Jets at ePIC, Status & Prospects

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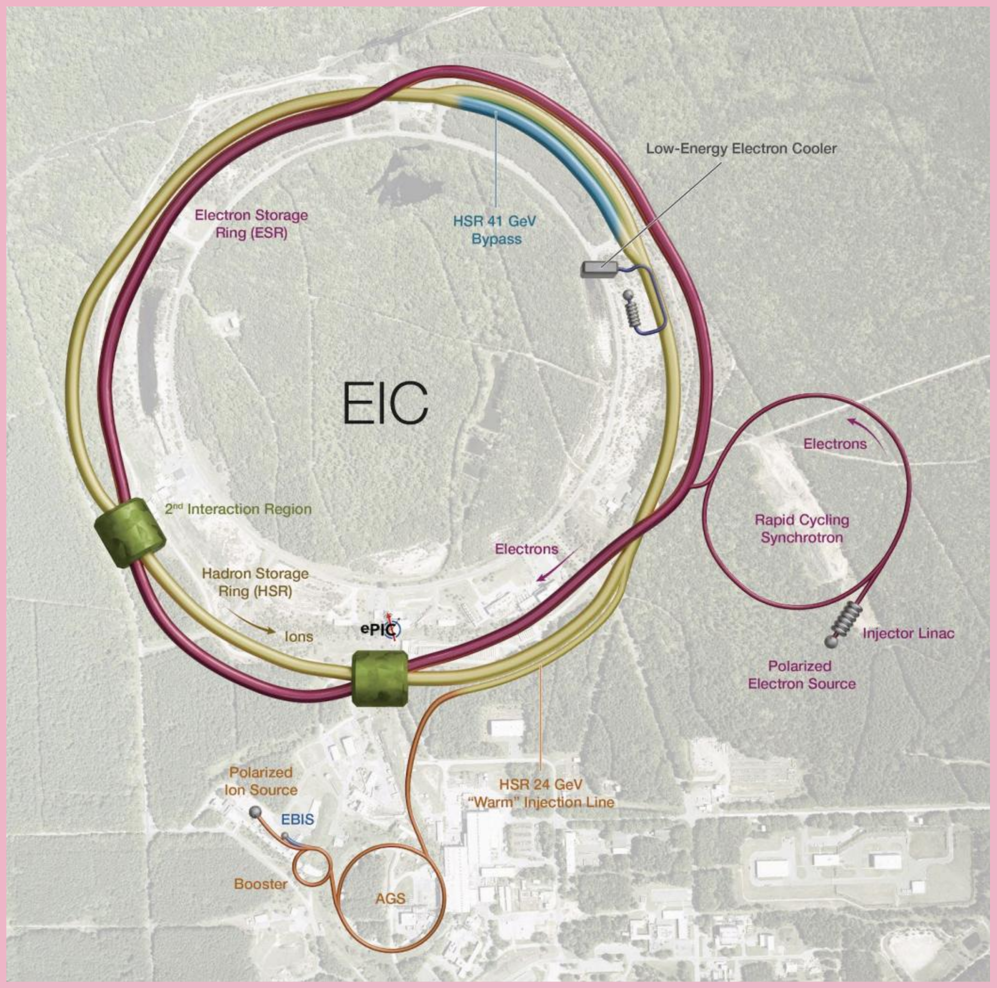
For the ePIC Collaboration

Outline

1) **Introduction,** EIC Physics Goals
2) **Jets in DIS**
3) **ePIC,** a summary
4) **Ongoing Jet Efforts**
5) **Conclusion**

Introduction | The EIC

- **The Electron-Ion Collider (EIC):** add electron storage ring alongside existing RHIC yellow ring, new electron acceleration ring
  - Hosted jointly by BNL & JLab
  - ☞ **Also see:**
    - EIC/ePIC Session [05.20]
    - HF at ePIC [D. Dongwi, 05.20]
    - ePIC: status & plans [D. Brandenburg, 05.23]

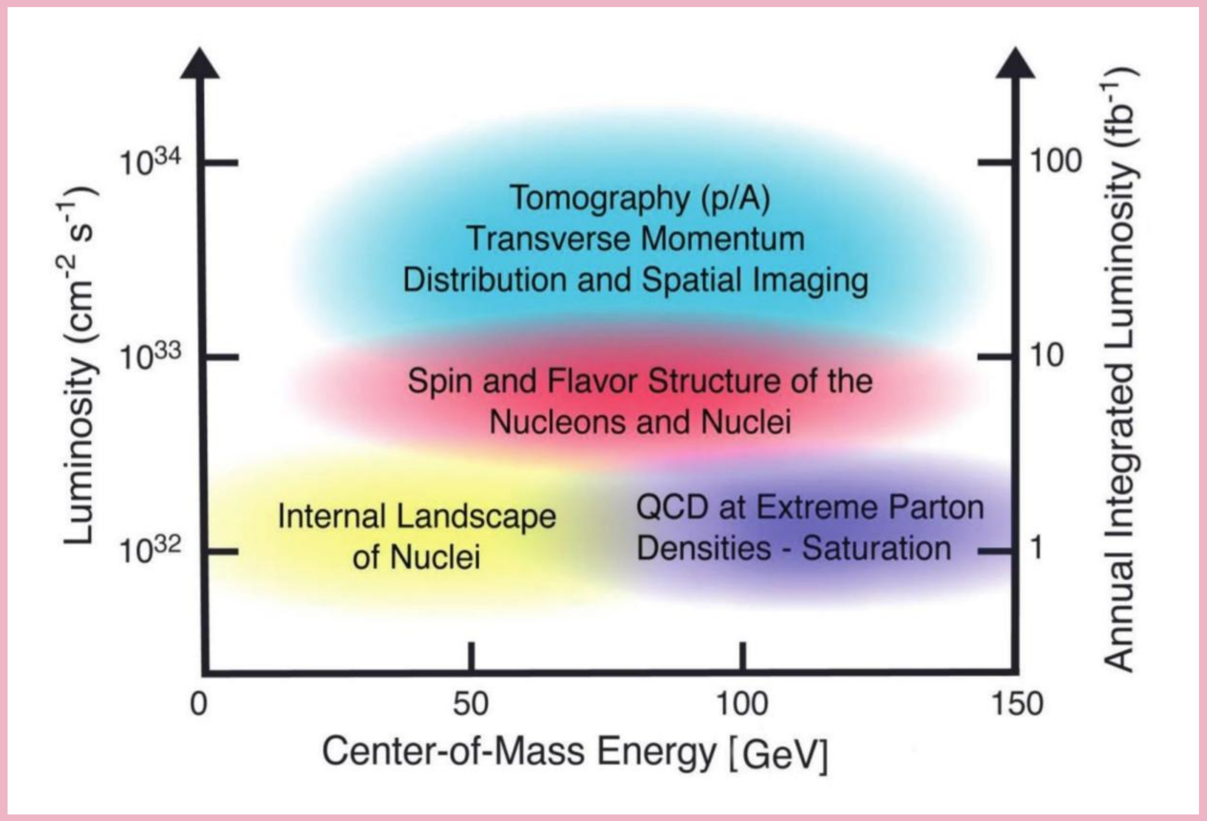


- **A few details:**
  - e^- energies = 5 – 18 GeV
  - Ion energies = 40 – 275 GeV
    - $\Rightarrow \sqrt{s} = 29 - 141$ GeV/u
  - Ion species from proton – Uranium
    - ☞ Up to 70% polarization for light ions (p – He)

Introduction | EIC Physics Program (1/2)

- **EIC purpose-built to study internal structure of nuclei and the emergent dynamics of QCD**

- **Right:** major topics to be explored at EIC vs. required luminosities & CoM energy
  - **(n)PDFs**
  - **Spin/flavor structure of nuclei**
  - **Saturation/extreme parton density**
  - **TMDs/GPDs**
- Accessed via wide variety of channels:
  - NC DIS
  - CC DIS
  - SIDIS
  - Exclusive



☞ **Where do jets fit in?**

Introduction | EIC Physics Program (2/2)

- **EIC purpose-built to study internal structure of nuclei and the emergent dynamics of QCD**

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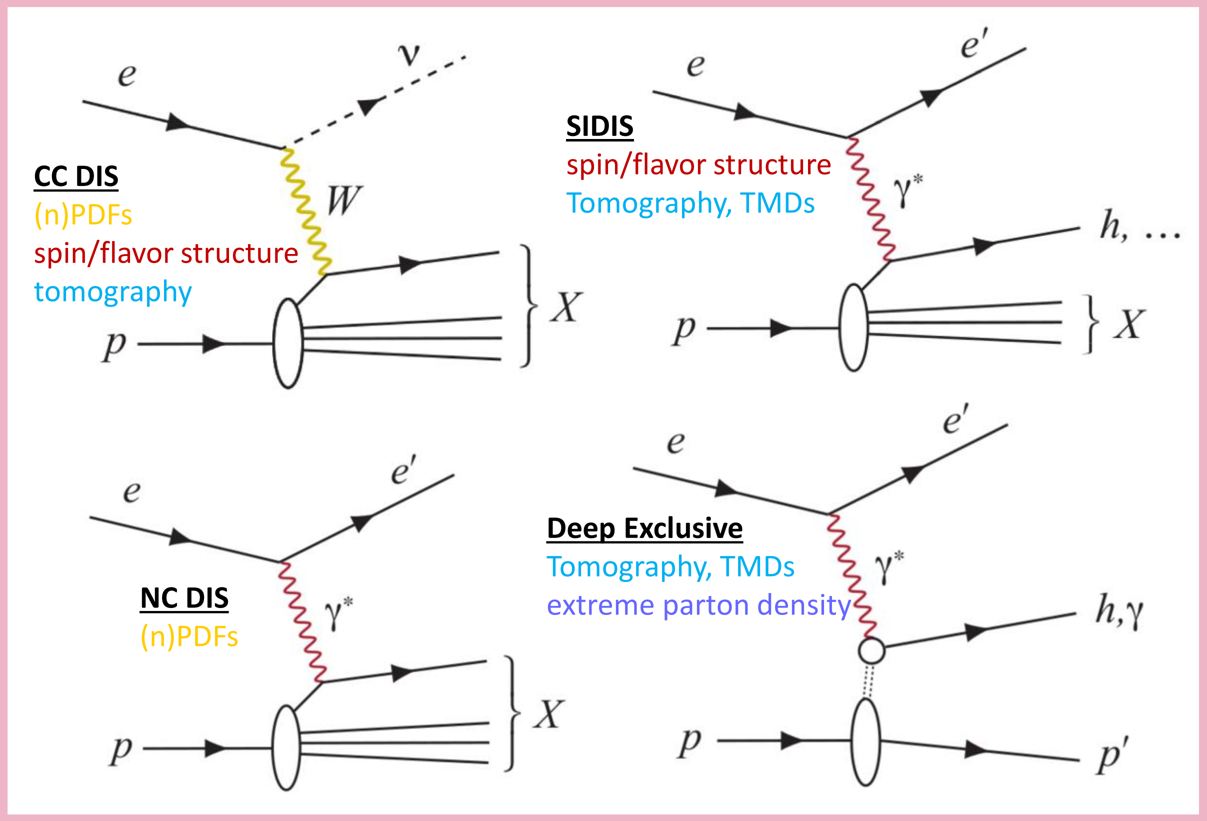
☞ **Where do jets fit in?**

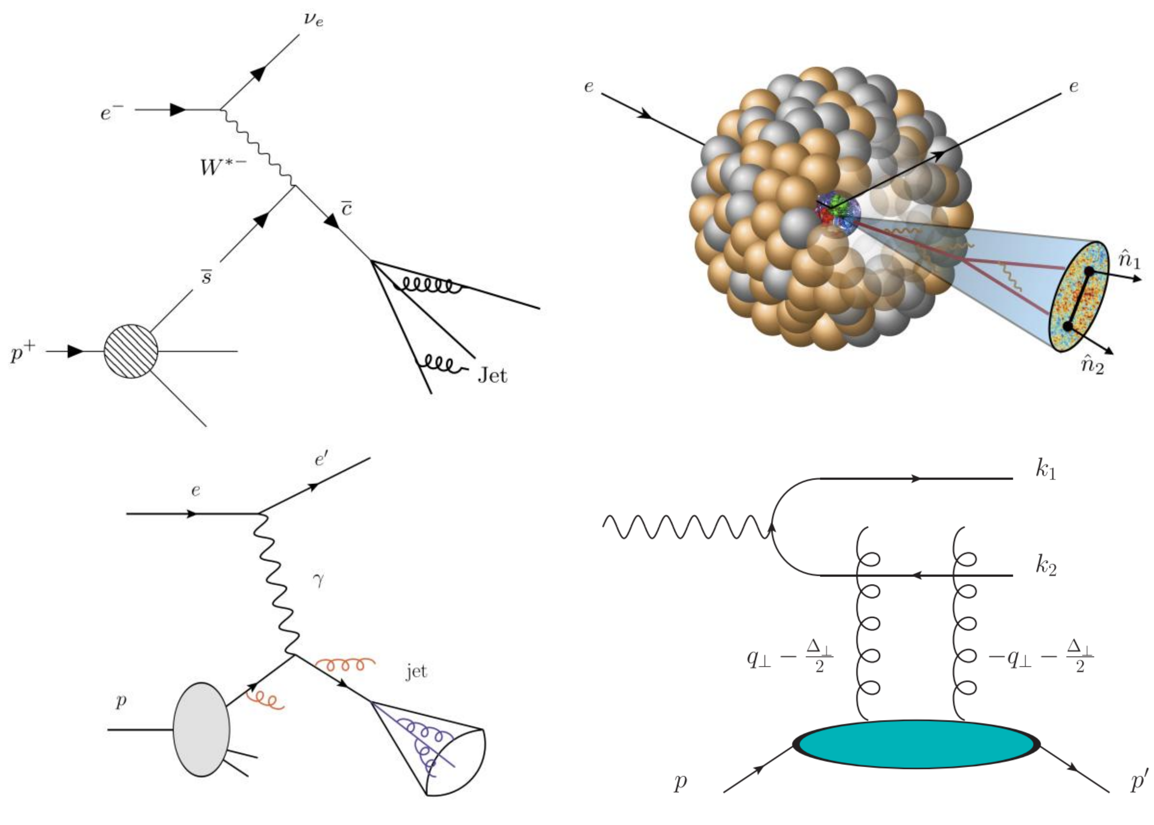


Introduction | Jets vs. EIC Physics Goals

- **Jets are extremely powerful probes!**
  - Dynamically generated, sensitive to ***many*** scales
  - Good proxy for parton kinematics
  - Like SIDIS (multiple particles in FS), but also encode correlations b/n particles
    - ☞ **Via both jet clustering & substructure**

- Can provide input on all areas of EIC physics program
  - **(n)PDFs,**
    - › e.g. PRD 102, 074015 (2020)
  - **Spin/flavor structure of nuclei,**
    - › e.g. PRD 103, 074023 (2021)
  - **Saturation/extreme parton density,**
    - › e.g. PRL 116, 202301 (2016)
  - **TMDs/GPDs,**
    - › e.g. PRL 116, 202301 (2016)
  - **Cold nuclear matter effects,**
    - › e.g. arXiv:2308.08143

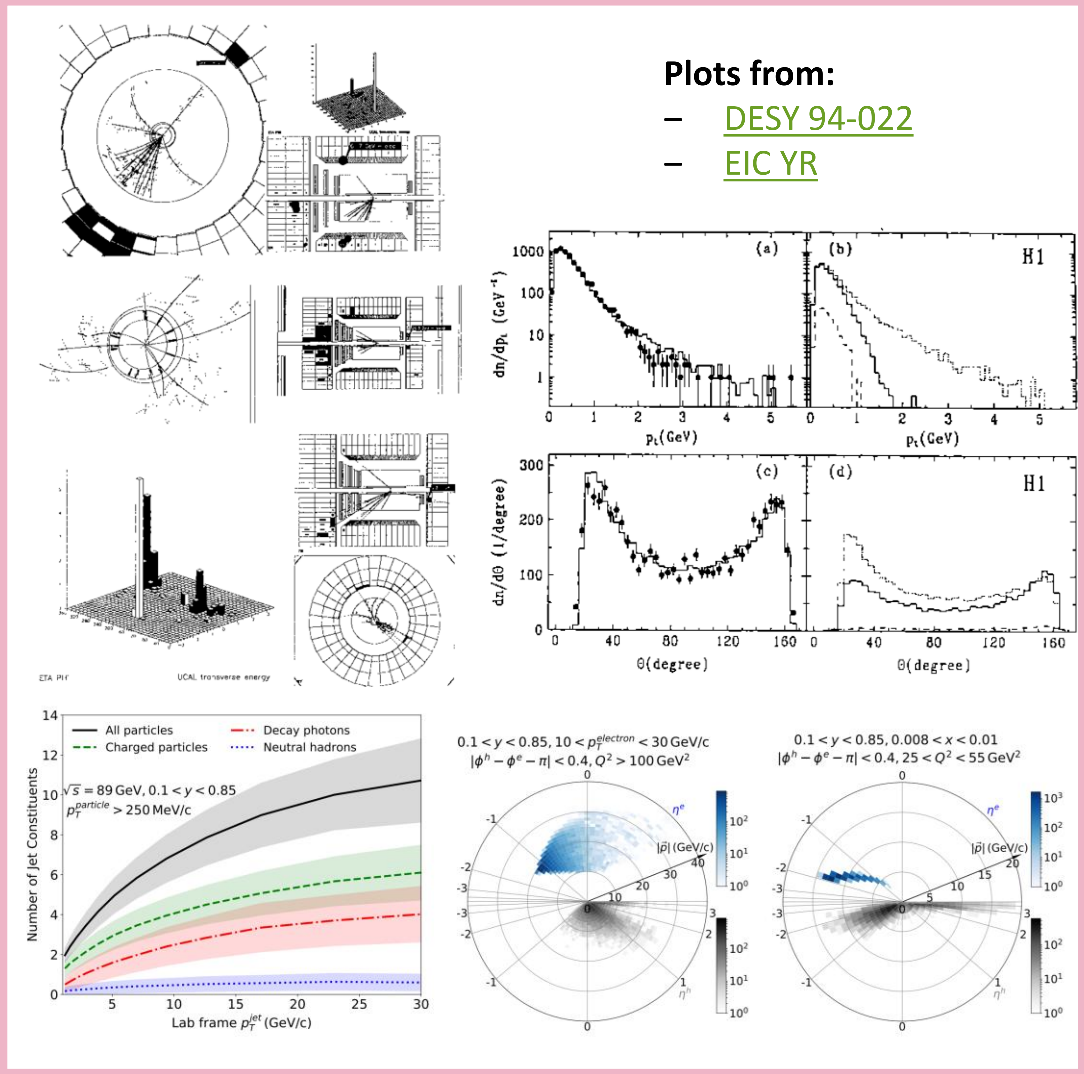
PRD 103, 074023 (2021) | arXiv:2308.08143



PRD 102, 074015 (2020) | PRL 116, 202301 (2016)

Jets in DIS | Differences Between EIC & RHIC

- Jet-finding very similar between e+h, h+h collisions, but there are key differences:
  - **Kinematics**
    - In DIS, scattered lepton completely determines event kinematics
    - *Strong* correlations b/n kinematic variables
  - **Asymmetric collisions**
    - Other frames than lab (e.g. Breit Frame) useful
    - Algorithms other than anti-k_T also useful (next slide)
  - **Much lower multiplicities**
    - e+p $\Longrightarrow \mathcal{O}(< 10)$ charged particles
    - e+Au $\Longrightarrow \mathcal{O}(10)$ charged particles
  - Wide variety of production mechanisms (previous slide)
  - Much smaller σ_{int},
    - e.g. DIS σ_{int} $\mathcal{O}(100)\times$ smaller than σ_{int} at RHIC/LHC…



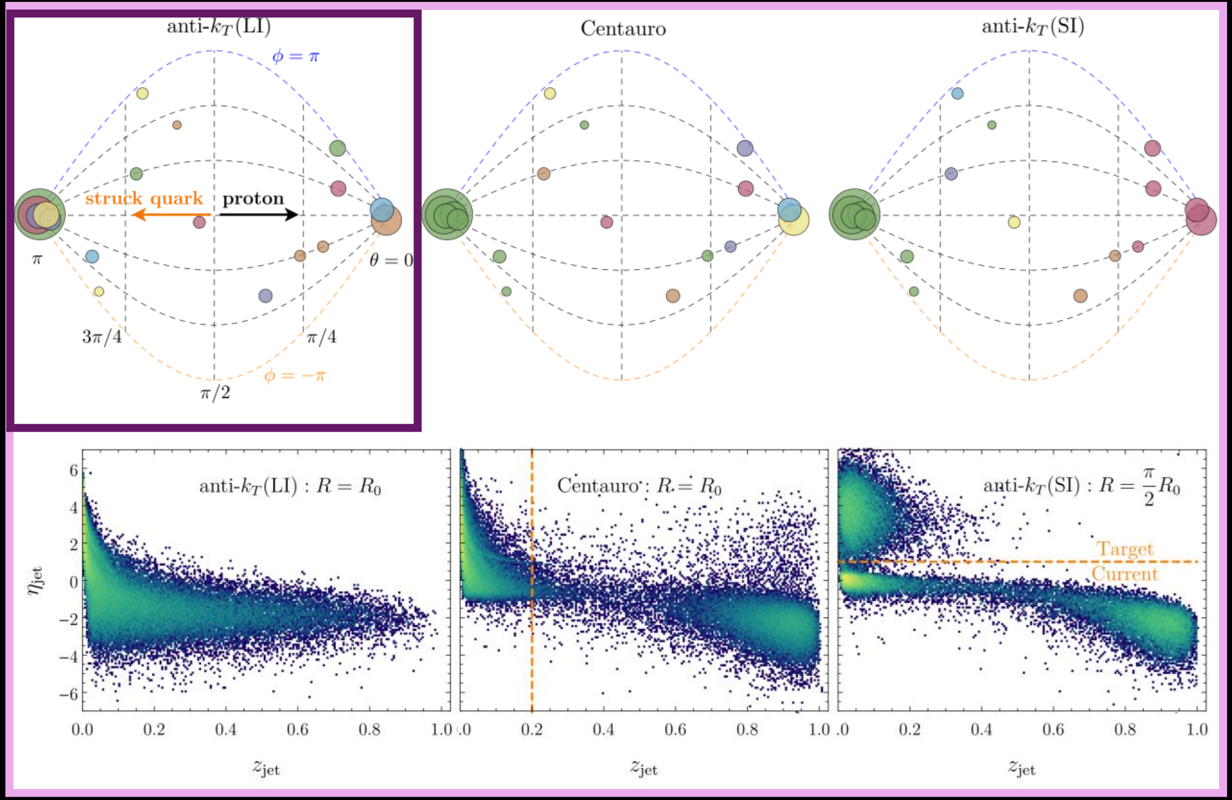
Jets in DIS | Clustering Algorithms (1/3)

- Standard in h+h collisions are (anti-) k_T algorithms

$$d_{ij} = \min\left(p_{T,i}^{2p}, p_{T,j}^{2p}\right) \Delta R_{ij}^2 / R^2,$$
$$d_{iB} = p_{Ti}^{2p}$$

  ☞ Longitudinally invariant! But not necessarily appropriate for Breit frame…
    - $p_T \sim 0$ despite large E
    - η diverges as you approach beamline

- **Right:** illustration of clustering in DIS for different algorithms



PRD 104, 034005 (2021)

$z_{jet} = P \cdot p_{jet} / P \cdot q$

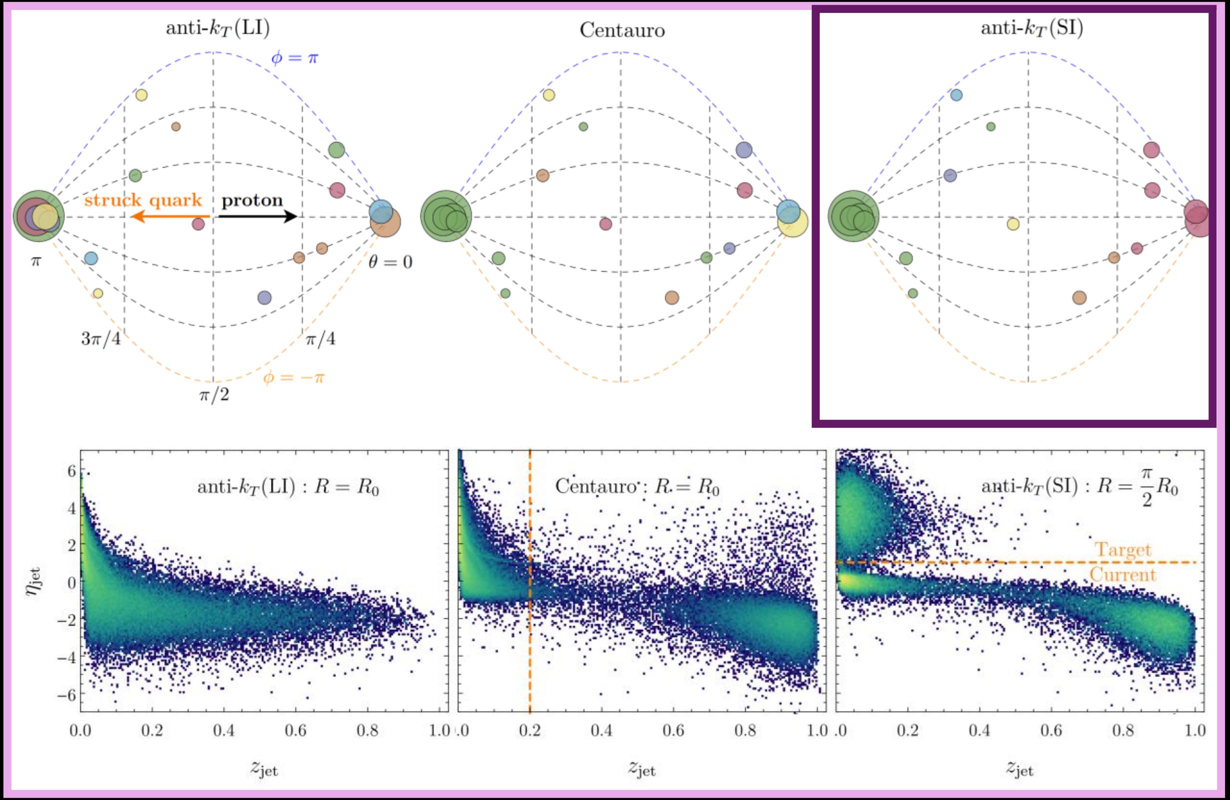
Jets in DIS | Clustering Algorithms (2/3)

- **One option:** spherically-symmetric (anti-) k_T algorithms

$$d_{ij} = \min\left(E_i^{2p}, E_j^{2p}\right)(1-\cos\theta_{ij})/(1-\cos R),$$
$$d_{iB} = E_i^{2p}$$

  ☞ Nicely separates target & current regions! But not longitudinally invariant…
  - › LI useful for multijet events,
  - › Or separating forward jets from beam

- **Right:** illustration of clustering in DIS for different algorithms



PRD 104, 034005 (2021)

$z_{jet} = P \cdot p_{jet} / P \cdot q$

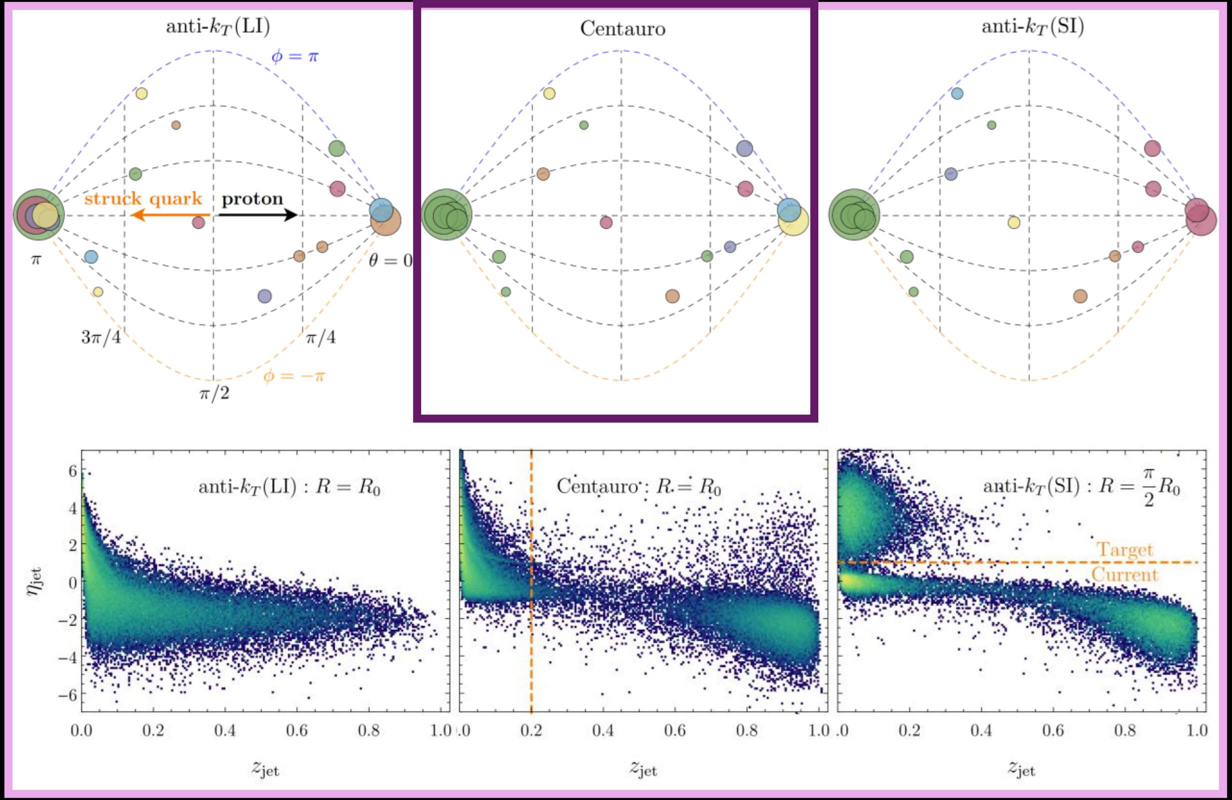
Jets in DIS | Clustering Algorithms (3/3)

- **Another option:** asymmetric algorithms, e.g. Centauro

$$d_{ij} = \left[(\Delta f_{ij})^2 + 2 f_i f_j (1 - \cos\Delta\phi_{ij})\right]/R^2,$$
$$d_{iB} = 1,$$
$$f_i = f(\bar{n}_i) = \bar{n}_i + \mathcal{O}(\bar{n}_i),$$
$$\bar{n}_i = 2p_i^{\perp}/(E_i - p_{z,i})$$

  - ☞ Behaves like a k_T algorithm in forward region, like a spherically-symmetric algorithm in backward
    - › f_i can be tuned to match other algorithms in other regions

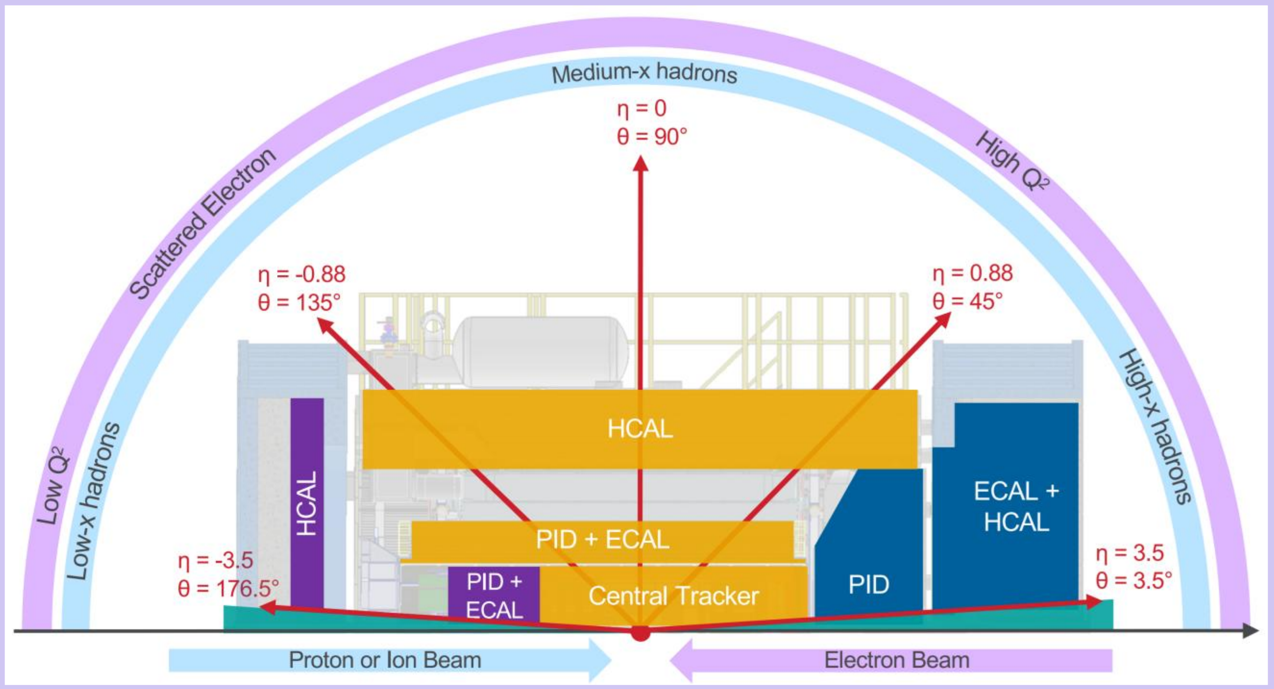
- **Right:** illustration of clustering in DIS for different algorithms



PRD 104, 034005 (2021)

$z_{jet} = P \cdot p_{jet} / P \cdot q$

ePIC | The ePIC Detector



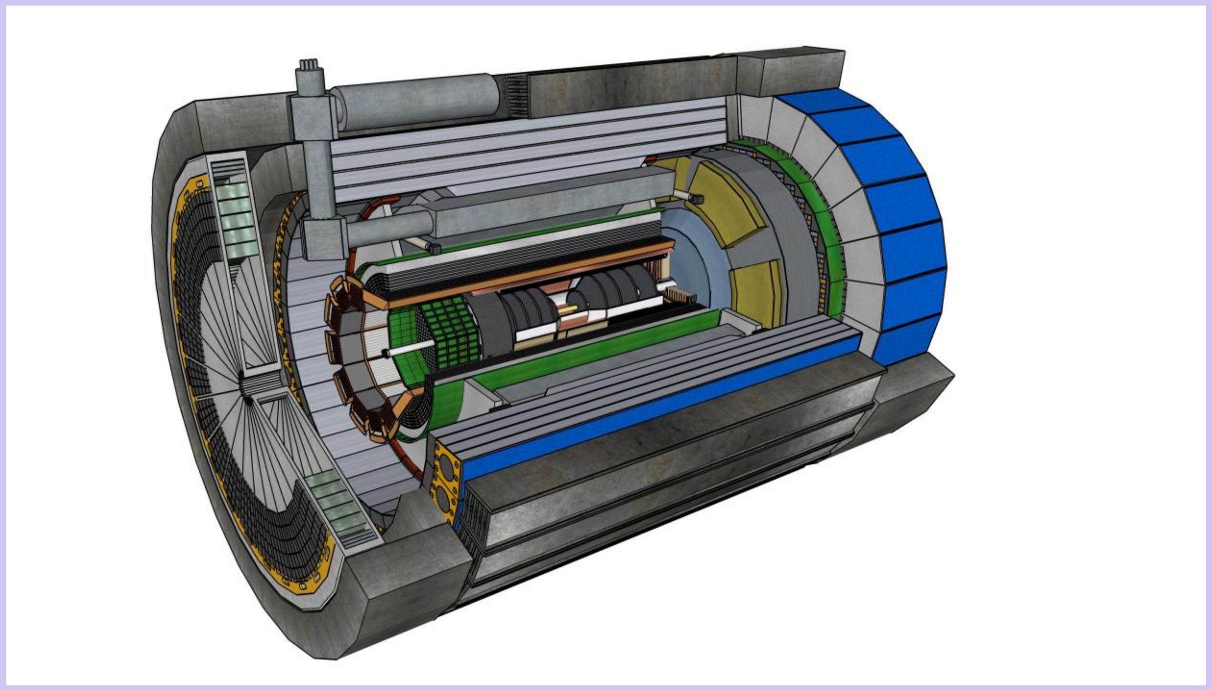


Figure by Sylvester Joosten

- **ePIC:** EIC project detector to be built at IP6
  - Fulfills EIC science mission & detector requirements
    - c.f. Yellow & NAS Reports
  - Collaboration formed in late 2022 – early 2023

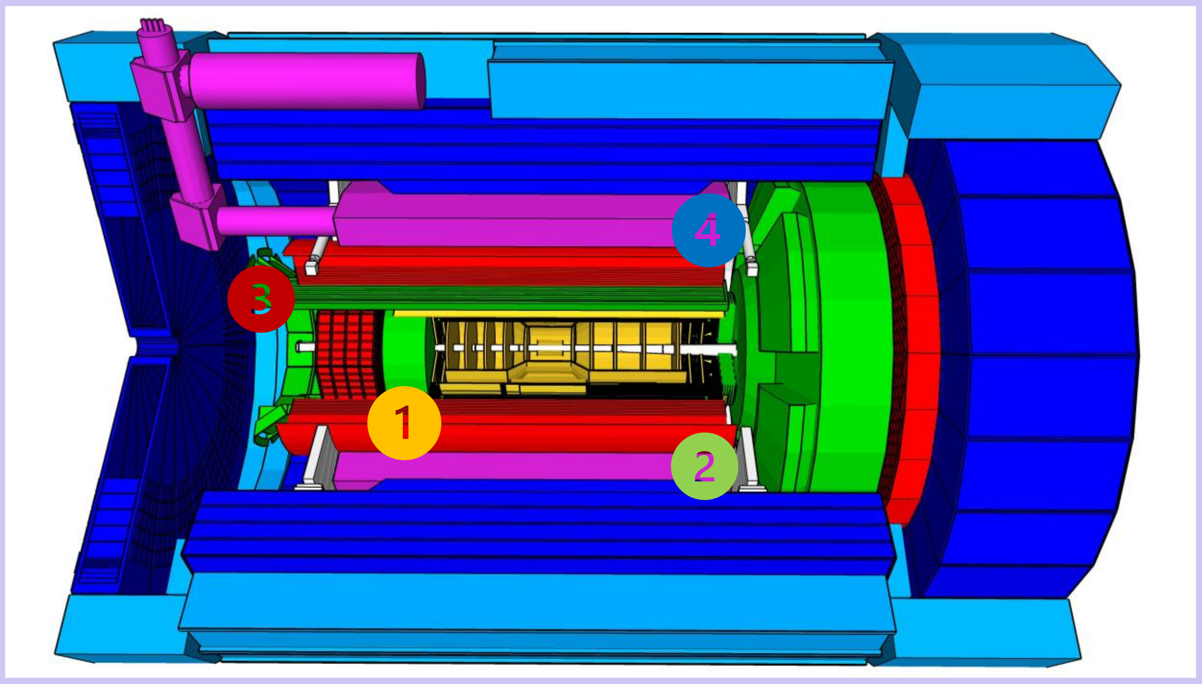
- (Almost) fully hermetic central detector with extensive coverage in forward, backward

☞ **See:**
  - HF at ePIC [D. Dongwi, 05.20]
  - ePIC: status & plans [D. Brandenburg, 05.23]

ePIC | Detector Subsystems (1/2)

Central Detector Subsystems:

1) Tracking
   - **Inner layers:** MAPS detectors
   - **Outer layers:** MPGDs (μRWELL, MMS)
2) Particle ID
   - **Barrel:** high-performance DIRC
   - **Forward:** dual-radiator RICH
   - **Backward:** proximity-focusing RICH
   - **TOF** (using AC-LGADs)
3) EM Calorimetry
   - **Barrel:** Imaging (Si + Pb/SciFi* matrix)
   - **Forward:** W-powder + SciFi*
   - **Backward:** PbWO4 crystals
4) Hadronic calorimetry
   - **Barrel:** Fe + scintillating tiles
   - **Endcaps:** Fe/W + scintillating tiles



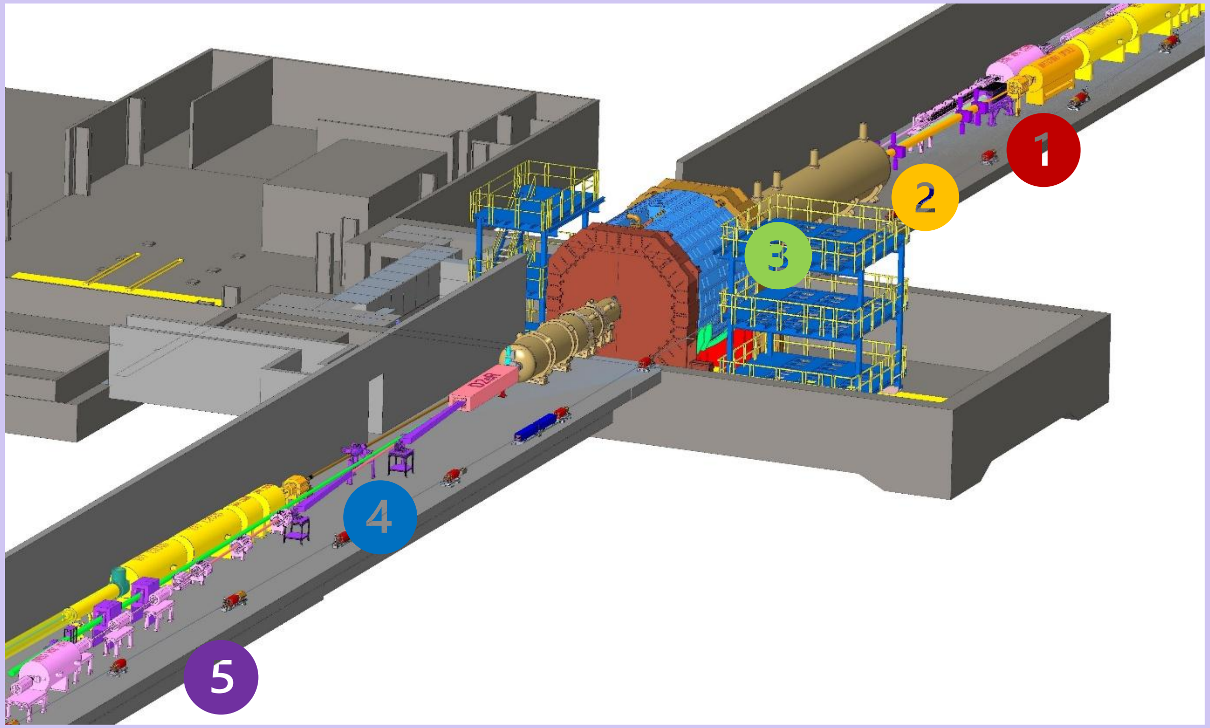
- **Note:** flux return steel (light blue) no longer part of design

* Scintillating-fibers

ePIC | Detector Subsystems (2/2)

Far Forward/Backward Subsystems:

1) ZDC
   - **EMCal:** PbWO4 crystals
   - **HCal:** Fe + scintillating tiles
2) Roman Pots, Off-Momentum Detectors
   - **Tracking:** AC-LGAD, 2 stations x 2 layers
3) B0 Spectrometer
   - **Tracking:** AC-LGAD, 4 layers
   - **EMCal:** PbWO4 crystals
4) Low-Q2 Taggers
   - **Tracking:** Si, 4 layers
   - **EMCal:** W-powder + ScFi*
5) Luminosity Monitor
   - **Tracking:** AC-LGAD, 2 layers
   - **EMCal:** W-powser + ScFi*

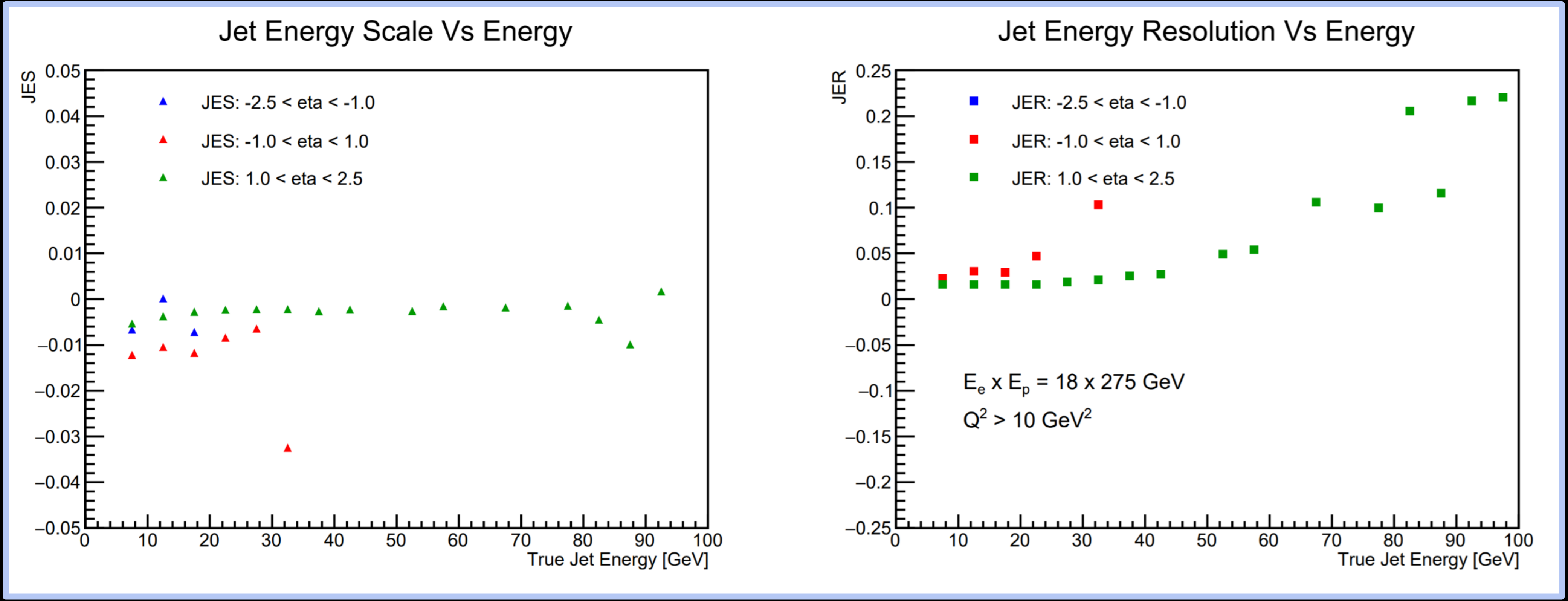


☞ **Full detector is 90 meters long!**

* Scintillating-fibers

Ongoing Efforts | Jet Energy Scale/Resolution

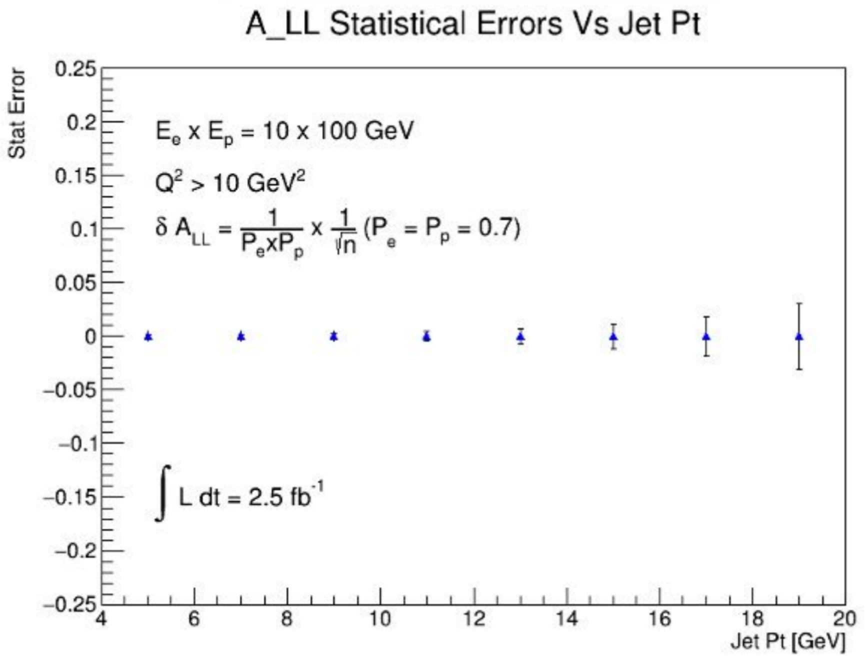
Work by Brian Page

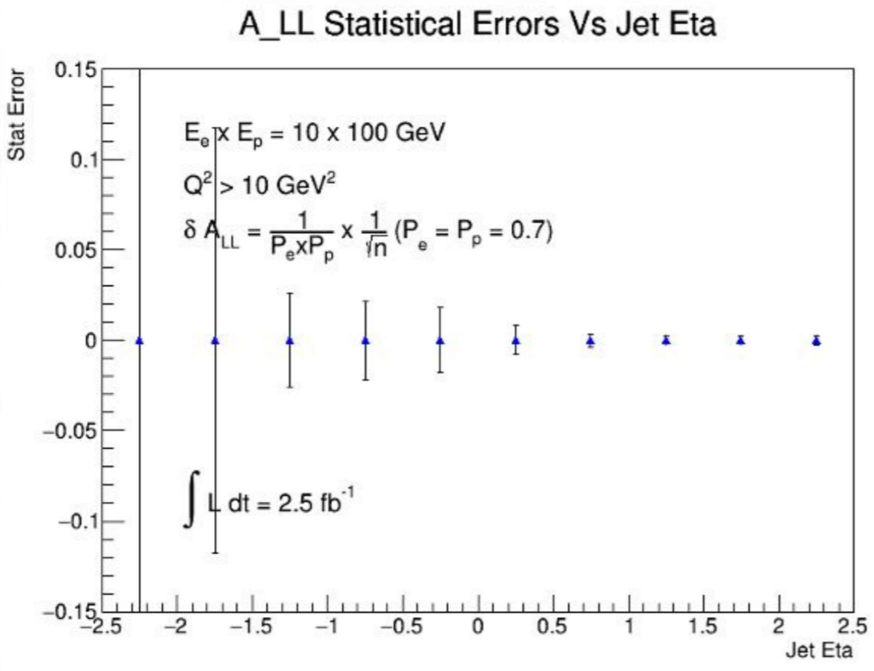


- **Above:** JES (left) & JER (right) for **charged jets**
  - Reco jets from tracks, truth jets from stable final particles
  - Jets matched via $\Delta r = \Delta\varphi \oplus \Delta\eta < 0.1$
- Only charged particles used due to lack of adequate PF algorithm , and **to assess tracking performance**
  - ☞ **Note:** baseline particle flow algorithm a development priority for 2025

Ongoing Efforts | Jet A_{LL}

Work by Brian Page

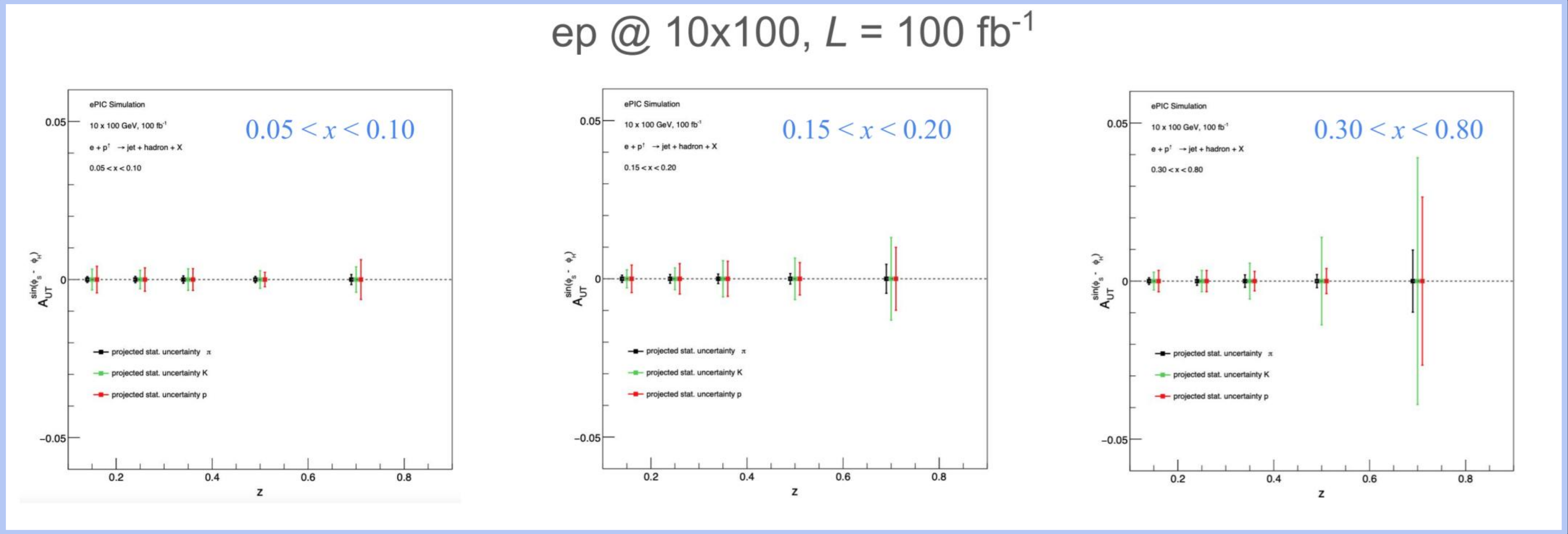




- **Above:** projected statistical precision for jet A_{LL}
  - CoM energy & luminosity approximate anticipated e+p conditions in years 2, 3 of EIC
- **Double-spin asymmetry (A_{LL}):** $(\sigma_{\rightrightarrows} - \sigma_{\leftrightarrows})/(\sigma_{\rightrightarrows} + \sigma_{\leftrightarrows})$
  - Measured $A_{LL} \propto$ sum of convolutions of parton helicity distributions
  - ∴ Provides crucial constraints on polarized PDFs

Ongoing Efforts | Collins Asymmetry

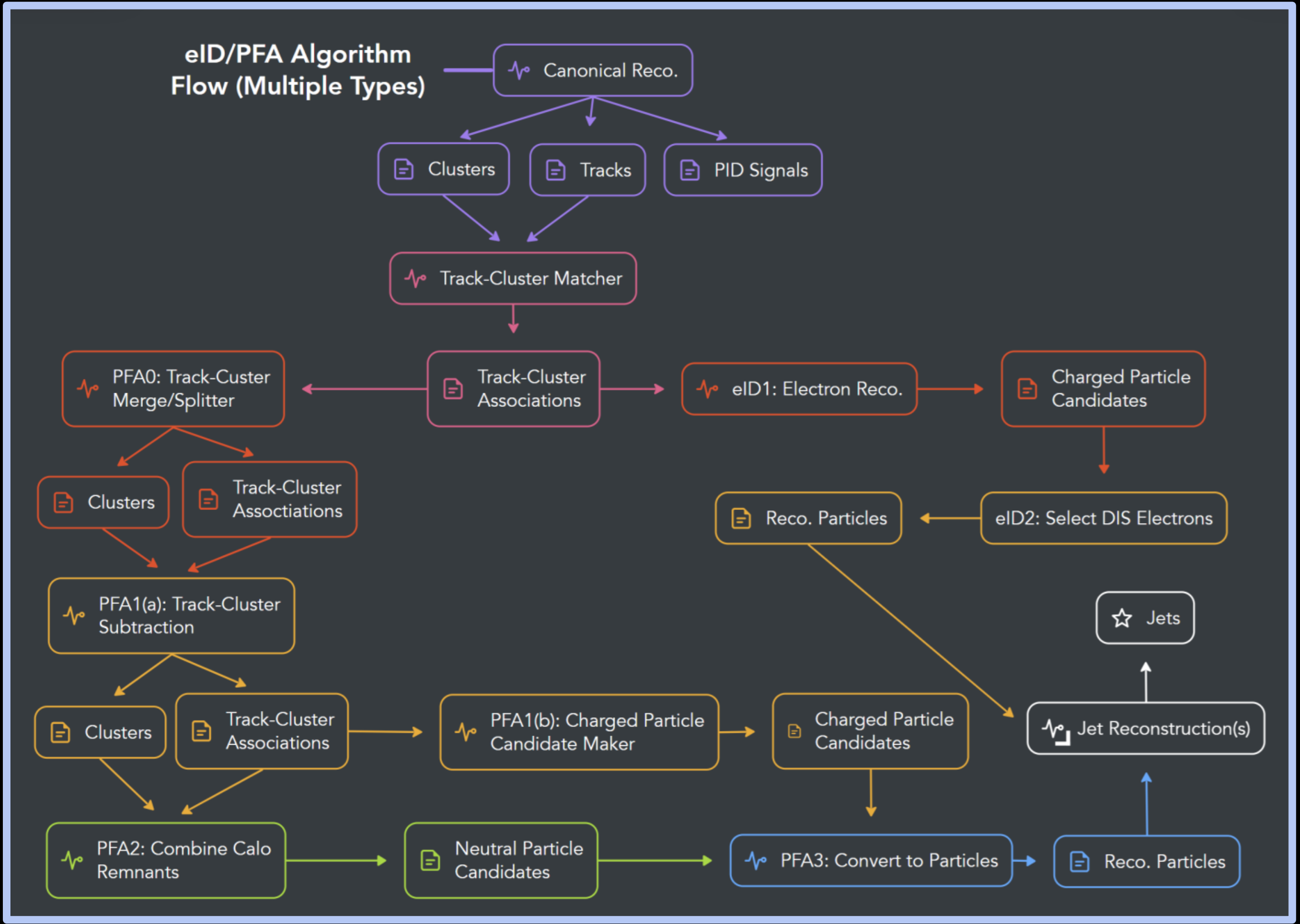
Work by Kevin Adkins



- **Above:** projected statistical precision for π, K, p Collins Asymmetry
  - CoM energy approximates anticipated e+p conditions in years 2, 3 of EIC
- **Collins Asymmetry:** effect due to convolution of quark transversity (h_1^q) and Collins FF ($H_{1\pi/q}^{\perp}$)
  - Advantage of jet+hadron Collins over single hadron SIDIS: jets provide proxy for fragmenting parton

Ongoing Efforts | Particle Flow

- **Note:** previous studies done for *charged* jets
  - Currently lacking mature particle flow algorithms (PFAs) to synthesize tracking, calorimetry, & PID information
  - ∴ **Implementing baseline PFA a critical development goal for this year**
- **Left:** proposed baseline, *PFAlpha*, currently under development
  - Flow chart illustrates the flow of component algorithms & datatypes
    - ☞ **Goal:** keep algorithm modular & support multiple PFAs concurrently!
  - Also illustrates interface between electron ID & jet finding
  - **Joint-work between Jet/HF PWG & Reconstruction WG**



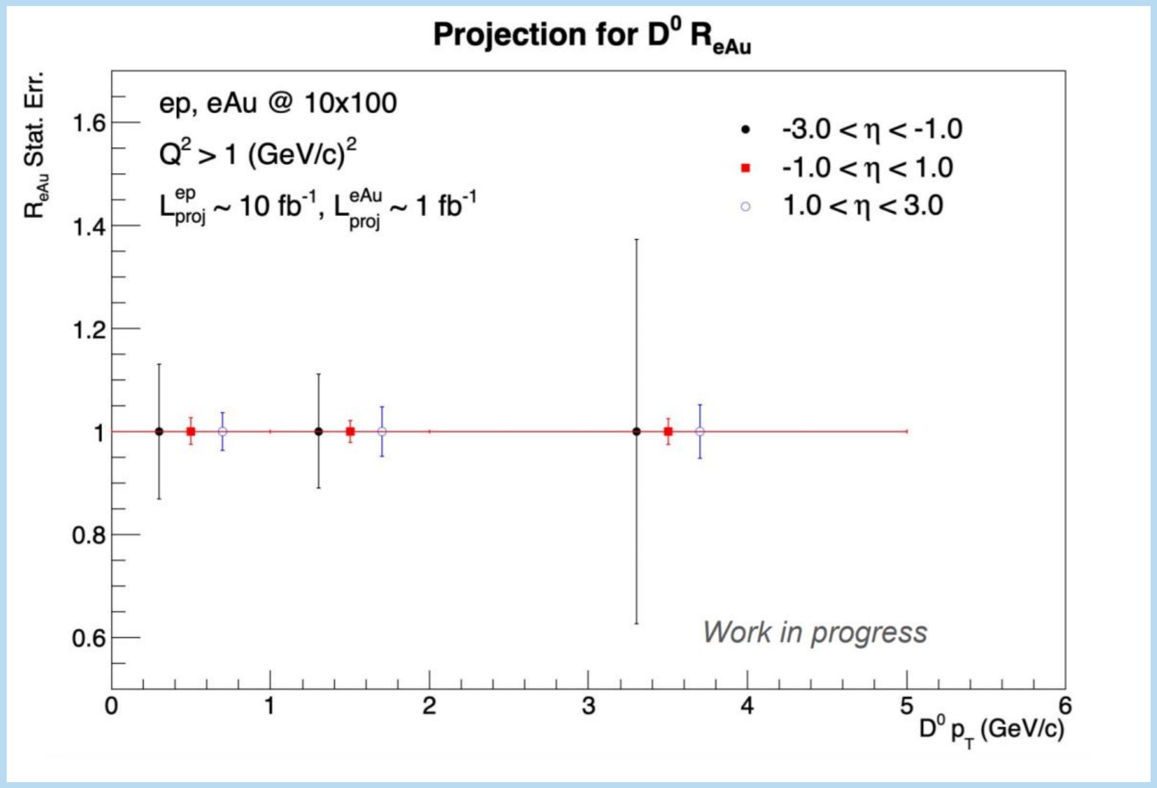
Work by Derek Anderson

Conclusion | Ongoing Jef/HF PWG Efforts

- Current Jet/HF PWG work mostly organized around
  - a) Preparation for the EIC TDR,
  - b) Early science
    - ☞ See Report on Early Science Workshop [R. Ma, 05.20]

- **Example:** some other ongoing efforts in PWG
  - › Open D0 reconstruction
    - › **Right:** projected statistical precision for $D^0\ R_{eAu}$
    - ☞ See HF at ePIC [D. Dongwi, 05.20]
  - › Assessing tracking performance

☞ **PWG meetings are every 1st, 3rd Tuesday at 11:30 am BNL time!**



Work by Rongrong Ma

Conclusion | Summary & Outlook

Conclusions

- Jets are crucial to the EIC science program
  - Valuable complement to other SIDIS observables!
  - Differences between RHIC & EIC
- ePIC is well-posed to make precision jet measurements
  - Close to hermetic central detector
  - Equipped with precision tracking & full (EM + hadronic) calorimetry

☞ **Lots of room to make contributions, so please join us!**

ePIC

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Thanks!

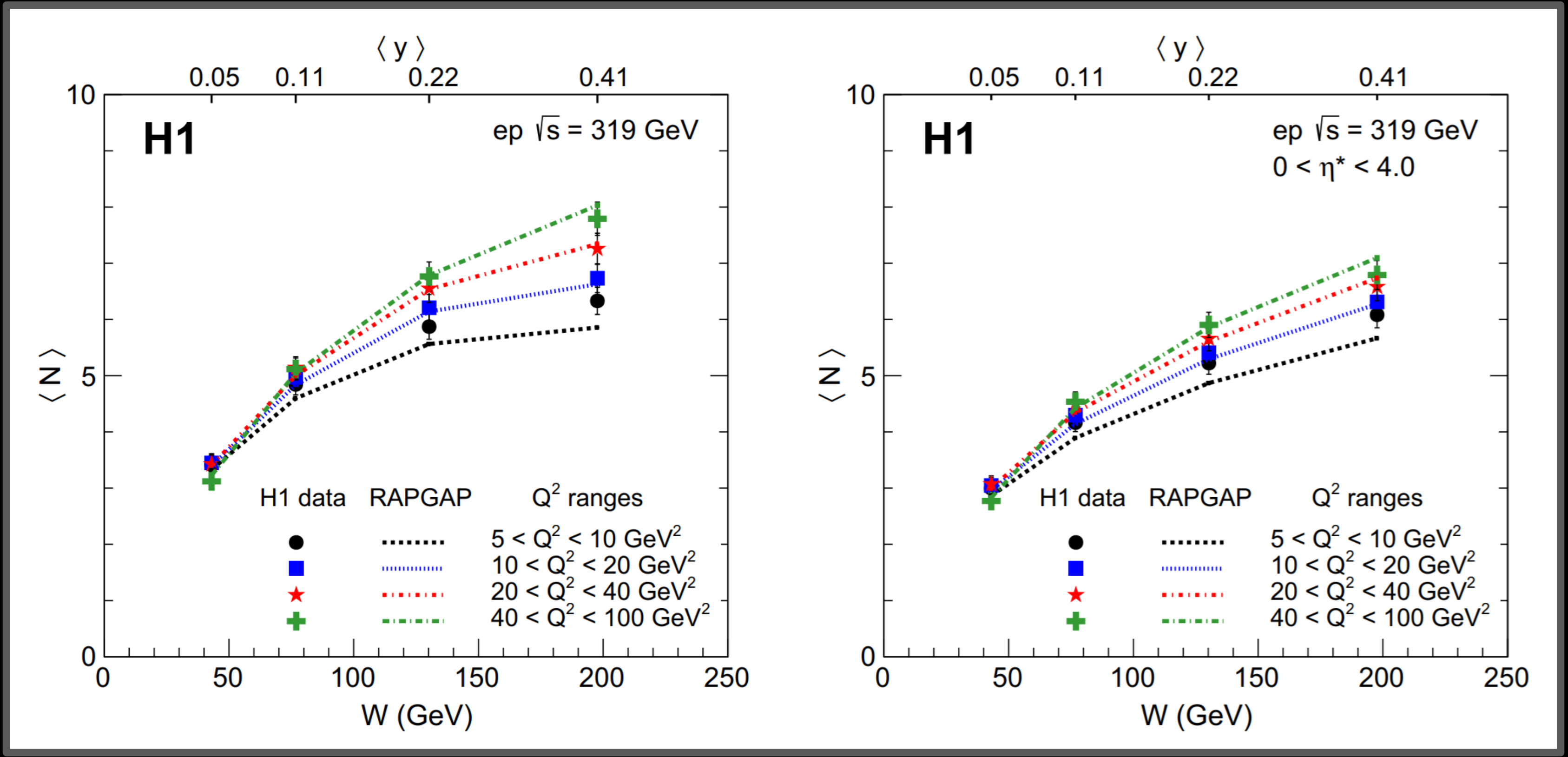
Backup | Early Science Matrix

	Species	Energy (GeV)	Luminosity/year (fb-1)	Electron polarization	p/A polarization
YEAR 1	e+Ru or e+Cu	10 x 115	0.9	NO (Commissioning)	N/A
YEAR 2	e+D e+p	10 x 130	11.4 4.95 - 5.33	LONG	NO TRANS
YEAR 3	e+p	10 x 130	4.95 - 5.33	LONG	TRANS and/or LONG
YEAR 4	e+Au e+p	10 x 100 10 x 250	0.84 6.19 - 9.18	LONG	N/A TRANS and/or LONG
YEAR 5	e+Au e+3He	10 x 100 10 x 166	0.84 8.65	LONG	N/A TRANS and/or LONG

Note: the eA luminosity is per nucleon

- Possible running scenarios for years 1 - 5 of EIC
  - Under discussion to maximize science & commissioning of machine
- From 2025 EIC Early Science Workshop
  - See Report on Early Science Workshop [R. Ma, 05.20]

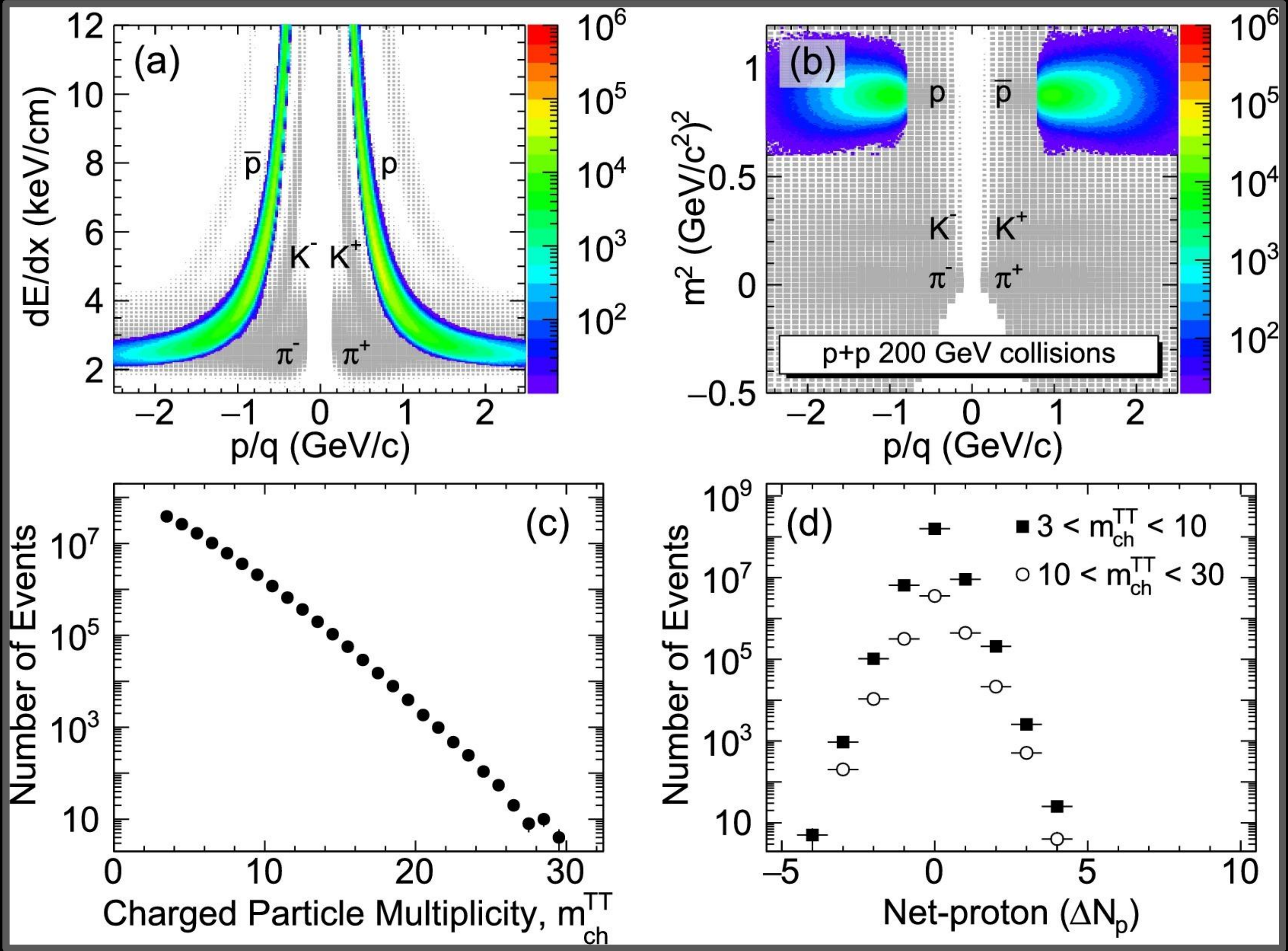
Backup | Multiplicity in e+p



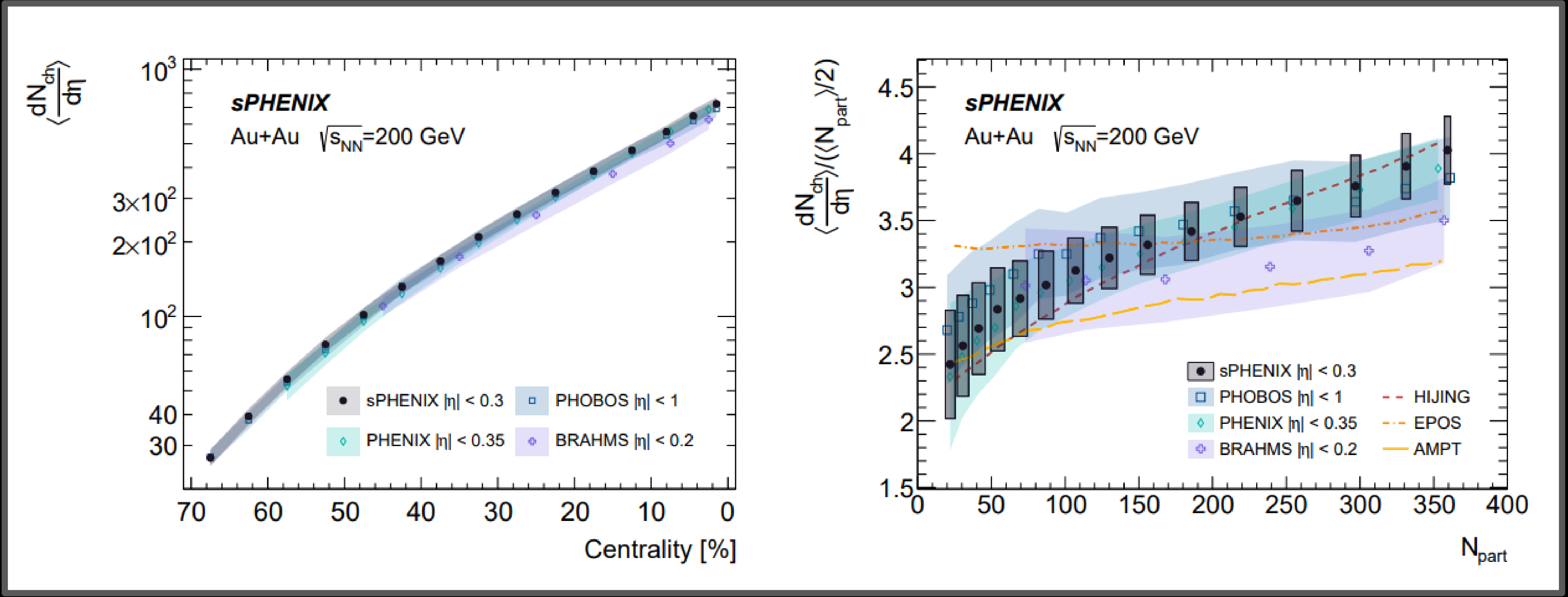
- Average charged particle multiplicity at H1 vs hadronic CoM energy, W, in 319 GeV e+p
  - ☞ From EPJC 81, 212 (2021)
- $W = \sqrt{sy - Q^2 - M_p^2}$
  - $y = 2E_e\Sigma/[\Sigma + E'_e(1-\cos\theta_e)]^2$
  - $\Sigma = \sum(E_i - p_{z,i})$

Backup | Multiplicity in p+p

- Charged particle multiplicity in the STAR TOF (lower left) in 200 GeV p+p
  - ☞ From PLB 857, 138966 (2024)



Backup | Multiplicity in Au+Au



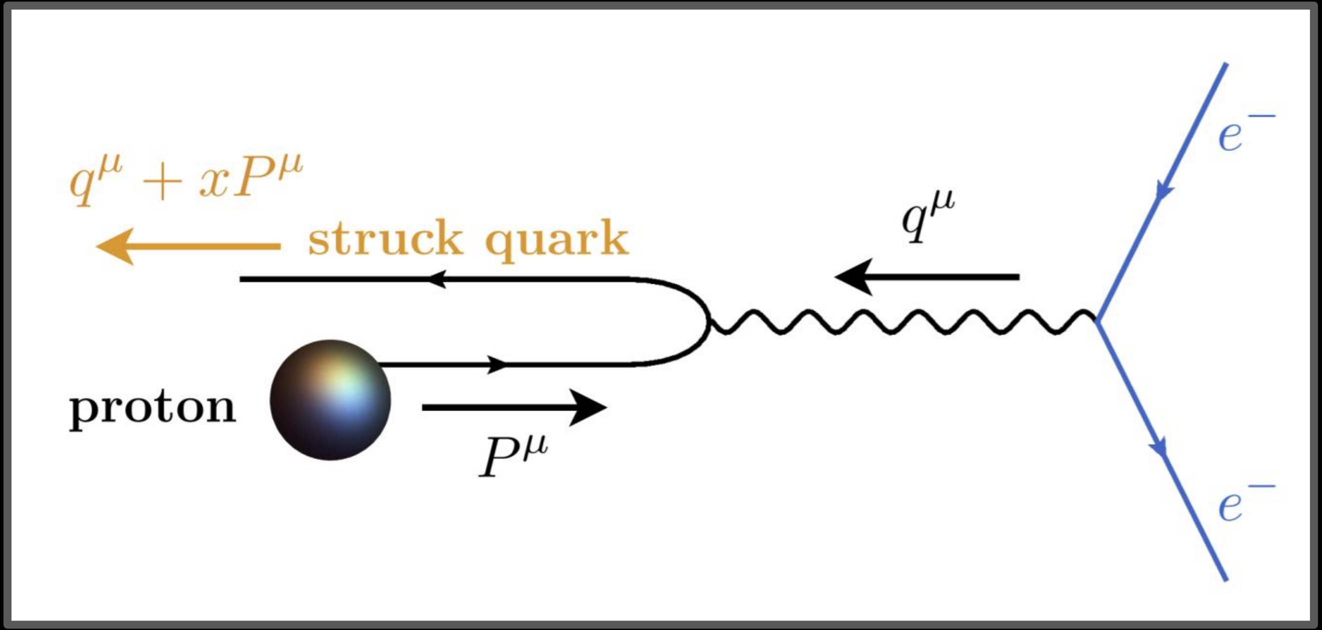
- Average charged particle multiplicity per unit eta in the sPHENIX INTT in 200 GeV Au+Au
  - ☞ From arXiv:2504.02240

Backup | Breit Frame Kinematics

- **Breit Frame:** struck quark has equal & opposite momentum to incoming quark
  - ☞ Allows for factorized TMD x-section in DIS like in Drell-Yan/$e^+e^- \rightarrow hh\ (jj)$

- **Kinematics:**
  - $q^\mu = \frac{Q}{2}(\bar{n}^\mu - n^\mu) = Q(0,0,0,-1)$
  - $P^\mu \approx \frac{Q}{2x_B} n^\mu = \frac{Q}{2x_B}(+1,0,0,-1)$
  - $p_q^\mu = xP^\mu + q^\mu \approx \frac{Q}{2}\bar{n}^\mu$
    - ☞ (At Born level)

- **Reminder:**
  - ☞ $x_B = Q^2/(2q \cdot p)$



PRD 104, 034005 (2021)

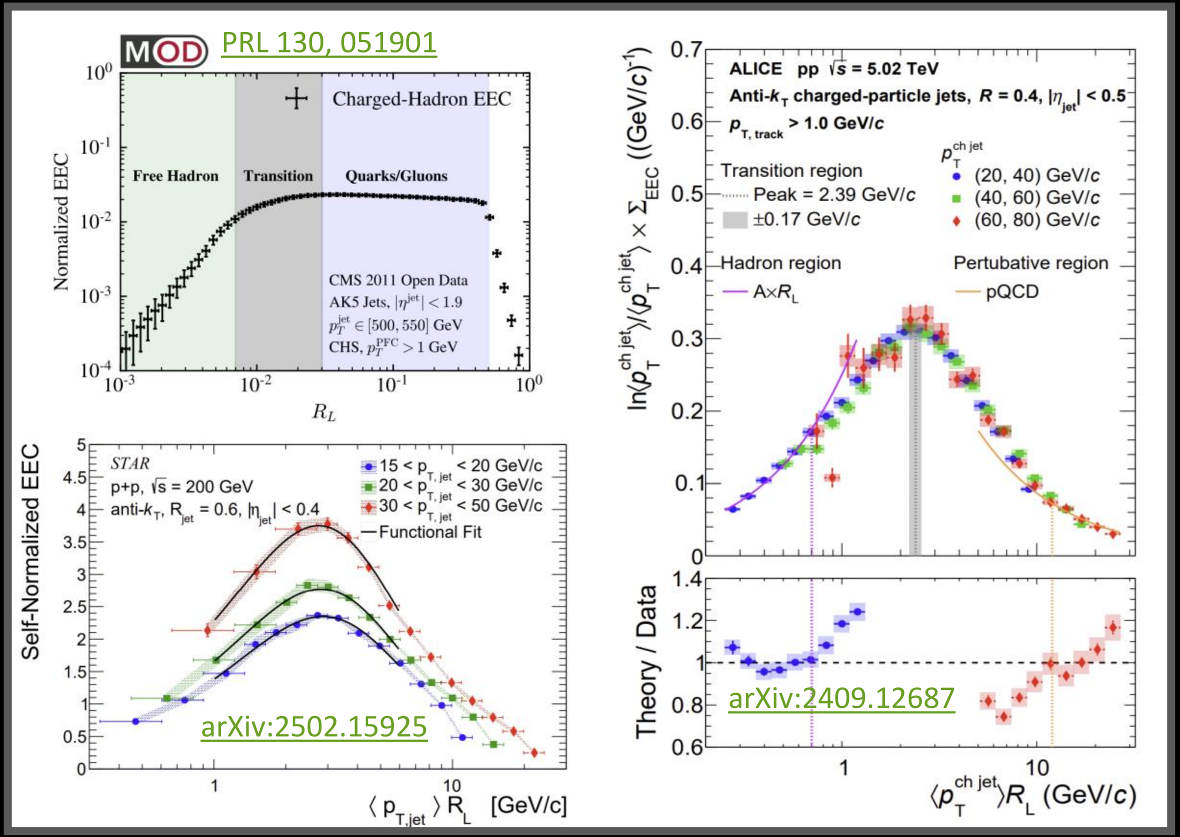
Backup | ENC in p+p

N-Point Energy Correlators (ENC)

$$\mathrm{ENC}(R_L) = \left(\prod_{k=1}^{N} \int d\Omega_{\vec{n}_k}\right) \delta(R_L - \Delta R_L) \frac{\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2) \ldots \mathcal{E}(\vec{n}_N)\rangle}{E_{\mathrm{jet}}^{N}}$$

- $\mathcal{E}(\vec{n}_i)$ = ith asymptotic energy operator
- R_L = longest distance out of N directions

- Cleanly image structure as a function of angular scale
  - **In vacuum:** allow for clear distinction b/n **perturbative** and **nonperturbative** regimes
  - ☞ PRL 130, 051901
- Recent studies demonstrate transition happens at $R_L p_T^{jet} \sim 2.5$ GeV/c **at RHIC and LHC**
  - ☞ See recent STAR & ALICE results



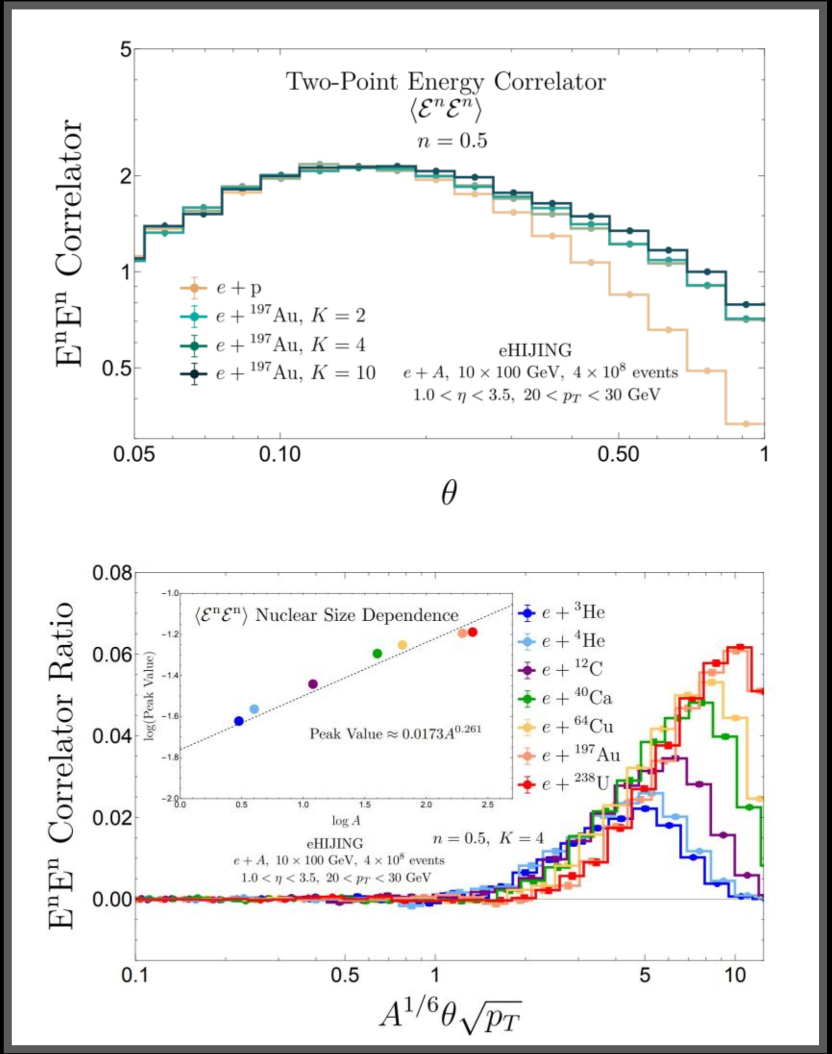
Backup | ENC in e+Au

N-Point Energy Correlators (ENC)

$$\mathrm{ENC}(R_L) = \left(\prod_{k=1}^{N} \int d\Omega_{\vec{n}_k}\right) \delta(R_L - \Delta R_L) \frac{\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2) \ldots \mathcal{E}(\vec{n}_N)\rangle}{E_{\mathrm{jet}}^N}$$

- $\mathcal{E}(\vec{n}_i)$ = i^{th} asymptotic energy operator
- R_L = longest distance out of N directions

arXiv:2303.08143



- Devereaux et al studied potential of ENC at EIC to analyze CNM effects
  - Considered simulated e+p/e+A collisions w/ eHIJING
  - Study suggests that ENC can:
    a) Cleanly identify characteristic scale of onset of nuclear medium modification **(upper plot)**
    b) Identify characteristic scale of modification associated with nuclear size **(lower plot)**
  - Ref: arXiv:2303.08143

∴ **ENC provide a strong observable to study CNM effects!**

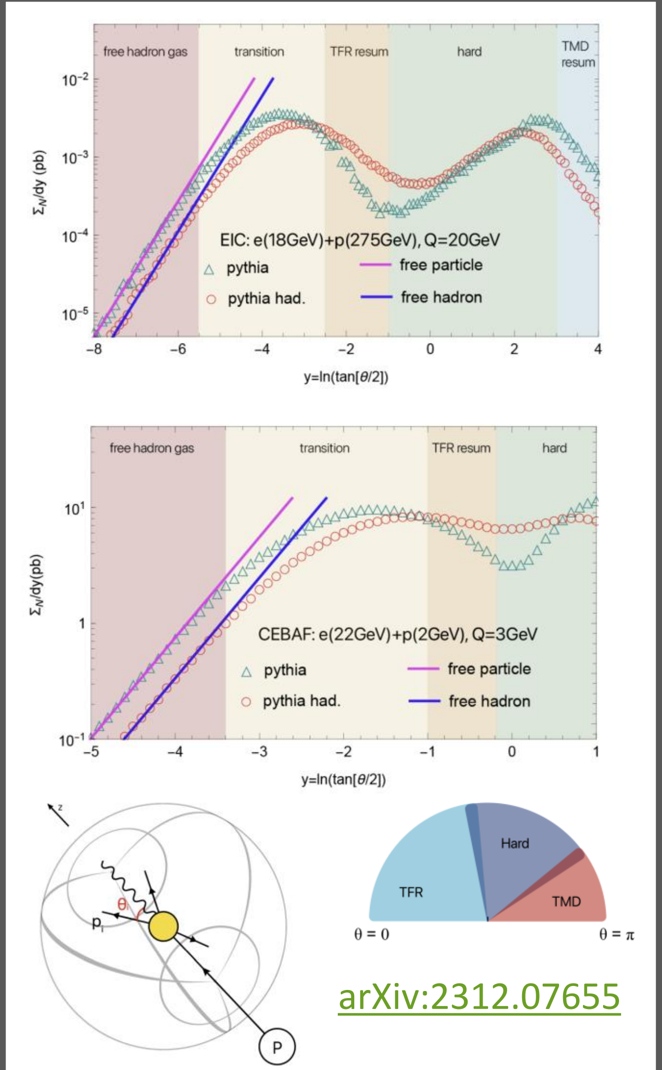
Backup | Nucleon EECs

Nucleon Energy-Energy Correlators (NEEC)

$$\text{NEEC} = \sum_i \int d\sigma(x_B, Q^2, p_i) x_B^{N-1} \frac{E_i}{E_p} \delta(\theta - \theta_i)$$

- E_i, θ_i = energy, Breit frame angle of i[th] particle
- E_p = energy of scattered proton

- *Nucleon EECs* (NEECs) provide a variation of EECs applicable to both collider & fixed target kinematics!
  - **In essence:** $R_L \rightarrow \theta_{breit}$
    - Enables sensitivity to different physics processes by selecting different θ_{breit}
  - ☞ See PRL 130, 091901, arXiv:2312.07655



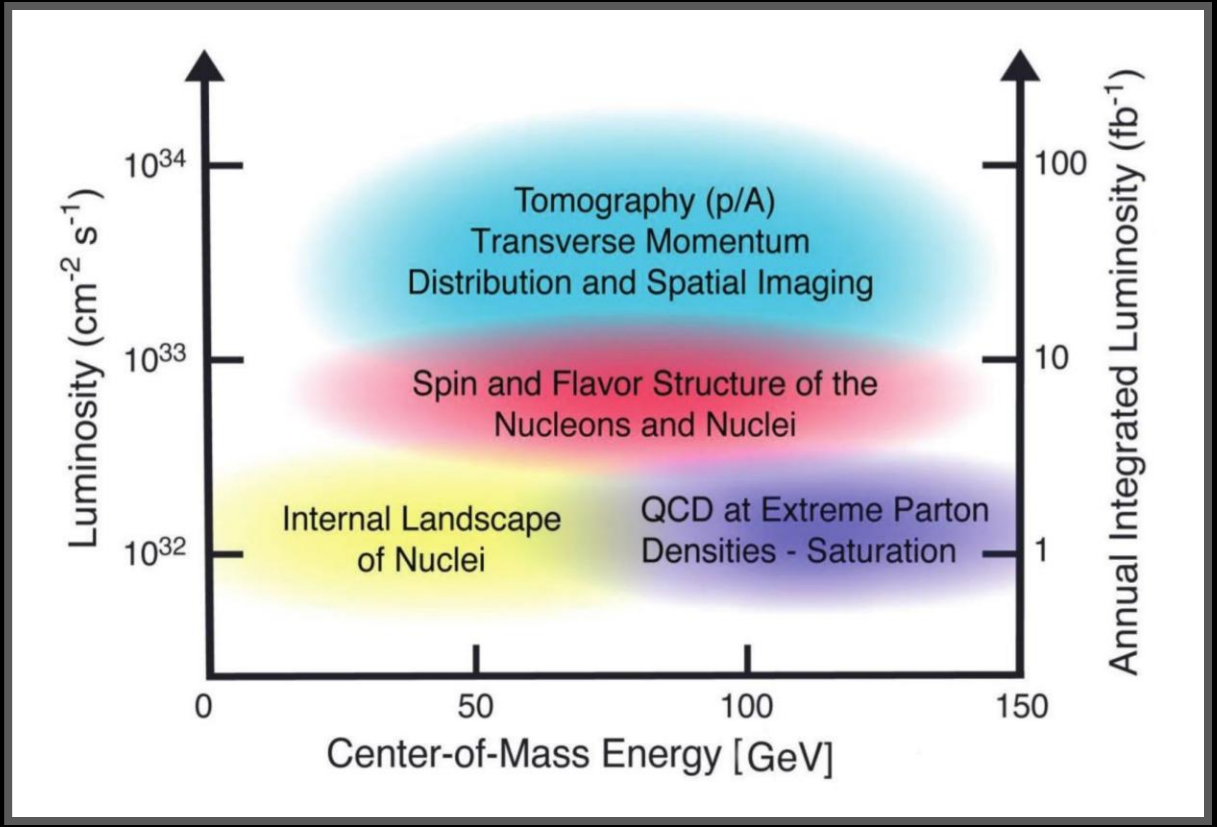
arXiv:2312.07655

Backup | EIC Goals and Luminosities (1/2)

- **Right:** major topics to be explored at EIC vs. required luminosities & CoM energy
  - **Anticipates $\mathcal{L}_{\mathbf{peak}} \sim \mathbf{10^{34}}$ (cm² s)⁻¹**
  - Translates to roughly 1.5 fb^{-1} per month
    - ☞ **Assuming:** 60% operation time & $\overline{\mathcal{L}} = \mathcal{L}_{\text{actual}}$

- **But:** typical σ_{int} is $\mathcal{O}(100) \times$ smaller than comparable σ_{int} at RHIC/LHC…
  - And there is wide variety of processes to record…
  - ⇒ **Streaming Readout (SRO) is a must if we want to fully unlock EIC scientific potential**

- For reference
  - › **RHIC:** $\overline{\mathcal{L}}_{pp} \sim 2.45 \times 10^{34}$ $(cm^2\ s)^{-1}$
  - › **LHC:** $\overline{\mathcal{L}}_{pp} \sim 1 \times 10^{34}$ $(cm^2\ s)^{-1}$



Backup | EIC Goals and Luminosities (2/2)

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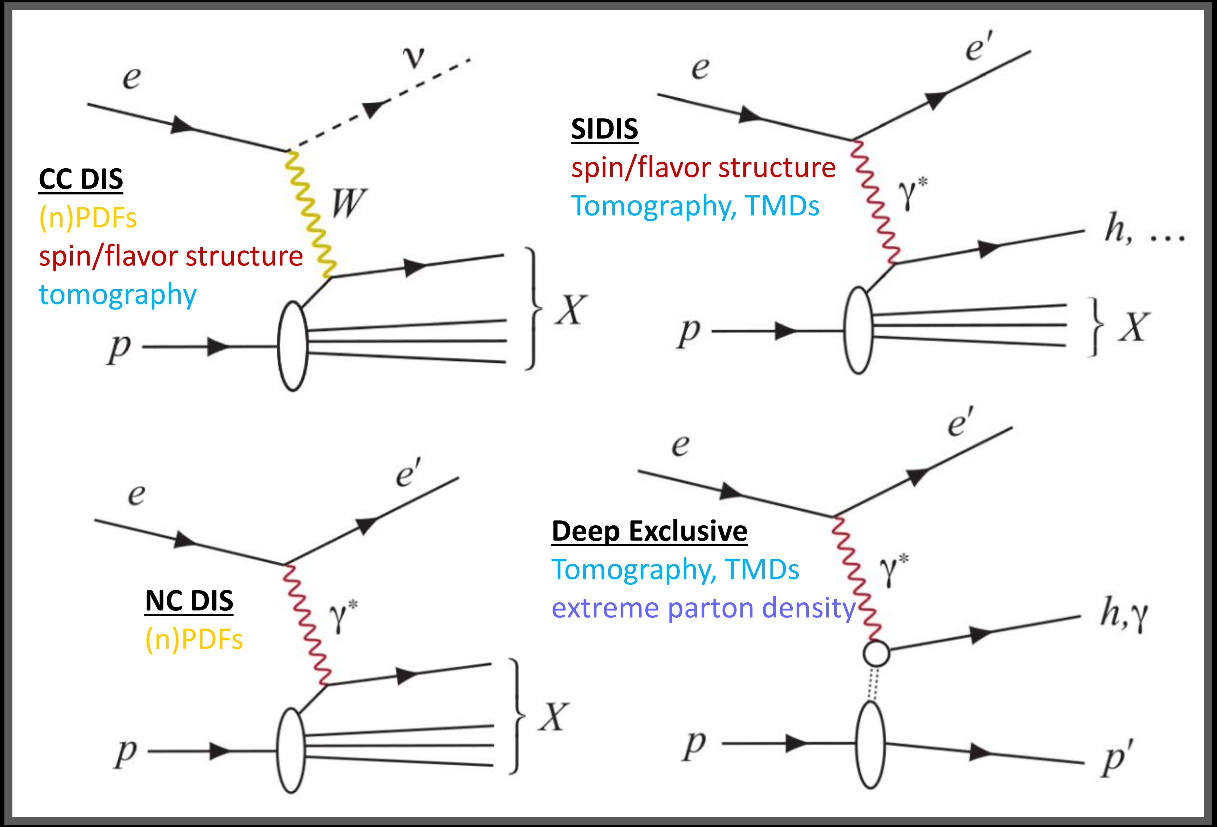
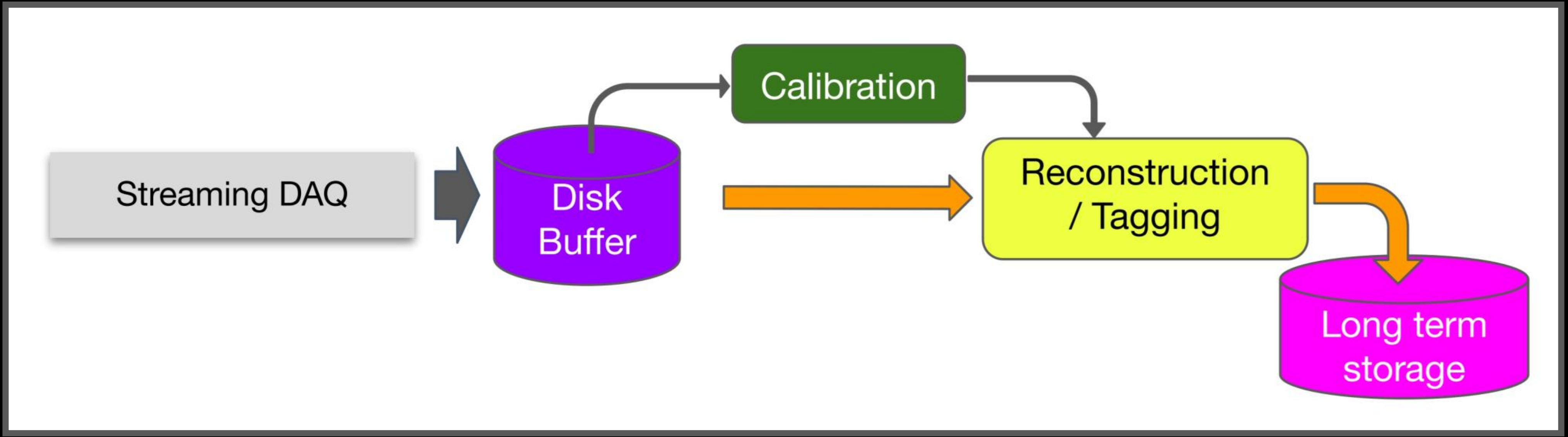


Backup | Streaming Readout

arXiv:2202.03085



- **Streaming readout (SRO):** data read out in continuous parallel streams
  - Each stream encodes when/where data was recorded
  - Data digitized at fixed rate & thresholds/zero-suppression applied locally
  - Event building, filtering, monitoring, etc. deferred until data in tiered storage
  - ☞ **See:** report on ePIC Streaming Computing Model

Current & Future Examples:

- LHCb
- Recent test implementation at JLab
- CLAS12
- sPHENIX
- And ePIC!

Backup | SRO Advantages & Fast Calibration

- Several advantages of SRO over traditional readout (RO)!
  a) Enables simplified & more flexible RO hardware
     - No custom trigger hardware/firmware!
  b) Provides access to detailed knowledge of background
  c) Allows workflows to be streamlined & utilize new technologies
     - ☞ e.g. AI/ML!

☞ See: arXiv:2202.03085 & ePIC Streaming Computing Model report

Building on (c):

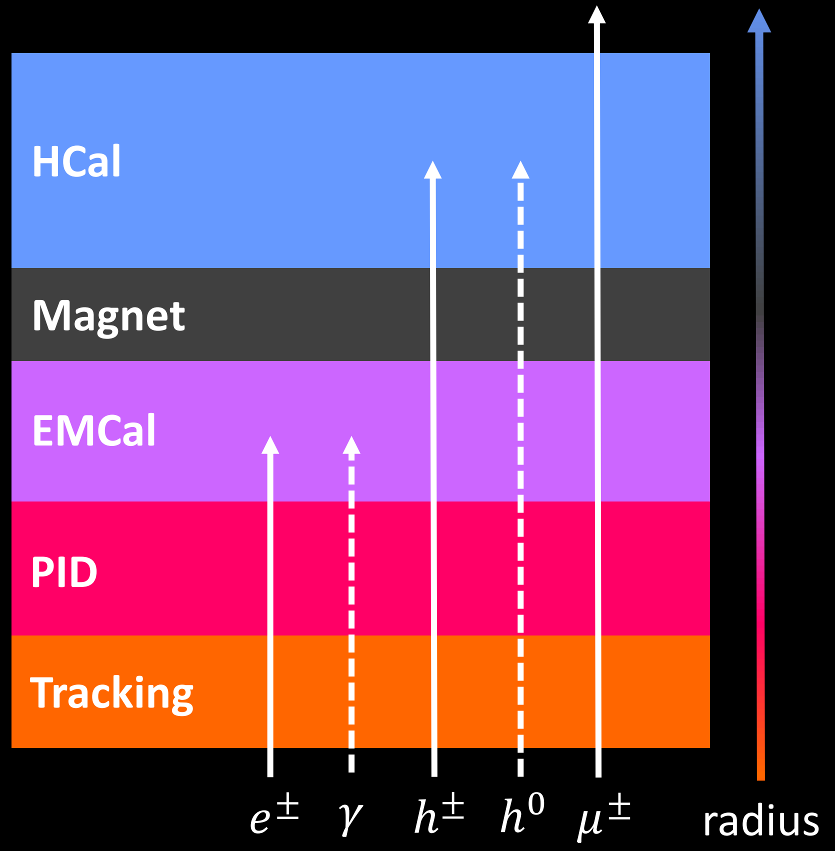
- Typically $\mathcal{O}(1)$ year between recording data & analyzing data
  - Due to complexity of HEP/NP experiments
  - Alignment, calibration, reconstruction, & validation are costly!
- Our goal for ePIC: 2 – 3 weeks between recording & analyzing data!
  - Timeline driven by calibration
- Can be accomplished by integrating computing & detector, esp. using AI/ML for:
  - Autonomous alignment/calibration
  - And rapid reconstruction + validation

Backup | BHCal Utility

- In barrel region ($|\eta| < 1$), jets are relatively soft
  - Tracker provides best momentum determination
  - But hadronic calorimeter would provide measurement of h^0

∴ The BHCal will serve several roles at ePIC
  a) Precise jet energy reconstruction
  b) Additional determination of e^- kinematics
  c) Solenoid flux return
  d) Possible $\mu^\pm$ identification

- **Right:** schematic diagram of a typical HEP/HENP experiment vs. radius



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- **Right:** feynman diagram for charged-current DIS
  - Kinematics determined via Jacquet-Blondel method
  - ☞ i.e. From all FS hadrons