Jet Physics in sPHENIX

Learning from the LHC and preparing for the EIC

Jet Physics: from RHIC/LHC to EIC
CFNS Workshop

1 July 2022

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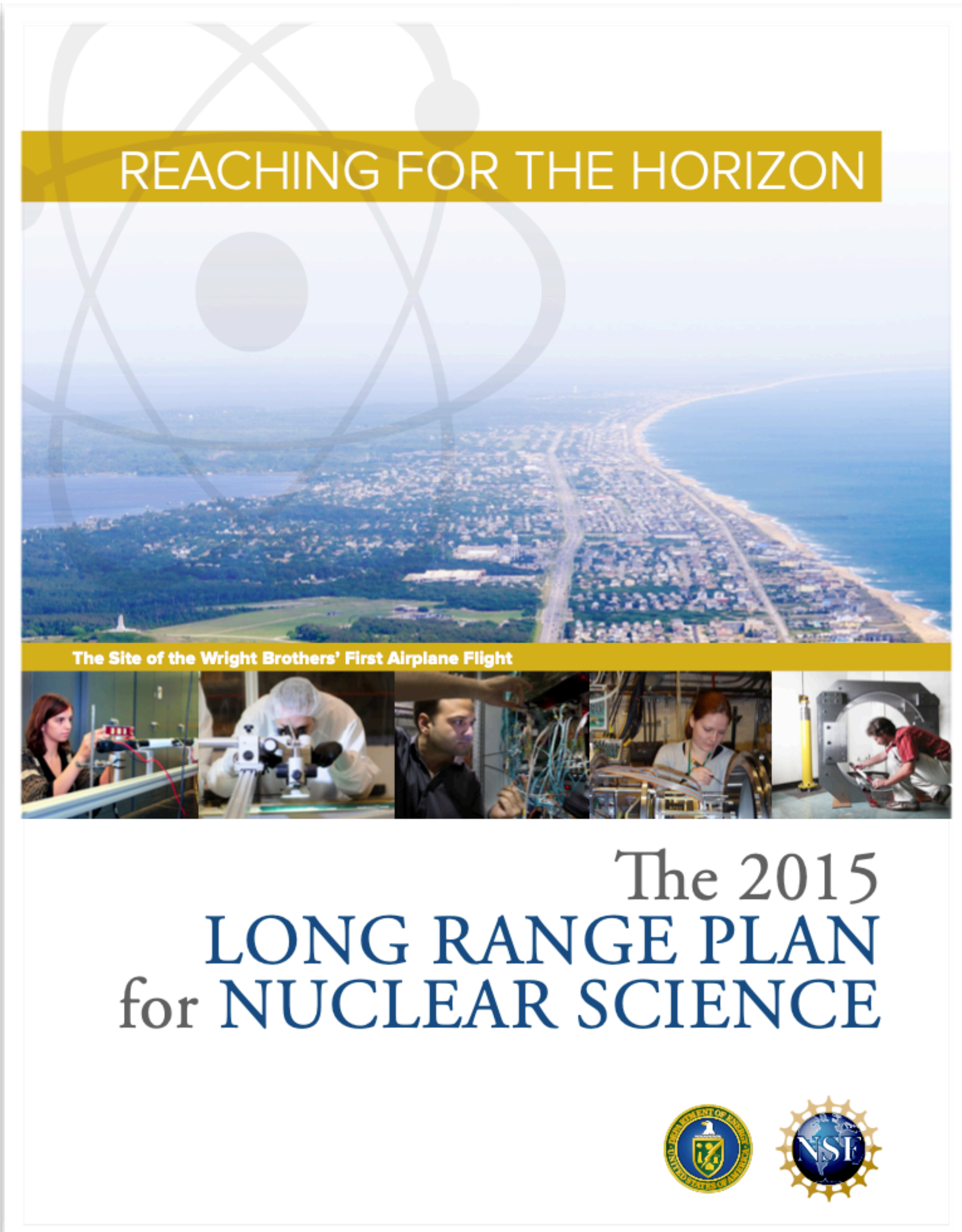
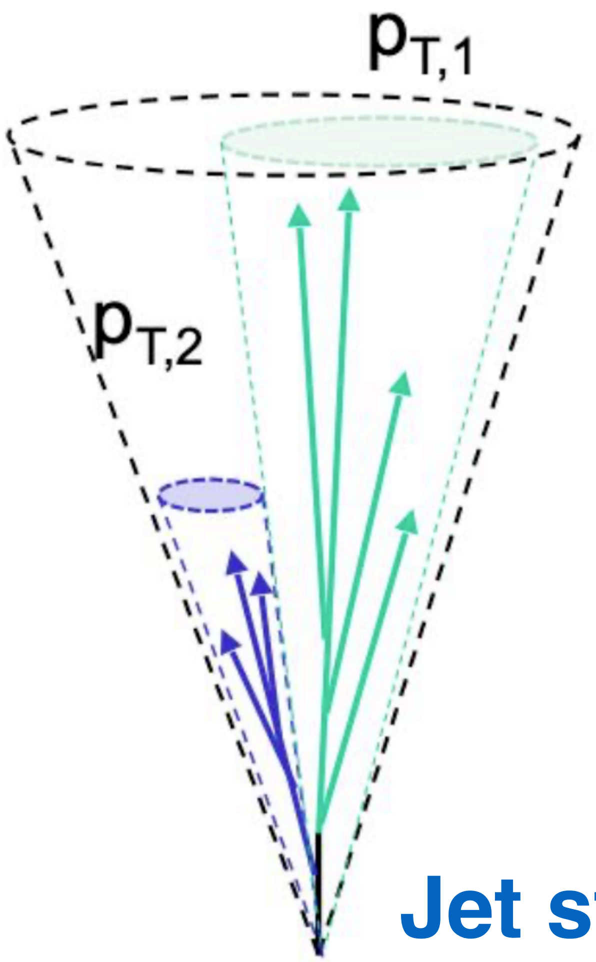
sPHENIX science



There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC: **(1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX. (2) Map the phase diagram of QCD with experiments planned at RHIC.**

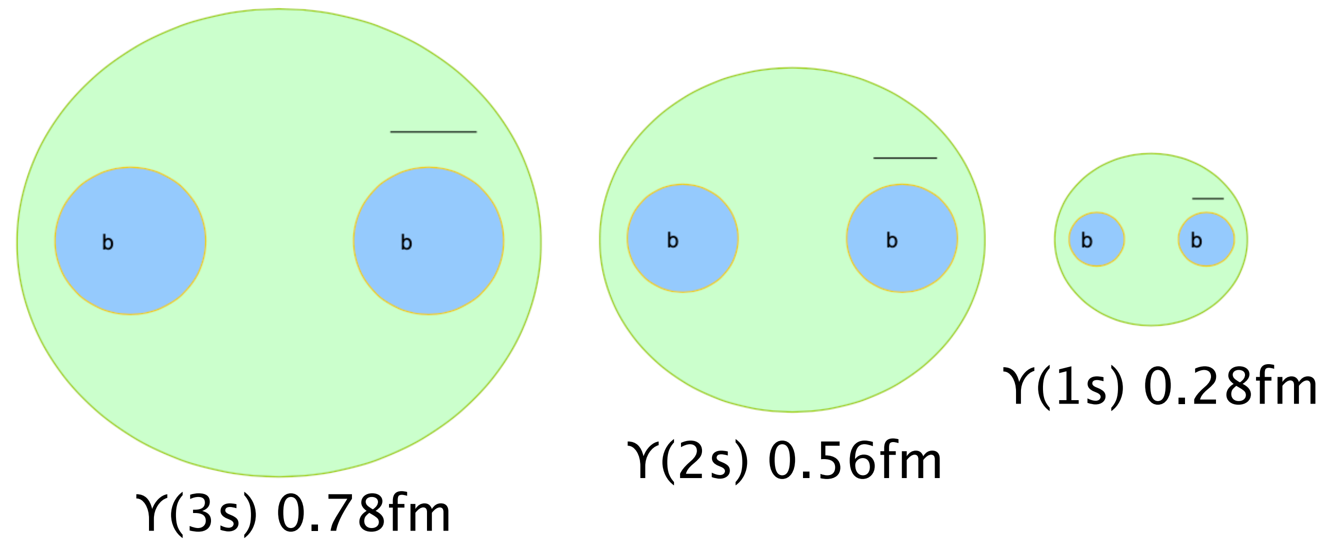
[2015 US NP LRP]

sPHENIX recognized by the U.S. Nuclear Physics community as the *essential* tool for QGP microscopy at RHIC



Jet structure

vary momentum/angular scale of probe

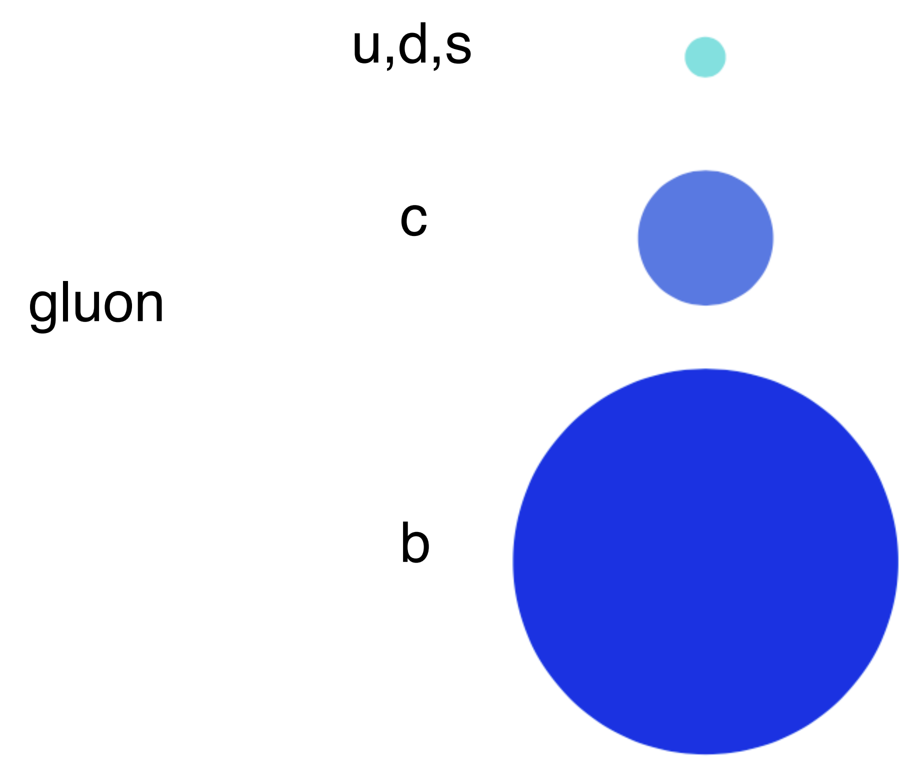


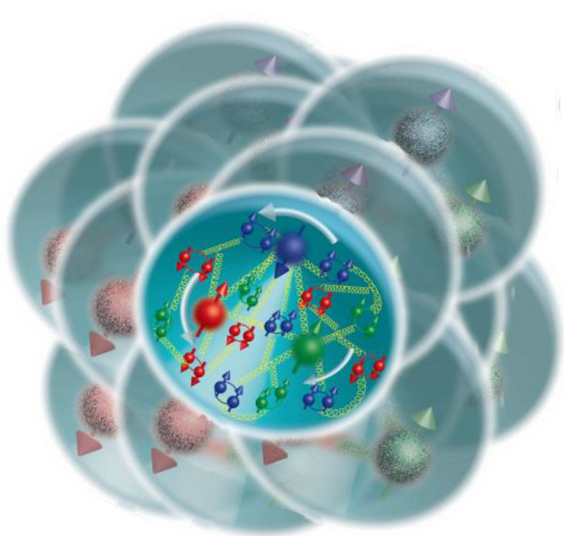
Quarkonium spectroscopy

vary size of probe

Parton energy loss

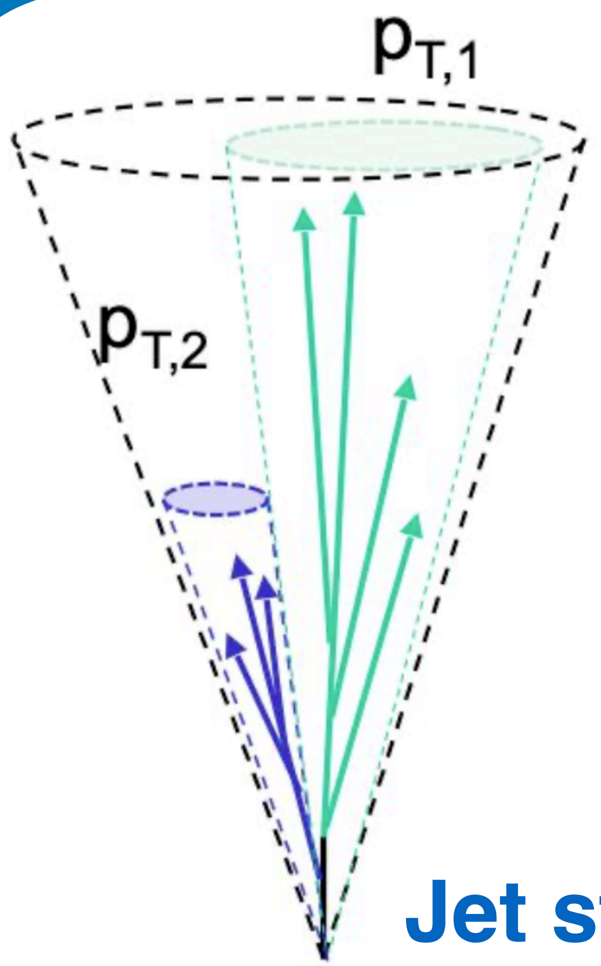
vary mass/momentum of probe





Cold QCD

study proton spin, transverse-momentum, and cold nuclear effects



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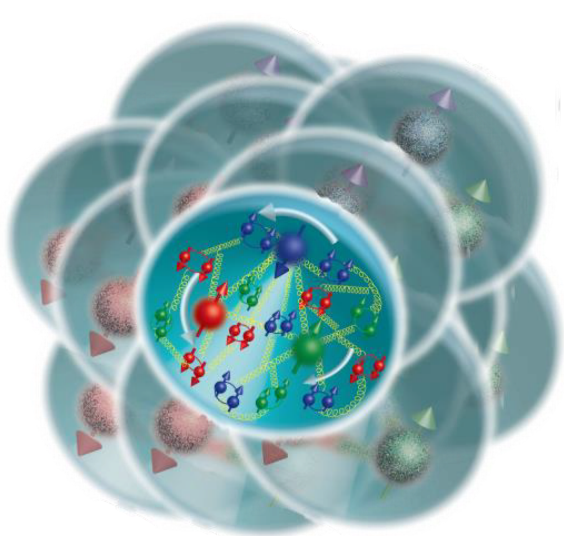

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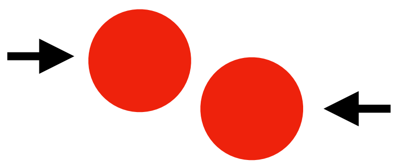
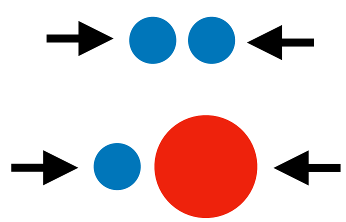
sPHENIX run plan (2023-2025)

Year-1



Commissioning the detector & first Au+Au collisions for physics (measurements of “standard candles”, early sPHENIX physics, etc.)

Year-2



Transversely polarized *p+p* and *p*+Au collisions:

vacuum baseline & reference for Au+Au physics

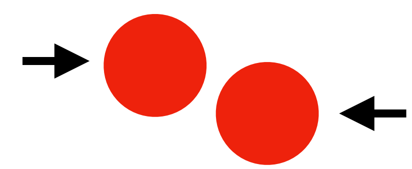
spin & “cold QCD” physics in their own right

from the <u>sPHENIX Beam Use Proposal 2022</u>

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}

Year-3

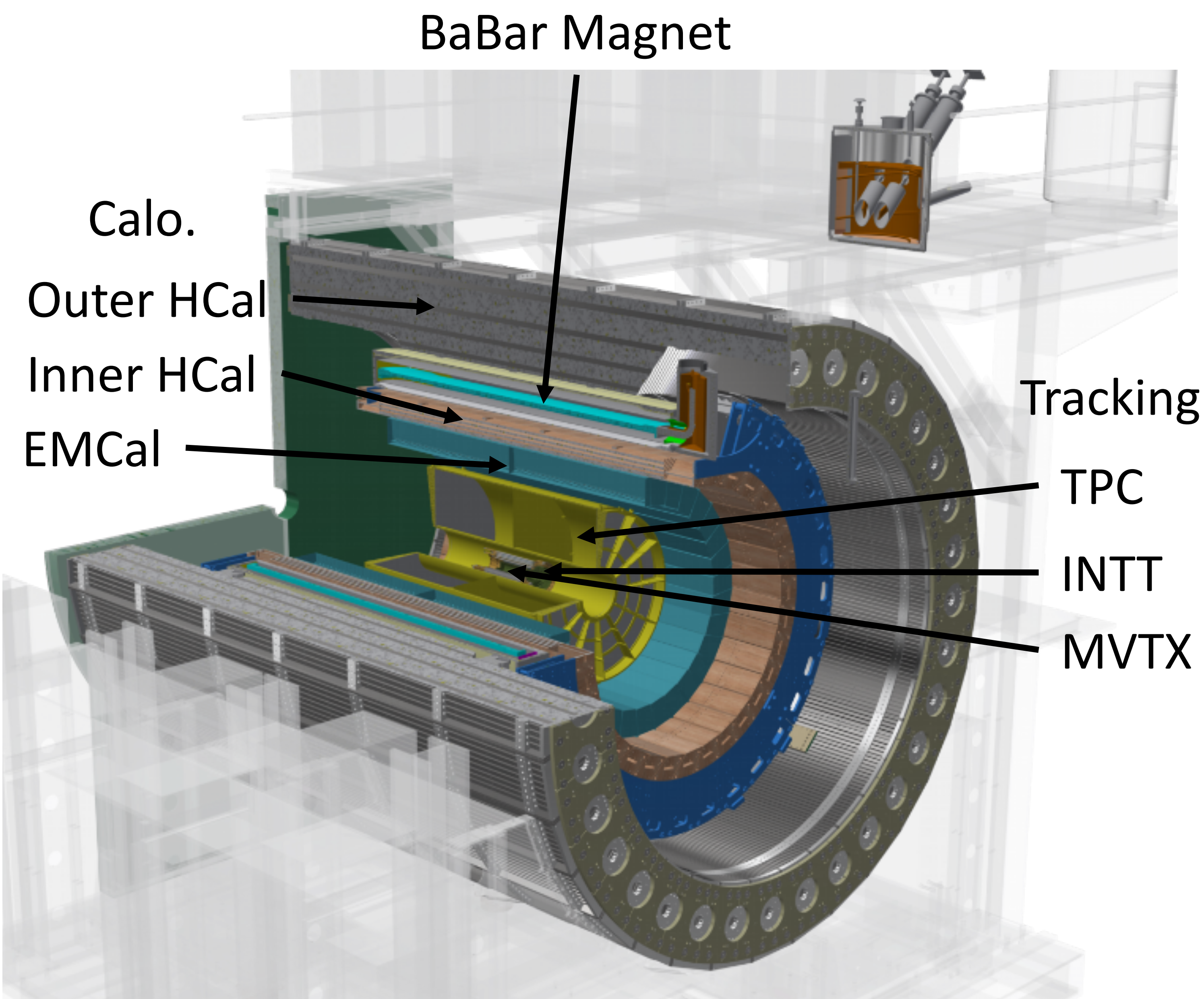


“Archival” high-luminosity Au+Au run

>140 **billion** fully min-bias Au+Au events(*) recorded to disk

(*) - |z| < 10cm, 28-cryoweek scenarios

sPHENIX detector



First run year	2023
$\sqrt{s_{NN}}$ [GeV]	200
Trigger Rate [kHz]	15
Magnetic Field [T]	1.4
First active point [cm]	2.5
Outer radius [cm]	270
$\lvert\eta\rvert$	$\leqslant$1.1
$\lvert z_{vtx}\rvert$ [cm]	10
N(AuAu) collisions*	1.43×10^{11}

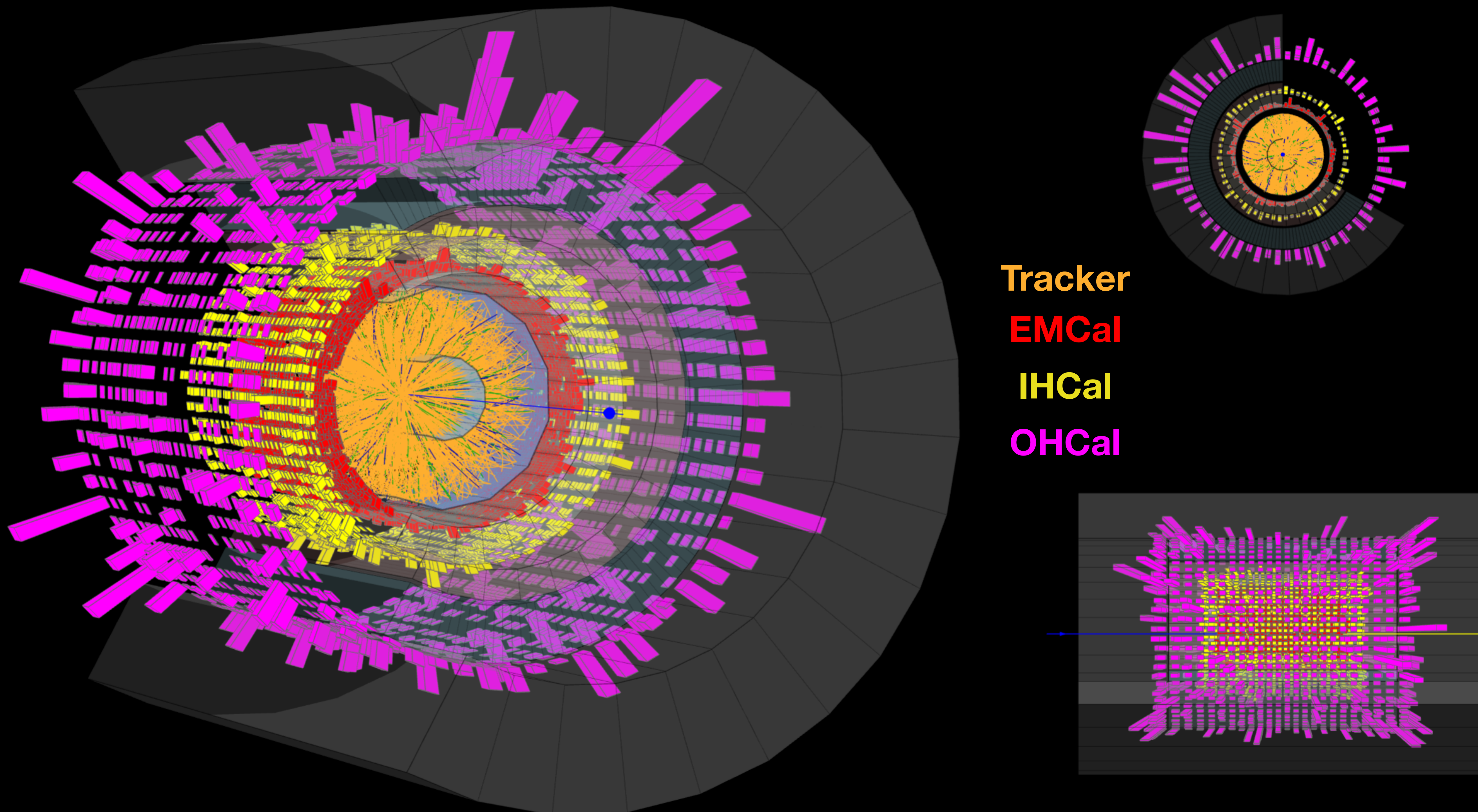
* In 3 years of running

Key sPHENIX advantages for hard probes at RHIC:

(1) large, hermetic acceptance, (2) huge data rate, (3) hadronic calorimeter, (4) precision tracking, (5) unbiased triggering


ABLE

GEANT4 simulation of Au+Au event in sPHENIX



➡ **Jet, HF, Quarkonia measurements happening in a large, fluctuating background with huge dynamic variations event by event!**

sPHENIX Collaboration

More than **360** members from **82** institutions in **14** countries as of 2022

- ➡ steady growth since collaboration formation with 40 institutions
- ➡ world-class expertise in physics, silicon, TPCs, calorimeter, electronics, computing, …

2016

Berkeley
TEMPLE UNIVERSITY
BERKELEY LAB

2017

PURDUE UNIVERSITY
cea

2018

FUDAN UNIVERSITY
IMP
SINAP
北京大学 PEKING UNIVERSITY

2019

UNC GREENSBORO
U. Sao Paolo
NCU, Taiwan
SEJONG UNIVERSITY
Florida AMU
LUND UNIVERSITY
PUSAN NATIONAL UNIVERSITY

Institutions joining after CD-0

2020

國立臺灣大學 National Taiwan University

2021

HANYANG UNIVERSITY
財團法人資訊工業策進會 INSTITUTE FOR INFORMATION INDUSTRY

RBRC Workshop - theorists welcome!

Home | Registration | Agenda | Logistics | Join Remotely | Contact Us

Motivation

This workshop will be a hybrid event and is not open to the public.

To complete the RHIC mission, sPHENIX was specifically designed to measure jet and heavy-flavor observables with a level of precision not previously achievable at RHIC. This will enhance our understanding of the quark-gluon plasma (QGP) properties and their temperature dependence beyond what is possible with existing and planned data from the LHC and other RHIC experiments.

A major goal of the sPHENIX program is to address the question of the approach to thermalization of the quark-gluon plasma and its transport properties using hard probes such as jets and heavy flavor. The current three-year run plan includes Au+Au, p+Au and p+p collisions at 200 GeV. The Au+Au dataset provides a large QGP system to study the QGP properties. The p+Au dataset will allow for additional studies of the intriguing behavior observed in flow measurements from other RHIC experiments as well as transport properties of cold QCD matter and proton/nuclear structure. The p+p collisions provide a necessary reference for Au+Au and p+Au collisions and also allow for additional studies of proton structure. Anticipated measurements include but are not limited to, jet substructure observables, photon and heavy flavor tagged jets as well as comparisons of the production of the different upsilon states in all three collision systems.

Important Dates

April 20, 2022	General registration opens
June 7, 2022	Registration closes
June 7, 2022	Additional guest registration for non-U.S. citizens closes

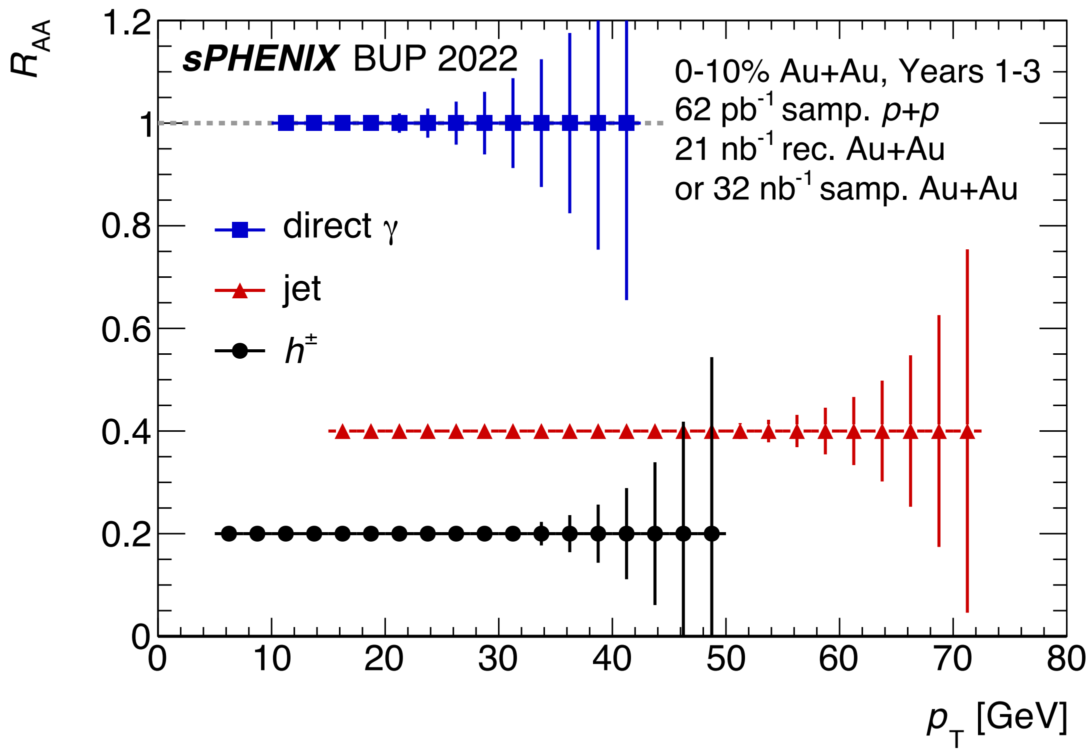
Workshop Information

Dates: July 20–22, 2022
Event ID: 0000004154

Workshop Venue
Brookhaven National Laboratory
Upton, NY 11973 USA

Meeting location and directions
Join the Event

Jet physics at sPHENIX



Signal	Au+Au 0–10% Counts	p+p Counts
Jets $p_T > 20$ GeV	22 000 000	11 000 000
Jets $p_T > 40$ GeV	65 000	31 000
Direct Photons $p_T > 20$ GeV	47 000	5 800
Direct Photons $p_T > 30$ GeV	2 400	290
Charged Hadrons $p_T > 25$ GeV	4 300	4 100

Table 4.1: Projected counts for jet, direct photon, and charged hadron events above the indicated threshold p_T from the sPHENIX proposed 2023–2025 data taking. These estimates correspond to the 28 cryo-week scenarios.

Large luminosity for inclusive R_{AA} measurements (*left*) and detailed study (*right*)

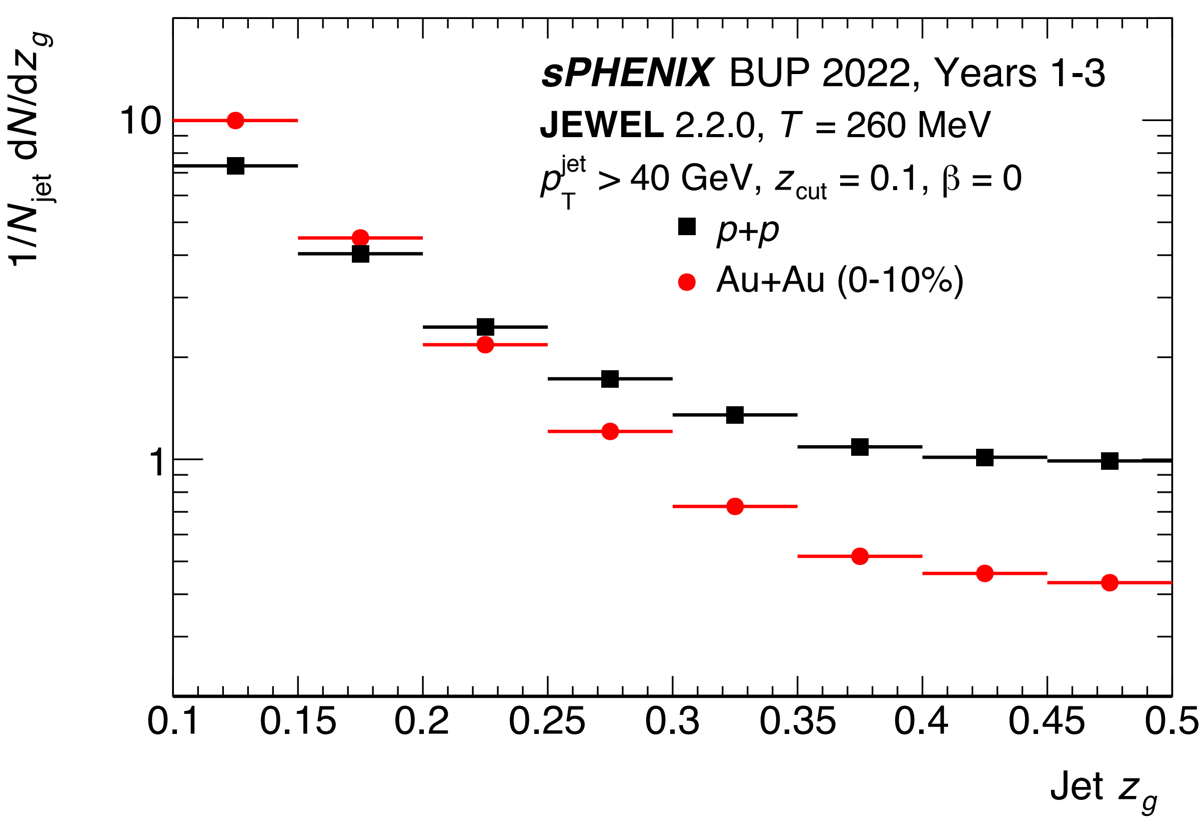
➡ **reconstructed jets** to ~70 GeV - fate of R_{AA} at very high p_T

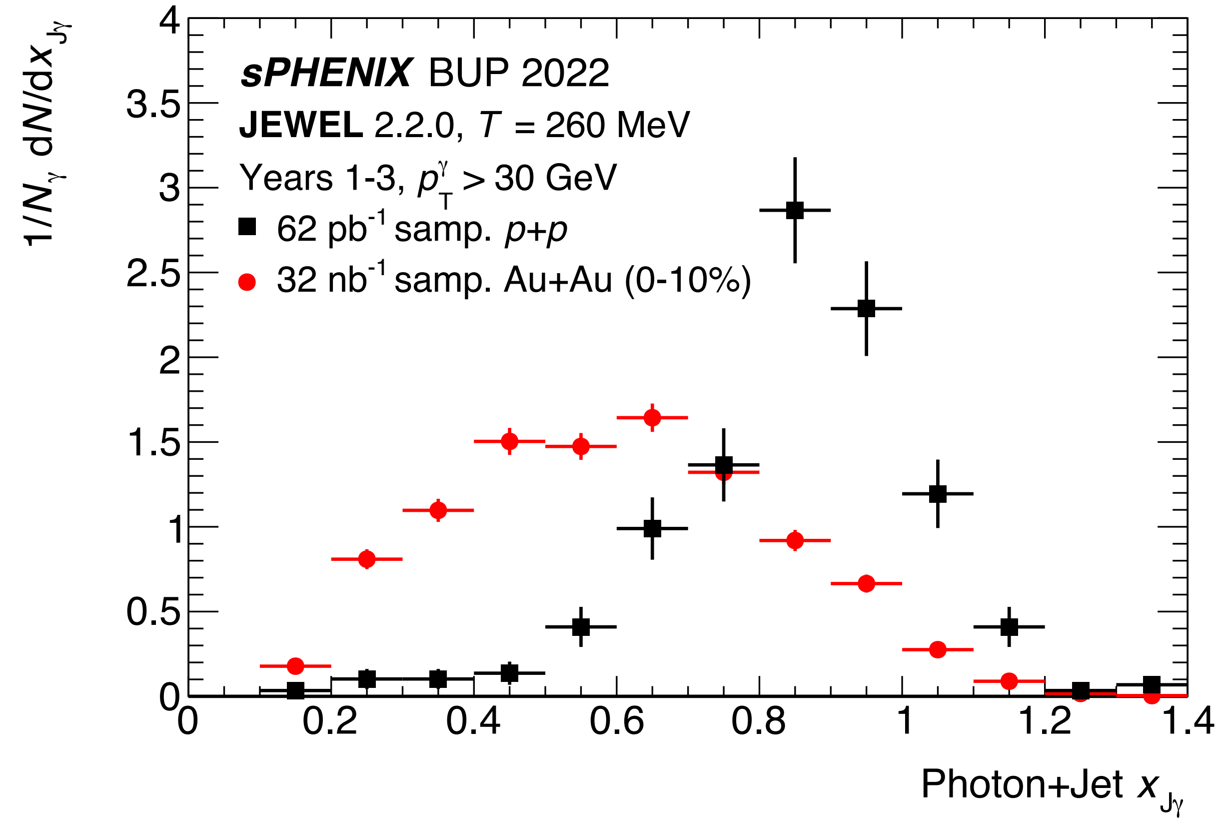
➡ **charged particles** to ~45 GeV - fragmentation functions out to high-*z*

➡ **direct photons** to ~40 GeV - precise check of nuclear geometry

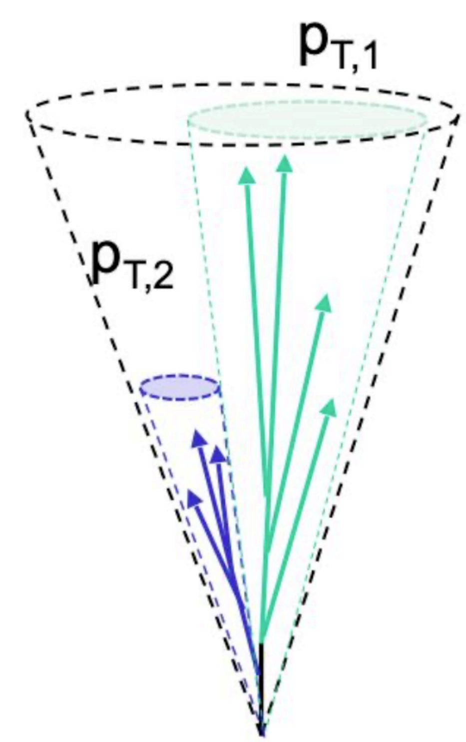
➡ high rate & unbiased triggering allows for true *p*+*p* baseline!

Jet physics: structure & correlations





Statistical projections for ***p+p*** and **0-10% Au+Au**



➡ *Left*: subjet fraction z_g for >40 GeV jets - very large yield for inclusive jet (sub-)structure - full variety of measurements limited only by our creativity!

➡ *Right*: γ+jet p_T balance mapped in *detail* (distribution of energy loss values, not just averages)

Why do this physics at RHIC,
rather than the LHC?

Two arguments from physics, and
two arguments from kinematics:

sPHENIX advantages: physics

1. Jet evolution closer to QGP medium scales - stronger interplay of parton shower with QGP degrees of freedom

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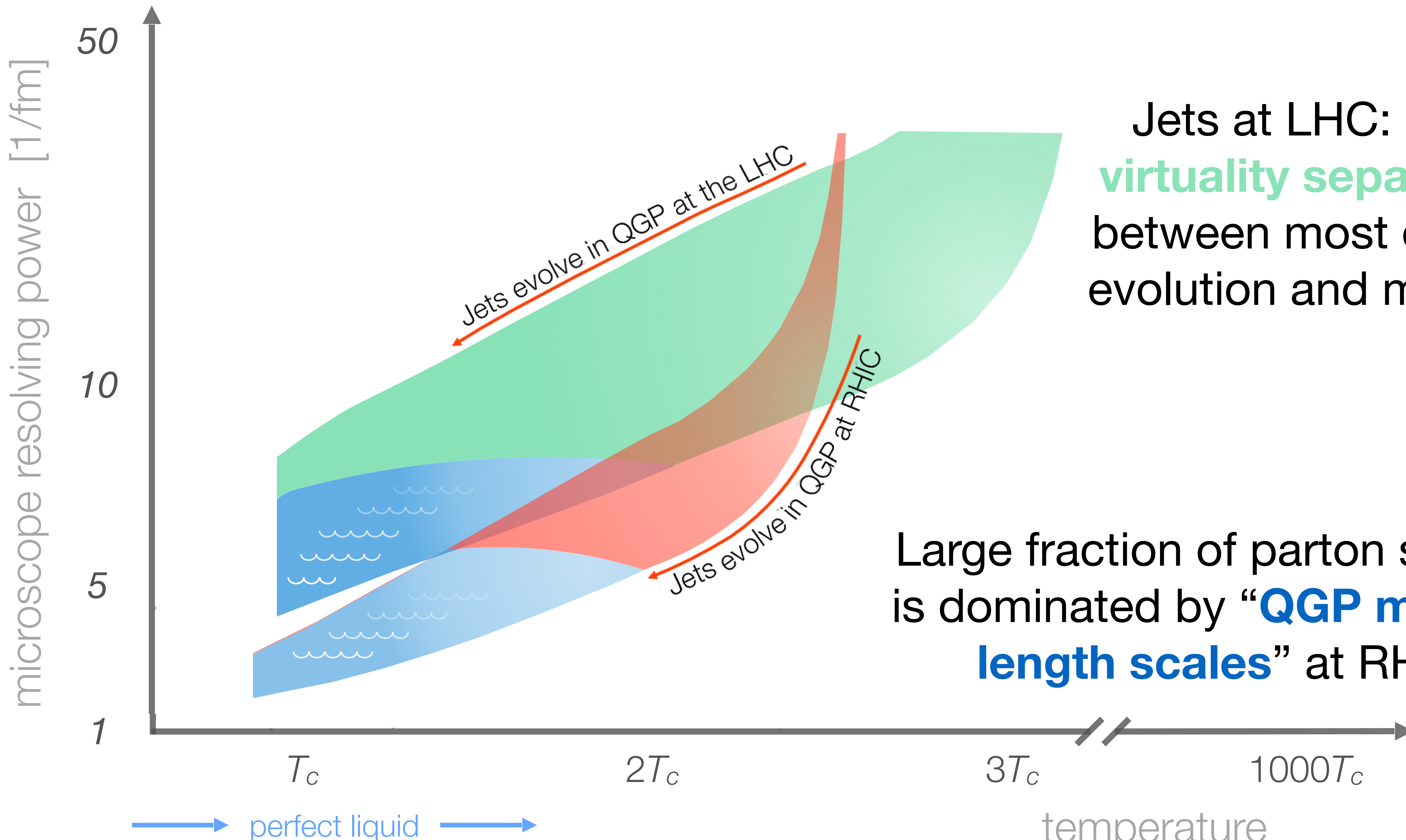

Jets at LHC: large **virtuality separation** between most of their evolution and medium

Large fraction of parton shower is dominated by "**QGP medium length scales**" at RHIC

sPHENIX advantages: physics

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2. Closer to QGP transition temperature - a more strongly-coupled, perfect liquid! (as seen in $\eta/s(T)$ extraction)

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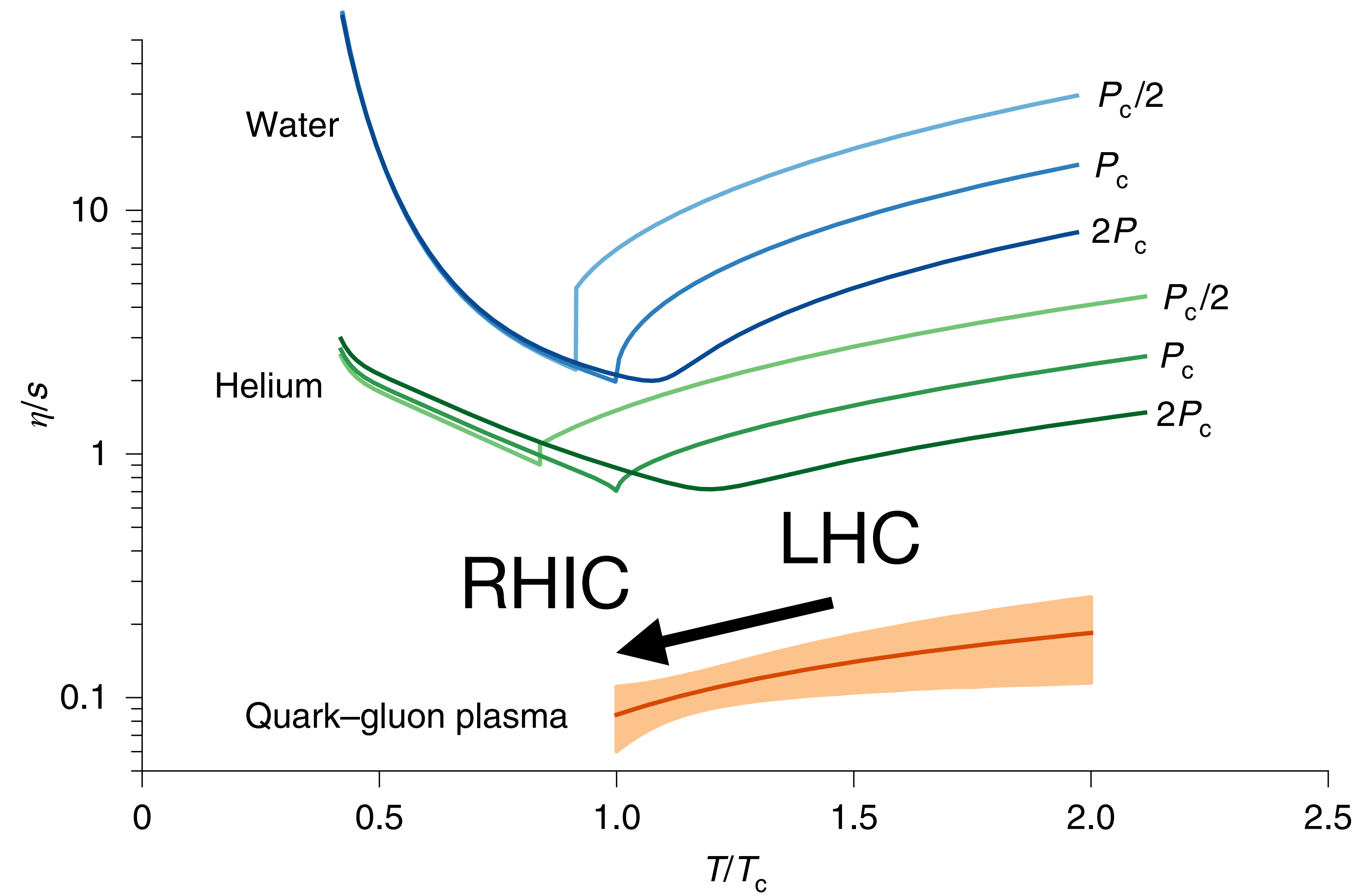

Nature Physics 15 (2019) 1113

sPHENIX advantages: kinematics

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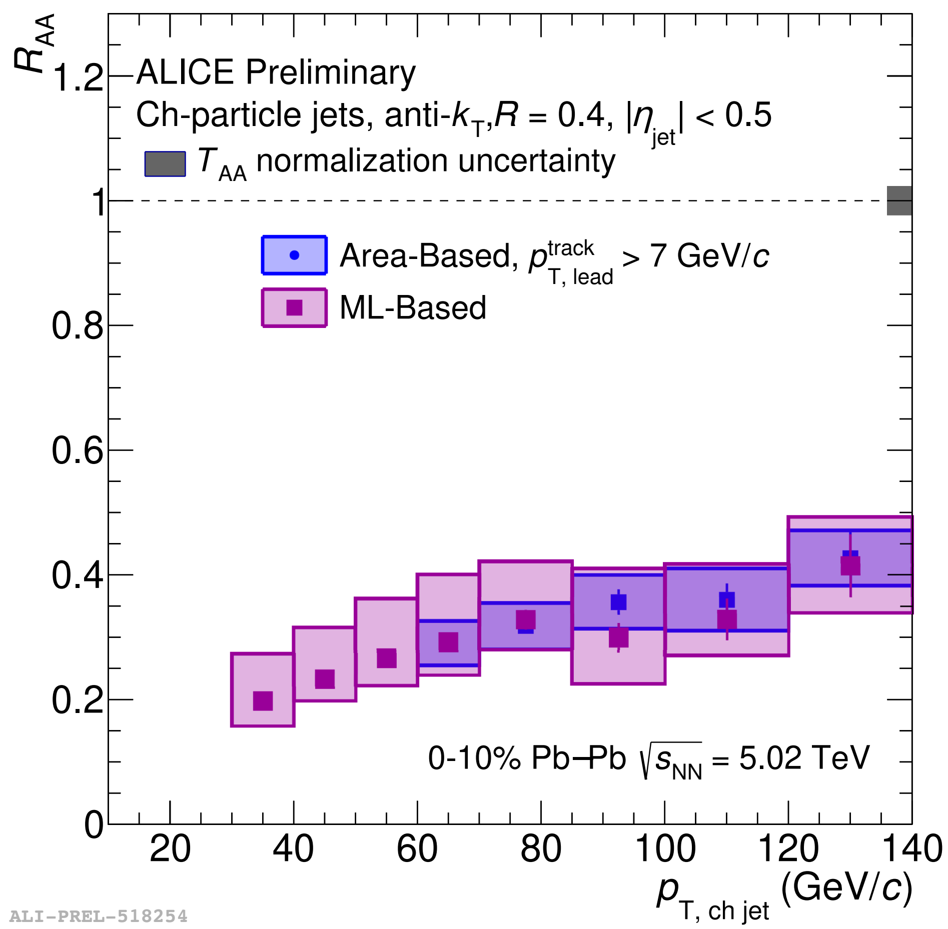

ALICE extending measurements to low jet-p_T using trained ML algorithm

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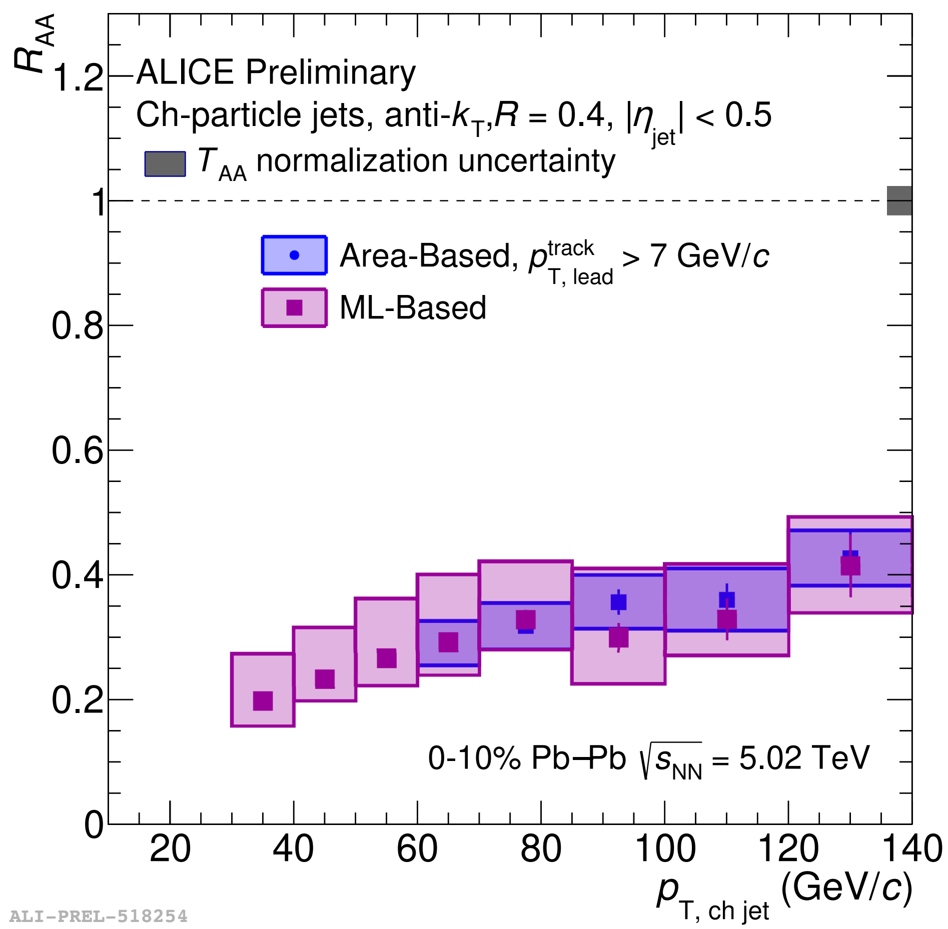

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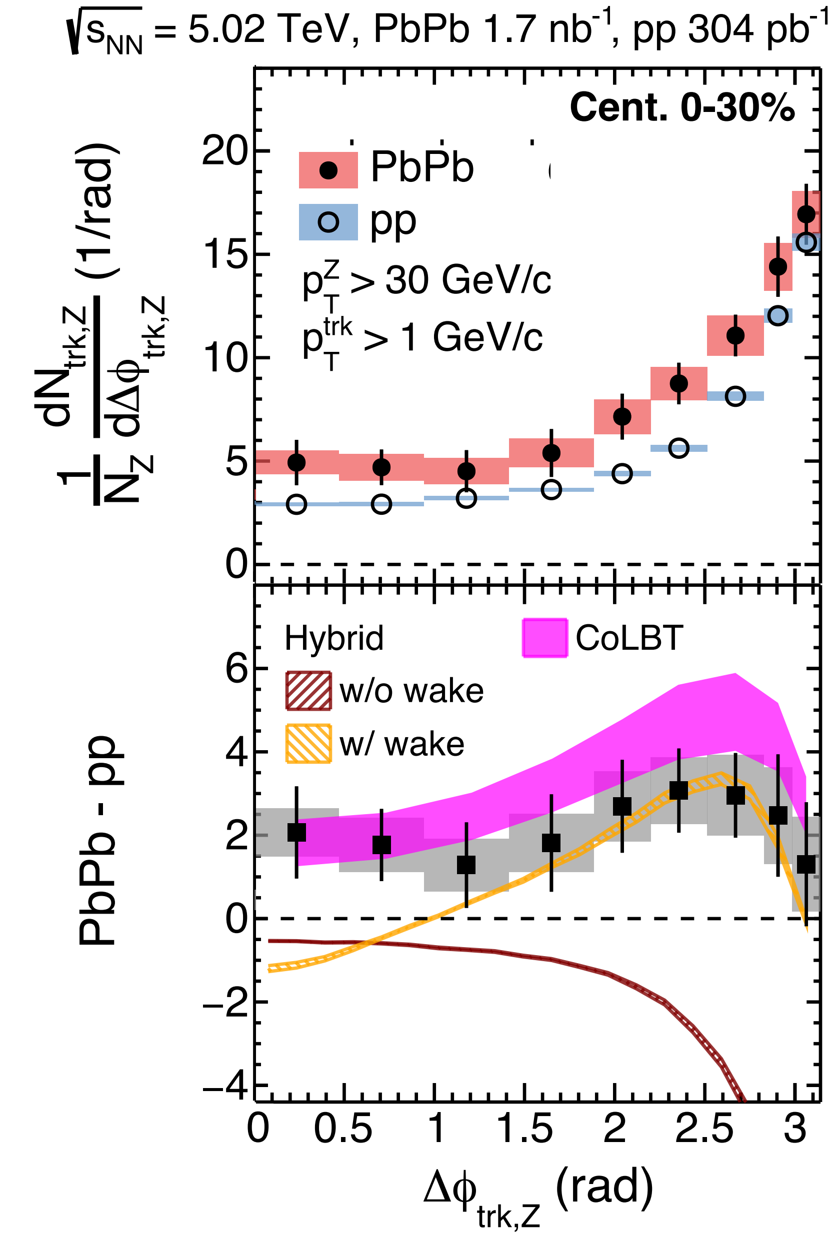

CMS, PRL 128 (2022) 122301

CMS Z-tagged hadron yields - sensitive to subtraction method & treatment of MPI!

(Yang et al, PRL 127 (2021) 082301)

sPHENIX advantages: kinematics

1. Softer underlying event - easier to measure low-p_T jets, medium response, etc.

2. Small phase space for Initial-State and Final-State Radiation (ISR & FSR) - fewer complicated multi-jet process and more “back-to-back” topologies

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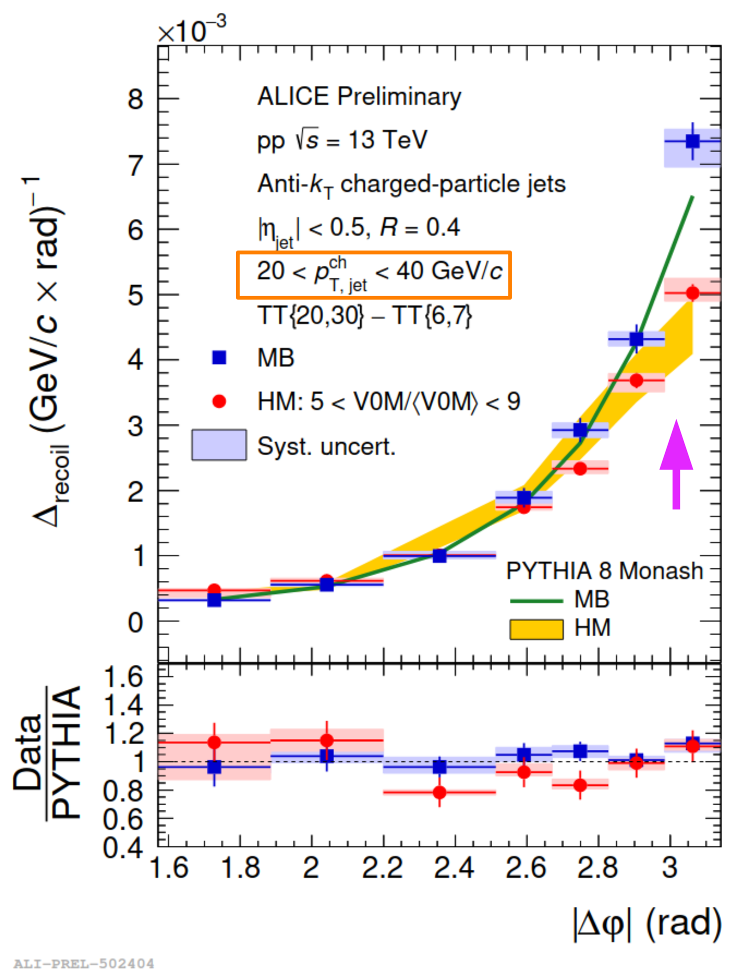

ALICE search for jet quenching in high-multiplicity p+p

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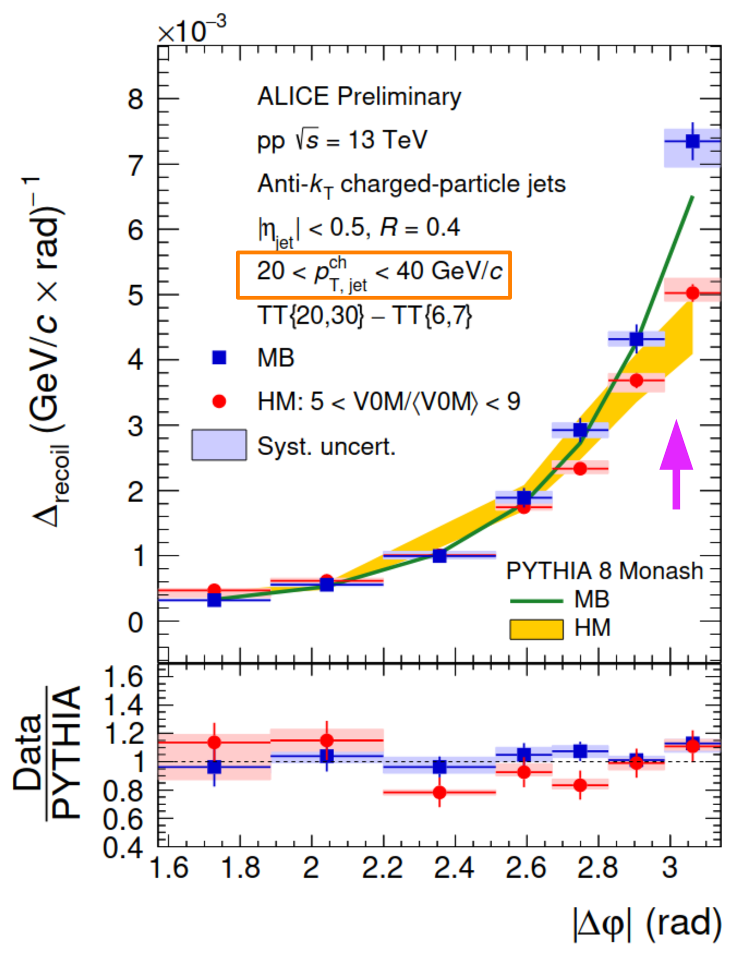

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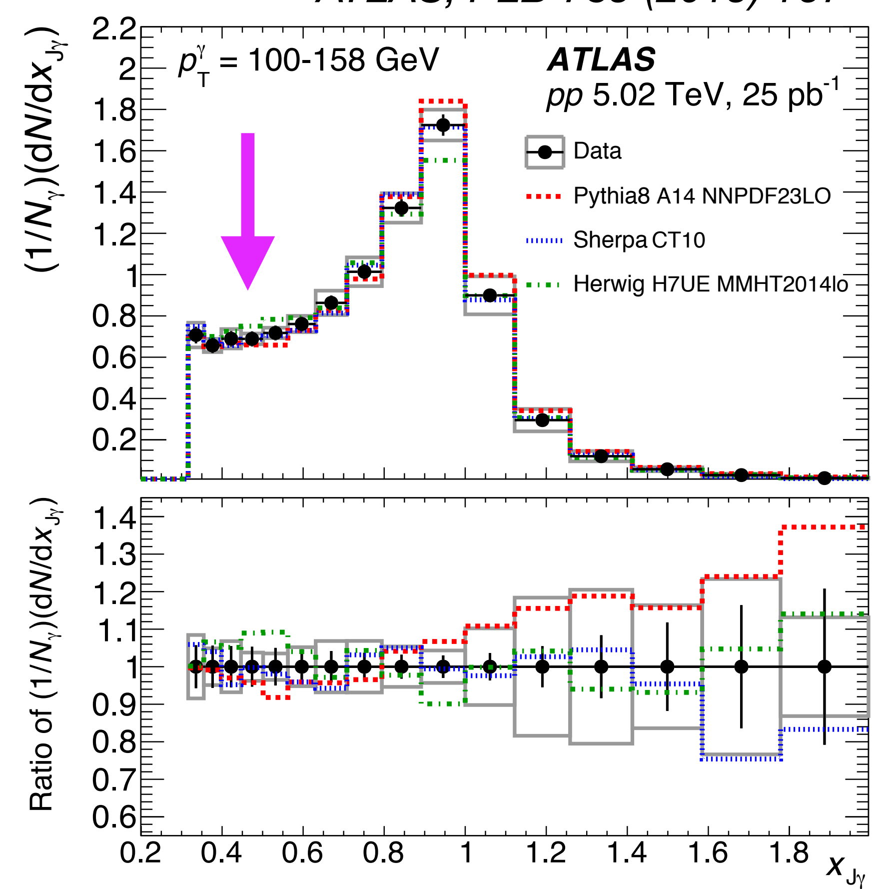
ATLAS, PLB 789 (2019) 167

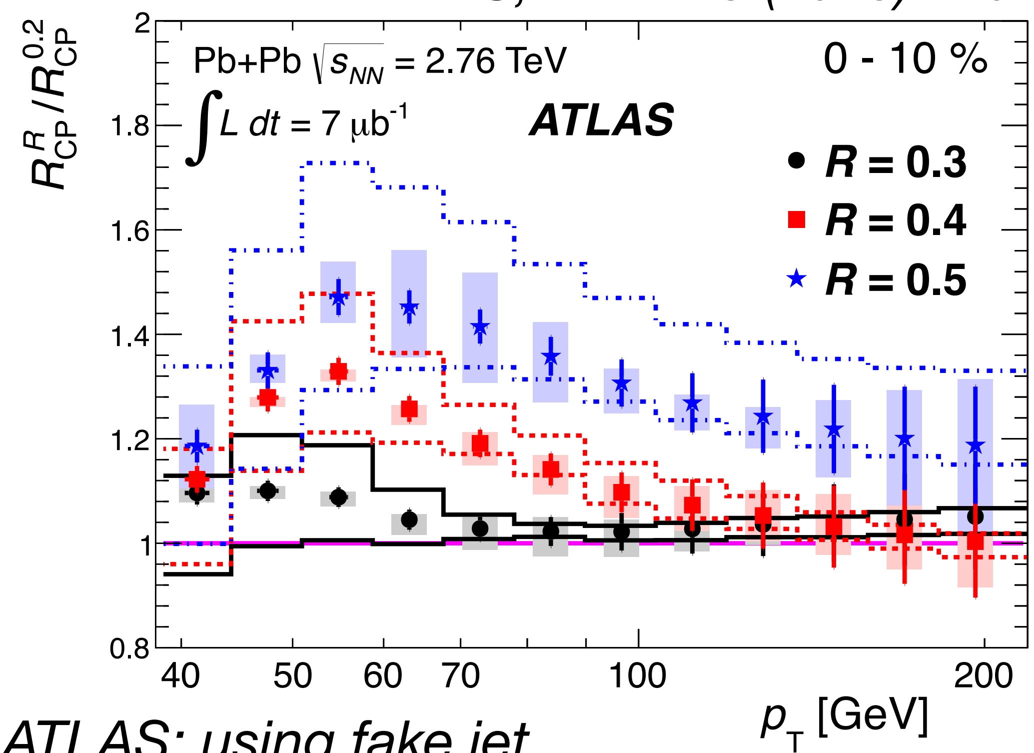


ATLAS photon+jet p_T balance baseline in p+p

Learning from the LHC

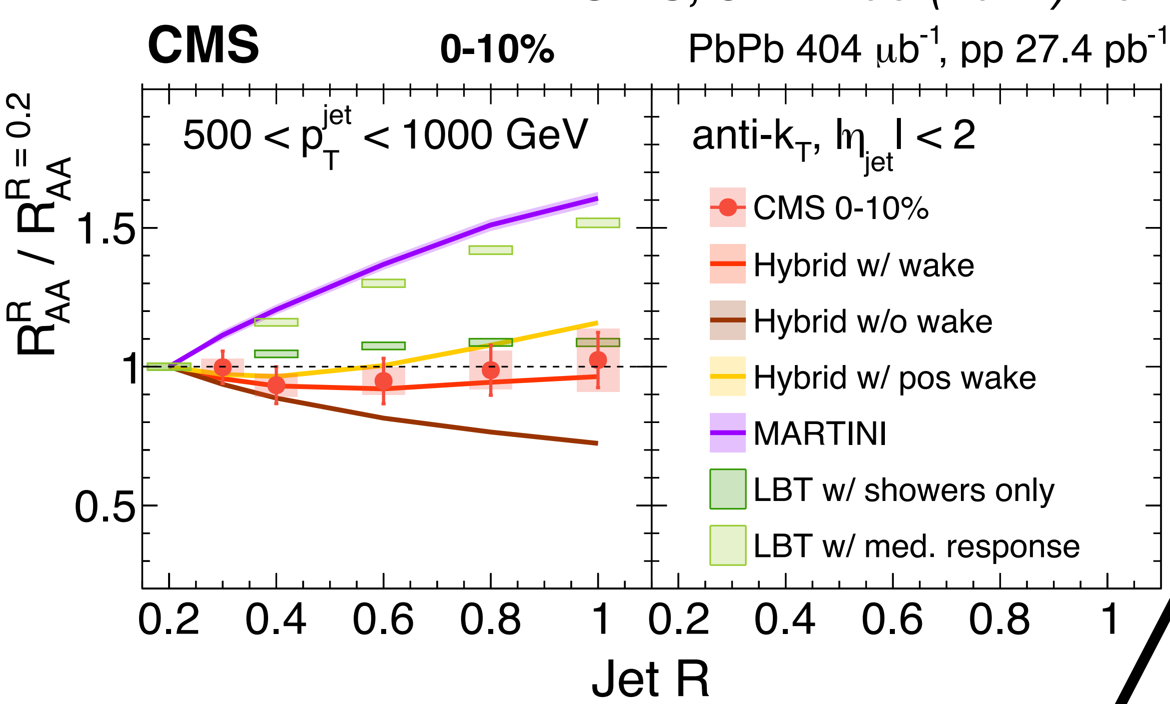
How suppressed are Large-*R* jets?

ATLAS, PLB 719 (2013) 220



ATLAS: using fake jet rejection, energy recovery(?)

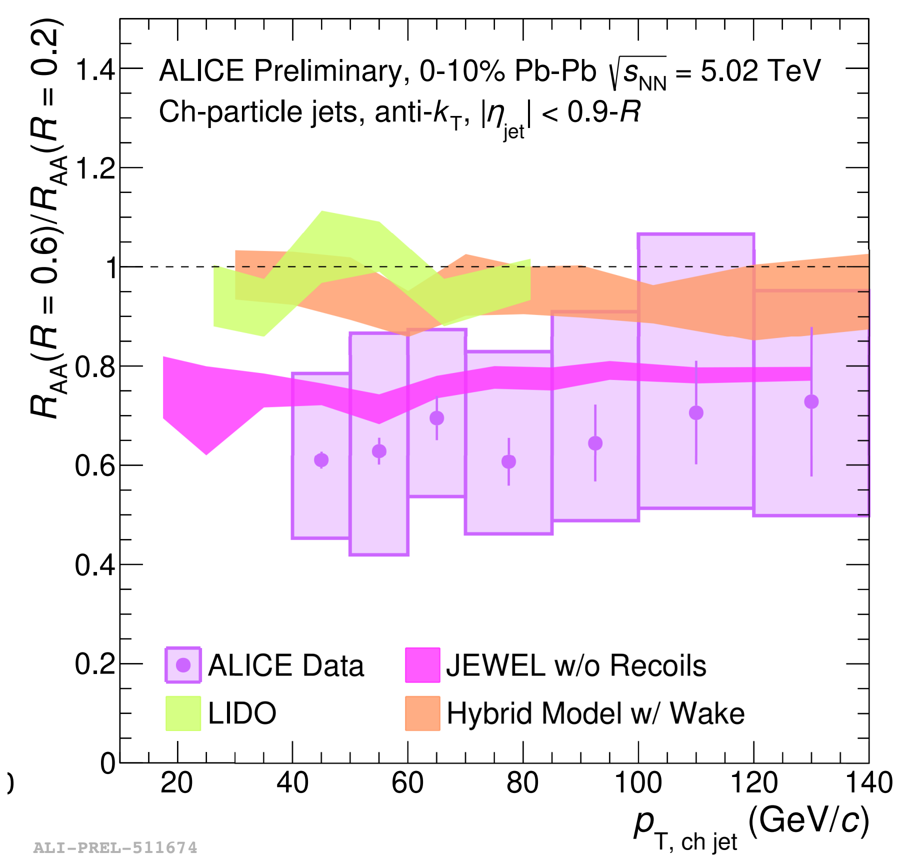
CMS, JHEP 05 (2021) 284



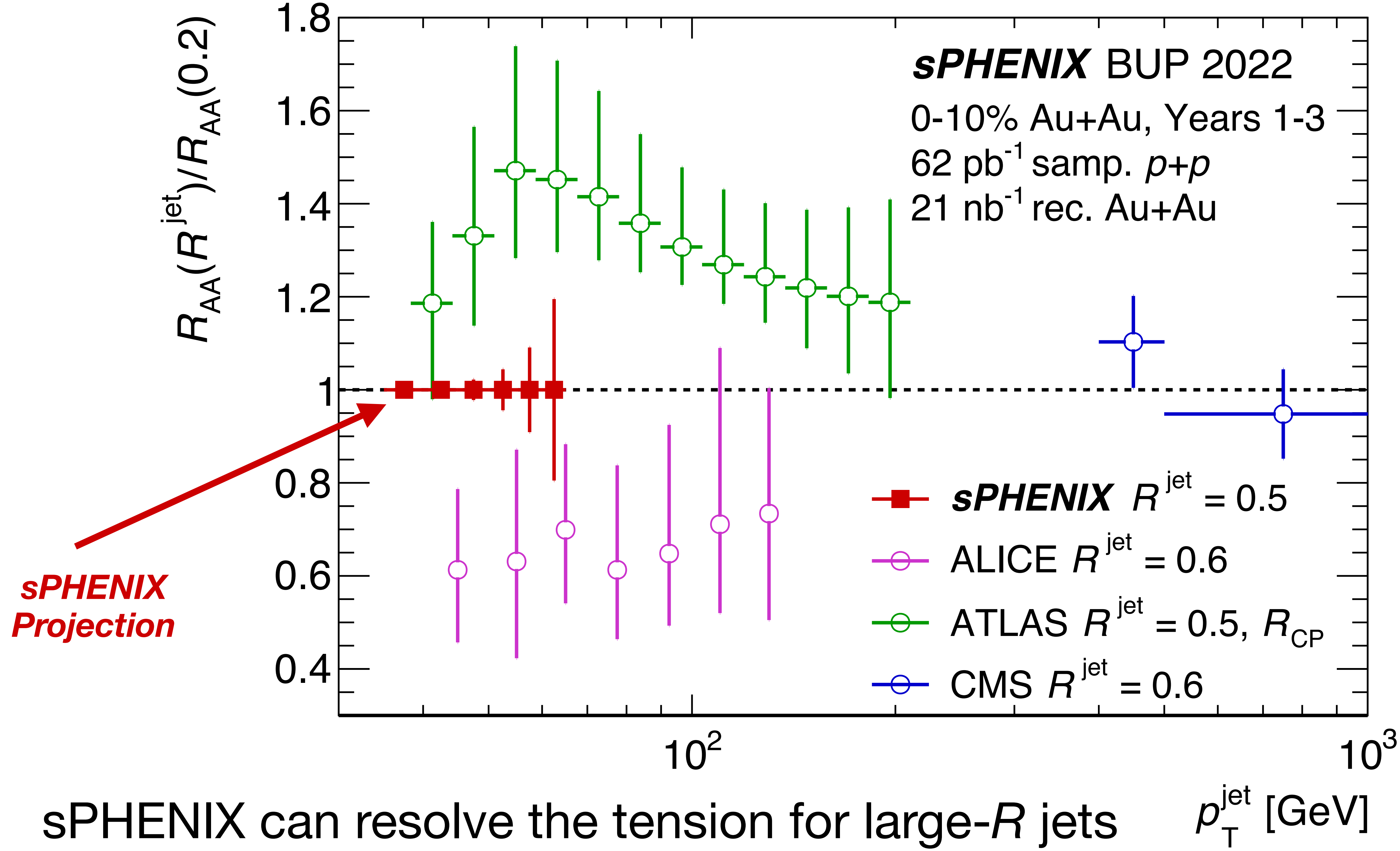
CMS: no cone size dependence at very high p_T

low p_T

ALICE: using ML-guided subtraction, continued narrowing(?)

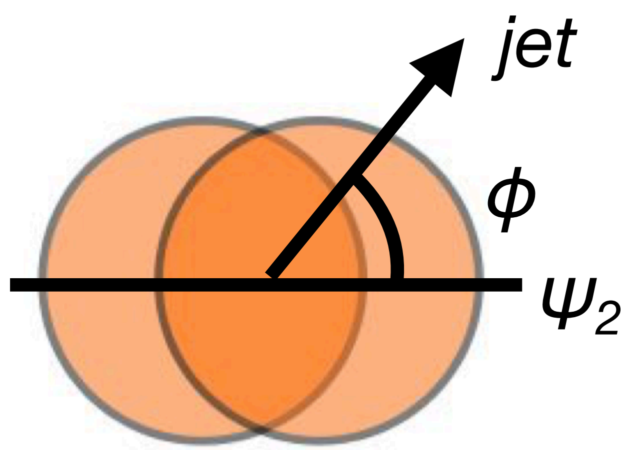


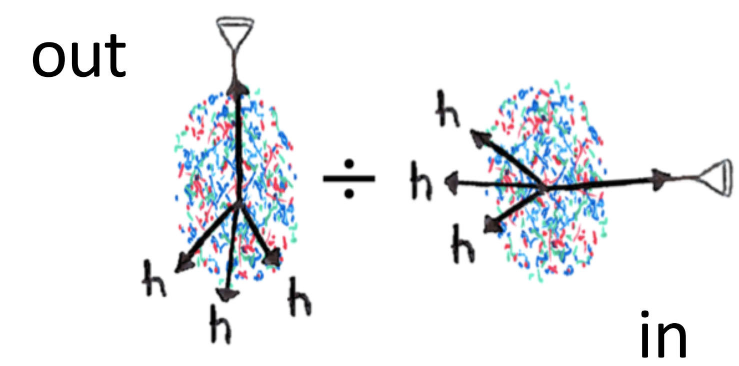
How suppressed are Large-*R* jets?

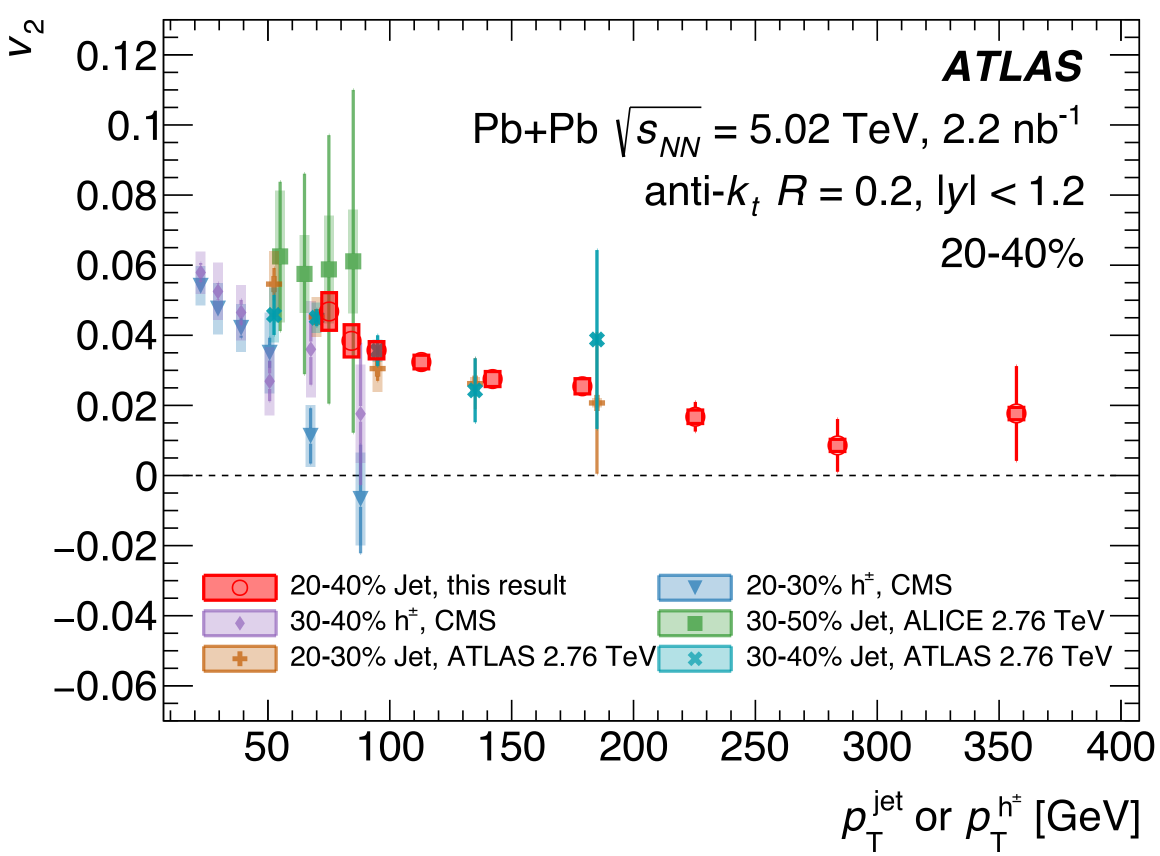


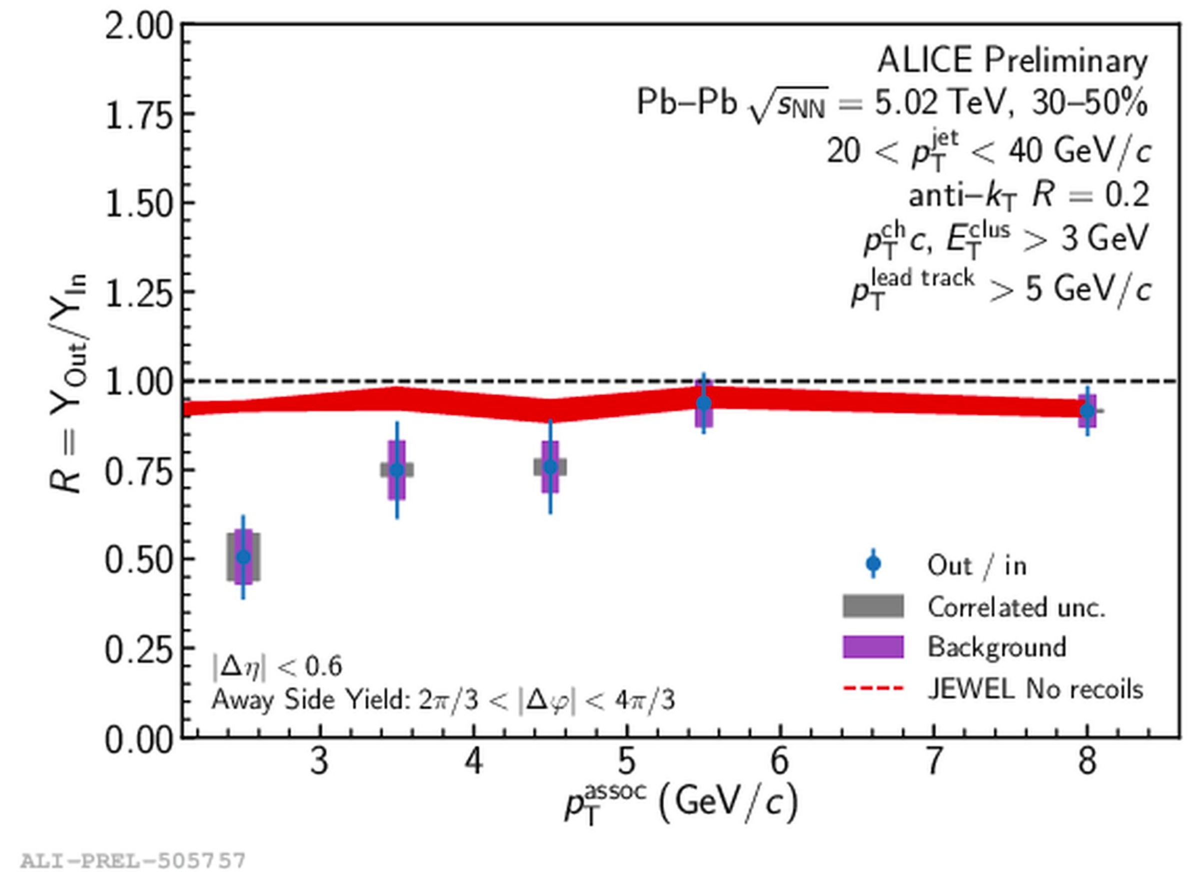
sPHENIX can resolve the tension for large-*R* jets at low p_{T}, without model dependent methods!

Do jets feel the shape of the QGP?







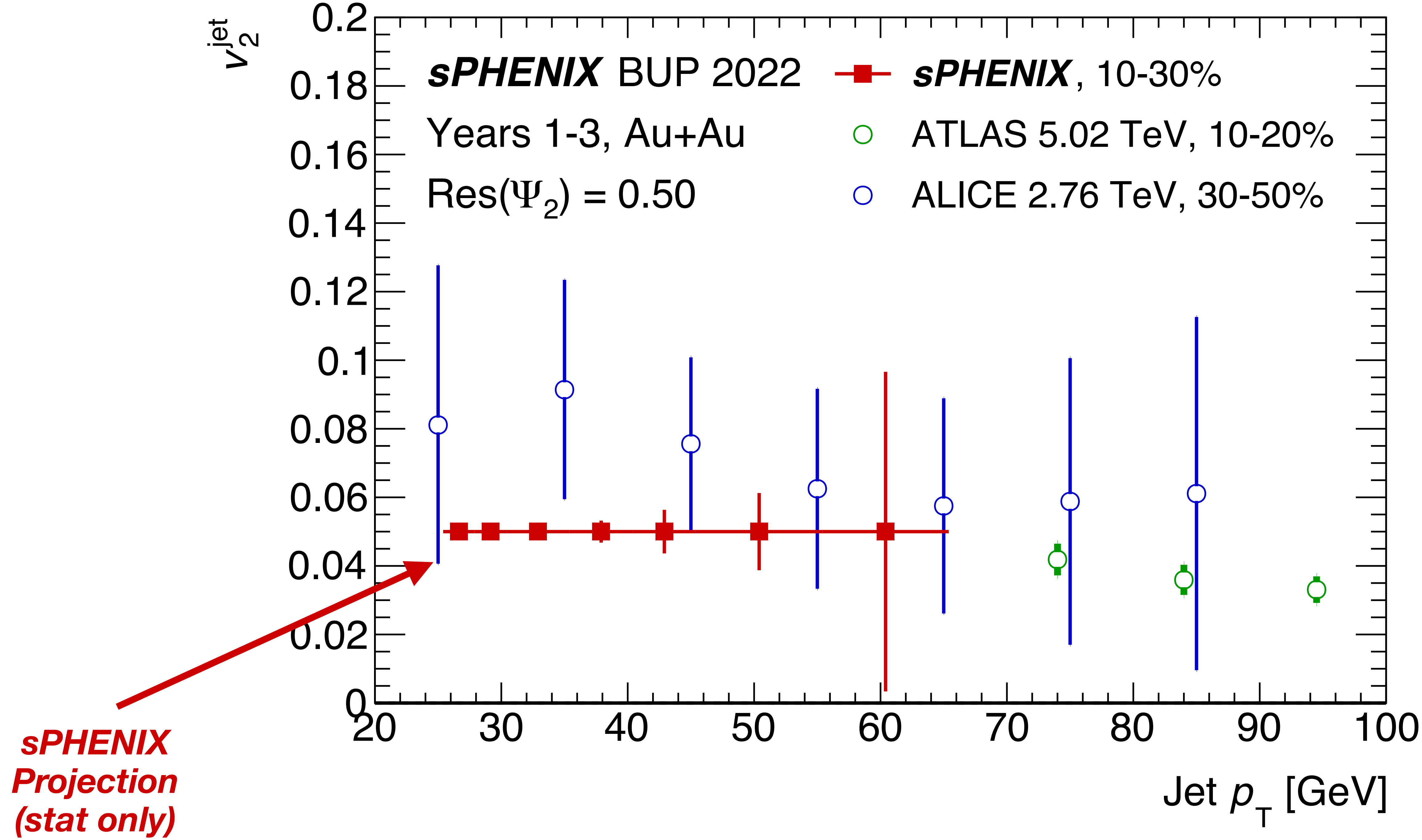


Difficult to measure for jets with p_T < 100 GeV at the LHC

ALICE: large, reaction-plane dependent change in fragmentation(?)

ATLAS, PRC 105 (2022) 064903

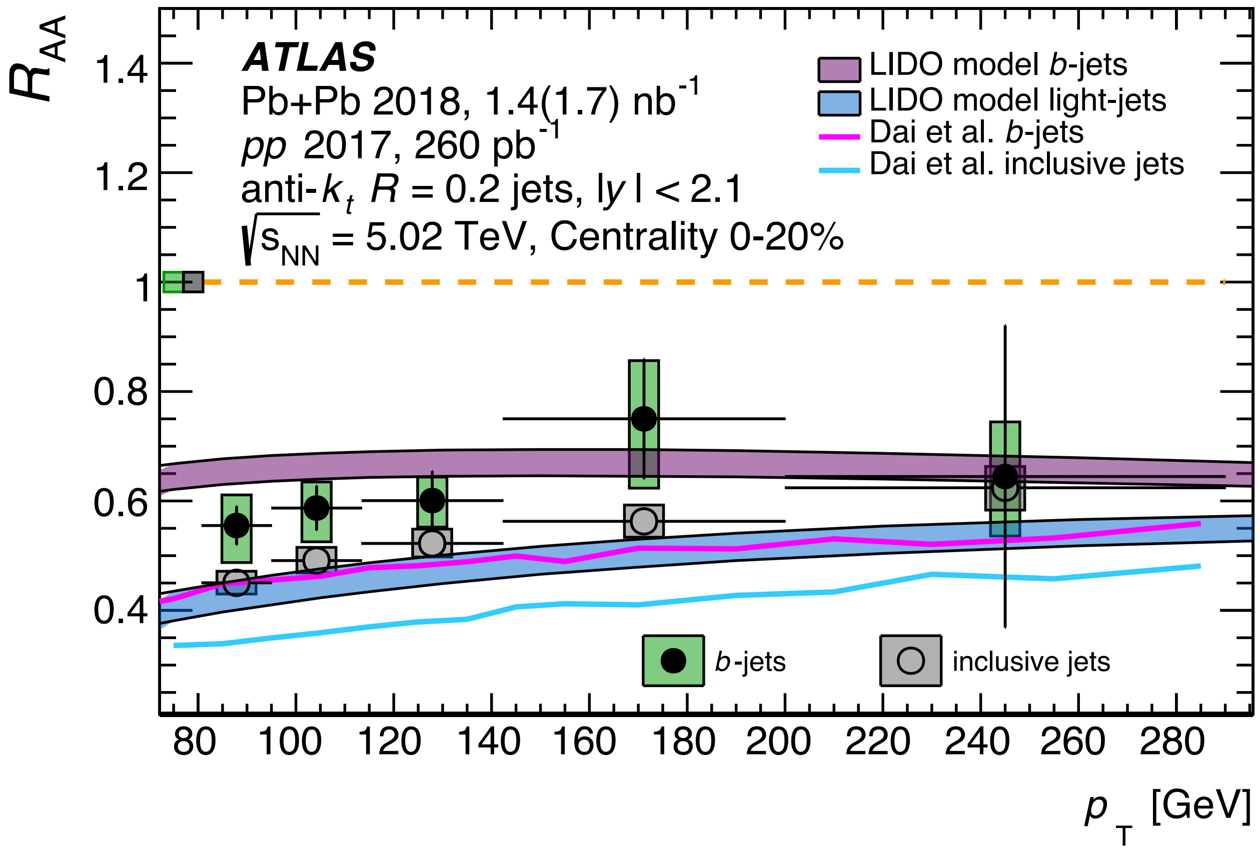
Do jets feel the shape of the QGP?

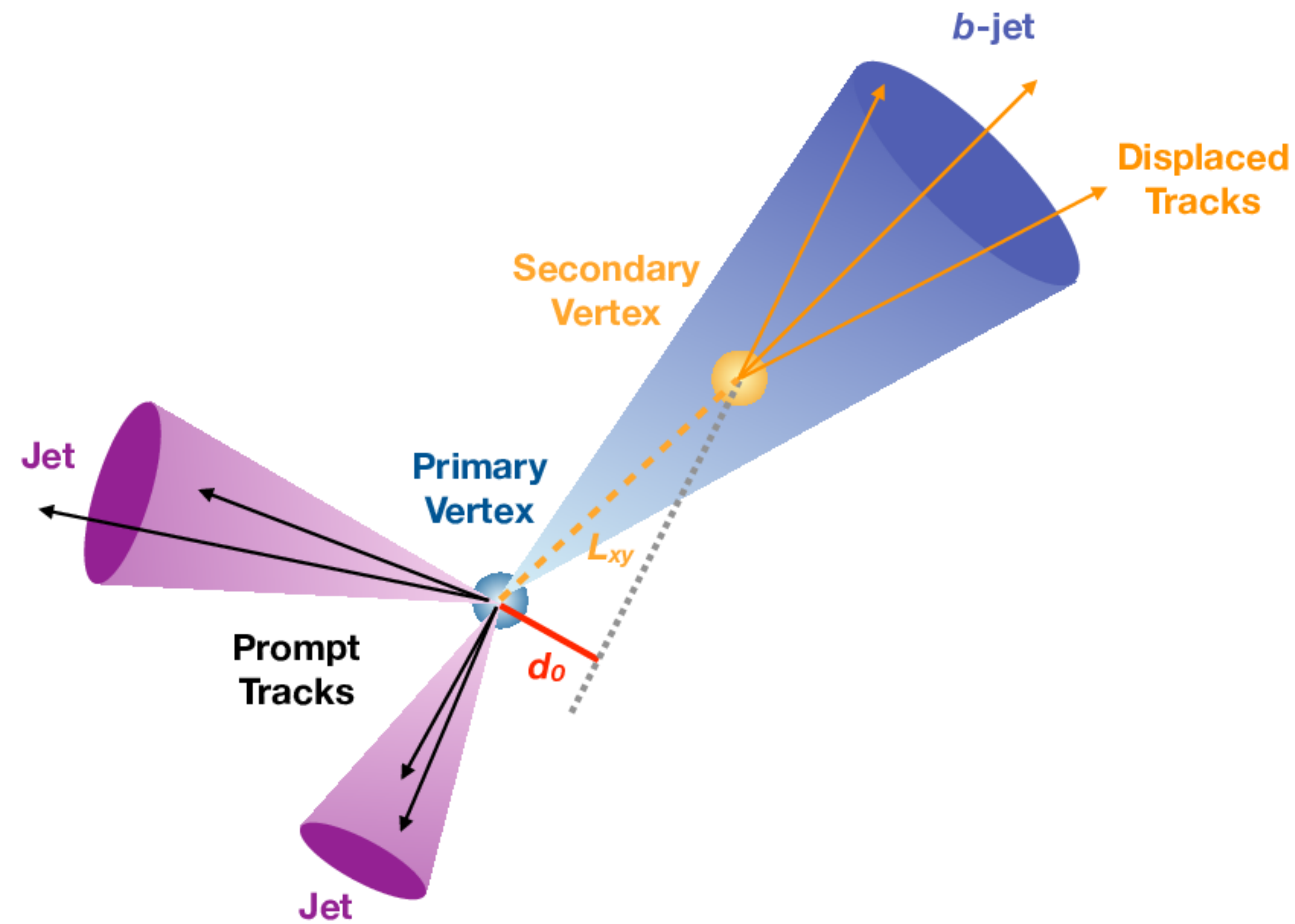


sPHENIX can study the $v_{2,3}$ for low-p_T jets with good control on event plane (no balancing jets in EP detector)!

What is the color & mass dependence?

nucl-ex/2204.13530





*ATLAS: fully **b-tagged jets**, less suppressed than **inclusive jets**?*

but note: p_T^{jet} >80 GeV(!)

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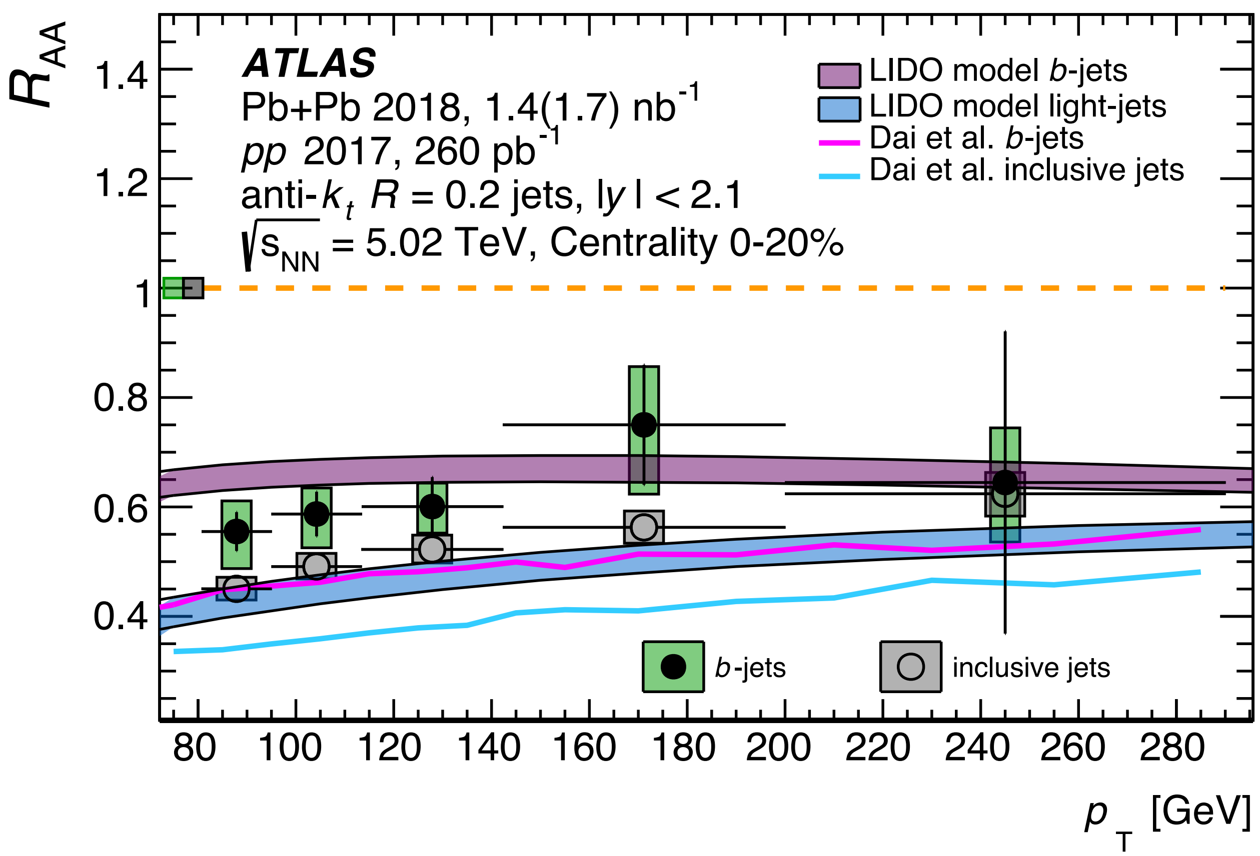
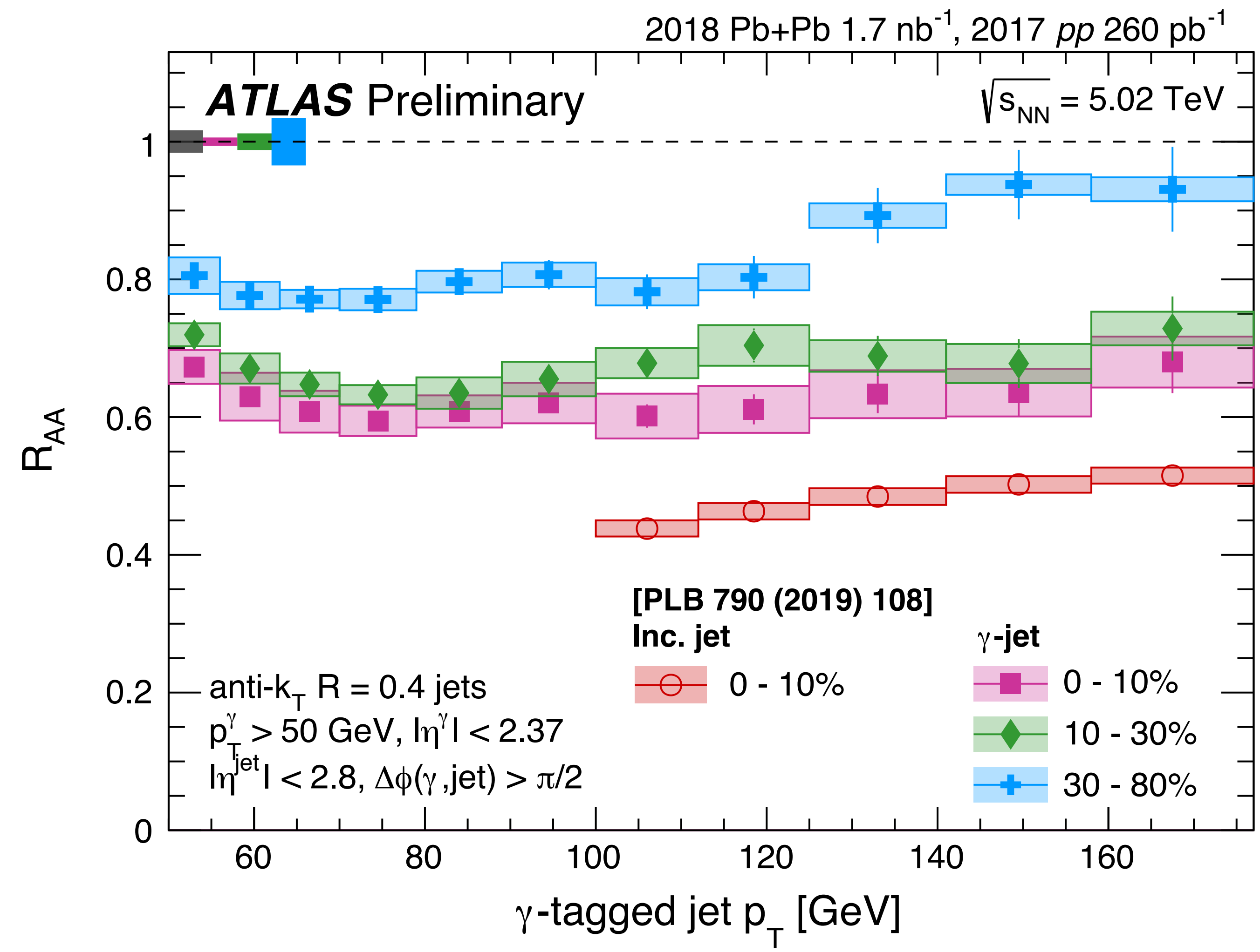


ATLAS-CONF-2022-019



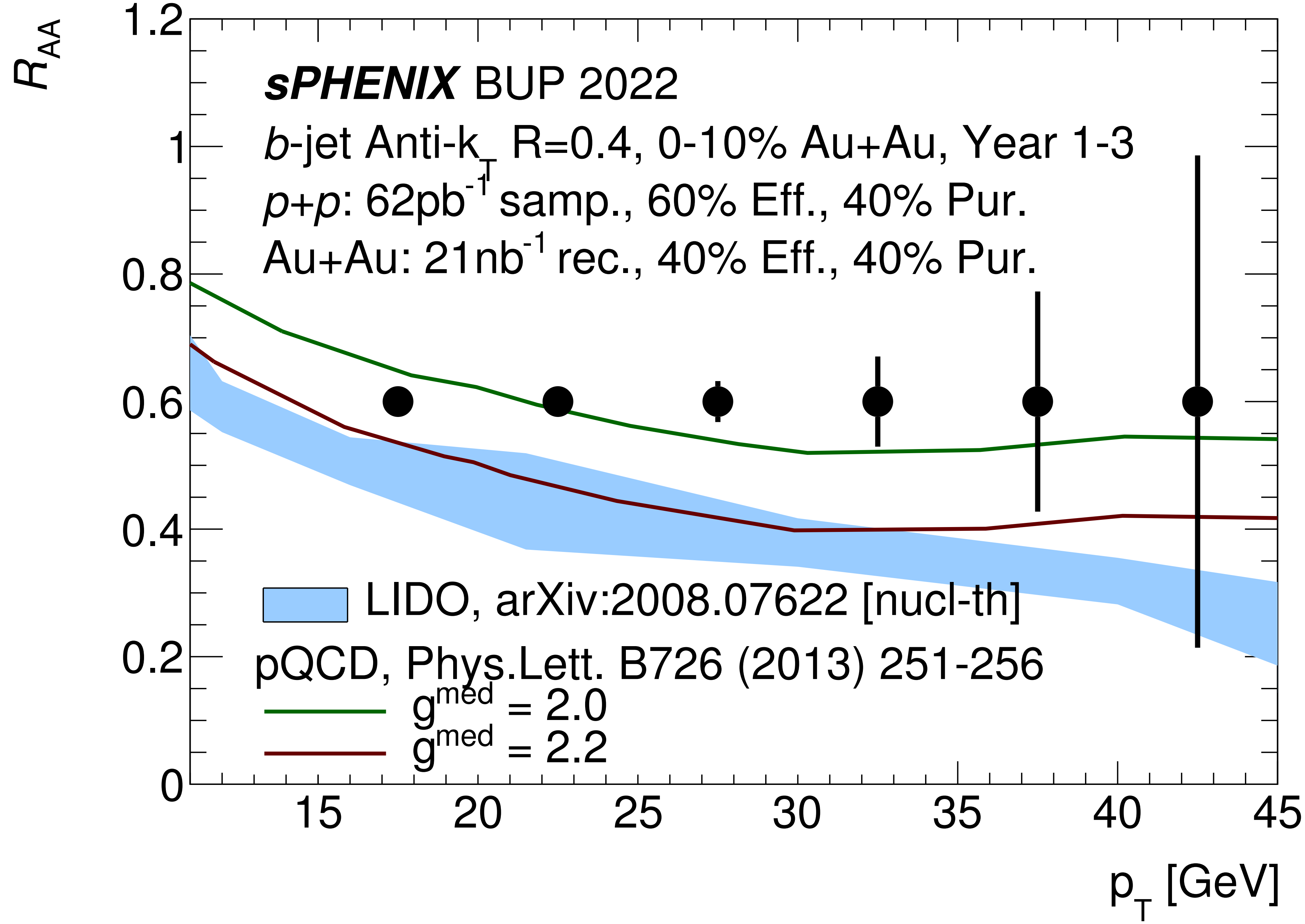
*ATLAS: fully **b-tagged jets**, less suppressed than **inclusive jets**?*

but note: p_T^{jet} >80 GeV(!)

… <u>or</u> is this just the color charge difference?

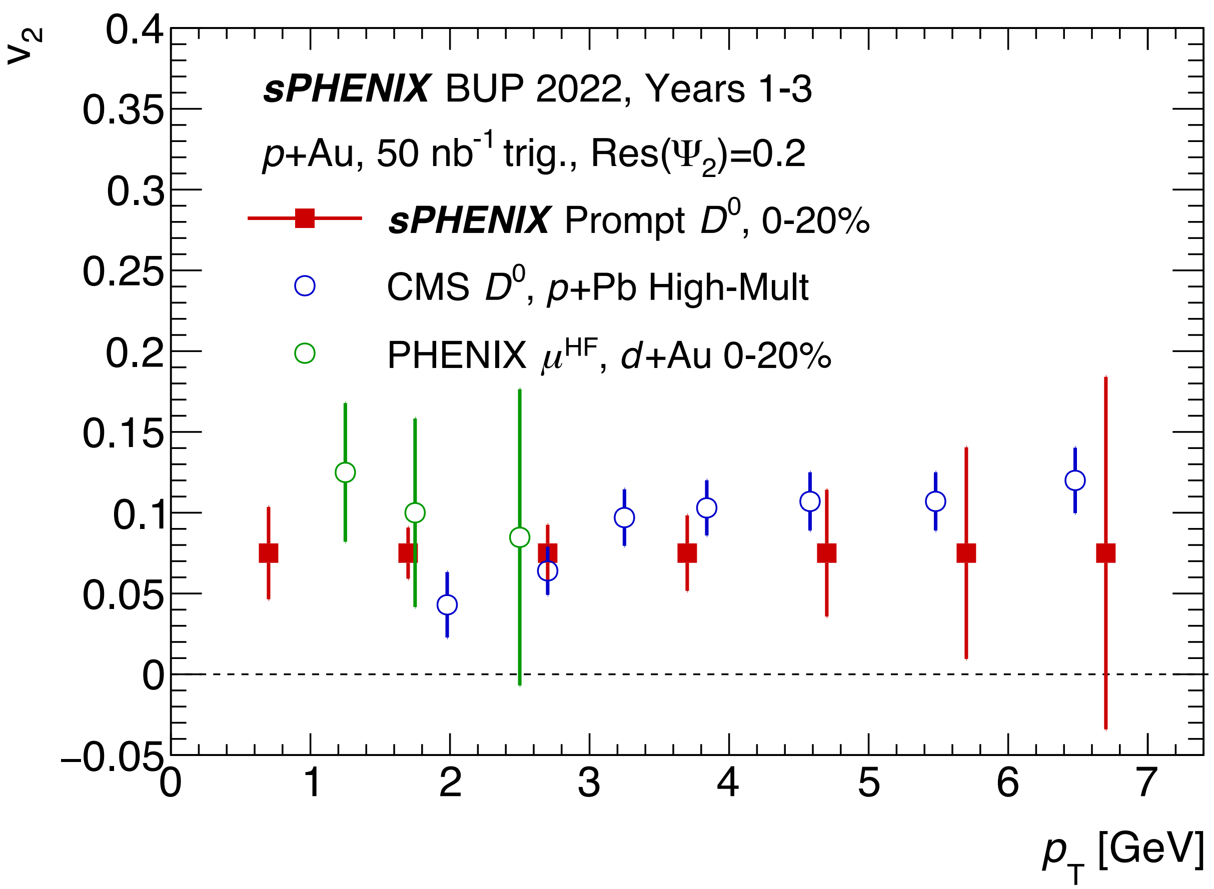
*ATLAS: **photon-tagged jets** have higher R_{AA} than **inclusive jets** - quarks have weaker parton-QGP interaction than gluons*

What is the color & mass dependence?

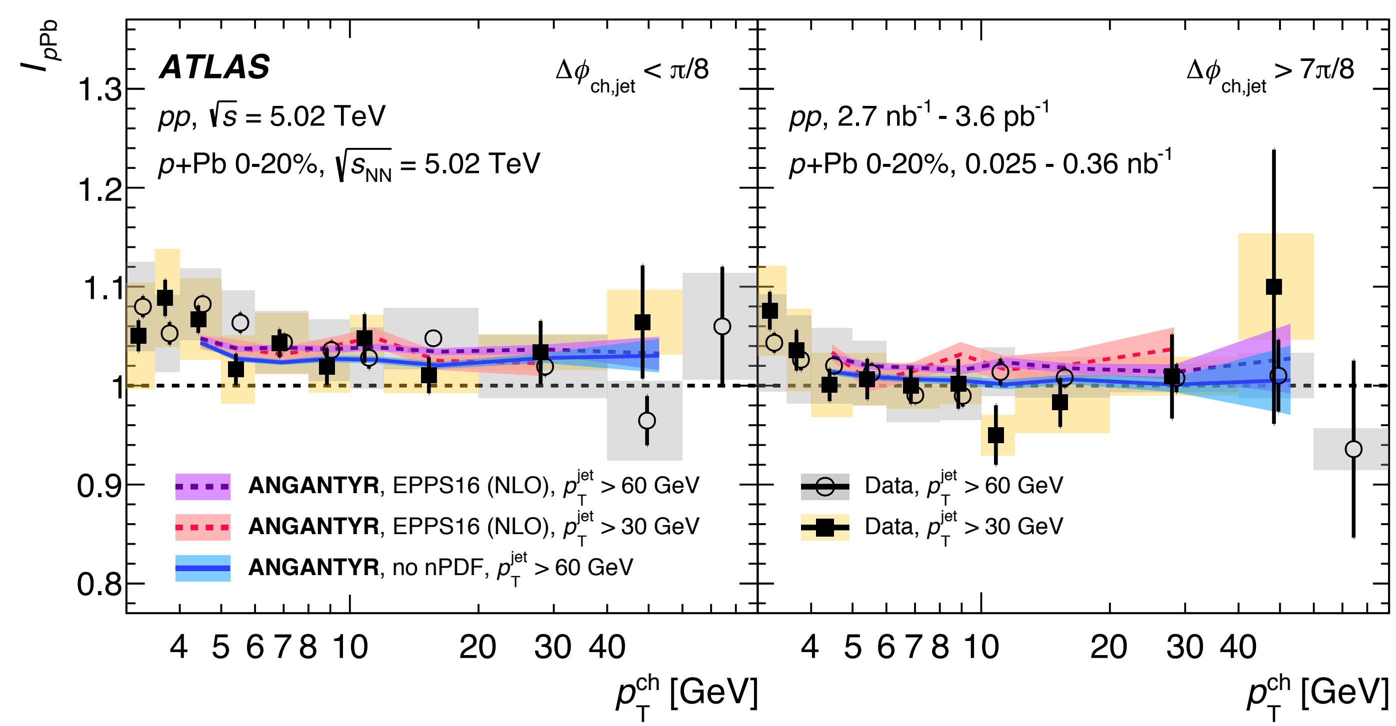


sPHENIX can measure fully b-tagged jets in a p_T region where the large *b* mass should have an impact!

Small system collectivity & jet modification?



nucl-ex/2206.01138



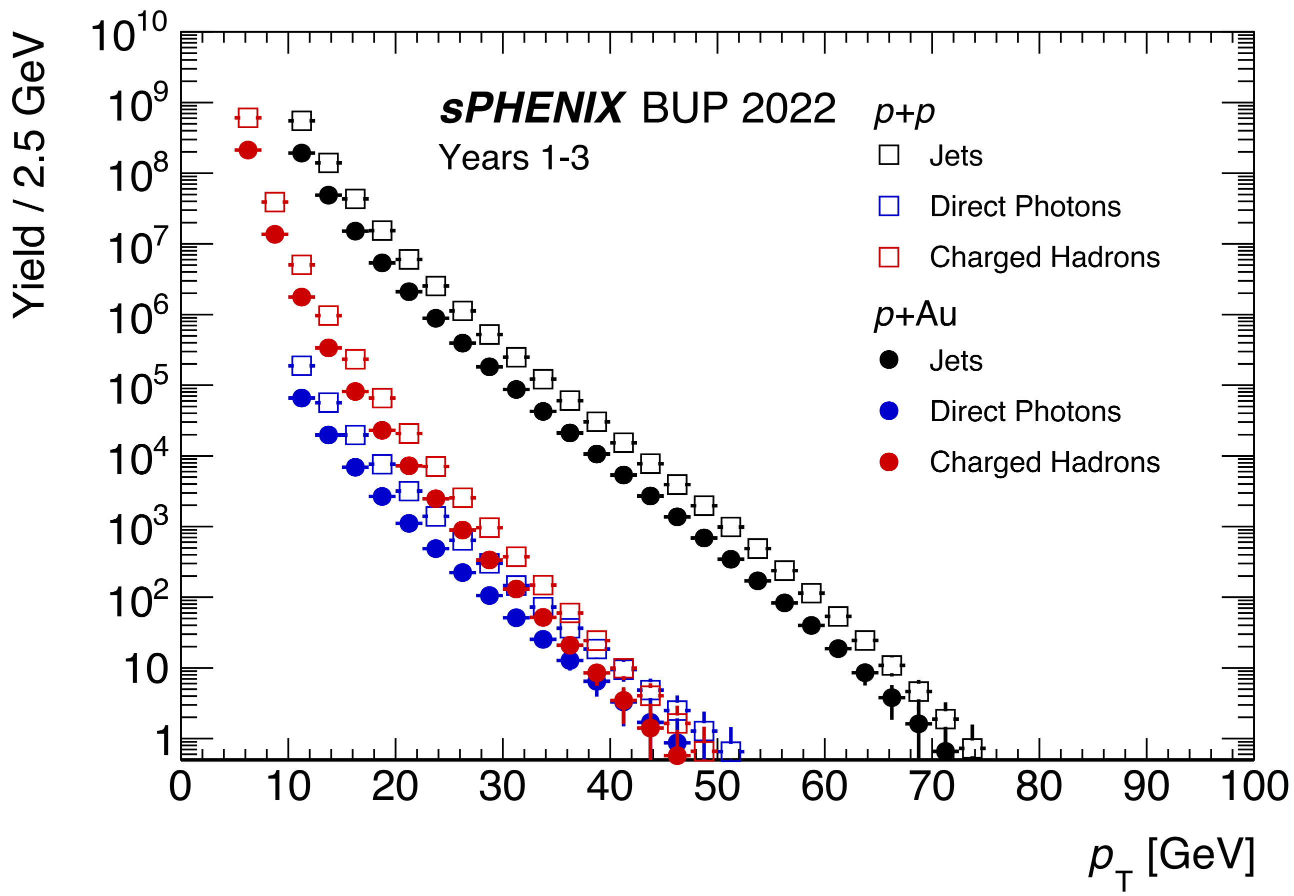
Streaming readout of sPHENIX trackers in p+Au allows for detailed study of multi-particle cumulants and (above) heavy flavor collectivity

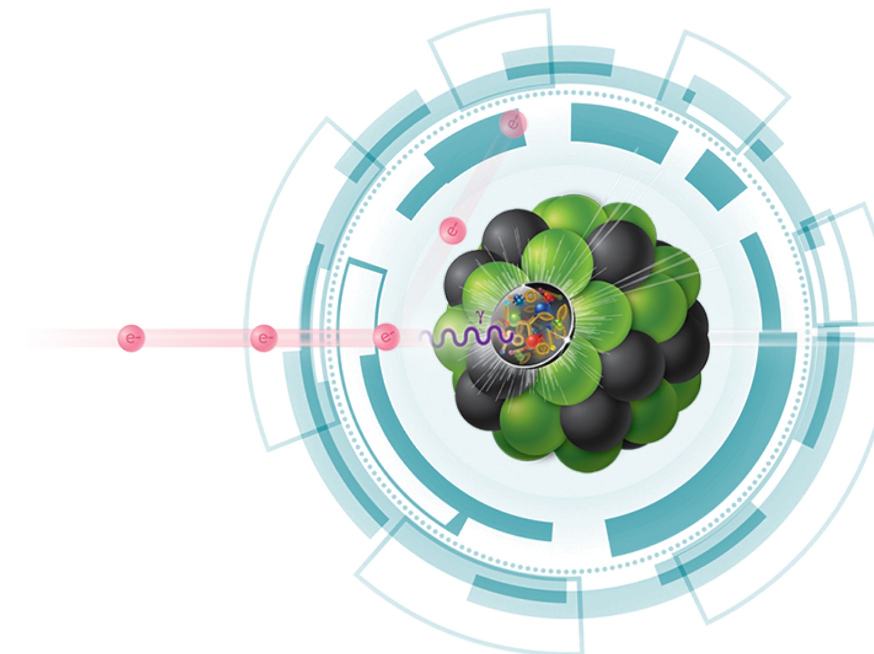
ATLAS: jet modifications limits from jet-hadron correlations in p+Pb

large jet yields & high-efficiency tracking in sPHENIX!

Preparing for the EIC

p+A: unpolarized physics





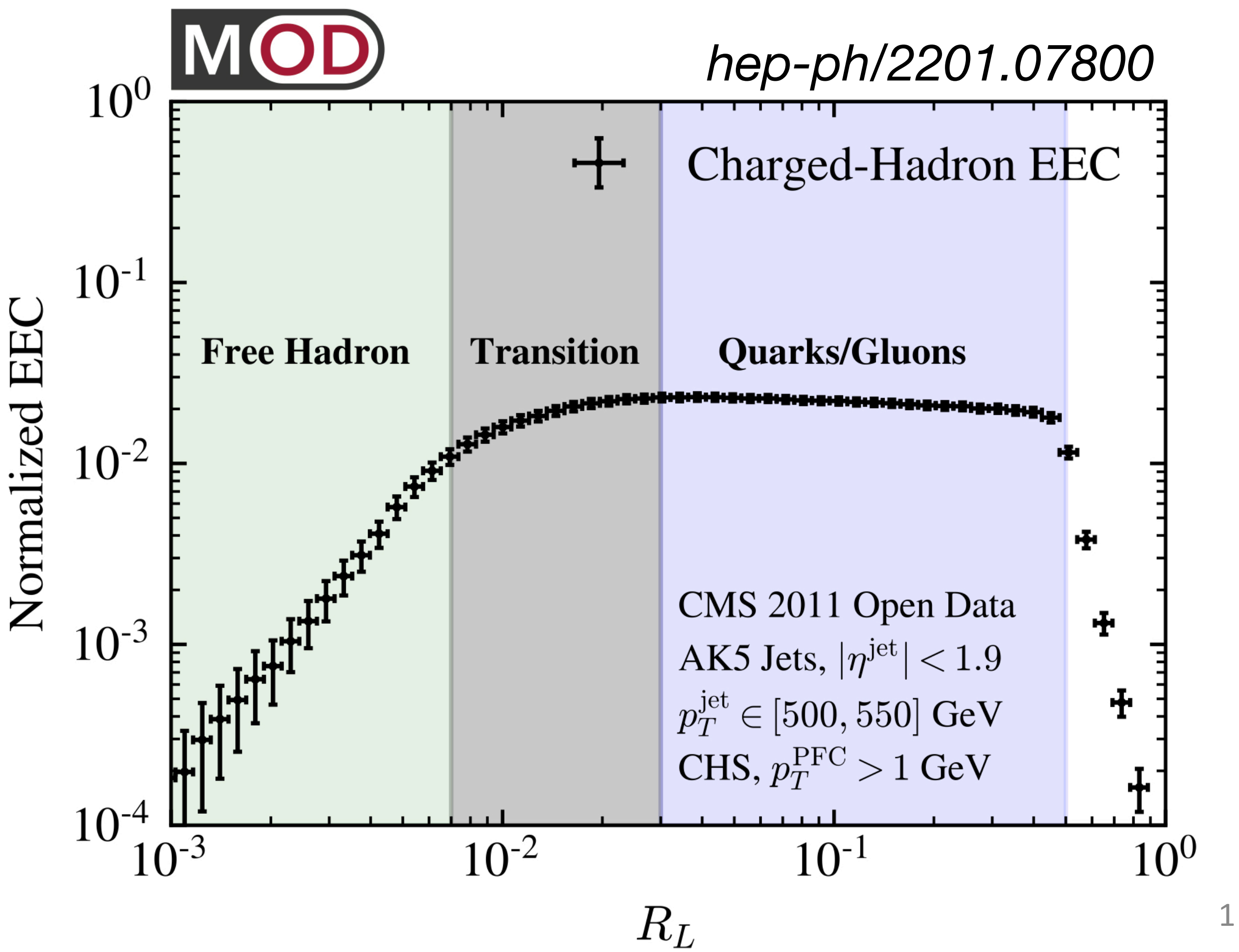
Above: large yields for unpolarized *p*+A measurements

➡ nuclear PDF modification extending deep into EMC region & cold nuclear energy loss

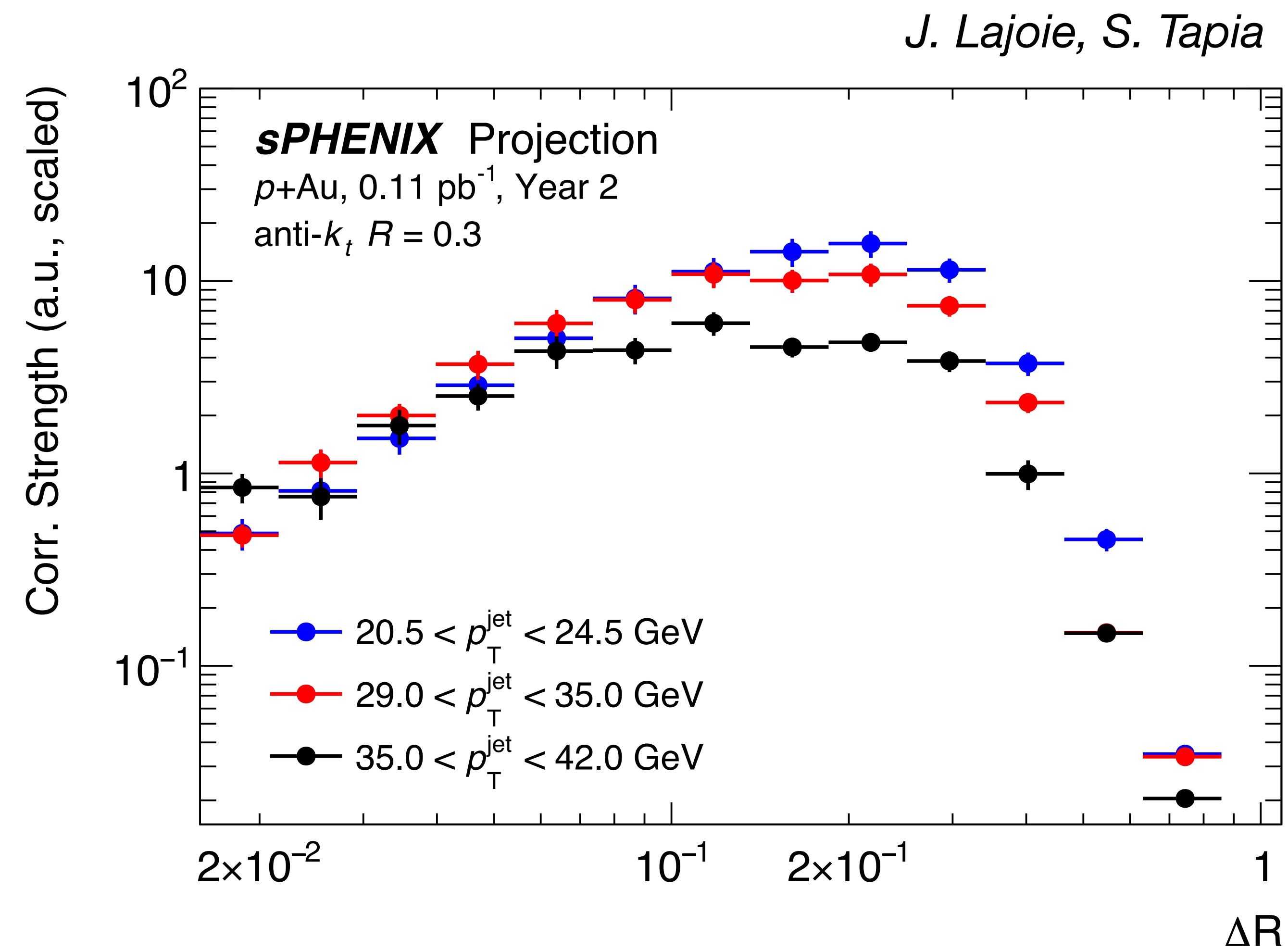
➡ measurements looking towards EIC, using EIC Detector-1 instrumentation

  ➡ e.g. hadronization in nuclear medium via jet structure

p+A: unpolarized physics

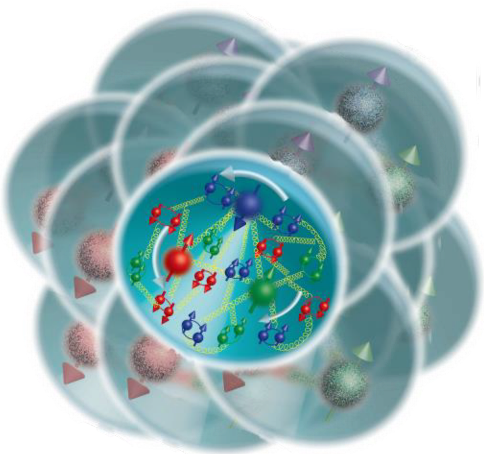


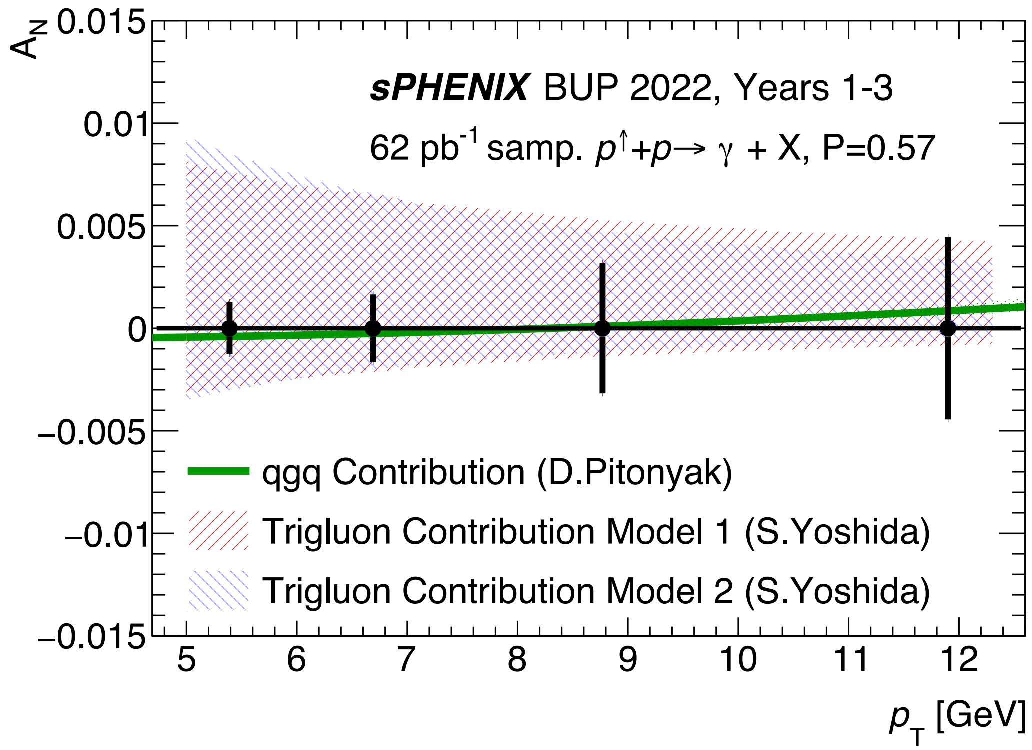
N-point energy correlators inside jets as a way to probe parton → hadron transition

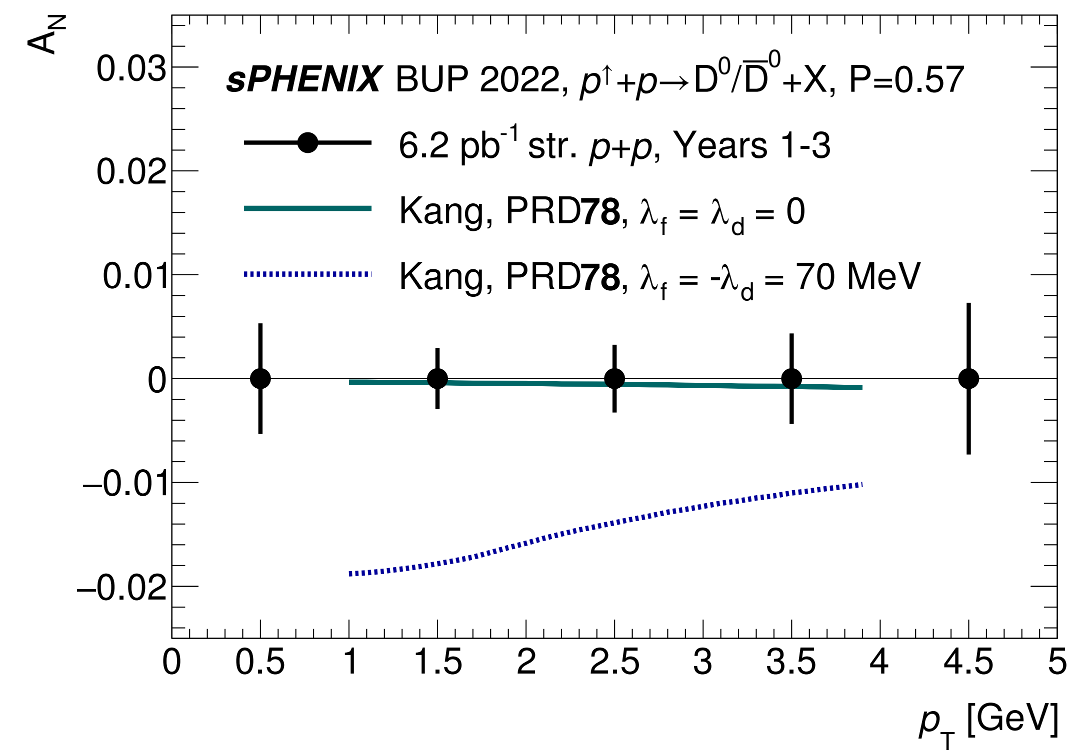


sPHENIX projection for differential study as a function of $(p_{\mathrm{T}}^{\mathrm{jet}}, \Delta R)$ - with p+p data reference!

$p+p$: polarized physics







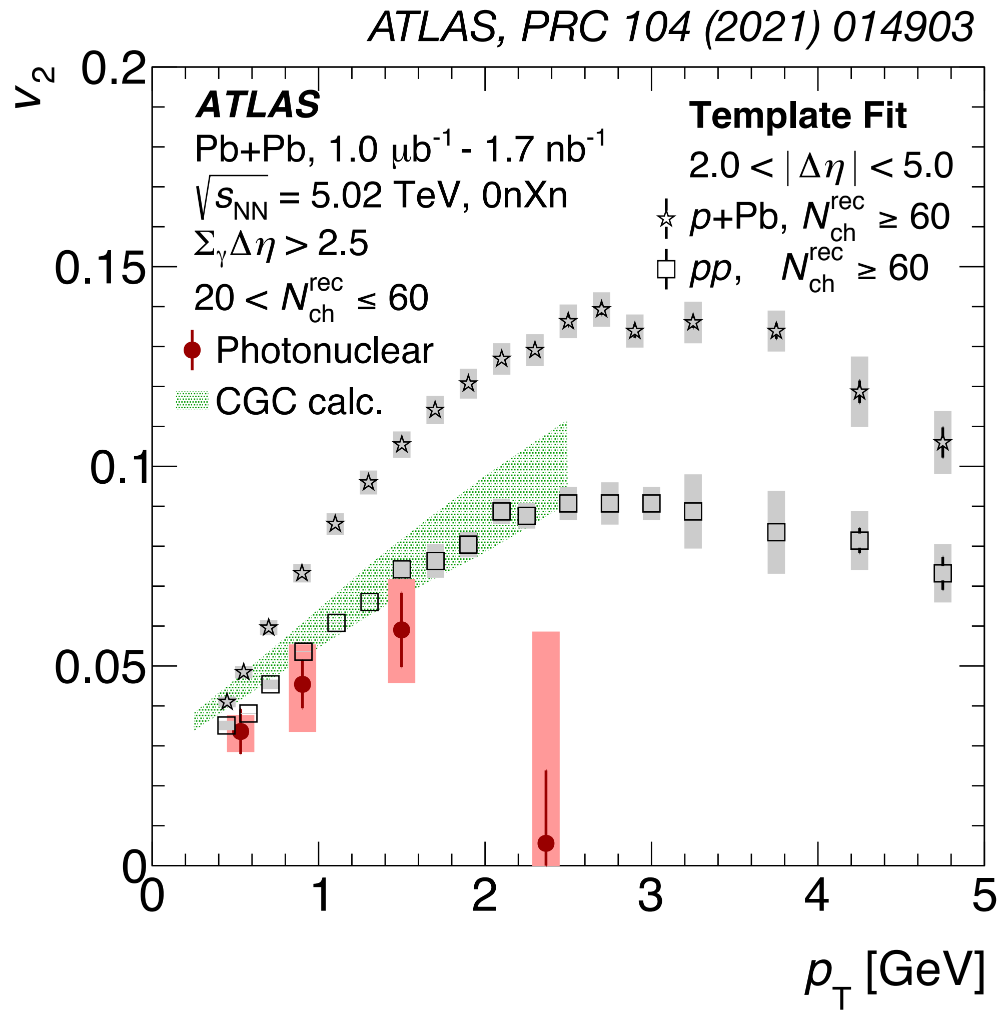
Use sPHENIX capabilities for TSSA of direct photons (left) and heavy flavor hadrons (right)

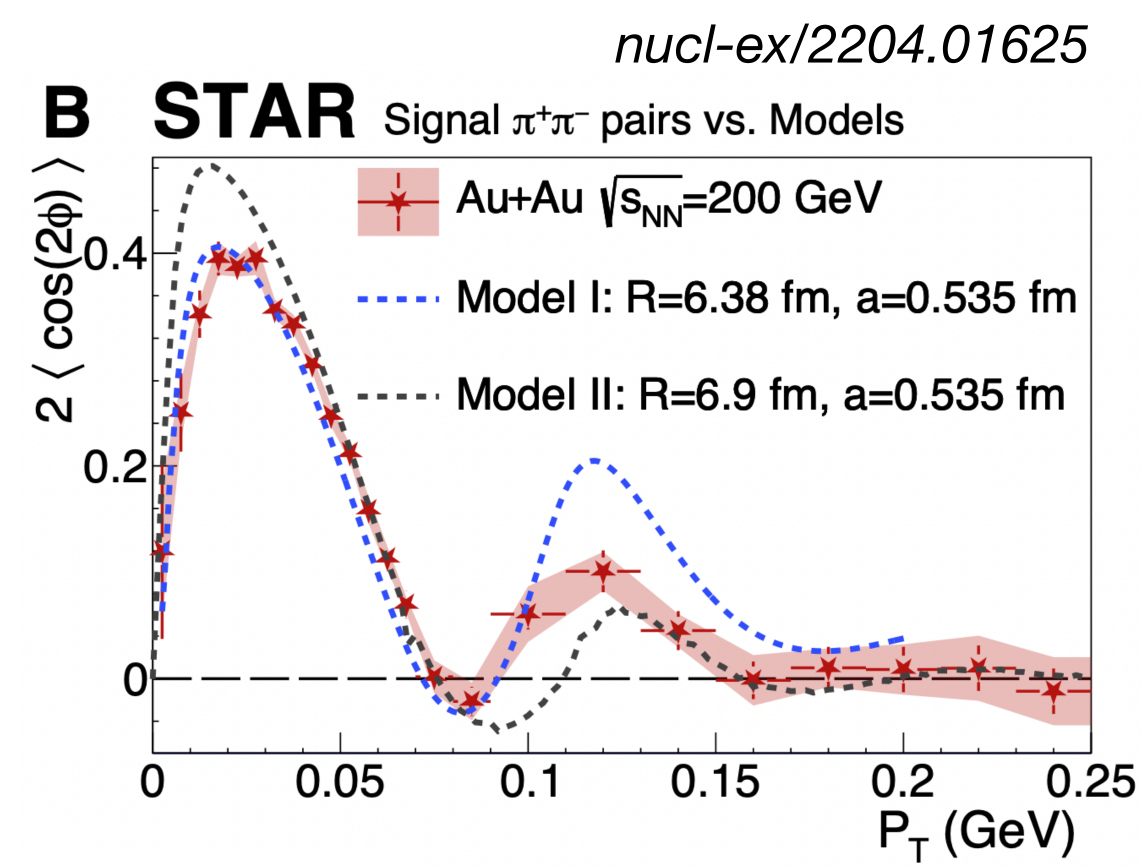
➡ probe gluon dynamics in transversely polarized nucleons through tri-gluon correlation function

➡ connected with the poorly constrained gluon Sivers TMD function

➡ check universality with HF A_N at the EIC

Ultra-peripheral collisions





Theory claim: use γ+A as benchmark for **CGC signal** in EIC

Shi et al., PRD 103 (2021) 054017 Zhao et al, nucl-th/2203.06094

Nuclear tomography via polarized photon+gluon interaction (coherent $\rho \to \pi^+\pi^-$)

Photo-nuclear collisions - photoproduction limit of nuclear DIS

➡ opportunity to do some “EIC-like” physics **now**?

➡ sPHENIX has large acceptance for a program like this…

Conclusion

- sPHENIX is a dedicated jet detector for QGP microscopy, with unique, purpose-built capabilities never deployed at RHIC
- Learning from the LHC:
  - ➡ some significant physics and kinematic advantages at RHIC
  - ➡ complementary to LHC program, while also breaking new ground in regions unique to sPHENIX
- Preparing for EIC:
  - ➡ dedicated *p*+Au physics program
  - ➡ opportunity to start testing analysis strategy, Detector-1 components ***now***

Thank you!