First suite of physics results from sPHENIX

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Overview

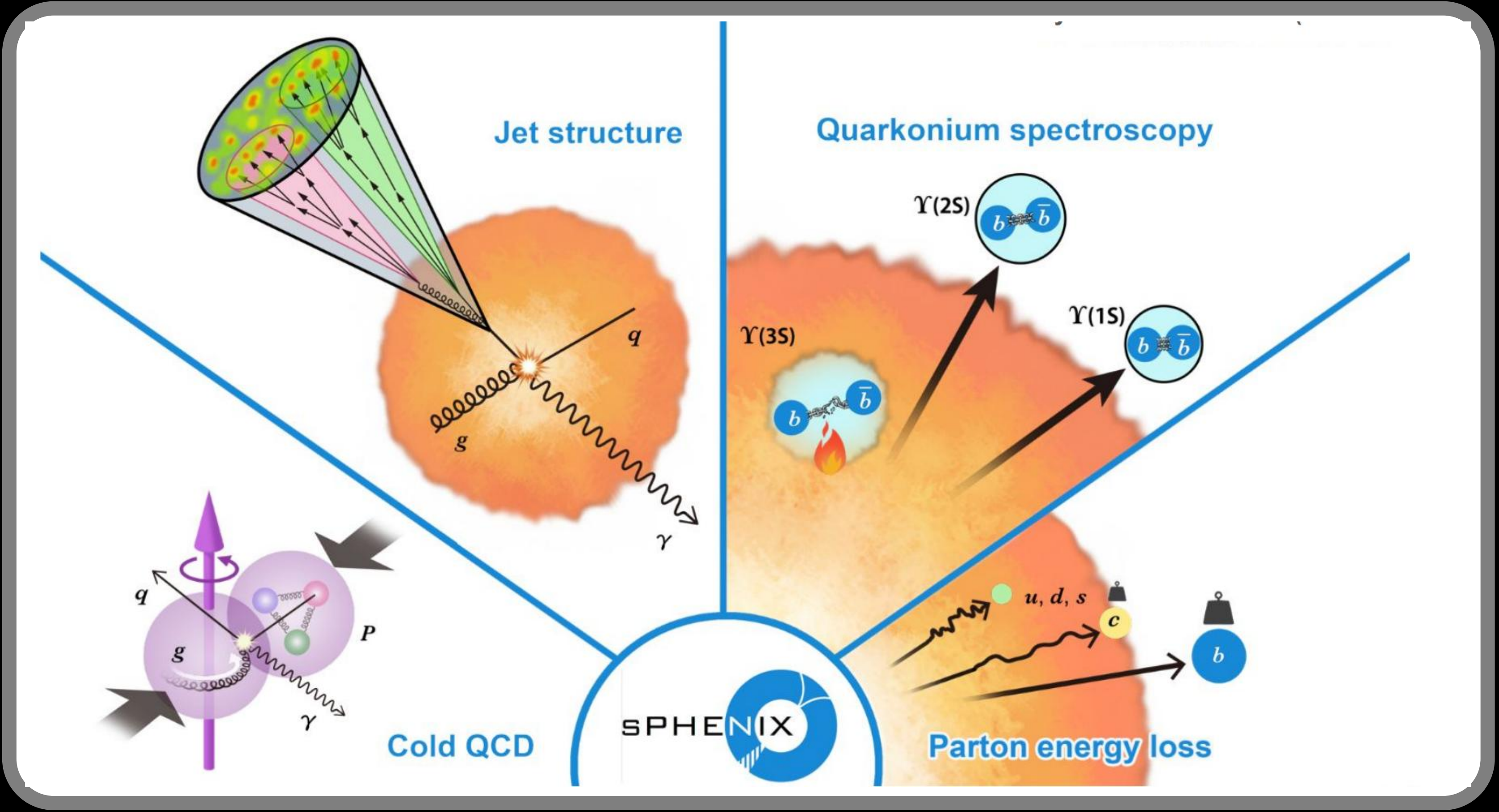
- Detector & data-taking
- Bulk measurements
- Jets
- Photons
- Heavy flavor

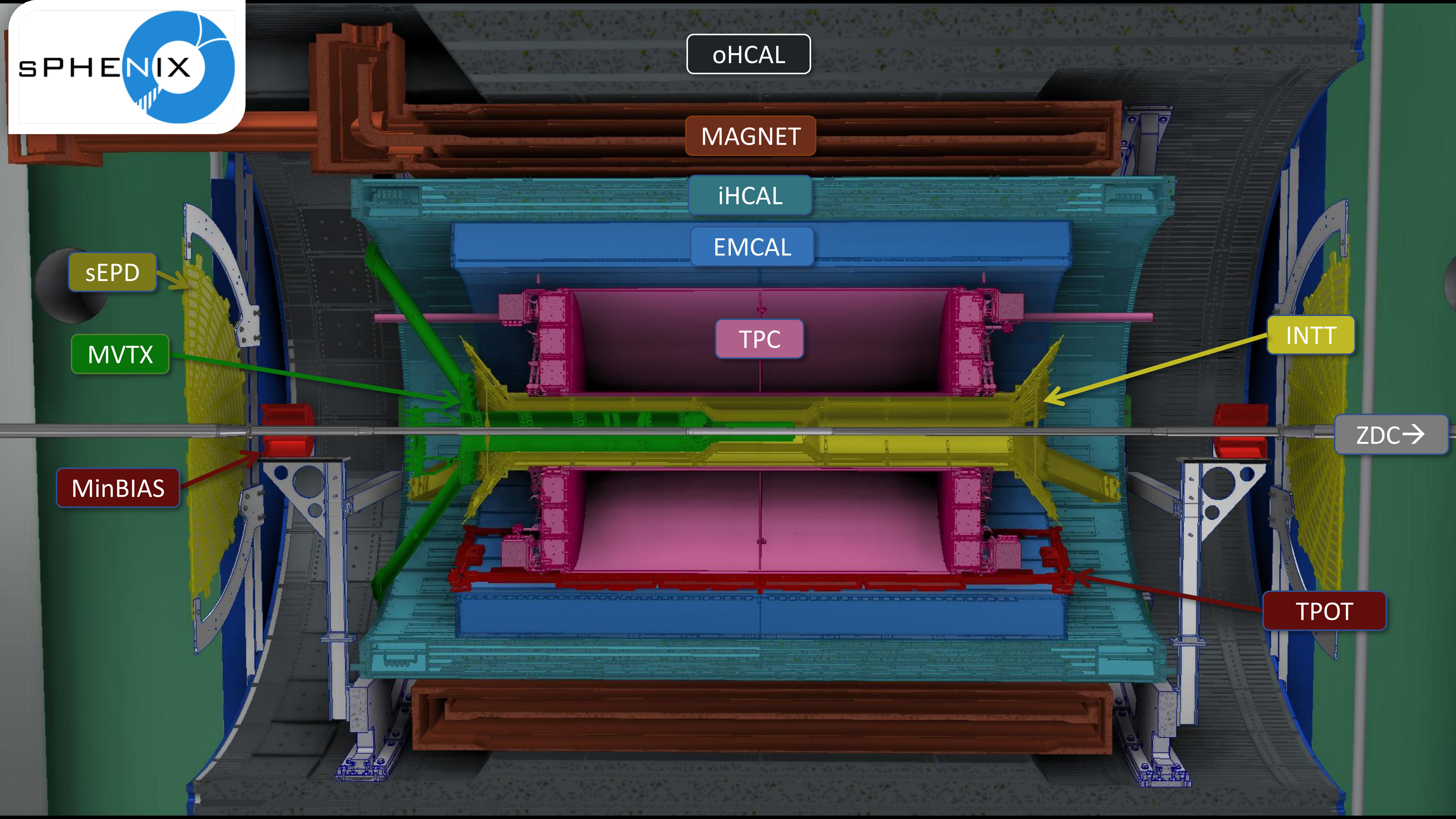
Motivation for sPHENIX

- Study high-pT and heavy probes of the quark gluon plasma

<u>What this requires</u>

- QGP (Au+Au) and a reference (p+p)
- Powerful DAQ and trigger system
- Large acceptance in η and ϕ
- Acceptance for hadrons and EM particles
- Precision tracking





oHCAL
MAGNET
iHCAL
EMCAL
sEPD
TPC
MVTX
INTT
ZDC→
MinBIAS
TPOT

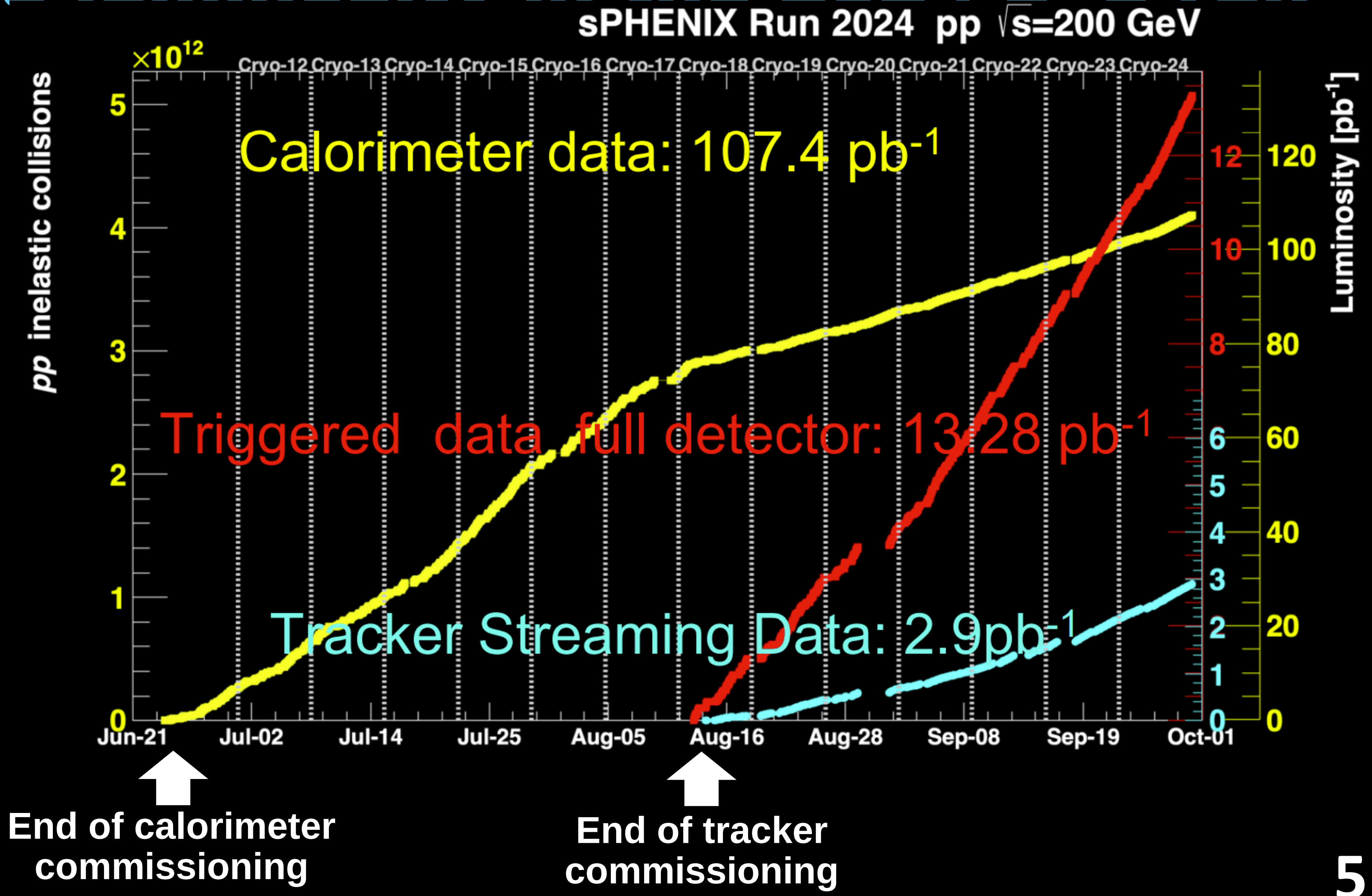
Sampled luminosity in the 2024 p+p run

<u>2023</u>
Au+Au commissioning

<u>2024</u>
p+p physics

Au+Au commissioning

<u>Upcoming</u>
7 nb^{-1} Au+Au



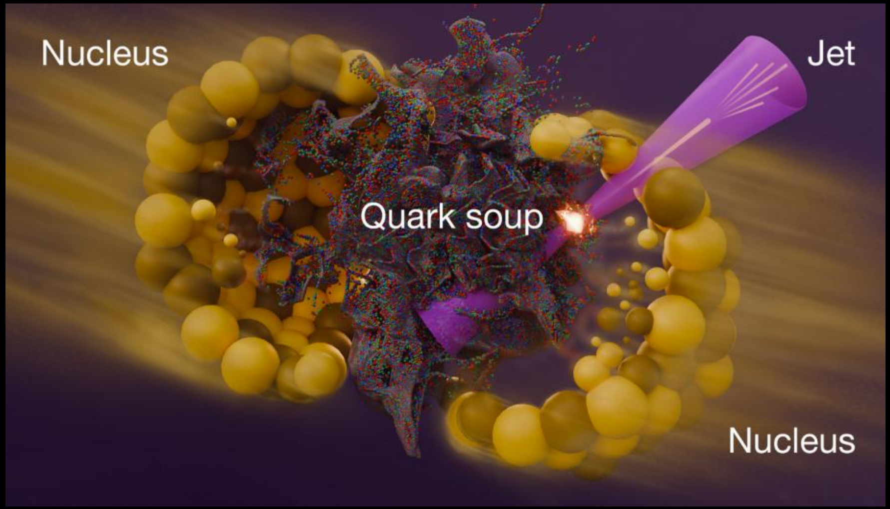
Overview

- Detector
- **Bulk physics measurements**
- Jets
- Photons
- Heavy flavor

Bulk physics measurements

Motivation

- Energy deposition in heavy ion collisions measures
  - collision geometry,
  - gluon shadowing
  - saturation
- sPHENIX is expected to match previous experiment's measurements of $dE_T/d\eta$ or $dN_{ch}/d\eta$
- These first sPHENIX serve as standard candles to evaluate calorimeter calibrations, pixel efficiency, centrality calibration..

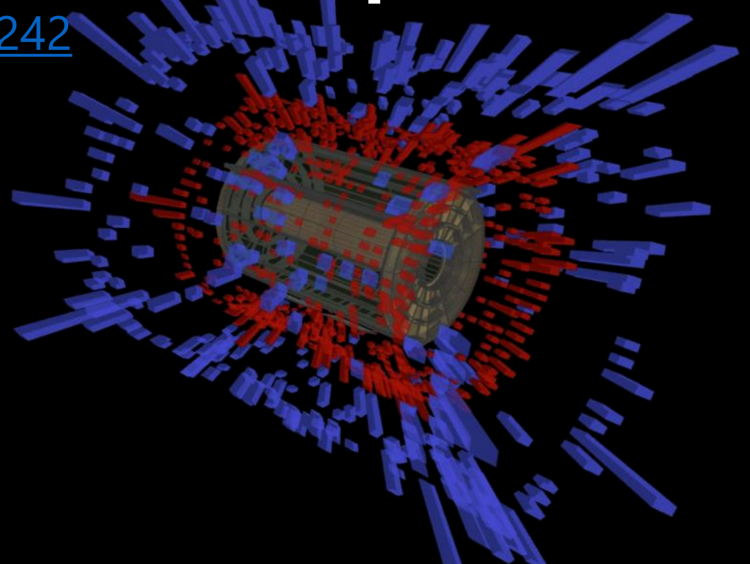


$dN_{ch}/d\eta$ in Au+Au

arXiv:2504.02240

Calorimeter $dE_T/d\eta$ in Au+Au

arXiv:2504.02242



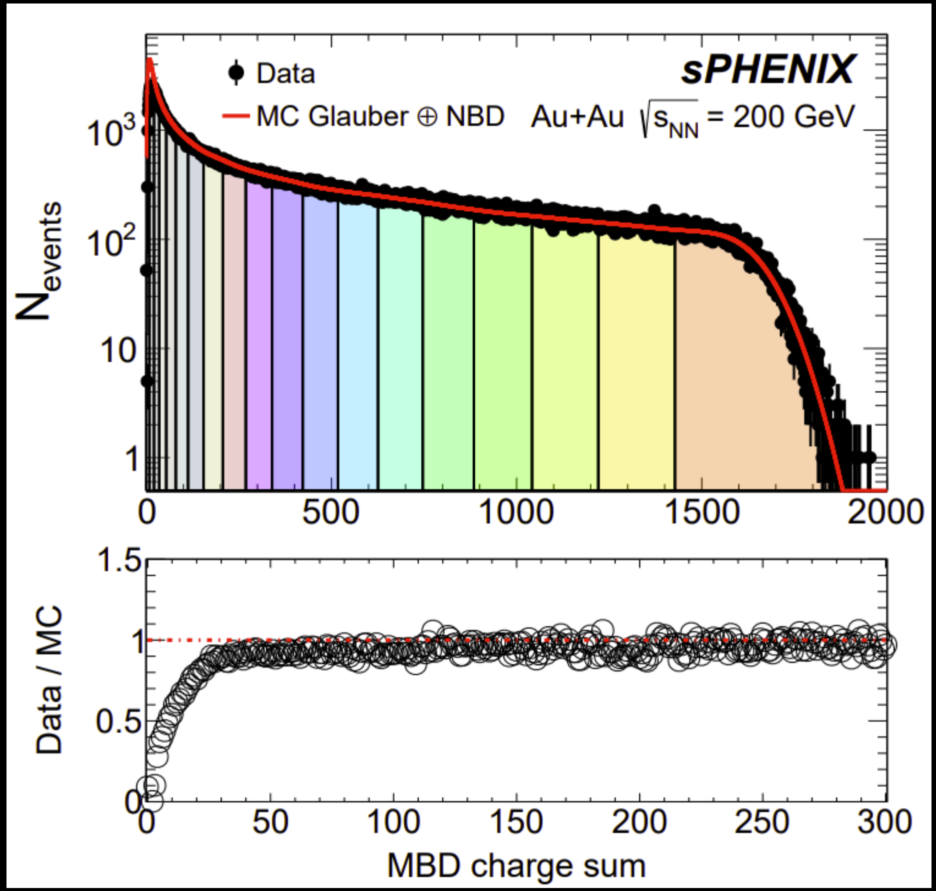
Event selection and global detectors

Minimum Bias Detector (MBD)

- Cherenkov tubes
- Trigger
- O(0.1ns) timing → vertex z measurements
- Centrality

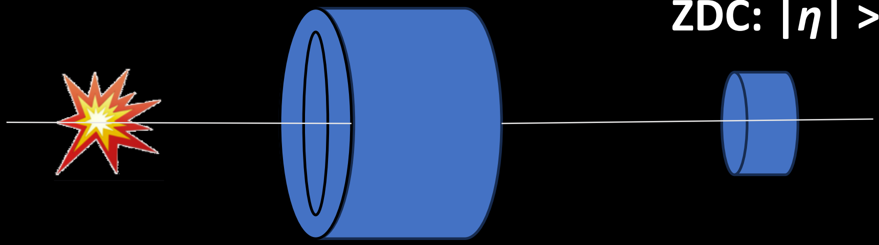
Zero Degree Calorimeter (ZDC)

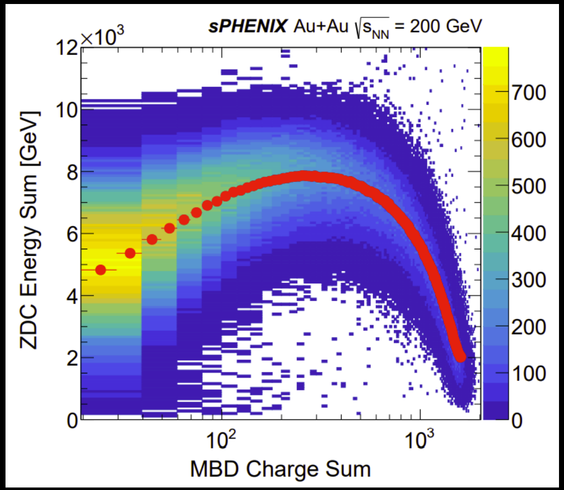
- Cherenkov fiber sampling calorimeter
- Event selection to remove backgrounds



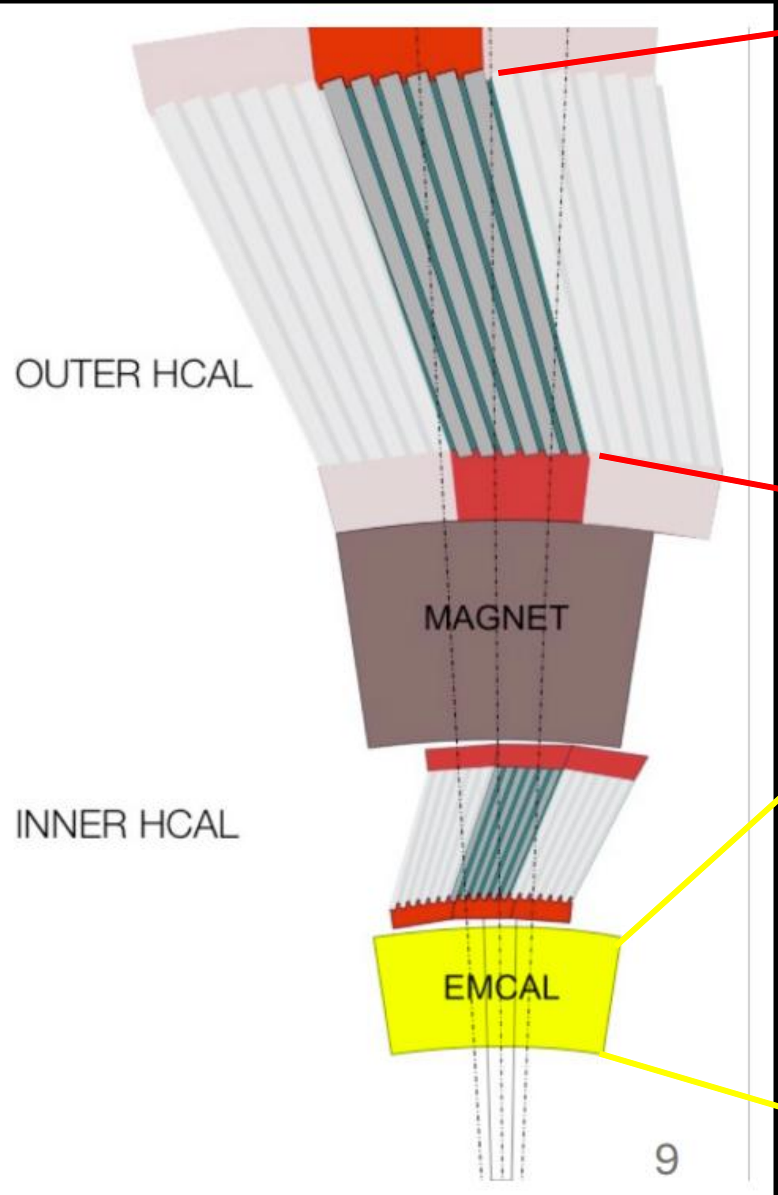
MBD: 3.51 < |η| < 4.61

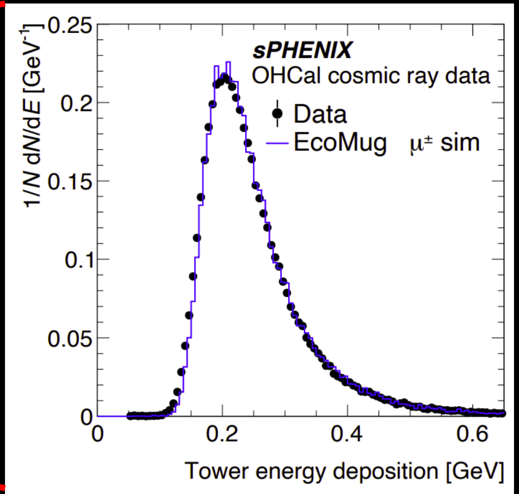
ZDC: |η| > 6





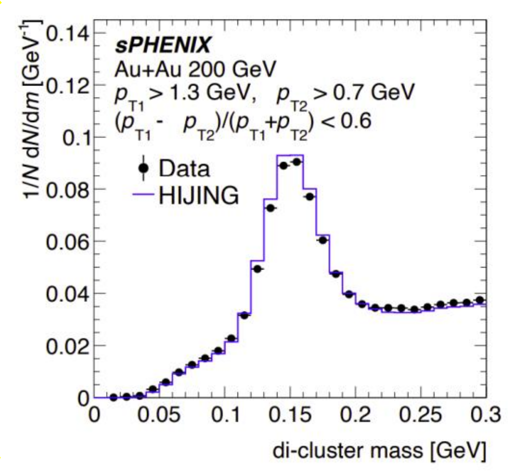
Calorimetry





HCal

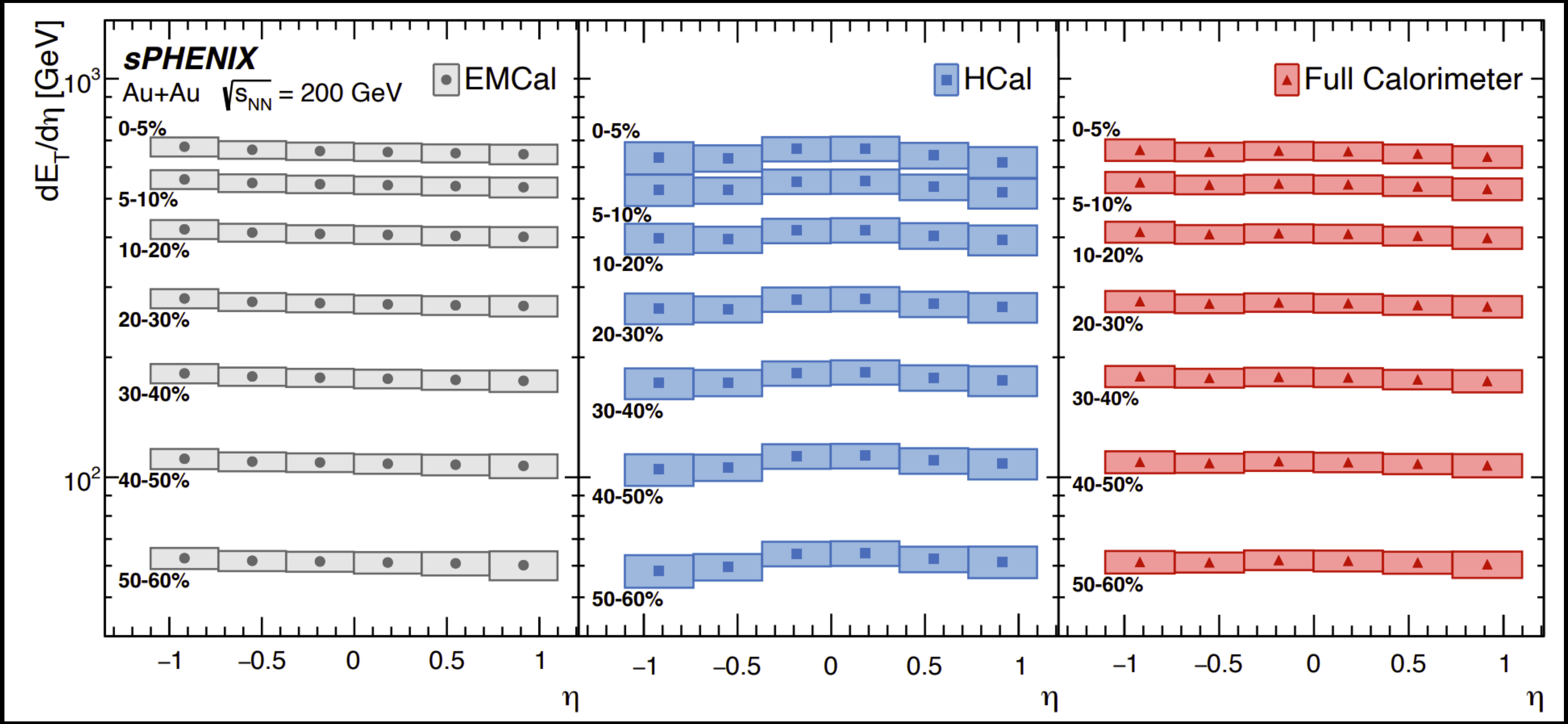
- $\Delta\phi$x$\Delta\eta$: 0.1x0.1
- Steel-plate scintillating-tile sampling calorimeter
- Projective geometry
- Calibration: compare measured MIP peak from cosmic ray muons in data to simulation

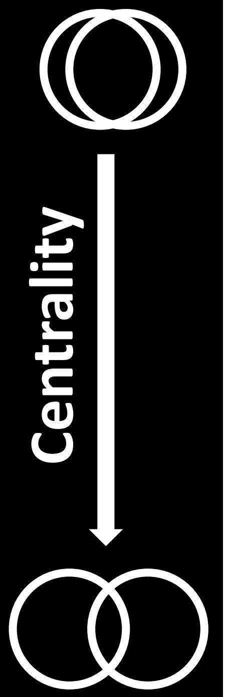


EMCal

- $\Delta\phi$x$\Delta\eta$: 0.025x0.025
- Tungsten-scintillating fiber sampling calorimeter
- Projective geometry
- Calibration: $\pi^0\rightarrow\gamma\gamma$ mass peak to match between data and simulation

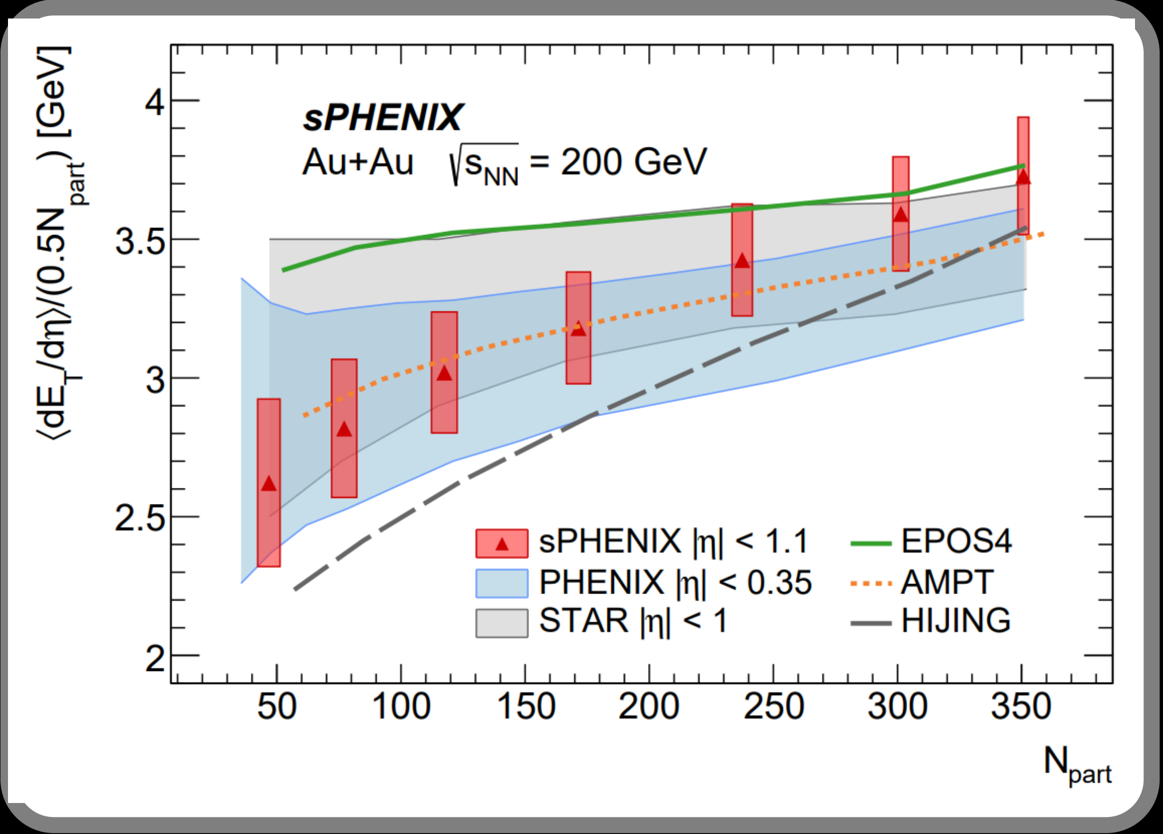
$dE_T/d\eta$ in Au+Au collisions





- **Excellent consistency between EMCal and HCal**
  - sensitive to energy deposit from different particle species
  - Excellent cross check of calibrations

$dE_T/d\eta$ in Au+Au collisions

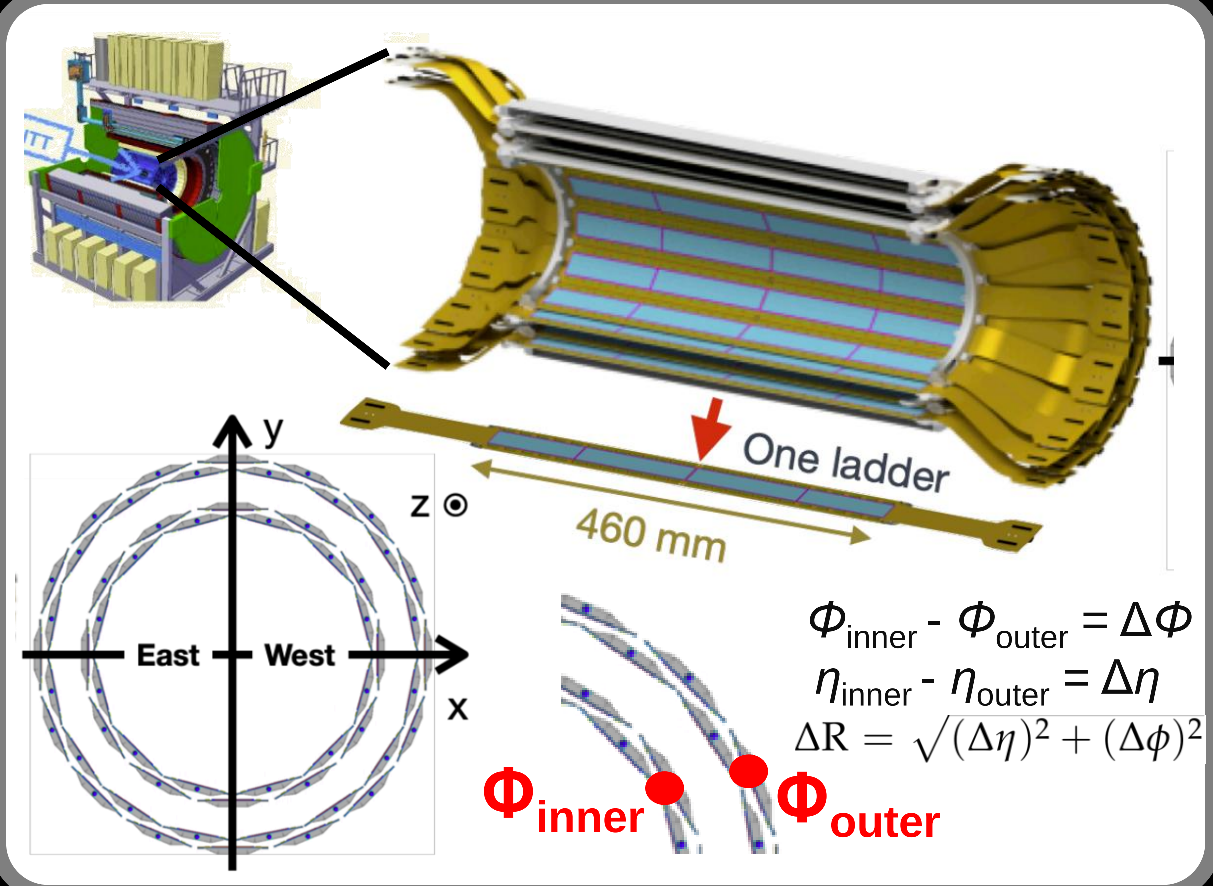


arXiv:2504.02242

- ➢sPHENIX measurement is consistent with previous RHIC results
- ➢improved precision in peripheral collisions
- ➢AMPT best describes the sPHENIX dET/dη measurement

INTT - INTermediate silicon Tracker

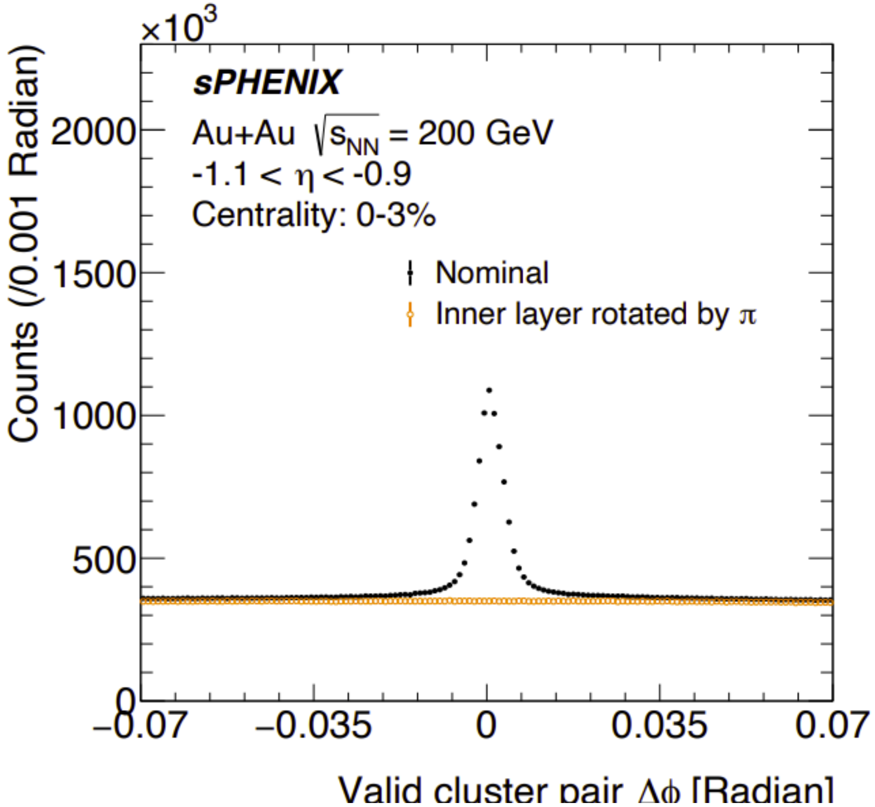
- **Silicon Semiconductor Strip Detectors**
  - 78 μm x 16 or 20 mm
- **56 staves/2 layers**
  - 7 < r < 11 cm, |η| < 1.1, full φ
- **Precision Timing + Hit Interpolation**
  - <u>O(100 ns) - resolves bunch x-ing</u>
  - O(10 μm) resolution in r-φ
  - O(1 cm) resolution in z

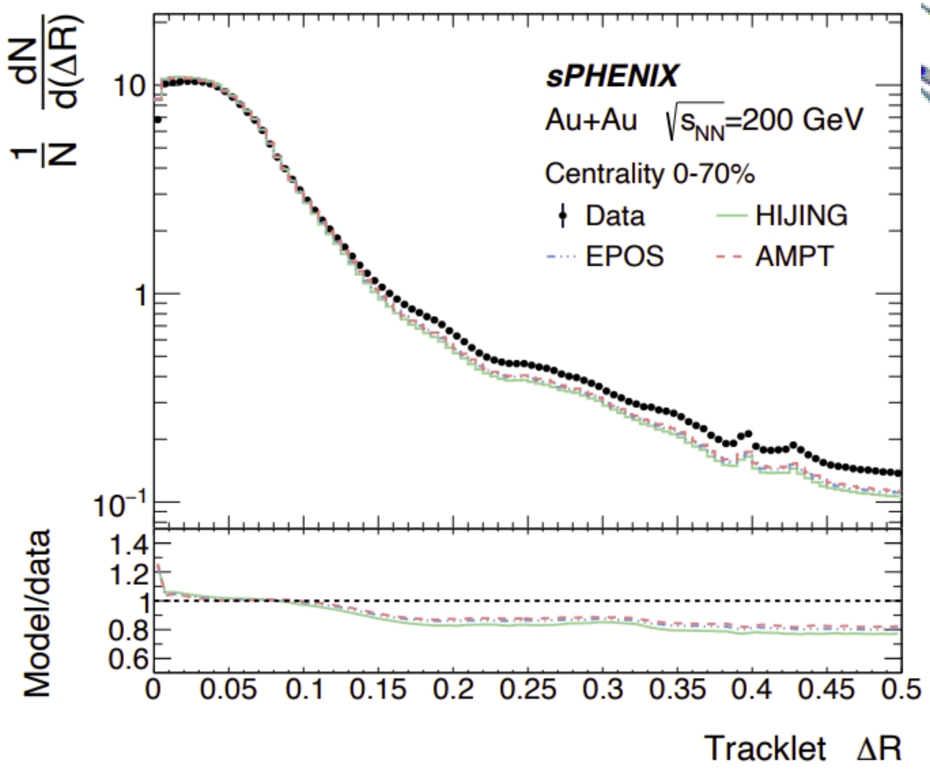


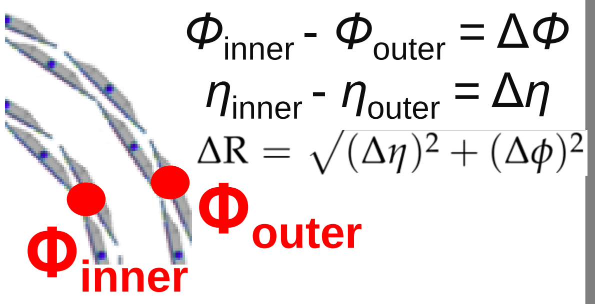
The 2-layed INTT is used for tracklet reconstruction to measure dN_{ch}/dη

dN_{ch}/dη in Au+Au collisions

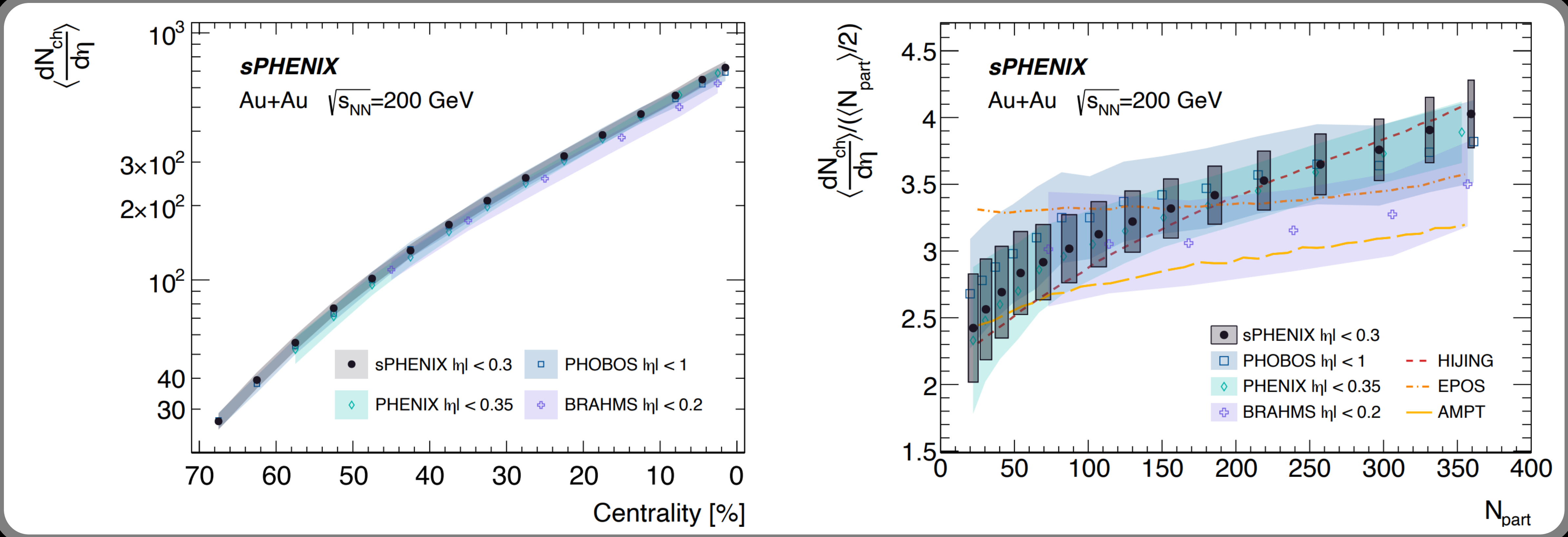
- **Two analysis methods to count tracklets, cluster pairs that point back to the event vertex in events with no magnetic field**
  - The combinatoric method - closely follows the PHENIX/PHOBOS measurement
  - The closest-match method - adapted from the CMS measurements







$dN_{ch}/d\eta$ in Au+Au collisions



arXiv:2504.02240

- ➢The sPHENIX measurement is consistent with previous RHIC publications.
- ➢HIJING best describes the sPHENIX dNch/dη measurement

Overview

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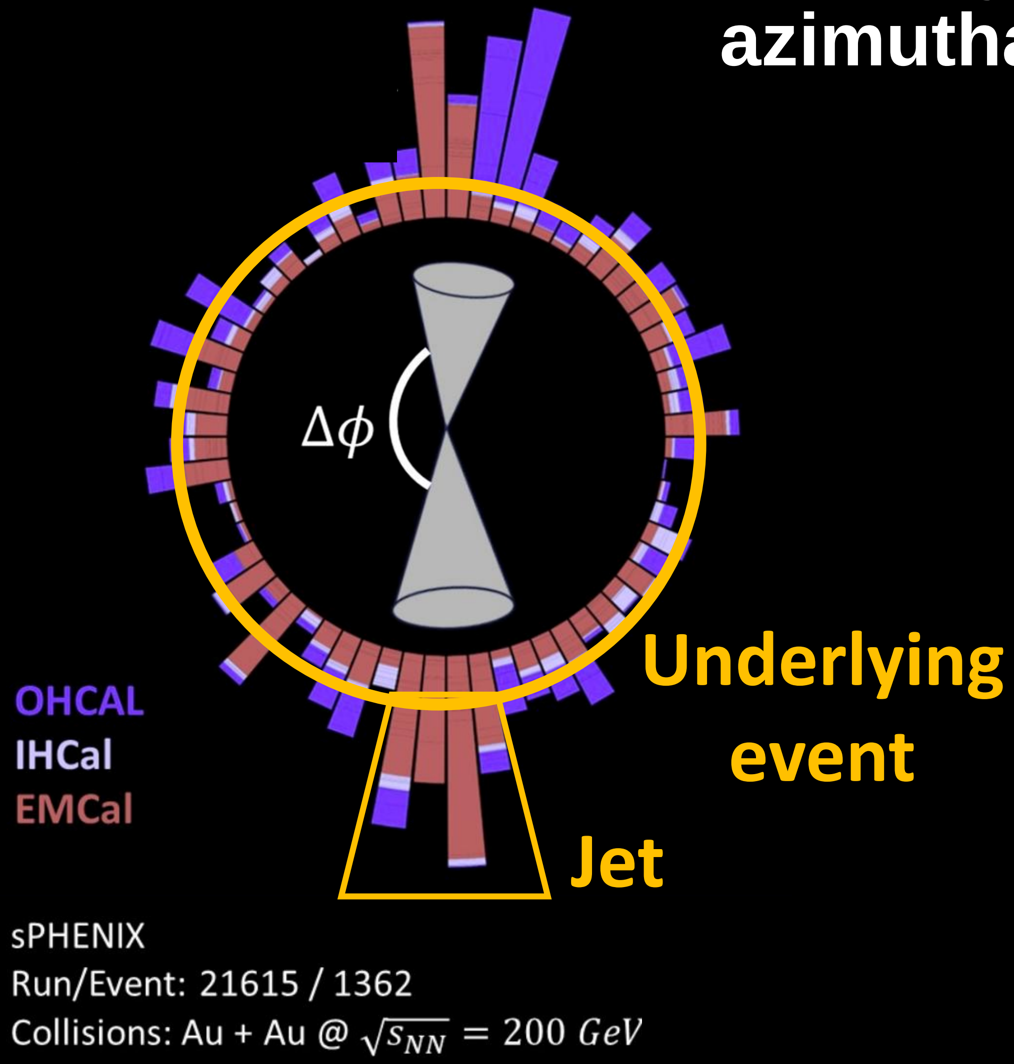
- Bulk measurements
- Jets
- Photons
- Heavy flavor

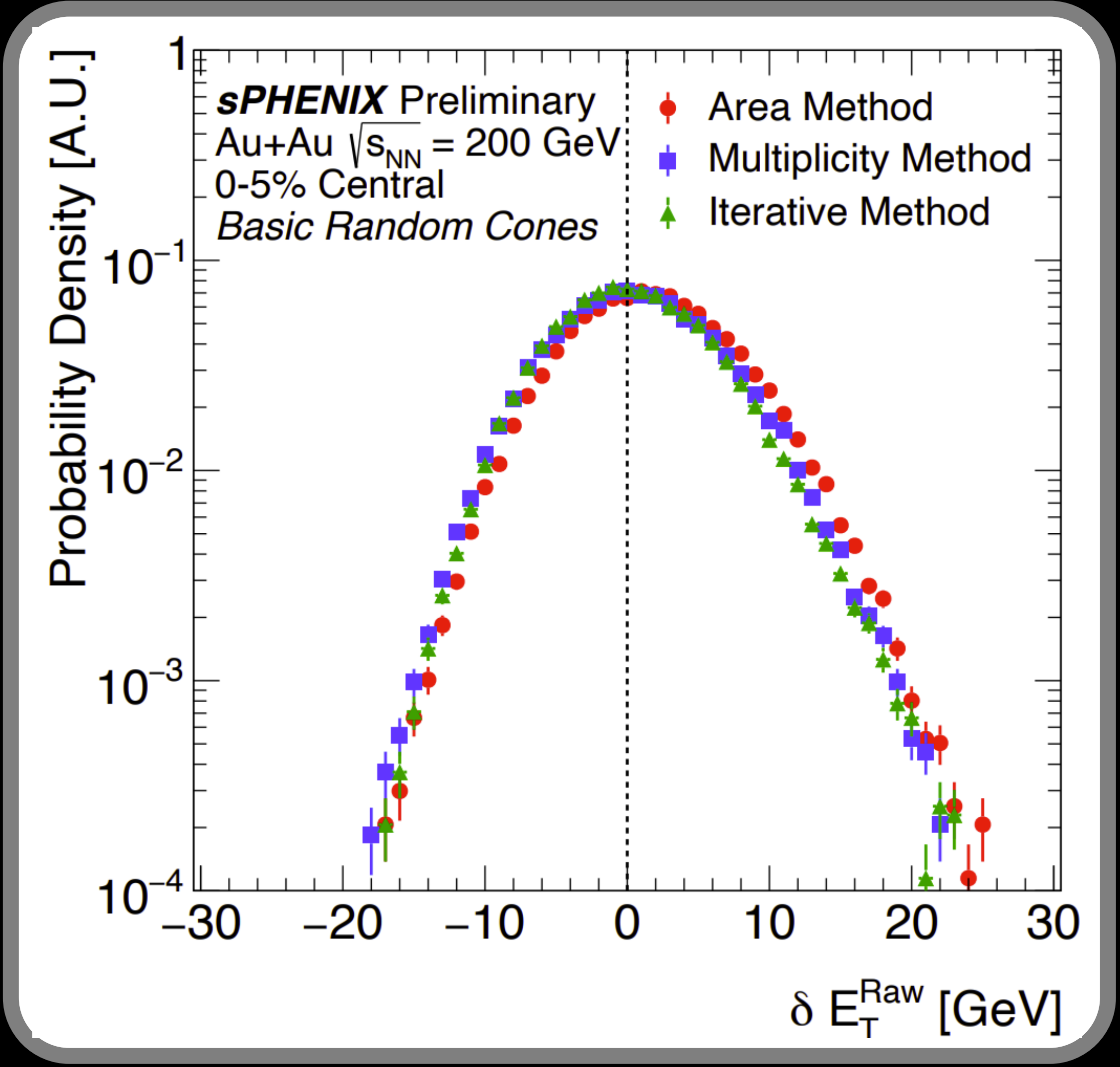
Underlying event (UE) in Au+Au



In heavy ions, jets sit on top of a fluctuating azimuthally-modulated underlying event

- **Local fluctuations in the UE drive the jet energy resolution**
- **Proper understanding of UE is needed for understanding jet performance**
- **UE has been quantified in different ways**
  - Area: subtracts the average energy (ALICE)
  - Multiplicity: subtracts based on jet constituent multiplicity (new : Phys. Rev. C, 108(2):L021901)
  - Iterative: subtracts mean energy from towers, estimated with surrounding towers removing areas from jets (ATLAS)

Underlying event subtraction techniques



- **Fluctuations quantified by placing cones with R = 0.4 randomly in minimum bias events and measuring E_T after UE subtraction**
- **Three methods yield similar results, with slightly smaller fluctuations in iterative method**
- **Distributions are centered around 0 → successfully subtracted UE!**

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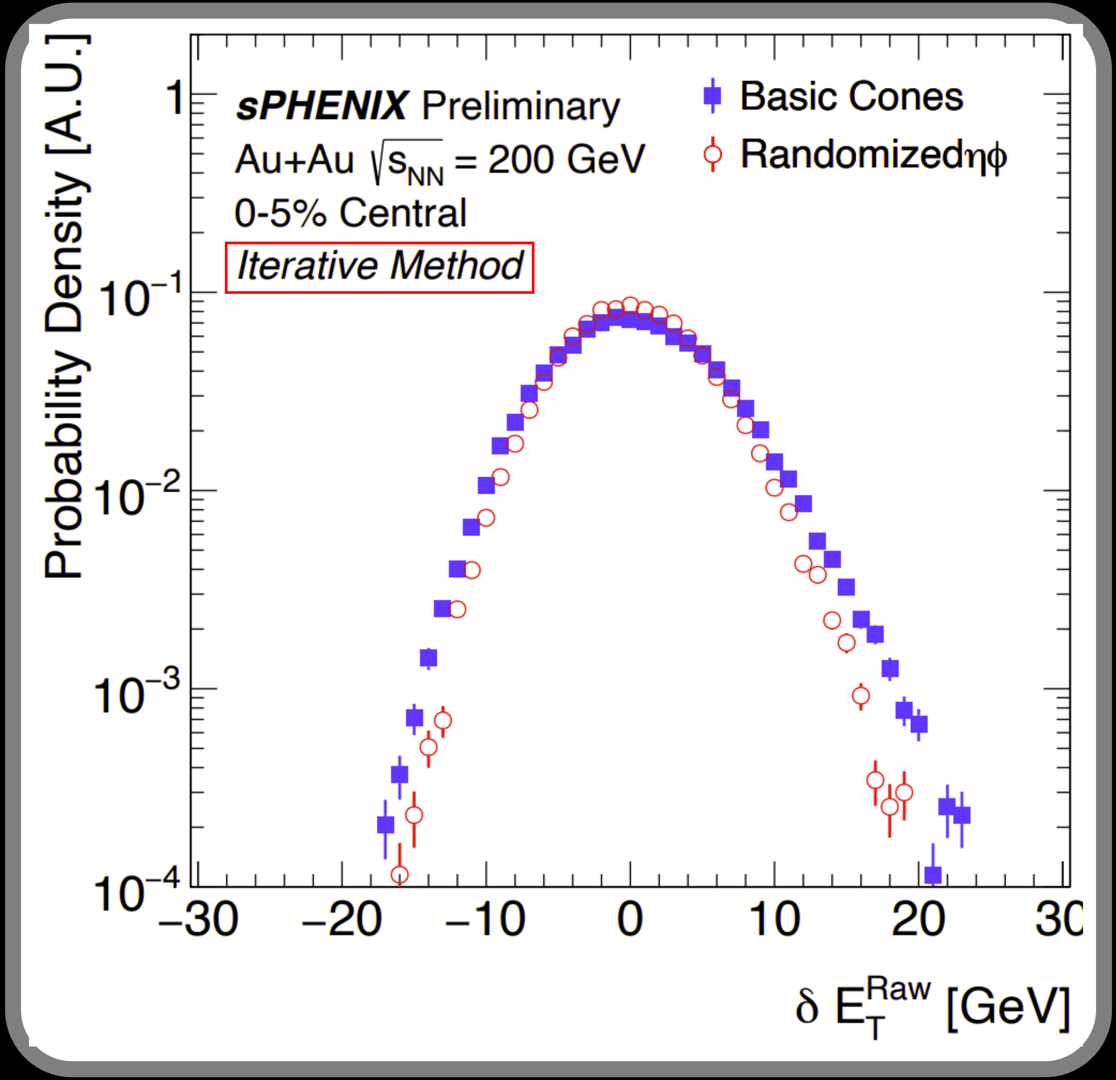
Underlying event fluctuations in Au+Au

Procedure

➢**Random cones**

➢**Randomized**

1. Randomize tower positions
2. UE subtraction
3. Random cones



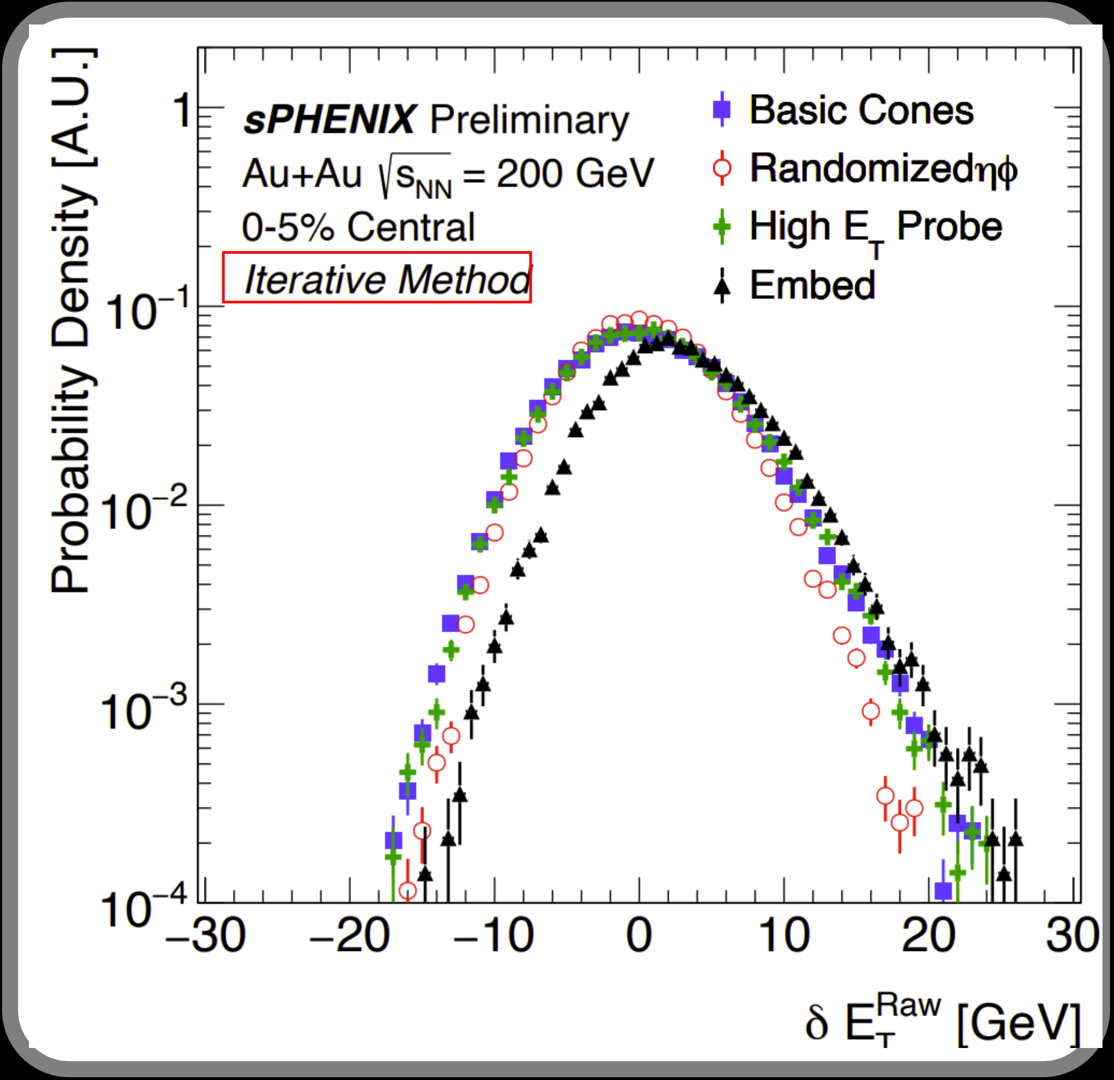
➢**Correlated fluctuations**

Underlying event fluctuations in Au+Au

Procedure

- **Random cones**
- **Randomized**
  1. Randomize tower positions
  2. UE subtraction
  3. Random cones
- **Introduce single tower jets → does not impact UE estimation**
- **Introduce Pythia hard scattering**

- **Correlated fluctuations**
- **Non-zero residual UE with full Pythia dijet event**



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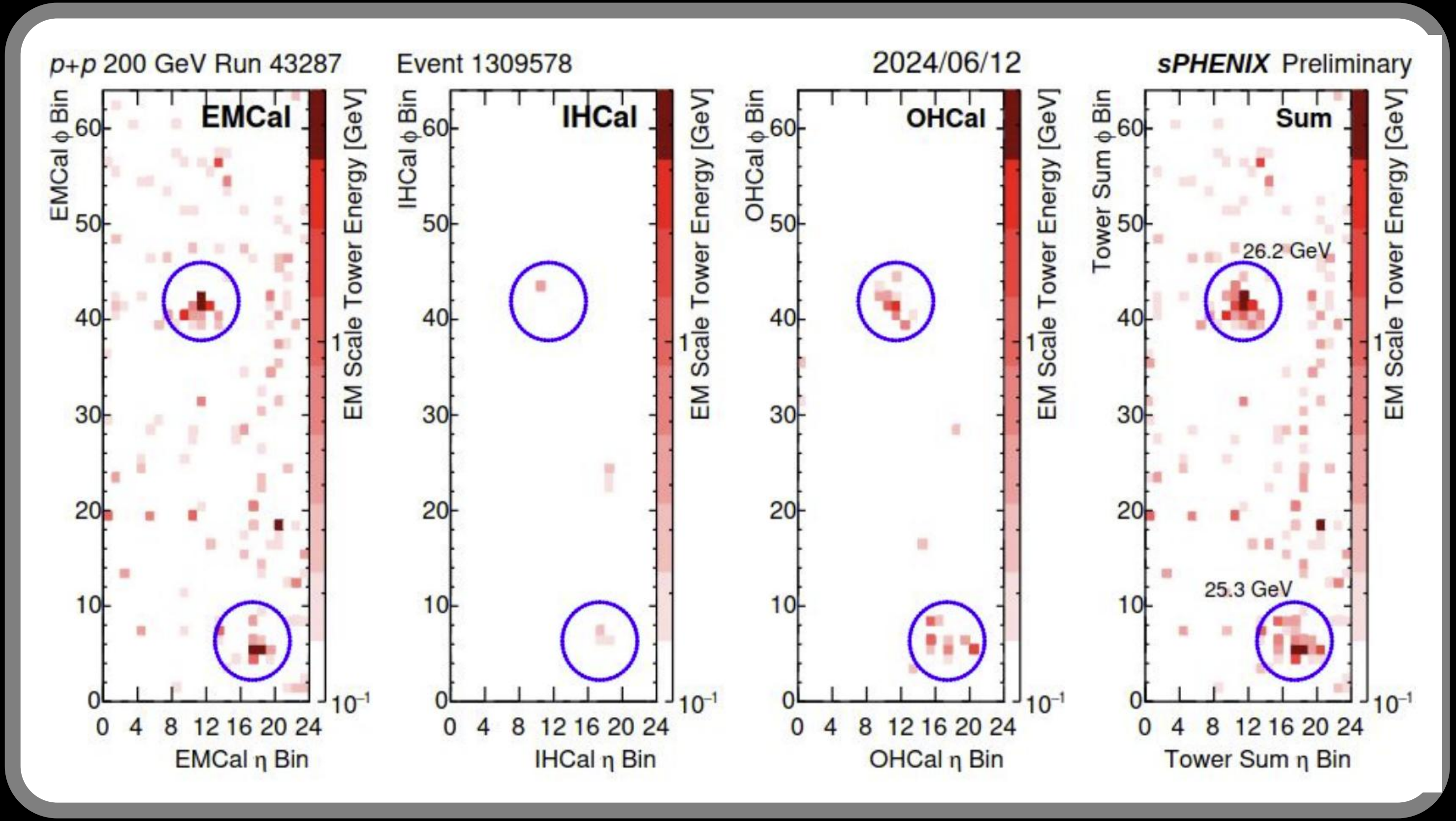
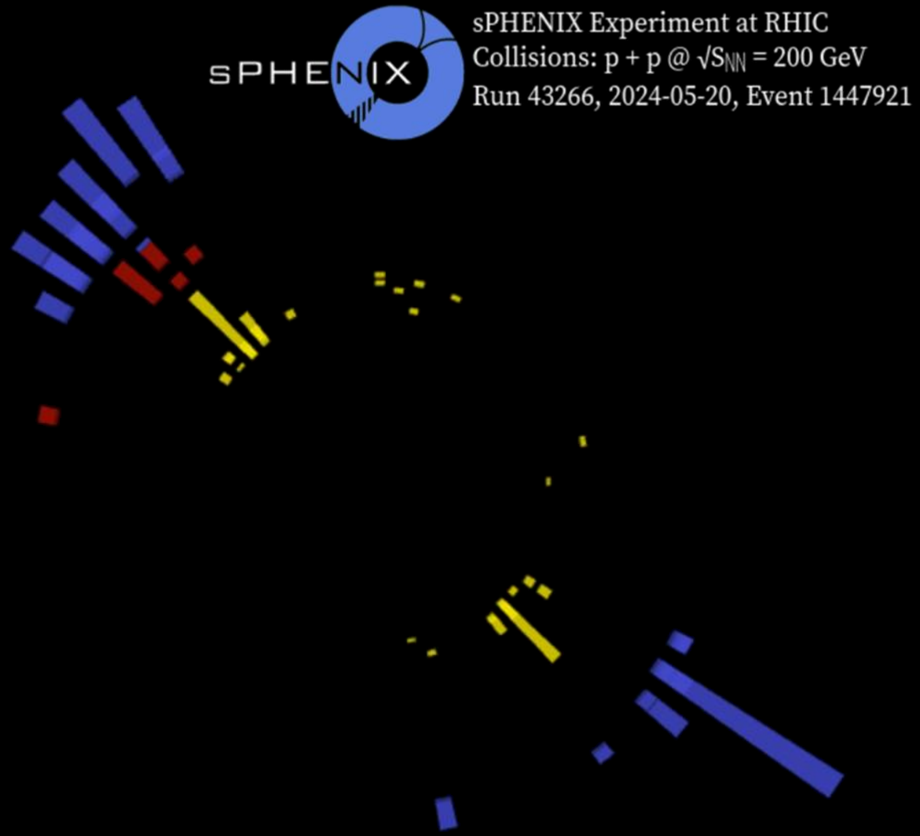
Au+Au commissioning data → p+p

Calorimetric jet measurements



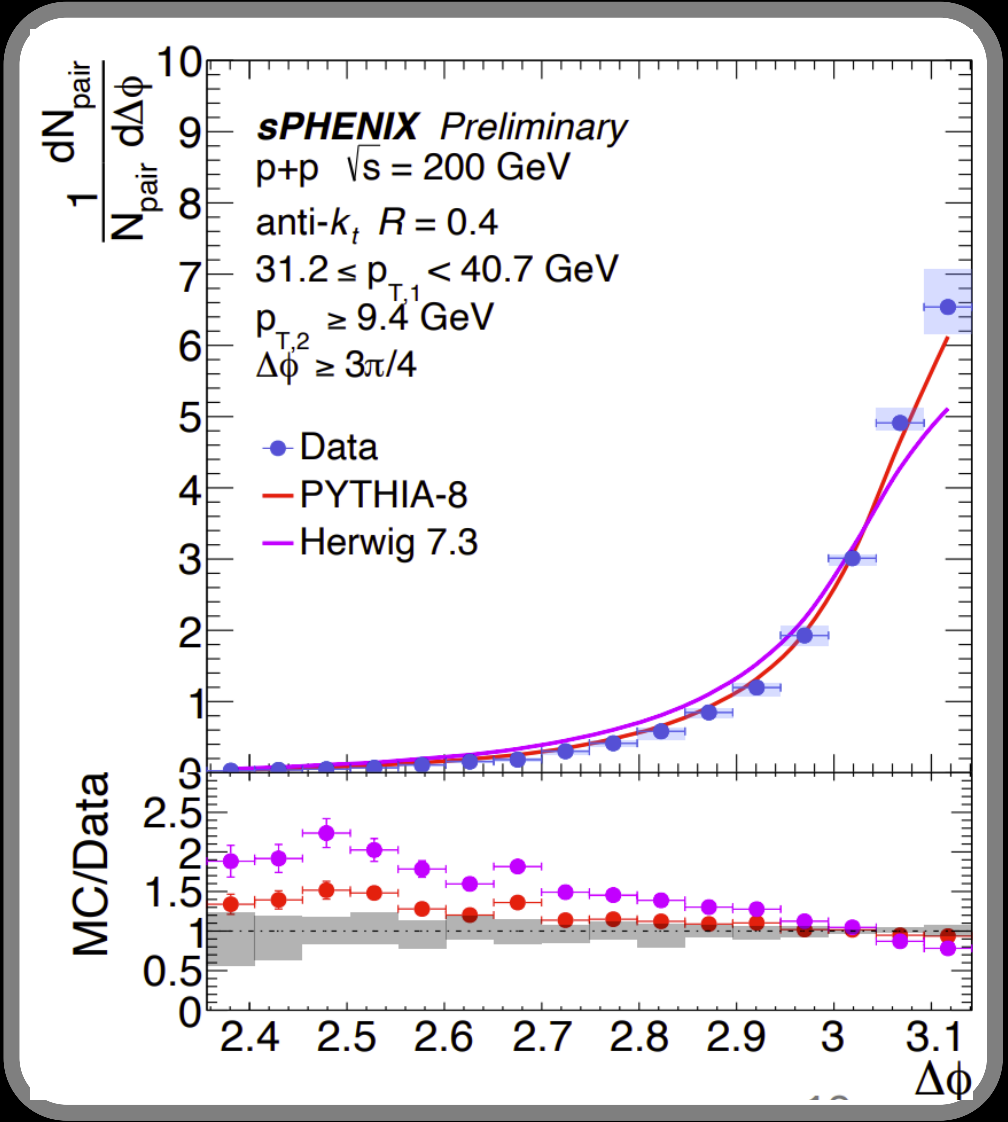


Dijets are useful for: jet calibration, understanding jet resolution, measurements of jet quenching in Au+Au collisions, …

Anti-k_T R=0.4 jets, clustered from massless calorimeter tower

Dijet Δϕ distributions

- Δϕ between jets corrected bin-by-bin based on truth to reco
- Pythia agree with data best in most back- to-back region
- Data more sharply peaked than Herwig simulations



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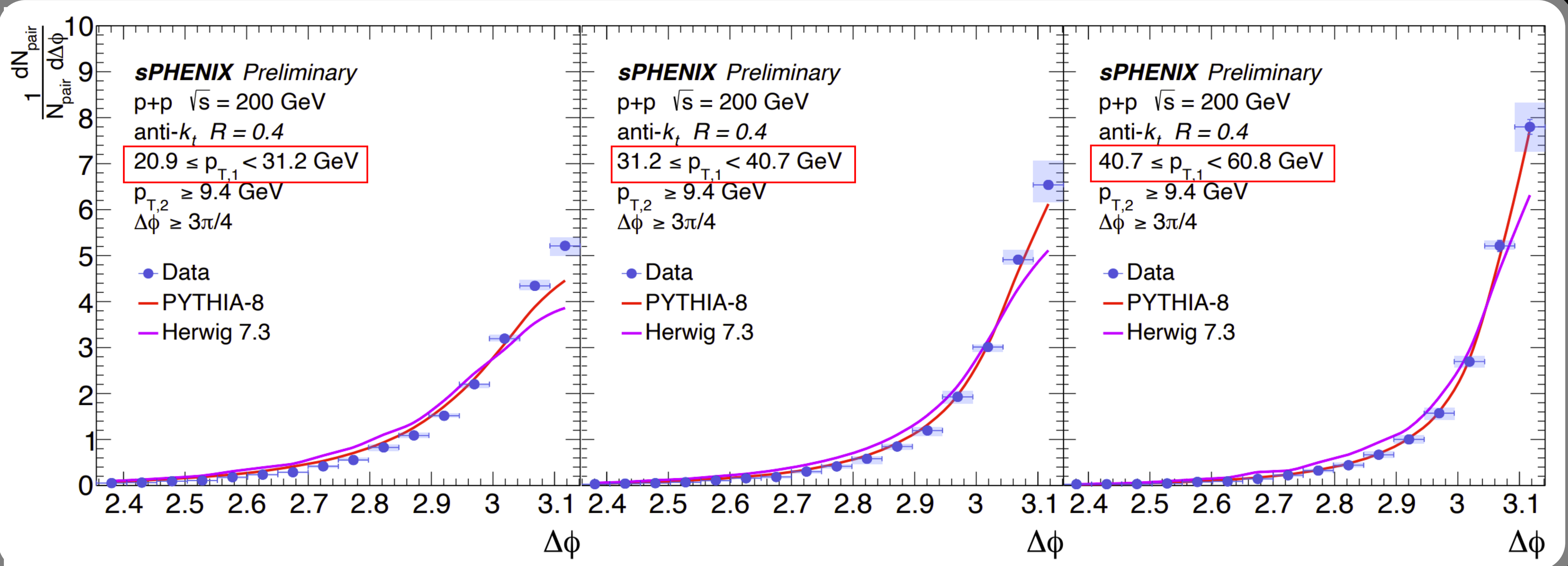
Dijet Δϕ distributions

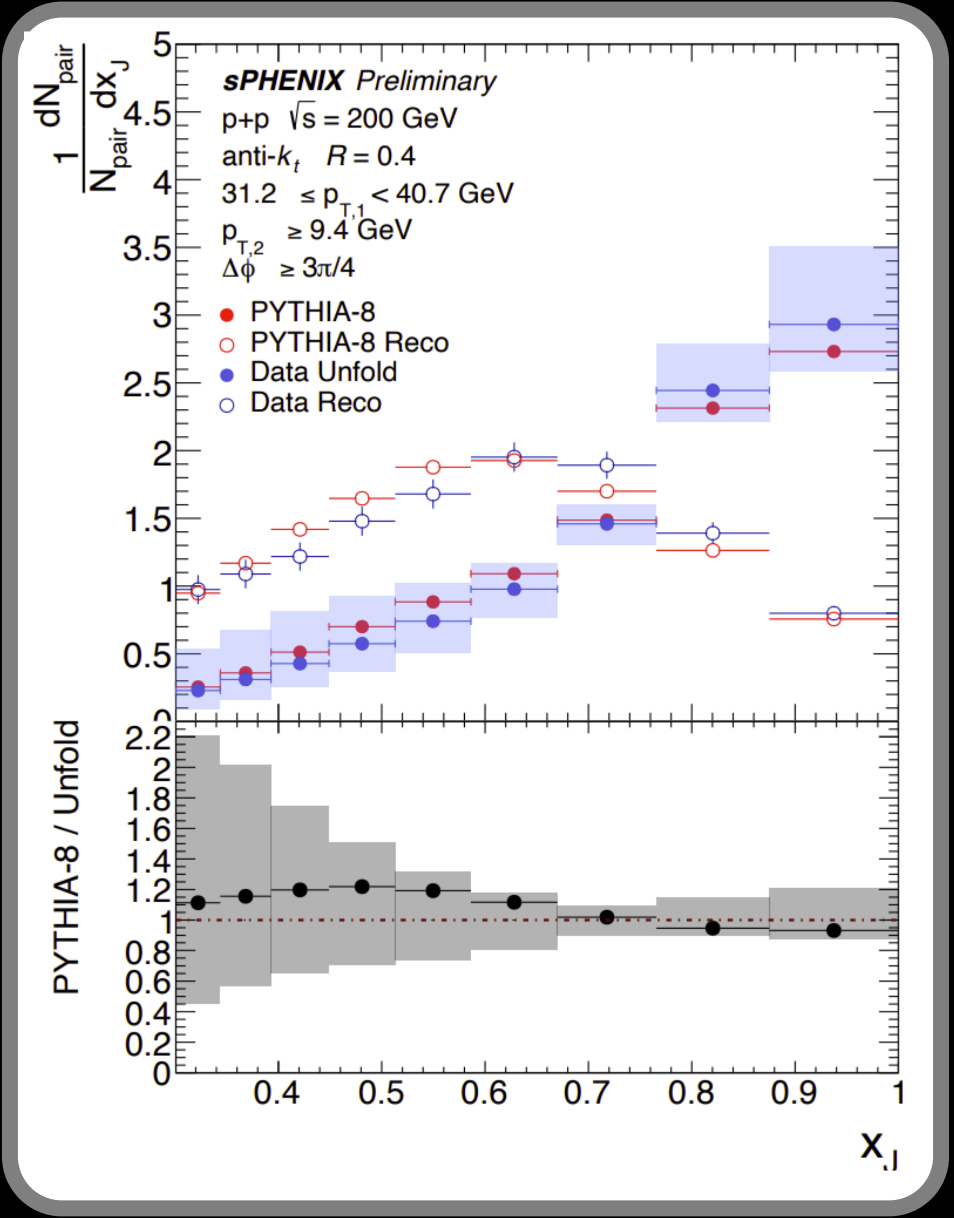


Raw and unfolded dijet x_J

$$x_J = p_{T,2}/p_{T,1}$$ Where p_{T1} is the leading jet

Analysis procedure

- Back-to-back jets are selected $\Delta\phi > 3\pi/4$
- Pythia + Geant4 similar to data at detector level (open markers)
- 2D unfolding in p_{T1} and p_{T2}
- Jet energy resolution dominates systematic uncertainty
- Pythia agrees with unfolded data within uncertainties



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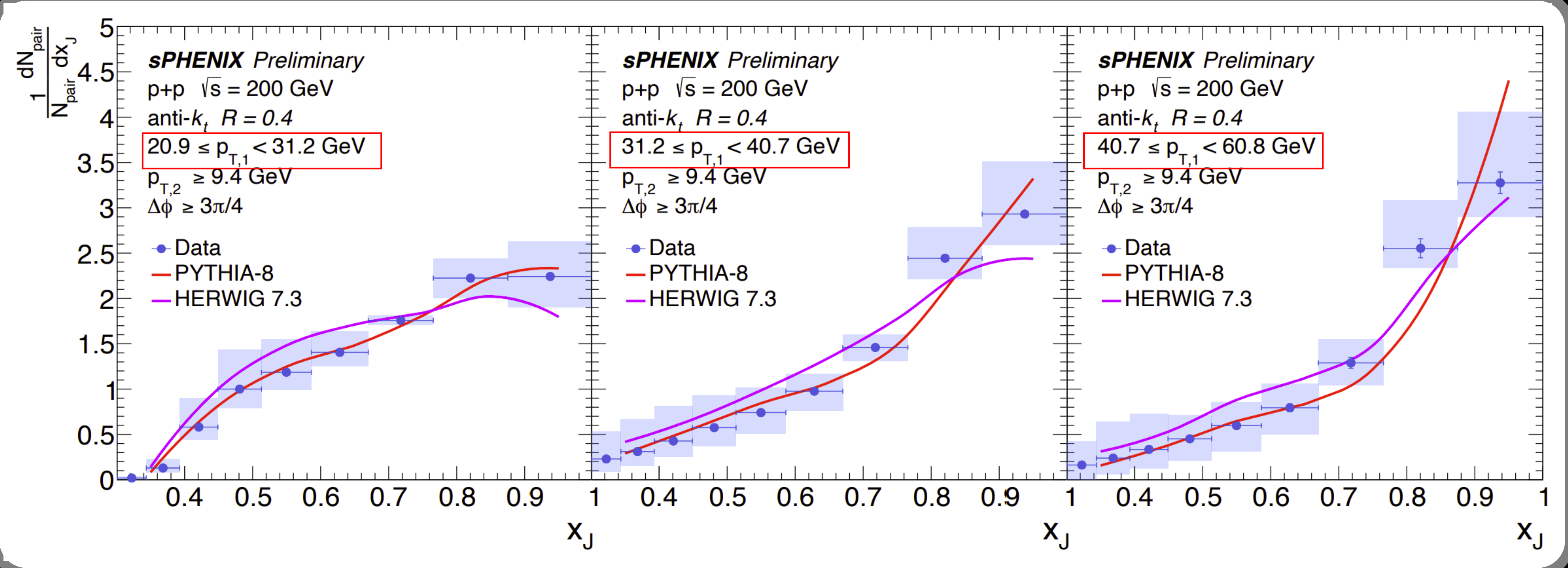
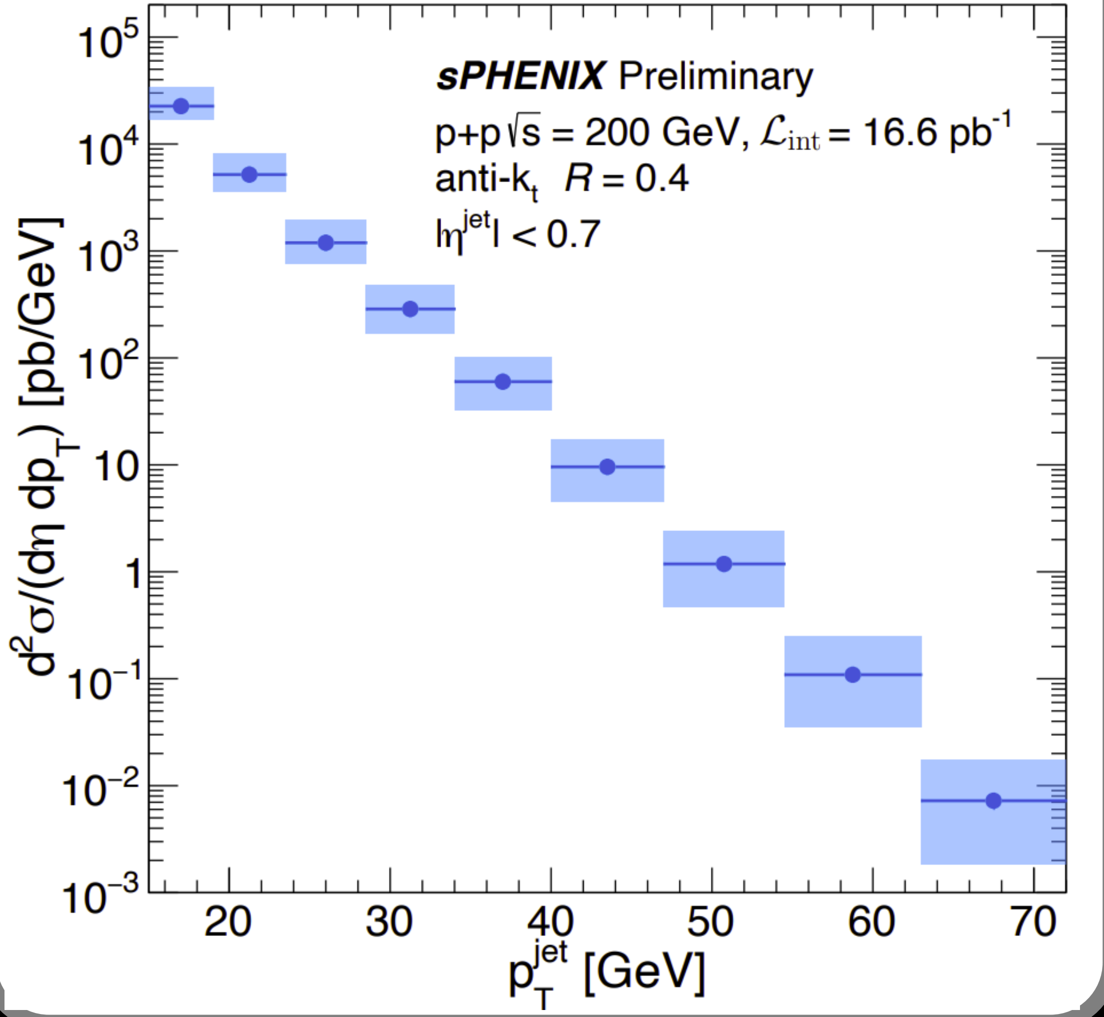
dijet x_J (all p_T)



Inclusive jet cross section in p+p



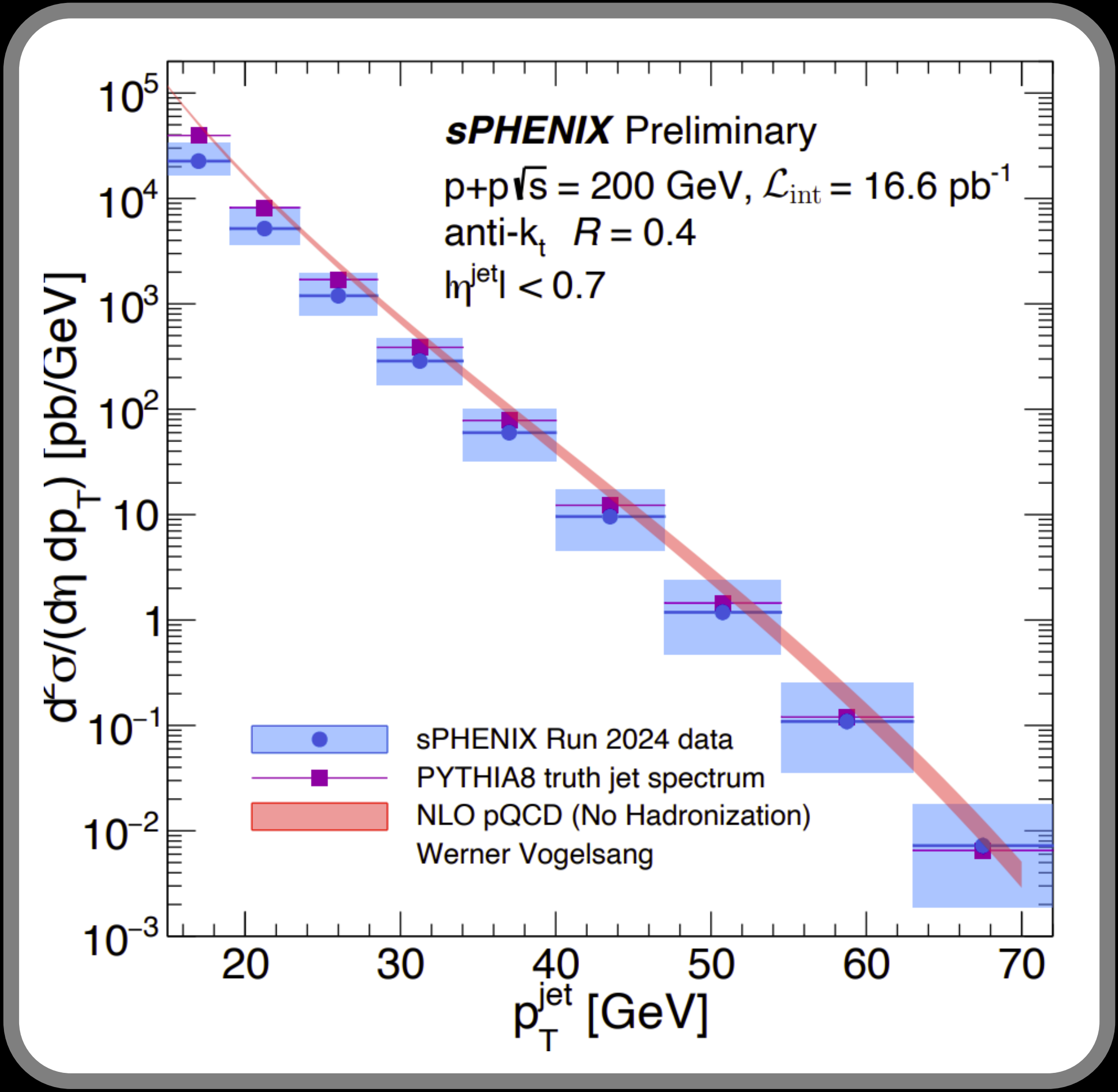
sPH-CONF-JET-2025-03

- Unfolded cross section of R=0.4 anti-k_t jets in p+p collisions
- Data corresponds to ~15% of total luminosity recorded in 2024
- Minimum bias event counting used for luminosity

Systematic uncertainty

- dominated by jet energy scale uncertainty on the hadronic response
- Expected to improve significantly with future in-situ hadronic shower studies

Inclusive jet cross section in p+p



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- Pythia8 Detroit tune agrees within uncertainties with data
- Comparison to NLO pQCD calculation
    - Calculation does not include hadronization

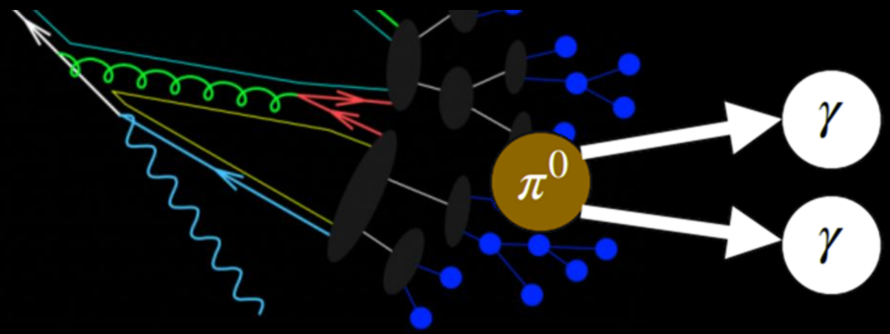
Overview

- Detector
- Bulk measurements
- Jets
- Photons
- Heavy flavor

Identified probes of the initial state

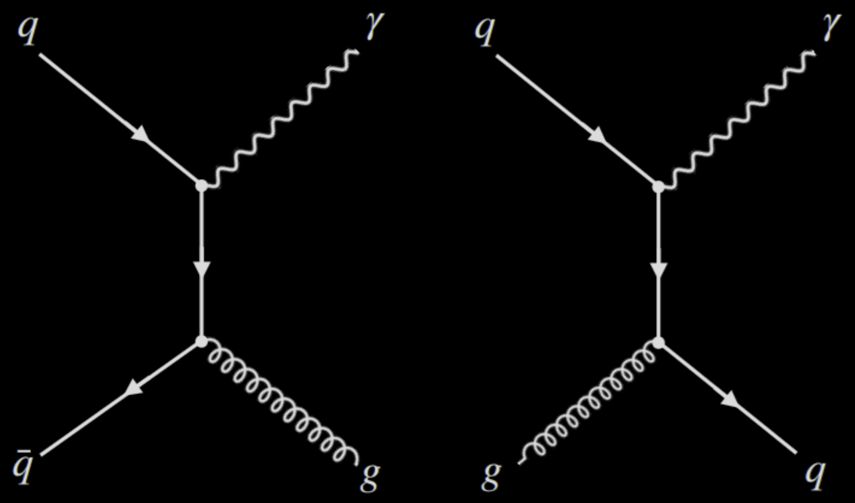
Neutral mesons

- ➢Input for PDF/TMDs & test for NLO pQCD
- ➢Used for calibration of the electromagnetic calorimeter

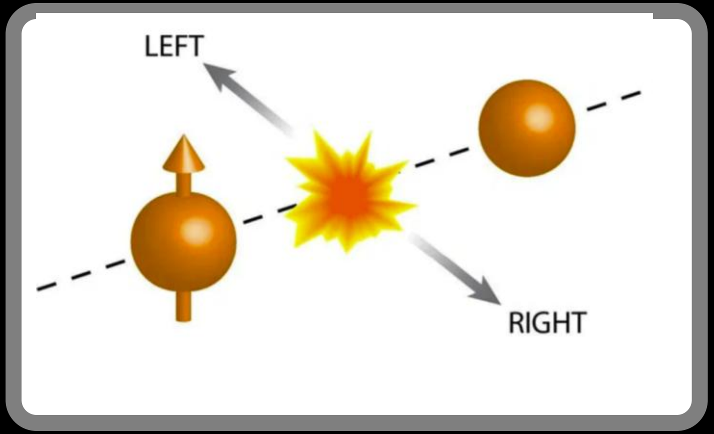


Direct photons

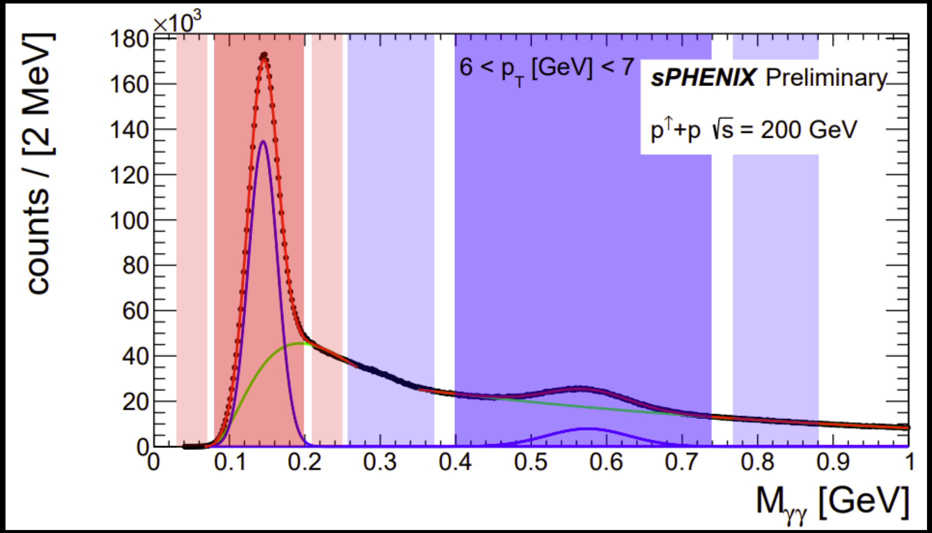
- ➢Primarily produced via hard scattering
  - Direct access to initial state PDFs
  - Measure of recoiling parton in studies of energy loss



Single-spin asymmetry

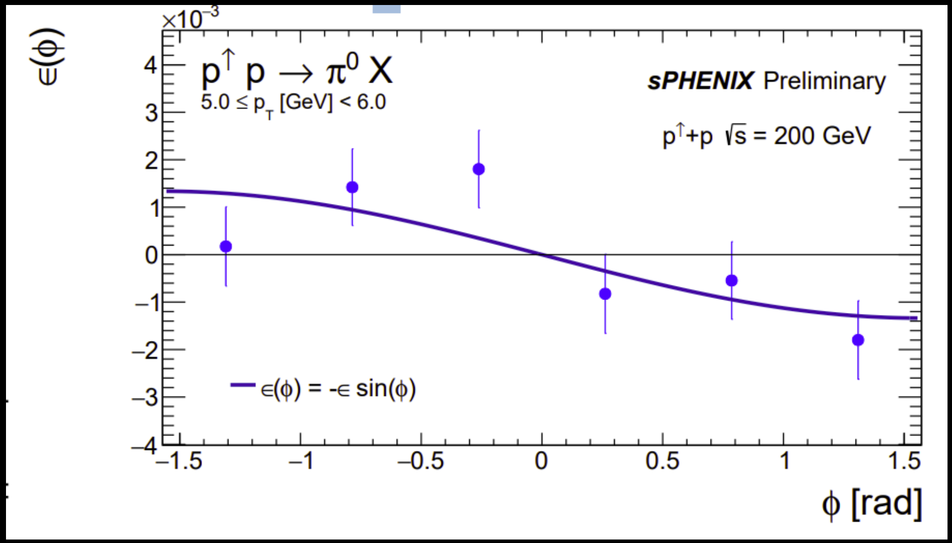


- Probe the spin structure, transverse momentum distributions, of the proton
- Use identified π^0 η in singly polarized collisions with EMCal



Calculate yields $N(\phi_{\gamma\gamma})$ in signal and bkg regions

$$\frac{\sqrt{N^{\uparrow}(\phi)N^{\downarrow}(\phi+\pi)}-\sqrt{N^{\downarrow}(\phi)N^{\uparrow}(\phi+\pi)}}{\sqrt{N^{\uparrow}(\phi)N^{\downarrow}(\phi+\pi)}+\sqrt{N^{\downarrow}(\phi)N^{\uparrow}(\phi+\pi)}}$$



Yield combinations as a function of $\phi_{\gamma\gamma}$

Fit with $\epsilon(\phi) = -\epsilon \sin(\phi)$

Final observable $A_N = \epsilon / P$

Transverse single-spin asymmetry

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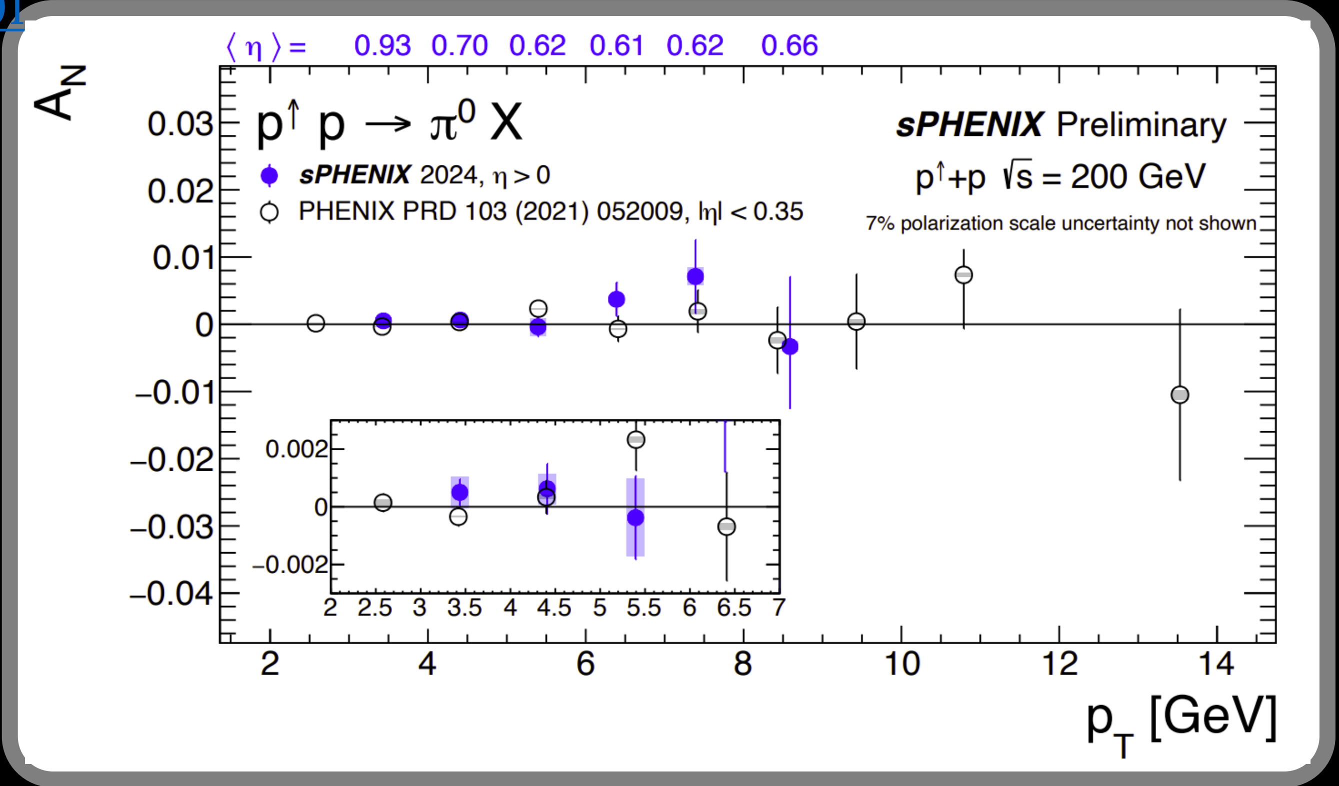
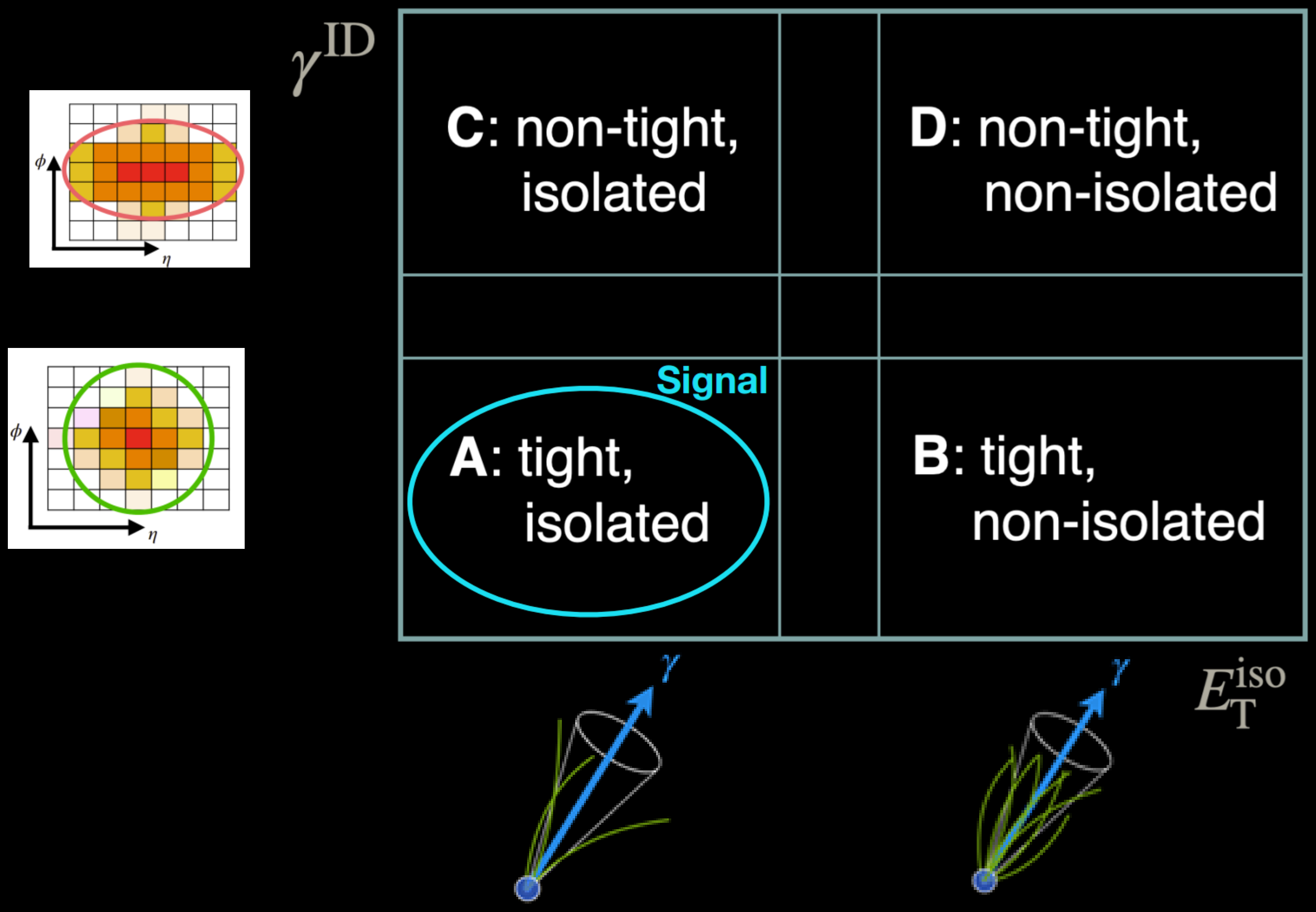
$$A_N \propto \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$



- ➢Compatible with zero and agreement with previous PHENIX results (35% of total luminosity used for sPHENIX)
- ➢With larger acceptance and the use of forward collision vertices, a wide range of rapidity differential measurements are possible.

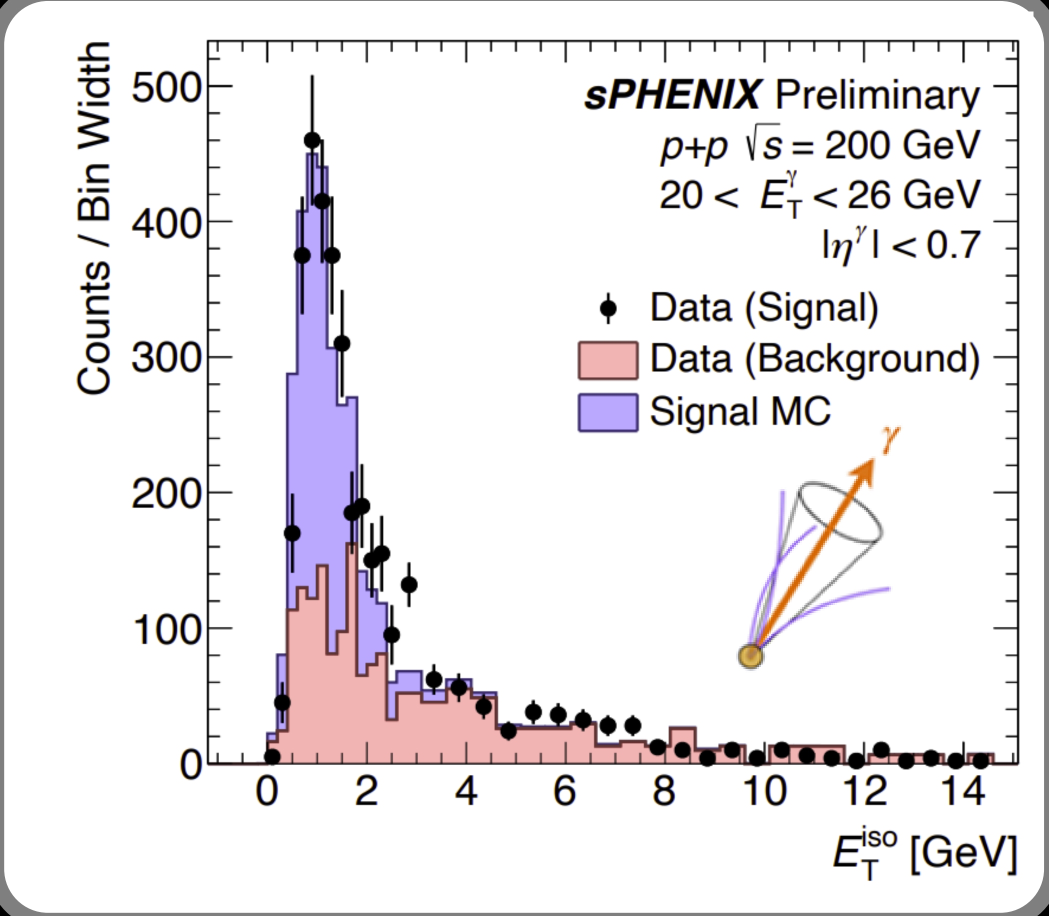
Direct photons Signal Extraction of

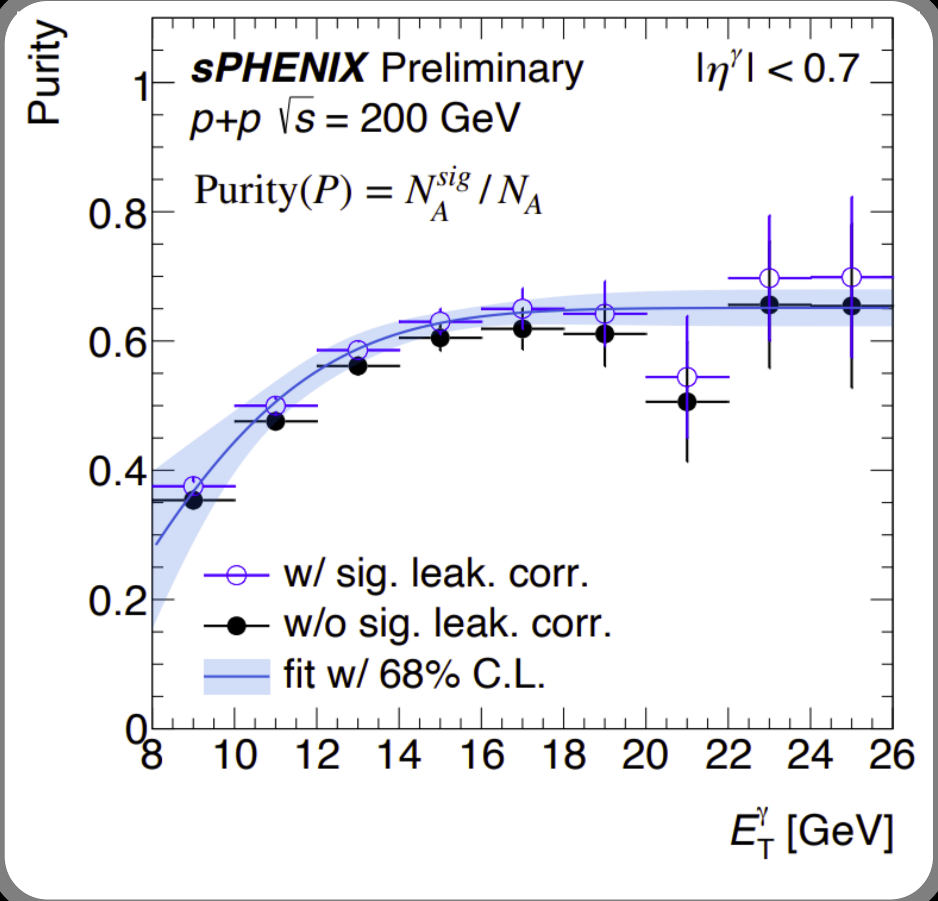


- **Signal**
  - Isolated EMCal cluster (little near-by particle production)
  - EMCal cluster which is consistent with a single photon
- **Background (π^0, η,..)**
  - Come in jets, non-isolated
  - EMCal cluster consistent with multiple incident photons
- **Irreducible background in signal region → must statistically subtract.**
- **Data-driven purity measurement**

Signal yields : $$N^A_{signal} = N^A_{raw} - \left[(N^B_{raw} - f^{B,MC} N^A_{signal}) \cdot \frac{(N^C_{raw} - f^{C,MC} N^A_{signal})}{(N^D_{raw} - f^{D,MC} N^A_{signal})} \right]$$

Purity of prompt isolated photons



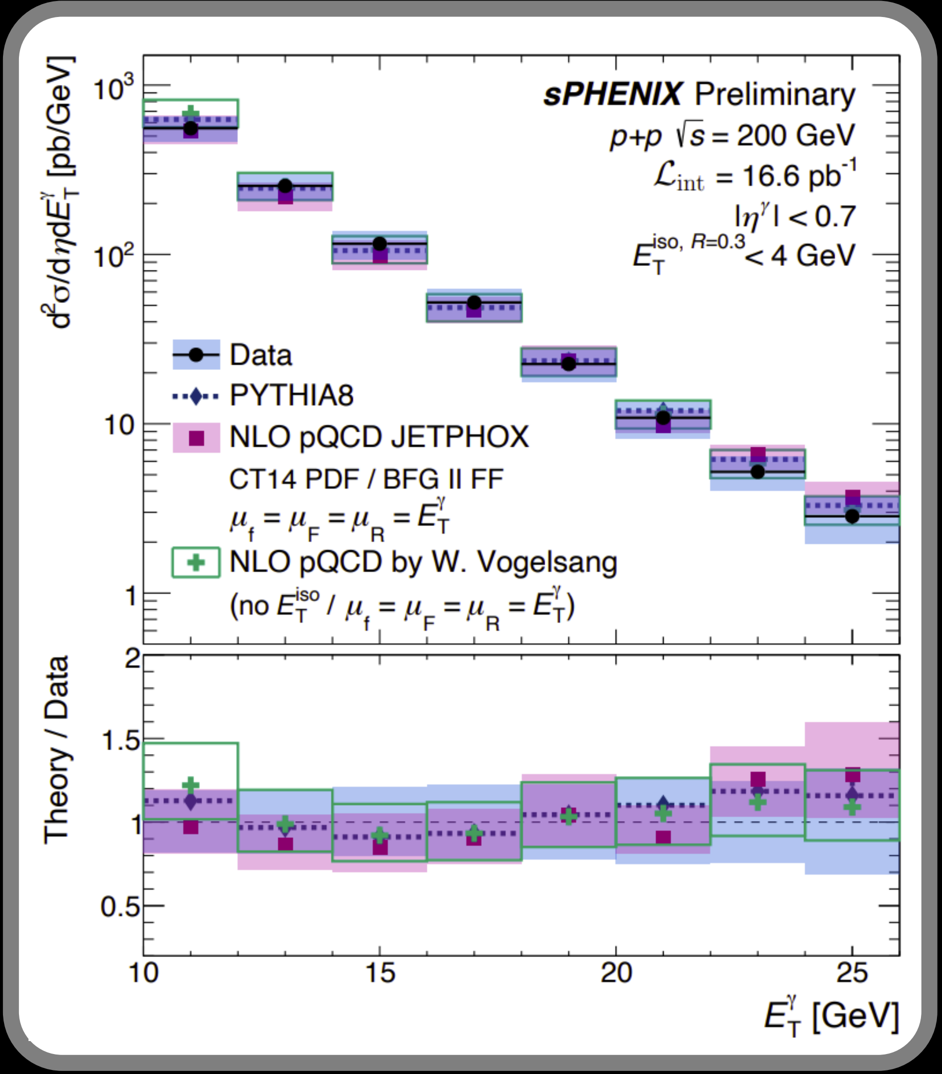


Example isolation energy distribution for data compared to background enhanced data and signal MC

Measured purity

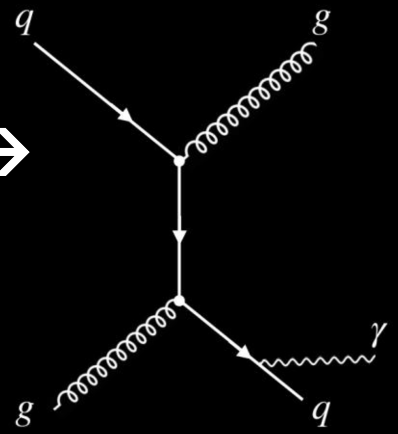
Only small corrections from MC

$d\sigma/dp_T$ of prompt isolated photons



Data

- ➢Results unfolded for detector effect
- ➢15% of the full p+p dataset used
- ➢EM energy scale dominant source for systematic unc. → Expect to be improved with the full dataset
- ➢Includes fragmentation photons →



Generator / Theory

- ➢Pythia8 Detroit tuning
- ➢JETPHOX: NLO pQCD, CT14LO PDF + BFG II fragmentation functions,
- ➢NLO pQCD W. Vogelsang : no iso cut

sPH-CONF-JET-2025-02

Overview

- Detector
- Bulk measurements
- Jets
- Photons
- Heavy flavor

Tracking system

MVTX: Maps-based VerTeX detector

- ➢Inner most detector
- ➢3 layers
  - O(10 μm) vertex position resolution
  - 4 μs integration time
  - Copy of ALICE ITS2 inner barrel

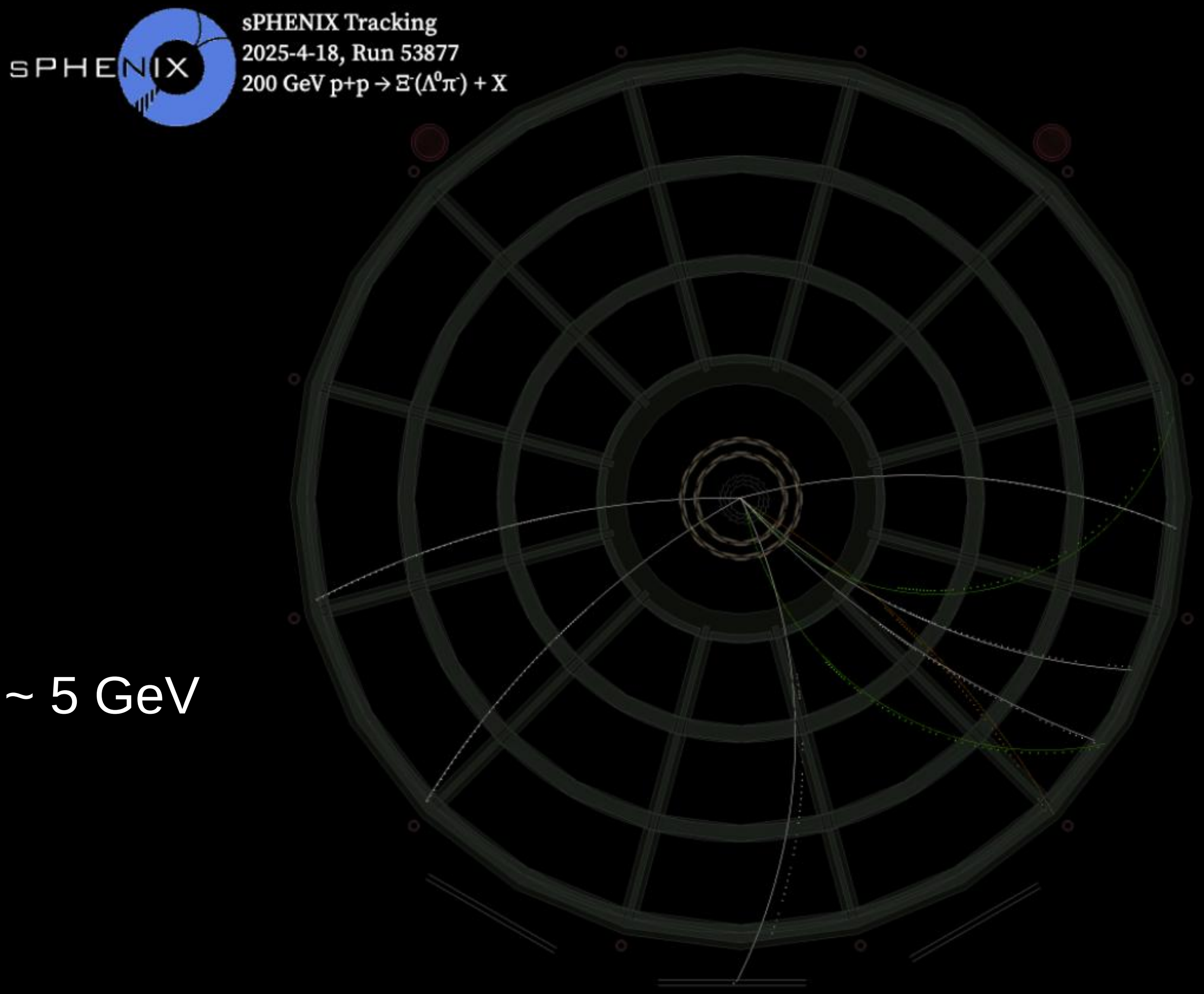
INTT: Discussed earlier

TPC: Time Projection Chamber

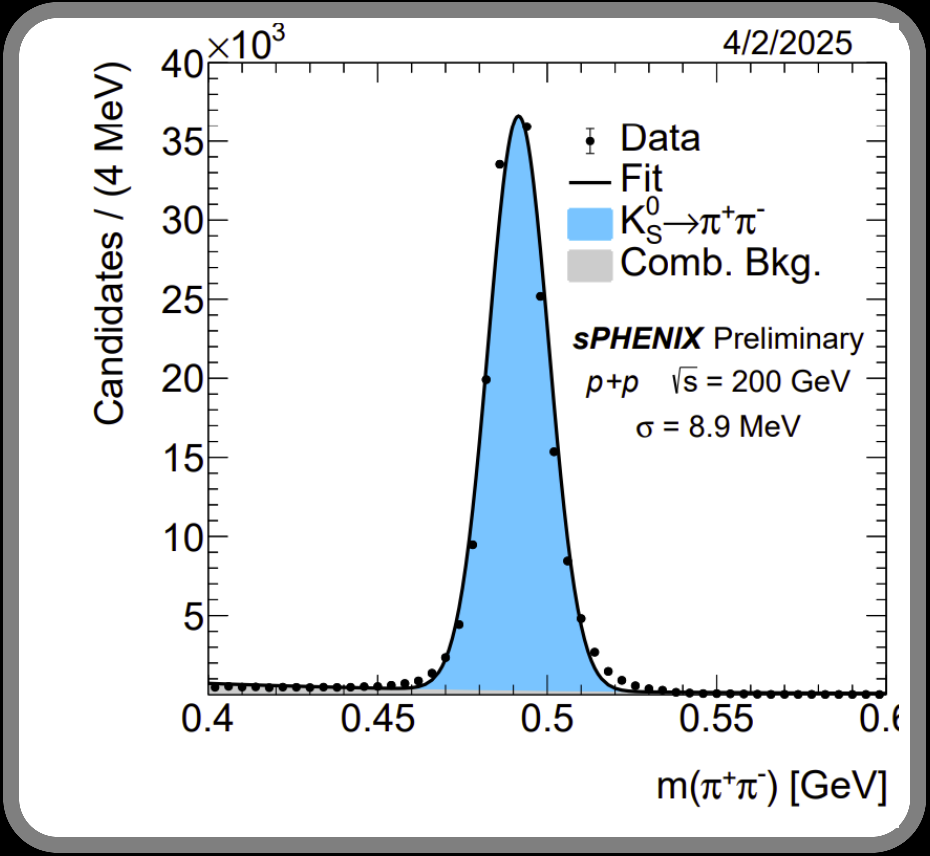
- ➢GEM based gaseous trift detector
- ➢Target momentum res.: $\Delta p/p = 0.02$ at ~ 5 GeV
- ➢14 μs drift time

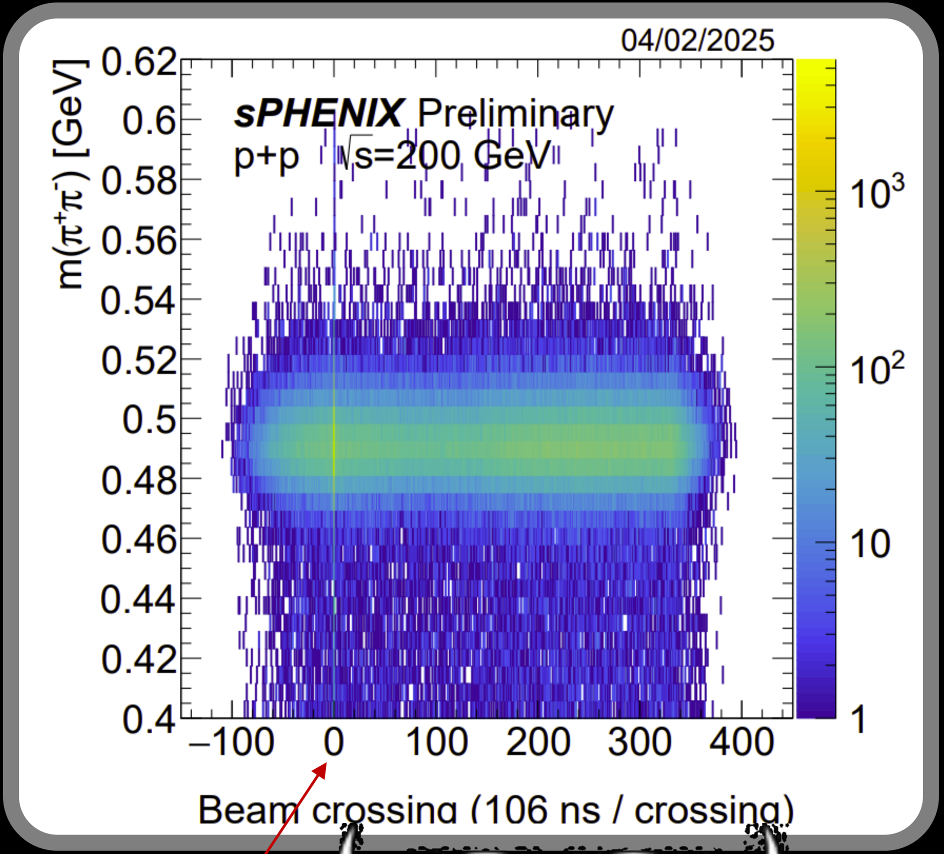
TPOT: TPc Outer Tracker

- ➢Provides reference/calibration for TPC



K_s^0 reconstruction and performance





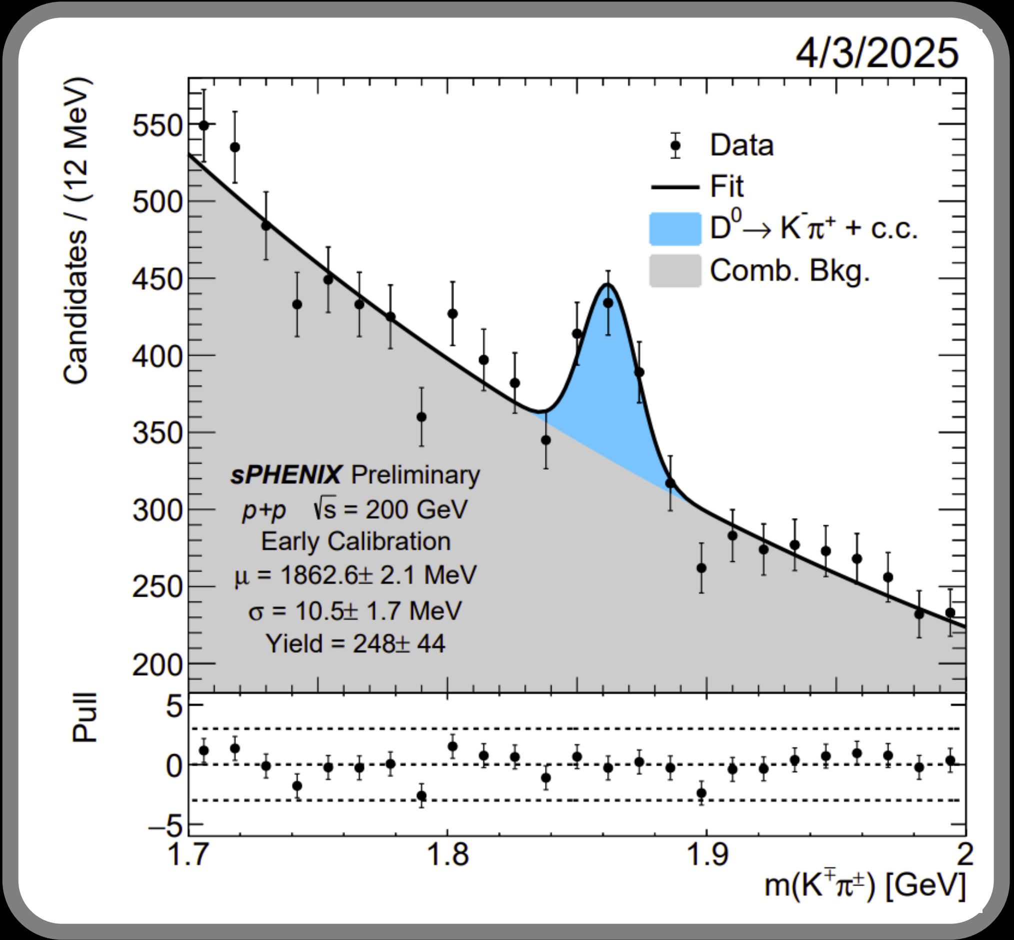
Triggered bunch crossing

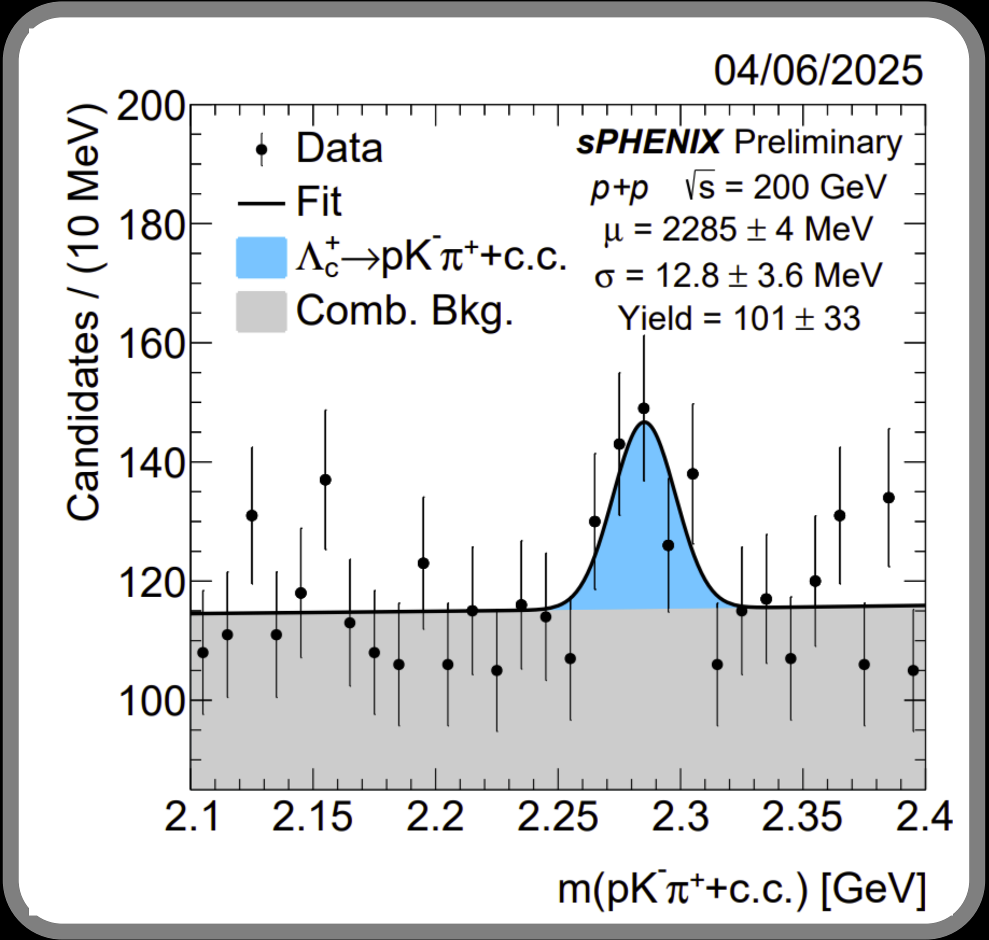
Data recorded after trigger bunch crossing ~40μs

First demonstration of successful extended streaming readout

Extended readout is critical for heavy flavor program

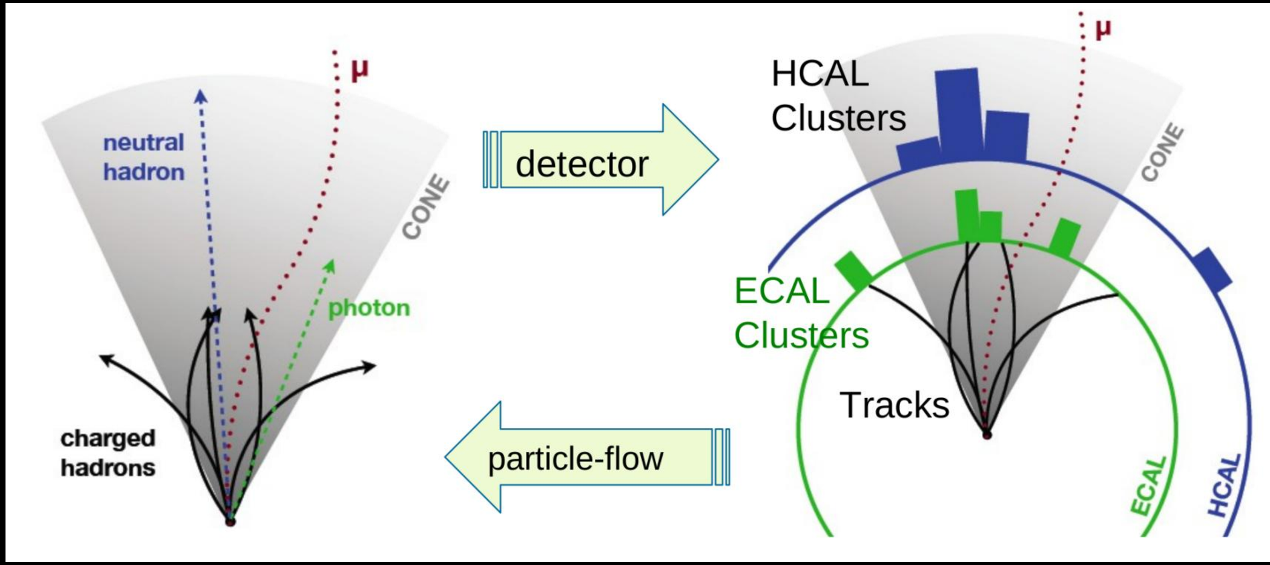
Heavy flavor mass peaks

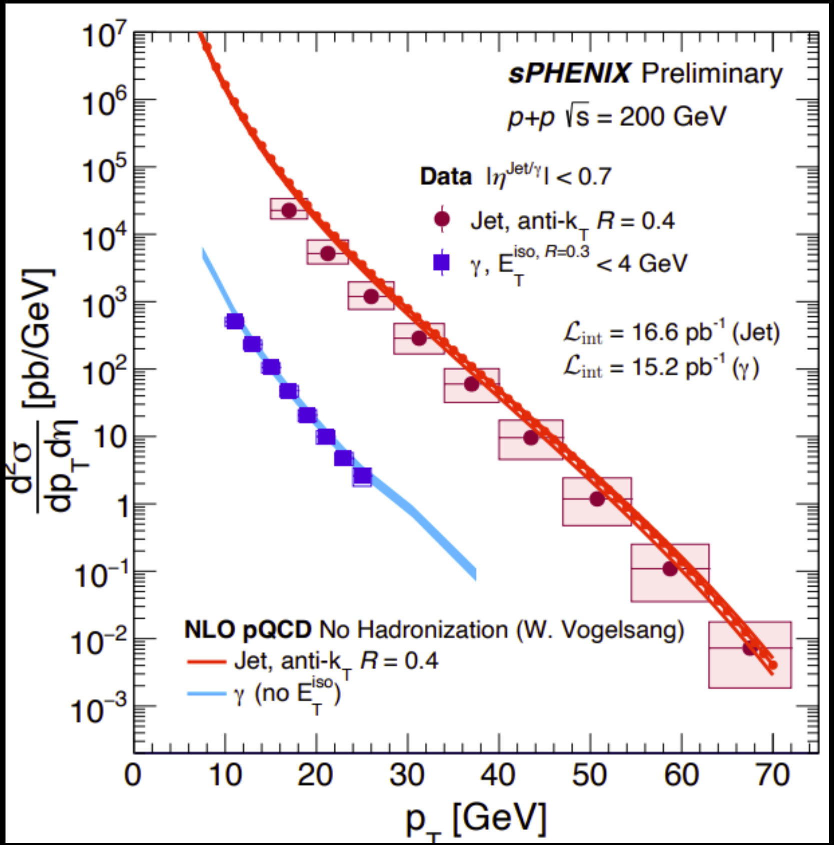




- **Observe first signal of D^0 and Λ_c decays**
- **from ~1 hour of p+p data and early stage calibrations**

Future: putting it together





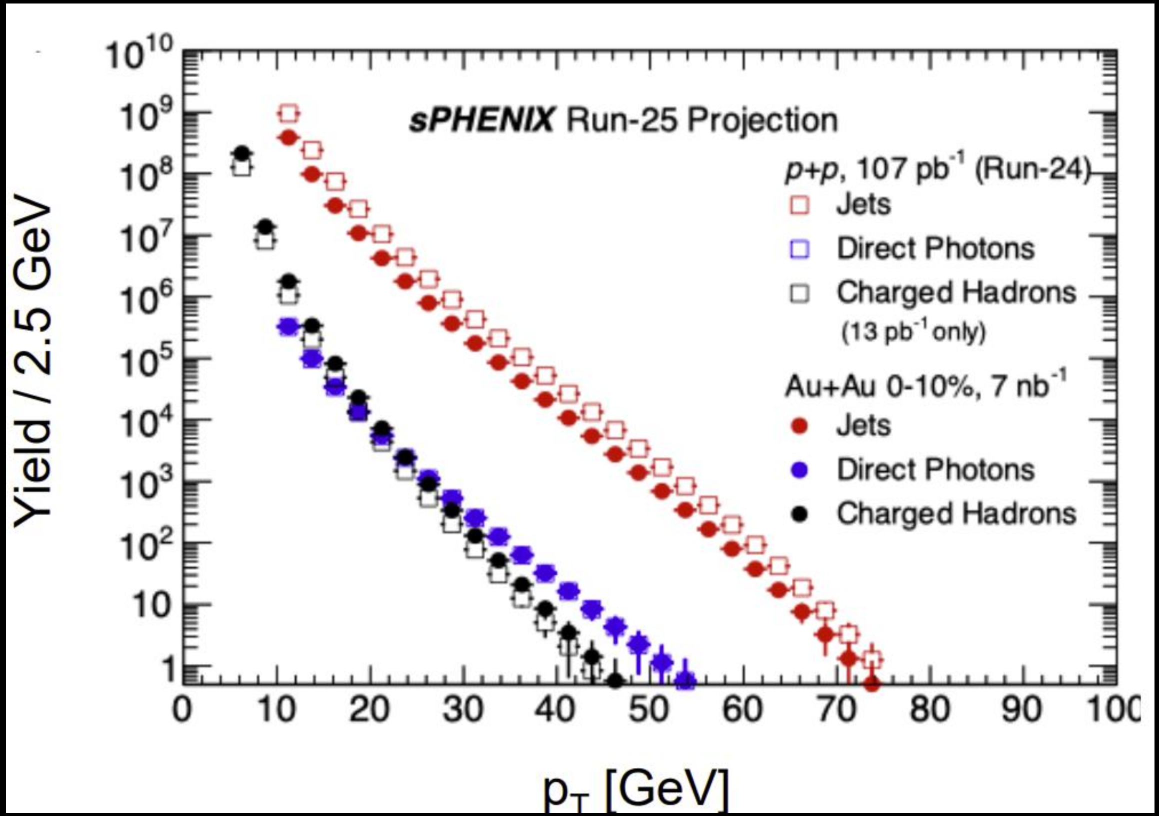
We have all the components to,

- Track-calorimeter matching to constrain hadronic response uncertainties, more precise EM scale, jet calibrations, etc.
- Combine signatures like *γ*-jet
- Large statistics tracking physics analyses
- Ready to analyze large statistic Au+Au

Upcoming collisions from RHIC

sPHENIX Physics Target in Run-25: 7 nb^{-1} **(50B events)**		
Collision Species	Cryoweeks	Projected luminosity, $\|z\| < 10$ cm
Au+Au 200 GeV	20	2.4 – 4.2 nb^{-1} recorded
Au+Au 200 GeV	28	3.6 – 6.4 nb^{-1} recorded

If Au+Au luminosity target is met, ordered priority list for additional running:		
Collision Species	Physics weeks	Projected luminosity, $\|z\| < 10$ cm
1. *p*+*p* 200 GeV	8	13 pb^{-1} sampled + 3.9 pb^{-1} streaming
2. *p*+Au 200 GeV	5	80 nb^{-1} sampled + 24 nb^{-1} streaming
3. O+O 200 GeV	2	13 nb^{-1} sampled + 3.9 nb^{-1} streaming



[Beam use proposal]

Summary

- **First sPHENIX publication of dE_T/dη and dN_{ch}/dη which achieved the expected performance of these standard candles**
- **Competitive preliminary jet measurements with a straight-forward path for improvement**
  - Similar for photon measurements
- **Demonstration of the successful triger+streaming readout and detector timing system for high-statistics precision tracking**
- **First reconstruction of D^0 and Λ_c**
  - Ready for large scale tracking physics analysis
- **Excited for the start of Au+Au beam time**

Thanks for listening

Underlying event methods

Iterative method

1. Identify seed jets
2. Measure the eta-dependent underlying event
3. Subtract measured underlying event at the tower level
4. Repeat 2 and 3 with improved seed jets
5. Find final jets

Area method

1. Measure average underlying event
2. Find jets and subtract average underlying event.

Multiplicity method

1. Measure average underlying event per tower
2. Find jets and subtract average underlying event based on estimate of number of background towers

Random cones

$$\delta E_T^{\mathrm{Iter}} = \sum_{i=0}^{N} E_{T,i}^{\mathrm{sub}}$$

$$\delta E_T^{\mathrm{Area}} = \sum_{i=0}^{N} E_{T,i} - \rho_{\mathrm{A}} \cdot A_{\mathrm{cone}}$$

$$\delta E_T^{\mathrm{Mult}} = \sum_{i=0}^{N} E_{T,i} - \rho_{\mathrm{M}} \cdot N$$

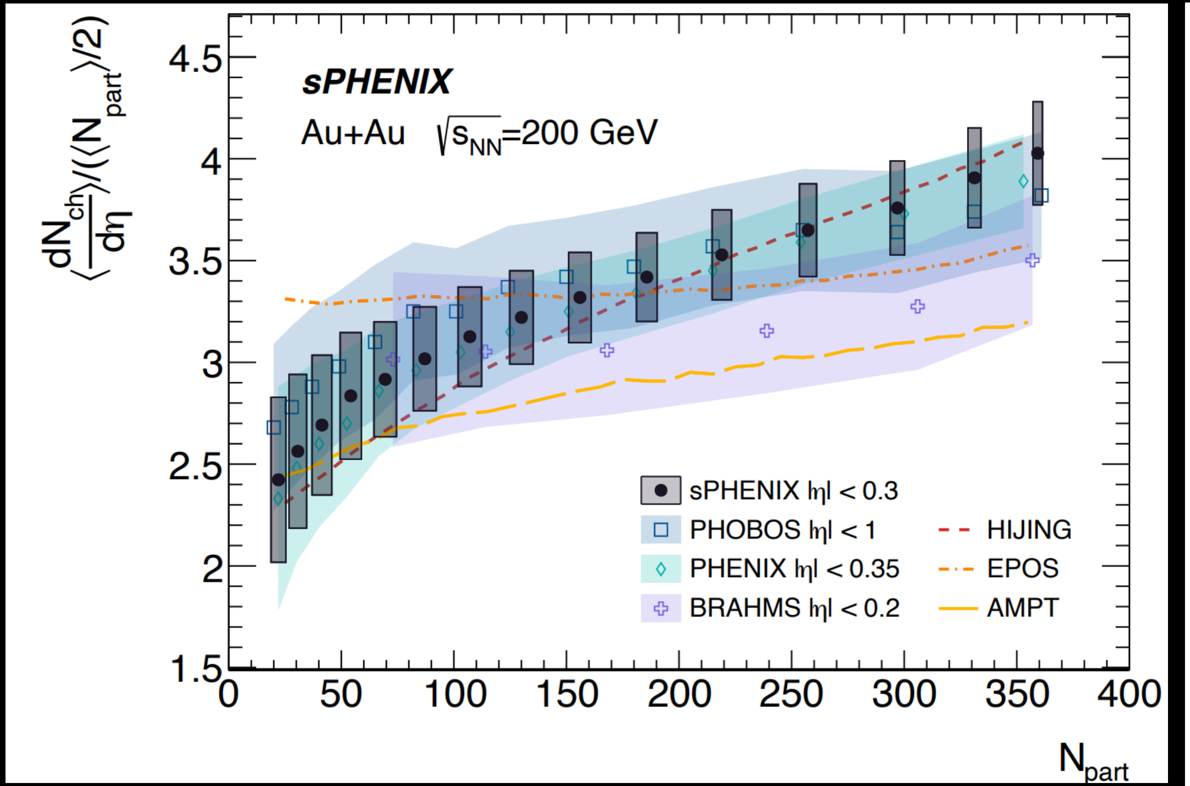
Embedding sim jets

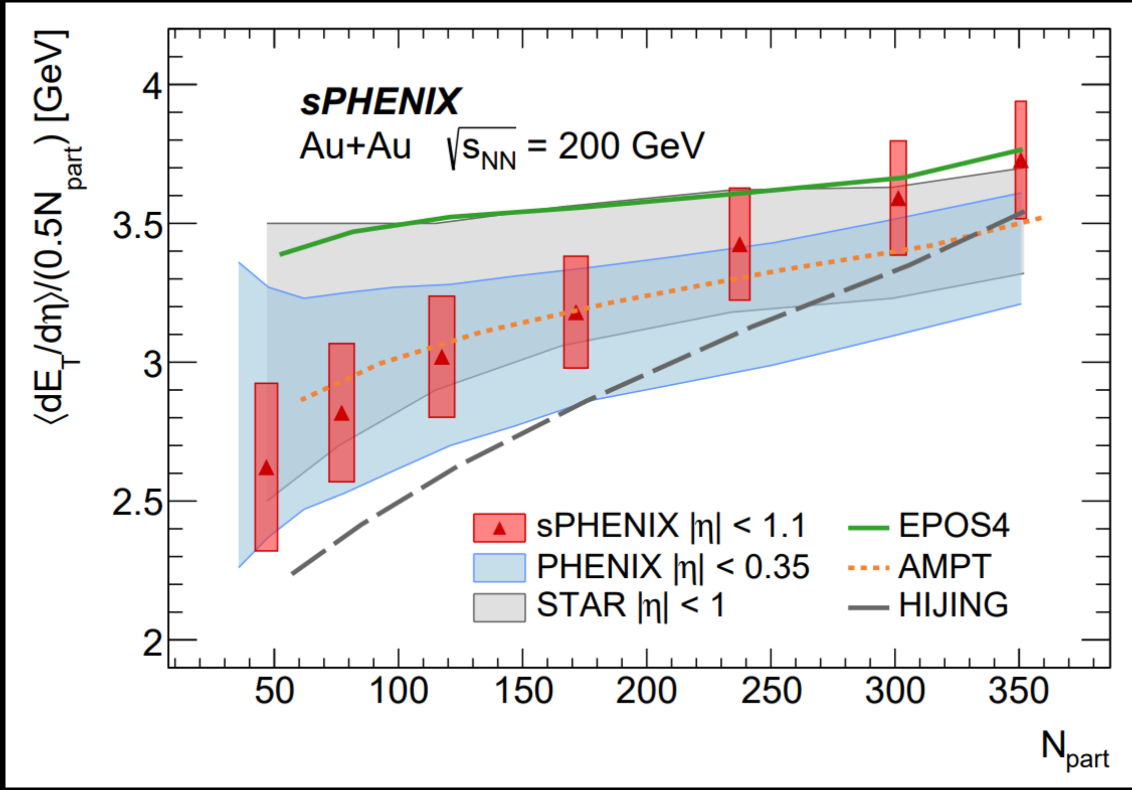
$$\delta E_{T,\mathrm{Iter}} = E_{T,\mathrm{jet}}^{\mathrm{sub.}} - E_{T,\mathrm{sim}}$$

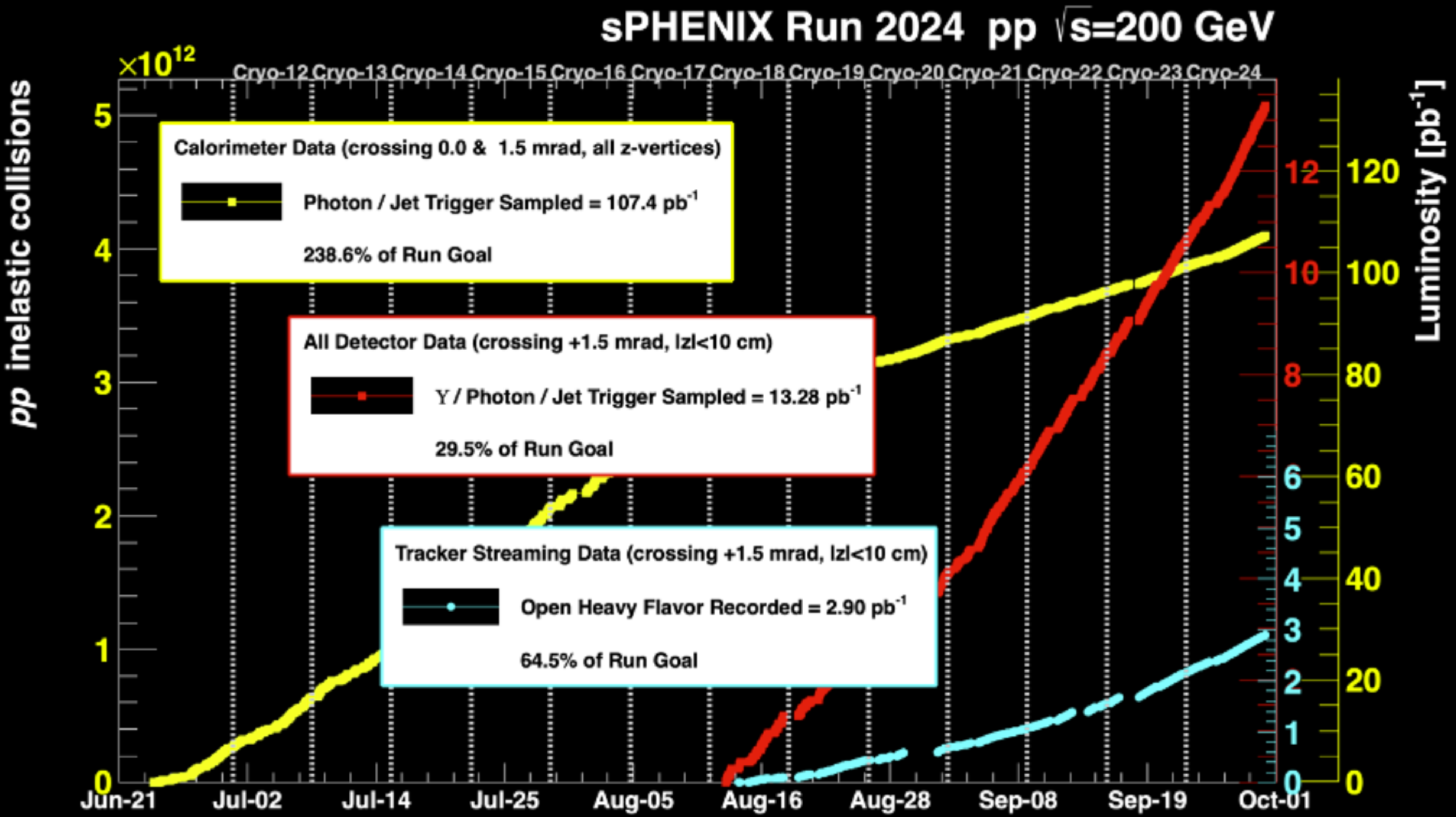
$$\delta E_{T,\mathrm{Mult}} = E_{T,\mathrm{jet}}^{\mathrm{Uncorr.}} - \rho_{\mathrm{M}} \cdot (N_{\mathrm{const}} - \langle N_{\mathrm{signal}} \rangle) - E_{T,\mathrm{sim}}$$

$$\delta E_{T,\mathrm{Area}} = E_{T,\mathrm{jet}}^{\mathrm{Uncorr.}} - \rho_{\mathrm{A}} \cdot A_{\mathrm{jet}} - E_{T,\mathrm{sim}}$$

$dN_{ch}/d\eta$ and $dE_T/d\eta$ in Au+Au collisions






sPHENIX Run 2024 pp √s=200 GeV
×10^12
Cryo-12 Cryo-13 Cryo-14 Cryo-15 Cryo-16 Cryo-17 Cryo-18 Cryo-19 Cryo-20 Cryo-21 Cryo-22 Cryo-23 Cryo-24
pp inelastic collisions
Luminosity [pb^-1]
Calorimeter Data (crossing 0.0 & 1.5 mrad, all z-vertices)
Photon / Jet Trigger Sampled = 107.4 pb^-1
238.6% of Run Goal
All Detector Data (crossing +1.5 mrad, |z|<10 cm)
Υ / Photon / Jet Trigger Sampled = 13.28 pb^-1
29.5% of Run Goal
Tracker Streaming Data (crossing +1.5 mrad, |z|<10 cm)
Open Heavy Flavor Recorded = 2.90 pb^-1
64.5% of Run Goal
Jun-21 Jul-02 Jul-14 Jul-25 Aug-05 Aug-16 Aug-28 Sep-08 Sep-19 Oct-01
0 1 2 3 4 5
0 2 4 6 8 10 12
0 1 2 3 4 5 6
0 20 40 60 80 100 120