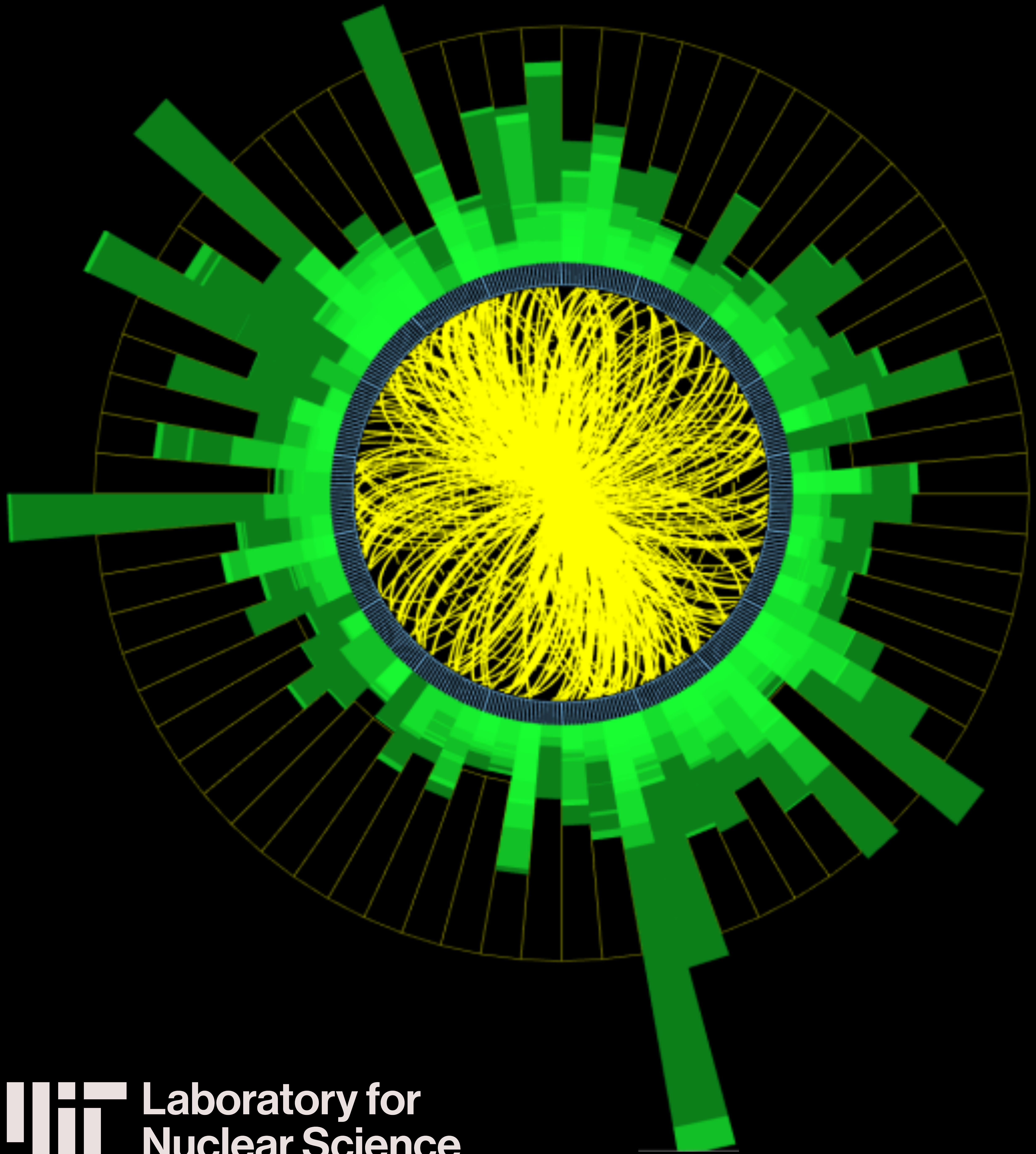


Recent jet measurements at the LHC

Hannah Bossi (MIT)
RHIC/AGS Users Meeting
BNL
May 11th, 2026

** Talk not on behalf of any experiment - all opinions expressed are my own!*

Laboratory for Nuclear Science

MIT HIG's work was supported by US DOE-NP

ROADMAP

WHERE ARE WE NOW IN THE EXPLORATION OF JET PHYSICS? HOW DID WE GET HERE?

WHAT HAVE WE LEARNED?

WHAT REMAINS UNKNOWN? HOW WILL NEW DATA CONTRIBUTE?

Bonus topic: What synergies exist between RHIC and LHC measurements. How can we best compare measurements at the two facilities?

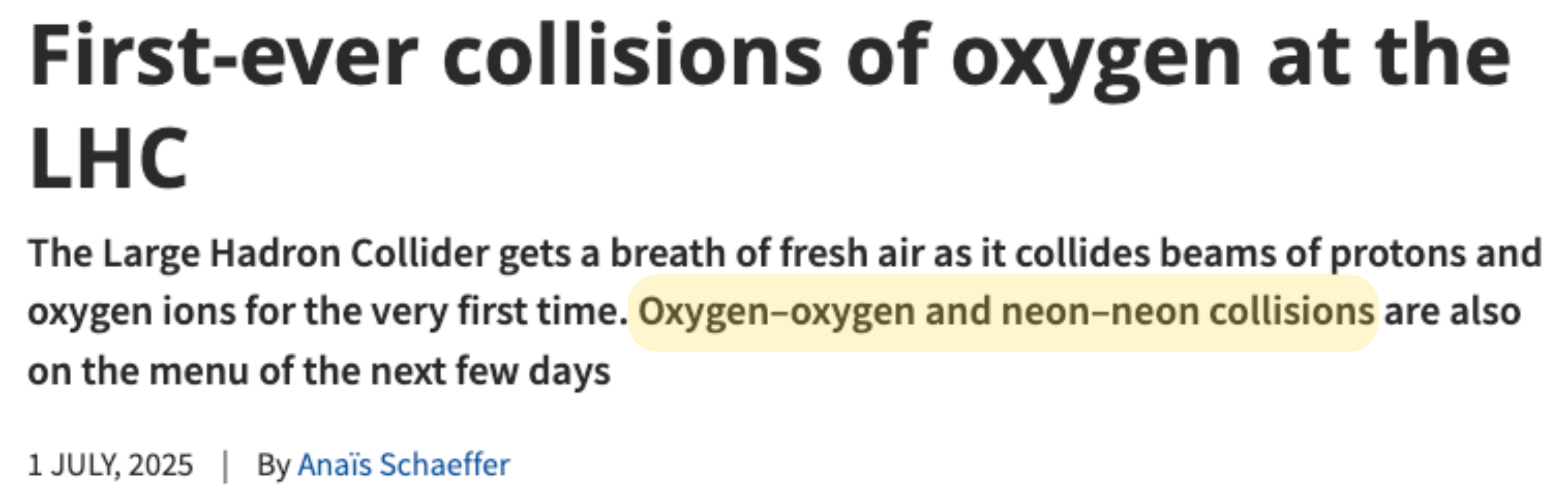
THE LARGE HADRON COLLIDER (LHC)

Geneva, Switzerland

Circumference ~27km

- Focus mostly on proton collisions at high energies ($\sqrt{s} = 13.6$ TeV)
  - Also collides Pb at $\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV

Four experiments each with different goals



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]

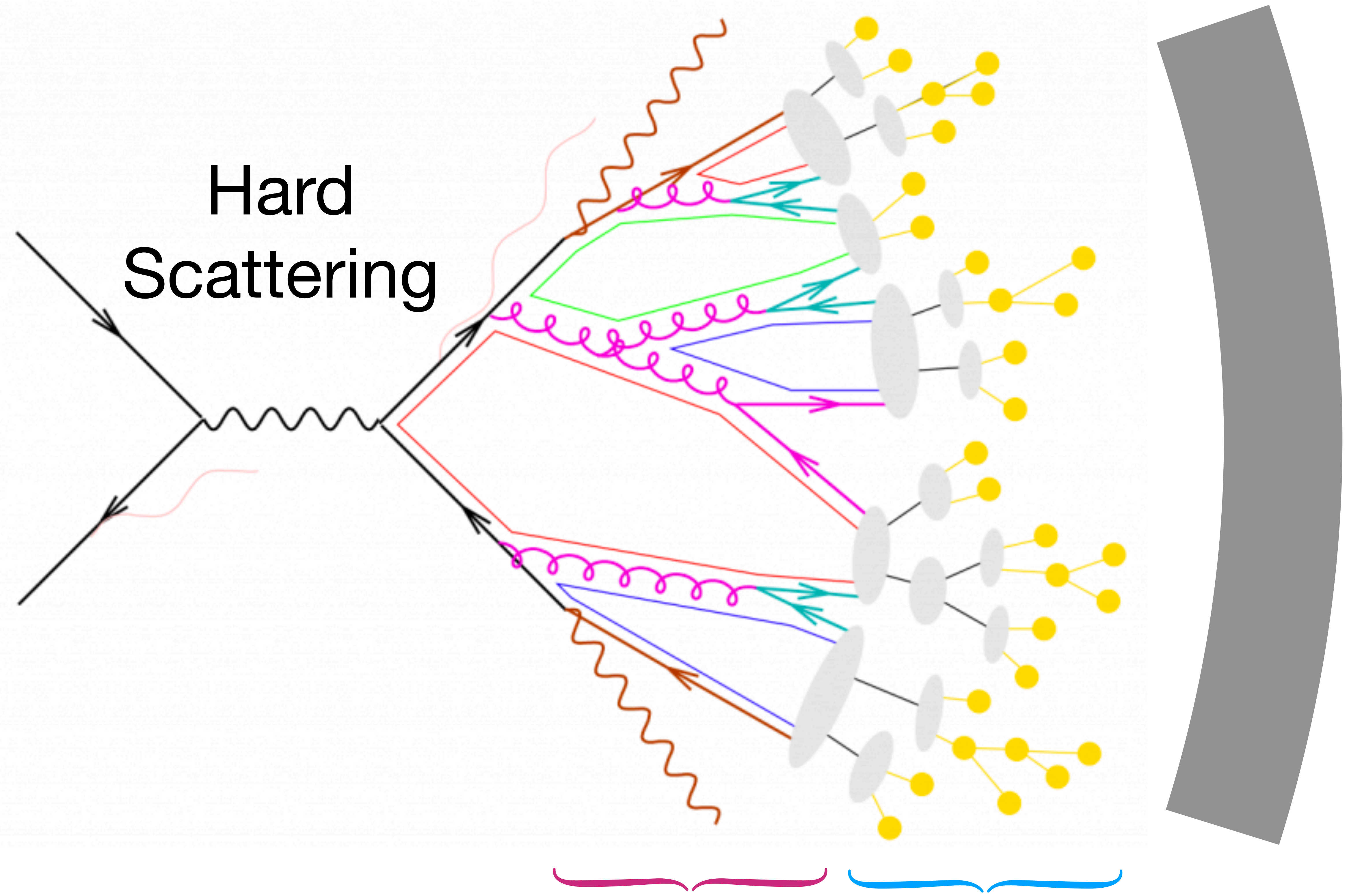
Heavy-ion run at the LHC begins

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

6 NOVEMBER, 2024 | By Chetna Krishna

[CERN News, November 2024]

HARD PROCESSES

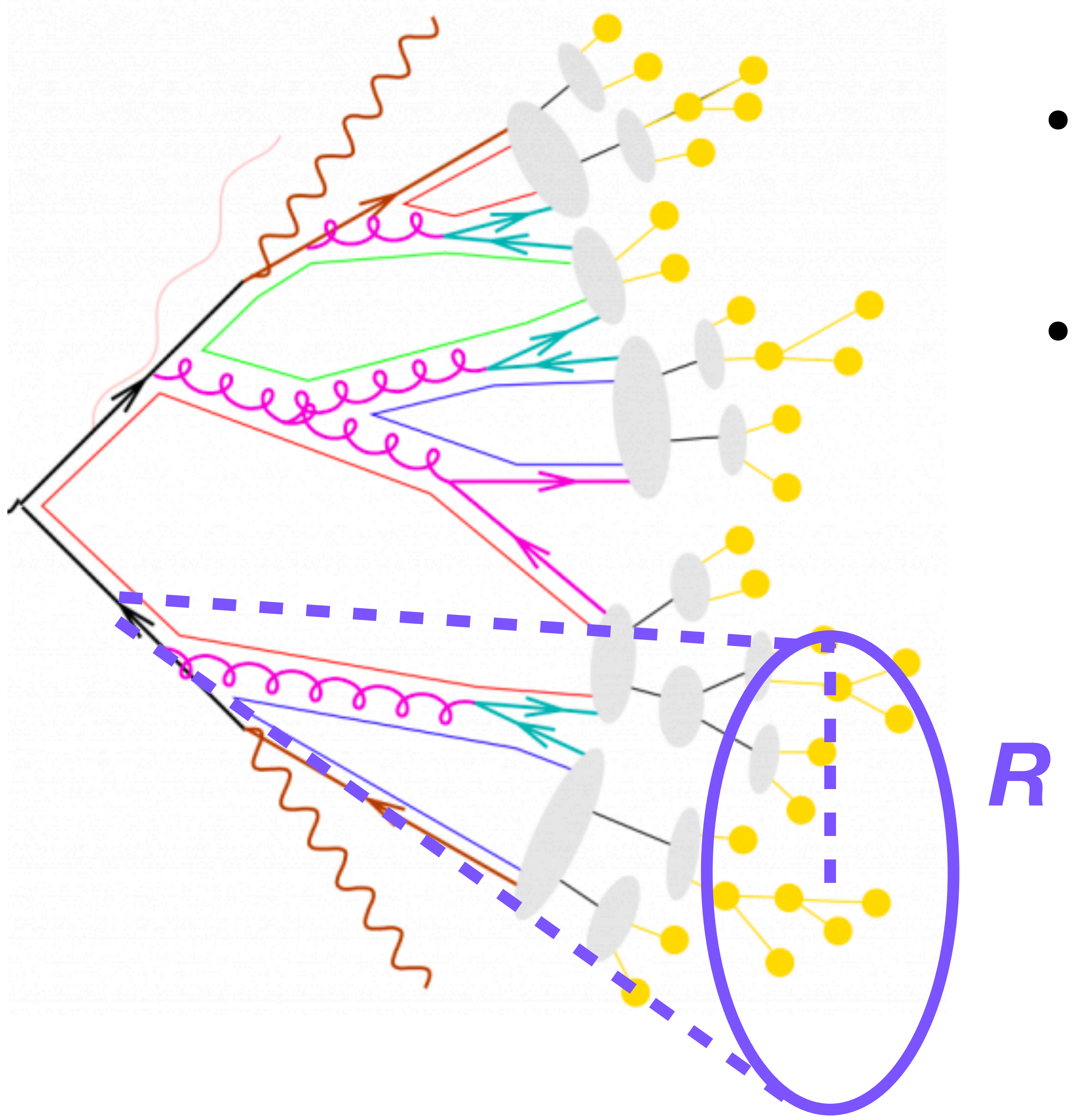


- Fundamental QCD processes that occur when partons scatter with high momentum transfer (“*hard*”).
- Parton fragments via a parton shower and eventually becomes confined inside hadrons via hadronization.

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

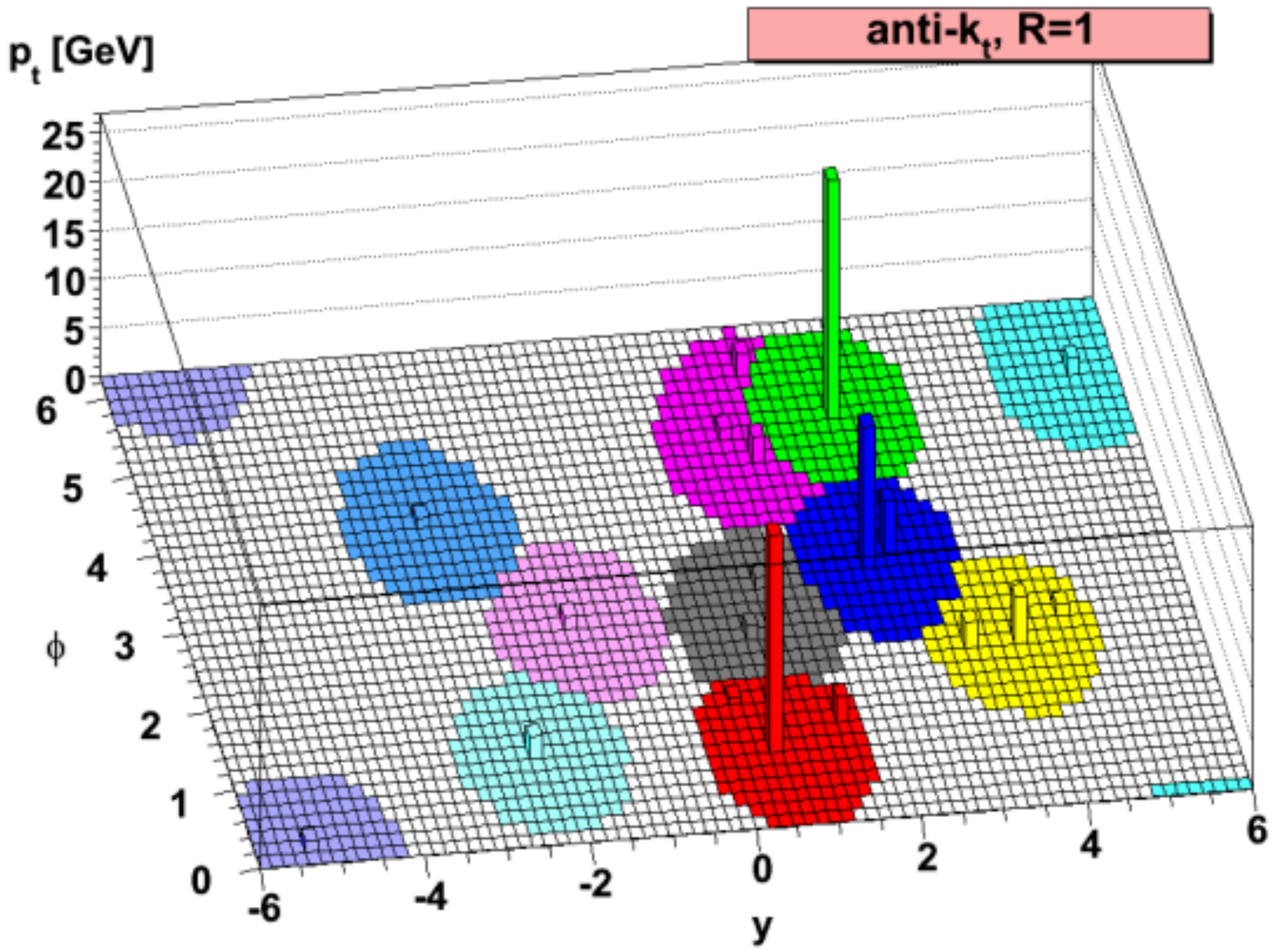
WHAT ARE JETS?

- Jets are experimental objects that are sensitive to the dynamics of the hard-scattered parton.
  - **Other observables like energy correlators also sensitive, this talk focuses on jets!**



- Hadrons deposit energy in the detector.

- Combine hadrons using jet clustering algorithms with a specified resolution parameter, related to the cone radius ***R***.



- Common choice is the anti-k_T algorithm.

[JHEP 0804:063 (2008)]

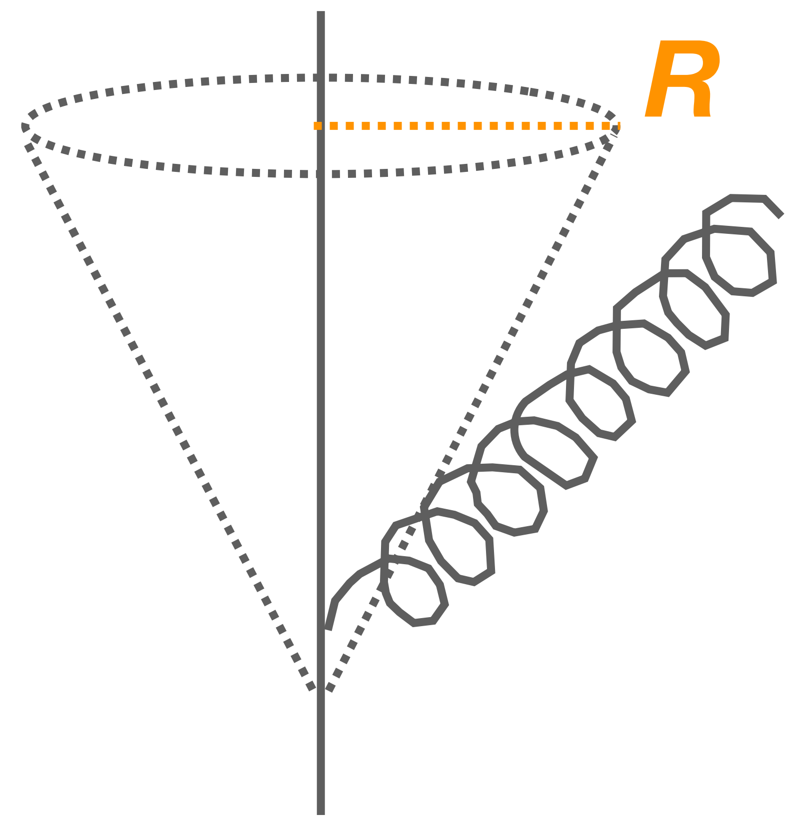
JETS IN REALITY

[JHEP 12 (2020) 082]

Experimental jets are not a *perfect* proxy for the dynamics of the hard-scattered parton.

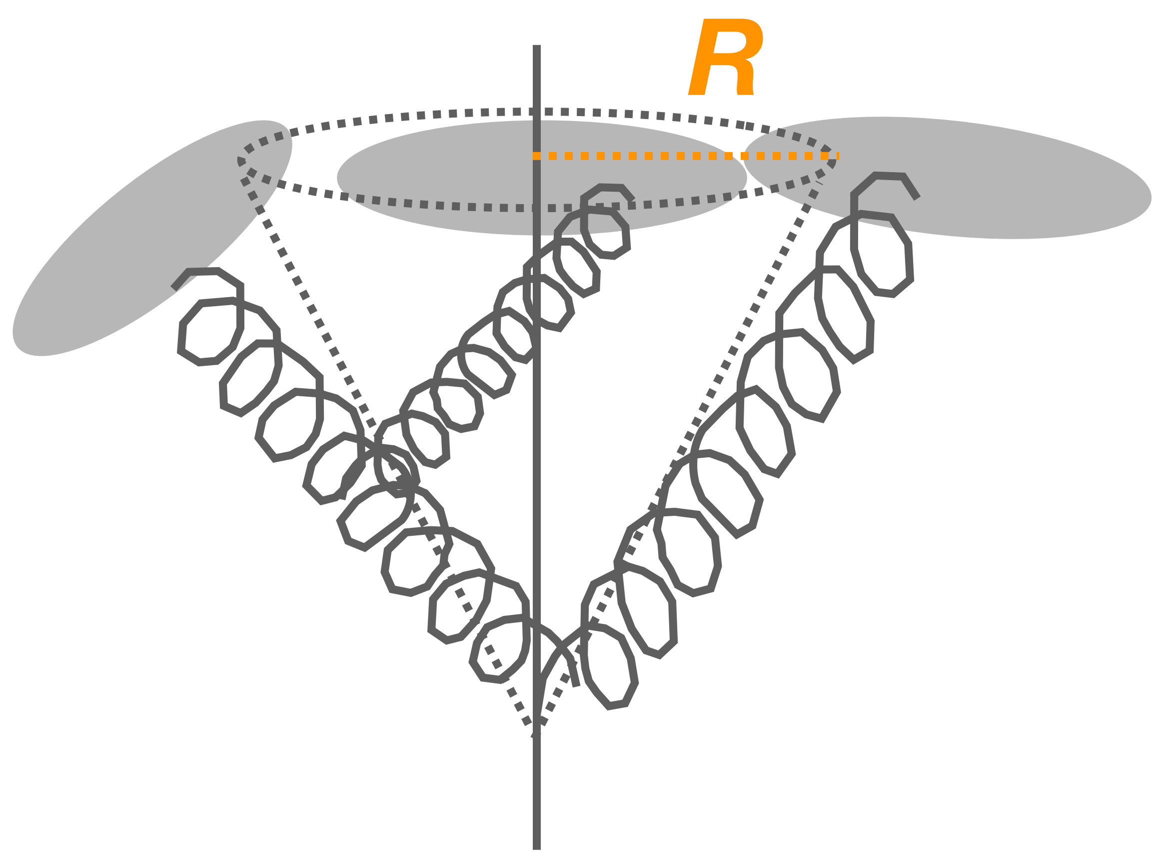
→Different physics effects can move energy **into** or **outside** of the experimental jet cone.

Parton Shower



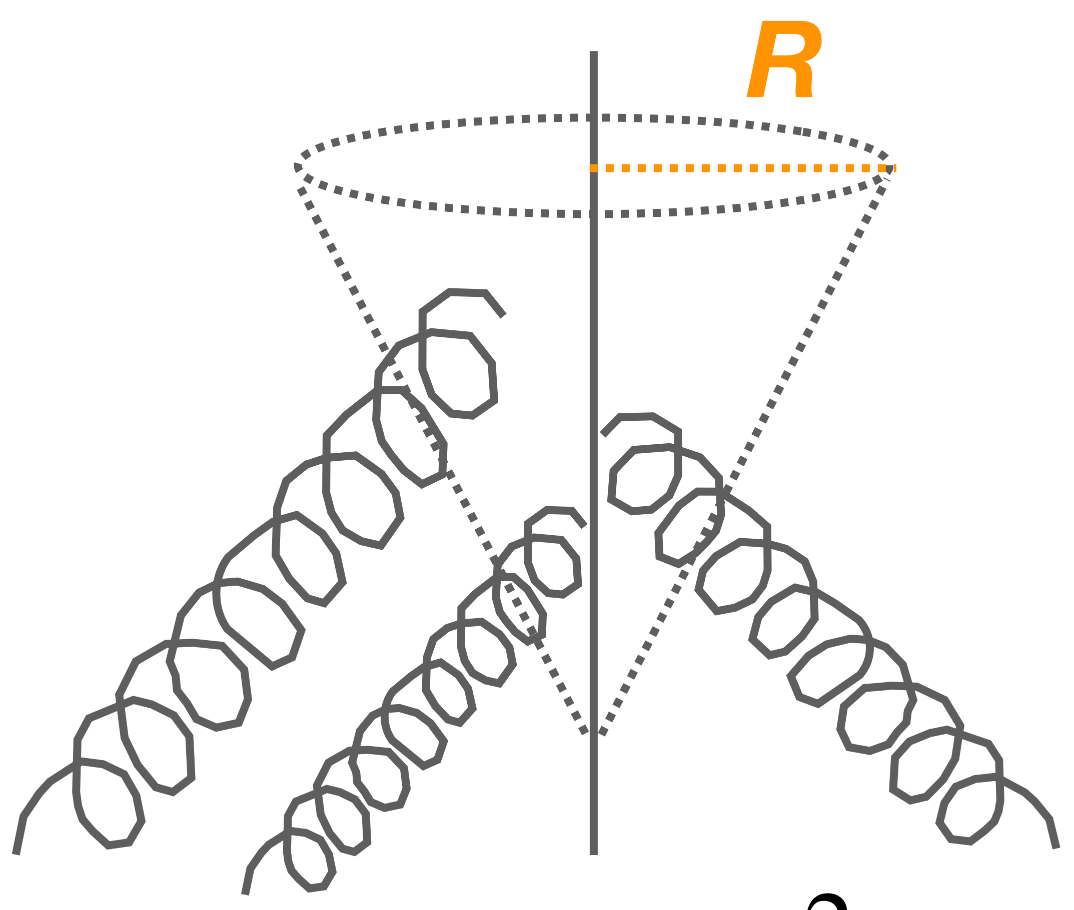
$\delta p_T \sim ln(1/R)$

Hadronization



$\delta p_T \sim 1/R$

Underlying Event



$\delta p_T \sim R^2$

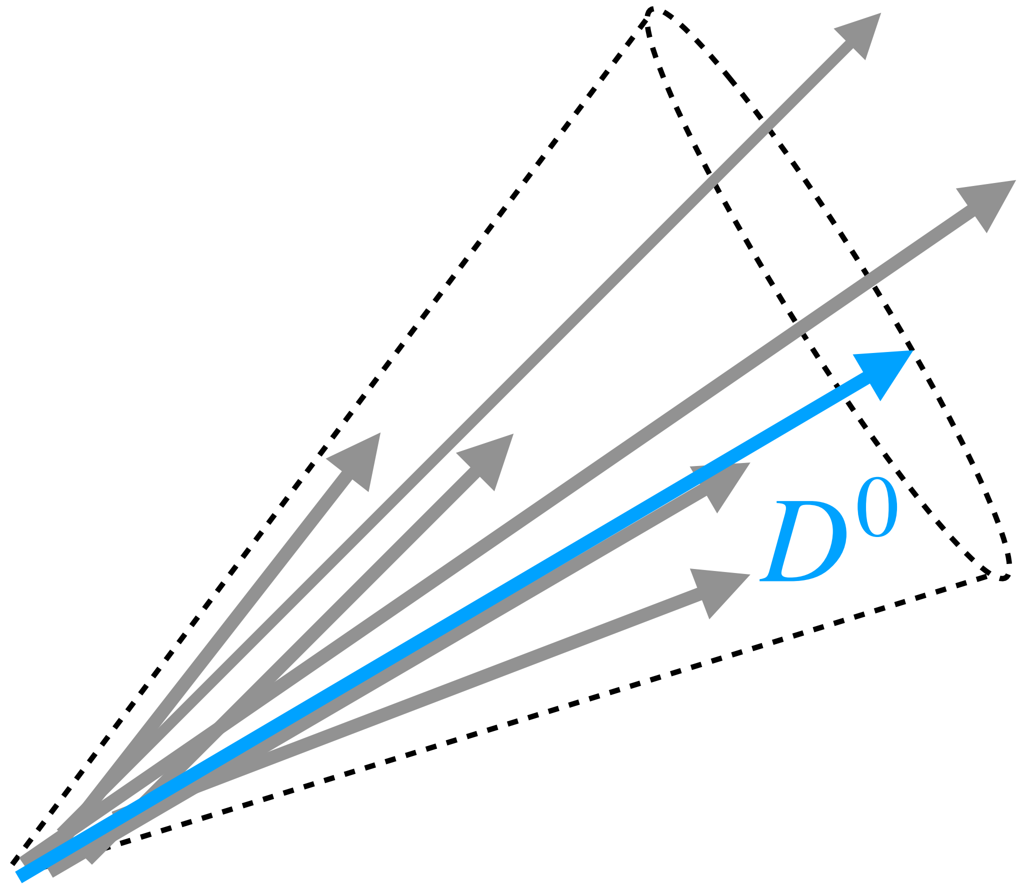
** Note these scalings represent change in p_T (δp_T) for full jets*

Effects such as hadronization and the underlying event are non-perturbative.

These effects scales differently with the R, jets can be used to study them!

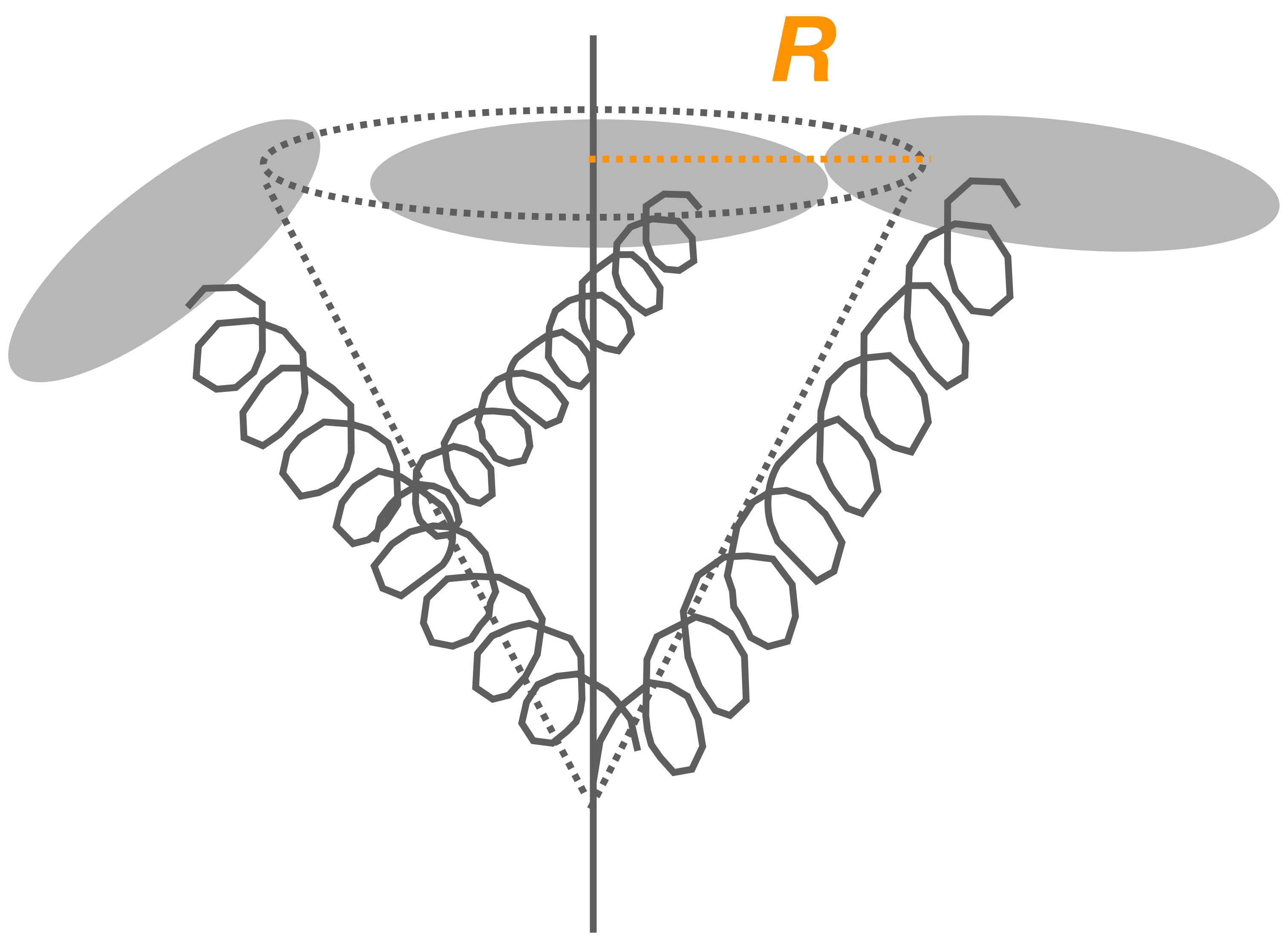
COMMON USES OF JETS

Studying processes of a specific origin



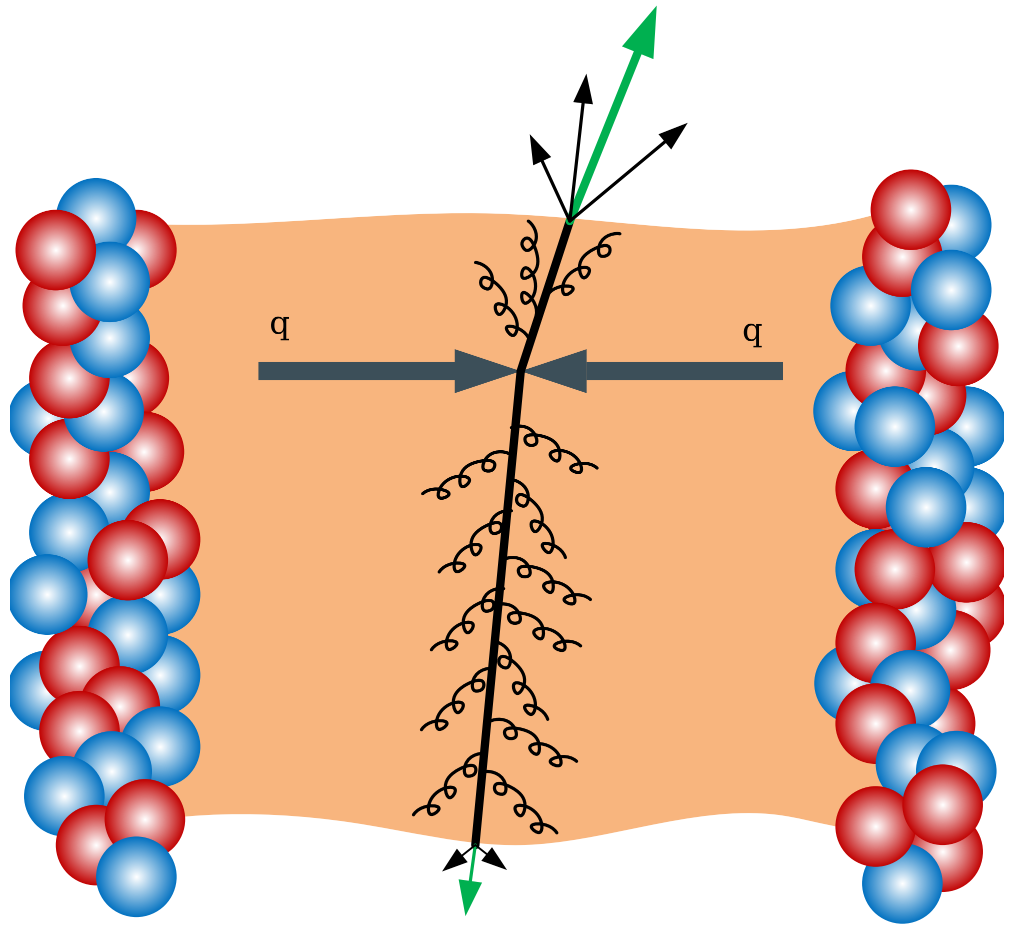
Ex: Boosted objects (Higgs, BSM), quark vs. gluon jets, heavy flavor jets

Testing Fundamental QCD



Both perturbative and non-perturbative effects!

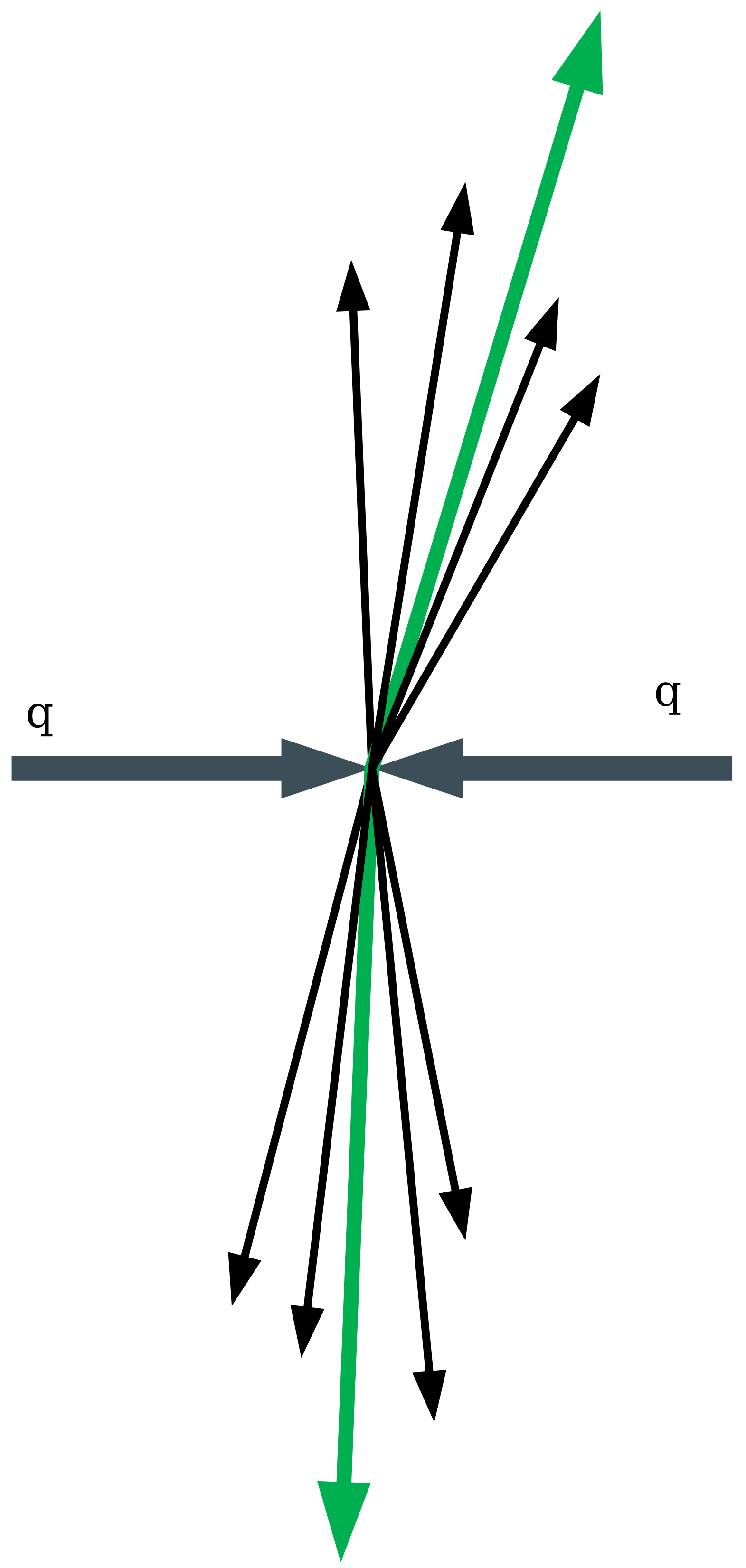
Probing the Quark-Gluon Plasma in Heavy-ion Collisions



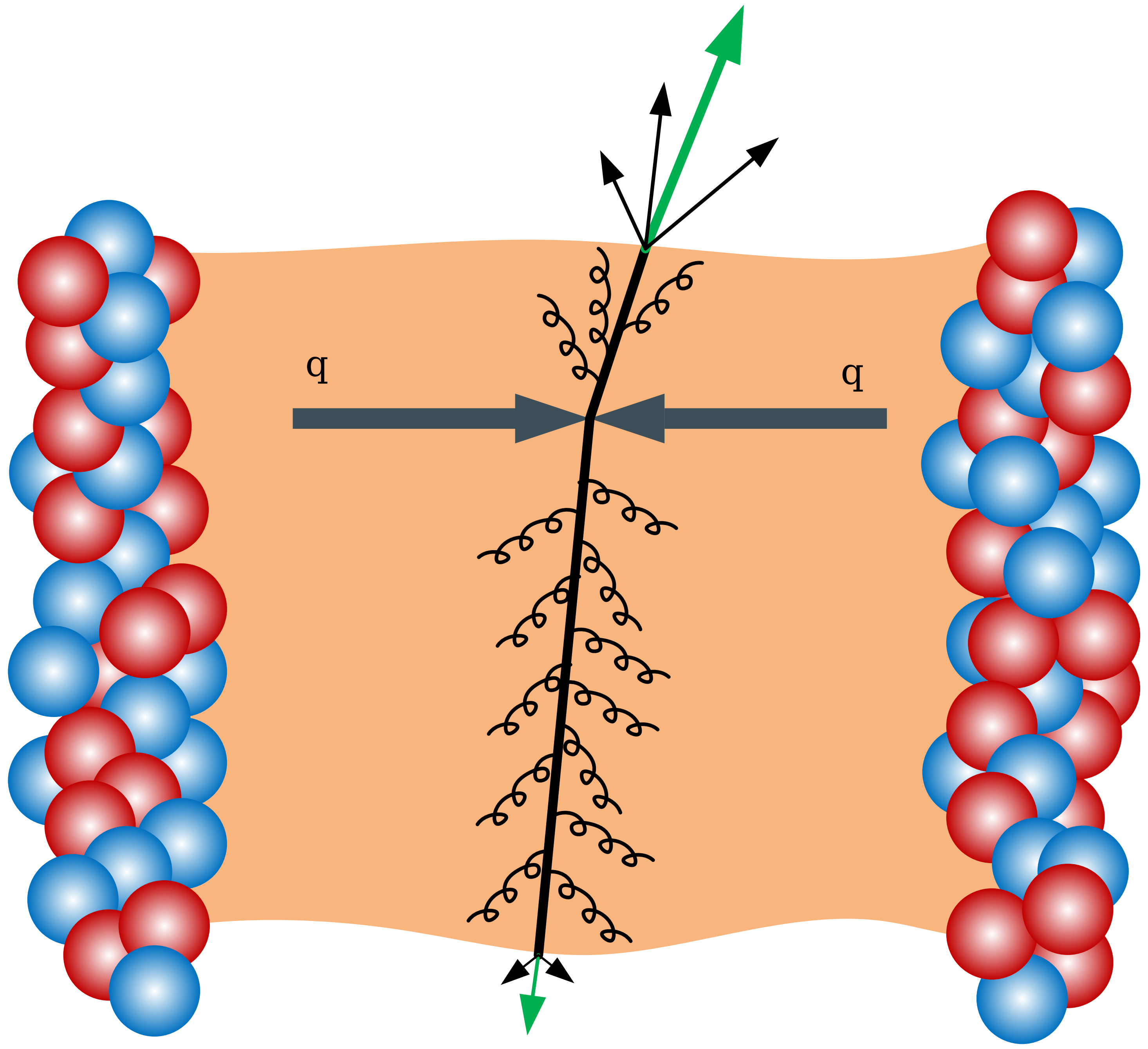
Look at modifications of jets and their substructure from the vacuum case.

Jet measurements provide a wealth of physics information!

JETS AS A PROBE OF THE QGP



pp



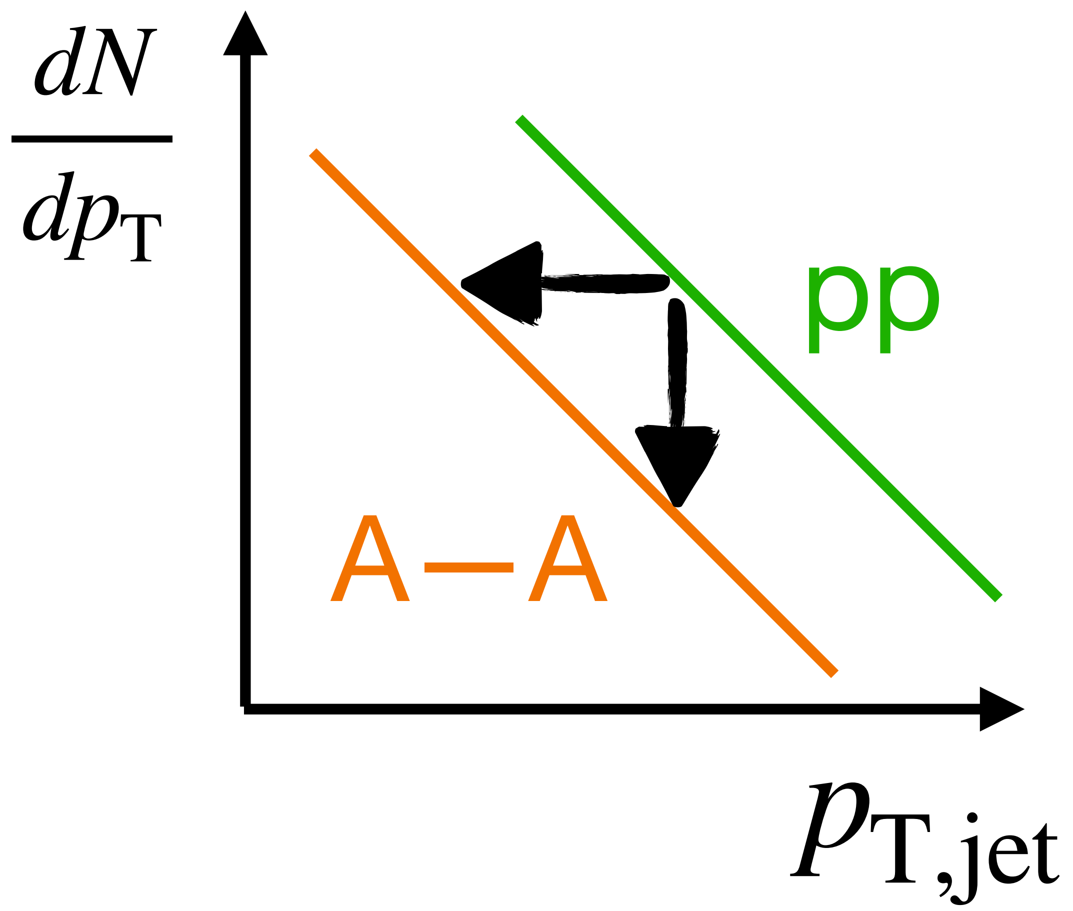
Heavy-Ions

- 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 jets are measured in vacuum, as a reference for no QGP.

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).



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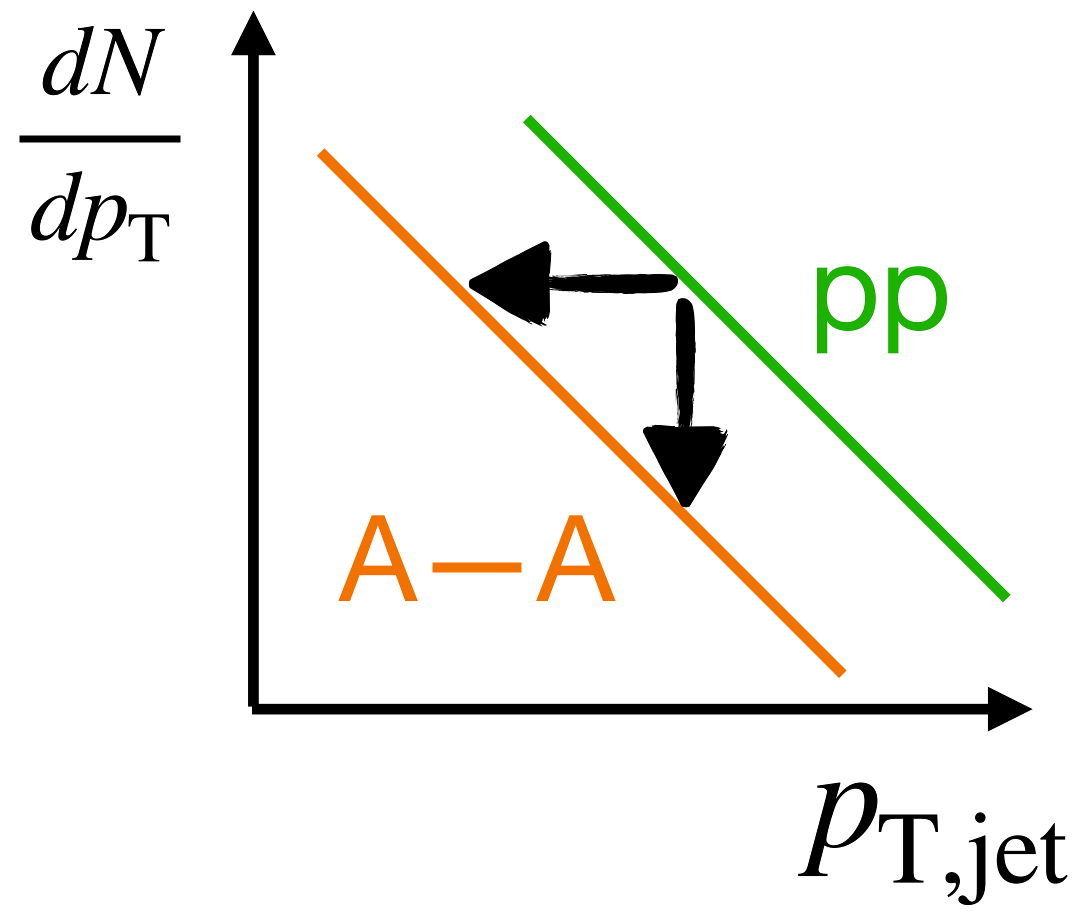
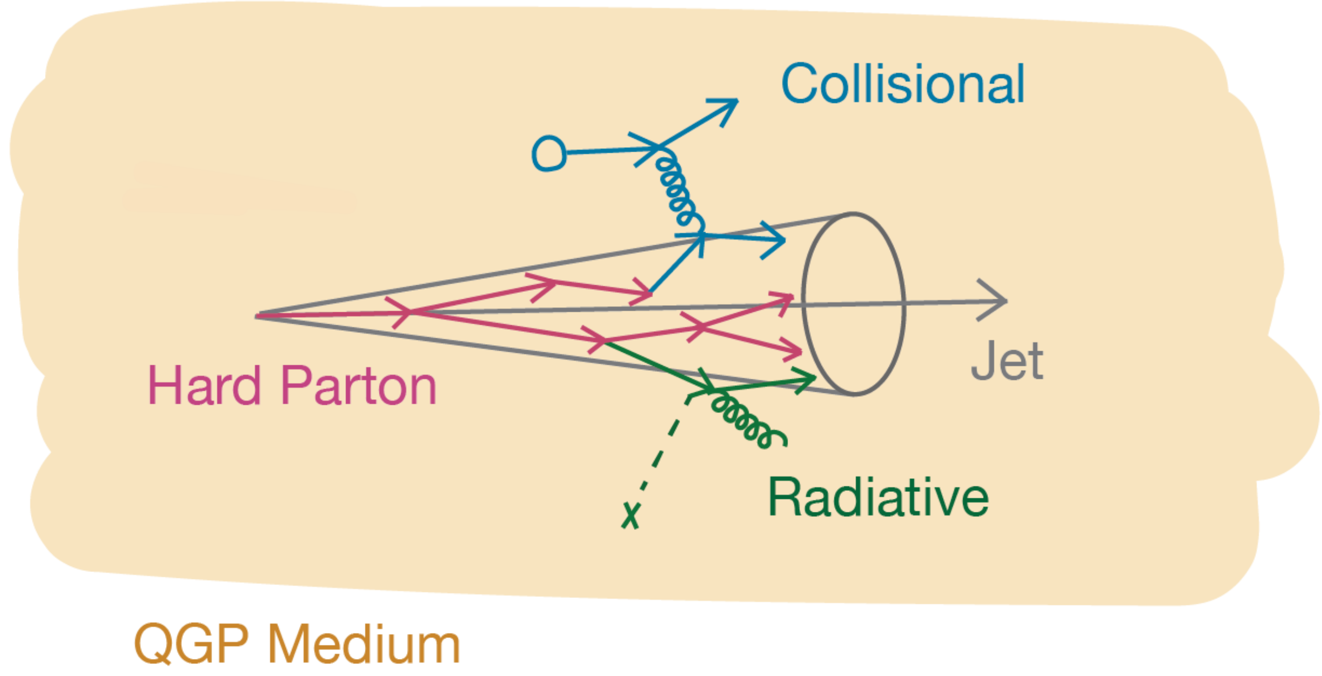
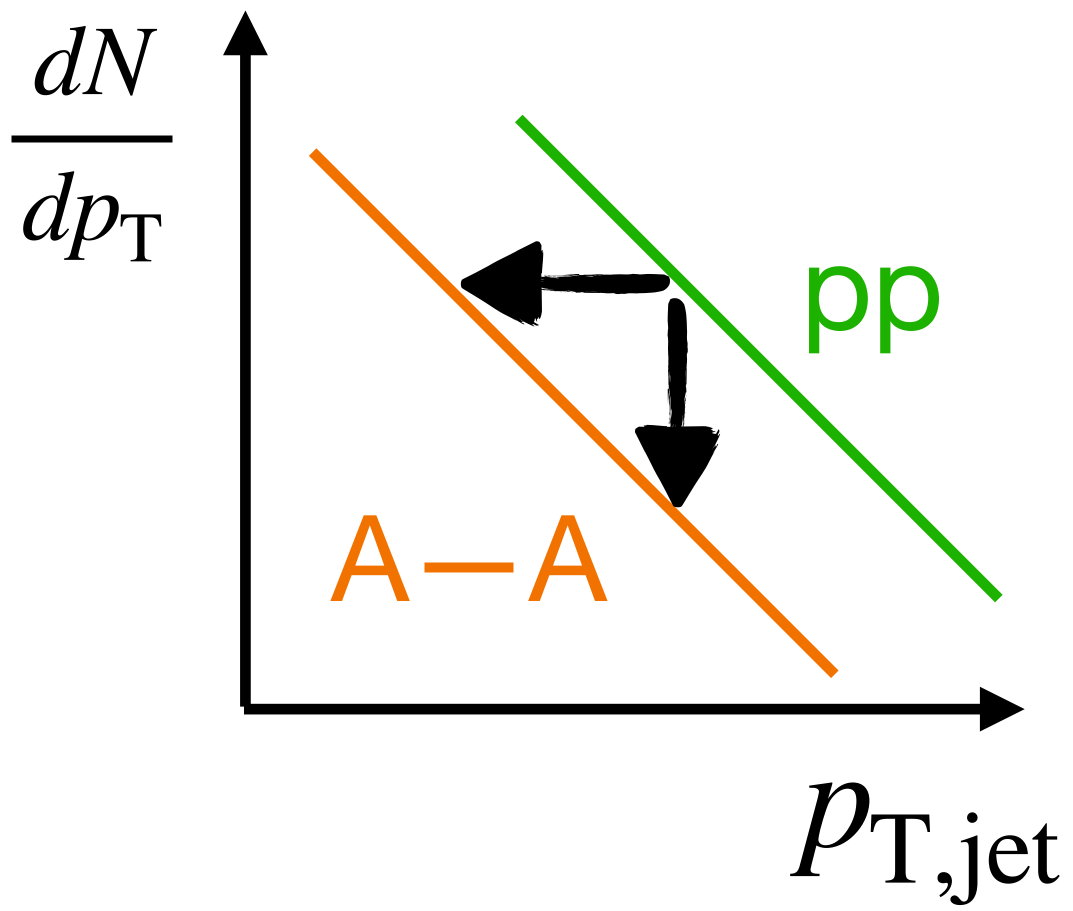


② **Internal structure modification**



EXPECTATIONS OF JET QUENCHING



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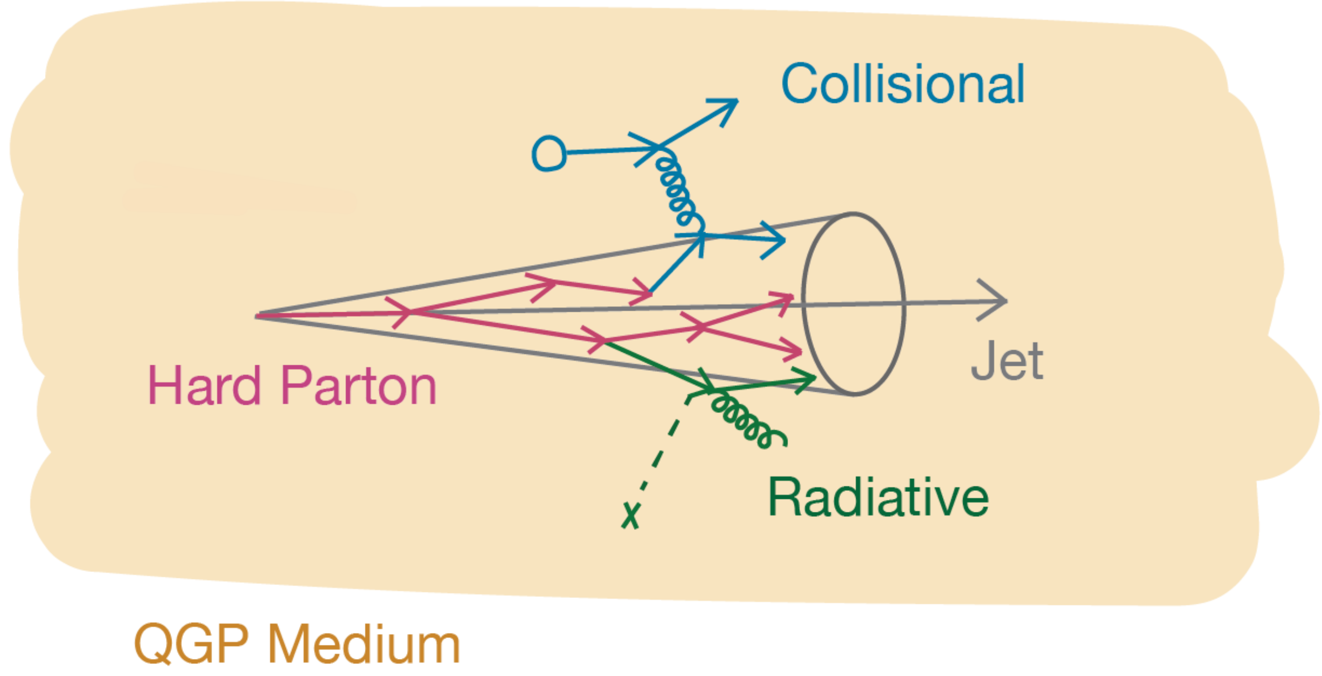
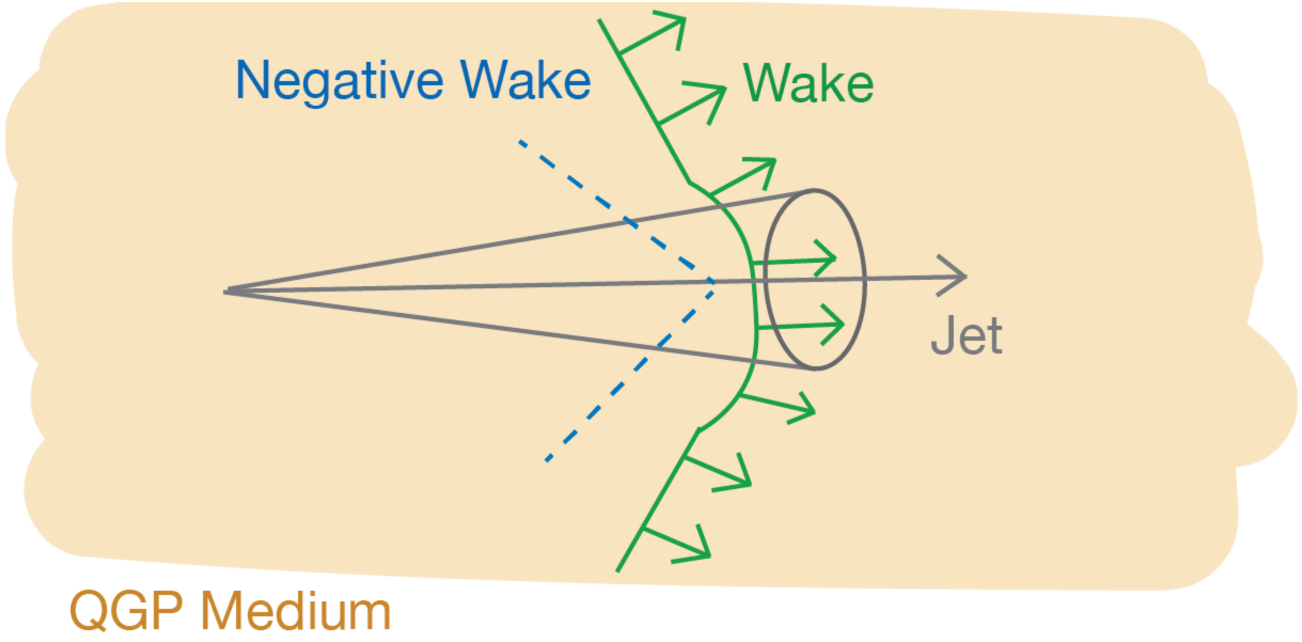


③ **Medium should respond to the presence of the jet**



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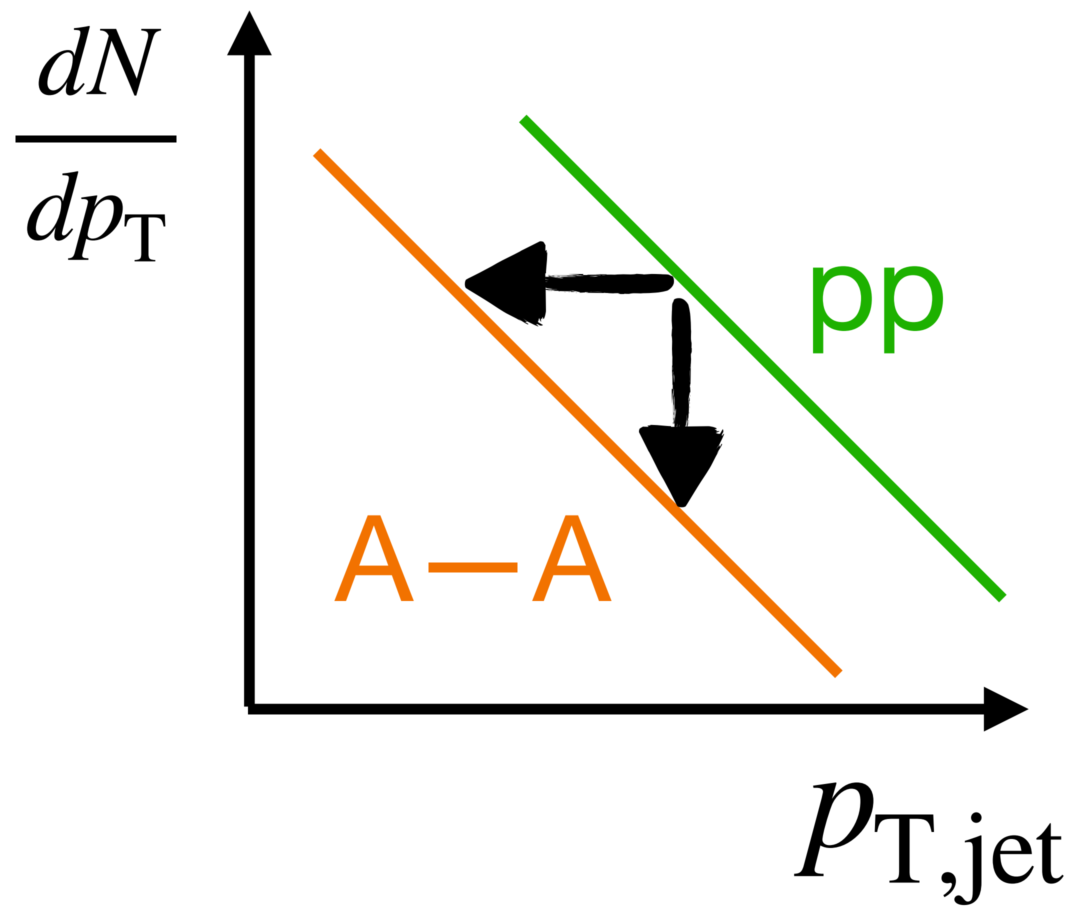

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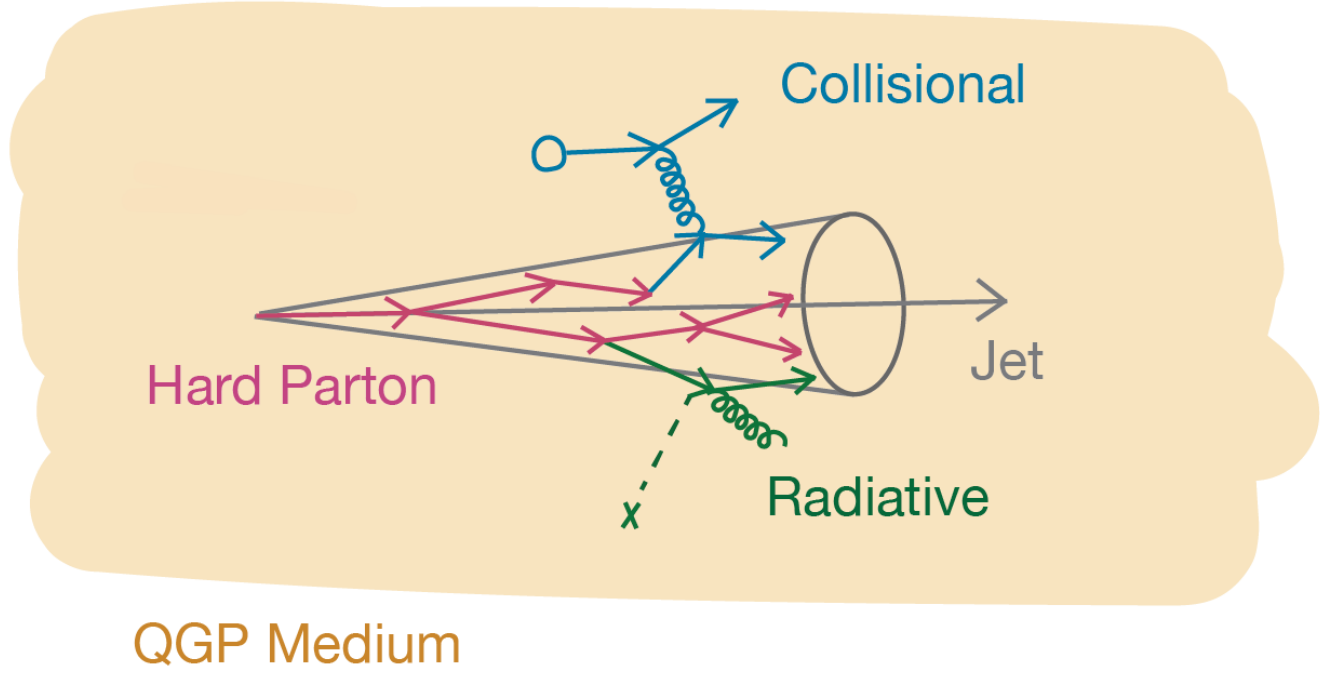

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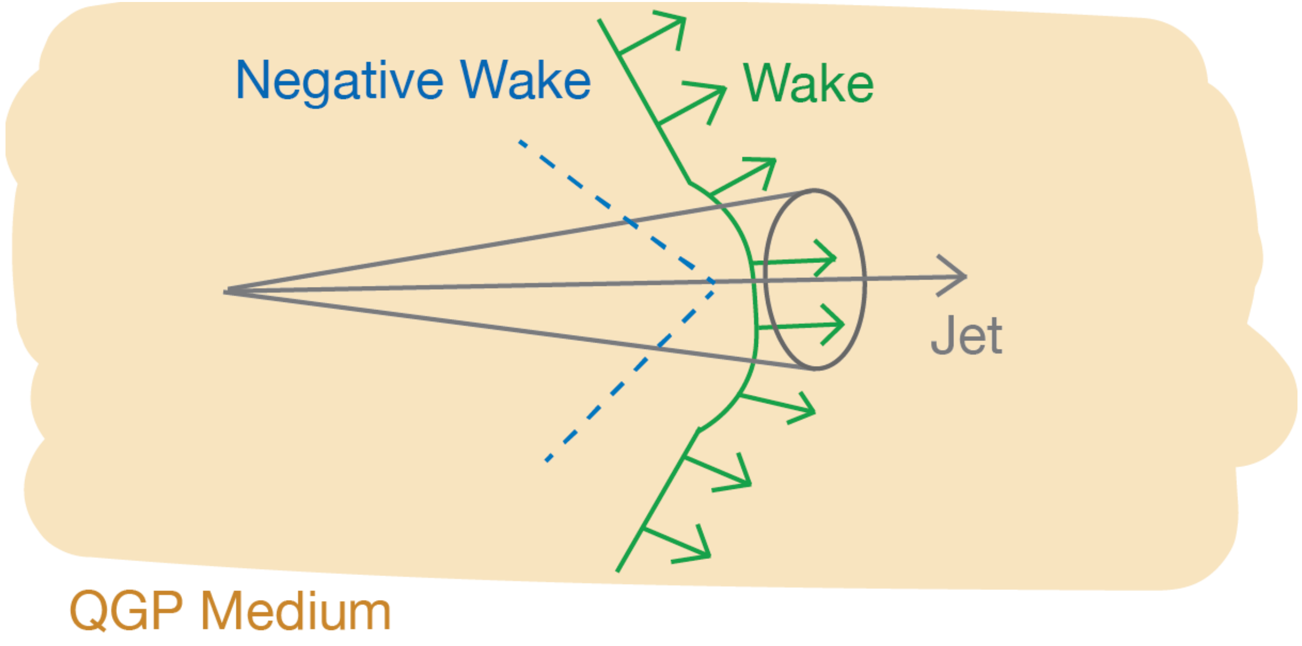
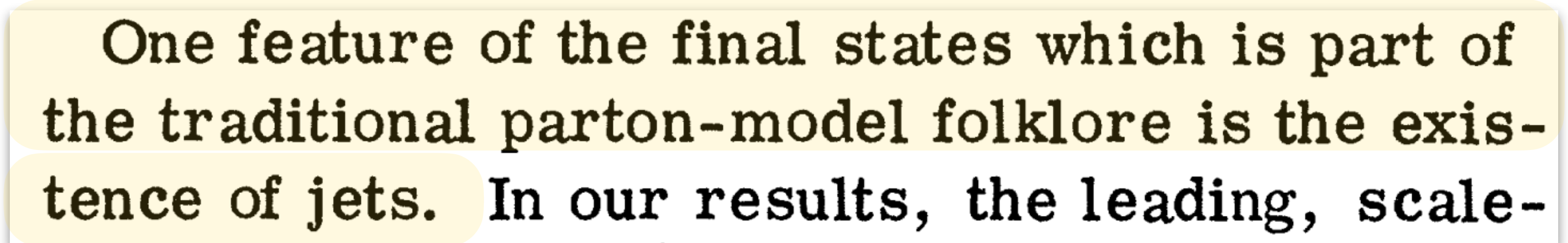


④ **Different jets lose energy differently** depending on different partonic structures, flavors, transverse momenta, path lengths through the medium, etc.

Differential measurements are key to understanding dynamical properties of QGP.

HISTORY OF JETS - THE EARLY YEARS



One feature of the final states which is part of the traditional parton-model folklore is the existence of jets. In our results, the leading, scale-

[Phys.Rev.D 8 (1973) 4000-4002]

Observation of jet-like structures in e^+e^-

[PRL 35 (1975) 1609]

3-jet events lead to discovery of gluon

[Phys. Lett. B 86, 243 (1979)]

1970

1975

1977

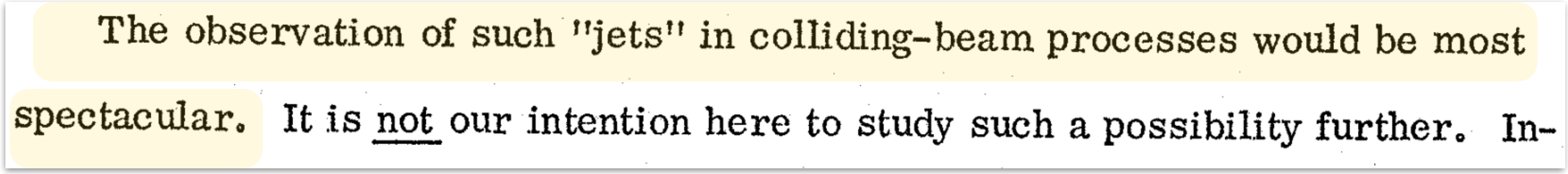
1979

Term "jet" first used by Bjorken and Brodsky

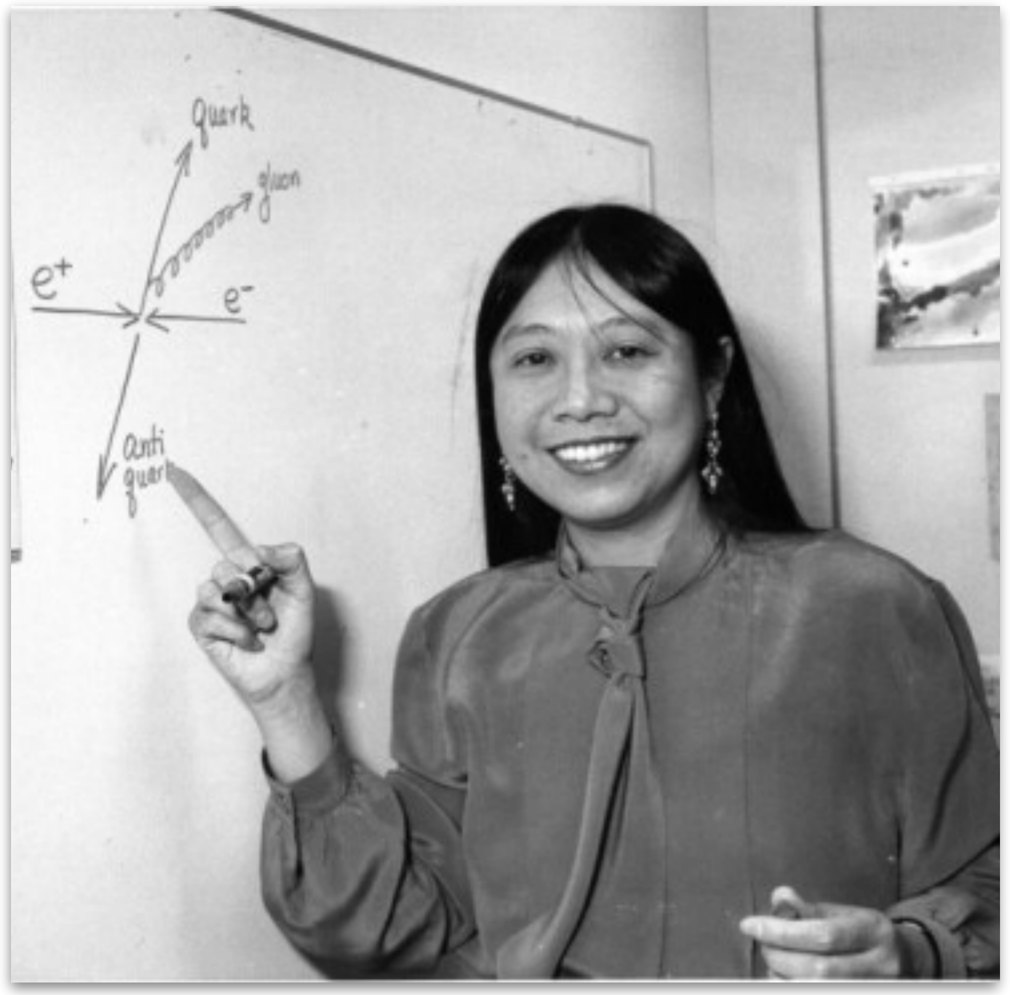
[Phys.Rev.D 1 (1970) 1416-1420]

Production of jets can be computed in QCD using perturbation theory

[PRL 39 (1977) 1436]



The observation of such "jets" in colliding-beam processes would be most spectacular. It is not our intention here to study such a possibility further. In-



Sau Lan Wu and the discovery of the gluon

HISTORY OF JETS - PATH TO THE "MODERN" ERA

1990

Jet quenching first proposed as a probe of QGP properties

[PLB 243 (1990) 432-438]

2001

[Quark Matter 2001]

First experimental results from RHIC favor jet quenching scenarios using high p_{T} hadrons

2008

anti-k_{T} jet clustering algorithm is published

[JHEP 04 (2008) 063]

2010

[PRL. 105 (2010) 252303]

Direct observation of jet quenching by ATLAS using dijet asymmetry

2014

Soft Drop grooming algorithm is published

[JHEP 1405 (2014) 146]

2016

First measurements of groomed jet substructure shown by LHC/RHIC experiments

[Hard Probes 2016]

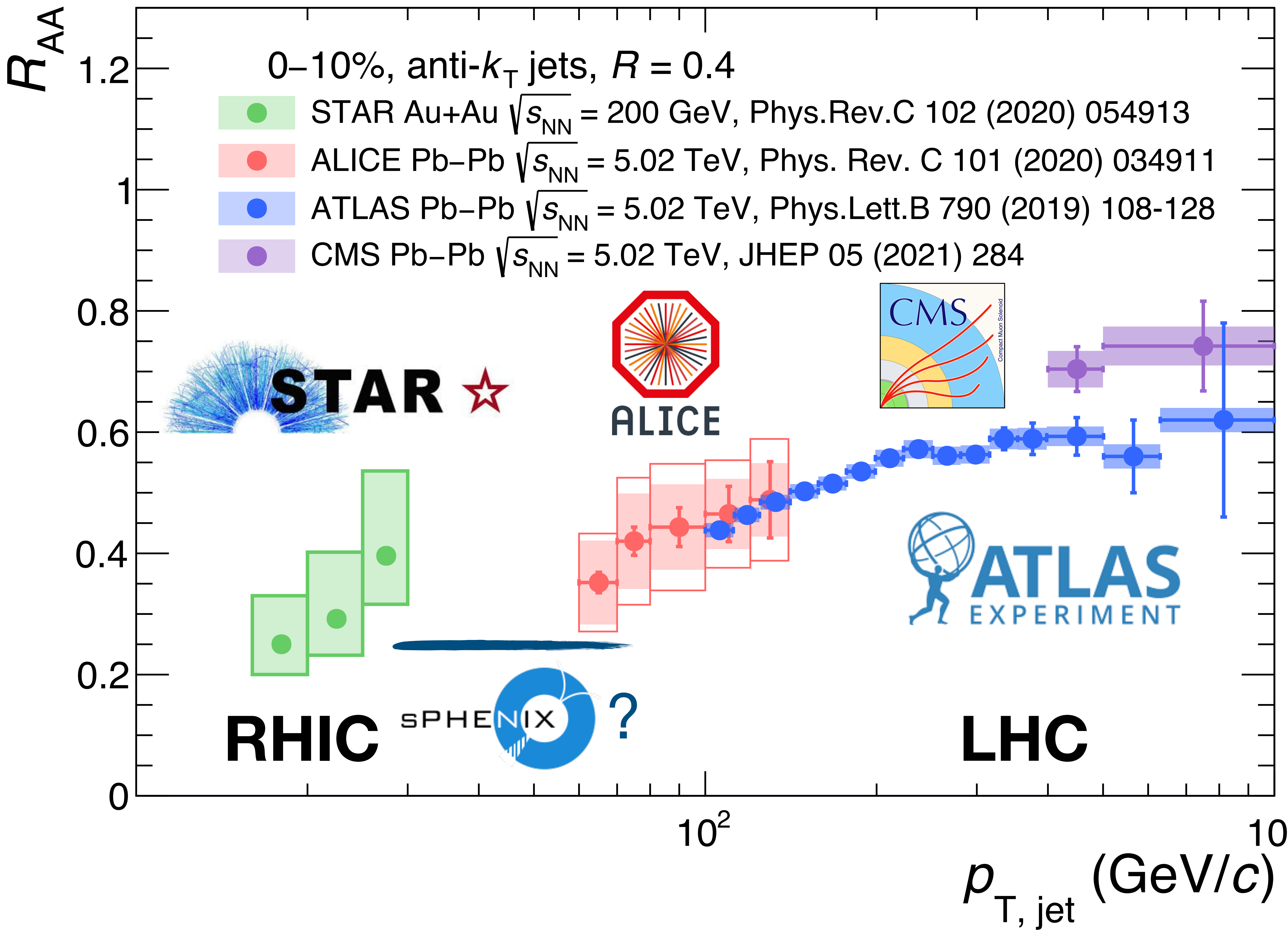
New data & techniques flourish in modern era

** Note context here is for heavy-ions, other points relevant in HEP*

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).

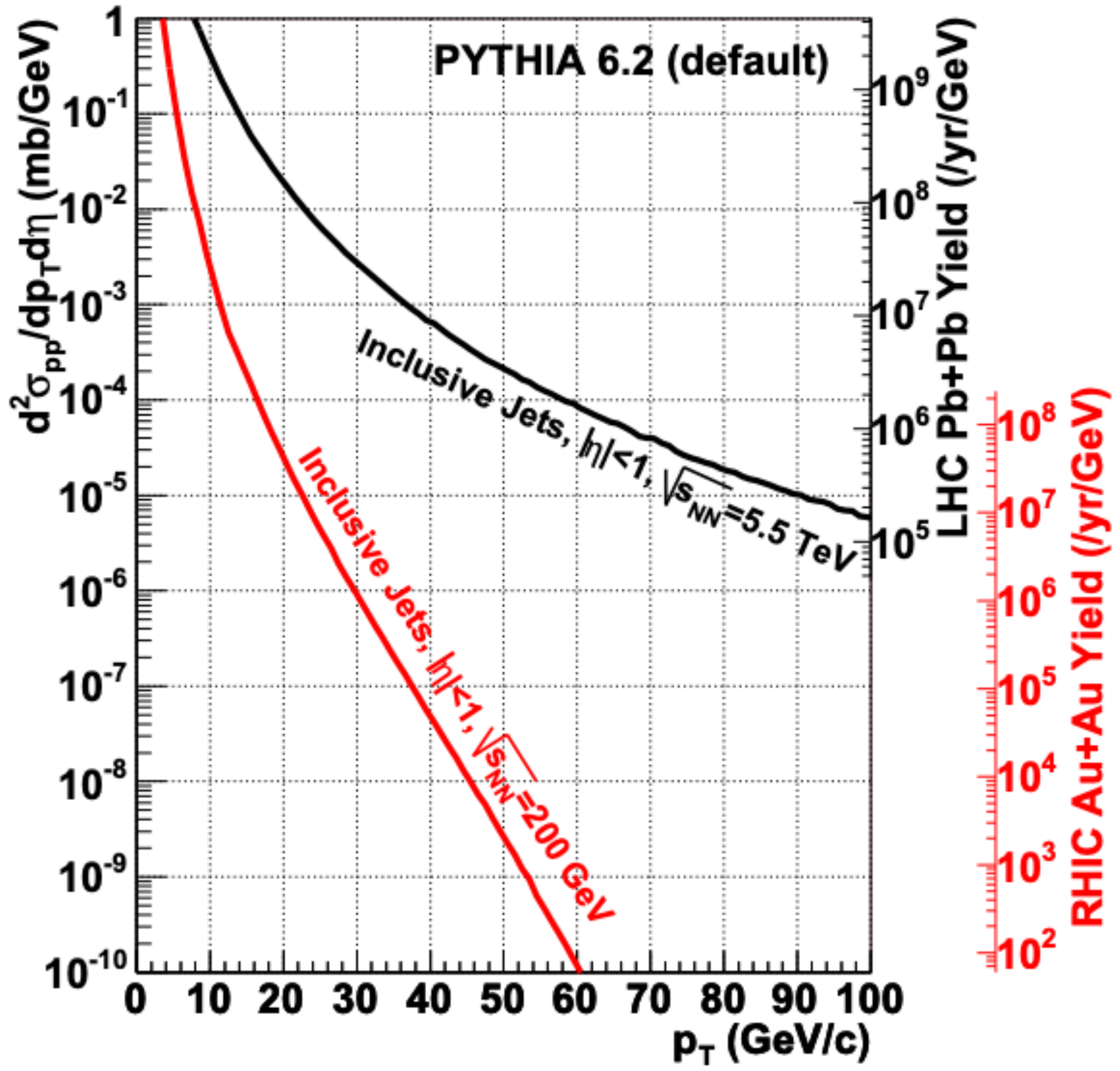
[EPJC 84 (2024) 3, 247]



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

Bonus: Can sPHENIX bridge the gap and explain why RHIC/ LHC report similar R_{AA}'s despite very different mediums, q/g, spectra shape etc.?

[arXiv:0609023]



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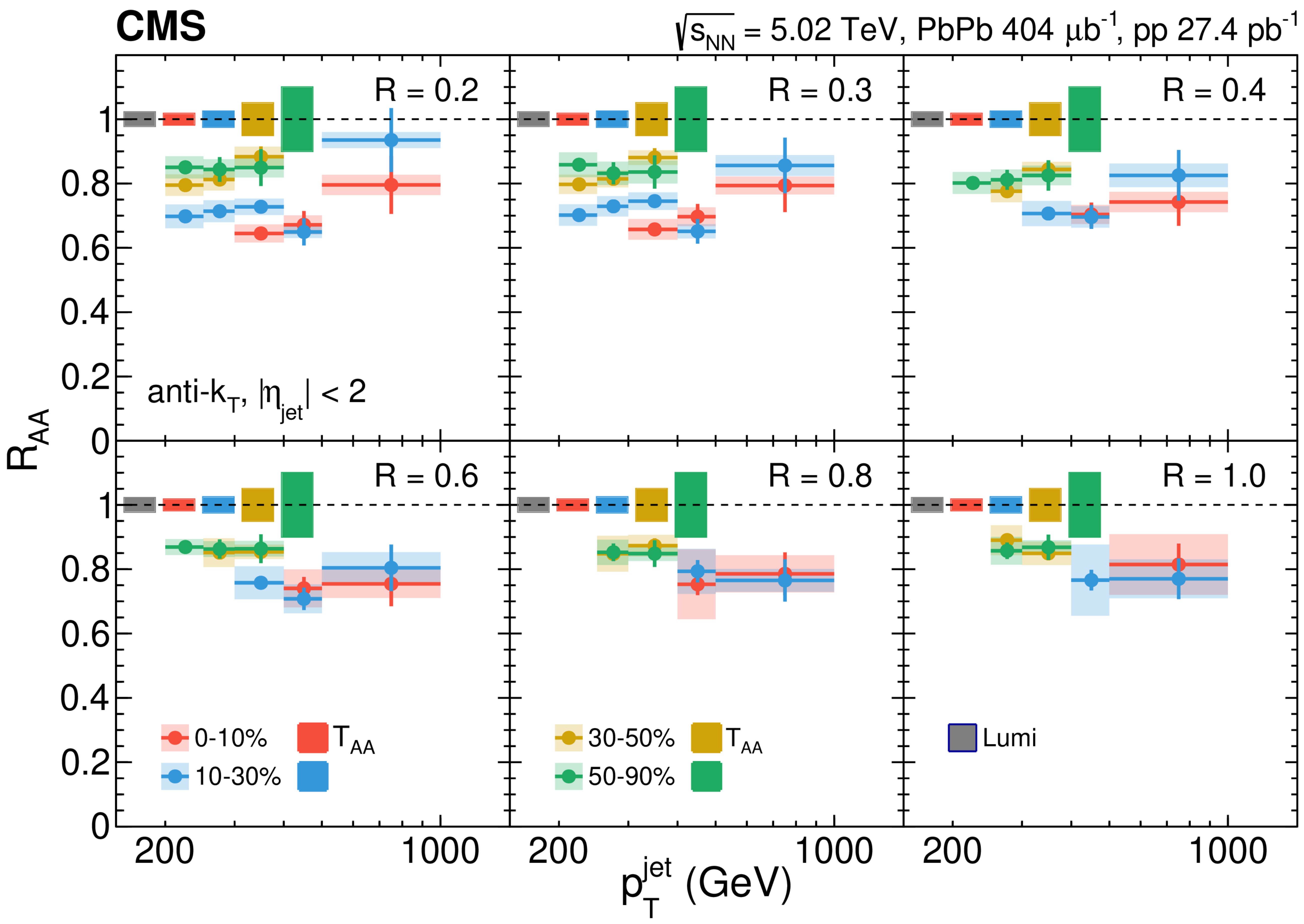

[JHEP 05 (2021) 284]

- *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?

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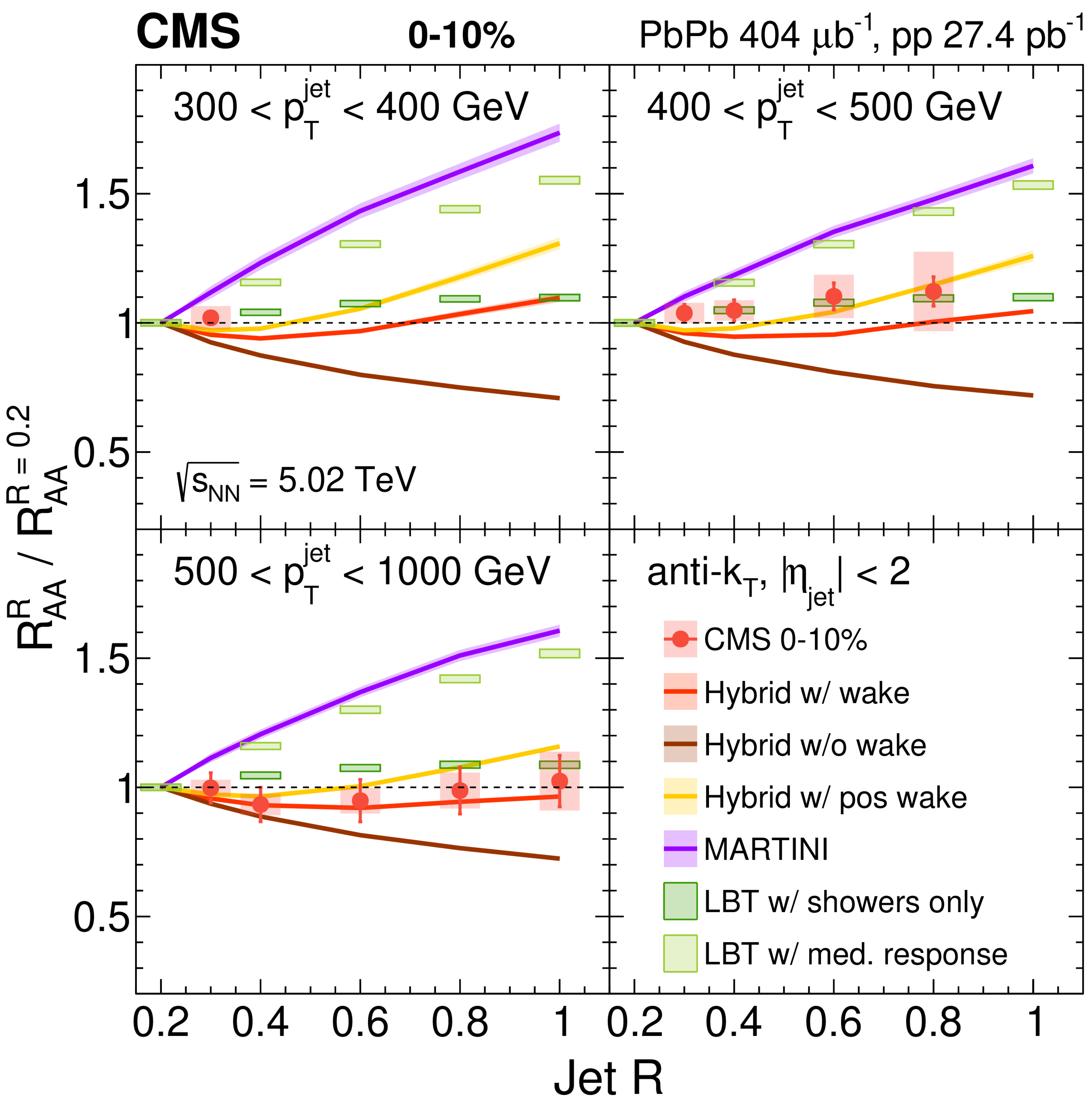
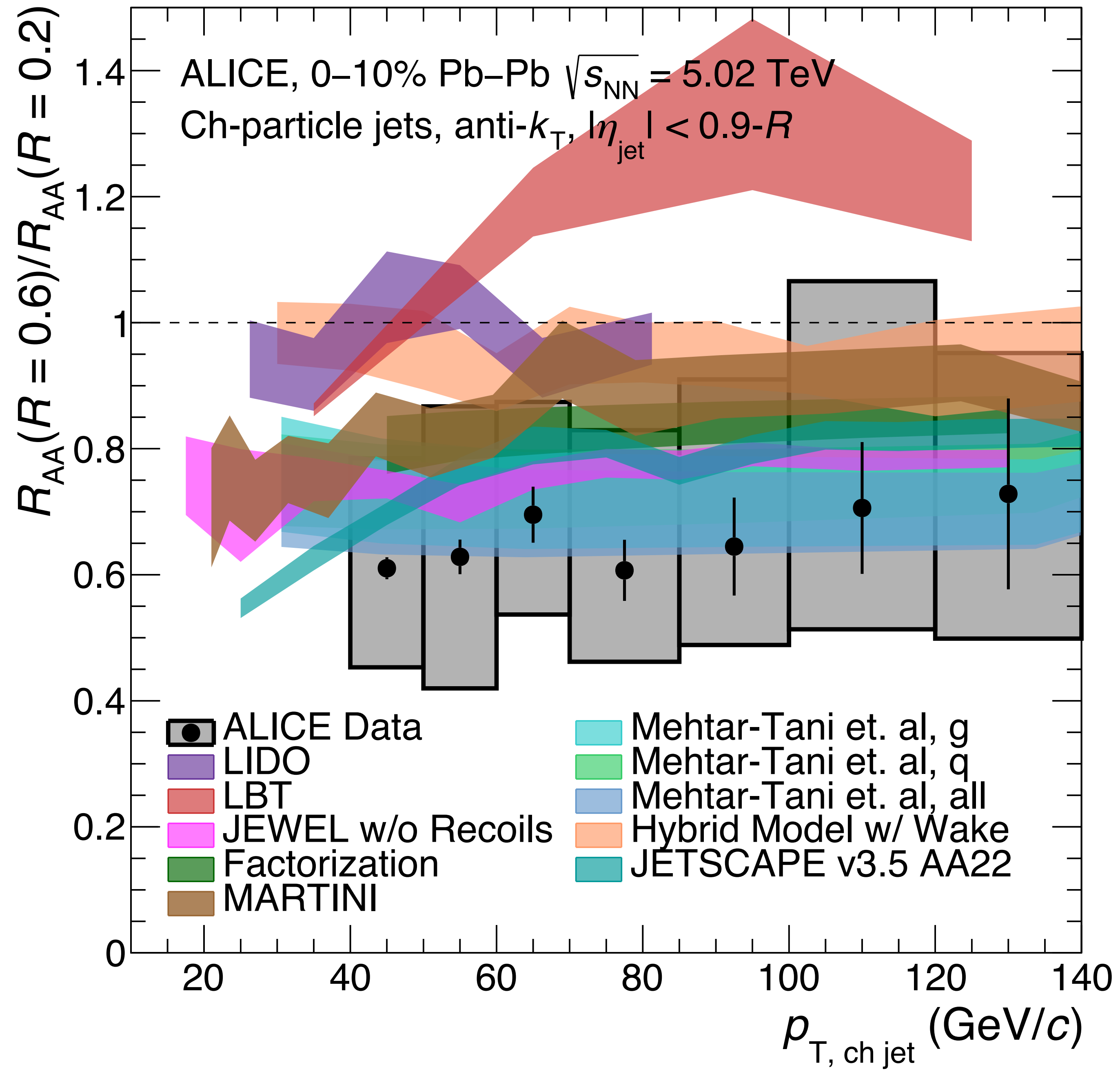


[JHEP 05 (2021) 284]

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

[PLB 849 (2024) 138412]



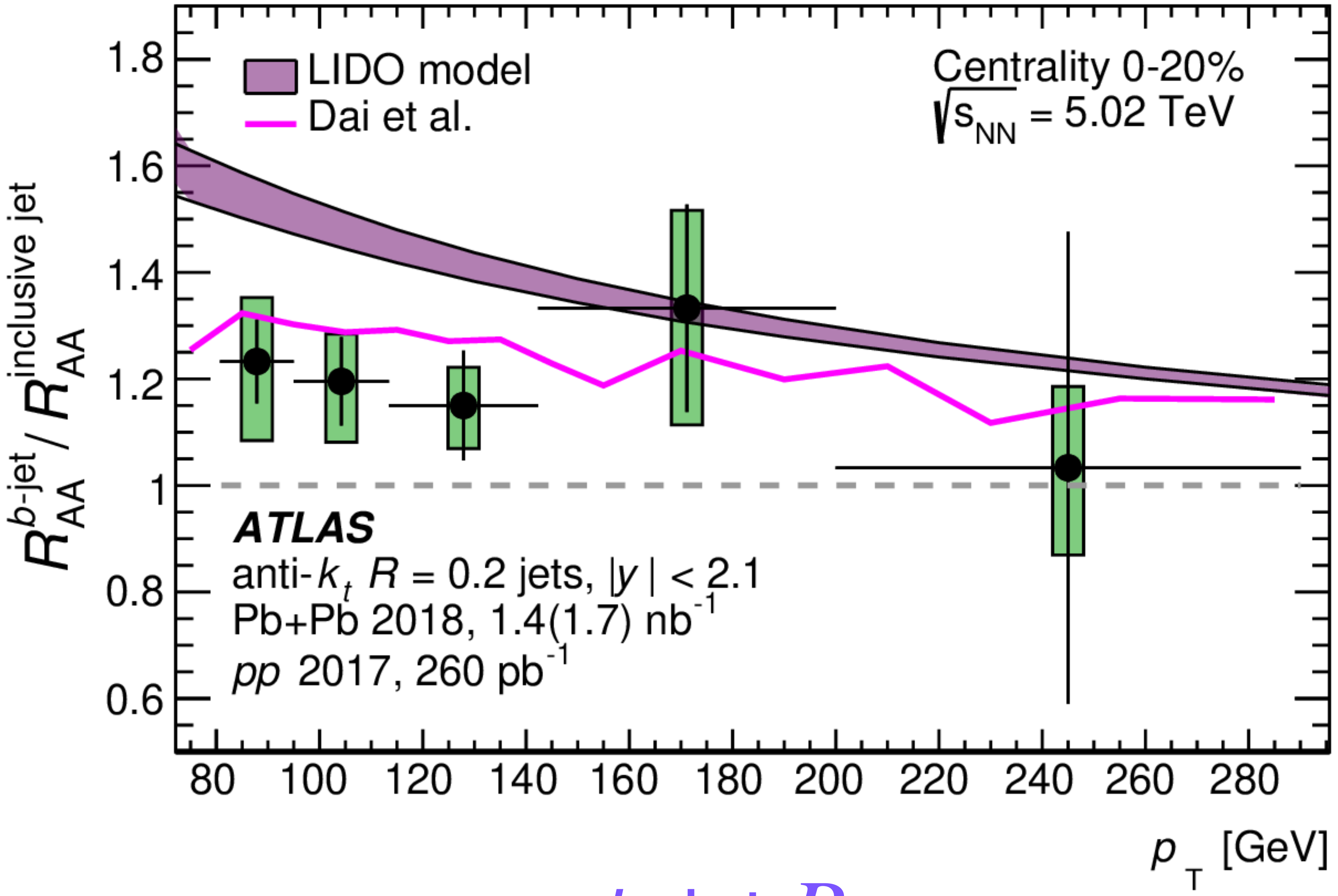
- We have some indications that the balance between competing mechanisms depends on $p_{\rm T}$

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).

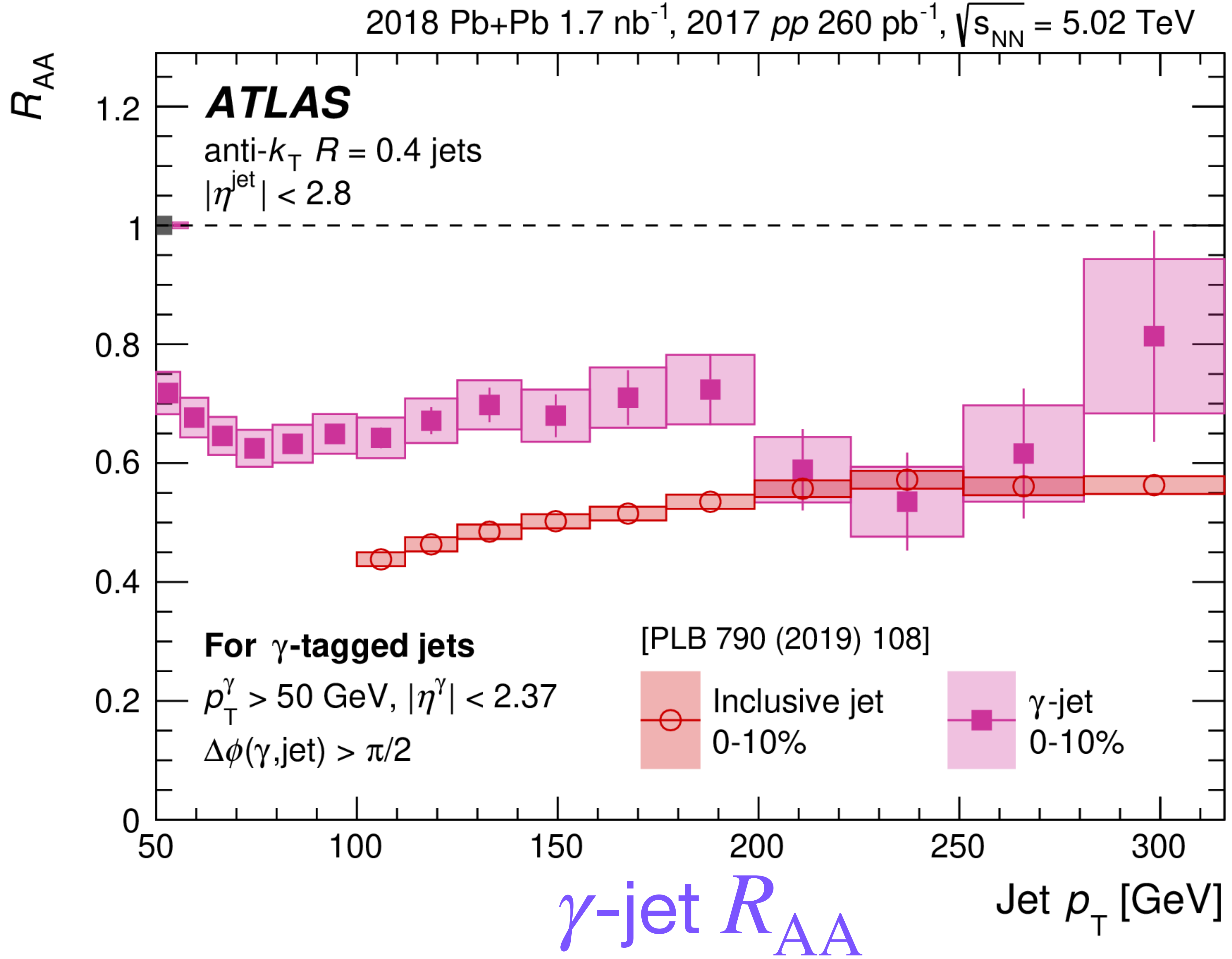
- *We have learned* that the amount of energy lost appears to depend color-charge

[EPJC 83 (2023) 438]



b-jet R_{AA}

[PLB 846 (2023) 138154]



γ-jet R_{AA}

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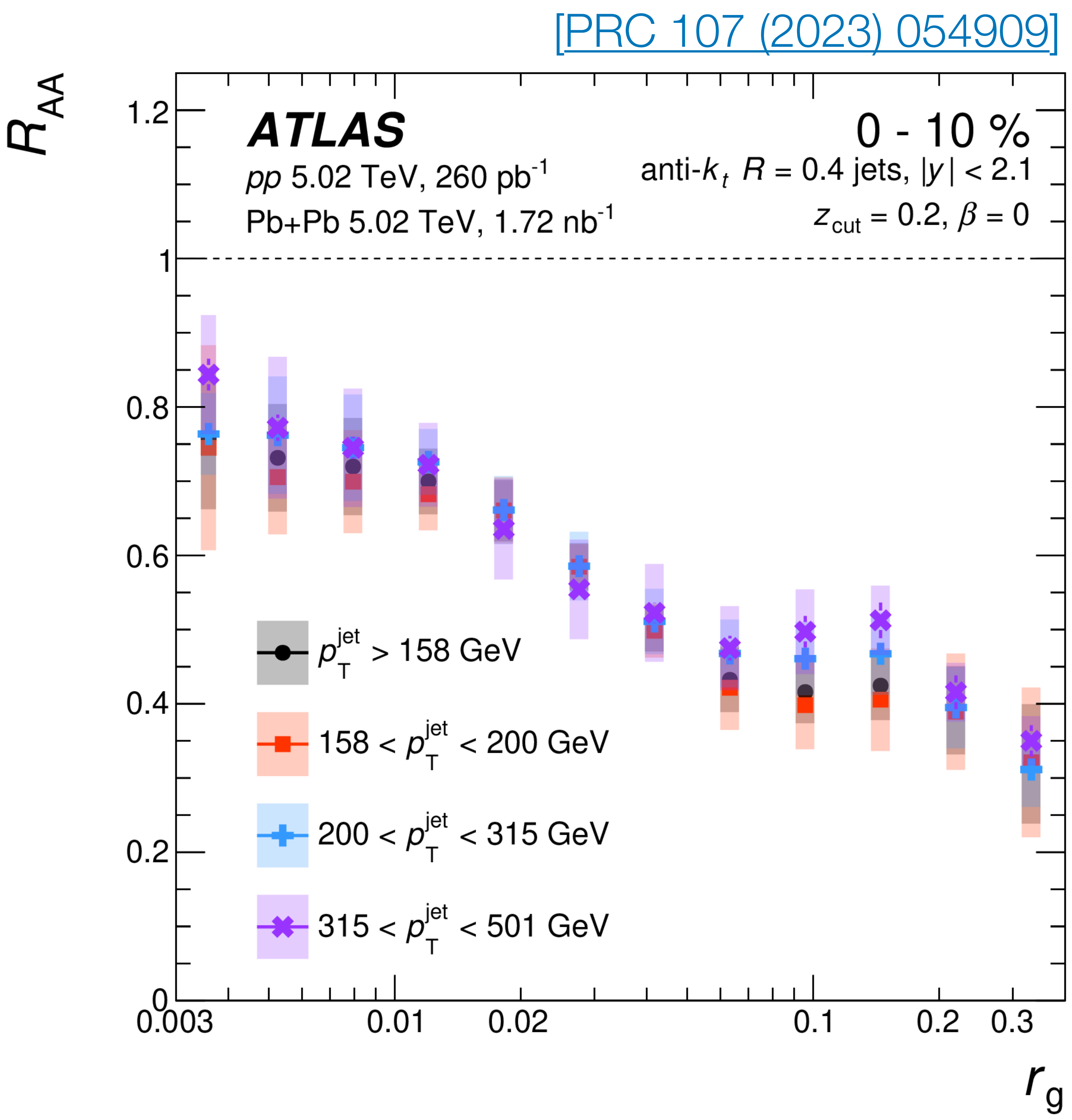
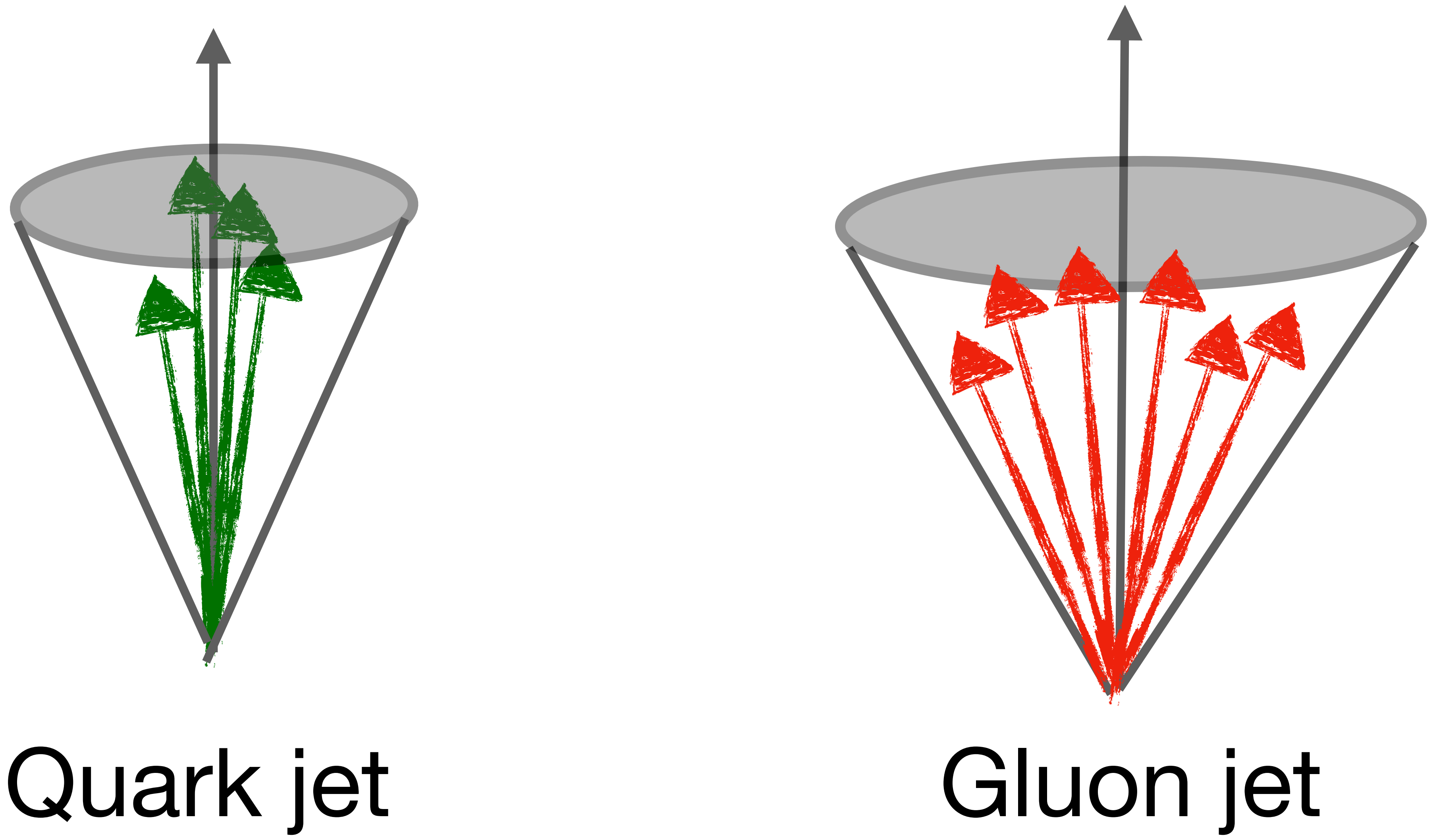


- *We have learned* that the amount of energy lost also depends on a jet's substructure
  - Color charge may also play a role, quark jets narrower than gluon jets.



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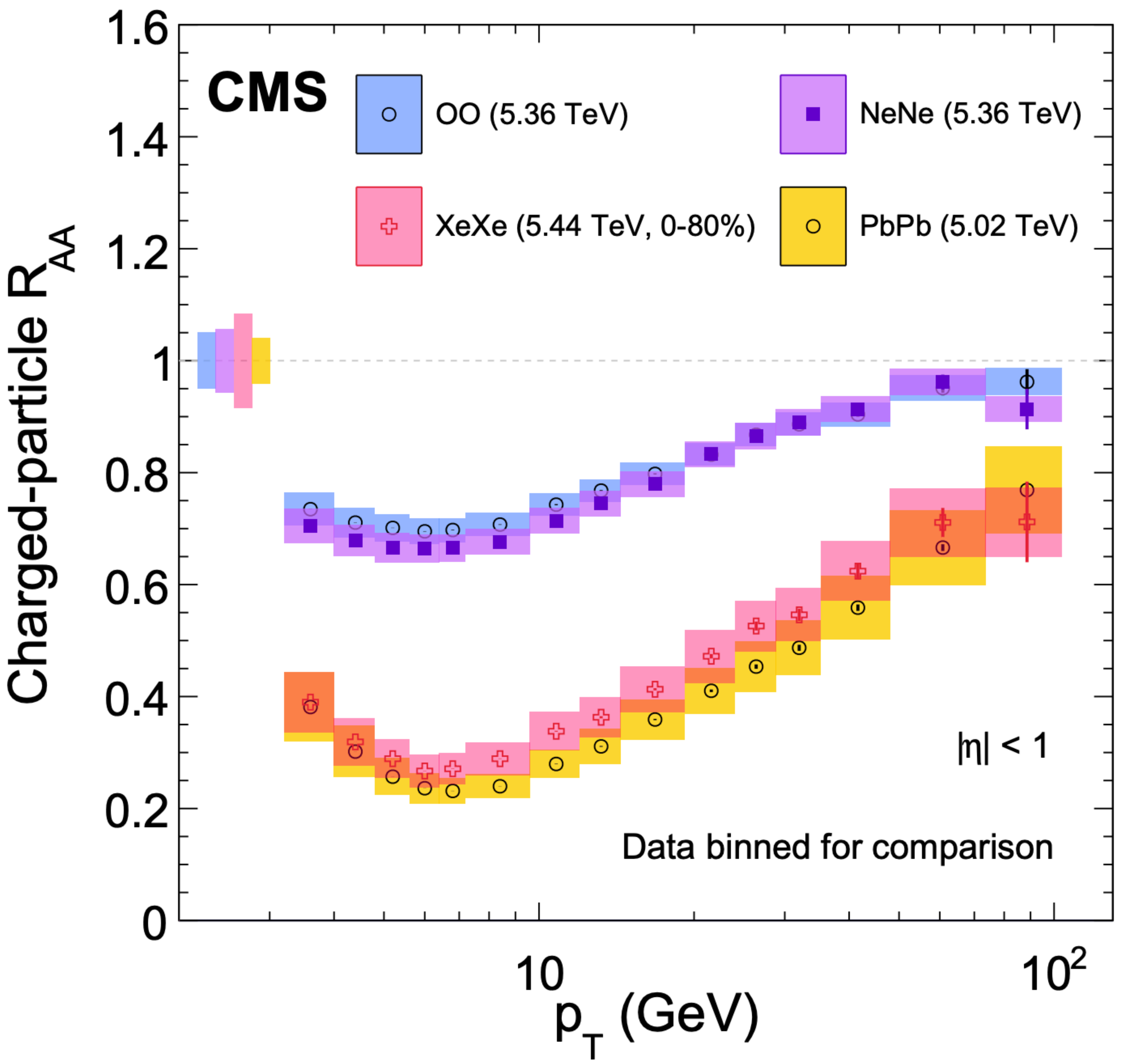
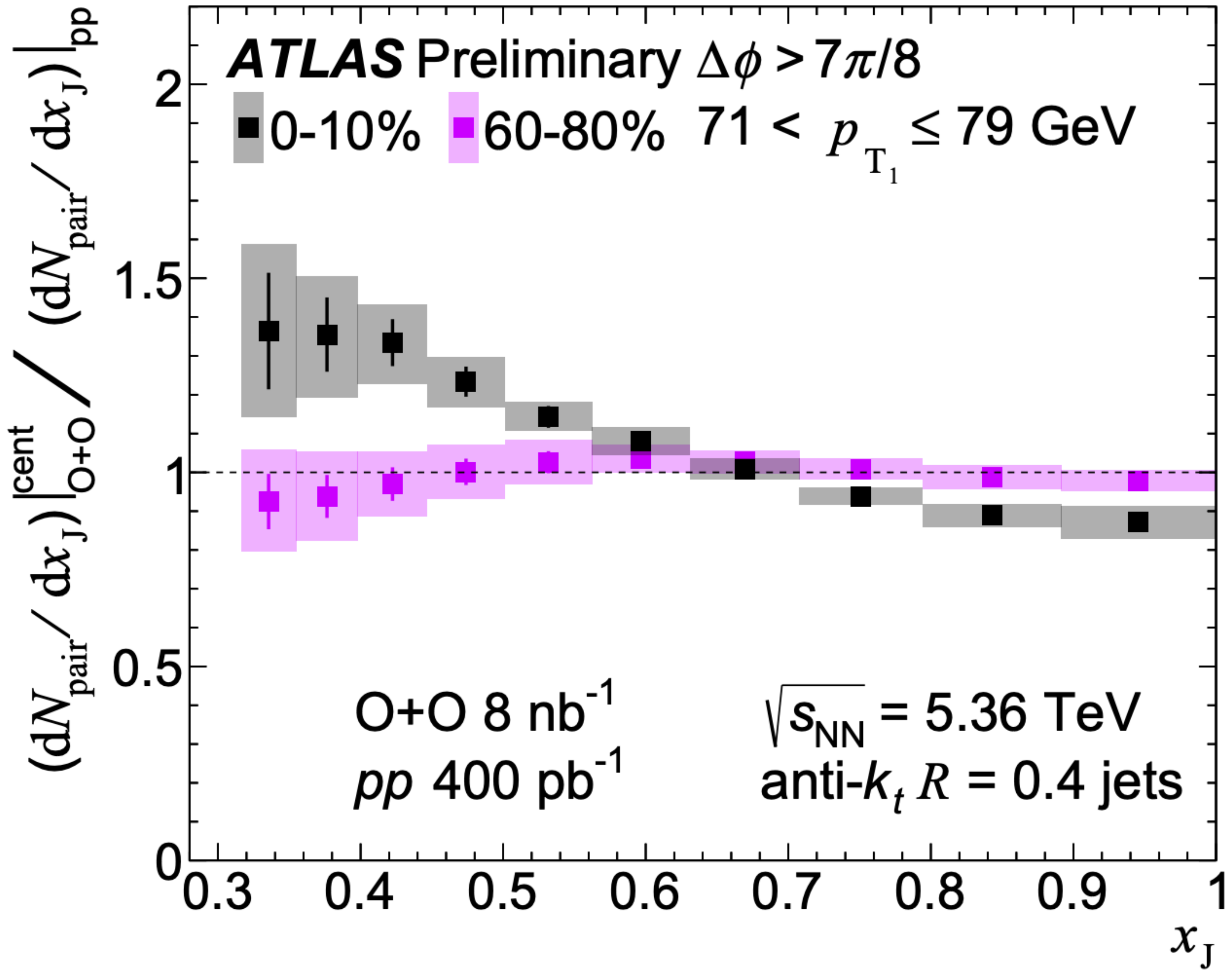




[arXiv:2602.21325] [PRL 136 (2026) 162301]

[ATLAS-CONF-2025-010]

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

Bonus: Similar indications at RHIC, unique opportunity to measure same ion system at both facilities!

[STAR, arXiv:2604.13935]

See Chris's Talk (Mon, 11:05) for more!

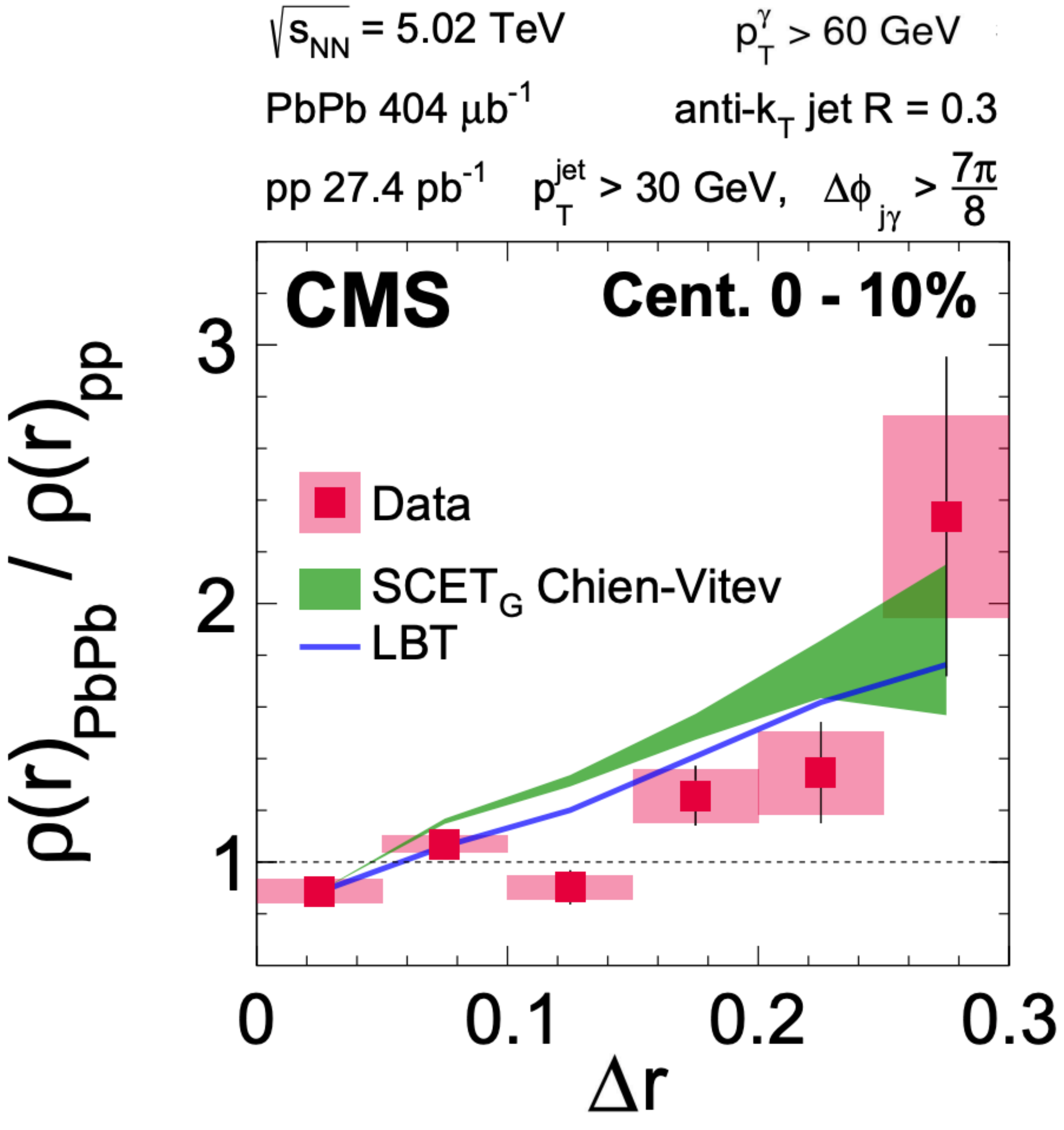
WHAT HAVE WE LEARNED SO FAR?

② Internal structure modification

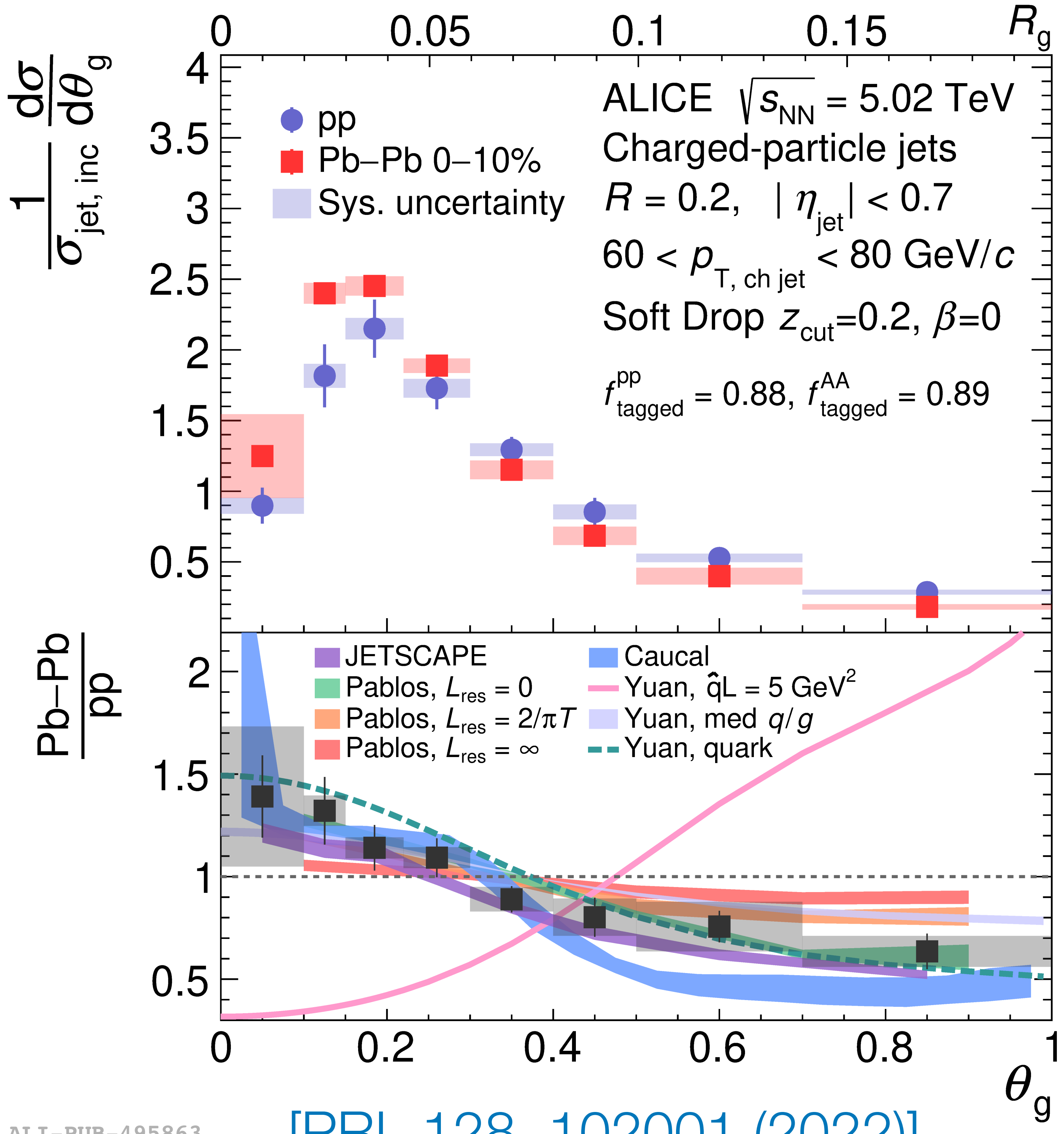
- *We have learned* that both the

jet structure: distribution of radiation

jet substructure: splitting pattern



[PRL 122, 152001 (2019)]



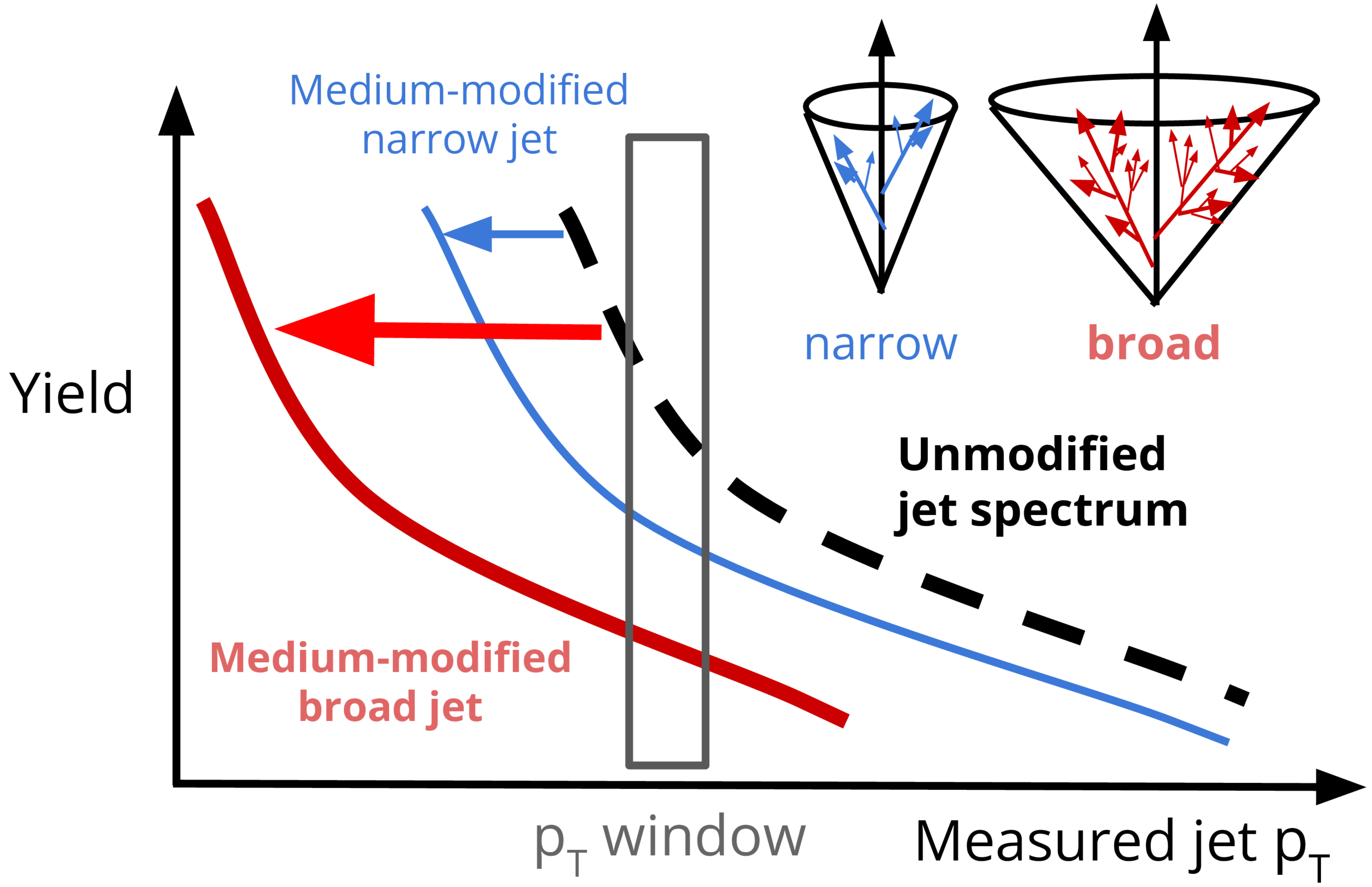
[PRL 128, 102001 (2022)]

are modified when you compare AA distributions to a pp reference

WHAT HAVE WE LEARNED SO FAR?

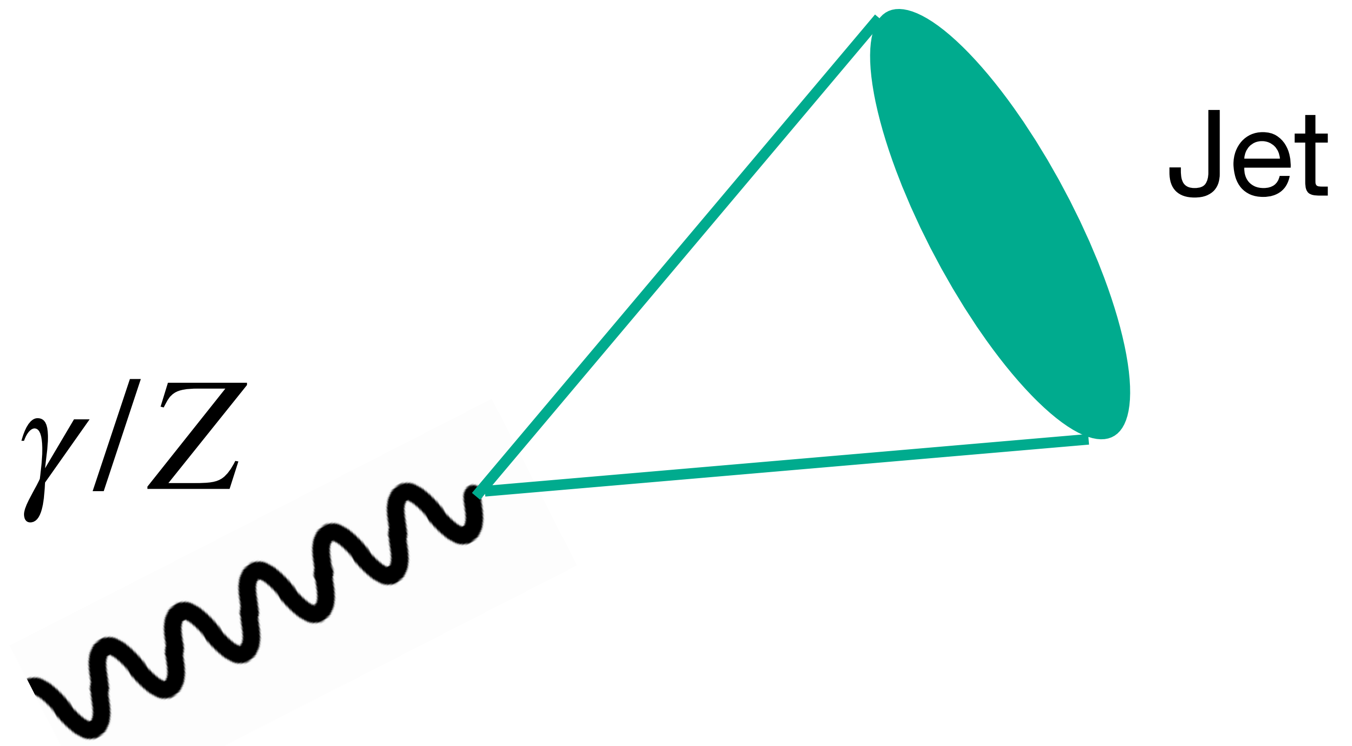
② Internal structure modification

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



[PLB 861 (2025) 139088]

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

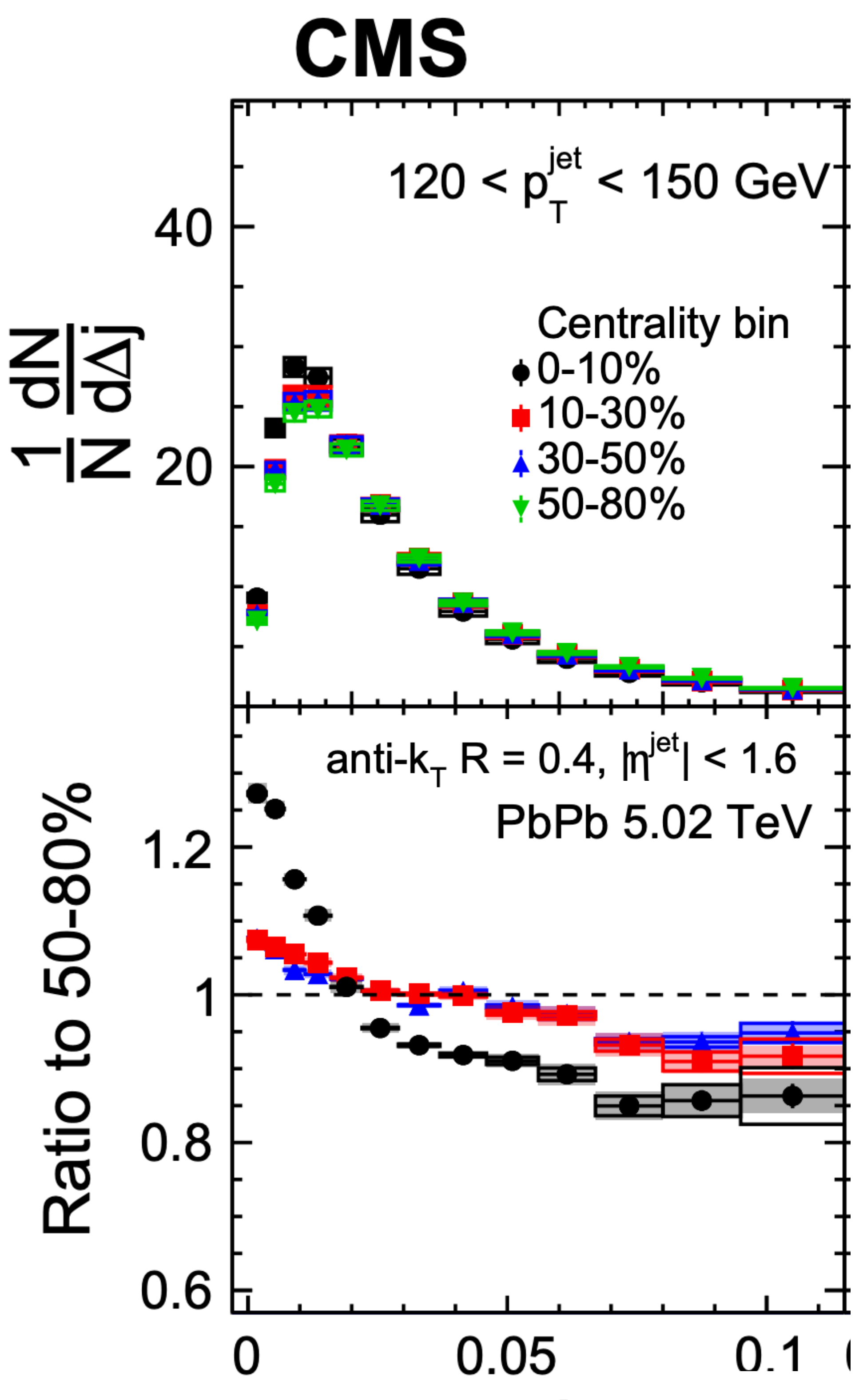


WHAT HAVE WE LEARNED SO FAR?

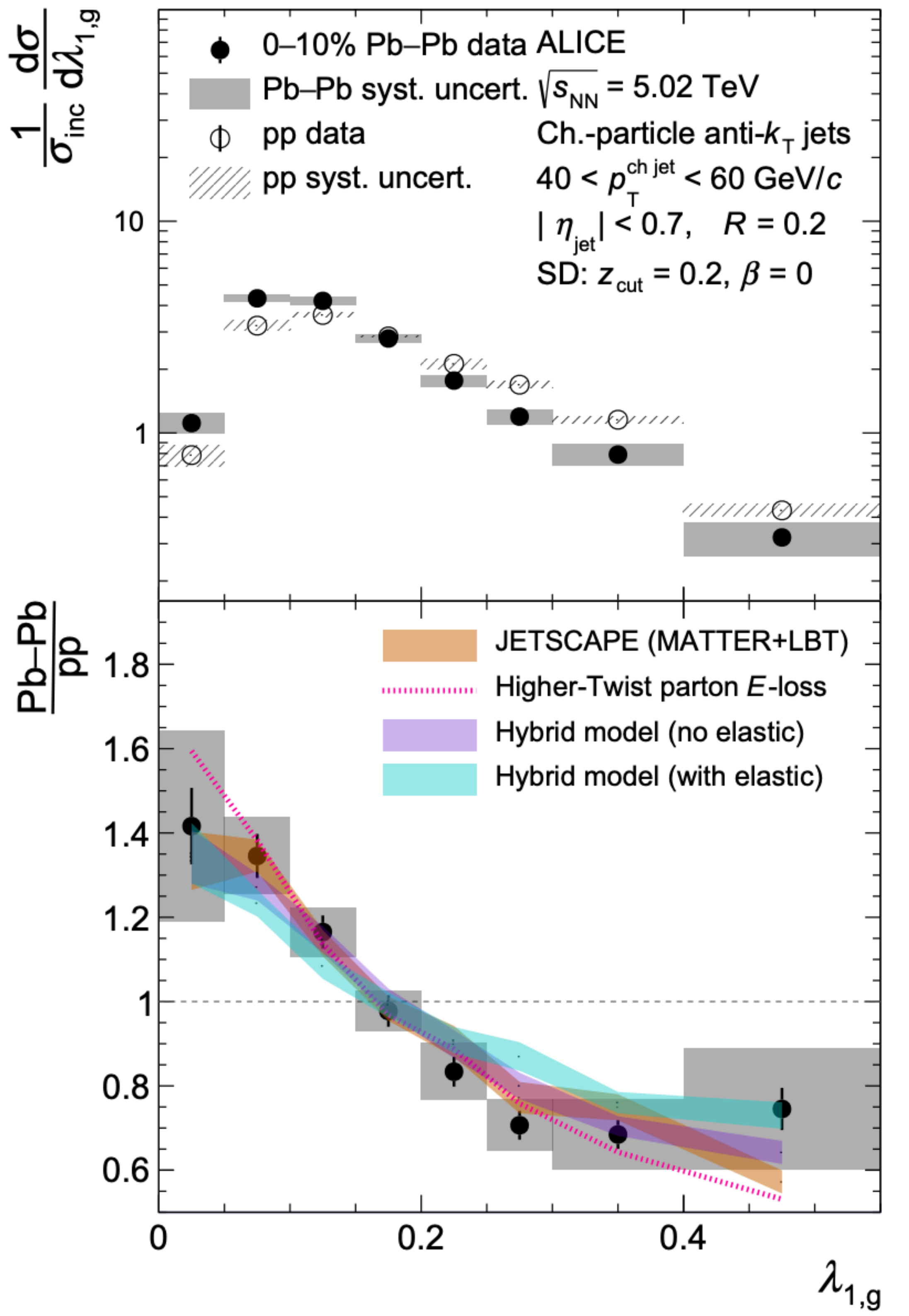
② Internal structure modification

- *We have learned* narrowing is everywhere!

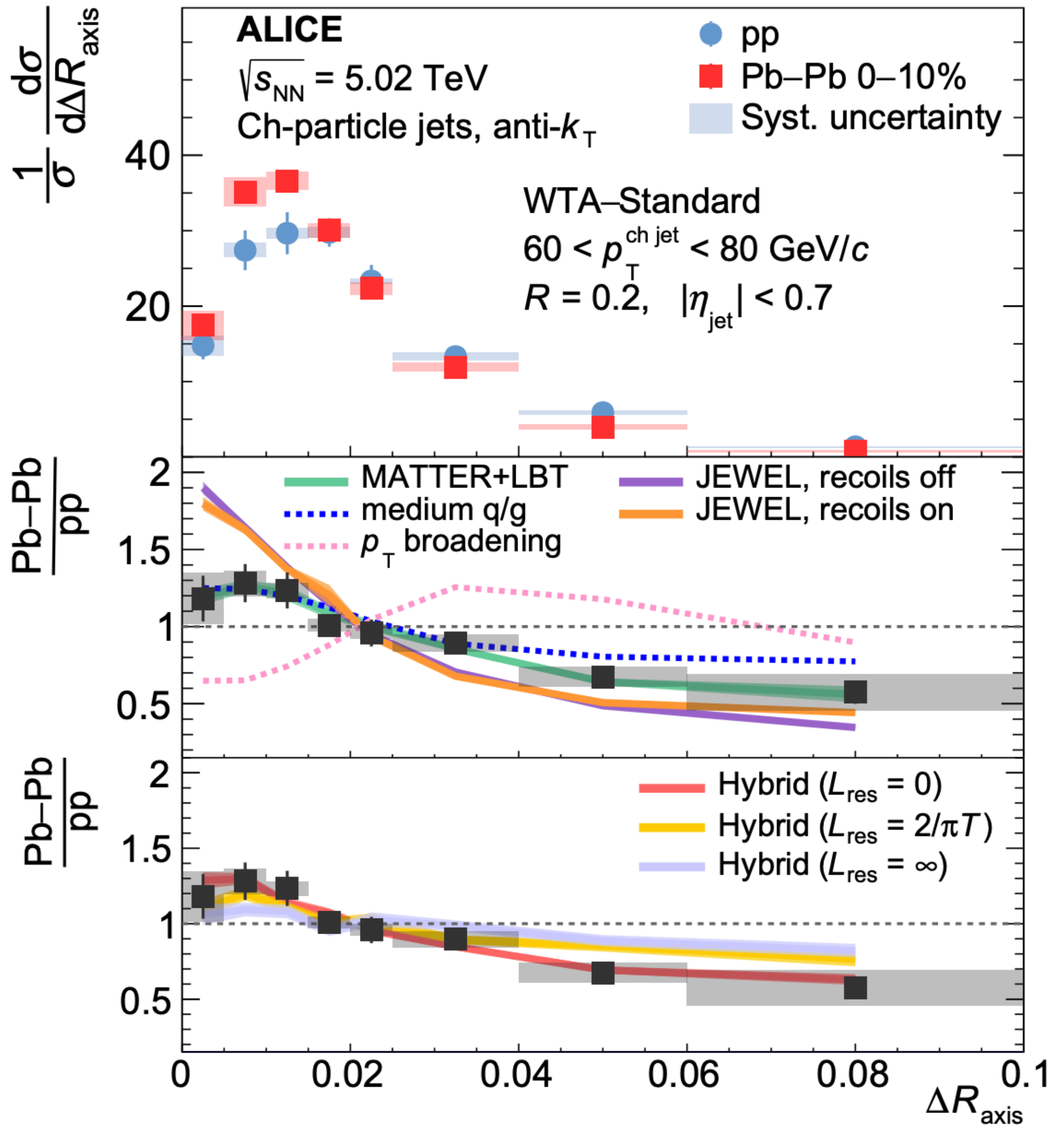
[JHEP 06 (2025) 120]



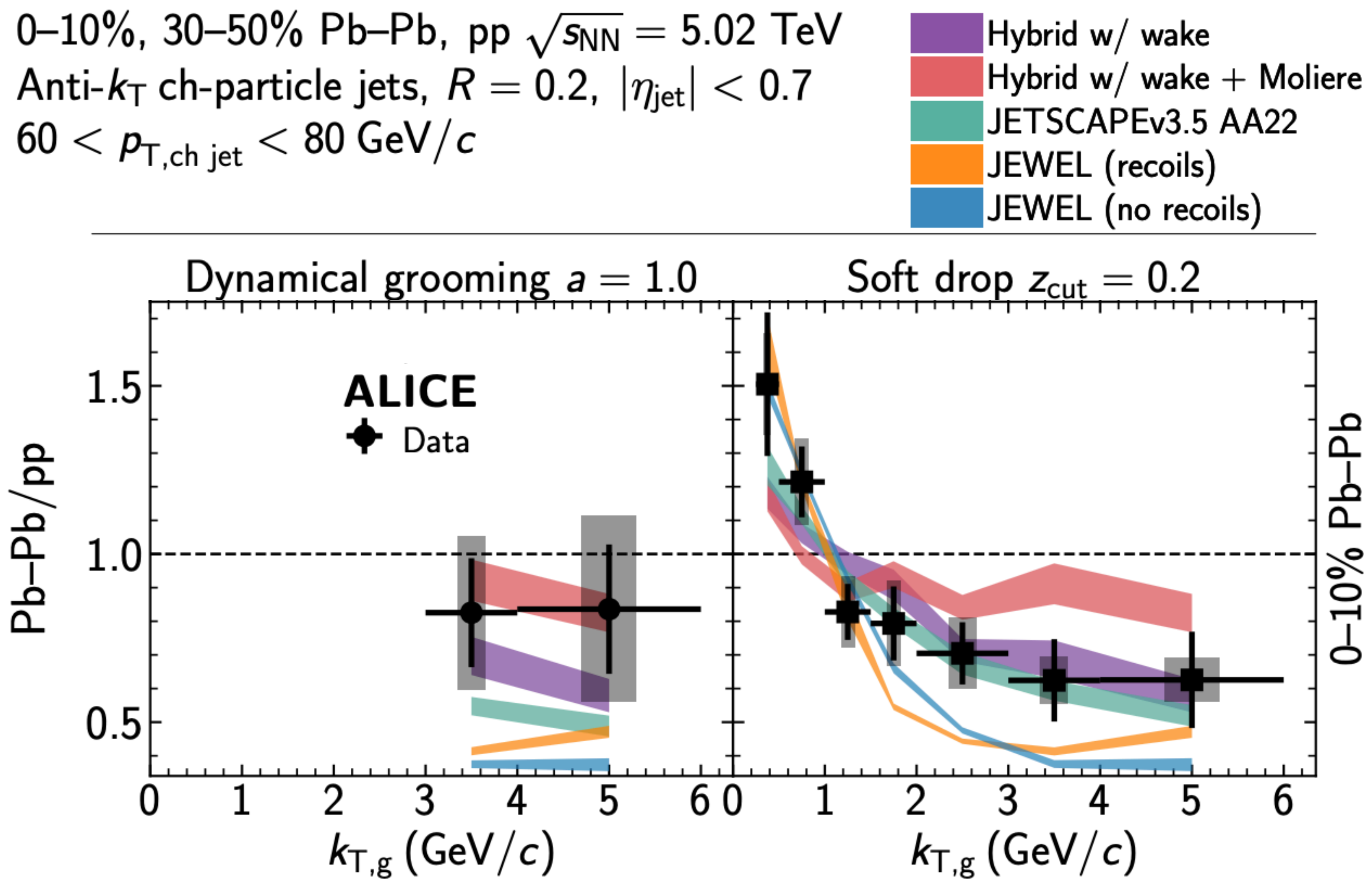
[PLB 864 (2025) 139409]



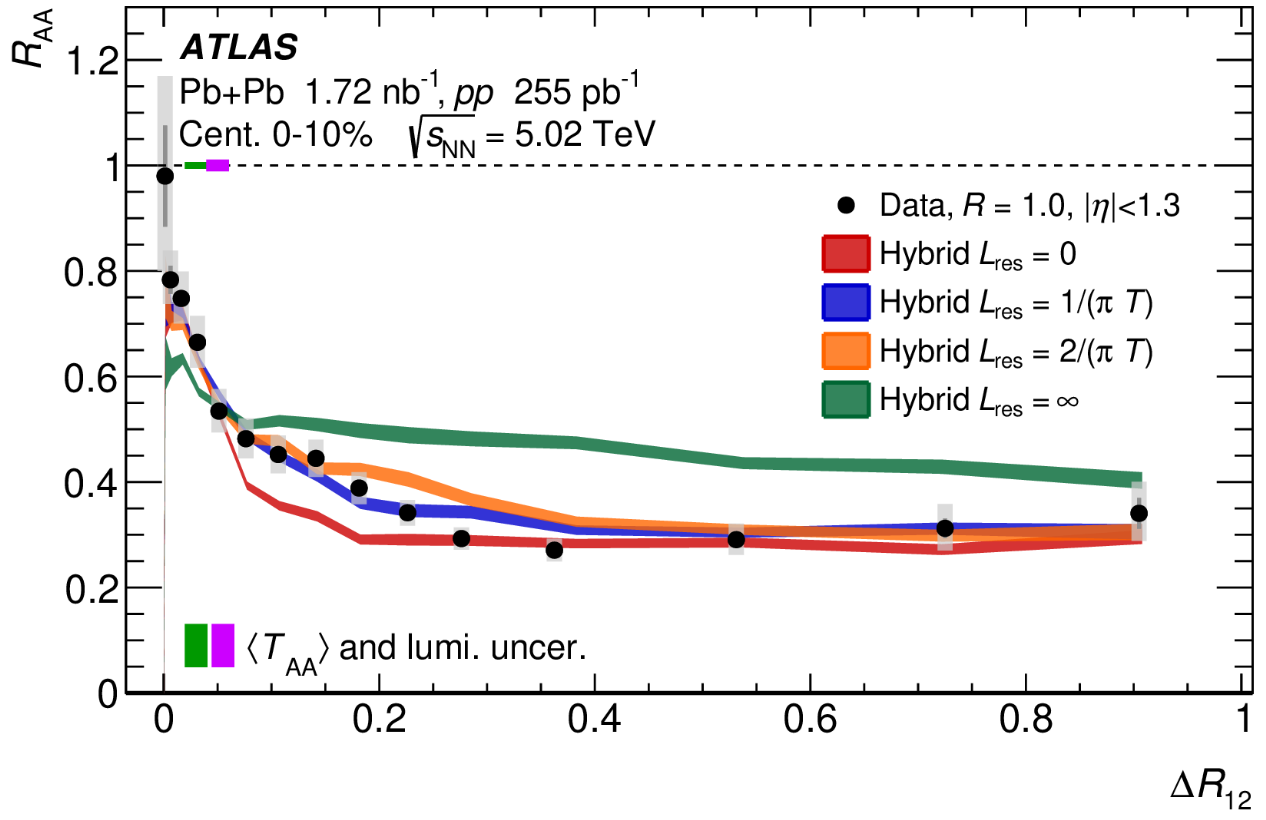
[PRC 113 (2026) 4, 044905]



[PRL 135, 031901 (2025)]

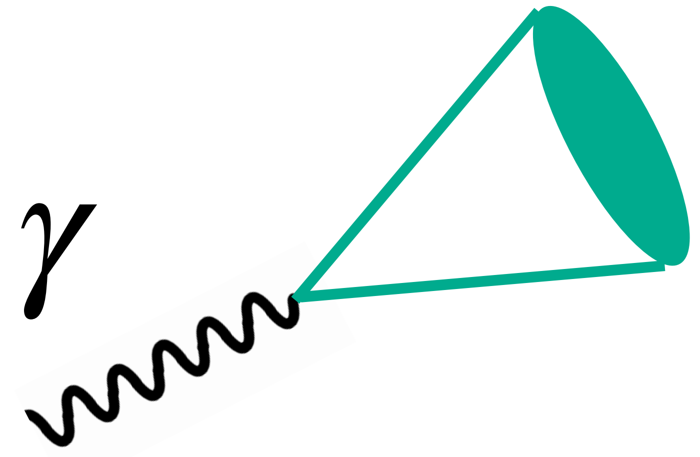


[PLB 871 (2025) 139929]

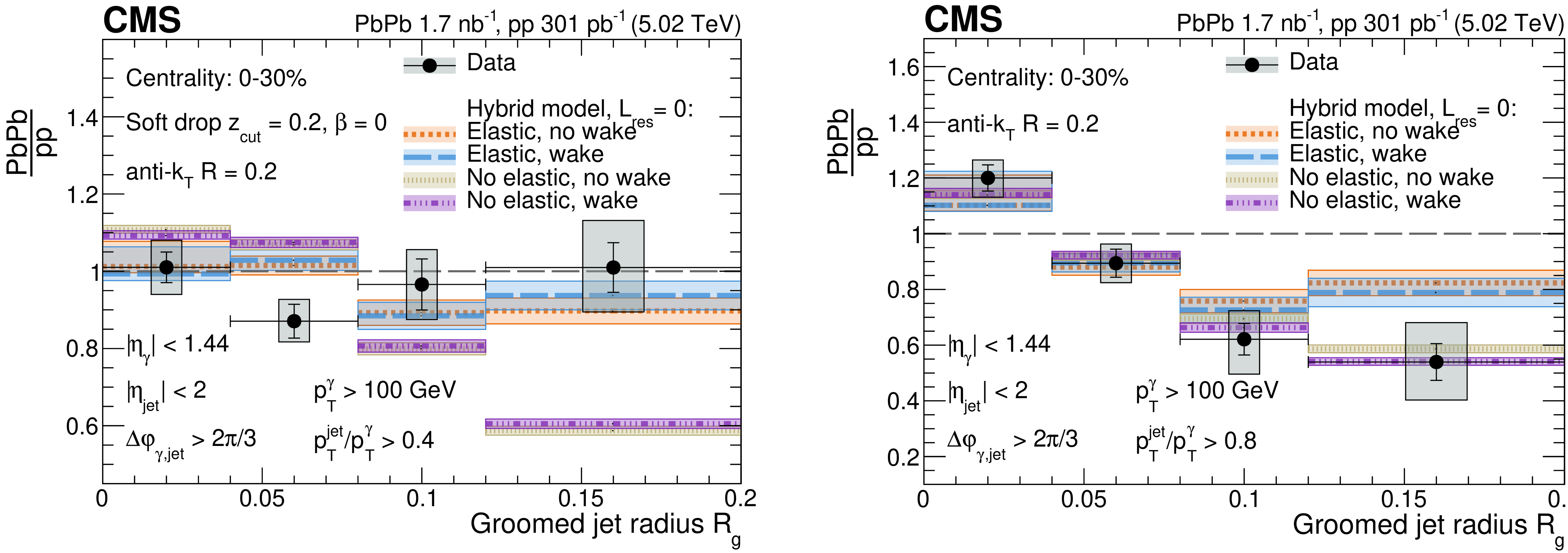


- This narrowing makes it very difficult to isolate effects!

WHAT HAVE WE LEARNED SO FAR?



② Internal structure modification



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

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

* *fragmentation photons can impact interpretation*

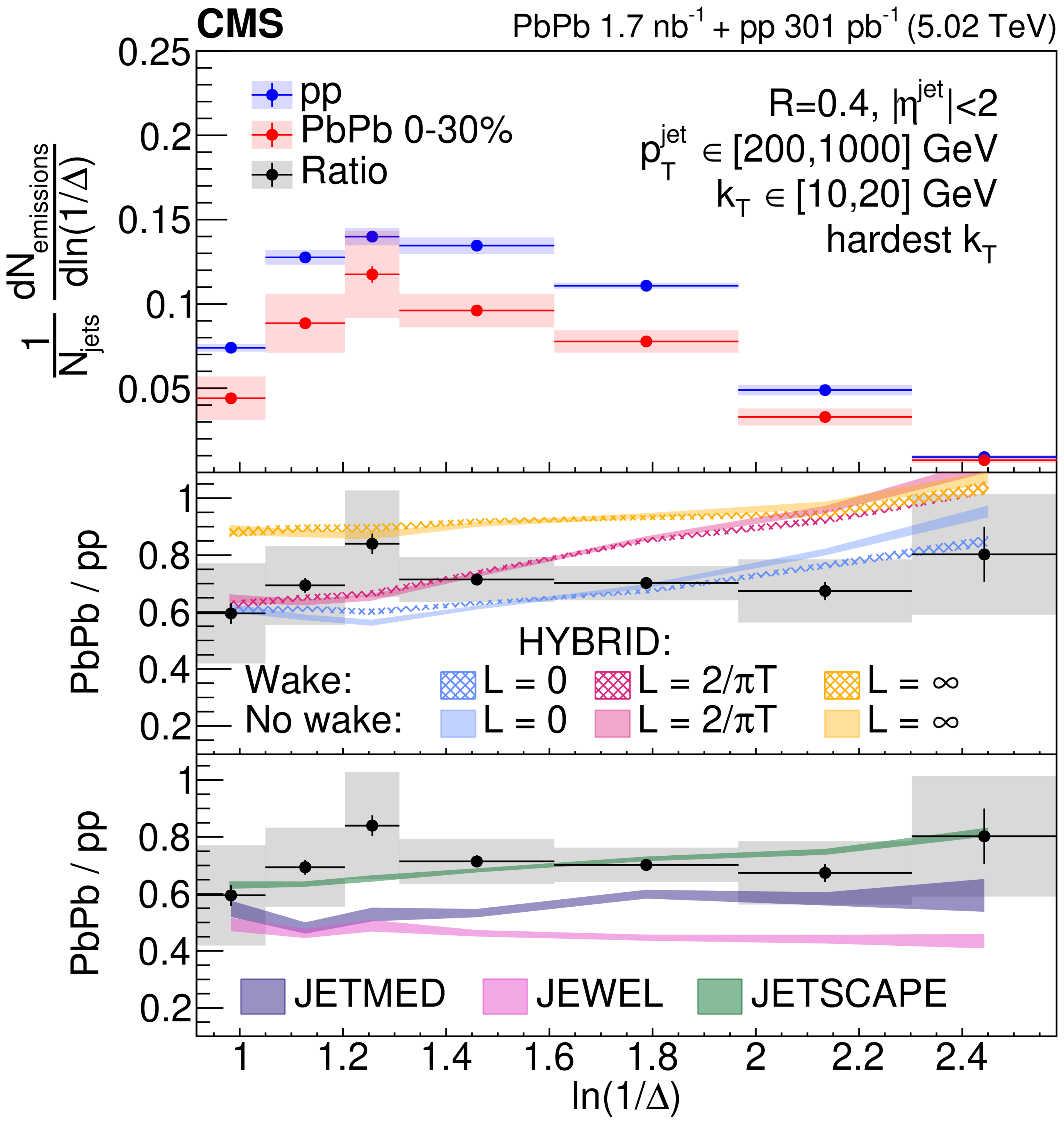
- *We have learned* $\gamma+$ jet is useful for removing selection bias, yet no single set of parameters describes data (pp reference issue?)

[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

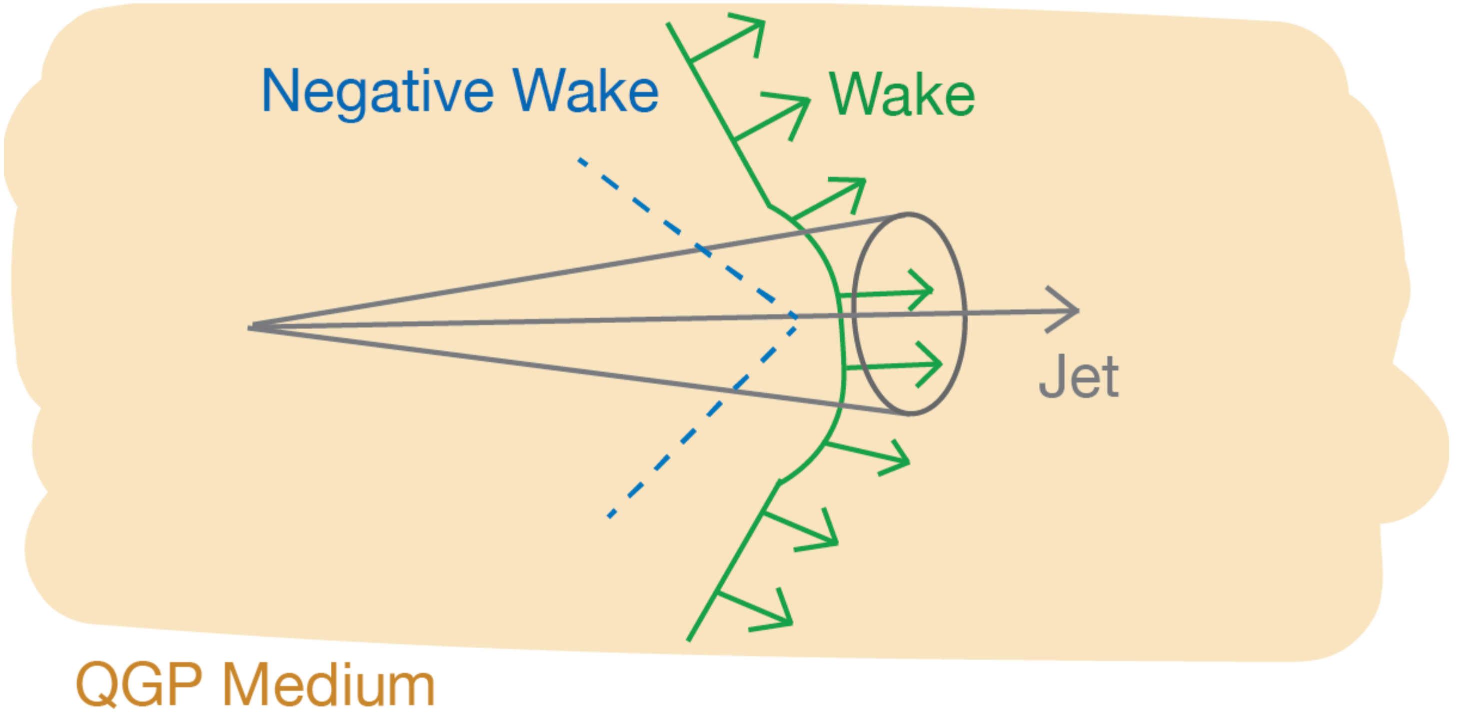


[HIN-24-016, arXiv:2602.09271 Submitted to PRL]

- 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.

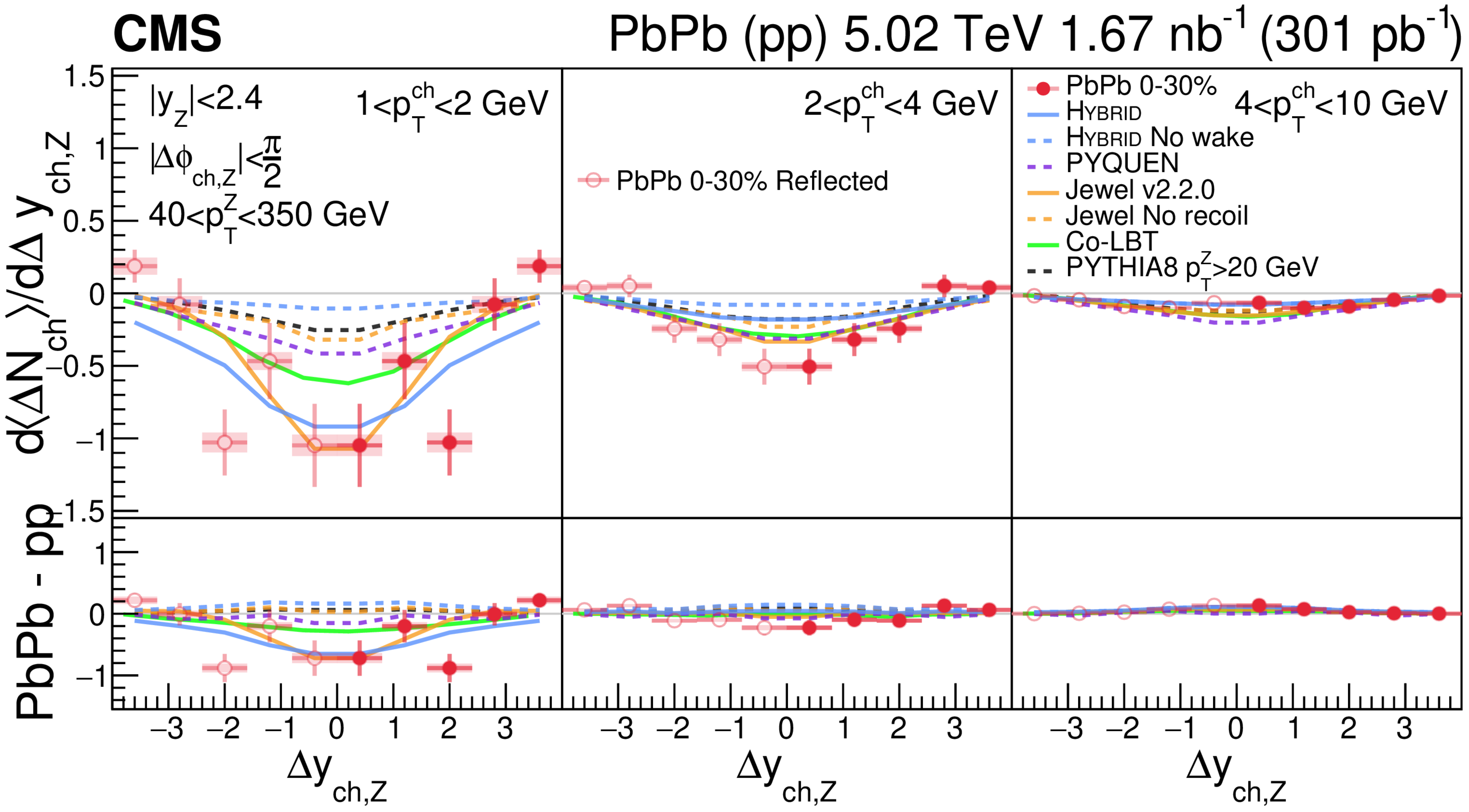
[Phys. Rev. D 110, 014015 (2024)]

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.

See also [PRC 111 (2025) 044909]

Massachusetts Institute of Technology

Hannah Bossi (hannah.bossi@cern.ch)

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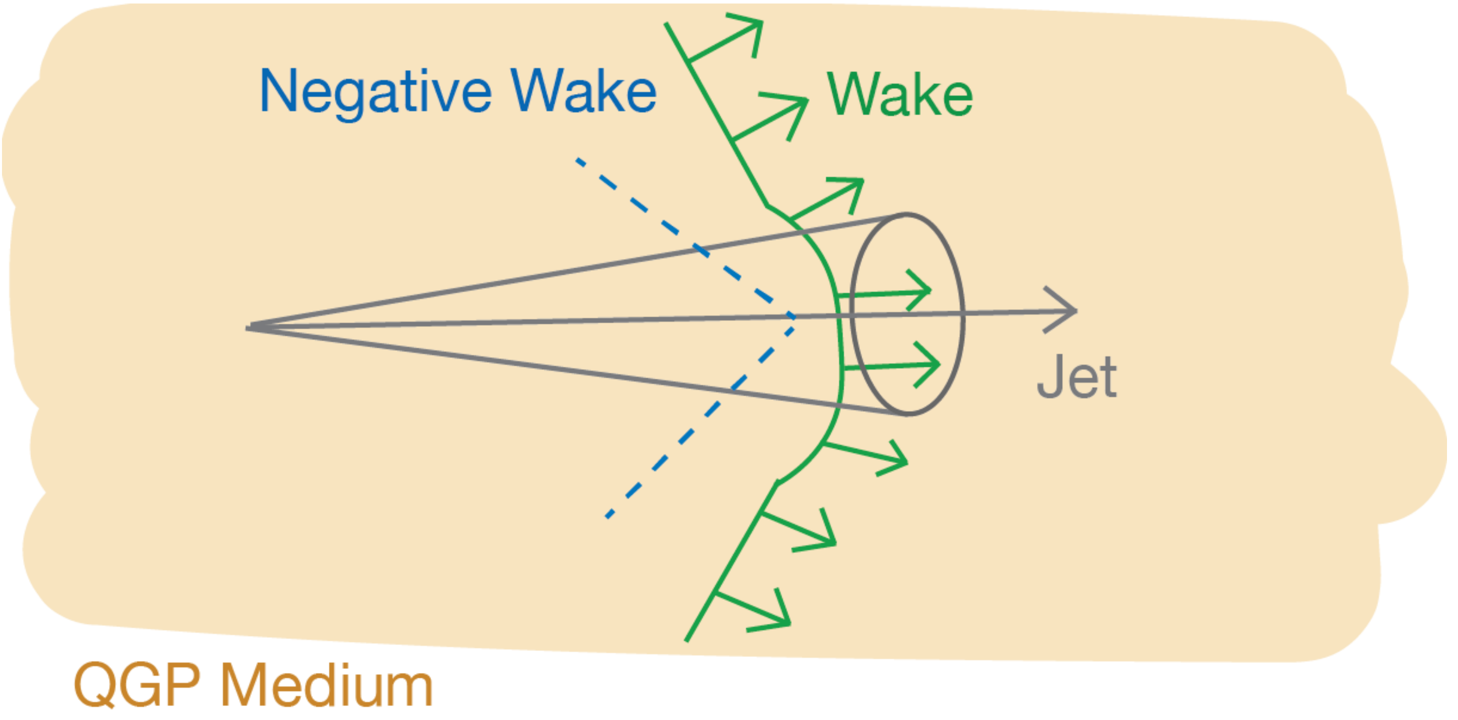
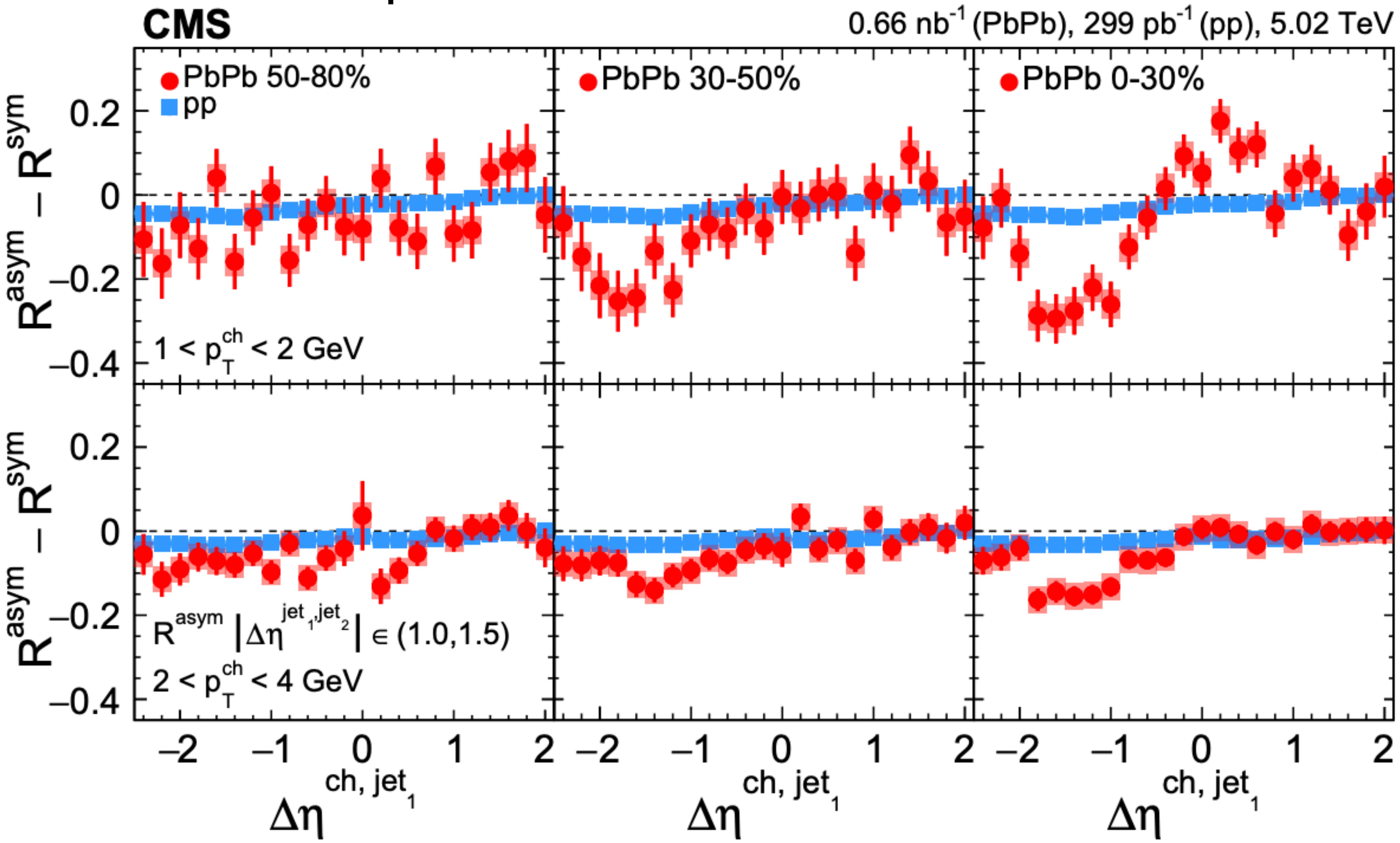
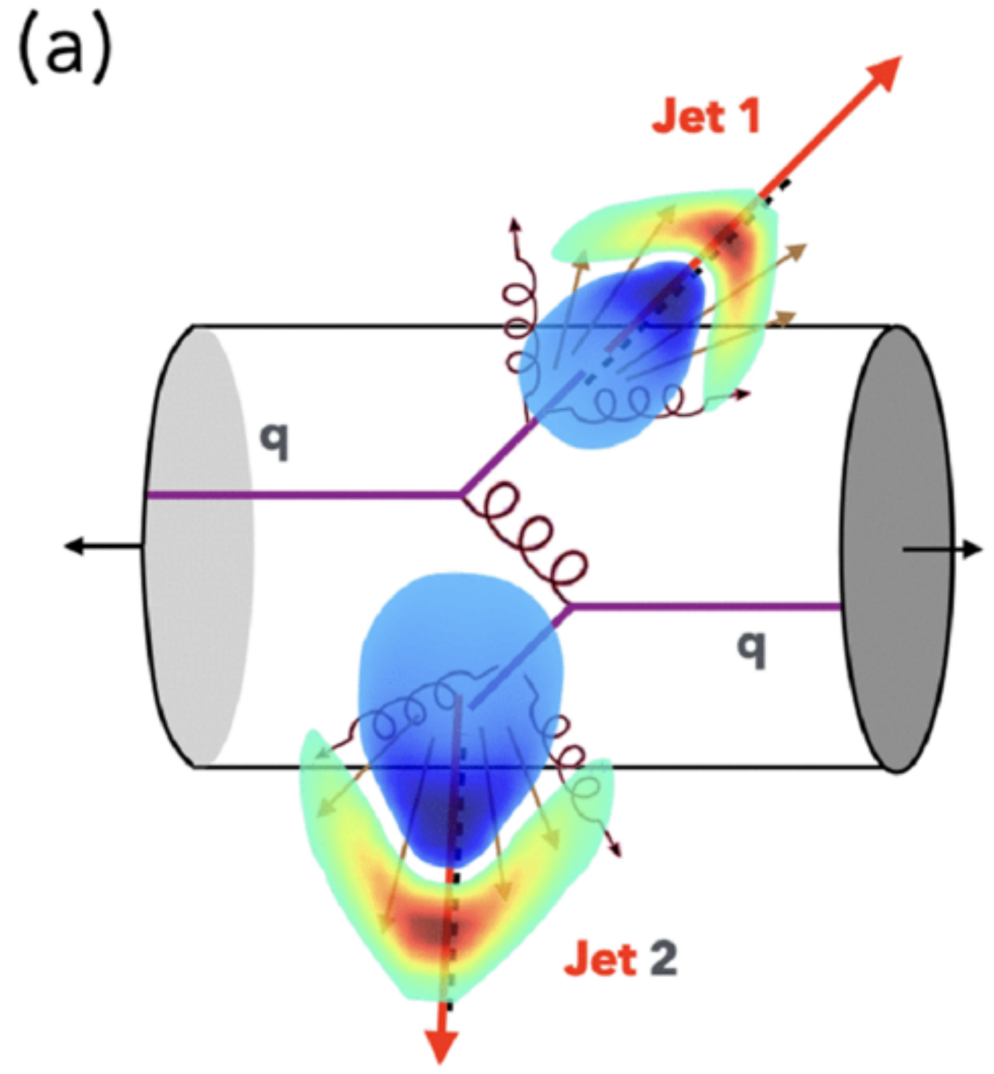




[arXiv:2602.19431]

- Similar signature observed with dijets via difference between symmetric and asymmetric dijet pairs.

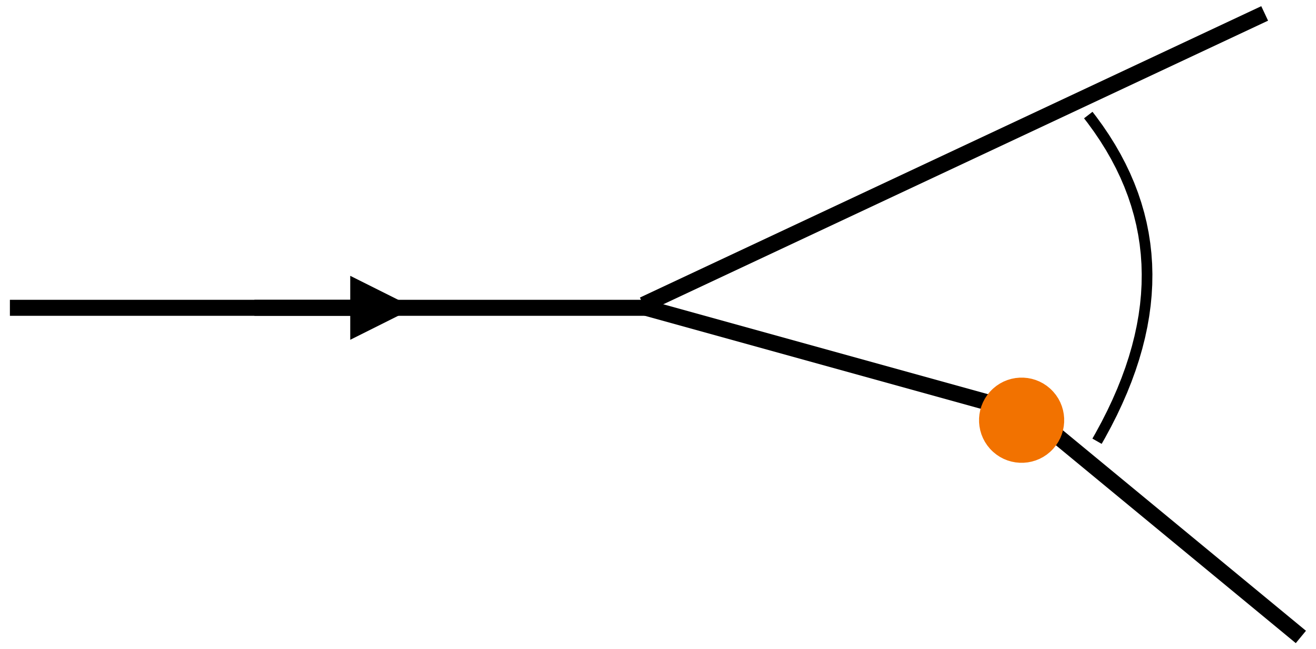


[PRL 135, 072302]

WHAT DO WE STILL WANT TO LEARN?

- Overall, *we have successfully isolated* many fundamental aspects of jet quenching.

- **(Part 1)** Still many phenomena remaining that we have yet to fully isolate.
  - Medium induced emissions
  - Quasi-particle structure of QGP (Moliere Scattering)
  - Mass dependence of quenching
  - Full dynamics of pp jet physics

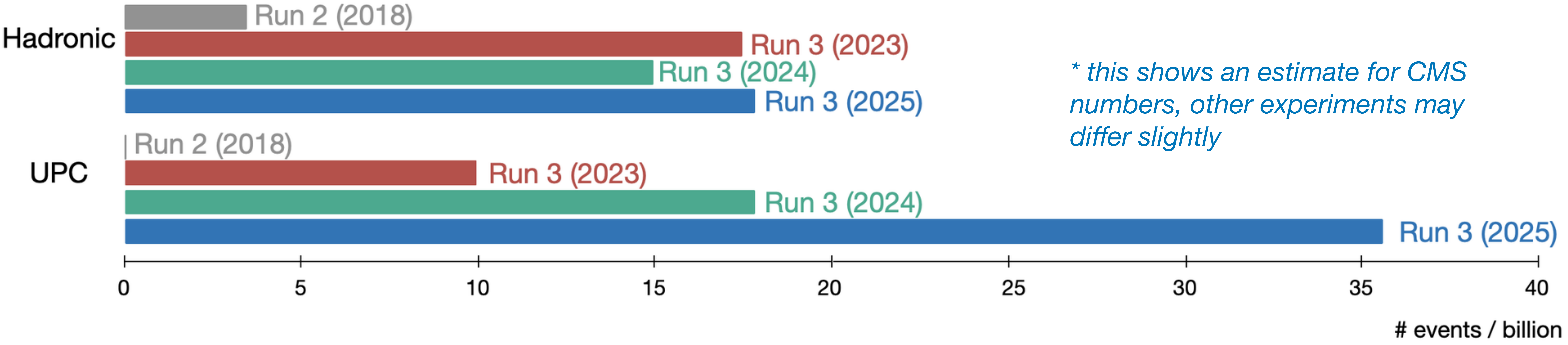


- **(Part 2)** Lacking a complete understanding of how these pieces fit together.
  - Transition between parton shower & hadronization in medium
  - How do different quenching effects balance one another? How does this depend on kinematic scales?
  - How do quenching effects scale with system size?

Hannah Bossi (hannah.bossi@cern.ch)

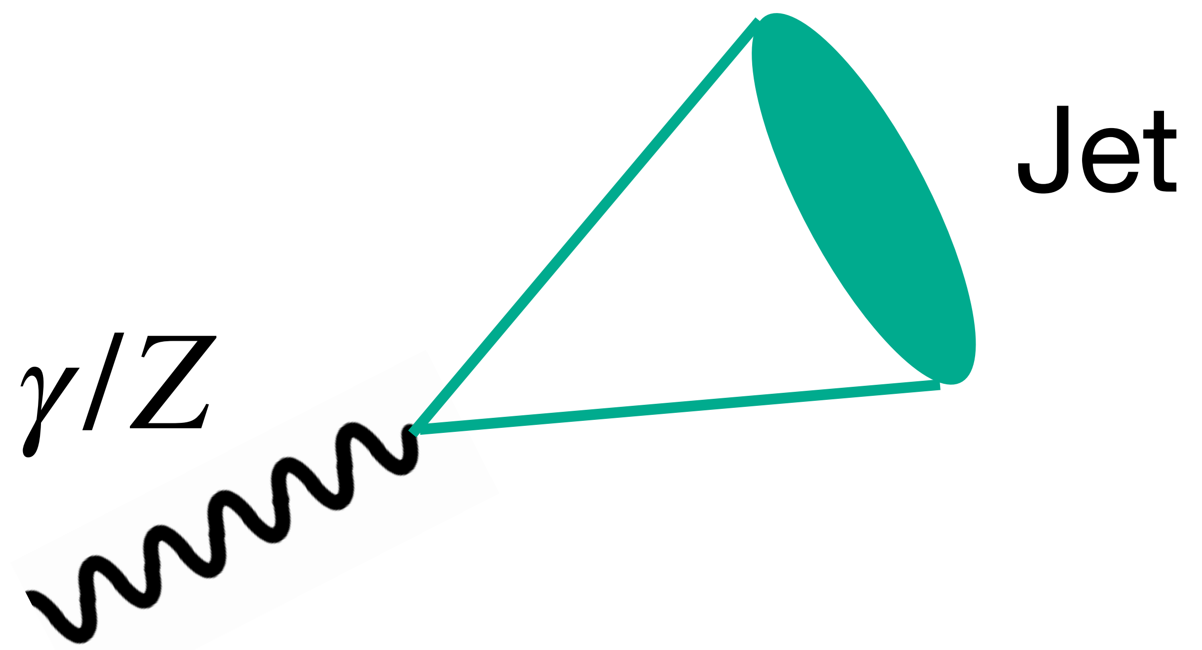
THE POWER OF LHC RUN 3

- High-statistics datasets provided by Run 3 at the LHC will be crucial!



** this shows an estimate for CMS numbers, other experiments may differ slightly*

- Stats especially useful for γ/Z + jet or differential jet measurements.



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

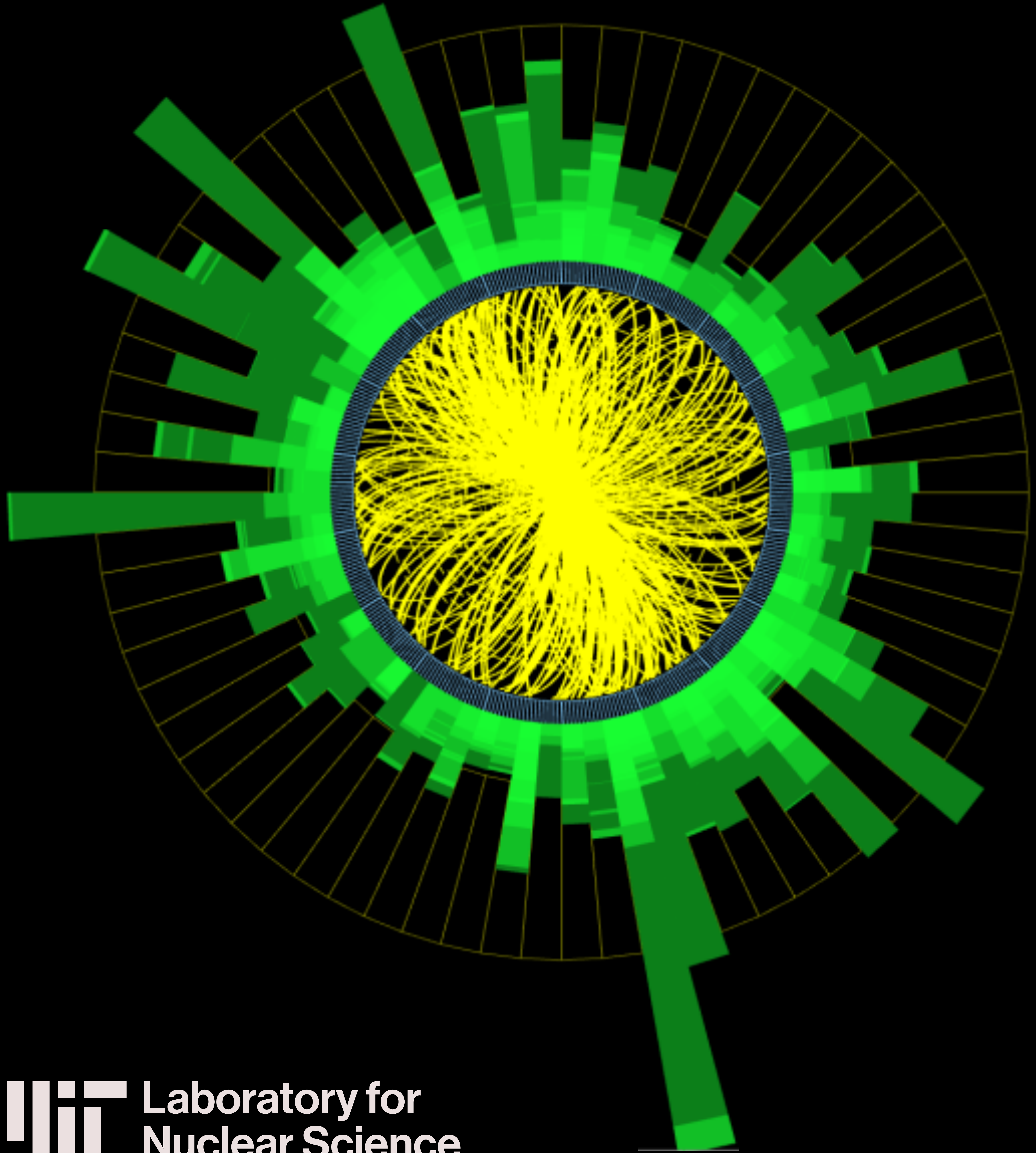
SUMMARY AND CONCLUSIONS

- **Over the ~ 50 years of jets we've managed to learn a lot!**
  - In this talk we've focused the expected signatures of jet quenching and the challenges that selection bias and model-dependence bring about.

- **Experimentally exploring synergies between RHIC and LHC very useful!**
  - Investigate impact of q/g fraction, balance of relative effects across kinematic scales. Having data with the same system (OO) makes this very timely.

- **Currently we are at the tail end of a very successful Run 3 of the LHC!**
  - Success both from the accelerator side and from the individual experiments! Now the focus pivots to fully exploiting the data!

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

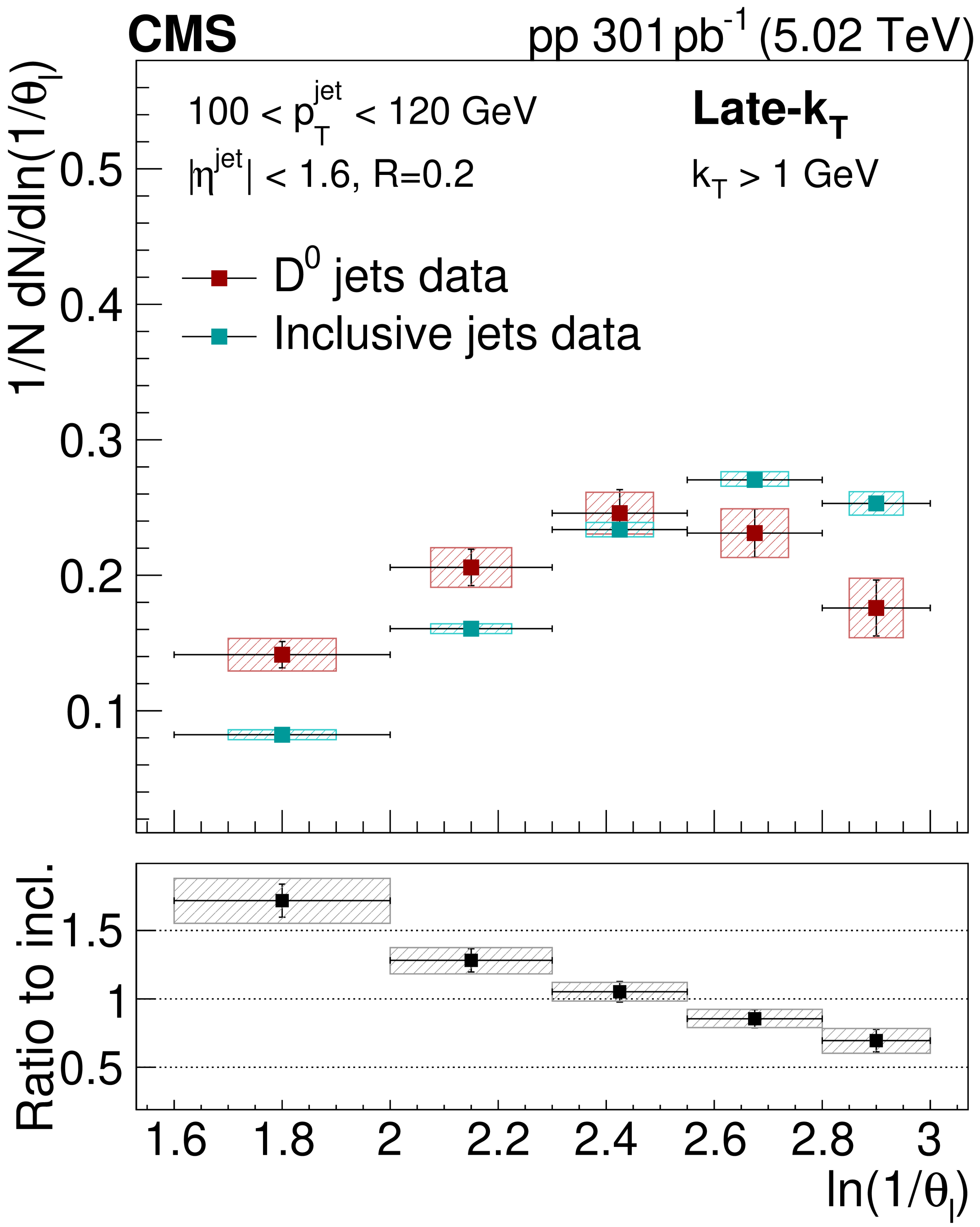


Backup

Laboratory for Nuclear Science

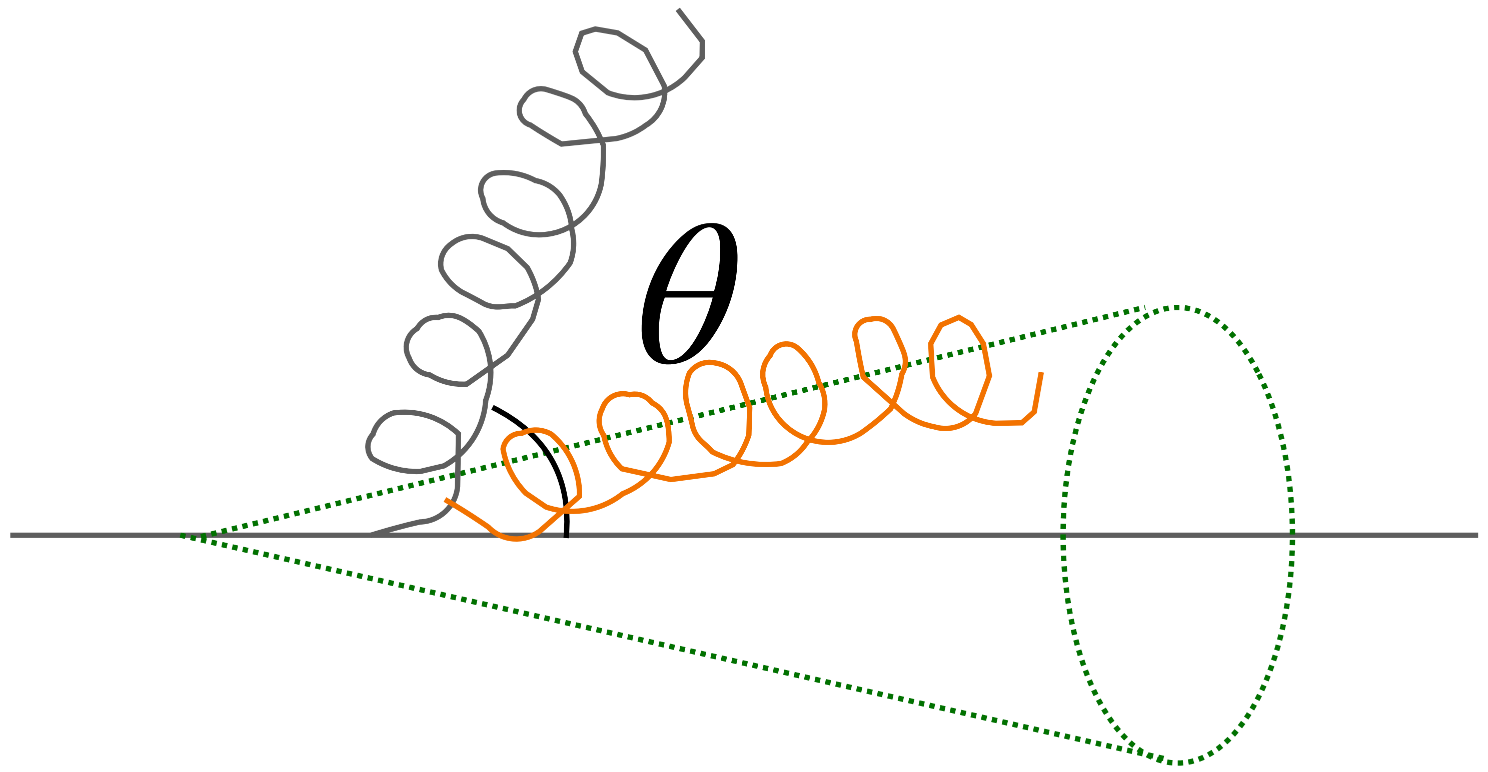
MIT HIG’s work was
supported by US DOE-NP

RHIC VS. LX



Exploit the power of the dead-cone for clean medium-induced emissions signal!

- Vacuum emissions suppressed in a cone of $\theta_0 = m/E$ (dead-cone) [ALICE, Nature 605 (2022) 440-446] [CMS, arXiv:2507.13469, Accepted by JHEP]
  - Lower energy experiments, larger cones.

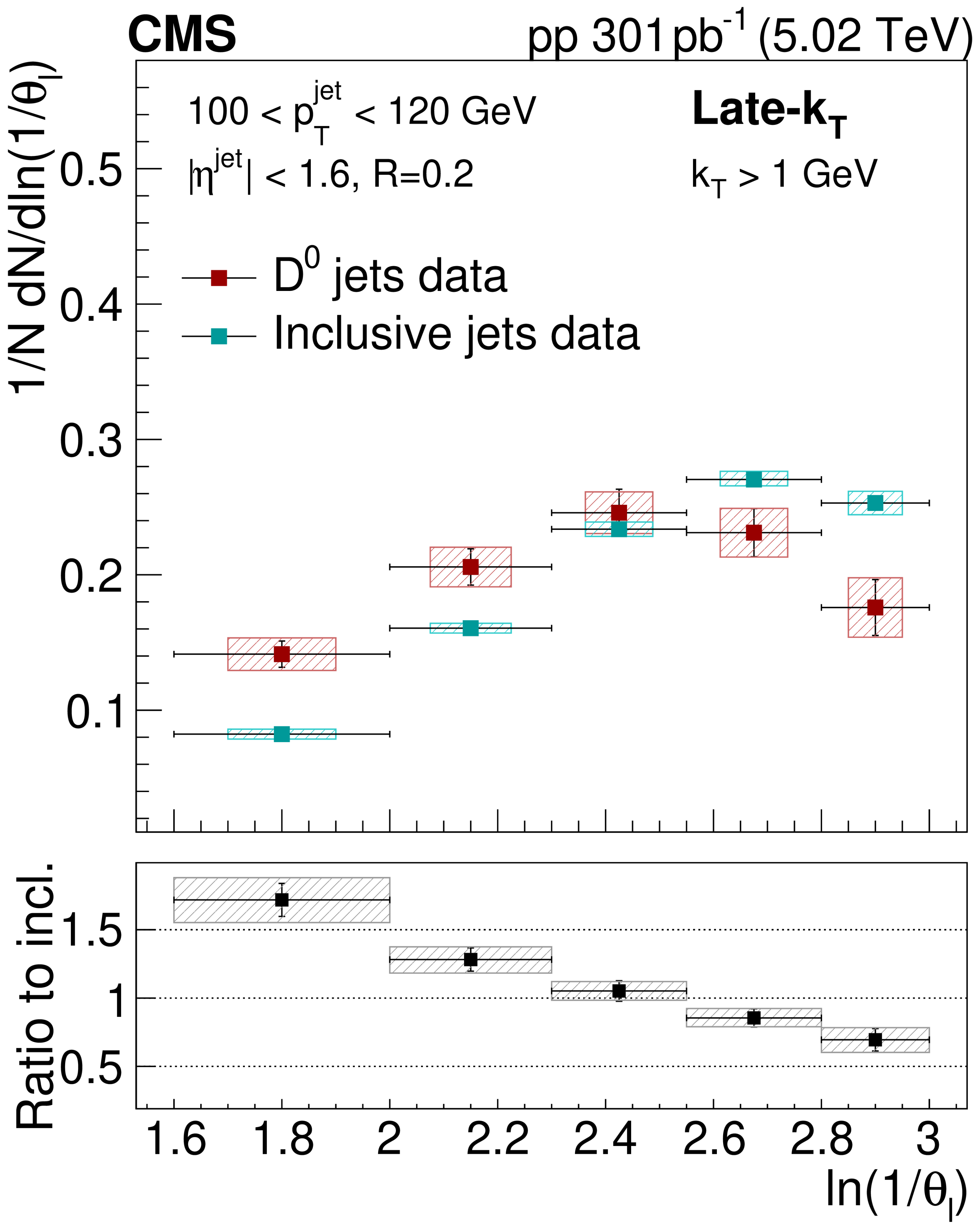


- In PbPb, the dead-cone effect has an interplay with coherence angle, θ_c.

- If $\theta_c < \theta_0$, then medium-induced emissions will fill the dead cone.
- If $\theta_c > \theta_0$, then the dead-cone will remain unfilled as in vacuum.

[Phys.Rev.D. 107 (2023) 9, 094008]

ISOLATING MEDIUM-INDUCED RADIATION



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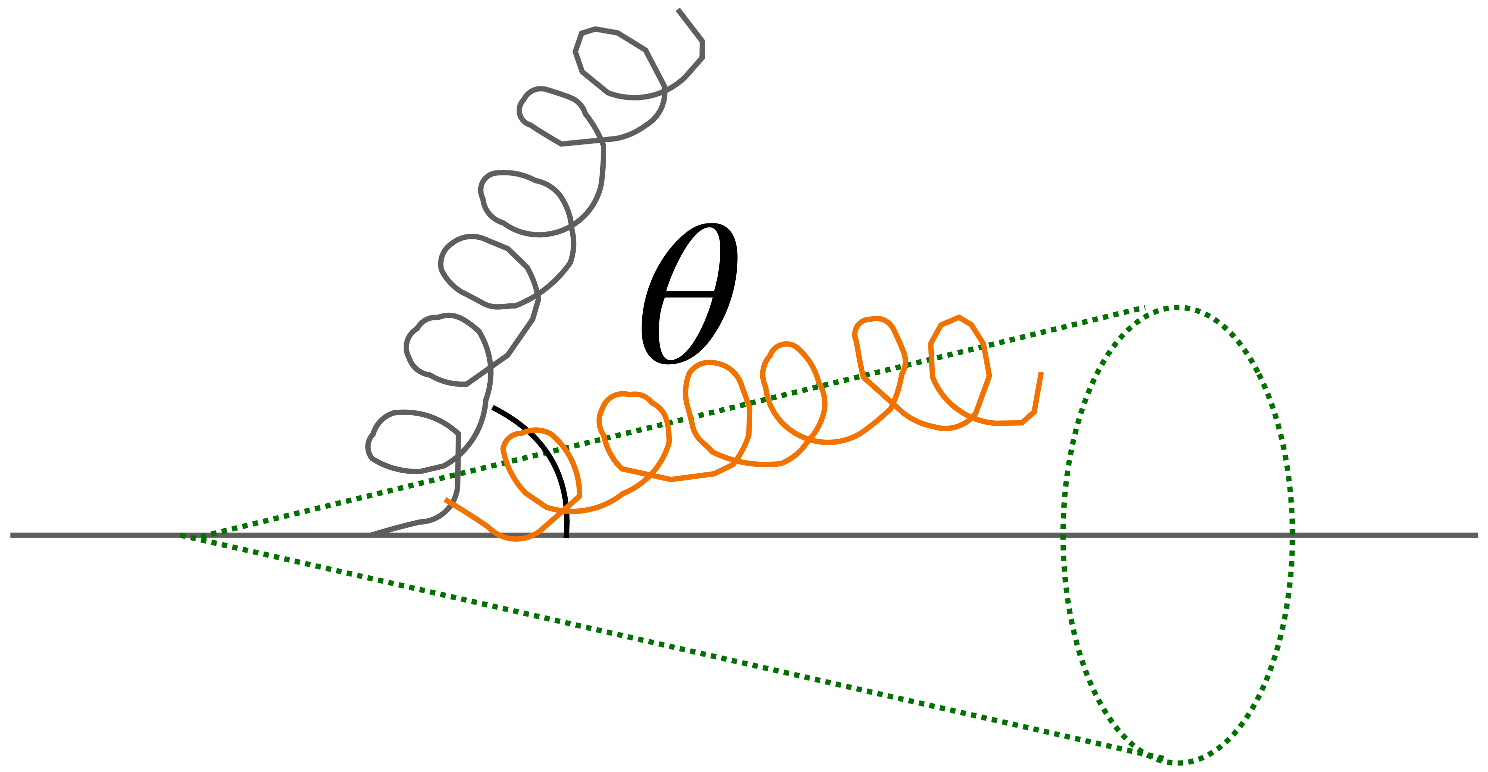

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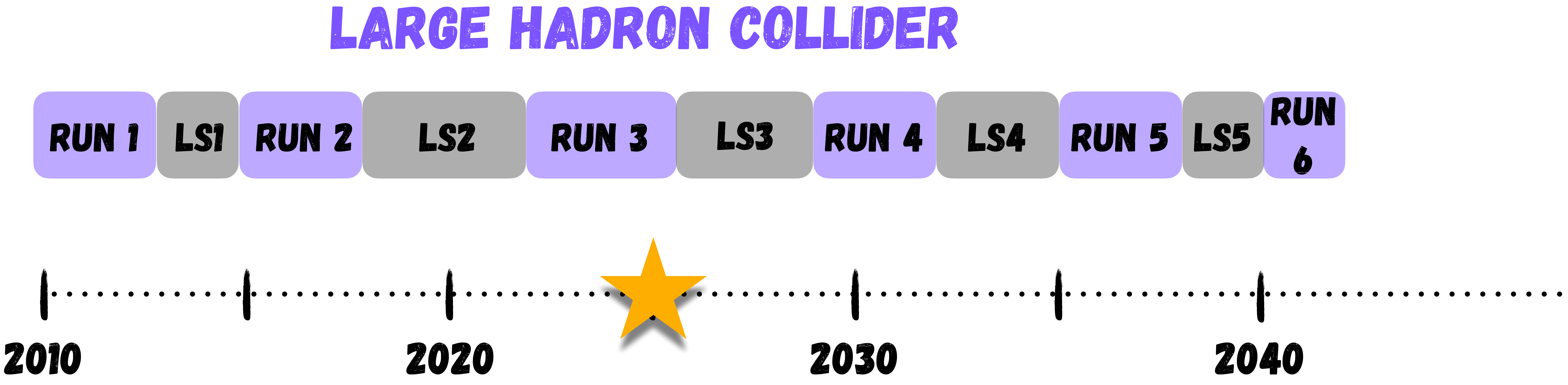
WHERE ARE WE NOW?



LARGE HADRON COLLIDER

RUN 1 | LS1 | RUN 2 | LS2 | RUN 3 | LS3 | RUN 4 | LS4 | RUN 5 | LS5 | RUN 6

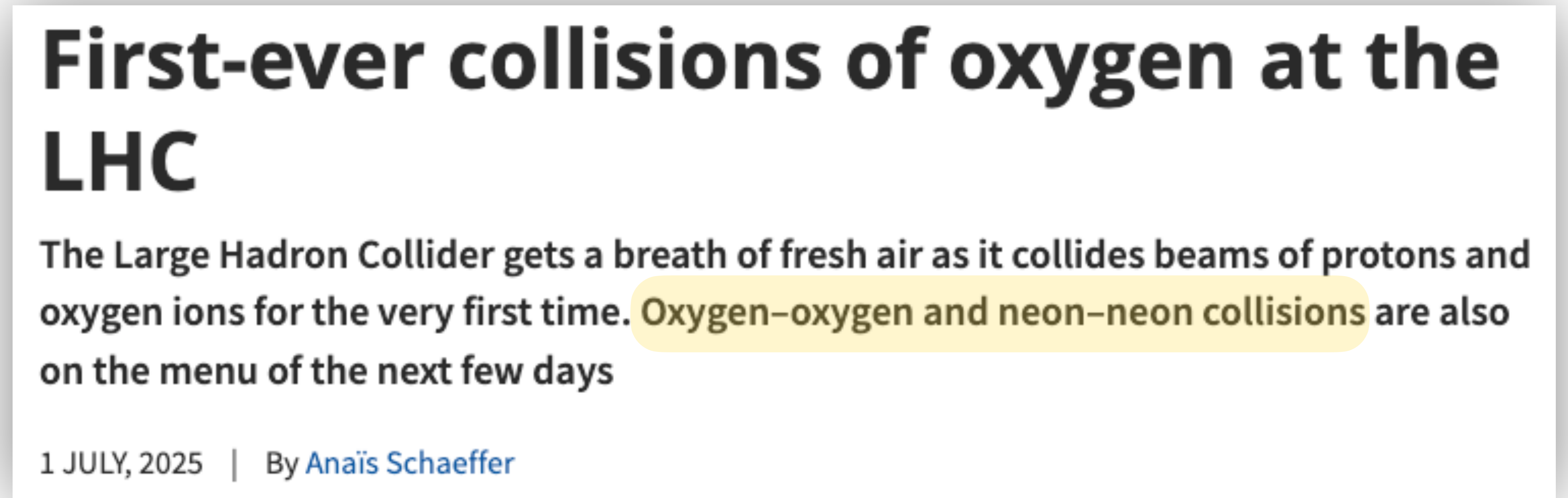
- We're approaching the end of Run 3 of the LHC! Incredible success!

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]



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]

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	$5.61\ \mathrm{pb}^{-1}$	$5.51\ \mathrm{pb}^{-1}$
PbPb	2.76 TeV	$0.194\ \mathrm{nb}^{-1}$	$0.183\ \mathrm{nb}^{-1}$
pp	5.02 TeV	$369.97\ \mathrm{pb}^{-1}$	$350.92\ \mathrm{pb}^{-1}$
PbPb	5.02 TeV	$2.48\ \mathrm{nb}^{-1}$	$2.35\ \mathrm{nb}^{-1}$
pPb	5.02 TeV	$36.67\ \mathrm{nb}^{-1}$	$36.01\ \mathrm{nb}^{-1}$
pPb	8.16 TeV	$188.3\ \mathrm{nb}^{-1}$	$180.2\ \mathrm{nb}^{-1}$
XeXe	5.44 TeV	$3.50 \times 10^{-3}\ \mathrm{nb}^{-1}$	$3.42 \times 10^{-3}\ \mathrm{nb}^{-1}$

Run 3

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

Collision System	COM Energy	Delivered Lumi	Recorded Lumi
pp	5.36 TeV	$520.43\ \mathrm{pb}^{-1}$	$483.10\ \mathrm{pb}^{-1}$
PbPb	5.36 TeV	$6.652\ \mathrm{nb}^{-1}$	$6.045\ \mathrm{nb}^{-1}$
pO	9.62 TeV	$48.4\ \mathrm{nb}^{-1}$	$46.5\ \mathrm{nb}^{-1}$
OO	5.36 TeV	$9.4\ \mathrm{nb}^{-1}$	$9.0\ \mathrm{nb}^{-1}$
NeNe	5.36 TeV	$0.91\ \mathrm{nb}^{-1}$	$0.9\ \mathrm{nb}^{-1}$

Hannah Bossi (hannah.bossi@cern.ch)

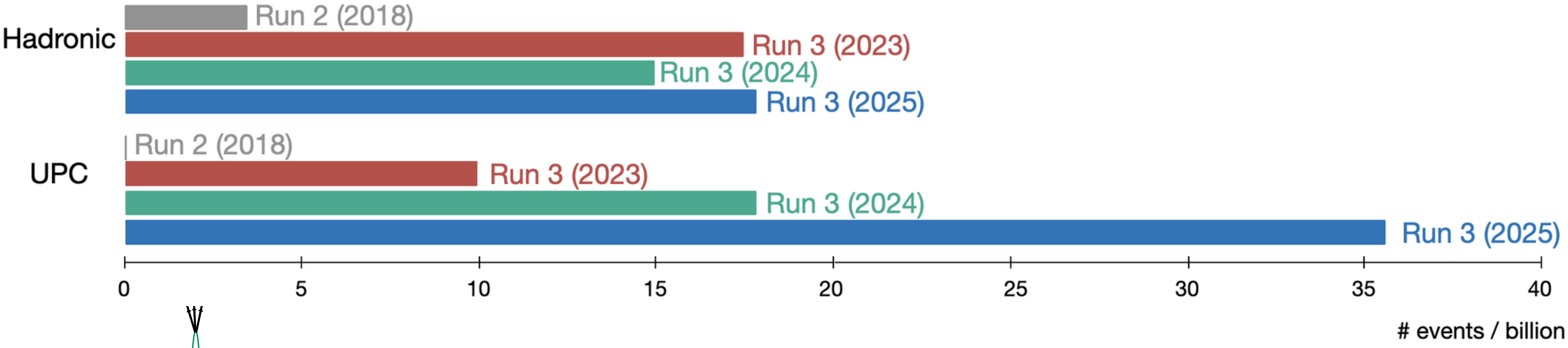
OF EVENTS IN RUN 3

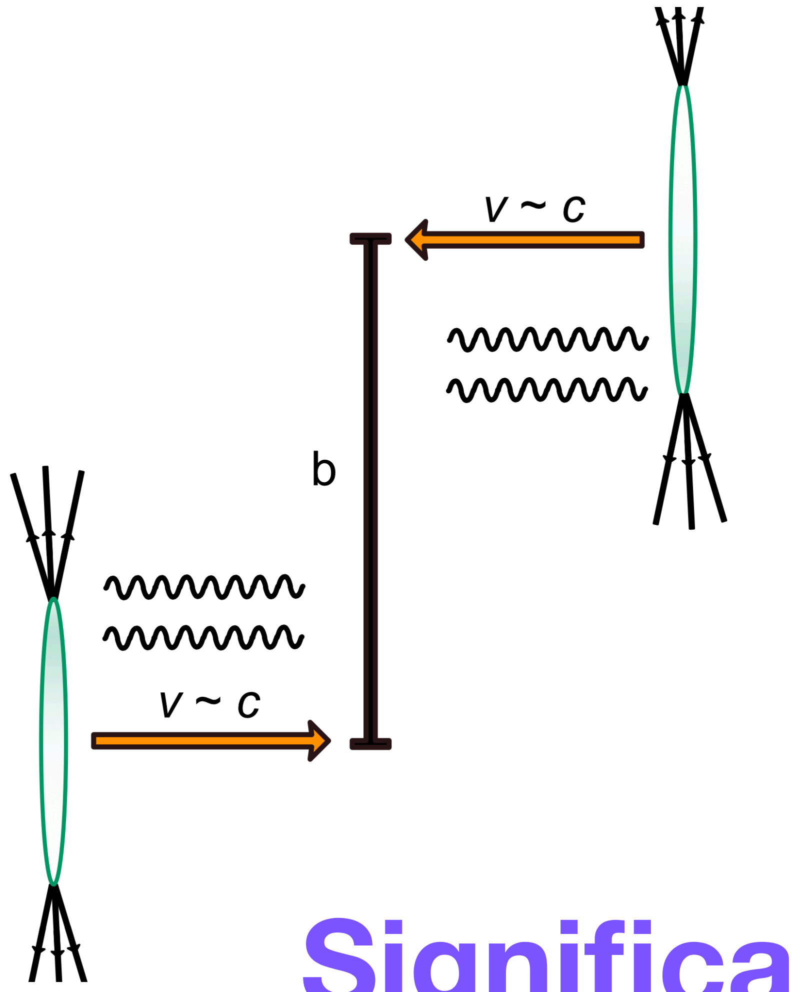
[CMS Public Lumi Totals]

[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.





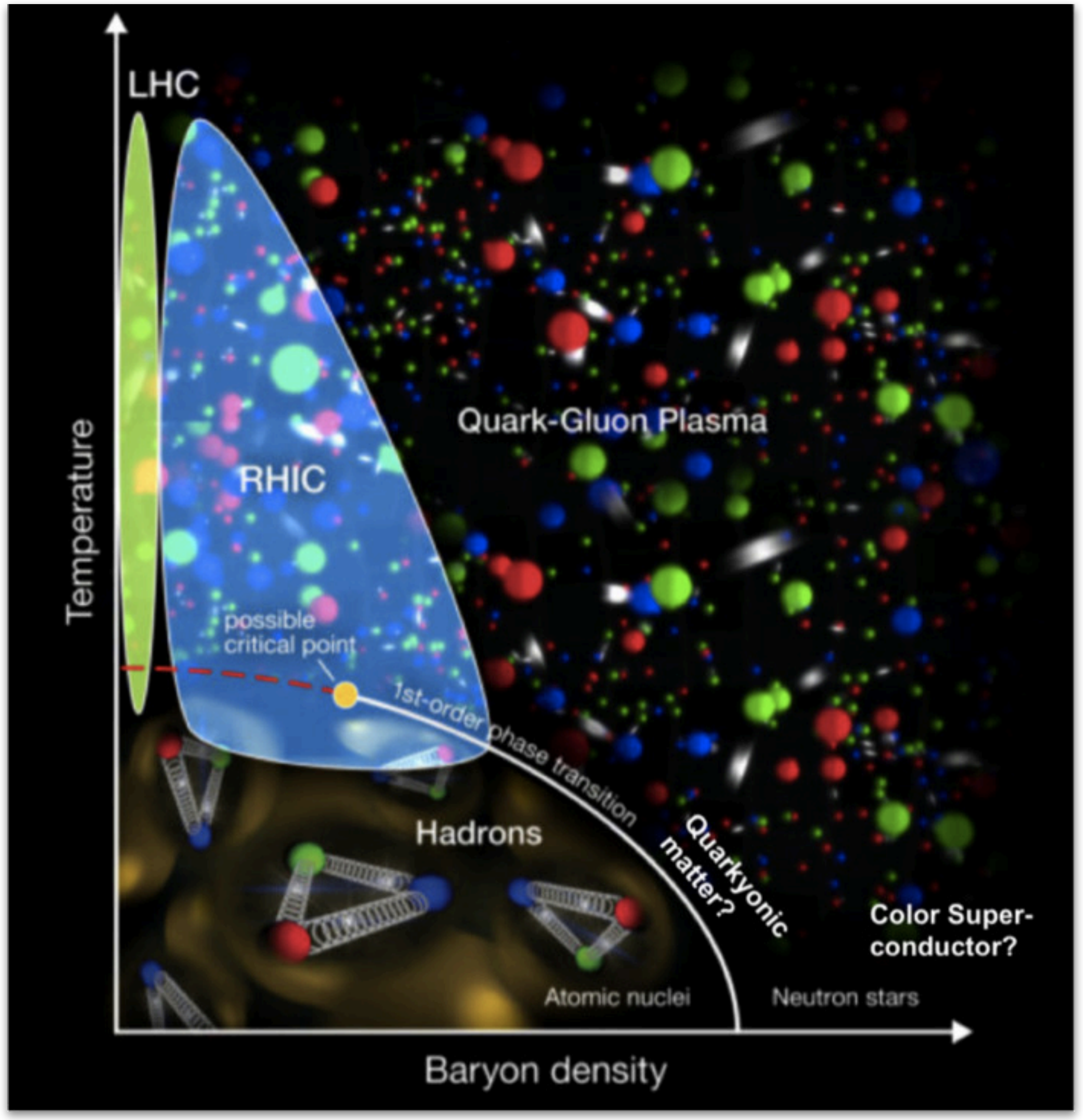
- Significant improvements made in # of ultra-peripheral collision events recorded!
  - Not the focus today, but lots of cool physics can be done here!

[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?

WHAT DO WE USE HEAVY-ION DATA FOR?

- *Short answer* → to study the quark gluon plasma (QGP)
  - What happens to QCD when we release the confinement potential?

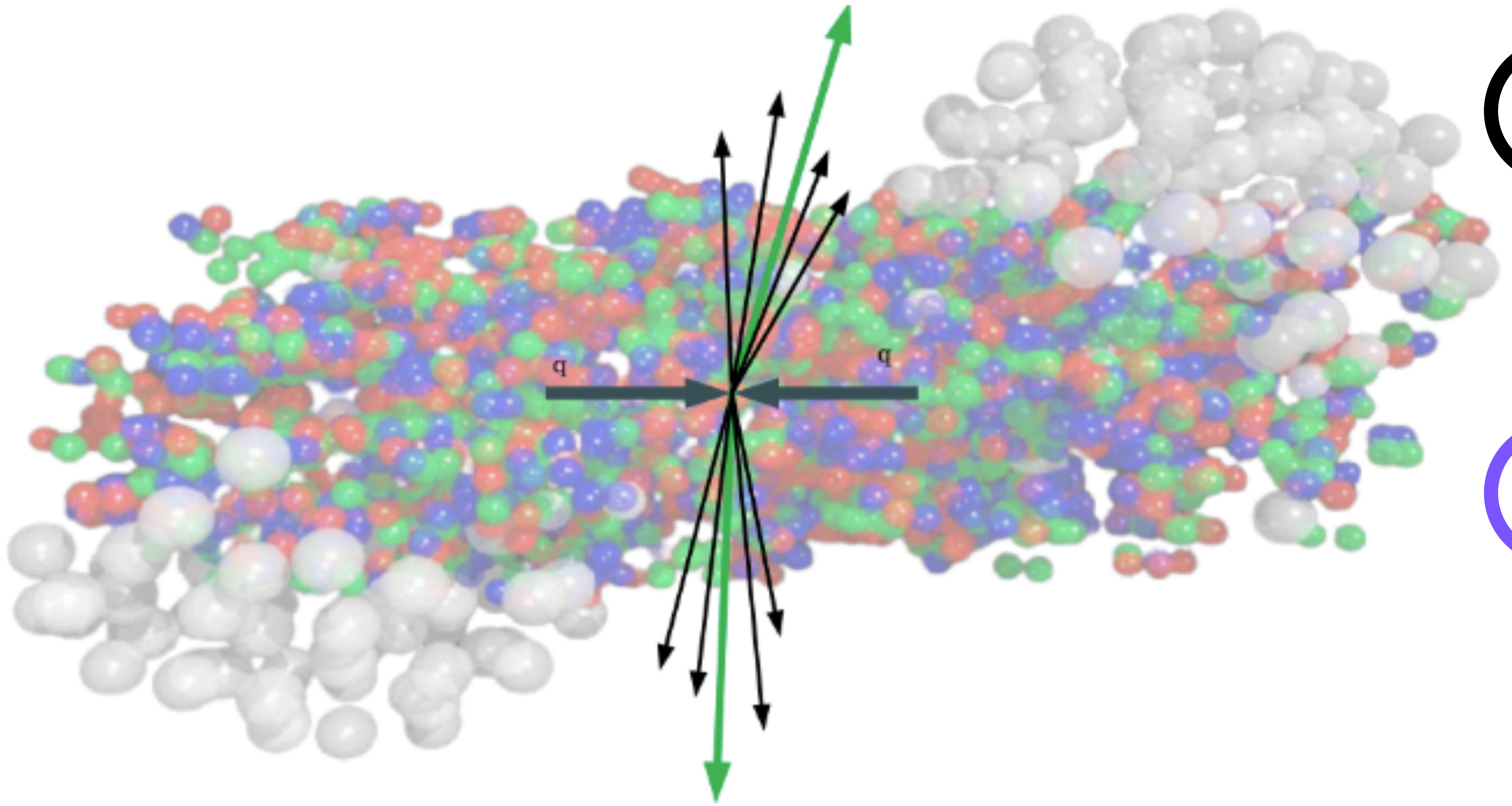


[Image Credit: Brookhaven National Lab]

- QCD matter becomes a deconfined state of quarks and gluons called the **Quark-Gluon Plasma (QGP)**.
  - Can recreate in a lab with heavy-ion collisions!
- What are the intrinsic and dynamical properties of the QGP?
  - How does the QGP evolve into hadronic matter?
- How are fundamental QCD processes like the parton evolution and hadronization modified?
  - Does the QCD phase diagram have a critical point, if so, where?

HOW DO WE USE HEAVY-ION DATA?

- *Short answer* → measure a wide variety of physics phenomena, each with different goals



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.

WHY DO HARD PROBES STUDIES NEED LOTS OF DATA?

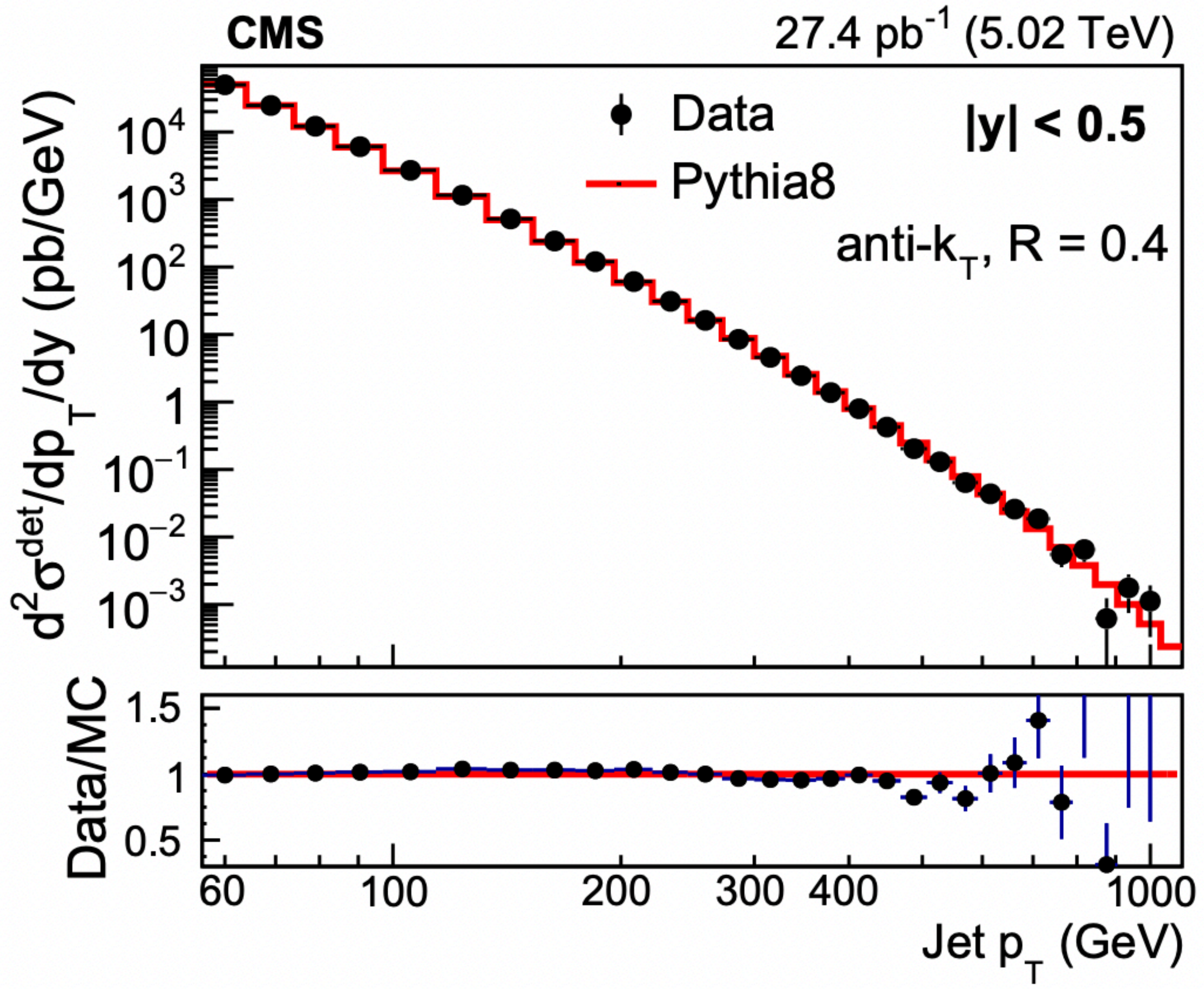
Let’s say we have 10 billion minimum bias pp events …

R = 0.4 jets w/ $p_{\mathrm{T}} > 100$ GeV and $|\eta| < 2$

$$N_{\text{jets}} \approx N_{\text{events}} \times \left(\frac{\sigma_{\text{jet}}(p_{\mathrm{T}} > p_{\mathrm{T,min}})}{\sigma_{inel}}\right) \approx \text{15 million jets}$$

[PLB 759 (2016)641]

[JHEP 01 (2025) 011, 2025]



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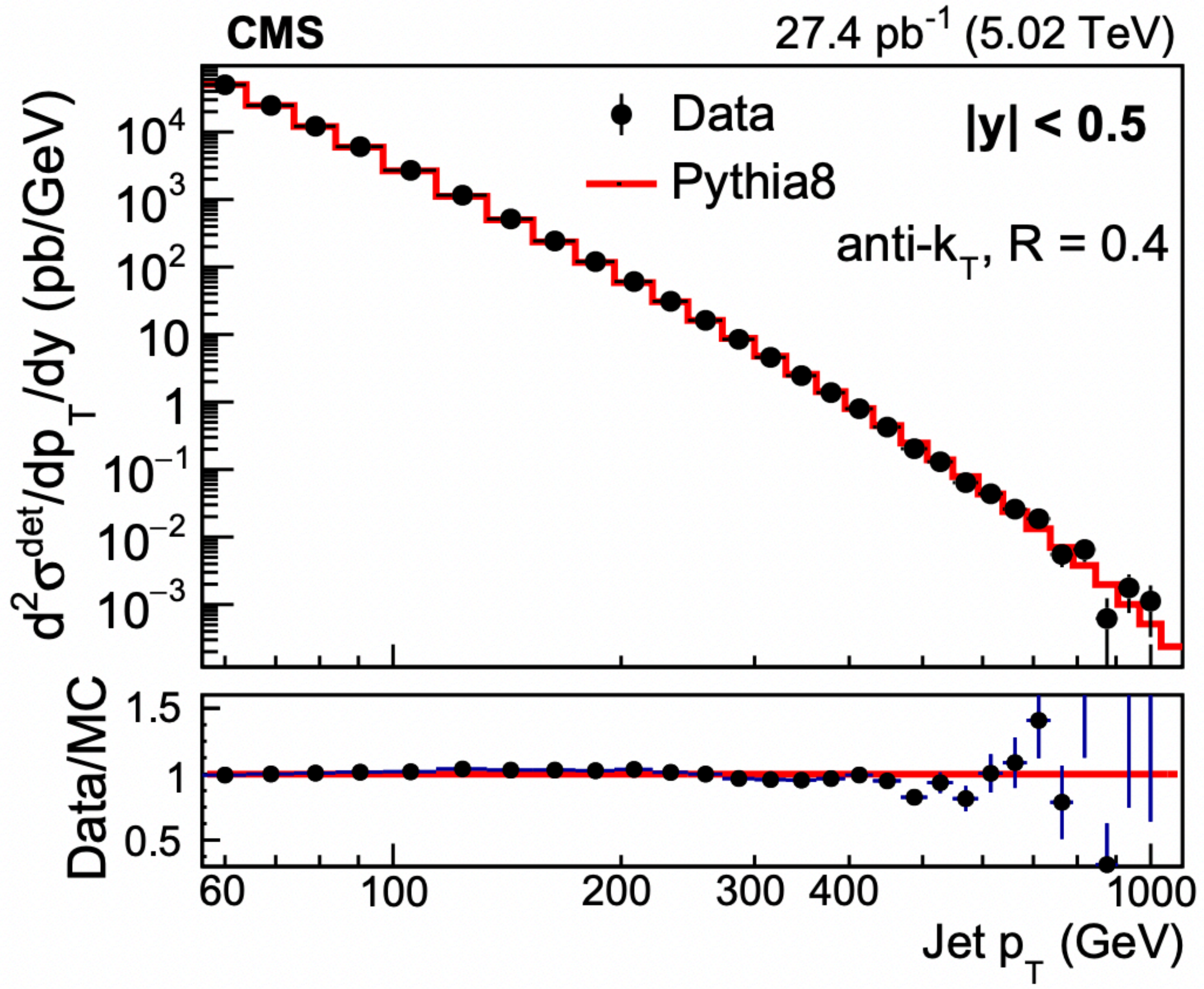

How many jets with a recoiling photon would we have?

*** Note, no experimental cuts considered for γ/Z, upper bound!**

15 million jets, $\approx$ 150,000 γ + jet events

[JHEP 07 (2020) 116]

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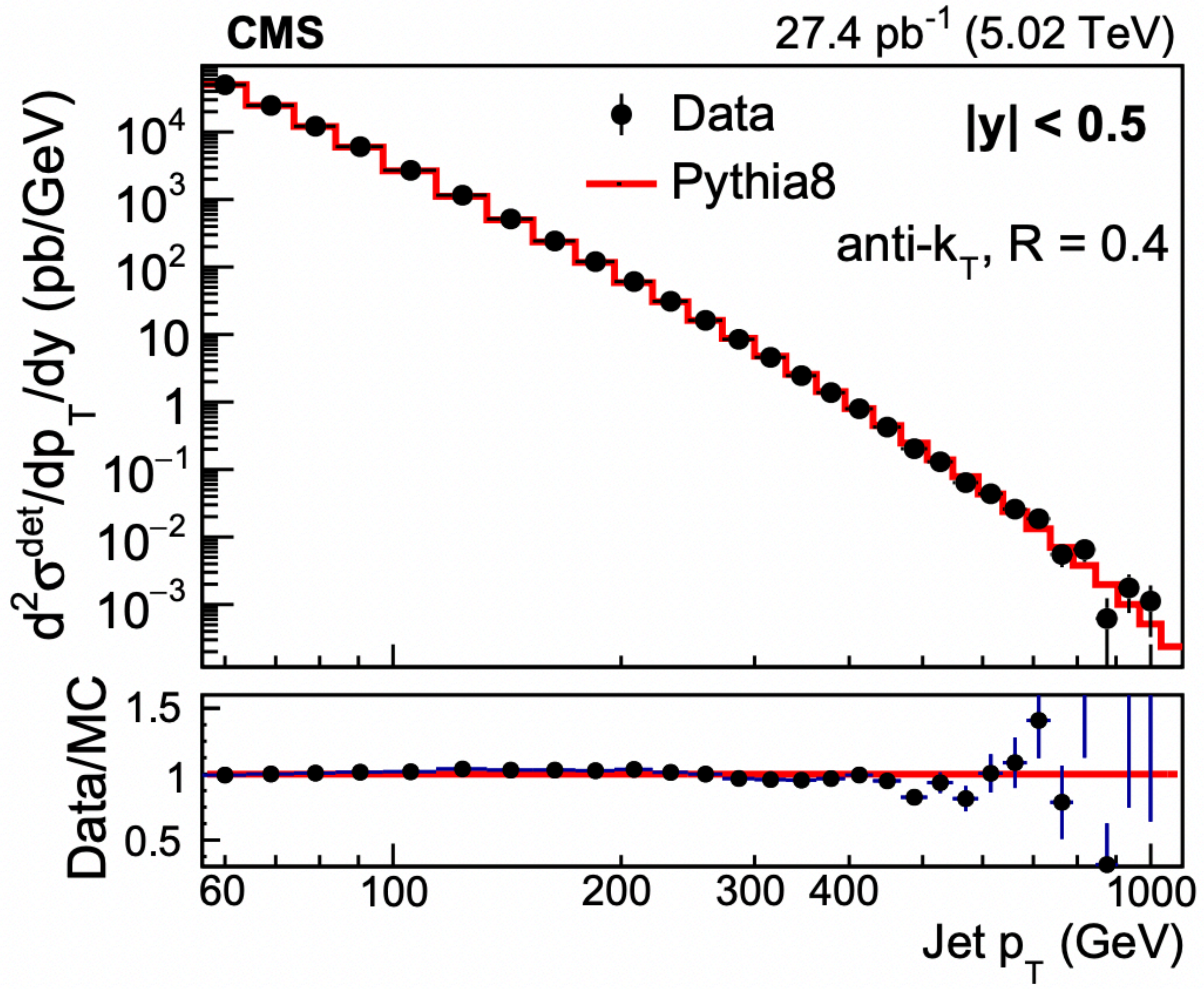
[PLB 759 (2016)641]

[JHEP 01 (2025) 011, 2025]



How many jets with a recoiling photon would we have?

*** Note, no experimental cuts considered for γ/Z, upper bound!**

15 million jets, ≈ 150,000 γ + jet events

[JHEP 07 (2020) 116]

How many jets with a recoiling Z boson would we have?

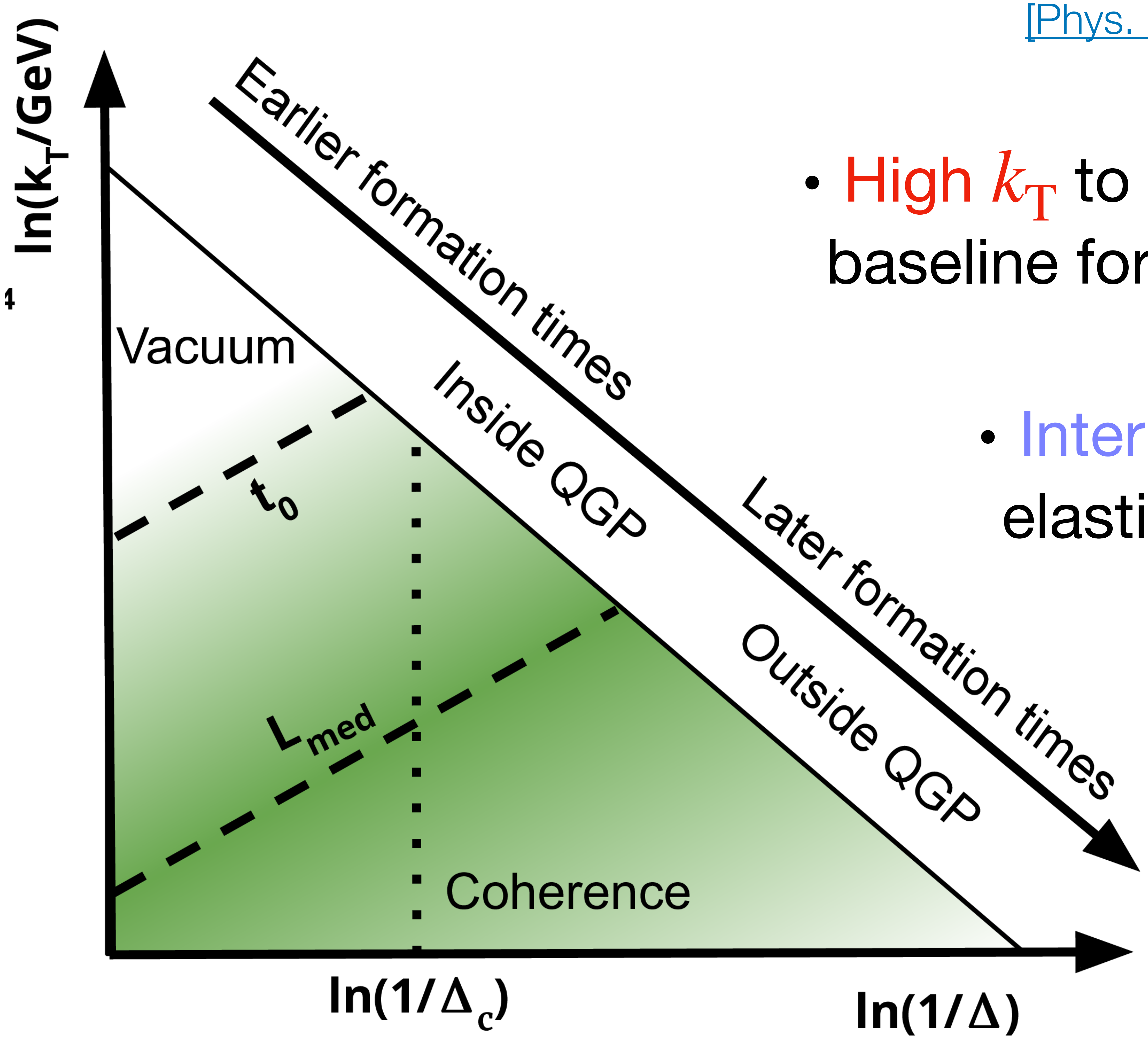
15 million jets, ≈ so 15,000 Z + jet events

[JHEP 04 (2025) 162]

ISOLATING PERTURBATIVE SCALES

- Exploit the high p_T reach and statistics to enable isolation of perturbative from medium scales using targeted differential measurements of jet substructure w/ Lund Plane.

[Phys. Rev. D 110, 014015 (2024)] [See Mateusz's Talk this week for more]



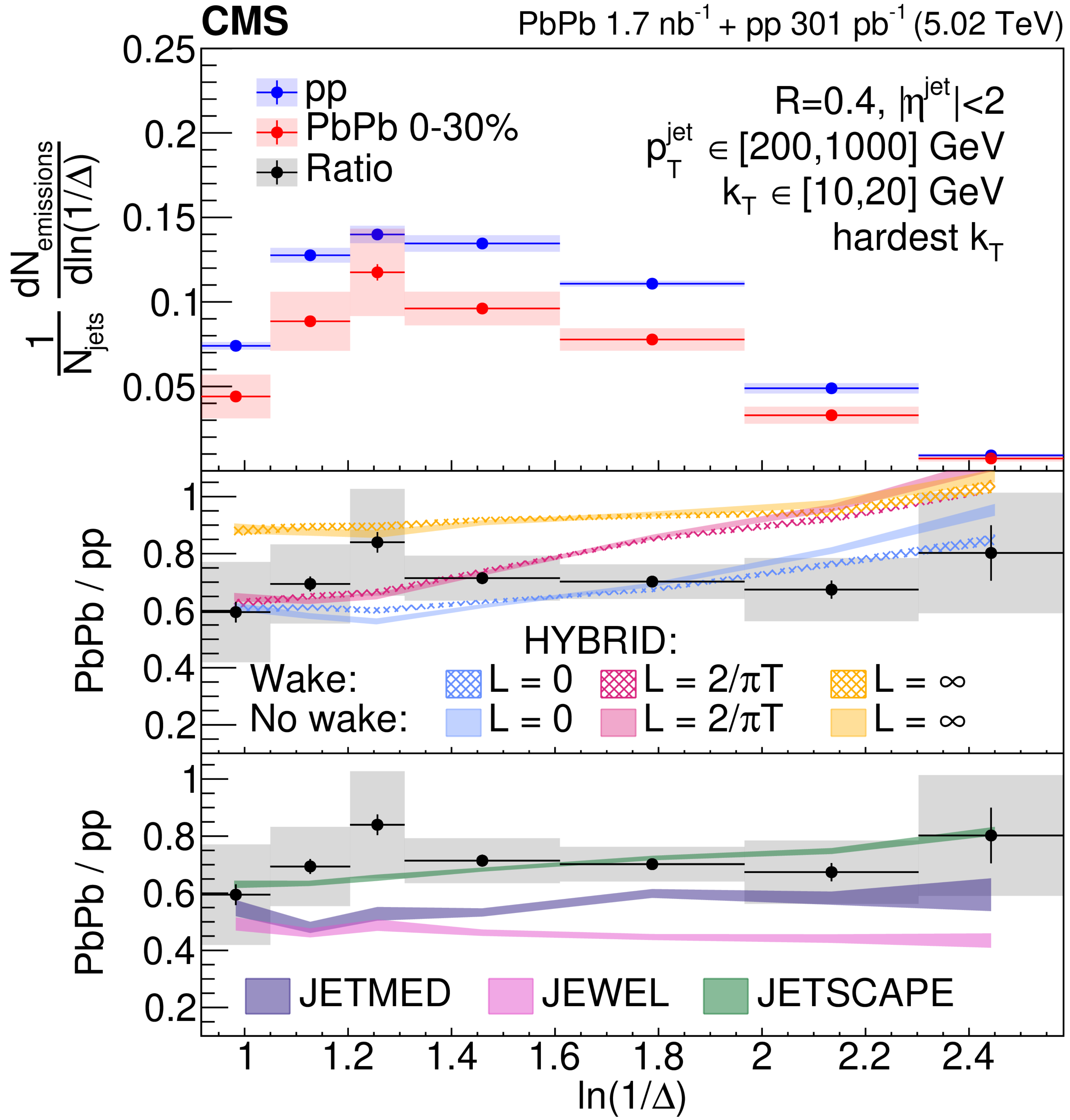
- High k_T to isolate vacuum-like splittings creating a new baseline for heavy-ion collisions.

- Intermediate k_T to explore color resolution scale or elastic scatterings

- Low k_T to explore non-perturbative region and the medium response

ISOLATING PERTURBATIVE SCALES

- CMS has measured focusing on hardest k_{T} for jets with $200 < p_{\mathrm{T}}^{\mathrm{jet}} < 1000$ GeV



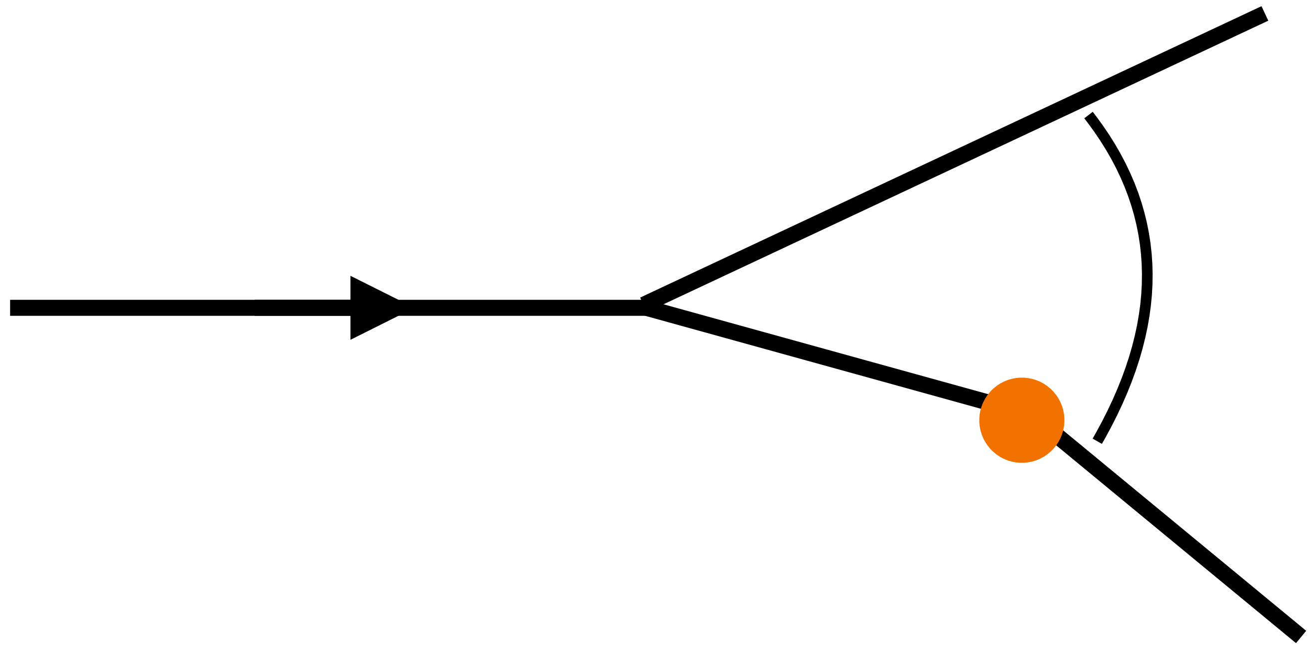
[HIN-24-016, arXiv:2602.09271 Submitted to PRL]

- 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)]

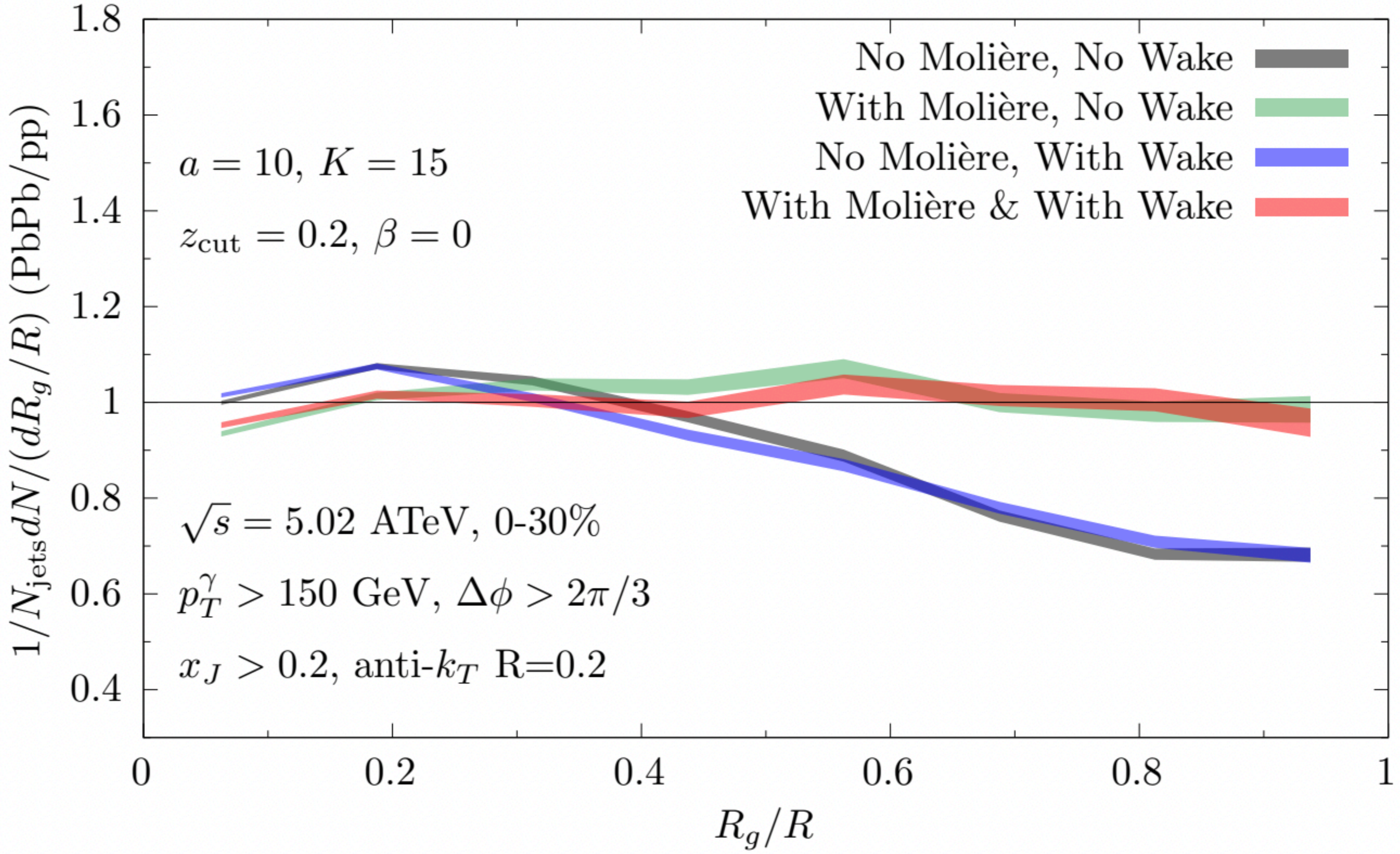
With new data, can explore other parts of phase space in more detail, extend to higher p_{T}, *R*-scan…

ISOLATING QUASIPARTICLE STRUCTURE OF QGP

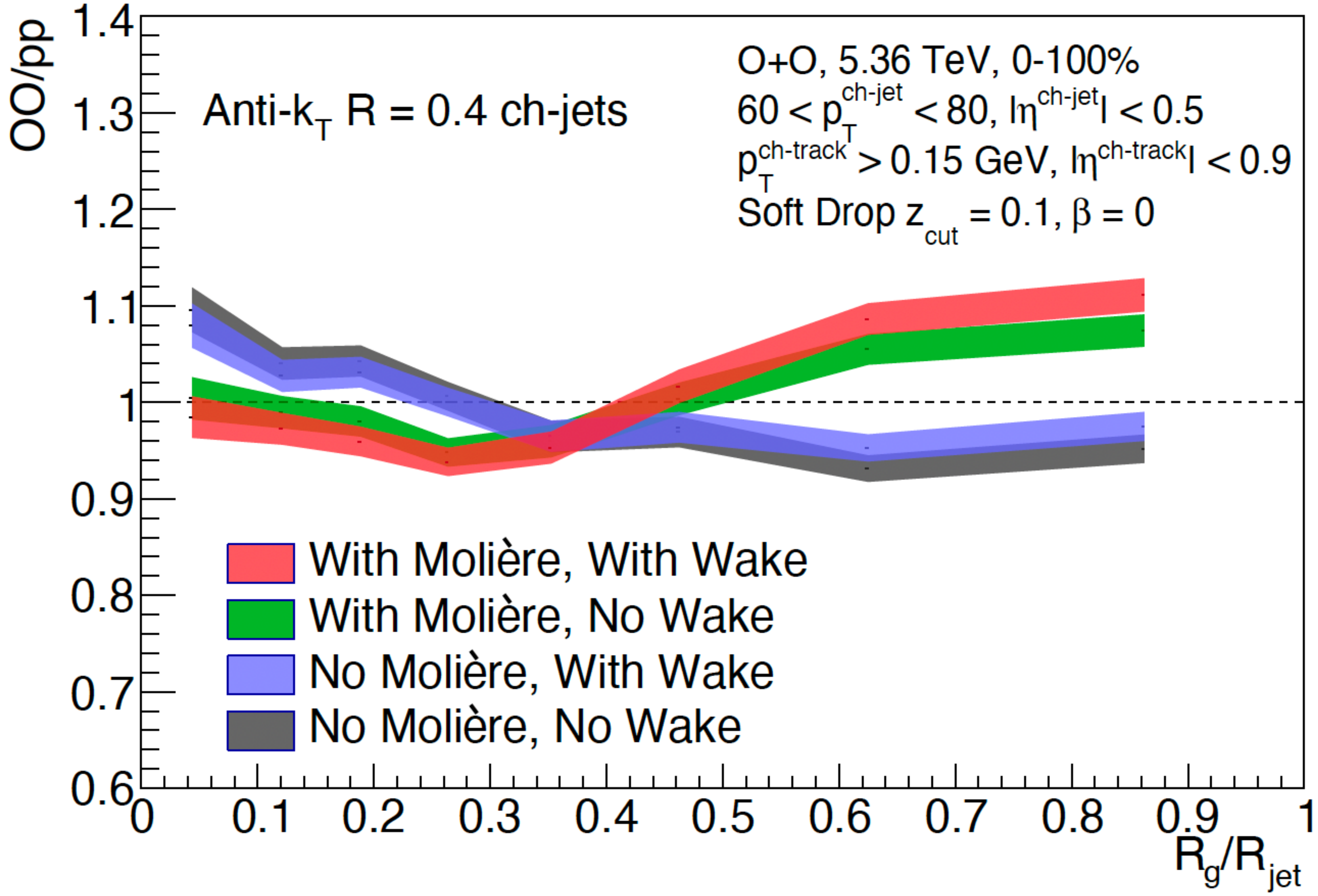


- Parton traversing QGP can undergo 2 → 2 Molière scatterings off of medium quasiparticles.
  - Jets are ideal probes of quasi-particle structure of QGP.

[Hulcher et. al arXiv:2603.08776]



[Arjun Kudinoor's Talk, light ion workshop]



- Recent calculations indicate γ + jet and OO are good places to look!

Hannah Bossi (hannah.bossi@cern.ch)

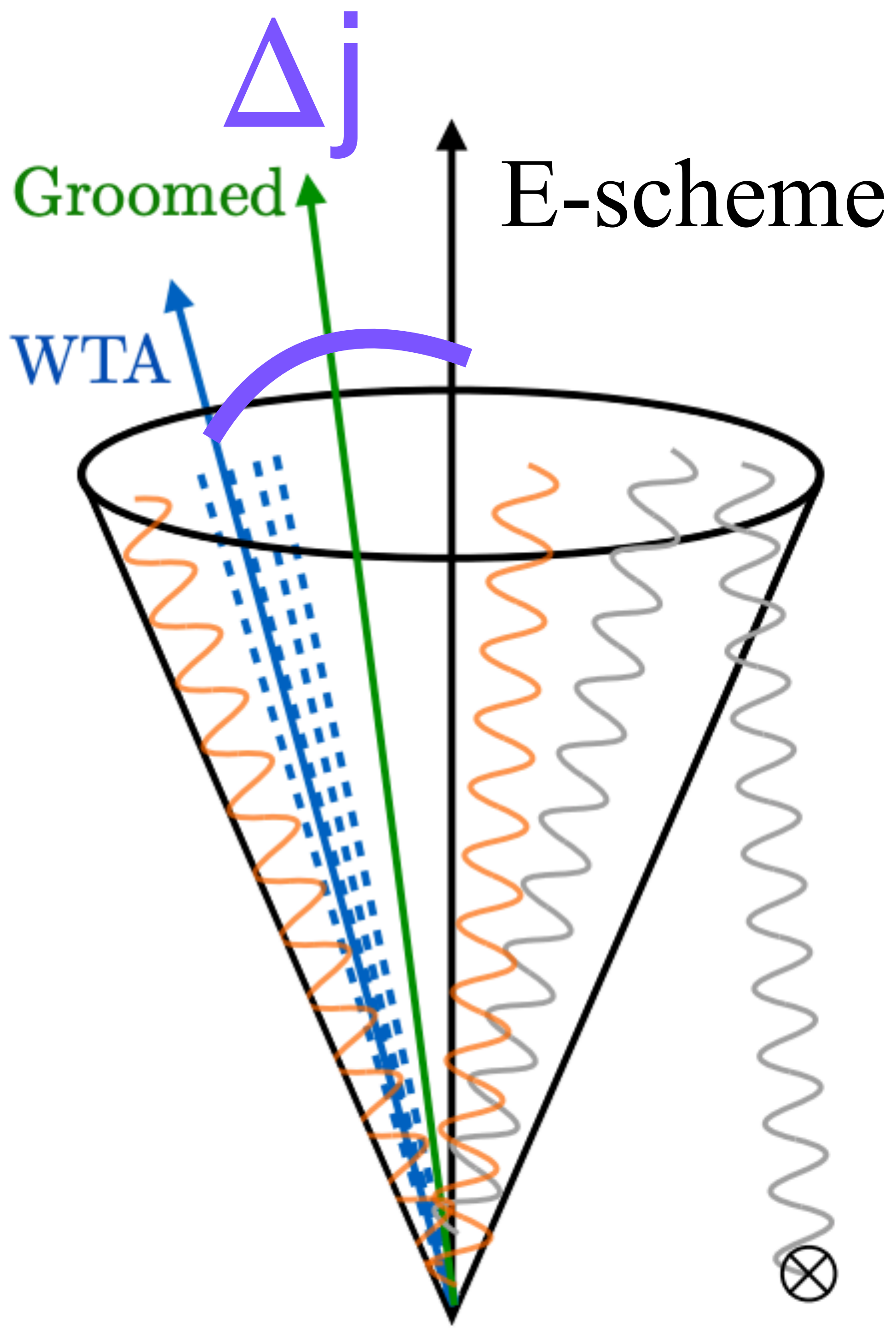
ISOLATING THE MASS DEPENDENCE

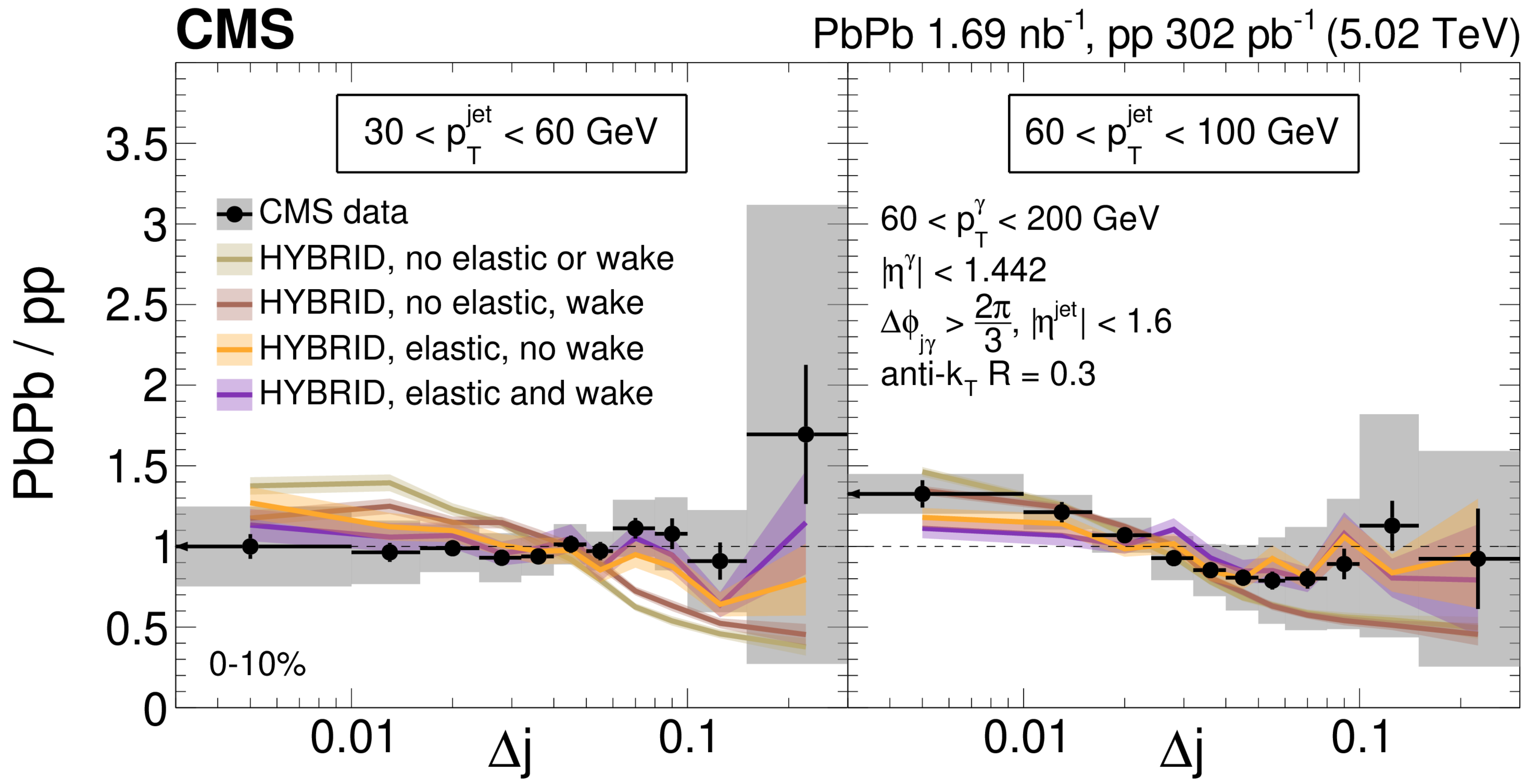
- Want to isolate how the mass of the initiating parton impacts jet modification.
  - Lots to explore here! One candidate: jet axis decorrelation.

$$\Delta j = \sqrt{(\eta^{\mathrm{E-scheme}} - \eta^{\mathrm{WTA}})^2 + (\phi^{\mathrm{E-scheme}} - \phi^{\mathrm{WTA}})^2}$$

- CMS has measured already with inclusive jets and with γ-tagged jets [HIN-21-019, arXiv:2602.18279, submitted to PLB]

[JHEP 06 (2025) 120]



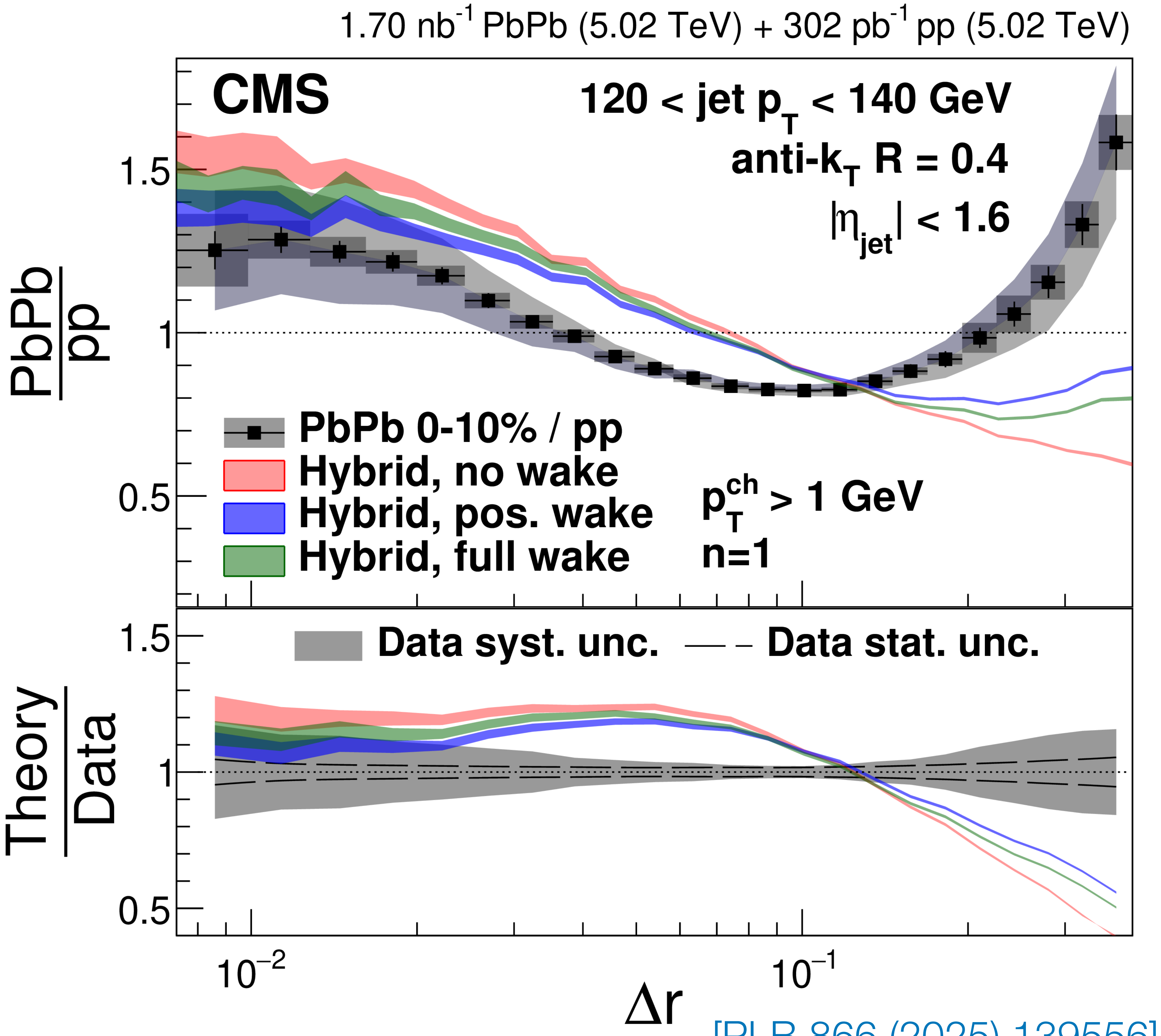


- Very doable to repeat this with heavy-flavor tagged jets.

Many more topics: HF-Jet R_{AA}, X(3872), HF-tagged EECs, ….

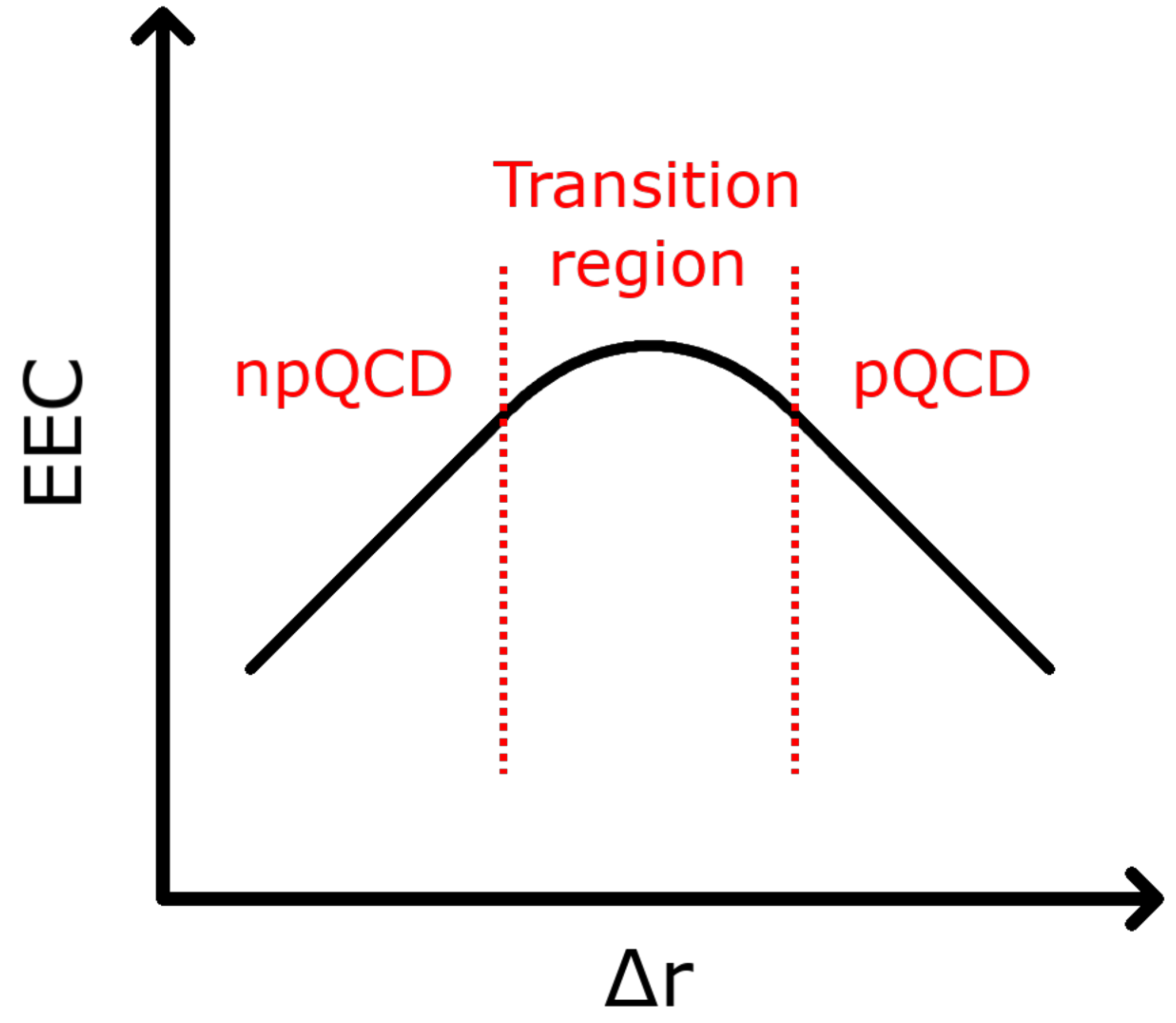
PROBE THE TRANSITIONS BETWEEN REGIMES W/ EECS

- Key part in how the various pieces work together is understanding the behavior of the ***transition region*** between different regimes.



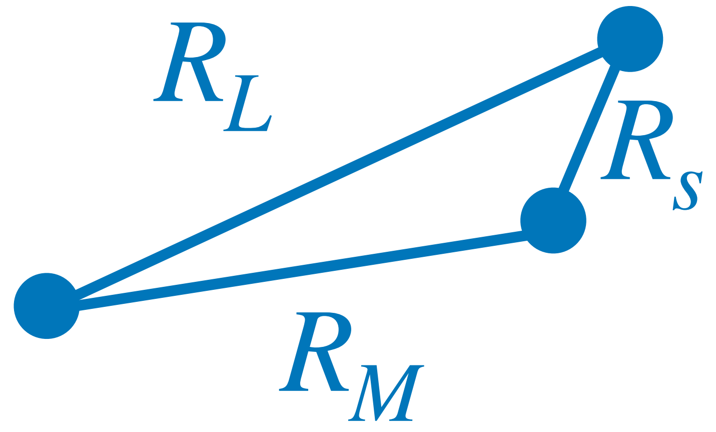
[PLB 866 (2025) 139556]

- ***Energy correlators*** separate scales in a way that is ideal to probe transition regions.

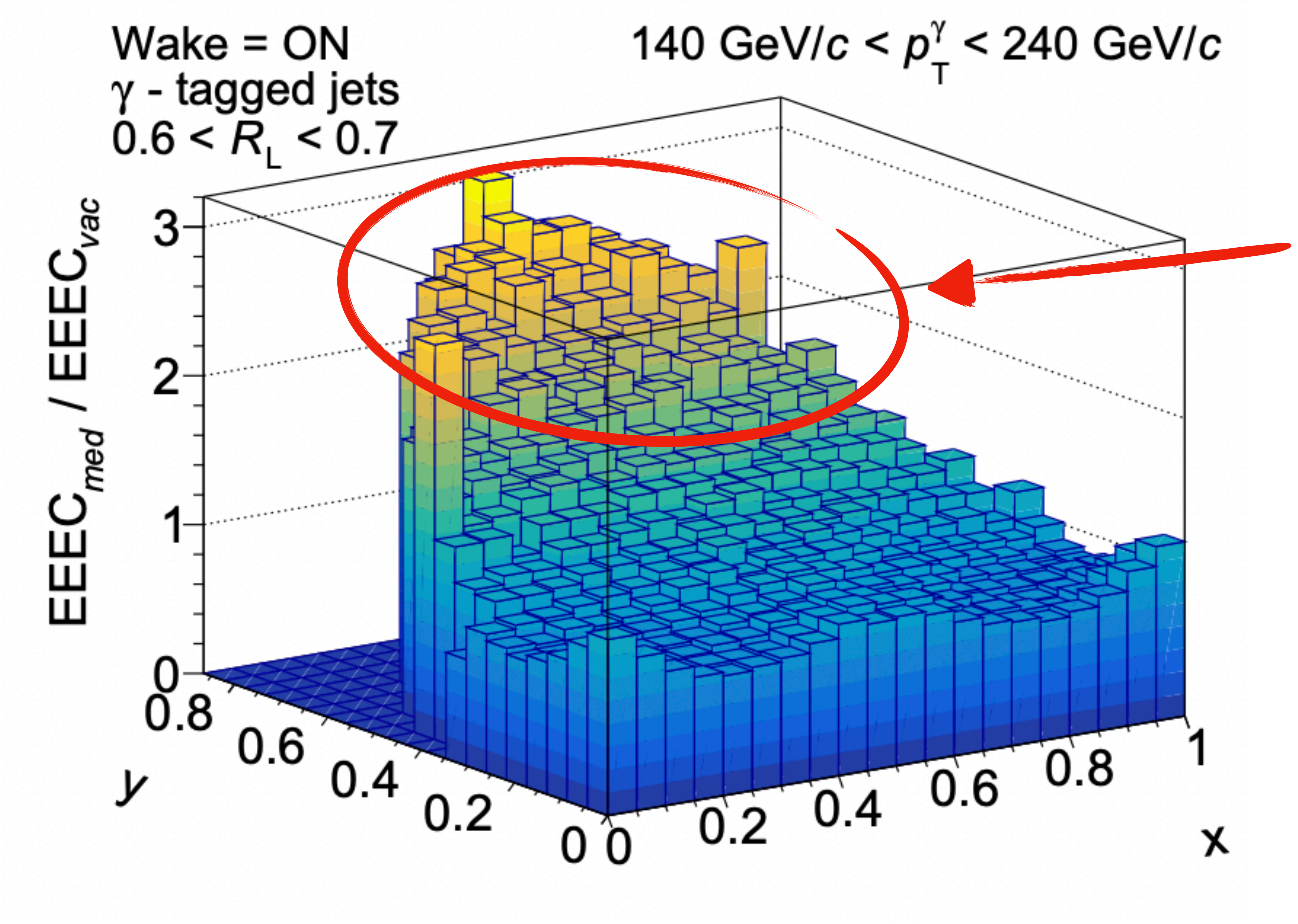


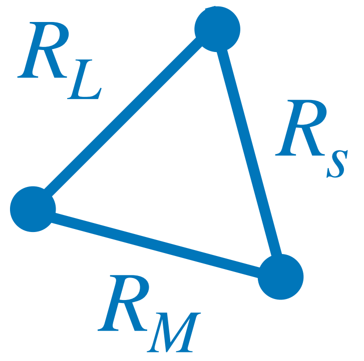
- Should explore more differential measurements of the energy correlator!
  - ex: higher point correlators, full event correlators, correlators of identified particles, …

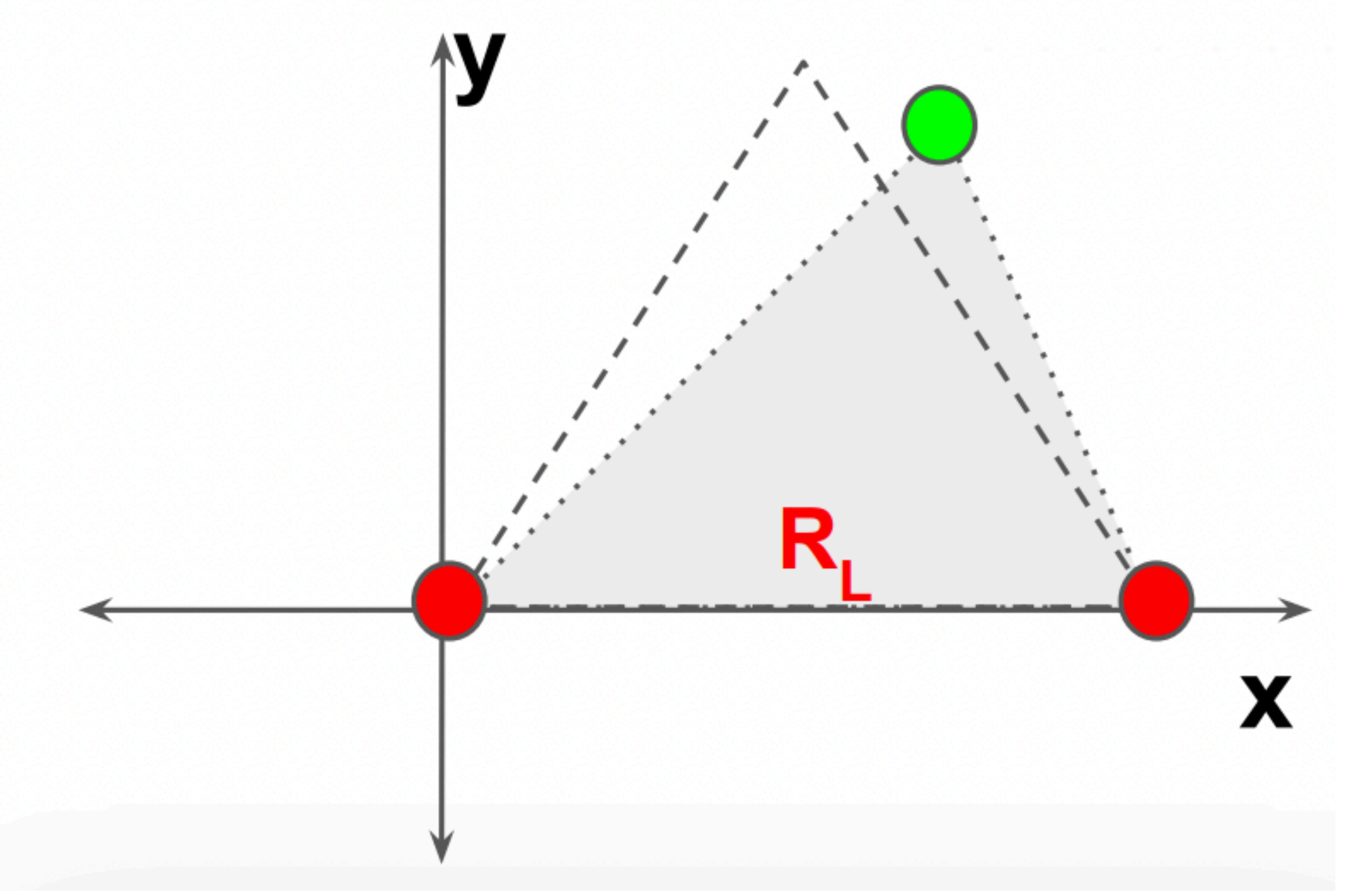
UNDERLYING DYNAMICS OF QCD



- Projected correlator allows for the study of *angular scaling* behavior.
  - Useful, but tell you nothing about the dynamics themselves!
    - **For this you need the full shape-dependent energy correlators.**







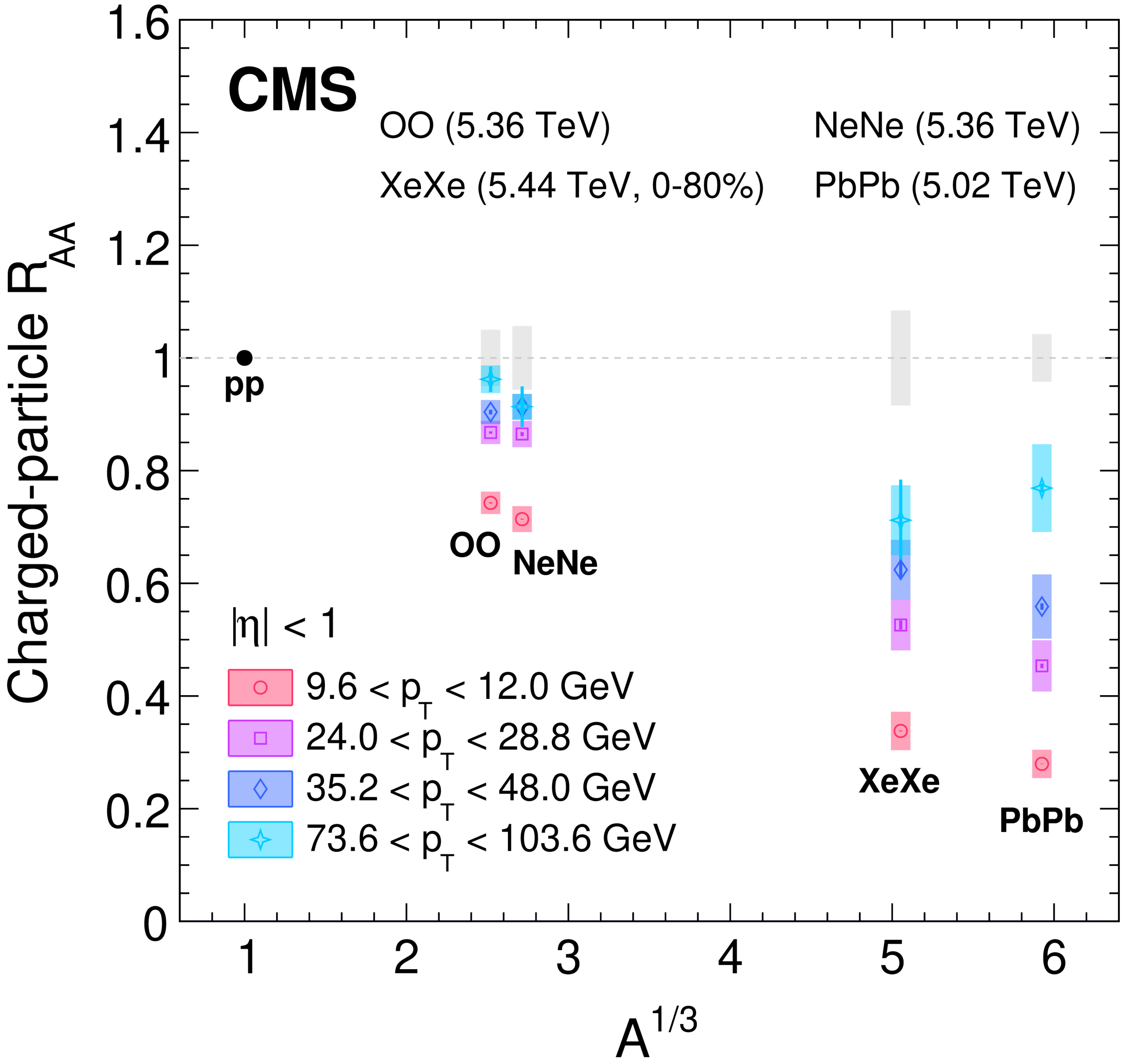
- $\gamma +$ jet is a significantly cleaner signature
  - Removal of selection bias, removing effect of superposition of wakes.

[JHEP 12 (2024) 073]

HOW DO JET QUENCHING EFFECTS SCALE W/SIZE

- **To understand how various pieces fit together, need to know how they scale with system size → light-ion data very useful for this!**

[arXiv:2602.21325, Submitted to PLB]



- Current data is indicative of measurable energy loss signatures w/ minimal background.

[ALICE, light ion workshop]
[ATLAS, ATLAS-CONF-2025-010]
[CMS, arXiv:2510.09864]

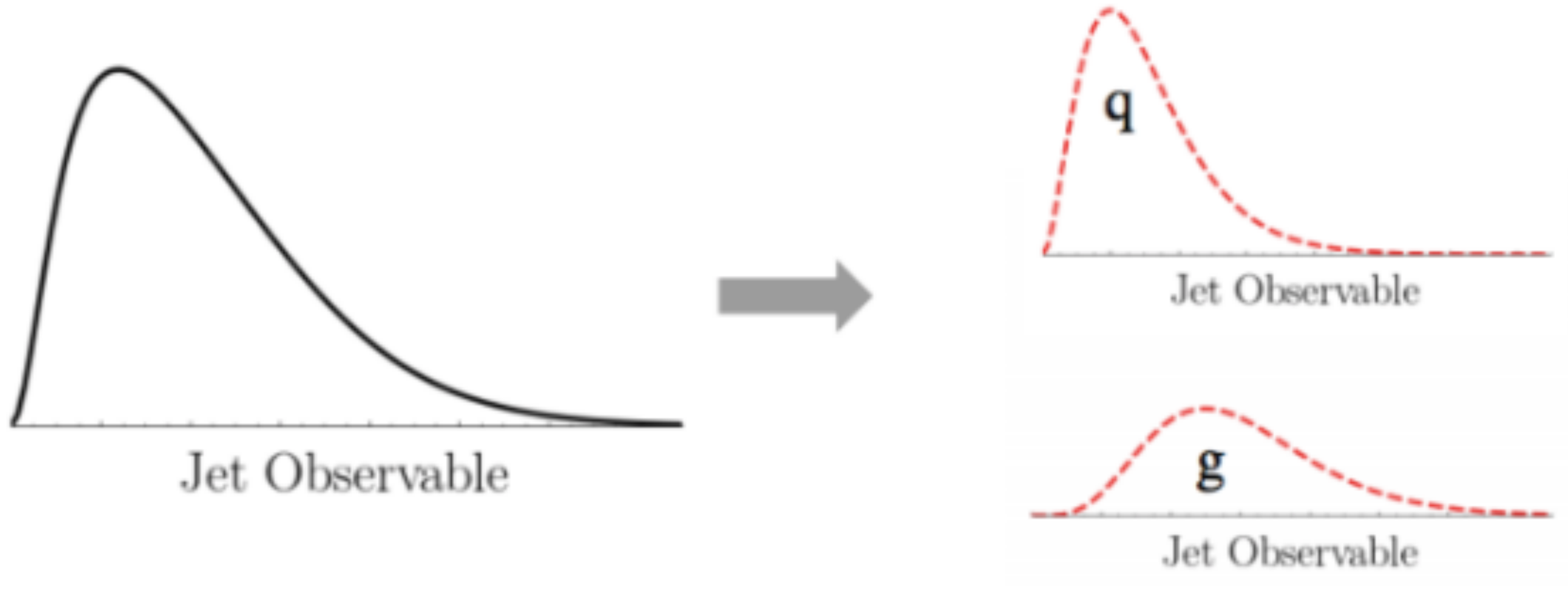
- Other jet quenching signatures like substructure modification and medium response, yet to be explored.

Lots left to learn from this data! Just the beginning!

DATA-DRIVEN REMOVAL OF SELECTION BIAS

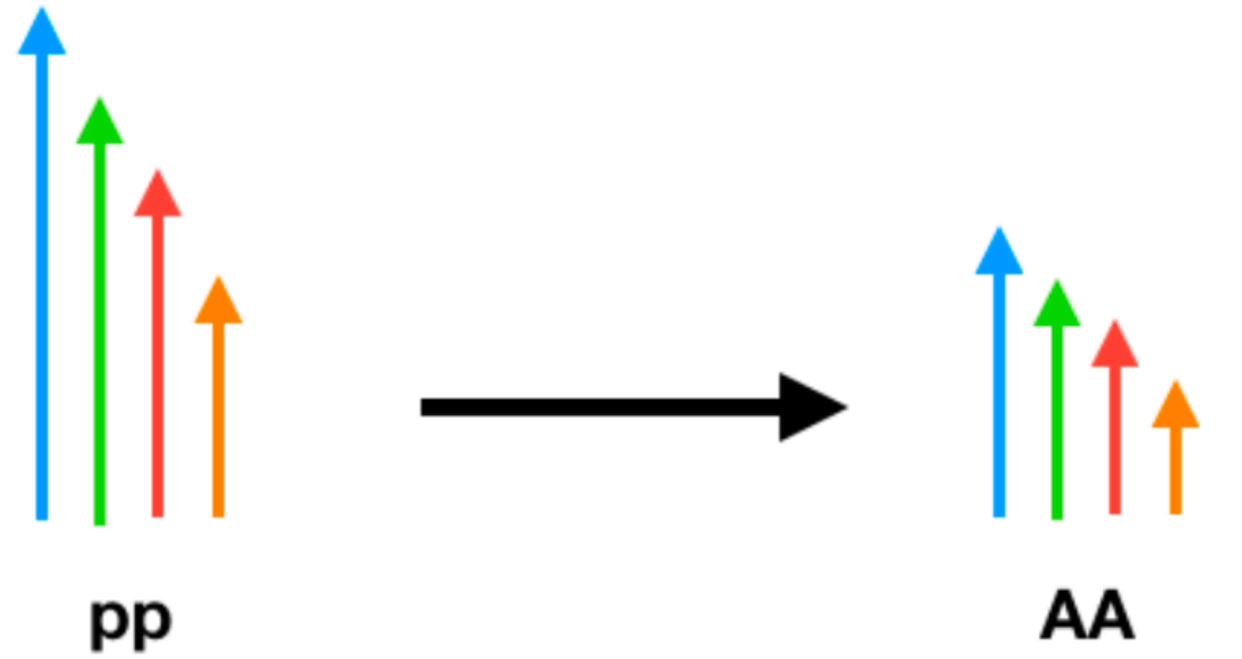
- With availability of large datasets, data-driven methods to remove the selection bias are becoming experimentally more viable.

- **Method 1: Topic Modeling**
  - Decompose jet sample into topics of jets that lose different amounts of energy.

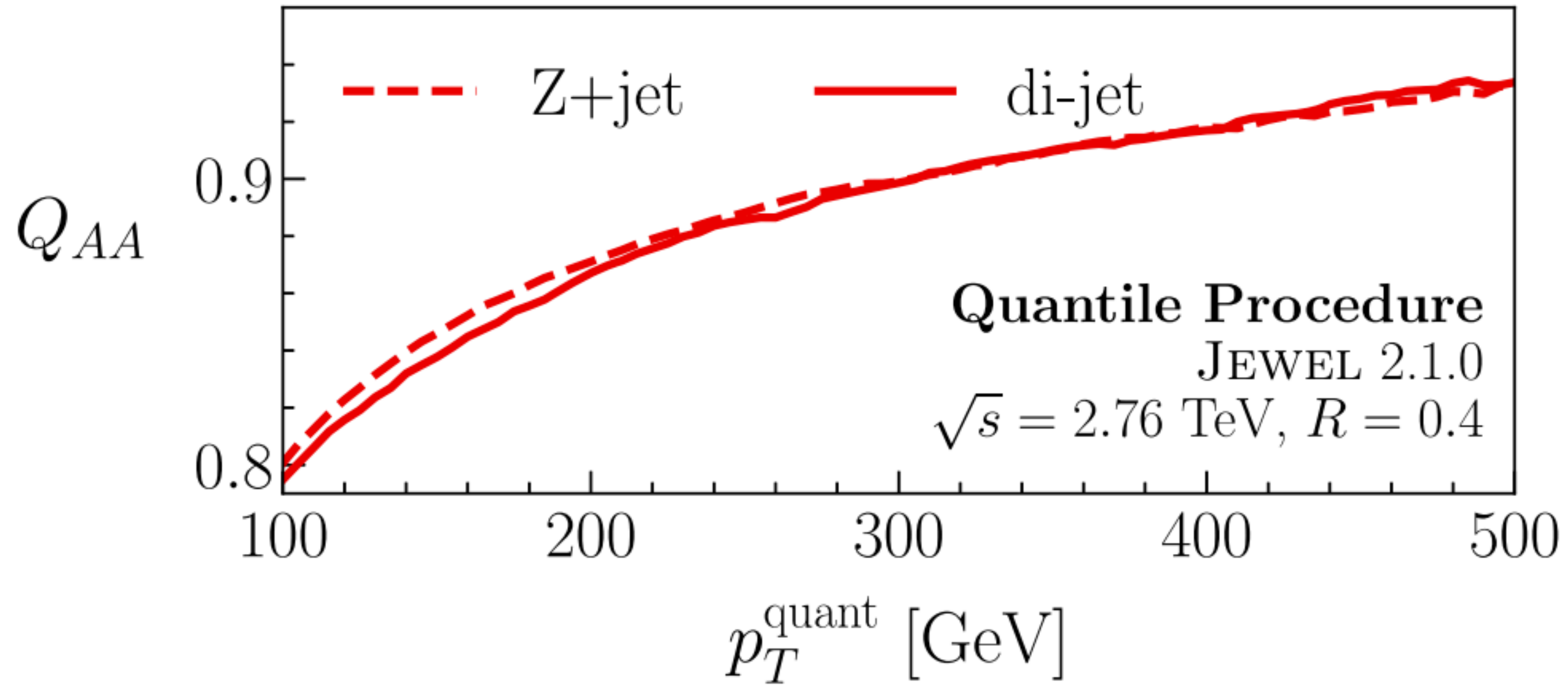


[Ying, Brewer, Chen, Lee CERN-TH-2022-057]

- **Method 2: Quantile Analysis**



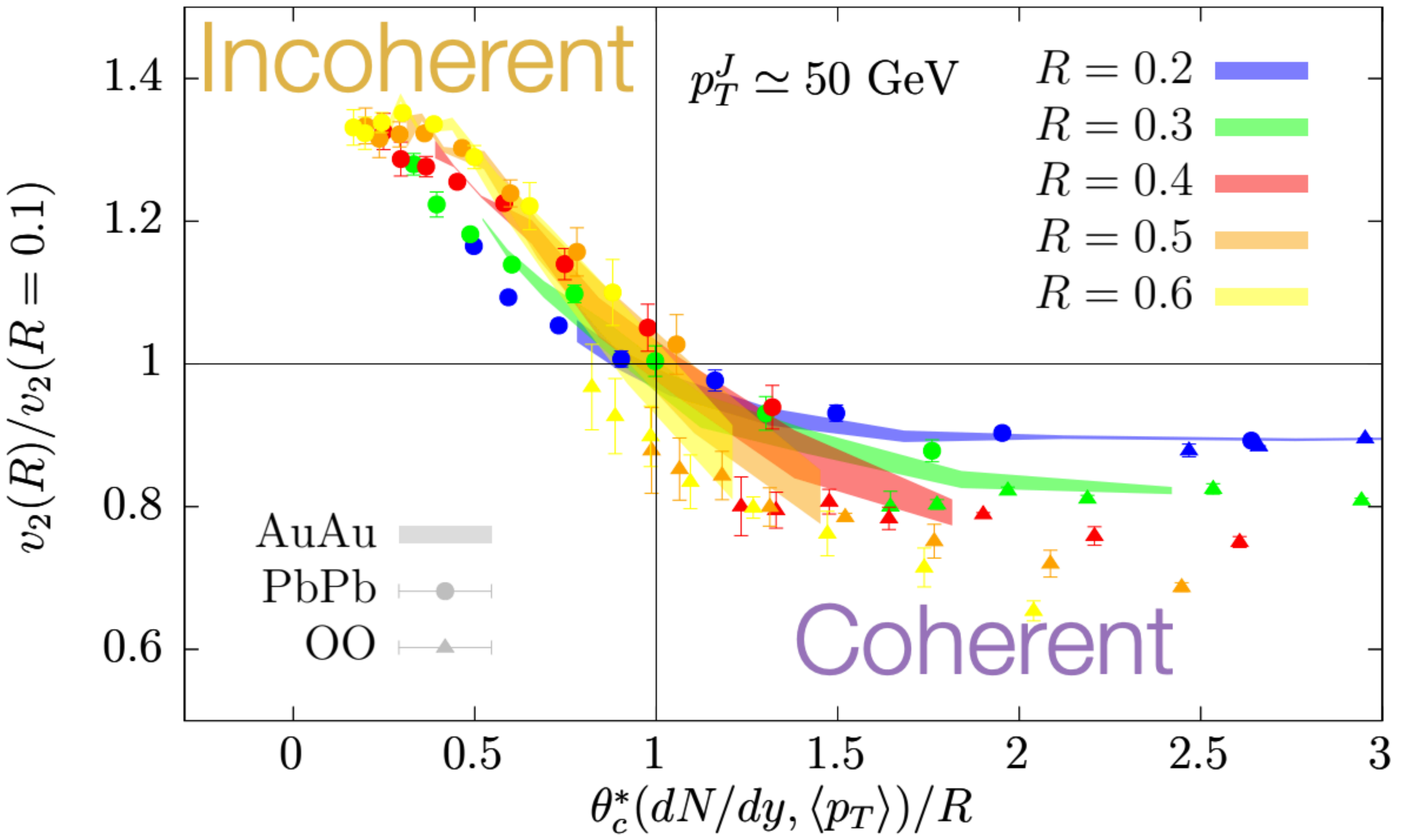
  - Statistical treatment relying on monotonic energy loss.



Brewer, Milhano, Thaler PRL 122 222301 (2019)

R-DEPENDENT V2

- Oxygen is the only species to be run at both RHIC and the LHC.
  - Unique opportunity to answer why R_{AA} and v_2 look remarkably similar despite drastically different mediums.



- Jet v_2 double ratios (wrt R = 0.1) as a function of the angle normalized by R.
- Crossing point of double ratio with unity allows for experimental extraction of coherence angle.
- Pros: Experimentally (relatively) easy (info visible without going to large R), extraction of coherence angle that is not model-dependent.

- Challenge: Need at least a few R, more reliable once baseline measurements established.

[Talk by Alba Soto-Ontoso] [Backup slide from talk by Adam Takacs]

ANALYSIS METHOD FOR DIJET WAKES

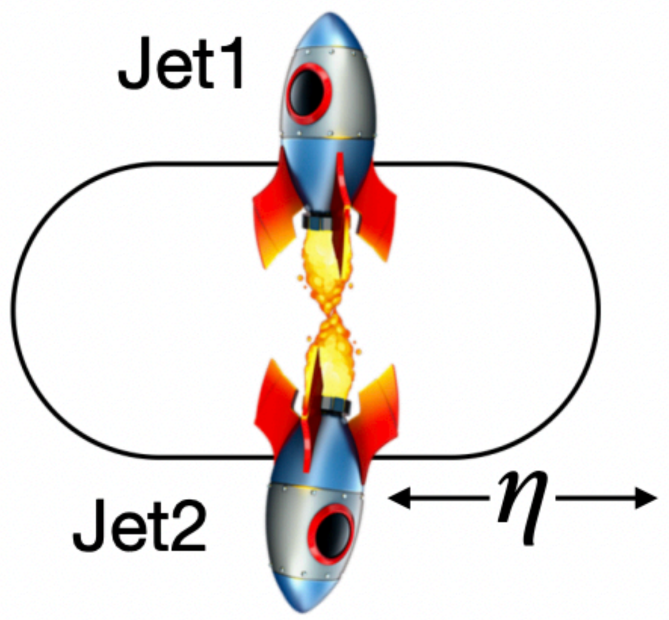
[HIN-25-012, arXiv:2602.19431]

We used the existing and well-established jet—track correlation method:

$$\frac{1}{\mathrm{N_{dijet}}}\frac{\mathrm{d^2N_{corr}}}{\mathrm{d}\Delta\eta\ \mathrm{d}\Delta\phi} = \frac{1}{\mathrm{N_{dijet}}}\frac{\mathrm{d^2N_{sig}}}{\mathrm{d}\Delta\eta\ \mathrm{d}\Delta\phi}\left[\frac{\mathrm{ME}(\Delta\eta=0,\ \Delta\phi=0)}{\frac{1}{\mathrm{N_{dijet}}}\frac{\mathrm{d^2N_{mix}}}{\mathrm{d}\Delta\eta\ \mathrm{d}\Delta\phi}}\right]$$

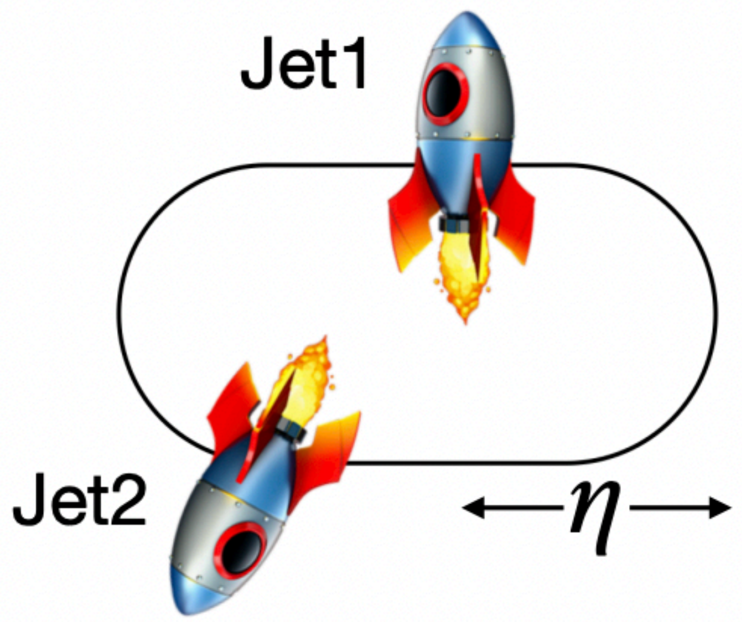
Measured correlation for two configurations:

Denoted as $\mathrm{R^{sym.}}$



$|\Delta\eta(\mathrm{Ld.\ jet,\ Sub\ Ld.\ jet})|\ < 0.5$

(small gap, symmetric)



Denoted as $\mathrm{R^{asym.}}$

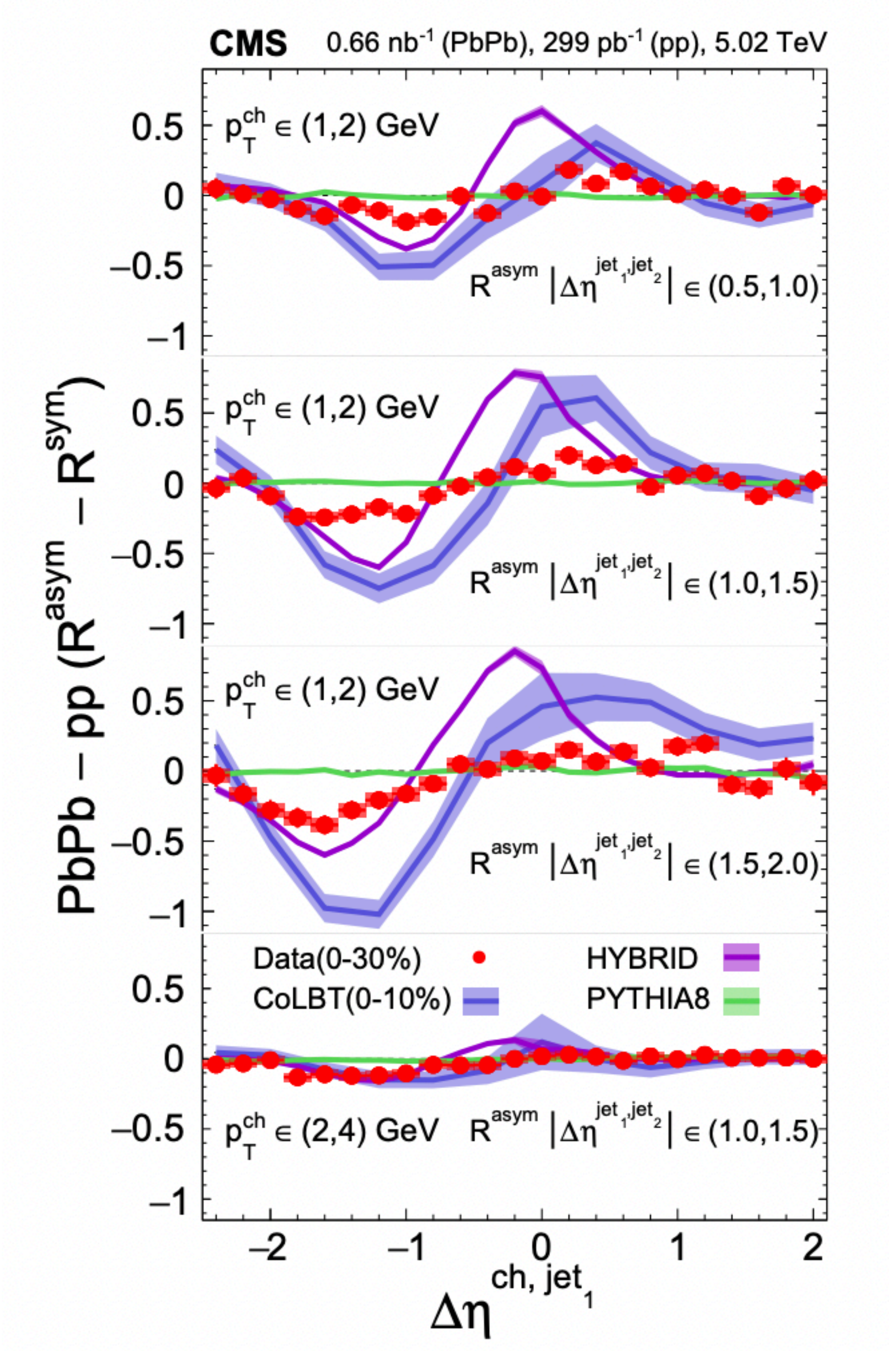
$|\Delta\eta(\mathrm{Ld.\ jet,\ Sub\ Ld.\ jet})|\ \in (1.0,1.5)$

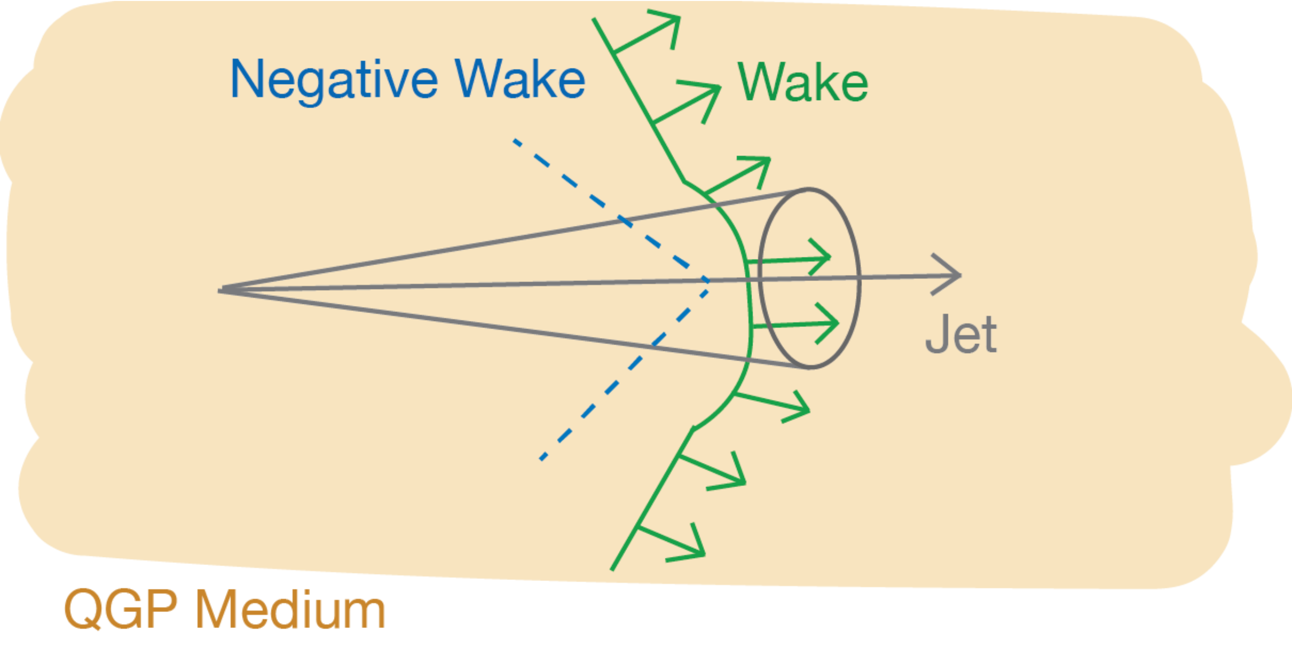
(large gap, asymmetric)

- Symmteric and asymmetric configurations should have similar UE level as the leading jet $|\eta^{\mathrm{jet}}| < 1.0$
- Subtract the symmetric case from the asymmetric case to search for the wake effect (depletion in the subtracted correlation)

MODEL COMPARISONS FOR DIJET WAKES

[HIN-25-012, arXiv:2602.19431]

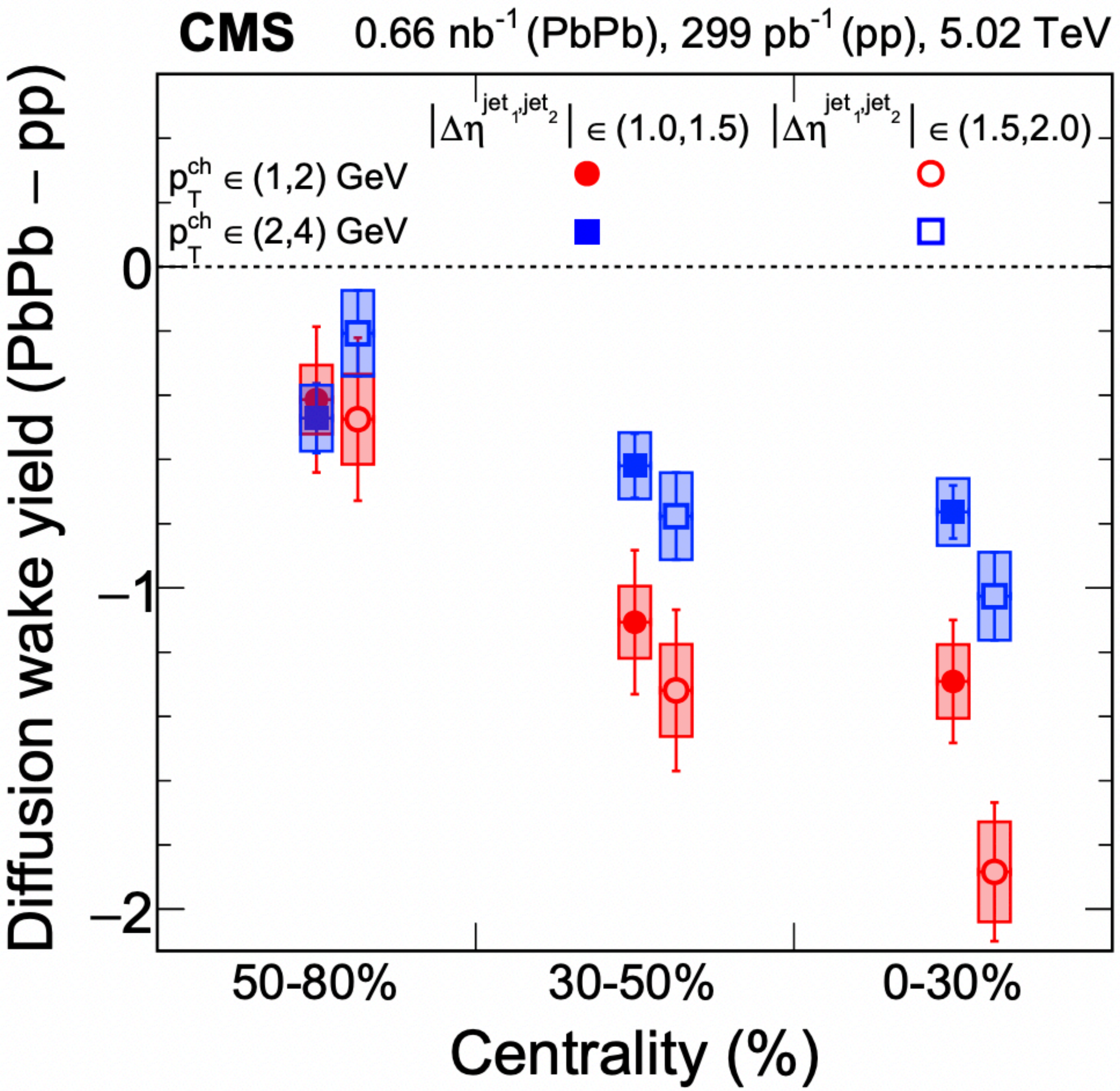




- Models predict negative wake signature to be larger than what is seen in data.

SUMMARY OF DIJET WAKE YIELD

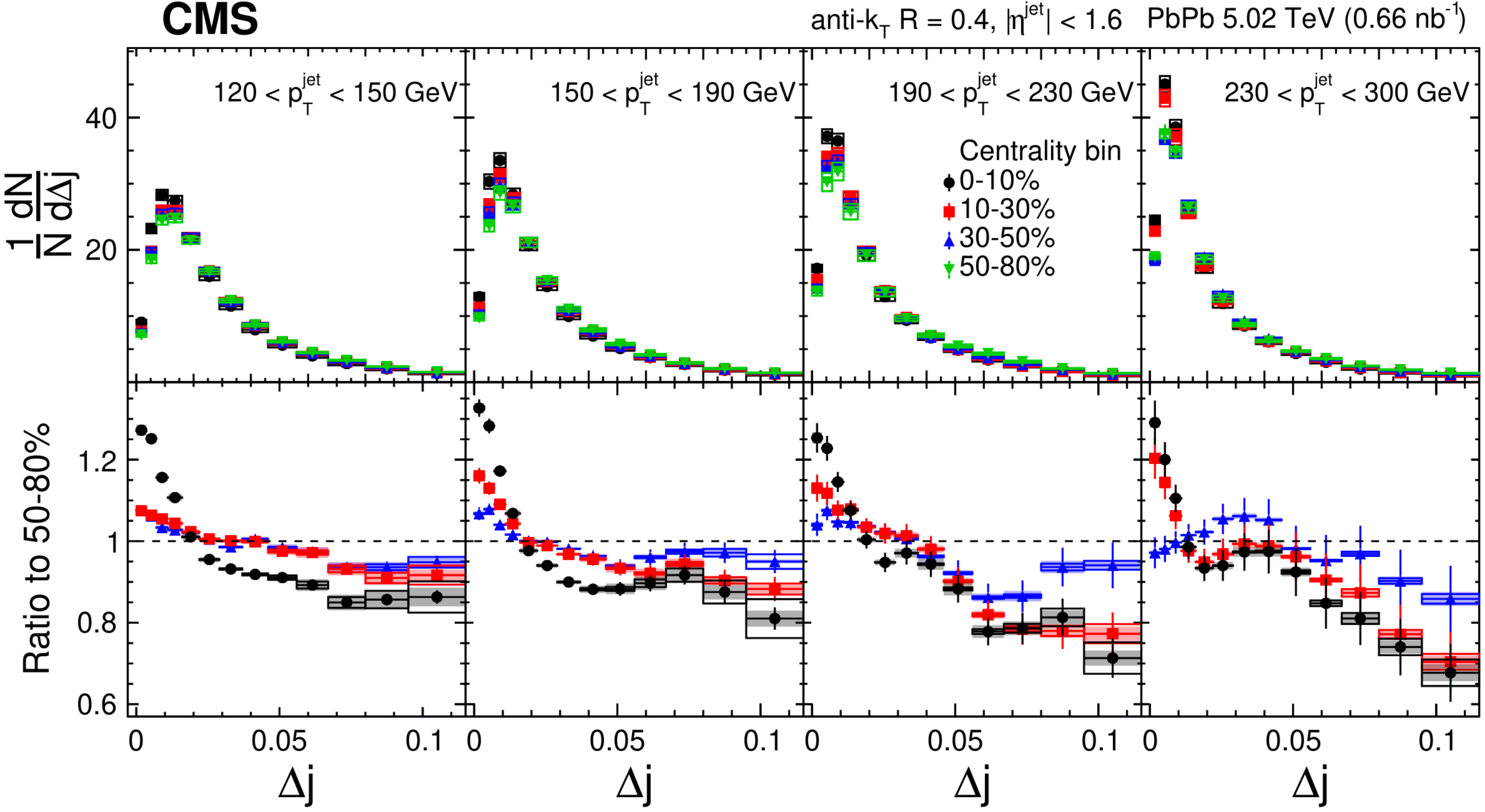
[HIN-25-012, arXiv:2602.19431]



INCLUSIVE JET AXIS DECORRELATIONS

[JHEP 06 (2025) 120]

Increasing p_T^{jet}



- Compare most central to most peripheral bin to get an idea of quenching effects.
- Narrowing observed in all measured p_T^{jet} bins, most significant in 0-10% centrality.

- Qualitatively consistent w/ ALICE measurement [arXiv:2303.13347]

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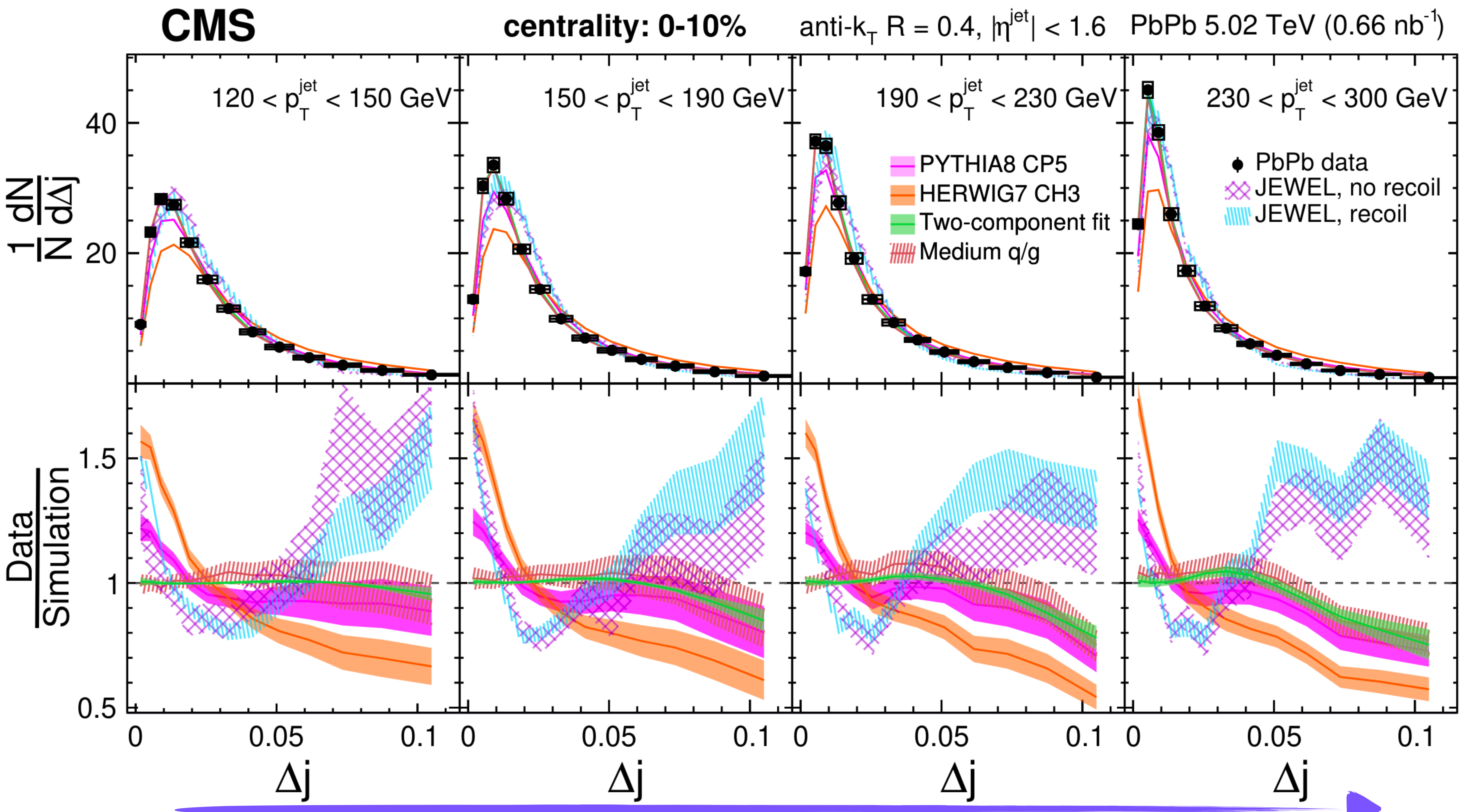
Hannah Bossi (hannah.bossi@cern.ch)

MODEL COMPARISONS (0–10%)

[JHEP 06 (2025) 120]

- Compare with models differentially in p_T to investigate underlying mechanisms.

0-10%



Increasing $p_\mathrm{T}^{\mathrm{jet}}$

- PYTHIA 8 CP5: p_T-ordered shower, Lund string hadronization.

[Comput.Phys.Commun. 191 (2015) 159-177]

- HERWIG7 CH3: angular-ordered shower, cluster hadronization.

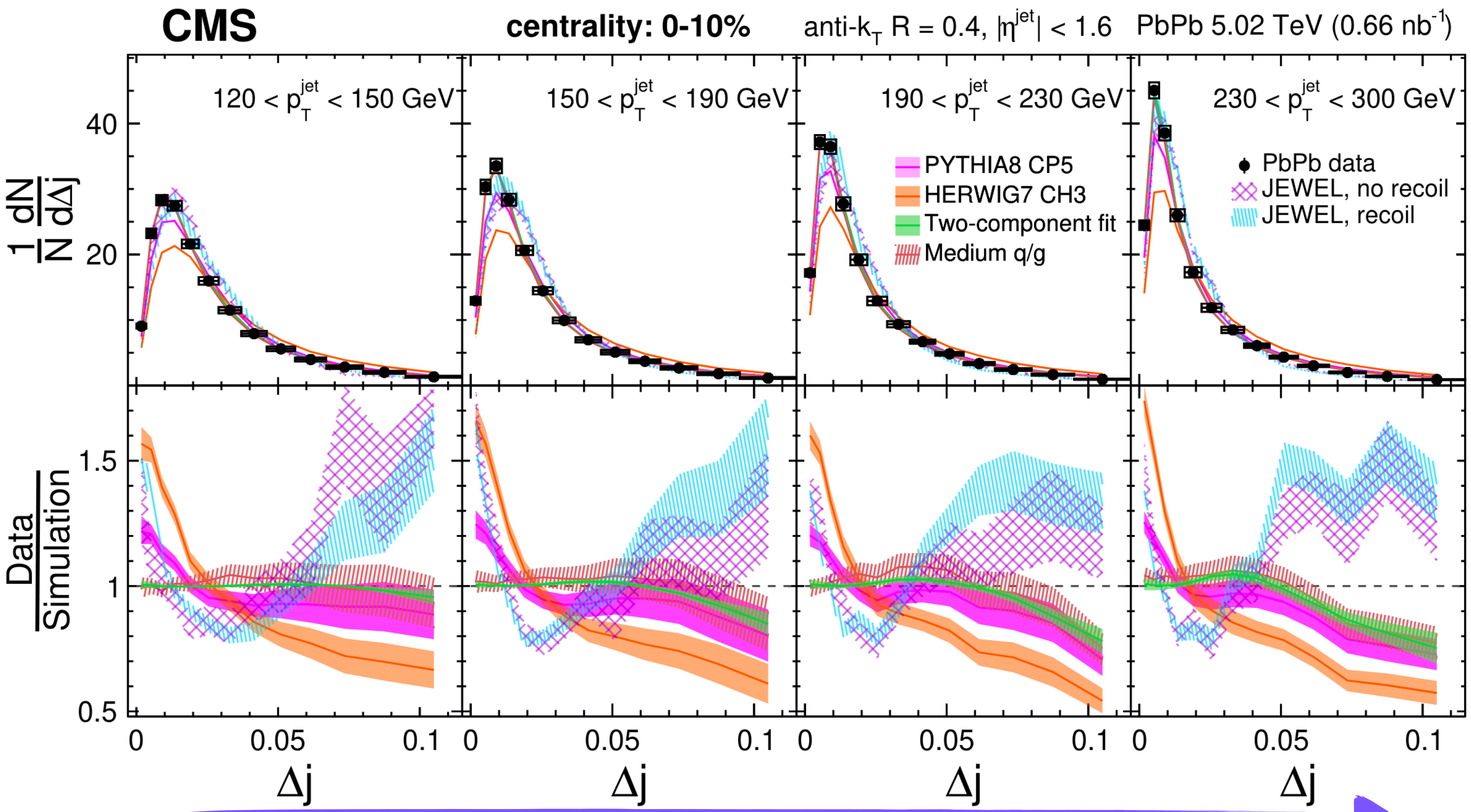
[Eur.Phys.J.C 76 (2016) 4, 196]

- Data inconsistent with no-quenching scenario.

MODEL COMPARISONS (0-10%)

[JHEP 06 (2025) 120]

- Compare with models differentially in p_{T} to investigate underlying mechanisms.



Increasing $p_{\mathrm{T}}^{\mathrm{jet}}$

0-10%

- JEWEL implements energy loss via weak coupling w/ collisional and radiative sources.

[JHEP 03 (2013) 080]

- Performed with and without recoils as a medium-response.

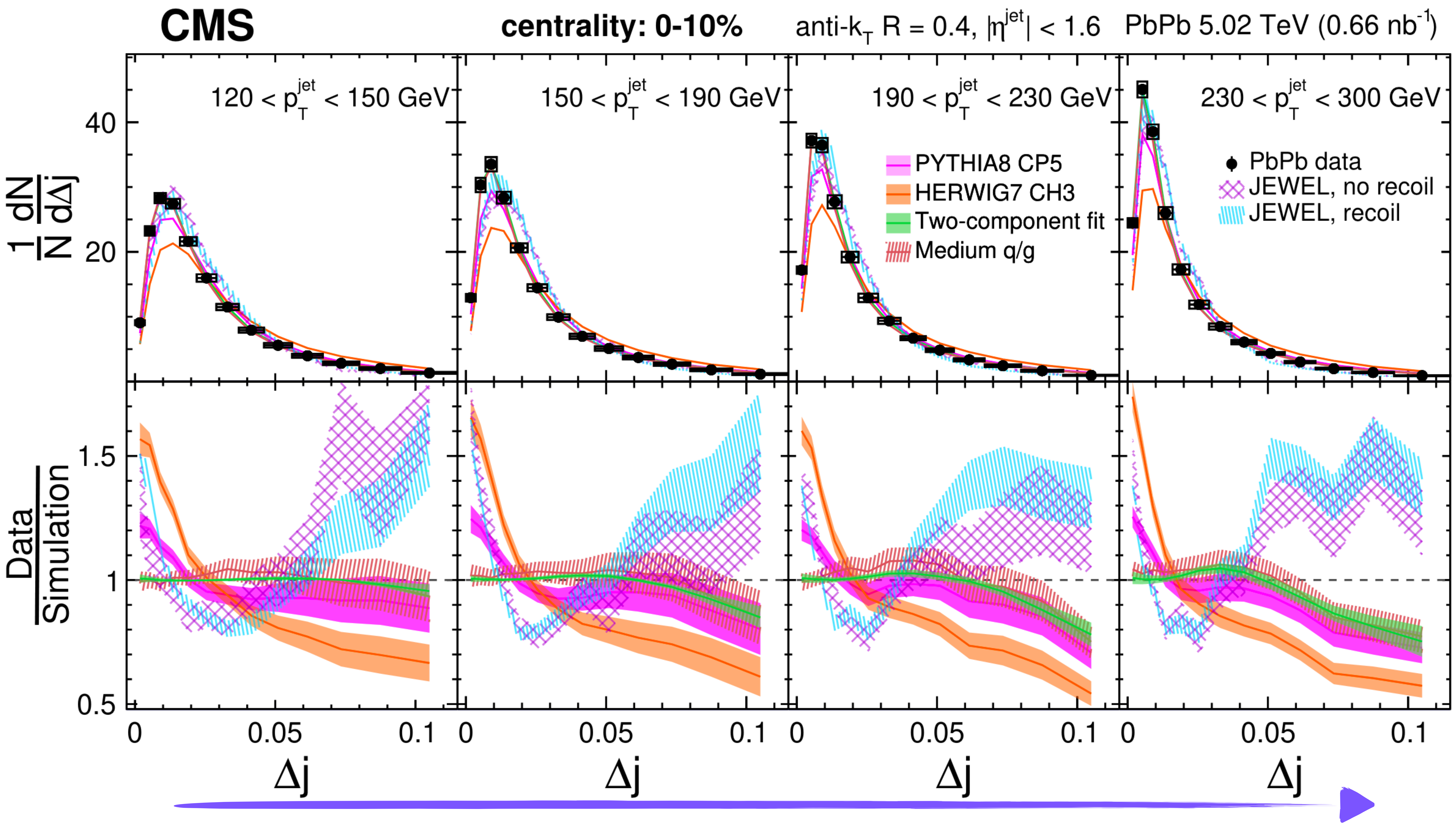
- Both implementations fail to describe data across all $p_{\mathrm{T}}^{\mathrm{jet}}$ ranges, observable appears insensitive to medium response.

MODEL COMPARISONS (0-10%)

[JHEP 06 (2025) 120]

- Compare with models differentially in p_T to investigate underlying mechanisms.

0-10%



Increasing $p_\mathrm{T}^\mathrm{jet}$

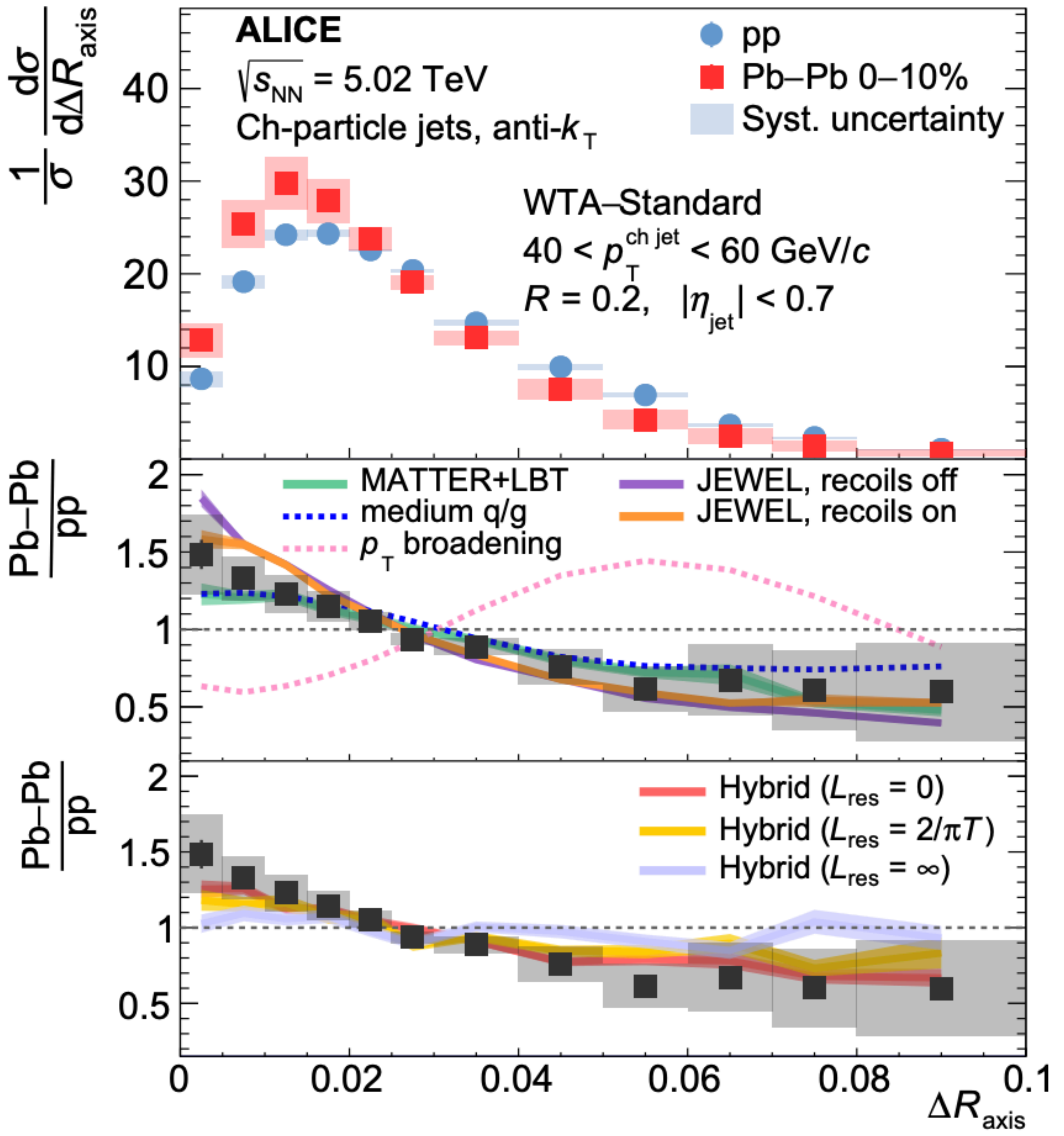
- Medium q/g model is reweighted PYTHIA based on a modified q/g fraction from Ref.

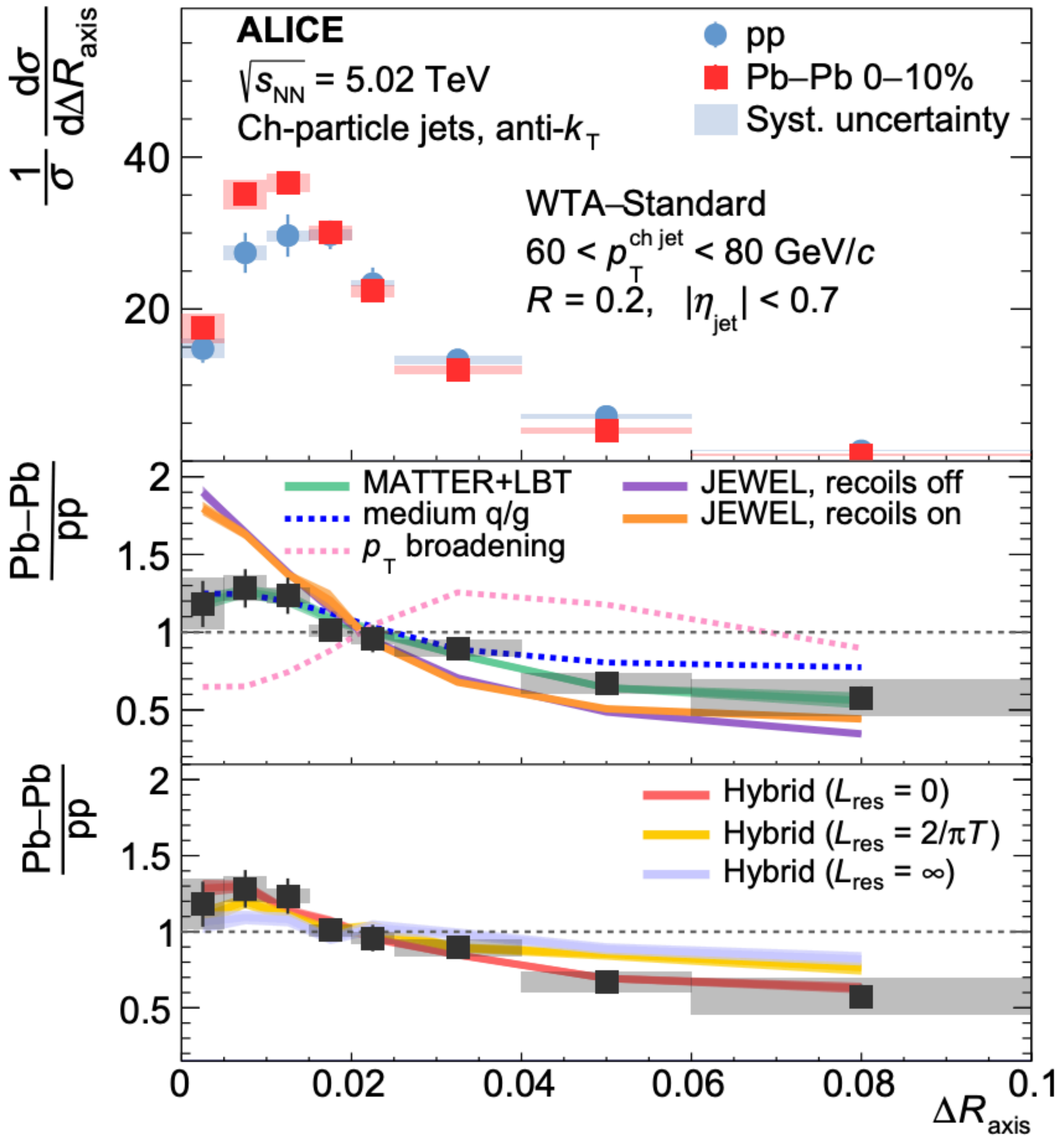
[Phys. Rev. Lett. 122, 252301]

- Two-component PYTHIA-based template fit to unfolded data provides good description except for central collisions and high $p_\mathrm{T}^\mathrm{jet}$.

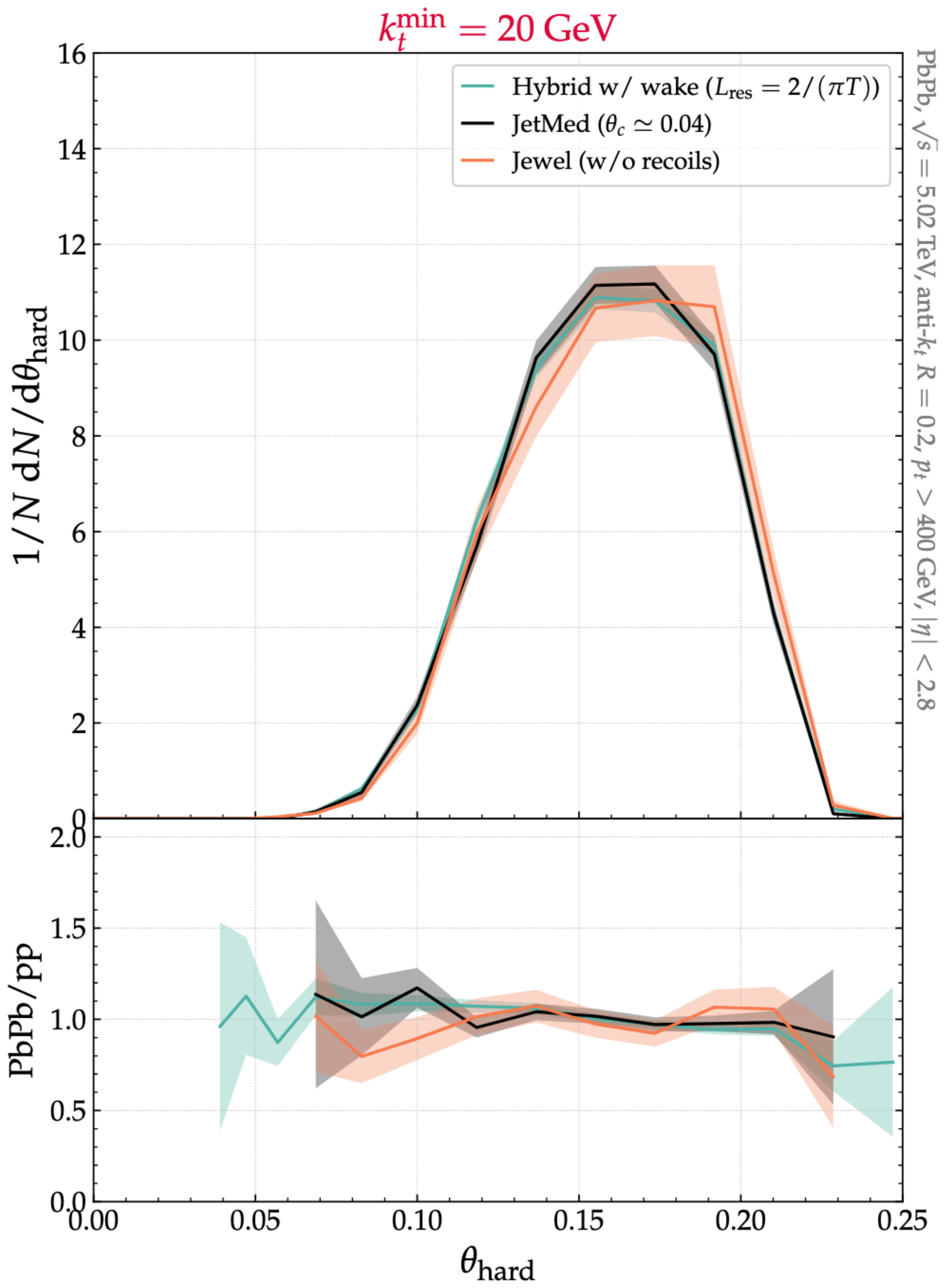
PREVIOUS RESULTS

[arXiv:2303.13347]





ISOLATING PERTURBATIVE SCALES



- Choosing high-values of $k_{\rm T}$ chooses effectively a vacuum line baseline.

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

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JET QUENCHING

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

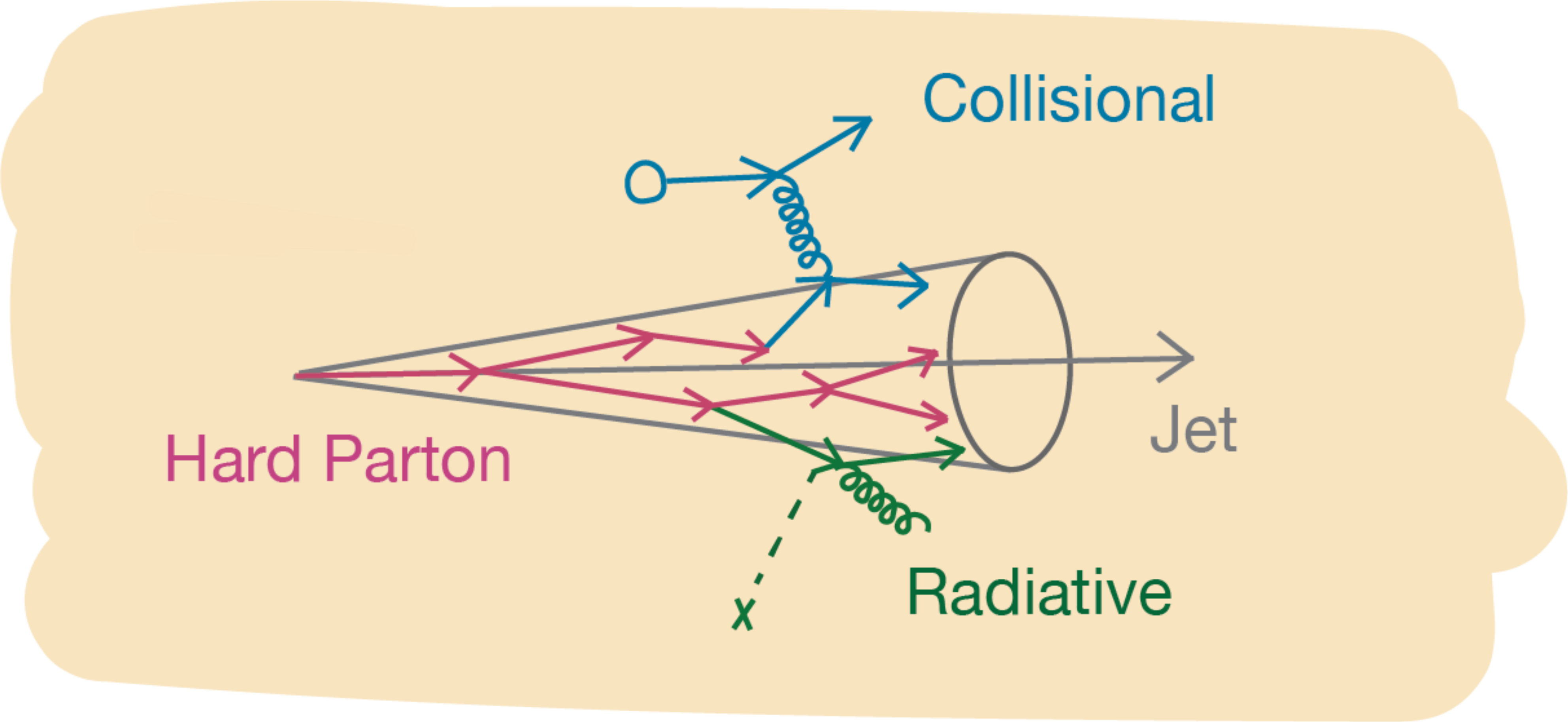
Impact of the medium on the jet → jet energy loss

Ⓐ Weak coupling limit

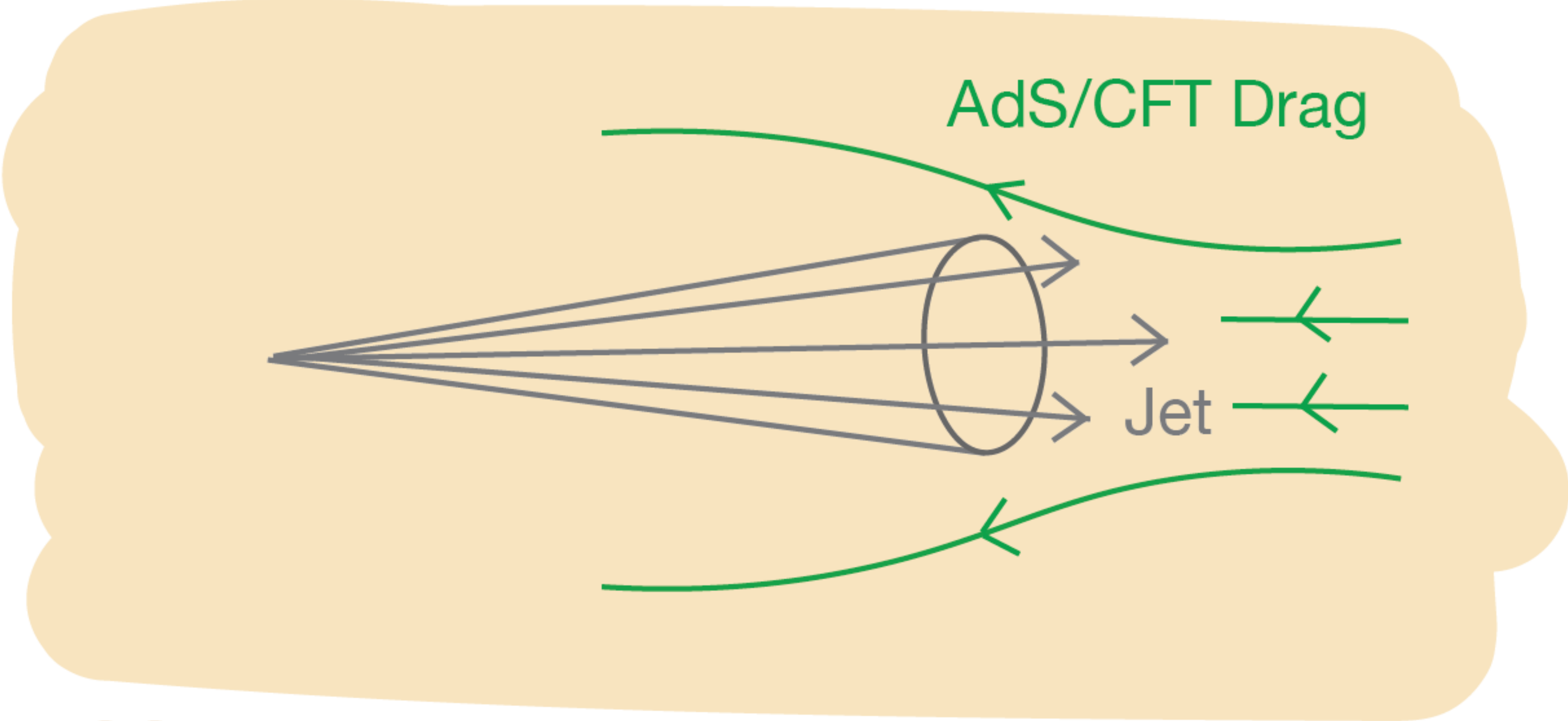
- → Collisional
- → Radiative

Ⓑ 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!

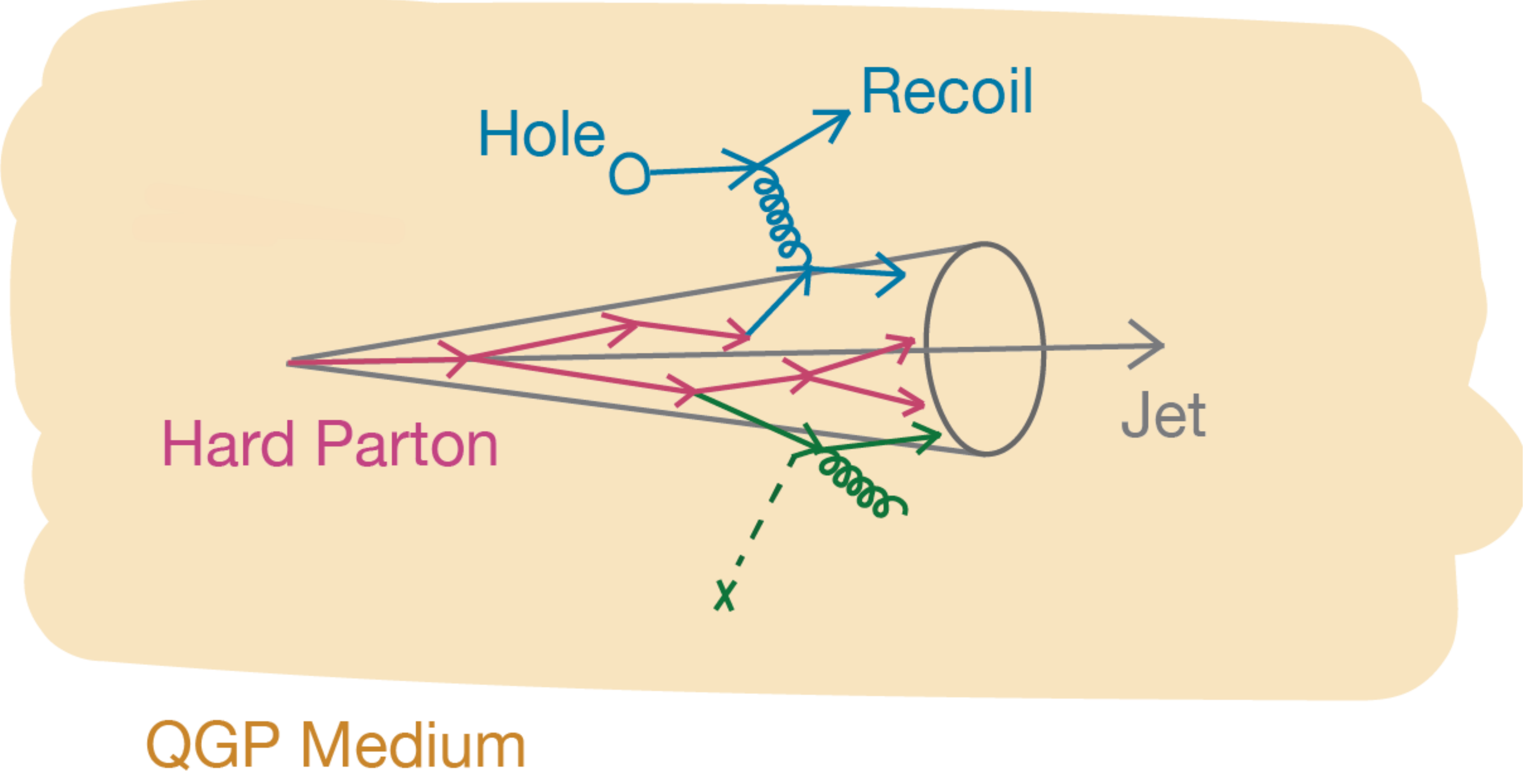
JET QUENCHING

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

② Impact of the jet on the medium → medium response

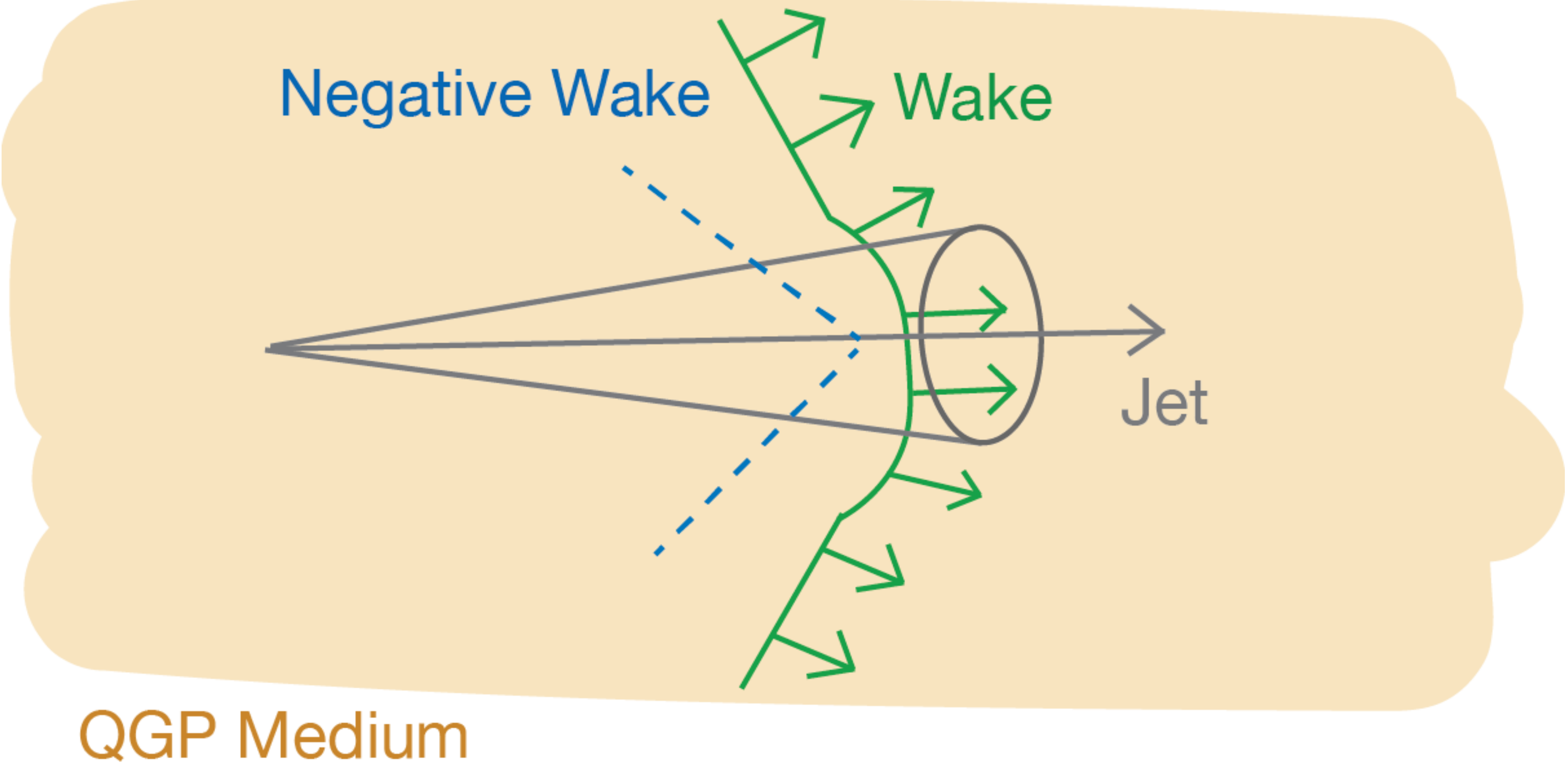
Ⓐ Weak coupling limit

→ Recoils (Kinetic based approach)



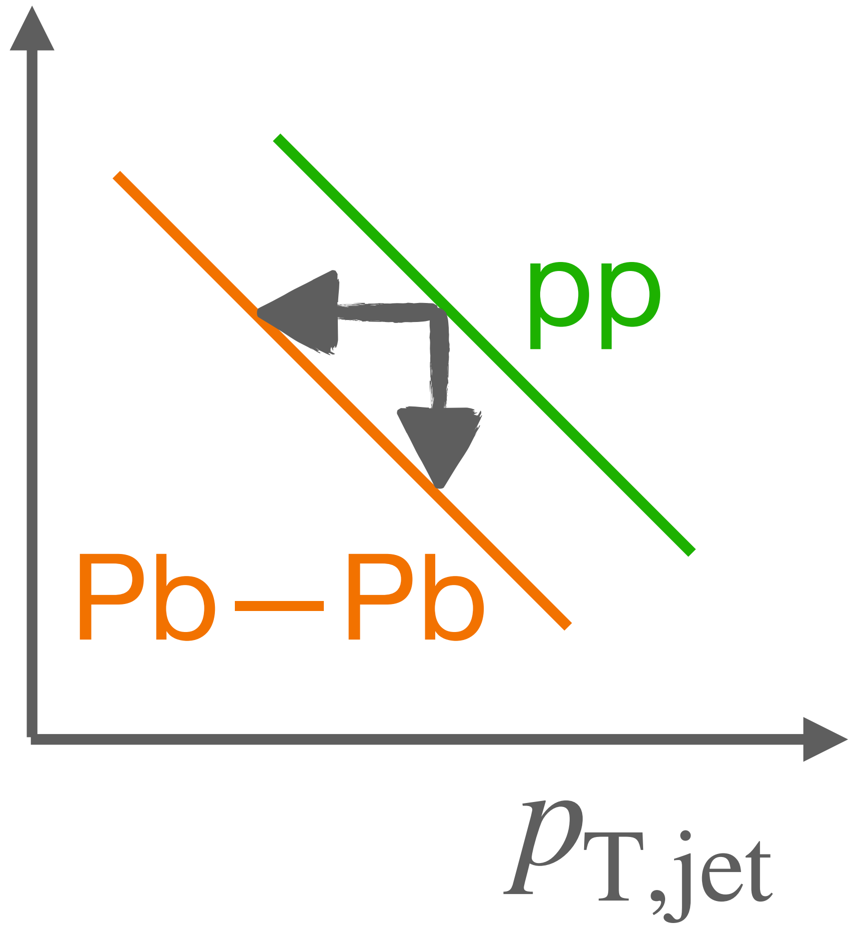
Ⓑ Strong coupling limit

→ Wake
(Hydrodynamics based approach)



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

NUCLEAR MODIFICATION FACTOR

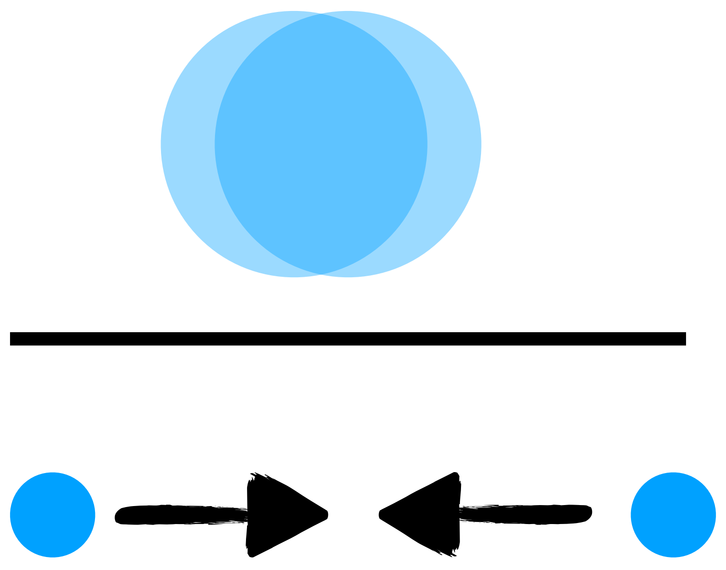


Parton energy loss will lead to a suppression of jet yields in heavy-ions (A+A) in comparison to vacuum (pp).

→ 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.

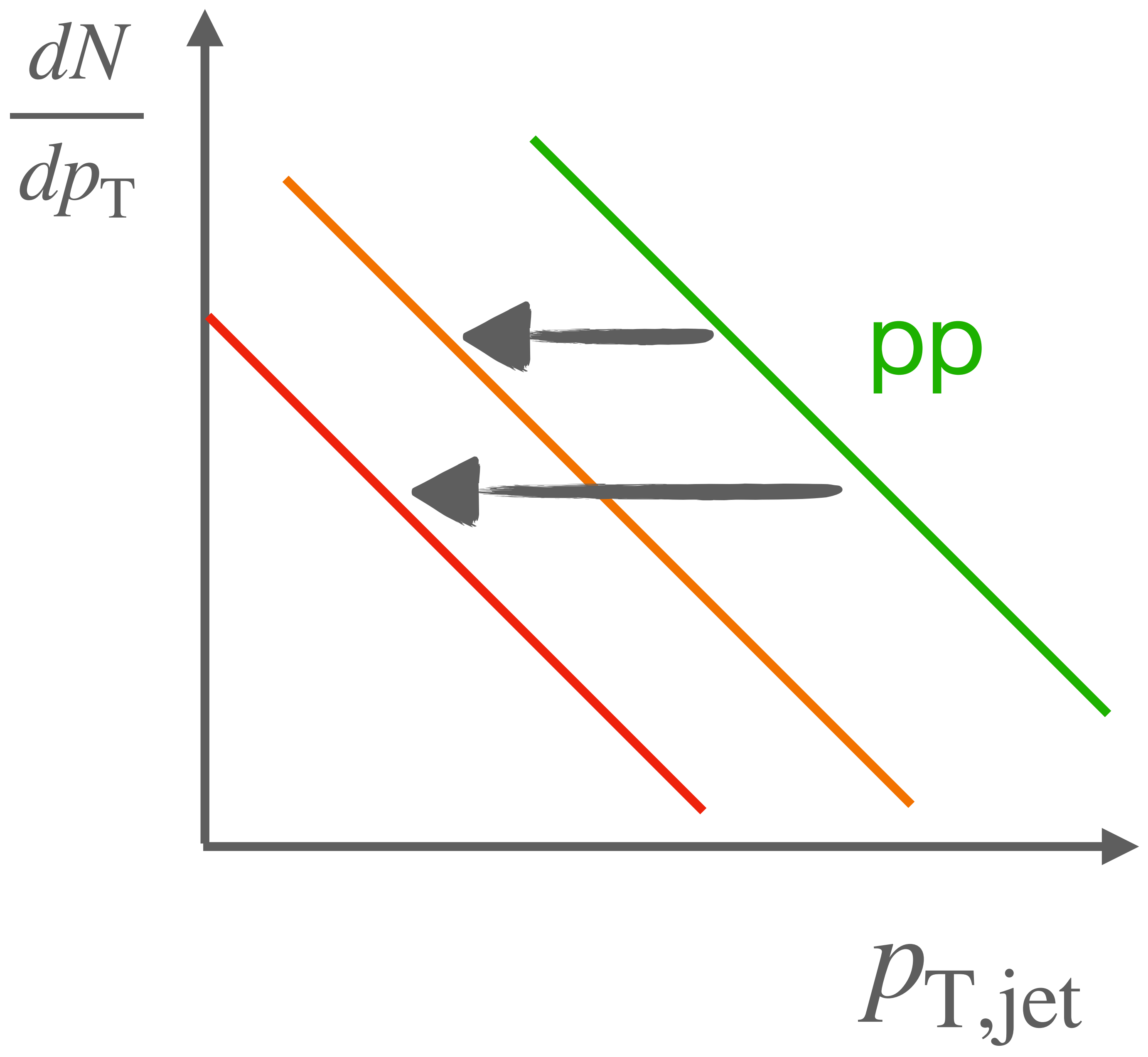
$$R_{\mathrm{AA}} = \frac{\left.\frac{1}{N_{\mathrm{event}}}\frac{d^2N^{\mathrm{PbPb}}_{\mathrm{jet}}}{dp_{\mathrm{T}}dy}\right|_{\mathrm{cent}}}{\langle T_{\mathrm{AA}}\rangle \frac{d^2\sigma^{\mathrm{pp}}_{\mathrm{jet}}}{dp_{T}dy}} =$$



$R_{\mathrm{AA}} < 1 \rightarrow$ 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

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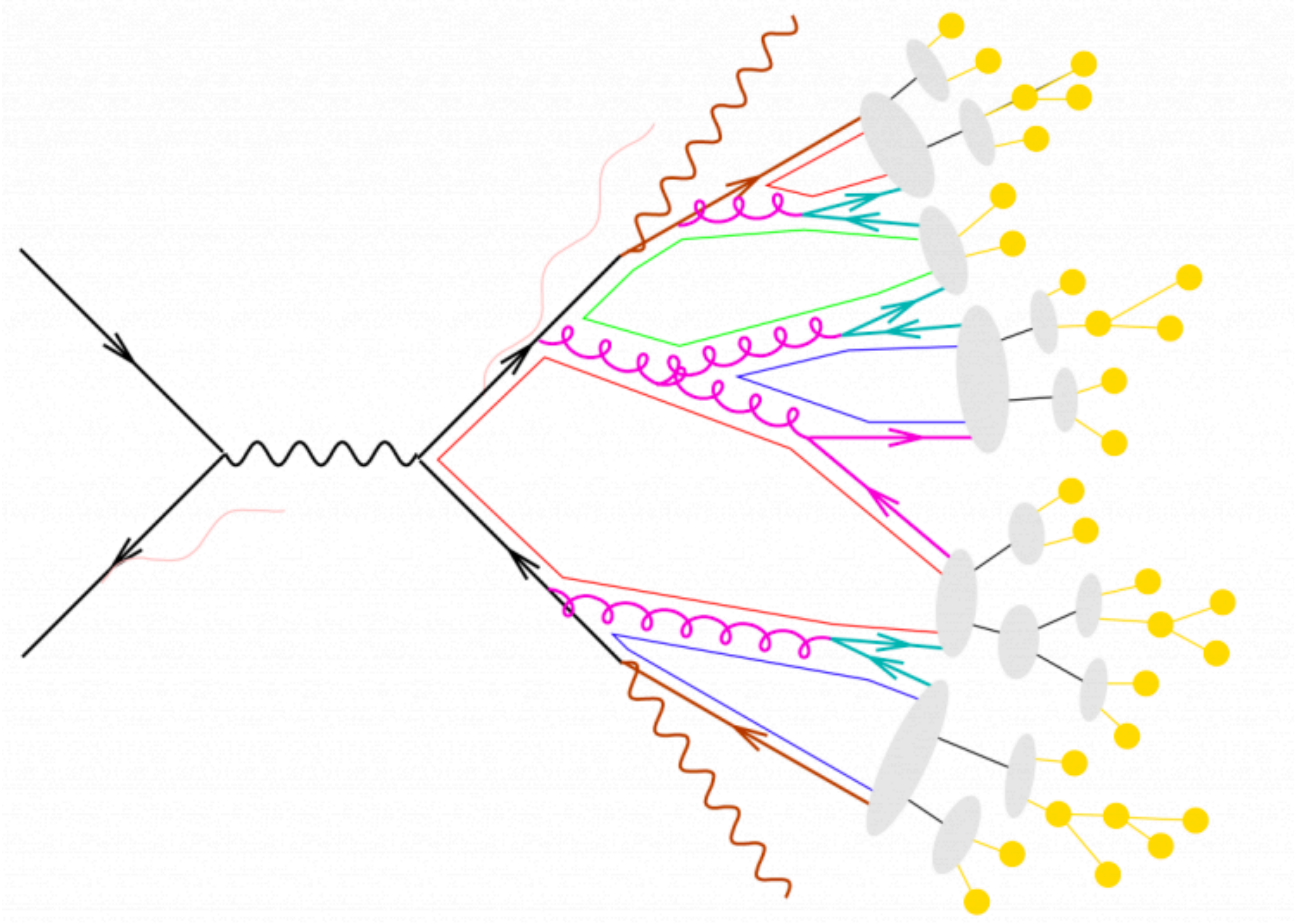
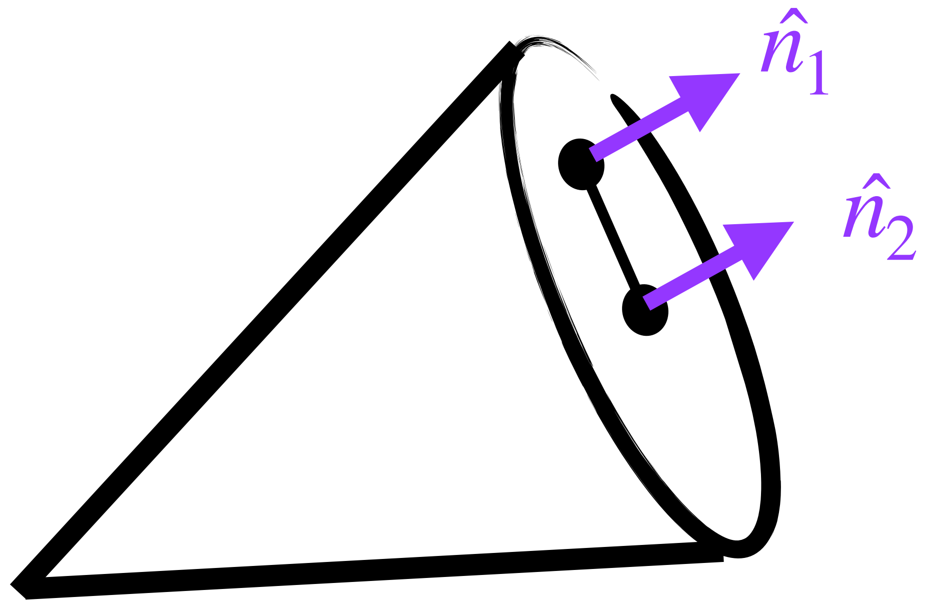
ENERGY CORRELATORS





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

Defined as the correlation of energy flow operator

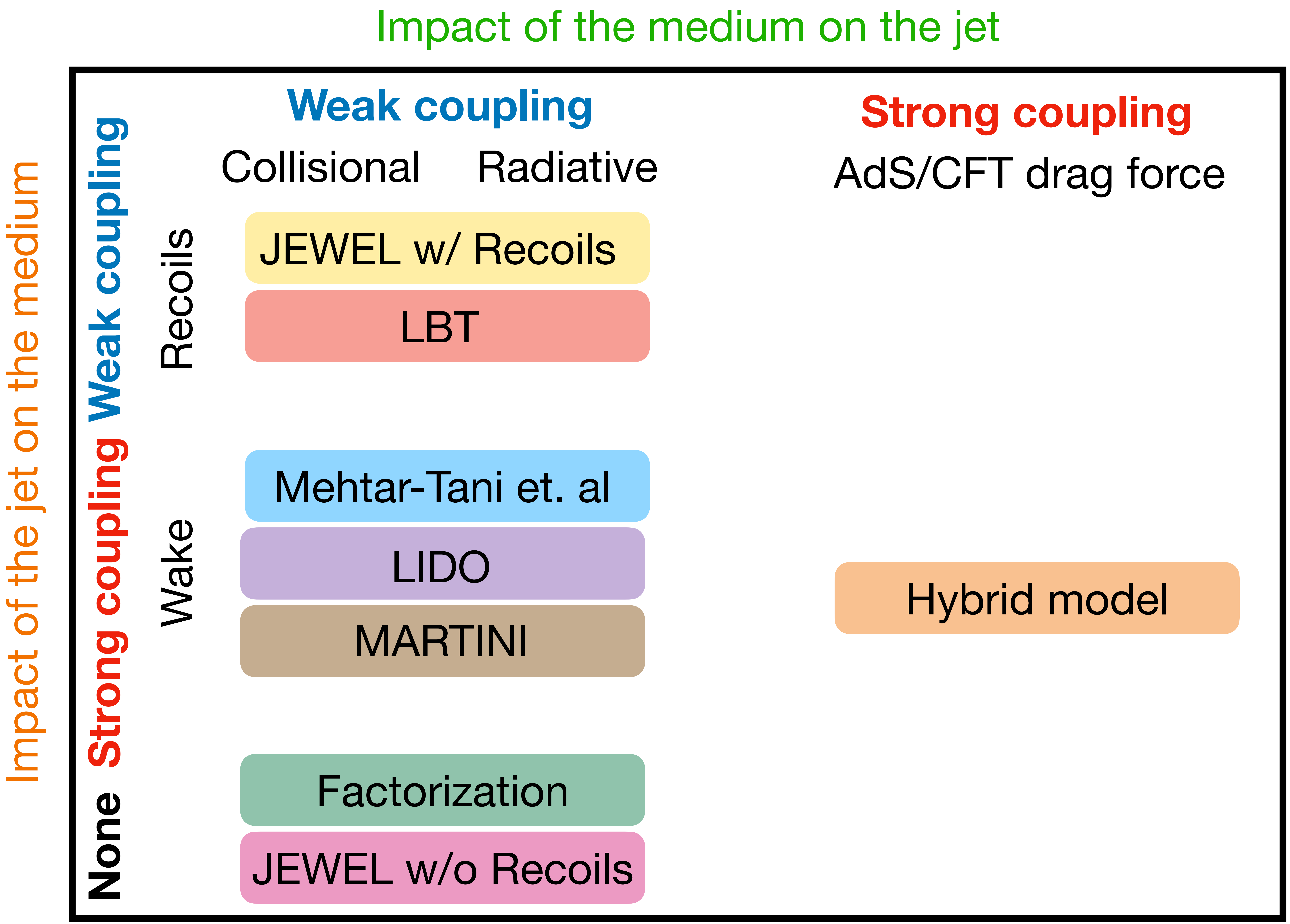
$$\mathscr{E}(\vec{n}_1) = \lim_{r\to\infty} \int \mathrm{d}t r^2 n_1^i T_{0i}(t, r\vec{n}_1)$$

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

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

In hadron collider environments, instead of $\hat{n}_1$ use $\Delta R = \sqrt{\Delta y^2 + \Delta\phi^2}$

MODELS



Impact of the medium on the jet

Impact of the jet on the medium

Weak coupling

Collisional Radiative

Strong coupling

AdS/CFT drag force

Weak coupling

Recoils

JEWEL w/ Recoils

LBT

Strong coupling

Wake

Mehtar-Tani et. al

LIDO

MARTINI

Hybrid model

None

Factorization

JEWEL w/o Recoils

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