Ivan Vitev

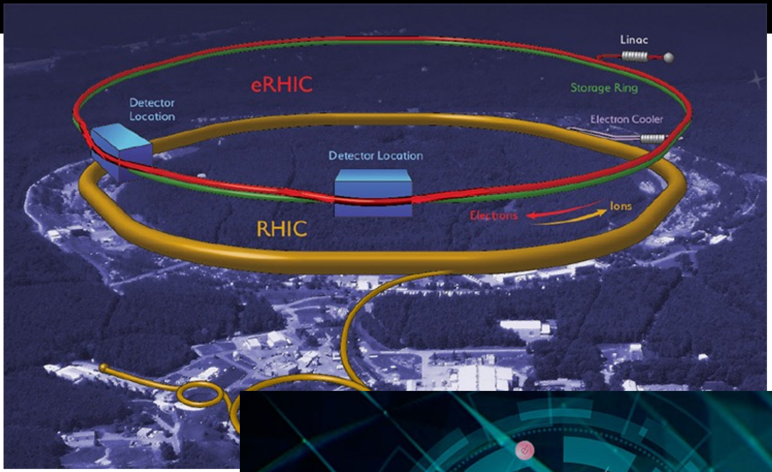
(T)EEC Correlators at the EIC and thoughts on EEEC

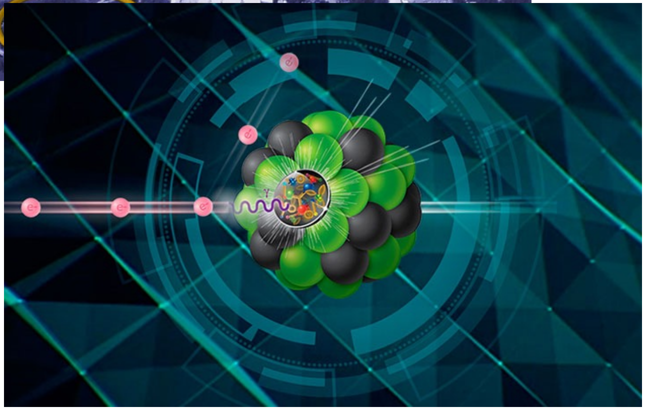
Credit for this work goes to other presenters here and to my collaborators
H.Li, Y.J. Zh, Y. Makris

E05 Snowmass Working Group meeting
Sept. 27, 2021, Online

Outline of the talk

- A word about the EIC
- TEEC and BEEC at the EIC
- Speculation on EEEC





This work is supported by the TMD topical collaboration and the LANL LDRD program

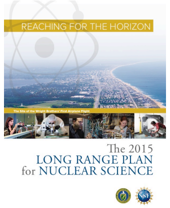
References

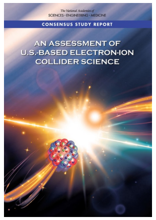
ArXiv: ***2006.02437, 2102.05669***, 2011.02492, 2103.16526

A word about the EIC

Long Range Plan recommendations

- We recommend a high-energy high-luminosity polarized Electron-Ion Collider (EIC) as the highest priority for new facility construction following the completion of Facility for Rare Isotope Beams (FRIB)



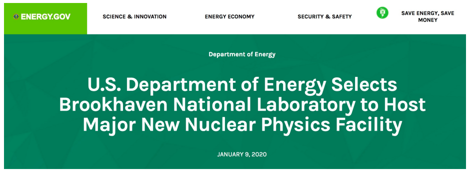


D. Geesaman *et al*, 2015

G. Baym *et al*, 2018

National Academy of Sciences

- EIC essential for US leadership in nuclear physics and accelerator design
- Physics at EIC has very close connections to solid state and atomic physics, high energy physics, astrophysics and computing
- …



CD-0 and site selection announced Jan. 9, 2020
CD-1 now achieved

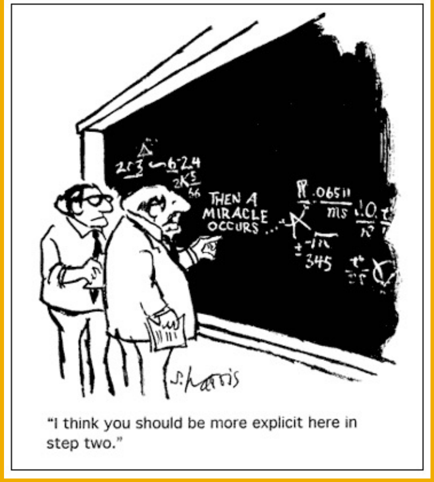
Dan Brouilette, Secretary of DOE

Tim Hallman, Director or Nuclear Physics at DOE's Office of Science

Chris Fall – Director of DOE's Office of Science

– **High energy** (nucleon/nucleus energy 30-250 GeV), **High intensity** ($10^{33} – 10^{34}$ $cm^{-2}s^{-1}$), **High collision frequency** (~100 MHz) – mandated by NAS

I. (Transverse) Energy-Energy Correlations - as first defined



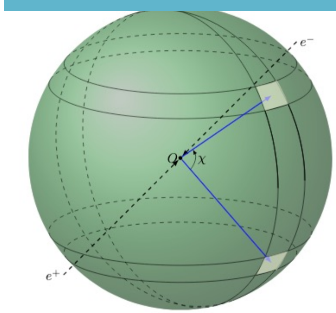
"I think you should be more explicit here in step two."

TMD physics

Introduction to TEEC

electron-positron collider: Basham et al. (1978)

e^+e^- Collisions

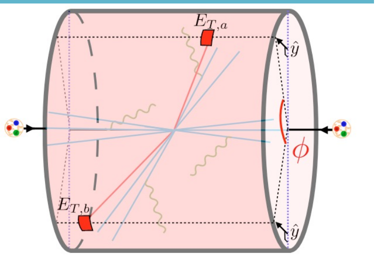


$$\mathrm{EEC} = \sum_{a,b} \int d\sigma_{V \to a+b+X} \frac{2E_a E_b}{Q^2 \sigma_{\mathrm{tot}}} \delta(\cos(\theta_{ab}) - \cos(\chi))$$

- sum over all the jets for each event
- sum over all the particles for each event

hadronic collider: Ali et al. (1984)

Hadronic initial state



observable

$$\mathrm{TEEC} = \sum_{a,b} \int d\sigma_{pp \to a+b+X} \frac{2E_{T,a} E_{T,b}}{|\sum_i E_{T,i}|^2} \delta(\cos\phi_{ab} - \cos\phi)$$

Detector lack hermiticity of ones in e+ e- collisions

- Event shape variables can be used to determine the strong coupling αs and test asymptotic freedom, to tune the nonperturbative Quantum Chromodynamics (QCD) power corrections, and to search for new physics phenomena

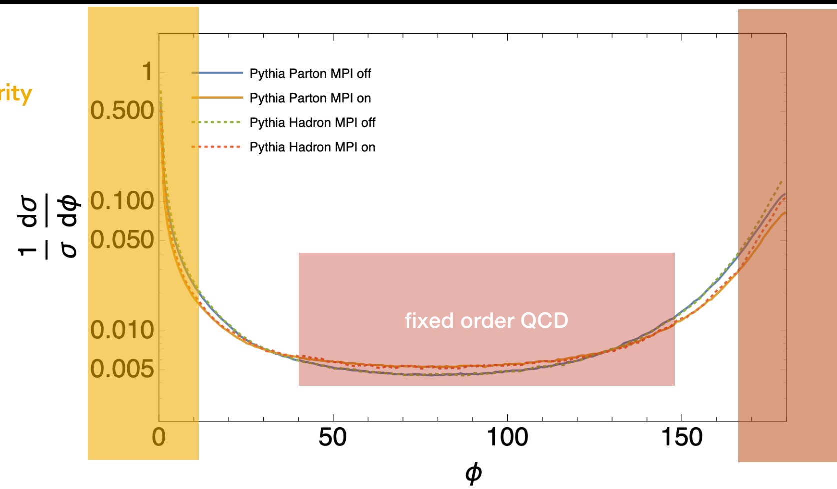
TEEC in the dijet limit and in DIS

$\cos\phi_{ab} \to 0$

Collinear singularity

$J \otimes H$

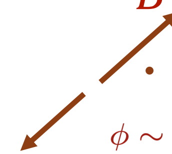
$\phi \sim 0$



Collinear and soft singularity

$\cos\phi_{ab} \to -1$

$B \otimes H \otimes J \otimes S$



$\phi \sim \pi$

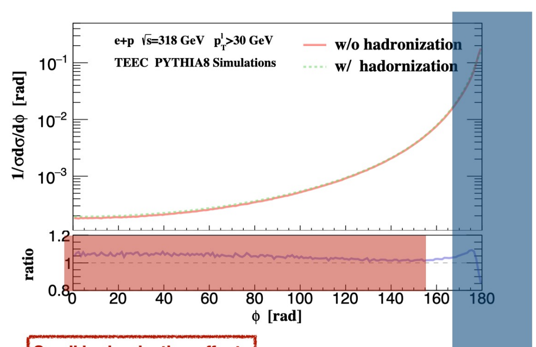
Gao et al. (2018)

Defined as the correlations between the lepton and hadrons in the final state

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

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

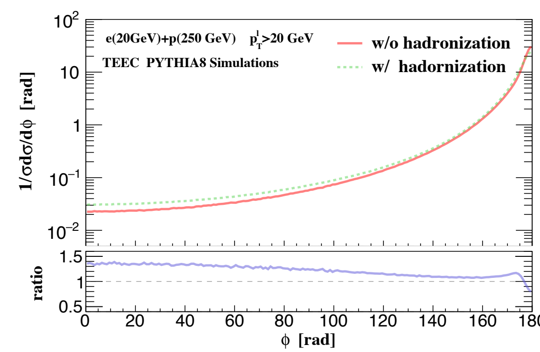
- ☑ Easier to be measured in DIS
- ☑ NO Collinear singularity when $\phi \to 0$
- ☑ Hadronization effects are suppressed



Small hadronization effects

Soft and Collinear radiations dominate

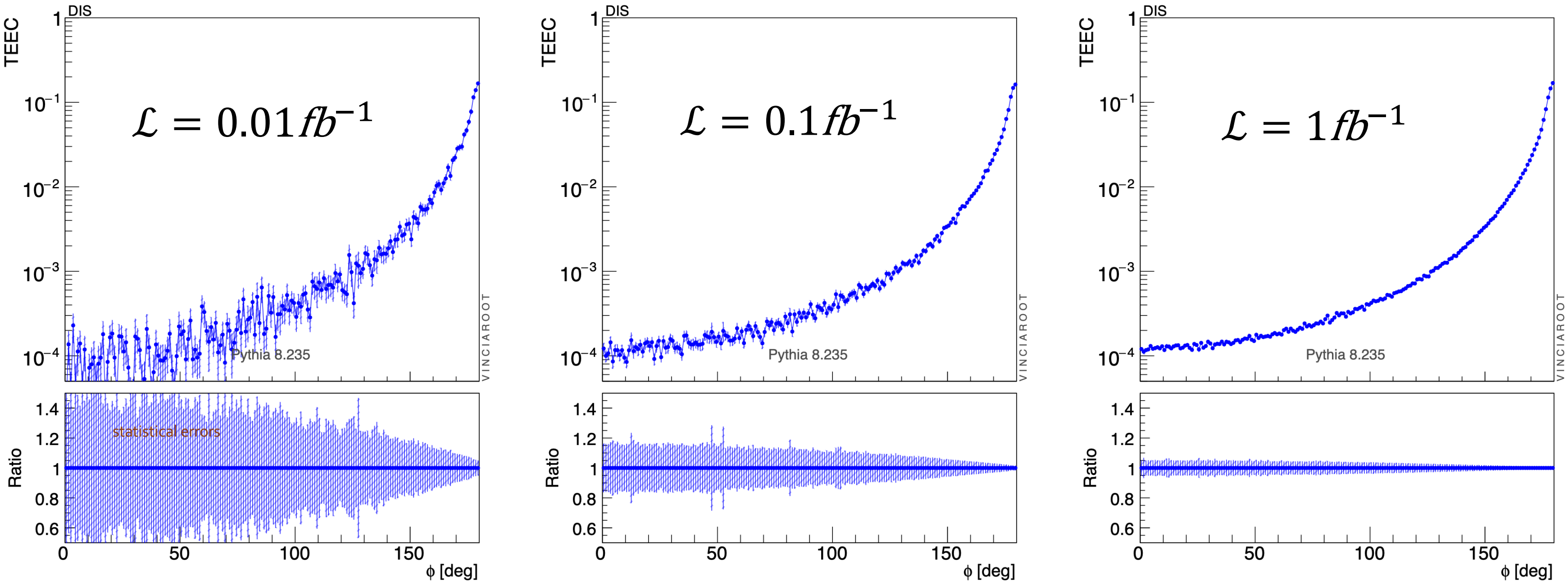
Hadronization effects is less than 20%



hadronization effects at EIC energy

Simulation of TEEC in EIC

e(18GeV) + p(275GeV) Select events with $p_{T,l} > 20\text{GeV}$, $-1 < \eta_h < 3$



The precision with $10 fb^{-1}$ and $100 fb^{-1}$ will be unprecedented
It does not depend on uncertainties related to the jet radius and jet finding algorithm

It is possible to study this observable in percent level

Factorization in the back-to-back limit

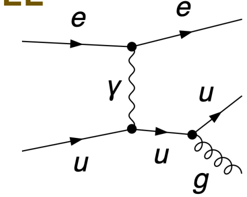
$ep \to e + \text{jet}$ $$\frac{d\sigma^{(0)}}{d\tau} = \sum_f \int \frac{d\xi dQ^2}{\xi Q^2} Q_f^2 \sigma_0 \int \frac{db}{2\pi} e^{-2ib\sqrt{\tau}p_T} H(p_T, Q, \mu) S(b, Q, \mu, \nu) B_{f/N}(b, \xi, \mu, \nu) J_f(b, \mu, \nu)$$

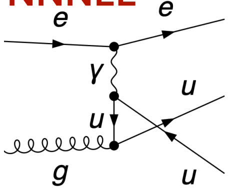
$$\sum_{i=1} \alpha_s^i L^{2i} + \sum_{i=1} \alpha_s^i L^{2i-1} + \sum_{i=1} \alpha_s^i L^{2i-2} + \sum_{i=2} \alpha_s^i L^{2i-3} + \sum_{i=2} \alpha_s^i L^{2i-4} + \sum_{i=3} \alpha_s^i L^{2i-5}$$

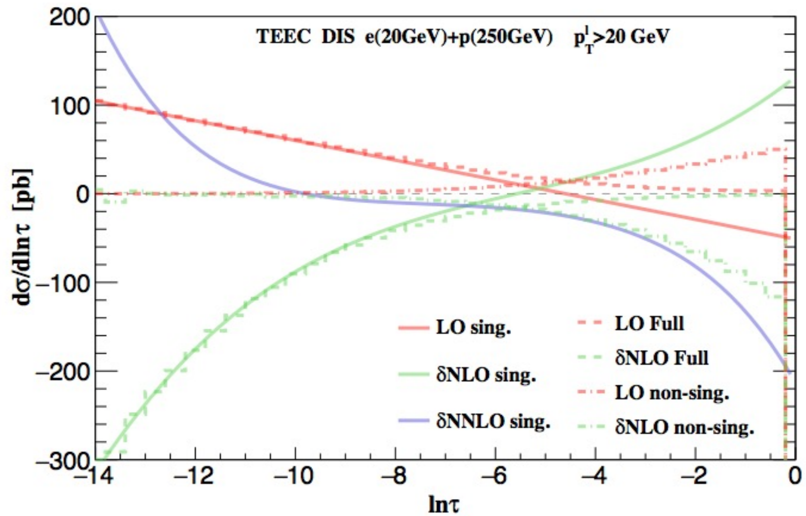
NLL NNLL NNNLL

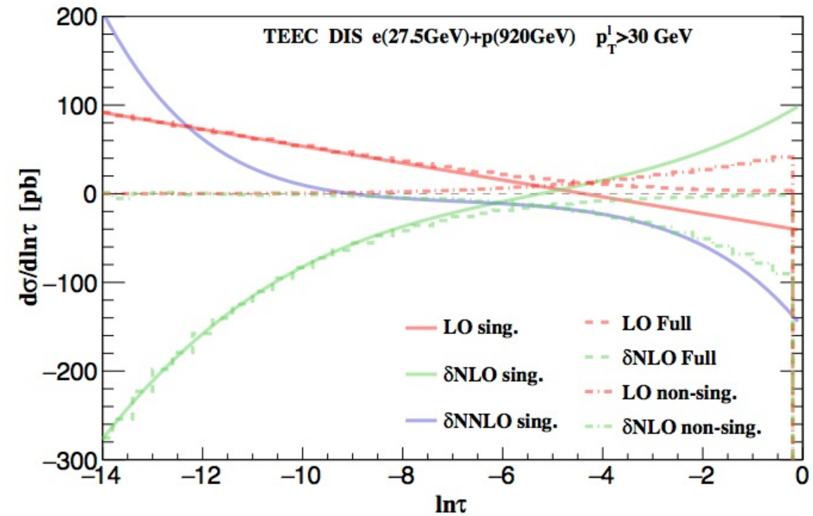
Fixed order in back-to-back limit

The leading order process is



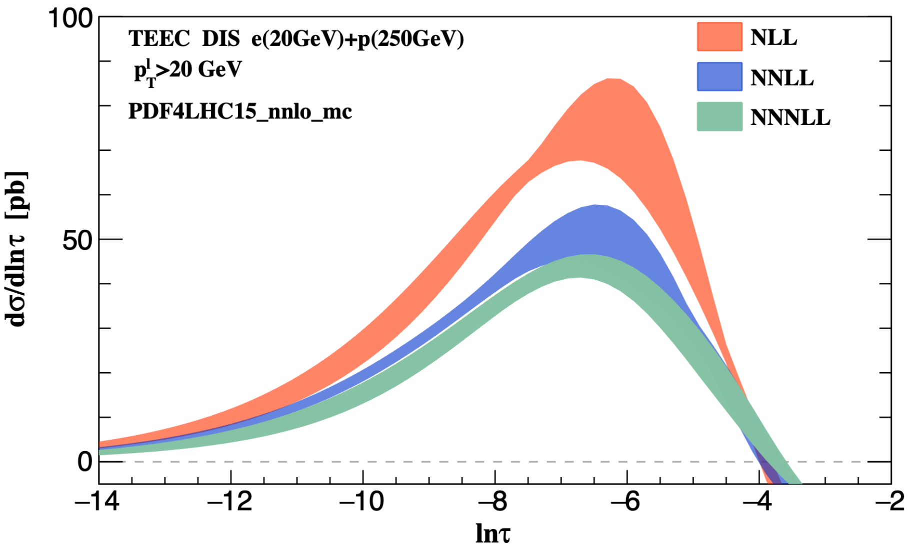


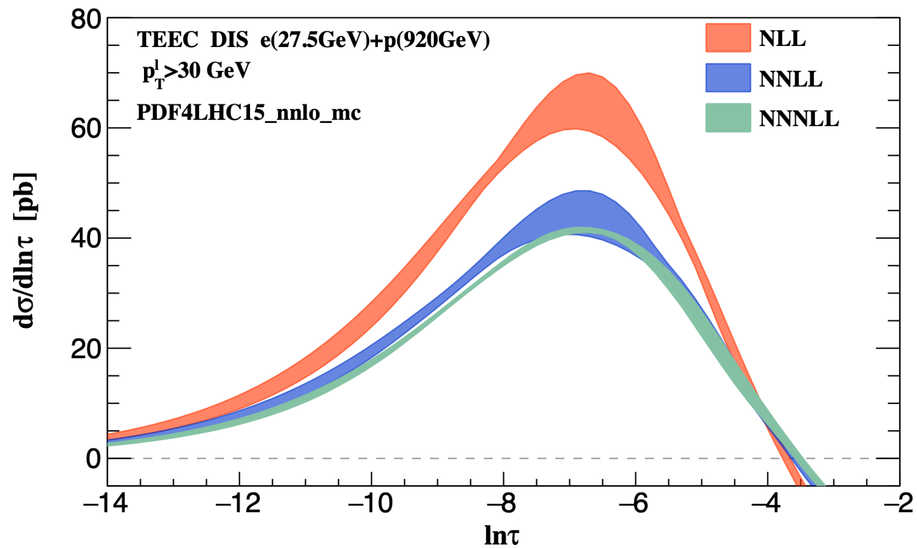




Full control of the distributions in the back-back limit

Resummation in the back-to-back limit





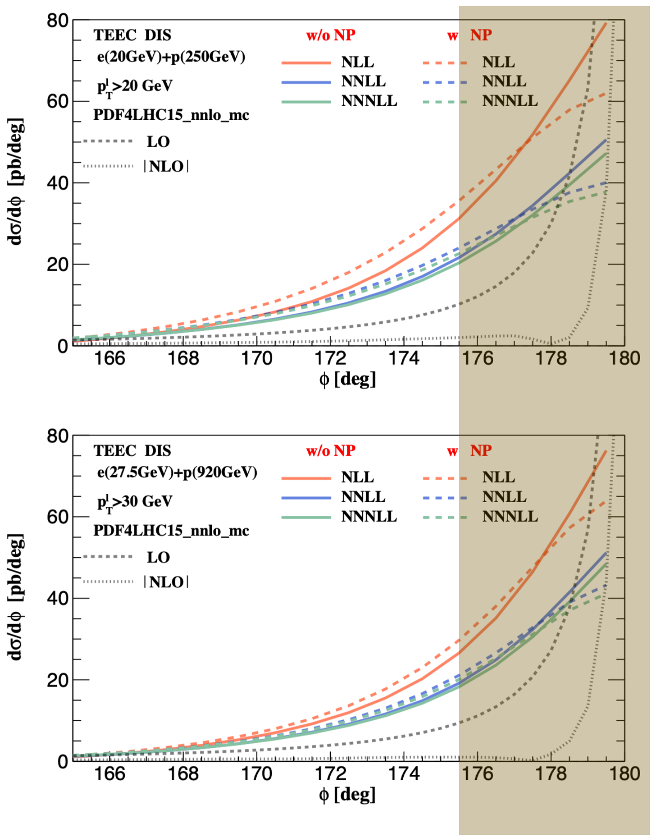
This is the highest resummed accuracy achieved in DIS

- Convergence in back-to-back limit after resummation
- Resummation works better for higher energy collider due to larger scale hierarchy
- Huge difference from NLL to NNLL and good perturbative convergence from NNLL to NNNLL
- Reduction of scale uncertainties order by order from NLL to NNNLL

Final results and NP corrections

$$S_{NP} = \exp[-0.106 b^2 - 0.84 \ln Q/Q_0 \ln b/b^*]$$

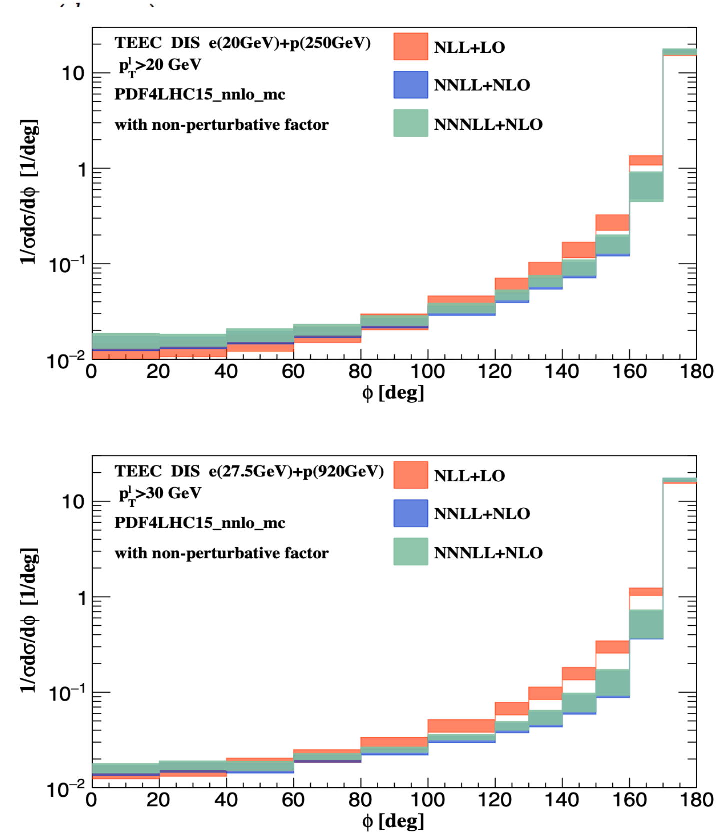
$$\frac{d\sigma_{\mathrm{N^kLL+N^kLO}}}{d\tau} = \frac{d\sigma_{\mathrm{N^kLL}}}{d\tau} + \frac{d\sigma_{\mathrm{N^kLO}}}{d\tau} - \left(\frac{d\sigma_{\mathrm{N^kLO}}}{d\tau}\right)_{\mathrm{sing.}}$$



Finite after resummation

Relative large NP effects

Nuclear matter effects are expected in this region



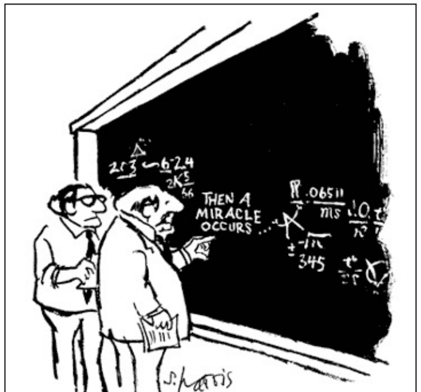
NP shifts the cross section

NNLO matching will improve the predictions

Uncertainties from fixed order are dominated

Prediction in full ϕ range

II. Energy Energy Correlations in the Breit frame



"I think you should be more explicit here in step two."

TMD physics

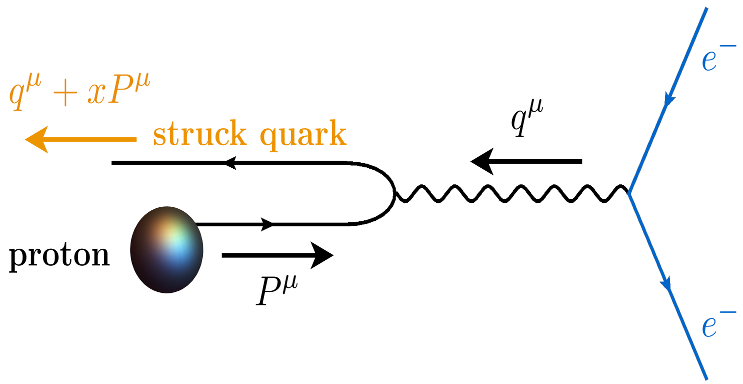
The Breit frame

Traditionally used in DIS

$$q^\mu = \frac{Q}{2}(\bar{n}^\mu - n^\mu) = Q(0,0,0,-1)$$

$$p_q^\mu = xP^\mu + q^\mu \simeq (Q/2)\bar{n}^\mu$$

$$P^\mu \simeq Q/(2x_B)n^\mu = Q/(2x_B)(1,0,0,+1)$$



$$z_a = \frac{P\cdot p_a}{P\cdot q} \xrightarrow[\text{frame}]{\text{Breit}} z_a = n\cdot p_a/Q = p_a^+/Q$$

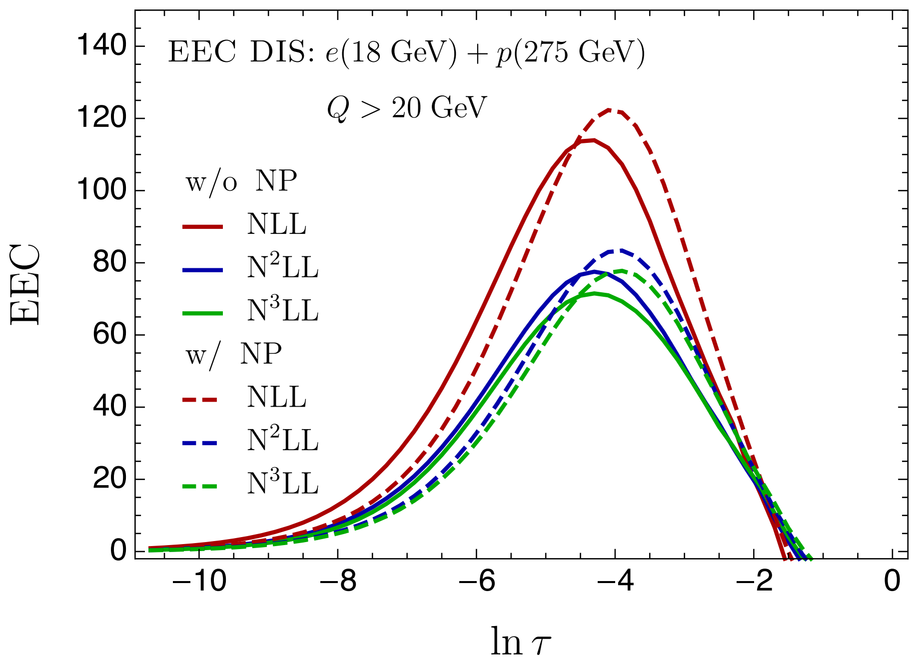
$$\sum_a z_a = 1$$

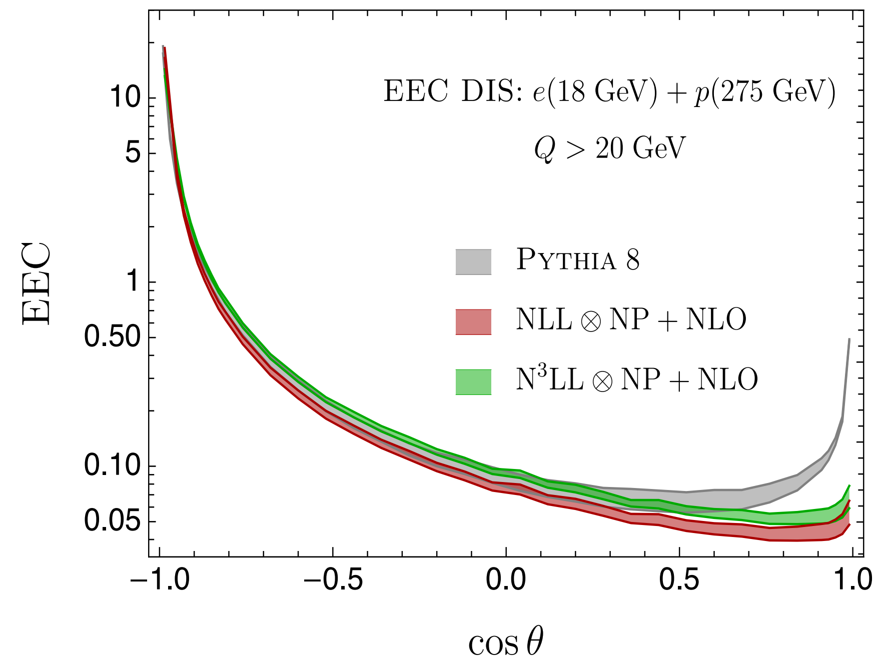
- Invariant energy fraction taken by the particle
- Sum over all particles form the struck quark, no scattered lepton included

Goal: ``Backward-EEC" (or BEEC) to emphasize that this is a new definition which focuses to the contribution of the back-scattered struck quark direction

Definition spherically invariant

Numerical results – non-perturbative effects, comparison





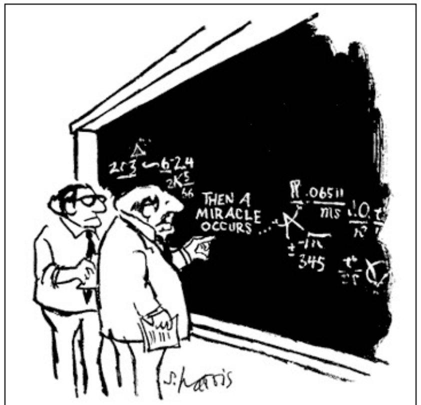
Resummed ln(tau) distributions without (solid) and with non-perturbative factor.

$$f_{\rm NP} = \exp\left(-0.106\, b^2 - 0.84 \ln Q/Q_0 \ln b/b^* \right)$$

Non-perturbative factor

Comparison of cos(theta) distributions between the SCET Predictions and PYTHIA simulations. The dark red and dark green bands are the NLL+NLO and N3LL+NLO. The gray band are from PYTHIA 8 simulations with the default settings for uncertainty bands.

II. Energy Energy Energy correlators inside jets



“I think you should be more explicit here in step two.”

spin correlations?

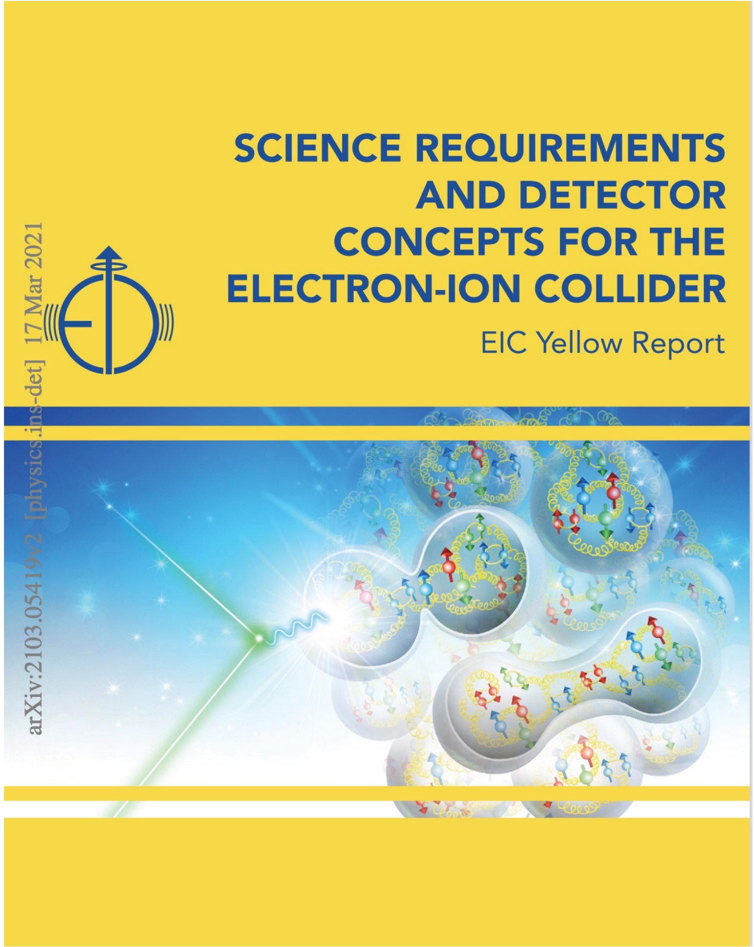
I was asked can those effects be observable

Your reference is the recently completed Yellow Report

- Has physics but also CM energies and kinematics, detector coverage, luminosities

Note that the energies are very different from what you are used to at the LHC.
The absolute kinematic cutoff for jets is pT = 70 GeV at the highest CM energy, probably 40 is the largest usable.

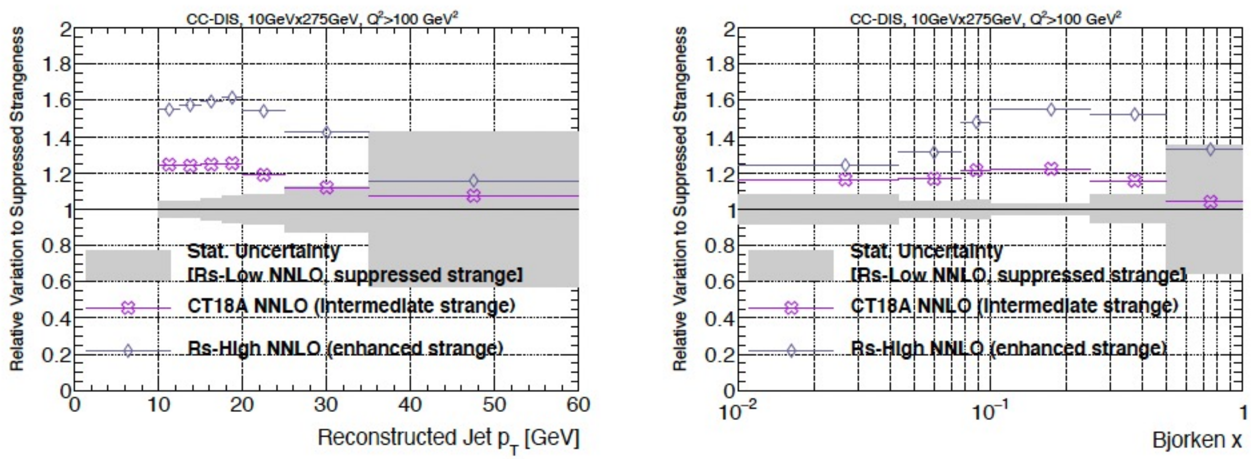
Without simulations the discussion will remain academic



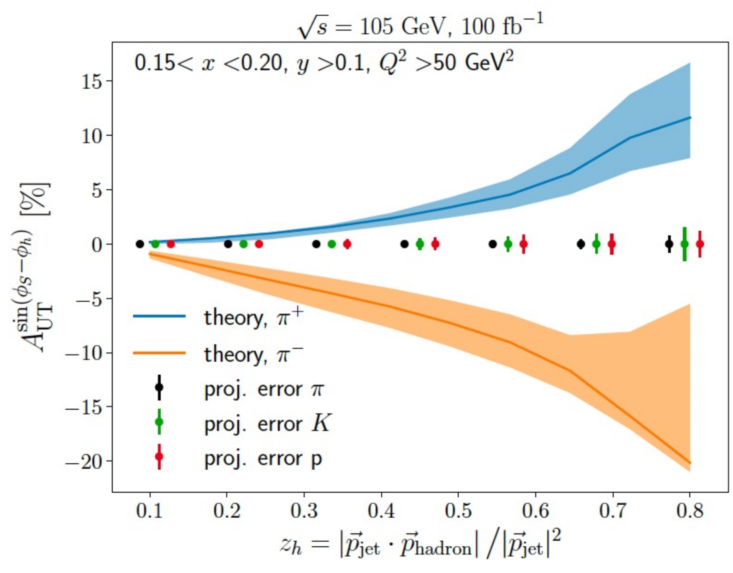
•e-Print: 2103.05419 [physics.ins-det]

Sensitivity to relatively weak signals

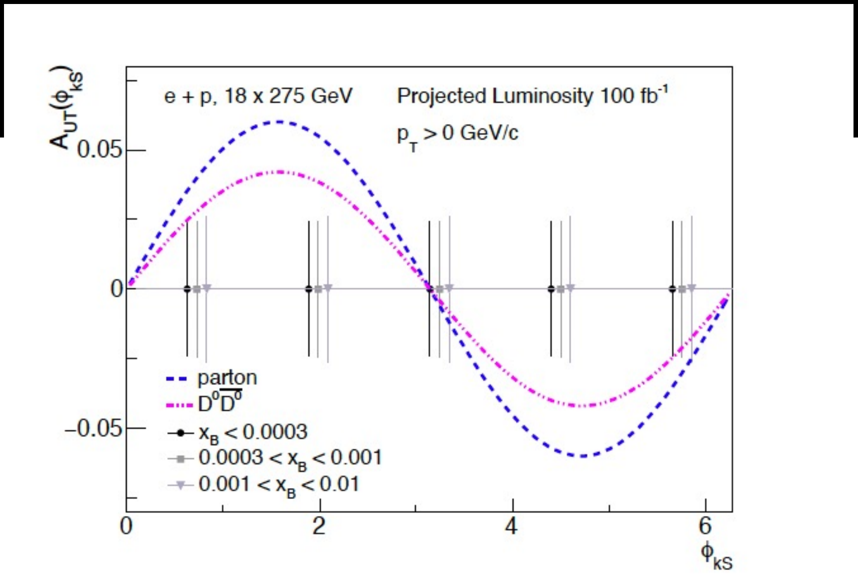
Charge current DIS with 10 years of EIC running - uncertainties from a few % to 40%



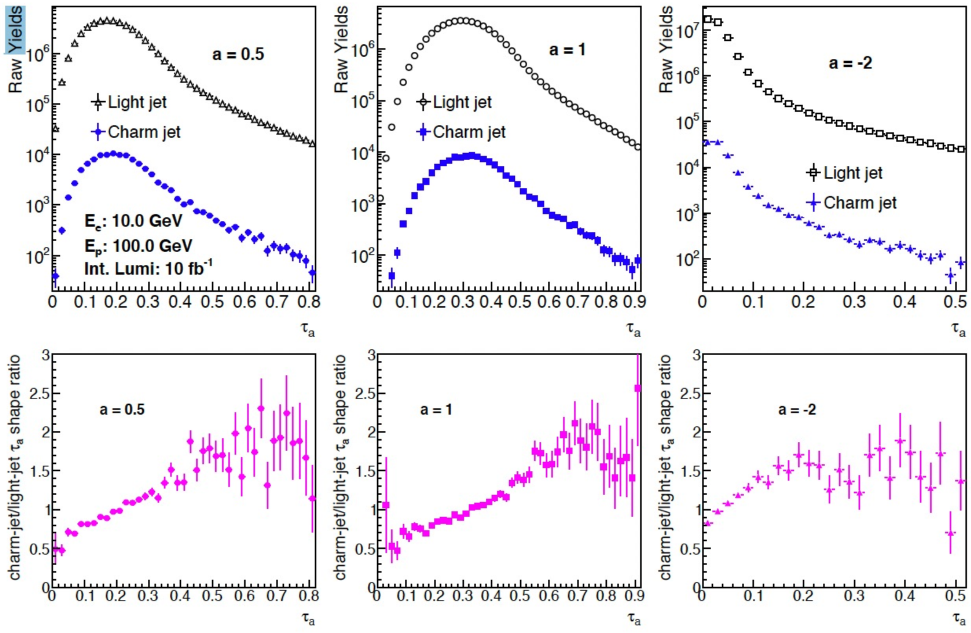
Production of hadrons in jets and their asymmetry - from sub 1% to a few % uncertainty for 10 y of running the EIC



Sensitivity to relatively weak signals



Back to back D – D-bar correlations 10 years of EIC running - uncertainties 2 % to 3%

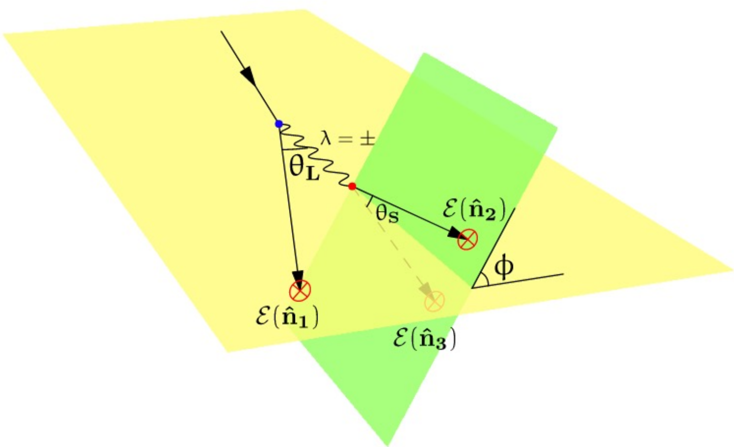


Non spin dependent pbservables are easier to measure 1 year of EIC running - uncertainties few % to 10 %

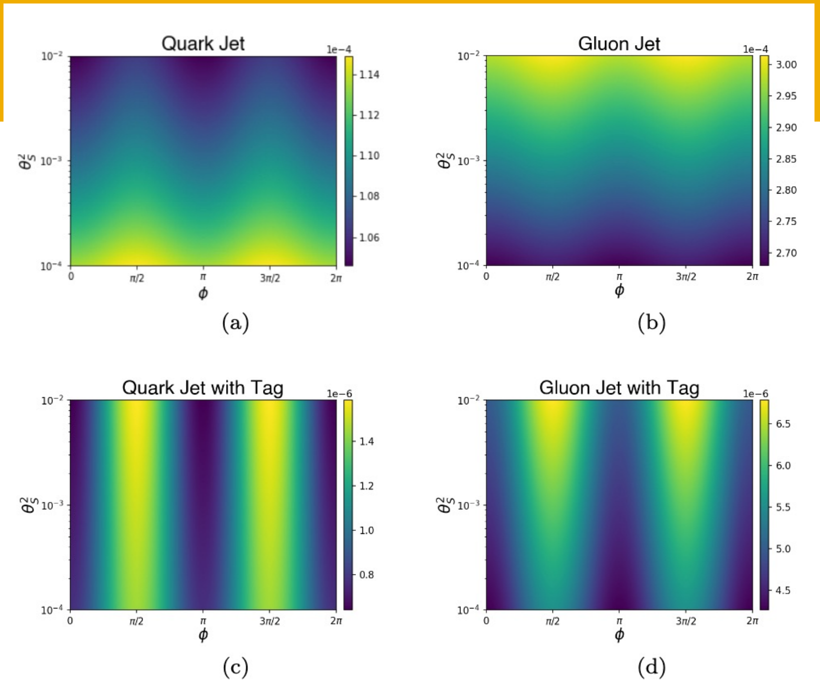
$$\tau_a = \frac{1}{p_T} \sum_{i \in J} p_T^i (\Delta R_{iJ})^{2-a}$$

EEEC correlations

If I understand correctly come at an order higher (relative to more traditional intrajet observables that we have creatively renamed substrcture)



(b)

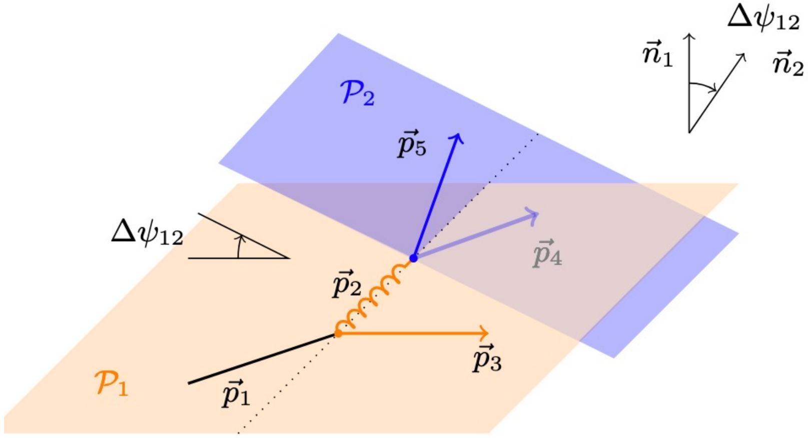


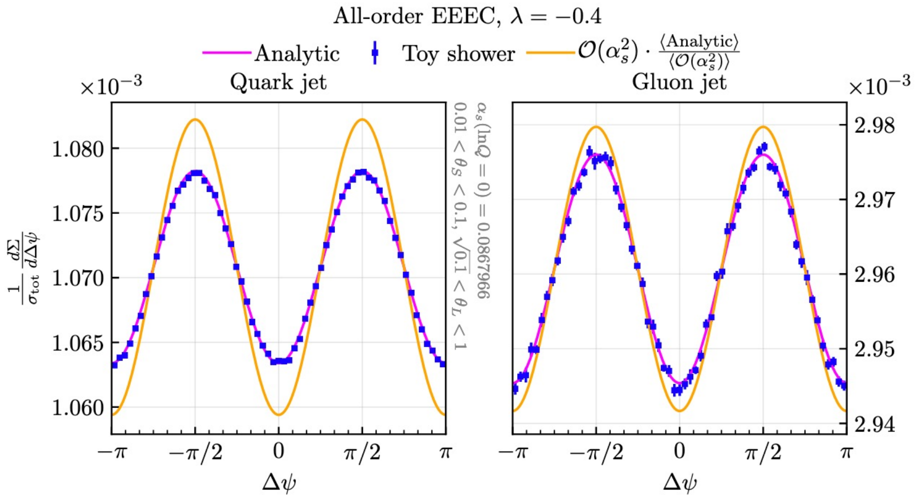
Do I read this correctly – the color legend to be O(0.1%) effect ?

Thanks to the first speakers that clarified in their talk the magnitude of the modulation O(1%) but strategies can be implemented to enhance it to ~ 10% at the partonic level

EEEC correlations

If I understand correctly come at an order higher (relative to more traditional intrajet observables that we have creatively renamed substrcture)





The authors comment that the correlation is small It is 0.1%

Thanks to the first speakers that clarified in their talk the magnitude of the modulation O(1%)

EEEC correlations summary

Theoretically very interesting

I think I. Moult, D. Neill, … are looking at such observable at the EIC

It seems to me that the *effect it will be very difficult to measure at the EIC even with 10 years of running. If strategies are applied to enhance it – could be doabe*

Of course the answer can only be gotten with simulation …

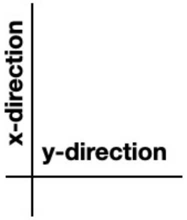
Hadronization effects should be considered and will likely reduce the asymmetries

Perhaps focus on the simpler energy-energy correlator inside the jet first

Conclusions

- Transverse energy-energy correlators TEEC to DIS - promising way to study TMD physics and non-perturbative effects
- Backward energy-energy correlators in the Breit frame BEEC – to further elucidate the connection to TMD physics. Less sensitive to rapidity cuts
- EEEC are theoretically very interesting. No work yet at the EIC. The effects are very small – 1%. Likely difficult to measure but simulations needed
- Pay attention to non-perturbative effects

Kinematics and connection to hadron production

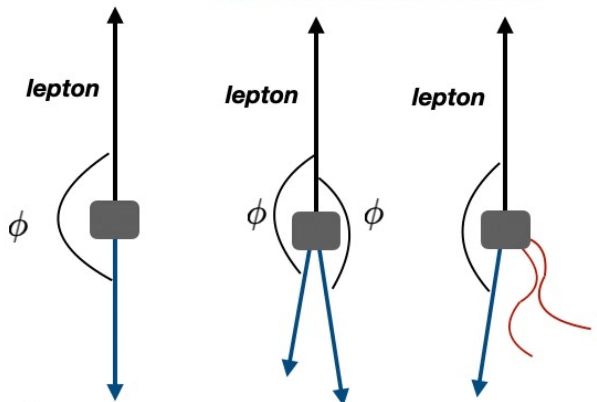


Define scattering plane: x-z

To LO y=o

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

Collinear&Soft radiation



$$\tau = \frac{1+\cos\phi}{2} \qquad \delta(\tau) \qquad A\delta(\tau) + B\frac{1}{\tau} + C\frac{\ln\tau}{\tau}\cdots$$

For Hadron production

$$\frac{d\sigma_h}{d^2p_\perp} = \sum_f \int \frac{d\xi dQ^2}{\xi Q^2} Q_f^2 H(Q,\mu) \int \frac{db}{2\pi} e^{ib_\perp\cdot p_\perp} \boxed{f_{f/N}\left(b,\xi,\mu,\nu\right)} \boxed{S\left(b,\frac{n_2\cdot n_4}{2},\mu,\nu\right)} \boxed{\int \frac{dz}{z^2} F_{h/f}\left(z,b/z,E_4,\mu,\nu\right)}$$

TMD PDF

TMD soft

TMDFF

For TEEC

- ☑ Transverse energy weighted
- ☑ Measuring vector sum in 1-dimensional
- ☑ sum over all hadrons in the final state

$$\frac{d\sigma_h}{d\tau} = \sum_f \int \frac{d\xi dQ^2}{\xi Q^2} Q_f^2 H(Q,\mu) \int dk_y \int \frac{db}{2\pi} e^{-ib_y\cdot k_y} f_{f/N}\left(b,\xi,\mu,\nu\right)$$

$$S\left(b,\frac{n_2\cdot n_4}{2},\mu,\nu\right) \sum_h \int zdz\; F_{h/f}\left(z,b/z,E_4,\mu,\nu\right) \delta(\tau-\tau(k_y))$$

$$\tau = \frac{\left|k_{2,y} - k_{s,y} + \frac{k_{4,y}}{\xi_4}\right|^2}{4p_T^2}$$

Y component generated by soft and collinear radiation

Factorization ingredients

Effectively $(b_x, b_y) \to (0, b_y)$ TMD PDFs can be used

$$S_{\rm DIS}(b) \equiv \frac{1}{N_c}\,{\rm Tr}\left\langle 0 \left| \bar{T}\left[Y_{n_2}(0)Y^{\dagger}_{n_4}(0)\right]^{\dagger} T\left[Y_{n_2}(0)Y^{\dagger}_{n_4}(0)\right] \right| 0 \right\rangle$$

TEEC soft function $S\left(b, \frac{n_2 \cdot n_4}{2}, \mu, \nu\right) = S_{\rm TMD}\left(L_b, L_\nu + \ln\frac{n_2 \cdot n_4}{2}\right)$ **TMD soft function**

Jet function

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

FFs — Matching Coefficients

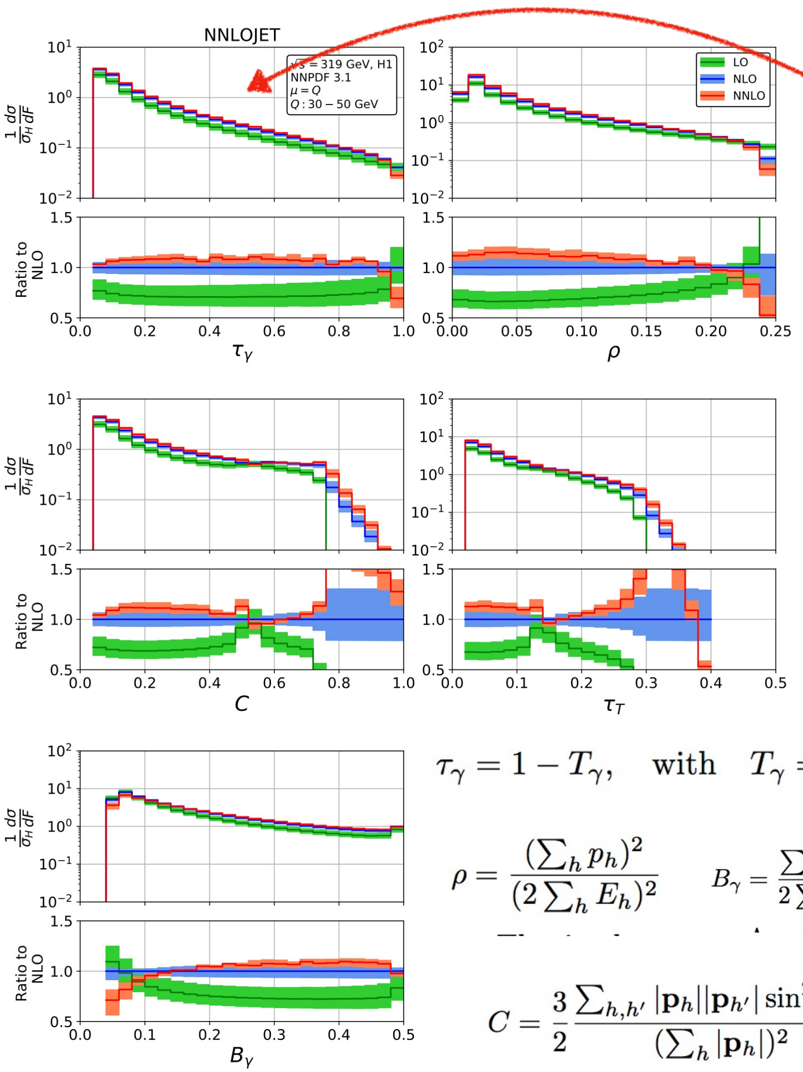
$$\sum_N \int_0^1 dzz F_{N/q}\left(z, b_\perp/z, \nu\right) = \sum_{i,N}\int_0^1 dzz \int_z^1 \frac{d\xi}{\xi}\, \boxed{d_{N/i}(z/\xi)}\, \boxed{\mathscr{C}_{iq}\left(\xi, b_\perp/\xi, \nu\right)} + \mathcal{O}\left(b_T^2\Lambda^2_{\rm QCD}\right) = \sum_{i,N}\int_0^1 dxx\mathscr{C}_{iq}\left(x, b_\perp/\xi, \nu\right)\boxed{\int_0^1 d\xi\xi d_{N/i}(\xi)} + \mathcal{O}\left(b_T^2\Lambda^2_{\rm QCD}\right)$$

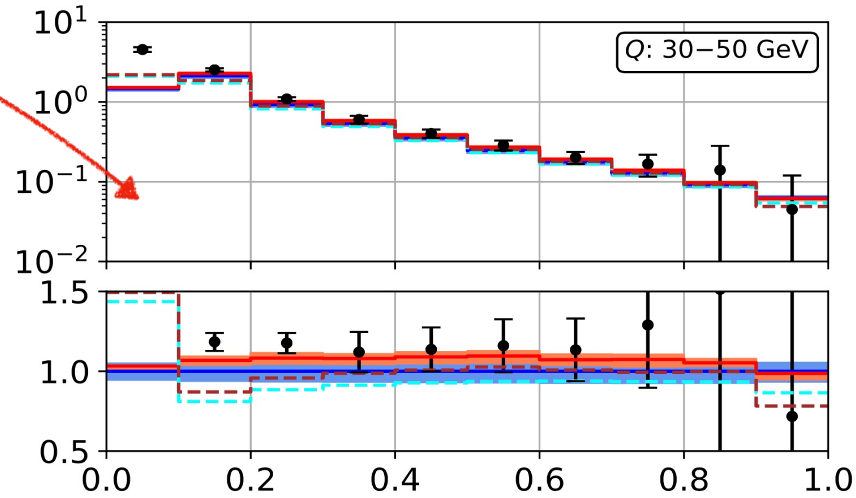
Momentum conversvation

The jet function is the second Mellin-moment of the matching coefficients

$$J^q\left(b_\perp, \mu, \nu\right) = \sum_i \int_0^1 dxx\mathscr{C}_{iq}\left(x, b_\perp/x, \mu, \nu\right)$$

NNLO event shapes





with non-perturbative corrections

$$\tau_\gamma = 1 - T_\gamma, \quad \text{with} \quad T_\gamma = \frac{\sum_h |p_{z,h}|}{\sum_h |\mathbf{p}_h|}$$

$$\rho = \frac{(\sum_h p_h)^2}{(2\sum_h E_h)^2} \qquad B_\gamma = \frac{\sum_h |\mathbf{p}_{t,h}|}{2\sum_h |\mathbf{p}_h|}$$

$$C = \frac{3}{2}\frac{\sum_{h,h'} |\mathbf{p}_h||\mathbf{p}_{h'}|\sin^2\theta_{hh'}}{(\sum_h |\mathbf{p}_h|)^2}$$

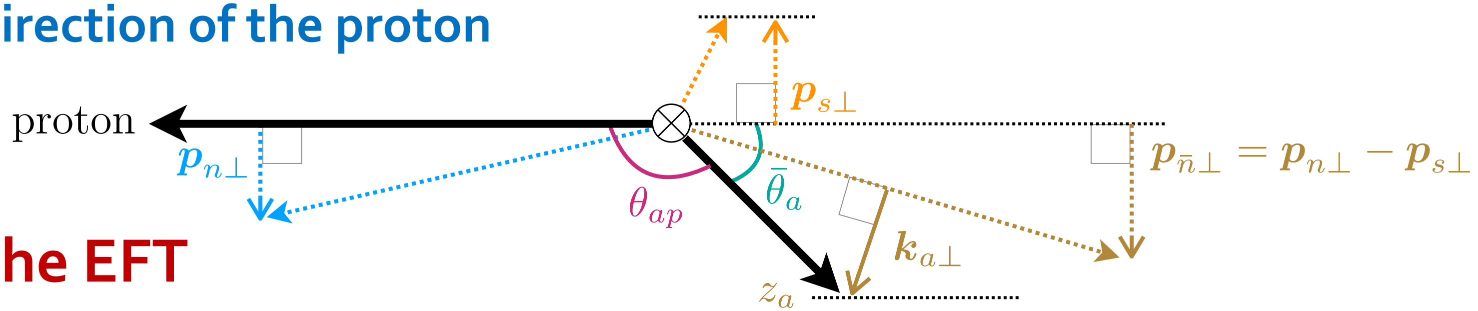
- It is not always to be true that NLO will improve the theoretical uncertainties
- NNLO corrections reduce the uncertainties
- Large nonperturbative corrections for most of event shape variables

Gehrmann, Huss, Mo, Niehues, 2019

BEEC Definition, EFT modes, factorization

$$\text{BEEC} = \frac{1}{\sigma}\sum_a \int d\sigma(\ell + h \to \ell + a + X)\, z_a\, \delta(\cos\theta_{ap} - \cos\theta)$$

θ_{ap} **Opening angle between the direction of the particle and the direction of the proton**



Modes in the EFT

$$n\text{-collinear}: \quad p_n^\mu \sim Q(\lambda^2, 1, \lambda)$$

$$\bar{n}\text{-collinear}: \quad p_{\bar{n}}^\mu \sim Q(1, \lambda^2, \lambda)$$

$$\text{soft}: \quad p_s^\mu \sim Q(\lambda, \lambda, \lambda)$$

- Expanding around the quark direction one sees the relation to TMD physics

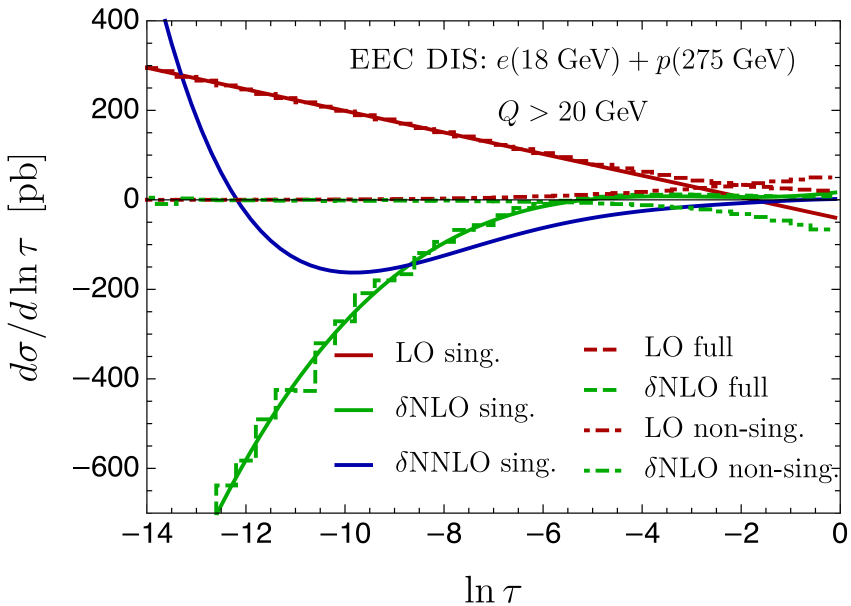
$$\frac{\pi - \theta_{ap}}{2} = \frac{\bar{\theta}_a}{2} \simeq \frac{|\boldsymbol{q}_\perp|}{Q} \simeq \frac{1}{Q}\left|\frac{\boldsymbol{k}_{a\perp}}{z_a} + \boldsymbol{p}_{n\perp} - \boldsymbol{p}_{s\perp}\right|$$

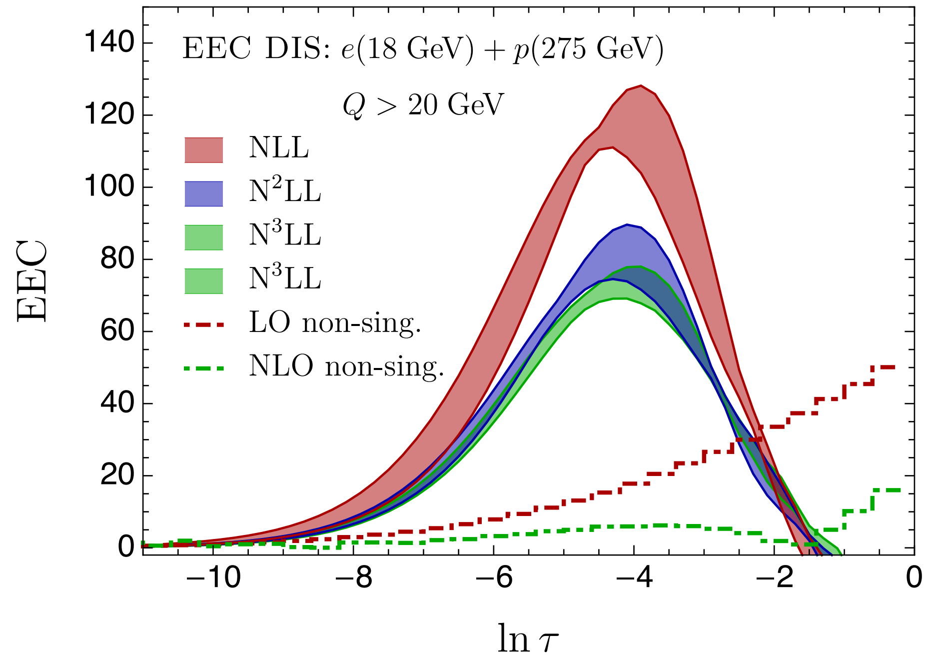
$$\frac{d\sigma_a}{dx\,dQ^2\,dz\,d\tau} = \int d\boldsymbol{q}_\perp \frac{d\sigma_a}{dx\,dQ^2\,dz\,d\boldsymbol{q}_\perp}\delta\left(\tau - \frac{|\boldsymbol{q}_\perp|^2}{Q^2}\right)$$

$$\frac{d\sigma_a}{dx\,dQ^2\,dz\,d\boldsymbol{q}_\perp} = \sigma_0(Q,x,y)H_{ij}(Q,x;\mu)\int\frac{d\boldsymbol{b}}{(2\pi)^2}$$
$$\exp(-i\,\boldsymbol{b}\cdot\boldsymbol{q}_\perp)B_{j/P}(x,b;\mu,\nu)D_{i/a}(z,b;\mu,\nu)S(b;\mu,\nu)$$

TMD factorization

Numerical results – FO calculations and resummation





Fixed order full QCD cone with NLOJET++

Fixed-order ln(tau) distributions in z -> 1 limit. The solid lines represent the singular distribution prediction by SCET. The dashed lines are the fixed order QCD results. The dash-dotted lines are power corrections.

Resummed ln(tau) $ distributions for EEC. The dark red, dark blue, and dark green bands correspond NLL, NNLL, and NNNLL distribution. The dot-dashed lines are the LO non-singular distributions (dark red) and the absolute value of NLO non-singular ones (dark green)