Jets in e-A at the EIC, an experimental viewpoint

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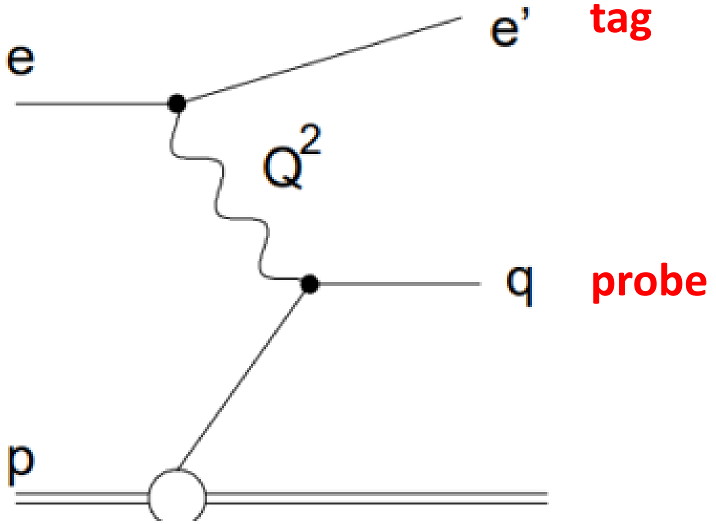
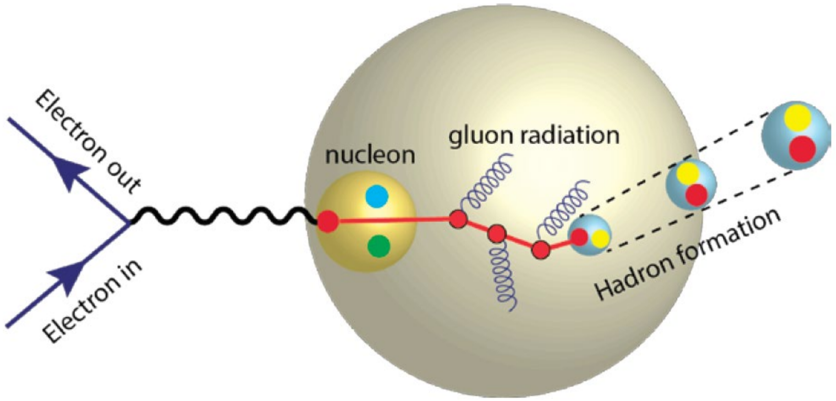
Outline

- Breit frame or not Breit frame
- Target vs current fragmentation at EIC, the case for jets
- Observables: lepton-jet correlations
- Experimental considerations

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

DIS Feynman diagrams

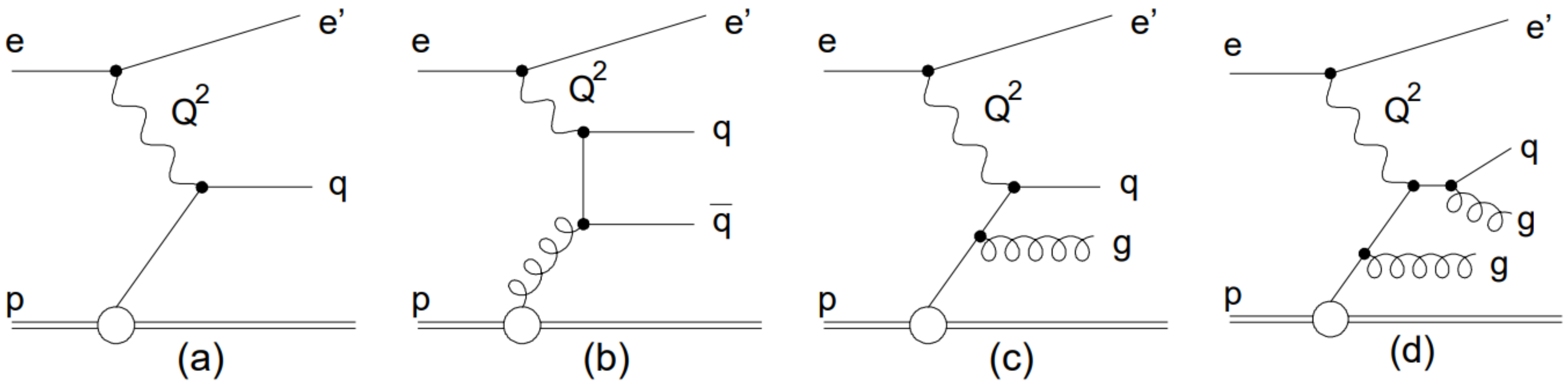
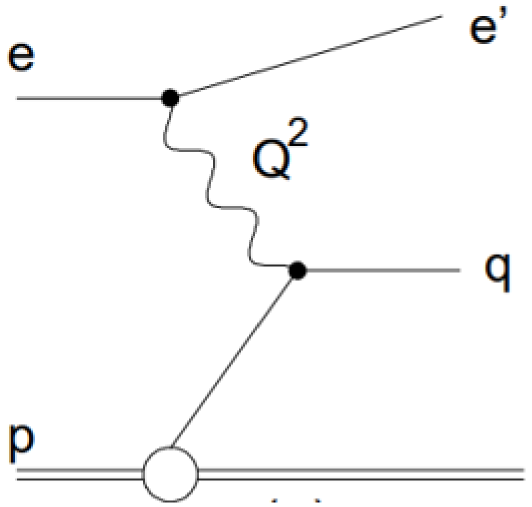
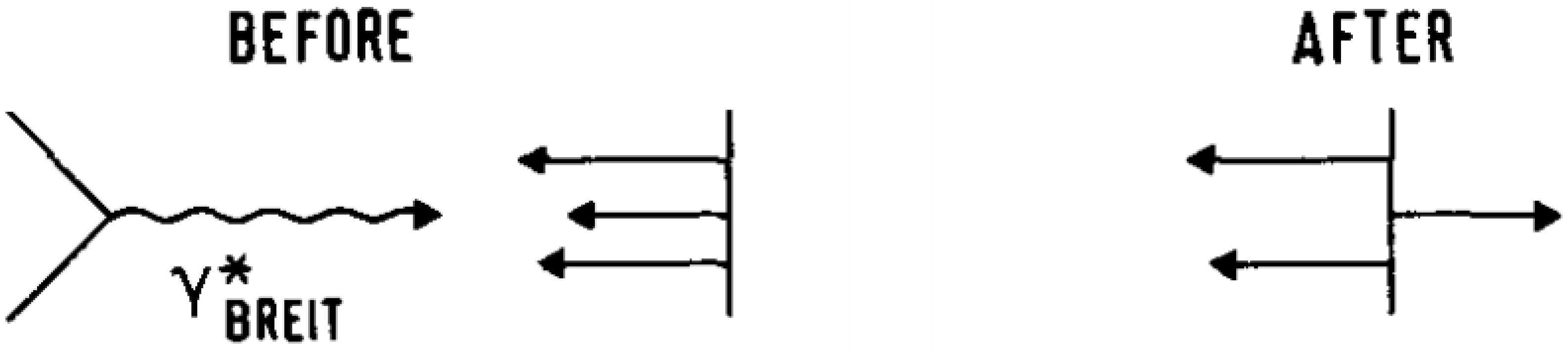


Figure 1: Deep-inelastic *ep* scattering at different orders in α_s: (a) Born contribution to inclusive NC DIS ($\mathcal{O}(\alpha_{\mathrm{em}}^2)$), (b) photon-gluon fusion ($\mathcal{O}(\alpha_{\mathrm{em}}^2\alpha_s)$), (c) QCD Compton scattering ($\mathcal{O}(\alpha_{\mathrm{em}}^2\alpha_s)$) and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

- If you want to be sensitive to alpha and/or are interested in gluon densities, then you would want the higher-order diagrams. The LO diagram would your background. <u>This was the case for HERA experiments.</u>

Jets in Breit frame, leading order:

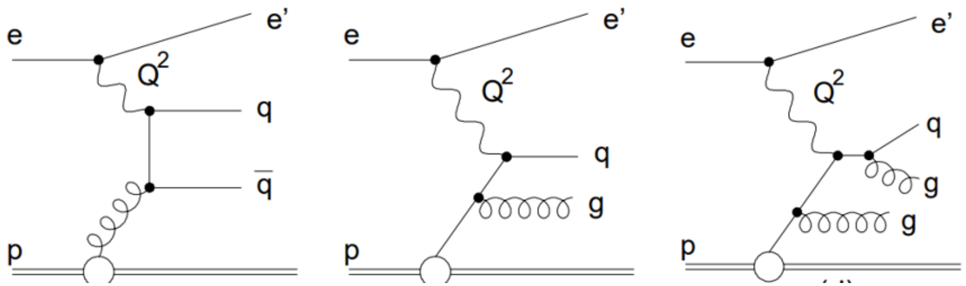




This jet has 0 transverse momentum in this frame (if masses and intrinsic kT are neglected)

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

Jets in Breit frame, higher-order processes



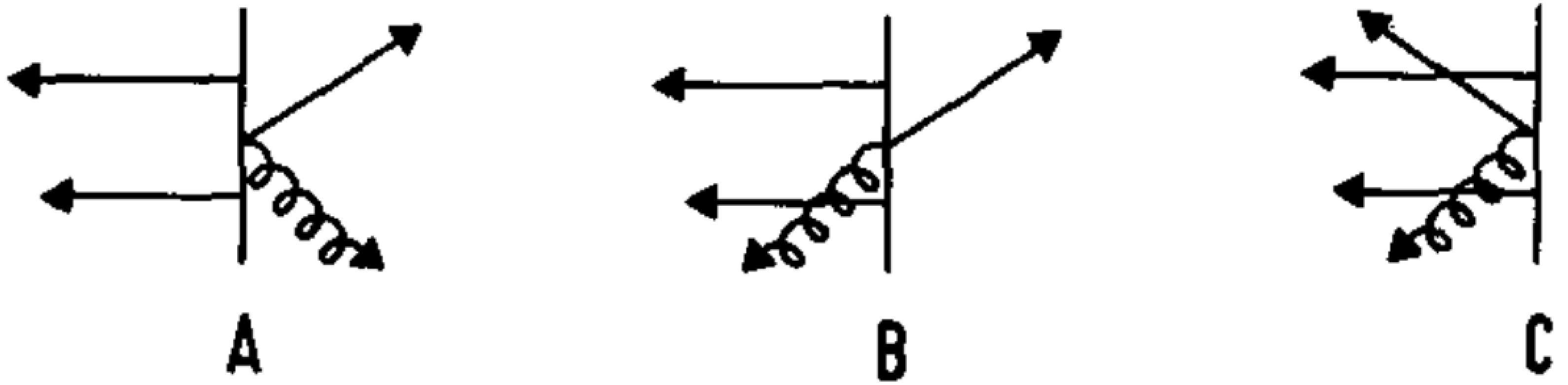


Fig. 3. Quark and gluon configurations after the absorption of the virtual photon in the Breit frame

These jets (dijets) can have large pT in this frame

Zeitschrift für Physik C Particles and Fields
September 1979, Volume 2, Issue 3, pp 237–242 | Cite as

Quark and gluon jets in the breit frame of lepton-nucleon scattering

Authors Authors and affiliations

K. H. Streng, T. F. Walsh, P. M. Zerwas

"A direct proof in high-energy experiments for the existing of the building blocks of the theory, quarks and gluons, does not (yet) exist"

"Assuming that gluons reveal themselves a jets we have shown in the preceding paragraphs that the Breit frame analysis of deep inelastic lepton-nucleon scattering is expected to provide ***clean signatures of hard gluon bremsstrahlung and quark pair production out of gluons****"*

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.

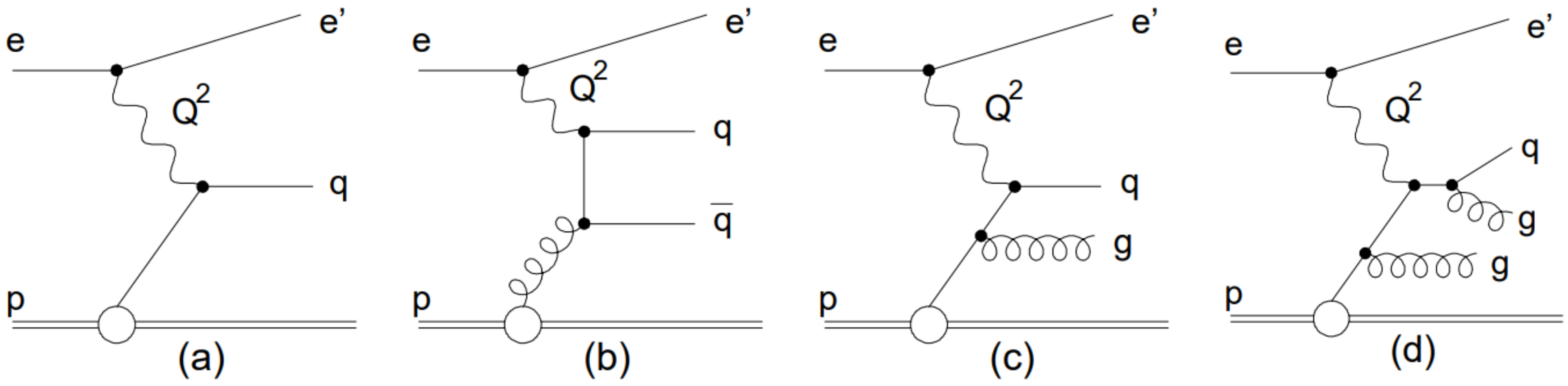
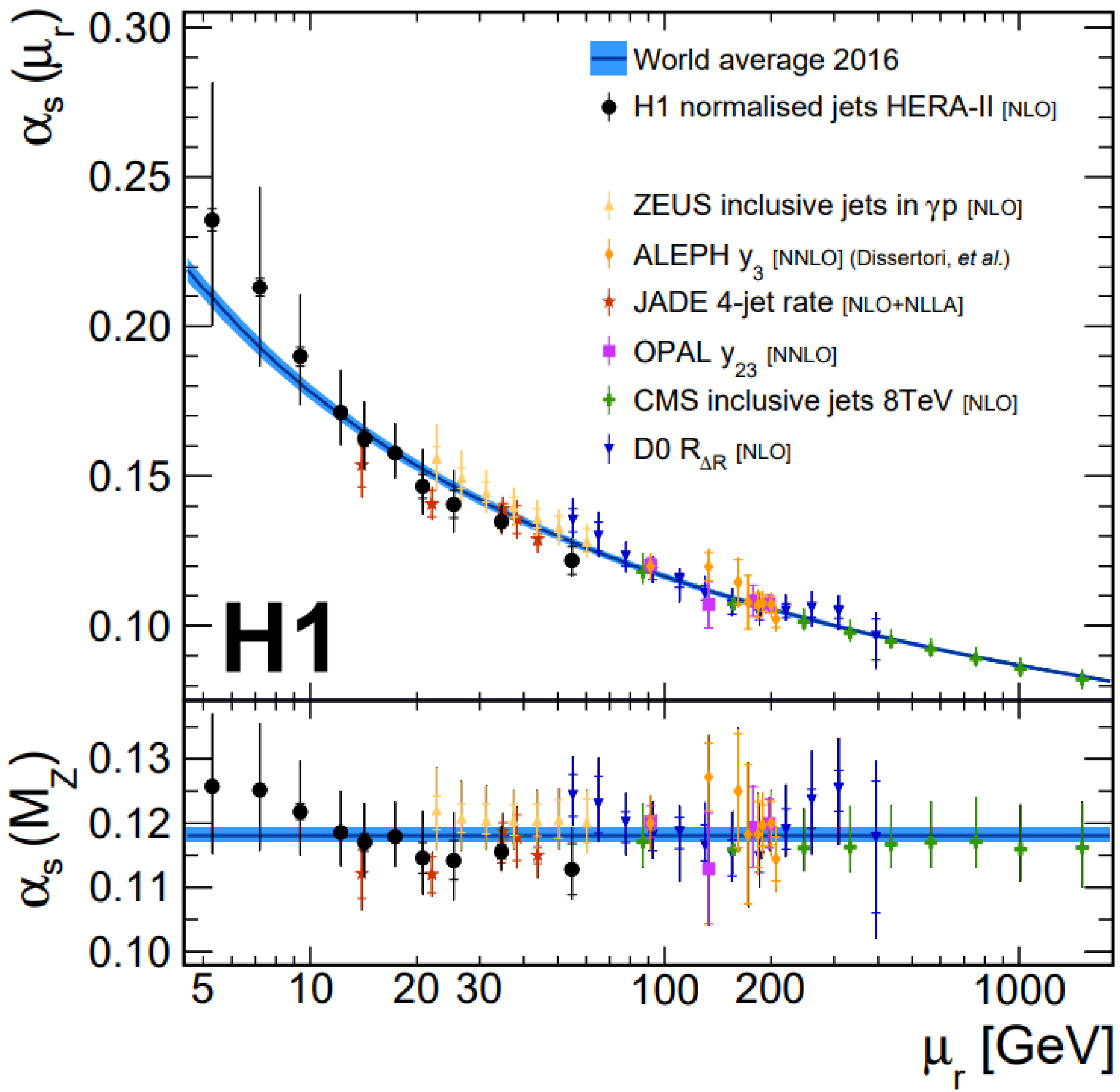


Figure 1: Deep-inelastic ep scattering at different orders in α_s: (a) Born contribution to inclusive NC DIS ($\mathcal{O}(\alpha_{\rm em}^2)$), (b) photon-gluon fusion ($\mathcal{O}(\alpha_{\rm em}^2\alpha_s)$), (c) QCD Compton scattering ($\mathcal{O}(\alpha_{\rm em}^2\alpha_s)$) and (d) a trijet process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



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

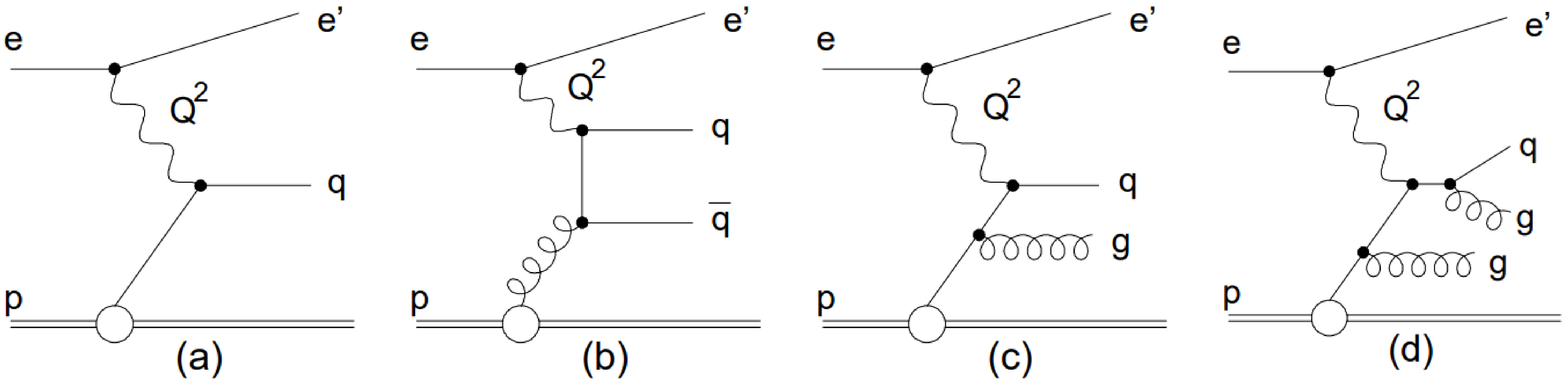
For using jets as precision tool at the EIC, we want the opposite

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 exactly the opposite than HERA did: 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).
  Coupled by the fact that EIC luminosity will be x1000 HERA, which was already large, you get enormous data samples.
- It is not a trivial matter, in HERA experiments jet pT < ~4 GeV (in Breit Frame) where simply not reported. Need high pT in a given frame to provide perturbative scale for pQCD calculations.

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,

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

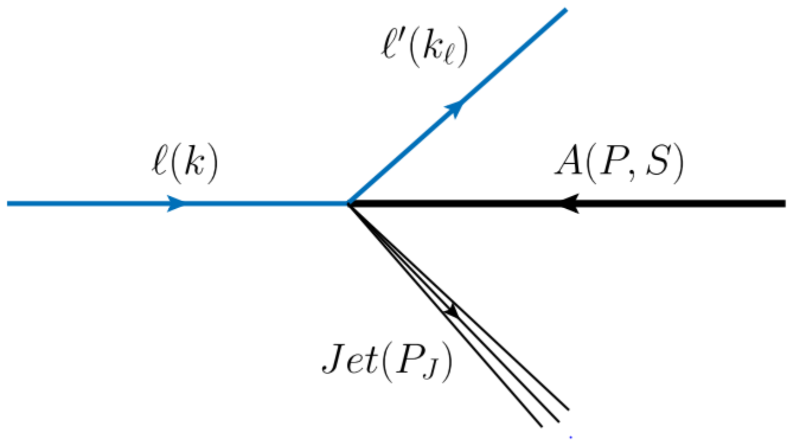


FIG. 1. Lepton-jet correlation for the tomography of the nucleon or nucleus at the EIC.

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

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

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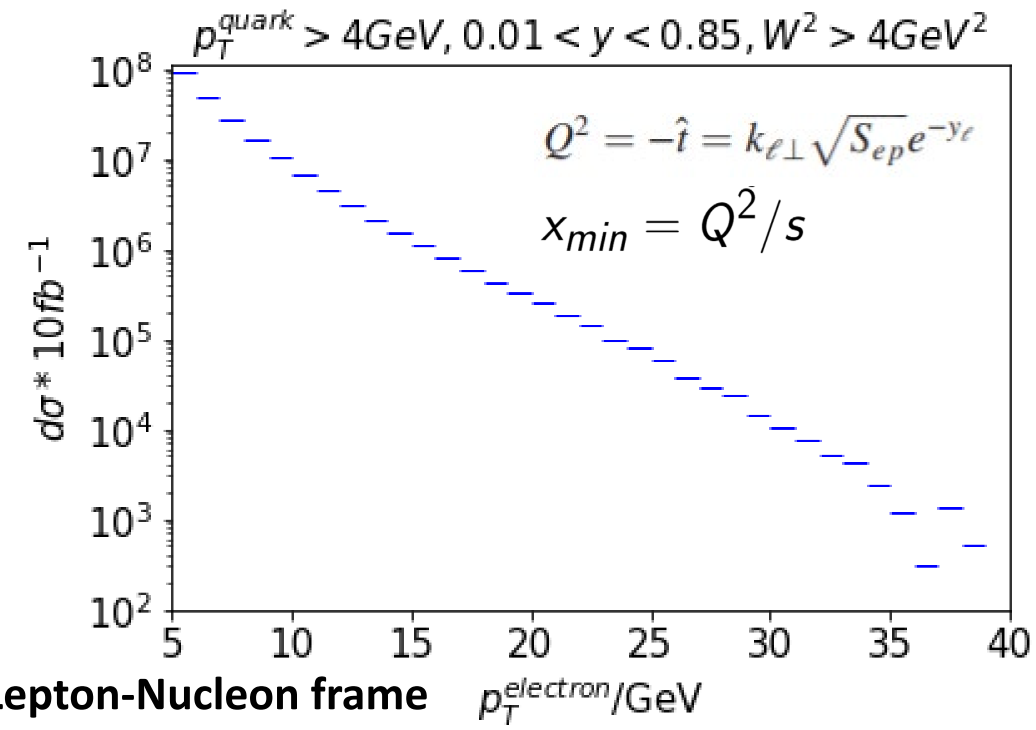
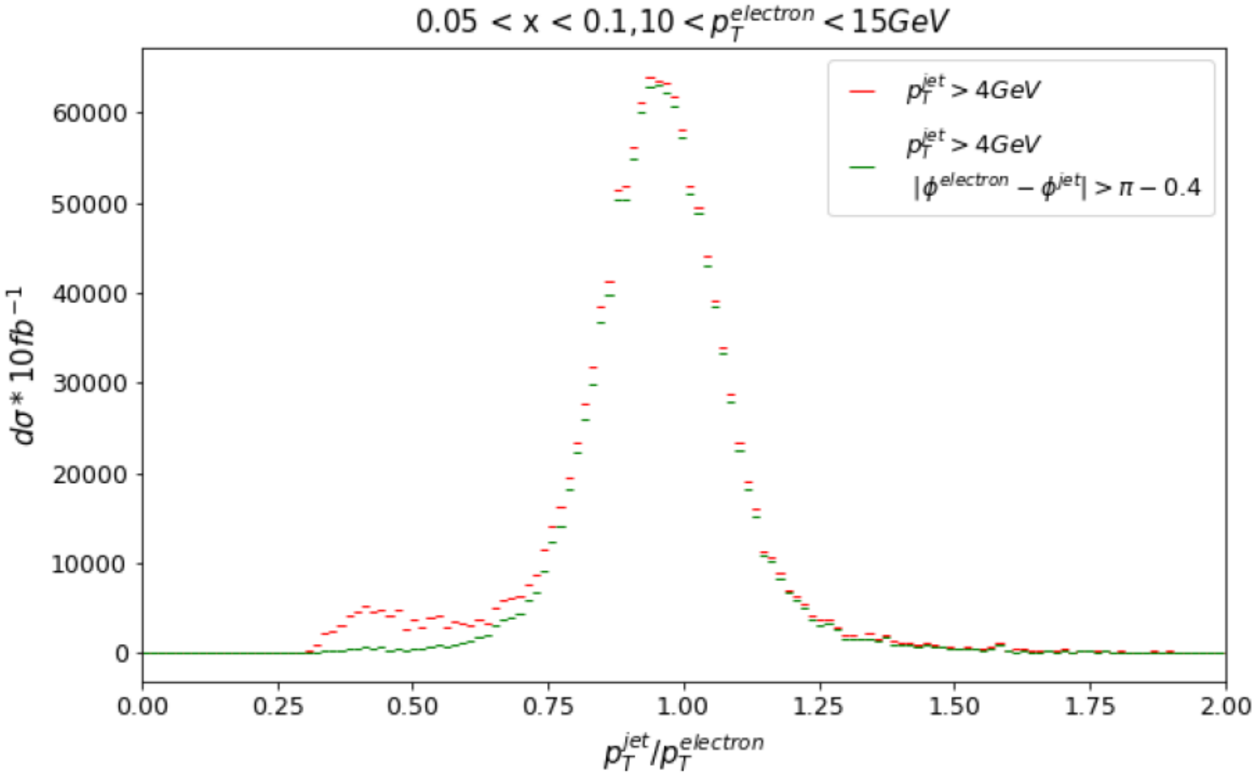
Lepton jet correlations, for e-A cold matter studies

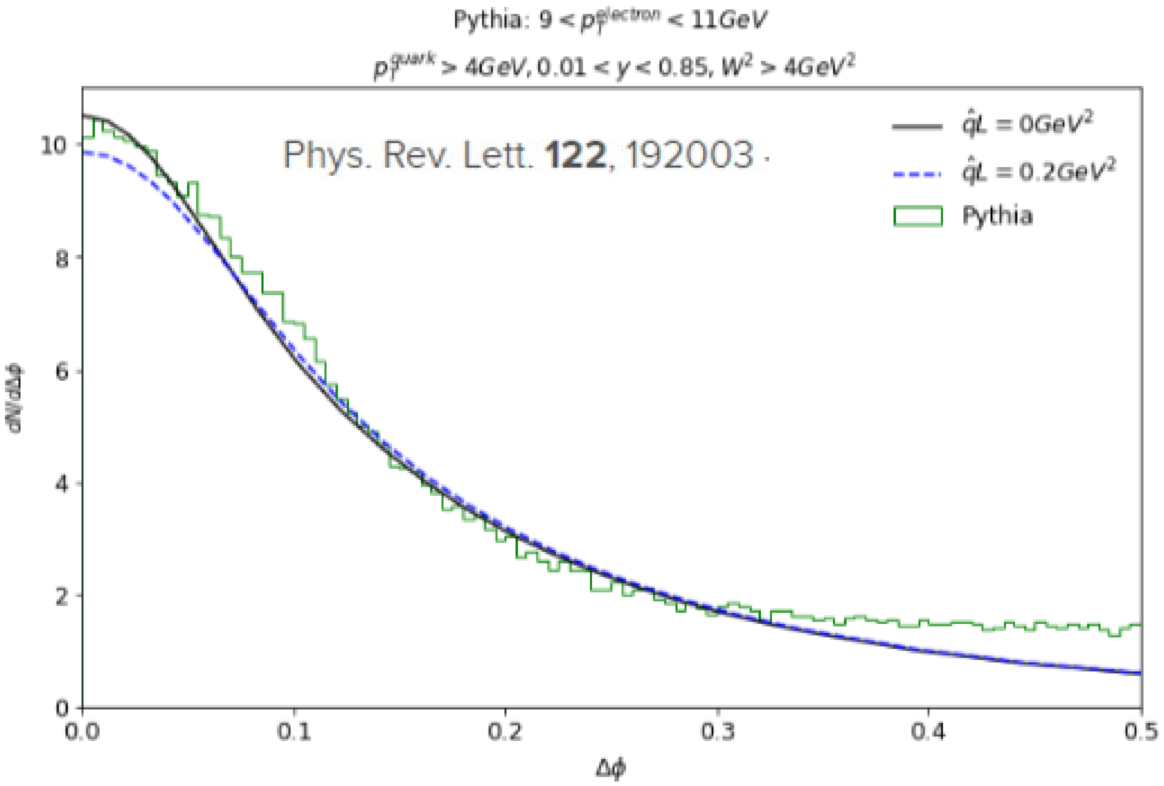


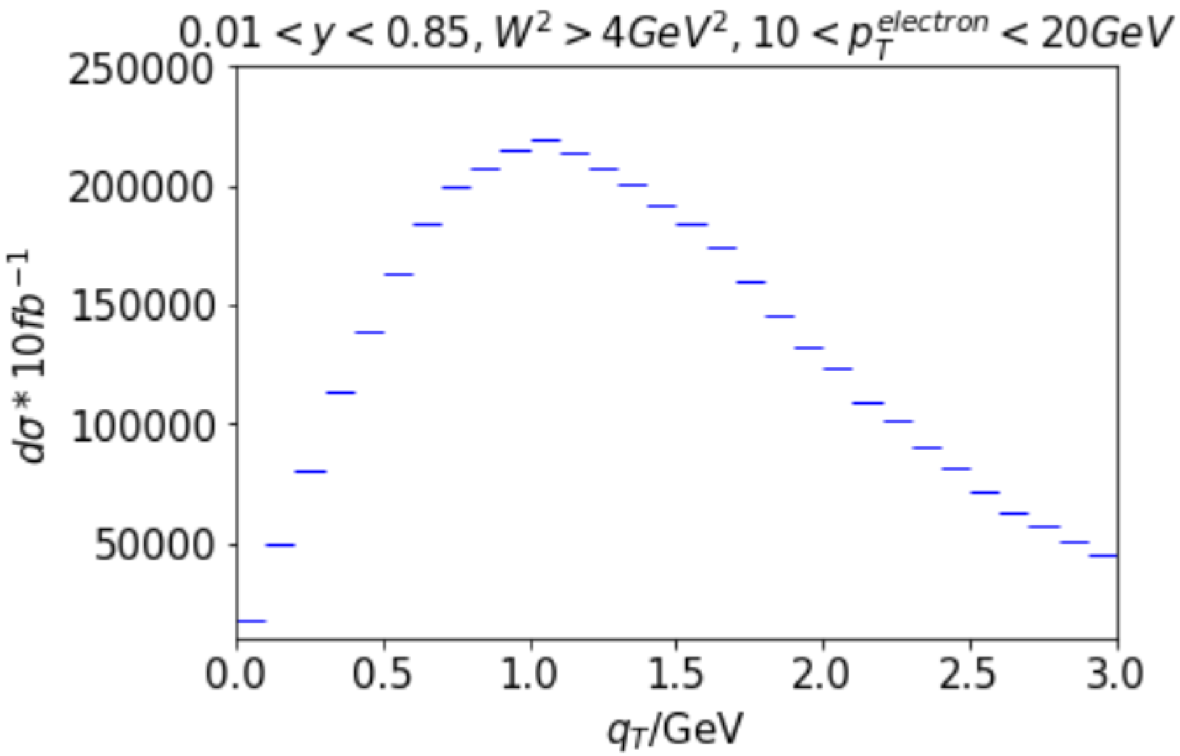
Lepton-Nucleon frame



- 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 $|\vec{k}_{\ell\perp} + \vec{P}_{J\perp}|$

- Azimuthal angle measurement preferred over qT, which requires jet energy measurement

Note, same observable is interesting for TMD studies (e-p)

"Probing Transverse-Momentum Distributions With Groomed Jets"
JHEP 1908 (2019) 161 , Daniel Gutierrez-Reyes etl a.

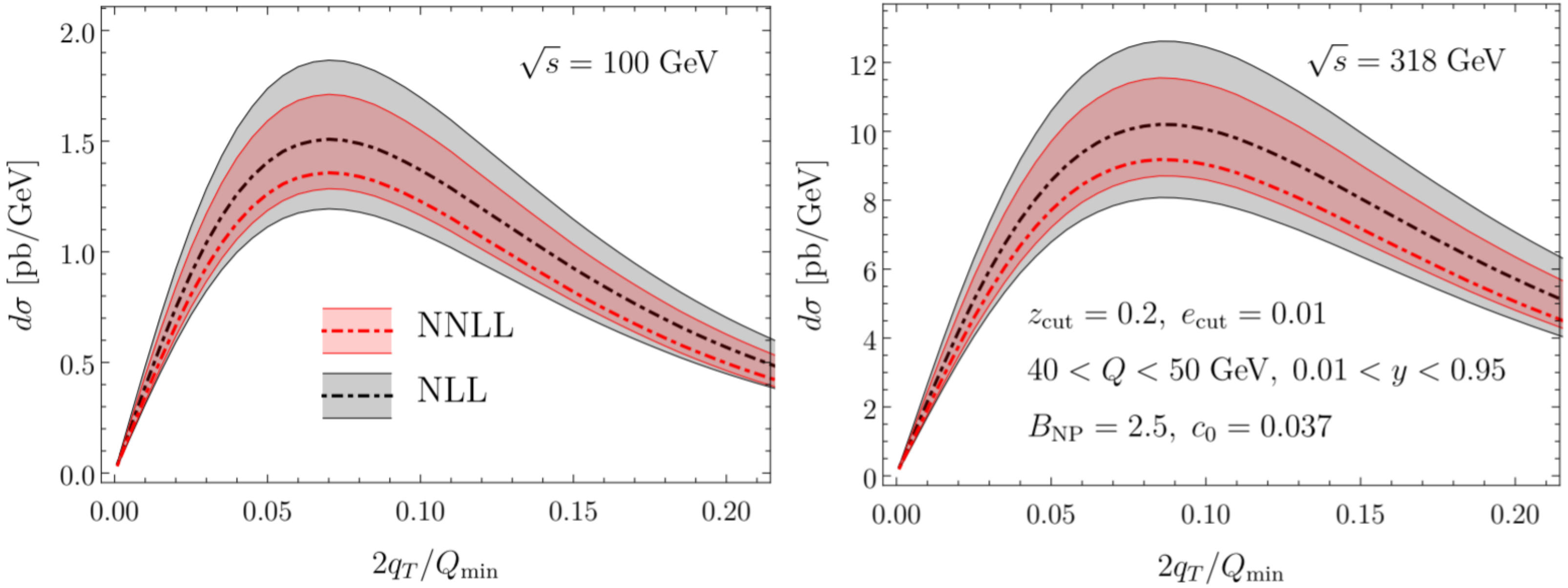
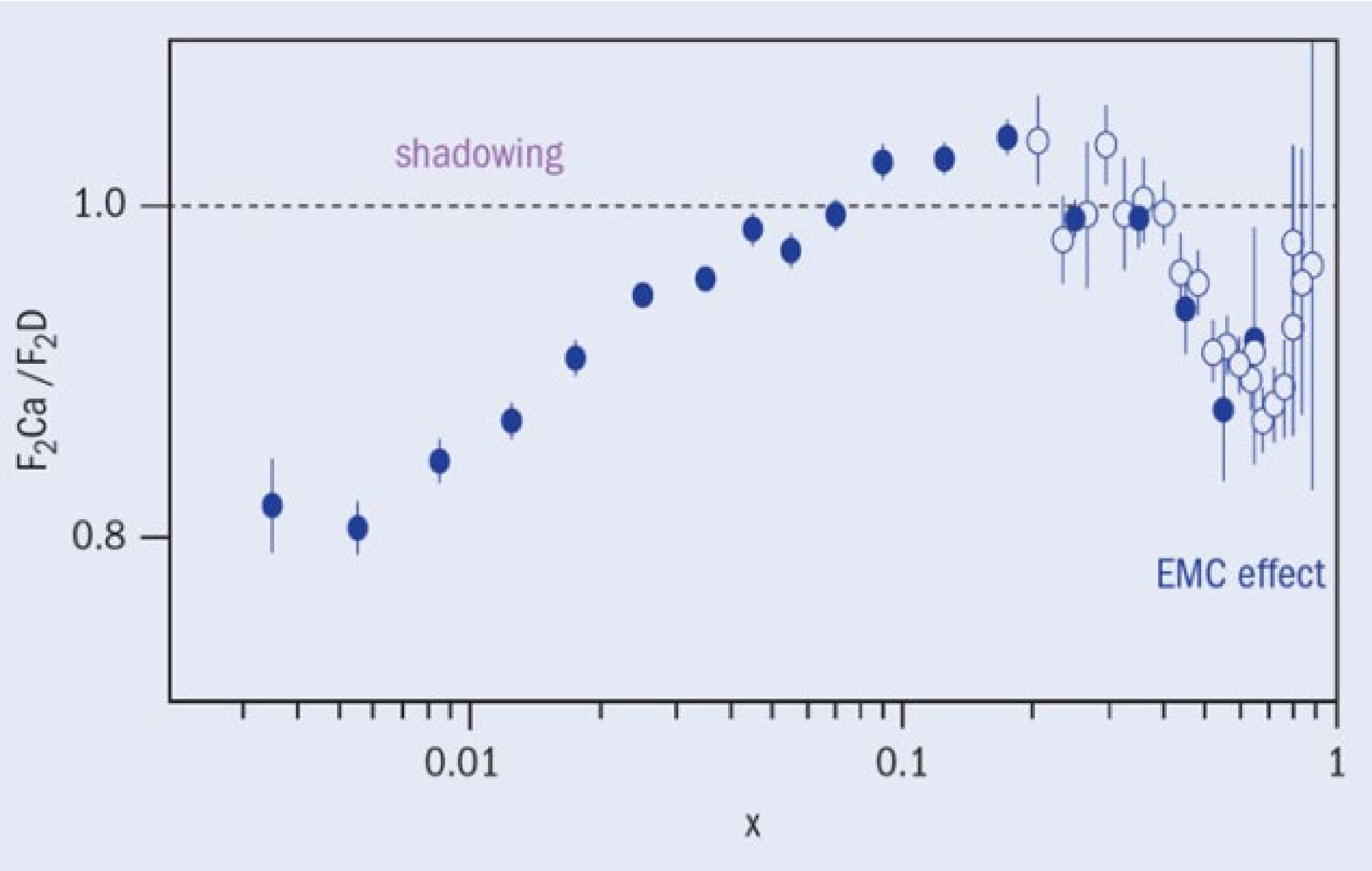


Figure 7. The NLL and NNLL TMD spectra for groomed jets in DIS for EIC (left: $\sqrt{100}$ GeV) and HERA (right: $\sqrt{s} = 318$ GeV) kinematics. The cross section are integrated in $y = Q^2/(xs)$ and $Q = \sqrt{-q^2}$ (see details in the main text).

"…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 will play a crucial role of by-passing fragmentation
- 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.

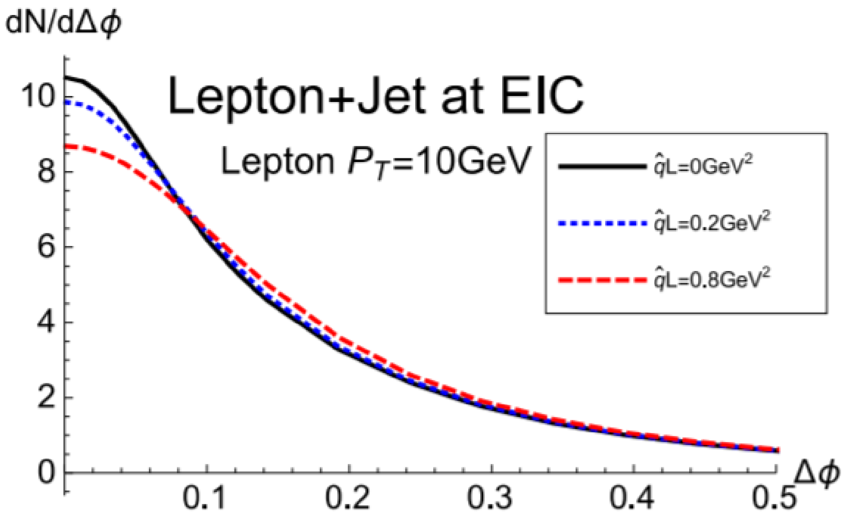
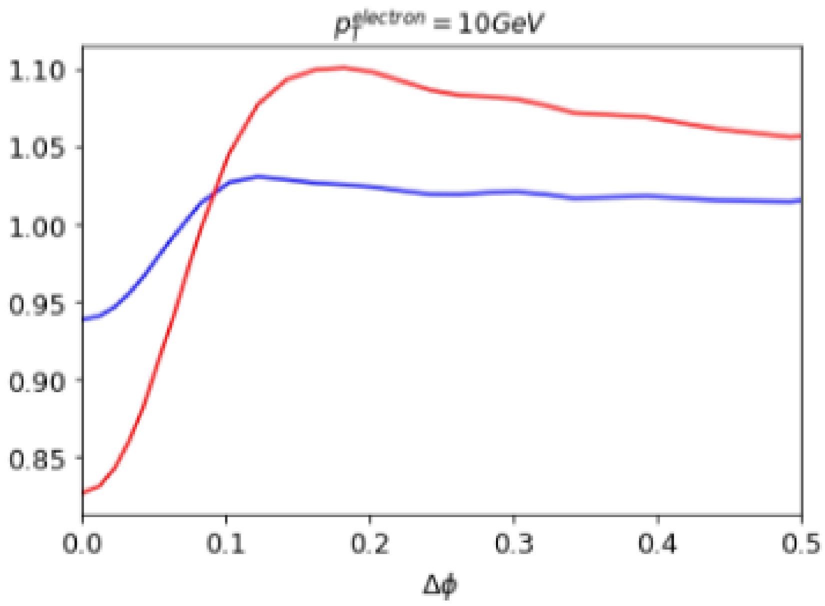


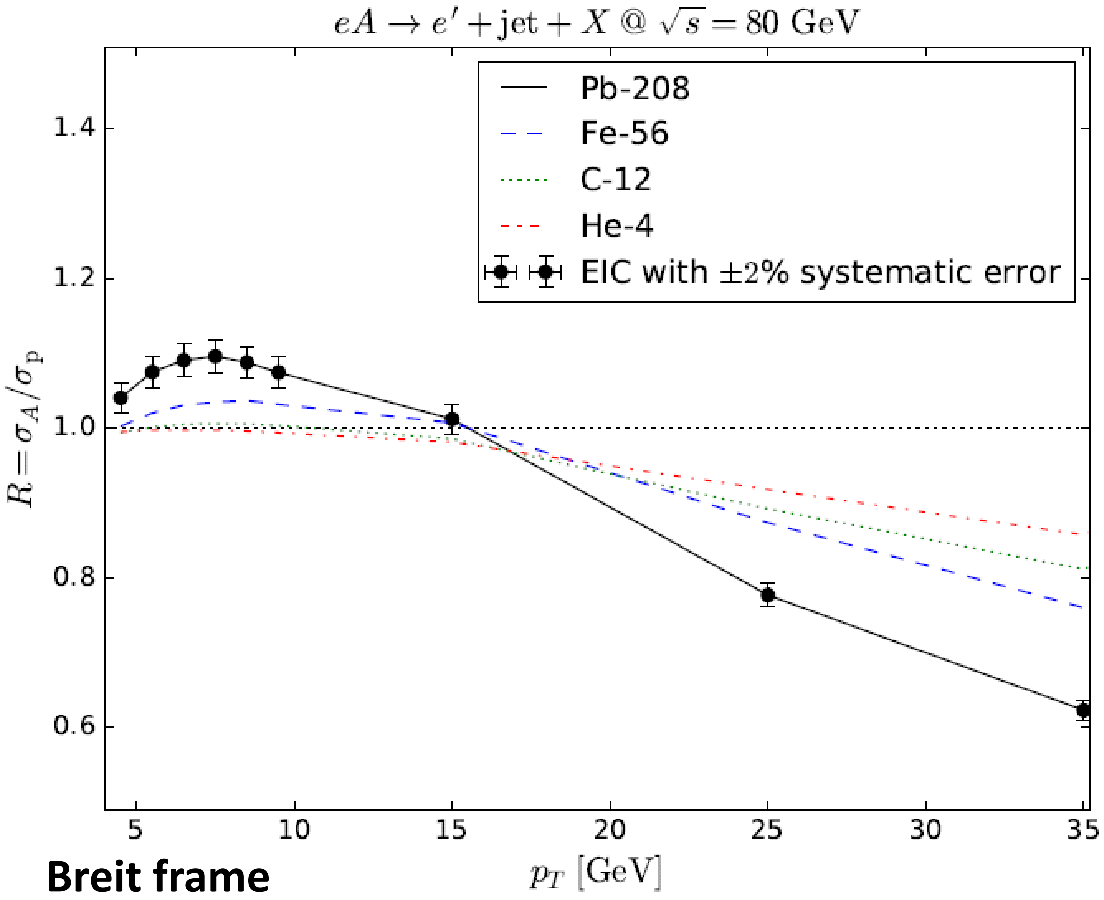
FIG. 4. P_T-broadening effects for the lepton jet azimuthal correlation due to the interaction with cold nuclear matter as a function of $\Delta\phi = |\phi_J - \phi_\ell - \pi|$ for two typical values of $\hat{q}L$.



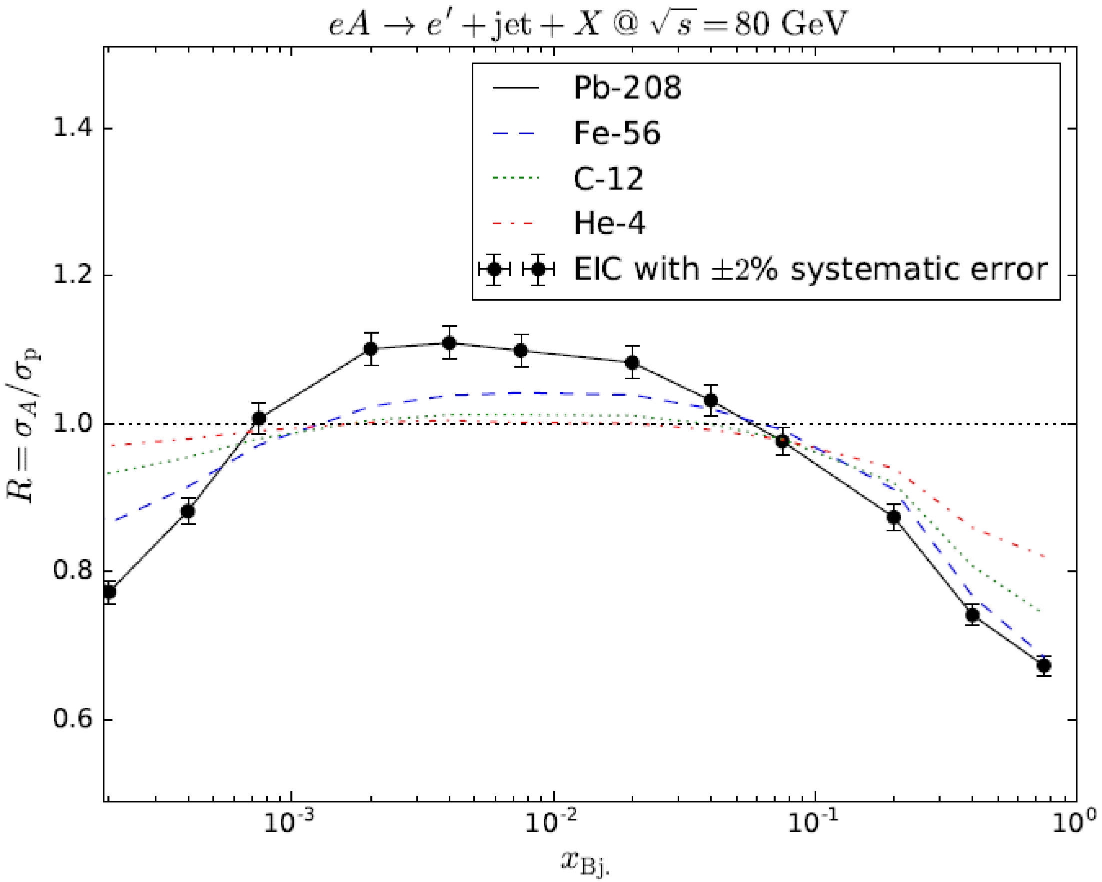
Phys. Rev. Lett. **122**, 192003

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

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



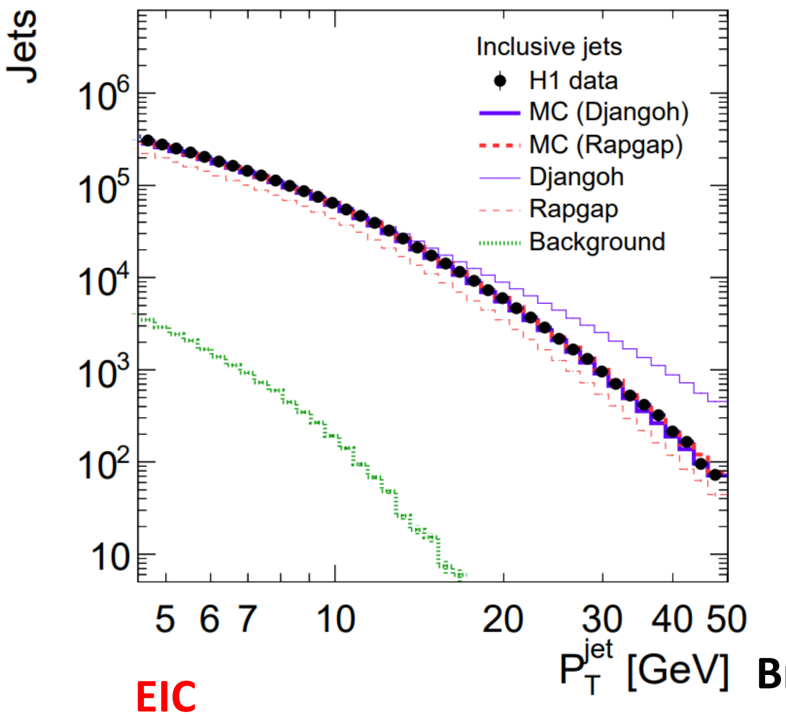
Breit frame



Statistical precision

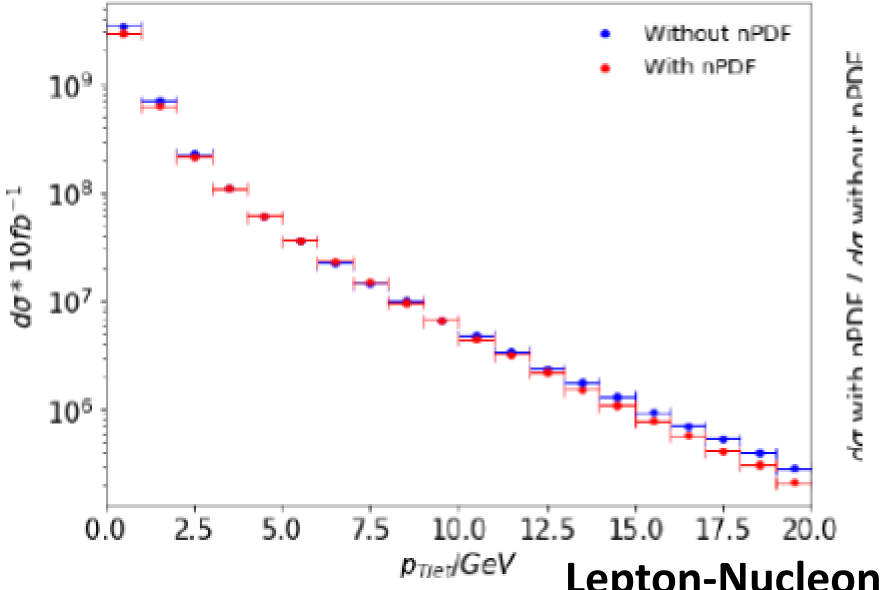
- EIC luminosity ~1000 HERA at least.
- Plus, if we do not suppress leading-order DIS like HERA experiments we gain factor ~100 in cross-section
- For most analyzes we will have a negligible statistical uncertainty, even with multi-differential measurements and for multiple nuclei.
- Obvious exception 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



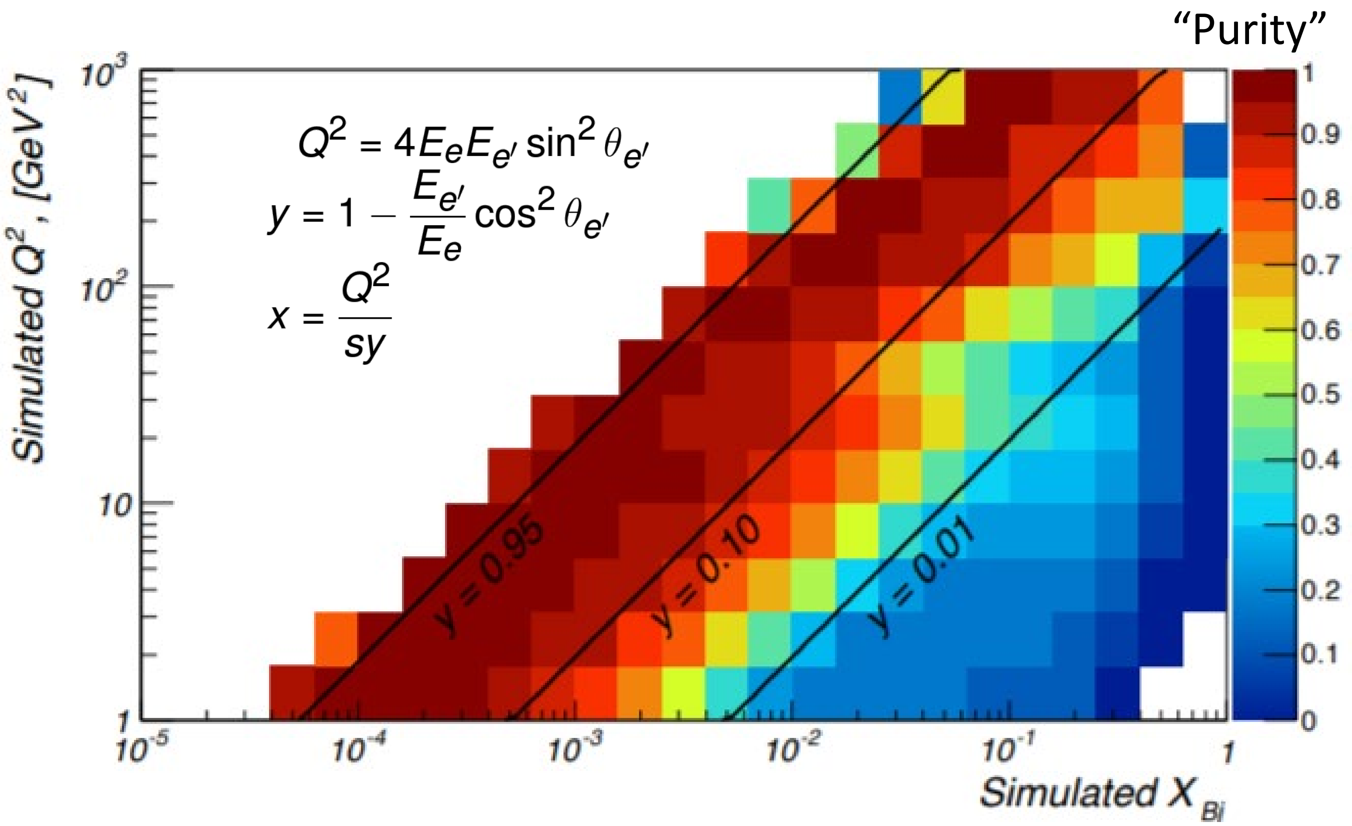
Breit-Frame

EIC



Lepton-Nucleon frame

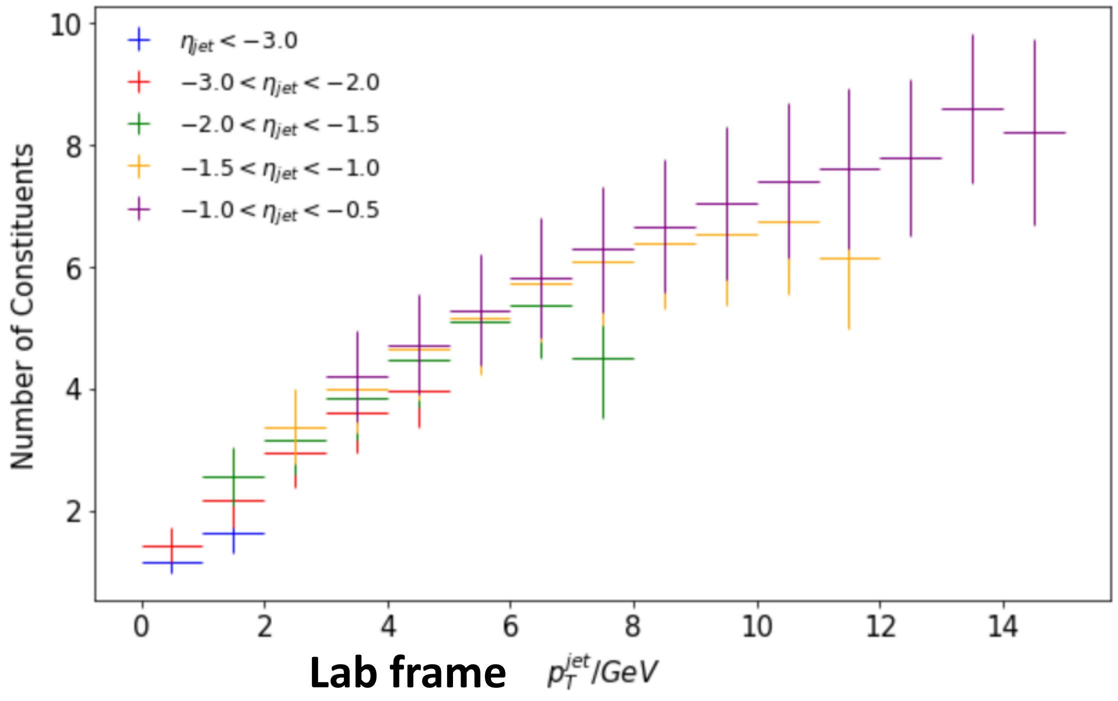
Requirement for lepton in “tag and probe” limits kinematic range

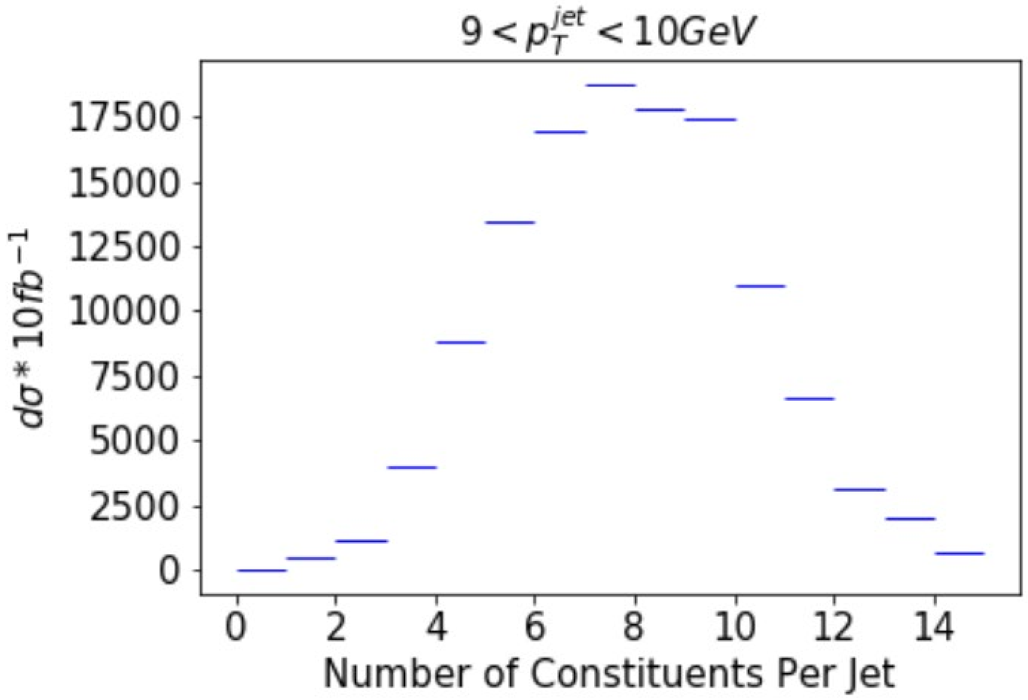


From EIC detector handboook,
includes both tracker and crystal EMCAL
sqrt(s) = 140 GeV.

- 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

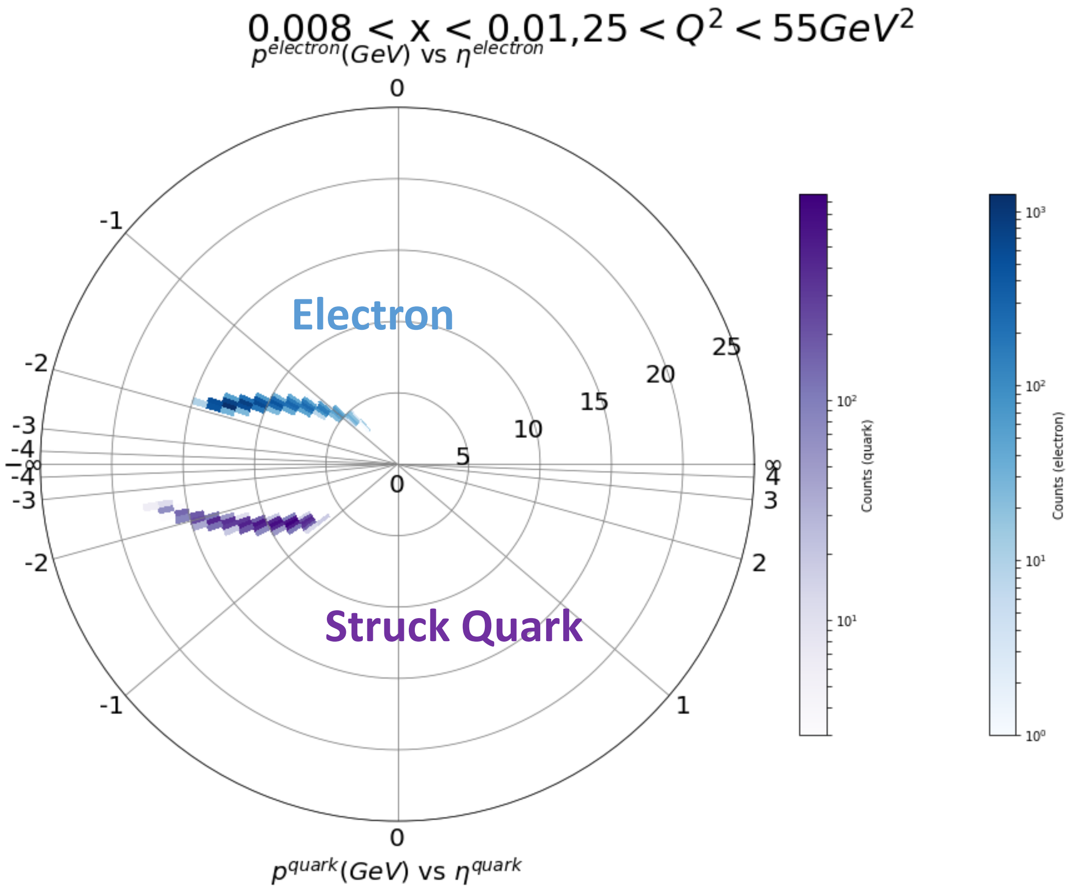
Number of particles in jet

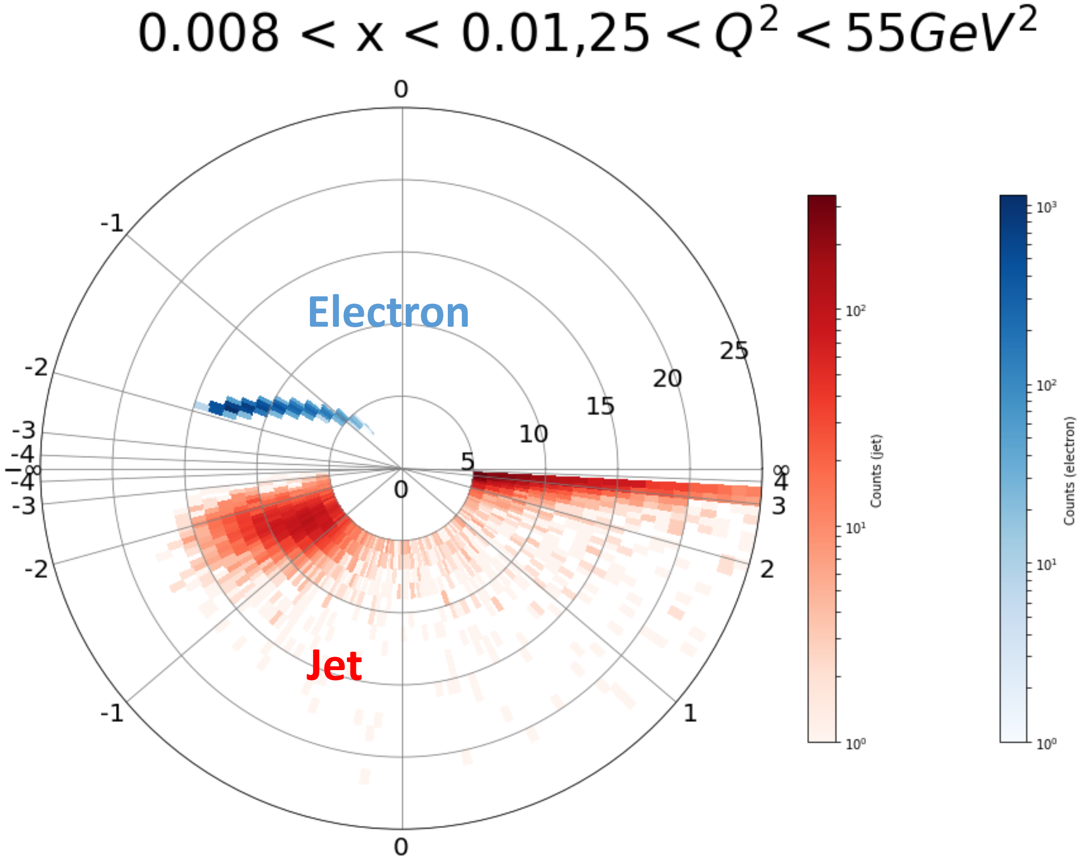




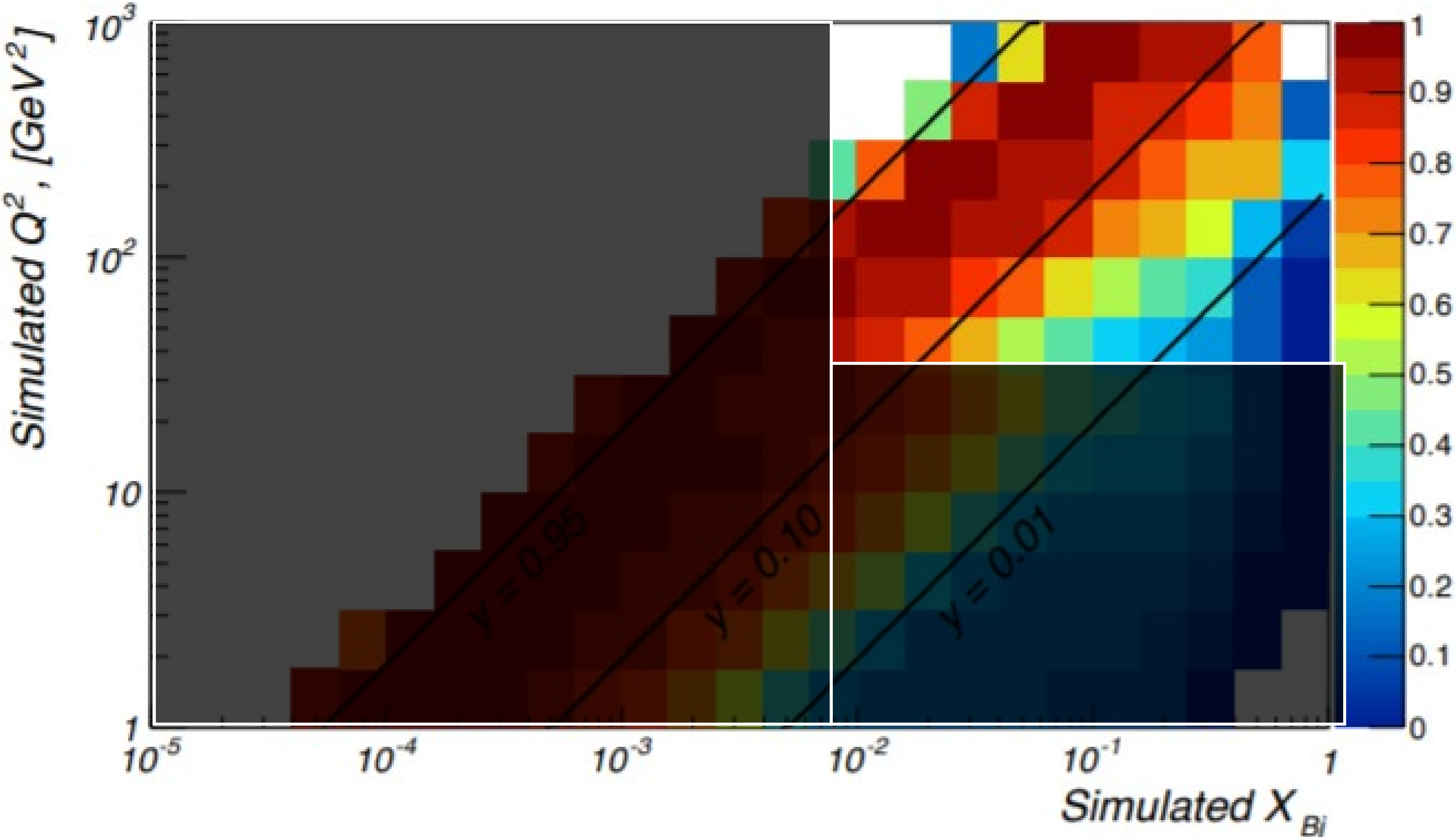
- Unlike LHC jets, EIC jets will be wimpy.
- Number of particles does depend on pT (not energy).
- HERA exp. did set precedent on ~4 GeV pT minimum (Breit Frame)

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

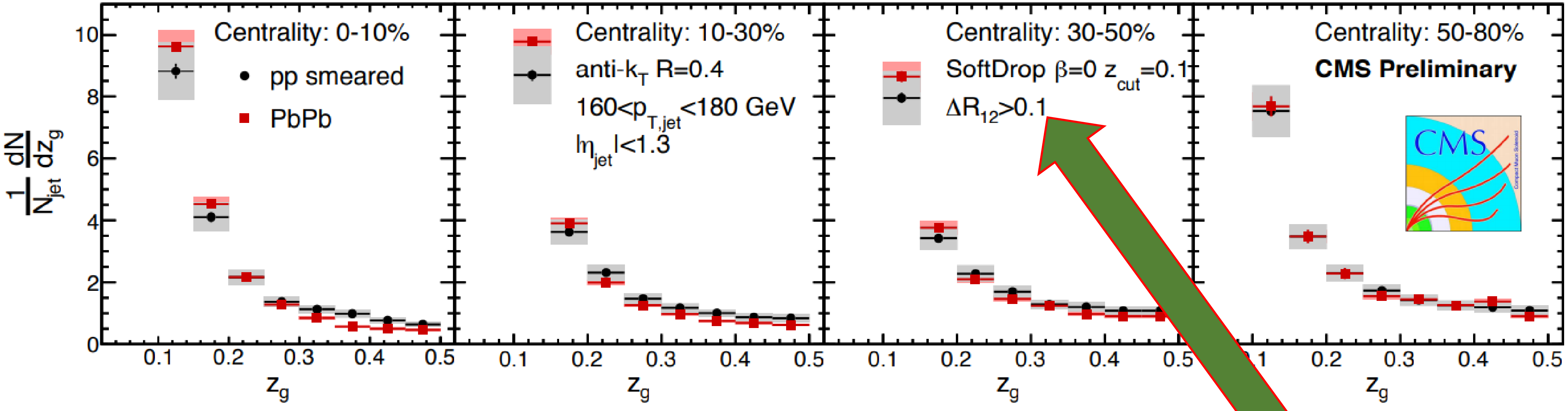
- Do we actually need luminosity in e-A?
  We can always report ratios and double-ratios:

$$\frac{\mathrm{d}^3\sigma^{\mathrm{h}}(x,Q^2,z)/\mathrm{d}x\mathrm{d}Q^2\mathrm{d}z}{\mathrm{d}^2\sigma^{\mathrm{DIS}}(x,Q^2)/\mathrm{d}x\mathrm{d}Q^2}. \qquad R_A^h = \frac{\left[N_h\left(z,p_T^2,Q^2,\nu\right)/N_{e^-}^{DIS}\left(\nu,Q^2\right)\right]_A}{\left[N_h\left(z,p_T^2,Q^2,\nu\right)/N_{e^-}^{DIS}\left(\nu,Q^2\right)\right]_D},$$

- 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 ~1-2%.

Cautionary tale on calorimeter granularity for jet substructure

Phys. Rev. Lett. **120**, 142302

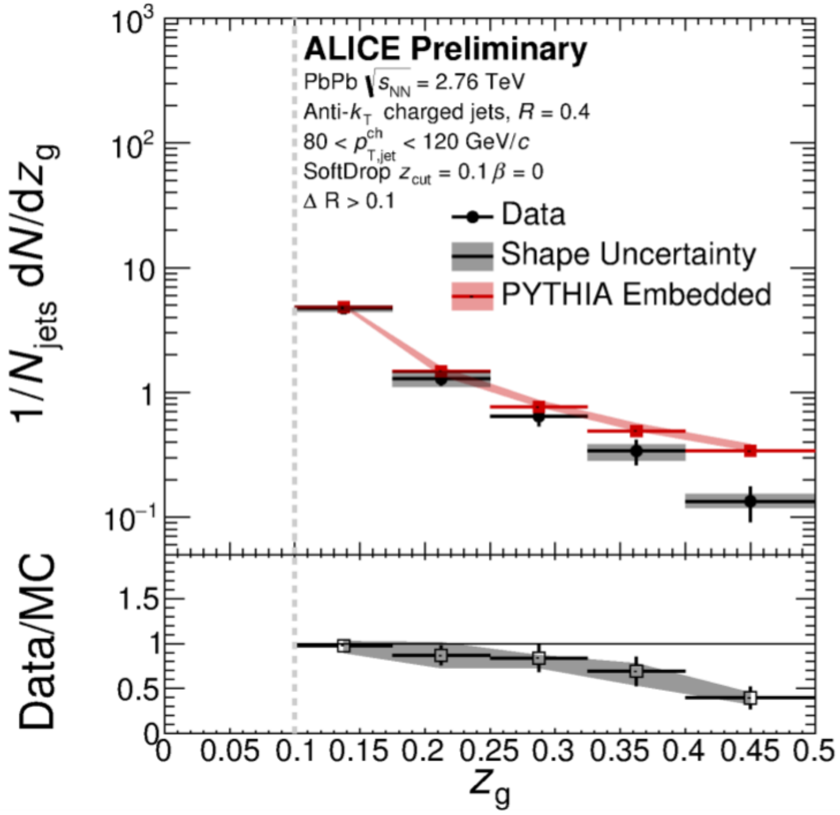


Groomed jets with a small distance between the two subjets frequently result from the ambiguous case where the two subjets cannot be distinctly resolved, leading to a significant misassignment of particle constituents to subjets. An additional selection of $\Delta R_{12} > 0.1$ is applied, removing 40% (60%) of the jets measured at low (high) $p_{T,\mathrm{jet}}$, to avoid an unphysical modification of z_g. This

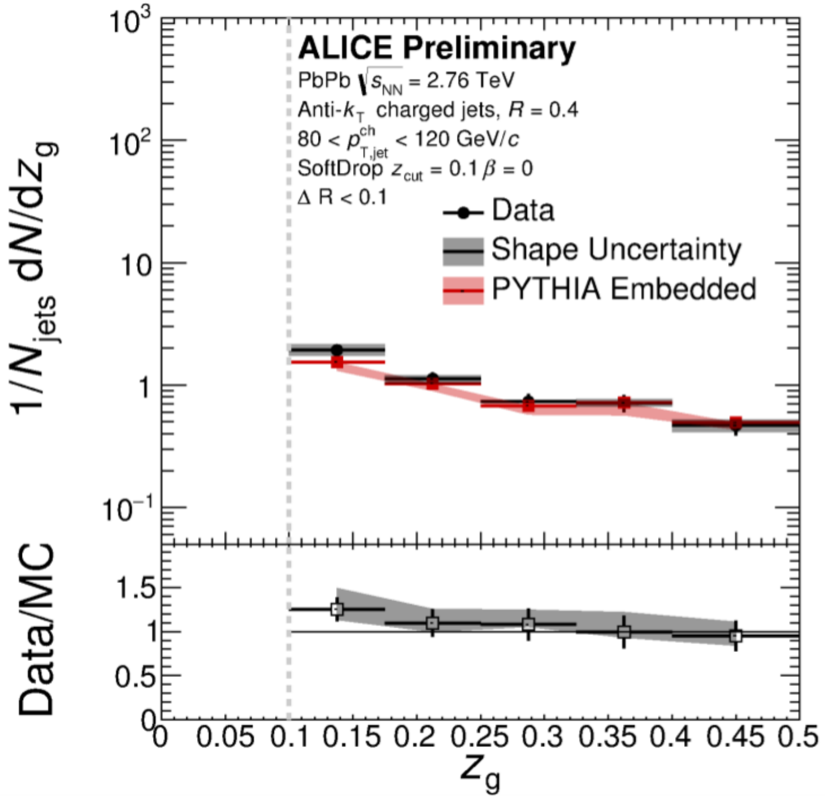
Required to separate "particle-flow objects", in part due to HCAL granularity

CMS granularity led to incomplete physics
ALICE followed up with precise (track-only) jets

$\Delta R > 0.1$



$\Delta R < 0.1$

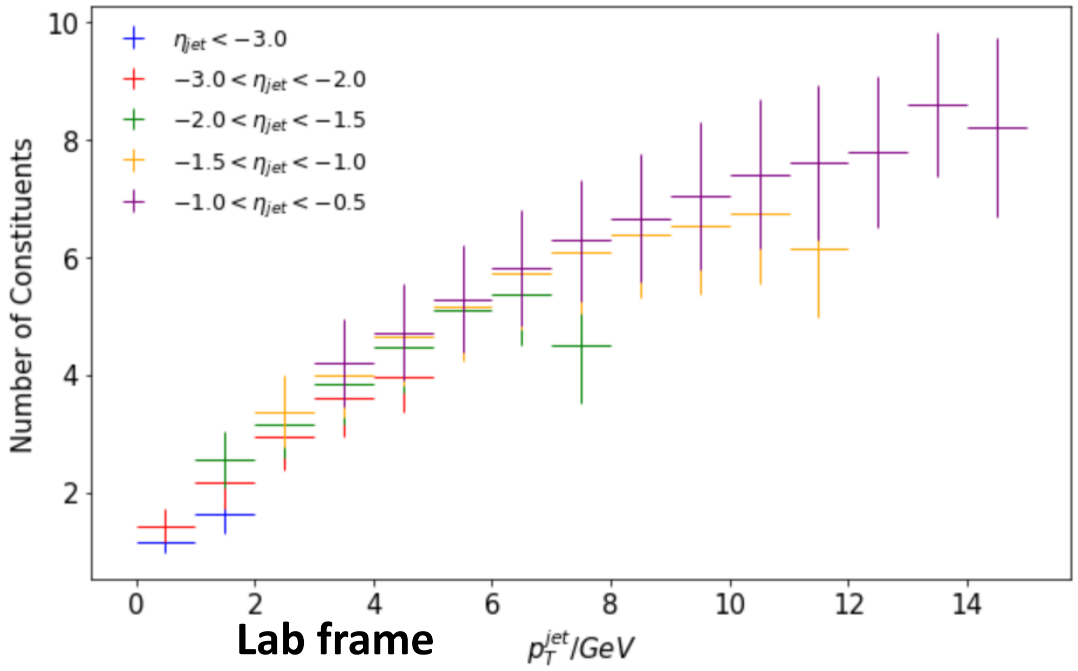


Contrary to CMS, no low z enhancement

These are unmodified (majority of jets!)

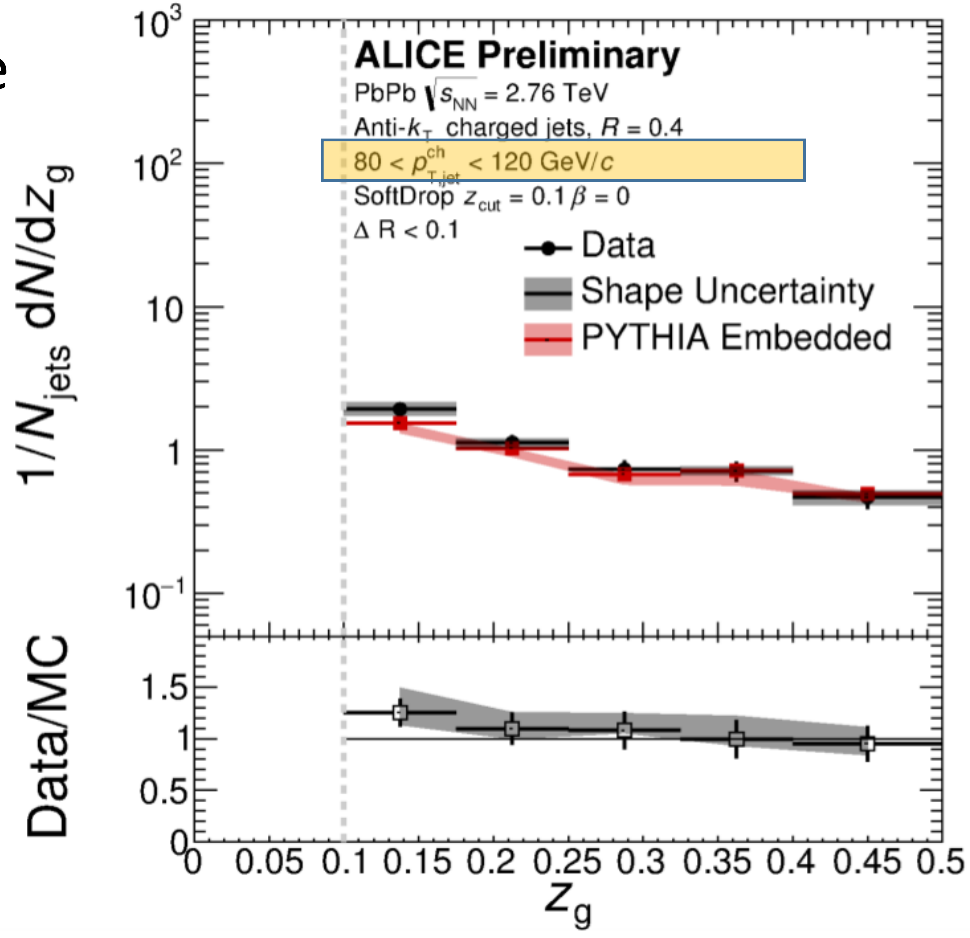
At EIC, “charged-only” jets might not work

- Much lower pT , so only a few charged particles
- It also introduces sensitivity to non-perturbative effects, which might limit goal of reaching a percent-level result



Lab frame

$$\Delta R < 0.1$$



Outline

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- Breit frame or not Breit frame
- Lepton-jet correlations
- Experimental limitations

“Target fragments” are easier to separate in collider mode

Fixed Target

Collider

- 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

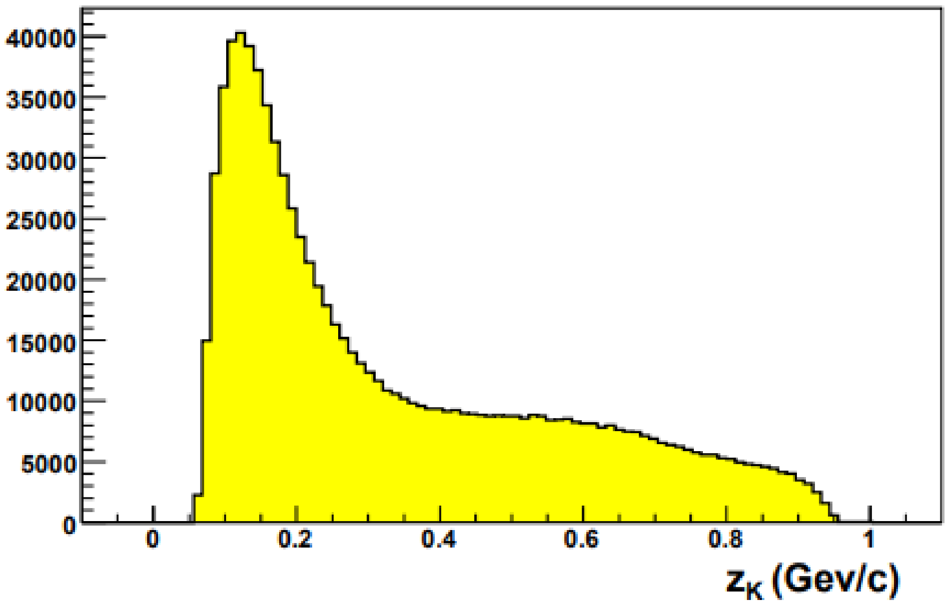


Fig. 13. Upper panel: x versus Q^2 distribution for kaons generated using PEPSI Monte Carlo and accepted in CLAS12. Lower panel: z distribution for kaons generated using PEPSI Monte Carlo and accepted in CLAS12.

(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)

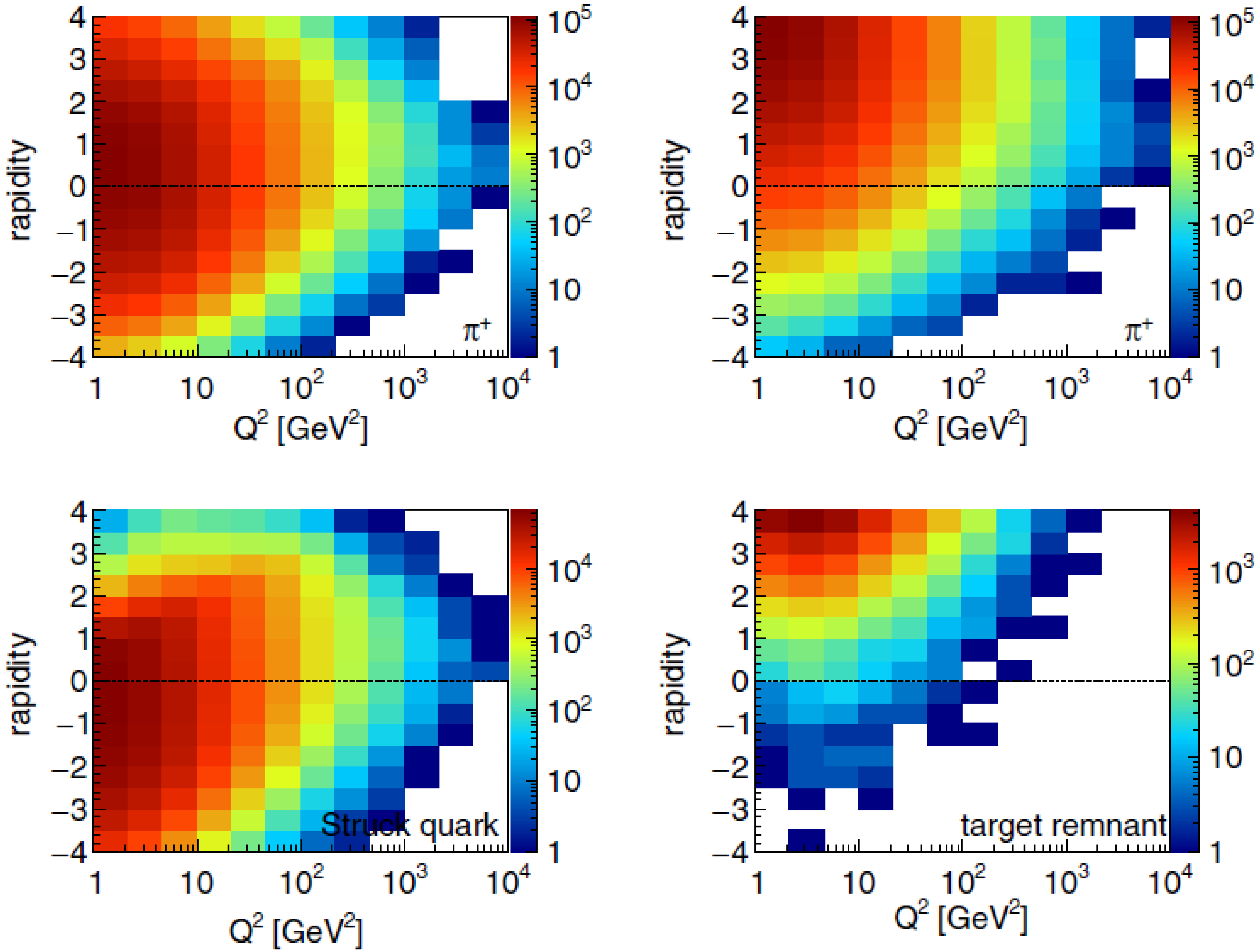
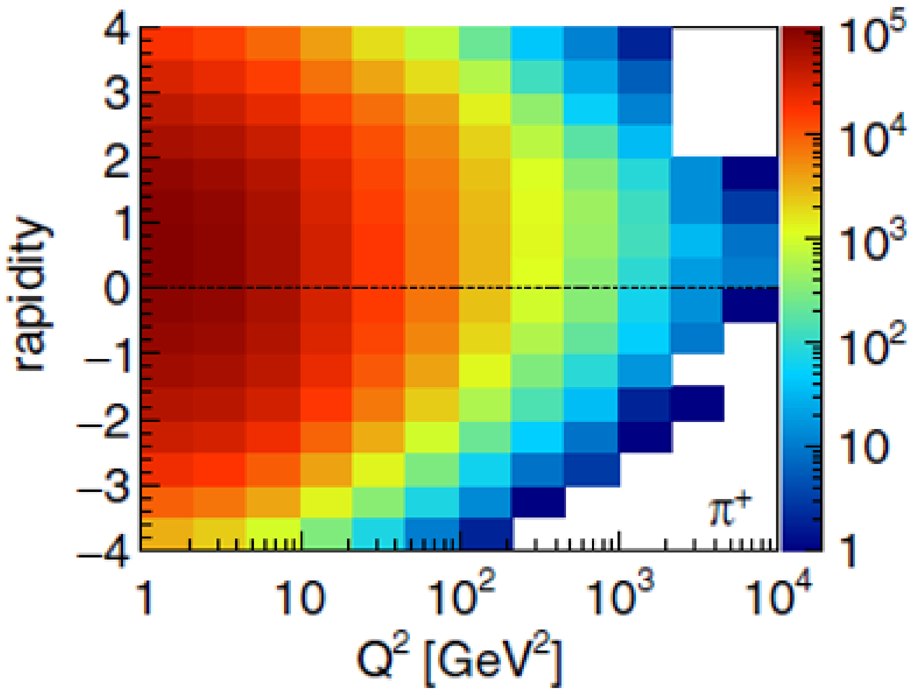


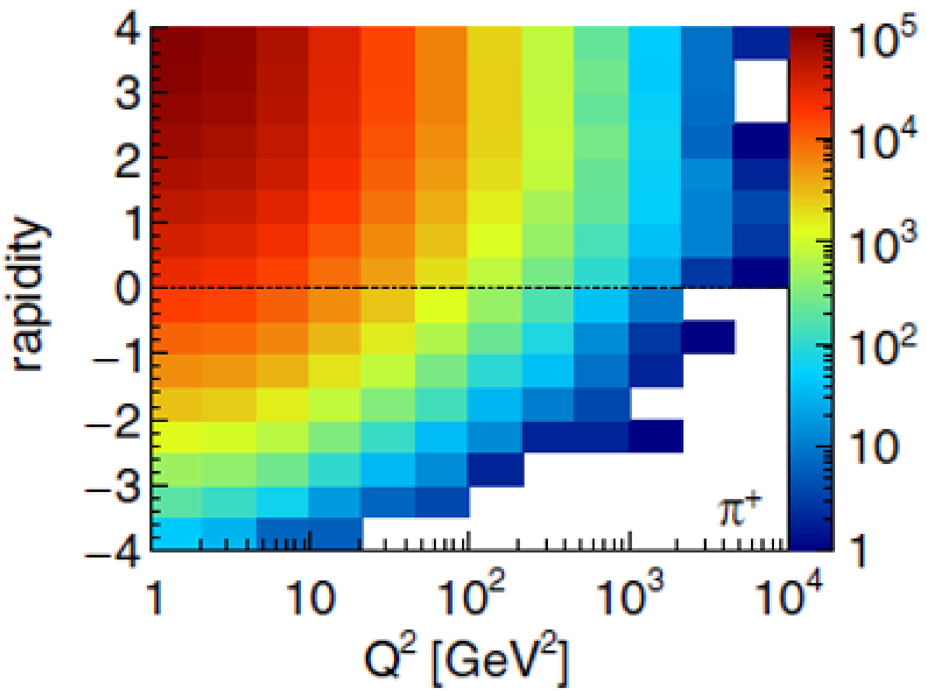
FIG. 4. Kinematic range in Q^2 and rapidity at $\sqrt{s} = 140$ GeV for pions originating from a struck quark (top left) and from the target remnant (top right), as well as for the struck quark (bottom left) and the target remnant (bottom right) themselves for the DIS subprocess $\gamma^* q \to q$ in PYTHIA-6.

Can we do better than this with jets?

From struck quarks



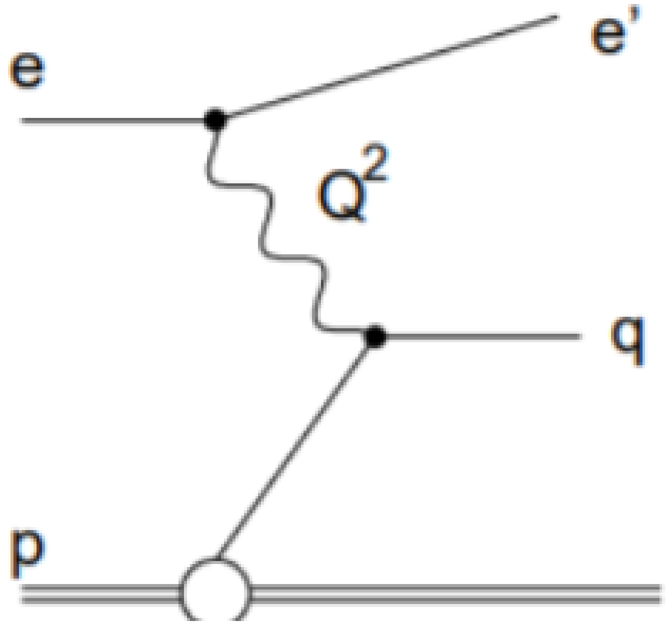
From beam remnant



PHYS. REV. D **99**, 094004 (2019)

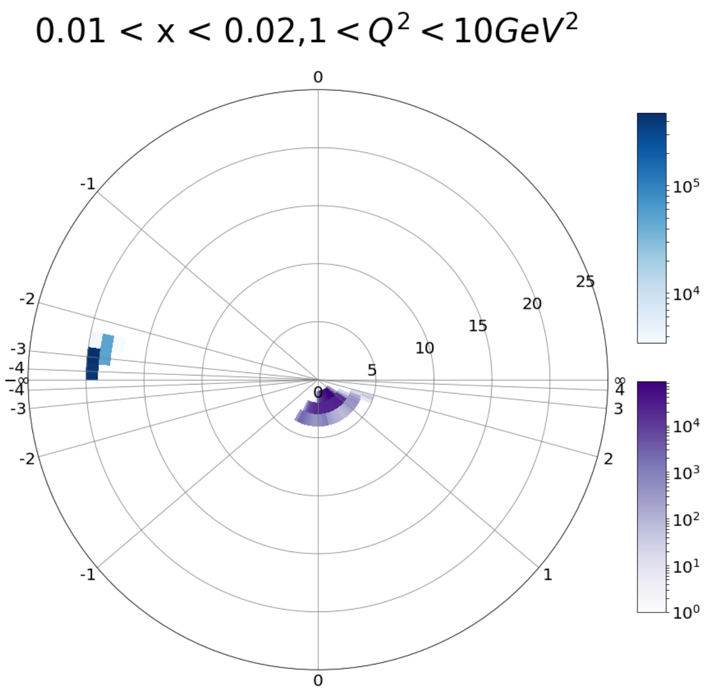
Simulation parameters

- Electron-proton deep inelastic scattering with $\sqrt{s} = 89$ GeV, $E^{proton} = 100$ GeV, $E^{electron} = 20$ GeV is simulated with Pythia 8.
- Event cuts: $0.01 < y < 0.85$, $W^2 > 4GeV^2$, $Q^2 > 1GeV^2$
- Jets are reconstructed with the anti-k_T algorithm with $R = 1.0$
- Particle cuts: $|\eta^{part}| < 4.5$, $p_T^{part} > 0.25GeV$

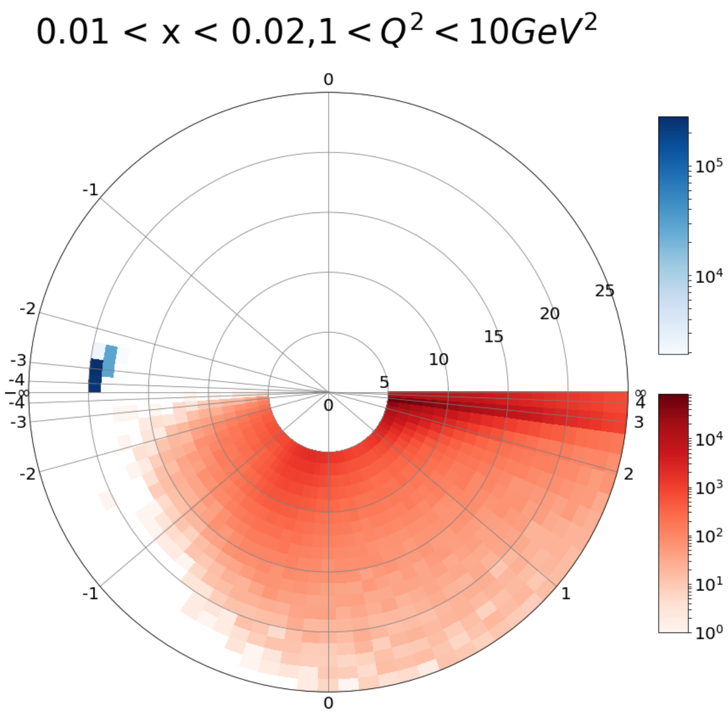


- **Youqi Song**

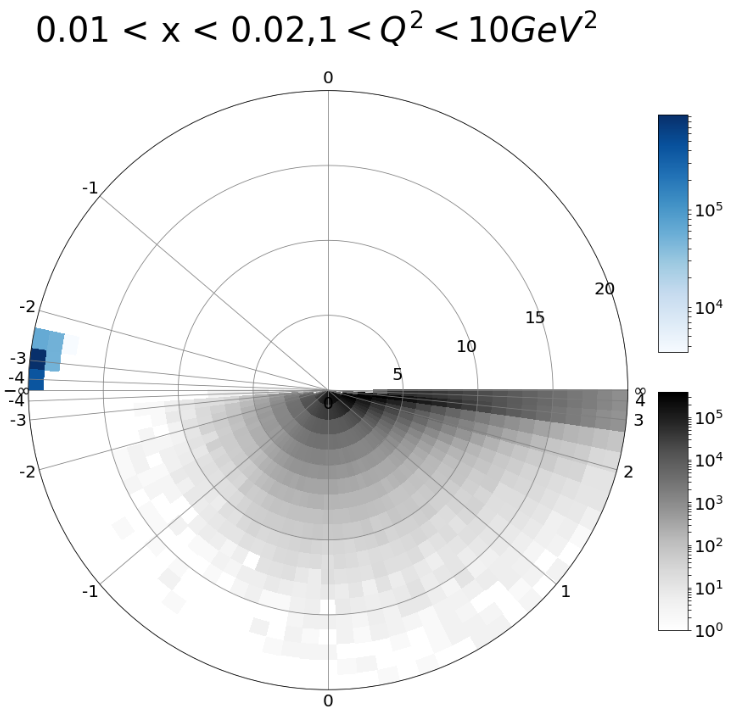
Low-Q2 events are very complicated



Quarks

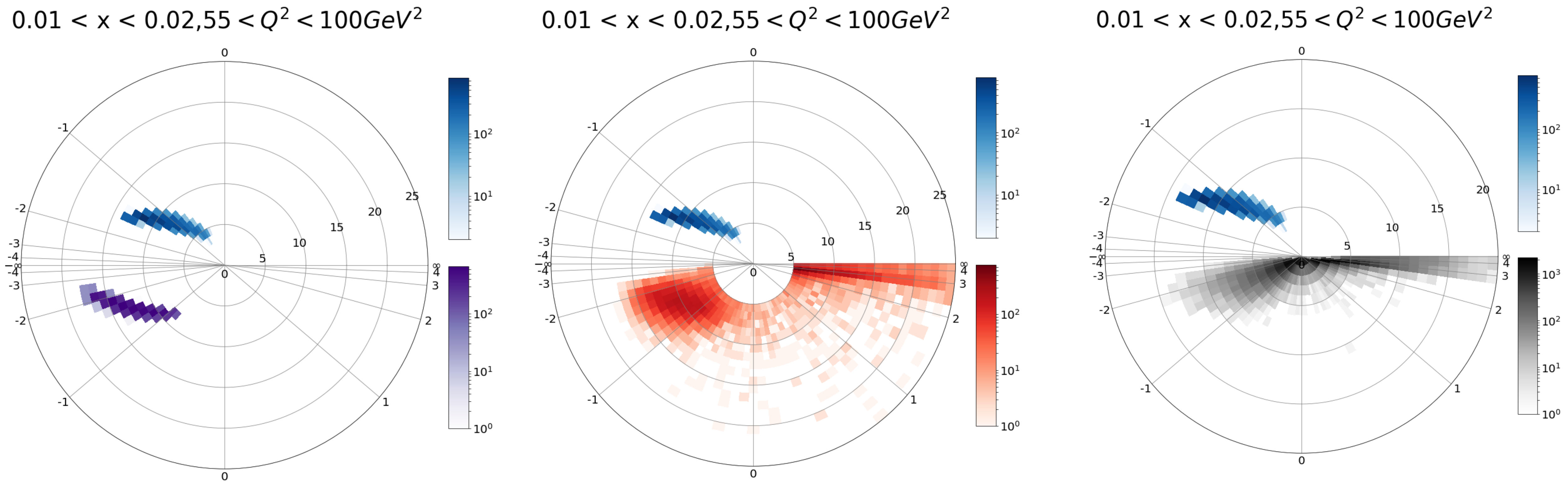


Jets

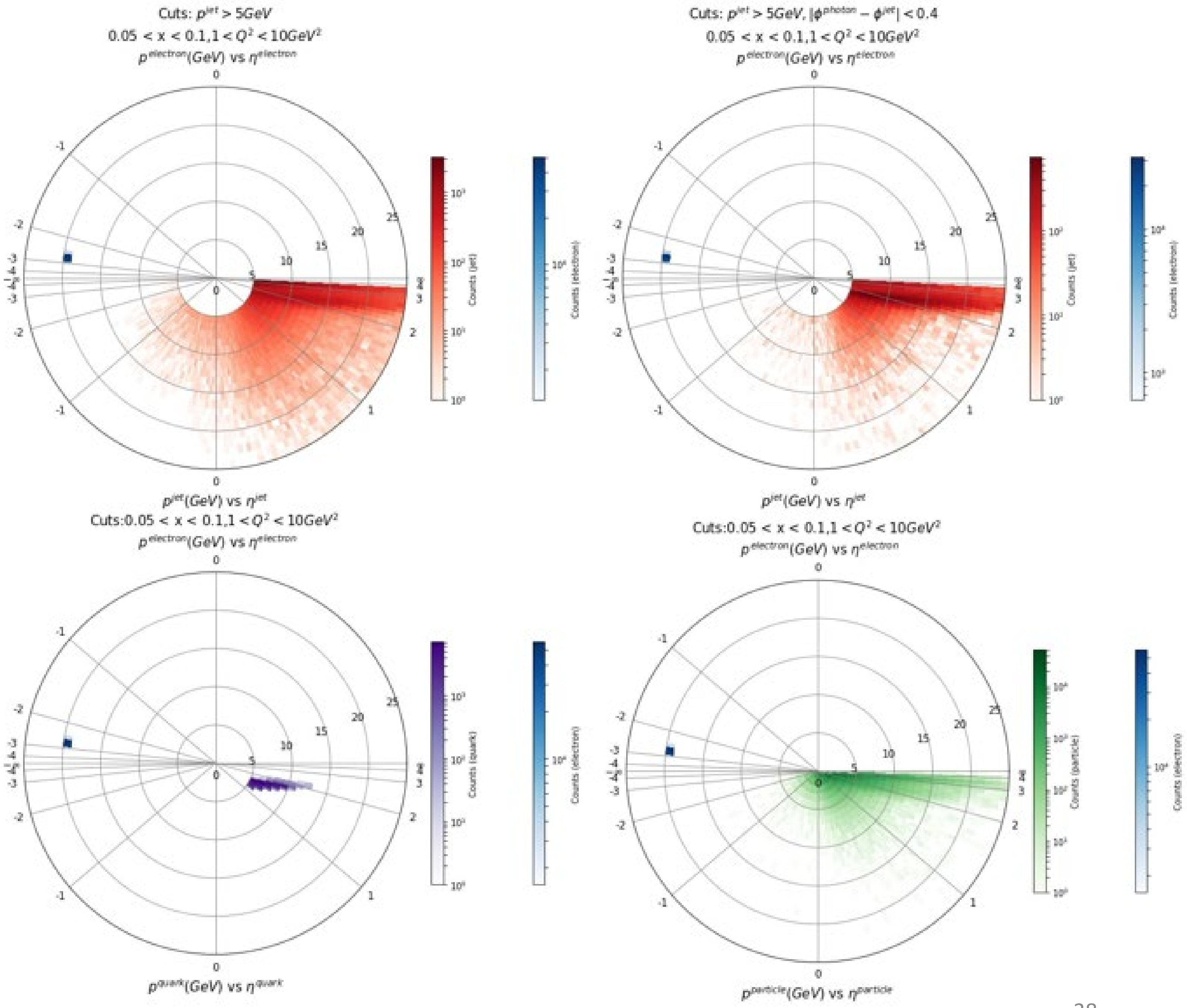


Hadrons

Higher Q2, cleaner separation

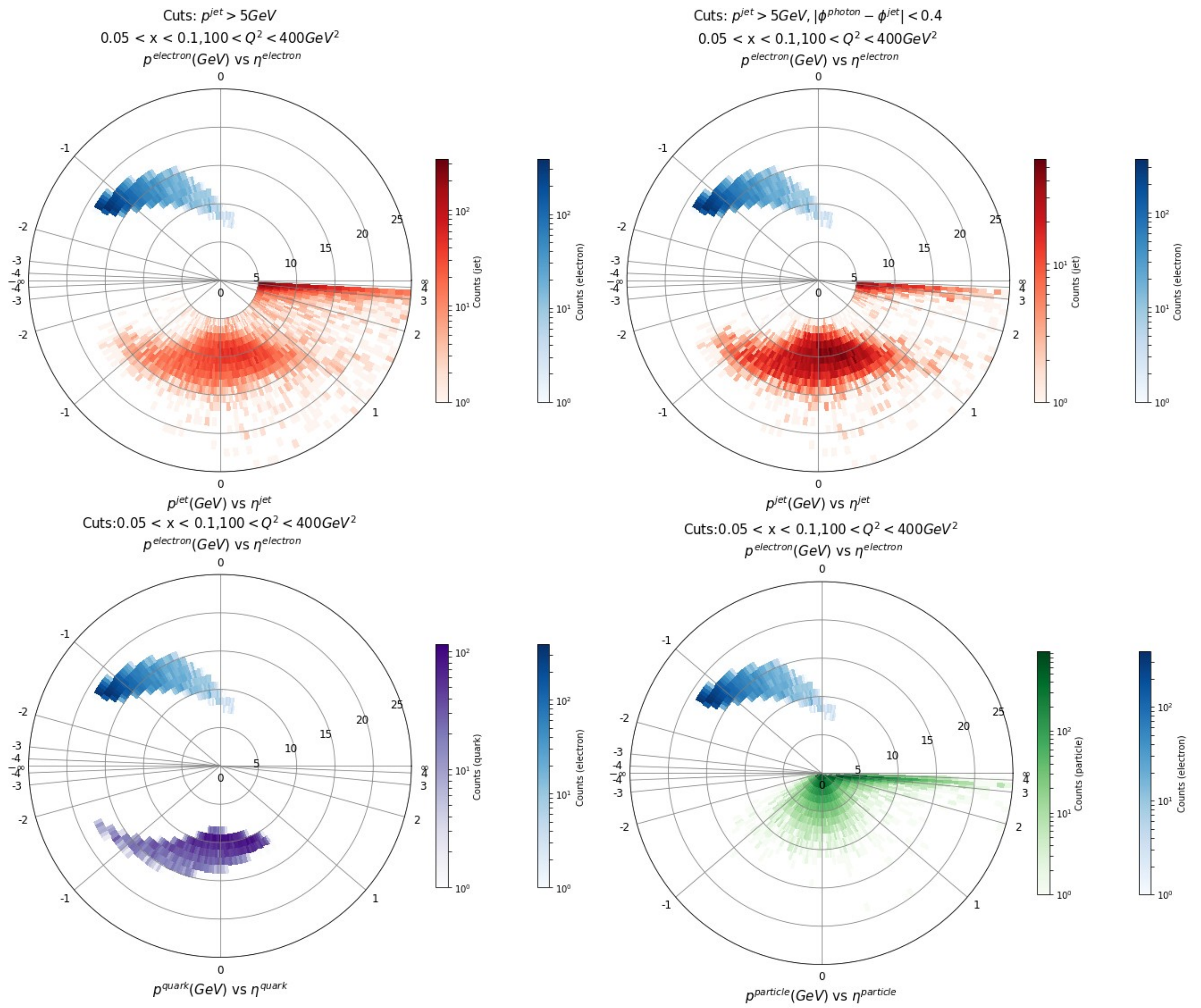


For higher x, it gets more complicated



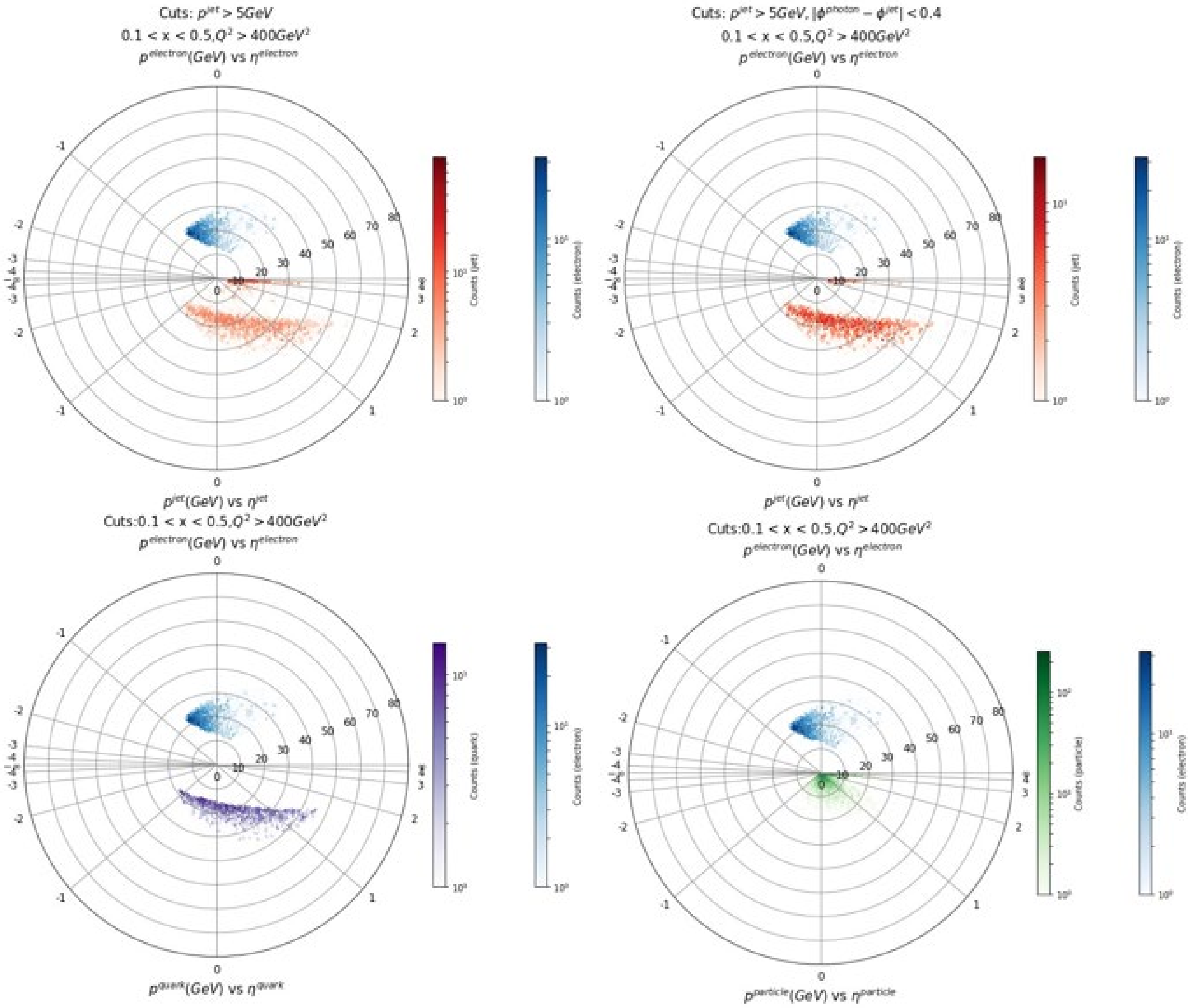
For higher x, it gets more complicated

But still feasible



For even higher x, it gets even more complicated

But still feasible



Conclusions

- For e-A tag and probe, we want the LO DIS and suppress higher-orders. Orthogonal to most HERA jet measurements.
- Plus, we need an unbiased measurement of jet kinematics (x, Q2 need to come from lepton)→ no “Jacque Blondet” method.
- Theory seems to demand ~1% measurements for “cold matter effects”
- Uncertainties in e-A/ep will mostly cancel, *but* not like in fixed-target mode. Need have large JES cancellation for differential measurements at 1% precision.
- “Current vs target” fragmentation separation is not trivial in collider mode, as it would naively seem.