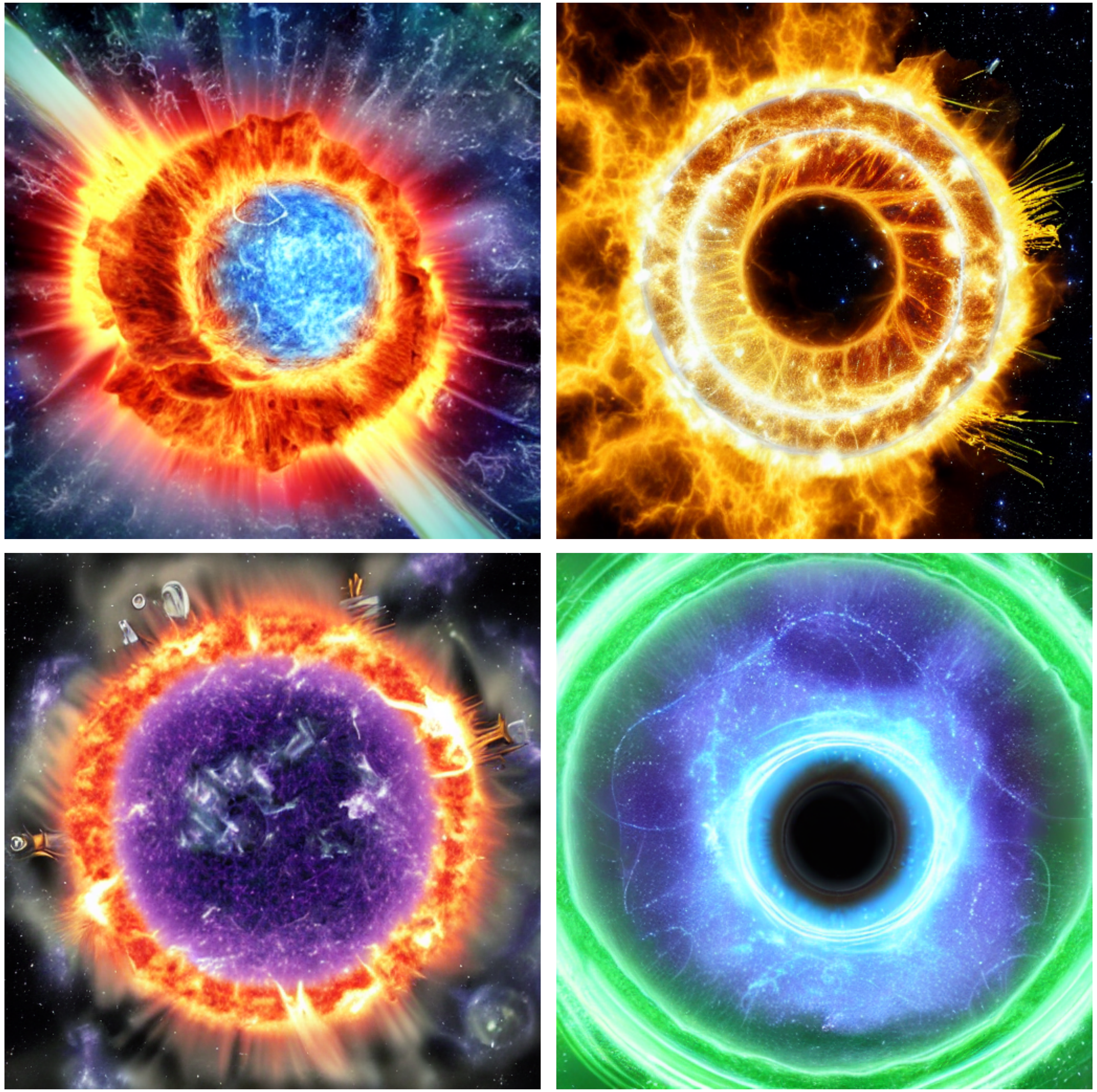
The Future of Experimental Hot QCD

QCD Town Hall for the U.S. Long Range Plan for Nuclear Physics

Dennis V. Perepelitsa
(University of Colorado Boulder)
MIT, 24 September 2022

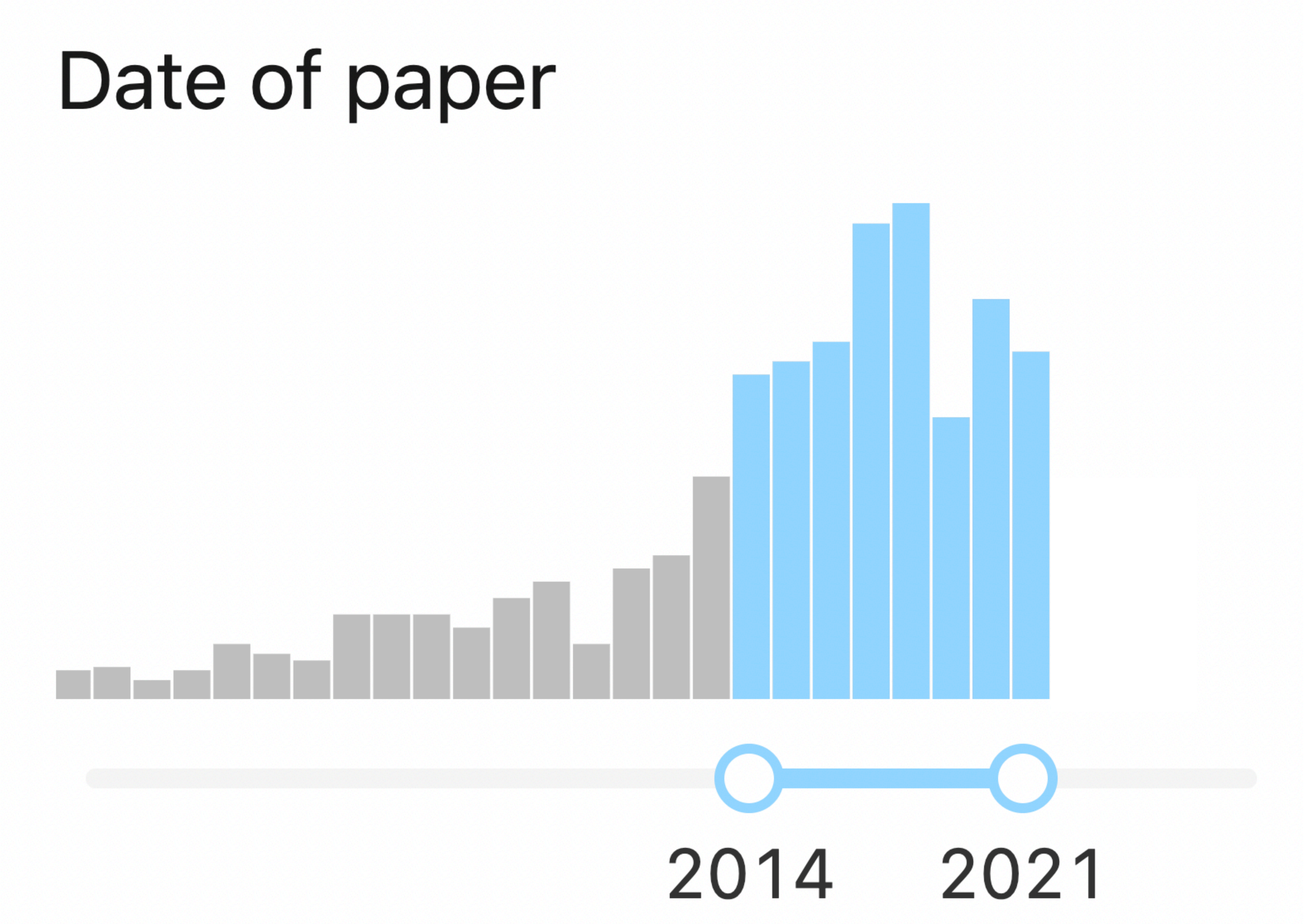


StabilityDiffusion AI generated images of “quark gluon plasma”

2014-2022 was a period of **complexity** and **growth**

Our field is the study of emergent, often unexpected, many-body physics phenomena - lots to study!

“quark gluon plasma” + nucl-ex



2014-2022 was a period of **complexity** and **growth**

Our field is the study of emergent, often unexpected, many-body physics phenomena - lots to study!

2023-2031 will be a period of **reductionism**

2014-2022 was a period of **complexity** and **growth**

Our field is the study of emergent, often unexpected, many-body physics phenomena - lots to study!

2023-2031 will be a period of **reductionism**

Scientific reductionism is the idea of reducing complex interactions and entities to the sum of their constituent parts, in order to make them easier to study.

Stanford Encyclopedia of Philosophy

2014-2022 was a period of **complexity** and **growth**

Our field is the study of emergent, often unexpected, many-body physics phenomena - lots to study!

2023-2031 will be a period of **reductionism**

New experimental capabilities

Multi-dimensional measurements

Qualitatively new channels

Increased precision & control

Isolate & identify underlying microscopic mechanisms

2014-2022 was a period of **complexity** and **growth**

Our field is the study of emergent, often unexpected, many-body physics phenomena - lots to study!

2023-2031 will be a period of **reductionism**

This is the long-term goal of all scientific fields!

New experimental capabilities

Multi-dimensional measurements

Qualitatively new channels

Increased precision & control

Isolate & identify underlying microscopic mechanisms

Our field is driven by experimental data

Our field is driven by experimental data

Collected Data

RHIC Au+Au

Run-14 200 GeV
PHENIX sampled 7/nb

Our field is driven by experimental data

Collected Data

PHENIX STAR

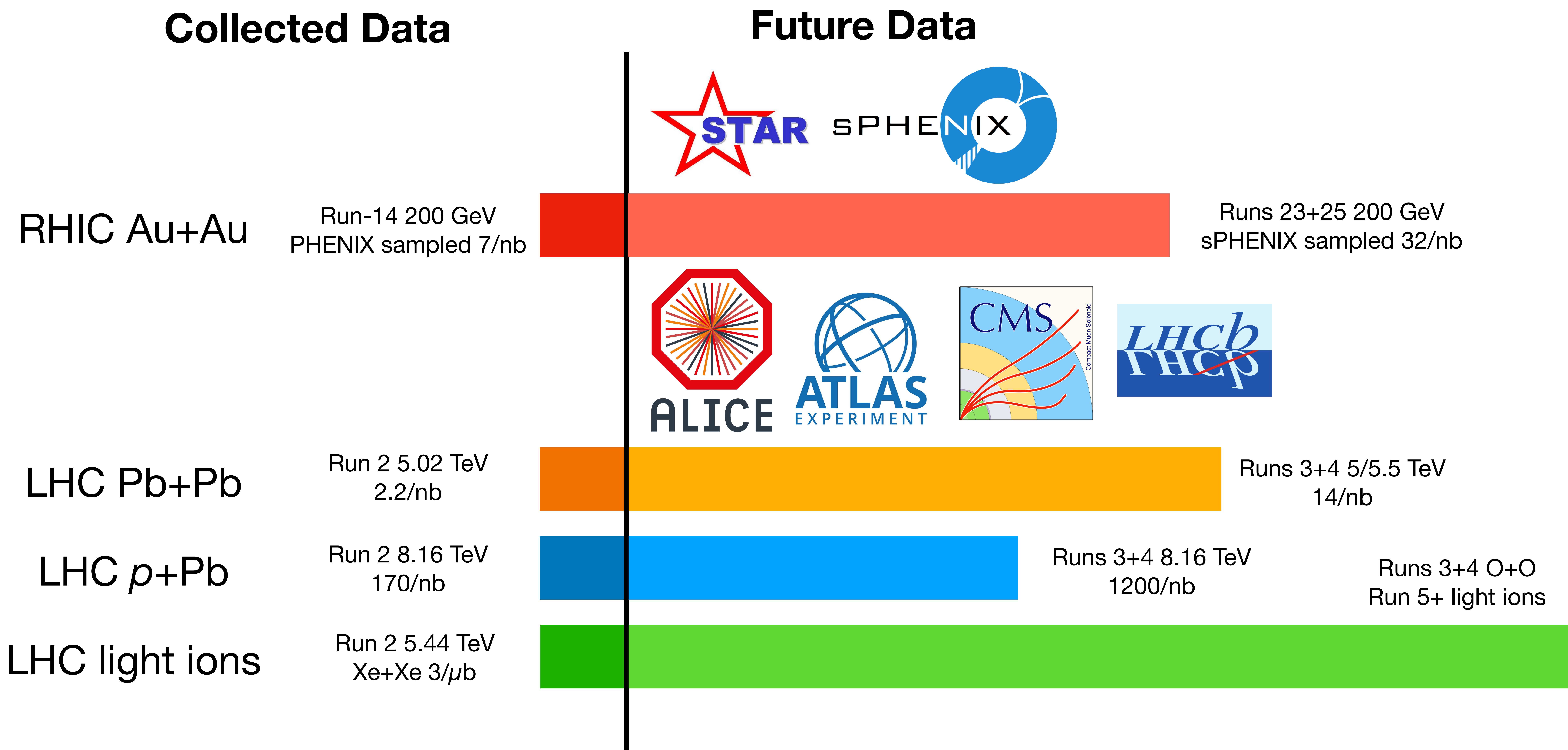
RHIC Au+Au	Run-14 200 GeV PHENIX sampled 7/nb
LHC Pb+Pb	Run 2 5.02 TeV 2.2/nb
LHC *p*+Pb	Run 2 8.16 TeV 170/nb
LHC light ions	Run 2 5.44 TeV Xe+Xe 3/μb

Our field is driven by experimental data

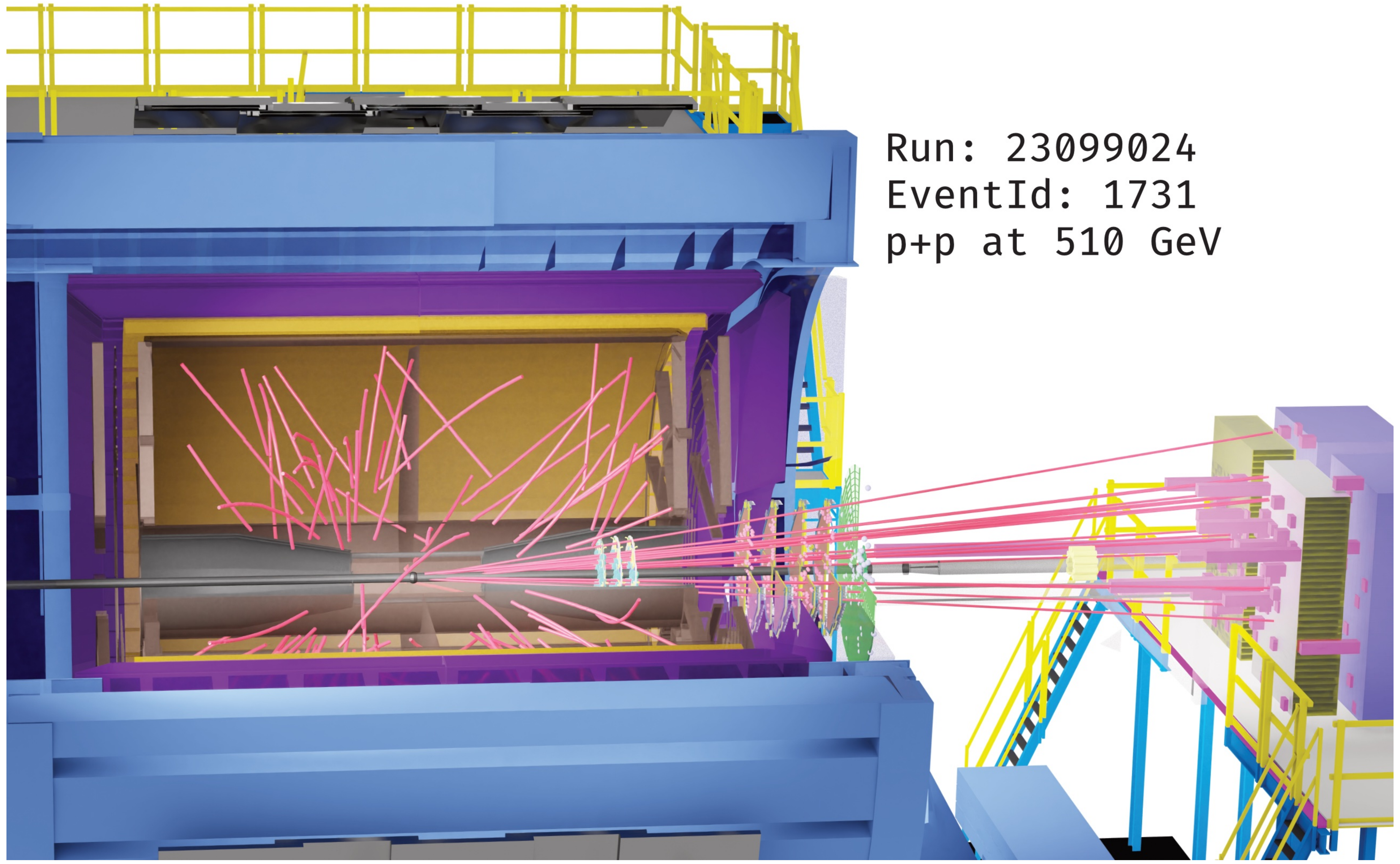
Collected Data

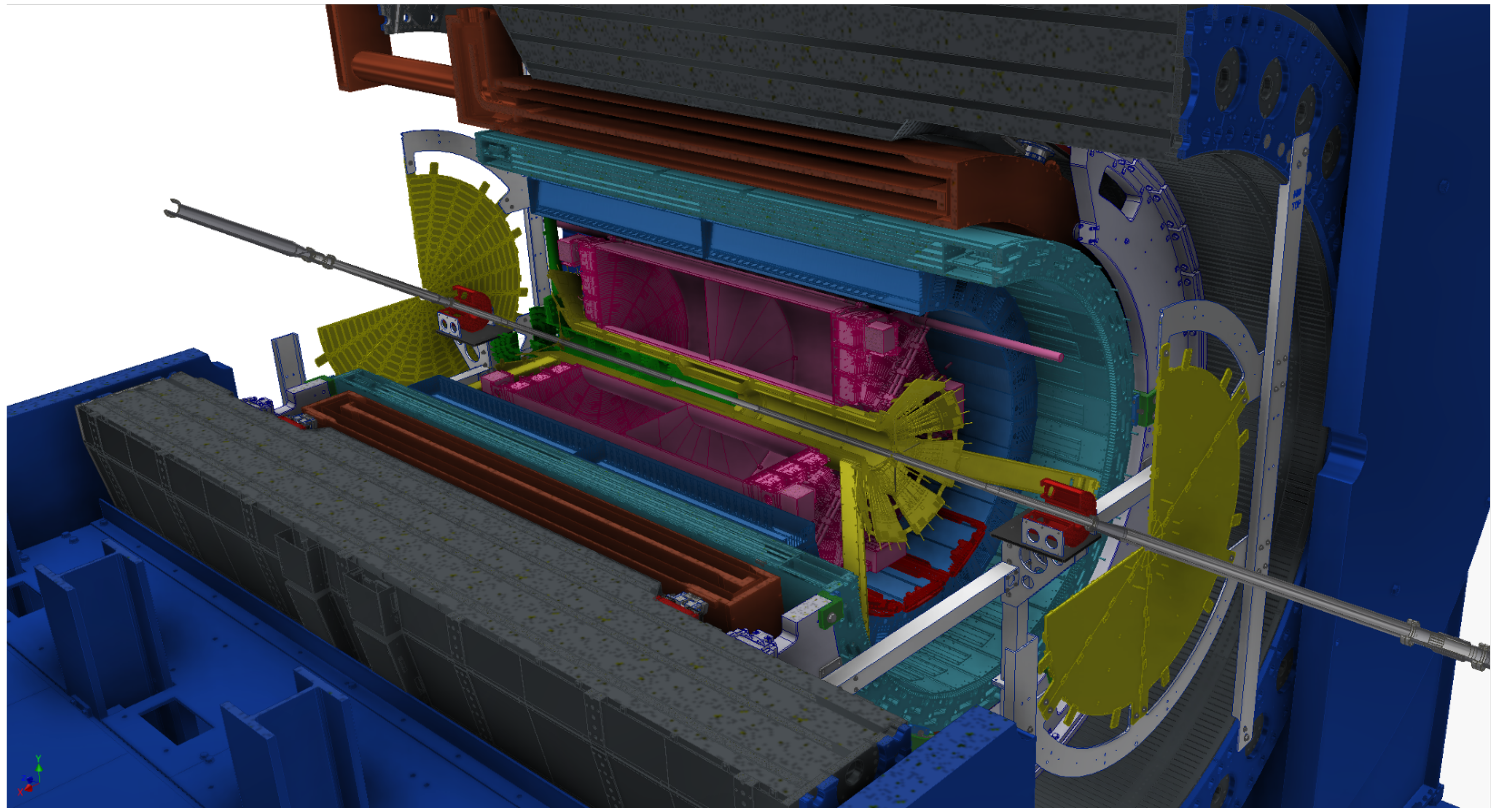
RHIC Au+Au	Run-14 200 GeV PHENIX sampled 7/nb
LHC Pb+Pb	Run 2 5.02 TeV 2.2/nb
LHC p+Pb	Run 2 8.16 TeV 170/nb
LHC light ions	Run 2 5.44 TeV Xe+Xe 3/μb

Our field is driven by experimental data



Start of Super-RHIC: 2023





Unique forward instrumentation:
tracking + calorimetry in $2.5 < |\eta| < 4$

+ other upgrades (increased TPC rate, etc.)

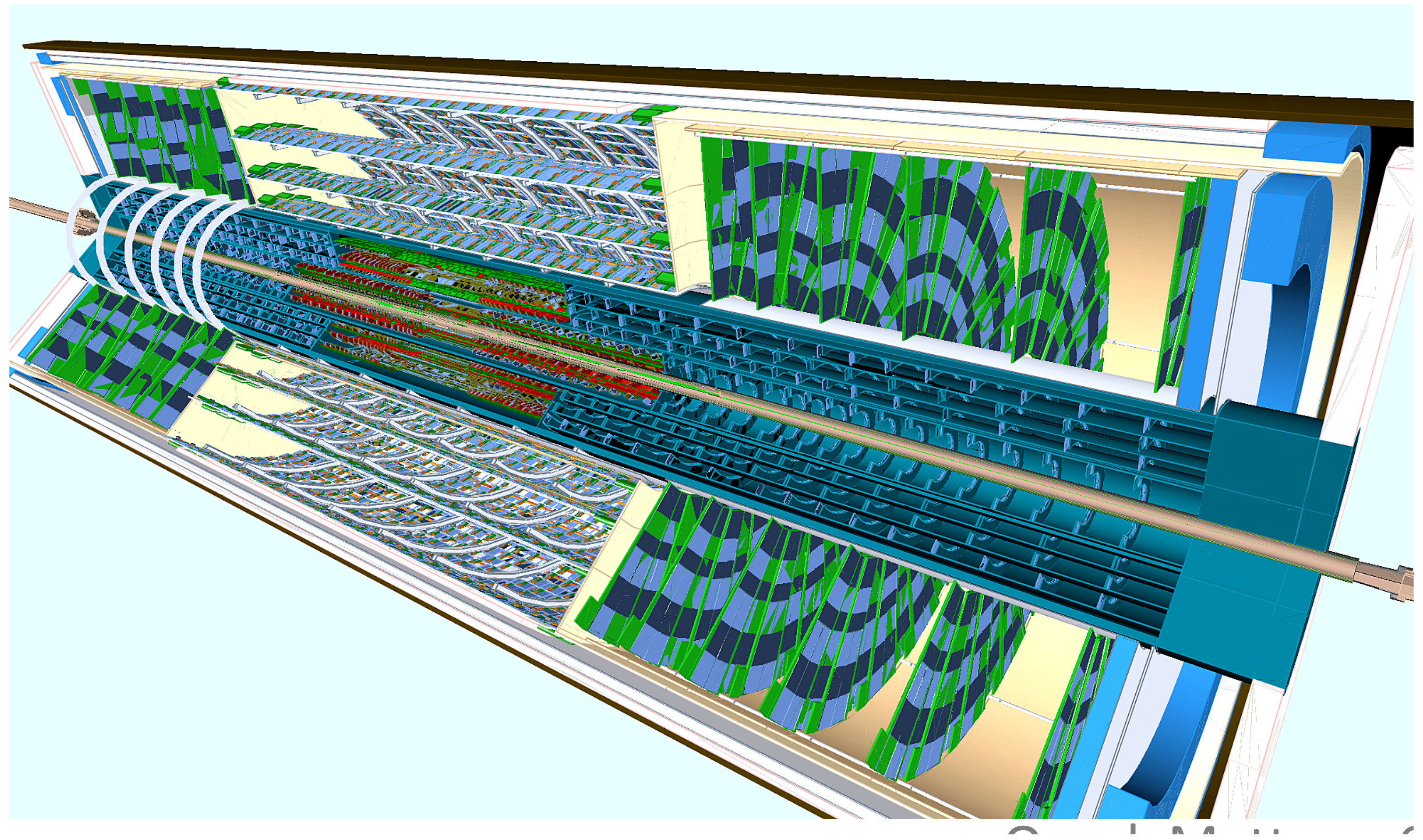
Completely re-imagined as **dedicated detector for jet, heavy flavor, upsilon physics**

Large rate, hermetic calorimetry, precision tracking

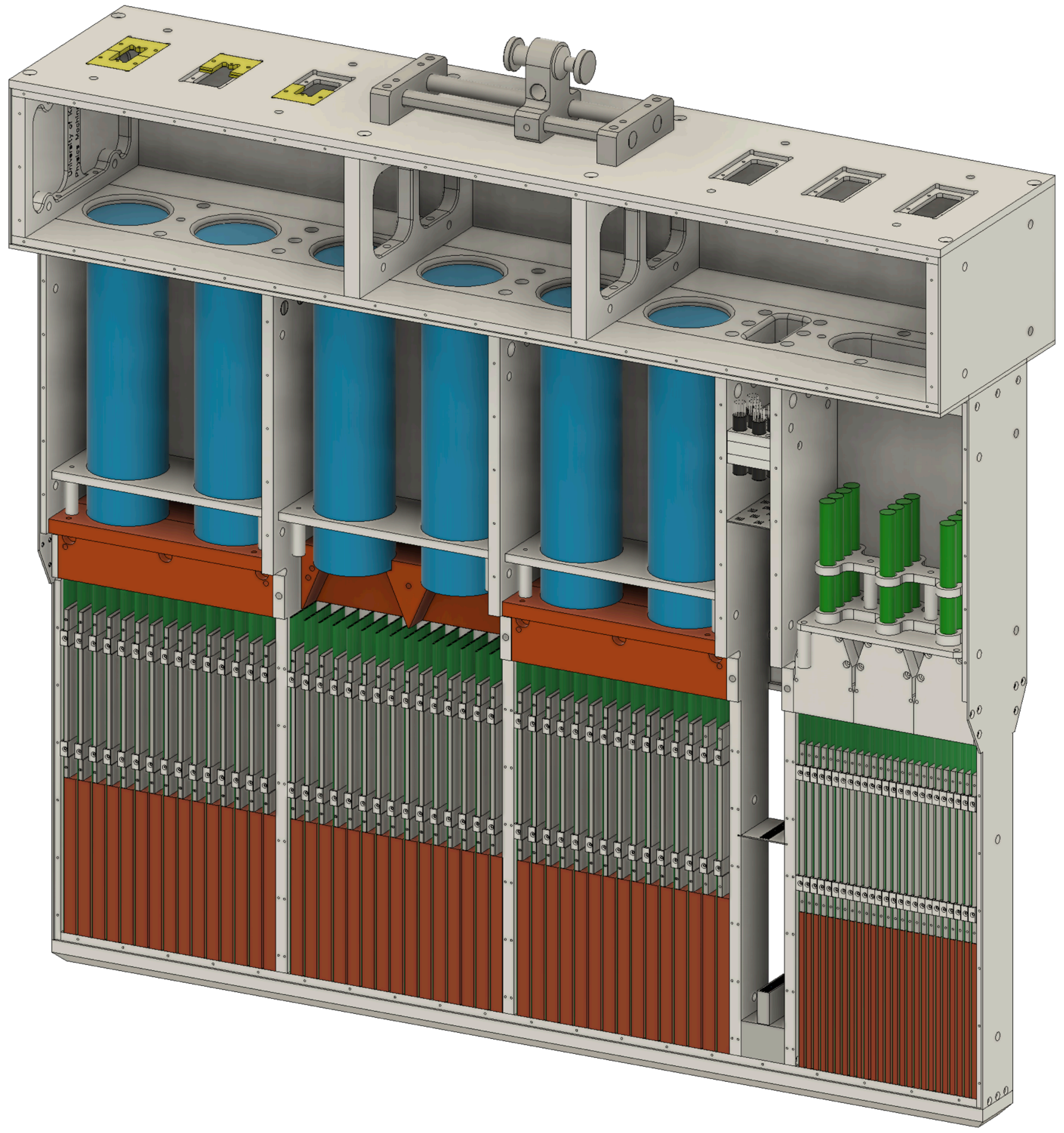
sPHENIX Inner Hadronic Calorimeter installation into OHCal+Magnet

ATLAS EXPERIMENT & CMS in Run 3 (2022-2025) and Run 4 (2029-2032)

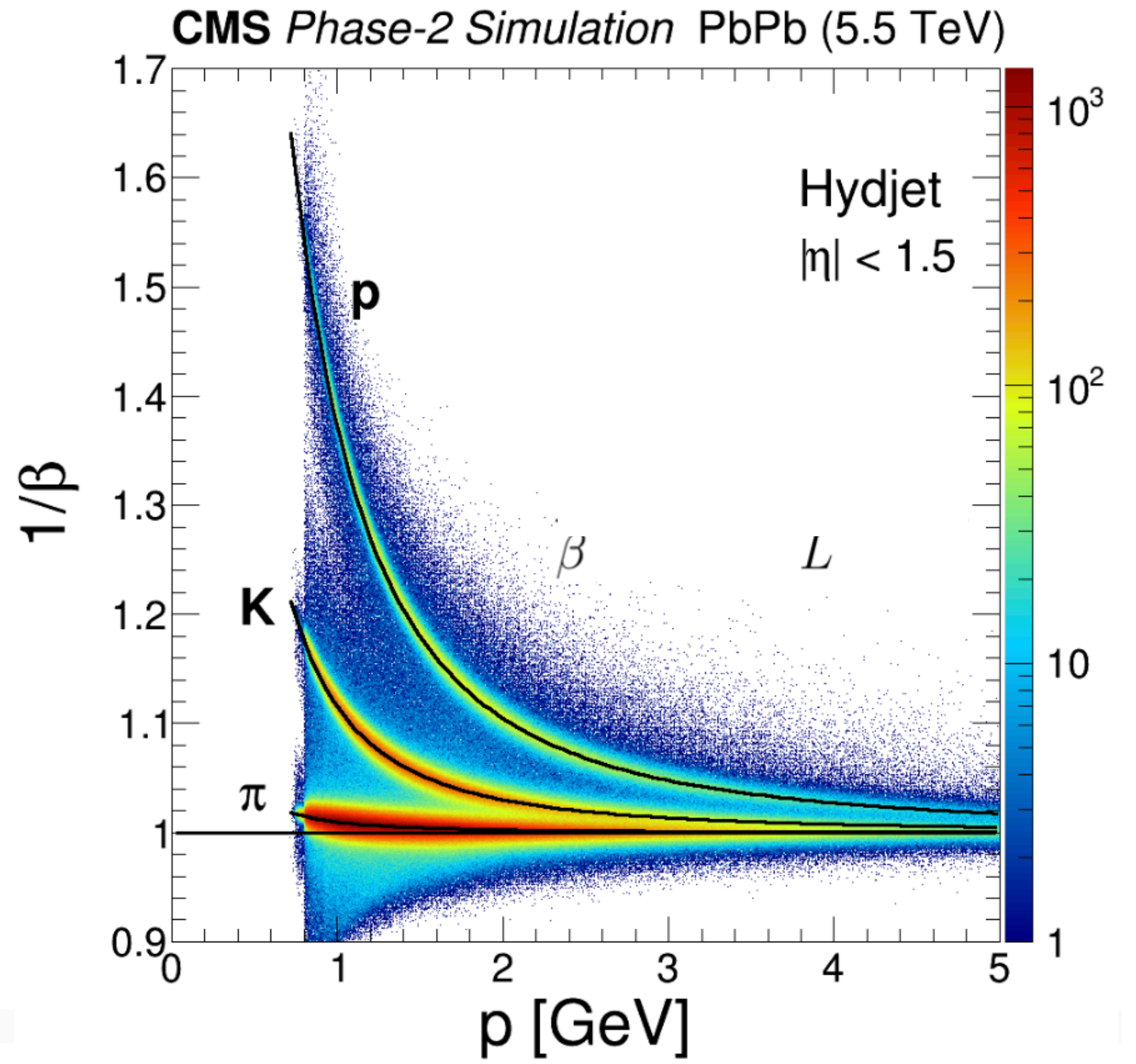
ATLAS ITk



ATLAS+CMS Run 4, major tracking upgrades: $|\eta| < 4$



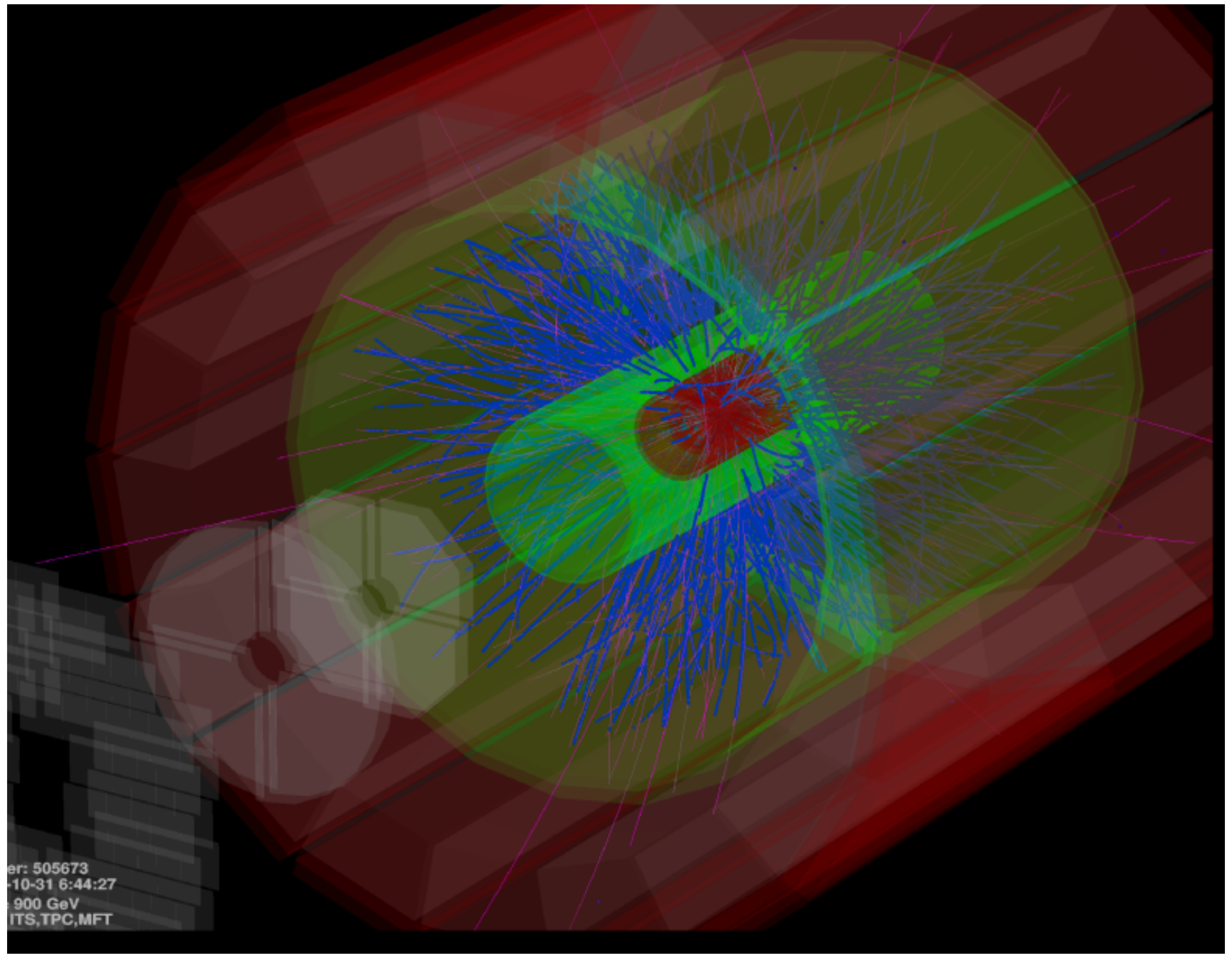
U.S. leads joint ATLAS-CMS HL-ZDC with reaction plane capability

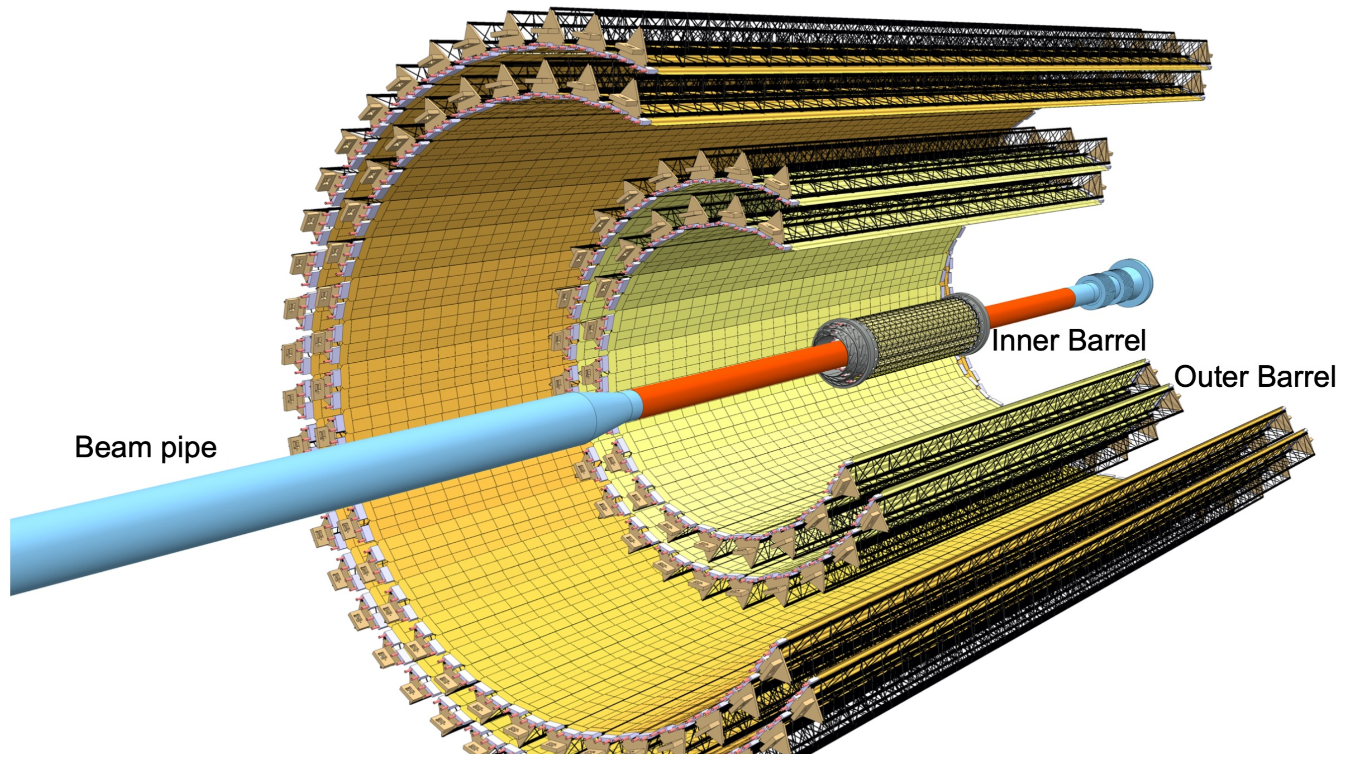


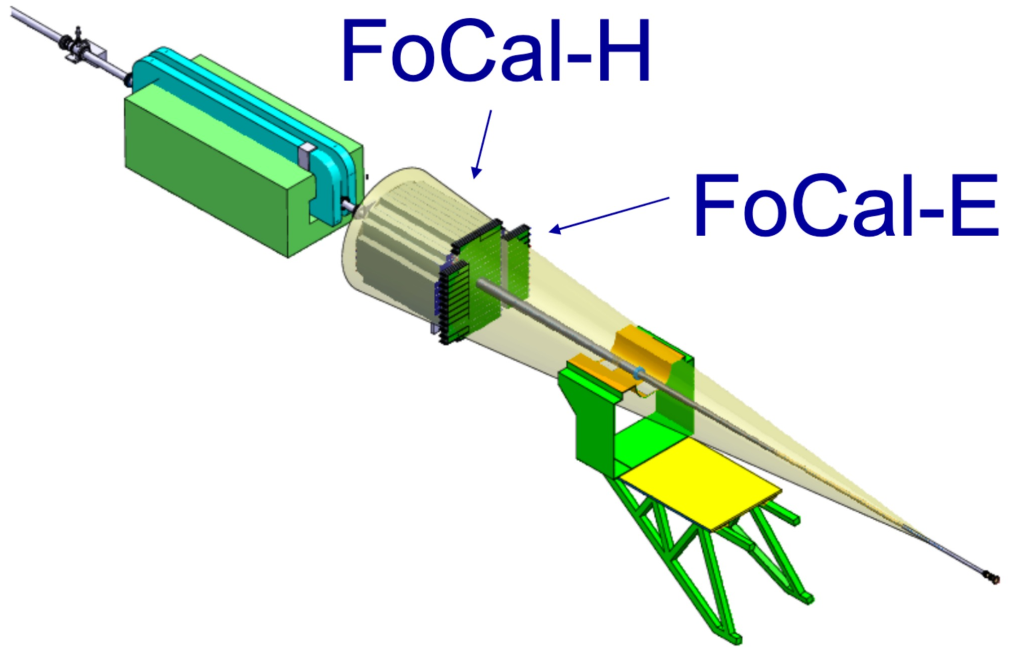
U.S. involvement in MIP Timing Detector (MTD) for CMS Run 4: particle ID within $|\eta| < 3$ in HI

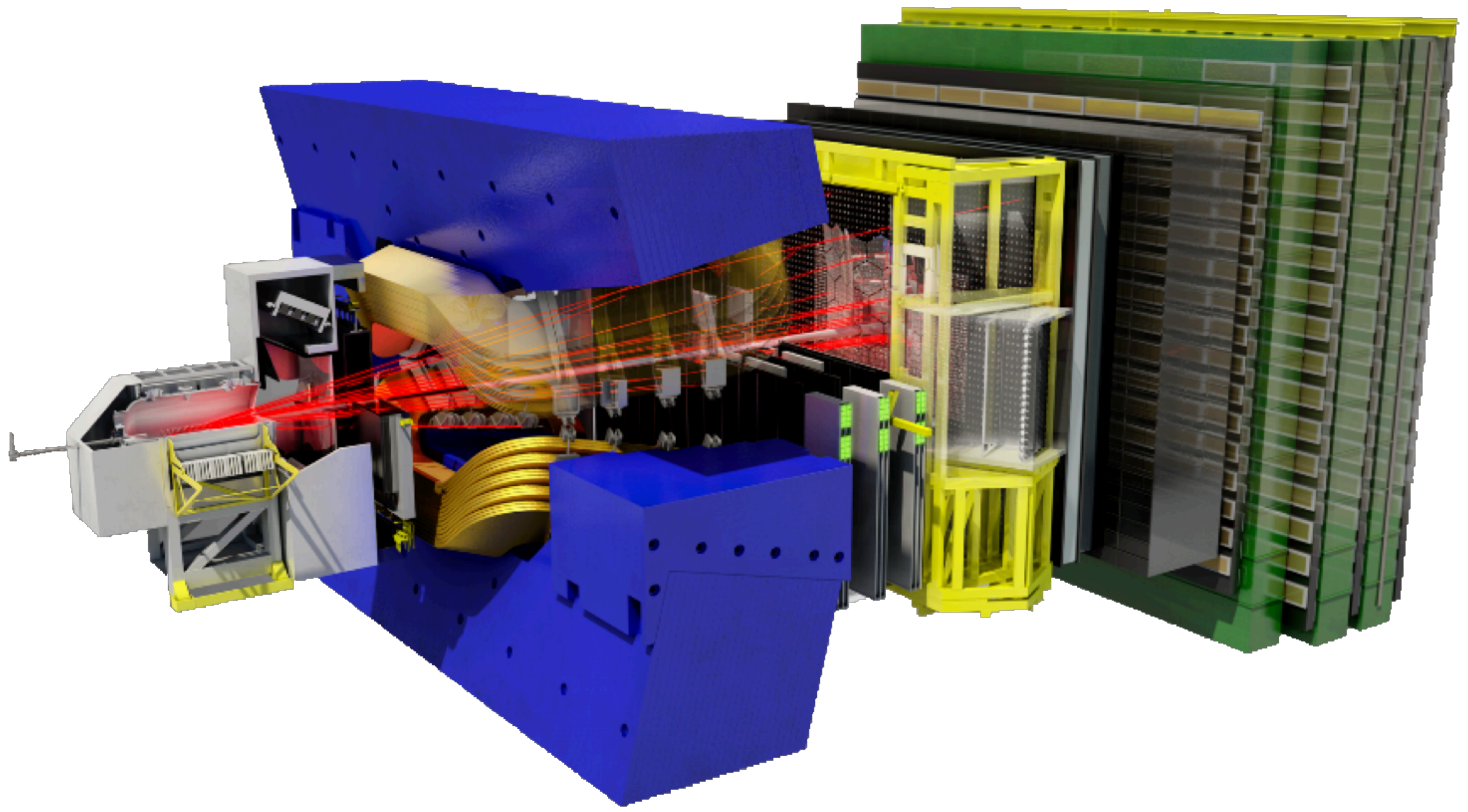
+ other upgrades (L1 and HLT trigger, muon detectors, endcap calorimetry, etc.)

ALICE 2 & LHCb Upgrades









LHCb: new tracking & readout, increase AA centrality coverage

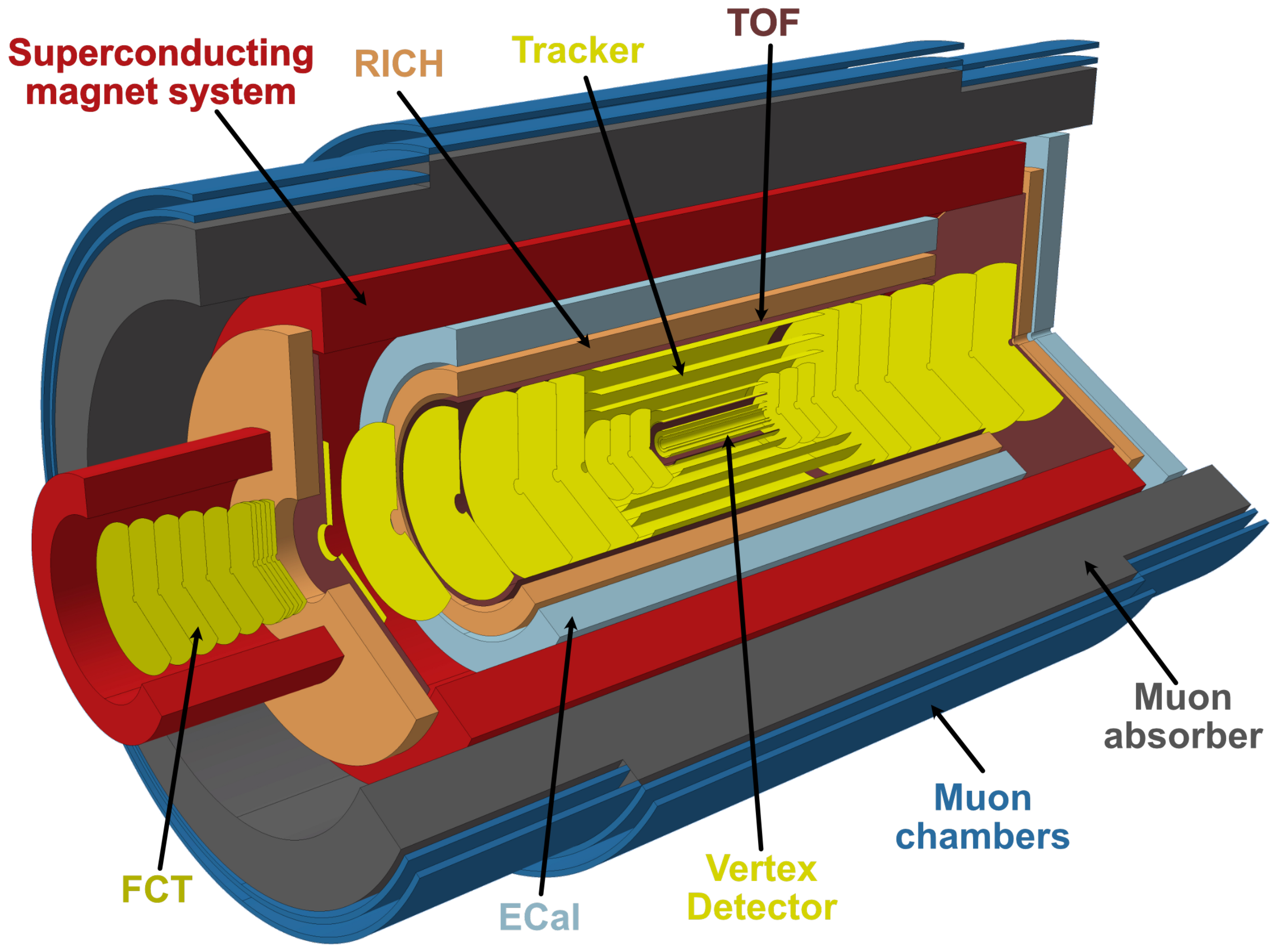
60-100% → 30-100%

ALICE 2: improved tracking system, muon capability, triggering & data rates

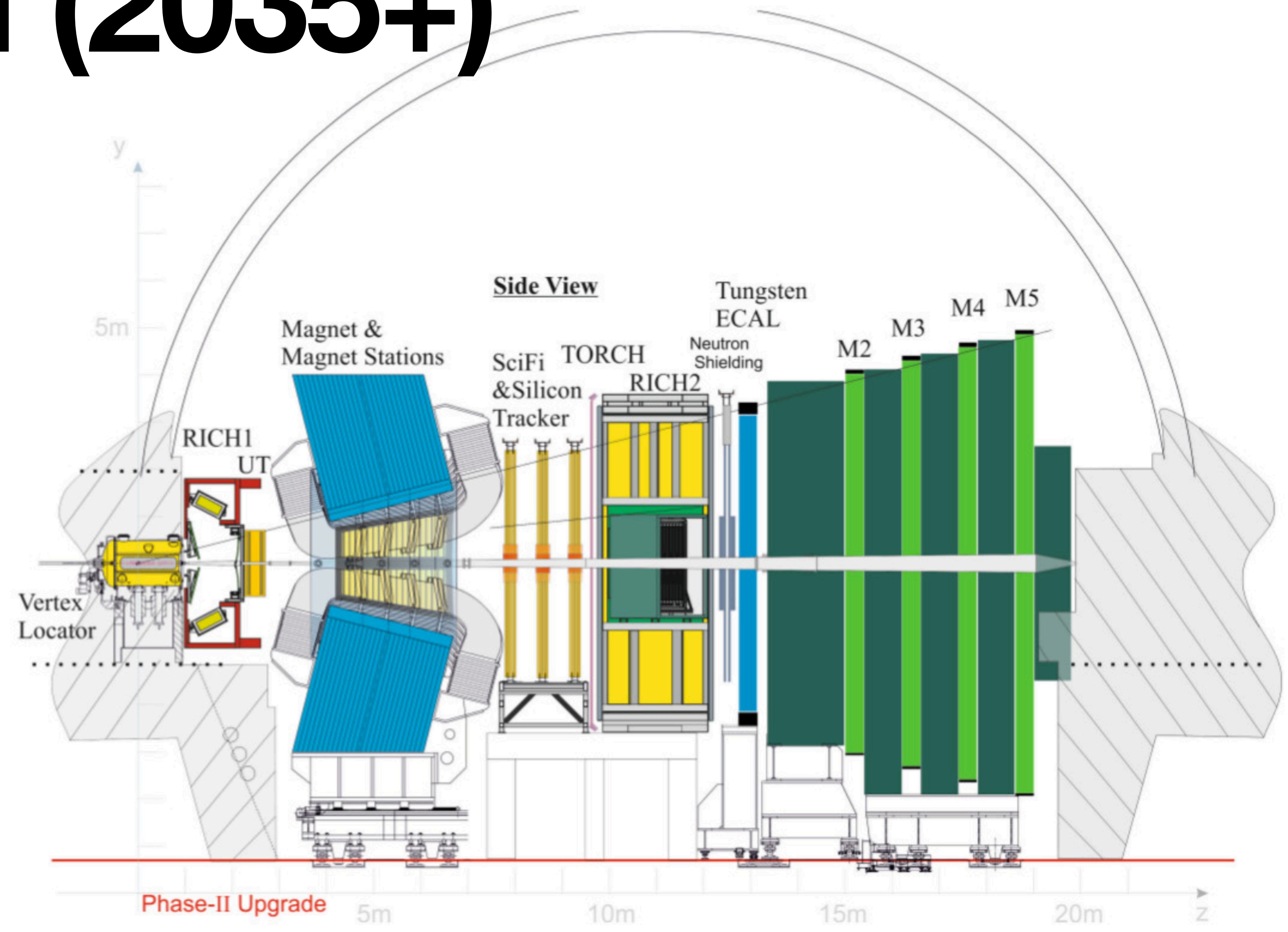
U.S. involvement in Barrel Tracking Upgrade (TPC + ITS2) for Run 3 and FoCal for Run 4

Unique SMOG2 program - novel small and intermediate nuclei in fixed target mode

LHC Run 5 and beyond (2035+)



ALICE 3: a **next-generation detector** with high-rate, large acceptance, precision tracking and particle ID



LHCb Upgrade II: re-imagining **all** sub-detectors for high luminosity

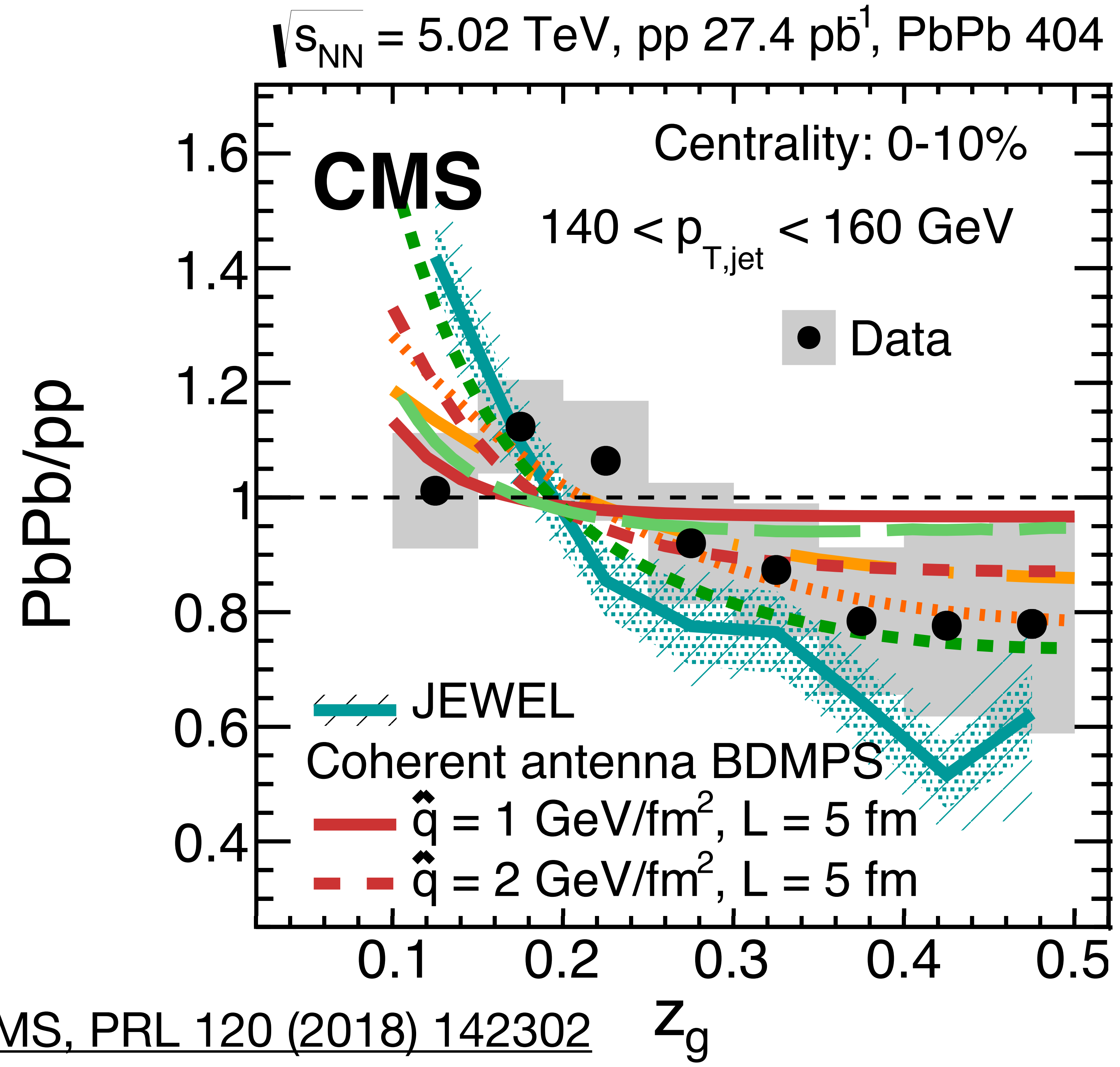
No more centrality limitation in AA

High precision flavor physics

Progress since the last Long-Range Plan, and future prospects

Rapid sophistication of jet sub-structure

2017



CMS, PRL 120 (2018) 142302

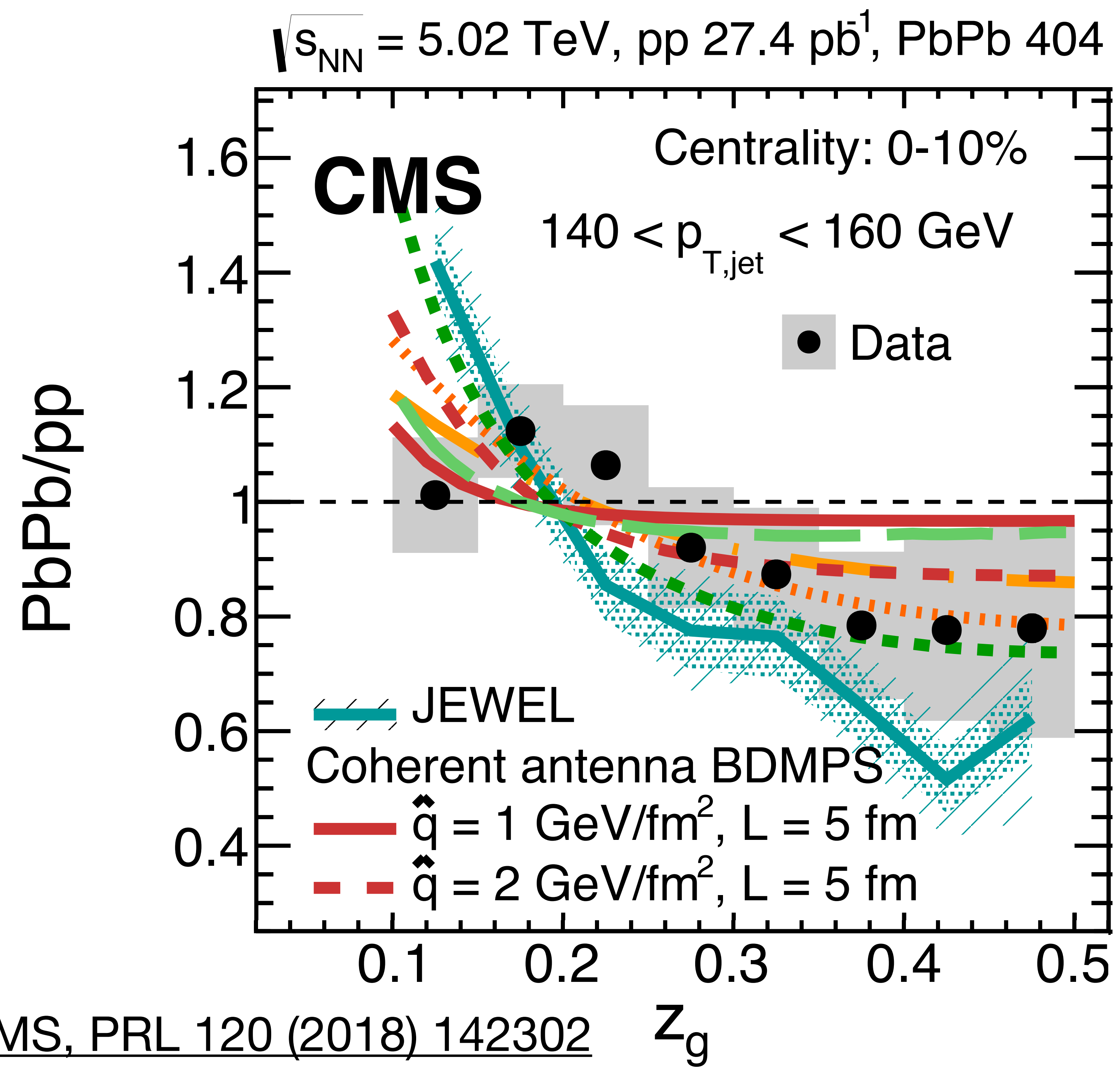
First tests of SS quantities

Relative shape only

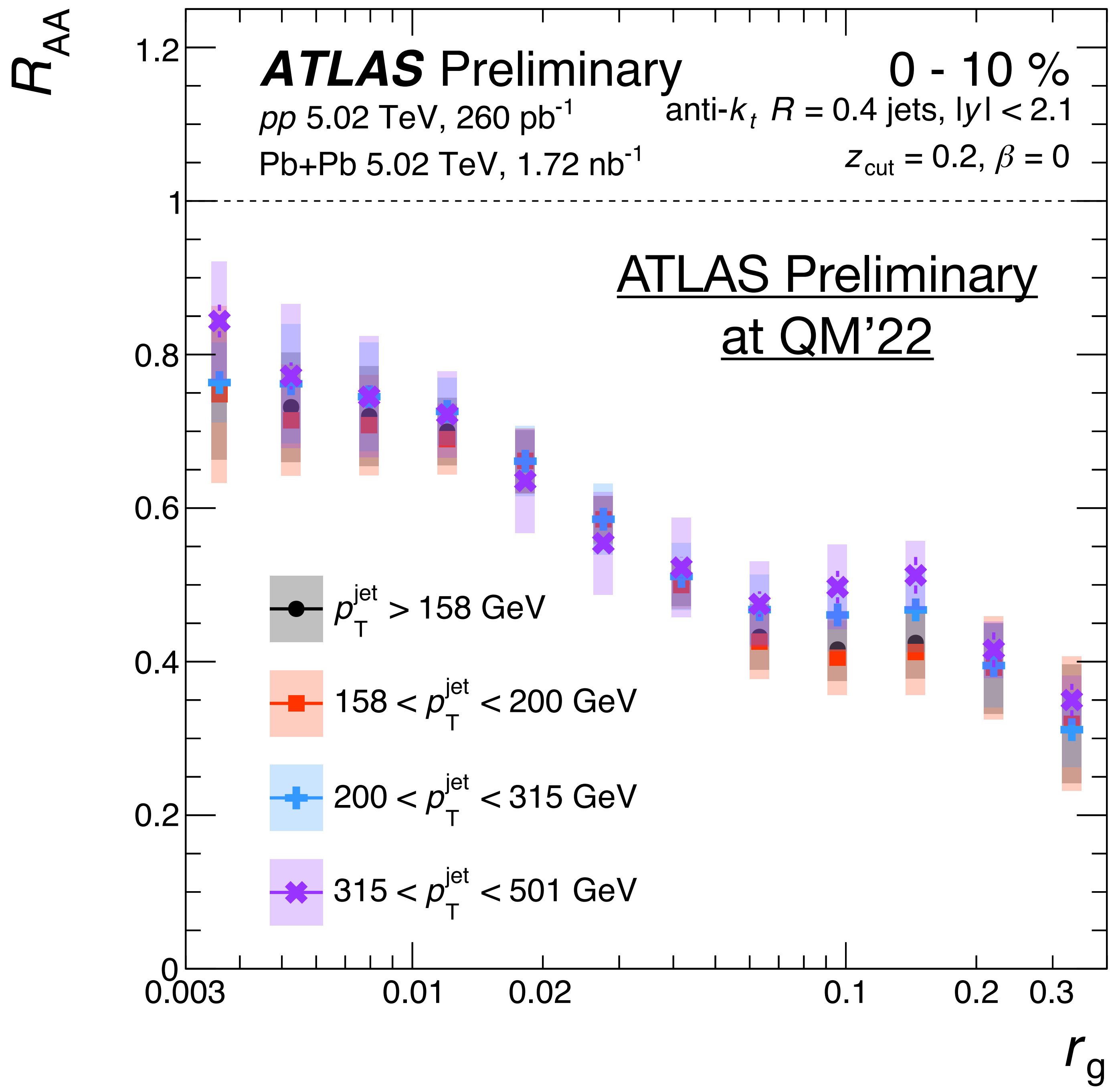
Smeared *pp*/Pythia references

Rapid sophistication of jet sub-structure

2017 → **2022**



CMS, PRL 120 (2018) 142302



First tests of SS quantities

Relative shape only

Smeared *pp*/Pythia references

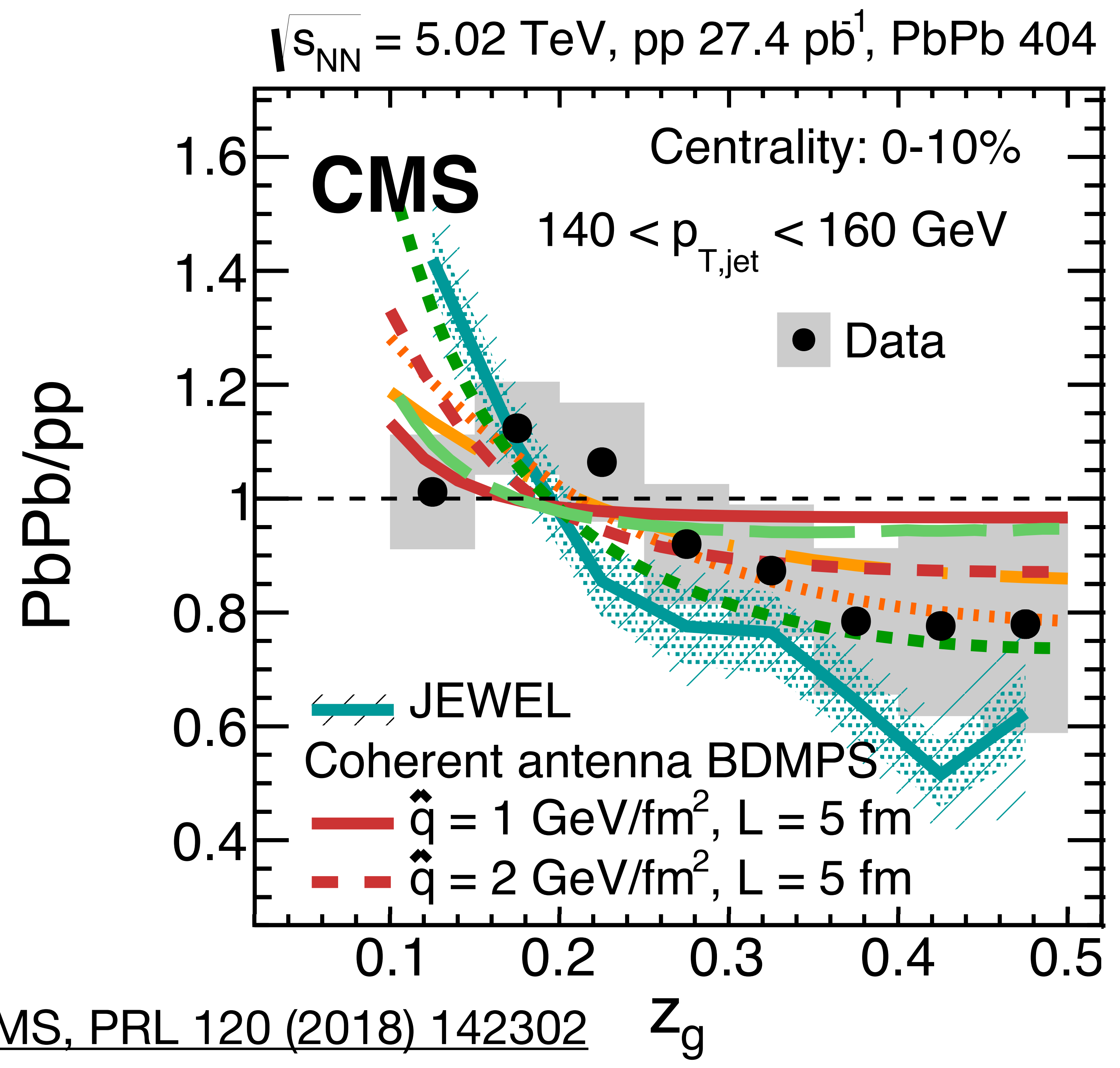
Identifying key observables

Fully unfolded

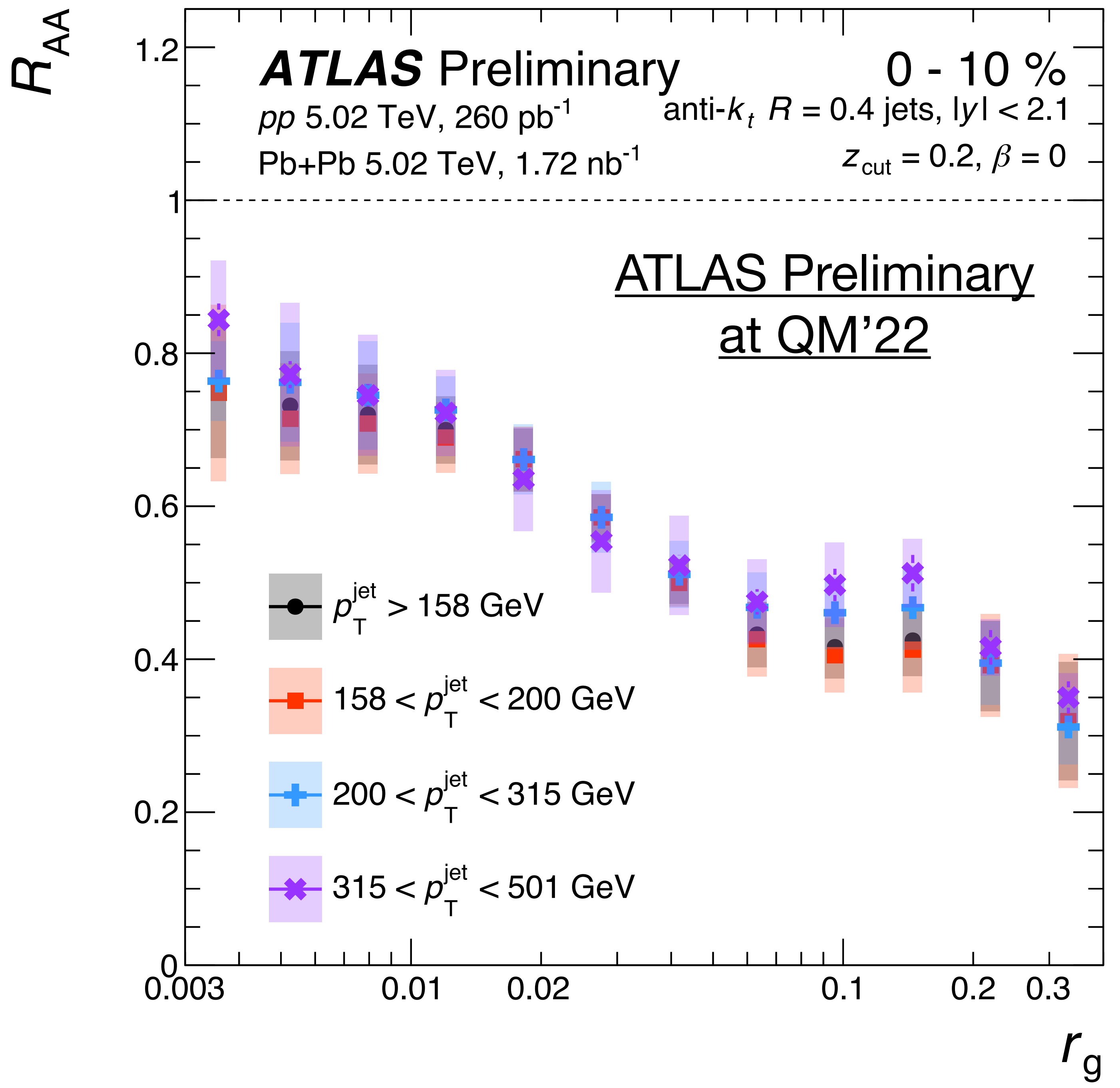
True R_{AA}

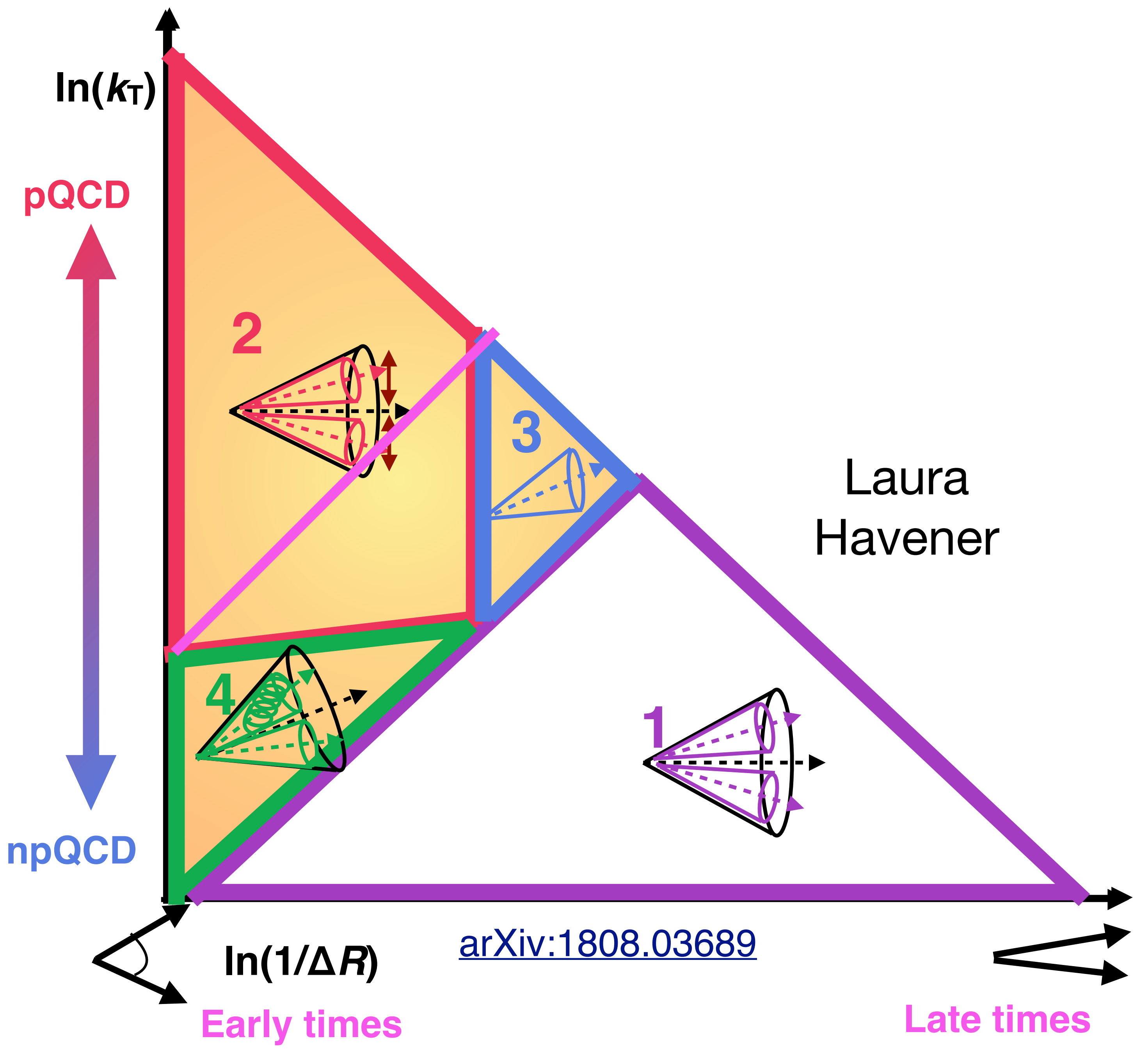
Rapid sophistication of jet sub-structure

2017 → **2022** → **Future**



CMS, PRL 120 (2018) 142302





First tests of SS quantities

Relative shape only

Smeared *pp*/Pythia references

Identifying key observables

Fully unfolded

True R_{AA}

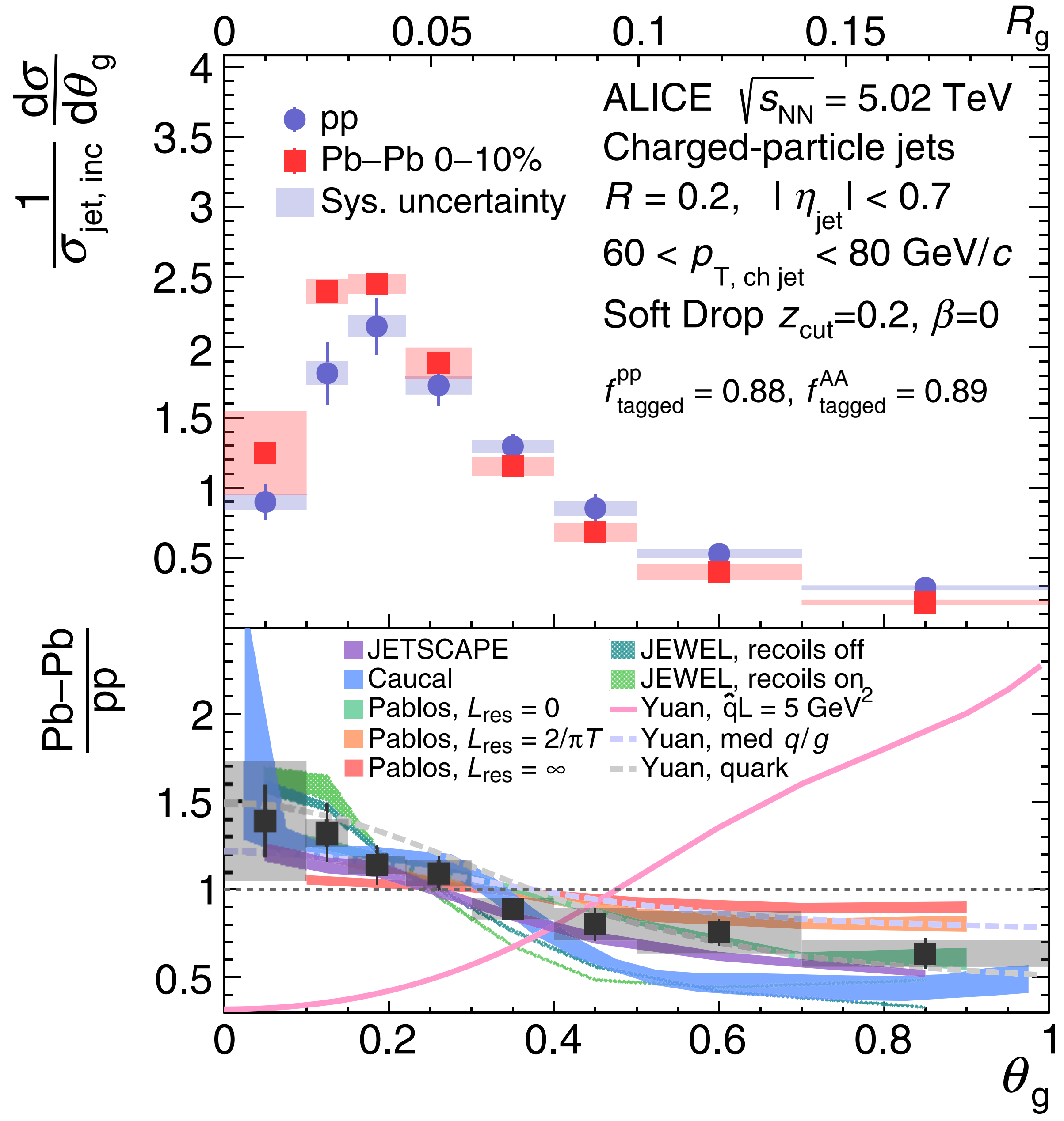
Resolve space-time picture of parton-QGP interaction

What governs parton energy loss?

Starting to perform controlled experiments to **isolate what controls the physics**

What governs parton energy loss?

ALICE, PRL 128 (2022) 102001

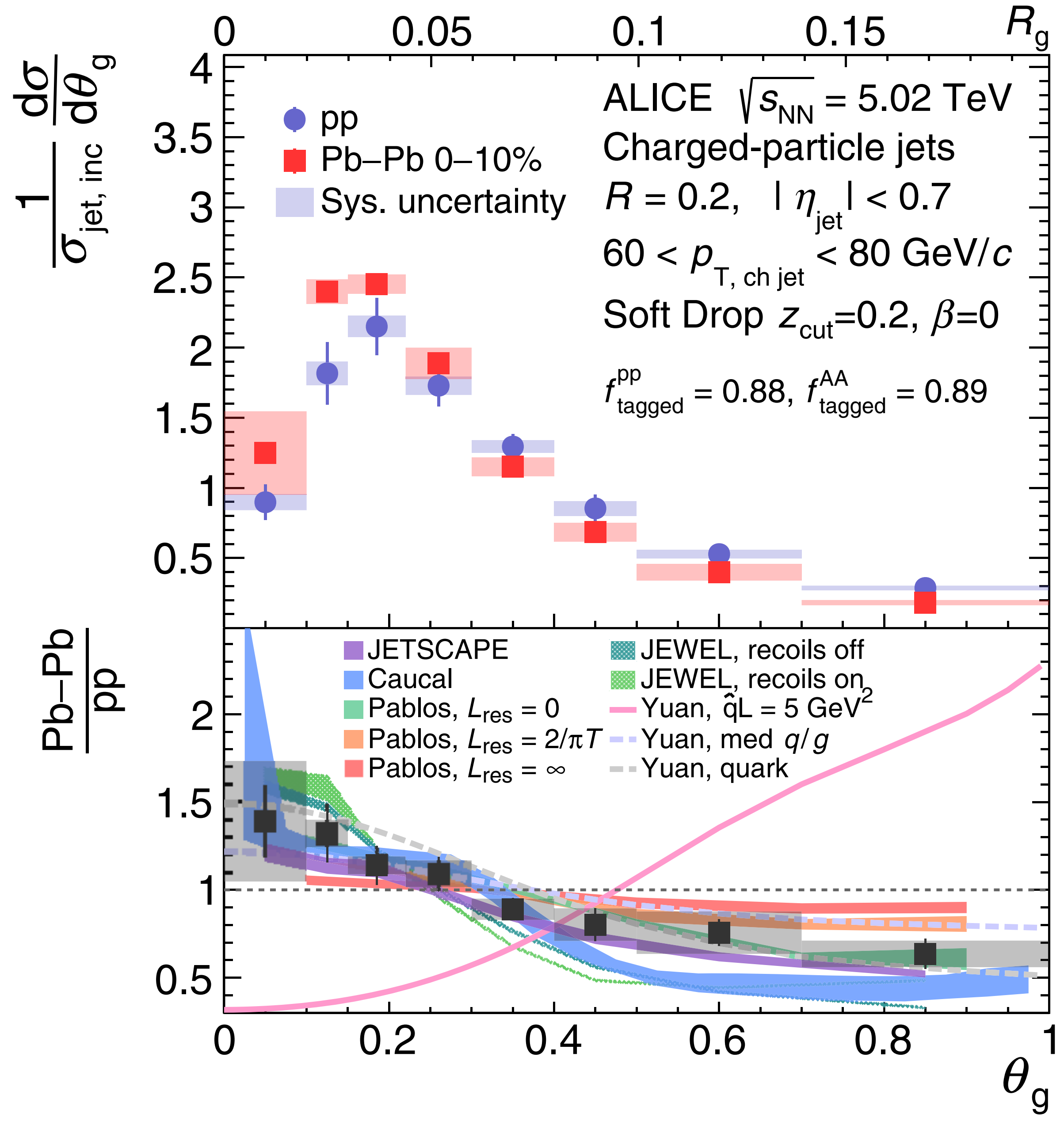


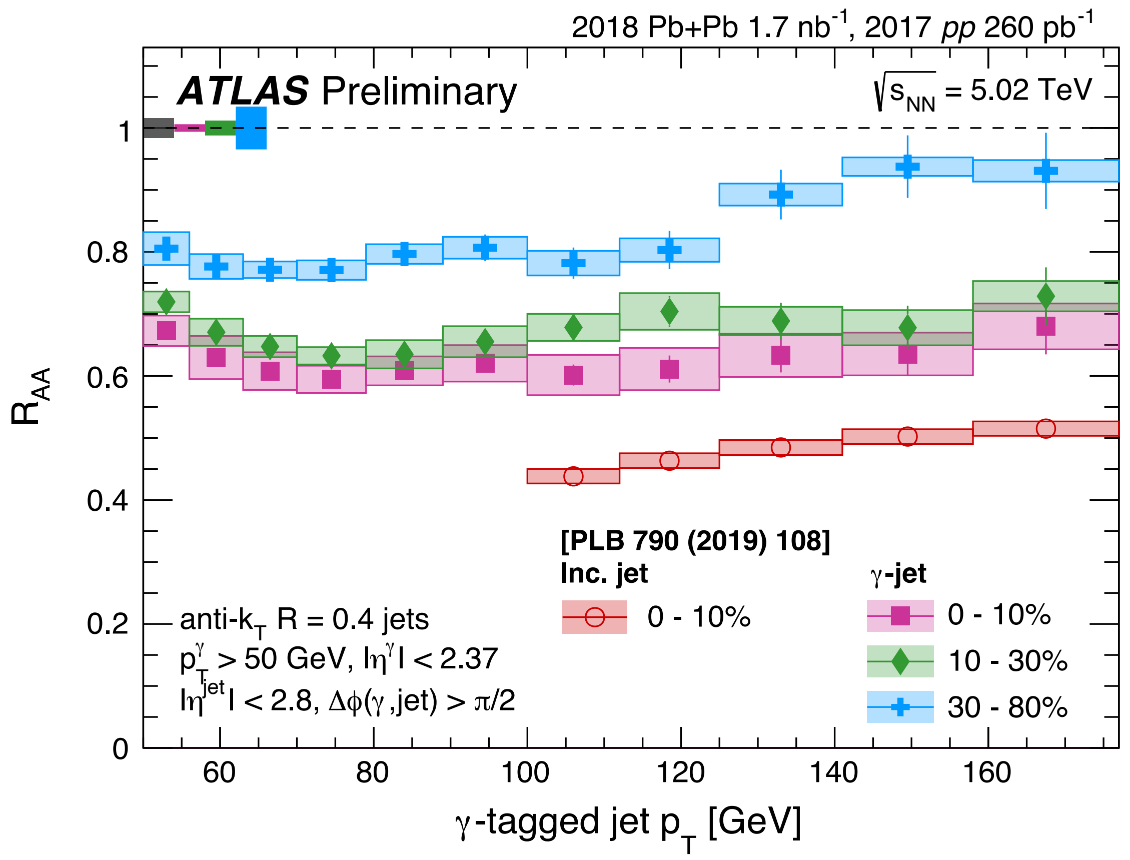
Prong structure?

Starting to perform controlled experiments to **isolate what controls the physics**

What governs parton energy loss?

ALICE, PRL 128 (2022) 102001





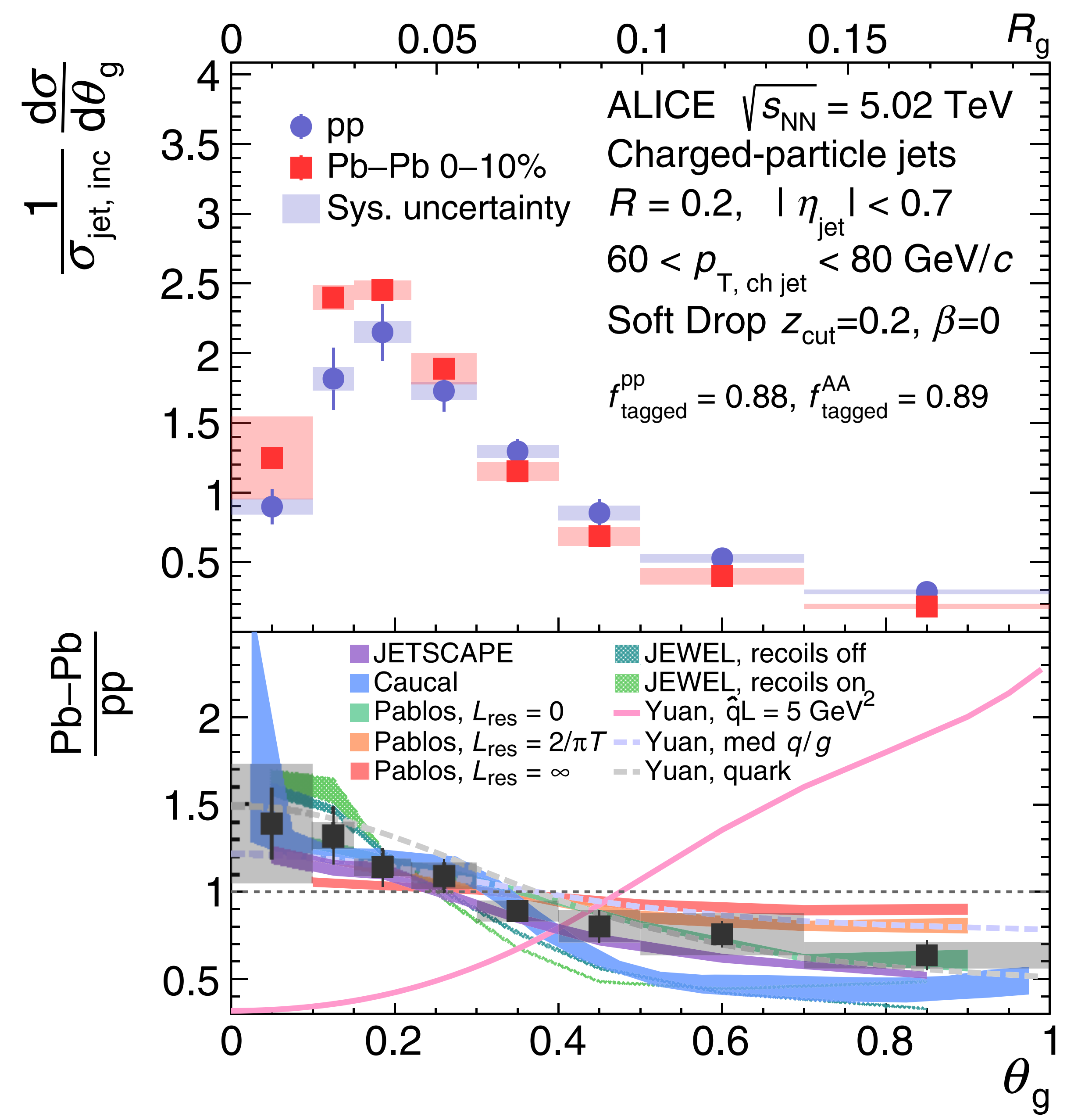
Prong structure?

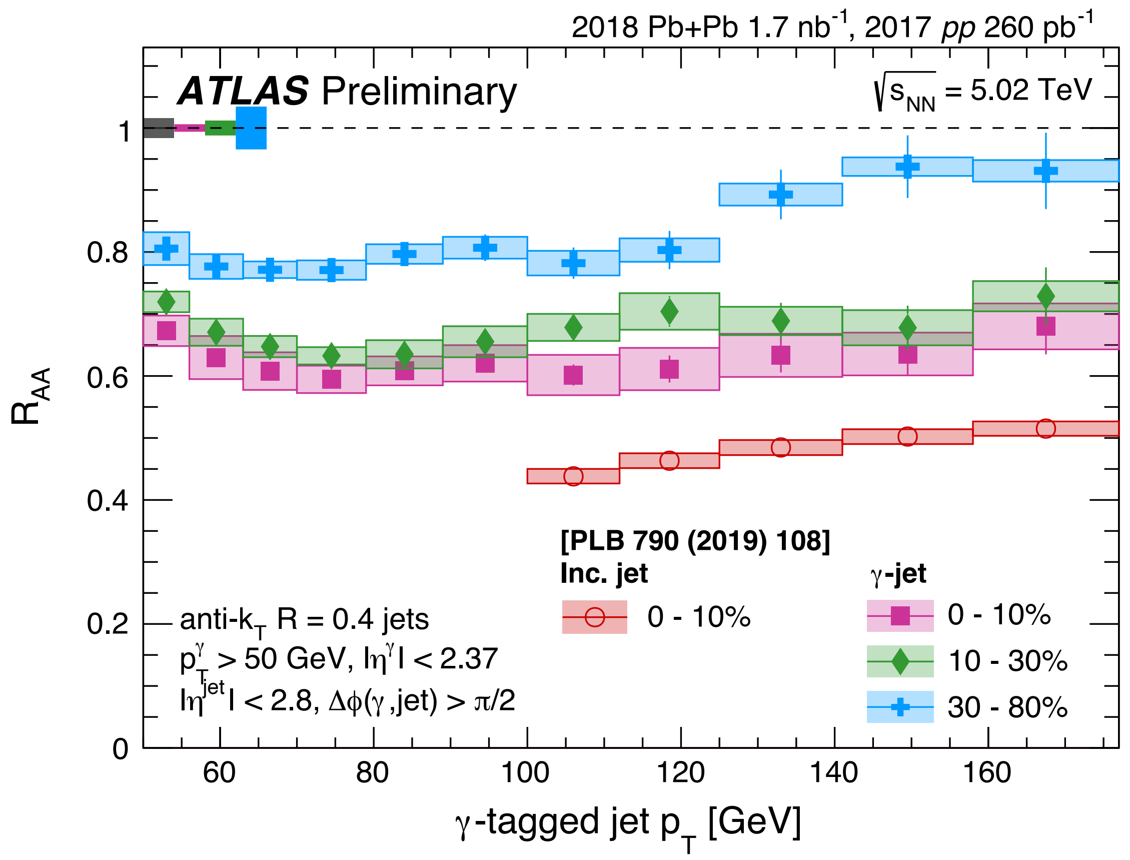
Color charge?

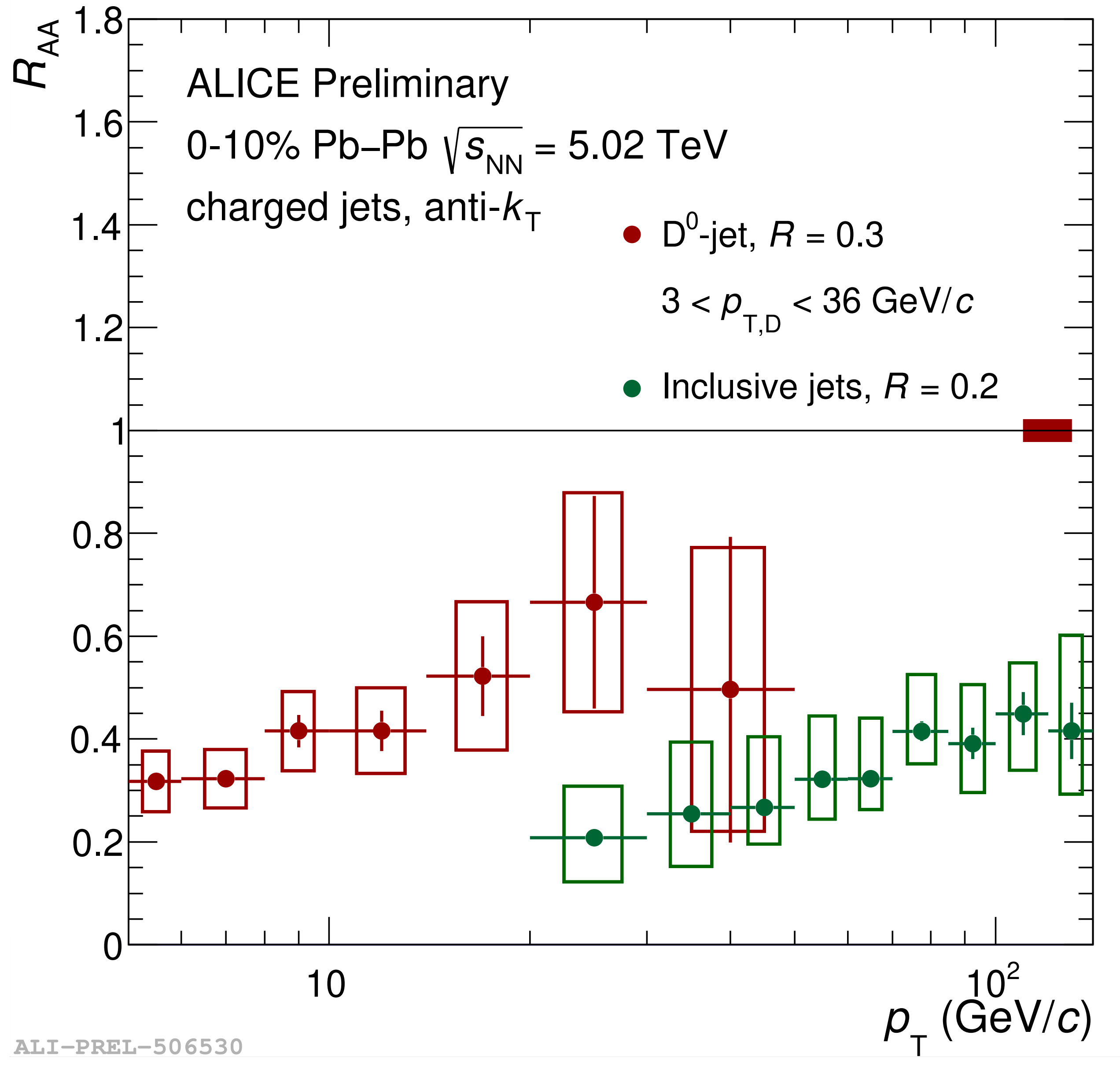
Starting to perform controlled experiments to **isolate what controls the physics**

What governs parton energy loss?

ALICE, PRL 128 (2022) 102001







Prong structure?

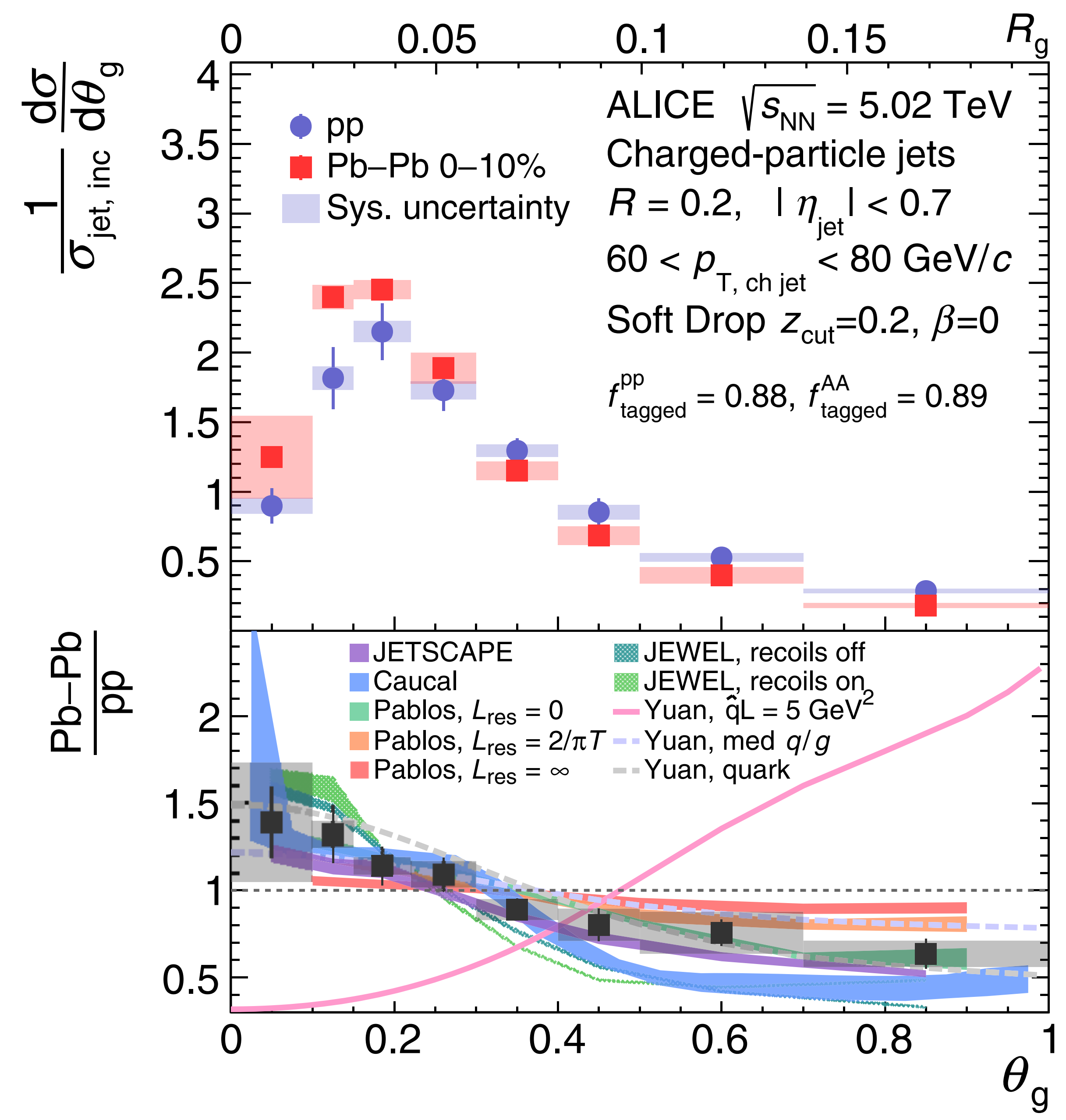
Color charge?

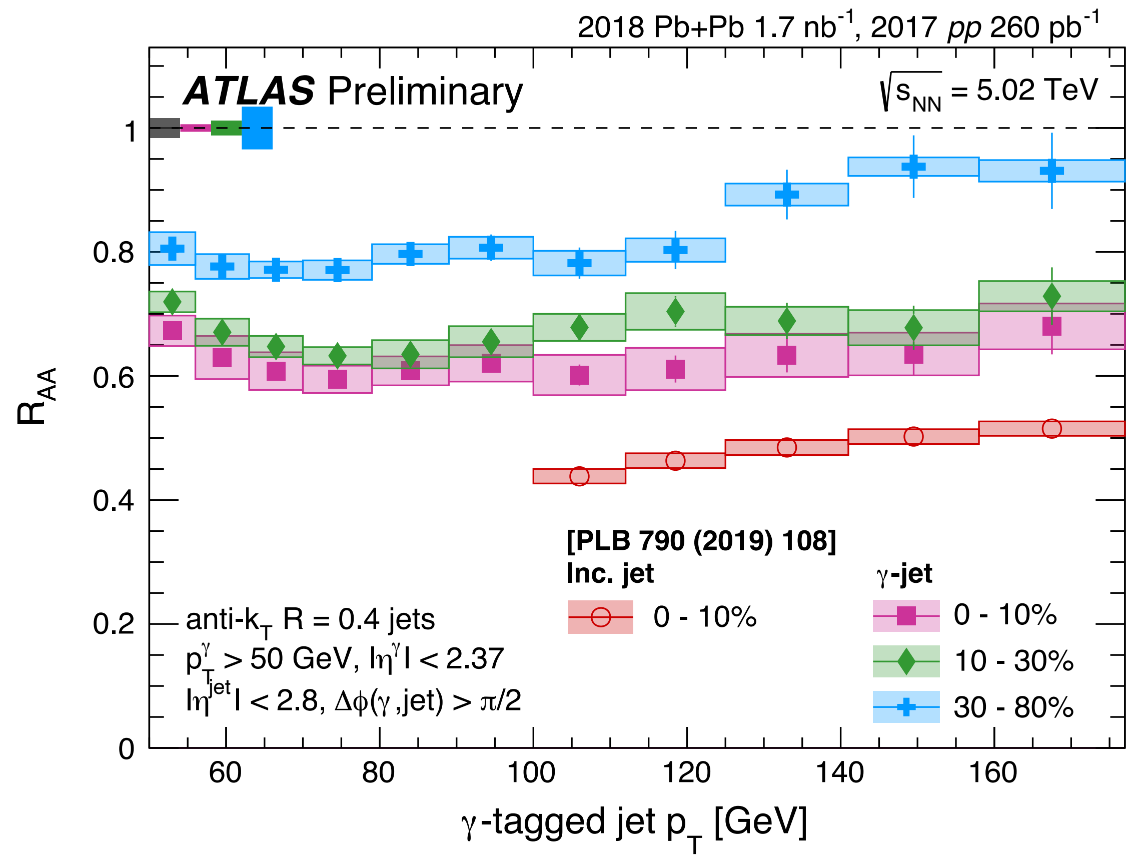
Parton mass?

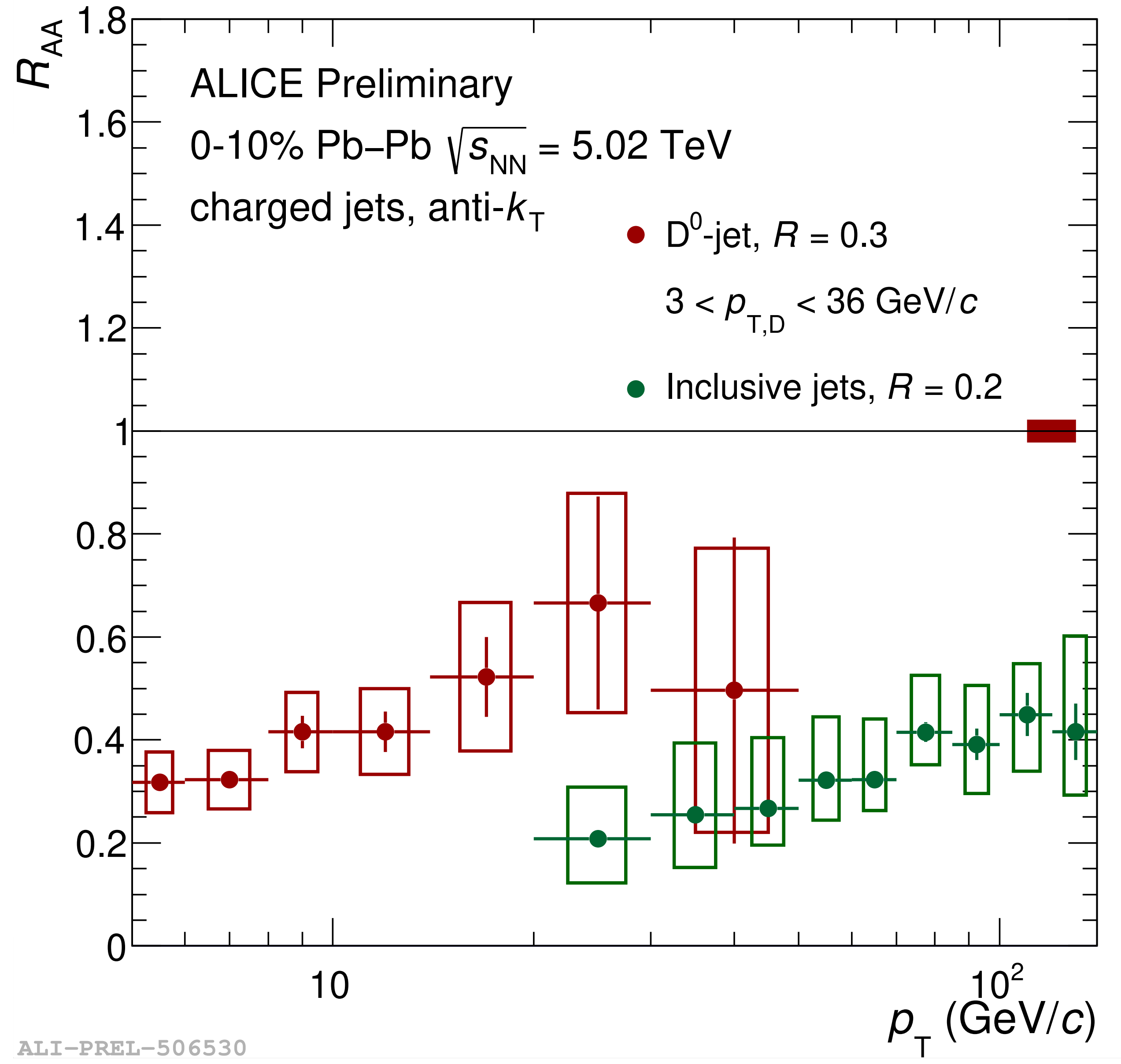
Starting to perform controlled experiments to **isolate what controls the physics**

What governs parton energy loss?

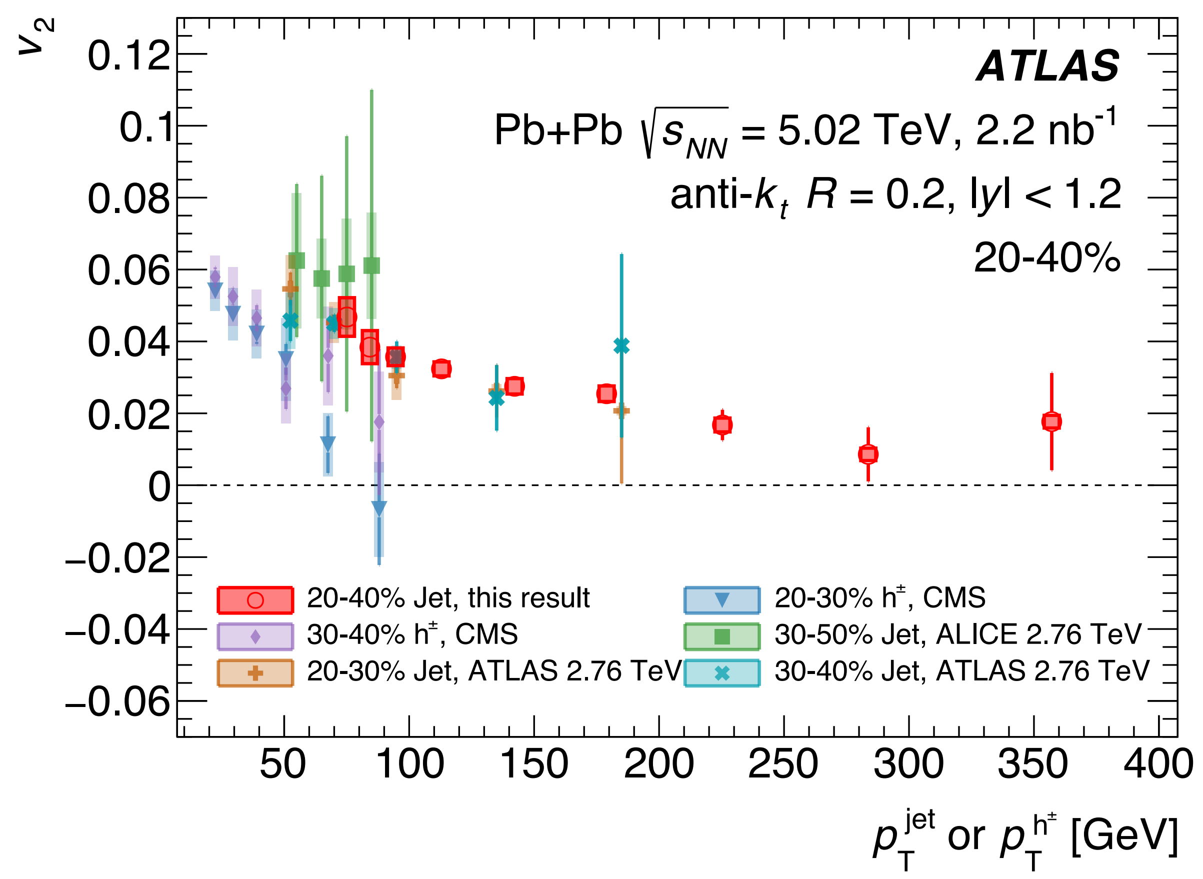
ALICE, PRL 128 (2022) 102001







ATLAS, PRC 105 (2022) 064903



Prong structure?

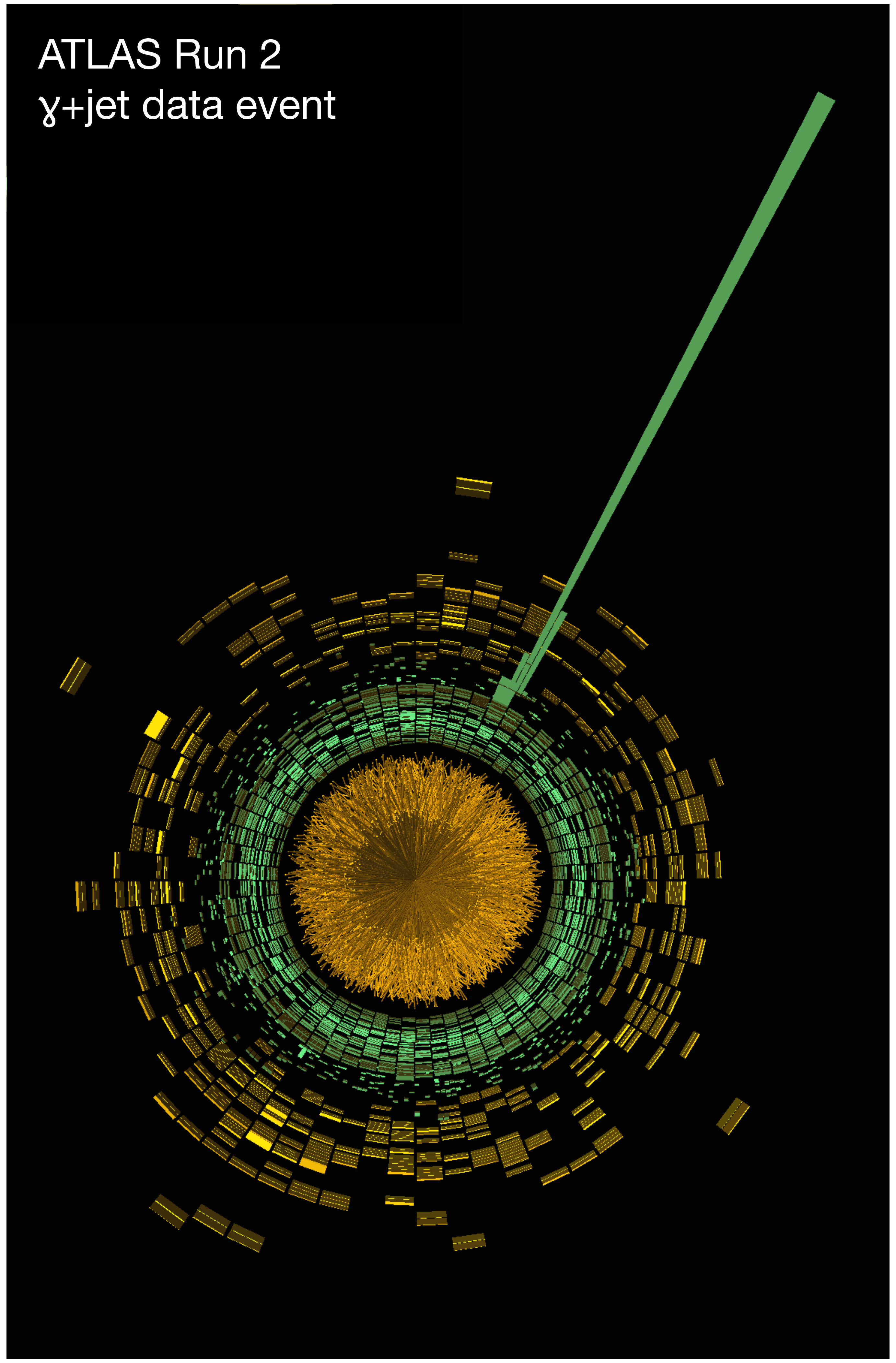
Color charge?

Parton mass?

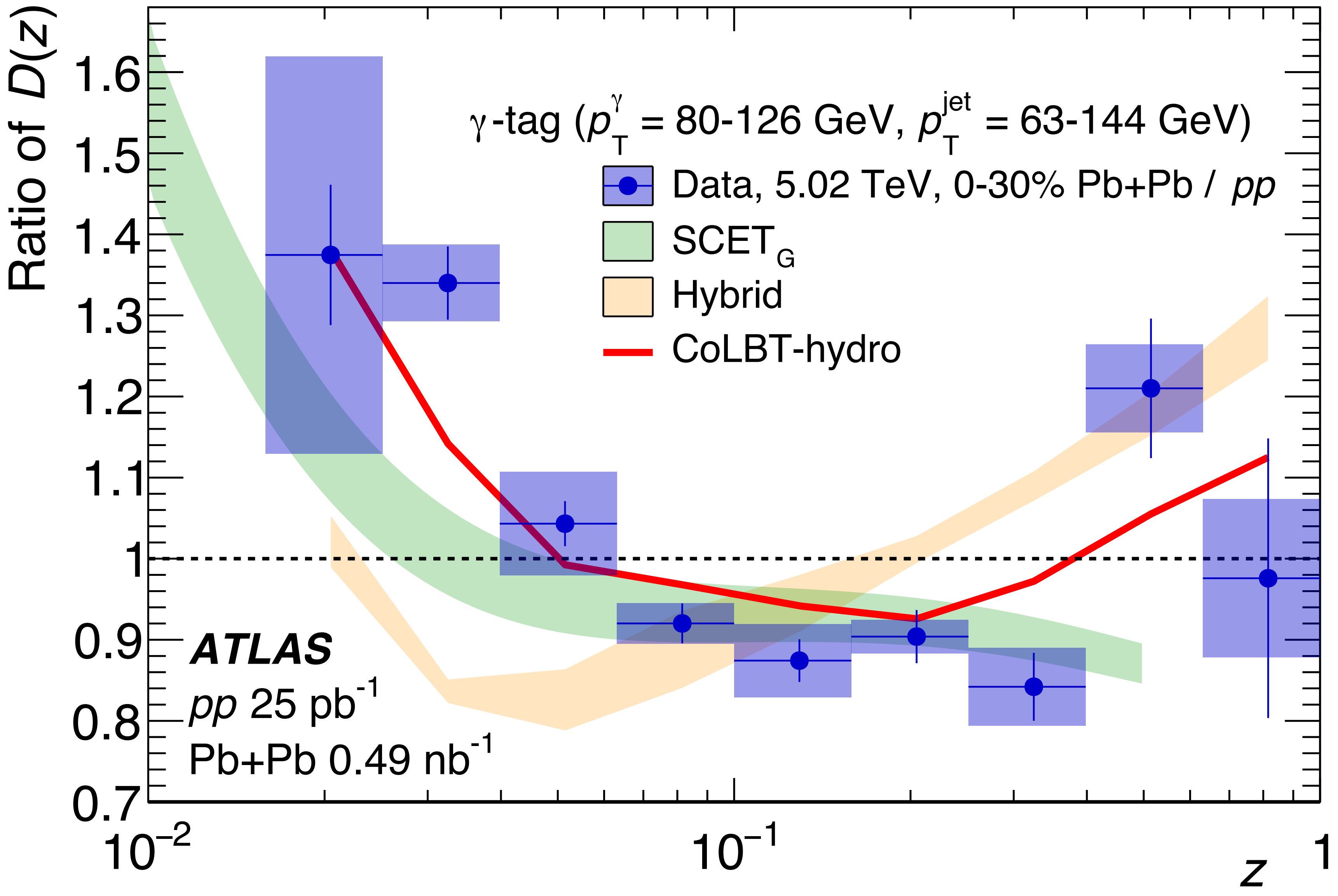
Path length vs. fluctuations?

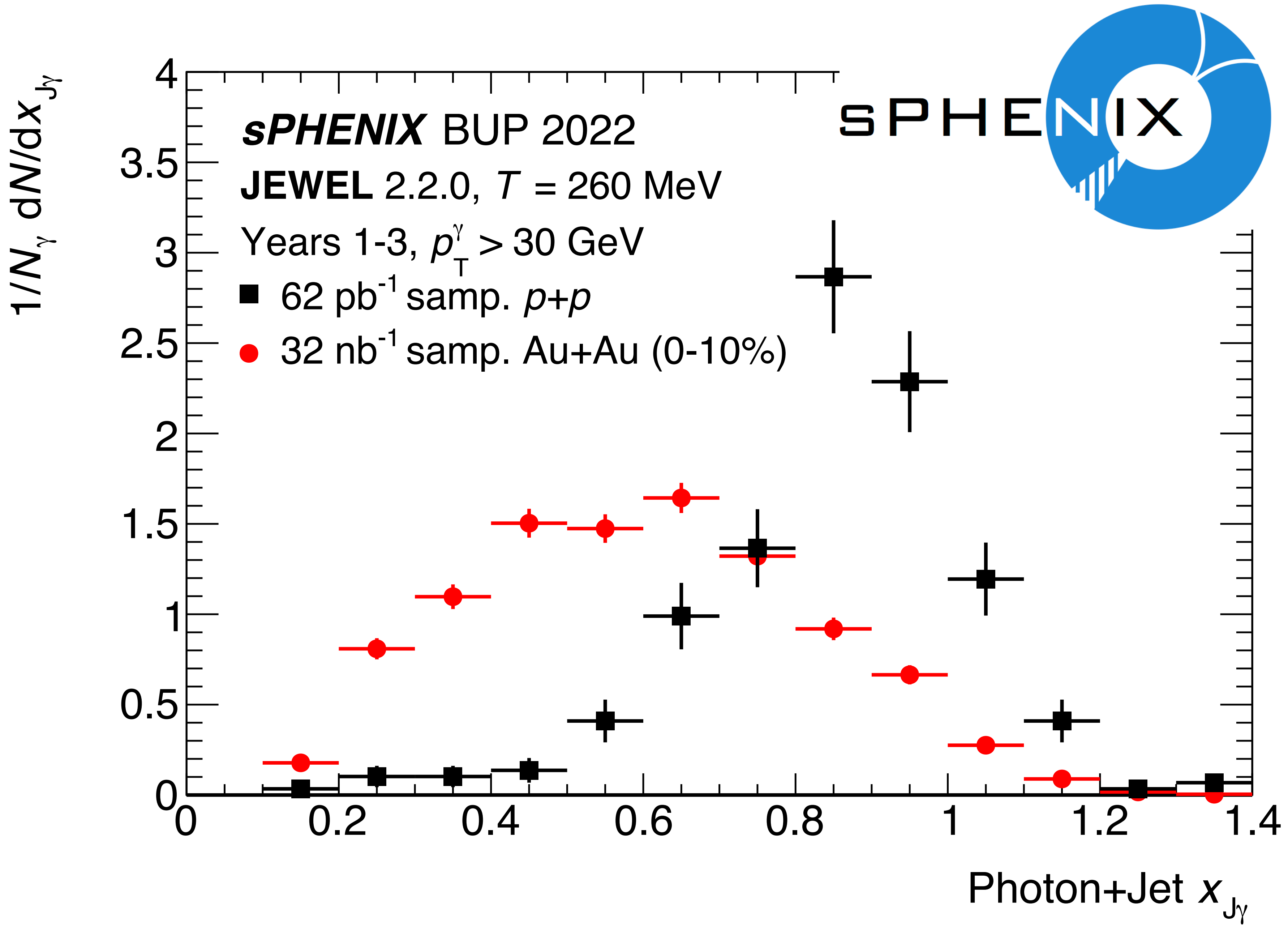
Starting to perform controlled experiments to **isolate what controls the physics**

Tomography with calibrated probes (ɣ/Z)



ATLAS, PRL 123 (2019) 042001





Jet quenching with **unbiased tag on initial kinematics**

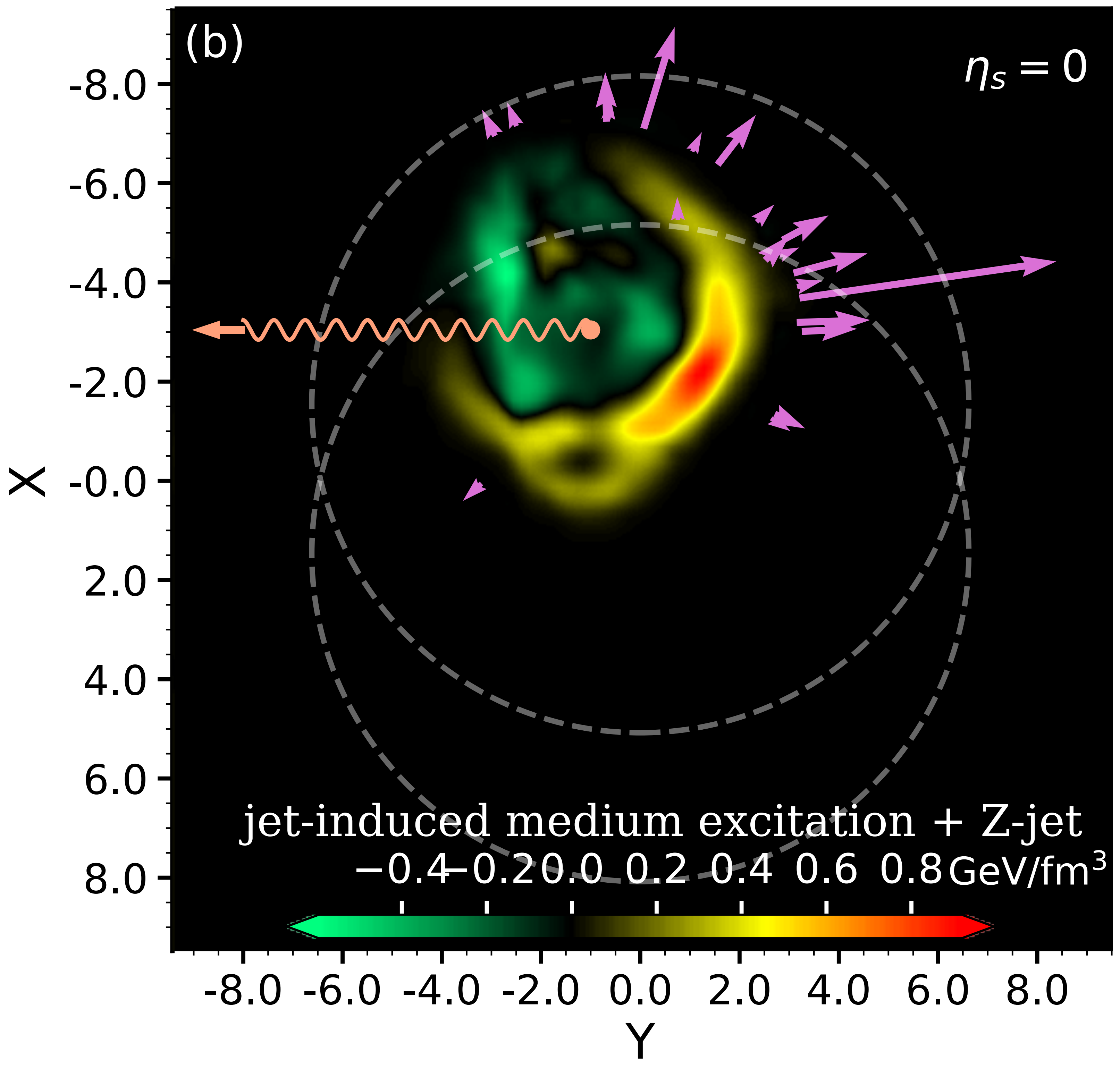
(ɣ/Z+jets in LHC Runs 3+4)
≈ # (inclusive jets in Run-1)

RHIC particularly suitable for Direct ɣ's: unprecedented statistics at sPHENIX+STAR

The aftermath of a jet's passage

Yang et al, PRL. 127 (2021) 082301

Recoiling boson ←



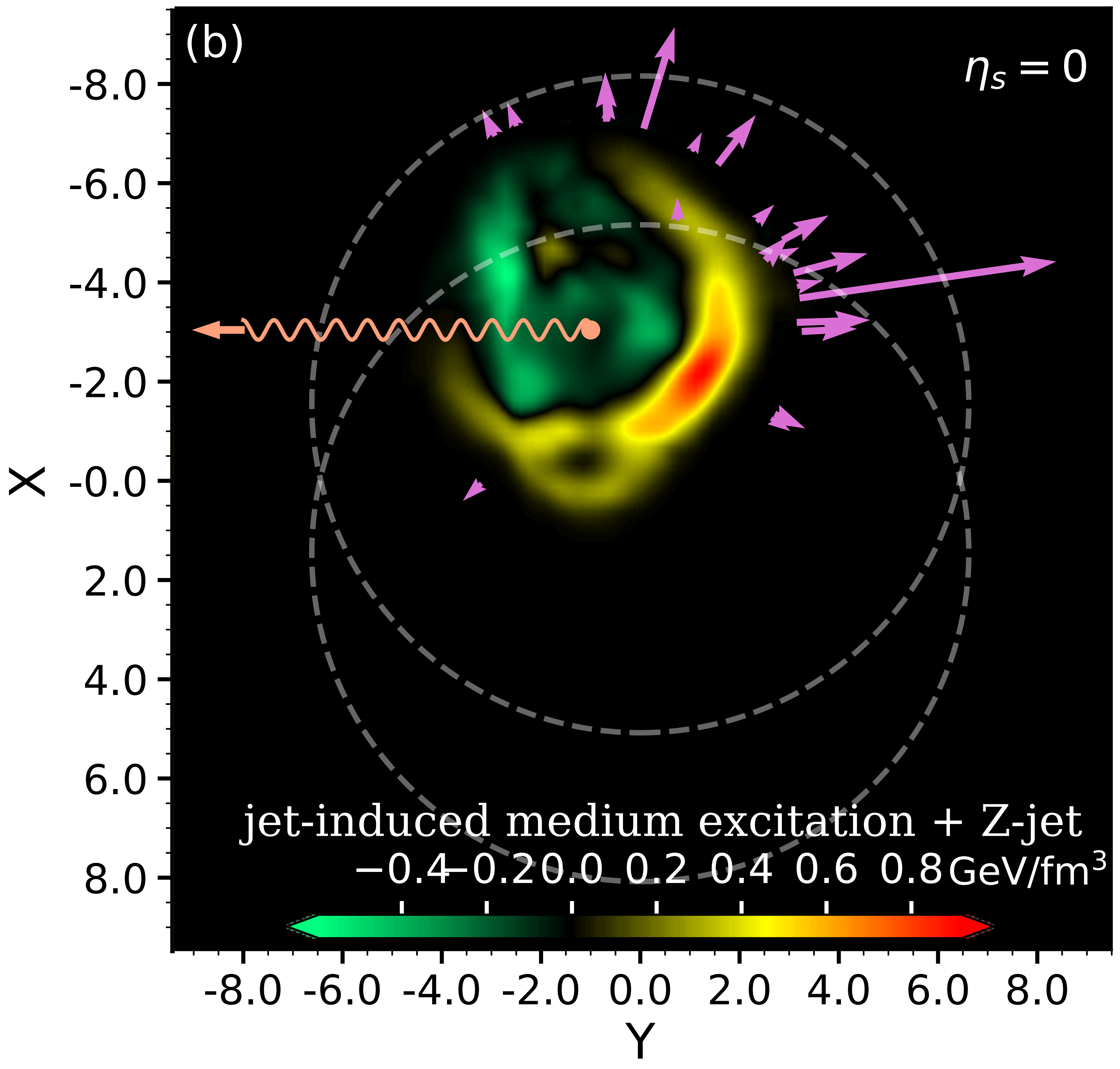
→ **Jet**

Study **thermalization process** with a source of deposited energy after QGP formation

The aftermath of a jet's passage

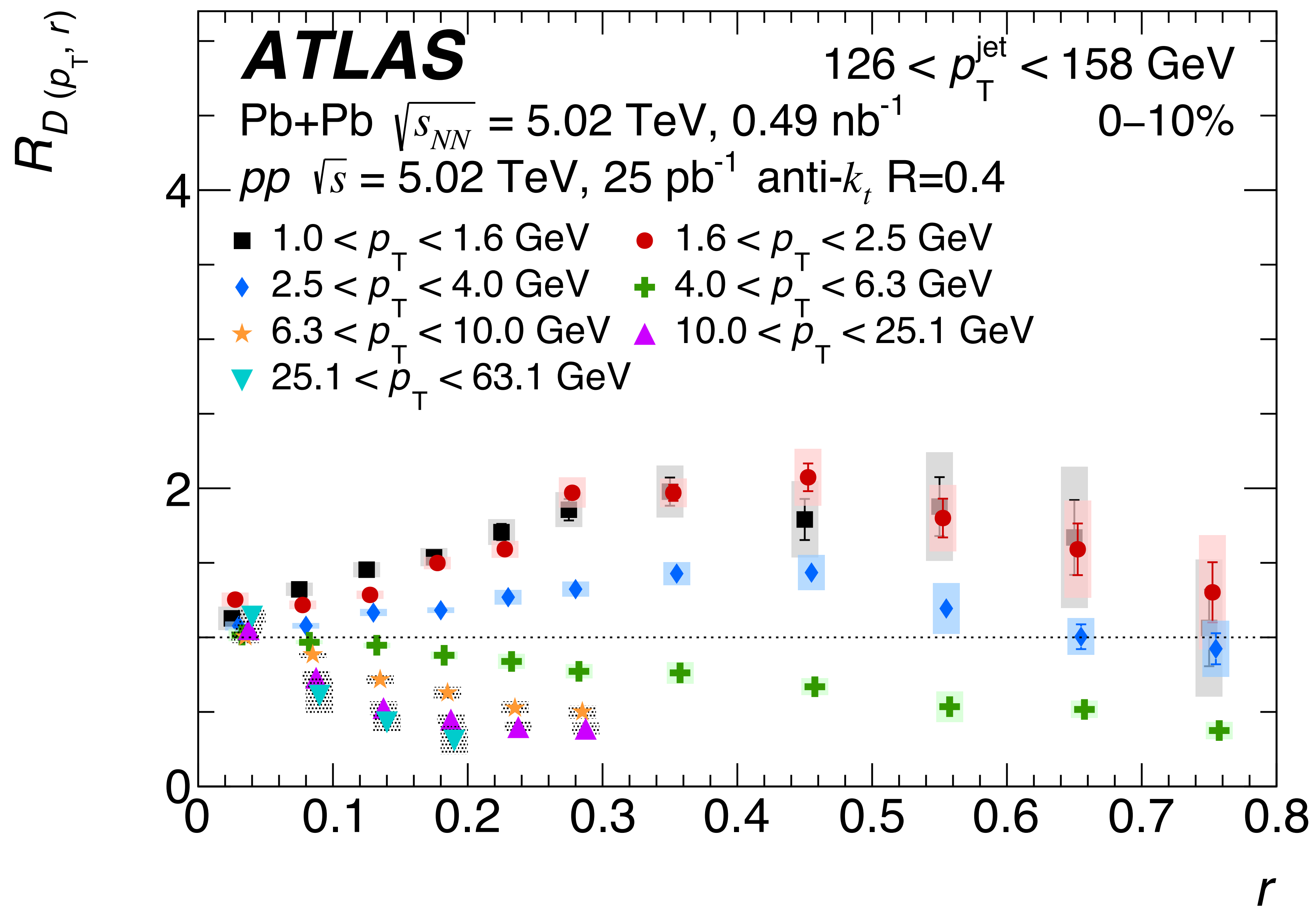
Recoiling boson

Yang et al, PRL. 127 (2021) 082301



Study **thermalization process** with a source of deposited energy after QGP formation

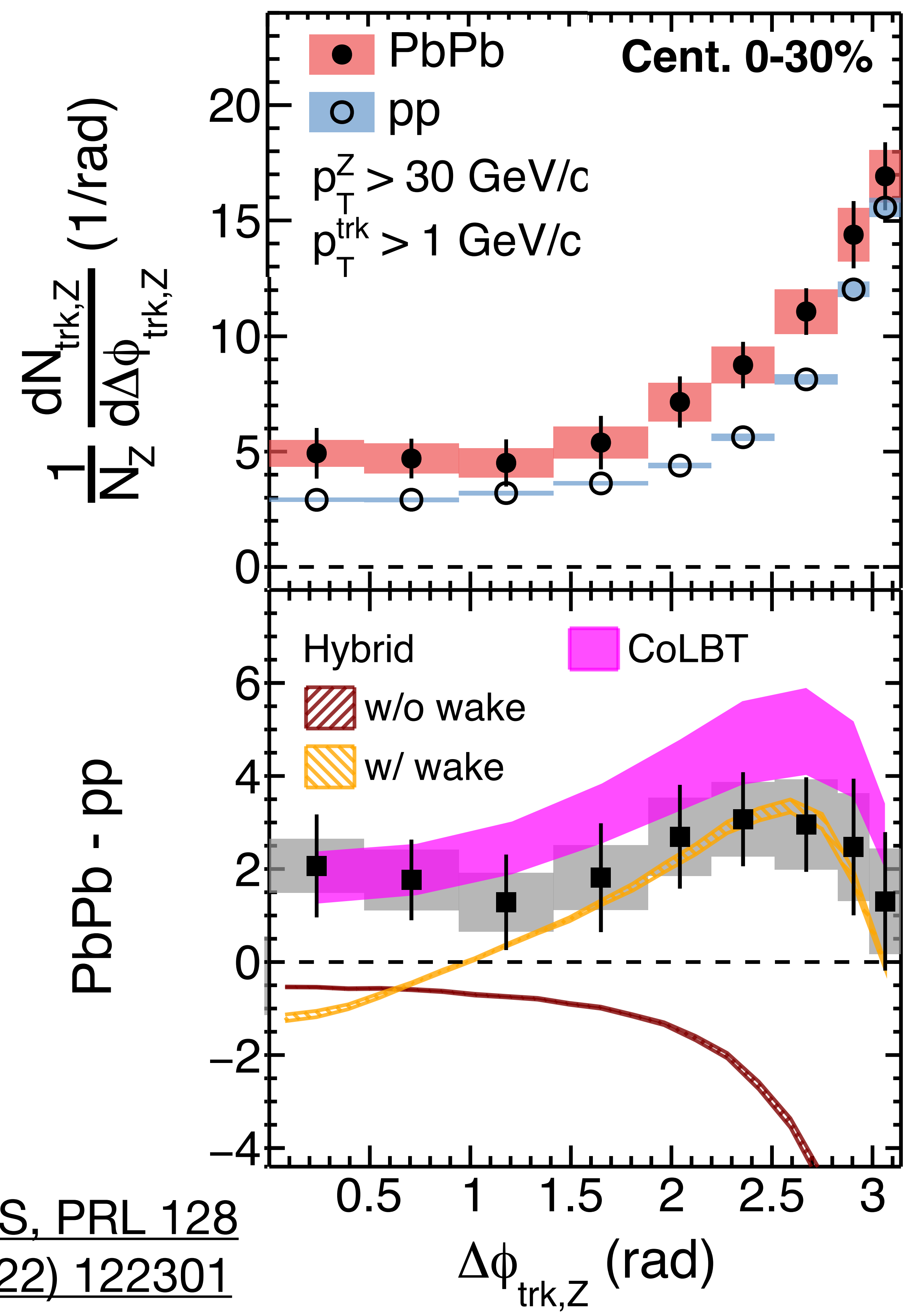
ATLAS, PRC 100 (2019) 064901



Map out flow of lost energy into **"medium-like" angular & momentum modes**

(also: Large-R jets)

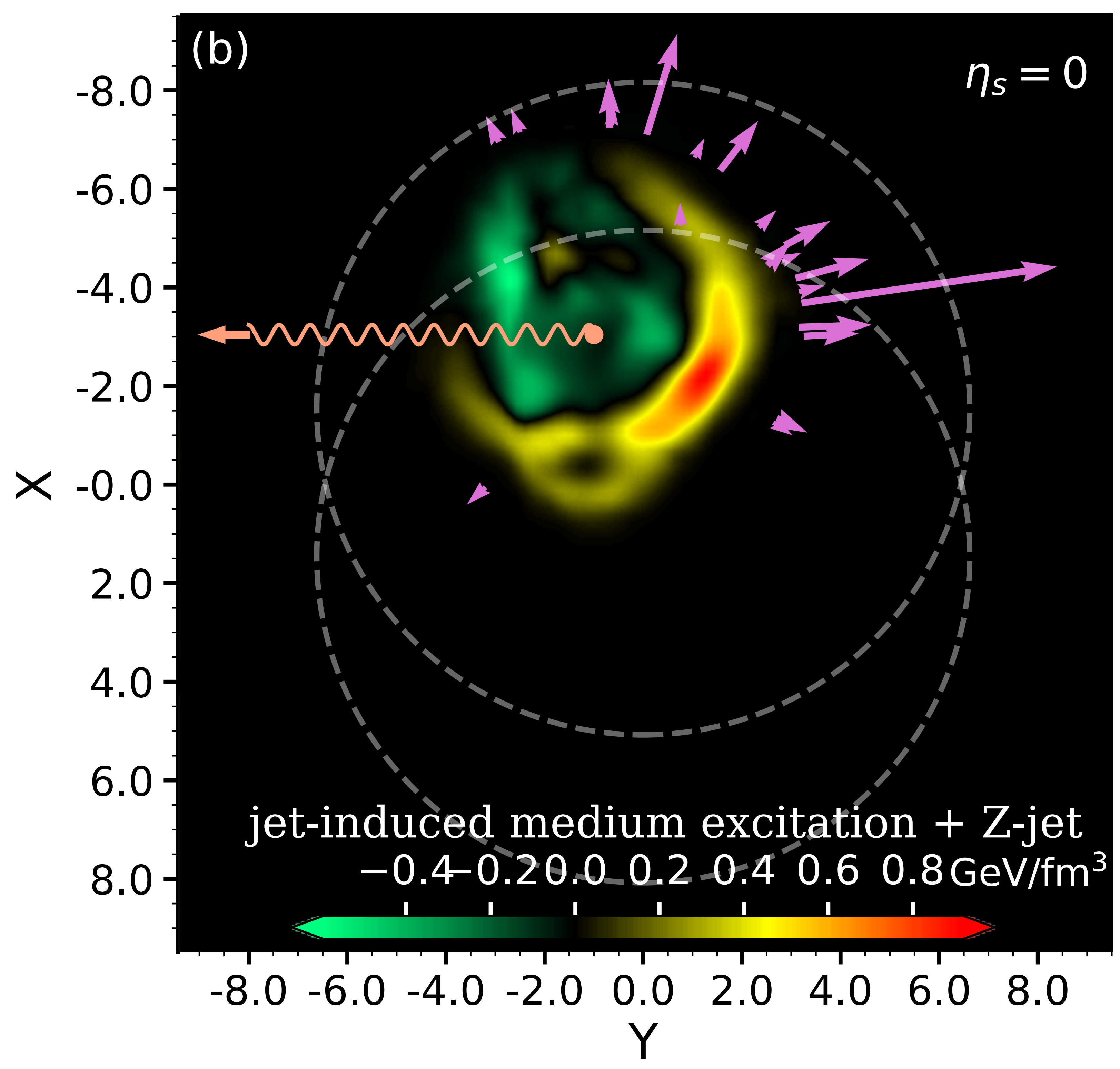
The aftermath of a jet's passage



CMS, PRL 128 (2022) 122301

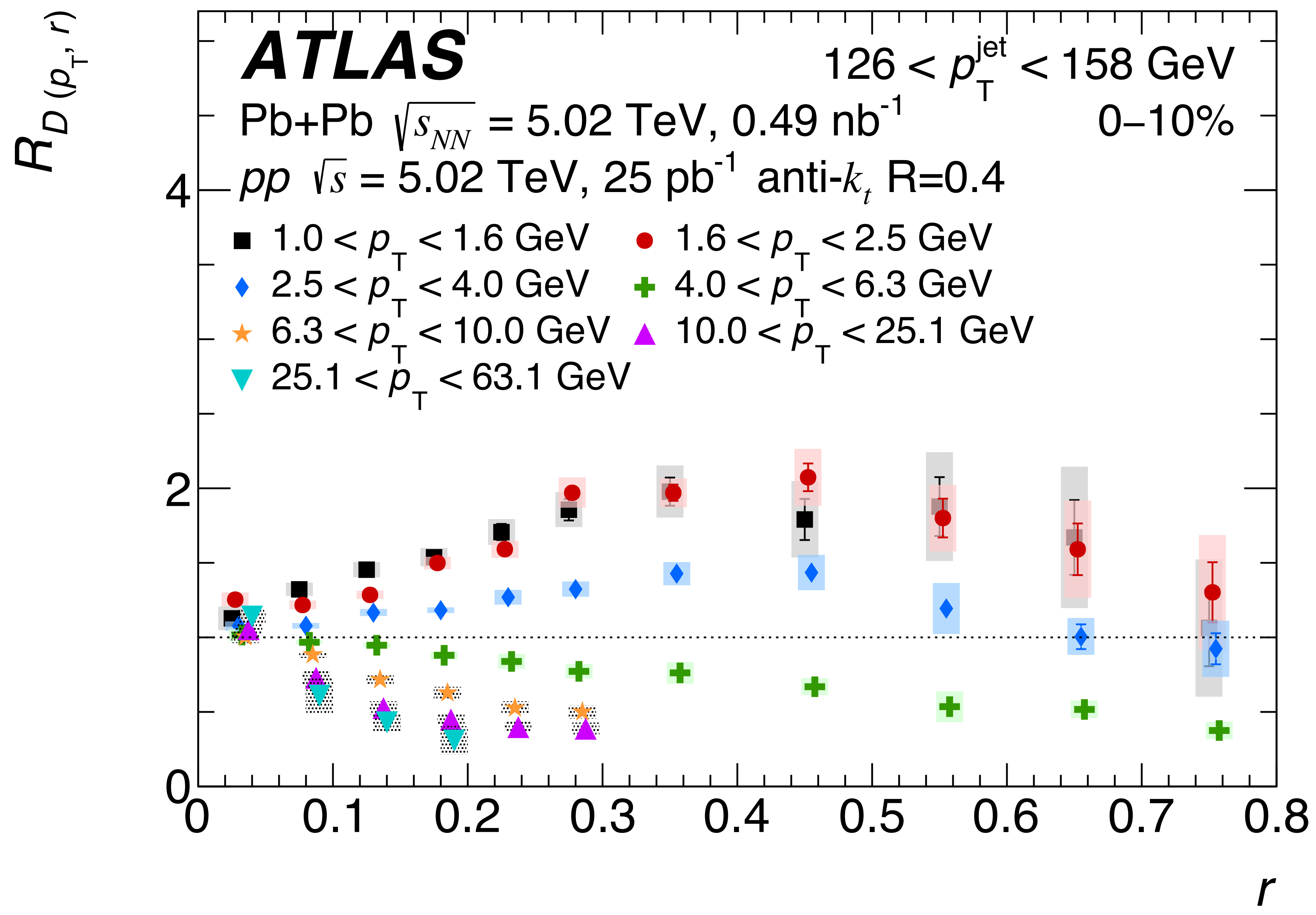
Searches for **diffusion wake** on the near-side - big experimental challenge

Yang et al, PRL. 127 (2021) 082301



Study **thermalization process** with a source of deposited energy after QGP formation

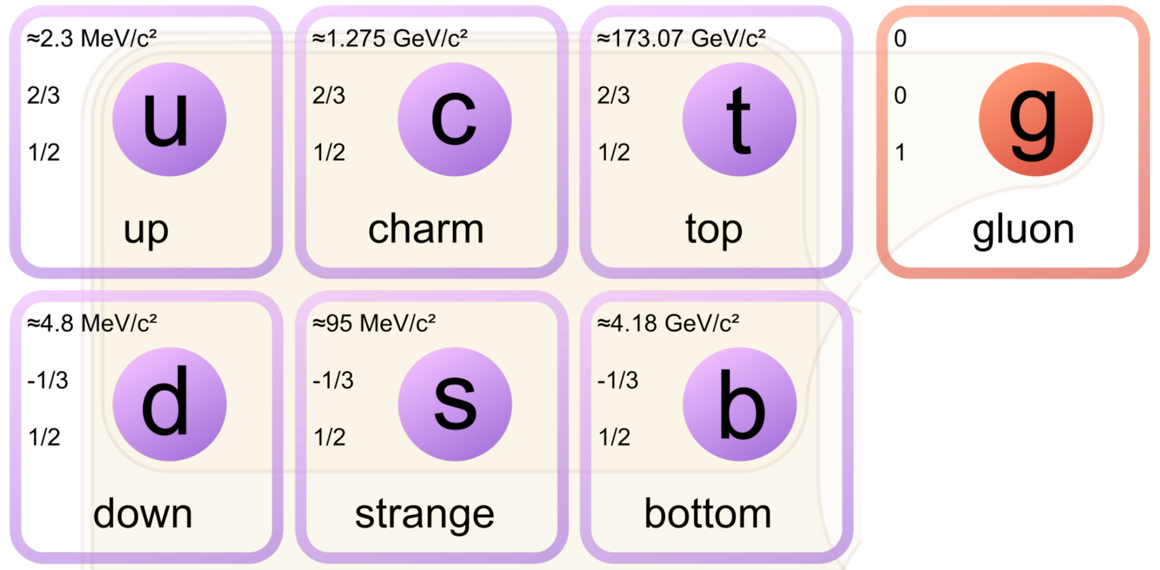
ATLAS, PRC 100 (2019) 064901



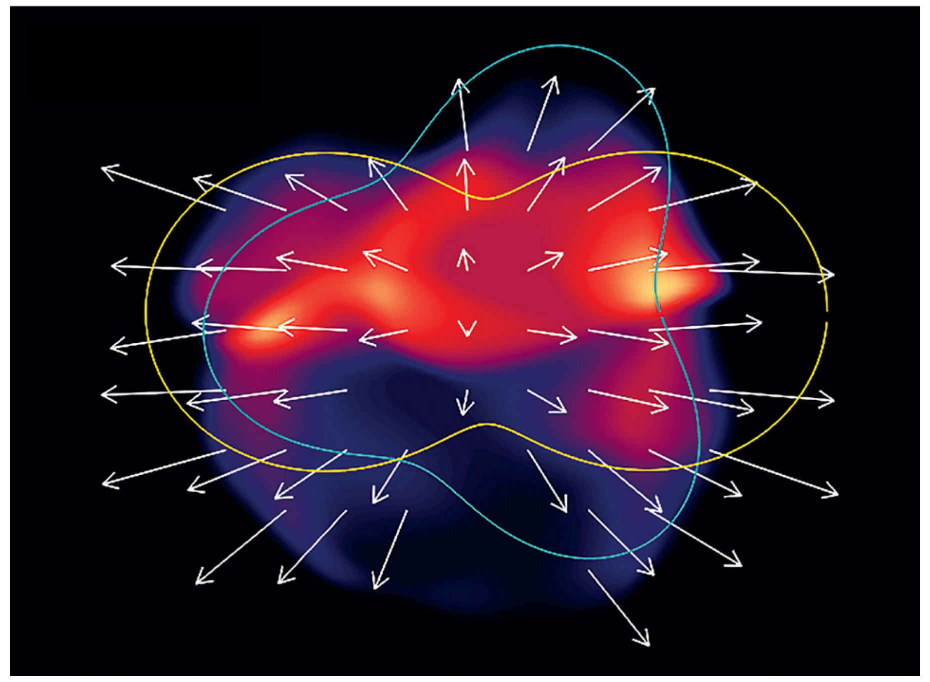
Map out flow of lost energy into **"medium-like" angular & momentum modes**

(also: Large-R jets)

Scale-dependent QGP structure

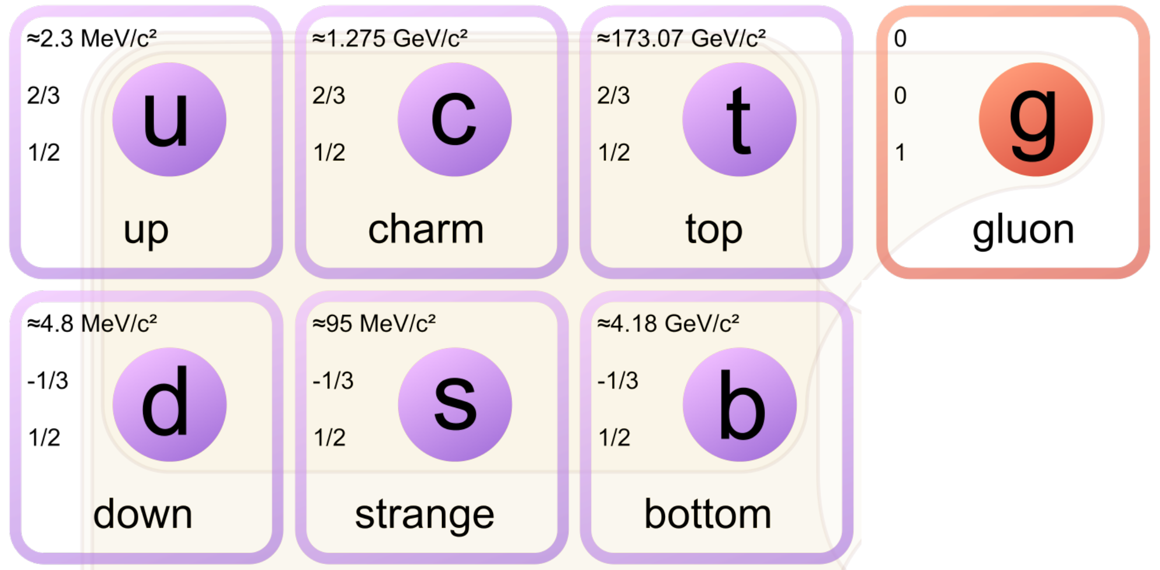


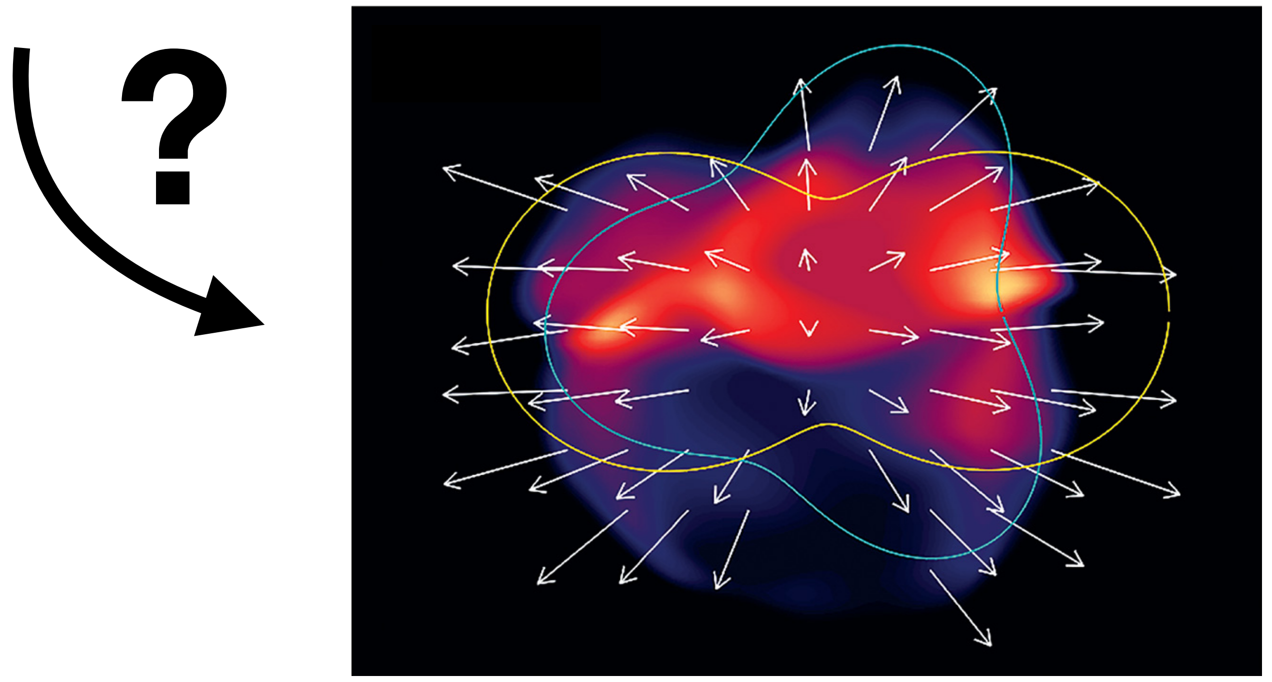
?

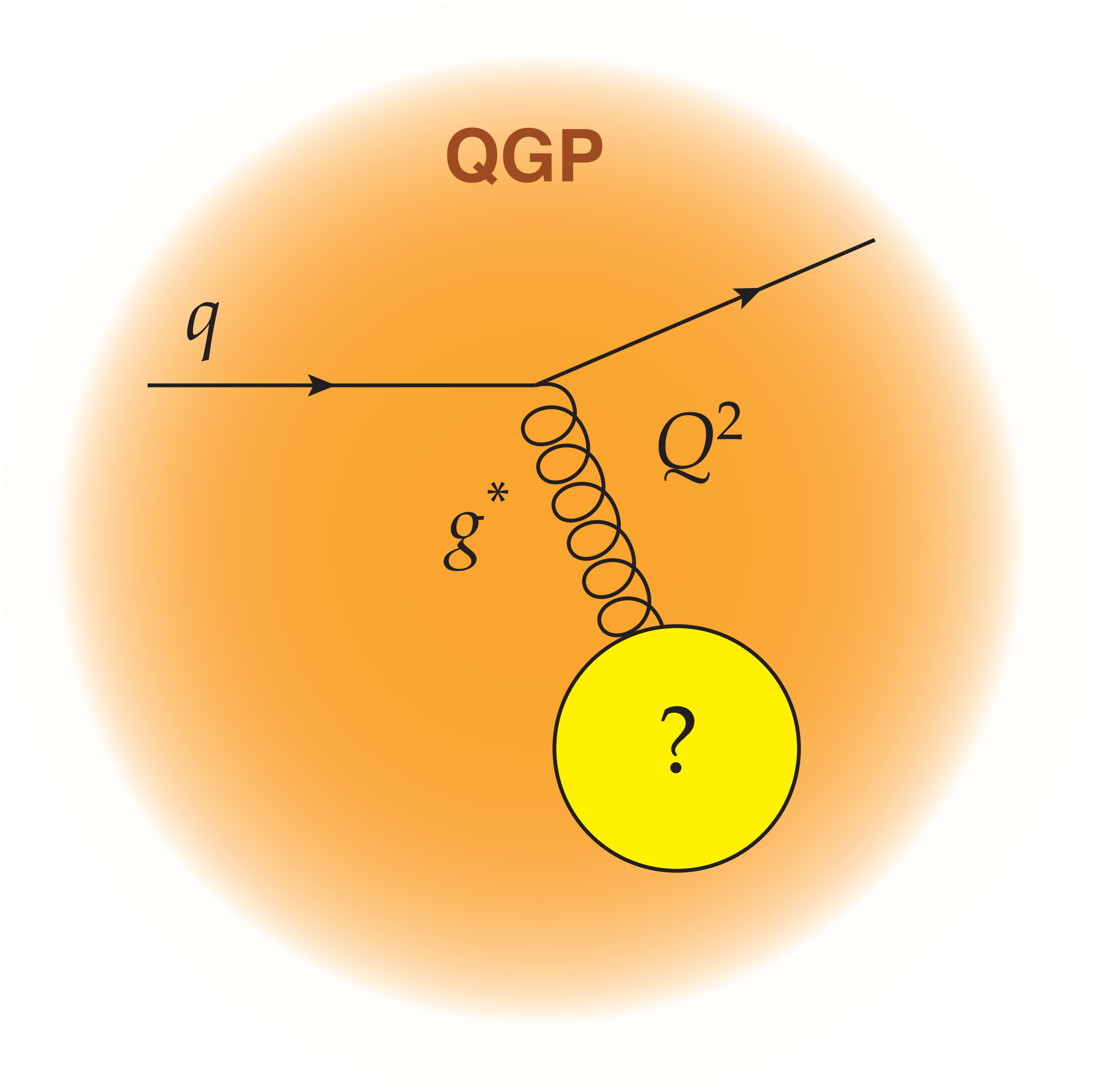


How does large-wavelength phenomena **emerge from QCD degrees of freedom**?

Scale-dependent QGP structure



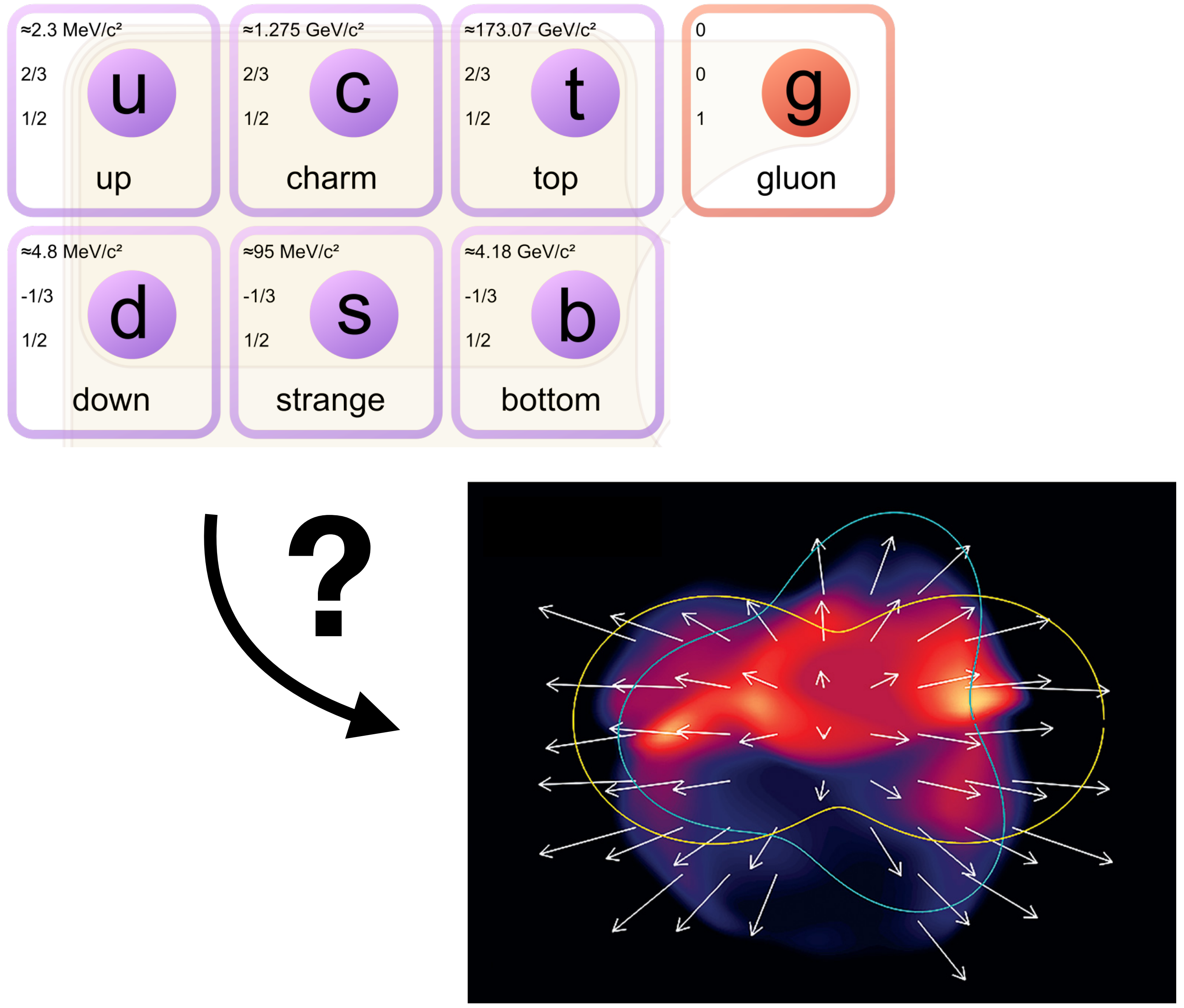


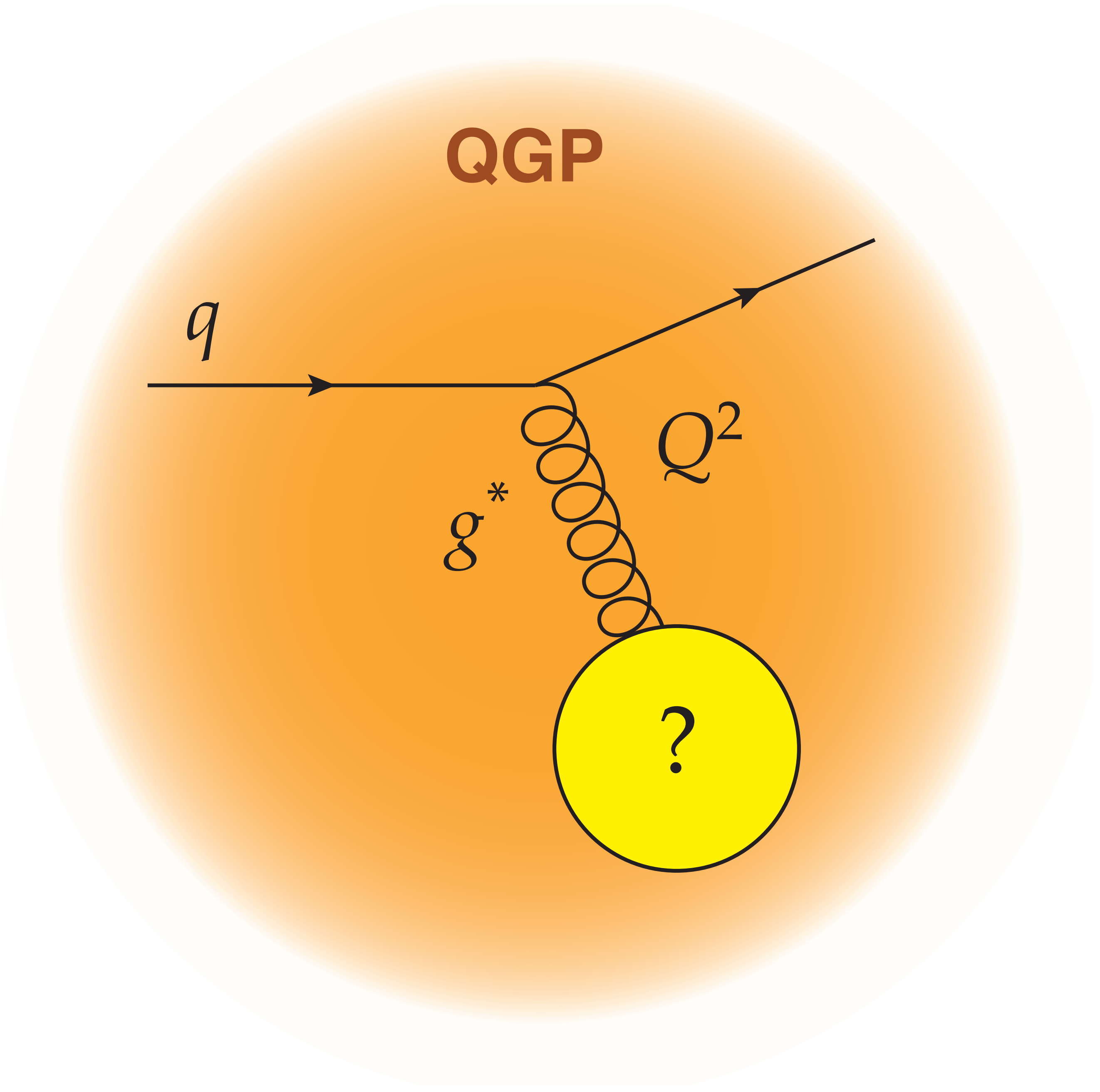


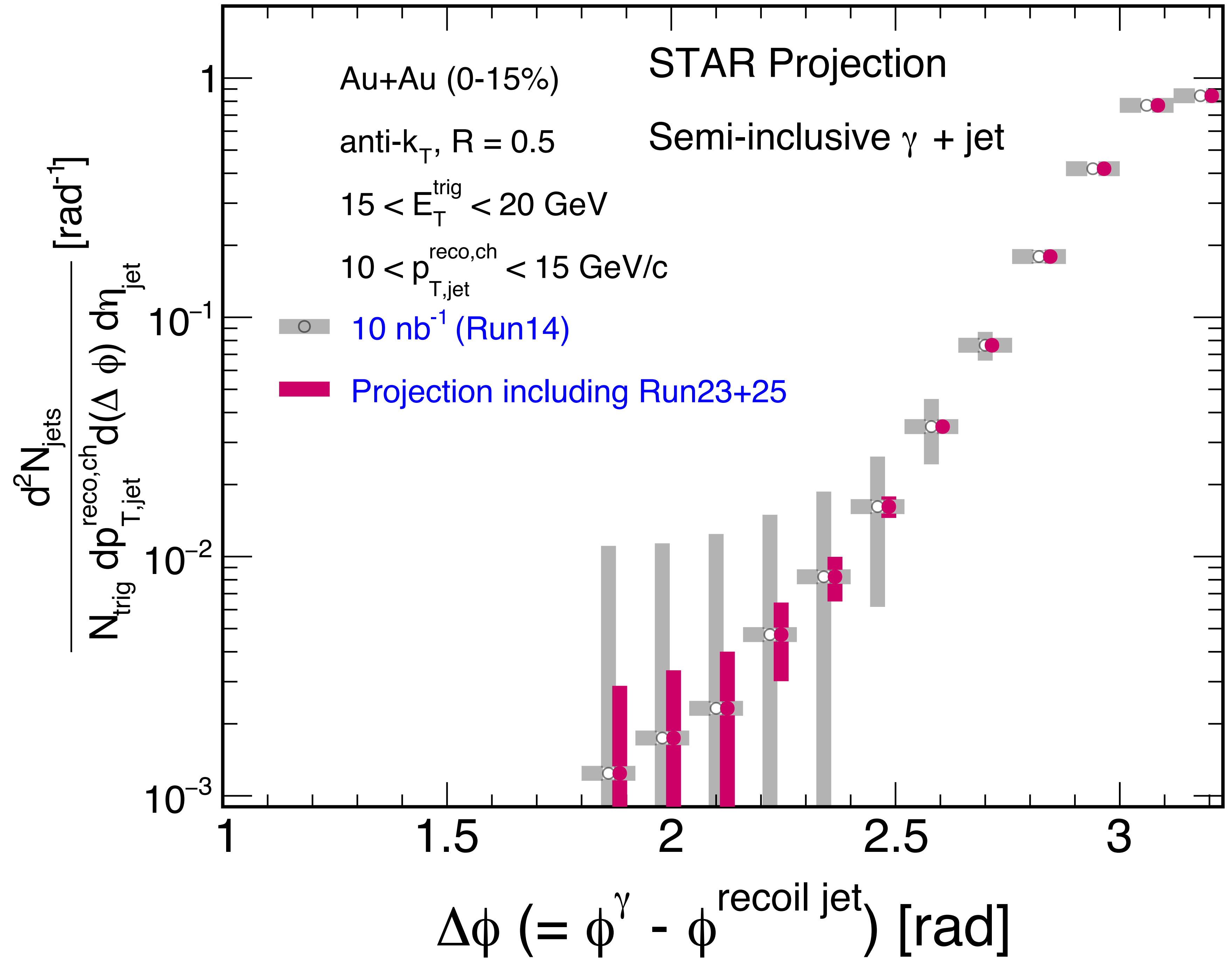
How does large-wavelength phenomena **emerge from QCD degrees of freedom?**

Molière scattering: opportunity to **identify intermediate scale structure of the QGP**

Scale-dependent QGP structure







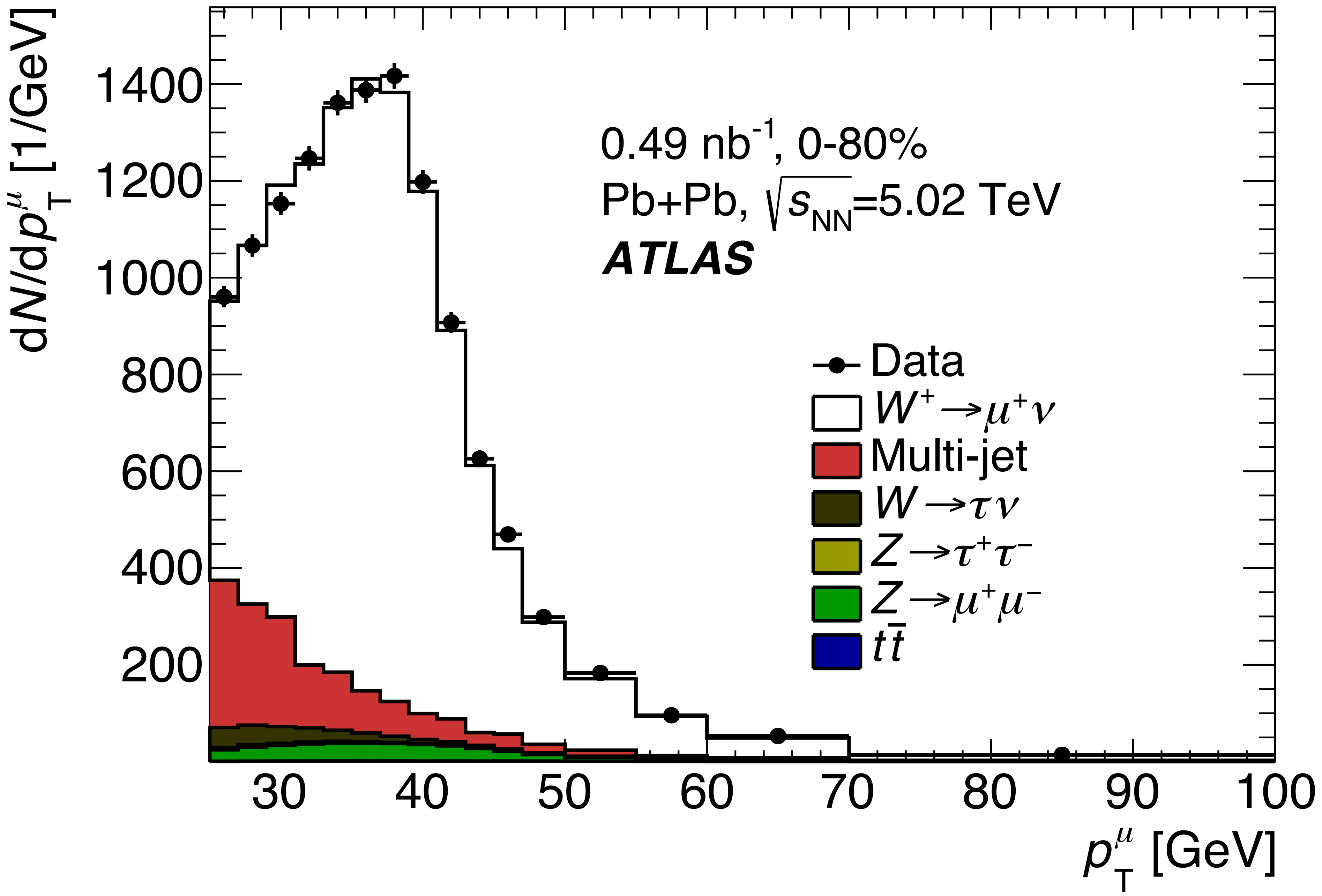
How does large-wavelength phenomena **emerge from QCD degrees of freedom**?

Molière scattering: opportunity to **identify intermediate scale structure of the QGP**

Do this measurement at RHIC - lower Q^2 and smaller competing vacuum/wake effects

New opportunities with $W^{\pm}$…

ATLAS, EPJC 79 (2019) 935

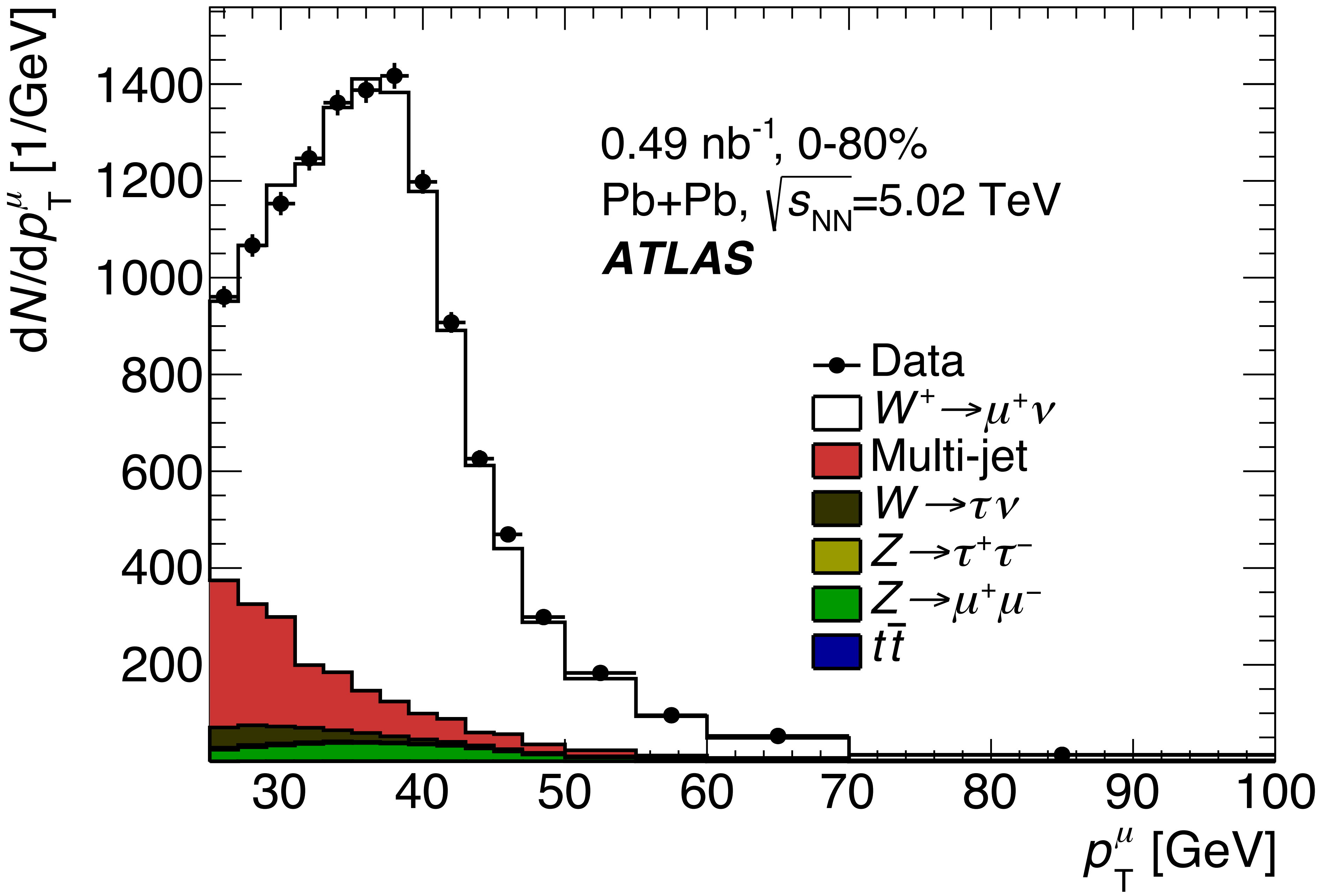


Experimentally demonstrated control in Run 2 Pb+Pb

$W^{\pm} \to l^{\pm}\nu$ is 8 times more numerous than $Z \to l^+l^-$!

New opportunities with $W^{\pm}$…

ATLAS, EPJC 79 (2019) 935

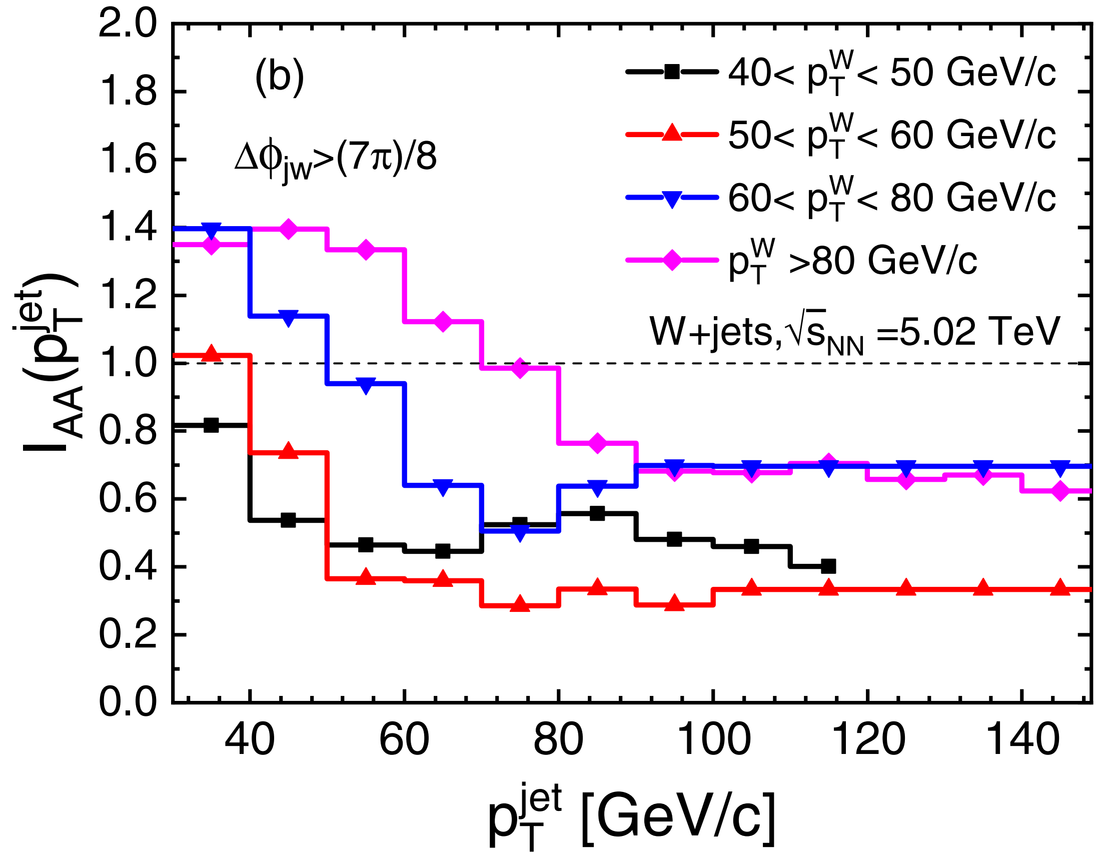


Experimentally demonstrated control in Run 2 Pb+Pb

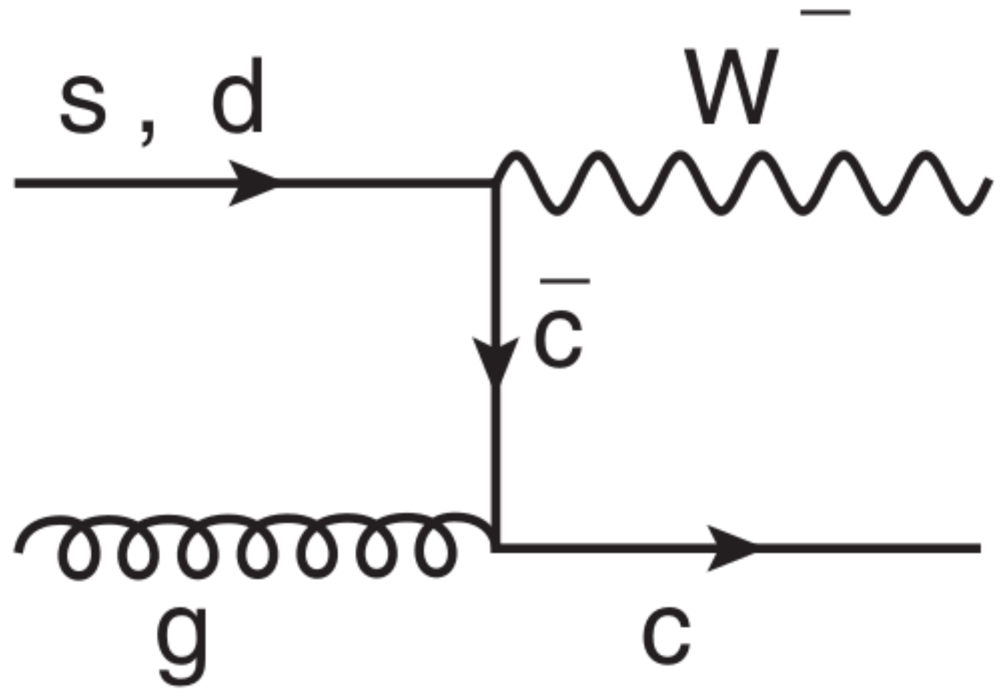
$W^{\pm} \to l^{\pm}\nu$ is 8 times more numerous than $Z \to l^+ l^-$!

1) "Standard" boson-tagged jet quenching

Zhang et al, PRC 105 (2022) 054902

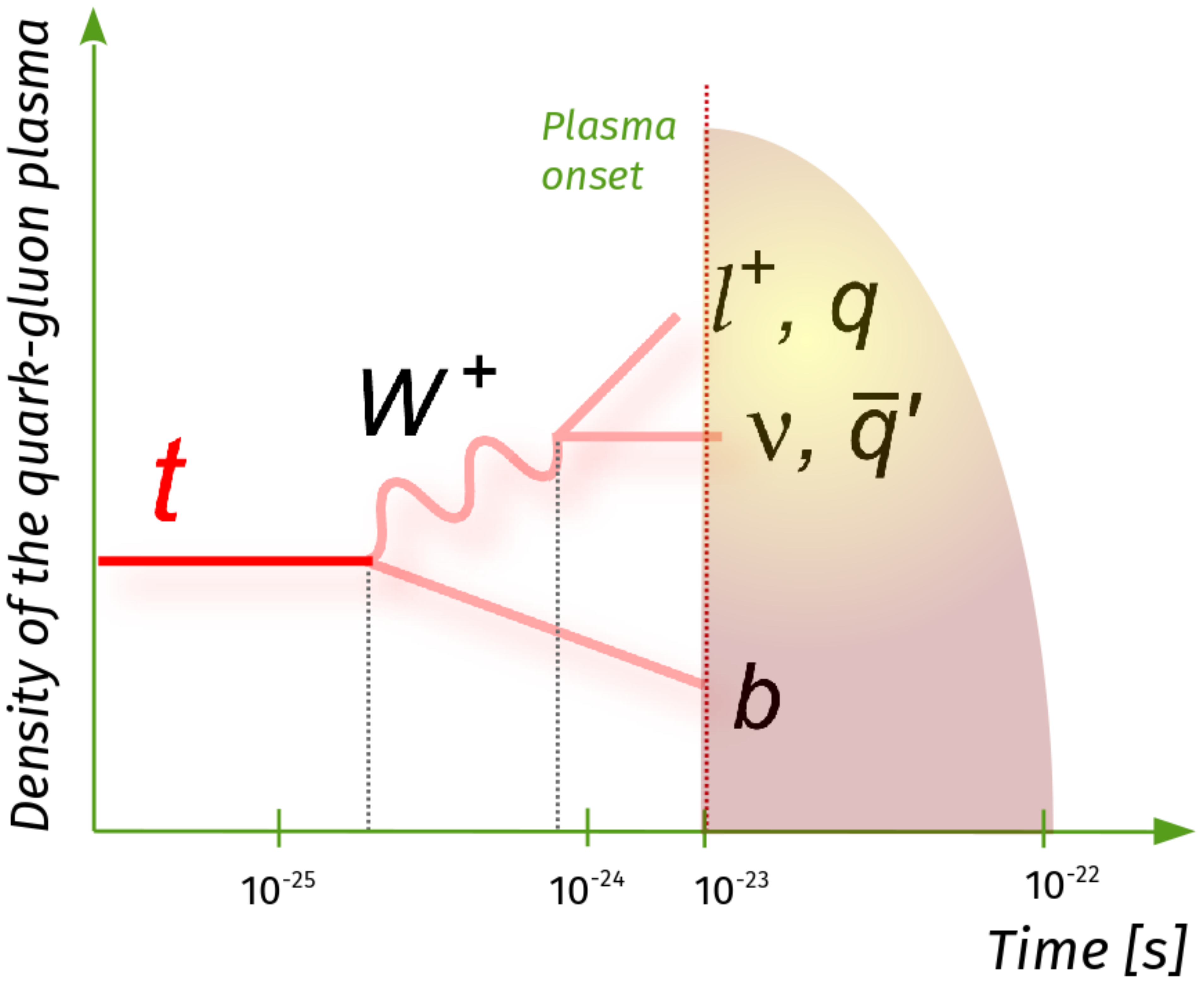


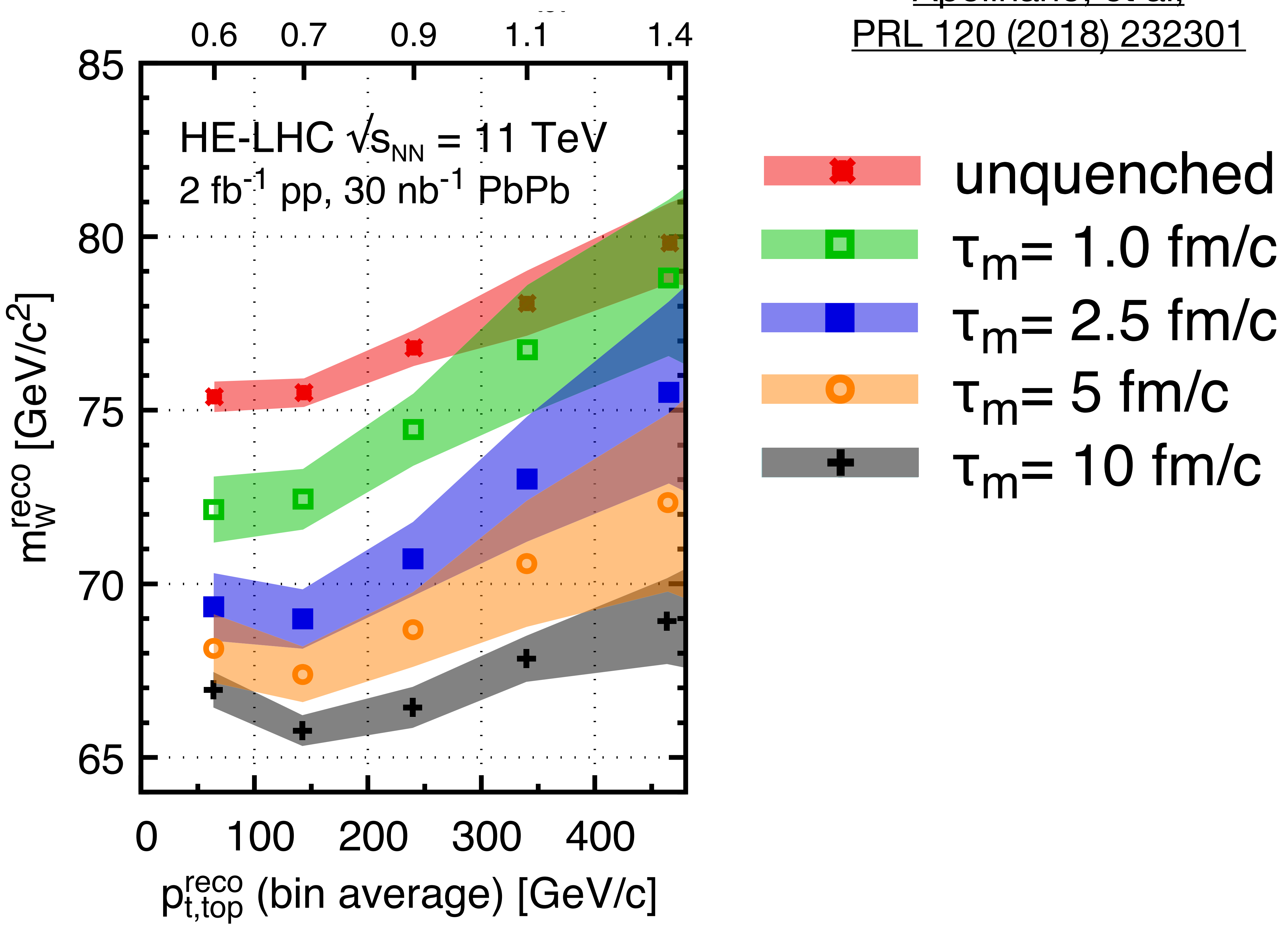
2) Access difficult-to-tag *c*-jets w/o assumption on fragmentation



3) Boosted $W \to q\bar{q}$ to control opening angle θ between emitters

New opportunities with $W^{\pm}$… and even $t\bar{t}$





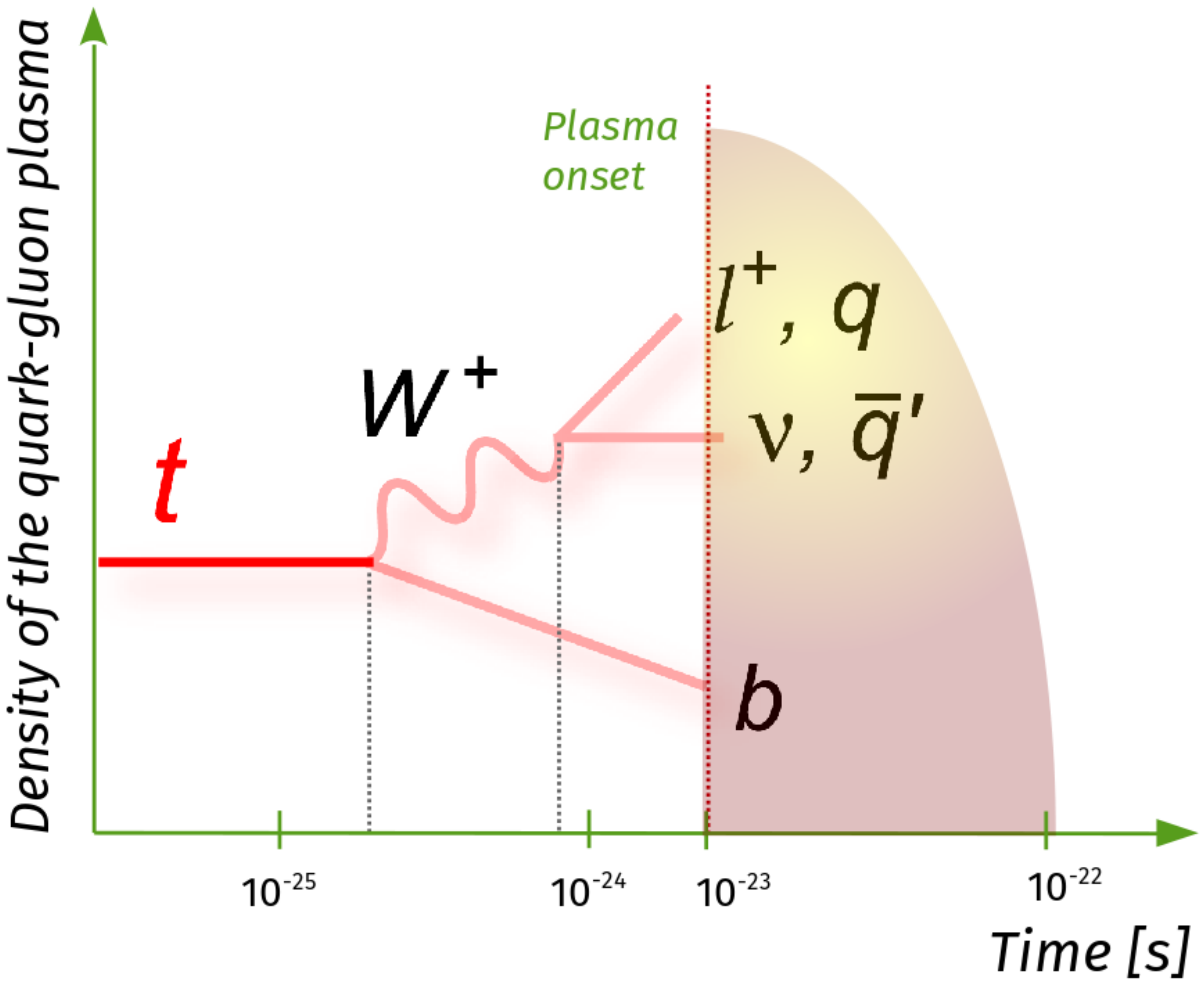
Apolinário, et al, PRL 120 (2018) 232301

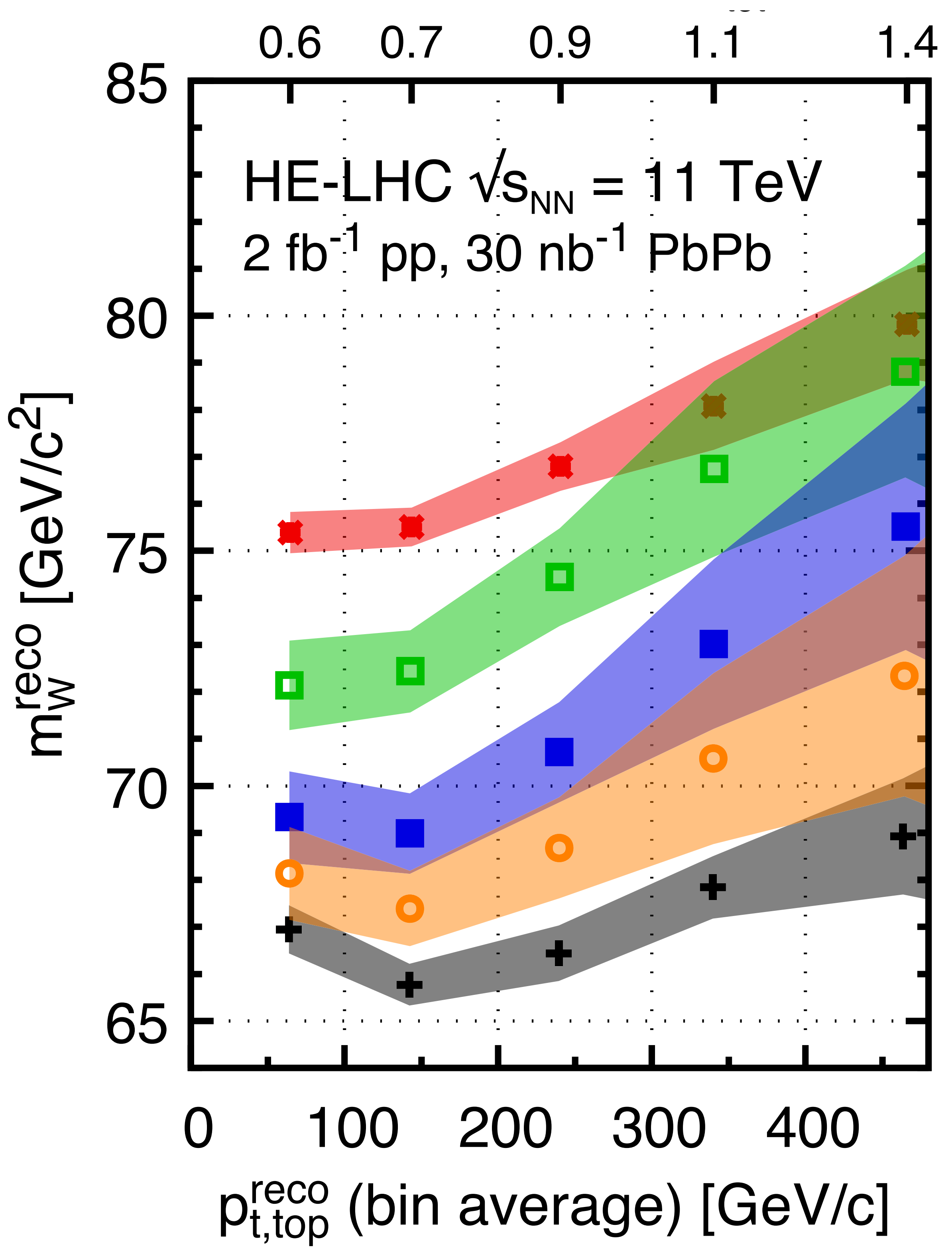
Period over which energy loss happens

Top quark-initiated jet quenching:

time-delayed decay chain for $t \rightarrow$jets

New opportunities with $W^{\pm}$… and even $t\bar{t}$

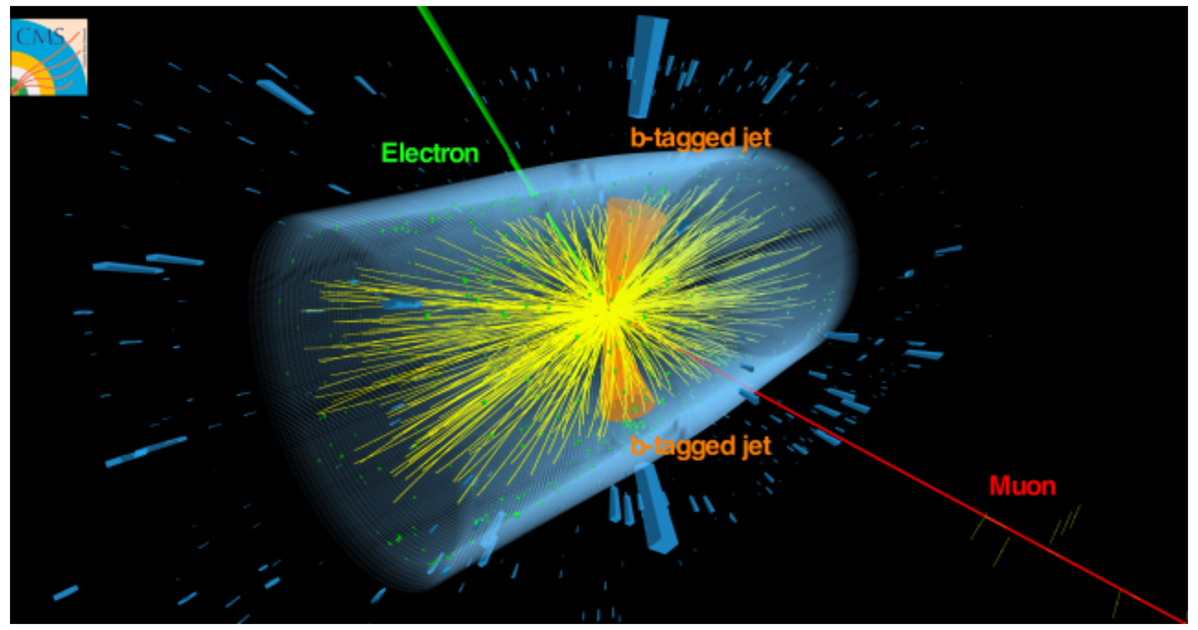




Apolinário, et al, PRL 120 (2018) 232301

Top quark-initiated jet quenching:
time-delayed decay chain for $t\rightarrow$jets

CMS, PRL 125 (2020) 222001



Observation in Pb+Pb!

But $t\rightarrow$jets probably only in Run 5+

First forays into AI/ML methods for jet quenching: observable design, precision measurement, interpretation, ...

Identifying quenched jets in heavy ion collisions with machine learning

Lihan Liu,[a] Julia Velkovska,[a] Marta Verweij[b]

Jet Tomography in Heavy-Ion Collisions with Deep Learning

Yi-Lun Du,[1,*] Daniel Pablos,[2,†] and Konrad Tywoniuk[1,‡]
[1]Department of Physics and Technology, University of Bergen, Postboks 7803, 5020 Bergen, Norway
[2]INFN, Sezione di Torino, via Pietro Giuria 1, I-10125 Torino, Italy

Deep learning jet modifications in heavy-ion collisions

Yi-Lun Du, Daniel Pablos and Konrad Tywoniuk

Probing heavy ion collisions using quark and gluon jet substructure

Yang-Ting Chien [a] and Raghav Kunnawalkam Elayavalli [b,c]

The information content of jet quenching and machine learning assisted observable design

Yue Shi Lai,[a] James Mulligan,[a,b] Mateusz Płoskoń,[a] Felix Ringer[a,c,d]

Machine-learning-based jet momentum reconstruction in heavy-ion collisions

Rüdiger Haake[1] and Constantin Loizides[2]
[1]Yale University, Wright Laboratory, New Haven, Connecticut, USA
[2]ORNL, Physics Division, Oak Ridge, Tennessee, USA

(Received 3 November 2018; revised manuscript received 17 April 2019; published 17 June 2019)

Explainable machine learning of the underlying physics of high-energy particle collisions

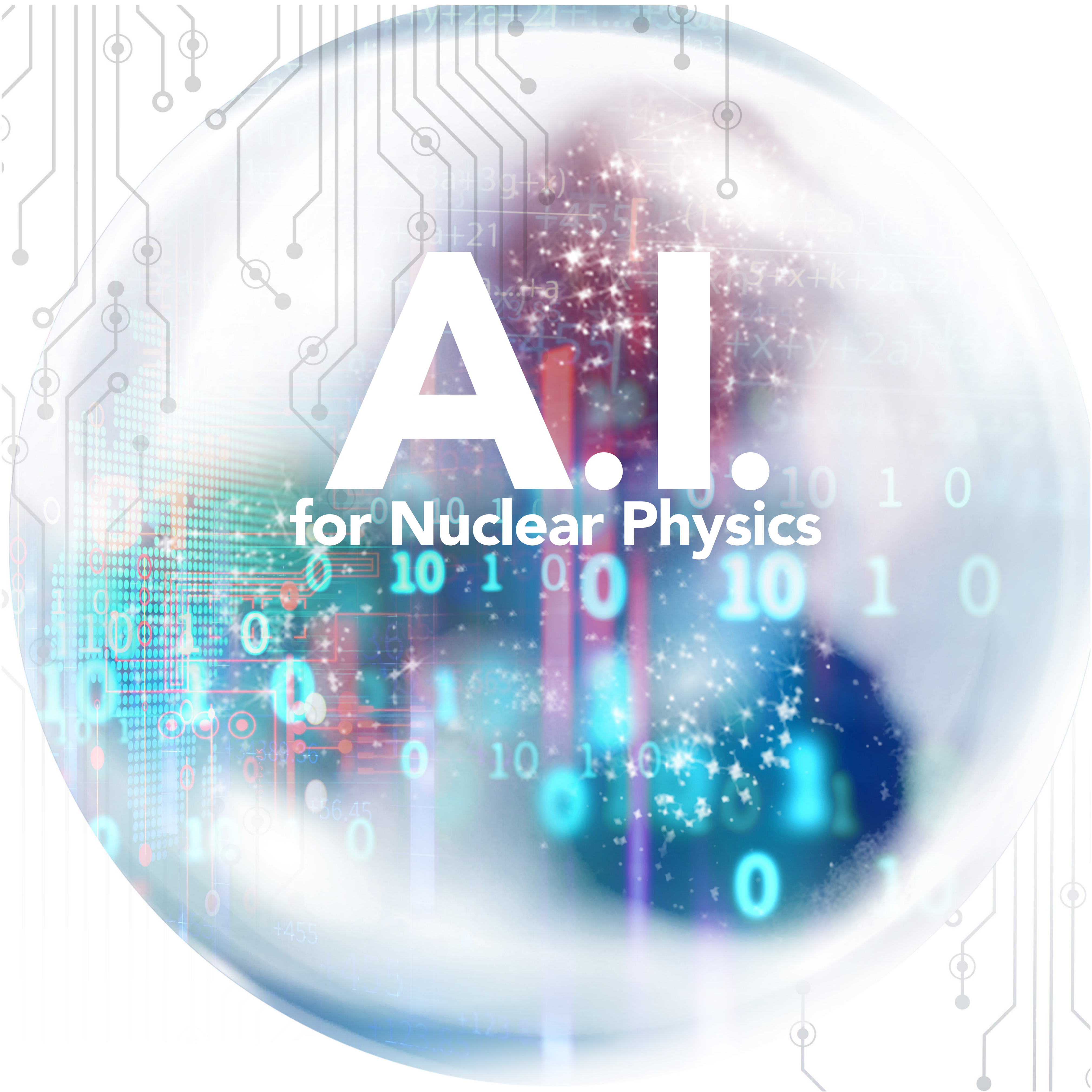
Check for updates

Yue Shi Lai [a,*], Duff Neill [b], Mateusz Płoskoń [a], Felix Ringer [a]

[a] Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[b] Theoretical Division, MS B283, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

Deep Learning for the classification of quenched jets

L. Apolinário,[a,b] N.F. Castro,[a,c] M. Crispim Romão,[a] J.G. Milhano,[a,b] R. Pedro[a] and F.C.R. Peres[a,d,e]



AI/ML methods have really come of age and are becoming broadly used in a variety of fields

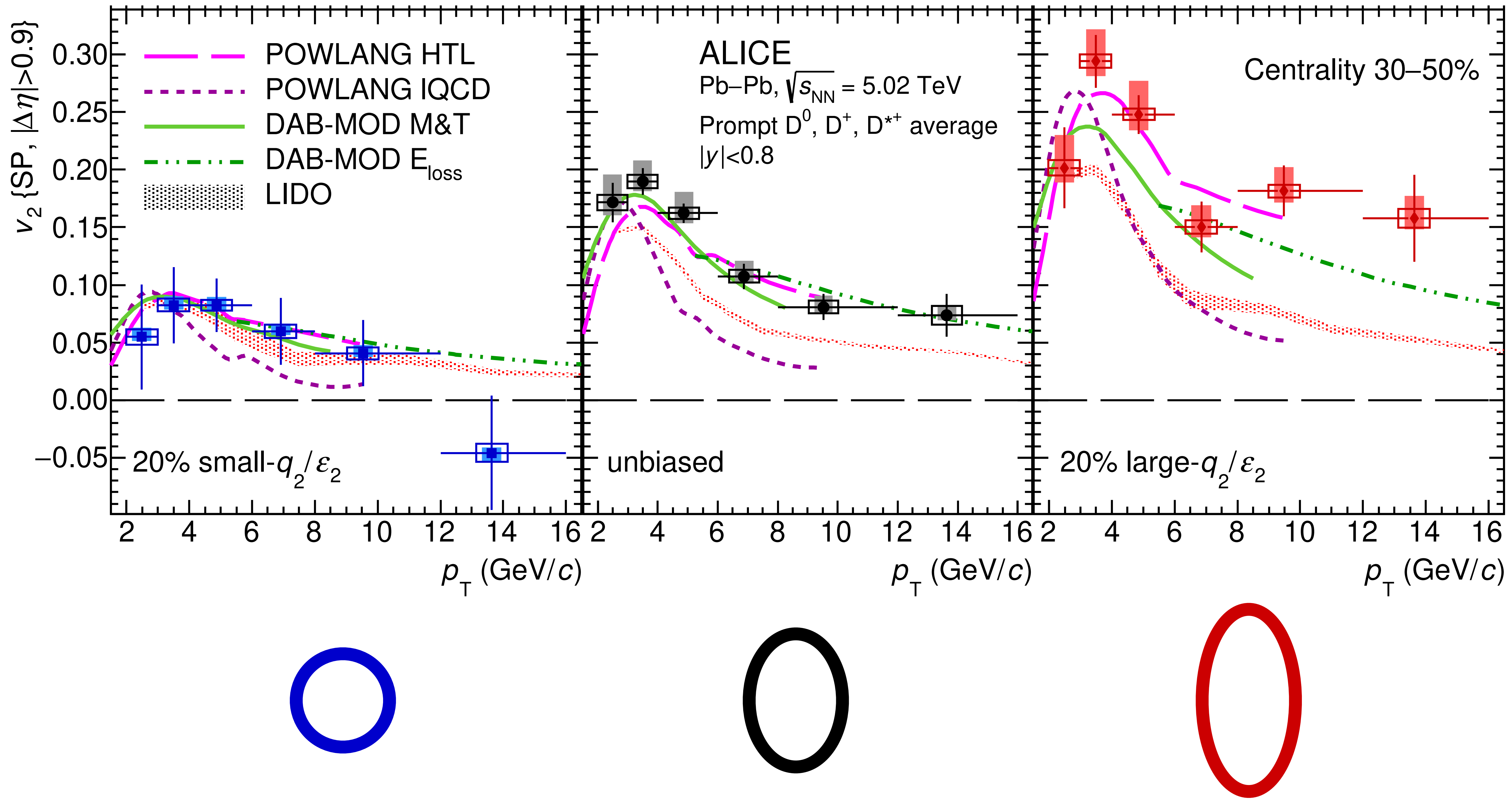
Clear technical priority area for agencies & lots to learn from HEP / broader data science community

Full steam ahead, but expect "growing pains" as with any new technology

(defining the right problems, applicability, model dependence, bias, etc.)

Thermalization of charm and bottom

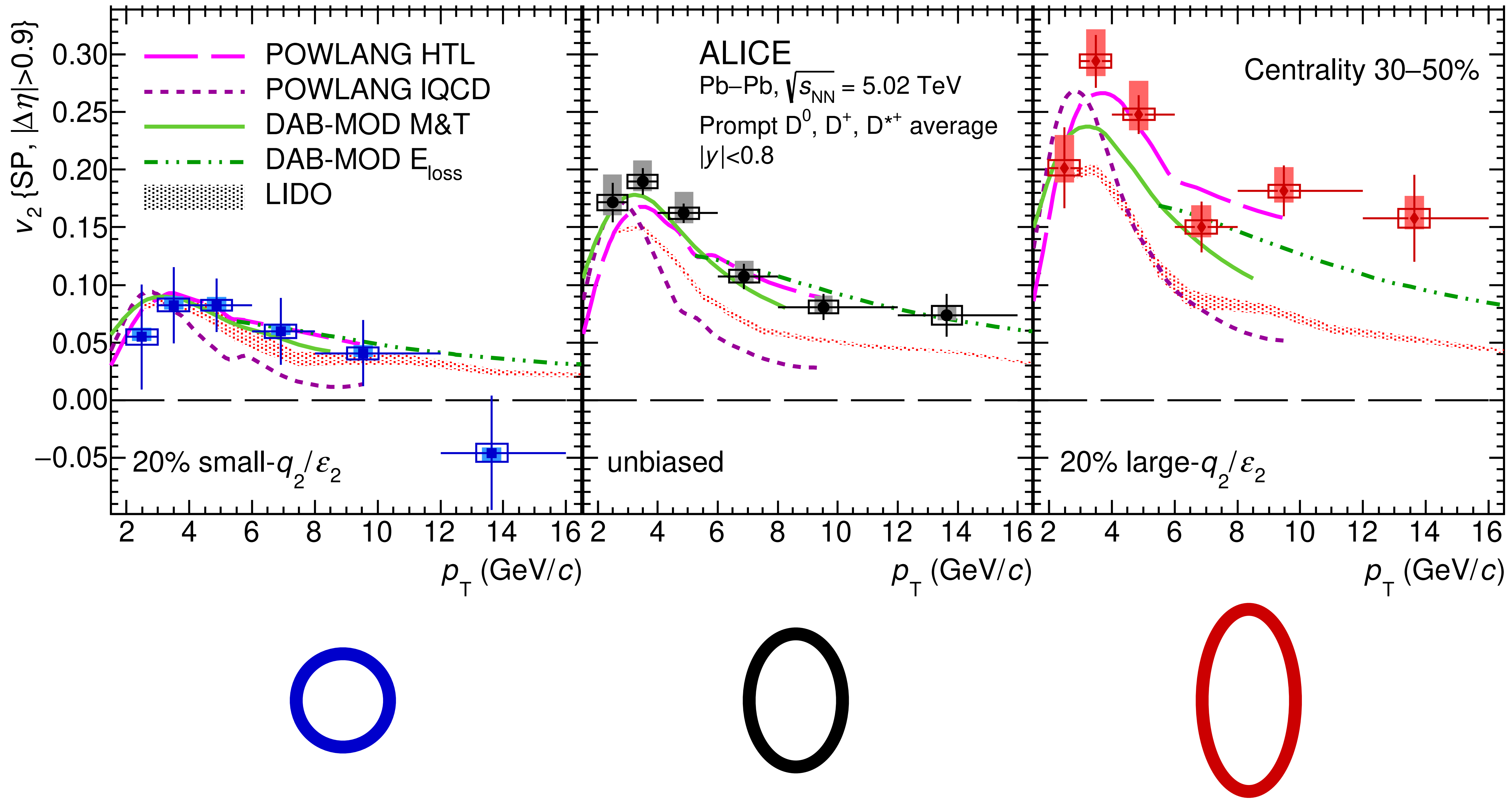
Detailed confirmation of fully thermalized charm



Remarkable demonstration that
charm “feels” the shape of the QGP

Thermalization of charm and bottom

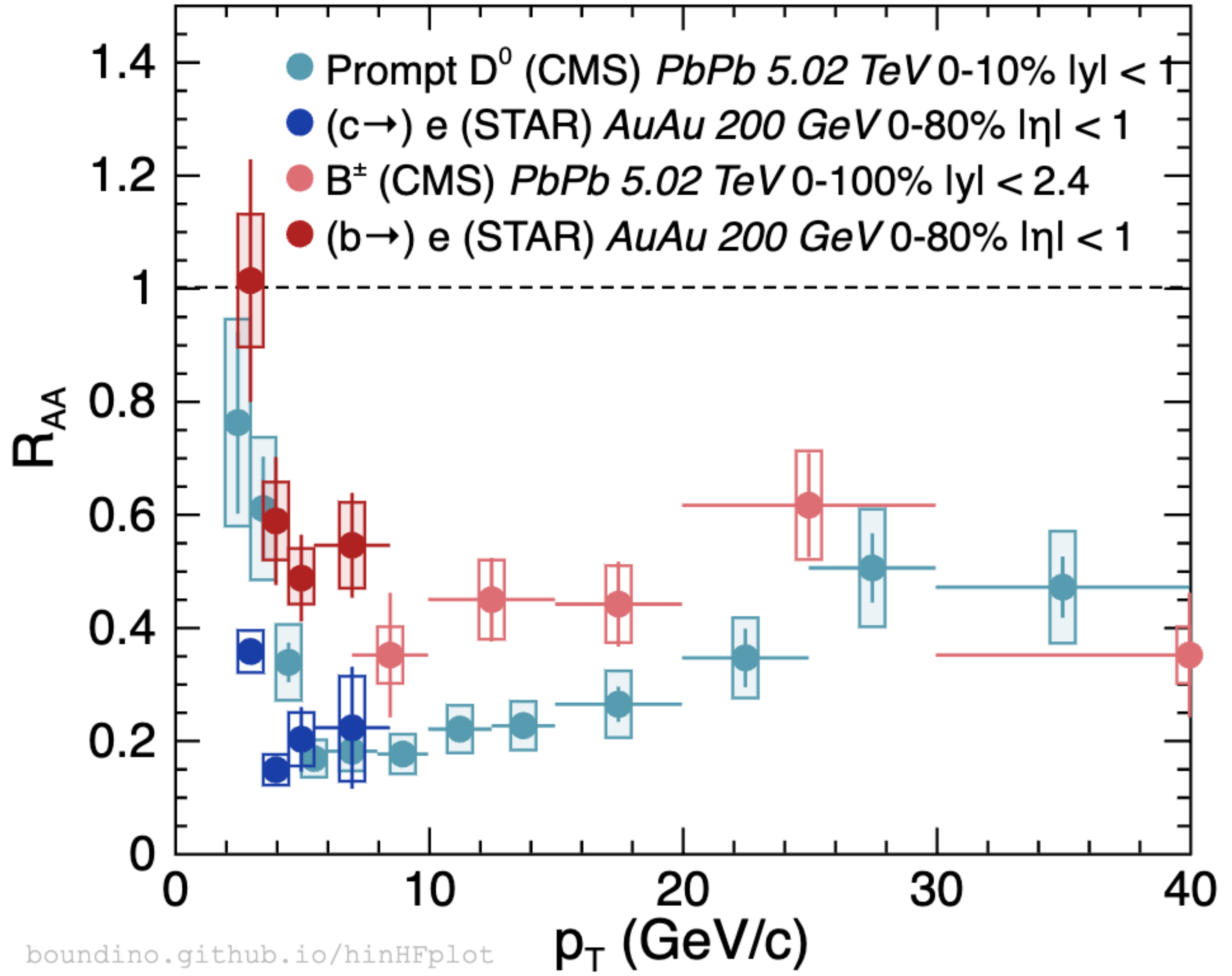
Detailed confirmation of fully thermalized charm



Remarkable demonstration that **charm "feels" the shape of the QGP**

https://boundino.github.io/hinHFplot/

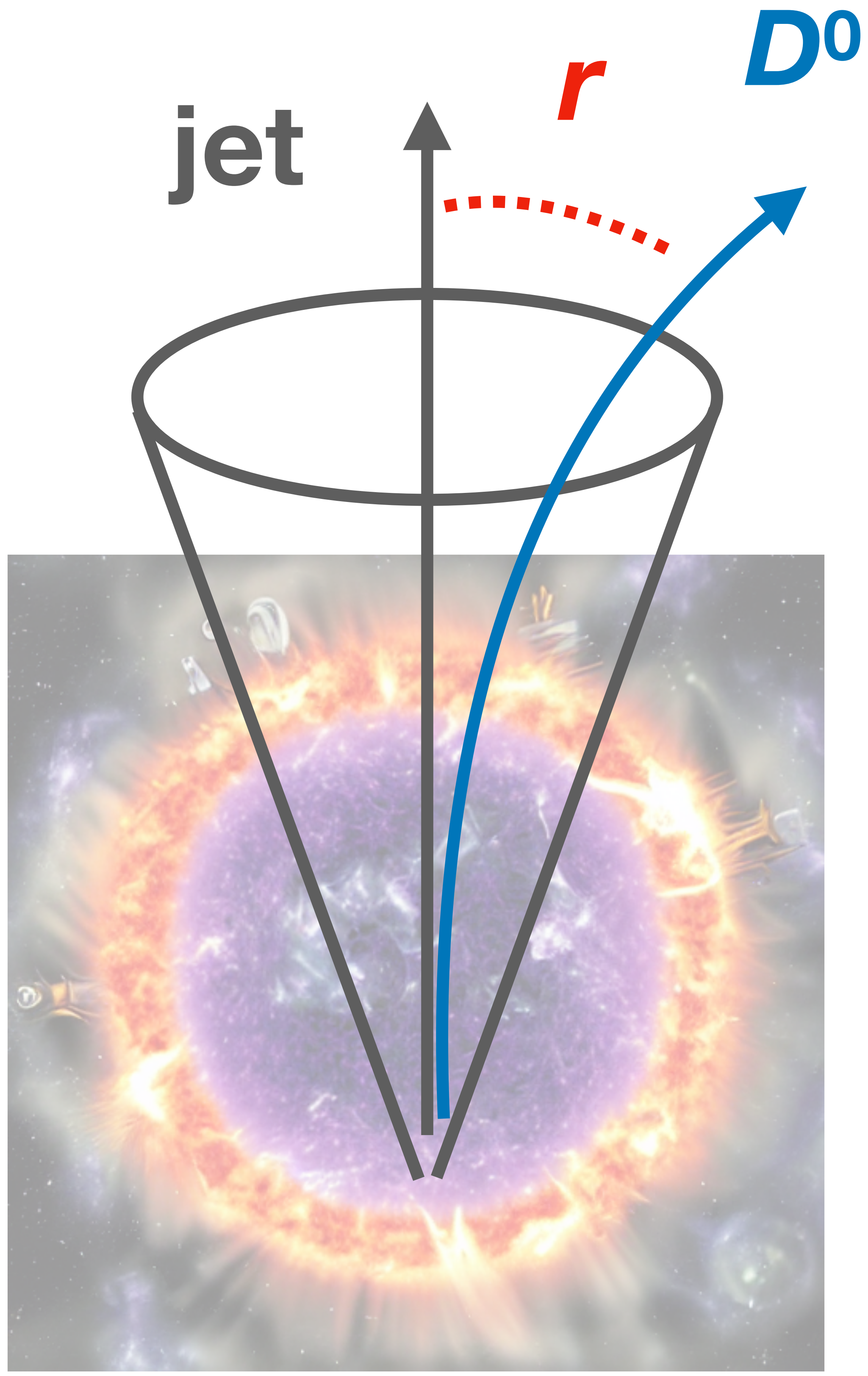
Open access tool for compilations of HF data by Jing Wang (MIT)

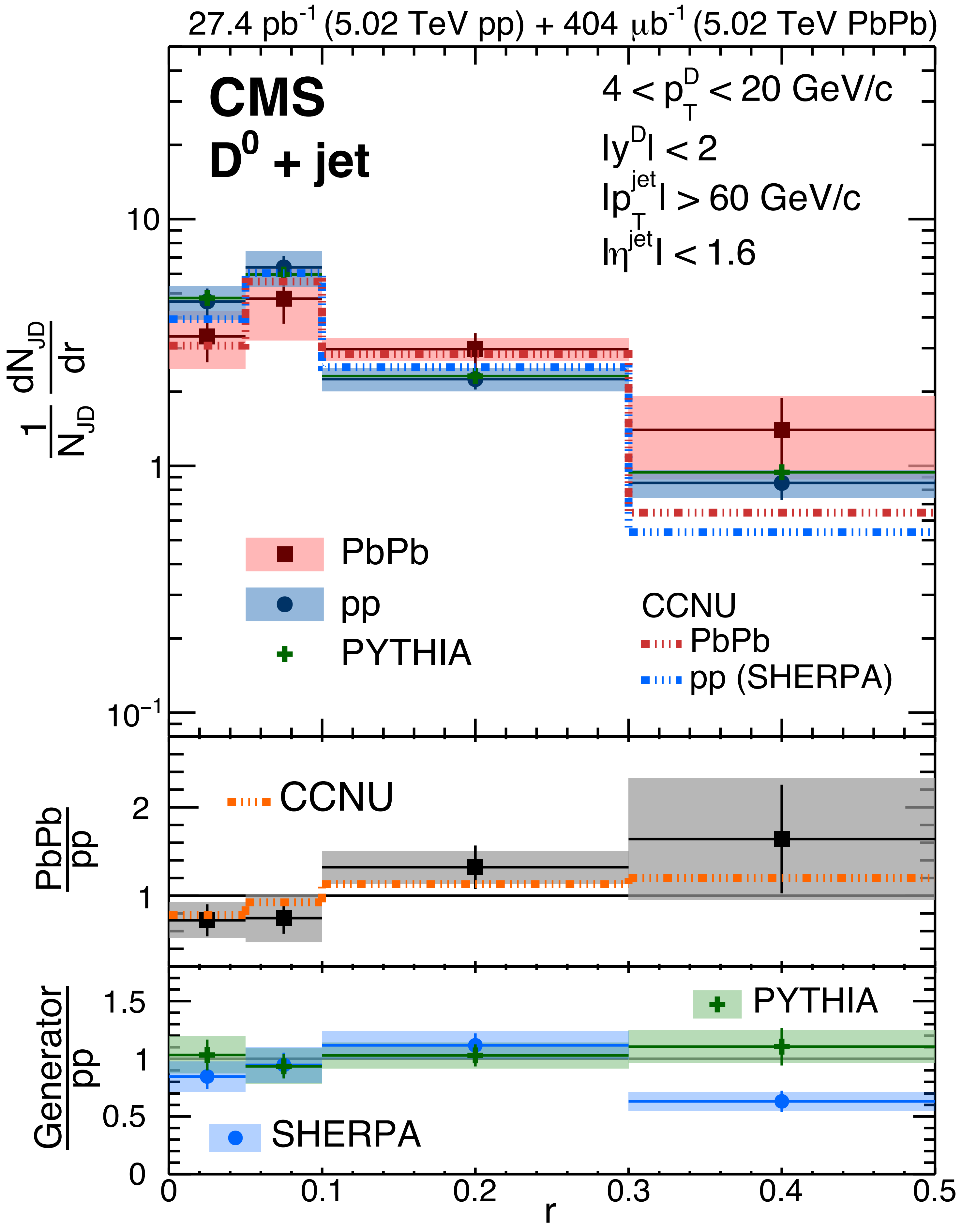


Established **clear mass hierarchy** between **charm** and **bottom**

(also: b-jets)

Next: Observe and control charm diffusion





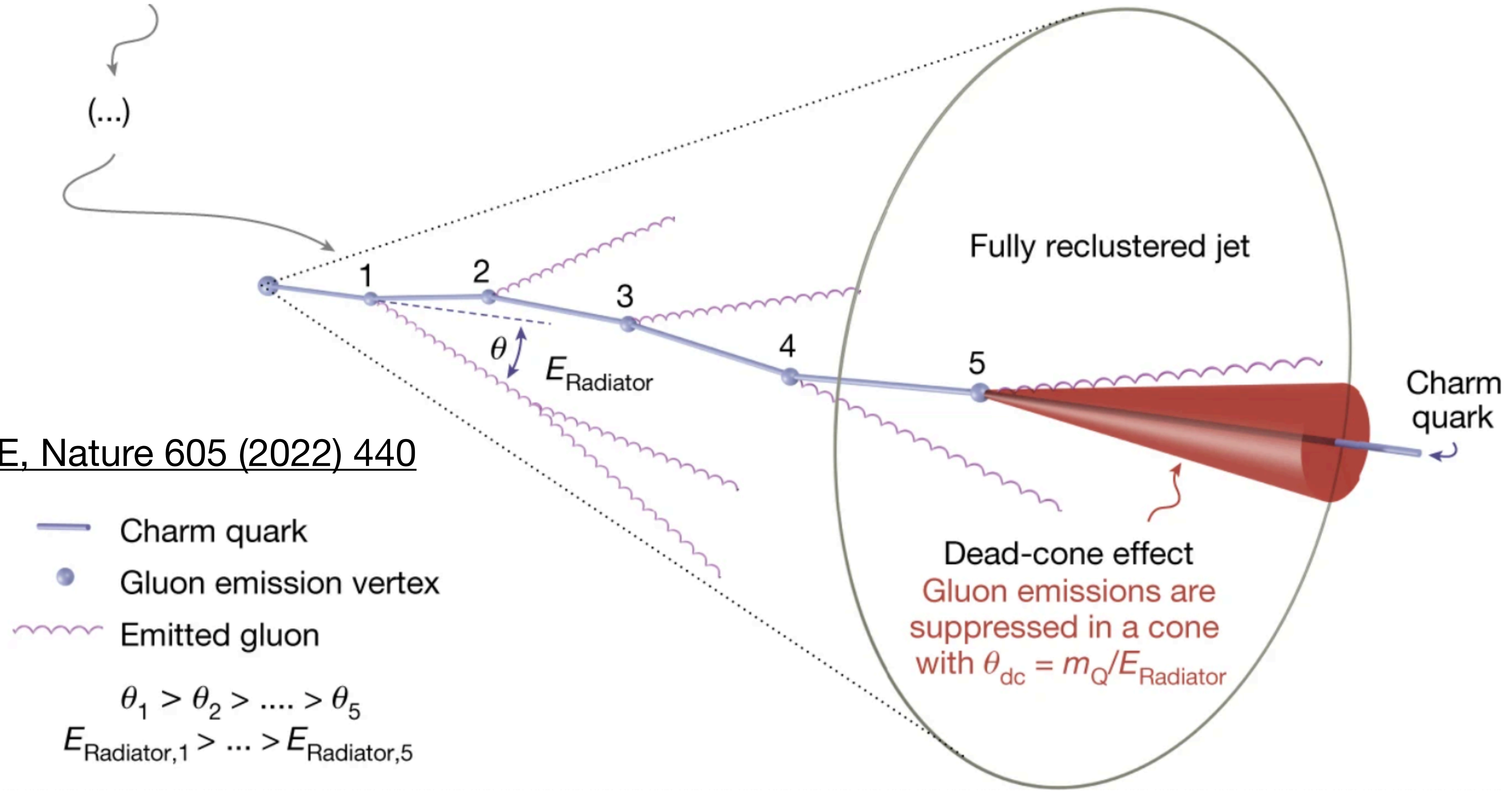
Use jet axis to set reference direction - nearing **direct evidence** of the Brownian motion of charm?

Next: high-statistics jet/$h + D^0$, $\gamma + D^0$, D-$\bar{D}$ correlations

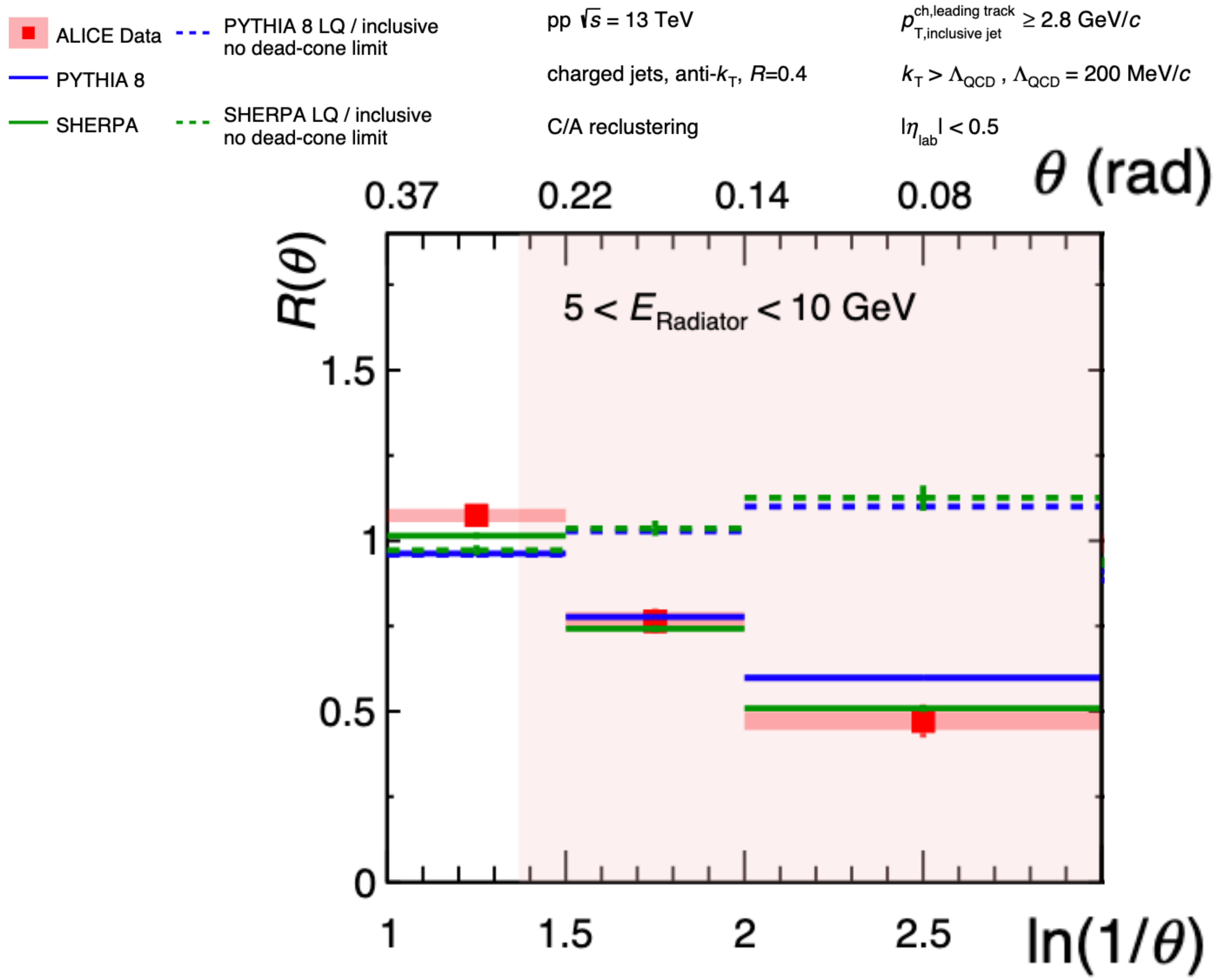
Tag direct production vs. identify late $g \to c\bar{c}$ splitting w/ jet sub-structure $\Rightarrow$ **control charm production time**

Next: Isolate medium-induced radiation

Observation of dead cone for charm in *pp*!



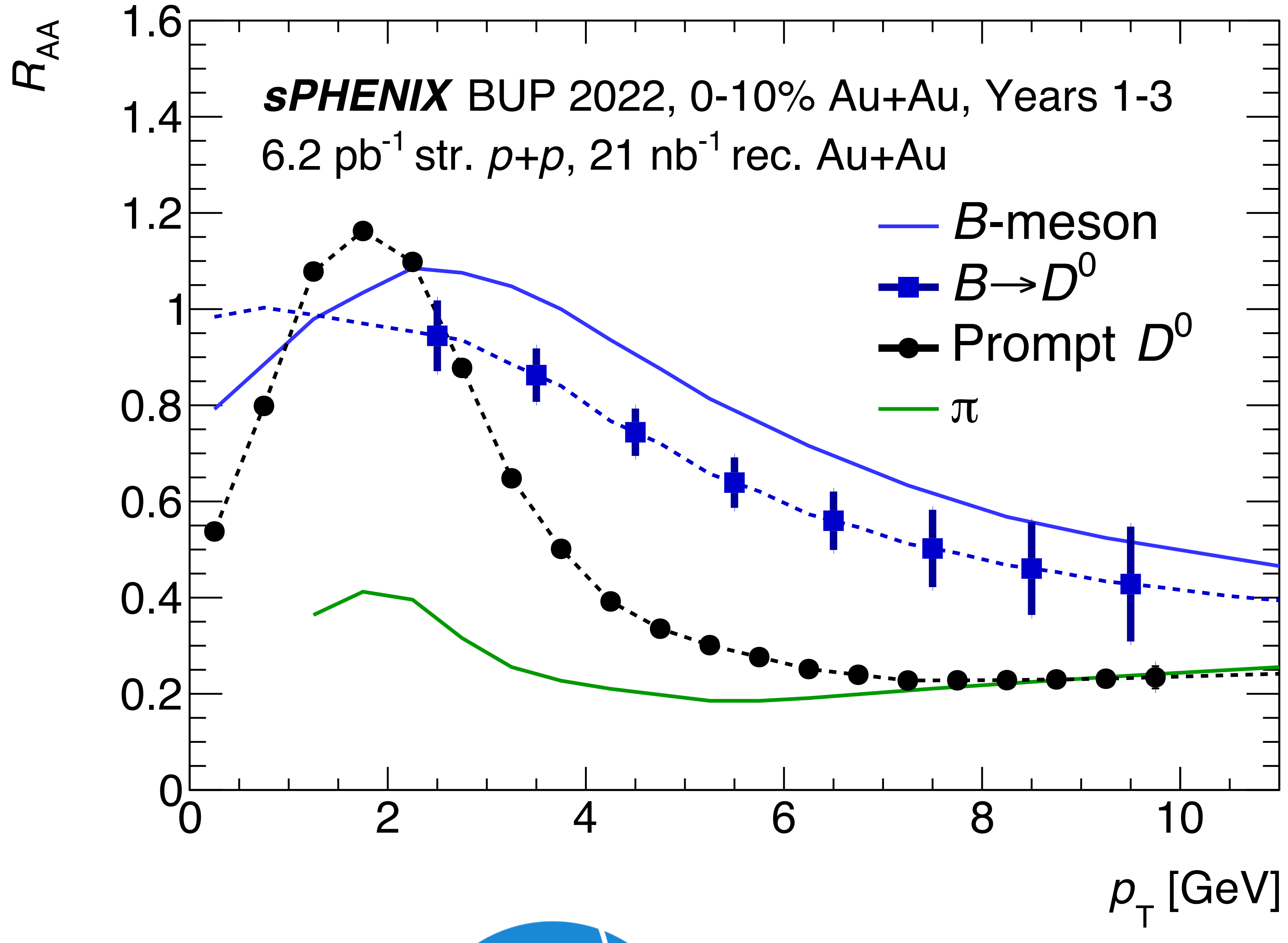
ALICE, Nature 605 (2022) 440



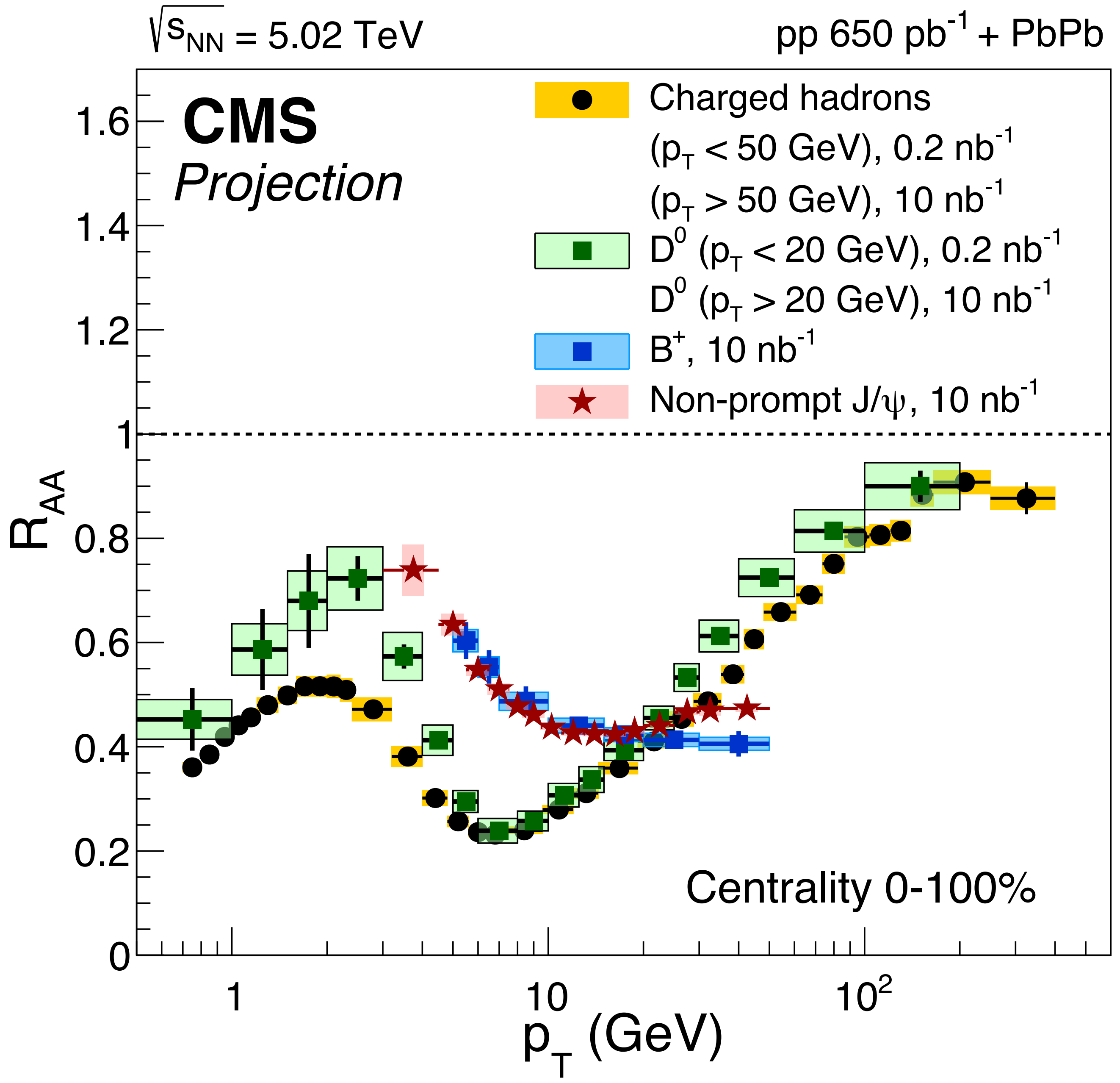
In Pb+Pb, radiation in the dead cone is **unambiguously induced by the medium**

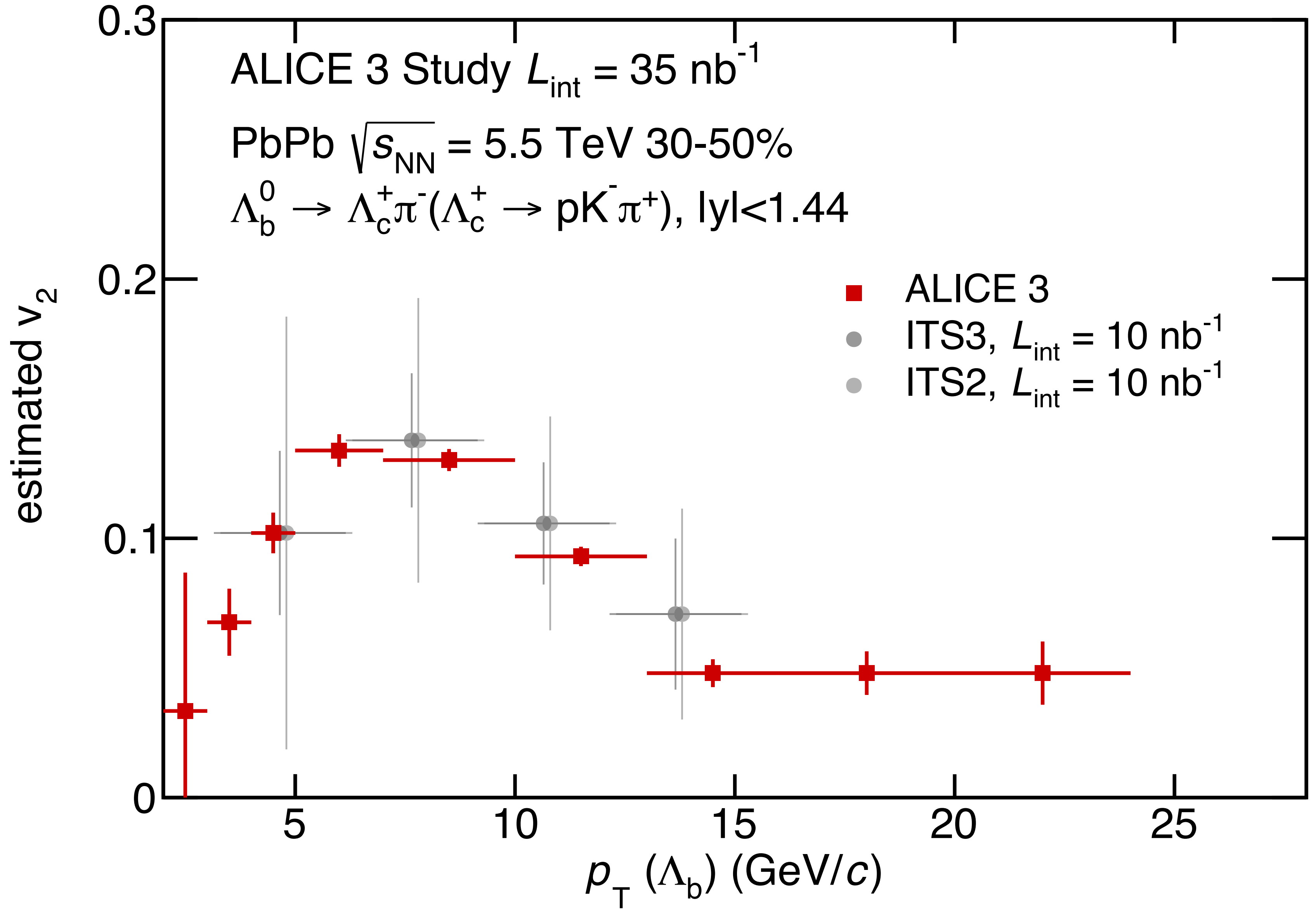
⇒ **confirmation of key theoretical picture** of QCD in-medium radiation

Next: bottom with charm-level precision



CERN Yellow Report on HI in Runs 3+4





sPHENIX @ RHIC ⟶ HL-LHC Runs 3-4 ⟶ ALICE 3 / LHC Run 5

Diffusion coefficient of bottom quarks (3x diffusion time ⇒ probe time-dependence)

Community goal: our **understanding of bottom in 2030 = charm in 2020**

The Quark-Gluon Plasma Cafe - Make-Your-Own-Jet Menu

Grand Opening 2023!!

The Quark-Gluon Plasma Cafe - Make-Your-Own-Jet Menu

Grand Opening 2023!!

Initiating parton:

- ☐ Gluon
- ☐ u/d/s quark
- ☐ c quark
- ☐ B quark

Path length:

- ☐ <4 fm
- ☐ 4-8 fm
- ☐ >8 fm

Radiation pattern:

- ☐ 1 emitter
- ☐ 2 emitters
- ☐ 3+ emitters

... with what opening angle?

r_g = ________

... with what shared momentum fraction?

z_g = ________

pT before quenching:

- ☐ 40-60 GeV
- ☐ 100-200 GeV
- ☐ >500 GeV

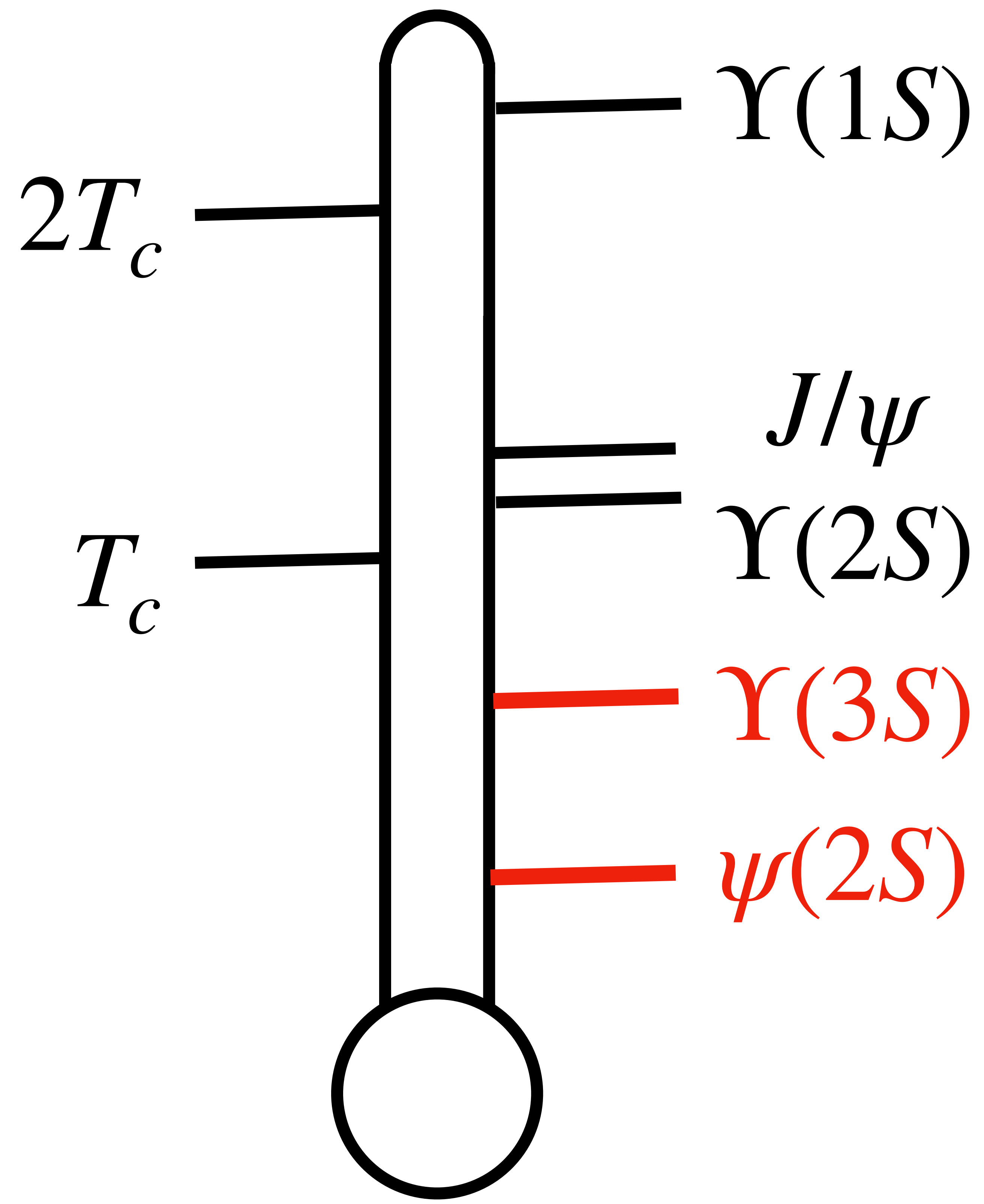
... with what rapidity?

η = _____

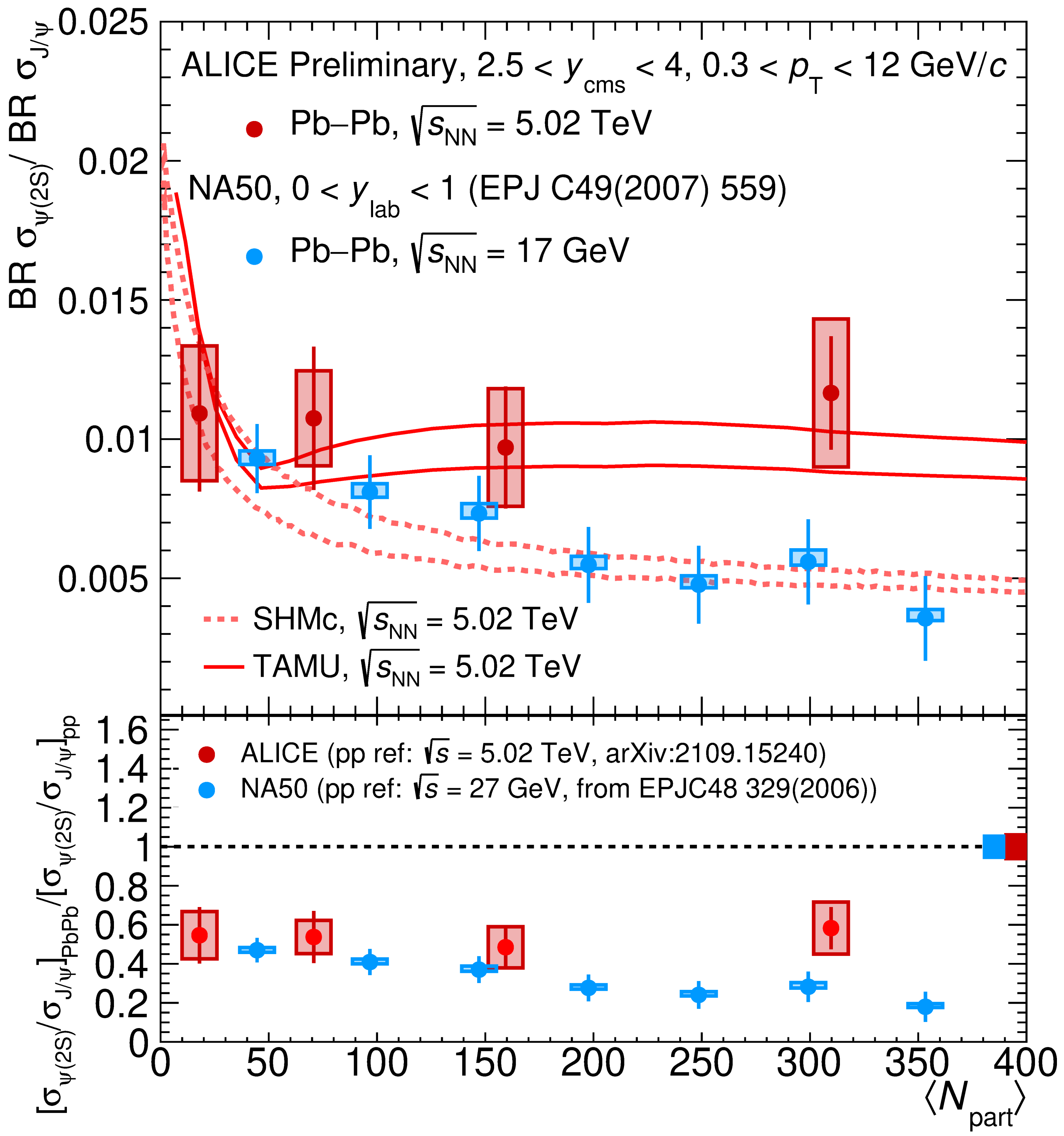
Delay production time?

- ☐ Yes
- ☐ No

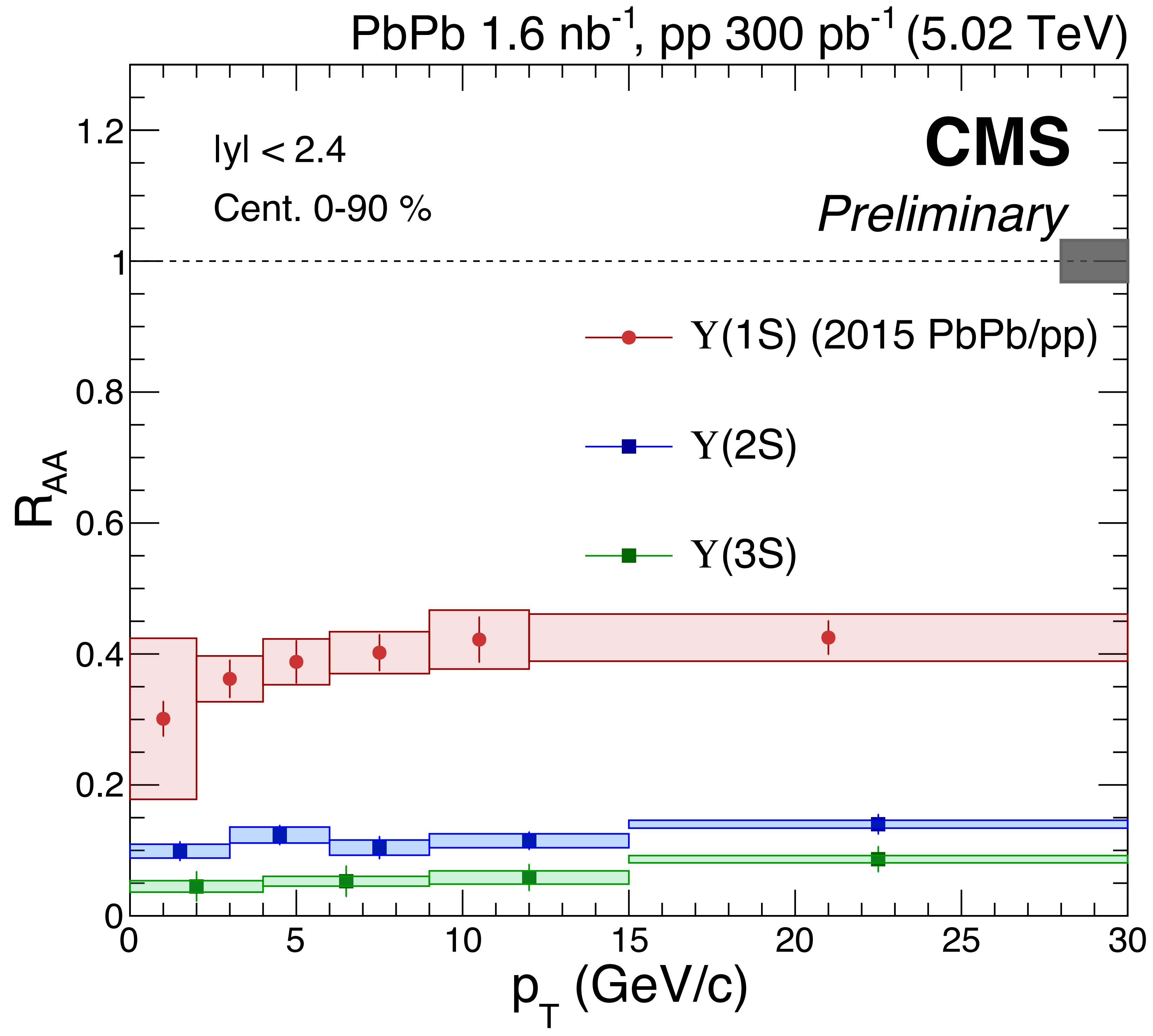
The QCD $q\bar{q}$ force in a deconfined medium



Calibrate the thermometer in the **region of strongest dissociation**

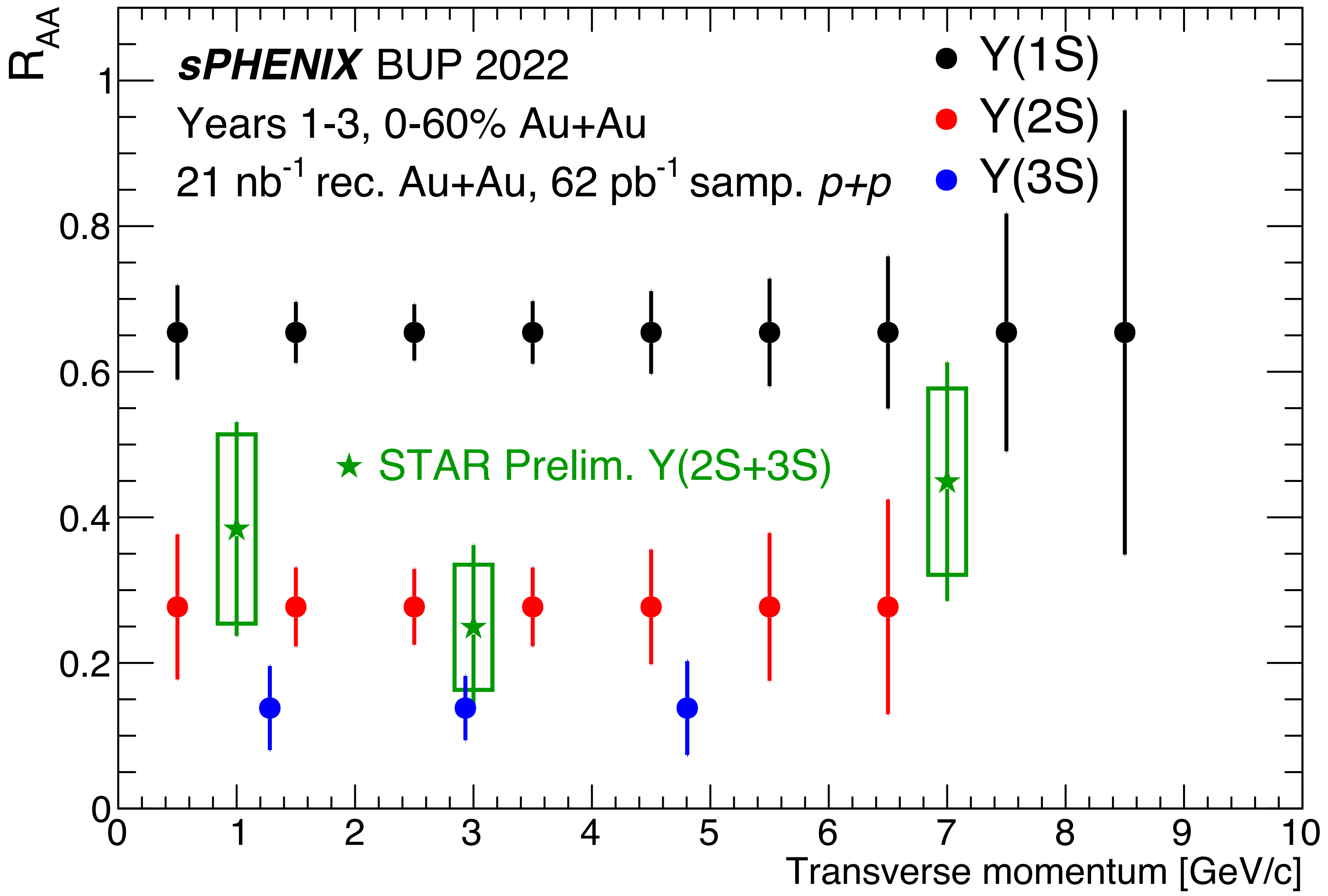


$\psi(2S)$ - observation of sequential suppression in charmonia?



Unexpected (small) survival of $\Upsilon(3S)$

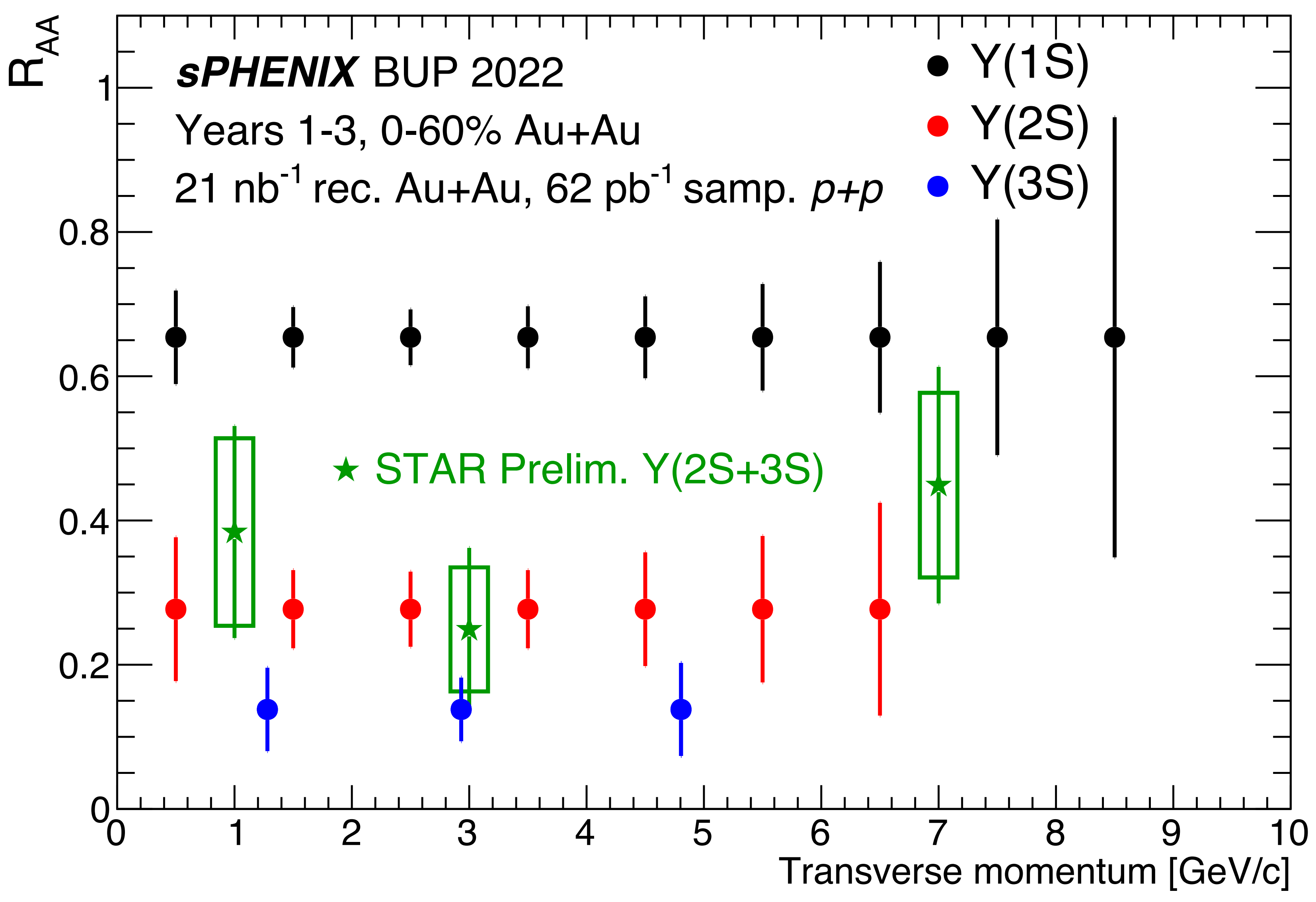
Addressing recombination and feed-down

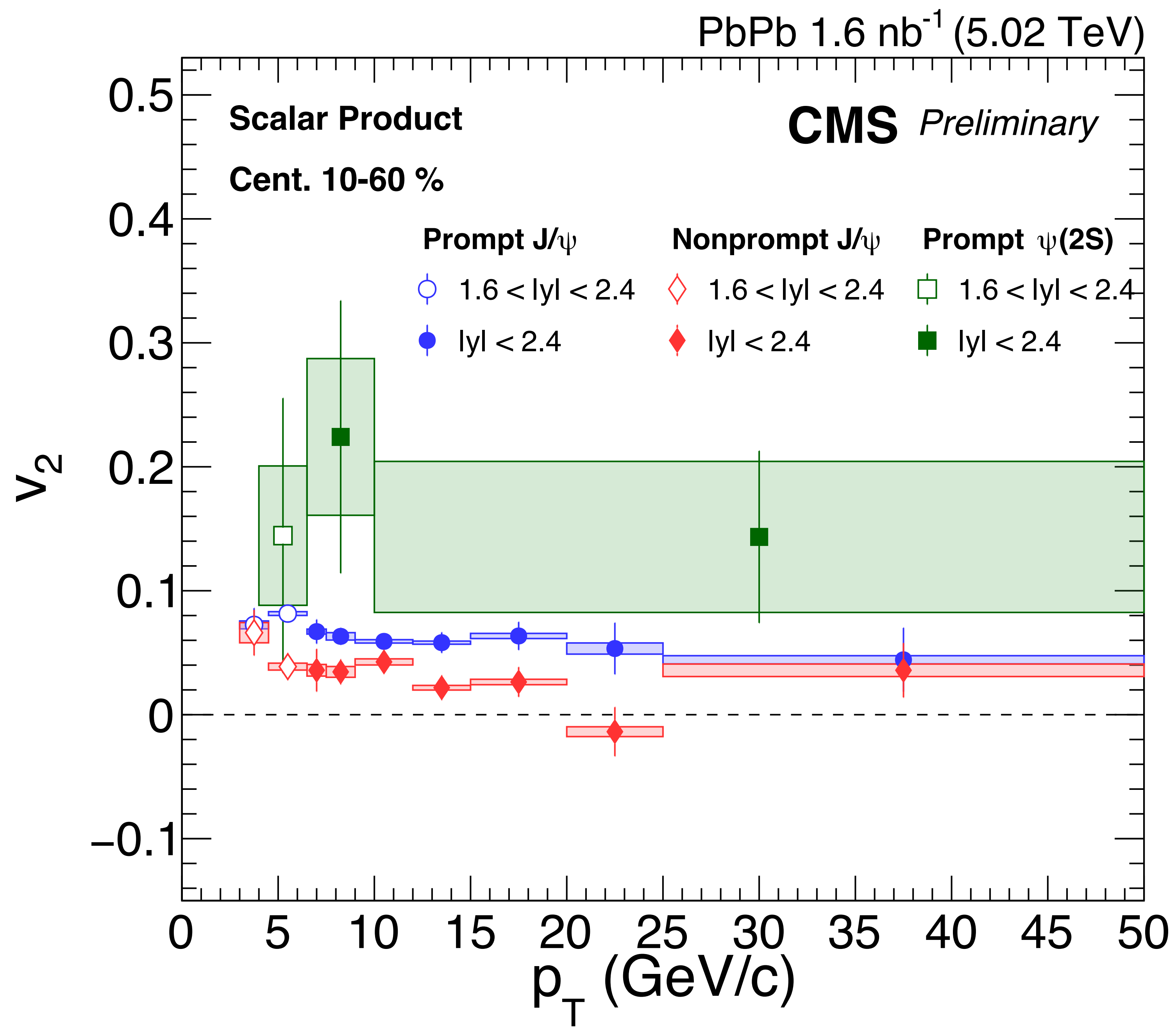


Change $\sqrt{s}$ - RHIC

sPHENIX

Addressing recombination and feed-down





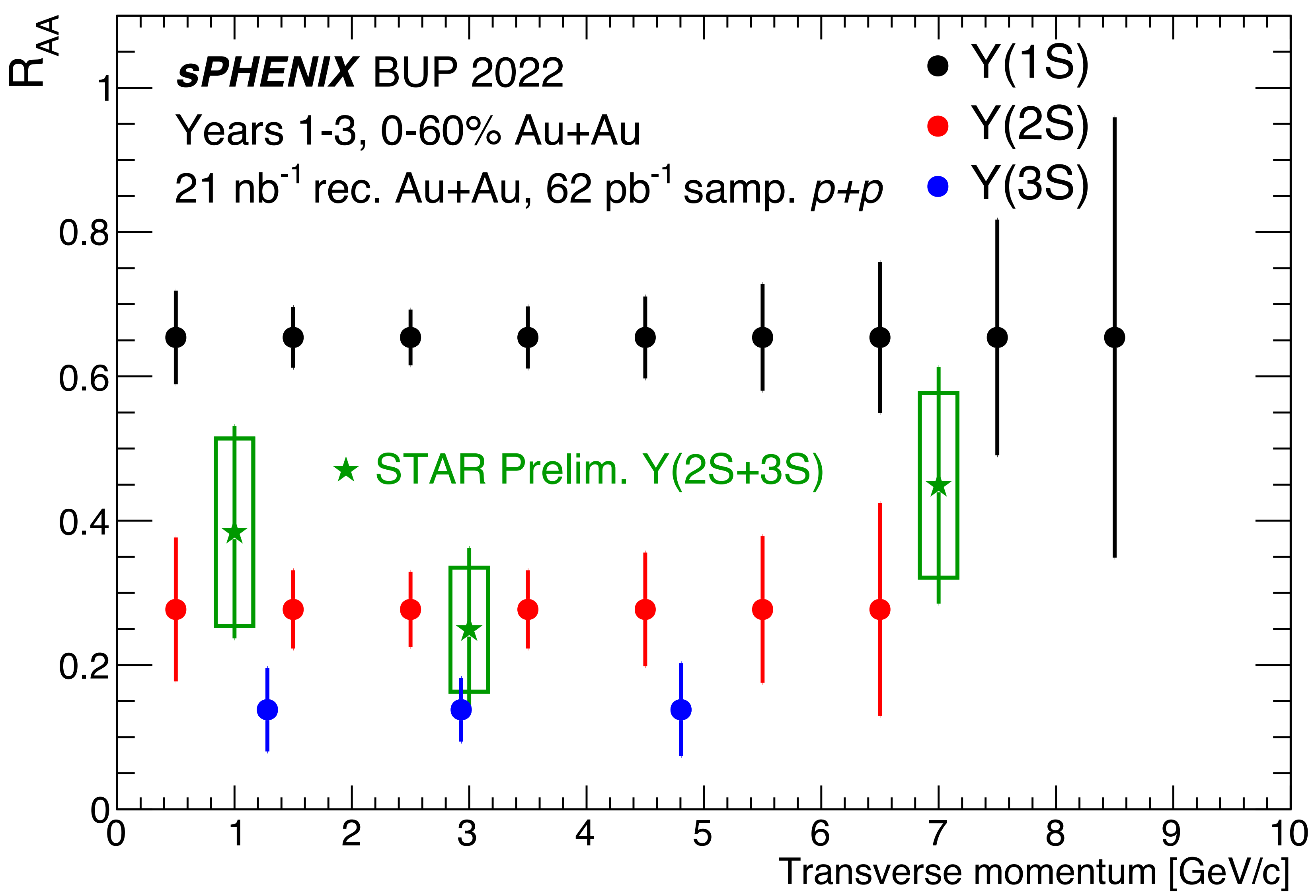
Change $\sqrt{s}$ - RHIC

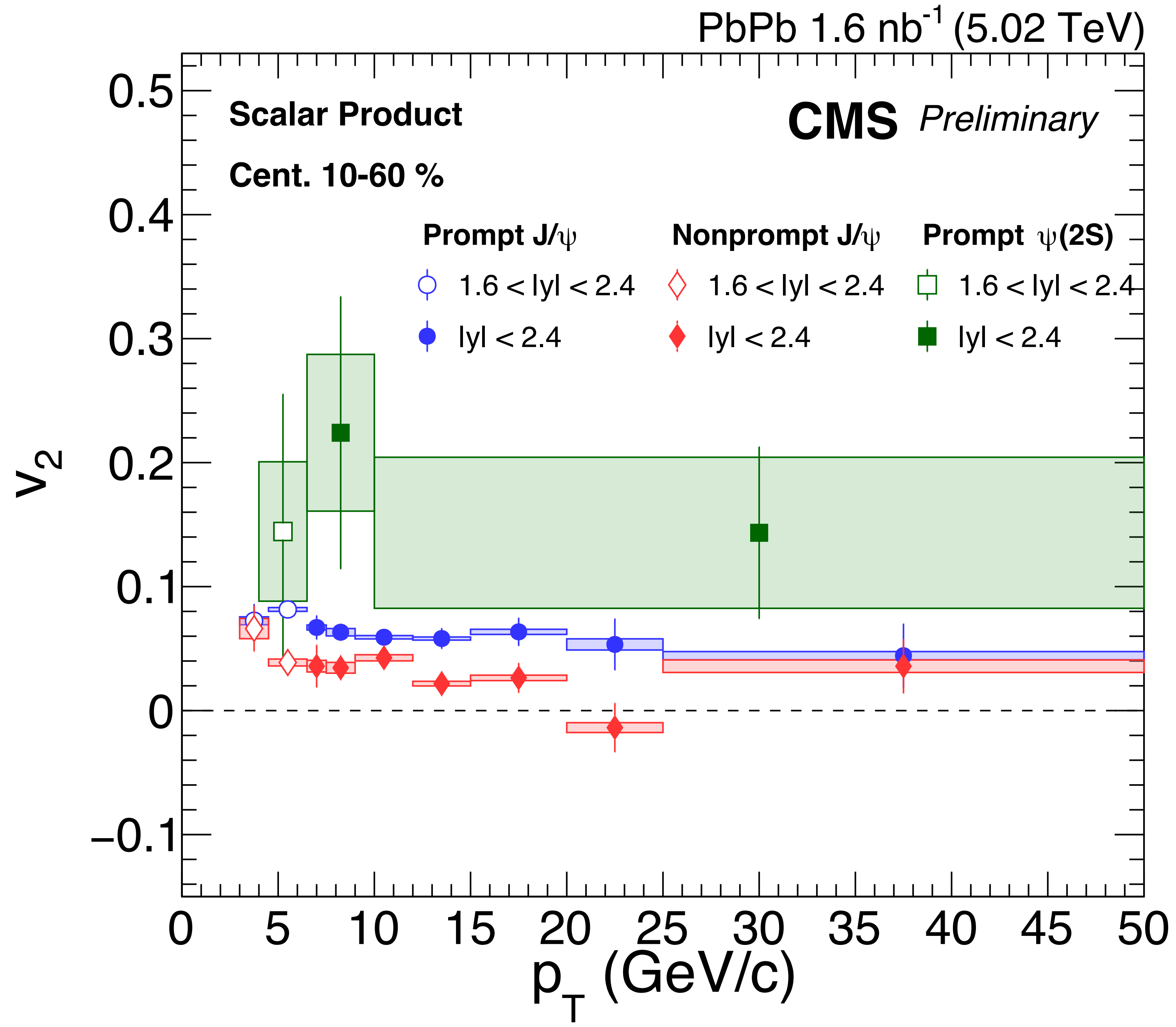
sPHENIX

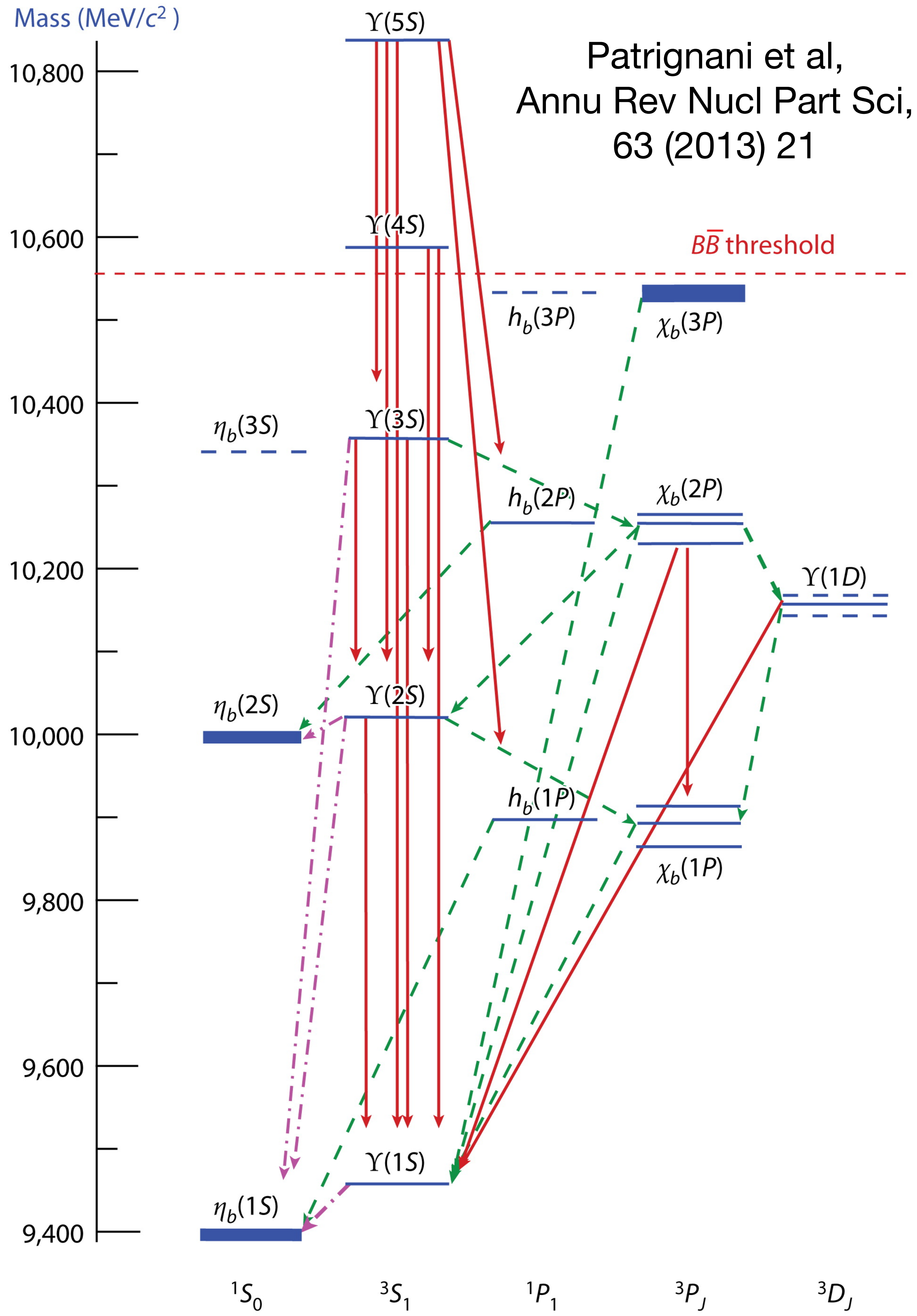
Flow of weakly-bound states ($\Psi(2S)$, Υ's, etc.)

LHC Run 3+

Addressing recombination and feed-down







Patrignani et al, Annu Rev Nucl Part Sci, 63 (2013) 21

Change $\sqrt{s}$ - RHIC

sPHENIX

Flow of weakly-bound states ($\Psi(2S)$, Υ's, etc.)

LHC Run 3+

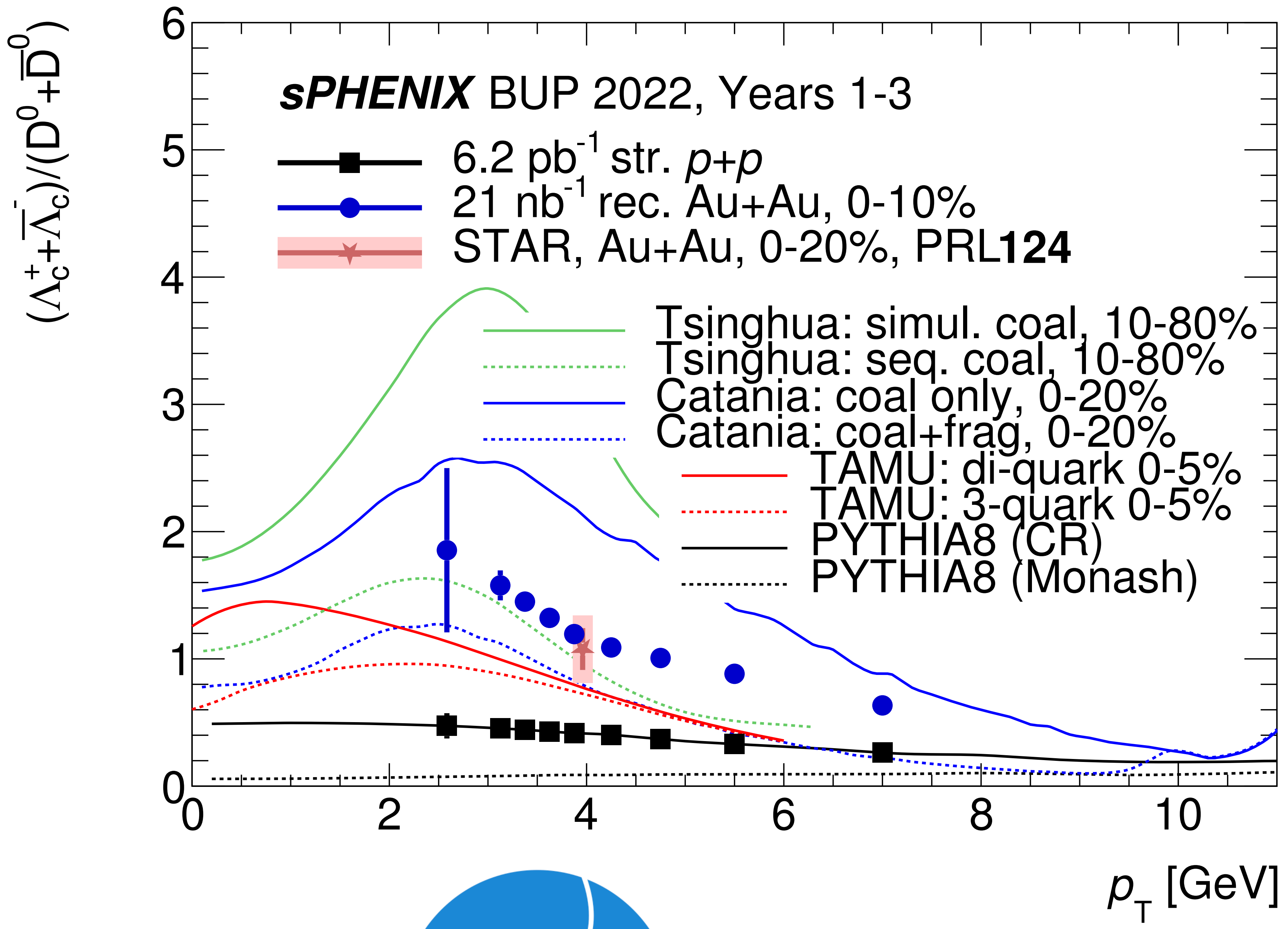
Measure χ_b - significant $\Upsilon(1S)$ feed-down

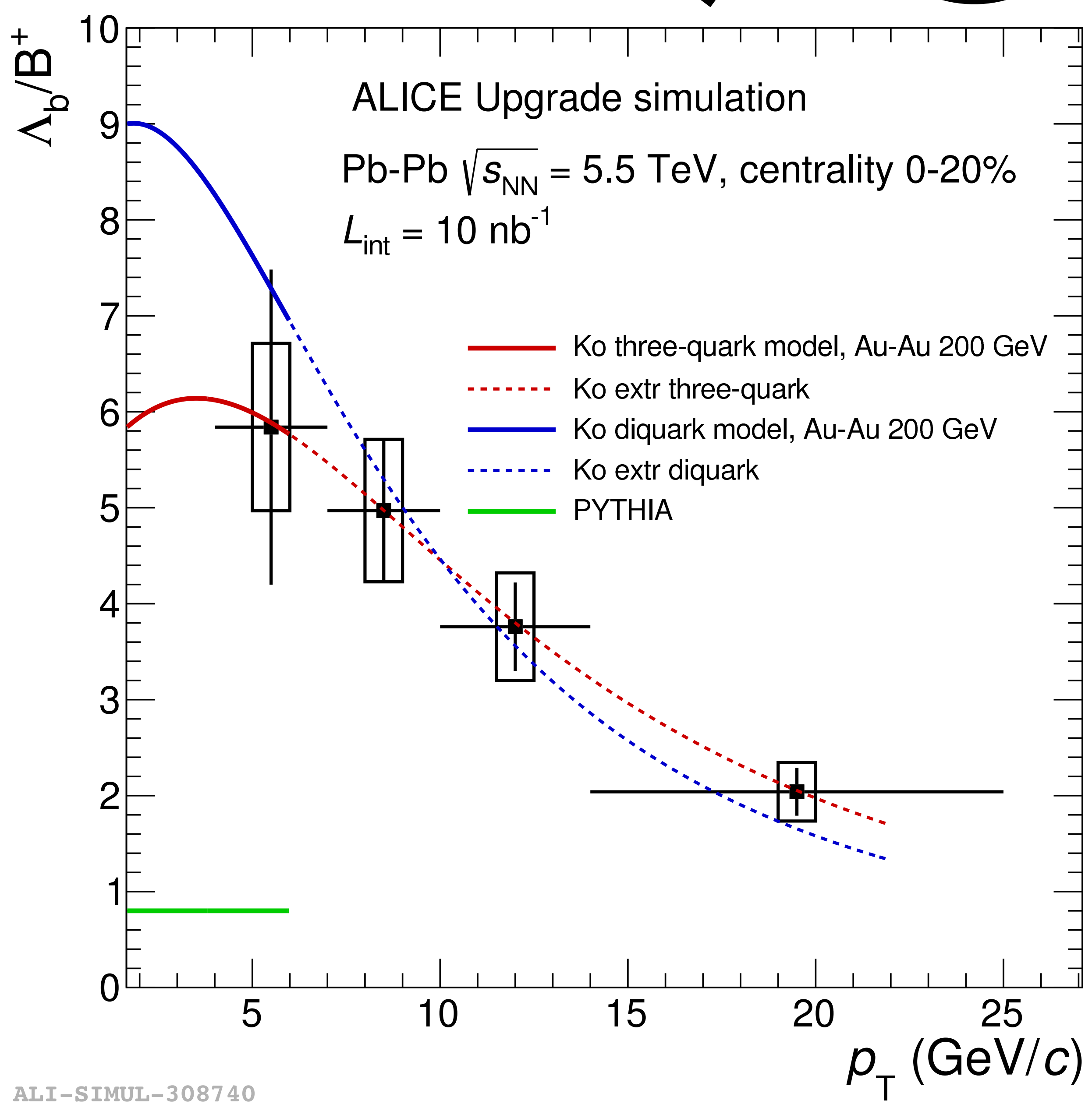
How do hadrons assemble themselves?

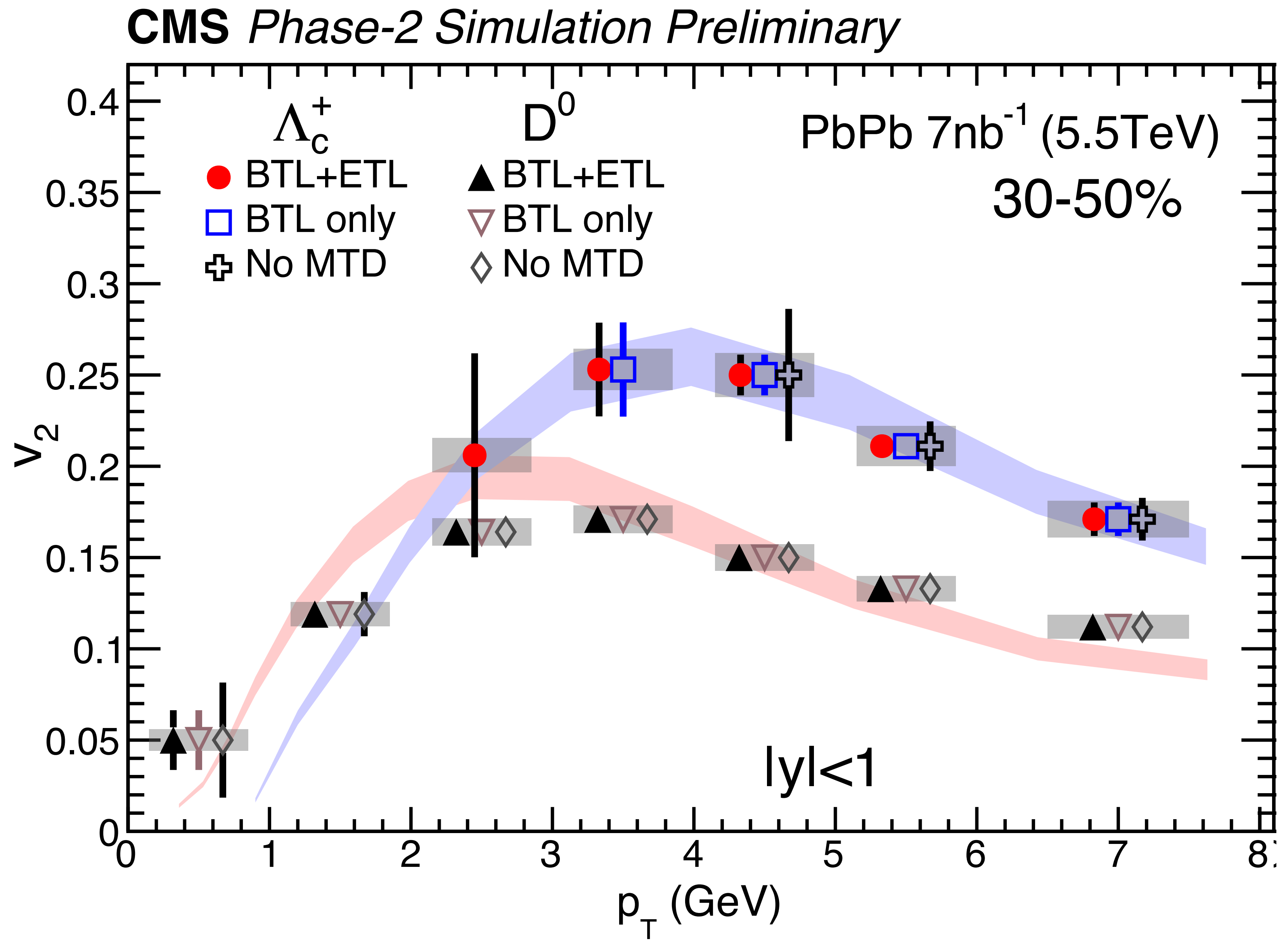
u d c / ū c

u d b / ū b

Also: D_s vs. D, B_s vs. B





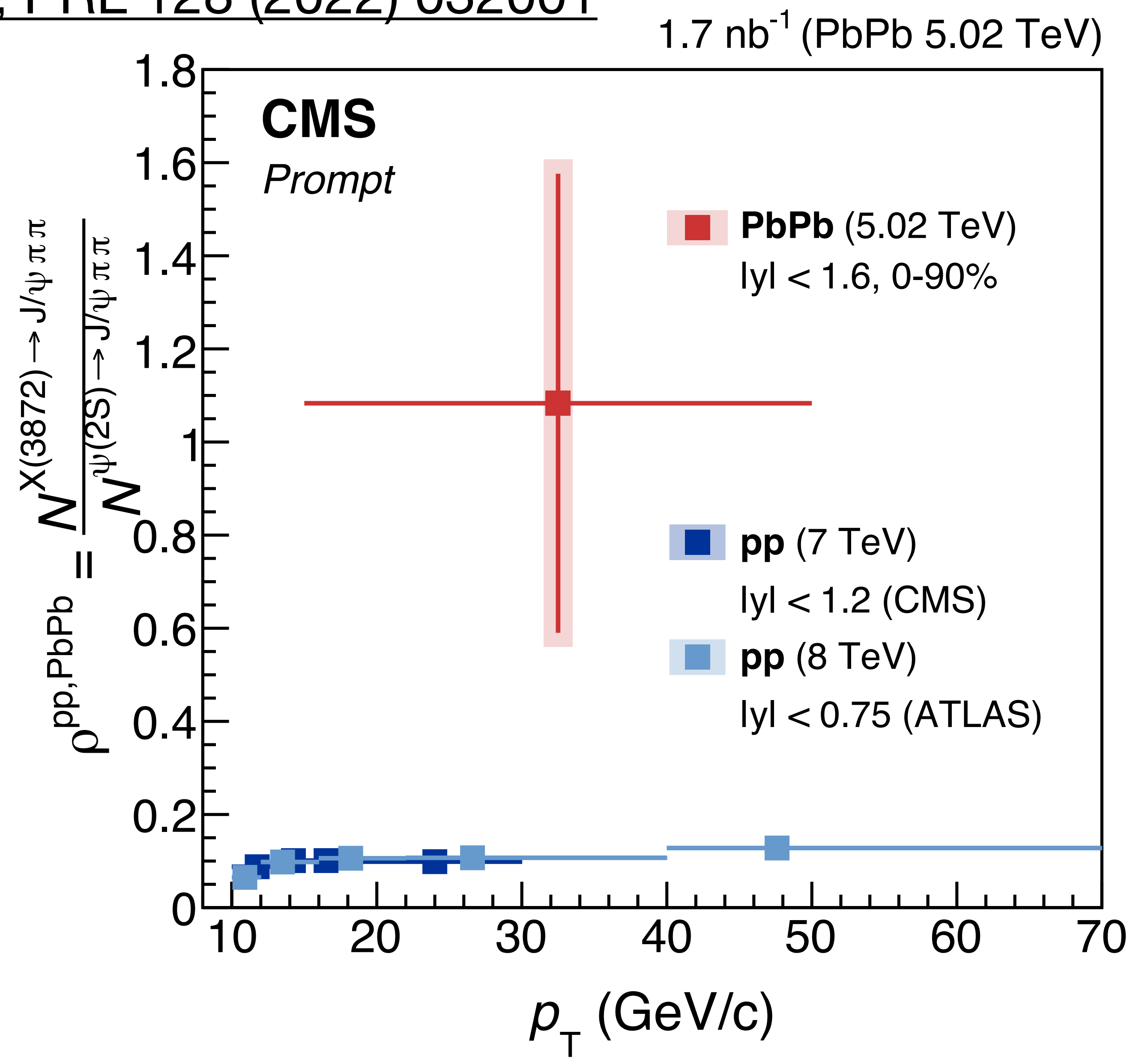


sPHENIX @ RHIC ⟶ ALICE 2 (Runs 3+4) ⟶ CMS LHC Run 4

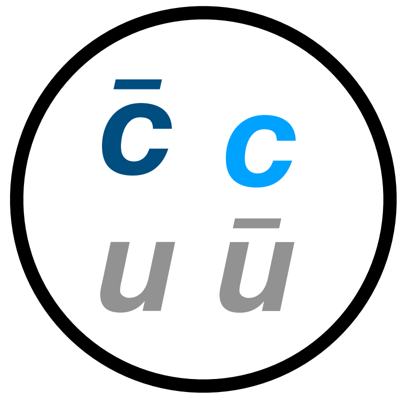
Study non-perturbative process of colorful partons forming colorless hadrons. Hadronization = **mechanism that enforces QCD confinement**

Medium-enabled production of rare hadrons

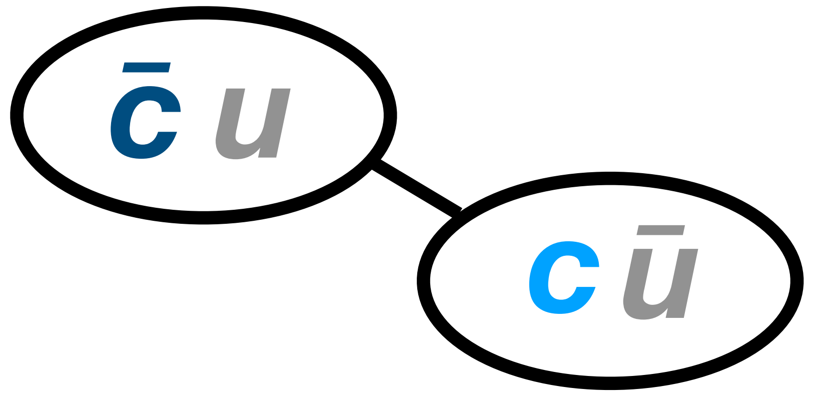
CMS, PRL 128 (2022) 032001



Dramatic difference in relative abundance of $X(3872)$ tetraquark in AA

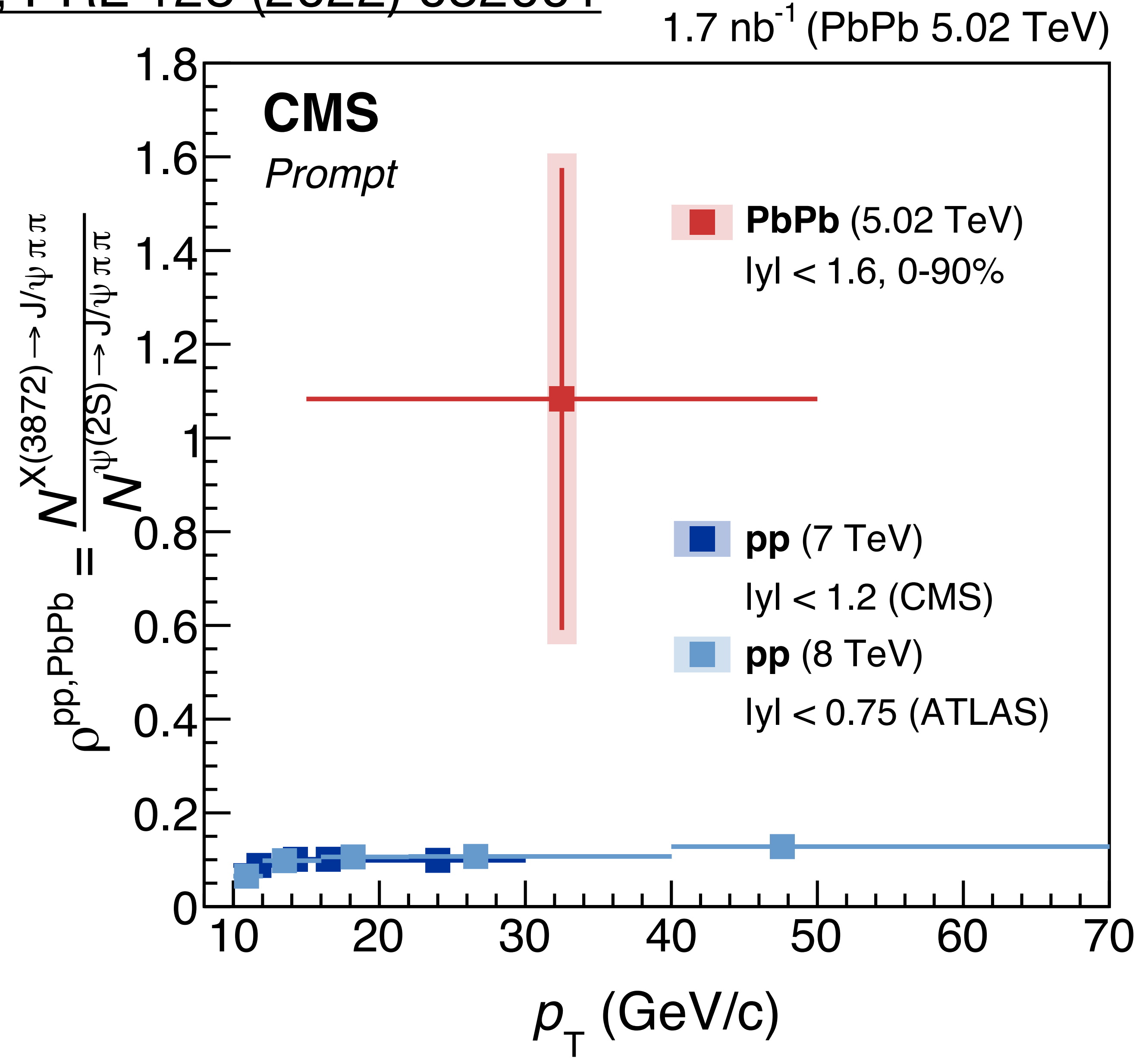


or

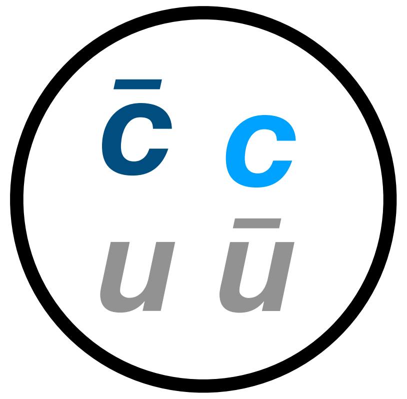


Medium-enabled production of rare hadrons

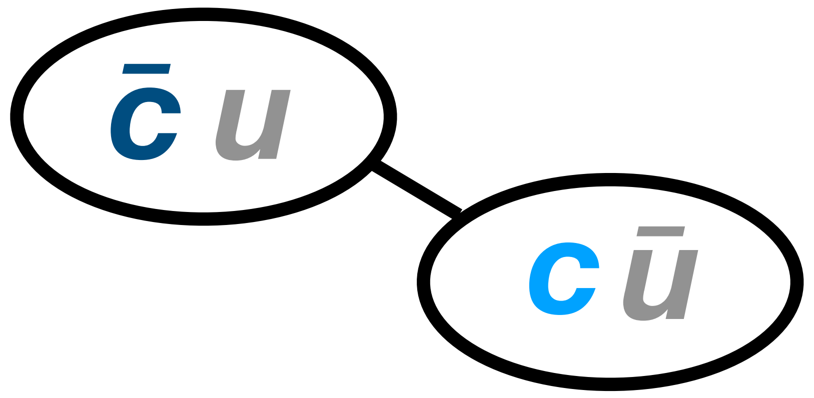
CMS, PRL 128 (2022) 032001



Dramatic difference in relative abundance of $X(3872)$ tetraquark in AA



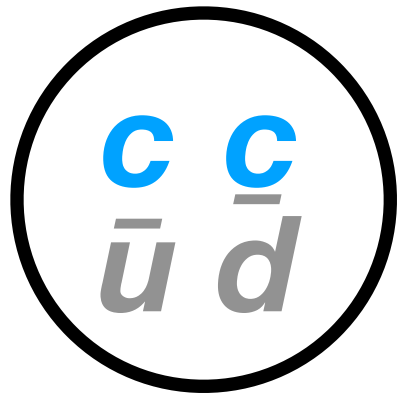
or



Potentially extreme enhancement:

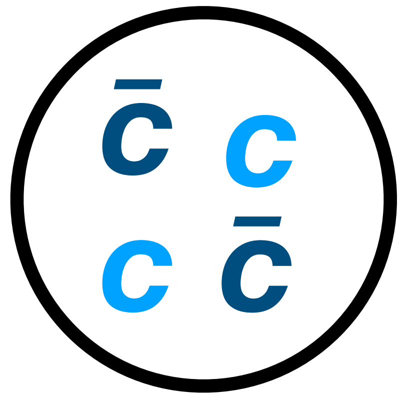
T_{cc}^{+}

$\to D^0 D^0 \pi^+$,

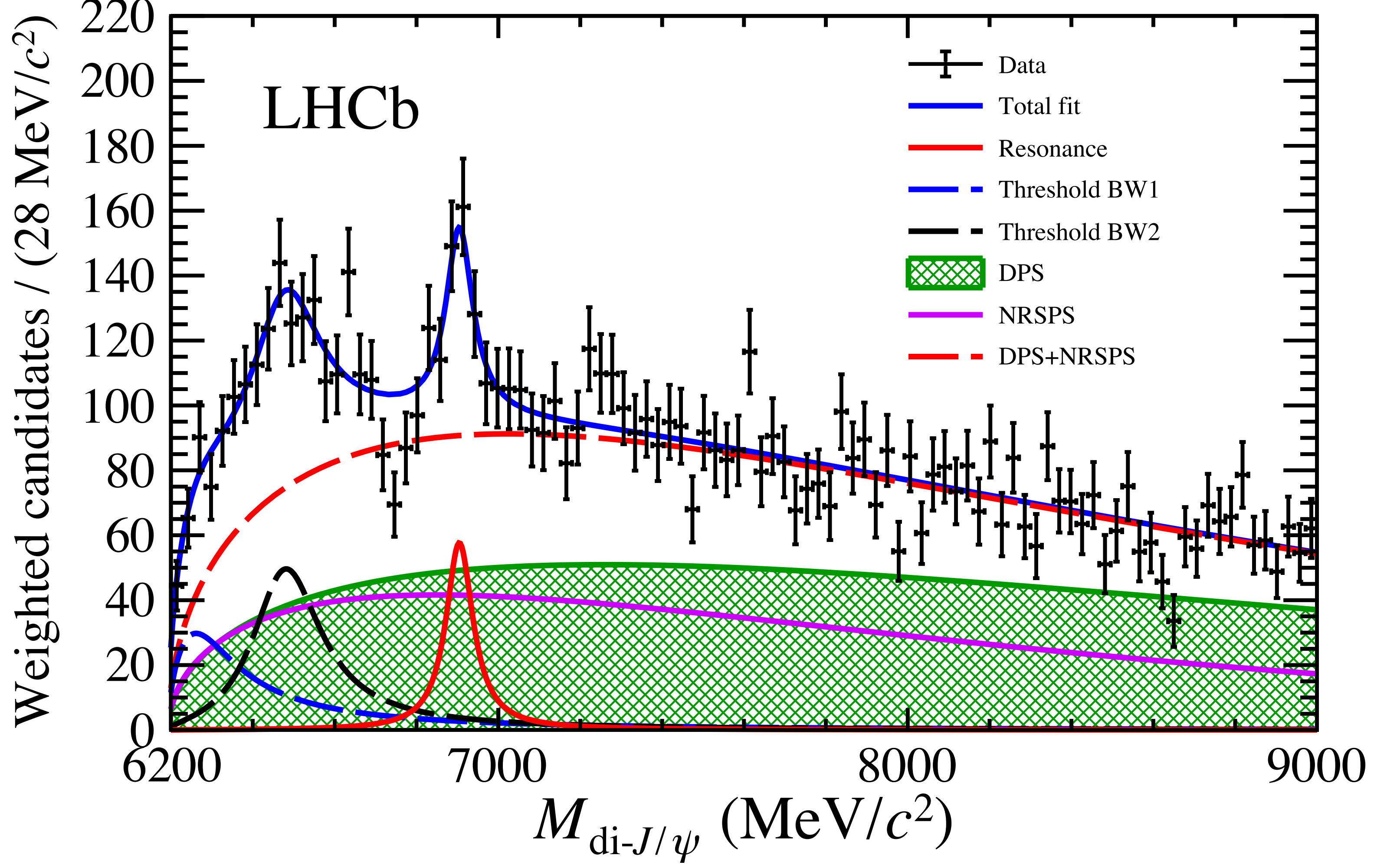


$X(6900)$

$\to J/\psi J/\psi$

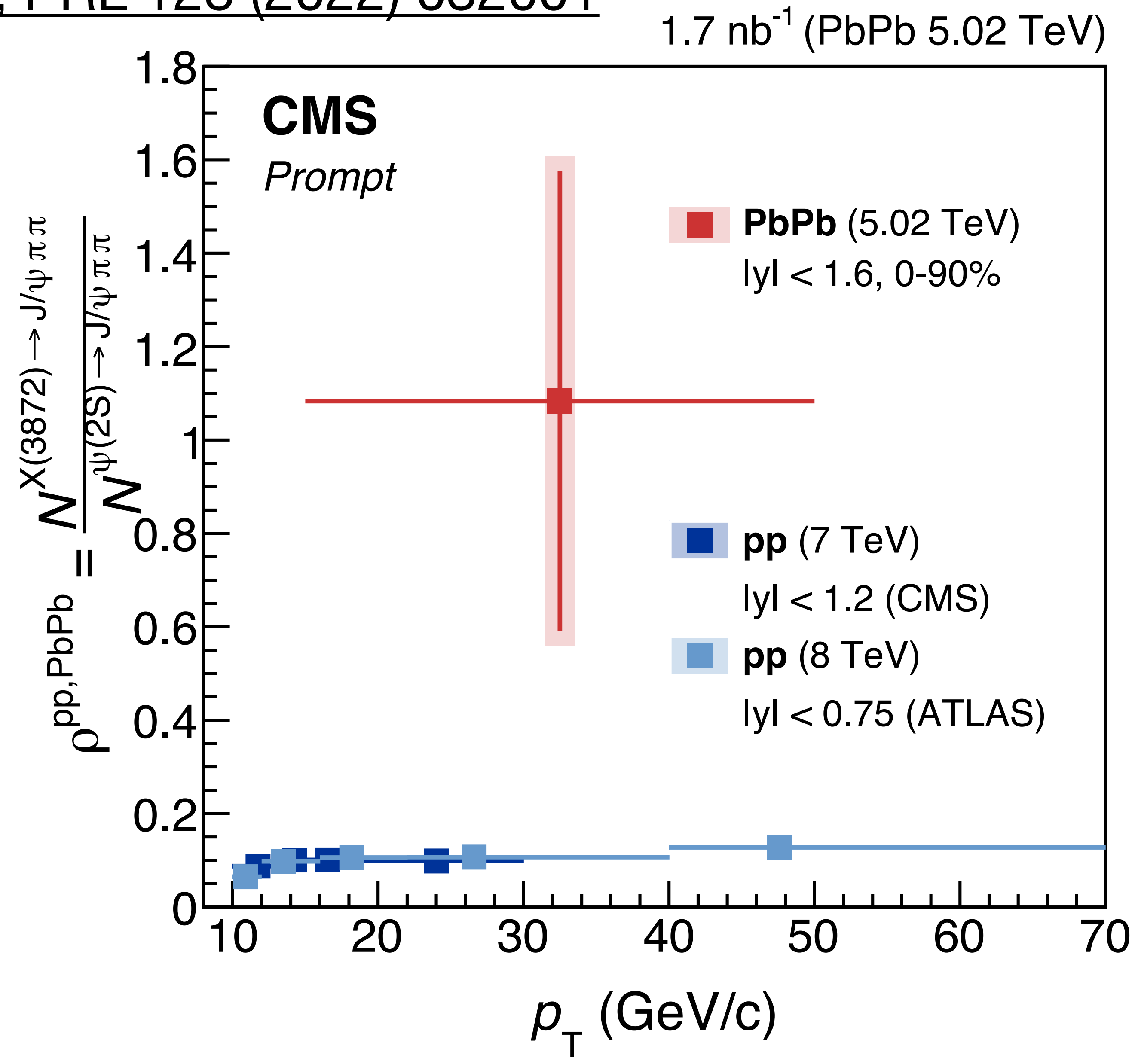


LHCb, *Nature Commun.* 13 (2022) 3351

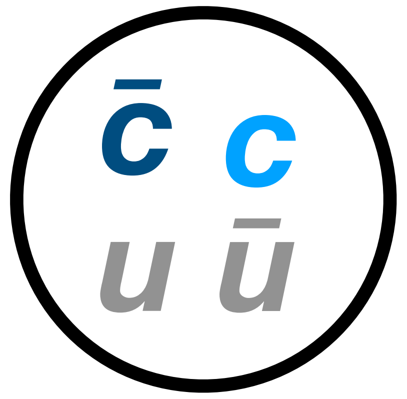


Medium-enabled production of rare hadrons

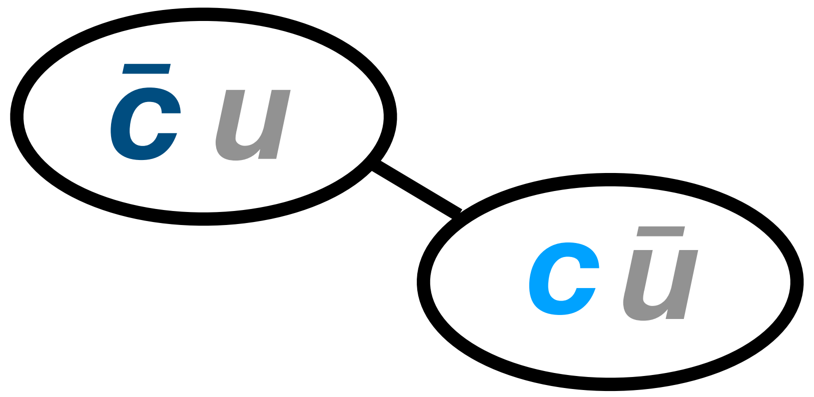
CMS, PRL 128 (2022) 032001



Dramatic difference in relative abundance of $X(3872)$ tetraquark in AA



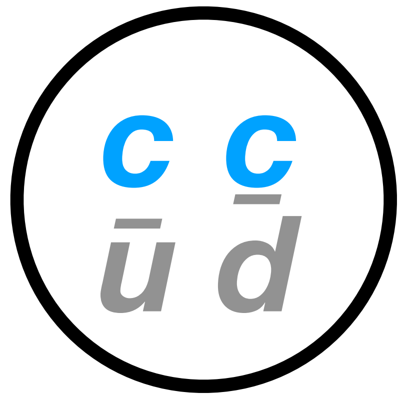
or



Potentially extreme enhancement:

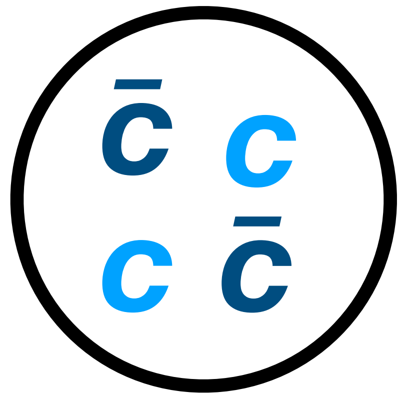
T_{cc}^{+}

$\rightarrow D^0 D^0 \pi^+$,

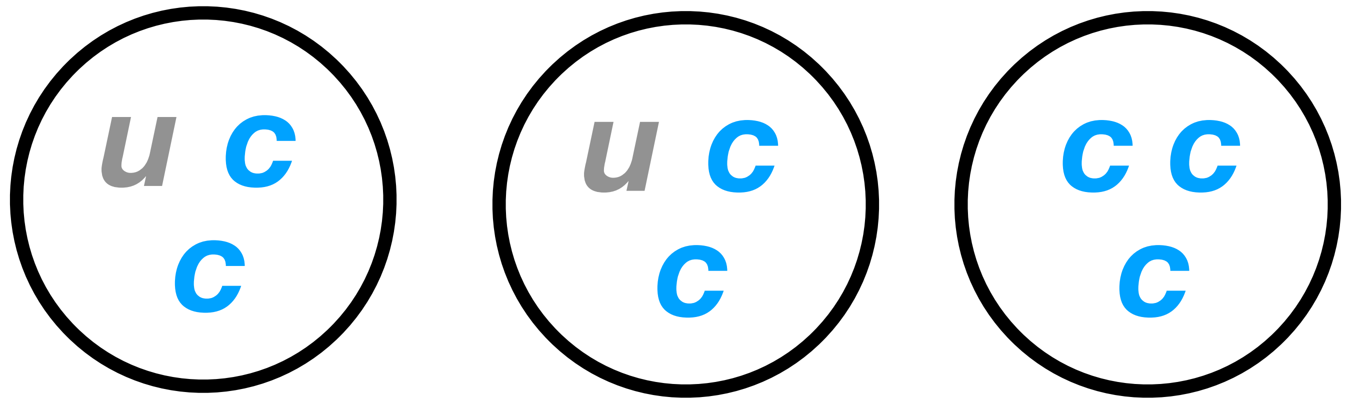


$X(6900)$

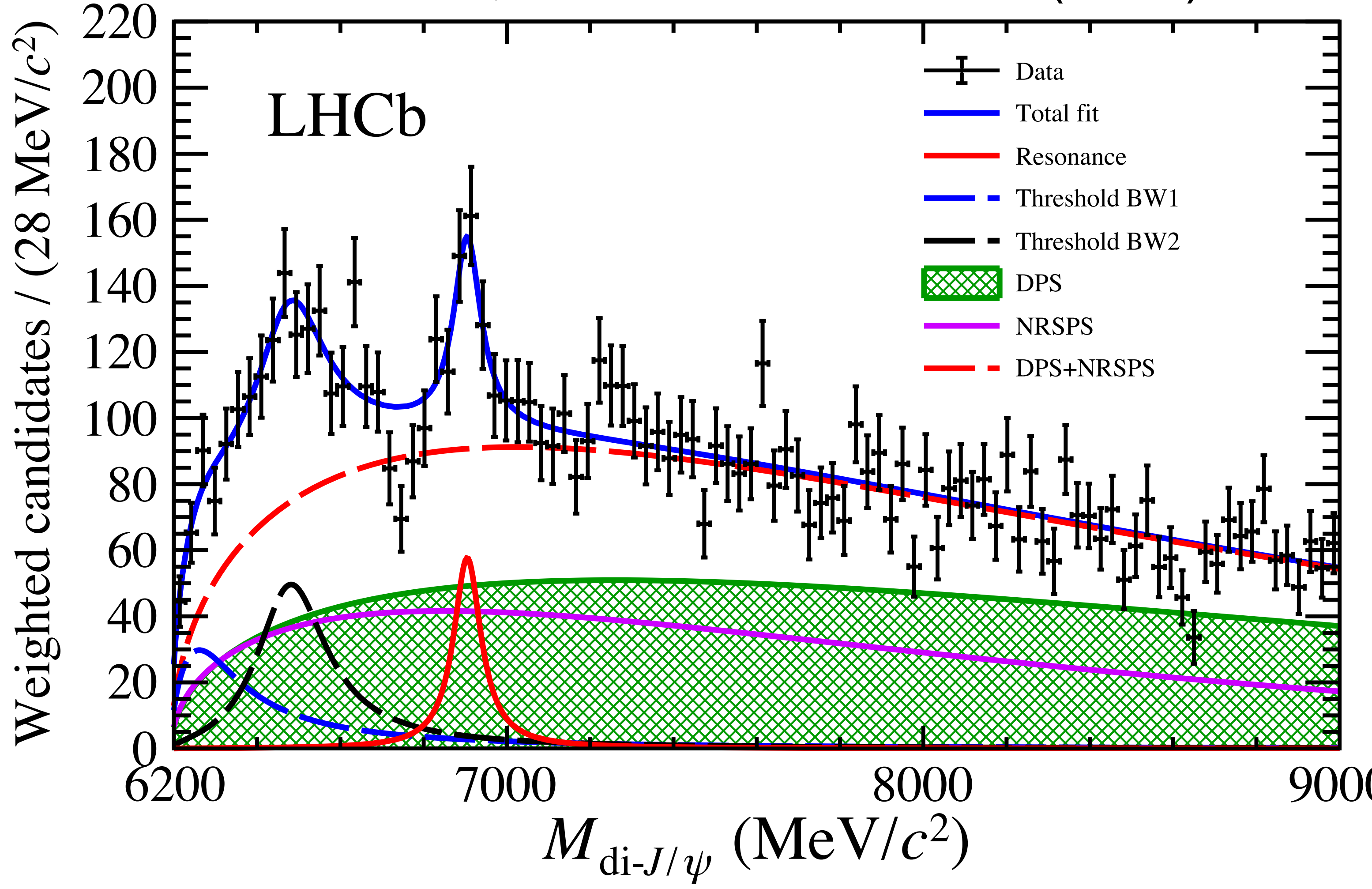
$\rightarrow J/\psi J/\psi$

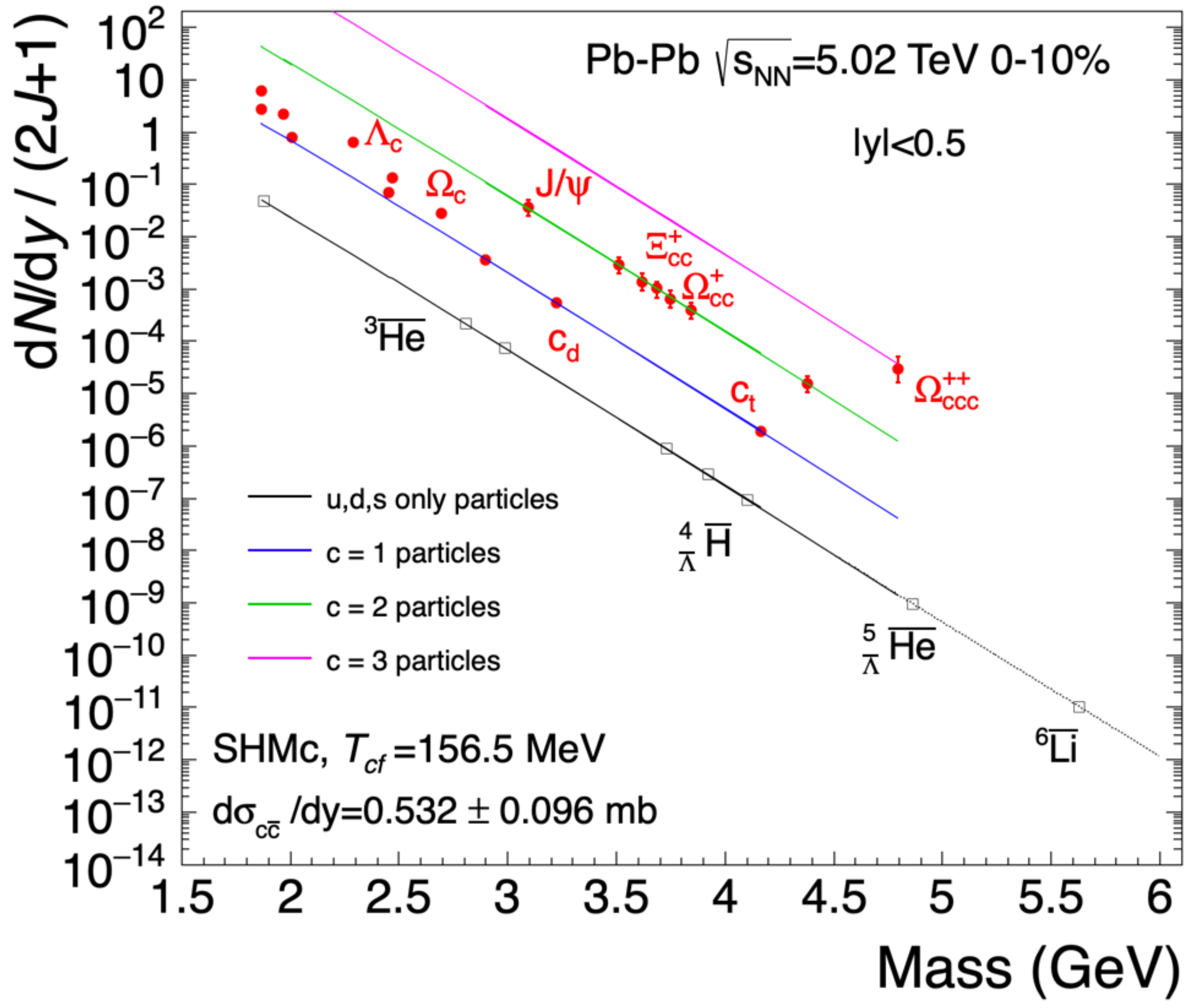


Multi-charm baryon program in ALICE 3

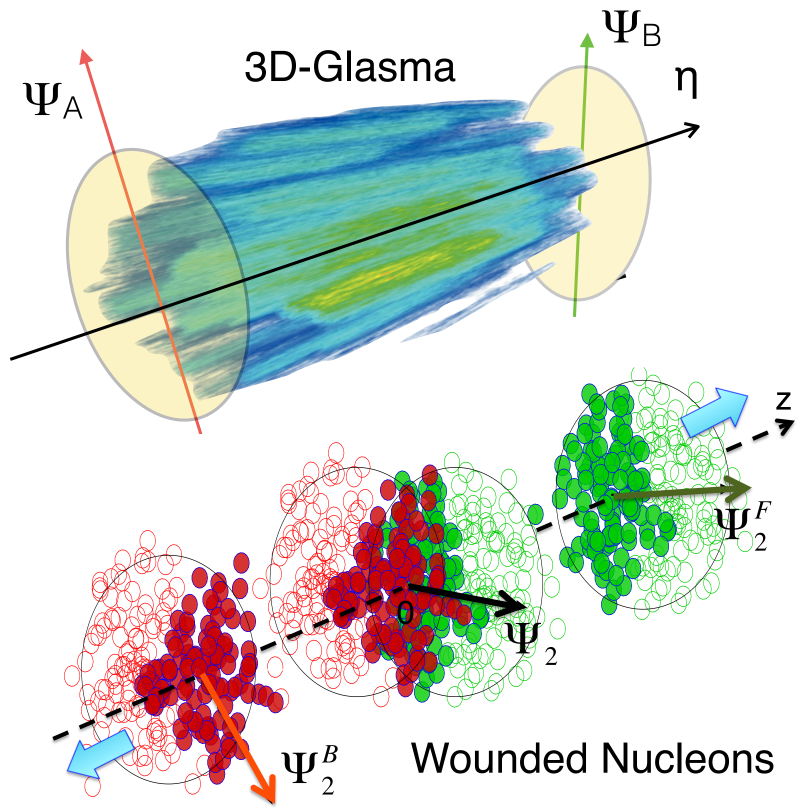


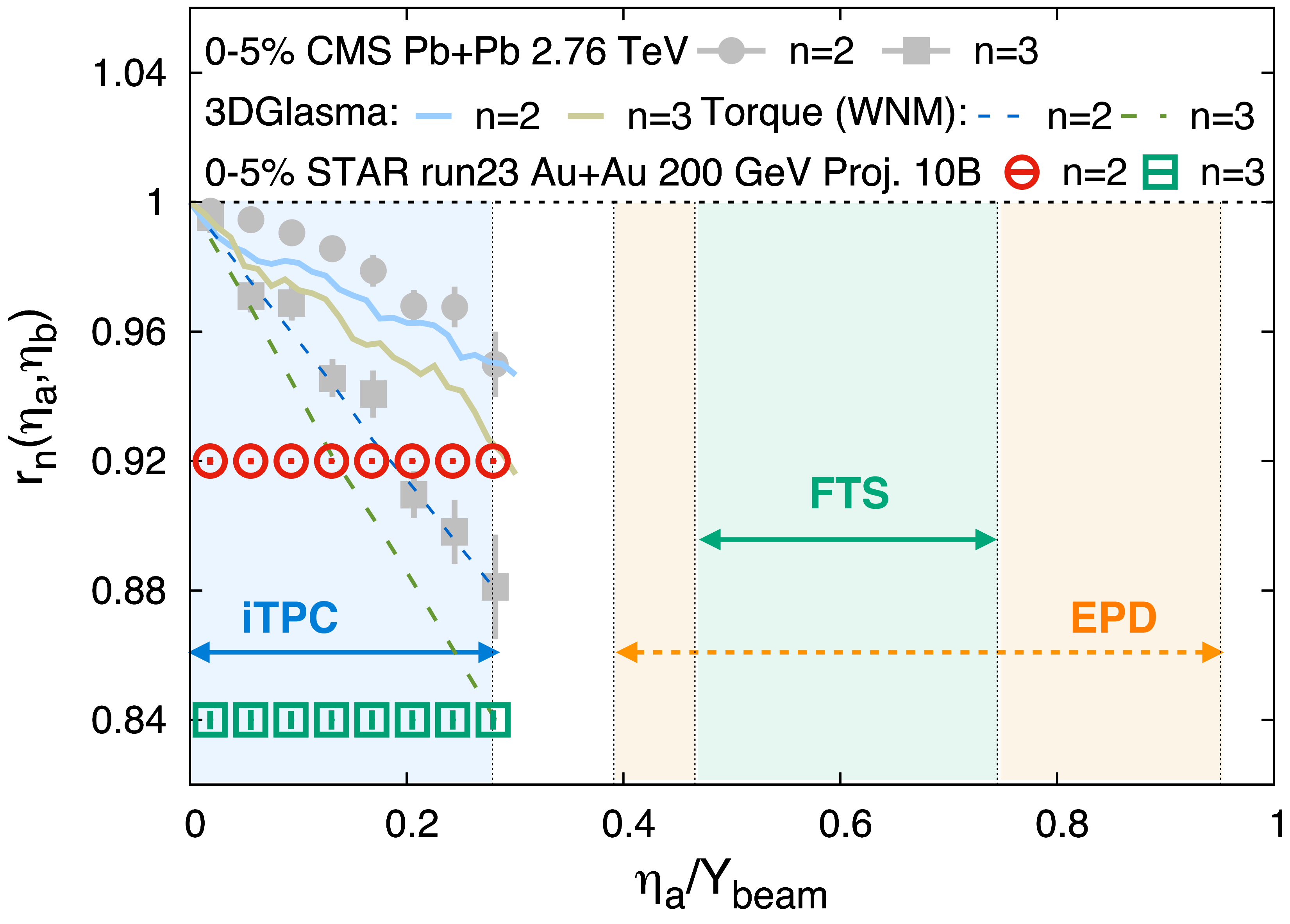
LHCb, *Nature Commun.* 13 (2022) 3351

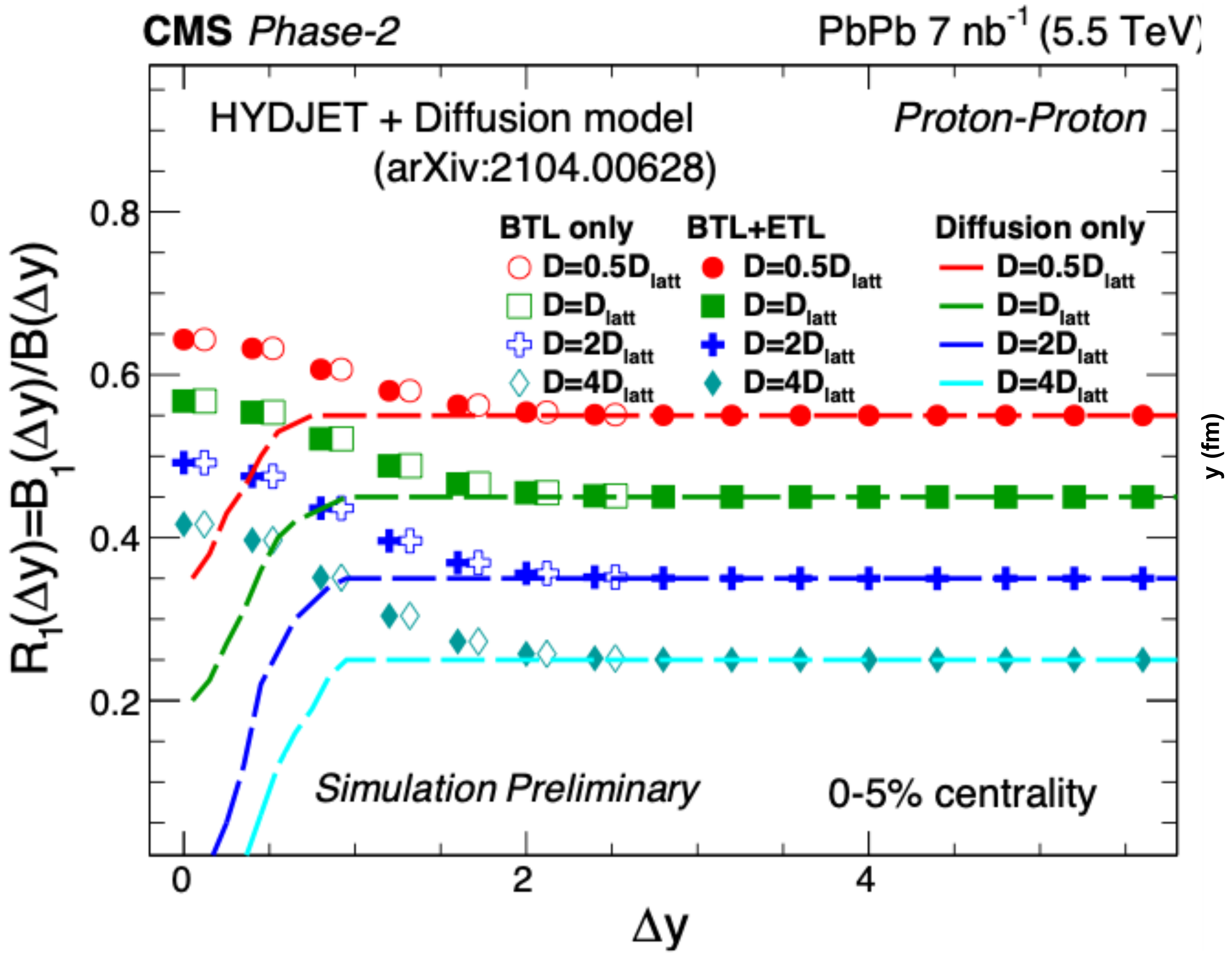


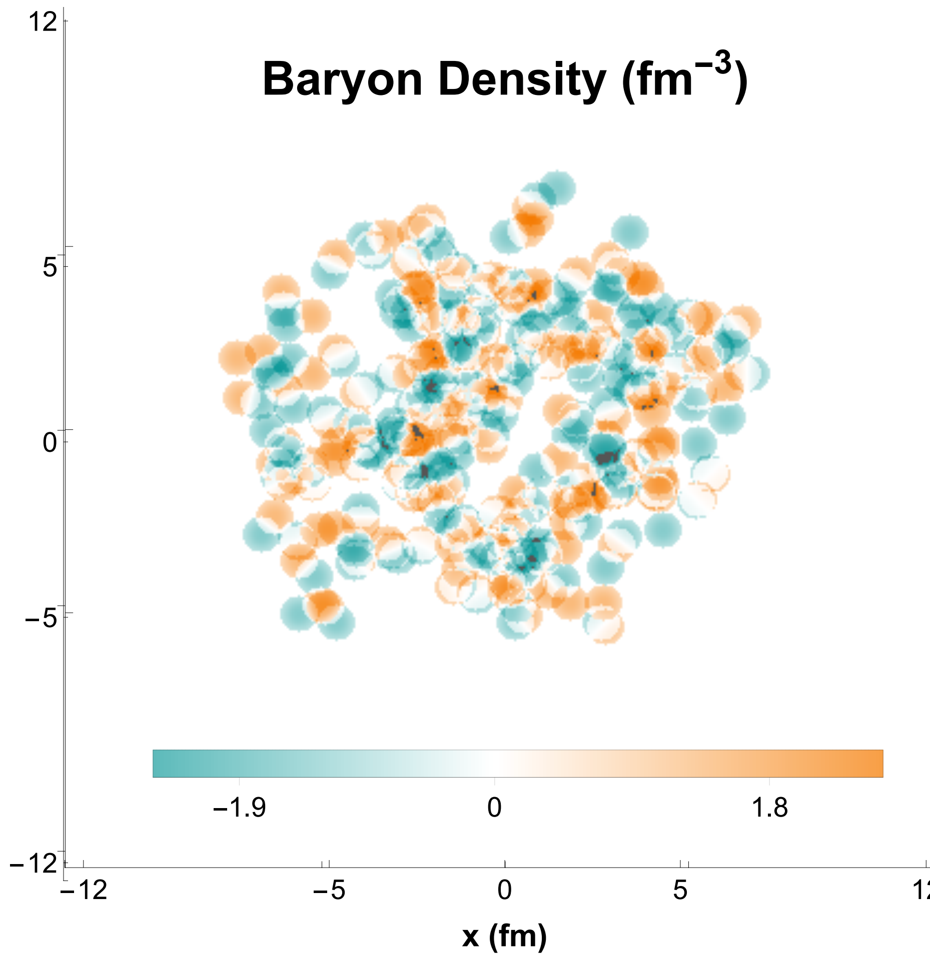


3-D imaging of nuclear collisions









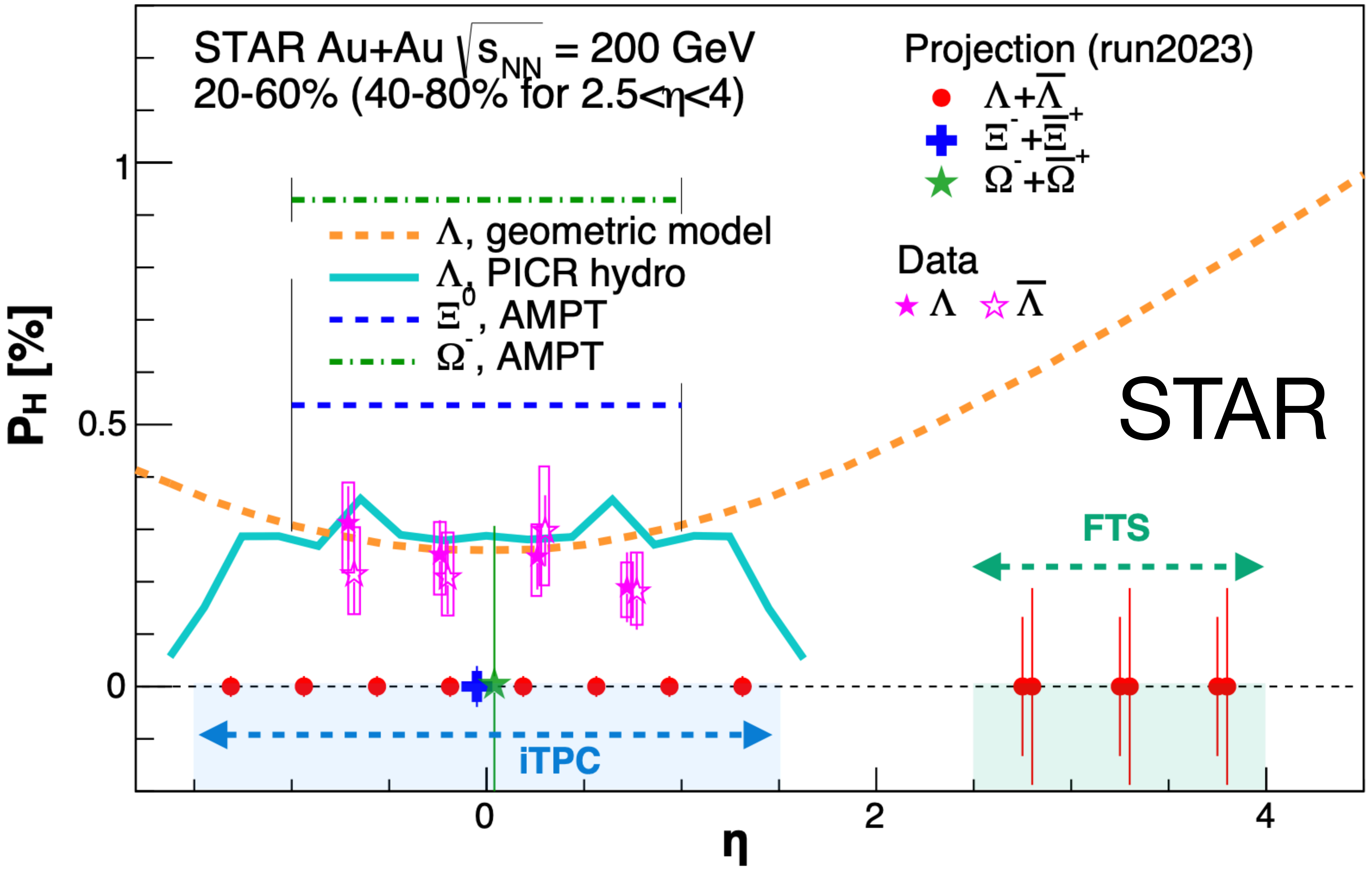
Longitudinal decorrelations out to ≈beam rapidity @ RHIC-STAR

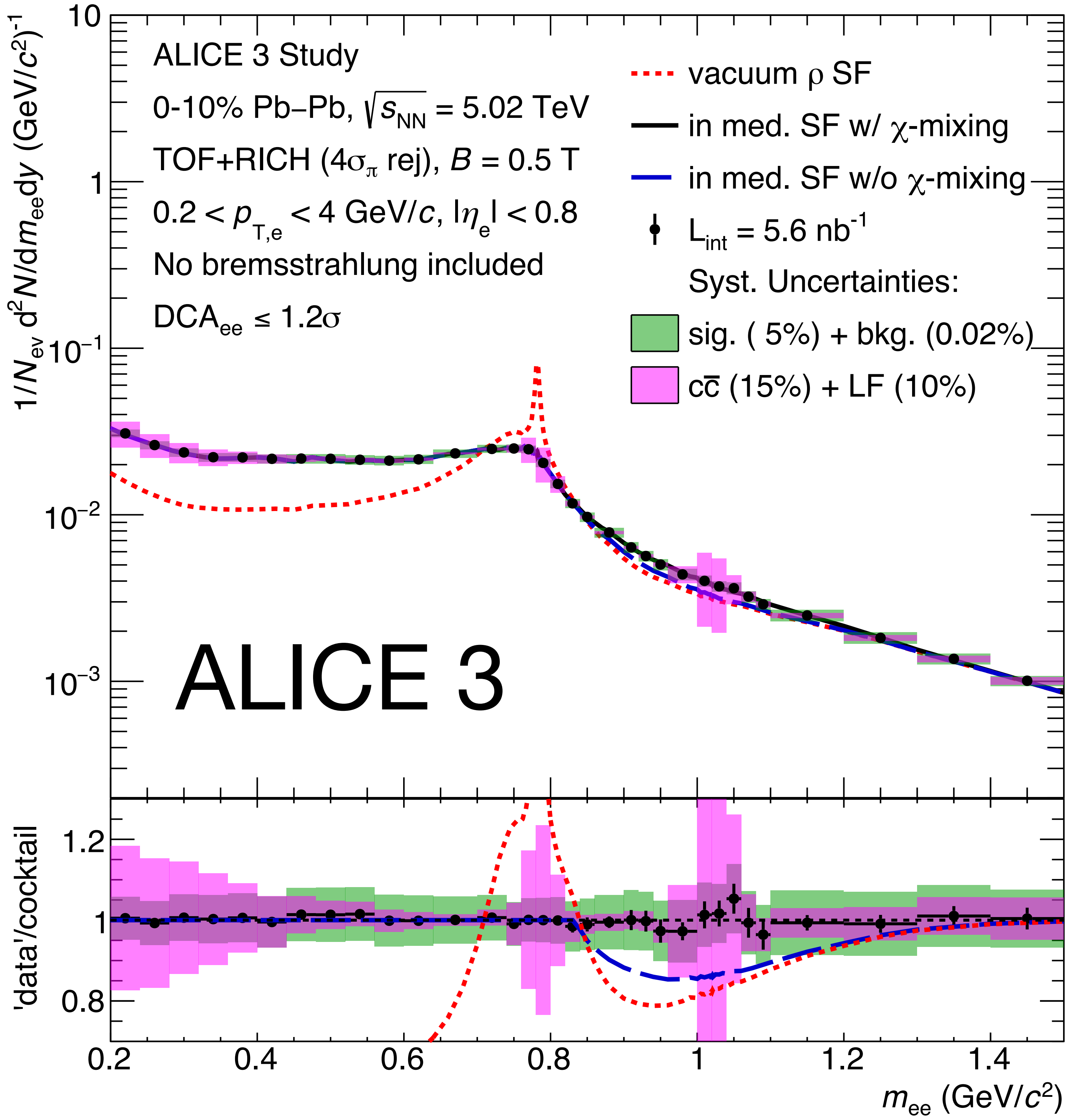
Use balance functions to track conserved charges out to $\Delta y \approx 6$ @ CMS Run 4

Measurements that **leverage unique forward capabilities**

Bulk properties of the Quark-Gluon Plasma

STAR, Nature 548 (2017) 62



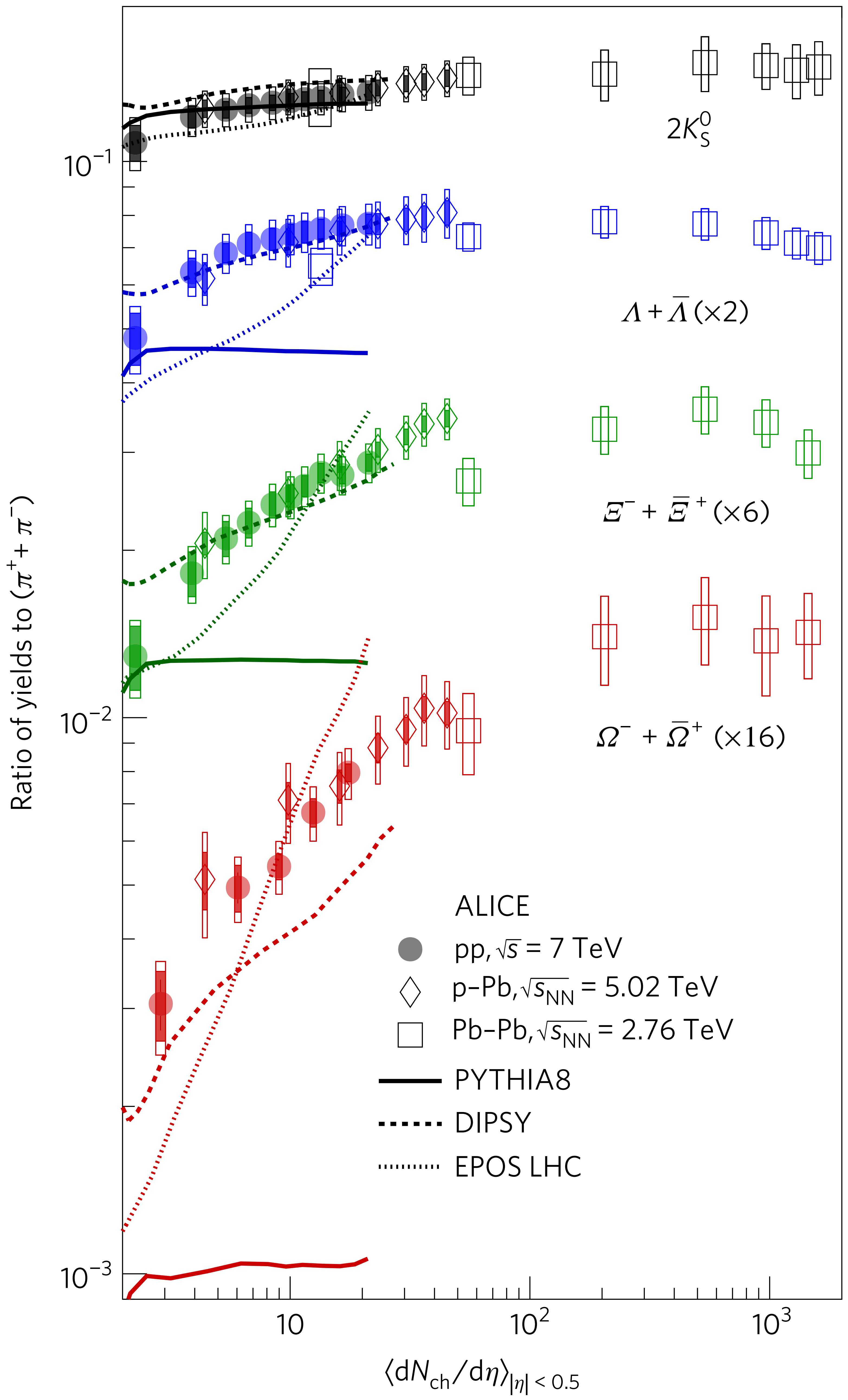


Campaign to understand how QGP transfers:

global vorticity → local fluid cell vorticity → angular momentum of final-state baryons ?

Multi-differential di-lepton measurements - Time evolution of thermally radiating QGP

ALICE, Nature Physics 13 (2017) 535



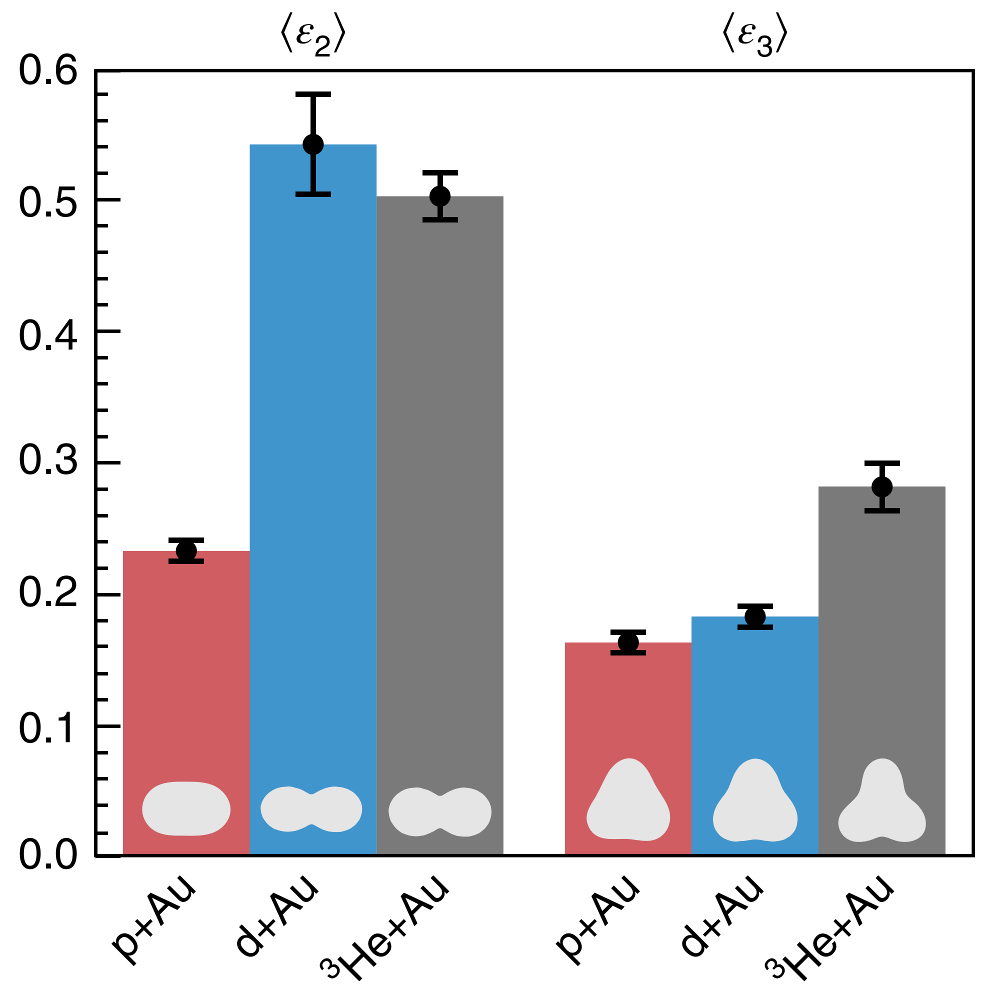
Progress in small systems

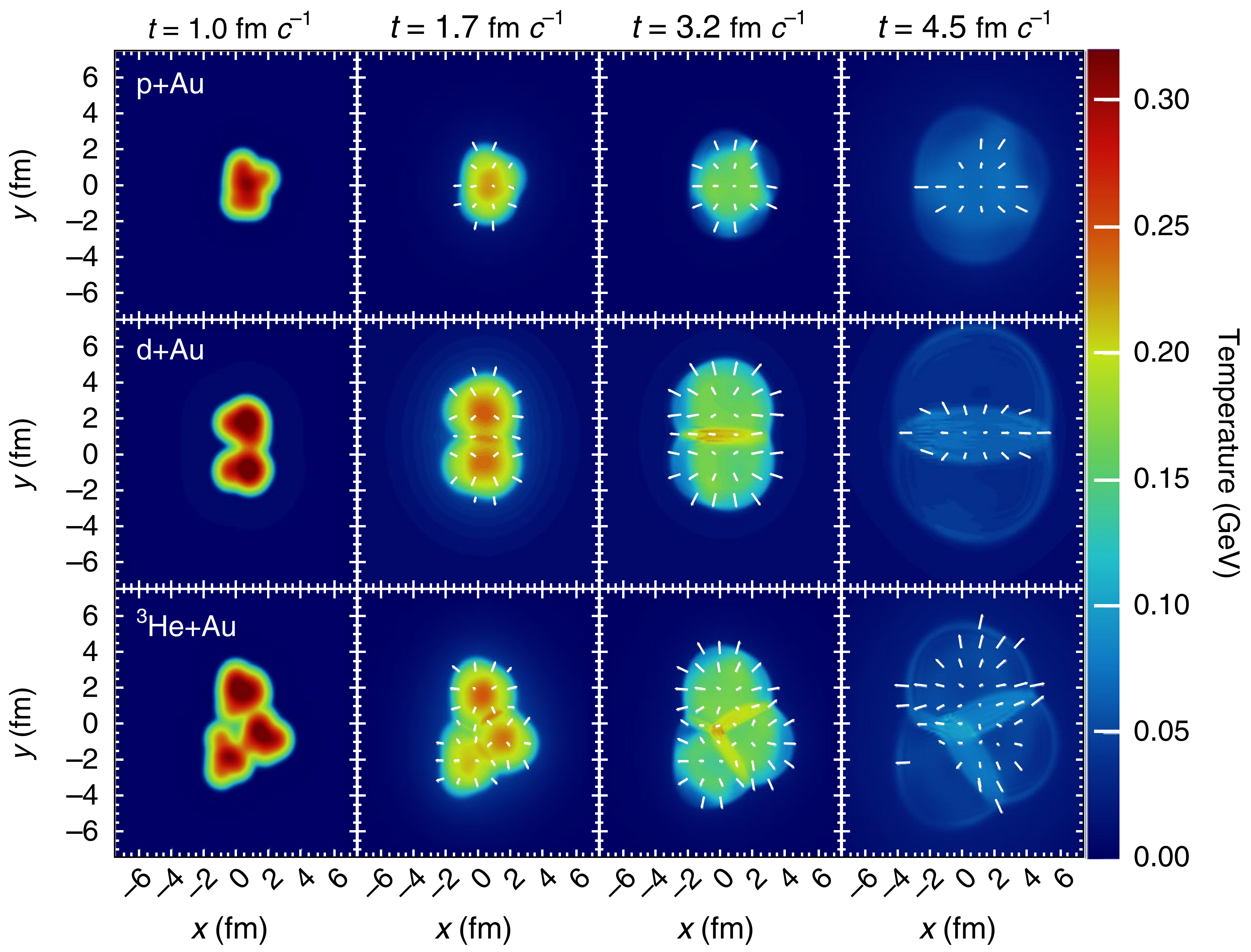
← Suggestion of a smooth continuum from

$$AA \rightarrow pA \rightarrow pp$$

Established geometry + final-state interactions as the **clear origin of collective motion** for soft particles

PHENIX, Nature Phys 15 (2019) 214

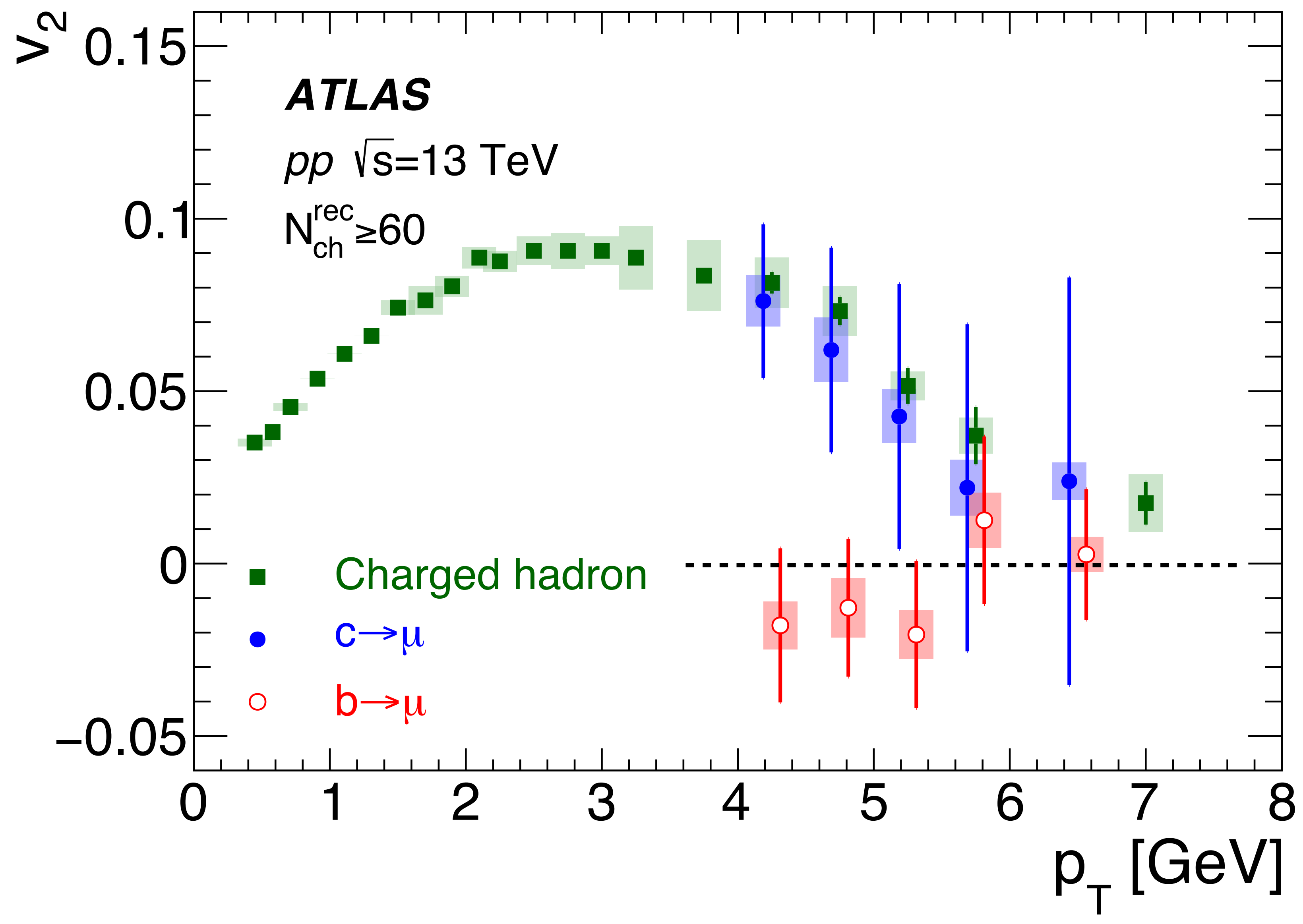


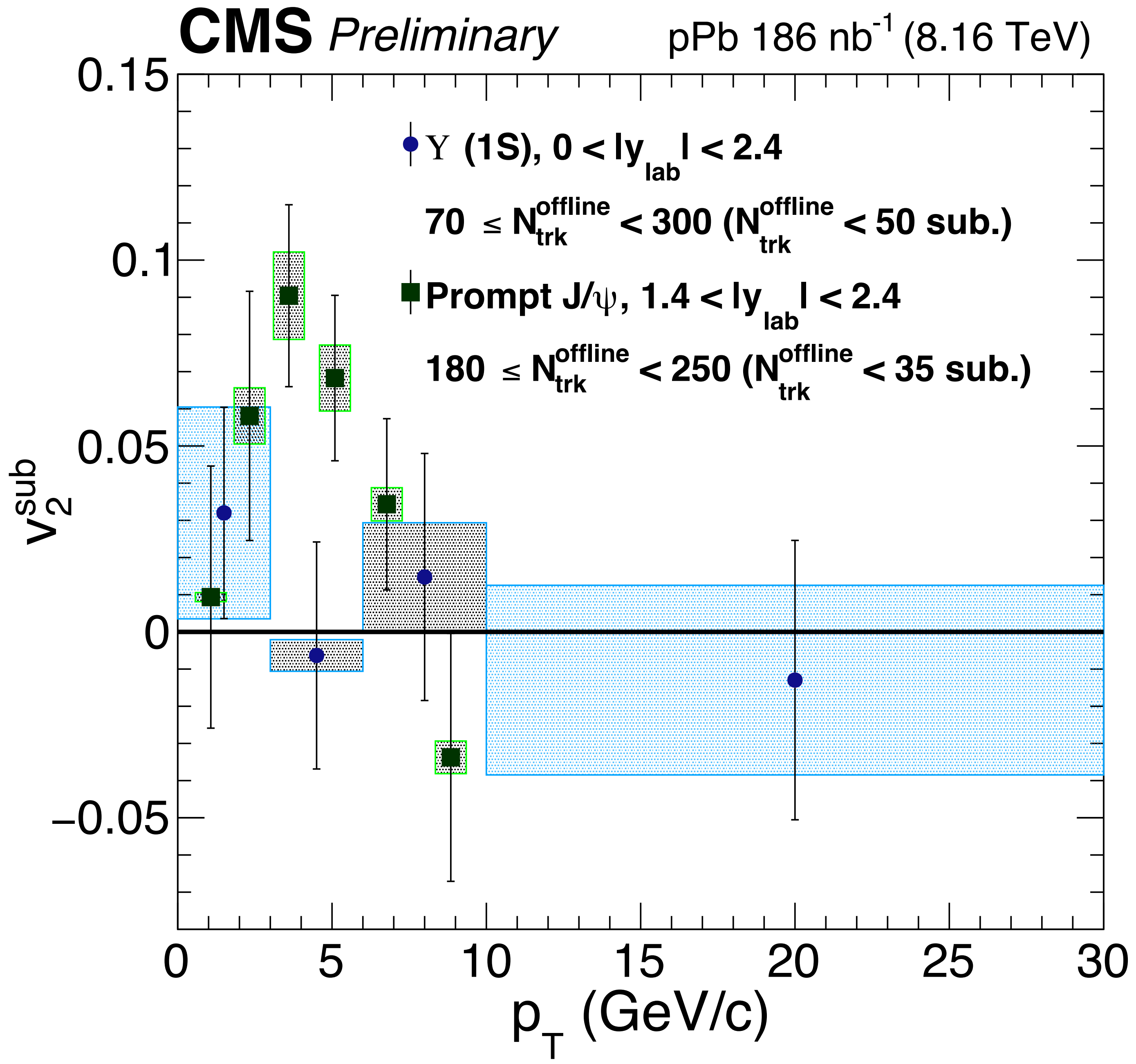


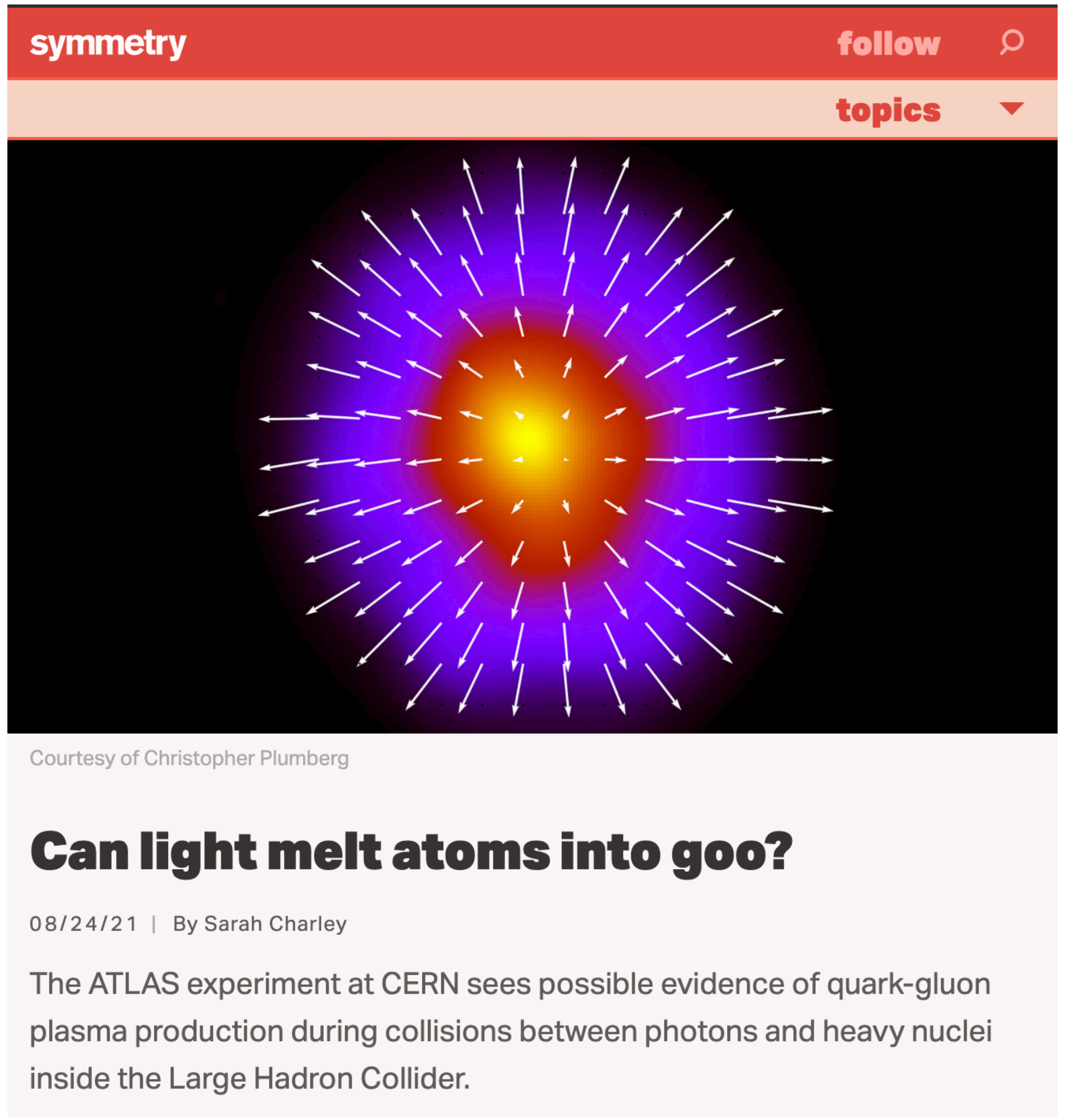
What are the limits of QGP formation?

ATLAS, PRC 104 (2021) 014903

ATLAS, PRL 124 (2020) 082301







Charm vs. bottom emerging as **key discriminator for collective behavior in small systems**

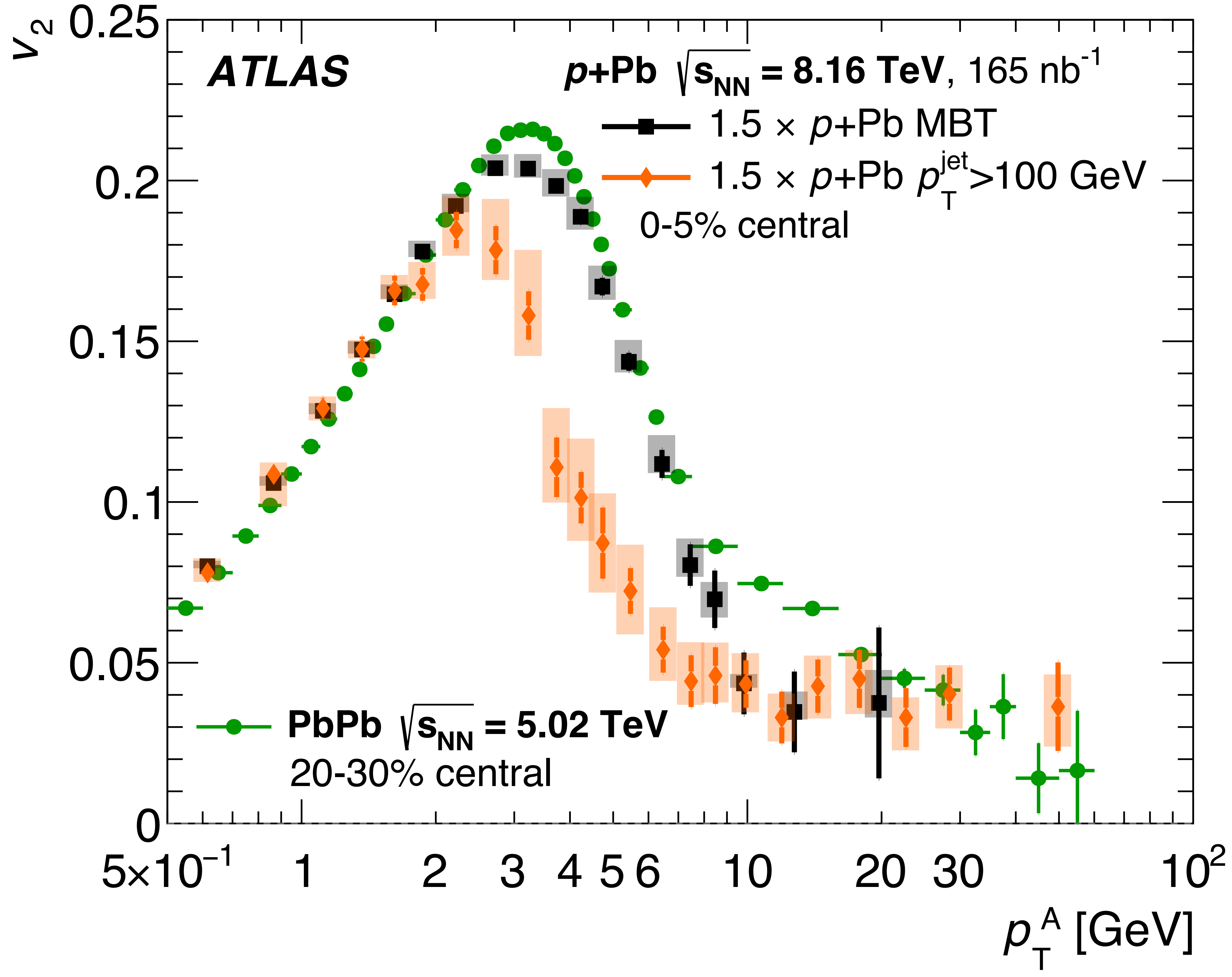
⇒ definitive answer with 1200 nb^{-1} of *p*+Pb in LHC Runs 3+4 + sPHENIX *p*+Au streaming readout

Flow-like signal in UPC

$\gamma + A$, searches in $\gamma + p$, archived e^+e^-, ep data, etc.

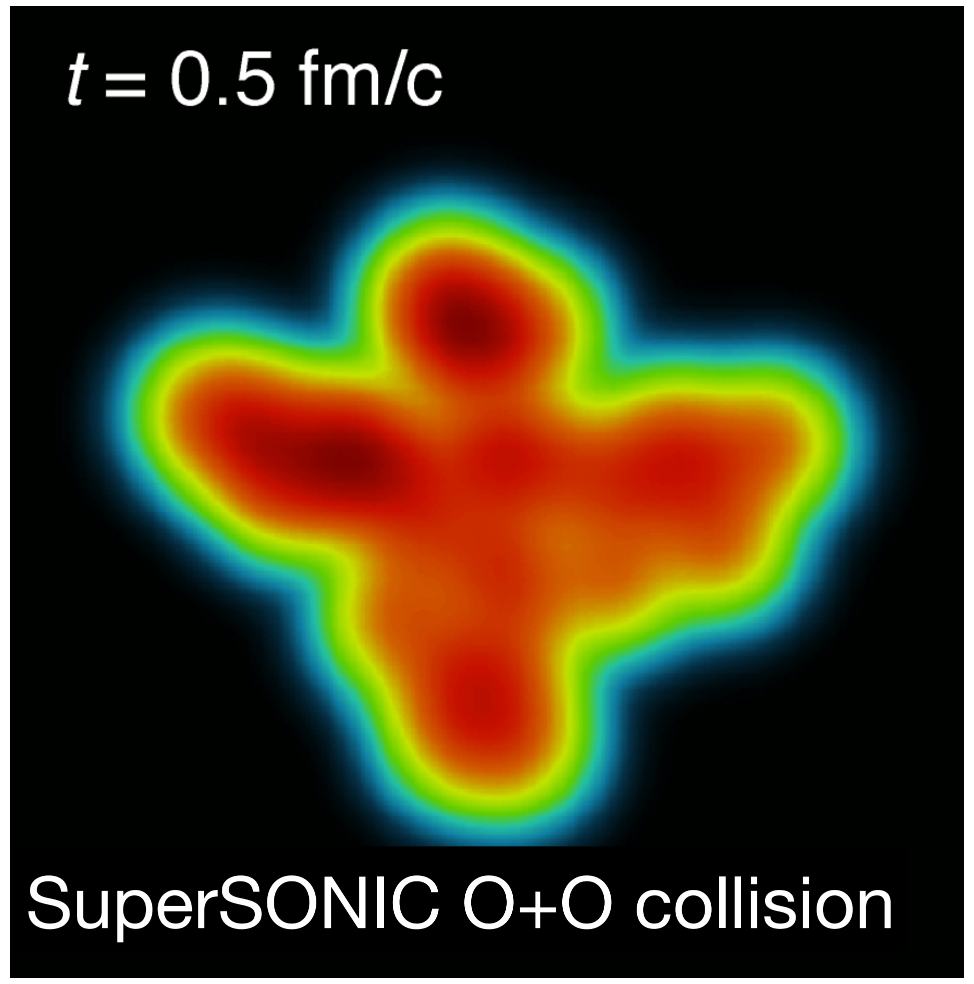
The mystery of small but dense systems

ATLAS, EPJC 80 (2020) 73

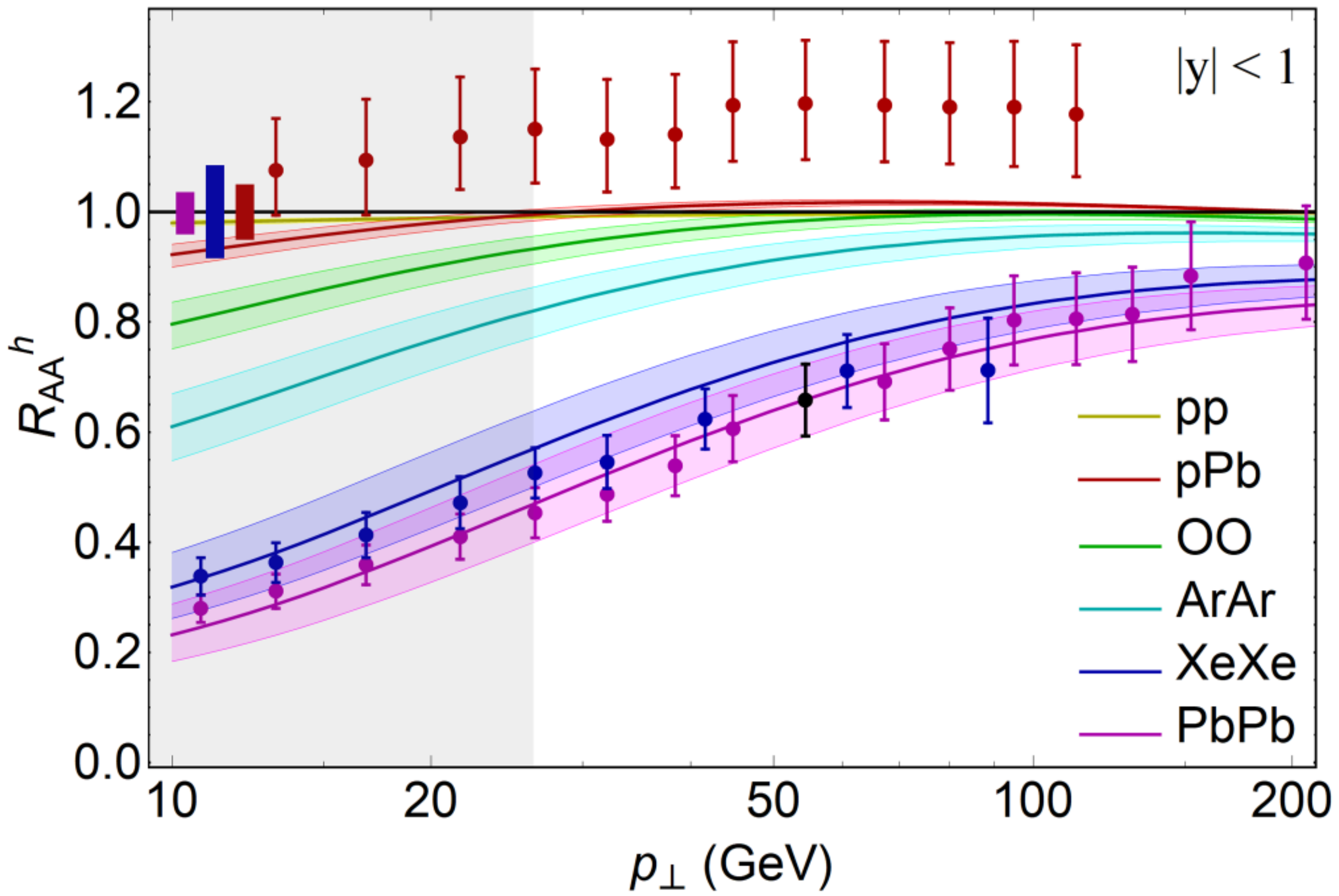


Collective motion of ≈ 50 GeV particles — but increasingly tighter constraints on quenching-like effects

Lim et al, PRC 99 (2019) 4, 044904



Huss et al., PRC 103 (2021) 054903



Major opportunity with **O+O collisions in LHC Run 3** — small system without difficult-to-control geometry of p+A

Run **small ions by default in LHC Run 5+6** - ultra-high luminosity, precision EW+jet

Reductionism

New experimental capabilities

Multi-dimensional measurements

Qualitatively new channels

Increased precision & control

Isolate & identify
underlying microscopic
mechanisms

Reductionism

New experimental capabilities

Multi-dimensional measurements

Qualitatively new channels

Increased precision & control

Isolate & identify underlying microscopic mechanisms

Resolve space-time picture of parton-QGP interaction

Observe direct evidence of charm diffusion

Confirm QCD in-medium radiation

Isolate the determining aspects of energy loss

Probe the QCD $q\bar{q}$ interaction

Explore the mechanism of QCD confinement

Identify point-like constituents of the QGP

Study the thermalization process

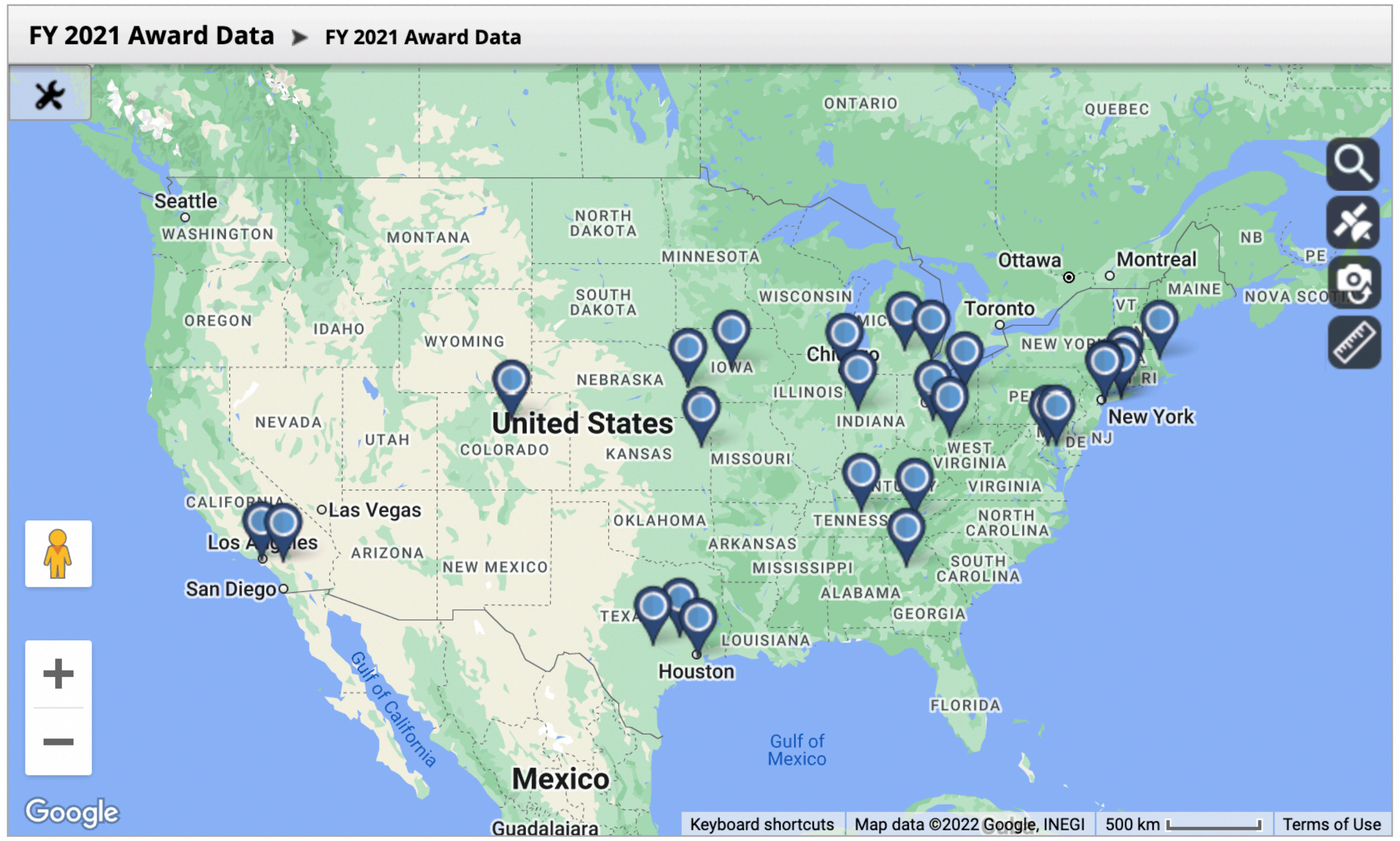
Minimal conditions for QGP creation

Questions for the Hot QCD community

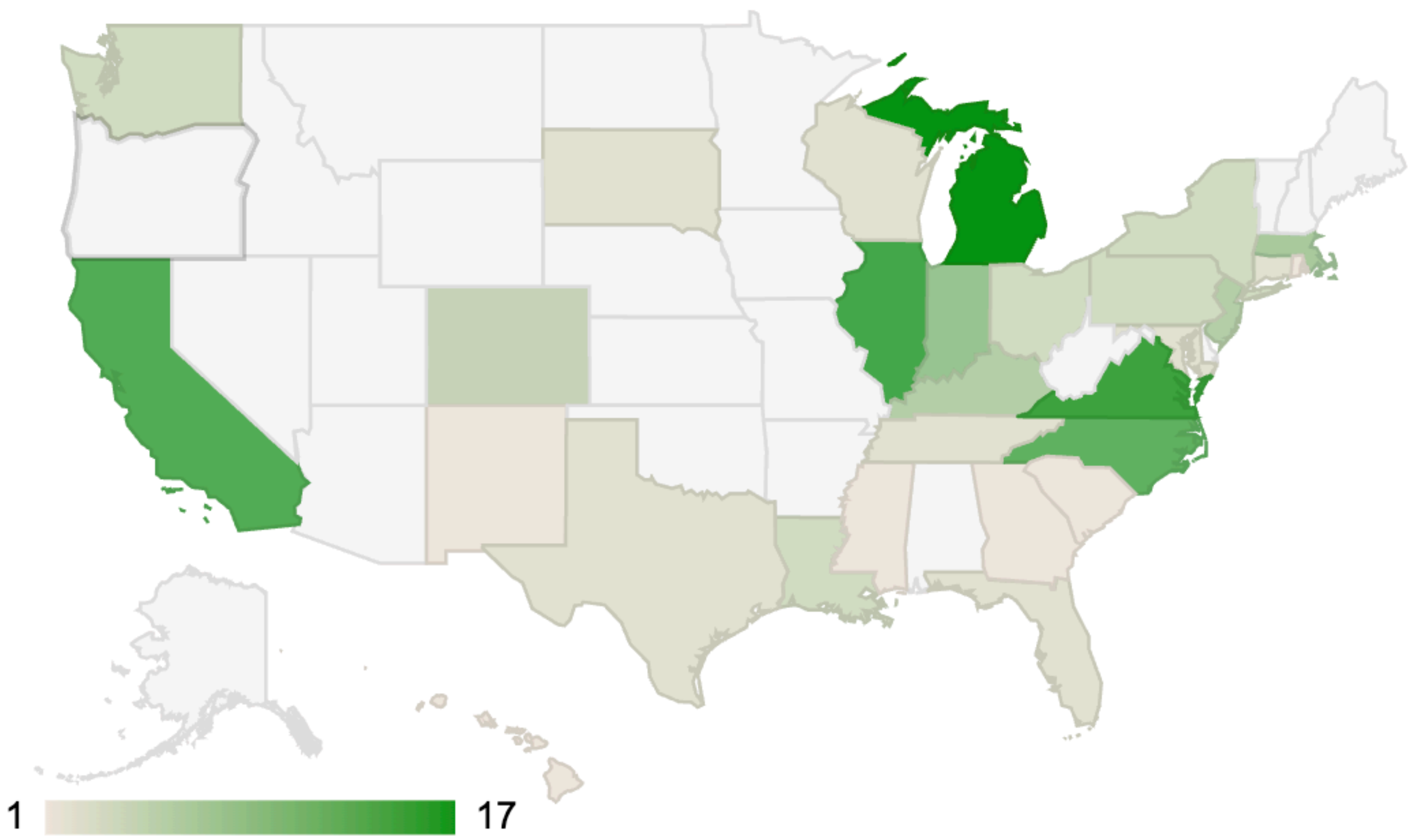
Questions for the Hot QCD community

How big should the experimental workforce be in the U.S.?

➡ What's the right # of University and Lab groups to do our physics?



science.osti.gov
DOE NP Heavy Ion supported institutions



[nsf.gov](nsf.gov)
NSF Nuclear Physics - Experiment active awards

BERKELEY LAB

Brookhaven National Laboratory

Los Alamos NATIONAL LABORATORY

Lawrence Livermore National Laboratory

OAK RIDGE National Laboratory

DOE Laboratories with Heavy Ion Physics groups

Questions for the Hot QCD community

How big should the experimental workforce be in the U.S.?

➡ What's the right # of University and Lab groups to do our physics?

What's the optimal distribution over experiments?

➡ Given substantial upgrades / new capabilities, should we re-organize?

Questions for the Hot QCD community

How big should the experimental workforce be in the U.S.?

➡ What's the right # of University and Lab groups to do our physics?

What's the optimal distribution over experiments?

➡ Given substantial upgrades / new capabilities, should we re-organize?

What is the key new instrumentation U.S. groups are interested in?

➡ What is our physics-motivated "ask" to agencies?

ALICE FoCal? CMS MTD-ETL? LHCb Upgrades? ALICE 3?

The way forward

The way forward

Finish the scientific mission of RHIC, our flagship domestic facility

➡ Reap the **full benefit of major investments** at RHIC

➡ Deliver the **luminosity of high-quality data** needed to complete the physics goals of sPHENIX and STAR

➡ Support RHIC research throughout data-taking and afterwards (computing, University groups, etc.)

The way forward

Finish the scientific mission of RHIC, our flagship domestic facility

➡ Reap the **full benefit of major investments** at RHIC

➡ Deliver the **luminosity of high-quality data** needed to complete the physics goals of sPHENIX and STAR

➡ Support RHIC research throughout data-taking and afterwards (computing, University groups, etc.)

Continue the strong tradition of U.S. leadership in Hot QCD at the LHC

➡ Consider U.S. involvement in **new instrumentation**

➡ Encourage the opportunity for physics-motivated **migration between experiments** (including RHIC → LHC after sPHENIX+STAR)

Many thanks for input from

ALICE
ATLAS
CMS
LHCb
PHENIX
sPHENIX
STAR
Parallel session speakers

any bias is mine alone and any
omission is strictly due to limited time!

Thank you!