Towards EEC in Cold QCD at the sPHENIX Experiment

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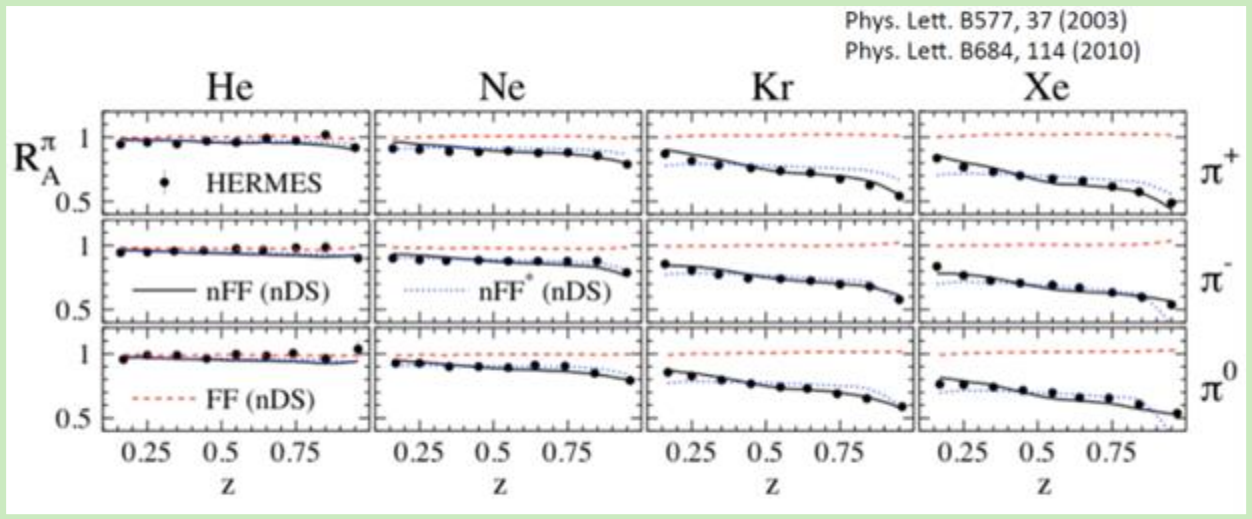
Introduction | Cold Nuclear Matter Effects

- 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

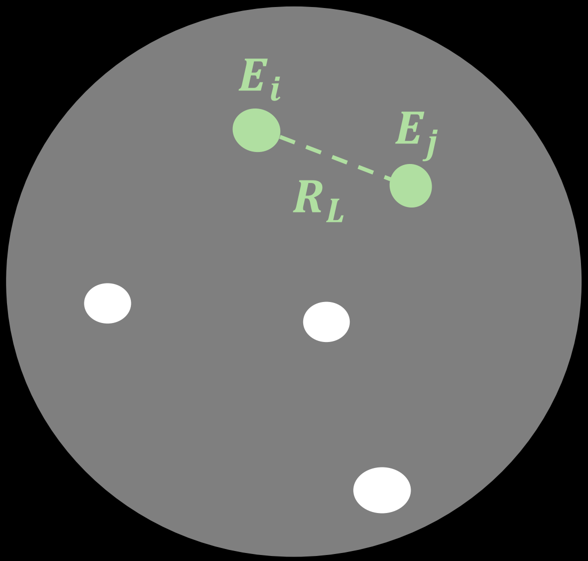
2-Point Energy Correlators (EEC)

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

N-Point Energy Correlators (ENC)

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

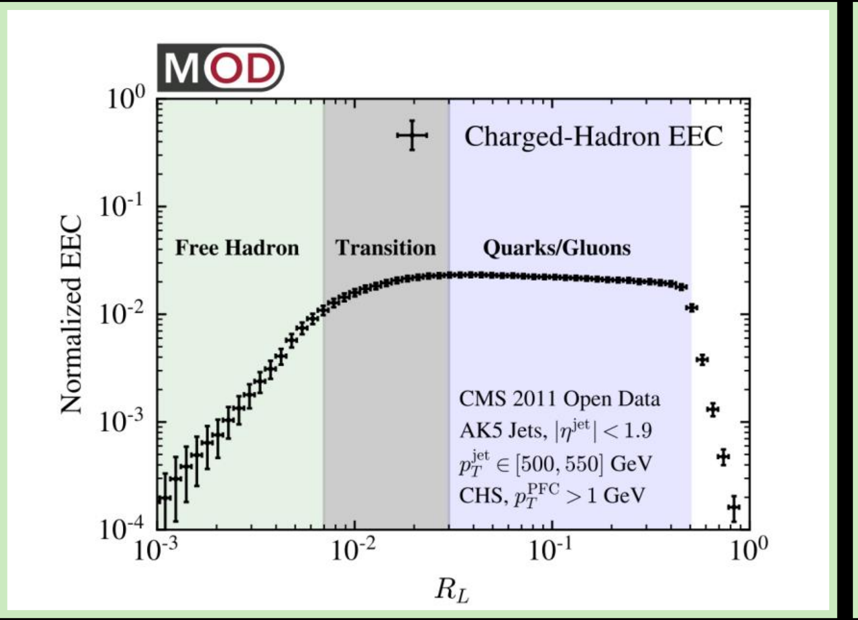
- $\mathcal{E}(\vec{n}_i)$ = i^{th} asymptotic energy operator
- R_L = longest distance out of N directions



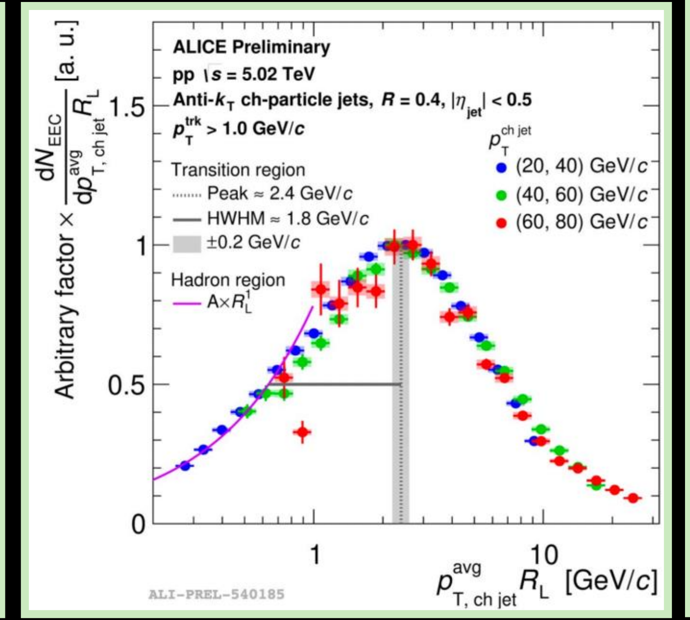
- **N-point energy correlators:** measure statistical correlations in energy flux within a jet
  - Inherently IRC safe
  - Calculable in pQCD

Introduction | ENC in Vacuum

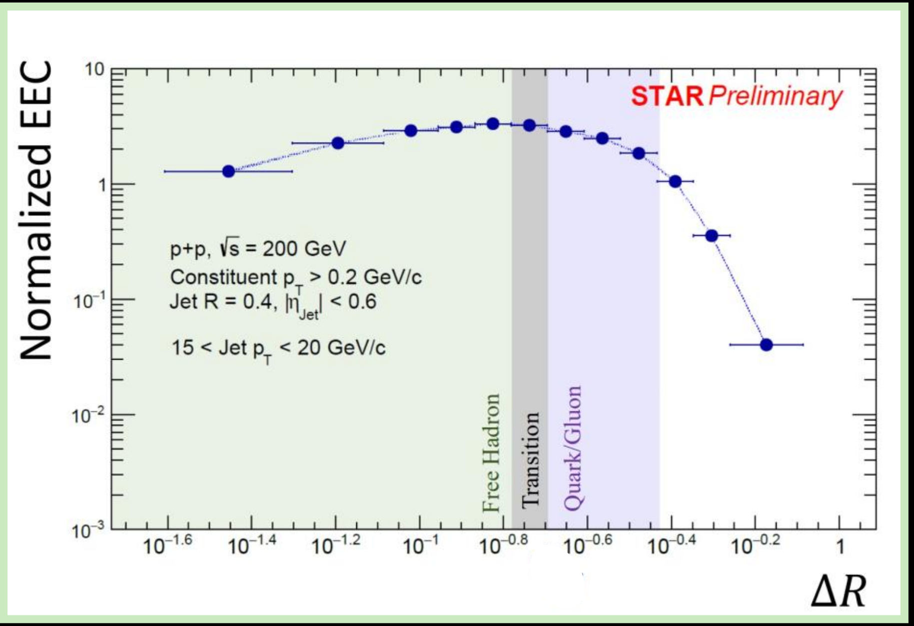
arXiv:2201.07800



ALICE @ HP2023



STAR @ HP2023



- **In vacuum:** allow for clear distinction b/n **perturbative** and **nonperturbative** regimes
  - Cleanly image structure as a function of angular scale
  - ☞ arXiv:2201.07800
- Recent studies demonstrate transition happens at $R_L p_T^{jet} \sim 2.5$ GeV/c **at RHIC and LHC**
  - ☞ See STAR & ALICE preliminary results at HP 2023

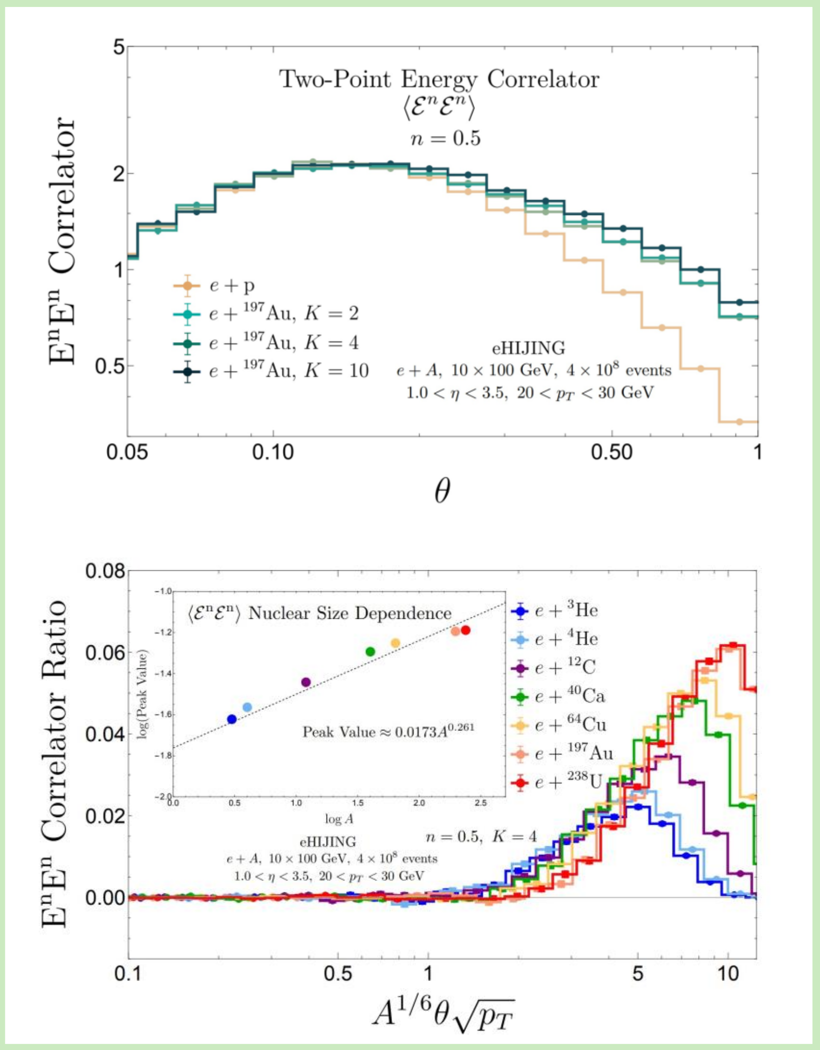
Introduction | ENC in Nuclei

arXiv:2303.08143

- ENC provide a clean observable to image jet fragmentation in vacuum
  - ☞ **But what about in nuclei?**

- **Recently:** 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!**



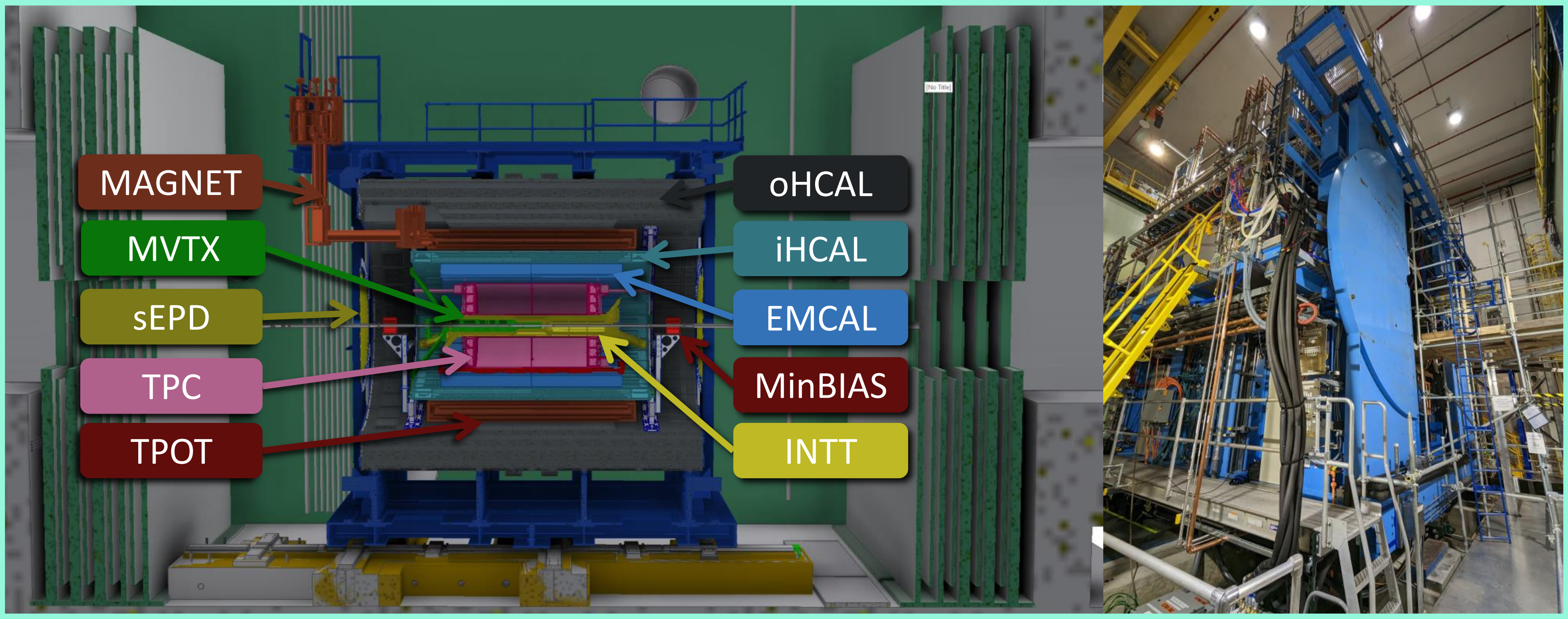
Introduction | Goal and Talk Outline

- Having a hadronic baseline for leptonic measurements will be valuable
  - **Recall:** IS-FS color exchanges will happen in p+p/p+A
  - **But won't happen in e+p/e+A!**
- **Our goal:** measure ENC in p+p (and p+Au, if available) at sPHENIX for baseline point of comparison
  - ☞ Kinematics at EIC most comparable to RHIC
- Also plenty of other physics opportunities for ENC in CNM systems
  - e.g. analyzing nPDFS!

Outline:

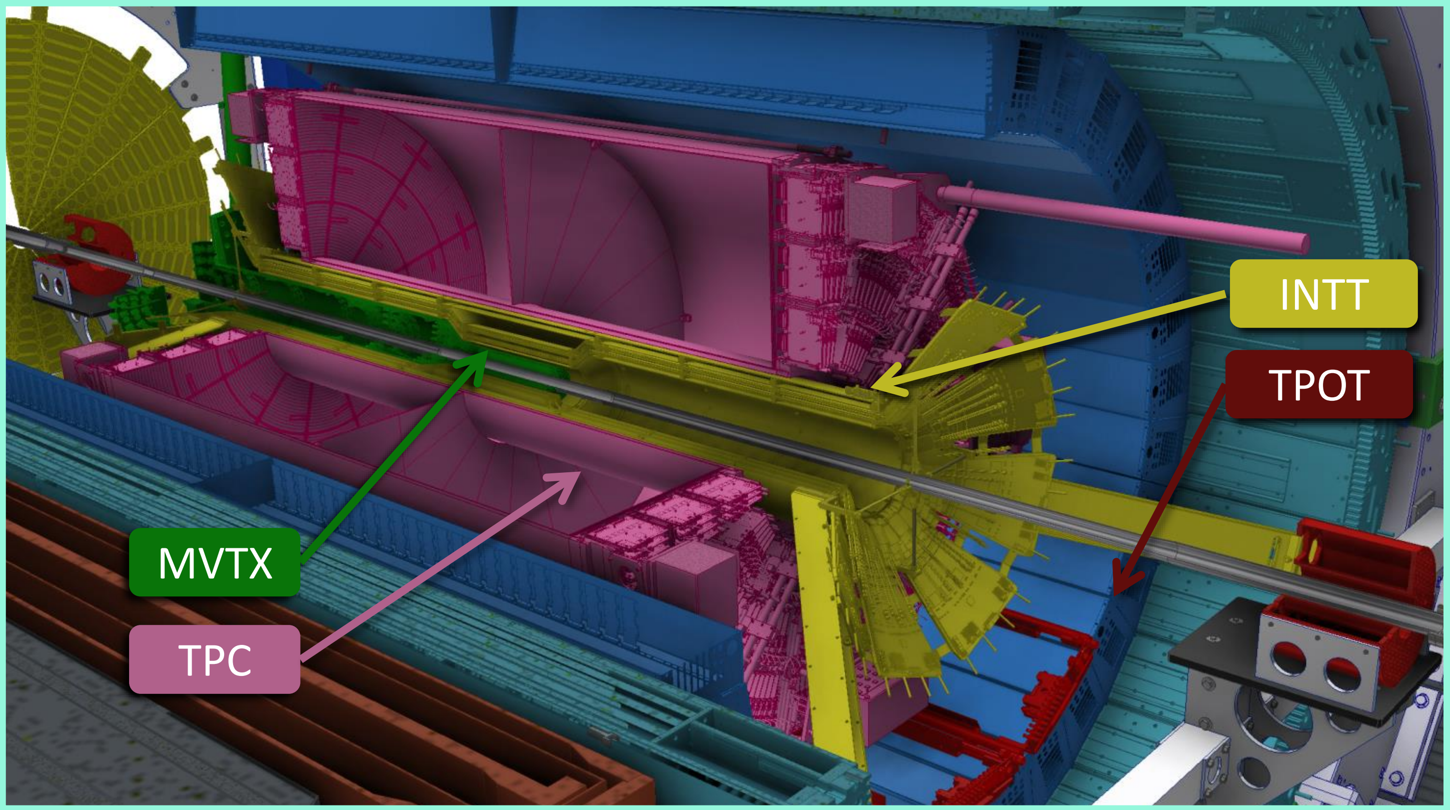
1) sPHENIX Overview
2) p+p Analysis
3) p+Au Analysis
4) Conclusions & Outlook

sPHENIX | Overview



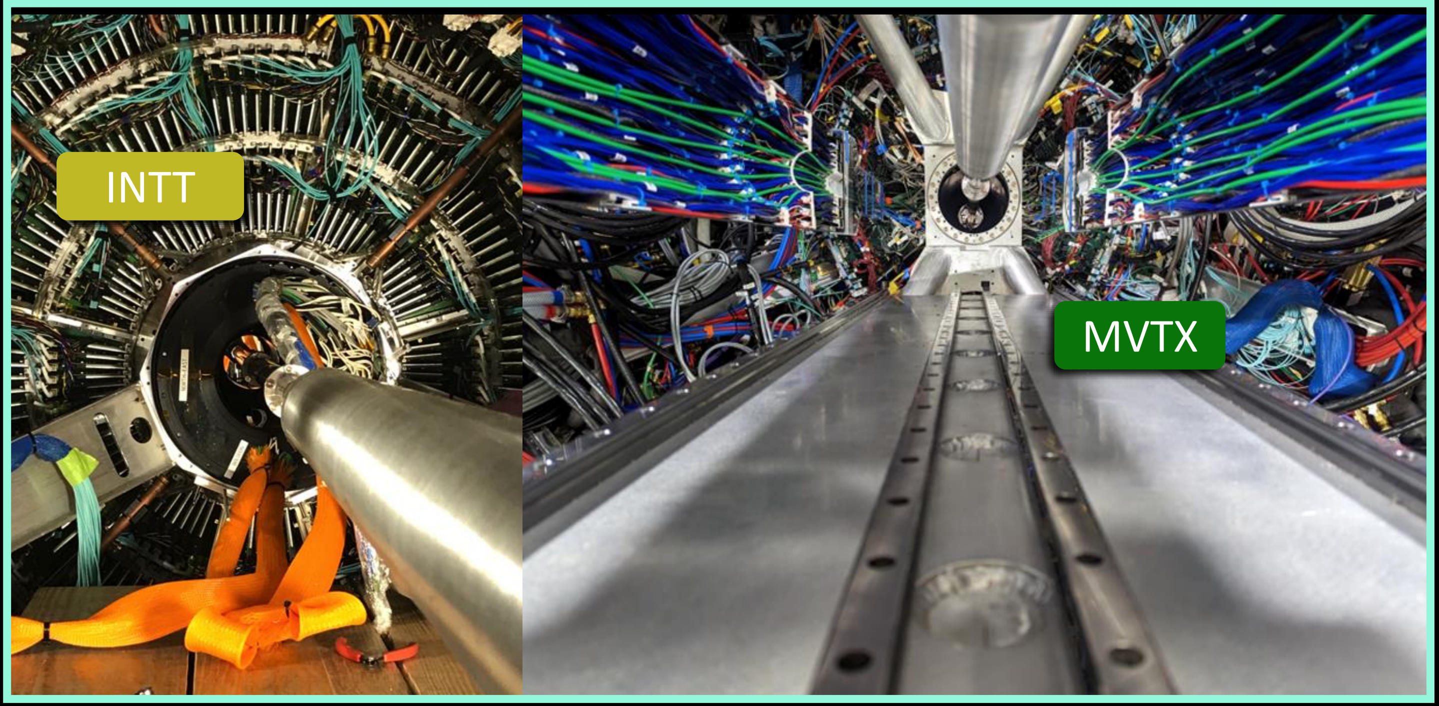
- **sPHENIX:** brand new, state of the art HENP experiment at RHIC
  - Purpose built for precision jet/HF studies and rare probes
- **Key features:**
  - Large acceptance (2π in φ, $|\eta| < 1.1$)
  - Full EM & Hadronic calorimetry
  - High precision tracking/vertexing system

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)**
    - Precision timing/vertexing
  - 2 outermost are gaseous **(TPC, TPOT)**
    - Momentum resolution (TPC)
    - Calibration (TPOT)
- **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)

sPHENIX | Tracking System



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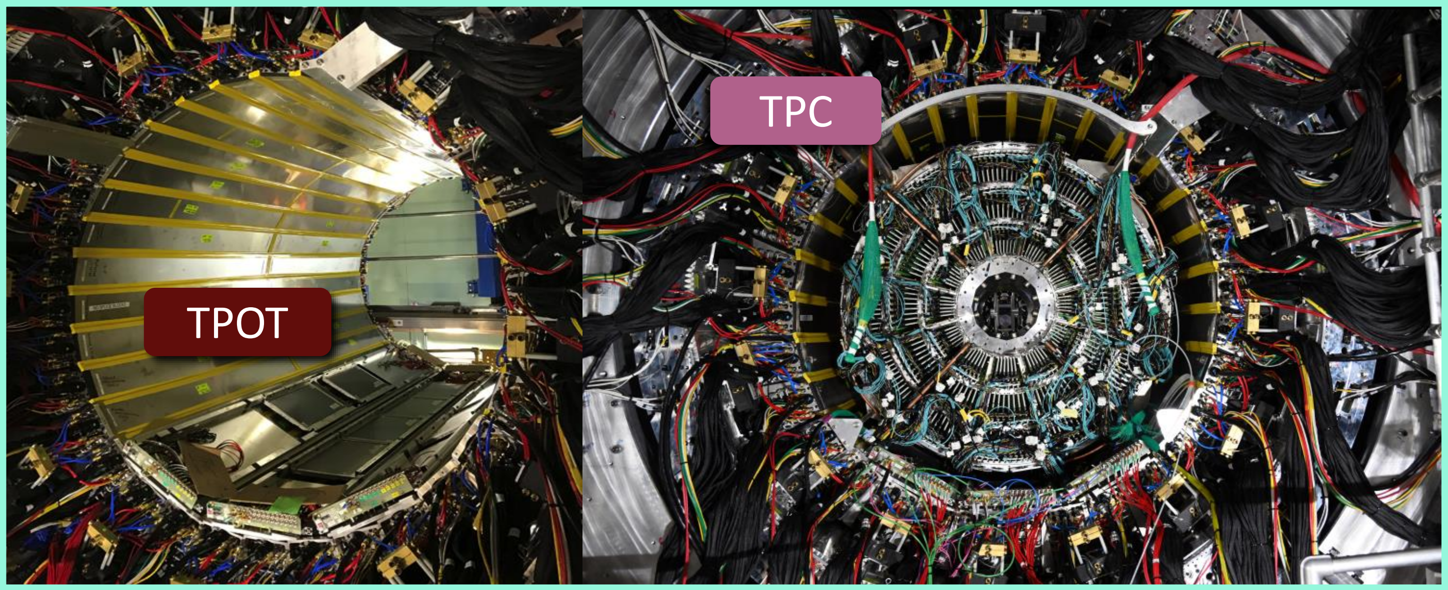

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Analysis (p+p) | Simulation Setup

p+p Simulation

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

Jet Definition

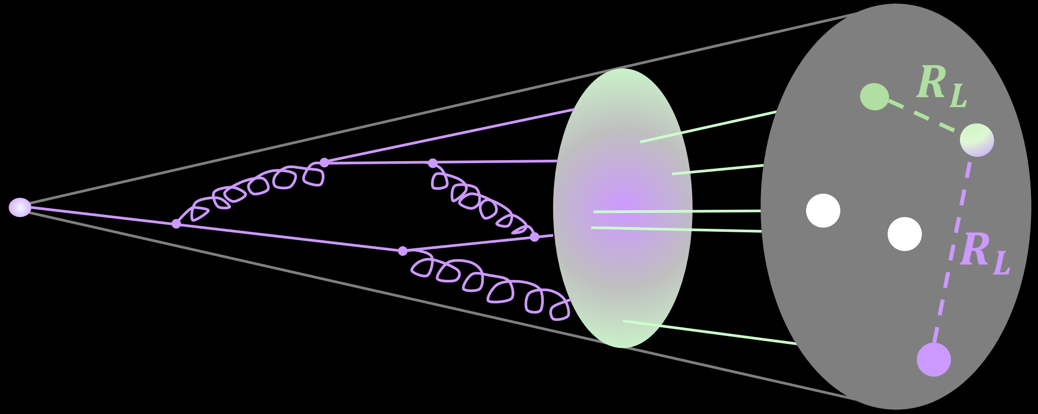
- Anti-k_T algo., p_T-recomb. scheme
- R = 0.4
- $|\eta^{jet}| < 0.7$

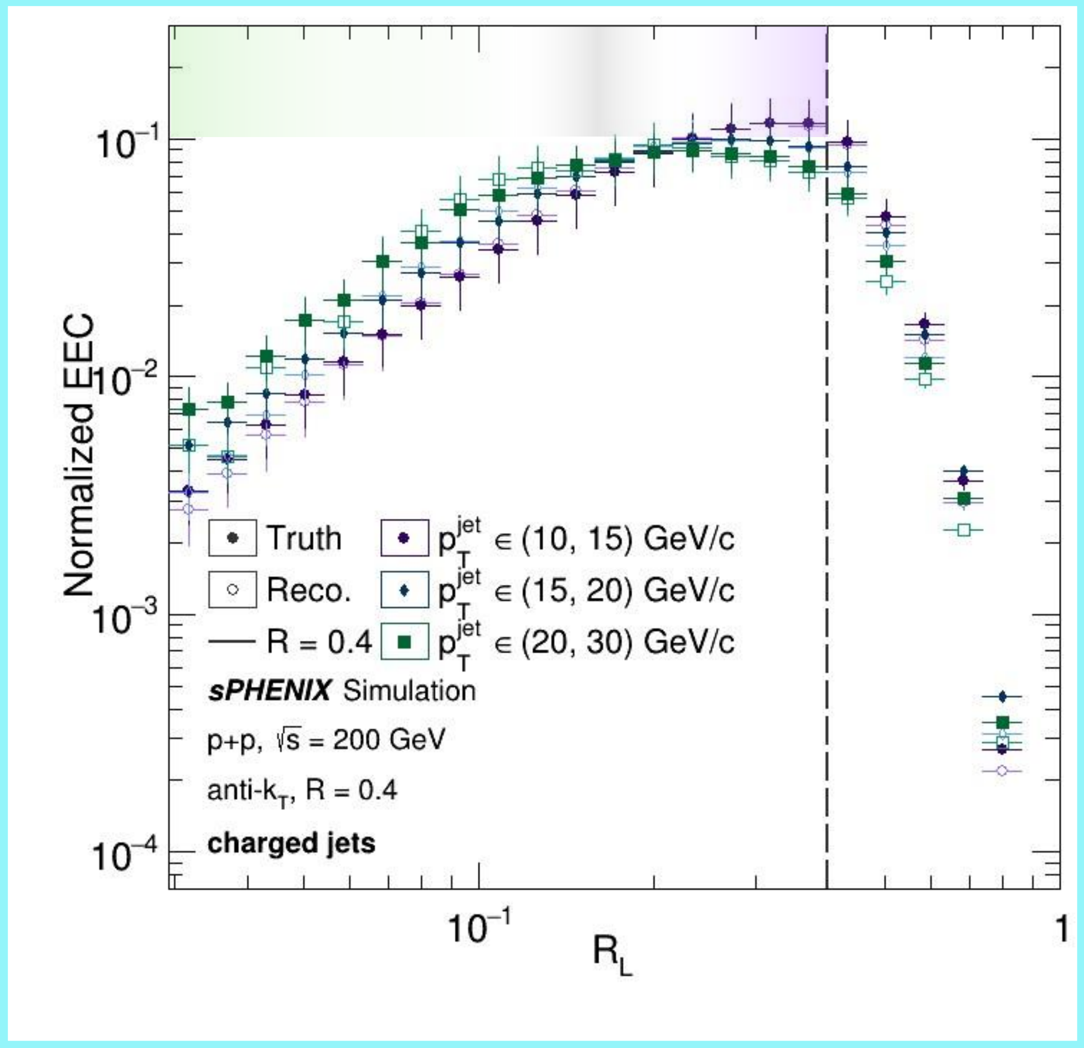
- p+p collisions and pileup simulated with PYTHIA-8
  - Processed by full sPHENIX reconstruction
  - **PYTHIA-8:** Sjöstrand et al; CPC 191, 159 (2015)
- Jets reconstructed with parameters in box from either:
  - Final-state charged MC particles **("truth jets")**
  - Or reconstructed tracks **("reco. 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
  - – **Note:** bars are variance of distribution for each R_L bin

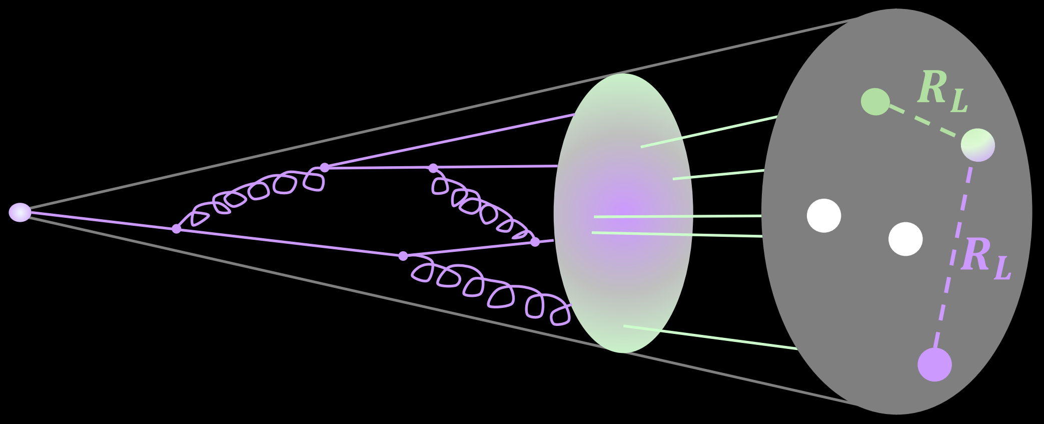
- **Closed markers:** EEC from truth jets
  Open markers: EEC from reco. jets

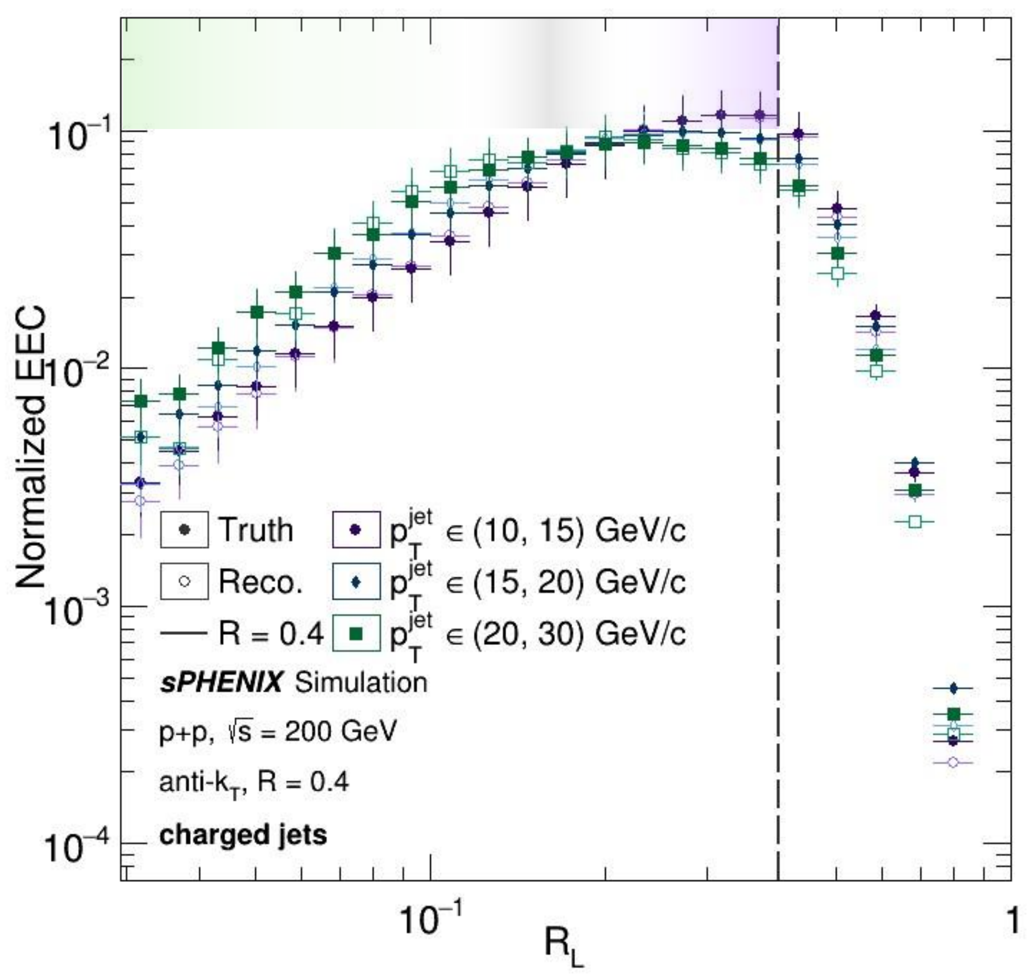




Analysis (p+p) | EEC in p+p

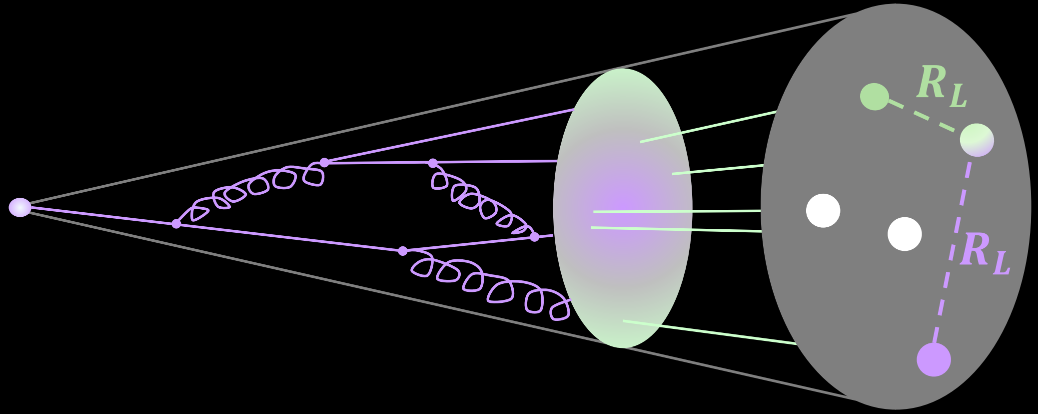
- Distributions normalized to unity to compare shape
  - Shading at top of plot roughly indicates **perturbative** & **free streaming** regions
  - Dashed line indicates $R = 0.4$
- With increasing p_T^{jet}:
  - Transition region broadens
  - **And** peak of transition happens at lower R_L!

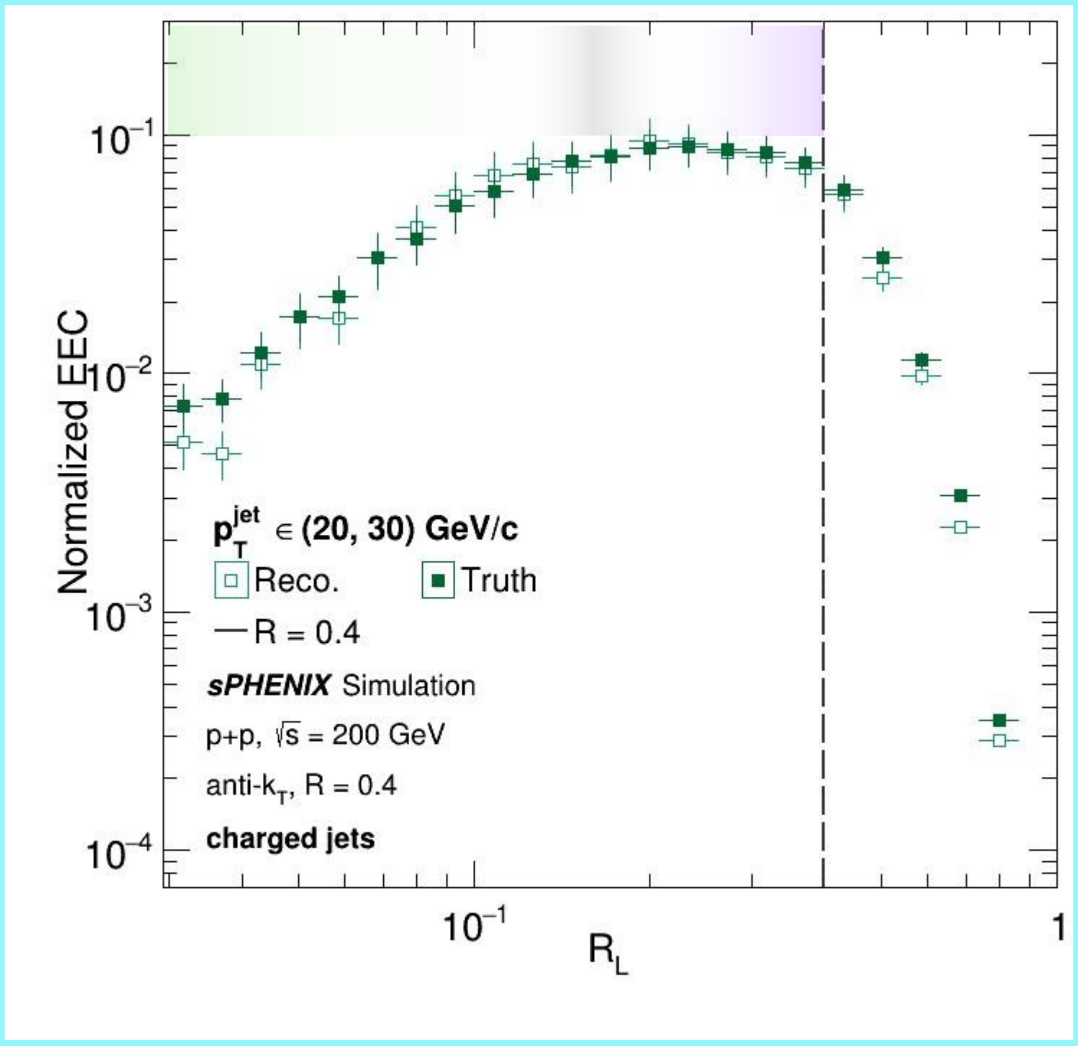




Analysis (p+p) | Truth vs. Reco. EEC

- **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

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

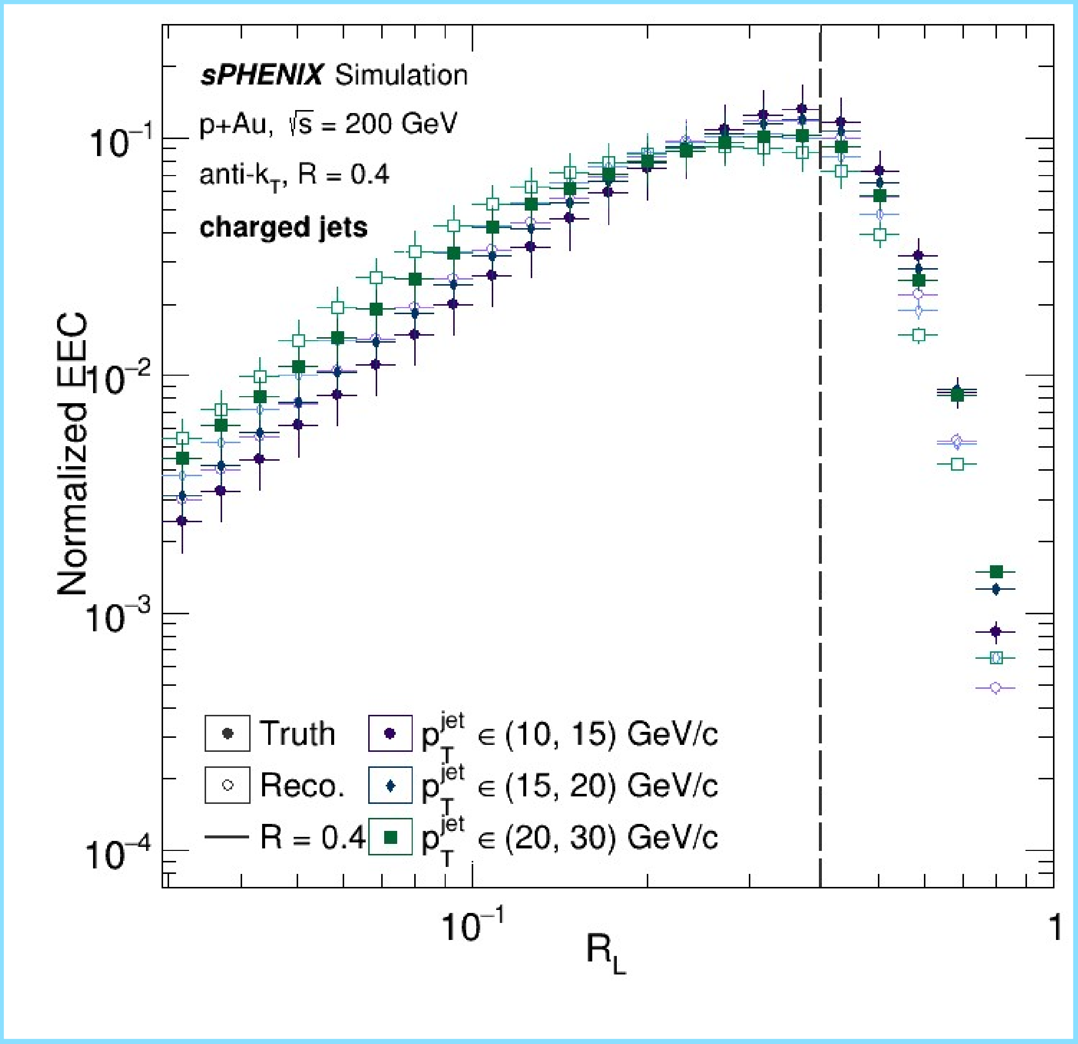
- Anti-k_T algo., p_T-recomb. scheme
- R = 0.4
- $|\eta^{jet}| < 0.7$

- 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

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

sPHENIX

- EEC calculated in min-bias p+Au for jets with same kinematic range as in p+p
- Larger differences between truth and reco EEC than in p+p!
  - ☞ Currently optimizing track selection to reduce this difference

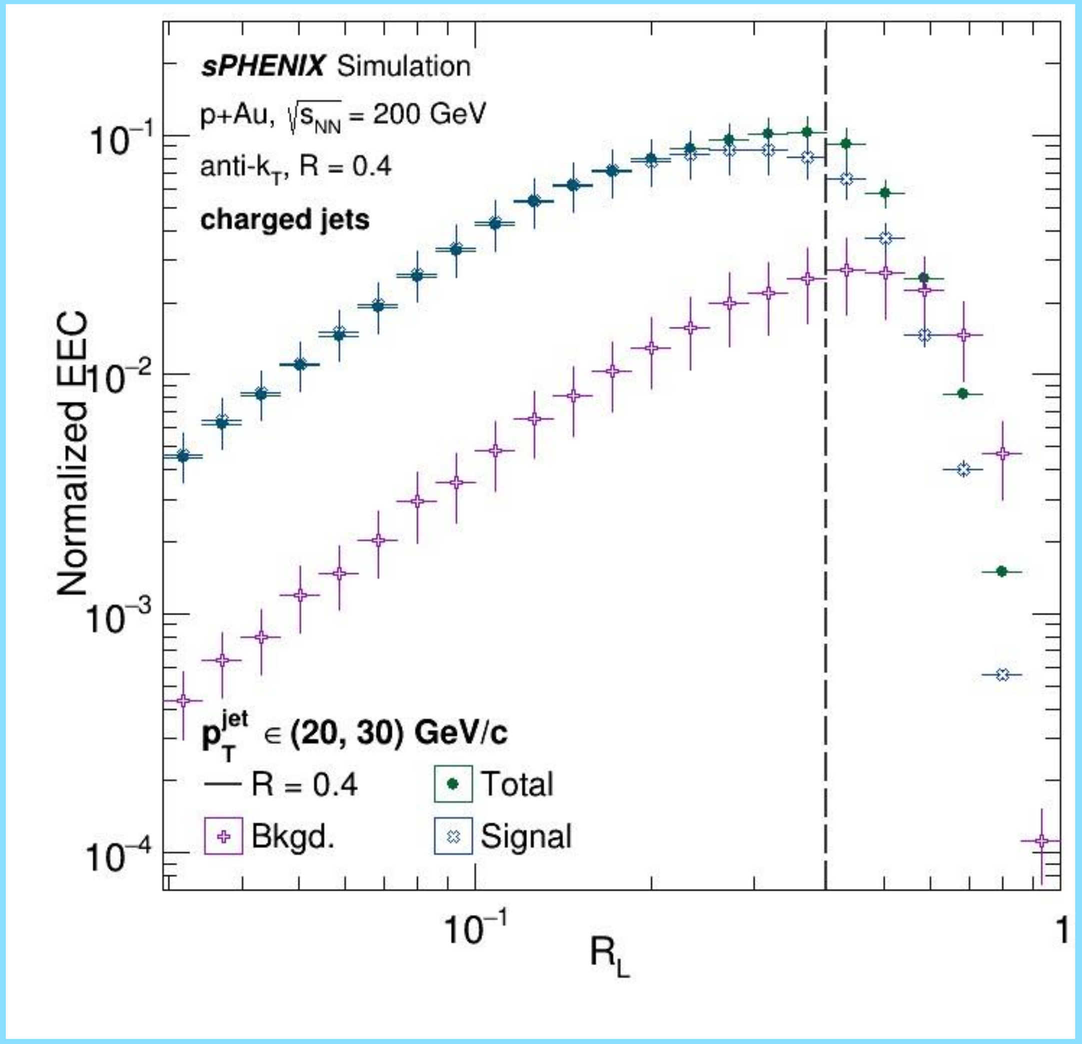


Analysis (p+Au) | UE Contribution in p+Au

- Total EEC spectrum in p+Au consists of 3 classes of correlations:
  - **signal-signal**,
  - **background-background**,
  - and **signal-background**

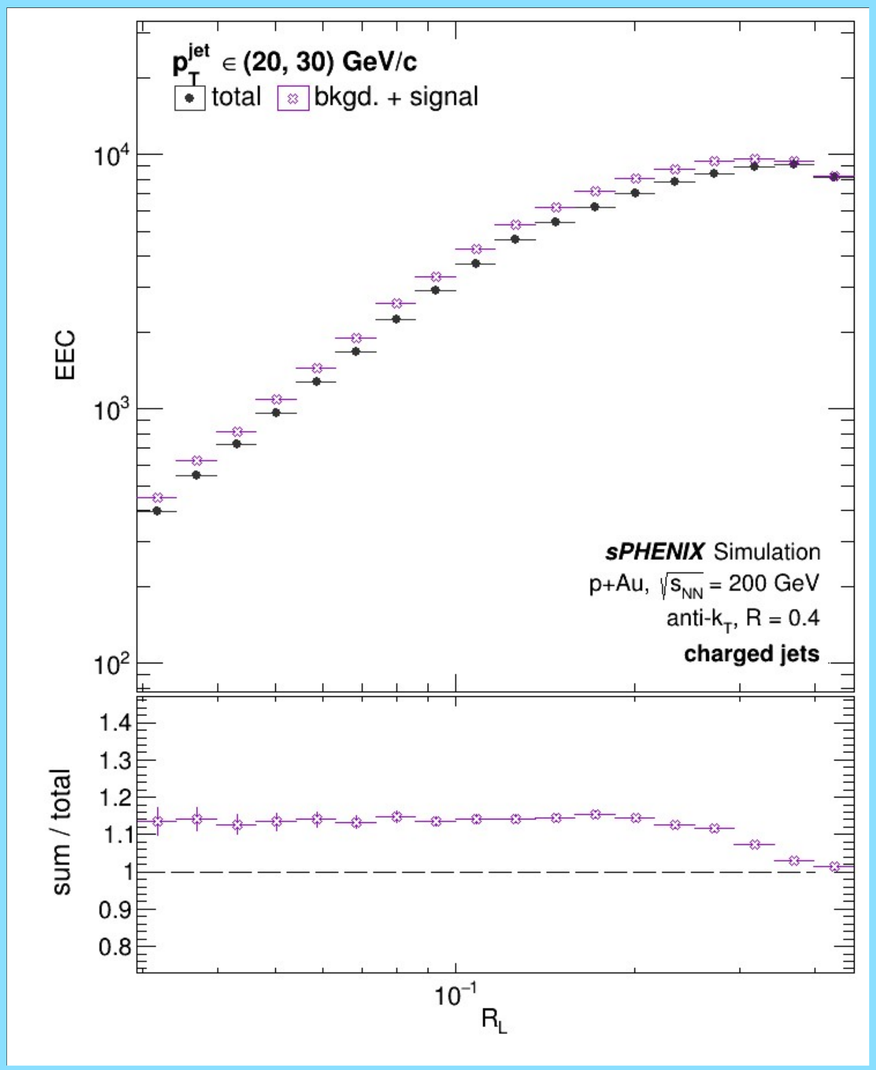
- **Right:** EEC for 20 – 30 GeV/c truth jets in p+Au calculated for 3 different popultions
  a) **Signal:** only PYTHIA-8
  b) **Background:** only p+Au HIJING
  c) **Total:** entire PYTHIA-8 + HIJING event

- **Note shapes:** background EEC largely follow free-streaming scaling behavior
  - ☞ Background & signal normalized relative to total

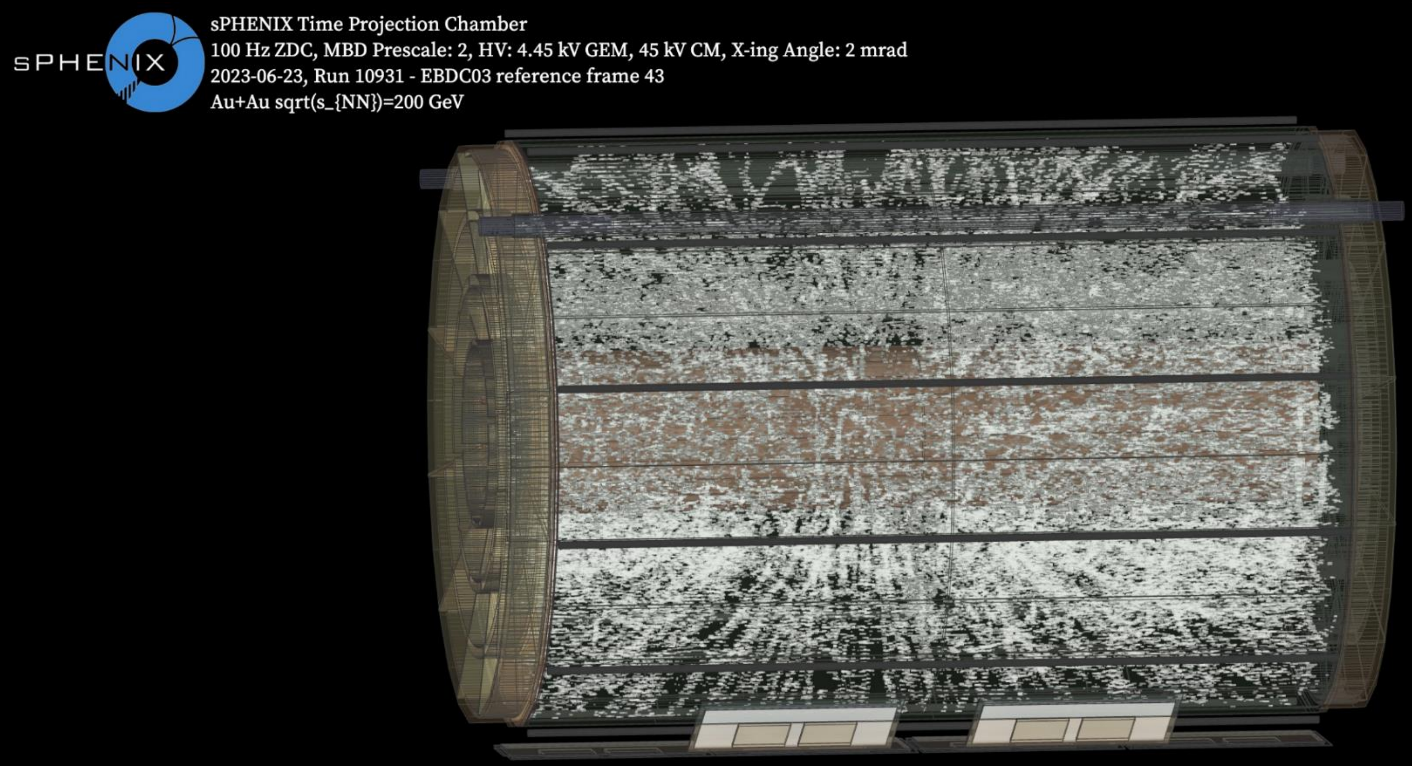


Analysis (p+Au) | Signal-Background Correlations

- To gauge size of signal-background correlations:
  - **Compare sum of signal & background EEC spectra to total**
  - No signal-background correlations → total would be sum of signal and background
- **Right:** sum of signal, background EEC spectra **(purple) vs.** total **(black)** for 20 – 30 GeV/c jets
  - Total differs by **no more than 20%**
  - But shape is clearly different!
- **Notes:**
  - R_l only shown from 0.03 to 0.4
  - bars on points are statistical errors (largely obscured by markers)
  - EEC are **not** normalized here



Conclusion | Outlook

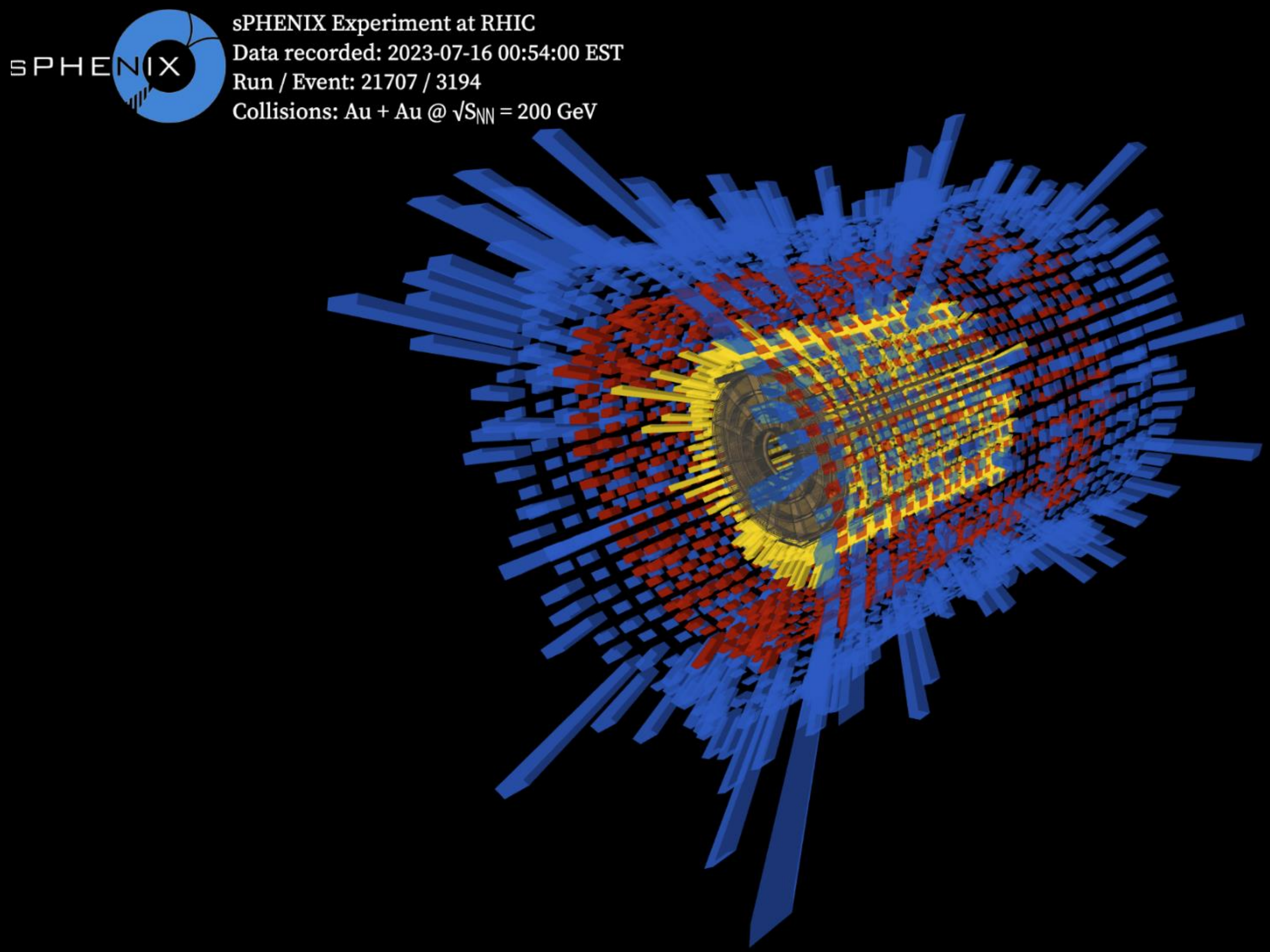


Towards Run 2024 and Beyond:

- RHIC valve-box incident ended Run 2023 early…
  - But sPHENIX made excellent progress in commissioning during run
  - More in **Joe Osborne's talk** (11/9 @ 3 pm)

☞ Well posed to complete commissioning and continue taking physics data in 2024!
- ENC in high luminosity p+p dataset will be valuable as baseline & complement at RHIC & EIC!

Conclusion | Summary



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

sPHENIX

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Thanks!

Backup | Simulations, Jets, and Selection Criteria

sPHENIX

p+p Simulation

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- Simulated 3 MHz of pileup p+p collisions
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p+Au Simulation

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- Simulated 50 kHz MHz of pileup p+Au collisions
- 3M events analyzed

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…**

Backup | sPHENIX BUP 2022 vs. 2023

sPHENIX

2022 BUP

Table 1: Summary of the sPHENIX Beam Use Proposal for years 2023–2025, as requested in the charge. The values correspond to 24 cryo-week scenarios, while those in parentheses correspond to 28 cryo-week scenarios. The 10%-*str* values correspond to the modest streaming readout upgrade of the tracking detectors. Full details are provided in Chapter 2.

Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $\|z\| < 10$ cm	Samp. Lum. $\|z\| < 10$ cm
2023	Au+Au	200	24 (28)	9 (13)	3.7 (5.7) nb^{-1}	4.5 (6.9) nb^{-1}
2024	$p^{\uparrow}p^{\uparrow}$	200	24 (28)	12 (16)	0.3 (0.4) pb^{-1} [5 kHz] 4.5 (6.2) pb^{-1} [10%-*str*]	45 (62) pb^{-1}
2024	$p^{\uparrow}$+Au	200	–	5	0.003 pb^{-1} [5 kHz] 0.01 pb^{-1} [10%-*str*]	0.11 pb^{-1}
2025	Au+Au	200	24 (28)	20.5 (24.5)	13 (15) nb^{-1}	21 (25) nb^{-1}

- **2022 vs. 2023 sPHENIX BUPs**
  - 2023 BUP driven by required p+p/Au+Au luminosities for physics & completing commissioning
  - PAC supported sPHENIX request for sufficient p+p luminosity

2023 BUP

Table 1: Summary of the sPHENIX Beam Use Proposal for 2024 and 2025, as requested in the charge. The values separated by slashes correspond to different cryo-week scenarios (20/24/28 in 2024 and 24/28 in 2025). The 10%-*str* values correspond to the modest streaming readout upgrade of the tracking detectors. Full details are provided in Chapter 2.

Species	$\sqrt{s_{NN}}$ [GeV]	Physics Weeks	Min. Bias Rec. Lum. $\|z\| < 10$ cm	Calo. Trigger Lum. $\|z\| < 10$ cm
Run-2024, Scenario A, 6 cryo-weeks Au+Au + 20/24/28 cryo-weeks p+p				
Au+Au	200	n/a	n/a (Commissioning running)	
p+p	200	13/17/21	0.34/0.44/0.54 pb^{-1} [@ 5kHz] 2.3/3.1/3.9 pb^{-1} [10%-str]	23/31/39 pb^{-1}
Run-2024, Scenario B, 20/24/28 cryo-weeks p+p + 6 cryo-weeks Au+Au				
p+p	200	9/13/17	0.23/0.34/0.44 pb^{-1} [@ 5kHz] 1.5/2.3/3.1 pb^{-1} [10%-str]	15/23/31 pb^{-1}
Au+Au	200	3	0.4 nb^{-1} (3B events)	not needed
Run-2025, 24/28 cryo-weeks				
Au+Au	200	20.5/24.5	5.2/6.3 nb^{-1} (35B/43B events)	not needed