Target jet substructure and correlation

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INT program: Heavy Ion Physics in the EIC Era
University of Washington, Seattle, August 14th, 2024

In collaboration with Kai-Feng Chen, Roli Esha, Meng-Hsiu Kuo, to appear soon

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Georgia State University

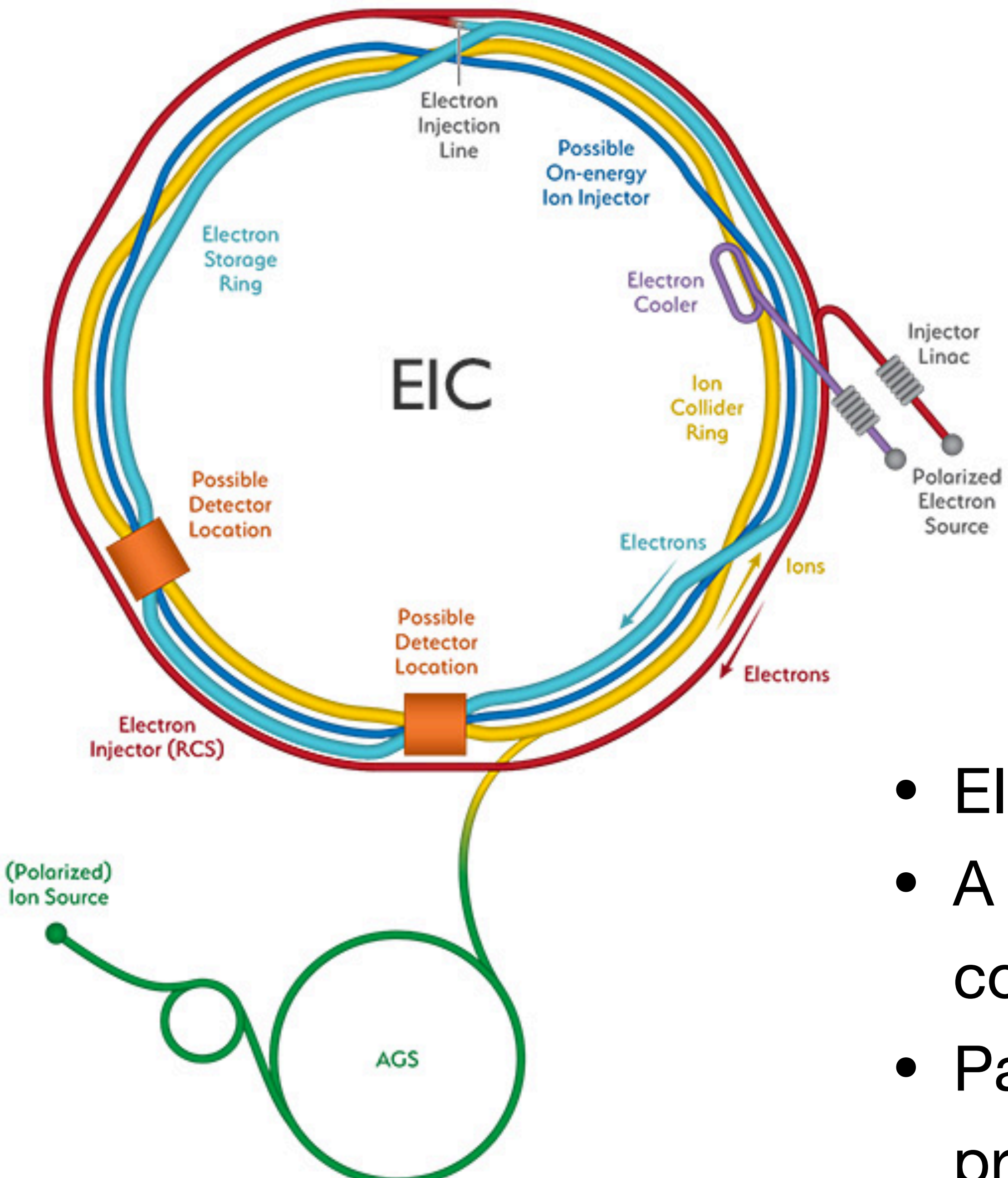
Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- Target fragmentation and target jet
- Target jet substructure and current-target correlation
  - Charge and energy flow
  - Tagging and nuclear dynamics
- ep, ed, eAu collisions in Pythia 8 and/or BeAGLE simulations
- Two-particle correlation neural network (2PCNN)
- Conclusion and outlook

Electron Ion Collider



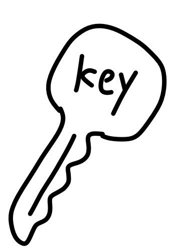
January 9, 2020

U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

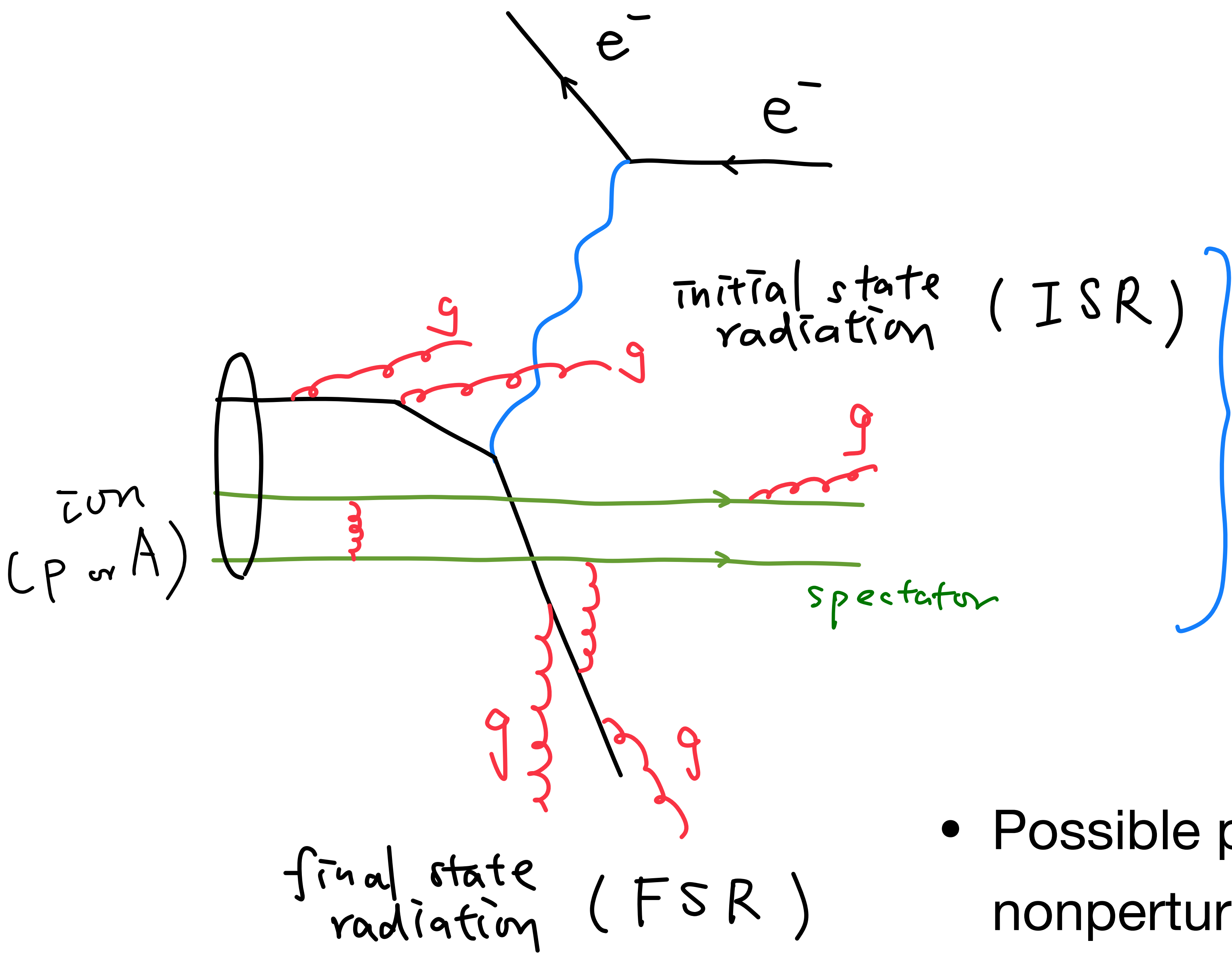
March 21, 2022
Project detector selected and ePIC collaboration being formed

- EIC has been making progress toward realization
- A control over spin and polarization d.o.f. allows a complete tagging of partonic quantum numbers
- Particle ID and high statistics are important for precision extraction of proton 3D structure
- What is the role the second detector should play? What phase space can it look into?

Particle ID
High statistics



A schematic picture of target fragmentation for DIS



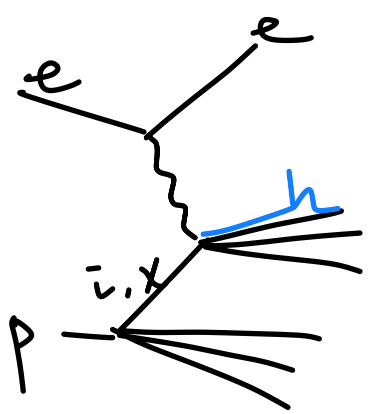
This whole sector is typically very forward, theoretically captured by "fracture function"

Trentadue & Veneziano (1994)

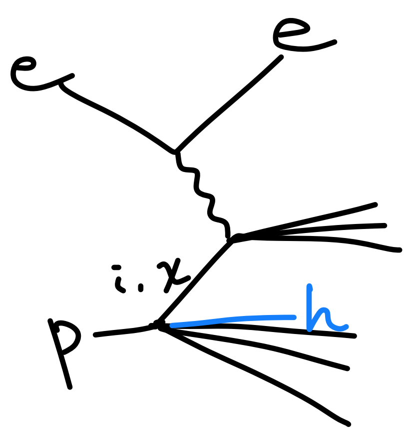
- Possible perturbative ISR contribution and nonperturbative spectator hadronization

Semi-inclusive deep inelastic scattering

$e\,p \to e\,\underset{z}{h}\,X$ measuring 1 hadron



current



target

$$\sigma_{target}(z, Q) = \int_0^{1-z} \frac{dx}{x}\, \underbrace{M^i_{p,h}(z, x, Q)}_{\text{fracture function}}\, \sigma^i_{hard}(x, Q)$$

fracture function

$$Y \equiv \frac{1}{2\pi b} \ln\left(\frac{\alpha_s(\mu^2)}{\alpha_s(Q^2)}\right)$$

spectator contribution

$$\frac{\partial}{\partial Y} M^j_{ph}(x, z, Y) = \int_{\frac{x}{1-z}}^{1} \frac{du}{u} P^j_i(u)\, M^i_{ph}\left(\frac{x}{u}, z, Y\right)$$

Trentadue & Veneziano (1994)

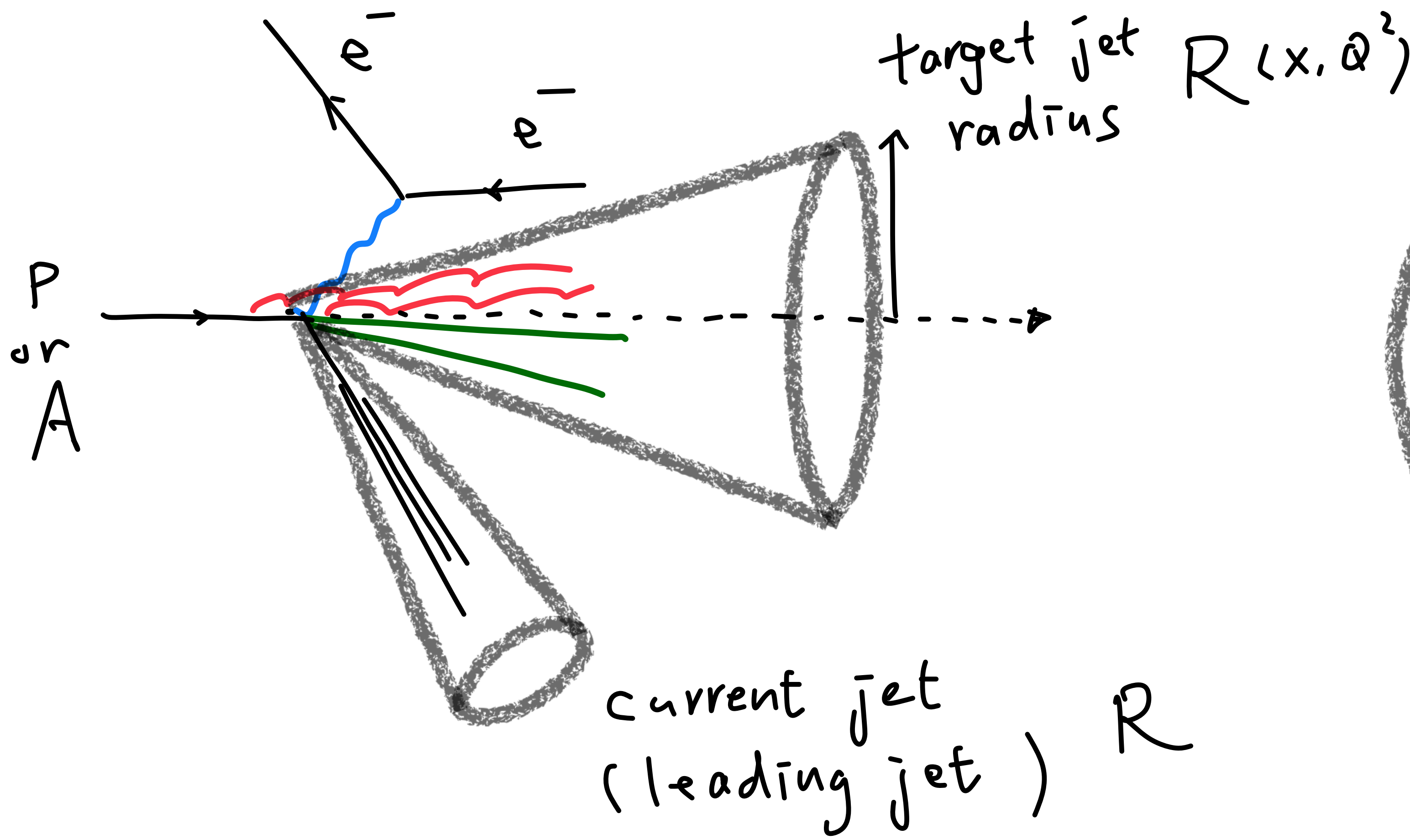
$$+ \int_x^{\frac{x}{x+z}} \frac{du}{u(1-u)} \hat{P}^{jl}_i(u) \left(\frac{u}{x}\right) D_{lh}\left(\frac{zu}{x(1-u)}, Y\right) F^i_p\left(\frac{x}{u}, Y\right)$$

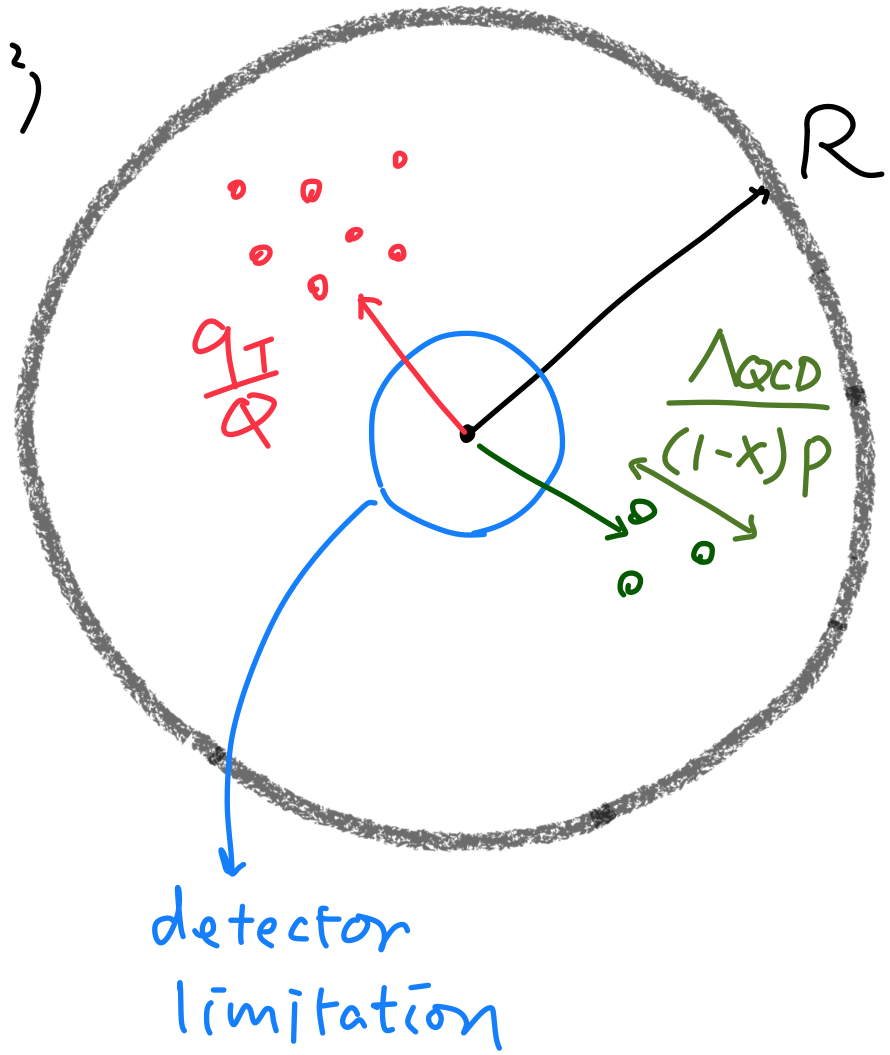
ISR

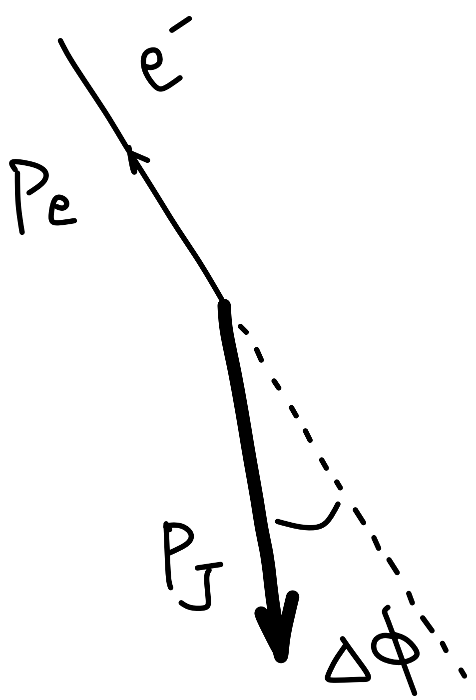
fragmentation fn

PDF

Electron-leading jet and target jet





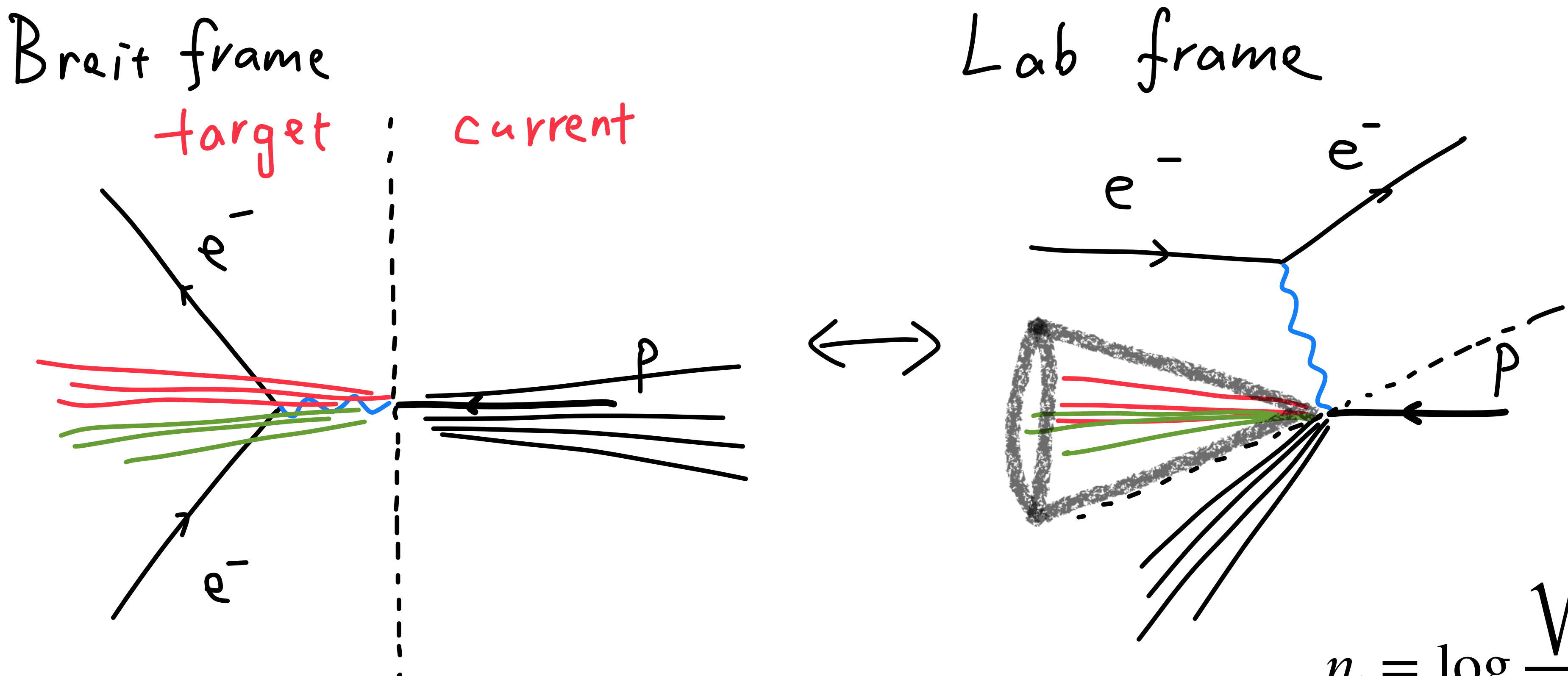


$q_T = |(\vec{P_e} + \vec{P_J})_T|$

$\Delta\phi$: azimuthal angle decorrelation

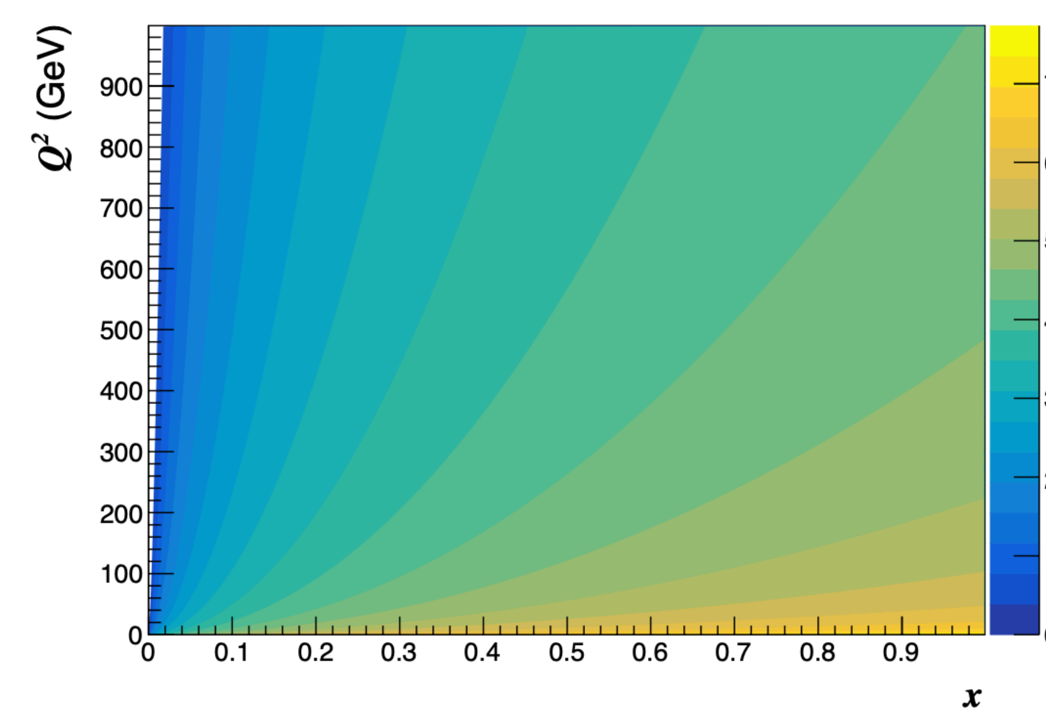
- Carving out two collinear energy flows

Target jet definition



$$\eta_t = \log \frac{\sqrt{1 + \frac{E_e}{x^2 E_p} \frac{Q^2}{E_{CM}^2 - Q^2/x}} - 1}{\sqrt{\frac{E_e}{x^2 E_p} \frac{Q^2}{E_{CM}^2 - Q^2/x}}}$$

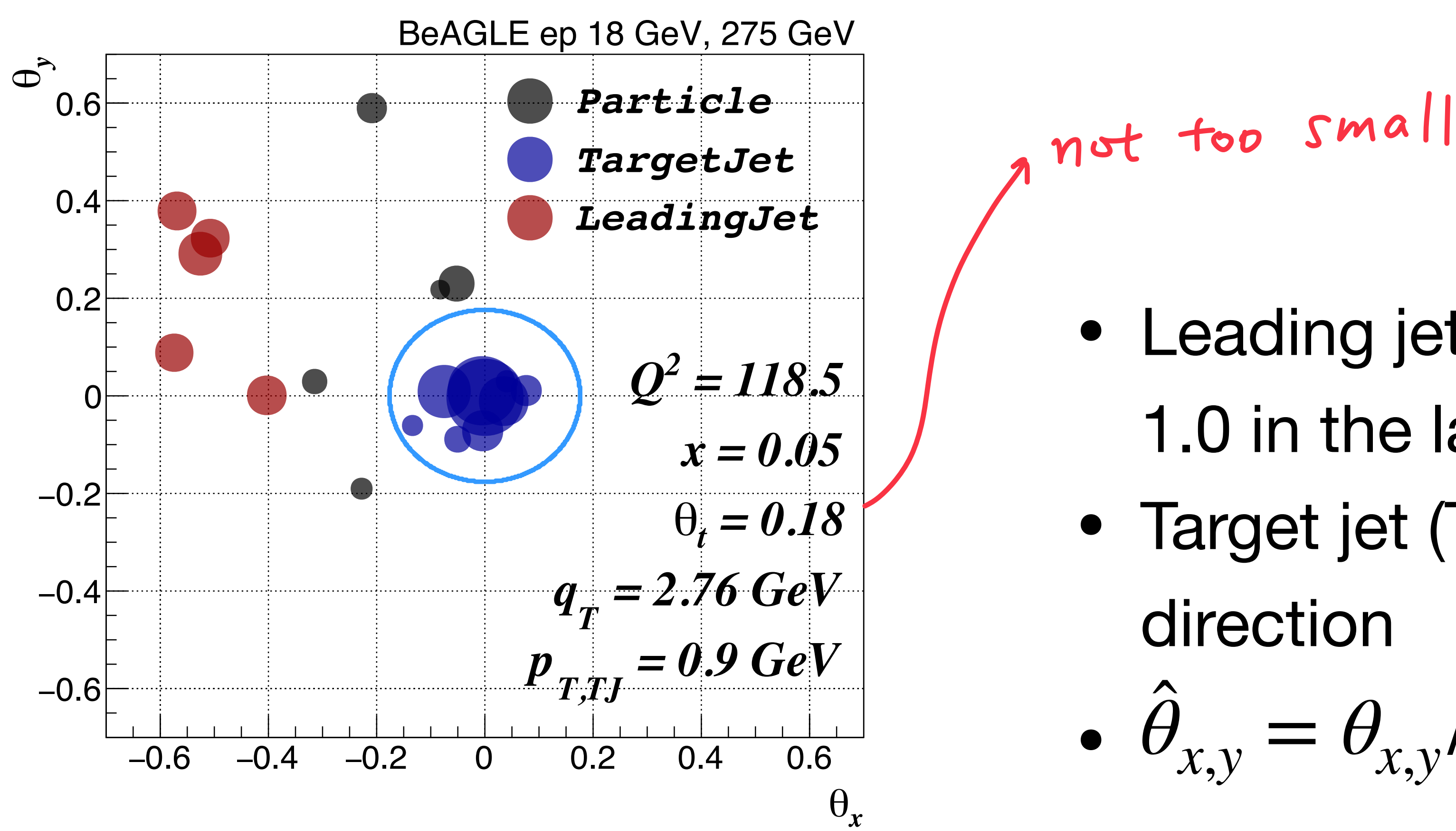
- It is quite intuitive to define current and target region in Breit frame
- What is the corresponding analysis strategy in the lab frame?
- Target jet radius as a function of the boost between Breit and lab frames: a function in x and Q^2

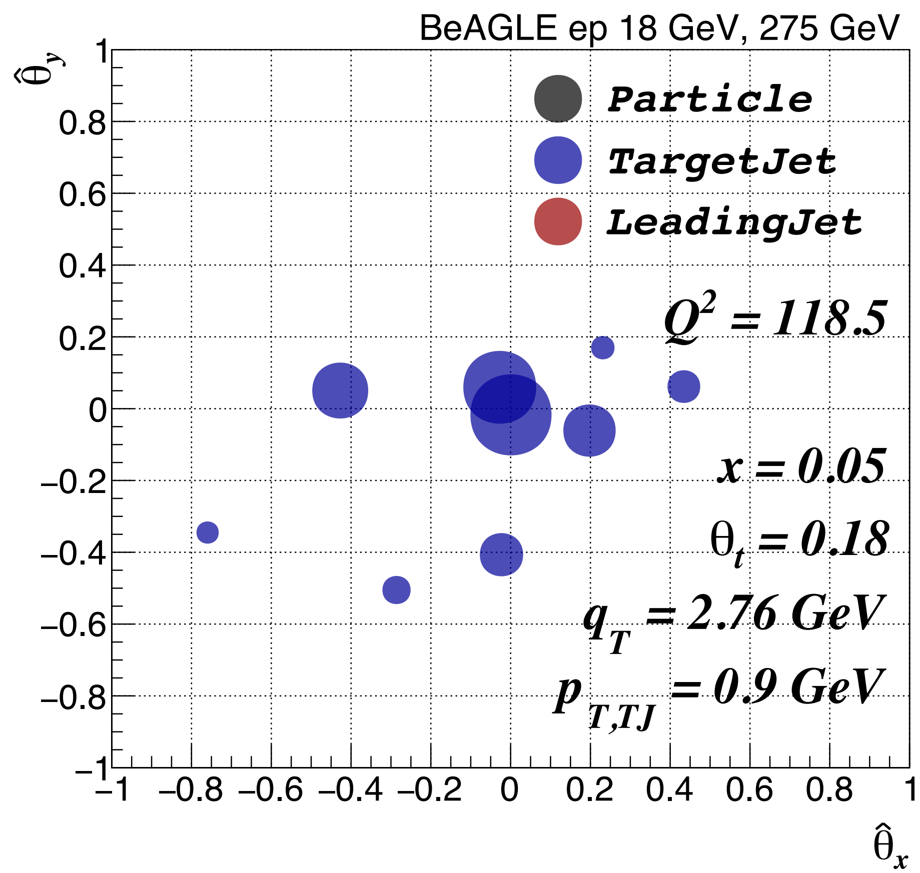


Monte Carlo simulations

- 18 GeV electron beam + 275 GeV proton beam
- 10 GeV electron beam + 100 GeV ion (deuteron, gold) beam
- BeAGLE - Benchmark eA Generator for LEptoproduction
  - Built on Pythia 6, FLUKA, DPMJet, PyQM, LHAPDF5
  - Special thanks to Kong Tu and Mark Baker for help with simulation
- For ep collisions we also compare with Pythia 8 to help with simulation development
  - QED shower and ISR contributions
- Impose $Q^2 > 100\ \mathrm{GeV}^2$ so that we have higher p_T current jet

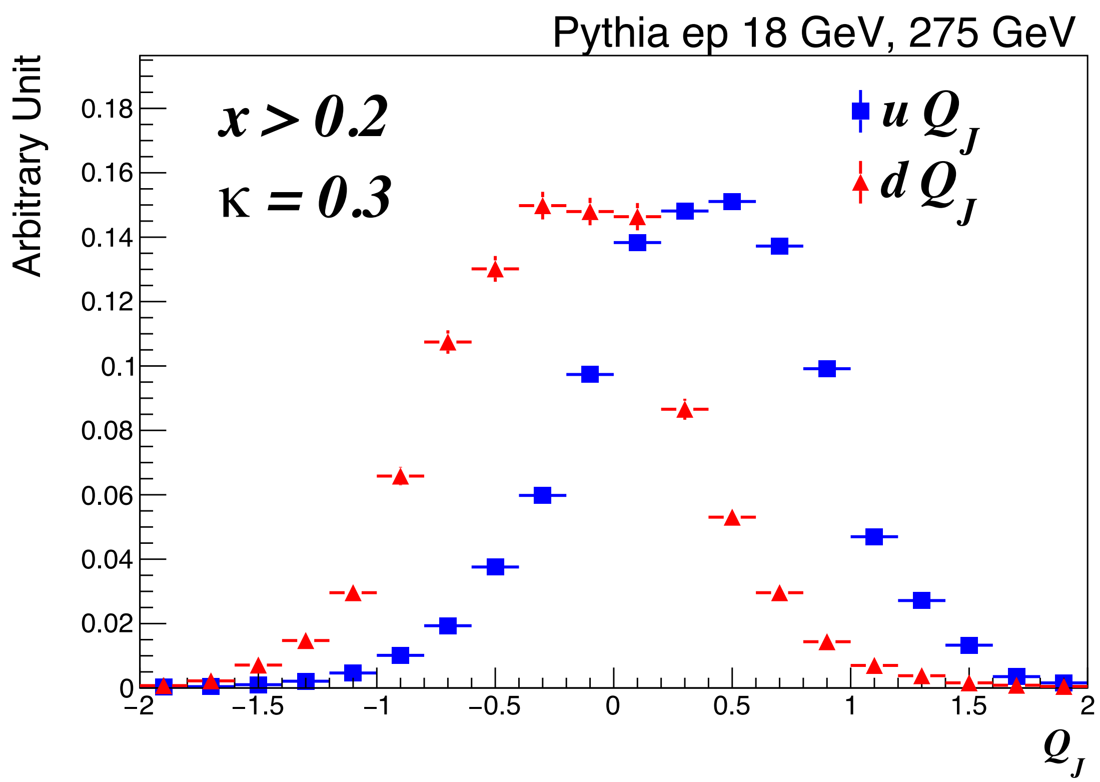
Forward event display

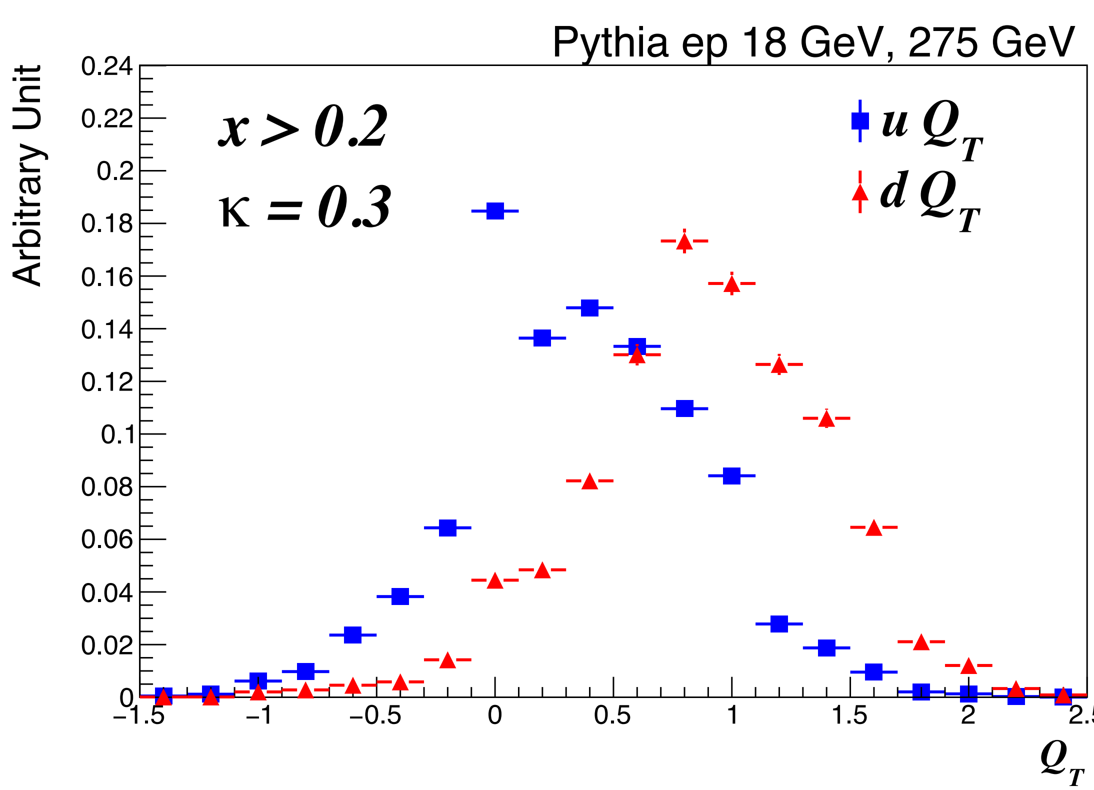




- Leading jet reconstructed using anti-kt R = 1.0 in the lab frame
- Target jet (TJ) as a cone along the beam direction
- $\hat{\theta}_{x,y} = \theta_{x,y}/\theta_t$: geometric angle normalized by the target jet angle θ_t

Leading jet and target jet charge





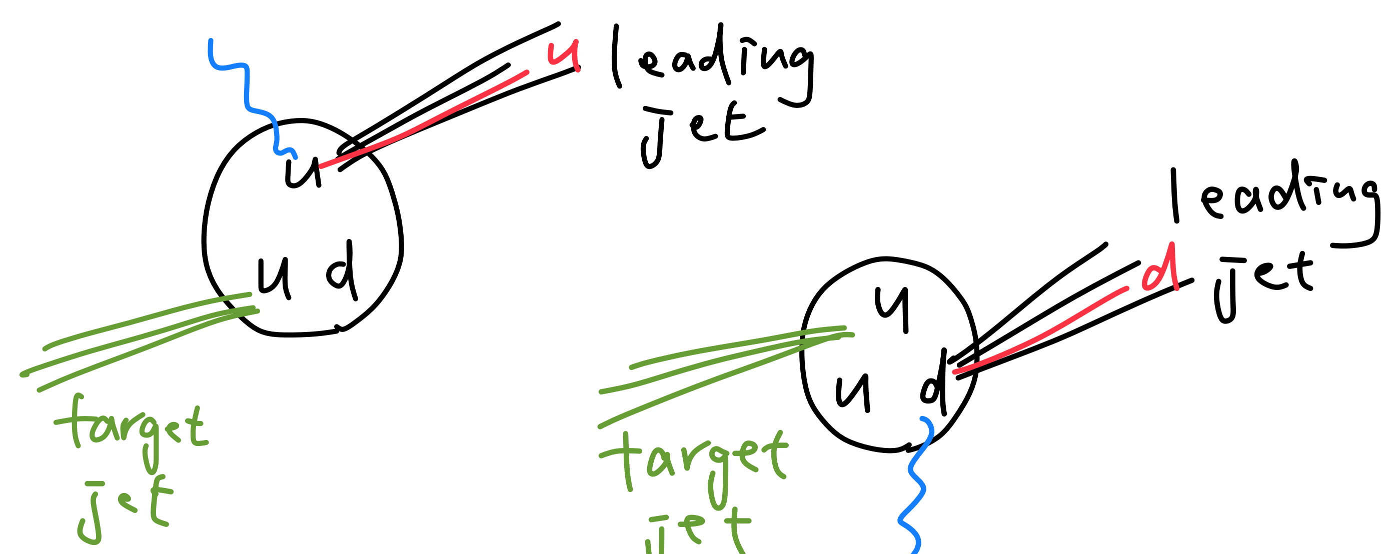
$$Q_J = \sum_{i \in L_J} z_i^{\kappa} Q_i \ , \qquad z_i = \frac{p_{T,i}}{p_{T,L_J}}$$

$$Q_T = \sum_{i \in T_J} z_i'^{\kappa} Q_i \ , \qquad z_i' = \frac{e_i}{e_{T_J}}$$

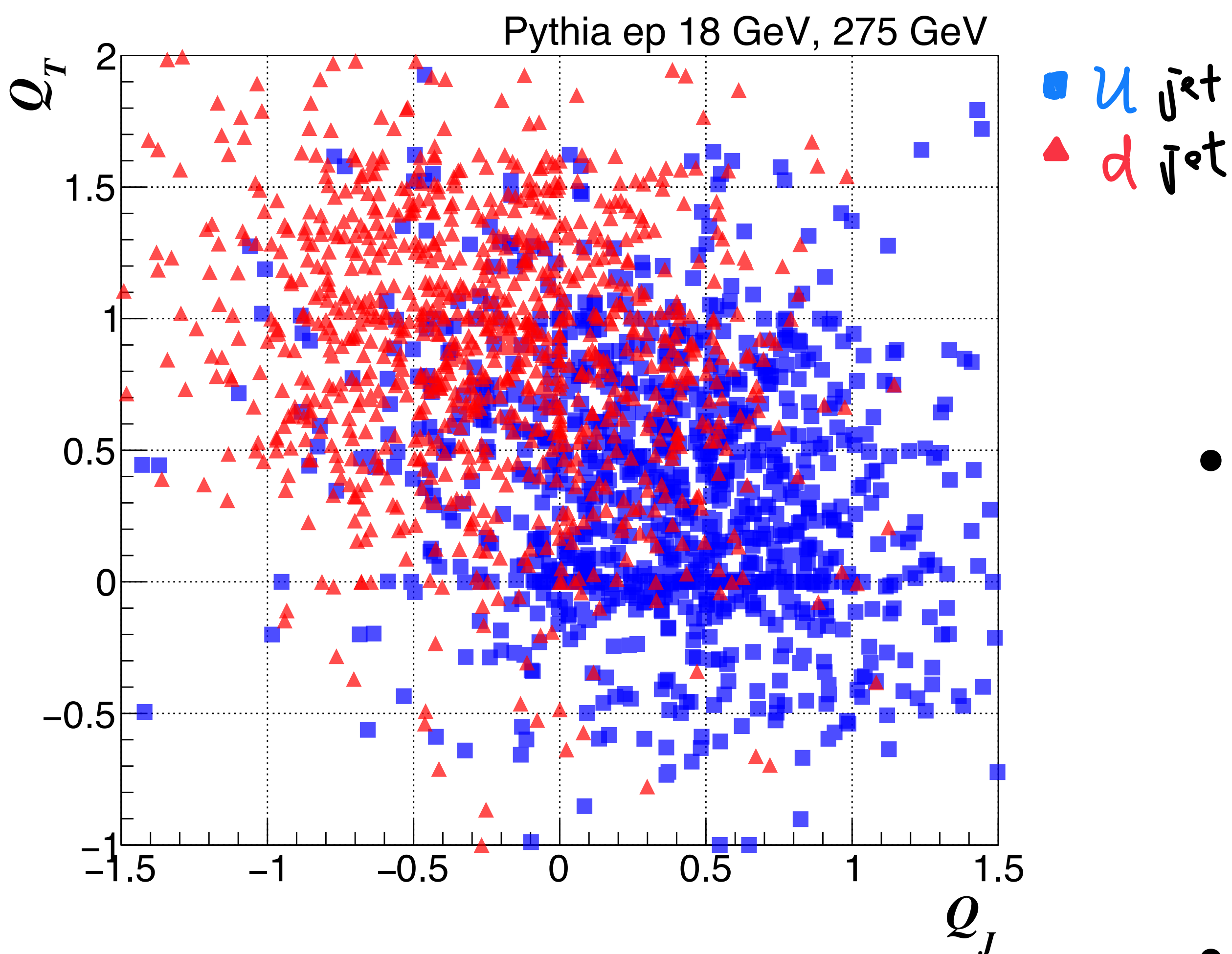
Jet charge

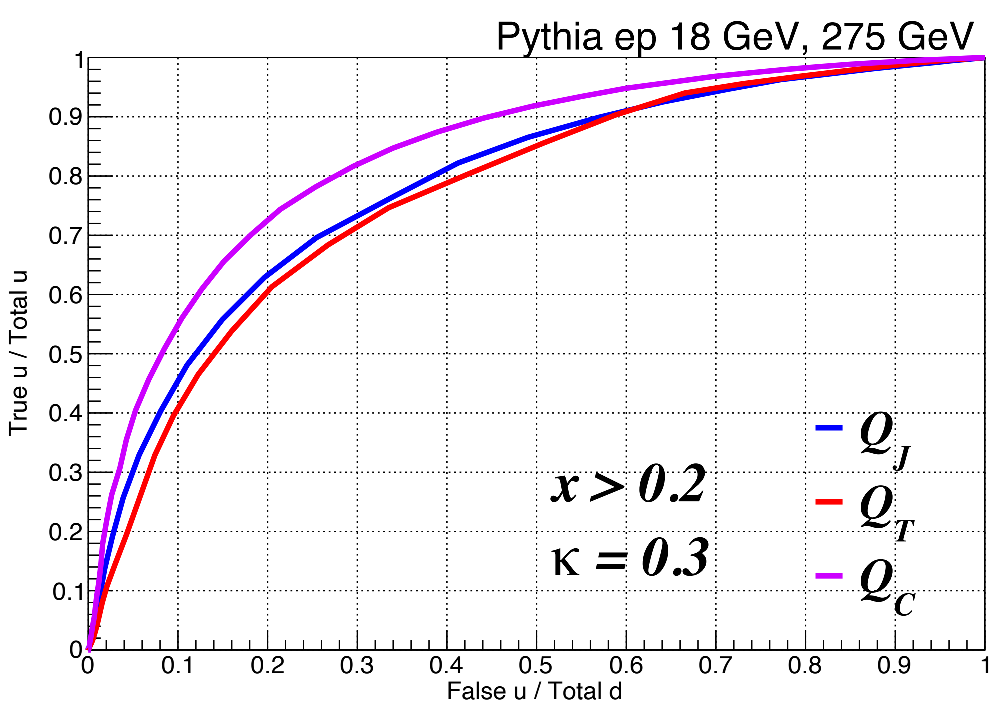
Field & Feynman (1978)

- u (+2/3) quark jet v.s. ud (+1/3) diquark remnant
- d (-1/3) quark jet v.s. uu (+4/3) diquark remnant



Leading jet and target jet charge

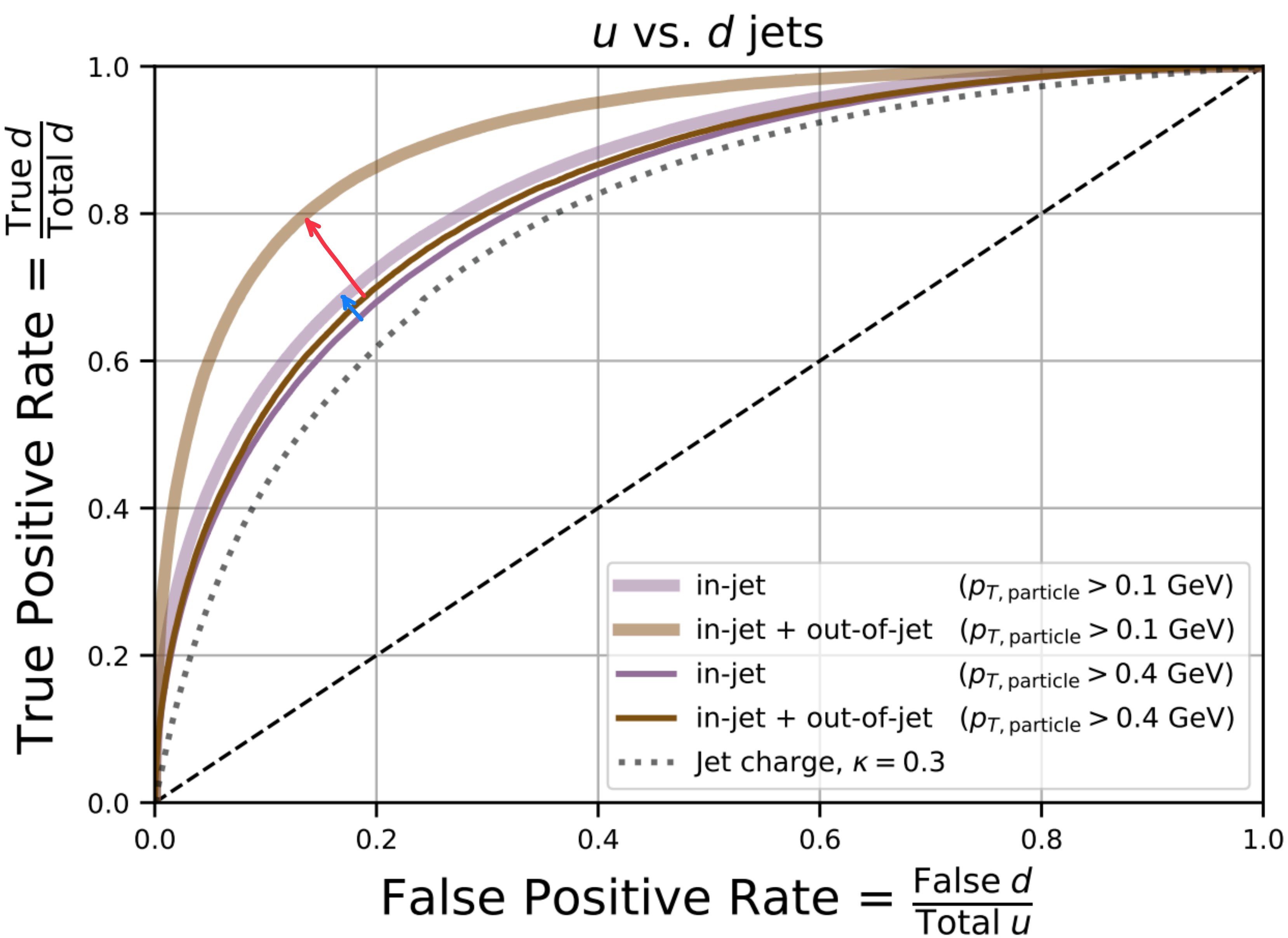




- Evaluate the information content with leading jet tagging
  - Using leading jet charge
  - Using target jet charge
  - Using both
- Target jet charge provides significantly extra information and improves the tagging performance

Related studies using machine learning:
JHEP 03 (2023) 085

Information outside jet

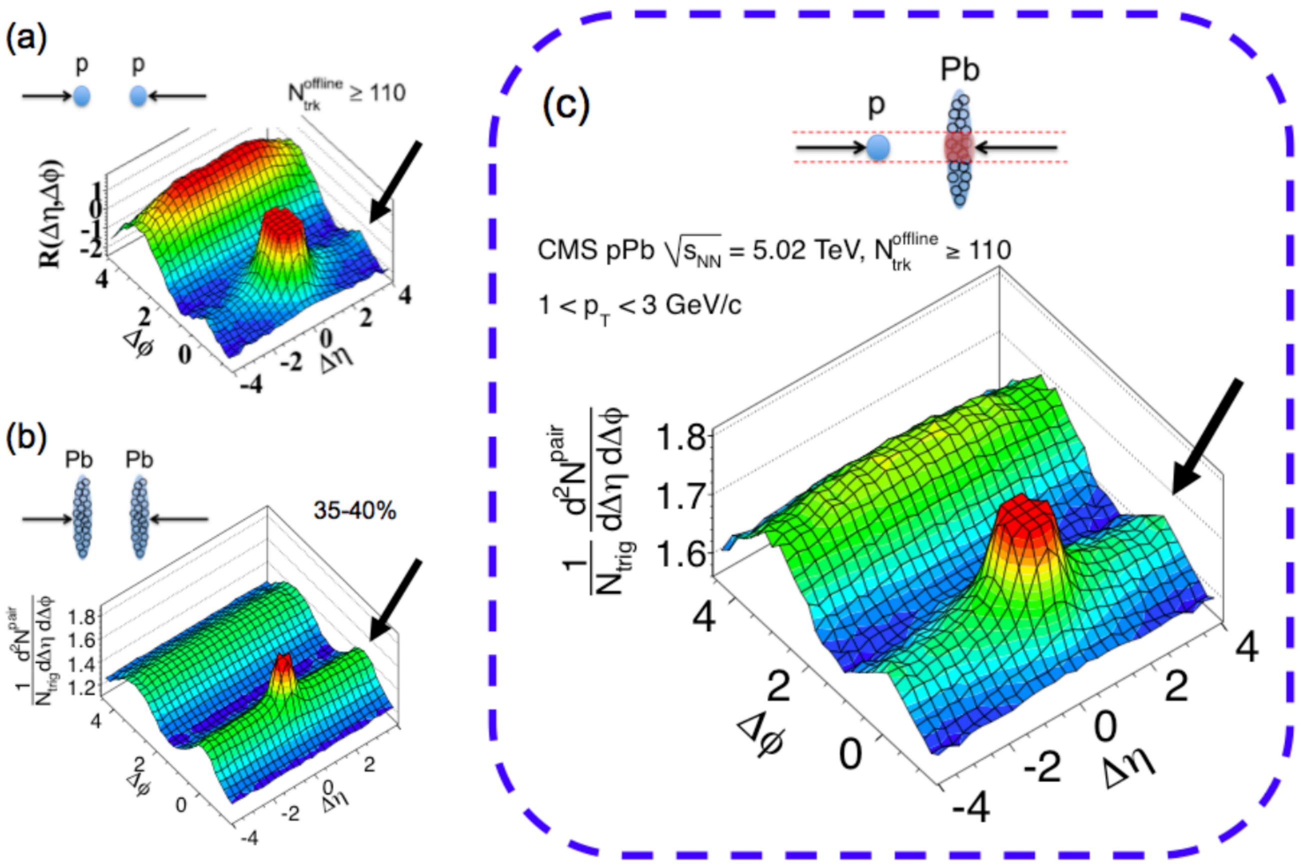


- Used Particle Flow Network (PFN)
- Huge performance gain by including low p_t particles outside jet
- Are they “soft” particles?

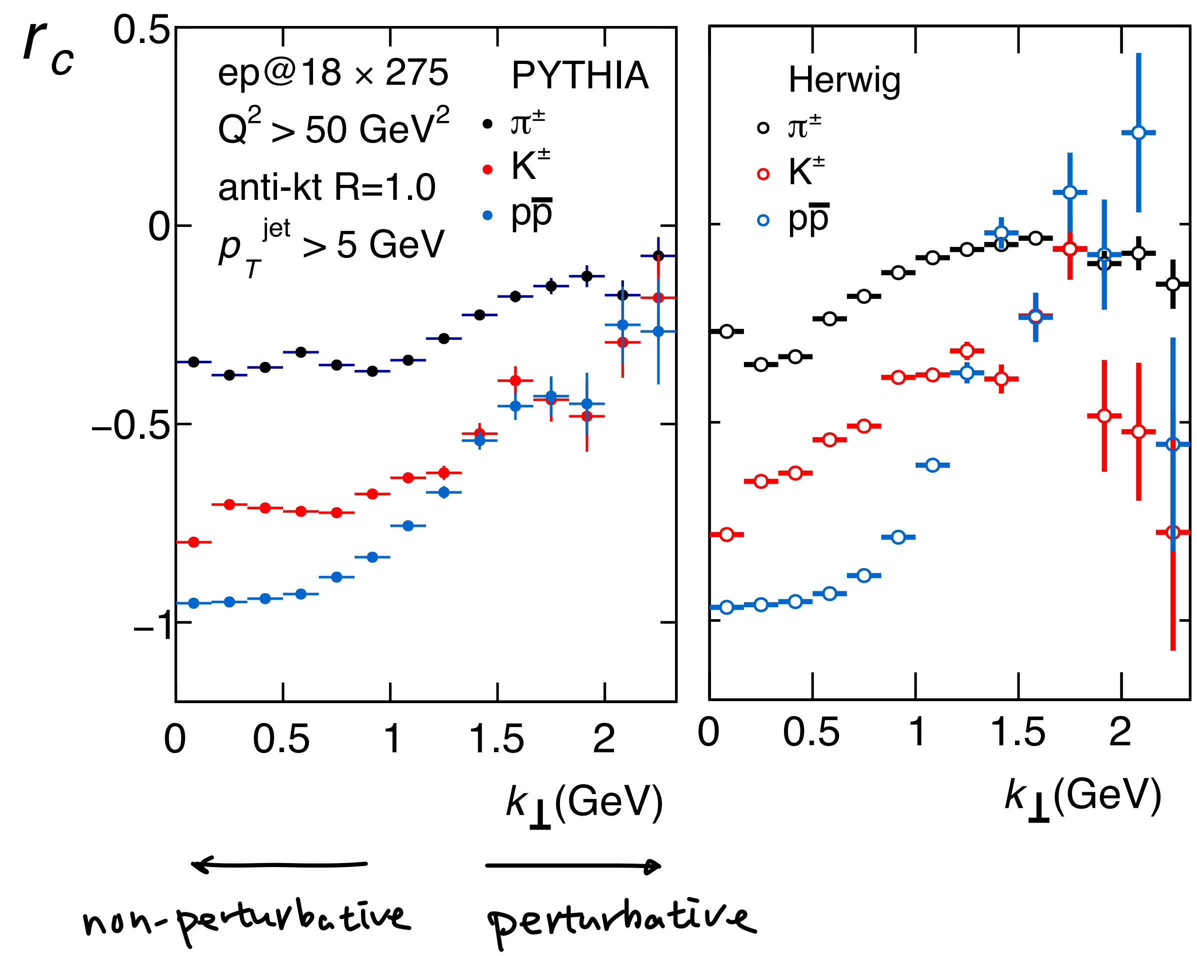
JHEP 03 (2023) 085, F. Ringer et al

Two-particle correlation (2PC) — some digression

- Long-range, two-particle correlation ($\Delta\phi \approx 0$, $\Delta\eta$ large) in heavy ion collisions, a signature of QGP collective behavior
- Flavor correlation between leading two particles in jets is connected to hadronization
- 2PC is an essential step beyond single particle distribution

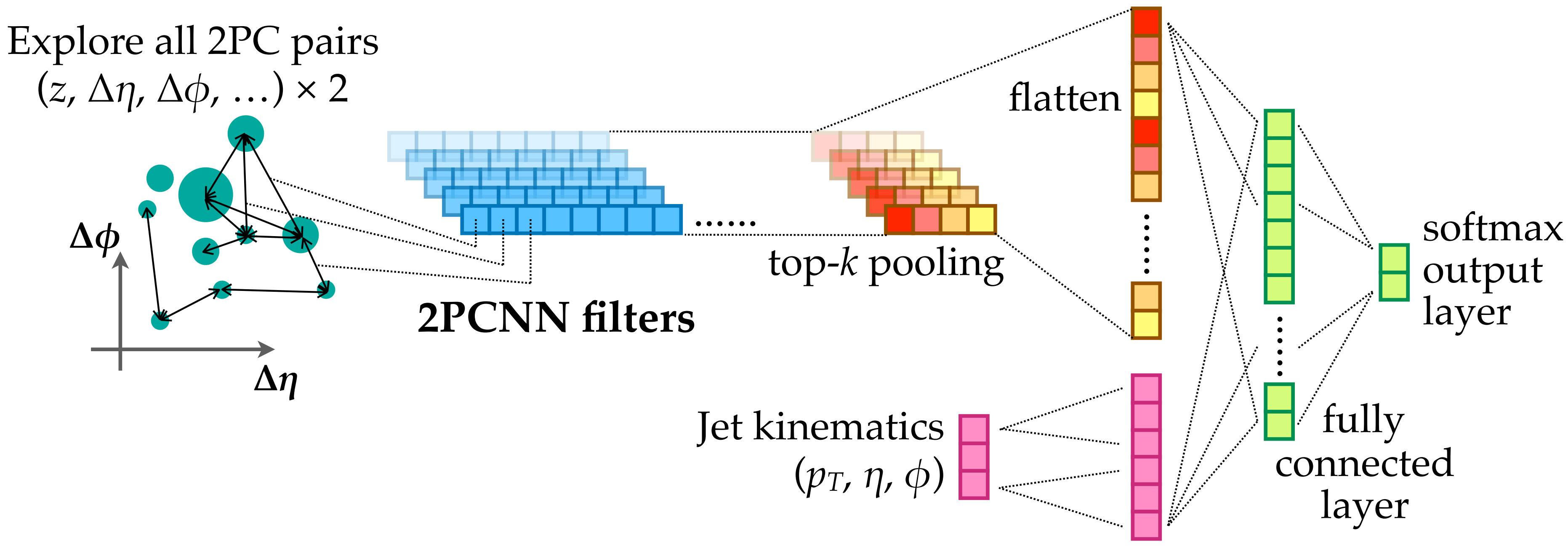


CMS, Phys. Lett. B 718 (2013) 795,
JHEP 09 (2010) 091, JHEP07(2011)076



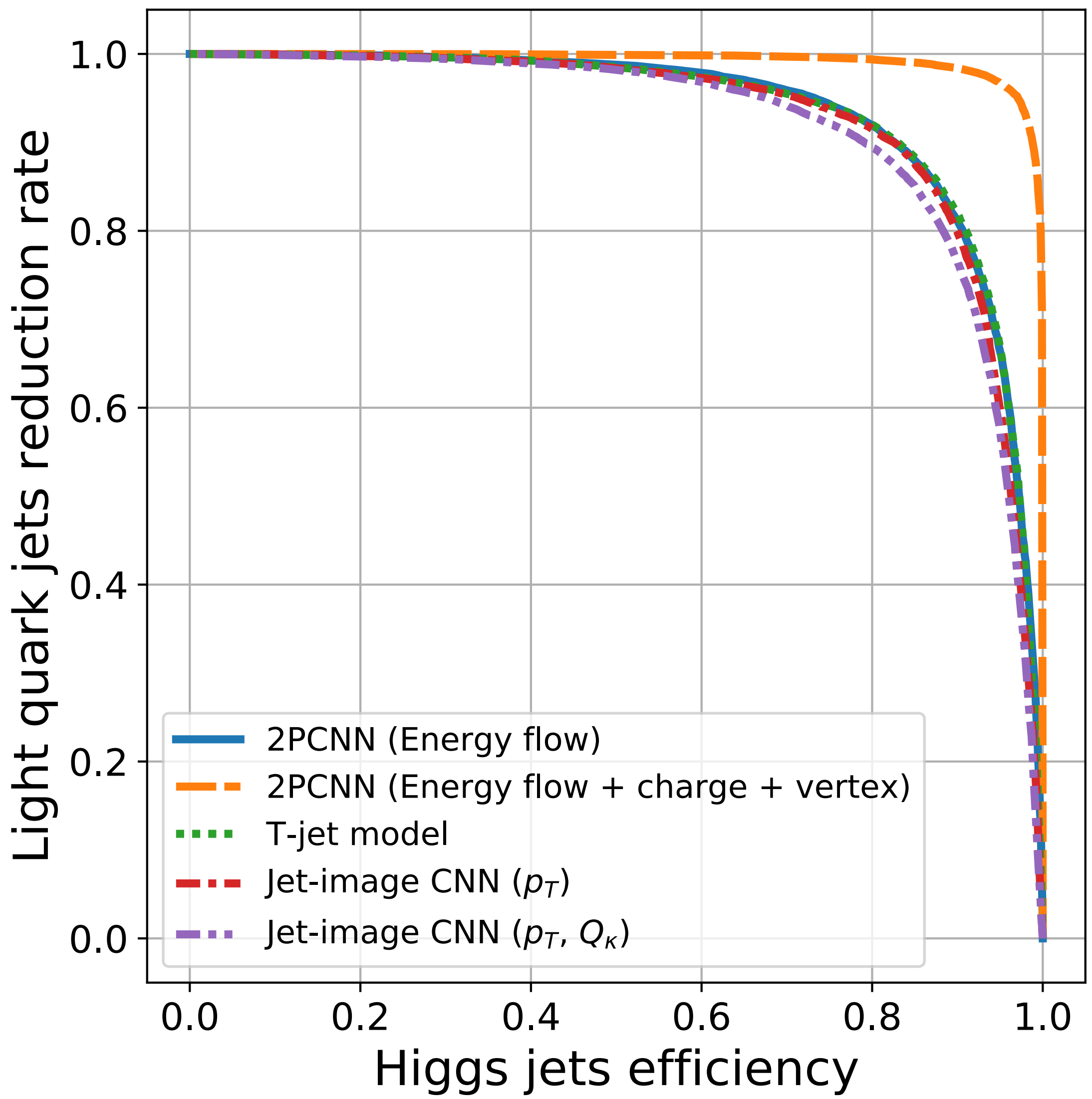
Phys.Rev.D 105 (2022) 5, L051502

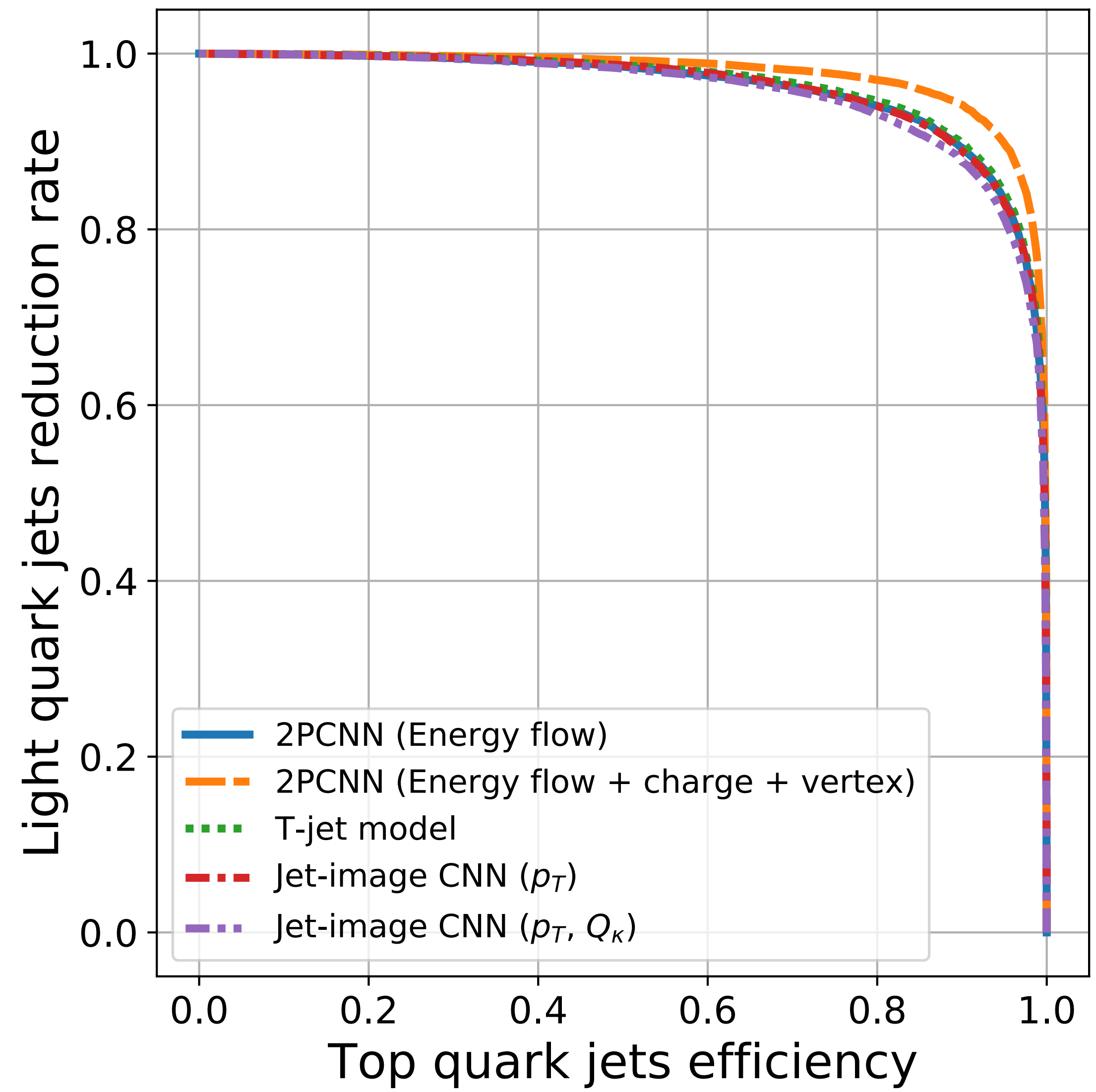
2PC neural network (2PCNN) using Keras and TensorFlow



- 2PC input: $z = p_t^i / p_t(\text{jet})$, $\Delta\eta = \eta^i - \eta(\text{jet})$, $\Delta\phi = \phi^i - \phi(\text{jet})$ + rotation (preprocessing)
  - Basic input layer consists of energy flow information
  - An extra layer consists of track information (charge and 2PC vertex)
- Use a collection of filters (64, 32 for the track layer) with shared weight to process 2PCs
  - Each filter is a fully connected dense network which gives outputs to all the 2PCs
  - Top-k (e.g. k=4) ranked 2PCs are kept as inputs for the subsequent decision-making, fully connected network
- Baseline jet kinematic information is included with a dense network
- Outputs of 2PCNN layer and dense network are followed by a fully connected layer (128 nodes, ReLU) and two output nodes (softmax)
- We use cross-entropy loss function and Adam optimizer

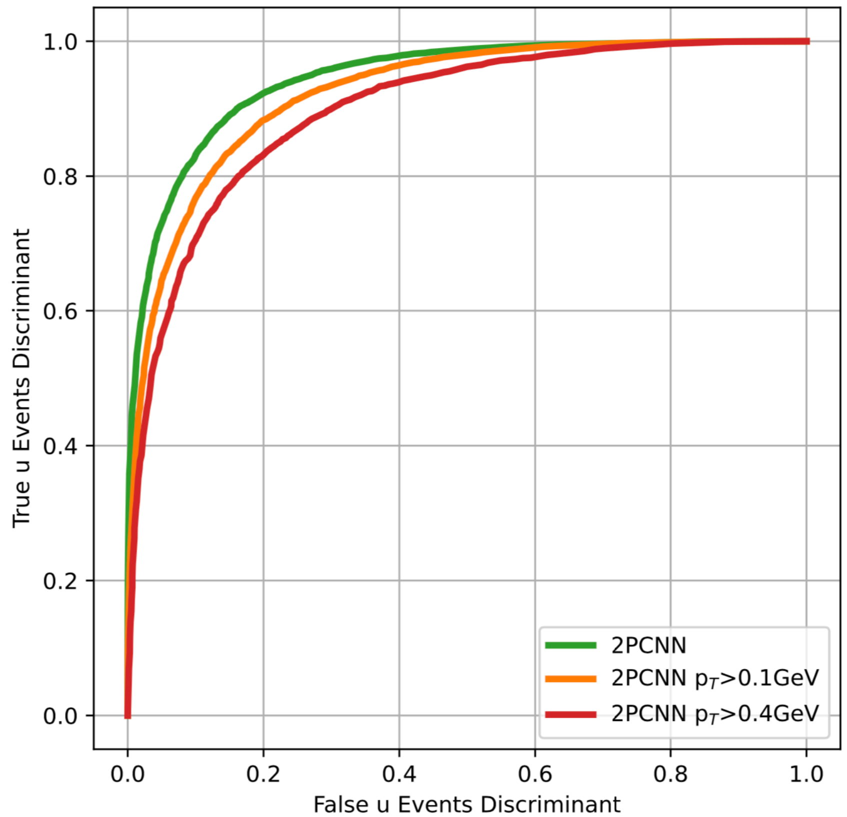
Higgs and top tagging performance

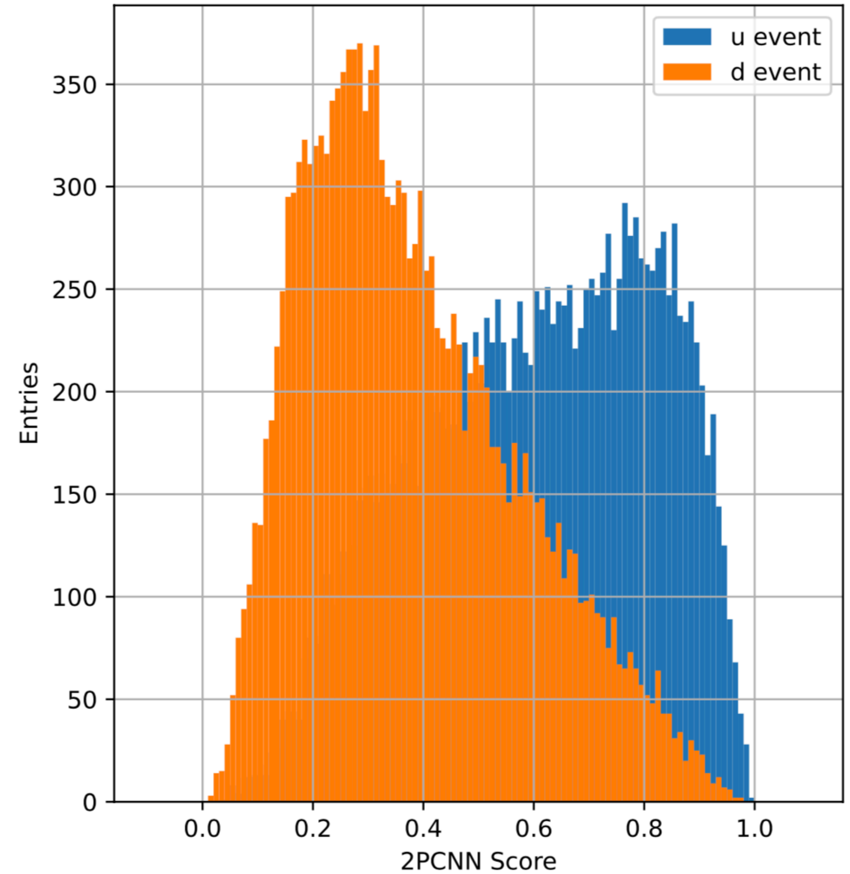


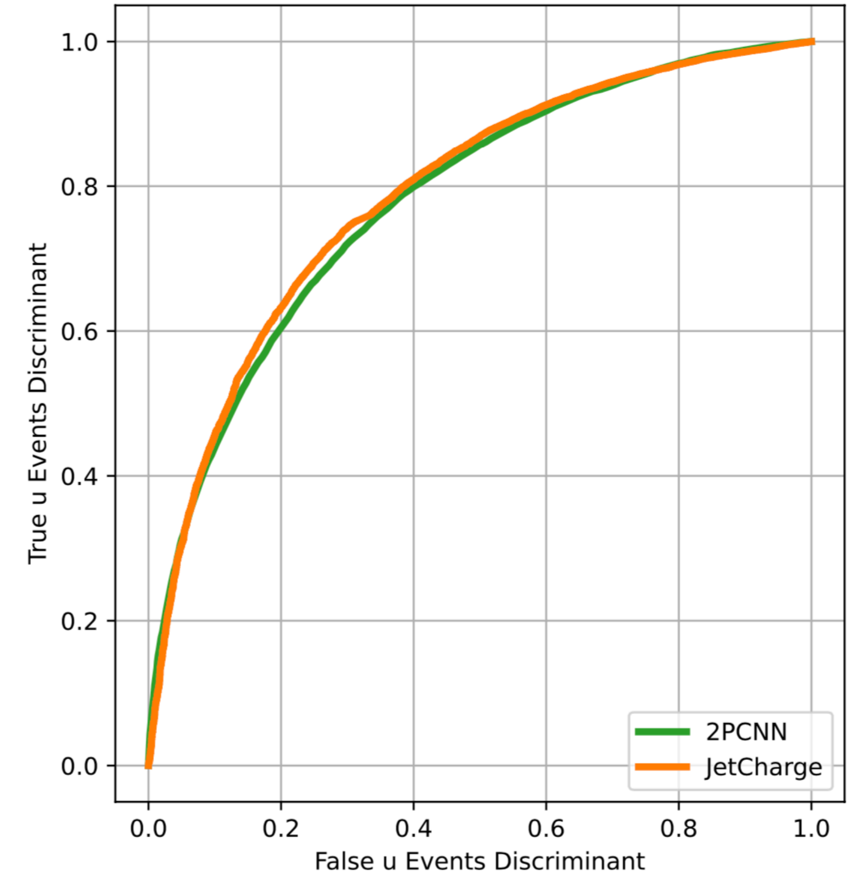


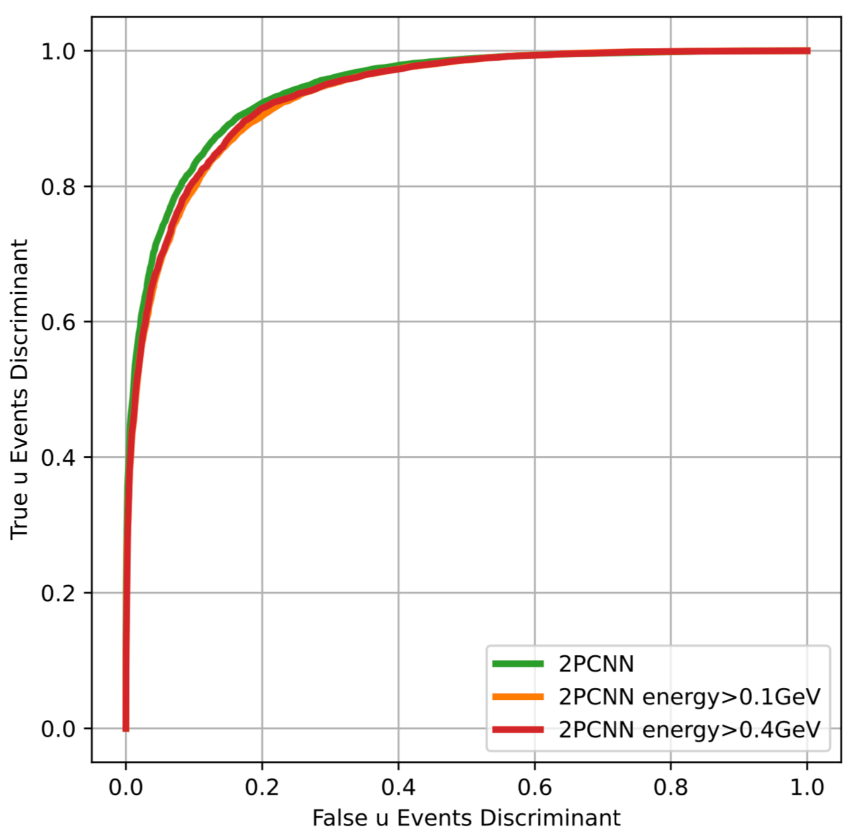
- Receiver operating characteristic (ROC) curves illustrating the performance
- Performance based on energy flow information is comparable to or higher than T-jet
  - A consistency check and a benchmark of 2PCNN performance
- Vertex information is useful because of the secondary b vertex in $h \rightarrow b\bar{b}$ and $t \rightarrow W + b$

Information inside target jet



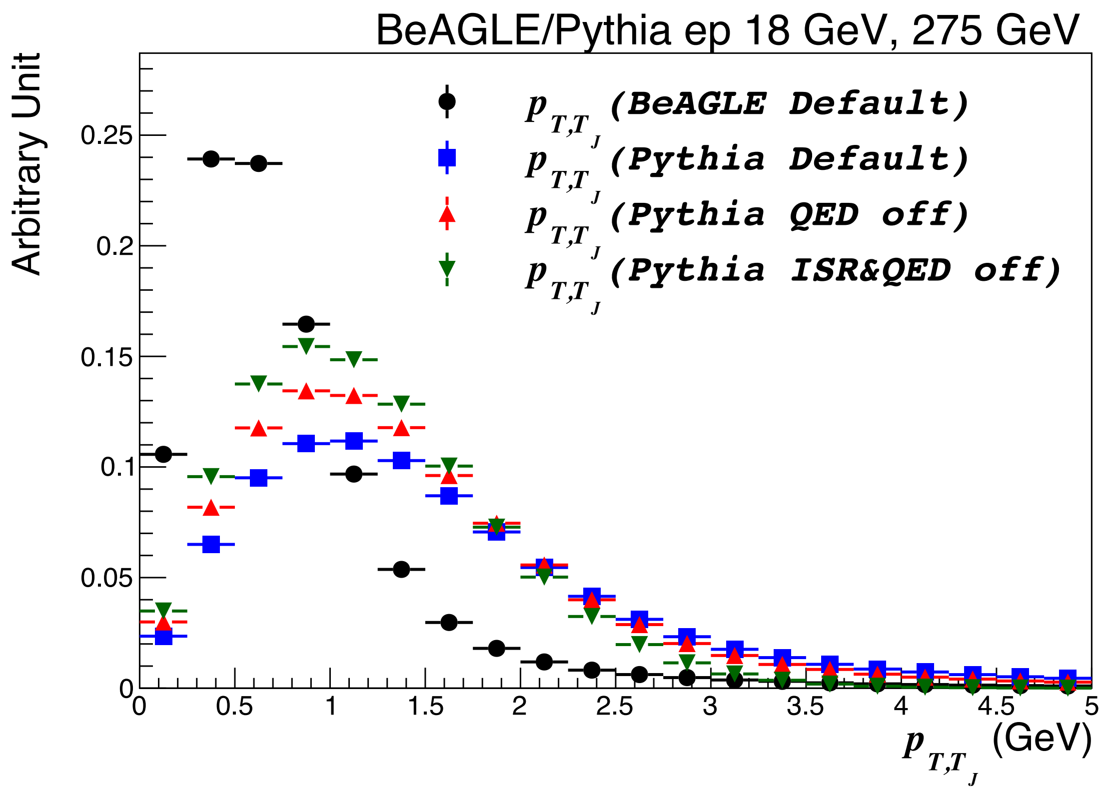


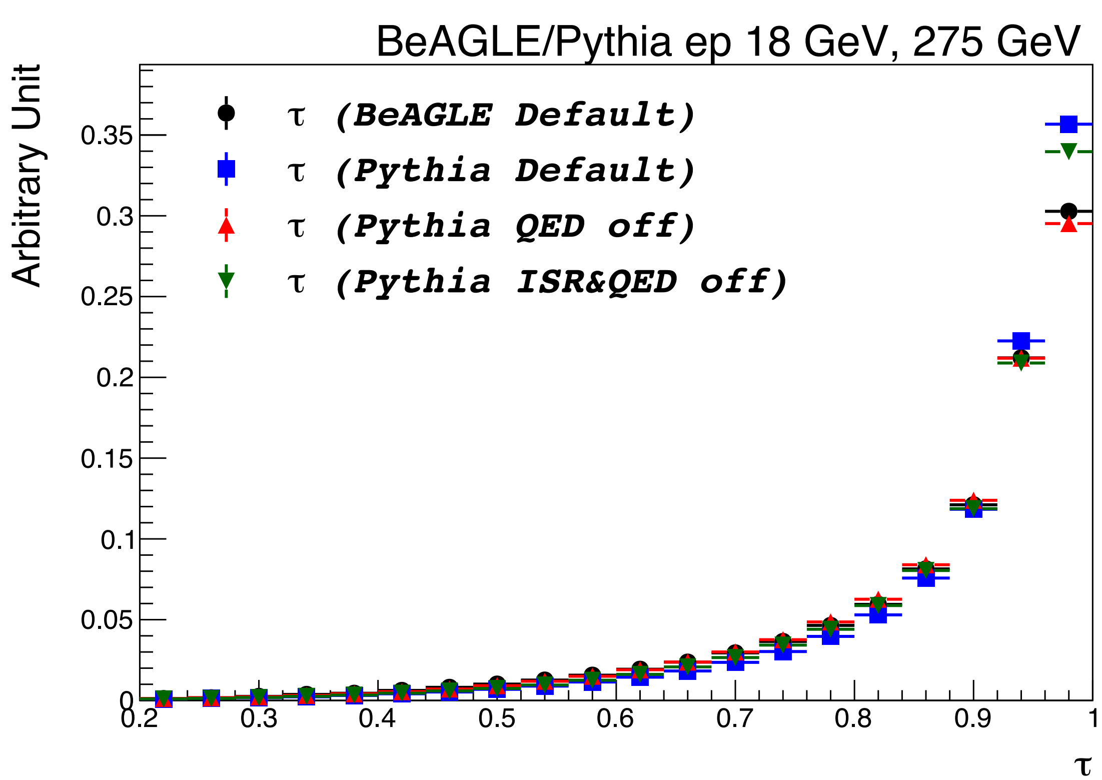




- Significant information carried by target jet particles, low pt but high energy (BeAGLE)
- 2PCNN applied only to jets seems not extracting more information beyond jet charge (yet)

Target jet kinematics — back to our main topic



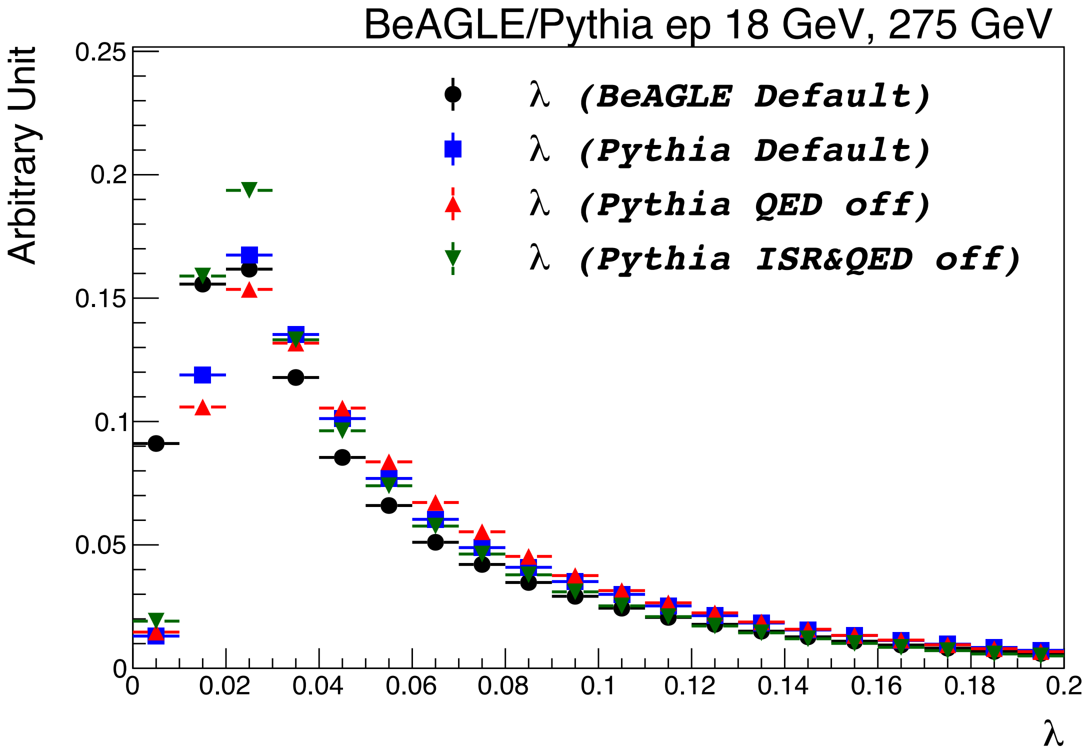


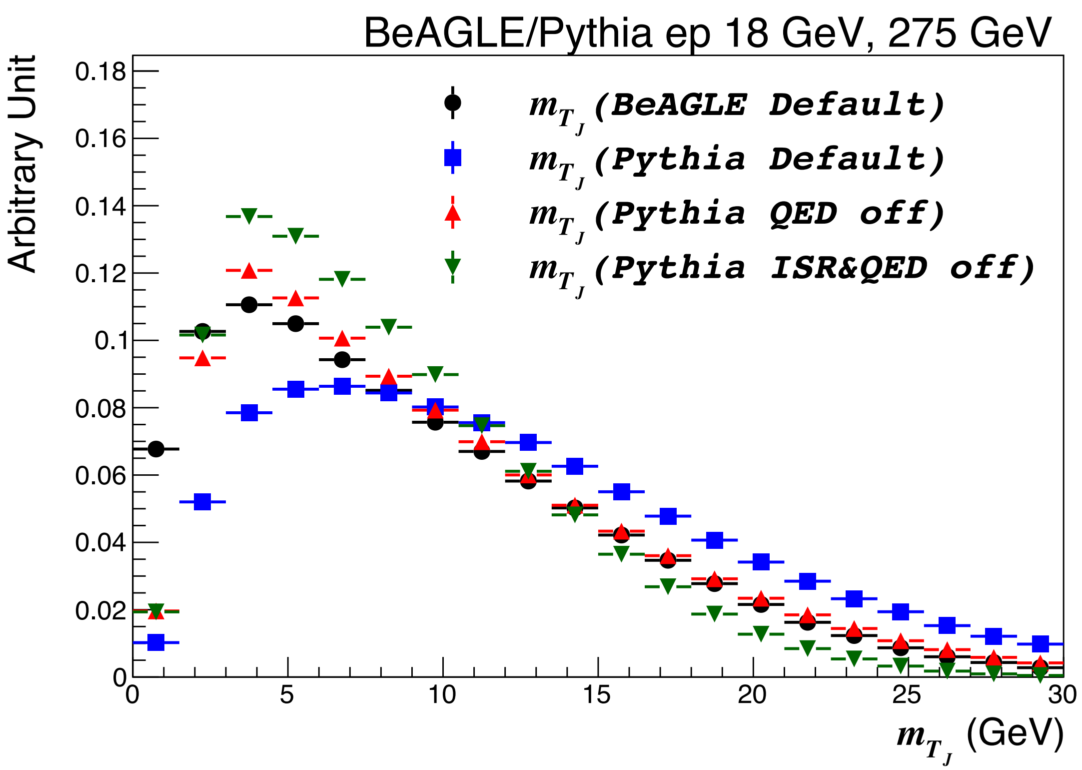
- The kinematic distribution of target jet
  - Transverse
  - Longitudinal
- Target jet has transverse momentum therefore asymmetric w.r.t. beam direction
- Significant difference between BeAGLE and Pythia 8
- Sizable effects from QED shower and ISR implemented in Pythia 8

$$\tau = \frac{p_{z,T_J}}{E_p}$$

* Related to PDF
$\tau \longleftrightarrow 1-x$?
* Target jet thrust

Target jet substructure





$$\lambda = \sum_{i \in S_T} \frac{e_i}{e_{T_J}} \left(\frac{\Delta R_i}{R_{T_J}} \right)^{\alpha}$$

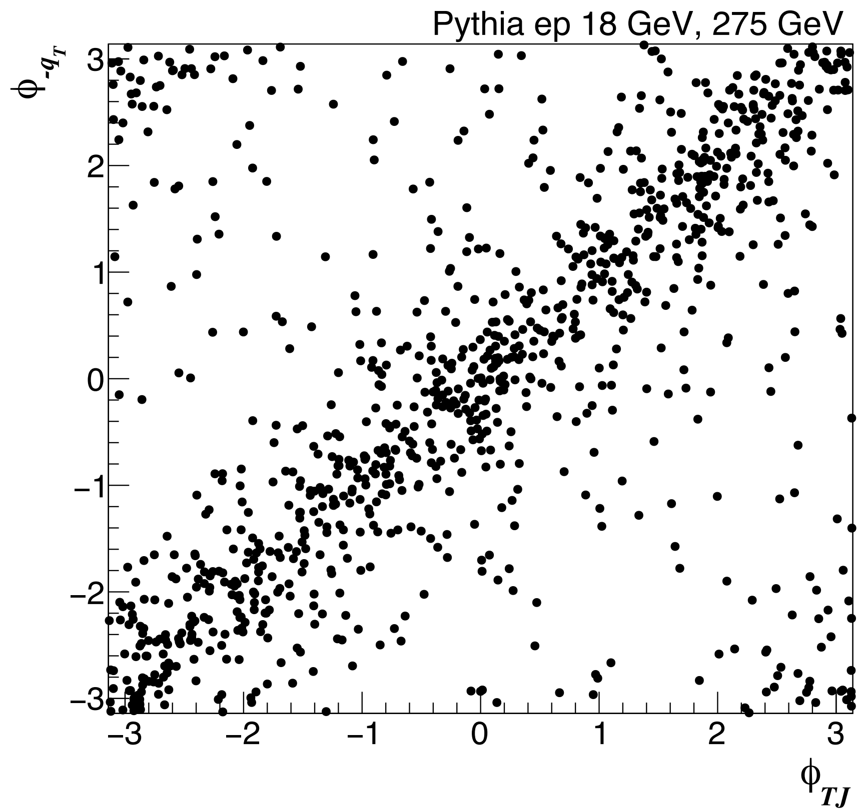
$\alpha = 1$

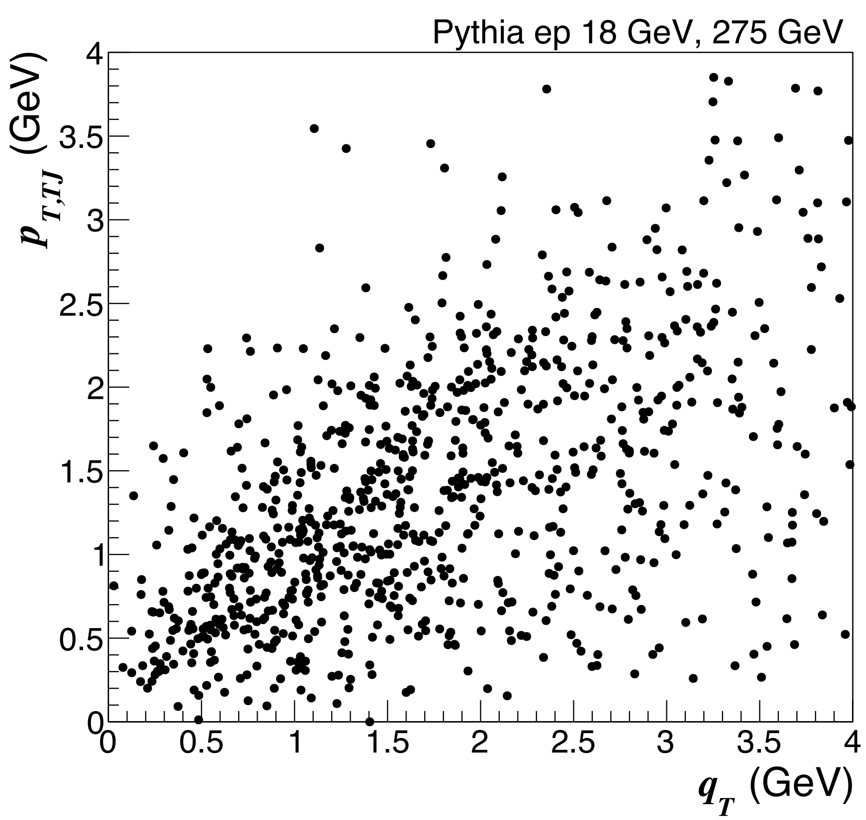
$\alpha = 2 \rightarrow$ mass

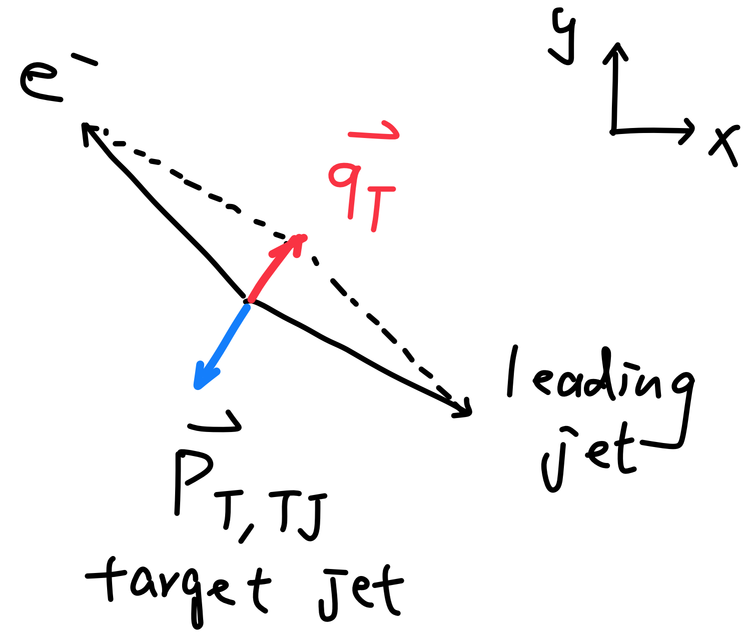
- Angularity and mass probe the spread out of target jet
- Target jet mass scale quite high
- Significant difference between BeAGLE and Pythia 8
- Sizable effects from QED shower and ISR implemented in Pythia 8

Related studies for using energy correlator:
Phys.Rev.Lett. 130 (2023) 9, 091901

Current-target kinematic correlation

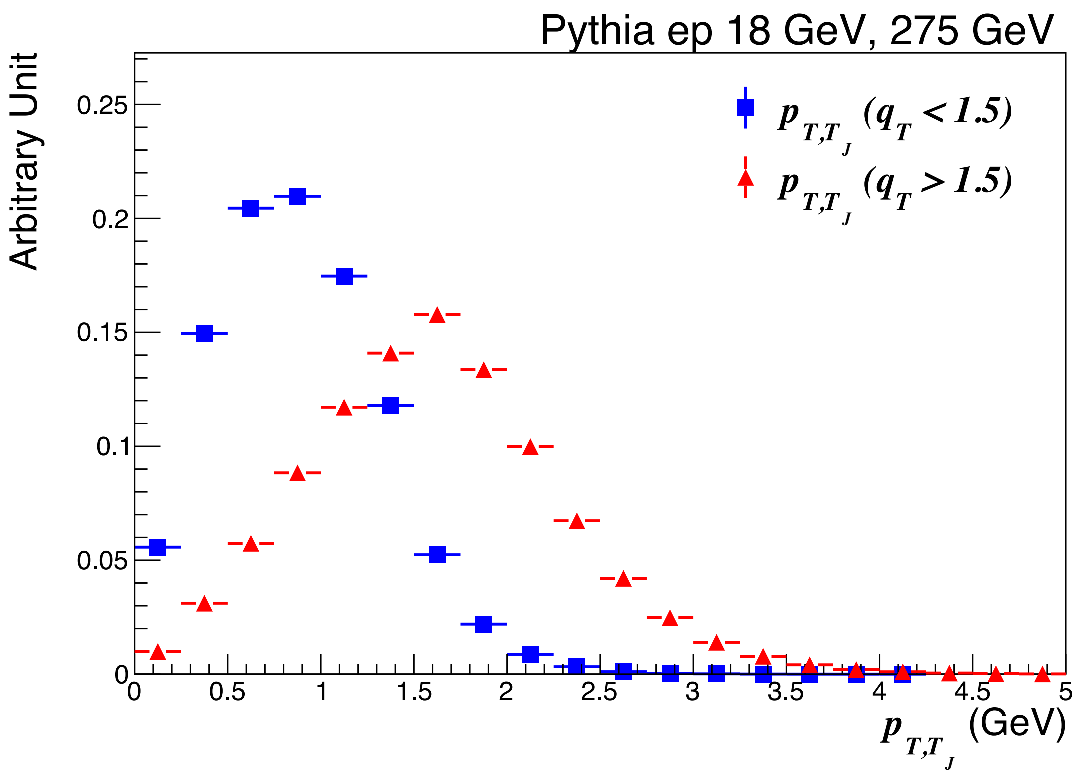


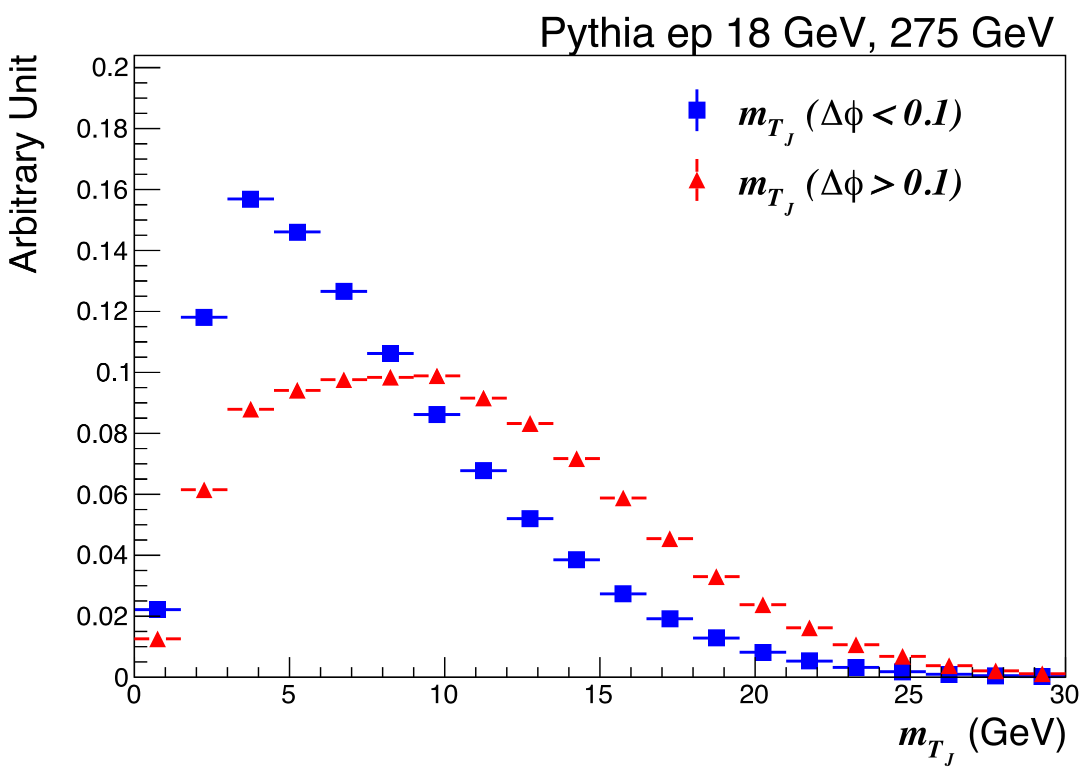




- q_T and target jet mostly back-to-back
- Target jet transverse momentum increases with q_T
- Strong current-target kinematic correlation
  - Energy-momentum conservation at play within these two energy flows

Current-target kinematic correlation

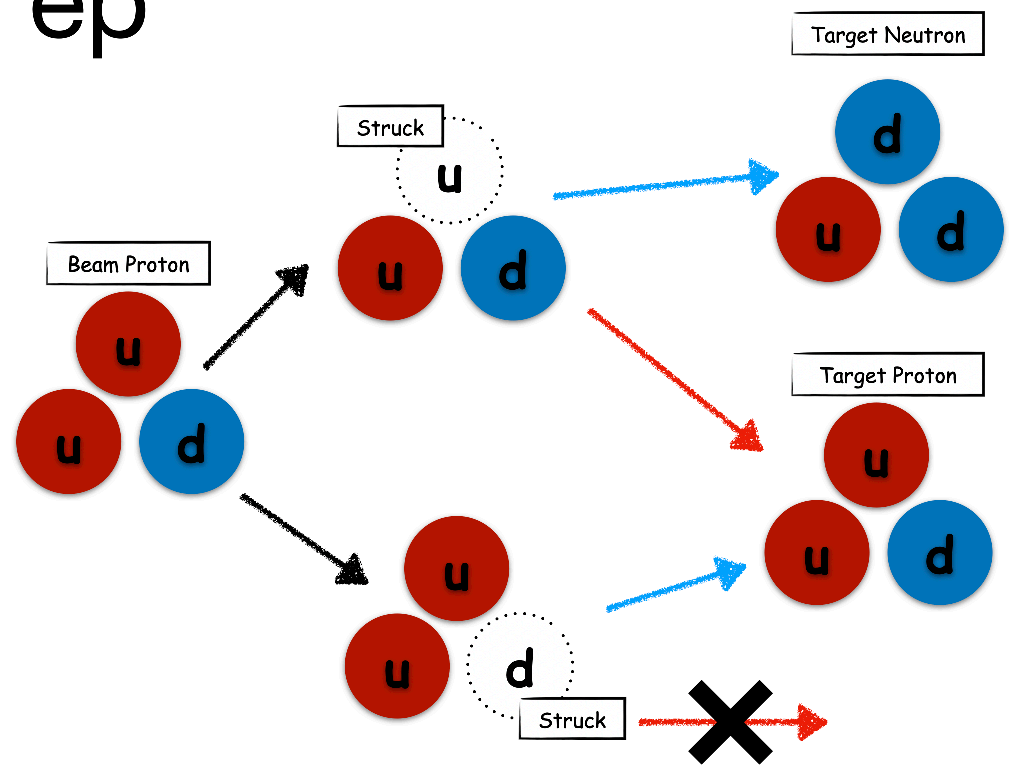


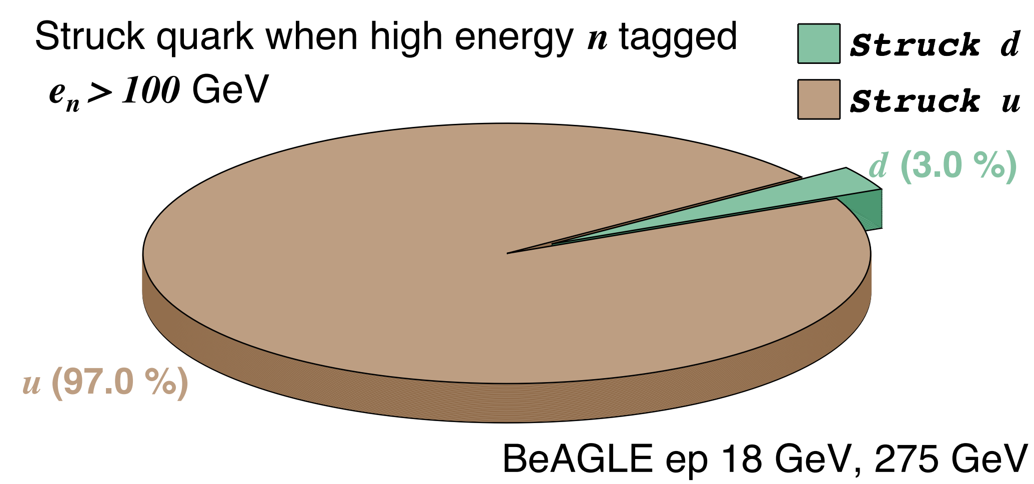


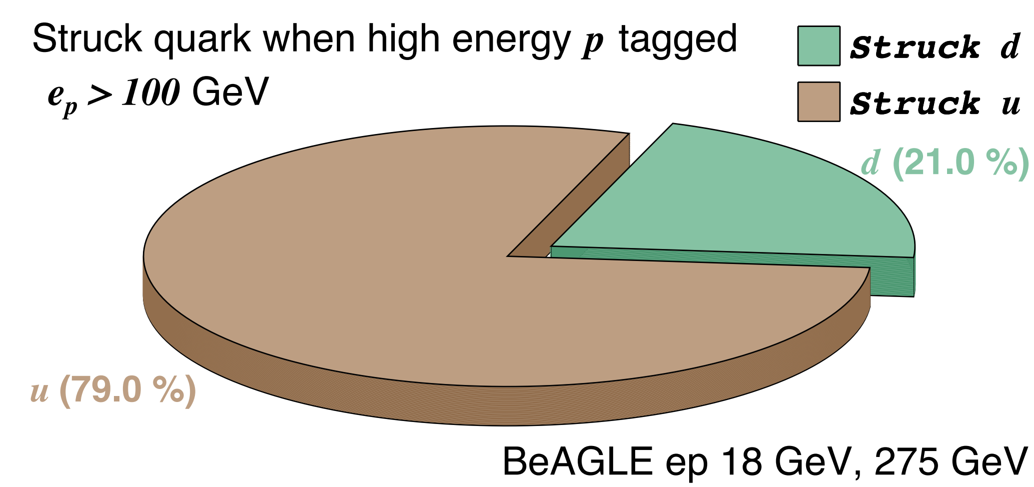
- Current activity (momentum imbalance between electron and leading jet) affecting target activity
    - Both kinematics and substructure

Target tagging: ep

- Effect of tagging forward, energetic neutron
  - High probability of knocking out the u quark, directly probes u distribution
  - Having to knock out a u to turn proton into neutron?
- Effect of tagging forward, energetic proton
  - Both partonic channels are possible
  - How does uu diquark hadronize?



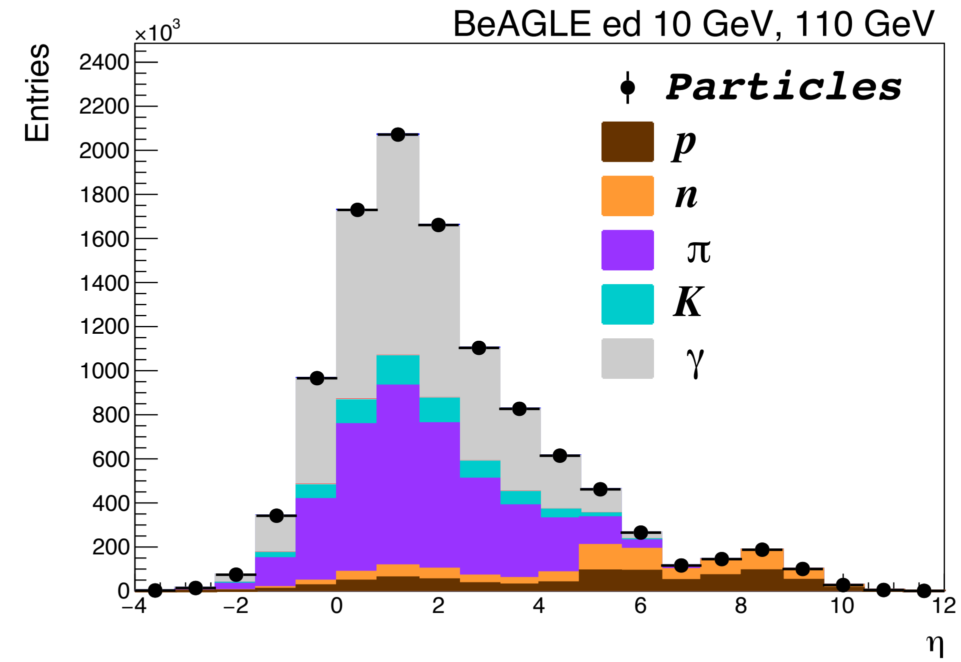


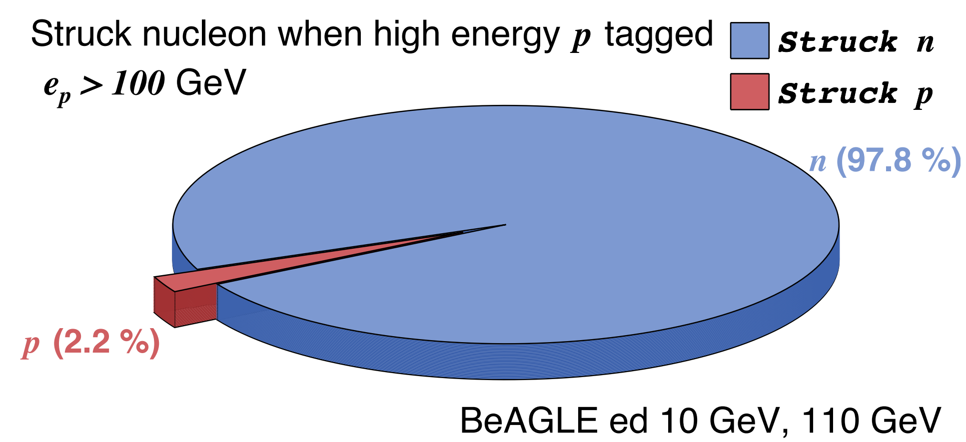


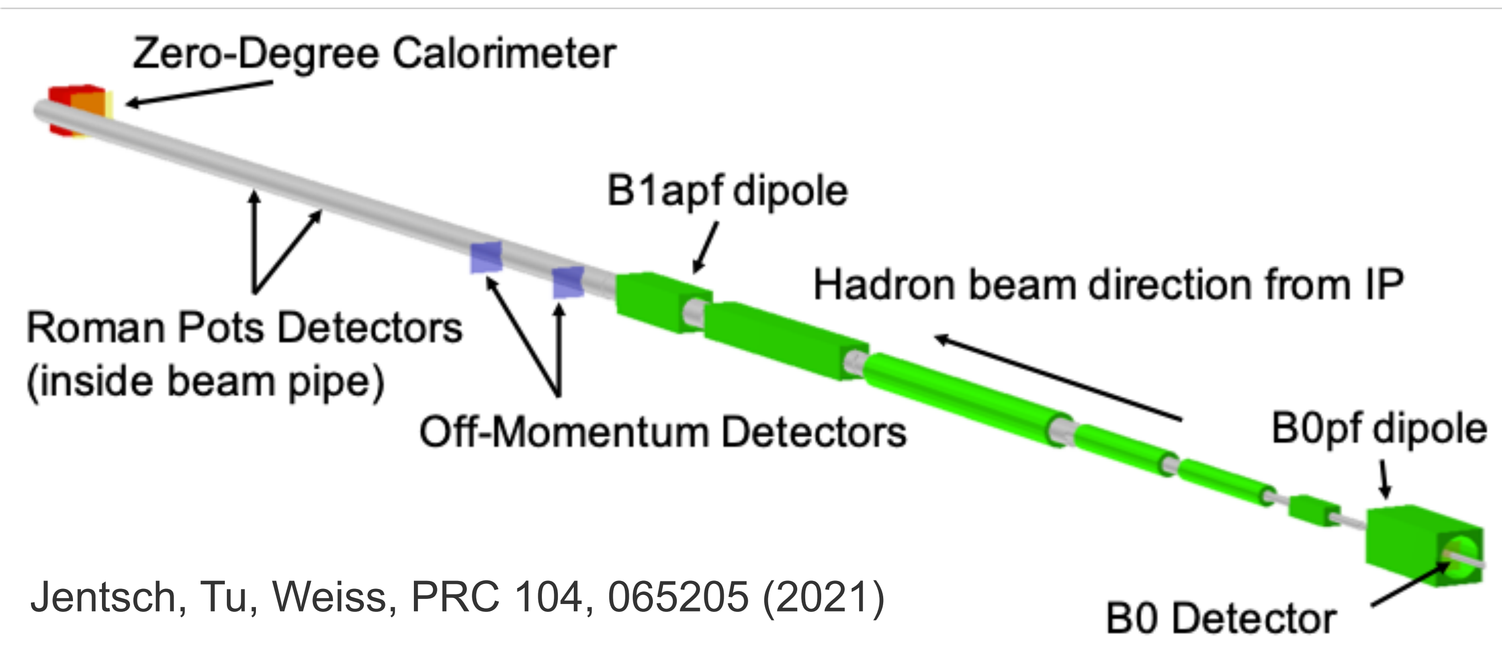
Target tagging: ed

- Proton and neutron within deuteron tends to be more “self-contained”
  - Knocking one out would have the other released
  - Opportunity to probe neutron concretely

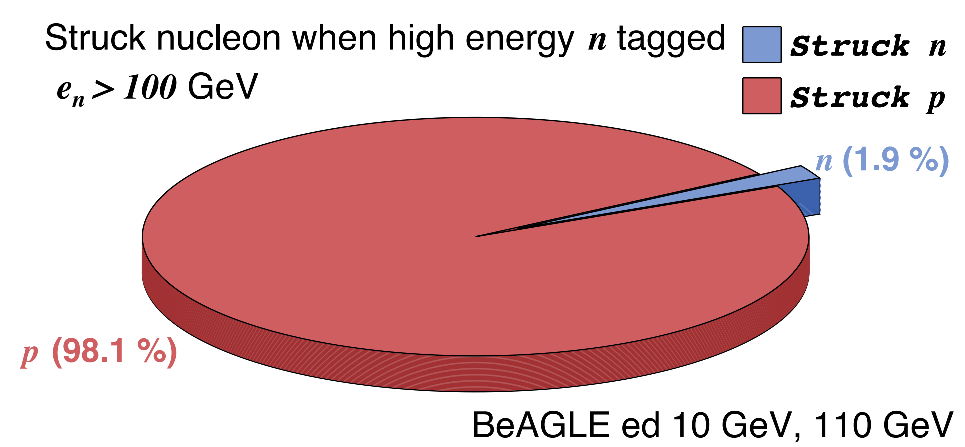
BLAST: annurev-nucl-100809-131956



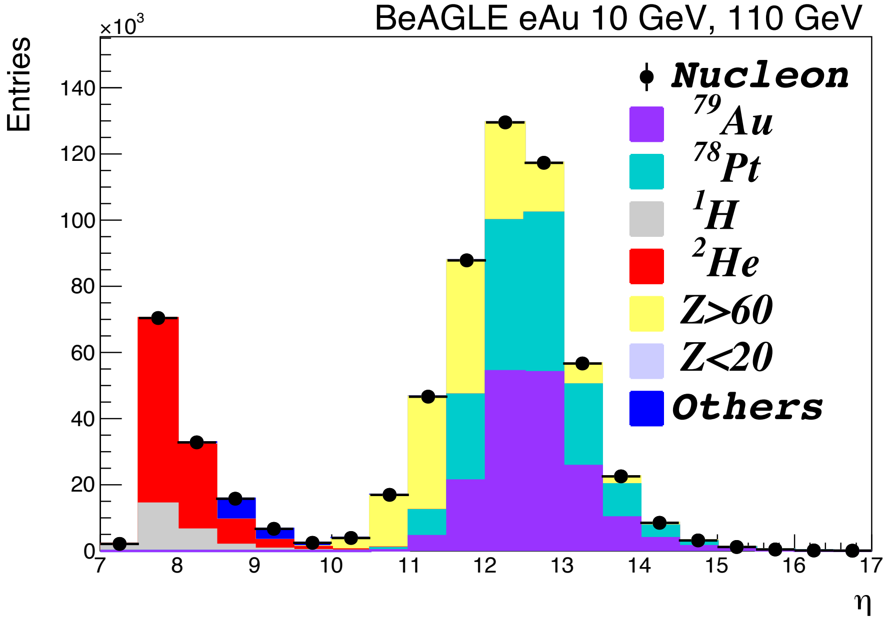


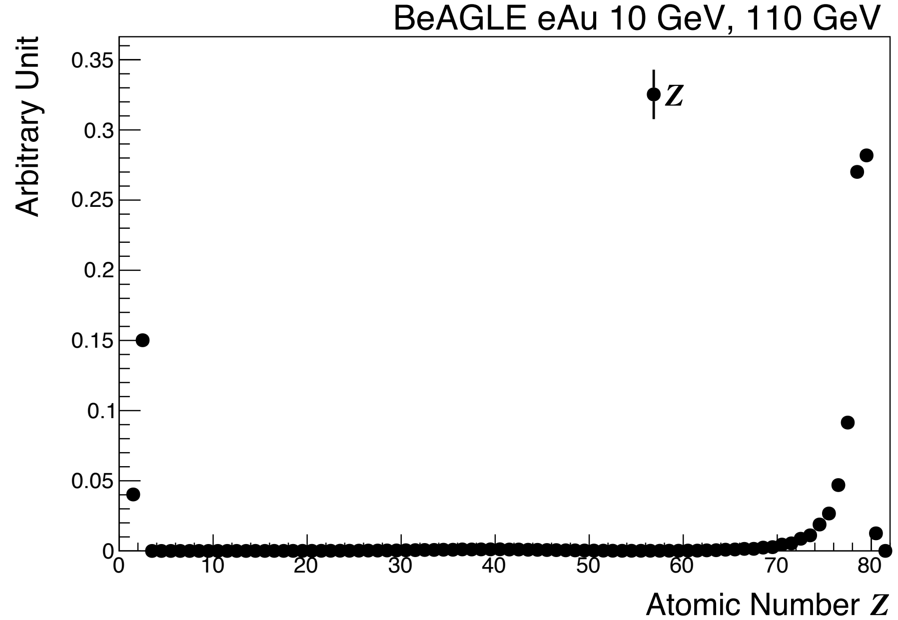


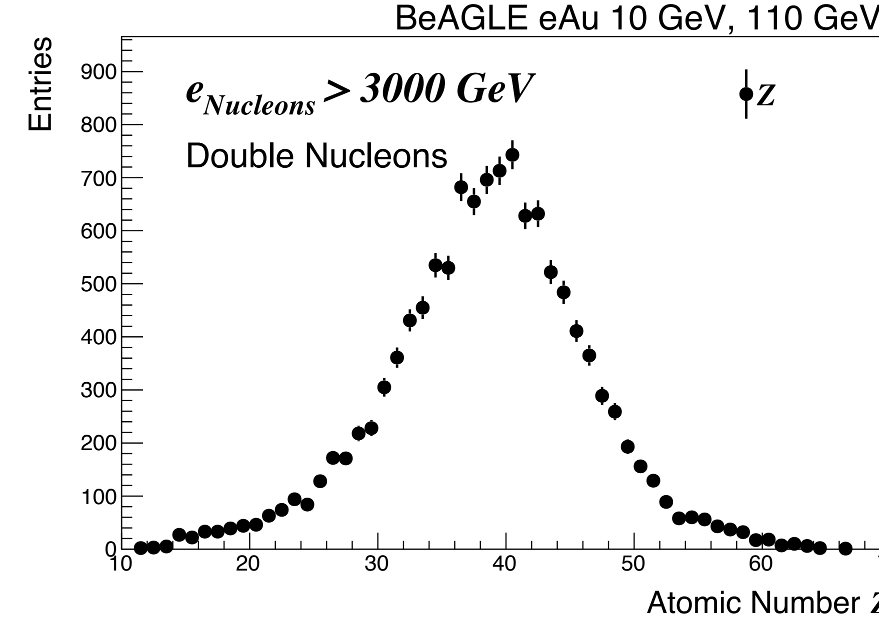
Jentsch, Tu, Weiss, PRC 104, 065205 (2021)



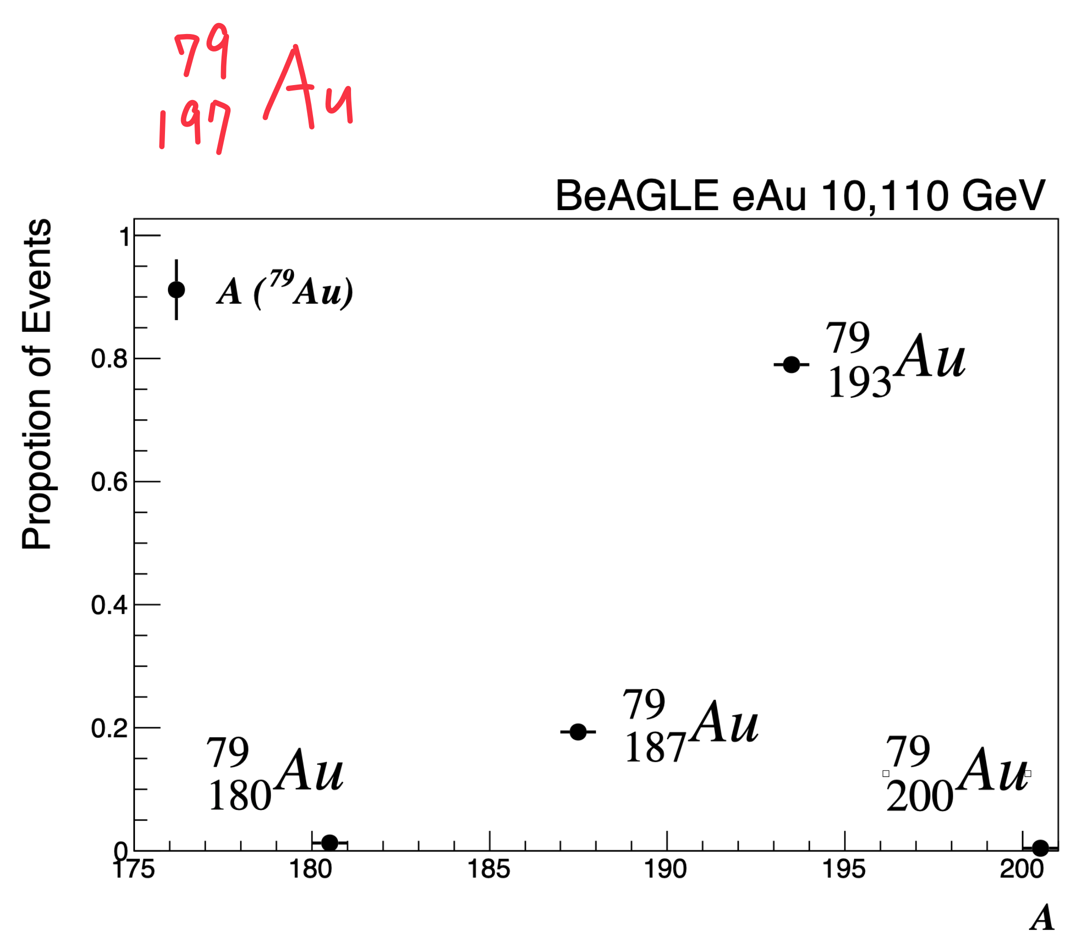
Target tagging: eAu



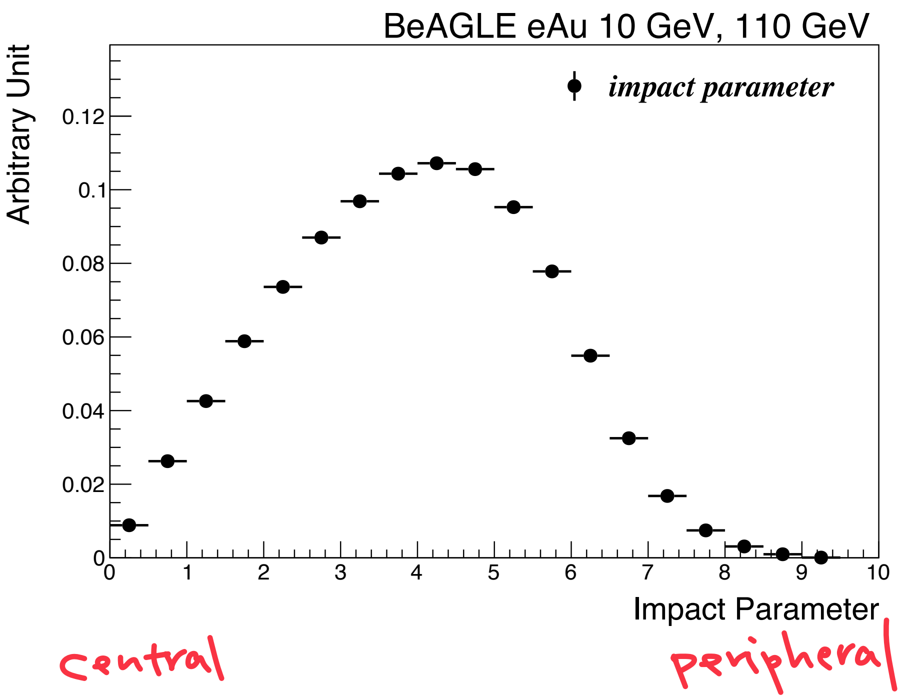


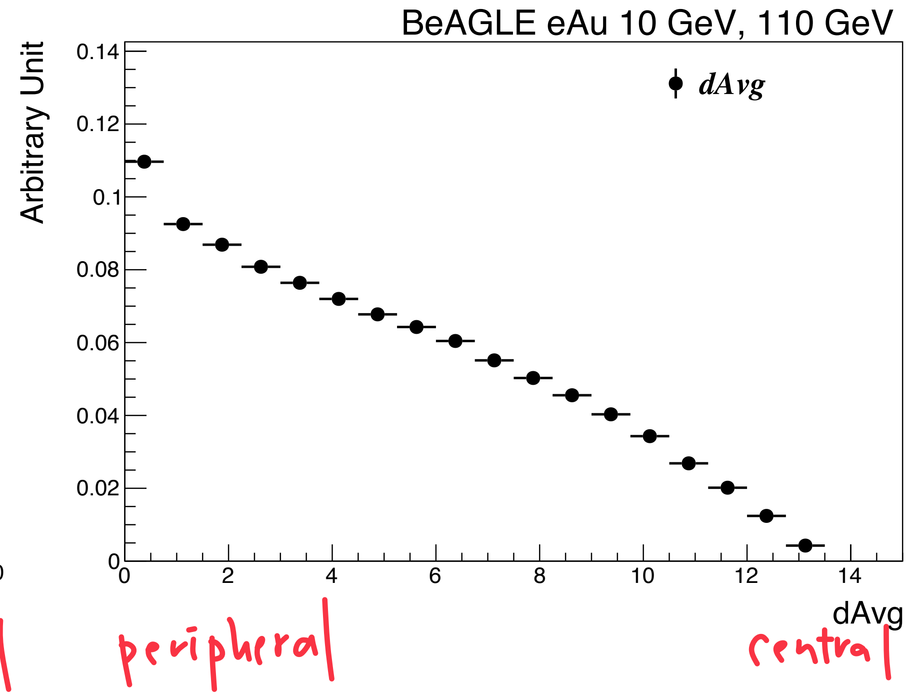


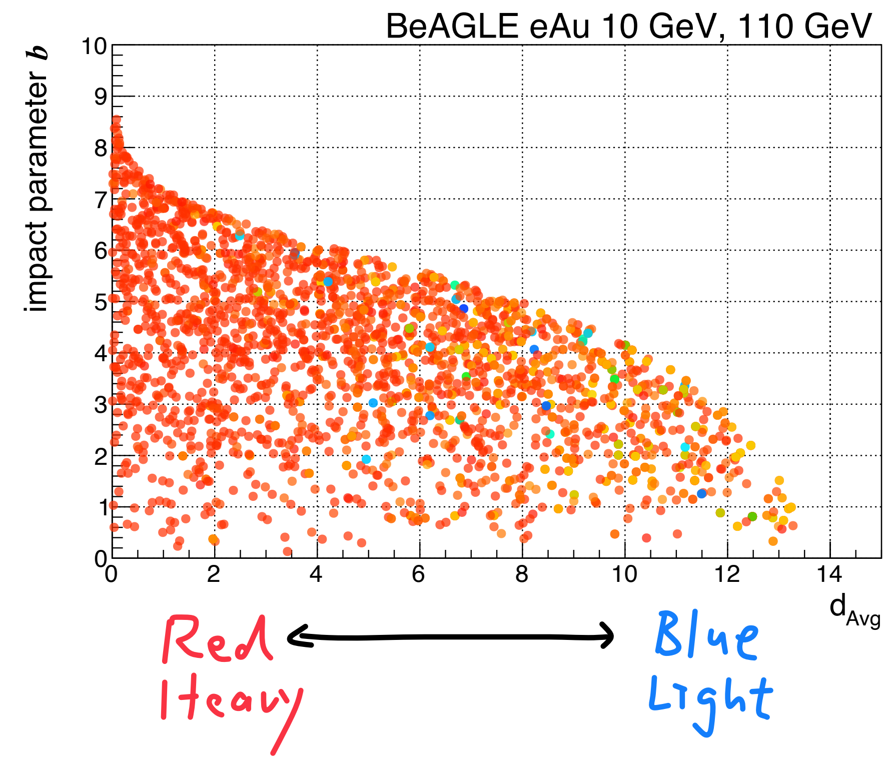
- Most of the time Au breaks very asymmetrically
- Sometimes Au breaks quite symmetrically
- Neutron content of Au can change significantly



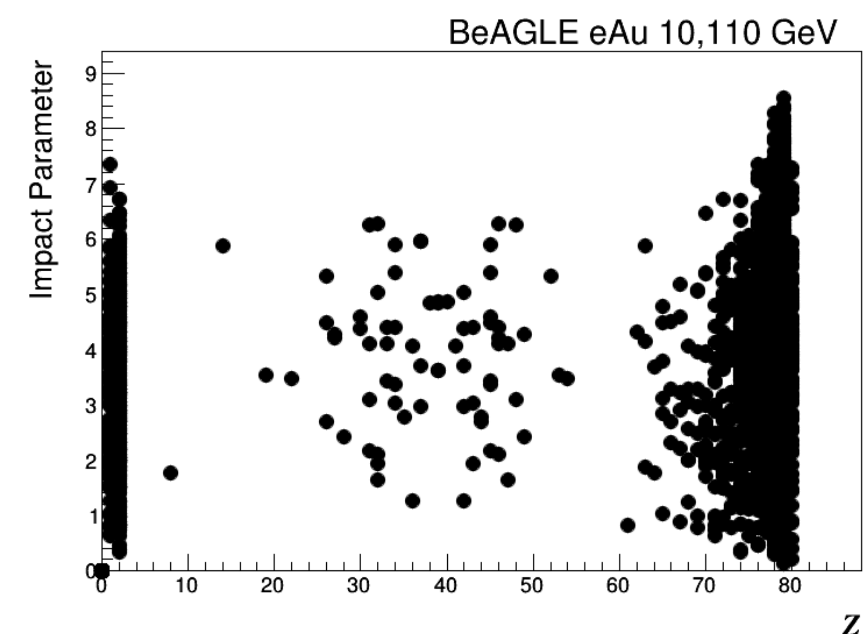
Where does DIS happen?







- Mapping DIS position using impact parameter and dAvg
  - dAvg: average density-weighted distance from all inelastic collisions to the edge of the nucleus
  - Connection to nuclear breakup and other final state particles to be explored



Conclusions

- Target jet contains rich information awaiting us to uncover, if we can measure it
- Knowledge of target jet not only broadens the scope of EIC physics into nuclear dynamics, through current-target correlation it can also help constrain proton and ion 3D structure
- An “ultimate” QCD machine may not want to miss this sector of phenomenology
- Many of the target jet substructure studies ongoing, including soft-drop grooming, factorization, etc.