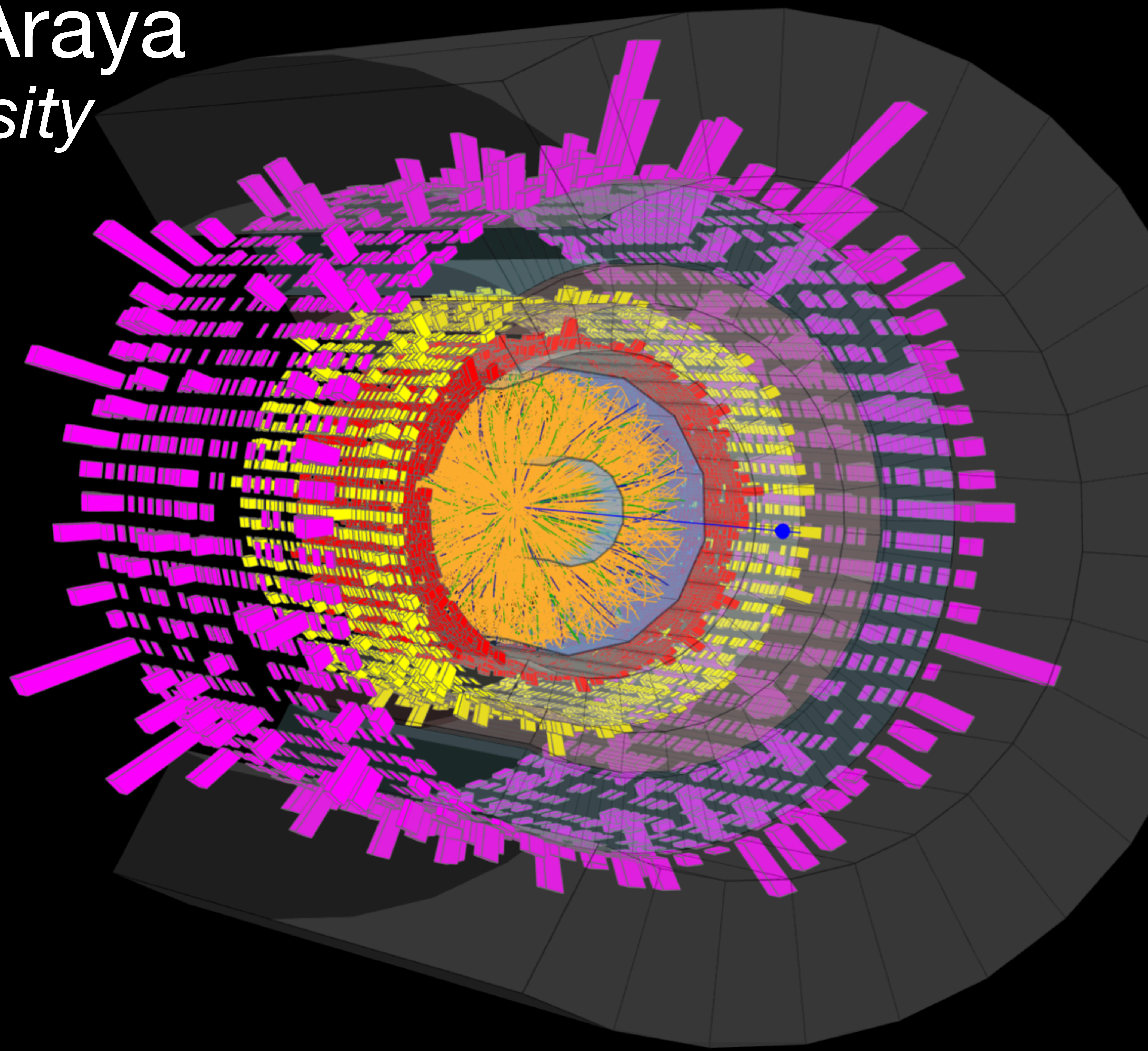
Jet physics at sPHENIX

Sebastian Tapia Araya
Iowa State University



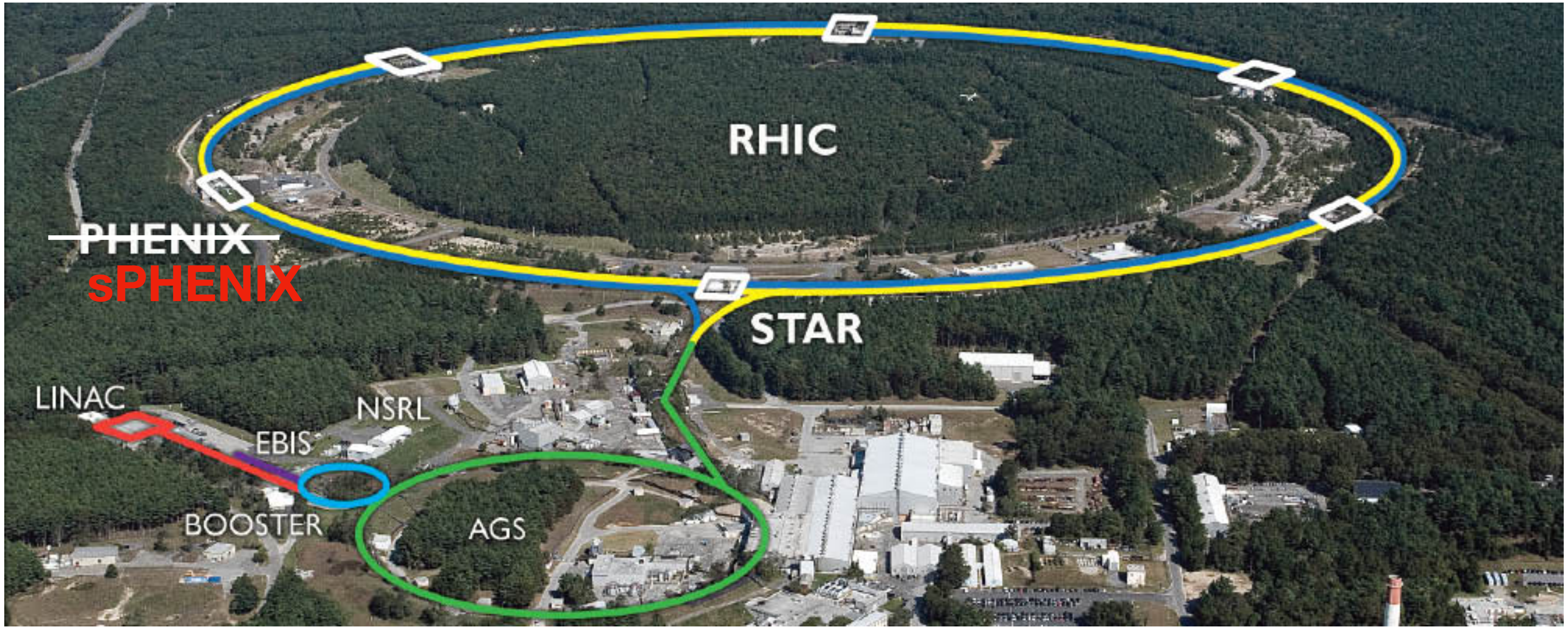
Fixed target experiments at LHC

22 Jun 2022

What is sPHENIX?

- sPHENIX is **under construction** at BNL in the PHENIX experimental hall
- sPHENIX is the first new detector at any hadron collider in over a decade!
- sPHENIX has unique, purpose-built capabilities never before deployed at RHIC

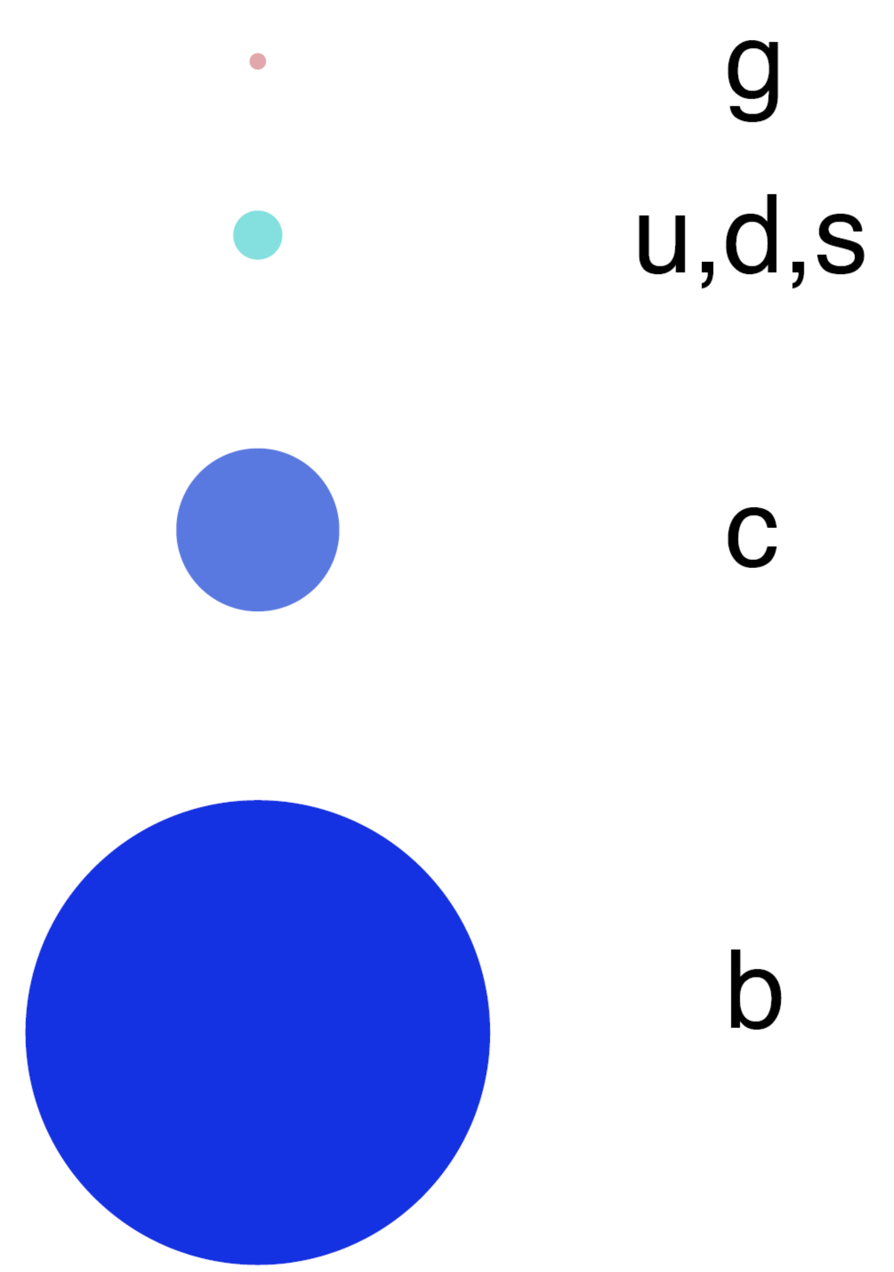
…to complete the scientific journey
started at RHIC over twenty years ago!



sPHENIX physics program

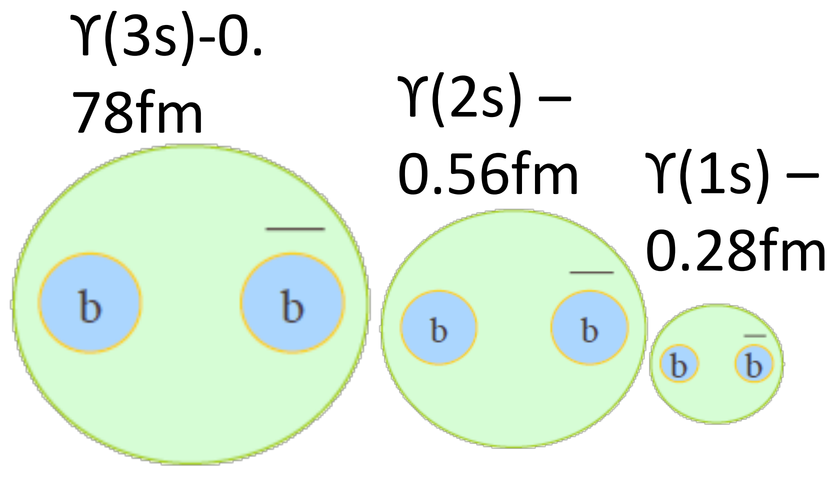
Parton energy loss

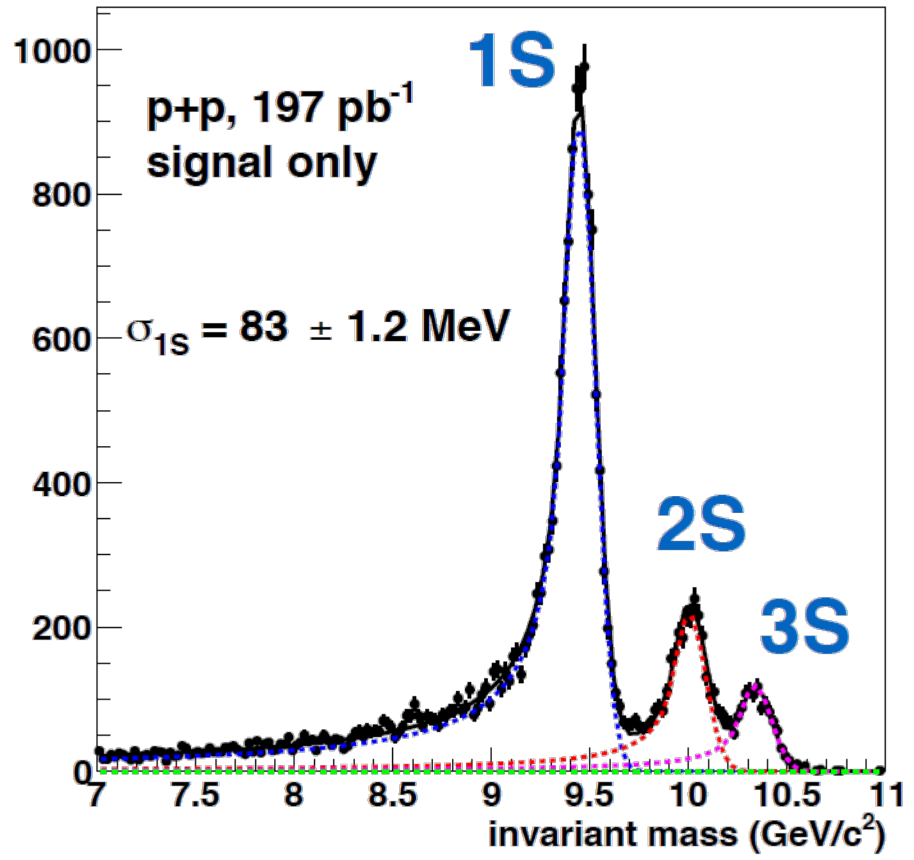
Vary mass/momentum of probe



Upsilon spectroscopy

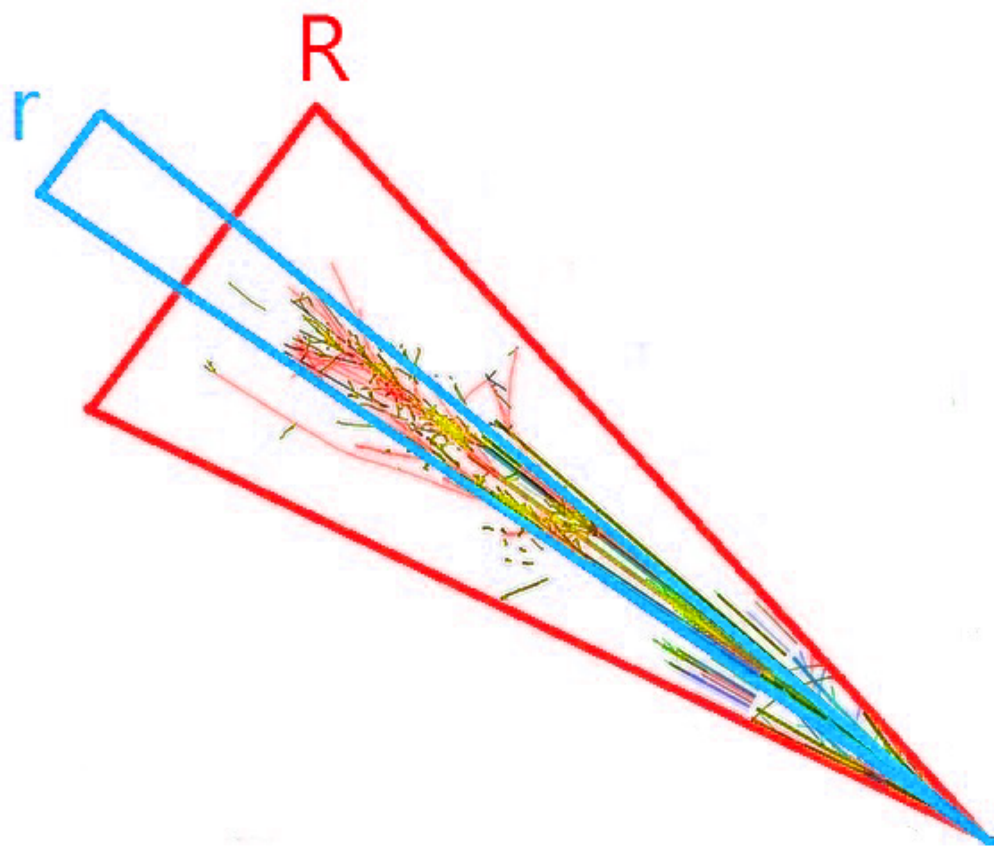
Vary size of the probe





Jet cor. & substructure

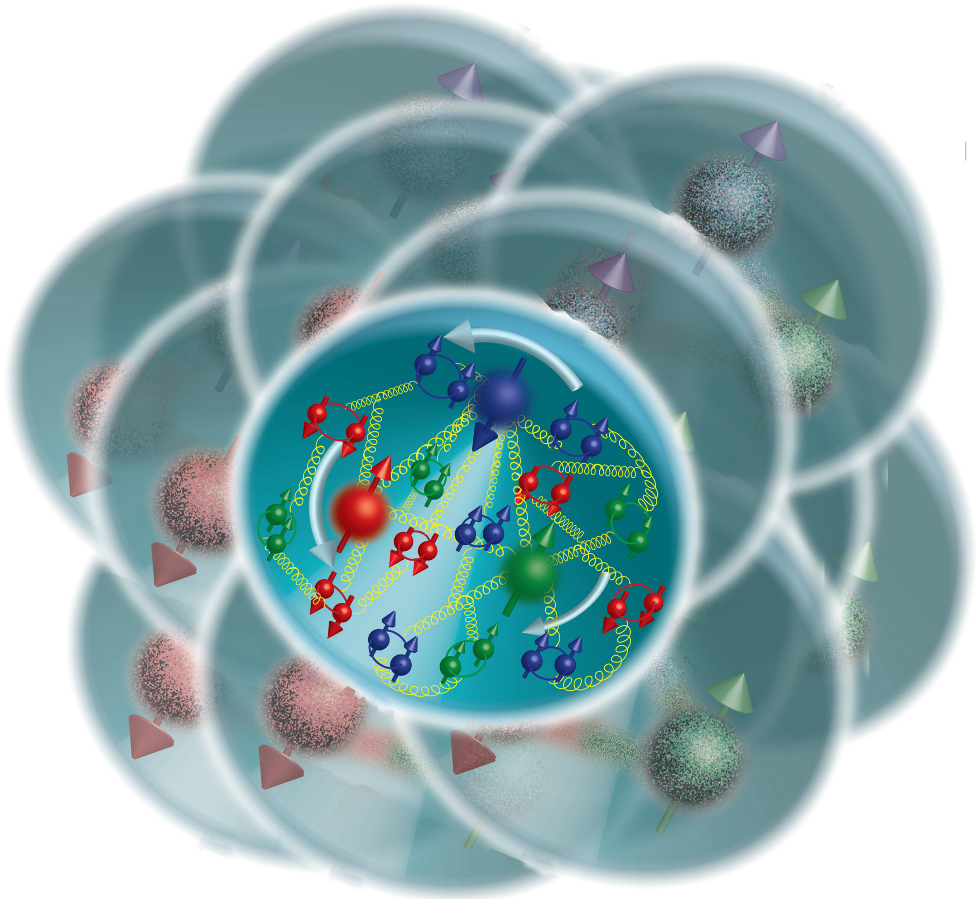
Vary momentum/angular size of probe



Cold QCD

Spin-orbit correlations in the nucleon

CNM effects and hadronization

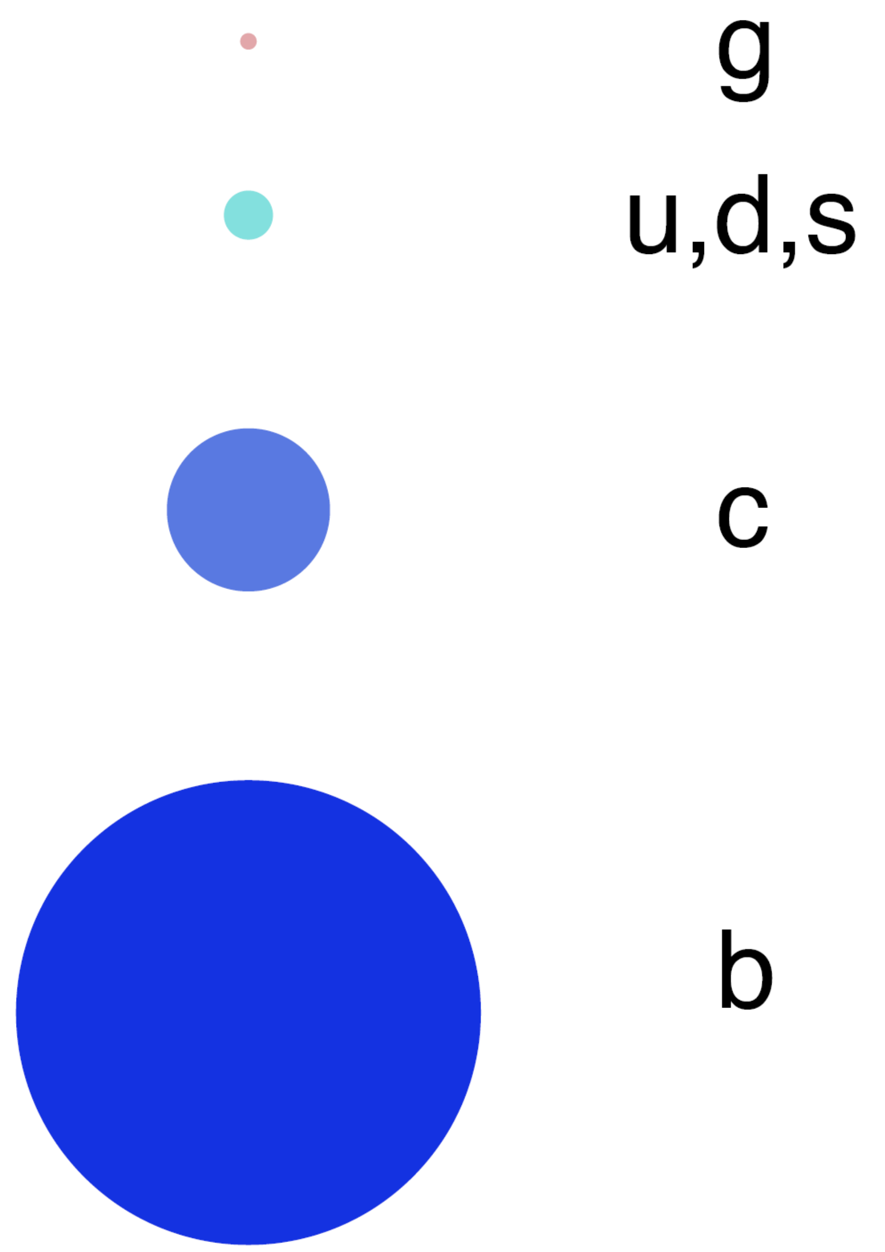


The Goal: Probe the inner work of Quark-Gluon-Plasma

sPHENIX physics program

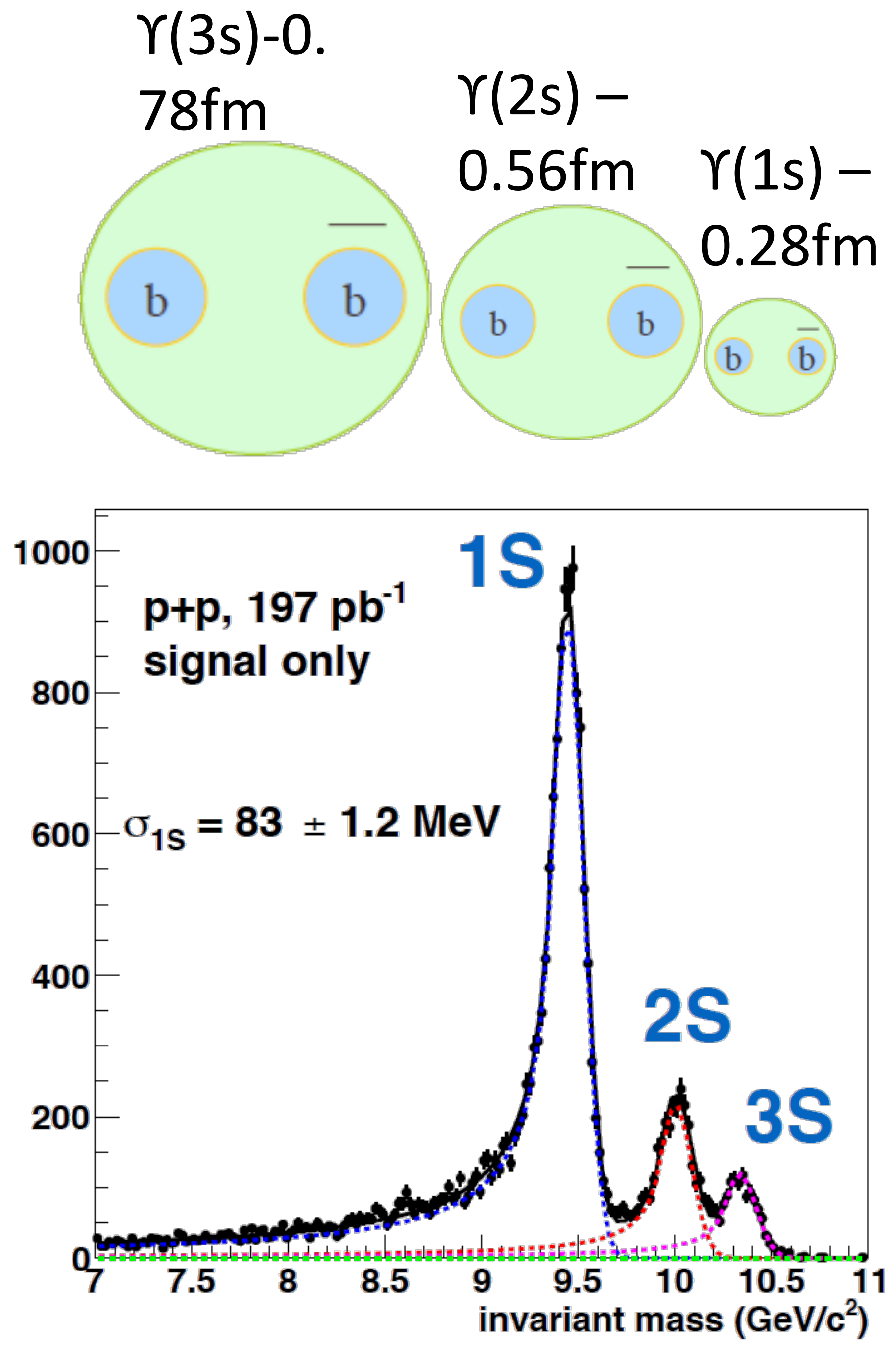
Parton energy loss

Vary mass/momentum of probe



Upsilon spectroscopy

Vary size of the probe



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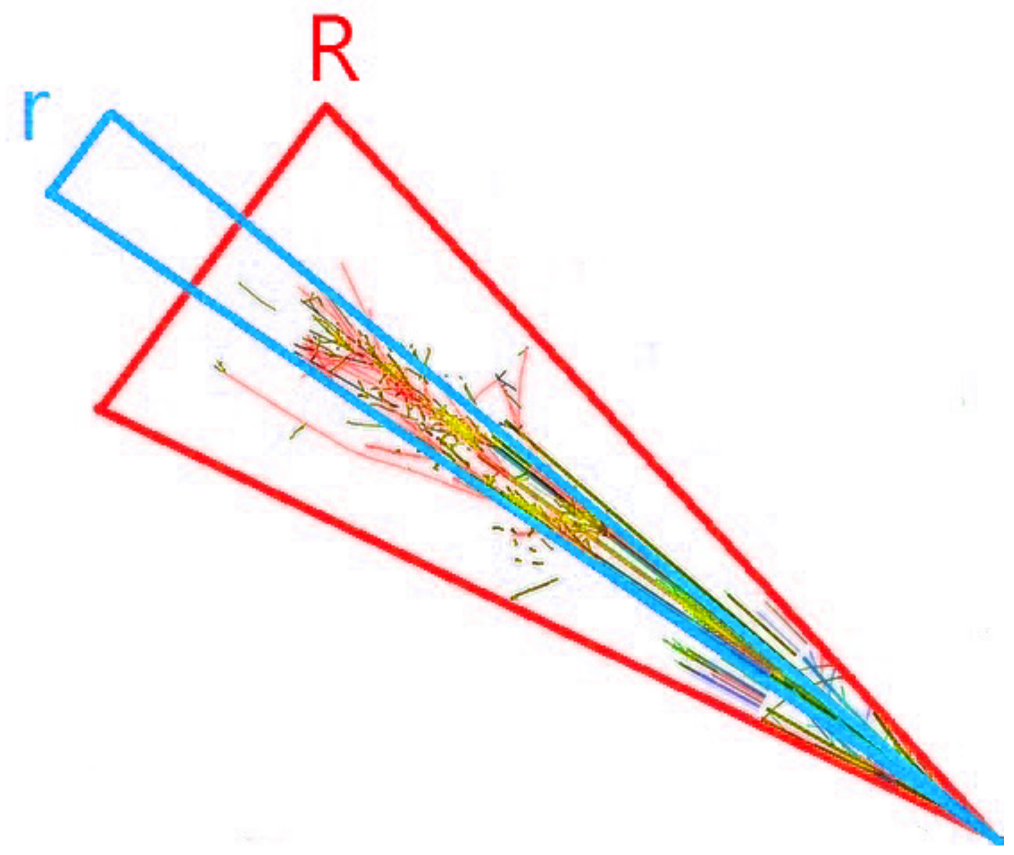

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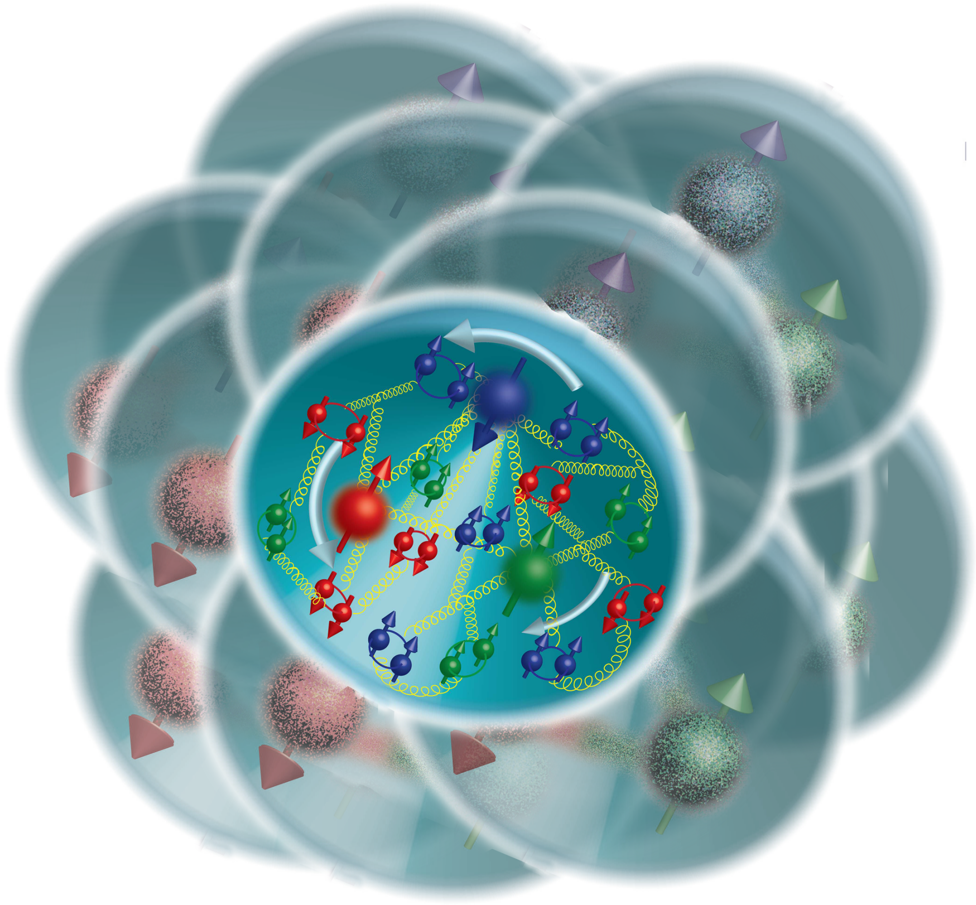
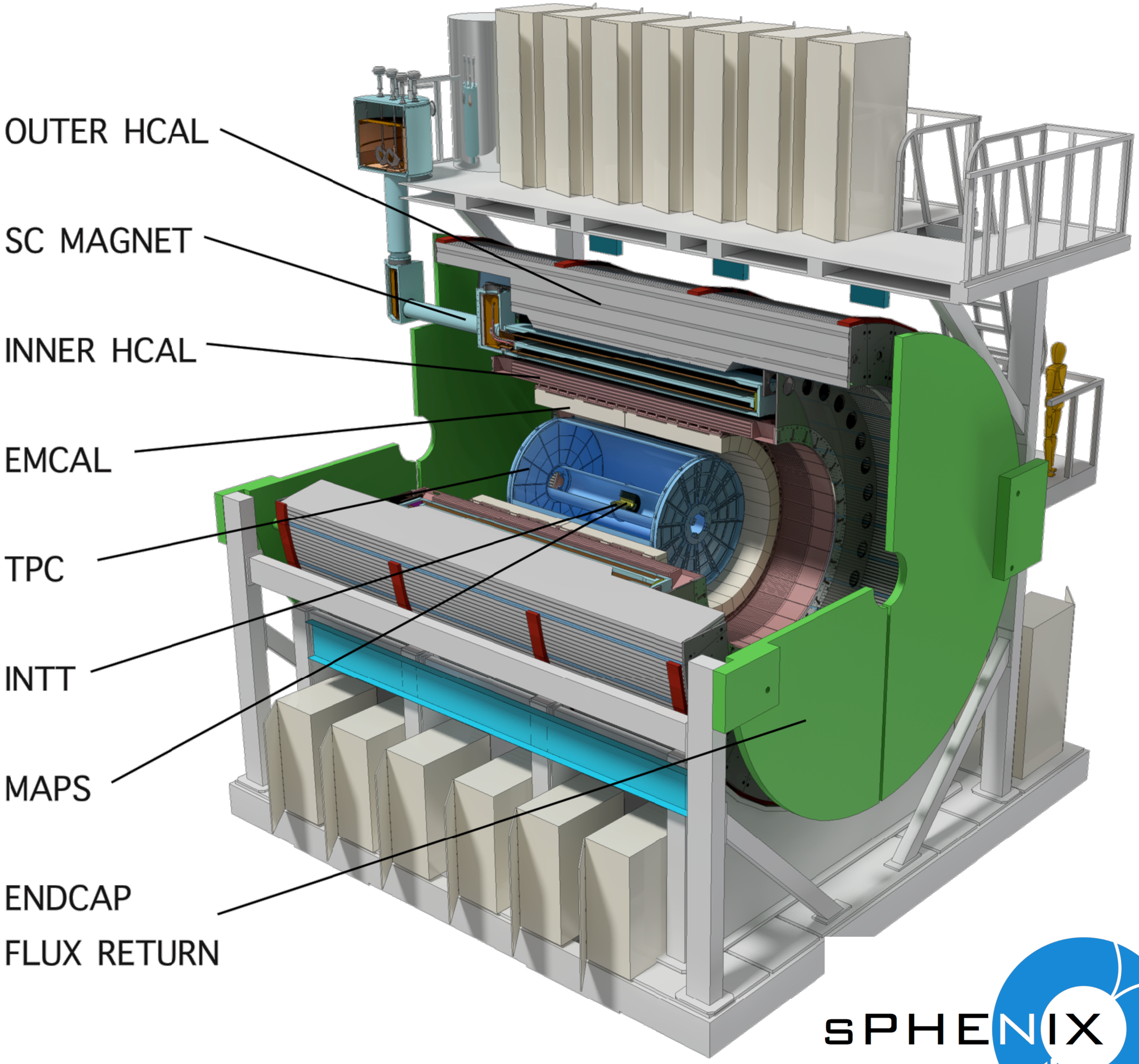


Focus of this talk

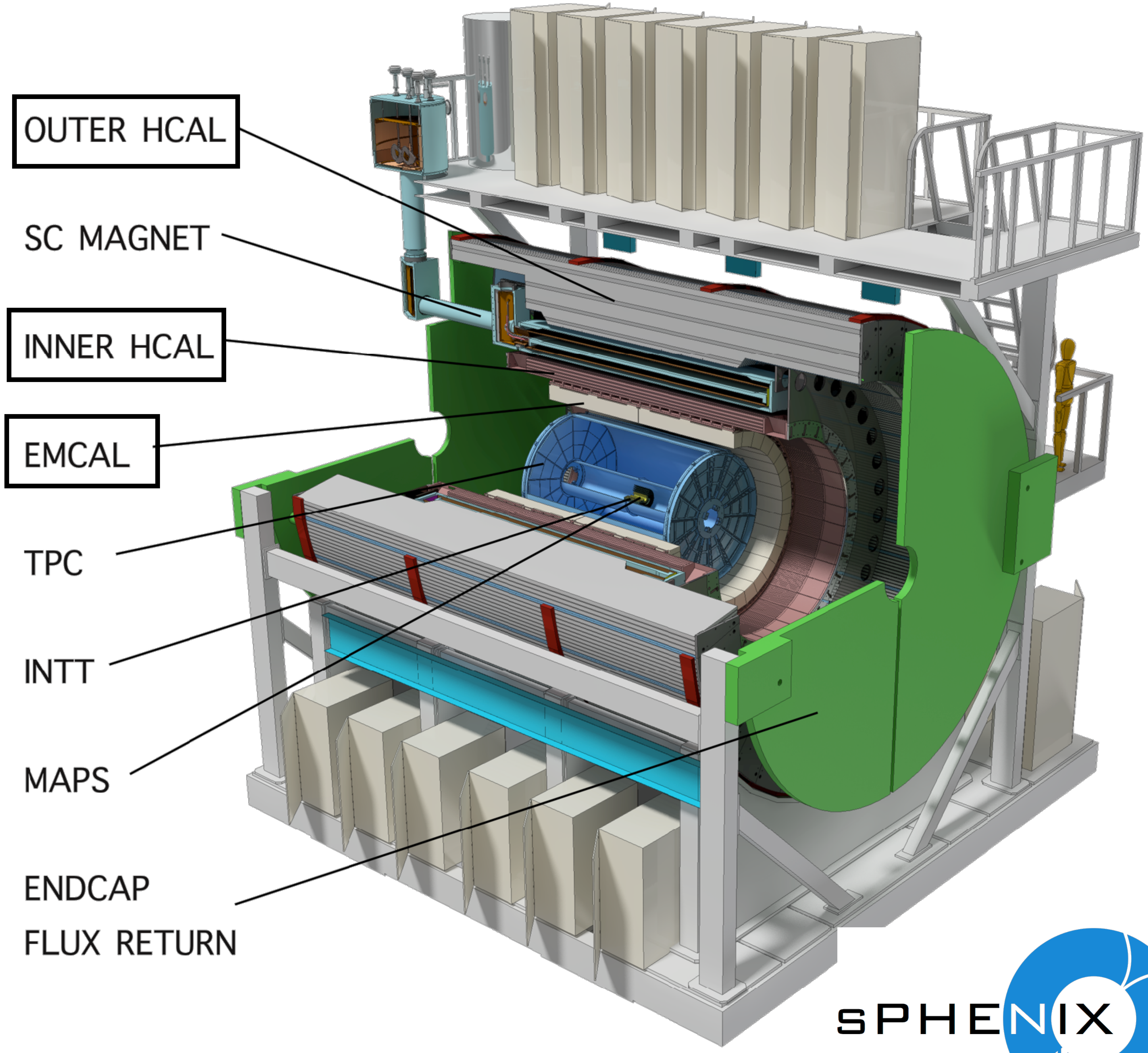
sPHENIX detector



15 kHz calo trigger + 10% streaming DAQ
10 GB/s data logging

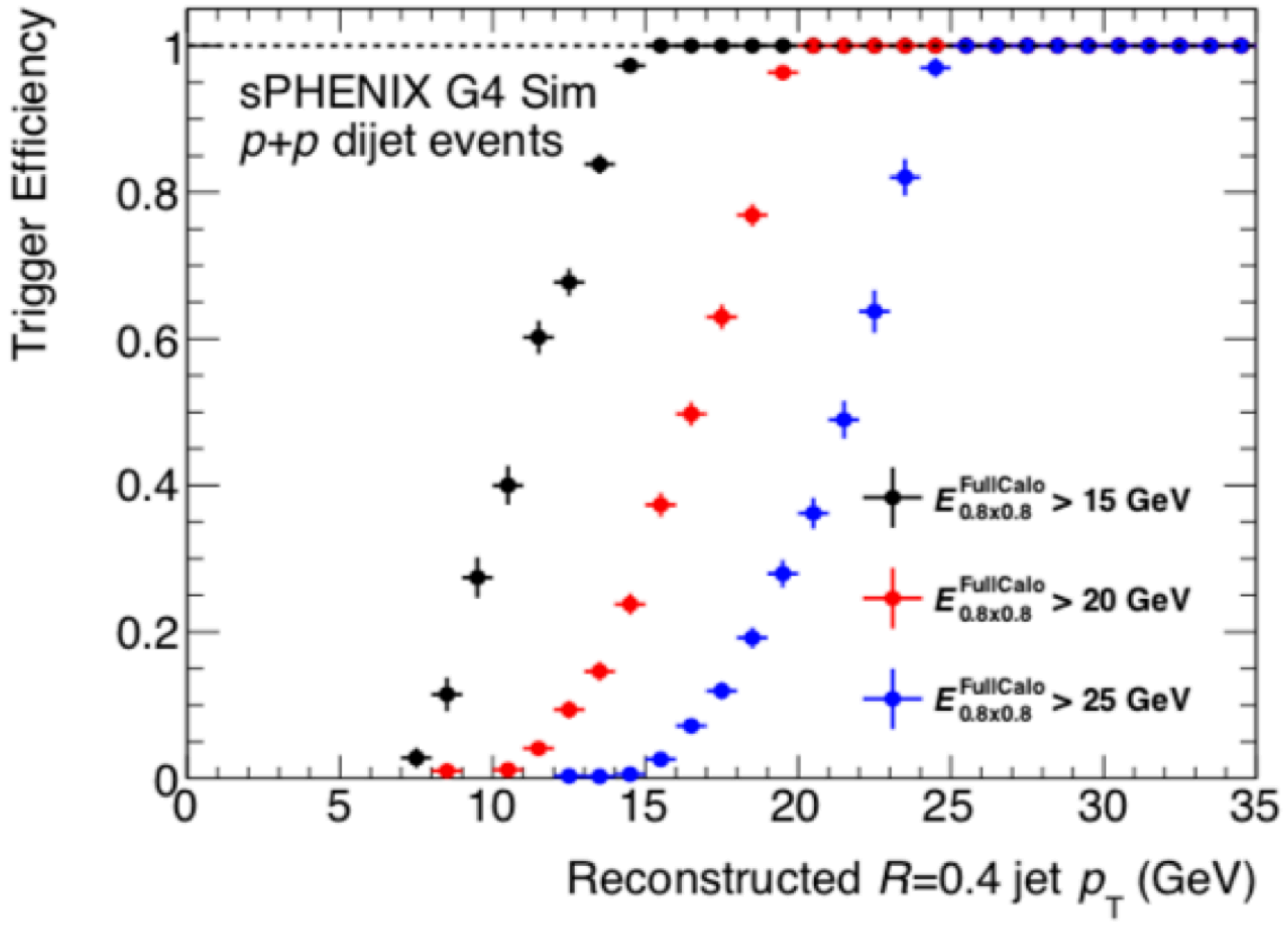
sPHENIX Calorimeter system

- HCAL and EMCAL covering 2π in azimuth, |η| < 1.1, 15kHz read-out rate
- First mid-rapidity hadronic calorimeter at RHIC
- Allows to capture full jet energy
  - reduce fragmentation bias and improve resolution
- Allows systematic comparison of **particle flow** vs **calo** vs **track jets**
- Allows unbiased jet trigger in p+p

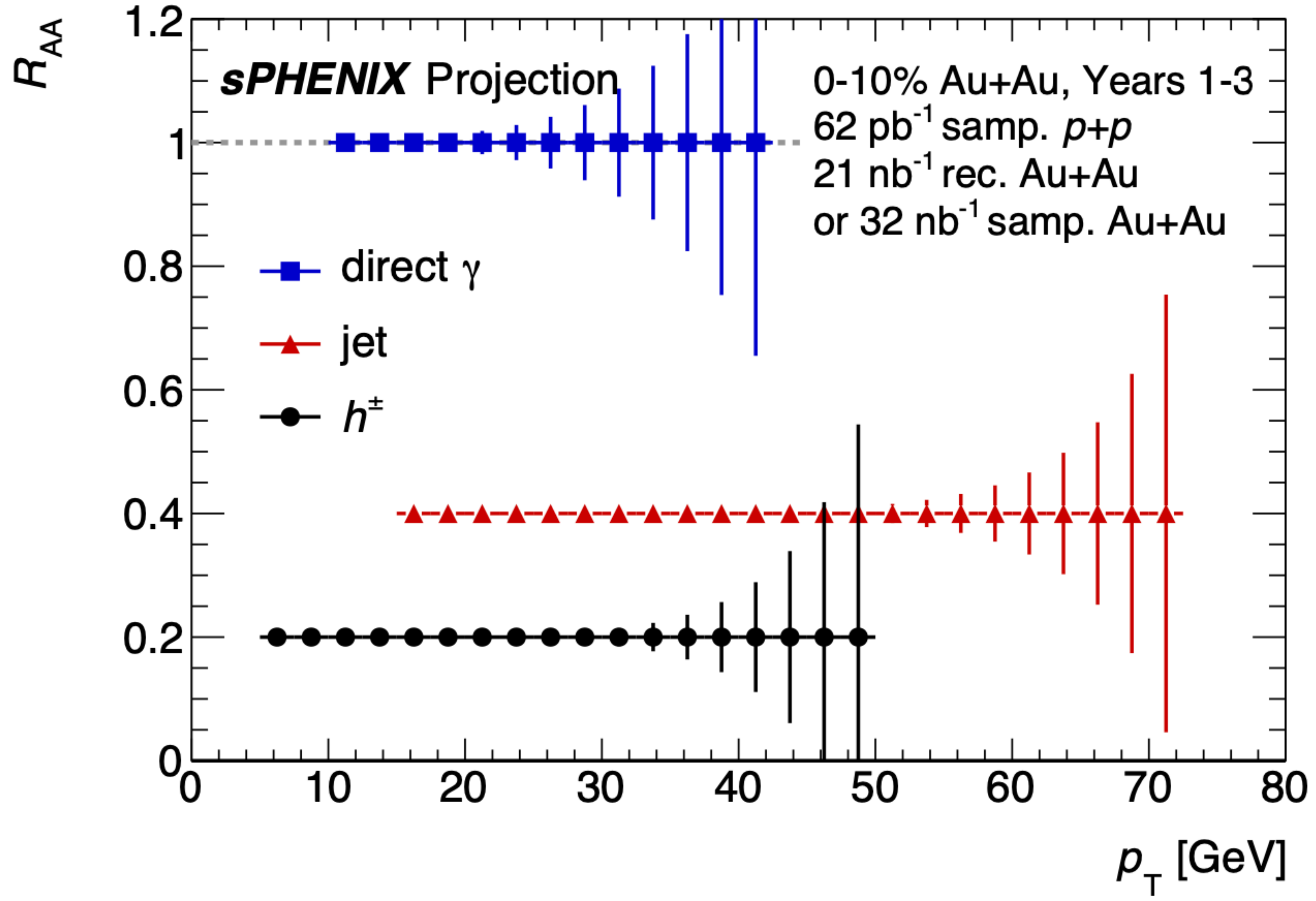


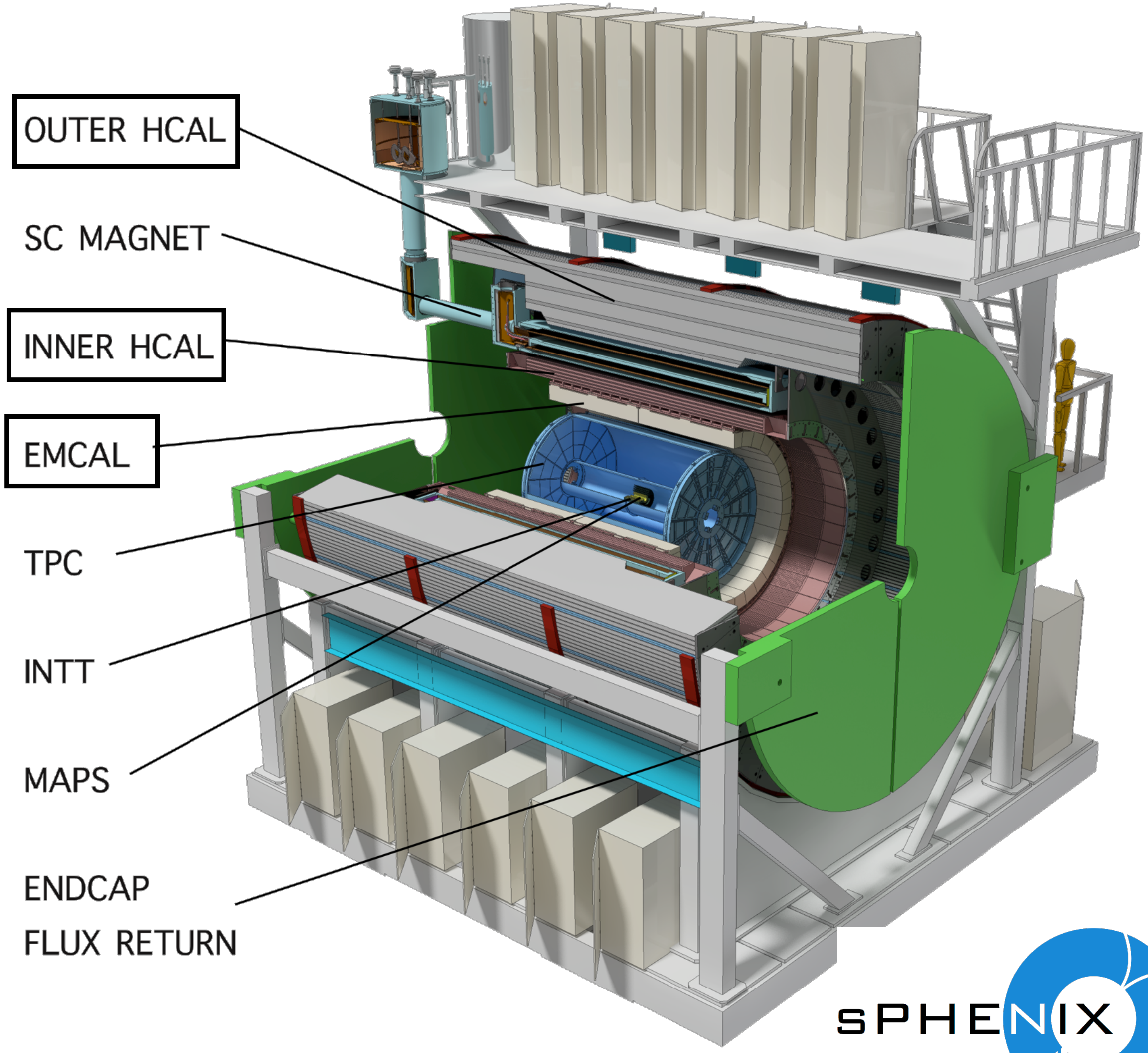
sPHENIX Calorimeter system == Unbiased jet trigger in p+p

Jet trigger turn-on curve (pp)



Jet R_{AA} up to 70 GeV for central Au+Au





sPHENIX Tracking system

Vertexing:

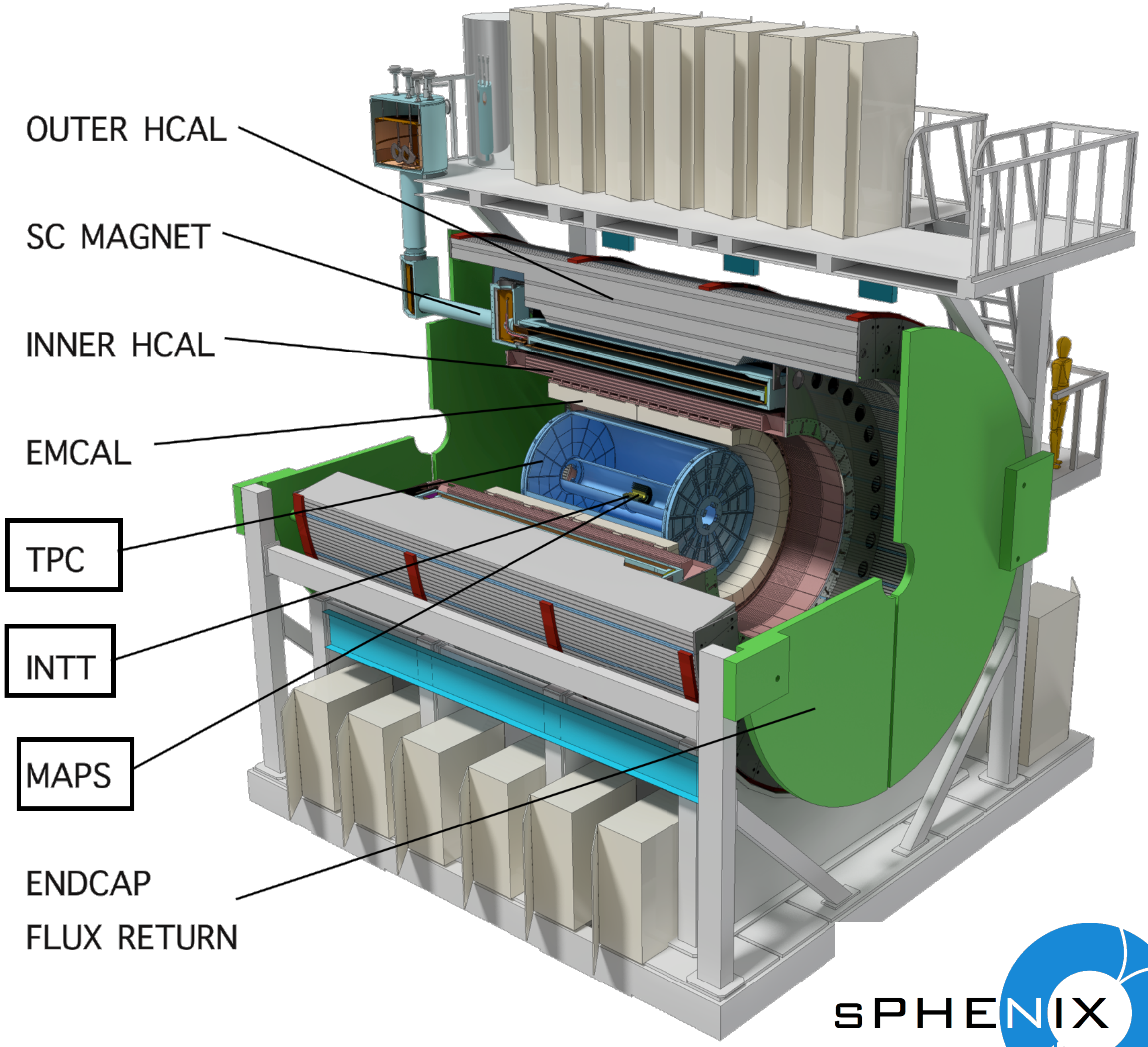
- MAPS-based micro-VerTeX detector (MVTX)
- 3-layers

Timing:

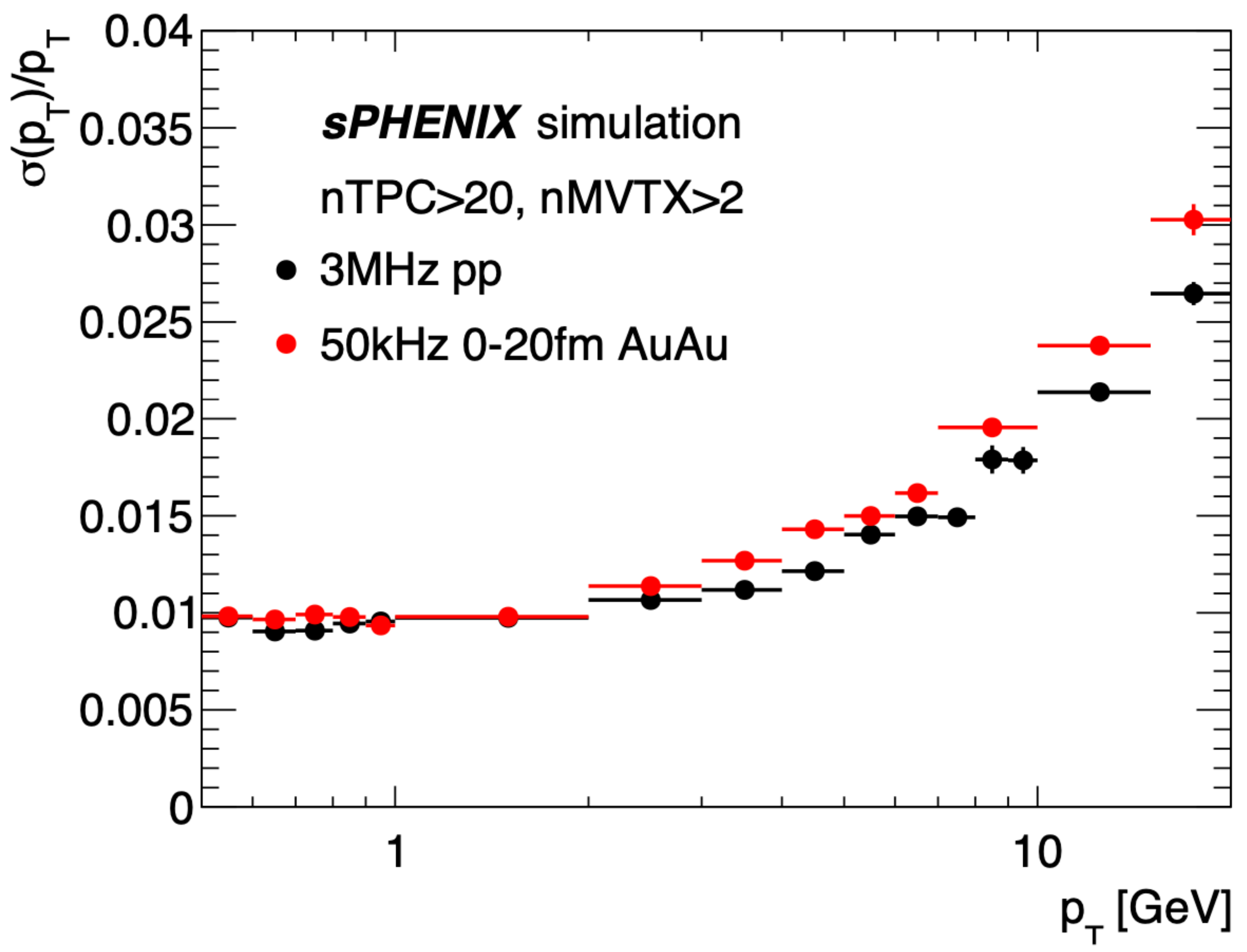
- Intermediate Silicon Tracker (INTT)
- 4-layers

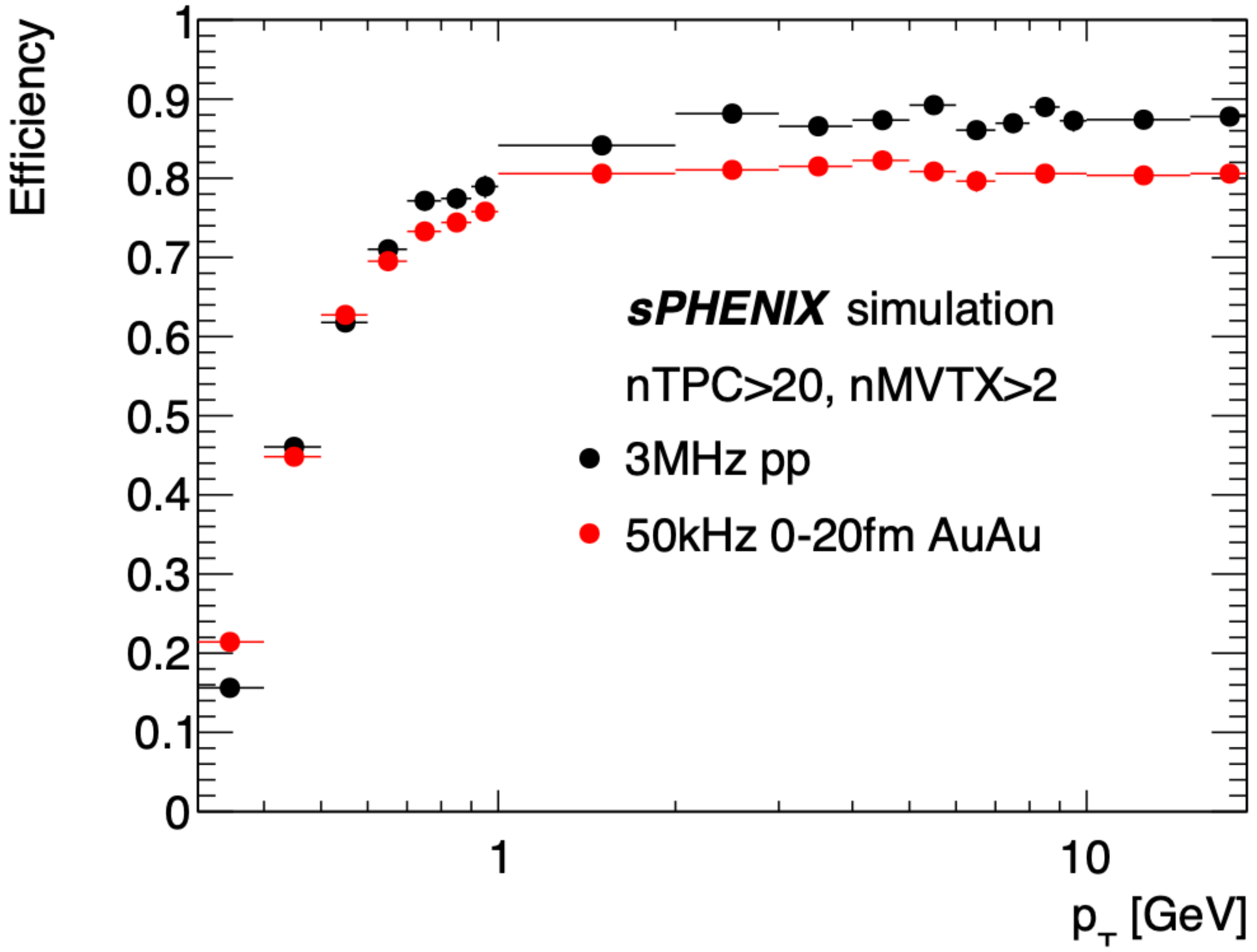
Momentum:

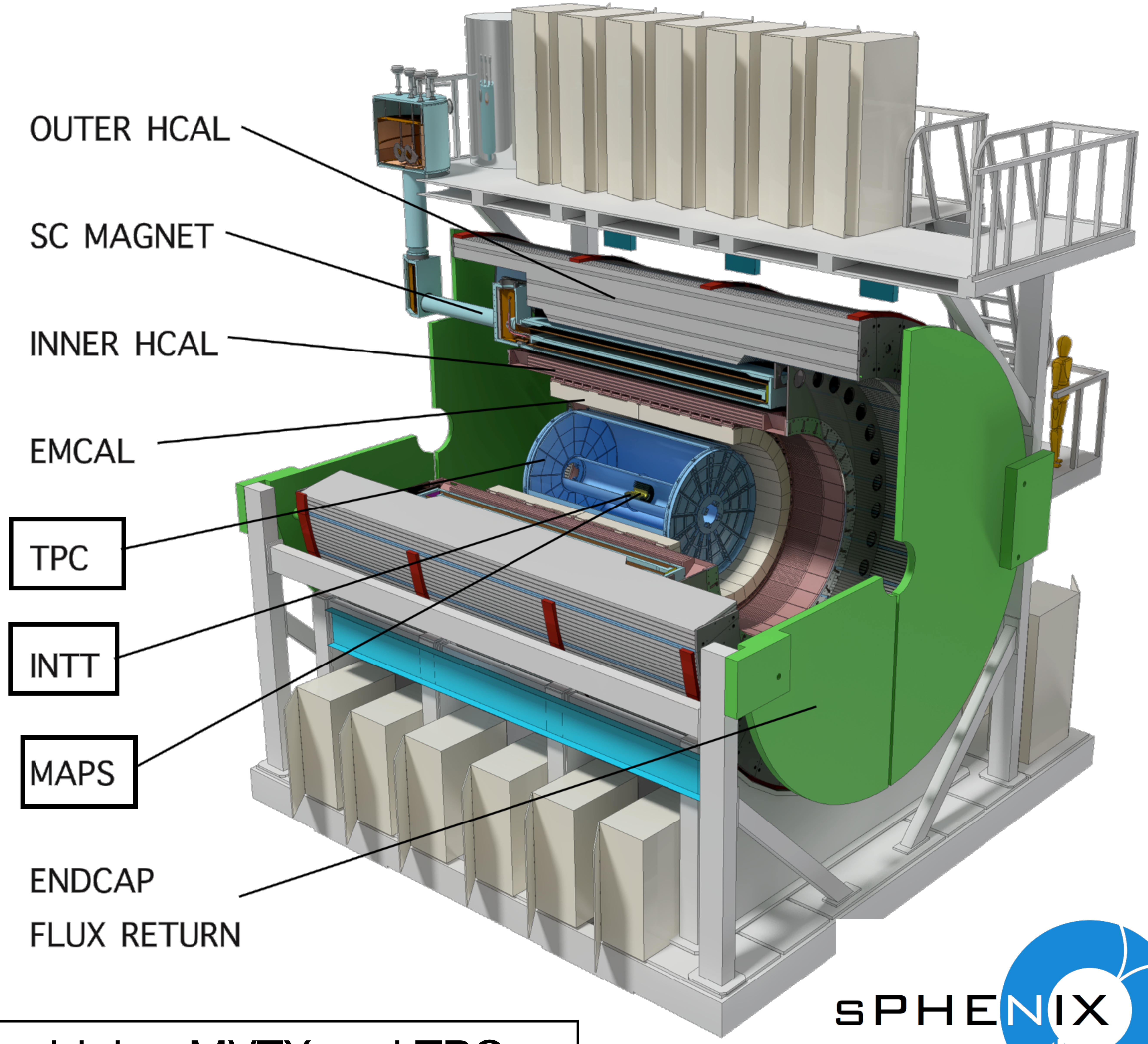
- Time Projection Chamber (TPC)
- 48-layers
- $\Delta p/p \sim 1\%$ at 5 GeV/c
- R-ϕ resolution ~ 150 μm



sPHENIX Tracking system



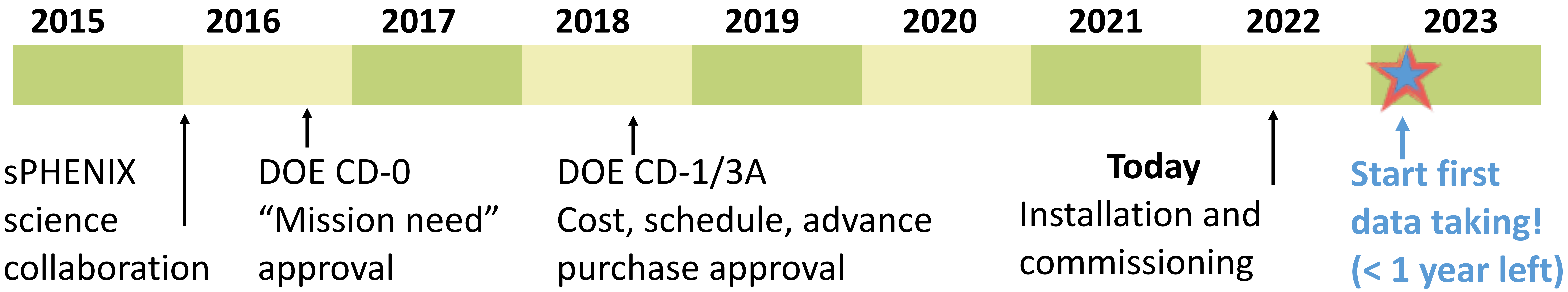




sPHENIX

Good efficiency and momentum resolution by combining MVTX and TPC

sPHENIX run plan



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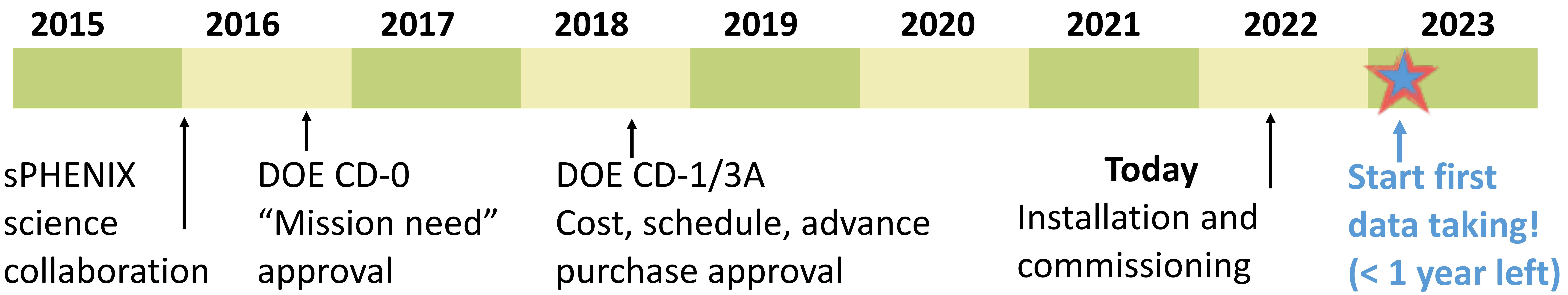


Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $\lvert z\rvert$ <10 cm	Samp. Lum. $\lvert z\rvert$ <10 cm
2023	Au+Au	200	24 (28)	9 (13)	3.7 (5.7) nb^{-1}	4.5 (6.9) nb^{-1}
2024	$p^{\uparrow}p^{\uparrow}$	200	24 (28)	12 (16)	0.3 (0.4) pb^{-1} [5 kHz] 4.5 (6.2) pb^{-1} [10%-*str*]	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}

Extensive **3-year** data taking starting in < 1 year

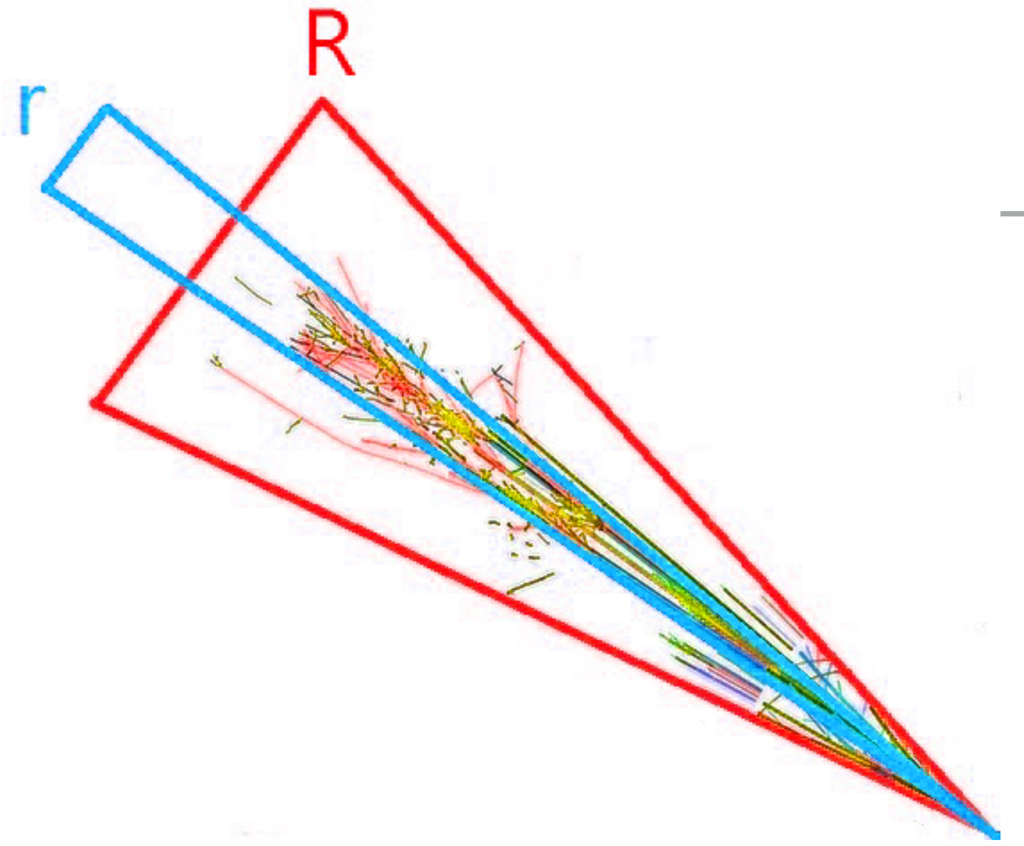
Year-1: commissioning and first physics

Year-2: p+p and p+Au runs for heavy-ion reference and cold QCD physics

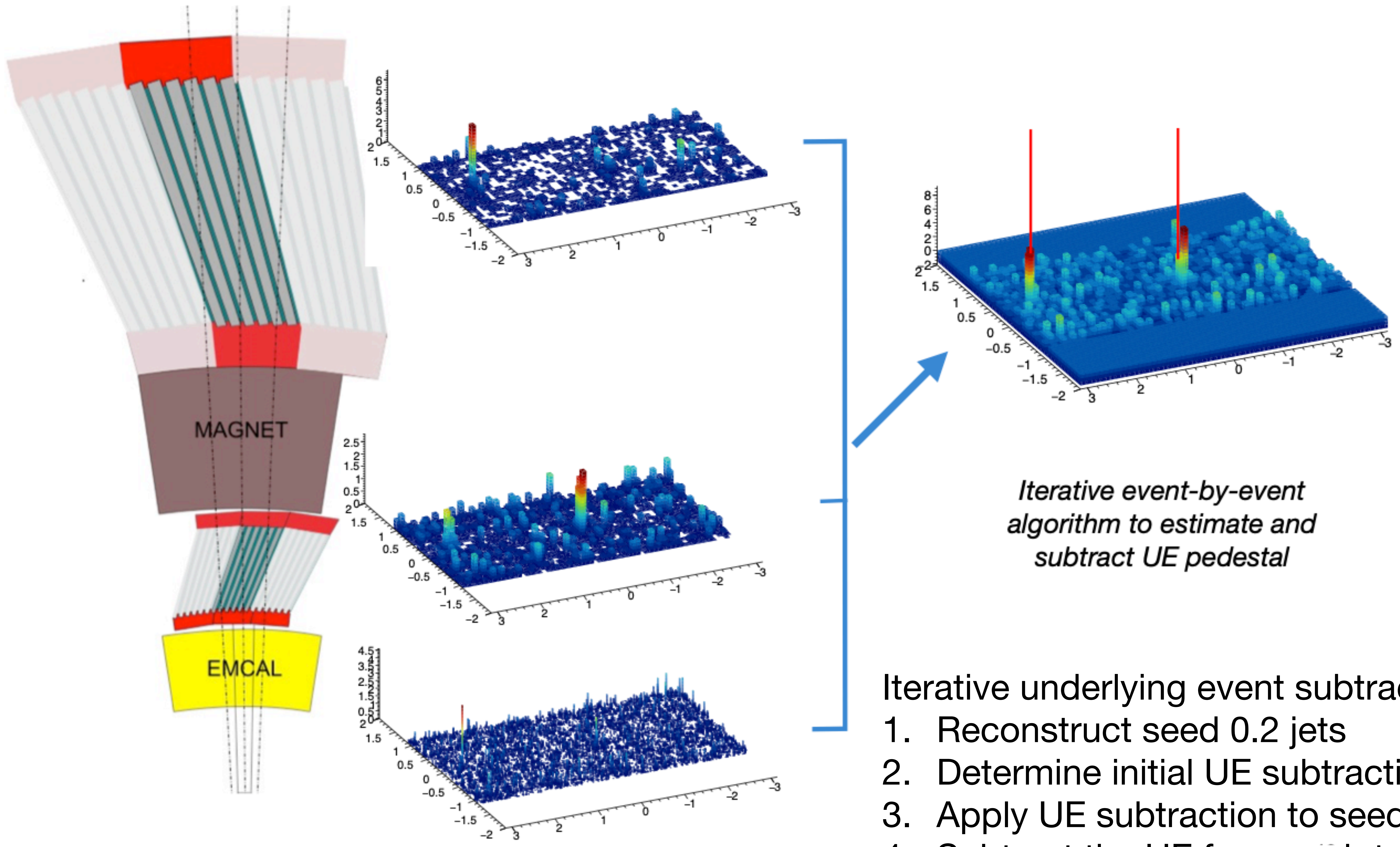
Year-3: very large Au+Au dataset (145B events in total)

sPHENIX Calorimeter Jet reconstruction

sPHENIX Calorimeter Jet reconstruction



Jet = shower of particles arising from hard-scattered partons produced in the early stages



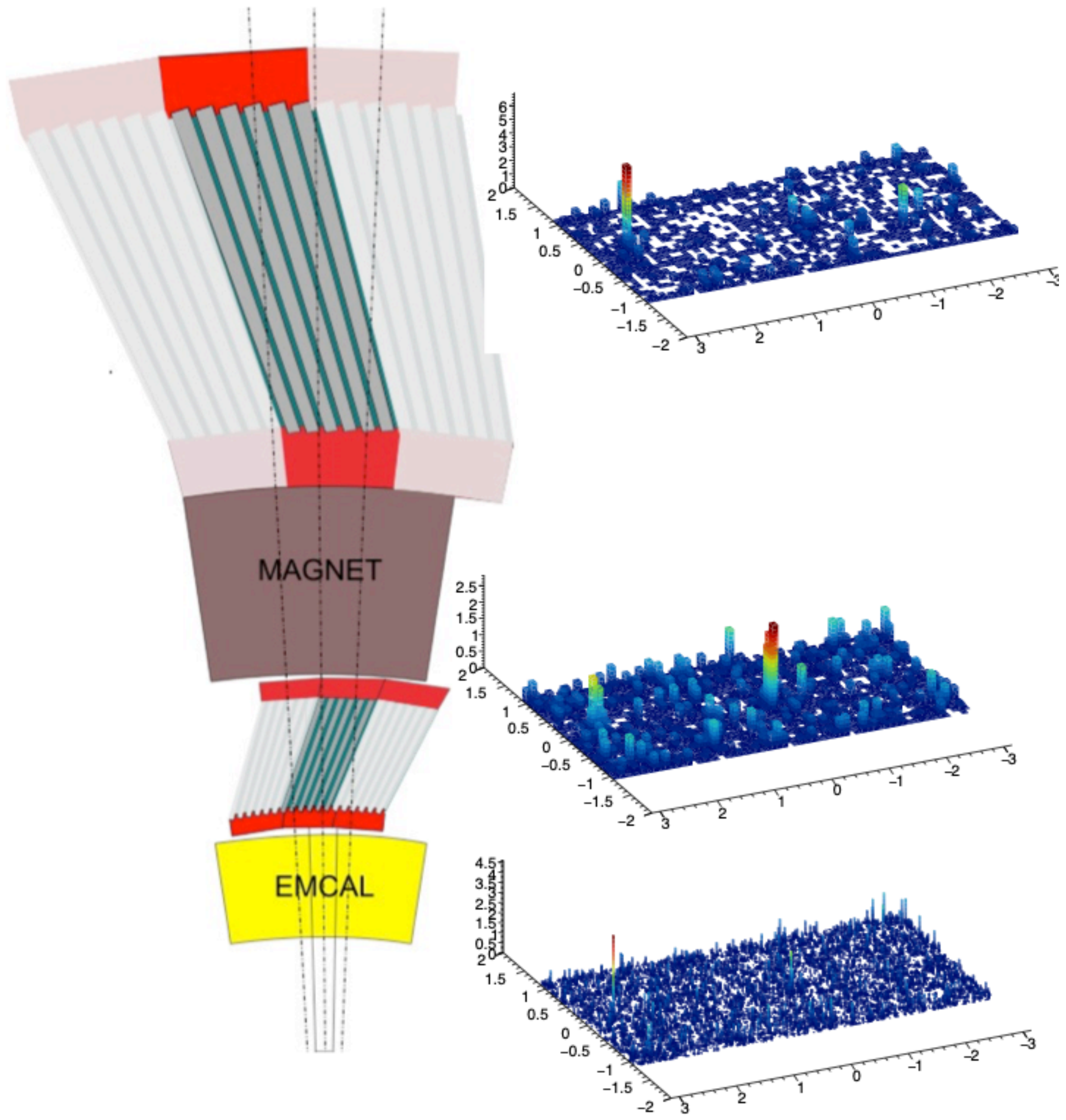
Iterative event-by-event algorithm to estimate and subtract UE pedestal

Iterative underlying event subtraction procedure:

1. Reconstruct seed 0.2 jets
2. Determine initial UE subtraction (including v_n modulation)
3. Apply UE subtraction to seed jets and redetermine the UE estimation
4. Subtract the UE from each tower in the calorimeters

The subtracted towers are then used to produce the anti-k_T jets

sPHENIX Calorimeter Jet reconstruction



UE determined event-by-event

$$\frac{d^2E_T}{d\eta\, d\phi} = \frac{dE_T}{d\eta}\left(1 + 2\sum_n v_n \cos\left(n\left(\phi - \Psi_n\right)\right)\right)$$

Average energy density, excluding regions with jet candidates

Flow modulation: v_2, v_3, v_4

Method from: [Phys.Rev.C 86 (2012) 024908]

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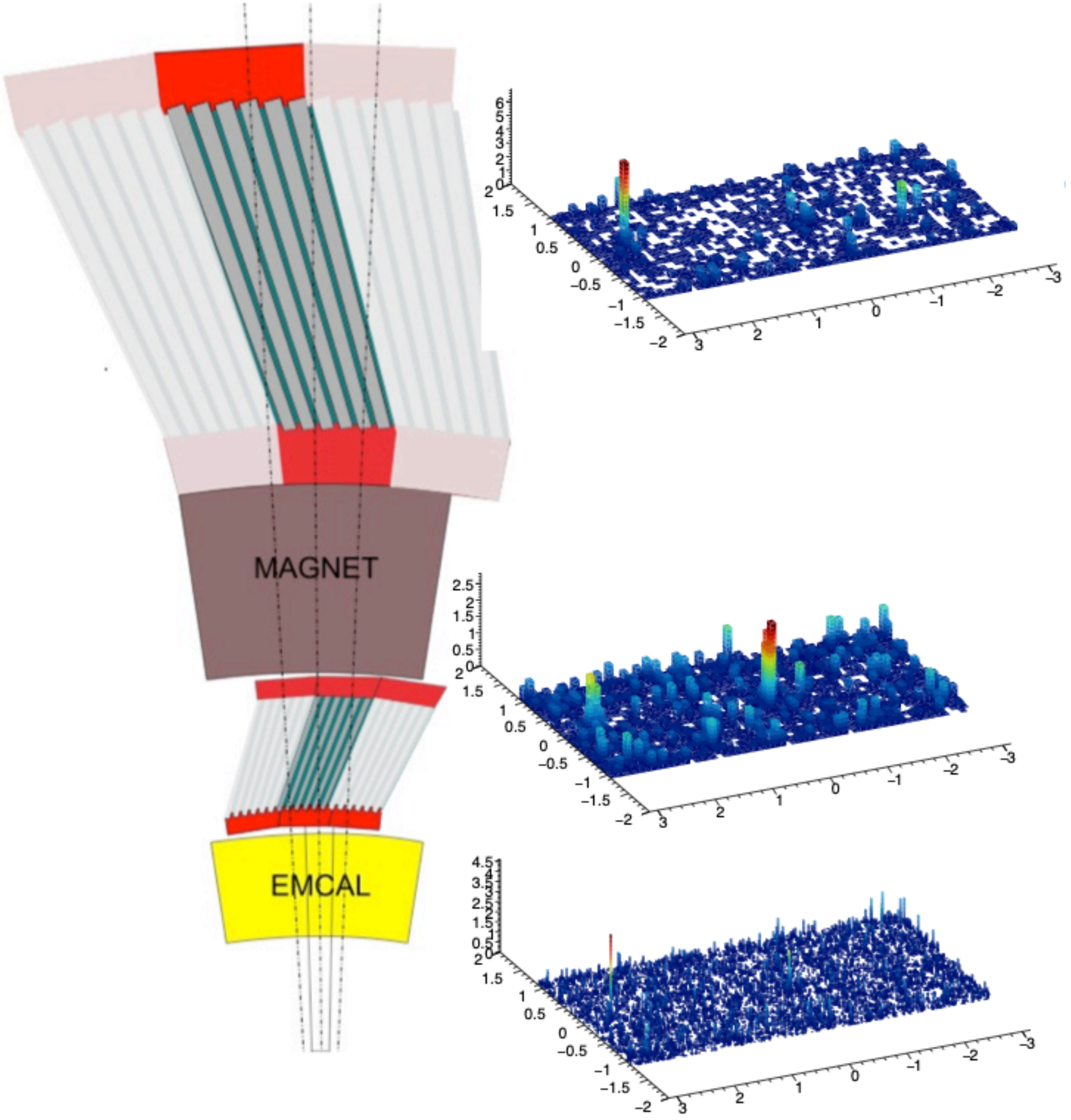
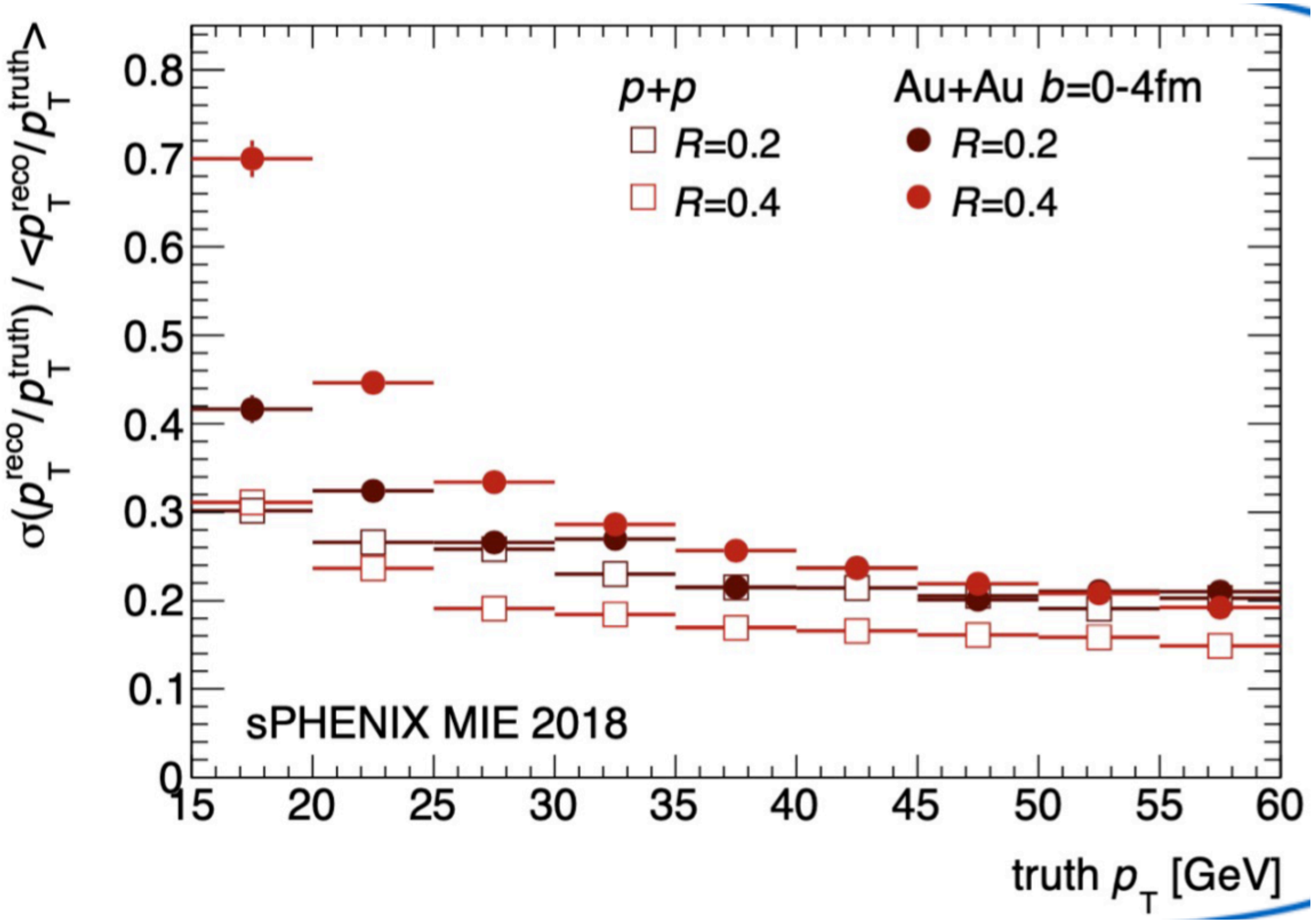
sPHENIX Calorimeter Jet reconstruction



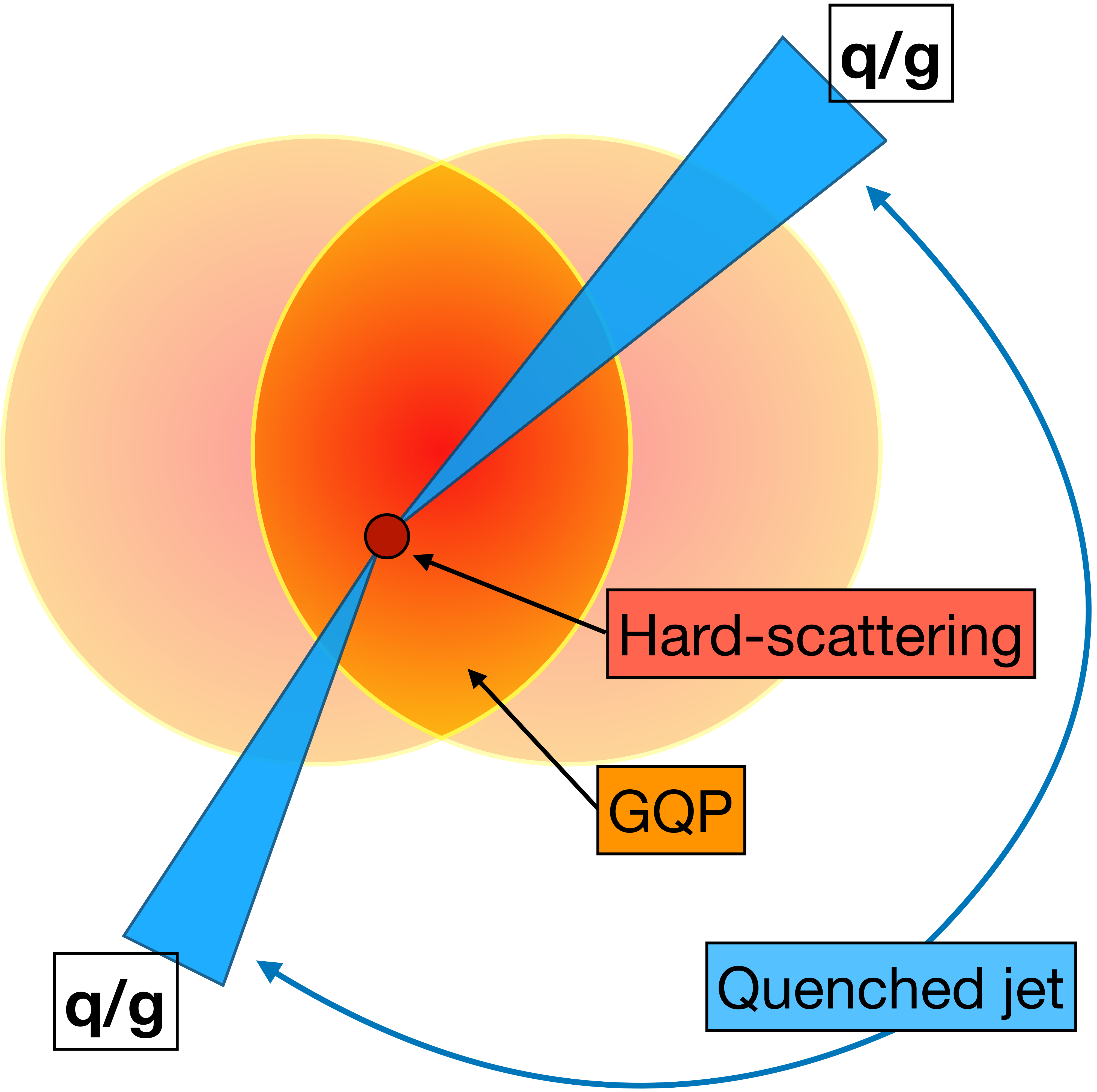


- Good energy resolution in p+p and Au+Au
- Au+Au is limited by UE fluctuations

sPHENIX Jet physics

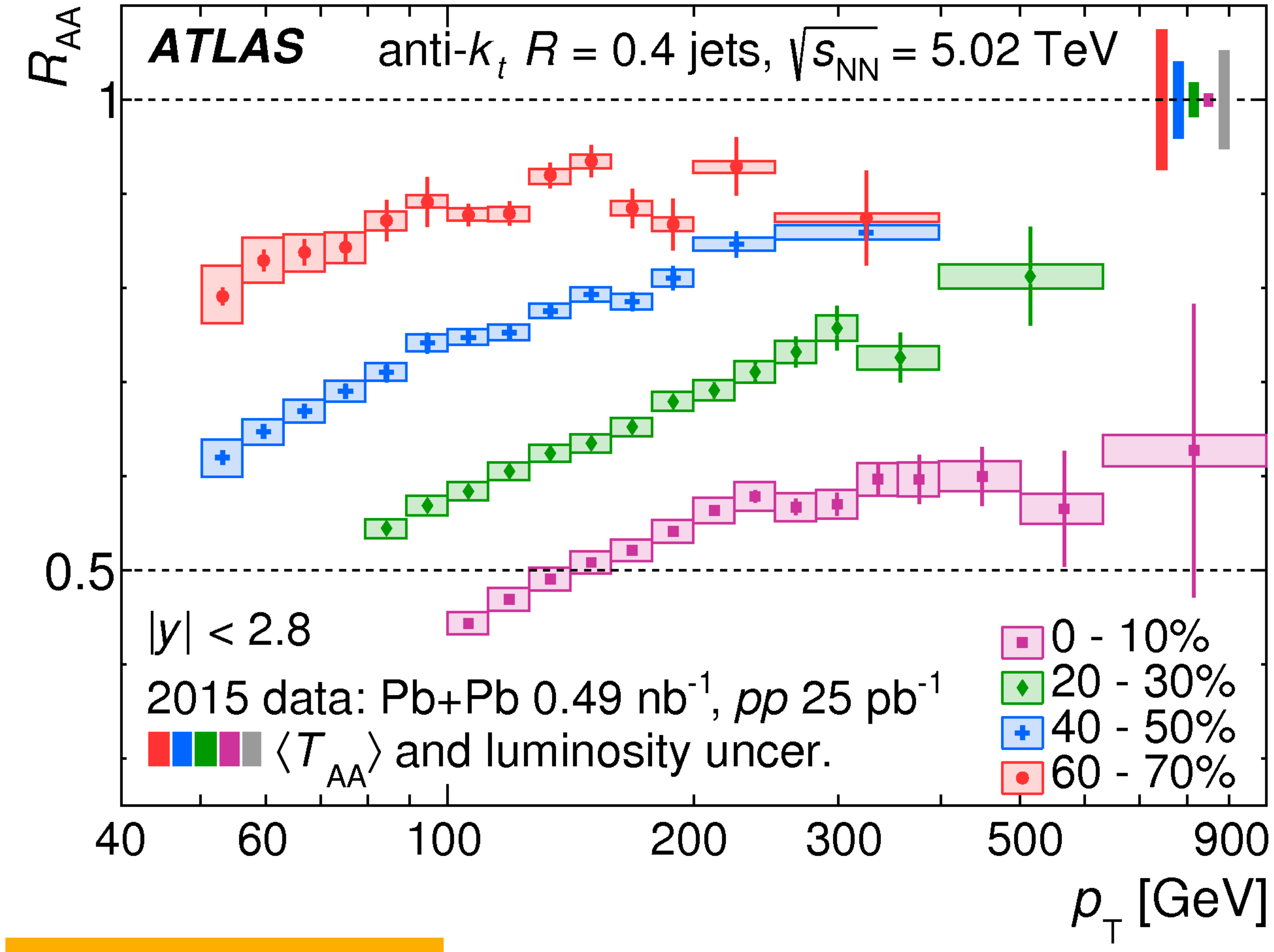
Jet Quenching

Jets are known to lose energy when going through the Quark-Gluon-Plasma



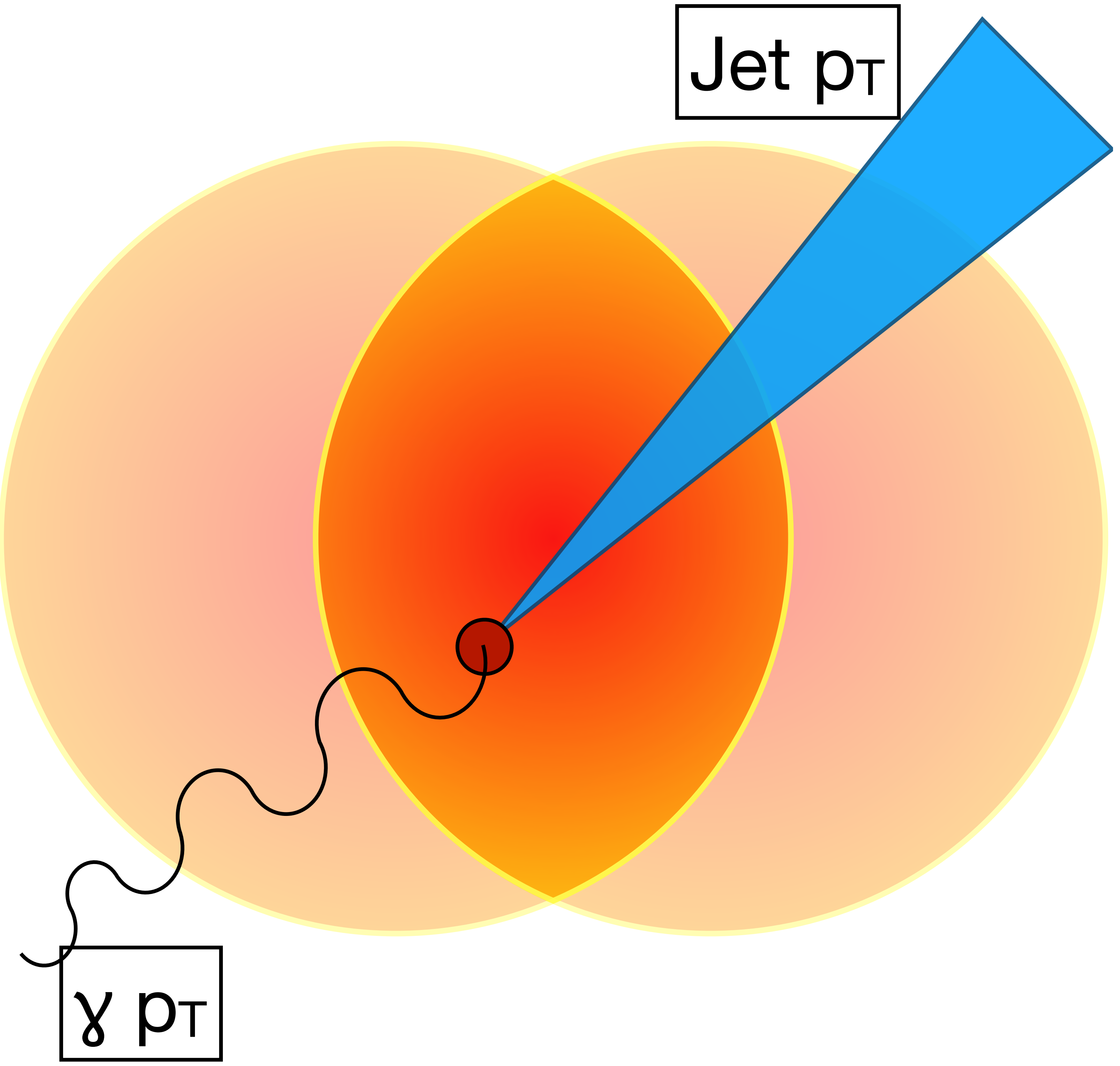
$$R_{AA} = \frac{N_{AA}}{T_{AA}\sigma_{pp}}$$

Inclusive jets R_{AA}



Phys. Lett. B 790 (2019) 108

Photon-Jet correlations



Z/γ-tagged jets are useful for two reasons:

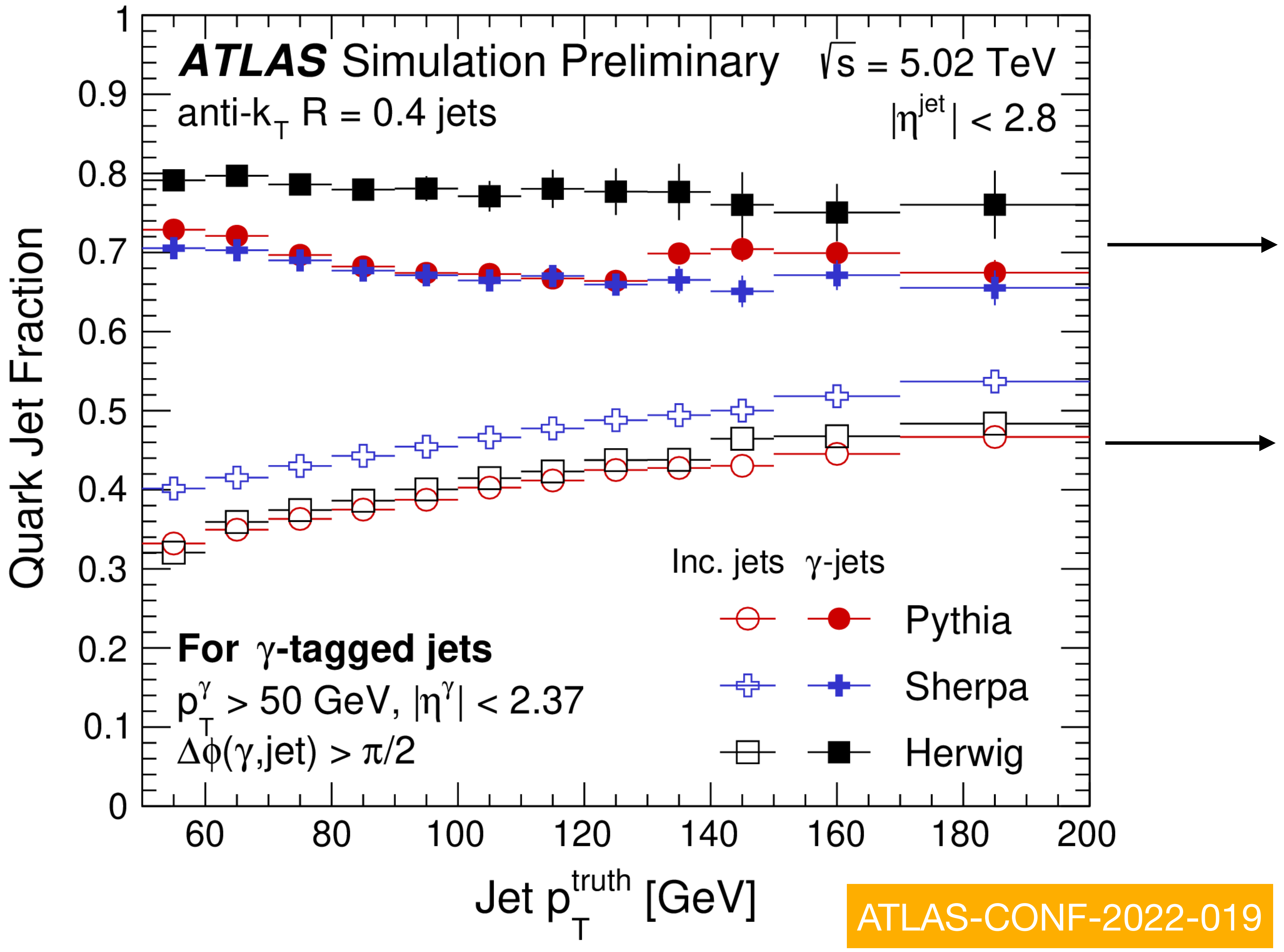
1) Constraining the jet flavor

2) Constraining initial the jet momentum

- E/W bosons do not interact strongly with QGP
- Different than di-jets where both jets are quenched

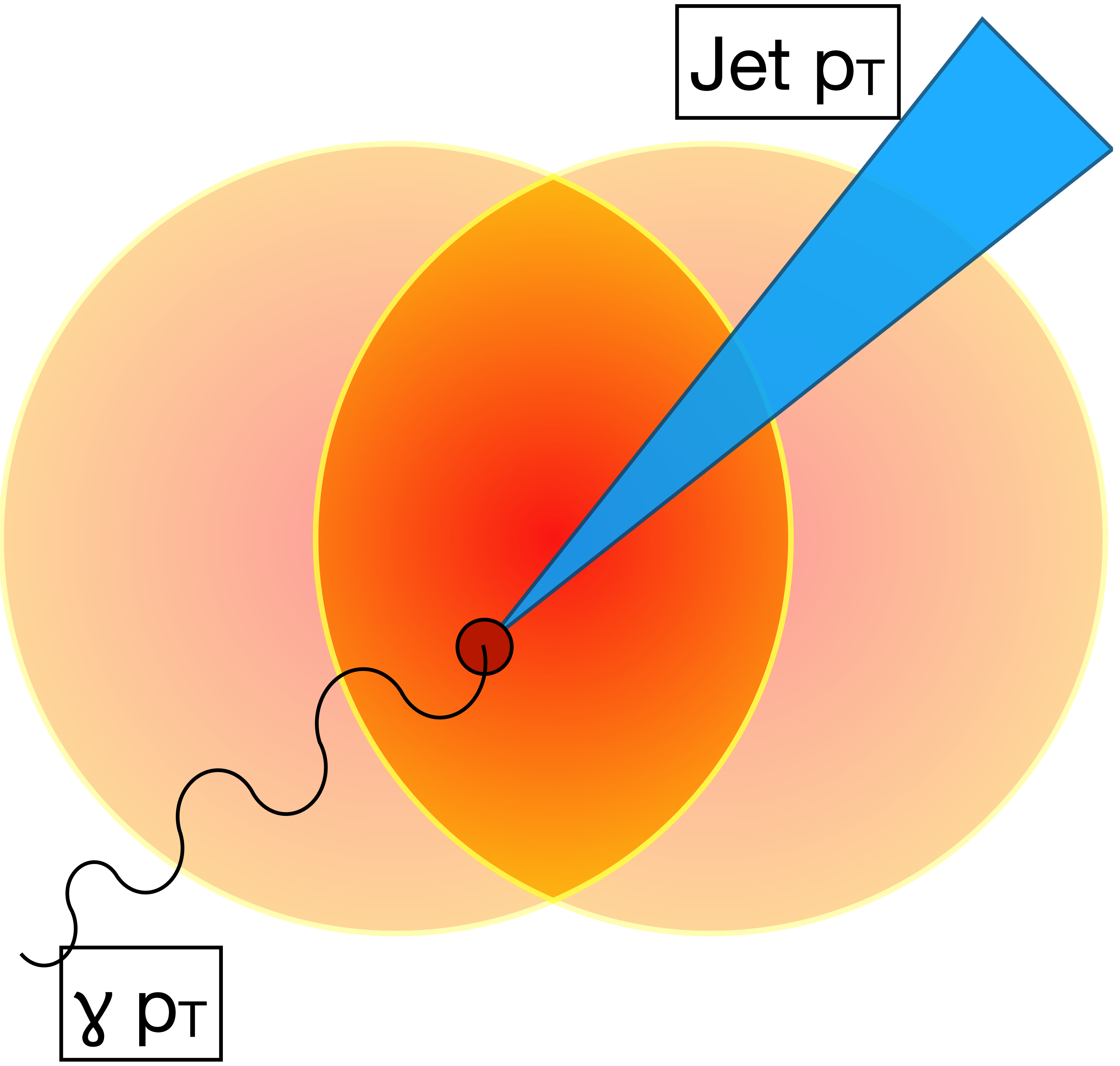
Momentum imbalance:

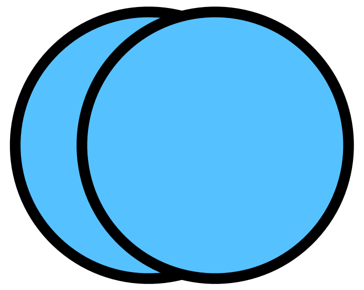
$$x_{j\gamma} = p_T^{jet}/p_T^{\gamma}$$

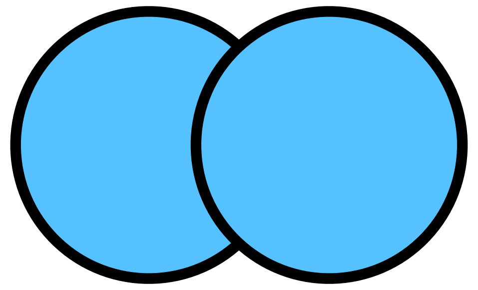


ATLAS-CONF-2022-019

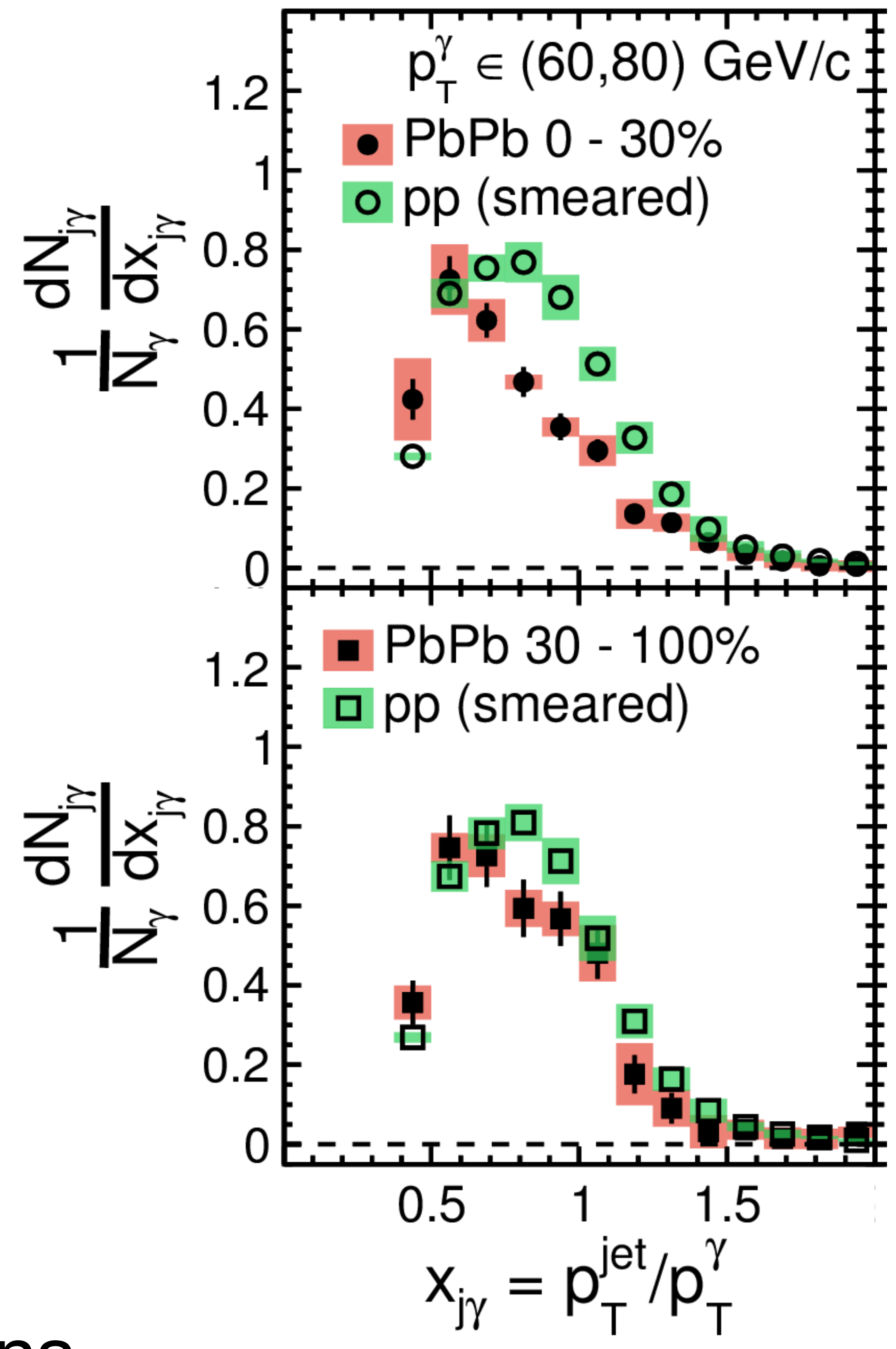
Photon-Jet correlations





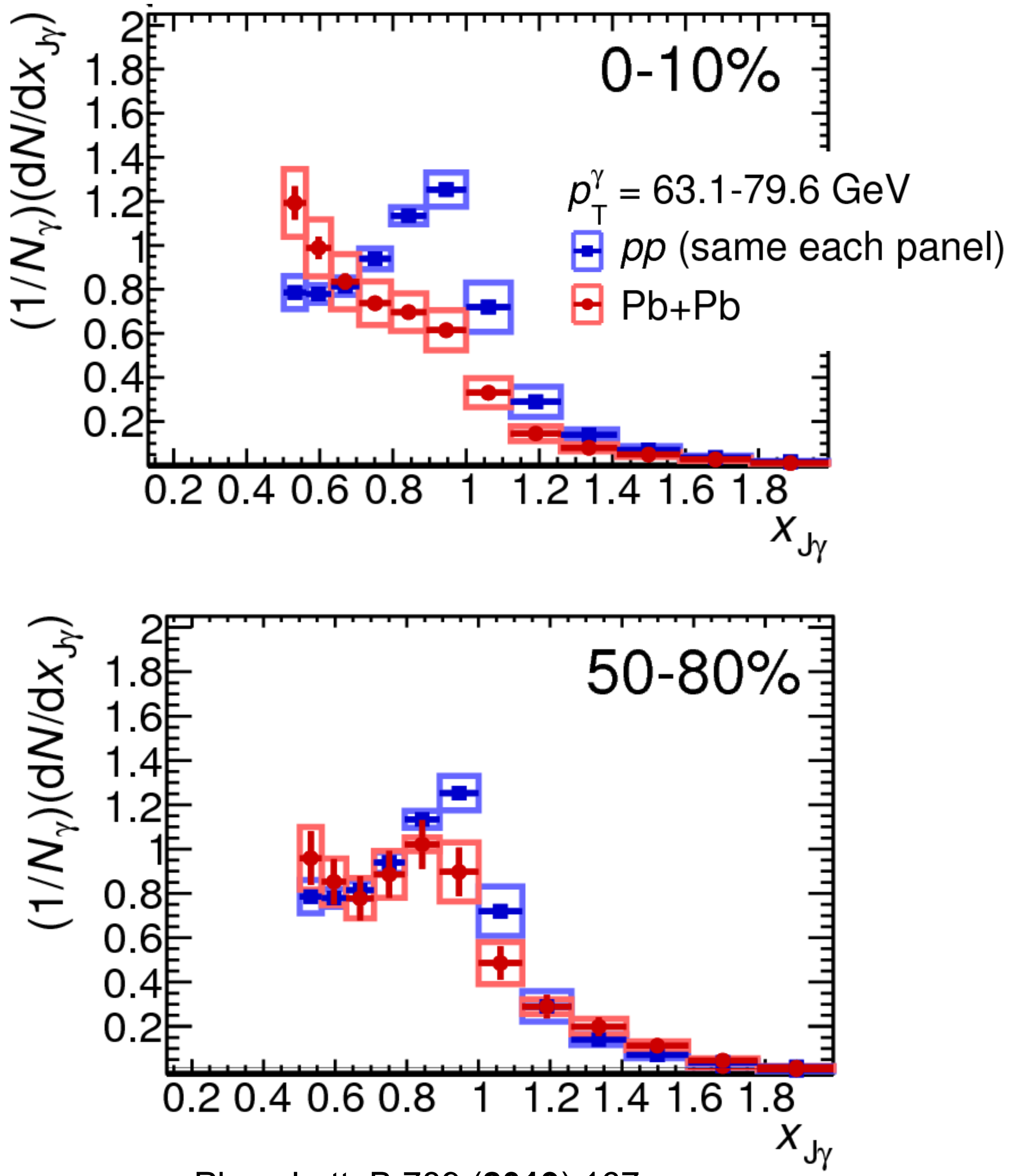


CMS $\Delta\phi > 7\pi/8 \quad p_T^{jet} > 30\ GeV \quad |\eta^{jet}| < 1.6 \quad |\eta^{\gamma}| < 1.44$



Phys. Lett. B 785 (**2018**) 14

ATLAS $\Delta\phi > 7\pi/8 \quad p_T^{jet} > 31.6\ GeV \quad |\eta^{jet}| < 2.8 \quad |\eta^{\gamma}| < 2.37$



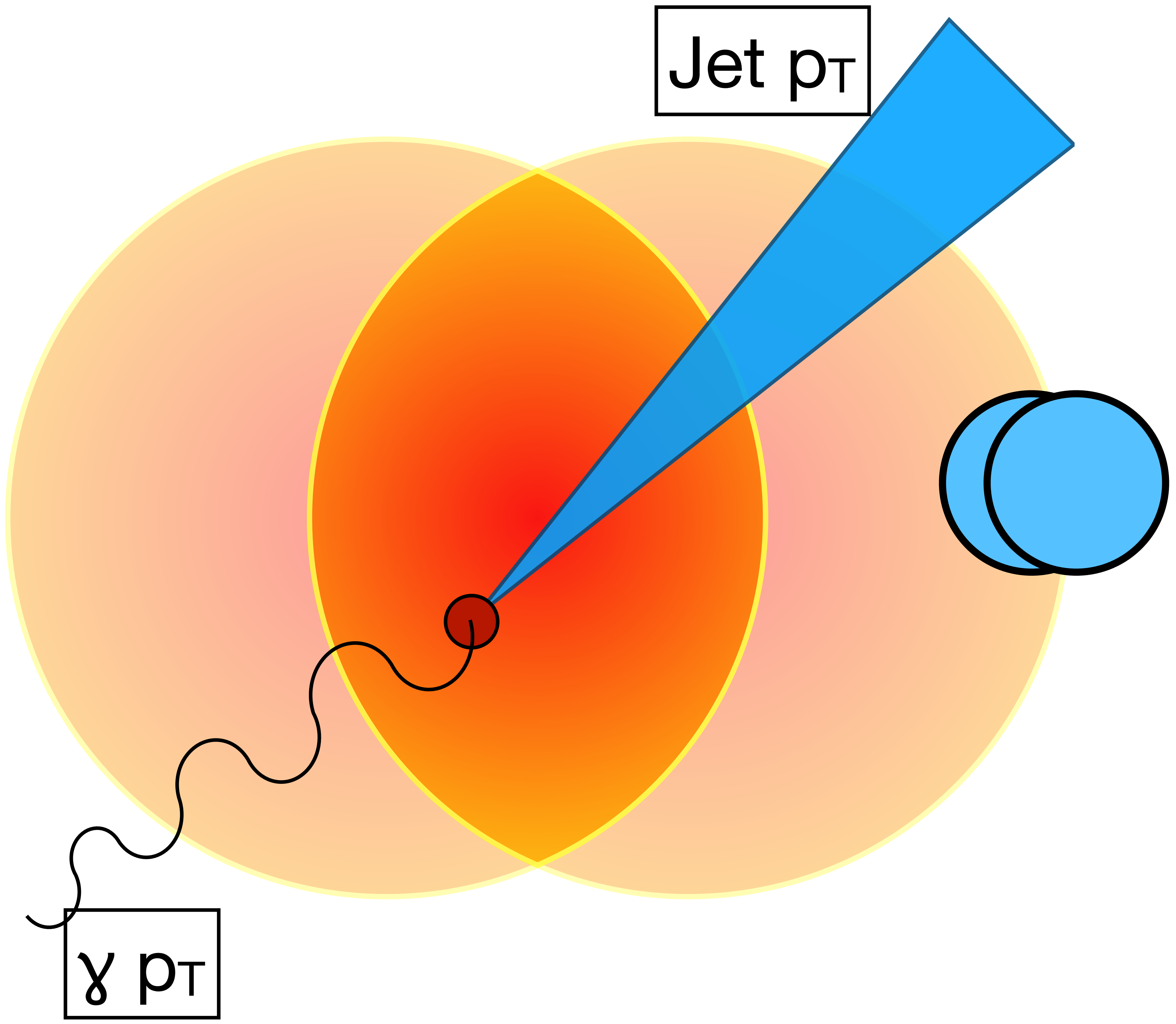
Phys. Lett. B 789 (**2019**) 167

Momentum imbalance:

$$x_{j\gamma} = p_T^{jet}/p_T^{\gamma}$$

- Consistent results between detectors
- Jets loss more energy in central collisions
- p_T > 60 GeV

Photon-Jet correlations



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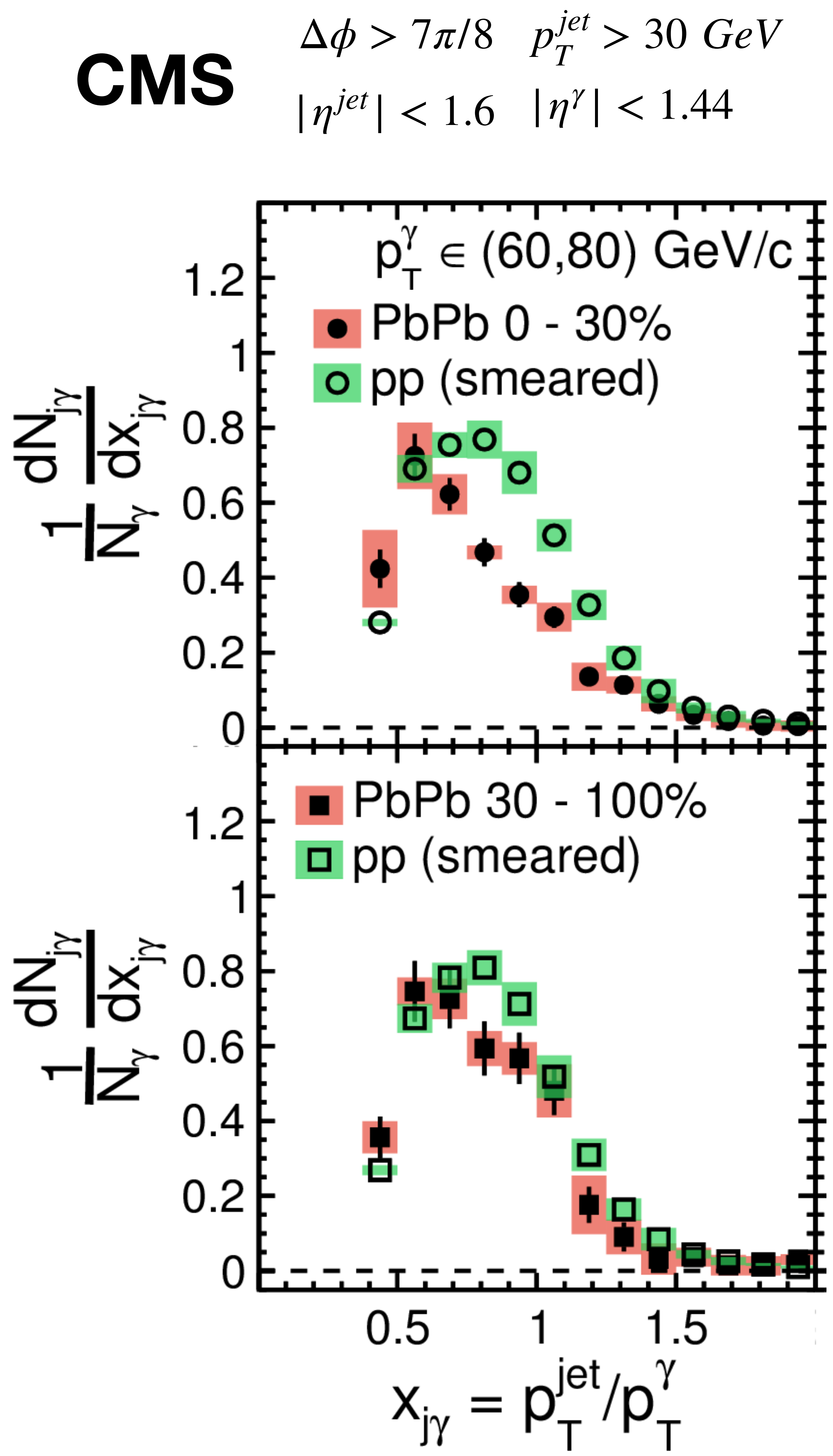

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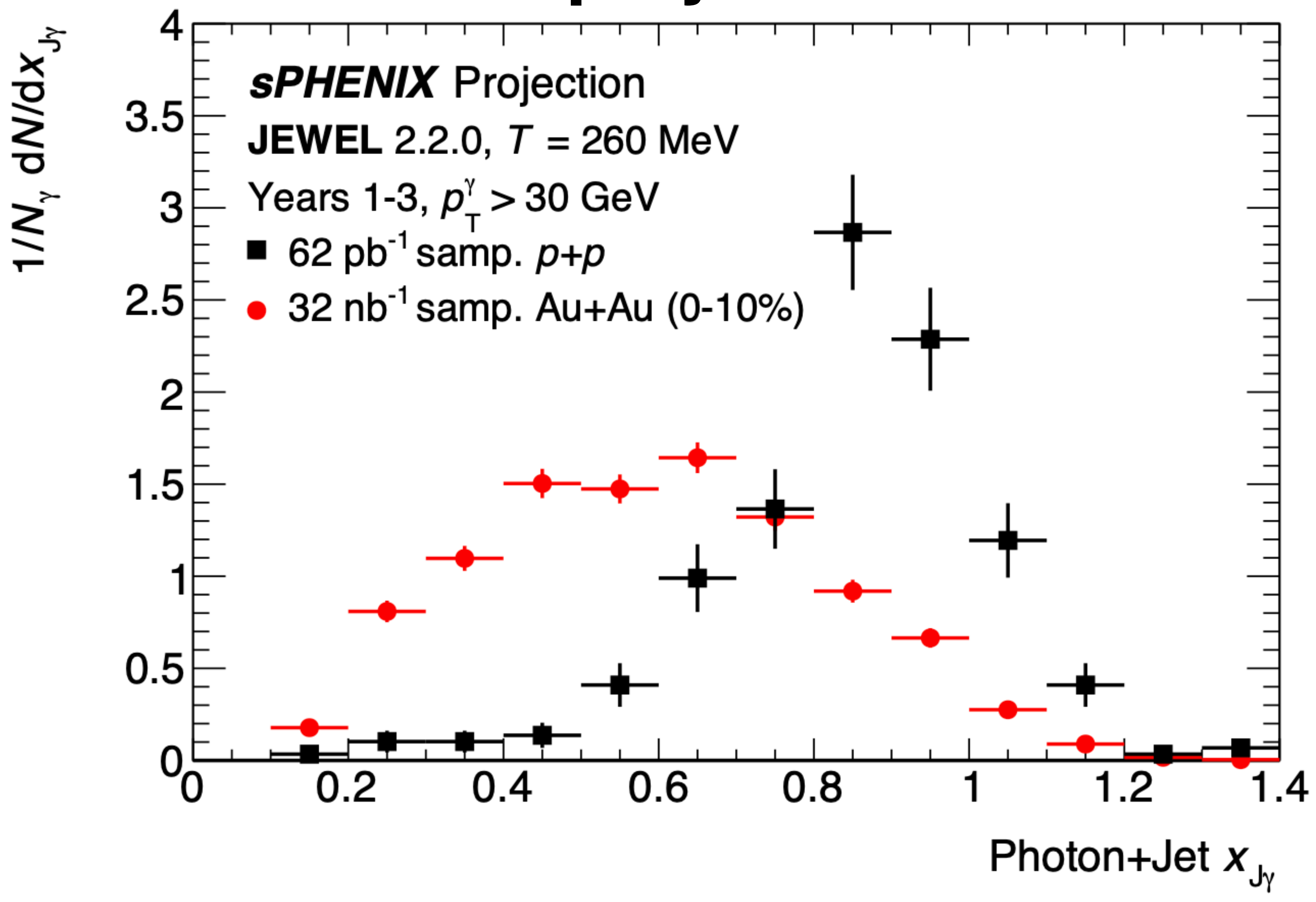
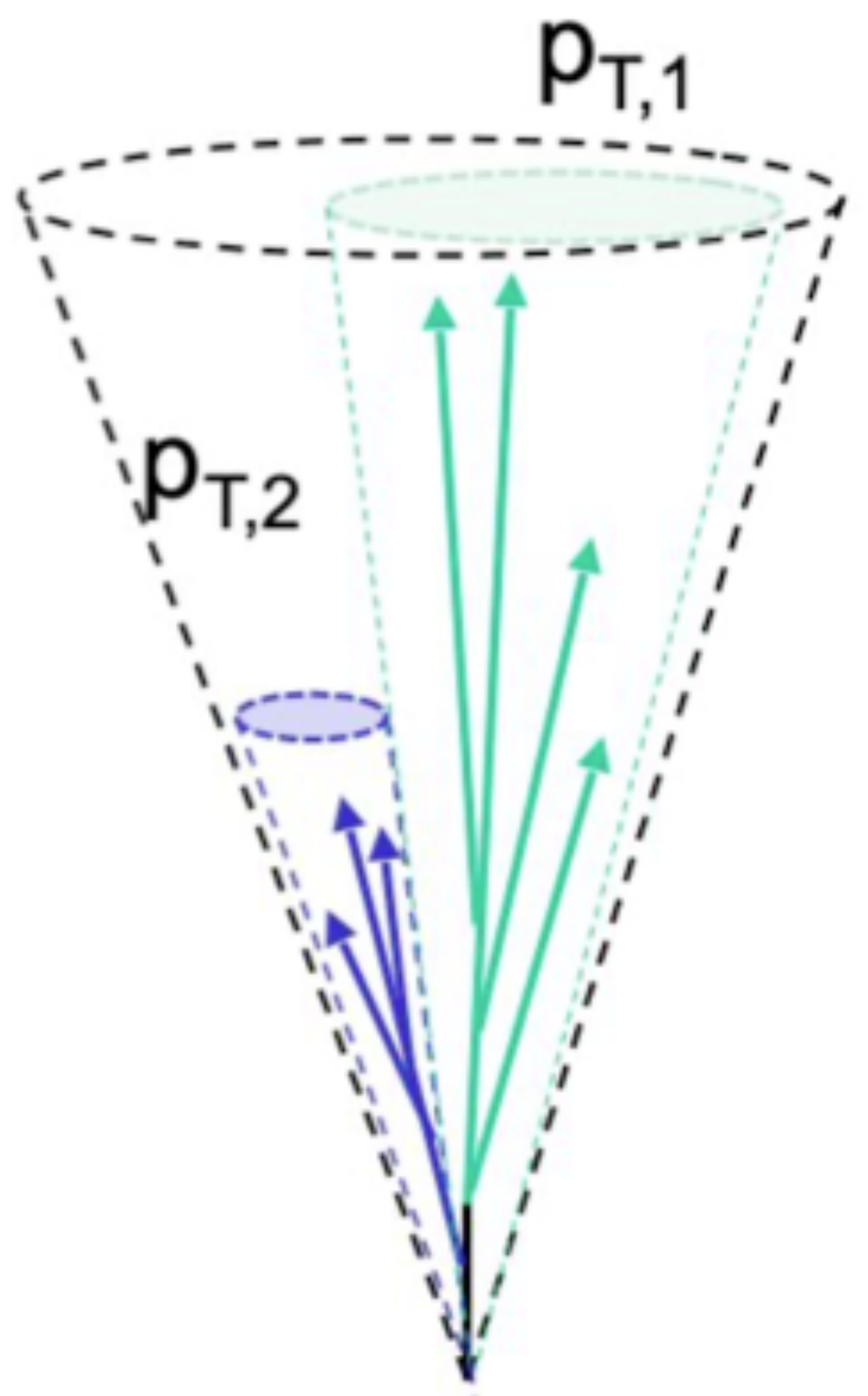
sPHENIX projection



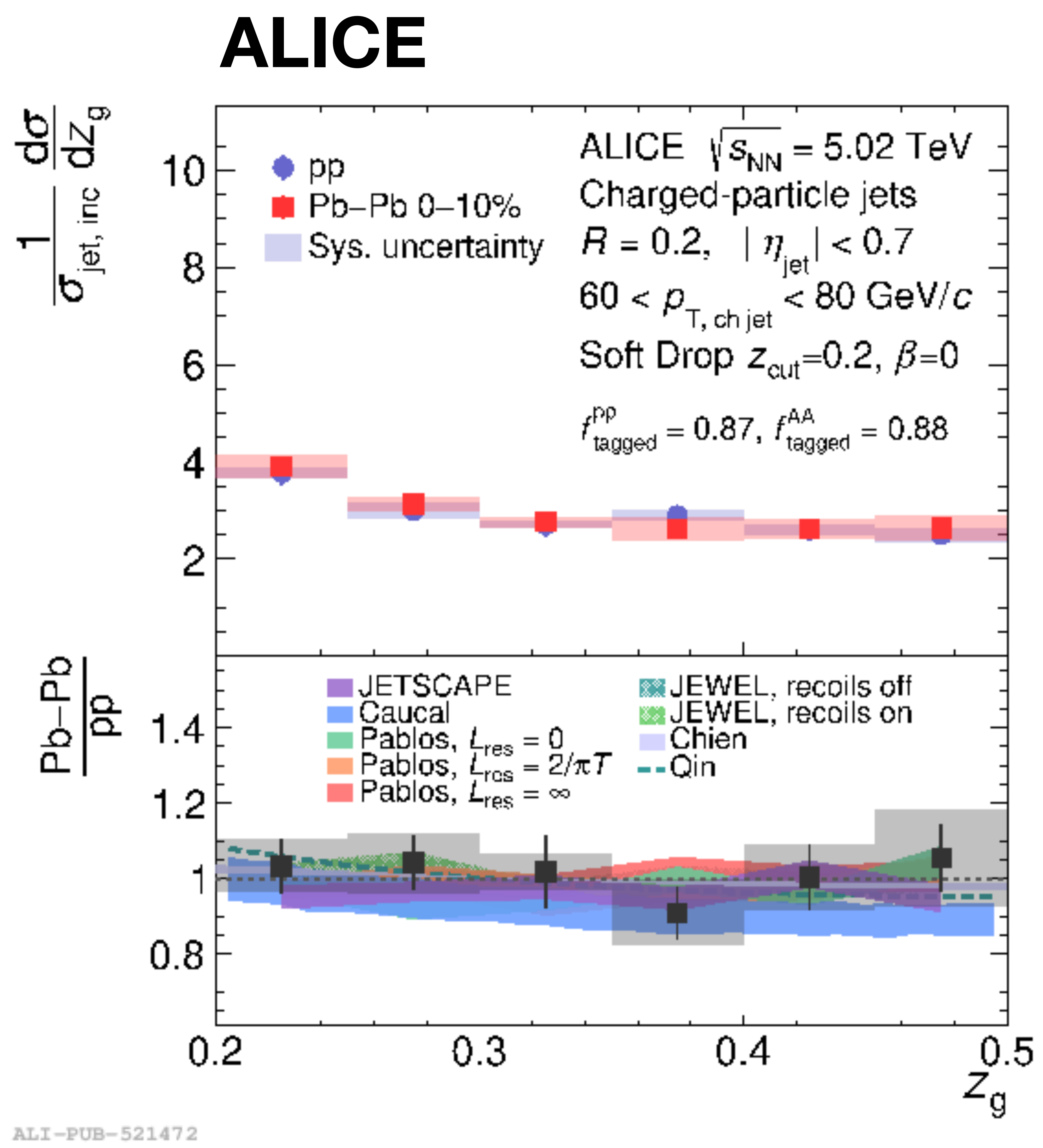
- Statistical projections for **p+p** and **0-10% Au+Au** (shape taken from **JEWEL**)
- Study **path-length** and **flavor dependence** of energy loss
  - Lower p_T than LHC

Jet substructure



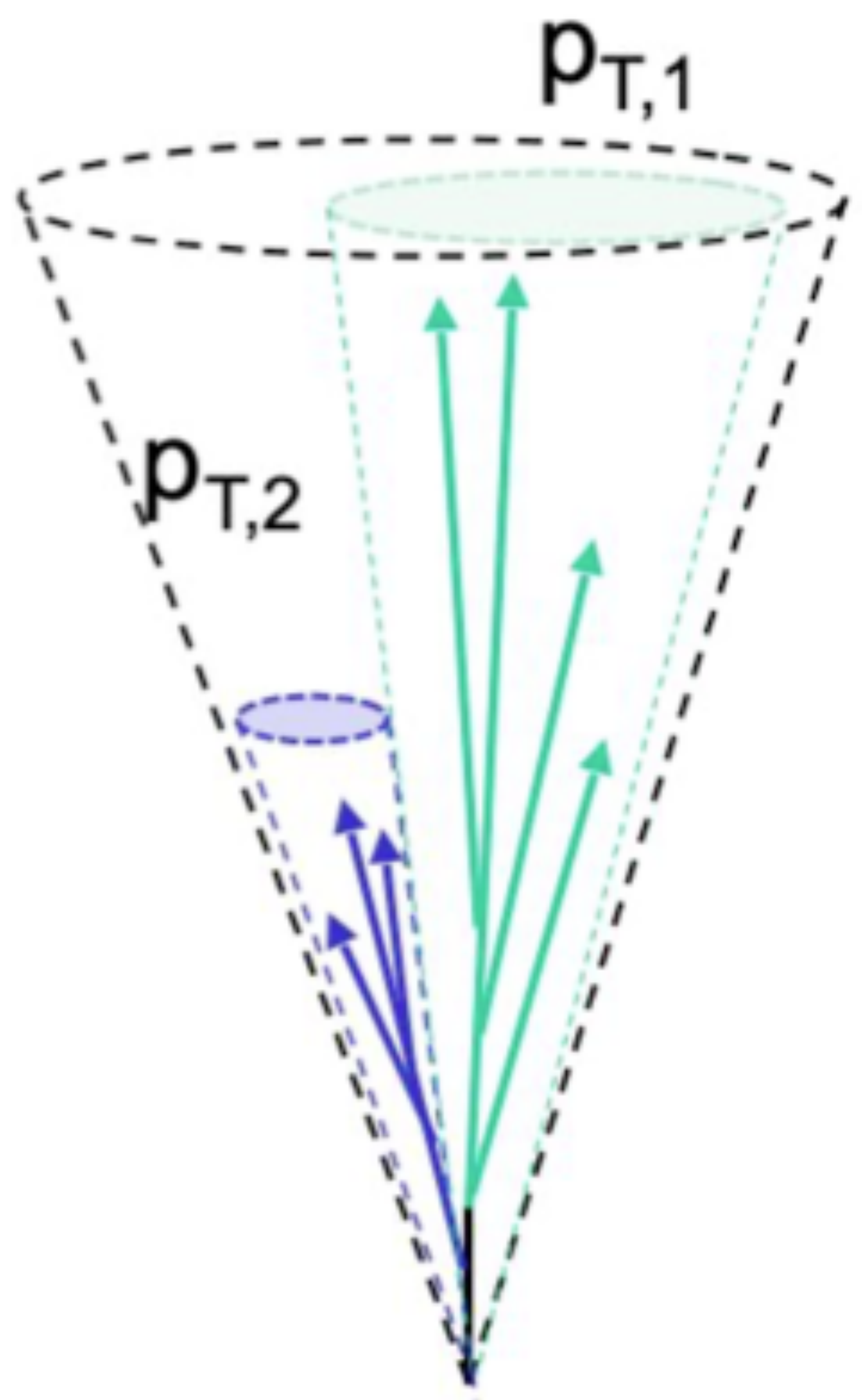
Groomed momentum fraction

$$z_g = \frac{min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$



- No significant modification
- Mostly consistent with models

Jet substructure



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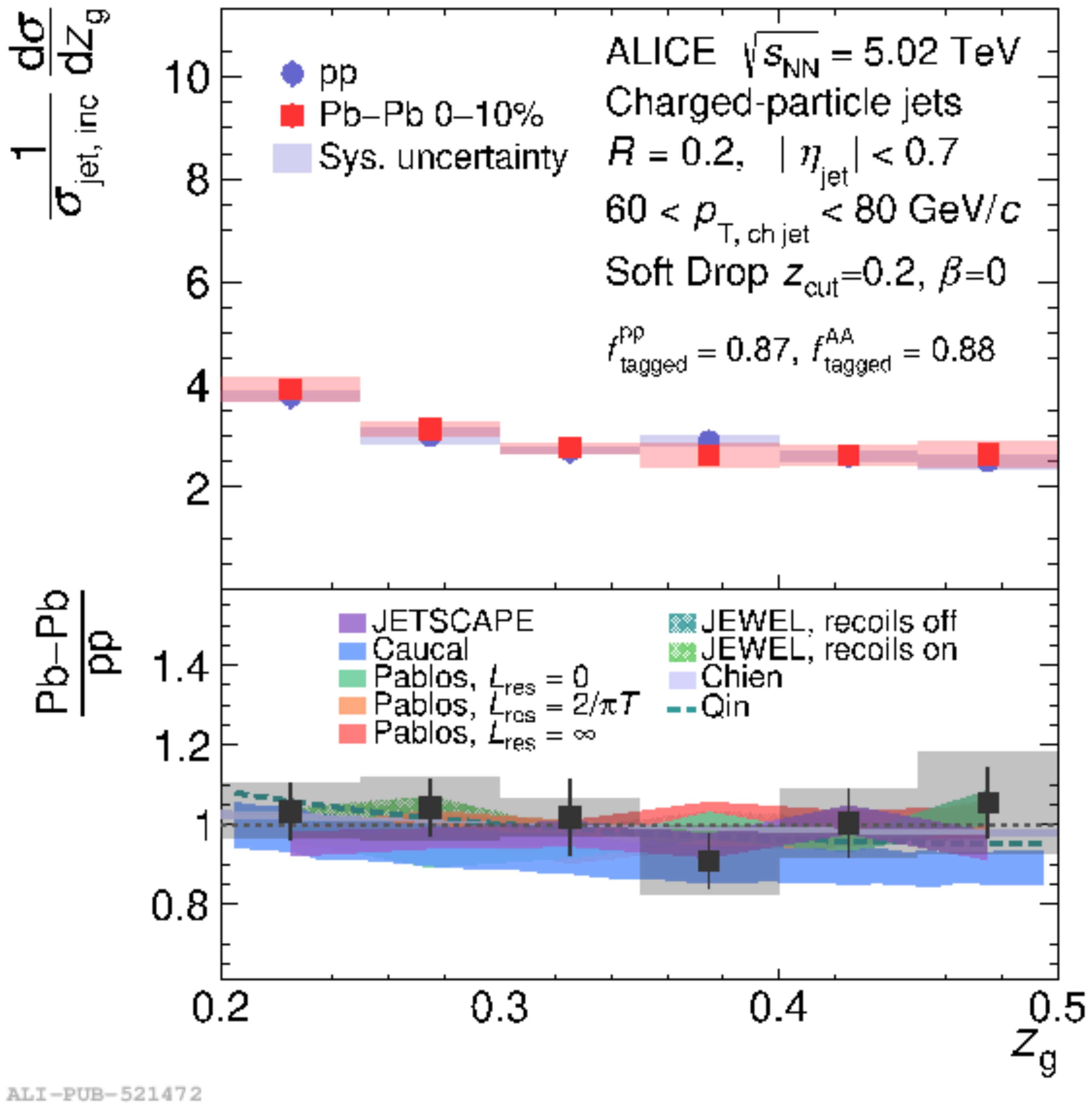
ALICE



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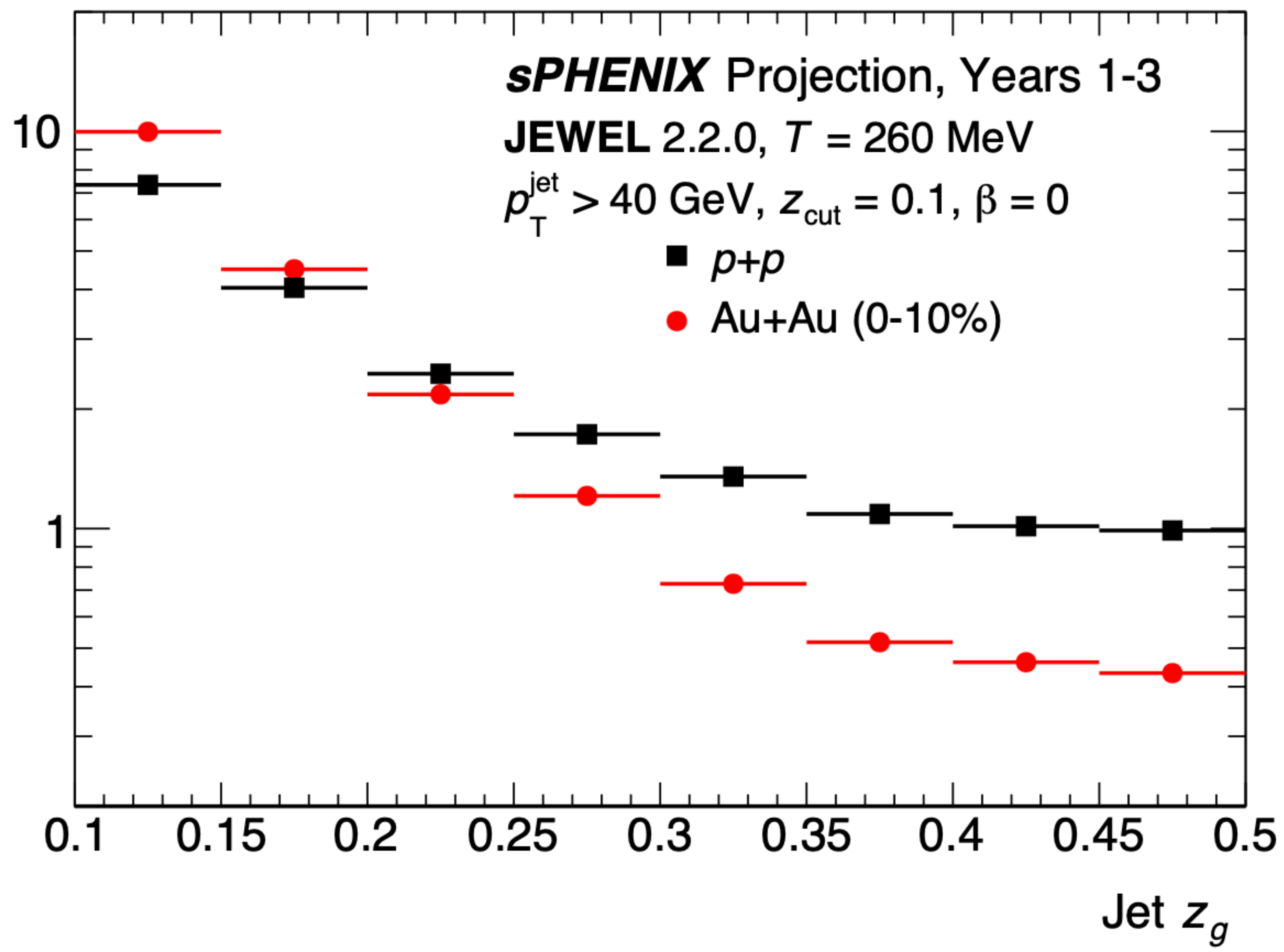
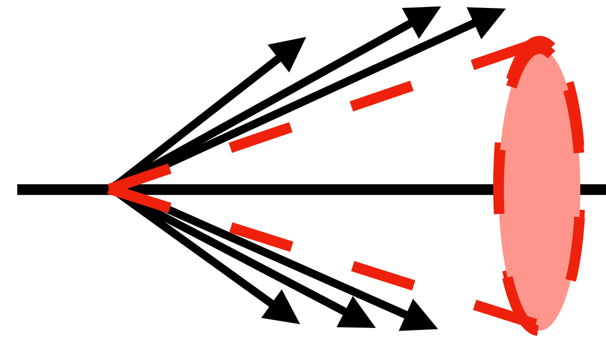


- Jet substructure measurements with fine segmentation of calorimeter+good tracking resolution
- Study evolution of parton shower
  - Lower p_T than LHC

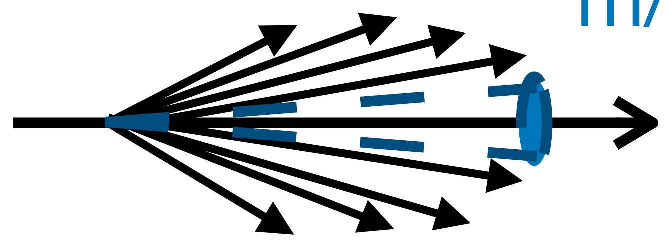
B-tagged Jets

Mass dependence expected due to “dead-cone effect”

Large parton mass

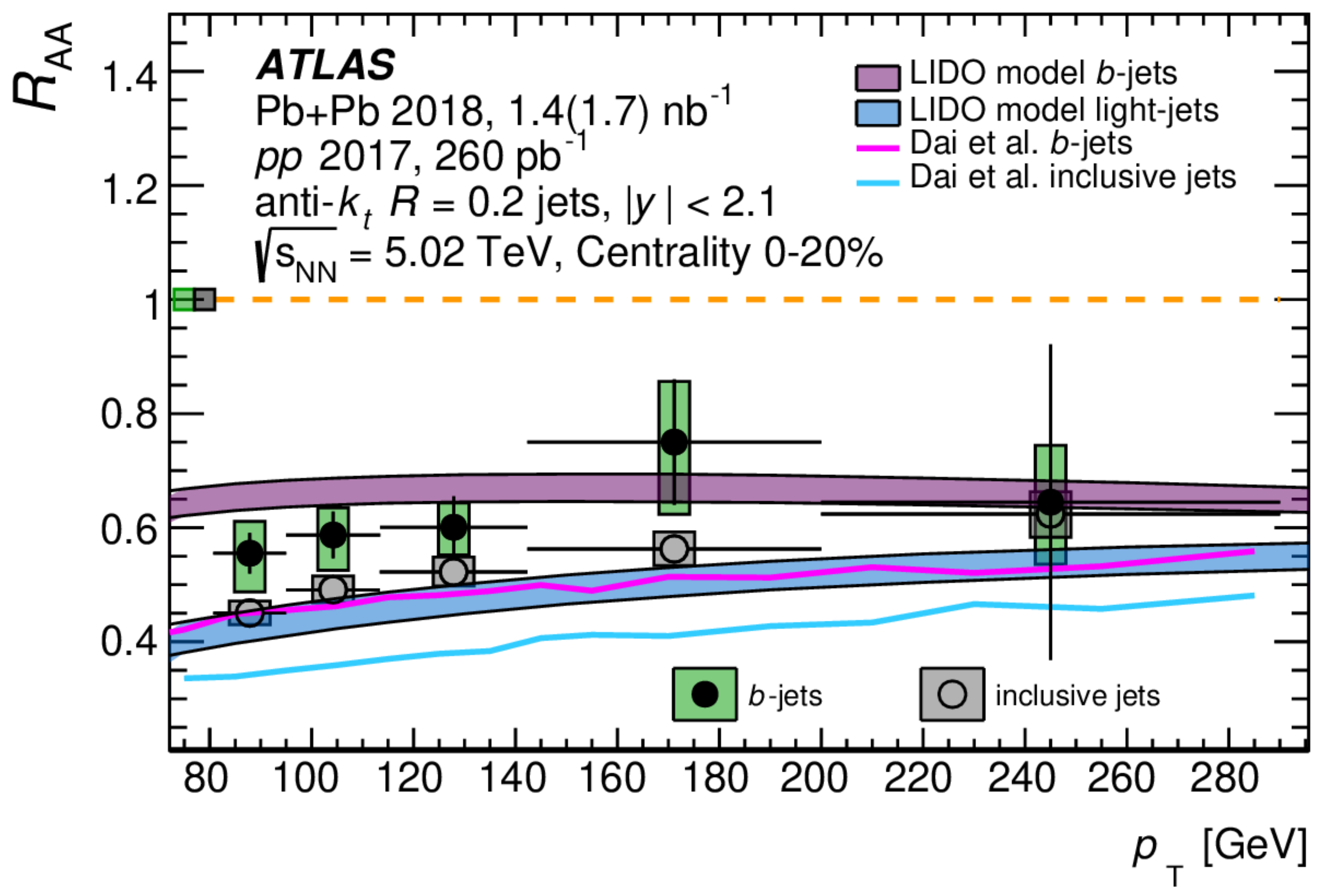


Small parton mass



Radiation is suppressed in θ < m/E

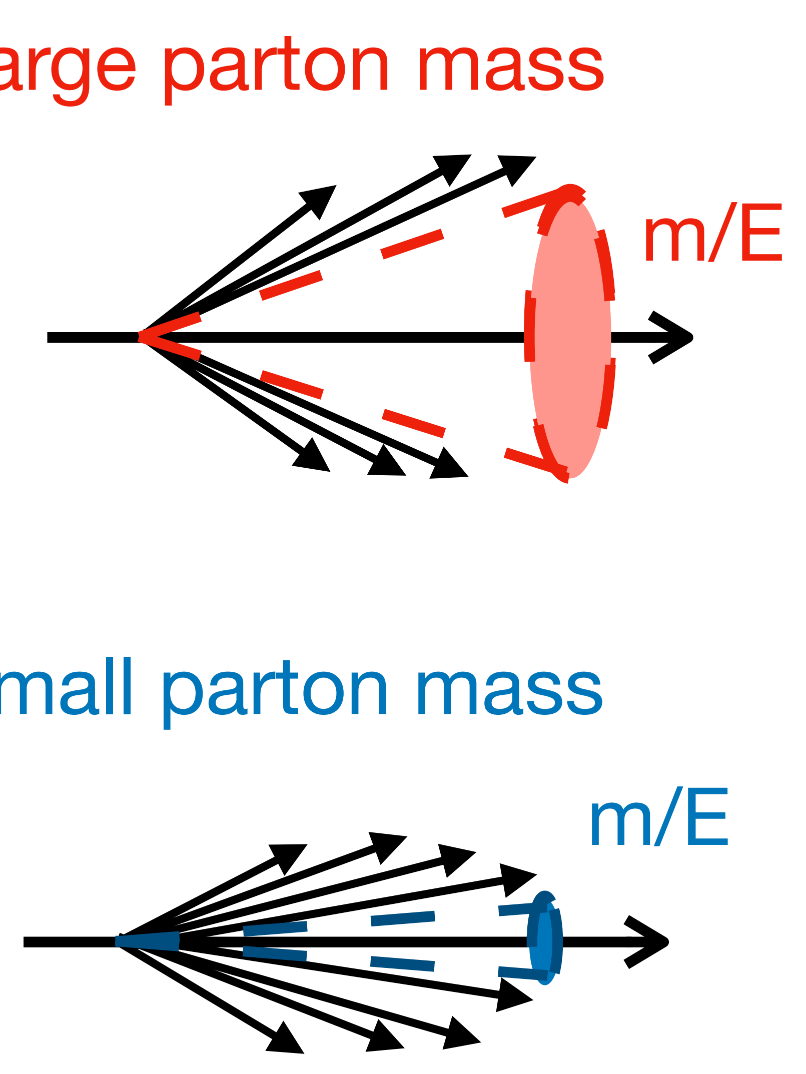
ATLAS



- *b*-jet found to be **less suppressed** than inclusive jets in central collisions
- p_T > 80 GeV

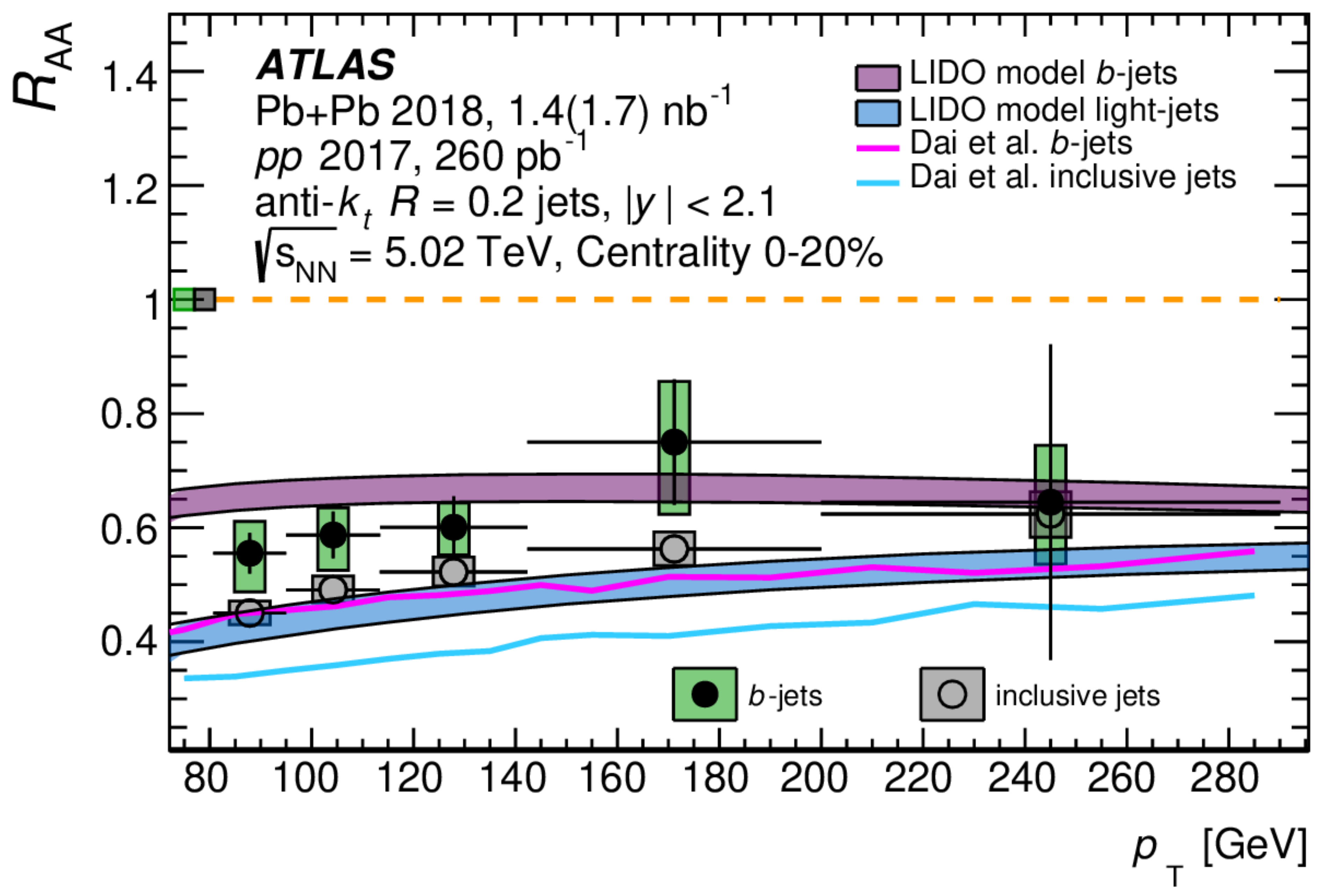
B-tagged Jets

Mass dependence expected due to “dead-cone effect”



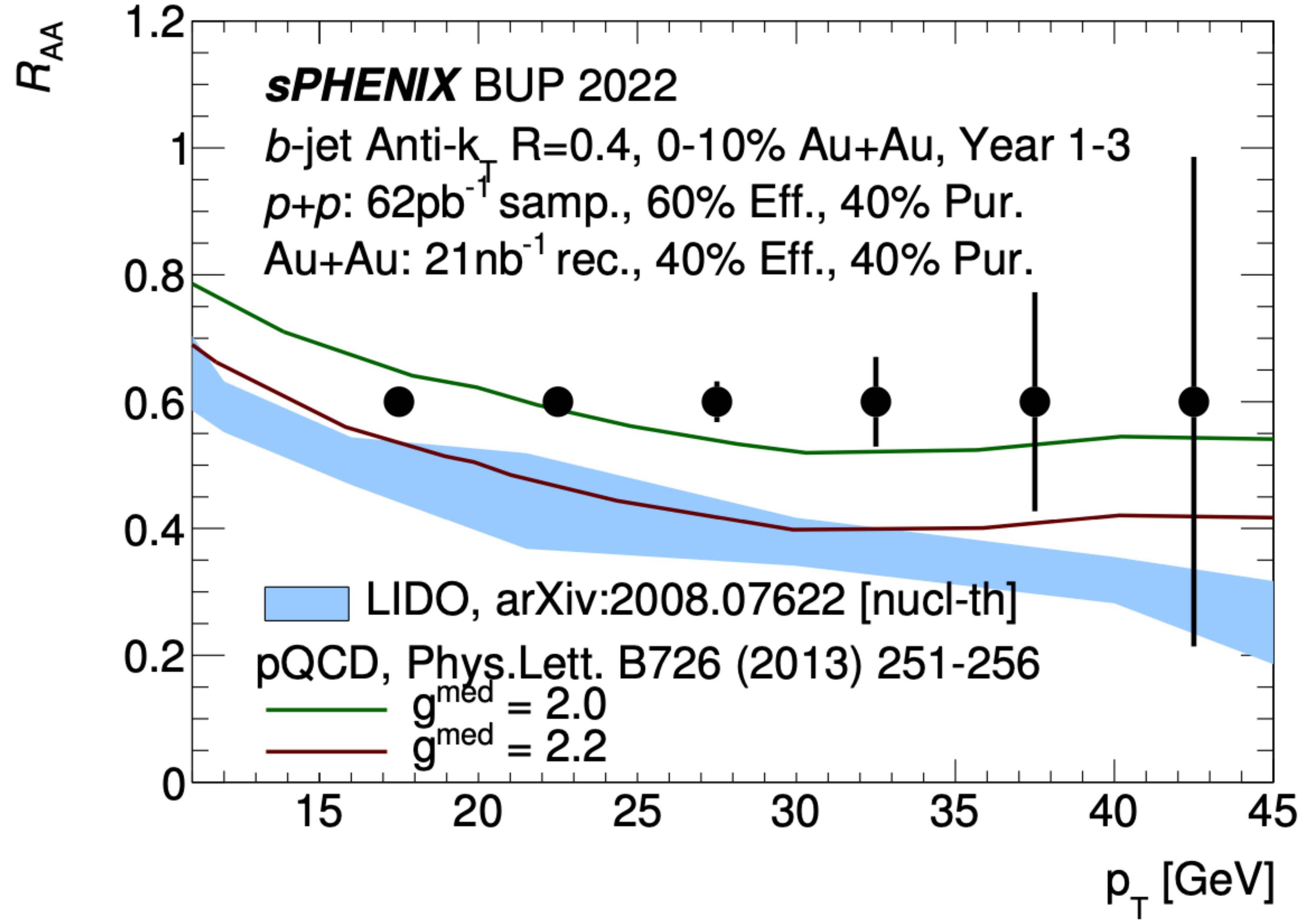
Radiation is suppressed in θ < m/E

ATLAS



- *b*-jet found to be **less suppressed** than inclusive jets in central collisions
- $p_T > 80$ GeV

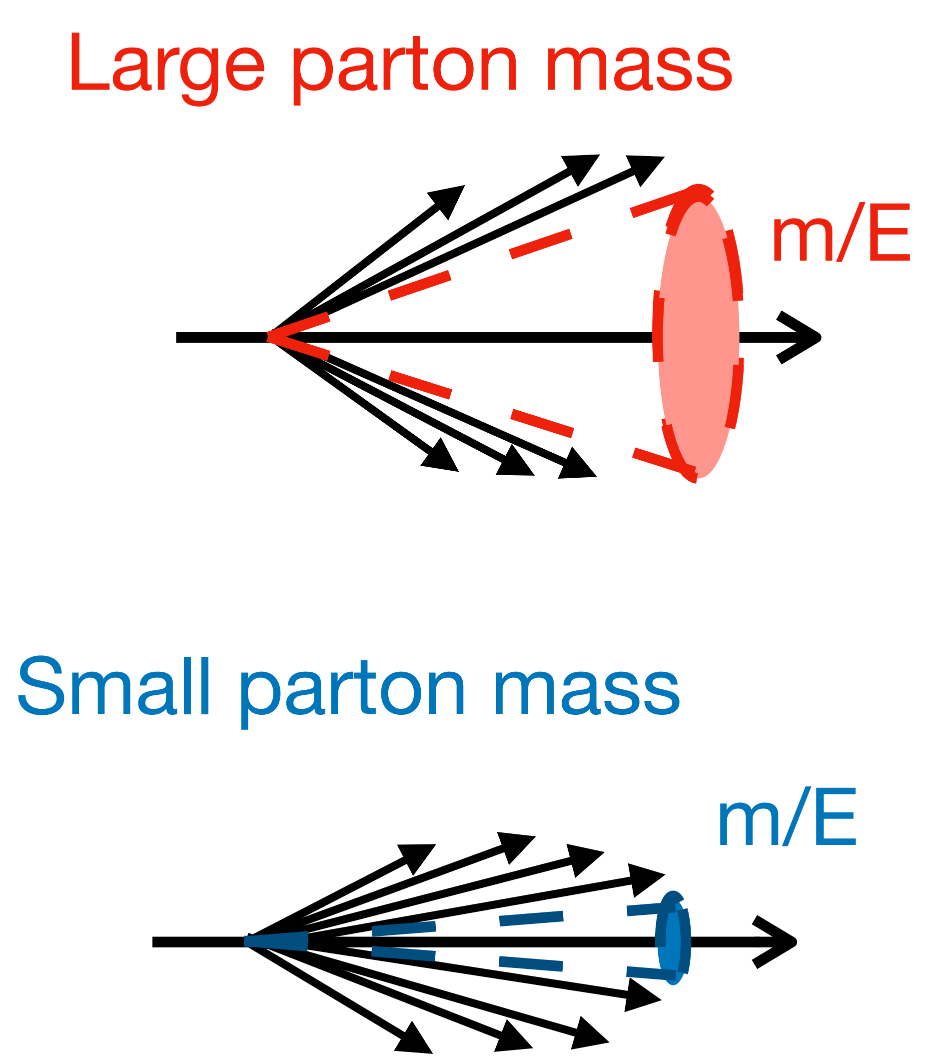
sPHENIX projection



- Completely new channel at RHIC - unique sPHENIX capability
- $p_T > 15$ GeV

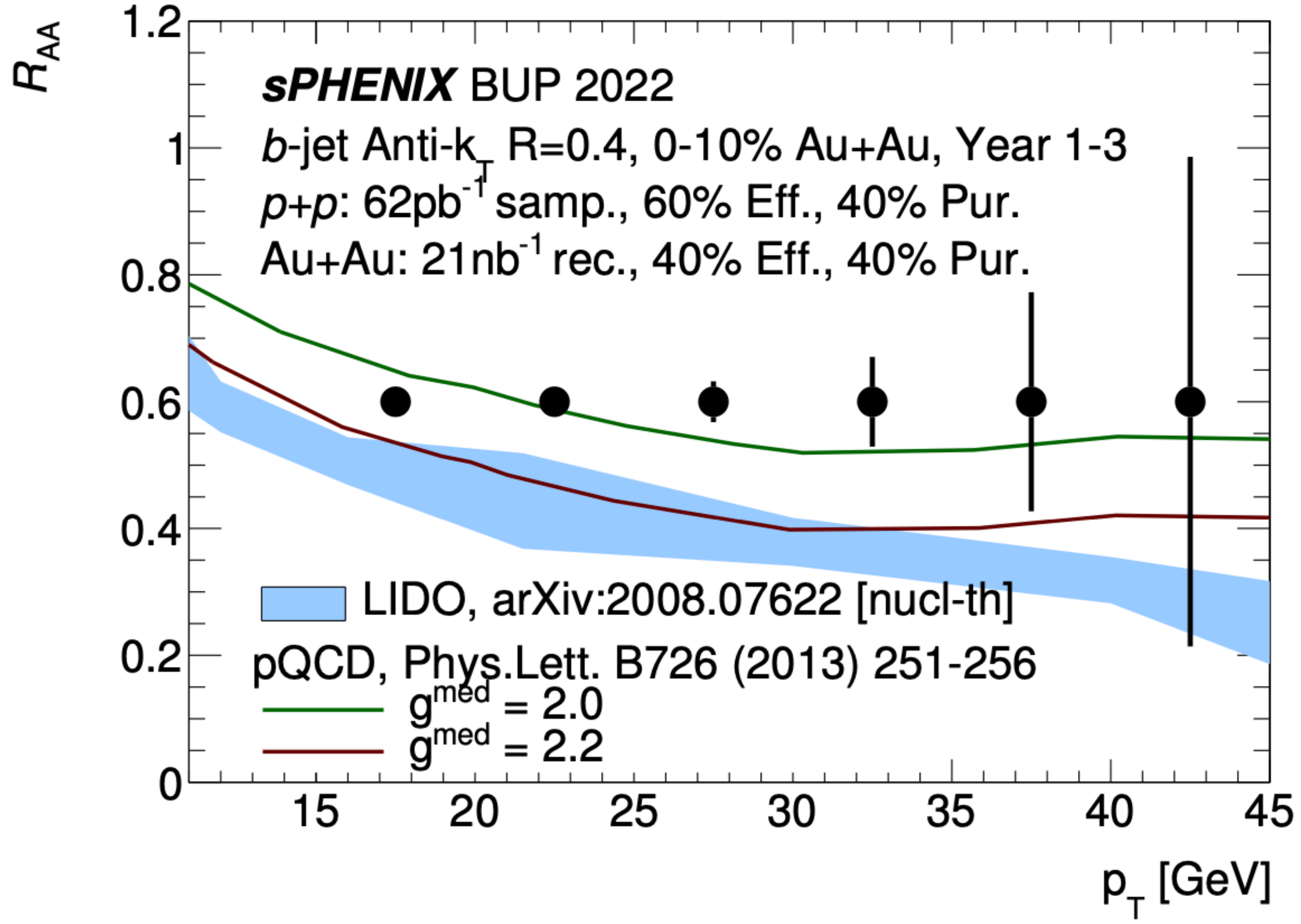
B-tagged Jets

Mass dependence expected due to “dead-cone effect”



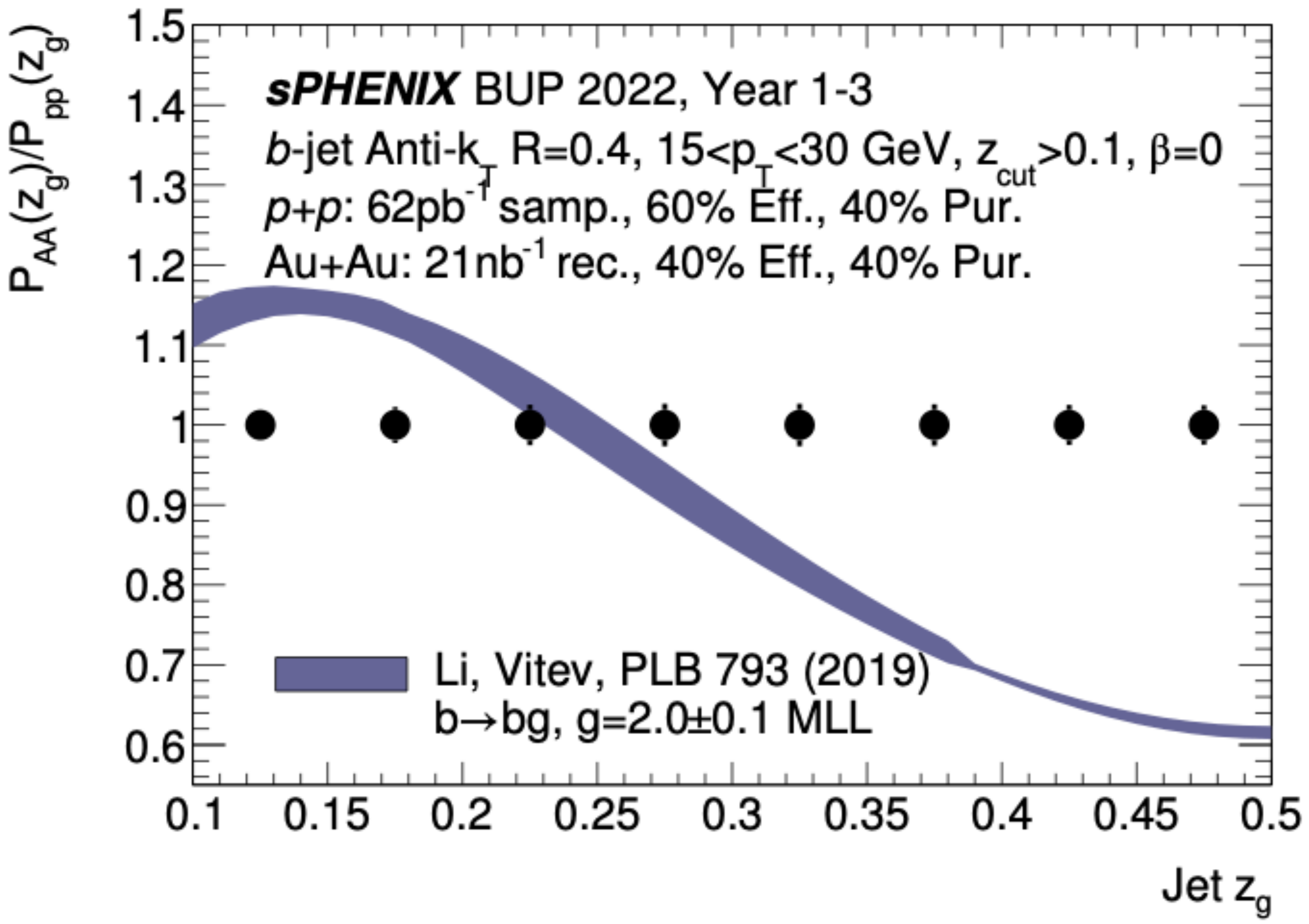
Radiation is suppressed in θ < m/E

sPHENIX projection



- Completely new channel at RHIC - unique sPHENIX capability
- p_T > 15 GeV

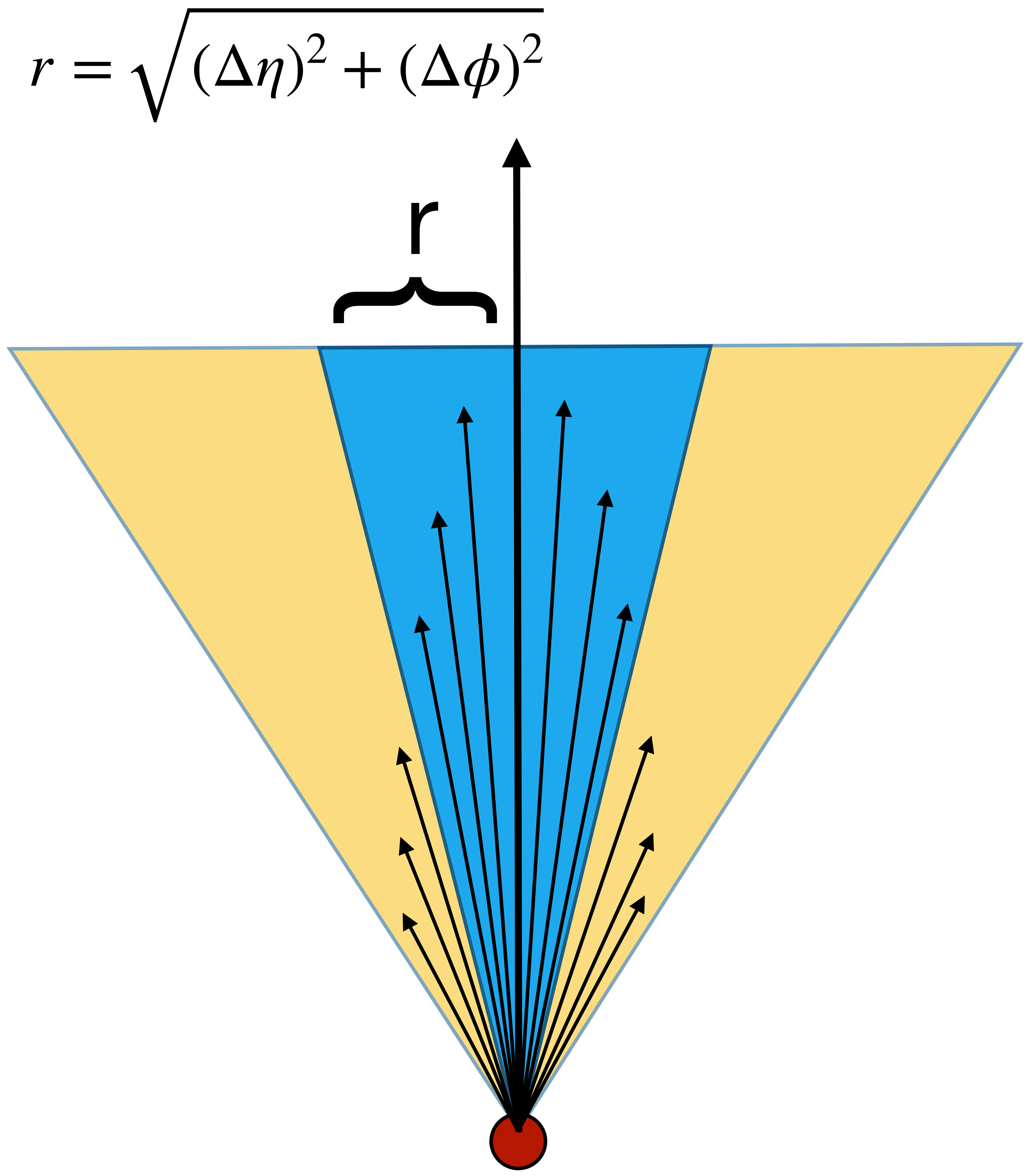
sPHENIX projection



- Sufficiently large yield to look at b-jet structure, e.g. ratio of z in Au+Au/p+p

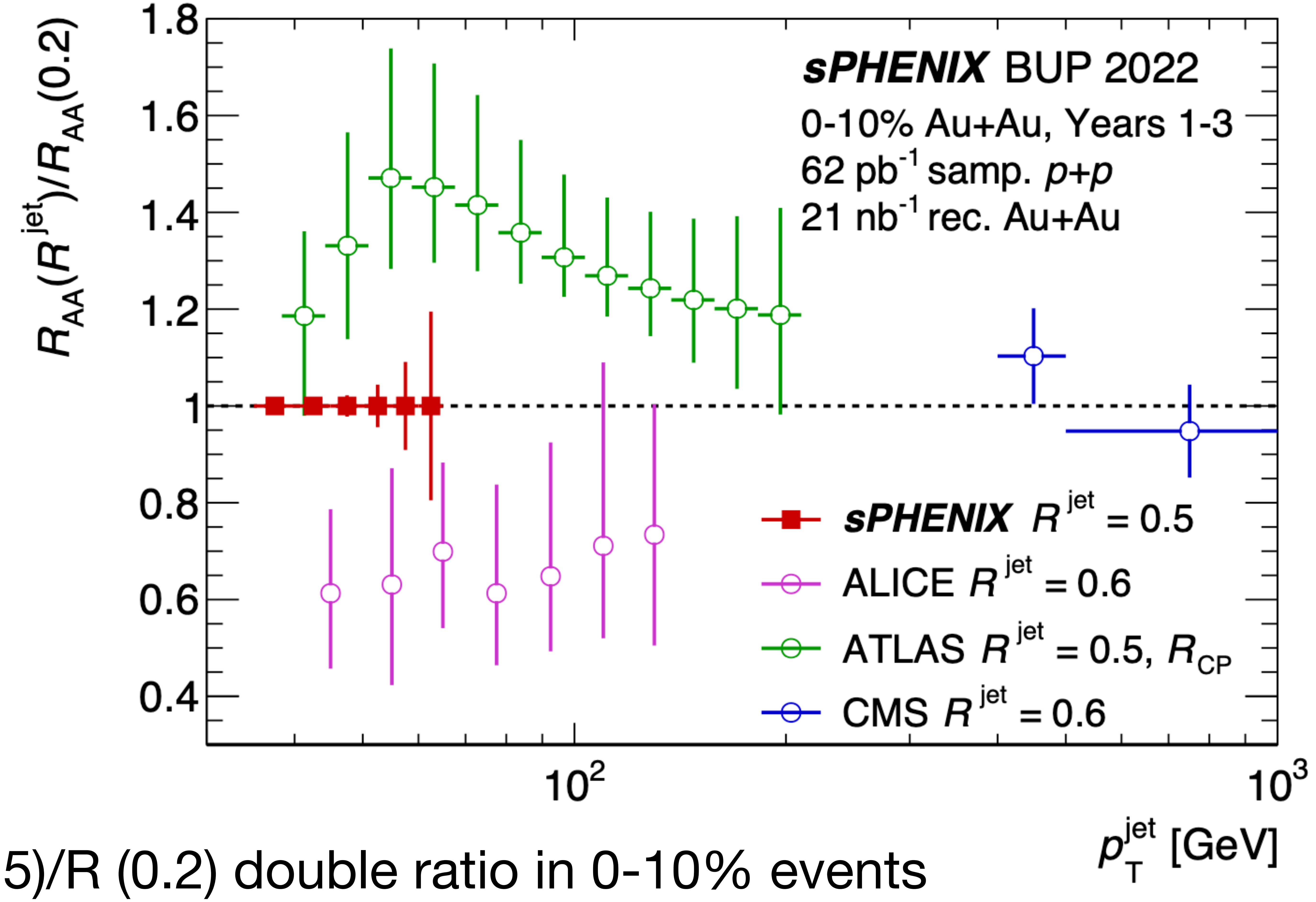
$$z_g = \frac{min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

Jets: open questions from LHC



Tension in Jet R-dependence

- key info on jet-shape modification and geometry dependence
- Difficult to measure at LHC in pT < 50 GeV region where effects may be large

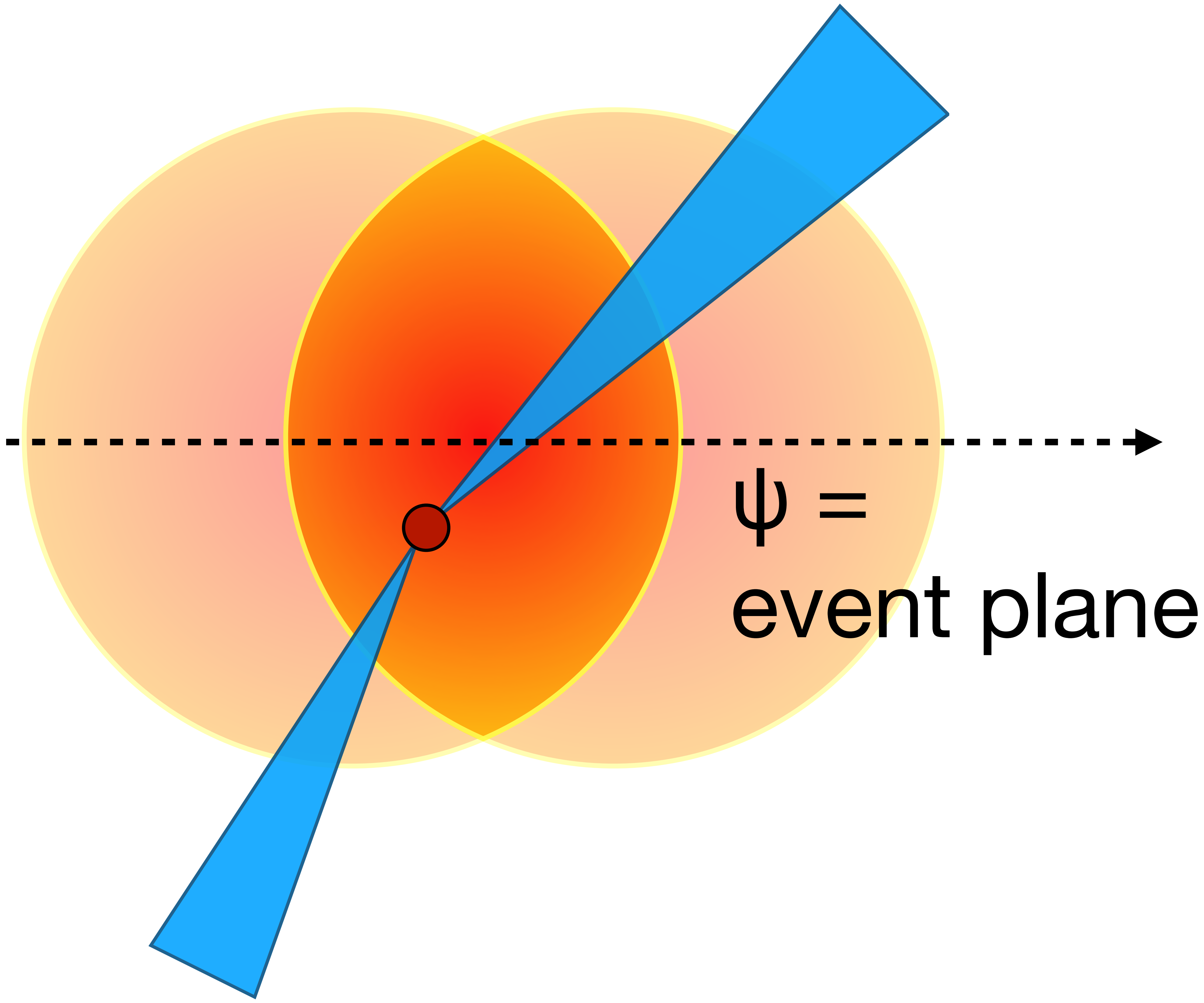


- Projected R(0.5)/R (0.2) double ratio in 0-10% events

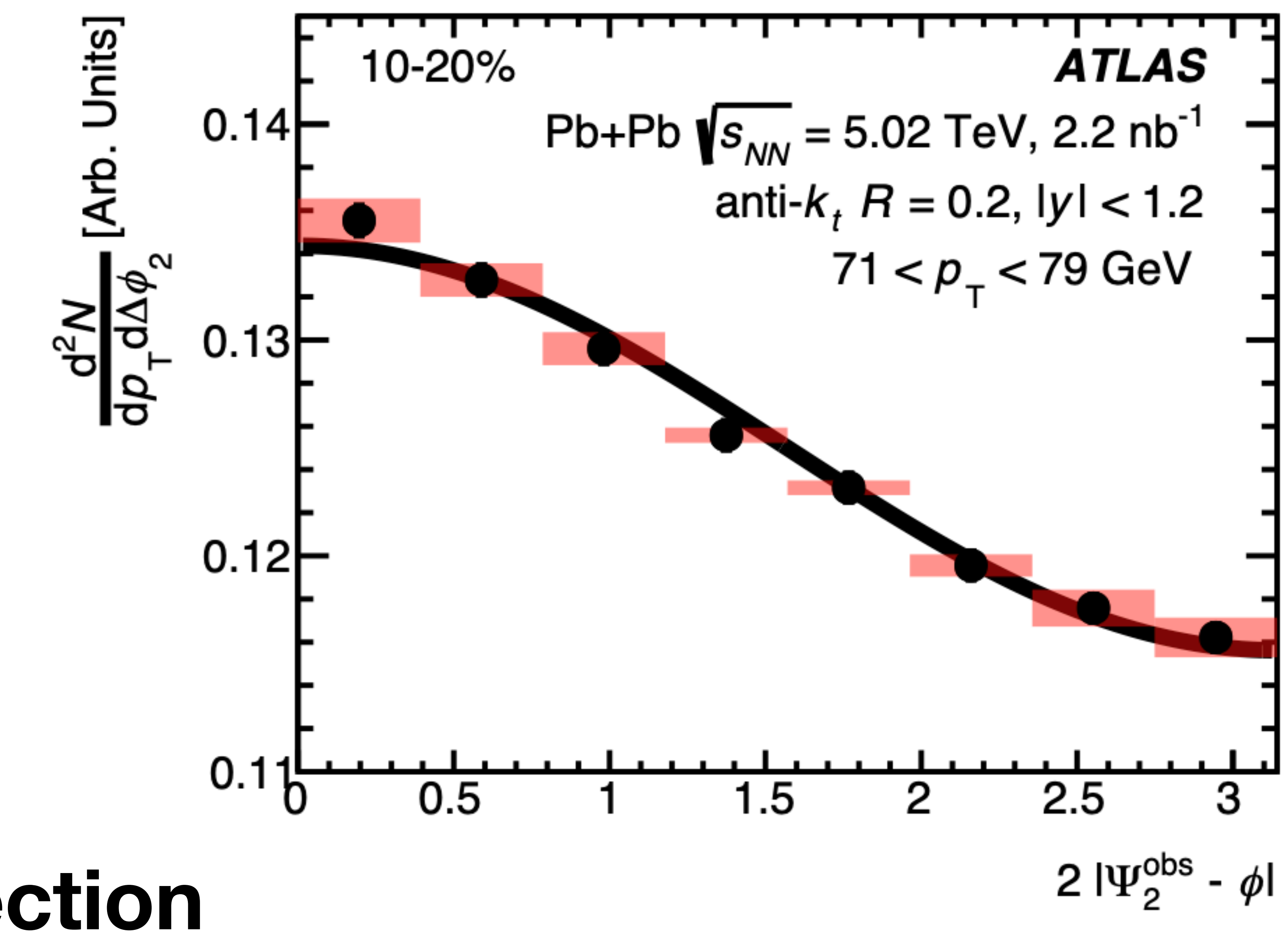
Jets: open questions from LHC

Correlation of jets with the event planes, ψ

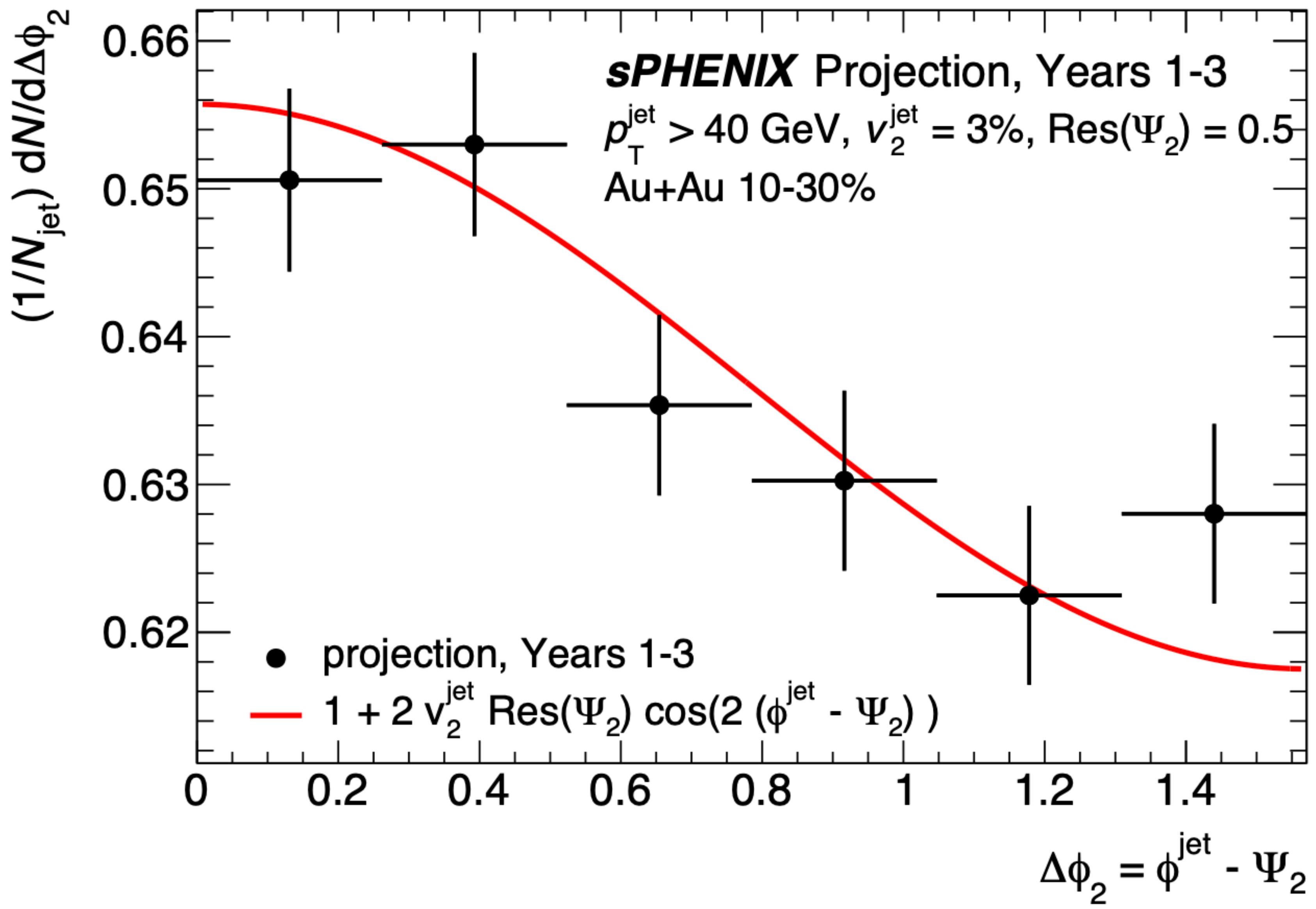
- Sensitive to overall event geometry & path length energy loss



ATLAS



sPHENIX projection



Jets: open questions from LHC

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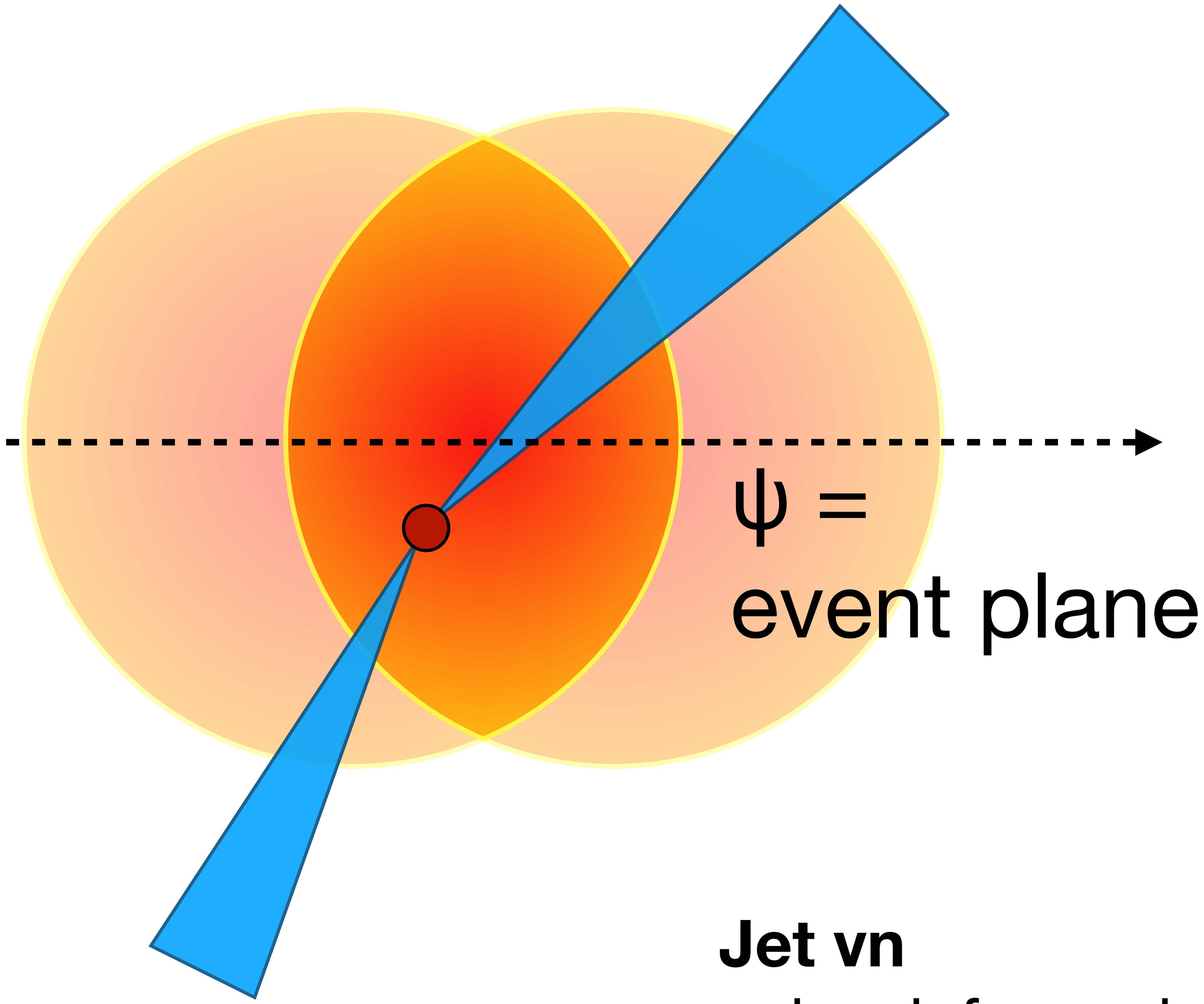
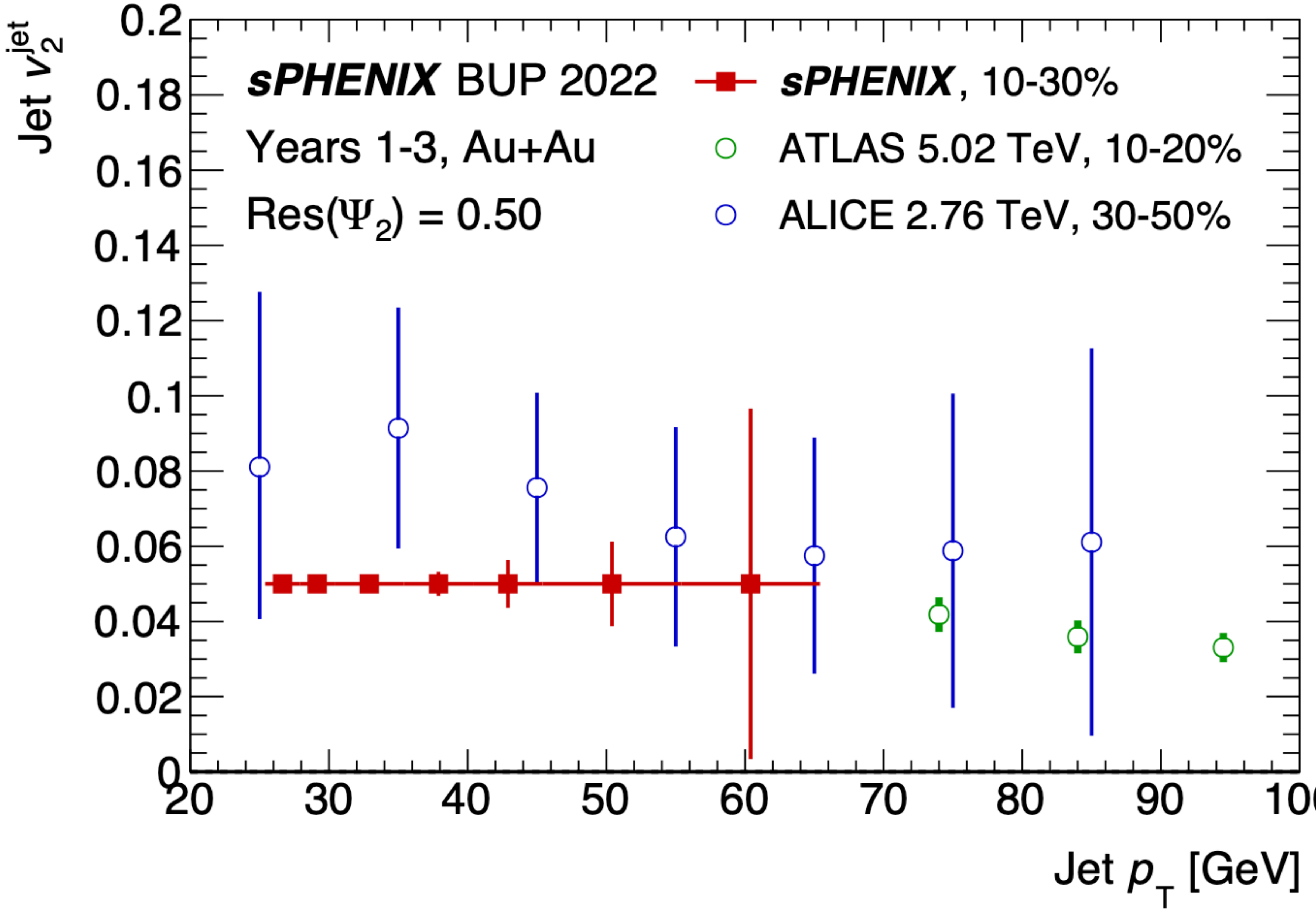


sPHENIX projection



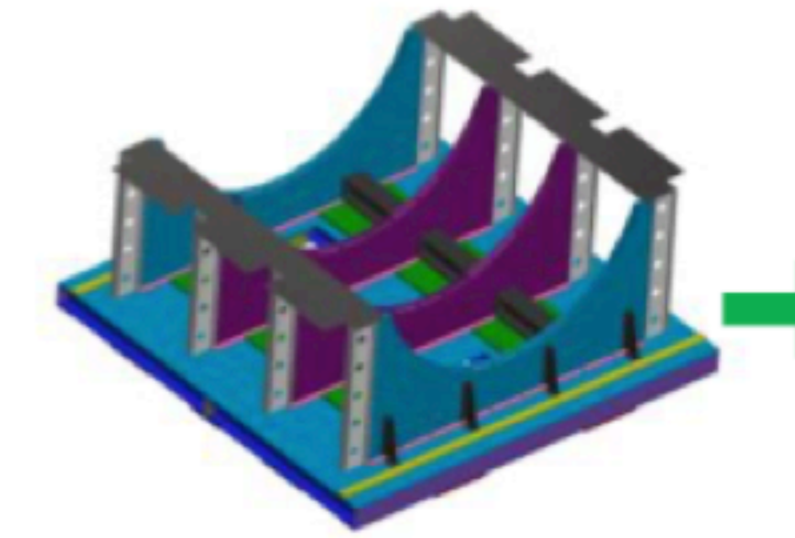
Jet vn

- key info on shape modification and geometry dependence
- Difficult to measure at LHC in p_T < 50 GeV region where effects may be large

sPHENIX construction — where are we?

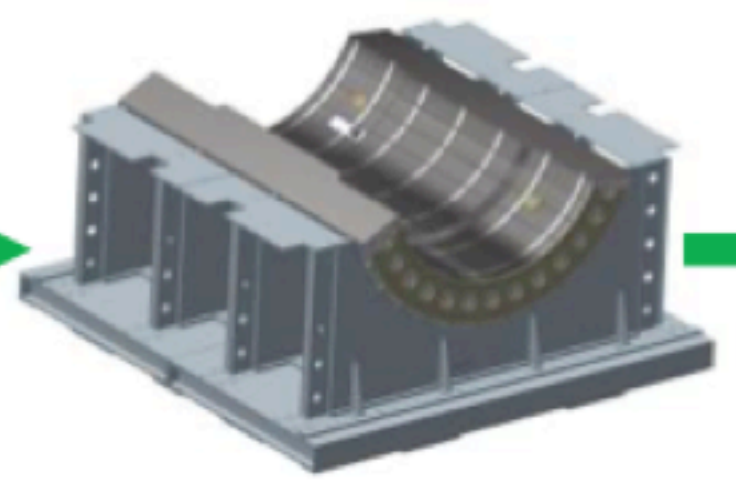
sPHENIX construction — where are we?

(1) Cradle Base, AH



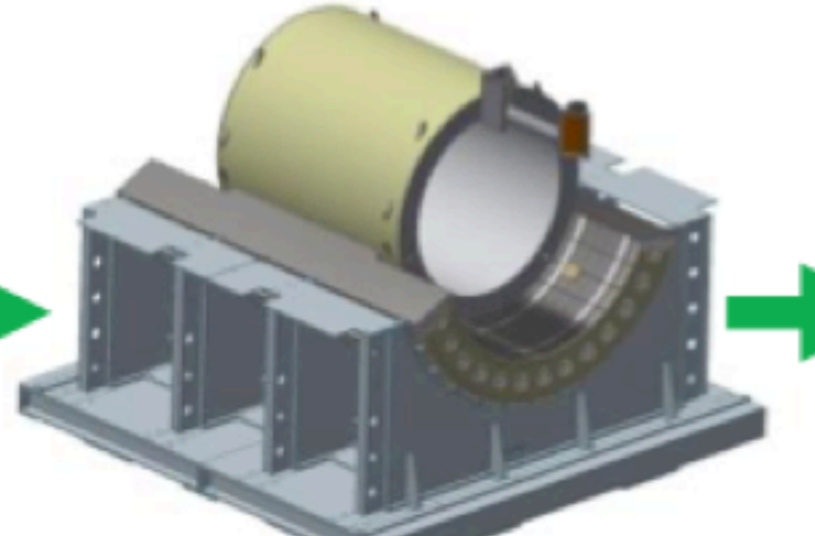
The base will be built on top of the AH rails

(2) oHCAL Sector 1-13, AH



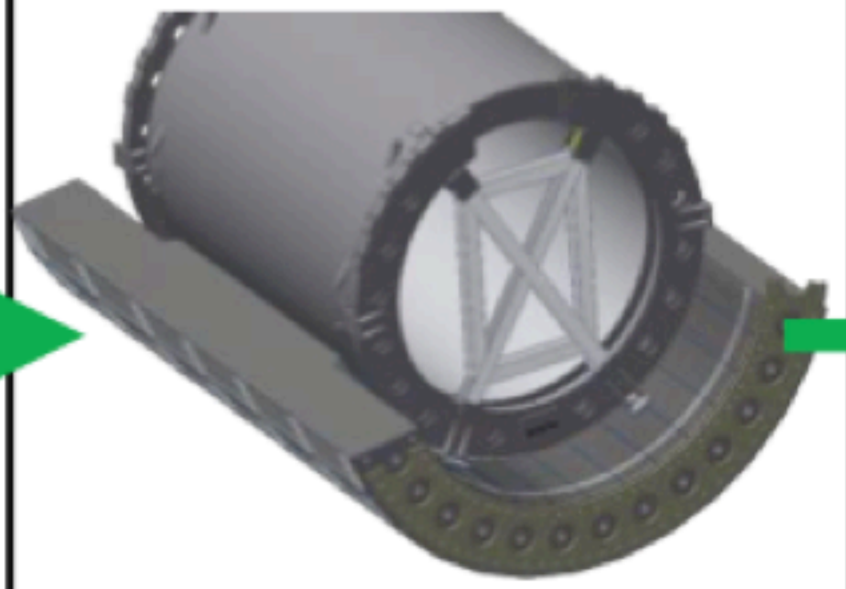
Magnet mount hardware is also attached

(3) Magnet mount, AH



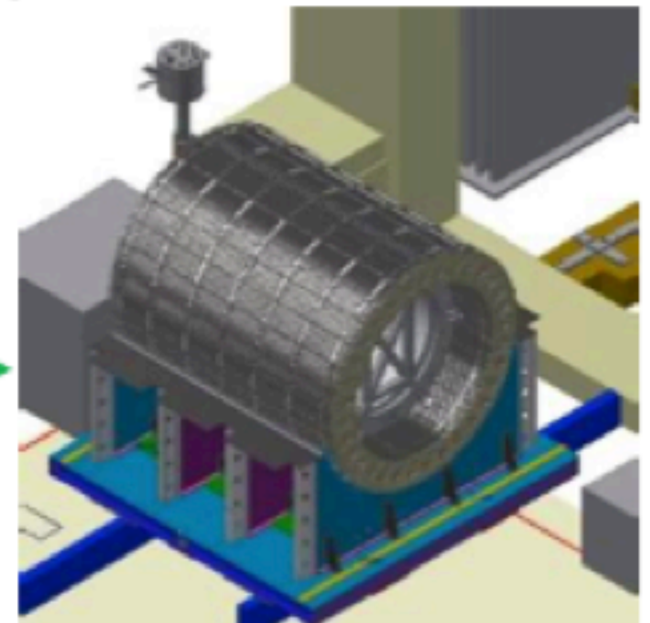
The magnet is lowered in to the oHCAL bore

(4) Inner Rings, AH



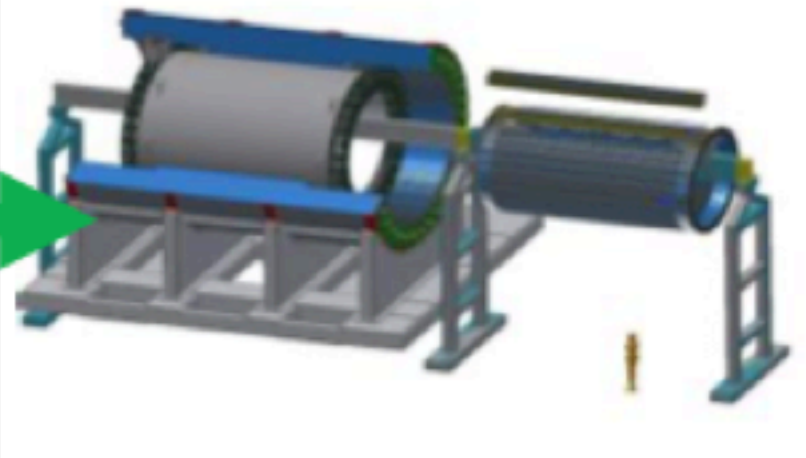
The rings also work to stabilize the magnet

(5) oHCAL Sector 14-32, AH



The full oHCAL barrel weighs ~480 tons

(6) Inner HCAL



The iHCAL barrel slides in from the North

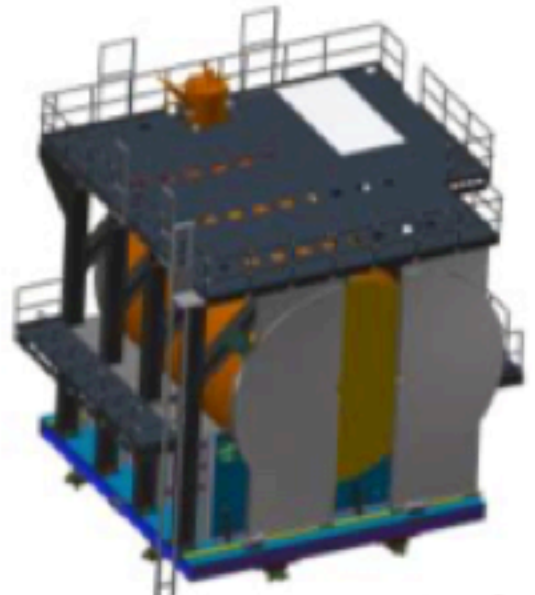
(7) EMCAL

There are 64 EMCAL sectors each installed one at a time with a special tool

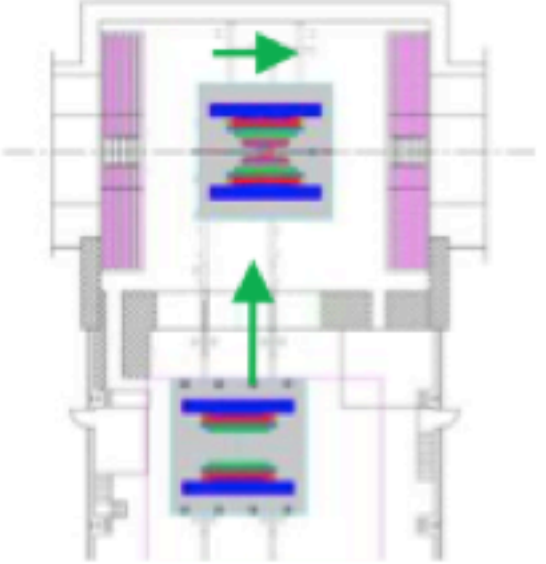
(8) Open Shield Wall

Work on sPHENIX will stop for the time needed to remove the shield wall

(9) Carriage, platforms, Pole Tips, AH

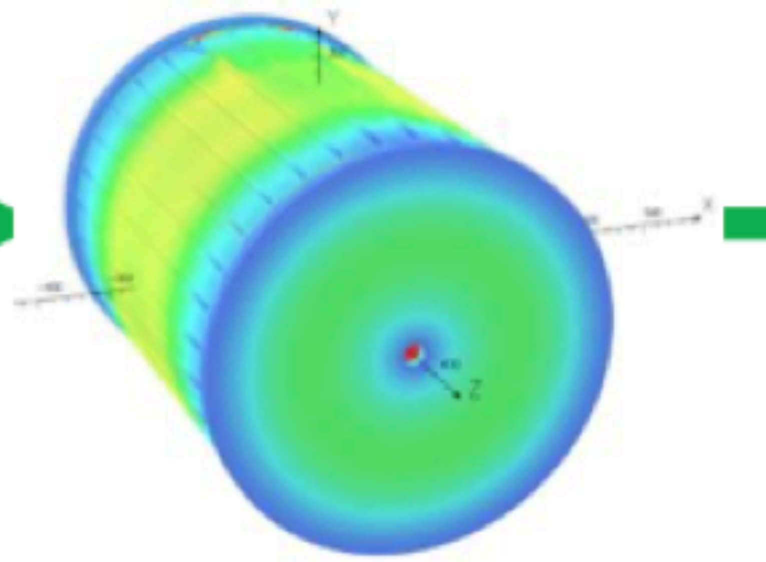


(10) Move sPHENIX to IR



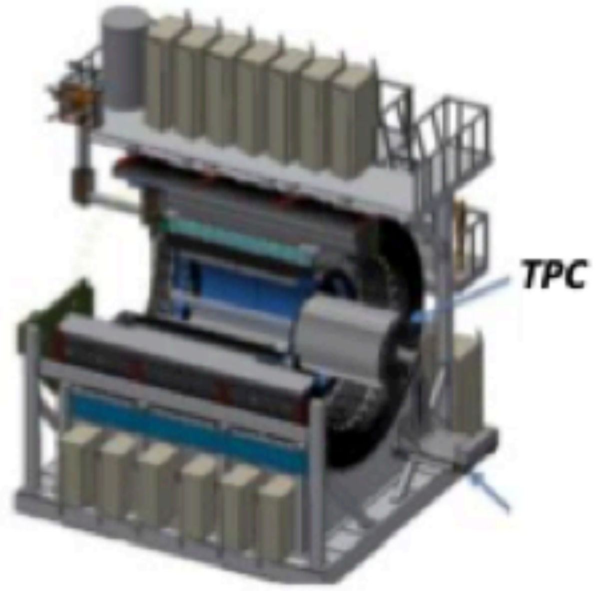
There is a 5-foot move North in the IR

(11) Connect, Map Magnet



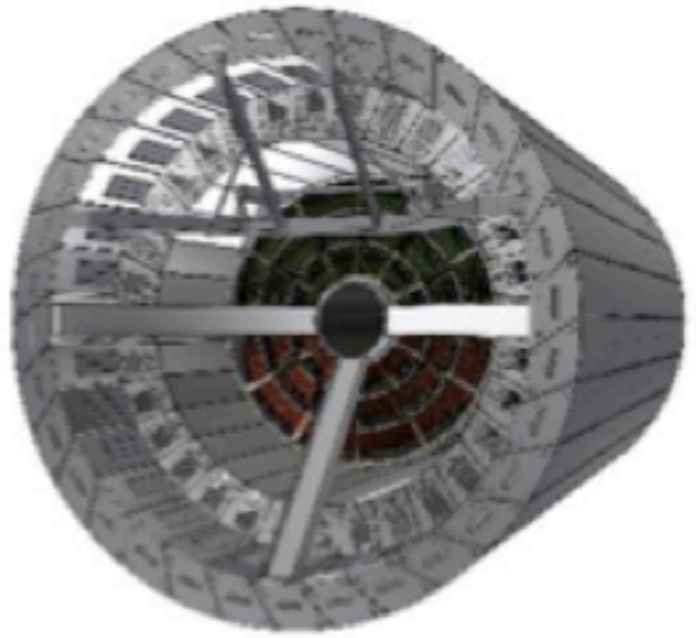
Results from an sPHENIX OPERA EM FEA

(12) TPC, IR



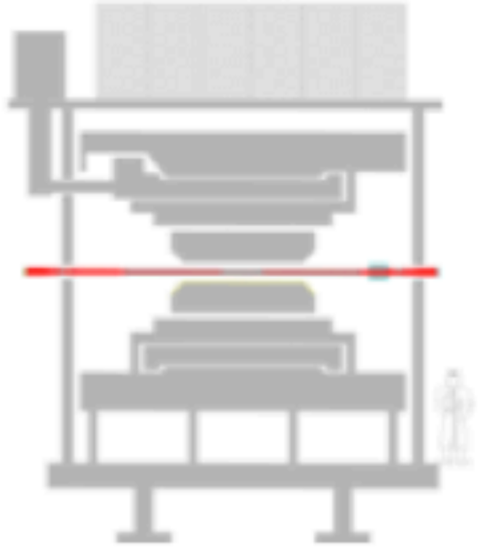
TPC slides in the EMCAL bore from North

(13) INTT Supports, IR



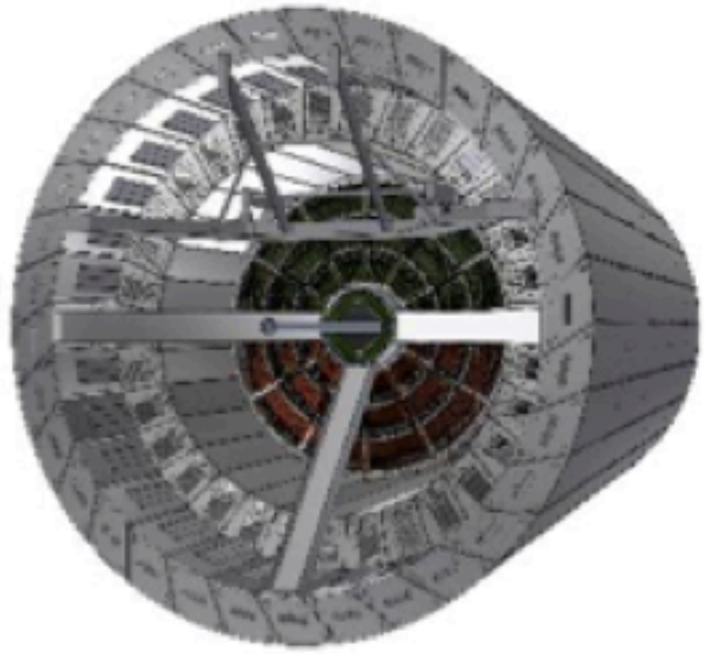
iHCAL, EMCAL, TPC and INTT Supports

(14) Beam Pipe Install. IR



Beam pipe is supported temporarily as a few locations for MVTX installation

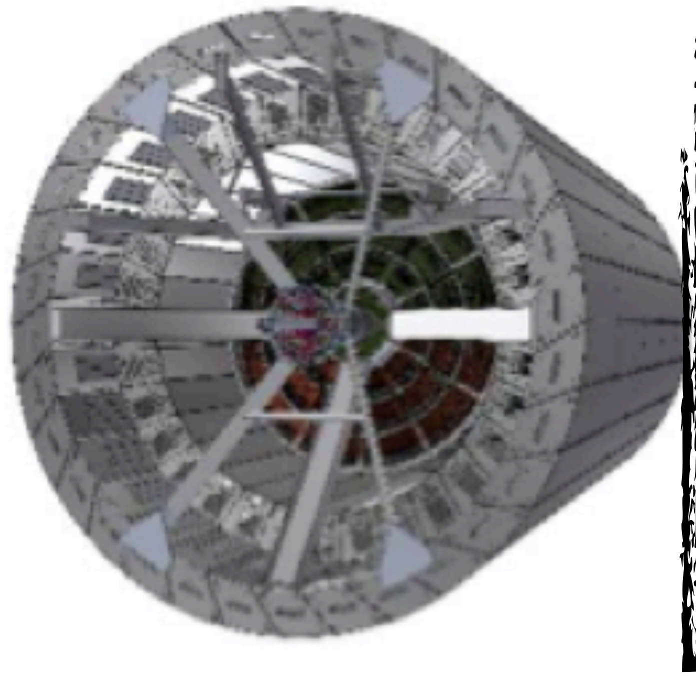
(15) INTT Device, IR



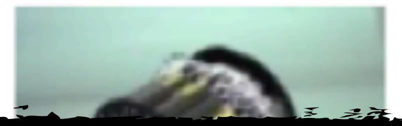
(16) MVTX, IR

MVTX has a 2mm clearance to the beam pipe

(17) Secure Beam pipe, IR



(18) MBD, IR



Ready for beam Feb 22 2023

sPHENIX construction — where are we?

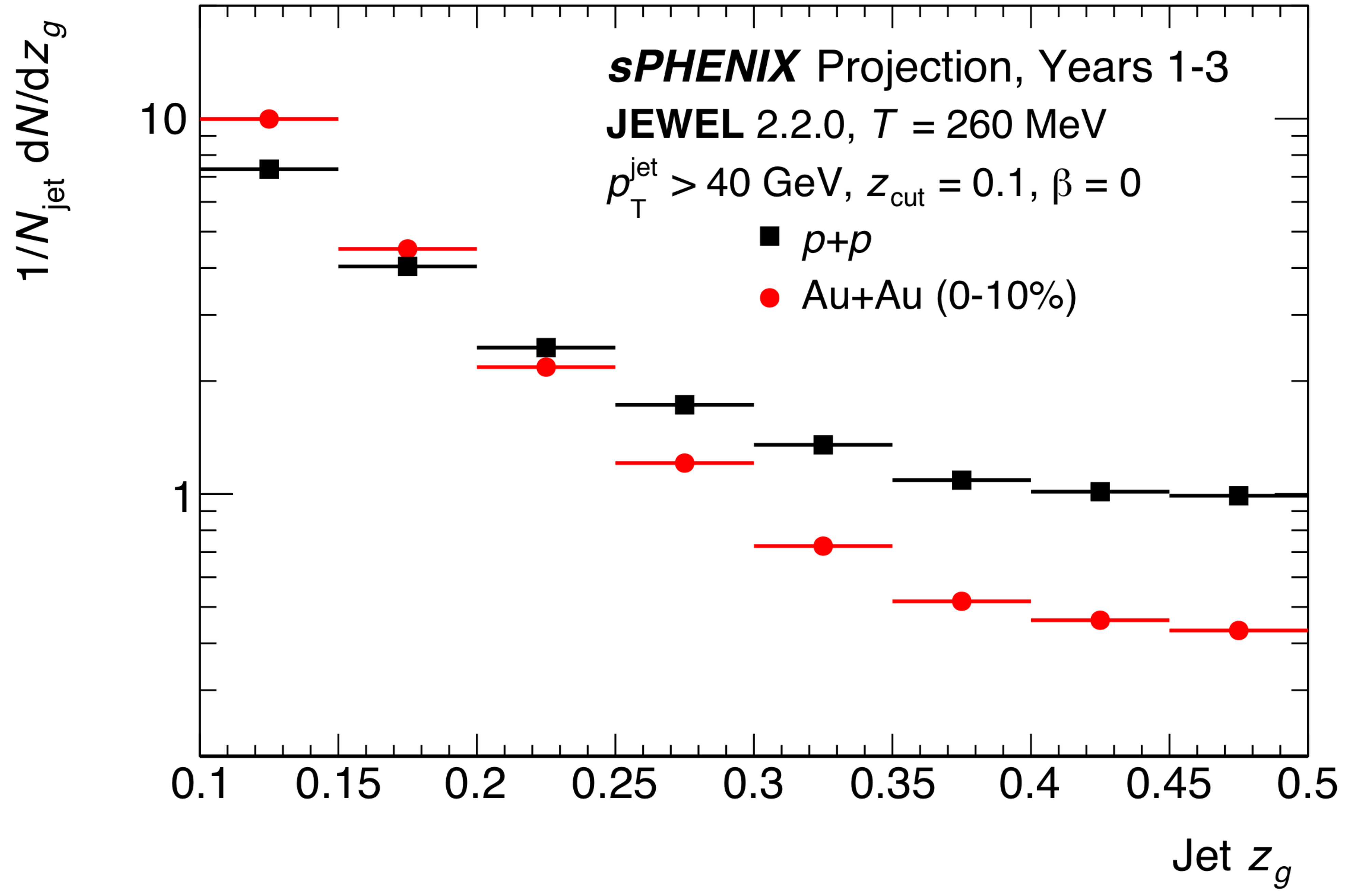
Thank you!!

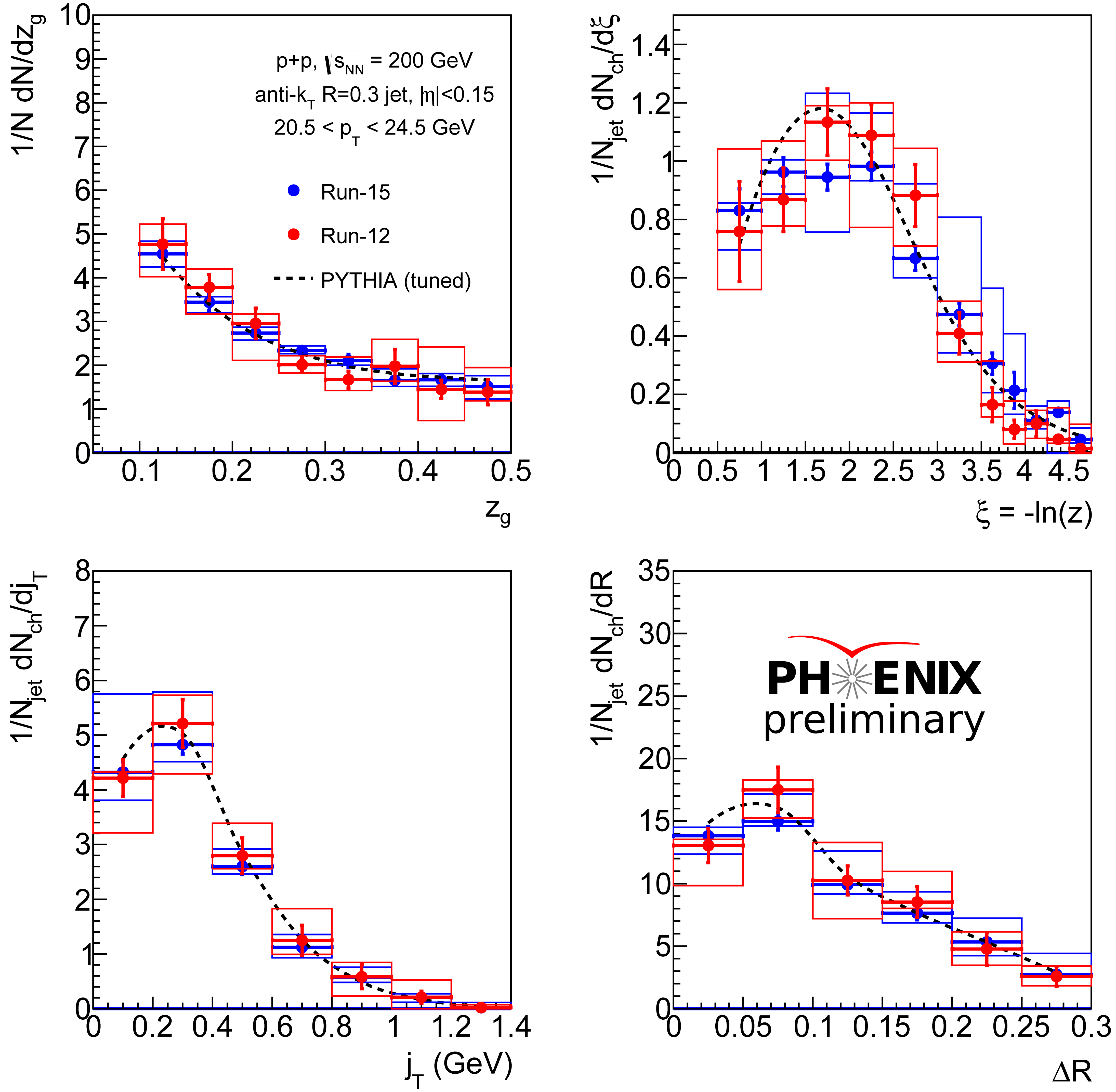
Jet Substructure at RHIC

Results in the pipeline for PHENIX, STAR...
...but PHENIX and STAR were not designed as Jet detectors!

- Substantial corrections to the JES and fragmentation bias
- Relatively large systematic errors, hard to look for subtle effects

sPHENIX will enable a full suite of jet measurements with full tracking and calorimetry coverage.
This is necessary to understand hadronization in CNM!





Energy Correlations in Jets

Analyzing N-point Energy Correlators Inside Jets with CMS Open Data
https://arxiv.org/pdf/2201.07800.pdf

$$ENC(R_L) = \left(\Pi_{k=1}^{N} \int d\Omega_{\vec{n}_k}\right) \delta(R_L - \Delta\hat{R}_L) \cdot \frac{1}{(E_{jet})^N} \langle \epsilon(\vec{n}_1)\epsilon(\vec{n}_2)\dots\epsilon(\vec{n}_N)\rangle$$

ϵ, is the asymptotic energy flow operator

2-points correlation:

$$\frac{1}{\sigma}\frac{d\Sigma}{d\phi} \equiv \frac{1}{N}\sum_{A=1}^{N}\frac{1}{\Delta\phi}\sum_{pairs\ in\ \Delta\phi}\frac{E_{T_a}^{A}E_{T_b}^{A}}{(E_T^A)^2}$$

More information:

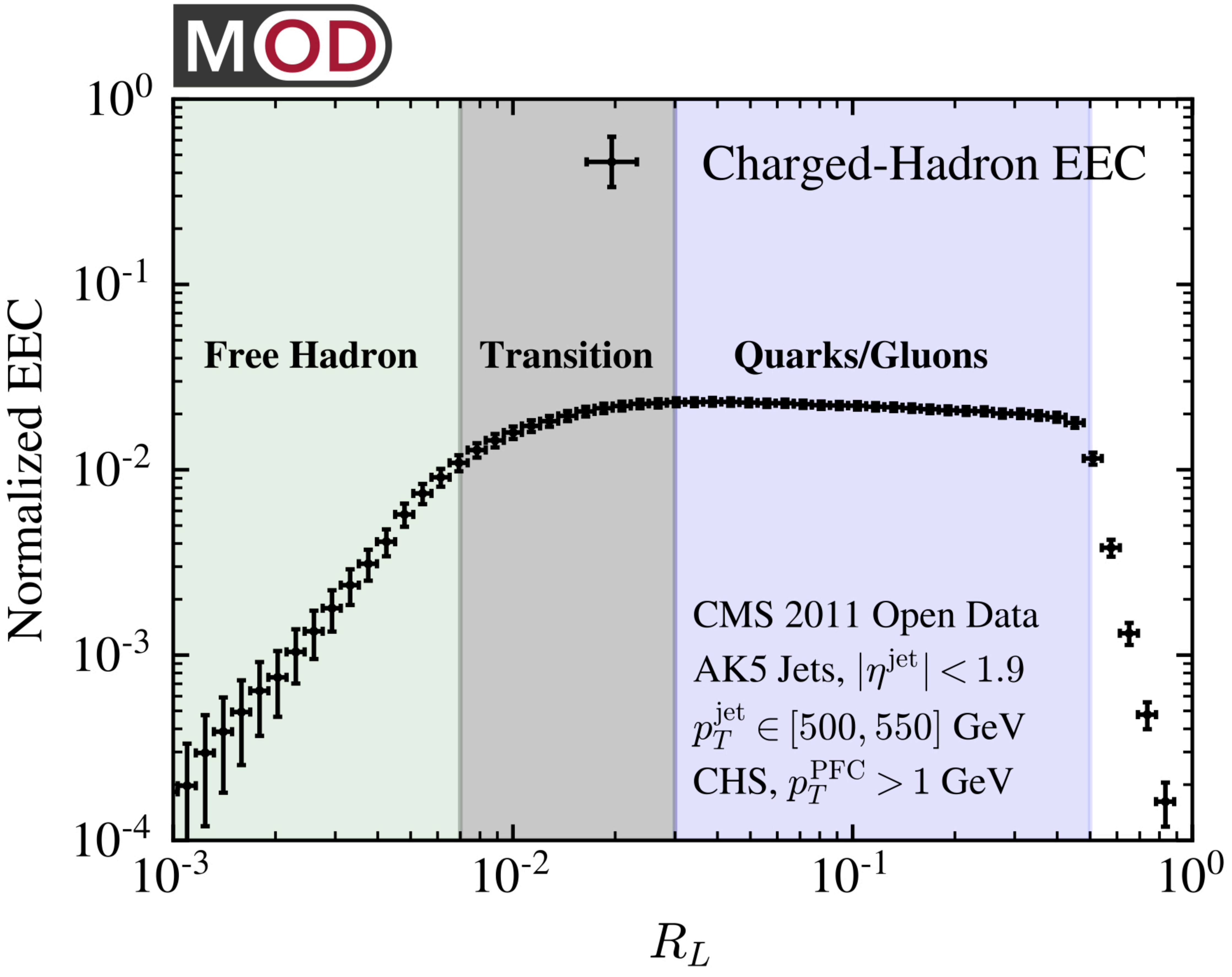
arxiv:1205.1689
- TEEC in NLO in α_S at the LHC

arxiv:1707.02562
- α_S measurement from multijet events by ATLAS

Analyzing N-point Energy Correlators Inside Jets with CMS Open Data

Patrick T. Komiske,[1,*] Ian Moult,[2,†] Jesse Thaler,[1,‡] and Hua Xing Zhu[3,§]
[1] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[2] *Department of Physics, Yale University, New Haven, CT 06511*
[3] *Zhejiang Institute of Modern Physics, Department of Physics, Zhejiang University, Hangzhou, 310027, China*

Jets of hadrons produced at high-energy colliders provide experimental access to the dynamics of asymptotically free quarks and gluons and their confinement into hadrons. In this paper, we show that the high energies of the Large Hadron Collider (LHC), together with the exceptional resolution of its detectors, allow multipoint correlation functions of energy flow operators to be directly measured within jets for the first time. Using Open Data from the CMS experiment, we show that reformulating jet substructure in terms of these correlators provides new ways of probing the dynamics of QCD jets, which enables direct imaging of the confining transition to free hadrons as well as precision measurements of the scaling properties and interactions of quarks and gluons. This opens a new era in our understanding of jet substructure and illustrates the immense unexploited potential of high-quality LHC data sets for elucidating the dynamics of QCD.

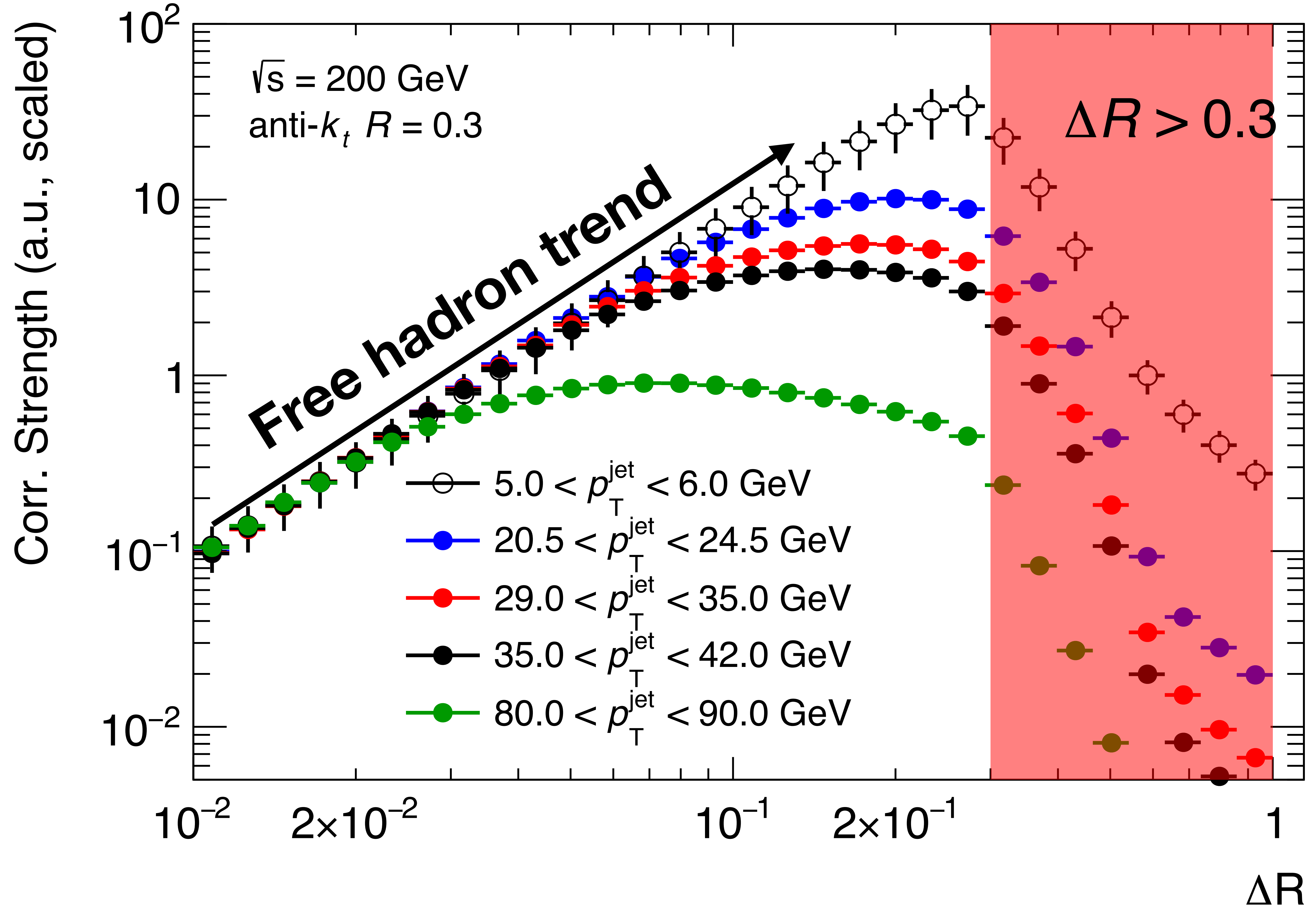


2-Point Correlations in Simulation

Details:

- anti-kt R = 0.3
- |η| < 1
- Only charged tracks
- Assuming 90% tracking efficiency

Using public code at https://github.com/pkomiske/EnergyEnergyCorrelators
from Analyzing N-point Energy Correlators Inside Jets with CMS Open Data
https://arxiv.org/pdf/2201.07800.pdf



Assuming jet p_T > 20 GeV trigger