MC4EIC

CTEQ-EICUG-HSF-MCnet Workshop on MCEGs for the EIC

November 16-18, 2022 https://indico.bnl.gov/event/17608/

Jet and Heavy Flavor Measurements at the EIC

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Outline

- Overview of EIC goals and jet / HF probes
- Select Jet and HF measurements (Yellow Report)
- Implications for MCEG needs
- Summary

Biases and Caveats

- There is of course much I need to leave out
  - Saturation
  - Diffraction
  - Beam Effect Simulation

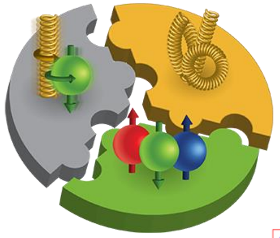
- The results shown and discussion revolve mostly around PYTHIA as this is the MCEG that has been most heavily used in the YR / Proposals / EPIC work so far. We of course need to make an effort to incorporate other general purpose MCEGs and hopefully this can begin once the EPIC core software stabilizes and analyses for the pre-TDR have begun.

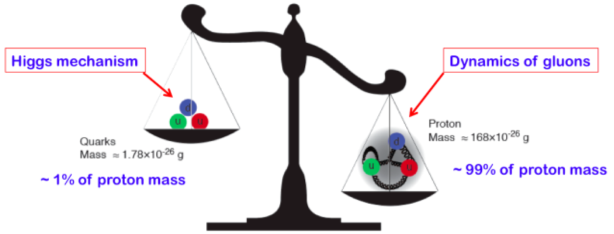
- As always, any mistakes or misrepresentations are on me

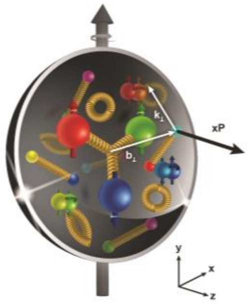
The EIC Physics Pillars

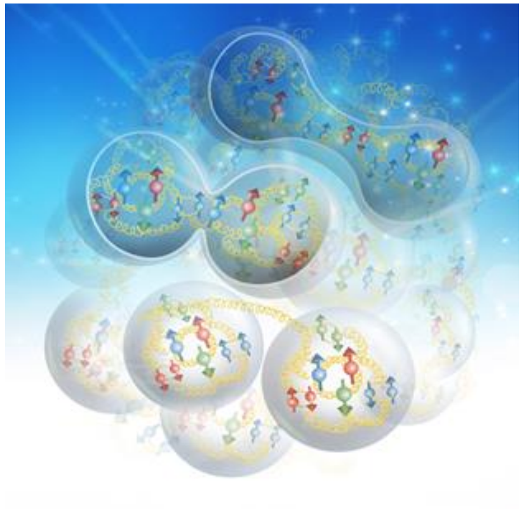
How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

How do the nucleon properties emerge from them and their interactions?









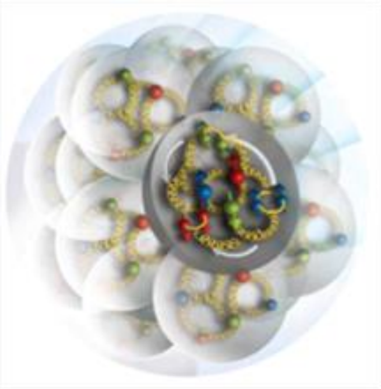
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

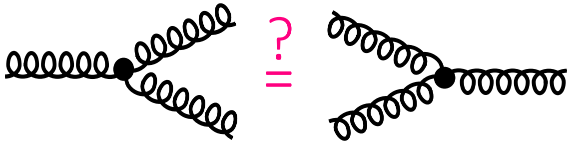
How do the confined hadronic states emerge from these quarks and gluons?

How do the quark-gluon interactions create nuclear binding?

How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?





Why Look at Jets / HF?

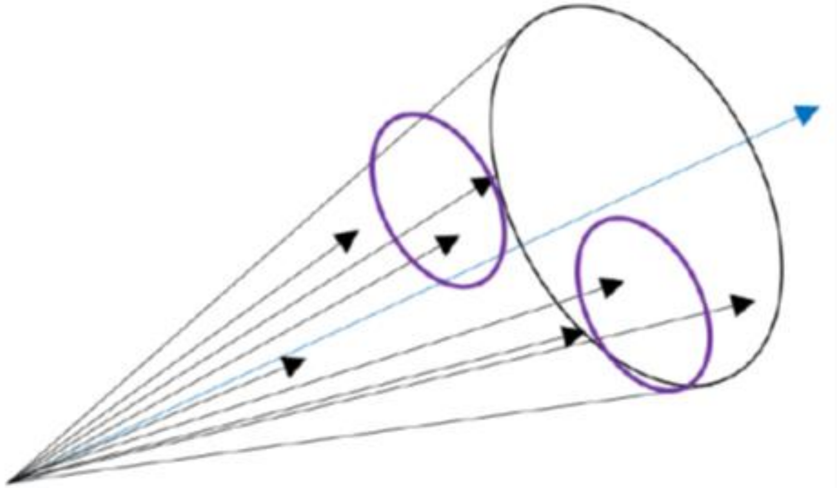
- Jets are comprised of the same particles used in traditional SIDIS (or diffractive) analyses – what benefits arise from forming a jet? – Why explicitly reconstruct HF?

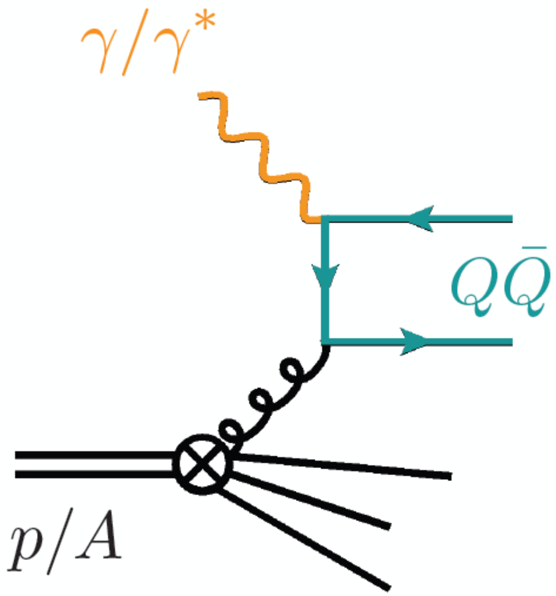
- Jets represent the kinematics of the underlying parton better than single particle observables

- Jet showers probe QCD from hard interaction to hadronization scale within the same event – can explore dynamics at different time (angular) scales and trace evolution of shower. Precision tools exist to probe shower evolution

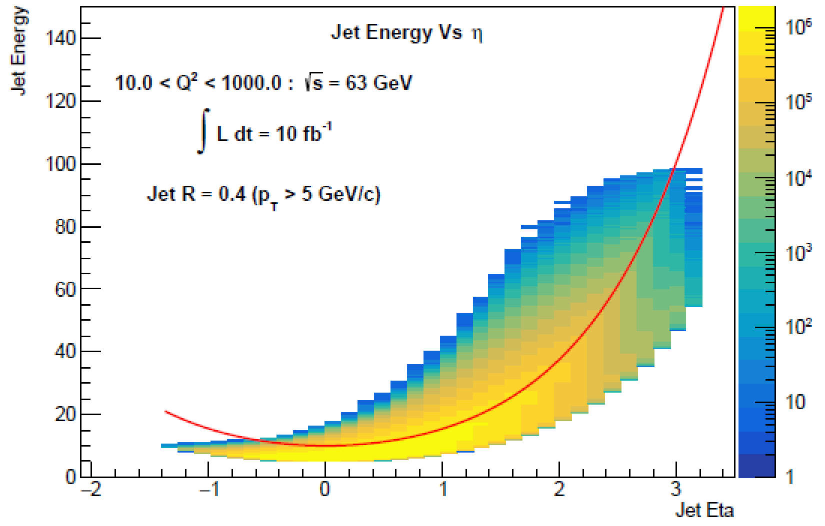
- Heavy flavor arises predominantly from a single subprocess (PGF) which is complimentary to (semi) inclusive DIS

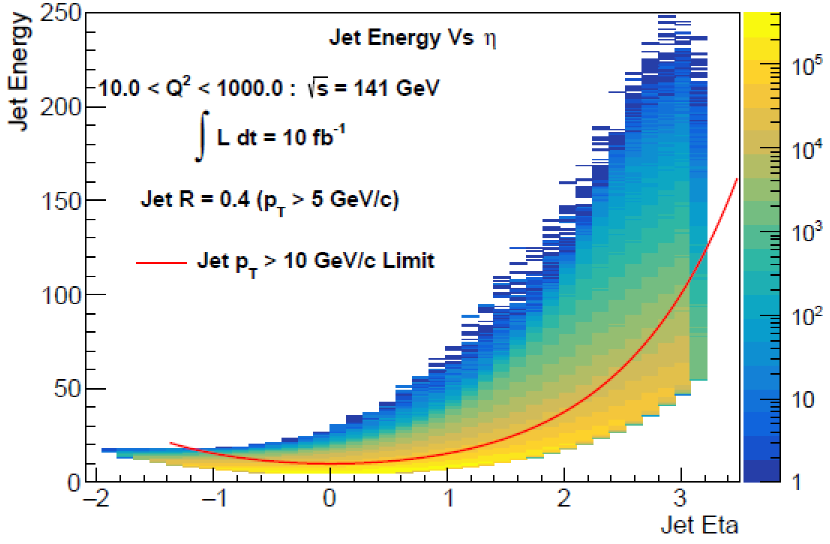
- Larger mass scale will affect hadronization and propagation of heavy quarks in the nuclear medium

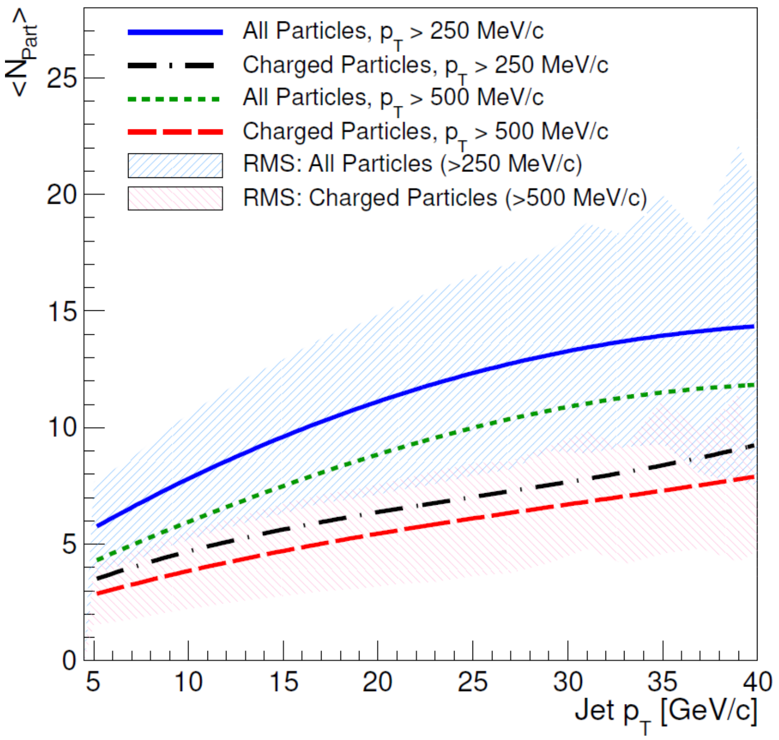




Jet Kinematics

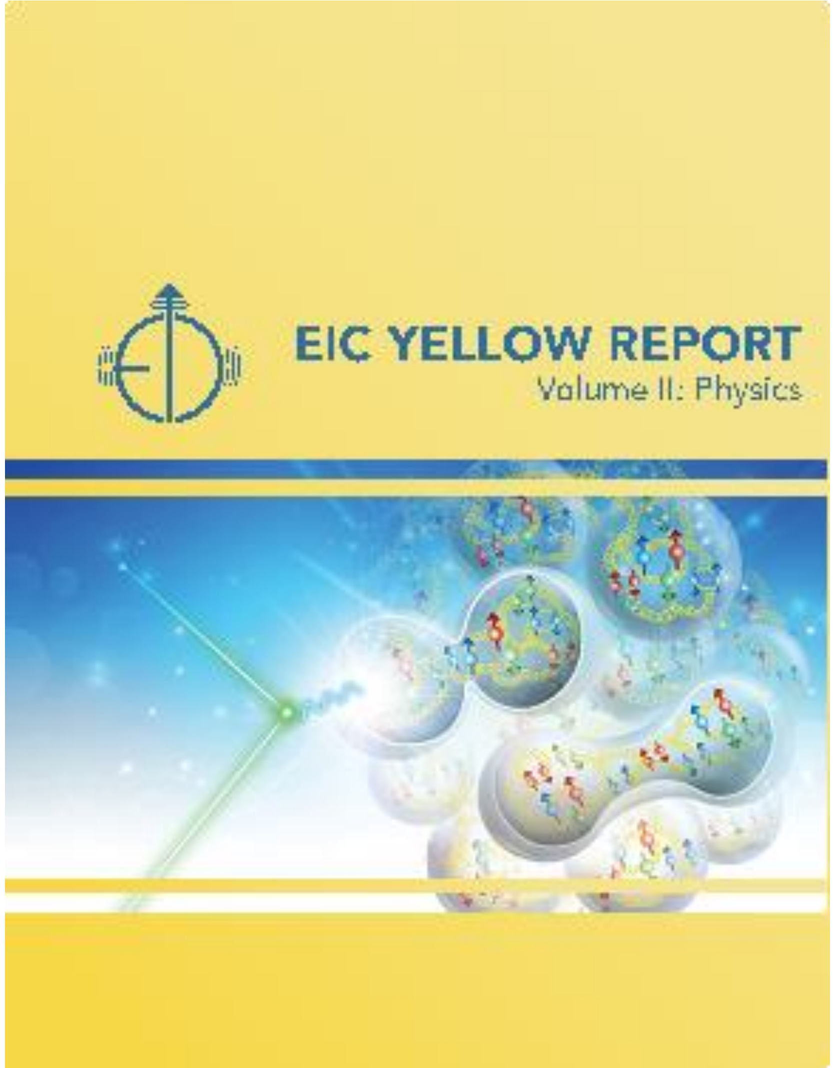






- Bulk of jets produced at the EIC will be low energy / low pT
- Pushing to analyze the lowest energy jets will provide access to the lowest x values, which will be important for spin structure and saturation studies
- In addition to being relatively low energy, jets will be quite broad and have few particles
- Must ensure theory and MC can make robust predictions for low energy jets and hadronization models can handle low multiplicity jets

EICUG Yellow Report Effort (Physics)



Explore measurements needed for new and existing physics topics and quantify implications for detector requirements (Physics Group)

Study detector concepts based on requirements defined by the Physics Group and quantify impacts on physics measurements (Detector Group)

Physics Working Group:

Inclusive Reactions

Semi-Inclusive Reactions

Jets, Heavy Quarks

Exclusive Reactions

Diffractive Reactions & Tagging

Detector Working Group:

Tracking + Vertexing
Particle ID
Calorimetry
DAQ/Electronics
Polarimetry/Ancillary Detectors
Central Detector: Integration & Magnet
Far- Forward Detector & IR Integration

The EIC Users Group: EICUG.ORG
Report: https://arxiv.org/abs/2103.05419

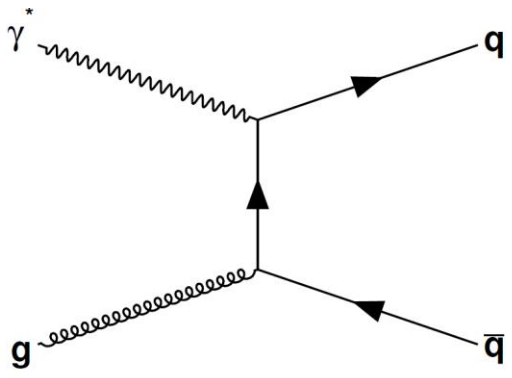
Jets and HF in the Yellow Report

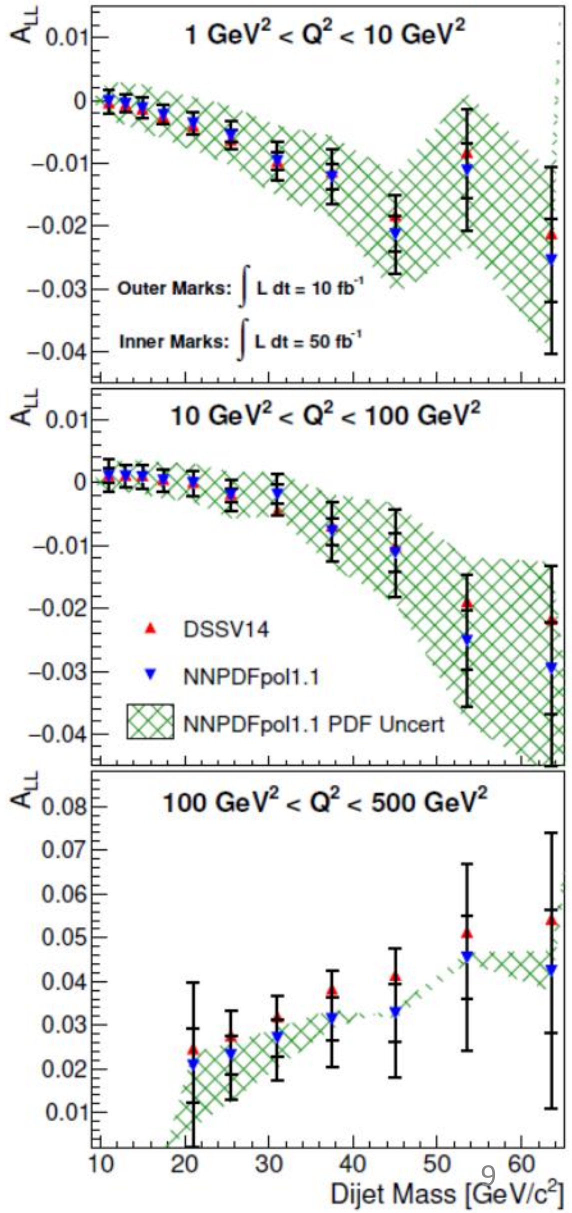
The EIC Measurements and Studies

- Global properties and parton structure of hadrons
  - Unpolarized parton structure of the proton and neutron
  - Spin structure of the proton and neutron
  - Inclusive and hard diffraction
  - Global event shapes and the strong coupling constant
- Multi-dimensional imaging of nucleons, nuclei and mesons
  - Imaging of quarks and gluons in momentum space
  - Wigner functions
- The nucleus: a laboratory for QCD
  - High parton densities and saturation
  - Particle propagation in matter and transport properties
  - Special opportunities with jets and heavy quarks
- Understanding hadronization
  - Hadronization in the vacuum
  - Hadronization in the nuclear environment

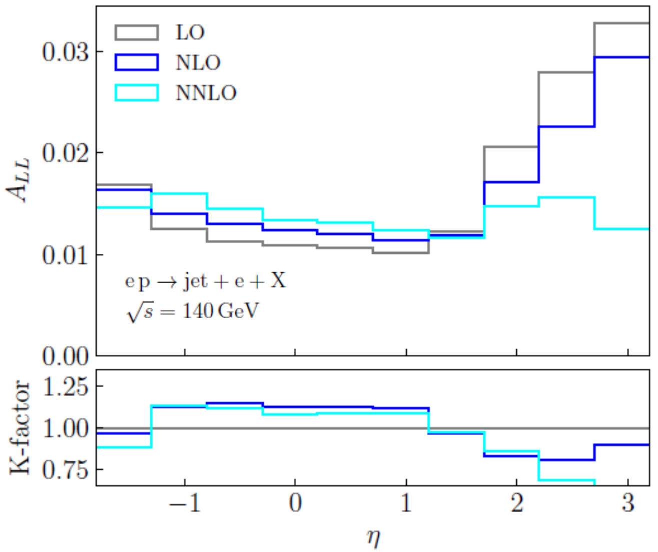
Longitudinal Spin Structure with Jets / HF

- Recent results on inclusive jet A_{LL} at NLO and NNLO both with and without tagged lepton
- NLO formalism for HF production from polarized DIS also recently developed
- Feasibility studies for dijet A_{LL} in the Breit frame and D^0 A_{LL} have been preformed and show ability to constrain ΔG

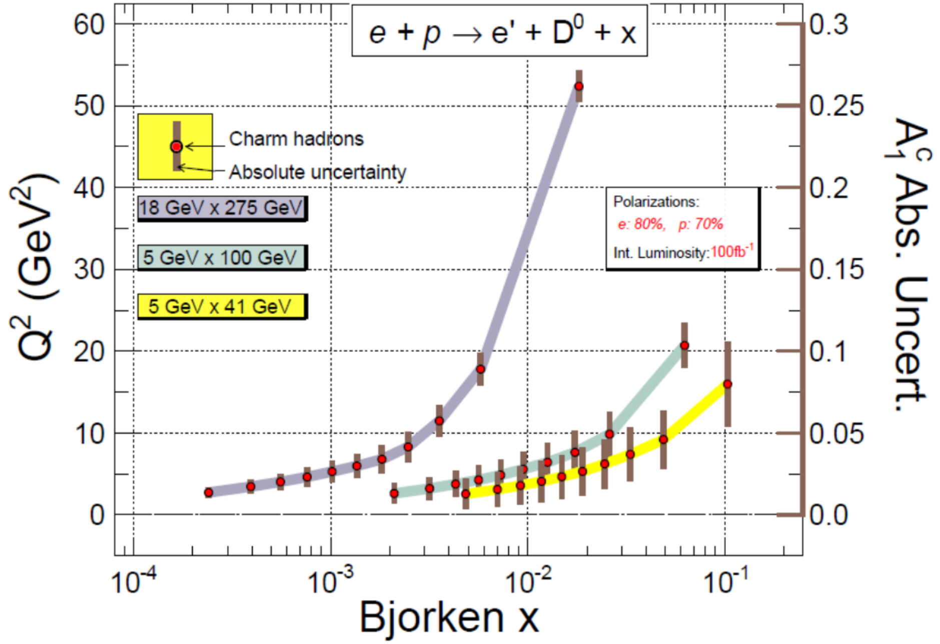




Page, Chu, Aschenauer `20



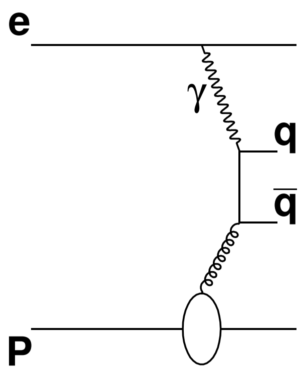
Borsa, de Florian, Pedron `20

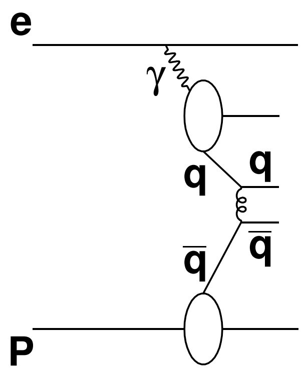


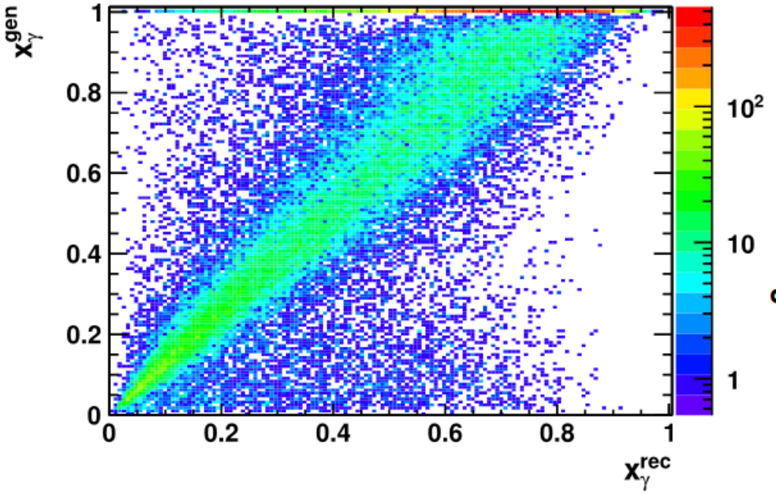
Phys.Rev.D 104 (2021) 11, 114039

(Polarized) Photon Structure

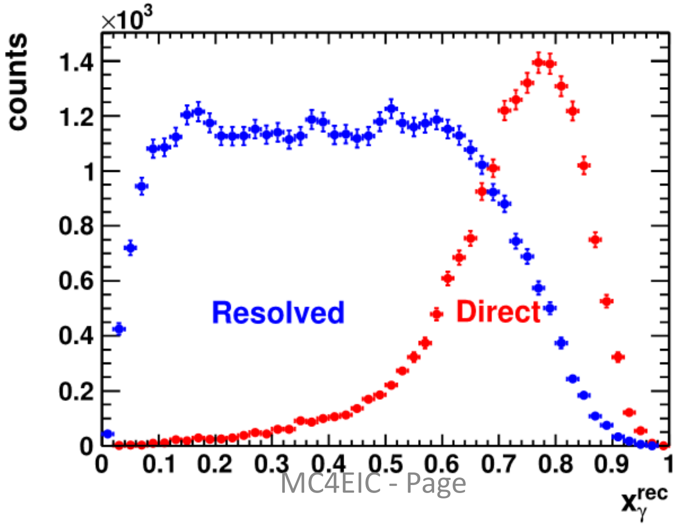
- At low Q2, virtual photon can behave hadronically and initiate 2->2 type scattering events
- Results in a quark/anti-quark final state with high transverse momentum
- Dijet allows to reconstruct event characteristics to separate signal and background and characterize the structure of the photon

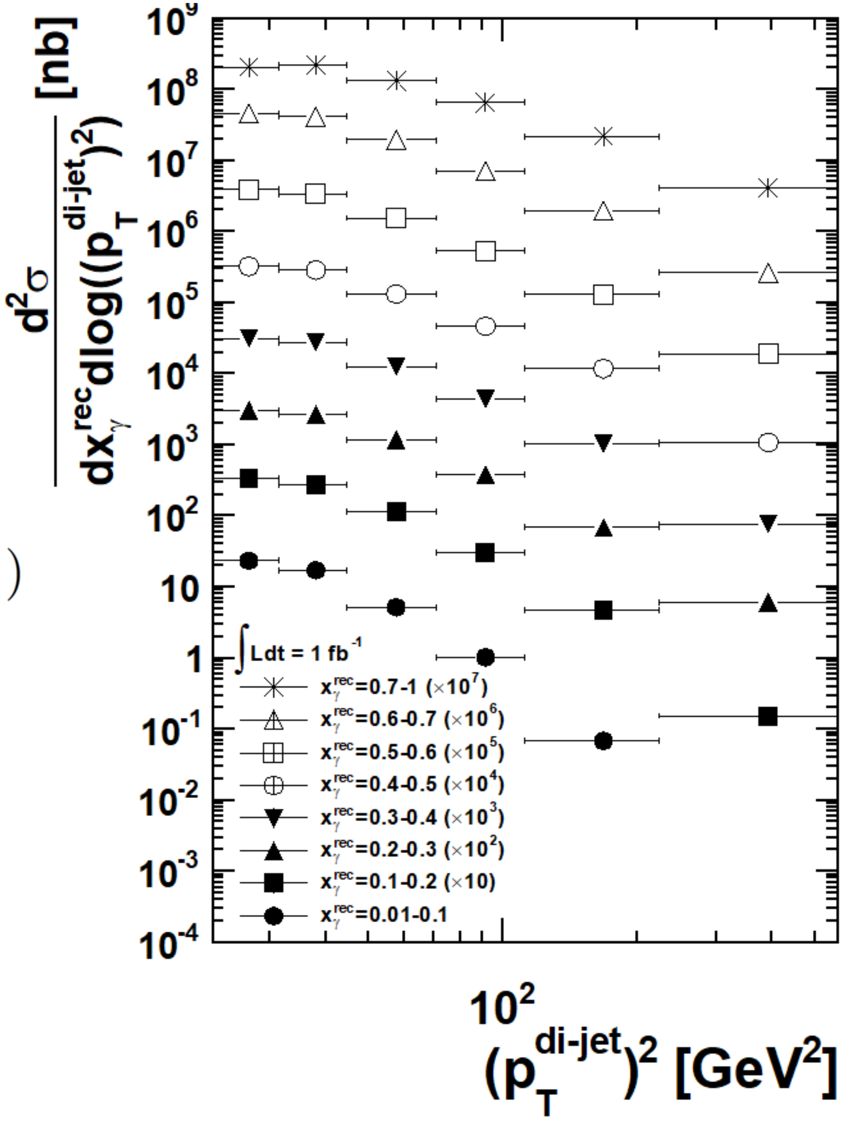




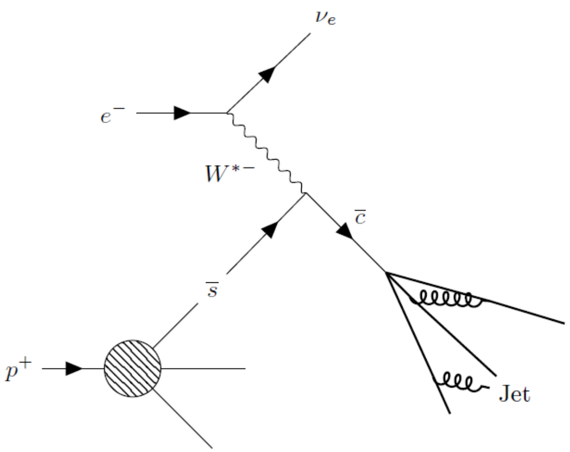


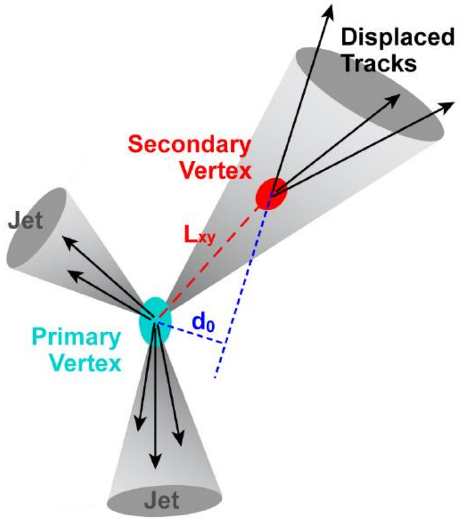
$$x_\gamma^{rec} = \frac{1}{2E_e y}(p_{T1}e^{-\eta_1} + p_{T2}e^{-\eta_2})$$

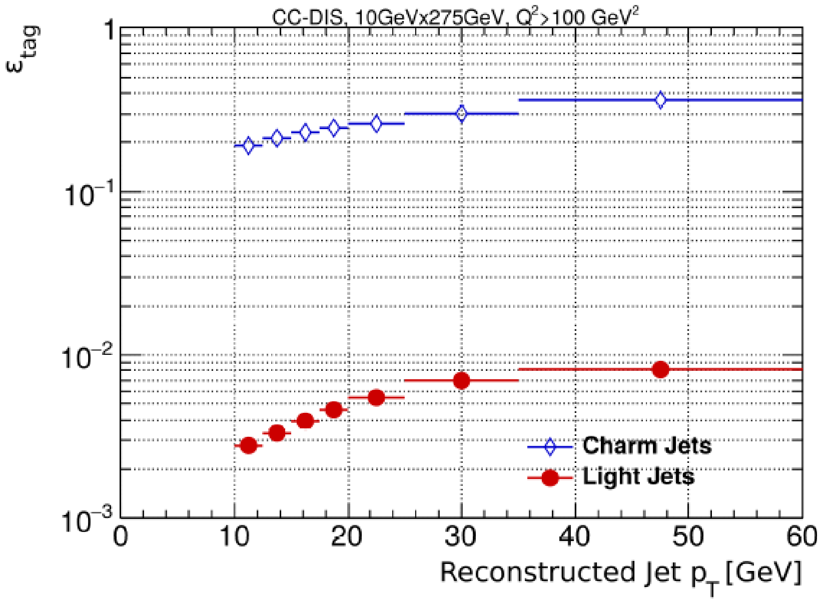




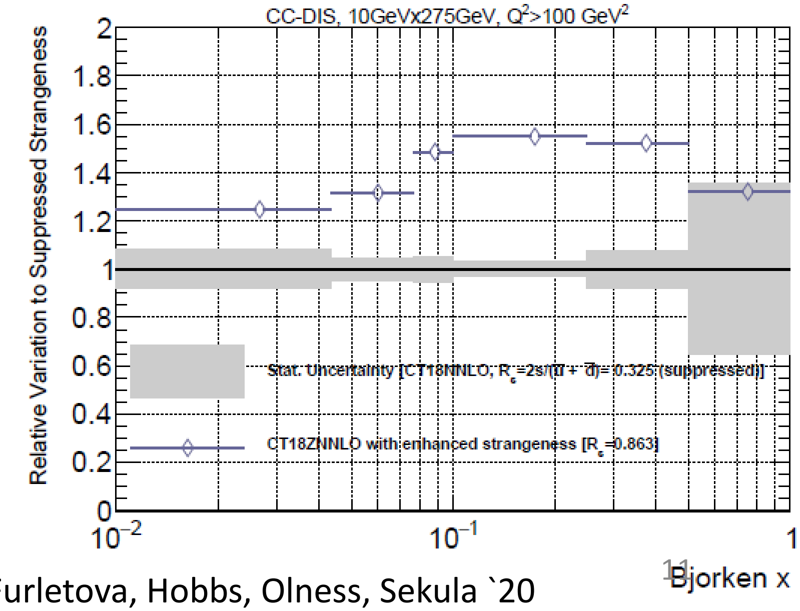
Charm Jet Tagging for Strangeness







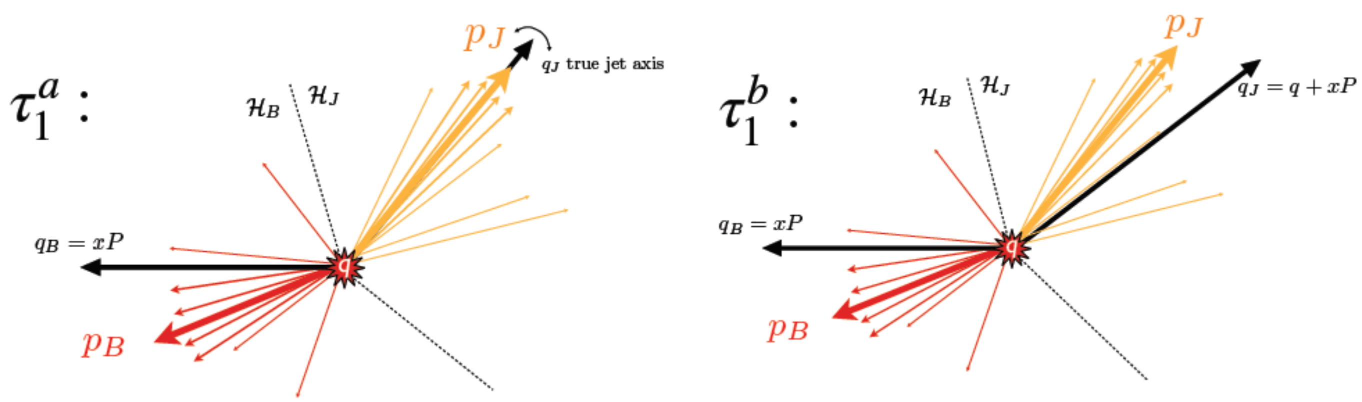
- Tension exists between neutrino DIS and SIDIS measurements of strange content and LHC extractions
- EIC is sensitive to strange content via charm production in charged-current DIS
- Charm is tagged within a jet via the presence of displaced tracks – good charm efficiency is seen, and methods are being refined
- Charm jet measurements at EIC should be able to discriminate between low and high strangeness scenarios

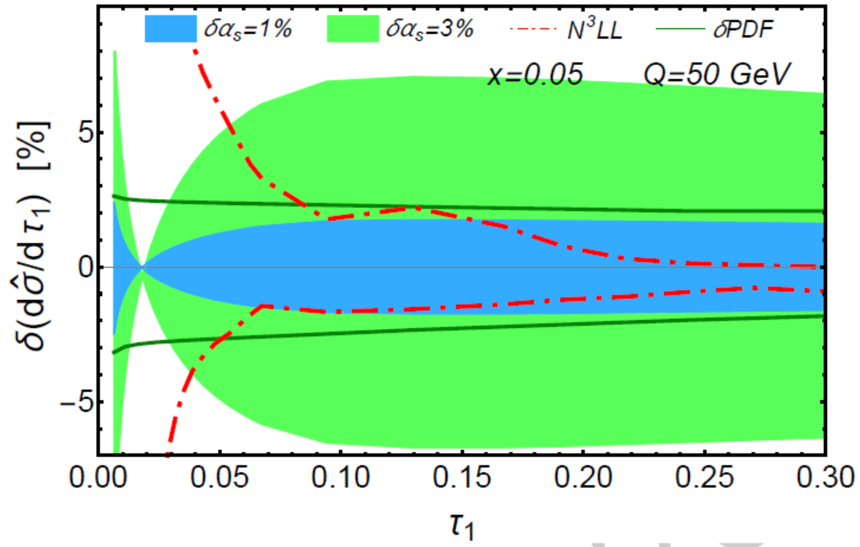


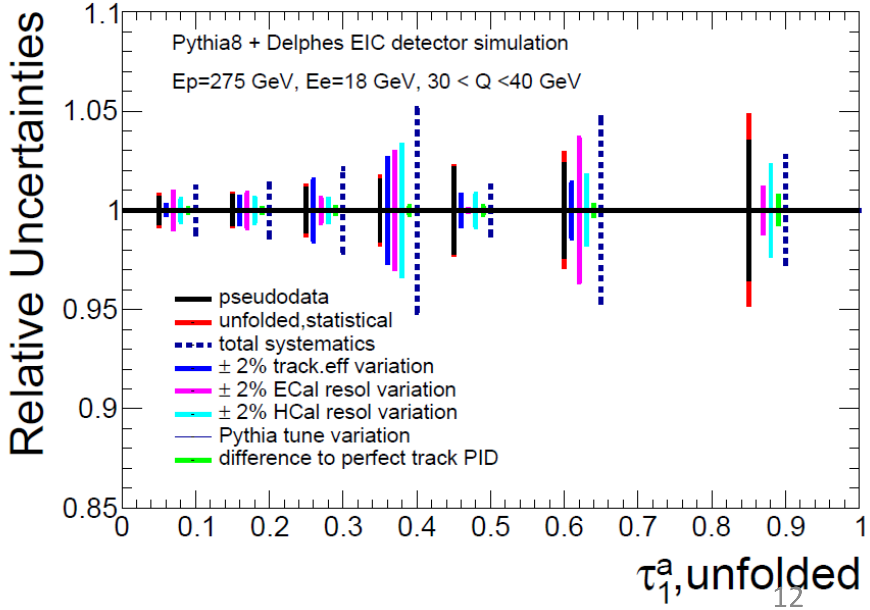
Arratia, Furletova, Hobbs, Olness, Sekula `20

Global Event Shapes

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

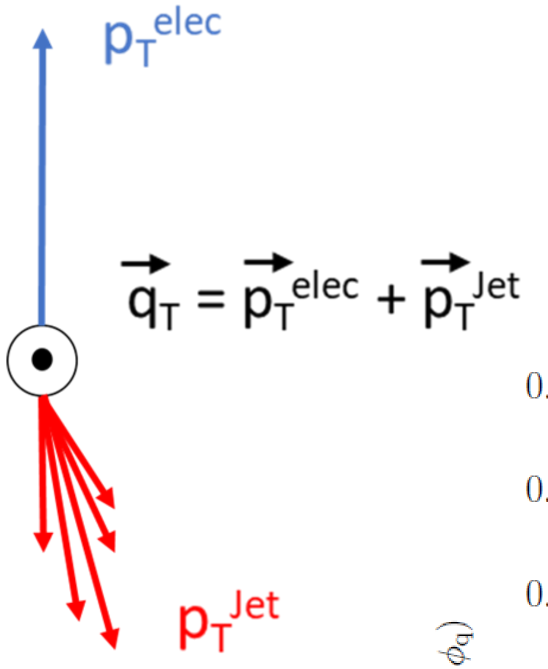




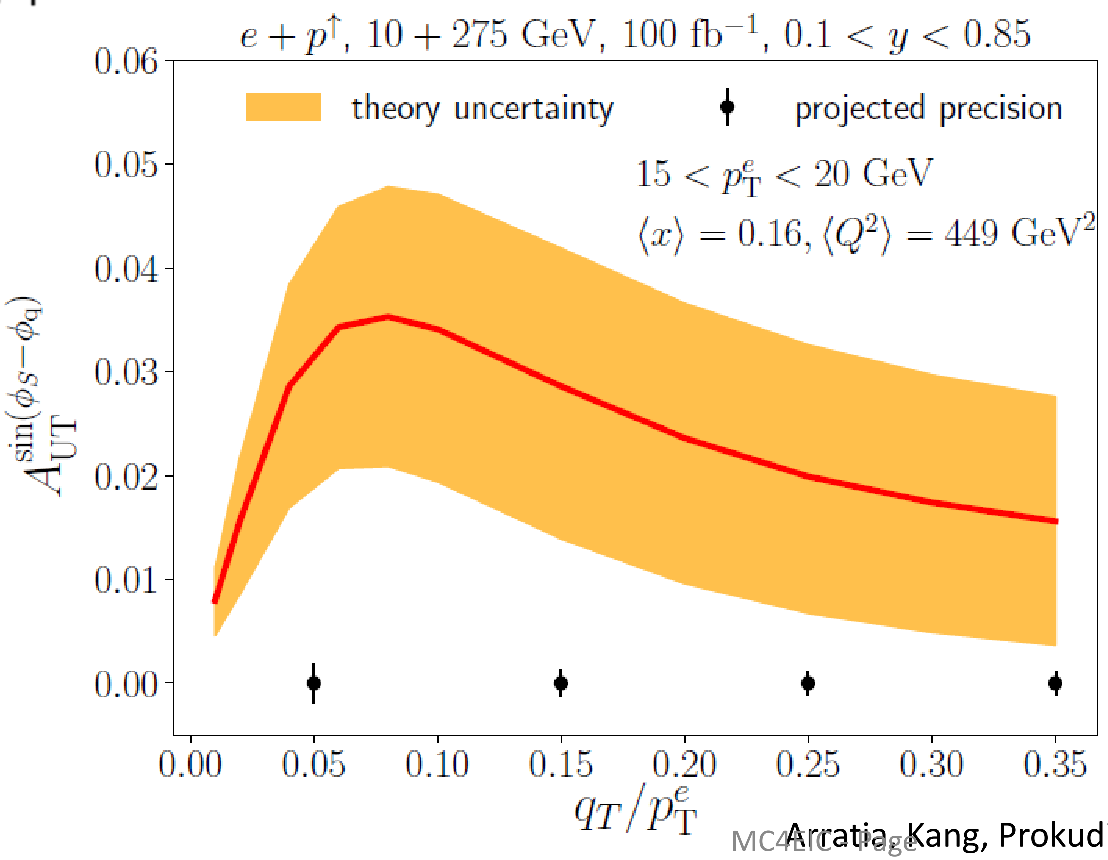


- Global event shapes offer possibility of very high precision measurements for extractions of non-perturbative parameters such as the strong coupling constant
- Feasibility study of 1-jettiness measurement was carried out for the YR effort with total 2-4% statistical and systematic error – better if using only charged tracks
- At N^{3}LL, roughly 1% precision is possible, challenging experimental problem, but recent studies show promise

TMDs with Jets



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

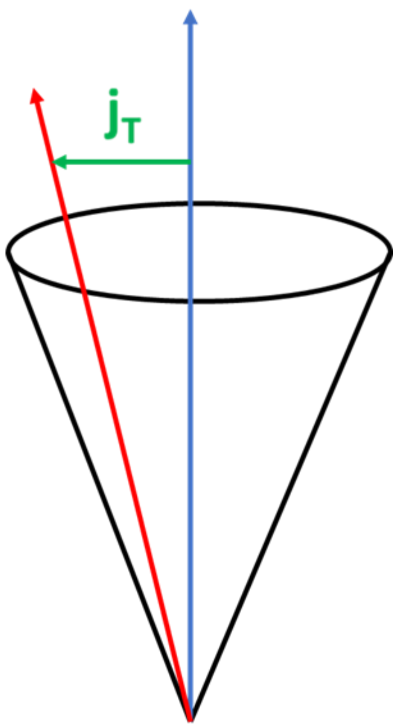


Arratia, Kang, Prokudin, Ringer `20

- ❑ Jets are complementary to standard SIDIS extractions of TMDs and provide better surrogates for parton kinematics while allowing cleaner separation of target and current fragmentation regions
- ❑ Jet measurements allow independent constraints on TMD PDFs and FFs from a single measurement
- ❑ Azimuthal correlation between jet and lepton sensitive to TMD PDFs (Sivers)

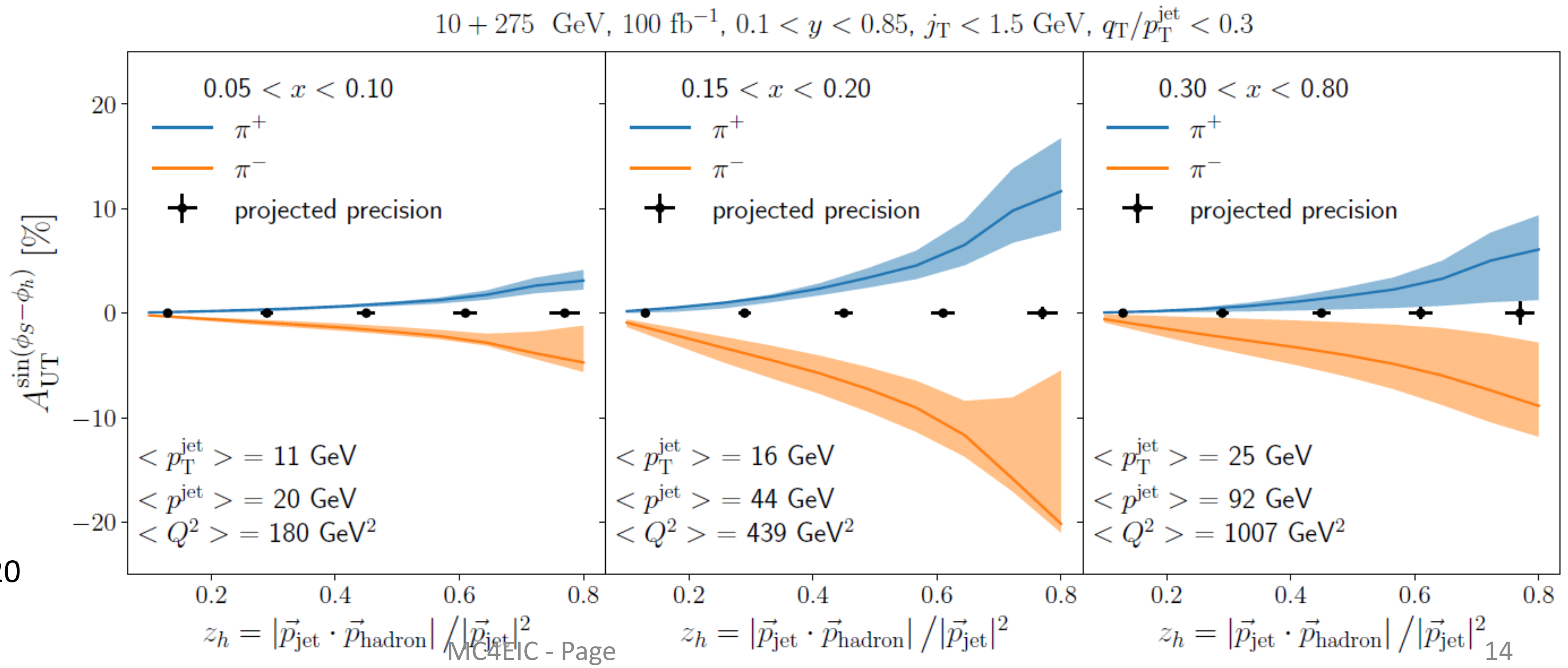
TMDs with Jets

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



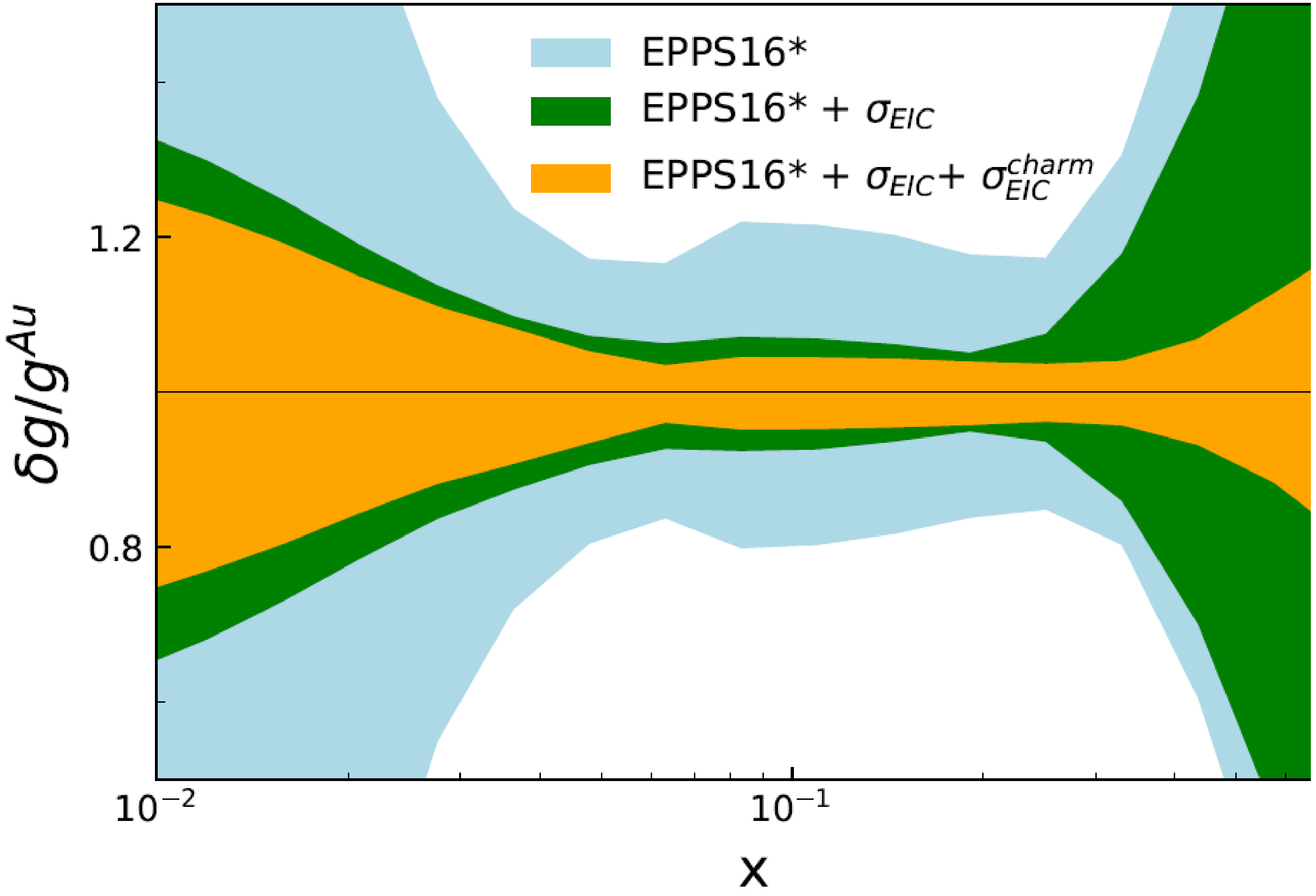
Arratia, Kang, Prokudin, Ringer `20

- Measurement of hadrons within jet give access to TMD FFs
- Relevant variables are j_T – transverse momentum of the hadron with respect to the jet and z – fraction of jet momentum carried by hadron
- Collins asymmetry correlates proton spin vector with j_T
- Identified hadrons allow for flavor separation of Collins FF



Nuclear PDFs

Phys. Rev. D96, 114005 (2017) and YR



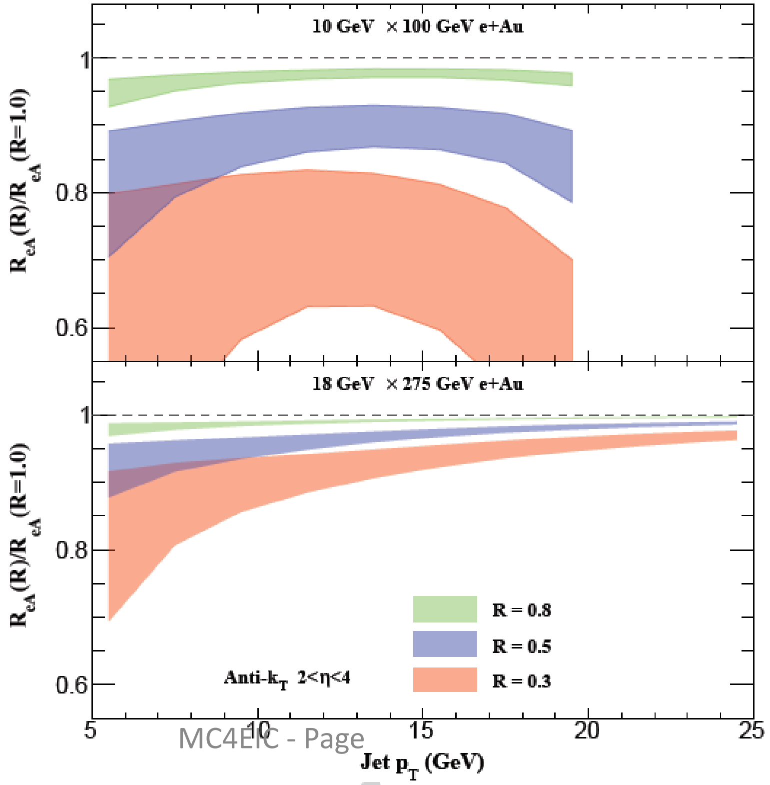
- With its large kinematic coverage and ability to run a variety of nuclear beams, the EIC will vastly improve our knowledge of nuclear PDFs
- Fully inclusive data will improve nPDFs for valence and sea distributions, along with gluons for much of the relevant x-range
- Adding charm data will greatly reduce uncertainties for the gluon nPDF in the high-x region

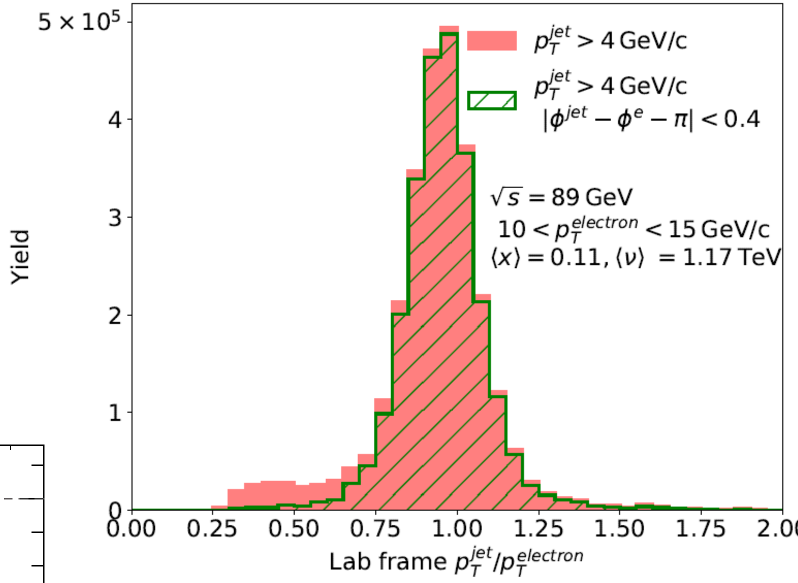
Jets in the Medium

- Many opportunities to study the properties of cold nuclear matter with jets
- Simple comparisons of jet yields in ep vs eA will be informative – double ratio $R_{eA}(R)/R_{eA}(R = 1.0)$ will reduce impact from nPDFs and enhance final state effects
- Lepton – Jet correlations in Born level DIS can be thought of as analogous to boson – Jet measurements with the lepton as the tag and the jet as the probe of the medium
- Dijets and gamma-dijet correlations also expected to be powerful probes of saturation / small-x dynamics

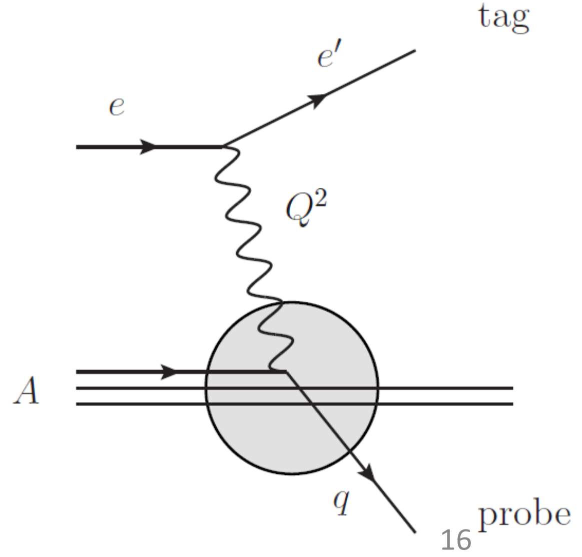
$$R_{eA}(R) = \frac{1}{A} \frac{\int_{\eta 1}^{\eta 2} d\sigma / d\eta dp_T \big|_{e+A}}{\int_{\eta 1}^{\eta 2} d\sigma / d\eta dp_T \big|_{e+p}}$$

Li & Vitev ‘20



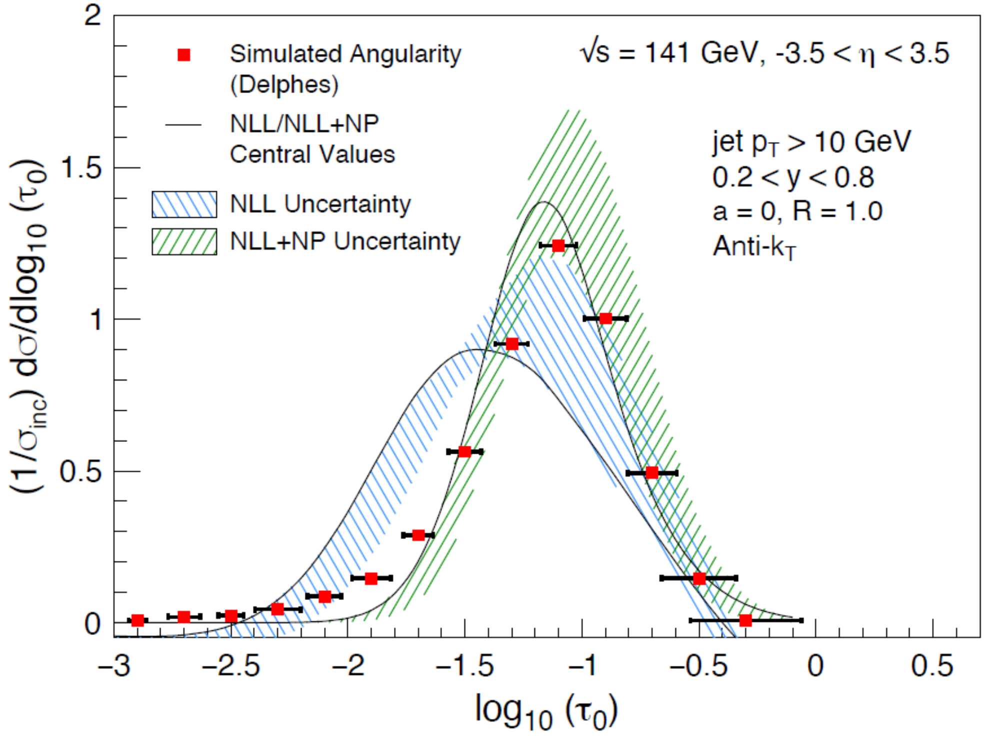


Arratia, Song, Ringer, Jacak ‘20



Hadronization with Jets and HF

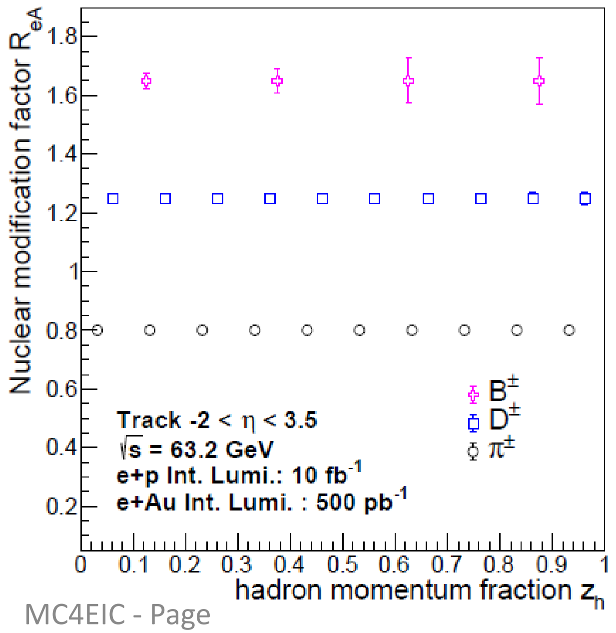
$$\tau_a \equiv \frac{1}{p_T} \sum_{i \in J} p_T^i \left(\Delta R_{iJ}\right)^{2-a}$$

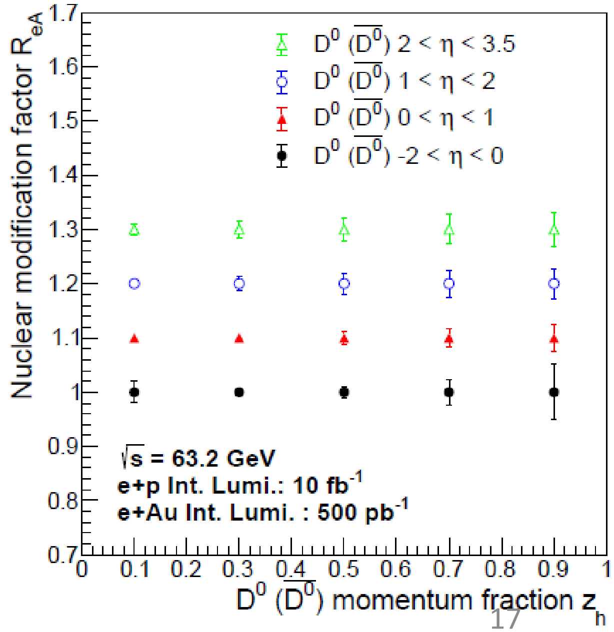


Aschenauer, Lee, Page, Ringer `20 & ATHENA Proposal

$$F_\kappa(k) = \left(\frac{4k}{\Omega_\kappa^2}\right) \exp\left(-\frac{2k}{\Omega_\kappa}\right)$$ NP Effects

- Both jets and HF observables are well suited to the study of hadronization, both in vacuum and the nuclear medium
- Jet substructure will allow measurements of the flow of energy within a shower and shower evolution
- Nuclear modification (R_{eA}) of heavy mesons will be particularly sensitive to details of energy loss / hadronization





Implications for MCEGs

- EIC measurements will cover both the photoproduction and electroproduction regions
- Many different subprocesses (DIS, H.O., diffractive) will be relevant for different measurements in different kinematic regions

→

General purpose MCEGs need to be able to 'smoothly' move between photoproduction and electroproduction regimes with consistent subprocess cross section behavior. A 'min-bias' setting that automatically incorporates all subprocesses in a given Q^2 range in the appropriate ratios would be very useful.

- Nearly every measurement at the EIC will require precise knowledge of event kinematics (x, Q^2, etc)
- This is especially true of measurements to constrain PDFs

→

General purpose MCEGs should incorporate precise QED radiative corrections so impacts on kinematics can be determined and correction / mitigation strategies developed

Implications for MCEGs

- Exploration of spin structure of the nucleon will be a primary focus of the EIC
  - Helicity PDFs
  - TMDs

General purpose MCEGs should incorporate polarization into all stages of simulation: initial state, hard-scattering, and shower / hadronization to reduce biases and systematic effects in measurements

Including transverse momentum dependence into initial and final states will also help reduce biases in those measurements

Implications for MCEGs

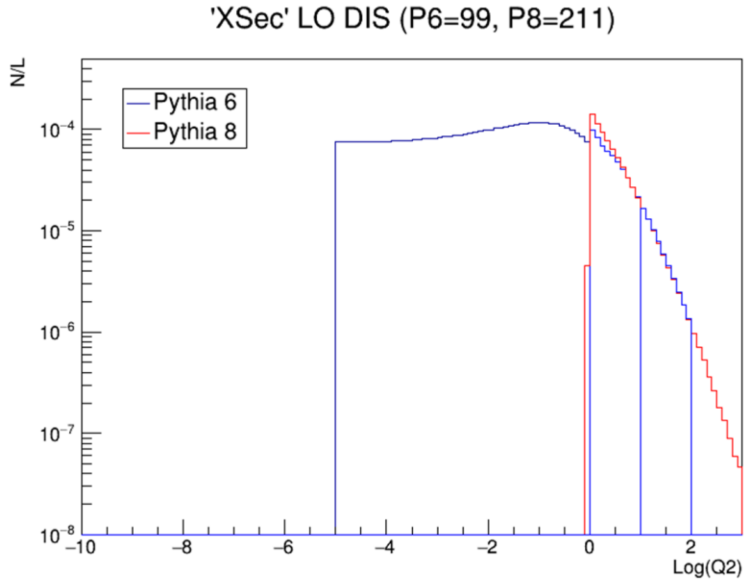
- The study of the properties of cold nuclear matter and how energetic color charges interact with that matter will be another pillar of the EIC physics program

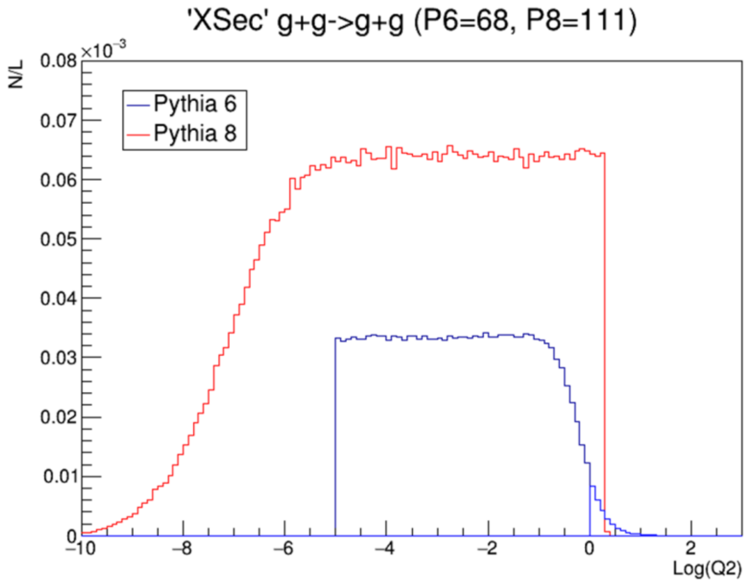
→ It would be useful to have eA capability with tunable energy loss and transport properties as well as nuclear breakup effects. (Aware of course of BeAGLE, JETSCAPE, Angantyr, etc.) Modeling of collective effects and transition to a saturated regime will also be important.

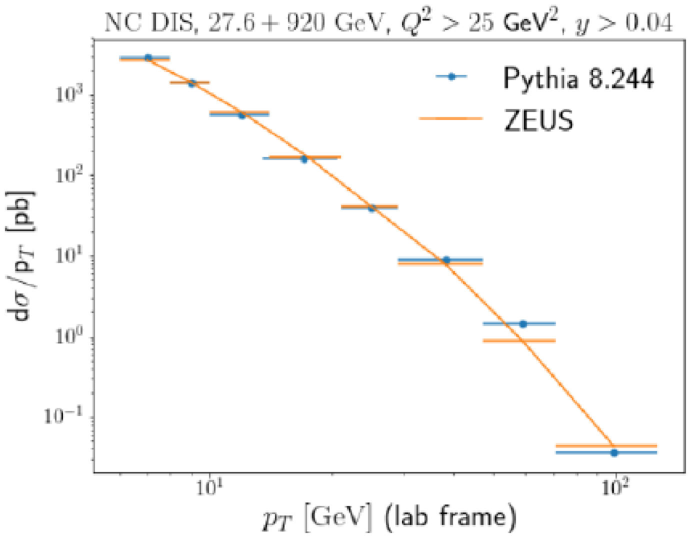
- The detailed study of the hadronization process is another key aspect of the EIC program
- Study hadronization in vacuum and medium with a variety of probes including HF and very differential jet observables (substructure)

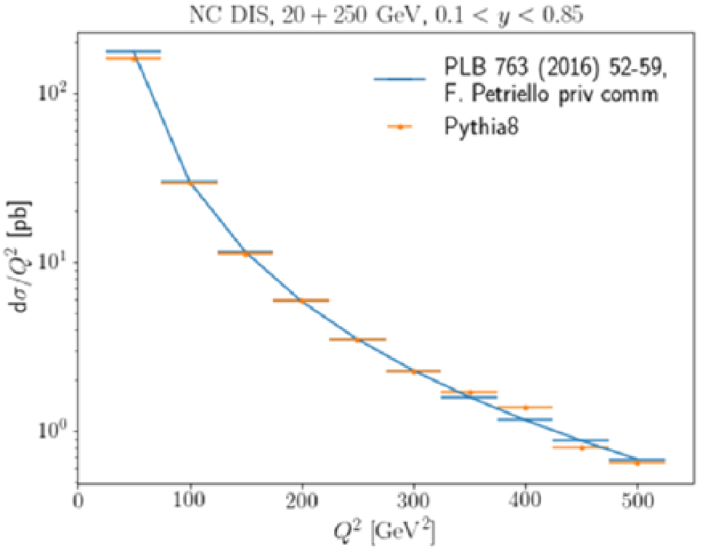
→ Different hadronization models should be available which describe both vacuum and medium hadronization, can handle HF propagation, and describe the structure of low multiplicity jets.

A Few Observations on Cross Section









- At high energy (HERA energies) and high Q^2 (> ~10-20 GeV^2), PYTHIA-8 does a good job describing the inclusive jet cross section
- As we move into the Q^2 region below 10 GeV^2, we begin to see discrepancies between PYTHIA-8 and PYTHIA-6 (which we know describes HERA data reasonably well), with the LO cross section starting to diverge
- For $Q^2 < 1$, we see starkly different behavior, no LO cross section at all for PYTHIA-8 and large differences in cross sections for other processes and artificial cutoff behavior

Summary

- The EIC will be an incredibly powerful tool for the exploration of strongly interacting matter and it will take close coordination between all stakeholders (experiment, theory, phenomenology, simulation, data science, etc) to ensure the EIC reaches its full potential

- Jet and HF measurements will provide critical input on many of the major topics the EIC is being designed to address

- To fully support jet and HF measurements at the EIC, MCEGs will need to accurately describe jet properties at low energy and multiplicity as well as heavy quark energy loss and hadronization in vacuum and the nuclear medium

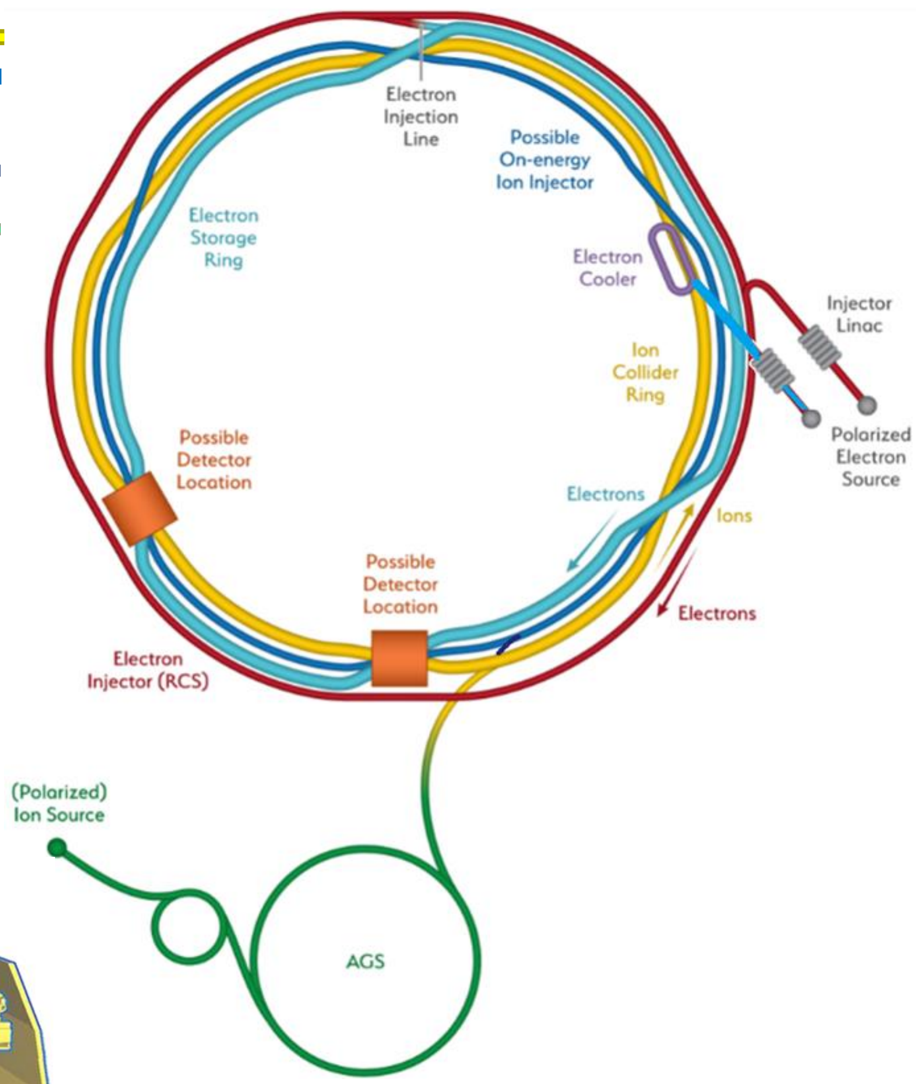
- Other MCEG needs apply more broadly to the EIC science program and include things like a consistent across Q2, inclusion of polarization and TMD effects, support for nuclear effects (medium effects, breakup, saturation, etc), and multiple hadronization models

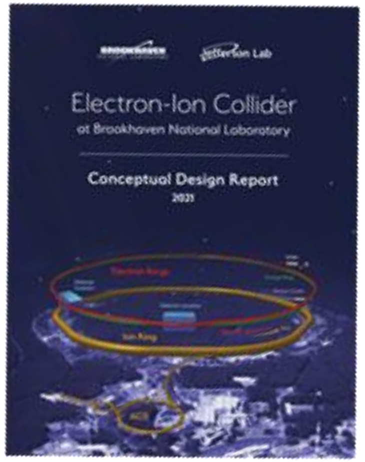
Backup

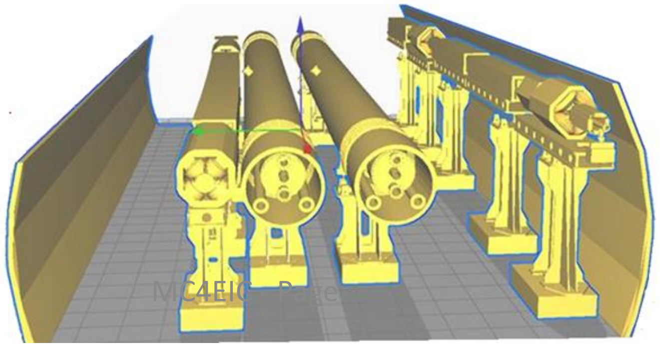
The EIC Concept

Design based on **existing** RHIC,
RHIC is well maintained, operating at its peak

- **Hadron storage ring 40-275 GeV** (existing)
  - RHIC Yellow Ring
  - many bunches, 1160 @ 1A beam current
  - bright beam emittance ε_{xp}= 9 nm, flat beam
  - need strong cooling
- **Electron storage ring (2.5–18 GeV, new)**
  - many bunches,
  - large beam current (2.5 A) ➔10 MW S.R. power
  - s.c. RF cavities
  - Energy independent radiation damping
- **Electron rapid cycling synchrotron** (new)
  - 1-2 Hz
  - Spin transparent due to high periodicity
- **High luminosity interaction region(s)** (new)
  - L = 10^{34}cm^{-2}s^{-1}
  - Superconducting magnets
  - 25 mrad Crossing angle with crab cavities
  - Spin Rotators (longitudinal spin)
  - Forward hadron instrumentation

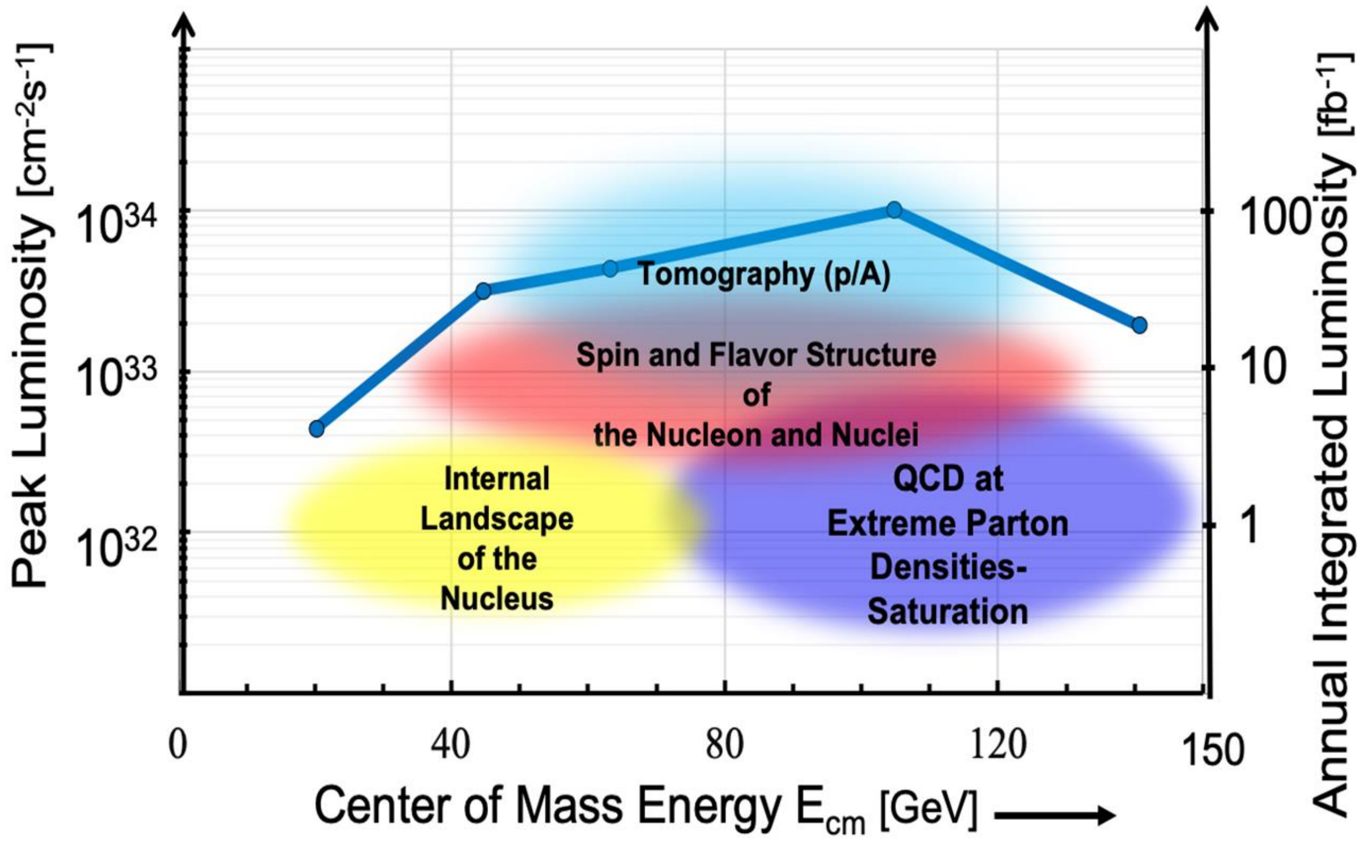






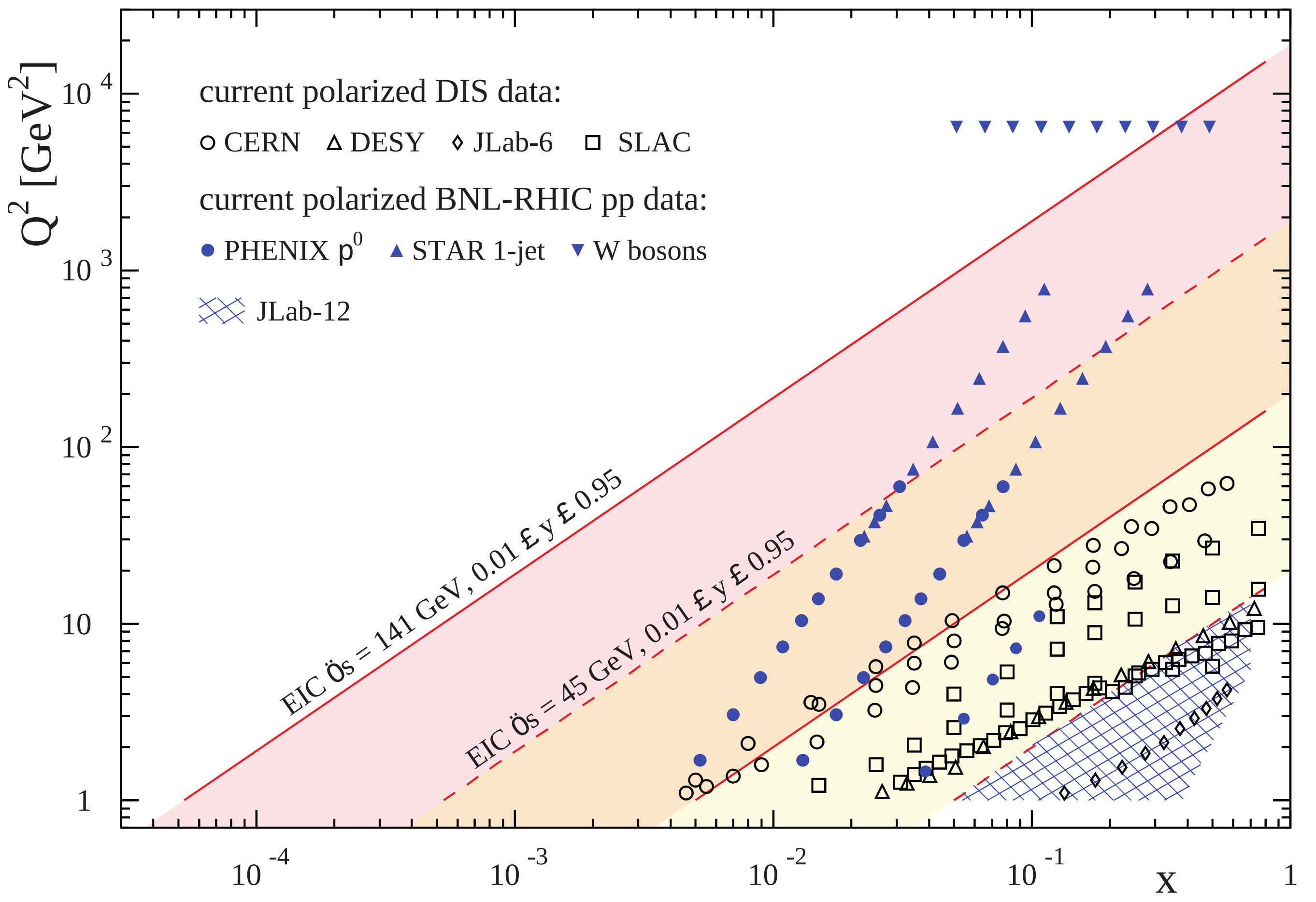
CDR: https://www.bnl.gov/ec/files/EIC_CDR_Final.pdf

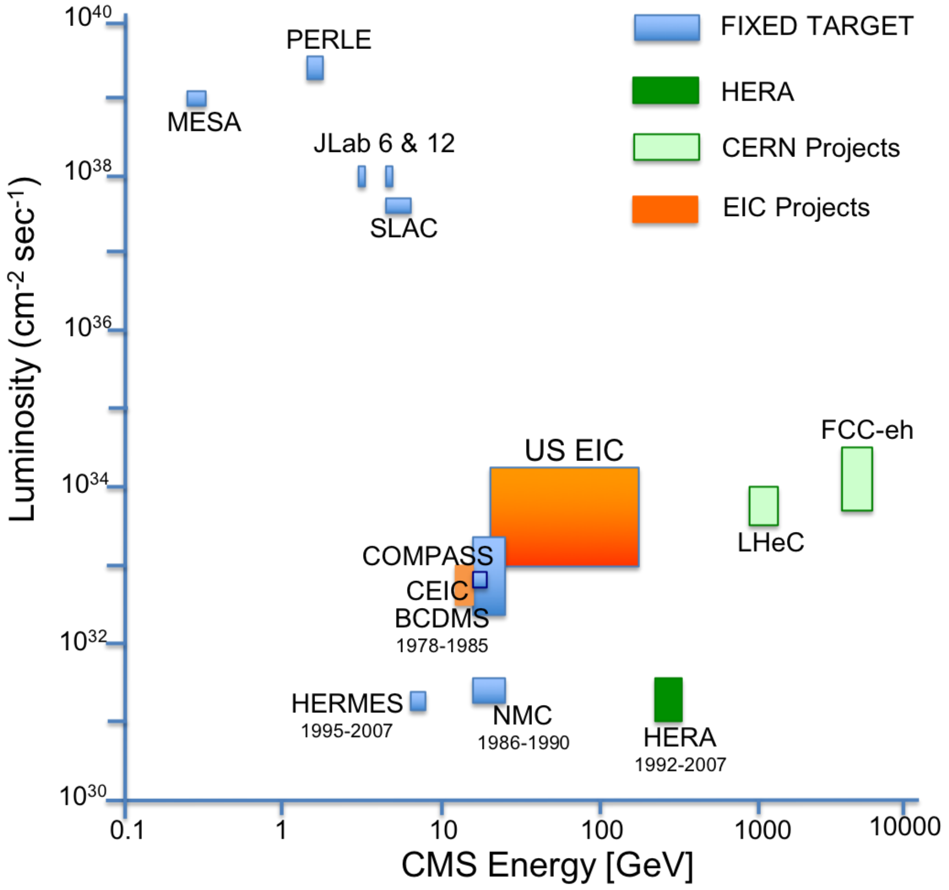
Machine Requirements



- ❑ Large Kinematic Coverage
  - ➢ Center of Mass energies √s: 20 – 140 GeV
  - ➢ Access large range in x and Q^2
- ❑ High luminosity
  - ➢ $10^{33} – 10^{34}$ $cm^{-2}s^{-2}$
  - ➢ Mapping structure of nucleons and nuclei in 3D
- ❑ Polarized electron and hadron (p, ^{3}He) beams
  - ➢ Explore spin structure of nucleons and nuclei
- ❑ Nuclear Beams (D to Pb)
  - ➢ Access high gluon densities – saturation
  - ➢ Study properties of cold nuclear matter

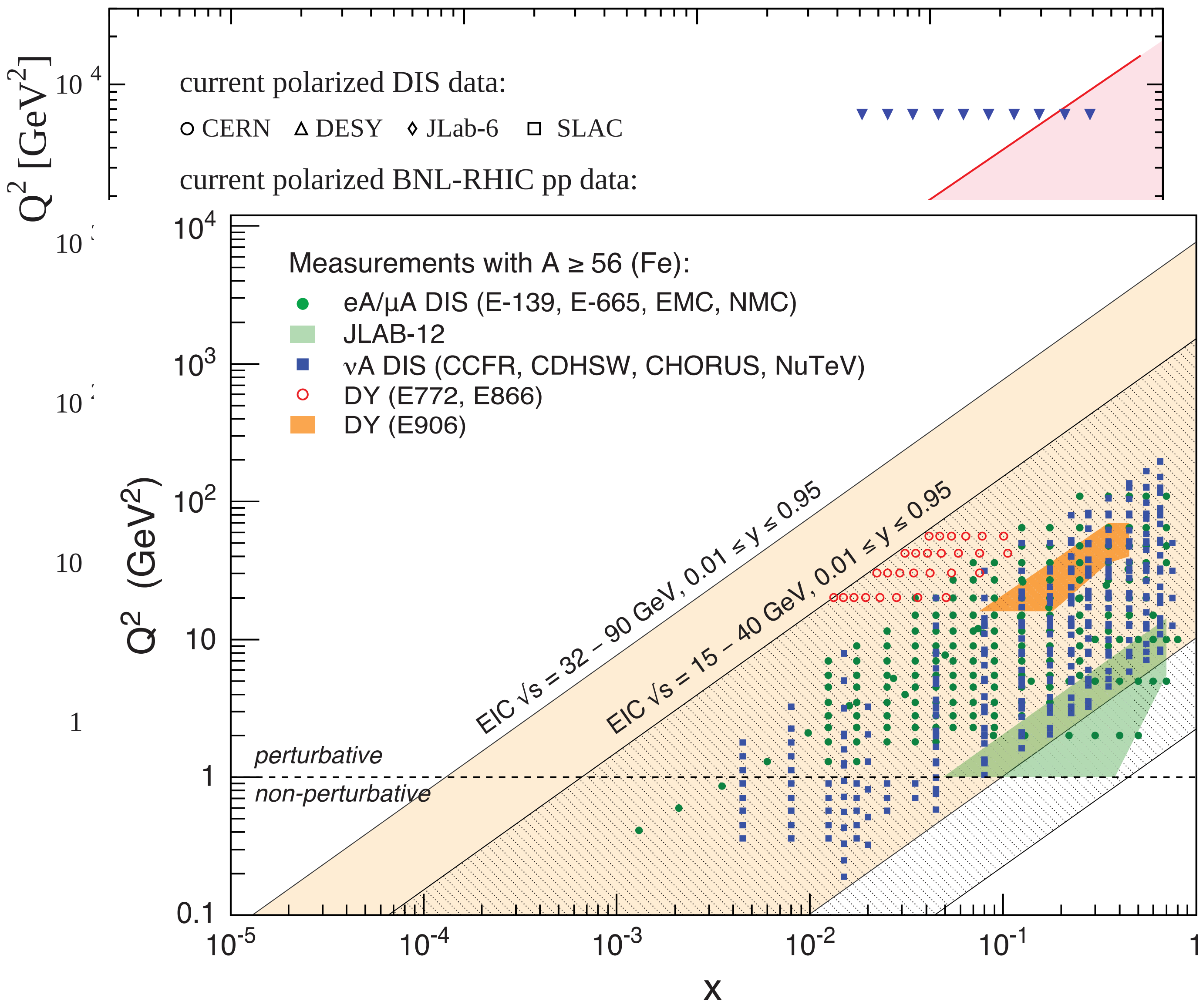
The EIC In Context

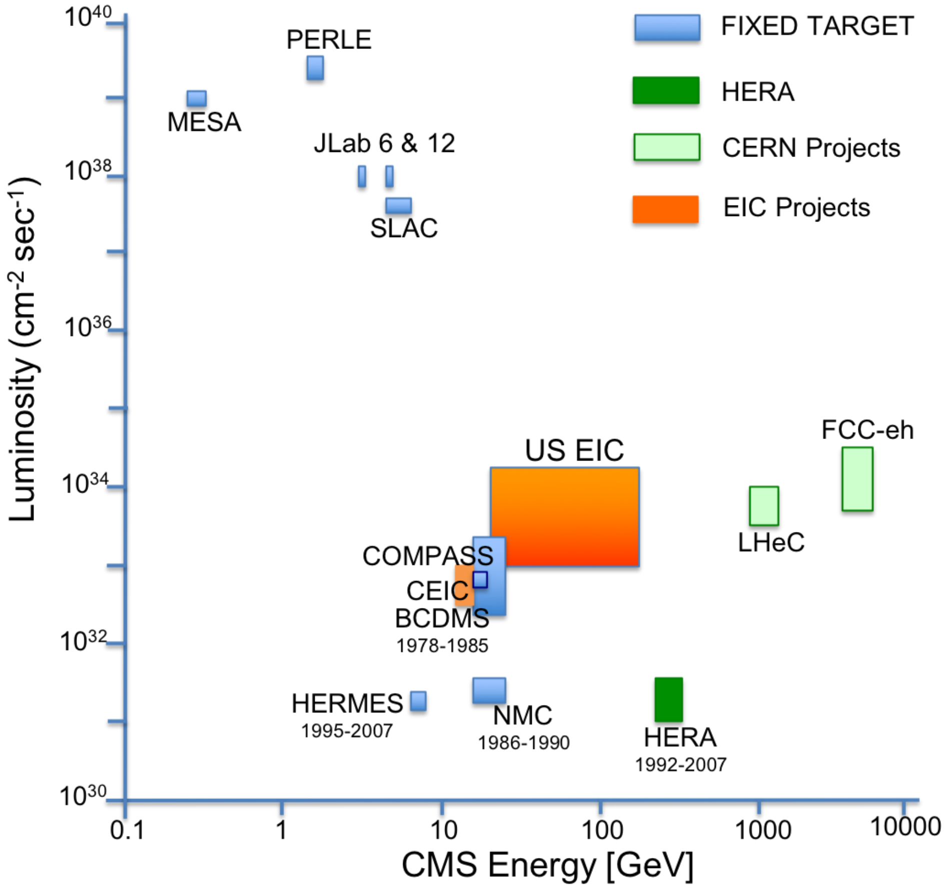




The luminosity, center-of-mass energy range, polarization, and ability to collide various ions make the EIC unique among all existing and planed machines world-wide

The EIC In Context





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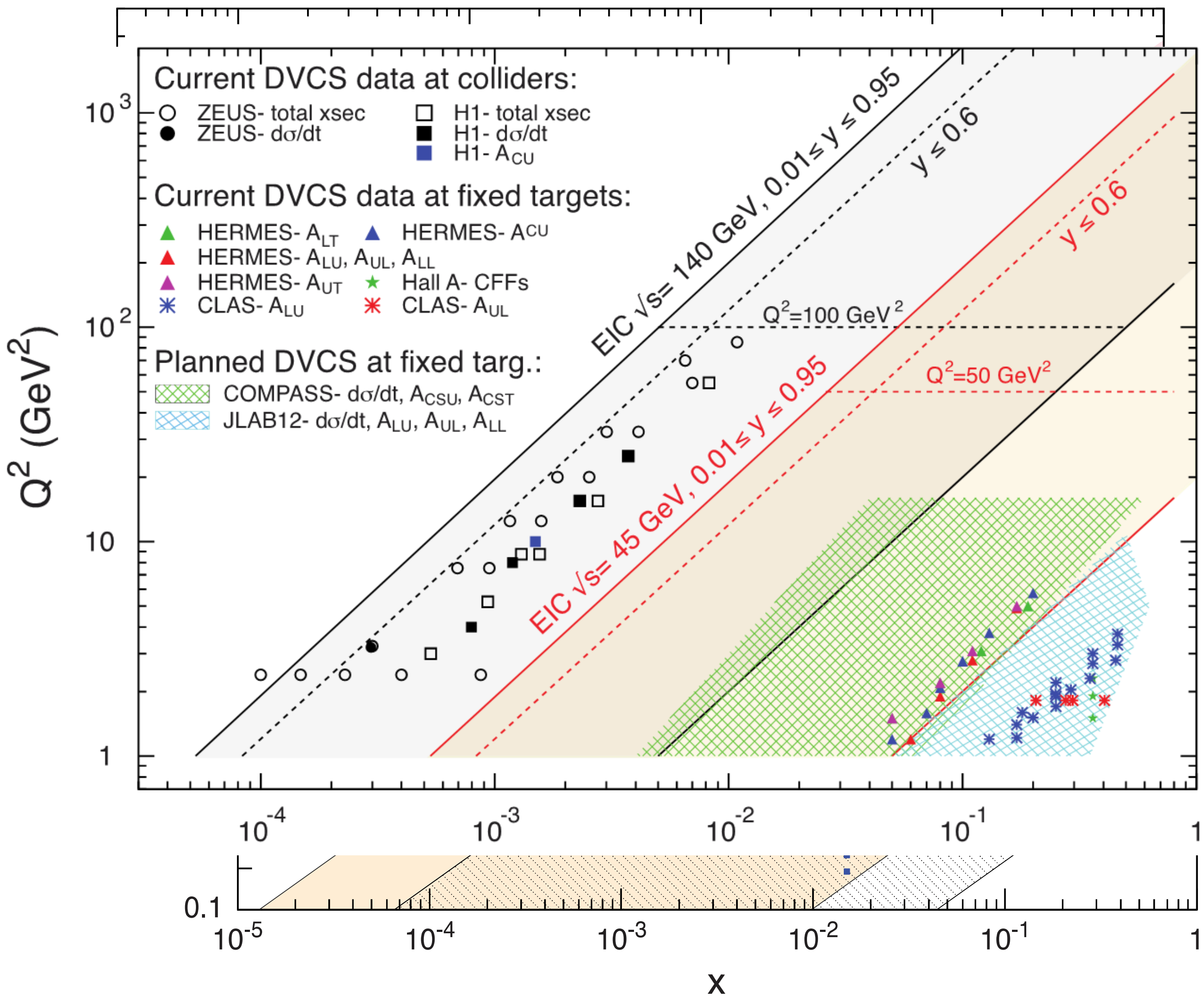
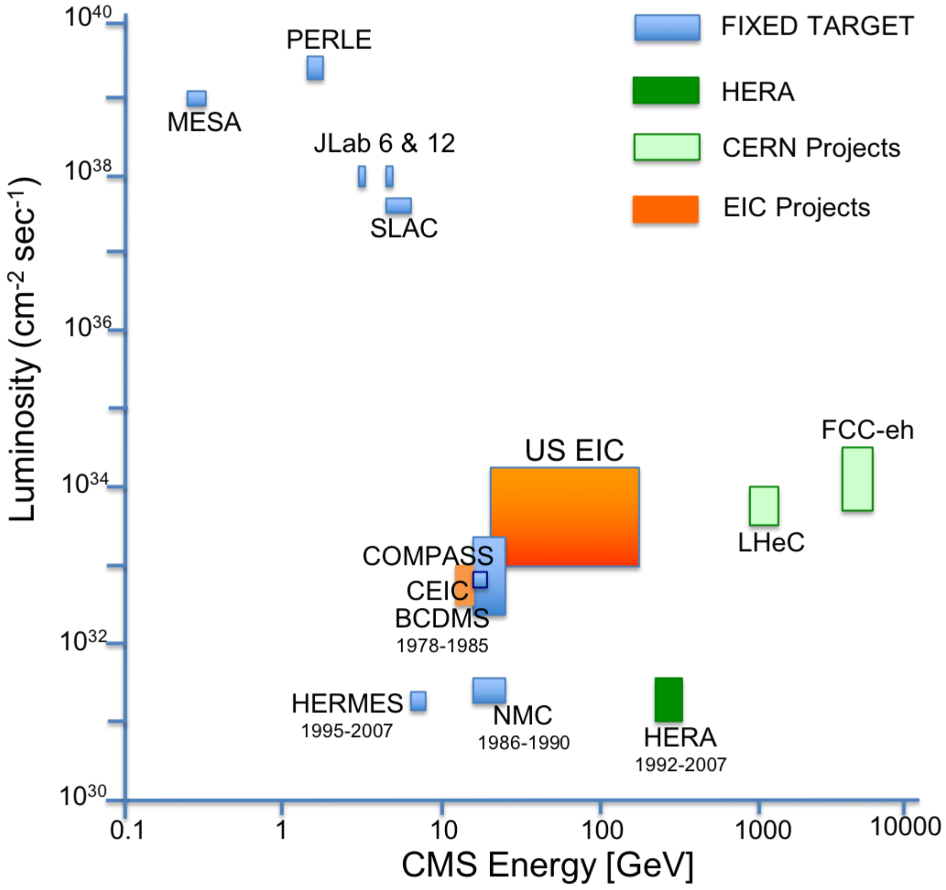




The luminosity, center-of-mass energy range, polarization, and ability to collide various ions make the EIC unique among all existing and planed machines world-wide

Yellow Report Physics Decomposition

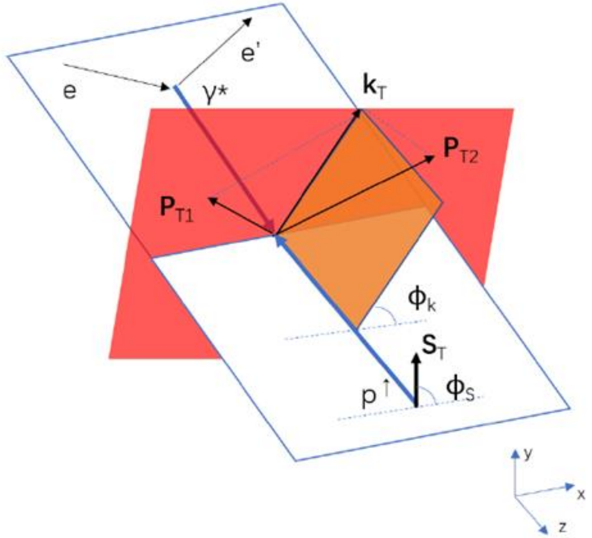
- Yellow Report Physics Working Groups divided by process
- Break EIC physics into a number of topics
- Relate topics to processes

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

Red entries are measurements covered in EIC Whitepaper and/or NAS report

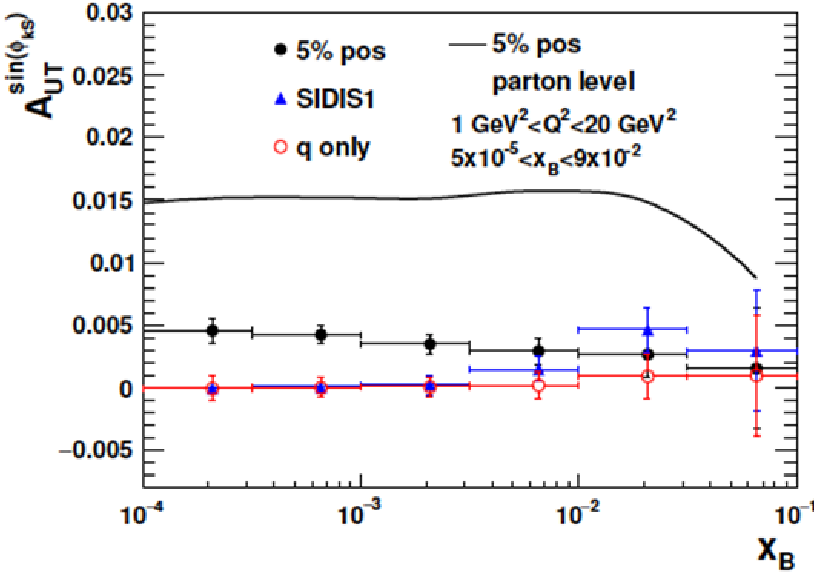
Gluon Sivers Function

Phys. Rev. D 98, 034011 (2018)

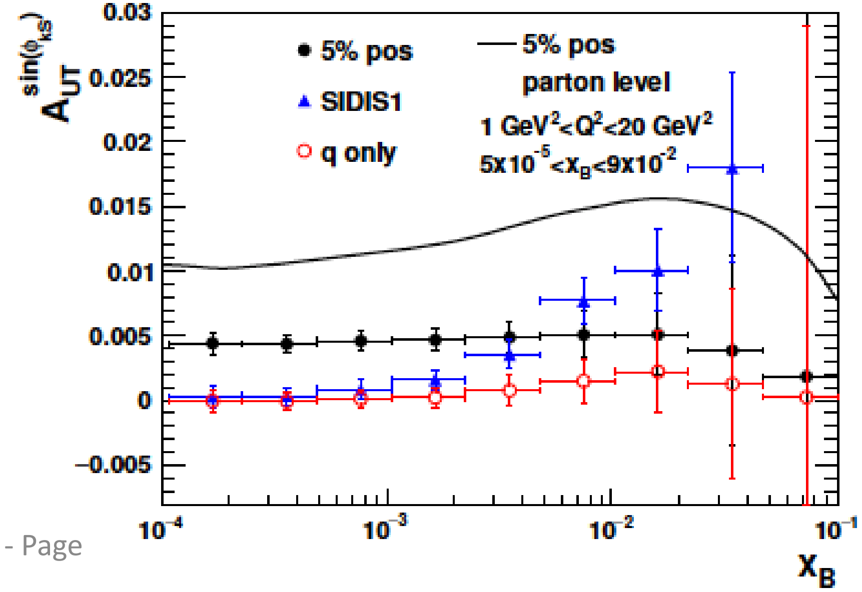


- Modulations of the angle between the proton spin vector and the sum of the di-parton system provide access to gluon sivers function
- Use of dijets has several advantages over di-hadrons including lower dilution of asymmetry and better separation between models of gluon sivers effect
- Jets don't suffer from uncertainties arising due to fragmentation (although hadronization still a concern)

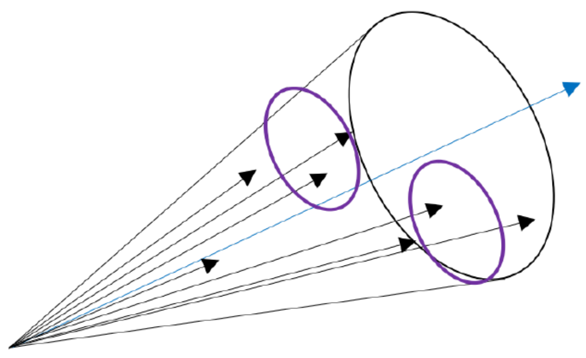
Di-Hadrons



Dijets



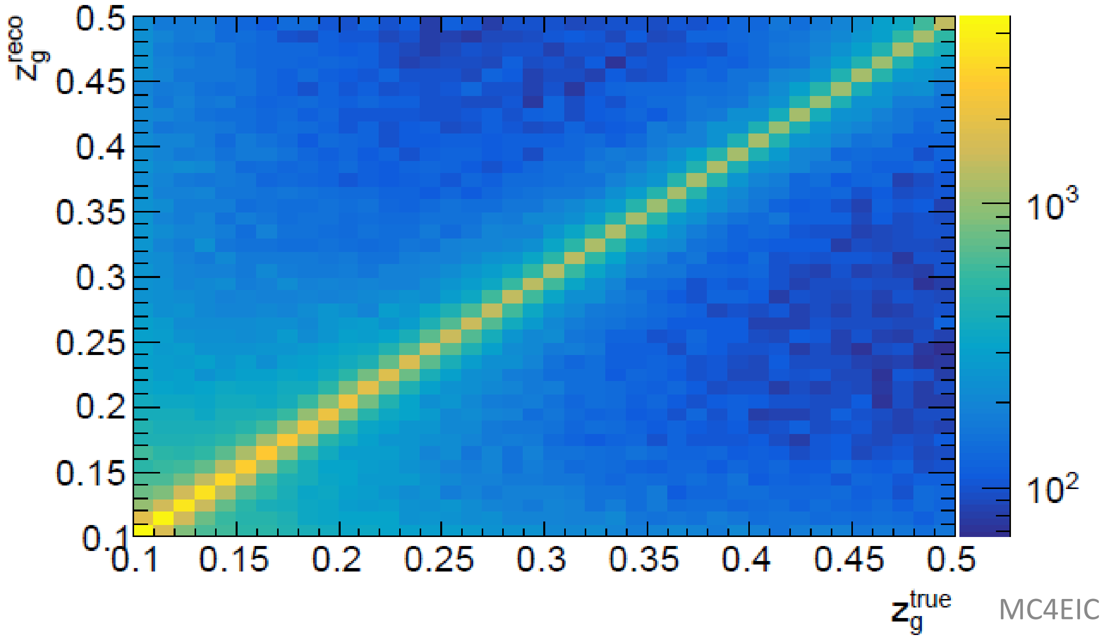
Soft Drop (Heavy) Jet Substructure

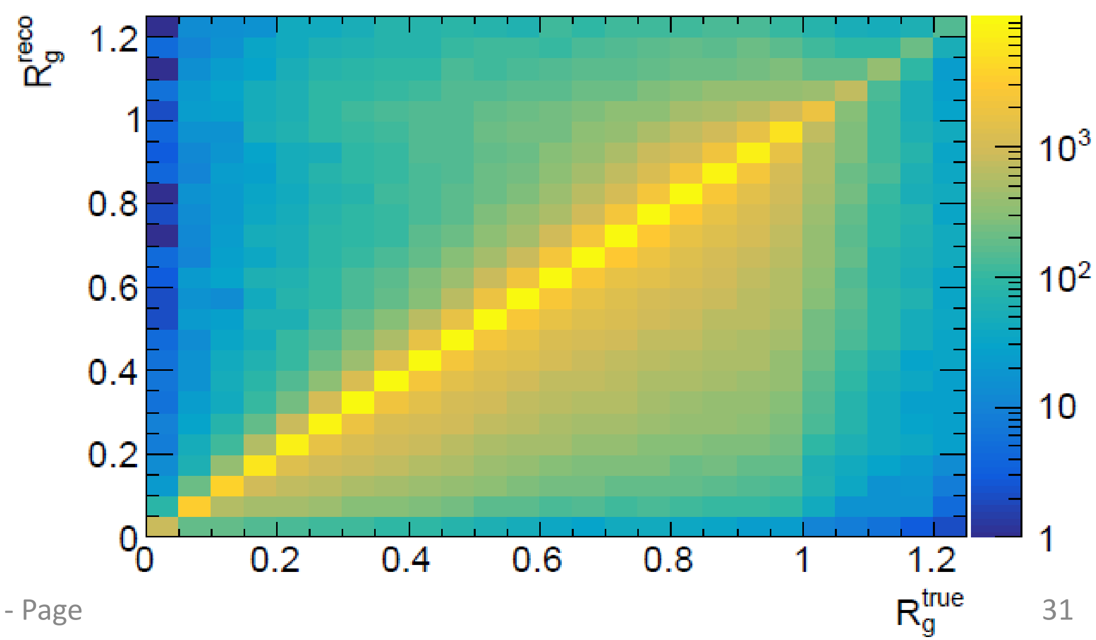


$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

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

- Techniques such as soft drop declustering / grooming will allow us to trace the ‘history’ of parton fragmentation
- Comparing ep and eA will tease out differences in fragmentation and hadronization in vacuum vs the nuclear medium – groomed heavy quark jets for mass dependence
- Given low number of particles in jets at the EIC, no guarantee grooming will work – initial studies are promising





Angularity

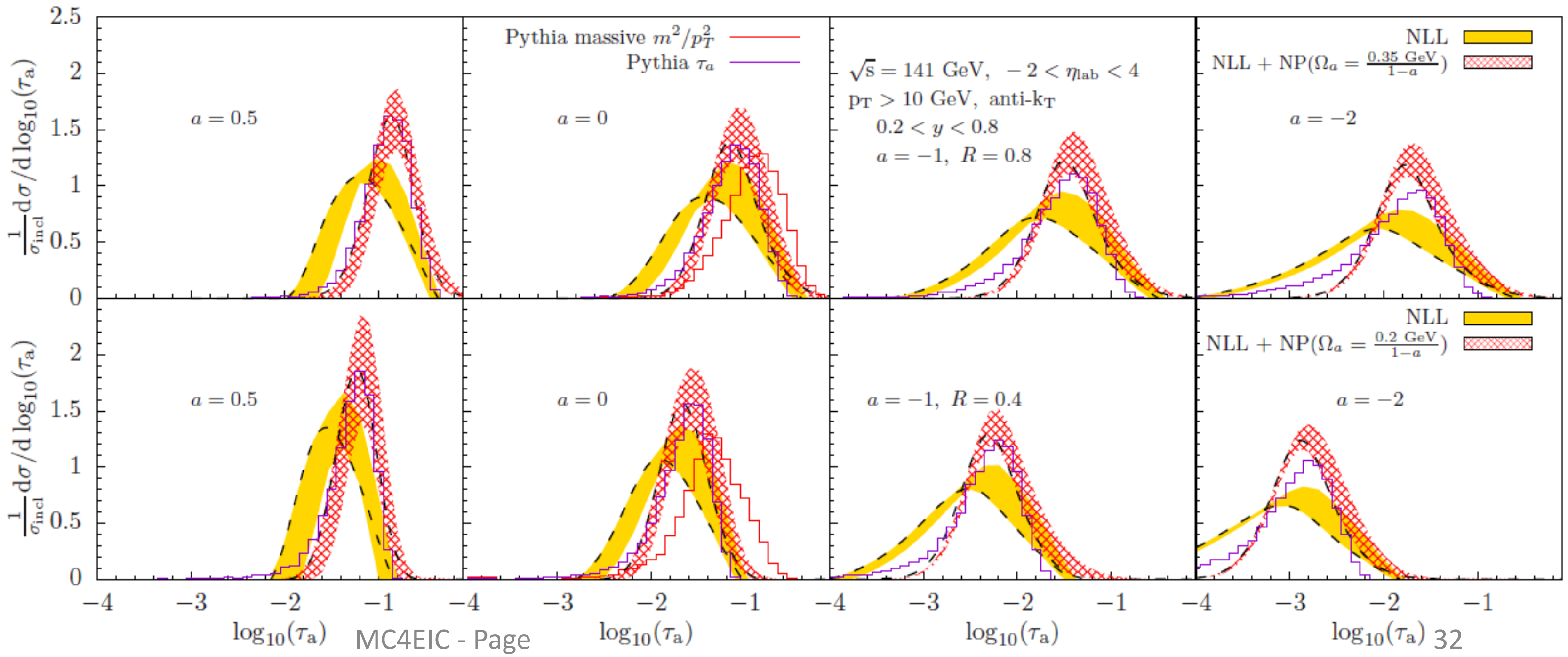
$$\tau_a \equiv \frac{1}{p_T} \sum_{i \in J} p_T^i \left(\Delta R_{iJ}\right)^{2-a}$$

- Jet angularity are a family of one-parameter substructure observables correlating momentum and radial distance of particles in a jet
- Different choices of 'a' parameter interpolate between familiar substructure observables such as mass and broadening
- Comparison with alternative definition allows quantification of significance of sub-leading power corrections

- Angularity is sensitive to hadronization effects via a convolution with the non-perturbative shape function Ω1
- Values are seen to be much less than at LHC
- Look at changes between ep and eA

$$F_\kappa(k) = \left(\frac{4k}{\Omega_\kappa^2}\right) \exp\left(-\frac{2k}{\Omega_\kappa}\right)$$

Aschenauer, Lee, Page, Ringer `20



New (and Not-so-New) Tools

- Renewed interest in jet charge as a method for disentangling light quark flavors in a number of settings

$$d_{ij} = \left[(\Delta f_{ij})^2 + 2 f_i f_j (1 - \cos \Delta\phi_{ij})\right] / R^2$$

- New longitudinally invariant asymmetric clustering algorithm for jet finding in the Breit frame

Asymmetric measure is necessary

$$f(x) = x + \mathcal{O}(x^2)$$

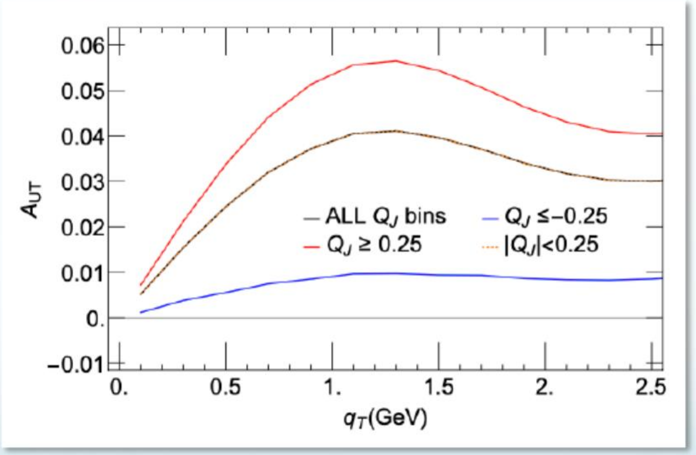
$$\bar{\eta}_i = -\frac{2Q}{\bar{n} \cdot q} \frac{p_i^\perp}{n \cdot p_i}$$

$$\bar{\eta}_i(\mathrm{BF}) = 2 p_i^\perp / p_i^+$$

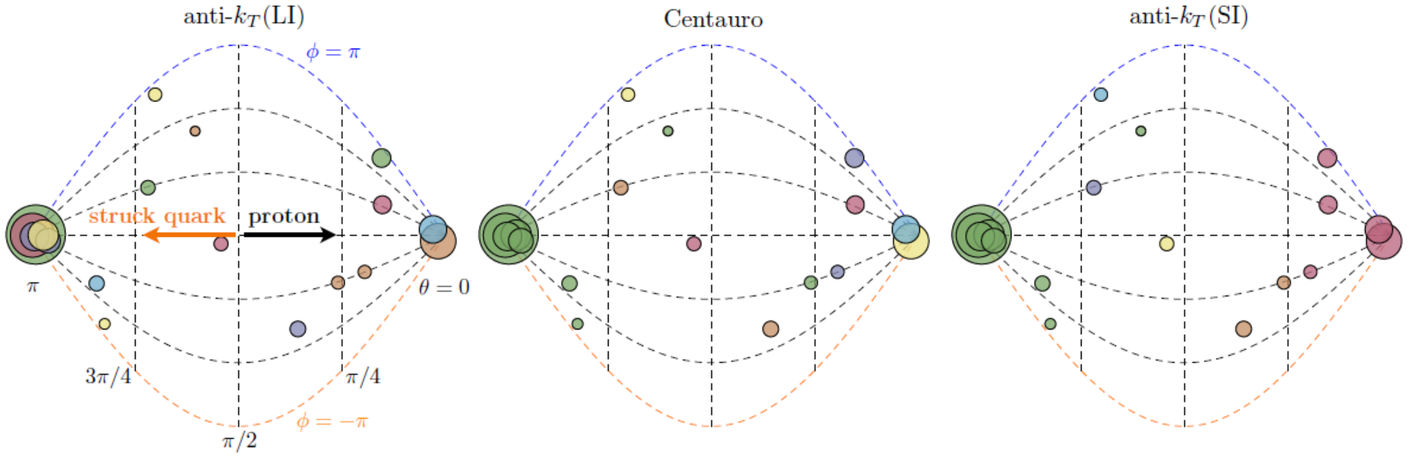
Kang, Liu, Mantry, Shao `20

$$Q_\kappa = \sum_h Q_\kappa^h \equiv \sum_{h \in \mathrm{jet}} z_h^\kappa Q_h$$

$$A_{UT}(Q^N_{\kappa,\mathrm{bin}}) = \frac{d\sigma(S^\uparrow) - d\sigma(S^\downarrow)}{d\sigma(S^\uparrow) + d\sigma(S^\downarrow)} = \frac{d\sigma_{UT}(Q^N_{\kappa,\mathrm{bin}})}{d\sigma_{UU}(Q^N_{\kappa,\mathrm{bin}})}$$



Arratia, Makris, Neill, Ringer, Sato `20



Longitudinally invariant Symmetric | Longitudinally invariant Asymmetric | Spherically invariant Symmetric