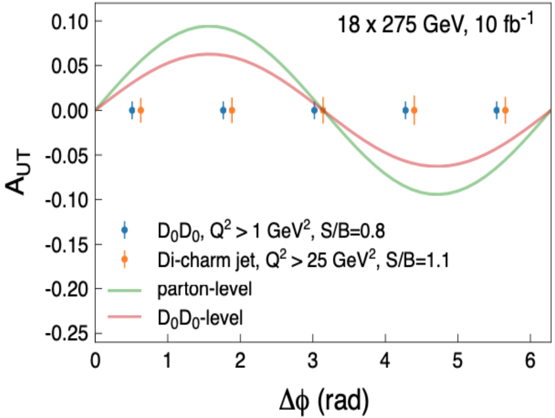


Nucl. Phys. A 1026 (2022) 122447

Heavy Flavor Production

Sensitivity for Di-charm Sivers asymmetry

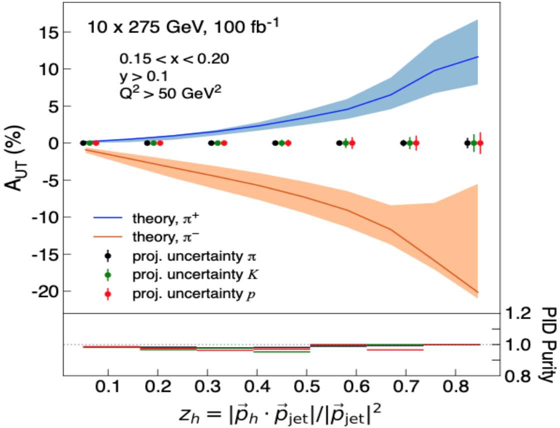
- Di-charm Sivers asymmetry measured with D0 and charm jet pairs
- Sensitivity to (anti-) quark and gluon TMD PDFs



JINST 17 (2022) P10019

Projection for Hadron-in-jet Collins Asymmetry

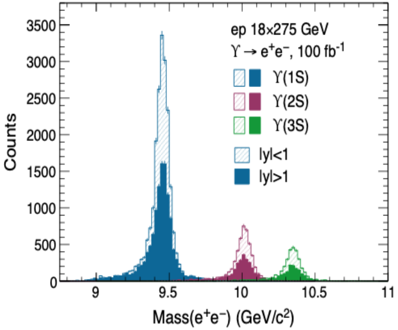
- Hadron-in-jet Collins asymmetry projections for charged pions, kaons and protons.
- Projected precision for hadron-in-jet Collins asymmetry probes quark Transversity, TMD fragmentation functions

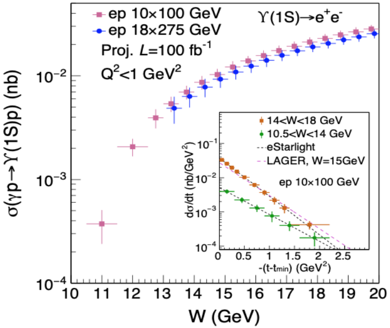


JINST 17 (2022) P10019

Exclusive Production of Υ via Di-electron Channel

- Projected uncertainty of the total and differential cross-sections of $\Upsilon(1S)$ near-threshold for photoproduction in e+p collisions
- Excellent PID performance of ATHENA for both electron and muon decay pairs of the $\Upsilon(1S)$

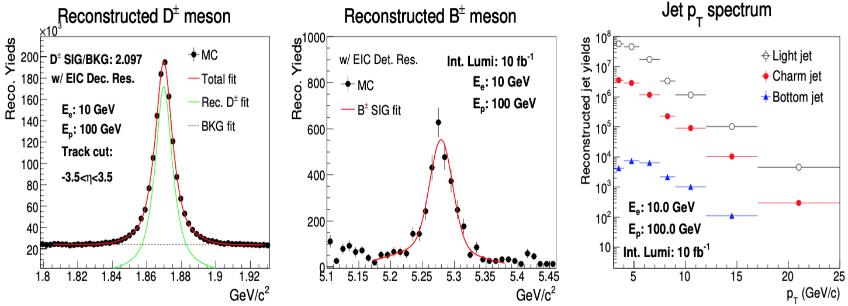




NIM A 1046 (2023) 167606

The ePIC Detector Performance for Heavy Flavor

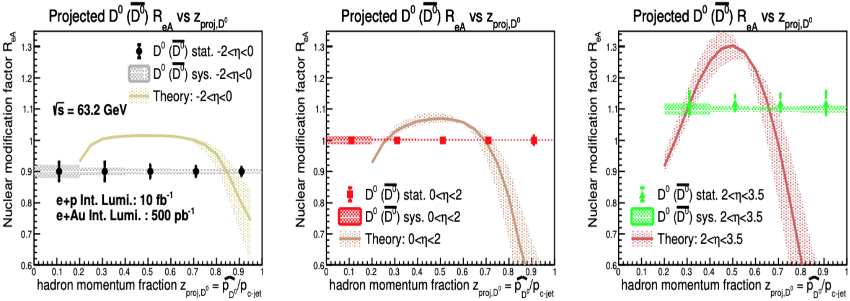
- Invariant mass spectrums of reconstructed $D^{\pm}$ and reconstructed $B^{\pm}$ in 63.2 GeV e + p simulation
- Excellent PID performance of ATHENA for both electron and muon decay pairs of the $\Upsilon(1S)$



arXiv:2311.10875

The ePIC Detector Performance for Heavy Flavor

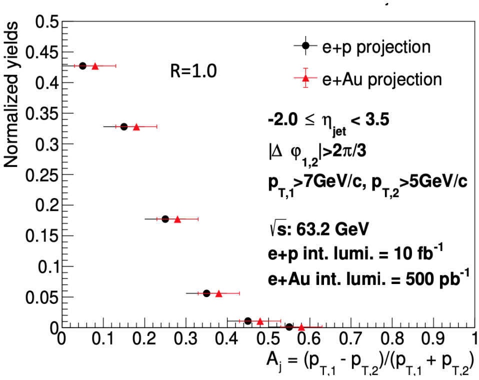
- Projected accuracy of hadron momentum fraction z_{proj,D^0} dependent nuclear modification factor R_{eAu}
- Reconstructed $D^0\bar{D}^0$ inside jet within $-2 < \eta < 0$ (left), $0 < \eta < 2$ (middle) and $2 < \eta < 3.5$



arXiv:2311.10875

The ePIC Detector Performance for Dijets

- We can constrain the gluon (or heavy quark) transport coefficient properties in cold nuclear medium by measuring heavy flavor di-jets in e+p and e+A collisions



arXiv:2311.10875

Summary

- Jets measurements at EIC will contribute to nearly every aspects of the EIC science goals
- Measurement based on Lepton+jet momentum and Azimuthal correlations in dijets will help in constraining TMD PDFs
- Near future development in jets clustering, jet substructure measurement tools, machine learning applications (to classify partons and hard processes, correct for detector effect) etc. will open new opportunities in jet physics at EIC
- Heavy flavor measurements at the EIC will explore both initial and final state effects with great precision

BACKUP

Common DIS Kinematics Observables

- Photon virtuality (negative of electron four-momentum transfer squared)
$$Q^2 = -q^2 = -(k - k')^2 = sxy \approx 4E_e E'_e \sin^2(\tfrac{\theta_e}{2})$$
- The energy transferred by the electron
$$\nu = \frac{p \cdot q}{m_p} = E'_e - E_e$$
- Inelasticity (fraction of the electron energy transferred to the proton)
$$y = \frac{p \cdot q}{p \cdot k} = \frac{\nu}{E_e} \approx 1 - \frac{E'_e}{E_e} \sin^2(\tfrac{\theta_e}{2})$$
- Bjorken - x (momentum fraction of proton carried by the struck quark)
$$x = \frac{Q^2}{2p \cdot q} = \frac{Q^2}{2m_p \nu}$$
- Squared centre-of-mass energy of the electron-proton collision system
$$s = (k + p)^2$$
- Squared centre-of-mass energy of the photon-proton collision system
$$W^2_{\gamma p} = (q + p)^2 = M^2_X = m^2_p - Q^2 + sy$$

Dijets Production Specific Observables

- Invariant Mass the hadronic final state excluding the leading proton

$$M_X^2 = P_X^2$$

- The longitudinal momentum fraction lost by the incoming proton

$$x_{\mathbb{P}} = \frac{q \cdot (p - p')}{q \cdot p}$$

- The four-momentum transfer squared at the proton vertex

$$t = (p - p')^2$$

- Longitudinal momentum fraction of photon (entering hard sub-process)

$$x_\gamma = \frac{p \cdot u}{p \cdot q}$$

- Longitudinal momentum fraction of Pomeron (entering hard sub-process)

$$z_{\mathbb{P}} = \frac{q \cdot v}{q \cdot (p - p')}$$

- Invariant mass of the dijet system M_{12}^2 (c.o.m of the hard sub-process)

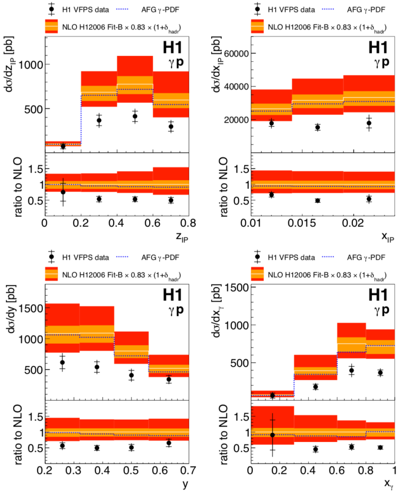
$$M_{12}^2 = (u + v)^2$$

Event Selection and MC Generator inputs

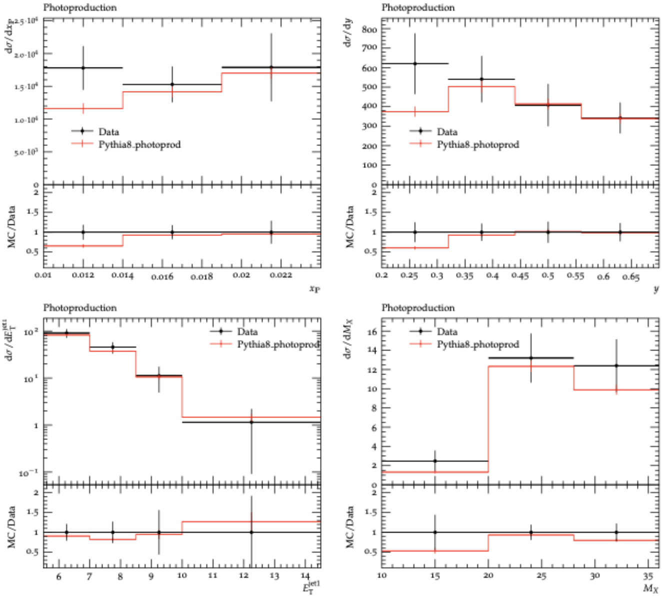
- Beam energies of the proton & positron are 920 GeV and 27.5 GeV resp.
- $Q^2 < 2$ GeV^2 and $0.2 < y < 0.7$
- $0.010 < x_{\mathbb{P}} < 0.024$, $z_{\mathbb{P}} < 0.8$ and $|t| < 0.6$ GeV^2
- $E_T^{jet1} > 5.5$ GeV, $E_T^{jet2} > 4.0$ GeV and $-1 < \eta^{jet} < 2.5$

Diffractive Dijets in Photoproduction - NLO QCD

- NLO QCD calculations based on the H12006 Fit-B DPDF set overpredicts the data

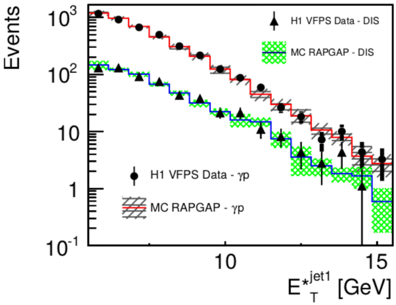


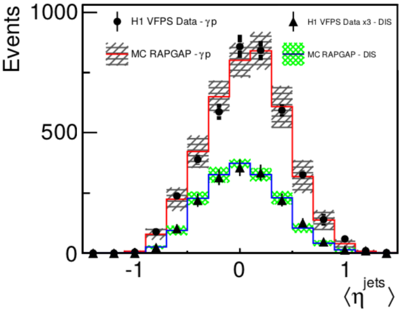
Diffractive Dijets in Photoproduction - NLO QCD



Diffractive Dijets in Photoproduction - RAPGAP

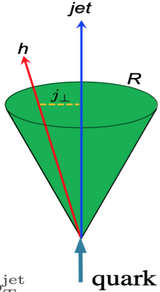
- RAPGAP generator results compared with the data





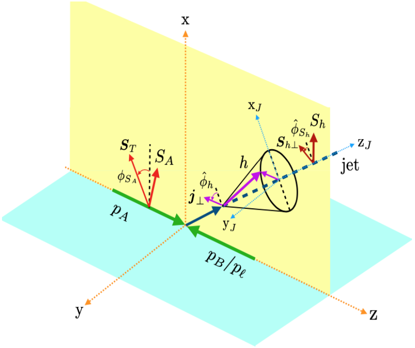
Projections for Hadron-in-jet Collins asymmetry

- Distribution of hadrons inside the jet



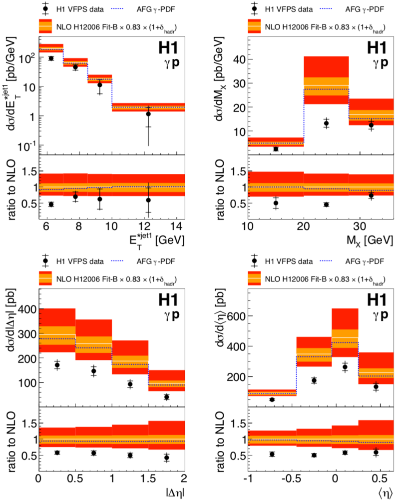
$z_h = p_T^{\mathrm{h}}/p_T^{\mathrm{jet}}$

$j_\perp$: hadron transverse momentum with respect to the jet



Diffractive Dijets in Photoproduction - NLO QCD

- NLO QCD calculations based on the H12006 Fit-B DPDF set overpredicts the data



Diffractive Dijets in Photoproduction - RAPGAP

- RAPGAP generator results compared with the data