



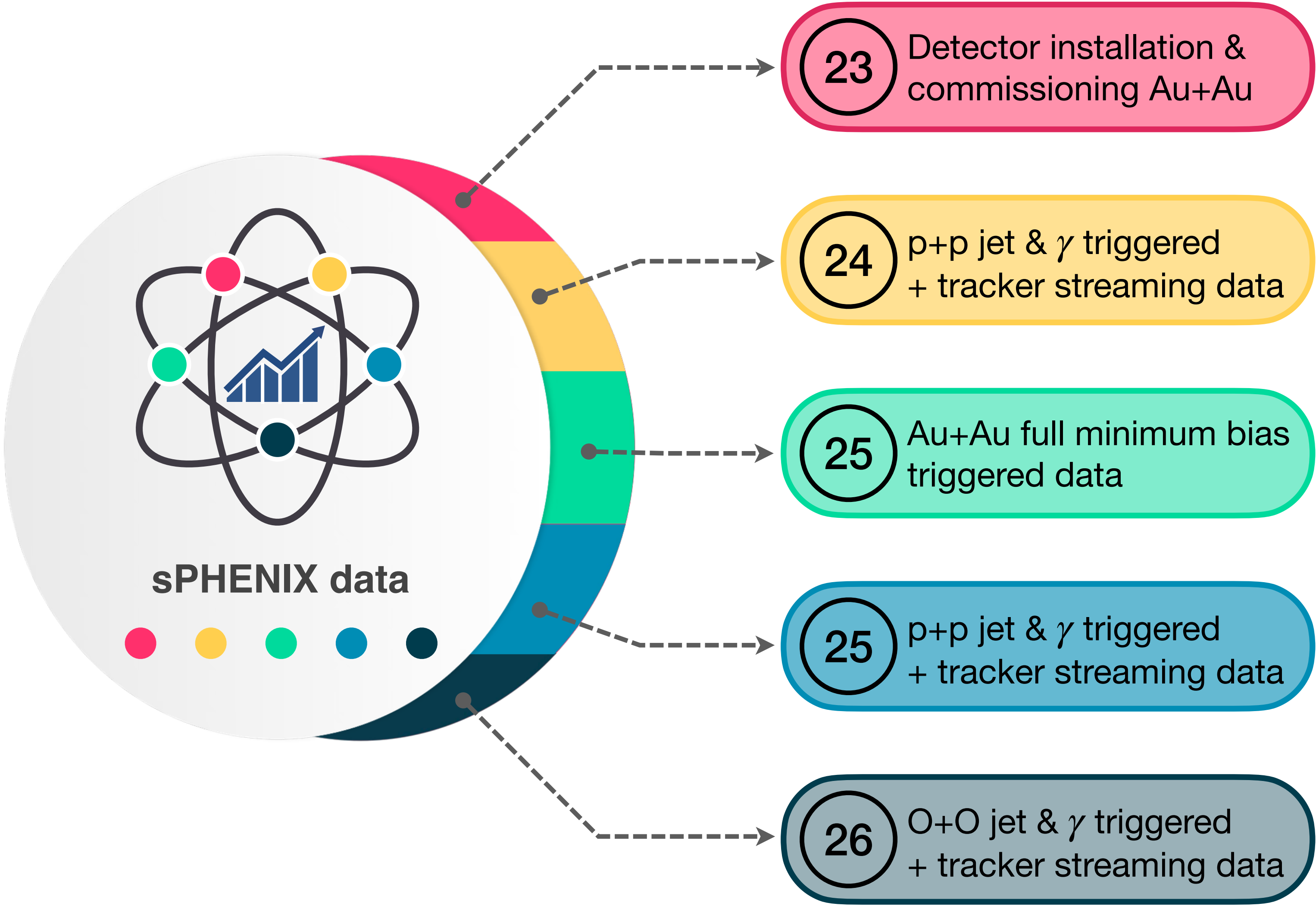
Hunting QGP across system-size landscape: Jet quenching in O+O with sPHENIX

JaeBeom Park (University of Colorado Boulder)

— *BNL Nuclear Physics Seminar* —

2026. 08. 04

sPHENIX running and dataset



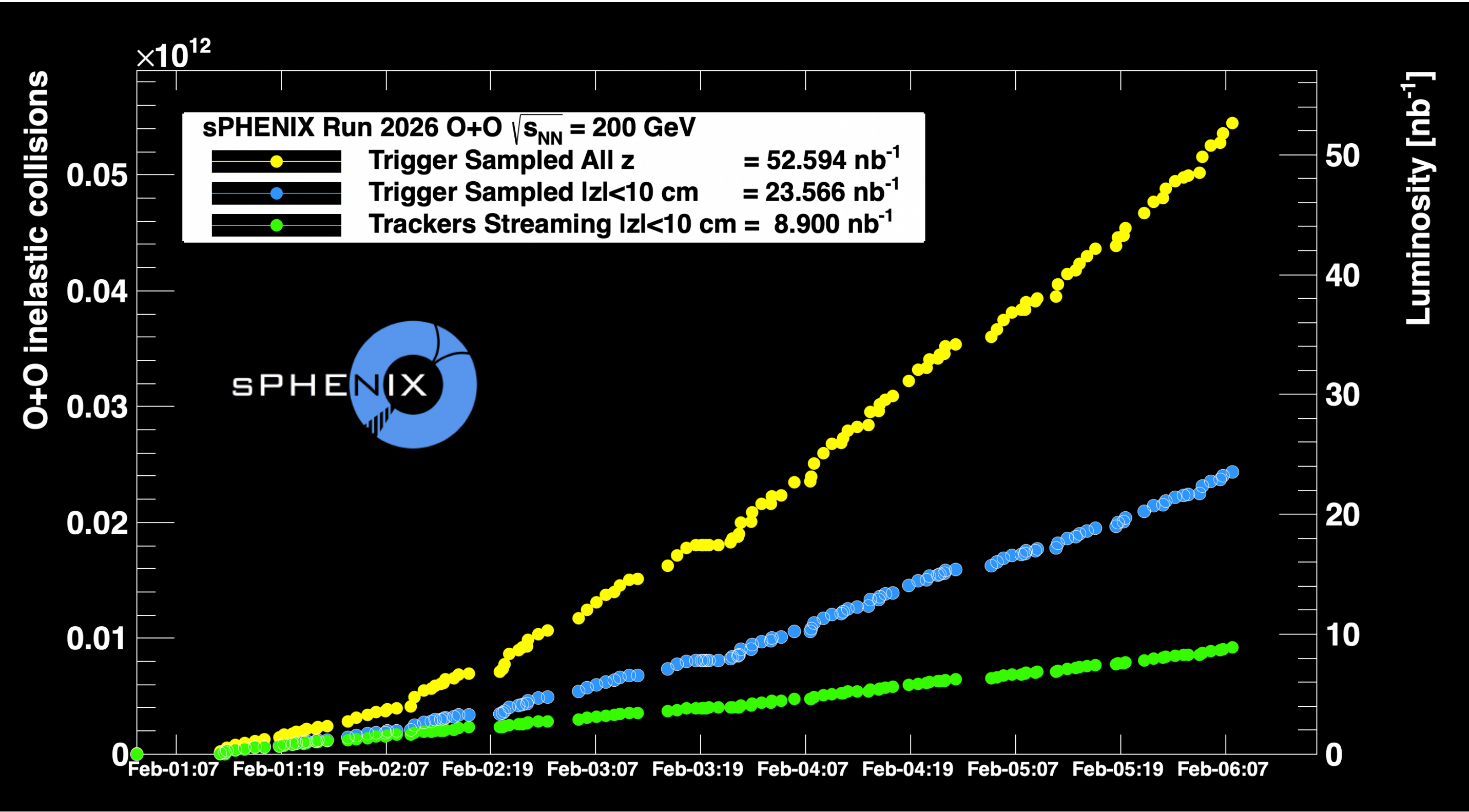
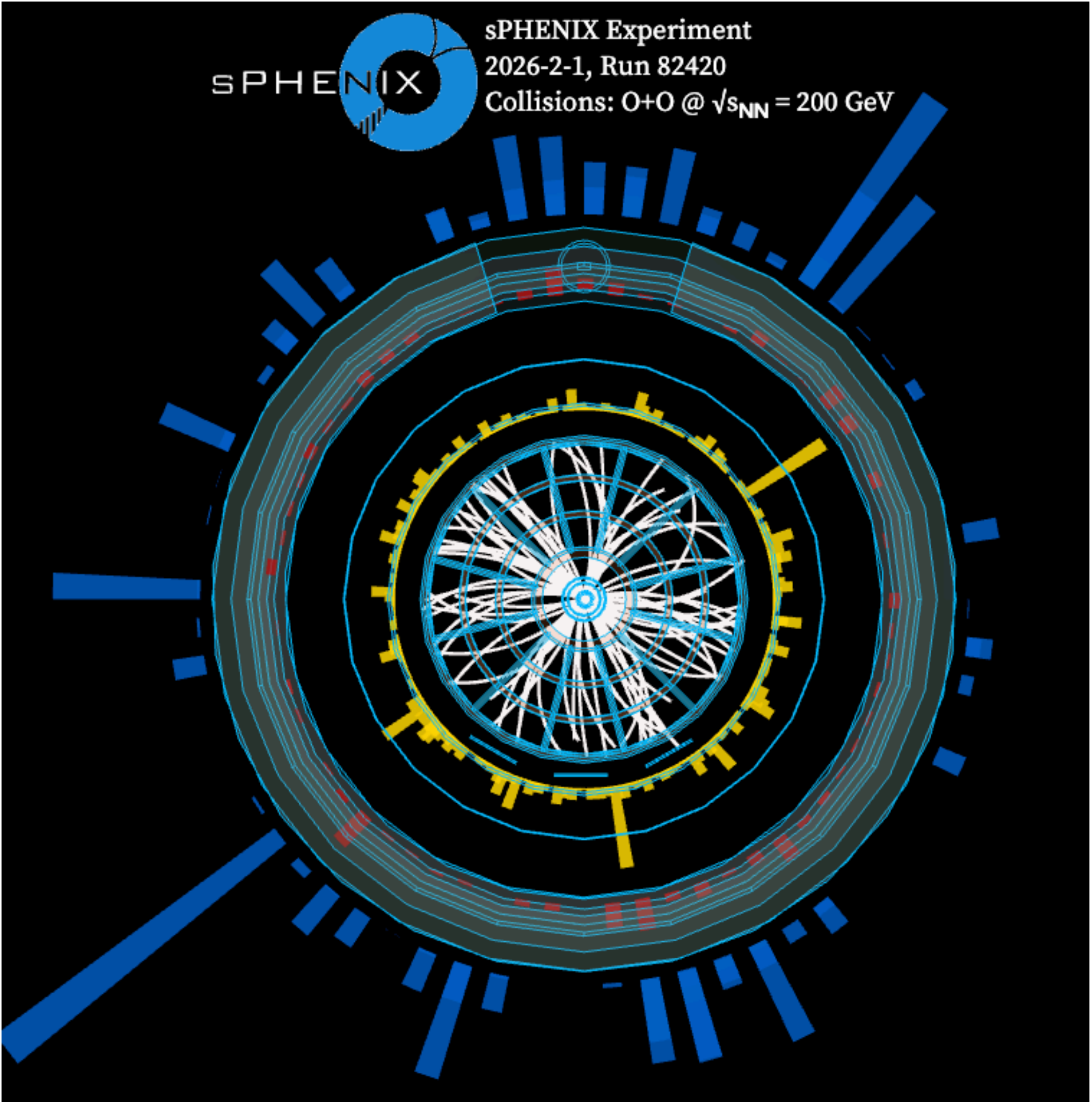
Detector installation in 2023

Data taking completion in Feb. 2026

p+p	Au+Au	O+O
Jet/ γ triggers 115 pb ⁻¹	MB trigger 6.6 nb ⁻¹	Jet/ γ triggers 53 nb ⁻¹
Tracker streaming 11 pb ⁻¹		Tracker streaming 8.9 nb ⁻¹

Total 300 PB

sPHENIX Oxygen+Oxygen running



- **53 nb⁻¹** of jet & photon triggered sample
- Valuable for studying **system-size landscape**

Selected sPHENIX Jet physics analyses



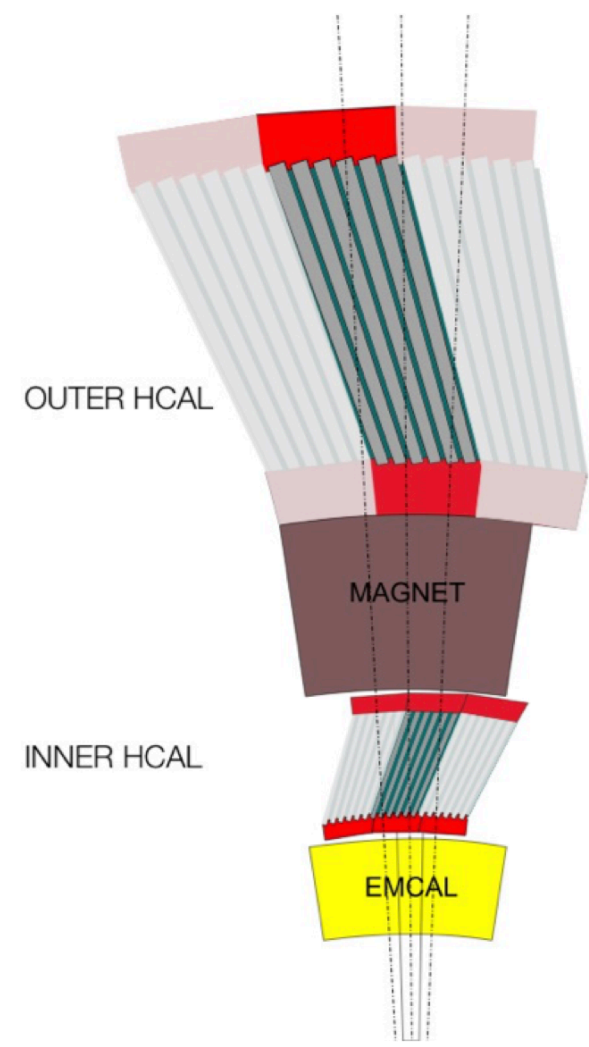
- Dijet momentum imbalance in p+p 200 GeV (Final) : [arXiv:2606.17184](#)
- Isolated photon cross section p+p 200 GeV (Final) : [arXiv:2607.03892](#)
- Dijet momentum imbalance in Au+Au 200 GeV (Preliminary) : [sPH-CONF-JET-2025-05](#)
- Inclusive jet cross section in p+p 200 GeV (Preliminary) : [sPH-CONF-JET-2025-03](#)
- Underlying event fluctuations in Au+Au 200 GeV (Preliminary) : [sPH-CONF-JET-2025-04](#)
- Jet and UE correlation in p+p 200 GeV (Preliminary) : [sPH-CONF-JET-2026-03](#)
- In-situ jet energy scale in p+p 200 GeV (Preliminary) : [sPH-CONF-JET-2026-01](#)
- Jet R_{AA} / R_{CP} in O+O 200 GeV (Preliminary) : [sPH-CONF-JET-2026-02](#)

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sPHENIX jet measurement

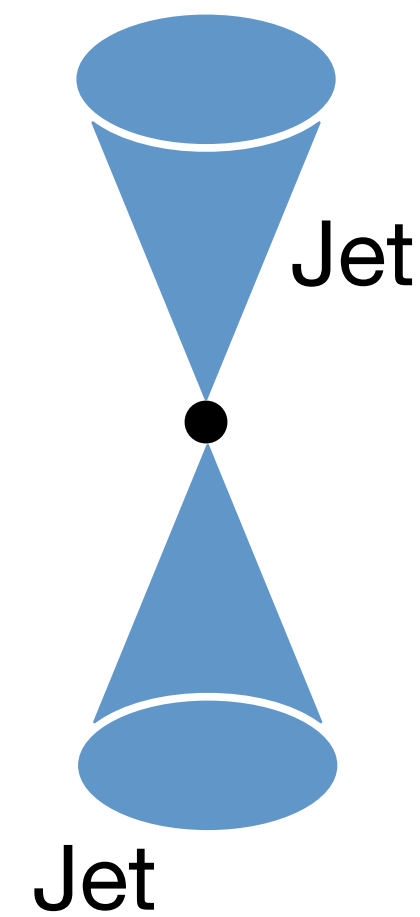


Full jet reconstruction
using EMCal + HCal

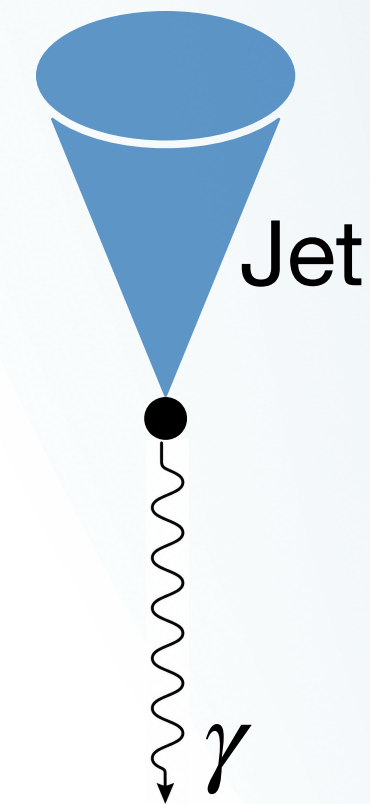
Full unfolding for detector
response + UE subtraction
in heavy ion collisions

In situ jet energy scale
(JES) and jet energy
resolution (JER) correction

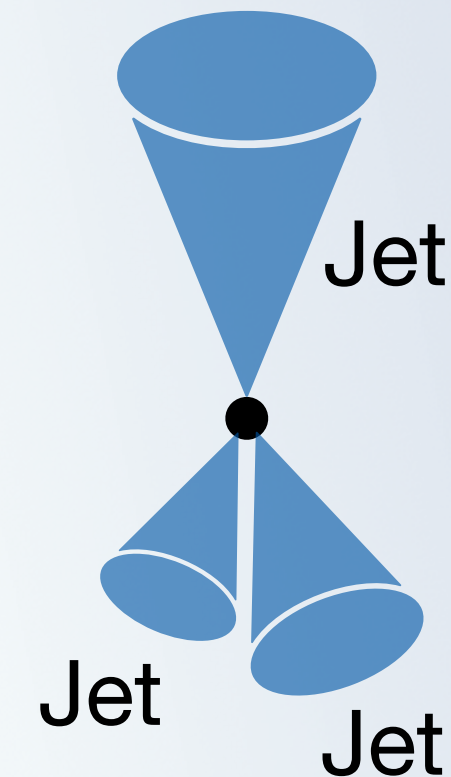
Dijet



γ -jet

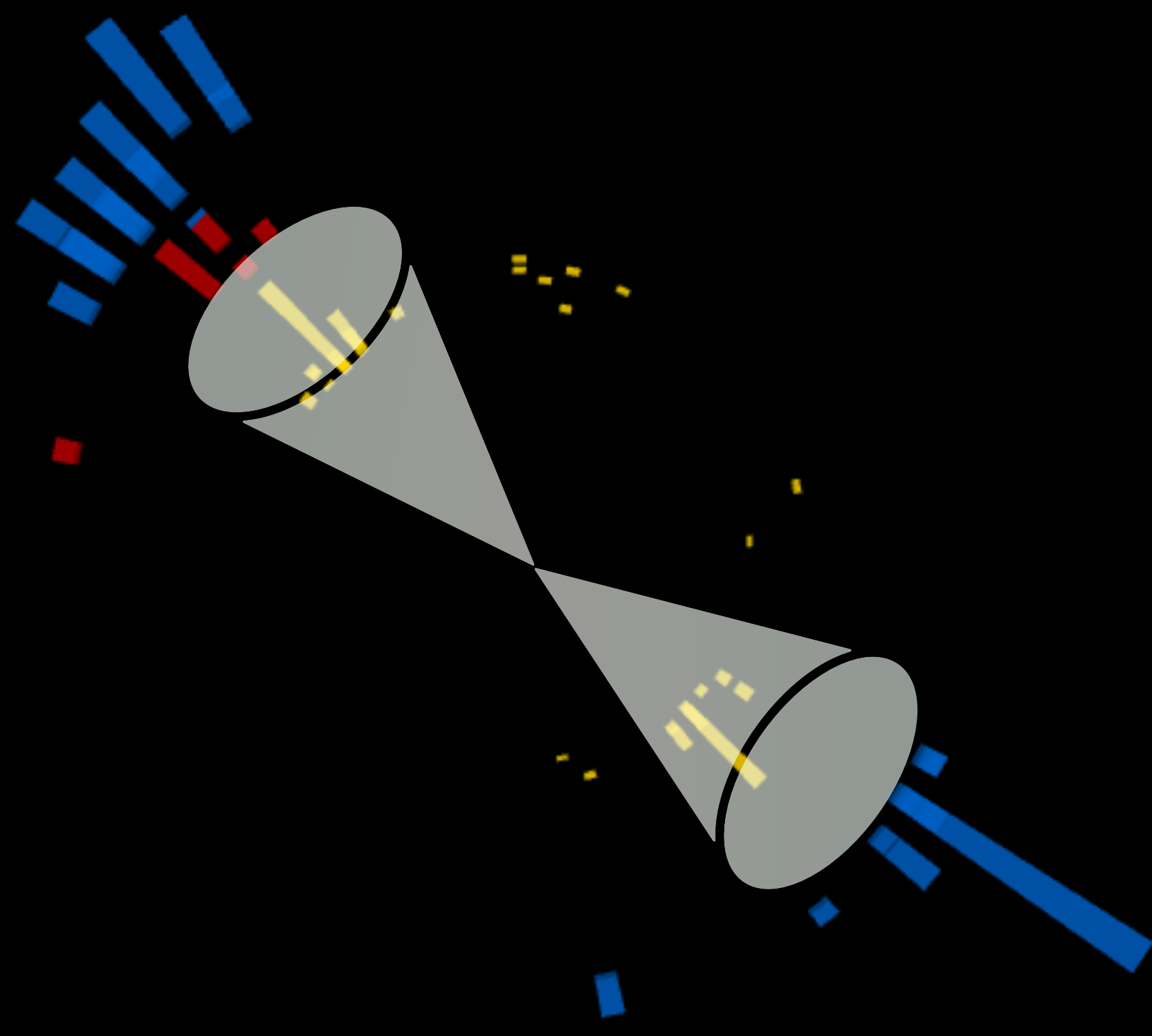


Multi-jet





sPHENIX Experiment at RHIC
Collisions: $p + p$ @ $\sqrt{s_{NN}} = 200$ GeV
Run 43266, 2024-05-20, Event 1447921



Outer Hadronic
Calorimeter (oHCAL)

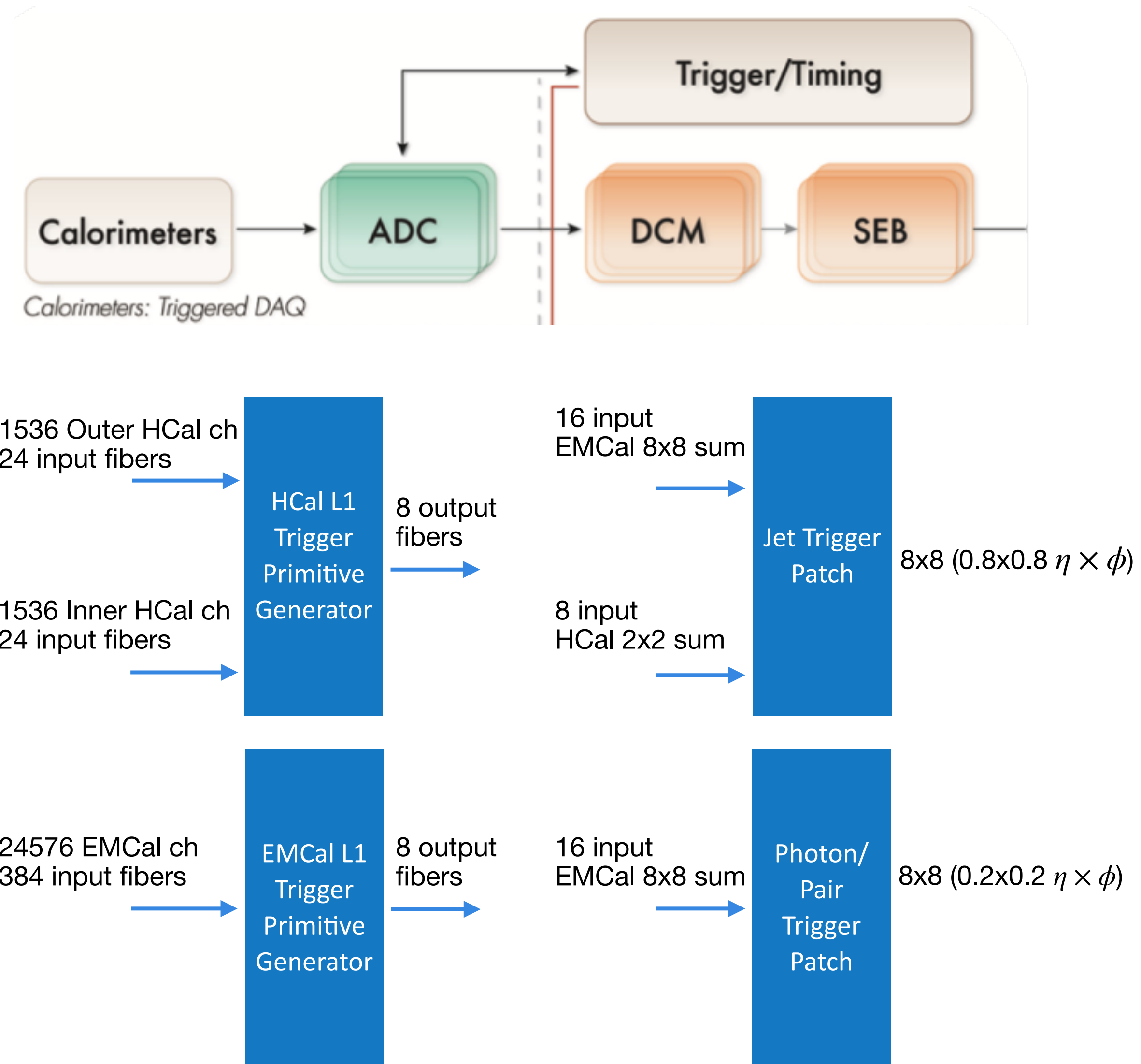
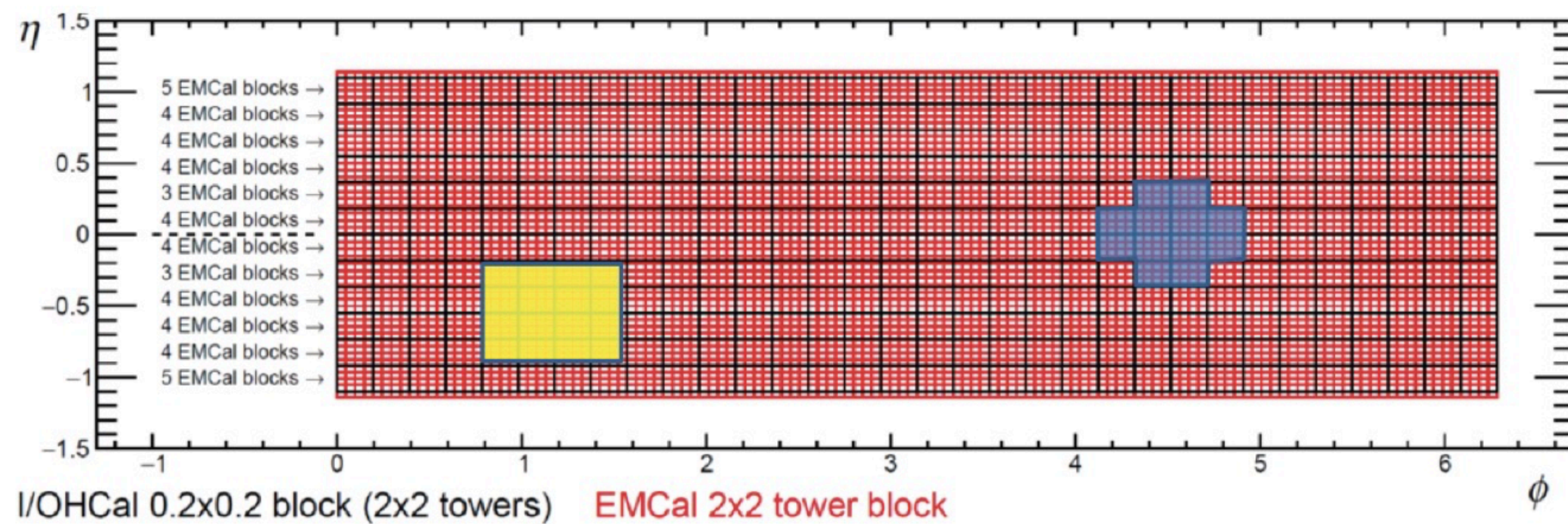
Inner Hadronic Calorimeter
(iHCAL)

Electromagnetic
Calorimeter (EMCAL)

Jet trigger in sPHENIX

Jet triggers using stacked EMCal + Inner HCal + Outer HCal

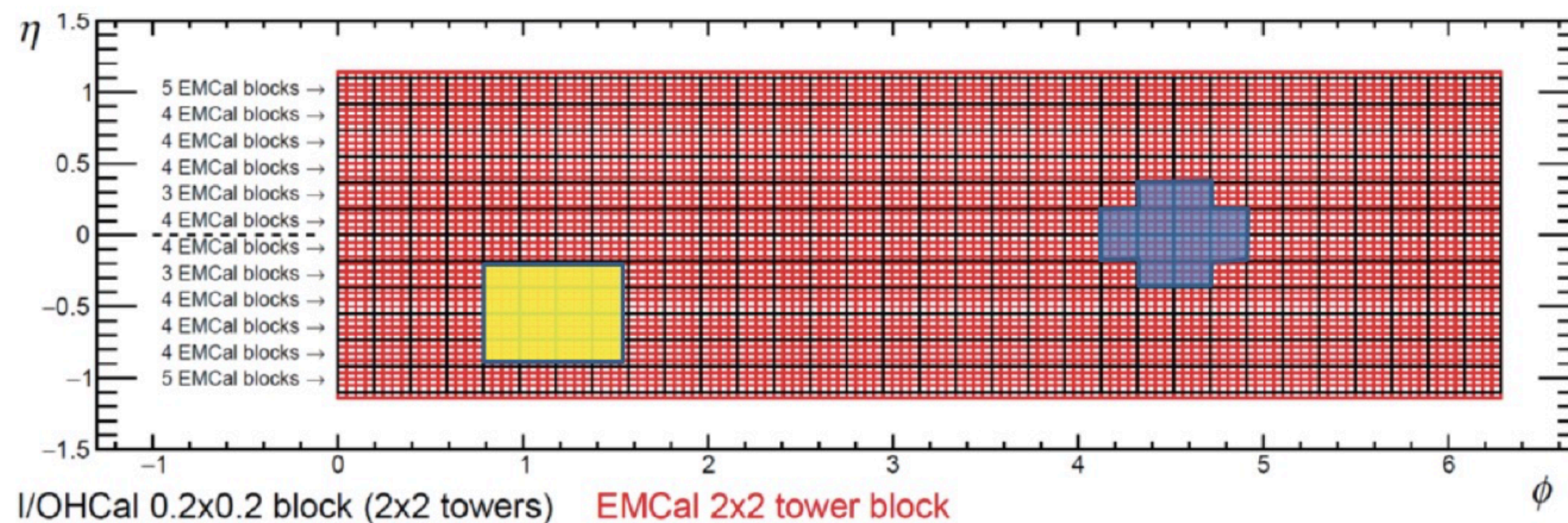
- Trigger daughter cards sum for unit of 2x2 towers
- Energies combine into $\Delta\eta \times \Delta\phi = 0.8 \times 0.8$ as jet patch
- Overlapping sliding window across full acceptance
- Various thresholds used for efficiency estimation



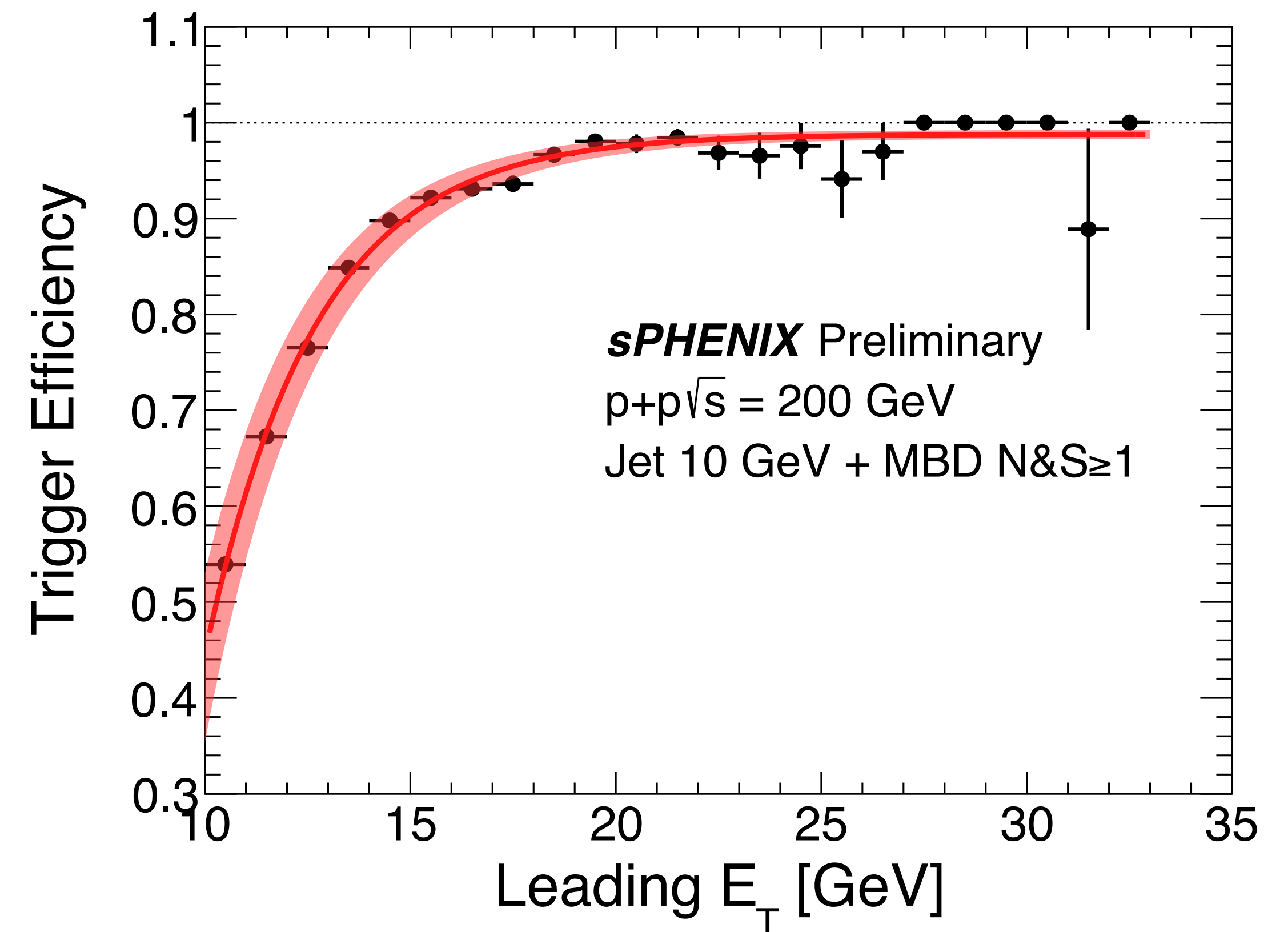
Jet trigger in sPHENIX

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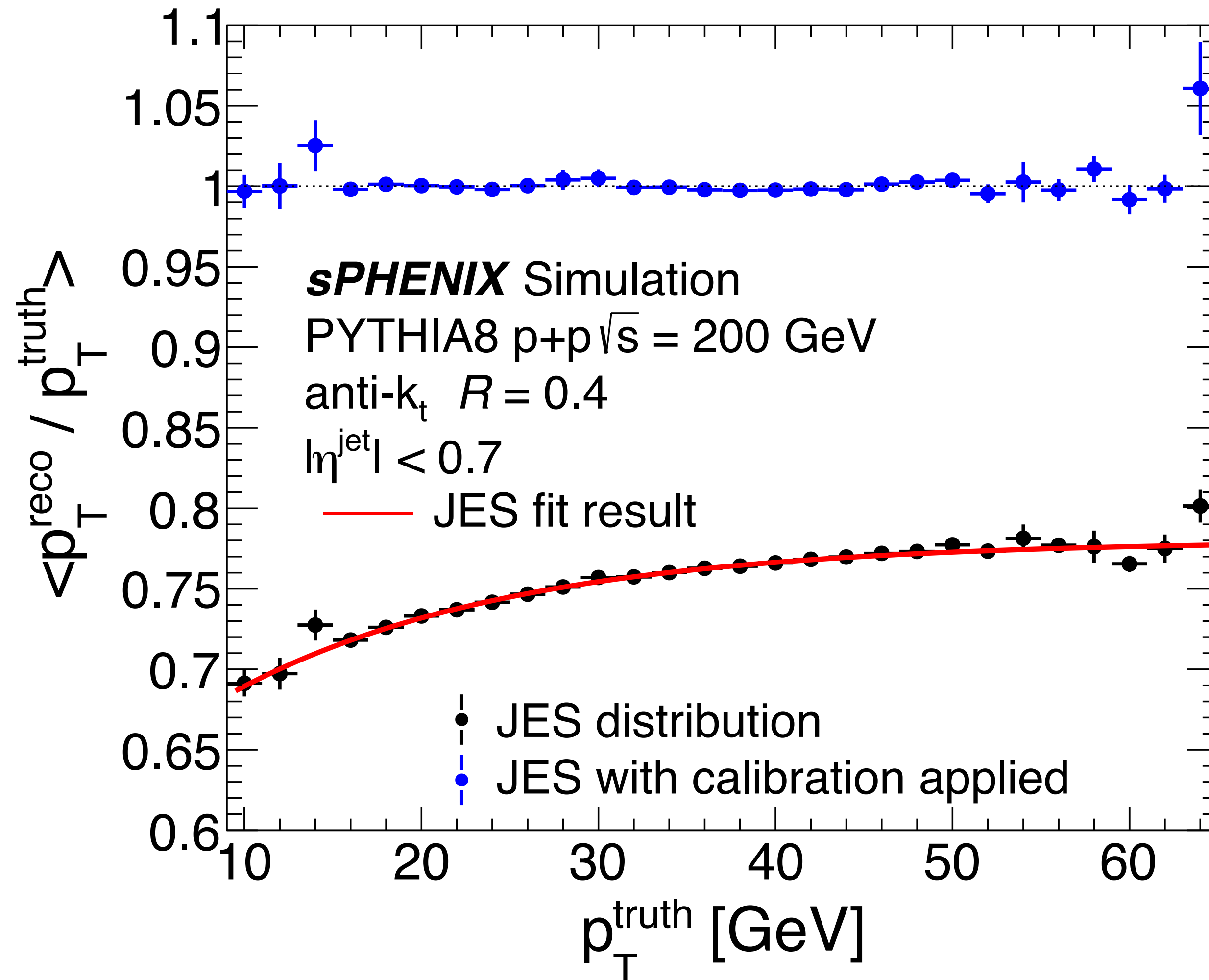
- Trigger daughter cards sum for unit of 2x2 towers
- Energies combine into $\Delta\eta \times \Delta\phi = 0.8 \times 0.8$ as jet patch
- Overlapping sliding window across full acceptance
- Various thresholds used for efficiency estimation



Good turn on trigger efficiency towards high- p_T

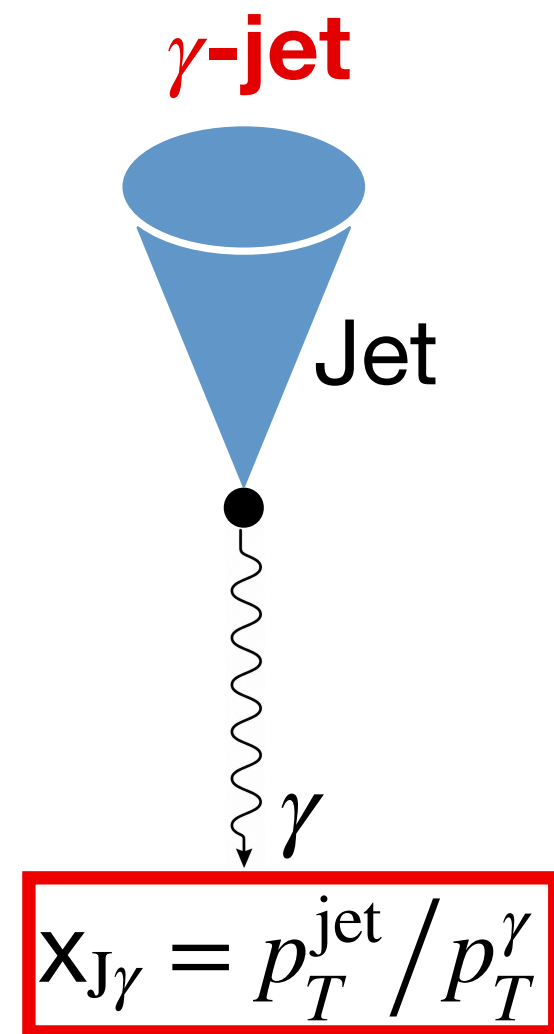
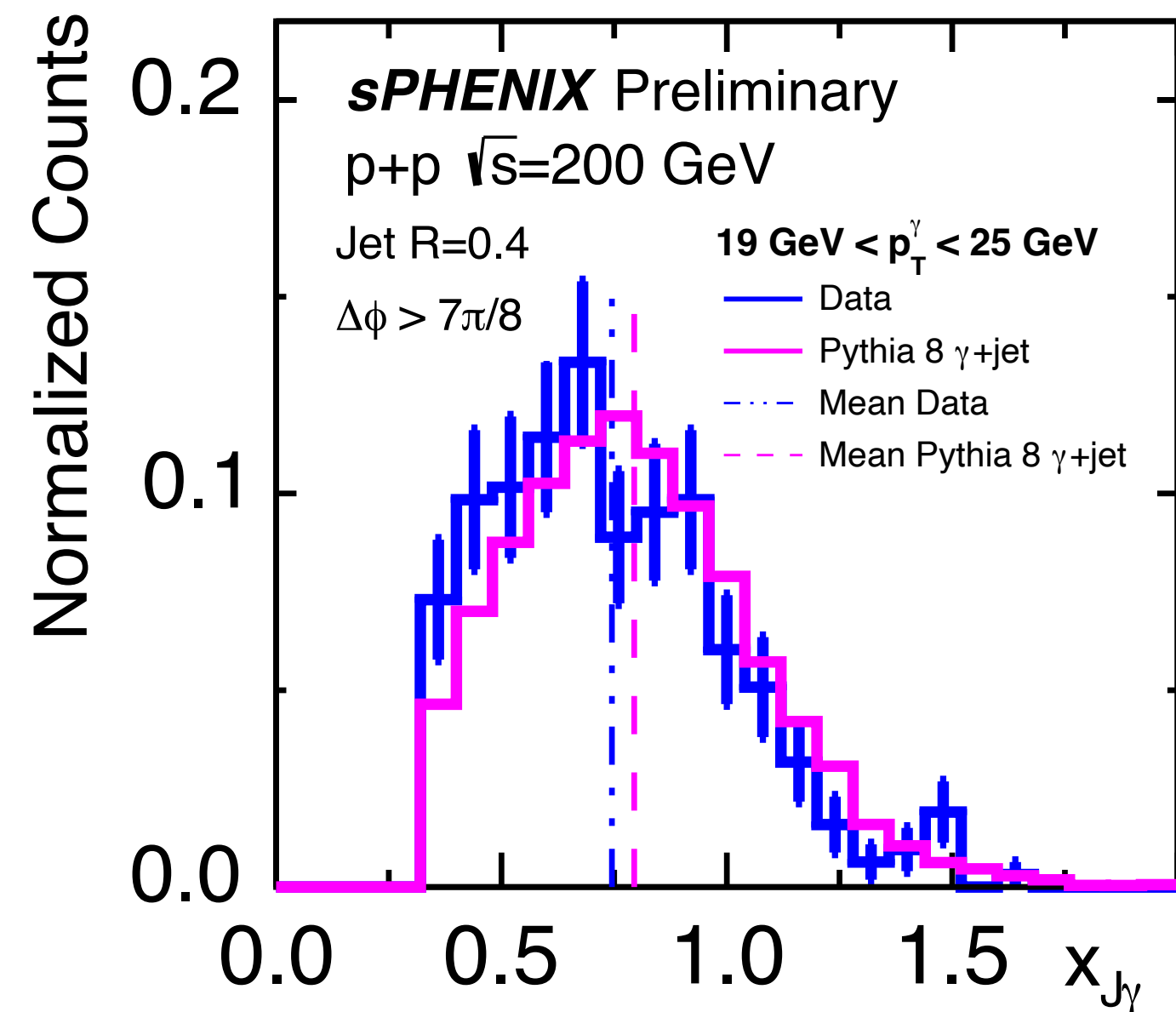


Jet energy scale response



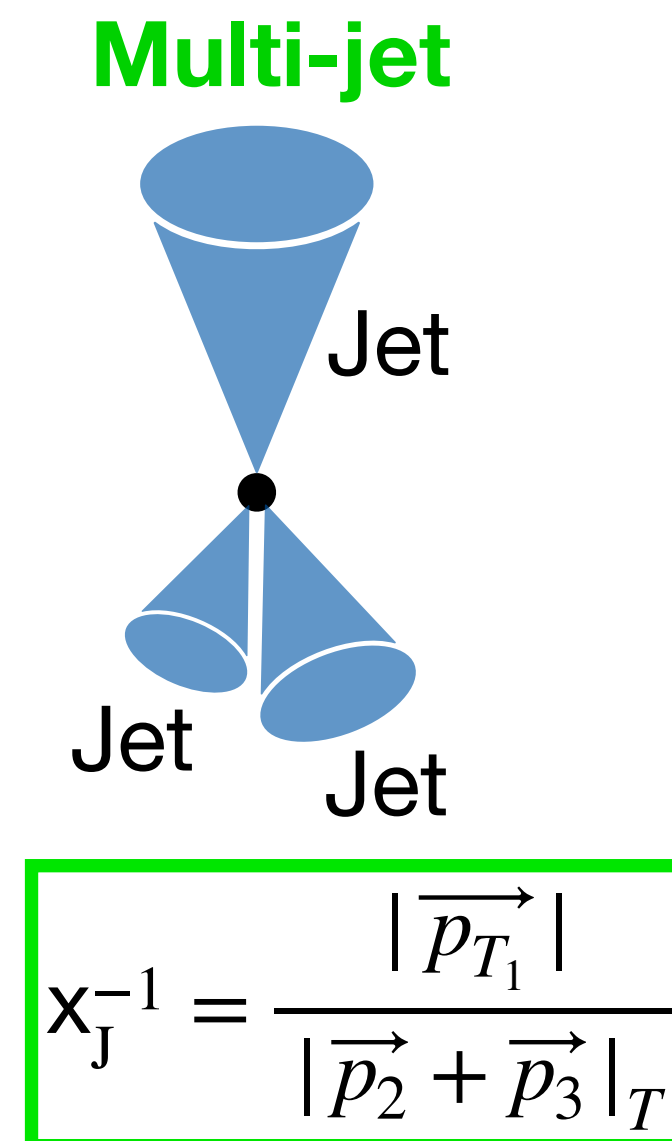
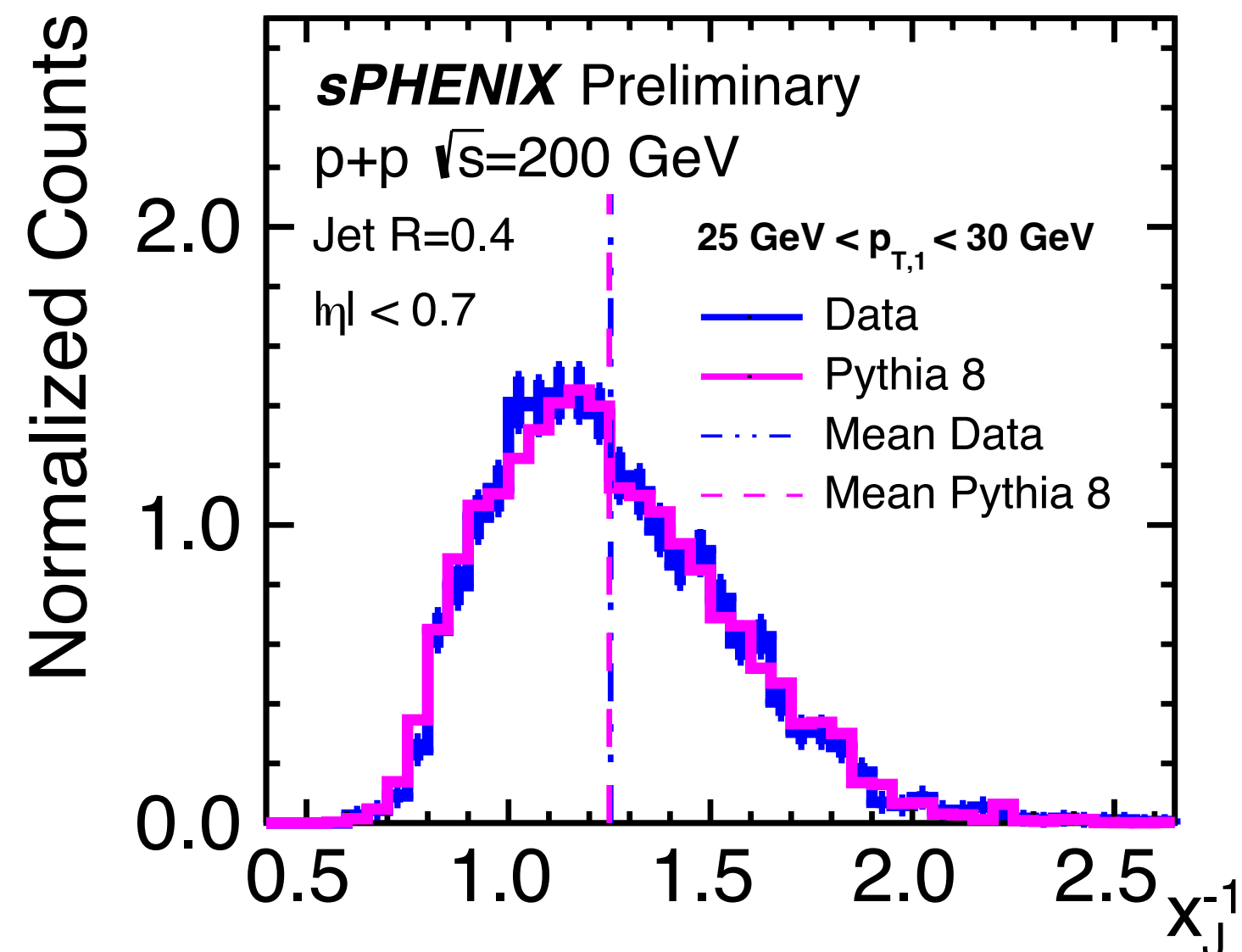
- Initial HCal calibration to EM scale MIPs
- Jet energy scale account for hadronic scale
- In-situ methods applied for data-to-MC corrections (next slides)

In-situ jet energy scale (JES)

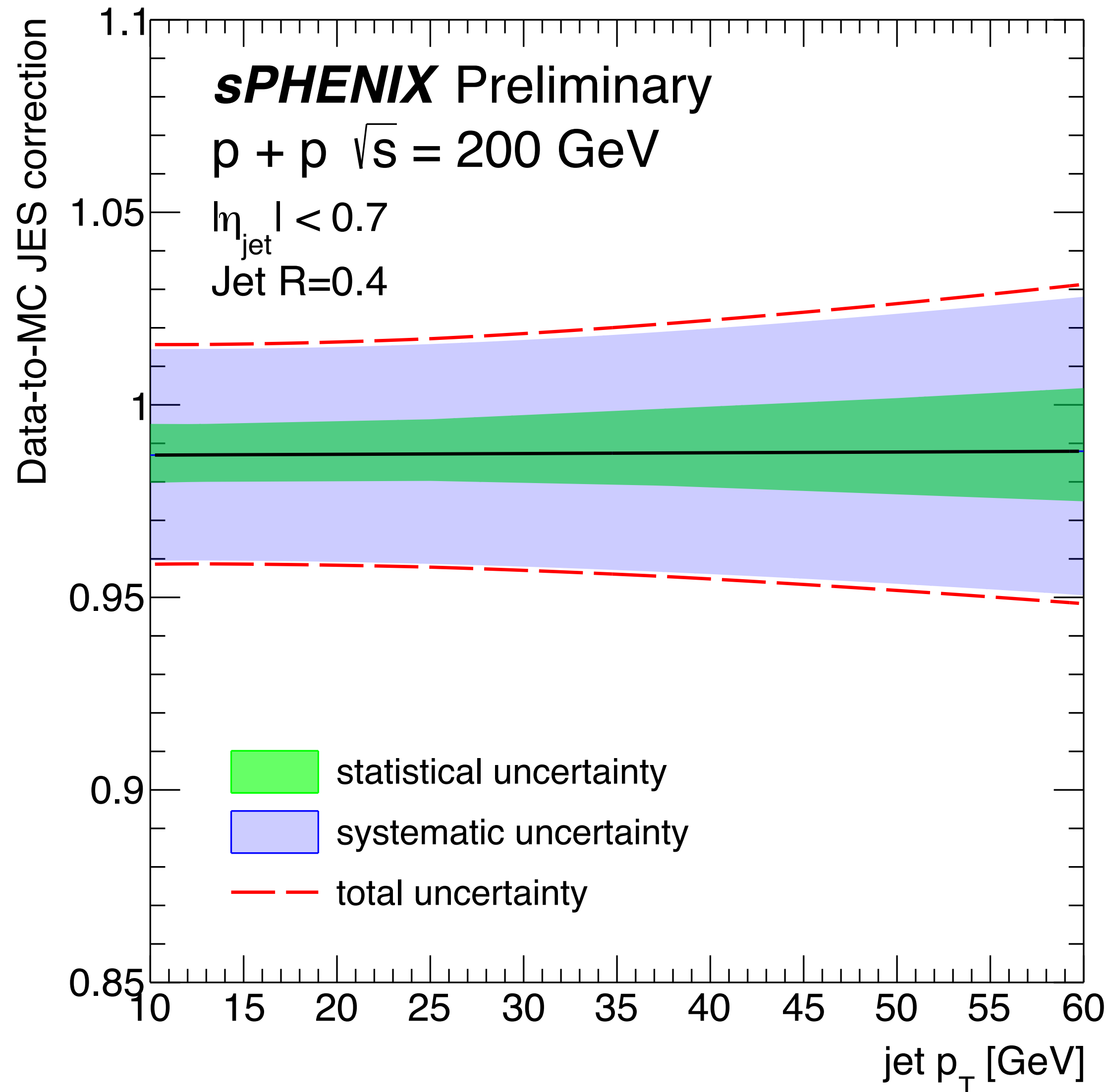


Preliminary absolute jet energy scale

- Use **γ -jet** and **multi-jet** channels to calibrate the jet energy scale over a wide range $10 < p_T^{\text{jet}} < 60 \text{ GeV}$



In-situ jet energy scale (JES)



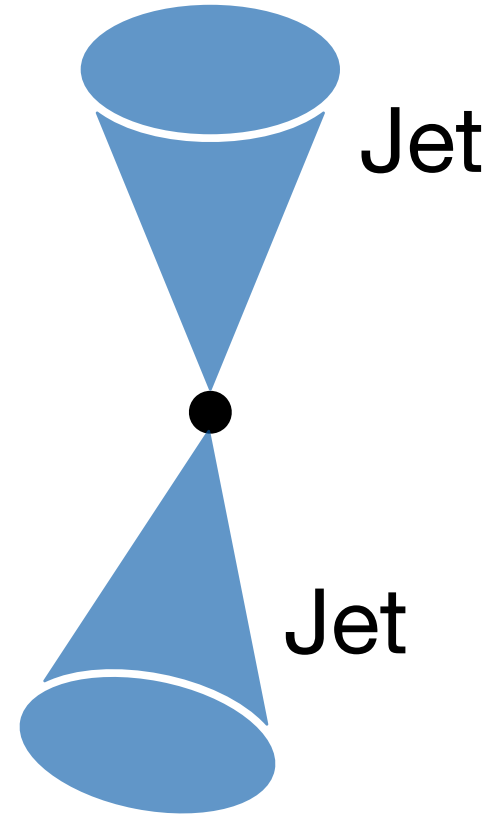
Preliminary absolute jet energy scale

- Use **γ -jet** and **multi-jet** channels to calibrate the jet energy scale over a wide range $10 < p_T^{\text{jet}} < 60 \text{ GeV}$
- **Global Data-to-MC fit** derived using both channels to determine absolute JES correction and uncertainties

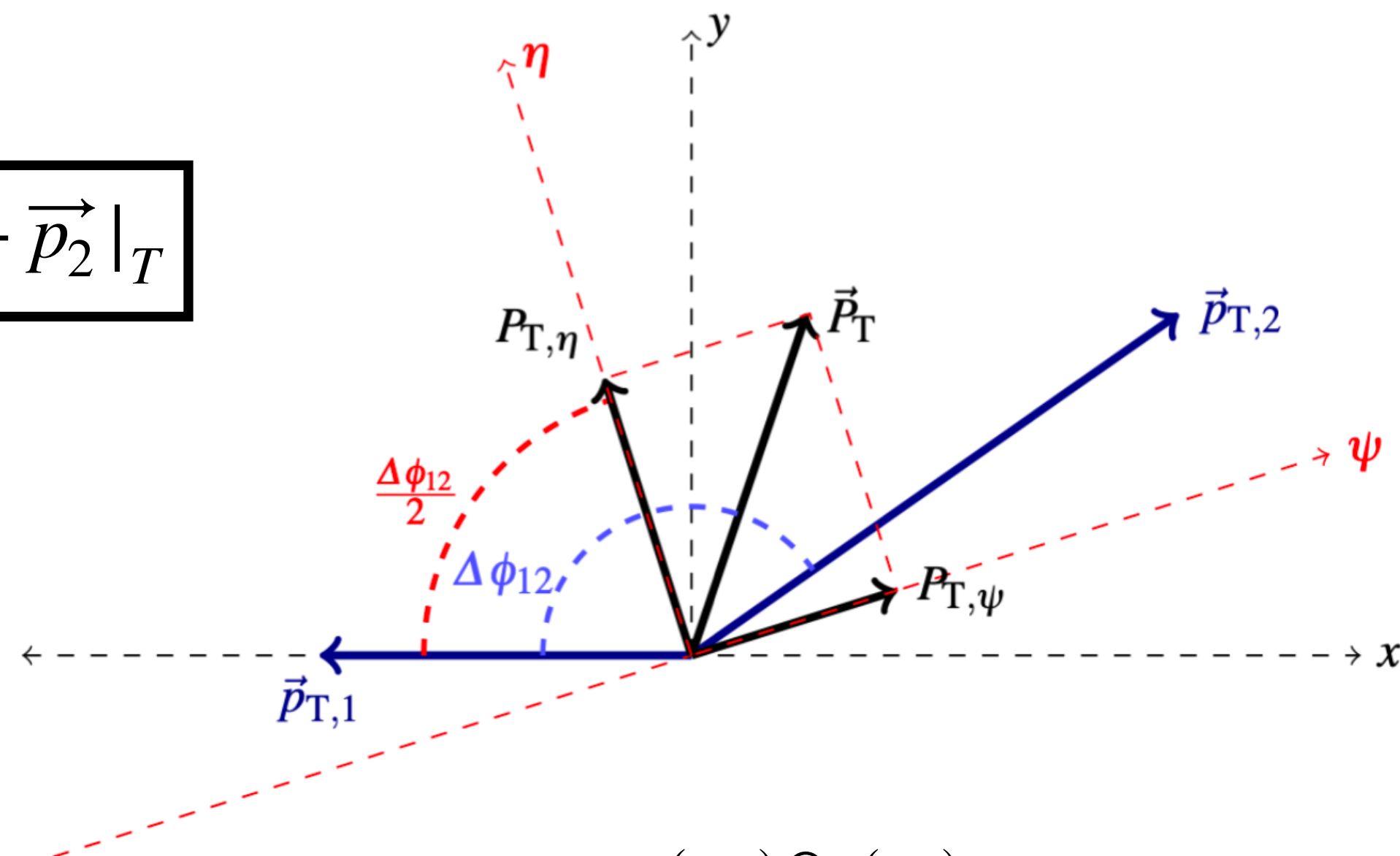
Data-driven jet energy resolution (JER)

1. Bisector method

- Assuming soft radiation imbalance is isotropic
- Detector smearing affects only jet magnitude into ψ projection



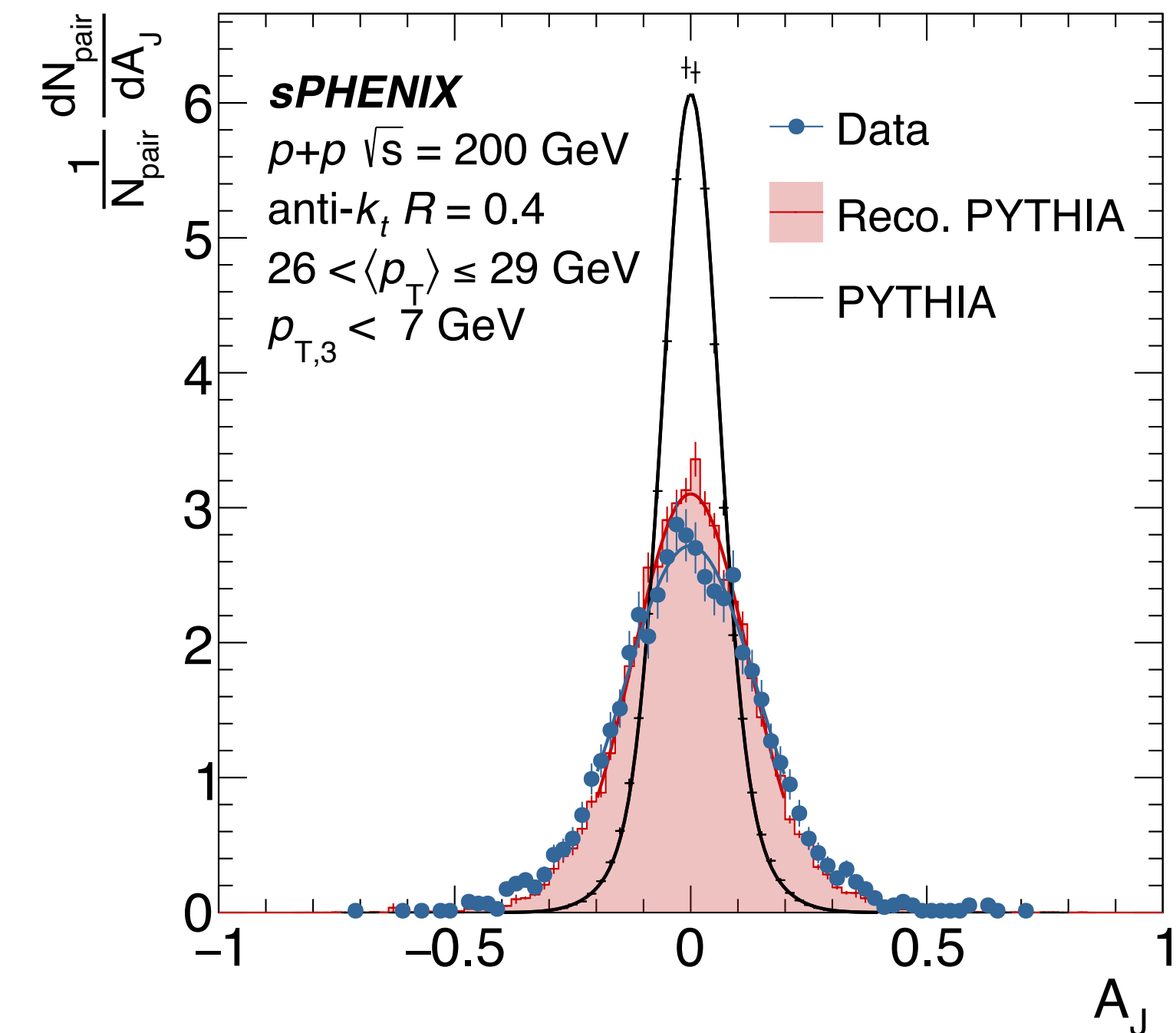
$$\langle p_T \rangle = |\vec{p}_1 + \vec{p}_2|_T$$



$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma(p_{T\psi}) \ominus \sigma(p_{T\eta})}{\sqrt{2} \langle p_T \rangle \sqrt{\langle |\cos \Delta\phi| \rangle}}$$

2. Momentum imbalance

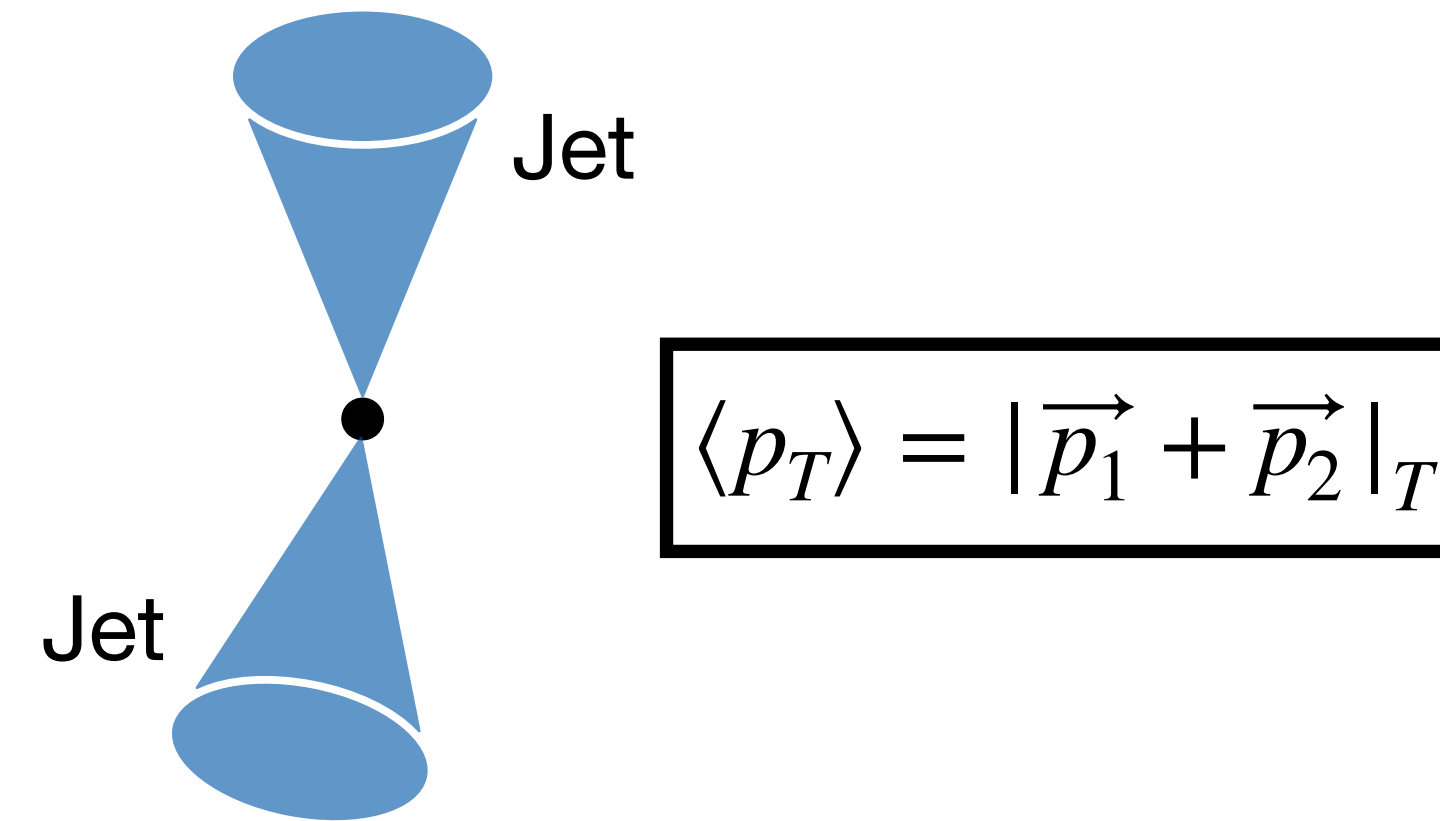
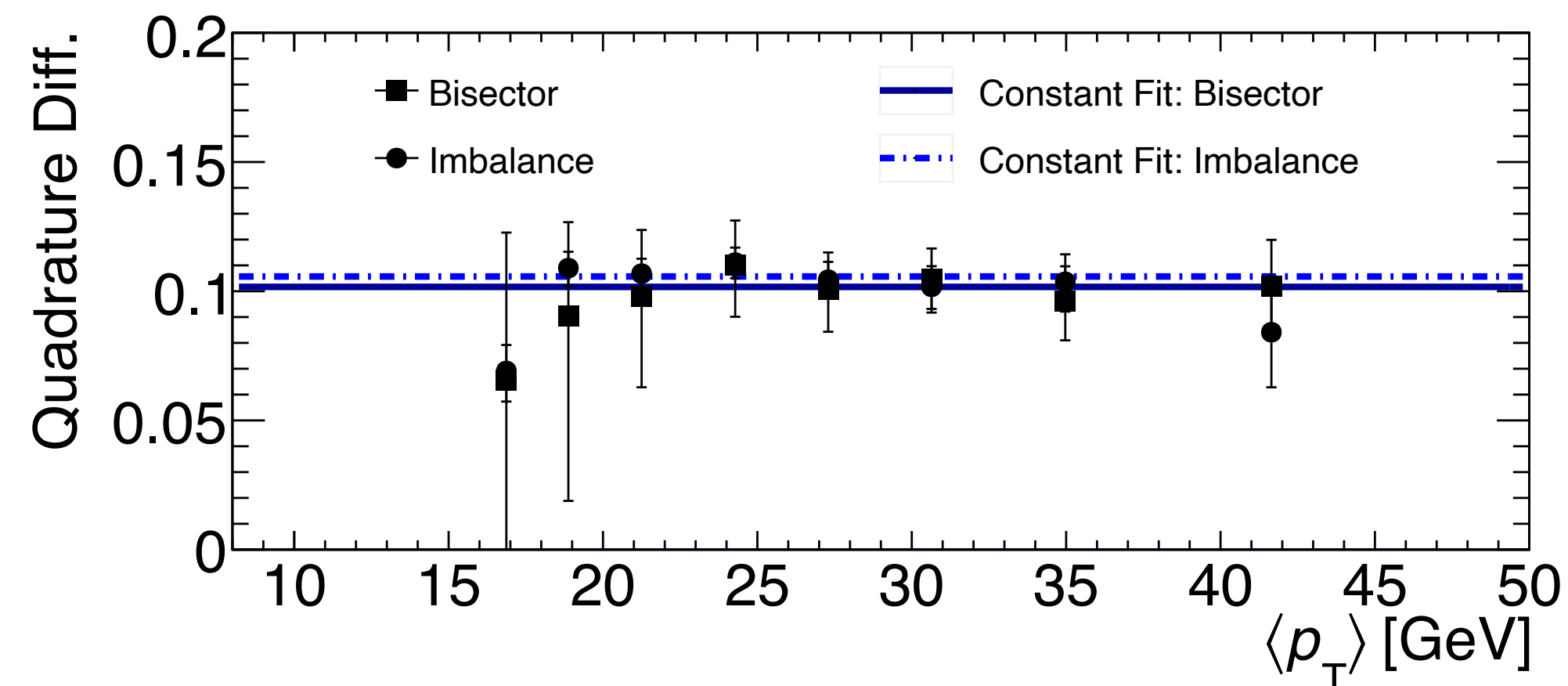
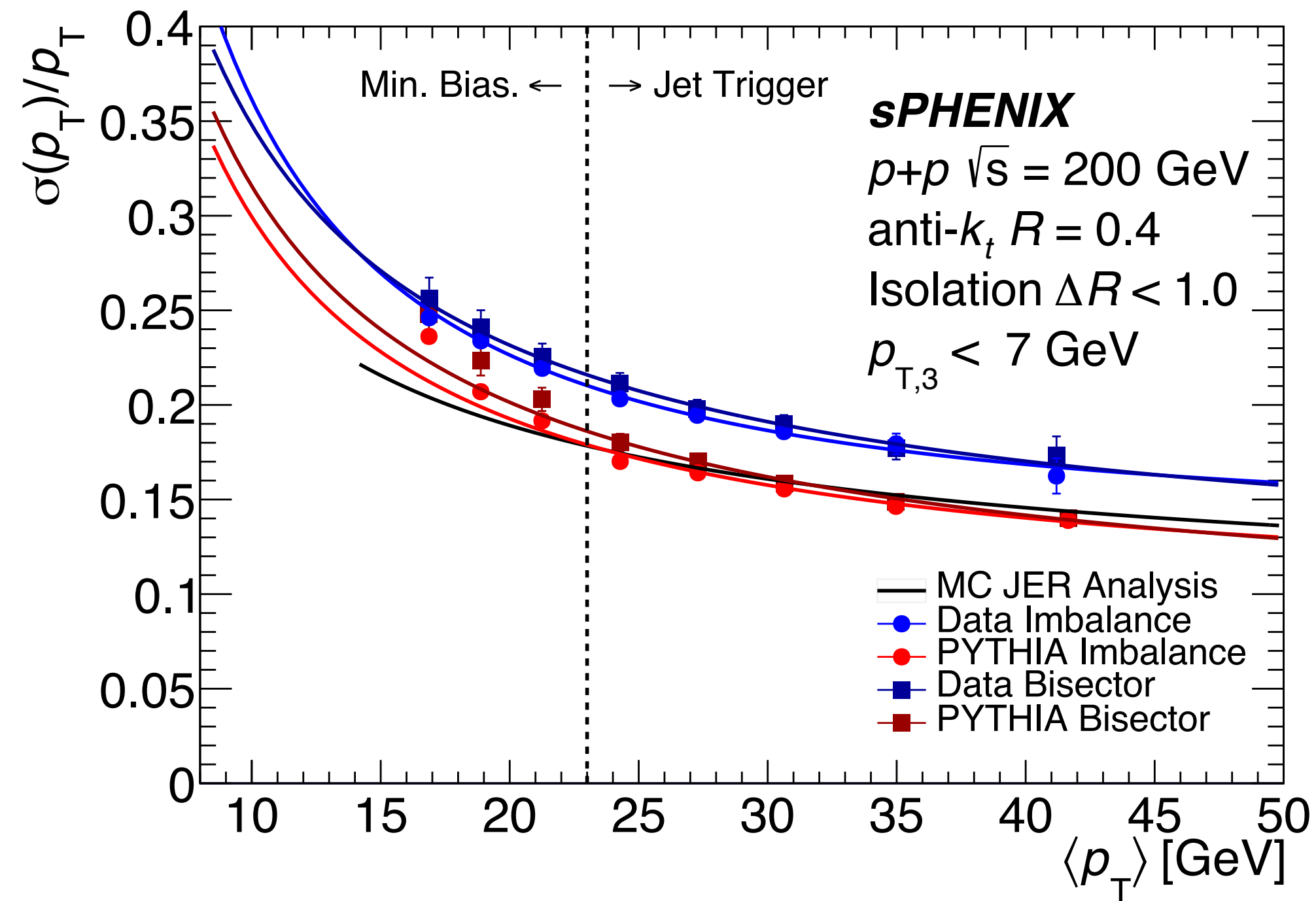
- Assuming detector smearing and physics are in quadrature (Gaussian independent)
- Extrapolating to no third jet (hard veto)



$$A_J = \frac{p_{T1} - p_{T2}}{p_{T1} + p_{T2}}$$

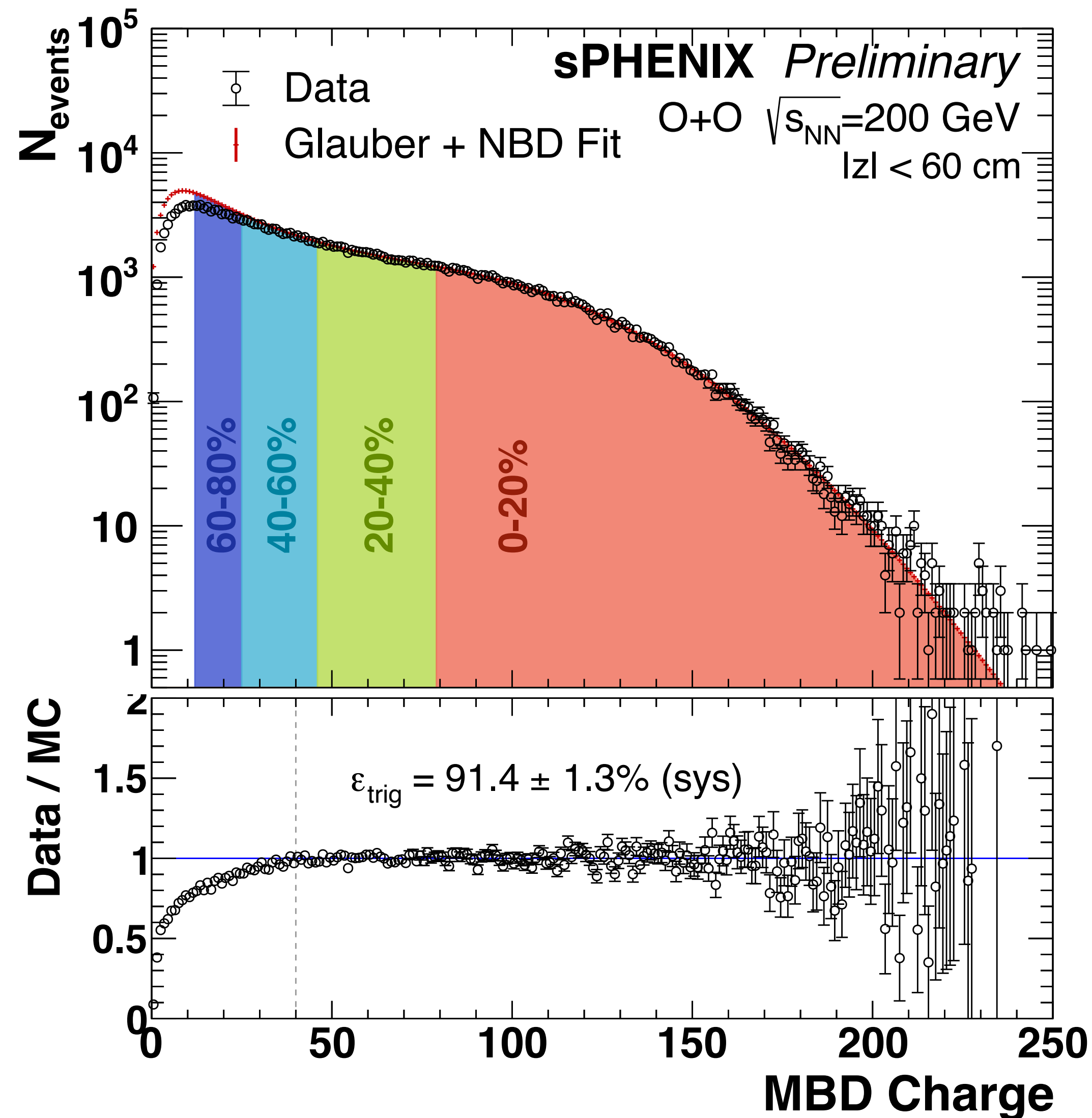
$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma_{A_J, \text{det}}}{\sqrt{2}} = \frac{\sqrt{\sigma_{A_J, \text{reco}}^2 - \sigma_{A_J, \text{truth}}^2}}{\sqrt{2}}$$

Data-driven jet energy resolution (JER)



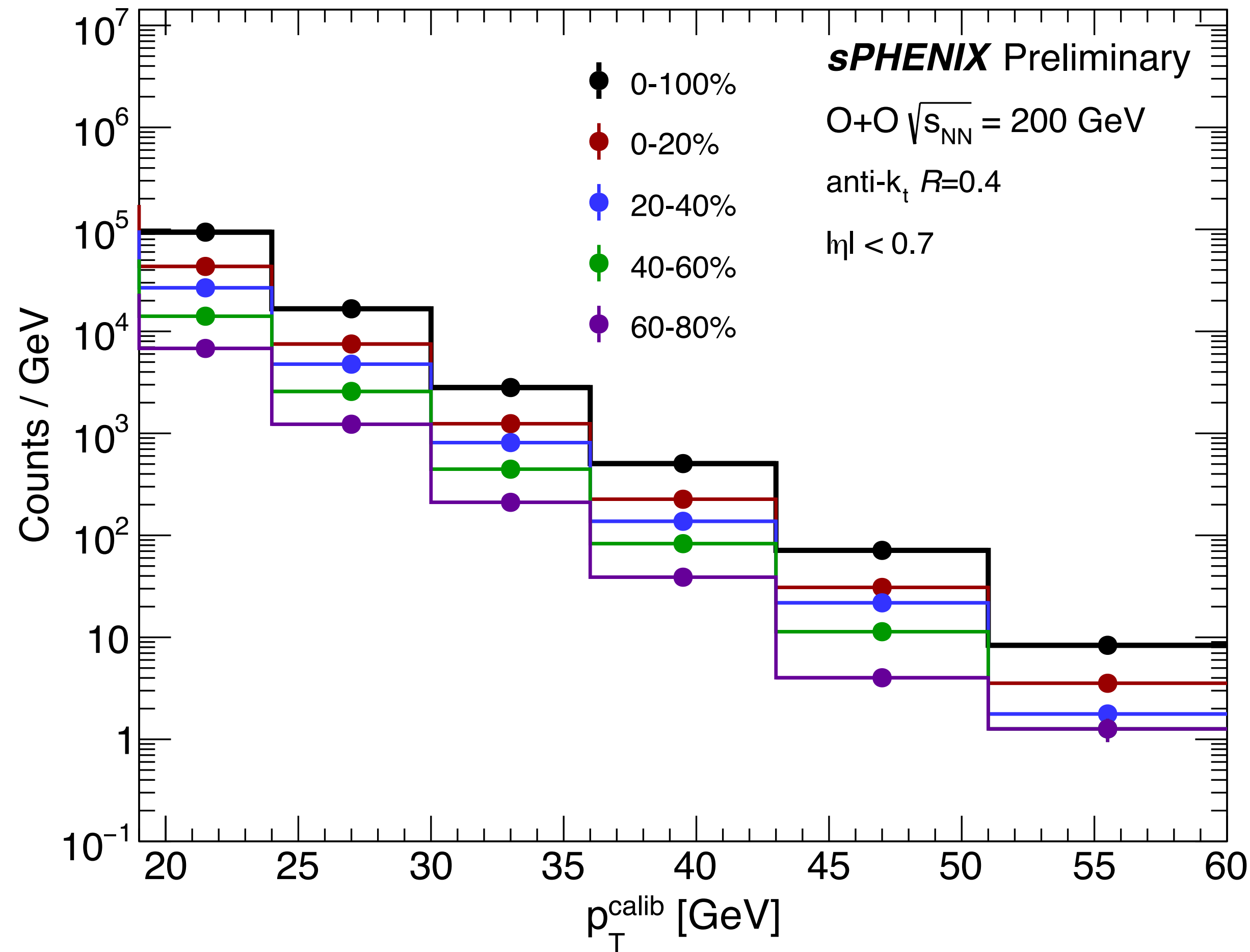
- **JER** compared for **data** and **MC** using **bisector & imbalance** methods
- **Similar results** within data and MC for the **two method** (very different assumptions)
- **MC smeared** to match the JER in data

Centrality in Oxygen-Oxygen 200 GeV



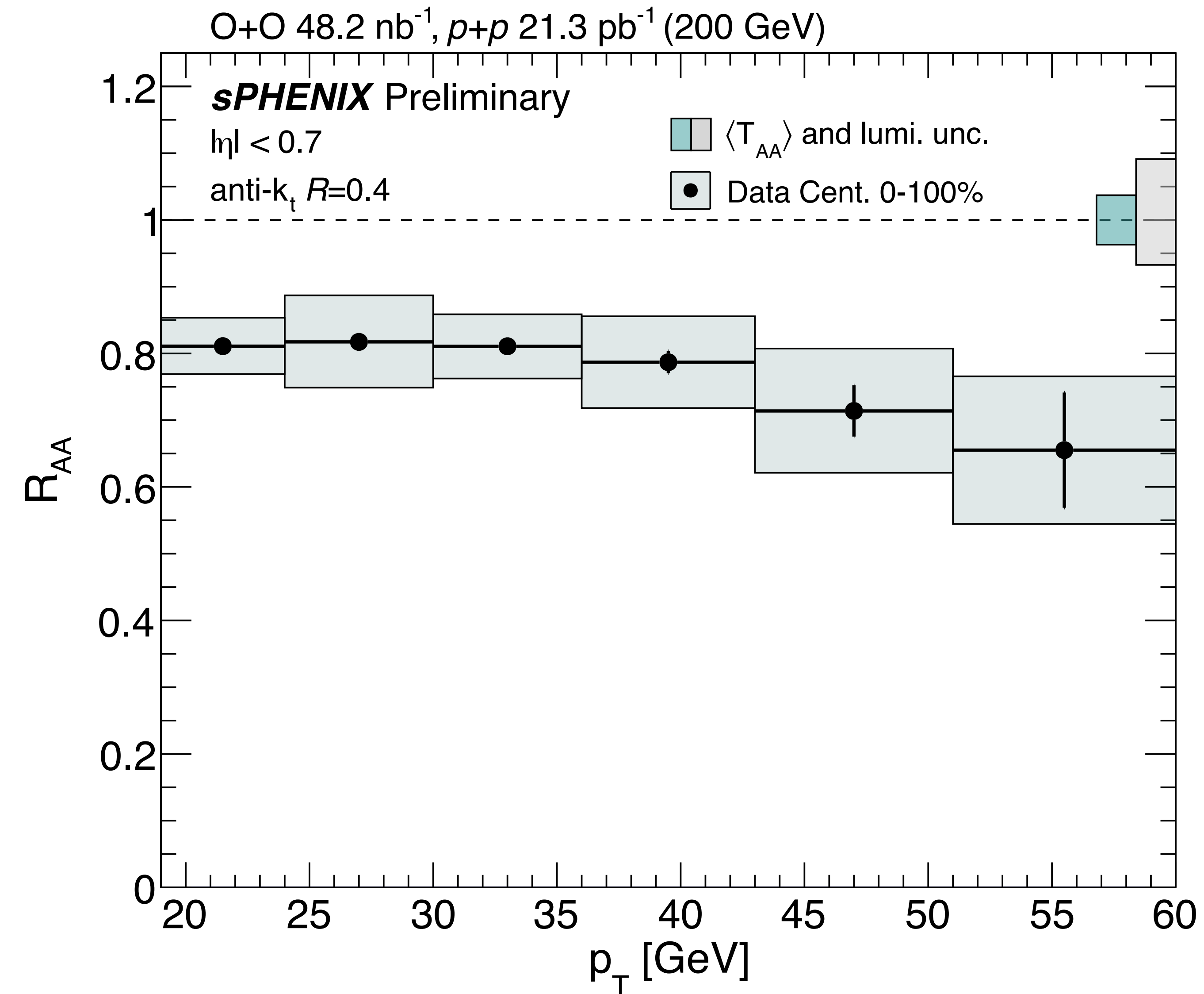
- Forward minimum bias detector (MBD) used for centrality calibration
- Well calibrated for Glauber + NBD fit using simple N_{part} scaling
- Uncertainties on calibration and Glauber variables fairly constrained within $< 5\%$

Jet spectra in Oxygen+Oxygen 200 GeV



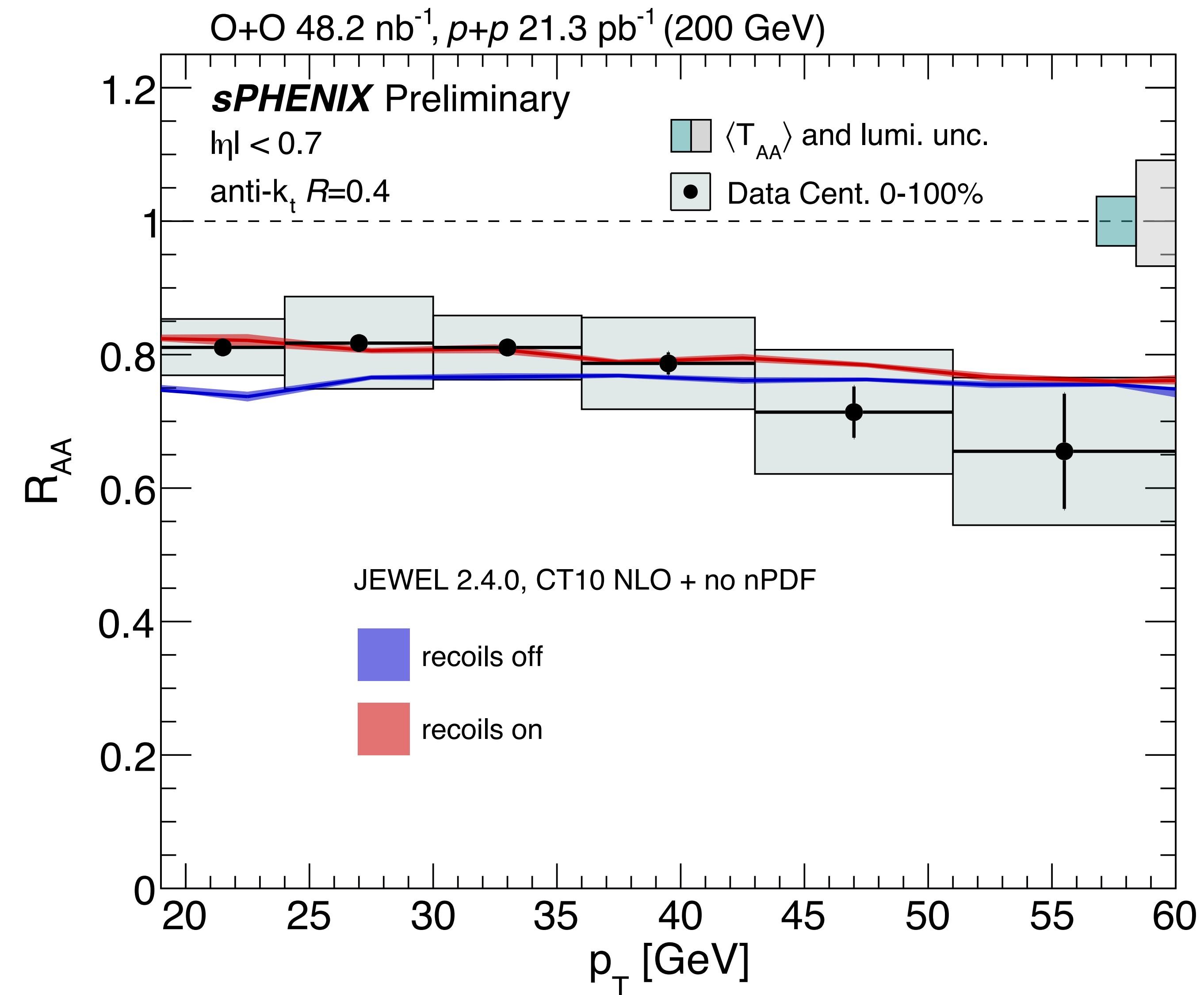
- Jet reconstructed for anti- k_t $R=0.4$
- Measured jet spectra over wide range of p_T 19-60 GeV
- UE estimated using iterative method
 - 0.5-1.0 GeV up to 2.5-3.0 GeV from peripheral to central collisions in $R=0.4$

Jet R_{AA} in Oxygen-Oxygen 200 GeV



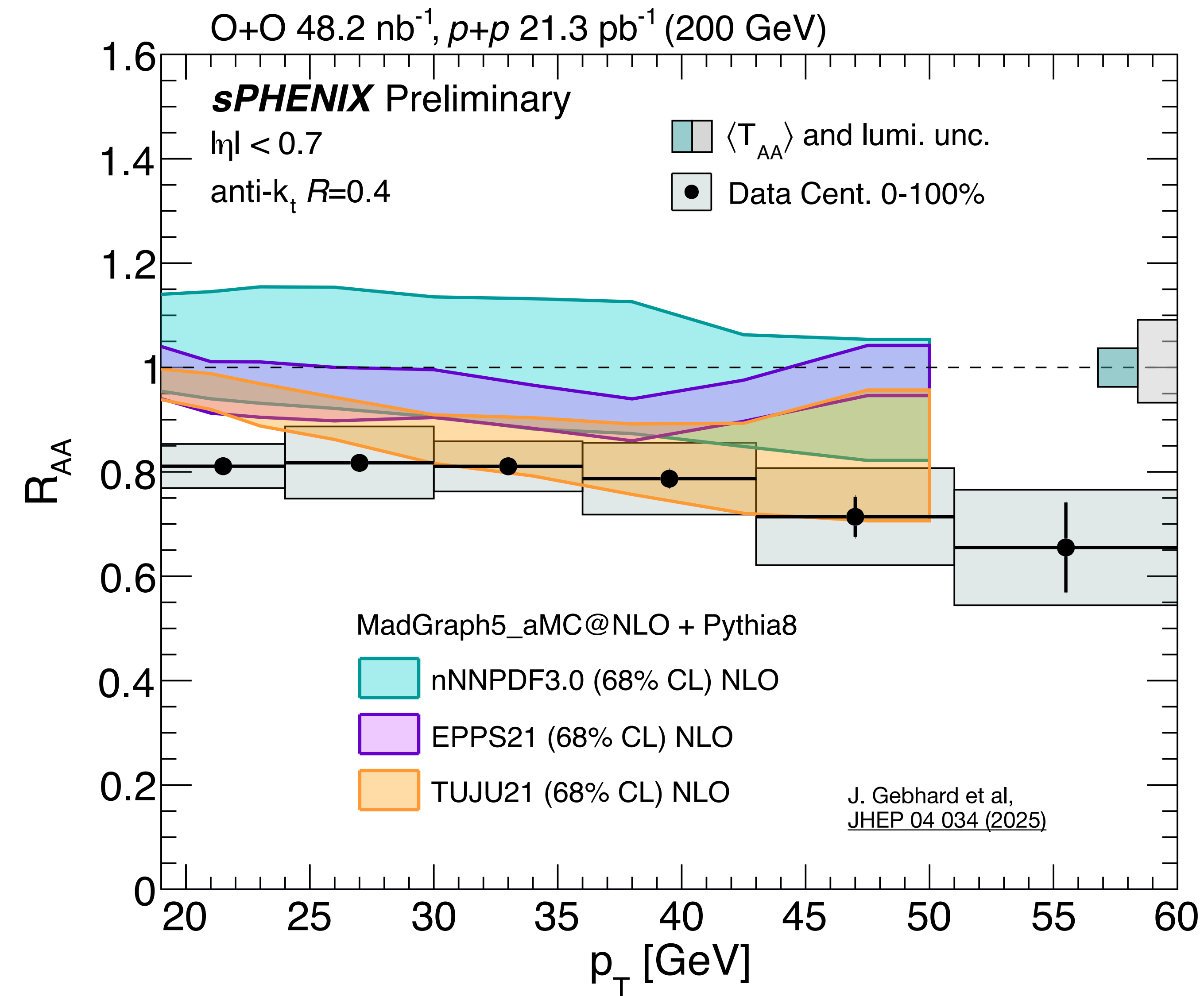
- **Suppression** of jet yields in O+O
- **Weak** dependence on p_T

Jet R_{AA} in Oxygen-Oxygen 200 GeV



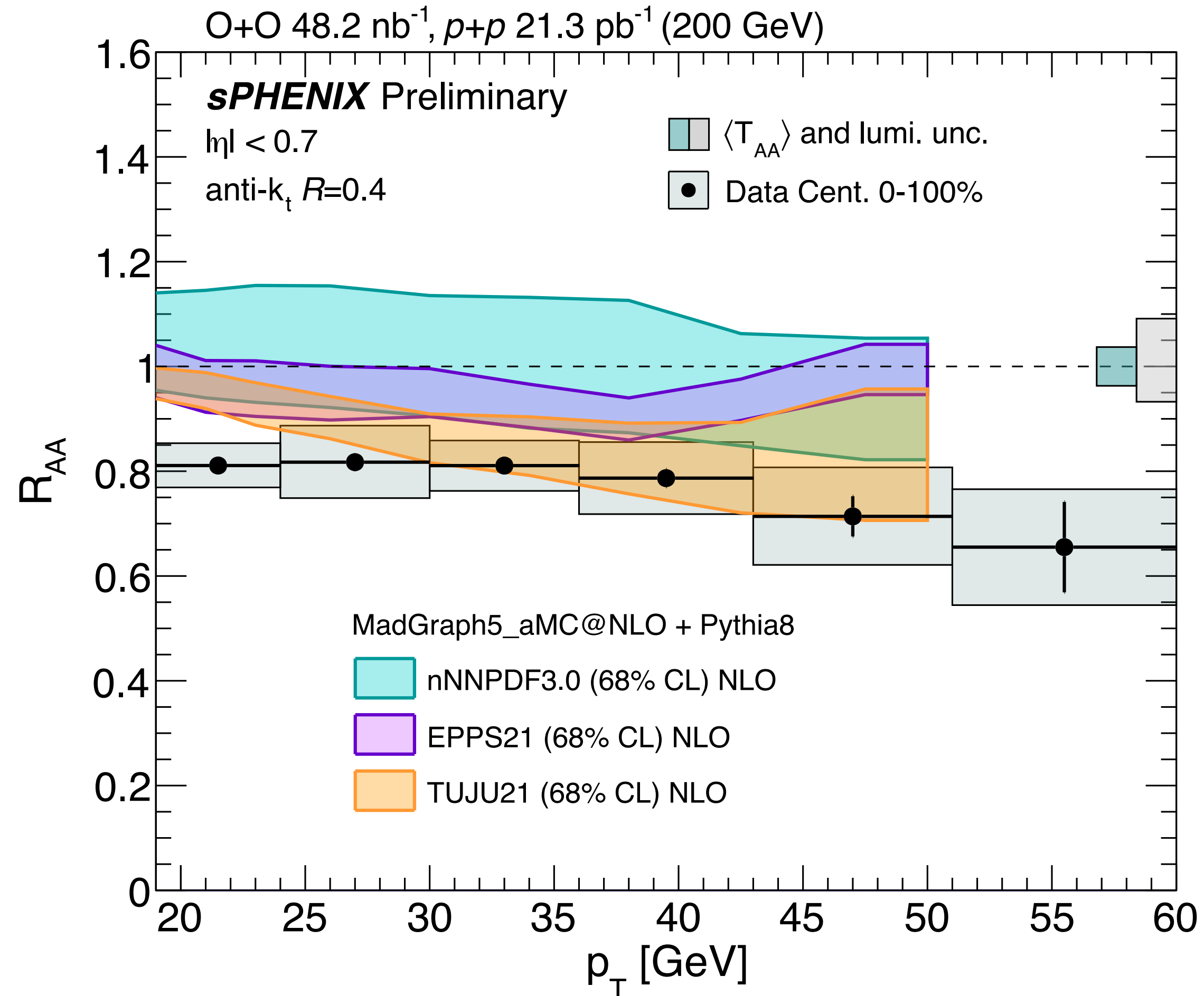
- **Suppression** of jet yields in O+O
- **Weak** dependence on p_T
- Compared to JEWEL calculations
 - **Modest** effect with **recoils** enabled

Jet R_{AA} in Oxygen-Oxygen 200 GeV



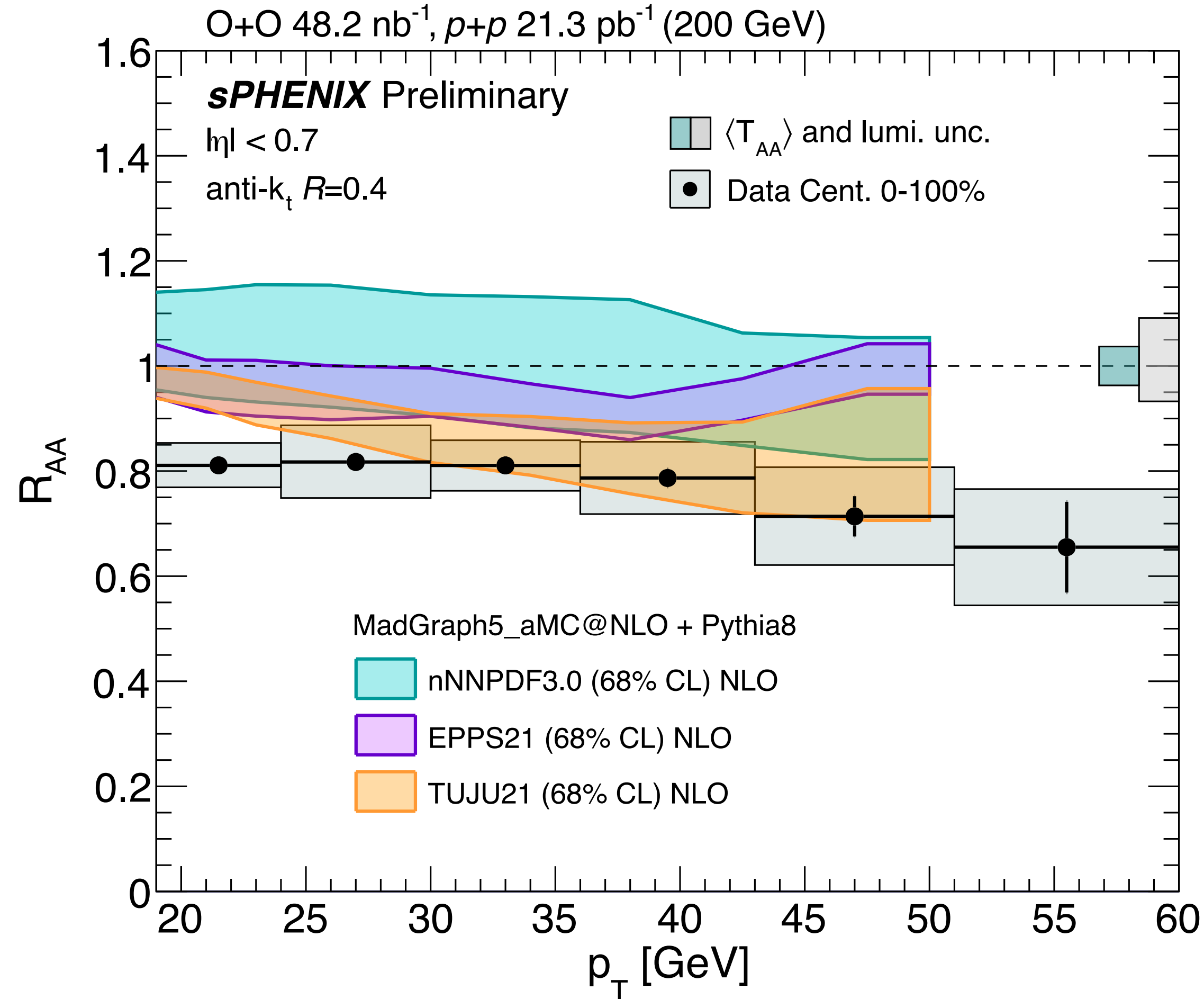
- **Suppression** of jet yields in O+O
- **Weak** dependence on p_T
- Compared to JEWEL calculations
 - **Modest** effect with **recoils** enabled
- Smaller R_{AA} than **no-quenching nPDF** baseline calculations
 - Large uncertainties on nPDF (R_{AA} near the edge of lower band)
 - No p+O at RHIC —> Need other constraining tools

nPDF constraints for O+O for RHIC energies

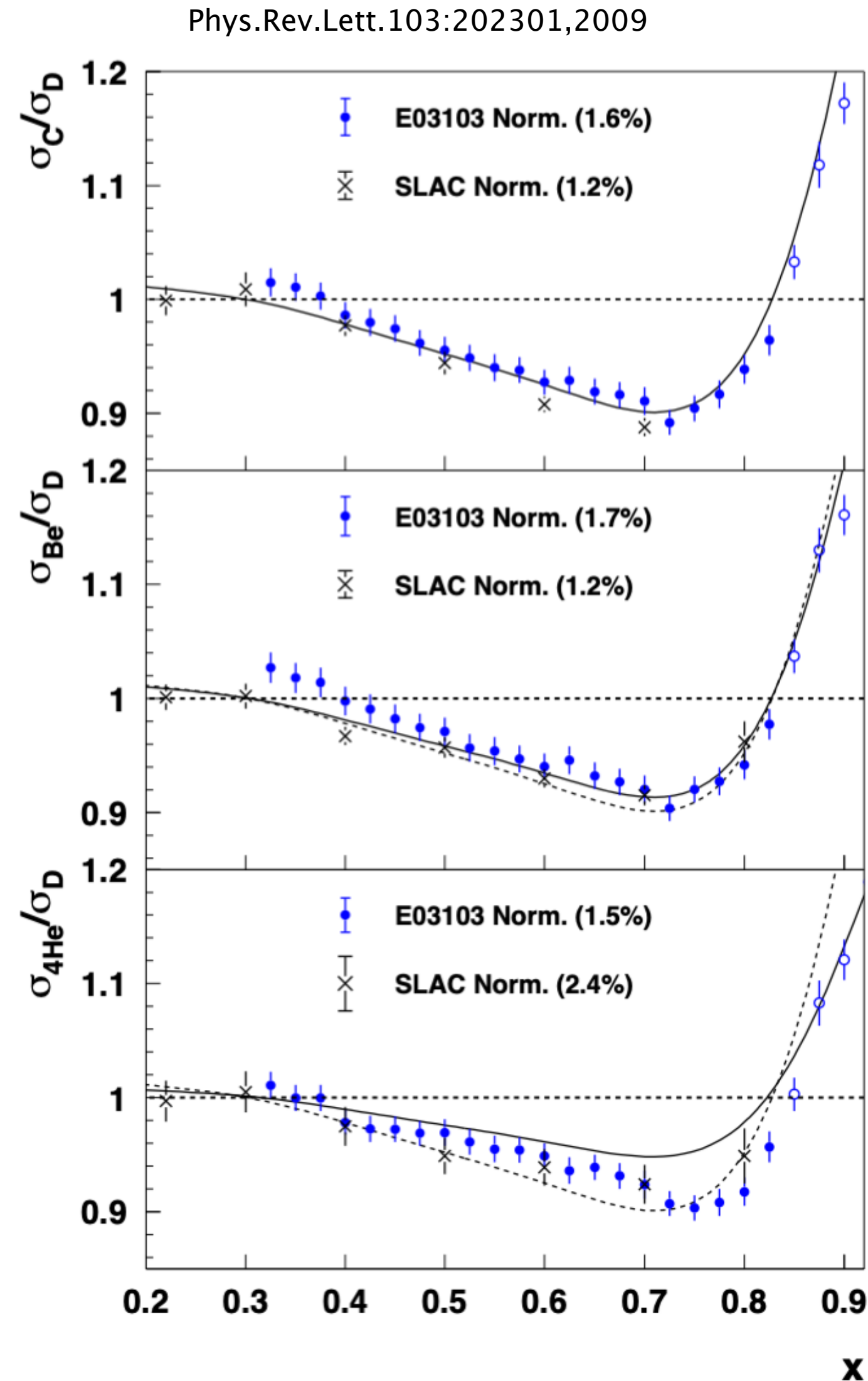


- nNNPDF3.0 assumes no constraints on oxygen
 — others do an A-scaling from heavier nucleus results
- High-x at RHIC ($x=0.5$ for $p_T=50$ GeV) near EMC region

nPDF constraints for O+O for RHIC energies



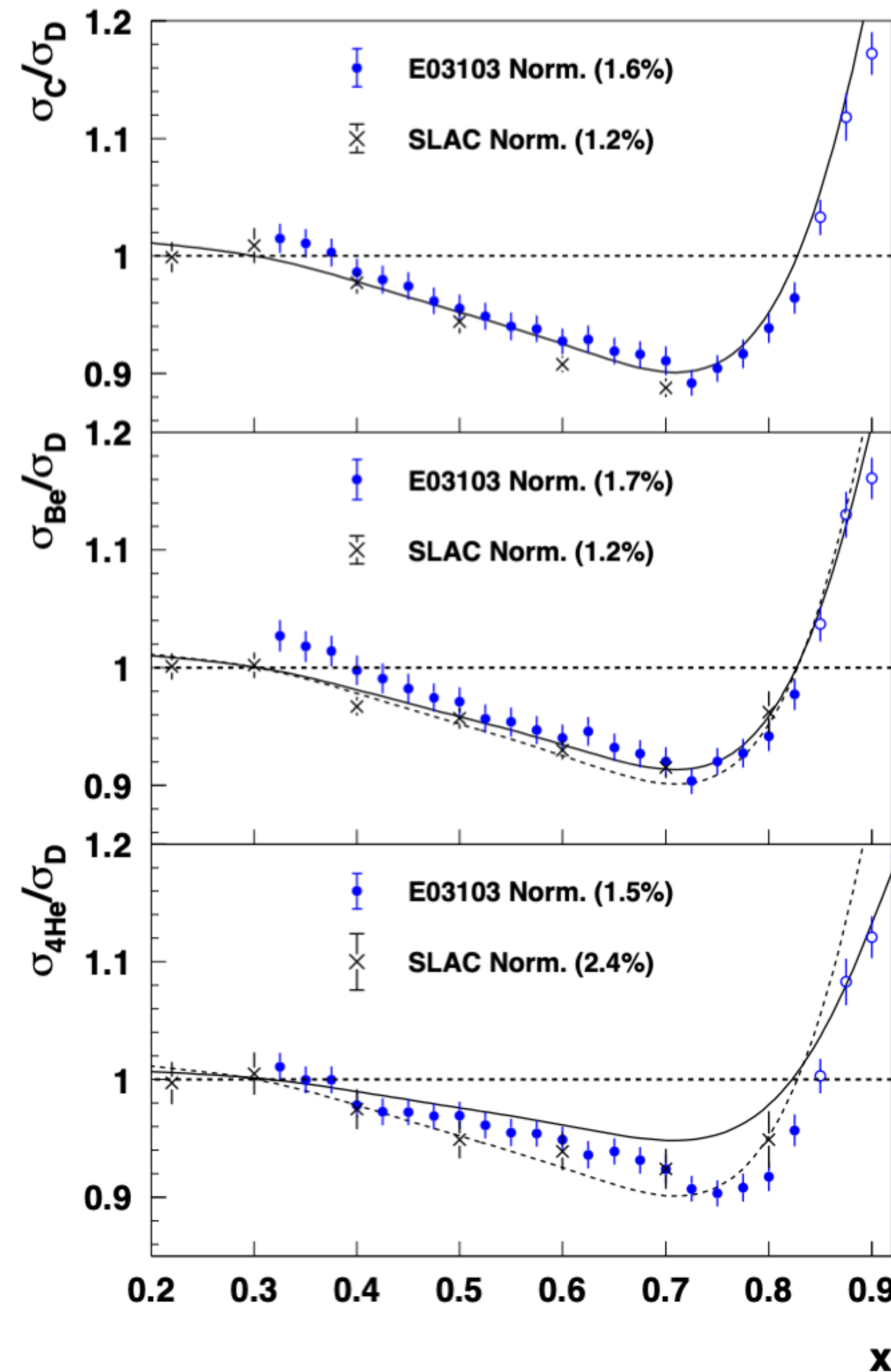
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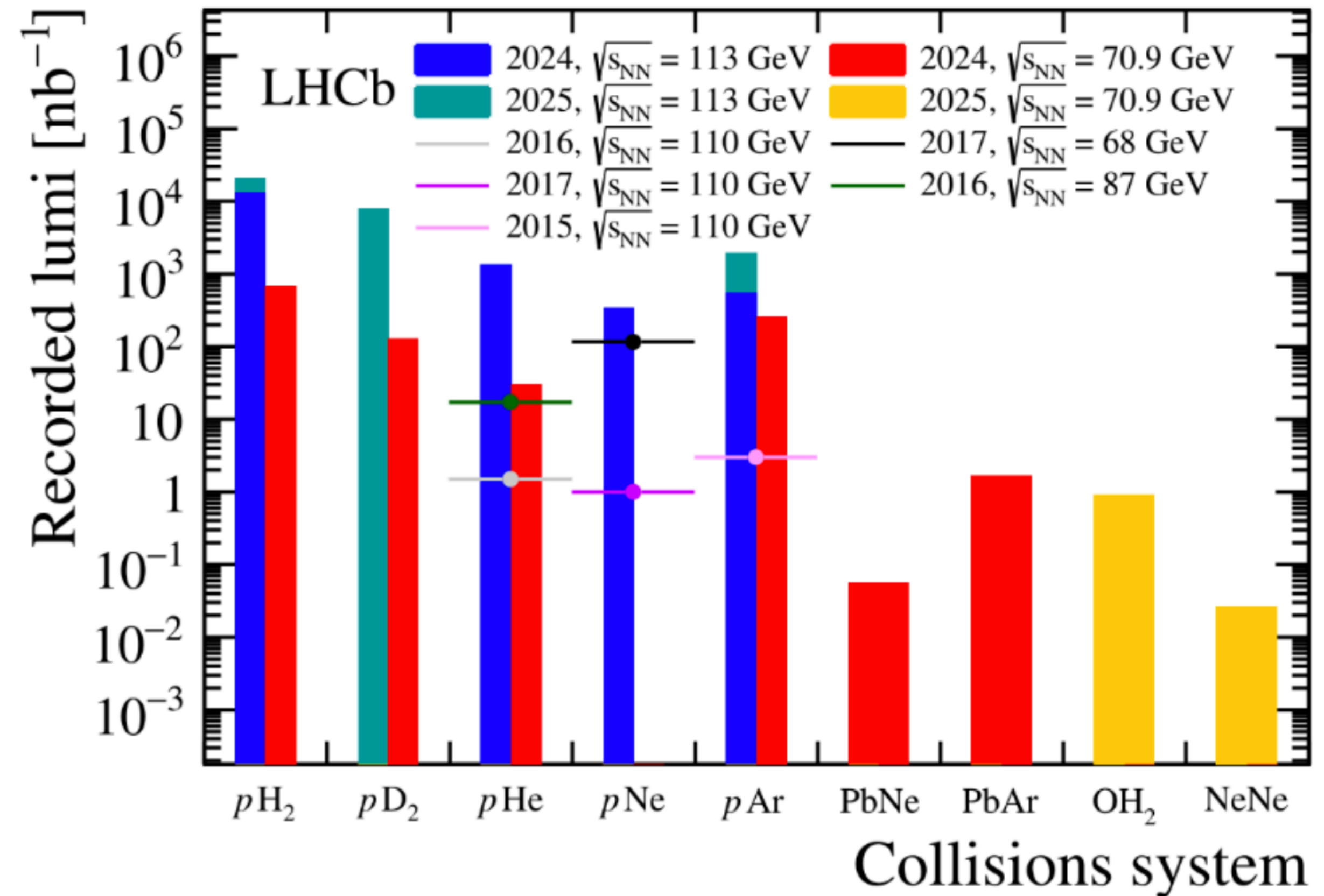
- EMC effect measured at JLab for 3He, 4He, 9Be, 12C etc.
- No strong dependence on nucleus with max. ~10%
- Limitations with Oxygen target experiment but could use other light ion results for nPDF constraints?

nPDF constraints for O+O for RHIC energies

Phys.Rev.Lett.103:202301,2009



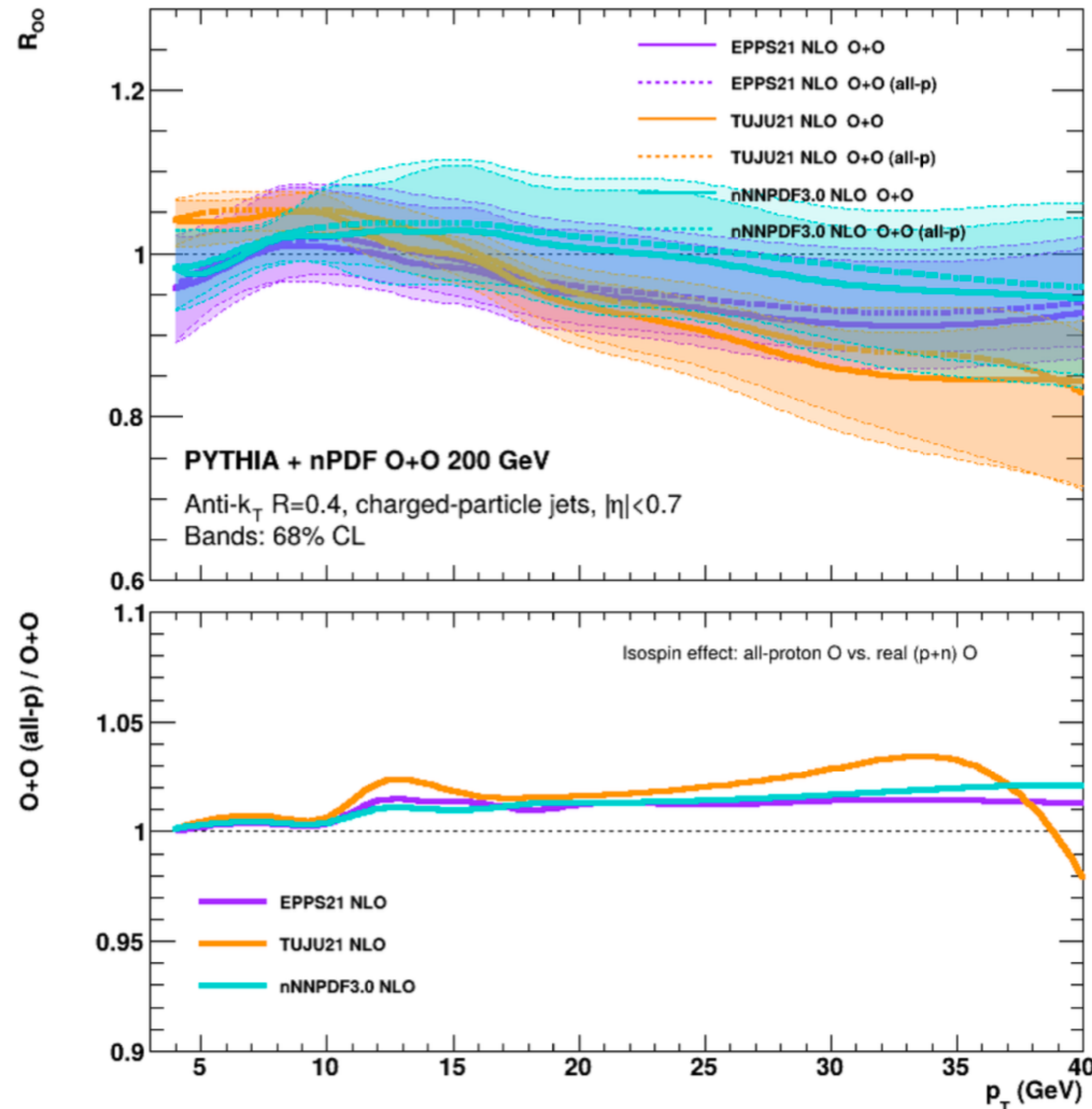
ep-news web



- Oxygen + H_2 gas experiment with SMOG2 at LHCb
- J/ψ , D^0 mesons to probe up to $x \sim 0.5-0.6$

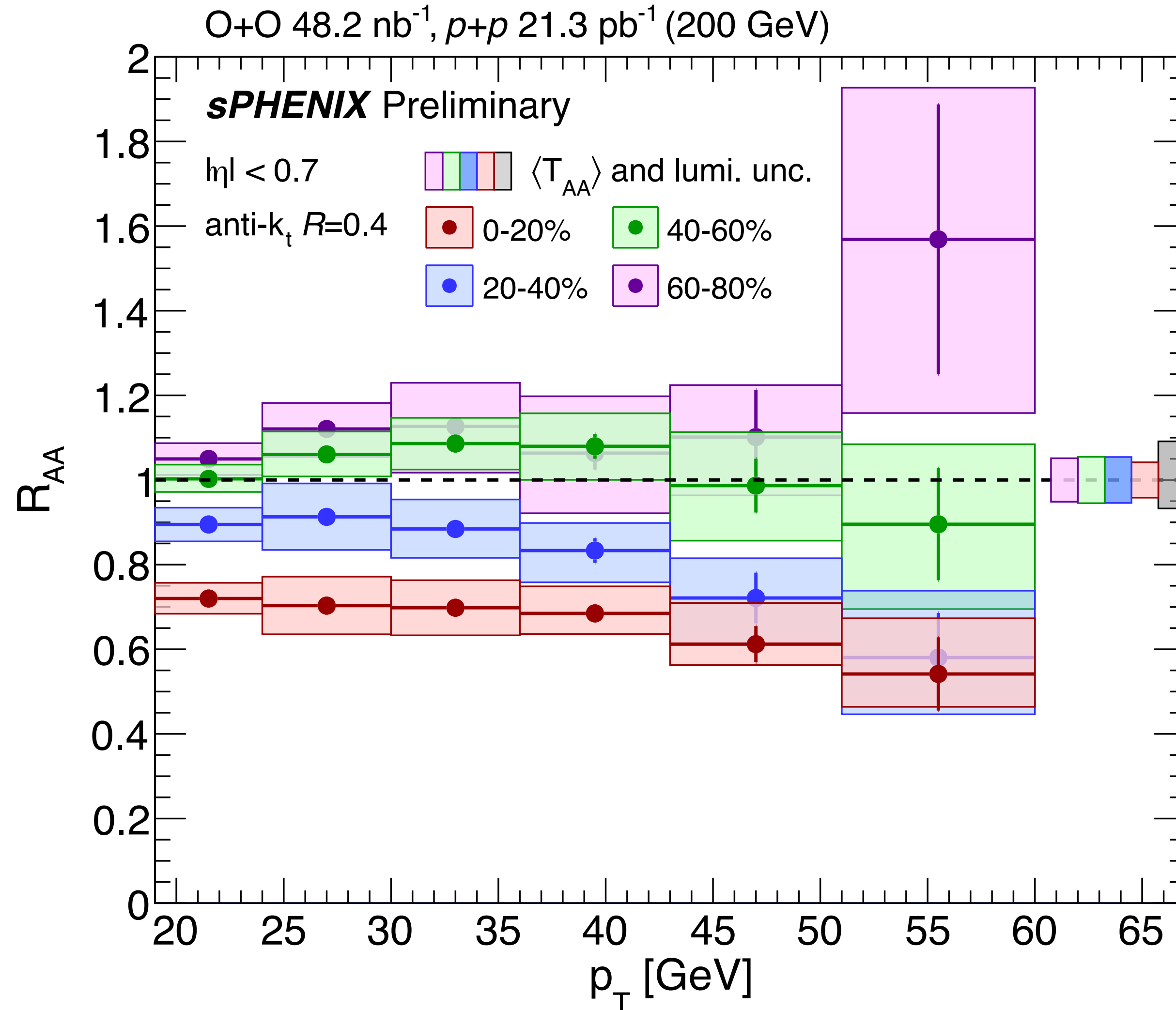
nPDF studies with MC generators

[Plots from J. Nagle]



- Check on isospin dependence as Oxygen nucleus has the same number of protons and neutrons
- Validation test on Oxygen as if for 16 protons (all-p) compared to nominal proton/neutron ratio
- Effect found to be max. $\sim 3\%$ (very small)

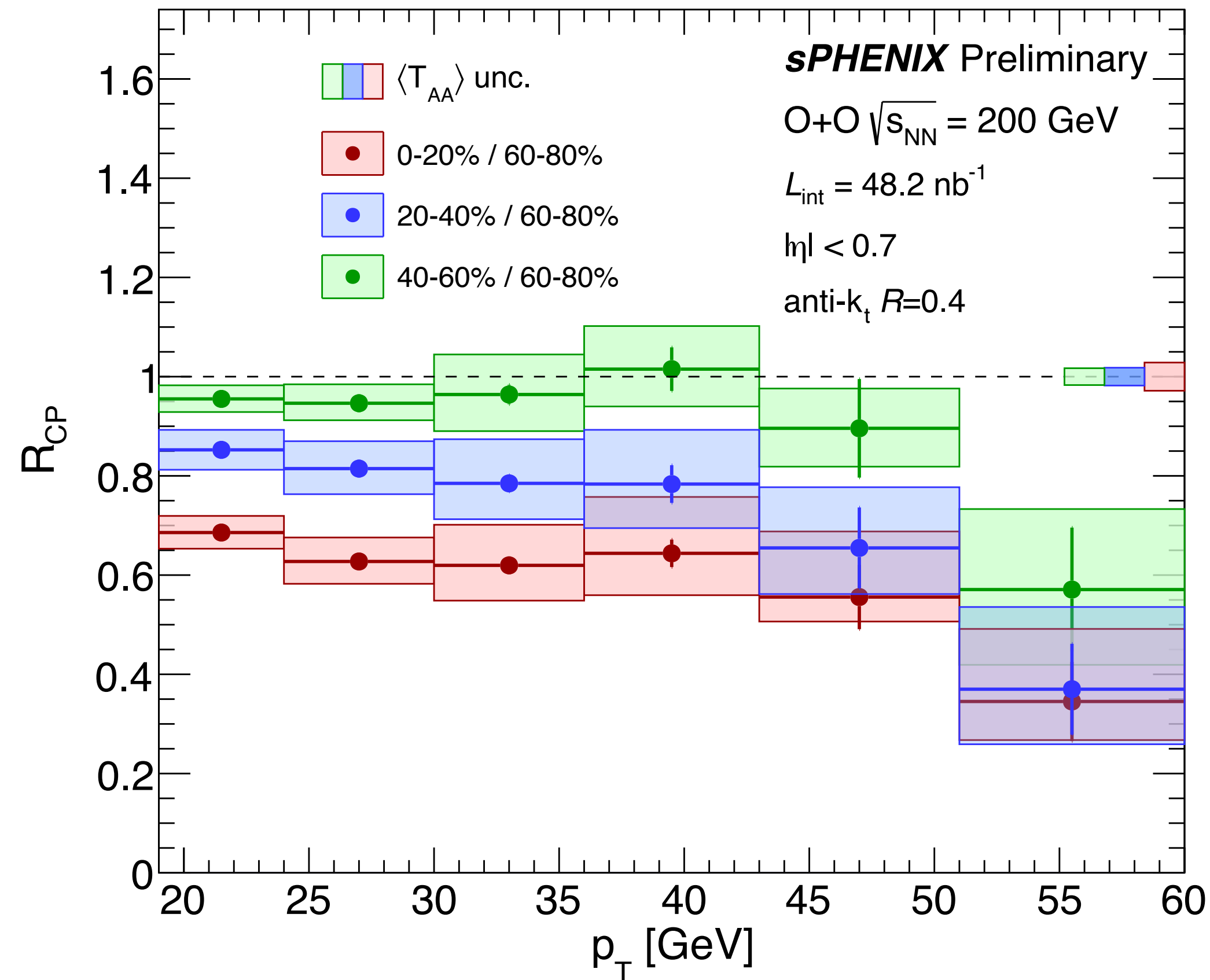
Centrality dependent jet suppression



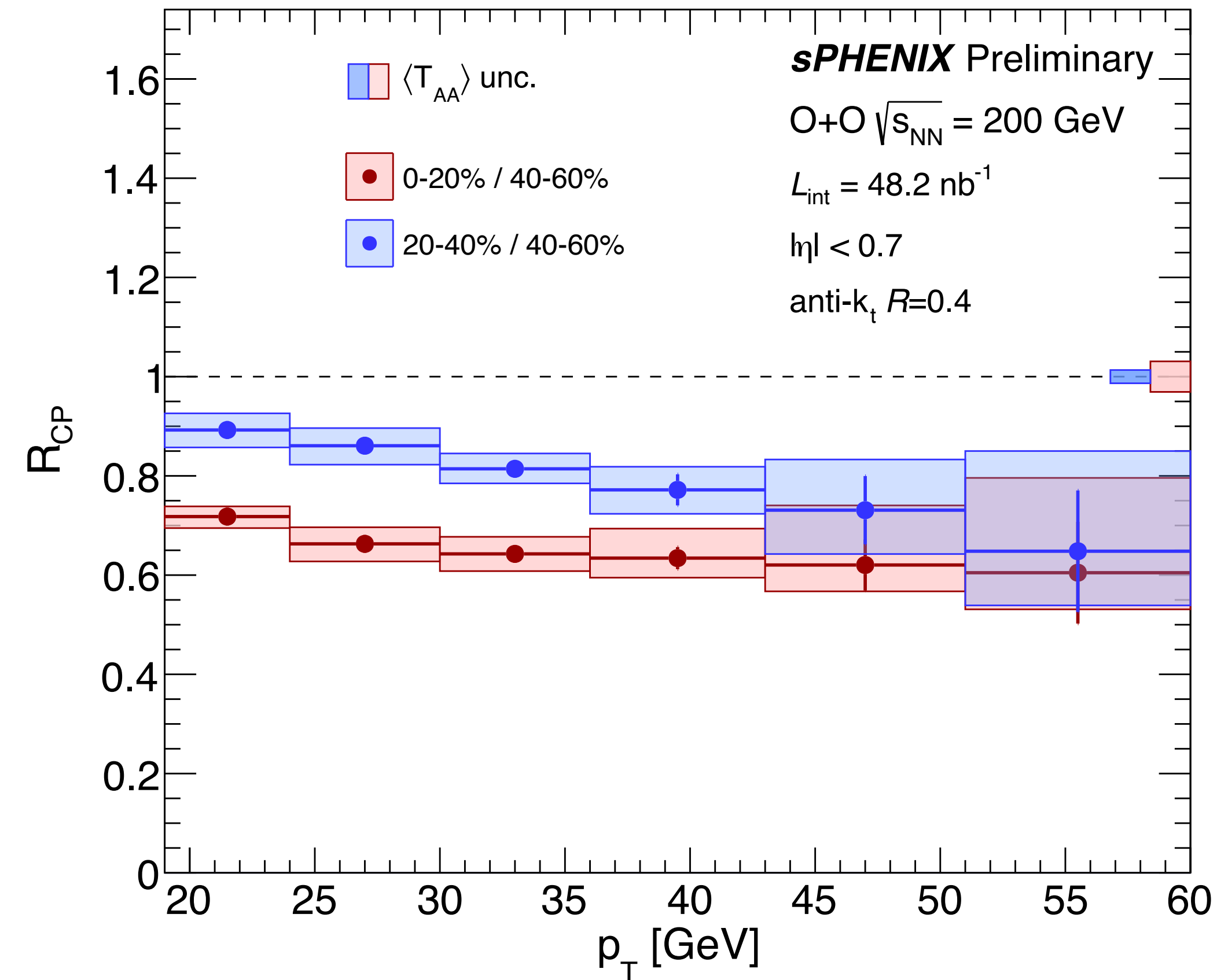
- **Centrality-dependent** absolute yield comparison between **p+p** and **O+O**
- **Clear hierarchy** towards central collisions
- Large cancellation in systematic uncertainties (JES & JER)

Jet R_{CP} in Oxygen-Oxygen 200 GeV

60-80% reference



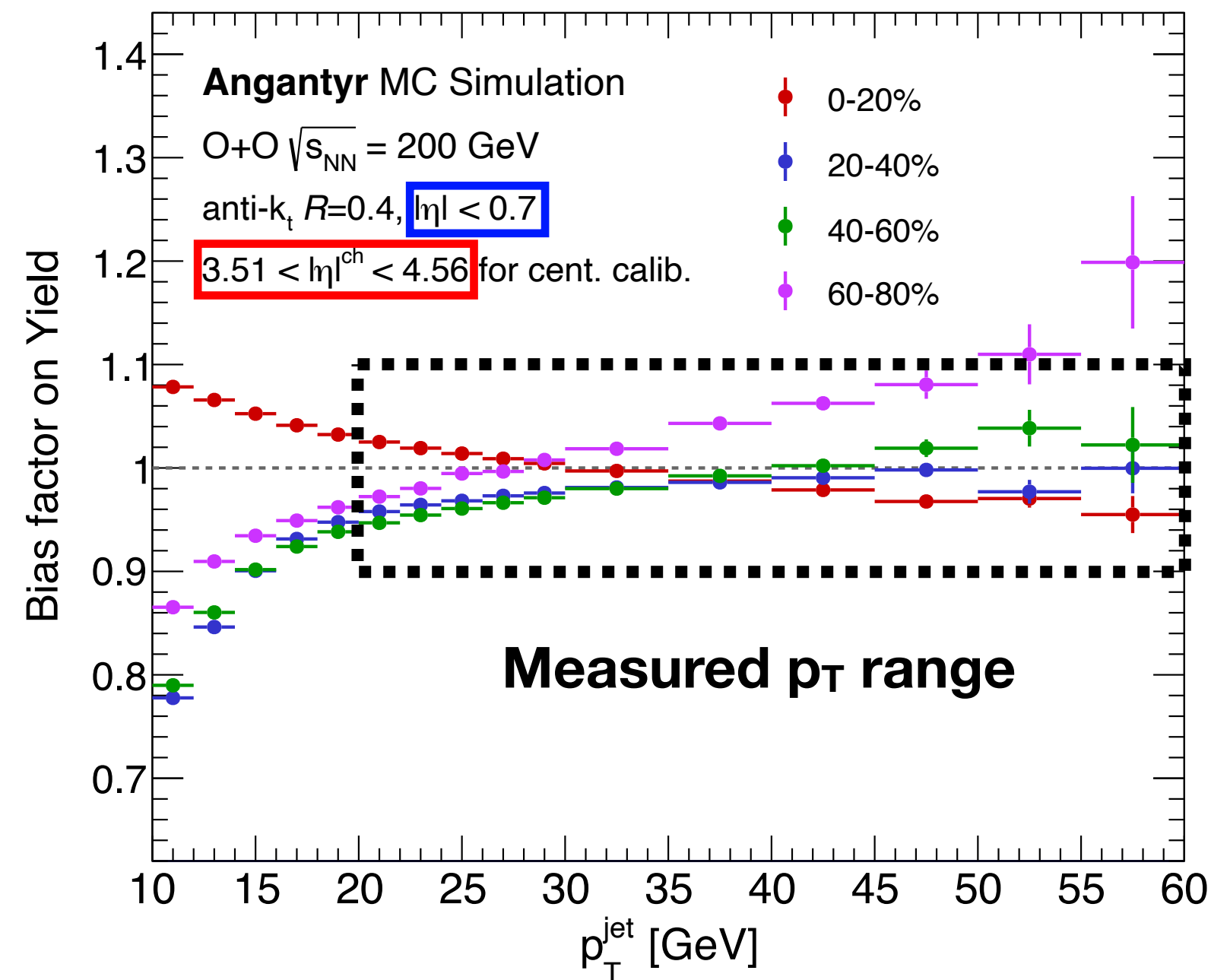
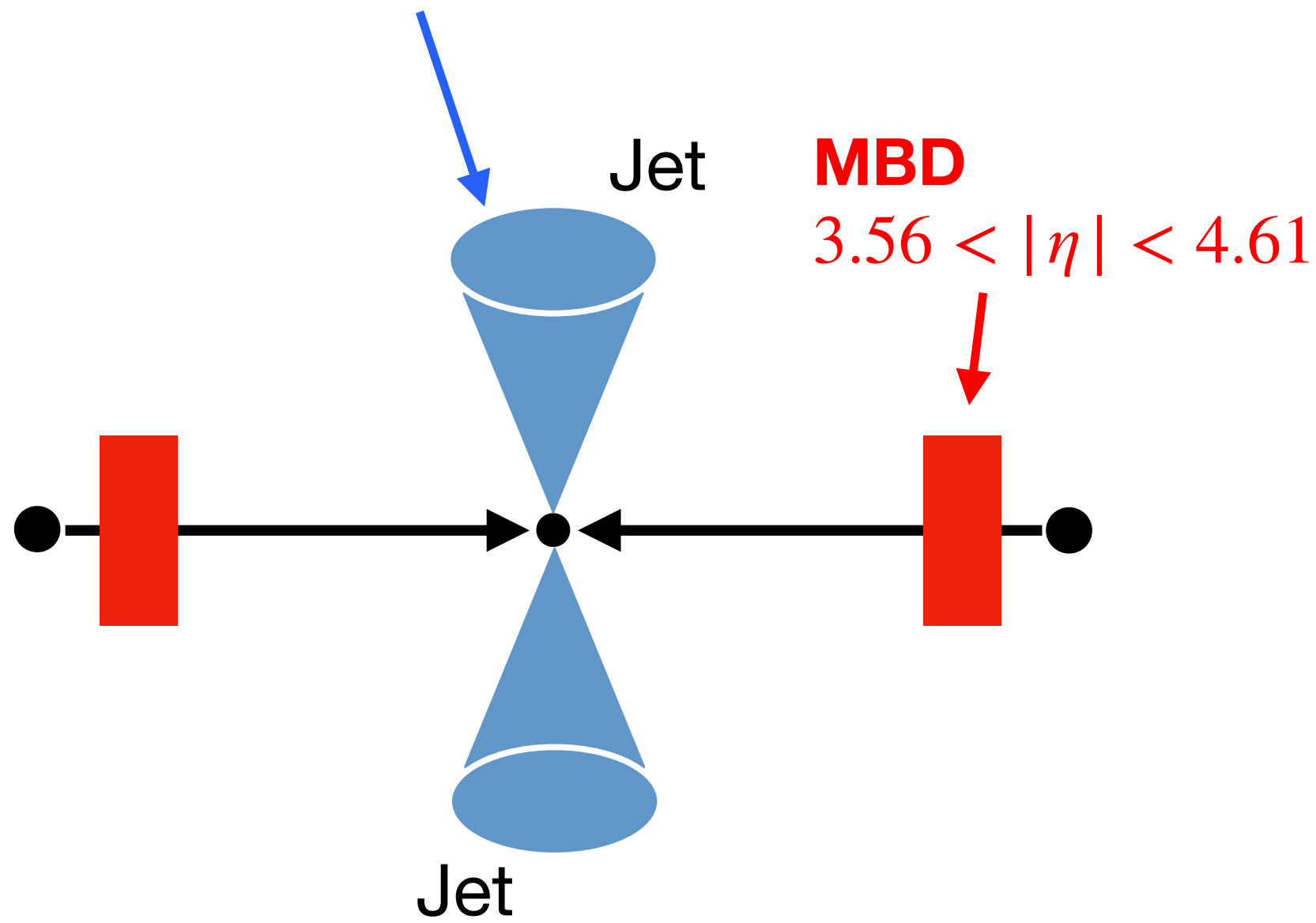
40-60% reference



- **Clearer** dependence in R_{CP} measurements with reduced uncertainties

Centrality bias effects in small collision systems

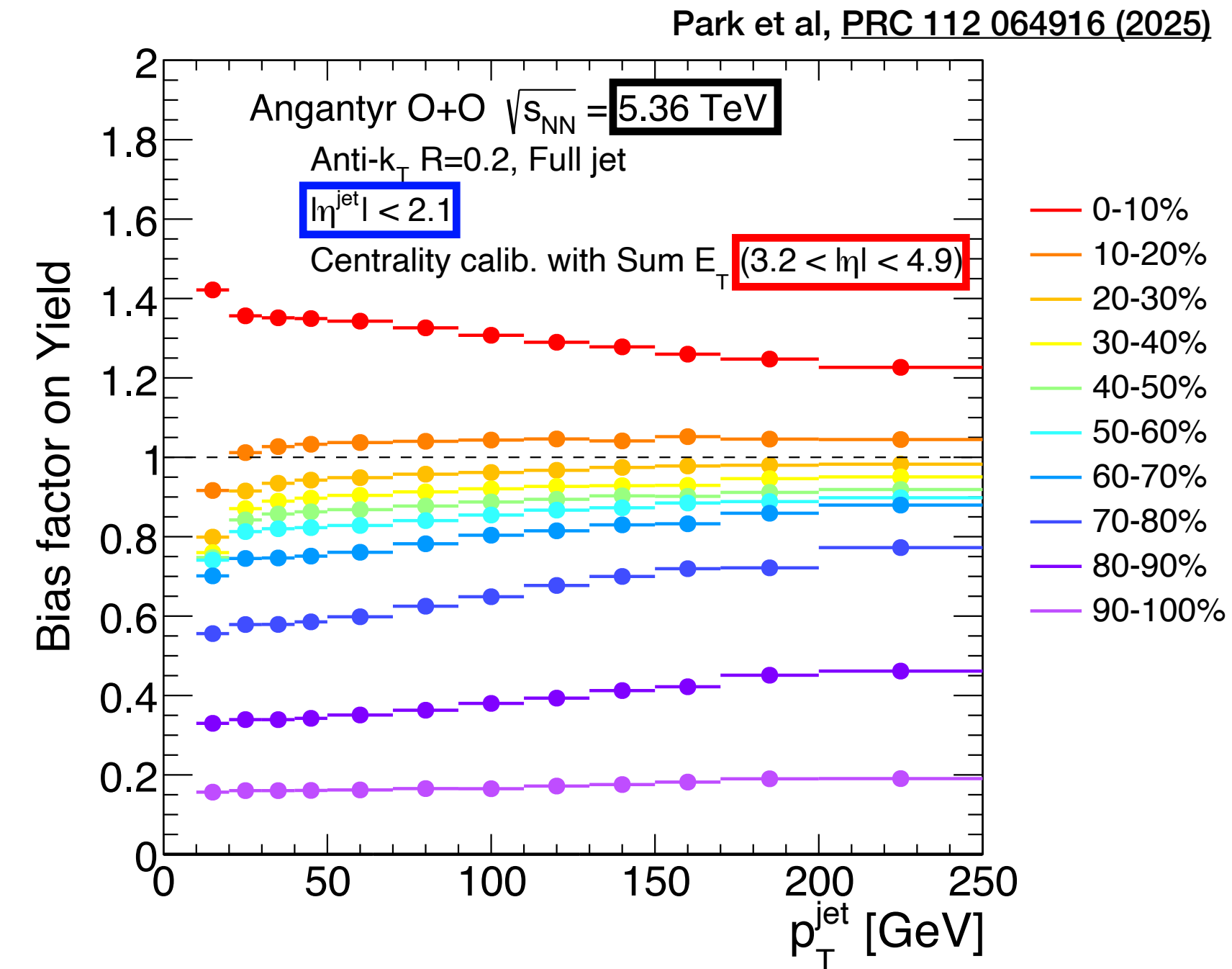
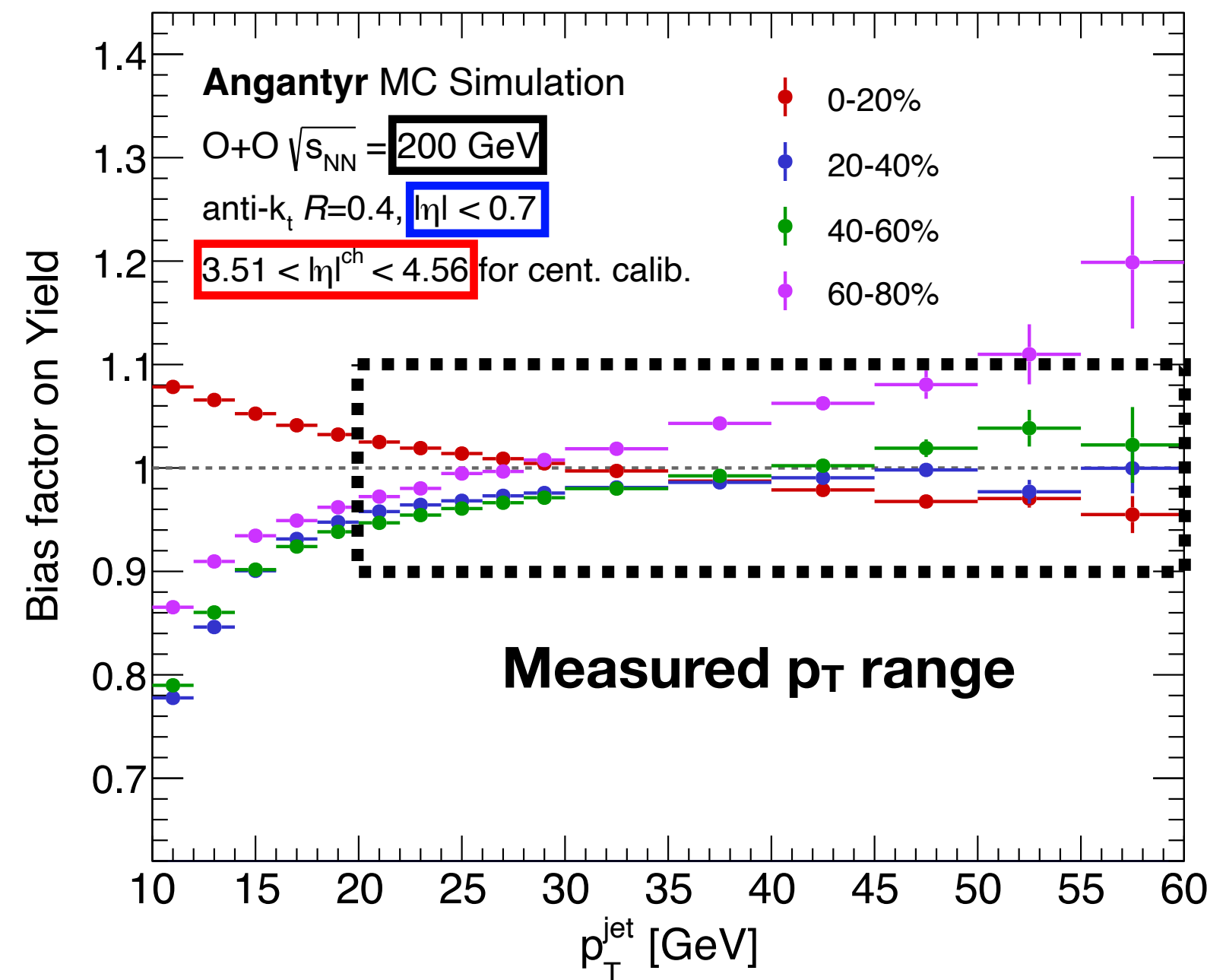
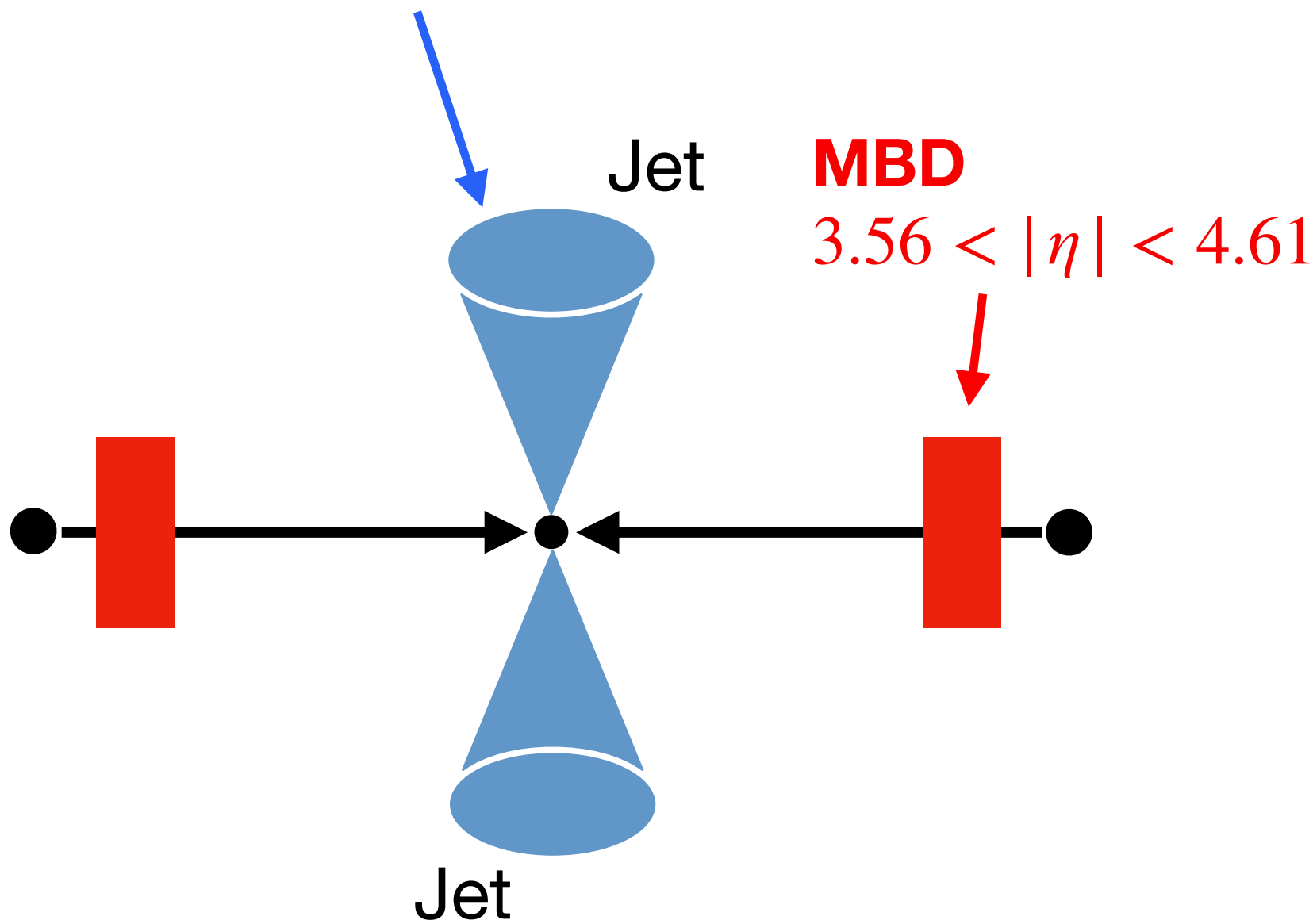
Calorimeter jet $R=0.4$ $|\eta| < 0.7$



- Centrality bias caused by **hard probes** in **mid- η** and **soft particle** production in **forward- η**

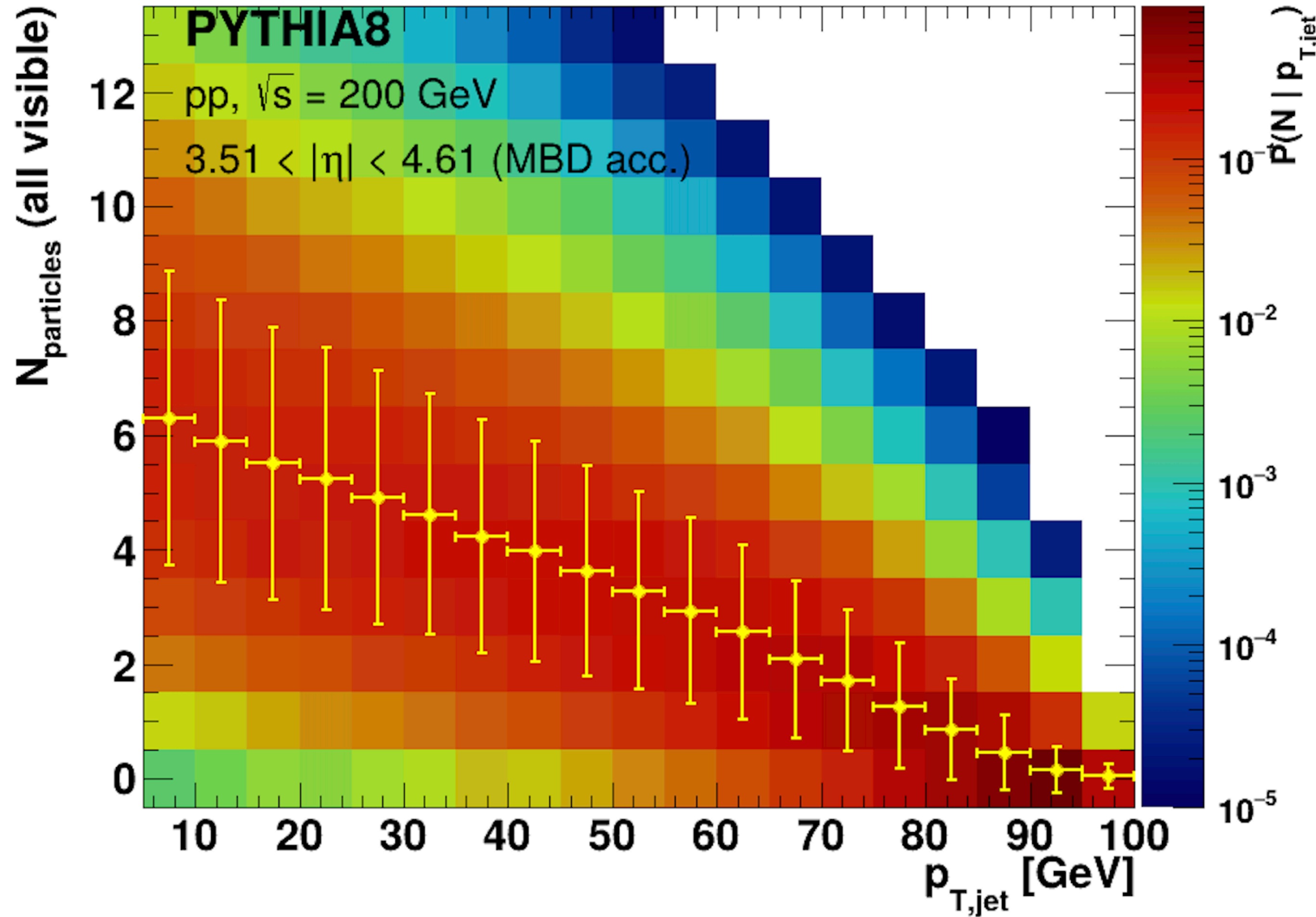
Centrality bias effects in small collision systems

Calorimeter jet $R=0.4$ $|\eta| < 0.7$



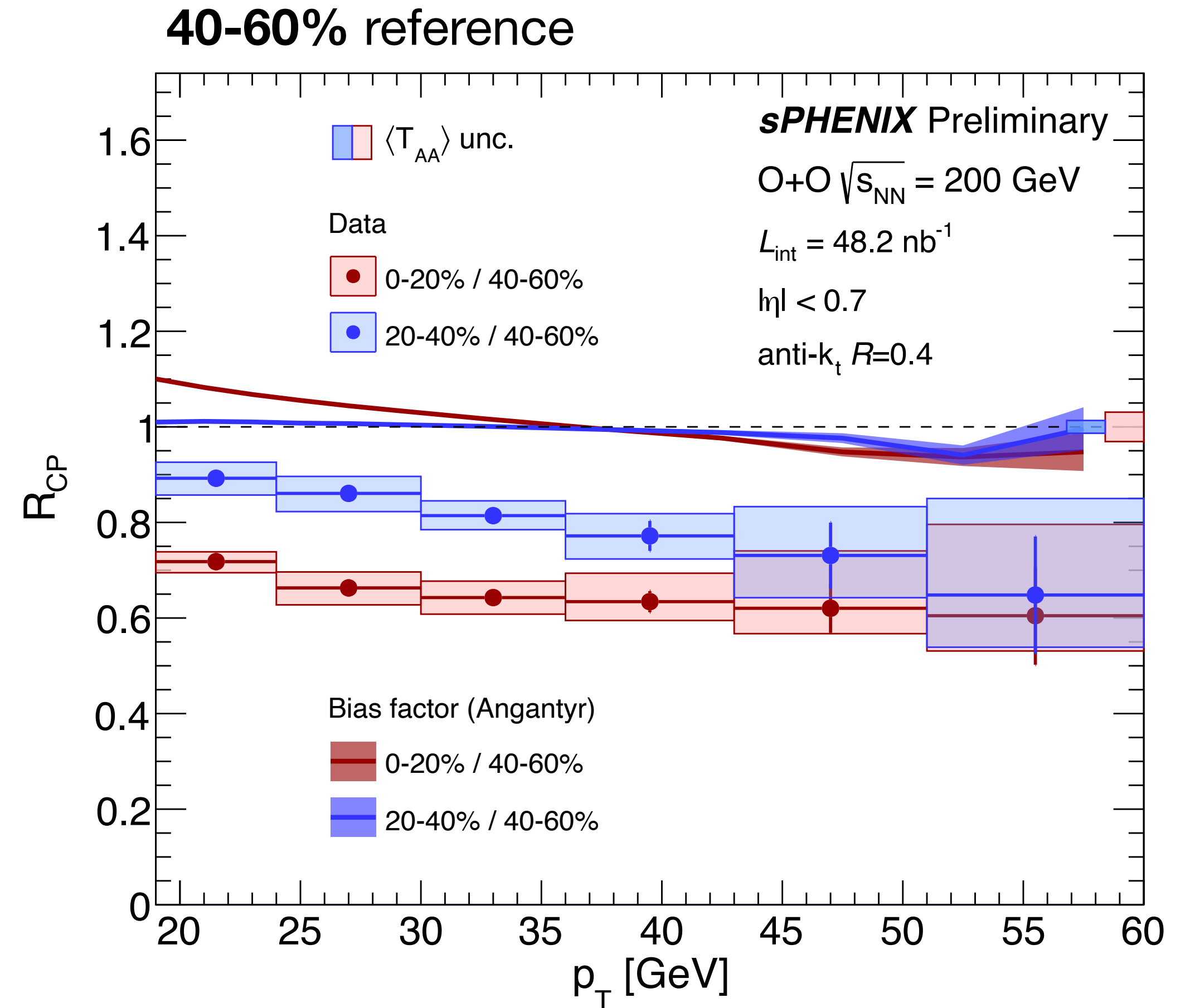
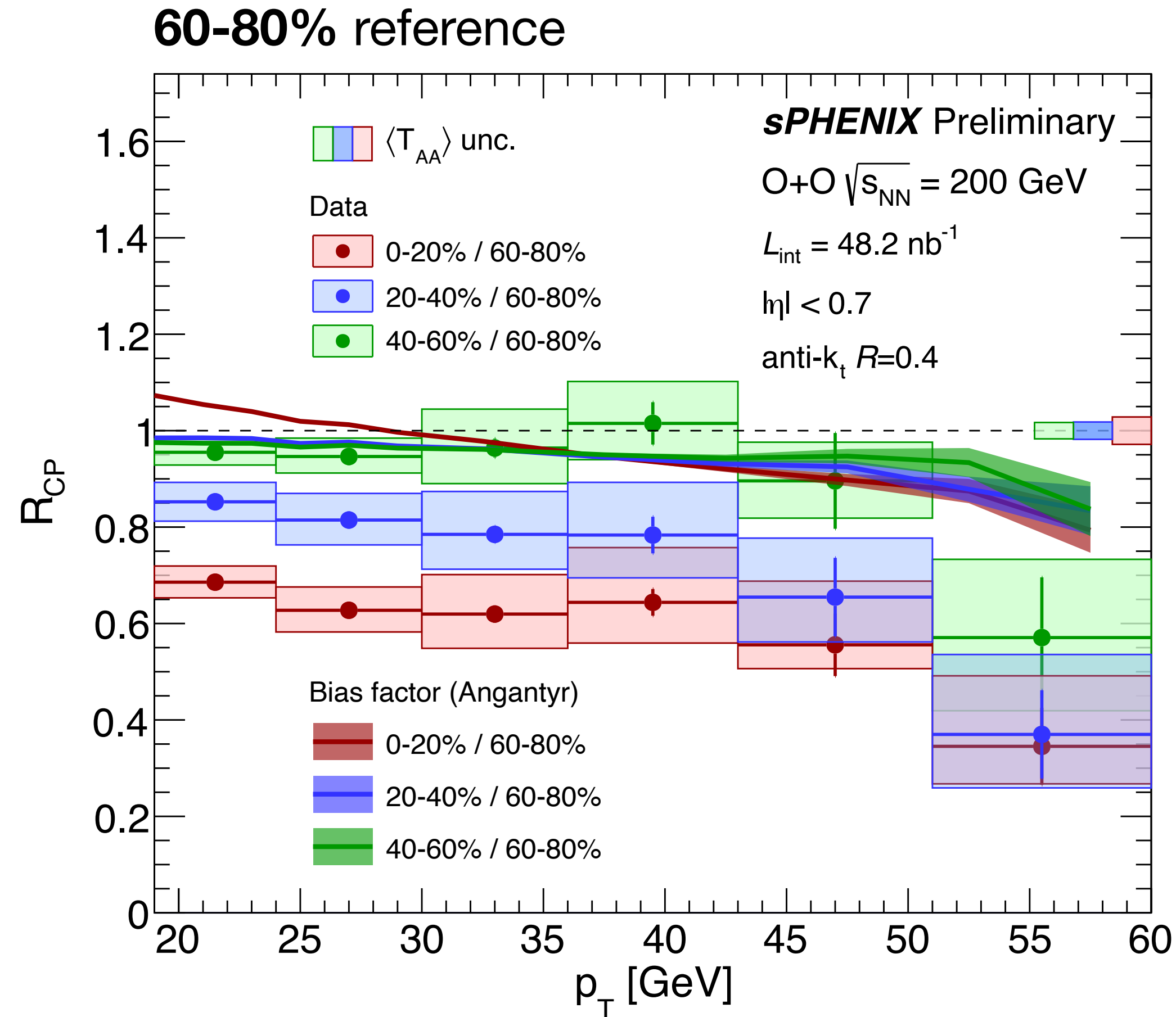
- Centrality bias caused by **hard probes** in **mid- η** and **soft particle** production in **forward- η**
- Much smaller bias effects at **RHIC energy** with **sPHENIX acceptance**

Energy conservation for bias effect



- Particle production in **forward** region decrease for higher p_T **hard probes in mid-rapidity**
- **Bias effect** strongly affectedly **energy conservation** in small systems at RHIC

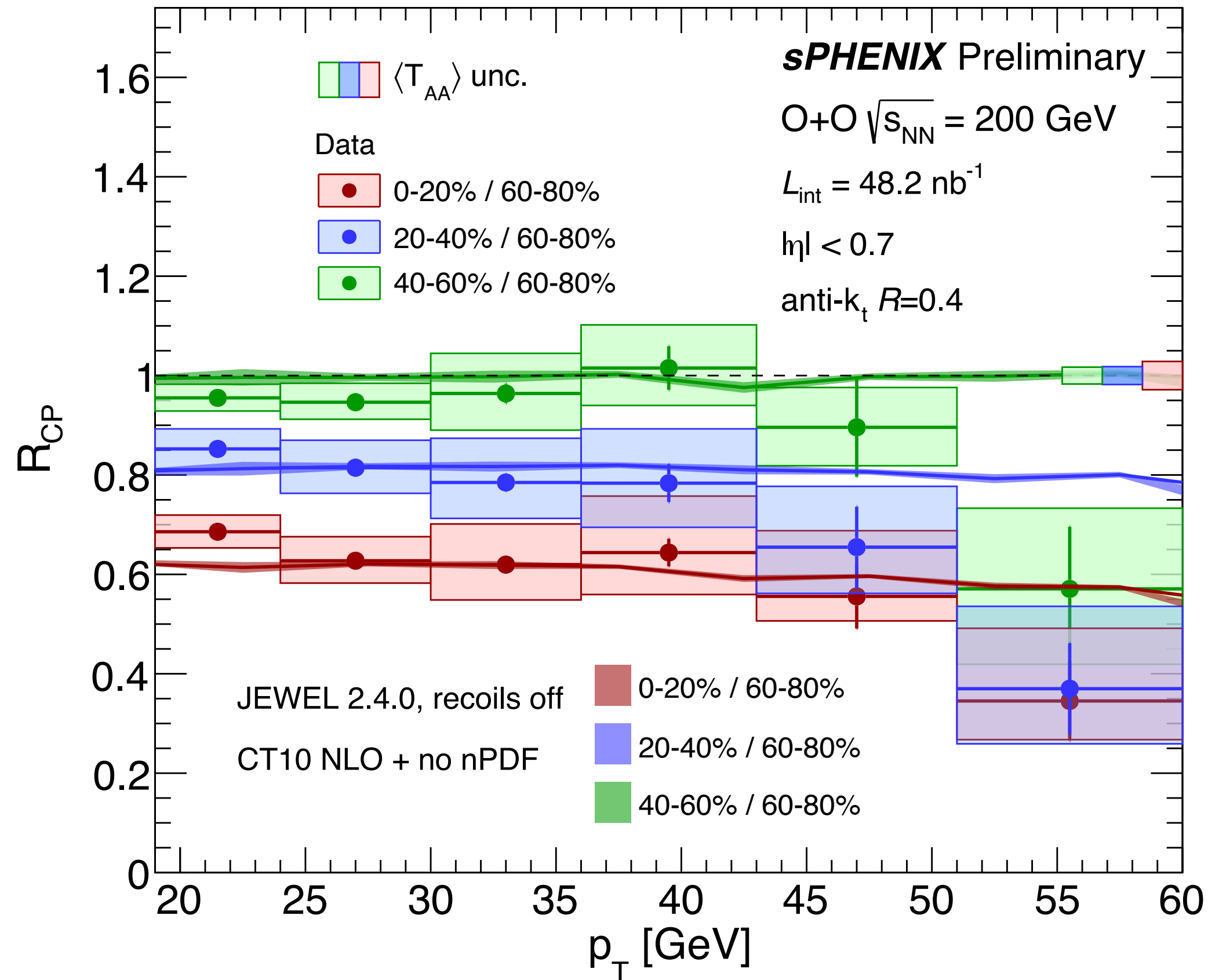
Results compared with bias factors



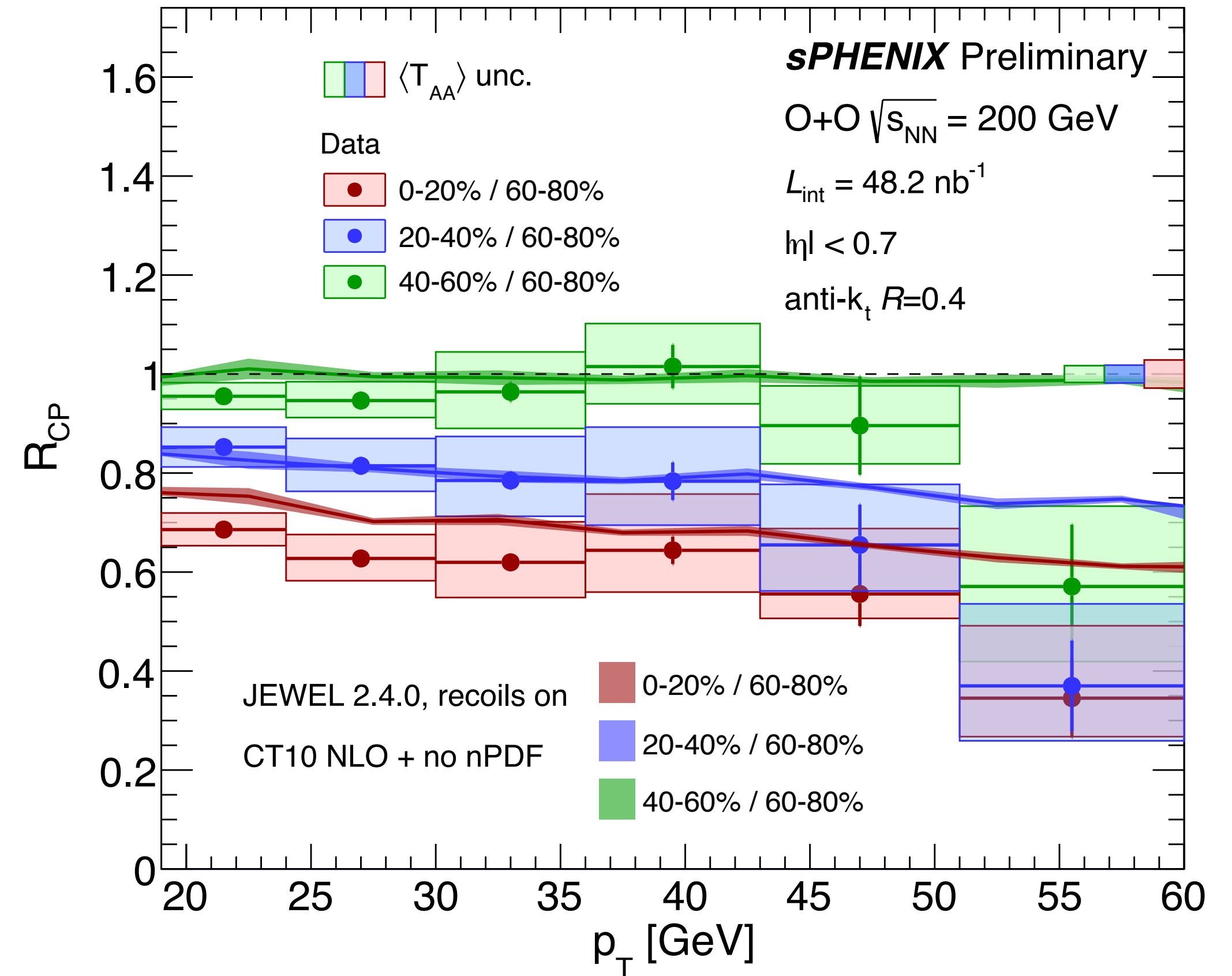
- Bias factors** found to be typically within $\pm 5\%$ $\rightarrow$ **Beyond centrality dependence** in data

Results compared with theory calculations

60-80% reference recoil off

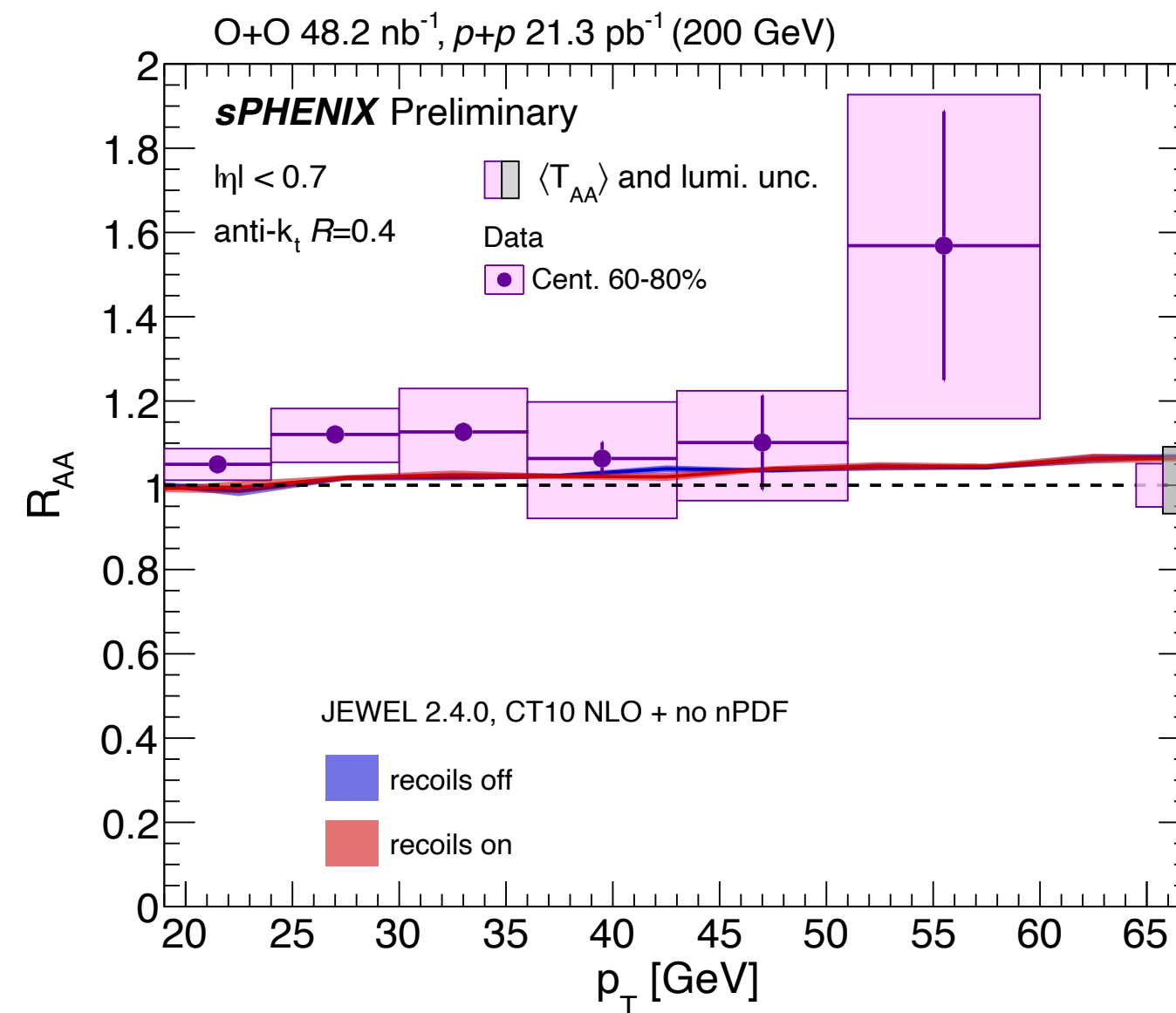
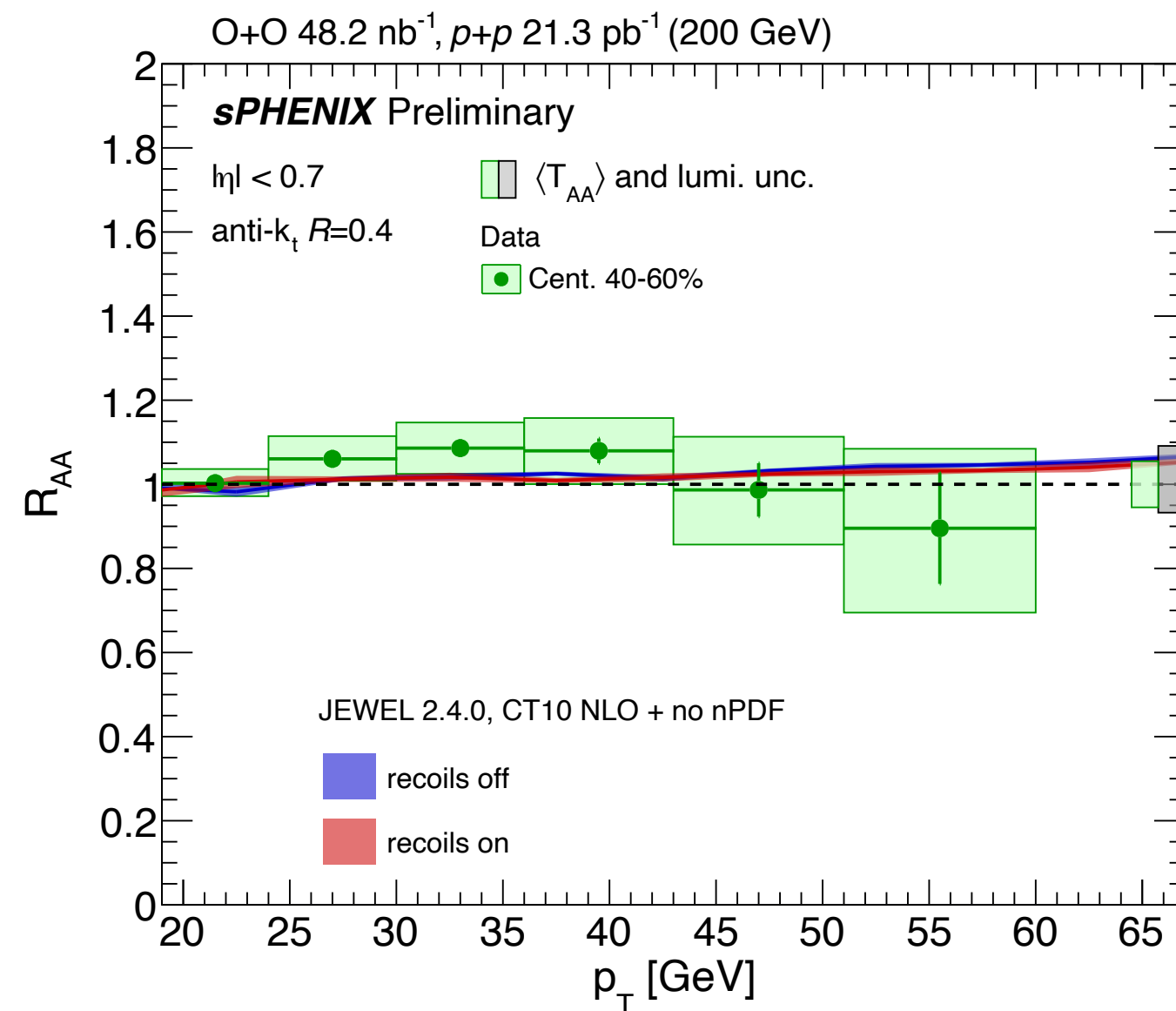
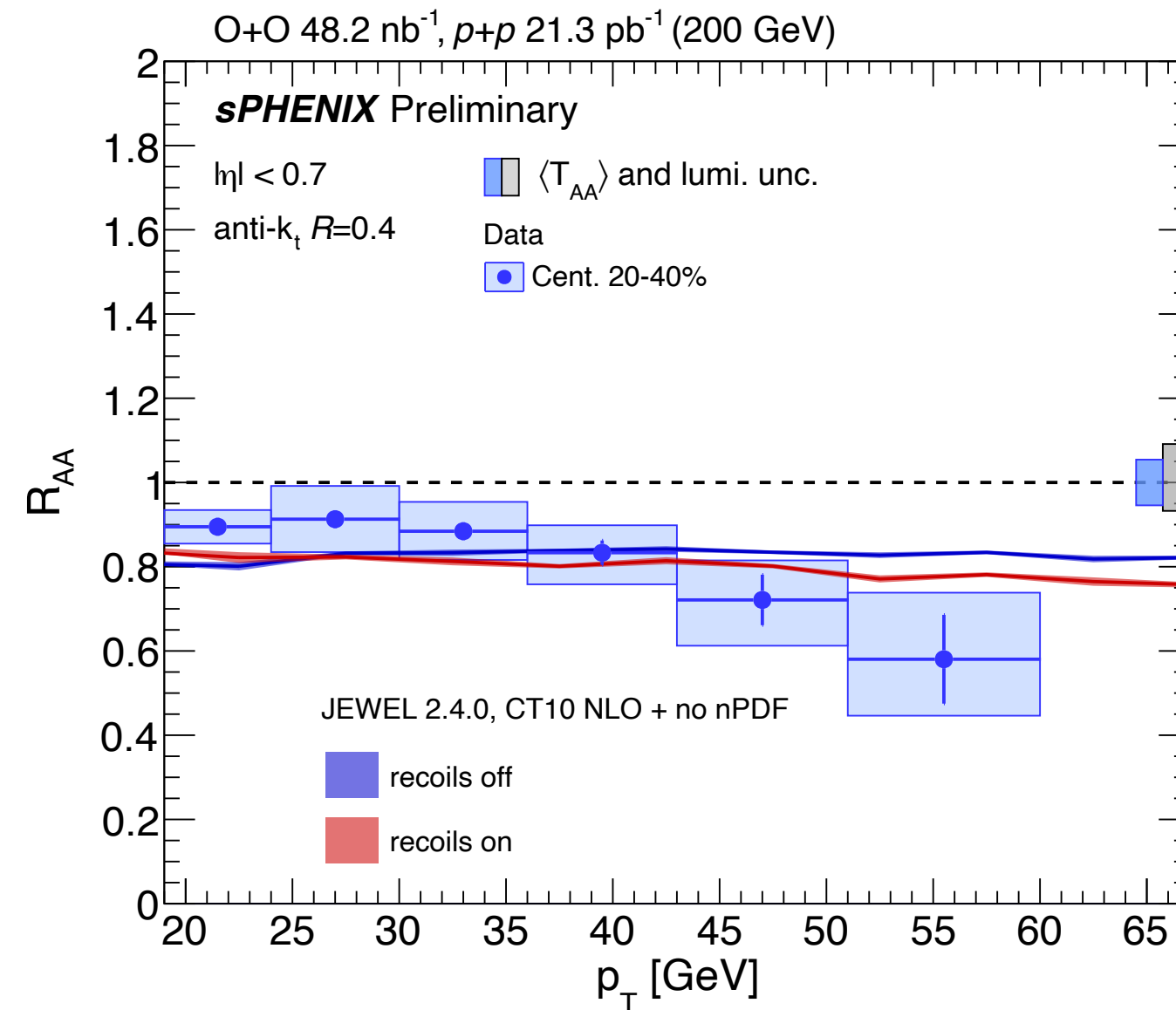
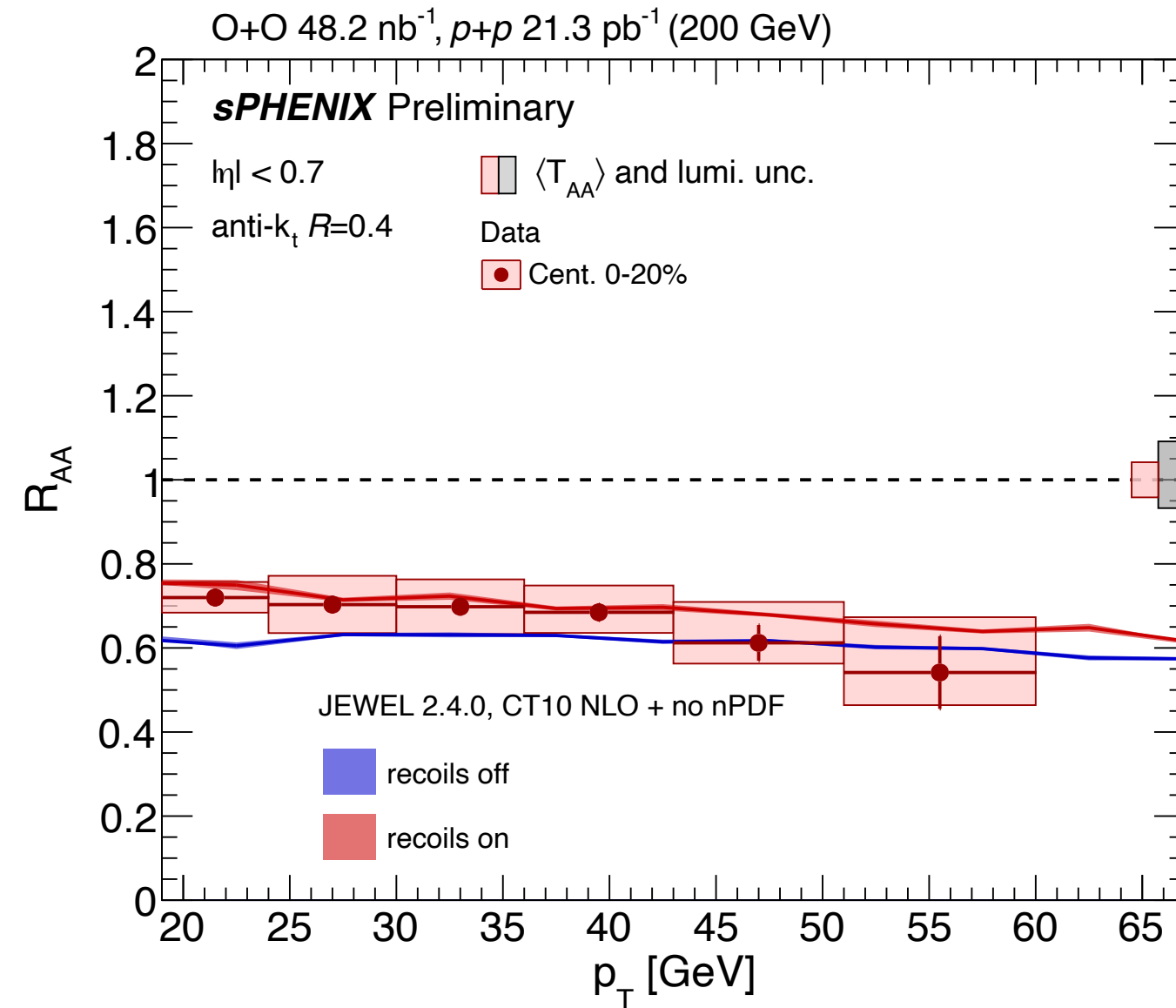


60-80% reference recoil on



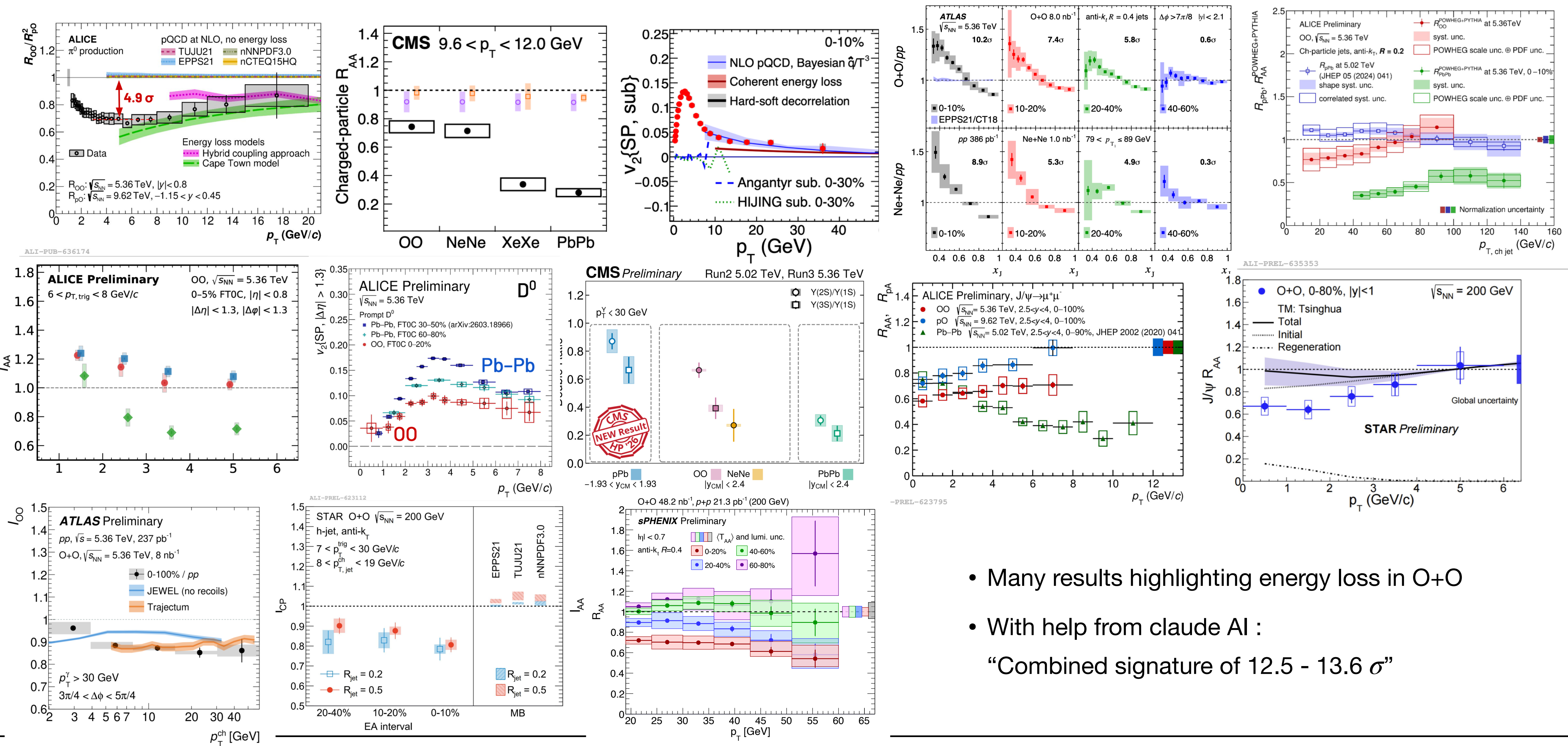
- **JEWEL (no nPDF) with recoil on vs recoil off** predictions in agreement with data

Results compared with theory calculations



- Centrality dependent **JEWEL** predictions consistent with results
- Recoil effect found to be modest in central O+O

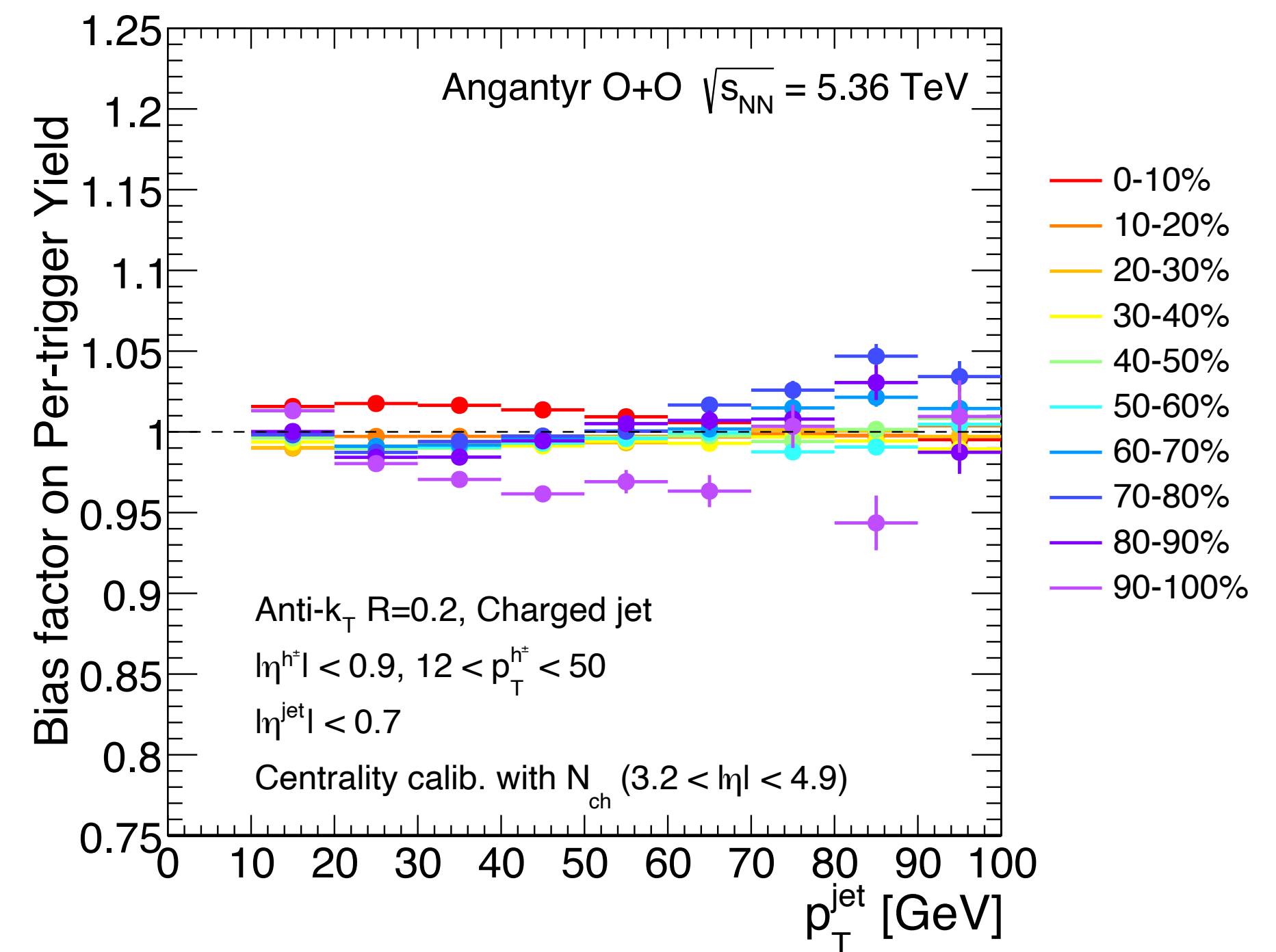
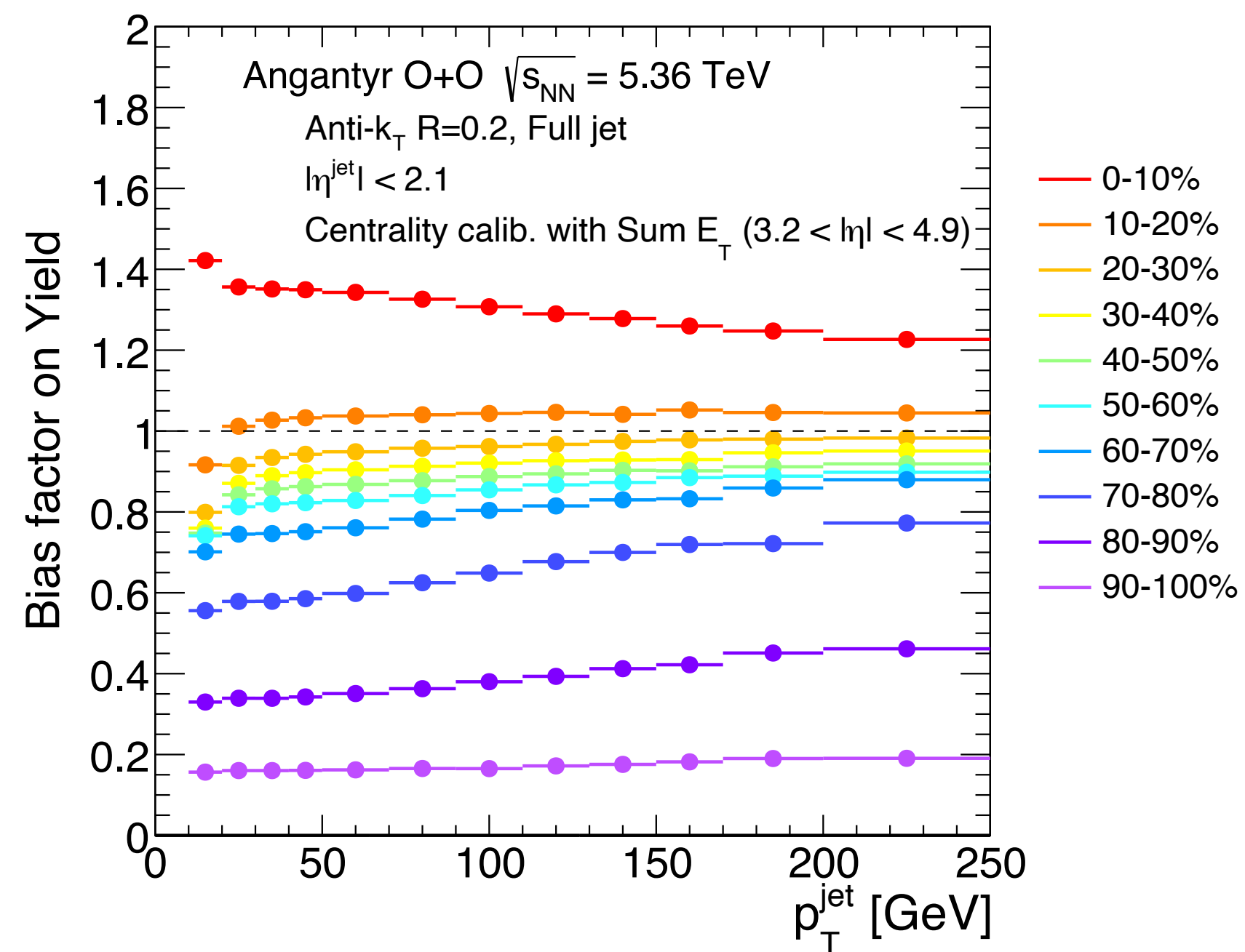
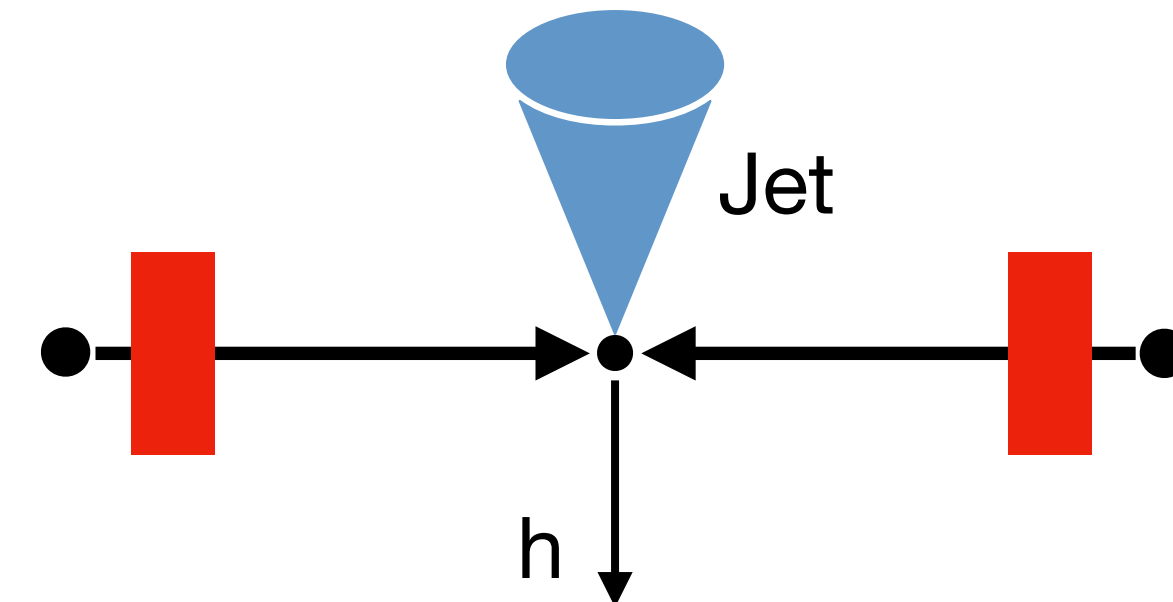
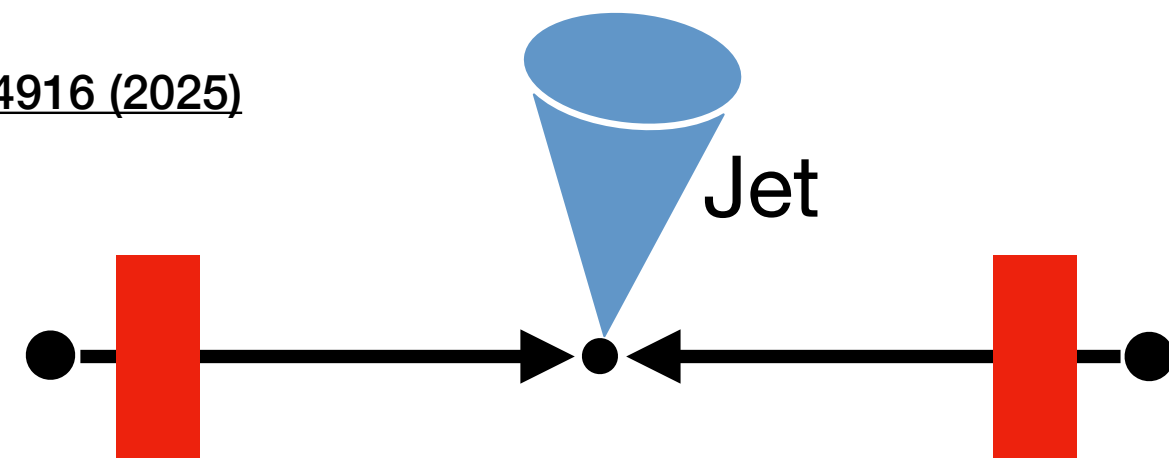
O+O results at RHIC and LHC



- Many results highlighting energy loss in O+O
- With help from claude AI :
“Combined signature of 12.5 - 13.6 σ ”

Bias effects study on physics observables

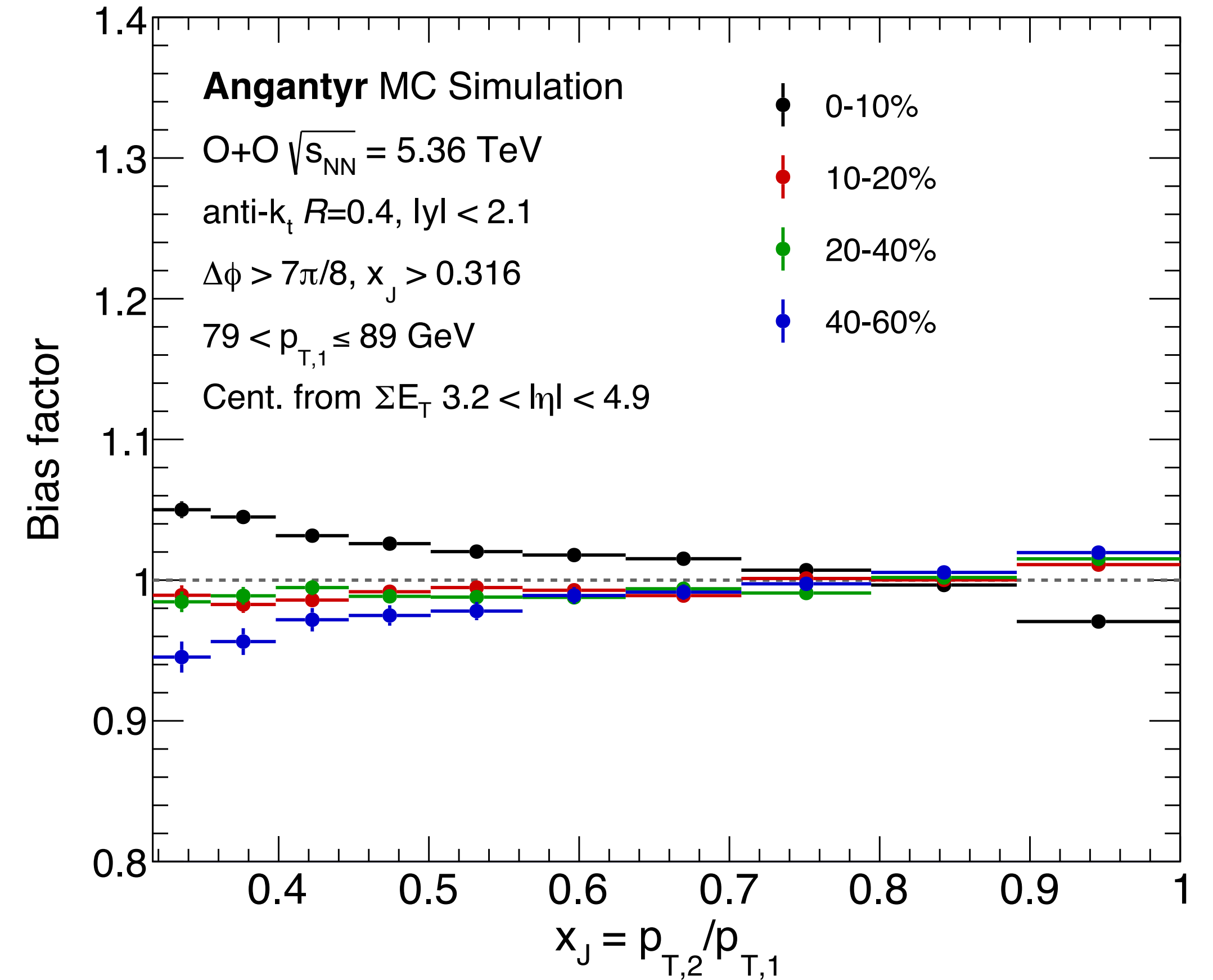
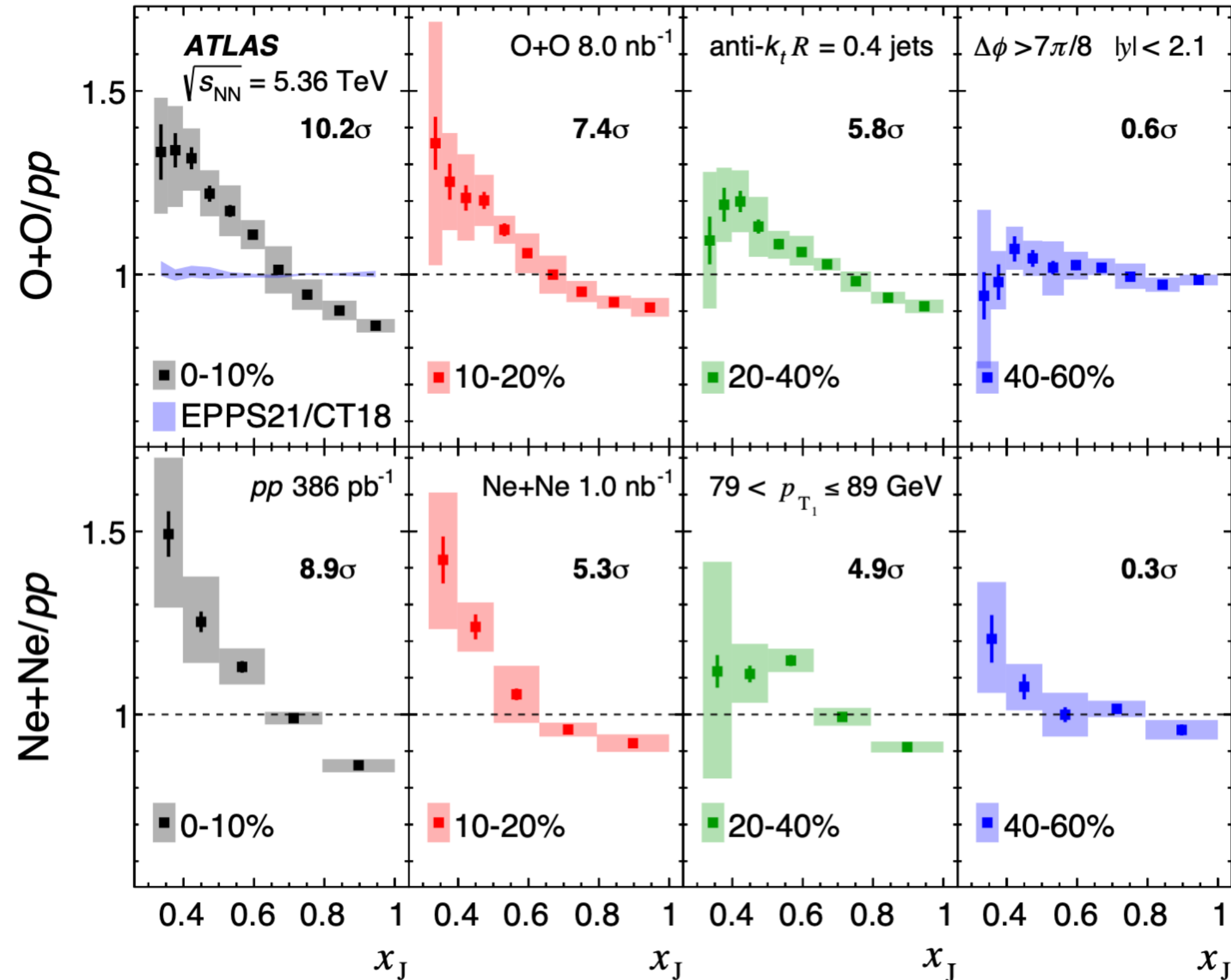
Park et al, PRC 112 064916 (2025)



- Bias effect significantly suppressed by correlation measurements

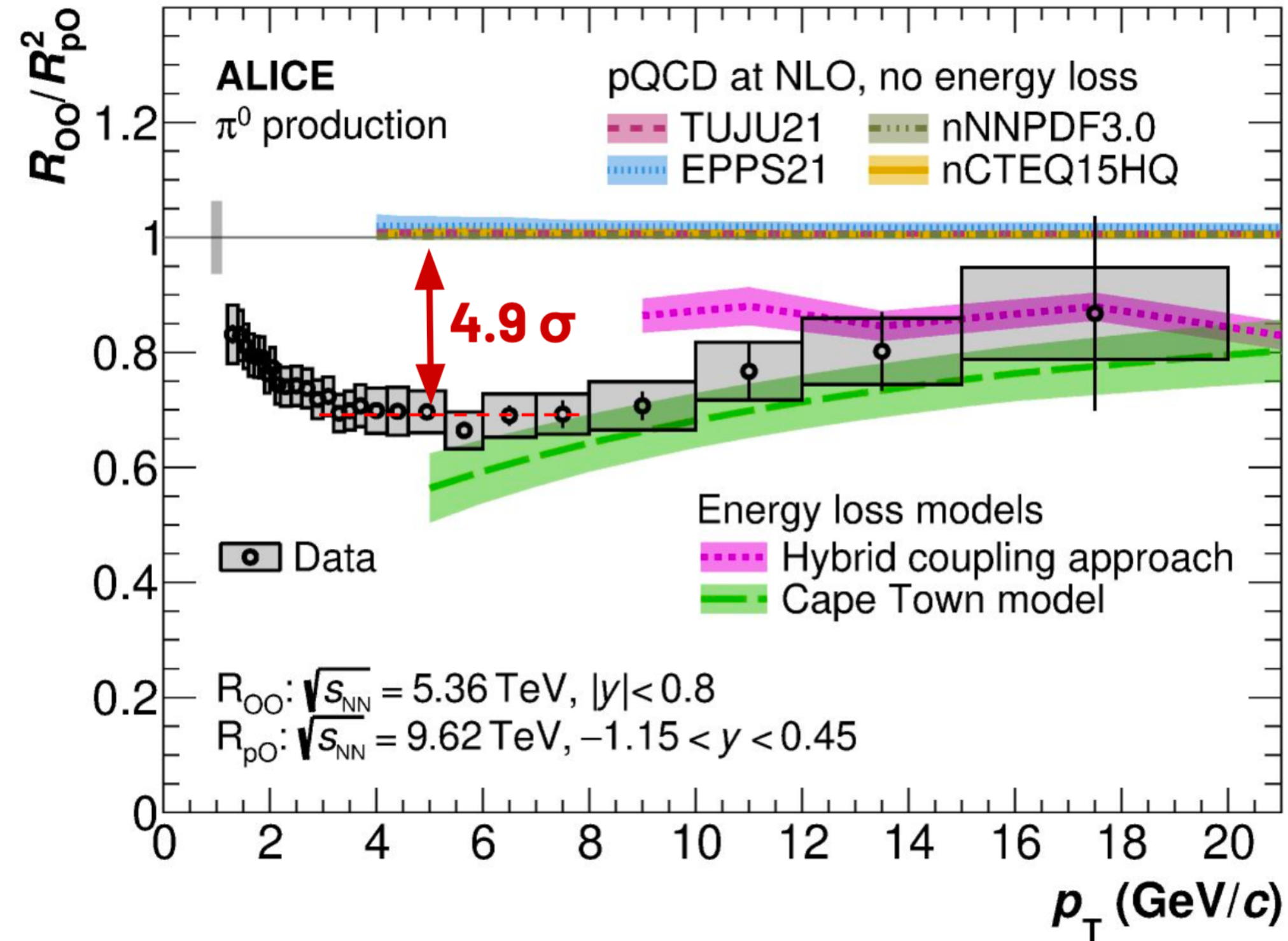
Bias effects study on physics observables

arXiv:2606.20463

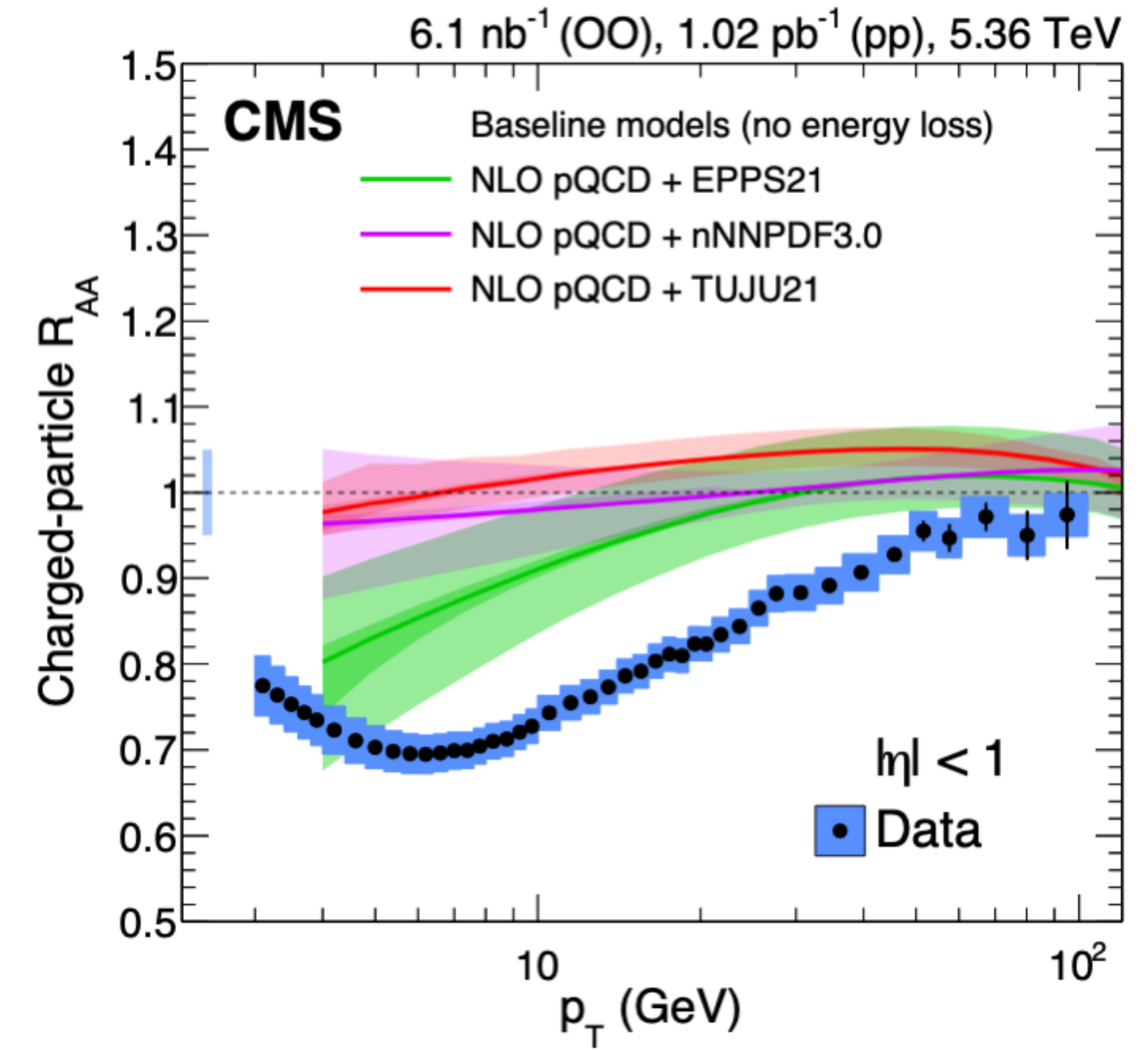


- Bias effect significantly suppressed by **dijet selection**
- At most 5% varying in **x_J representing** bias effect change of **subleading jet p_T**

Energy loss in O+O

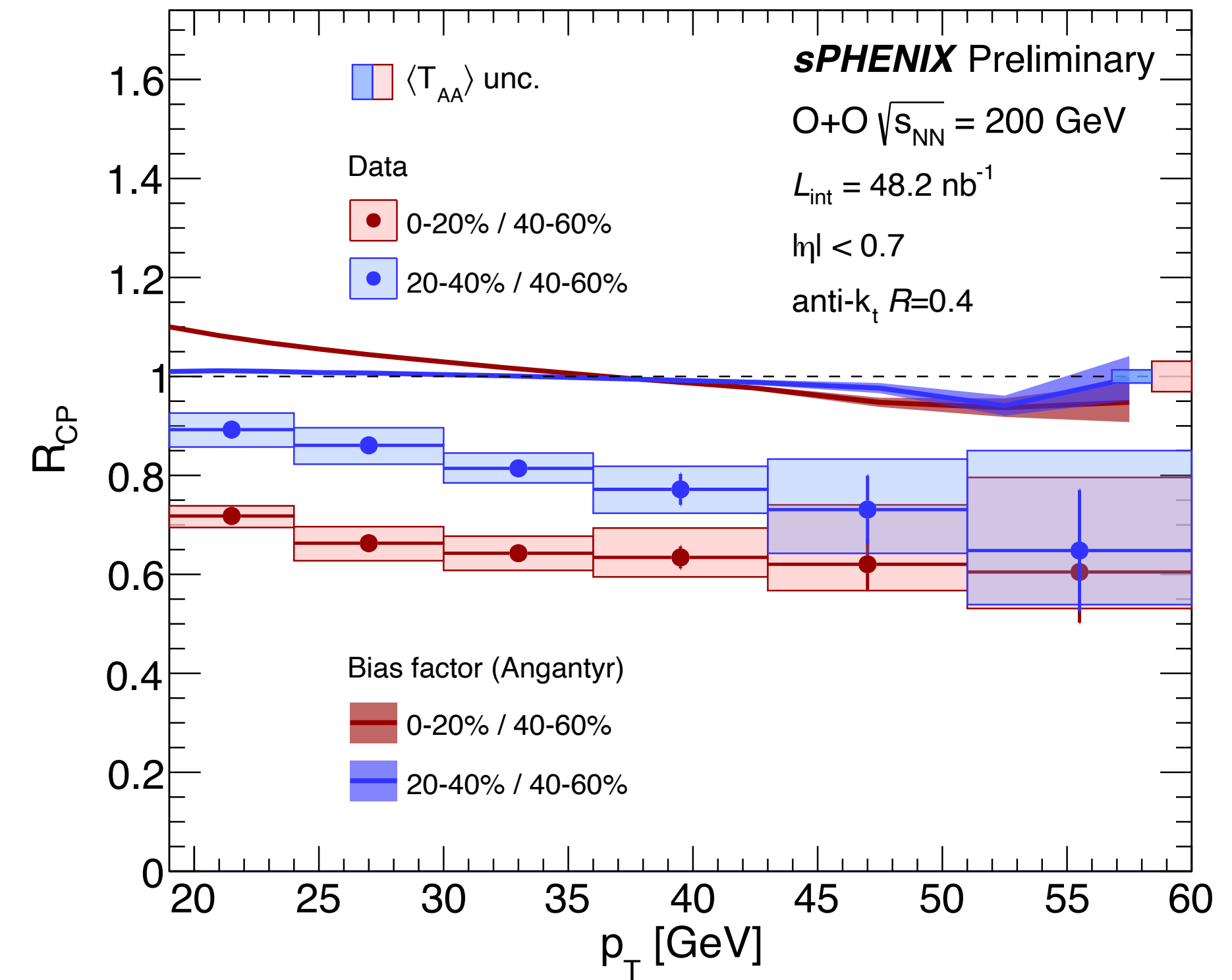
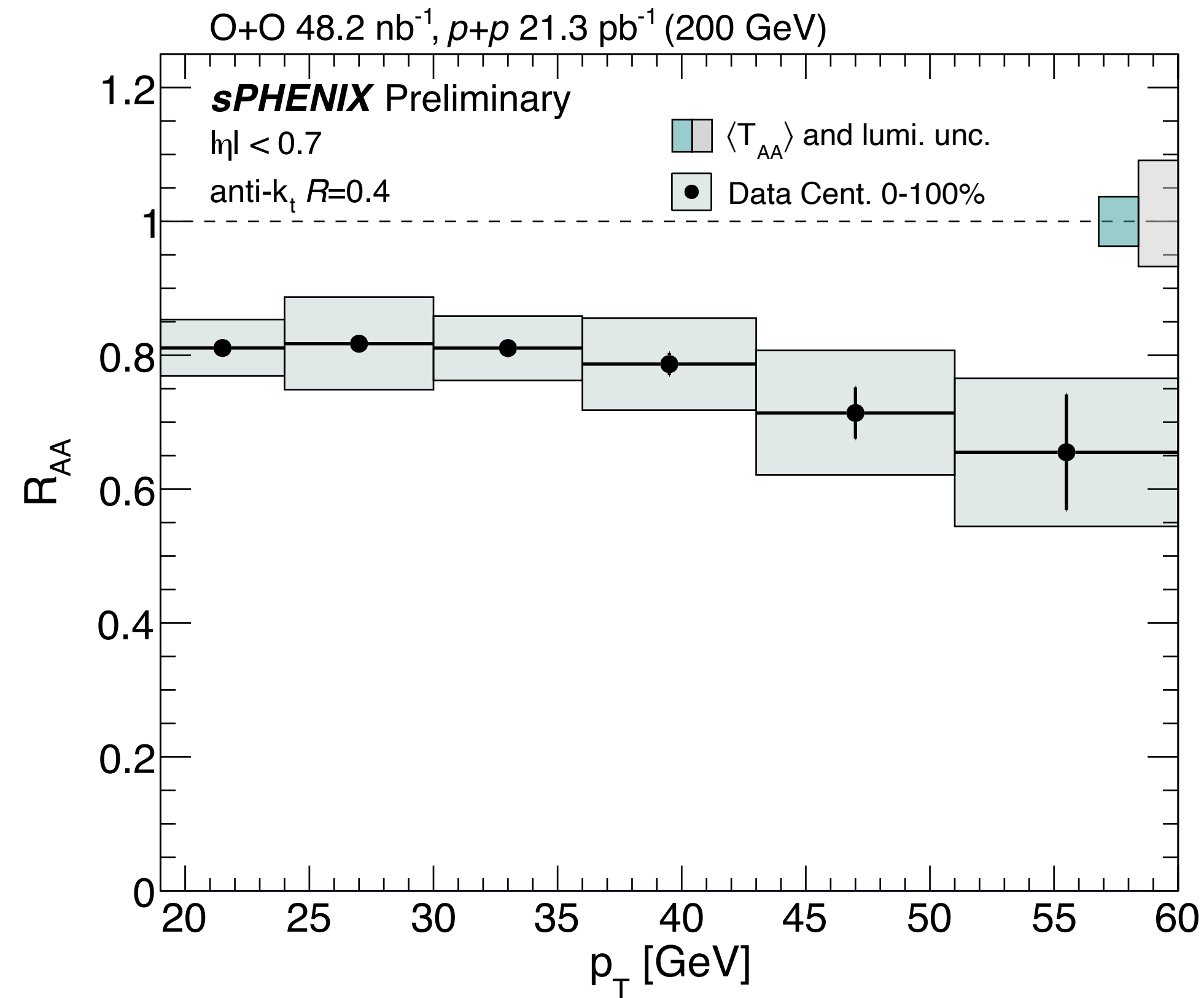


ALI-PUB-636174



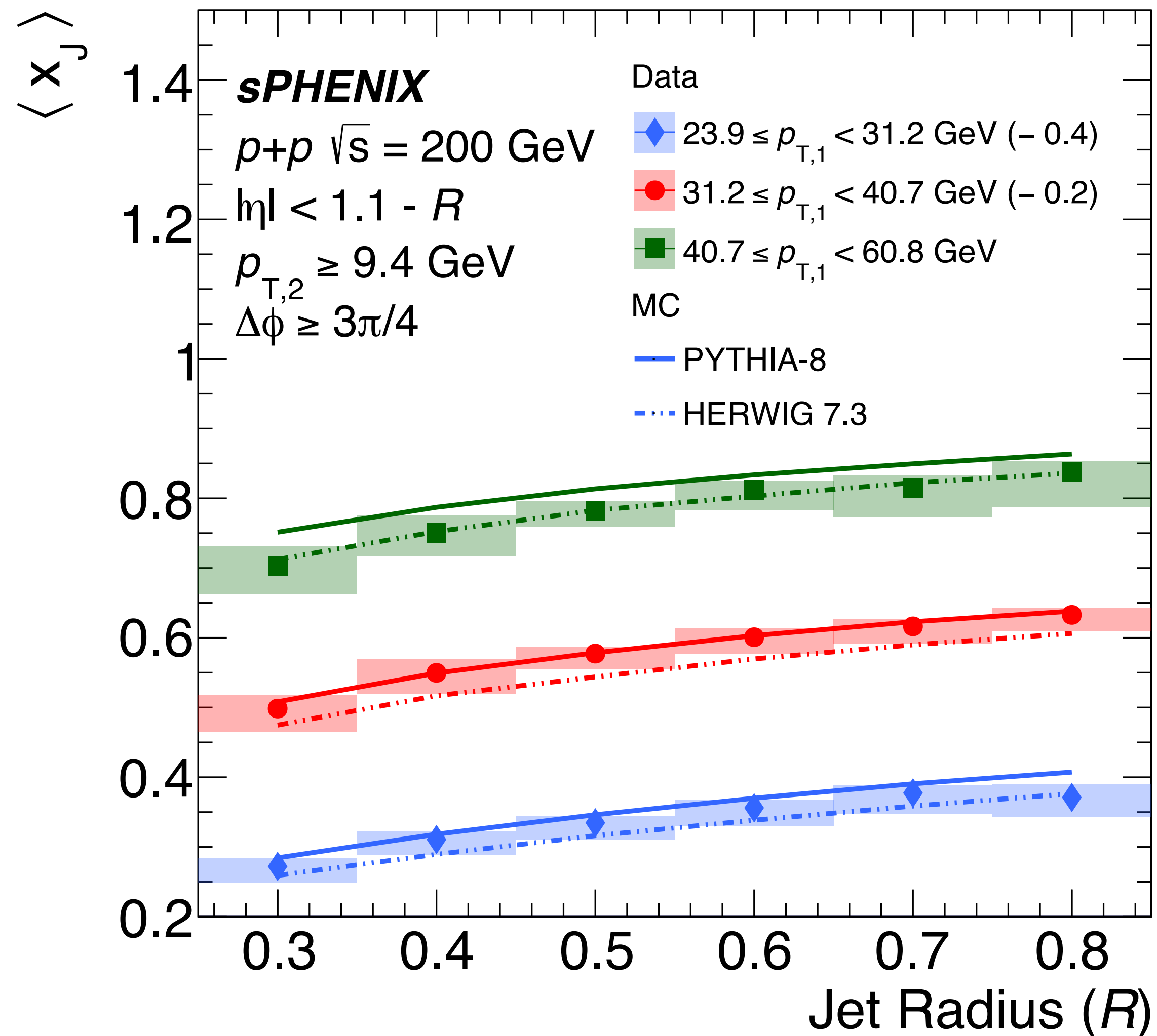
- Community seems to agree we saw energy loss in O+O at the LHC

Energy loss in O+O



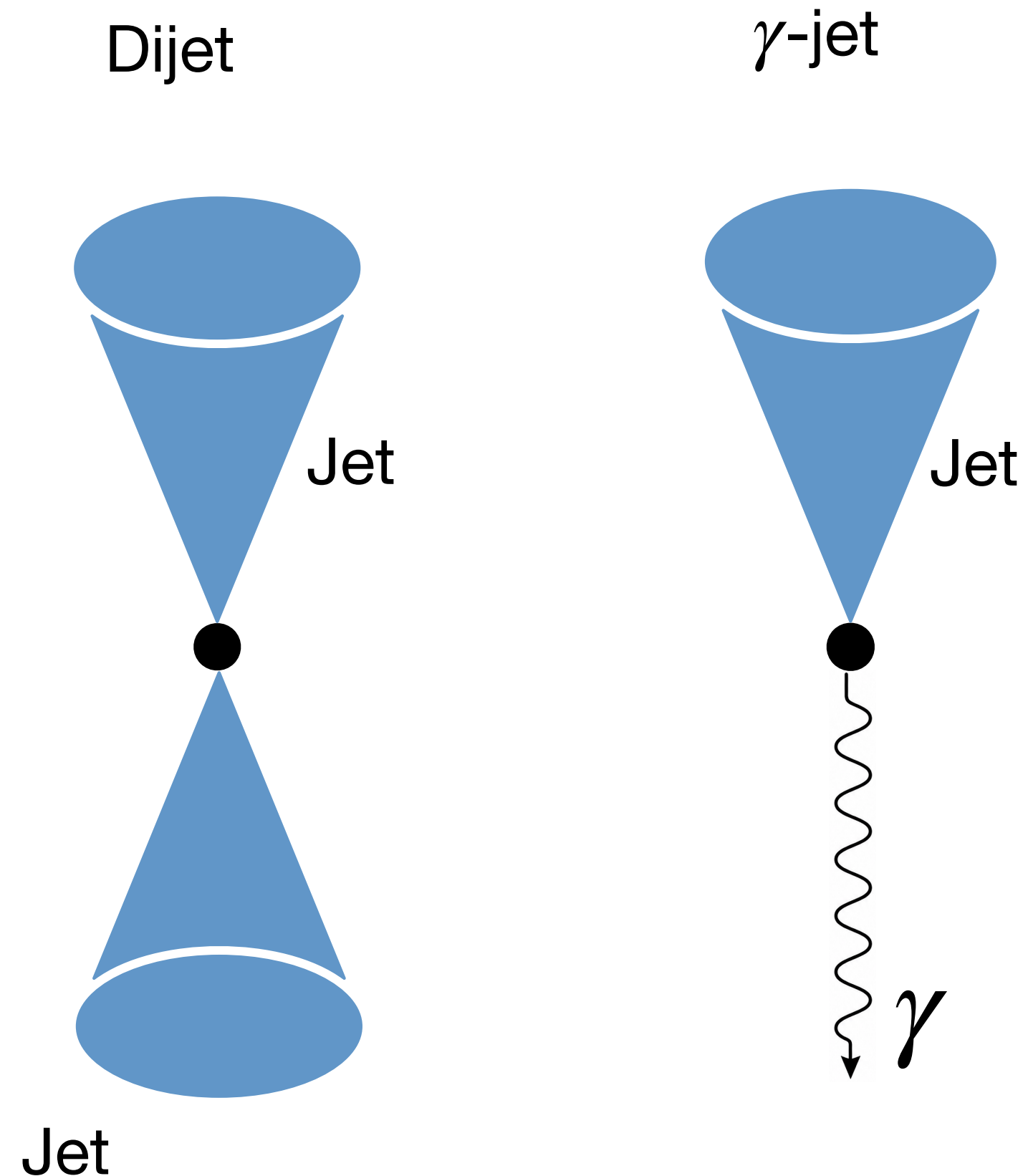
- Community seems to agree we saw energy loss in O+O at the LHC
- Clear Centrality dependence from sPHENIX RAA/RCP support also energy loss picture in O+O at RHIC

Future prospects (1) : Cone-size dependence



- Cone-size dependent measurements in p+p for **$R=0.3-0.8$** useful for constraints on MPI, hadronization etc.
- Interesting topic in O+O for **cone-size dependent modification** results

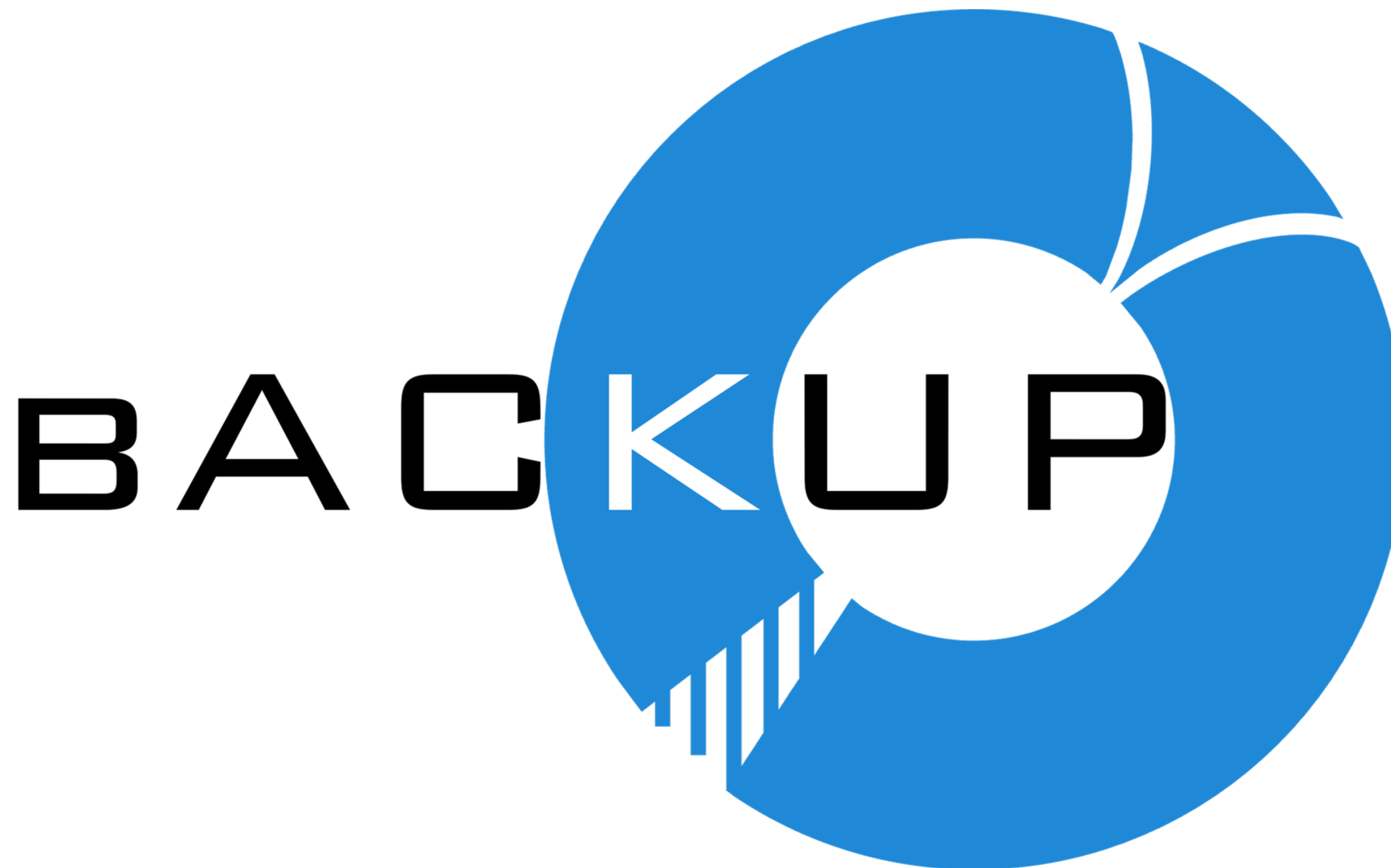
Future prospects (2) : Correlation measurements



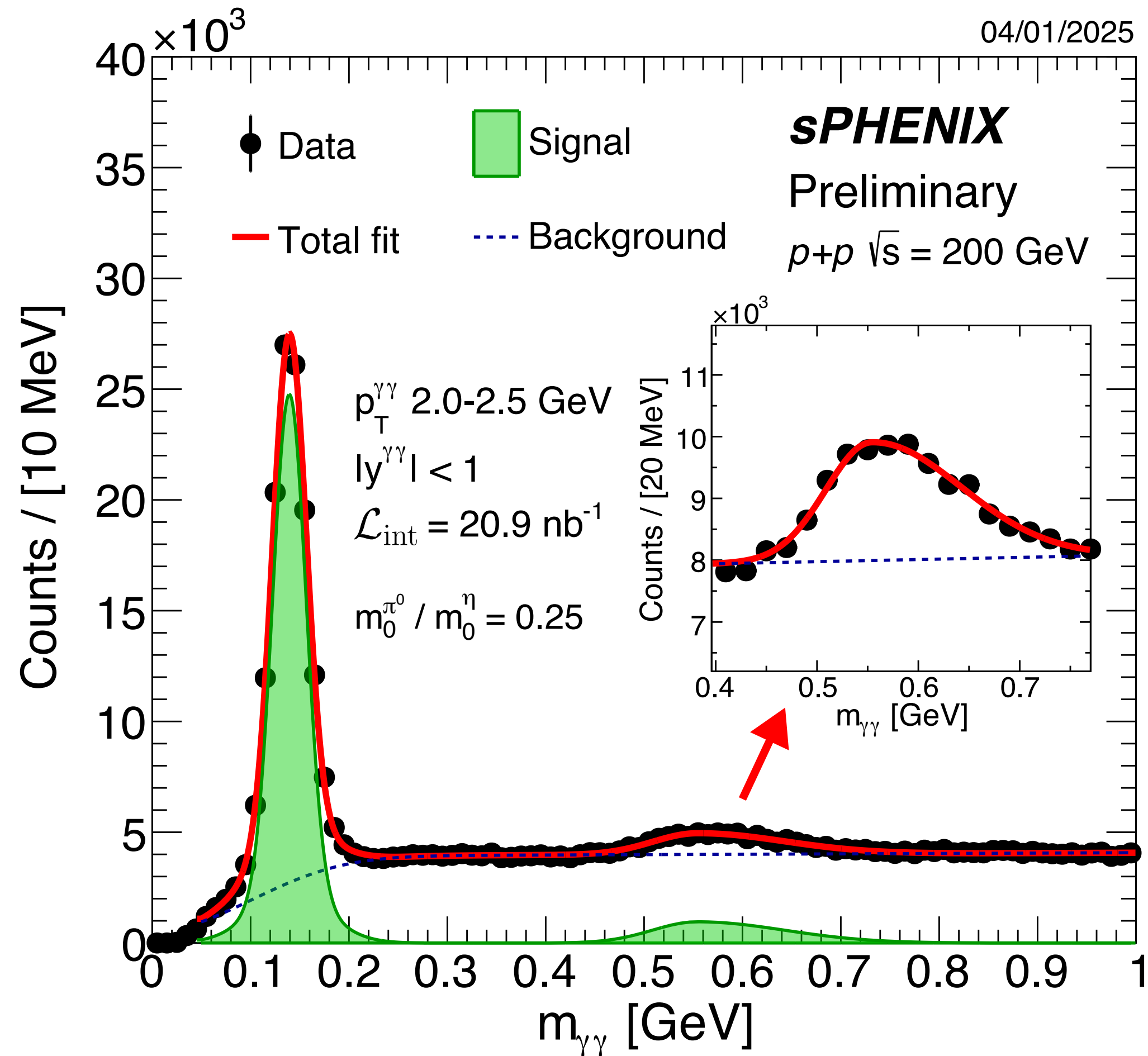
- Dijet asymmetry vs centrality in for precision medium probe in O+O
 - High statistics available
 - Large cancellation in uncertainties
- Photon-jet measurements e.g. $x_{J\gamma}$ comparison in p+p vs O+O
 - Better sensitivity in energy loss study
 - Limited statistics compared to dijet

Comprehensive jet physics program for O+O

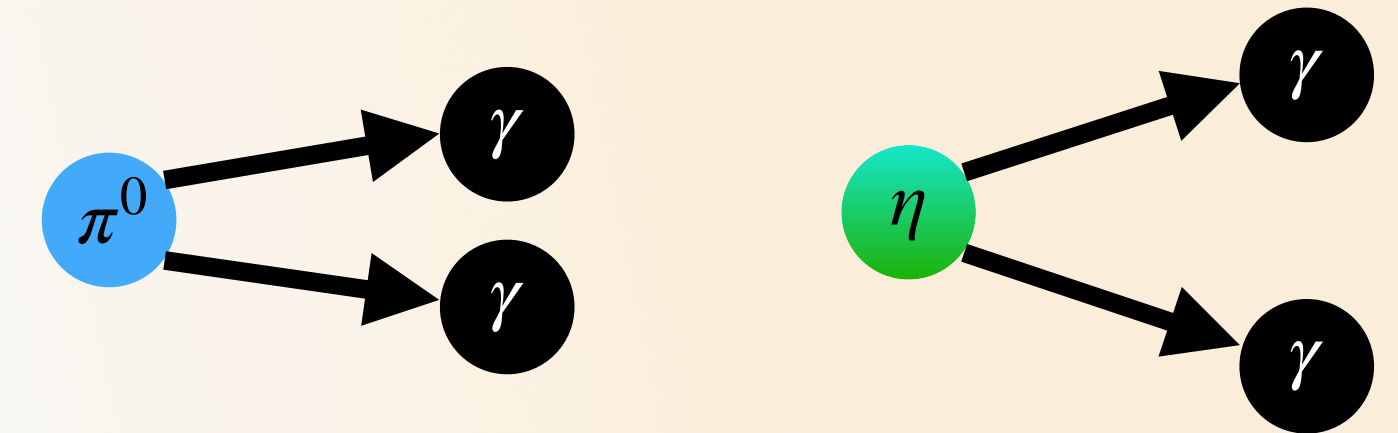
- **Data-driven** calibrations for **jet energy scale** and **jet energy resolution**
- Successful **centrality calibration** with simple **N_{part} scaling** using Glauber + NBD
- **Bias factor** for O+O found to be typically **within 5%** for sPHENIX acceptance of **jet measurement** and **centrality calibration detector**
- Jet suppression observed with clear **centrality ordering** beyond **selection bias**
- JEWEL predictions in agreement with data
- Useful measurement in constraining theory calculations together with LHC results



sPHENIX electromagnetic probe measurement



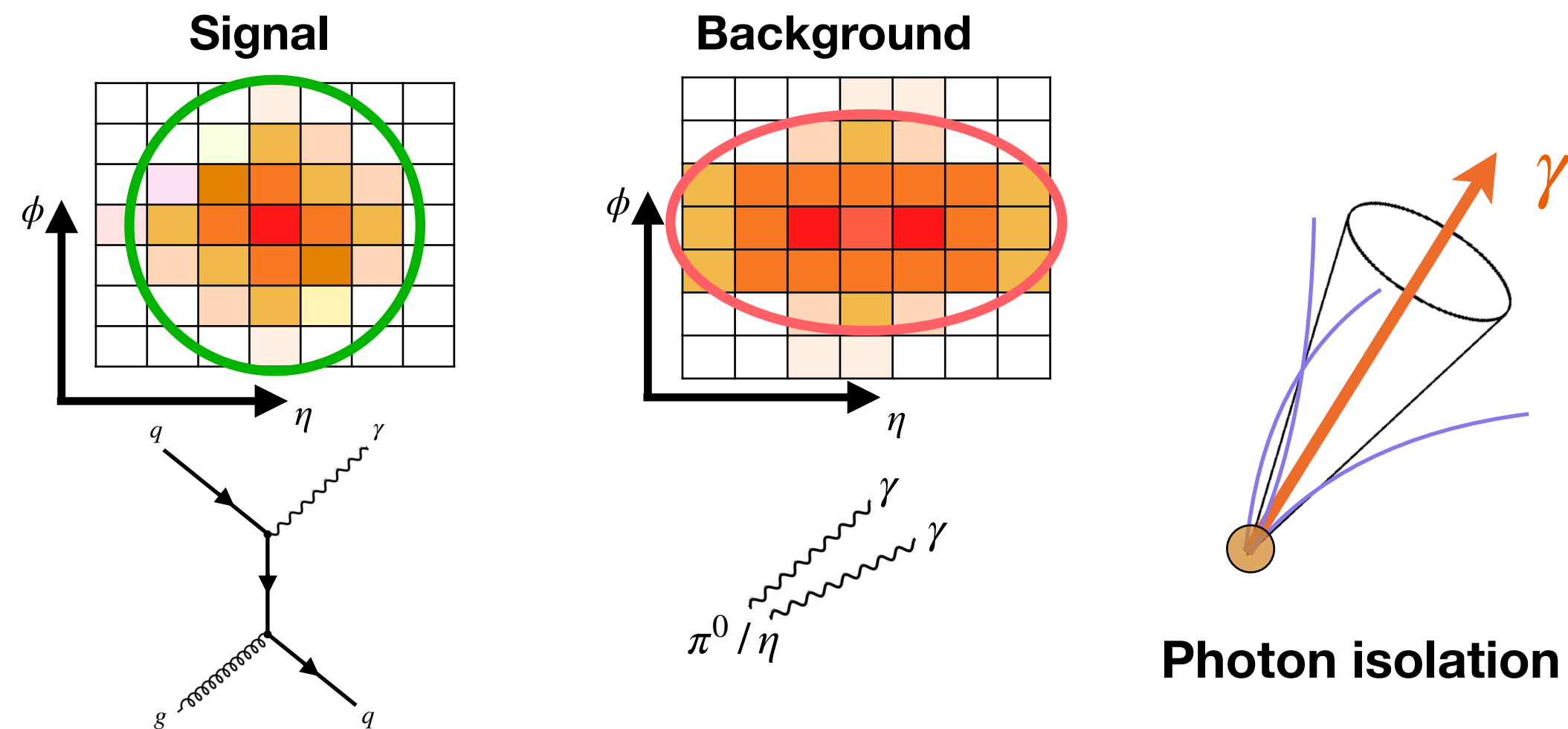
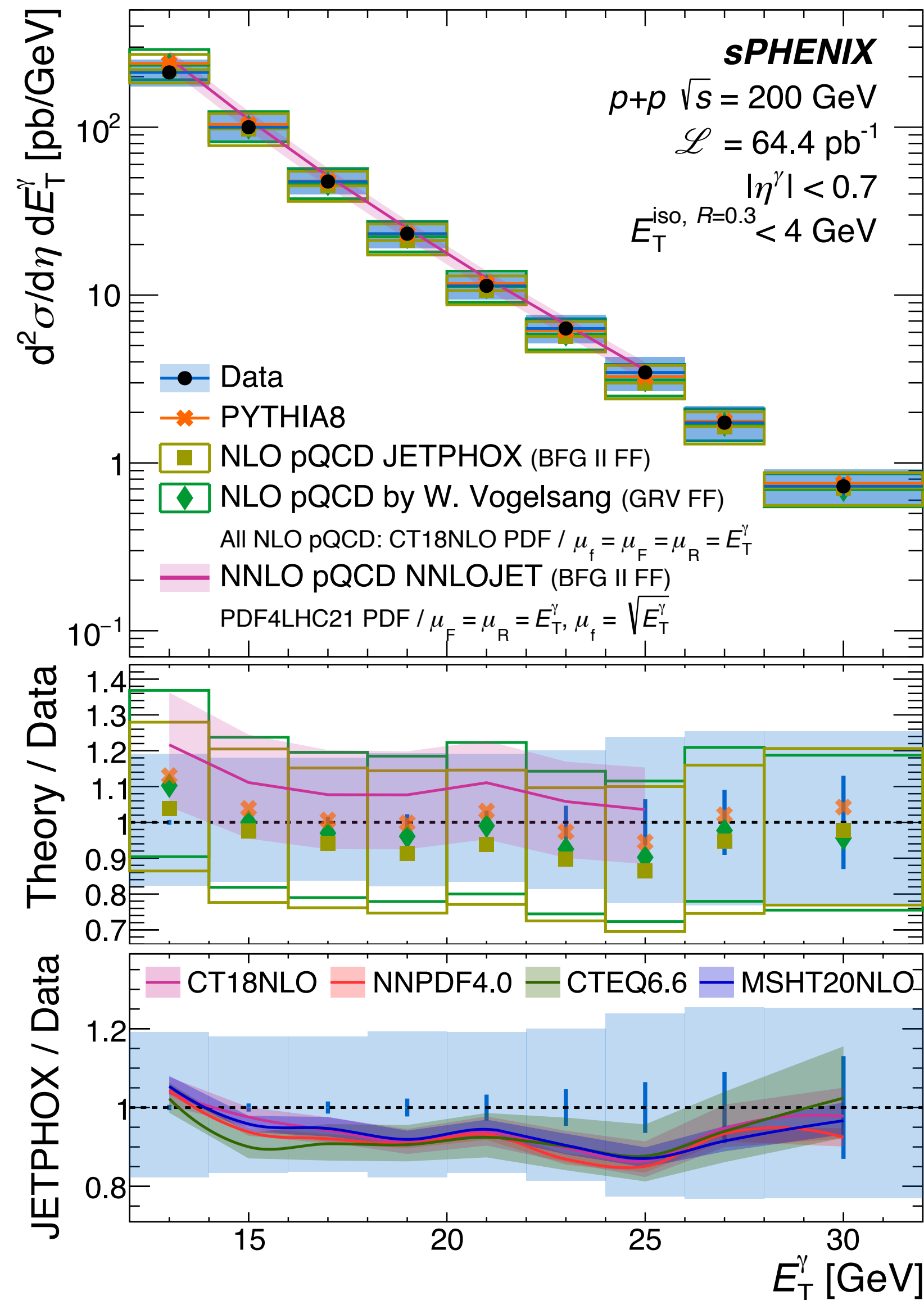
EMCal block



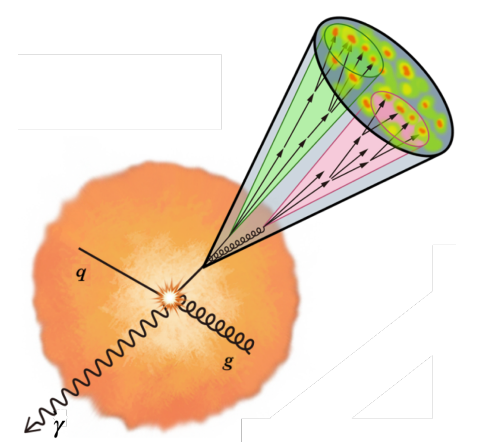
Electromagnetic probe

- EMCal clustering algorithm for reconstruction
- Neutral mesons used for detector calibration
- MC corrected to match energy scale and energy resolution observed in data

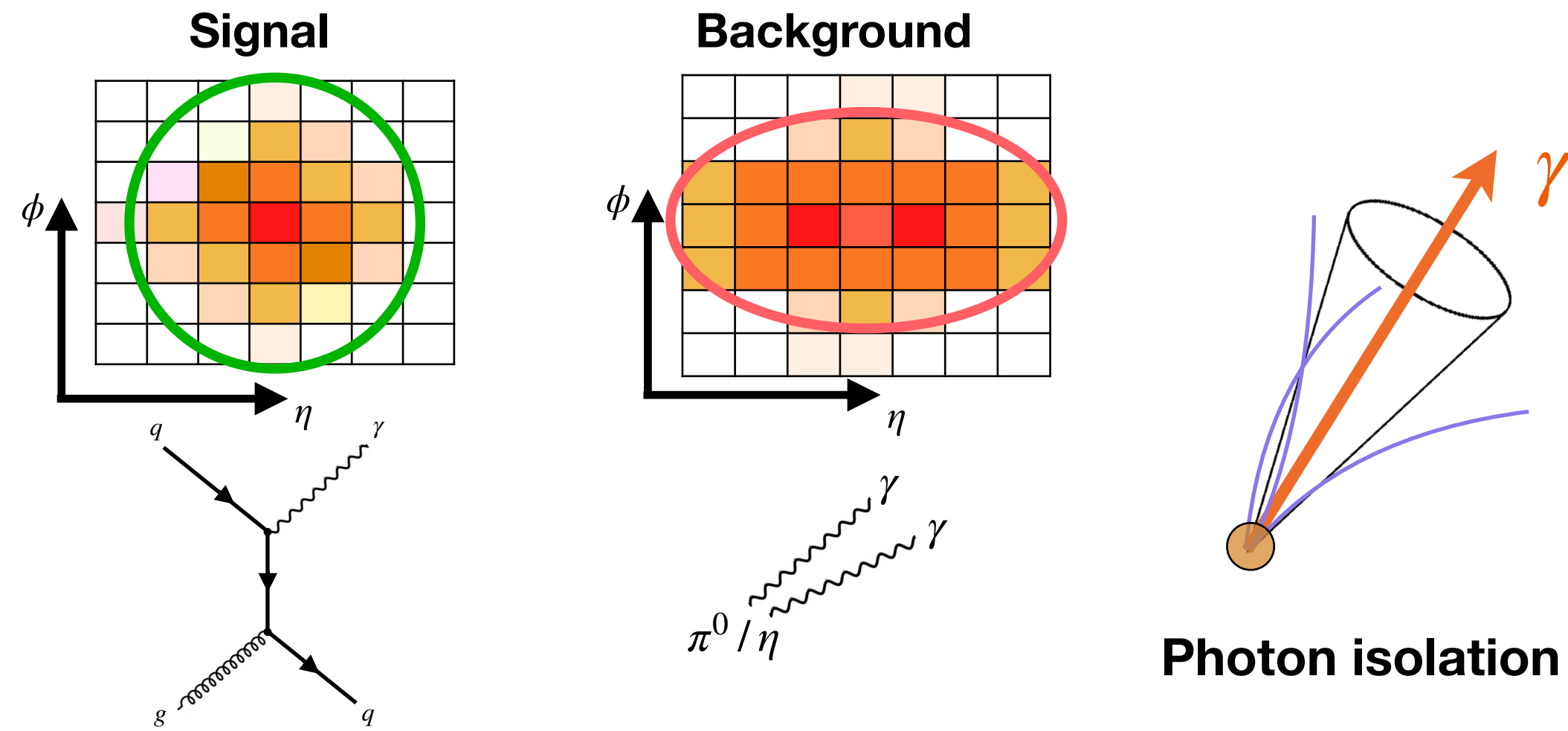
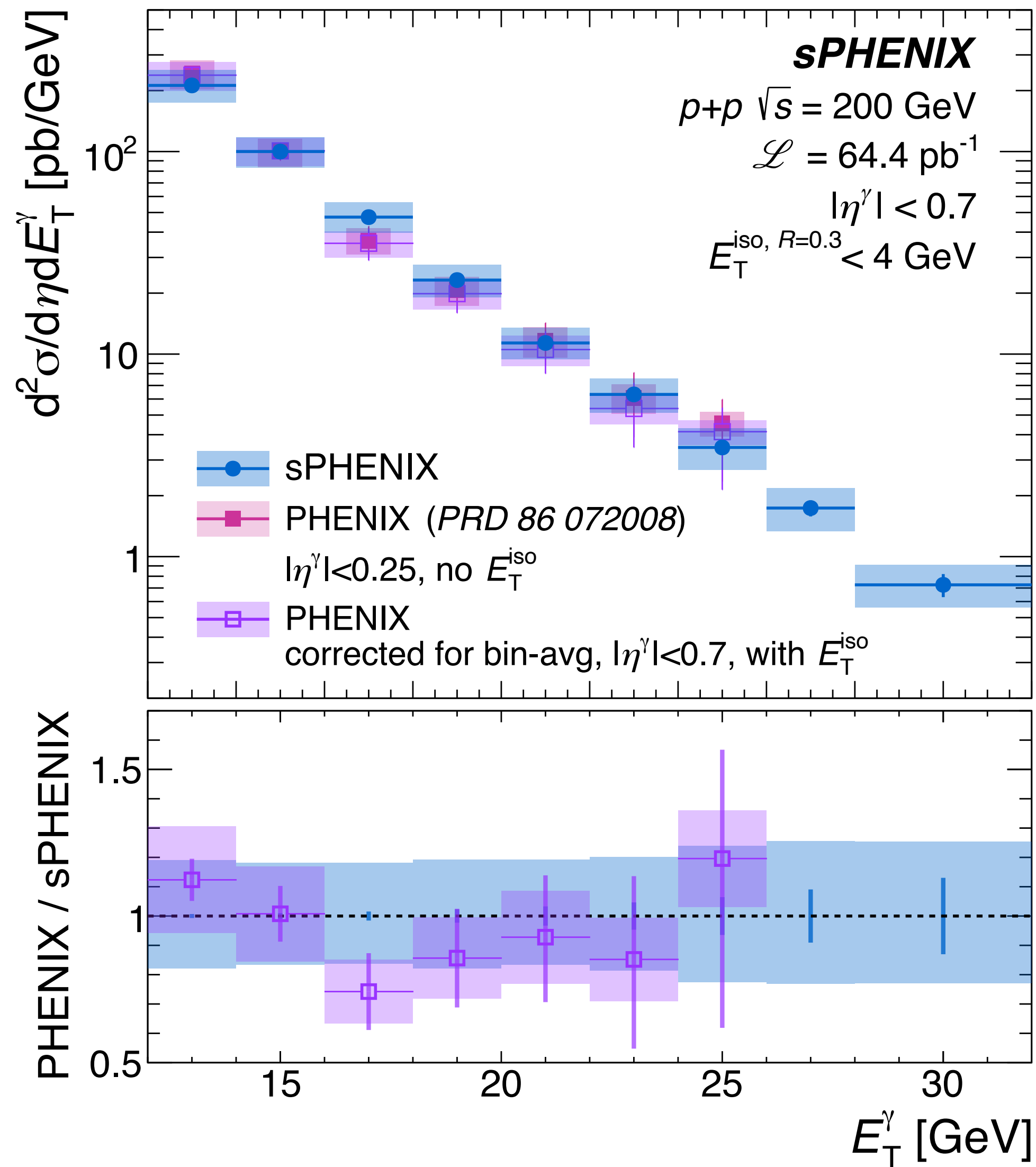
Isolated prompt-photon in p+p 200 GeV



- **2D side-band analysis with ML-based shower shape analysis** and **isolation with EMCal + HCal**
- **pQCD calculations** in good agreement with data
- Gateway to flagship **γ -jet** measurements

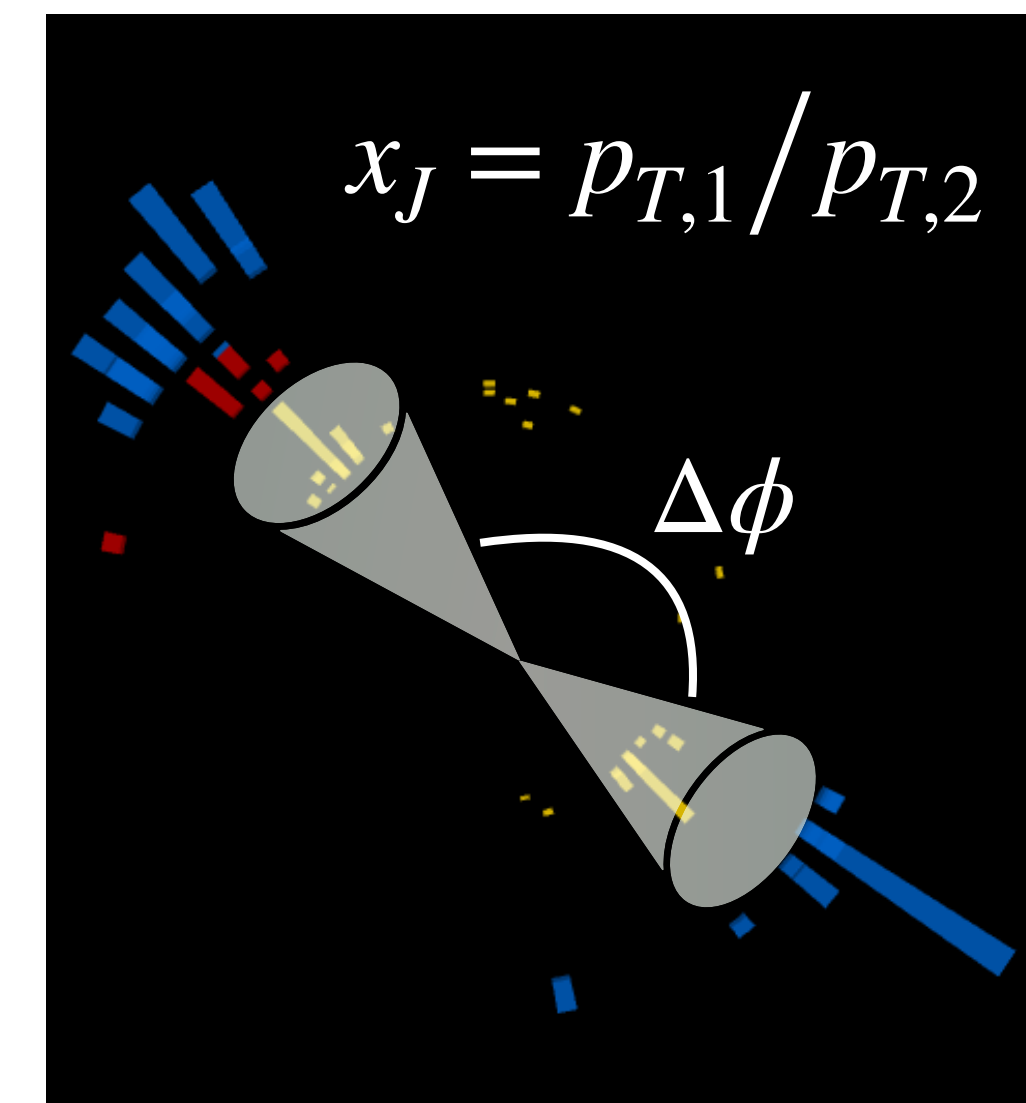
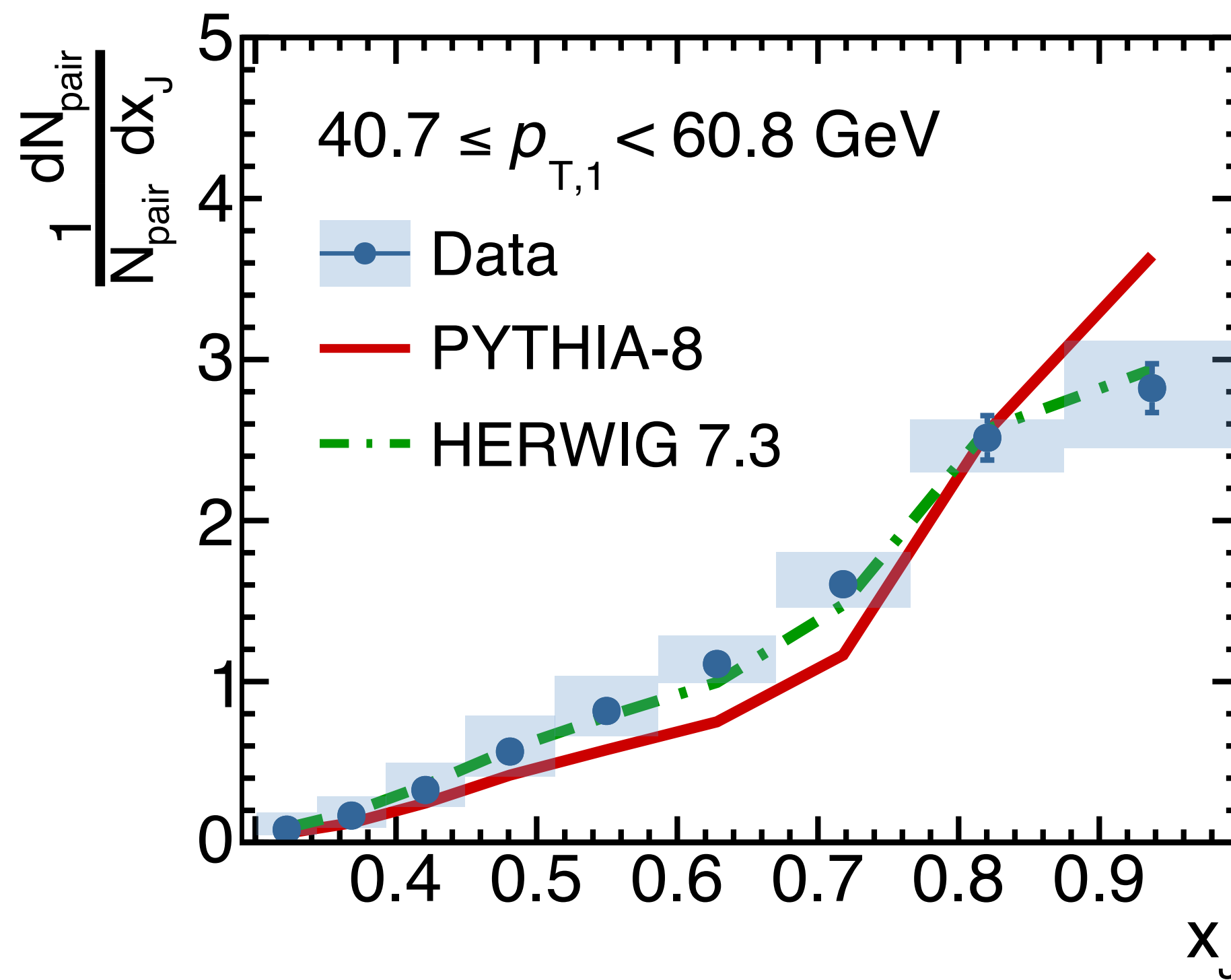
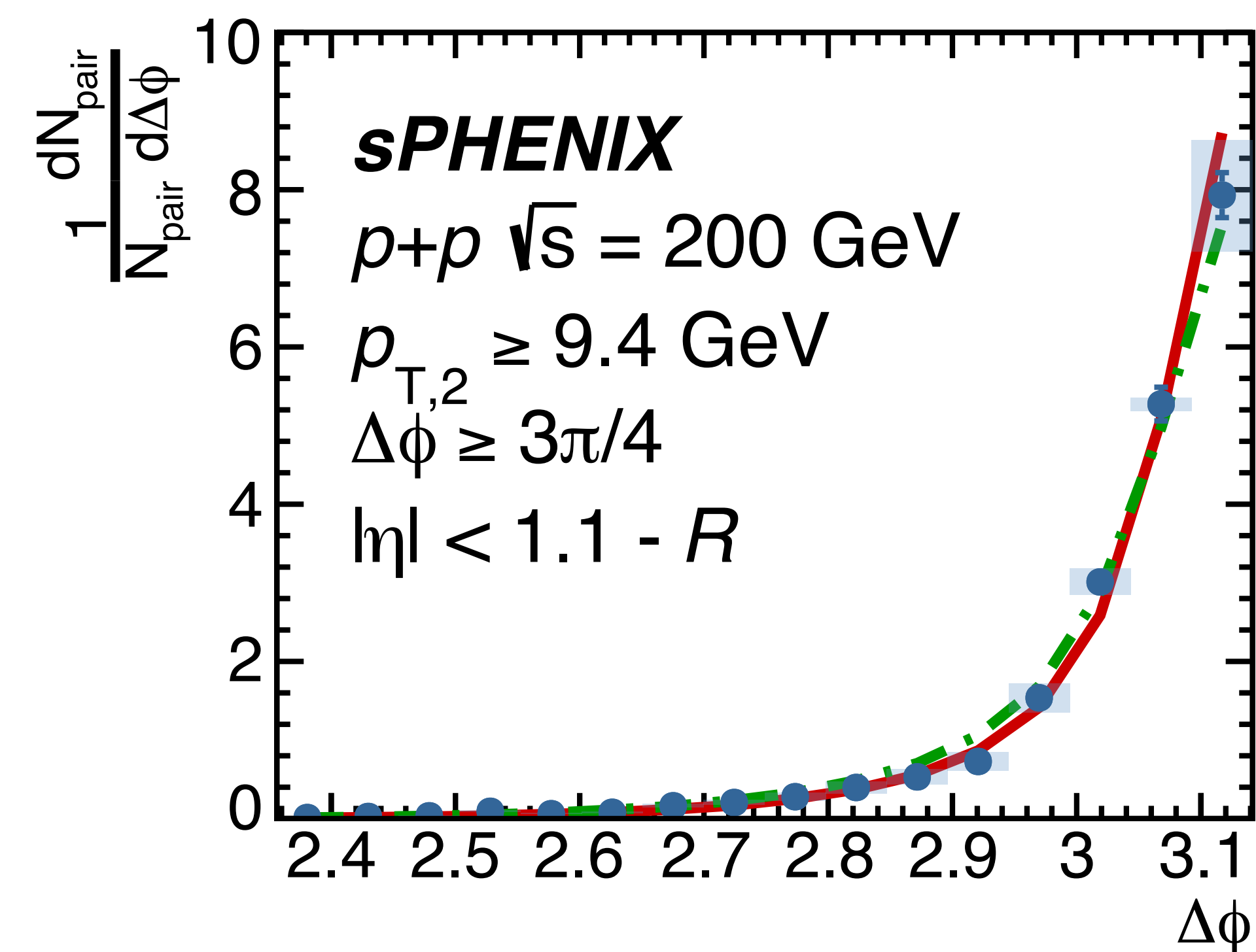


Isolated prompt-photon in p+p 200 GeV



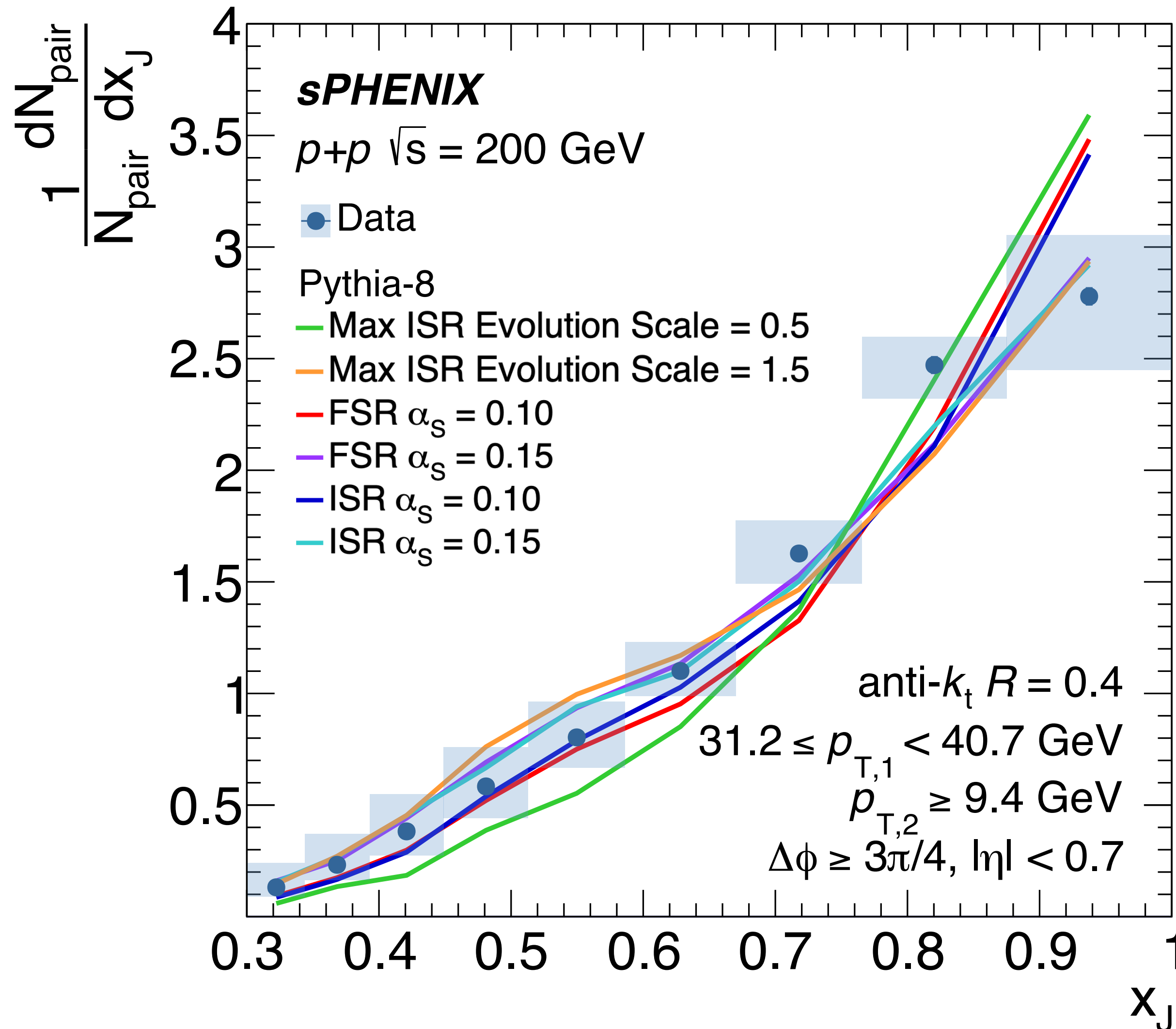
- **2D side-band analysis with ML-based shower shape analysis and isolation with EMCal + HCal**
- **Extended p_T range** with better statistical precision than previous RHIC measurements

Dijet Asymmetry in p+p 200 GeV



- Detector response corrected via full 2D unfolding
- Clear **back-to-back** dijets in $\Delta\phi$ and **symmetric momentum balance** in x_J
- Well described by both **Pythia** and **Herwig** generators

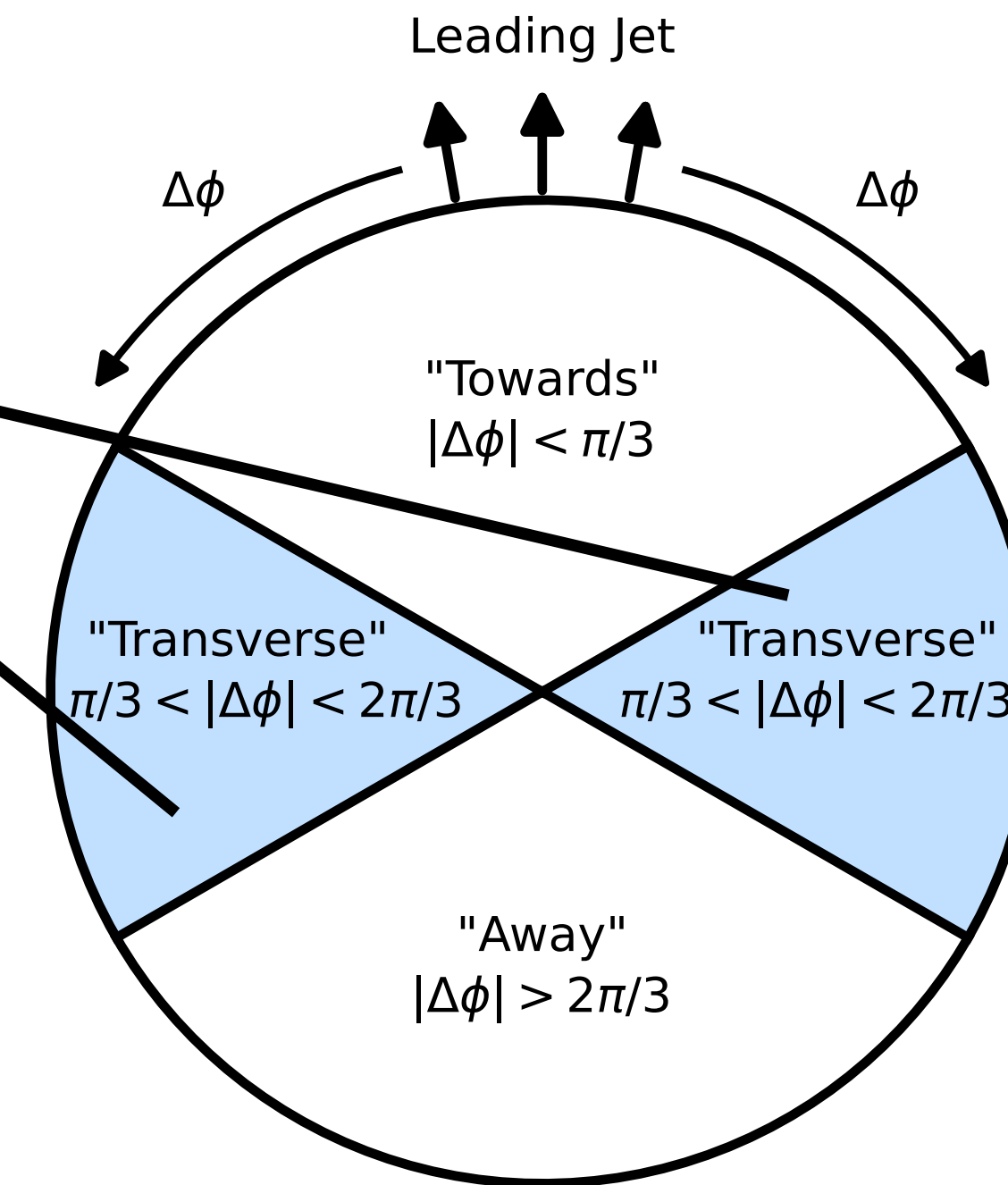
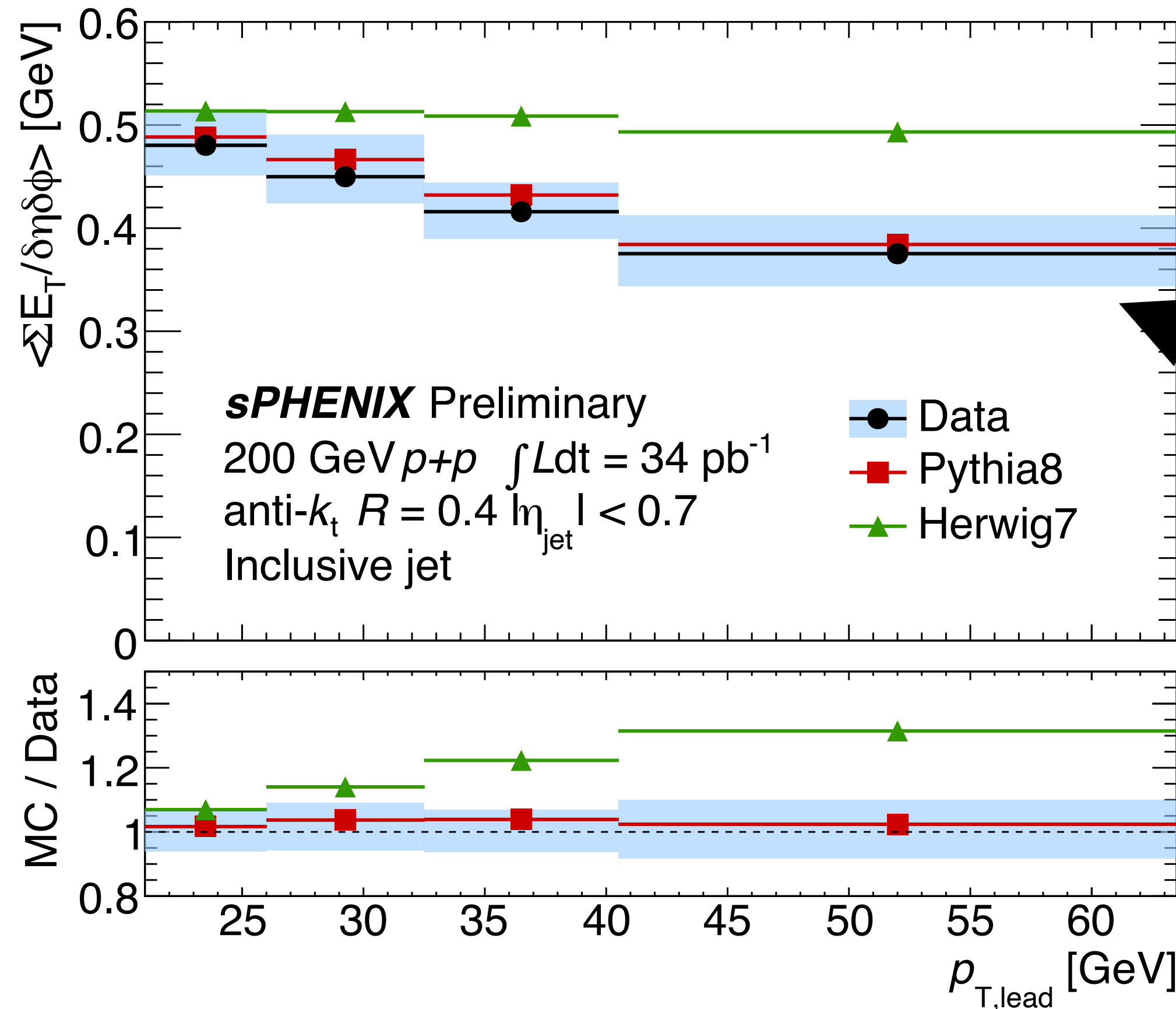
MC tuning with dijet asymmetry in pp 200 GeV



Sensitivity to **MC tuning**

- **ISR** / **FSR** bounds tuned for LHC jet measurements
- Current uncertainties in envelope of parameter variations
 - Multi-differential measurements providing useful constraints at RHIC energies

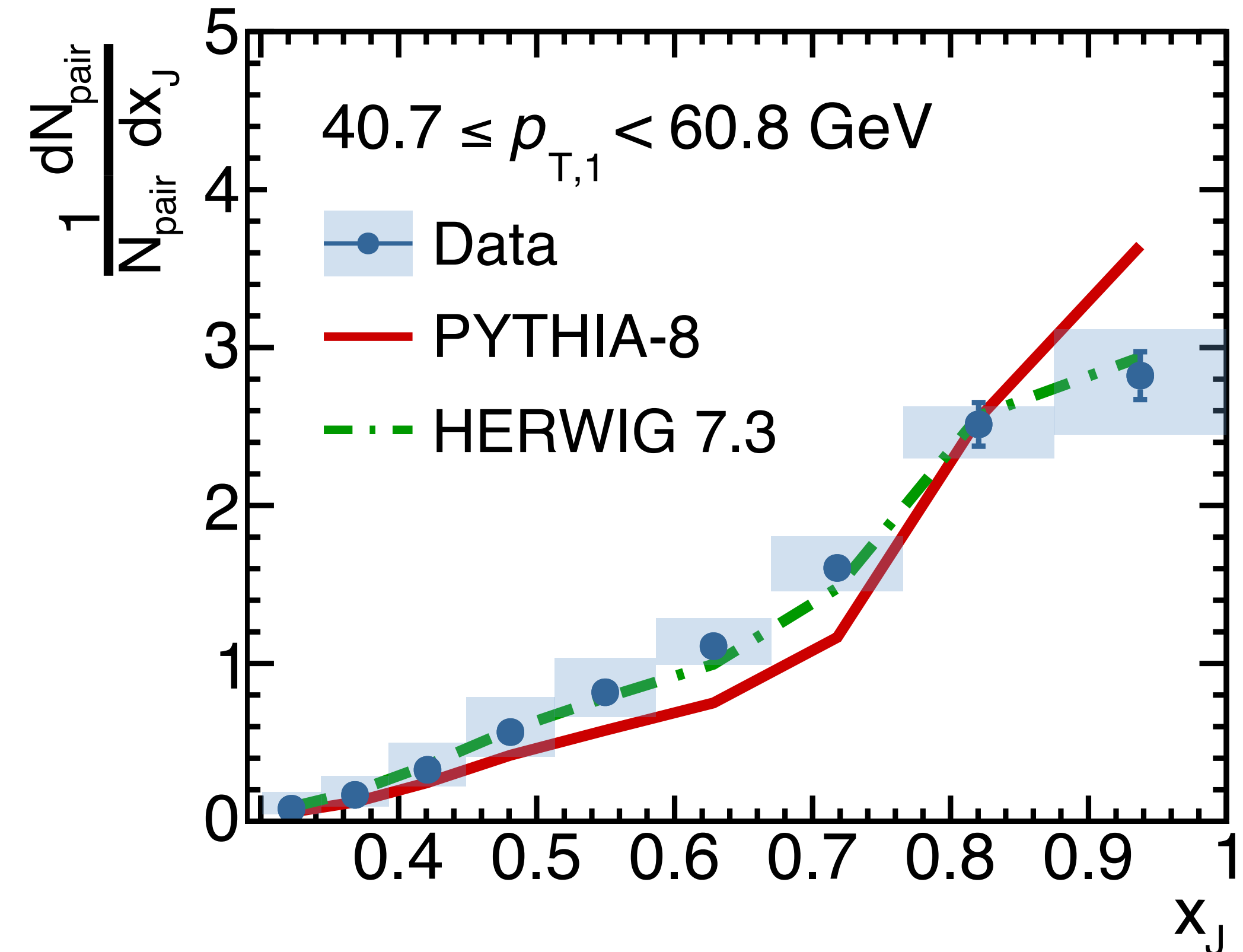
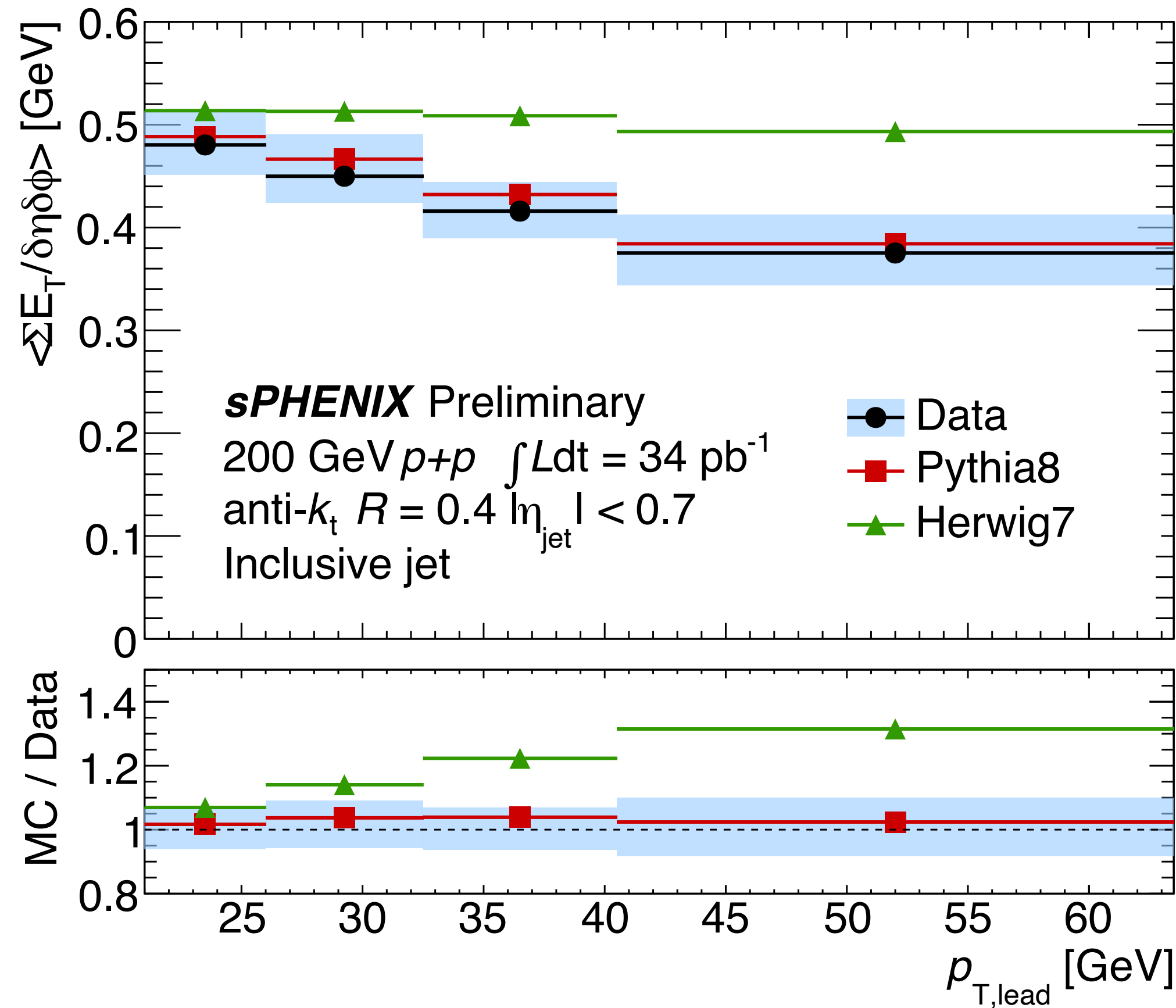
Underlying event and jet production correlation



UE in transverse region of leading jet

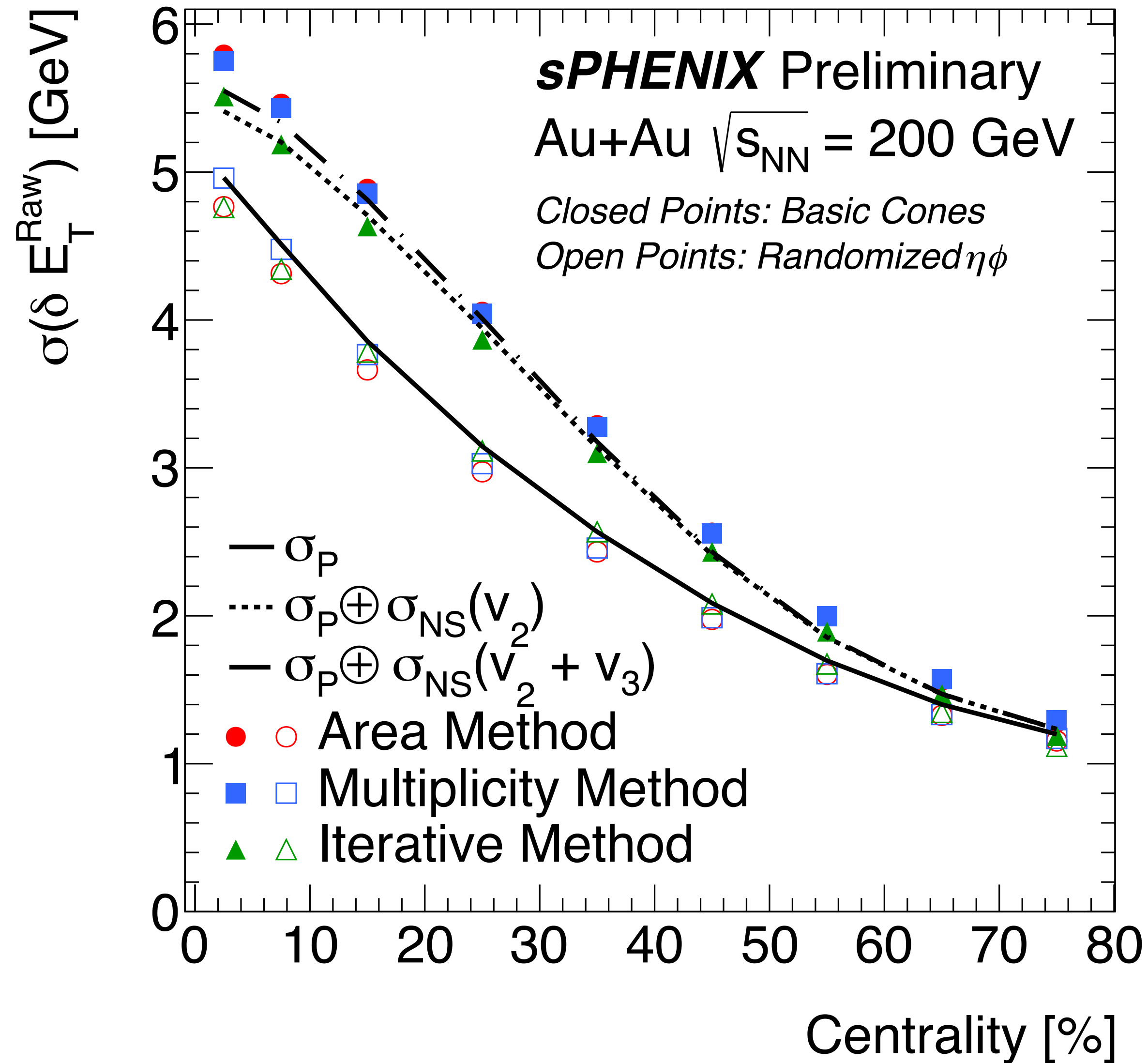
- **Clear correlation** observed between **soft** and **hard** processes
 - Related to modeling MPI & parton shower
- **Significant deviation** compared to **Herwig** generator

MC constraints with sPHENIX jet results



- **Strong constraints** using multiple measurements with sPHENIX on **MC generators at RHIC energies**

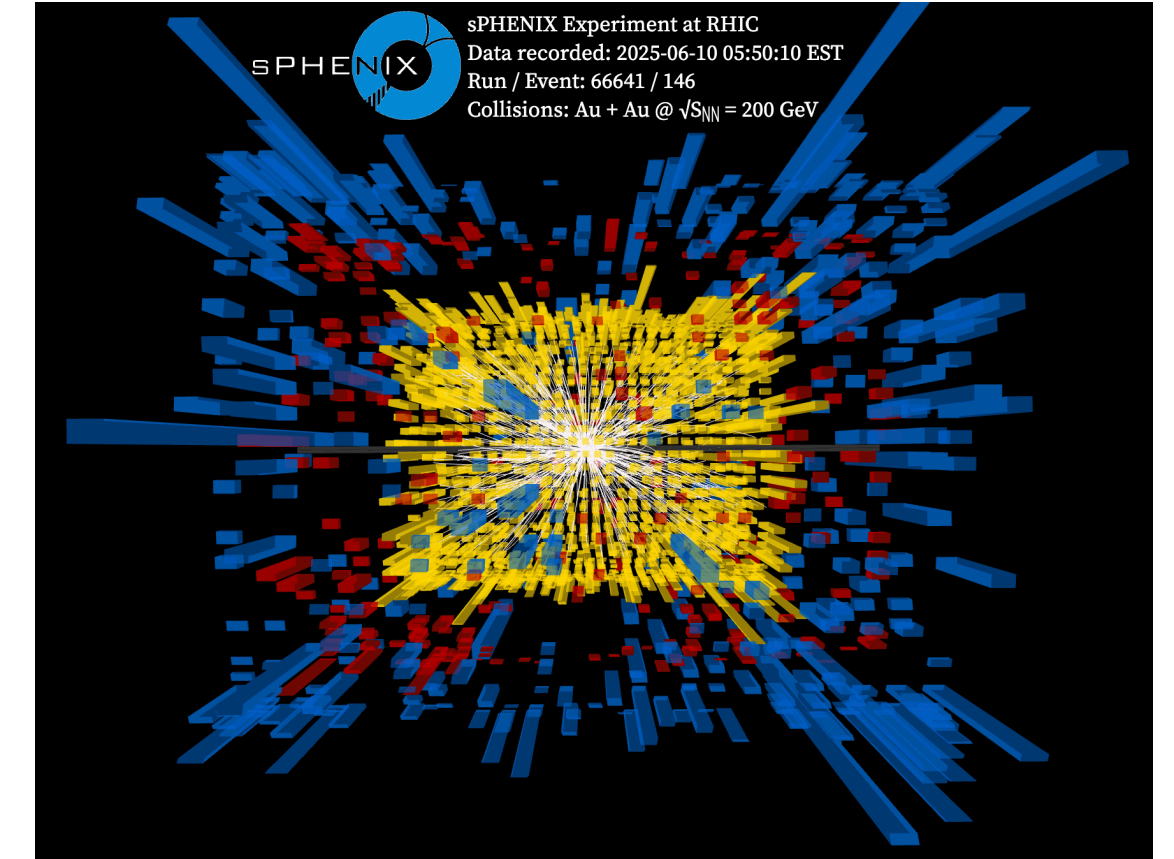
Underlying event characterization



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

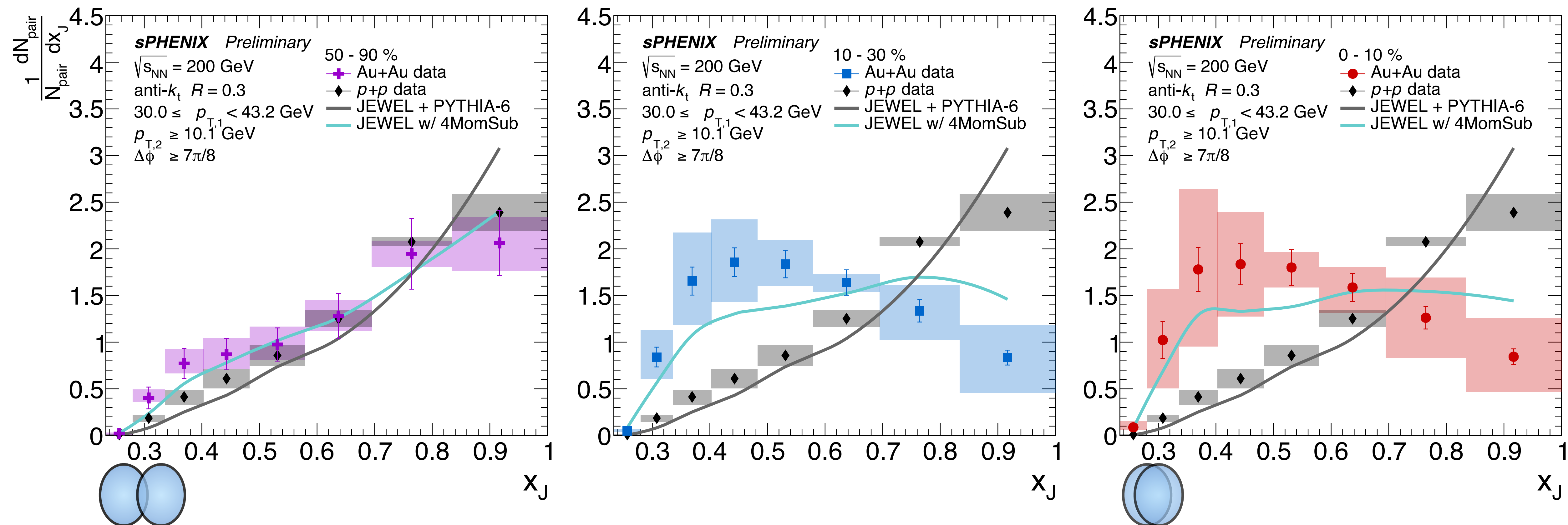
$$\delta E_T^{\text{Mult}} = \sum_{i=0}^N E_{T,i} - \rho_M \cdot N$$

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



- **Underlying event** studied using various subtraction methods
- Absolute fluctuation described by **statistical multiplicity-fluctuations** and **hydrodynamic correlations**

Dijet Asymmetry in p+p / Au+Au 200 GeV



- **Strong modification** in x_J from **peripheral collisions** to **central collisions**
- Only using **1%** of the **full sampled luminosity**
- **Trend** described by **jet-quenching** calculations

Intense work on calibration toward heavy flavor physics

- **sPHENIX trackers** operated stably in dual **triggered** + **streaming** readout mode
- Studies with early calibrations show capability of **streaming readout reconstruction** and **high-precision heavy flavor** measurements

Comprehensive jet physics program

- **Data-driven** calibrations for **jet energy scale** and **jet energy resolution**
- **Isolated prompt-photon** measurement with **2D side-band** method and described by **pQCD** calculations
- **Dijet asymmetry** and **jet-UE correlation** crucial for MC tuning at RHIC energies
- Significant modification in **dijet x_J** in **central Au+Au** compared to p+p
- **Jet suppression** observed in **O+O** with clear **centrality ordering** beyond selection bias