New answers and new questions in Hot QCD

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U.S. DEPARTMENT OF ENERGY
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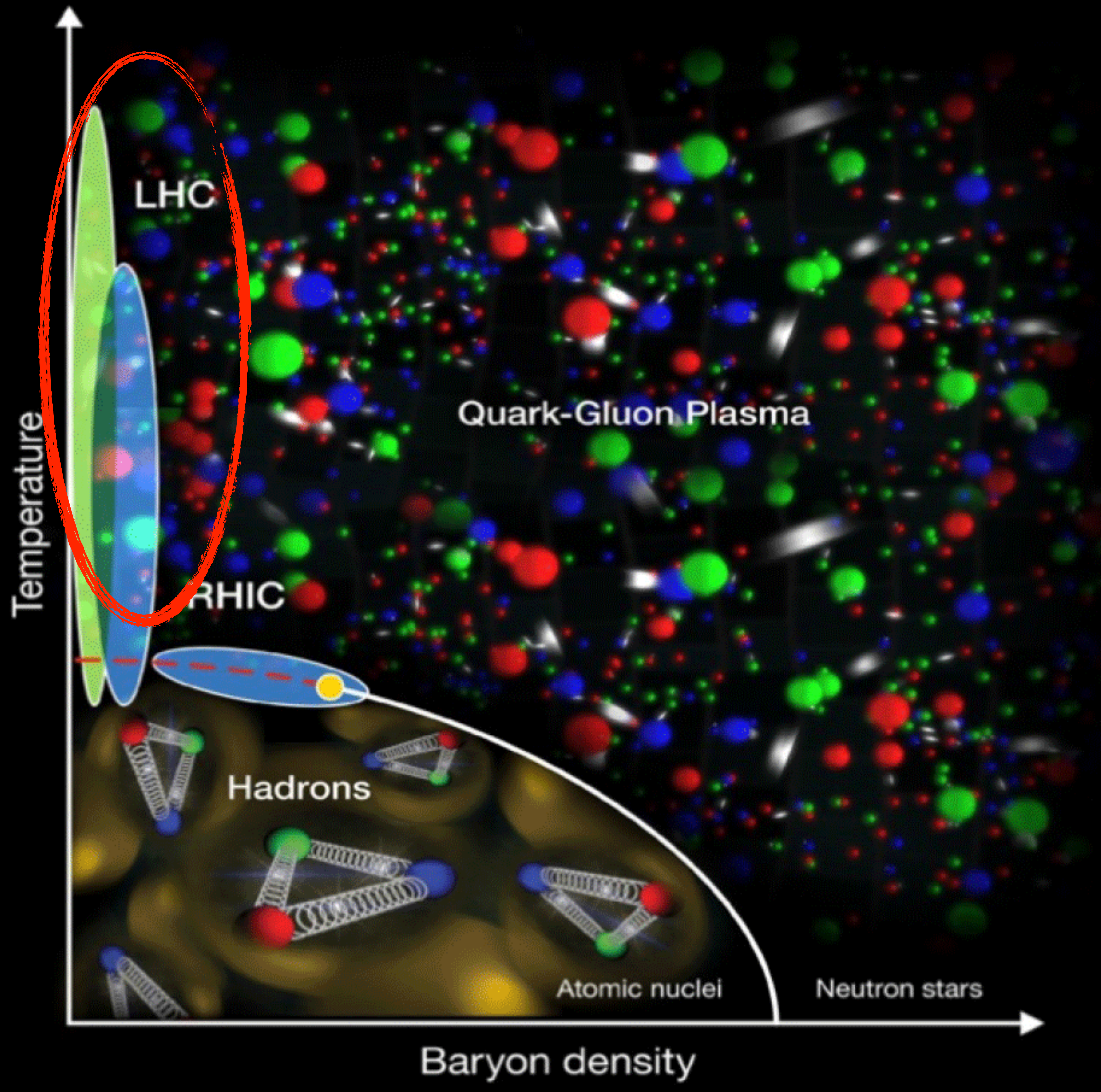
WILHELM UND ELSE HERAEUS-STIFTUNG

Study low μ_B region:

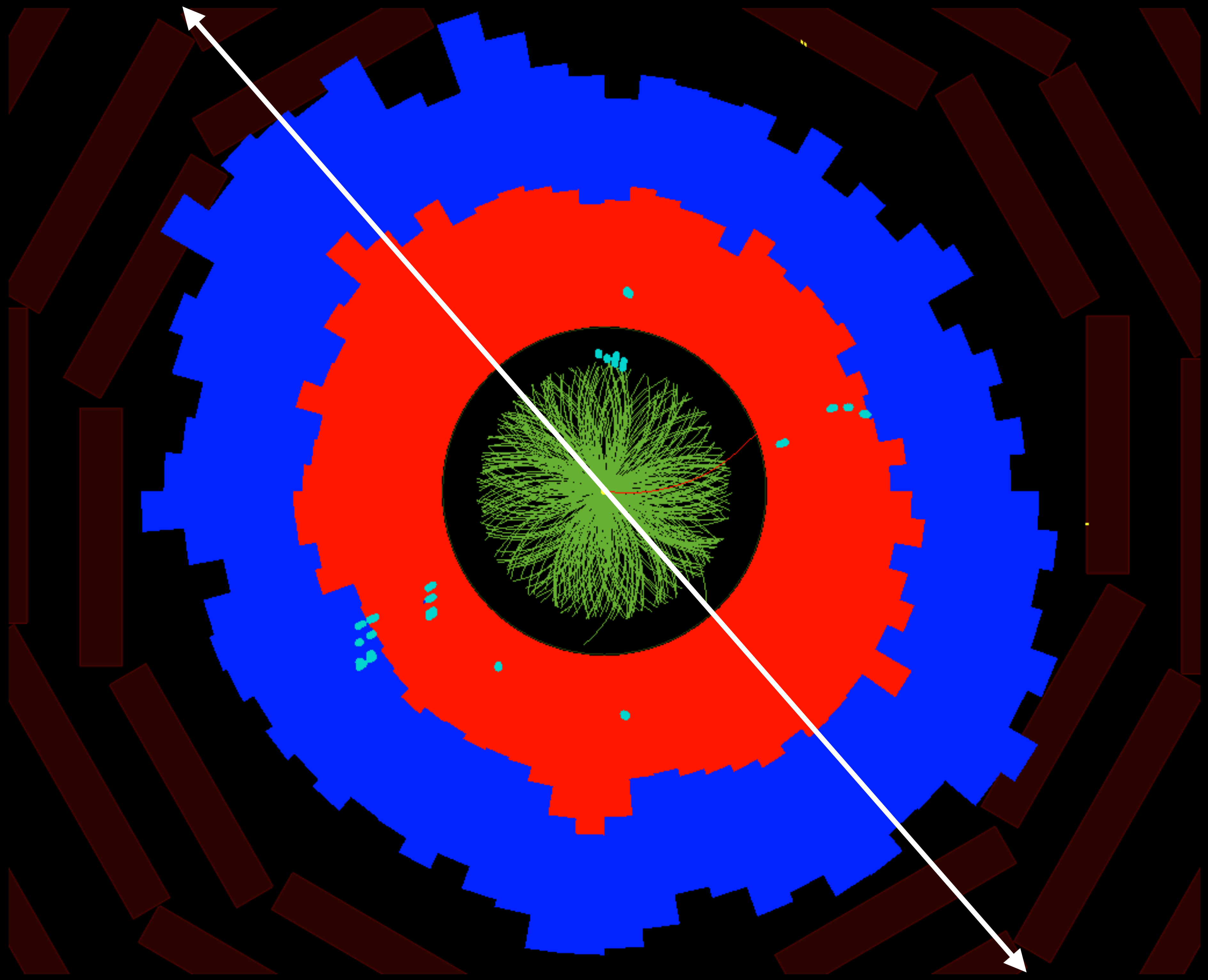
LHC and top RHIC energy

Cross-over from hadronic phase to QGP



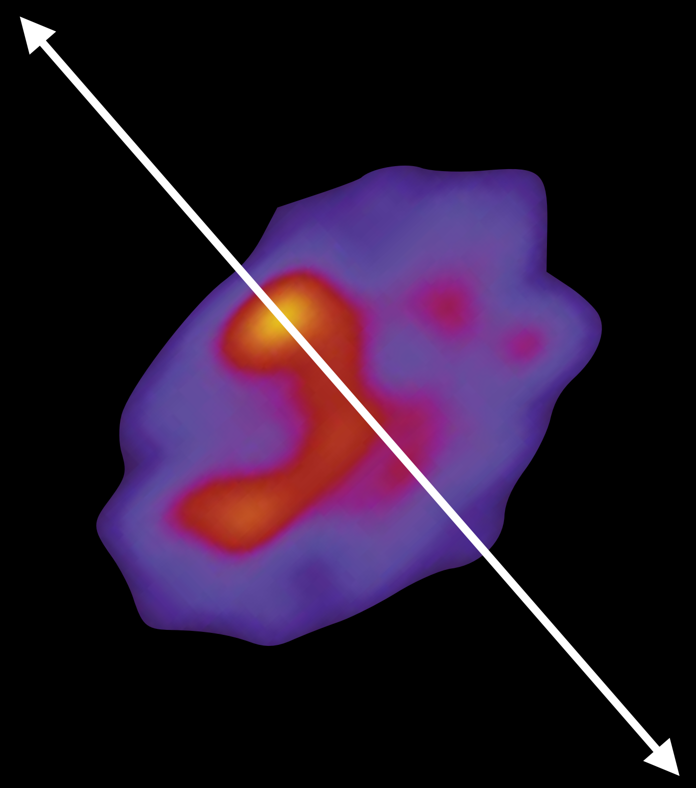
One sleep-deprived experimentalist's biased view…

$\pm$15% modulation in $dE_T/d\phi$,
carried by O(10k) particles



Transverse energy flow in CMS calorimeters
for single Pb+Pb collision at 2.76TeV

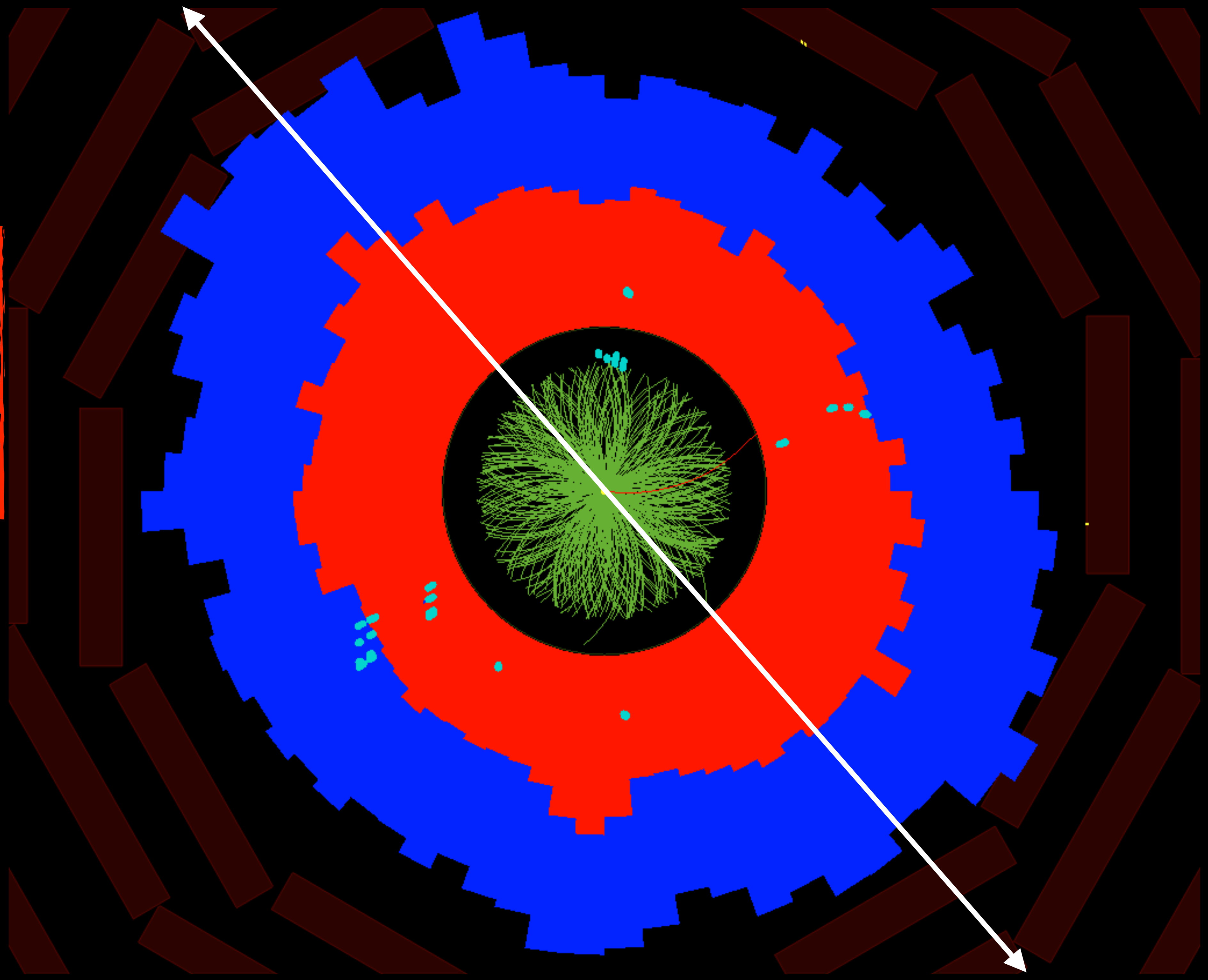
red = ECAL energy
blue = HCAL energy



Initial energy distribution
in collision overlap area

Hydrodynamic expansion translates initial configuration space anisotropy into final state momentum anisotropy

“Hydrodynamic flow”

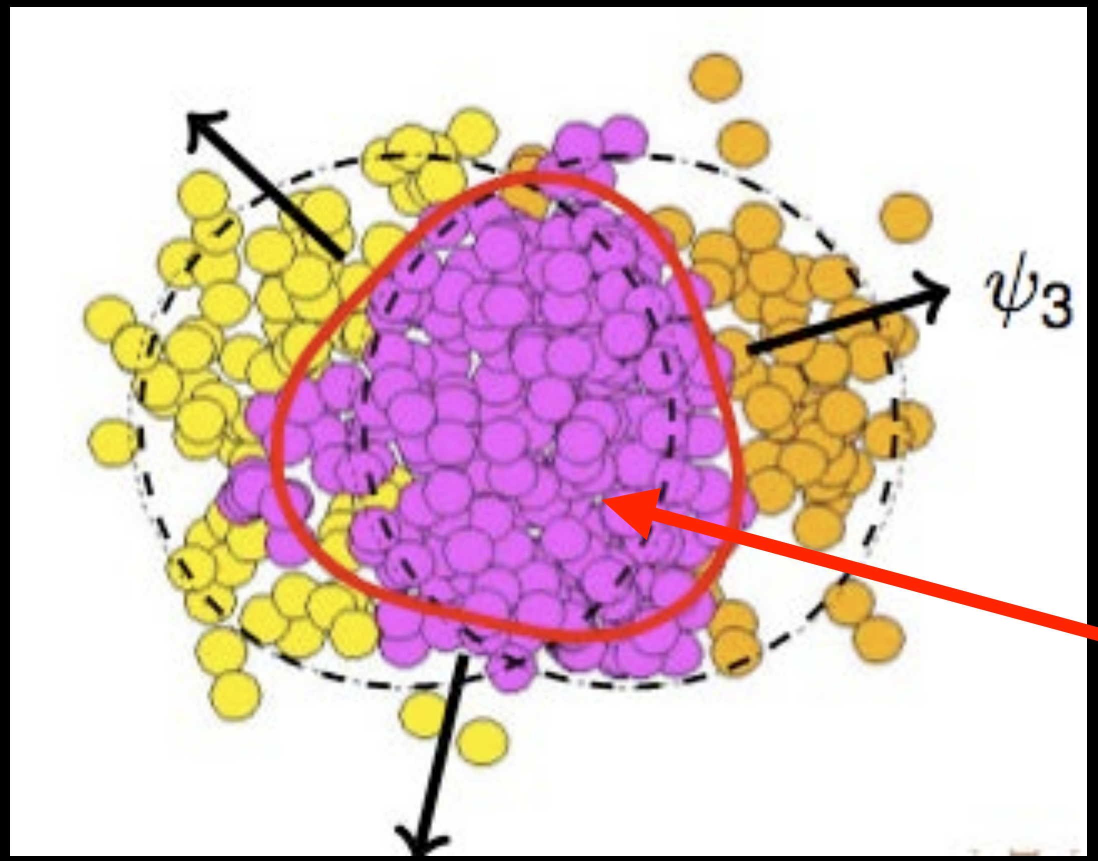


Transverse energy flow in CMS calorimeters
for single Pb+Pb collision at 2.76TeV

Fluctuations in initial geometry are essential ingredient for understanding physics of flow

Initial state

B. Alver, GR, Phys. Rev. C 81, 054905. arXiv:1003.0194



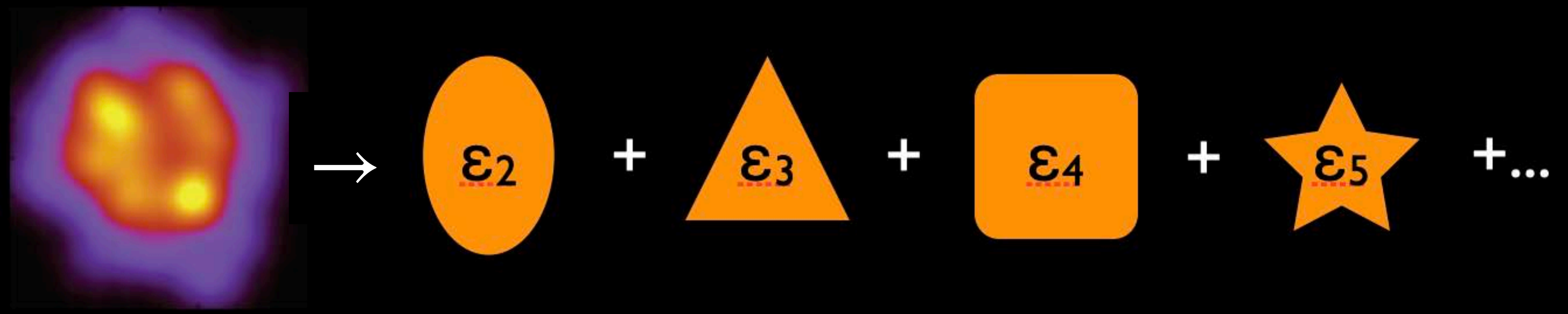
"Glauber MC"

Participants

Participant nucleon distributions characterized by eccentricities and corresponding angles:

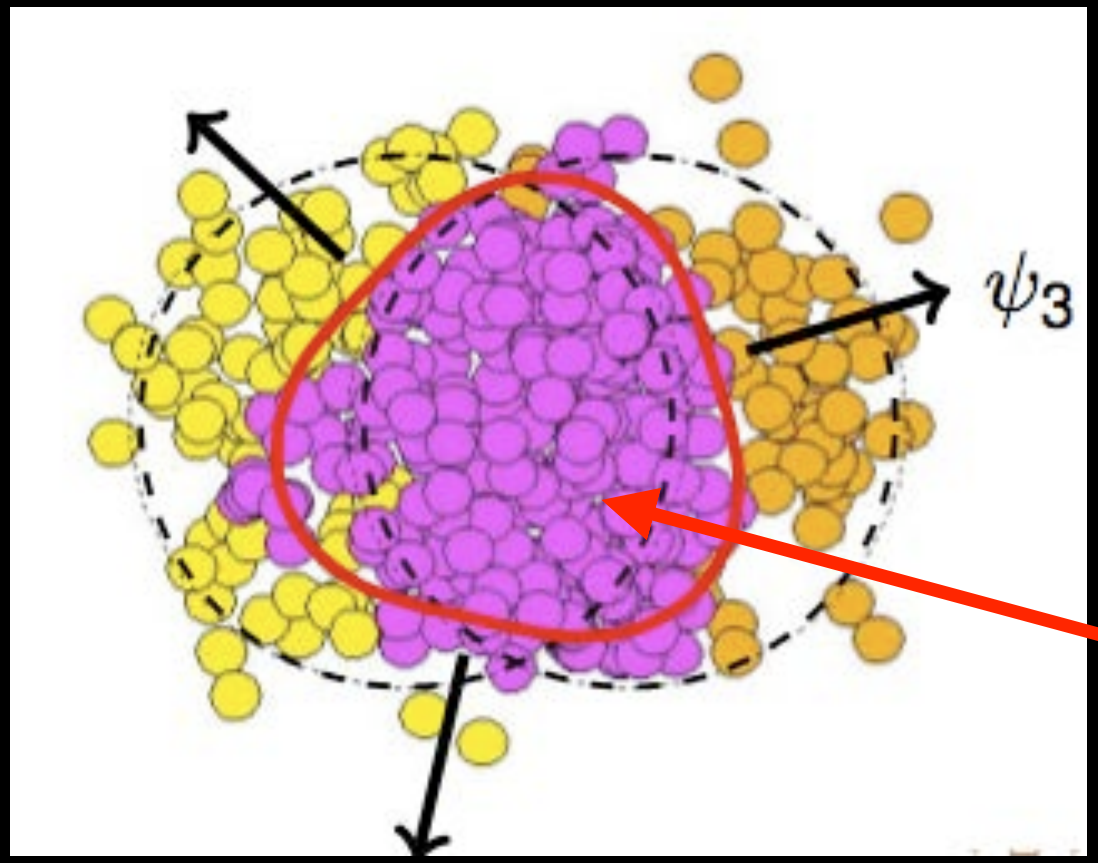
$$\epsilon_n = \frac{\sqrt{\langle r^2 \cos(n\phi_{part})^2 \rangle + \langle r^2 \sin(n\phi_{part}) \rangle}}{\langle r^2 \rangle}$$

$$\Psi_n = \frac{\text{atan2}(\langle r^2 \sin(n\phi_{part}) \rangle, \langle r^2 \cos(n\phi_{part}) \rangle) + \pi}{2}$$



Initial state

B. Alver, GR, Phys. Rev. C 81, 054905. arXiv:1003.0194



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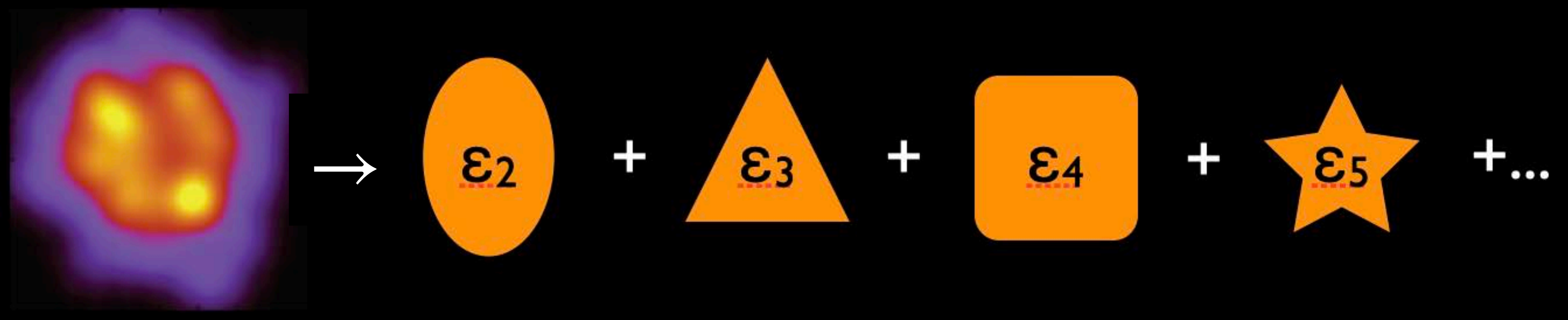
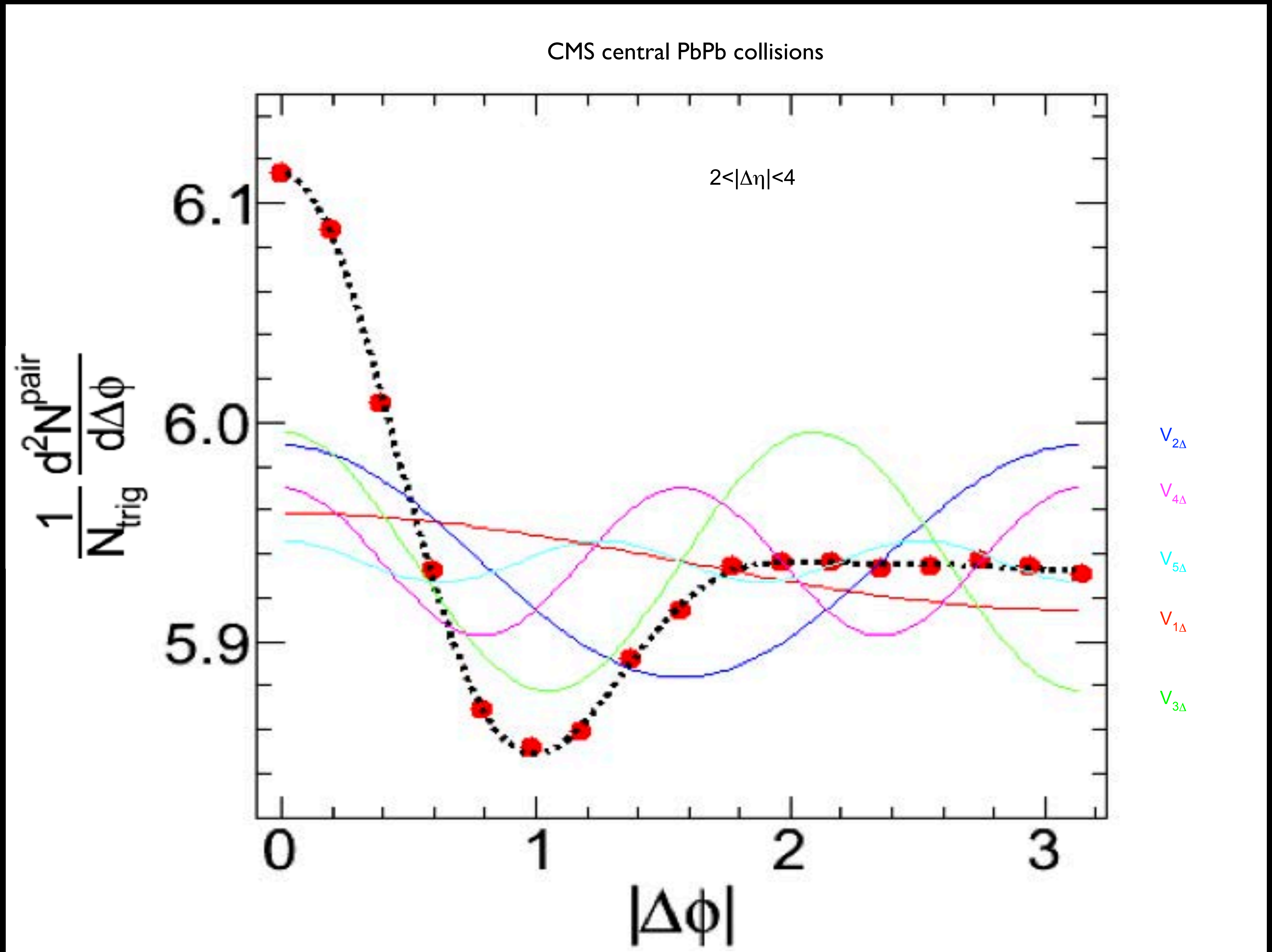
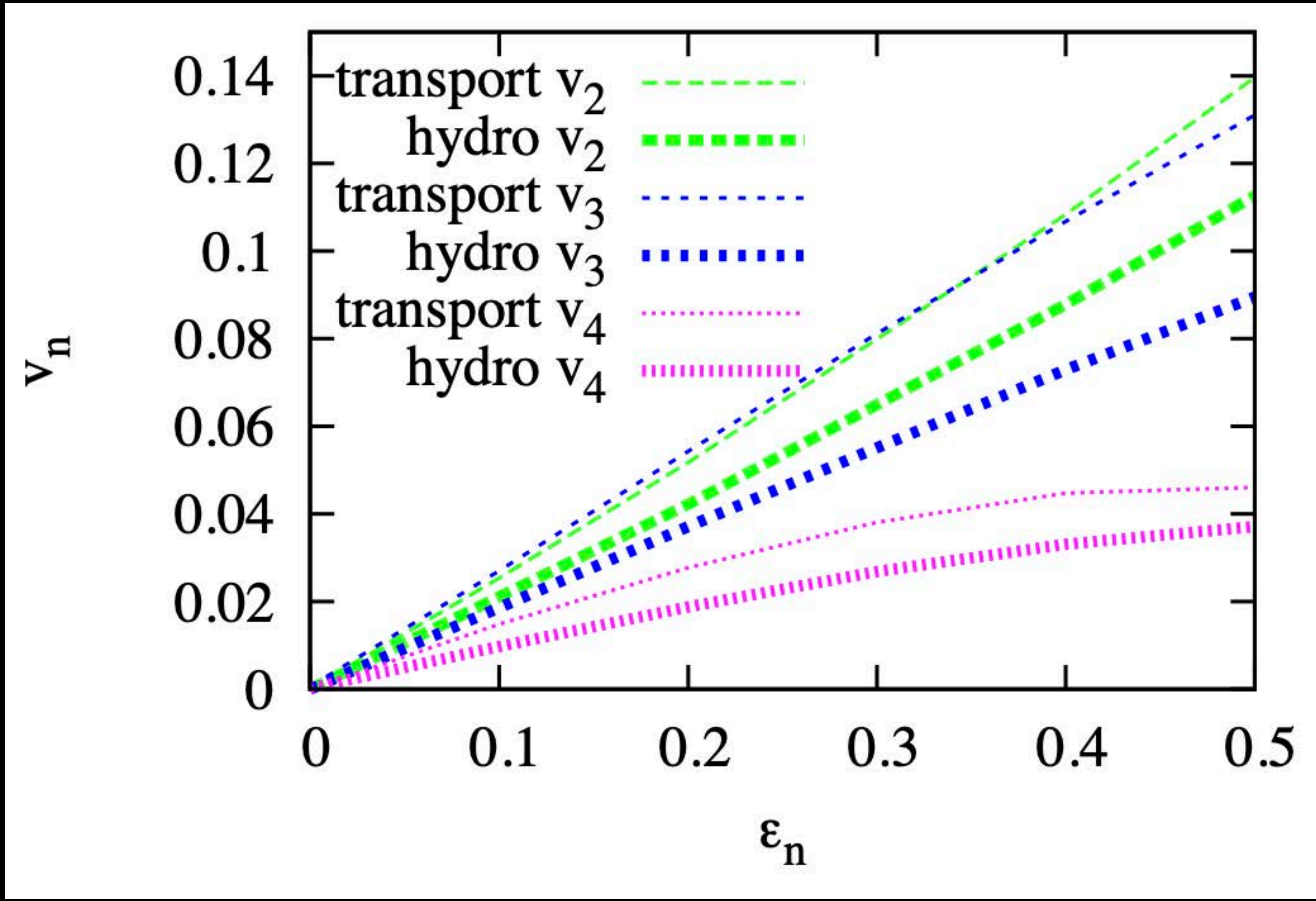


Final state



Final state angular distributions described by coefficients v_n in Fourier expansion:

$$dN/d\phi \propto 1 + \sum 2v_n \cos(n(\phi - \Psi_n))$$

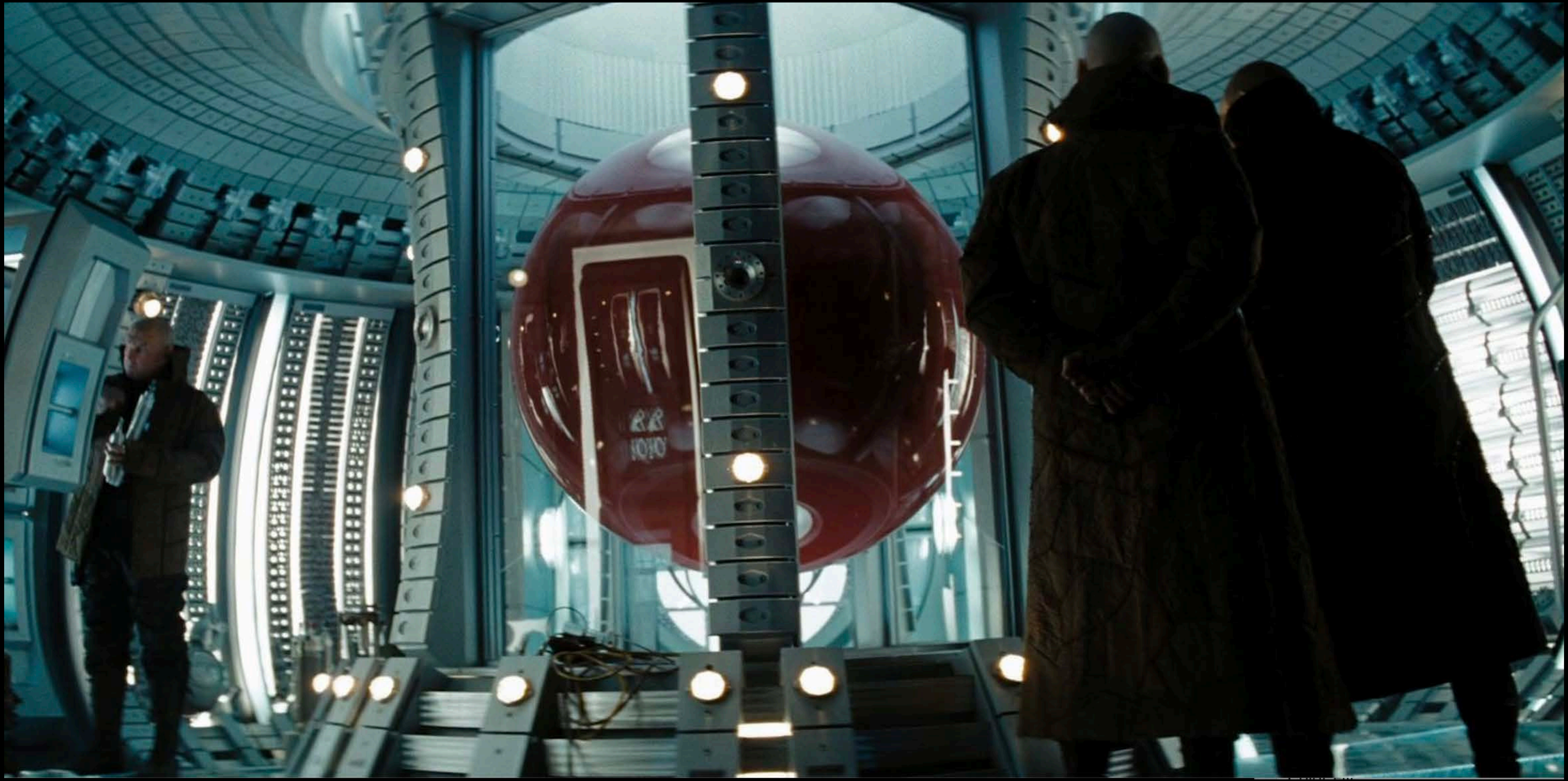


Hydrodynamics shows a nearly linear translation from initial state eccentricities ϵ_n to final state Fourier components v_n

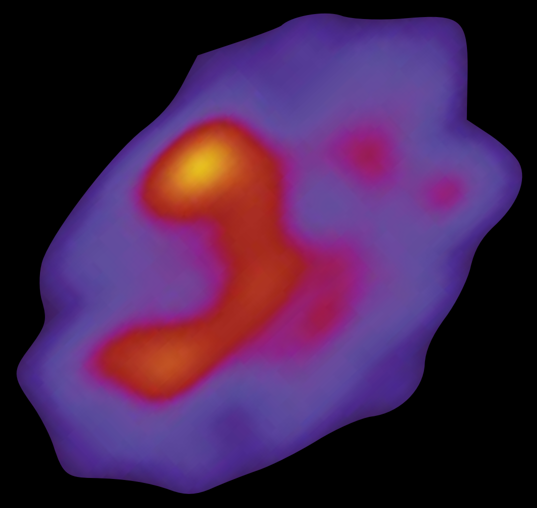
The magnitude of response (slope) is controlled by dimensionless **transport coefficient** η/s, the shear viscosity to entropy density ratio

Alver et al, https://arxiv.org/pdf/1007.5469.pdf

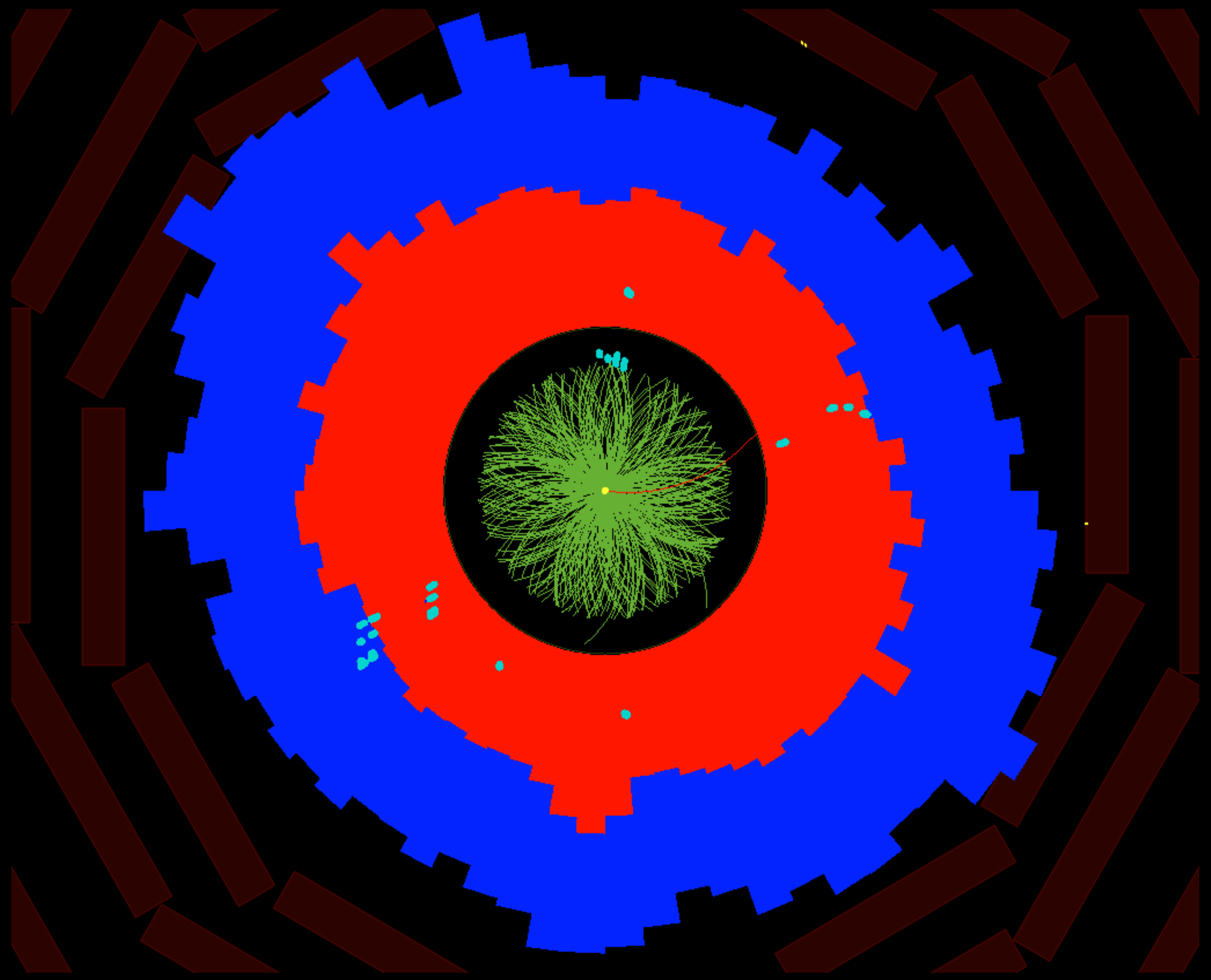
Applied QGP physics



A new direction (literally….)



linear



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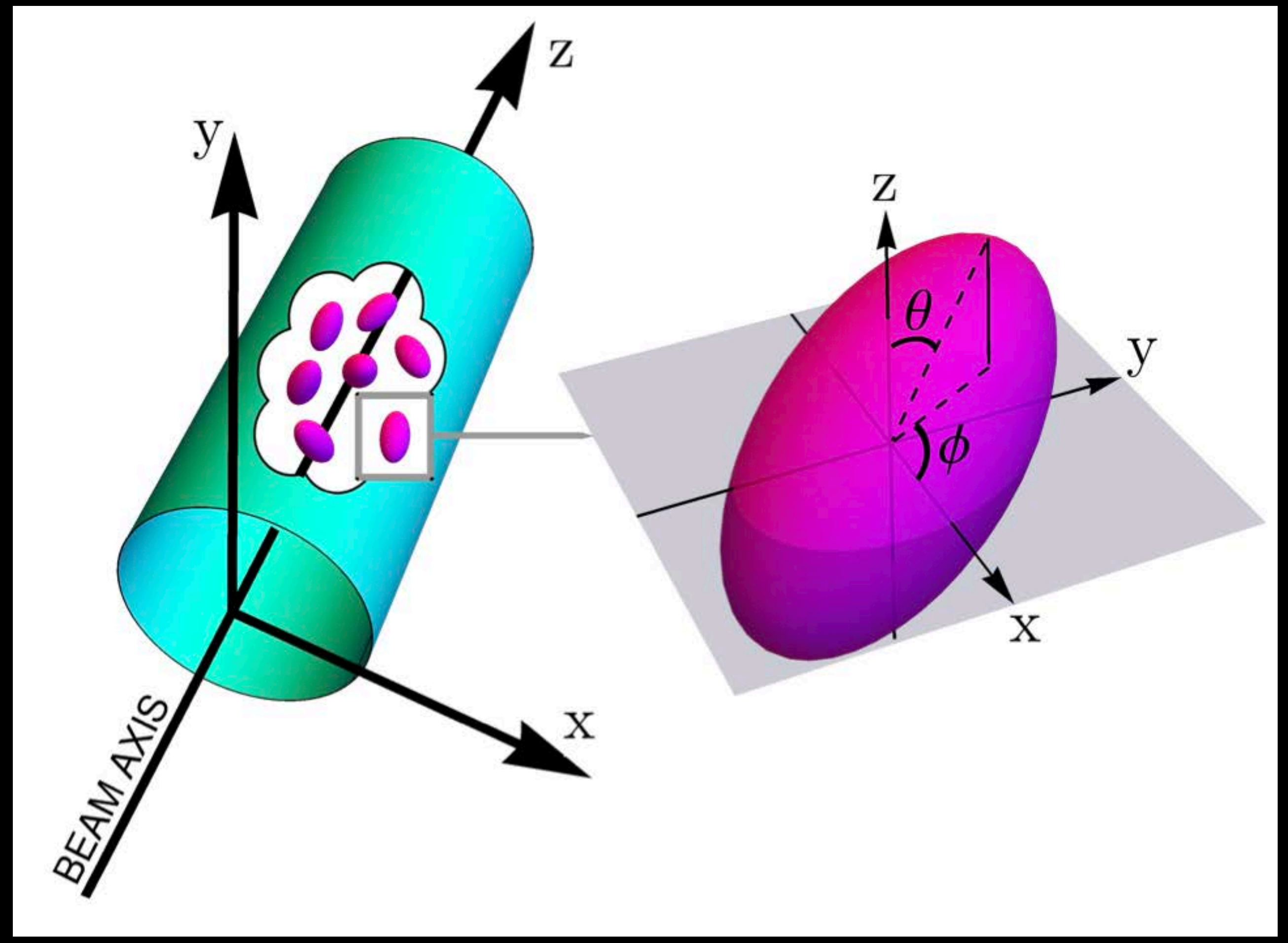
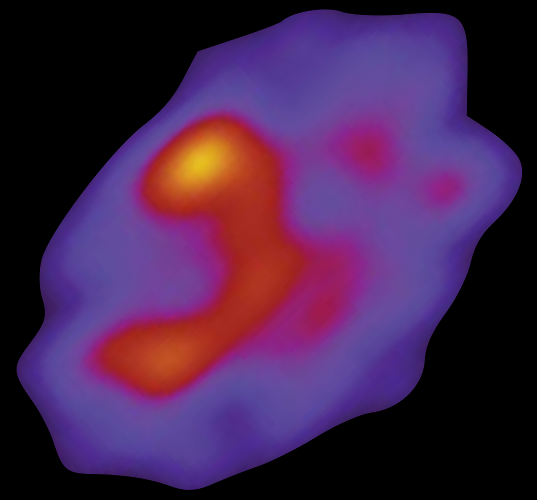
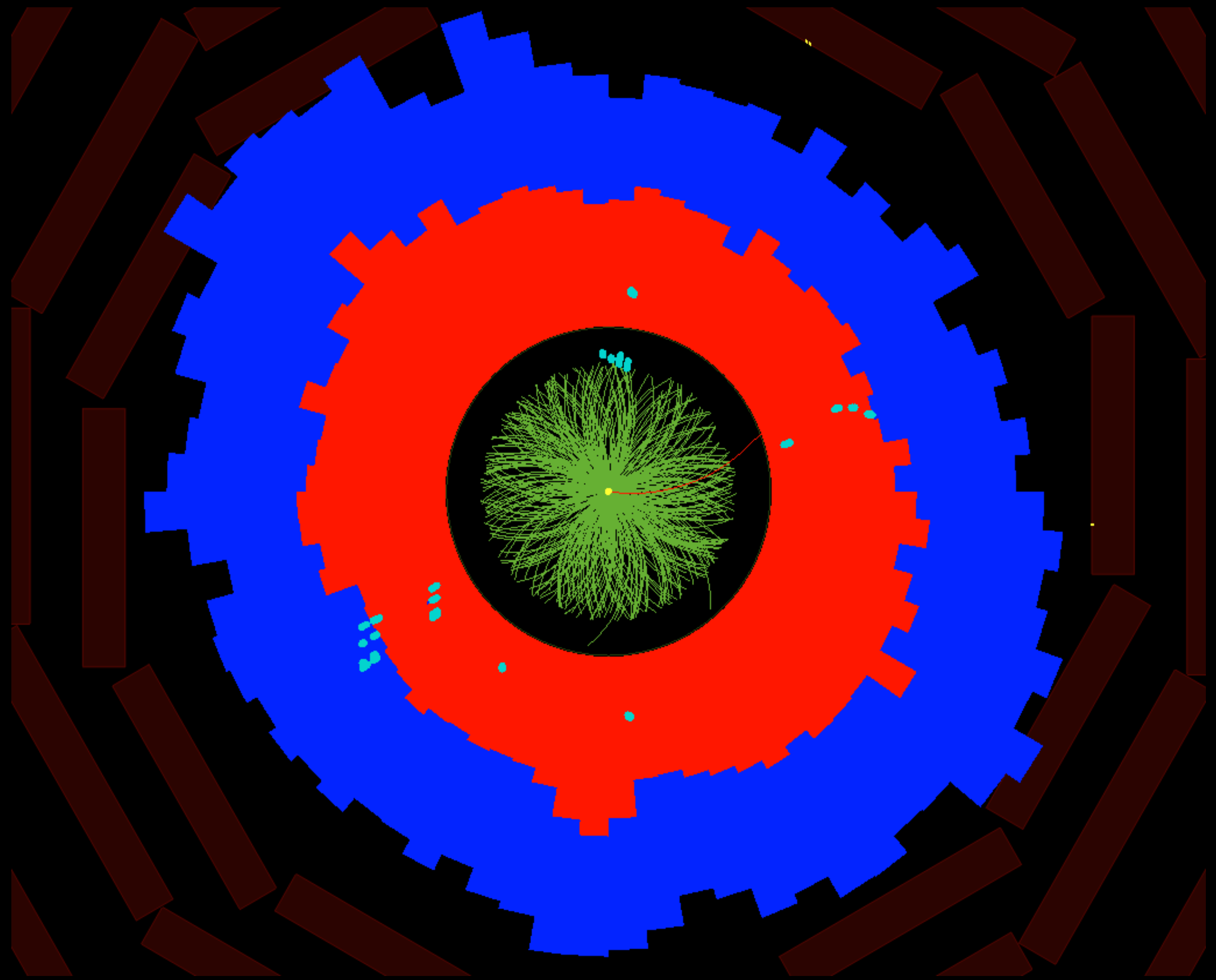
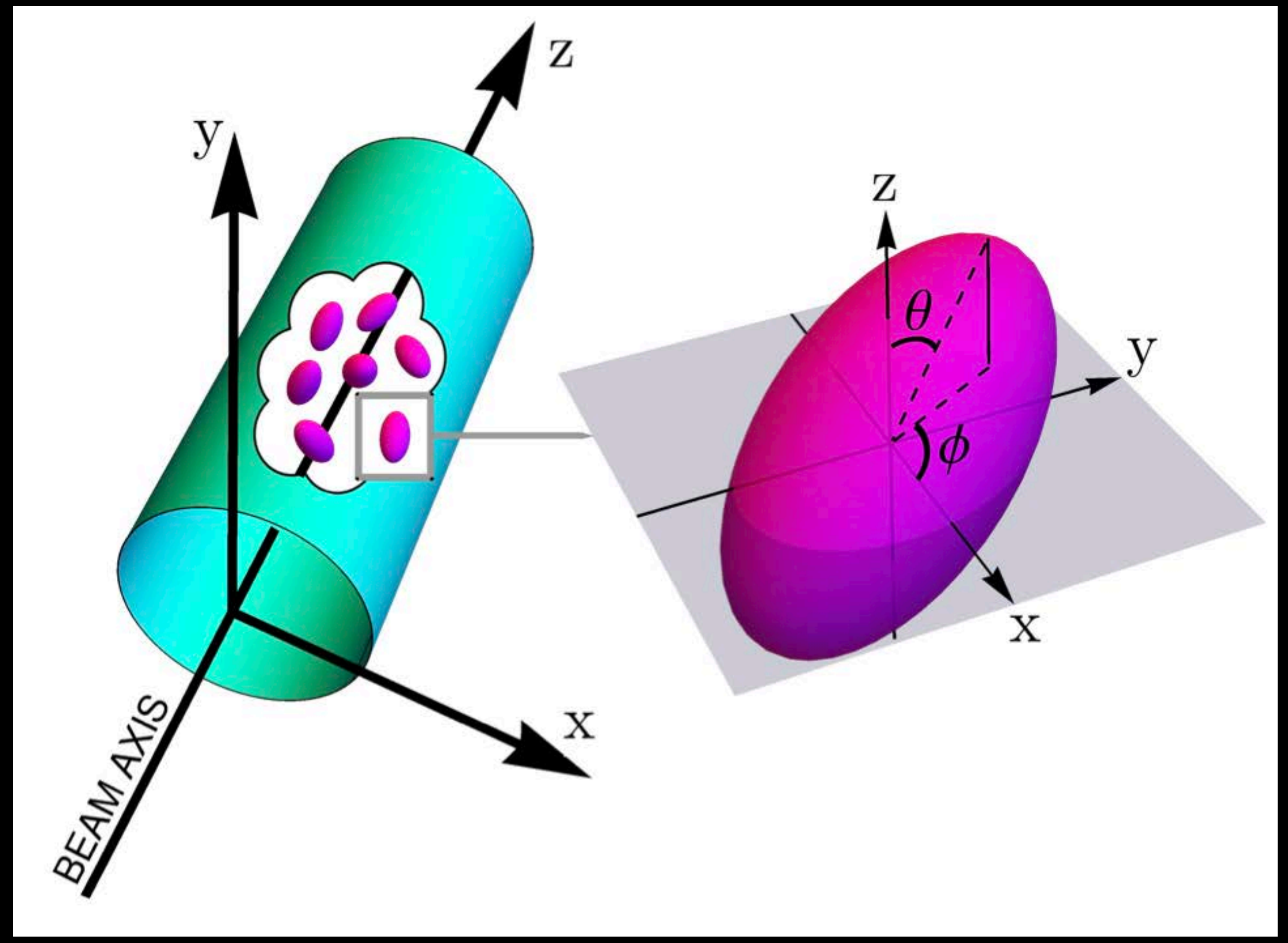


Giacalone,
https://arxiv.org/abs/1910.04673





A new direction (literally….)



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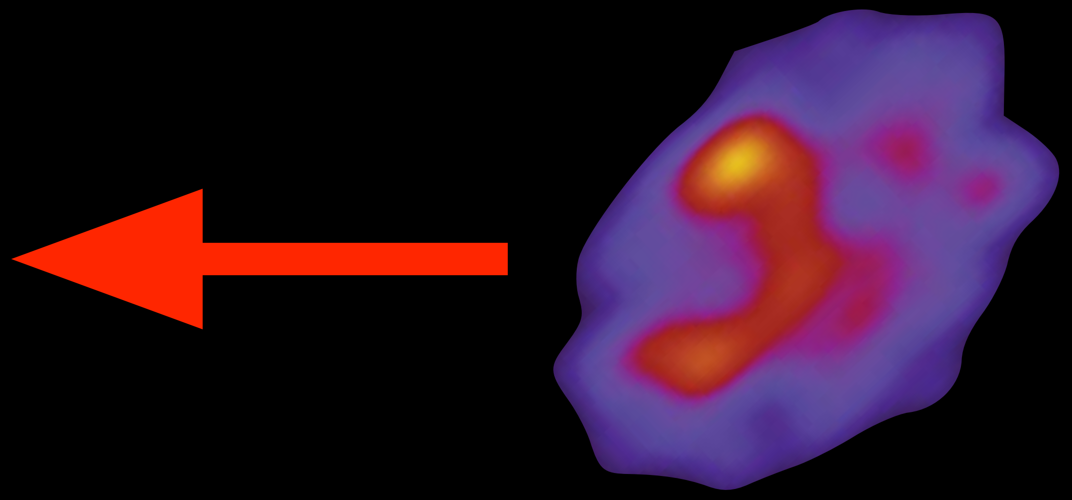
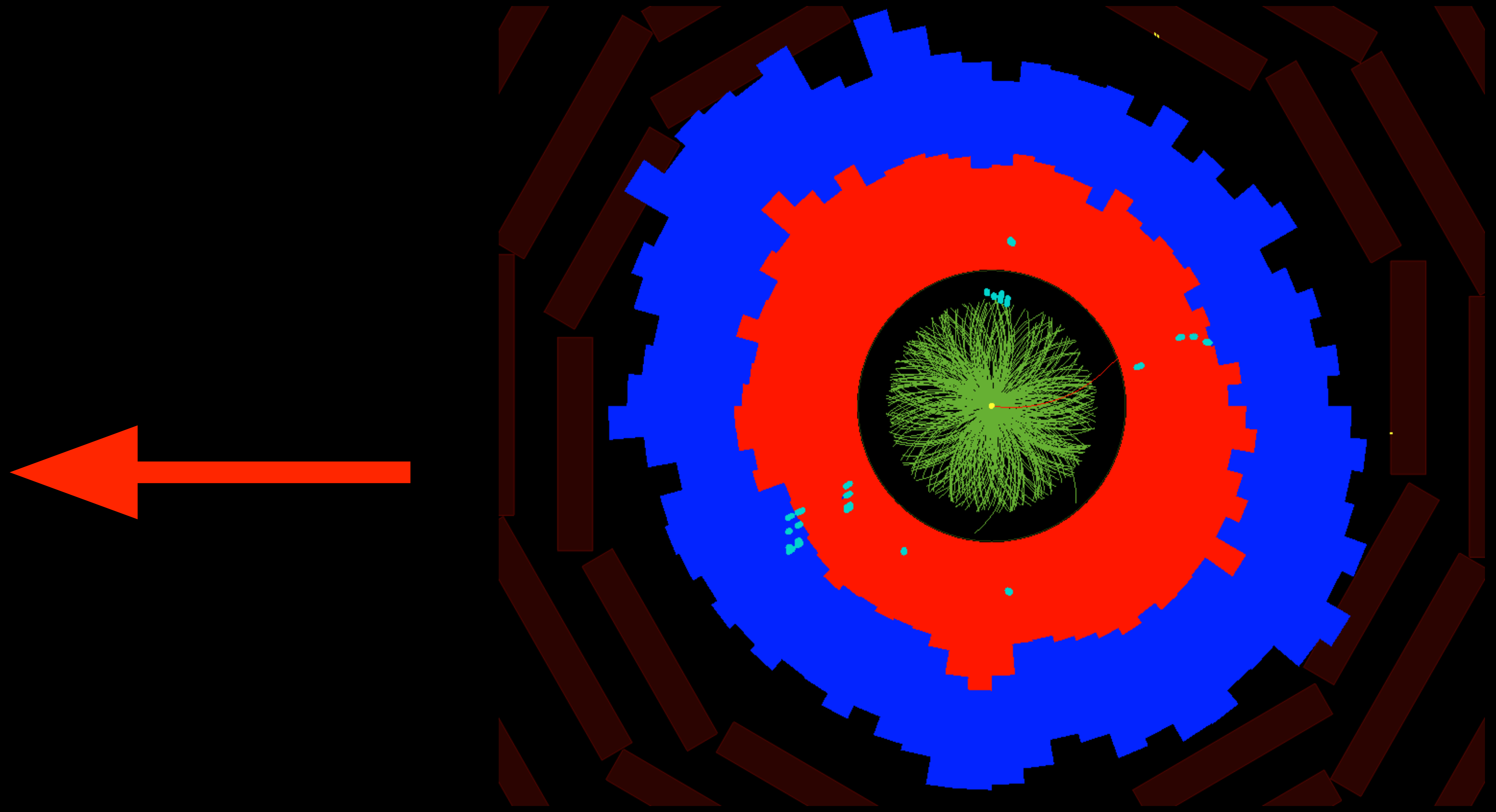
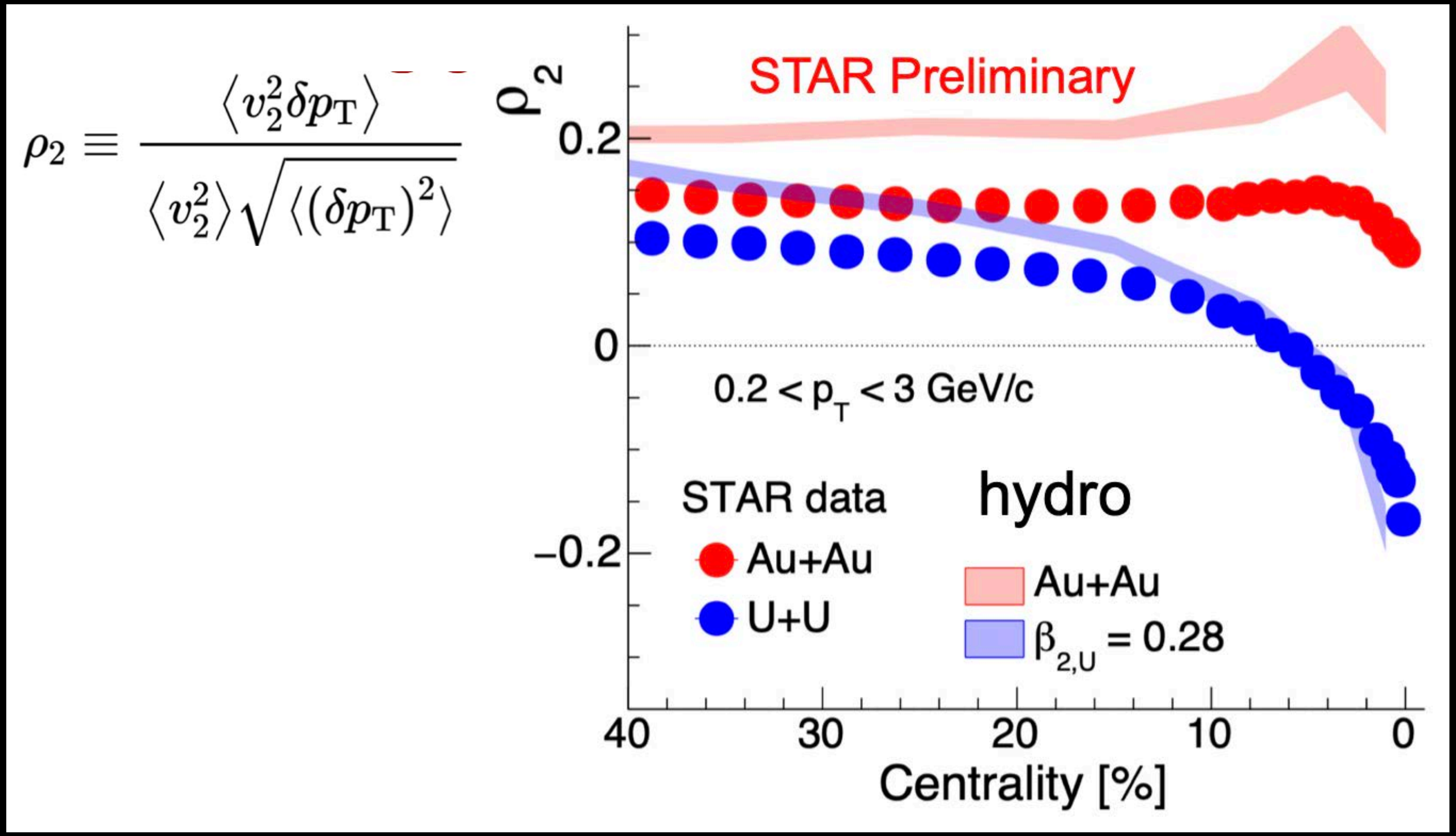






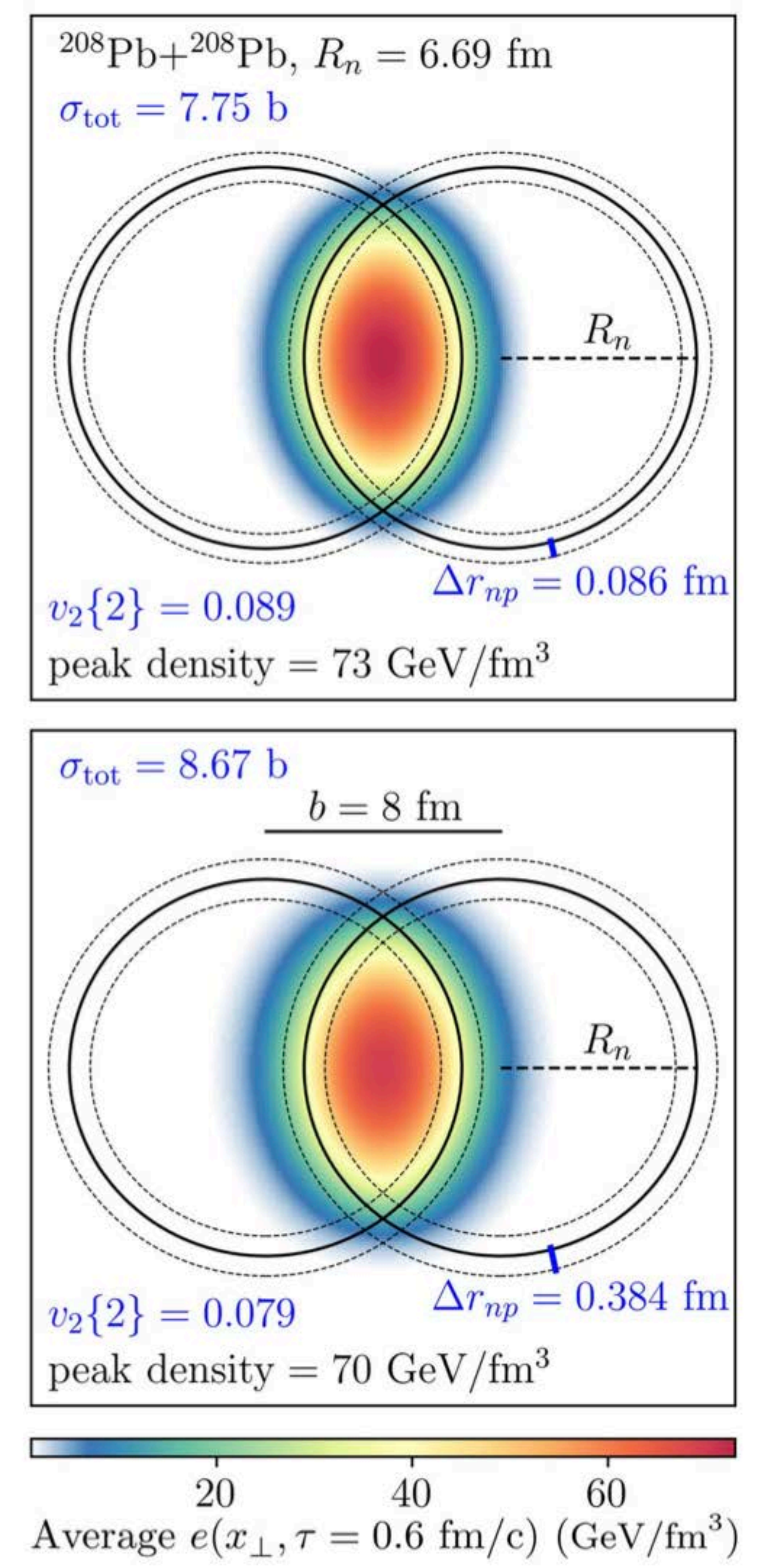
Exploit linear hydro response and nuclear shape dependence of initial fluctuations to learn about nuclear structure

Yoktosecond snapshot of nuclear shape

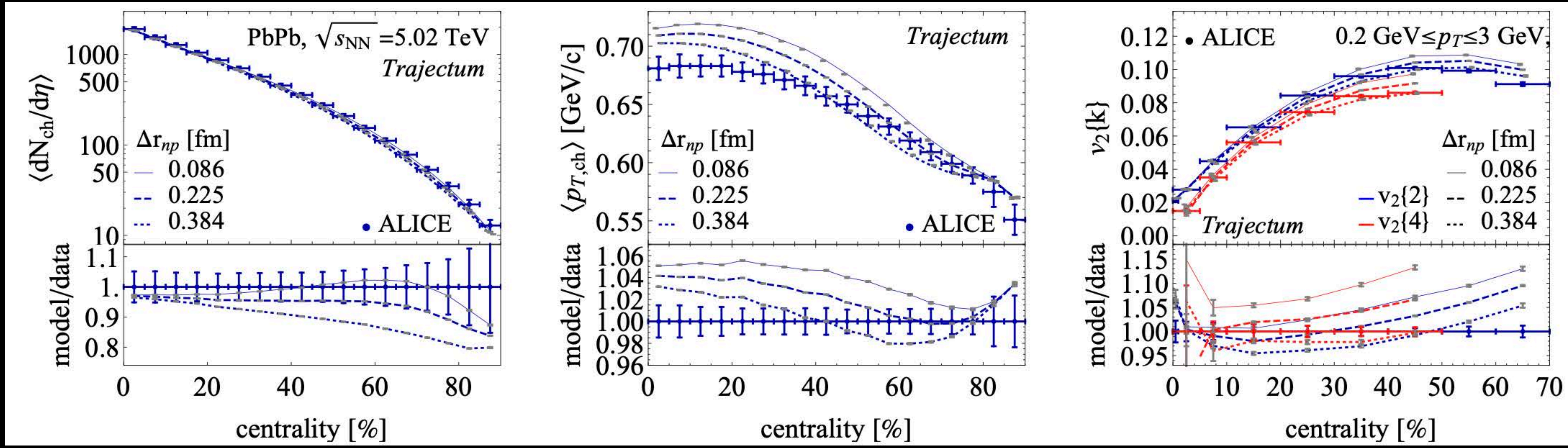
see e.g. J. Jia, https://arxiv.org/pdf/2109.00604.pdf

A new direction (literally….)

Trajectum framework

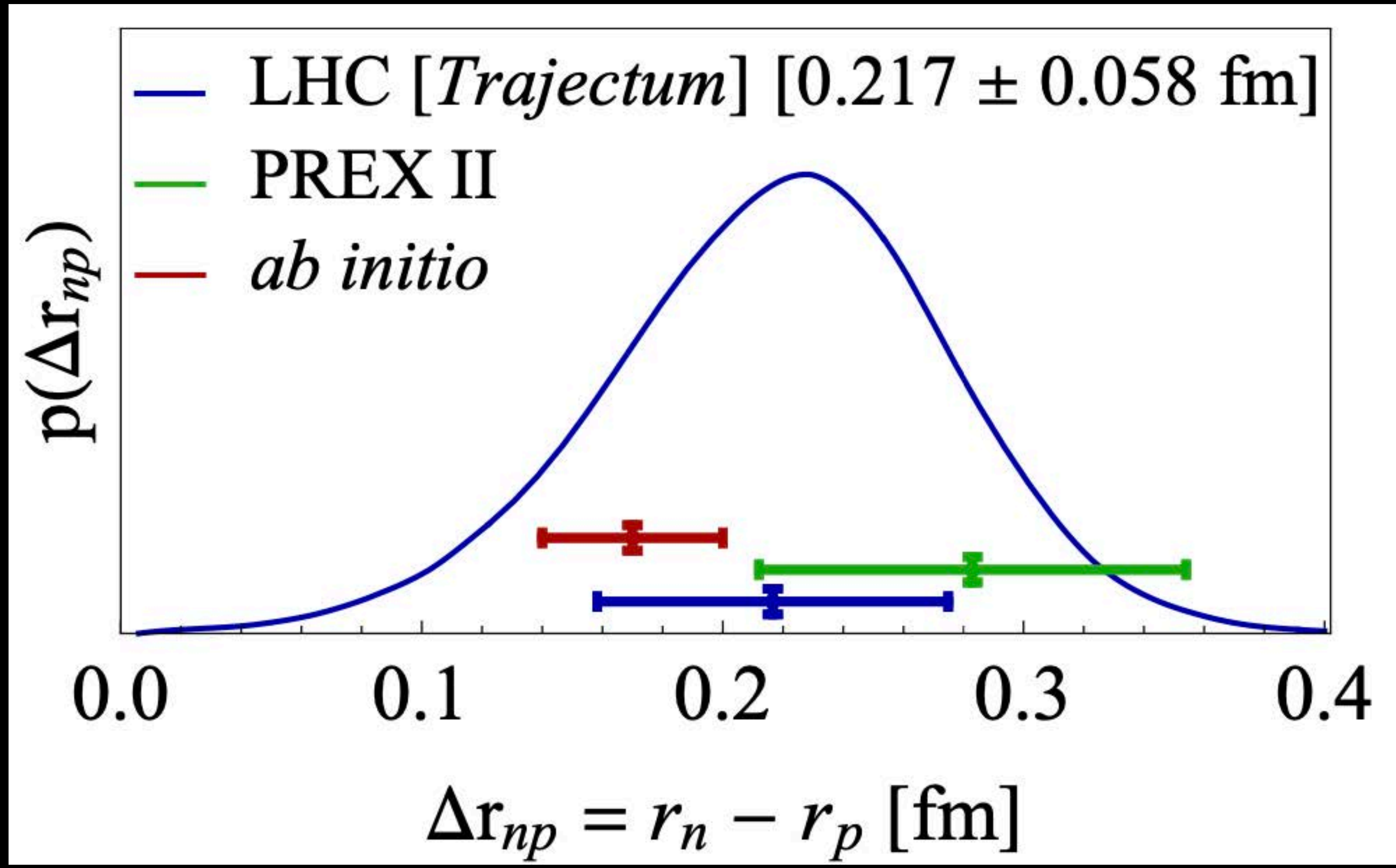


Change in neutron skin thickness changes average initial energy density distribution



Changing initial energy distribution is reflected in multiplicity, <p$_T$> and elliptic flow v$_2$

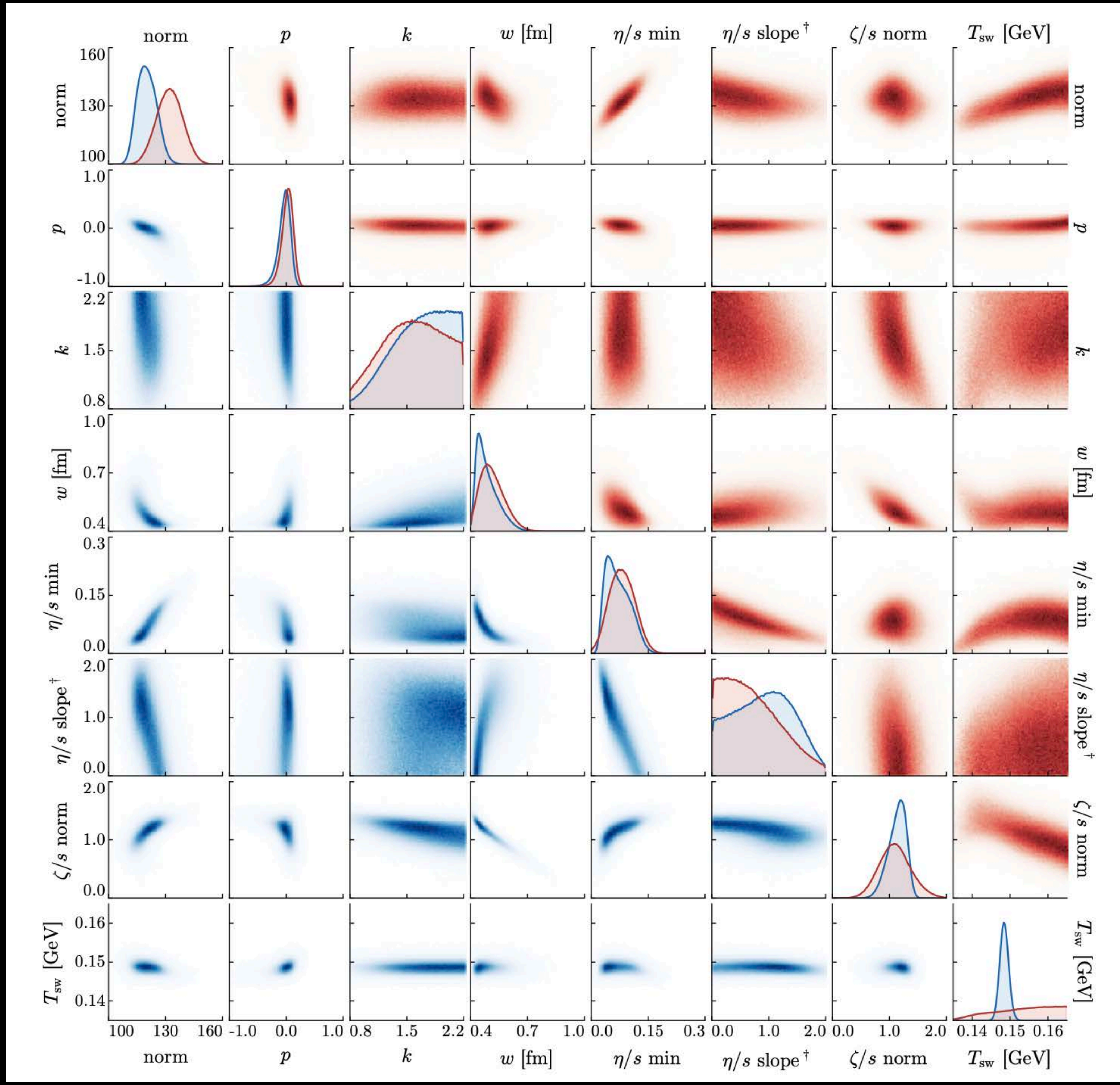
Bayesian analysis yields Δr_{np} likelihood distribution



Giacalone, Nijs, van der Schee, https://arxiv.org/pdf/2305.00015.pdf


END
DETOUR

Posterior distributions
red = using identified hadron data
blue = using charged particle data



Bernhard et al (Duke/Ohio State), https://arxiv.org/pdf/1605.03954.pdf

TABLE I. Input parameter ranges for the initial condition and hydrodynamic models.

Parameter	Description	Range
Norm	Overall normalization	100–250
p	Entropy deposition parameter	-1 to $+1$
k	Multiplicity fluct. shape	0.8–2.2
w	Gaussian nucleon width	0.4–1.0 fm
η/s hrg	Const. shear viscosity, $T < T_c$	0.3–1.0
η/s min	Shear viscosity at T_c	0–0.3
η/s slope	Slope above T_c	0–2 GeV^{-1}
ζ/s norm	Prefactor for $(\zeta/s)(T)$	0–2
T_{switch}	Particlization temperature	135–165 MeV

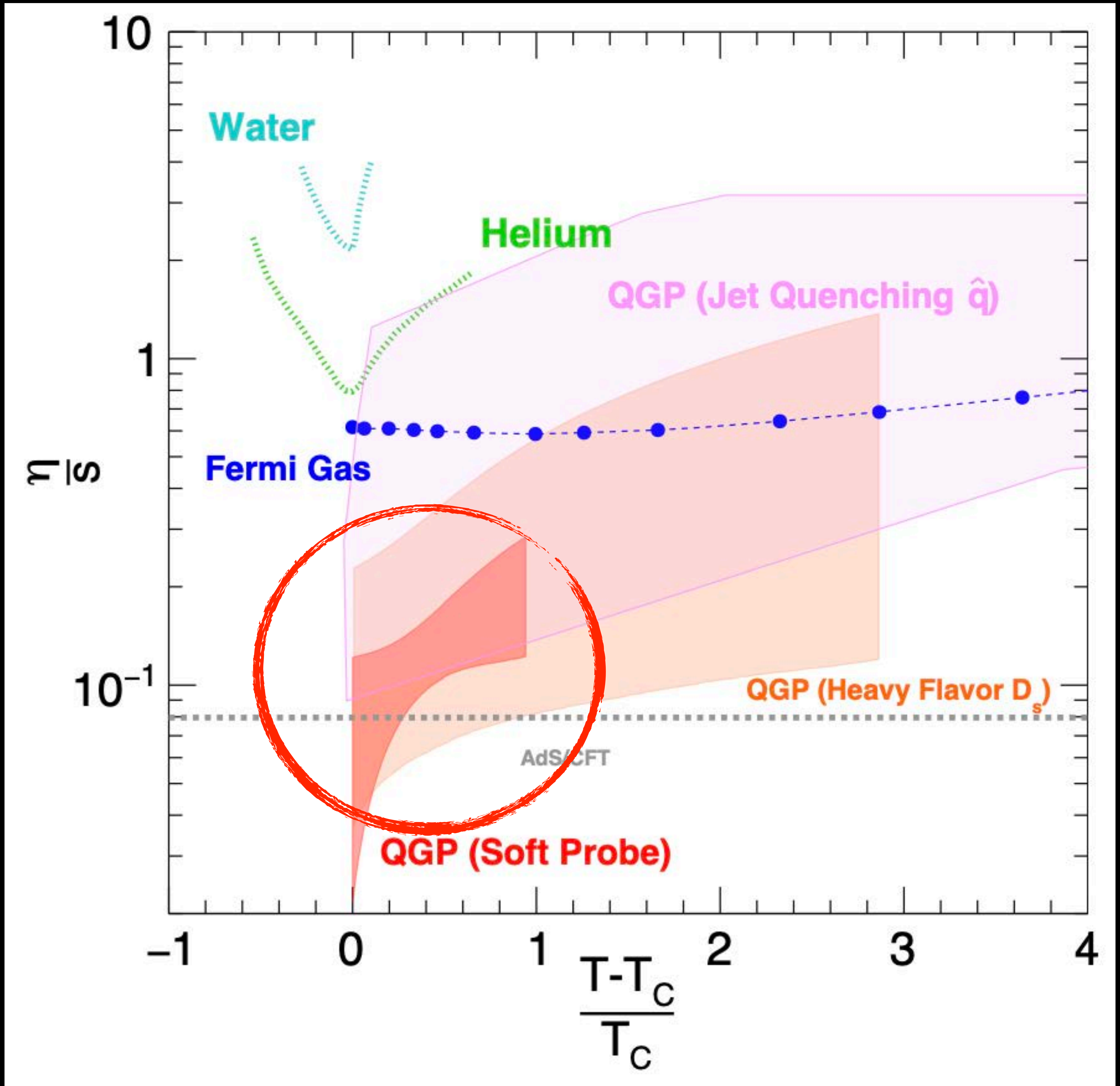
TABLE II. Experimental data to be compared with model calculations.

Observable	Particle species	Kinematic cuts	Centrality classes	Ref.
Yields dN/dy	$\pi^{\pm}$, $K^{\pm}$, $p\bar{p}$	$\lvert y\rvert < 0.5$	0–5, 5–10, 10–20, …, 60–70	[108]
Mean transverse momentum $\langle p_T \rangle$	$\pi^{\pm}$, $K^{\pm}$, $p\bar{p}$	$\lvert y\rvert < 0.5$	0–5, 5–10, 10–20, …, 60–70	[108]
Two-particle flow cumulants $v_n\{2\}$ $n = 2, 3, 4$	all charged	$\lvert\eta\rvert < 1$ $0.2 < p_T < 5.0$ GeV	0–5, 5–10, 10–20, …, 40–50 $n = 2$ only: 50–60, 60–70	[109]

“Industry standard”: Bayesian extraction of parameters of interest from large number/range of model parameters, using multiple data sets and observables

Typically employ Gaussian Process Emulators to reduce need for expensive full model runs

Review: Apolinario, Lee, Winn, https://arxiv.org/pdf/2203.16352.pdf



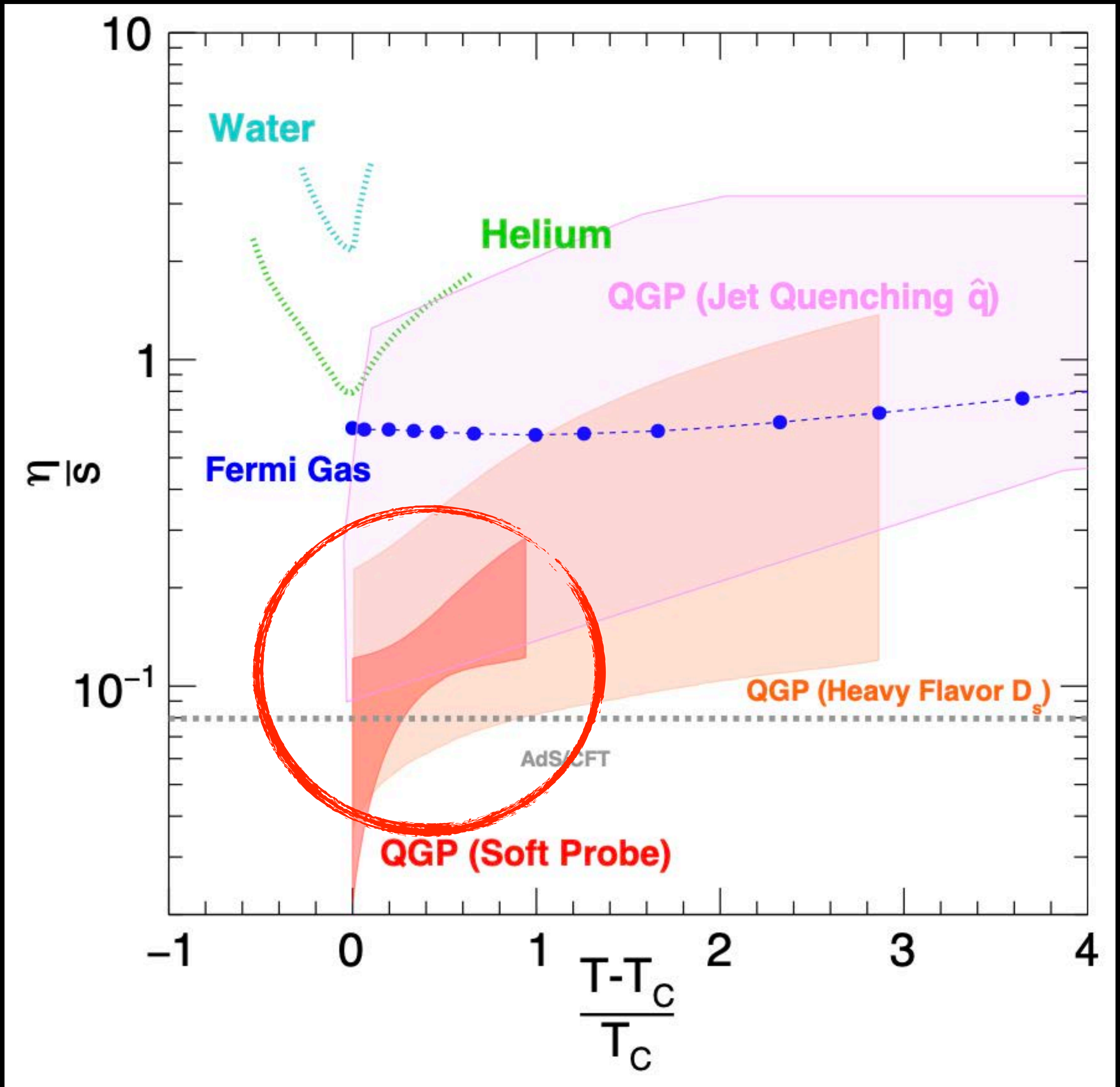
Consistent results from many independent groups/approaches:

$$\frac{1}{4\pi} < \langle \eta/s \rangle < \frac{1}{2\pi}$$

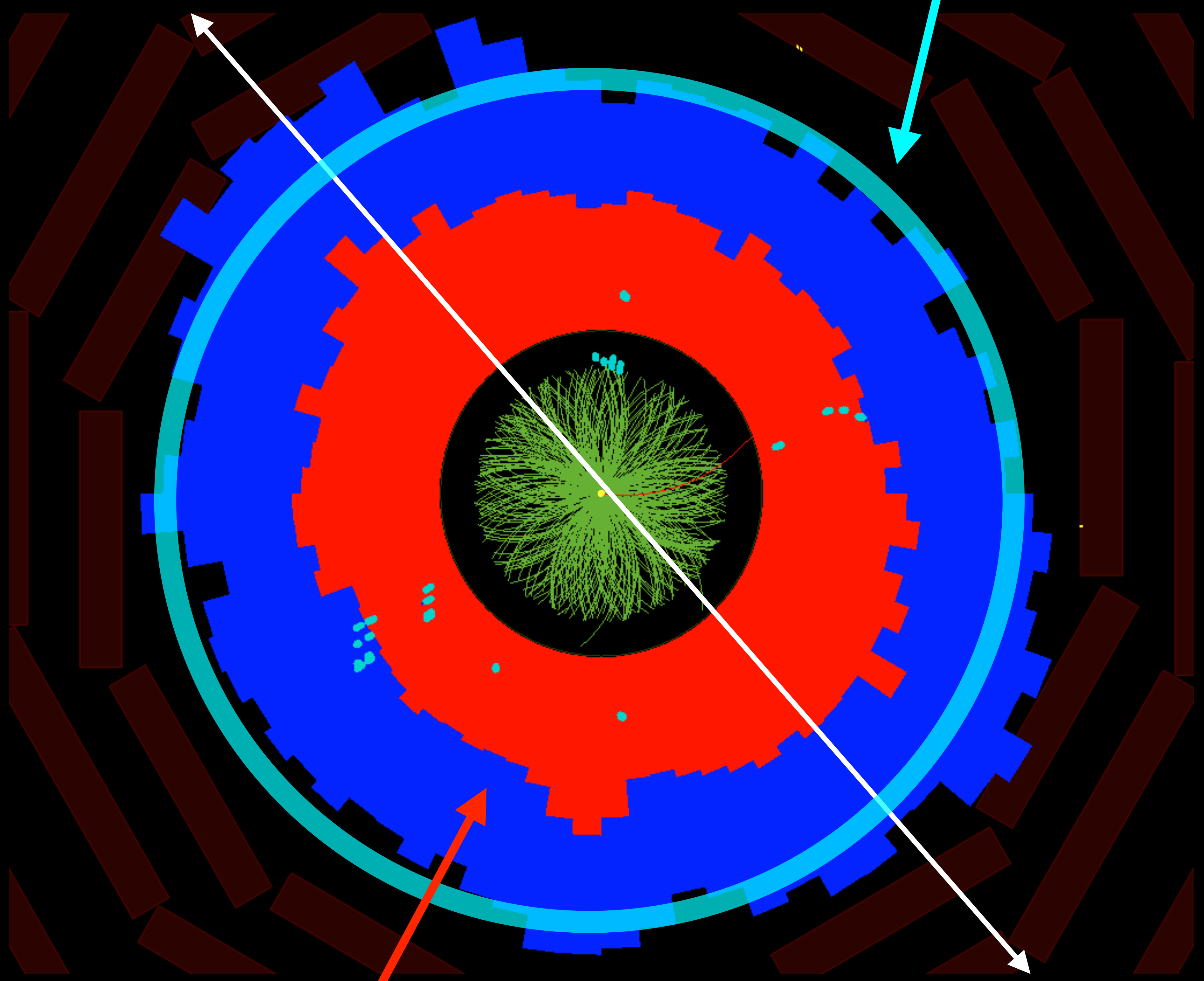
An order of magnitude smaller than for water

Close to $\frac{1}{4\pi}$ lower bound obtained by Son et al using AdS/CFT correspondence

Review: Apolinario, Lee, Winn, https://arxiv.org/pdf/2203.16352.pdf



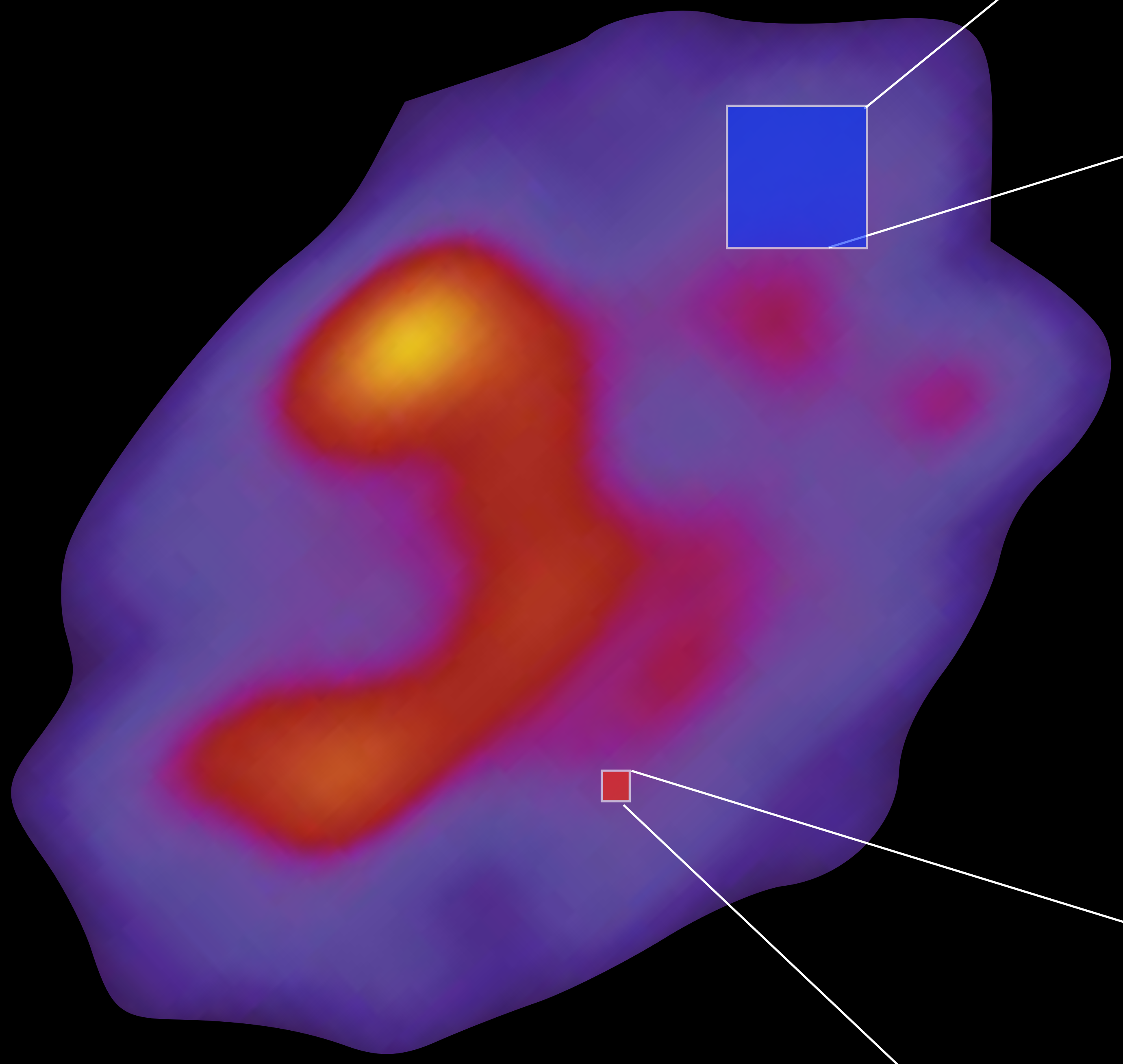
$\eta/s \approx 2.5$

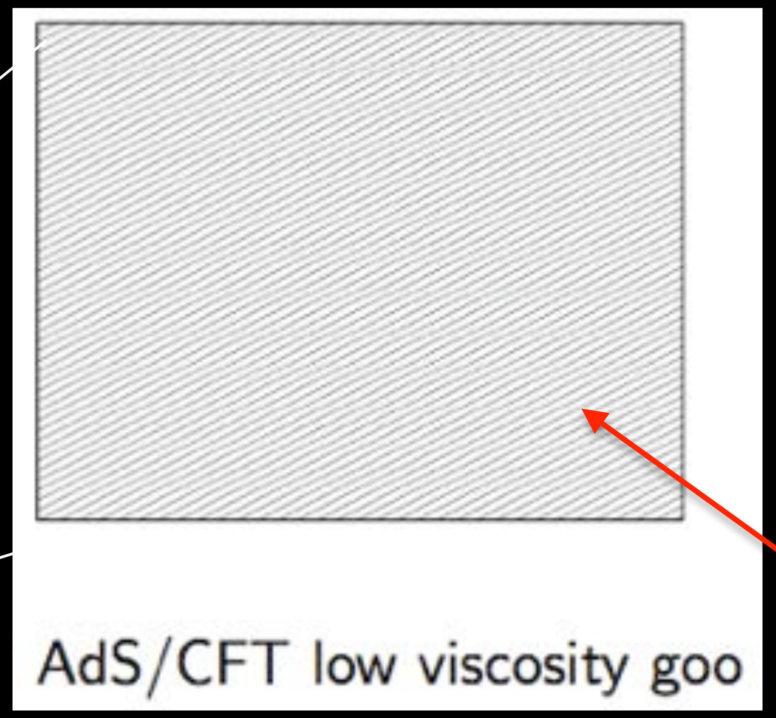


$\eta/s \approx 1/2\pi$

If the QGP had η/s of water, the final state anisotropy would be isotropic!

New question:

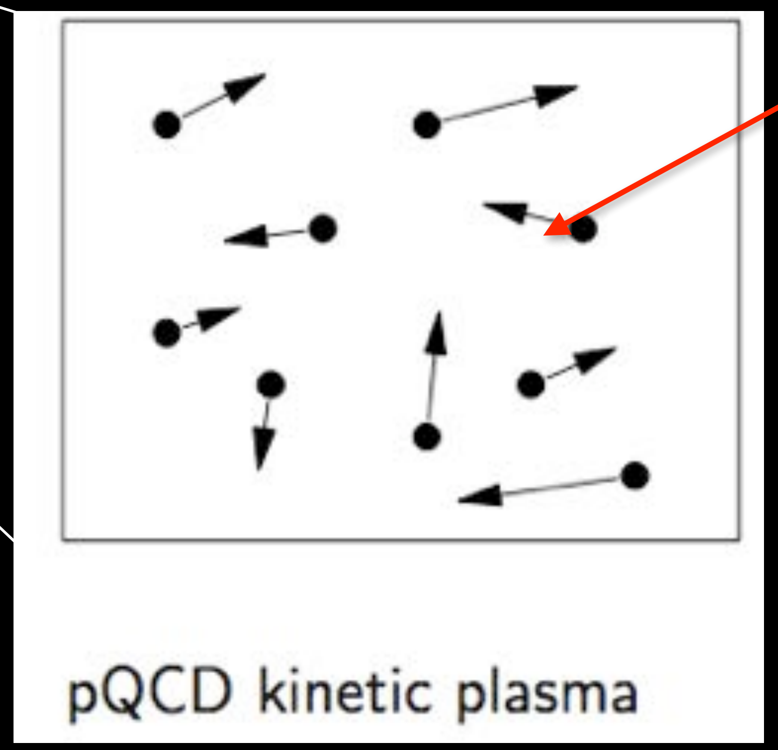




$\Delta x \approx 1$fm
$\Delta p \lessapprox 200$MeV

“Perfect Liquid”

How does long-wavelength behavior emerge from asymptotically free interaction at high T?

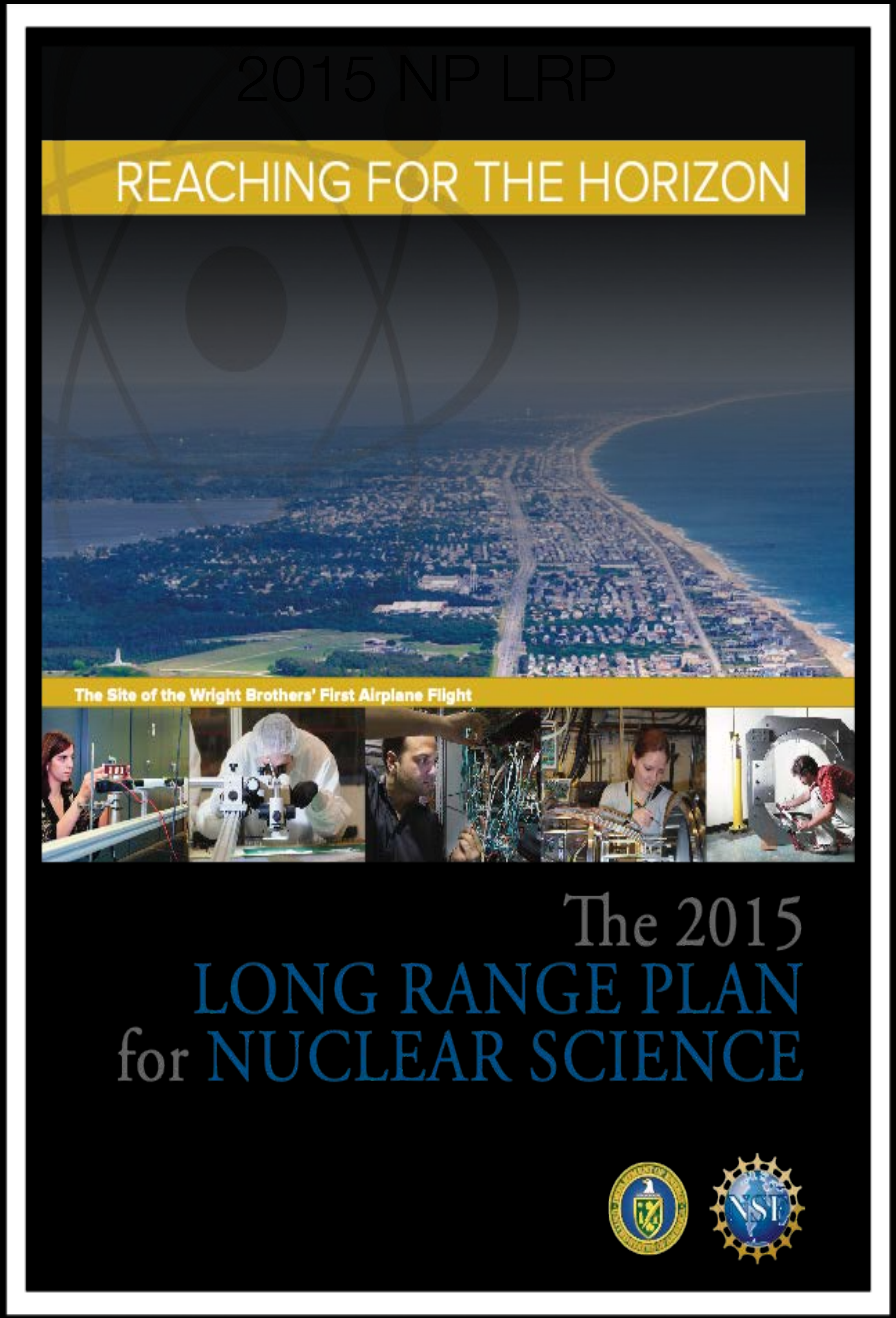


$\Delta x \ll 1$fm
$\Delta p >> 1$GeV

“Free quarks and gluons”

Cartoon from T. Schaefer

2015 NSAC Long Range Plan



2. Quantum Chromodynamics: The Fundamental Description of the Heart of Visible Matter

describe quark and gluon interactions, the emergent phenomenon that a macroscopic volume of quarks and gluons at extreme temperatures would form a nearly perfect liquid came as a complete surprise and has led to an intriguing puzzle. A perfect liquid would not be expected to have particle excitations, yet QCD is definitive in predicting that a microscope with sufficiently high resolution would reveal quarks and gluons interacting *weakly* at the shortest distance scales within QGP. Nevertheless, the η/s of QGP is so small that there is no sign in its macroscopic motion of any microscopic particlelike constituents; all we can see is a liquid. To this day, nobody understands this dichotomy: how do quarks and gluons conspire to form strongly coupled, nearly perfect liquid QGP?

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.**

This section is organized in three parts: characterization of liquid QGP, mapping the phase diagram of QCD by doping QGP with an excess of quarks over antiquarks, and high-resolution microscopy of QGP to see how quarks and gluons conspire to make a liquid.

EMERGENCE OF NEAR-PERFECT FLUIDITY

The emergent hydrodynamic properties of QGP are not apparent from the underlying QCD theory and were, therefore, largely unanticipated before RHIC. They have been quantified with increasing precision via experiments at both RHIC and the LHC over the last several years. New theoretical tools, including LQCD calculations of the equation-of-state, fully relativistic viscous hydrodynamics, initial quantum fluctuation models, and model calculations done at strong coupling in gauge theories with a dual gravitational description, have allowed us to characterize the degree of fluidity. In the temperature regime created at RHIC, QGP is the most liquidlike liquid known, and comparative analyses of the wealth of bulk observables being measured hint that the hotter QGP created at the LHC has a somewhat larger viscosity. This temperature dependence will be more tightly constrained by upcoming measurements at RHIC and the LHC that will characterize the varying shapes of the sprays of debris produced in different collisions. Analyses to extract this information are analogous to techniques used to learn about the evolution of the universe from tiny fluctuations in the temperature of the cosmic microwave background associated with ripples in the matter density created a short time after the Big Bang (see Sidebar 2.3).

There are still key questions, just as in our universe, about how the rippling liquid is formed initially in a heavy-ion collision. In the short term, this will be addressed using well-understood modeling to run the clock backwards from the debris of the collisions observed in the detectors. Measurements of the gluon distribution and correlations in nuclei at a future EIC together with calculations being developed that relate these quantities to the initial ripples in the QGP will provide a complementary perspective. The key open question here is understanding how a hydrodynamic liquid can form from the matter present at the earliest moments in a nuclear collision as quickly as it does, within a few trillionths of a trillionth of a second.

Geometry and Small Droplets

Connected to the latter question is the question of how large a droplet of matter has to be in order for it to behave like a macroscopic liquid. What is the smallest possible droplet of QGP? Until recently, it was thought that protons or small projectiles impacting large nuclei would not deposit enough energy over a large enough volume to create a droplet of QGP. New measurements, however, have brought surprises about the onset of QGP liquid production.

Measurements in LHC proton-proton collisions, selecting the 0.001% of events that produce the highest particle multiplicity, reveal patterns reminiscent of QGP fluid flow patterns. Data from p+Pb collisions at the LHC give much stronger indications that single small droplets may be formed. The flexibility of RHIC, recently augmented by the EBIS source (a combined NASA and nuclear physics project), is allowing data to be taken for p+Au, d+Au, and ^{3}He+Au collisions, in which energy is deposited initially in one or two or three spots. As these individual droplets expand hydrodynamically, they connect and form interesting QGP geometries as shown in Figure 2.9. If, in fact, tiny liquid droplets are being formed and their geometry can be manipulated, they will provide

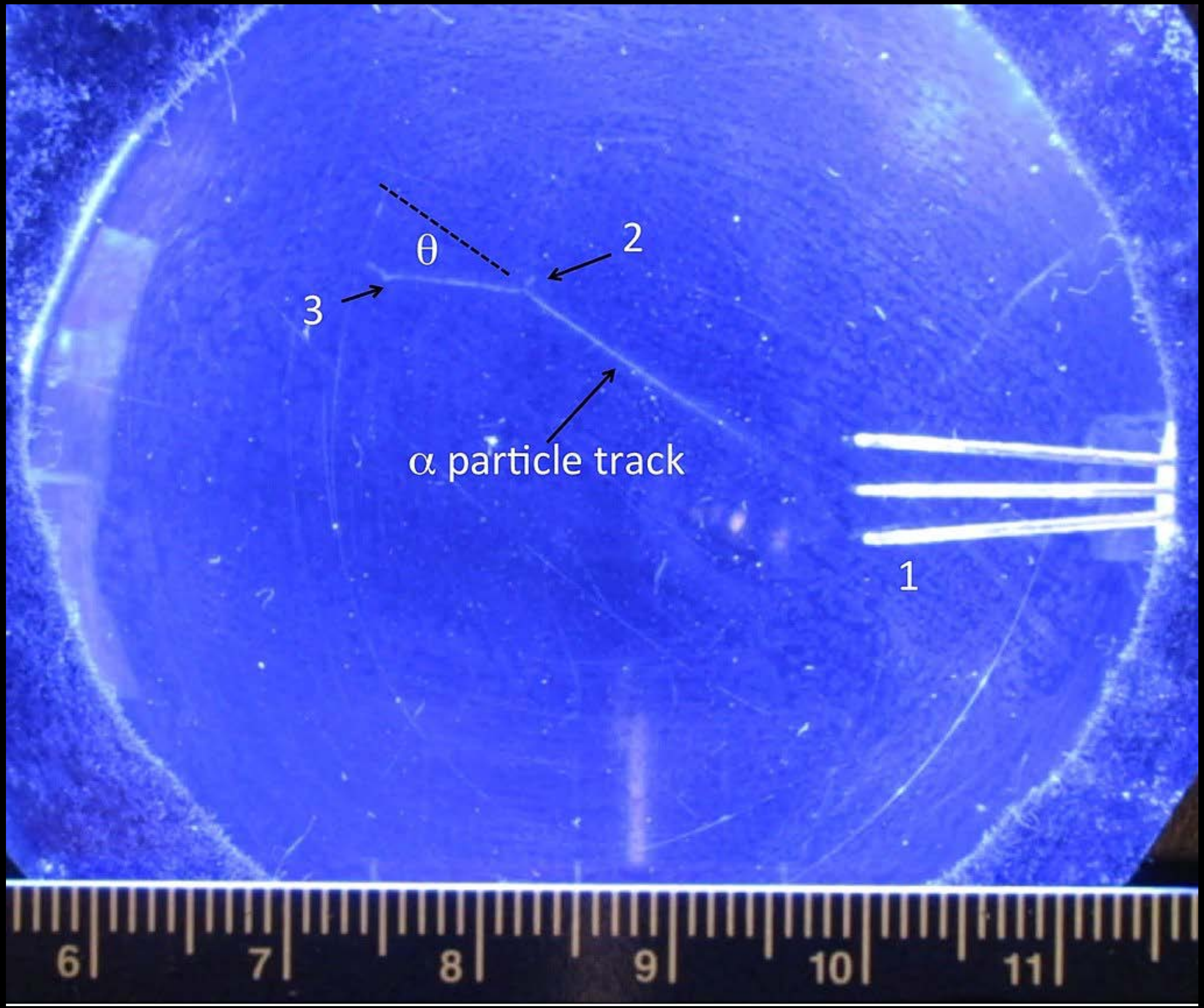
22

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.**

two facilities:

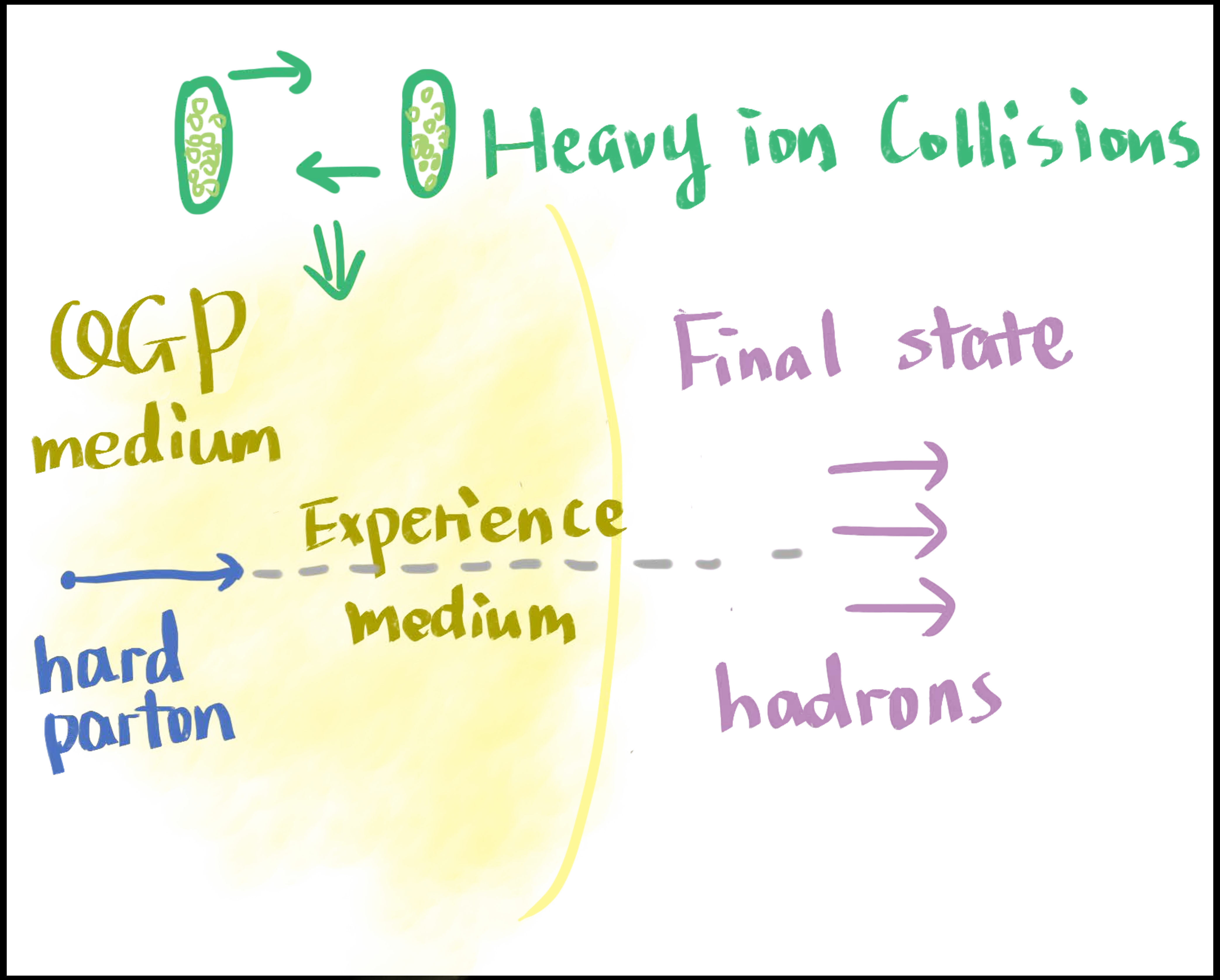
- RHIC (200 GeV collision energy)
- LHC (5400 GeV collision energy)

Priority (2), beam energy scan, has been completed, leaving sPHENIX as remaining priority for completion of RHIC scientific mission



Rule out structureless plum pudding

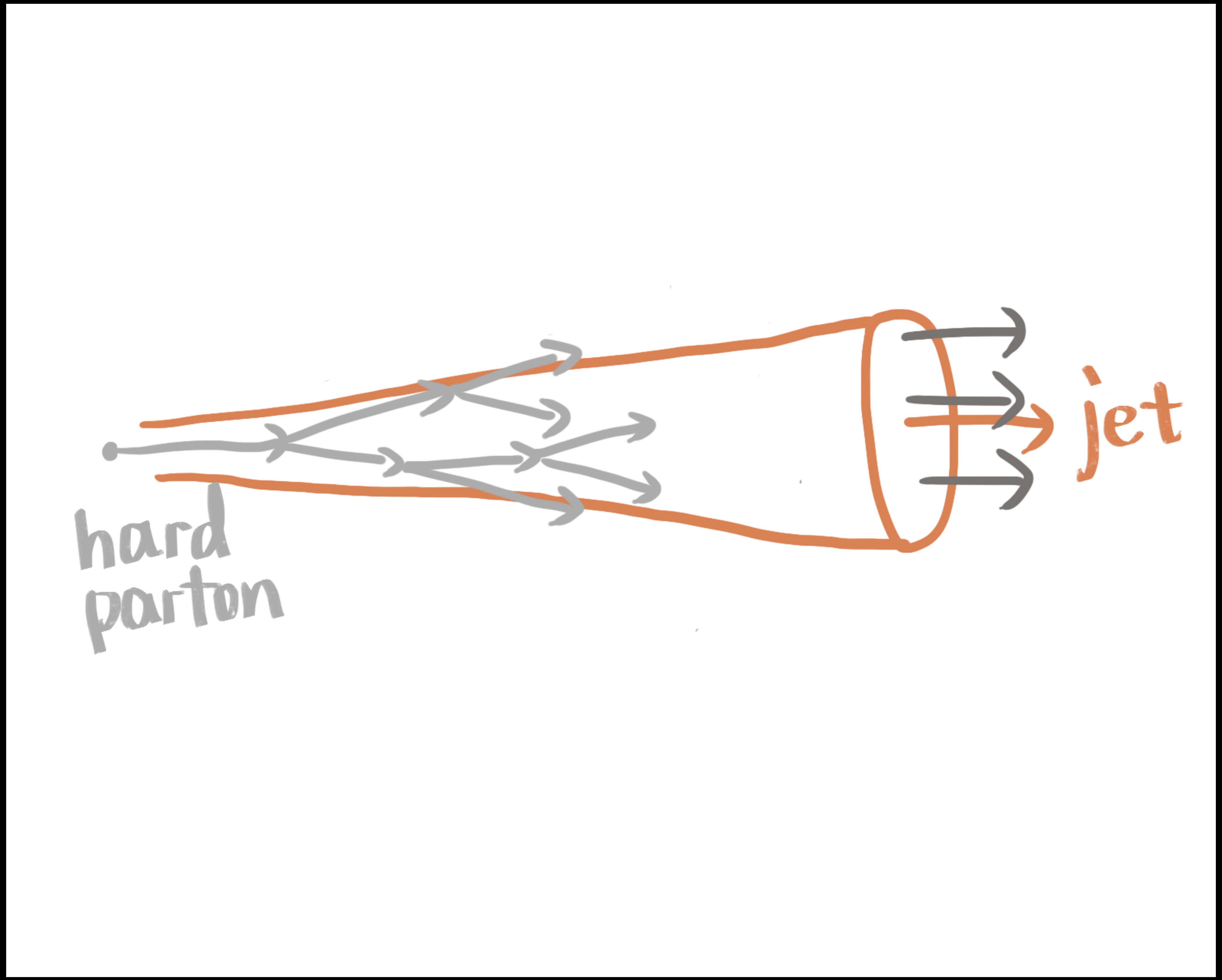
jet cartoons from Jing Wang, https://indico.cern.ch/event/900973/



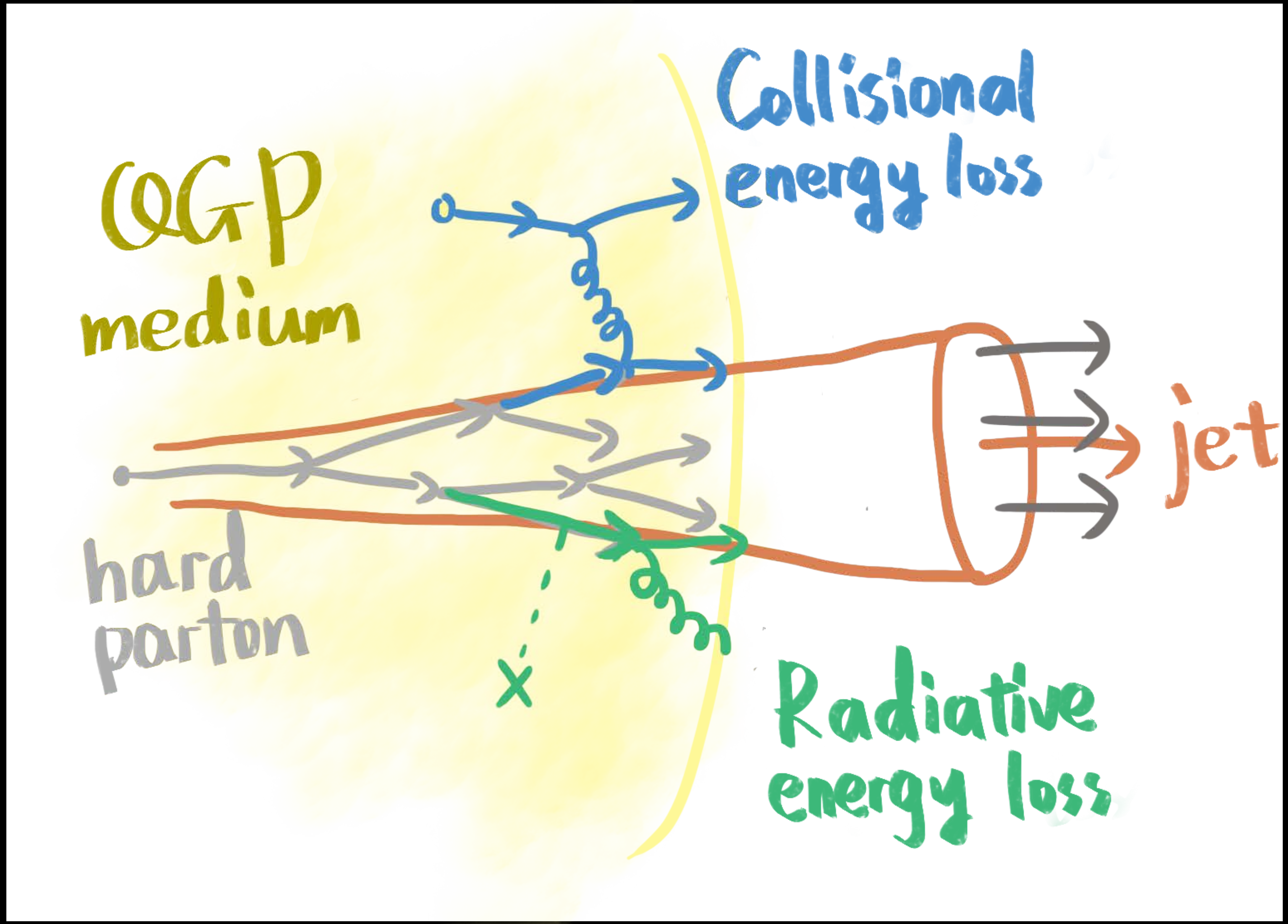
Find structure in QGP

Wikipedia

Jet 1, pt: 70.0 GeV
Jet 0, pt: 205.1 GeV



Jet in vacuum



Jet in medium

Energy loss through medium interactions

Broadly, two classes of energy loss models

- Weak coupling, pQCD
  - collisional energy loss
  - **medium induced gluon radiation**
  - *Many* different formalisms
    - AMY, BDMPS-Z, HT, LBT, LIDO, $SCET_G$, …
- Strong coupling, AdS/CFT
  - Drag force in QGP “goo”
    - Hybrid model

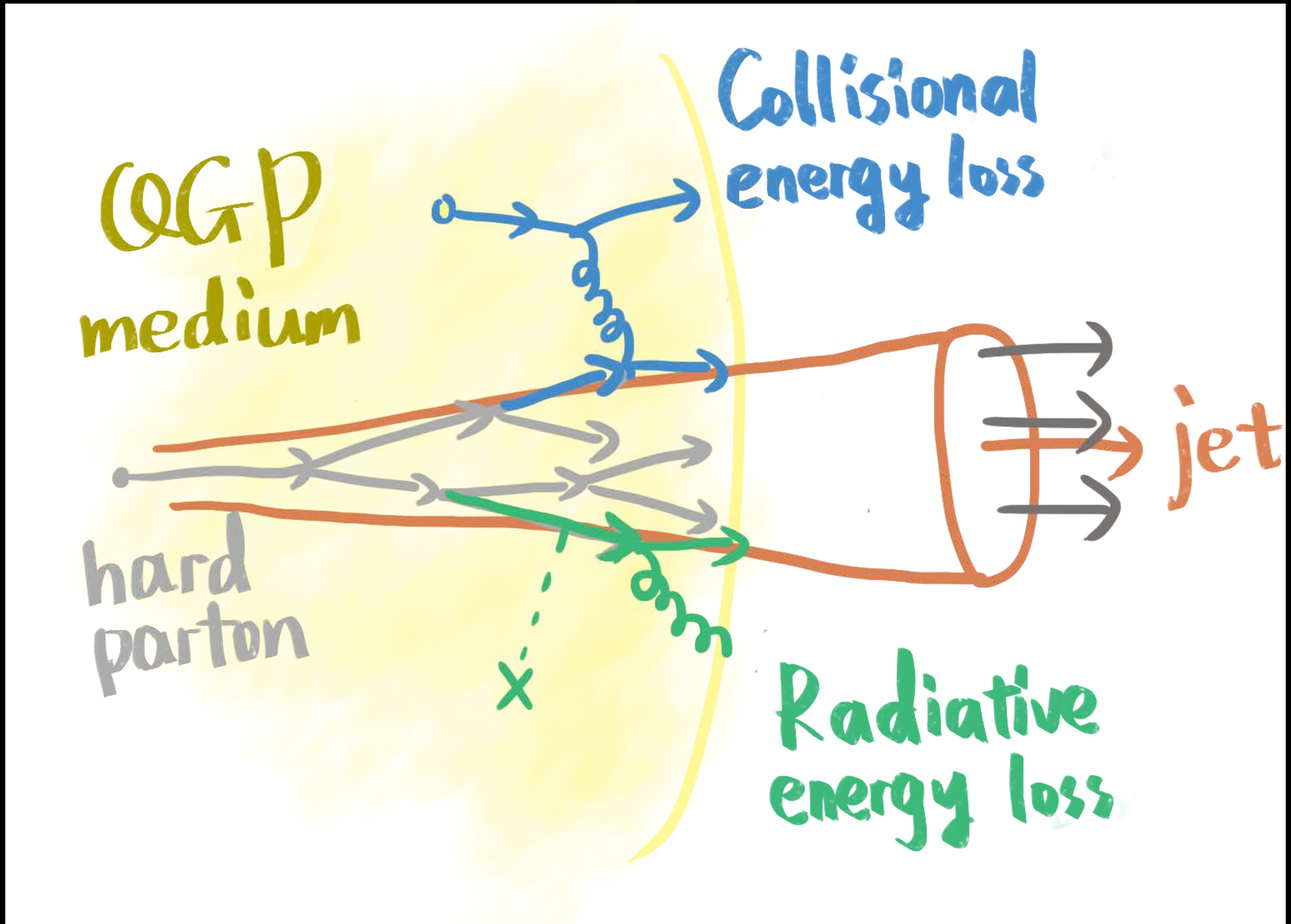
arXiv > hep-ph > arXiv:1405.3864

High Energy Physics – Phenomenology

[Submitted on 15 May 2014 (v1), last revised 4 Aug 2015 (this version, v3)]

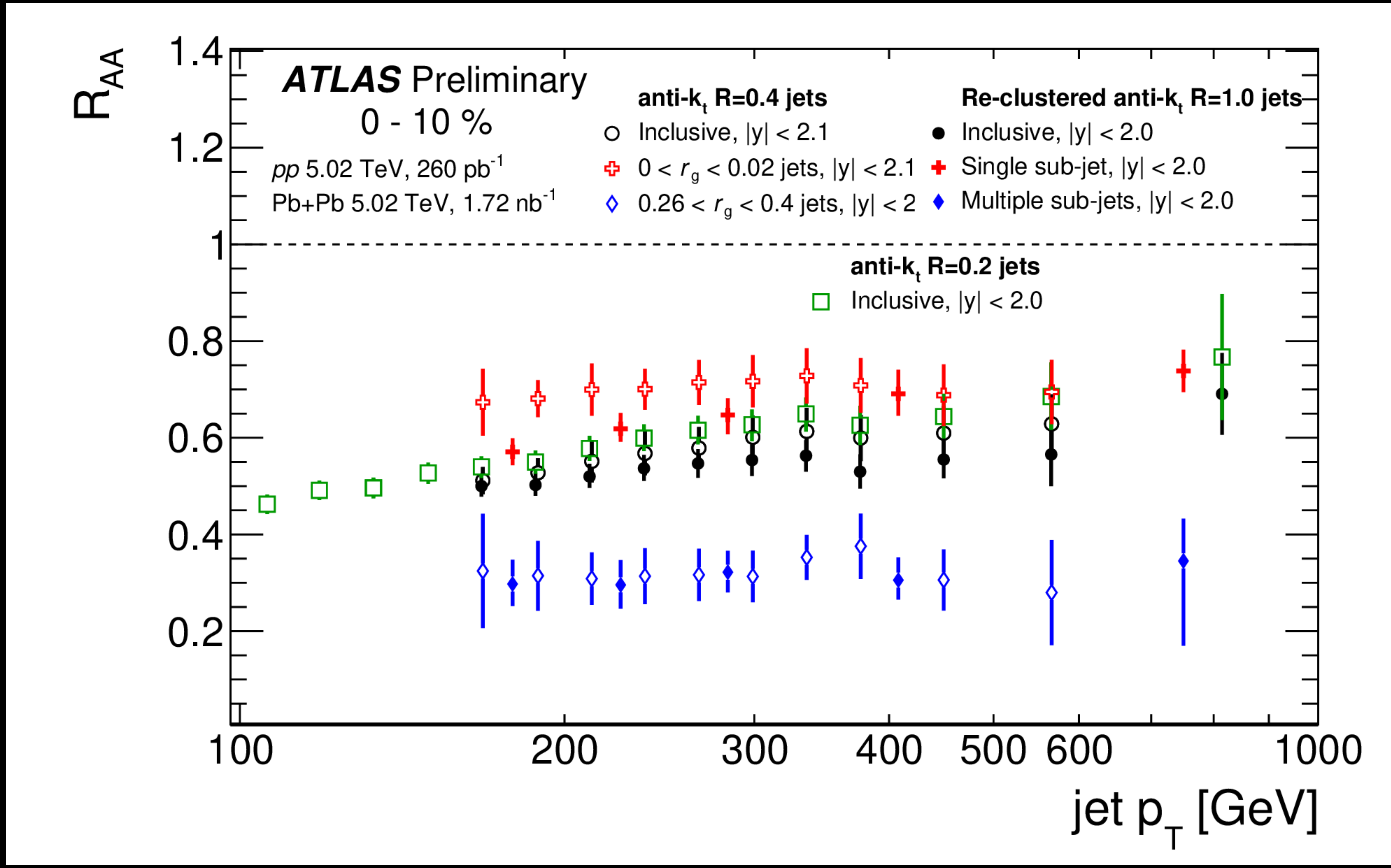
A Hybrid Strong/Weak Coupling Approach to Jet Quenching

Jorge Casalderrey-Solana, Doga Can Gulhan, José Guilherme Milhano, Daniel Pablos, Krishna Rajagopal

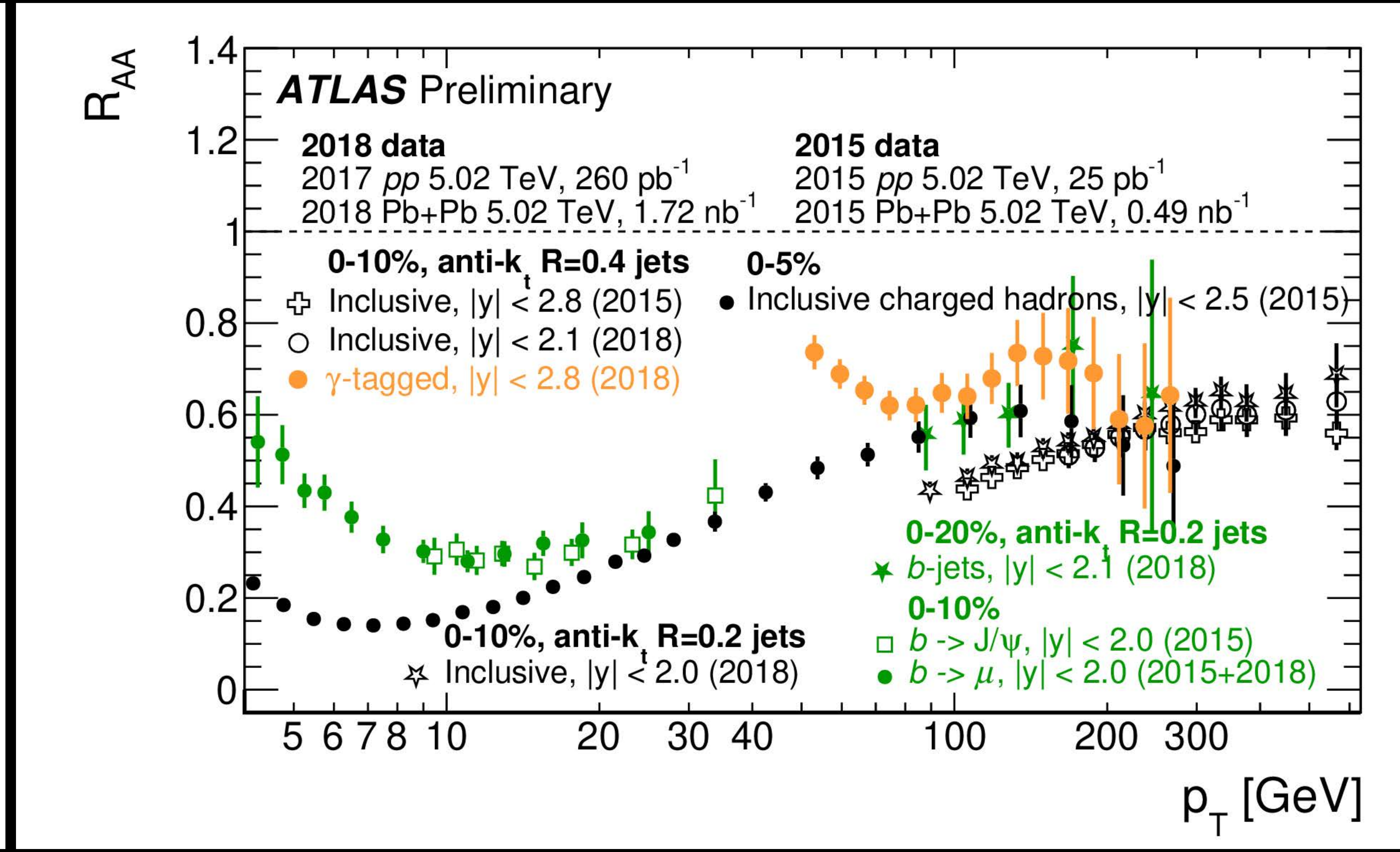


Jet in medium

Jets in different selections



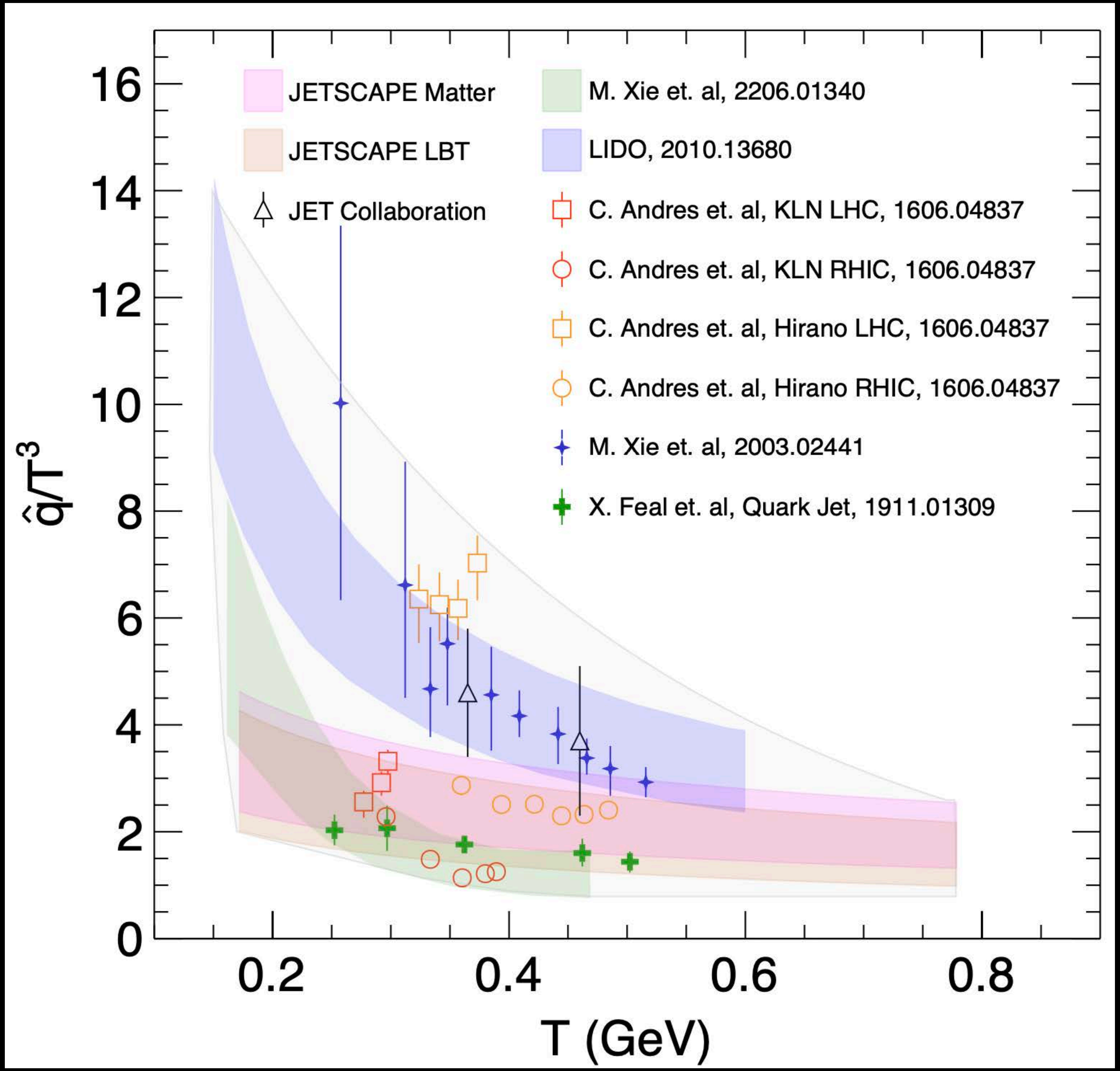
Jets and charged hadrons



Parton energy loss in QGP leads to suppression of yield of jets and charged hadrons compared to pp reference

Many other measurements by LHC and RHIC experiments

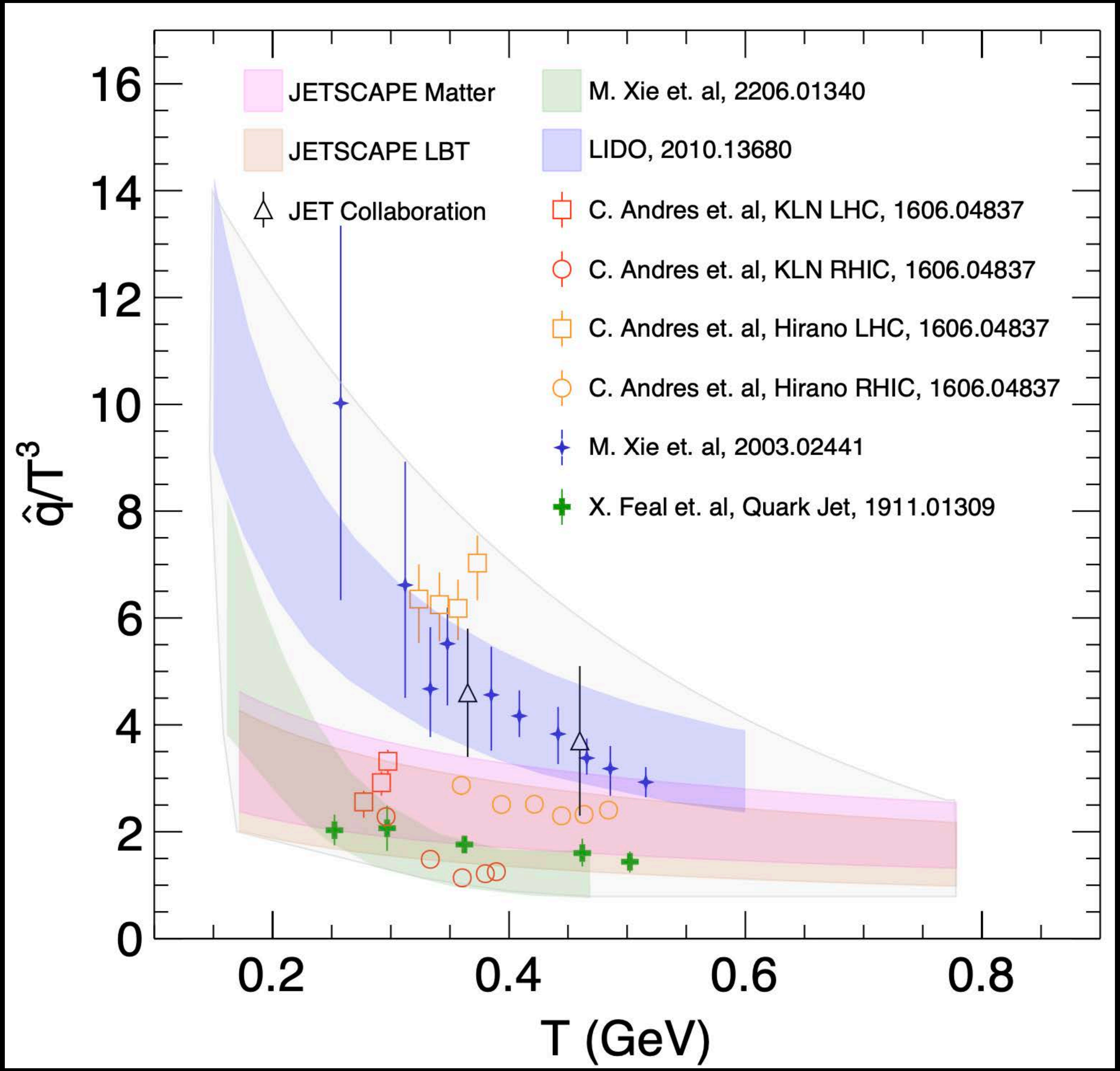
ATLAS, https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2023-009/fig_04.png

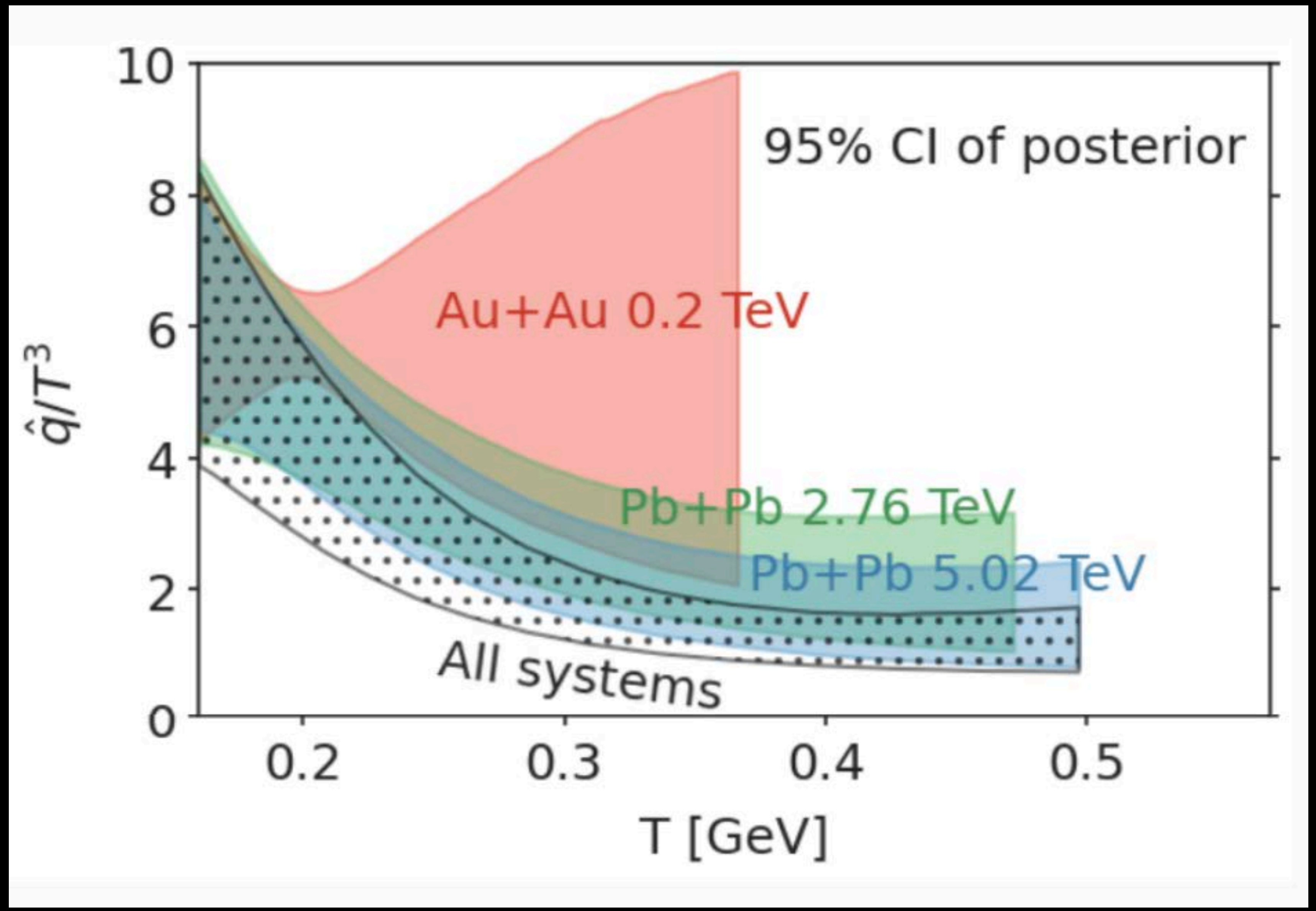


Again, model comparisons performed with Bayesian approach

But: Energy loss transport coefficient $\hat{q}$ (k_T kick per unit length) is highly model dependent: Large differences in $\hat{q}$ for different approaches using same input data

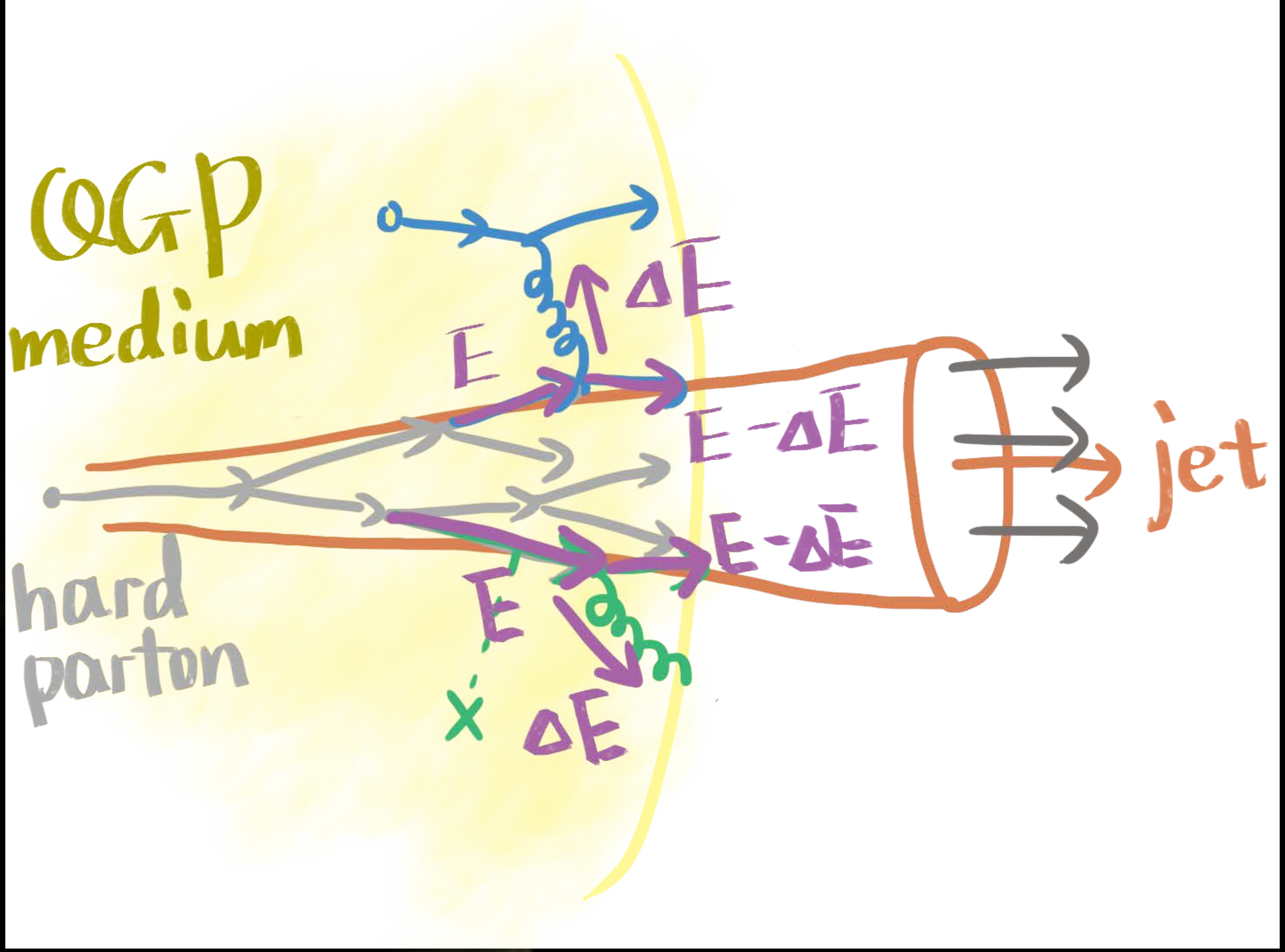
Models predict significant T dependence





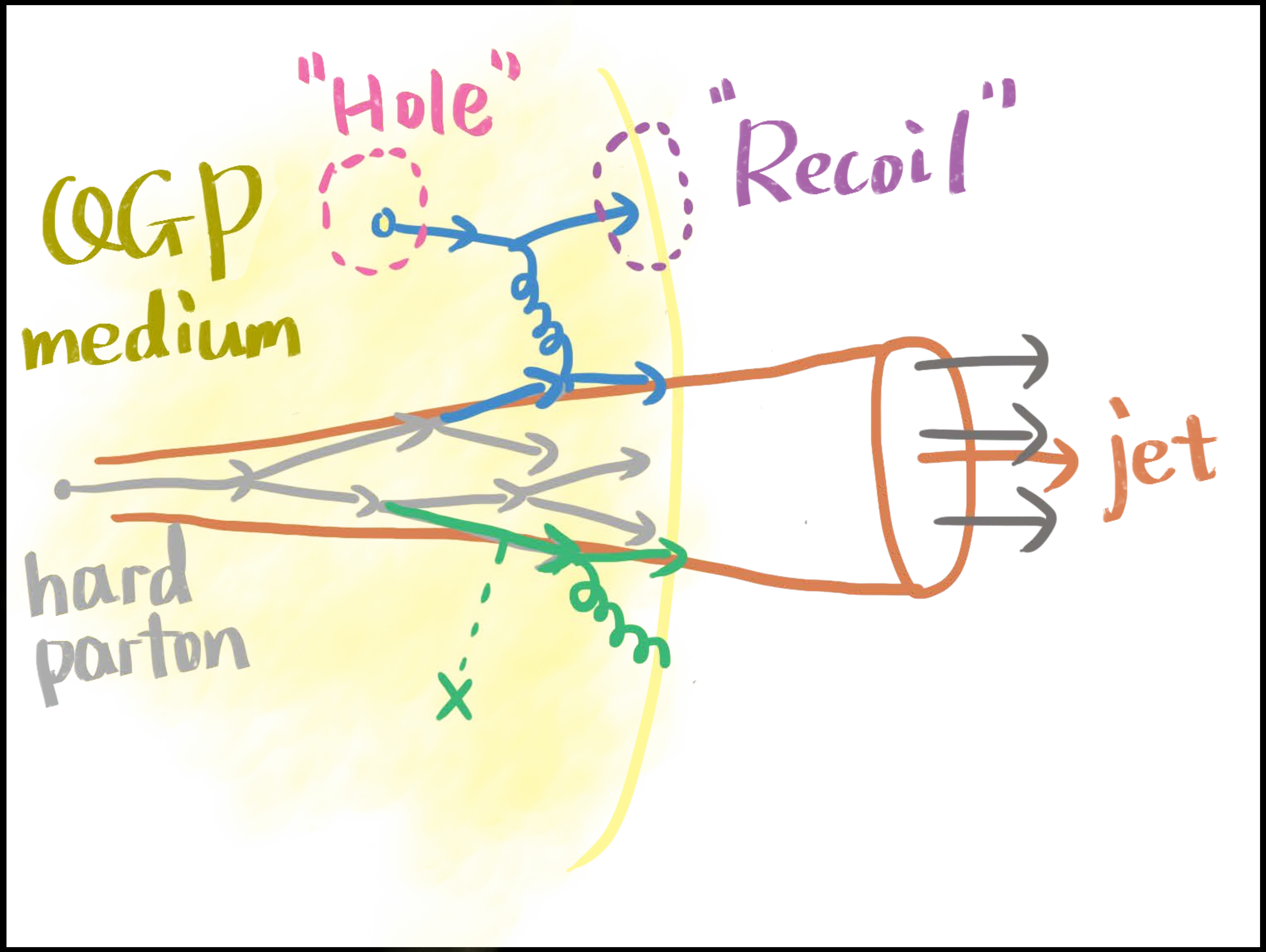
Improved data (particularly from RHIC!) will constrain $\hat{q}$ better *within each model*

What is the most salient aspect of jet modification in QGP?



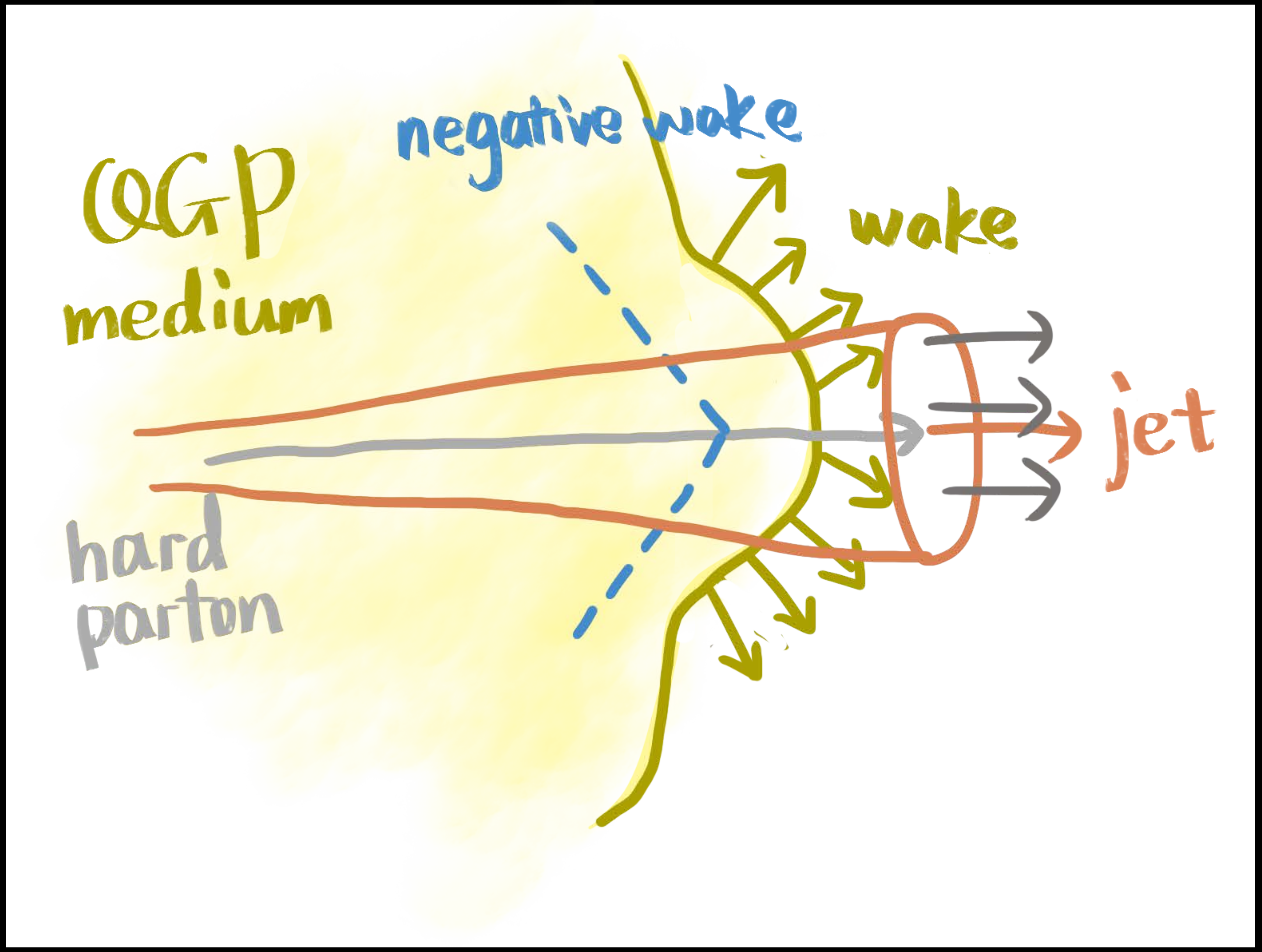
What happens with the energy transported out of the jet cone into the medium?

→ study **medium response** expected for the QGP liquid



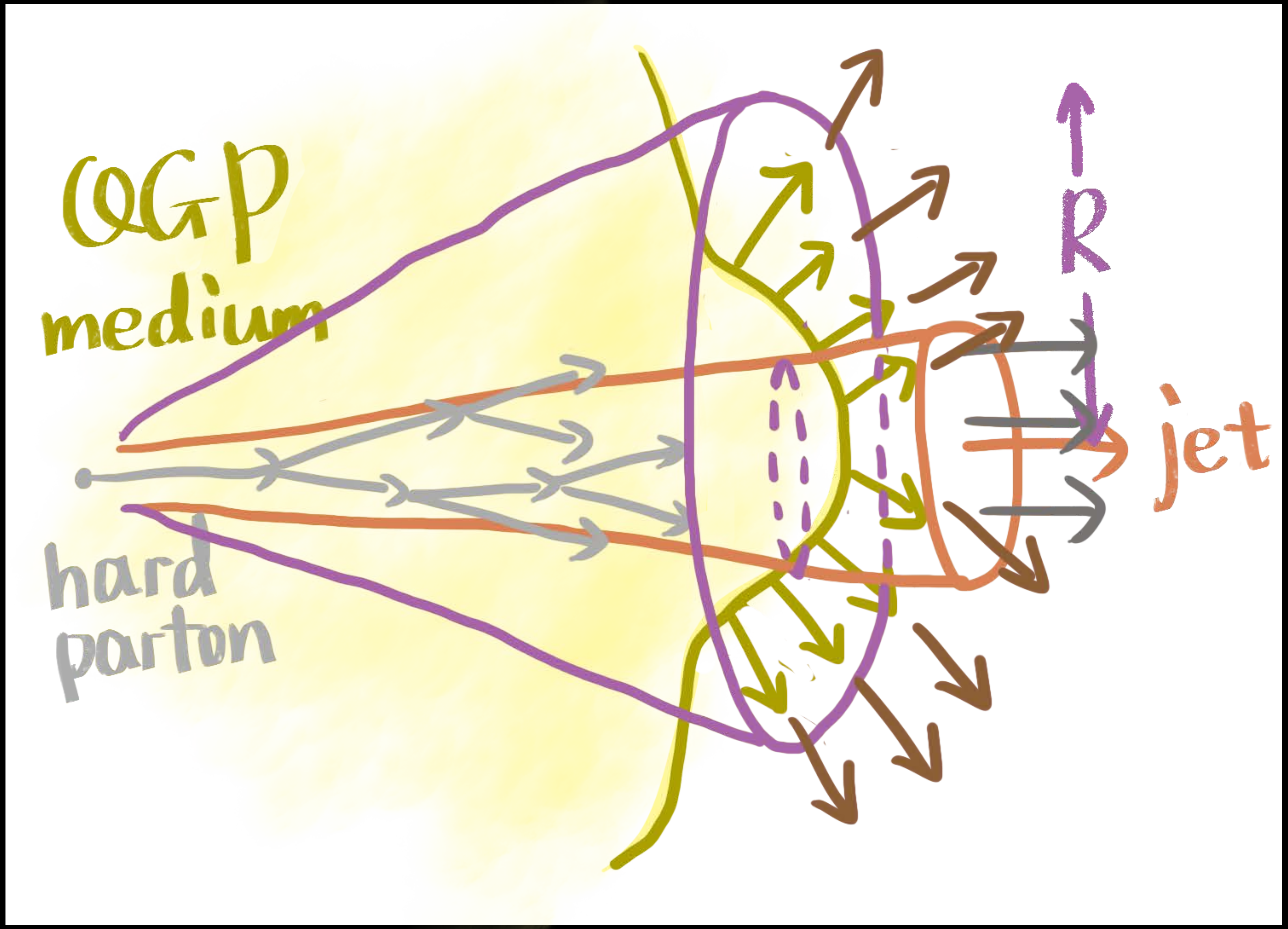
Kinetic theory

- Deposited energy picked up by medium partons (“recoil”) leaving behind “holes”
- Thermalization through interactions among partons



Hydrodynamics

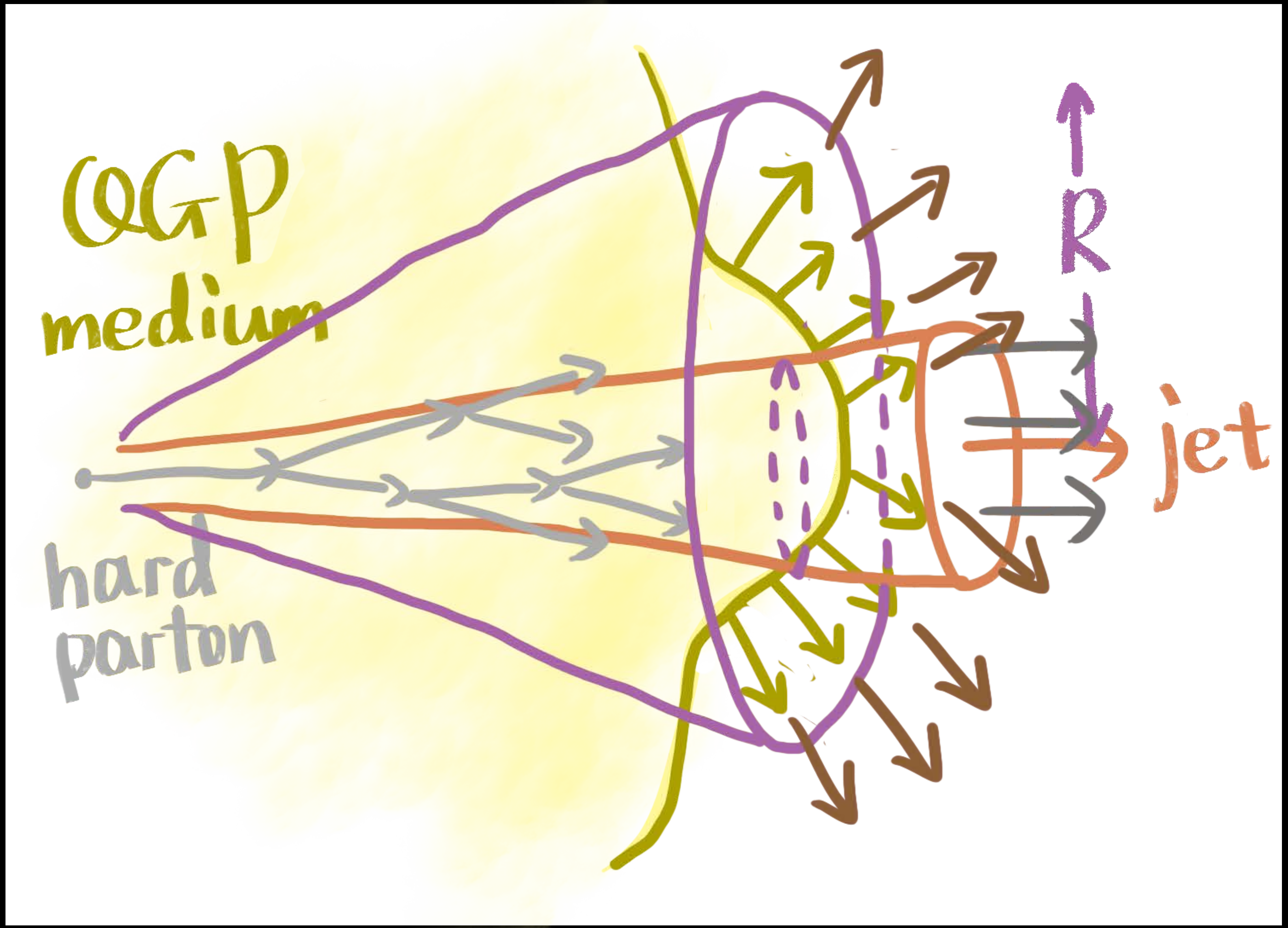
- Stay in strong coupling picture
- Deposited energy co-evolves with medium
- Diffusion wake (recoils) and negative wake (holes)



How can we test different pictures of energy loss and medium response?

There are many different measurements based on jet-hadron correlations, energy flow etc etc

One example → Vary radius parameter in jet reconstruction



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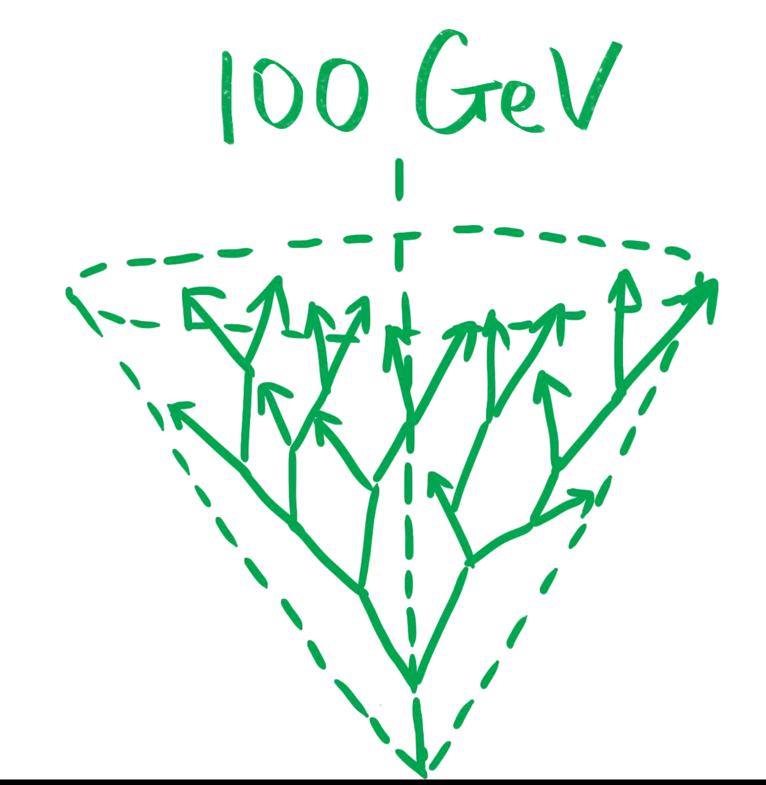
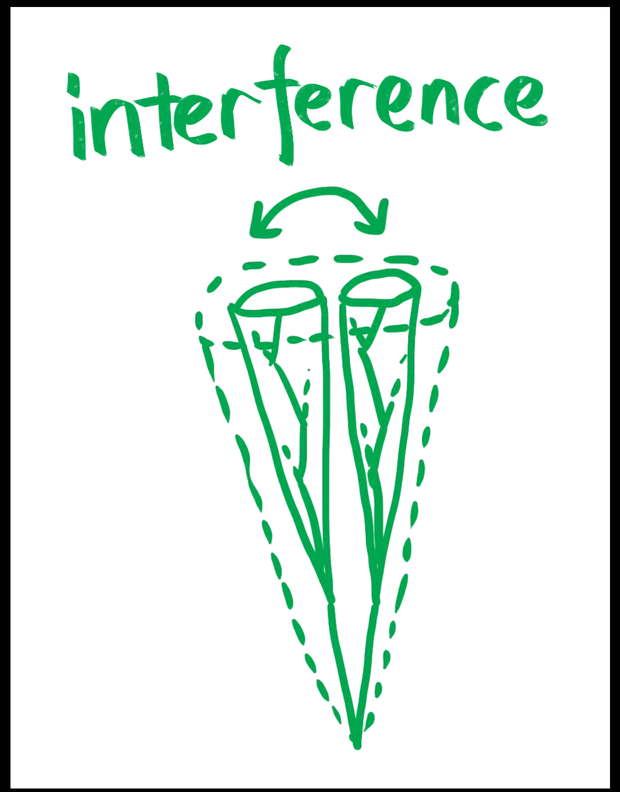
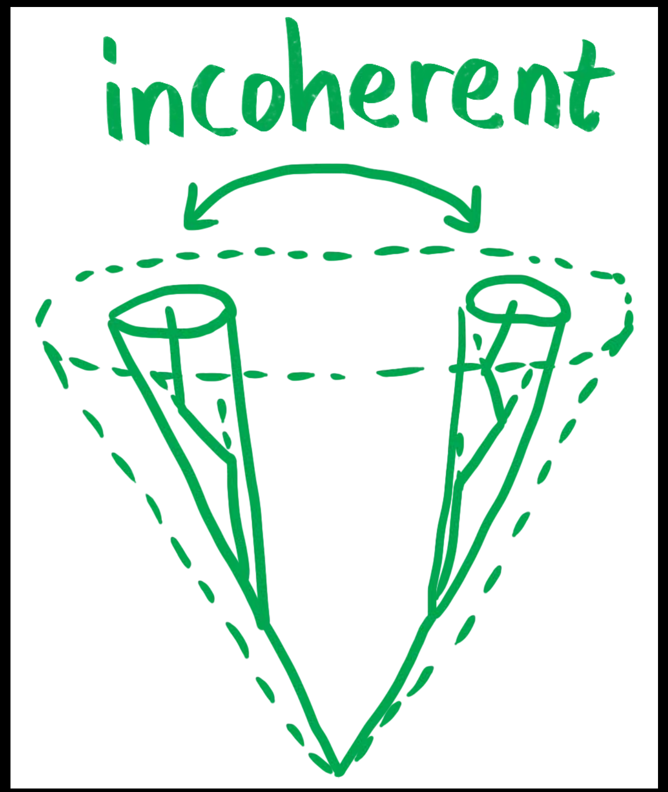


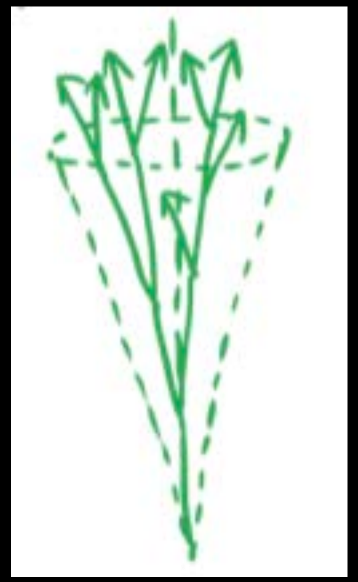
Quenching of skinny vs fat jets?

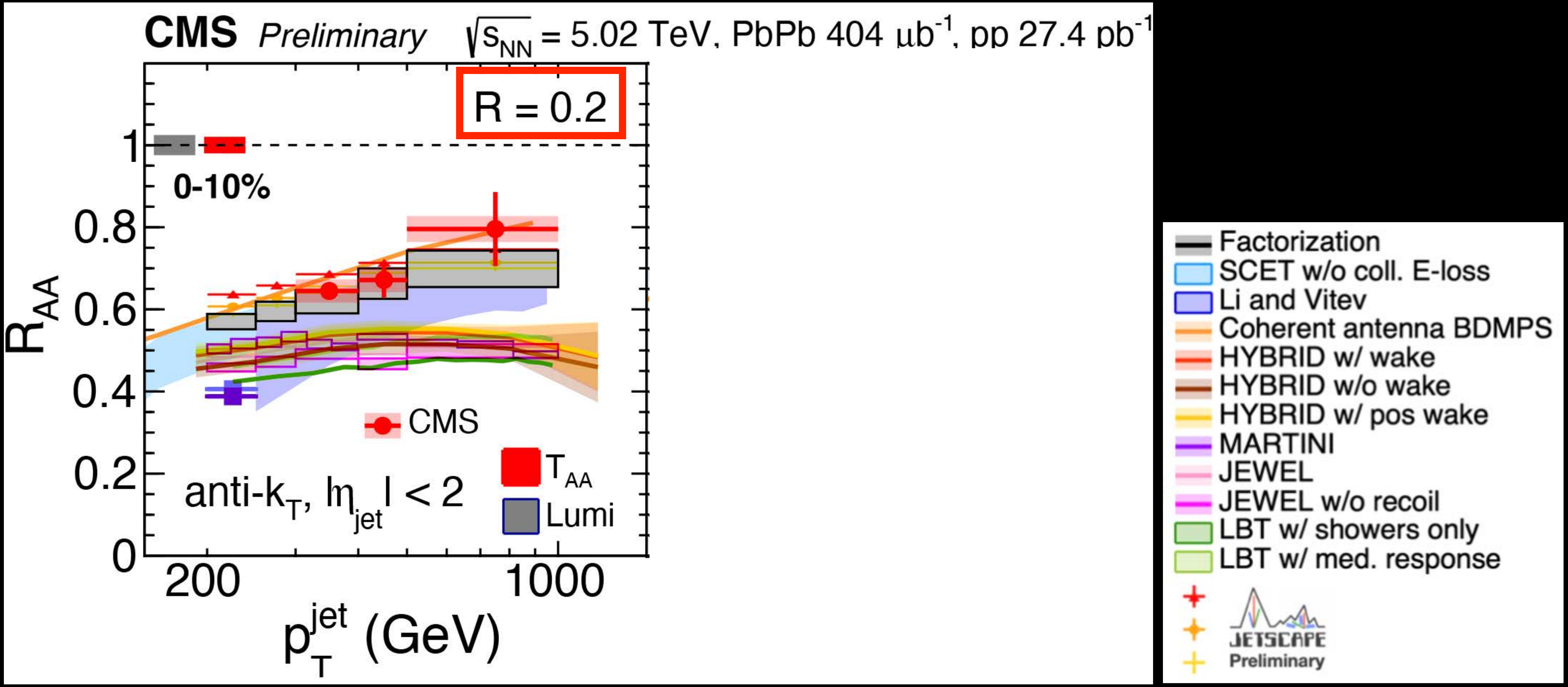


vs.



Coherent or incoherent interactions?

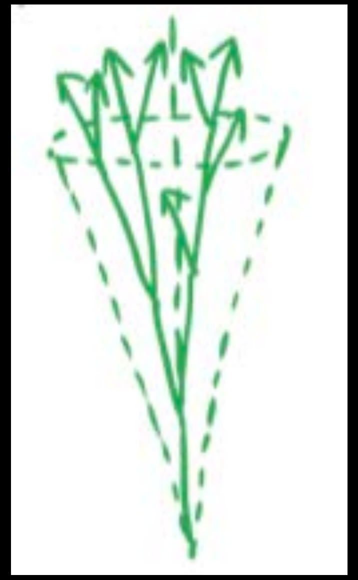


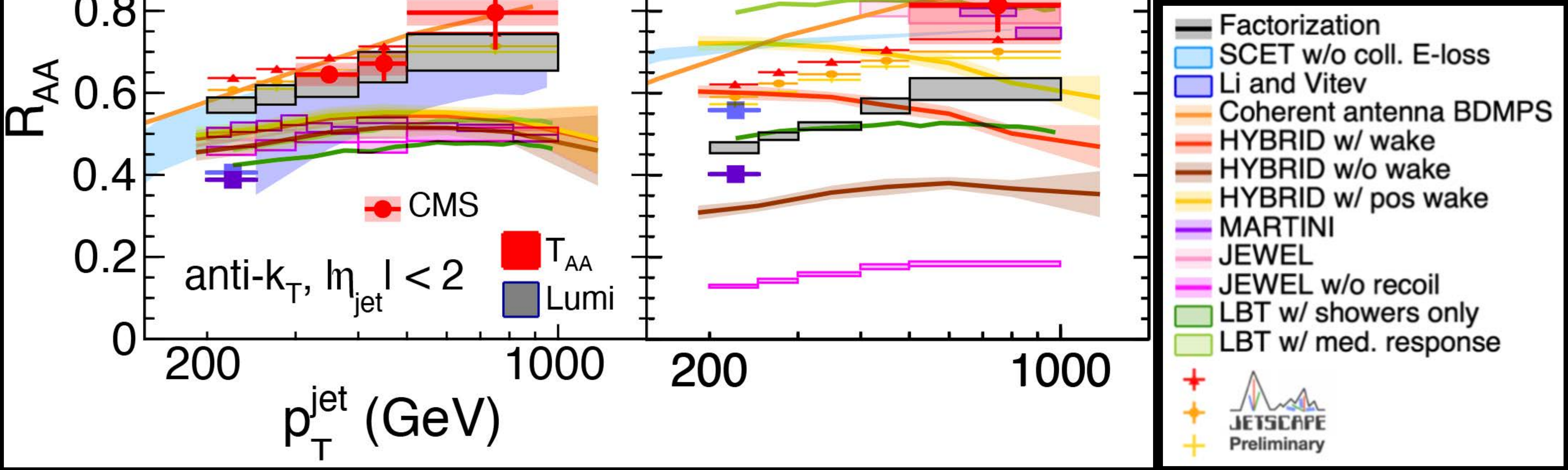


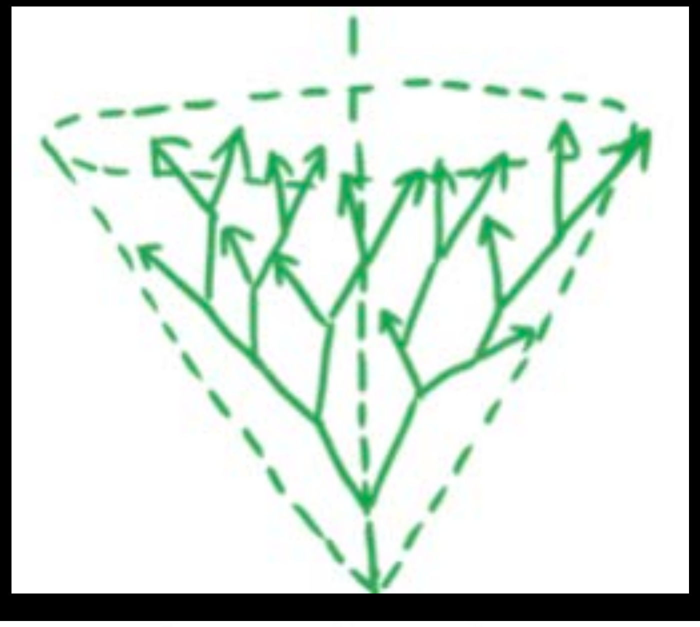
Models match or slightly overestimate energy loss for small radius jets

Typical R_{AA} measurements use R=0.3-0.4

CMS final: https://arxiv.org/pdf/2102.13080.pdf







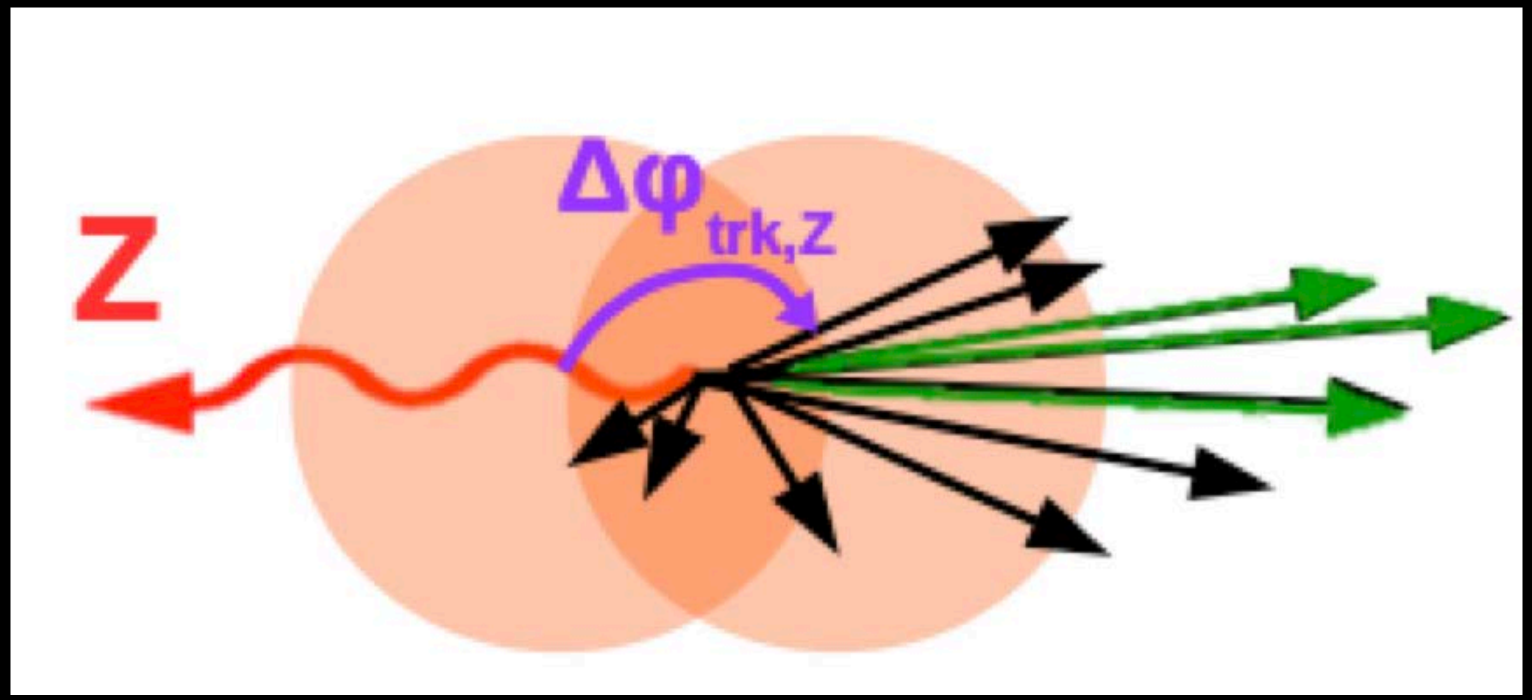
Models have a very hard time describing R dependence
Need improved understanding of:

- medium response
- fragmentation functions
- coherence effects

CMS final: https://arxiv.org/pdf/2102.13080.pdf

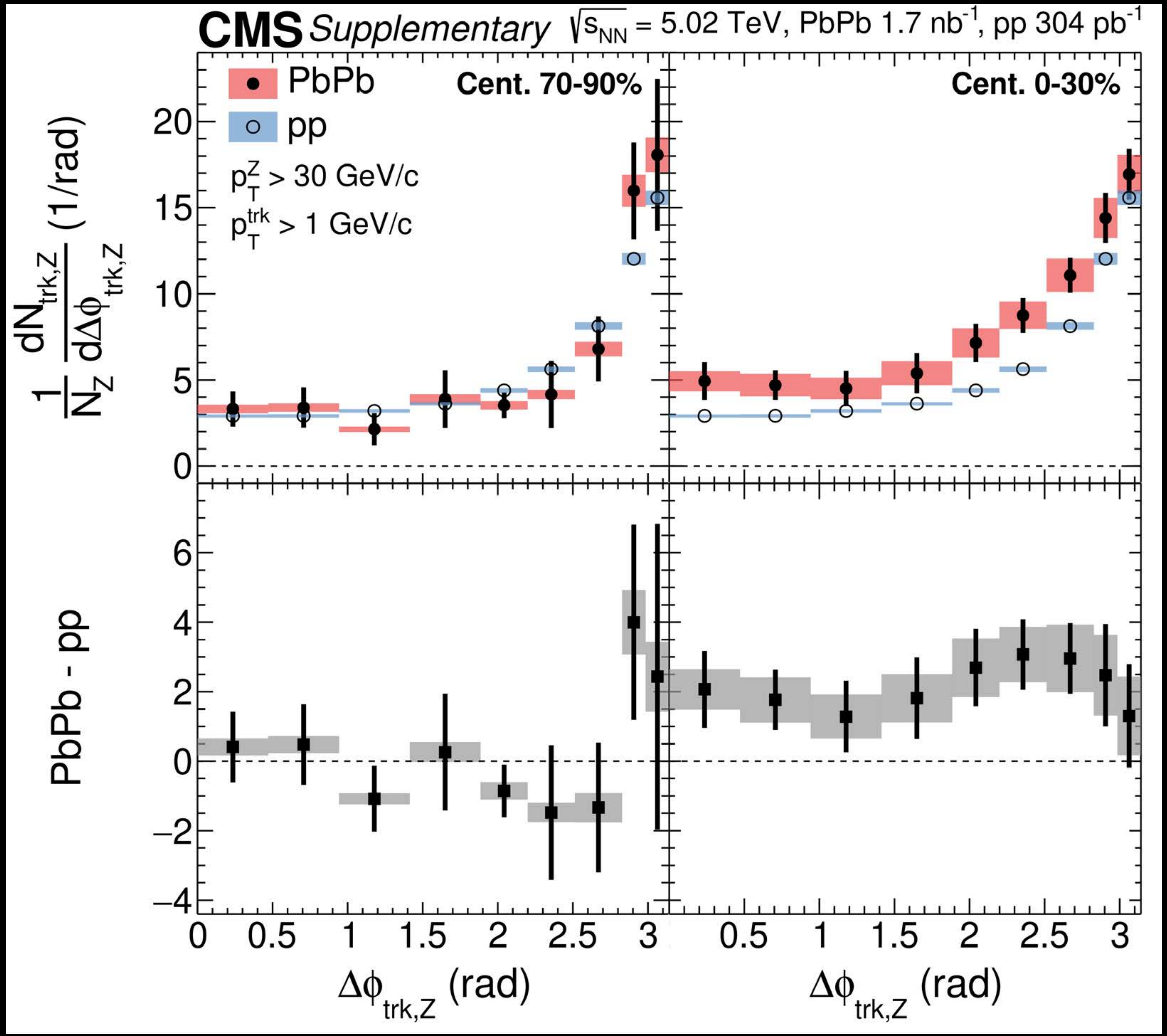
Why is this so difficult?

Look at angular correlations of hadrons with high p_T Z^0



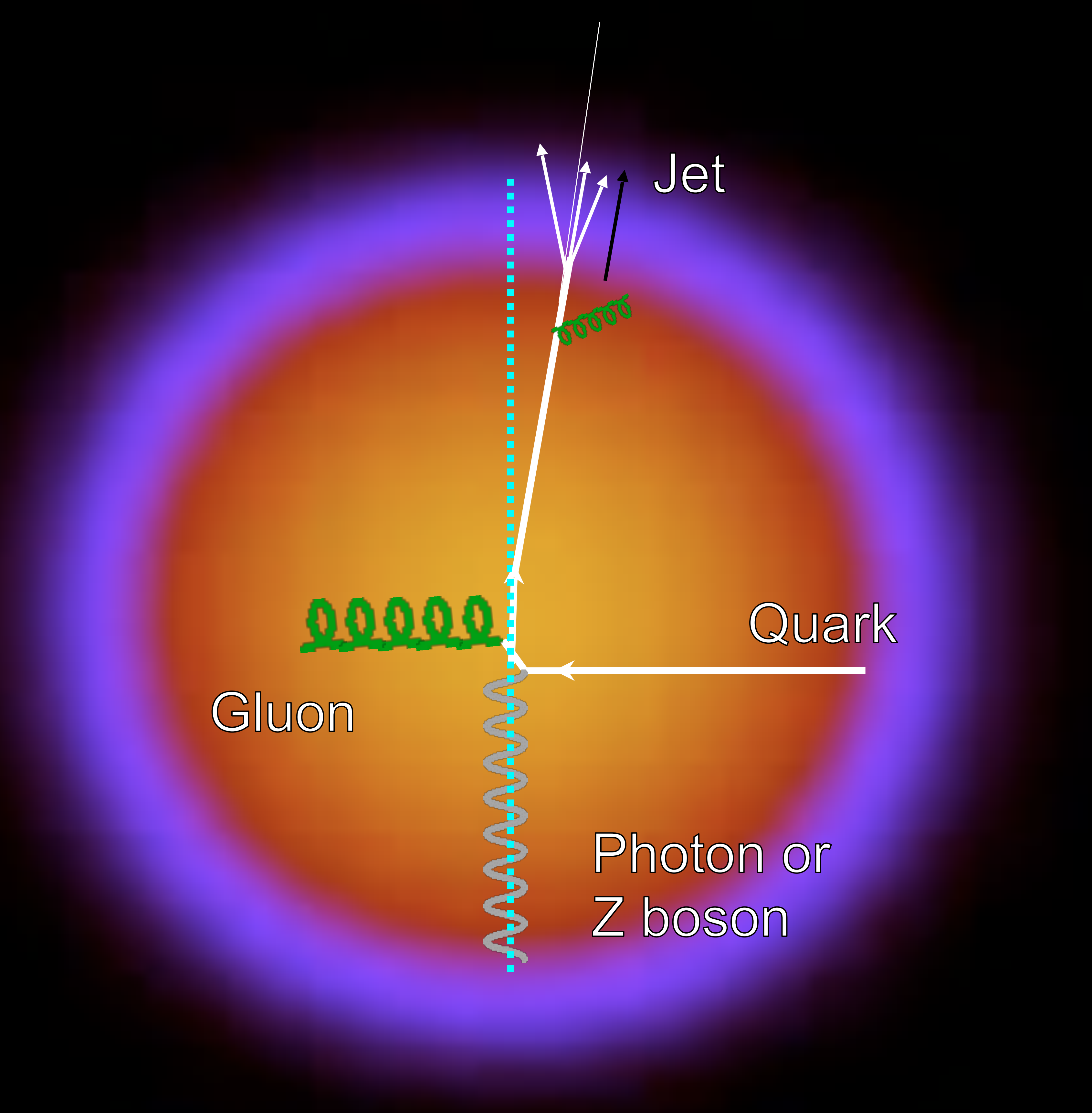
- Z0 will escape QGP unmodified
- Balancing jet will undergo energy loss
- Where do associated hadrons emerge?

→ excess yield distributed over full azimuth

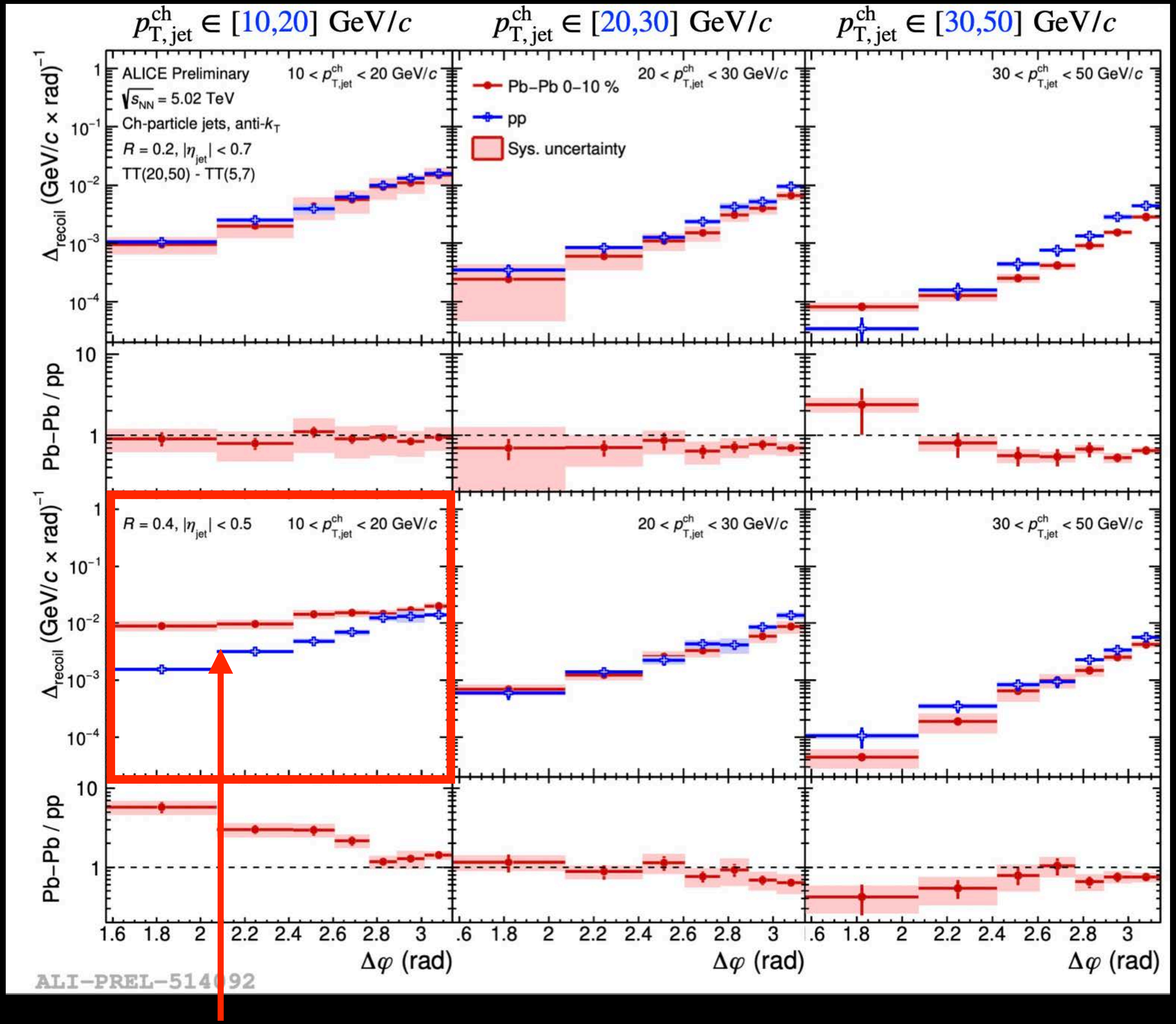


Models not only need to have right amount of energy loss, but also mechanism to transport energy/ particles across large angular range

But what about QGP structure?

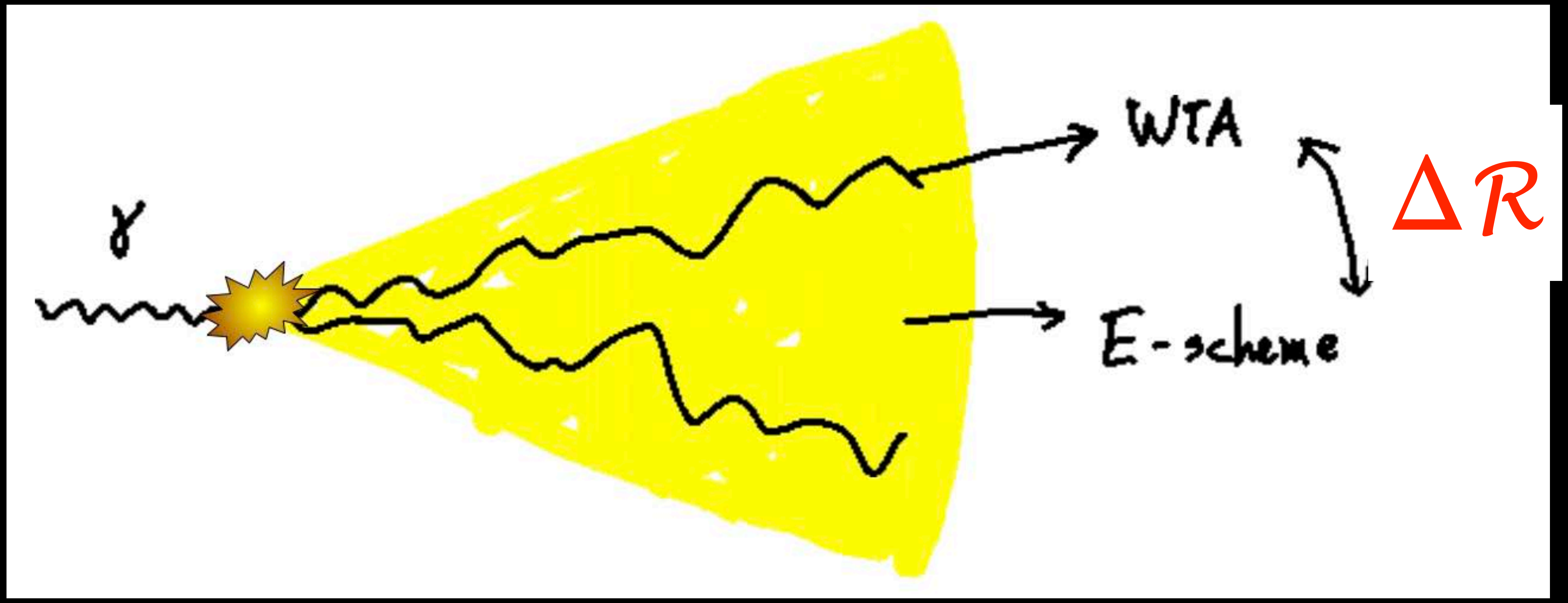


Can deflection of jets reveal quasiparticle structure of QGP?



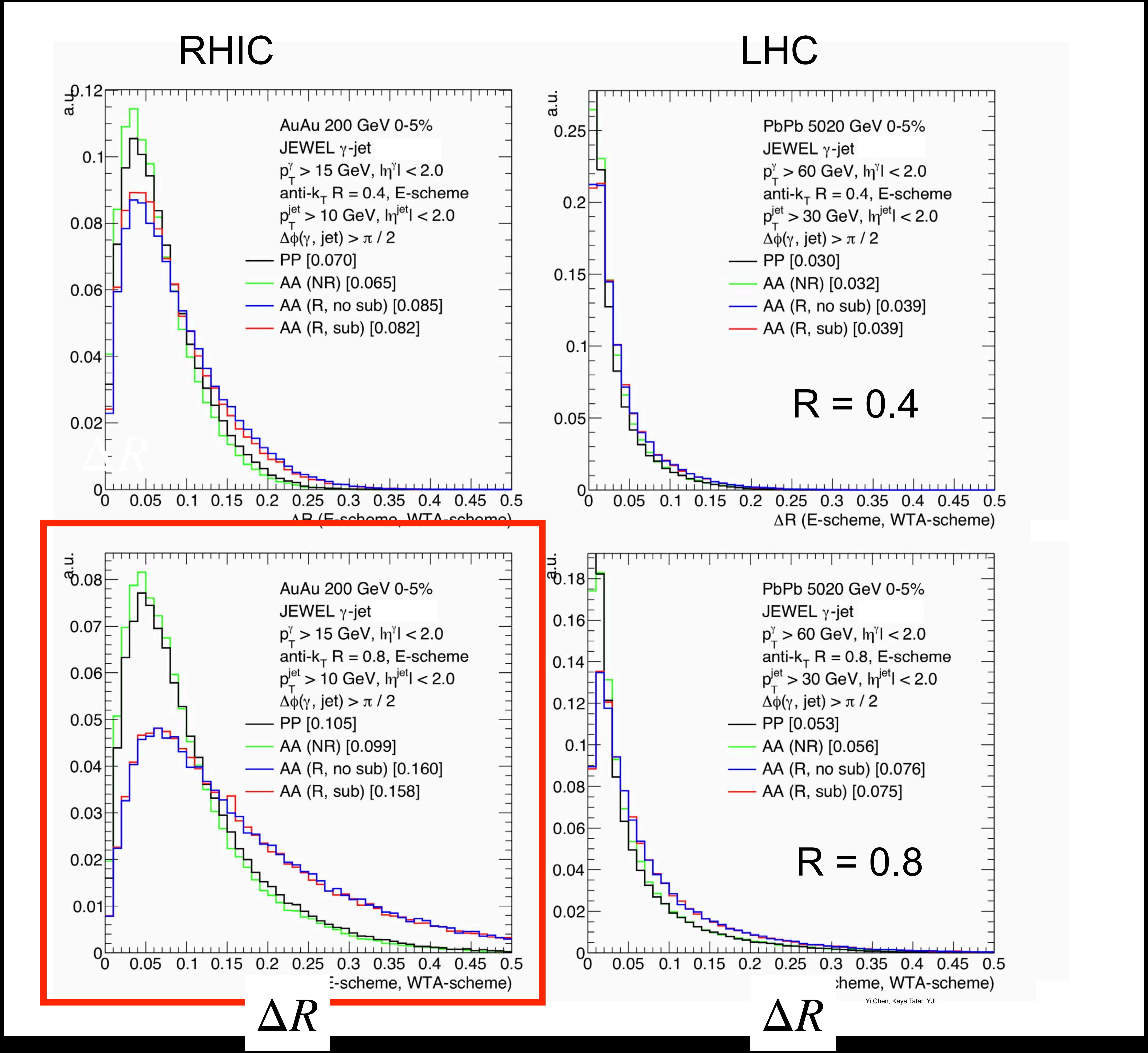
Decorrelation of hadron-jet angular difference fo in PbPb - likely caused by medium response, not deflection of initial/leading parton

Instead of jet deflection, study modification of jet structure

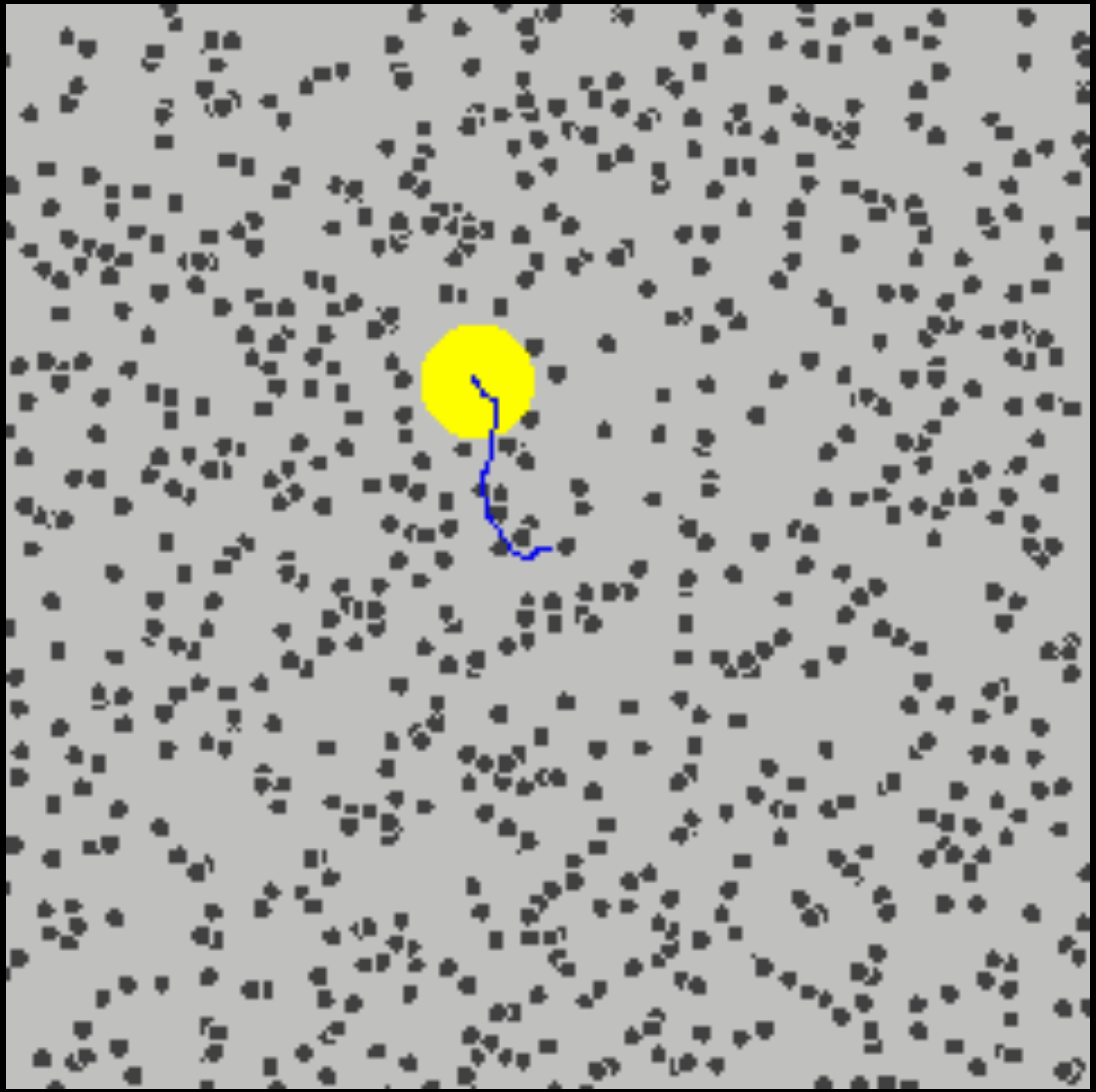


Compare winner-take-all and E-scheme jet axes. WTA more sensitive to momentum kicks

Much higher sensitivity for lower pT γ-jet events at RHIC vs LHC for large radius jets

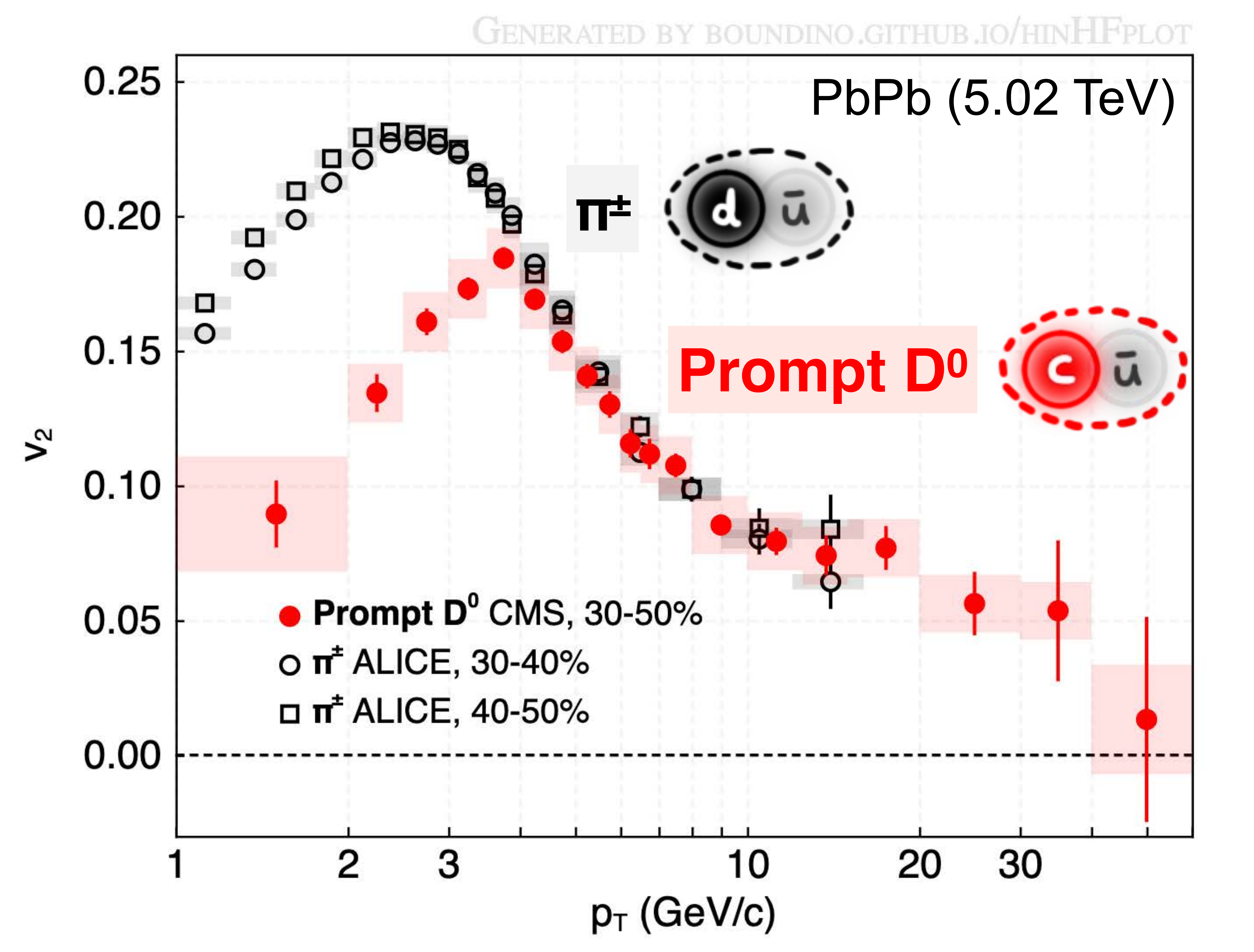


Use open heavy-flavor hadrons to measure in-medium drag force



Wikipedia

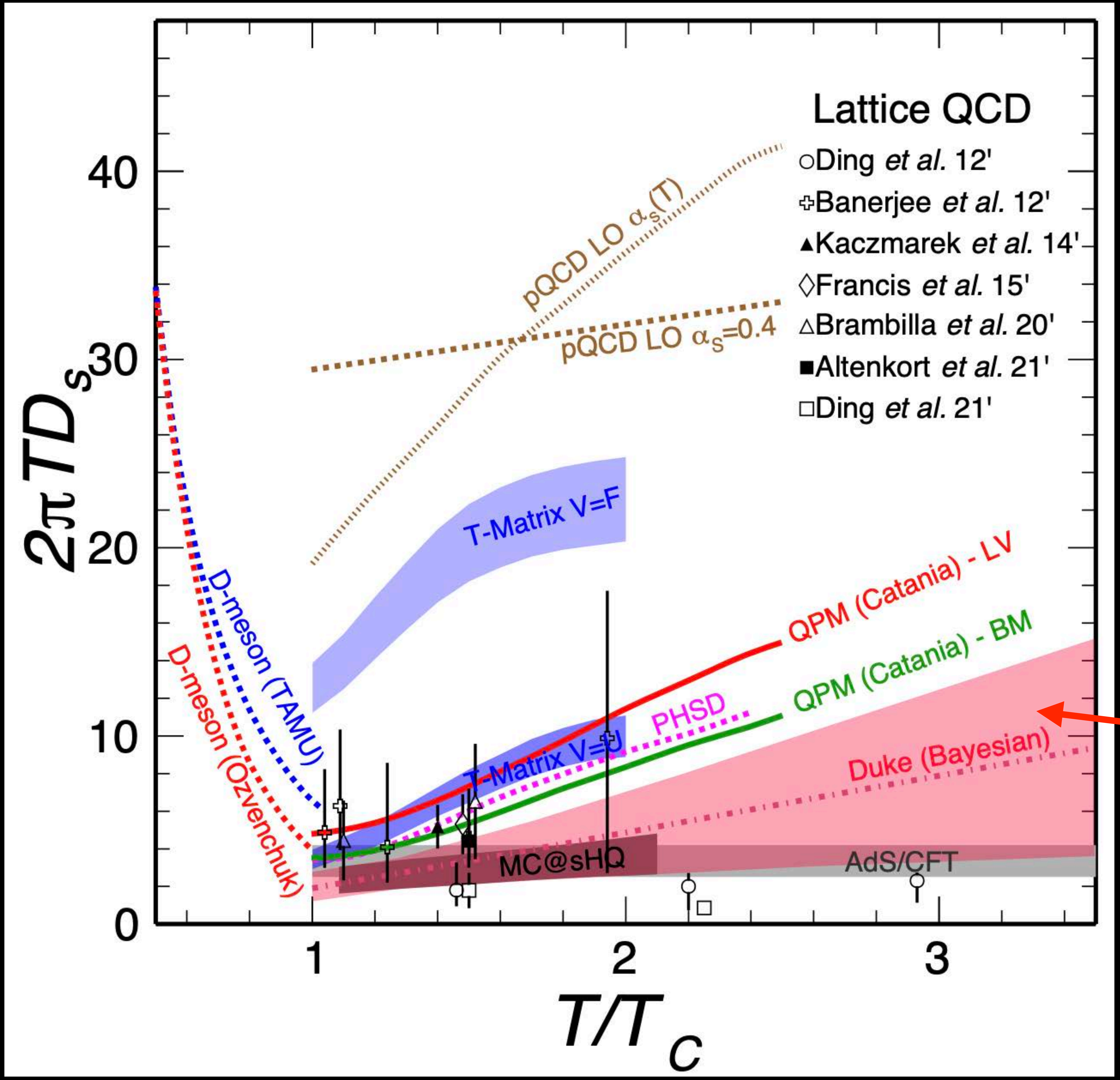
Key measurements: HF hadron yields, flow coefficients, correlations



PLB 816 (2021) 136253

JHEP 1809 (2018) 006

Use charm diffusion constant



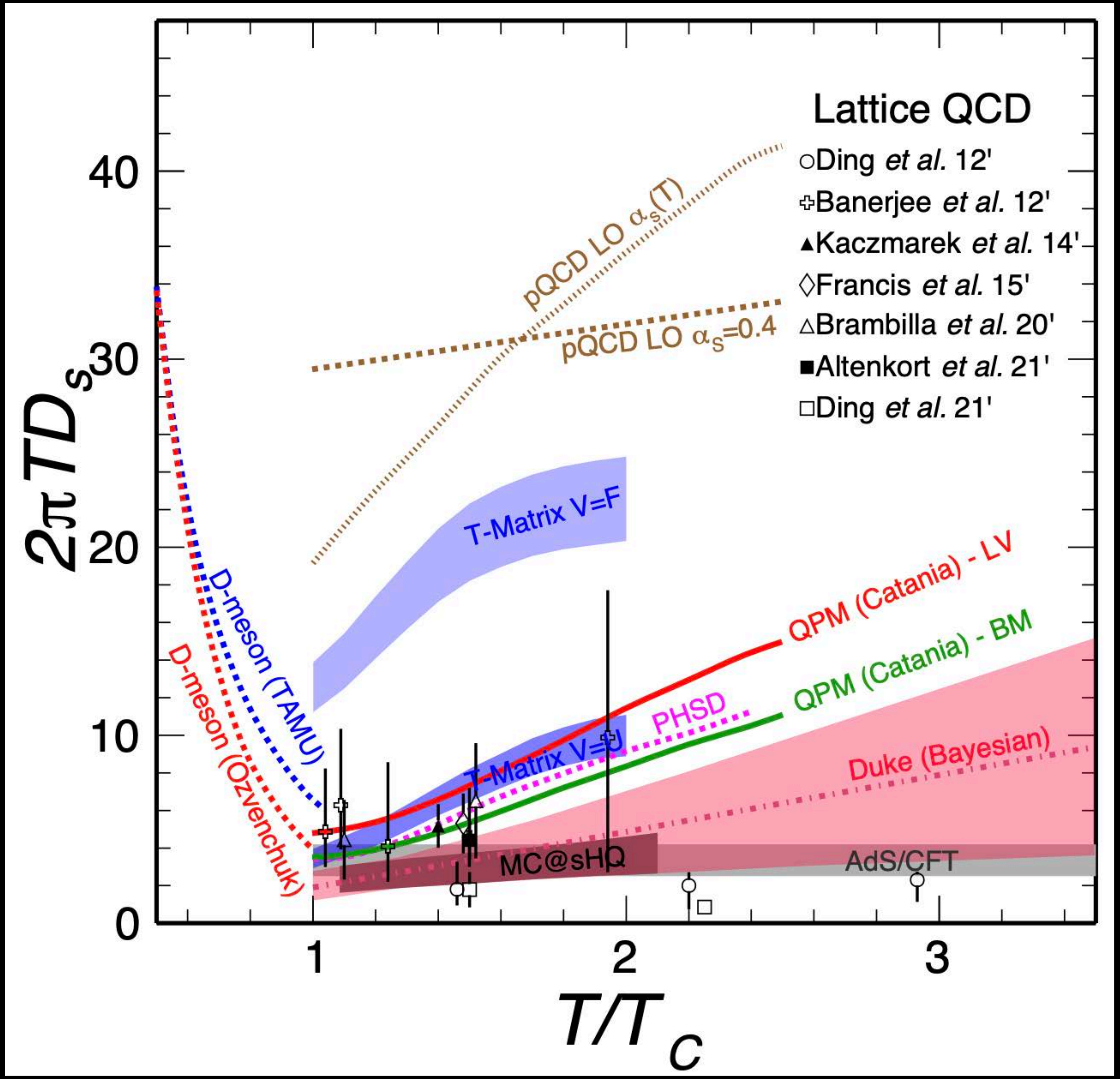
Xin Dong, YJL, Ralf Rapp, Ann.Rev.Nucl.Part.Sci. 69 (2019) 417-445

Diffusion coefficient can be calculated in a broad range of theoretical approaches from pQCD to Lattice

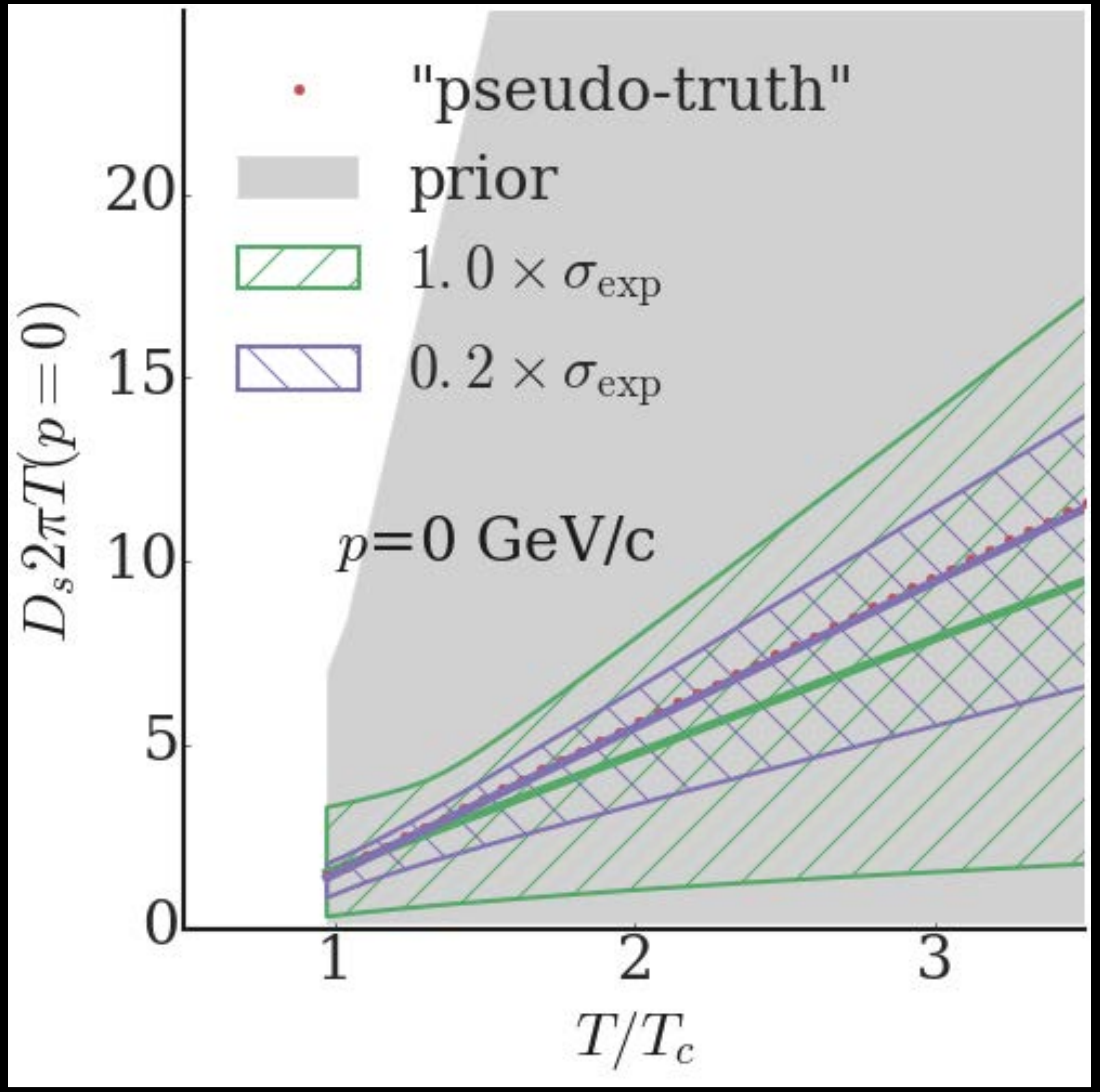
Many models predict significant T dependence

Many are ruled out

"Allowed" region based on Bayesian analysis of D^0 R_{AA} and v_2 data (Bass et al, Duke)



Xin Dong, YJL, Ralf Rapp, Ann.Rev.Nucl.Part.Sci. 69 (2019) 417-445



Study within Bayesian model using pseudo-data shows that more precise data can provide clear constraint on T dependence

Within reach in with present expt's

Another new direction:

Will It Blend? - iPhone

YouTube · Blendtec's Will It Blend? · Jul 10, 2007

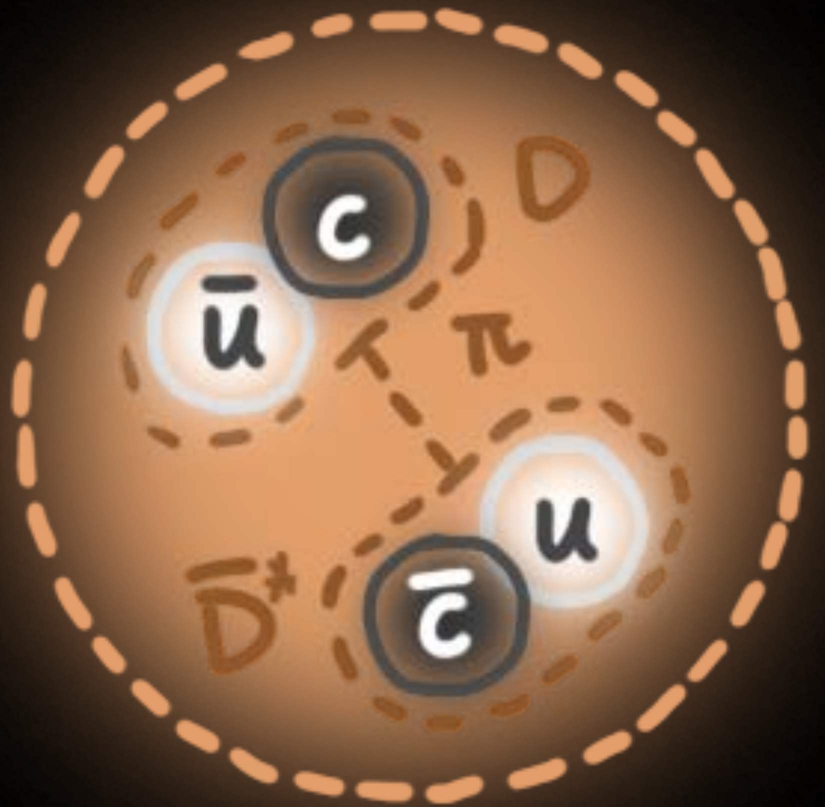
YouTube

Another new direction: X(3872) - will it blend?

Tetraquark

PRD 71 (2005) 014028

Hadron molecule

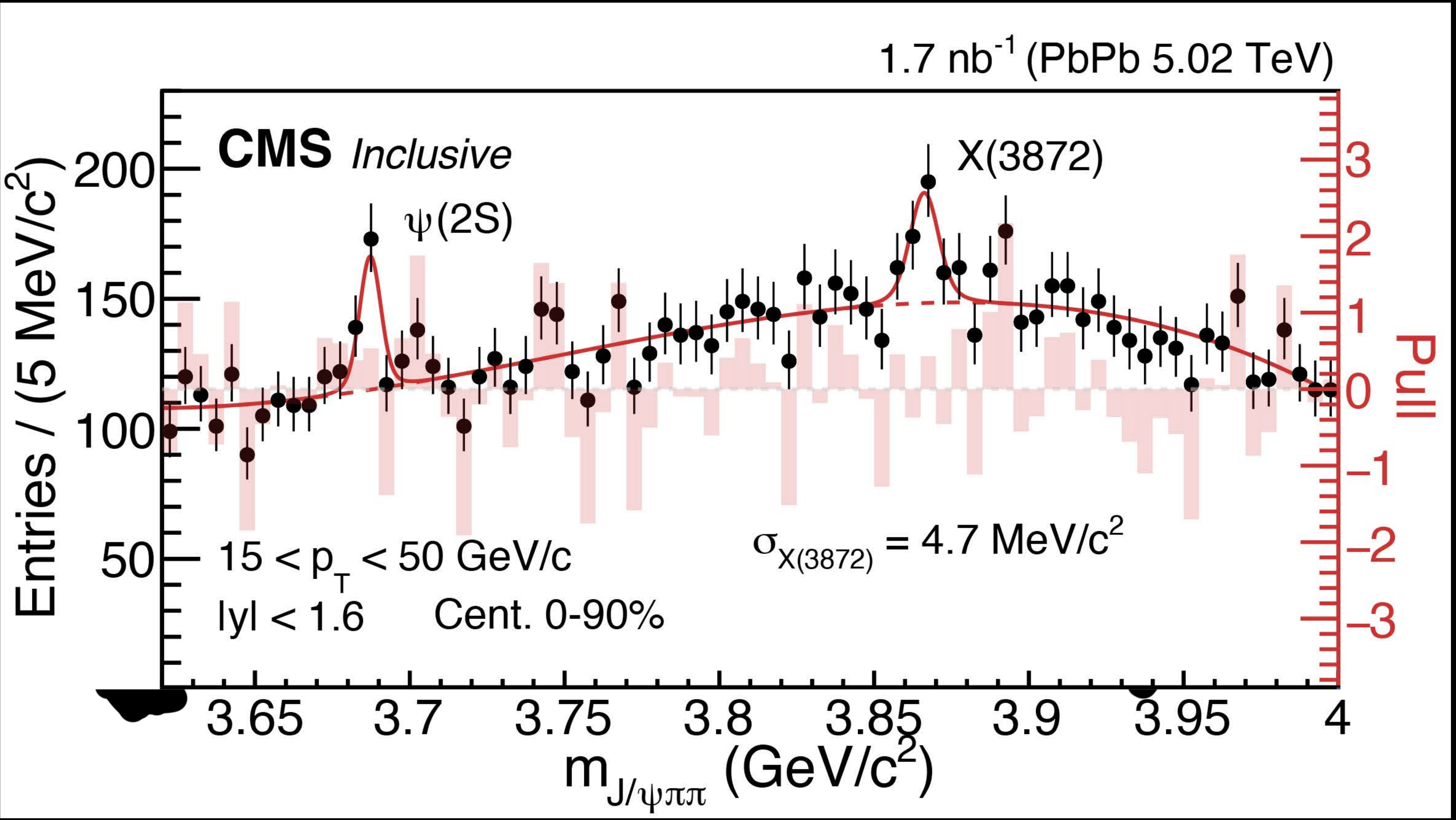


PLB 590 (2004) 209

Hybrid

EPJA 47 (2011) 101

PRL 128 (2022) 032001



First observation of X(3872) in heavy-ion collisions

Significance 4.2σ

Recall importance of coalescence (Puccio)

Unique point in time:

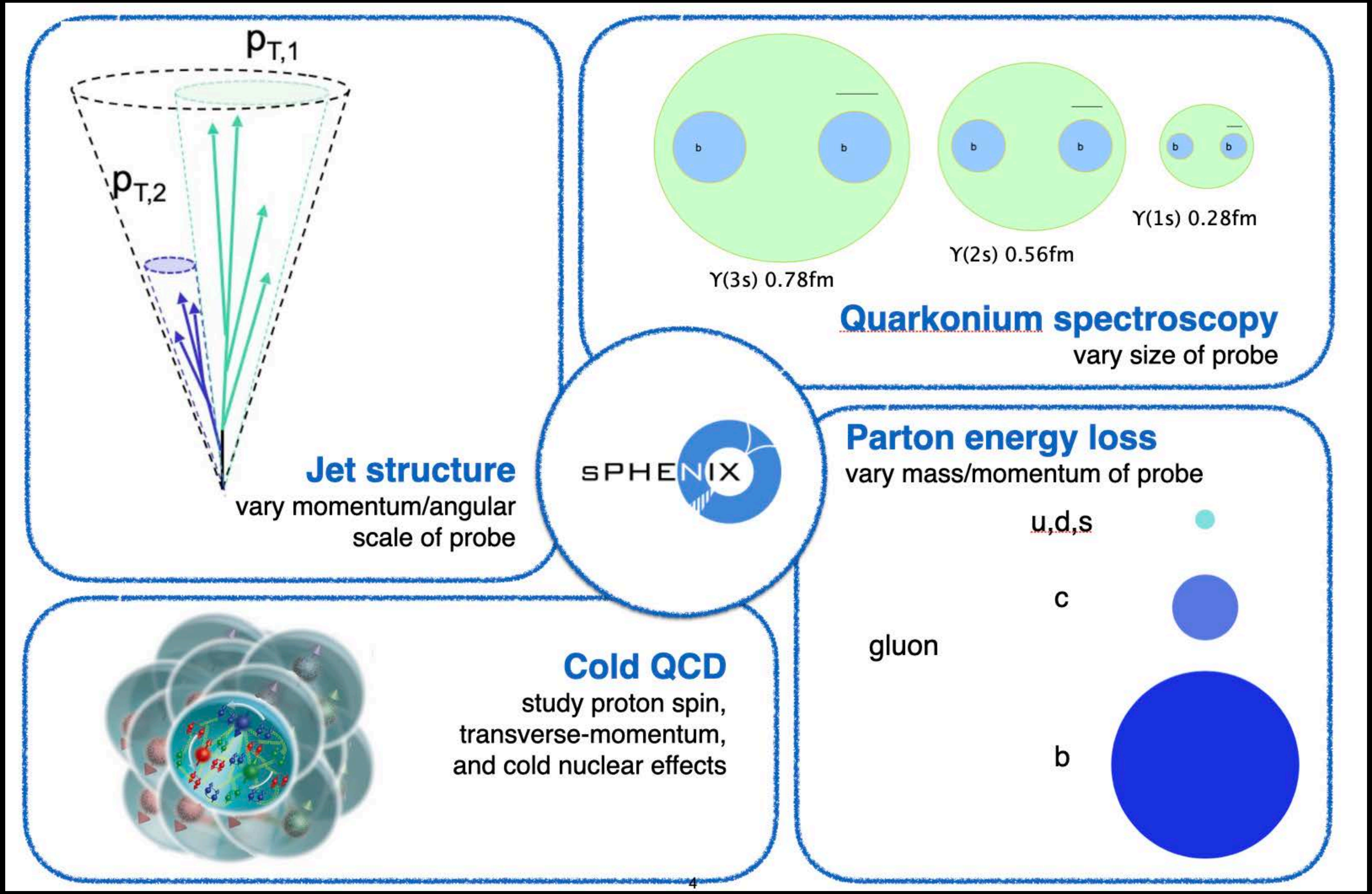
- Run 3 at LHC w/ major upgrades for ALICE, small upgrades for other experiments
- Run 24, 25 at RHIC, with new experiment, sPHENIX, and major upgrades for STAR

Will collect more heavy-ion data at LHC, RHIC from '23 to '26 than in the decade(s) prior!

Facility	**RHIC**	**LHC/HL-LHC**	**SppC / FCC-hh**
Timeline	→ 2025	→ 2041 (Runs 3 to 6)	> 2035 / > 2070
Collision system	pp, d-Au, Au-Au	pp, p-Pb and A-A (Pb-Pb, ^{16}O, ^{129}Xe, ^{84}Kr, ^{40}Ar, ...)	FCC: pp, p-A and A-A (Pb-Pb, ^{129}Xe, ^{84}Kr, ^{40}Ar, ...)
$\sqrt{s_{NN}}$ **(TeV)**	0.2	5.5	~39
Int. rate (kHZ)	~15 (Au-Au)	≳50 (x 3-4 in Run5) for Pb-Pb	~2500 (FCC)
Experiments	sPHENIX, STAR	ALICE, ATLAS, CMS, LHCb phase II of ATLAS and CMS **phase II-b of ALICE and LHCb**	up to four experiments

Luciano Musa, Quark Matter 2023, Houston

13 countries
80 institutions
350 collaborators



Detector design, computing effort and run schedule focussed on these goals

RHIC IR8 in 2016: PHENIX

RHIC IR8 in 2018

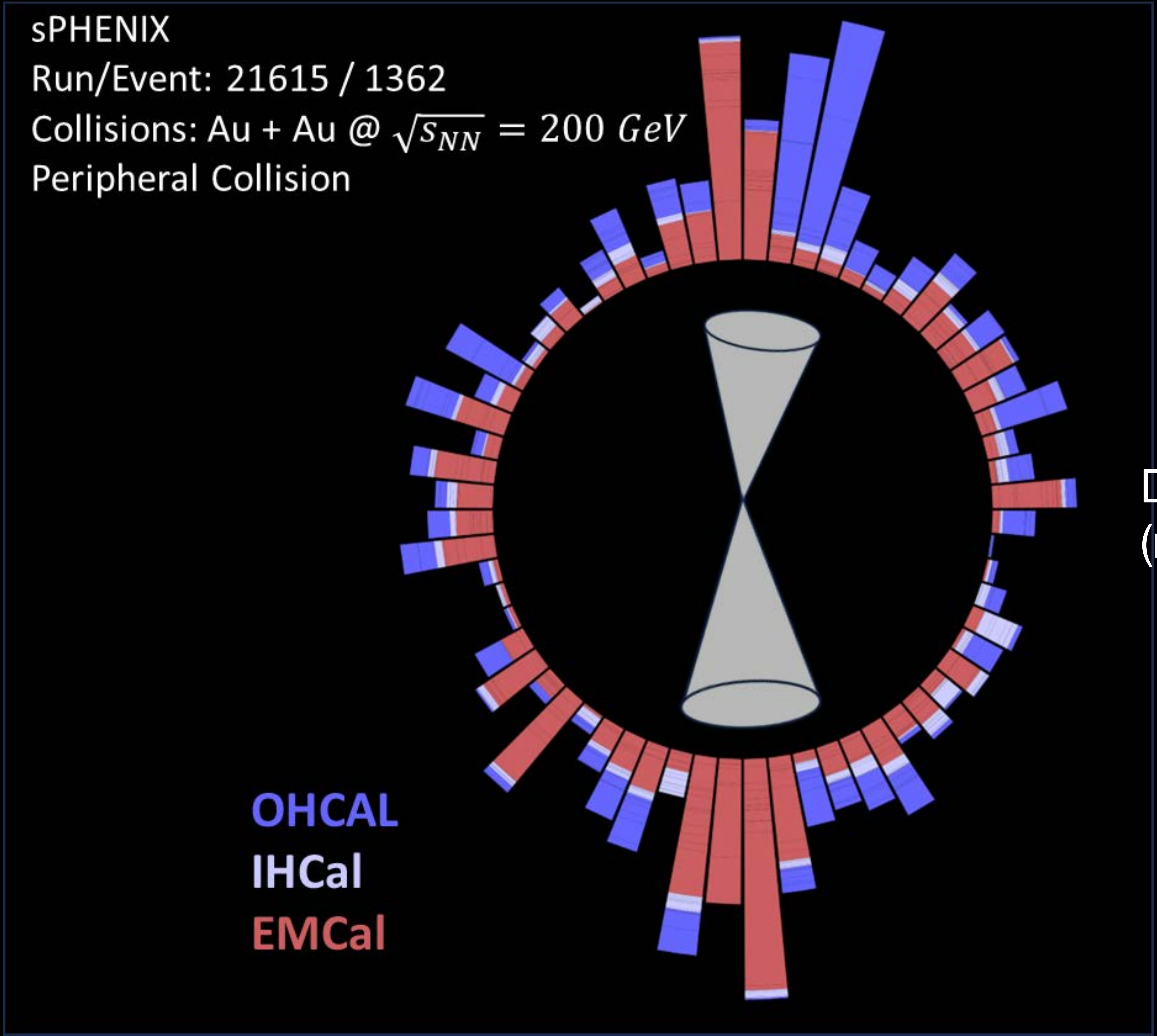
RHIC IR8 in April 2023: sPHENIX


oHCAL
MAGNET
iHCAL
EMCAL
sEPD
TPC
MVTX
INTT
MinBIAS
TPOT
sPHENIX

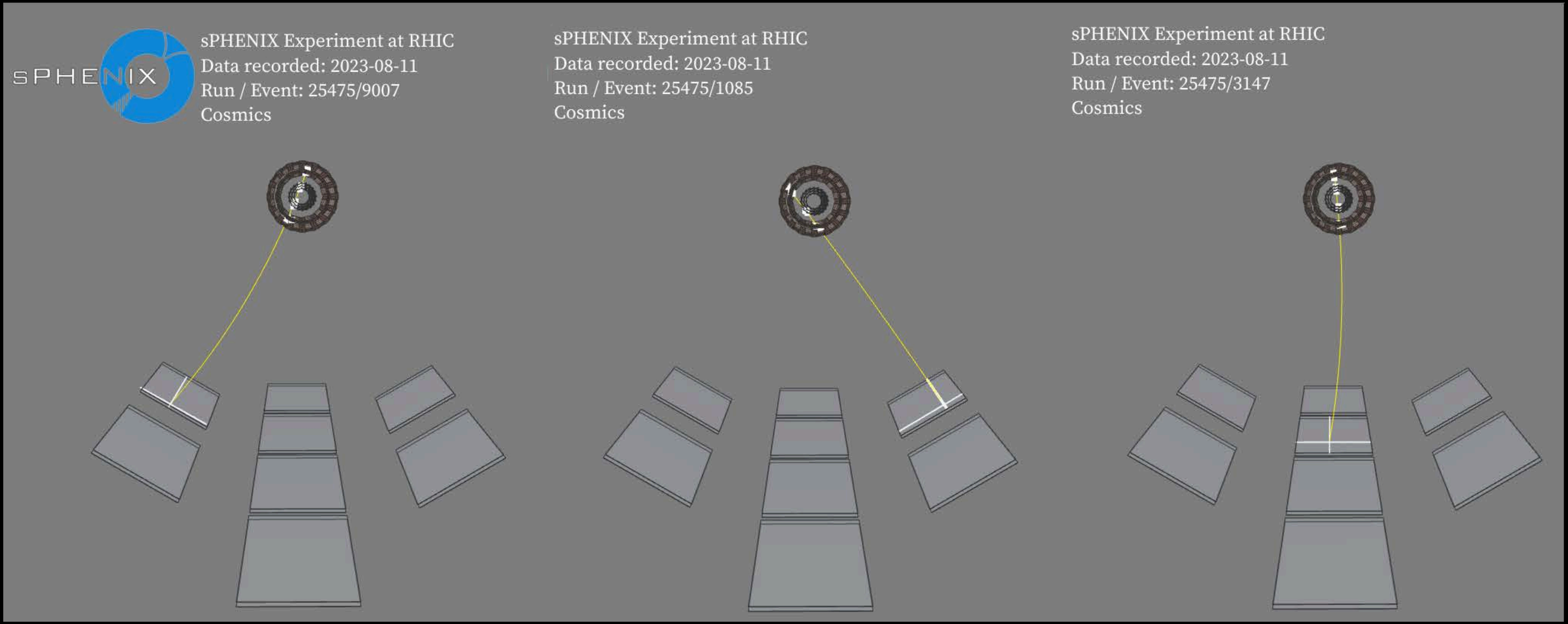

First hadronic calorimeter at RHIC for jet measurements
oHCAL
MAGNET
1.4T Superconducting solenoid
iHCAL
EMCAL
sEPD
TPC
MVTX
INTT
SRO tracker (MVTX, INTT, TPC)
MinBIAS
State of the art 3-layer MAPS micro vertex detector
TPOT
sPHENIX

Time Projection chamber

Central Au+Au collision at $\sqrt{s_{NN}} = 200$ GeV



Dijet event in calorimeter system
(no background subtraction)



Matching of cosmic ray muon tracks from inner silicon detectors to microMega TPC outer tracker → essential tool for correction of TPC space charge distortions

What is this?

IR8 DX magnet “splice can” after 7/31/2023 magnet quench

n.b. energy stored in RHIC magnets at full field is ~130 MJ

RHIC and sPHENIX will be back:

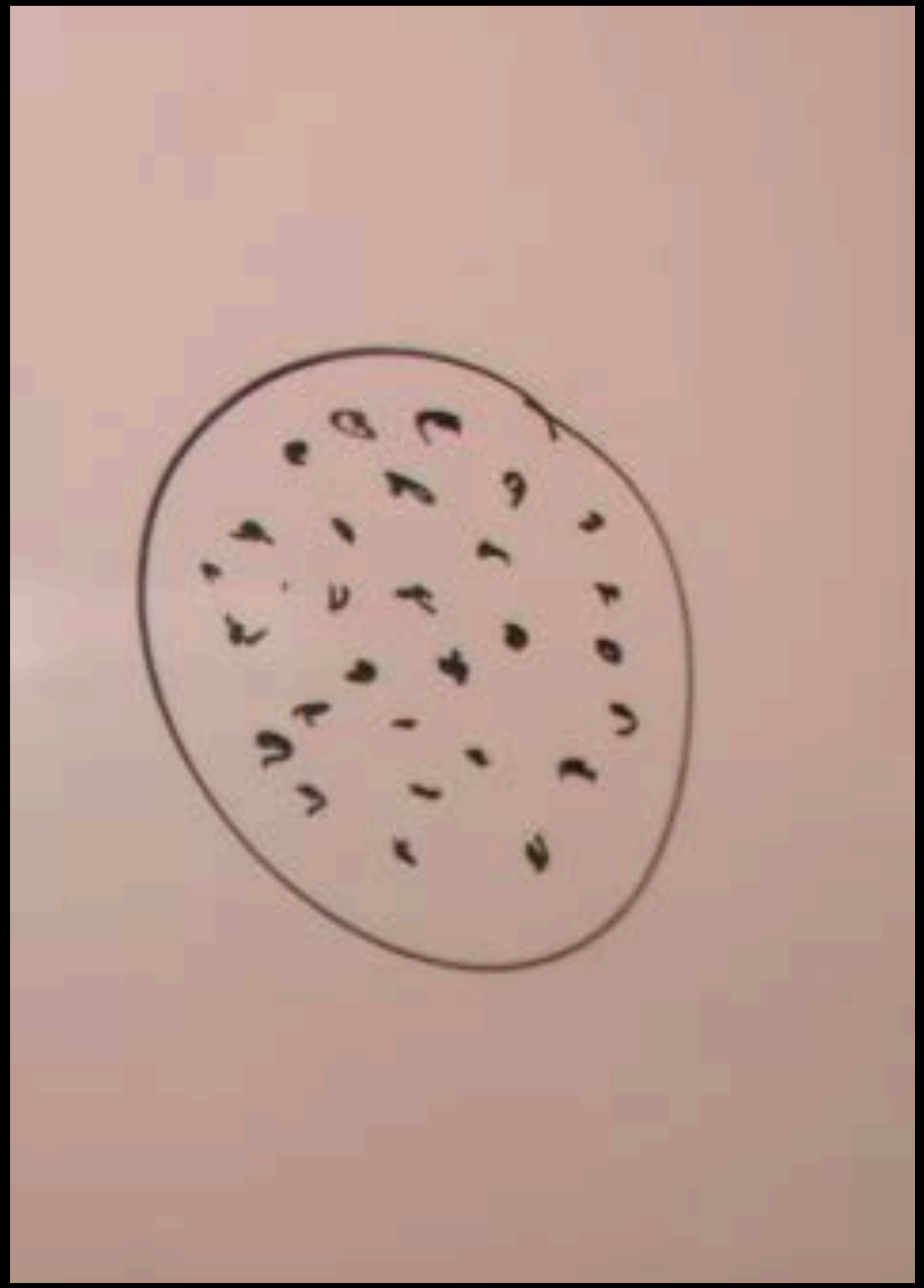
Repairs are essentially completed

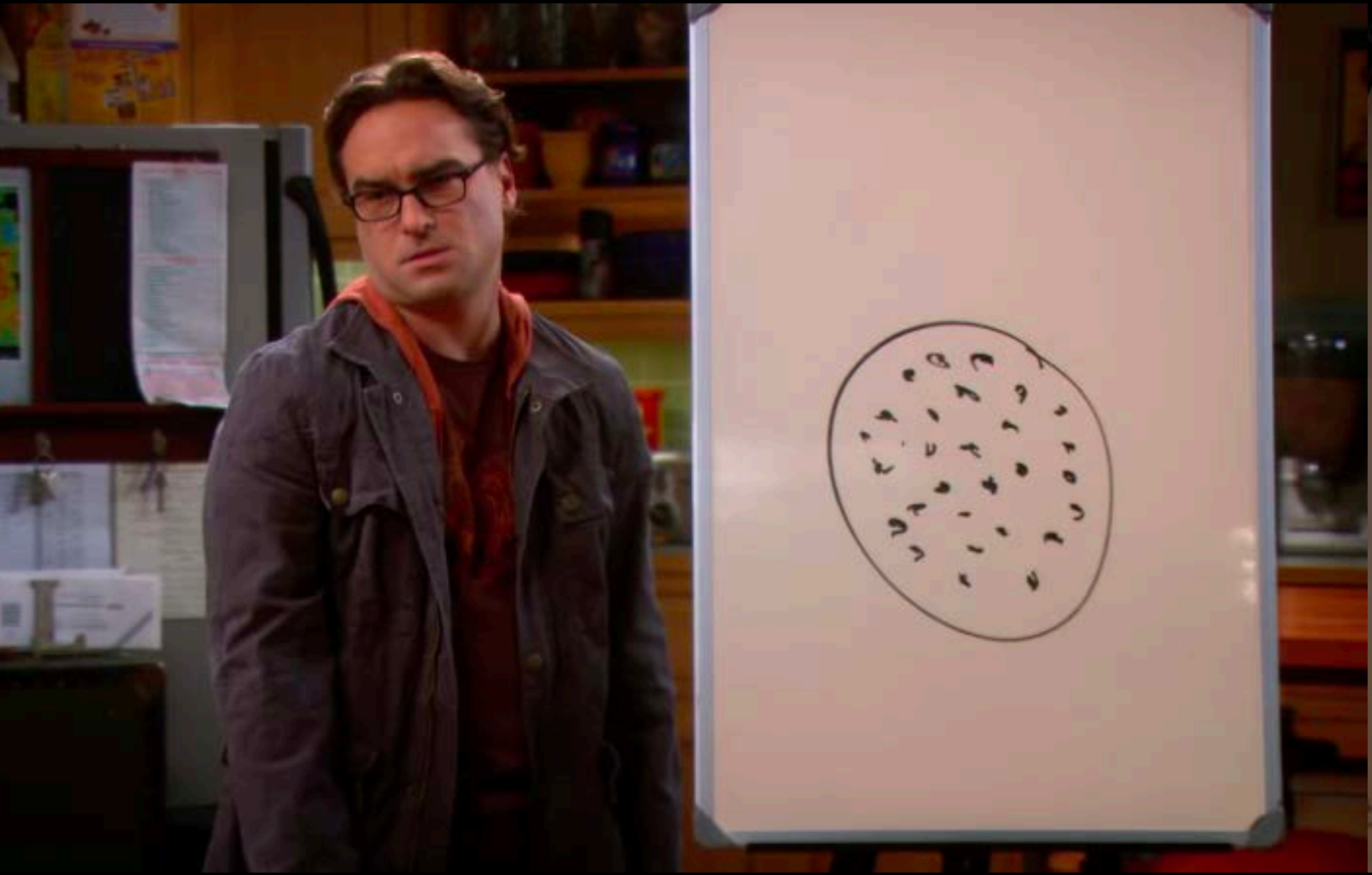
RHIC run 24 scheduled to begin mid-April
sPHENIX expects to collect 45/pb p+p data at $\sqrt{s} = 200$ GeV

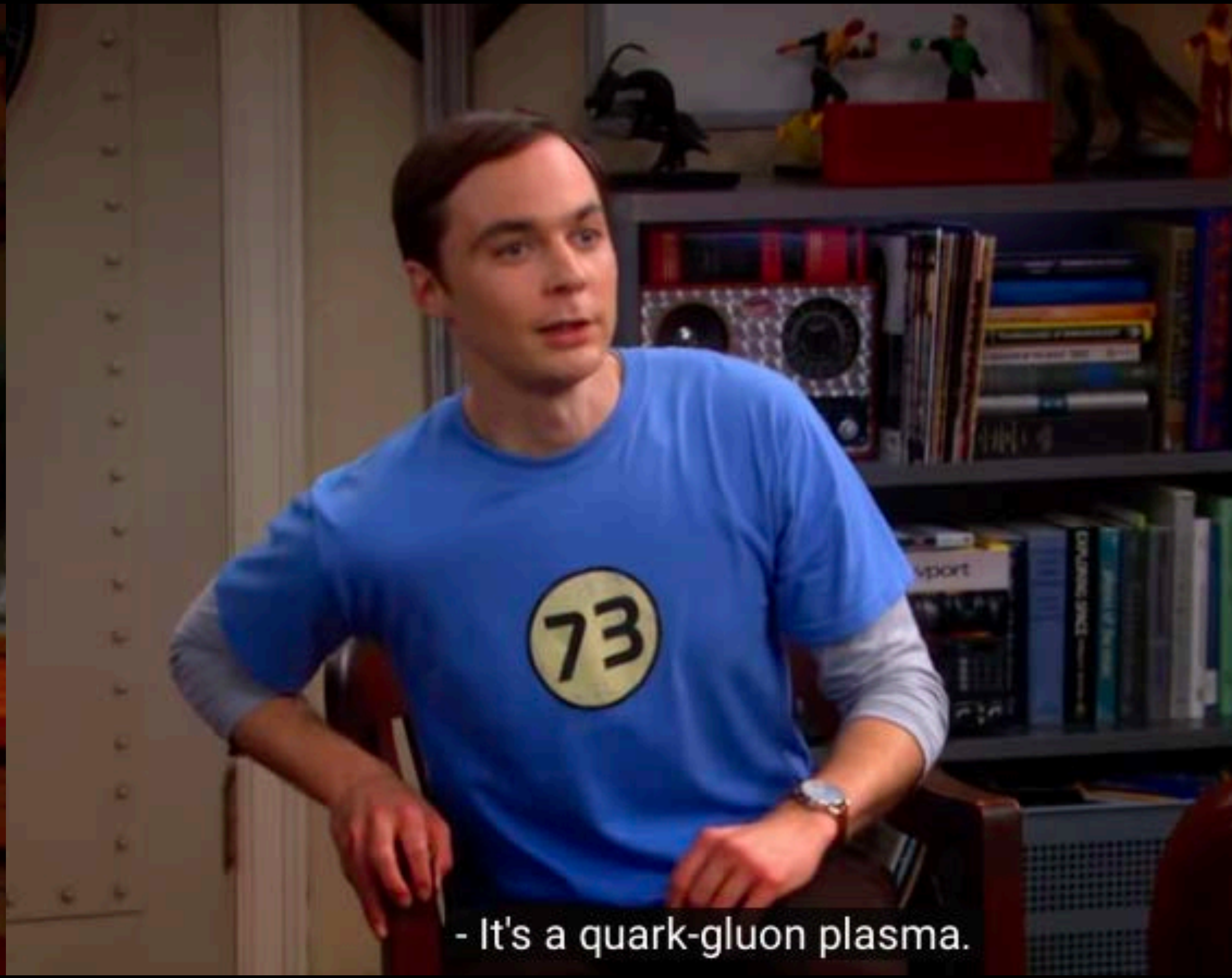
RHIC run 25 will begin in early 2025
sPHENIX goal is to collect > 6/nb of Au+Au data at $\sqrt{s} = 200$ GeV

STAR will also take data with significantly improved DAQ (5kHz) and detector upgrades (inner TPC, forward upgrade) seeing first Au+Au data

Quiz: What is this?






73
- It's a quark-gluon plasma.

- Experiments continue to demonstrate surprising transport properties of QGP
- Combined effort and new techniques allow extraction of key transport coefficients with increasing precisions
- Next years at RHIC and LHC will see vast increase in experimental precision
  - will allow fine tuning of existing models
  - high likelihood that new observables will challenge current theoretical approaches