Hadronization and Saturation with ECCE

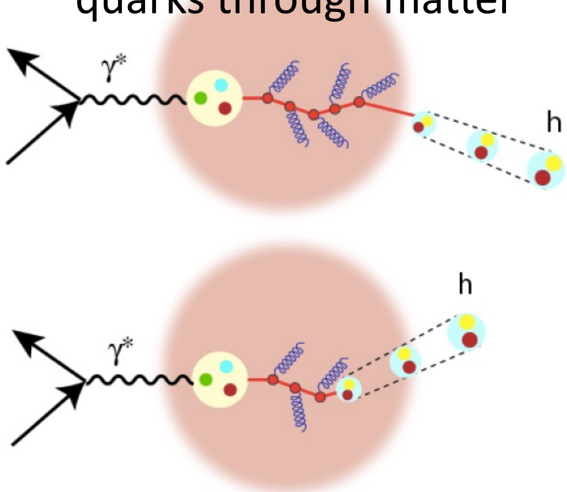
Cheuk-Ping Wong (cpwong@lanl.gov)
on behalf of ECCE

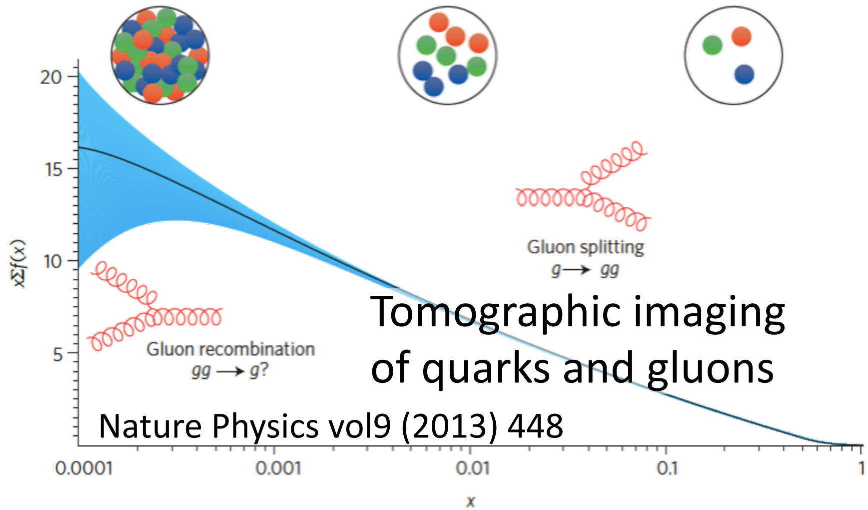
05-05-2022

LA-UR-22-23829

EIC Physics via HF and Jets

Propagation of energetic quarks through matter

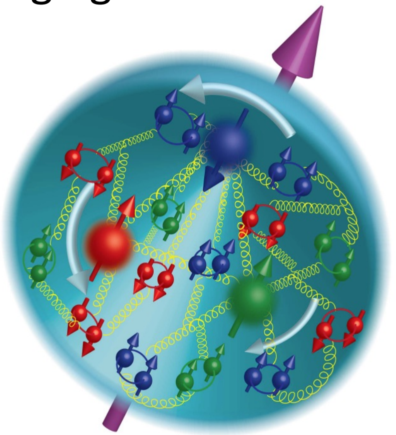




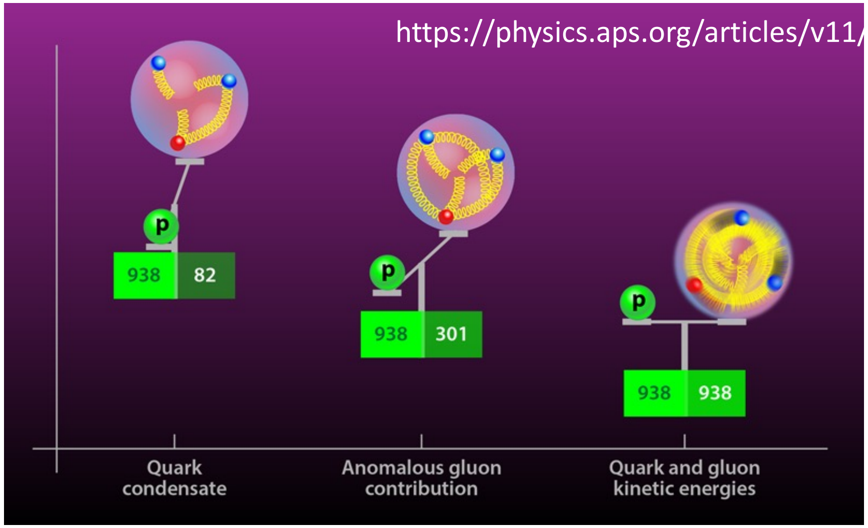
Tomographic imaging of quarks and gluons

Nature Physics vol9 (2013) 448

3D imaging in momentum space

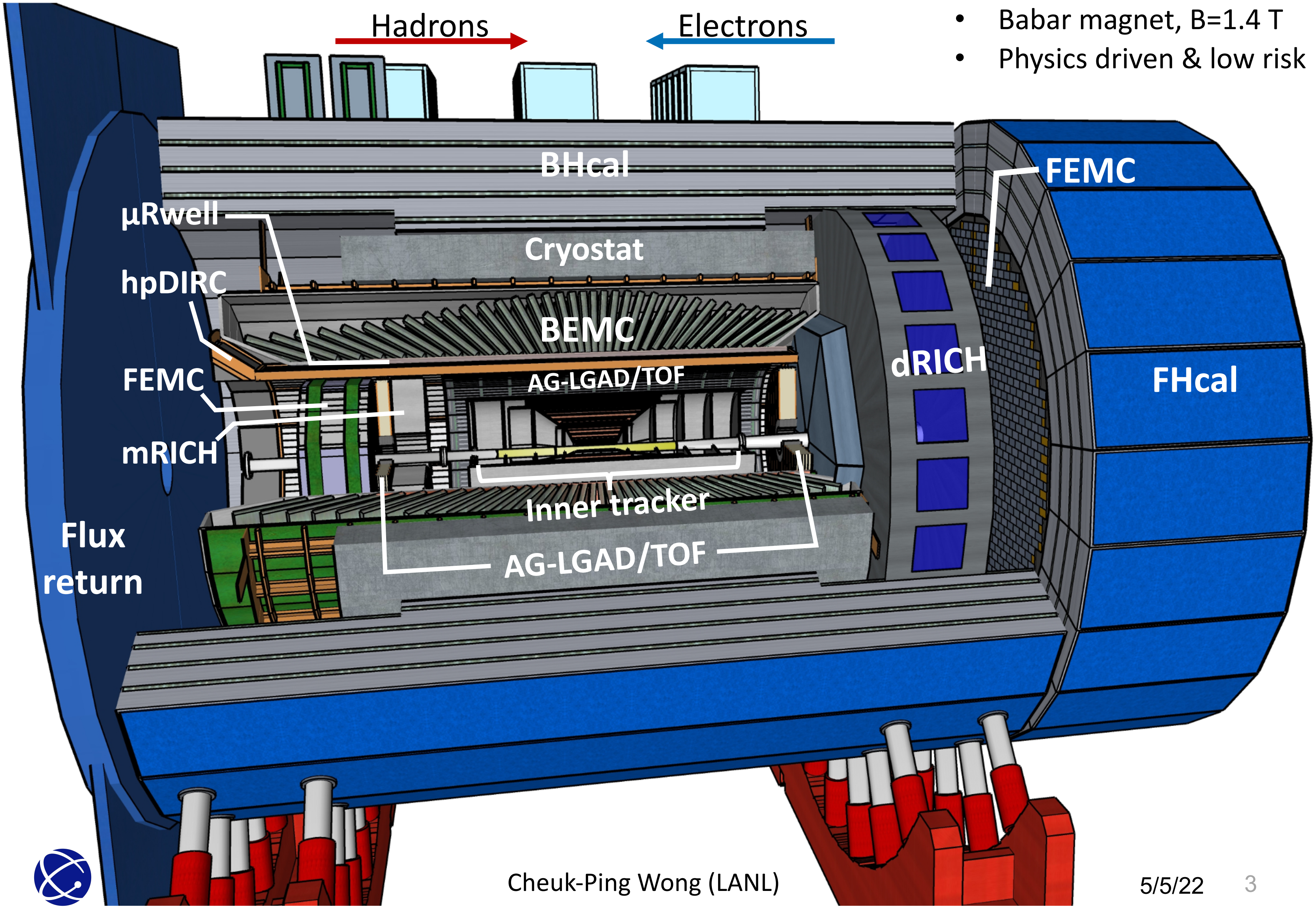


Origin of mass

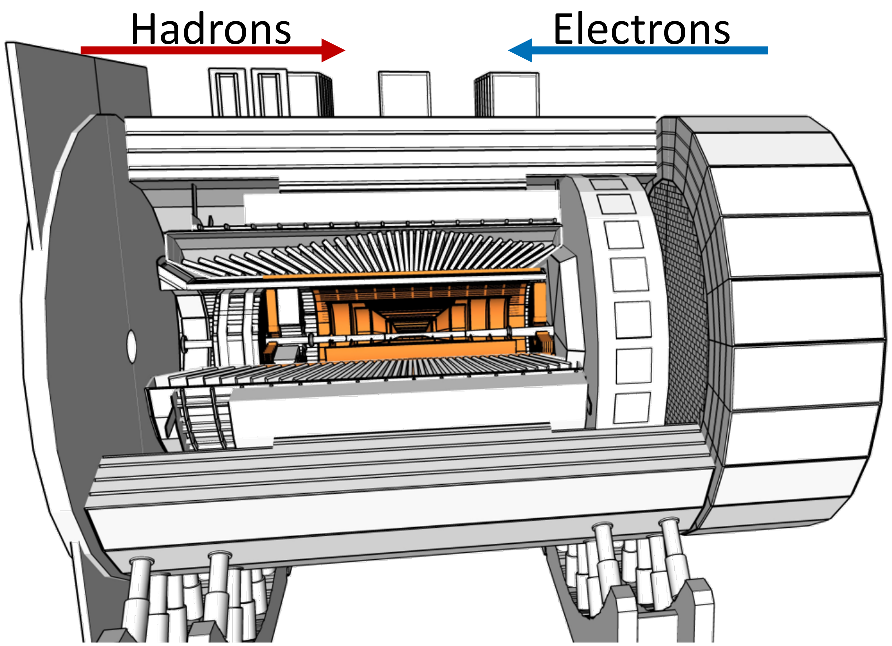


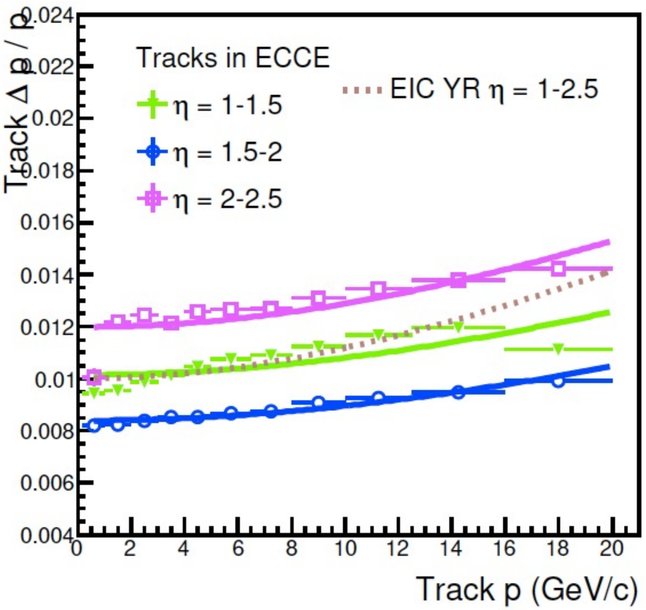
ECCE Detector Overview

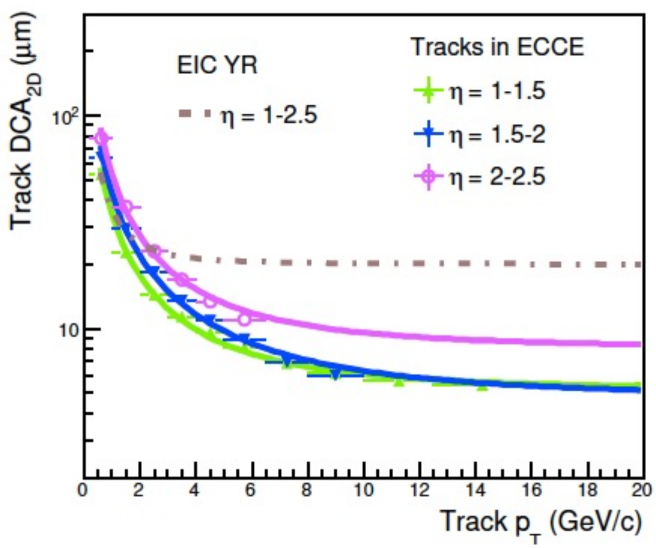
- Recommended design
- $-3.5 < \eta < 3.5$
- Babar magnet, B=1.4 T
- Physics driven & low risk



Tracking

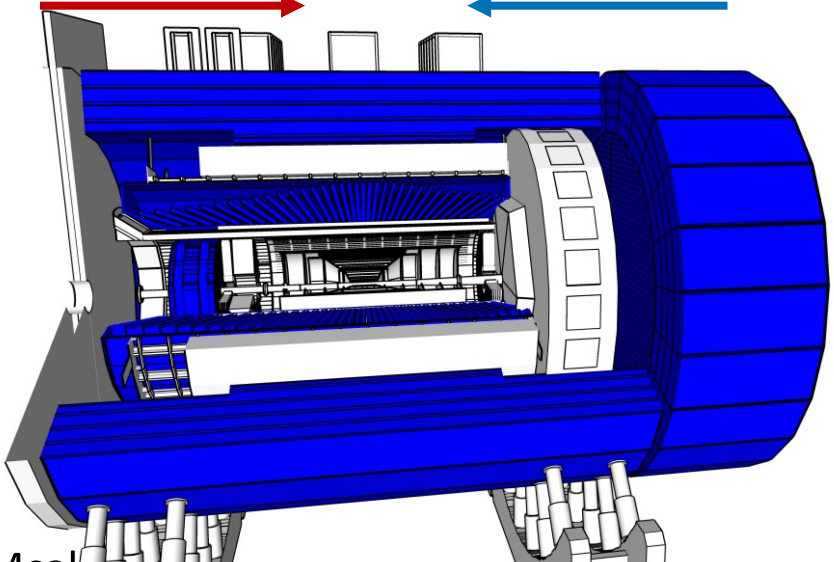






- Vertex and momentum reconstructions
- Barrel + Disks for endcaps
- 0.05% X/X0 per layer
- 10 μm pitch MAPS (Alice ITS3)
- Vertexing tracking performance fulfill EIC Yellow Report requirements

Calorimetry



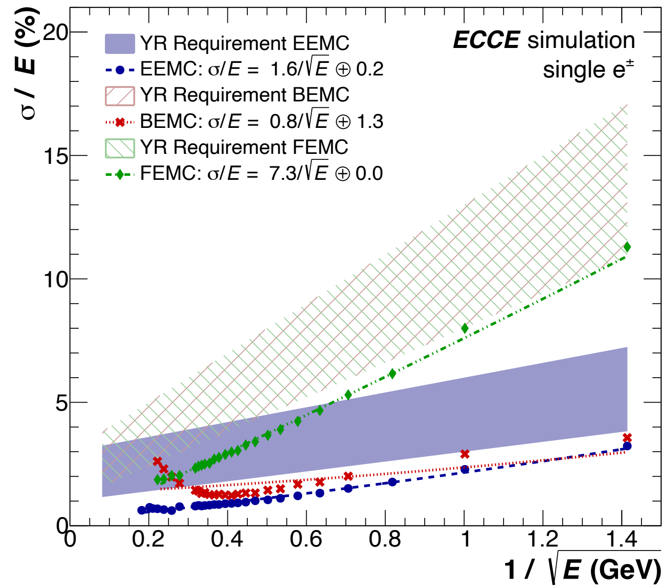
EMcal

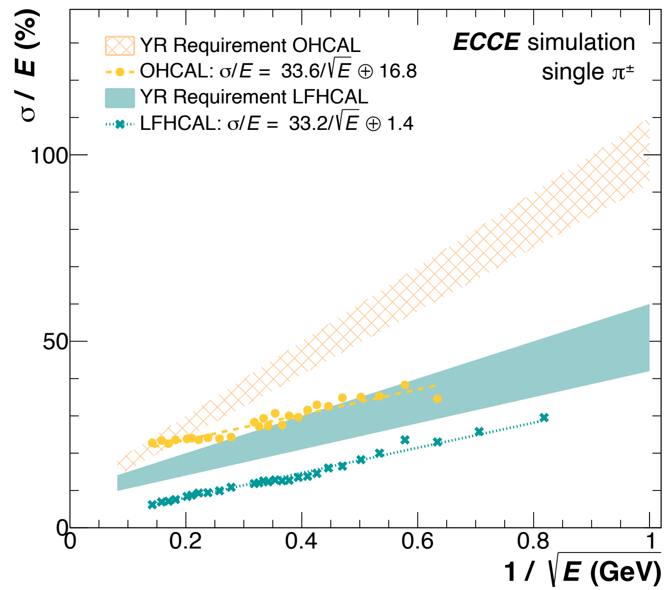
- Electron and photon measurements
- e^--going: high-res. $PbWO_4$ crystals
- Barrel: projective SciGlass
- h-going: highly-granular shashlik sampling

Hcal

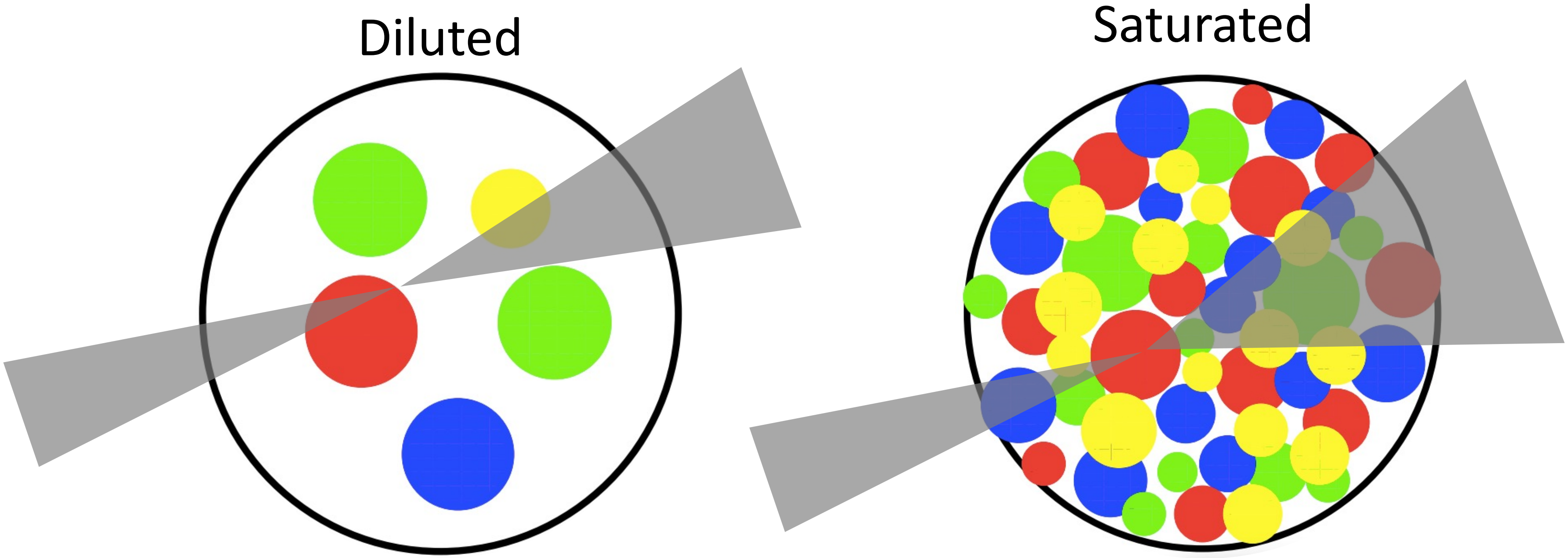
- Jet energy measurements
- Barrel: Fe/Sc tiles
- h-going: longitudinally segmented Fe/Sc, W/Sc, W tiles. Integrated with EMcal

Satisfy EIC YR requirements



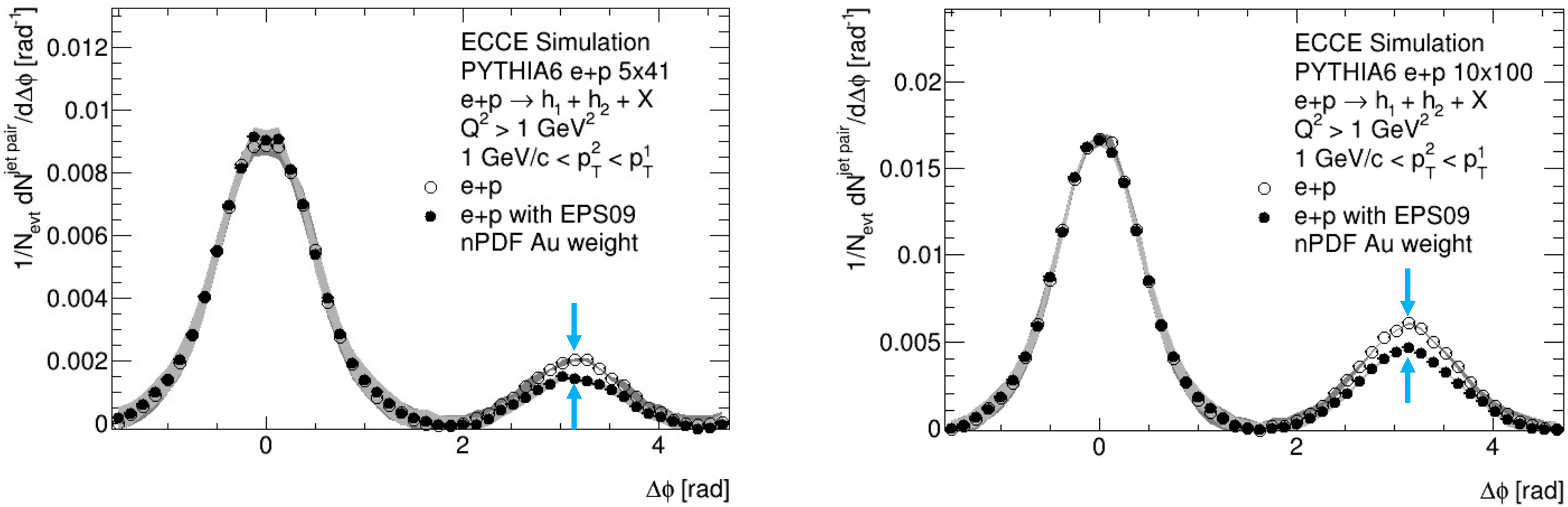


Tomographic imaging: Gluon Saturation



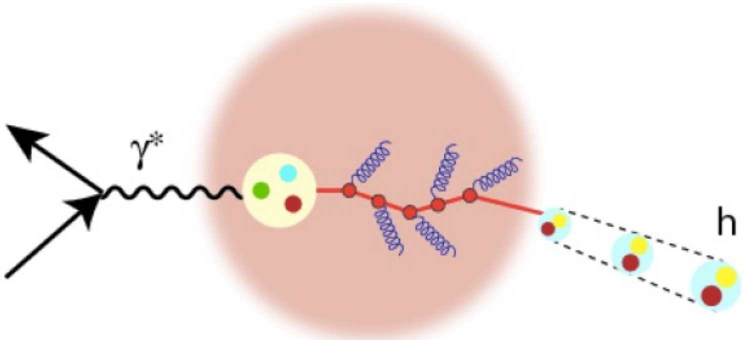
- Dense gluon field with a high transverse momentum ($Q_{sat} > Q$)
  → smearing of jet
  → **enhancement of di-jet imbalance in dihadron correlations**
- Probe the transverse momenta of the dense gluon fields, that is to be of the order of the saturation scale, i.e. $k_T \sim Q_{sat}(x, A)$

Projection of Dihadron Azimuthal Correlations

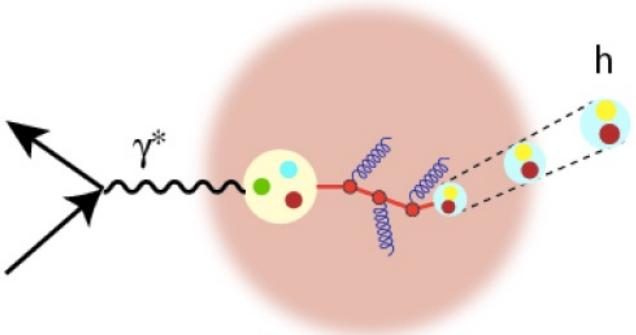


- Full simulations: Pythia 6 + GEANT4
- Tracks are boosted for the beam crossing angle
- Use EPS09 weighting to calculate the nPDF weight for eAu for each event
- Systematic errors are the differences between true and reconstructed e+p results
- ECCE can be able observed the away-side difference that is due to the saturation effect
- Detailed background studies are needed in the future

Propagation of energetic quarks through matter



Hadronization **outside** nuclear matter



Hadronization **inside** nuclear matter

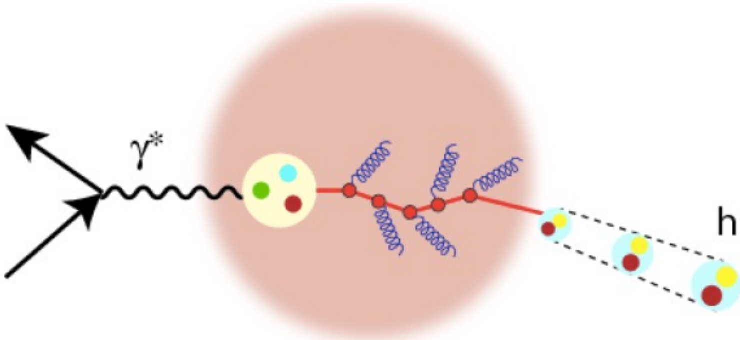
- Common observable in heavy-ion collisions: Nuclear modification factor

$$R_{AA} = \frac{\sigma_{A+A}}{\text{scaled } \sigma_{p+p}}$$

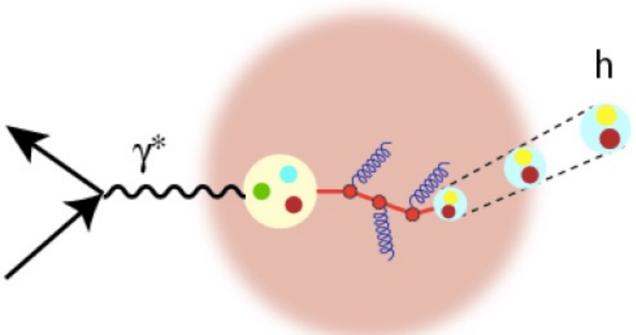
$$= \frac{d^2N_{A+A}/dp_T dy}{\langle N_{coll}\rangle \cdot d^2N_{p+p}/dp_T dy}$$

$$= \begin{cases} < 1 \text{ , suppression in A+A} \\ \quad 1 \text{ , no modification} \\ > 1 \text{ , enhancement in A+A} \end{cases}$$

Propagation of energetic quarks through matter



Hadronization **outside** nuclear matter



Hadronization **inside** nuclear matter

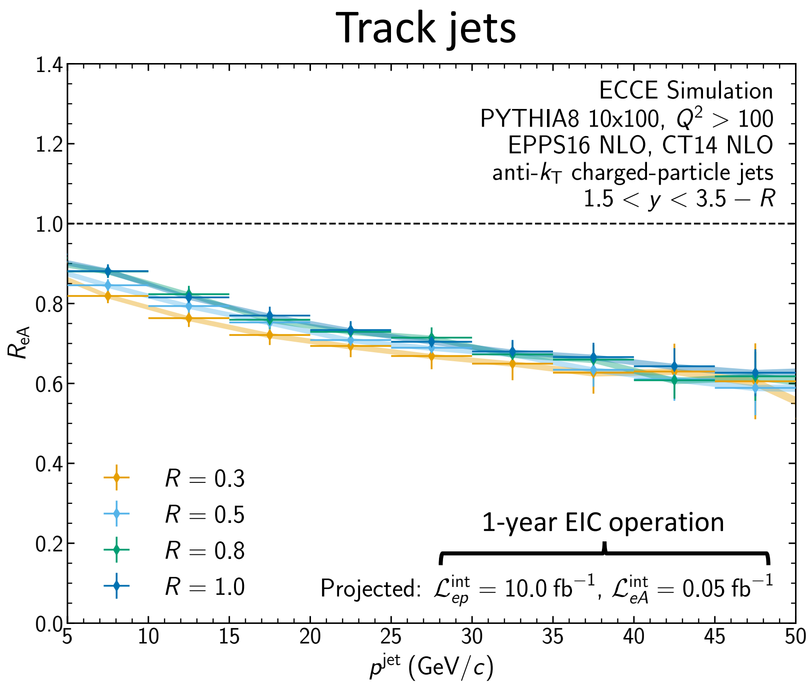
- Common observable in heavy-ion collisions: Nuclear modification factor

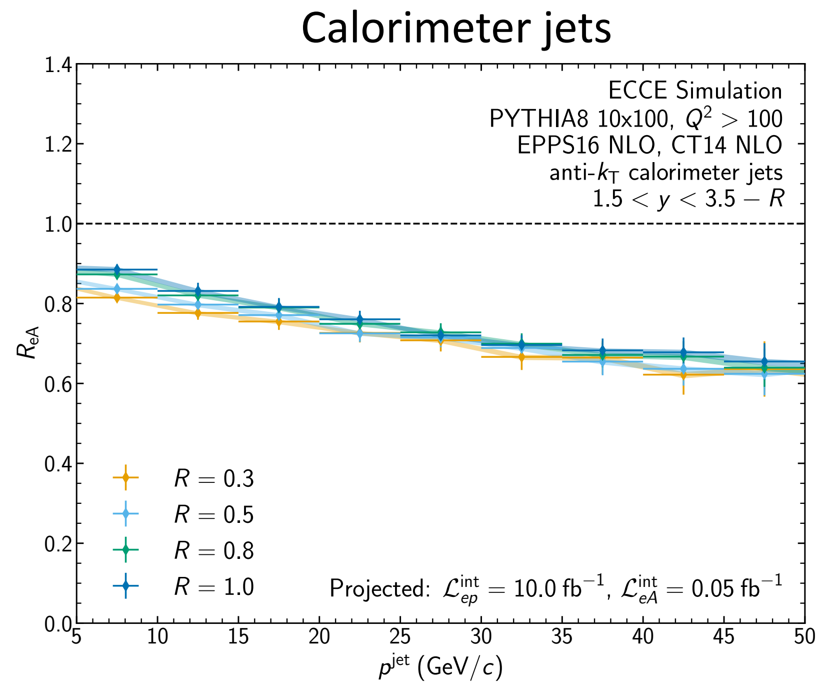
$$R_{eA} = \frac{\sigma_{e+A}}{\text{scaled } \sigma_{e+p}}$$

$$= \begin{cases} < 1 \text{ , suppression in e+A} \\ \quad 1 \text{ , no modification} \\ > 1 \text{ , enhancement in e+A} \end{cases}$$

- **R_{eA} of heavy flavor and jets**
  - Hadronization processes between light and heavy flavor
  - Detangle initial state (nPDF) and final state effects (cold nuclear matter effect) in heavy-ion collisions

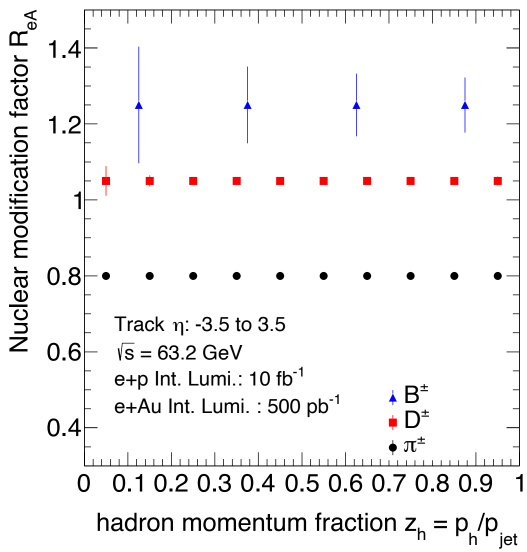
Projection of Jet R_{eA}





- Full simulations: Pythia 8 + GEANT4
- Use EPS09 weighting to calculate the nPDF weight for e+A for each event
- Uncertainty bands are from the systematic errors of nPDF
- ECCE can measure the modification of jet yields due to nuclear matter interactions
- To measure final state effect with different R selection, higher statistics (>1-year operation) may be required

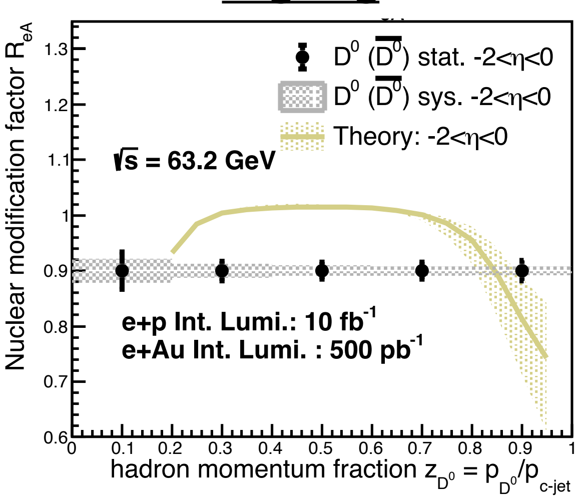
Projection of Heavy Flavor in Tagged Jet



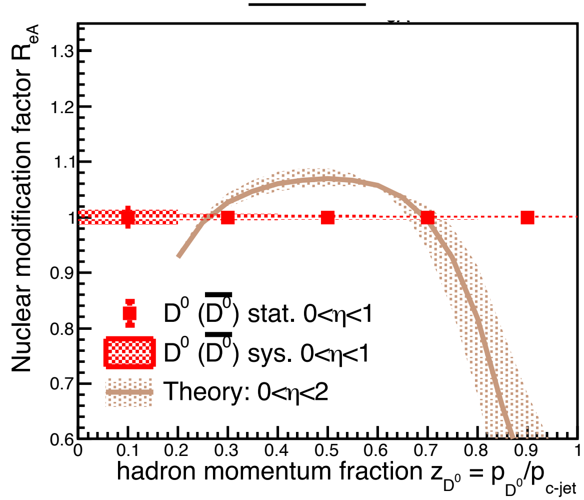
- Pythia 8 simulations with implementation of parameterized detector performance
- Jet radius, R=1
- Required at least 1 heavy flavor in a heavy flavor tagged jet
- Systematic errors obtained by changing the tracking system design
- ECCE can effectively differentiate between heavy flavor and light flavor tagged jets
- The projected errors from simulations indicate that ECCE can have the precision needed for heavy flavor R_{eA} study, and reduce uncertainty at the high z_h (>0.8) region

Theory curves: PLB 816 (2021) 136261

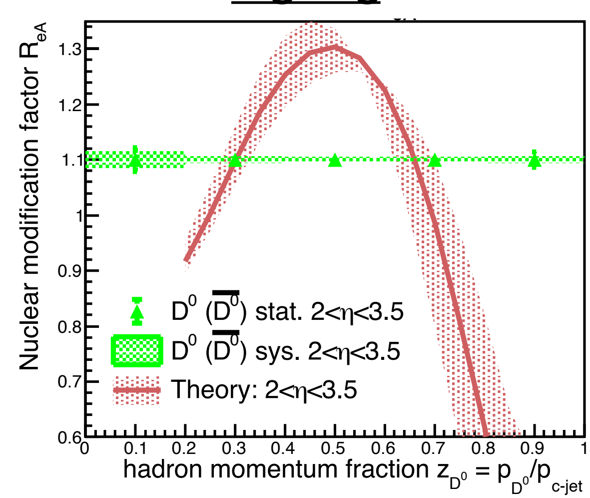
e^--going



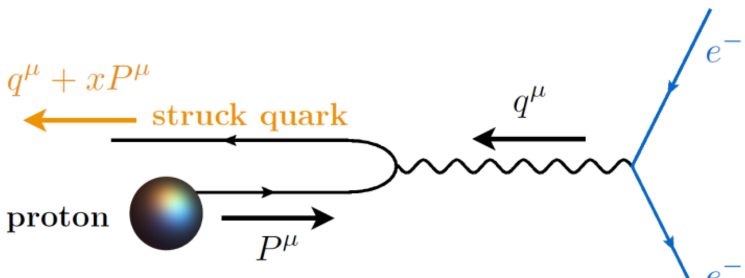
barrel



h-going

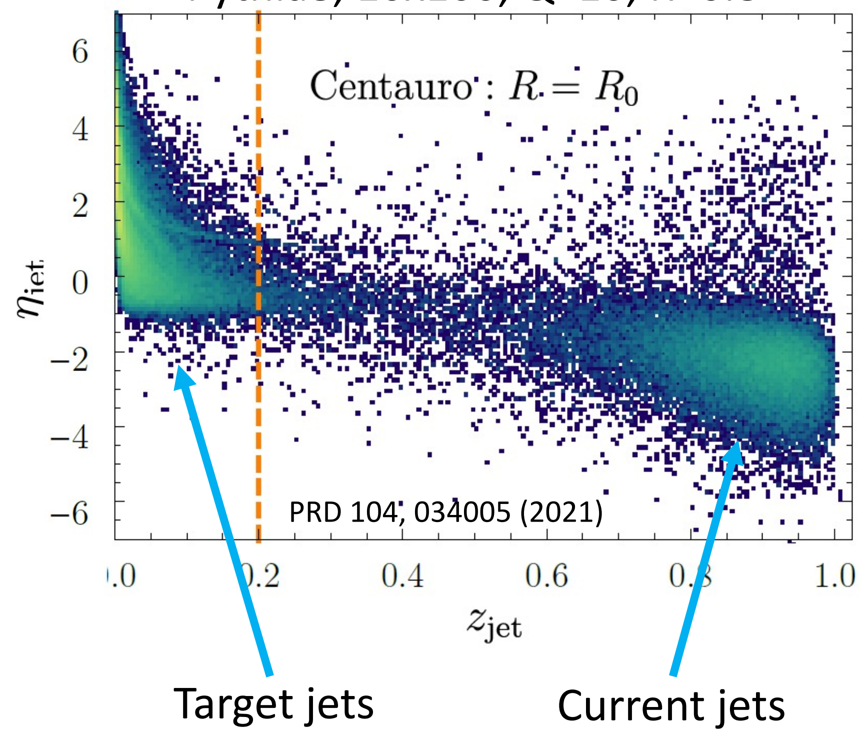


3D imaging in Momentum Space using Centauro Jets



DIS Born kinematics in the Breit frame
PRD 104, 034005 (2021)

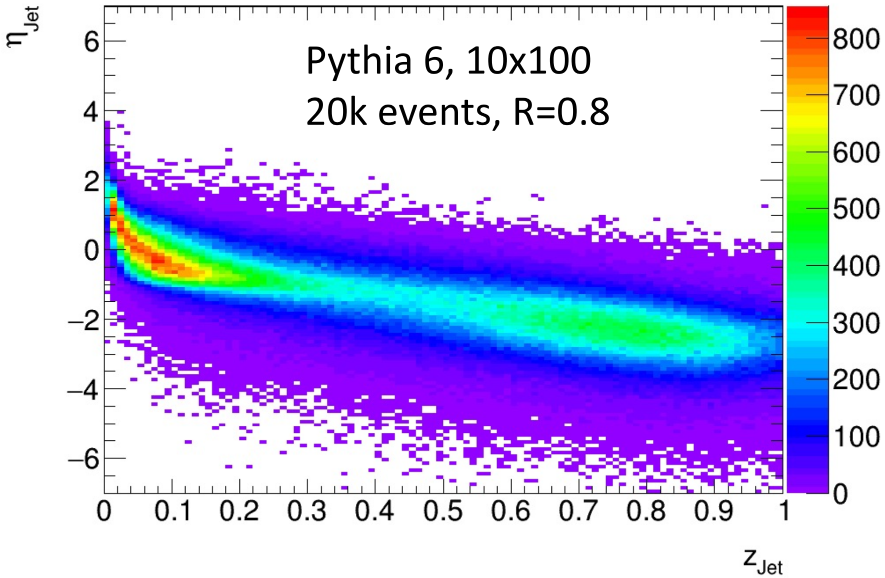
Pythia8, 10x100, Q>10, R=0.8

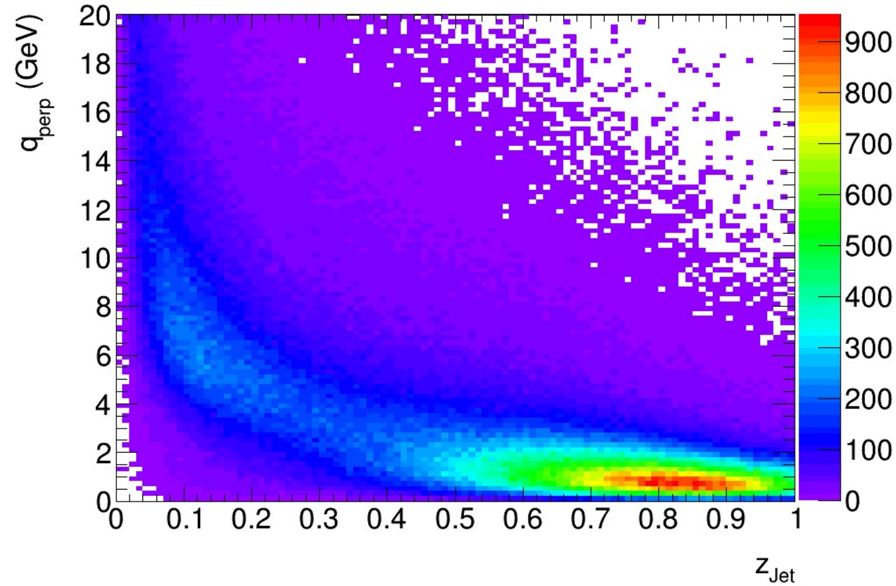


- A anti k_T algorithm that is longitudinally invariant (along z-axis in Breit frame)
- But matches features of spherical invariant algorithm that is beneficial for separating target (proton/hadron) and current (scattered quarks) jets
  → **probe scattered quarks kinematics**
- Can be used to obtain the transverse momentum distribution (TMD) of quarks inside the nucleons

Simulated Centauro Jets in ECCE

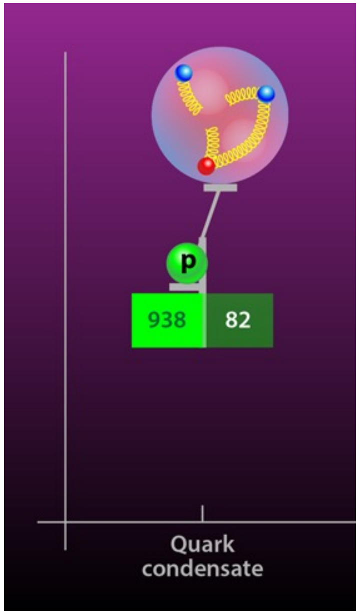
$q_T = p^{\perp}_{jet}/z_{jet}$





- Beam crossing angle is included in the simulations
- Track and EMcal jets with neutral clusters
- z_{jet} is the fraction of the scattered quark's momentum that is carried by the jet
- q_T is transverse momentum with respect to the scattered quark's direction
- Low q_T in $0.5 < z_{jet} < 1$: region of TMD phenomenology

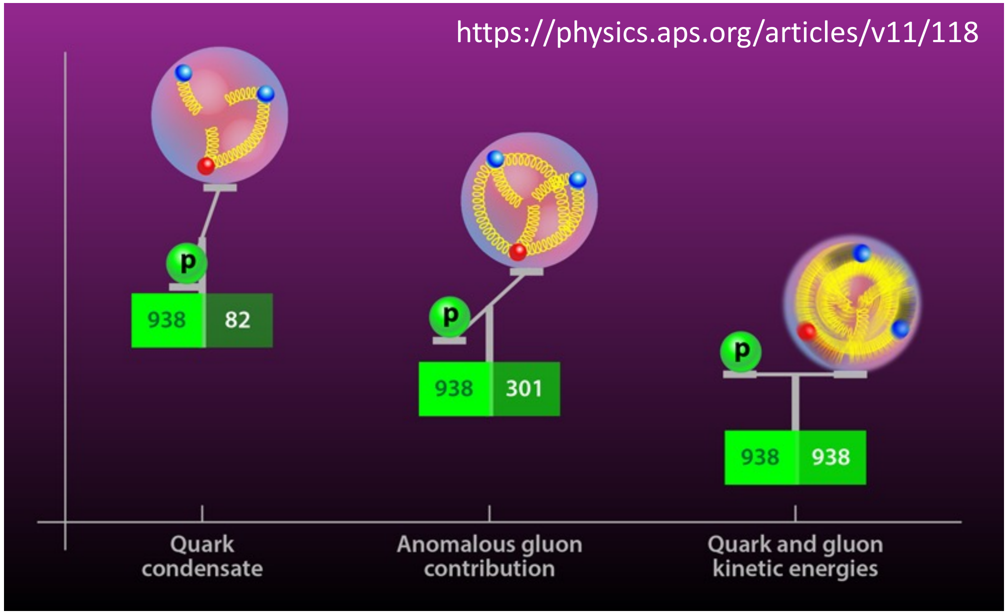
Origin of mass



$M_p > \quad M_m$ Quark mass

https://www.flickr.com/photos/obamawhitehouse/4921383047/

Origin of mass

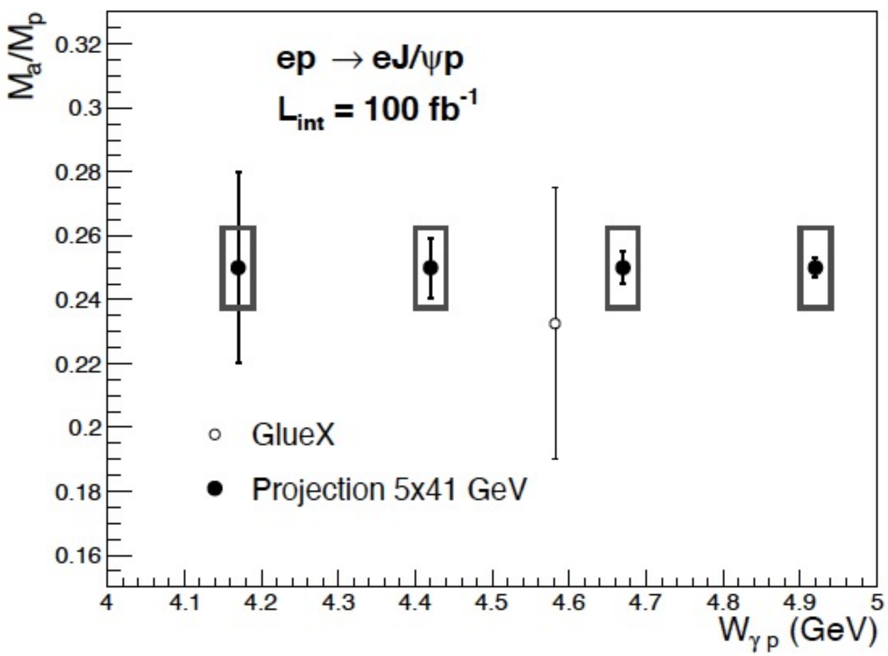


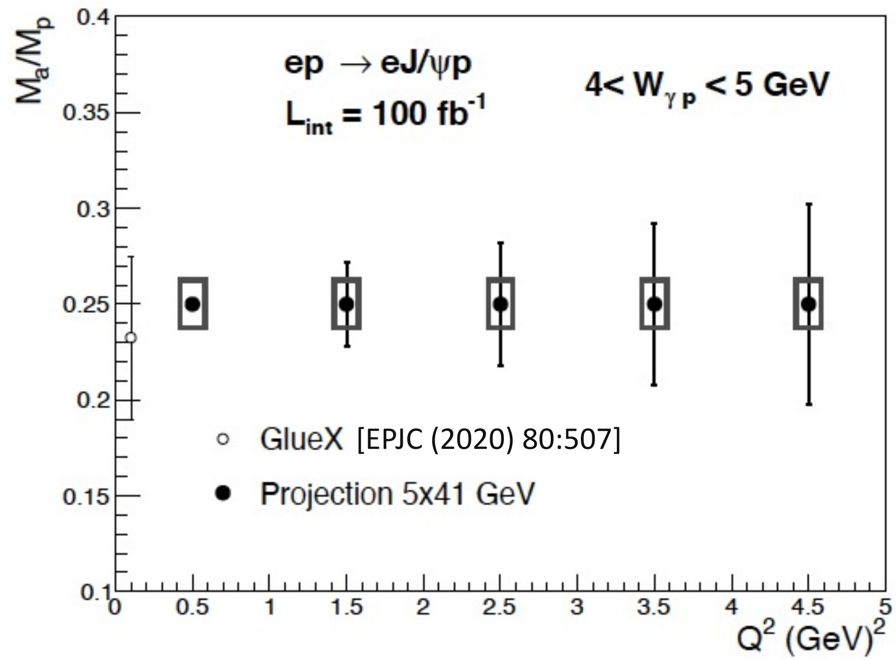
$$M_p = M_m$$ Quark mass
$$+M_q$$ Quark energy
$$+M_g$$ Gluon energy
$$+M_a$$ **Trace anomaly**

https://www.flickr.com/photos/obamawhitehouse/4921383047/

- Majority of hadron mass comes from the strong interaction that bind quarks and gluons
  → Decomposition of hadron mass helps understand QCD
- The trace anomaly, which is due to quantum effect, is sensitive to exclusive production of quarkonia such as J/ψ near threshold

Projection of Trace Anomaly Contribution to Proton Mass





- eSTARLight with implementation of parameterized detector performance
- J/ψ reconstruction from di-electron pairs
- Assume perfect electron identification in these initial study
- Systematic errors are the differences between true and reconstructed e+p results
- ECCE can provide precise measurement for the nucleon mass decomposition
- Additional Q^2 dependent measurement allows to constraint the production mechanism → reduce the model dependence of the M_a extraction.

Summary

- ECCE is a physics driven and low risk detector design for the future EIC experiments
- Simulations demonstrate the capability of the ECCE detector:
  - Tomographic imaging of quarks and gluons: gluon saturation
    Dihadron azimuthal angle correlation
  - Propagation of energetic quarks through matter
    HF and jet R_{eA}
  - 3D imaging in momentum space
    TMD with Centauro jets
  - Origin of mass: trace anomaly
    Exclusive J/ψ production
- Outlook:
  - Fine tuning detector design and developing a technical detector design
  - Extend physics simulations to include background study

Analyzers

- Jet reconstruction performance
  Tristan Protzman and Rosi Reed (Lehigh University)

- Dihadron azimuthal angle correlation
  Nathan Grau (Augustana University)

- HF and jet ReA
  Xuan Li (Los Alamos National Laboratory)
  Raymond Ehlers
  (Oak Ridge National Laboratory → Lawrence Berkeley National Laboratory)

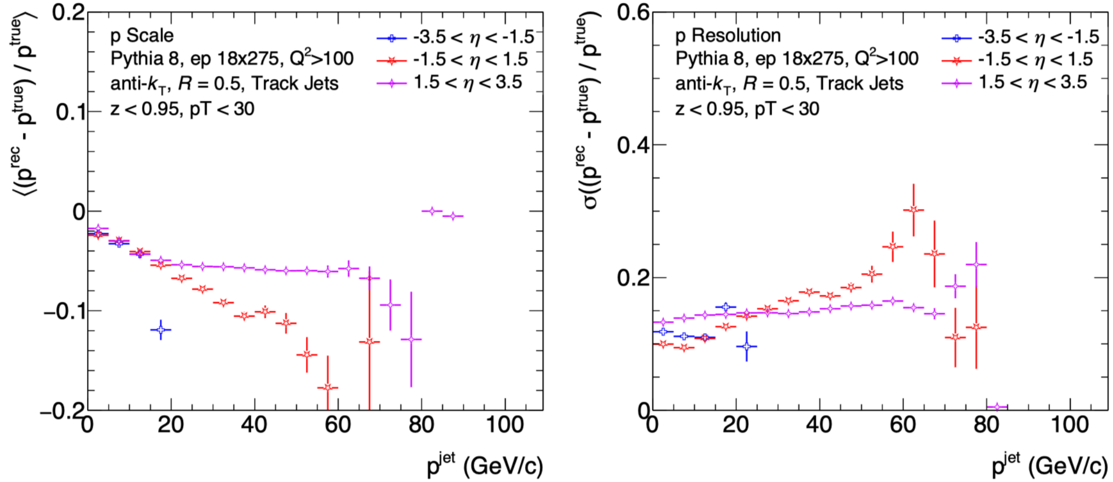
- Centauro jets
  John Lajoie (Iowa State University)

- Trace anomaly
  Xinbai Li and Wangmei Zha
  (University of Science and Technology of China)

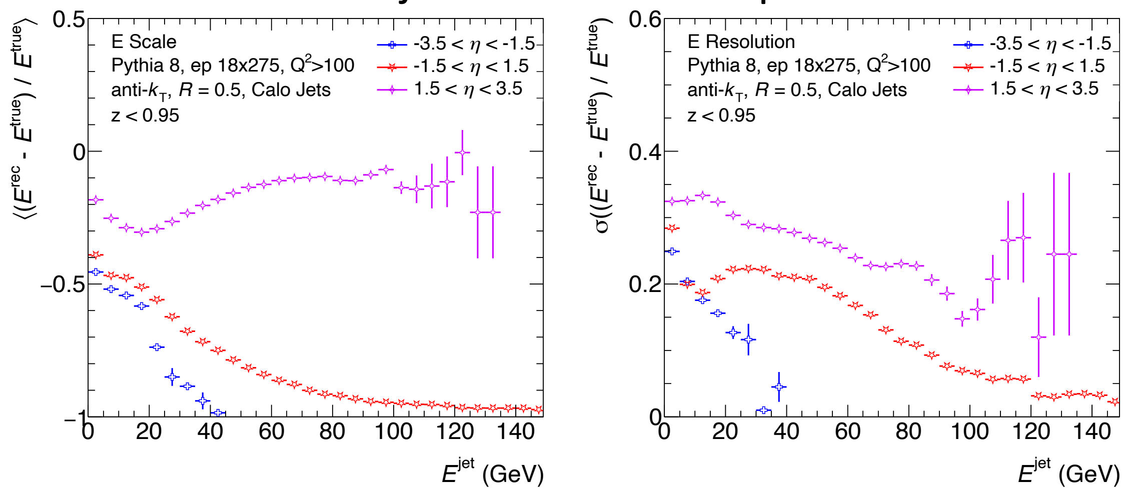
Back Up

Jet Reconstruction Performance

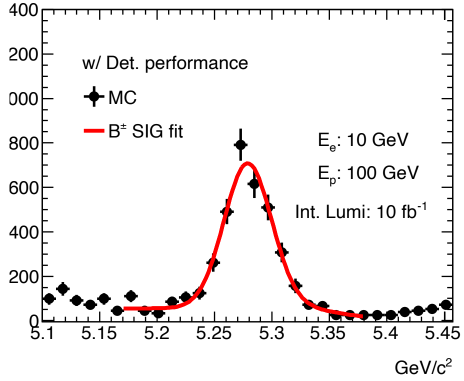
Track jet reconstruction performance

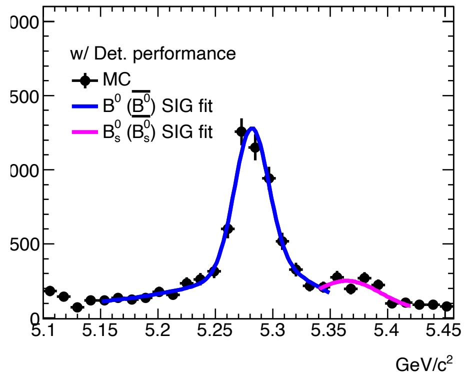


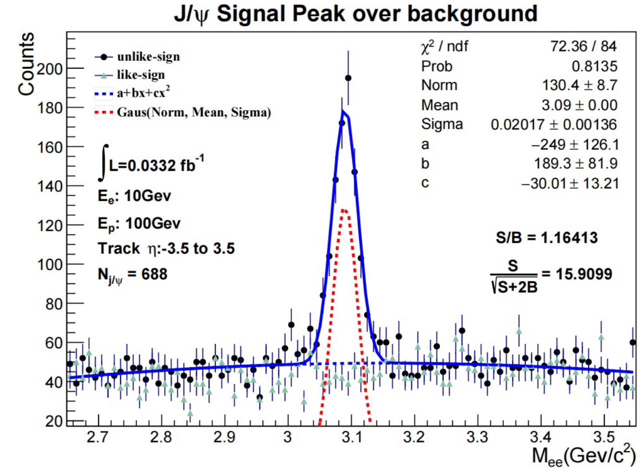
Calorimeter jet reconstruction performance

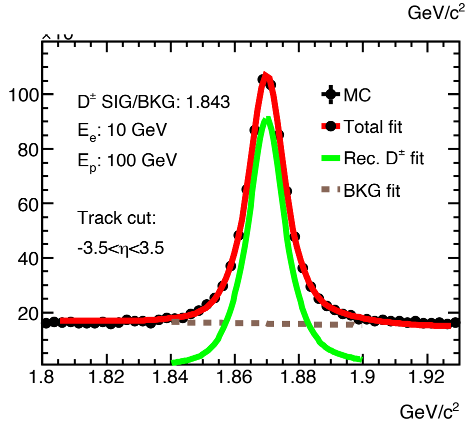


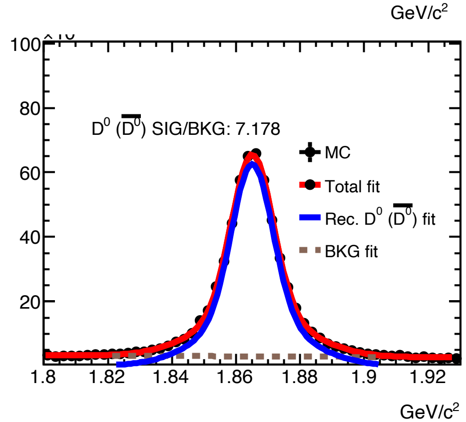
HF Reconstruction Performance

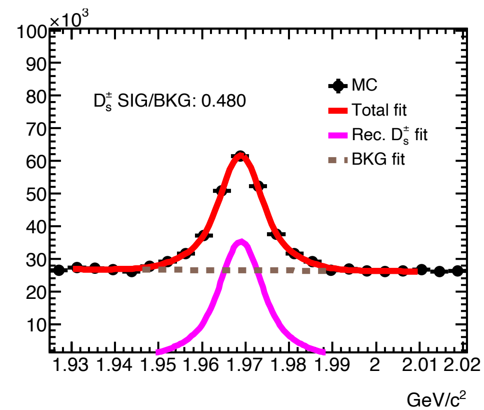




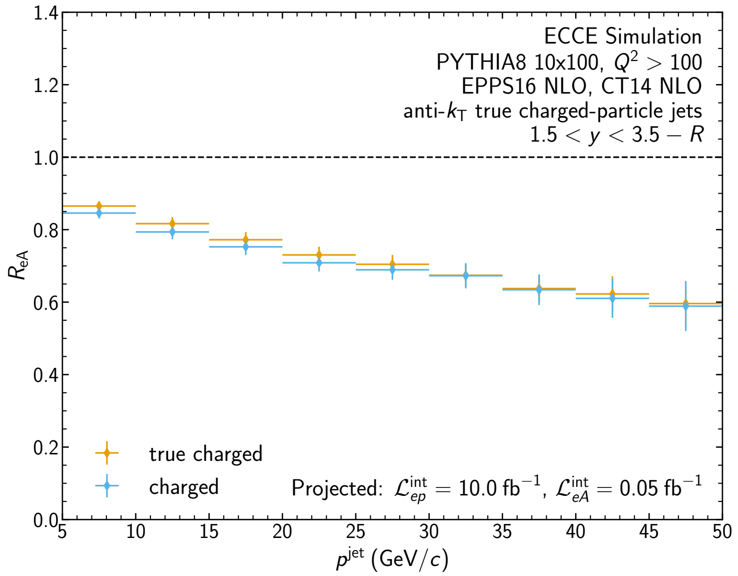


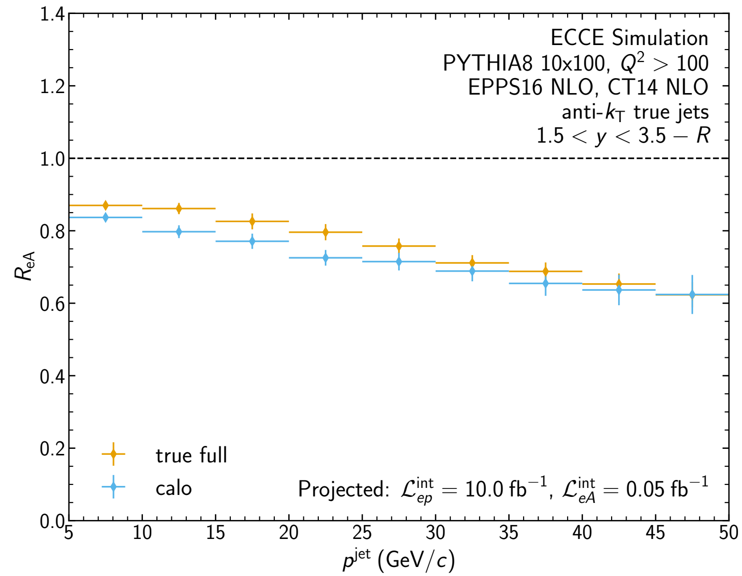






True and Reconstructed Jet R_{eA}





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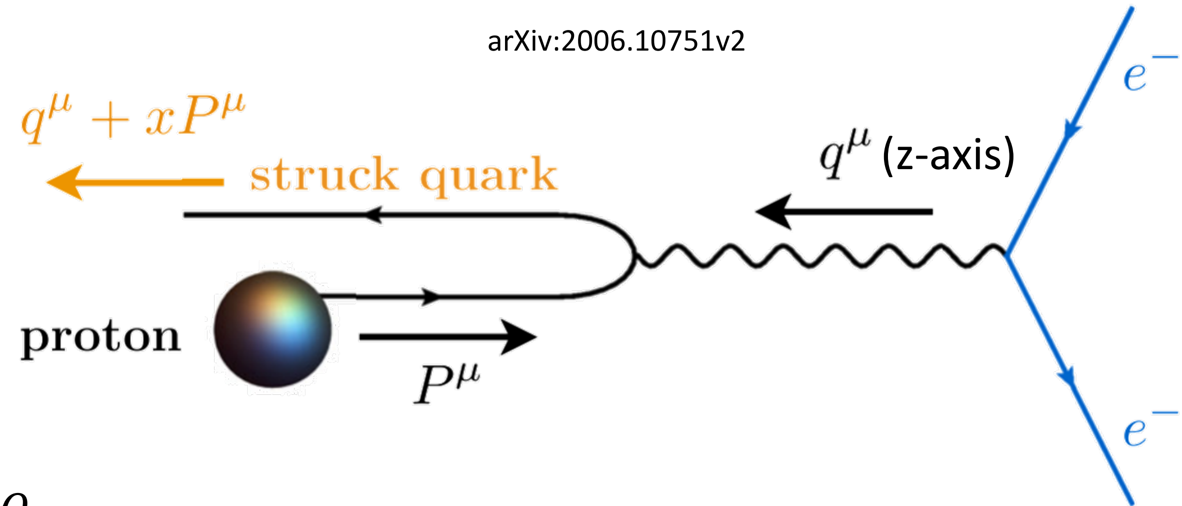


$$q^\mu = \frac{Q}{2}(\bar{n}^\mu - n^\mu) = Q \cdot (0,0,0,-1)$$

$$n^\mu = (1,0,0,1)$$

$$\bar{n}^\mu = (1,0,0,-1)$$

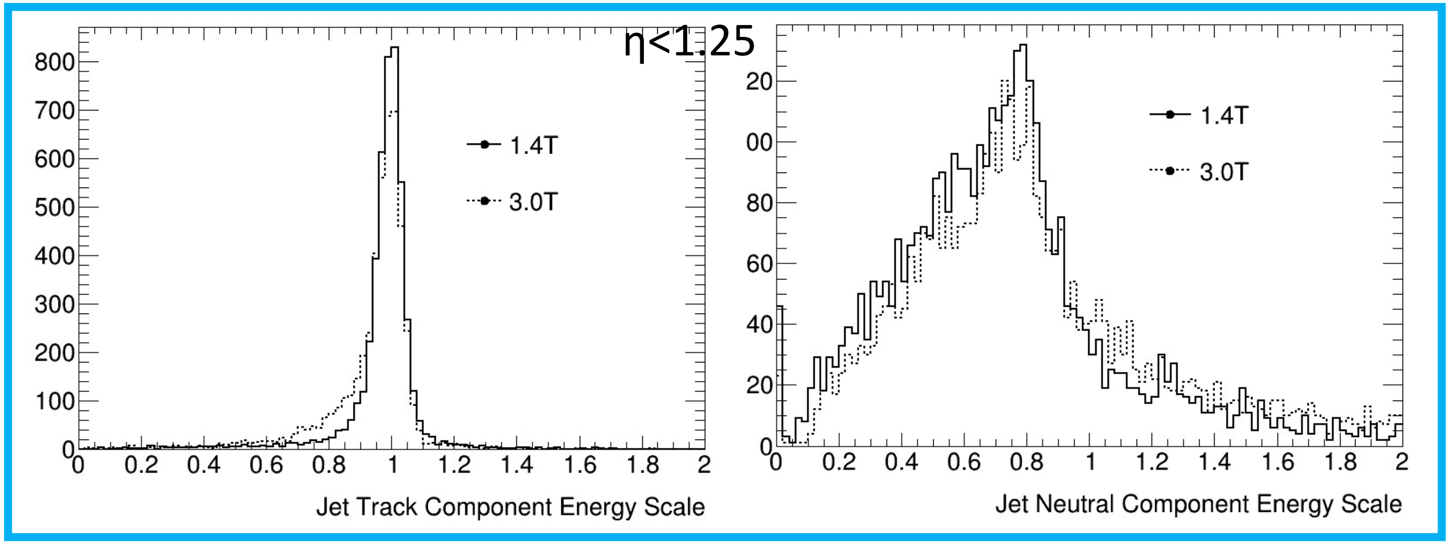
$$P^\mu \approx \frac{Q}{2x_B} \cdot n^\mu = \frac{Q}{2x_B} \cdot (1,0,0,1)$$

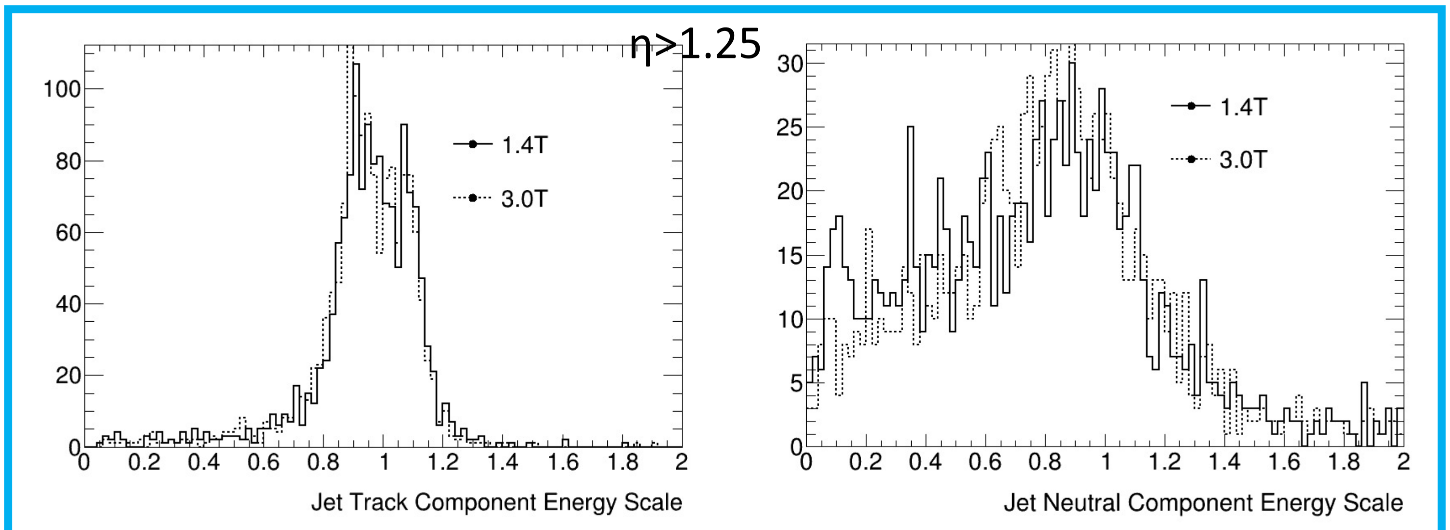
$$P_q^\mu = xP^\mu + q^\mu \approx \frac{Q}{2} \cdot \bar{n}^\mu$$

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

Reco. Jet Properties in Different Field Strengths

Using Centauro Algorithm



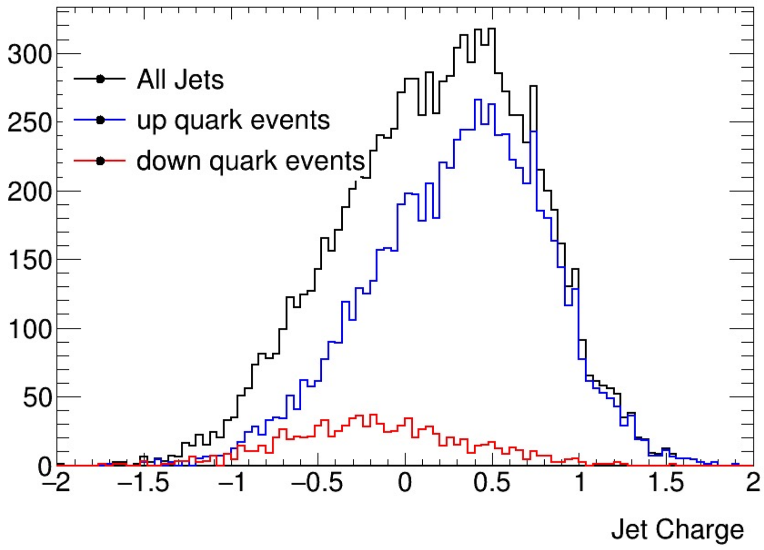


Jet Charge

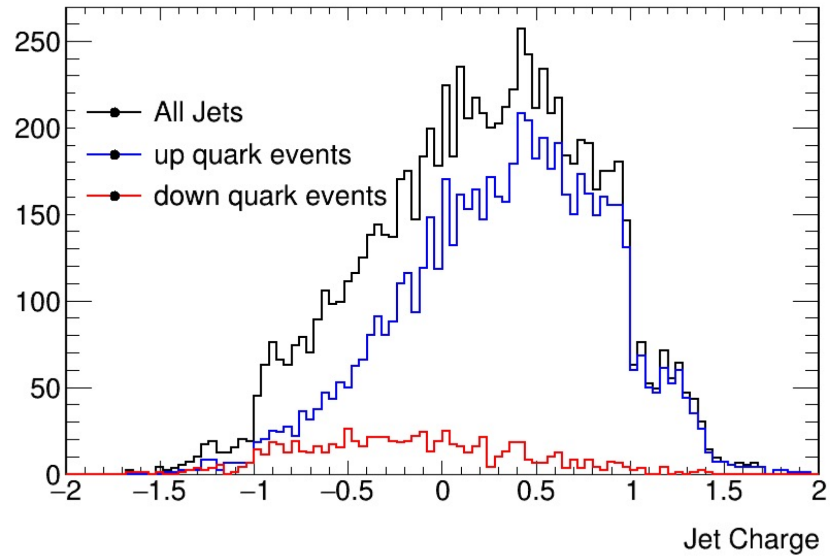
Using Centauro Algorithm

$$Q_{jet} = \frac{1}{\sqrt{p_T^{Jet}}} \sum_i q_i p_i^{0.5}$$

True



Reconstructed



Possible to isolate statistically enriched samples of u,d quarks jets

Projection of D^0 R_{eA} with Different Magnetic Field