Some Physics Goals with Jets in e-A collisions

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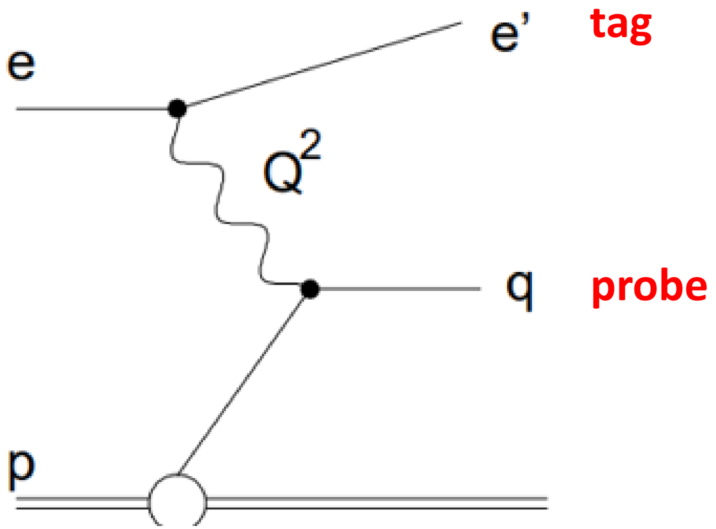
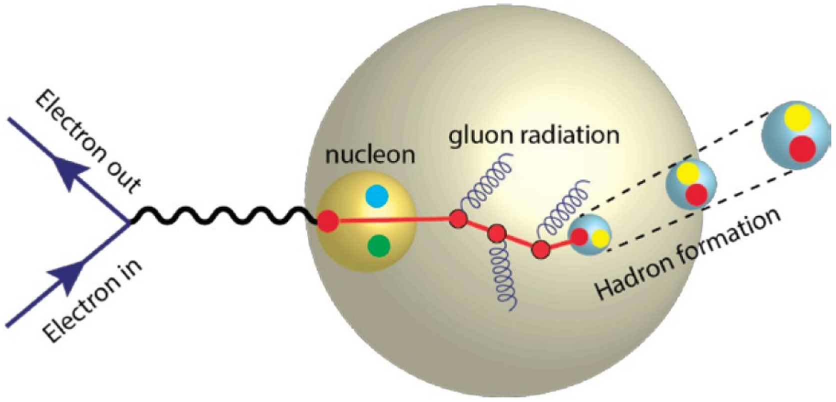
Some physics goals for first-ever jets in e-A

- Precision quark-nucleus interactions with
  "tag and probe" lepton-jet correlations.
- Nuclear tomography with lepton-jet correlations.
- Separate beam and target fragmentation
- Hadronization studies with jet substructure

Goal: Use DIS jets as precision tool in e-A collisions





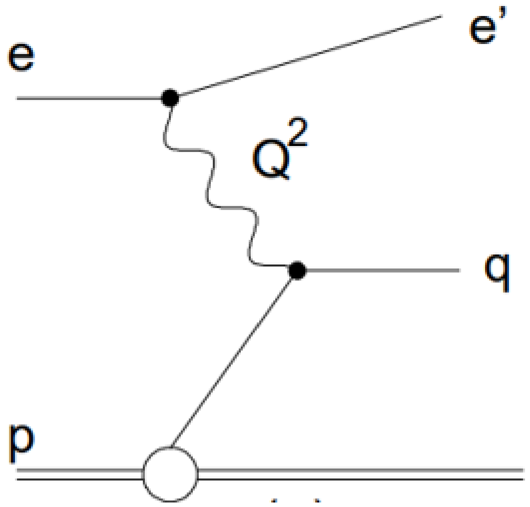
- To study quark propagation through nucleus, its quark structure, and hadronization.

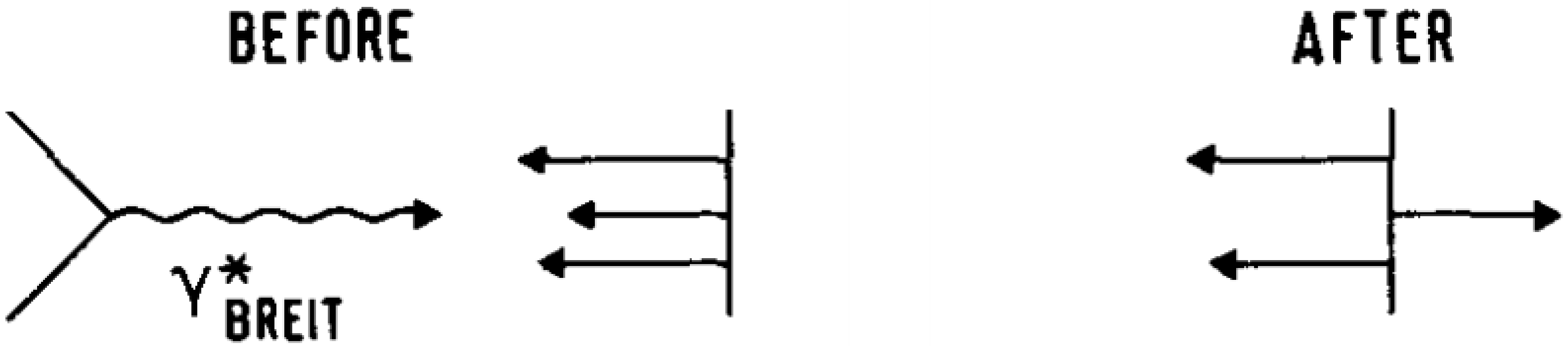
- Exploit that electron balances struck-quark jet providing "tag and probe"

- For this to work we need:
  - to measure electron
  - to find kinematic region where the "LO" diagram dominates
  - to identify jet from struck quark

Source: EIC white paper

Jets in Breit frame, leading order:





This jet has 0 transverse momentum in this frame (if masses and intrinsic kT are neglected)

Fig. 2. Parton configurations before and after the absorption of the virtual photon

HERA experiments did require high pT in the Breit Frame to suppress the dominant, LO diagram.

~ 0 pT in Breit frame
"Quark-Parton Model Background"

High pT in Breit frame
Signal.

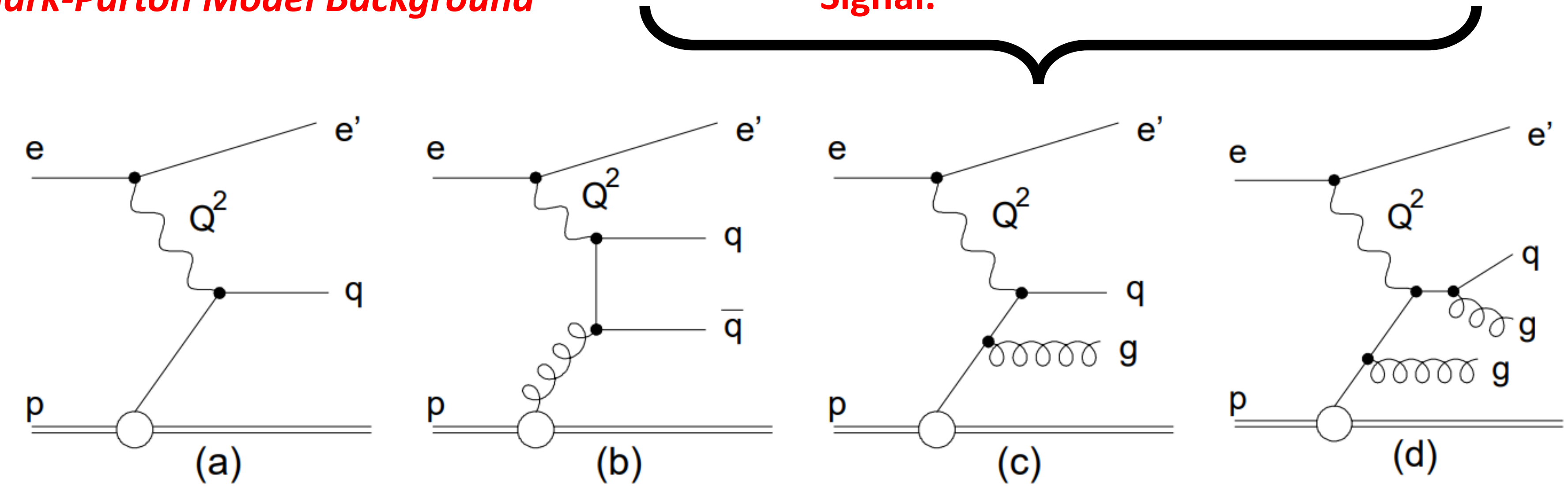
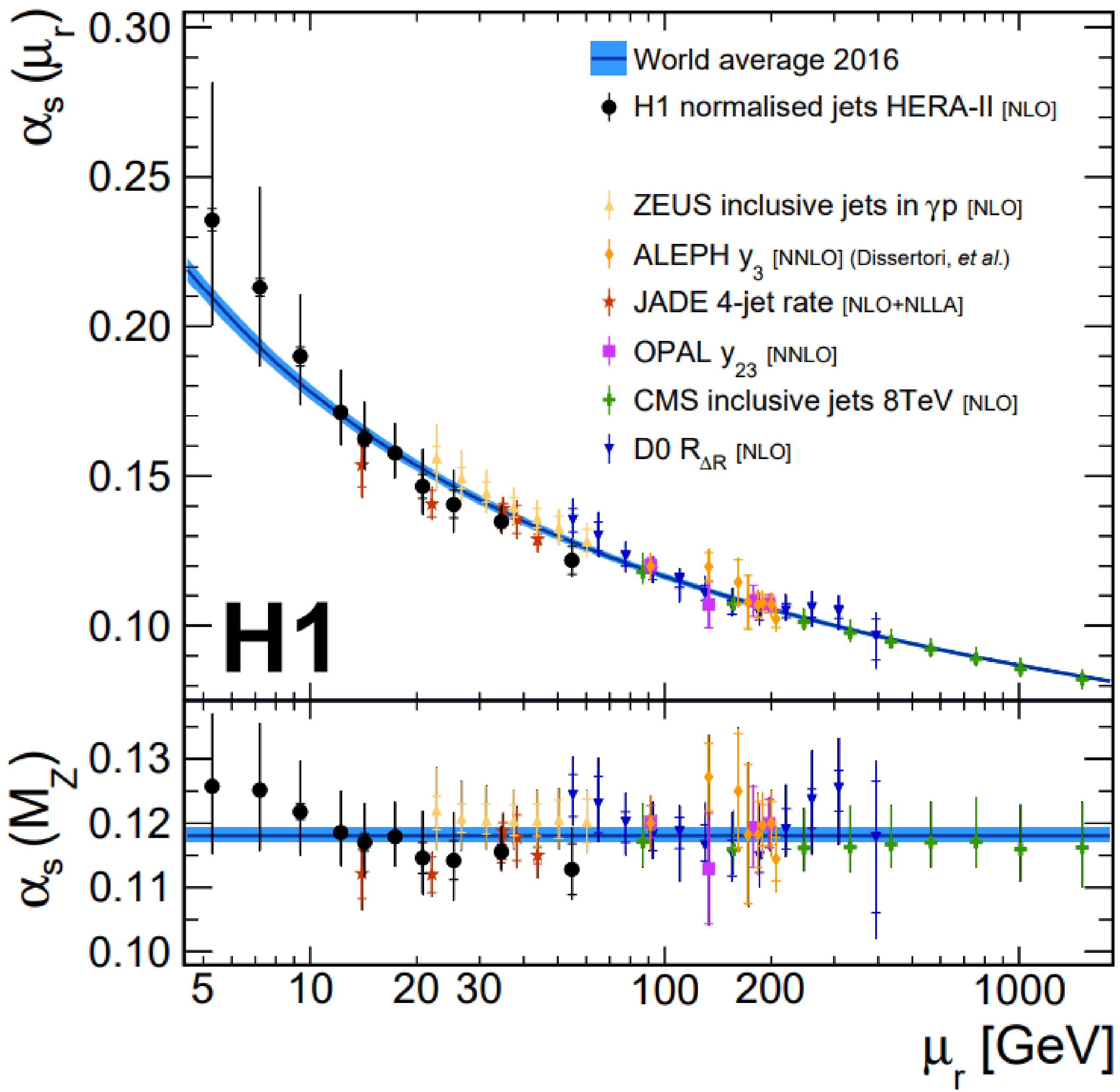


Figure 1: Deep-inelastic *ep* scattering at different orders in α_s: (a) Born contribution to inclusive NC DIS ($\mathcal{O}(\alpha_{\text{em}}^2)$), (b) photon-gluon fusion ($\mathcal{O}(\alpha_{\text{em}}^2\alpha_s)$), (c) QCD Compton scattering ($\mathcal{O}(\alpha_{\text{em}}^2\alpha_s)$) and (d) a trijet process $\mathcal{O}(\alpha_{\text{em}}^2\alpha_s^2)$.



By measuring higher-order processes you get sensitivity to alpha_s, which was the main objective of jet studies at HERA

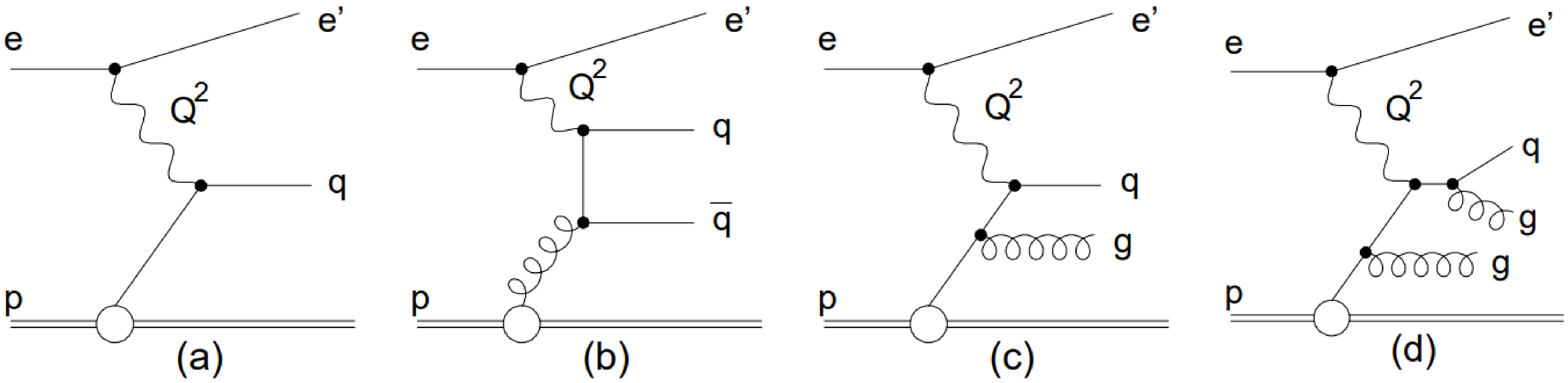
For using jets as precision tool at the EIC, we want the opposite

Electron fixes jet kinematic, perfect for "tag and probe" in e-A

Signal.

Electron does not fix jet kinematics, not useful for "tag and probe"

Background



On the Breit frame, summary

- For “tag and probe” studies with electron-jet correlation measurements, we need to do <u>exactly the opposite than HERA did</u>: enhance leading-order DIS and suppress higher-order DIS.
- By not suppressing LO DIS, the jet cross-sections are much higher (roughly by a factor 1/(alpha_s)^2 ~ 100).
  Moreover, EIC luminosity will be x1000 HERA.
- It is not a trivial matter, in HERA experiments jet pT < ~4 GeV (in Breit Frame) where simply not reported.

Lepton-Jet Correlations in Deep Inelastic Scattering at the Electron-Ion Collider

Xiaohui Liu, Felix Ringer, Werner Vogelsang, and Feng Yuan
Phys. Rev. Lett. **122**, 192003 – Published 15 May 2019

We focus on large transverse momentum lepton-jet production in the center of mass (c.m.) frame of the incoming lepton and nucleon, see Fig. 1,

$$\ell(k) + A(P) \to \ell'(k_\ell) + \mathrm{Jet}(P_J) + X, \qquad (1)$$

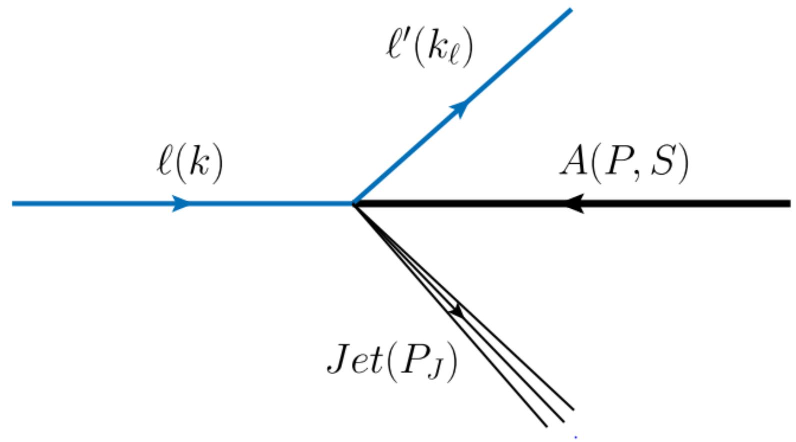
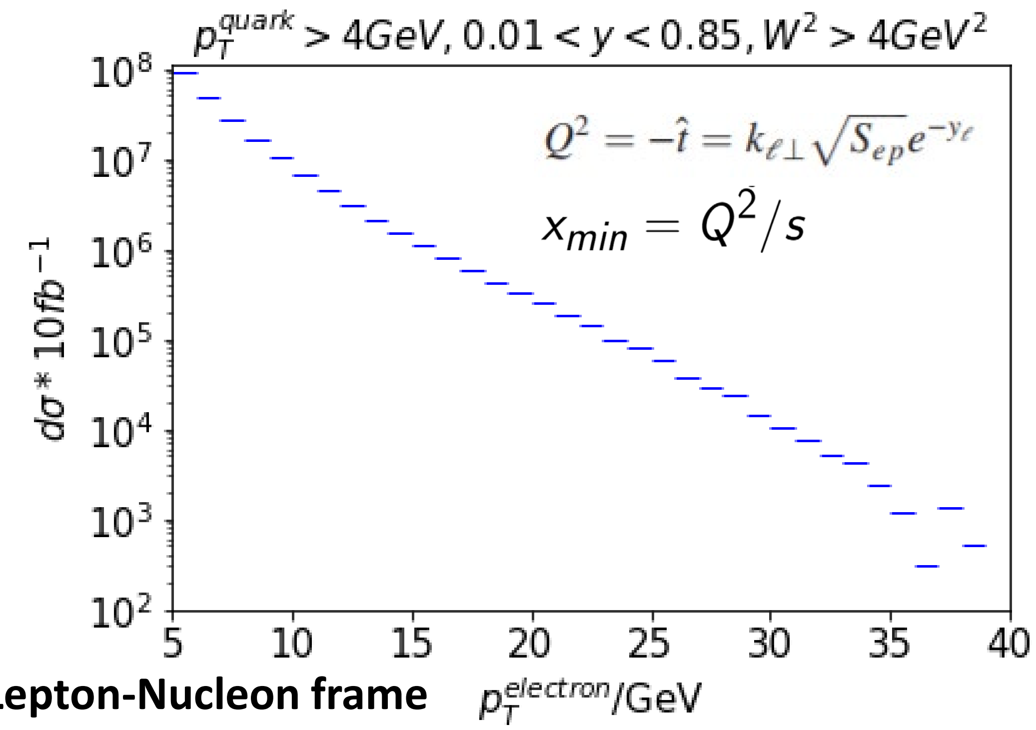


FIG. 1. Lepton-jet correlation for the tomography of the nucleon or nucleus at the EIC.

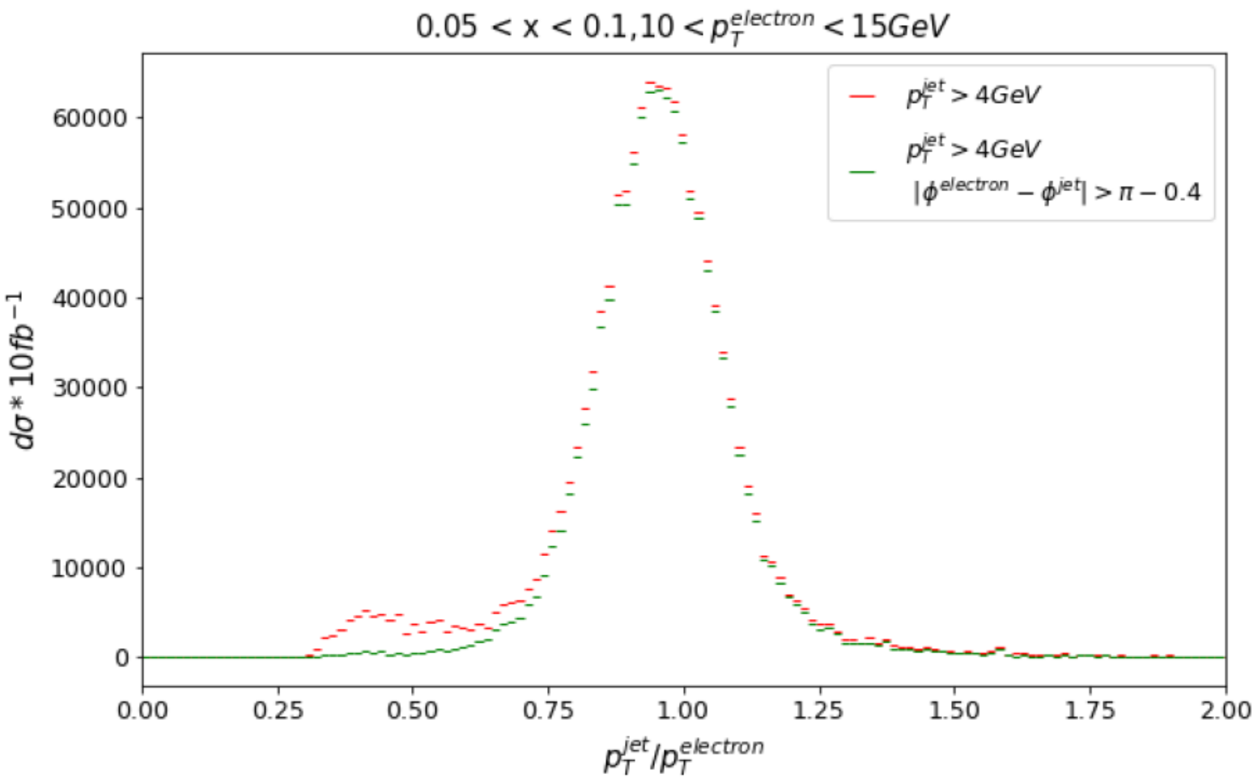
momenta as $k_{\ell\perp}$ and $P_{J\perp}$. All of these kinematic variables are defined in the c.m. frame of the incoming lepton and nucleon. This is very different from the jet measurements in previous DIS experiments such as those carried out at HERA [7–9], where the cross sections were measured in the c.m. frame of the virtual photon and nucleon. Similar

$$\frac{d^5\sigma(\ell p \to \ell' J)}{dy_\ell d^2k_{\ell\perp} d^2q_\perp} = \sigma_0 \int d^2k_\perp d^2\lambda_\perp x f_q(x, k_\perp, \zeta_c, \mu_F) \times H_{\mathrm{TMD}}(Q, \mu_F) S_J(\lambda_\perp, \mu_F)\, \delta^{(2)}(q_\perp - k_\perp - \lambda_\perp) \, .$$

Lepton-jet correlations, for e-A cold matter studies

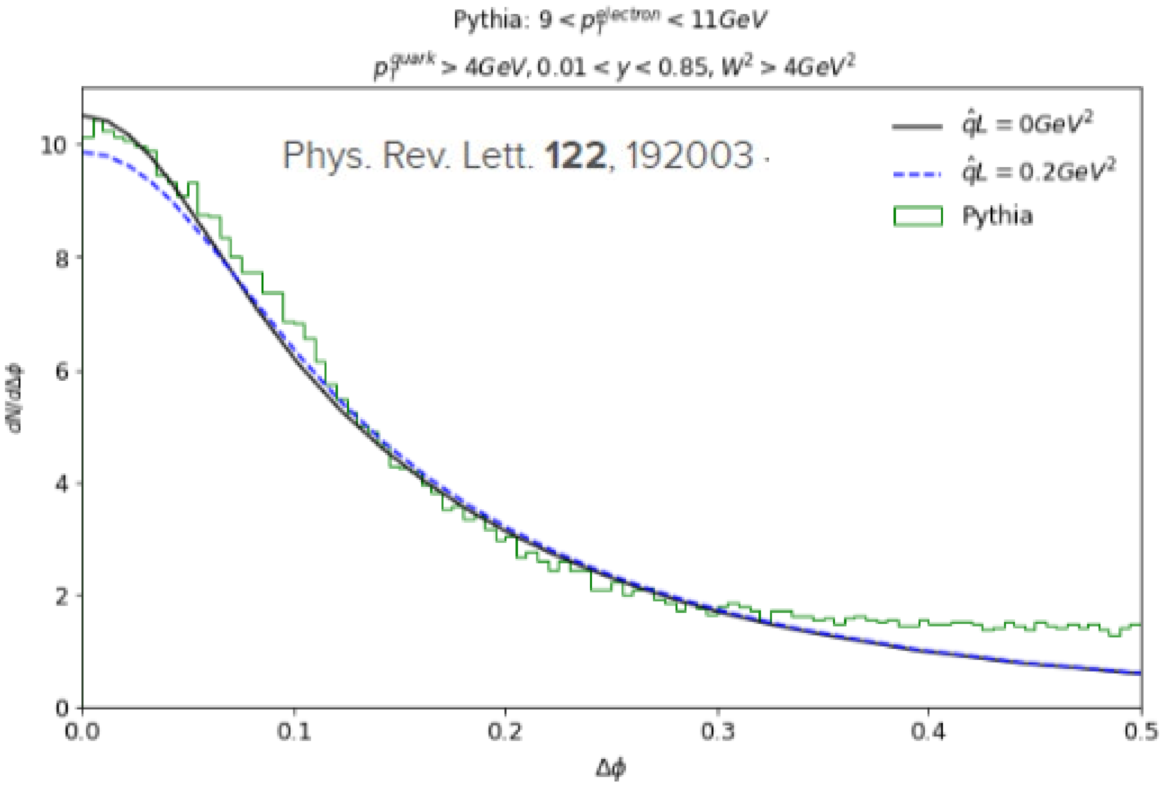


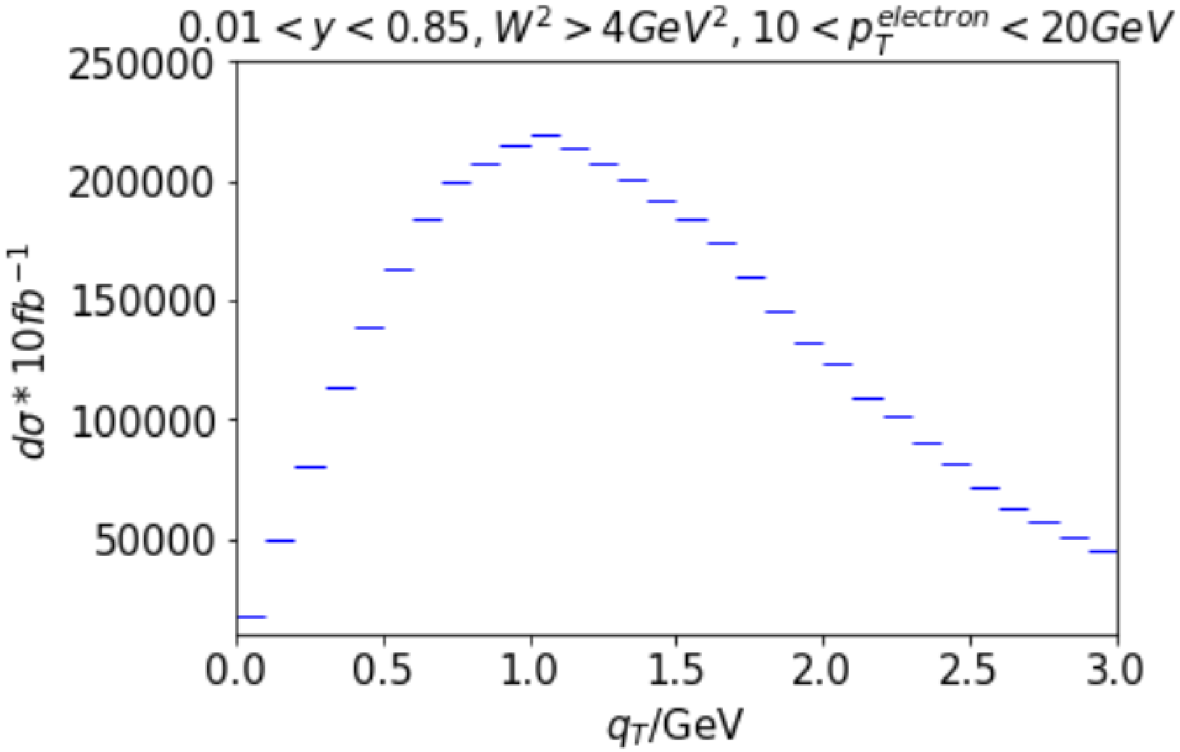
Lepton-Nucleon frame



- Event-by-event tagging for cold nuclear matter studies in e-A
- We will have plenty of statistics for lepton-jet measurements.

Lepton-jet correlations with qT





Vectorial sum of lepton and jet pT $|\vec{k}_{\ell\perp} + \vec{P}_{J\perp}|$

Some physics goals for first-ever jets in e-A

- Precision quark-nucleus interactions with
  “tag and probe” lepton-jet correlations.
- Nuclear tomography with lepton-jet correlations.
- Separate beam and target fragmentation
- Hadronization studies with jet substructure

Same observable is interesting for TMD studies.

Our e-A measurements could work for nuclear TMD studies

Transverse momentum dependent distributions in e^+e^- and semi-inclusive deep-inelastic scattering using jets

Daniel Gutierrez-Reyes, Ignazio Scimemi, Wouter J. Waalewijn, Lorenzo Zoppi

(Submitted on 8 Apr 2019 (v1), last revised 19 Apr 2019 (this version, v2))

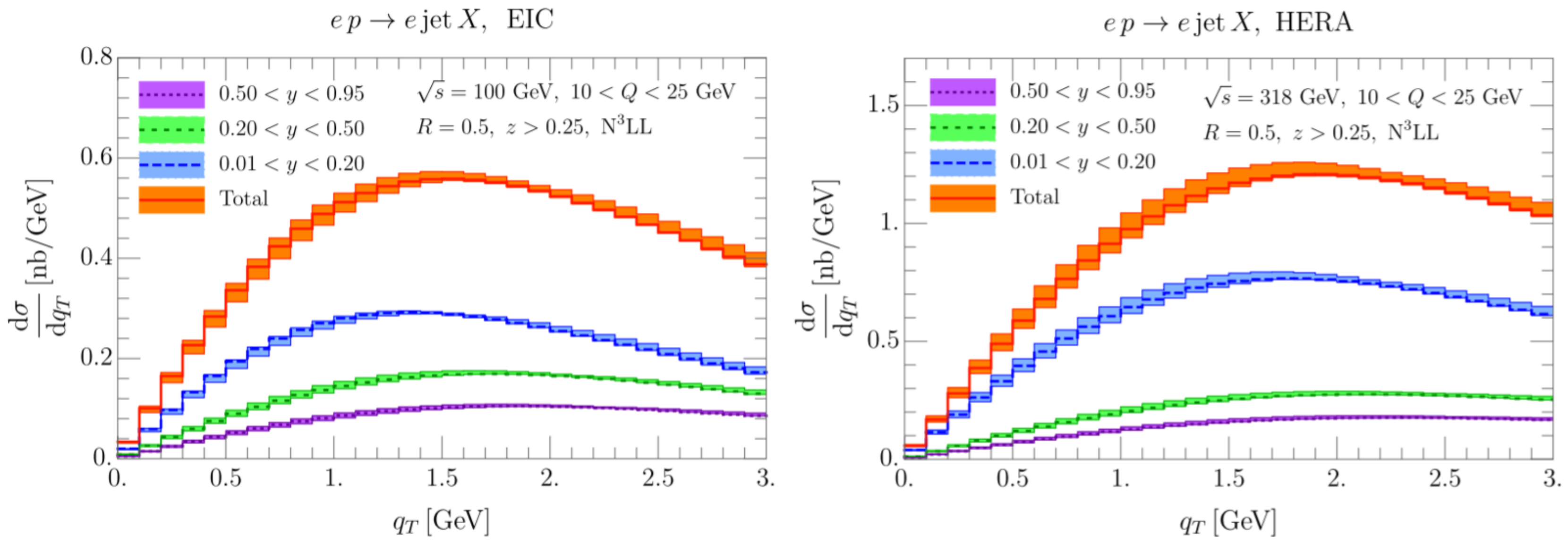


Figure 8. TMD cross section for SIDIS with jets at the EIC (left) and at HERA (right), with $10 < Q < 25$ GeV and different intervals in elasticity within the range $0.01 < y < 0.95$.

"A clear advantage is that the jet momentum can be calculated in perturbation theory, while the fragmentation of hadrons is an intrinsically nonperturbative process"

“Probing Transverse-Momentum Distributions With Groomed Jets”

JHEP 1908 (2019) 161 , Daniel Gutierrez-Reyes et al.

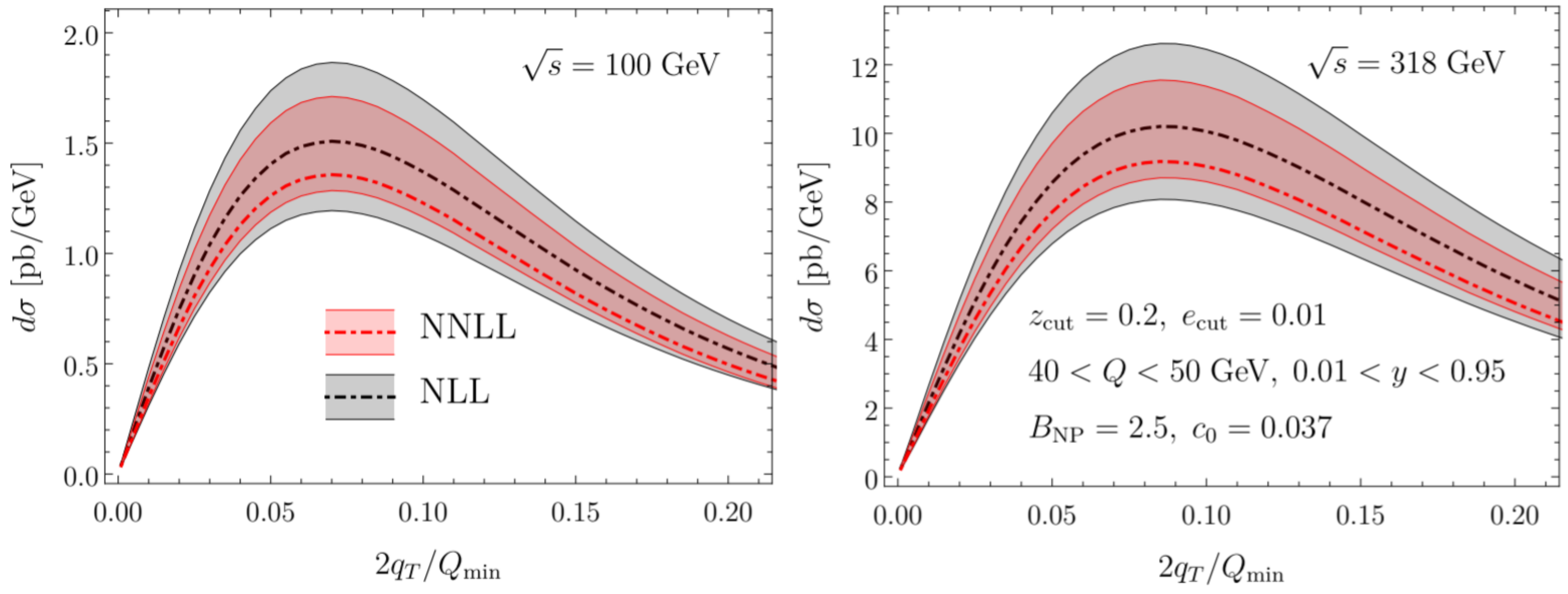
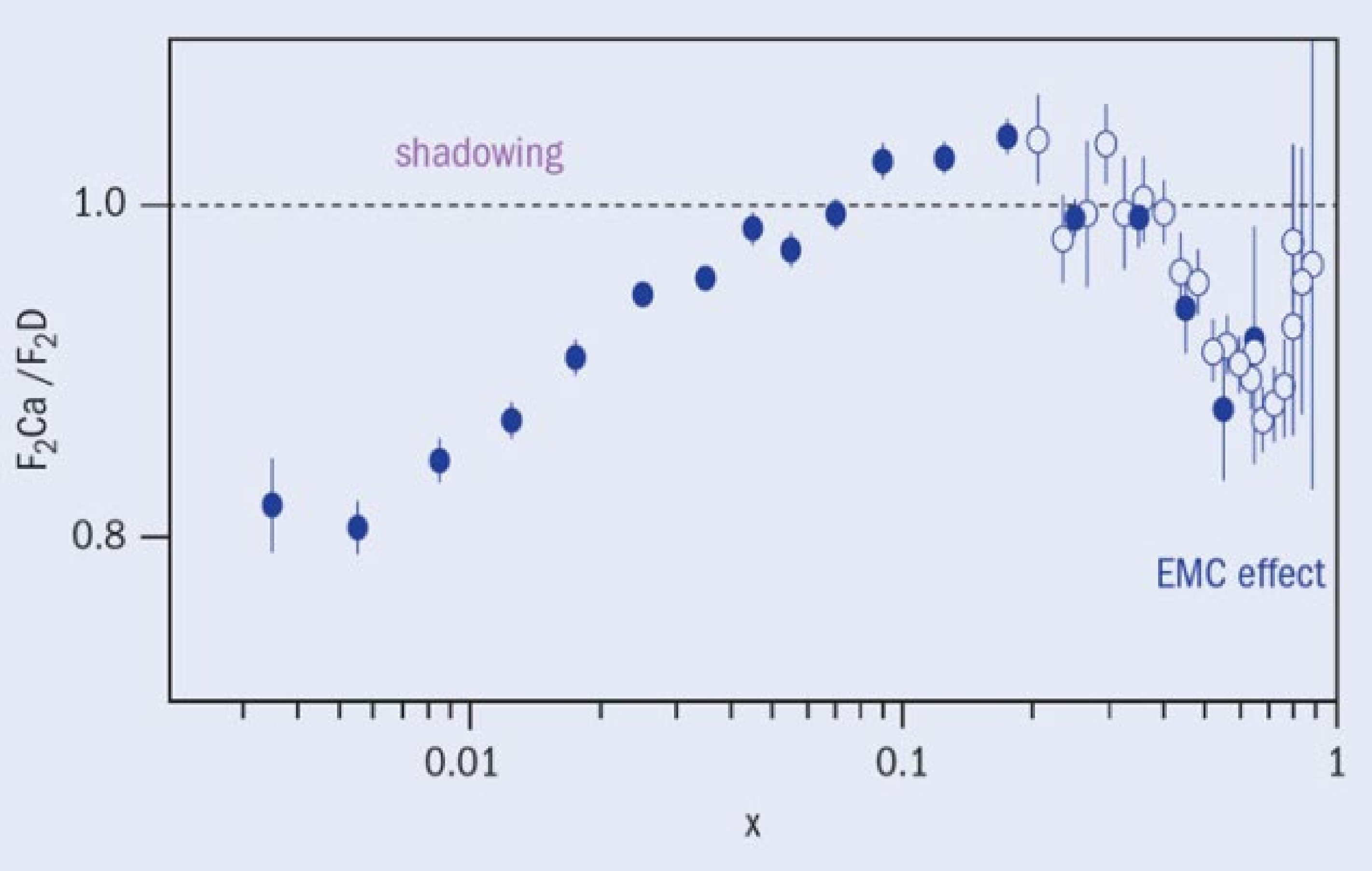


Figure 7. The NLL and NNLL TMD spectra for groomed jets in DIS for EIC (left: $\sqrt{100}$ GeV) and HERA (right: $\sqrt{s} = 318$ GeV) kinematics. The cross section are integrated in $y = Q^2/(xs)$ and $Q = \sqrt{-q^2}$ (see details in the main text).

“…it is possible to measure directly the hadronization effects due to grooming”

TMD studies in e-A could add more dimensions to this plot and help explain its origin



This entire x range can be covered with jets at the EIC

- No possible with inclusive DIS
- Jets could bypass fragmentation functions
- Jets can also provide flavor-tagging
- Could also include electron and nucleus polarization.

What is the level accuracy we need?

- Predicted cold-nuclear matter effects in e-A are at the 1% level.

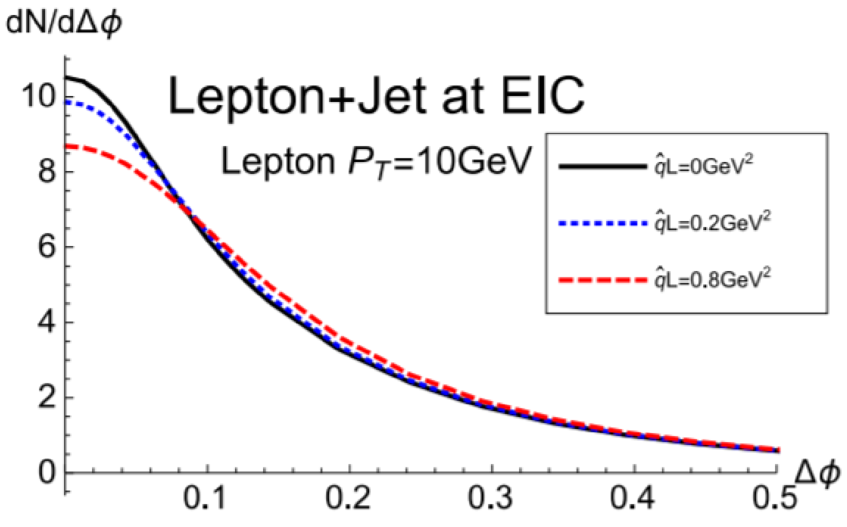
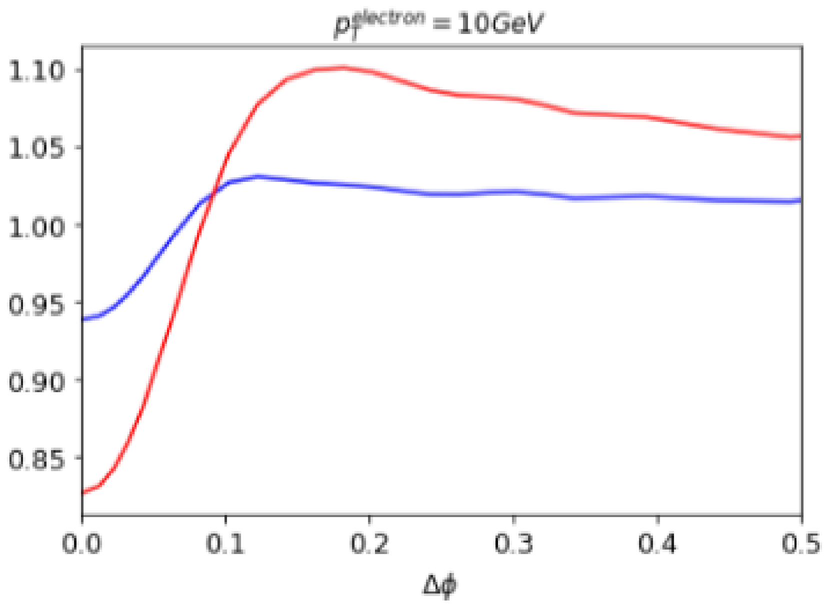


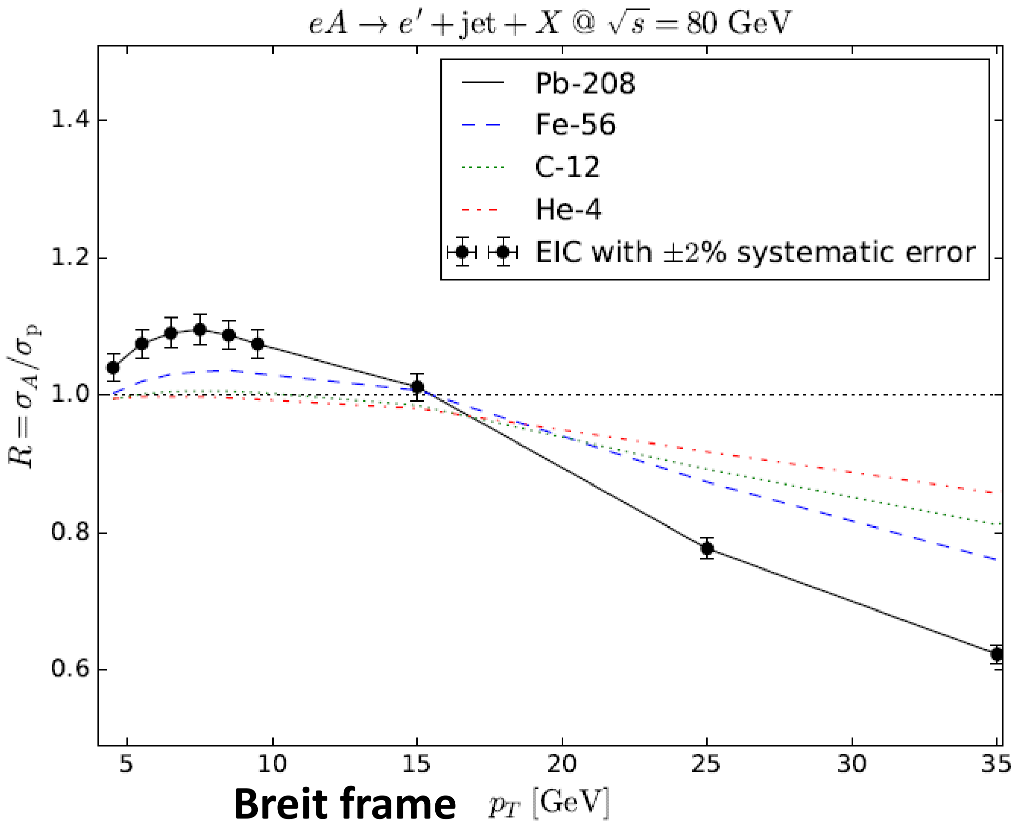
FIG. 4. P_T-broadening effects for the lepton jet azimuthal correlation due to the interaction with cold nuclear matter as a function of $\Delta\phi = |\phi_J - \phi_\ell - \pi|$ for two typical values of $\hat{q}L$.

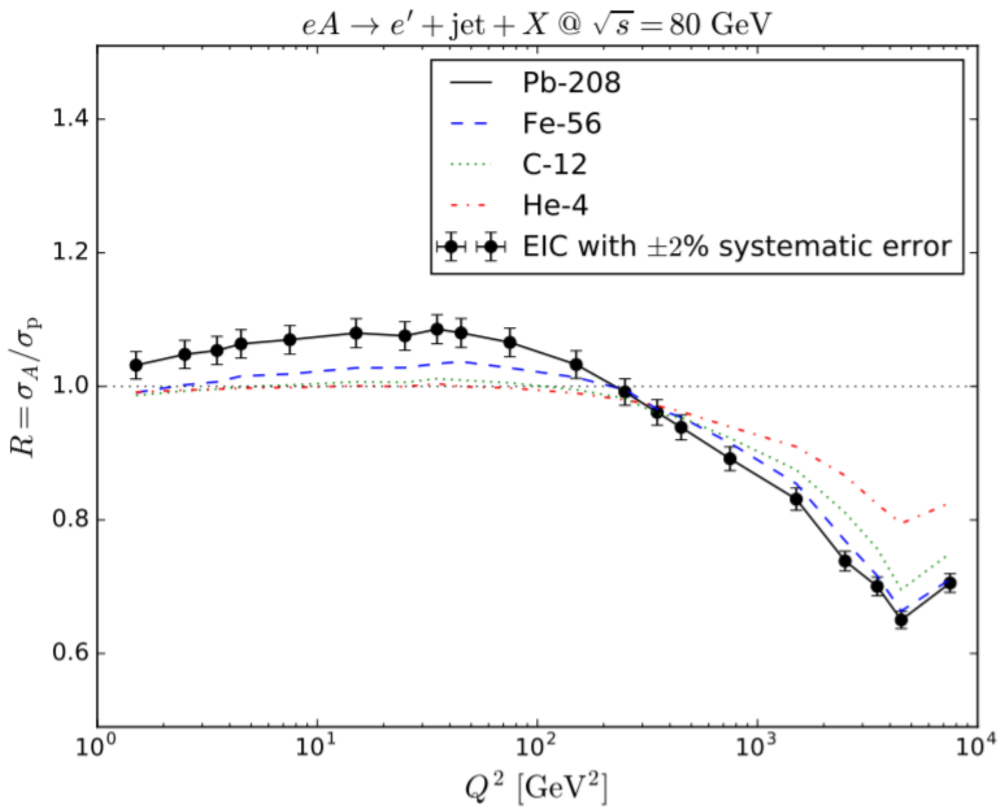


Phys. Rev. Lett. **122**, 192003

Klasen et al., Phys. Rev. D 97, 114013 (2018)

“Nuclear parton density functions from jet production in DIS at the EIC”





Quark Sivers effect (e-p). Why not also in e-A?

Phys. Rev. Lett. **122**, 192003 ·

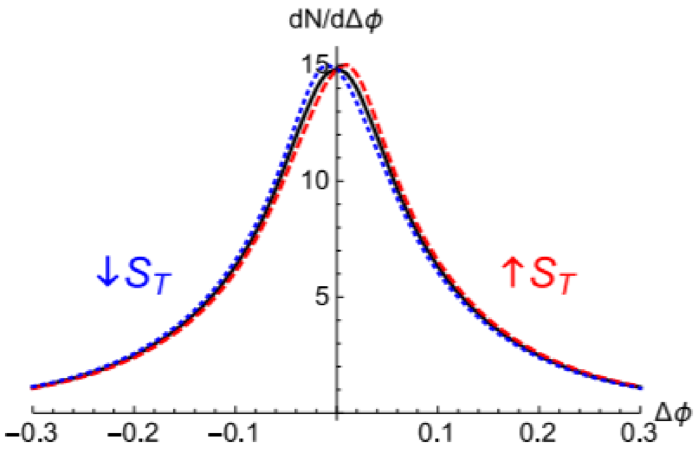


FIG. 2. The azimuthal angular correlation between the final state lepton and jet at equal rapidities $y_\ell = y_J = 1$ in the c.m. frame of the ep collisions at $\sqrt{S_{ep}} = 80$ GeV. We show $\Delta\phi = \phi_J - \phi_\ell - \pi$, where ϕ_J and ϕ_ℓ are the azimuthal angles of the jet and lepton, respectively. We choose $k_{\ell\perp} = 15$ GeV and integrate the jet transverse momentum over 10–20 GeV, with radius $R = 0.5$. The red and blue curves show the correlations when the spin of the transversely polarized nucleon is parallel or antiparallel to $\vec{k}_{\ell\perp}$, respectively.

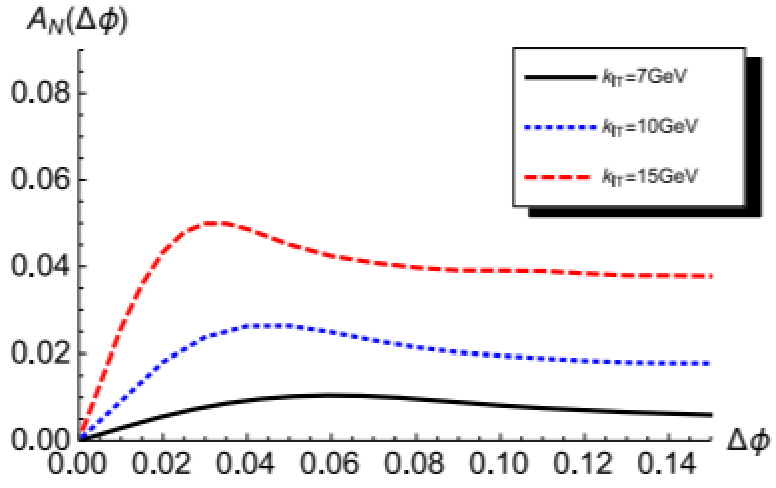


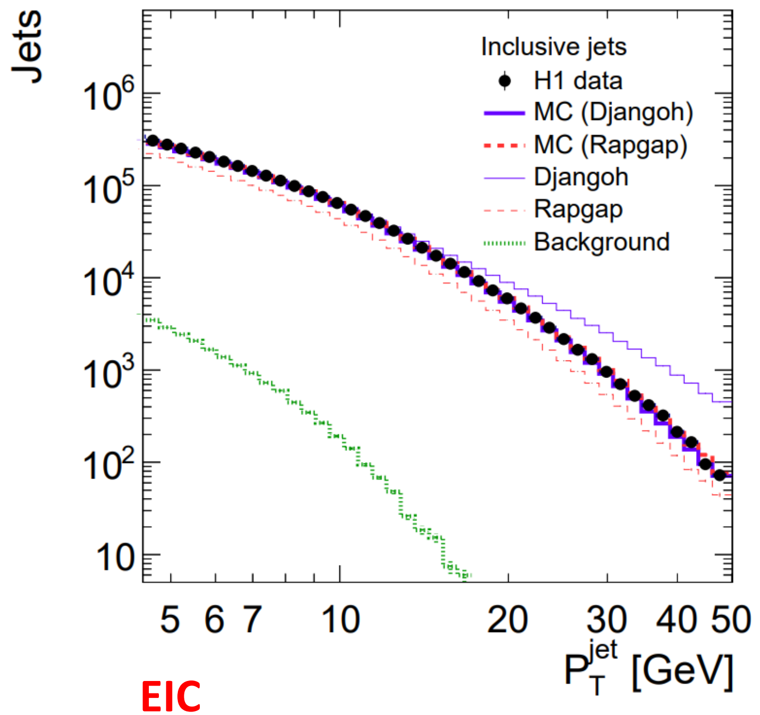
FIG. 3. The single transverse spin asymmetry as a function of $\Delta\phi = \phi_J - \phi_\ell - \pi$ for different lepton transverse momenta $k_{\ell\perp} = 7$, 10, and 15 GeV, respectively, which illustrates the transverse momentum dependence of the quark Sivers function.

"Compared to the Sivers asymmetry in SIDIS, this observable has the advantage that it does not involve TMD fragmentation functions"

Statistical precision

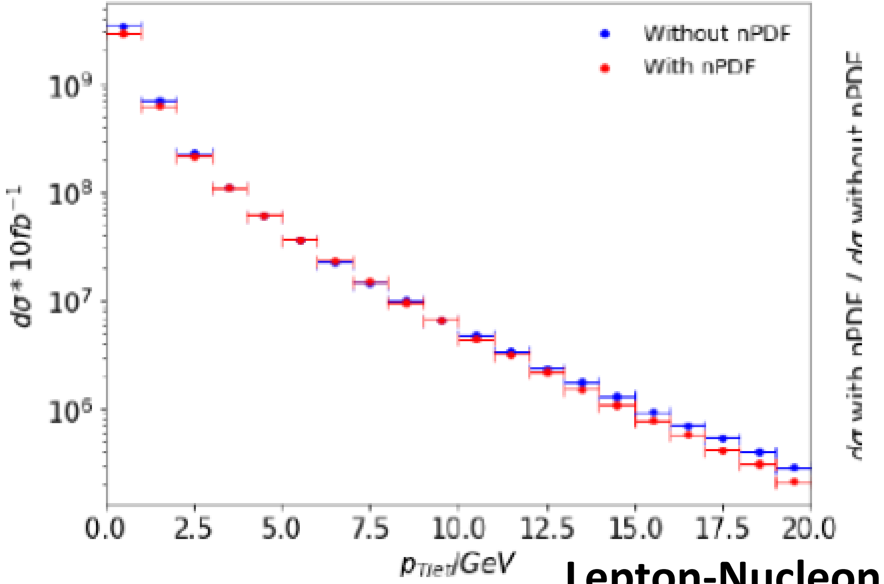
- EIC luminosity ~1000 HERA at least.
- Plus, if we do not suppress leading-order DIS like HERA experiments we gain factor ~100 in cross-section
- For most analyzes we will have a negligible statistical uncertainty, even with multi-differential measurements and for multiple nuclei.
- Obvious exception will be in the high-Q2 high x region.
- Which raises the question, what will we do in Day-2? There is room for ingenuity here.

HERA



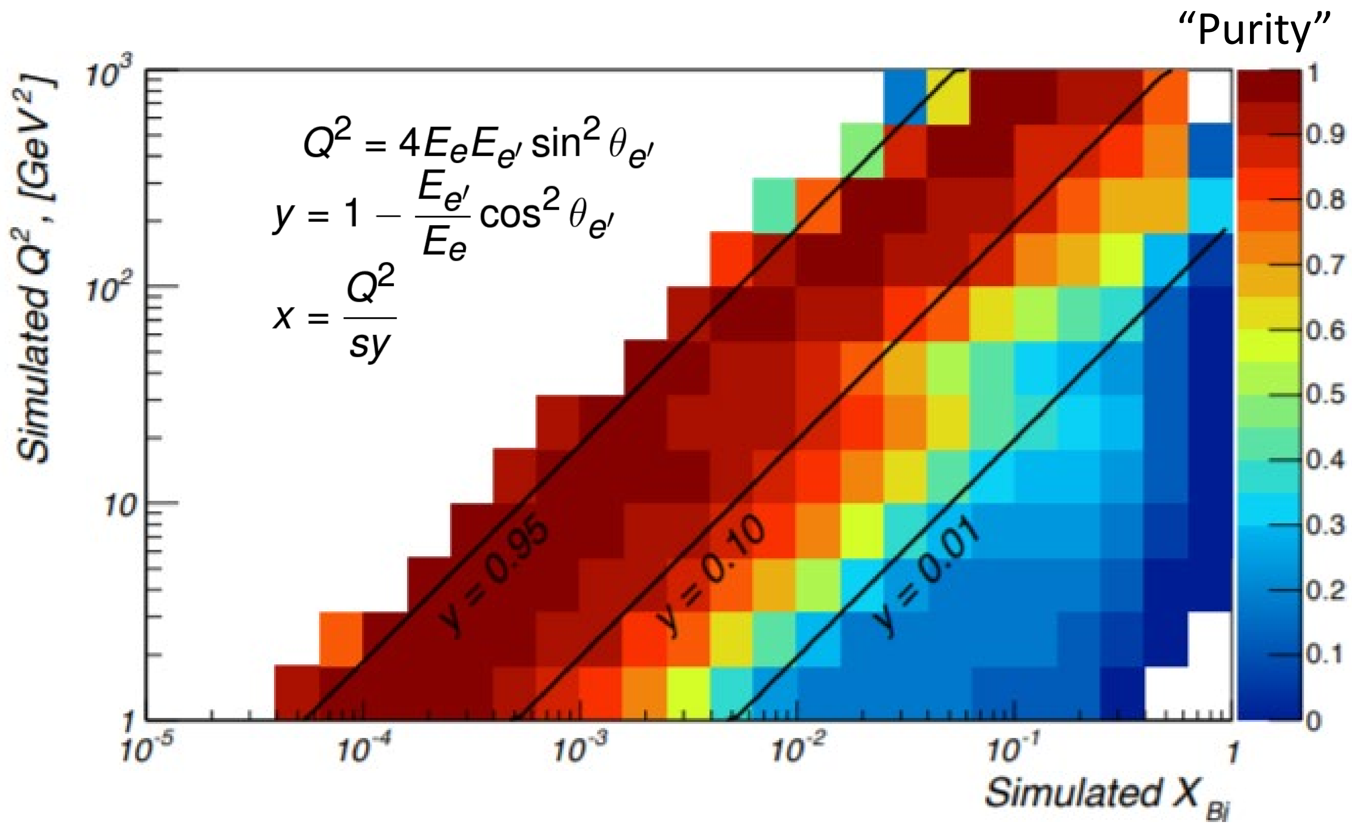
Breit-Frame

EIC



Lepton-Nucleon frame

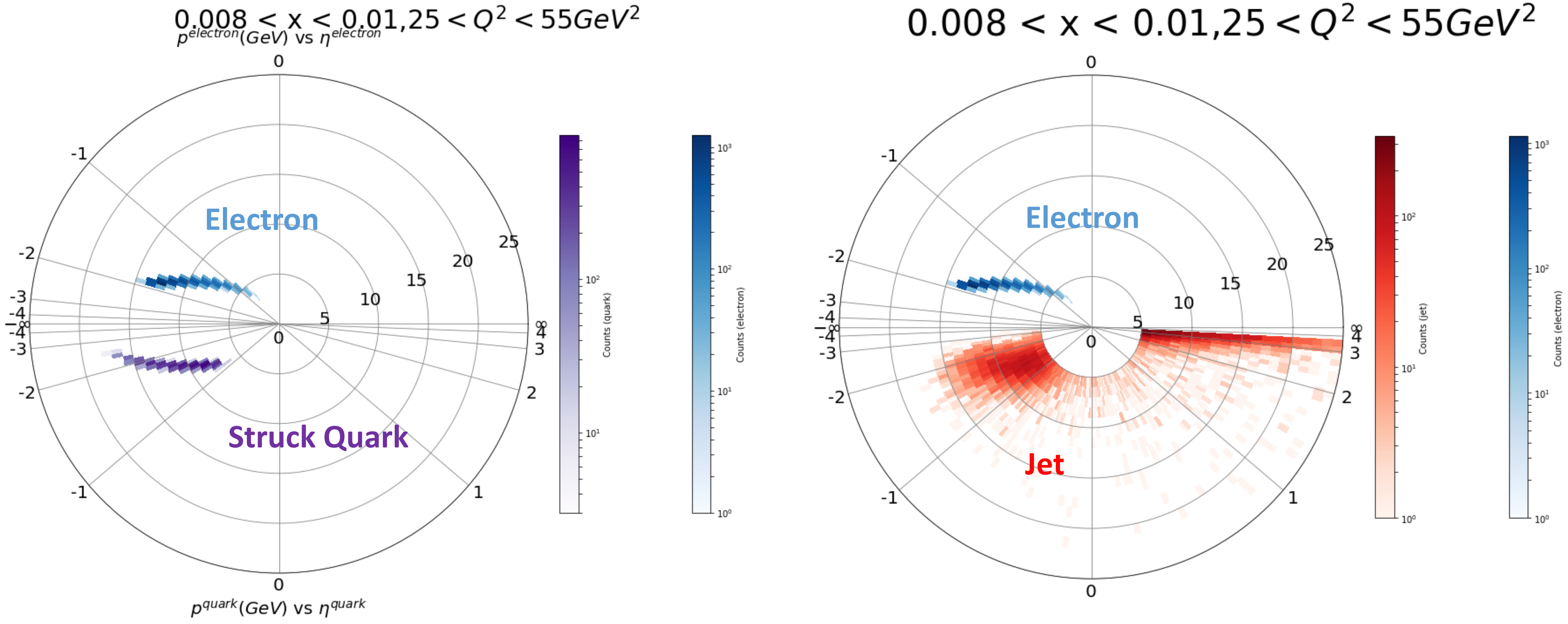
Requirement for lepton in “tag and probe” limits kinematic range



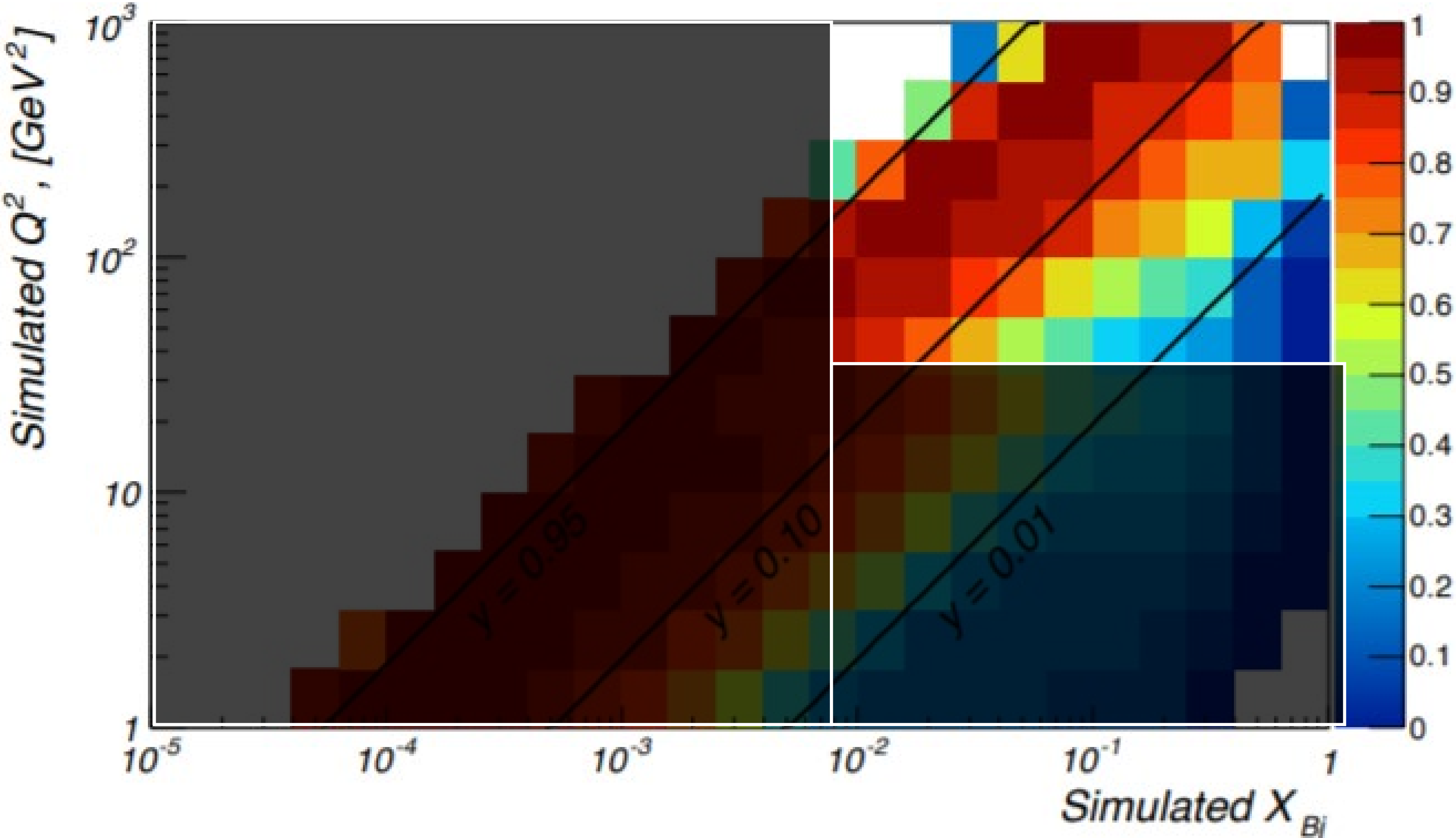
From EIC detector handboook, includes both tracker and crystal EMCAL sqrt(s) = 140 GeV.

- Electron measurements at large-x and low-Q2 region have little constrain on kinematics, as dx/x diverges at low y.
- Jet measurements can fix x and Q2 with x = pjet/pbeam, de-facto what the “Jacquet Blondel” method does.
- “Tag and probe” measurements are **impossible in this region,** unless one changes the cm energy

Requiring a measurable jet (~4 GeV) imposes a lower limit on x and Q2, which roughly is:



“Tag and probe studies” possible here:



Sqrt(s) = 140 GeV for this plot, should be 90 GeV for e-A

Jet energy scale (JES)

- ZEUS ultimately achieved a JES uncertainty of 1%, which led to ~5-10% in differential cross-section. (*ZEUS Collaboration / Nuclear Physics B 864 (2012) 1–37*)
- We will likely cannot get any better than that. But we can do e-A/ep ratios and cancel some of JES.
- Residual uncertainty in JES in **e-A/ep** ratio should be ~0.2% to get ~1--5% errors on the ratio of differential cross-sections.
- Unlike in fixed-target DIS, we cannot have both e-p and e-A at the same time. So time-dependent detector effects will mater.

Luminosity

- Do we actually need luminosity in e-A?
  We can always report ratios and double-ratios:

$$\frac{d^3\sigma^h(x,Q^2,z)/dxdQ^2dz}{d^2\sigma^{DIS}(x,Q^2)/dxdQ^2}.$$

$$R_A^h = \frac{\left[N_h\left(z,p_T^2,Q^2,\nu\right)/N_{e^-}^{DIS}\left(\nu,Q^2\right)\right]_A}{\left[N_h\left(z,p_T^2,Q^2,\nu\right)/N_{e^-}^{DIS}\left(\nu,Q^2\right)\right]_D},$$

- Ratios to DIS and double ratios cancel most of the "initial state effects"
- HERA experiments reached ~2% uncertainty. Mainly driven by acceptance of photon detectors.
- Theory error on QED cross-section negligible for e-p.
  But how about for e-A? how about with polarization?
- van der Meer scans at LHC for pp and p-A reached ~1-3%.

Some physics goals for first-ever jets in e-A

- Precision quark-nucleus interactions with
  “tag and probe” lepton-jet correlations.
- Nuclear tomography with lepton-jet correlations.
- Separate studies of beam and target fragmentation
- Hadronization studies with jet substructure

“Target fragments” are easier to separate in collider mode

- Only in collider mode, the nuclear fragments continue in beam direction
- Cleaner separation from struck quark.

In fixed target mode, the low-z region is dominated by target fragmentation

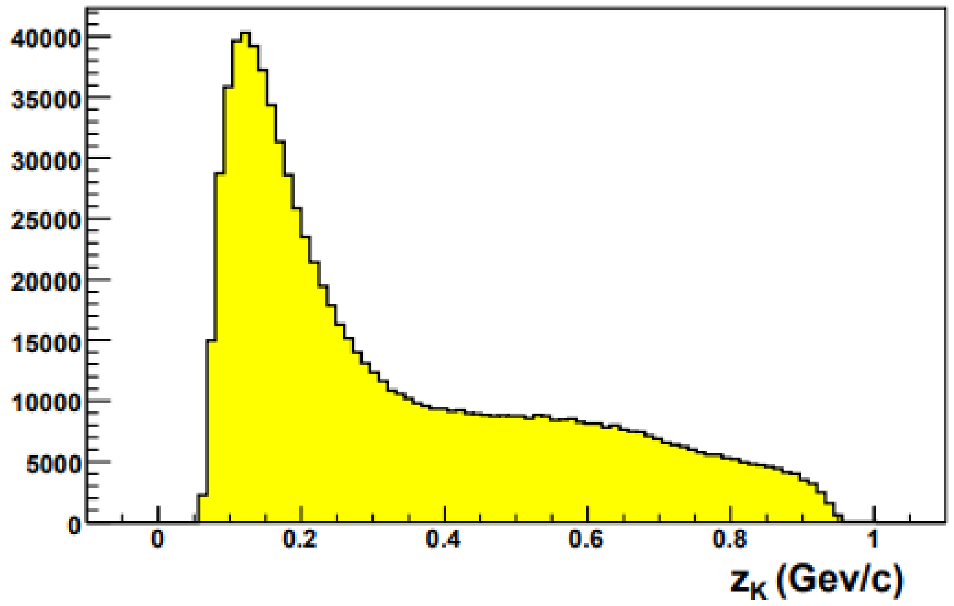


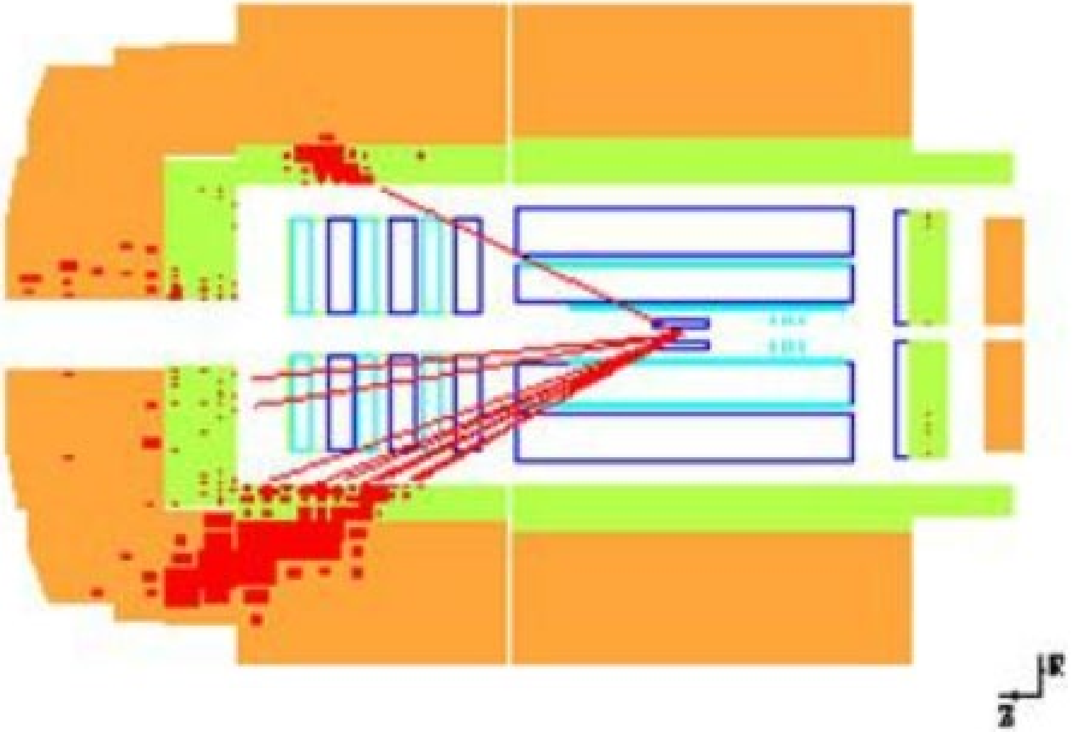
Fig. 13. Upper panel: x versus Q^2 distribution for kaons generated using PEPSI Monte Carlo and accepted in CLAS12. Lower panel: z distribution for kaons generated using PEPSI Monte Carlo and accepted in CLAS12.

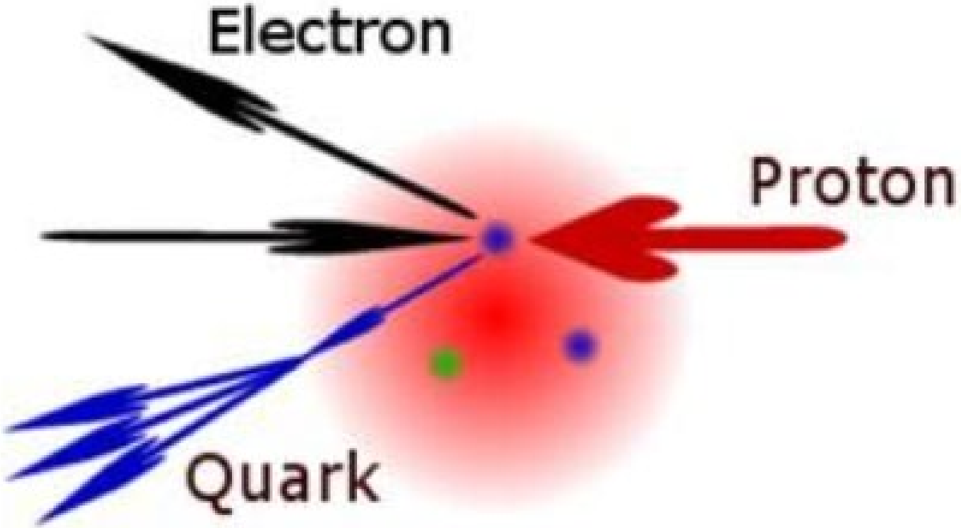
(CLAS12, PR12-09-007)

"For this measurements, we restrict the analysis to the z region between 0.4 and 0.7. *The reason for the lower z cut is to avoid as much as possible the target fragmentation region." (CLAS12, PR12-09-007)*

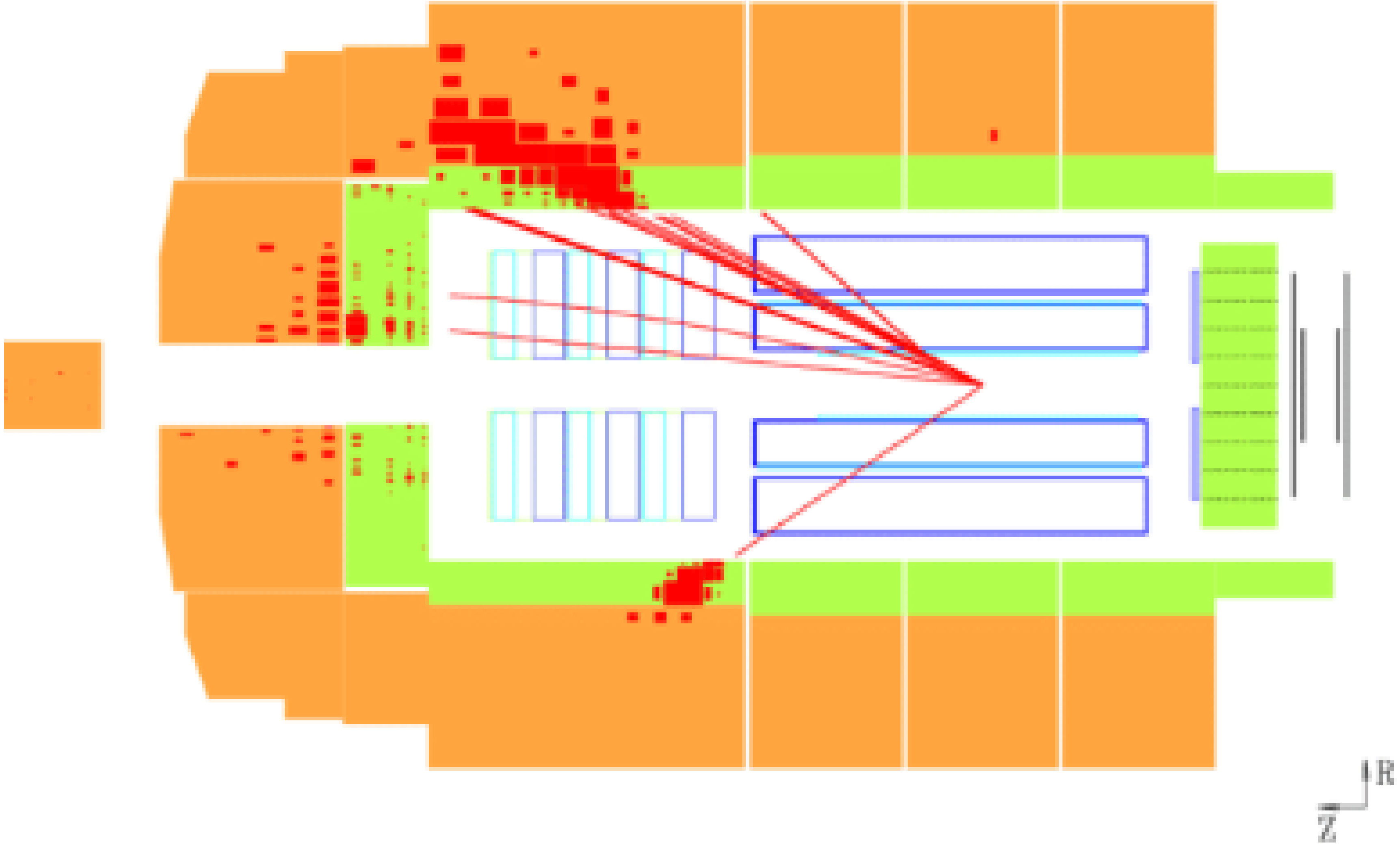
"…z is constrained to 0.2 < z < 0.85. The lower limit avoids the contamination from target fragmentation…" (COMPASS, PLB 767 133-141)

We have all seen these figures:



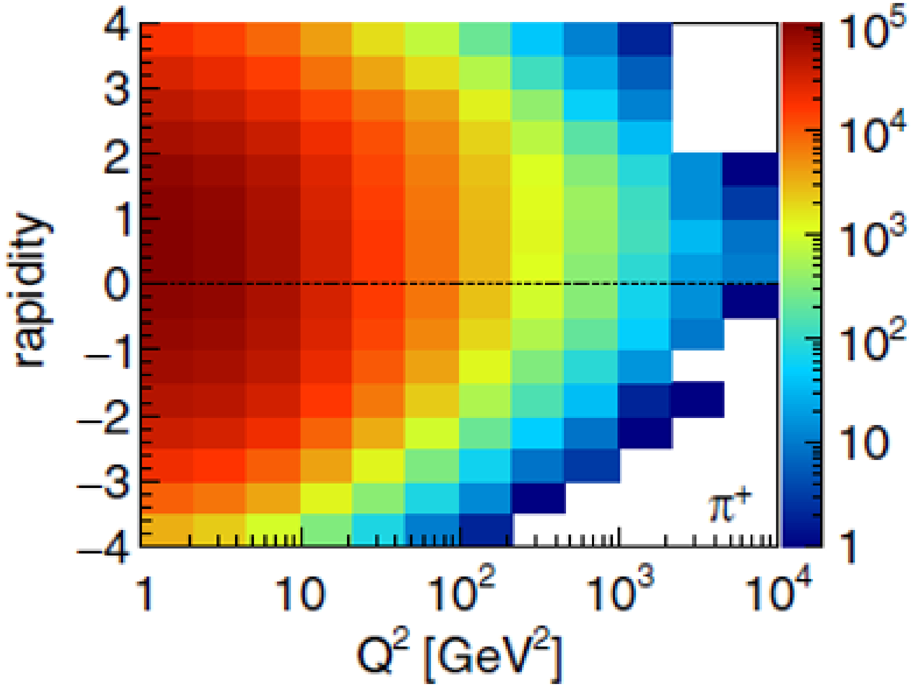


$Q^2 = 16950\ \mathrm{GeV}^2, \quad y = 0.44, \quad M = 196\ \mathrm{GeV}$

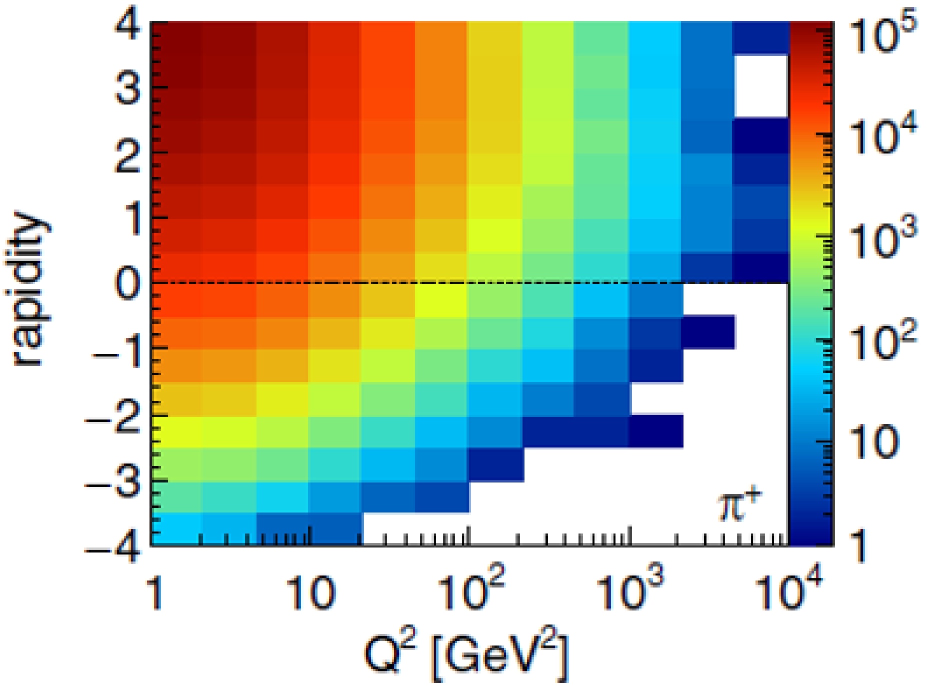


Can we do better than this with jets?

From struck quarks



From beam remnant



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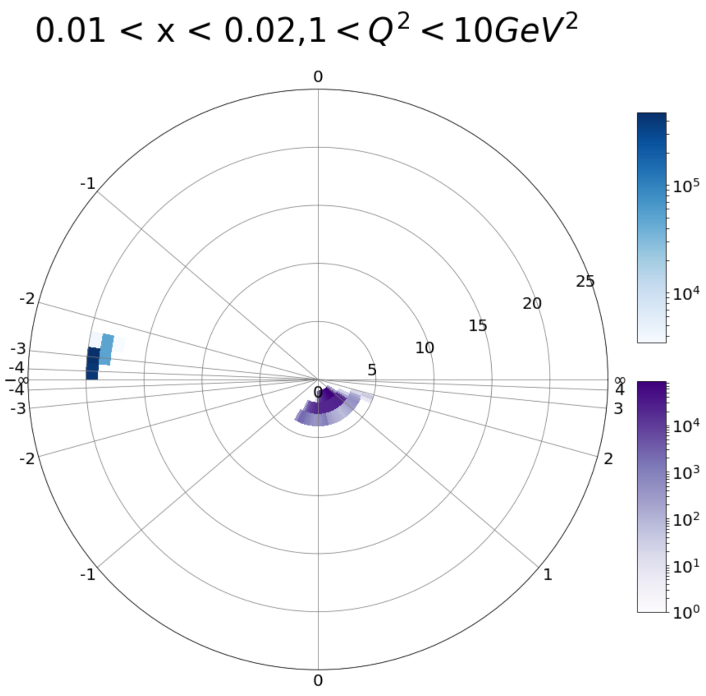
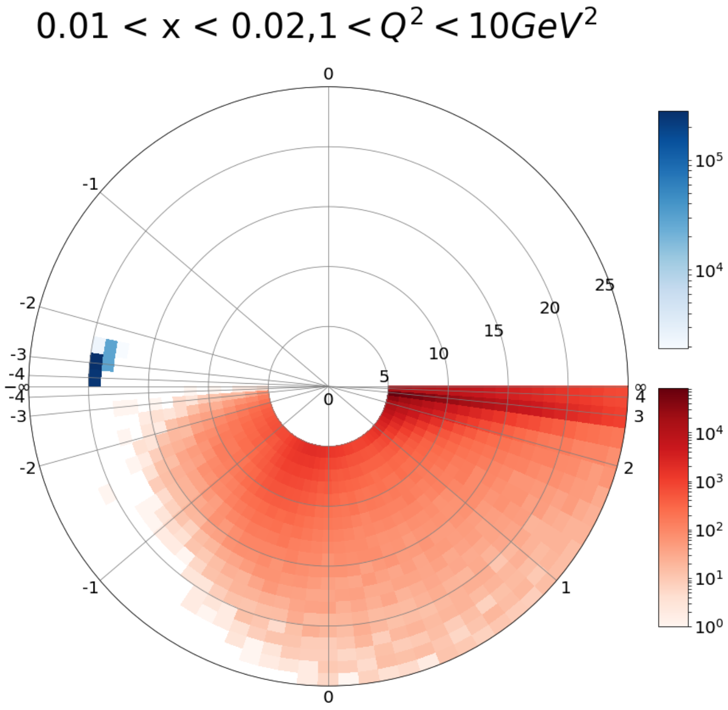
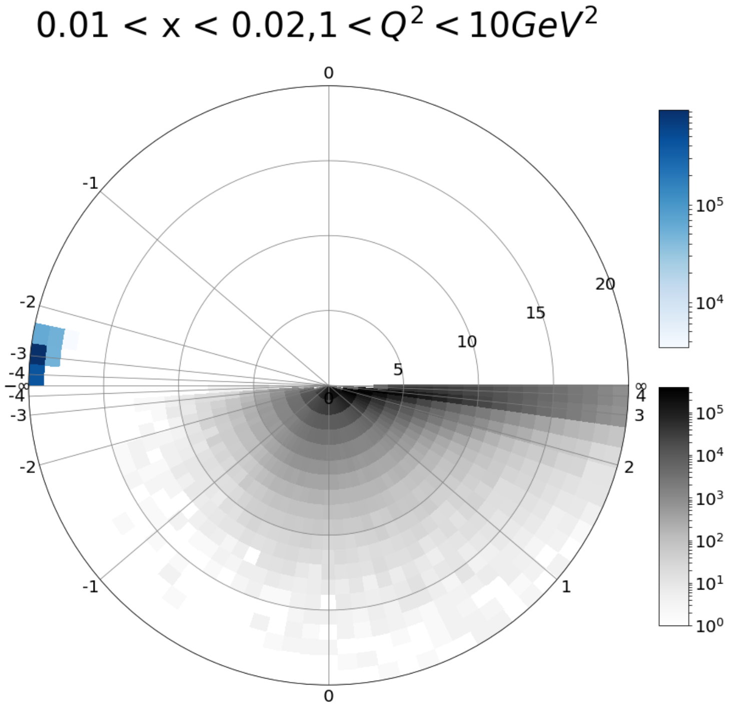
Low-Q2 events are very complicated



Quarks

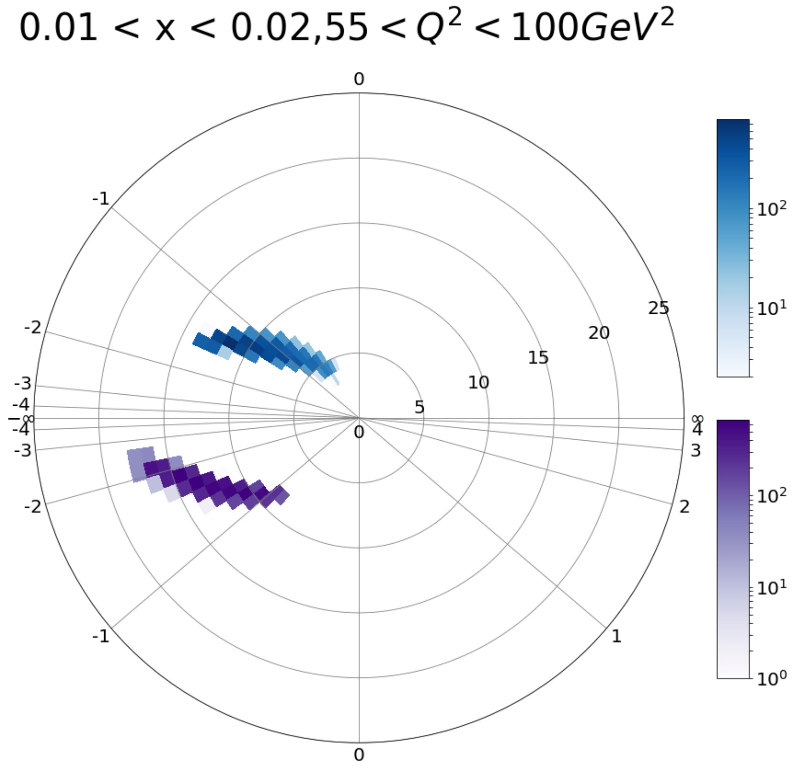


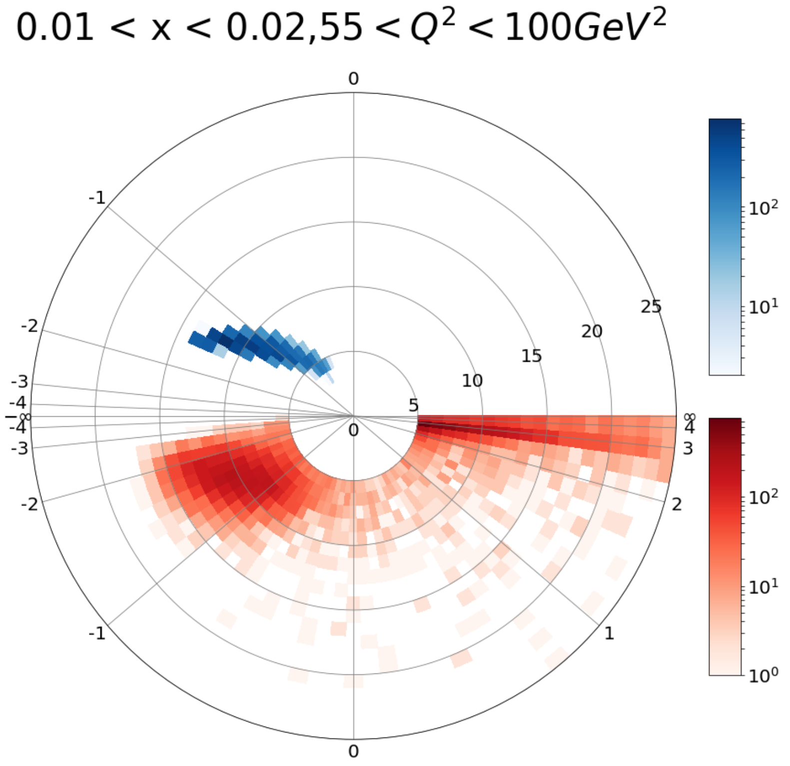
Jets

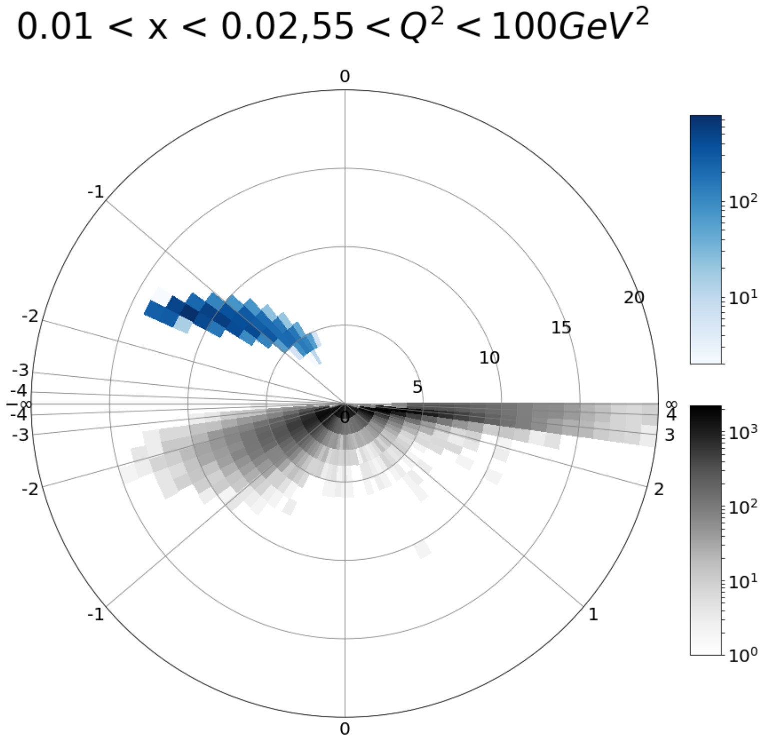


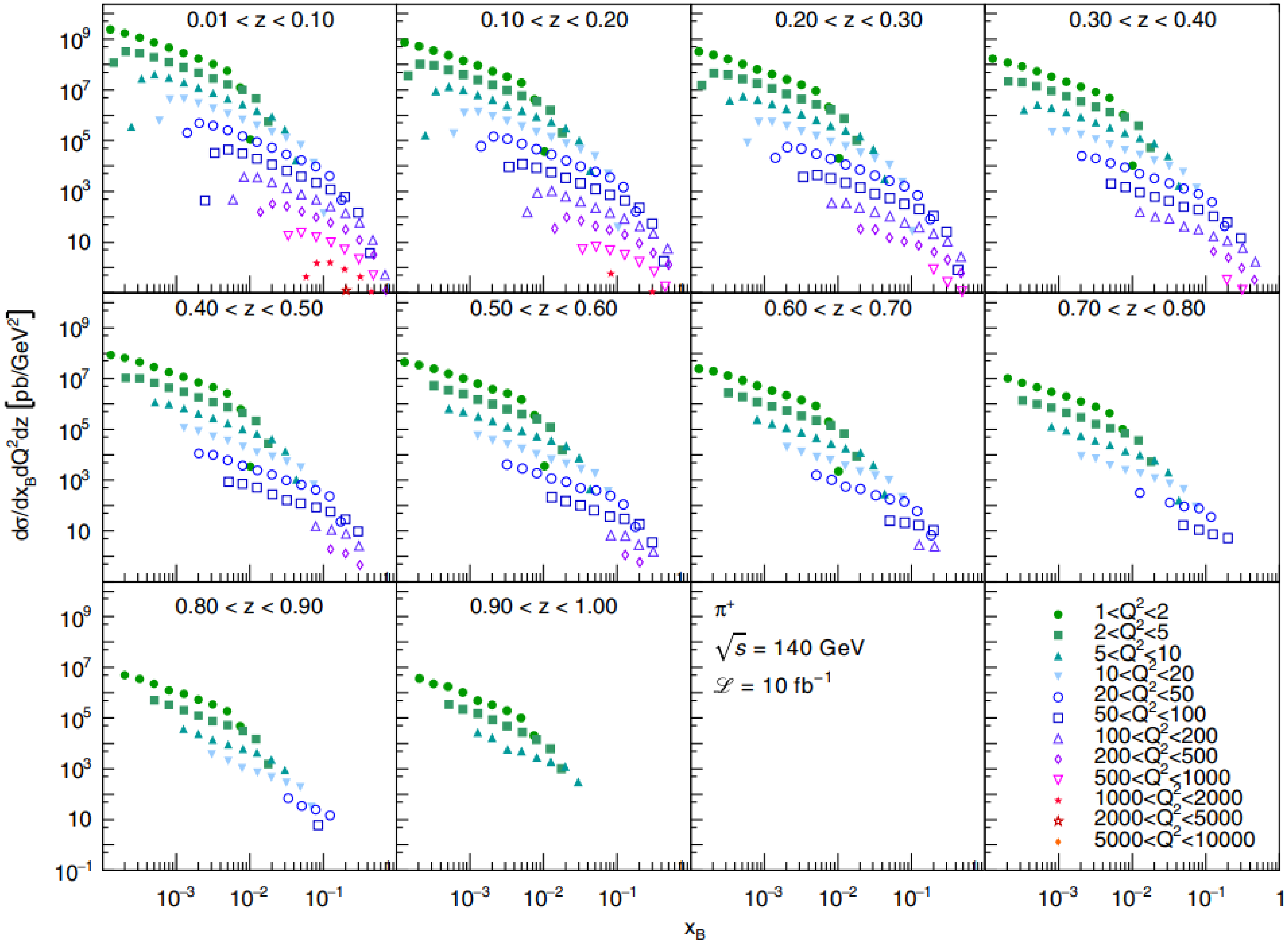
Hadrons

Higher Q2, cleaner separation







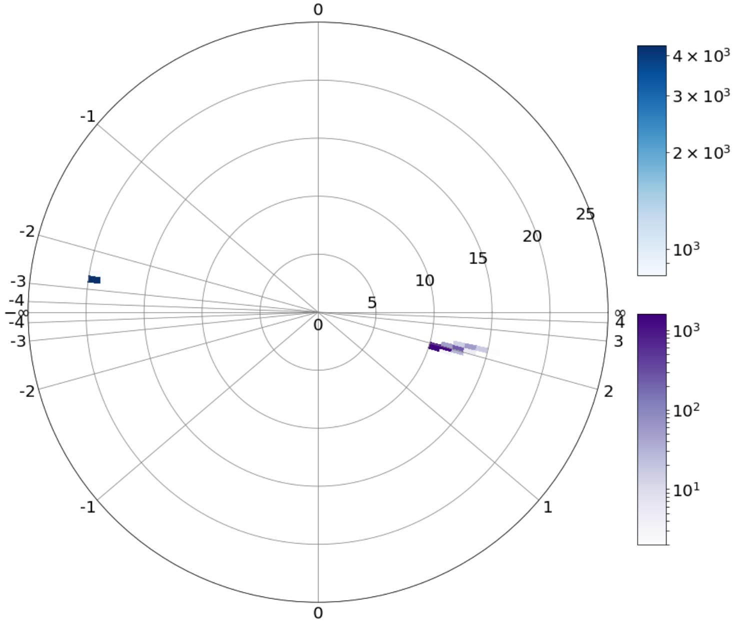


How much of this, which is dominated by low-Q2, is from current fragmentation?

FIG. 7. Differential cross section for pion production at $\sqrt{s} = 140$ GeV as a function of x_B for bins in Q^2 and z measurable at an EIC.

For higher x, it gets more complicated

$0.1 < x < 0.5, 1 < Q^2 < 10 GeV^2$



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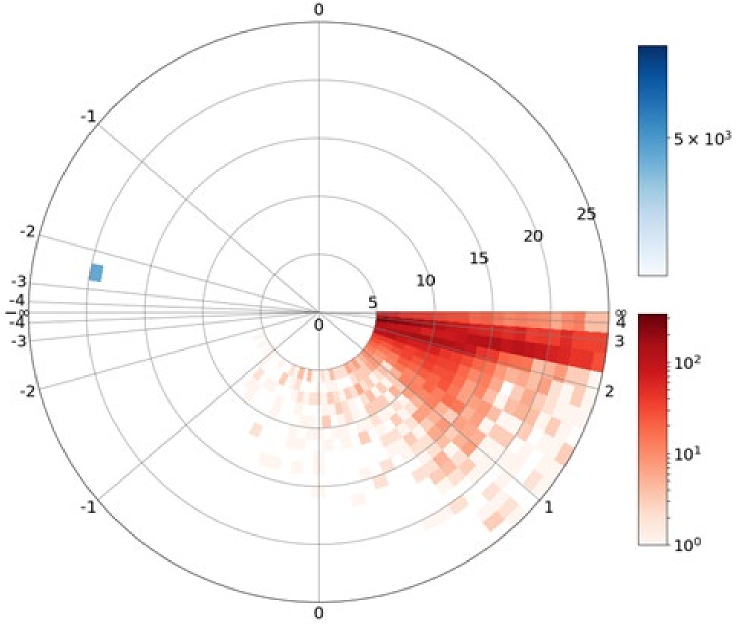

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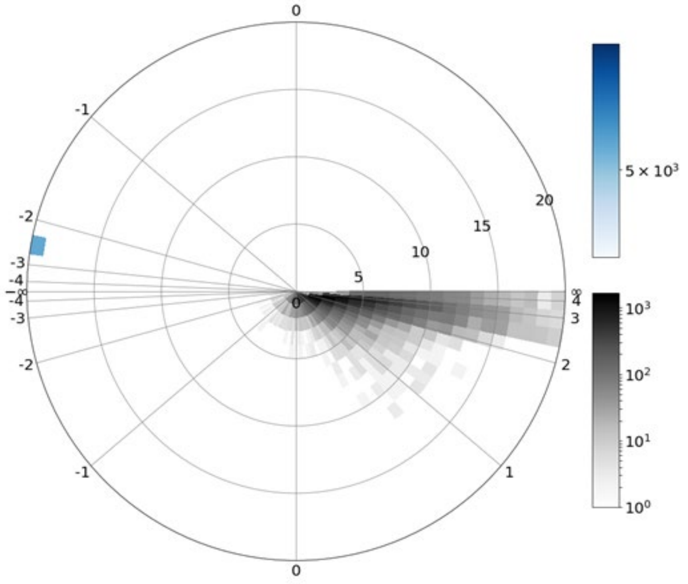
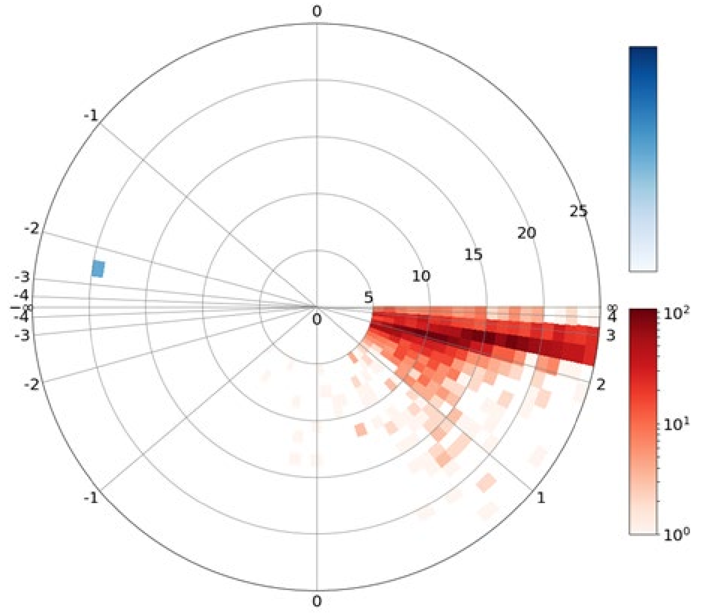
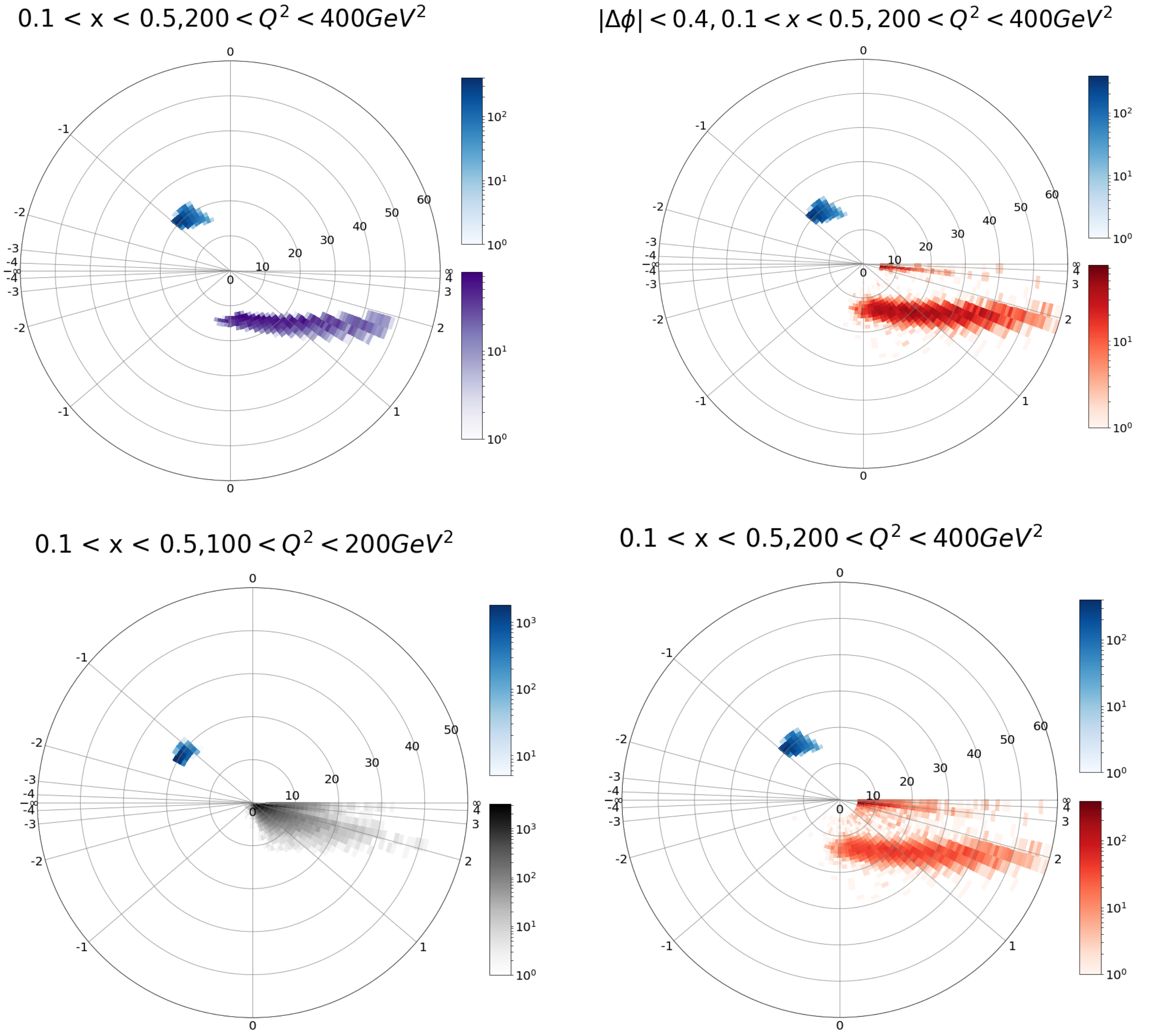


$|\Delta\phi| < 0.4, 0.1 < x < 0.5, 1 < Q^2 < 10 GeV^2$

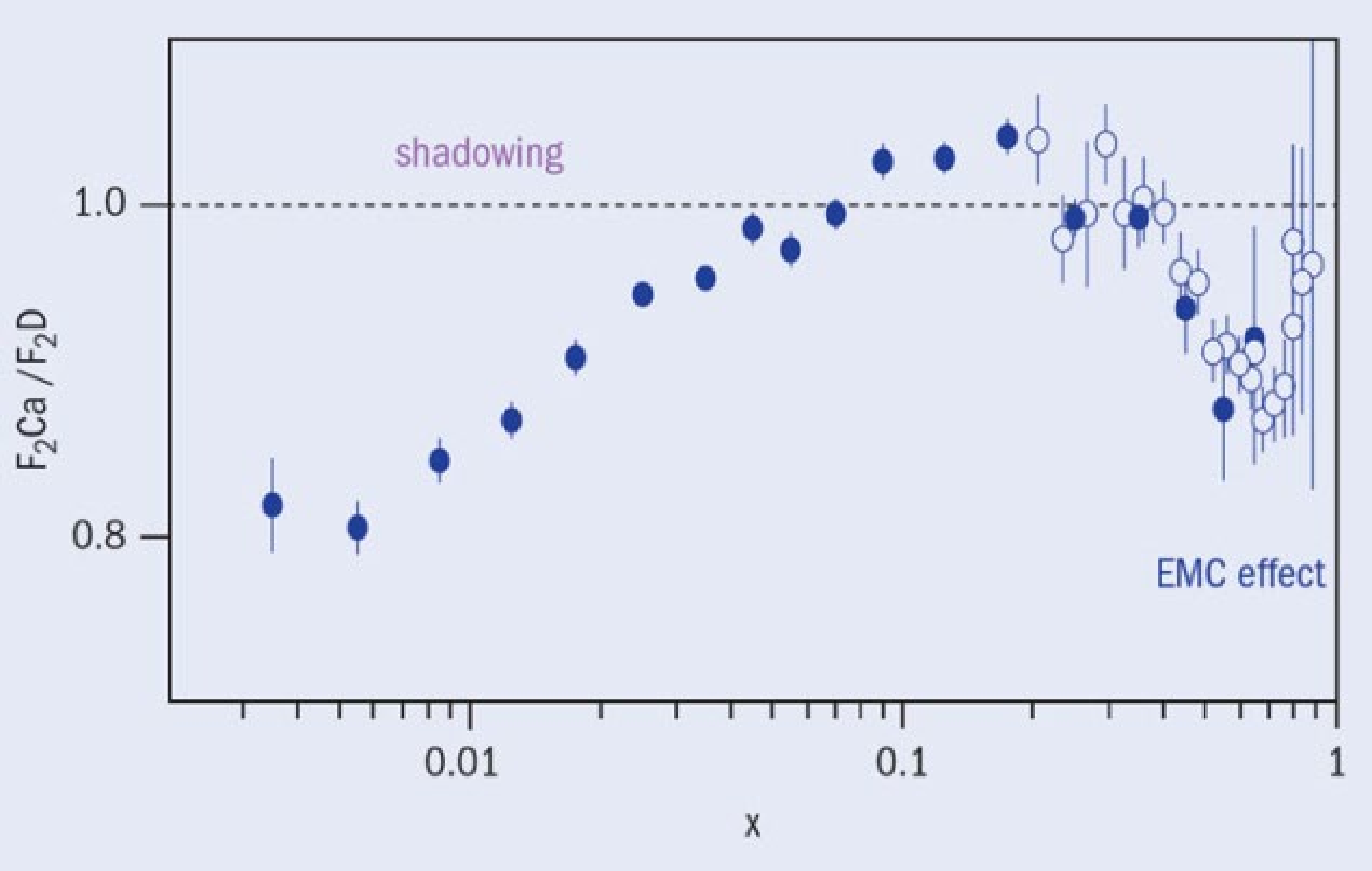


For higher x, it gets more complicated

But still feasible



TMD studies in e-A could add more dimensions to this plot and help explain its origin



- No possible with inclusive DIS
- Jets could bypass fragmentation functions
- Jets can also provide flavor-tagging
- Could also include electron and nucleus polarization.

This entire x range can be covered with jets at the EIC

The “polarized EMC effect”

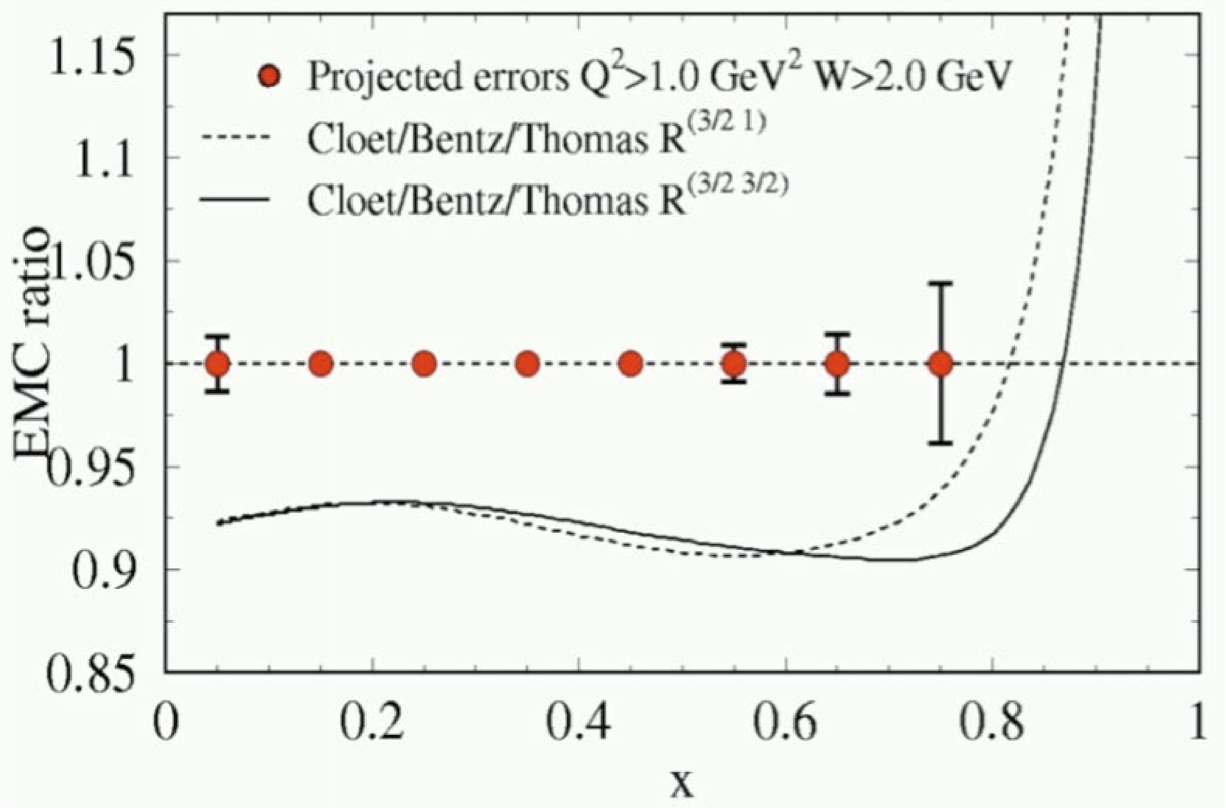


Figure 4: A plot of the polarized EMC effect for an 11 GeV beam, 40% target polarization, 80% beam polarization, and 70 PAC days measured in CLAS12. The two curves are for the two dominant

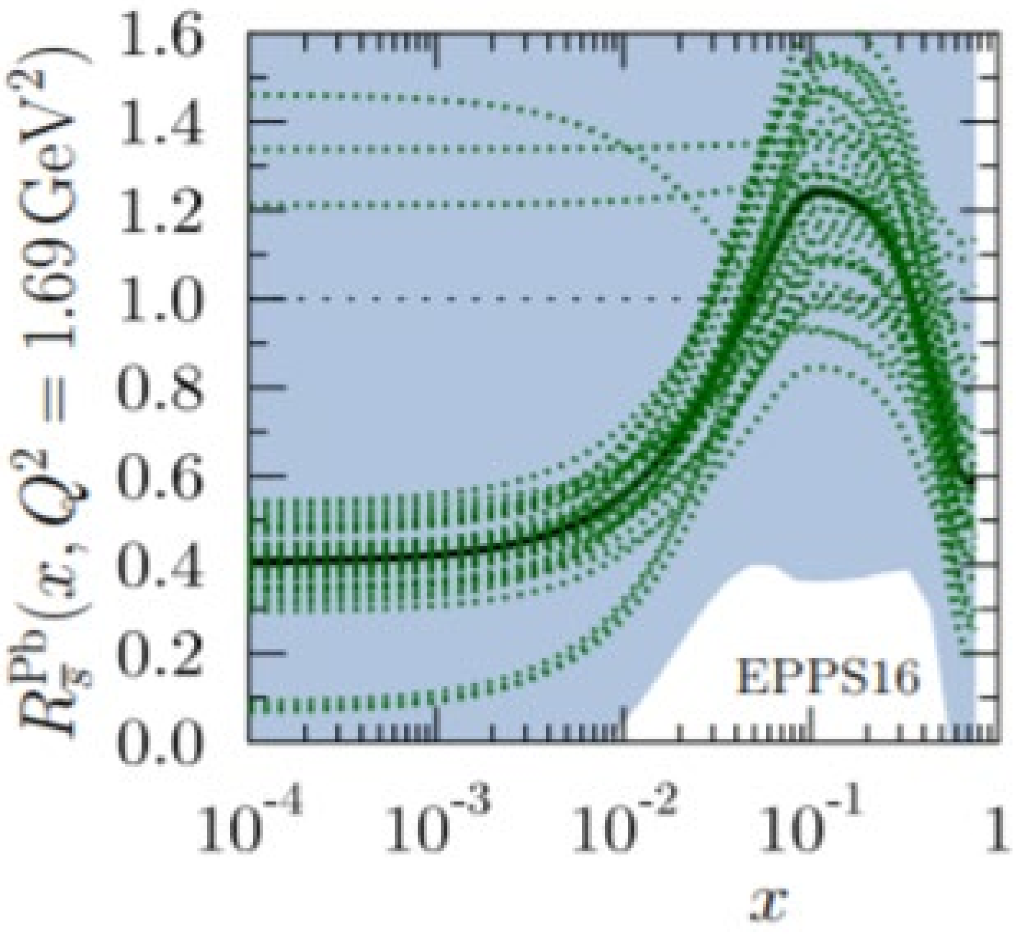
Jefferson Lab Experiment E1214001

The EMC Effect in Spin Structure Functions

- New take on EMC effect with polarized targets and electrons; inclusive DIS.
- Could study the transverse dynamics with jets in polarized SIDIS at the EIC??

Add flavor tagging exploiting PID capabilities, perhaps complementary kinematics to single-hadrons

Strange quark density in nuclei



Why it might be worth while to think about using jets for flavor tagging:

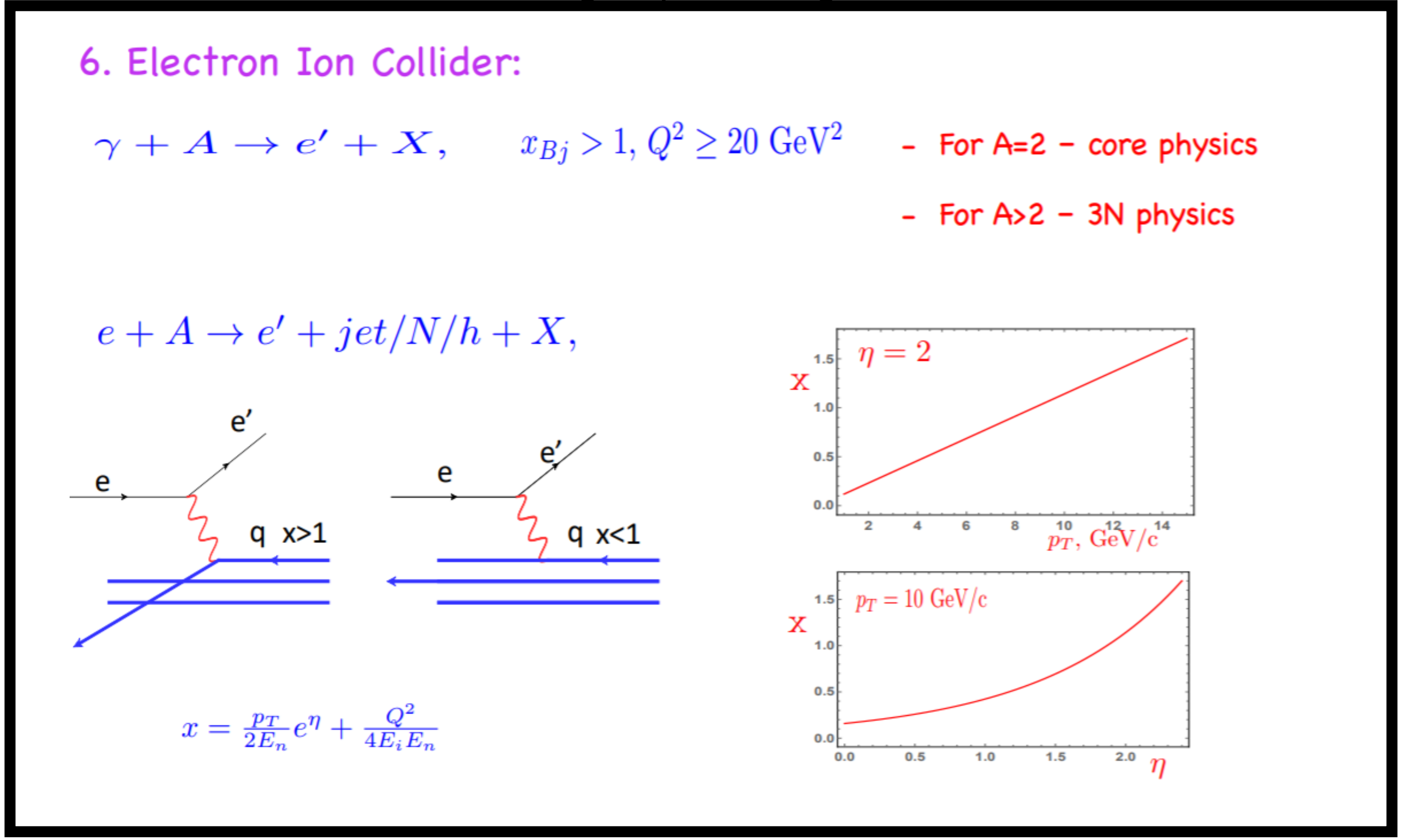
included in global analyses [1,3,4]. An appealing solution to this lack of stringent constraints for the sea quark distributions is to take advantage of data from hadron production in semi-inclusive deep-inelastic scattering (SIDIS), which probe different quark flavor combinations depending on the final-state hadron. The idea, originally proposed by Feynman and Field [5,6], has never been exploited in modern global PDF extractions, since on the one hand, it involves the cumbersome task of a simultaneous PDF and FF extraction [7], and on the other hand, it requires access to semi-inclusive data, of the same precision as the inclusive data. While recent semi-inclusive

PHYSICAL REVIEW D **99,** 094004 (2019)

Semi-inclusive deep-inelastic scattering, parton distributions, and fragmentation functions at a future electron-ion collider

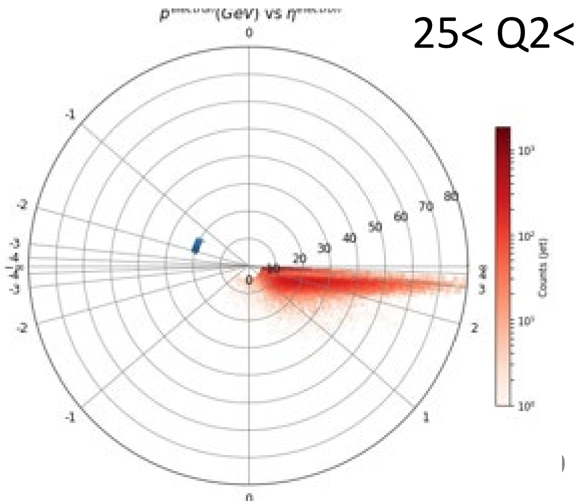
Jets from “Superfast quarks” in e-A?

Slide by M. Sargsian, “Probing high x structure of nuclei with EIC”
EIC Users group meeting, Paris, 2019



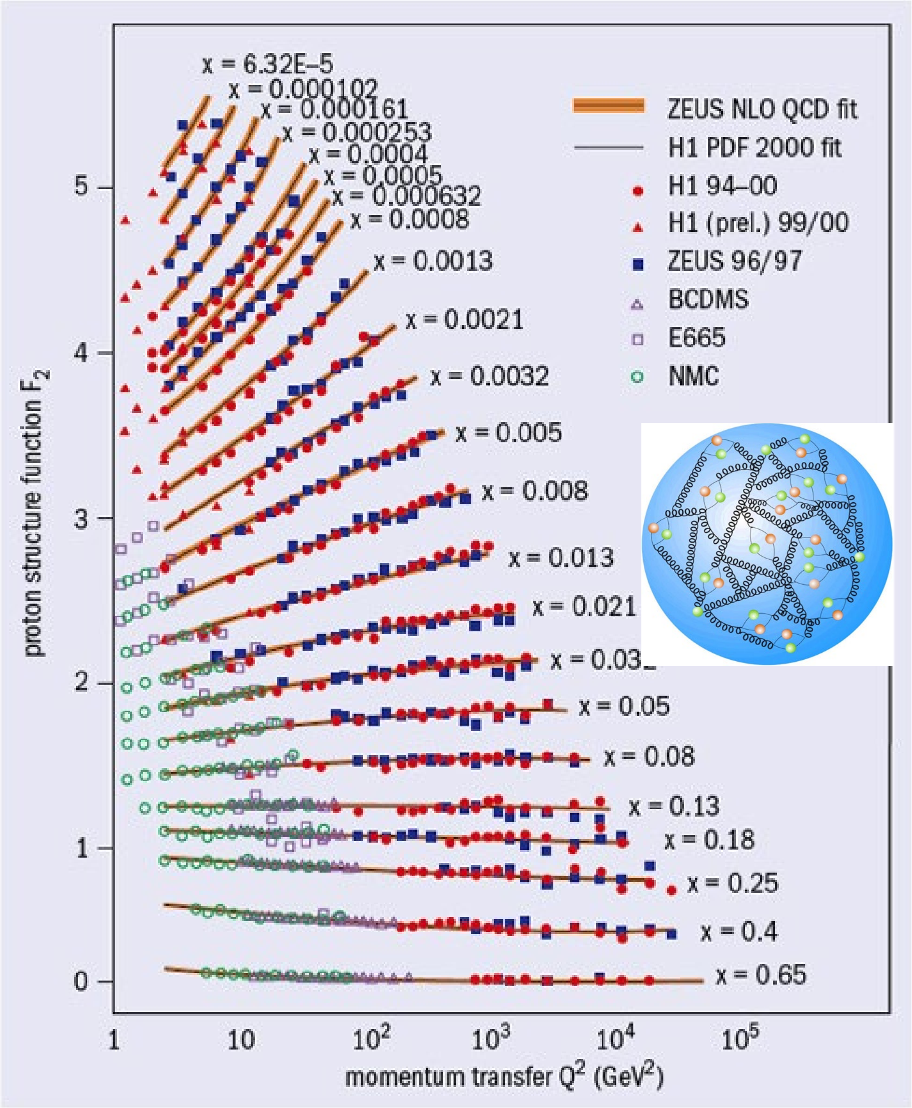
- **Recent development, in connection to short-range correlations**
- **Very challenging kinematics for jet reconstruction at the the EIC.**
- **Perhaps ? Possible at very high Q2.**

X = 0.1,
25< Q2<100



Also: *“Probing superfast quarks in nuclei through dijet production at the LHC”*, A. F M. Sargsian, M. Strikman Eur.Phys.J. C75 (2015) no.11, 534

HERA
The first e-p collider

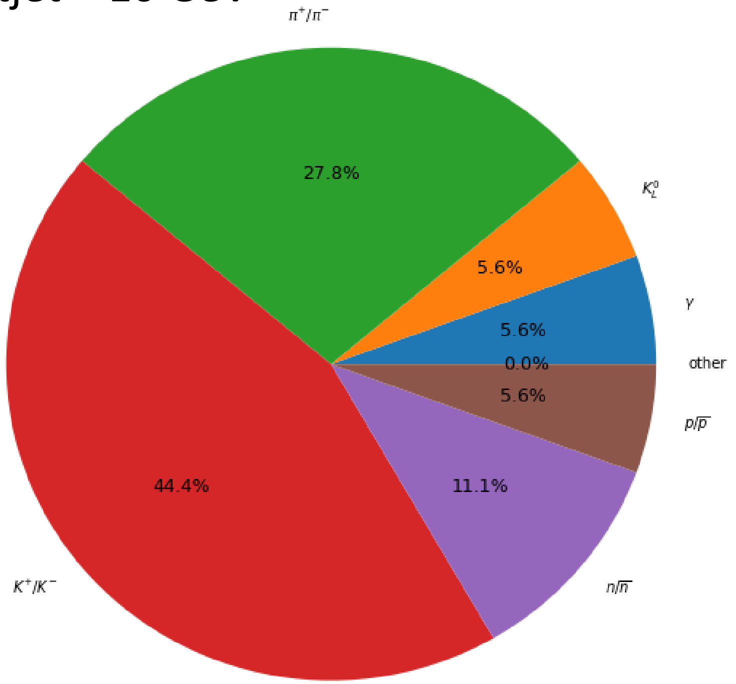


EIC
The first e-A collider

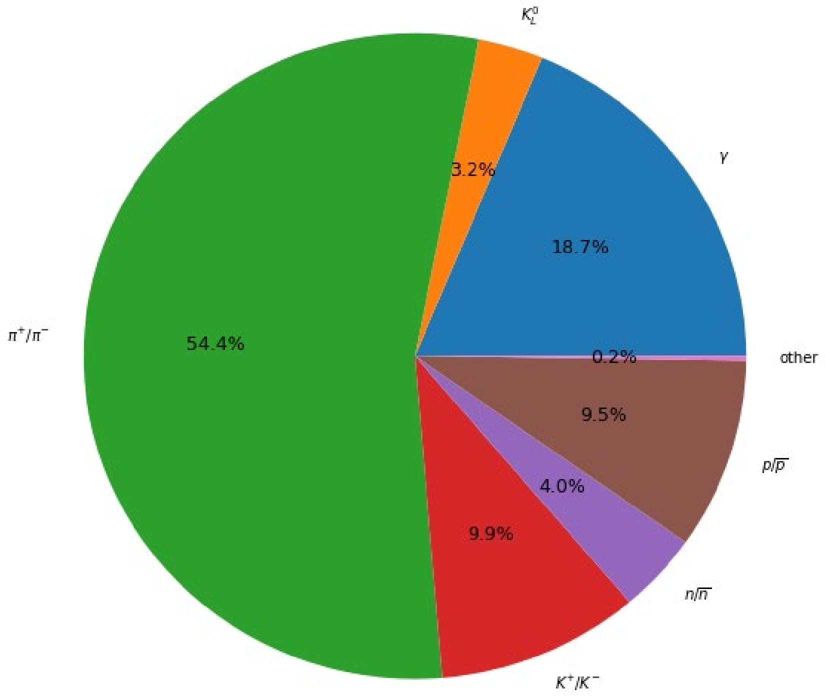
Open field, we should expect surprises!

Strange jets?

Leading particle from strange quark, ptjet = 10 GeV



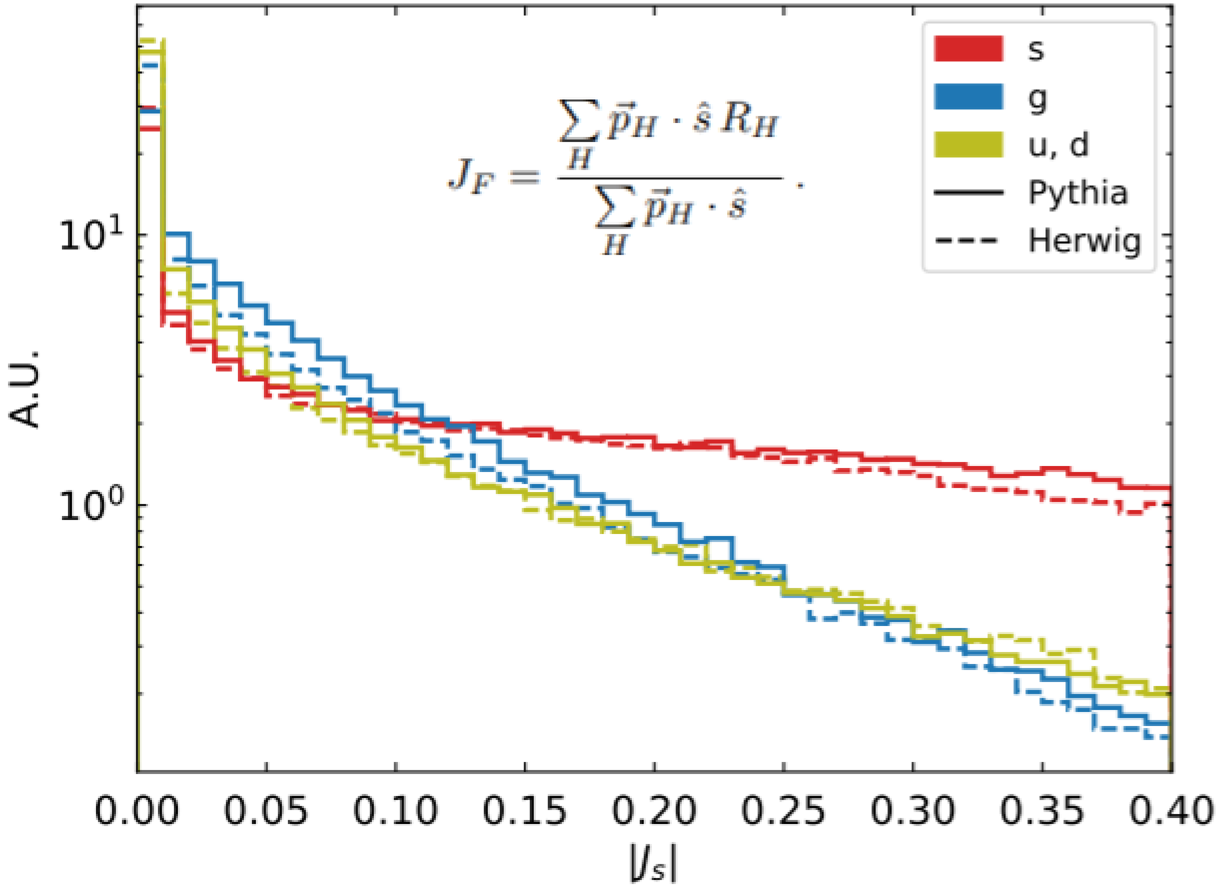
Leading particle from up quark ptjet = 10 GeV



Issues is that “leading Kaon” is not enough for tagging

Strange jets?

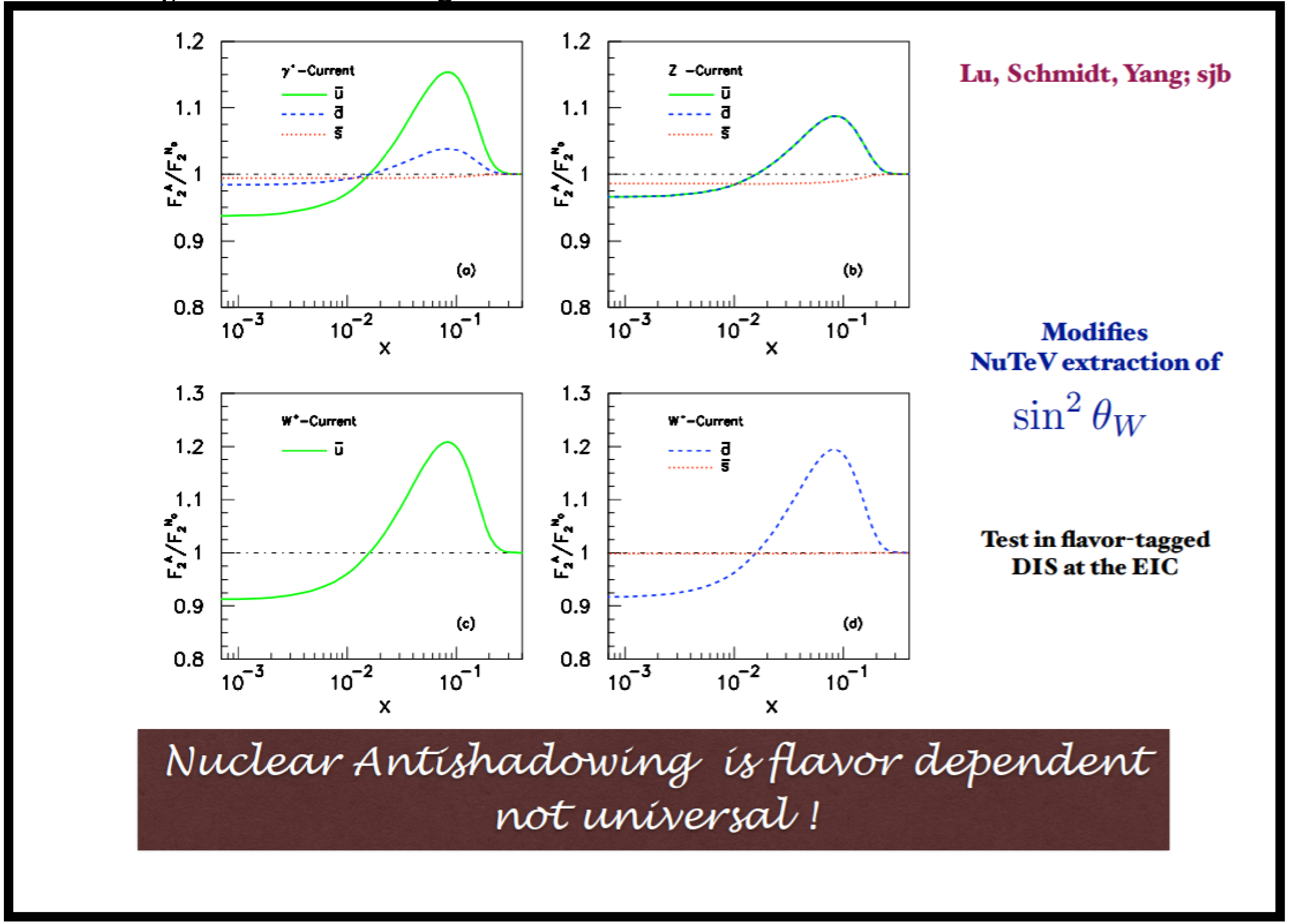
- *"Probing the strange Higgs coupling at lepton colliders using light-jet flavor tagging"* *arXiv:1811.09636v1*
- *"A tagger for strange jets based on tracking information using long short-term memory"* *arXiv:1907.07505*
- *"Deep Learning Strange Jets", Y. Nakai, Machine Learning for Jet Physics, November 2018*



Remember, we have plenty of statistics to spare…

Why would be studying flavor dependent nPDFs be interesting?

S. Brodsky, APS GHP meeting in Denver 2019:



Because one could test models of shadowing/anti-shadowing

S. J. Brodsky, I. Schmidt and J. J. Yang, "Nuclear Antishadowing in Neutrino Deep Inelastic Scattering," Phys. Rev. D 70, 116003 (2004) [arXiv:hep-ph/0409279].

Why would be studying flavor dependent nPDFs be interesting?

Searching for Flavor Dependence in Nuclear Quark Behavior

J. Arrington and N. Fomin
Phys. Rev. Lett. **123**, 042501 – Published 22 July 2019

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ABSTRACT

The observed correlation between the EMC effect and the contribution of short-range correlations (SRCs) in nuclei suggests that the modification of the quark distributions of bound protons and neutrons might occur within SRCs. This raises the possibility that the EMC effect may have an isospin dependence arising from the np dominance of SRCs. We discuss previous attempts to test this

- **Searching for flavor dependence in nuclear modification is also a scientific goal of Solid**

$$a_1 \approx \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\frac{u_A^+ - d_A^+}{u_A^+ + d_A^+},$$