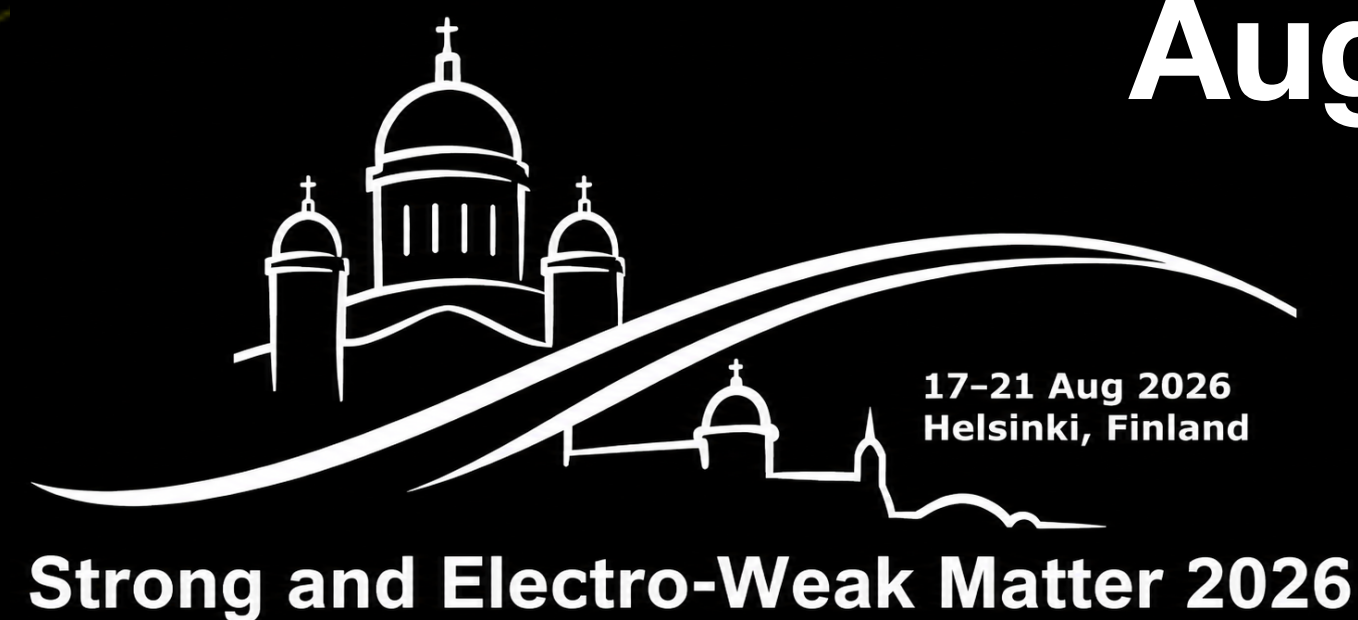
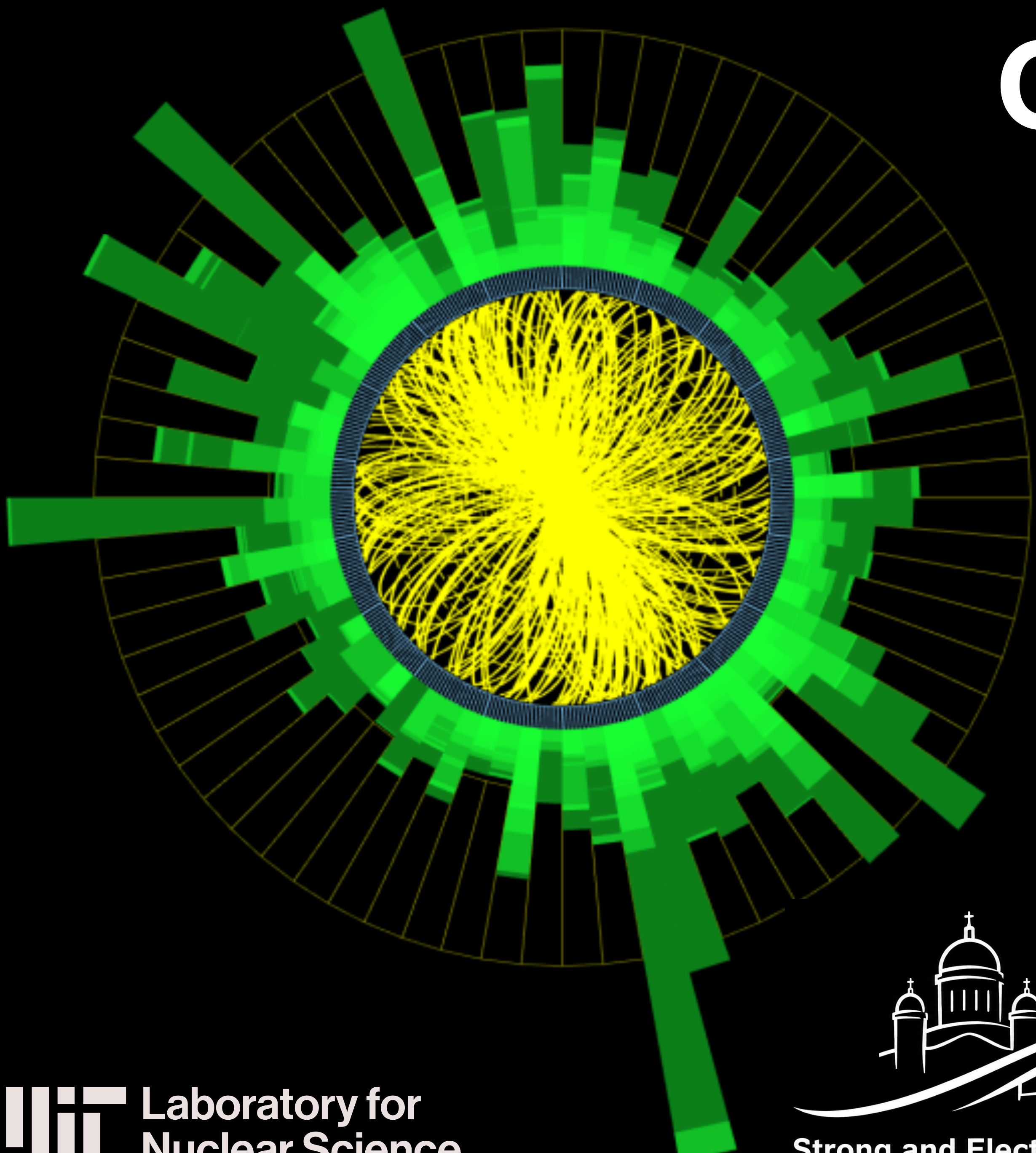


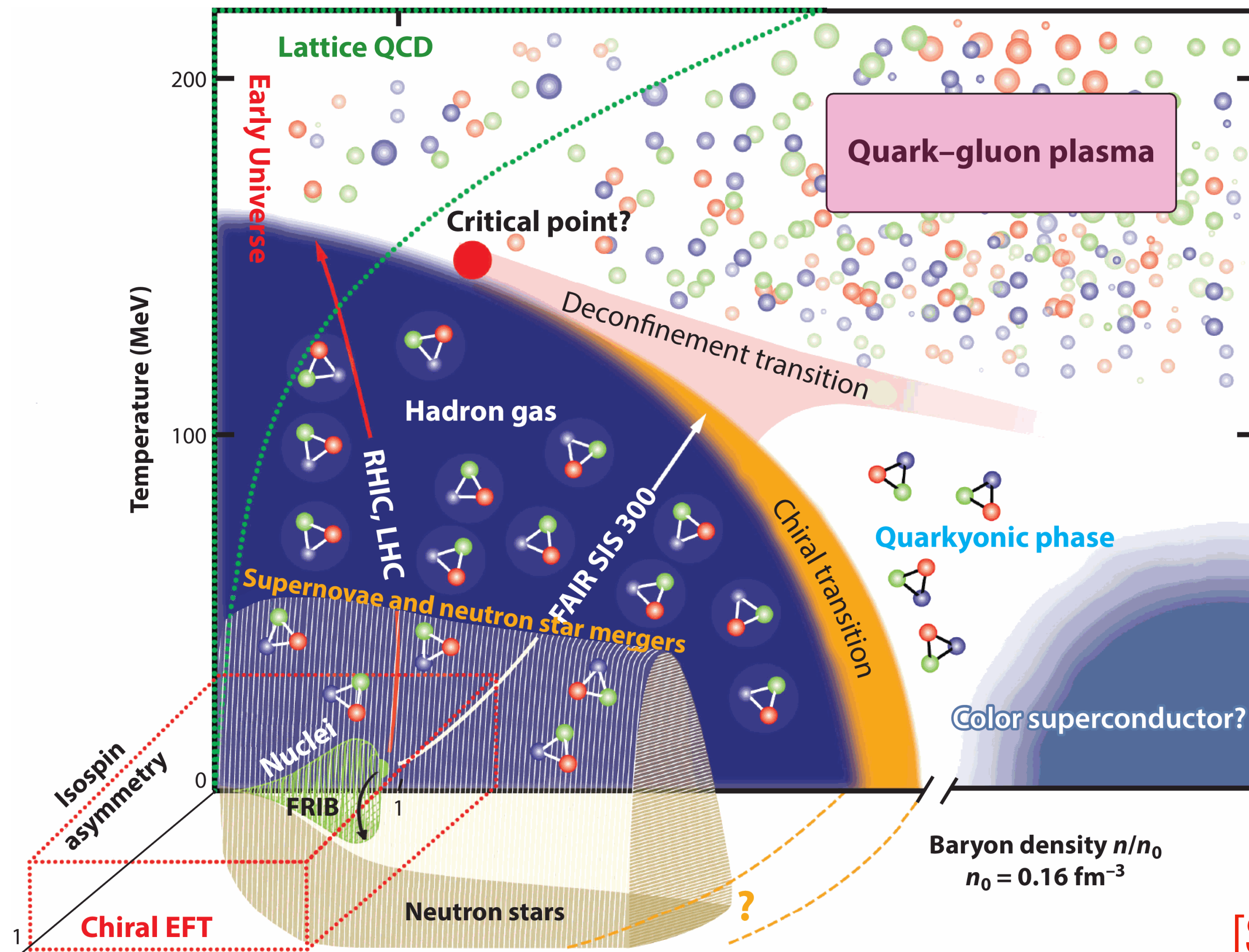
Overview of recent experimental progress in inferring QGP properties

Hannah Bossi (MIT)
Strong and Electroweak Matter
Helsinki, Finland
August 17th, 2026



PHASE DIAGRAM OF STRONGLY INTERACTING MATTER

[Ann. Rev. Nucl. Part. Sci. 71 (2021)]



- Strongly interacting matter has a complex phase diagram full of interesting phenomena!

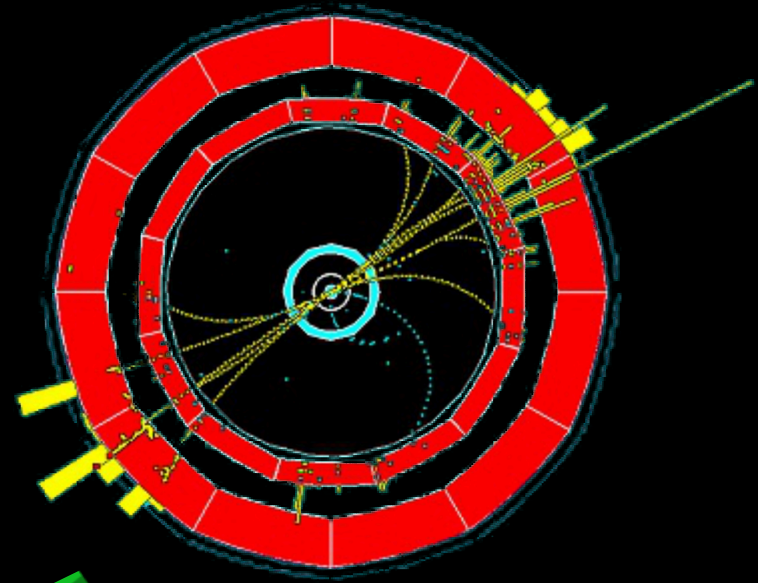
- Throughout this conference, we will explore this phase diagram as well as how the pieces fit together!

This Talk: Experimental perspective of the Quark-Gluon plasma

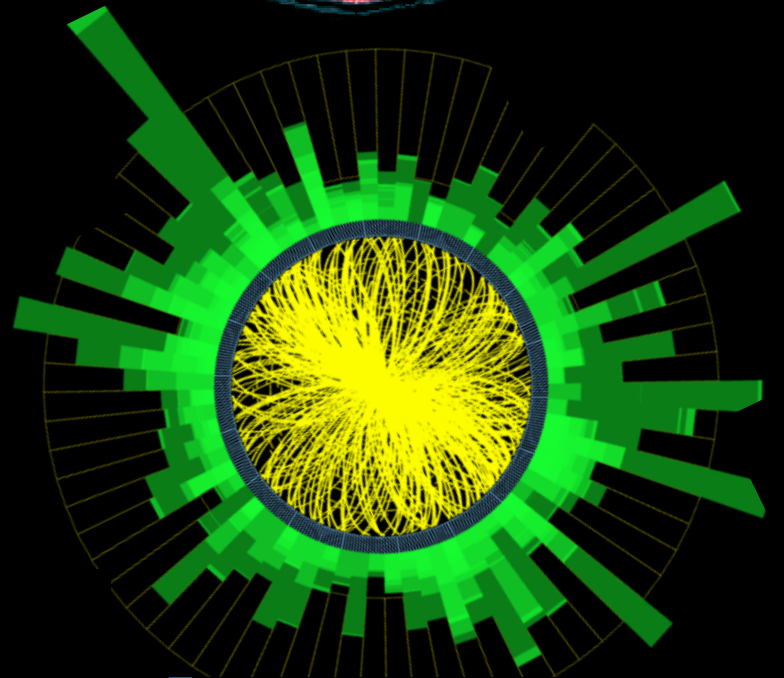
[See Dana Avramescu's Talk Mon. 09:00]

What we will talk about today

I won't dive into the experimental details! Goal is to give a sense of the big picture!

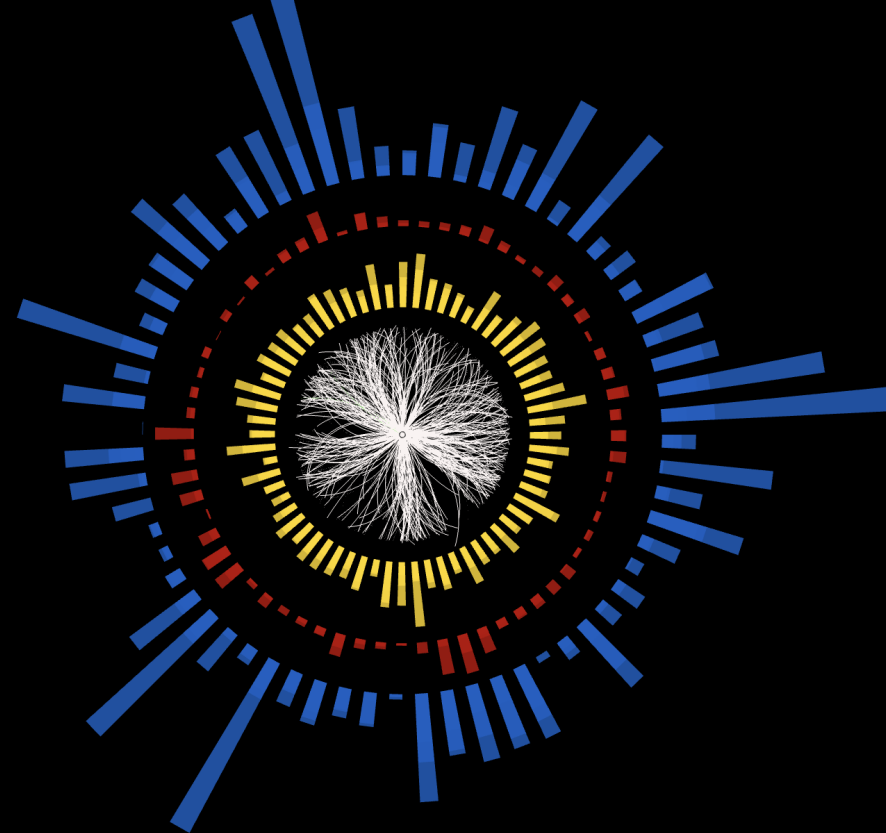


Part 1 : What is the QGP? How do we study it?



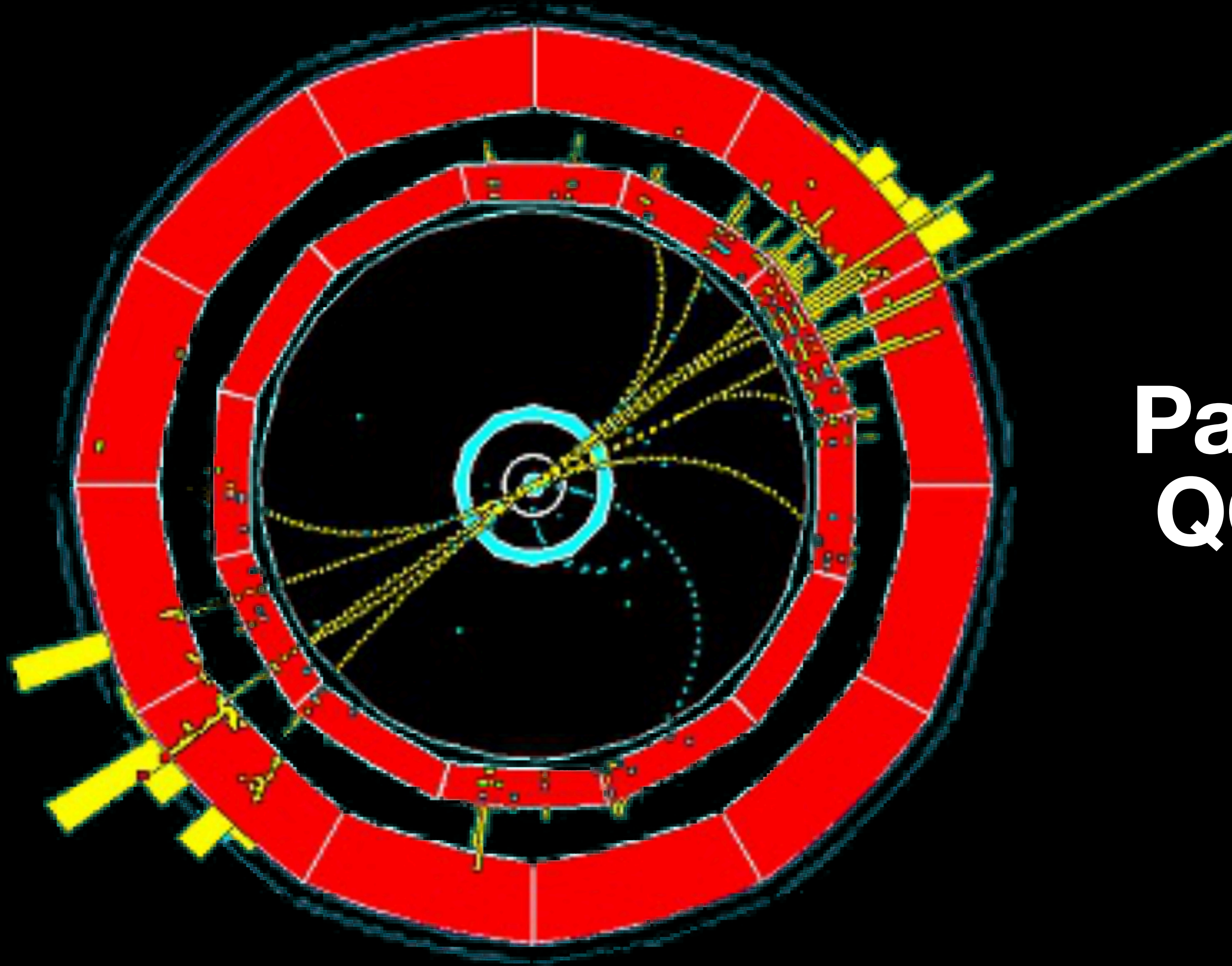
Part 2 : What have we learned about the QGP and its properties?

** lots I don't have time for, bias towards new & big picture things*



Part 3 : What will we do in the future?

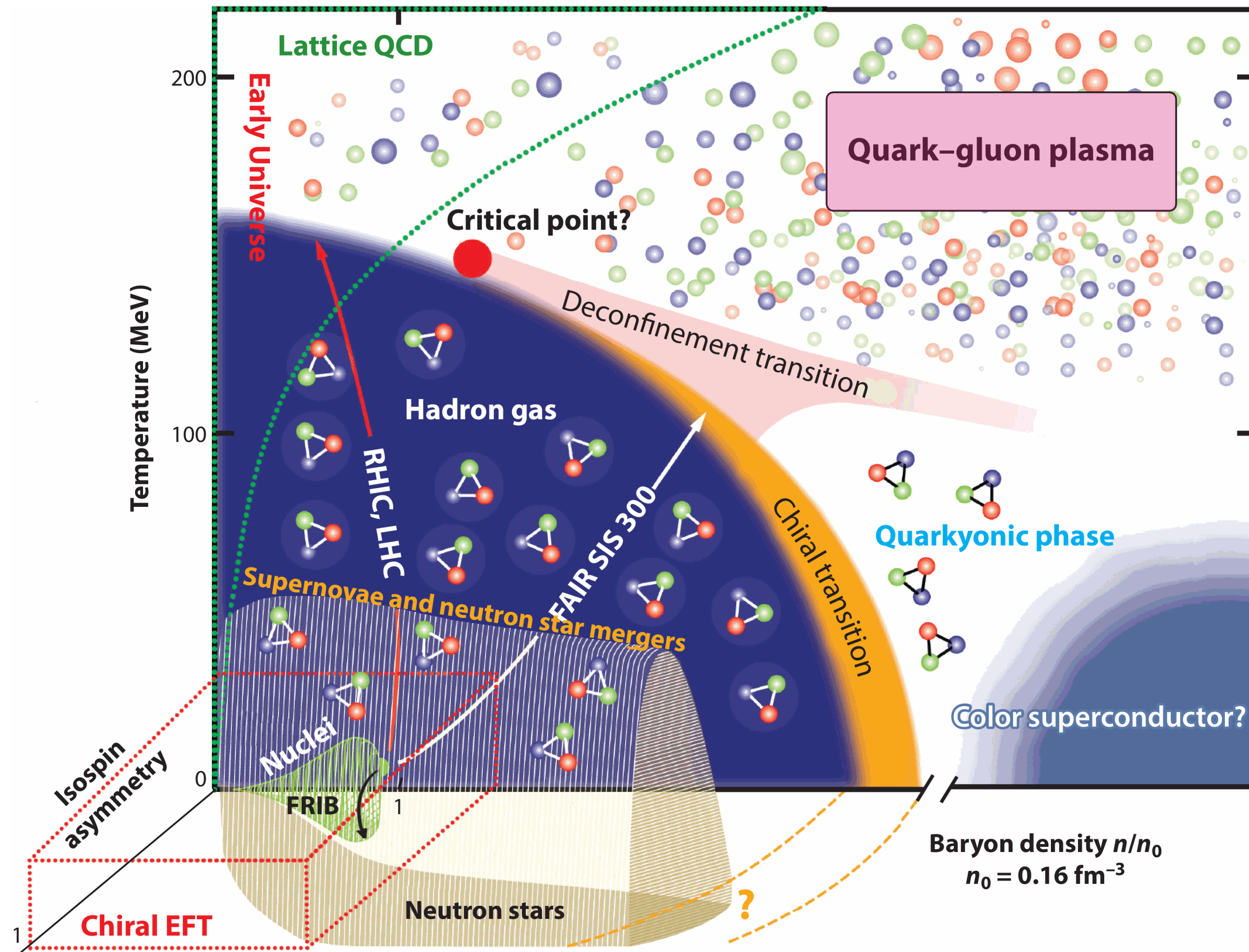
** what we've learned in blue * open questions/future directions in orange*



Part 1 : What is the QGP? How do we study it?

THE QUARK-GLUON PLASMA

[Ann. Rev. Nucl. Part. Sci. 71 (2021)]



- When QCD matter reaches sufficiently high temperatures it becomes a deconfined state of quarks and gluons called the **Quark-Gluon Plasma (QGP)**.
- Lattice QCD predicts a smooth crossover at $\mu_B = 0$ and $T_c \sim 150 \text{ MeV}$ ($\sim 10^{12} \text{ K}$).
 - 250,000 times hotter than the core of the sun
- Similar conditions thought to have existed **just a few μs after Big Bang**.

QUESTIONS TO ANSWER BY STUDYING THE QGP

What happens to QCD when we release the confinement potential?

What are the intrinsic and dynamical properties of the QGP medium? What is its quasiparticle structure? How do these features give rise to its behavior?

How are fundamental QCD processes like the parton evolution and hadronization modified in the QGP?

What is the equation of state of QCD matter? Does the QCD phase diagram have a critical point? If so, where?

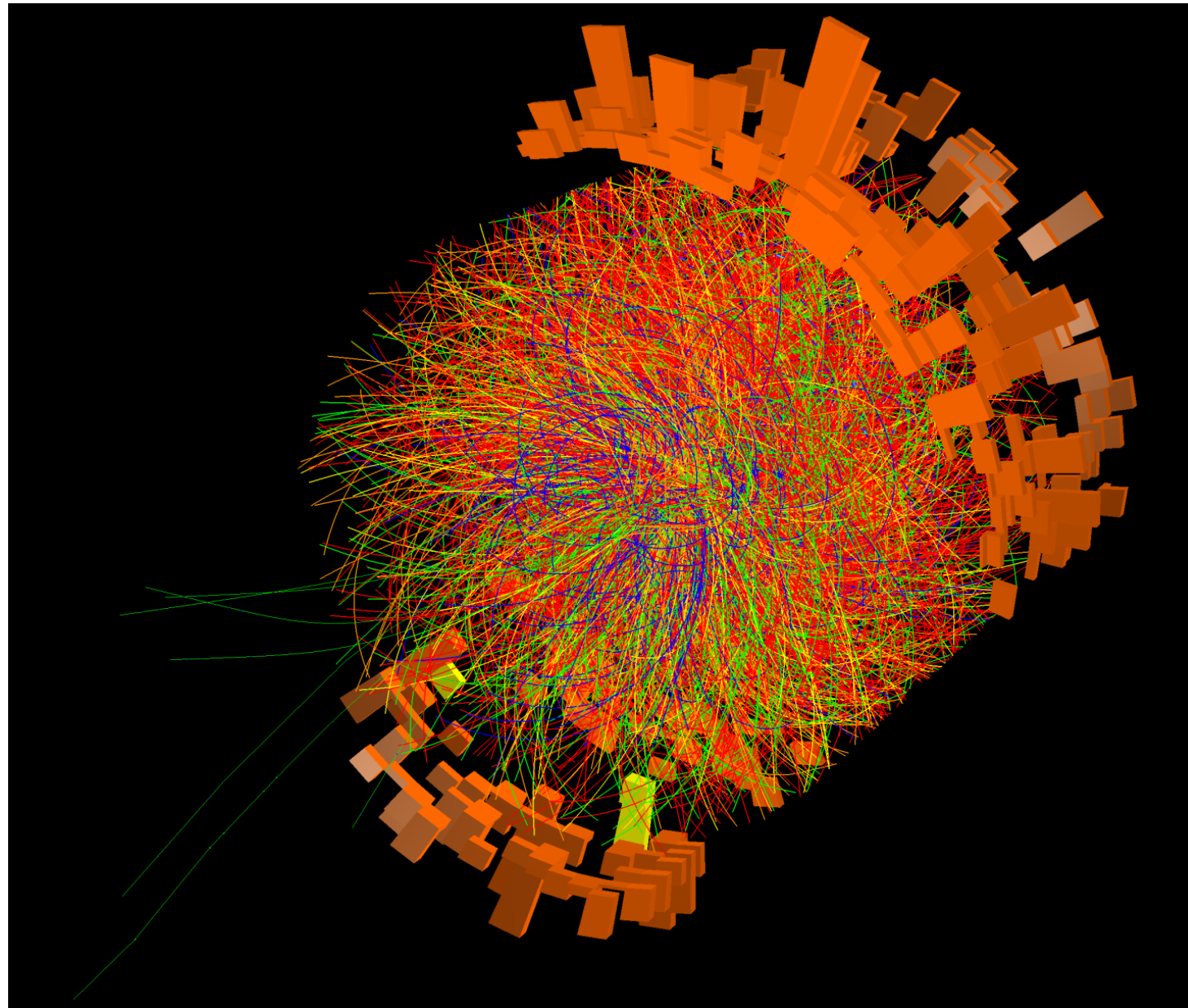
How does the QCD matter in these extreme conditions become confined into hadronic matter?

We need combination of theory + experiment to answer all of these questions!

[Heavy Ion Collisions: The Big Picture, and the Big Questions, Wit Busza, Krishna Rajagopal, Wilke van der Schee]

THE QGP IN THE LAB

- Since we can't revisit the early universe, instead we recreate these extreme conditions with the collisions of ultra relativistic heavy ions.



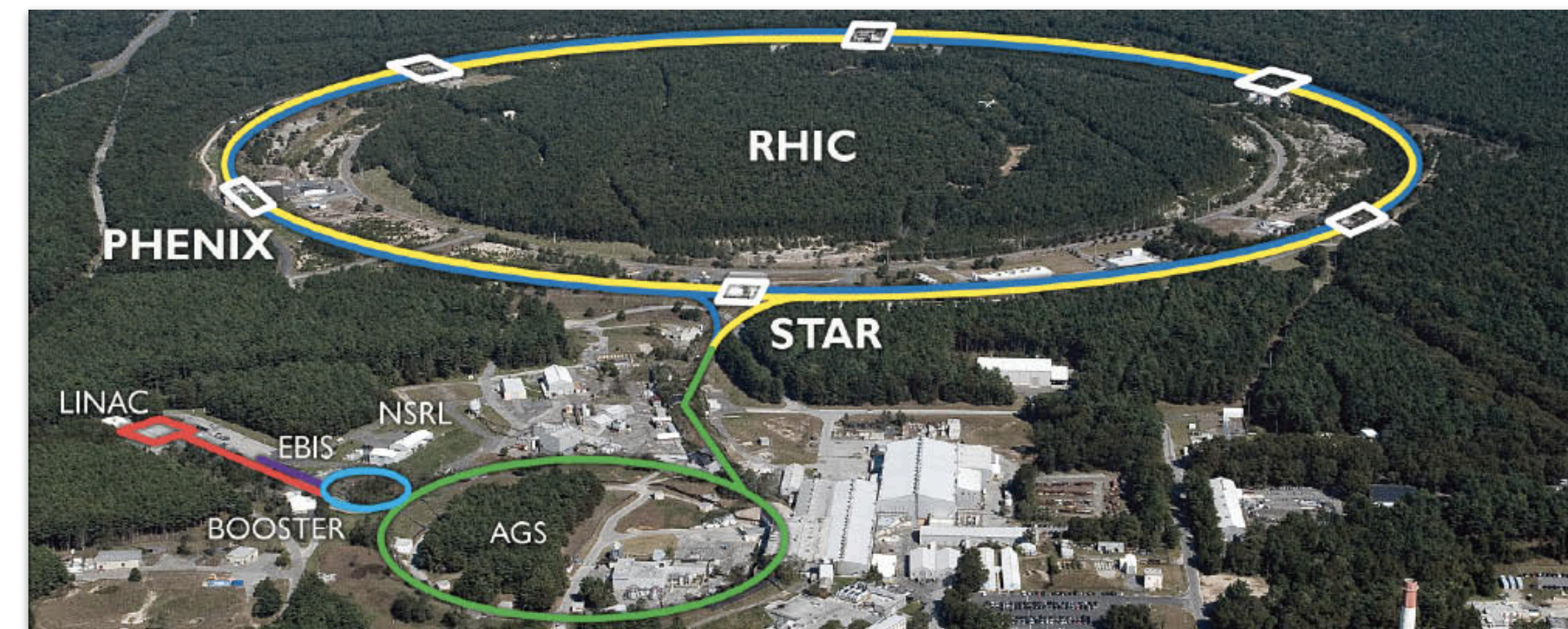
Heavy-ion collisions are a very experimentally complex & challenging environment -
like smashing two Swiss watches together to see how they work!

EXPERIMENTAL FACILITIES

Two complementary machines!



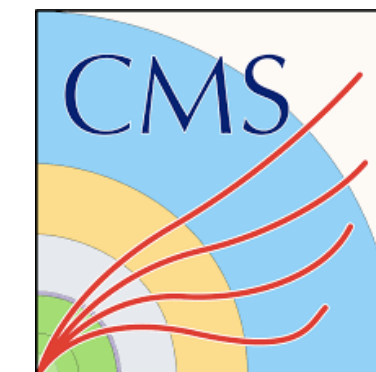
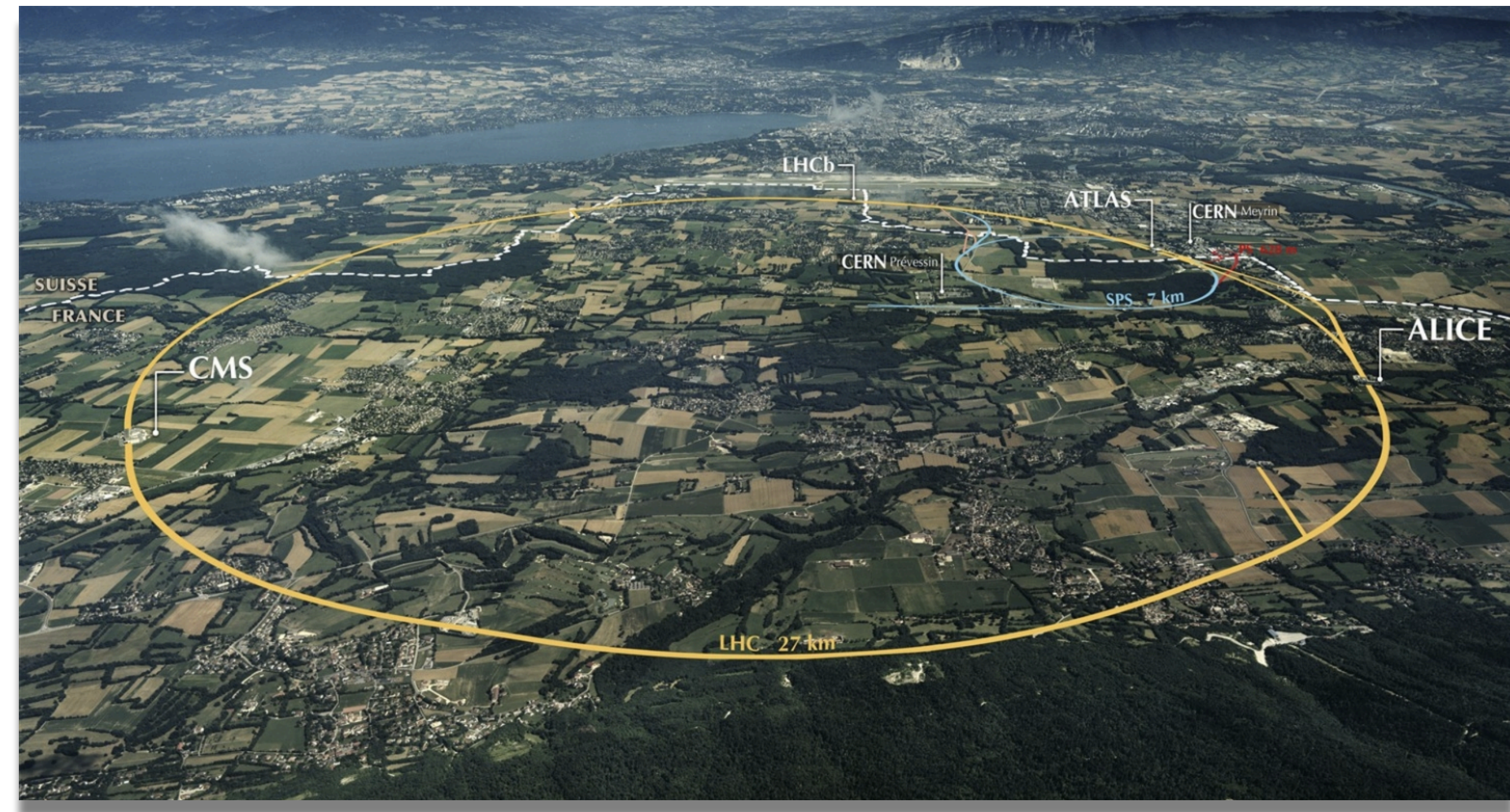
Relativistic Heavy-Ion Collider (RHIC)



- **RHIC** ($\sqrt{s} \sim 100 \text{ GeV}$), more flexible (more species + energies), polarized beams.



Large Hadron Collider (LHC)

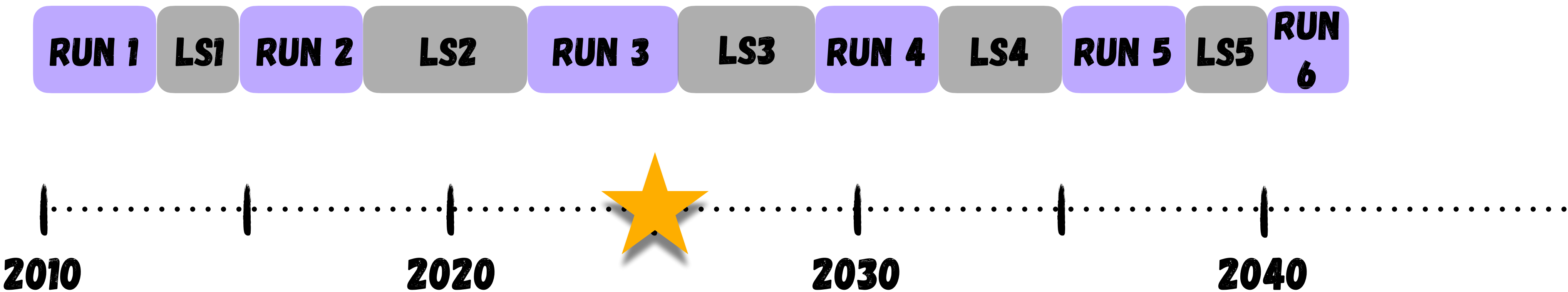


- **LHC** ($\sqrt{s} \sim 10 \text{ TeV}$), high energies, focus on proton-proton running, also heavy ion program

WHERE ARE WE NOW?



LARGE HADRON COLLIDER



RELATIVISTIC HEAVY ION COLLIDER



We've had a very busy last few years!

RECENT HIGHLIGHTS

First-ever collisions of oxygen at the LHC

The Large Hadron Collider gets a breath of fresh air as it collides beams of protons and oxygen ions for the very first time. Oxygen–oxygen and neon–neon collisions are also on the menu of the next few days

1 JULY, 2025 | By Anaïs Schaeffer

[\[CERN News, July 2025\]](#)

Relativistic Heavy Ion Collider (RHIC) Enters 25th and Final Run

Collisions of gold ions and other experiments will complete the RHIC science program and provide crucial insights for the future Electron-Ion Collider (EIC)

March 24, 2025

[\[BNL Newsroom, March 2025\]](#)

Common theme: Lots of firsts at high intensity!

Heavy-ion run at the LHC begins

For the next 17 days, every minute counts to take lead–lead collision data

6 NOVEMBER, 2024 | By Chetna Krishna

[\[CERN News, November 2024\]](#)

TOPIC: Accelerators

Accelerator Report: The 2026 run will be short but intense

Every day counts, so the LHC operations teams have mapped out a precise sequence of running phases to maximise the physics output during the machine's final months

Written by: Bettina Mikulec, Leader of the Operations Group (BE-OP)

12 March, 2026

[\[CERN News, Mar 2026\]](#)

First Physics Results from the sPHENIX Particle Detector

Measurements of charged particles and energy density from gold-gold smashups provide foundation for deep insight into early universe matter

July 17, 2025

[\[BNL Newsroom, July 2025\]](#)

IT'S THE END OF AN EXPERIMENTAL ERA

TOPIC: Accelerators

CERN bids farewell to the LHC and enters Long Shutdown 3

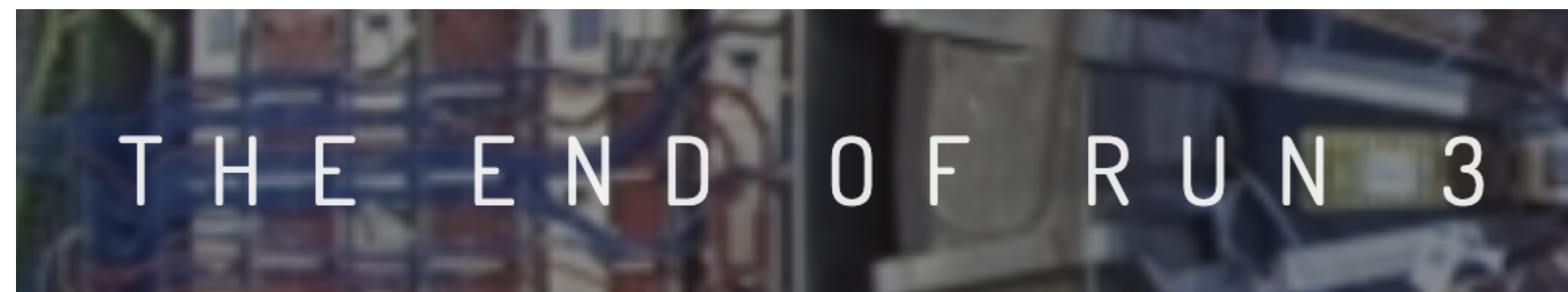
The Large Hadron Collider is embarking on its most ambitious upgrade yet

[\[CERN News, June 2026\]](#)

ATLAS enters the high-luminosity era

29 June 2026 | By [ATLAS Collaboration](#)

[\[ATLAS Press Statement, June 2026\]](#)



[\[CMS News, June 2026\]](#)

The last great U.S. particle collider is no more. What comes next could be even better

After 25 years, Brookhaven National Laboratory's Relativistic Heavy Ion Collider—the U.S.'s largest and only particle collider—has ceased operations, but its science lives on

[\[Scientific American, Feb. 2026\]](#)

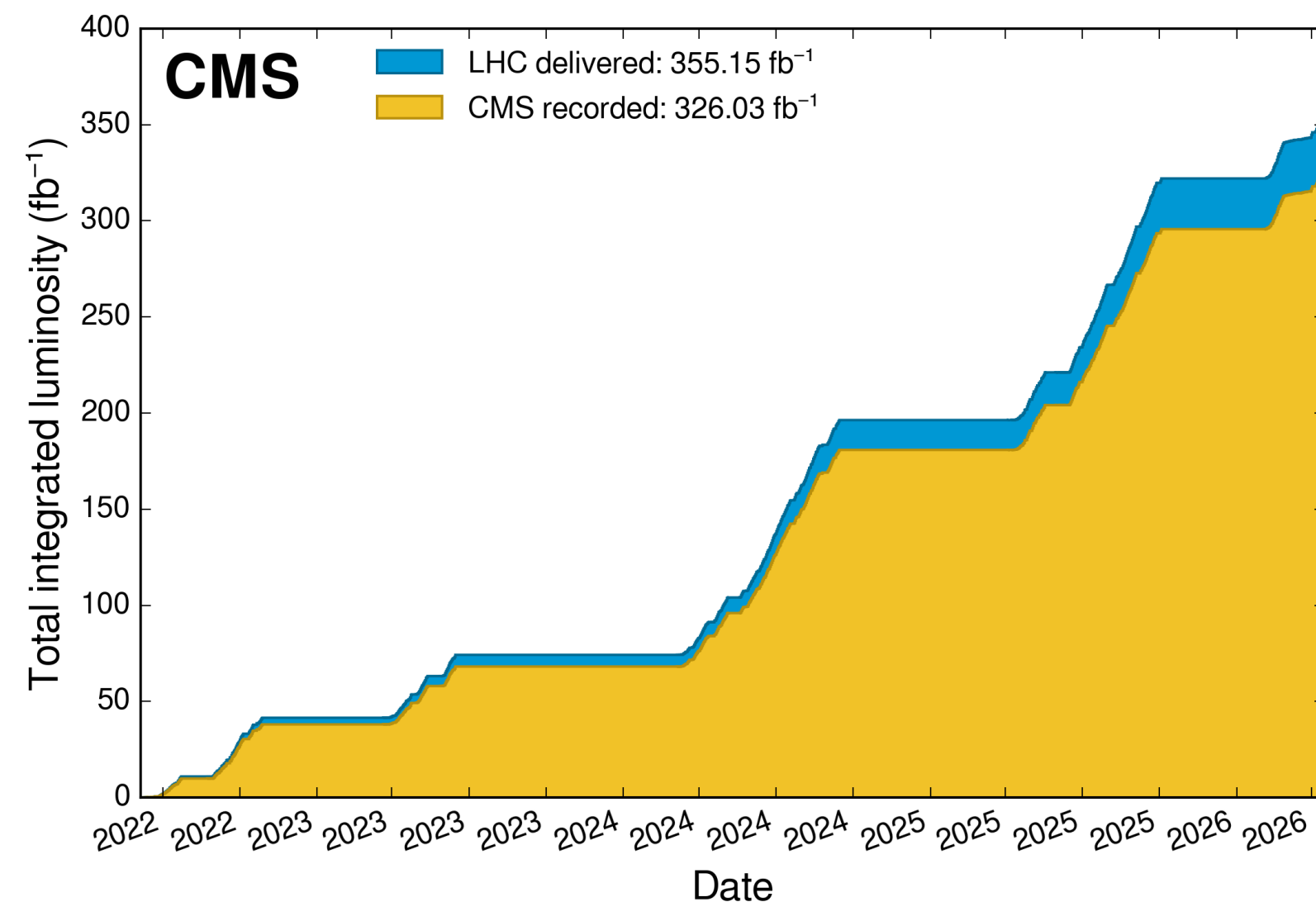


Last collisions at sPHENIX, February 6th

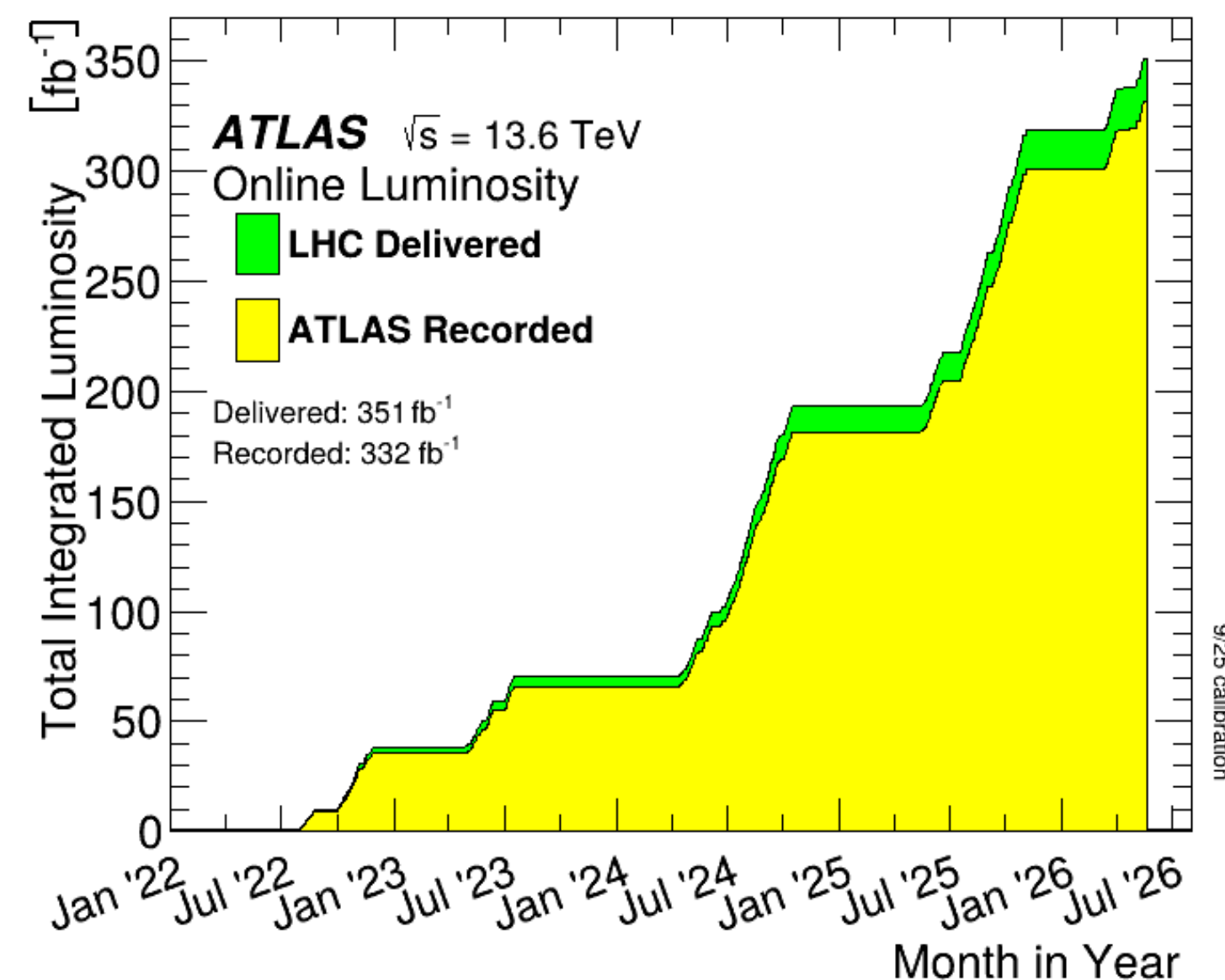
All data I will show in this talk was taken at colliders no longer operating. Will need to wait until 2030s for data from EIC & HL-LHC!

.... BUT WE HAVE A TREASURE TROVE OF DATA

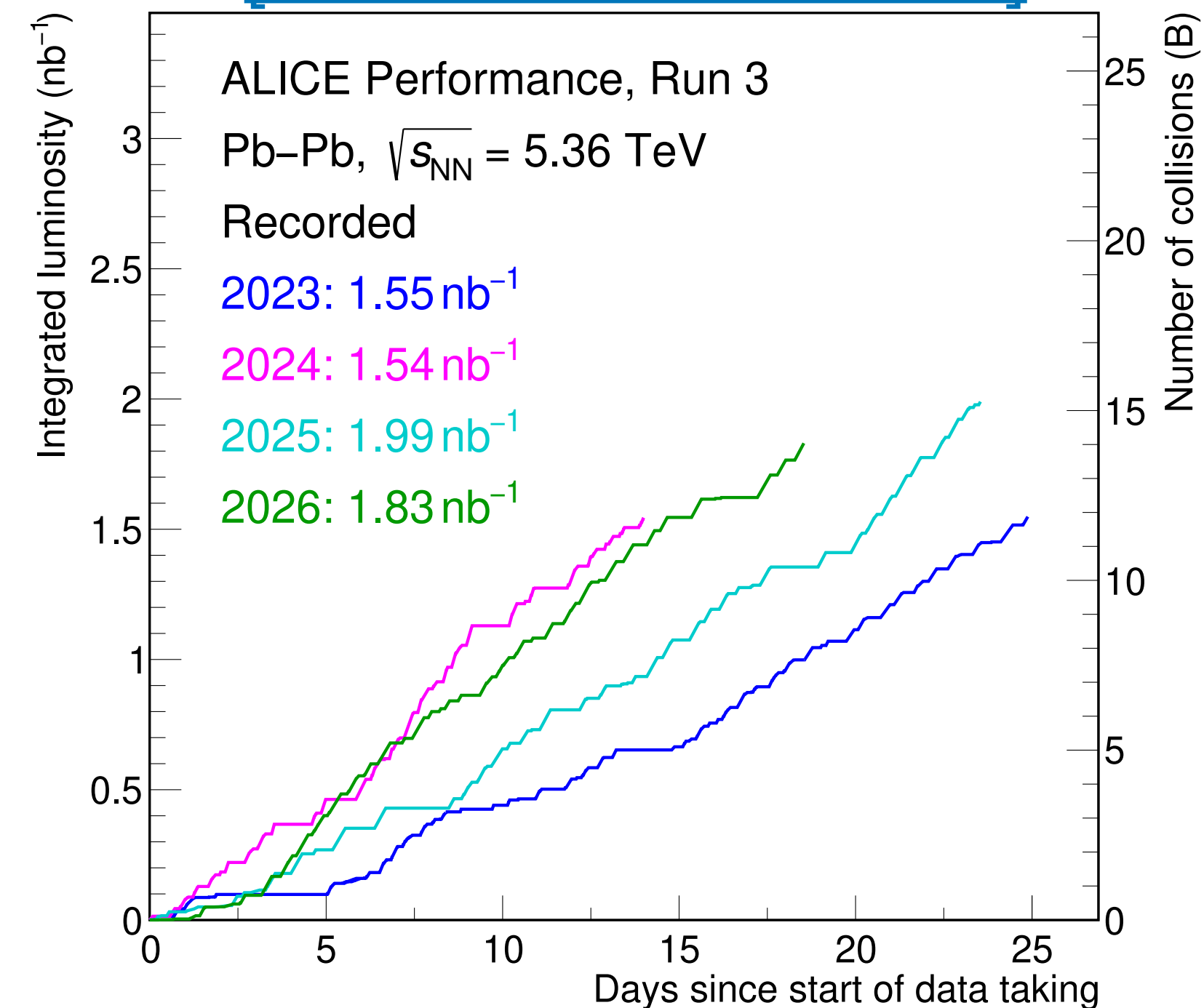
[CMS Public Lumi Totals]



[ATLAS Lumi Totals]

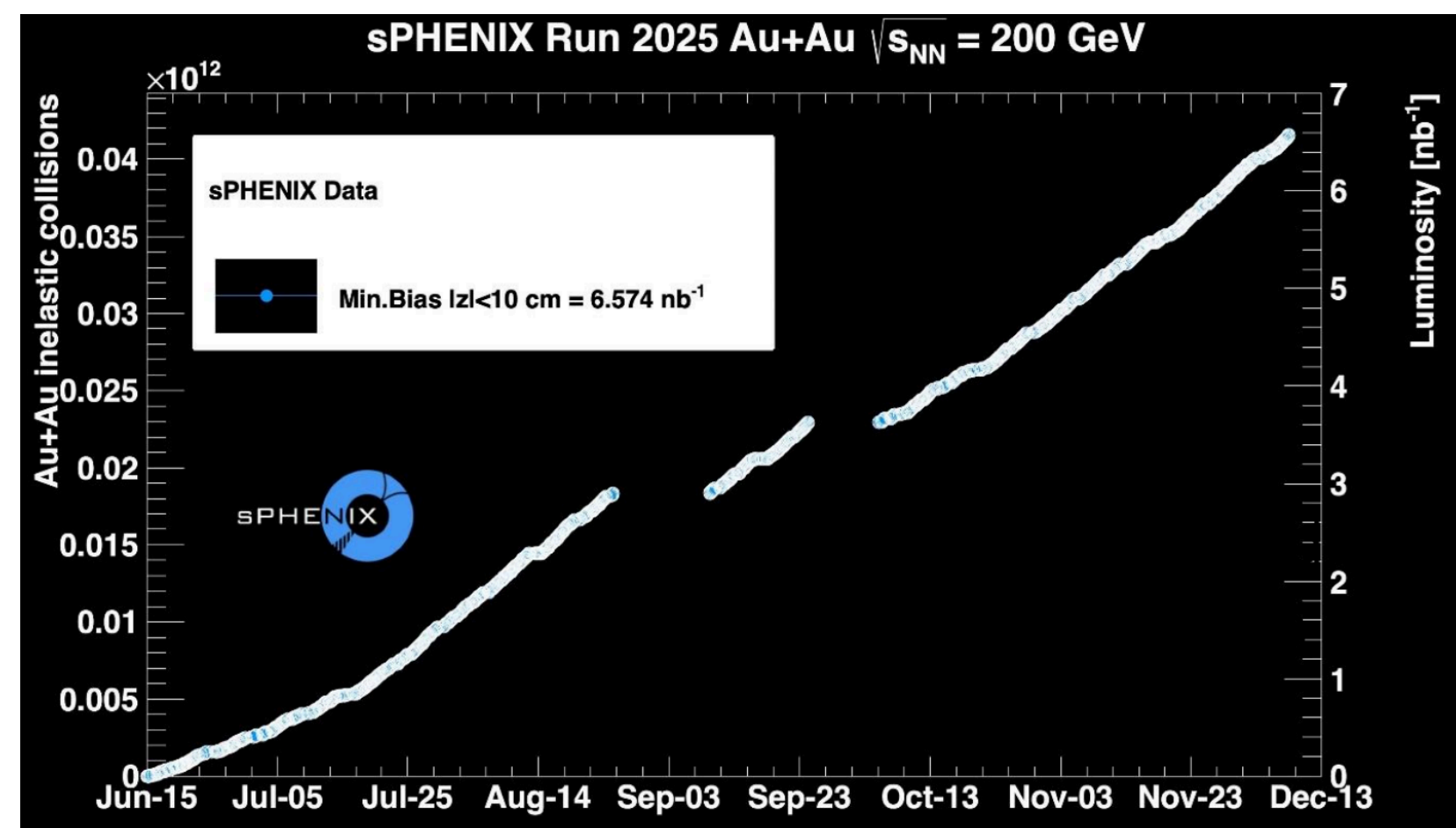


[ALICE Performance]



ALI-PERF-634120

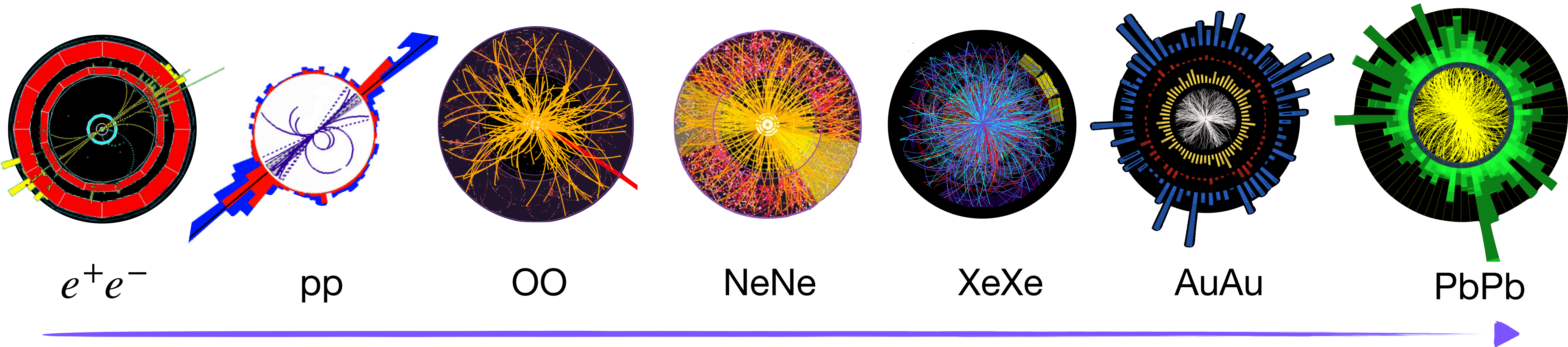
[sPHENIX Run 2025 Au total]



- Largest datasets to date.... by A LOT
- Only just now seeing the first few results from recently collected data at RHIC & LHC!!
- At the LHC only **~10-15% of total data we will collect**

... OVER MANY COLLISION SYSTEMS!

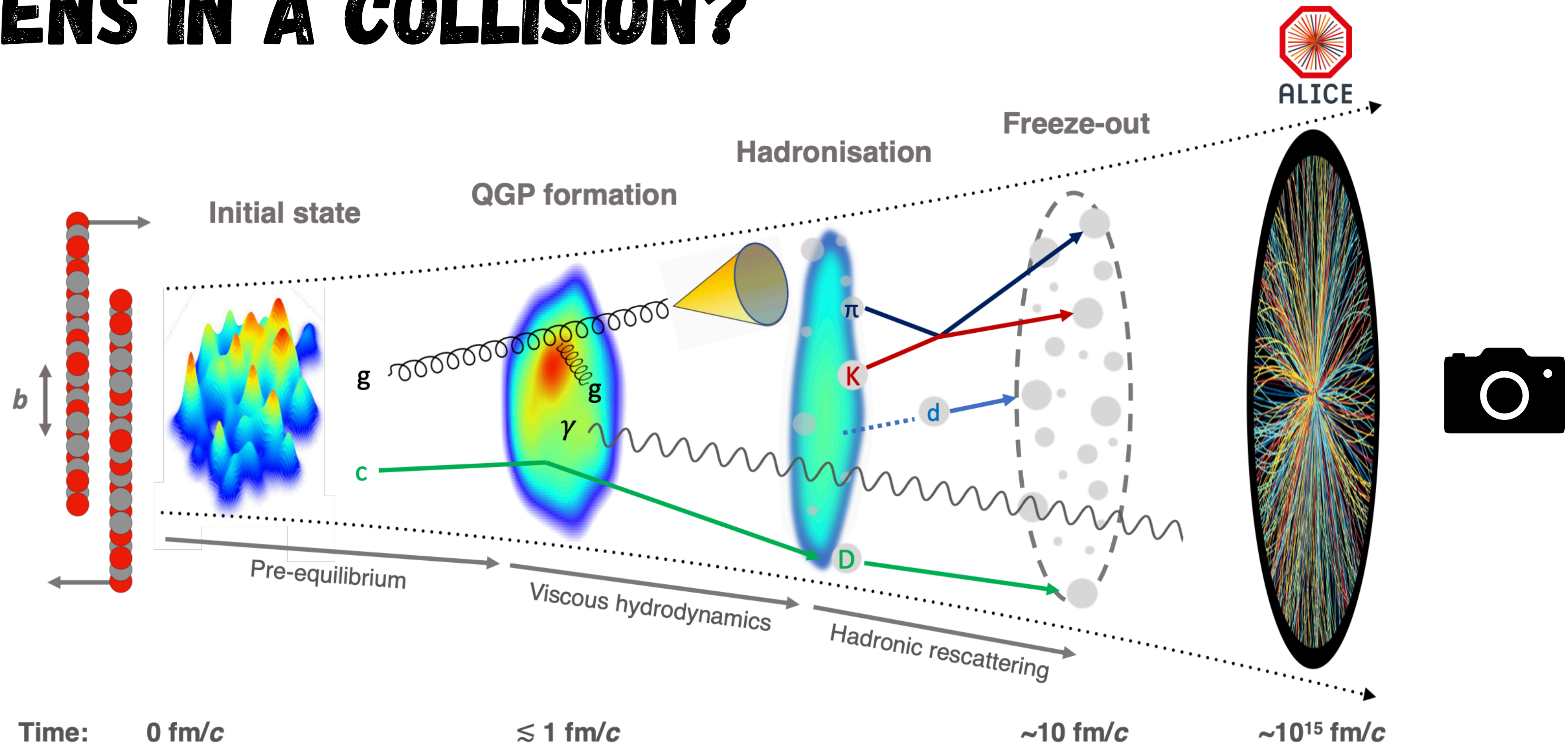
** Many more collision systems collided at RHIC/LHC not include here, including asymmetric collision systems.*



- Each collision system accesses different phenomena, important to measure across collision systems to understand the full range of complexity contained within QCD.
- Recent efforts to *re-analyze LEP data* and *new datasets in OO & NeNe* are crucial also for understanding QCD & the QGP.

WHAT HAPPENS IN A COLLISION?

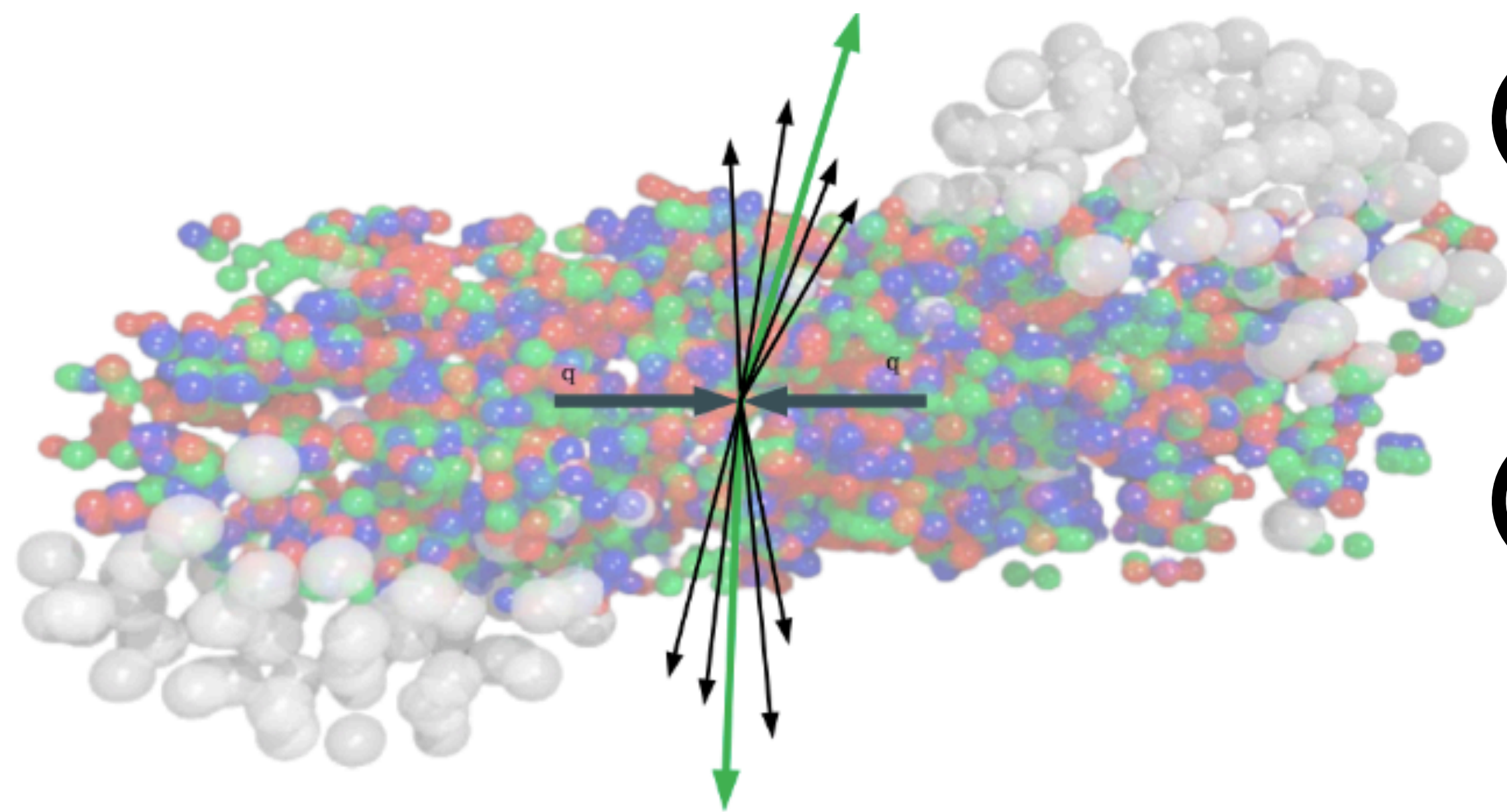
- QGP follows a hydrodynamical evolution, expands and cools, then hadronizes.
- All we see are the hadrons that free stream and are measured in the detector!



[ALICE, A journey through QCD]

- Use *different targeted probes* to collect information about *each stage of the collision*!
- Full picture allows us to characterize the QGP and provides a rich lab for studying QCD!

EXPERIMENTAL PROBES OF QGP PROPERTIES



① **Soft Probes:** hadronization products of the QGP medium

→ collective properties of QGP

② **Hard Probes:** products of early-stage hard scattering that interact with the QGP medium.

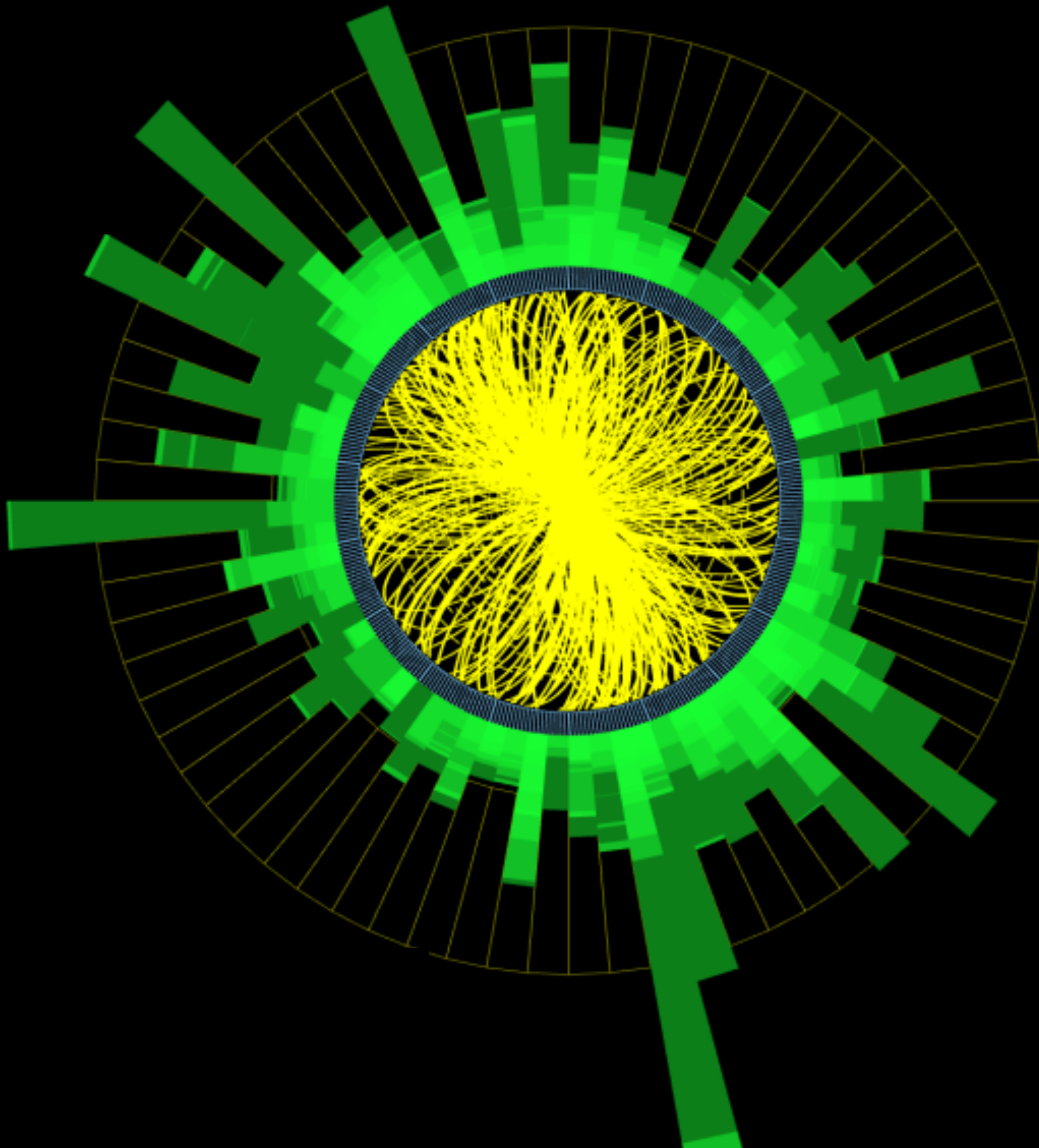
→ dynamical properties of QGP

③ **Electroweak Probes:** probes that have a long mean free path relative to the size of the QGP (negligible interactions)

→ effects of different stages of QGP formation

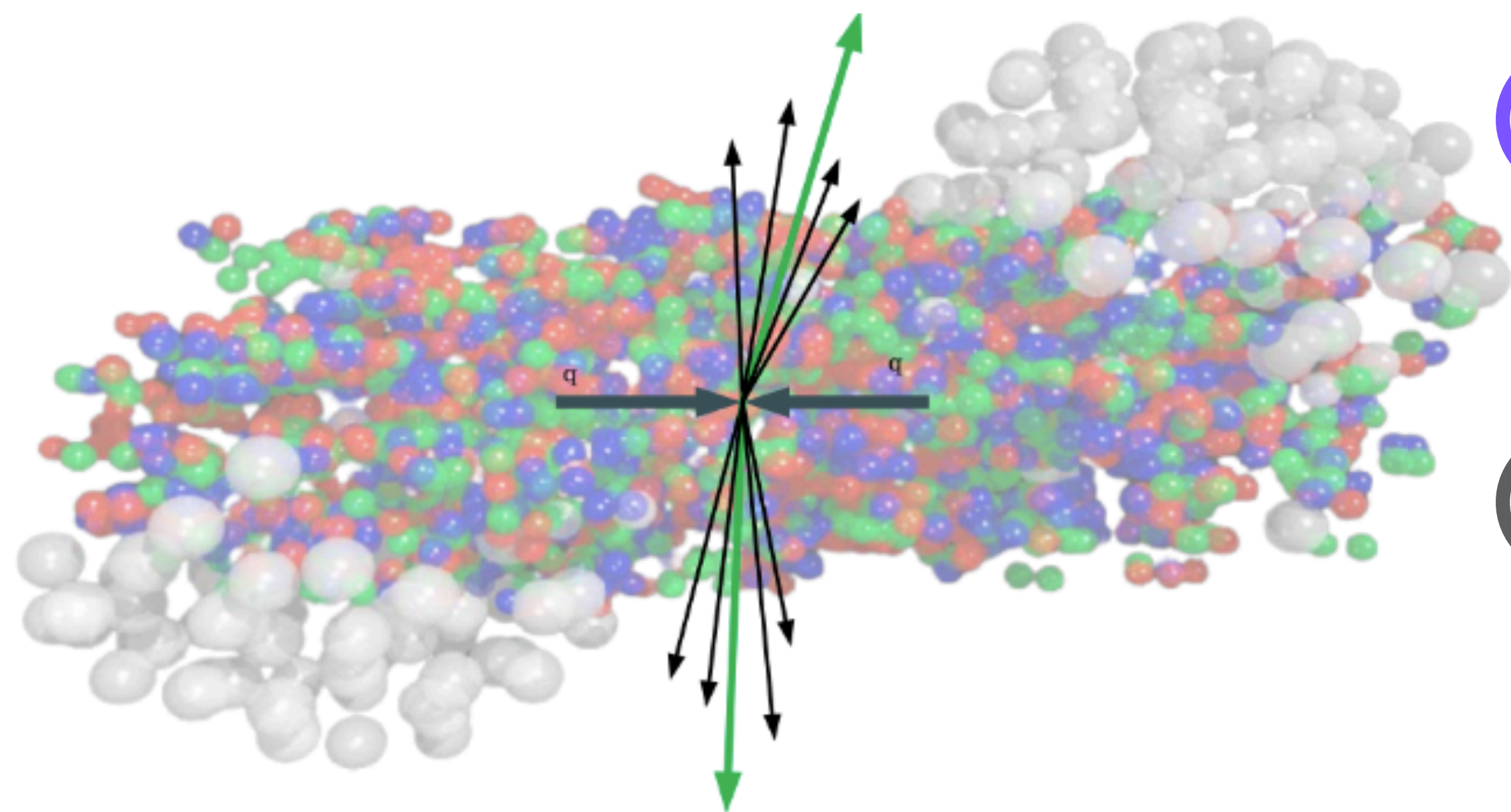


Use pp collision data at same energy as a reference, where difference is taken as an in-medium property.



Part 2 : What have we learned about the QGP and its properties?

EXPERIMENTAL PROBES OF QGP PROPERTIES



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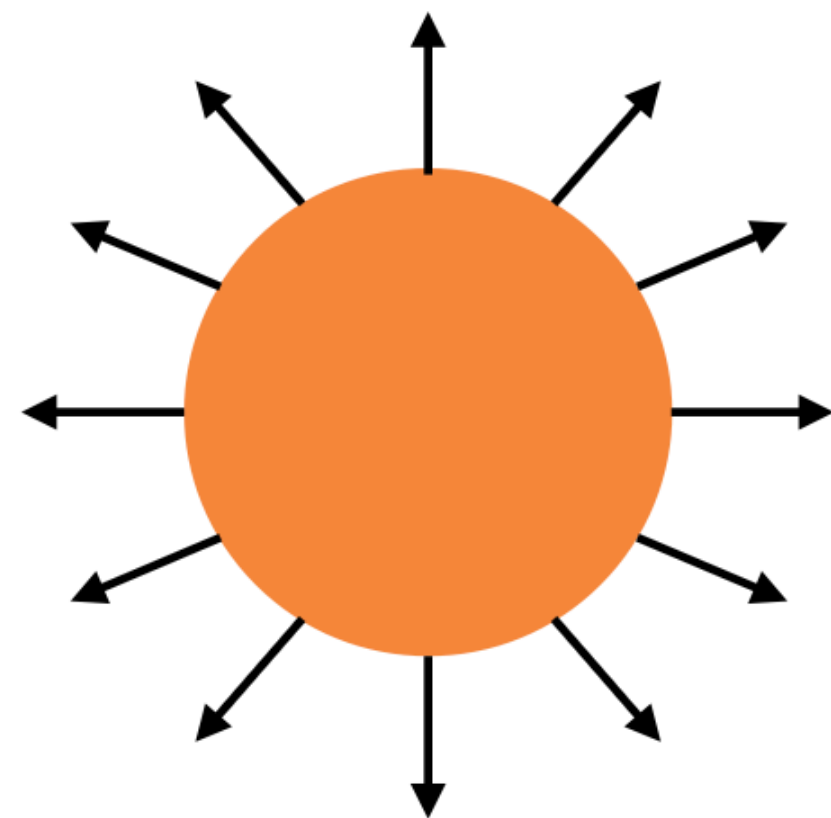


Use pp collision data at same energy as a reference, where difference is taken as an in-medium property.

EXPECTATIONS OF COLLECTIVITY

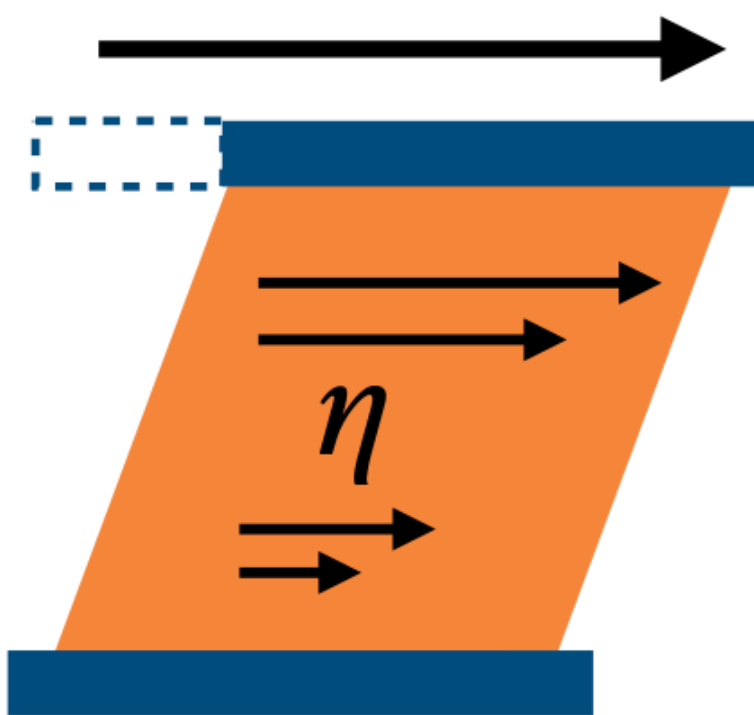


Bulk viscosity

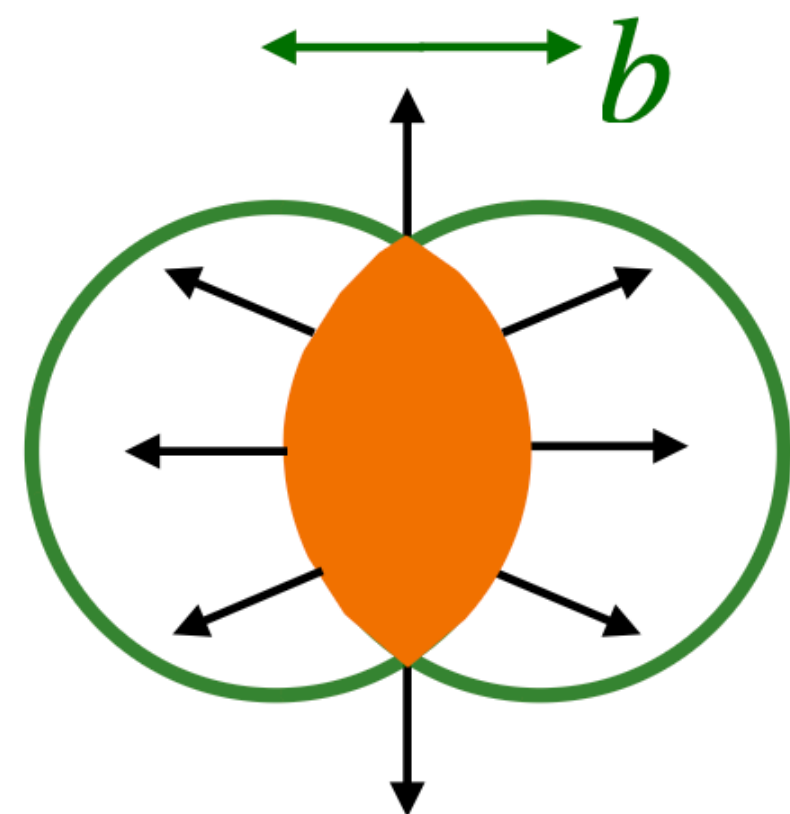


Radial Flow

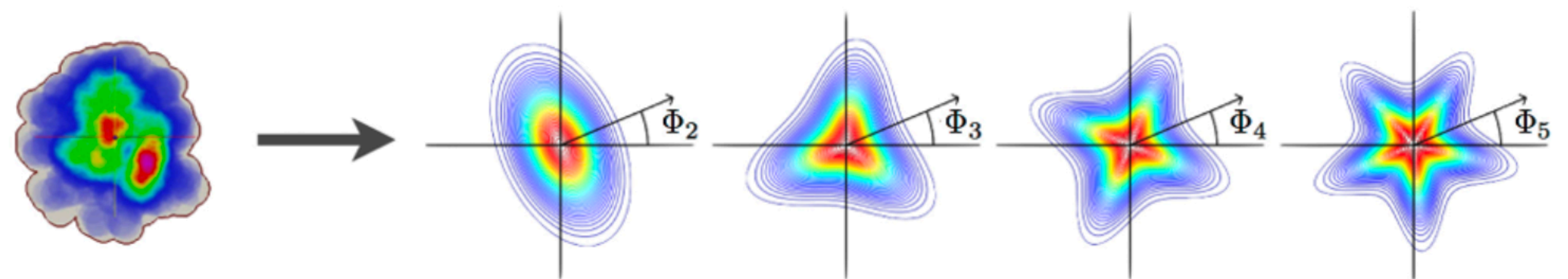
- QGP expanding into vacuum results in **radial flow**.
- Quantified by measuring the $\langle p_T \rangle$ of produced particles.
- Spatial anisotropies in the initial state create strong pressure gradients that result in **anisotropic flow**.
- Quantified by the Fourier decomposition of the flow harmonics.



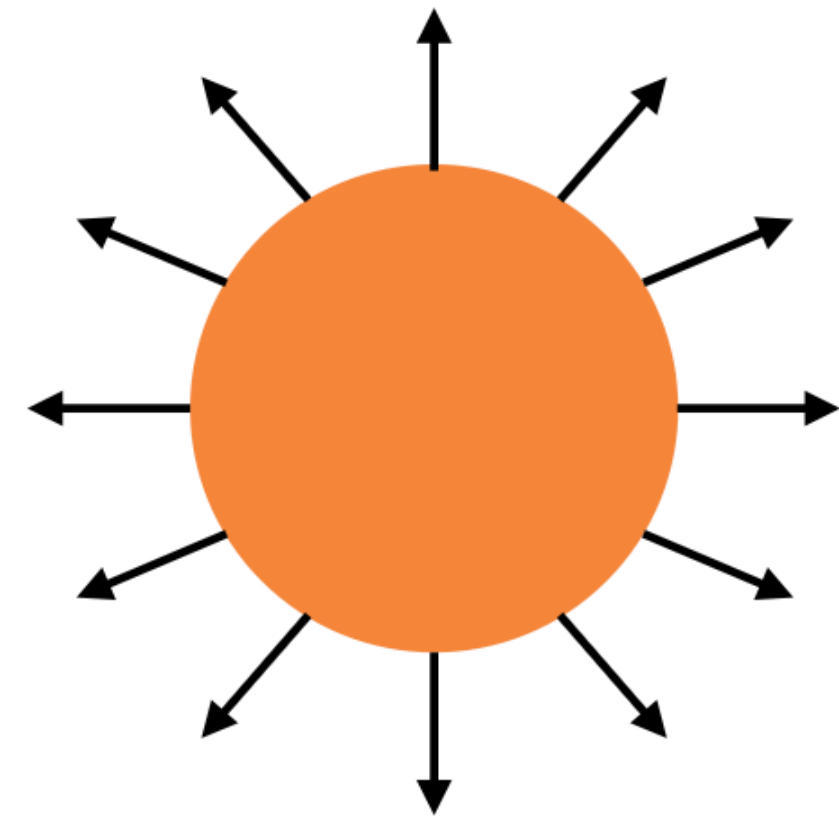
Shear viscosity



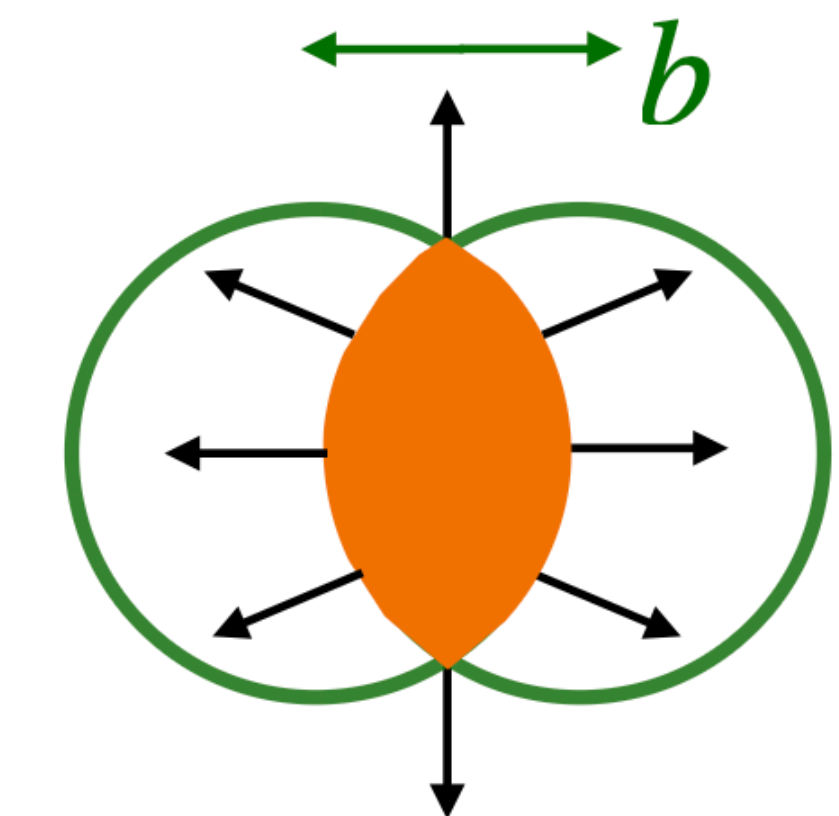
Anisotropic Flow



THE SUCCESS OF HYDRODYNAMICS

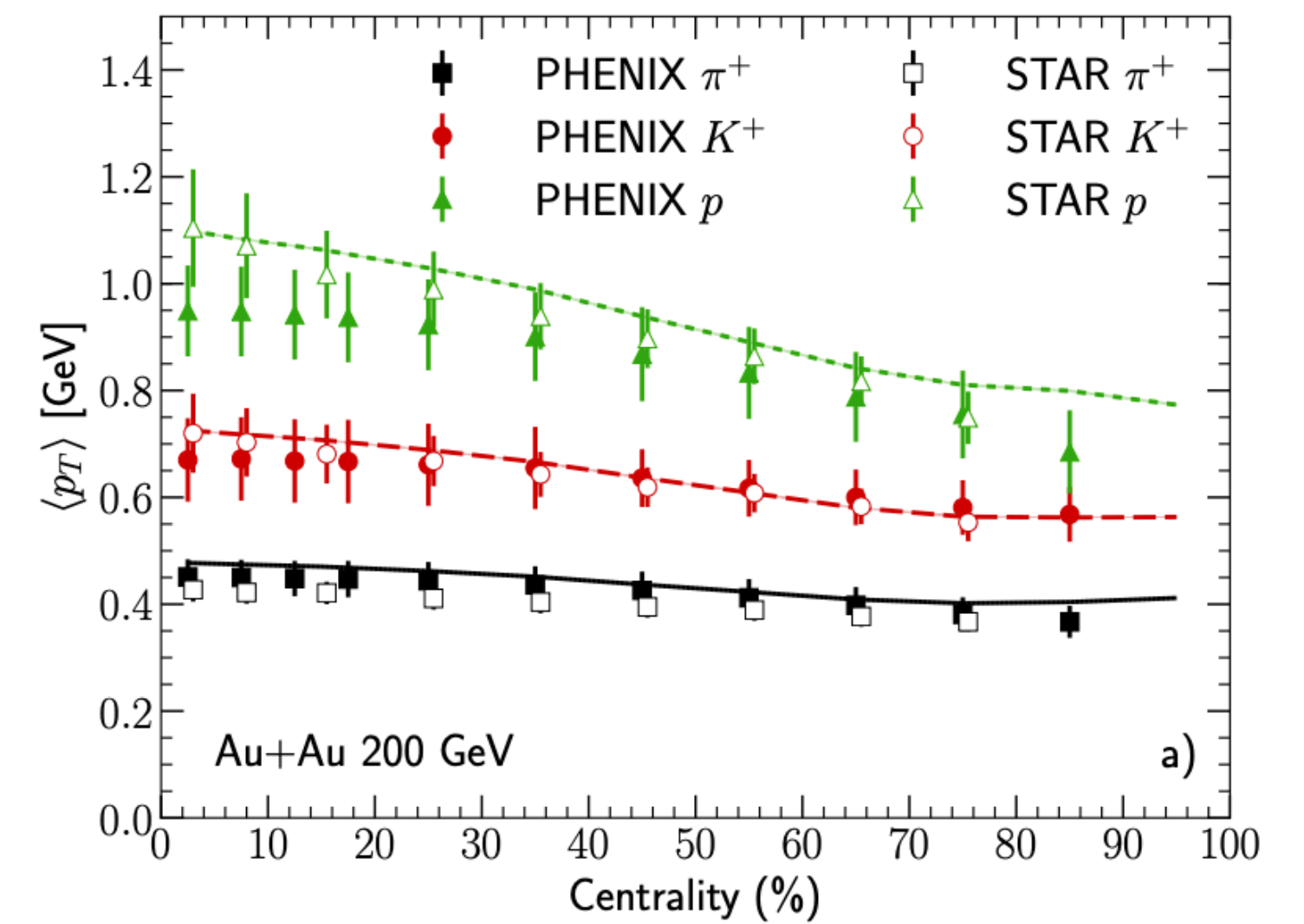
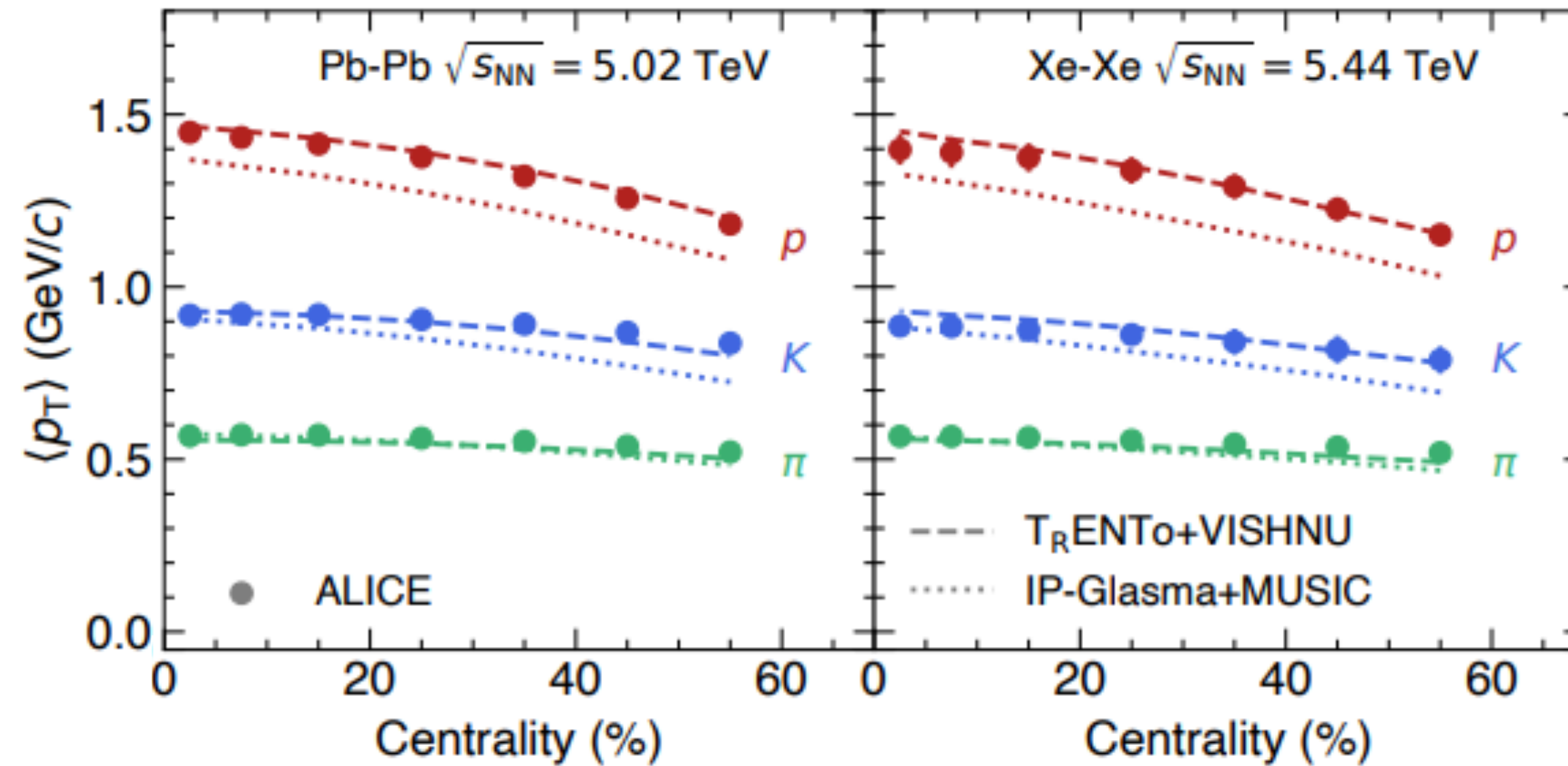


Radial Flow



Anisotropic Flow

[ALICE, A journey through QCD]

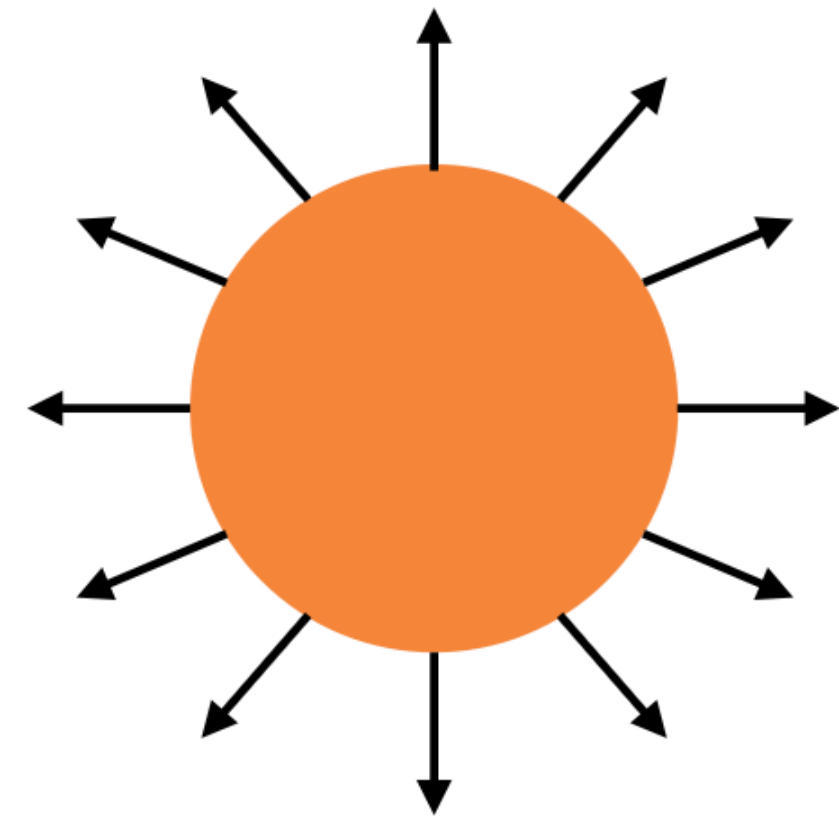


[PRC 102, 044905 (2020)]

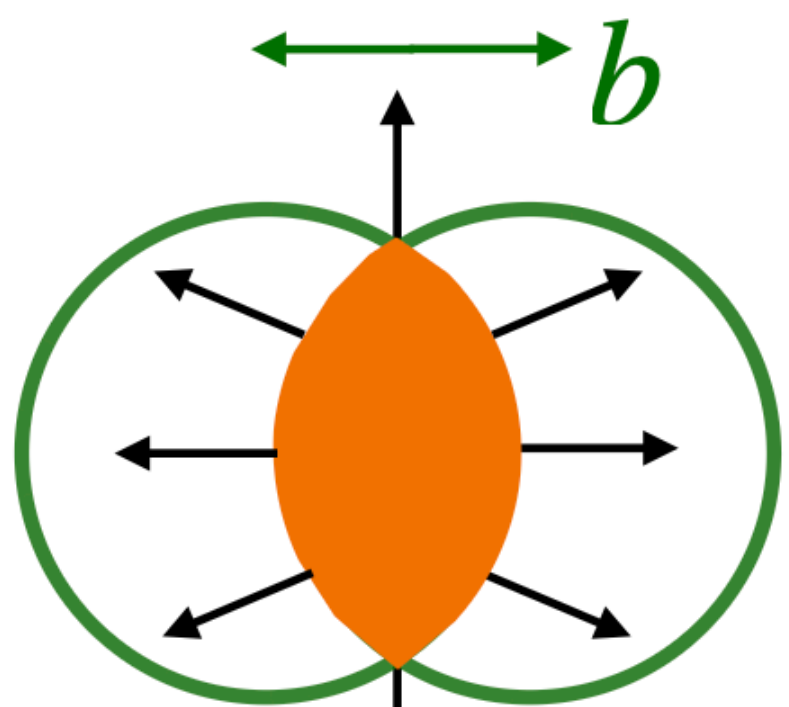
- *We have learned* that hydrodynamics provides a quantitative description of RHIC and LHC data across different initial state geometries with impressive precision.

[arXiv:2412.19393]

THE SUCCESS OF HYDRODYNAMICS

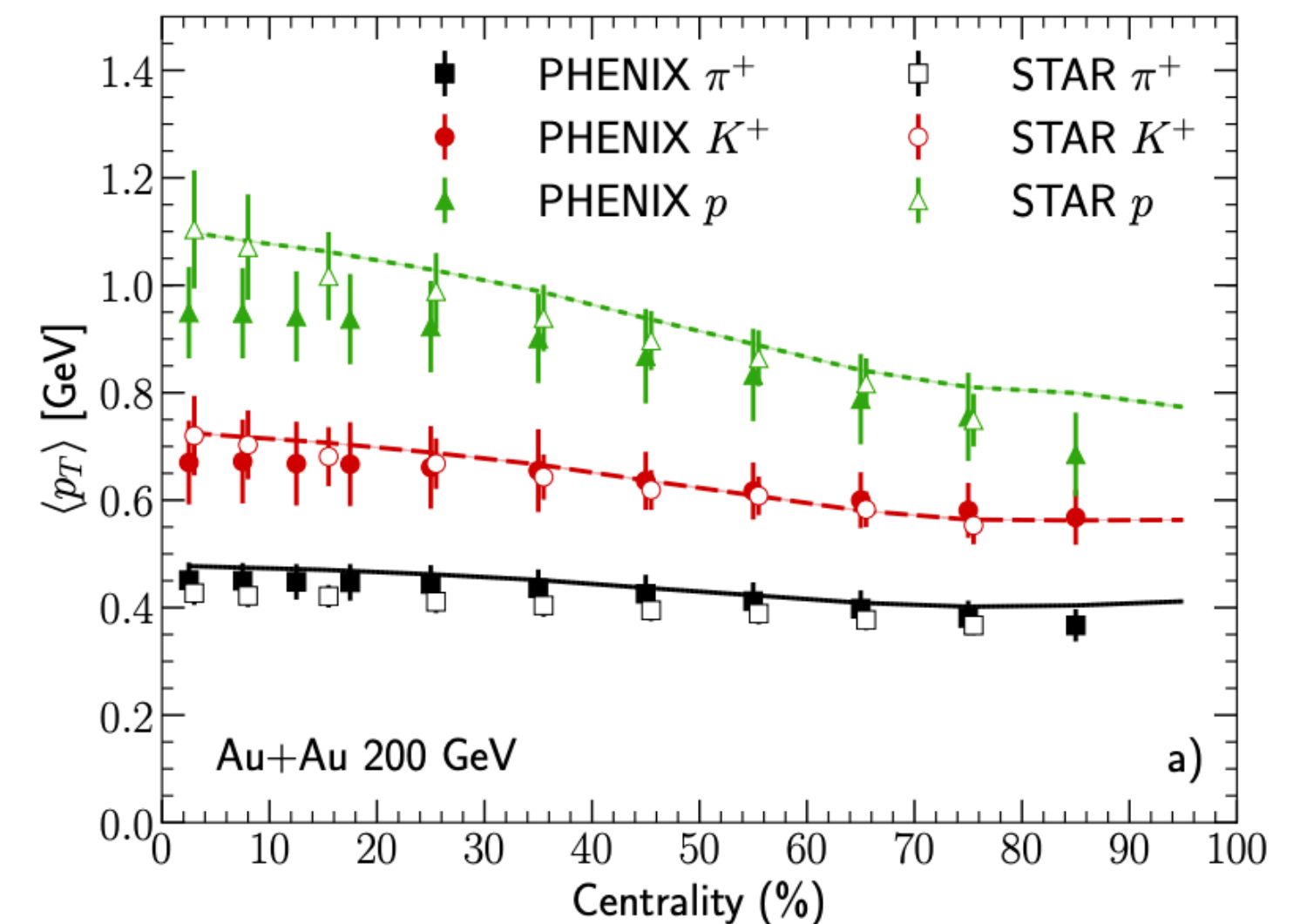
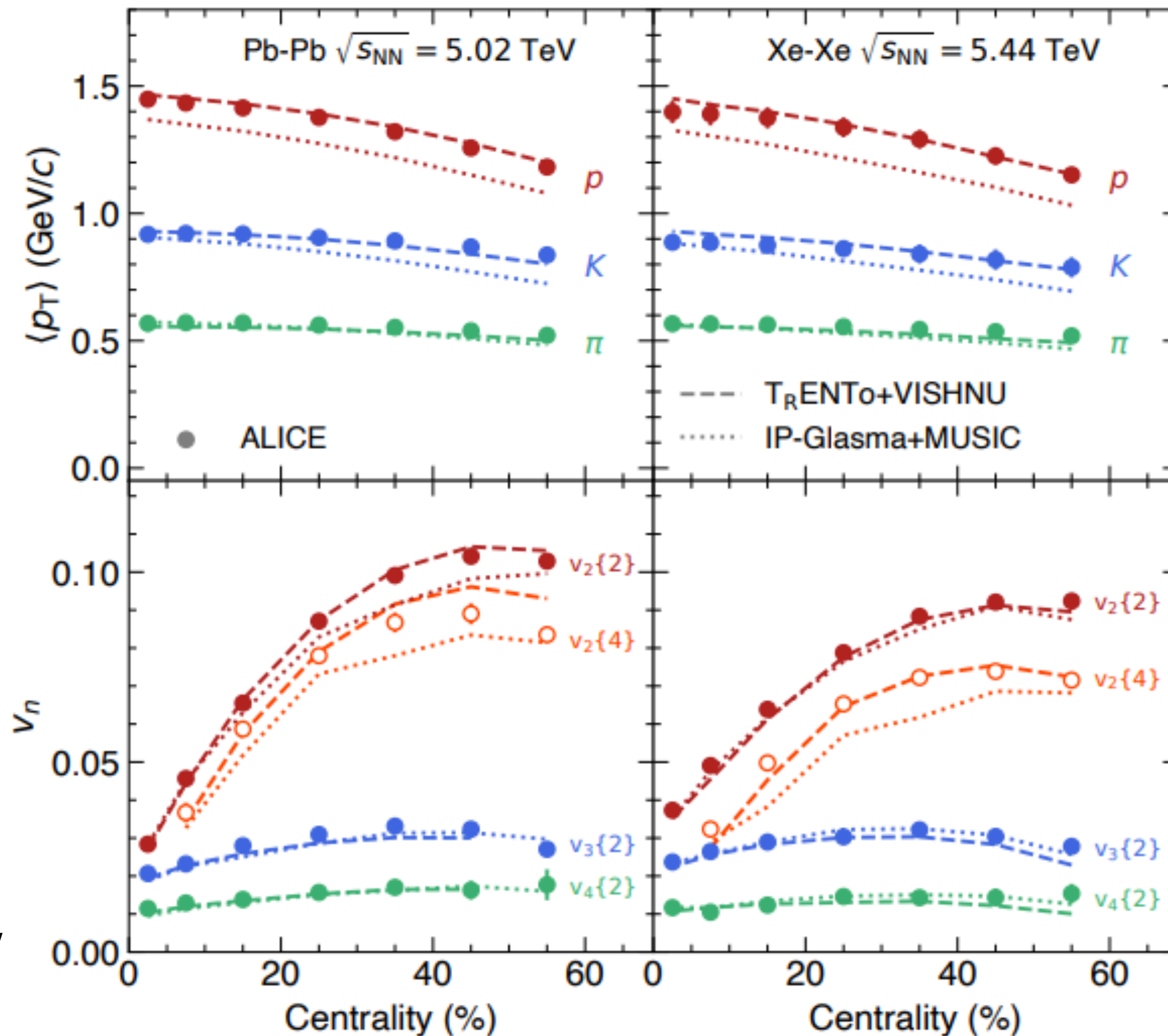


Radial Flow

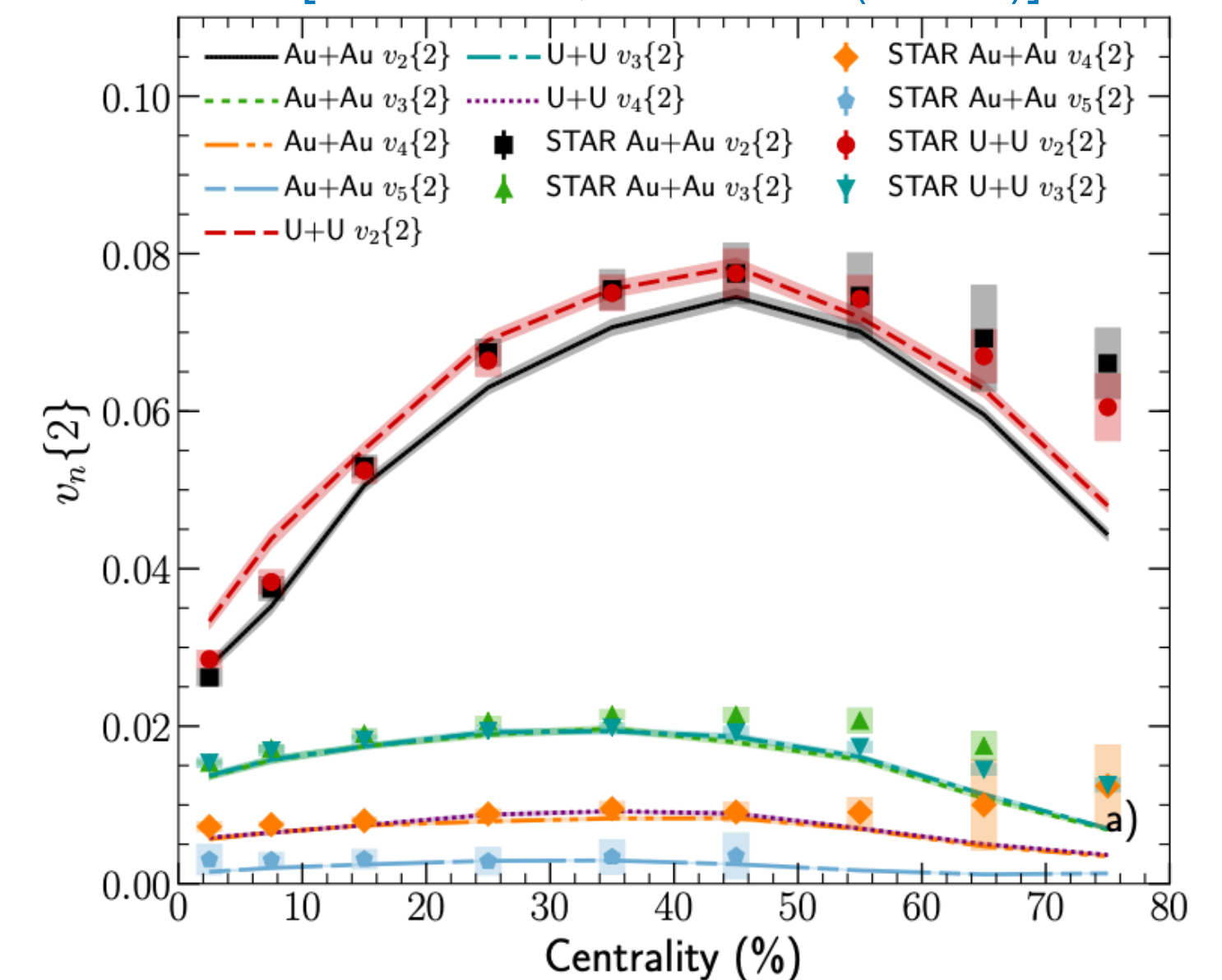


Anisotropic Flow

[ALICE, A journey through QCD]



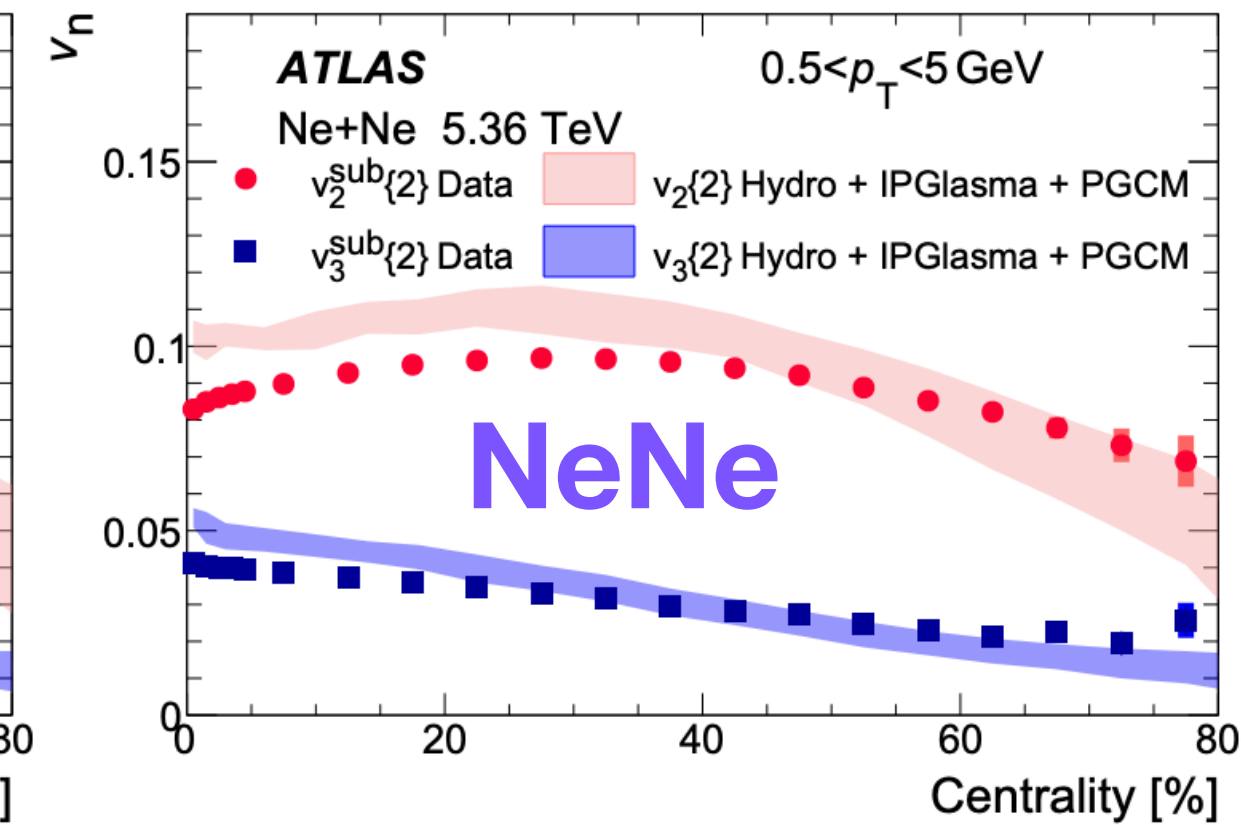
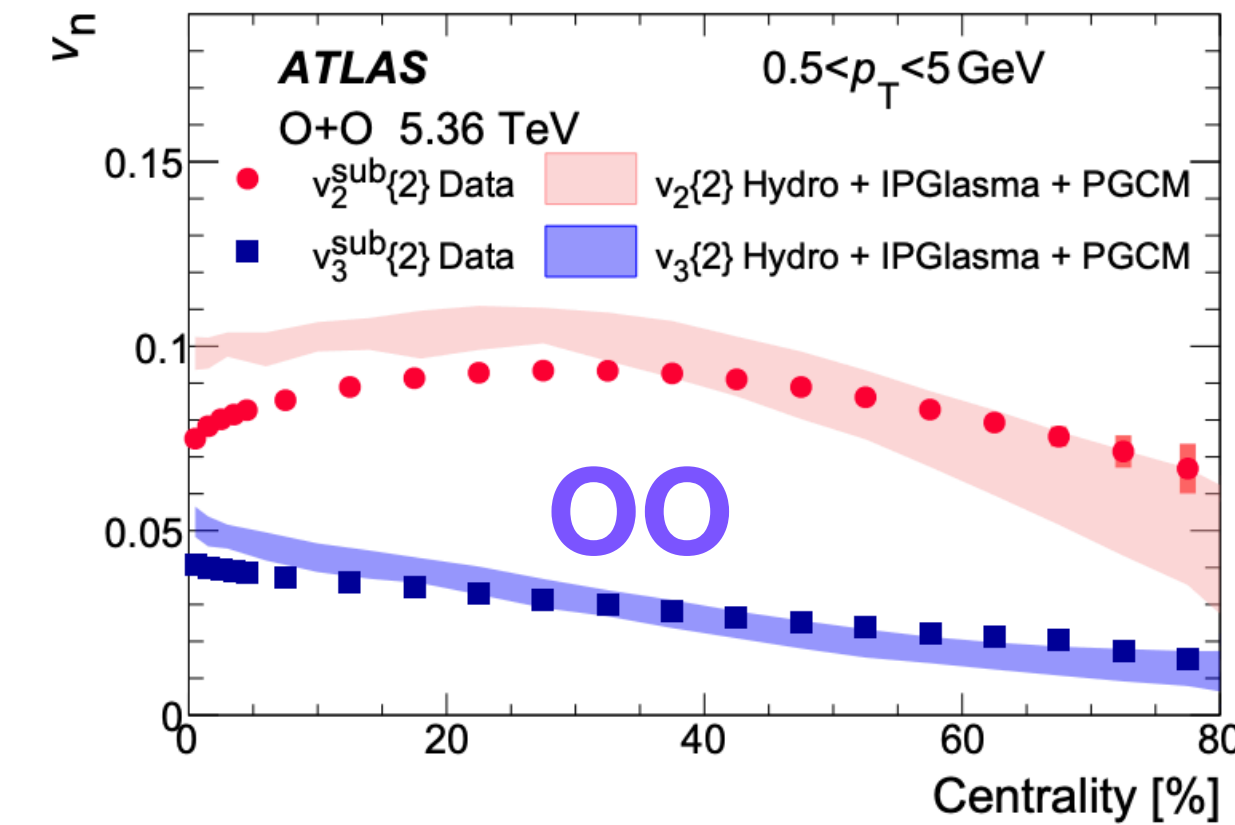
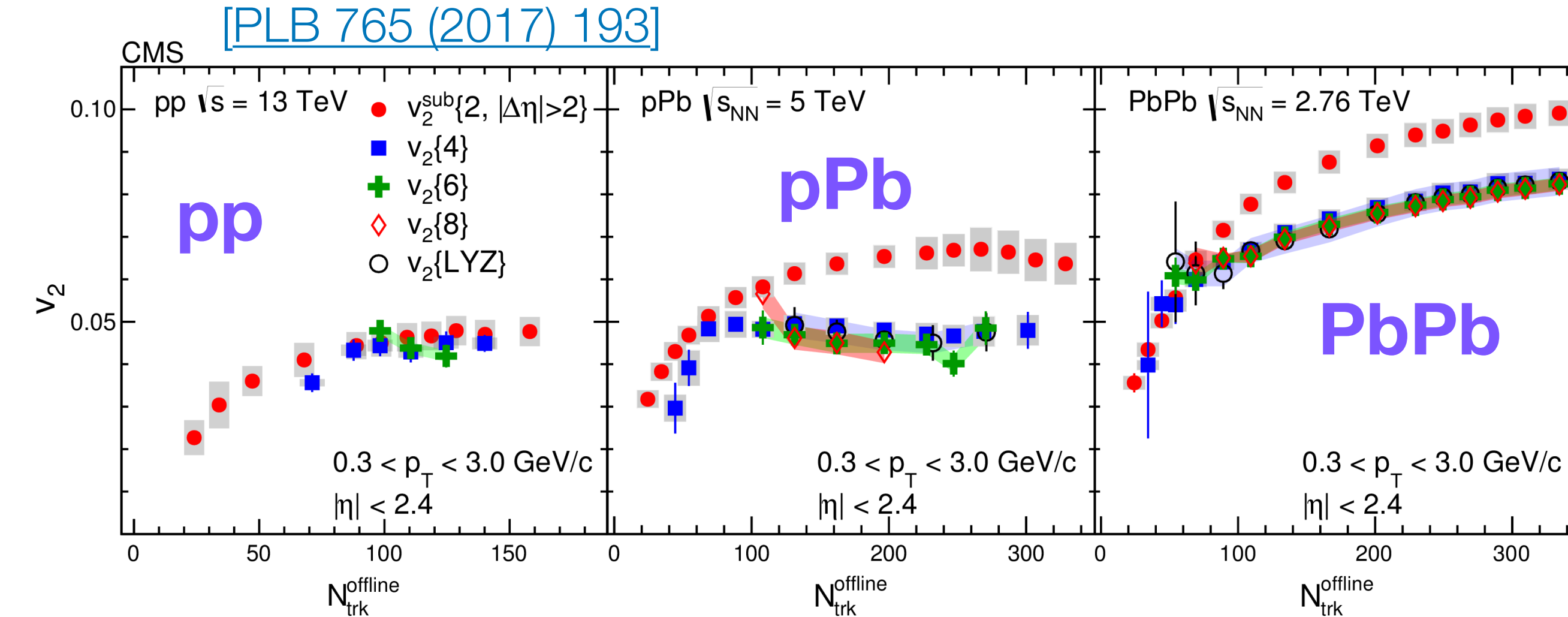
[PRC 102, 044905 (2020)]



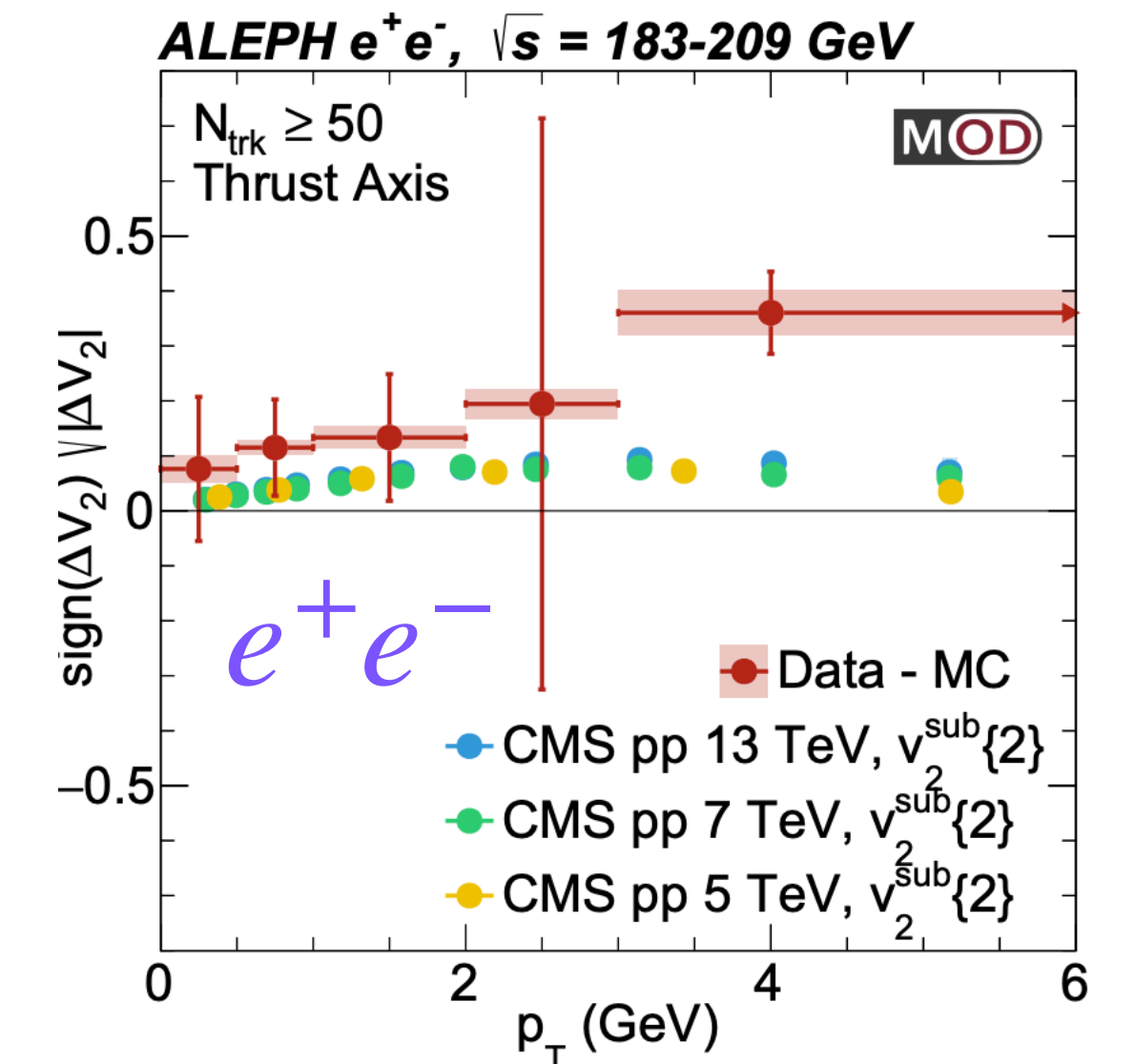
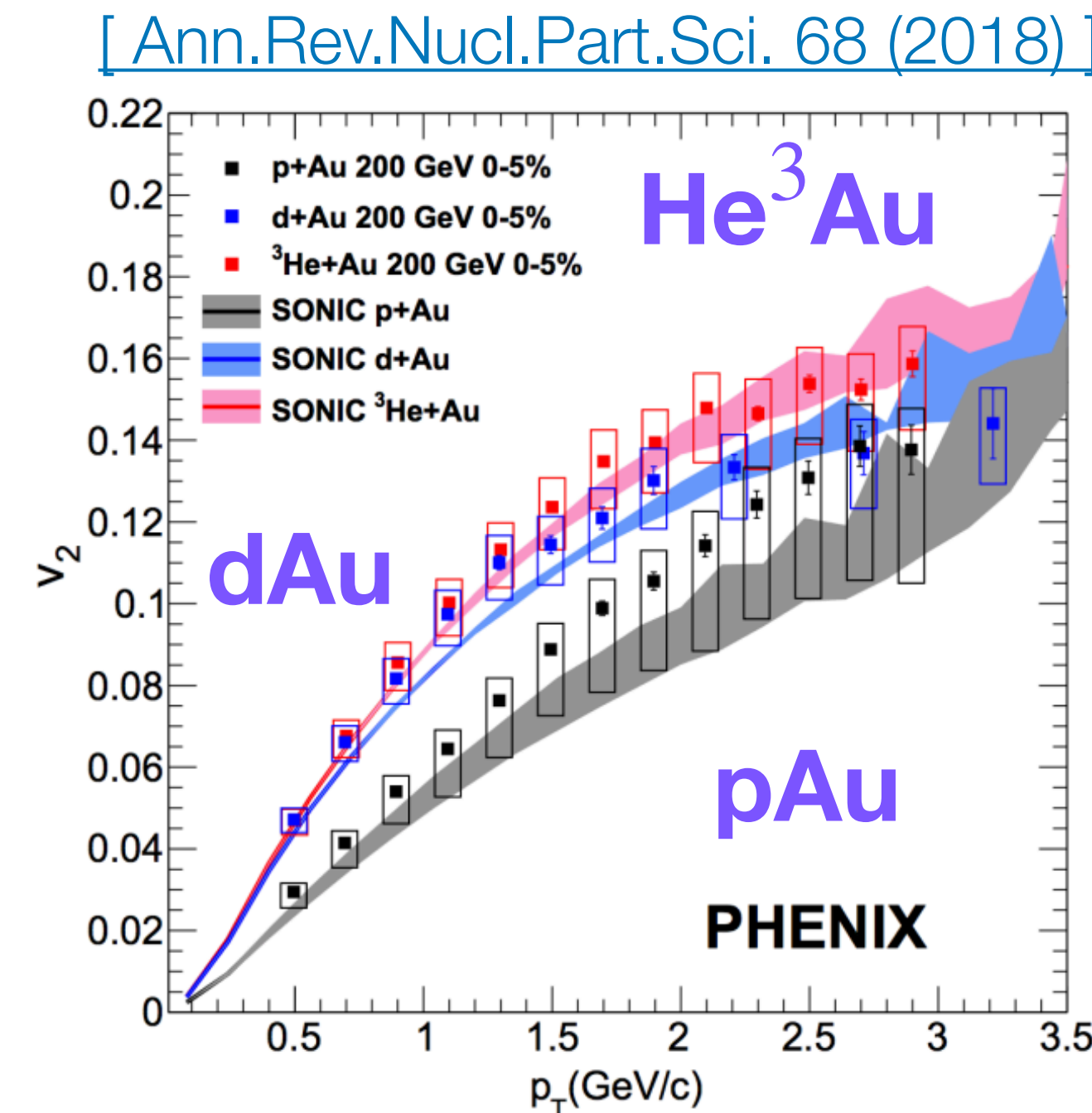
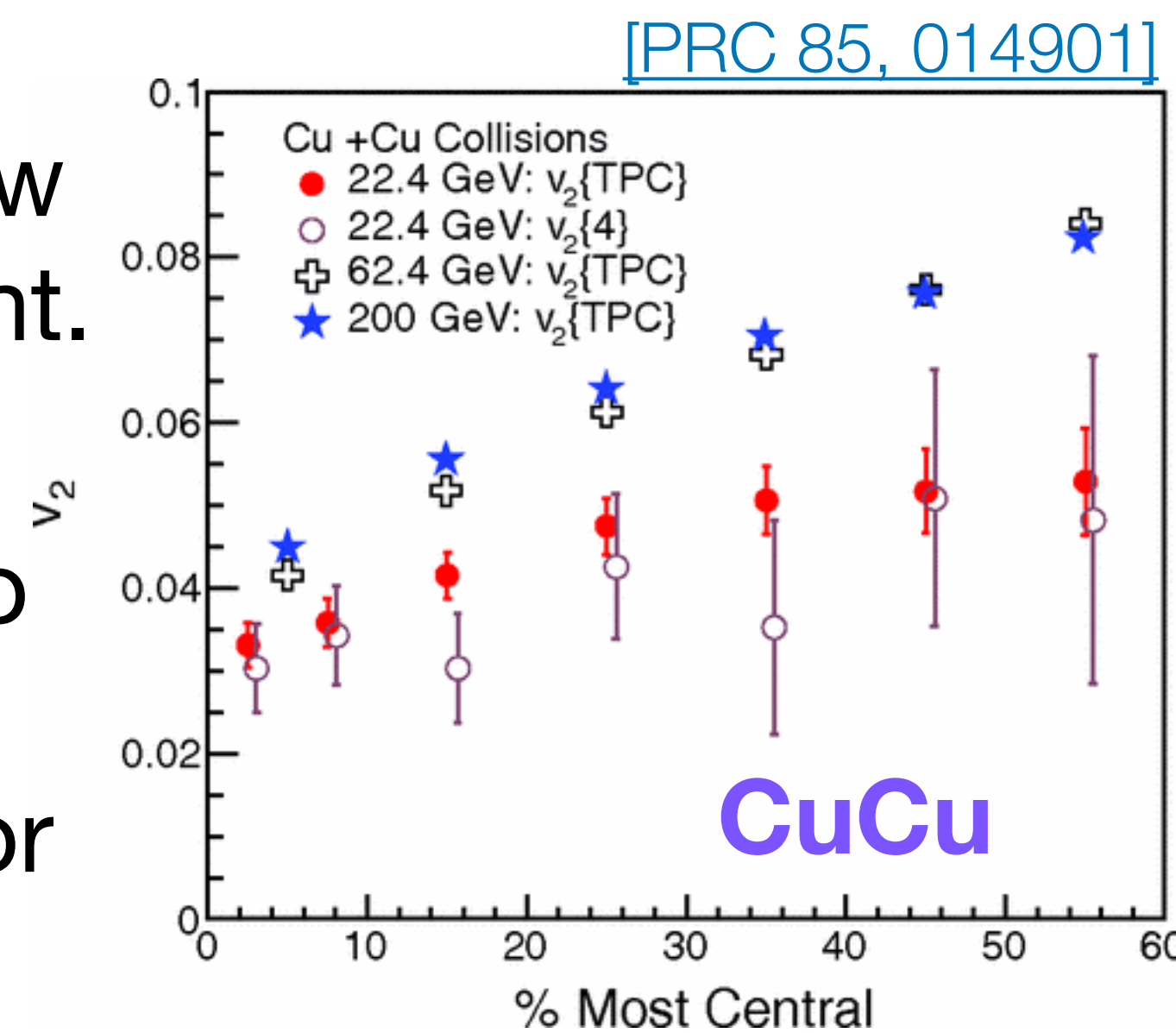
- We have learned* that hydrodynamics provides a quantitative description of RHIC and LHC data across different initial state geometries with impressive precision.

[arXiv:2412.19393]

DOES EVERYTHING FLOW? • *We have learned* that non-zero v_2 signals appear in collision systems where no QGP was expected.



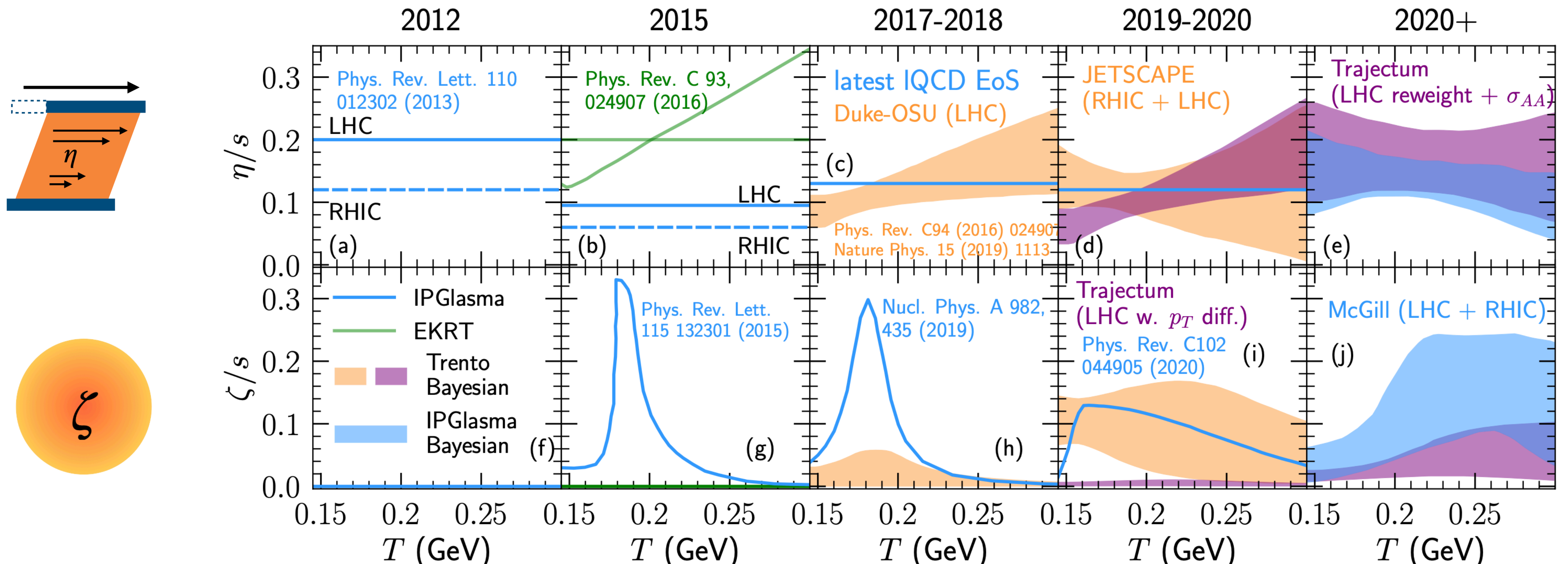
- Differential measurements of flow increasingly important.
- Prompted a small systems revolution to understand minimal conditions needed for QGP formation.



[PLB 856 (2024) 138957]

SHEAR AND BULK VISCOSITY OF THE QGP

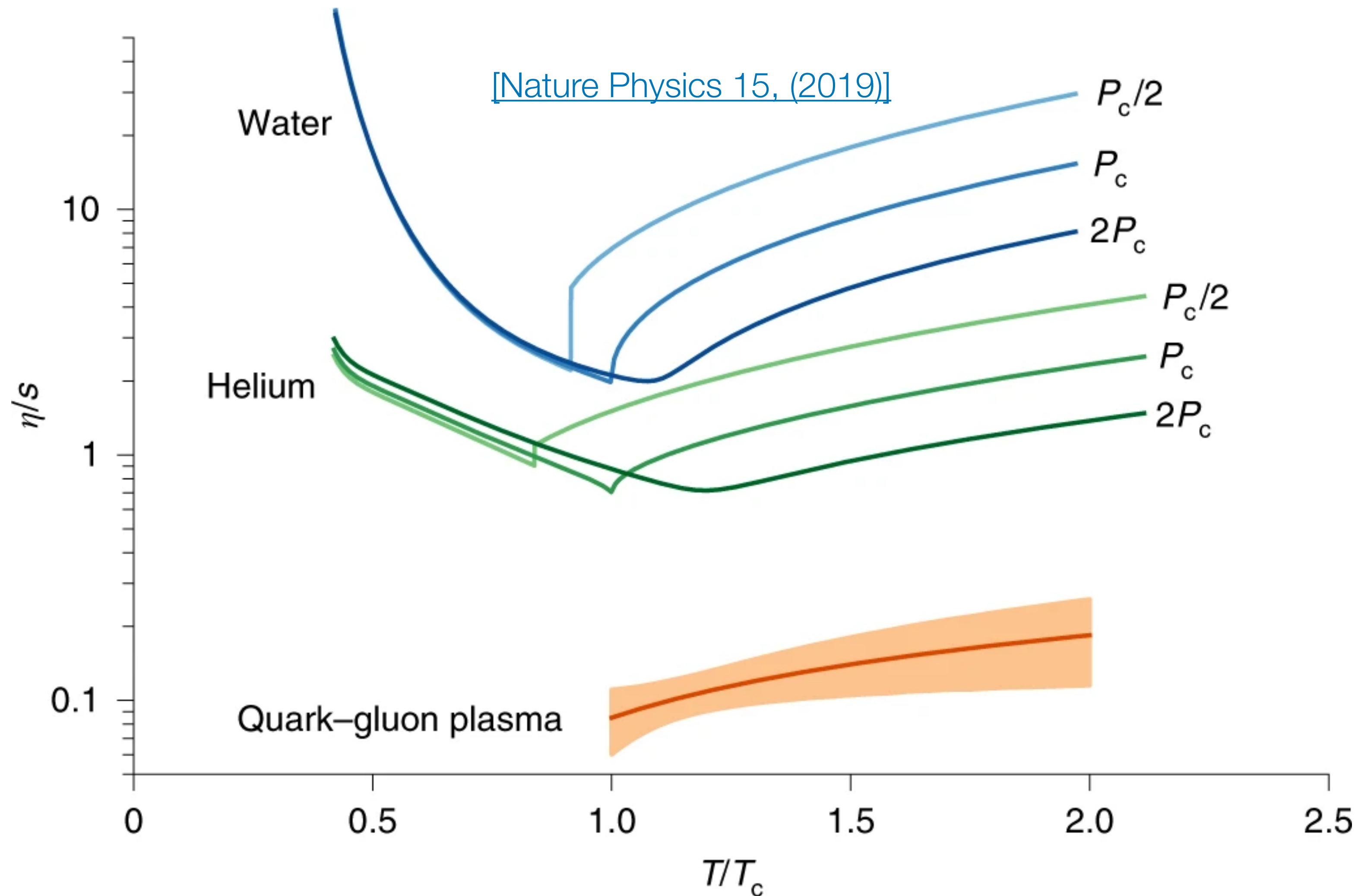
- *We have learned* that Bayesian analysis provides a clear path to extract QGP properties from experimental measurements w/ input from models. [\[Compilation by Chun Shen\]](#)



Significant improvement over the years! New data + new techniques!

[\[See Hari Niemi's talk Mon.15:45\]](#)

QGP AS A NEAR PERFECT LIQUID

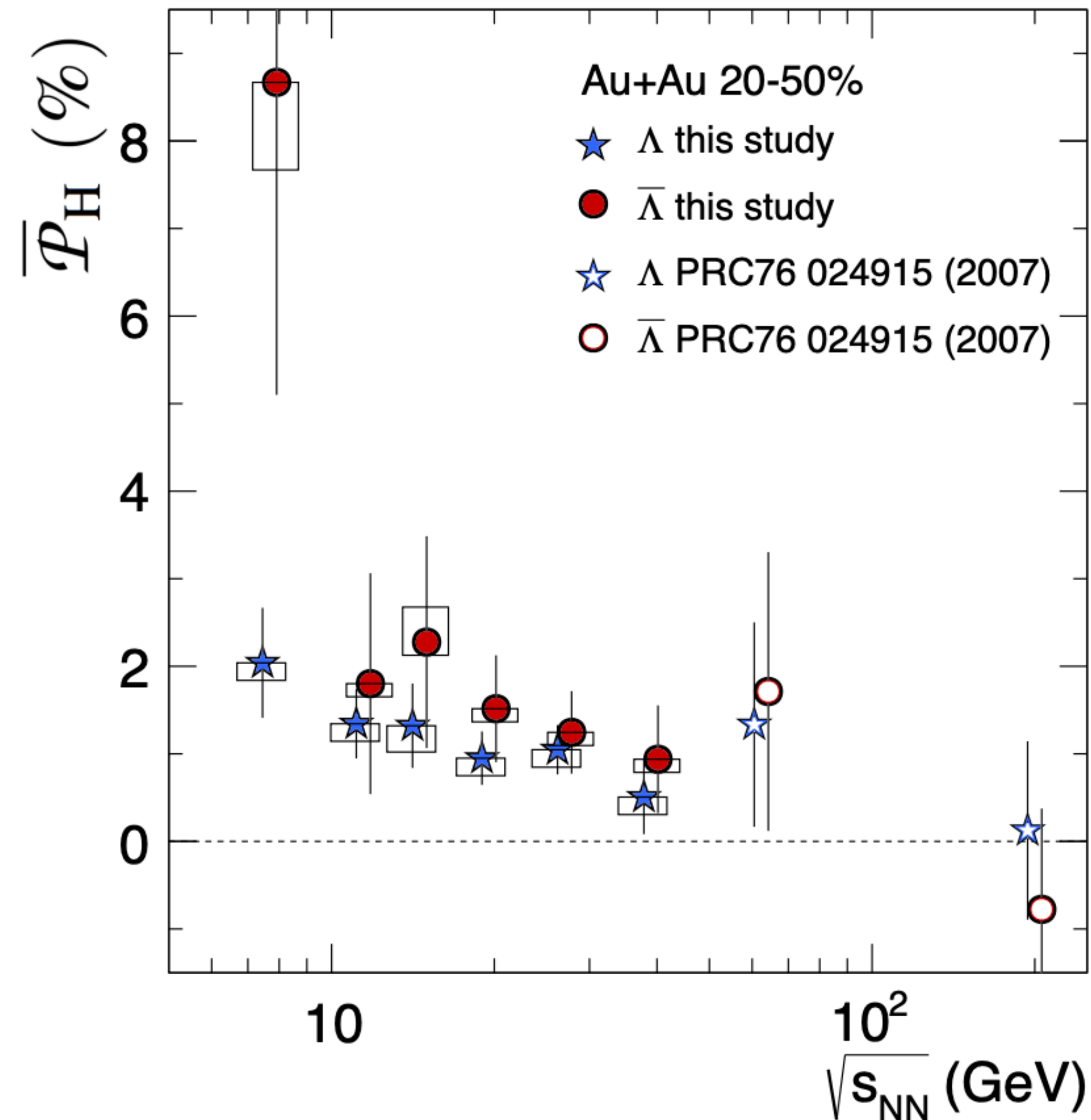


- Can compare Bayesian extractions of the shear viscosity over entropy density ratio, η/s
- QGP has a lower η/s than any known substance

- *We have learned* that the QGP is a near perfect liquid!

QGP AS A HIGHLY VORTICAL LIQUID

[[Nature 548 \(2017\)](#)]



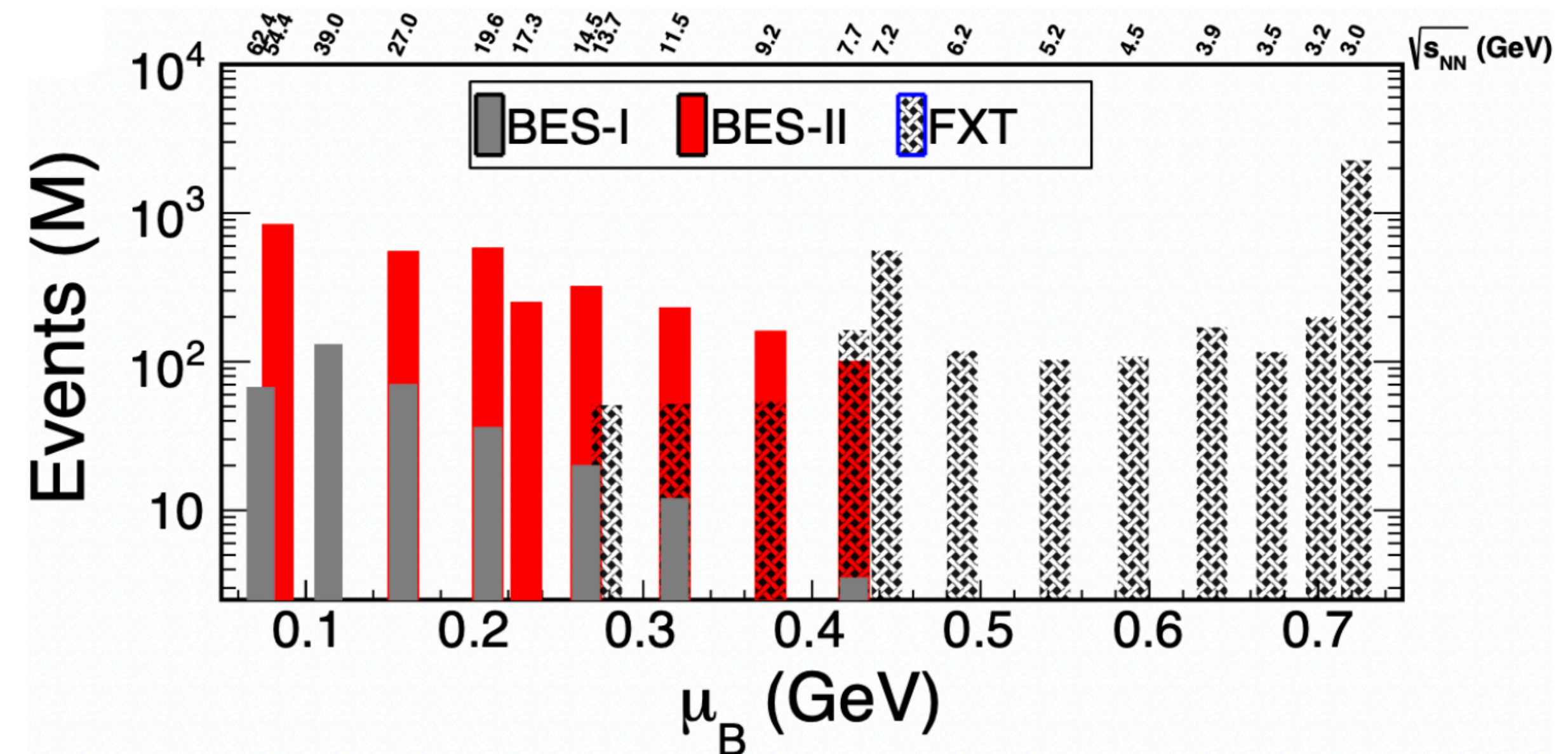
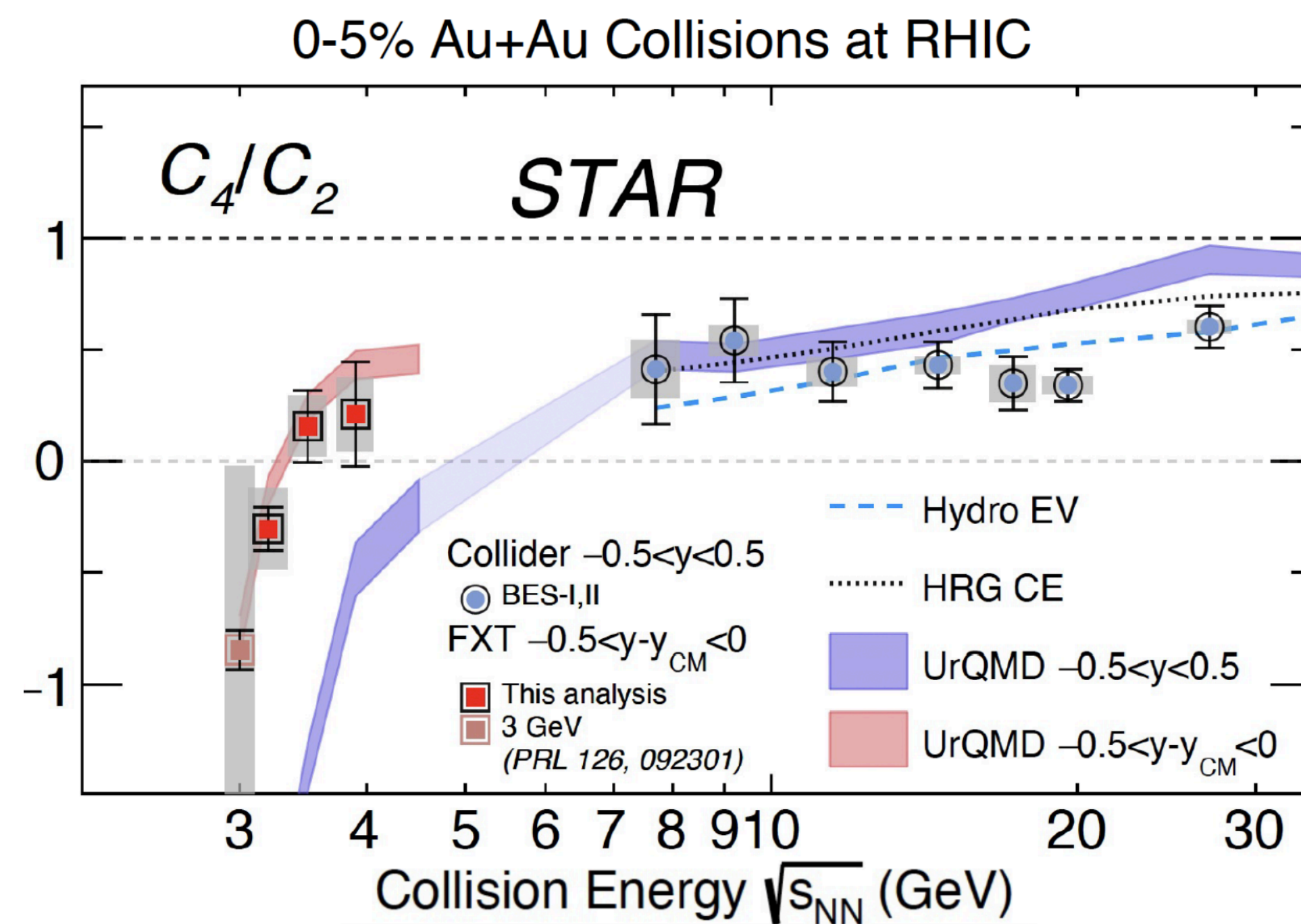
- Angular momentum of incoming nuclei results in polarization with respect to the reaction plane direction.
- Here, measure global hyperon (Λ) polarization.
- *We have learned* that the QGP is the most vortical system ever observed.

• **Future: Study how vorticity is transferred to fluid using new PID and tracking upgrades**

[[L. Ruan, KITP](#)]

THE SEARCH FOR THE CRITICAL POINT

- *We have taken two beam energy scans at RHIC* that have provided new insight to the search for the critical point.



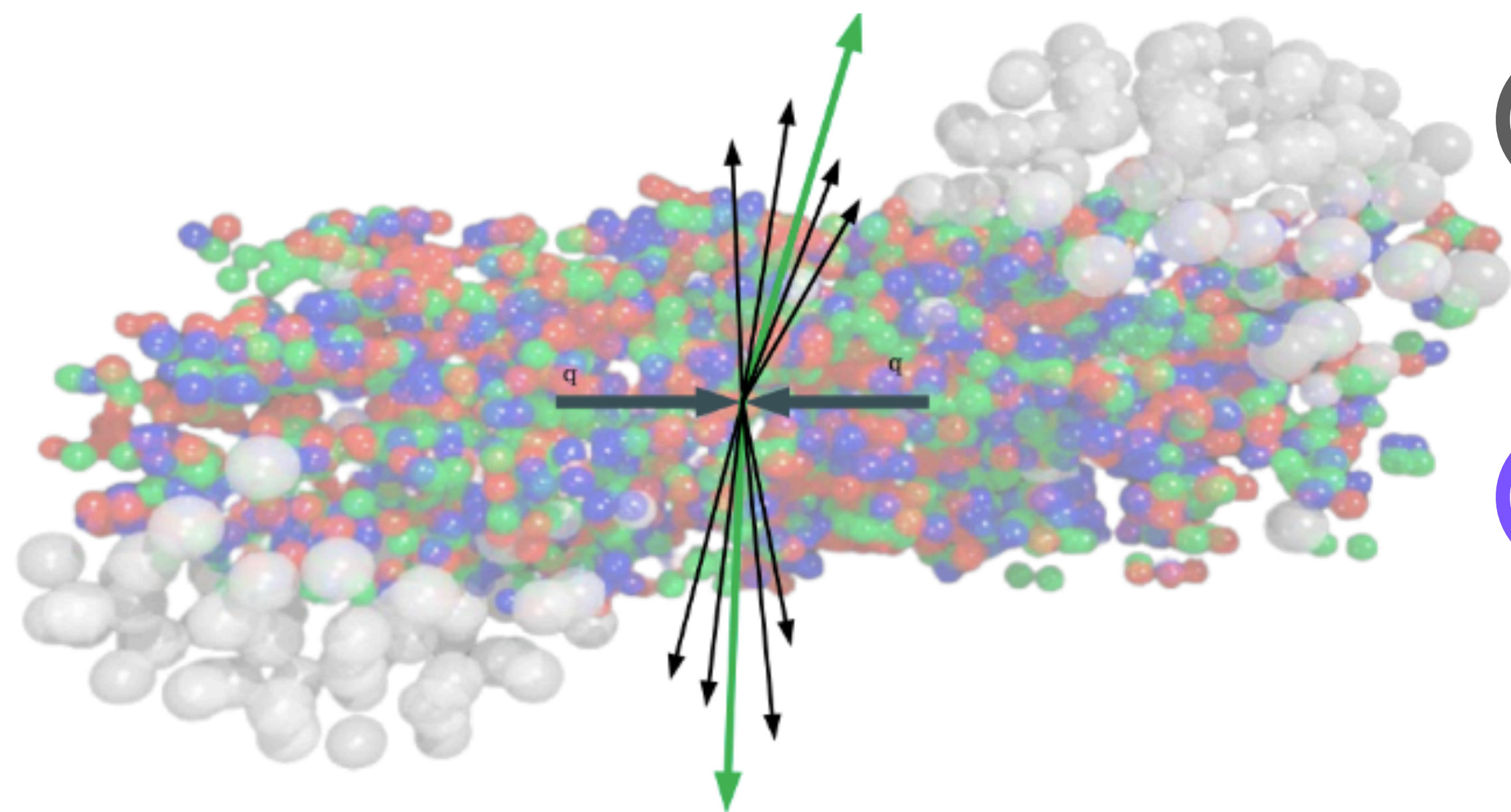
- Deviates from non-critical-point model calculations and peripheral collision 70-80% data, significance of deviation at $\sim 2 - 5\sigma$.

[\[PRL 135 \(2025\) 14, 142301\]](#)

Important area for additional theory input!

[\[See Thomas Schaefer's talk Mon. 14:00\]](#) [\[See Lorenz von Smekal's talk Mon. 14:30\]](#)

EXPERIMENTAL PROBES OF QGP PROPERTIES



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→ collective properties of QGP

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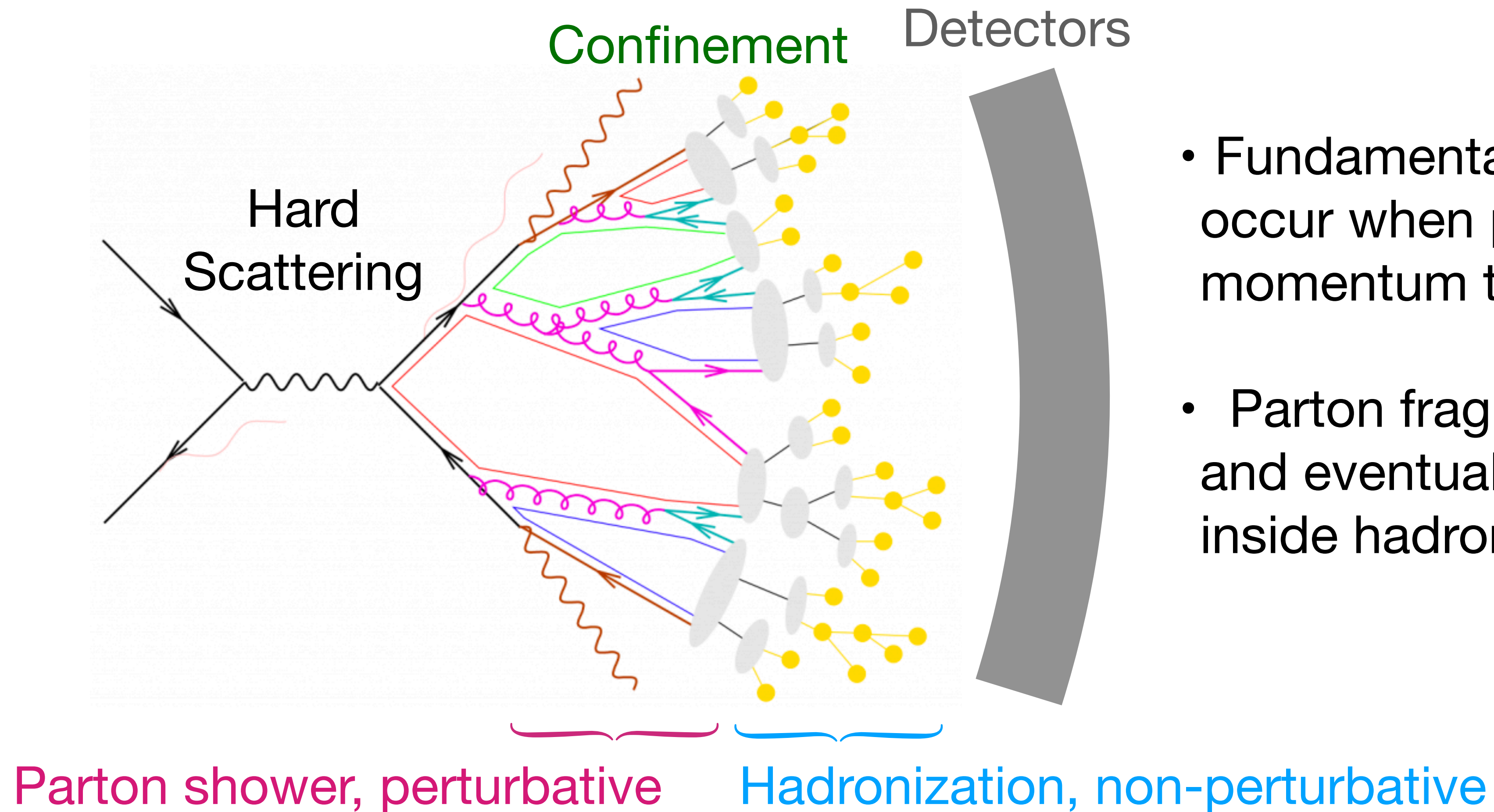
③ **Electroweak Probes:** probes that have a long mean free path relative to the size of the QGP (negligible interactions)

→ effects of different stages of QGP formation



Use pp collision data at same energy as a reference, where difference is taken as an in-medium property.

HARD PROCESSES



- Fundamental QCD processes that occur when partons scatter with high momentum transfer (“*hard*”).
- Parton fragments via a **parton shower** and eventually becomes confined inside hadrons **via hadronization**.

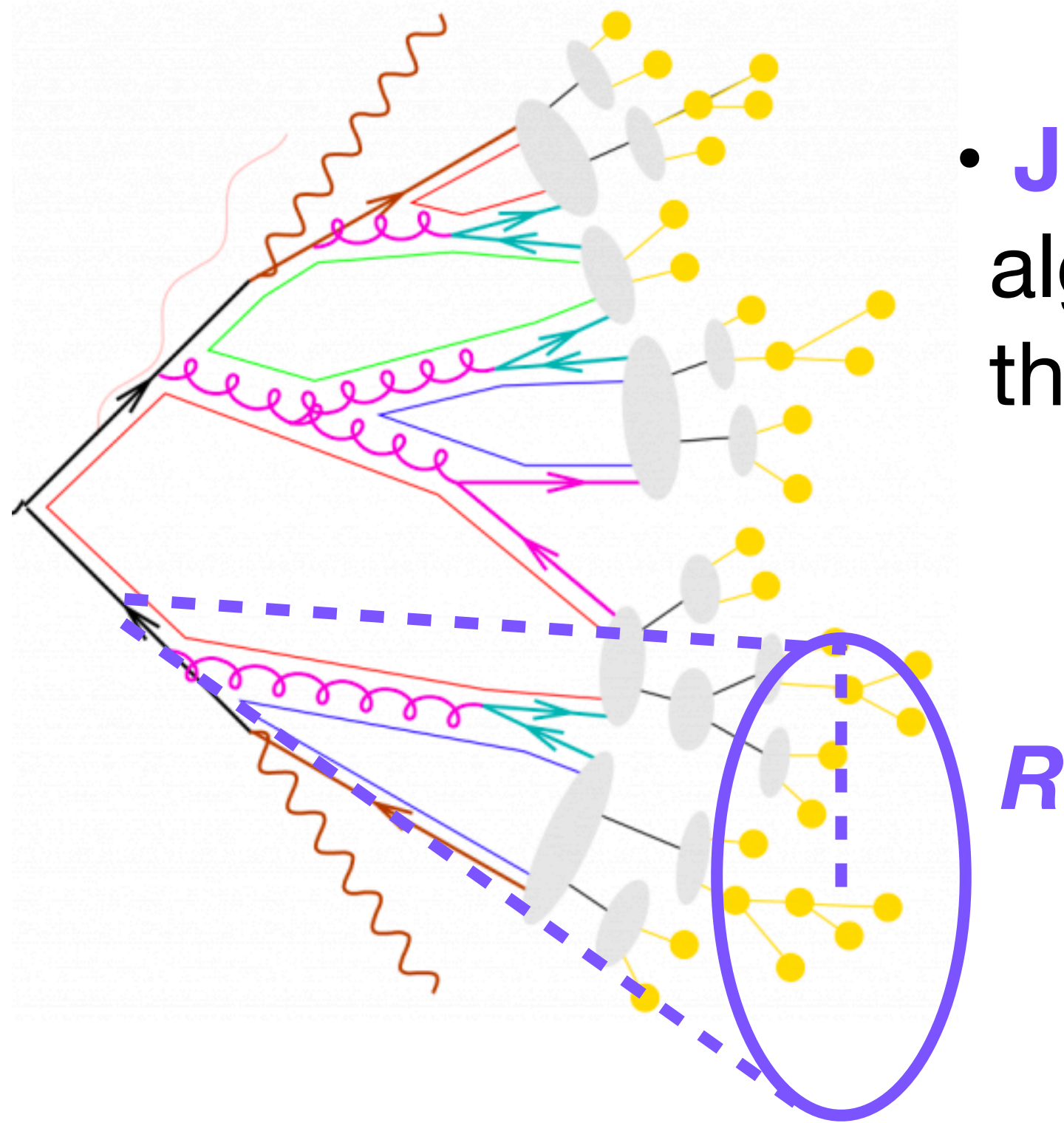
Essence of QCD is encoded across these scales →
construct observables sensitive to this!

JETS AND ENERGY CORRELATORS

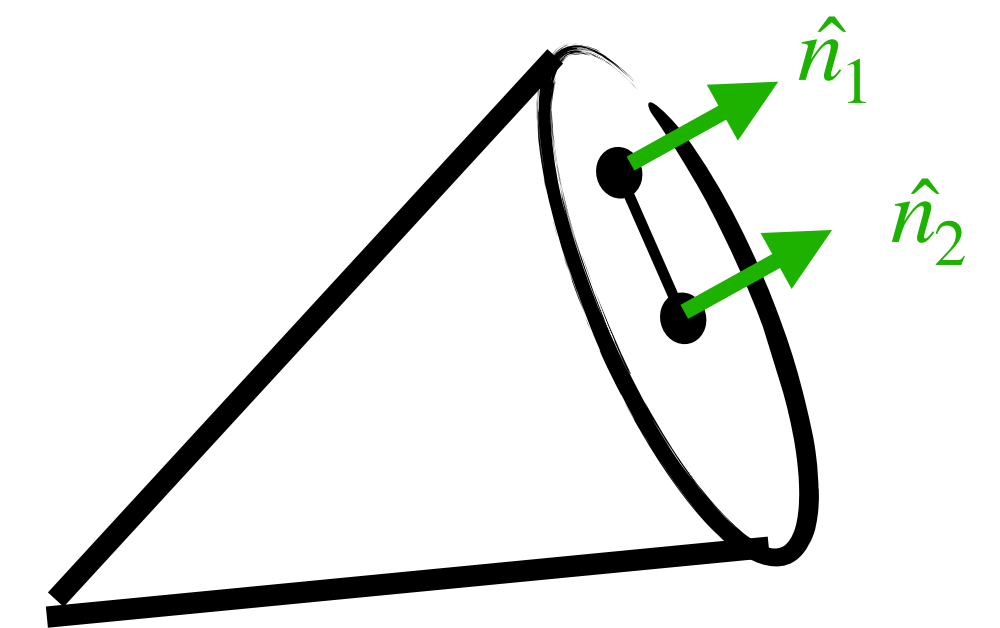
- **Jets** and **energy correlators** are two complementary types of observables that are sensitive to the underlying dynamics of the hard scattering!

- A spray of **hadrons** are created in a hard scattering.

- **Jets** are the result of combining **hadrons** using jet clustering algorithms with a specified **resolution parameter**, related to the cone radius **R** . [\[JHEP 0804:063 \(2008\)\]](#)



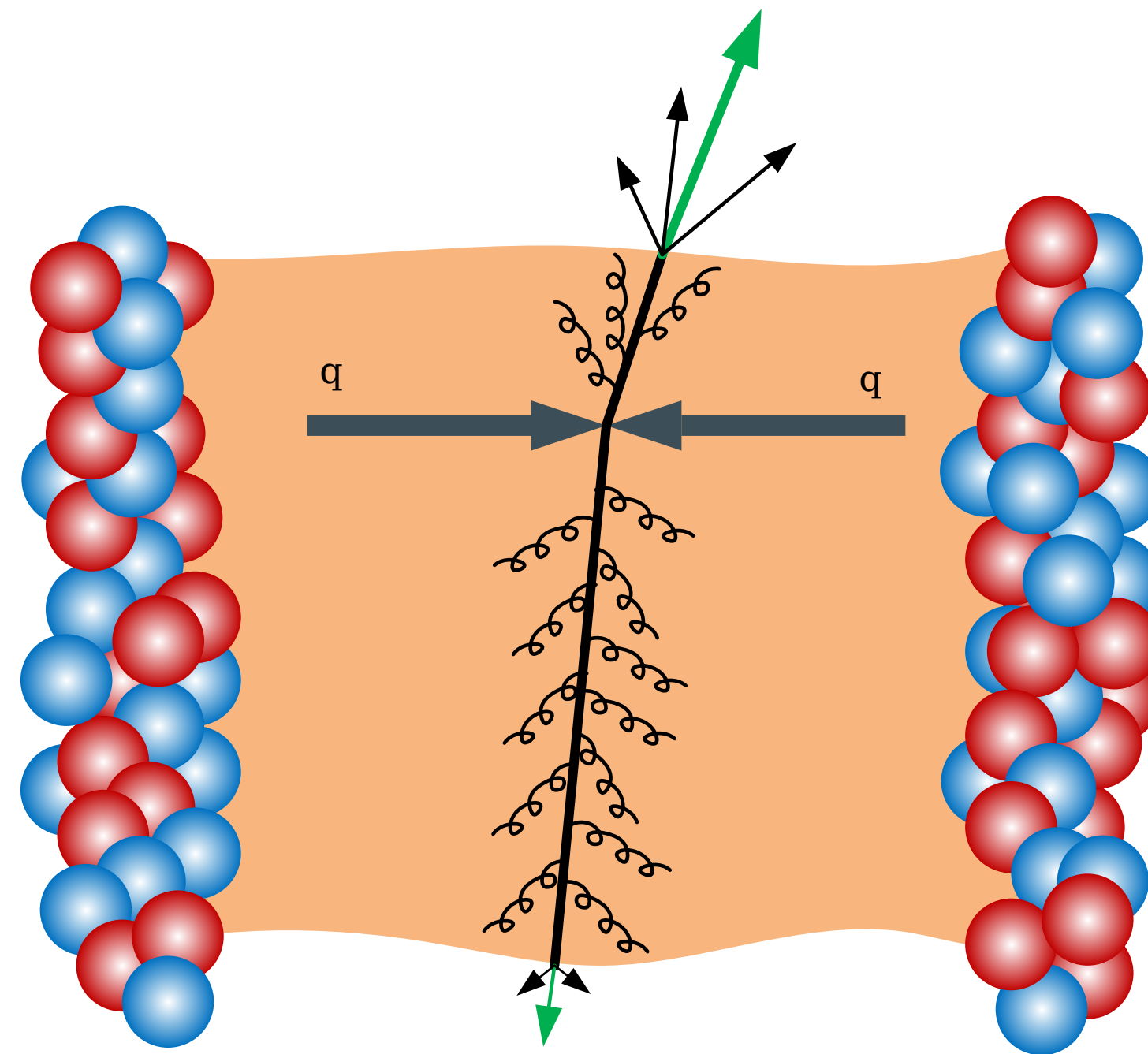
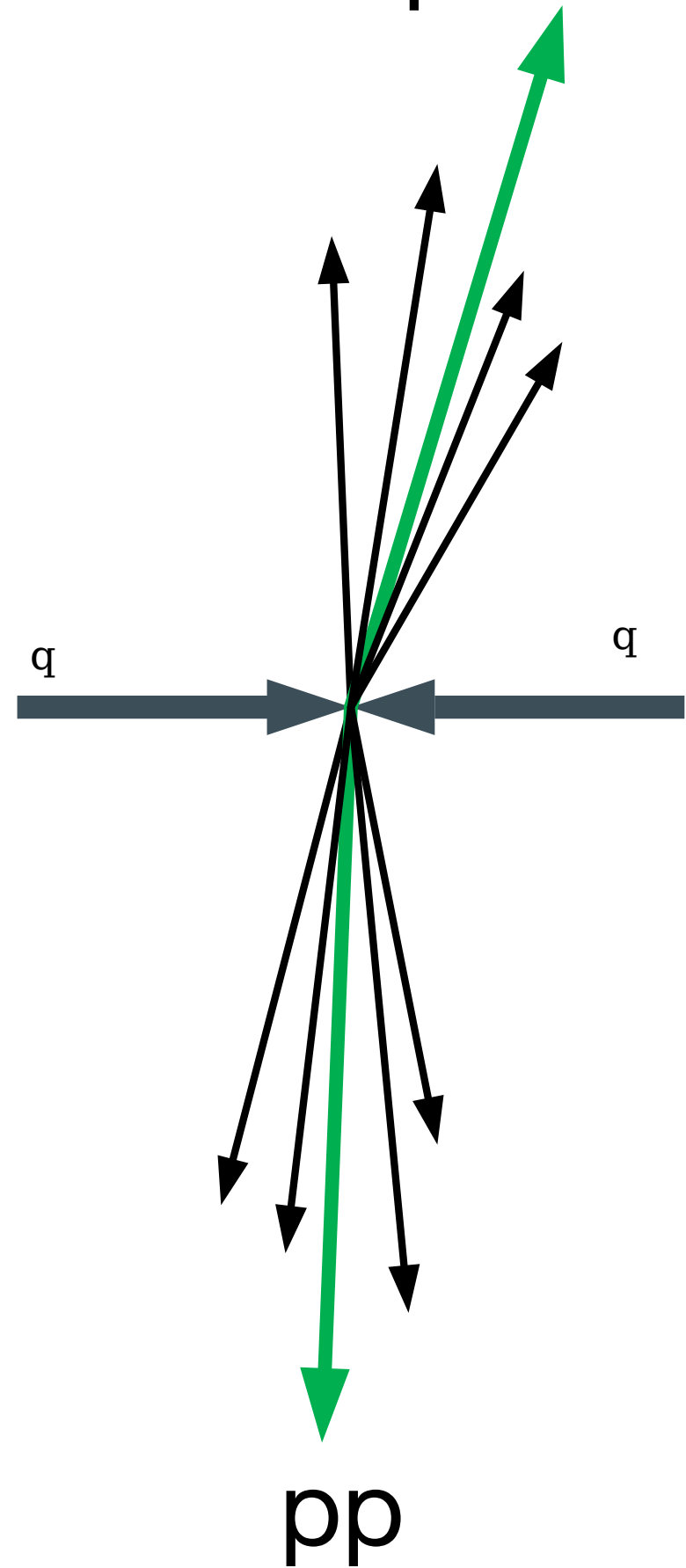
- **Energy correlators** look at correlations between energy flow deposits in a hard scattering.
- Can be computed amongst jet constituents or the whole event.



Defined as the correlation of energy flow operator $\mathcal{E}(\vec{n}_1) = \lim_{r \rightarrow \infty} \int dt r^2 n_1^i T_{0i}(t, r\vec{n}_1)$

HARD PROCESSES IN THE QGP

- Hard processes are expected to be modified in the QGP!



- High p_T parton is expected to lose energy in interactions with the QGP (**jet quenching**).
- Formed before QGP formation.
- A colored probe of the colored QGP medium!
 - Useful for understanding its dynamical properties.

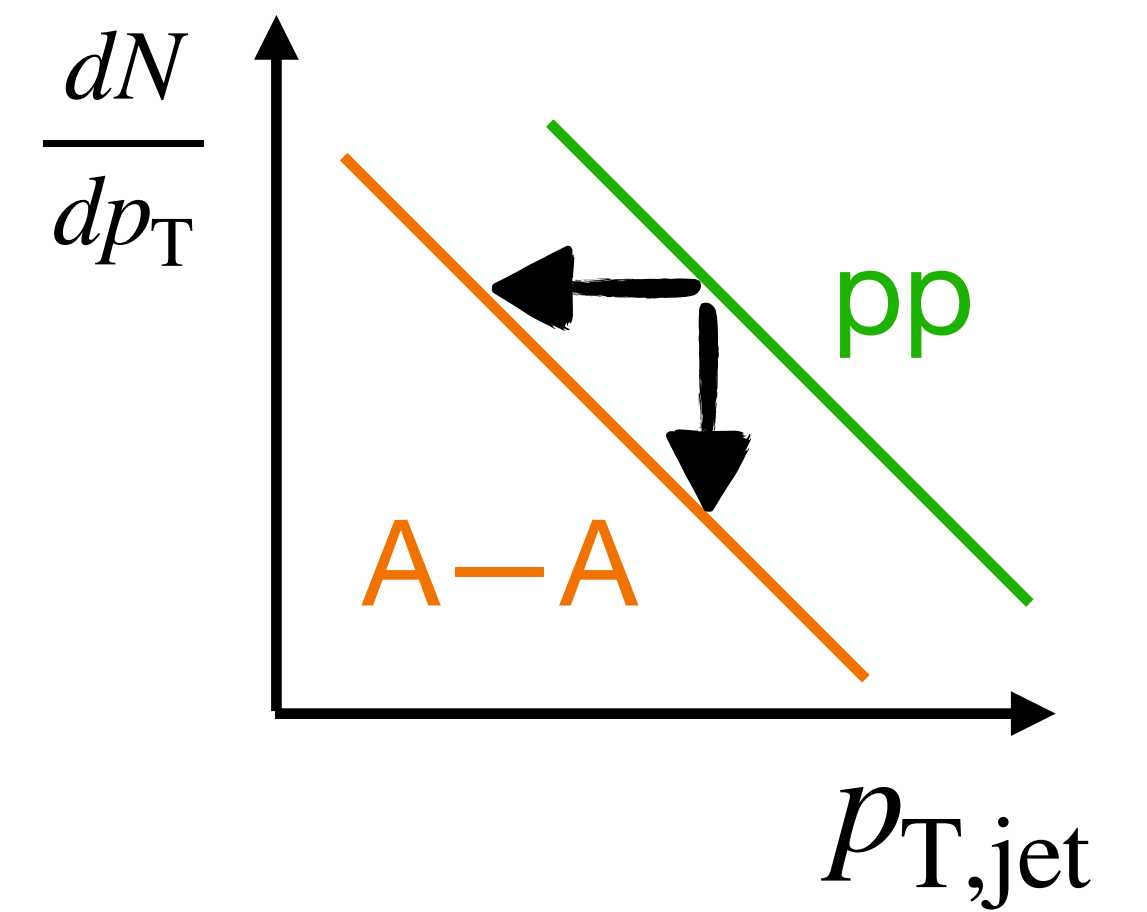
- Use pp, where measurements are performed in vacuum, as a reference for no QGP.

[See Adam Takacs's Talk Mon. 11:00] [See Florian Lindenbauer's Talk Mon. 11:30]

[See Min An's Talk Mon. 12:00]

EXPECTATIONS OF JET QUENCHING

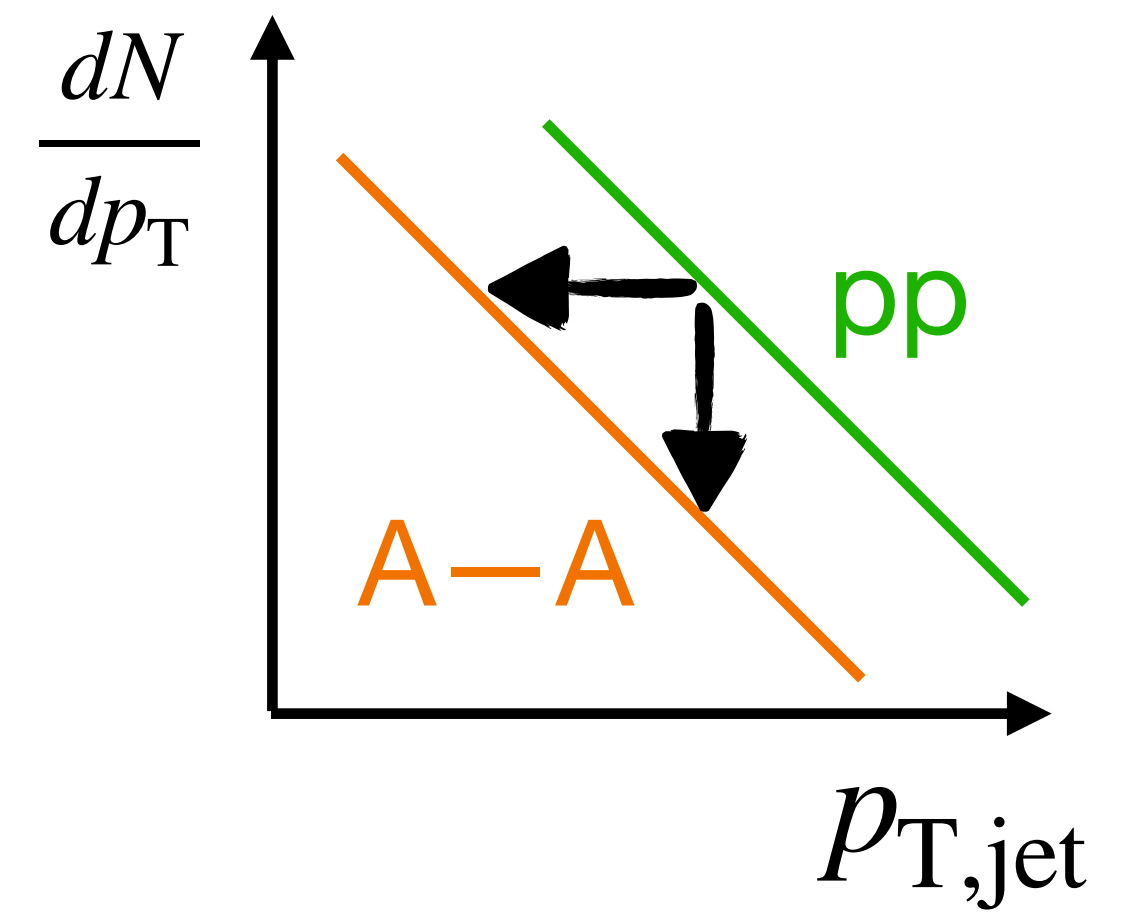
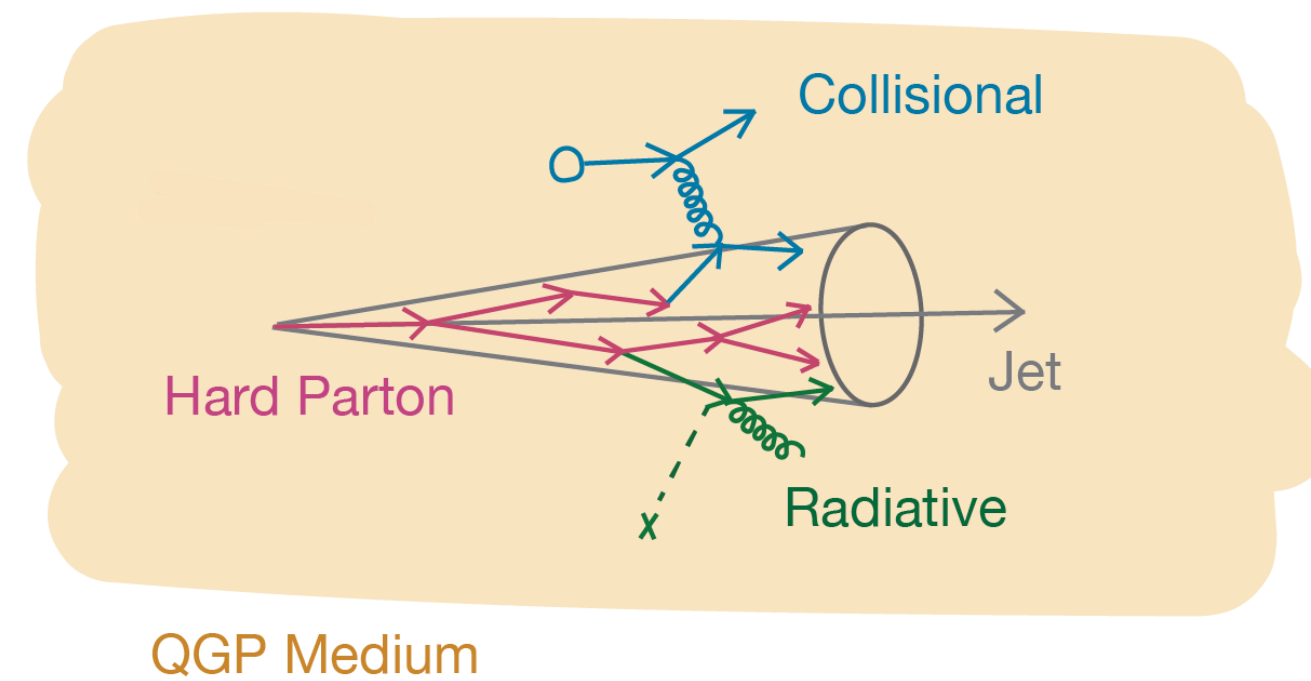
- ① **Parton energy loss** leading to a suppression of jet yields in heavy-ions (A—A) in comparison to vacuum (pp).



EXPECTATIONS OF JET QUENCHING

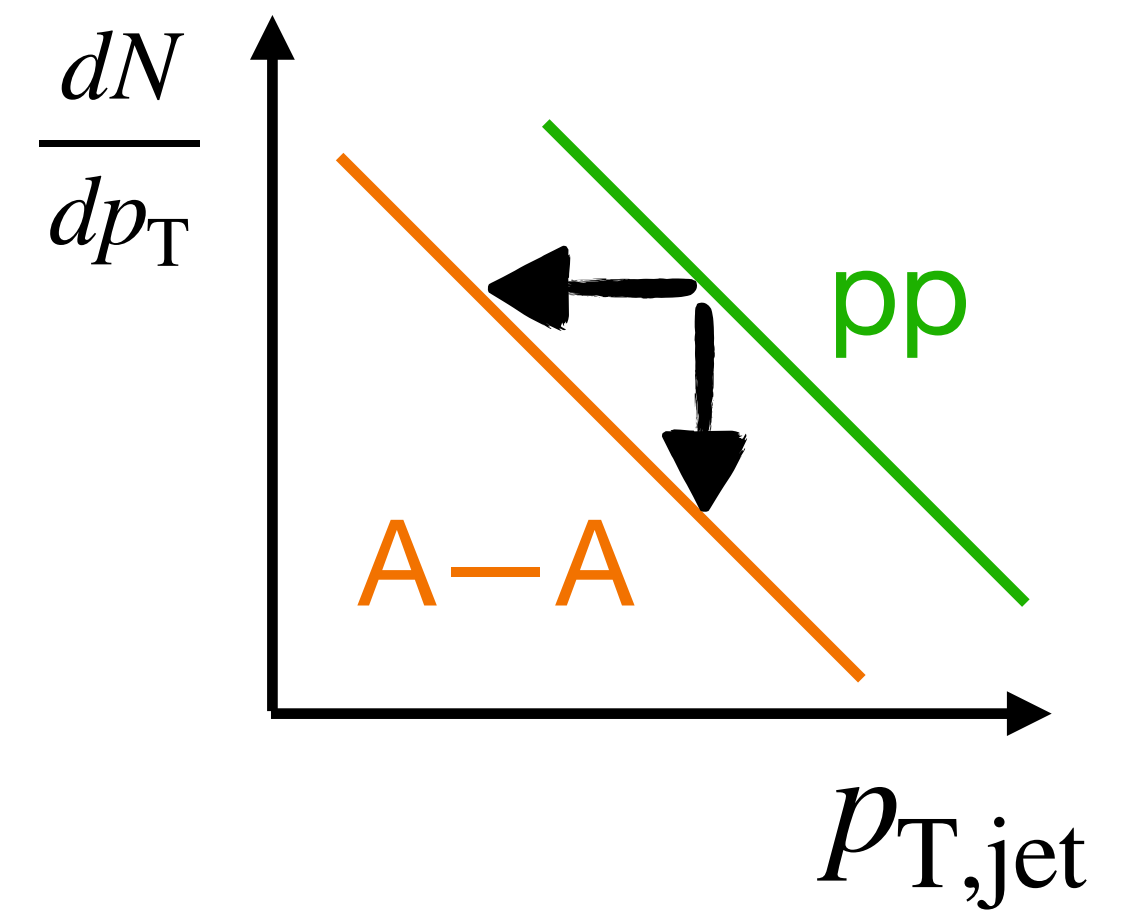
① **Parton energy loss** leading to a suppression of jet yields in heavy-ions (A—A) in comparison to vacuum (pp).

② **Internal structure modification**

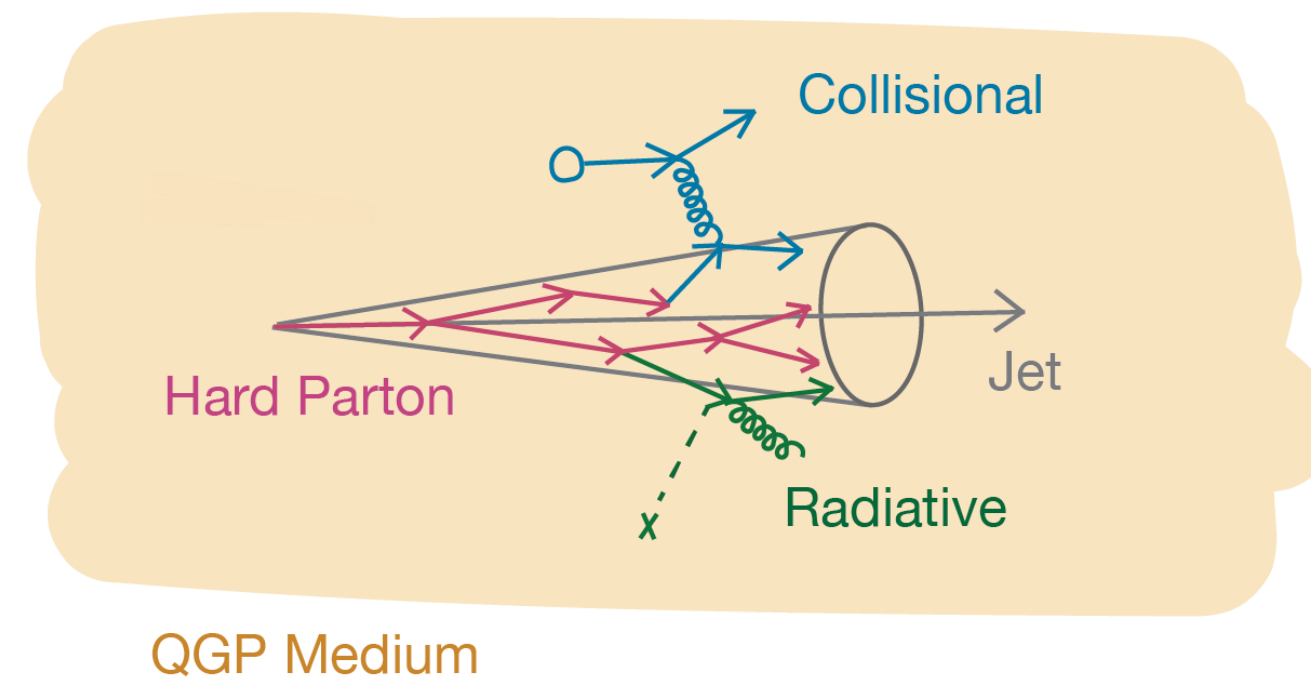


EXPECTATIONS OF JET QUENCHING

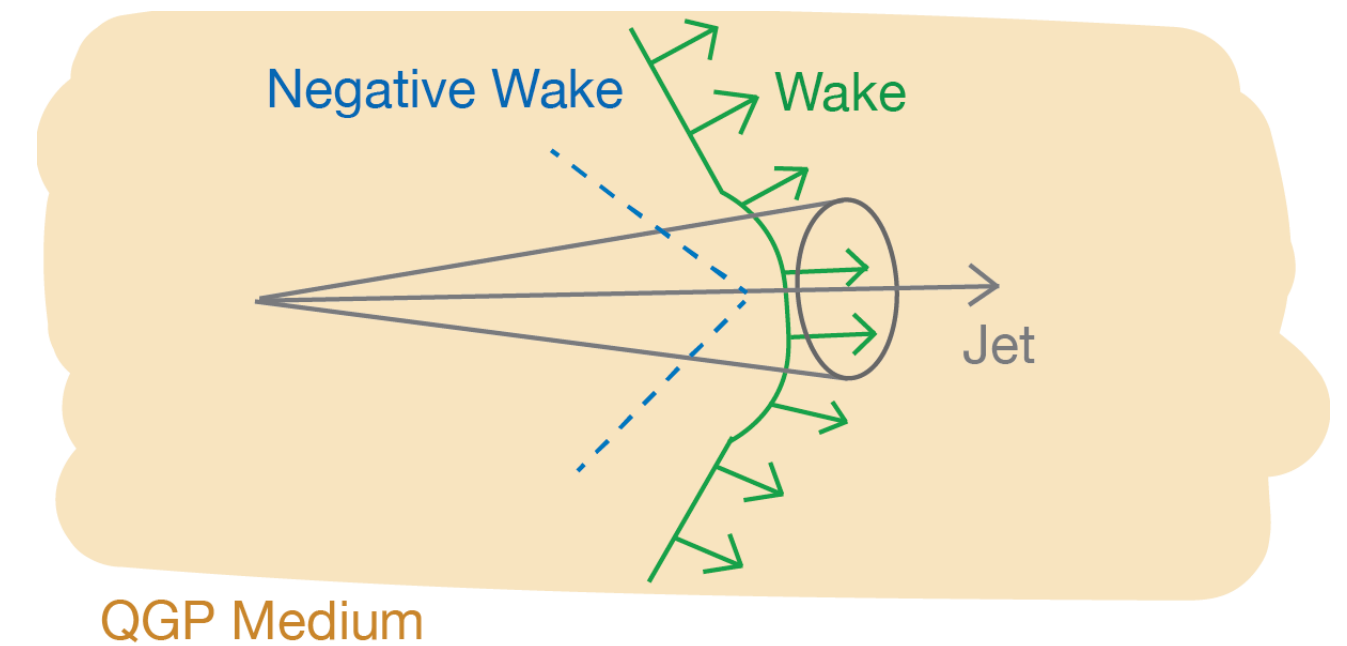
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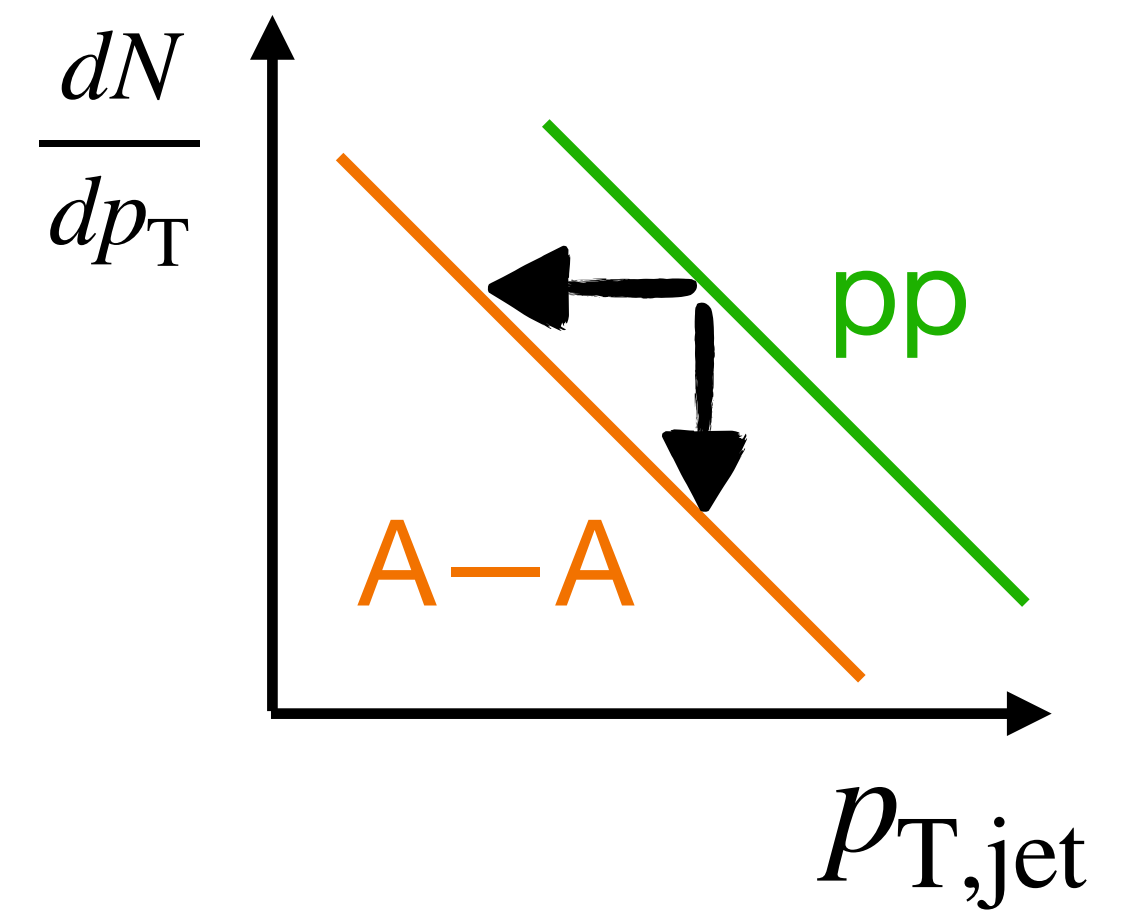


③ **Medium should respond to the presence of the jet**

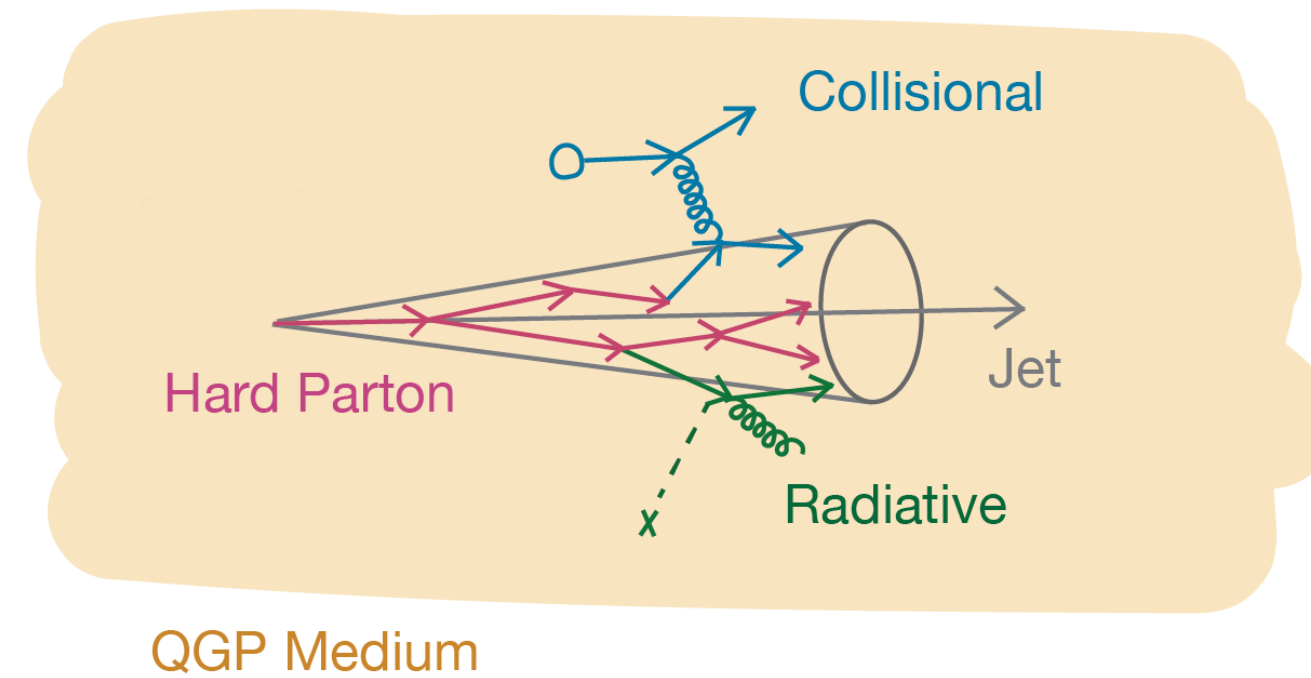


EXPECTATIONS OF JET QUENCHING

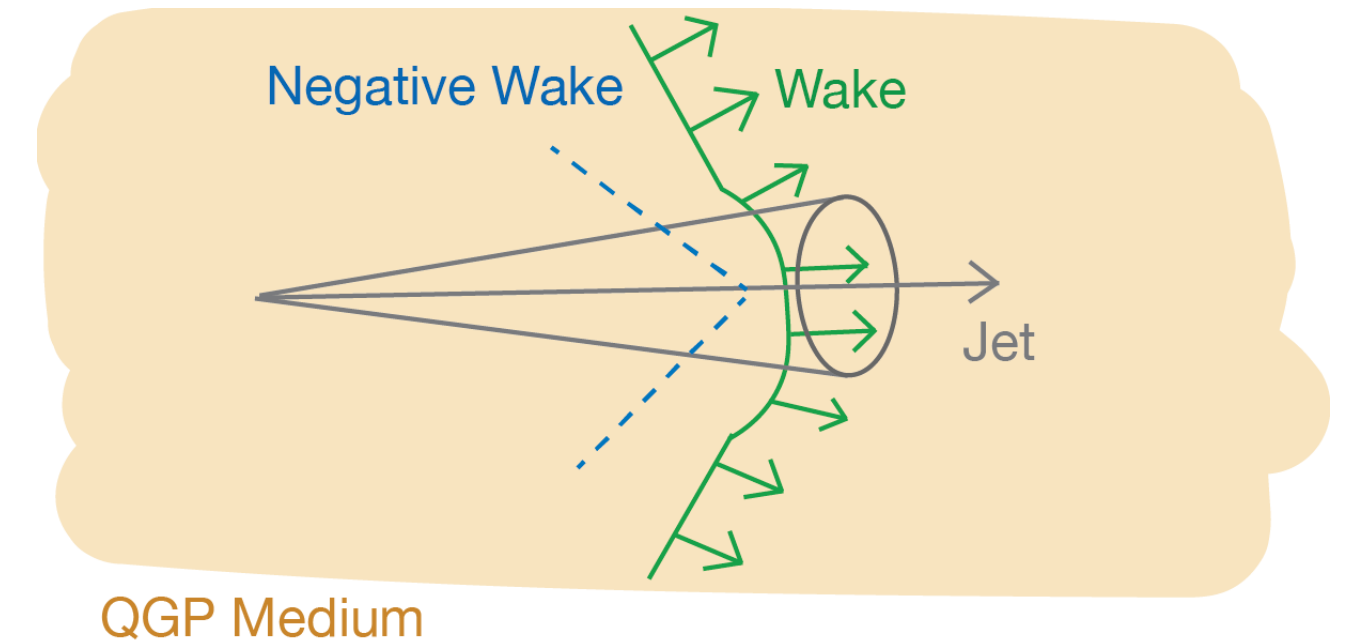
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② **Internal structure modification**



③ **Medium should respond to the presence of the jet**

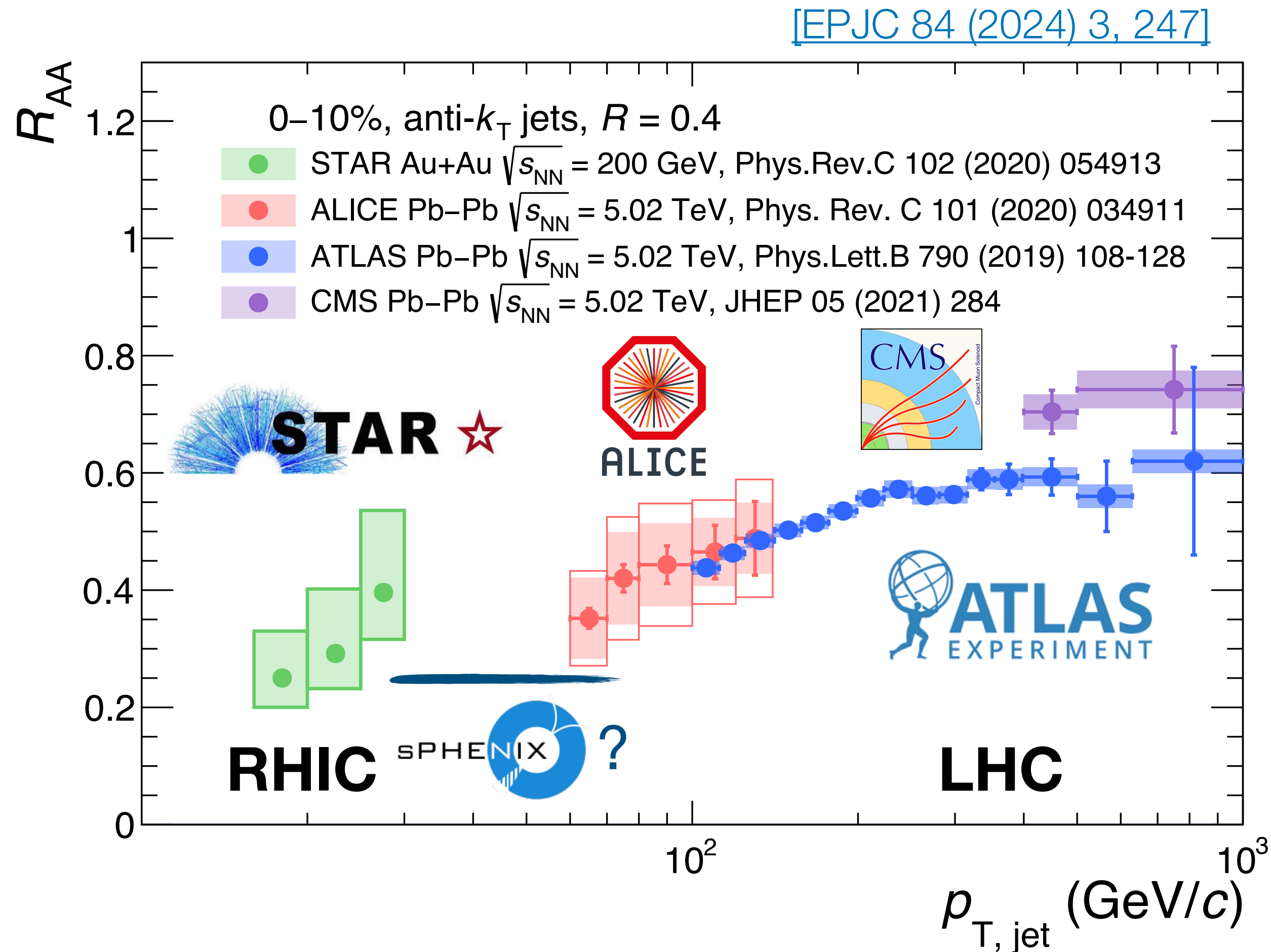


④ **Different jets lose energy differently** depending on different partonic structures, flavors, transverse momenta, path lengths through the medium, etc.

Differential measurements are key to understanding dynamical properties of QGP.

WHAT HAVE WE LEARNED SO FAR?

- 1 Parton energy loss leading to a suppression of jet yields in heavy-ions (A—A) in comparison to vacuum (pp).



- *We have learned* that jets are suppressed, indicating that partons lose energy.

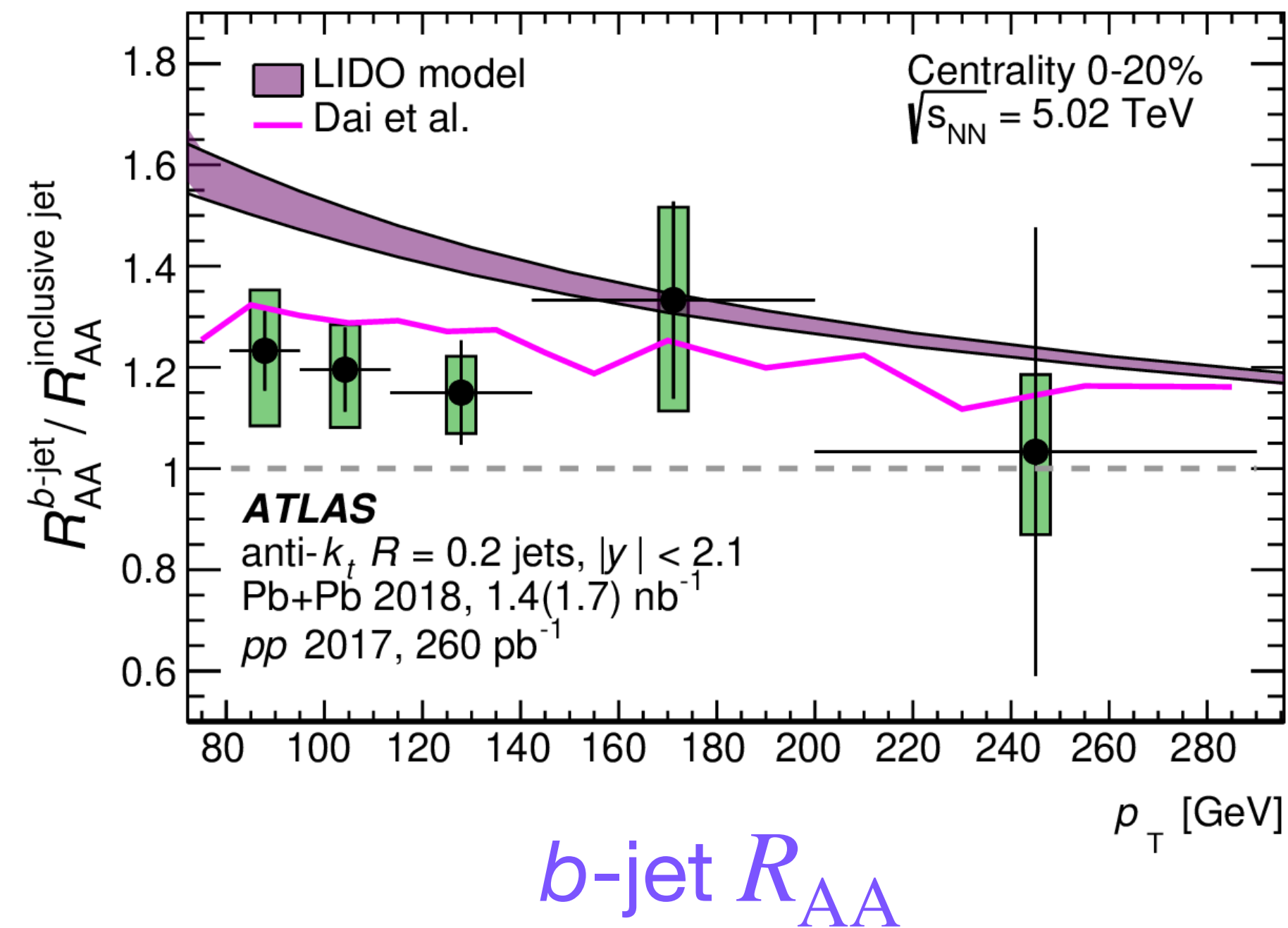
WHAT HAVE WE LEARNED SO FAR?

① **Parton energy loss** leading to a suppression of jet yields in heavy-ions (A—A) in comparison to vacuum (pp).

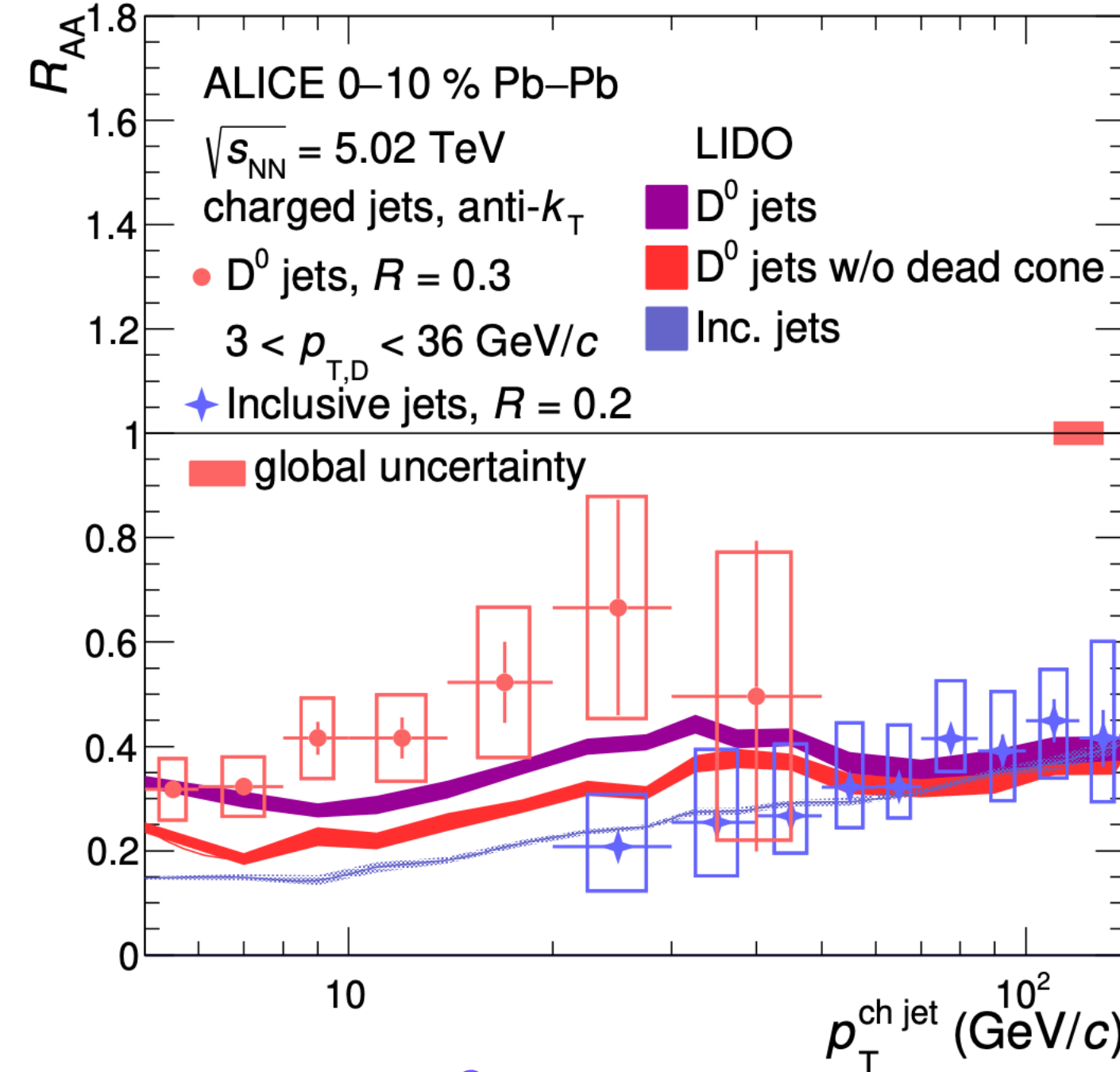
- We have learned* that the amount of energy lost appears to depend **color-charge**

[PLB 846 (2023) 138154]

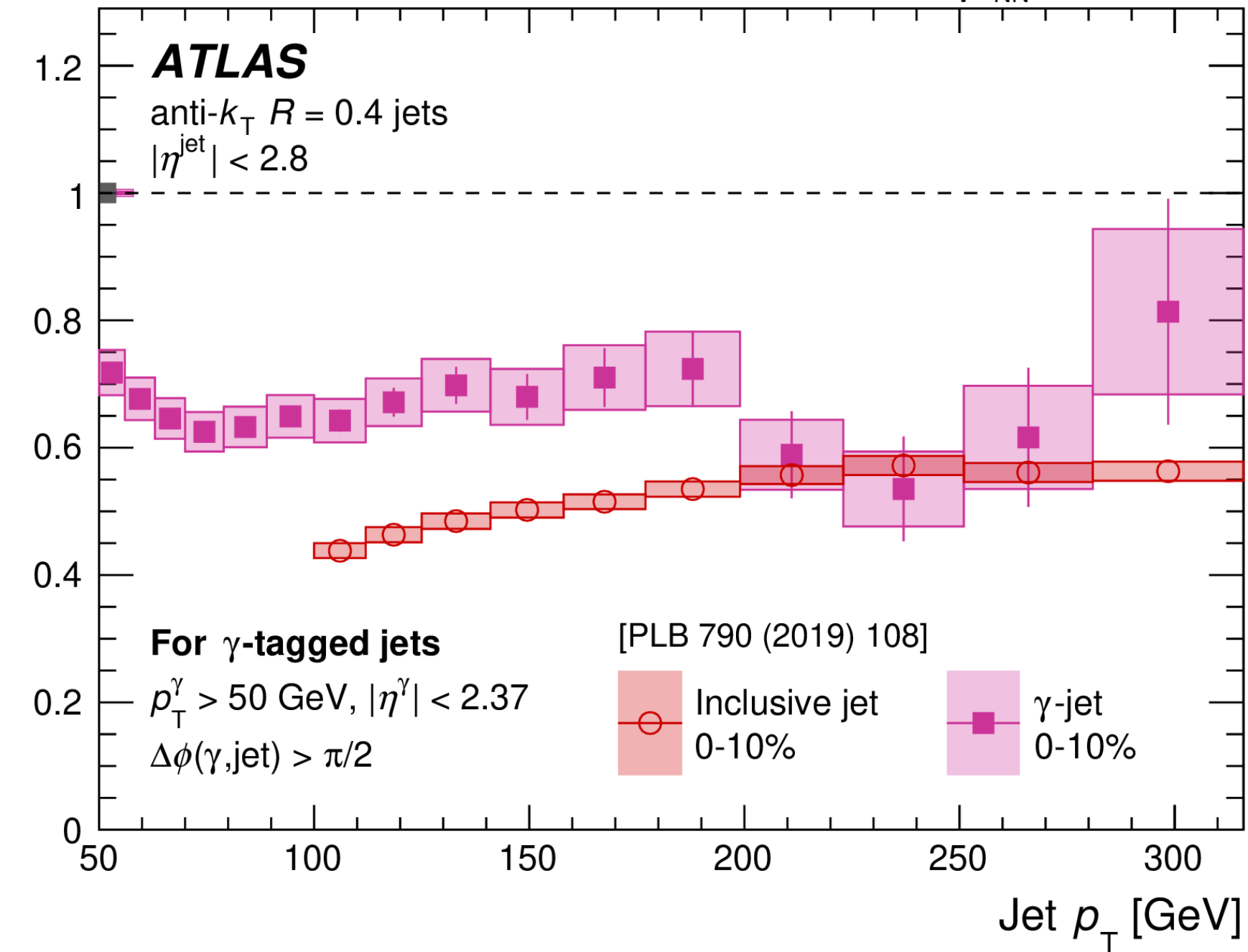
[EPJC 83 (2023) 438]



[PLB 875 (2026) 140299]



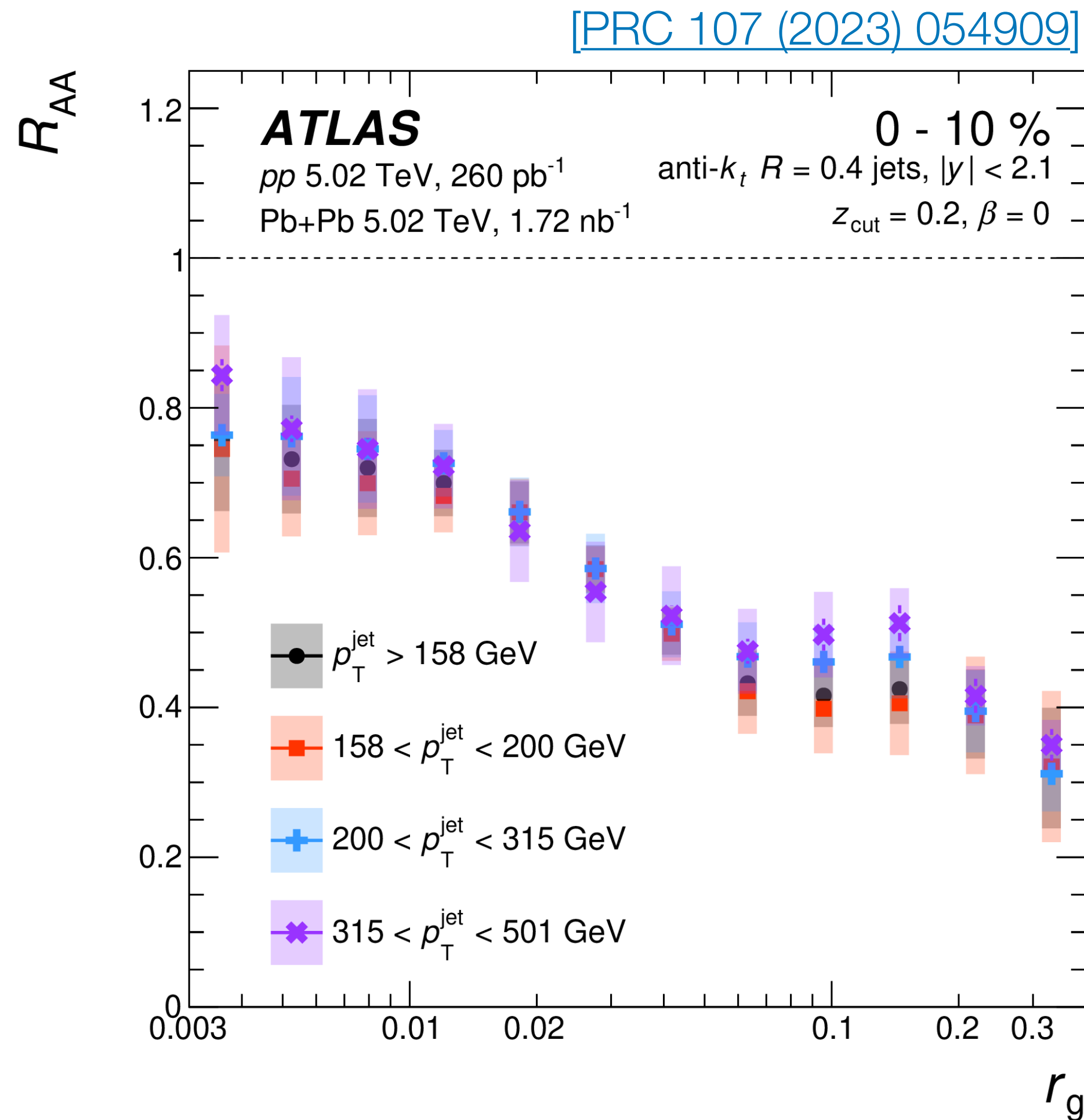
2018 Pb+Pb 1.7 nb⁻¹, 2017 pp 260 pb⁻¹, $\sqrt{s_{NN}} = 5.02$ TeV



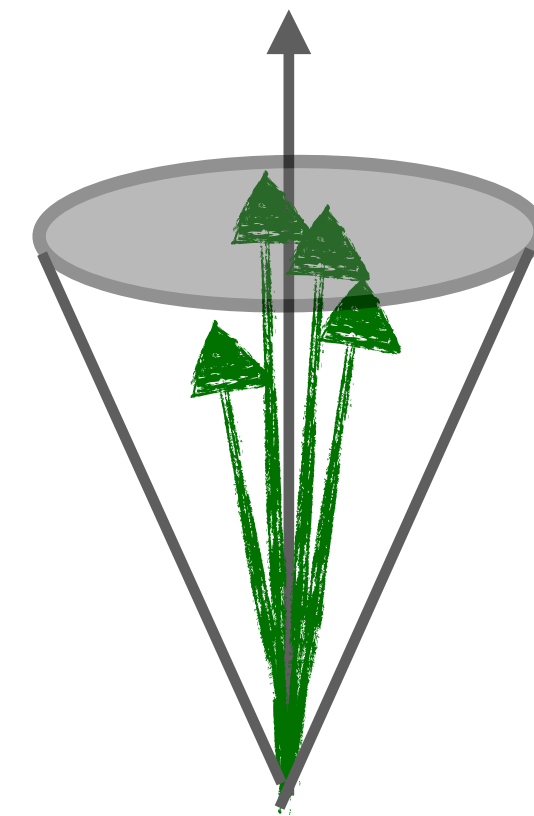
[See Jean Du Plessis's Talk Mon. 12:30]

WHAT HAVE WE LEARNED SO FAR?

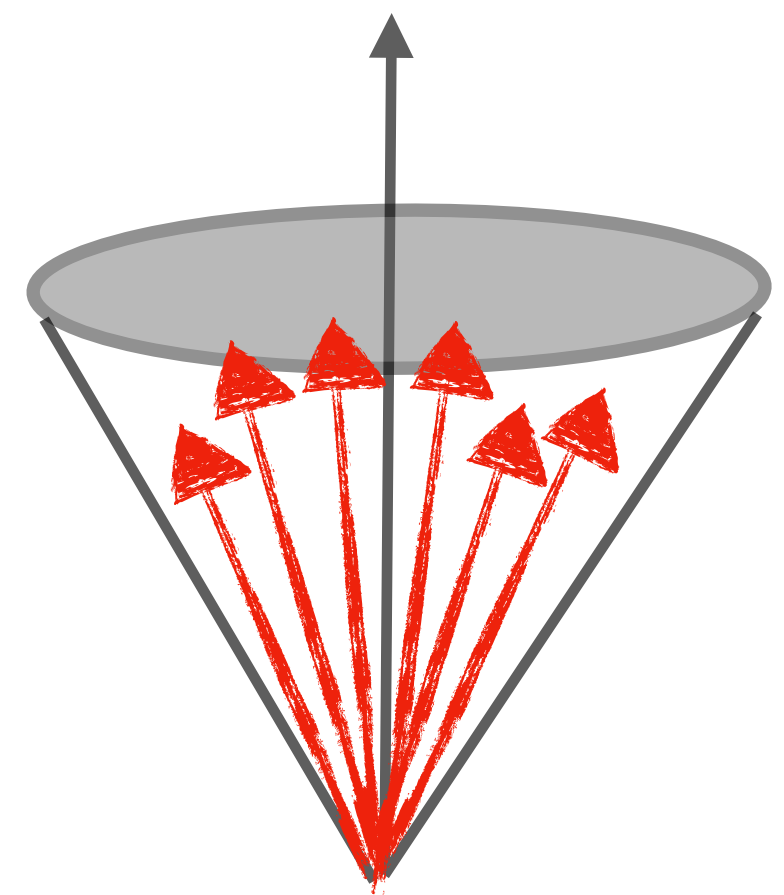
- 1 Parton energy loss leading to a suppression of jet yields in heavy-ions (A—A) in comparison to vacuum (pp).



- *We have learned* that the amount of energy lost also depends on a jet's substructure
 - Color charge may also play a role, quark jets narrower than gluon jets.



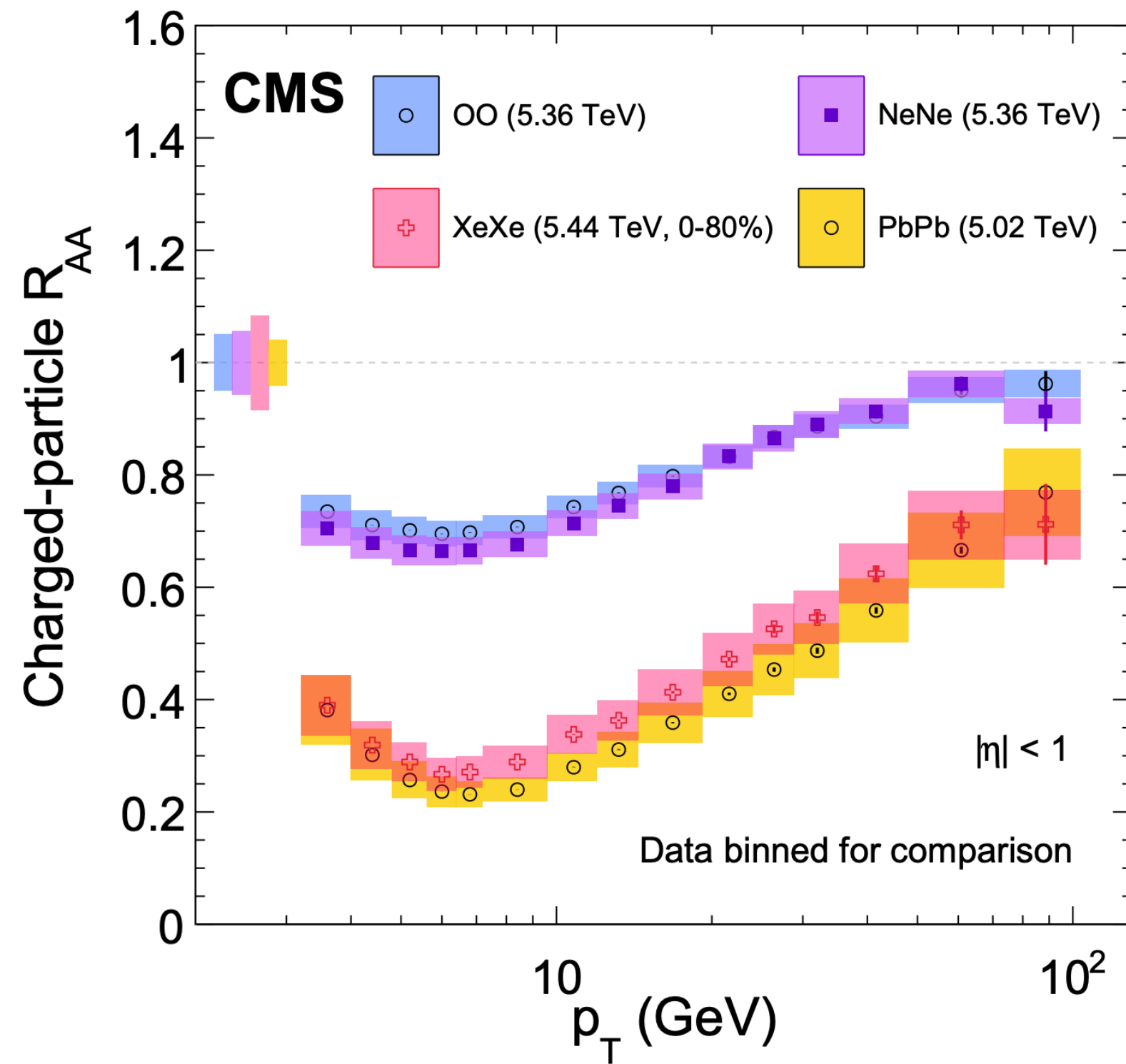
Quark jet



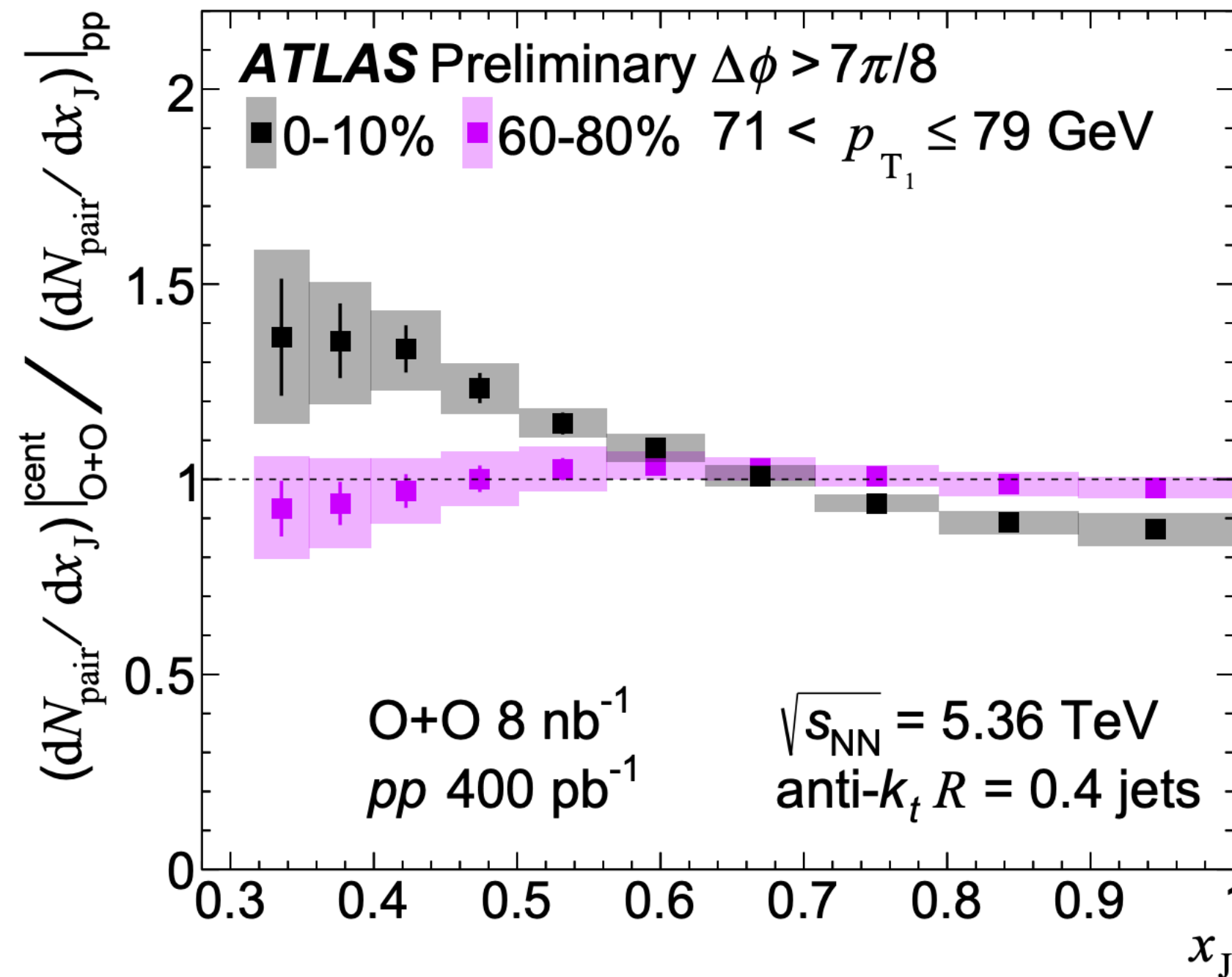
Gluon jet

WHAT HAVE WE LEARNED SO FAR?

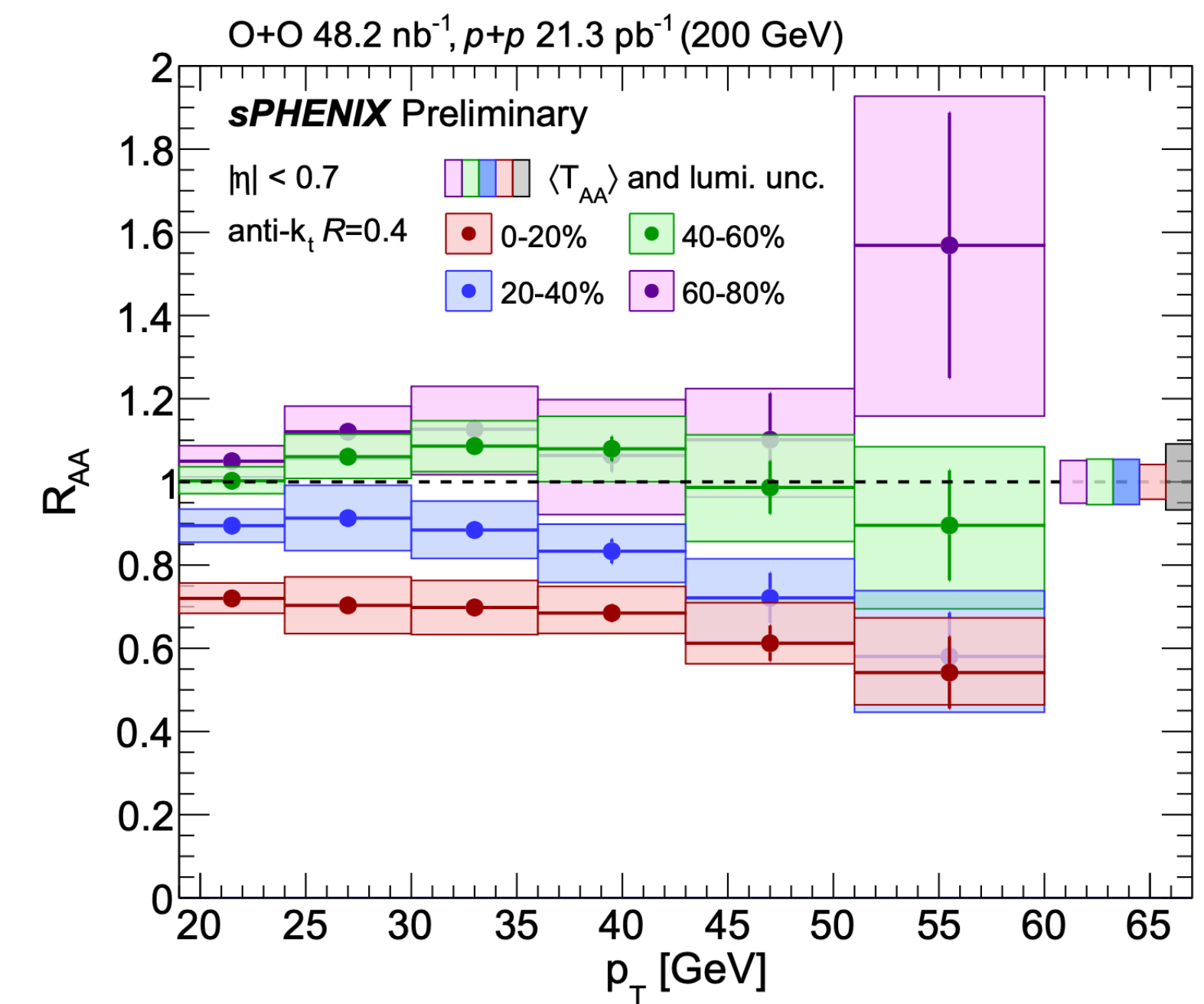
- 1 Parton energy loss leading to a suppression of jet yields in heavy-ions (A—A) in comparison to vacuum (pp).



[arXiv:2602.21325] [PRL 136 (2026) 162301]



[ATLAS-CONF-2025-010]



[sPH-CONF-JET-2026-02]

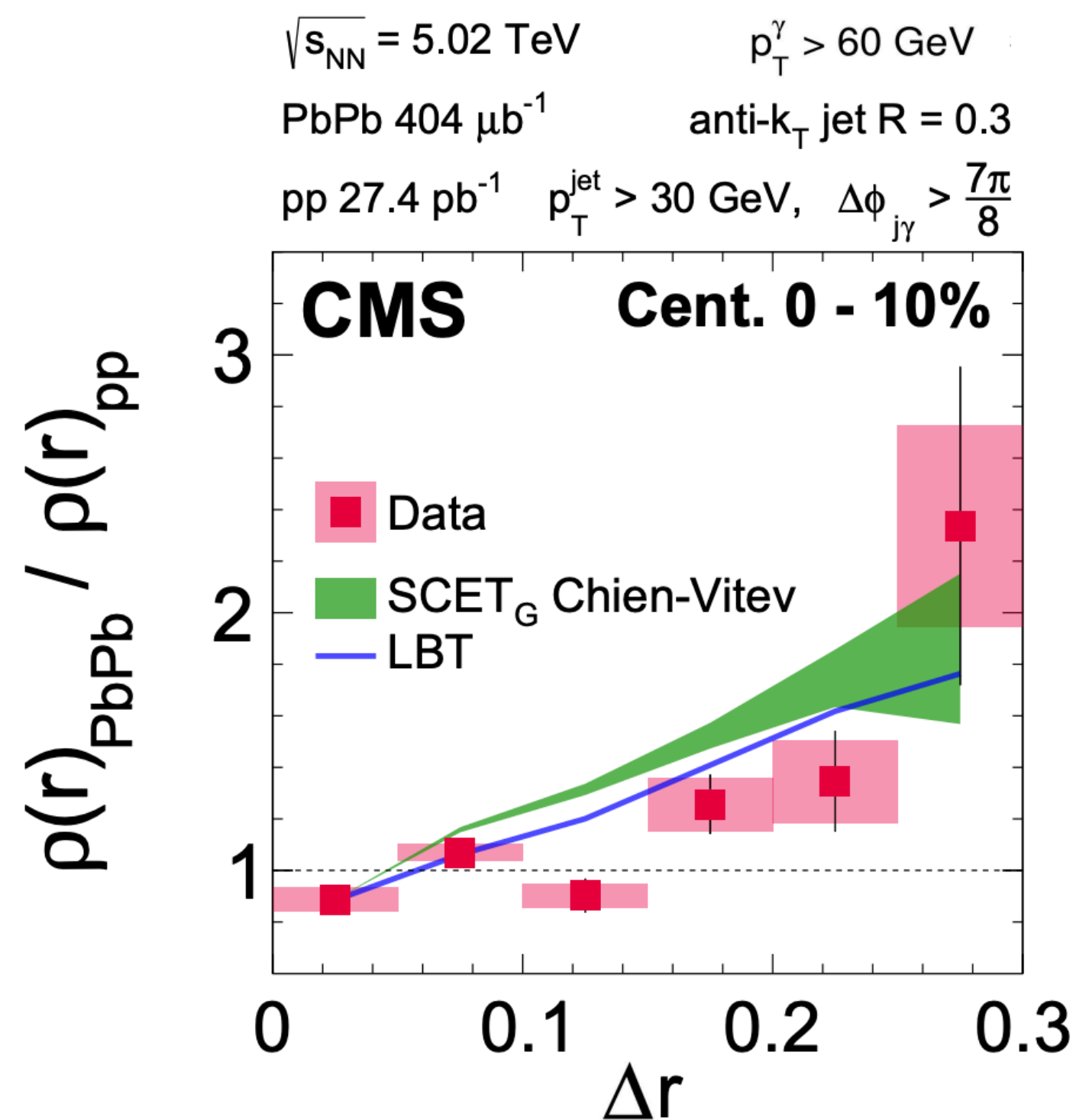
- *We have seen indications of parton energy loss in light ions!*

WHAT HAVE WE LEARNED SO FAR?

② Internal structure modification

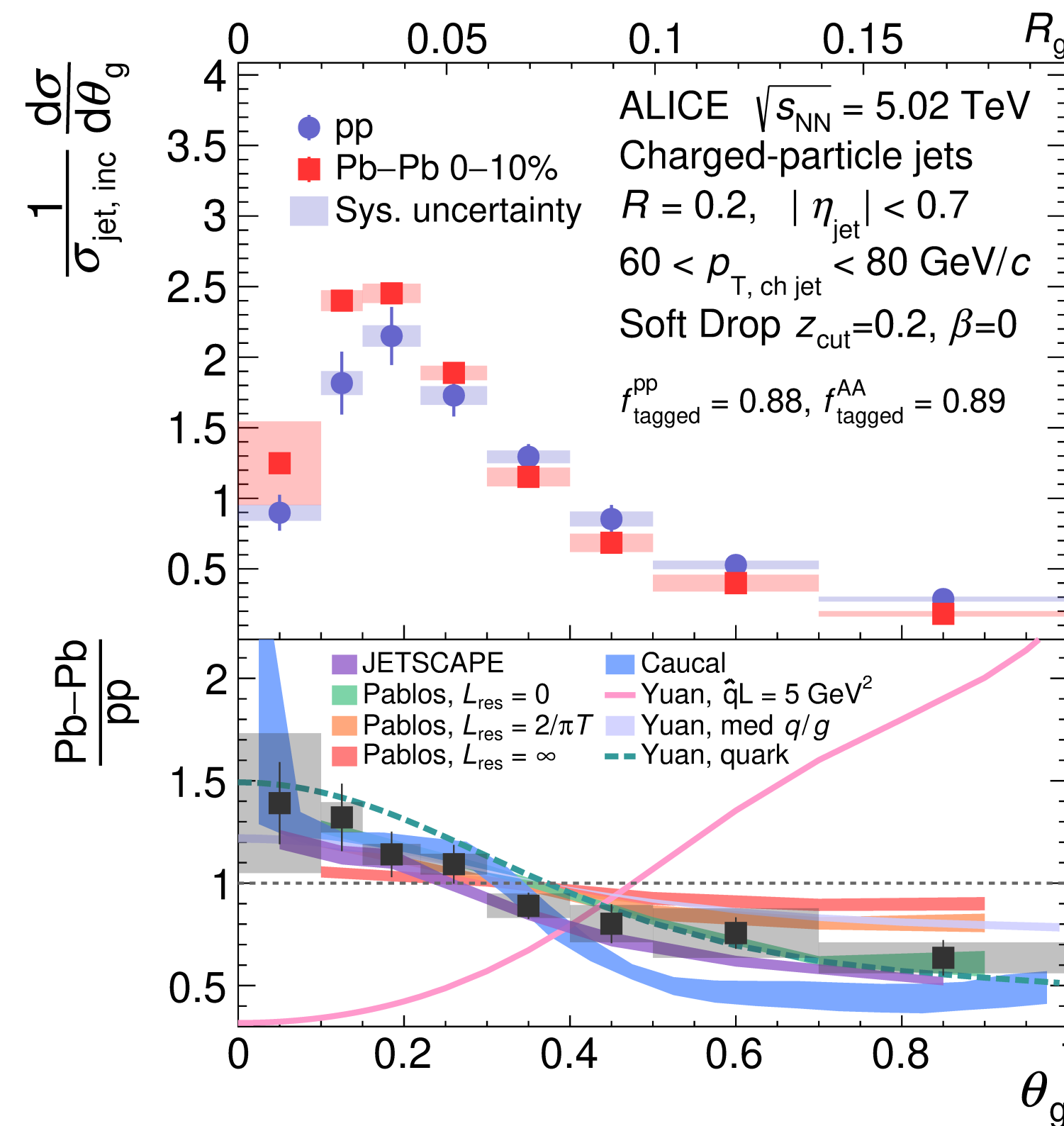
- *We have learned* that both the **jet structure** and **jet substructure** are modified when you compare AA distributions to a pp reference

jet structure: distribution of radiation



[PRL 122, 152001 (2019)]

jet substructure: splitting pattern



ALI-PUB-495863

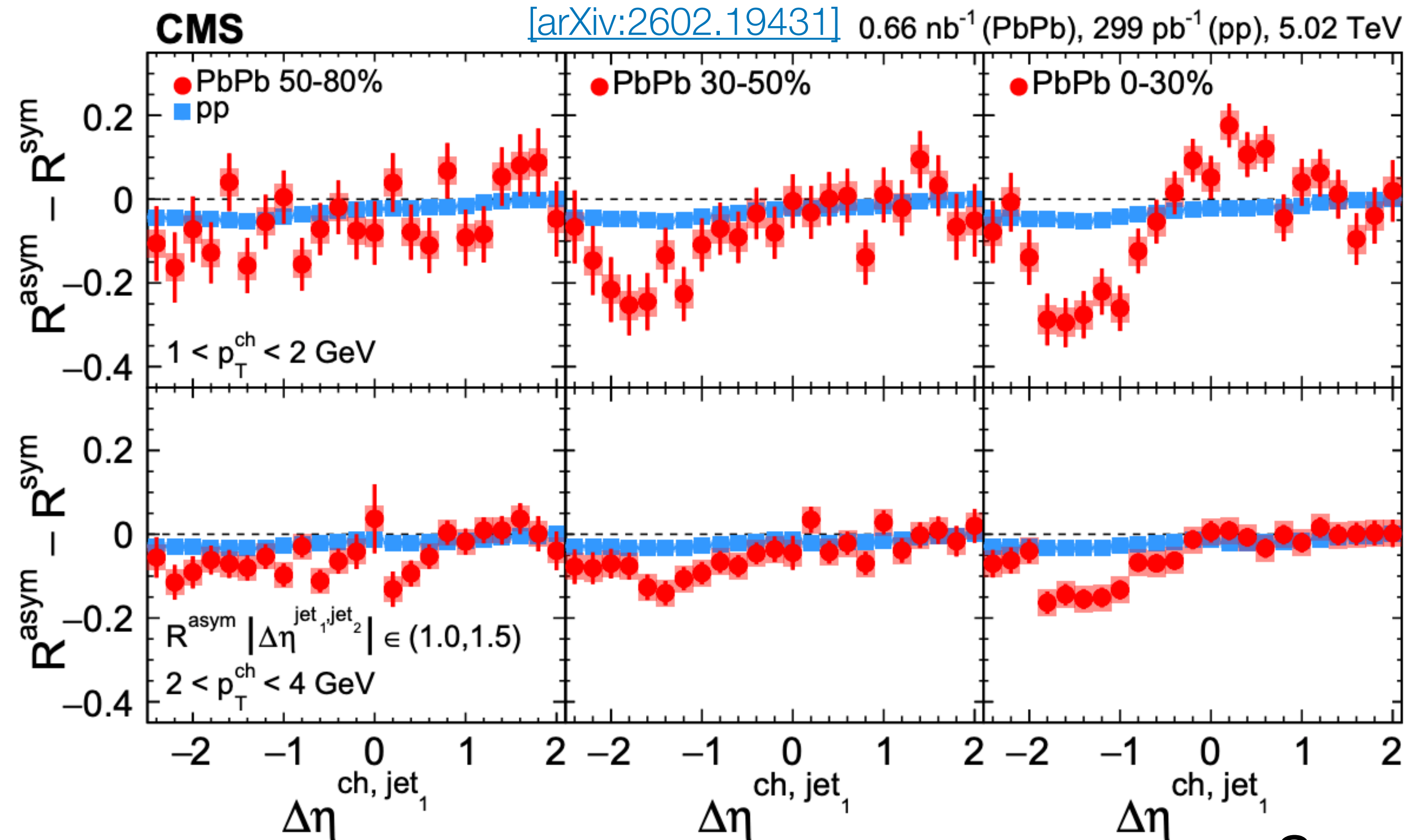
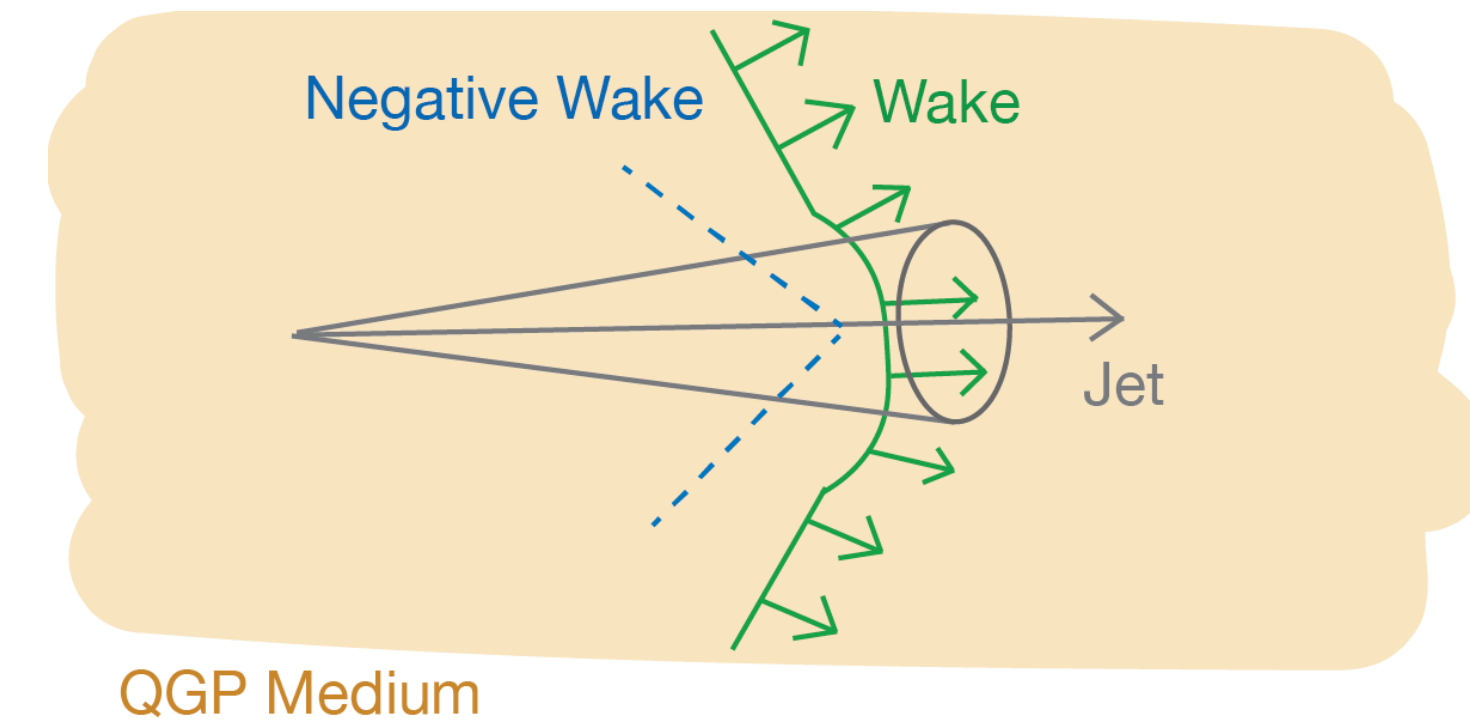
[PRL 128, 102001 (2022)]

... but we have also learned that selection bias effects can make this more difficult to interpret.

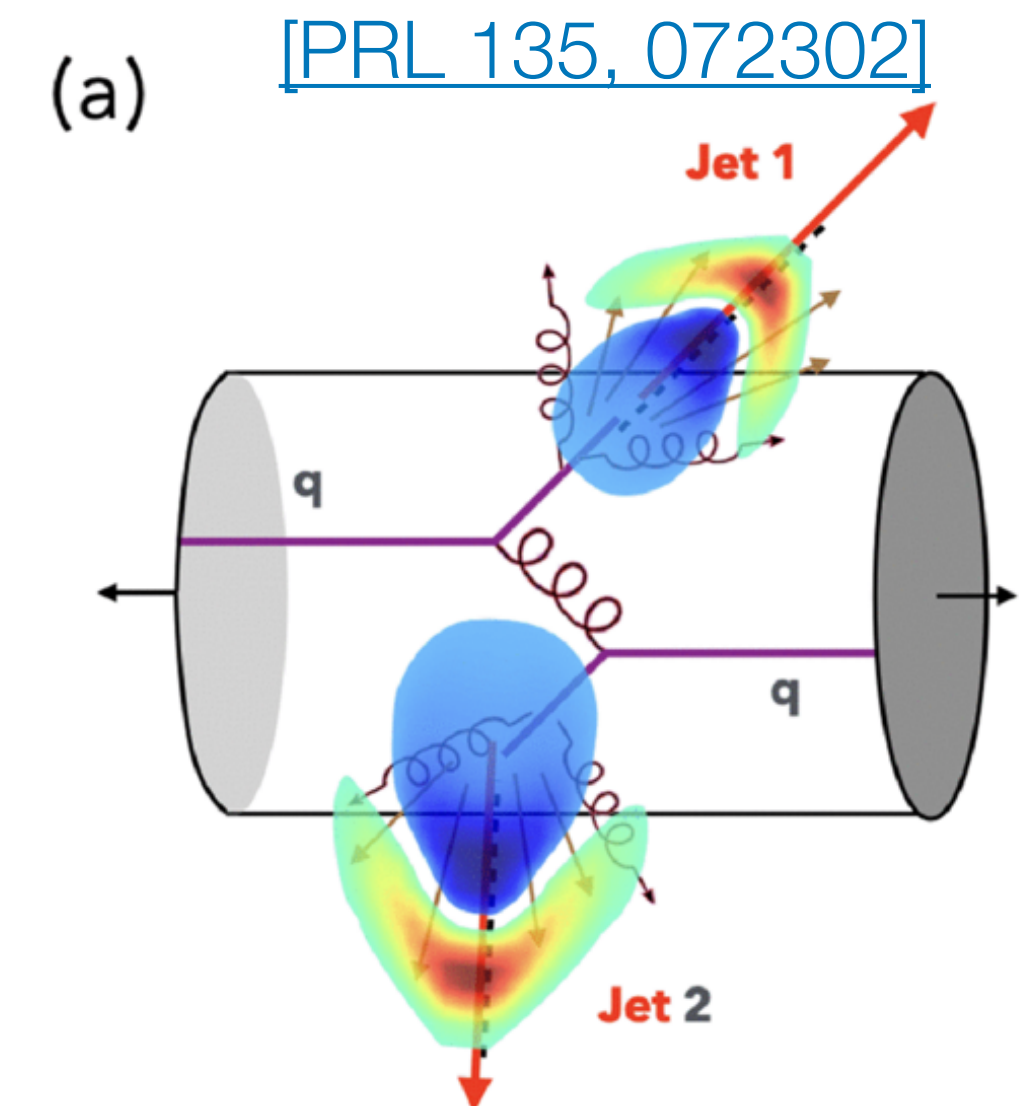
WHAT HAVE WE LEARNED SO FAR?

③ Medium should respond to the presence of the jet

- *We have learned* that (though difficult) you can measure the medium response!



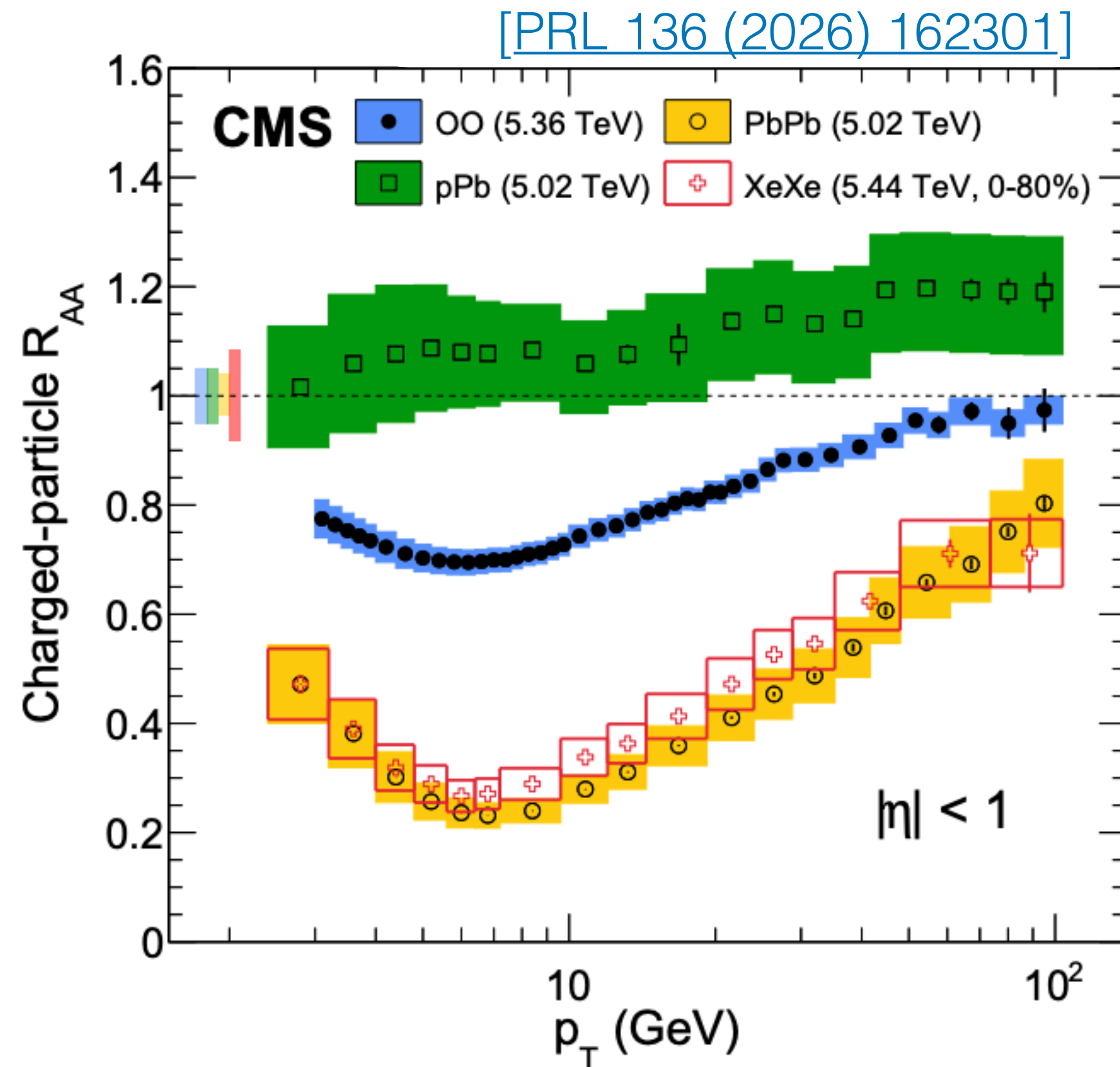
- Quantified by difference between symmetric and asymmetric dijet pairs.



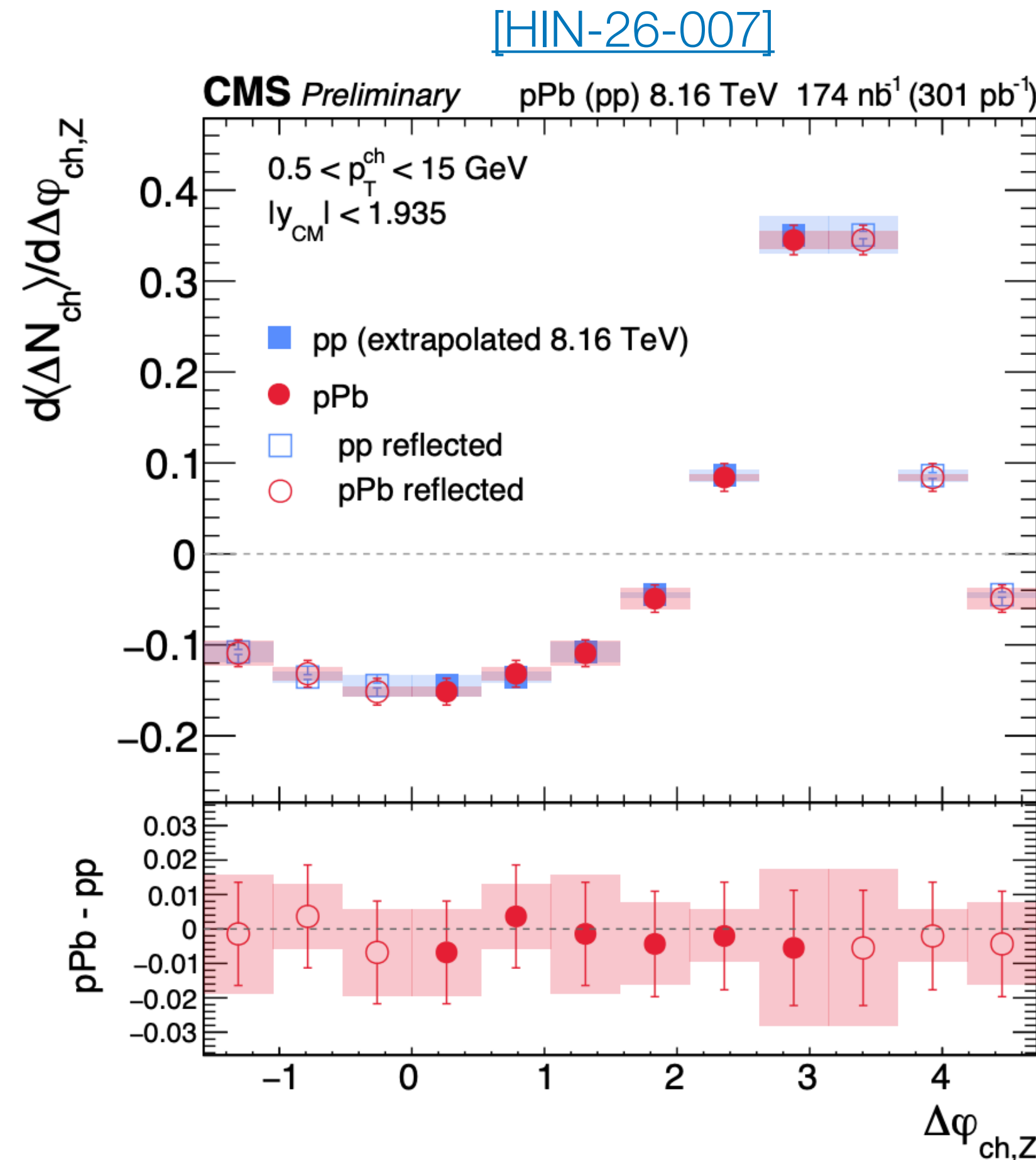
See also [\[PLB 874 \(2026\) 140120\]](https://arxiv.org/abs/2602.19431) [\[PRC 111 \(2025\) 044909\]](https://arxiv.org/abs/2504.04909)

BUT DO WE SEE JET QUENCHING EVERYWHERE?

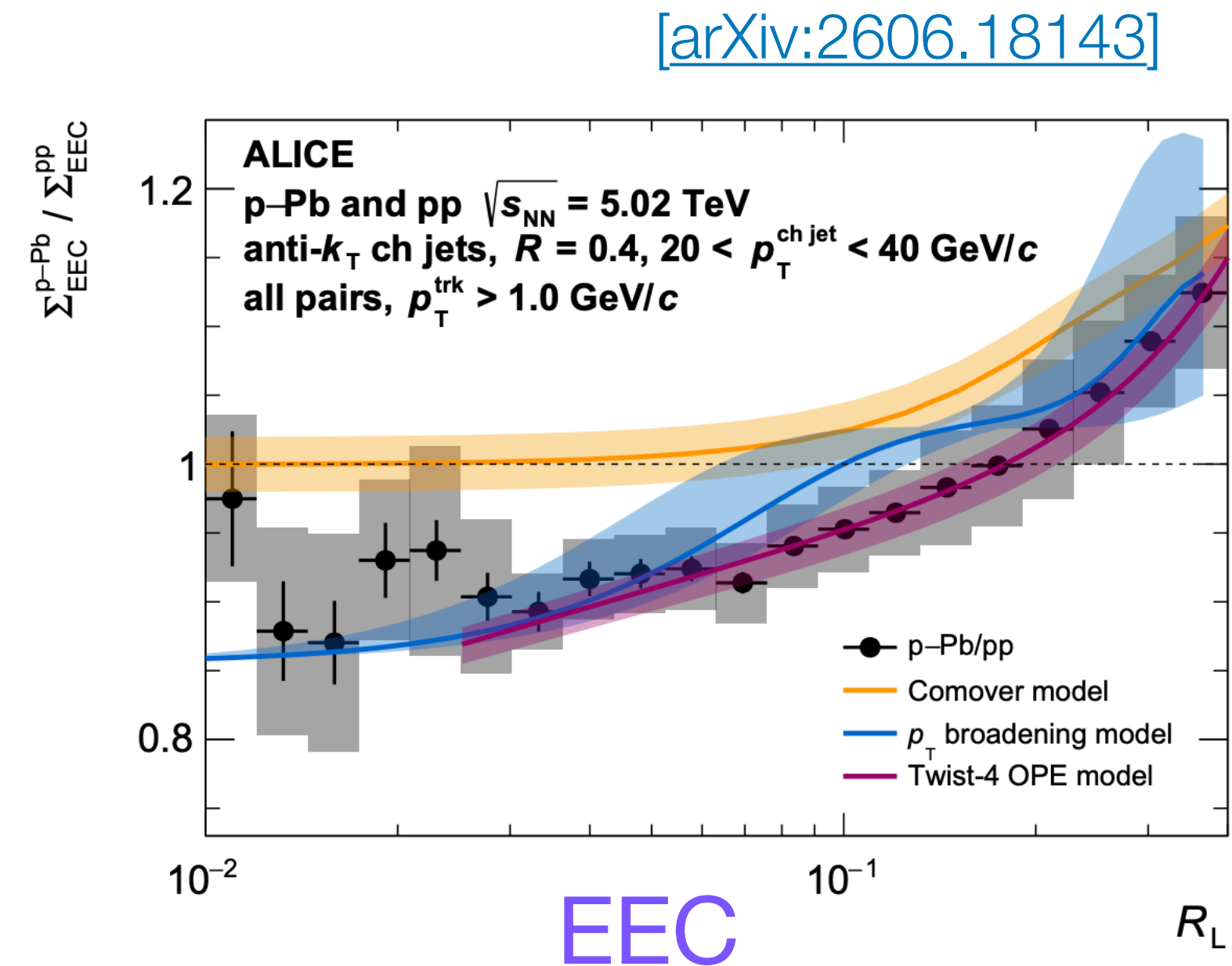
- *We have seen no such indications* of jet quenching in smaller systems



Charged particle R_{AA}



Z-hadron Correlations



- Low p_T wide angle enhancement in the EEC still not fully understood

[PRL 136 (2026) 12, 122301]

[PRL 134 (2025) 25, 251903]

[PRL 135 (2025) 11, 112302]

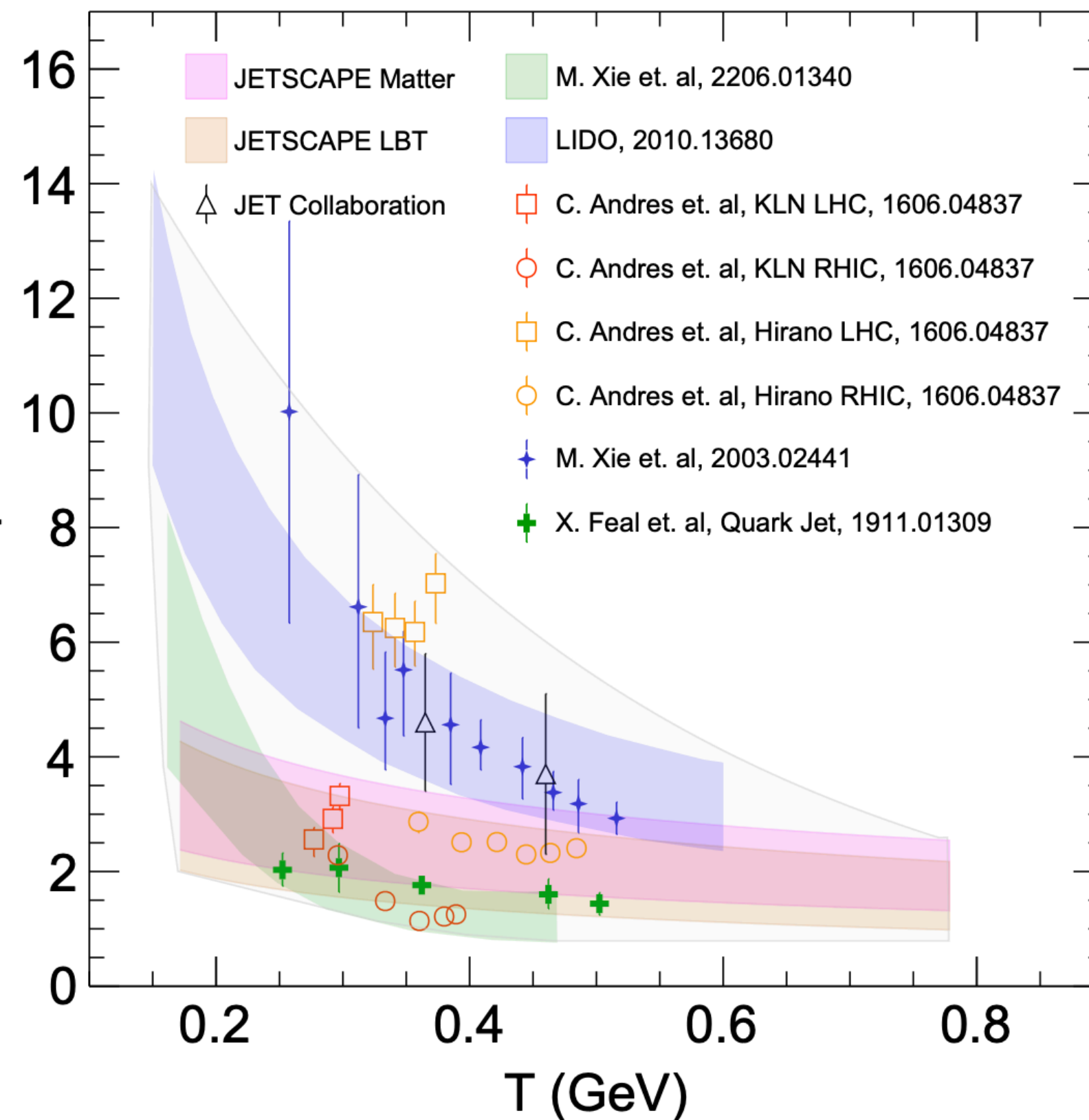
BAYESIAN EXTRACTION OF TRANSPORT COEFFICIENTS

- *We have learned* that Bayesian inference also useful for hard process transport coefficients

[Progress in Particle and Nuclear Physics, 103990 (2022)]

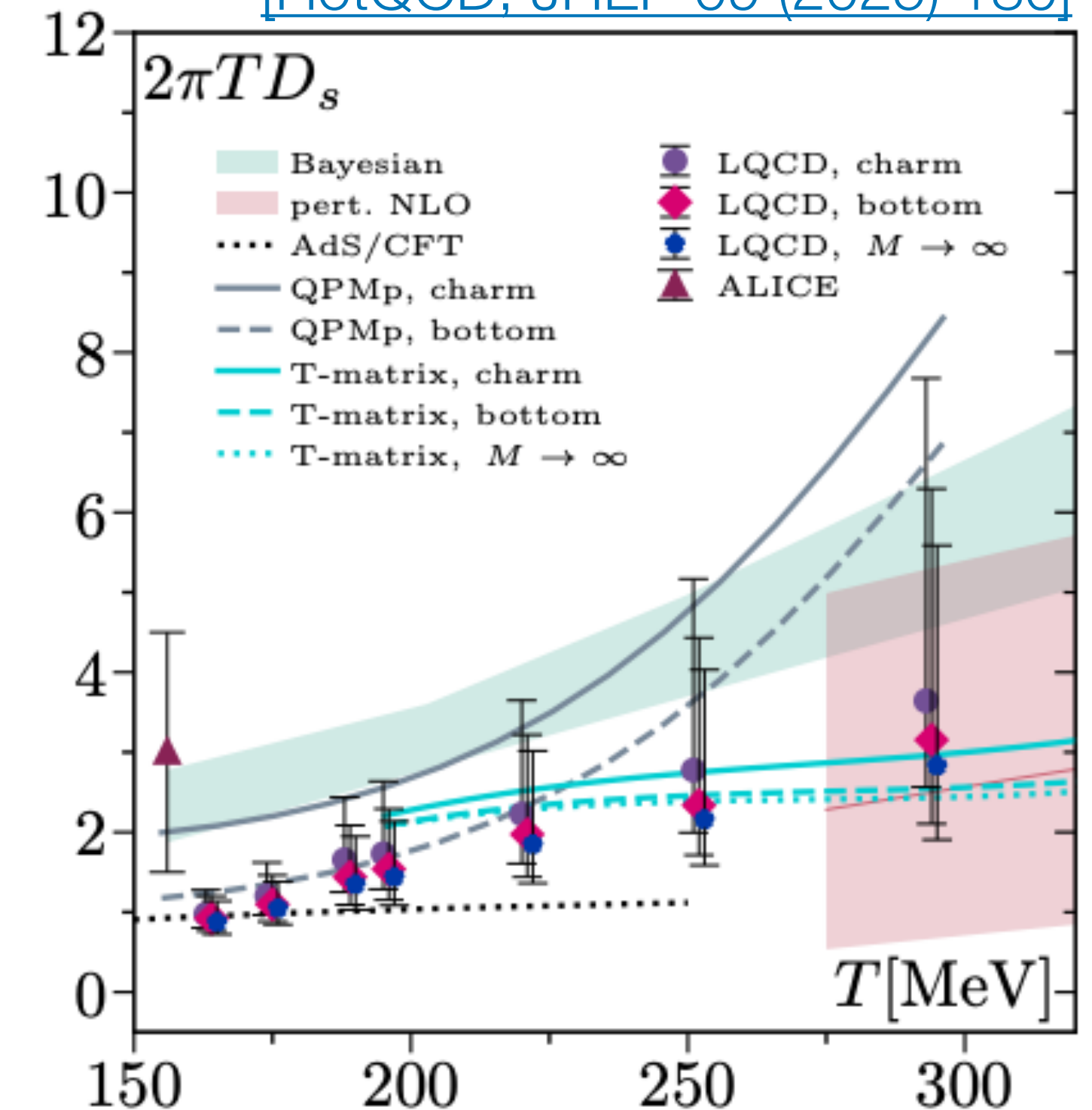
jet transport coefficient ($\hat{q}$)

$$\Delta E \approx \frac{\alpha_s N_c}{4} \hat{q} L^2$$



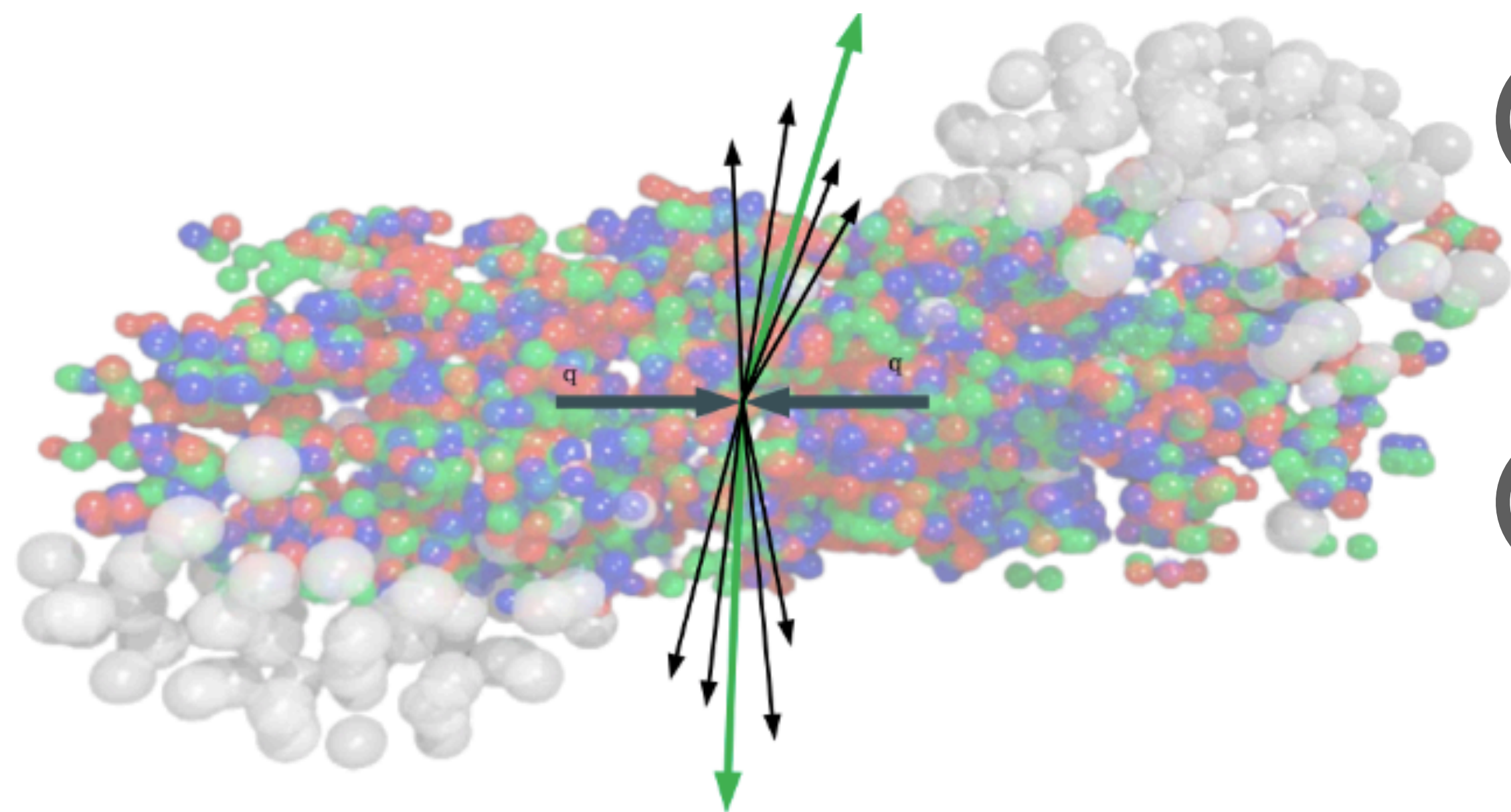
Heavy quark diffusion coefficient

[HotQCD, JHEP 09 (2025) 180]



- *We're in the process of learning* that including hard-soft correlations matters! [arXiv:2603.09584]

EXPERIMENTAL PROBES OF QGP PROPERTIES



① **Soft Probes:** hadronization products of the QGP medium

→ collective properties of QGP

② **Hard Probes:** products of early-stage hard scattering that interact with the QGP medium.

→ dynamical properties of QGP

③ **Electroweak Probes:** probes that have a long mean free path relative to the size of the QGP (negligible interactions)

→ effects of different stages of QGP formation

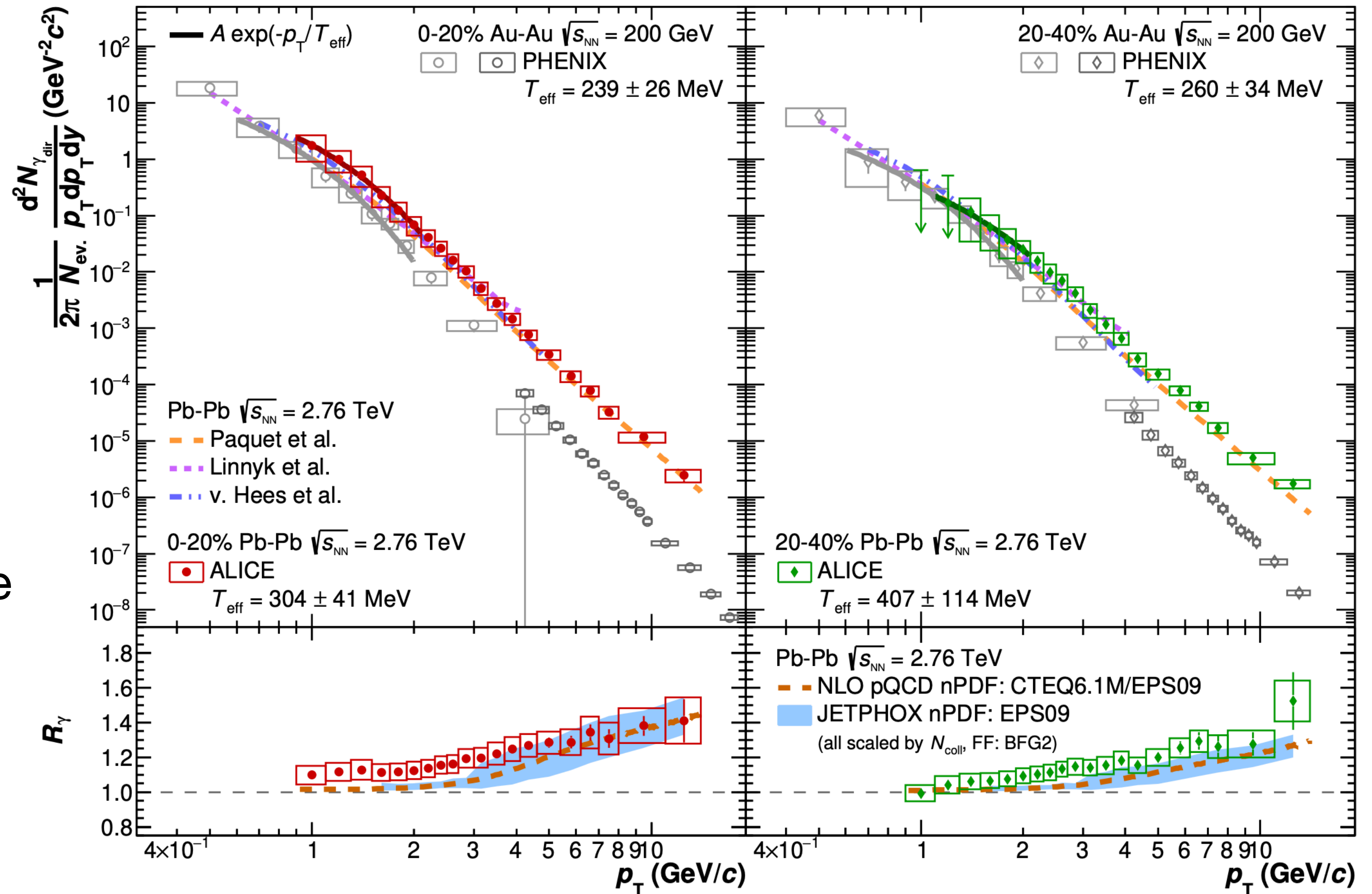


Use pp collision data at same energy as a reference, where difference is taken as an in-medium property.

DIRECT PHOTONS AS A QGP THERMOMETER

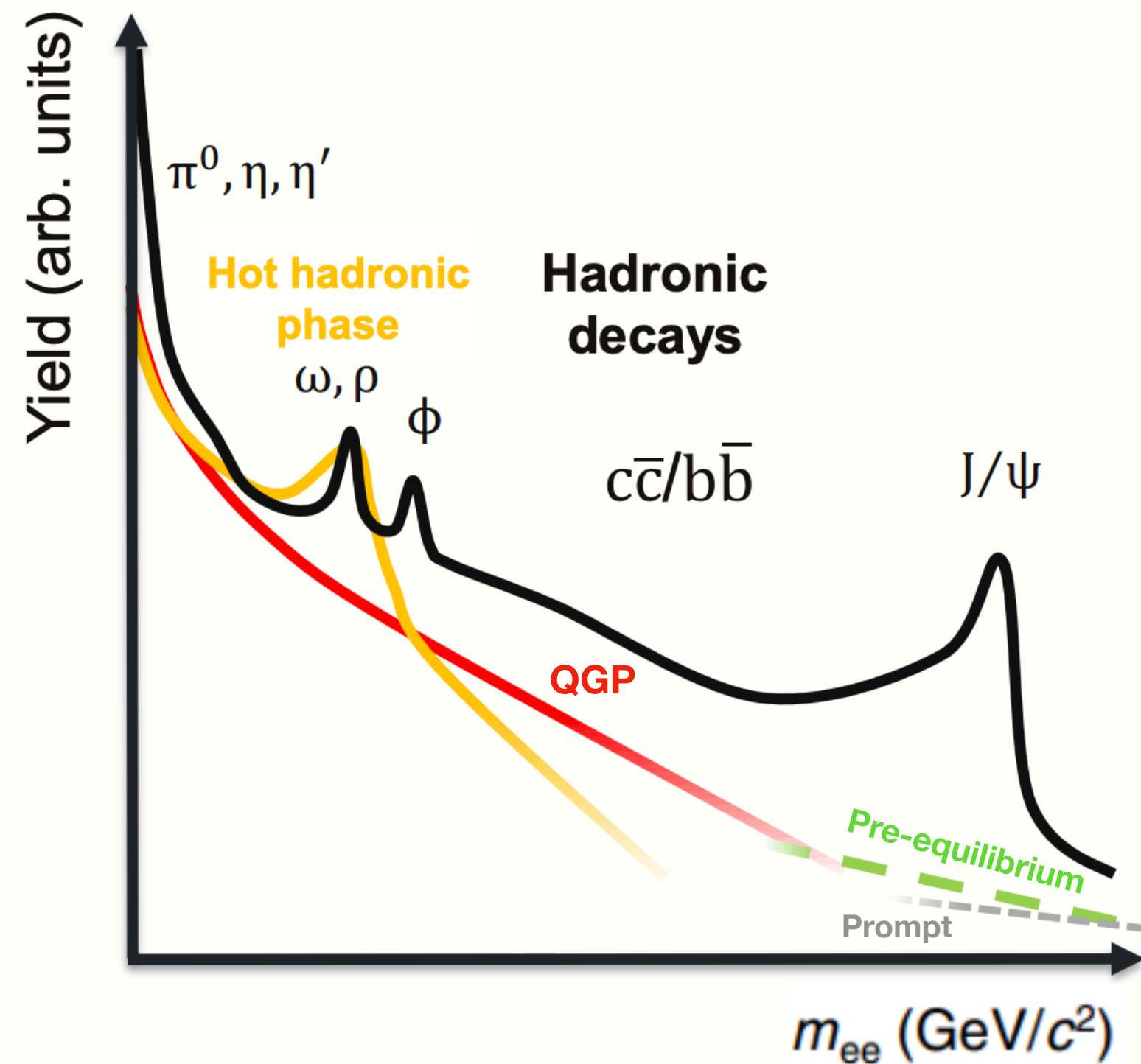
[ALICE, A journey through QCD]

- At low p_T the direct photon spectrum is dominated by thermal photons radiated during QGP evolution
- Possible to extract effective temperature with a fit.
- *We have learned* that the effective temperature of the QGP in central collisions ($T_{\text{eff}} = 304 \pm 41$ MeV) is significantly above $T_c \sim 150$ MeV

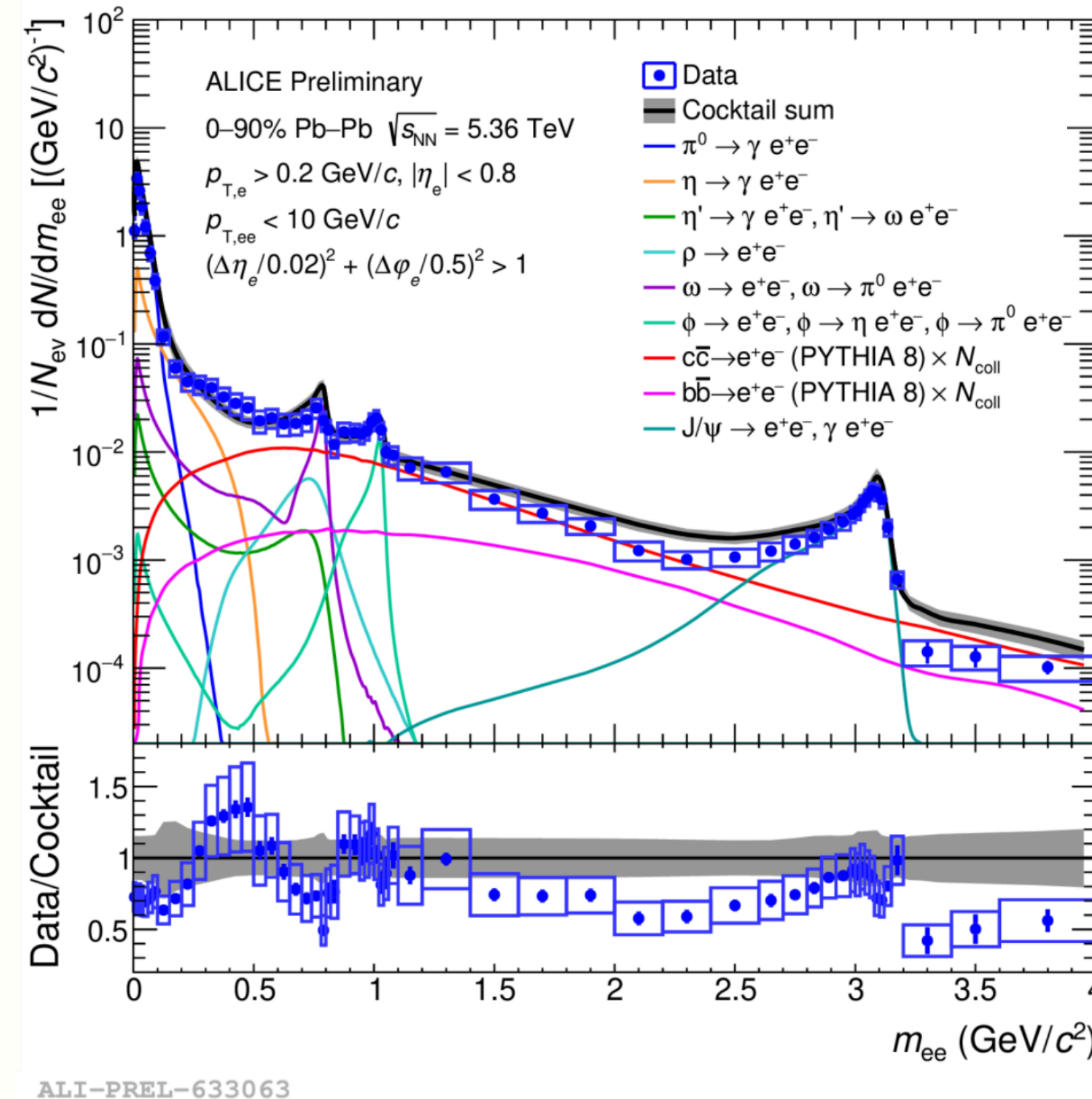


DILEPTON INVARIANT MASS

- Dilepton pairs from different stages of the collision have different invariant mass
- Can shed light on time-dependence of temperature, thermalization, possible chiral symmetry restoration in the hot hadronic phase.

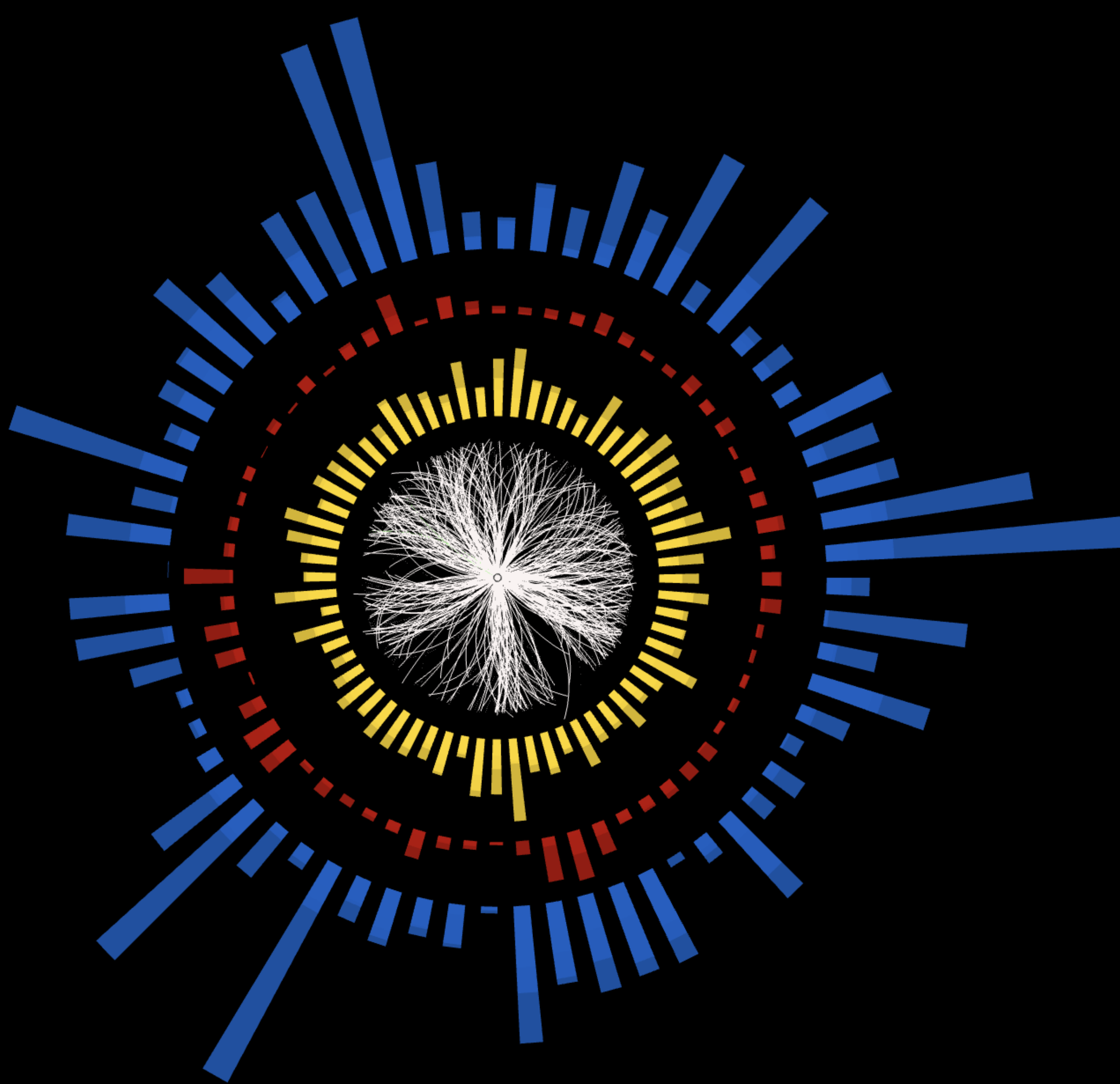


[Cartoon from Jerome Jung, Hard Probes]



- *We have created an ambitious program* to make dilepton measurements! Very challenging due to large backgrounds.
- LHC Run 3 data show improved precision, but large differences between data and cocktail

- **We're beginning to learn** how to topologically separate sources at intermediate masses!



Part 3 : What will we do in the future?

WHERE ARE WE GOING?

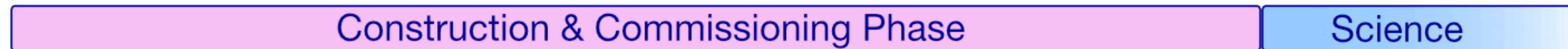
Facility Operations



Relativistic Heavy Ion Collider



Electron Ion Collider



Large Hadron Collider

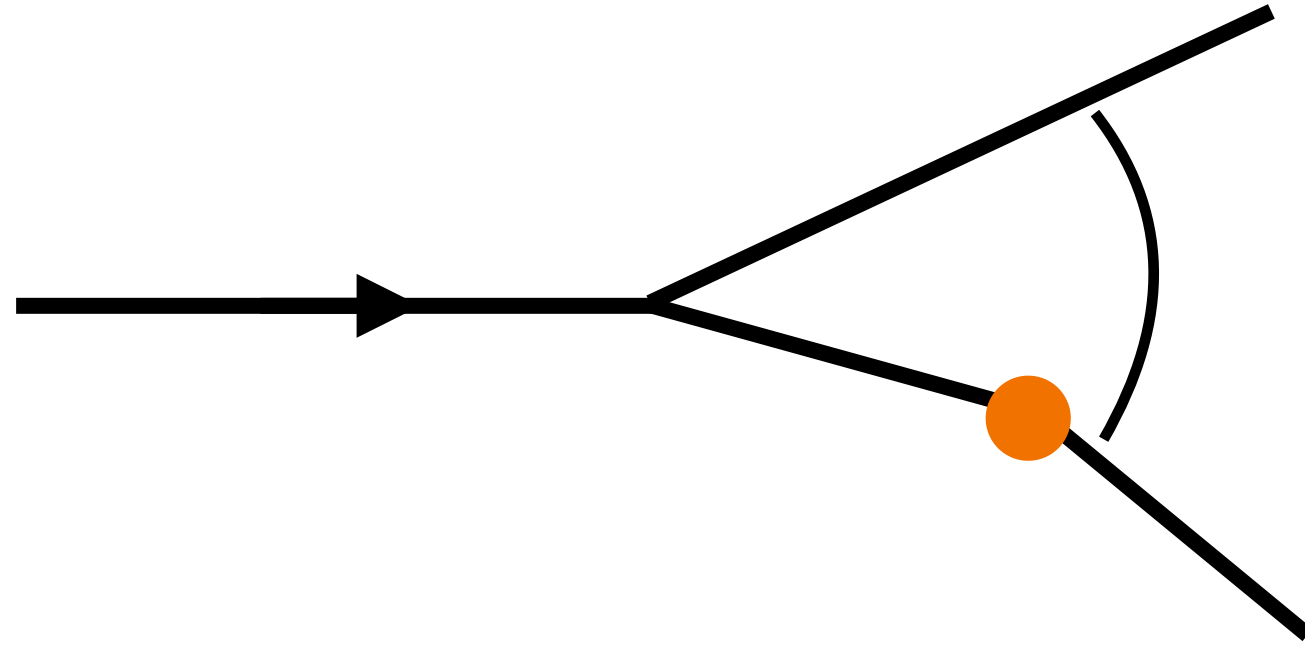


Electron Ion Collider and LHC Run 4 (HL-LHC) are in the not-too-distant future!

What can we hope to learn at these new facilities? What can we do in the meantime?

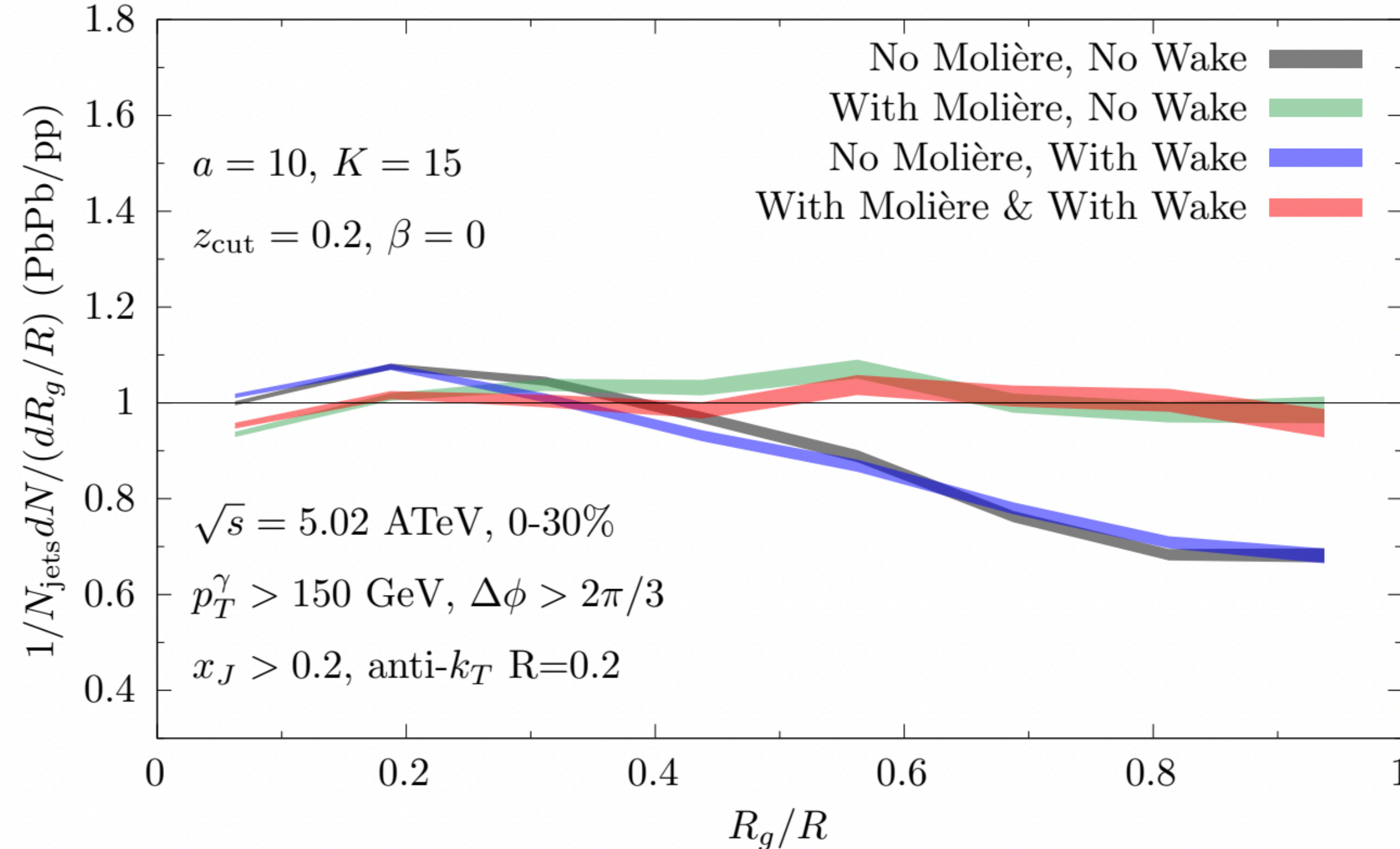
Many examples, let's highlight a few at each facility!

ISOLATING QUASIPARTICLE STRUCTURE OF QGP

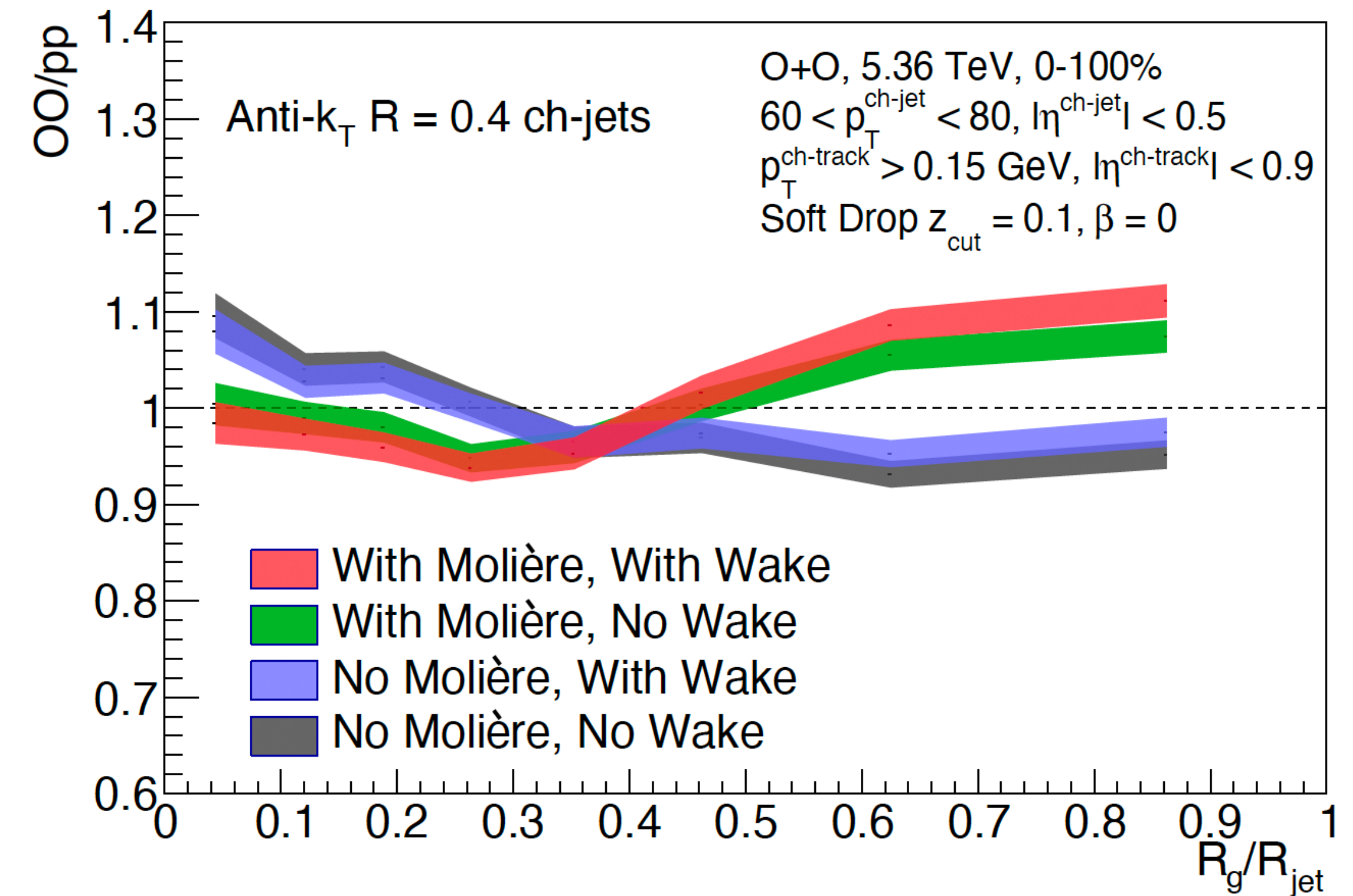


- Parton traversing QGP can undergo $2 \rightarrow 2$ Molière scatterings off of medium quasiparticles.
- Jets are ideal probes of quasi-particle structure of QGP.

[Hulcher et. al arXiv:2603.08776]



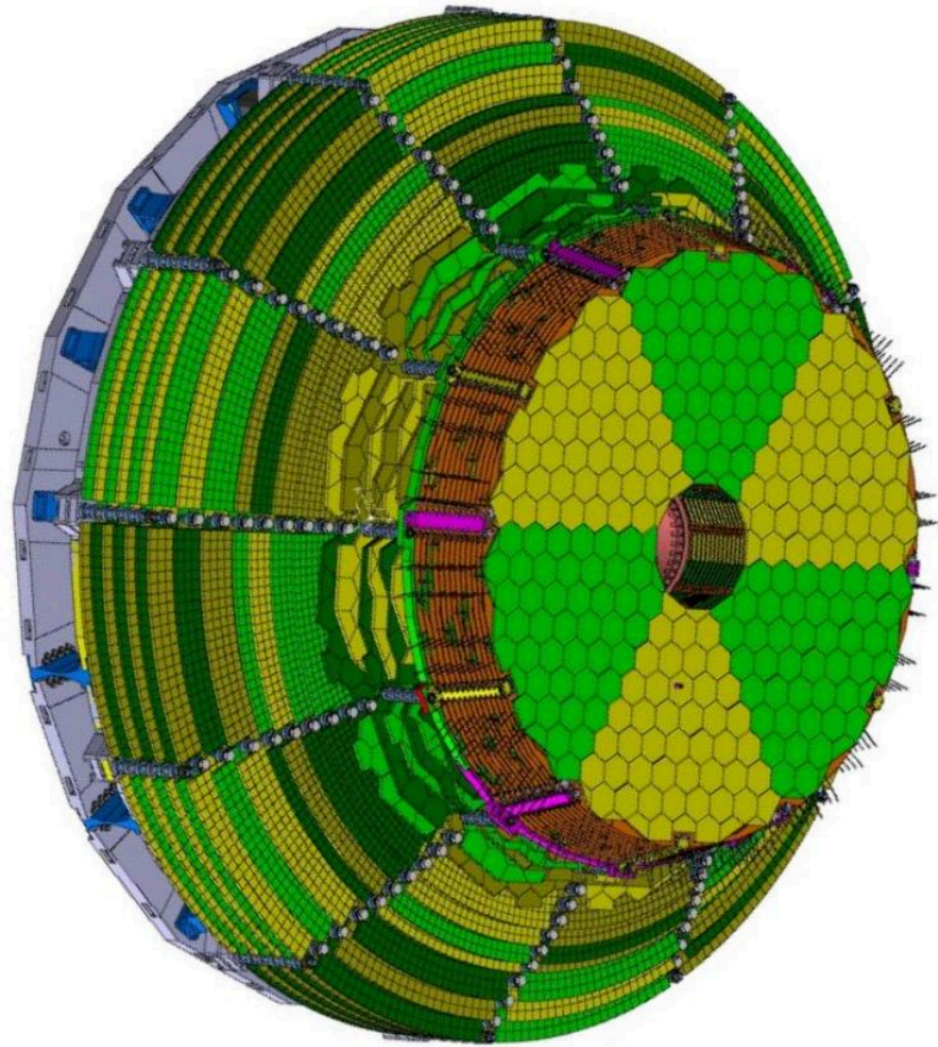
[Kudinoor et. al. arXiv:2603.2359]



• Recent calculations indicate $\gamma + \text{jet}$ and OO are good places to look! New data helps!

HL-LHC UPGRADES

- All detectors will be getting upgrades to increase the physics output, coupled with much higher instantaneous luminosity.



- **CMS & ATLAS:**

- Both experiments getting new all-silicon tracking systems that significantly extend forward coverage. **Useful for studies of quark and gluon dependence.**
- CMS will gain a new high granularity calorimeter, containing millions of channels - very high resolution!!
- ATLAS will have a high granularity timing detector to help with pileup created from high collision rates.



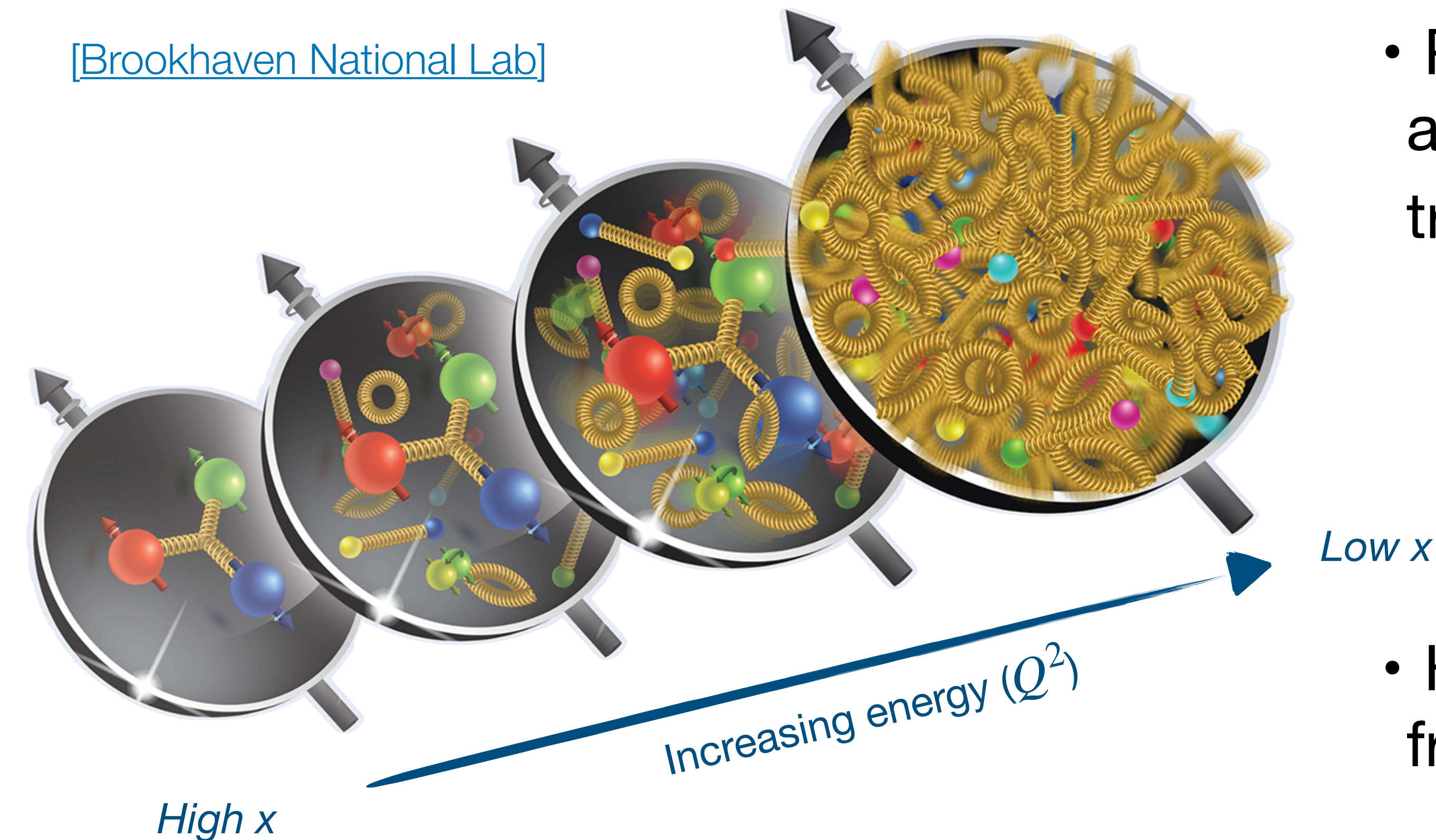
- **ALICE FoCAL:** Forward Calorimeter at $3.4 < \eta < 5.8$ extending coverage of ALICE to $x \sim 10^{-6}$ **complementary to EIC.**

QCD QUESTIONS FOR THE EIC

- What happens to protons & nuclei under the constraint of the confinement potential?

[\[See Krishna Rajagopal's Talk Mon. 16:30\]](#)

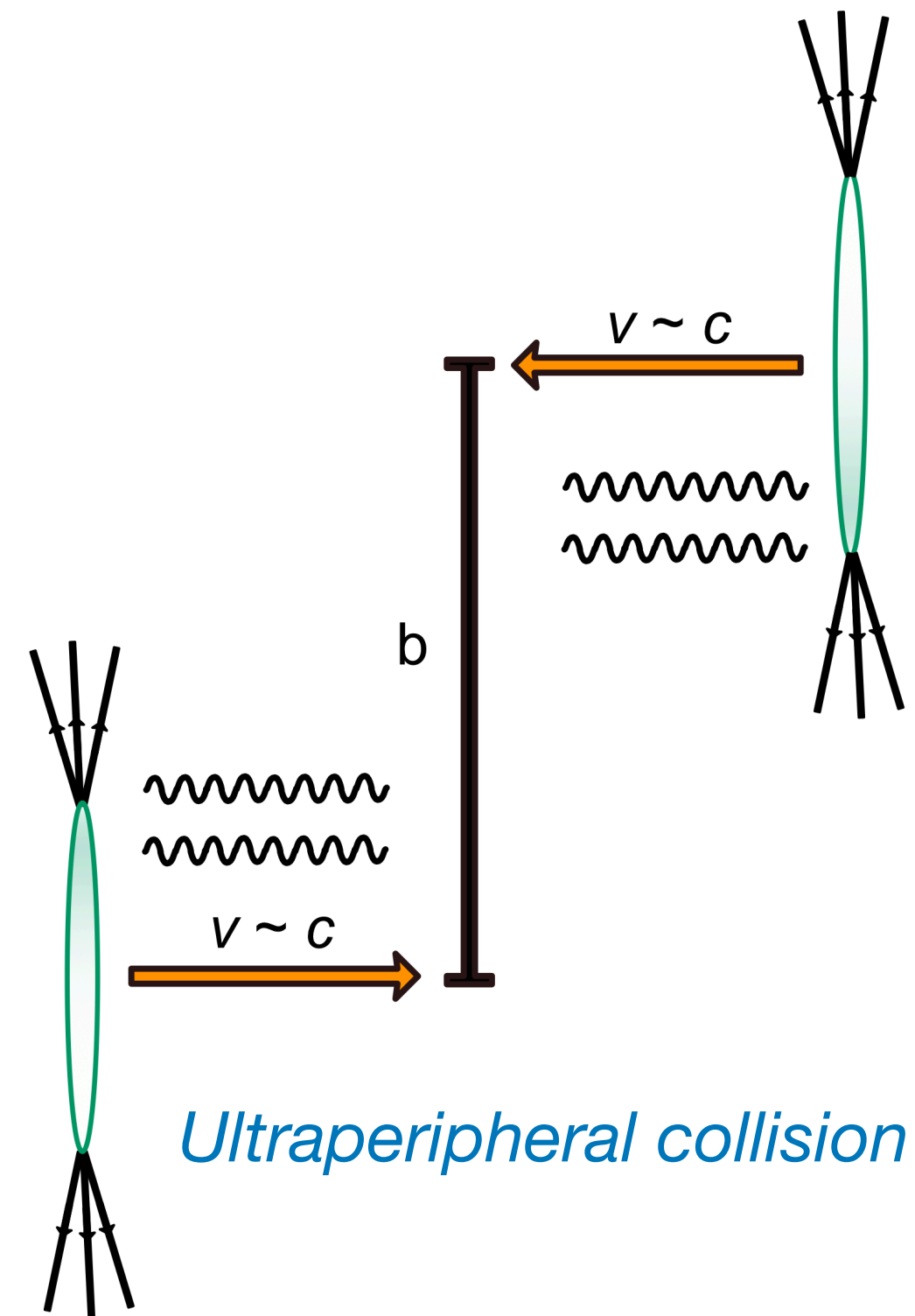
[\[Brookhaven National Lab\]](#)



- Parton distribution function (PDF) changes as a function of momentum fraction (x) and transfer (Q^2).
- How are quarks and gluons distributed in space and momentum inside nuclei?
- How do properties of nucleons emerge from partons and their interactions?

- What happens to the gluon density in nuclei? Does it saturate?

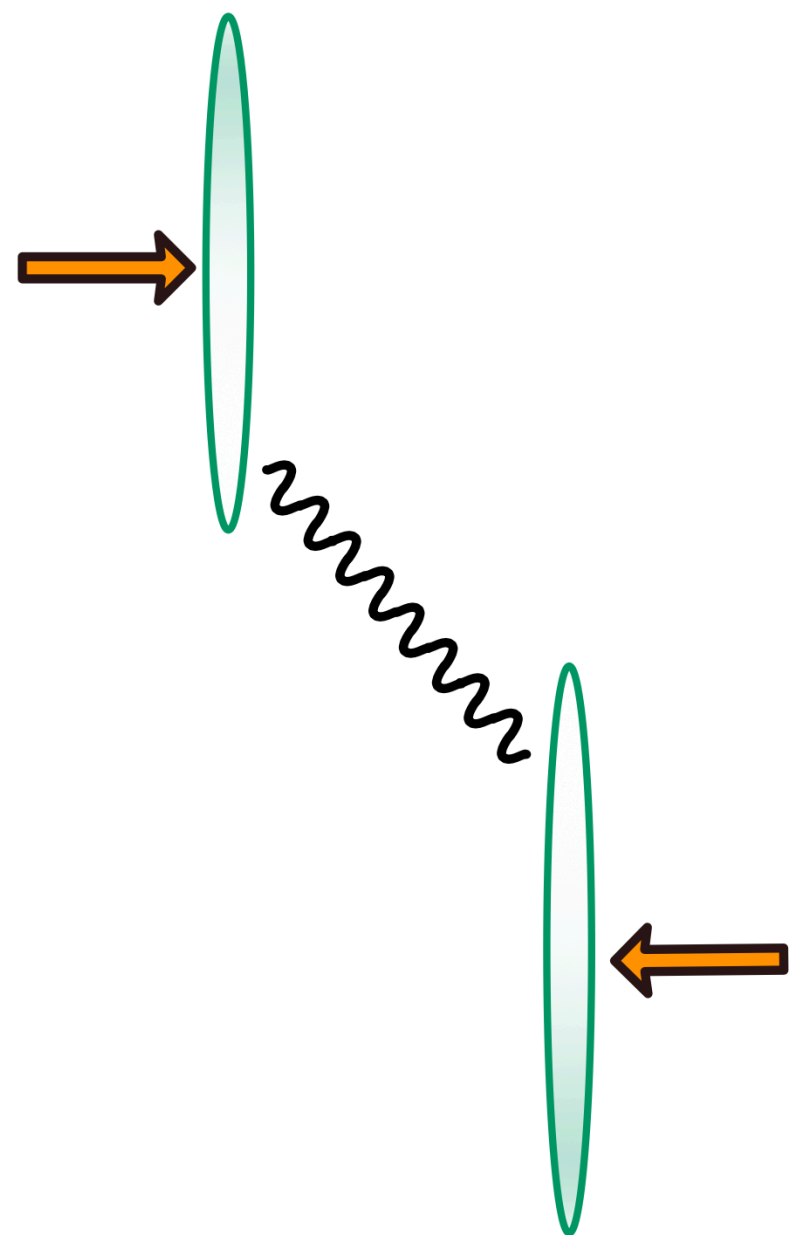
UPCS AS A CONNECTION TO THE EIC



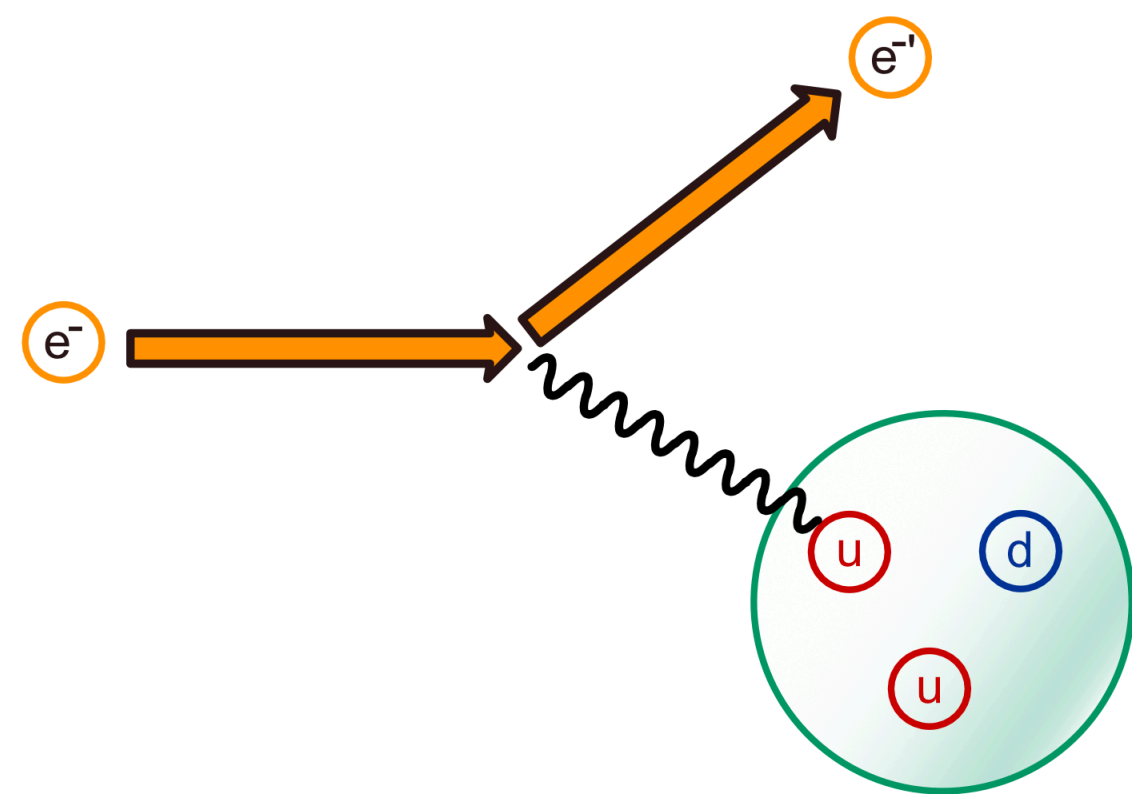
- In an **ultraperipheral collision (UPC)** $b > 2R$, suppressed strong interactions between nuclei.
- Generate large perpendicular electric fields, which can be approximated by an equivalent beam of quasi real photons.

UPCs effectively turn hadronic colliders into photon colliders!

UPCS AS A CONNECTION TO THE EIC



Photonuclear interaction



Deep inelastic scattering

- In an **ultraperipheral collision (UPC)** $b > 2R$, suppressed strong interactions between nuclei.
- Generate large perpendicular electric fields, which can be approximated by an equivalent beam of quasi real photons.

UPCs effectively turn hadronic colliders into photon colliders!

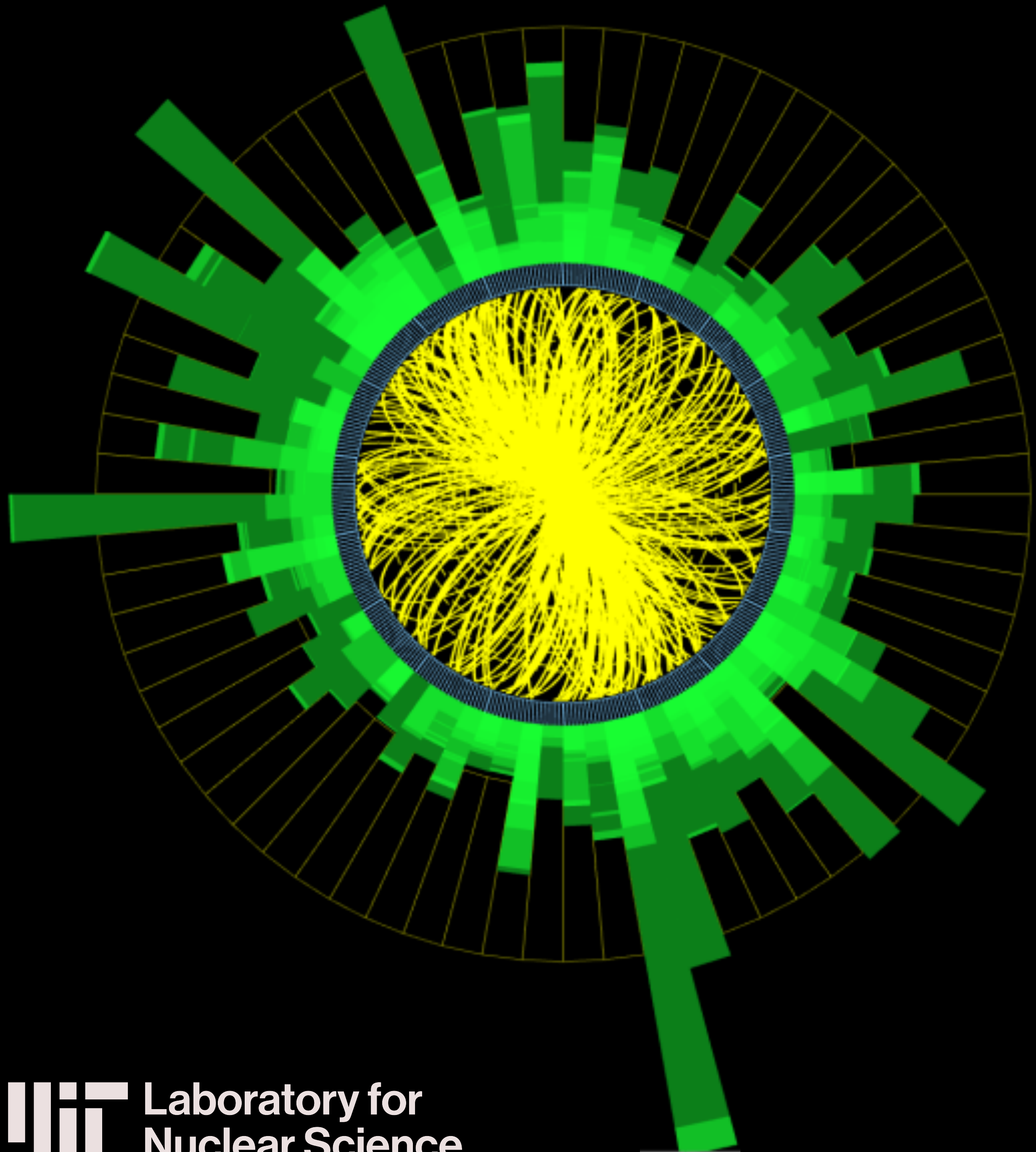
- EIC will do this at lower energies, better hard process kinematic control, better forward coverage, polarized beams
- We have already started to learn a lot from these! UPC studies will be greatly improved by new event selection systems in Run 3 data.

SUMMARY AND CONCLUSIONS

- **Studying the QGP is crucial for understanding QCD matter in extreme conditions.**
 - Experimentally very difficult and complex environment!
- **We've made considerable progress on experimental measurements of the QGP**
 - With new data, new techniques, and new theory inputs we've learned a lot over the last few years!
- **We have only scratched the surface of measurements w/ existing RHIC + LHC data!**
 - **Simultaneously lots to be excited about for EIC & HL-LHC in the 2030s.**

Feedback loop with theory is now more important than ever!!

Thanks to Dana Avramescu, Cristian Baldenegro, Chris McGinn, Krishna Rajagopal and Jing Wang for the useful discussions that helped with crafting the message for this talk.

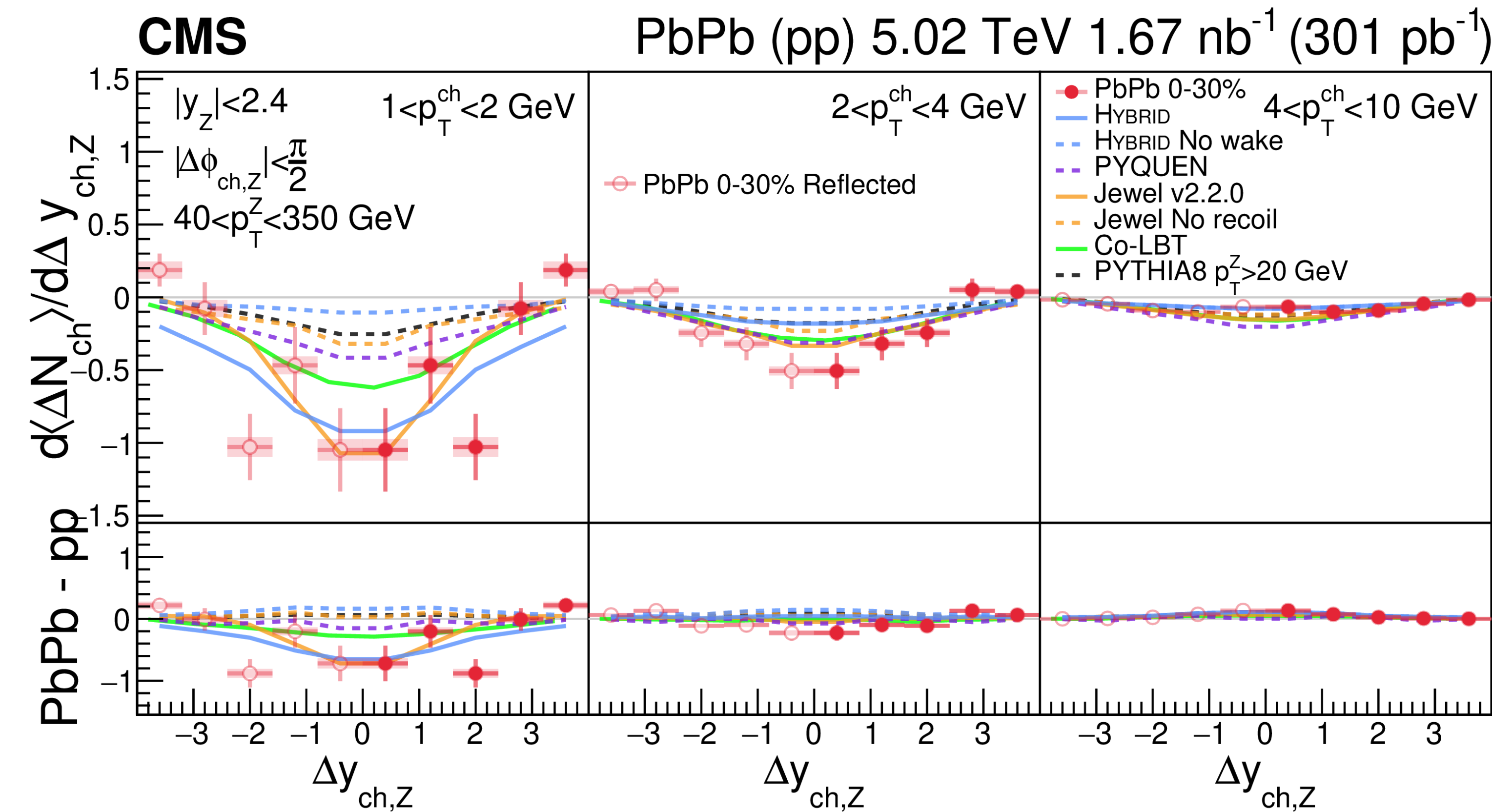
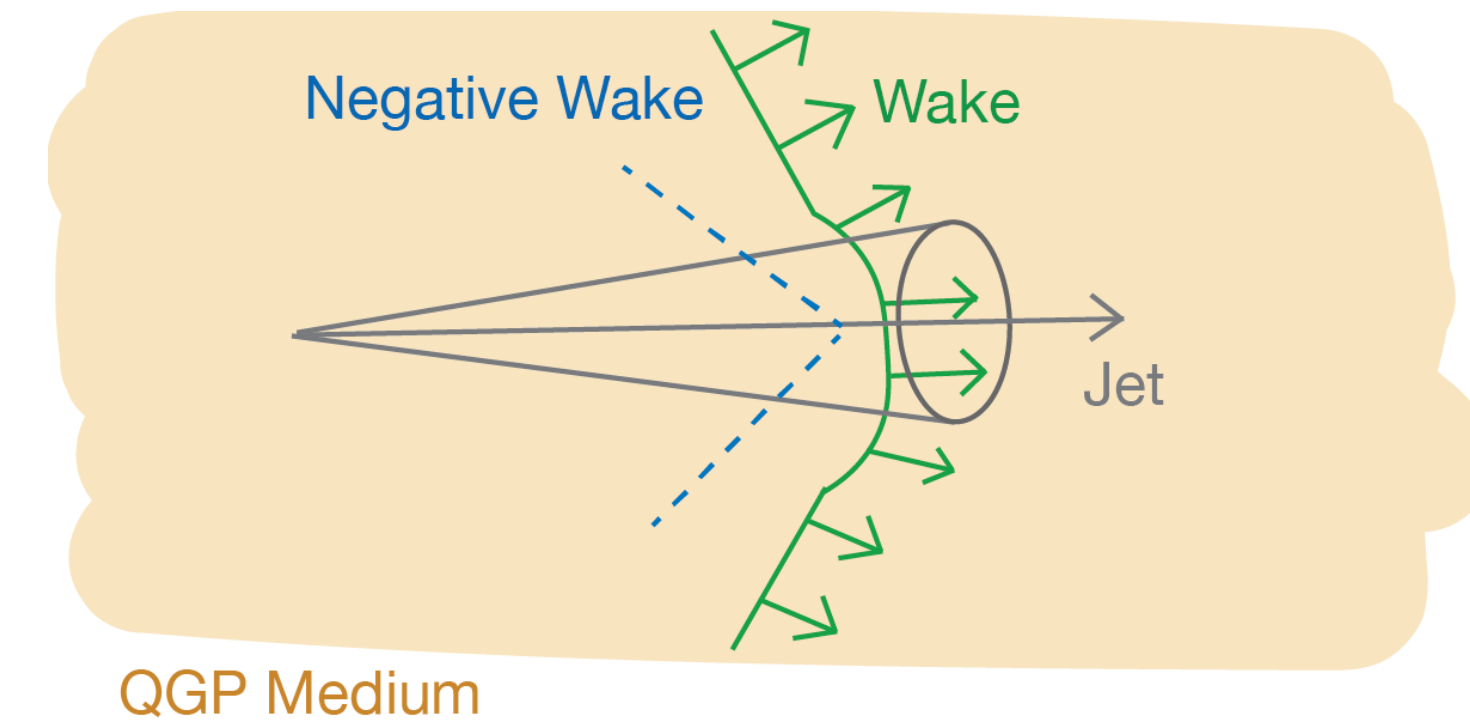


Backup

WHAT HAVE WE LEARNED SO FAR?

③ Medium should respond to the presence of the jet

- *We have learned* that (though difficult) you can measure the medium response!

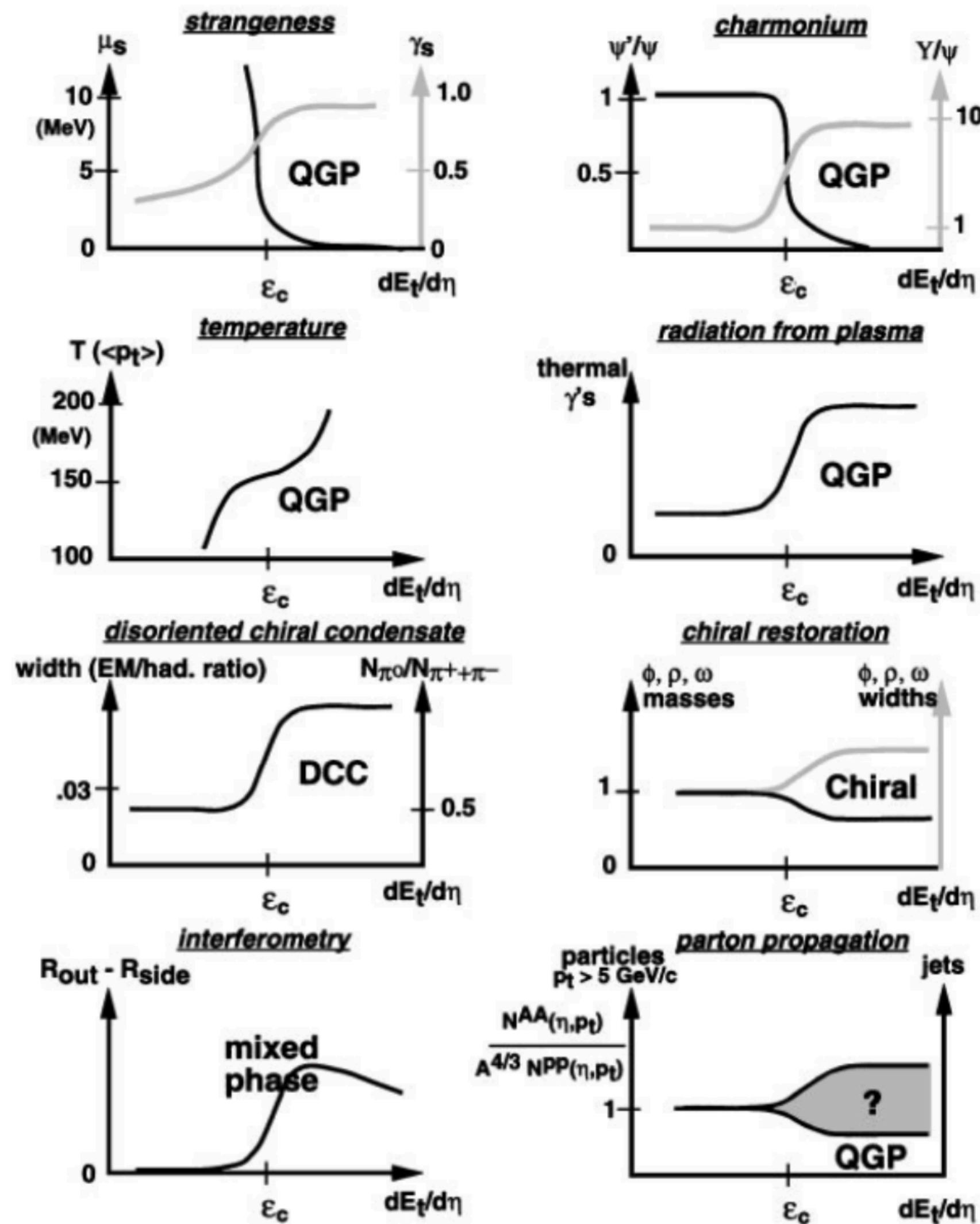


[PLB 874 (2026) 140120]

- Use Z+hadron correlations to have a way to study **negative contributions to medium response** without selection bias effects.
- Models w/ medium response describe data, regardless of underlying mechanism.

HOW DO WE KNOW A QGP IS FORMED?

SIGNATURES

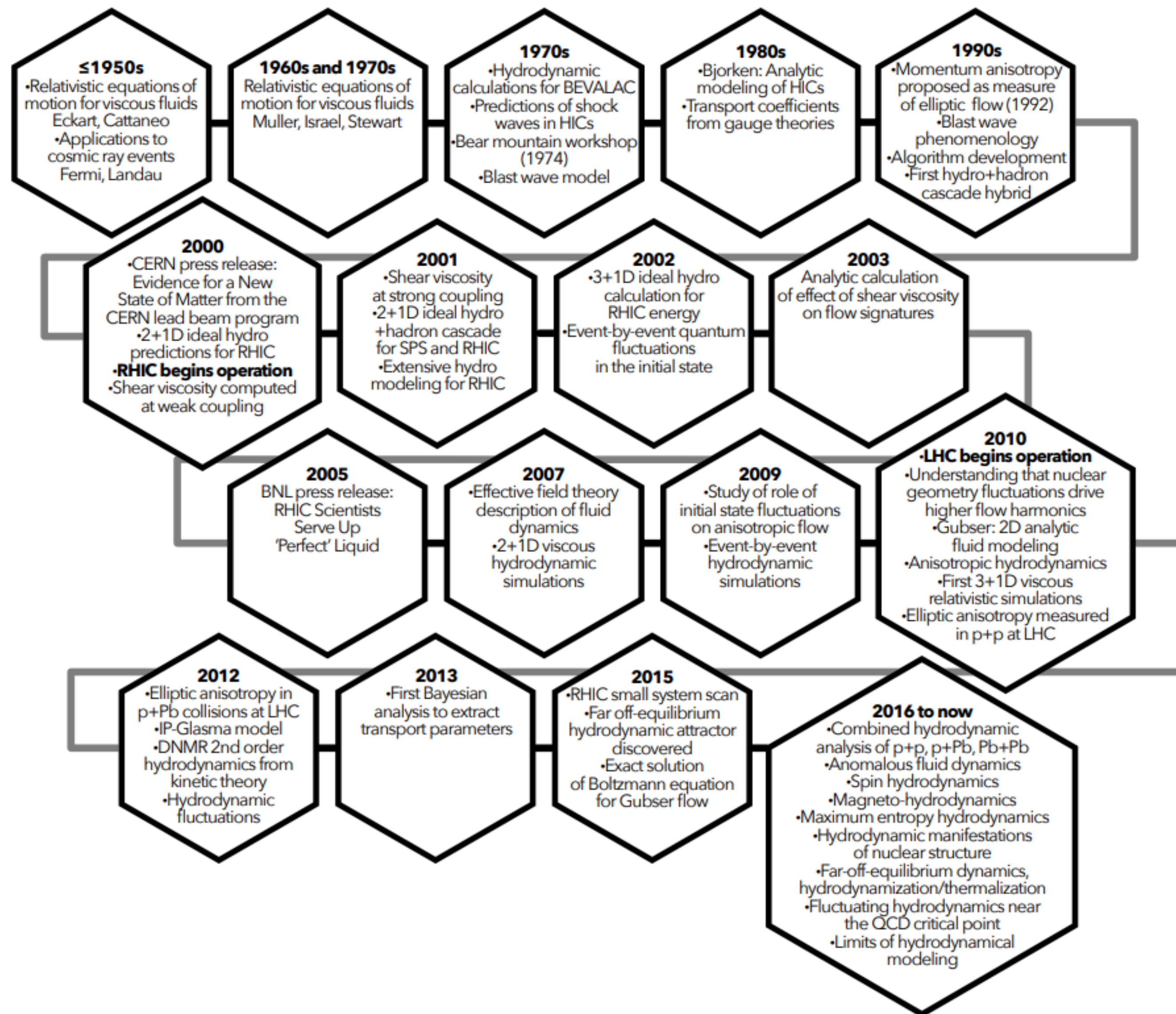


- Not much was known in the beginning of what should be expected, but there were some proposed “smoking gun” signatures of QGP.
- Looking closer
 - Most involve sharp changes around some scale ϵ_c
 - Very little numbers on the x-axis, where this scale appears

30 years later, some signatures are still unobserved and some have been extensively measured! Let's go through some of these.

[Ann.Rev.Nucl.Part.Sci. 46 (1996)] [EPJC 84 (2024) 3, 247]

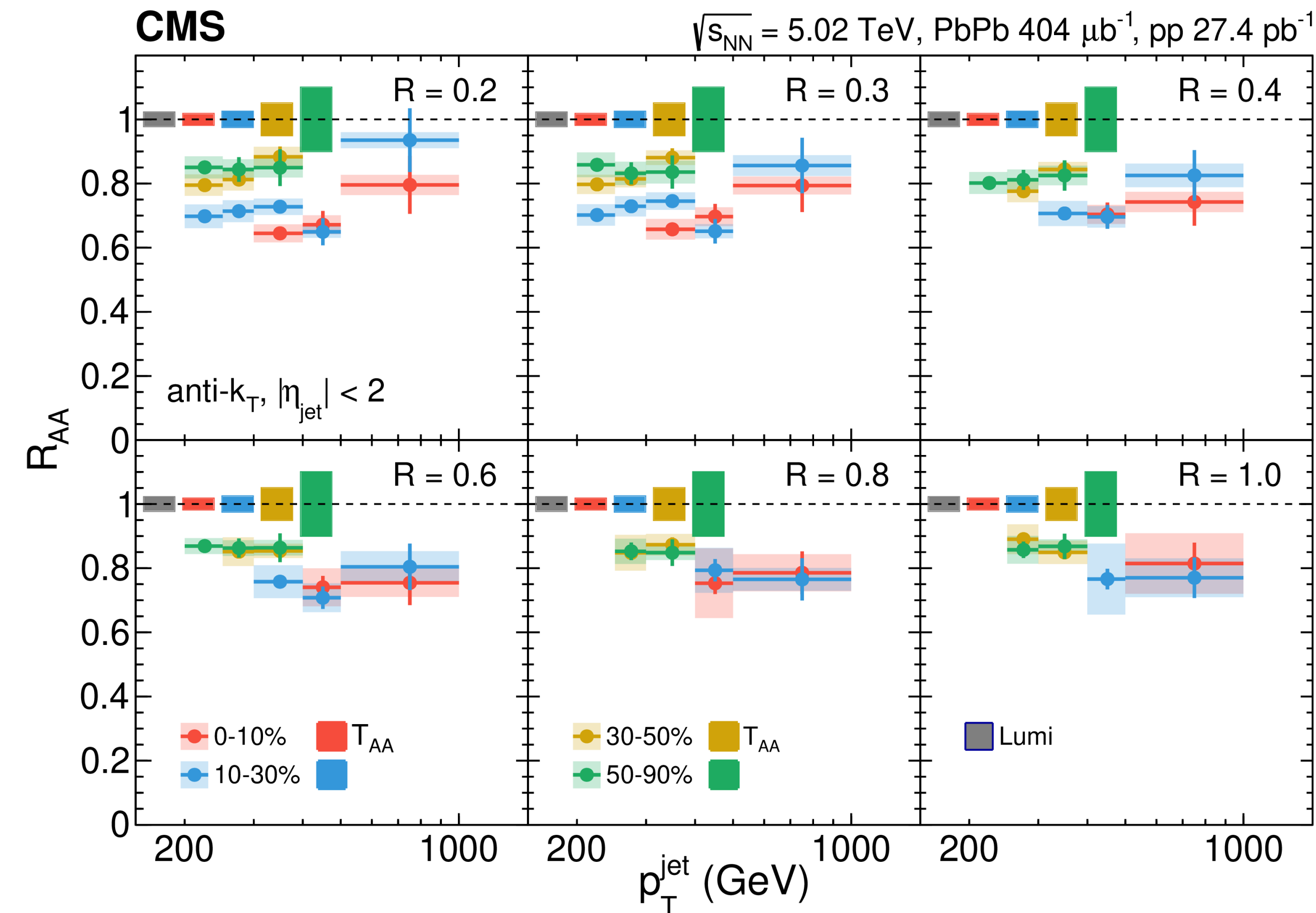
TIMELINE OF HYDRODYNAMIC DESCRIPTION



[arXiv:2412.19393]

WHAT HAVE WE LEARNED SO FAR?

- 1 Parton energy loss leading to a suppression of jet yields in heavy-ions (A—A) in comparison to vacuum (pp).

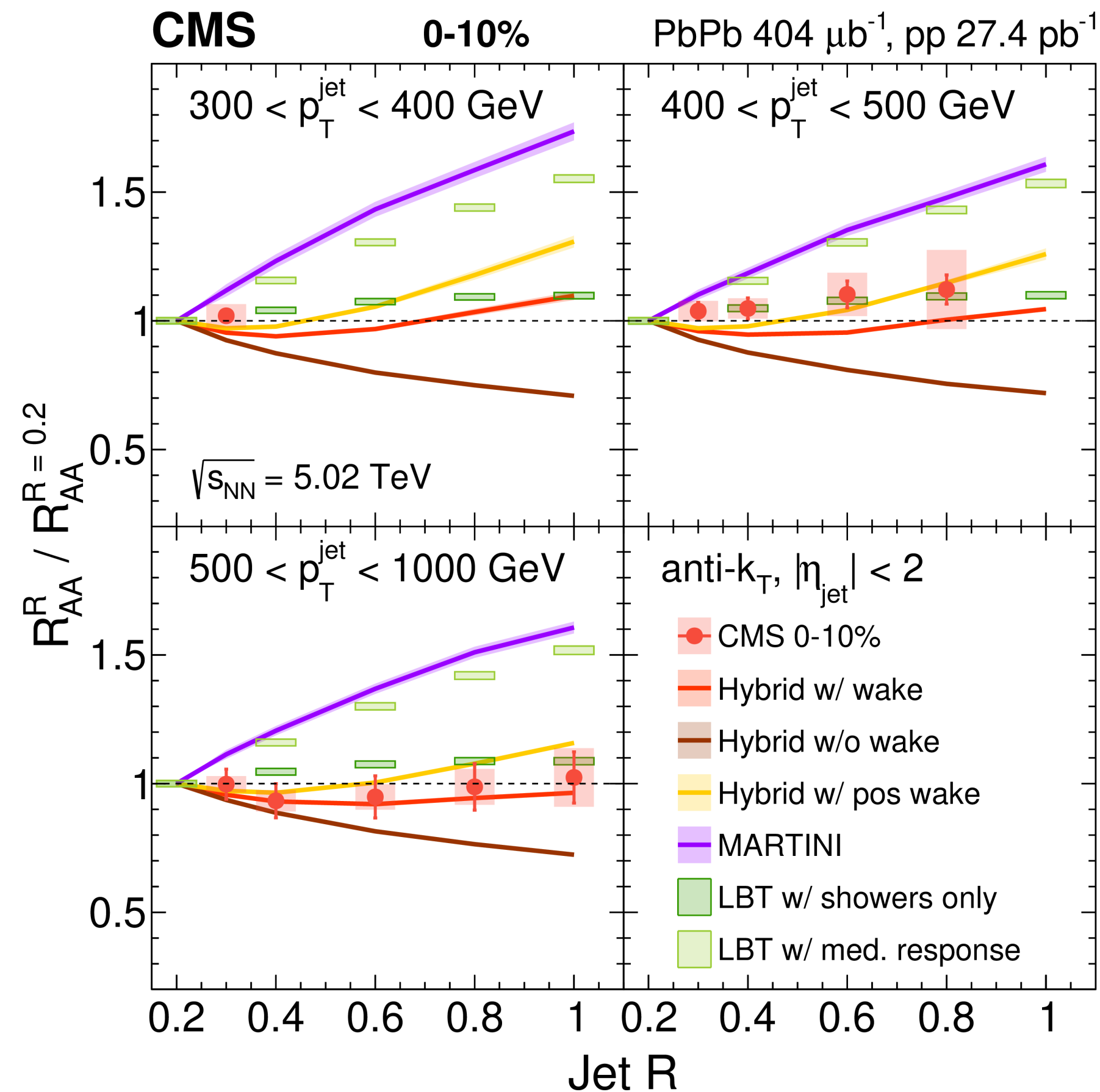


[JHEP 05 (2021) 284]

- *We have learned* that jets are suppressed, indicating that partons lose energy.
- *We have learned* that this happens even at...
 - very high transverse momentum (p_T)
 - for very large R
 - in peripheral collisions

WHAT HAVE WE LEARNED SO FAR?

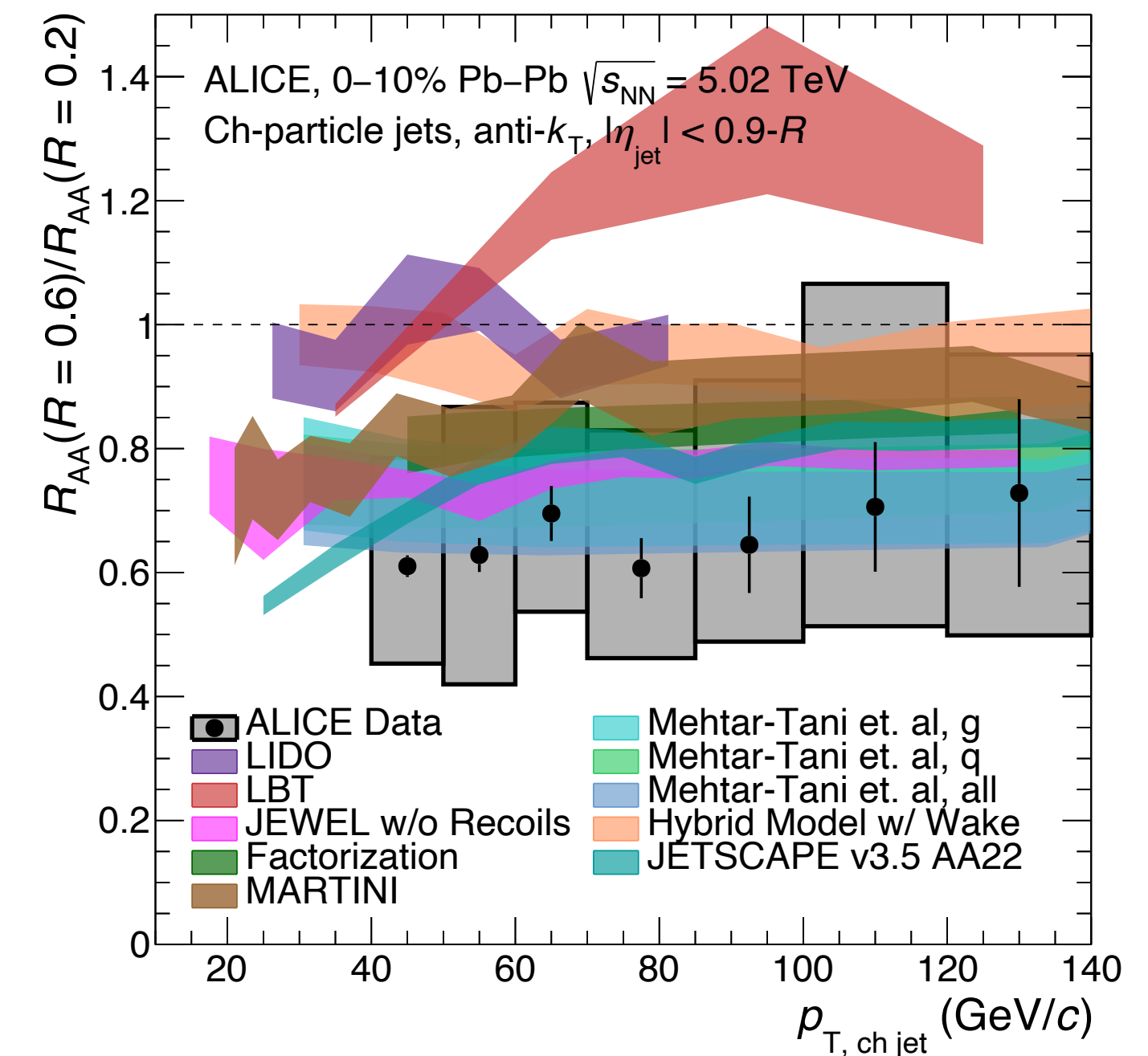
- 1 **Parton energy loss** leading to a suppression of jet yields in heavy-ions (A—A) in comparison to vacuum (pp).



[JHEP 05 (2021) 284]

- *We have also learned* that it is **very difficult** for a single model to simultaneously capture the differential evolution of “simple observables” (R_{AA}) across kinematic regions.

[PLB 849 (2024) 138412]

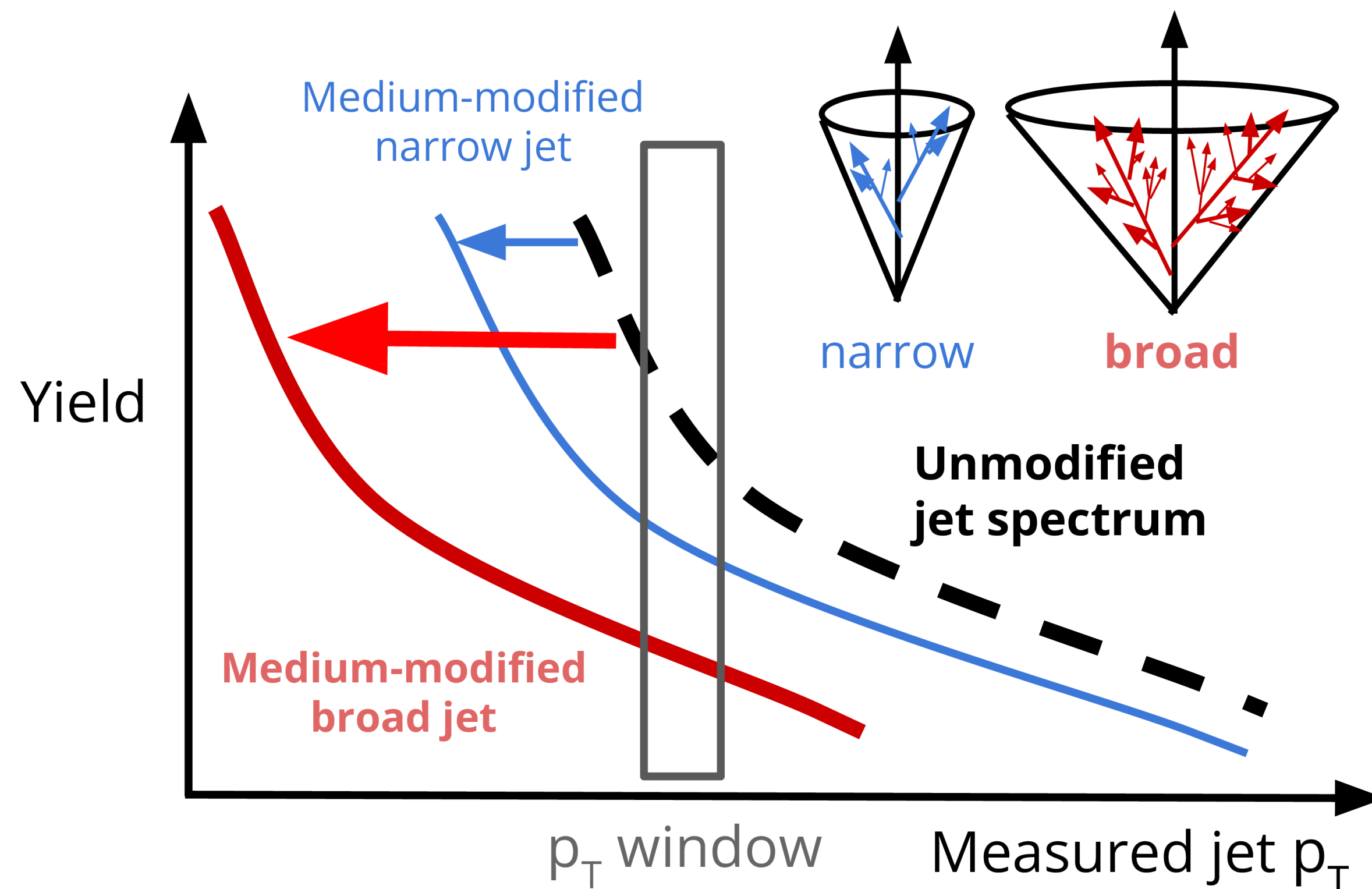


- We have some indications that the balance between competing mechanisms depends on p_T

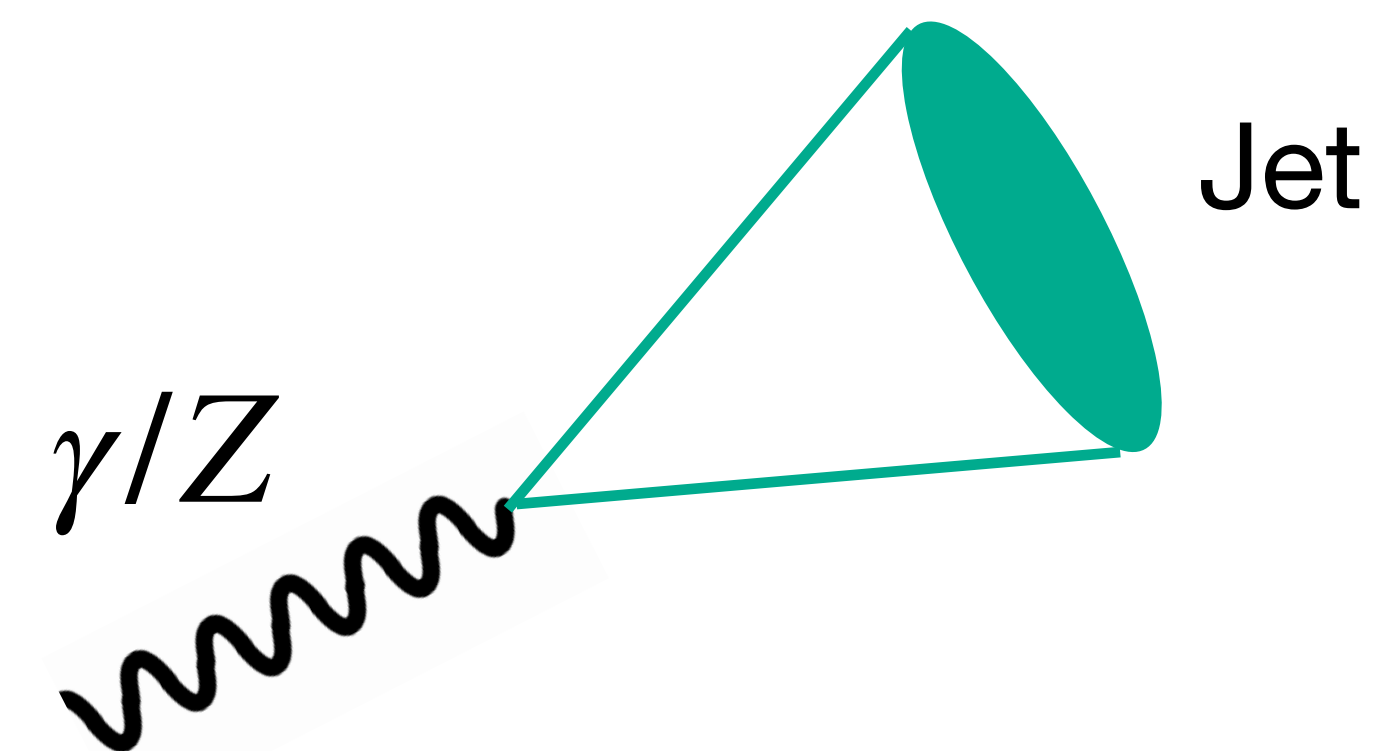
WHAT HAVE WE LEARNED SO FAR?

② Internal structure modification

- *We have learned* that selection bias plays a role in modification, inducing narrowing behavior that hides other effects of interest.



- **Electromagnetic probes** are a great way to remove selection bias, can access the unmodified p_T .



[PLB 861 (2025) 139088]

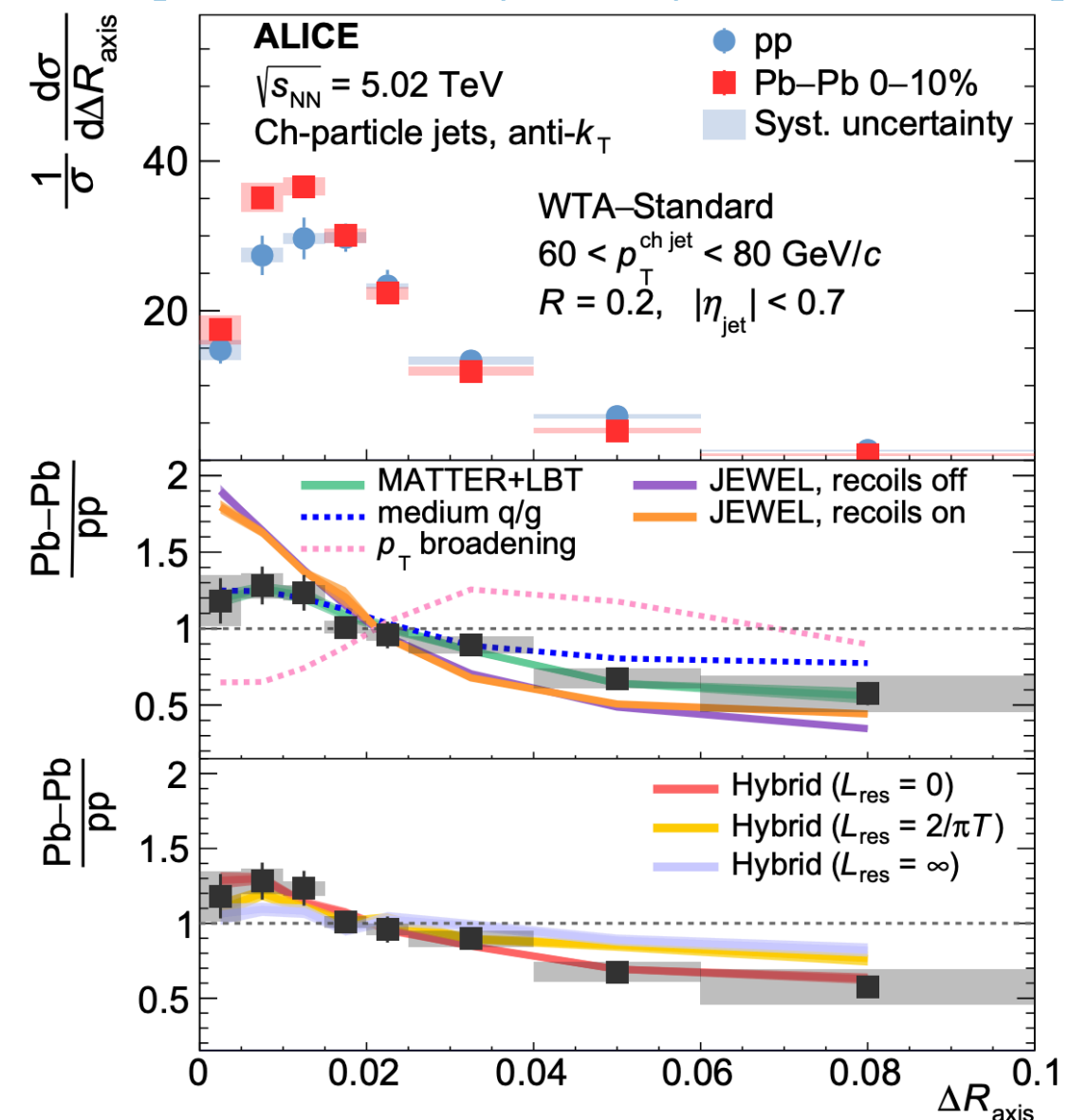
WHAT HAVE WE LEARNED SO FAR?

2

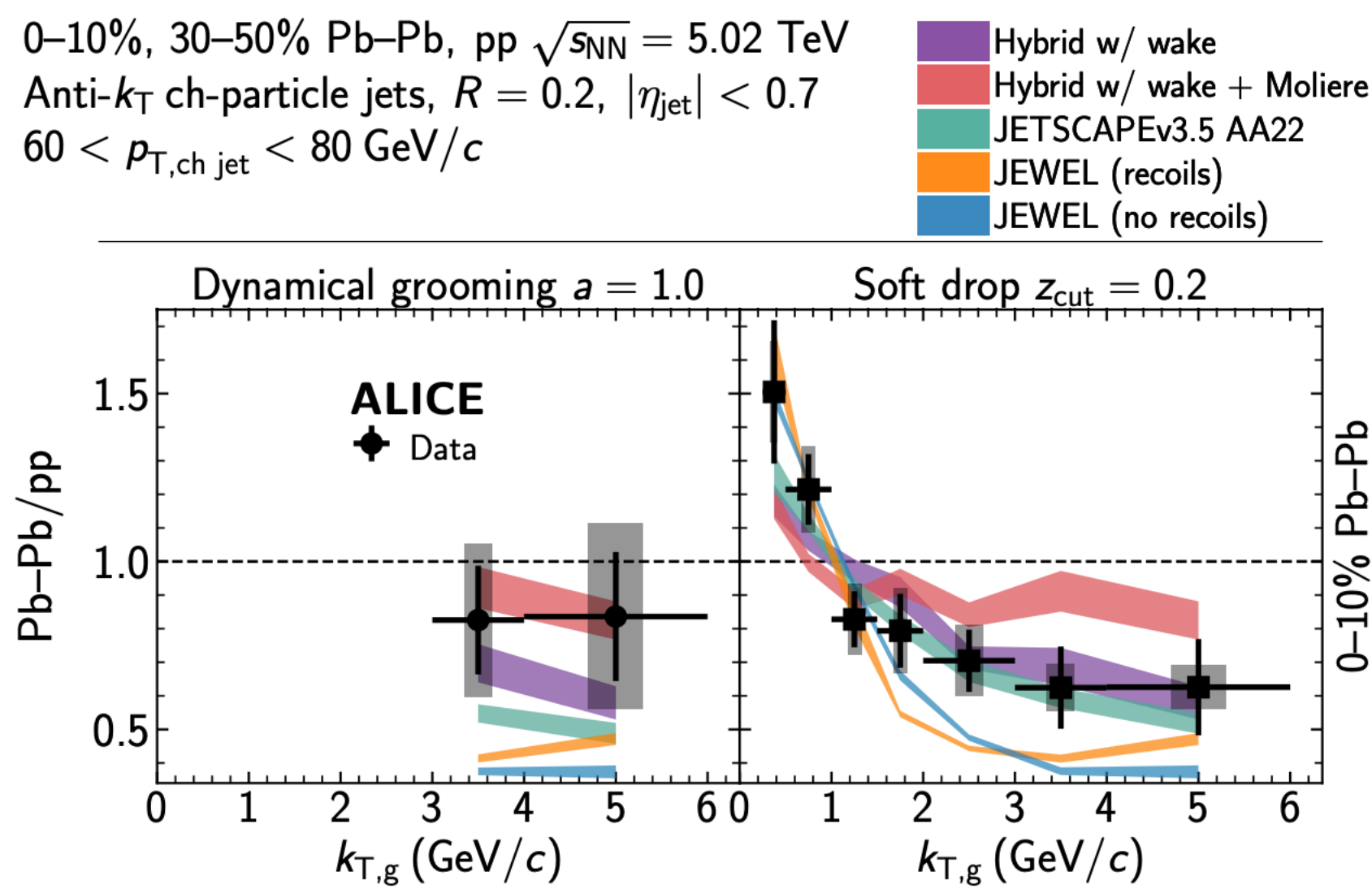
Internal structure modification

- We have learned* narrowing is everywhere!

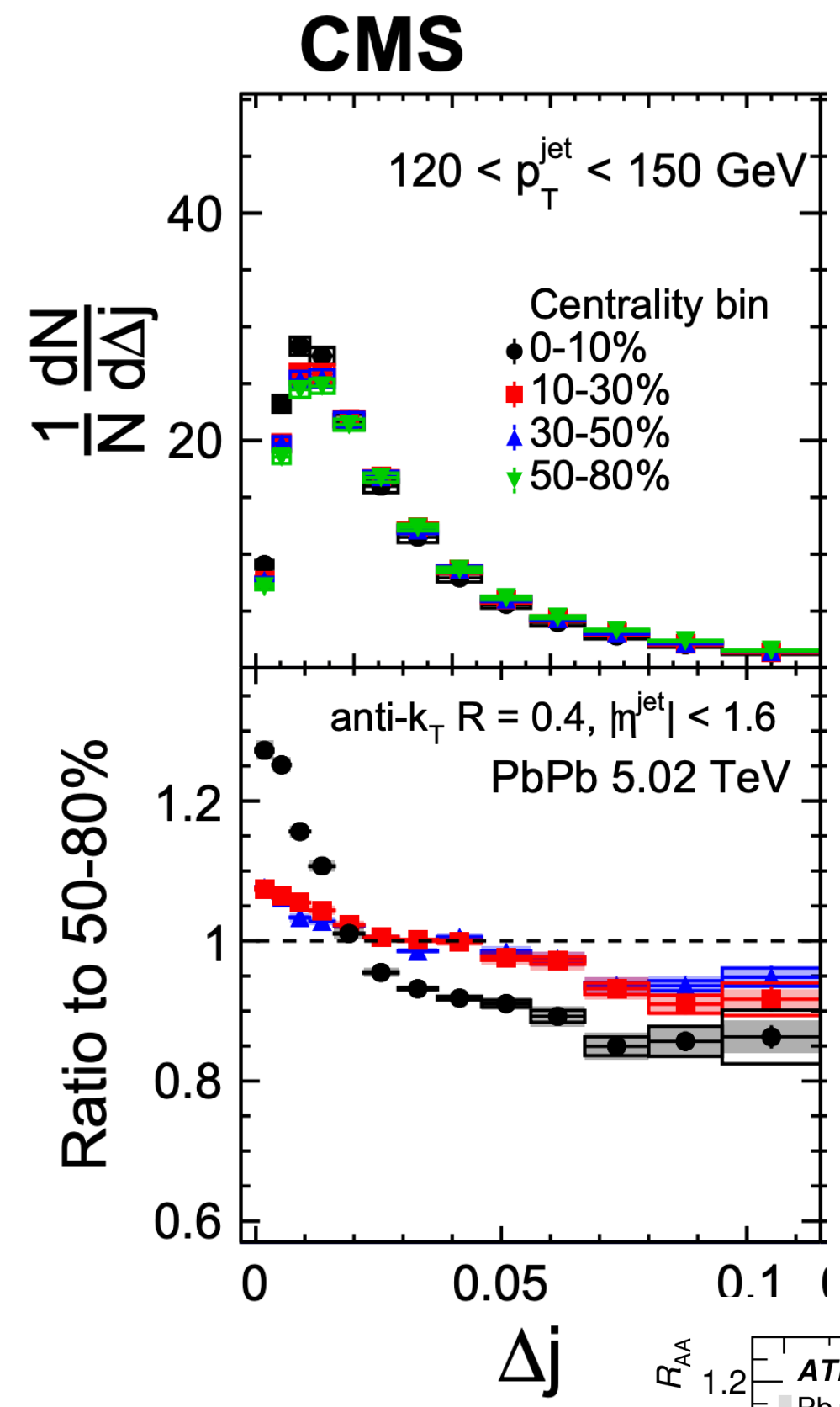
[PRC 113 (2026) 4, 044905]



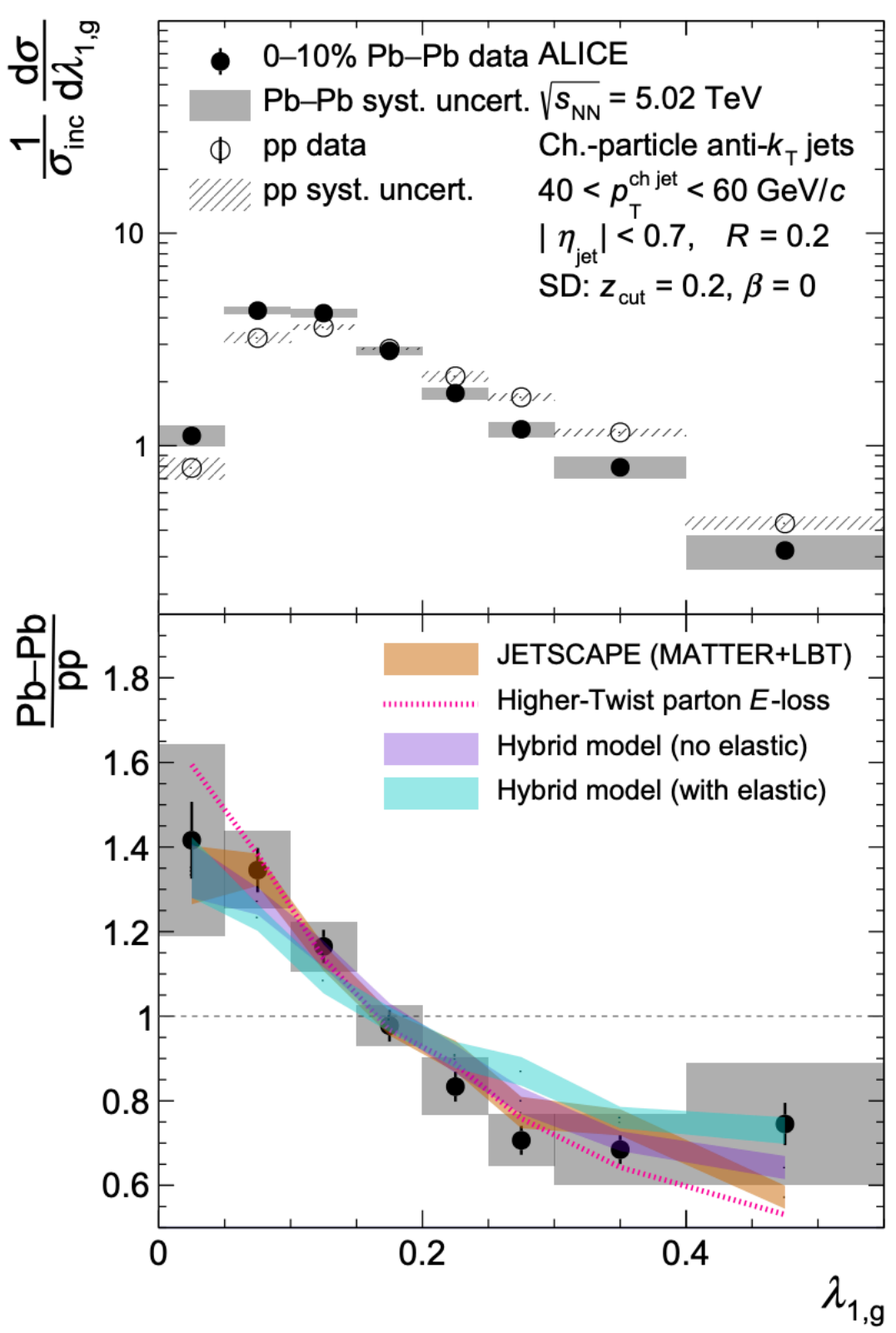
[PRL 135, 031901 (2025)]



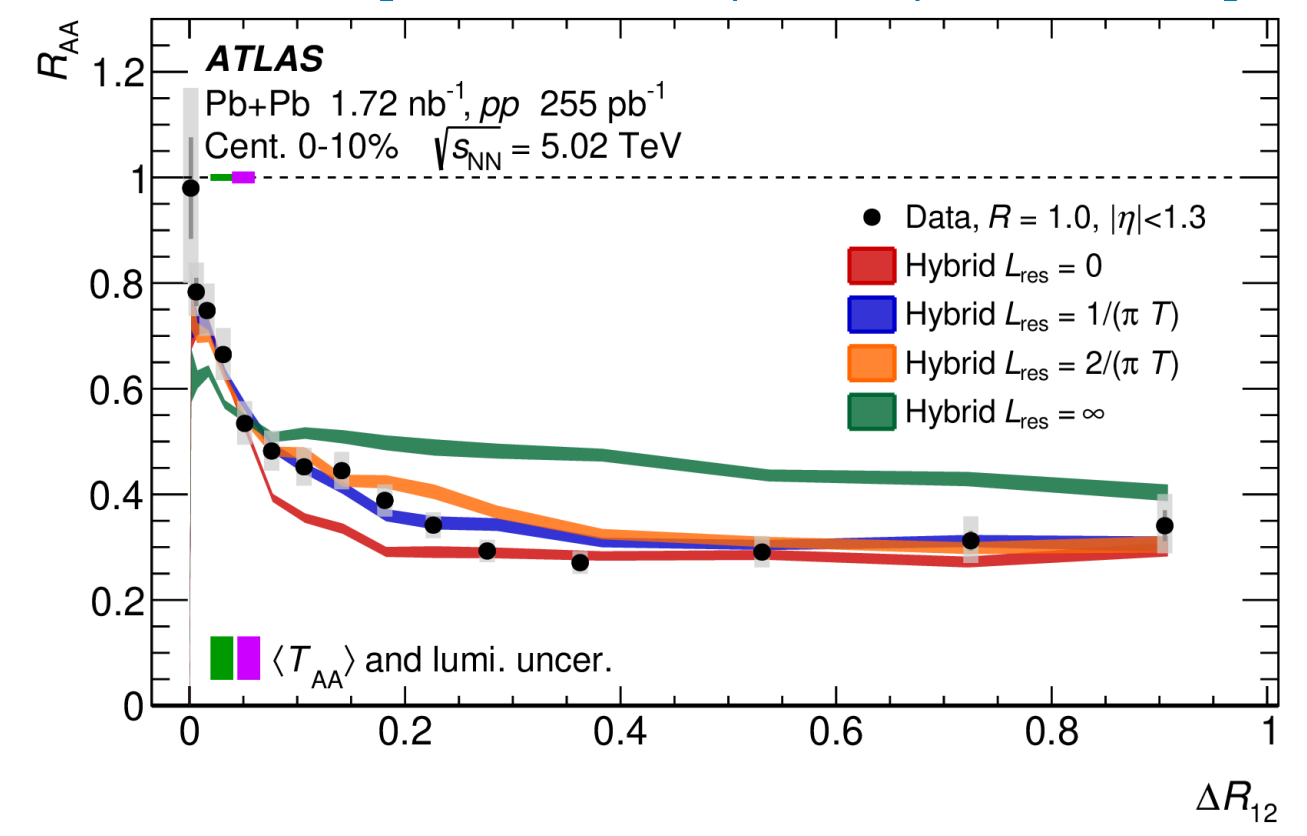
[JHEP 06 (2025) 120]



[PLB 864 (2025) 139409]

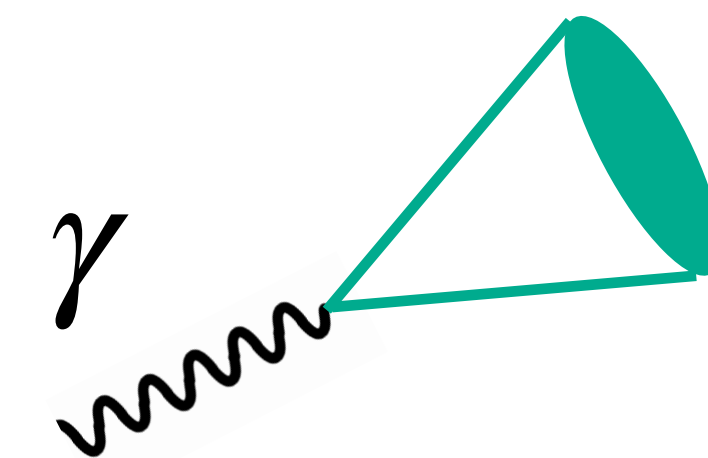


[PLB 871 (2025) 139929]

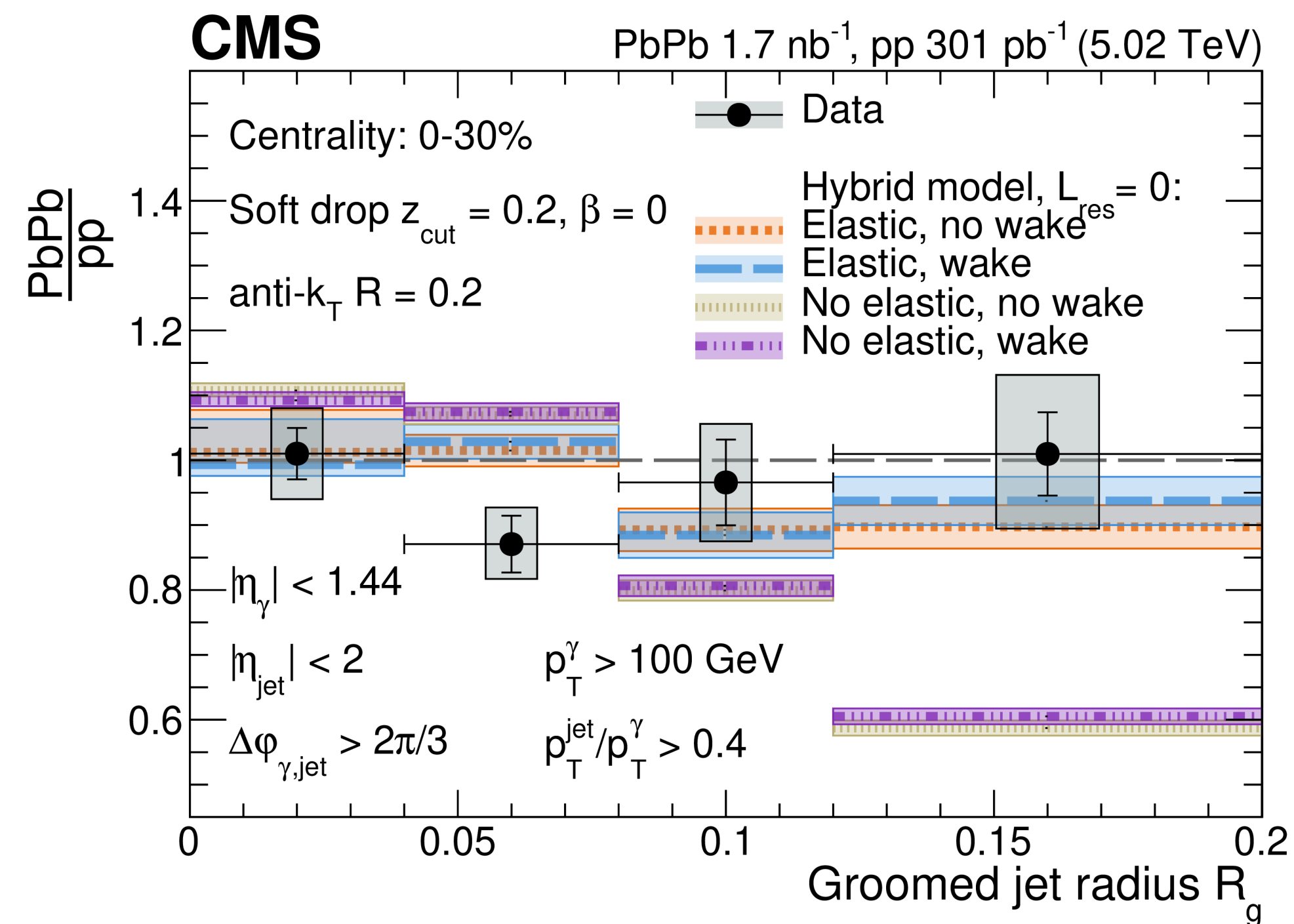


- This narrowing makes it very difficult to isolate effects!

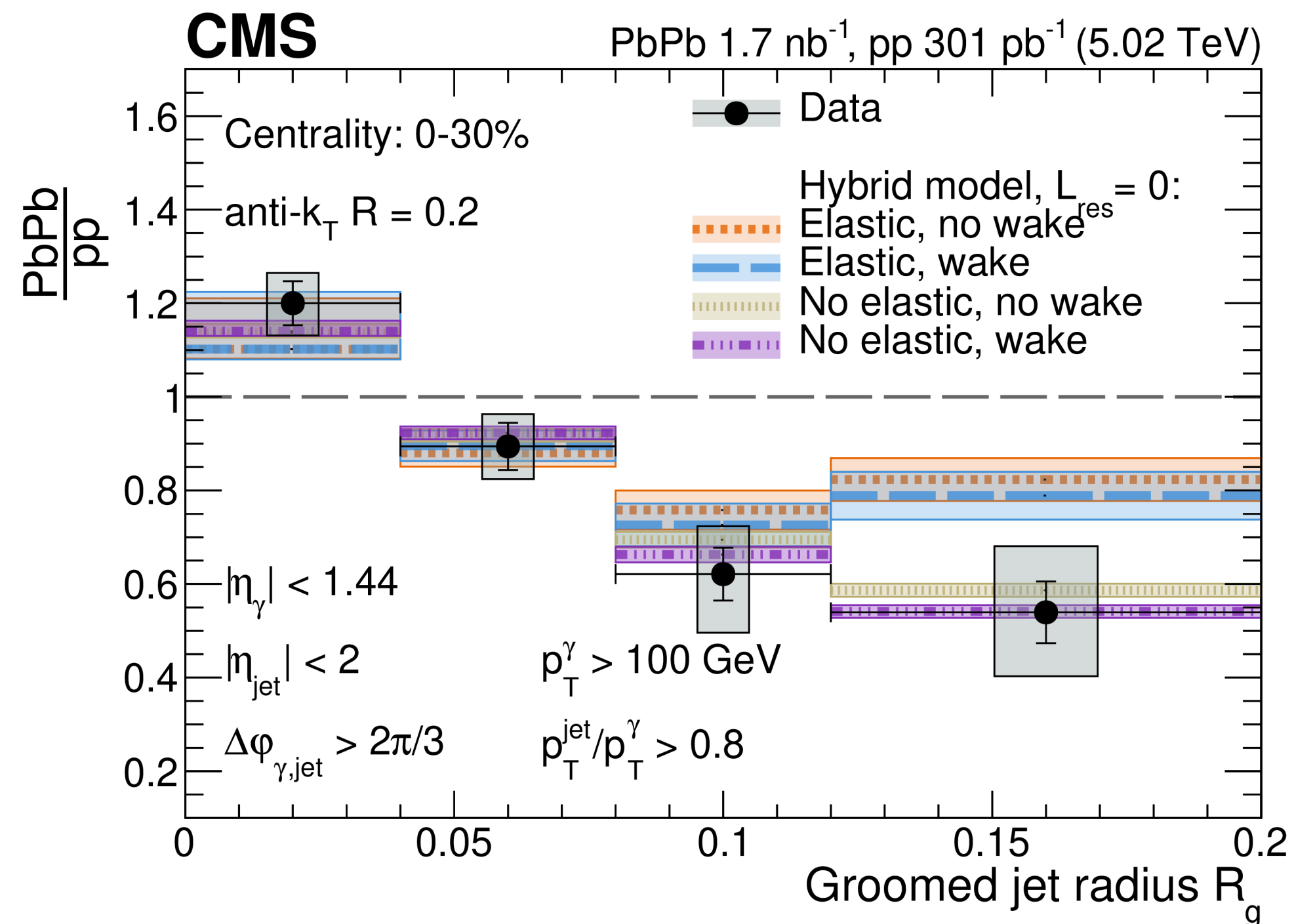
WHAT HAVE WE LEARNED SO FAR?



② Internal structure modification



$p_T^{\text{jet}}/p_T^\gamma > 0.4$: **Narrowing**
effect not seen for γ +jet



$p_T^{\text{jet}}/p_T^\gamma > 0.8$: **Selecting on less**
quenched jets restores narrowing.

* fragmentation photons can impact interpretation

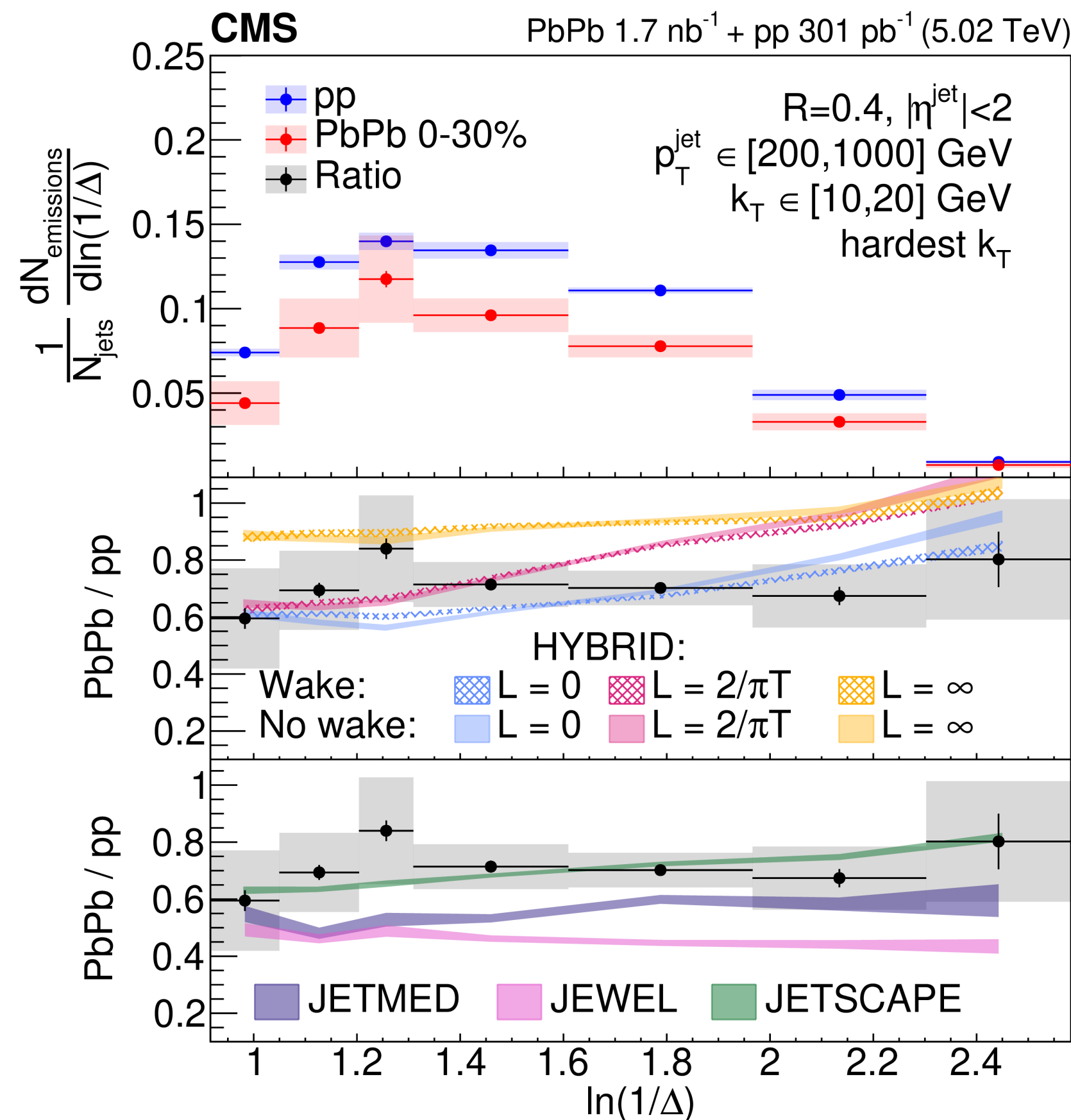
- *We have learned* γ + jet is useful for removing selection bias, yet no single set of parameters describes data (pp reference issue?)

[PLB 861 (2025) 139088]

WHAT HAVE WE LEARNED SO FAR?

② Internal structure modification

- *We have learned* that it is possible to isolate a population of vacuum-like splittings in heavy-ions



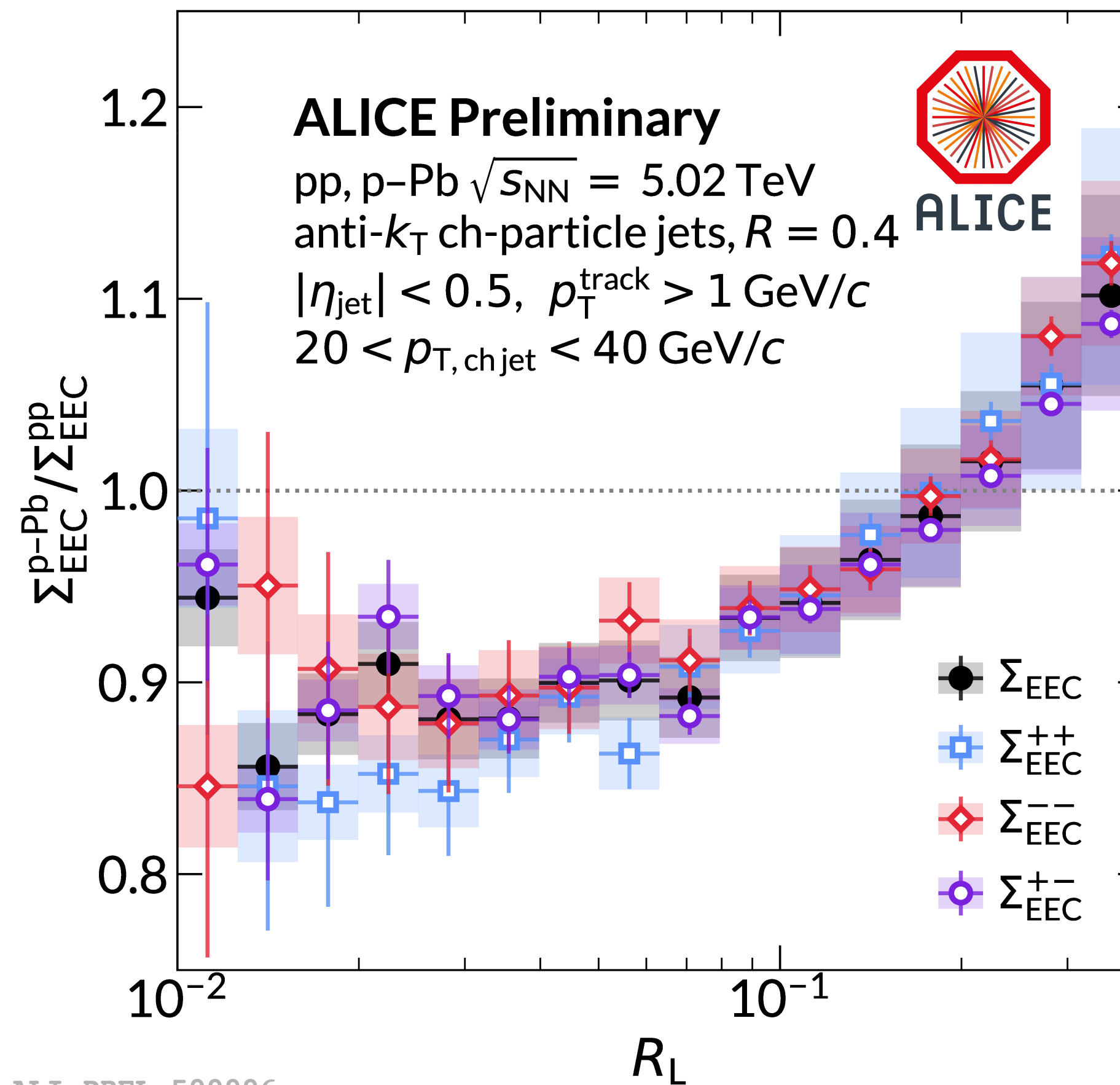
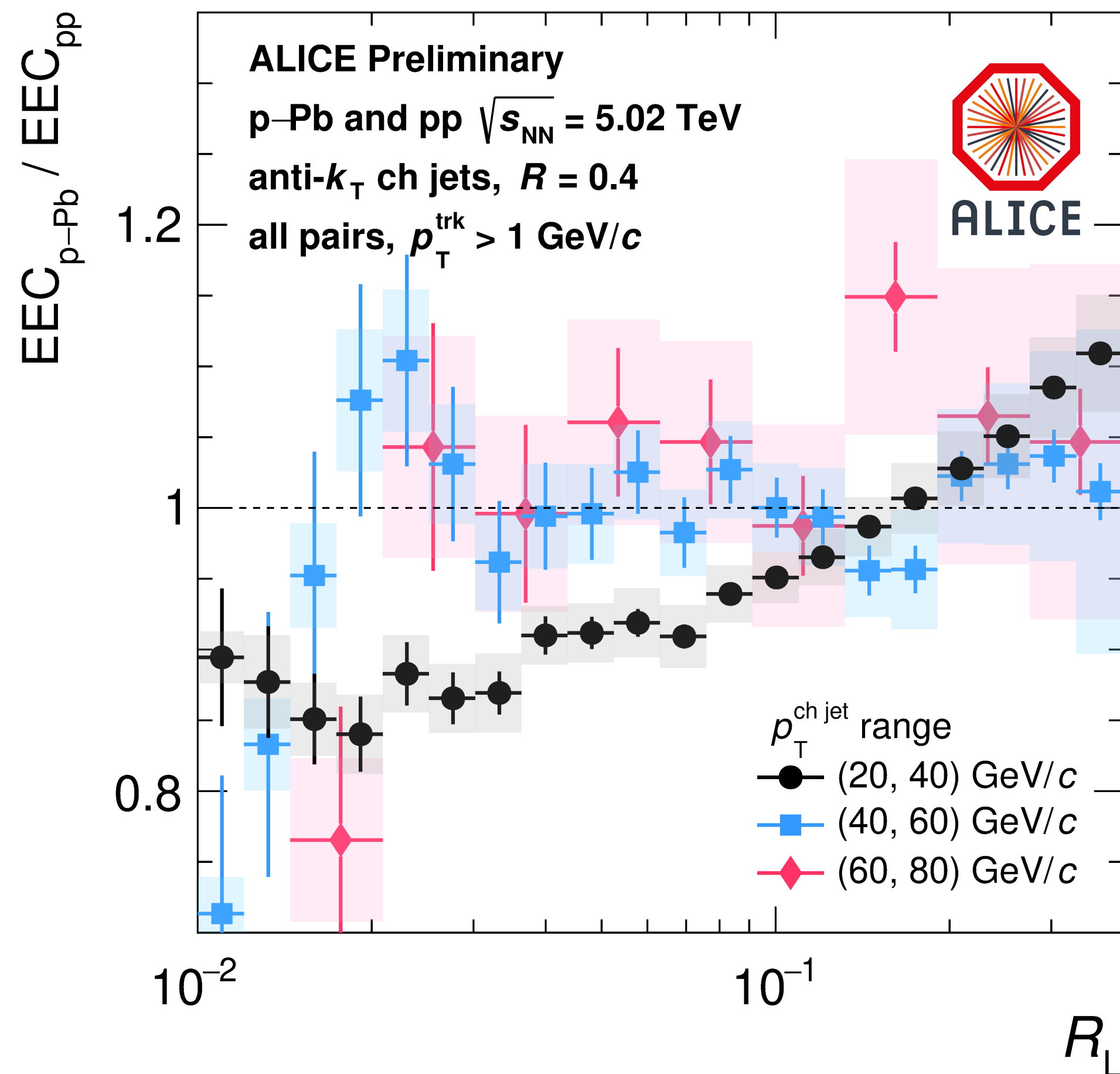
[HIN-24-016, arXiv:2602.09271 Submitted to PRL]

- Density of emissions in pp is higher than in PbPb.
 - Expected due to softening and broadening of the jet shower.
- Ratio is flat, relative shapes of angular distributions are independent angle.
 - Consistent with the hypothesis that earliest splittings are produced in vacuum.

[Phys. Rev. D 110, 014015 (2024)]

EECS IN PROTON-LEAD

[QM 2025 Poster, Tucker Hwang]



- Large angle enhancement in pPb collisions compared to pp.
- **Experimental result robust** against changes in p_T bin split, track p_T cut, charge, ...

- Can be described by enhancement of a number of theory predictions

[PRL 134 (2025) 25, 251903] [PRL 135 (2025) 11, 112302] [PRL 136 (2026) 12, 122301]

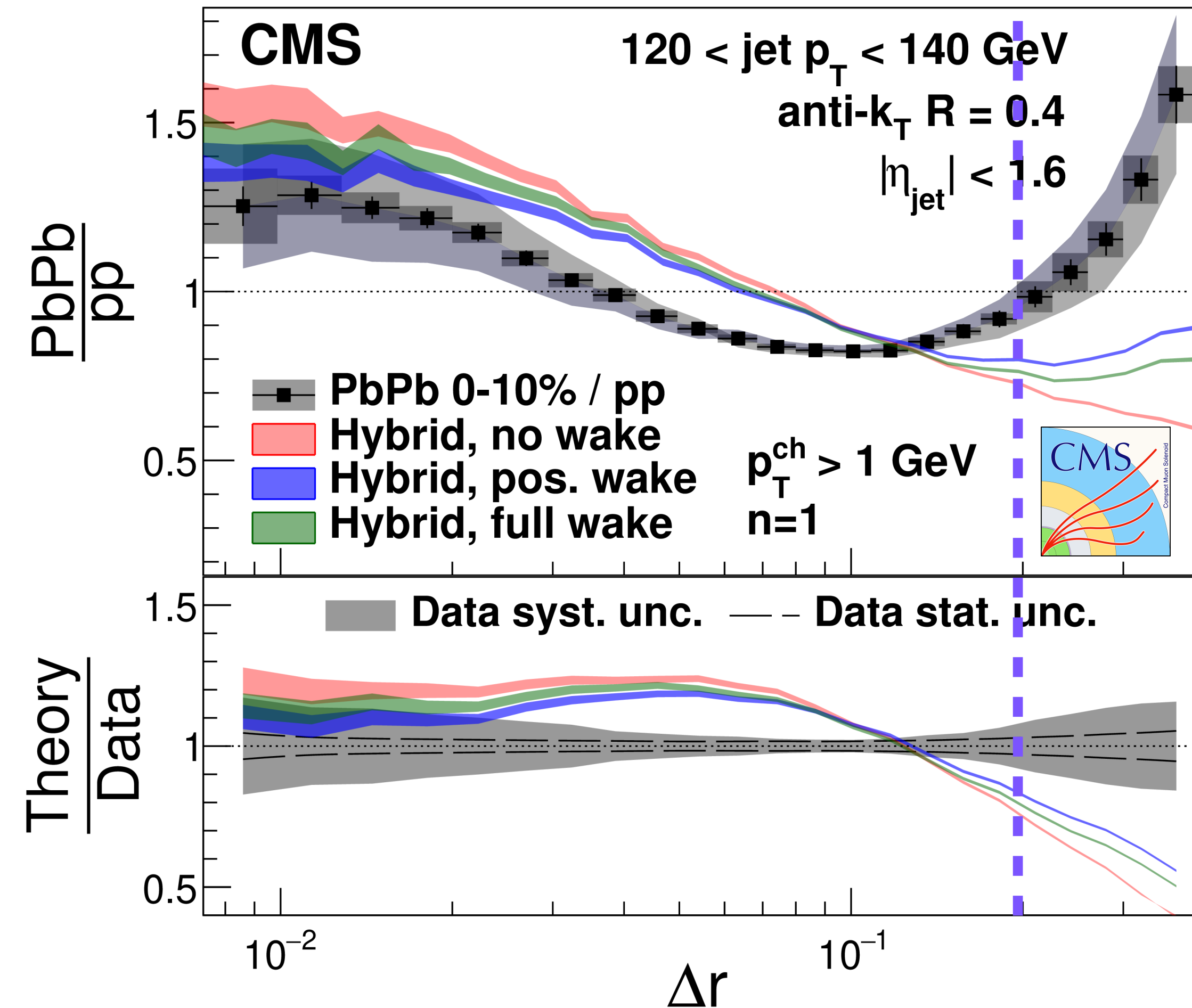
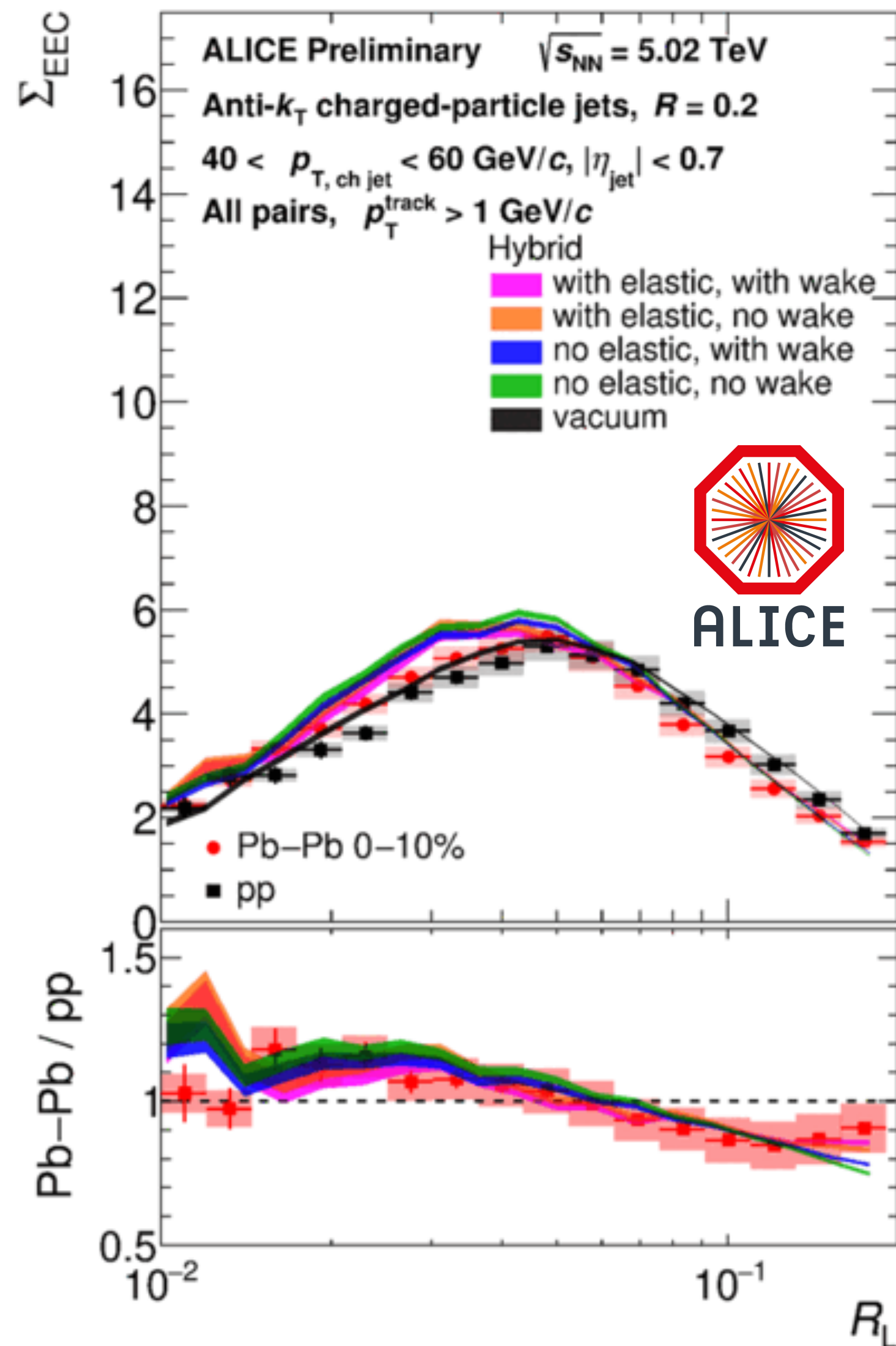
Does this effect only exist at low p_T (seems yes), useful to verify at high p_T .

MODIFICATION IN THE EEC

[PLB 866 (2025) 139556]

1.70 nb⁻¹ PbPb (5.02 TeV) + 302 pb⁻¹ pp (5.02 TeV)

[Ananya Rai Talk @ QM 2025]



- Large angle enhancement seen at CMS not seen in ALICE, likely due to cutoff from jet radius (0.2).
- Useful to push to larger radii, higher orders, etc!

LUMINOSITY TOTALS

[\[CMS Public Lumi Totals\]](#)

[\[Phys. Rept. 1115 \(2025\) 219\]](#)

Runs 1 + 2

Collision System	COM Energy	Delivered Lumi	Recorded Lumi
pp	2.76 TeV	5.61 pb ⁻¹	5.51 pb ⁻¹
PbPb	2.76 TeV	0.194 nb ⁻¹	0.183 nb ⁻¹
pp	5.02 TeV	369.97 pb ⁻¹	350.92 pb ⁻¹
PbPb	5.02 TeV	2.48 nb ⁻¹	2.35 nb ⁻¹
pPb	5.02 TeV	36.67 nb ⁻¹	36.01 nb ⁻¹
pPb	8.16 TeV	188.3 nb ⁻¹	180.2 nb ⁻¹
XeXe	5.44 TeV	3.50 × 10 ⁻³ nb ⁻¹	3.42 × 10 ⁻³ nb ⁻¹

Run 3

** Excluding 2026, which is yet to come!*

Collision System	COM Energy	Delivered Lumi	Recorded Lumi
pp	5.36 TeV	520.43 pb ⁻¹	483.10 pb ⁻¹
PbPb	5.36 TeV	6.652 nb ⁻¹	6.045 nb ⁻¹
pO	9.62 TeV	48.4 nb ⁻¹	46.5 nb ⁻¹
OO	5.36 TeV	9.4 nb ⁻¹	9.0 nb ⁻¹
NeNe	5.36 TeV	0.91 nb ⁻¹	0.9 nb ⁻¹

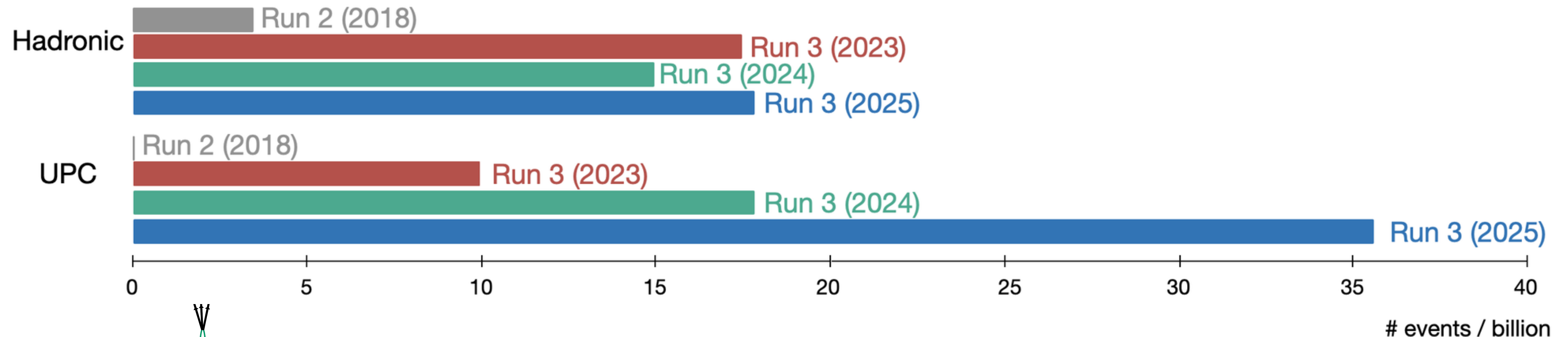
OF EVENTS IN RUN 3

[\[CMS Public Lumi Totals\]](#)

[\[Phys. Rept. 1115 \(2025\) 219\]](#)

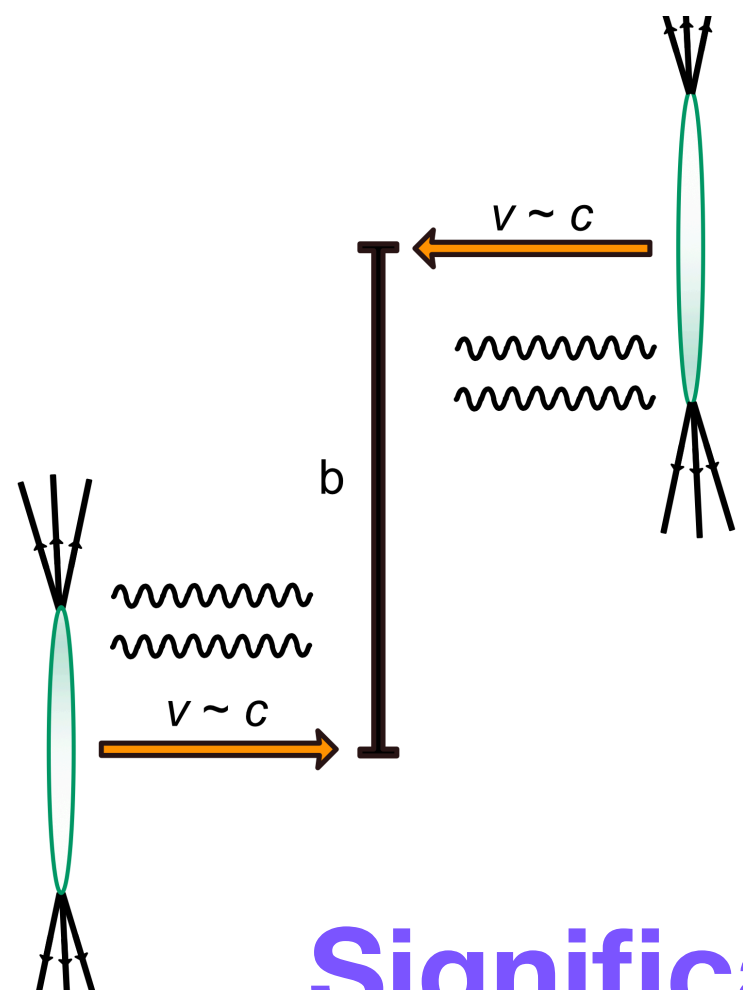
[\[CMS-DP-2024-002\]](#)

- Let's now look at this in terms of # of events.
- Dramatic increase in # of hadronic events as compared to Run 2.



- Significant improvements made in # of ultra-peripheral collision events recorded!
- Not the focus today, but lots of cool physics can be done here!

[See, for example, Gian Michele Innocenti's talk next week]



Significant improvements in Run 3 as compared to Run 2! What we do with this?

JET QUENCHING

***This categorization scheme is largely based off of great talk by Jing Wang.*

Impact of the medium on the jet → **jet energy loss**

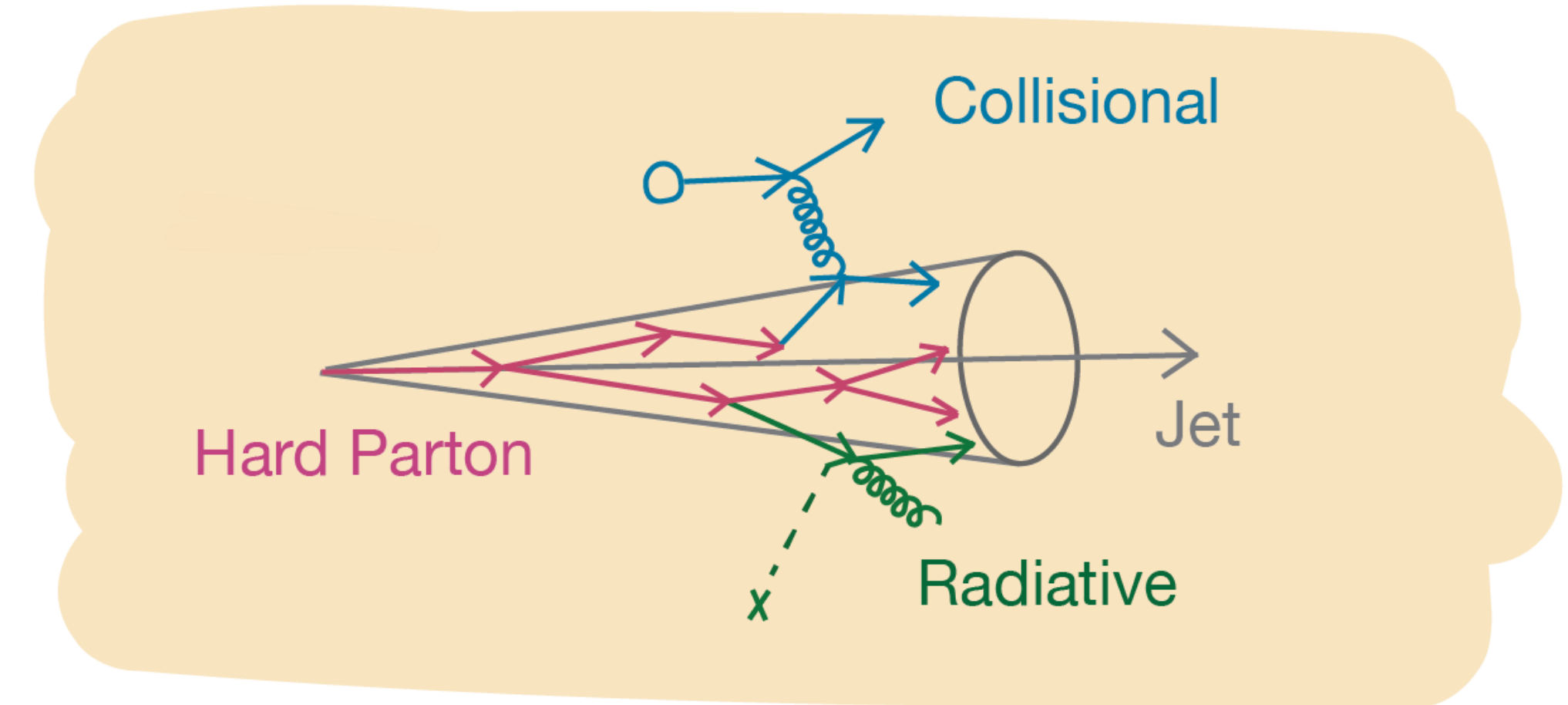
Ⓐ **Weak coupling limit**

→ Collisional

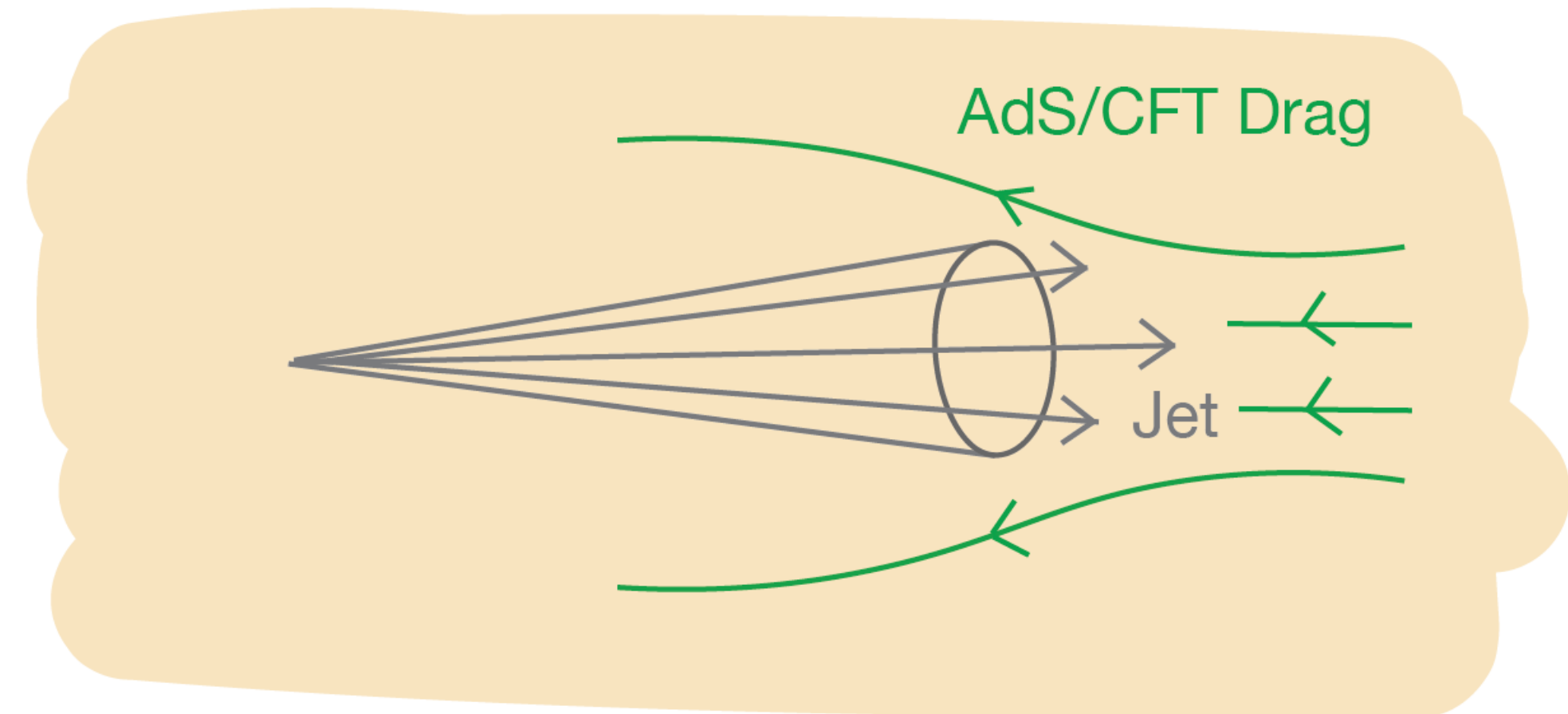
→ Radiative

Ⓑ **Strong coupling limit**

→ AdS/CFT drag force



QGP Medium



QGP Medium

Variety of ways to implement each category → all theories won't behave the same!

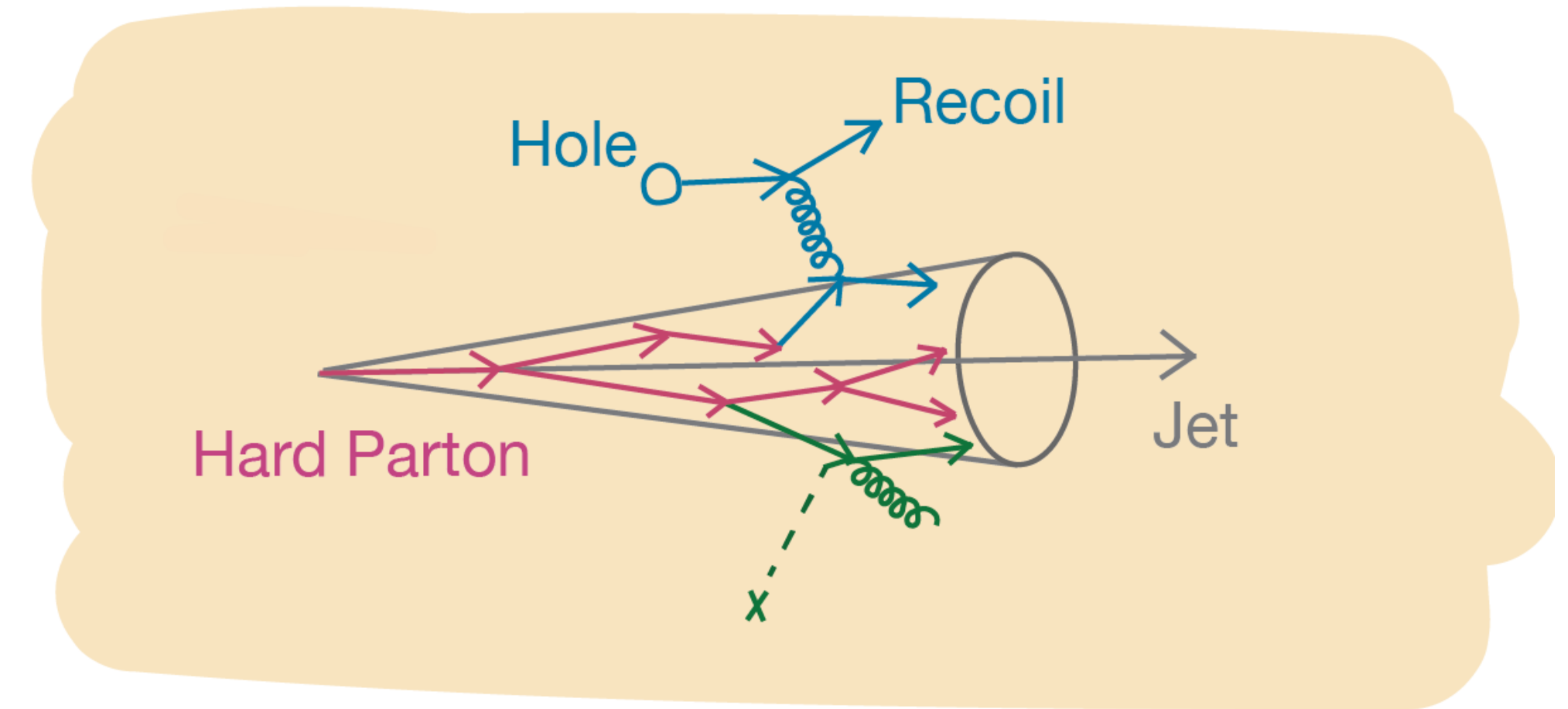
JET QUENCHING

***This categorization scheme is largely based off of great talk by Jing Wang.*

② Impact of the jet on the medium → **medium response**

① **Weak coupling limit**

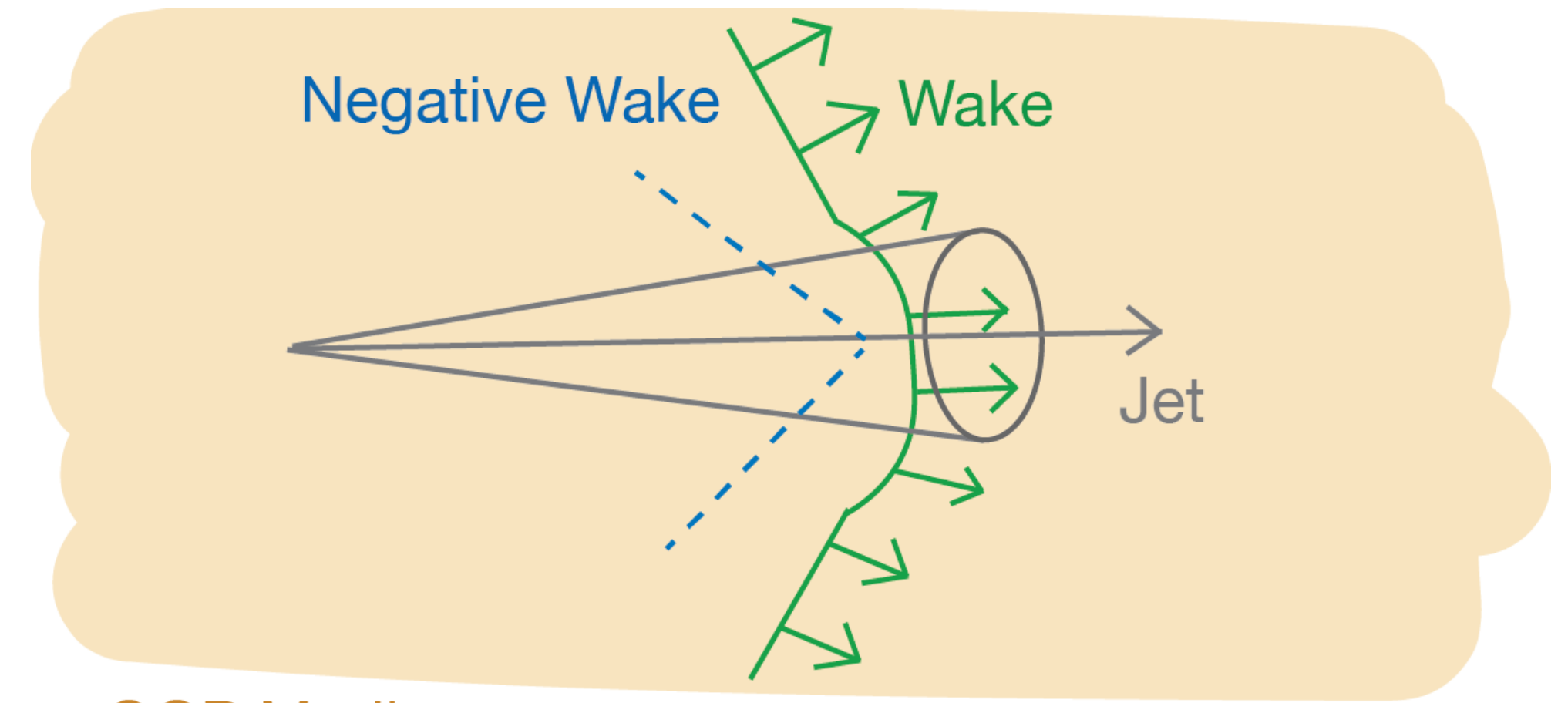
→ Recoils (Kinetic based approach)



QGP Medium

② **Strong coupling limit**

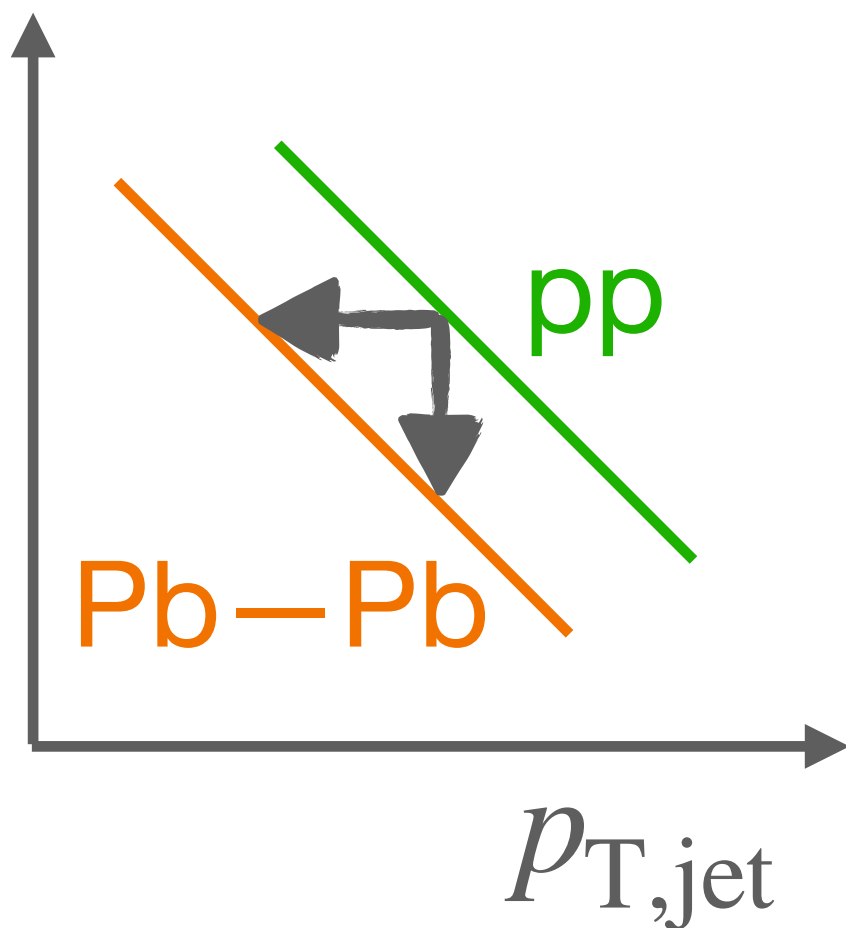
→ Wake
(Hydrodynamics based approach)



QGP Medium

Variety of ways to implement each category → all theories won't behave the same!

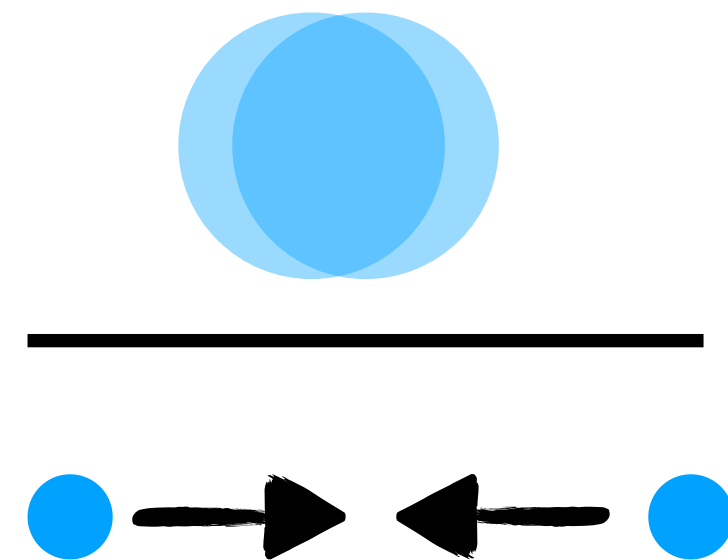
NUCLEAR MODIFICATION FACTOR



Parton energy loss will lead to a suppression of jet yields in heavy-ions (A+A) in comparison to vacuum (pp).

- We use the R_{AA} to probe this expectation.
- Ratio of the jet yield in AA compared to the expected yield if no hot or dense medium was present.

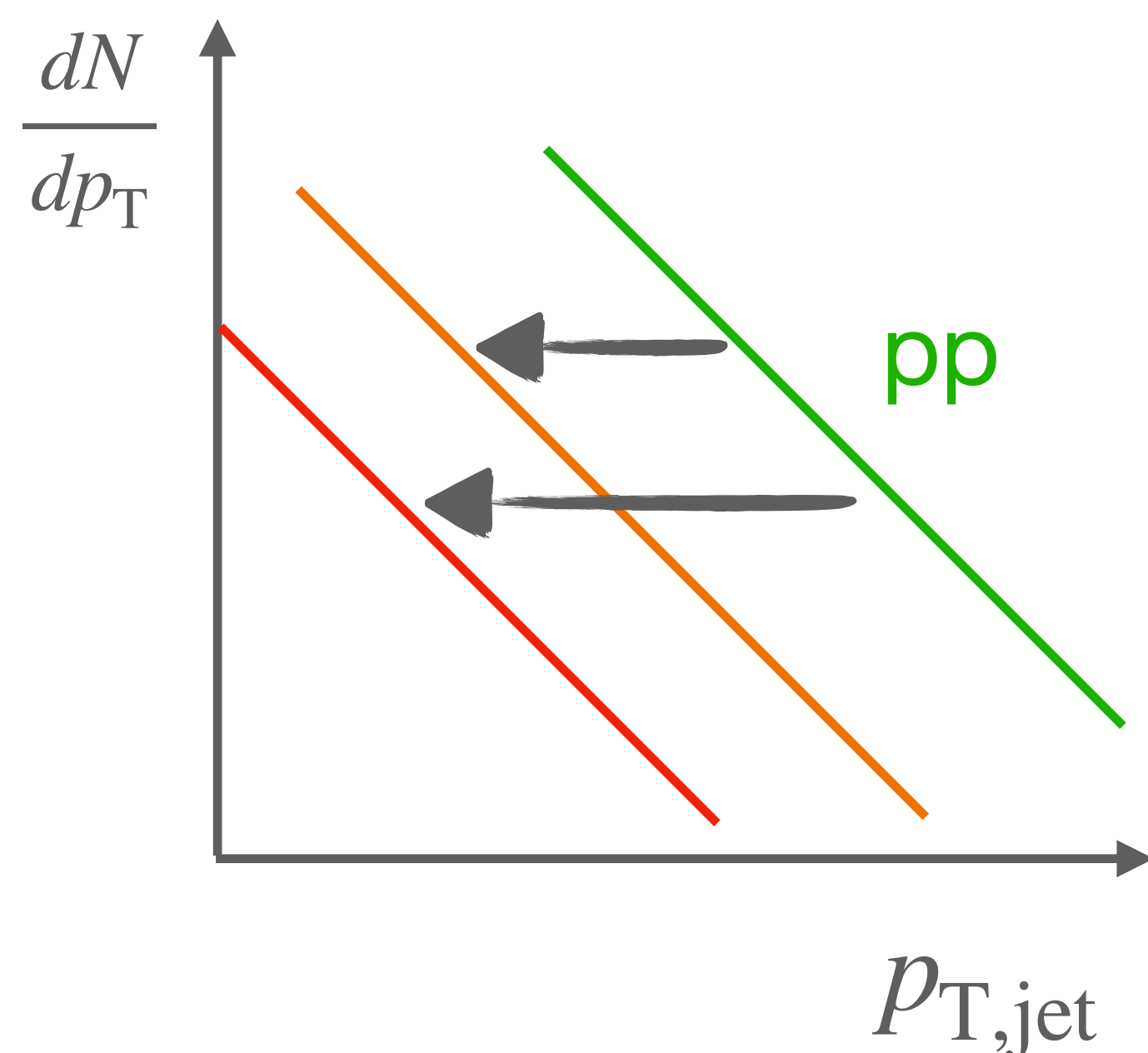
$$R_{AA} = \frac{\frac{1}{N_{\text{event}}} \frac{d^2 N_{\text{jet}}^{\text{PbPb}}}{dp_T dy} \Big|_{\text{cent}}}{\langle T_{AA} \rangle \frac{d^2 \sigma_{\text{jet}}^{\text{pp}}}{dp_T dy}} =$$



$R_{AA} < 1 \rightarrow$ Suppression

Jet suppression is a key signature of QGP formation!

SELECTION BIAS



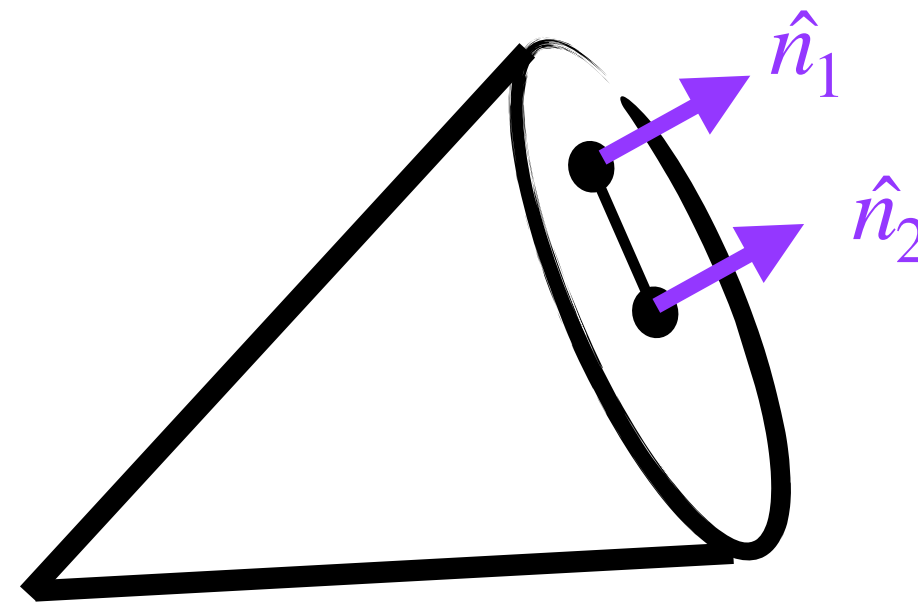
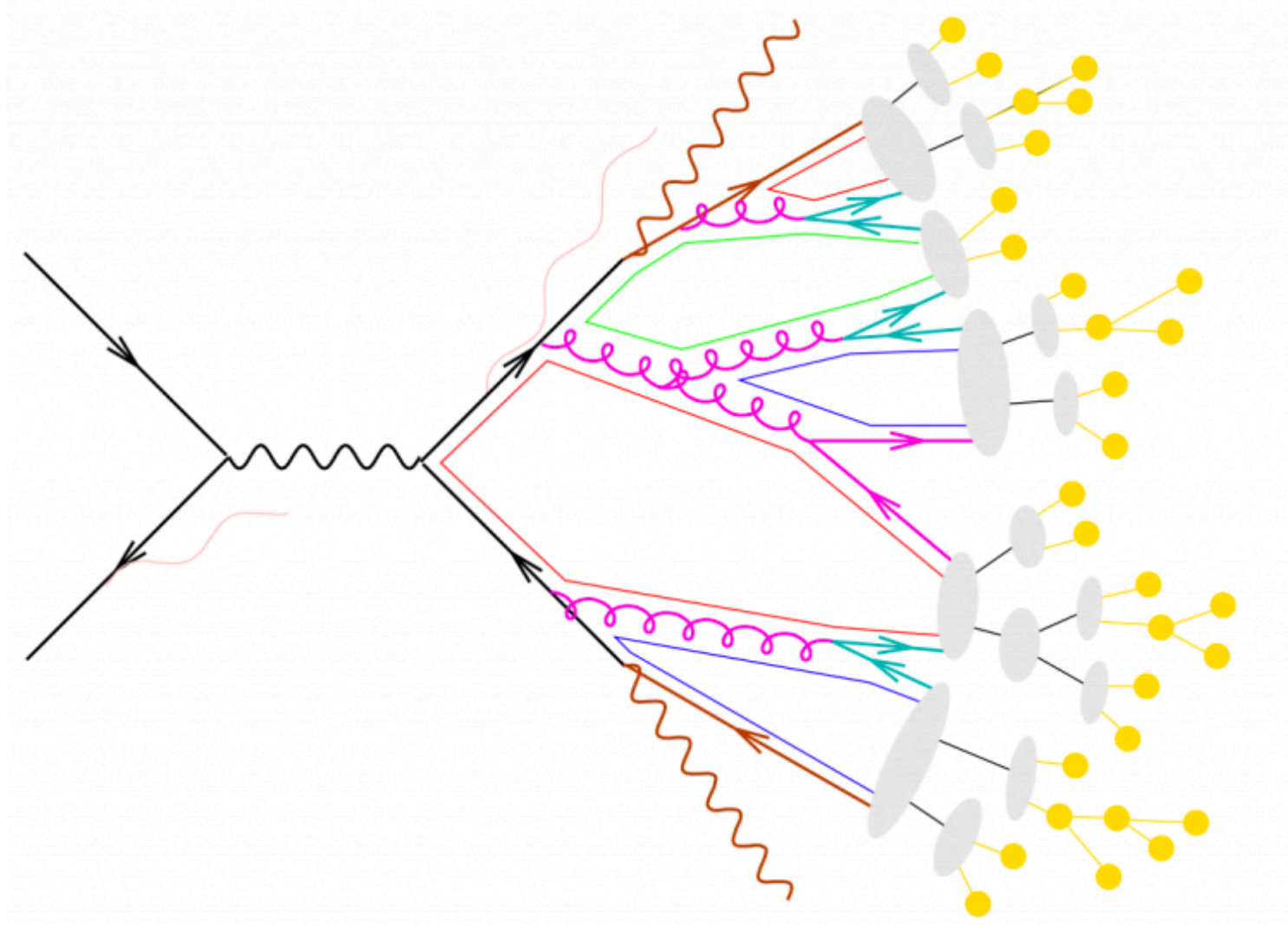
[Brewer et. al: Phys. Rev. Lett.122.222301]

- If some populations lose more energy than others, we will see a suppression purely from taking the ratio at a fixed p_T .
- Ideally for every jet in vacuum, want to see what it becomes in heavy-ion collisions

→ Potential ways to do this...

- ML techniques to access the initial jet p_T [JHEP. 2021, 206 (2021)]
- γ -tagged measurements of jets and their substructure

ENERGY CORRELATORS



Energy correlators look at correlations between energy flow deposits in a hard scattering.

Defined as the correlation of energy flow operator

$$\mathcal{E}(\vec{n}_1) = \lim_{r \rightarrow \infty} \int dt r^2 n_1^i T_{0i}(t, r\vec{n}_1)$$

where $\langle \Psi | \mathcal{E}(\vec{n}_1) \mathcal{E}(\vec{n}_2) \cdots \mathcal{E}(\vec{n}_k) | \Psi \rangle$

Characterizes the energy flux in the direction of $\hat{n}$

In hadron collider environments, instead of $\hat{n}_1$ use

$$\Delta R = \sqrt{\Delta y^2 + \Delta \phi^2}$$