Towards EEC in Cold QCD at the sPHENIX Experiment

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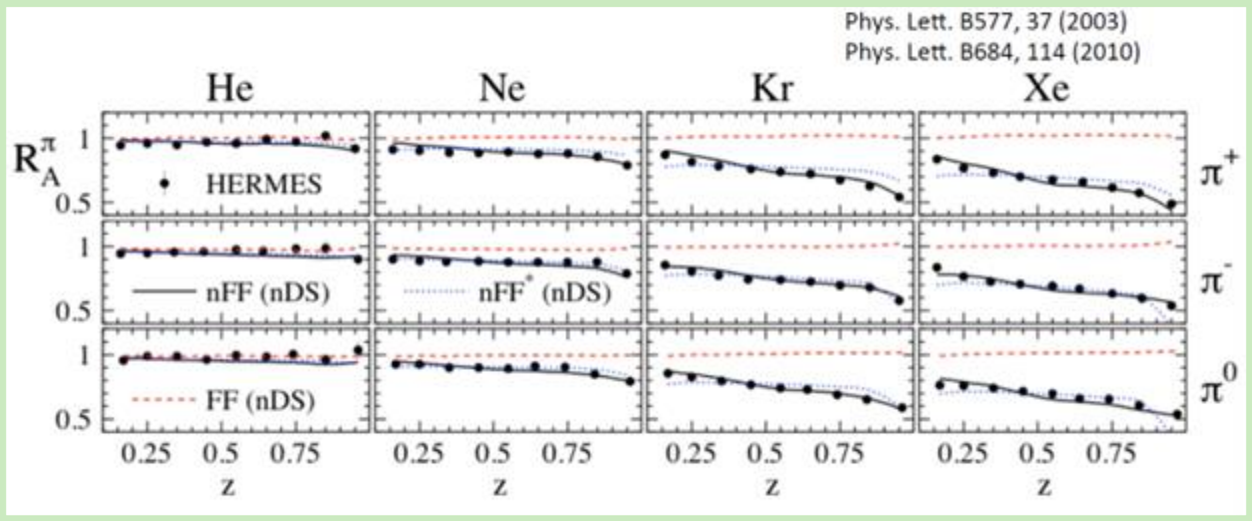
Introduction | Cold Nuclear Matter Effects

- Modification of parton fragmentation in nuclei is expected…
  - But measured jet yields convolute several different **Cold Nuclear Matter (CNM) effects**
  - Challenging to isolate effects experimentally!
- One example: **IS-FS Color Exchanges**
  - scattered partons exchange gluons w/ beam fragments
  - ⇒ **Leads to TMD Factorization breaking!**
- To study these color exchanges:
  - Need an observable sensitive to both nonperturbative & factorization scales…



HERMES; PLB 577, 37 (2003); PLB 684, 114 (2010)

Introduction | ENC Definition

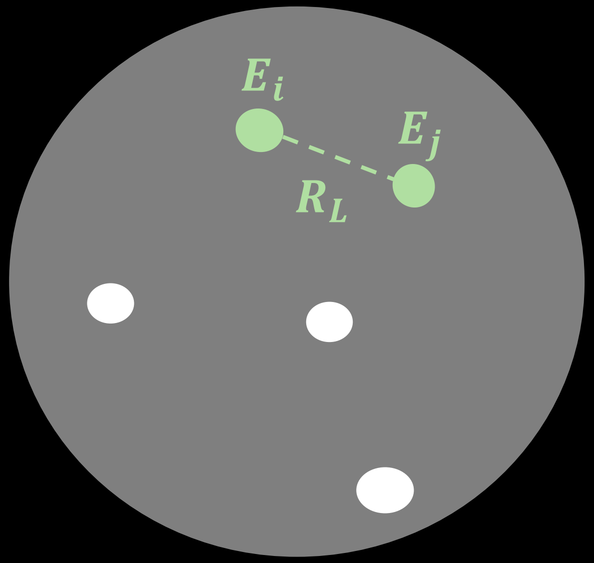
2-Point Energy Correlators (EEC)

$$\mathrm{EEC} = \sum_{\mathrm{jet}} \sum_{(ij)\in\Delta R} \frac{E_i E_j}{E_{\mathrm{jet}}^2}$$

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



- **N-point energy correlators:** measure statistical correlations in energy flux within a jet
  - Inherently IRC safe
  - Calculable in pQCD
  - Image jet structure as function of *angular scale*

Introduction | ENC Definition

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2-Point Energy Correlators (EEC)

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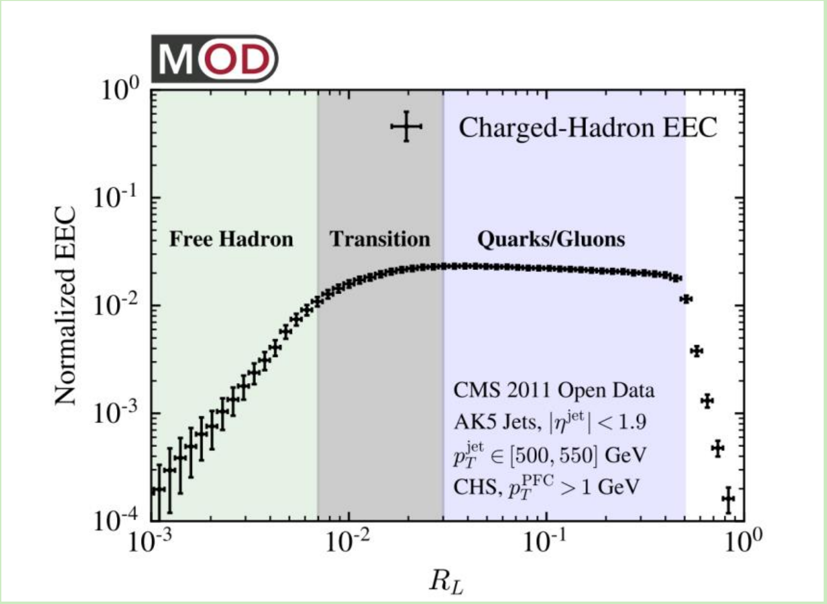
arXiv:2201.07800



- Allow for clear distinction b/n **perturbative** and **nonperturbative** regimes
  - May be sensitive to the scale-dependence of fragmentation!

∴ **Good observable for studying CNM effects!**
  - e.g. arXiv:2303.08143

Introduction | Goal and Talk Outline

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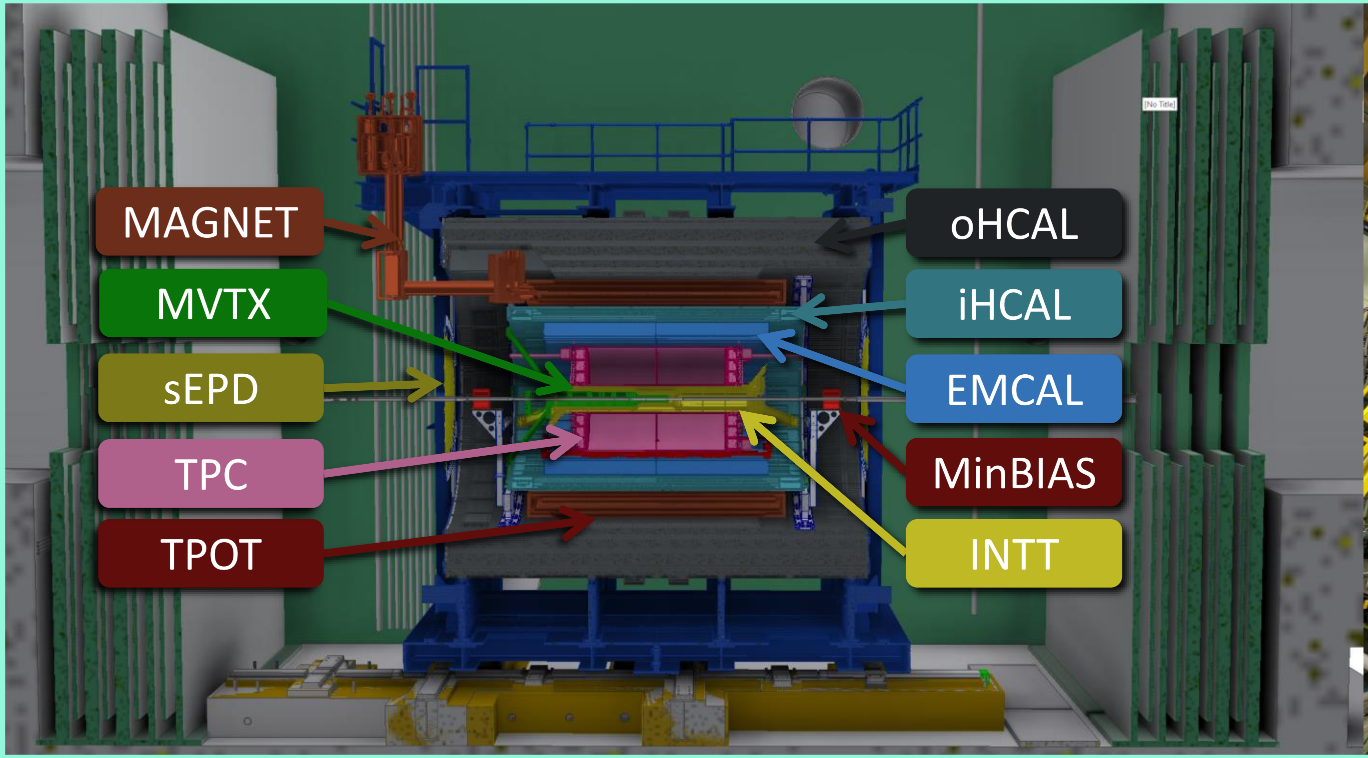
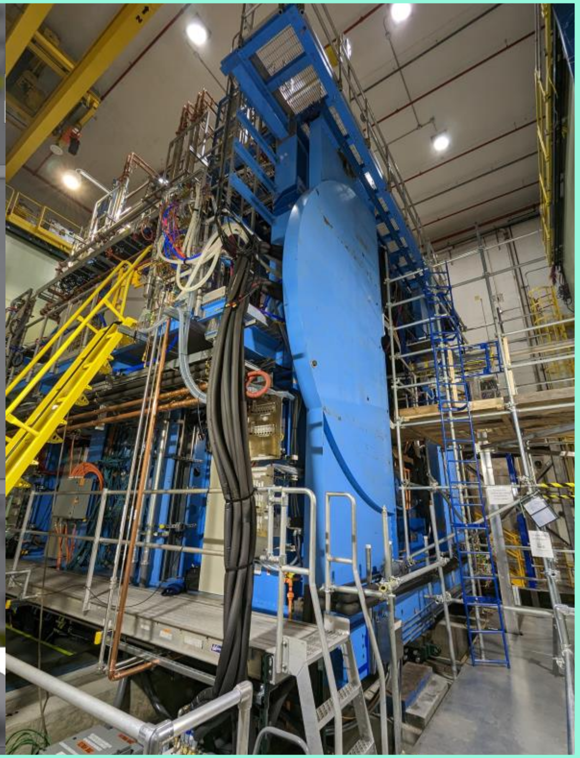
- **Our goal:** measure ENC in p+p (and p+Au if available) at sPHENIX
  - Will serve as points of comparison for **similar measurements in e+p (and e+A)** at the EIC
    - IS-FS color exchanges will happen in p+p/p+A
    - **But won't happen in e+p/e+A!**
- Also plenty of other physics opportunities for ENC in CNM systems
  - e.g. analyzing nPDFS!

Outline:

1) sPHENIX Overview
2) p+p Analysis
3) P+Au Analysis
4) Conclusions & Outlook

sPHENIX | Overview

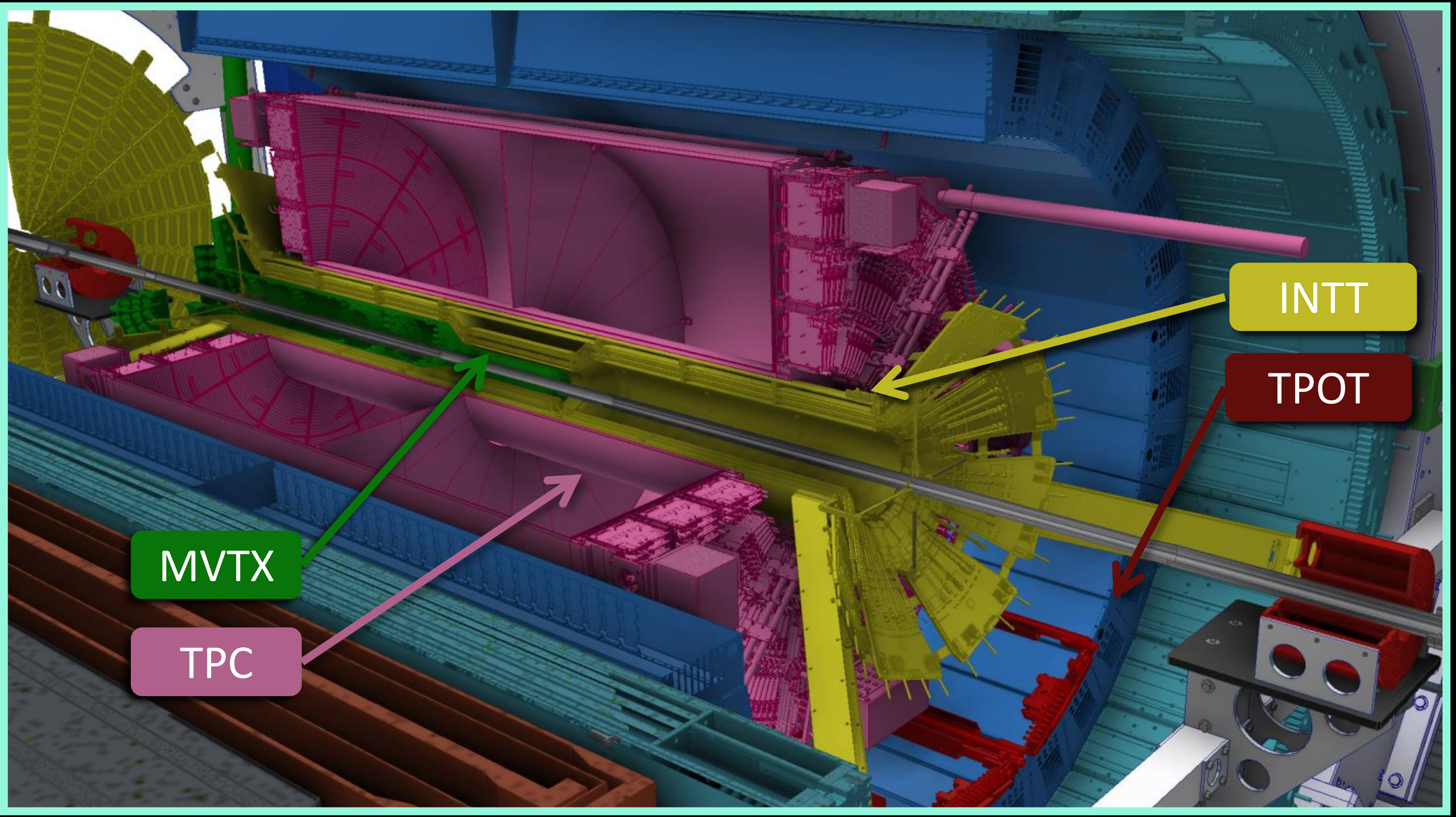




- **sPHENIX:** brand new, state of the art HENP experiment at RHIC
  - Purpose built for precision jet/HF studies and rare probes

- **Key features:**
  - Large acceptance (2π in φ, $|\eta| < 1.1$)
  - Full EM & Hadronic calorimetry
  - High precision tracking/vertexing system

sPHENIX | Tracking System



- Measuring ENC requires fine spatial resolution
  - ∴ **Will study track-based jets here**

- sPHENIX deploys a multi-staged tracking system
  - 2 innermost systems are Si-based (MVTX, INTT)
    - Provide precision timing/vertexing
  - TPC provides momentum resolution
  - TPOT provides additional fit point for calibration

- **For more info:**
  - HF Overview (Jin Huang: 11/6 @ 11:30 am)
  - **Tracking Highlights** (Charles Hughes: 11/9 @ 2:40 pm)
  - Calorimeter Highlights (Joe Osborn: 11/9 @ 3 pm)

Analysis (p+p) | Simulation Setup

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p+p Simulation

- PYTHIA-8, $\hat{p}_T > 7$ GeV/c
- Simulated 3 MHz of pileup p+p collisions
- 3M events analyzed

Jet Definition

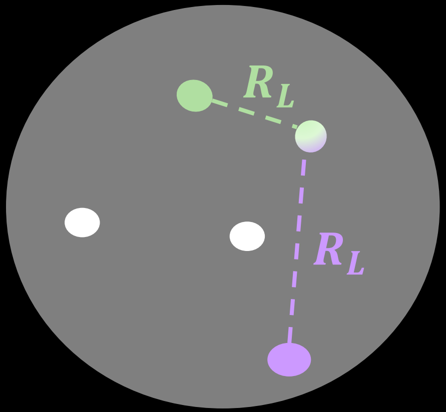
- Anti-k_T algo., p_T-recomb. scheme
- R = 0.4
- $|\eta^{jet}| < 0.7$

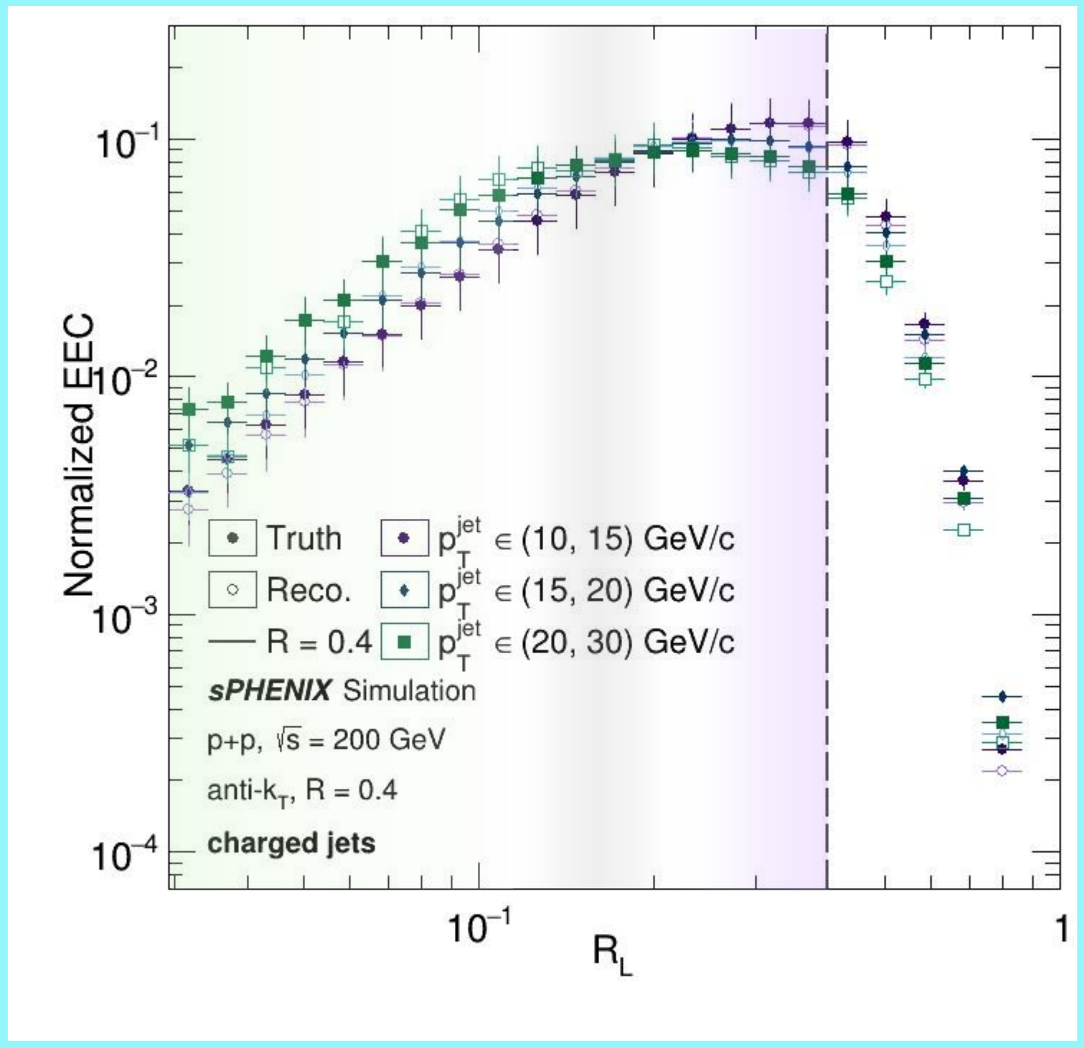
- p+p collisions and pileup simulated with PYTHIA-8
  - Processed by full sPHENIX reconstruction
  - **PYTHIA-8:** Sjöstrand et al; CPC 191, 159 (2015)
- Jets reconstructed with parameters in box from either:
  - Final-state charged MC particles **("truth jets")**
  - Or reconstructed tracks **("reco. jets")**
- Track selection criteria listed in backup

Analysis (p+p) | EEC in p+p

- EEC calculated in jets with $p_T^{jet} \in (10, 30)$ GeV/c down to $R_L \sim 0.03$
  - ☞ Aiming to push to lower R_L as tracking becomes better understood

- Distributions normalized to unity to compare shape
  - – With increasing p_T^{jet}:
    - › Transition b/n **P** & **NP** broadens
    - › **And** peak of transition happens at lower R_L!
  - ☞ Qualitatively consistent with similar studies from STAR (see backup)

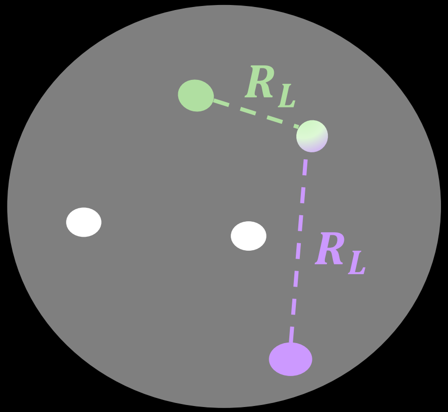


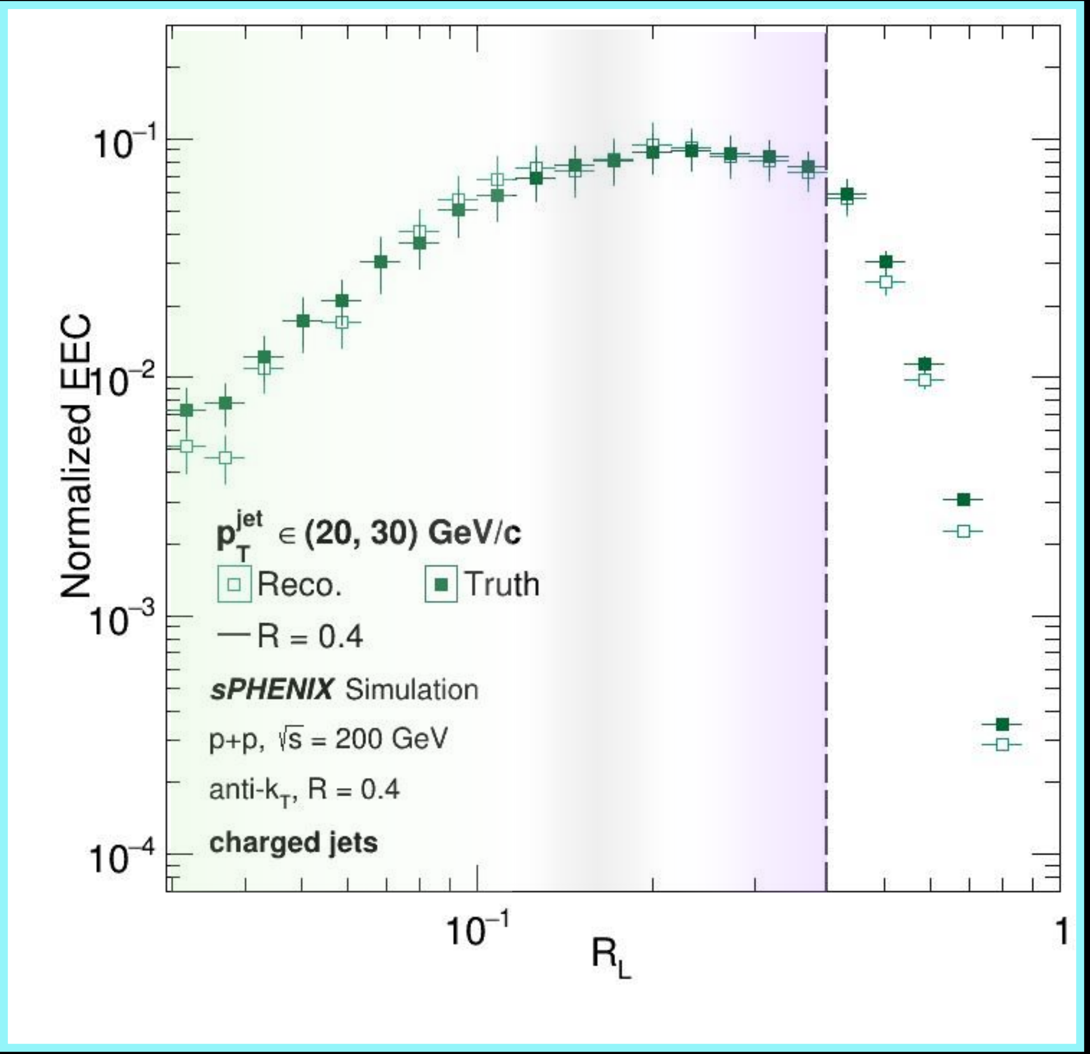


Analysis (p+p) | Truth vs. Reco. EEC

- **Right:** truth vs. reco. EEC for 20 – 30 GeV/c jets
  - Reco. jets include all detector effects (e.g. tracking efficiency) and pileup

- Differences between truth and reco. small
  - ⇒ **Corrections should be easily controllable!**





Analysis (p+Au) | Simulation Setup

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p+Au Simulation

- PYTHIA-8, $\hat{p}_T > 7$ GeV/c
- Embedded into p+Au HIJING (b = 0 – 10 fm)
- Simulated 50 kHz MHz of pileup p+Au collisions
- 14M events analyzed

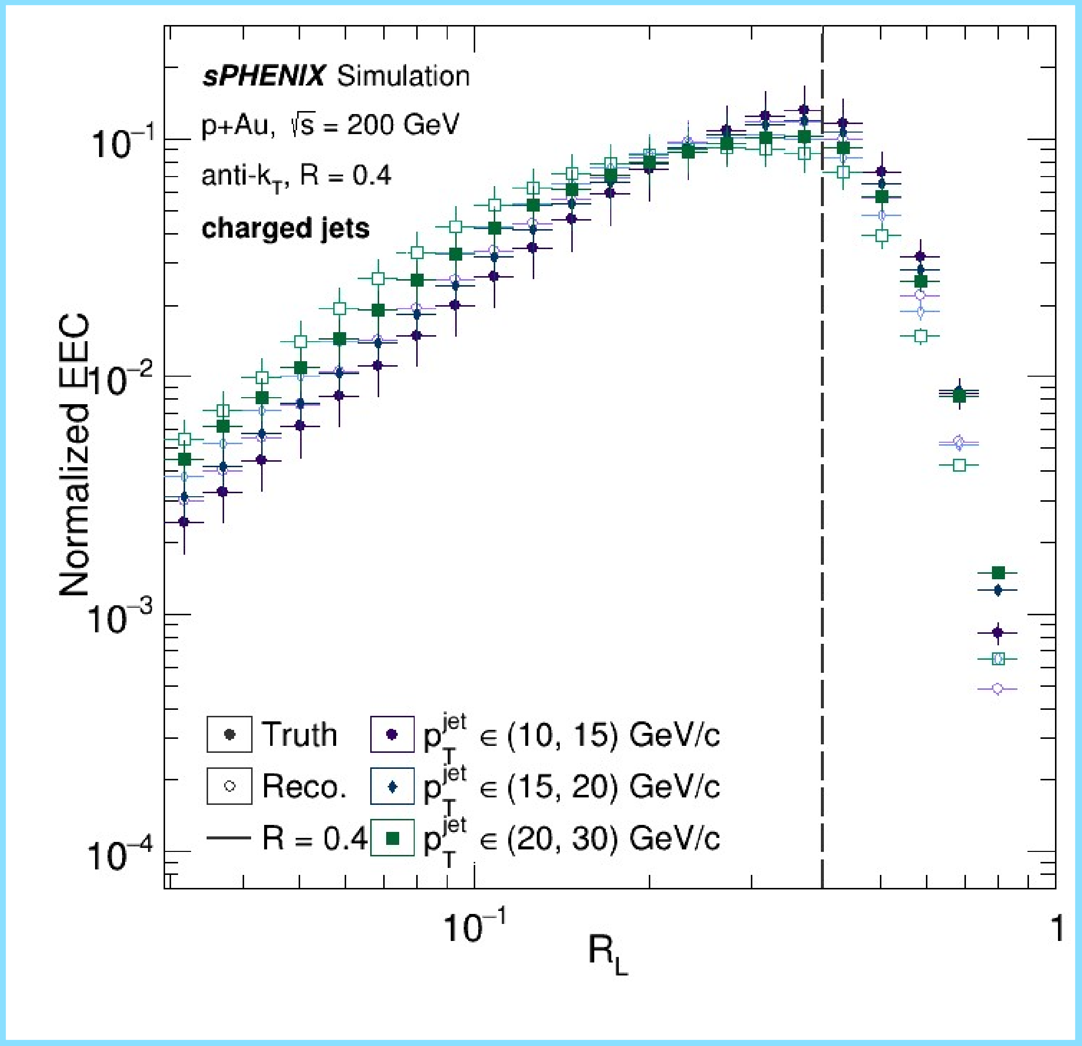
Jet Definition

- Anti-k_T algo., p_T-recomb. scheme
- R = 0.4
- $|\eta^{jet}| < 0.7$

- p+Au collisions simulated by embedding PYTHIA-8 into p+Au HIJING
  - **HIJING:** Wang, Gyulassey; PRD 44, 3501 (1991)
- Jets reconstructed with same parameters as in p+p
  - Looser track selection applied here than in p+p
  - ☞ Criteria still being optimized here and in p+p
- **Note:** following plots integrated over multiplicity!

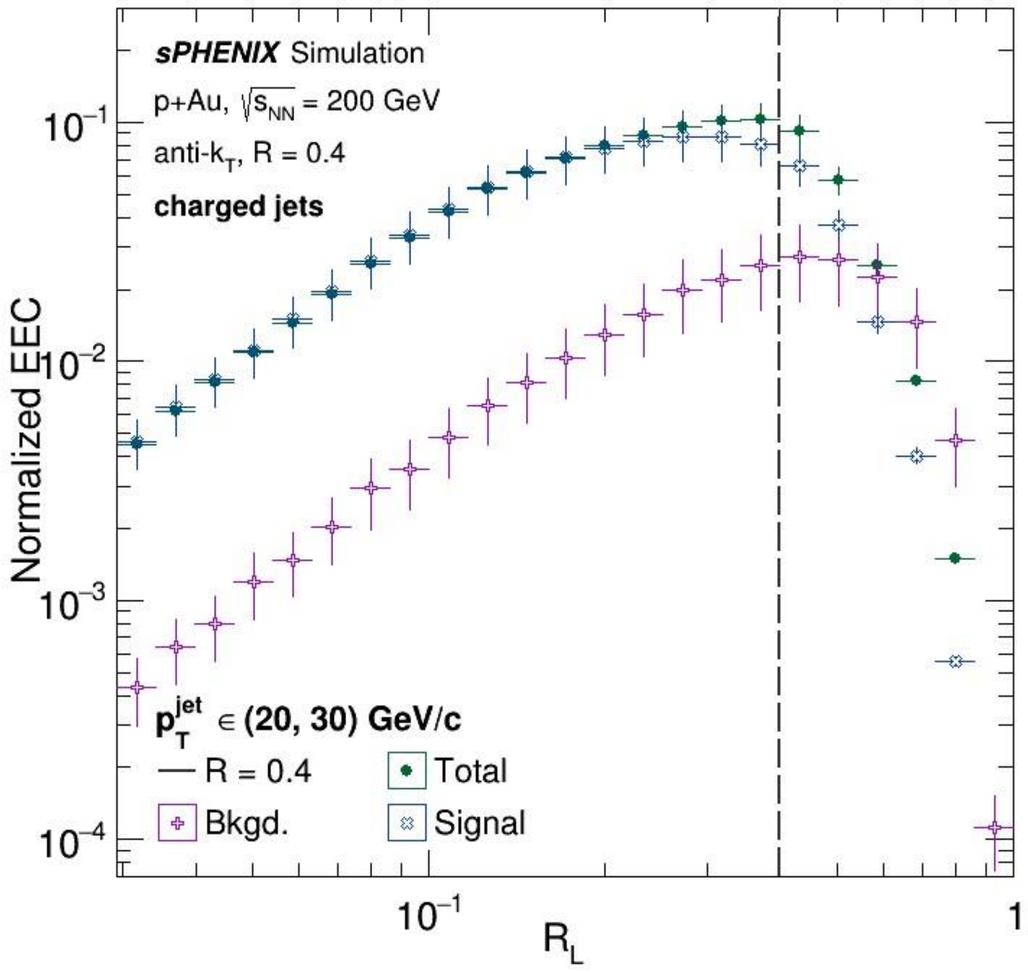
Analysis (p+Au) | EEC in p+Au

- EEC calculated in p+Au for jets for same kinematic range as in p+p
- Larger differences between truth and reco EEC than in p+p!
  - Not surprising:
    - Track selection could be further optimized
    - Also have the p+Au UE to do deal with…
- **Reminder:** no multiplicity selection applied



Analysis (p+Au) | UE Contribution in p+Au

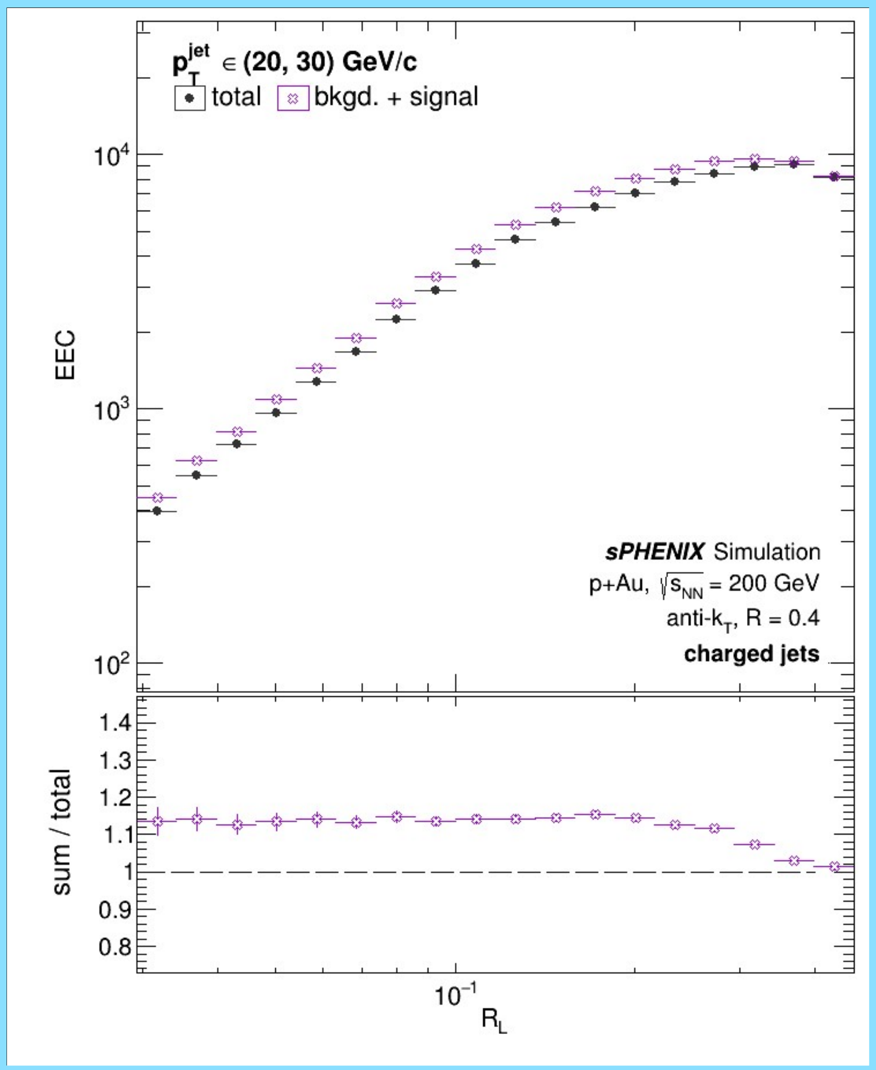
- **Right:** EEC for 20 – 30 GeV/c truth jets in p+Au split into 3 different populations
  - a) **Signal:** particles from embedded PYTHIA-8
  - b) **Background:** p+Au HIJING event signal embedded into & pileup p+Au events
  - c) **Total:** the entire signal+background event
  - ☞ **Background & signal normalized relative to total**
- **Note shapes:** background EEC largely follow free-streaming scaling behavior
- **Reminder:** no multiplicity selection applied



Analysis (p+Au) | Signal-Background Correlations

- Total EEC spectrum consist of 3 correlations: signal-signal, background-background, and **signal-background**
- W/o signal-background correlations, total spectrum would be sum of signal and background
  - To gauge size of signal-background correlations:
    - signal + background sum **(purple)** compared against total **(black)**
  - For $R_L \lesssim 0.4$:
    - Total differs by **no more than 20%**
    - But signal-background correlations clearly affect shape!

- **Notes:**
  - bars on points are statistical errors (largely obscured by markers)
  - EEC are **not** normalized here
- **Reminder:** no multiplicity selection applied



Summary & Outlook

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In Summary:

- ENC may offer valuable insight into CNM effects
- Correlator & Energy Flow program at sPHENIX in early stages
  - Presented some initial feasibility studies in this talk
  - Building understanding of expected detector effects & systematic uncertainties
- sPHENIX anticipates ability to measure well into free-streaming regime with well-controllable corrections

Towards Run 2024 and Beyond:

- sPHENIX made excellent progress in commissioning during Run 2023
  - ☞ Well posed to complete commissioning in Run 2024!
- ENC measured in high luminosity p+p running in 2024 will be critical
  - As baseline for similar measurements in Au+Au, p+Au, HF-tagged jets, and more
  - As baseline for future EIC measurements in e+P/e+A
  - For studies of CNM effects in their own right

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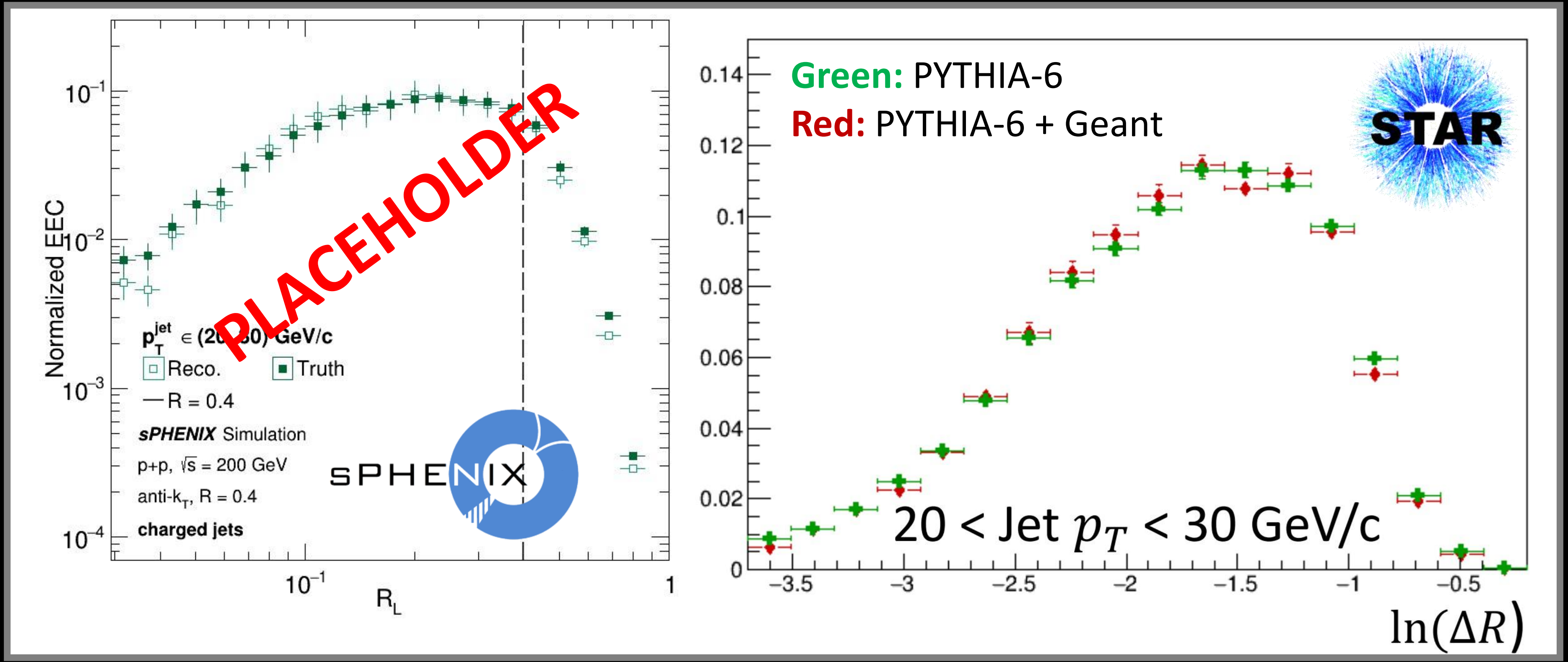
Thanks!

Backup | STAR vs. sPHENIX Simulation



- **Left:** EEC in p+p sPHENIX simulation
  Right: EEC in p+p STAR simulation
  - Detector effects simulated w/ GEANT simulation of STAR ca. 2012
  - ☞ HP2022 [ref goes here]

- **STAR simulation details:**
  - PYTHIA-6 (p+p), $\sqrt{s} = 200$ GeV
  - Charged jets, R = 0.4, $|\eta^{jet}| < 0.6$
  - $p_T^{cst} > 0.2$ GeV/c

Backup | Simulations, Jets, and Selection Criteria

p+p Simulation

- PYTHIA-8, $\hat{p}_T > 7$ GeV/c
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p+Au Simulation

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Jet Definition

- Anti-k_T algo., p_T-recomb. scheme
- R = 0.4
- $|\eta^{jet}| < 0.7$
- Constituents:
  [True] FS charged MC particles
  [Reco] tracks

Cuts Applied to Particles

- $p_T^{par} > 0$ GeV/c
- $|\eta^{par}| < 1$
- Is final state
- Is charged

Cuts Applied to Tracks

- $p_T^{trk} = 1 - 100$ GeV/c
- $|\eta^{trk}| < 1.1$
- Quality (χ^2/ndf) < 10
- $N_{mvtx}^{layer} > 2$
- $N_{intt}^{layer} > 1$
- $N_{tpc}^{layer} > 33$
- $|DCA_{xy}| < 0.06$ cm
- $|DCA_z| < 0.20$ cm
- $\delta p_T^{trk}/p_T^{trk} < 0.04$[1]

1. %-uncertainty on pt from ACTS fit

Backup | Corrections

- Corrections could be small, but they still need to be applied.
  - We are currently discussing strategies for unfolding/applying corrections
  - 2 potential options:
    a) Traditional 2D unfolding
    b) Omnifold

a) 2D Unfolding:

- Construct $\left(p_T^{jet}, p_T^{cst}\right)$ response matrix and reconstruction efficiency for each bin of R_L
- Unfold each 2D bin

b) Omnifold:

- Uses a ML model to “unfold” either multiple observables at once or the entire event
- In the latter case, the correlator calculation would be rerun correlator analysis on unfolded event

☞ **Might be beneficial to explore both going forward…**