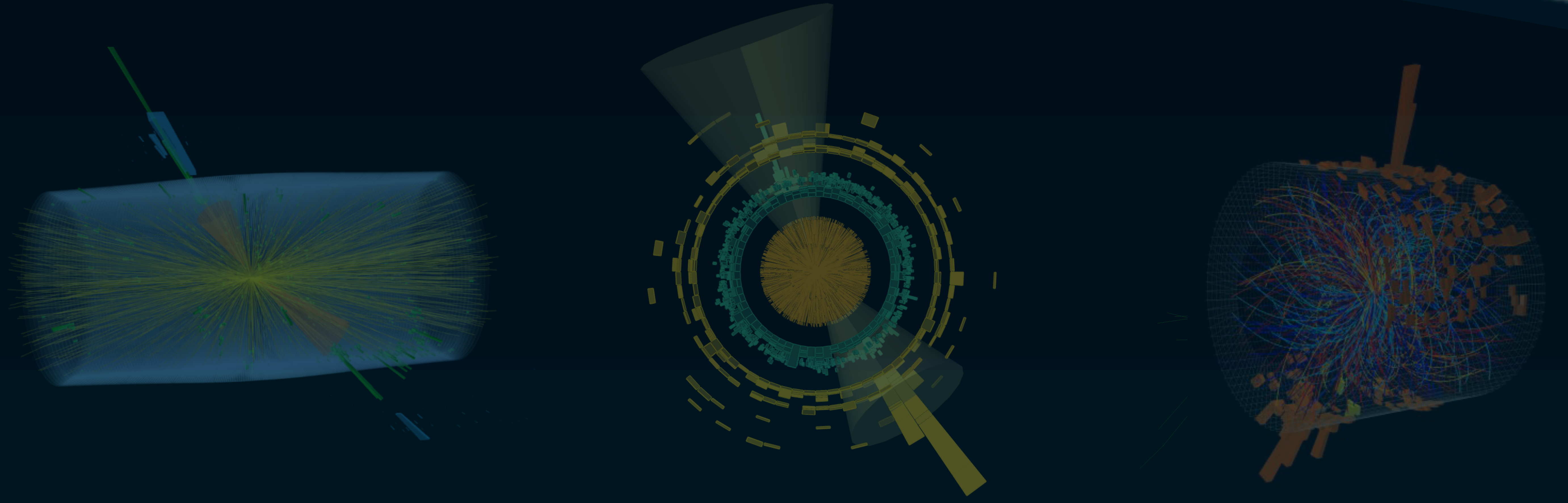
Jets at the LHC:

Selected results in large & small systems

Riccardo Longo

25th RHIC/AGS Users meeting

21st May 2025



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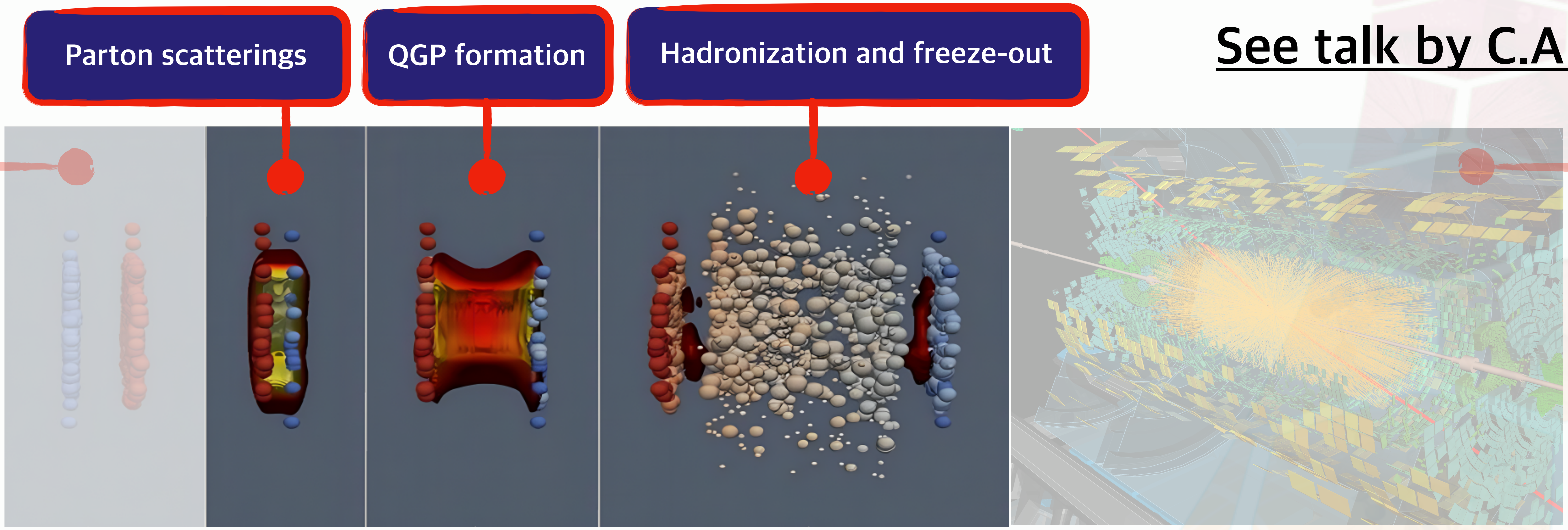
Jet modification as probe of the QGP

See talk by C.Andres



Collision evolution sketch from MADAI collaboration

Temperature

Time: $\tau = 0$ — τ ~1 fm/c ~10^{-23} s — τ ~ 10 fm/c ~10^{-22} s — τ > 10 cm/c ~10^{-11} s

System Size: Femtoscale — O(50m)

Jets are **ideal probes** to investigate the **microscopic** behavior of the **QGP!**

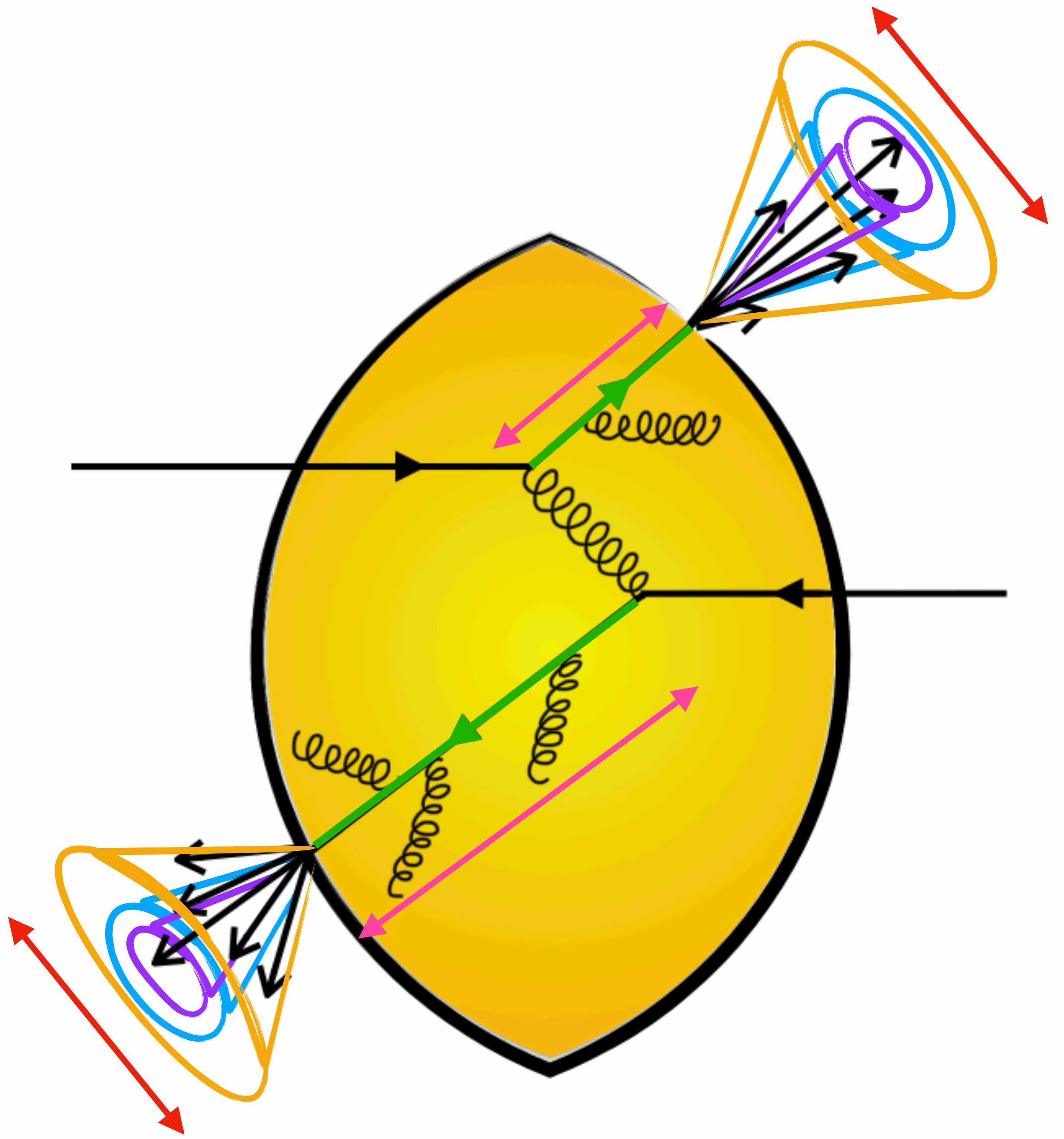
Jets are multi-scale, complex probes for the QGP

Jet quenching involves not only energy loss, but also other jet properties and medium modifications

E_{loss} dependence on **path length** traversed in the medium

E_{loss} dependence on **flavor** of the initiating parton

E_{loss} dependence on **jet substructure** of the initiating parton (related to medium color-charge resolution scale)

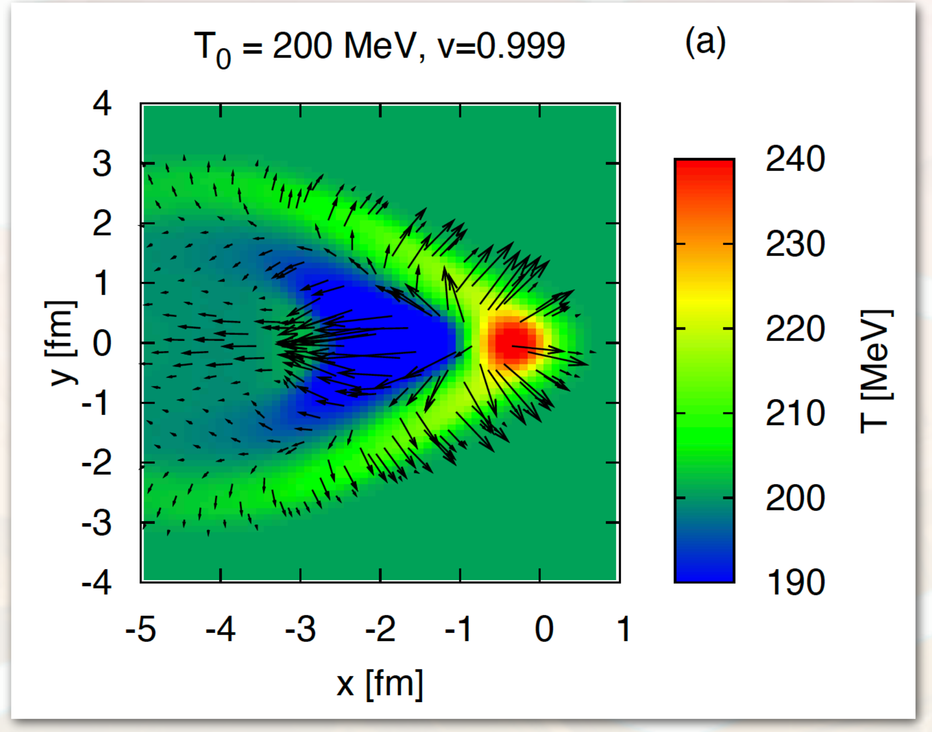


Soft gluon emissions can cause **momentum broadening** (jet widening)

The **medium responds to the jet** transit, causing wakes (positive and negative) of stoft particles

Molière-like scattering causes wide-angle decorrelation

...



Betz et al, PRC 79 (2009) 034902

Understanding and describing all these effects is a key to fully comprehending the microscopic structure of the QGP

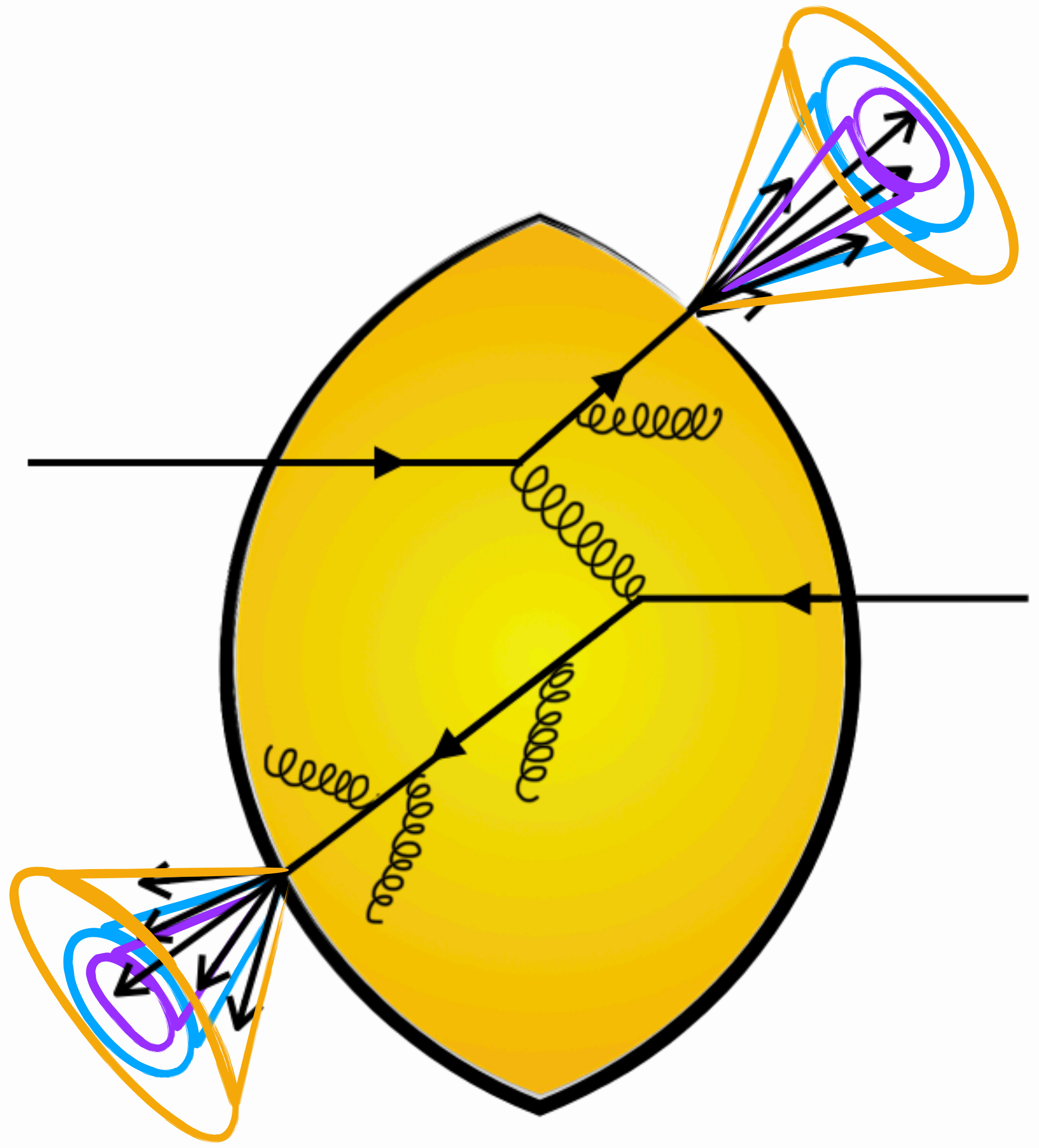
Path-length dependence

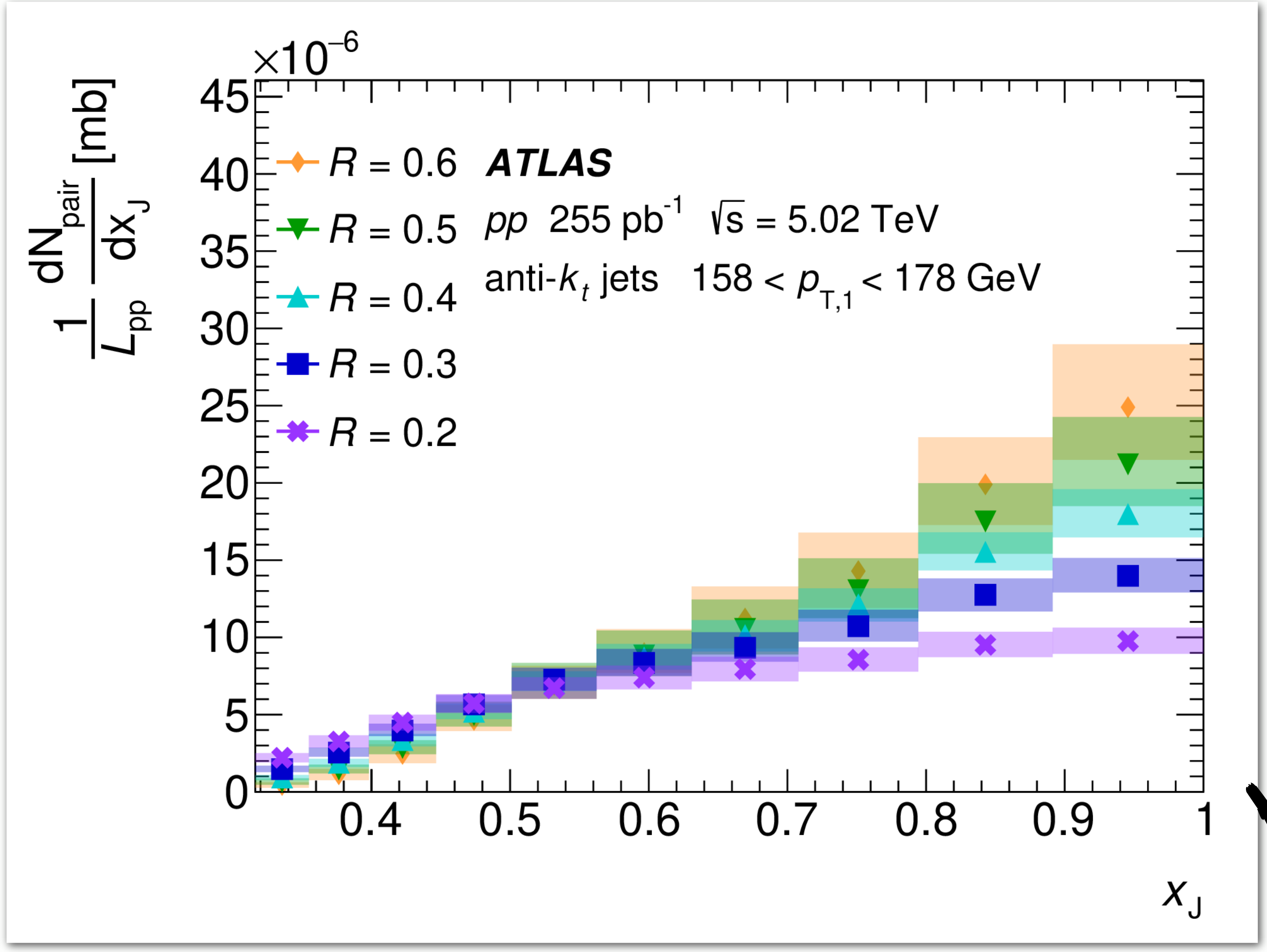
How does the energy loss depend on the length traversed in the medium?

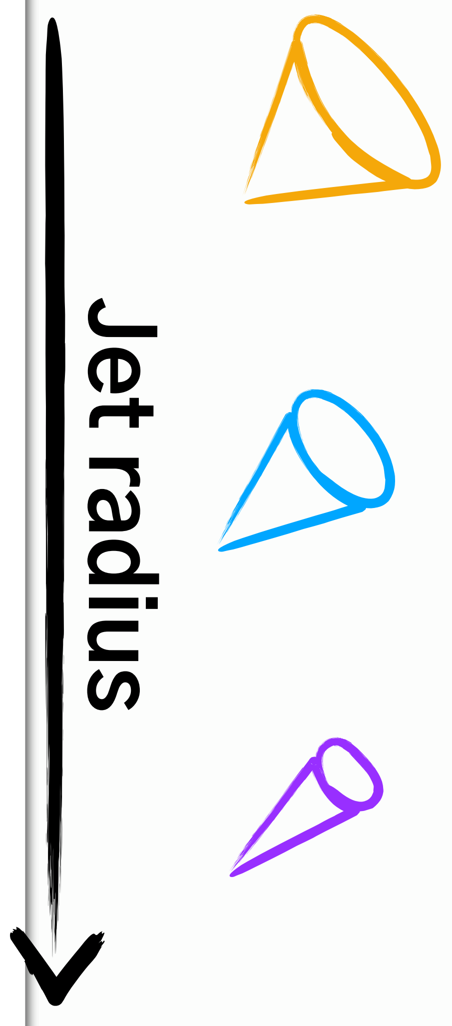
R-dependence of dijet momentum imbalance

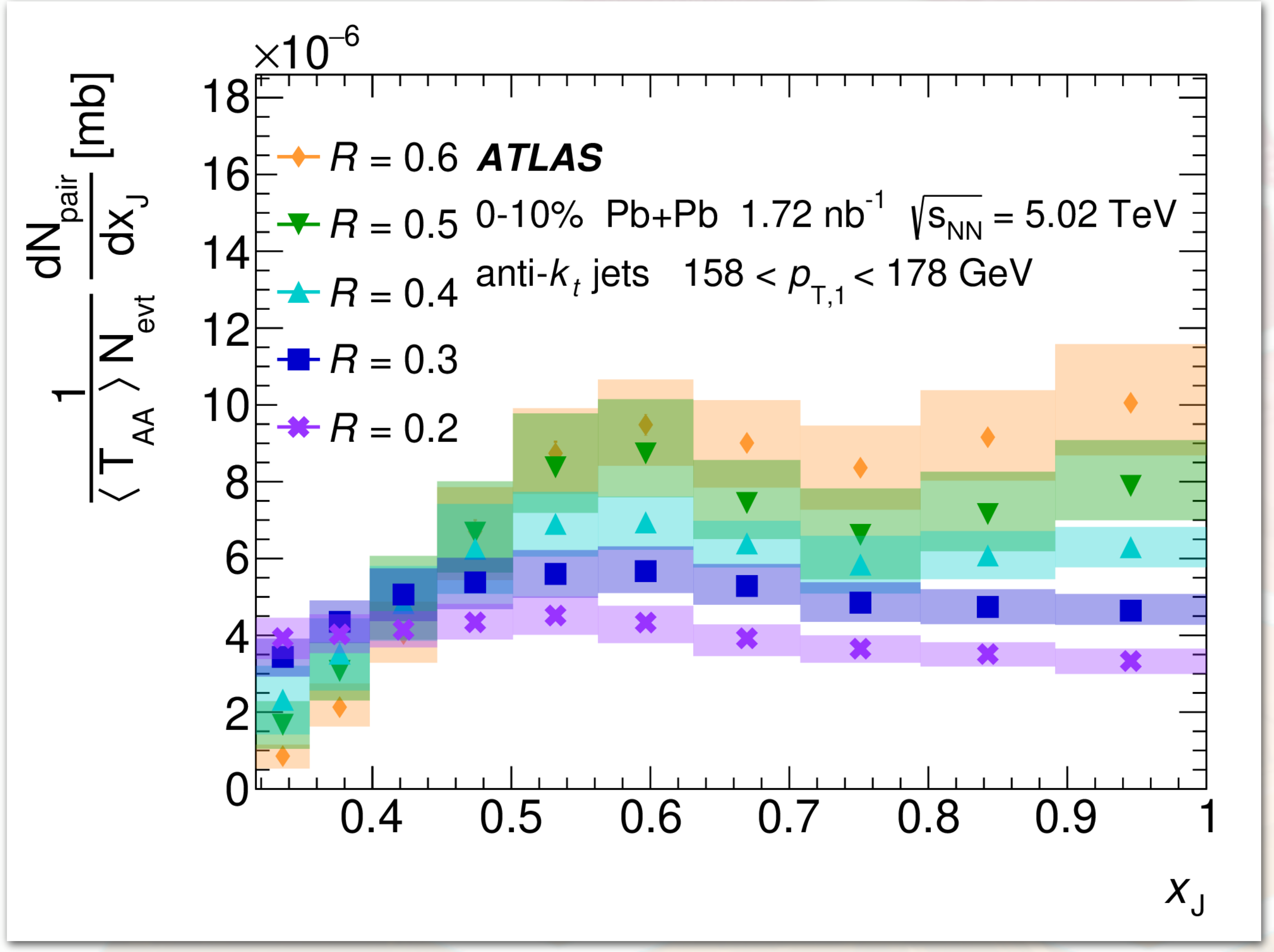
PRC 110 (2024) 054912

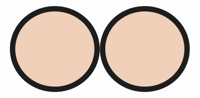
$$x_J = \frac{p_{\mathrm{T},2}}{p_{\mathrm{T},1}}$$

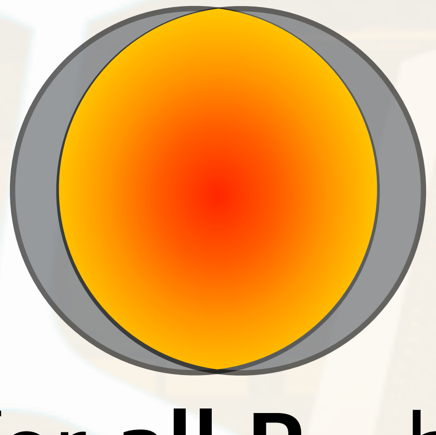








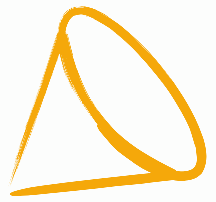
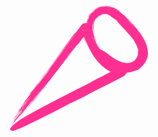


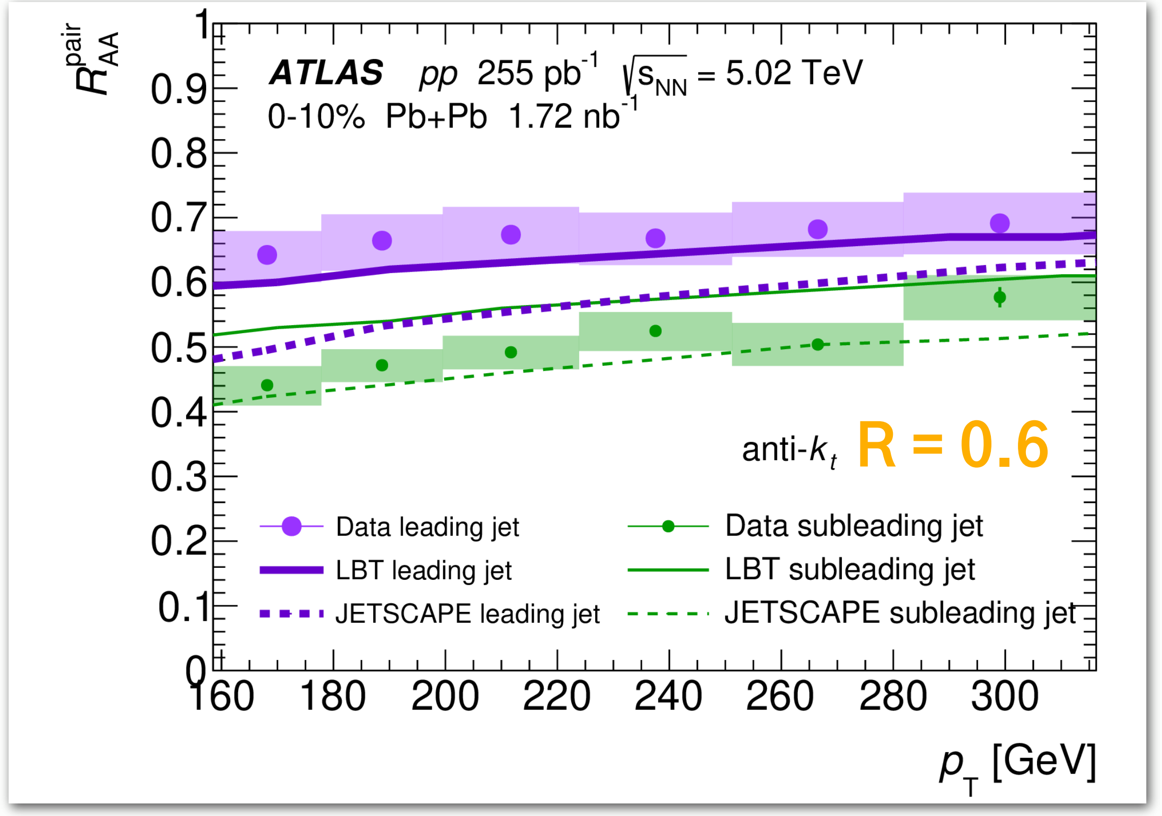


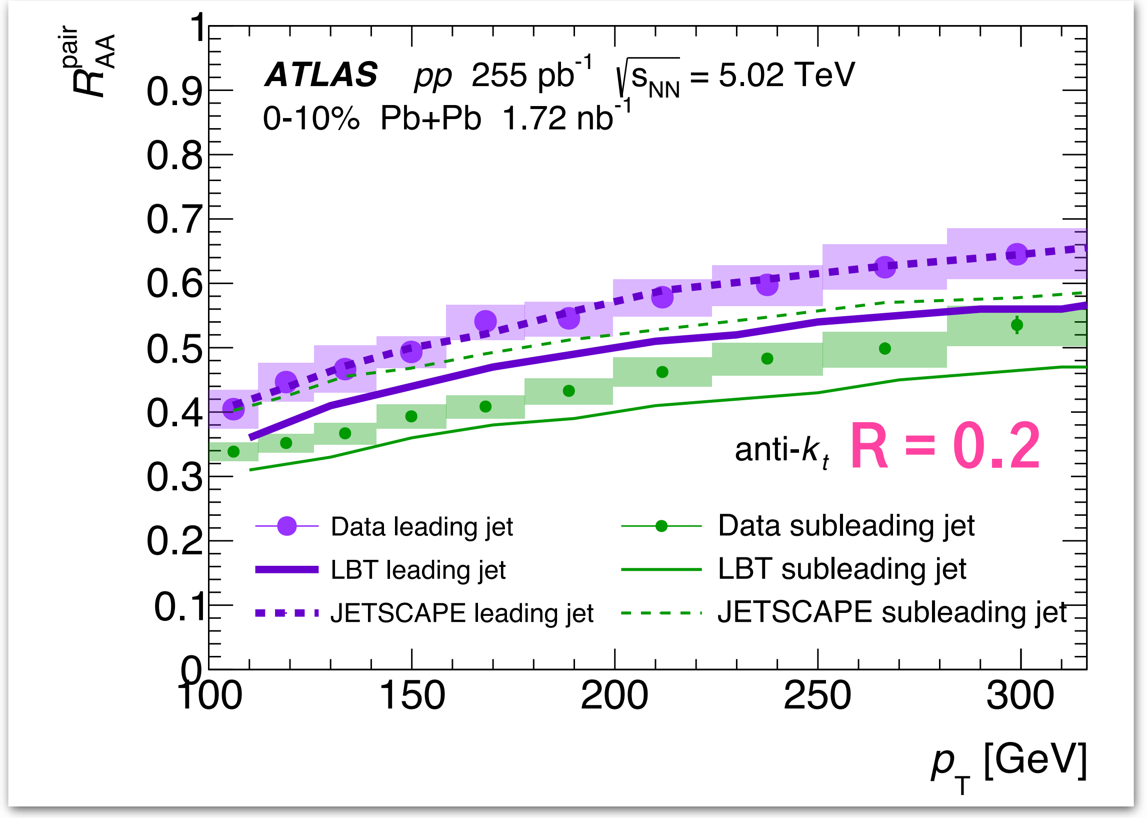
In **pp**, increasing jet radius leads to increasing fraction of balanced jets (in good agreement with MC)

In **Pb+Pb** – for **all R** – balanced jets are preferentially suppressed while a much smaller modification is observed for imbalanced jets

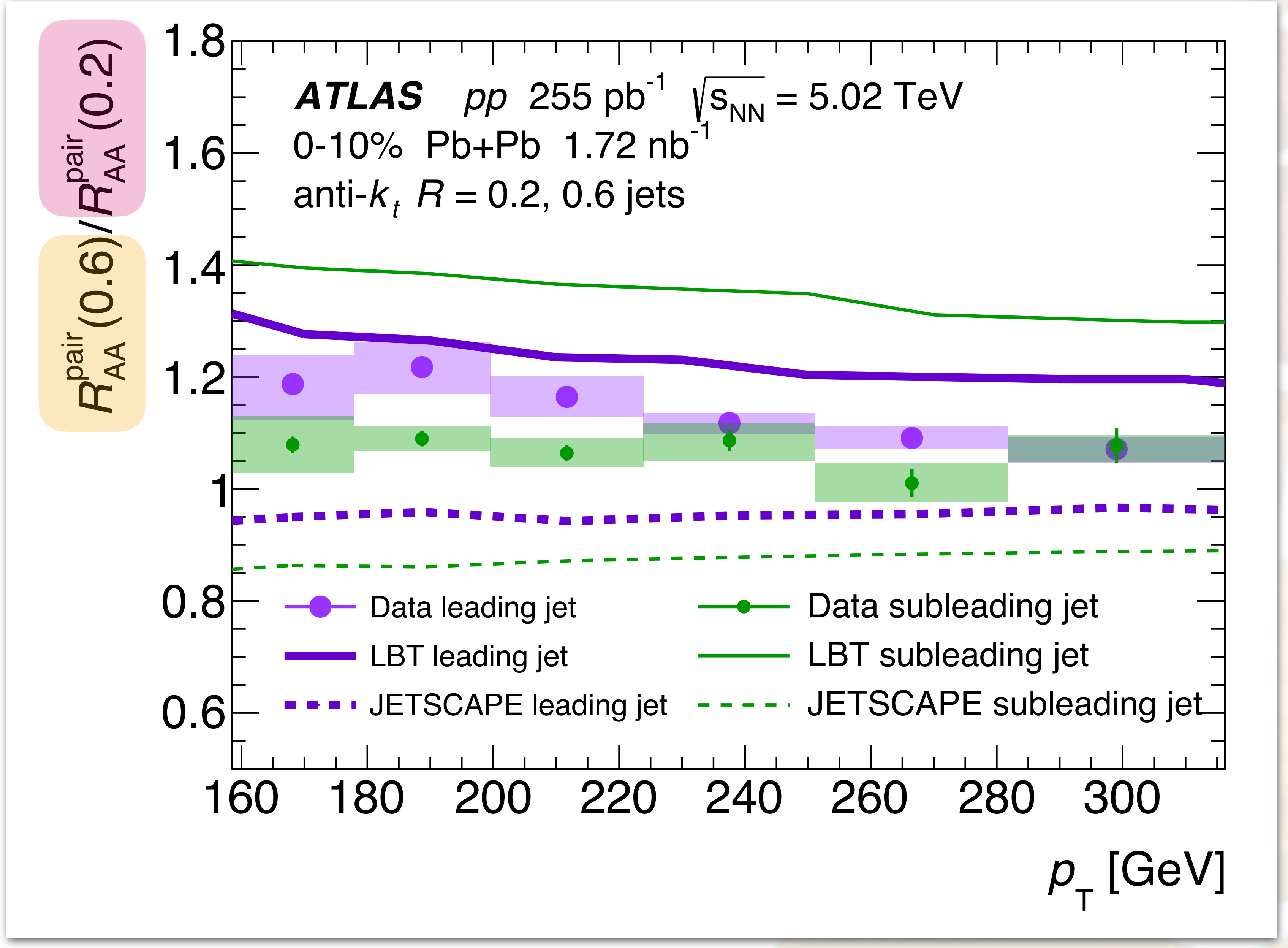
Nuclear modification of dijet pairs





ATLAS **PRC 110 (2024) 054912**

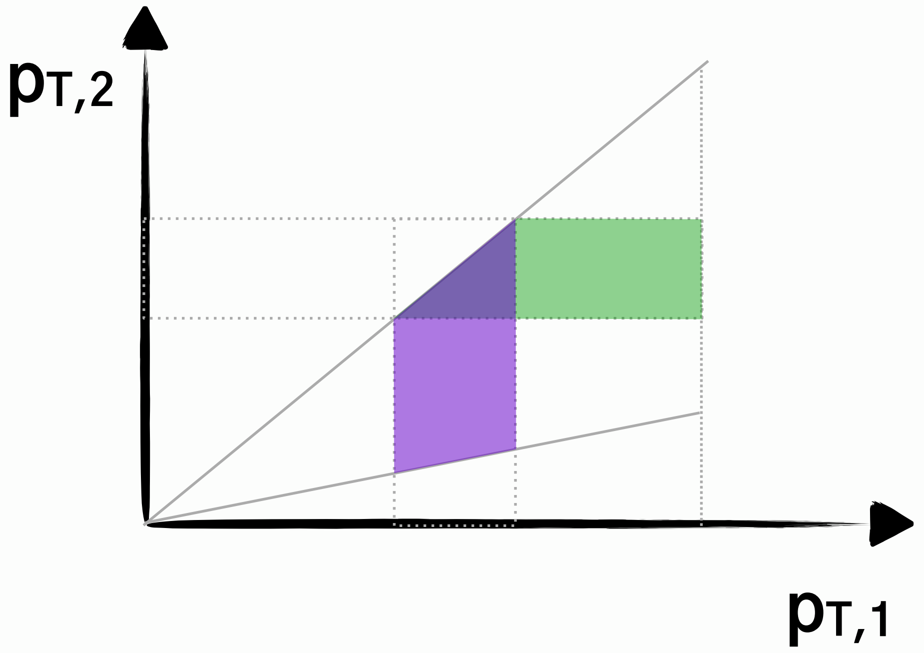


R_{AA}^{pair} () / R_{AA}^{pair} () > 1

$$R_{AA}^{pair}(p_{T,i}) = \frac{\frac{1}{\langle T_{AA}\rangle N_{evt}^{AA}} \int_{0.32\times p_{T,i}}^{p_{T,i}} \frac{d^2 N_{pair}^{AA}}{dp_{T,i} p_{T,j}} dp_{T,j}}{\frac{1}{L_{pp}} \int_{0.32\times p_{T,i}}^{p_{T,i}} \frac{d^2 N_{pair}^{AA}}{dp_{T,i} p_{T,j}} dp_{T,j}}$$

$i, j = \{1, 2\}$

$i, j = \{2, 1\}$

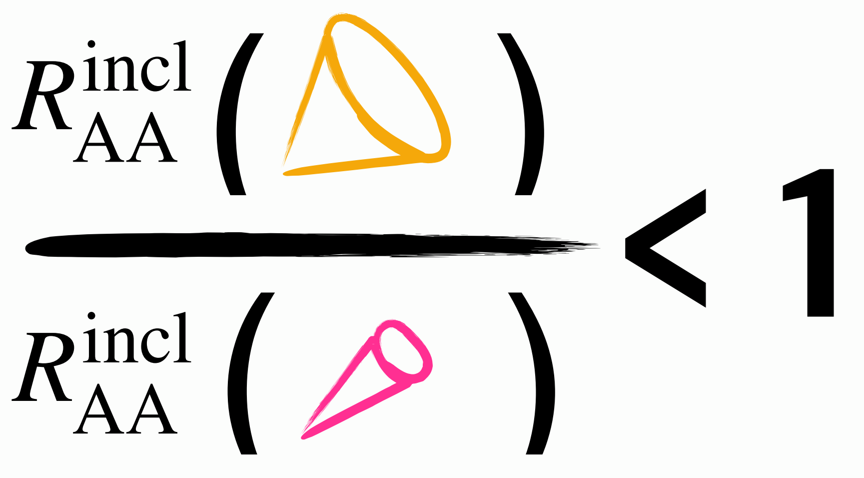


R = 0.6 jets are less suppressed compared to R = 0.2, for both leading and subleading jets in the dijet pair

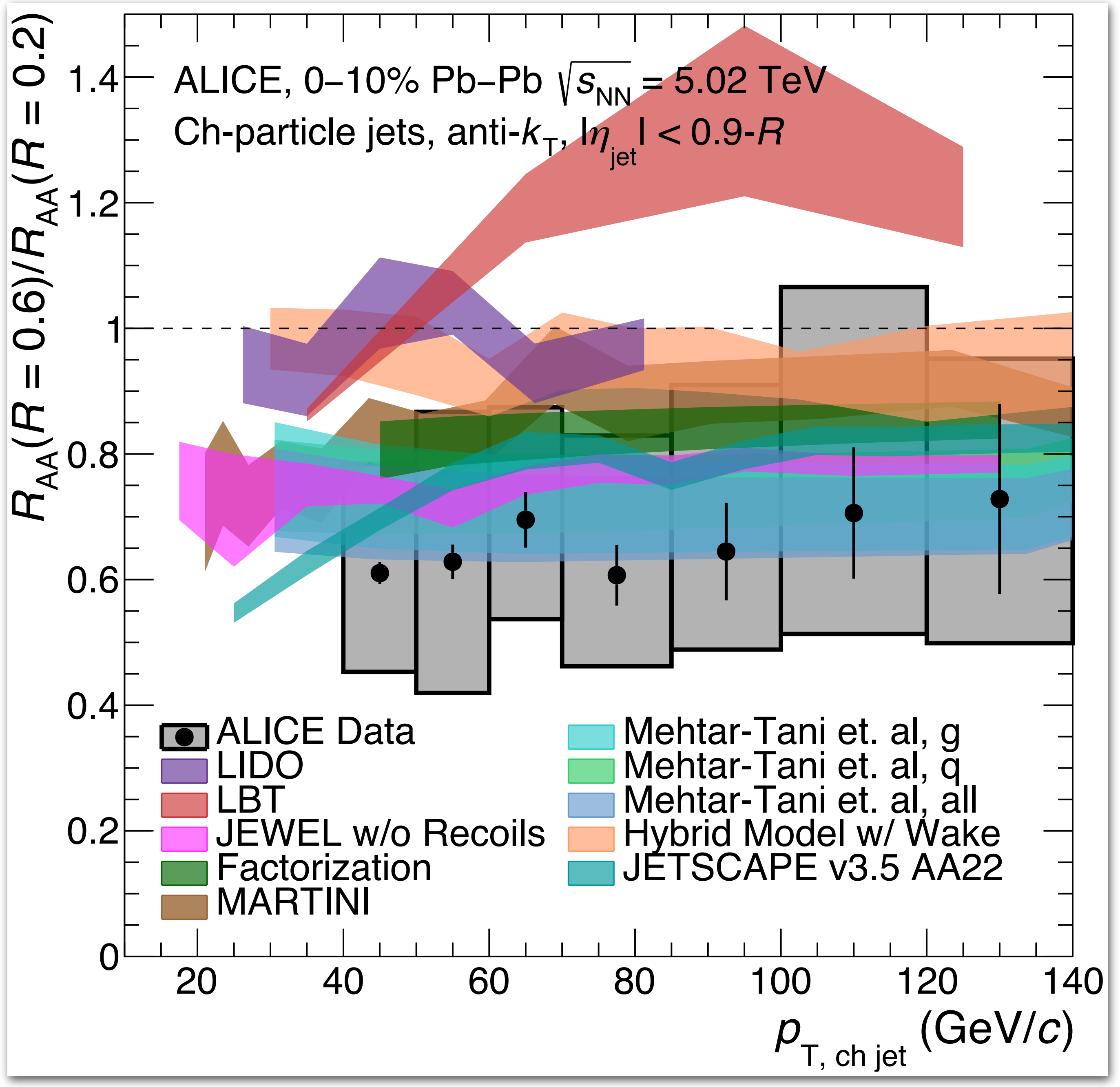
	LBT	JETSCAPE
R-suppression ordering	✔	✘
Leading-subleading suppression ordering	✘	✔

Neither LBT or JETSCAPE describe the data

Dijet vs inclusive R-dependence

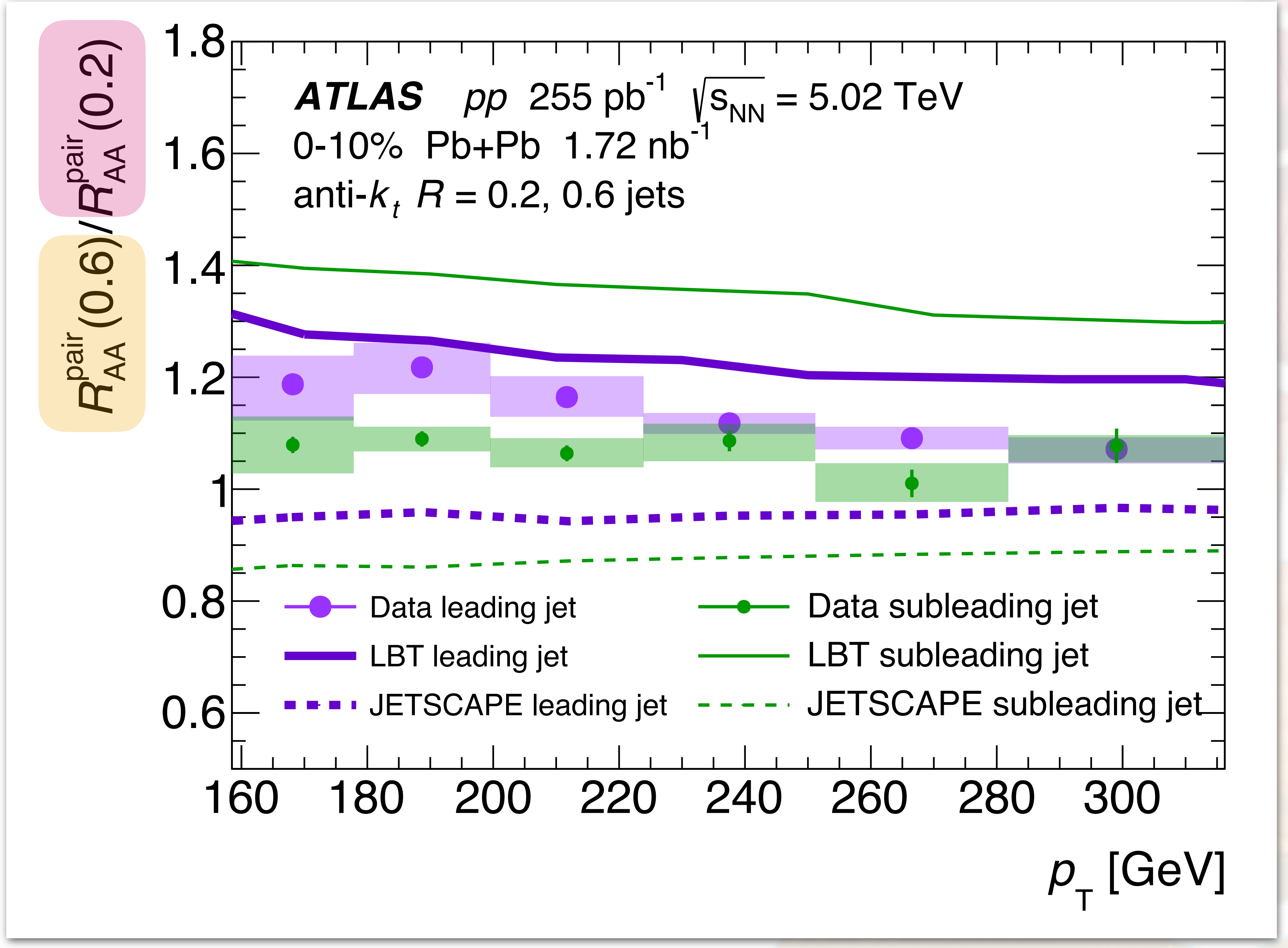


PLB 849 (2024) 138412

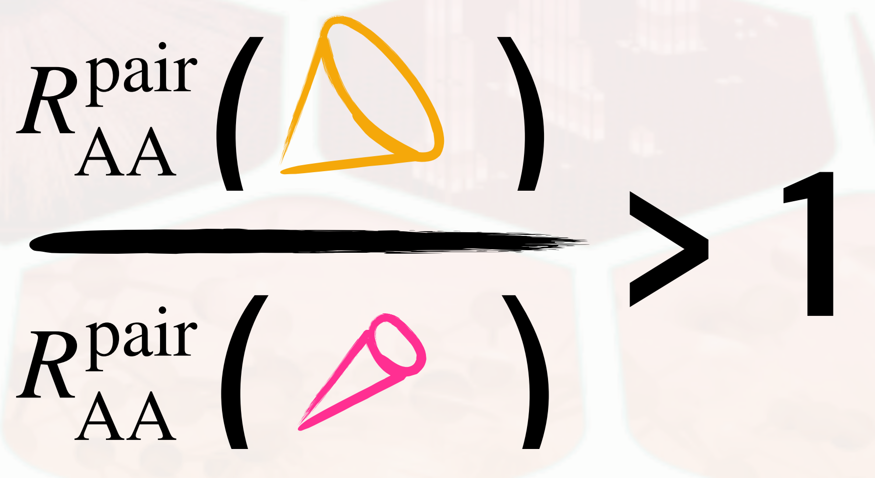


ALICE Radius dependence of **inclusive jets R_{AA} shows the opposite trend**

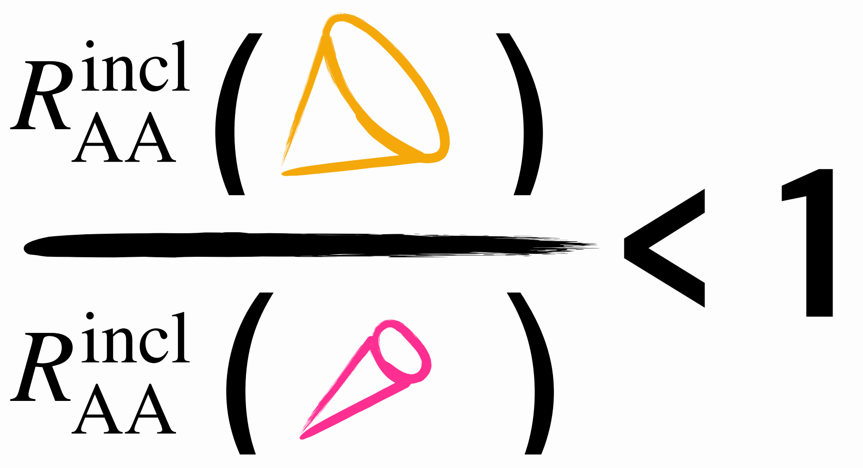
PRC 110 (2024) 054912



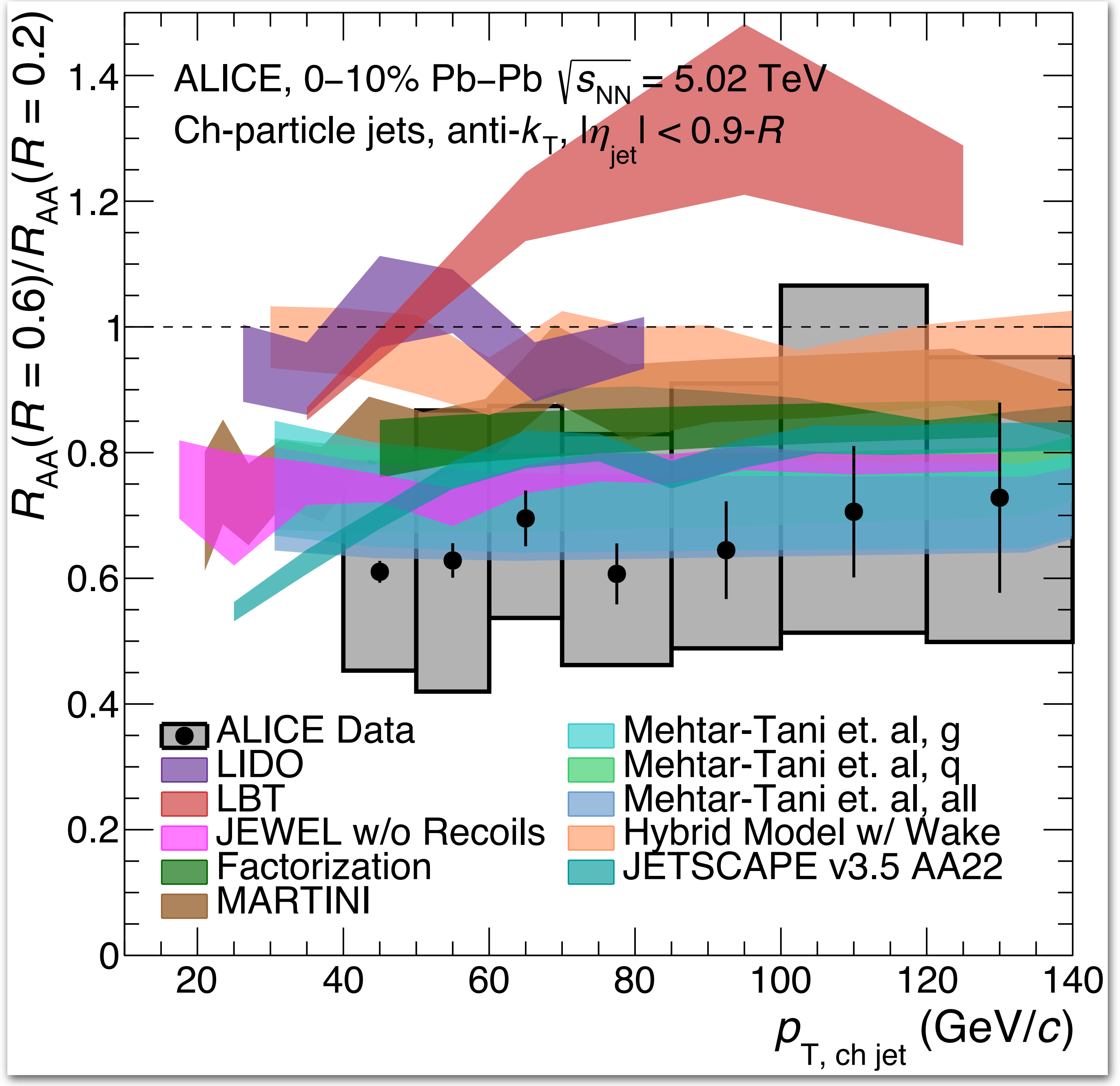
R = 0.6 jets are less suppressed compared to R = 0.2, for both leading and subleading jets in the dijet pair



Dijet vs inclusive R-dependence



PLB 849 (2024) 138412



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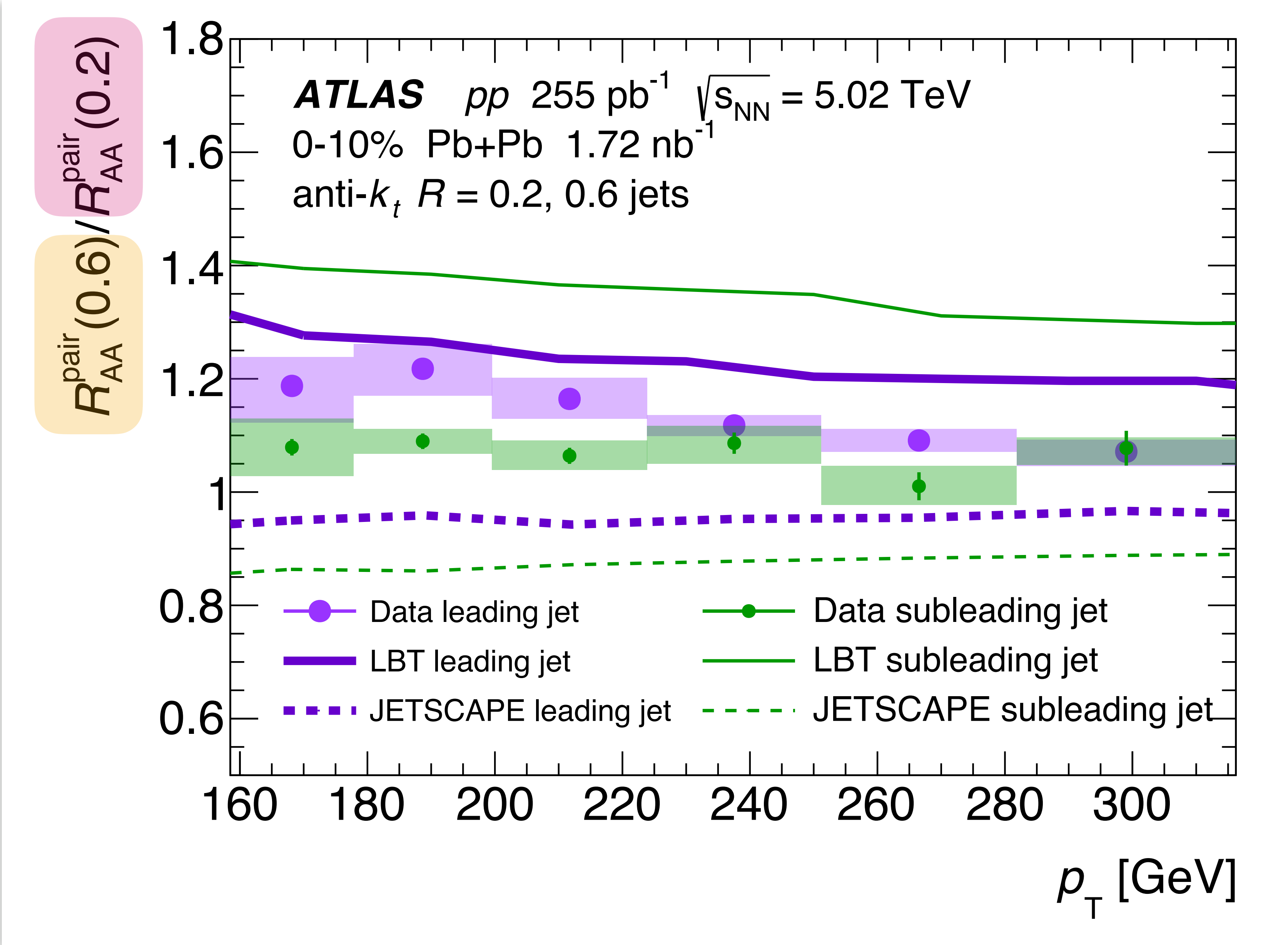

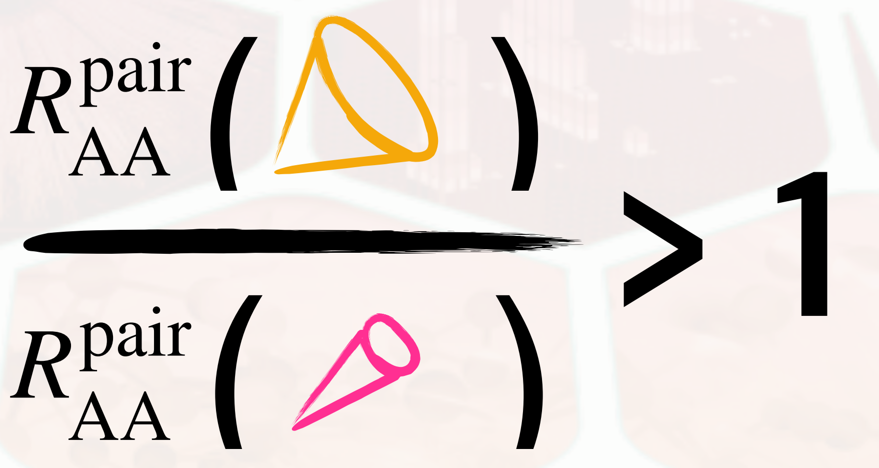

R = 0.6 jets are less suppressed compared to R = 0.2, for both leading and subleading jets in the dijet pair

How do we understand this?

Dijet vs inclusive R-dependence

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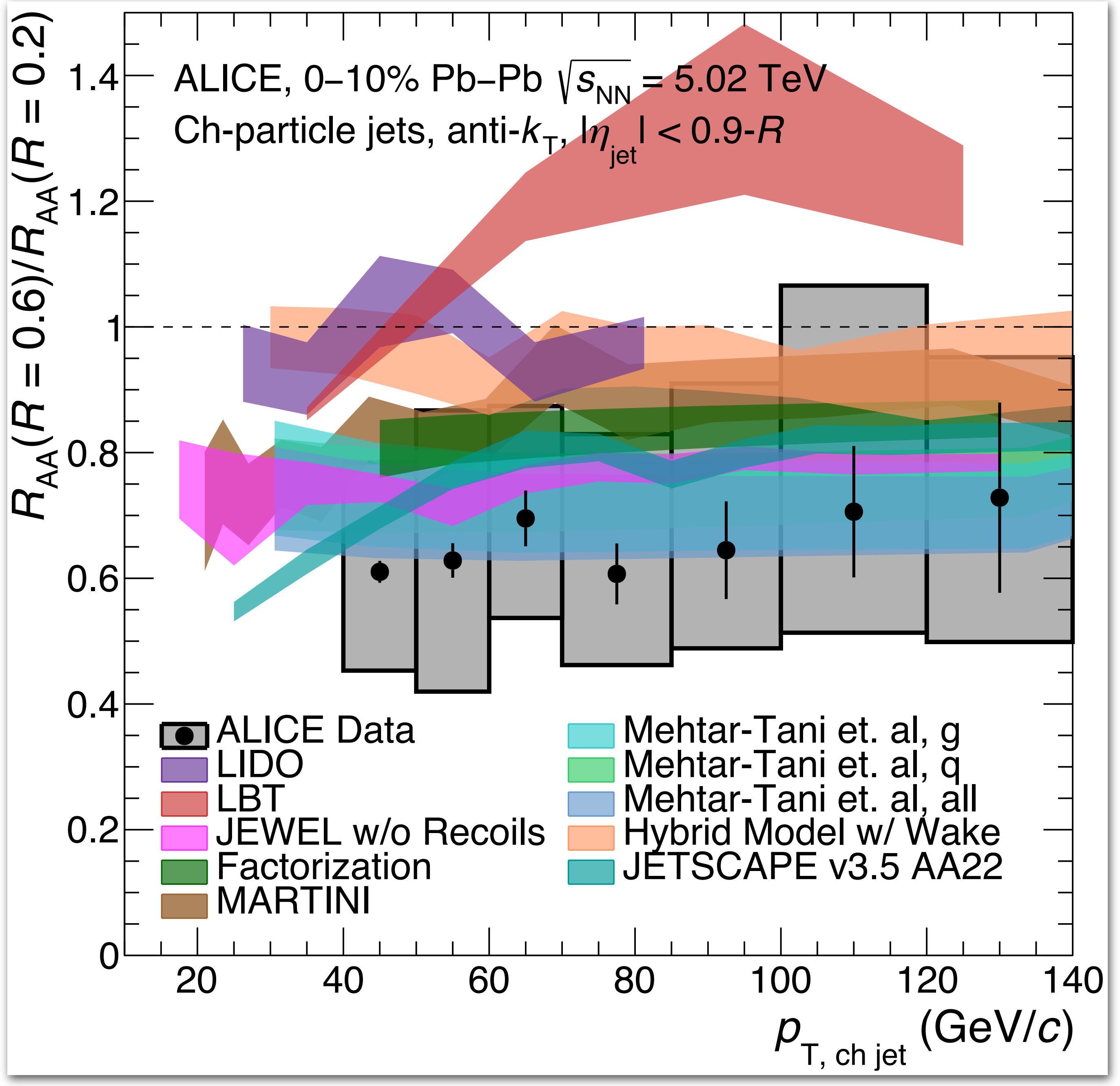
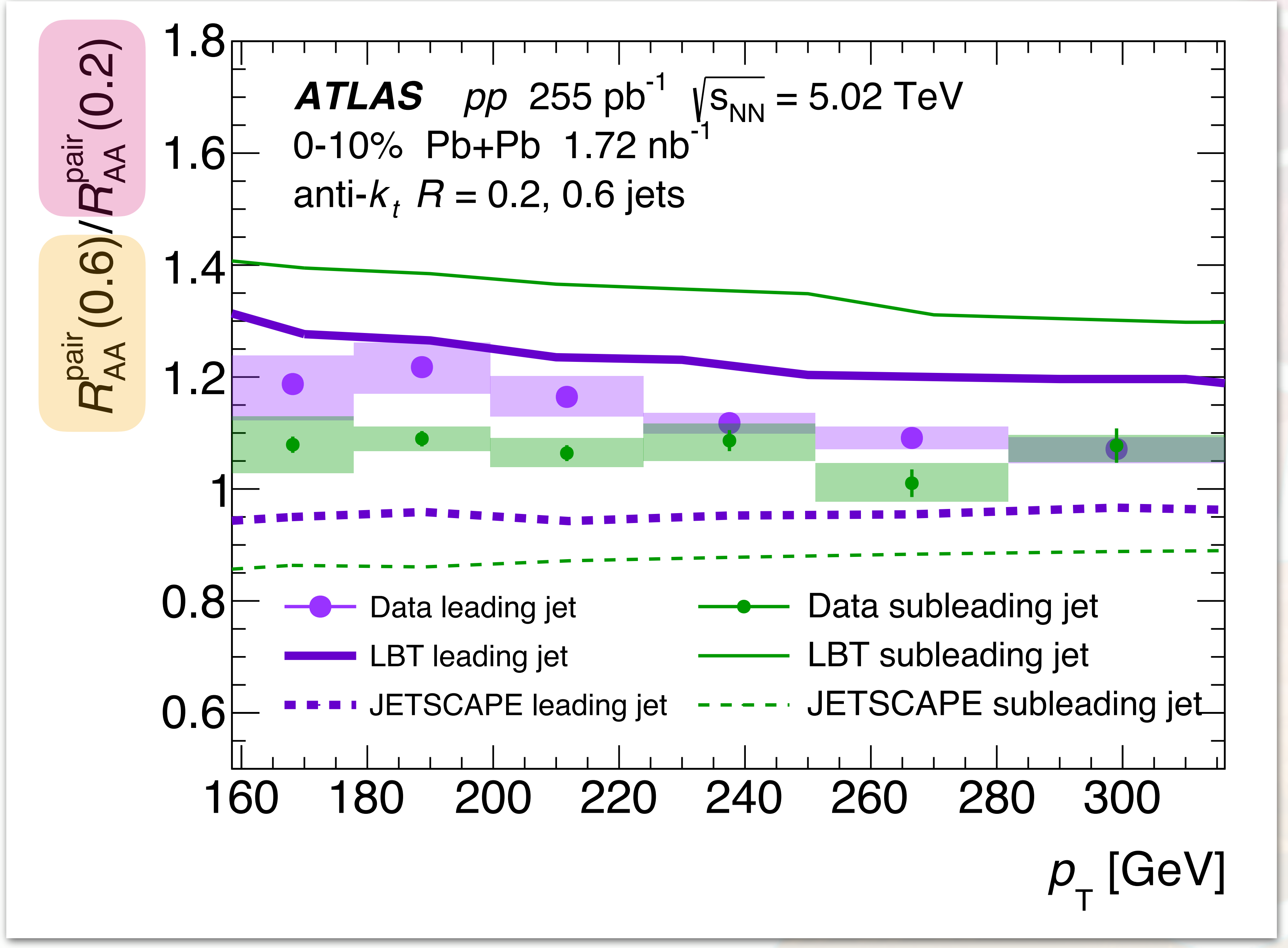


PRC 110 (2024) 054912



$$\frac{R_{AA}^{incl}(\;)}{R_{AA}^{incl}(\;)} < 1$$

$$\frac{R_{AA}^{pair}(\;)}{R_{AA}^{pair}(\;)} > 1$$

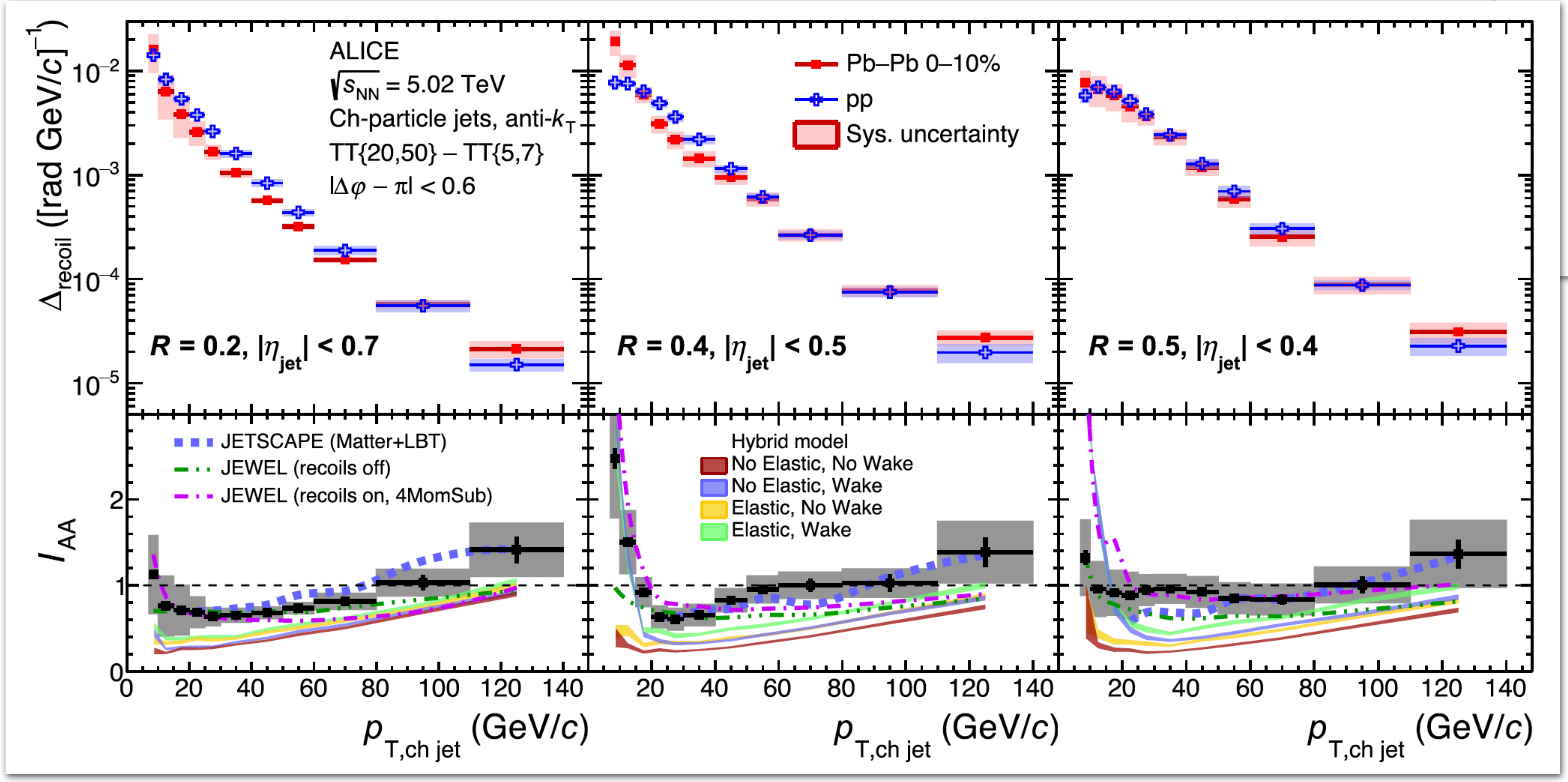
- Inclusive jets
- Charged jets
- |η| < 0.9-R

Results are not directly comparable…

- Dijets
- Calorimeter jets
- |y| < 2.1

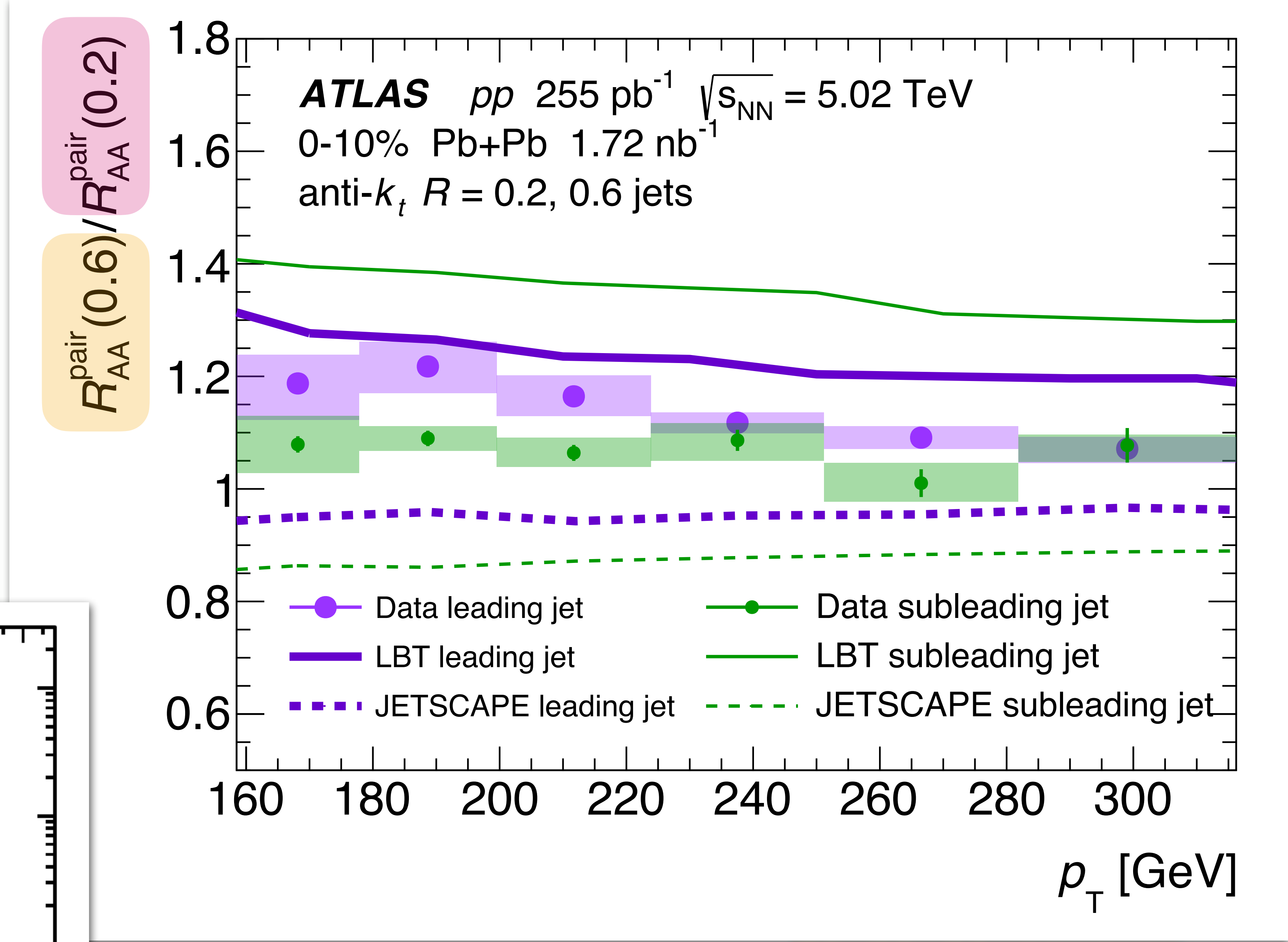
Dijet vs semi-inclusive R-dependence

$$\frac{I_{AA}^{incl}(\,\cdot\,)}{I_{AA}^{incl}(\,\cdot\,)} > 1$$



PRL 133, 022301 (2024)

PRC 110 (2024) 054912



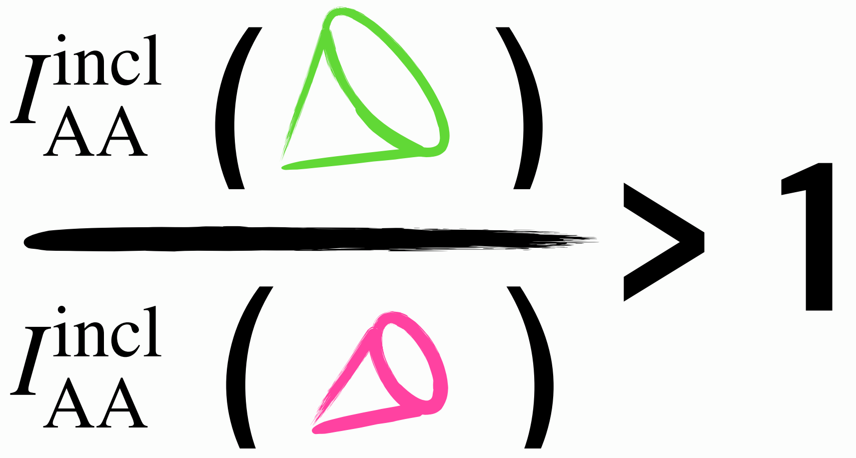
$$\frac{R_{AA}^{pair}(\,\cdot\,)}{R_{AA}^{pair}(\,\cdot\,)} > 1$$

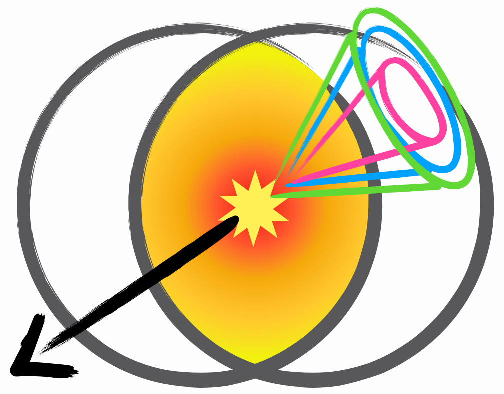
- h-triggerd jets
- Charged jets
- |η| < 0.9-R

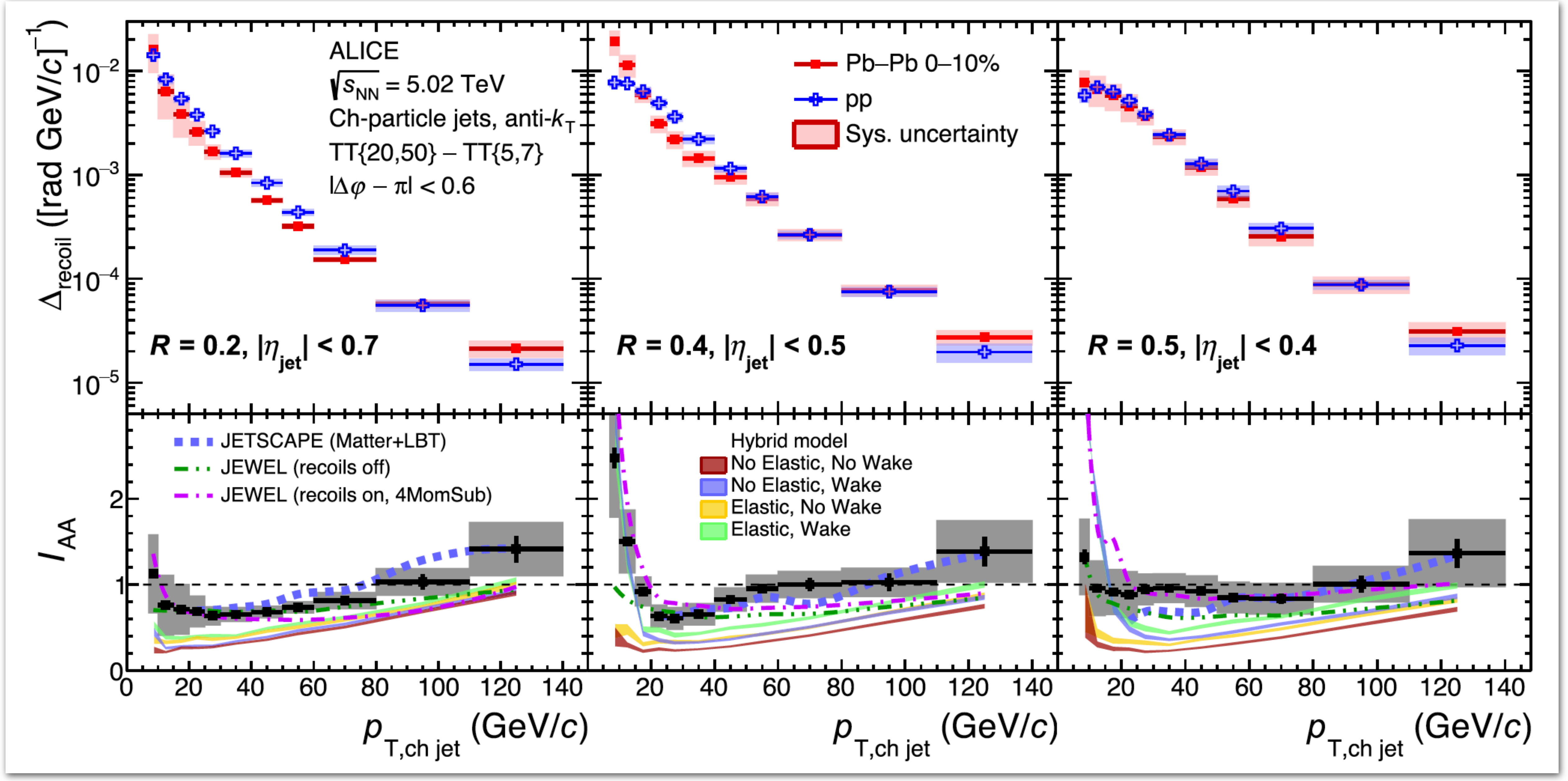
- Dijets
- Calorimeter jets
- |y| < 2.1

Similar R-depedence in this case…

A nice puzzle to play with







PRL 133, 022301 (2024)

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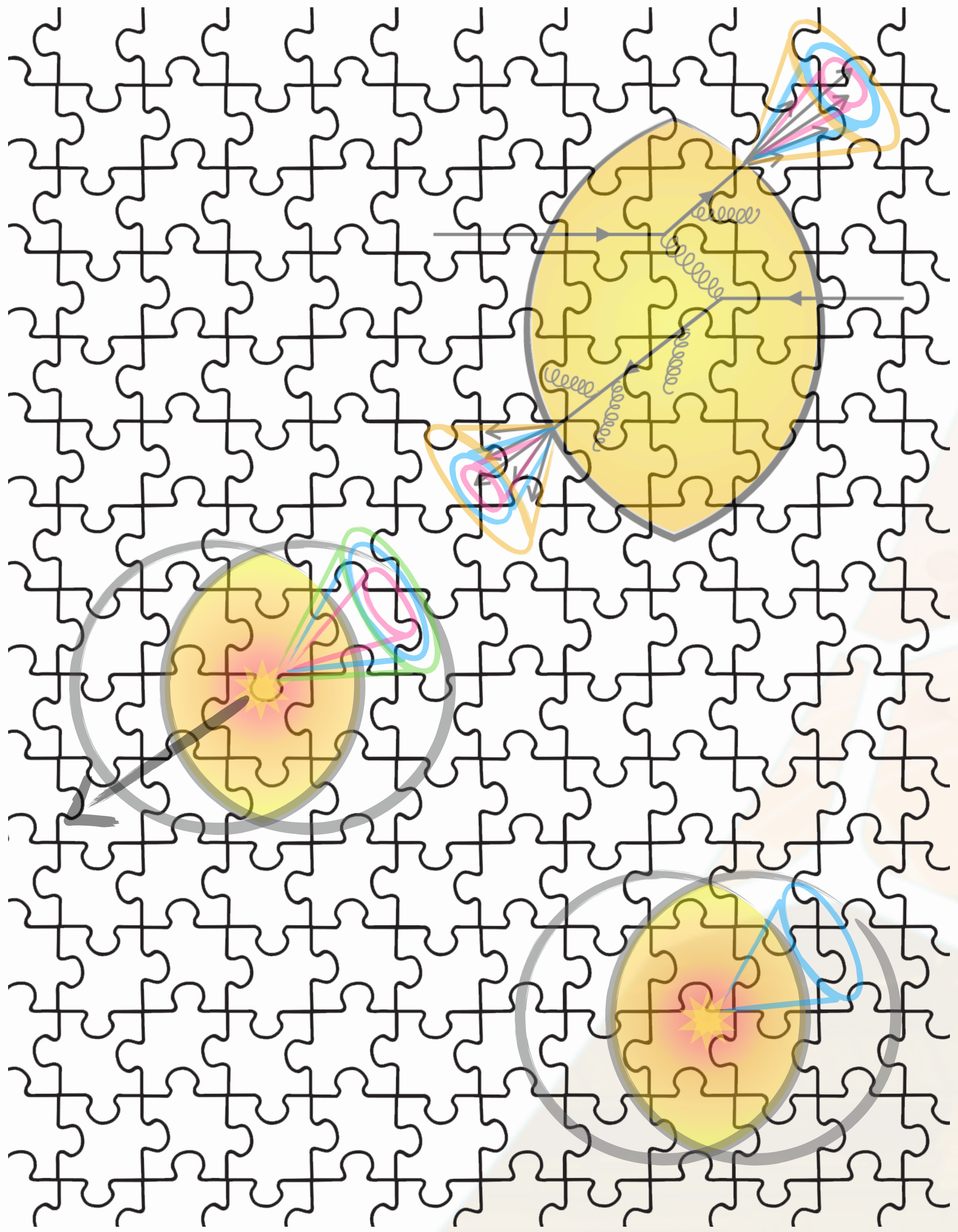

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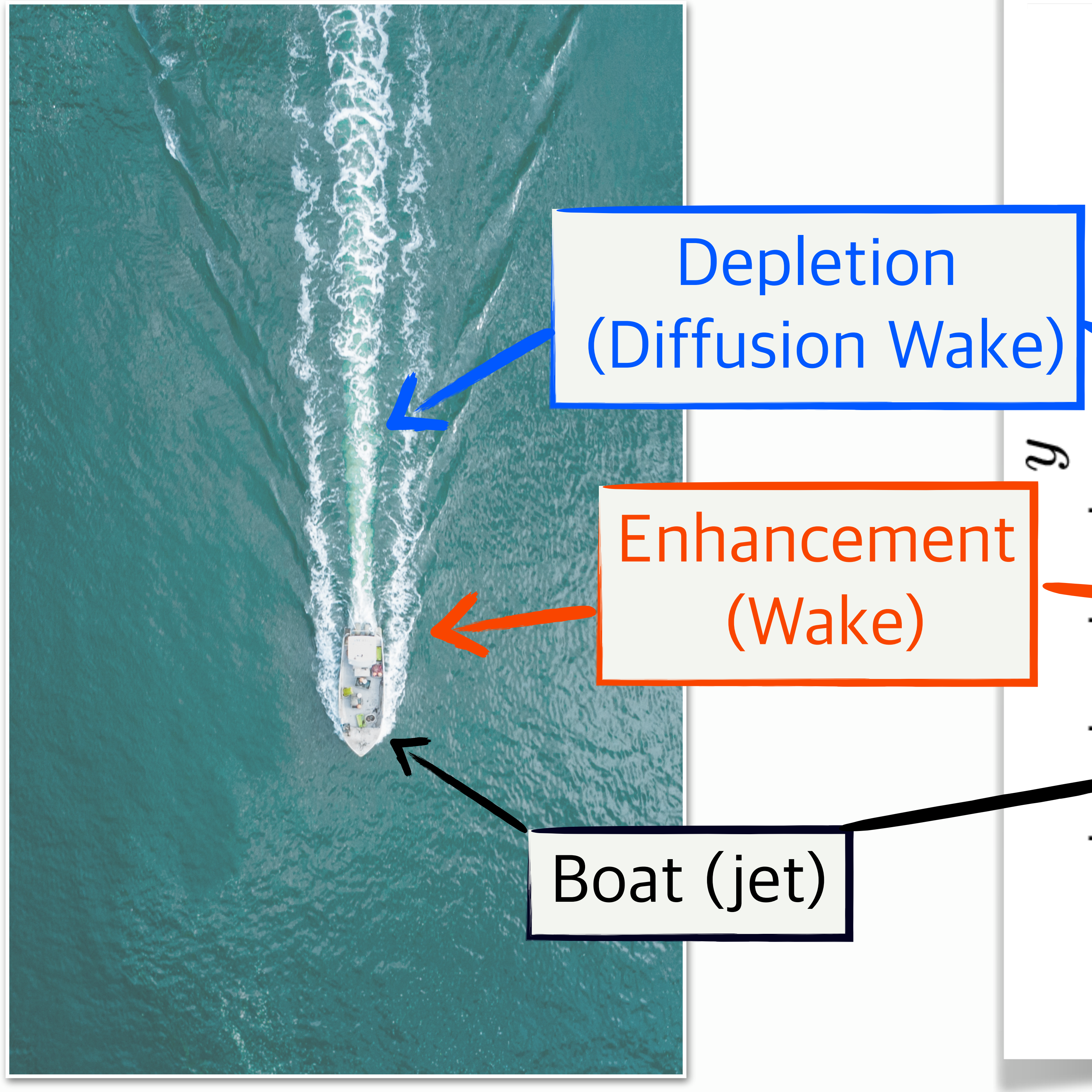
How do we understand this?

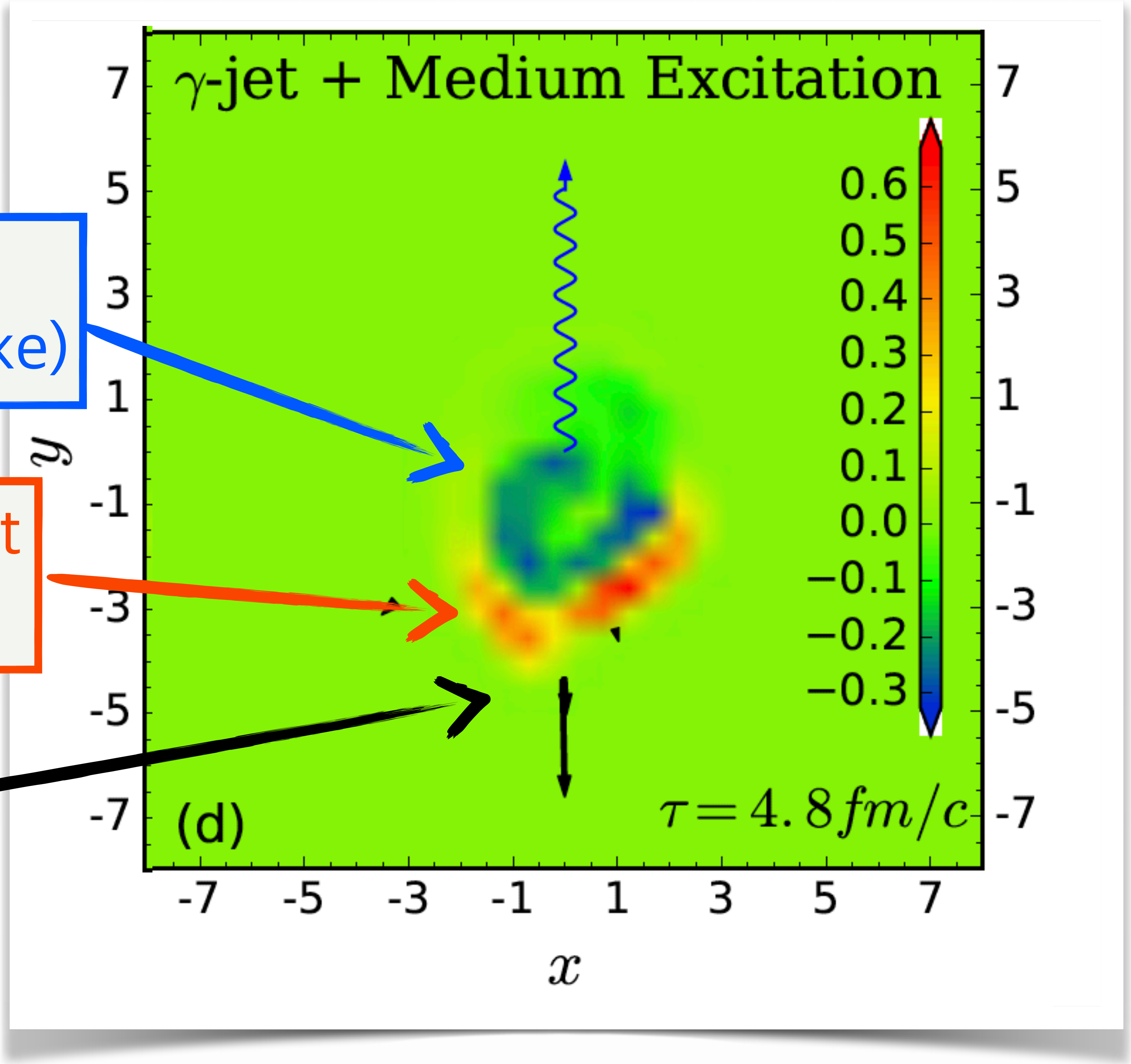
We have all the pieces to assemble the puzzle!

Medium response

The medium modifies jets, but how is the medium modified by the jets?

Waking the medium in different modes

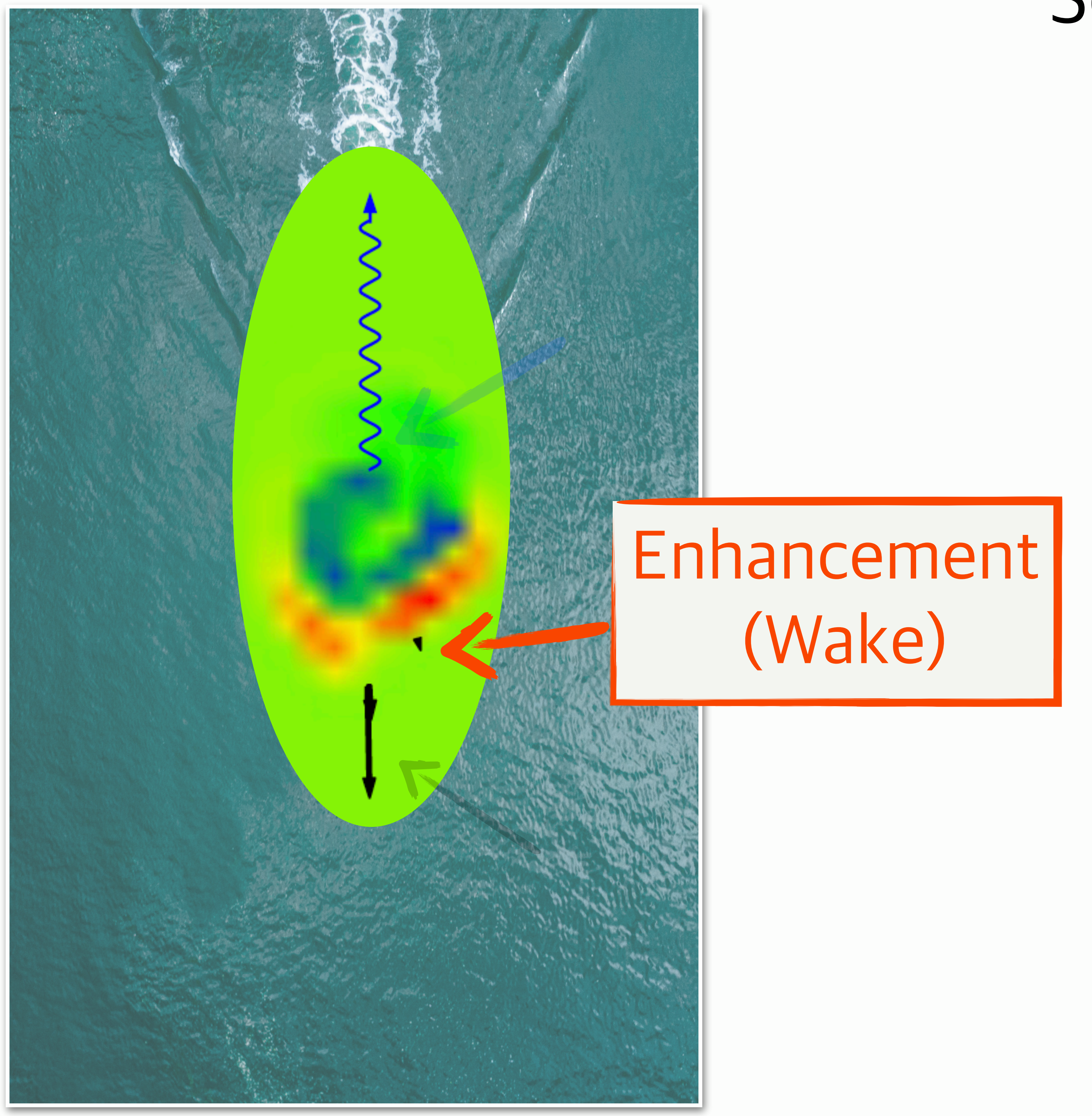




Phys.Lett.B 777 (2018) 86-90

A parton plowing through the medium induces different response in it

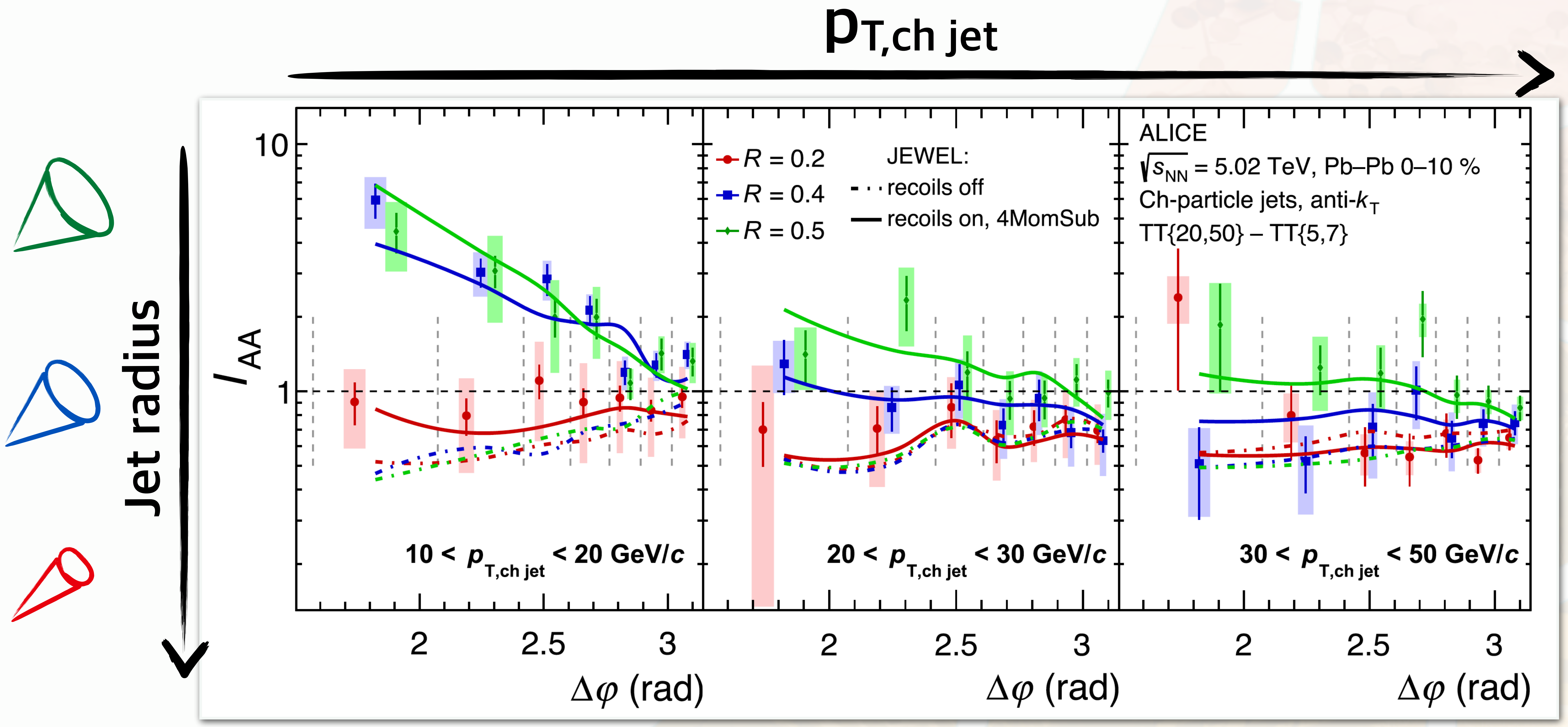
The Wake



Several experimental evidences of a wake effect in the direction of the jet

See for instance ATLAS PRL 126 (2021) 072301 and CMS PRL 128 (2022) 122301 for evidence of jet wake in Z+h events

Furher more recently - for instance ALICE in jet+h measurements



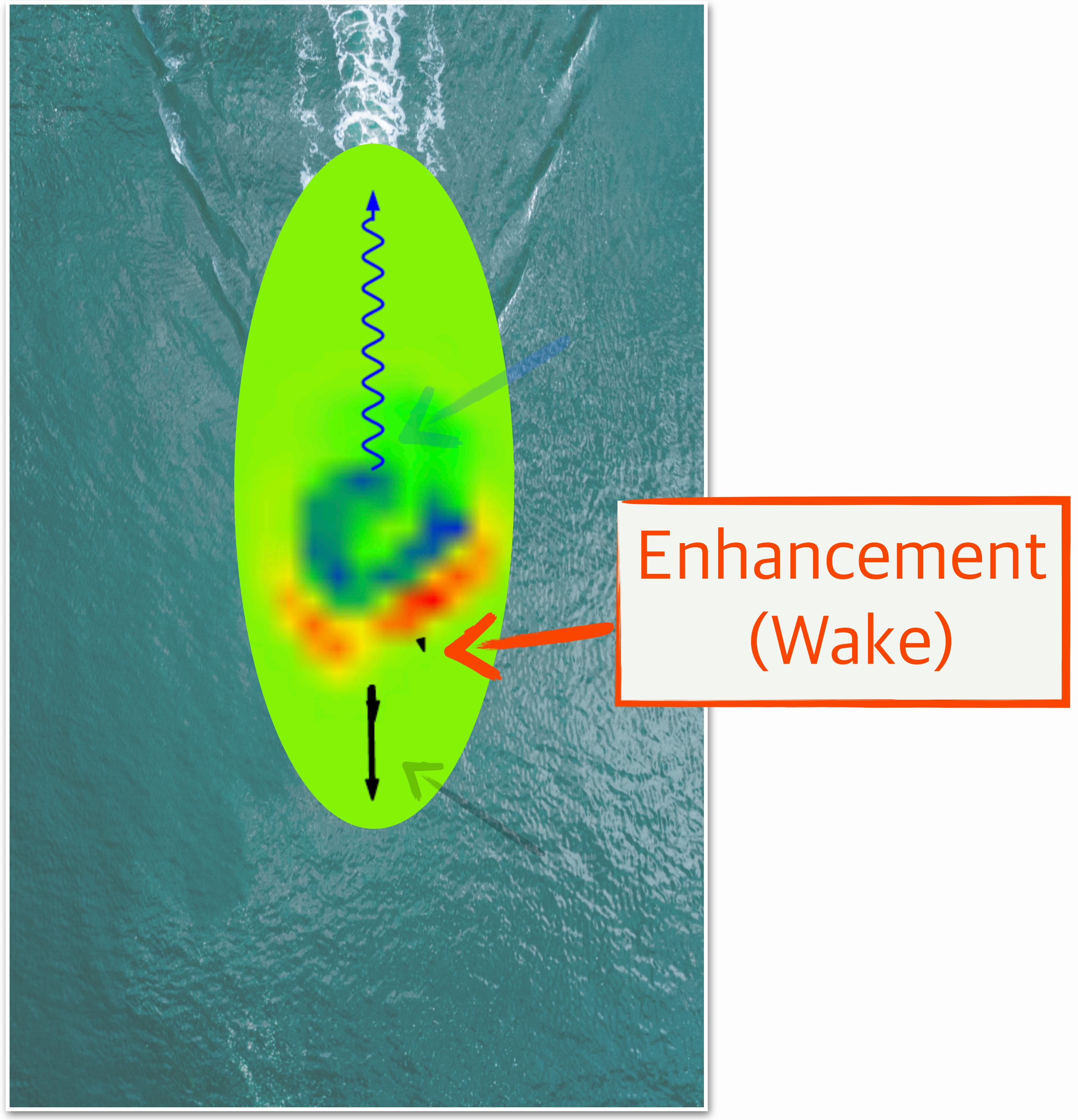
ALICE PRL 133, 022301 (2024)

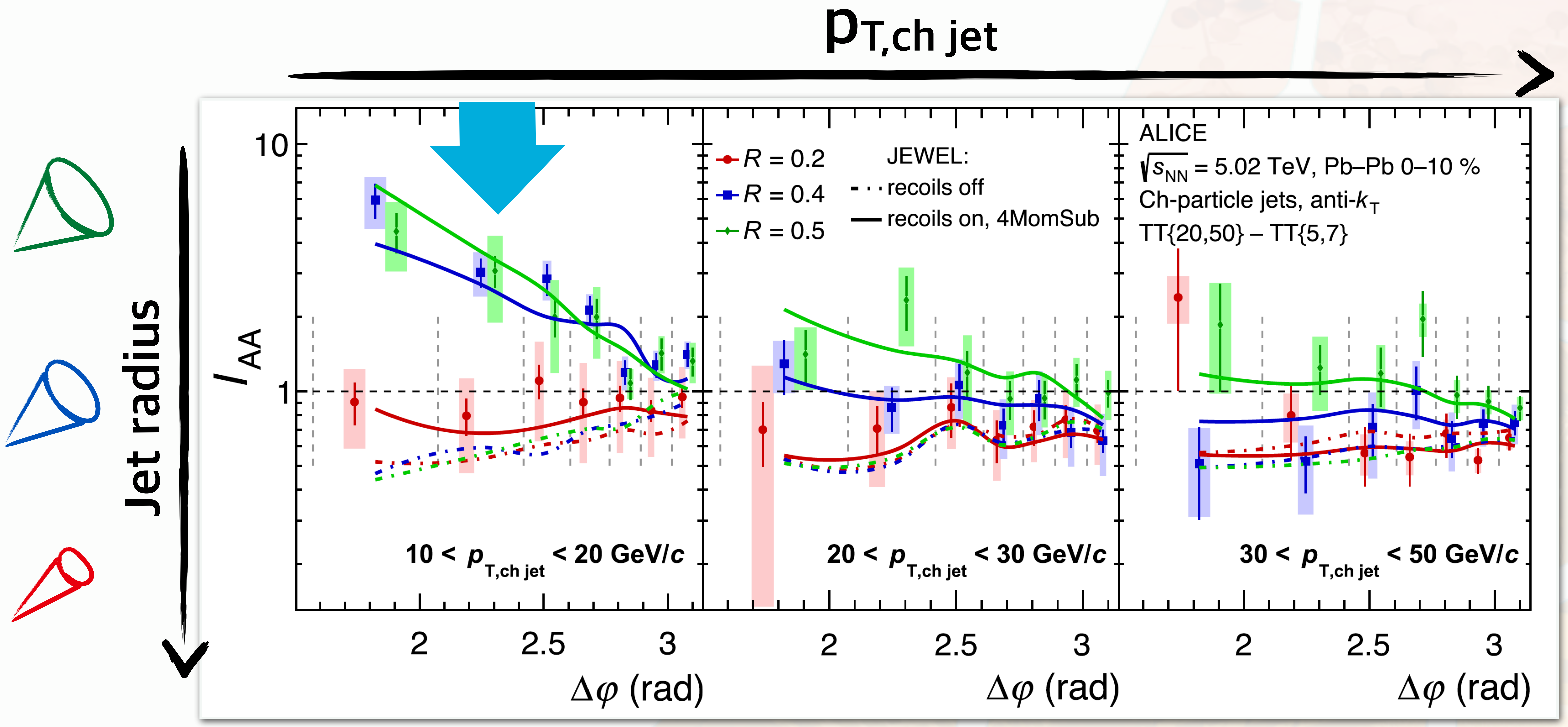
The Wake

Azimuthal decorrelation at low (< 20 GeV) $p_{T,ch\ jet}$ for R >= 0.4

JEWEL+recoils on describe this data but not inclusive results

Decorrelation possibly due to recapturing of radiation from the wake at larger R? Recent similar results by STAR in γ+jet and π^0+jet





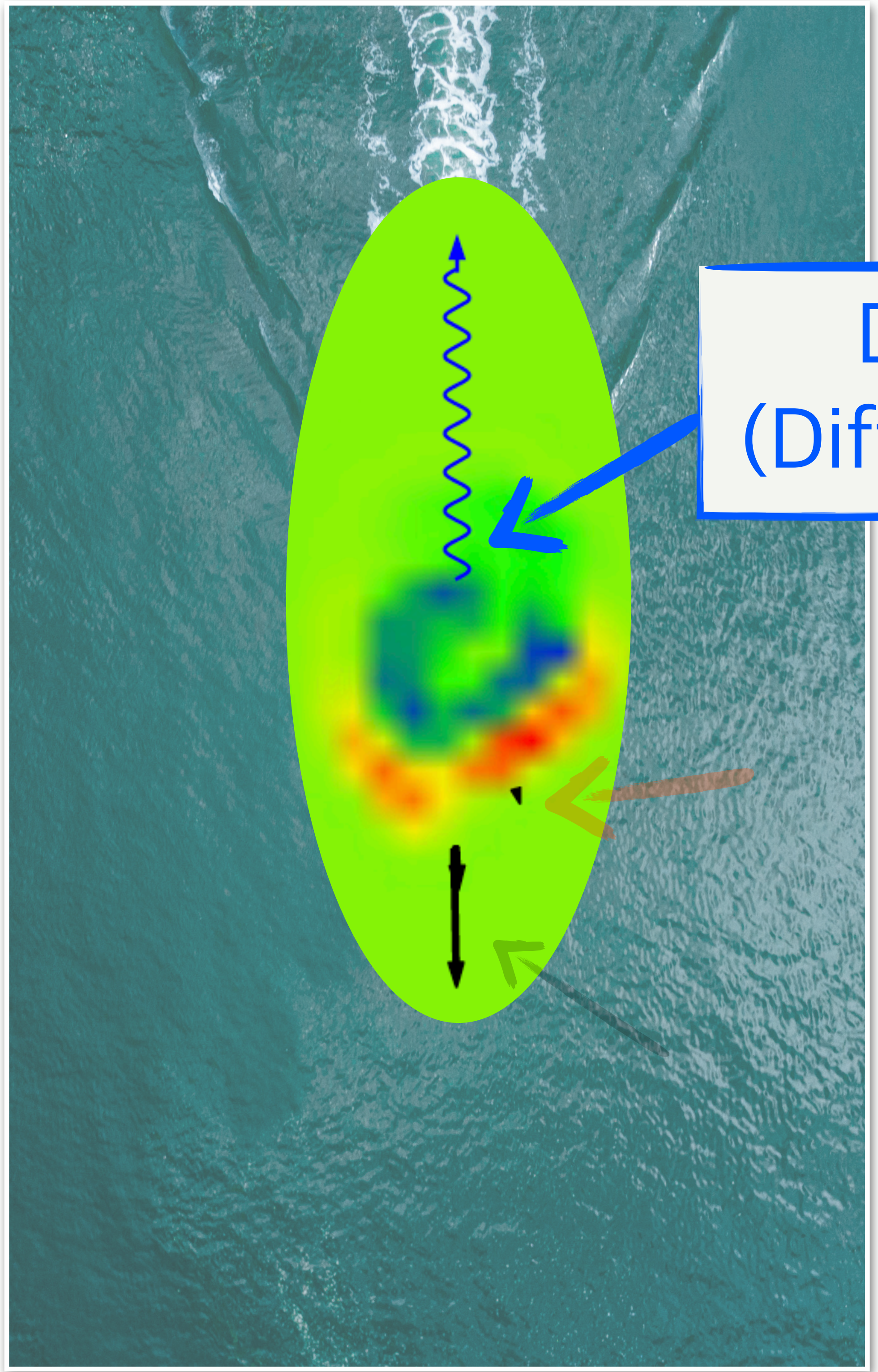
PRL 133, 022301 (2024)

The Diffusion Wake

Ideal measurement setting: **boson+jet system**

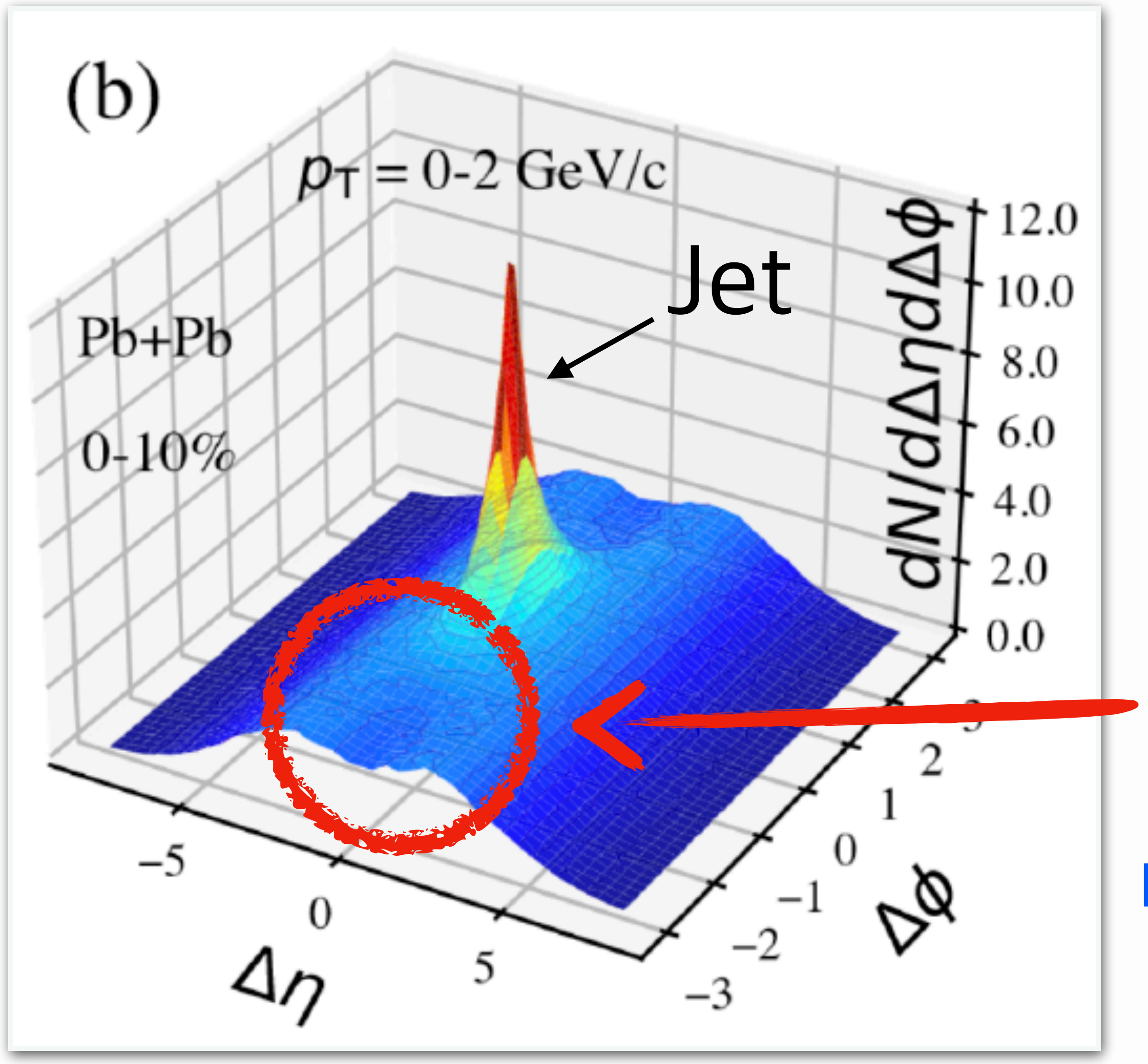
Experimental signature: depletion in particle production in the boson direction

Very **elusive signal** (<~ 1 particle depletion per unit of ϕ and η)



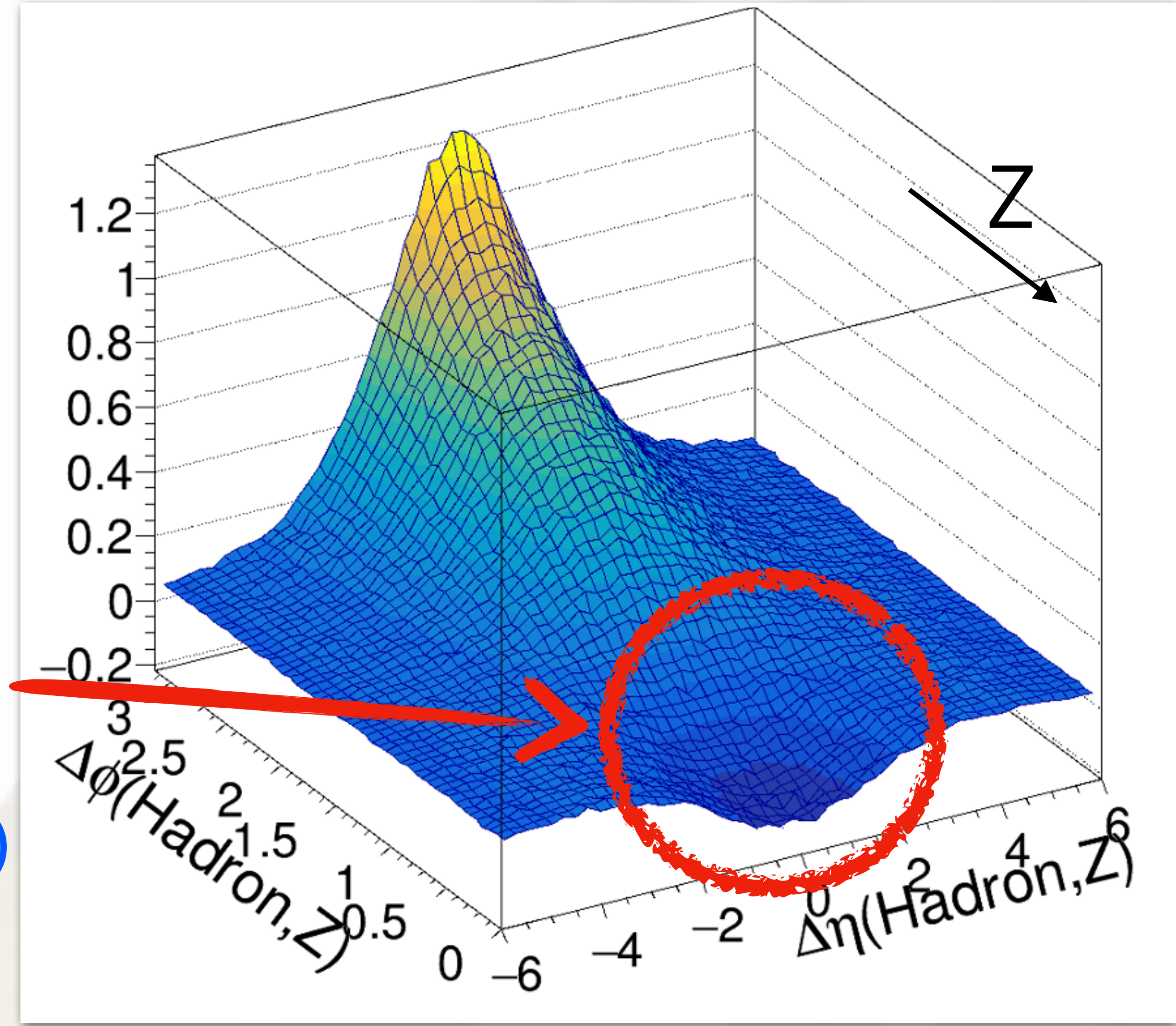
Depletion (Diffusion Wake)

PRL 130, 052301 (2023), CoLBT



Diffusion wake signal (very different magnitudes)

Pablos, Rajagopal, Lee



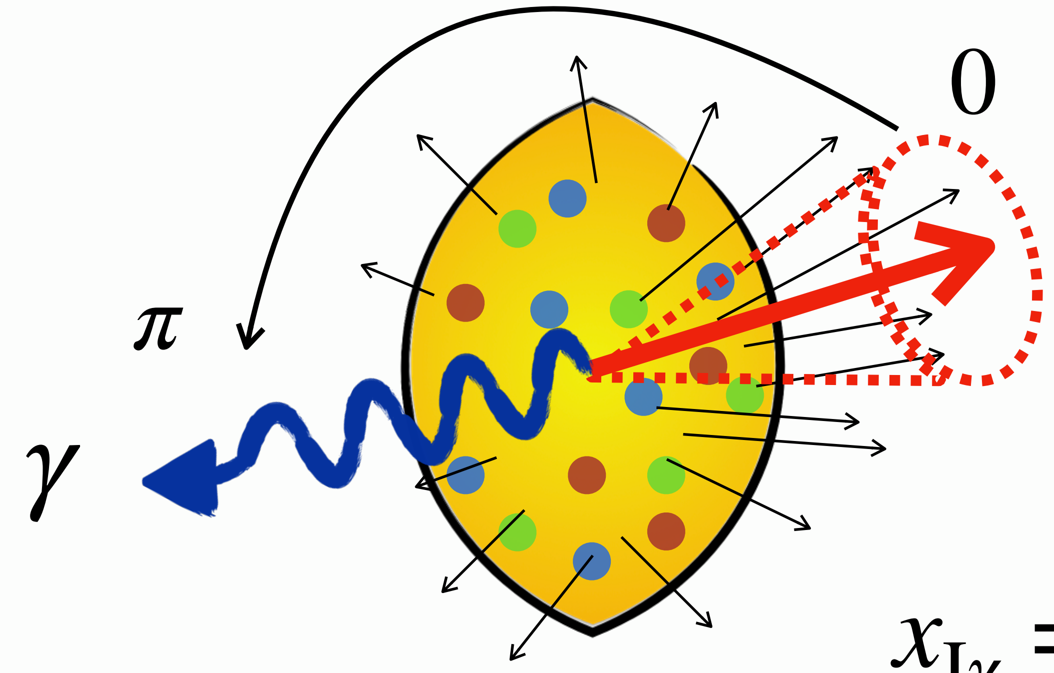
Photon-jet momentum balance ($x_{J\gamma}$) provides control on energy deposited in the medium quenching

Do not require the jet to allow access to events where it was most suppressed. Control on medium via centrality

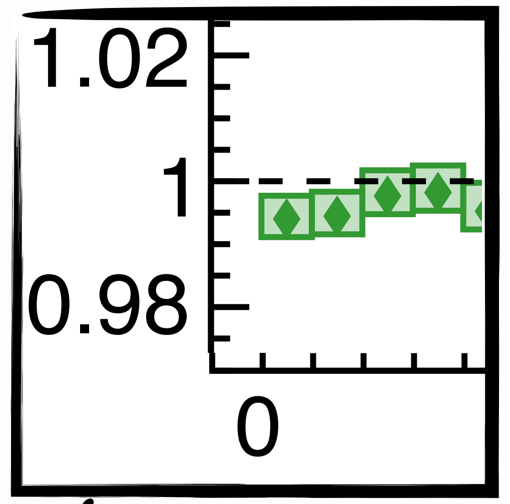
Diffusion Wake: ATLAS γ+jet results

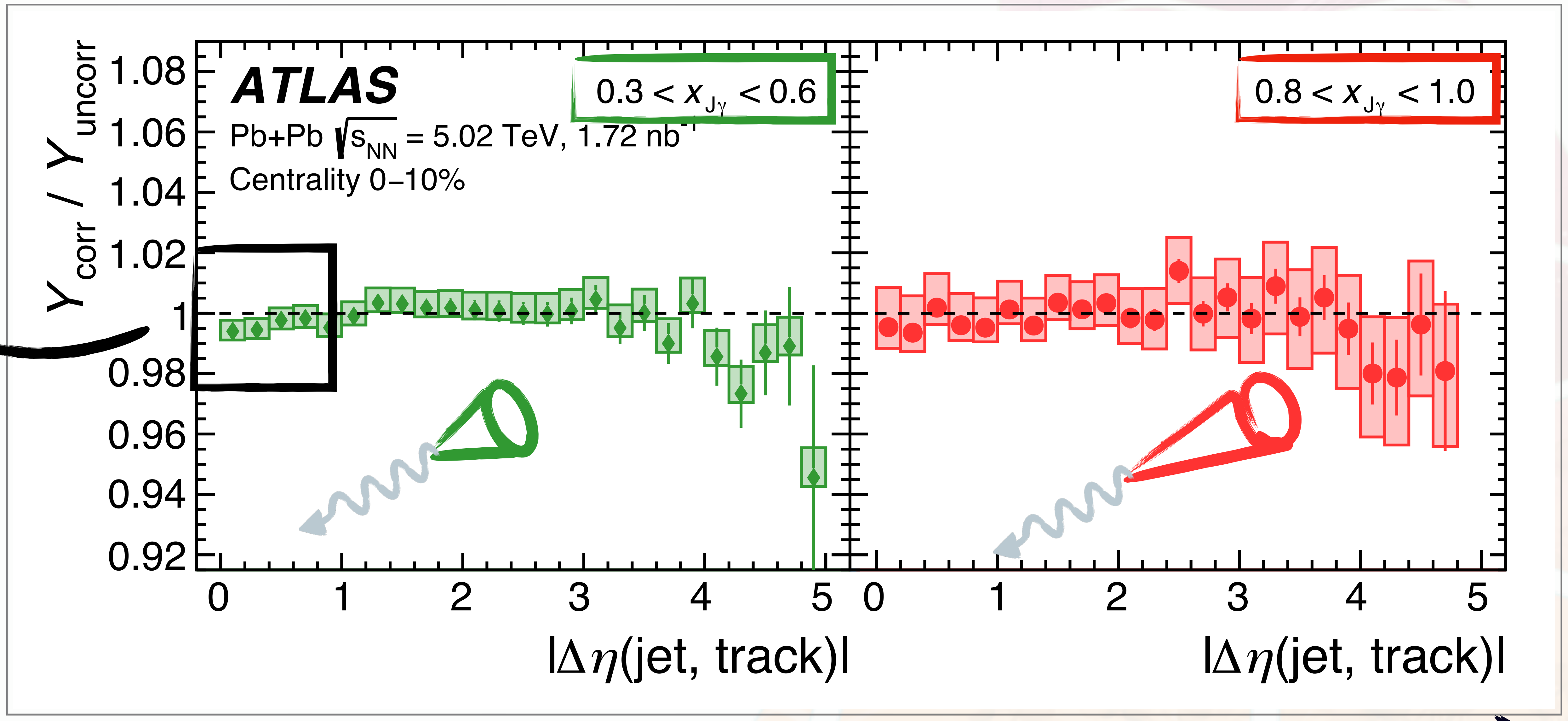
$\Delta\phi(h,\text{jet}), \Delta\eta(h,\text{jet})$

Phys. Rev. C 111 (2025) 044909

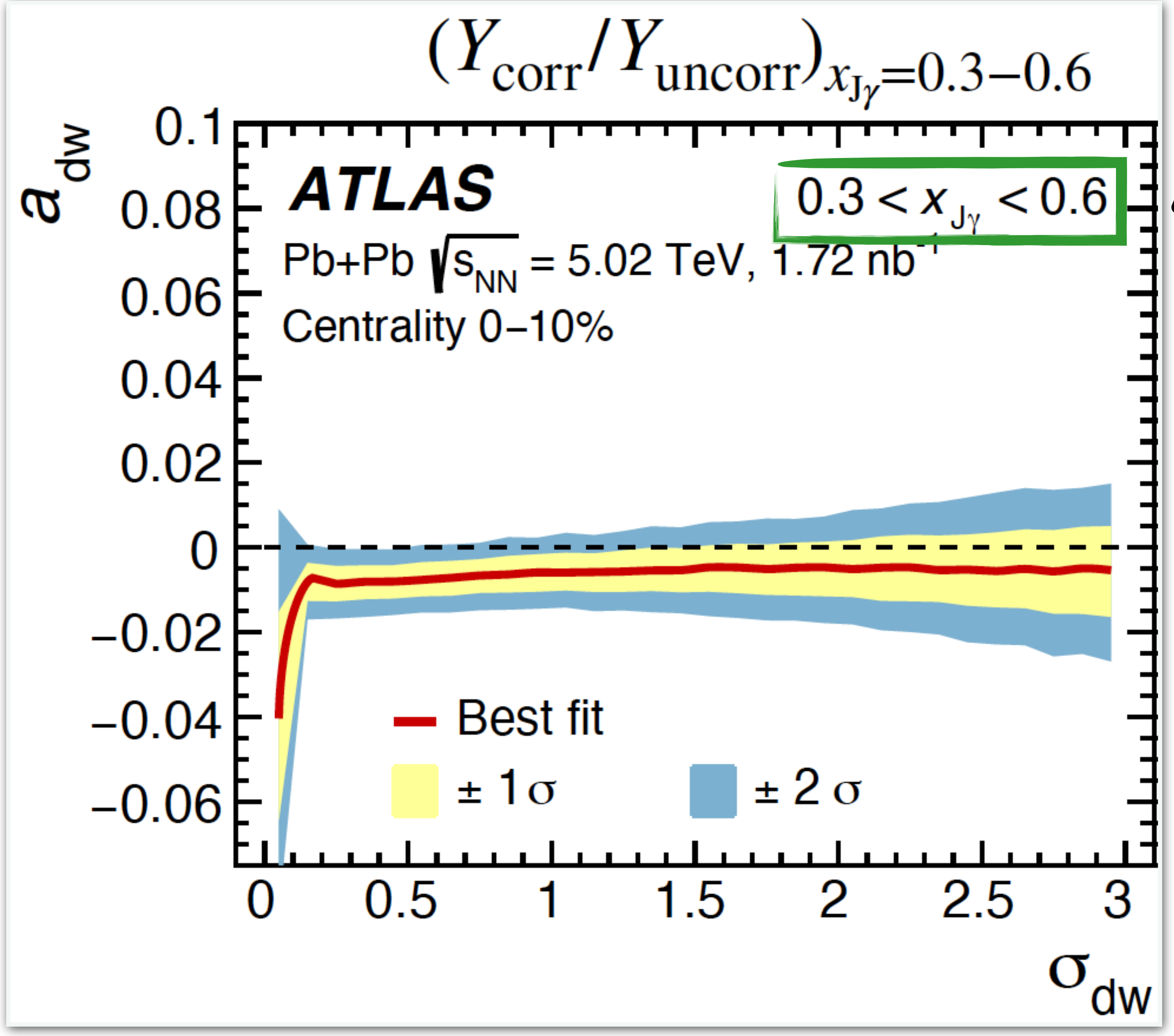


$$x_{J\gamma} = \frac{p_T^{\text{jet}}}{p_T^{\gamma}}$$





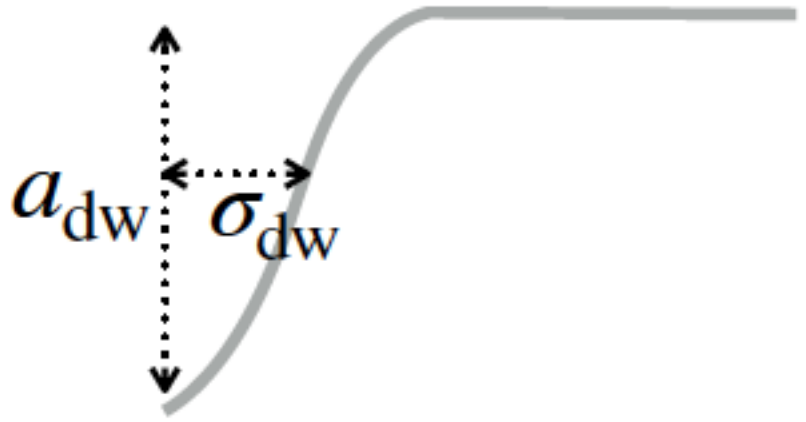
$x_{J\gamma}$



Is this a significant depletion?

Diffusion Wake Amplitude — Diffusion Wake Width

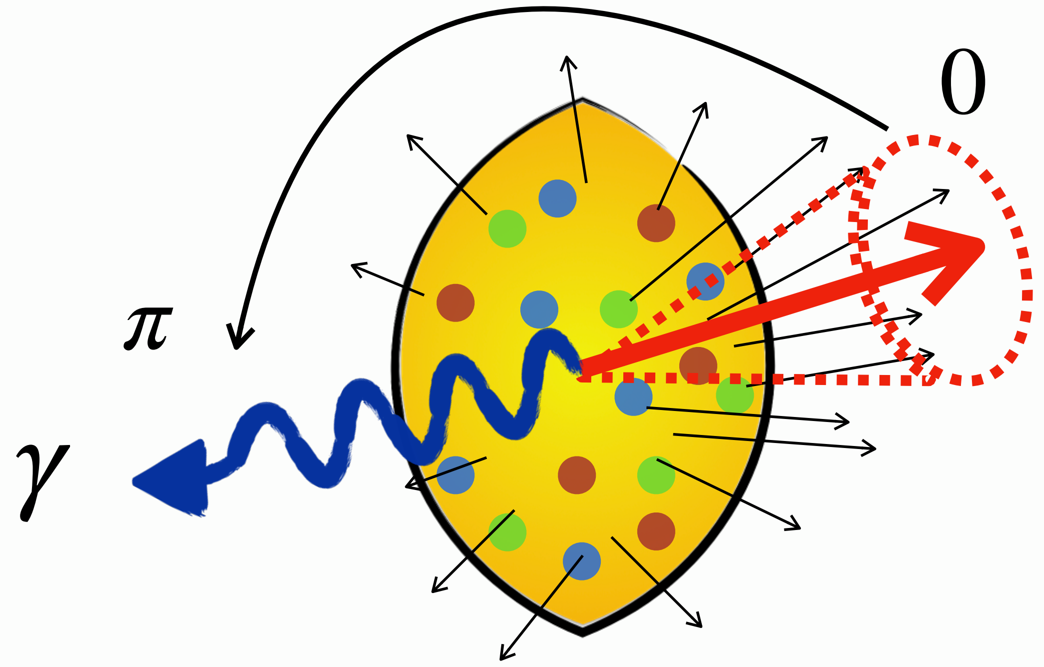
$$a_0 + a_{dw} \cdot e^{-|\Delta\eta(\text{jet,track})|^2/(2\sigma_{dw}^2)}$$

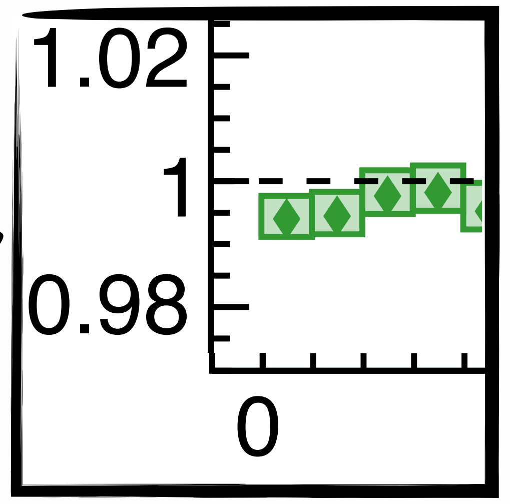


The **best fit** of the **diffusion wake amplitude** for the lowest $x_{J\gamma}$ (highest energy deposition in the medium) is about **0.5-0.8%** for the diffusion wake width range of 0.5-1.0.

How many particles?

$\Delta\phi(h,\text{jet}), \Delta\eta(h,\text{jet})$ Phys. Rev. C 111 (2025) 044909

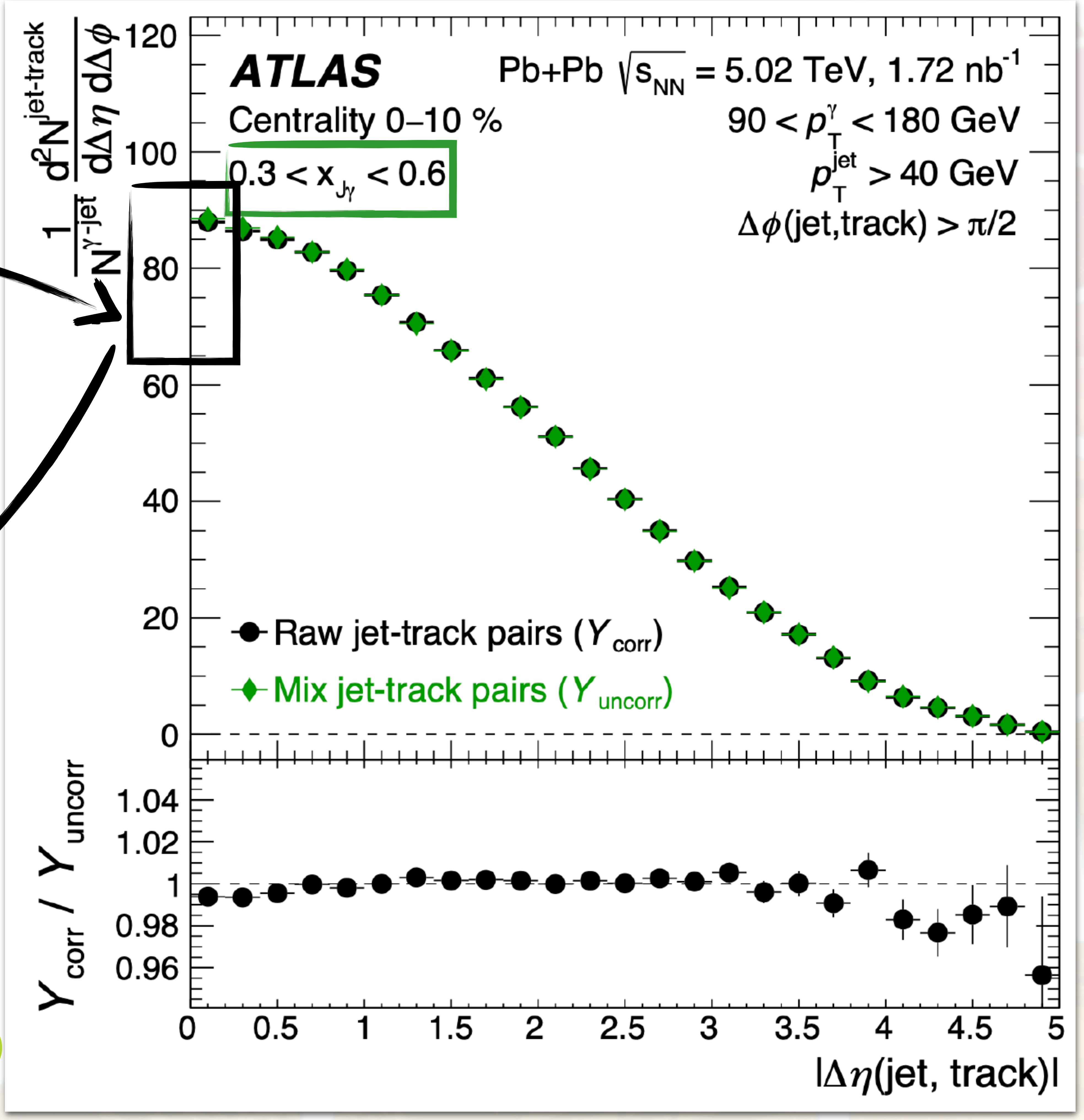




$$\frac{Y_{\text{corr}}}{Y_{\text{uncorr}}} - 1 \sim 0.5 - 0.8\,\%\ \text{at}\ |\Delta\eta(\text{jet, track})| \sim 0$$

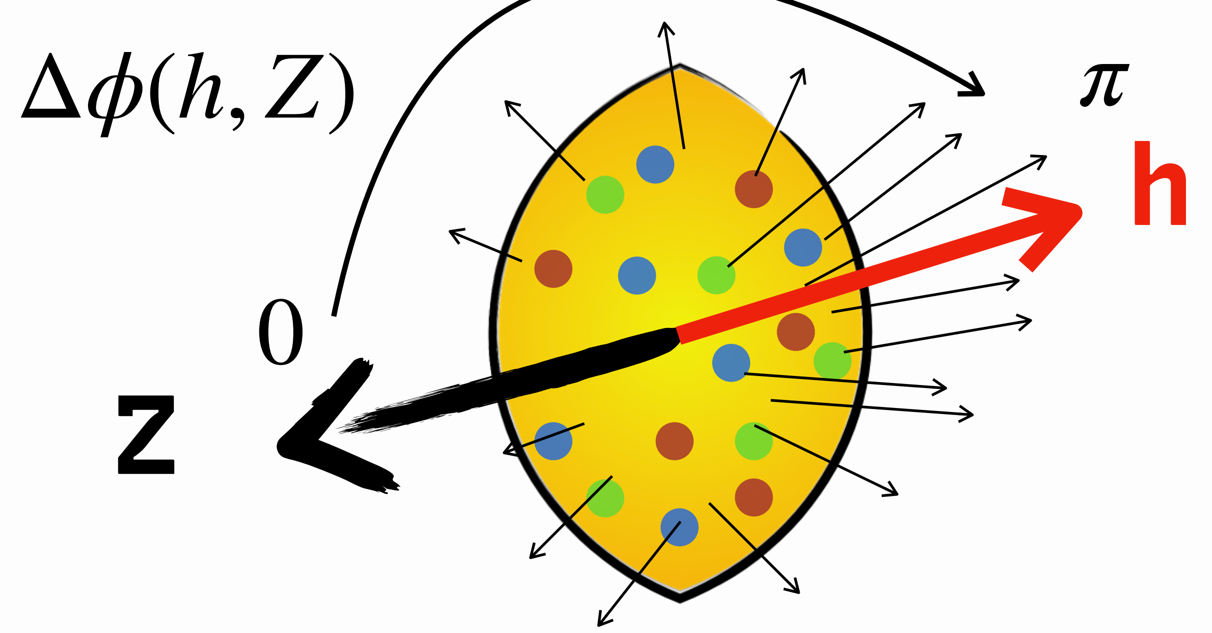
$$\frac{1}{N^{\gamma-\text{jet}}} \frac{d^2 N^{\text{jet}-\text{track}}}{d\Delta\eta d\phi} \sim 90\ \text{at}\ |\Delta\eta(\text{jet, track})| \sim 0$$

If there is a diffusion wake, 0.45-0.75 particles per unit of η, ϕ are reduced by it



Diffusion wake: CMS Z+h results

CMS-PAS-HIN-23-006



Double differential absolute measurement of $\Delta N_{\mathrm{ch}} = S - B$

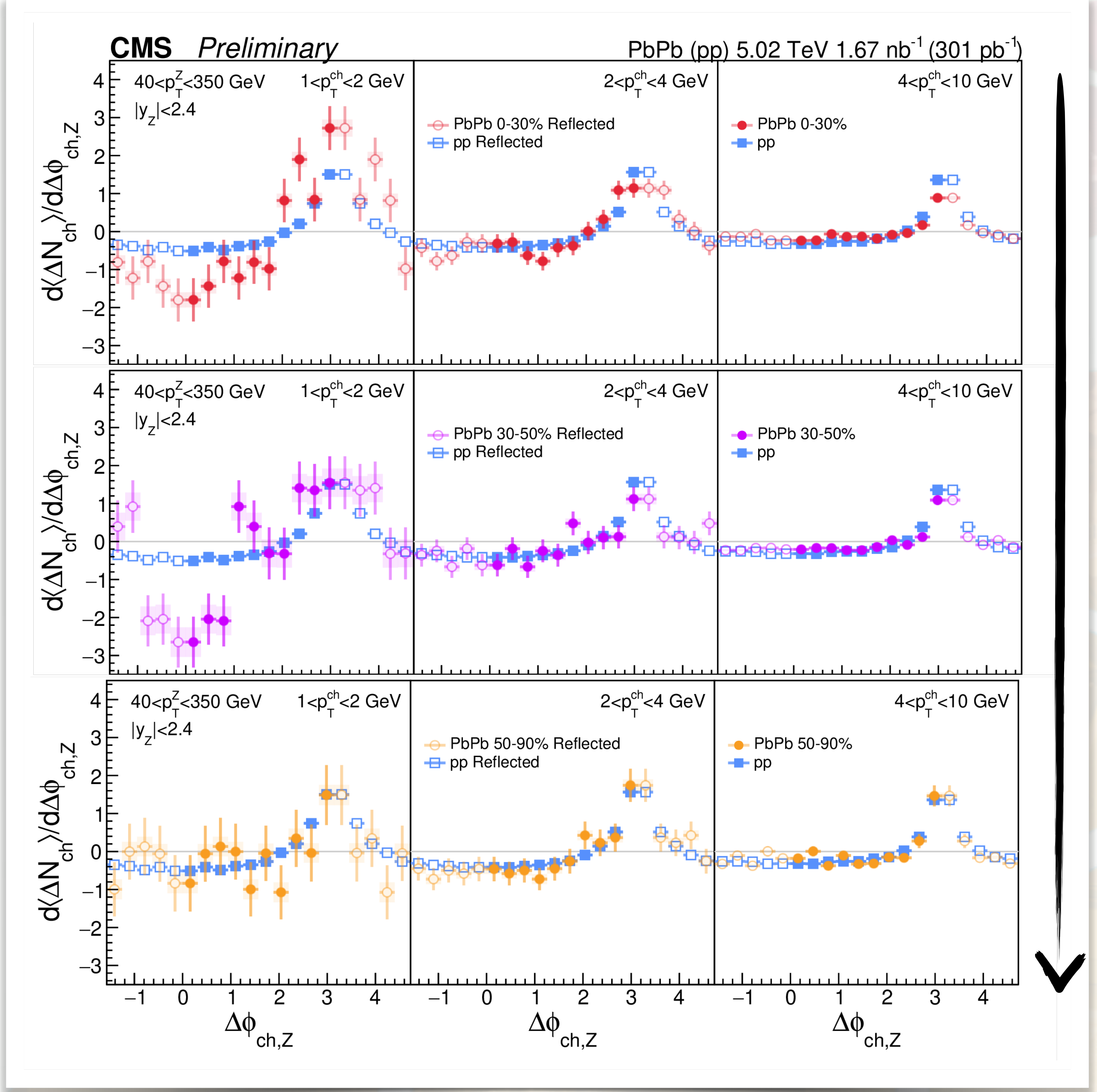
$\frac{d\langle \Delta N_{\mathrm{ch}} \rangle}{d\Delta\phi_{\mathrm{ch,Z}}}$ or $\frac{d\langle \Delta N_{\mathrm{ch}} \rangle}{d\Delta y_{\mathrm{ch,Z}}}$ In different selections of $p_{\mathrm{T}}^{\mathrm{ch}}$

Integral over the phase space set to 0

Distributions capture modification due to wake and diffusion wake simultaneously
=> Wake observation relies on modeling of the shape

Hadron p_T selection

Centrality

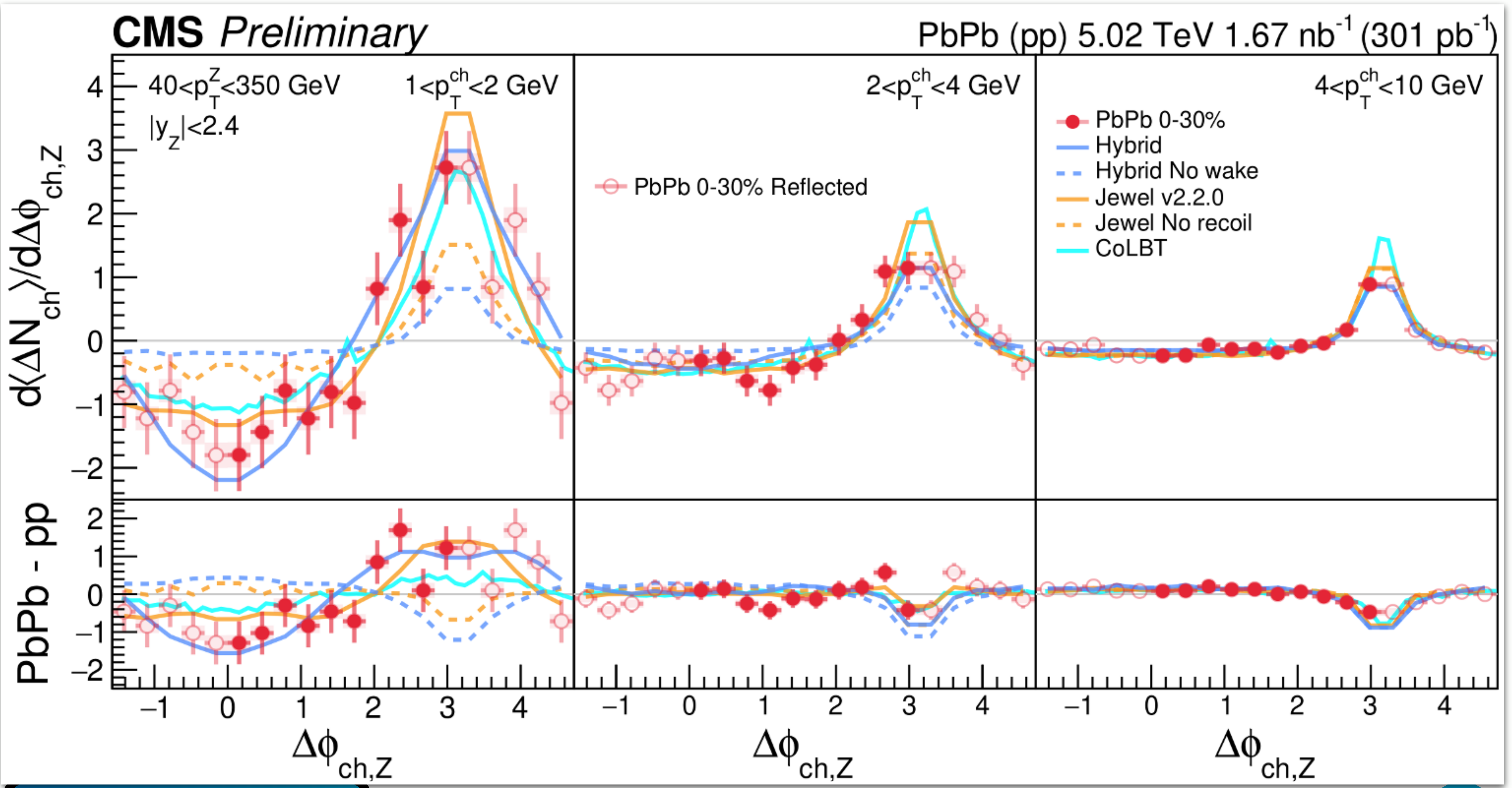


Diffusion wake: CMS Z+h results

CMS-PAS-HIN-23-006

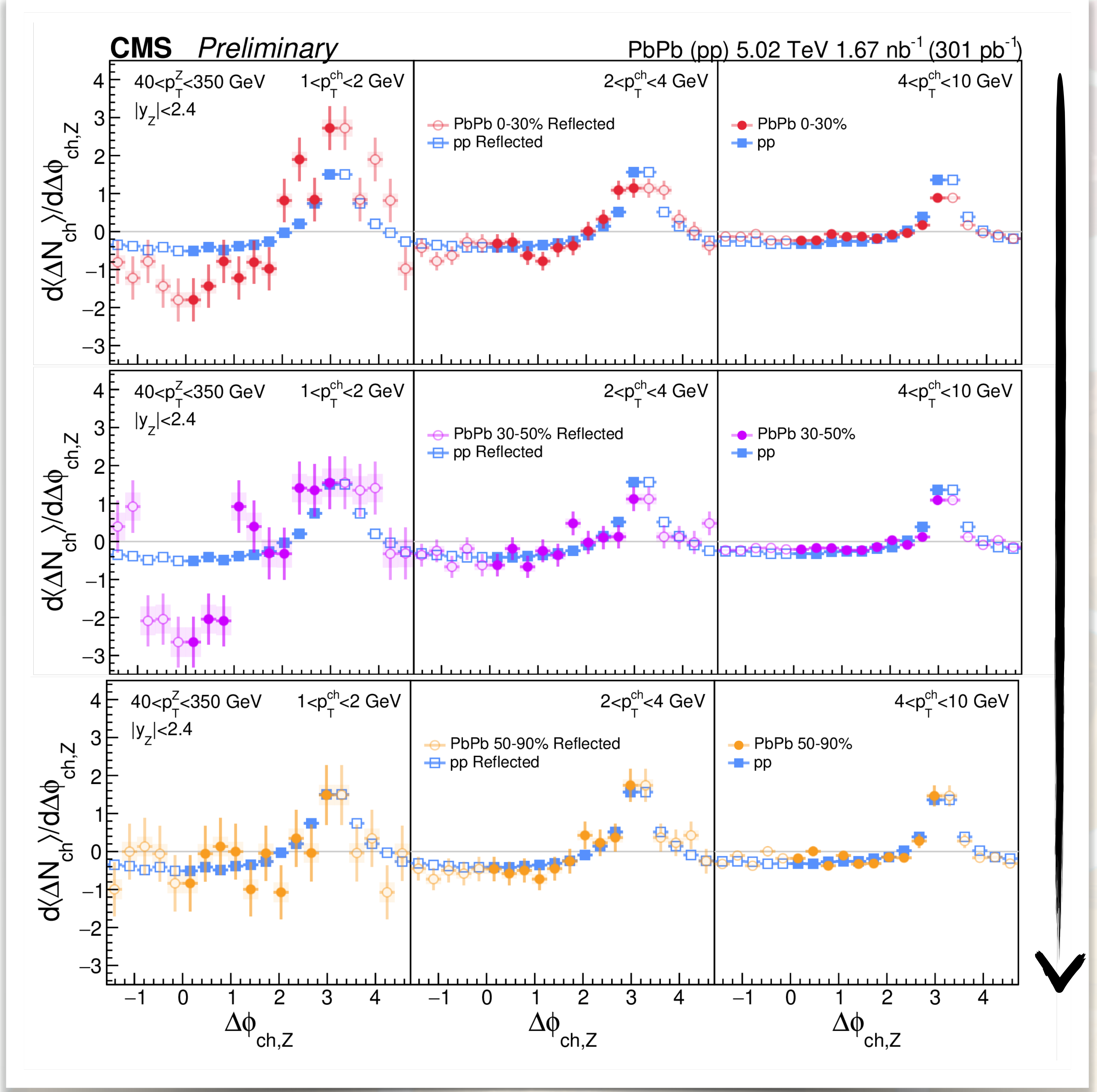
Checking most central events

- **Models w/o medium response** (dashed lines) underpredict magnitude at low hadron p_T
- Hybrid with wake, Jewel with recoil, and CoLBT with wake (solid lines) agree better with data for hadron p_T < 4 GeV



Hadron p_T selection

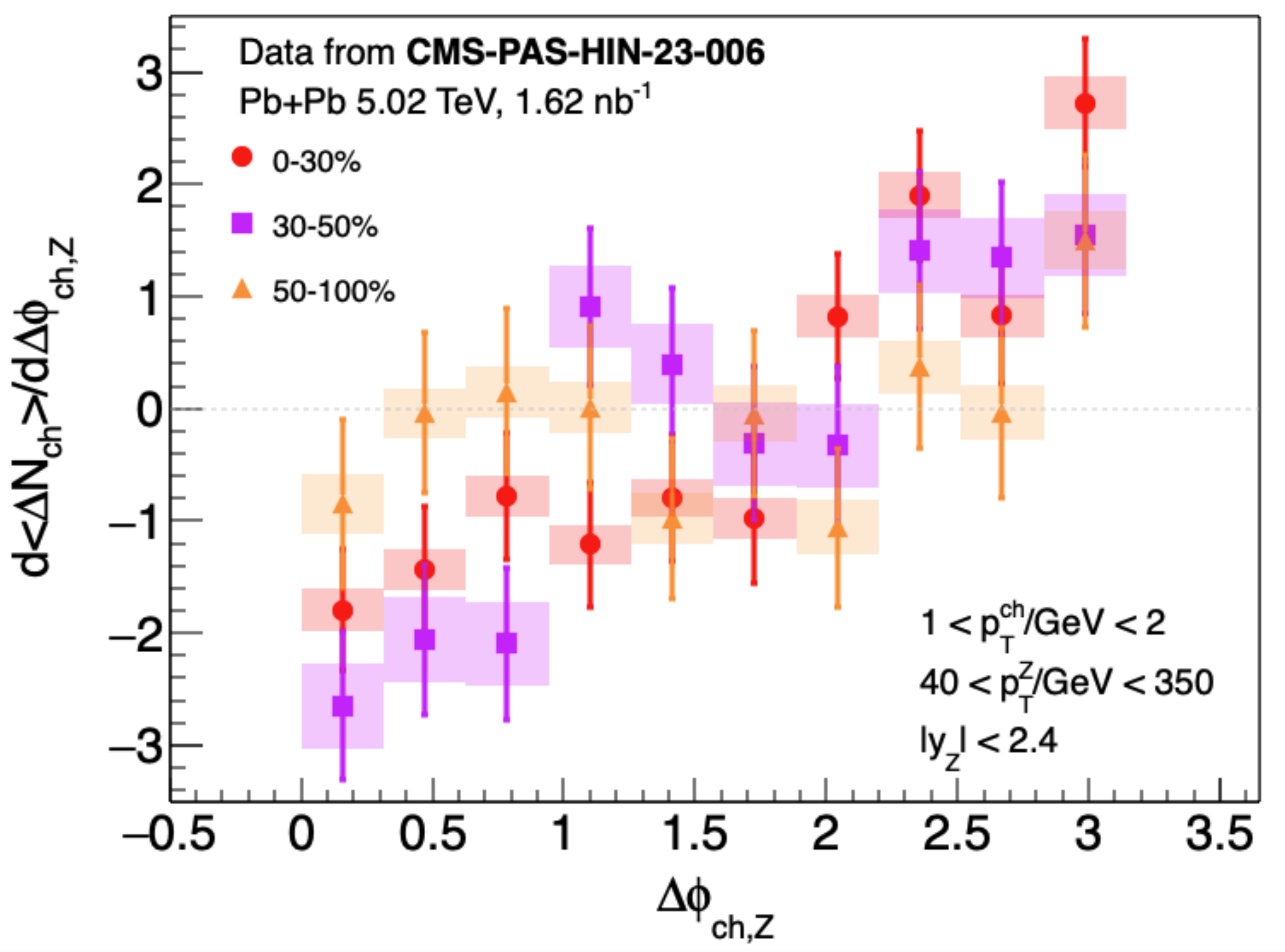
Centrality



Diffusion wake: CMS Z+h results

CMS-PAS-HIN-23-006

But other interesting features still to be understood…



…e.g. centrality ordering

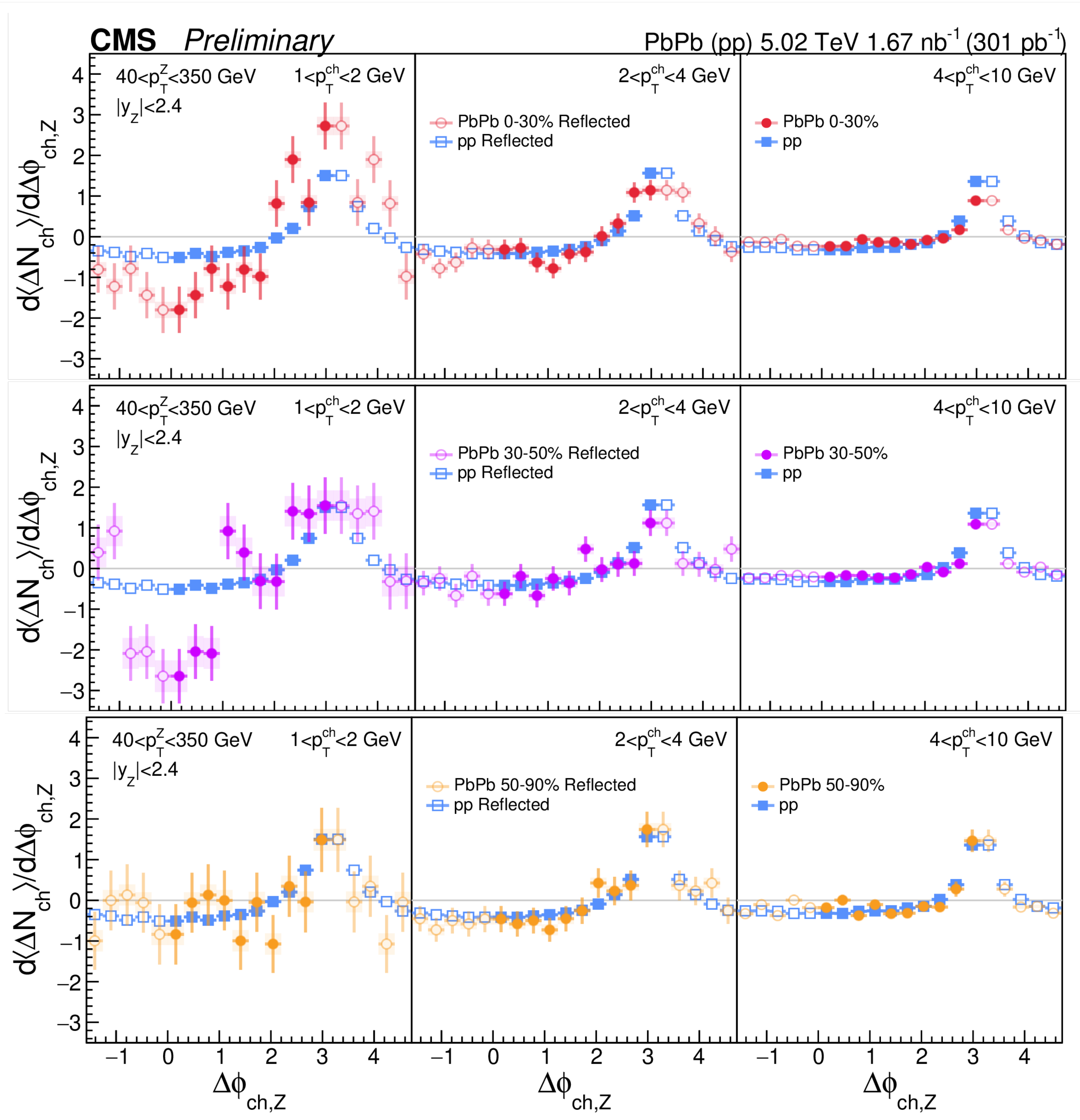
No data from ATLAS at different centralities for comparison

Can models capture also this behavior?

Do model describe other standard candles?

=> **Plenty of questions to answer with Run 3 high statistics samples!**

Hadron p_T selection



Centrality

Jet substructure & flavor dependence

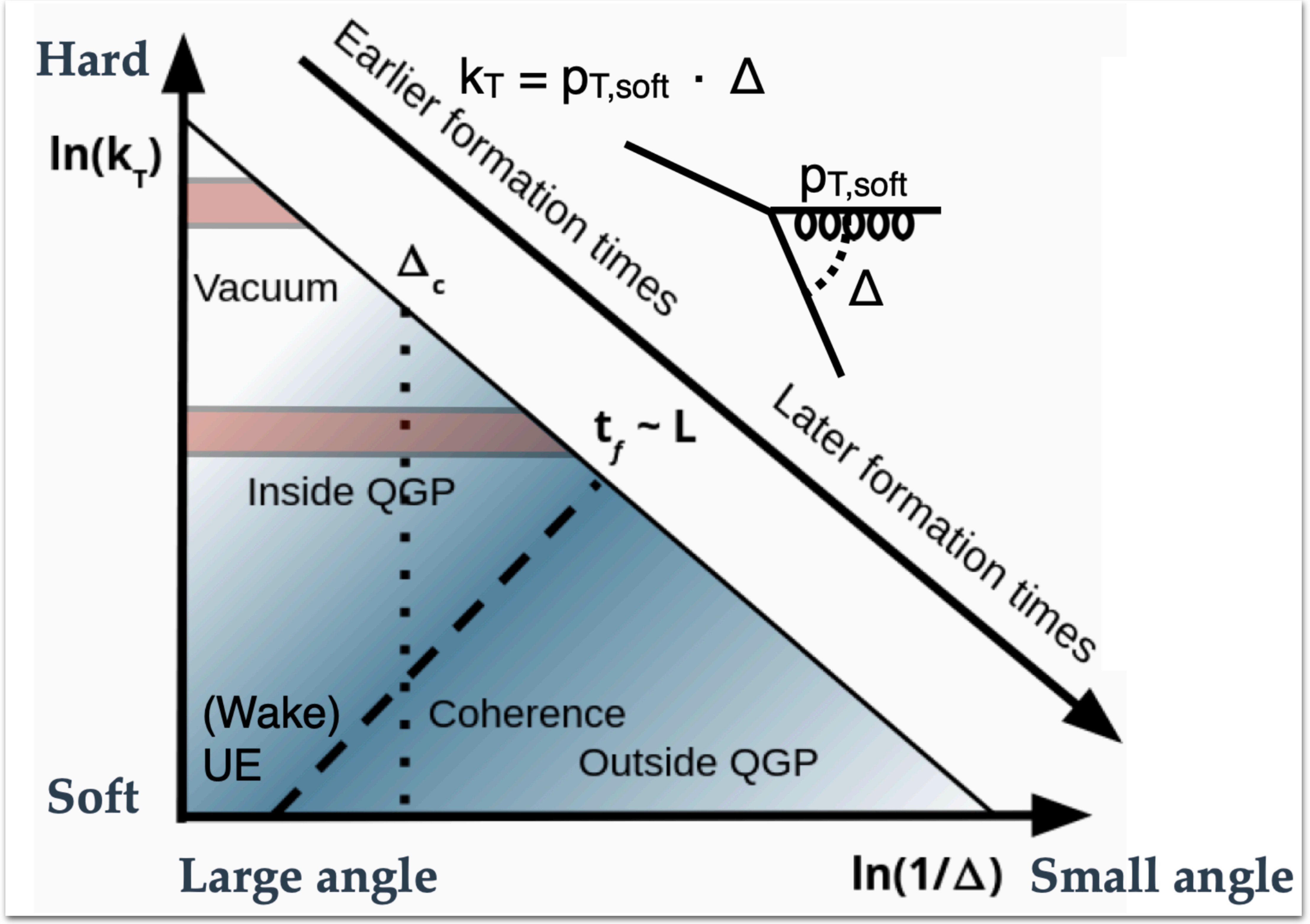
How are splitting patterns modified by the medium?

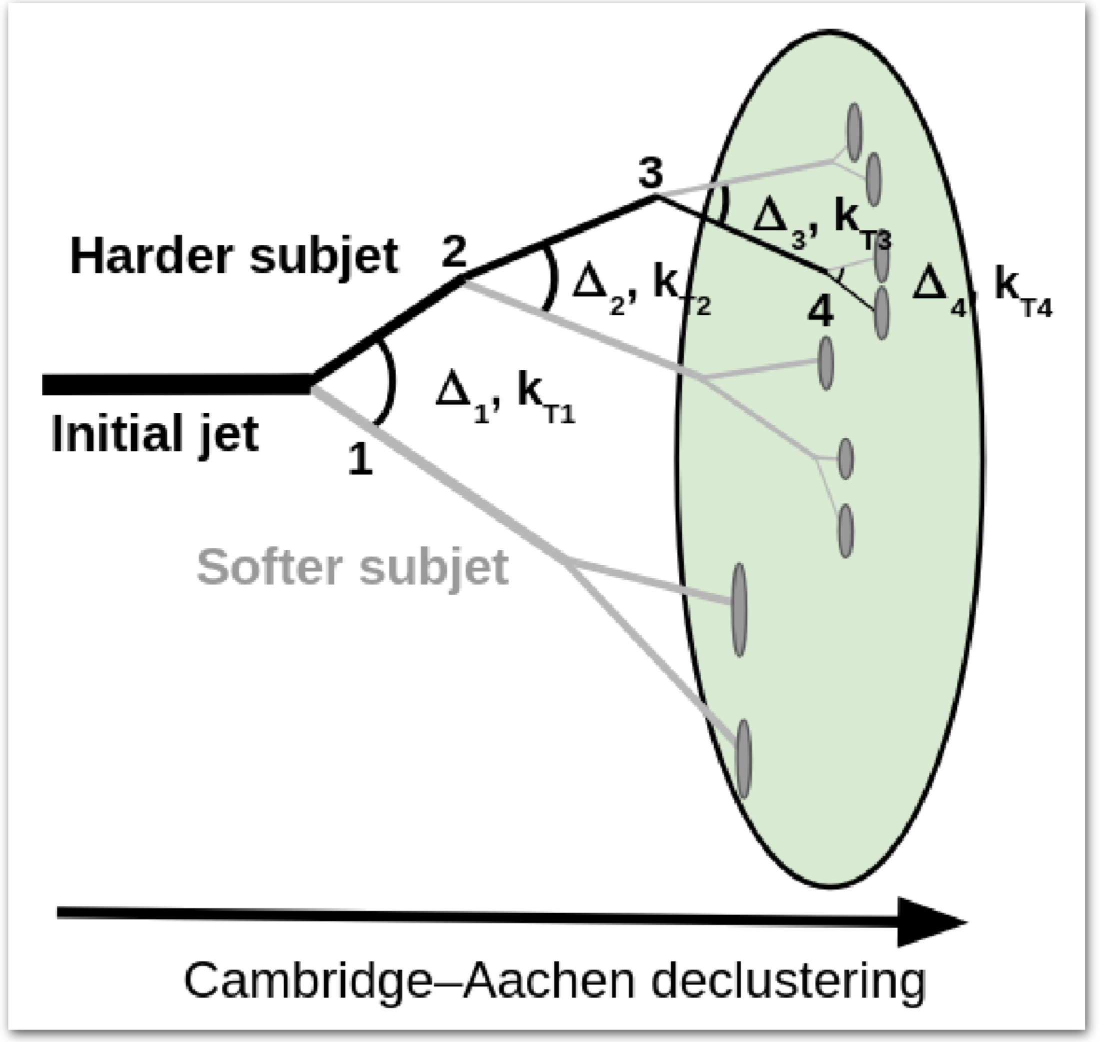
What is the color decoherence scale of the medium?

CMS Lund plane scan

Idea from Cunqueiro et al, PRD 110, 014015 (2024)

CMS-PAS-HIN-24-016





Lund plane: 2D visualization of jet shower phase space (jet tree from Cambridge-Aachen)

Different **k_T slices** isolate different effects in a "factorized" fashion:

- **Highest k_T:** examine the assumption of vacuum-like branching before QGP
- **Smaller k_T:** Onset of color decoherence (small angles)
- Not sensitive to medium response if k_T is not too low

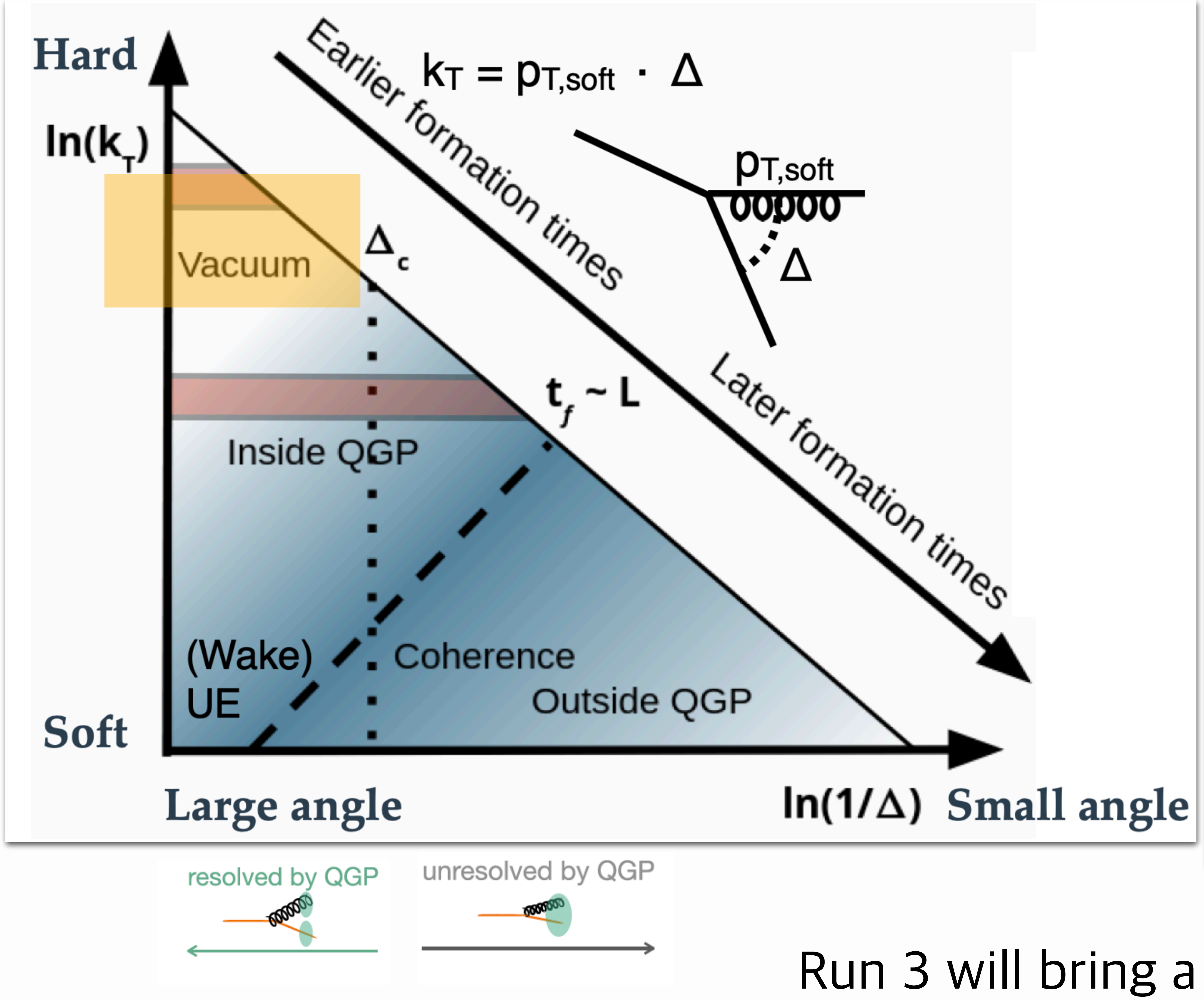
CMS Lund plane scan

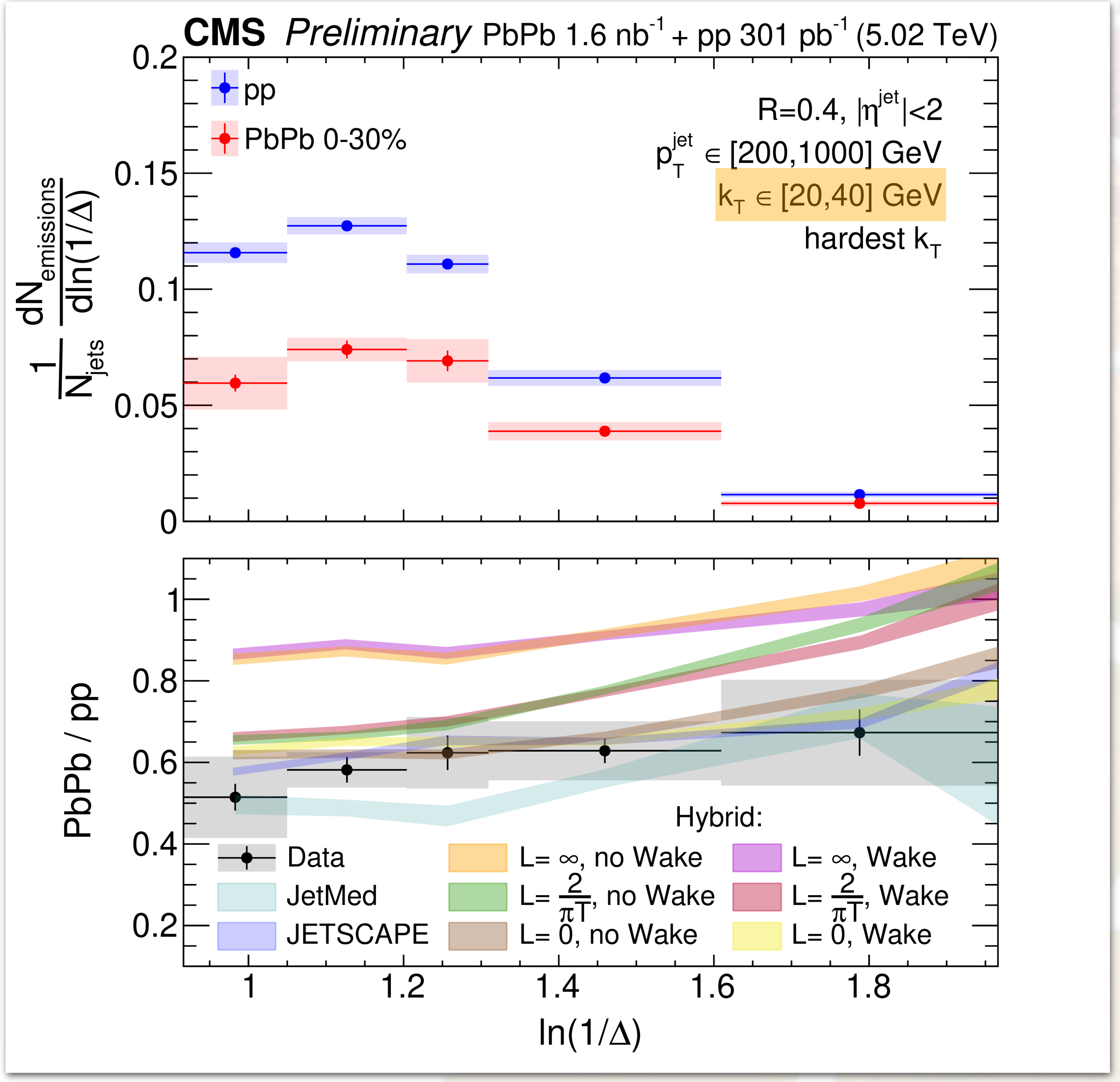
Idea from Cunqueiro et al, PRD 110, 014015 (2024)

CMS-PAS-HIN-24-016

Focus on the **hardest k_T splitting per jet**

Scan at high k_T (e.g. $k_T \in [20,40]$ GeV below)





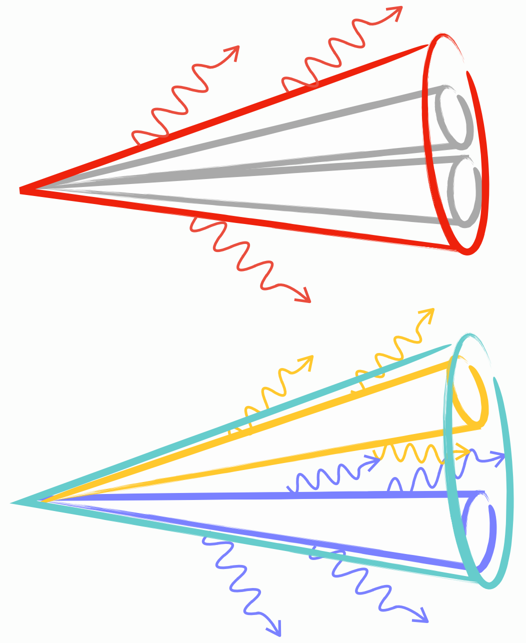
- Similar angular picture for **PbPb and pp (ratio ~flat)**
  → agrees with factorization of early vacuum-like branching
- **Favors** the picture in which **the medium resolves color charges incoherently** (short coherence length L)

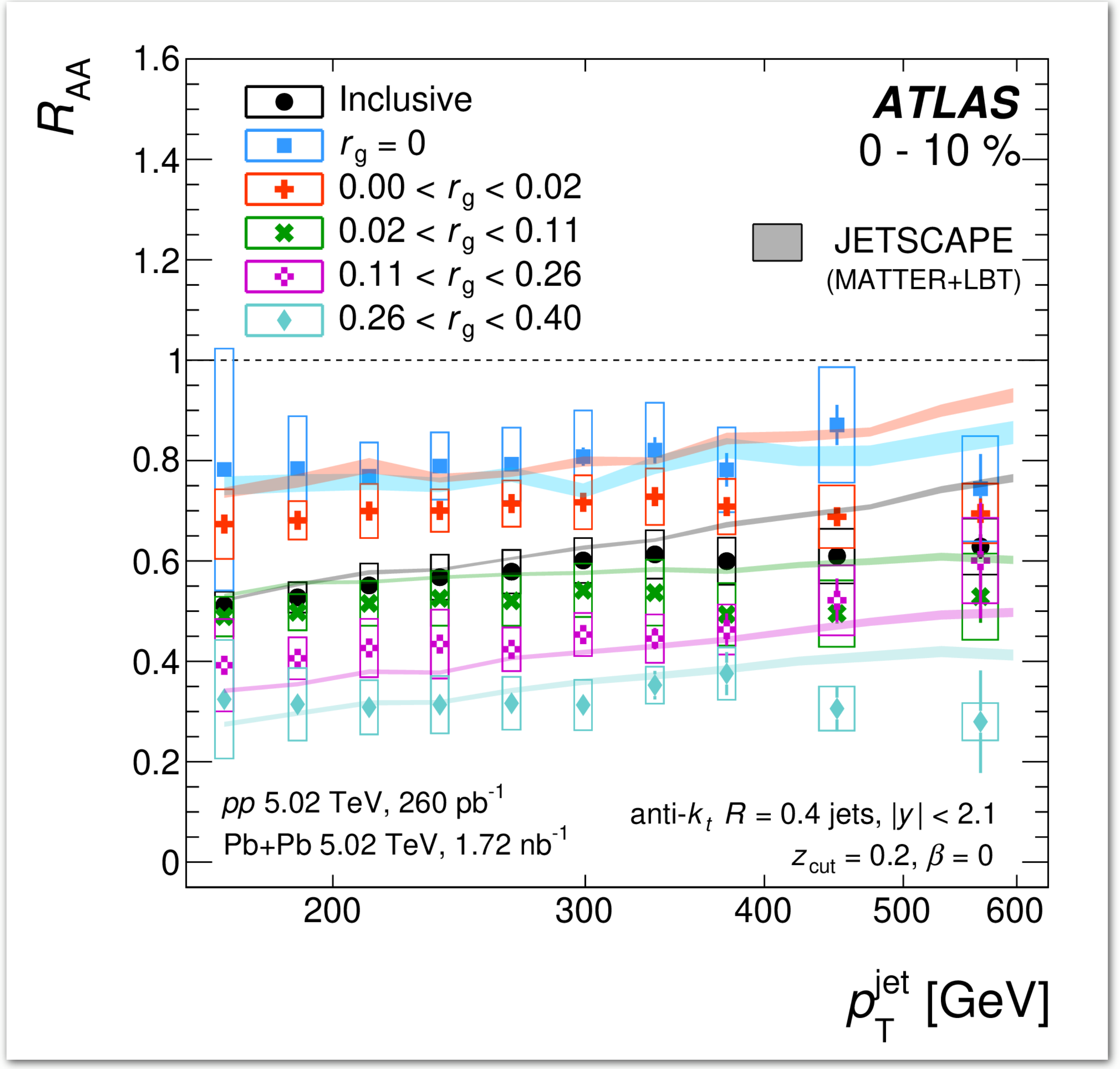
Statistically hungry measurement!

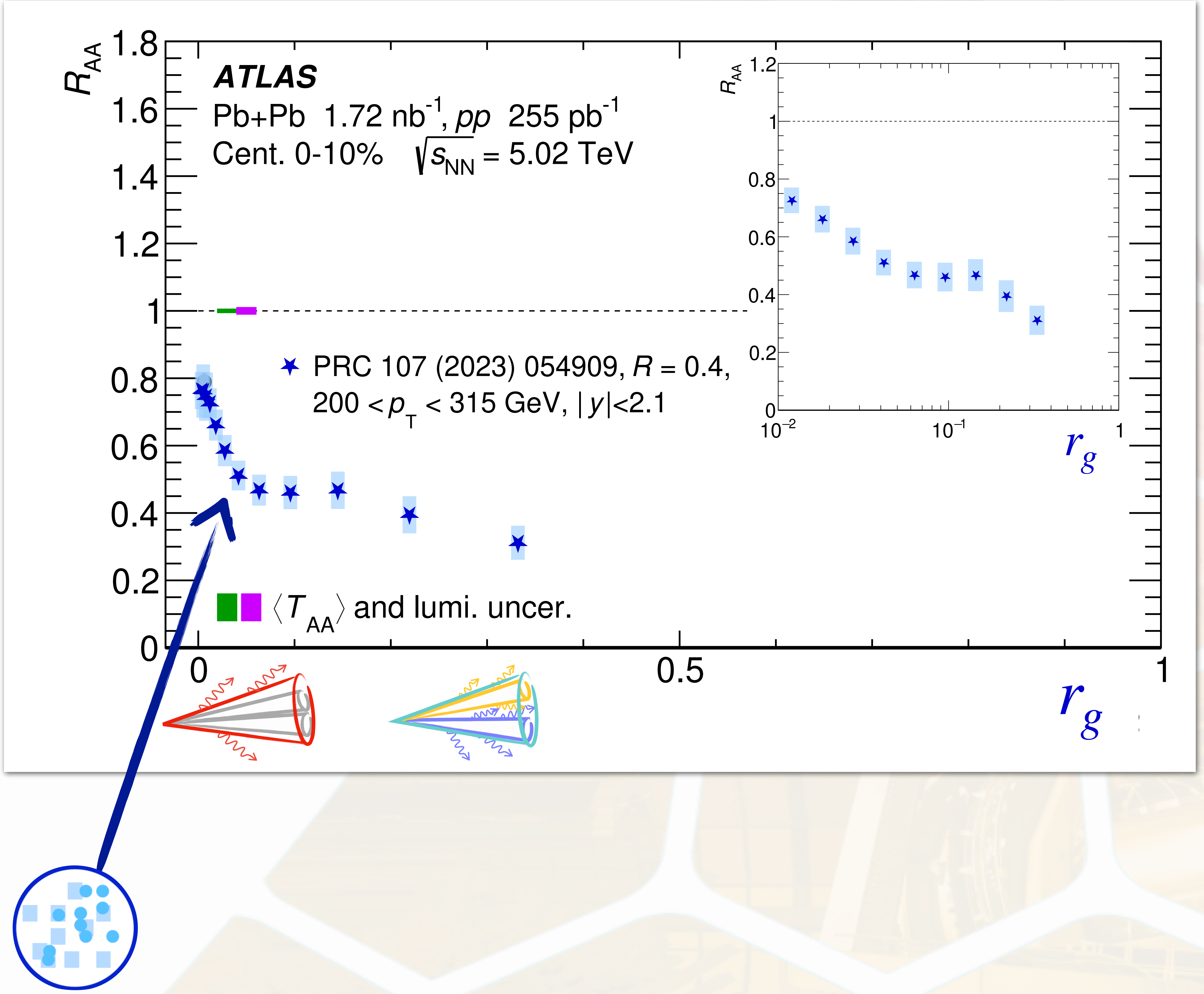
Run 3 will bring a significant leap in statistics to push these studies forward

ATLAS jet substructure: Episode 1

PRC 107 (2023) 054909







- SoftDrop ($z_{cut} = 0.2, \beta = 0$) applied to R = 0.4 jets
- **Narrow jets** are less suppressed than **wide jets**
- Mostly no p_T dependence

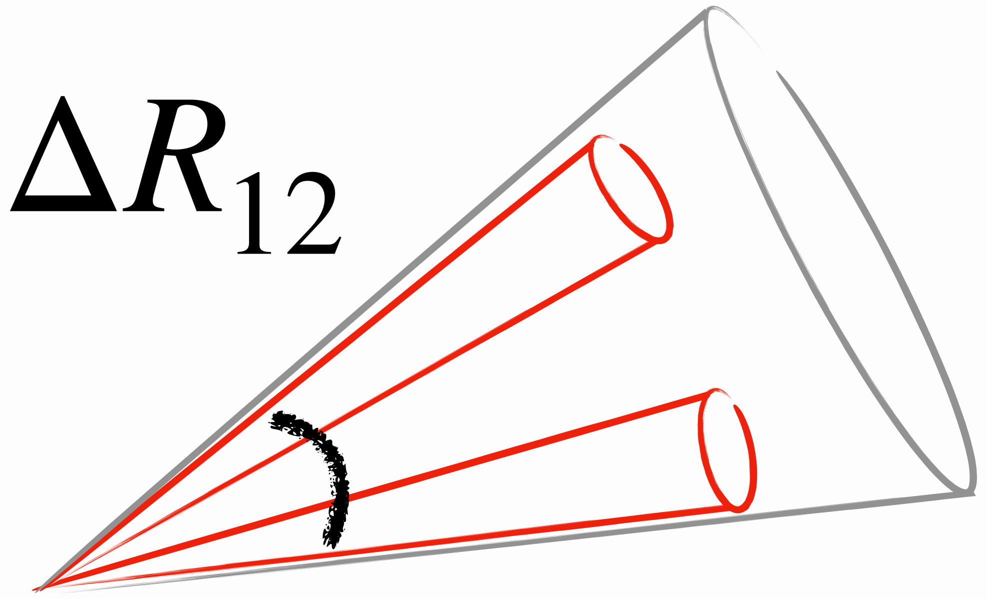
Standard size (R=0.4) de-clustered & groomed jets;
Substructure with tracks ( ) & calo-clusters ( )

ATLAS jet substructure: Episode 2

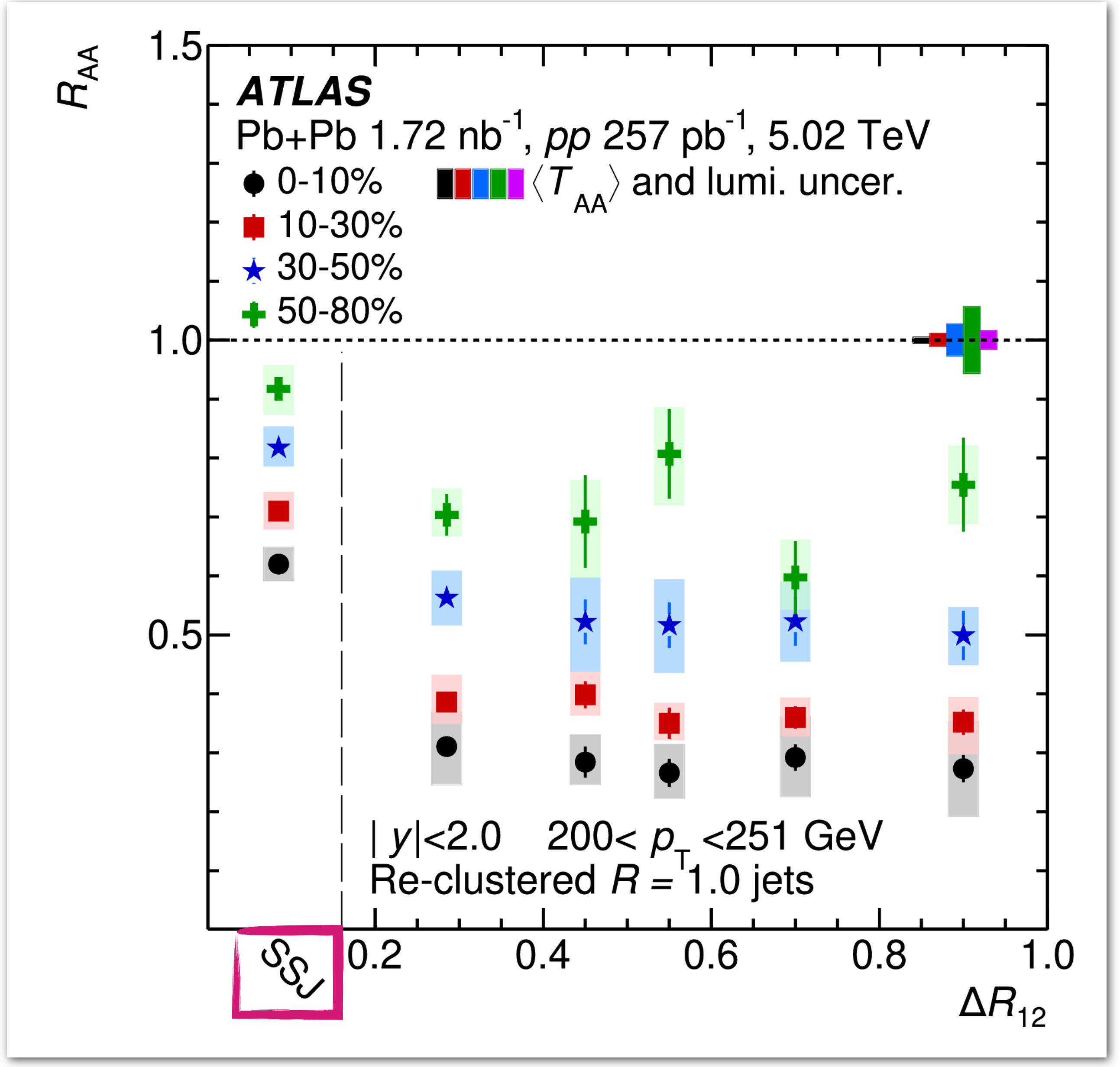
PRL 131 (2023) 172301

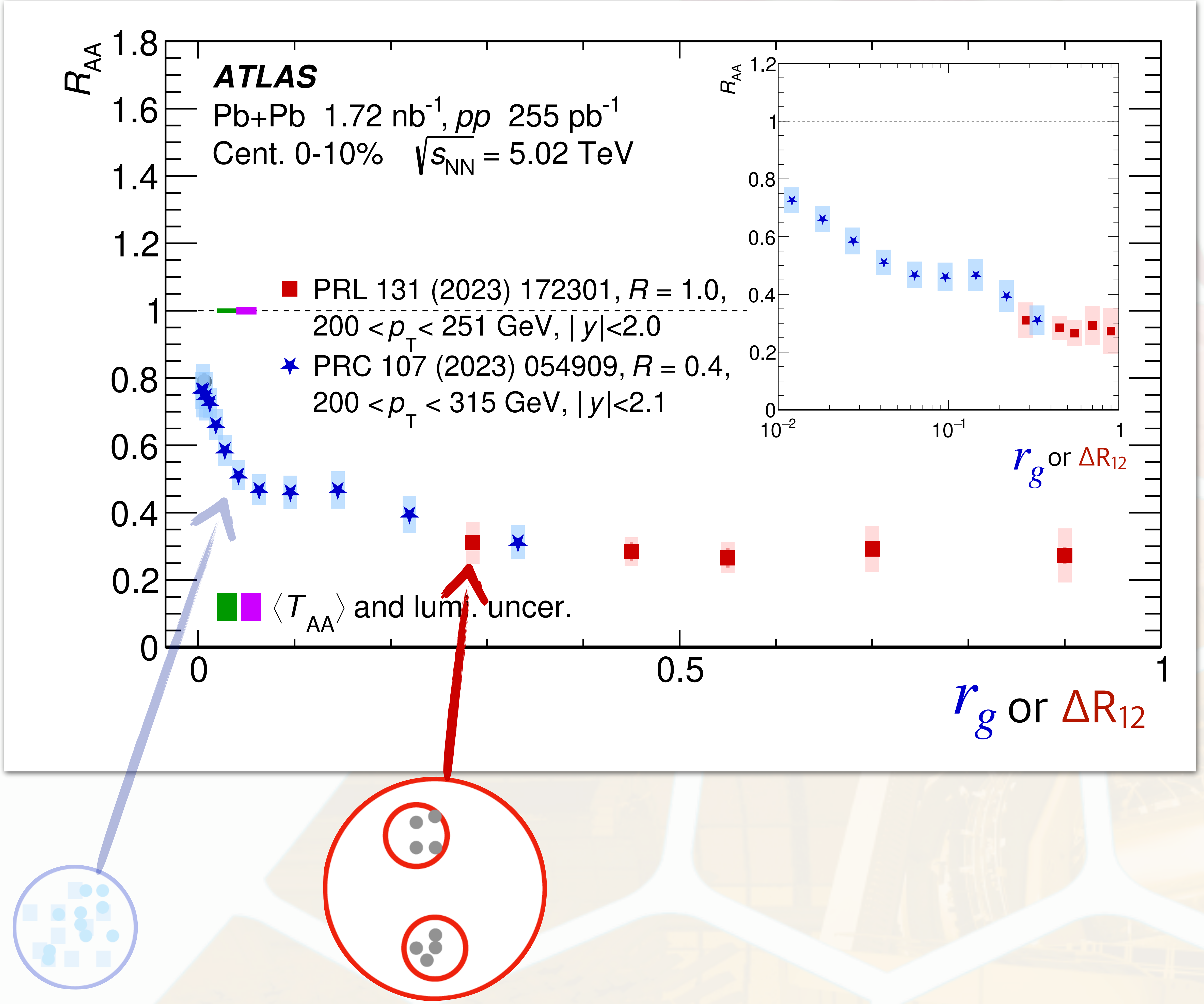
Angular separation $\Delta R_{12} = \sqrt{\Delta y_{12}^2 + \Delta\phi_{12}^2}$

ΔR_{12}



R = 0.2 sub-jets





Large R jets (R=1.0) re-clustered;
Substructure with R=0.2 jets

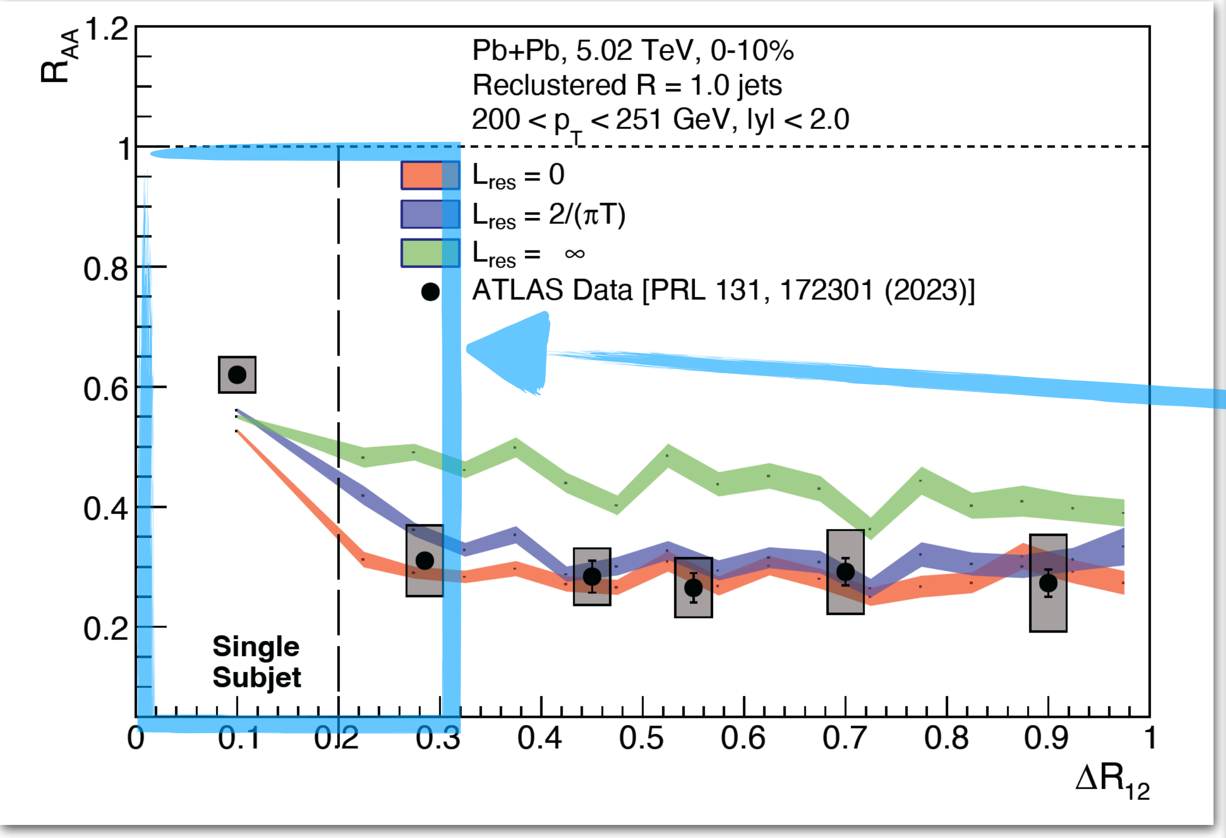
- **Single Sub-Jet (SSJ):** single R = 0.2 jet
- Jets with multiple sub-jets are significantly more suppressed

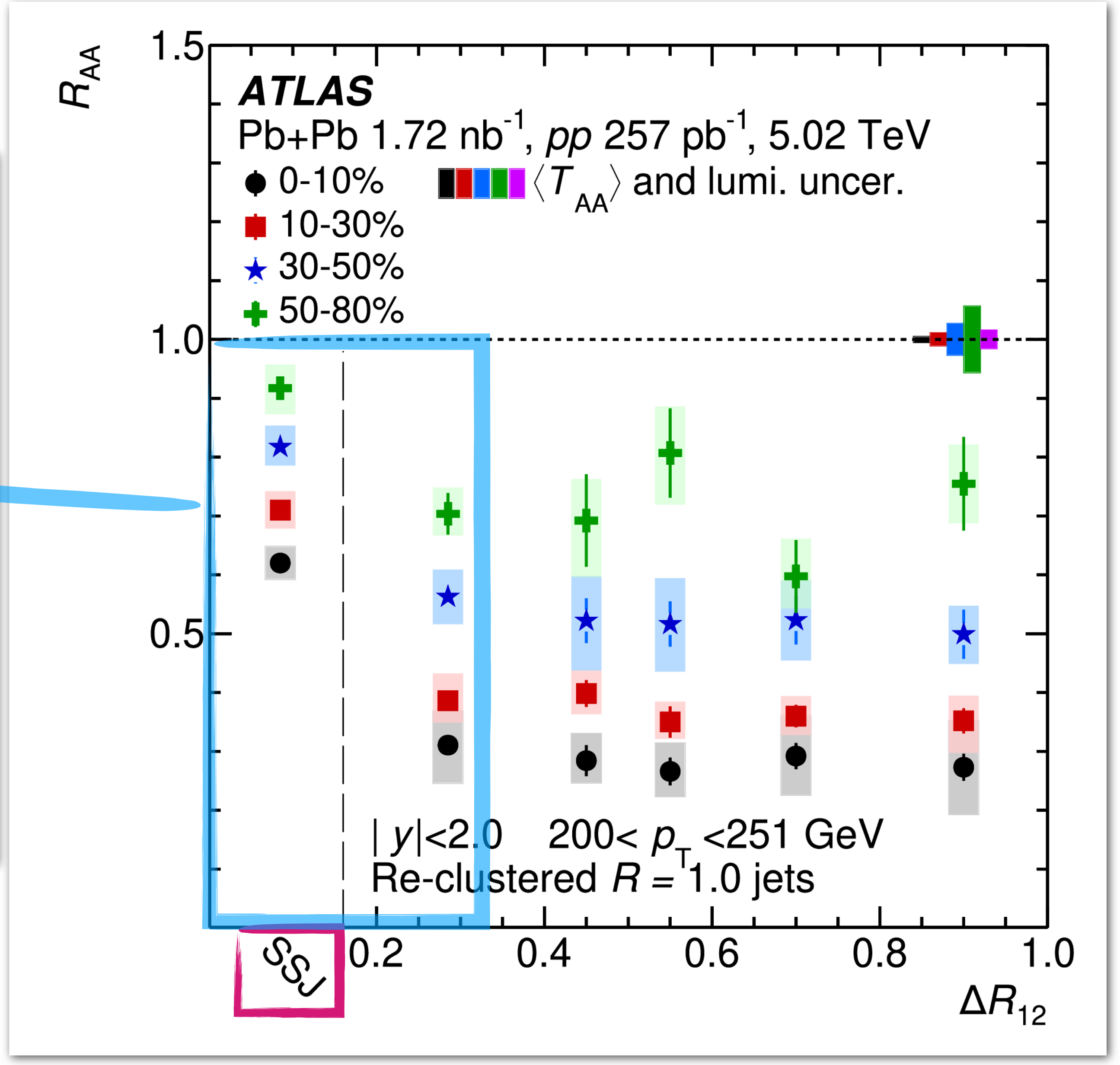
ATLAS jet substructure: Episode 2

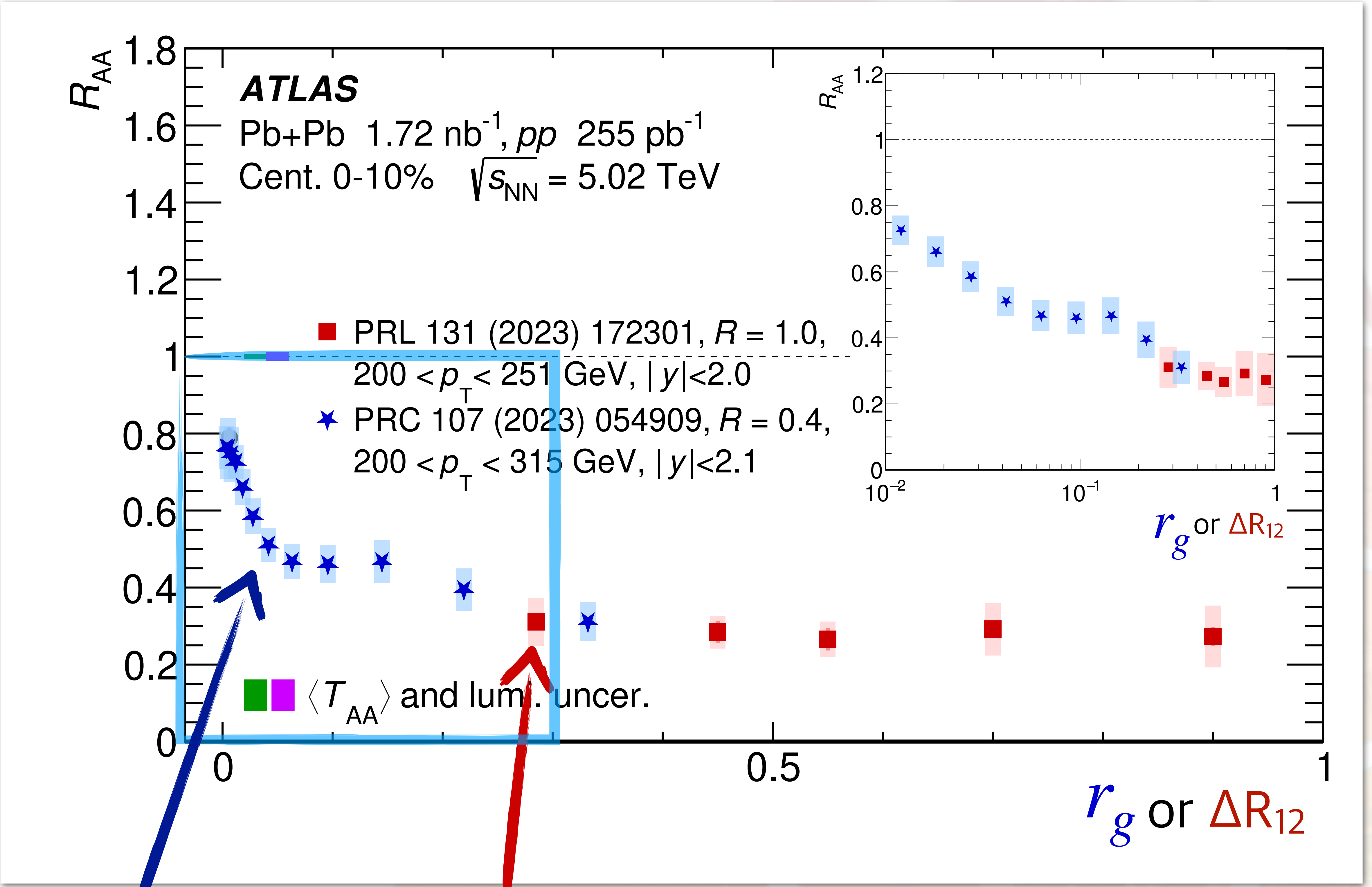
PRL 131 (2023) 172301

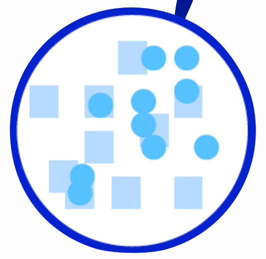
Angular separation $\Delta R_{12} = \sqrt{\Delta y_{12}^2 + \Delta\phi_{12}^2}$

Kudinoor, Pablos, Rajagopal
arXiv:2501.18683









Clear demand for more data to cover the full separation scale also from the modeling side

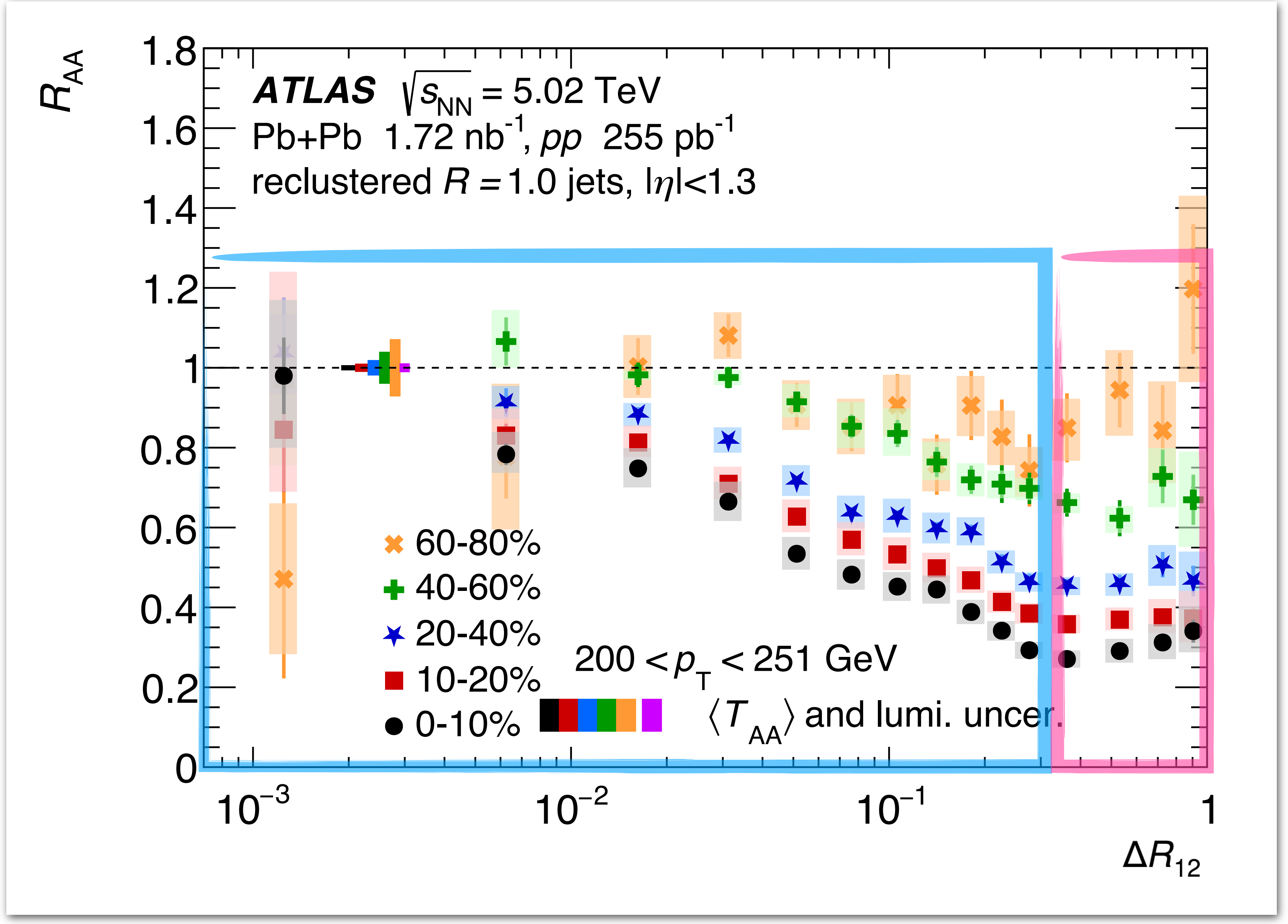
Standard size (R=0.4) de-clustered & groomed jets;
Substructure with tracks ( ) & calo-clusters ( )

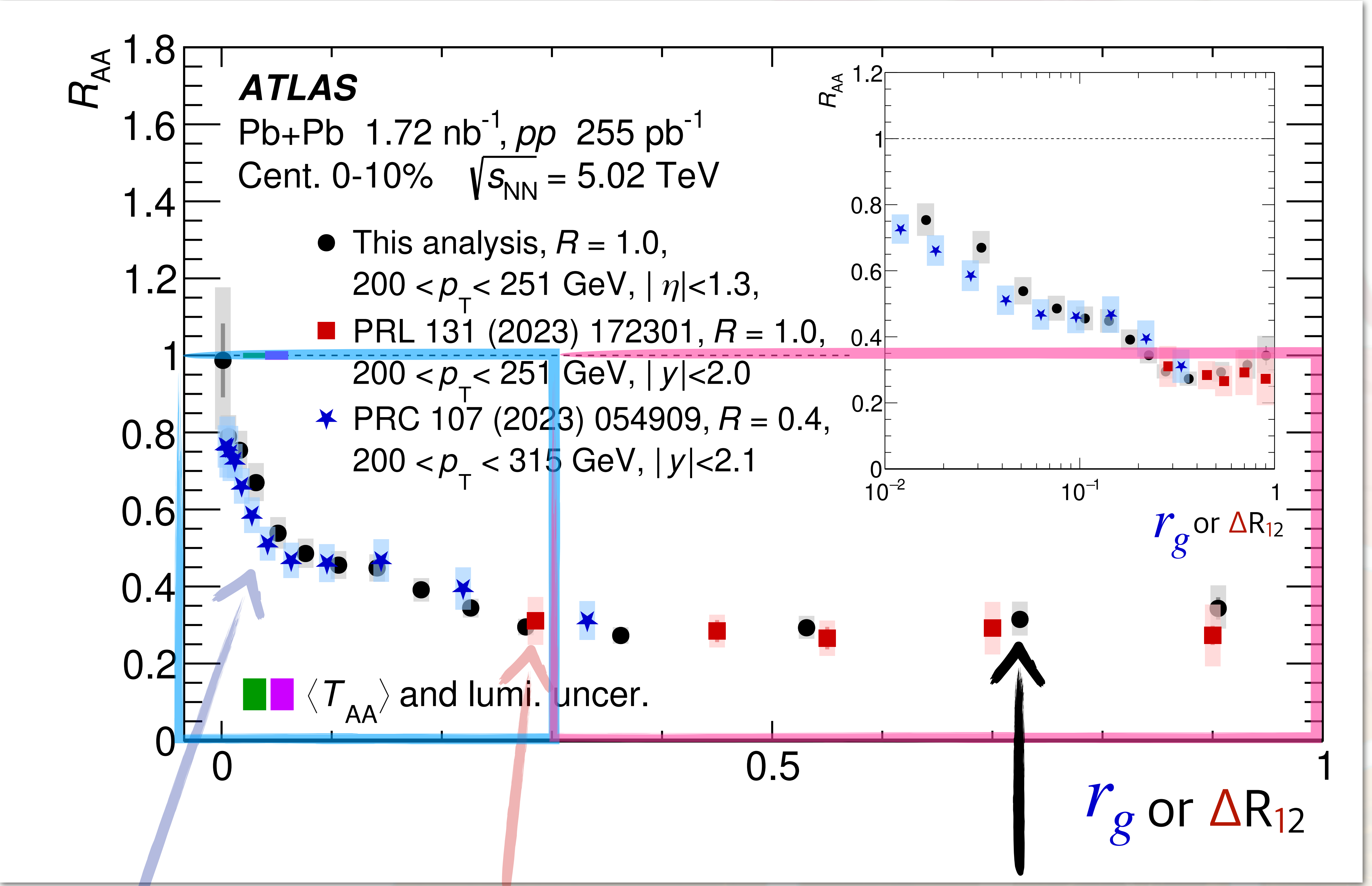
Large R jets (R=1.0) re-clustered;
Substructure with R=0.2 jets

ATLAS jet substructure: Episode 3

arXiv:2504.04805

Angular separation $\Delta R_{12} = \sqrt{\Delta y_{12}^2 + \Delta\phi_{12}^2}$





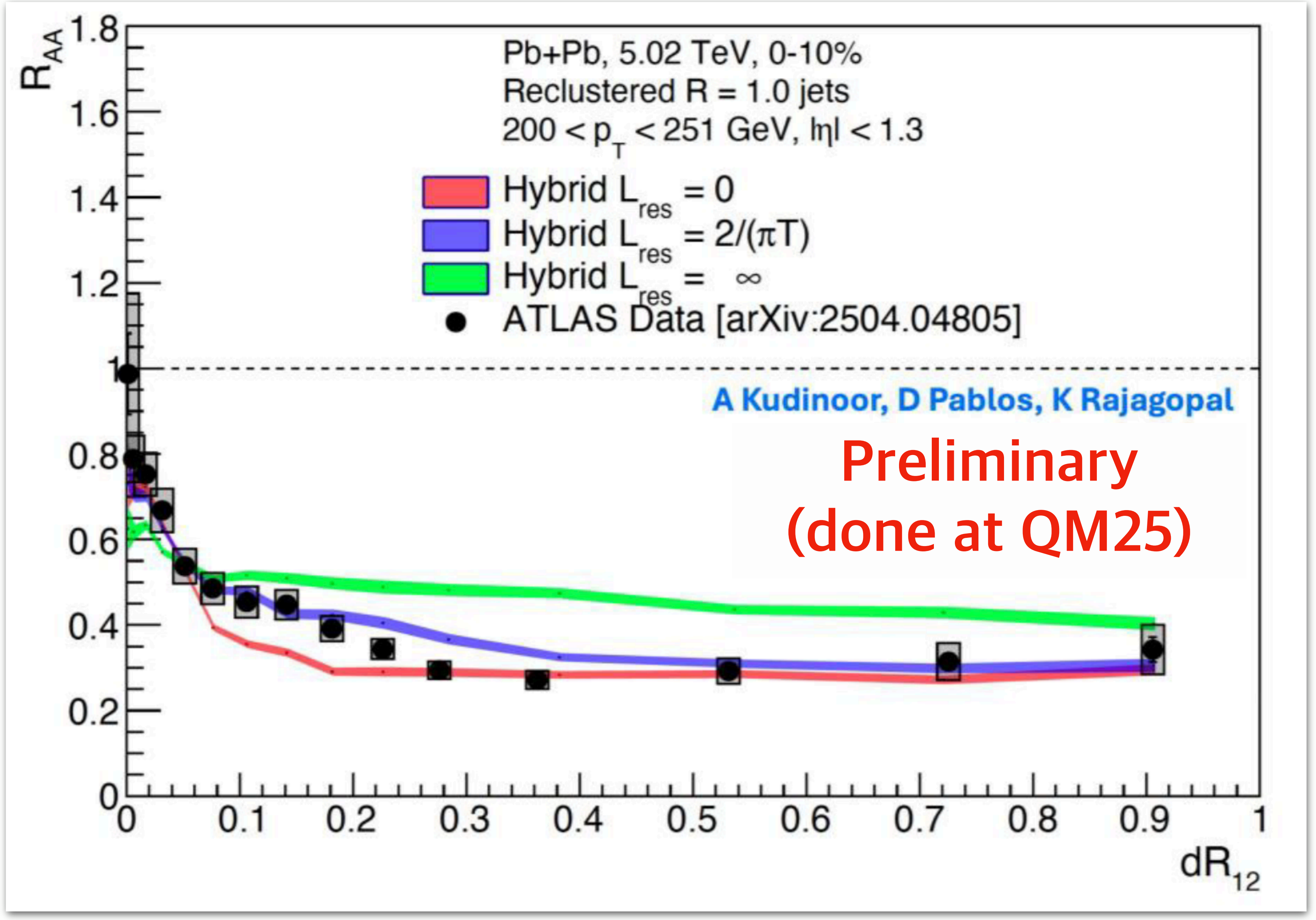
- Same R = 1.0 jets as PRL 131 (2023) 172301, with substructure evaluated using tracks with p_T > 4 GeV and SoftDrop ($z_{cut} = 0.15, \beta = 0$)

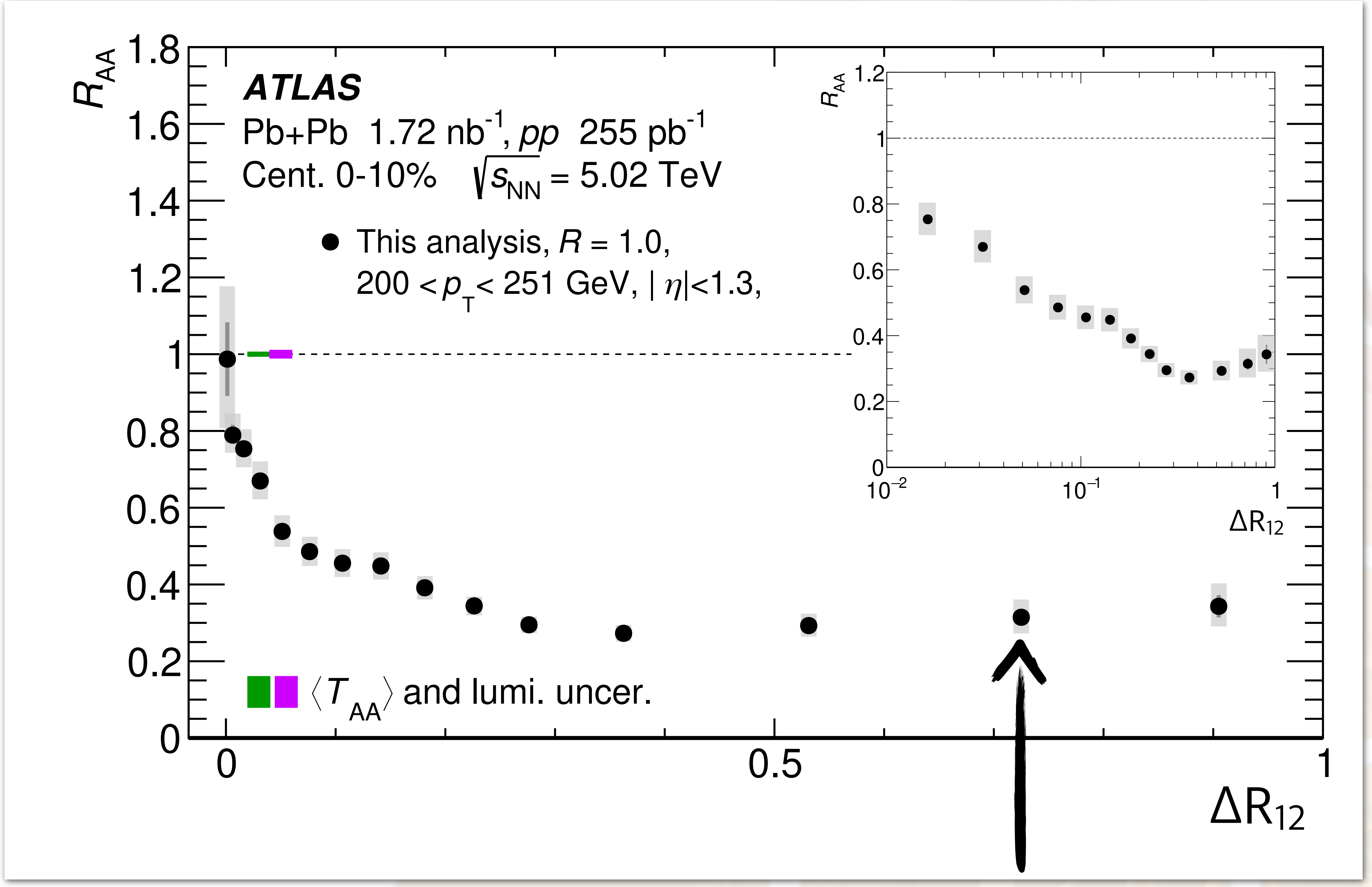
Large R jets (R=1.0) re-clustered; **Substructure with tracks**

- Sharp R_{AA} decrease with ΔR_{12}, followed by flattening behavior
- New analysis provides a **bridge** between the **previous** two **measurements**

Pinning down the QGP coherence scale

PRL 131 (2023) 172301



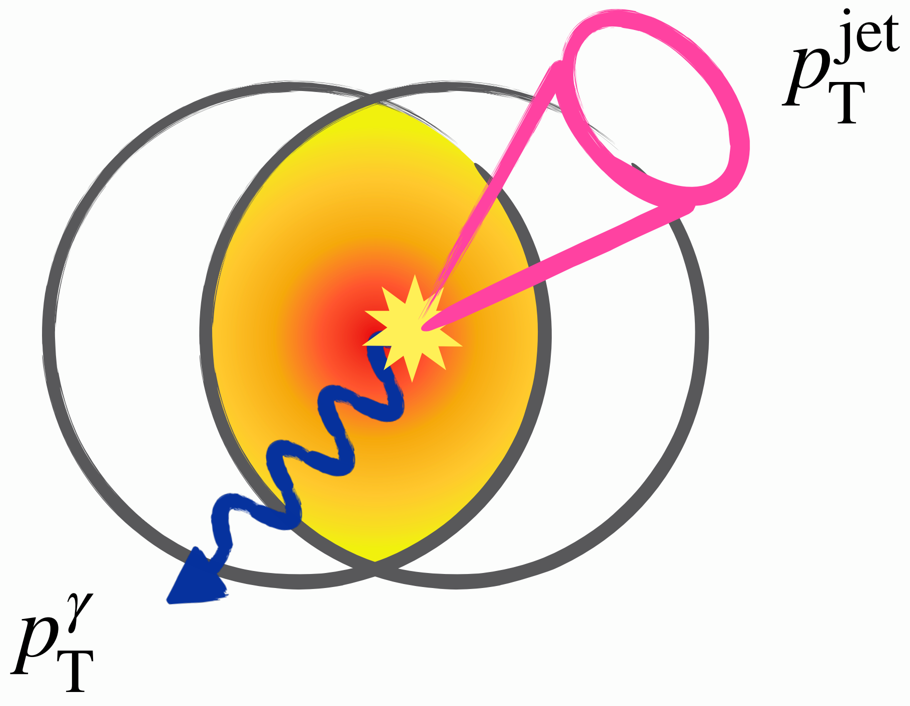


The data have the **power to** differentiate and **constrain** the **resolution length** of the medium!

Hint at small resolution scale (as in CMS Lund Plane analysis)

Large R jets (R=1.0) re-clustered;
Substructure with tracks

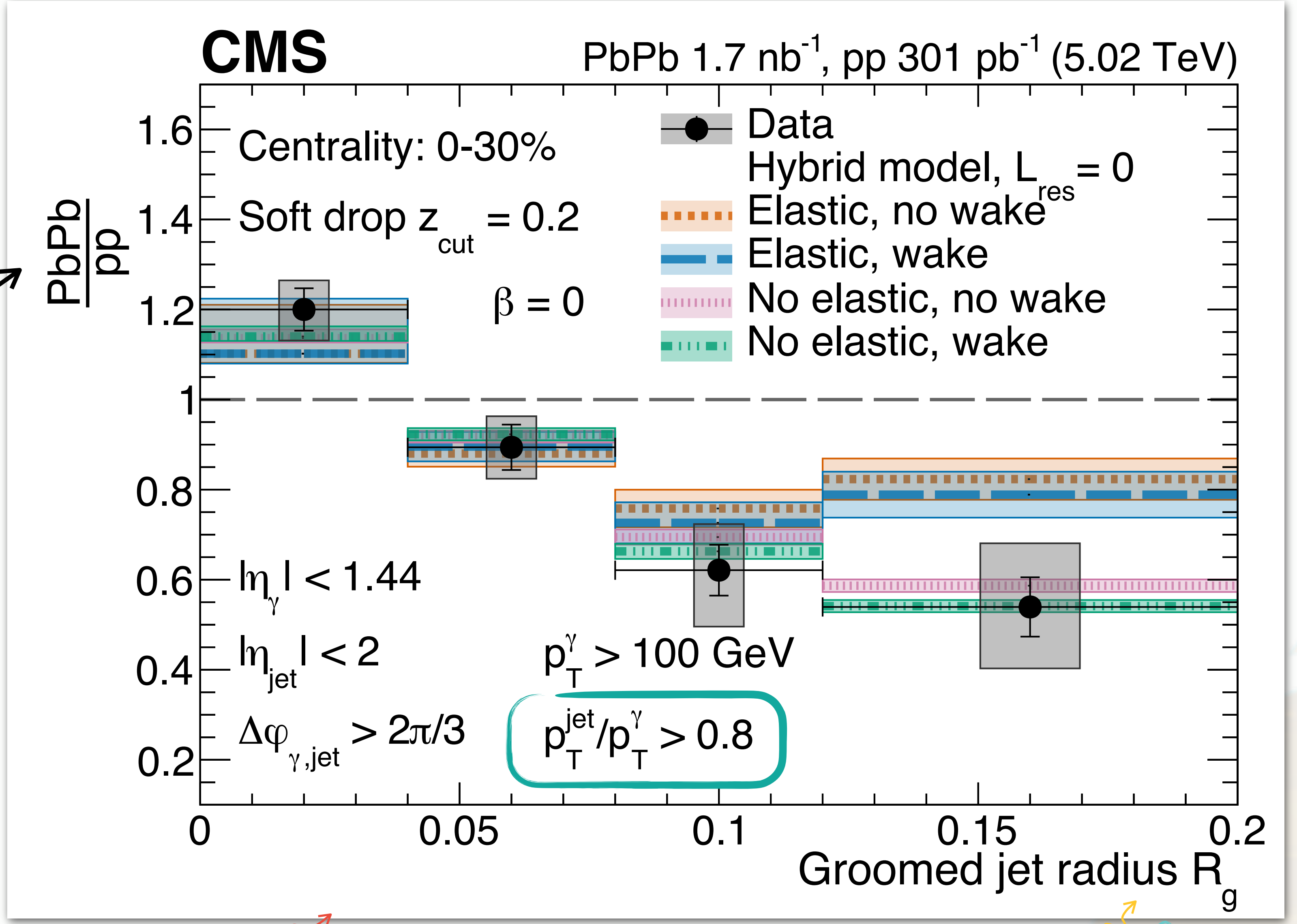
p_T selection bias: the boson-tagged workaround

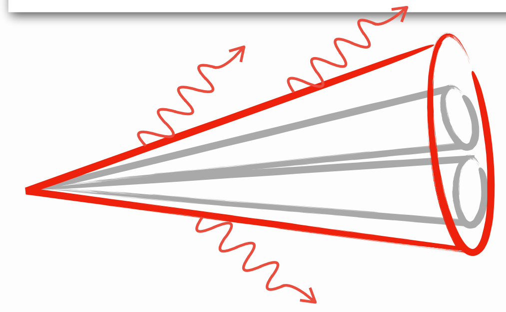


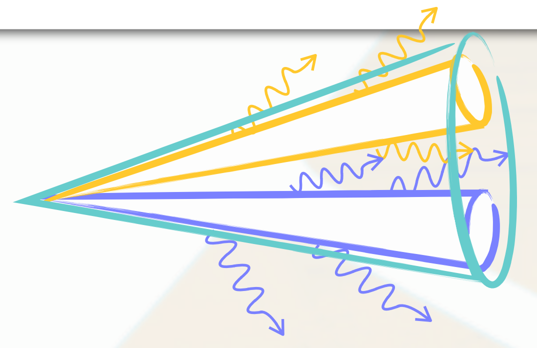
$$x_{\gamma j} = \frac{p_T^{jet}}{p_T^{\gamma}}$$

Use **high-momentum photons** as proxies for the recoiling parton initiating the jet shower, to **investigate selection biases**

Ratio of area normalized distributions for **R=0.2** jets

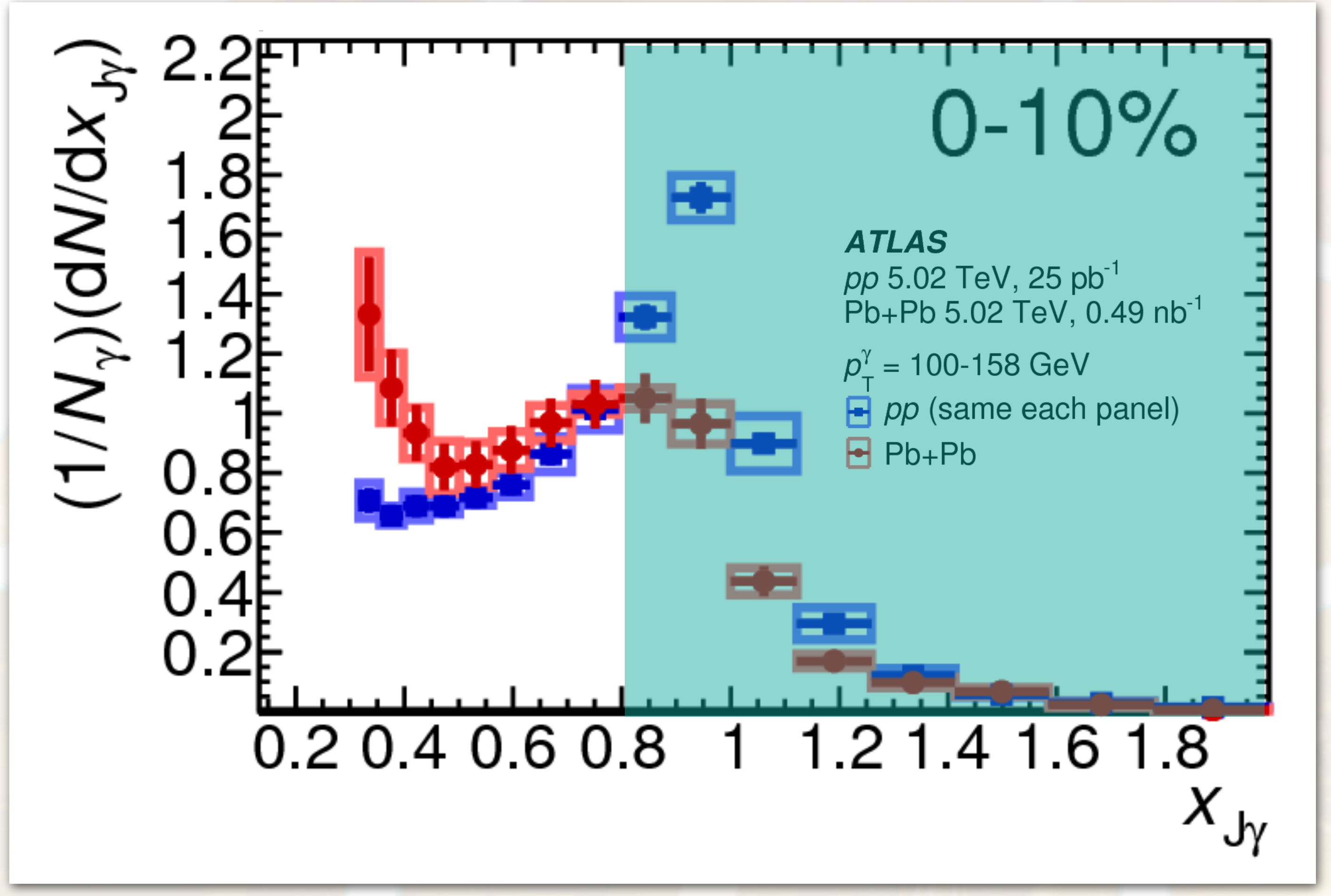






PLB 801 (2025) 139088

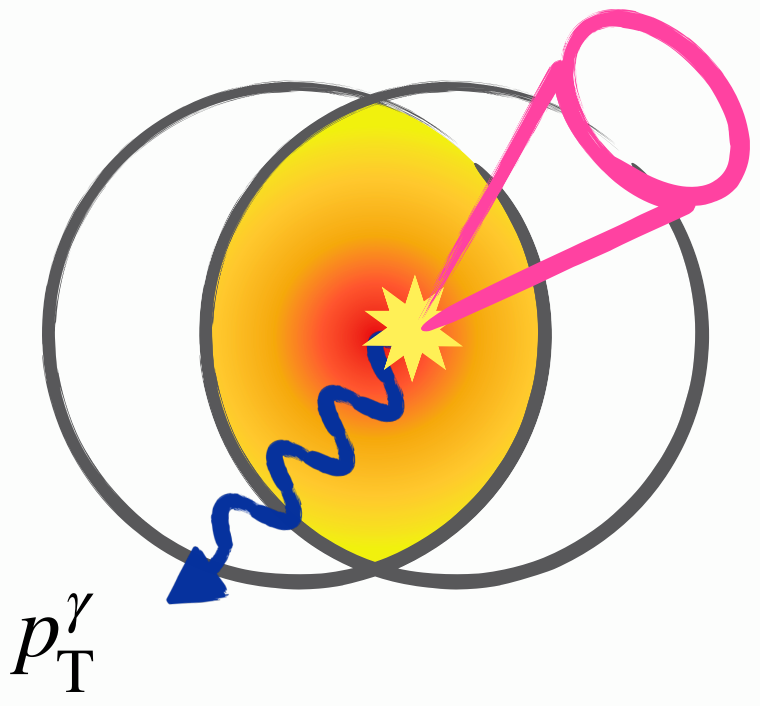
PLB 789 (2019) 167



Less quenched jet selection:

$$x_{\gamma j} > 0.8$$

p_T selection bias: the boson-tagged workaround



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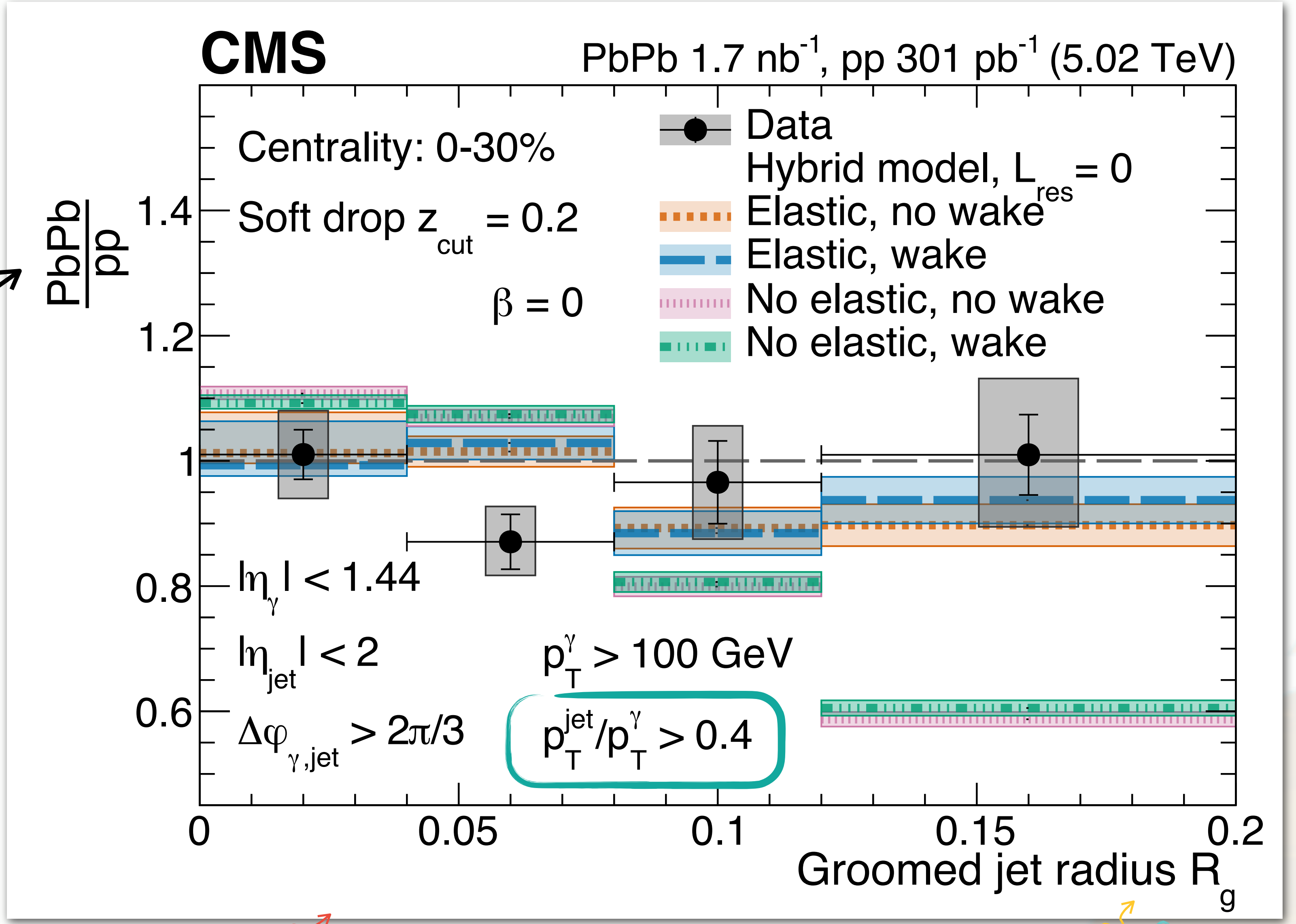
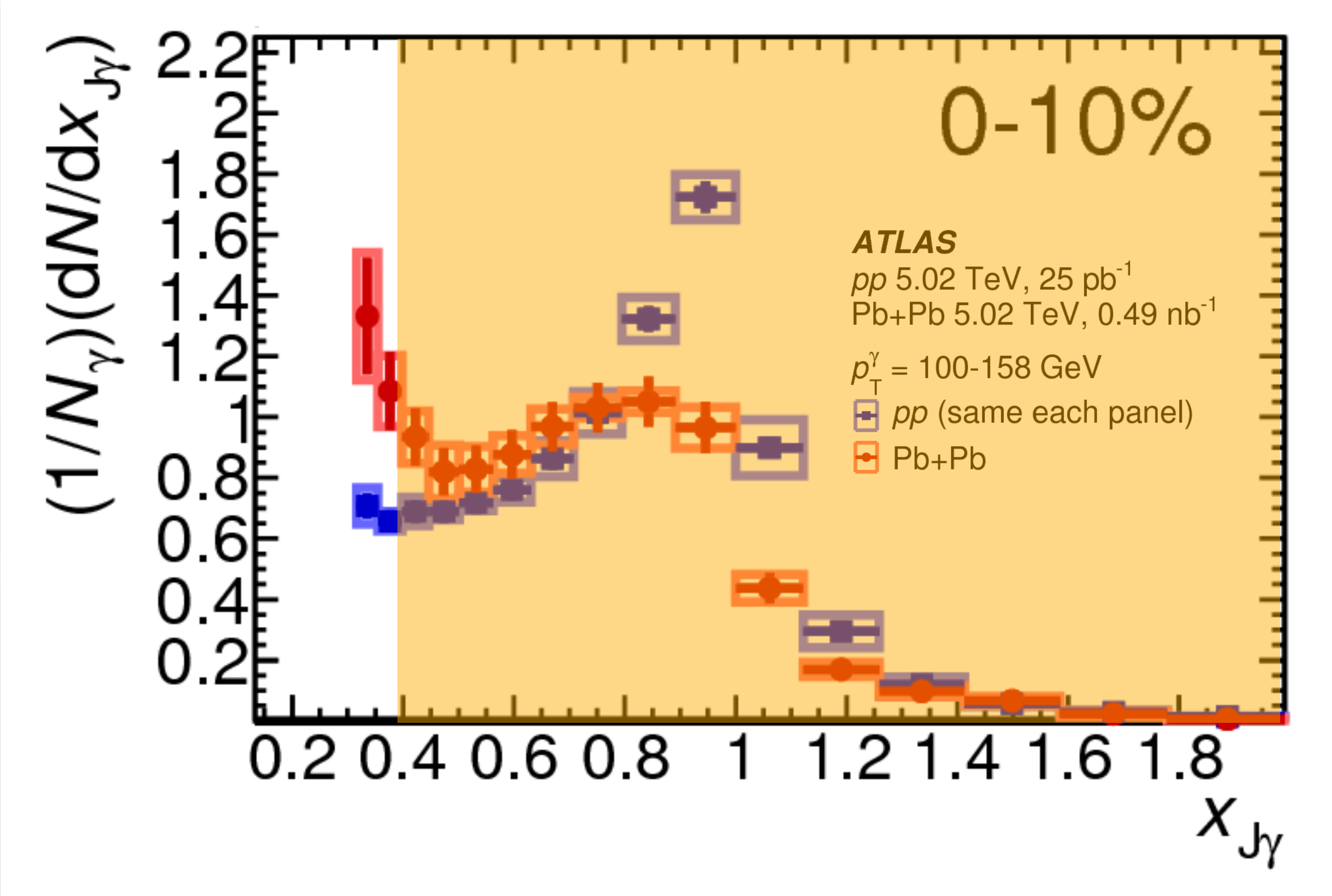


No narrowing observed with **less biased selection on $x_{J\gamma}$**

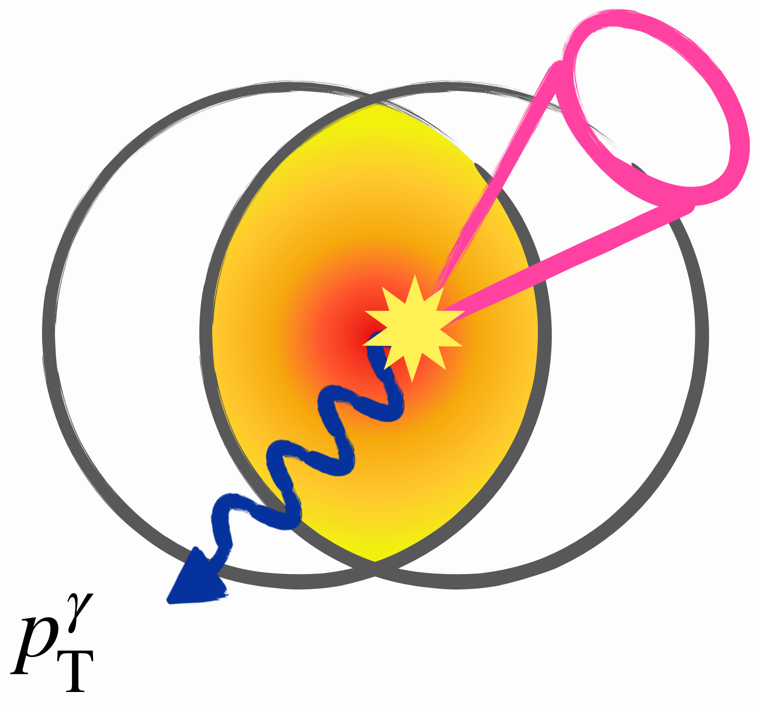
PLB 789 (2019) 167



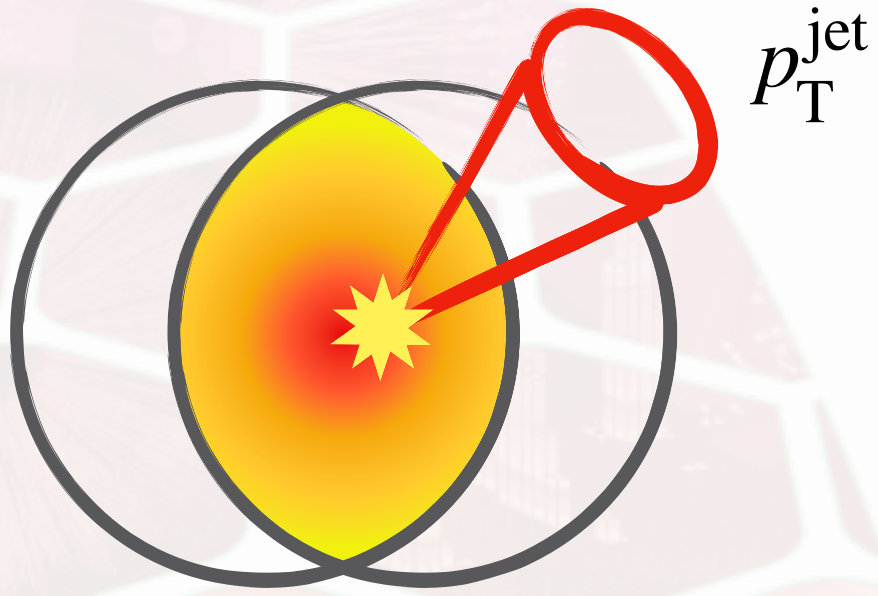
Quenched + unquenched jet selection: $x_{\gamma j} > 0.4$

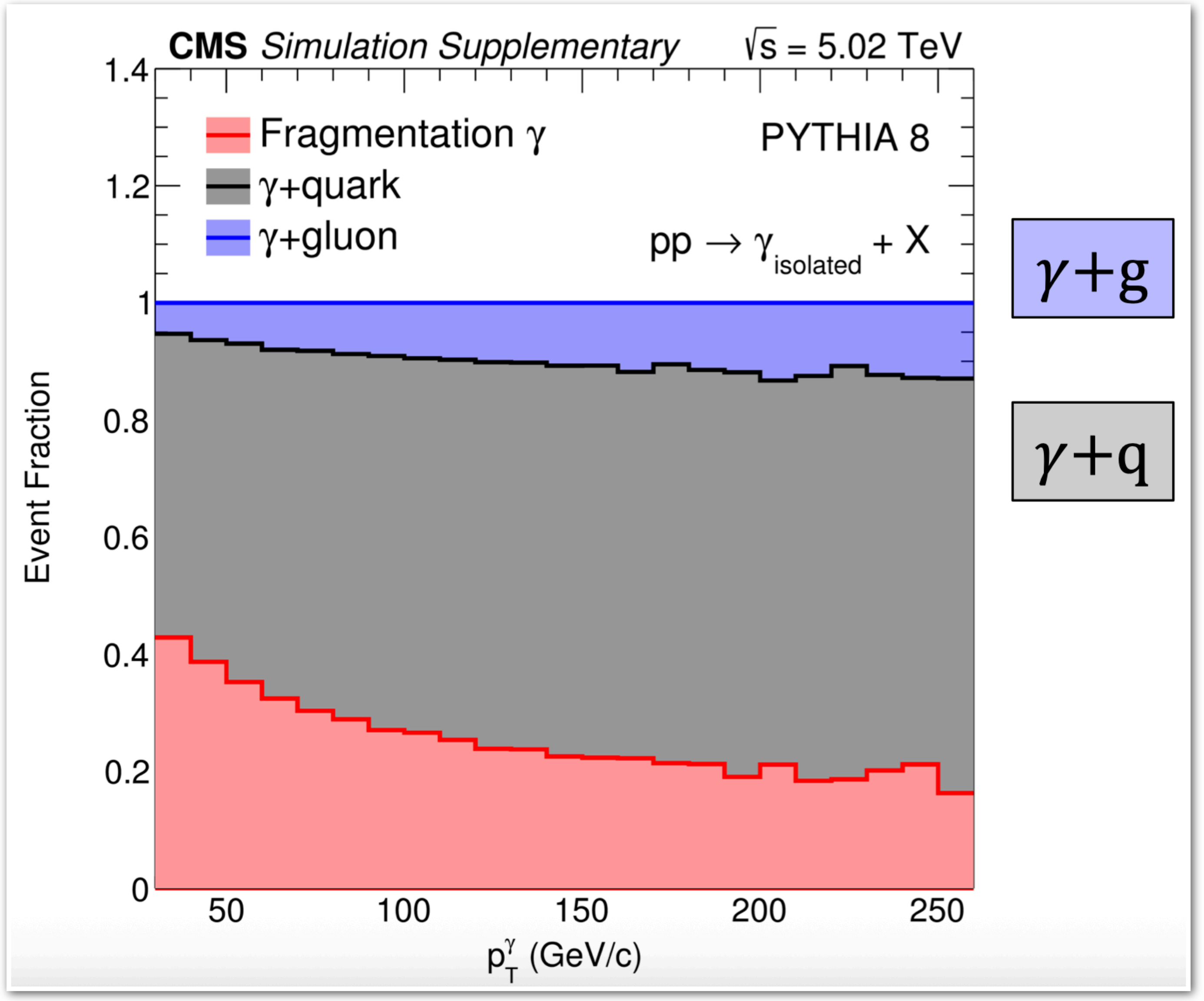
PLB 801 (2025) 139088

p_T selection bias vs flavor dependence

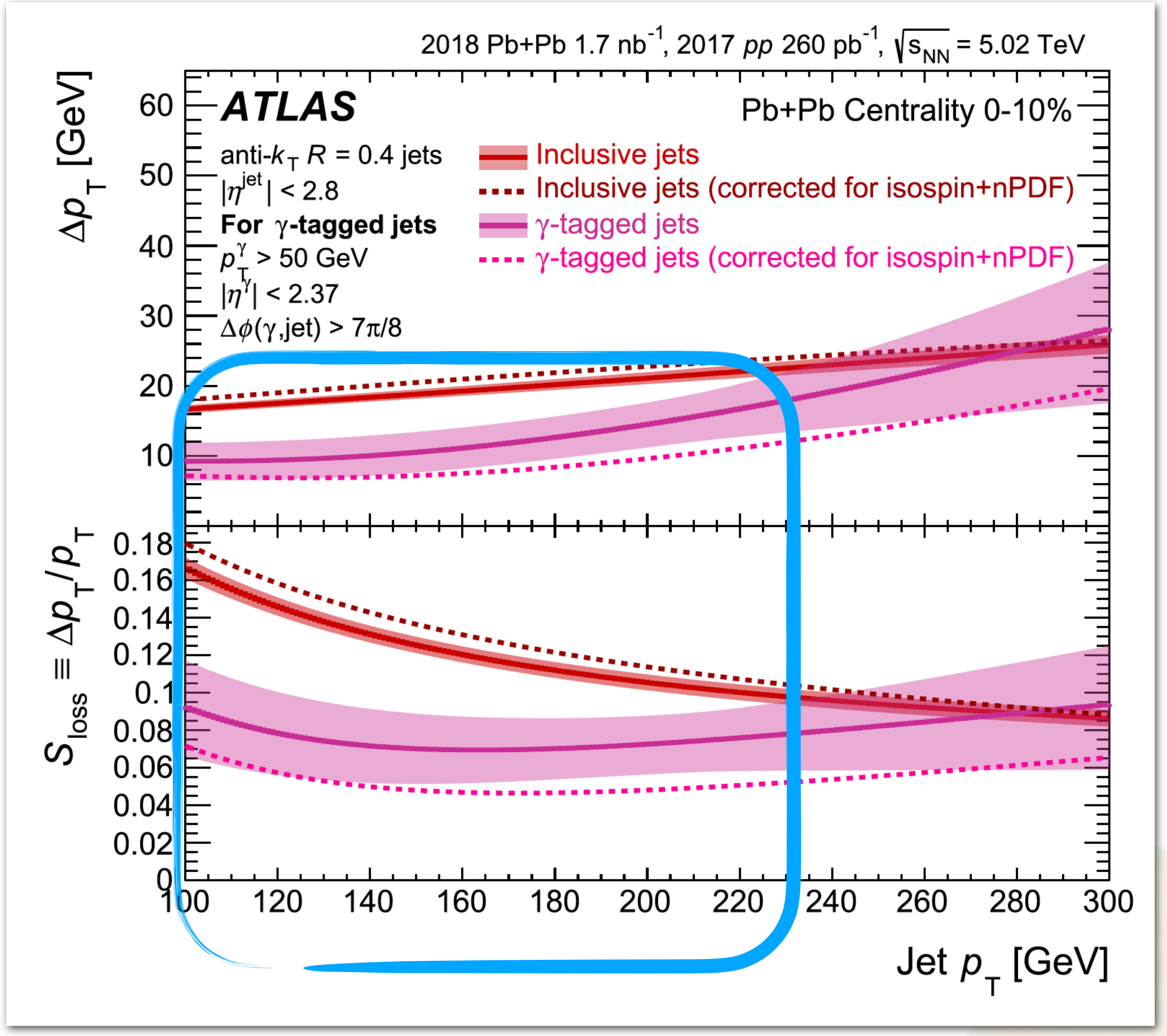


Keep in mind that γ-**tagged jets** are predominantly **quark-initiated**!
Conversely, **inclusive jets** are predominantly **gluon-initiated**.





PRL 122 (2019) 152001



PLB 846 (2023) 138154

- S_{loss} removes spectral shape dependence
- For p_T < ~220 GeV, **quark-initiated jets lose less energy** than **gluon-initiated** ones
- Reminder: with boson-tagged jets we are avoiding p_T selection bias but **picking a different flavor dependence**

Jets from large to small systems

What is the critical system size for the formation of the QGP?

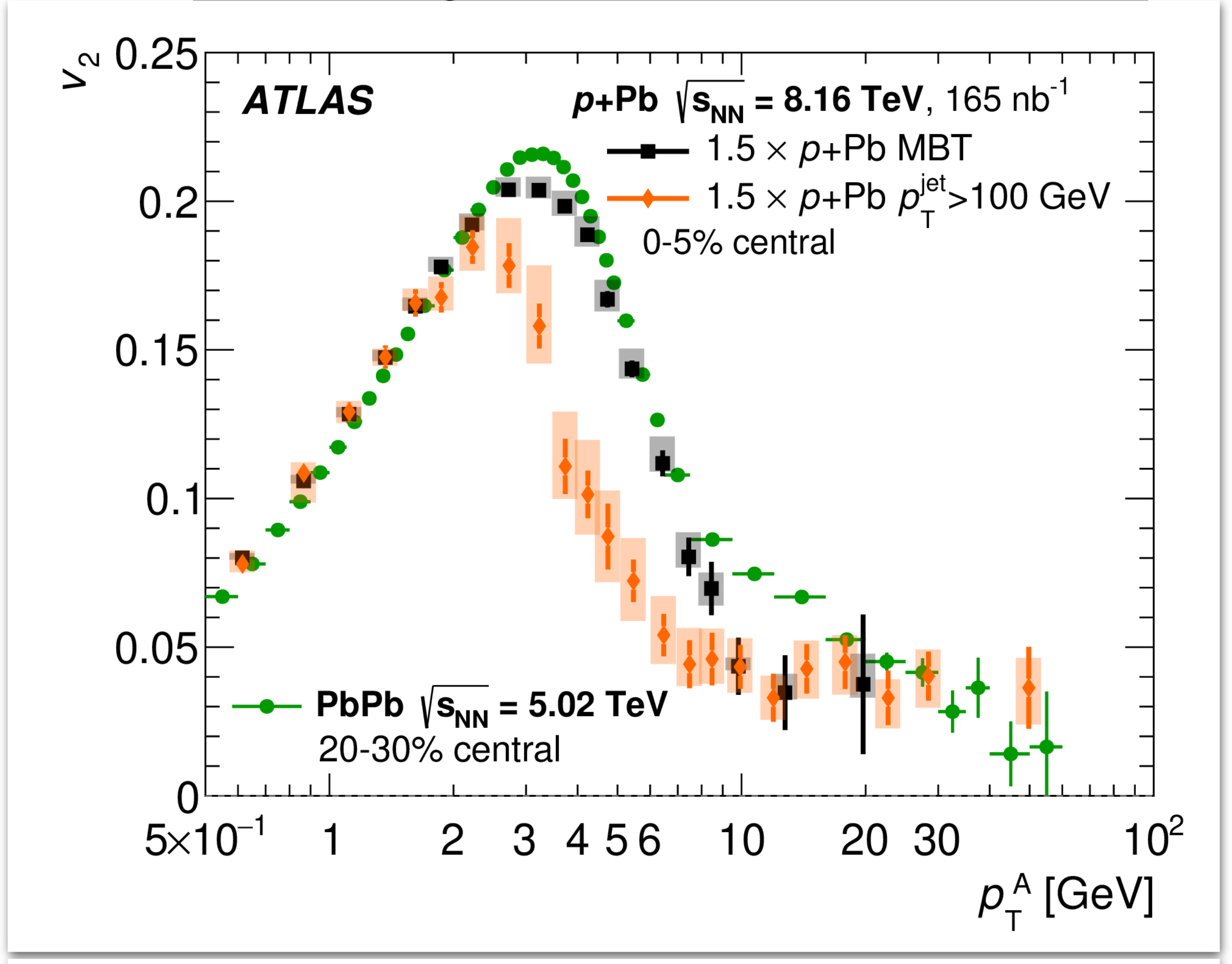
Jets from large to small systems

What is the critical system size for the onset of energy loss effects?

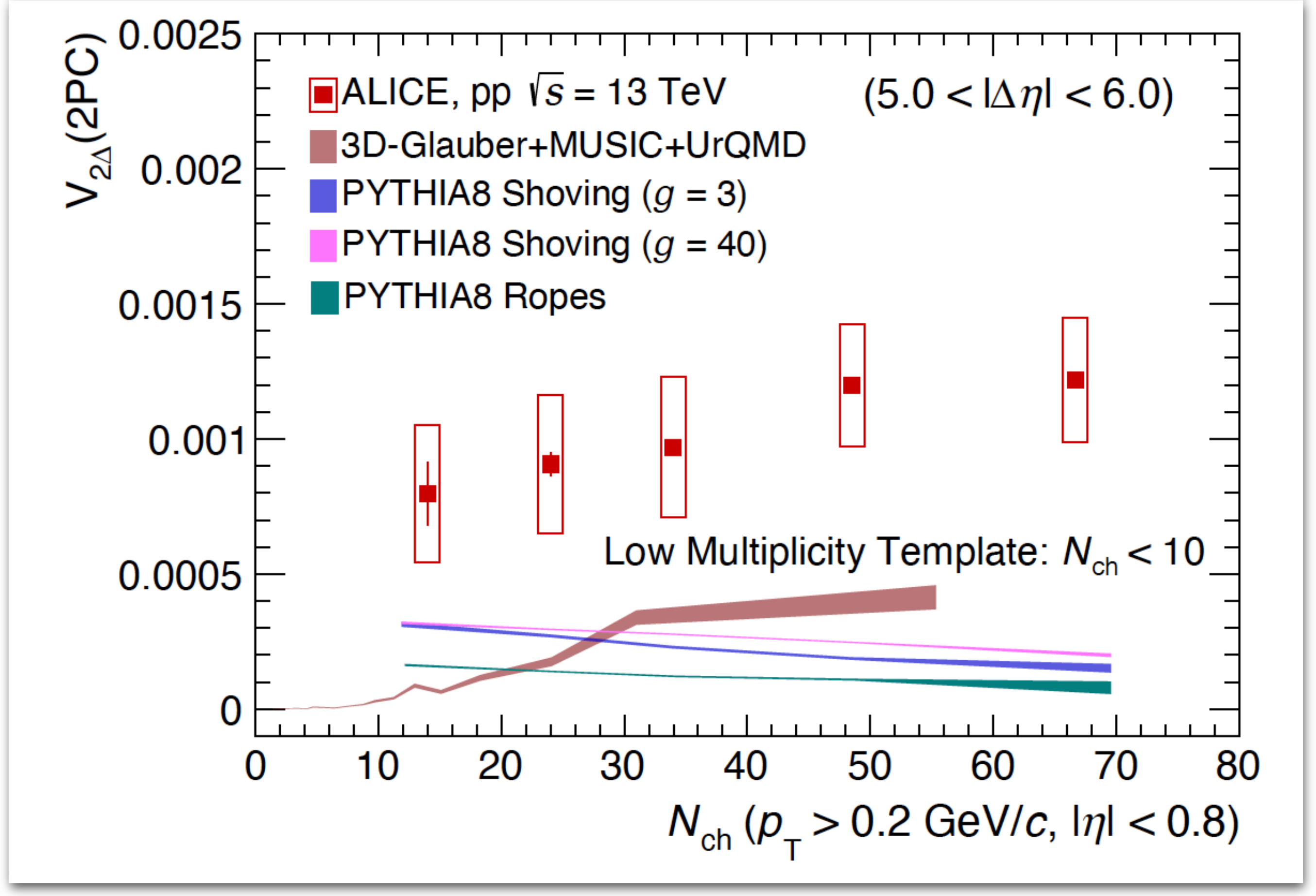
From AA to pA: the high p_T puzzle

Clear v_2 signal, similar to mid-central Pb-Pb observed in central p+Pb...

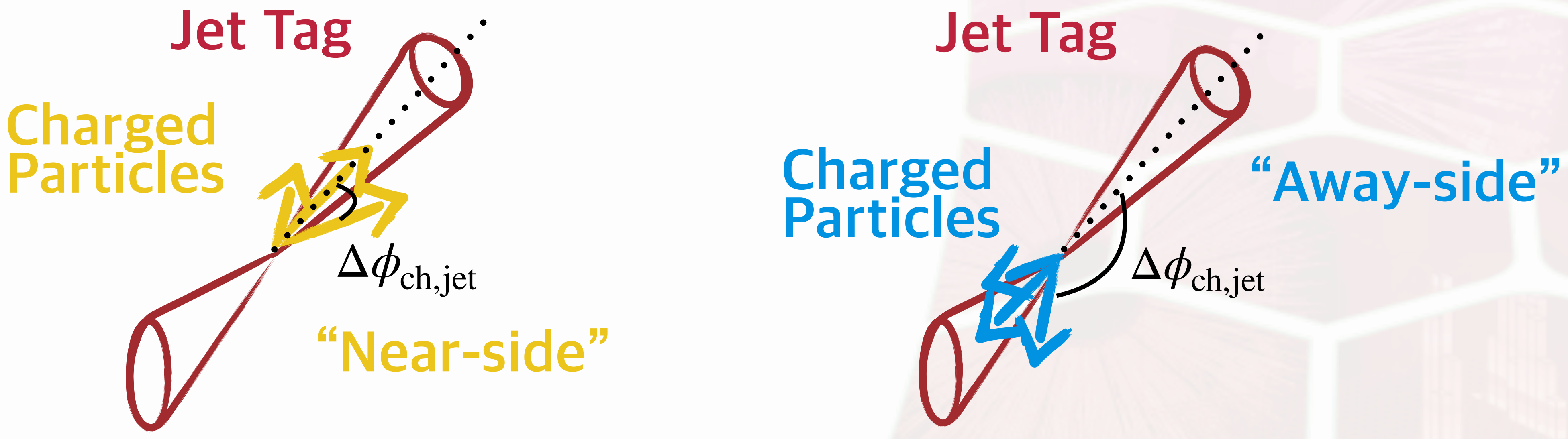
Eur. Phys. J. C 80 (2020) 73

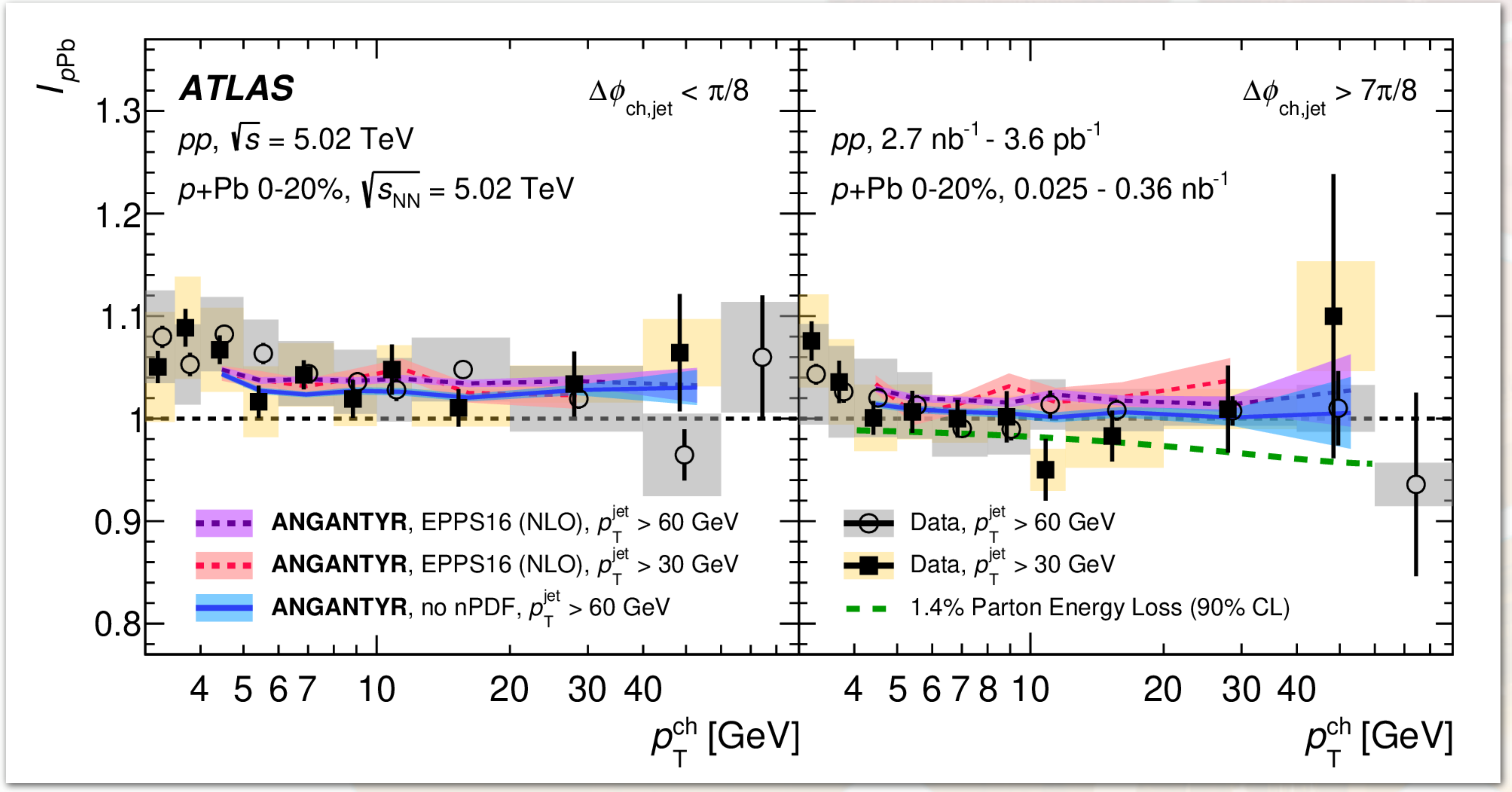


... not turning off completely also at very low multiplicities



arXiv:2504.02359



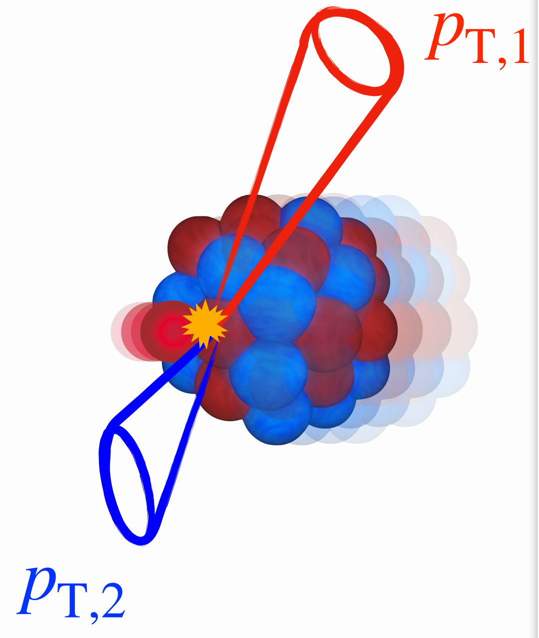


No evidence of **Jet quenching** in I_{pPb} observable

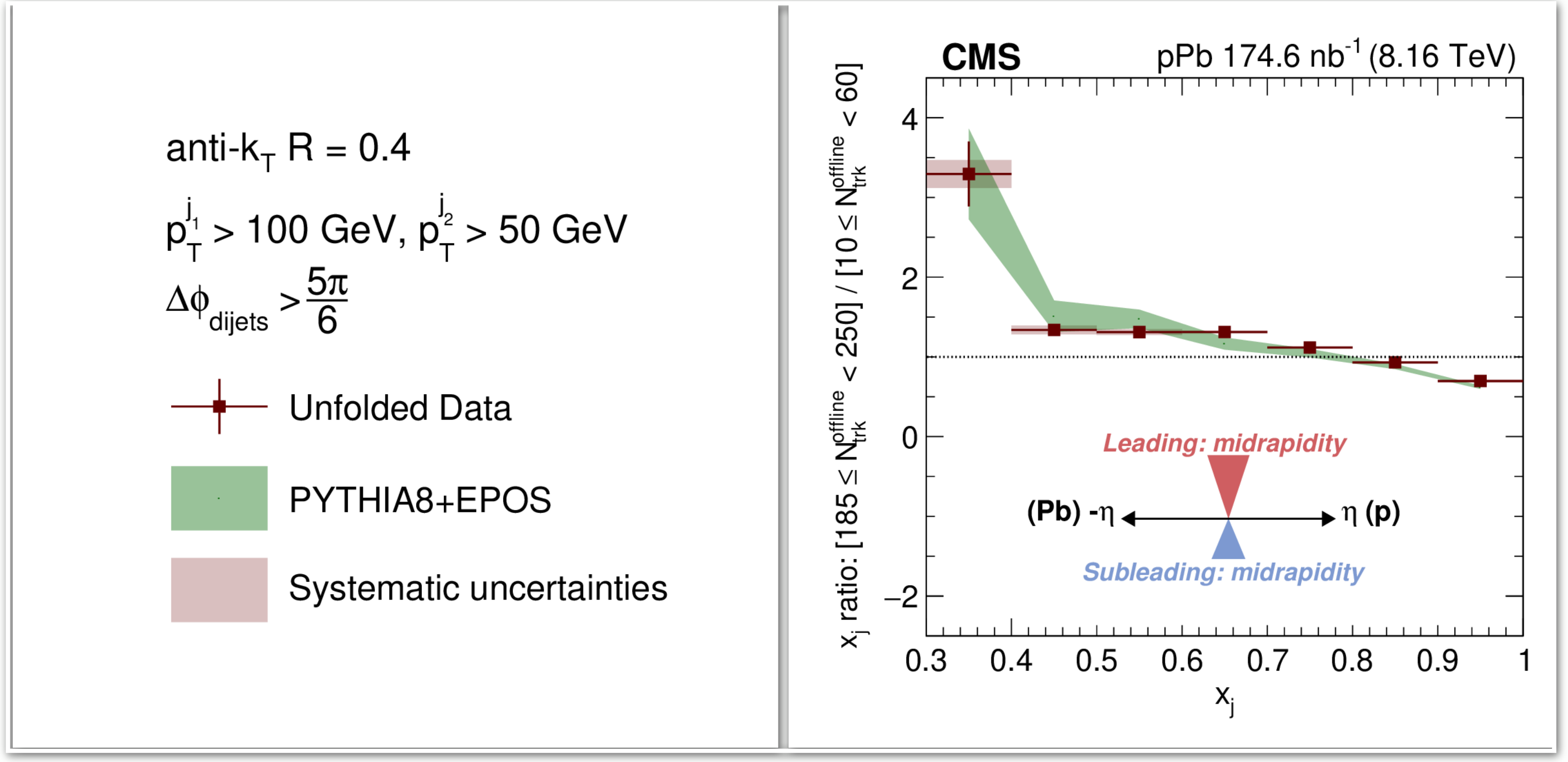
Strong parton energy loss constraint: 0.2 ± 0.5% and < 1.4% at 90% confidence level

Phys. Rev. Lett. 131 (2023) 072301

jet+h / dijet measurements



$$x_J = \frac{p_{T,2}}{p_{T,1}}$$

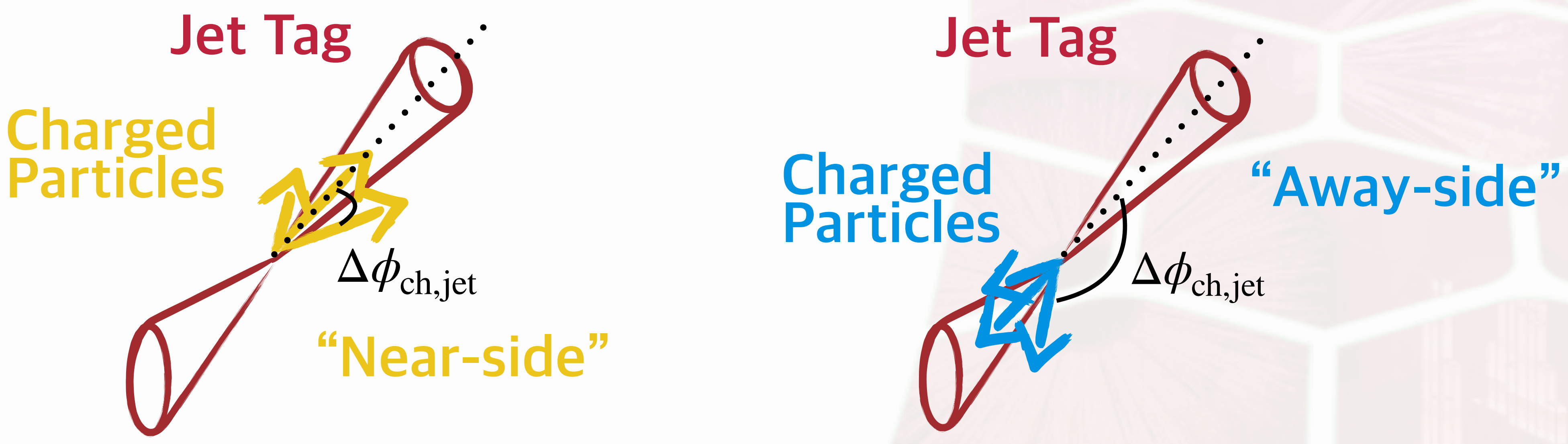


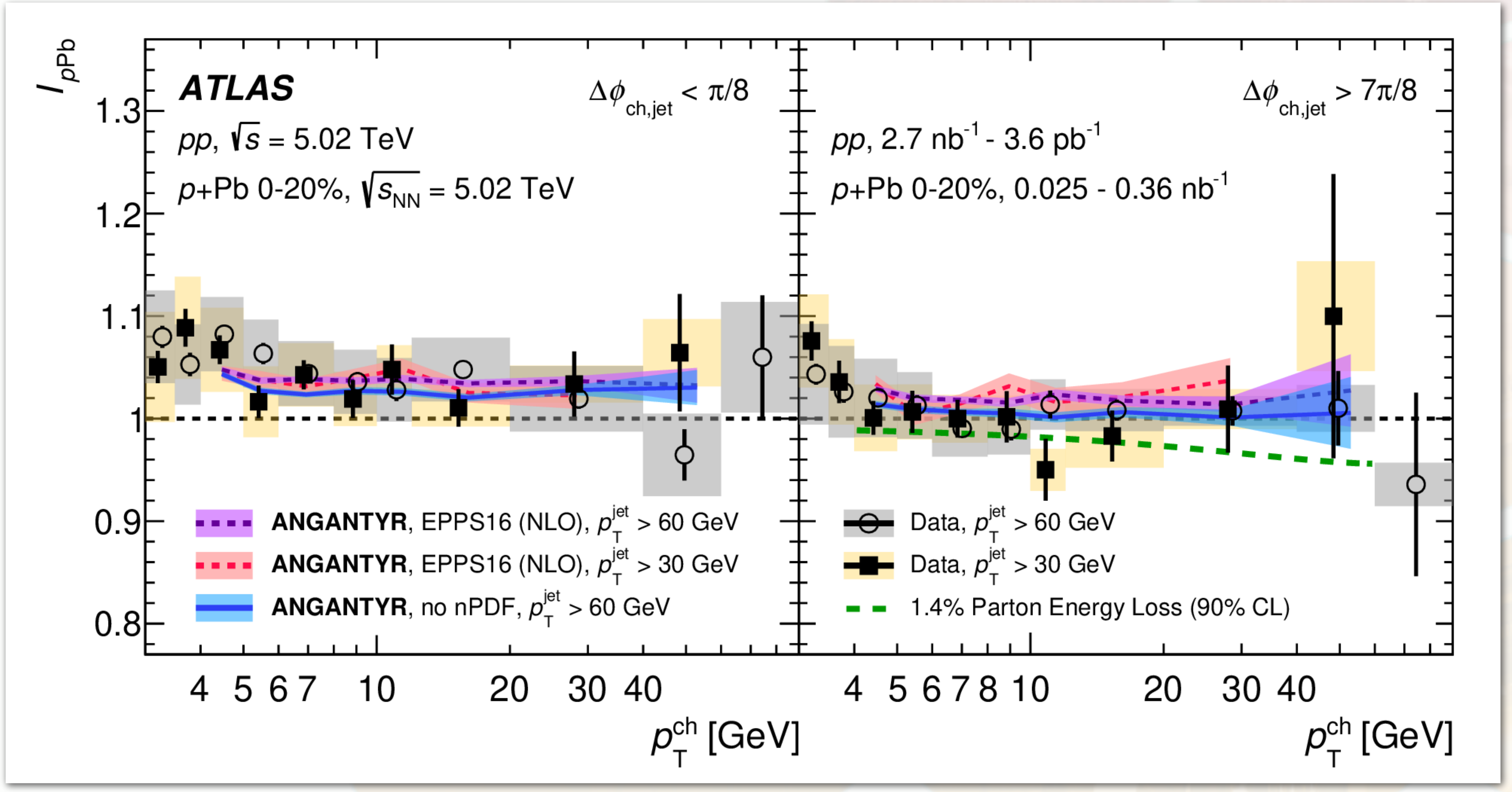
arXiv:2504.08507

No evidence of **jet quenching** also in dijet asymmetry from CMS

Comparison to Pythia8+EPOS (no hot-medium effects)

Upper-limit on medium-induced energy loss of the subleading jet of 1.26% of its transverse momentum at the 90% confidence level in high multiplicity p+Pb events





No evidence of **Jet quenching** in I_{pPb} observable

Strong parton energy loss constraint: 0.2 ± 0.5% and < 1.4% at 90% confidence level

Phys. Rev. Lett. 131 (2023) 072301

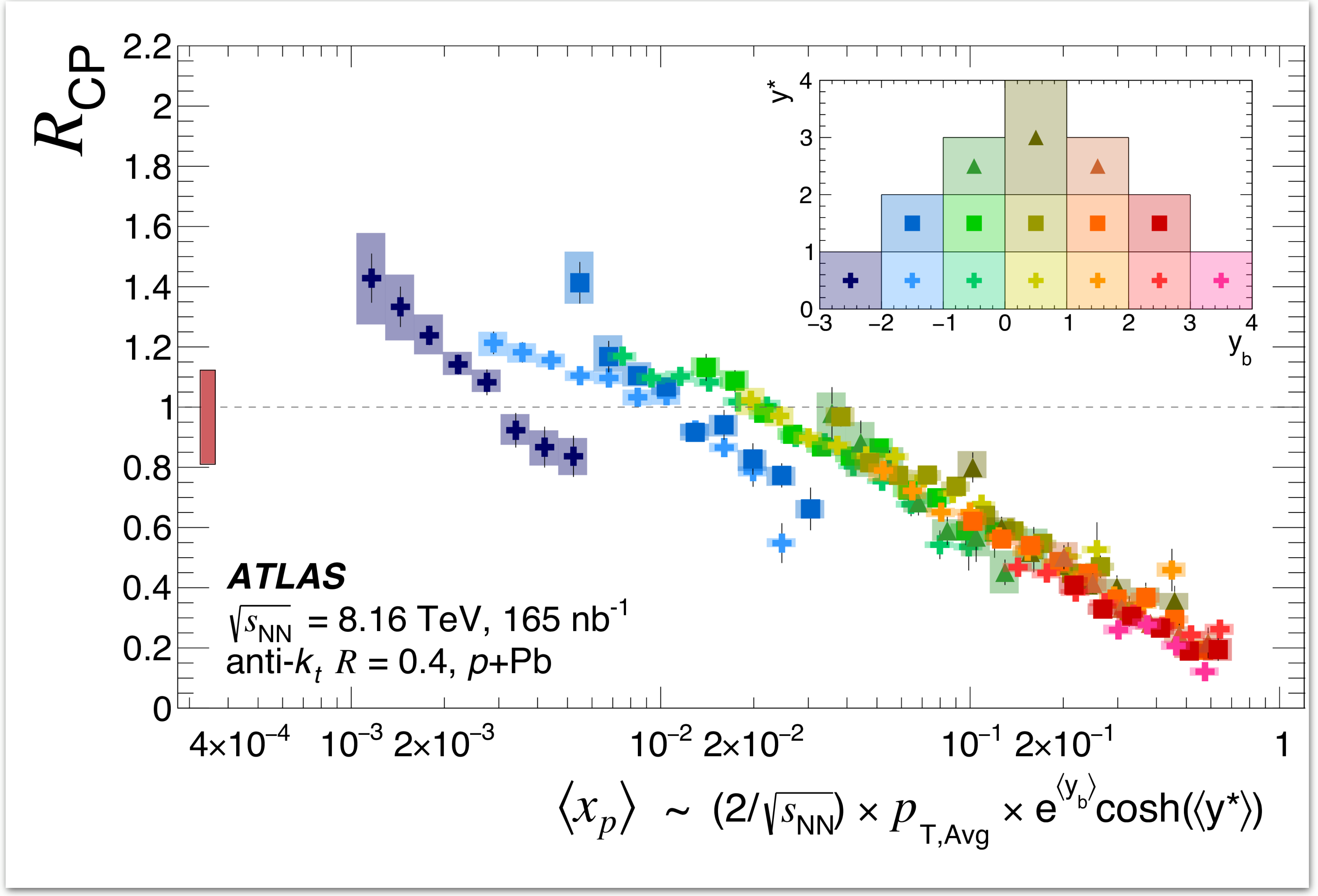
Initial State

What is the impact of the proton configuration in interpreting p+A collisions?

Since hot-QCD effects are little if not null, how can jets aid the study of cold nuclear matter effects?

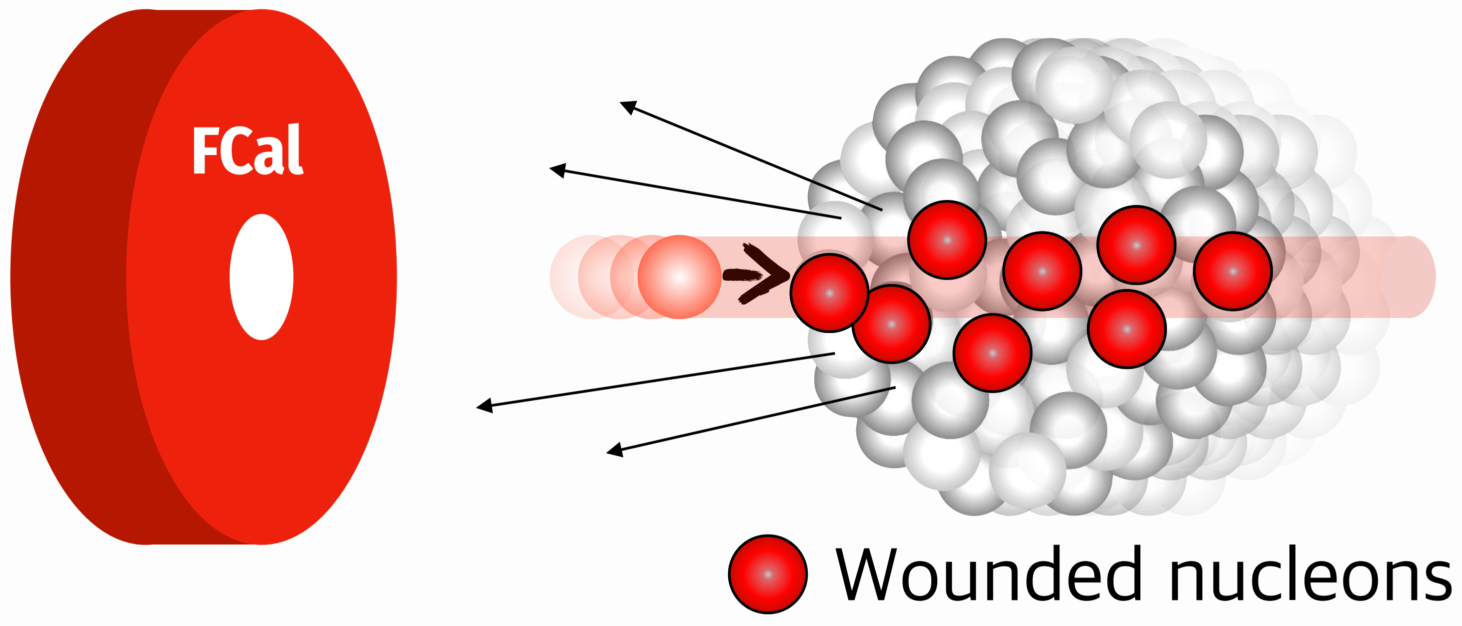
Effect of proton configuration in p+A

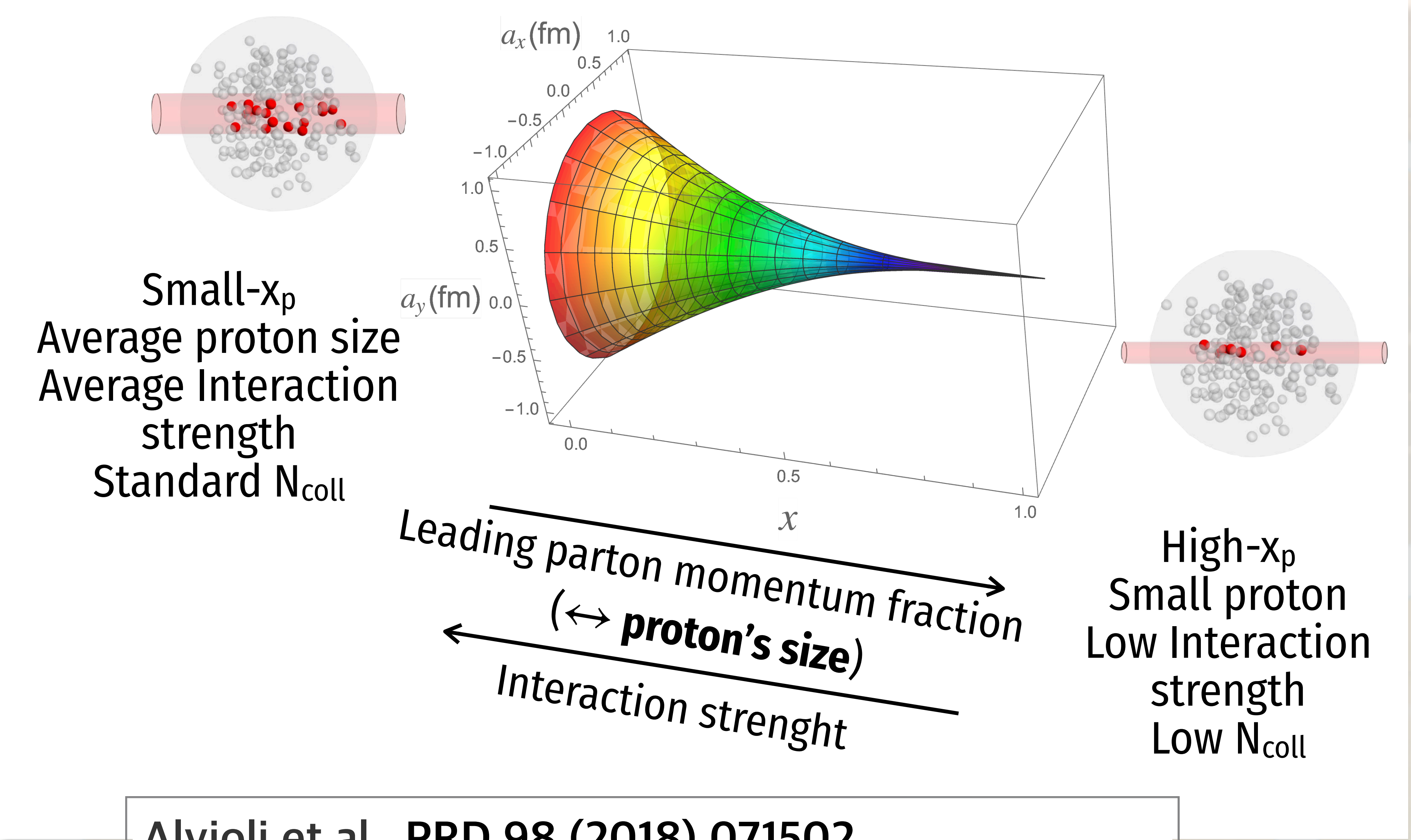
Reminder: ATLAS Run1 inclusive jets (and PHENIX jets!) in p/d+A showing strong R_{CP} dependence on jet energy while no sizable effects in R_{pPb} hinting at relation to the hard-scattering



Use dijets to **map R_{CP} on the kinematics of the initial state (x_p)**

- Strong x_p-driven event-activity bias in p+Pb for $x_p \gtrsim 0.02$
- Qualitatively in agreement with models proposing a shrinking size and interaction strength of the proton at high x_p

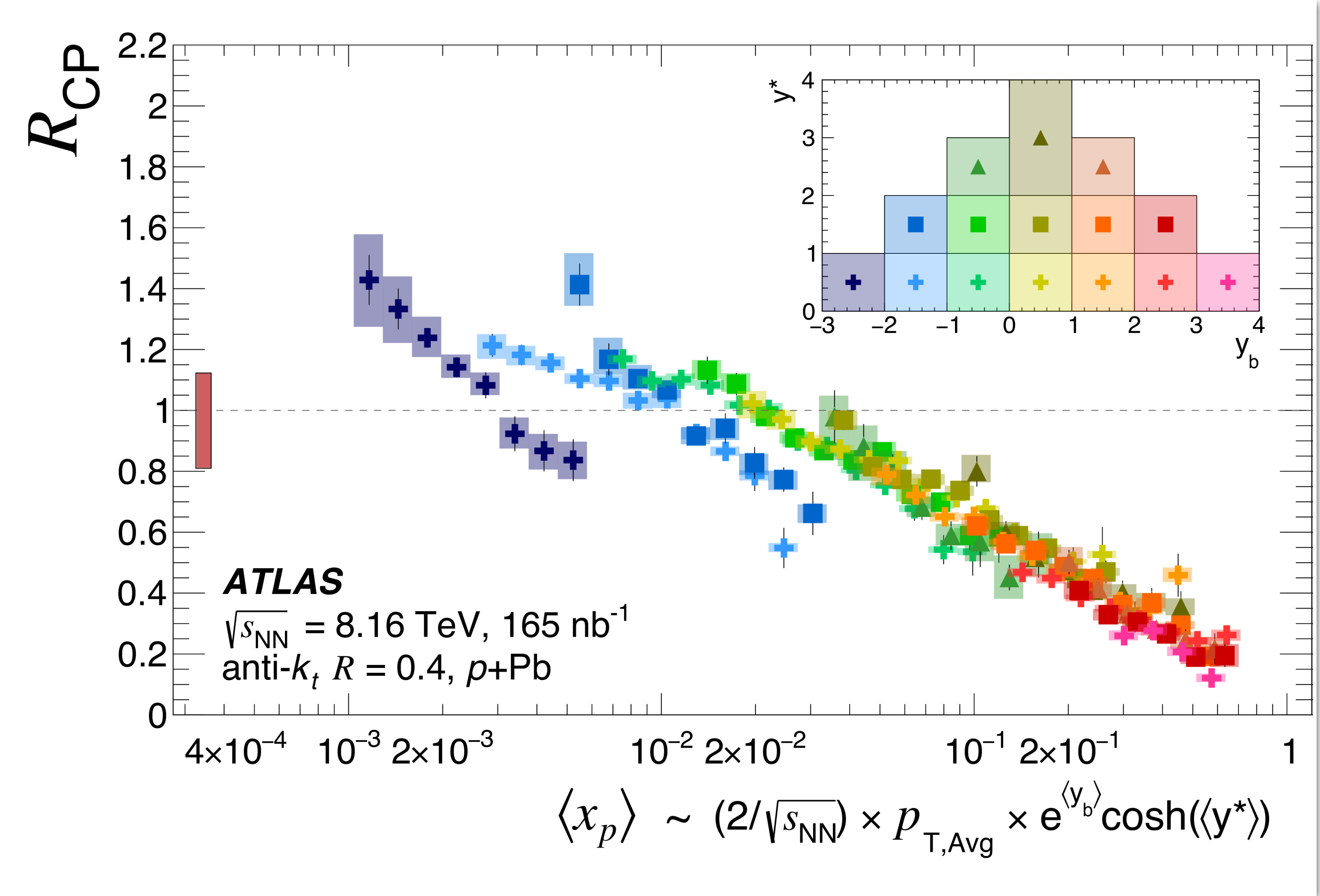




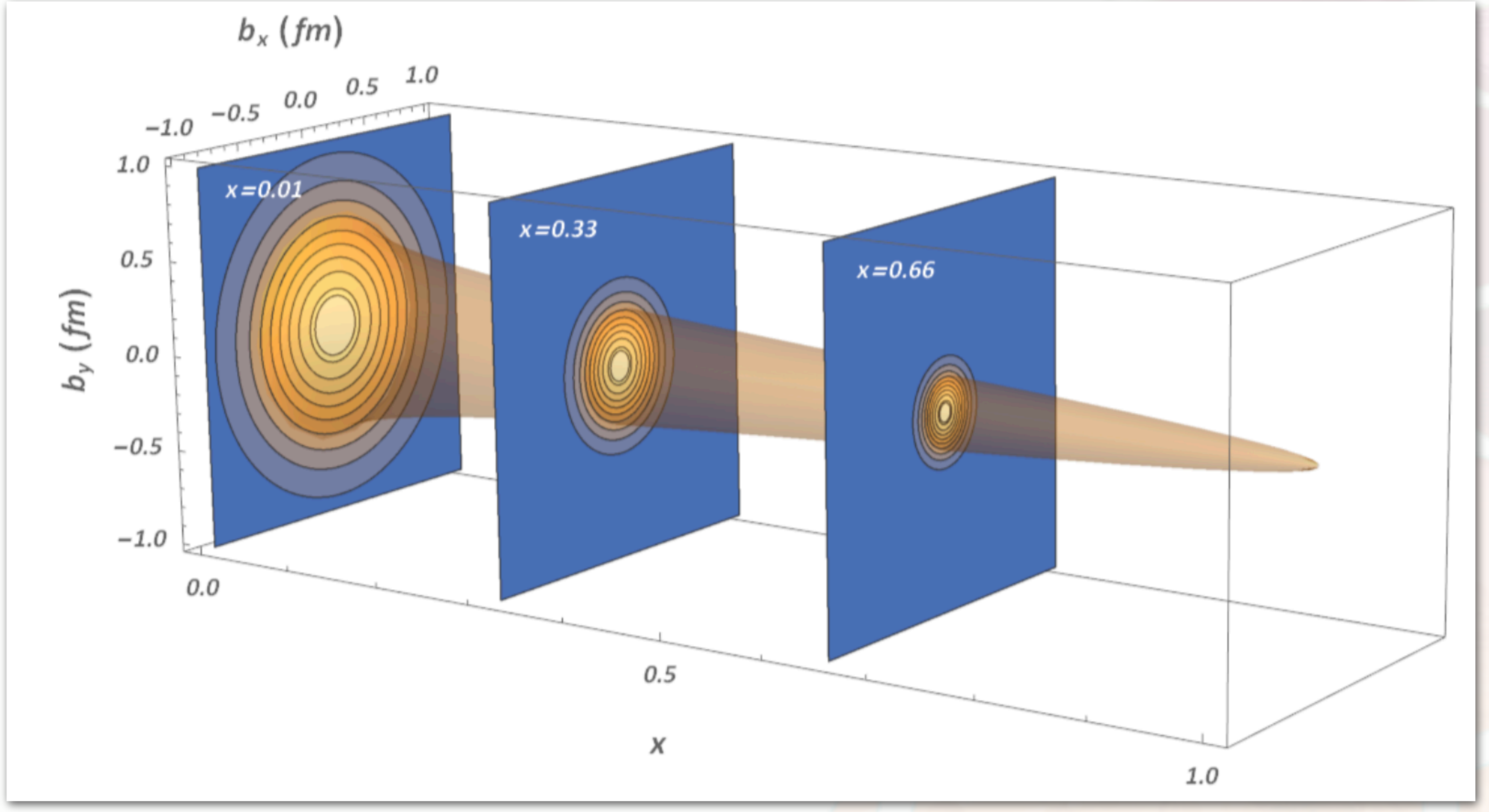
Alvioli et al., PRD 98 (2018) 071502
Brodsky et al., MDPI Physics 4 (2022) 2, 633-646

Effect of proton configuration in p+A

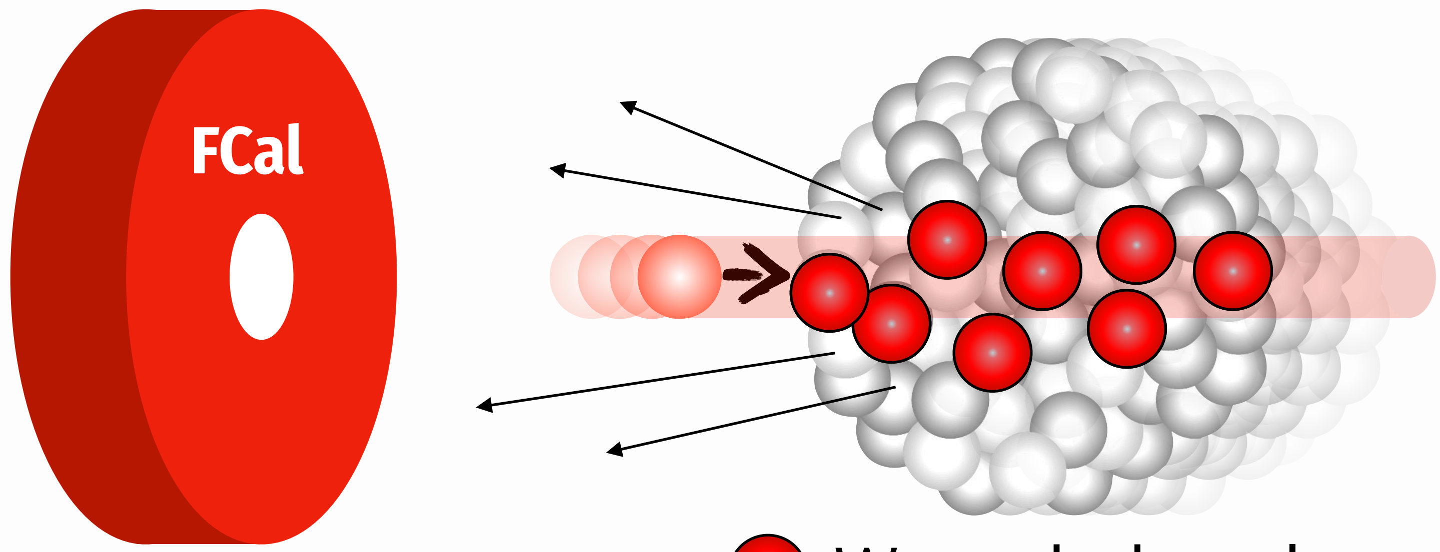
Are we looking at GPDs from another corner?

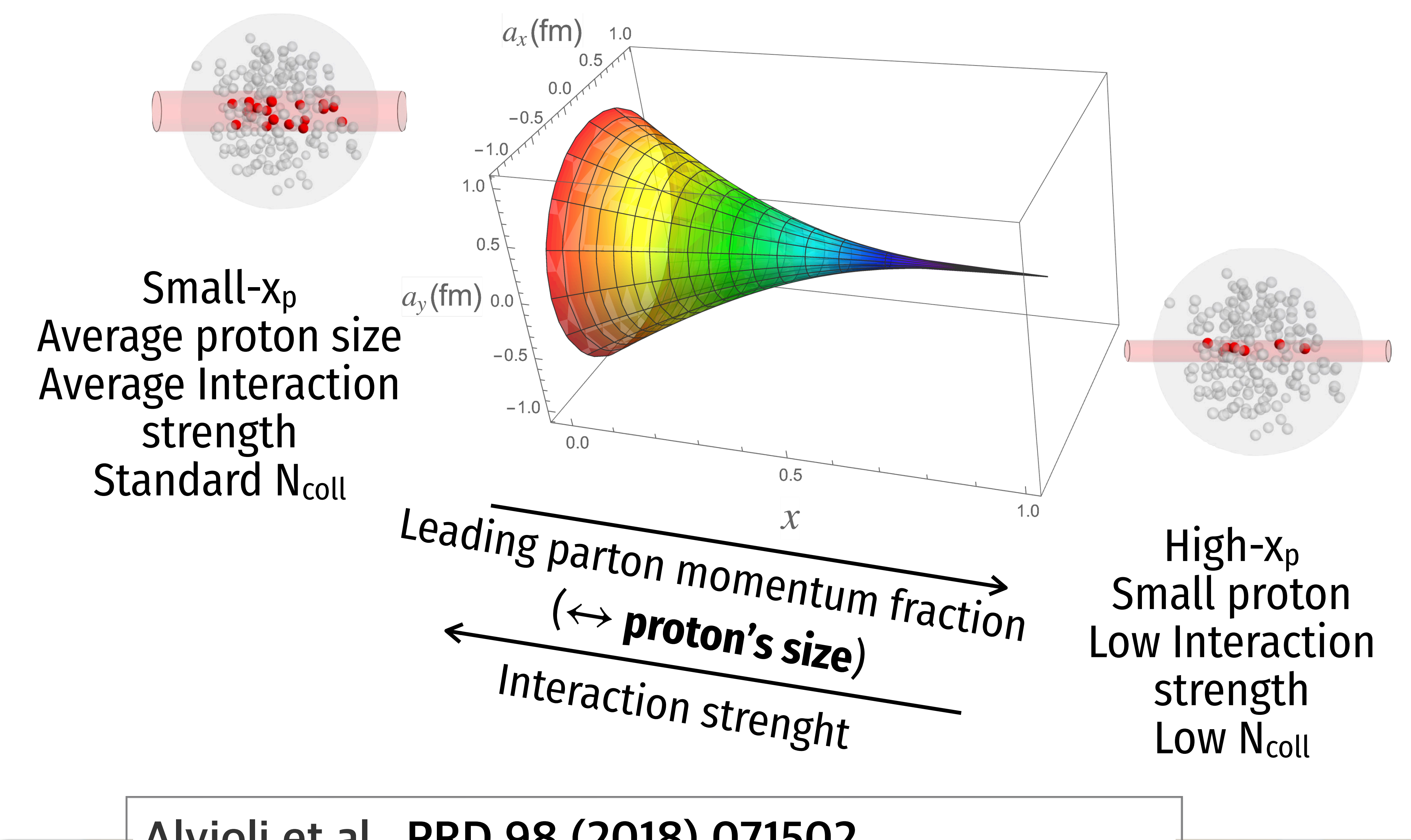


Potential point of contact with the EIC!



Dupré et al., PRD 95 (2017) 011501

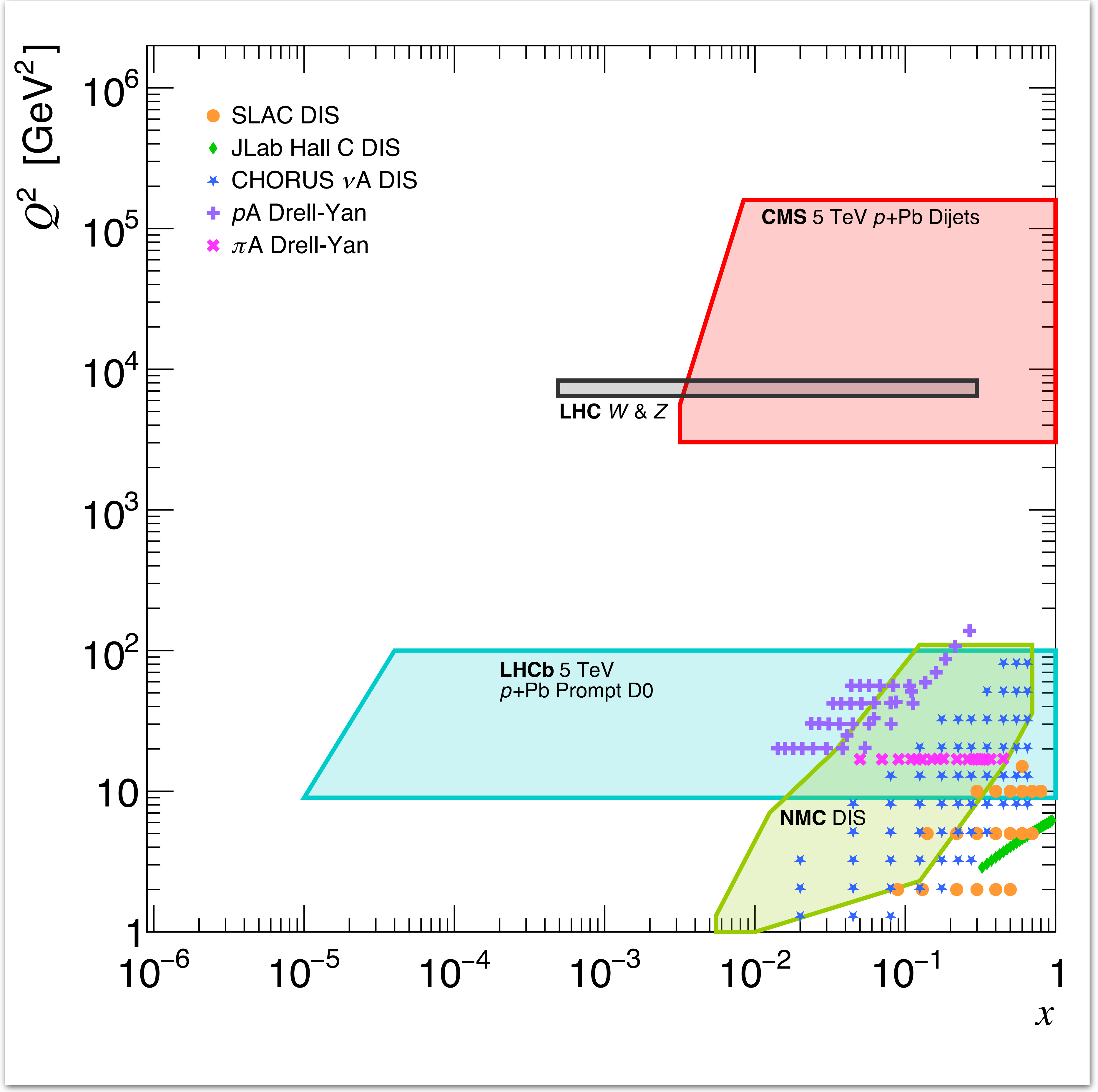




Alvioli et al., PRD 98 (2018) 071502
Brodsky et al., MDPI Physics 4 (2022) 2, 633-646

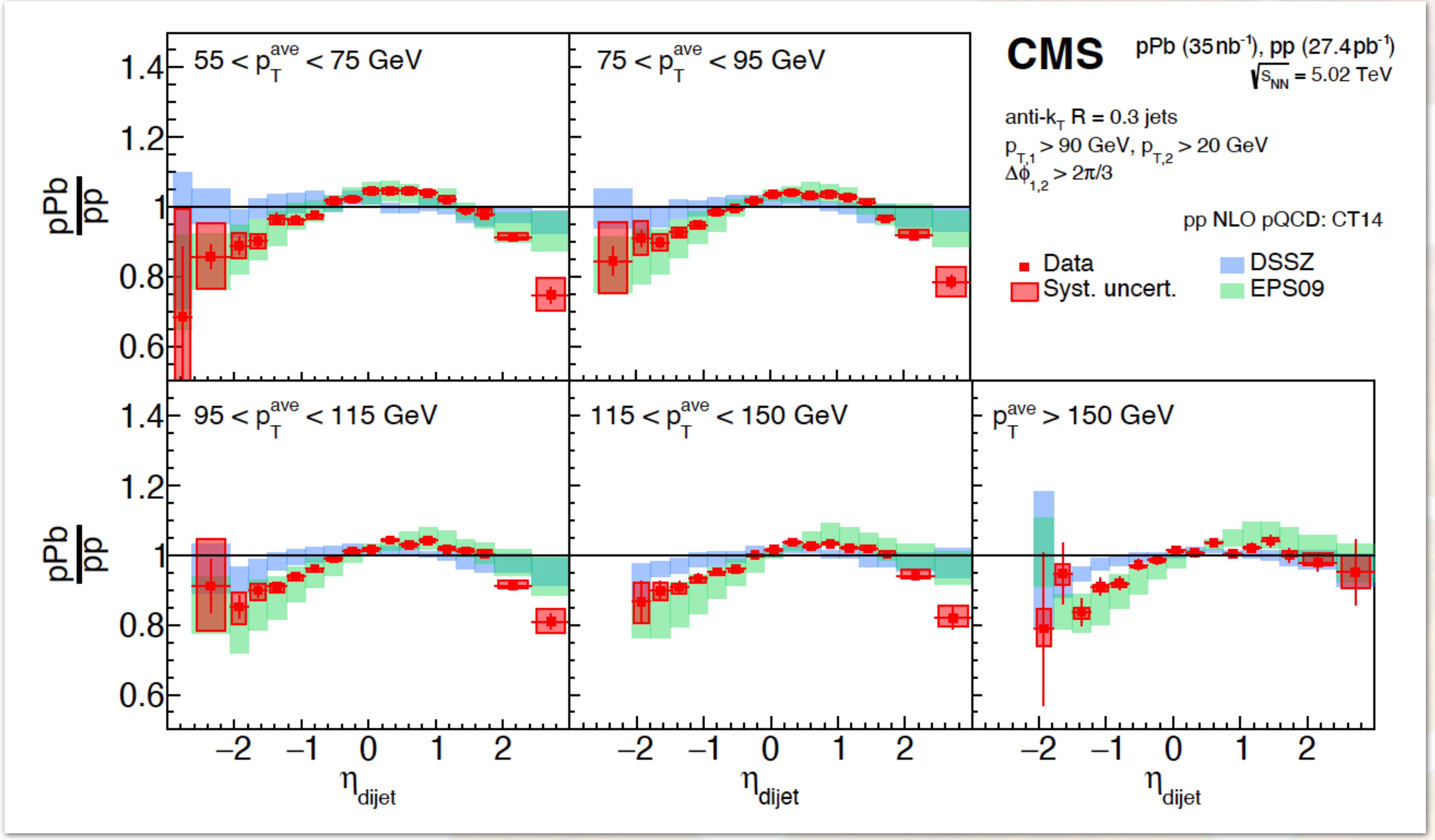
Dijet probes for nuclear PDFs in LHC regime

The last few years have marked a **golden age of dijet measurements** at the **LHC**



Data included in EPPS21 (**Eur.Phys.J.C 82 (2022) 5, 413**)

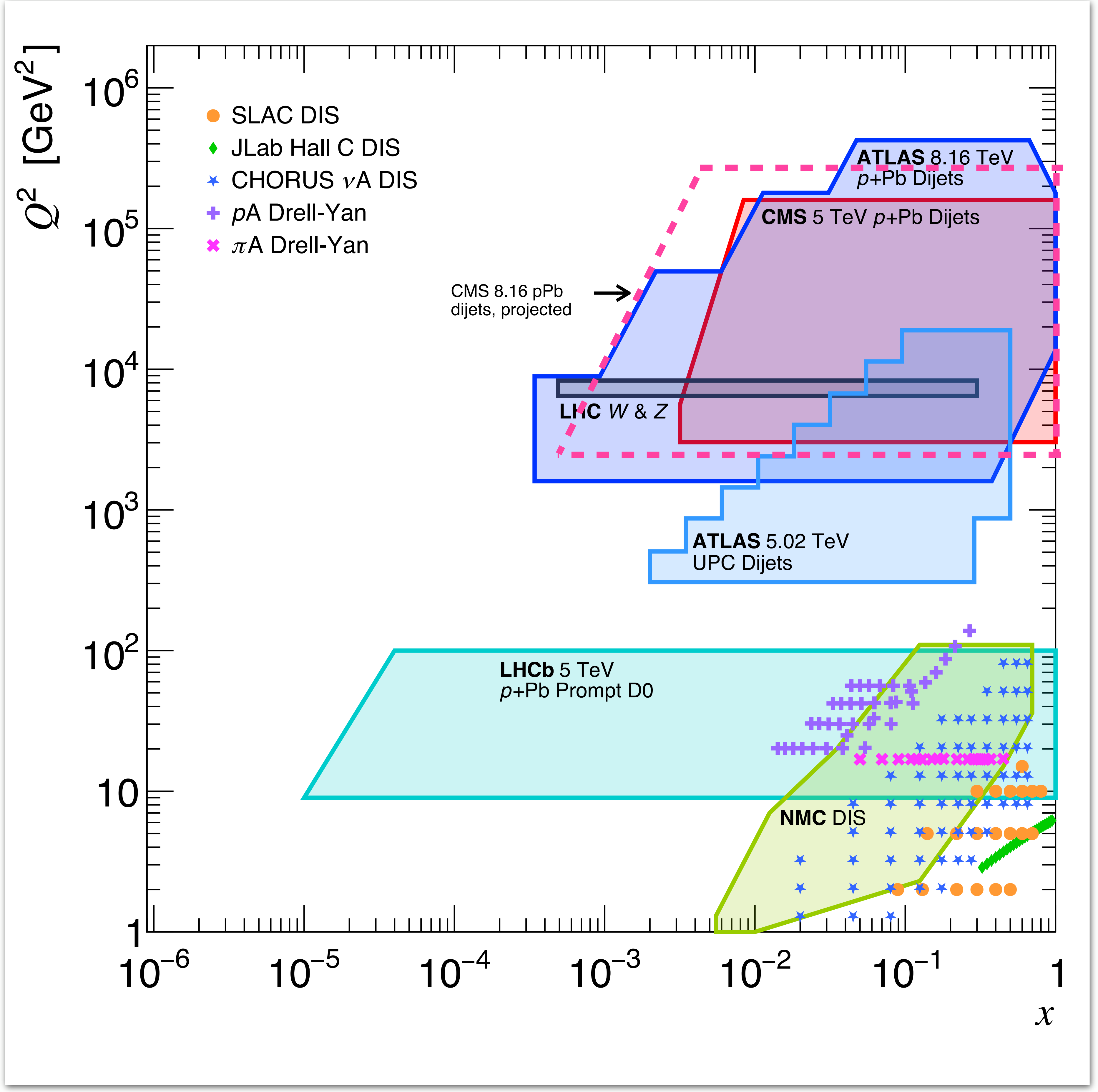
CMS dijets in p+Pb @ 5.02 TeV, **PRL 121 (2018) 6, 062002**



Dijet pseudorapidity distribution ratios between p+Pb and p+p in 5 p_T^{ave} bins

ATLAS UPC dijets @ 5.02 TeV

The last few years have marked a **golden age of dijet measurements** at the **LHC**



Data included in EPPS21 (**Eur.Phys.J.C 82 (2022) 5, 413**)

CMS dijets in p+Pb @ 5.02 TeV, **PRL 121 (2018) 6, 062002**

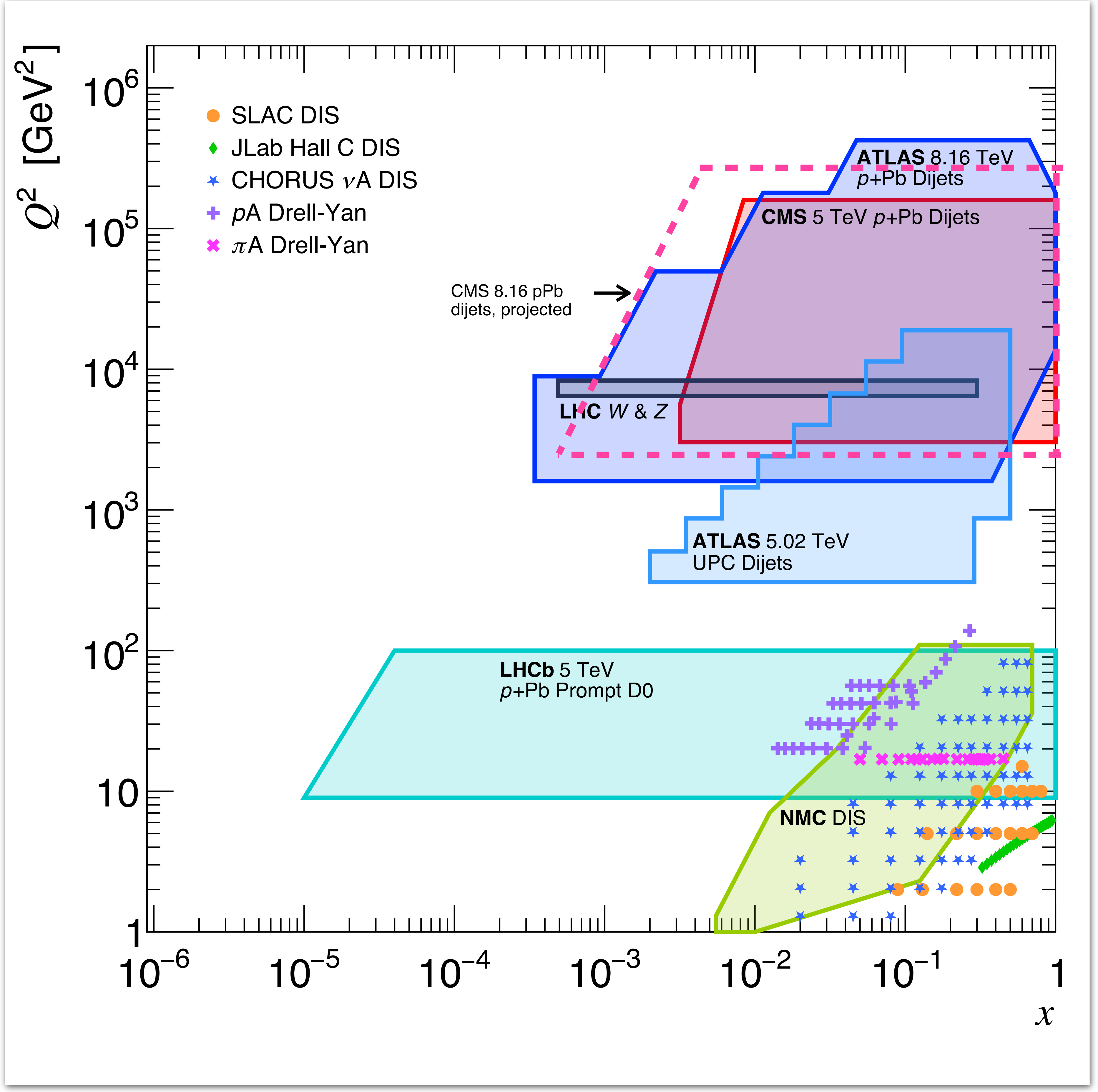
ATLAS dijets in p+Pb @ 8.16 TeV, **HION-2023-15**

CMS dijets in p+Pb @ 8.16 TeV, **CMS-PAS-HIN-24-014**

ATLAS UPC dijets in Pb+Pb @ 5.02 TeV, **PRD 111 (2025) 052006**

ATLAS UPC dijets @ 5.02 TeV

The last few years have marked a **golden age of dijet measurements** at the **LHC**



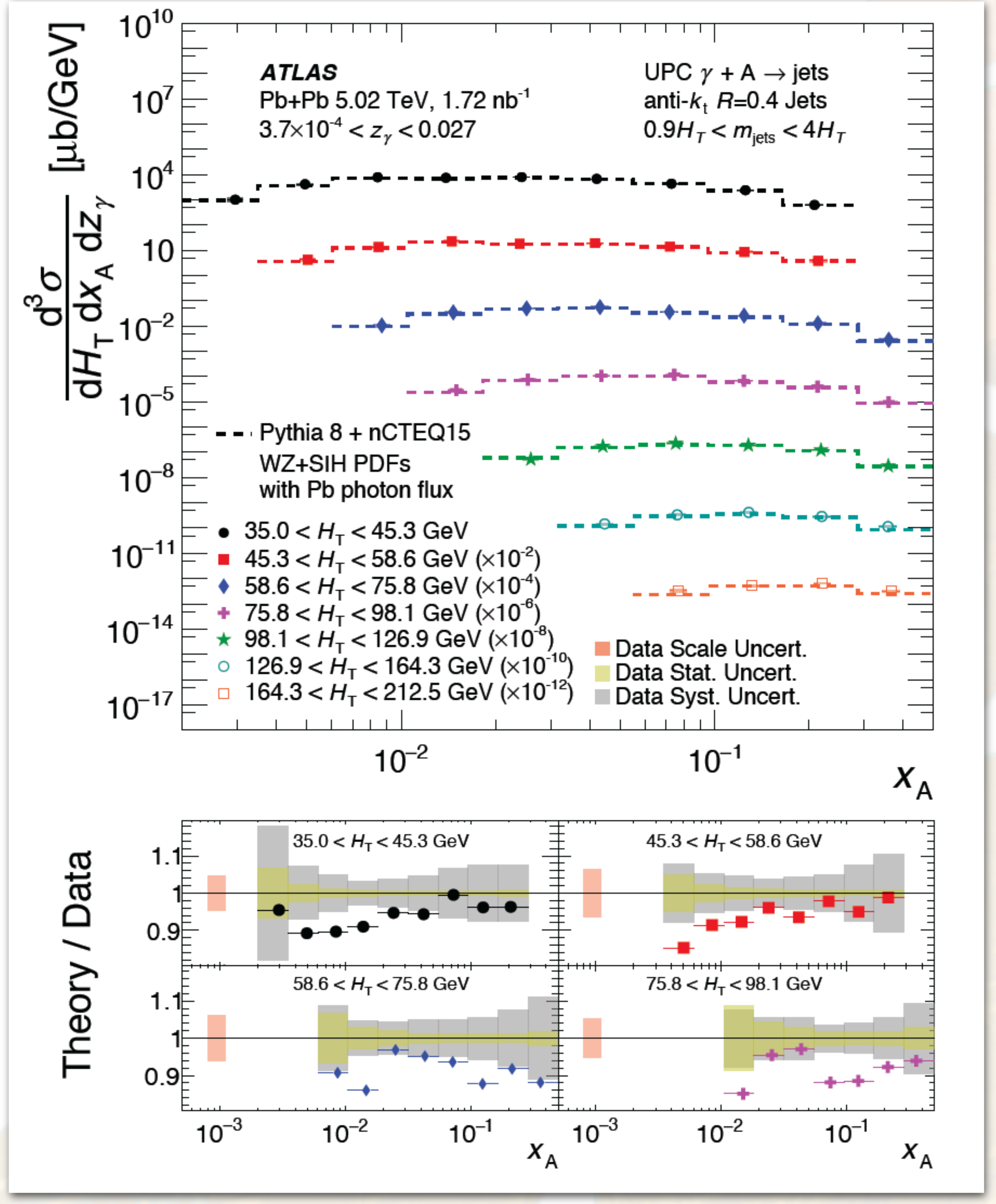
Data included in EPPS21 (Eur.Phys.J.C 82 (2022) 5, 413)

CMS dijets in p+Pb @ 5.02 TeV, PRL 121 (2018) 6, 062002

ATLAS dijets in p+Pb @ 8.16 TeV, HION-2023-15

CMS dijets in p+Pb @ 8.16 TeV, CMS-PAS-HIN-24-014

ATLAS UPC dijets in Pb+Pb @ 5.02 TeV, **PRD 111 (2025) 052006**

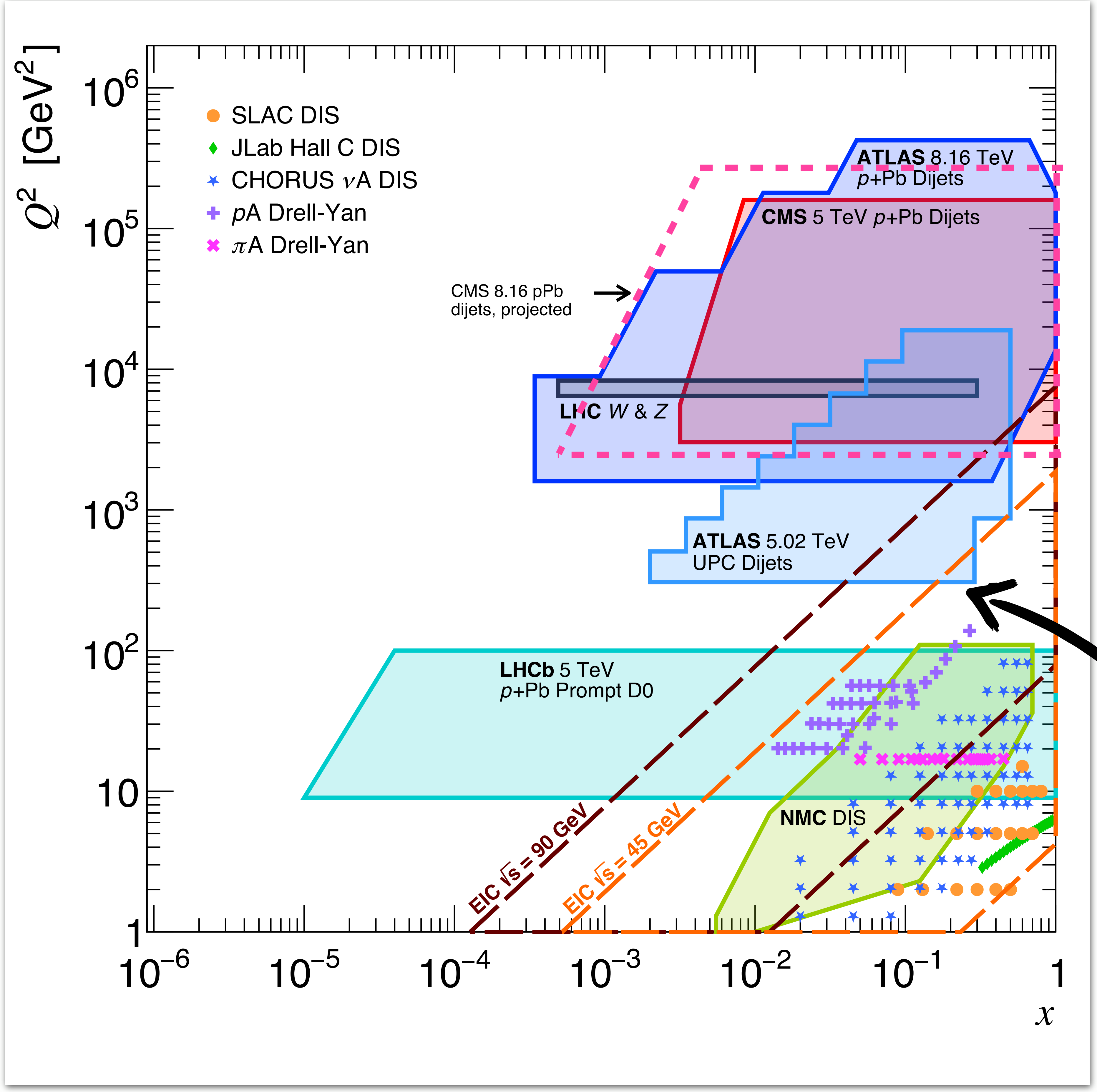


3D unfolded extraction of **UPC dijet cross-section** hard-scale, $\mathbf{H_T}$, photon resolution power, $\mathbf{z_\gamma}$, parton momentum fraction in the Pb, $\mathbf{x_A}$

unique (x,Q_2) phase space covered thanks to the photon energy

ATLAS UPC dijets @ 5.02 TeV

The last few years have marked a **golden age of dijet measurements** at the **LHC**



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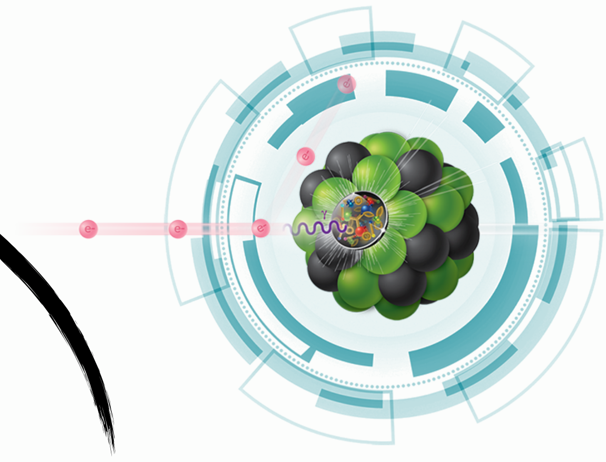
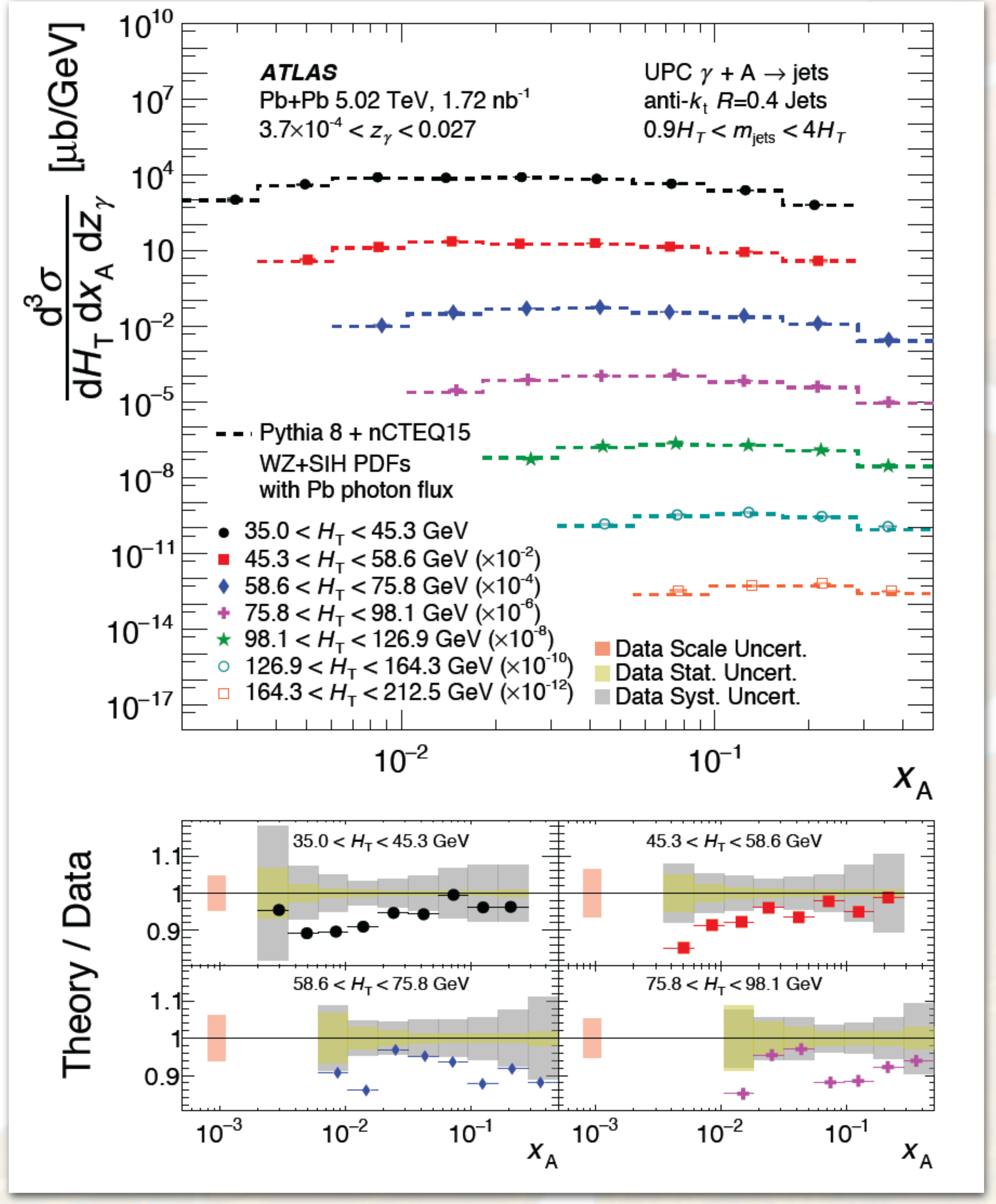
ATLAS UPC dijets in Pb+Pb @ 5.02 TeV, **PRD 111 (2025) 052006**



Direct bridge to the EIC phase space!



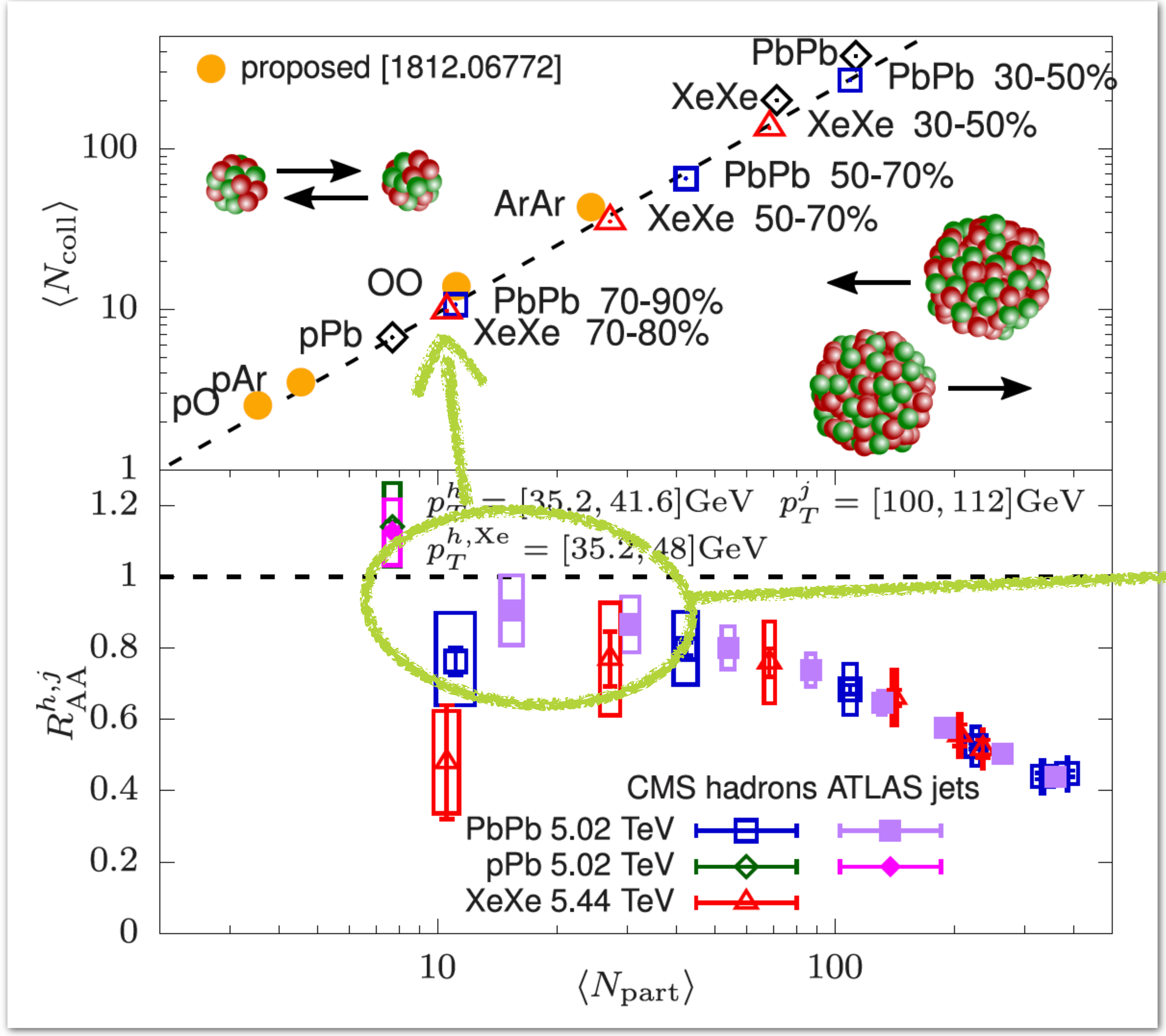
3D unfolded extraction of **UPC dijet cross-section**
hard-scale, $\mathbf{H_T}$,
photon resolution power, $\mathbf{z_\gamma}$,
parton momentum fraction in the Pb, $\mathbf{x_A}$

What’s next?

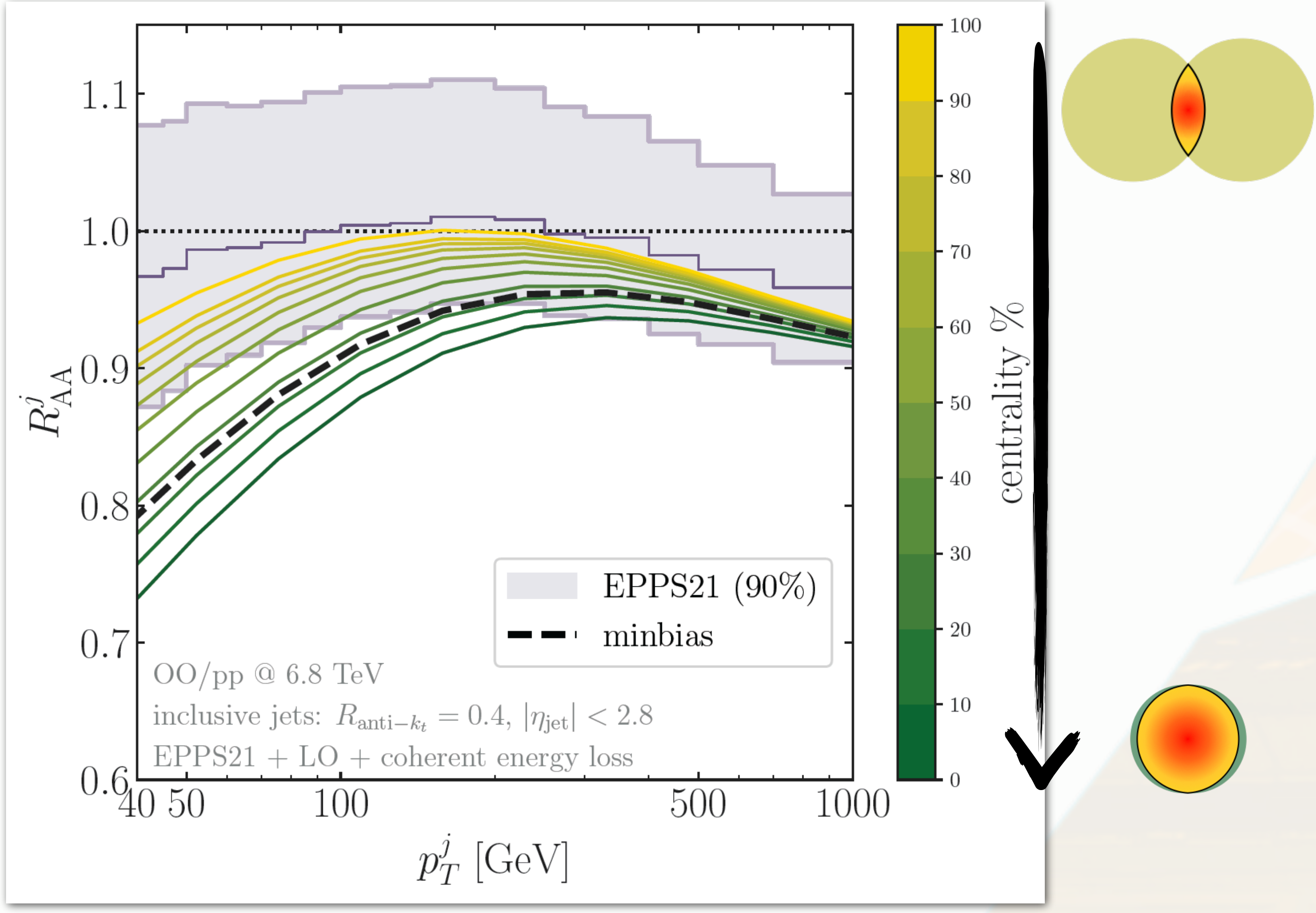
Here I had to pick really only a couple of interesting points, but there is a lot more in front of us…

Run 3 main novelty: the Oxygen run

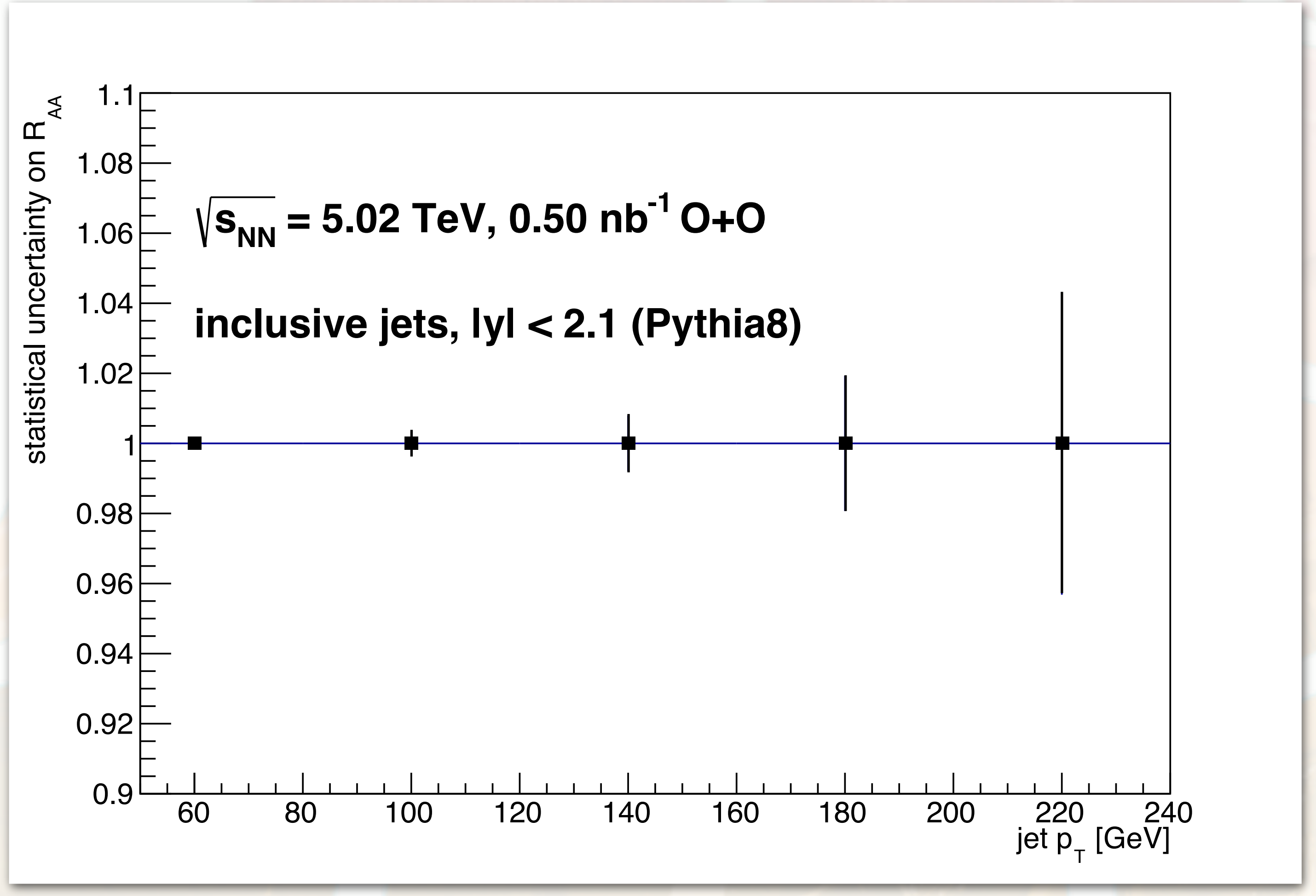
- **July 25:** First (pilot) oxygen run @ LHC! Gold mine for both Hot & Cold QCD
- **Hot QCD: 0.5-1 nb^{-1} of O+O @ 5.36 TeV [Energy tbc]**



A.Huss et al.,
PRL 126, 192301 (2021)

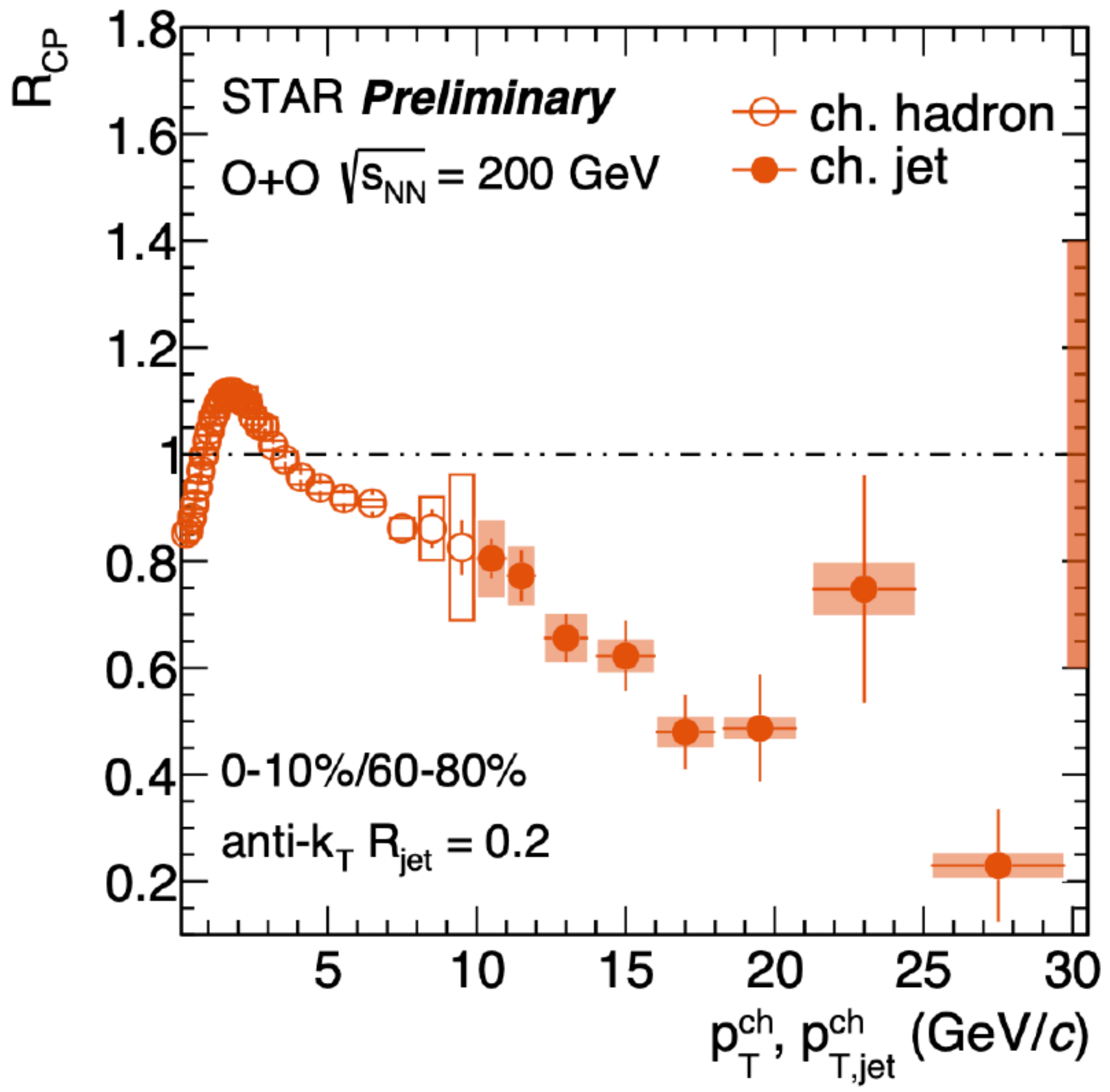


Jet R_{AA}, Preliminary predictions, from **A.Takacs @ 2024 Light ion workshop at CERN**



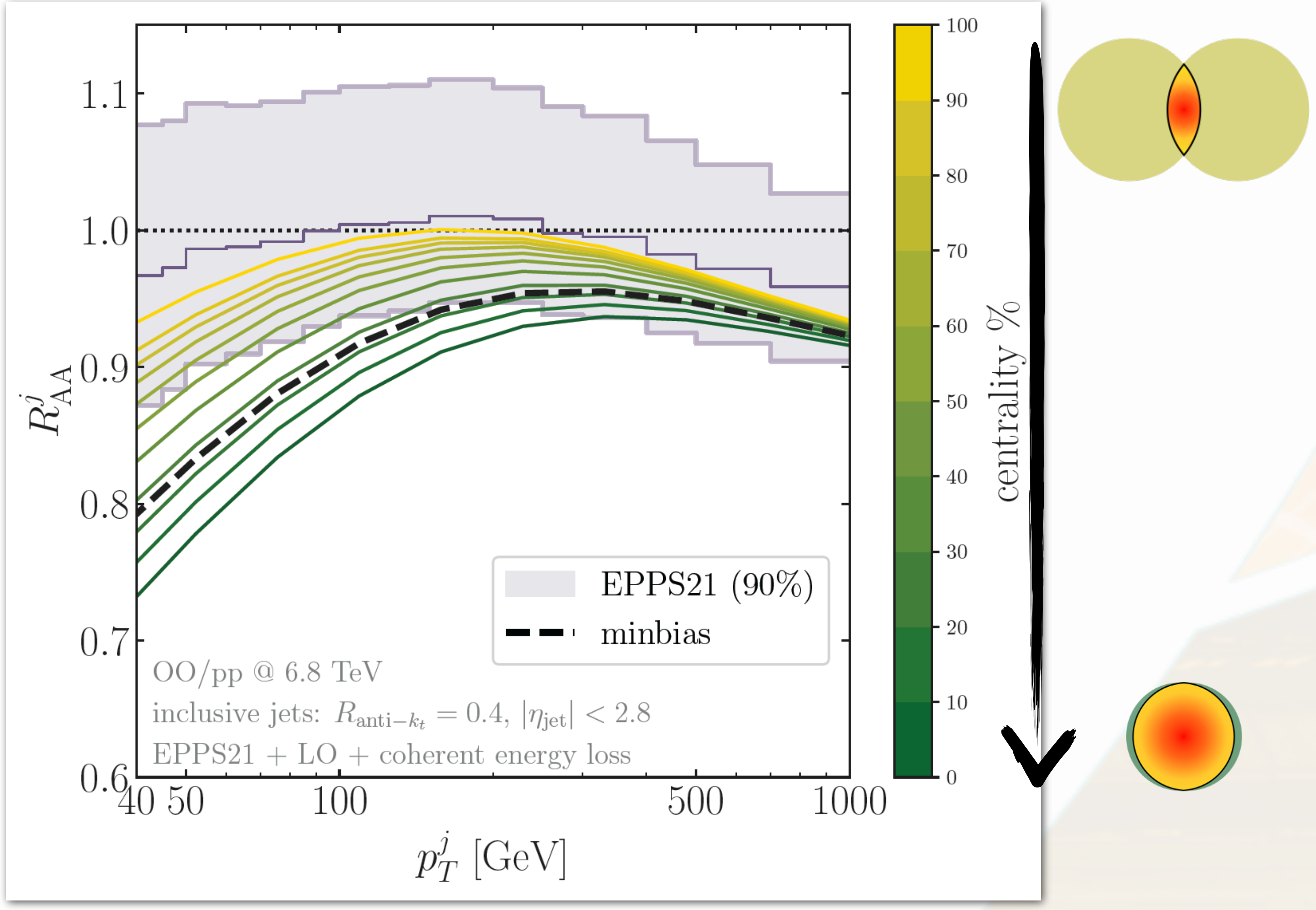
Projections from A. Sickles, centrality integrated
2021 Oxygen Workshop at CERN

Oxygen: LHC vs RHIC



Recent OO analyses at STAR increased the hype!

R_{CP} trends somewhat **reminiscent of R_{CP} in p+A** at RHIC and LHC (e.g., color fluctuation effects) => Will the matter in OO centrality determination?



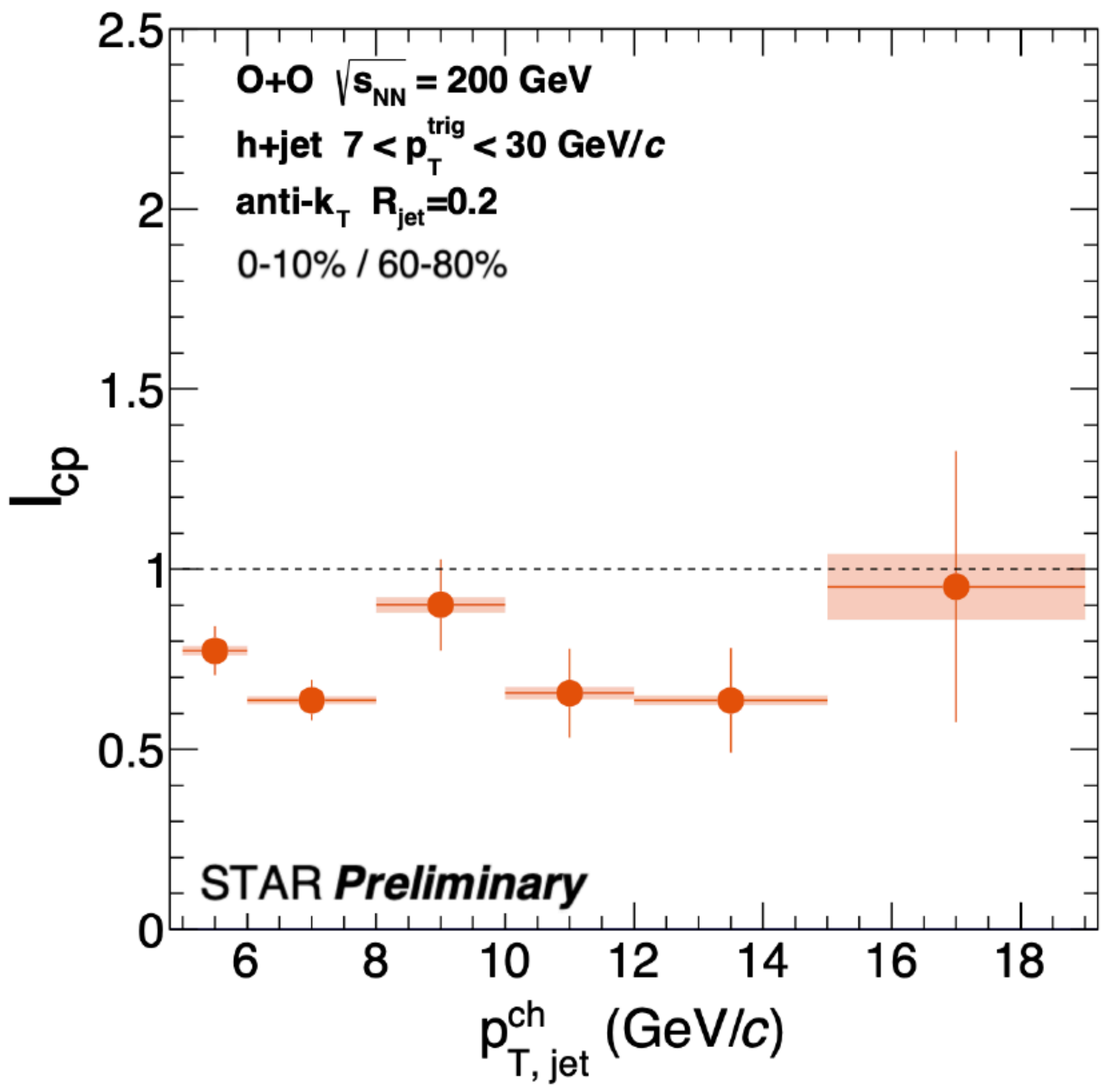
Jet R_{AA}, Preliminary predictions, from **A.Takacs @ 2024 Light ion workshop at CERN**

RHIC data legacy is a key to using unique RHIC datasets as input to solve the jet quenching onset puzzle…

See impact from ALEPH, H1 etc after so many years!

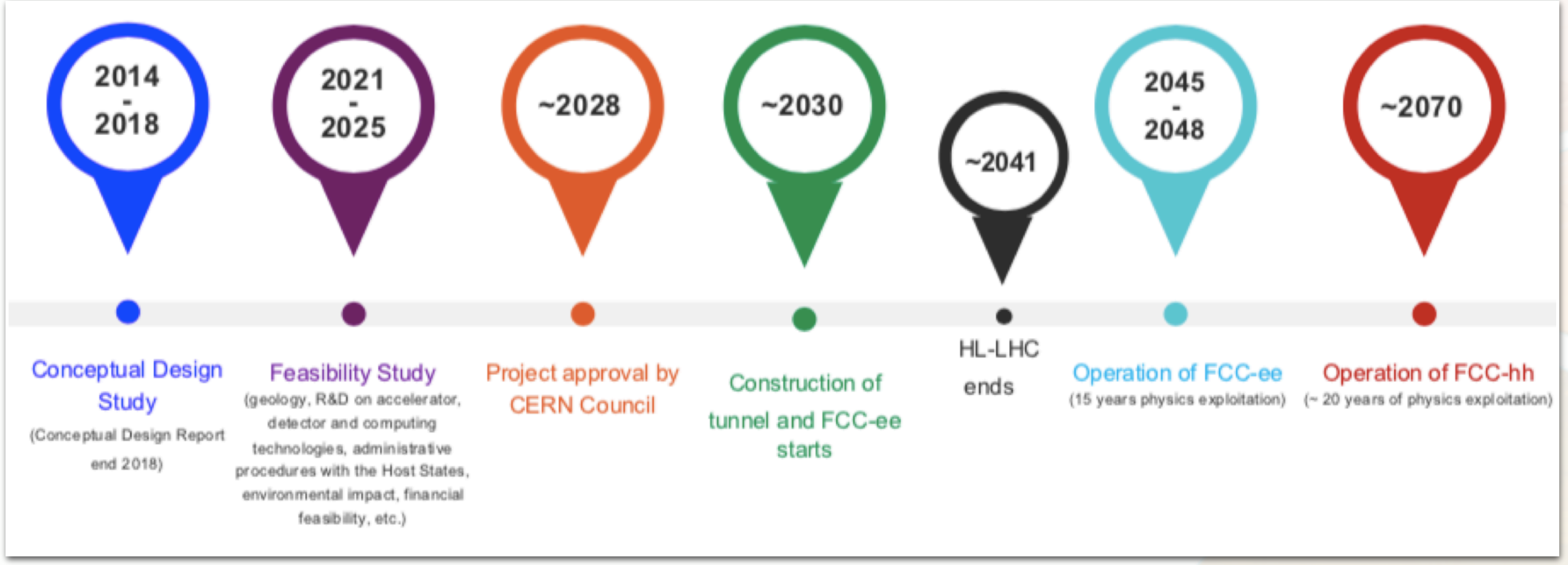
S.Zhang QM2025

See talk by A.Tamis



… that we need to carefully pave

- RHIC shutdown in the near future (~eoy) → **end of high-energy HI collisions in the US** (for the moment)
- The HL-LHC is foreseen to run until 2041
  - HI program currently approved until the end of Run 4 (2032)
  - Critical to secure HI time until end of HL-LHC lifetime because…



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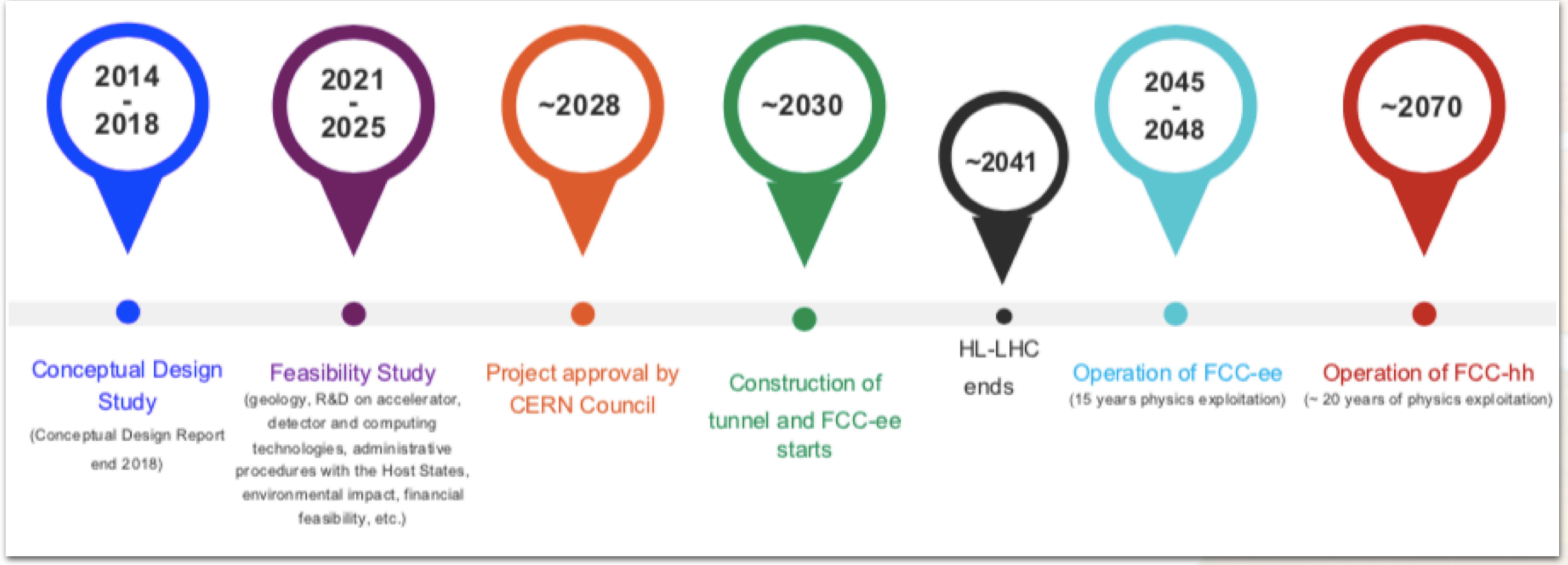
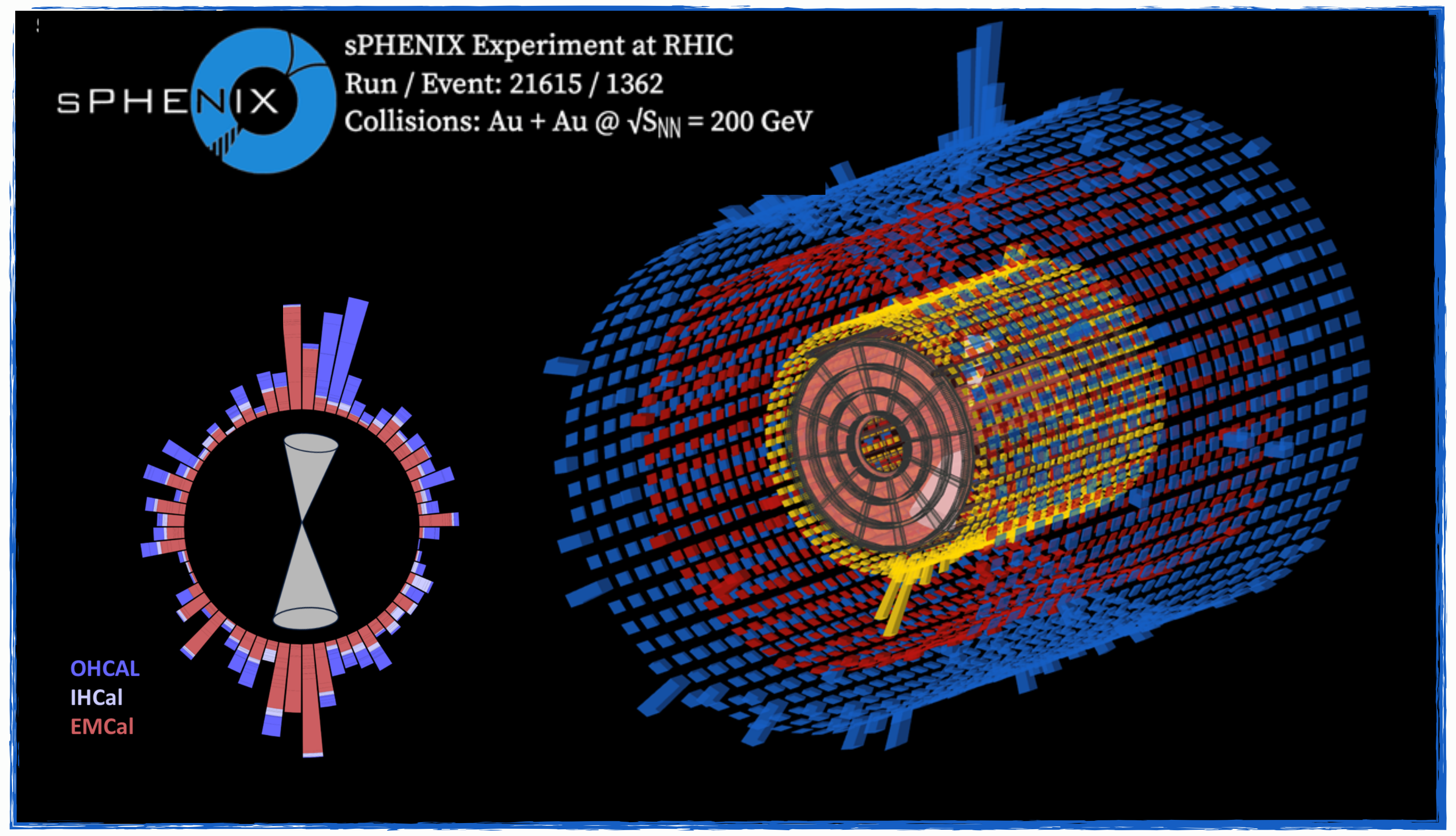


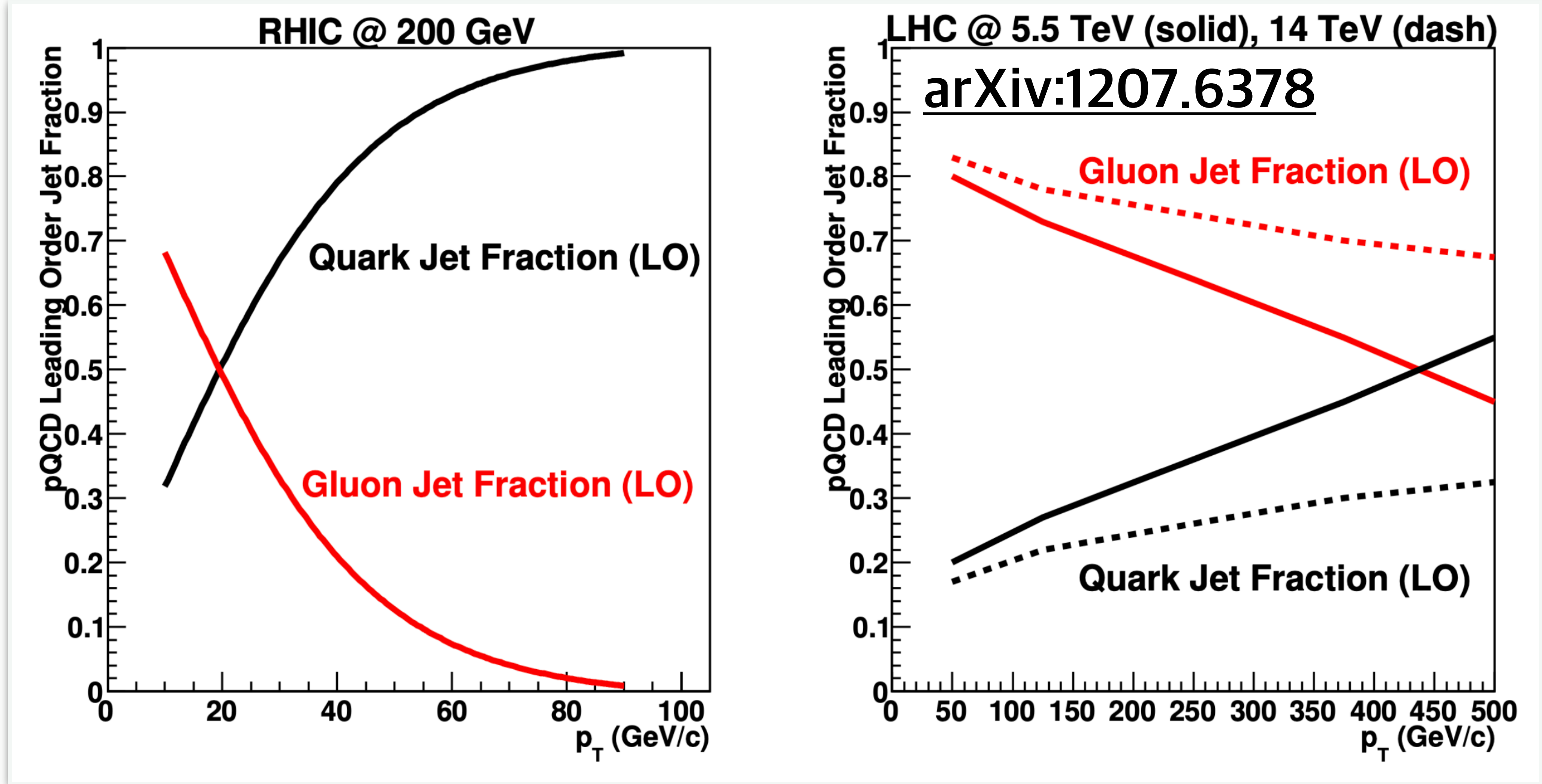
The next high-energy HI machine (FCC-hh) is currently planned for 2070!

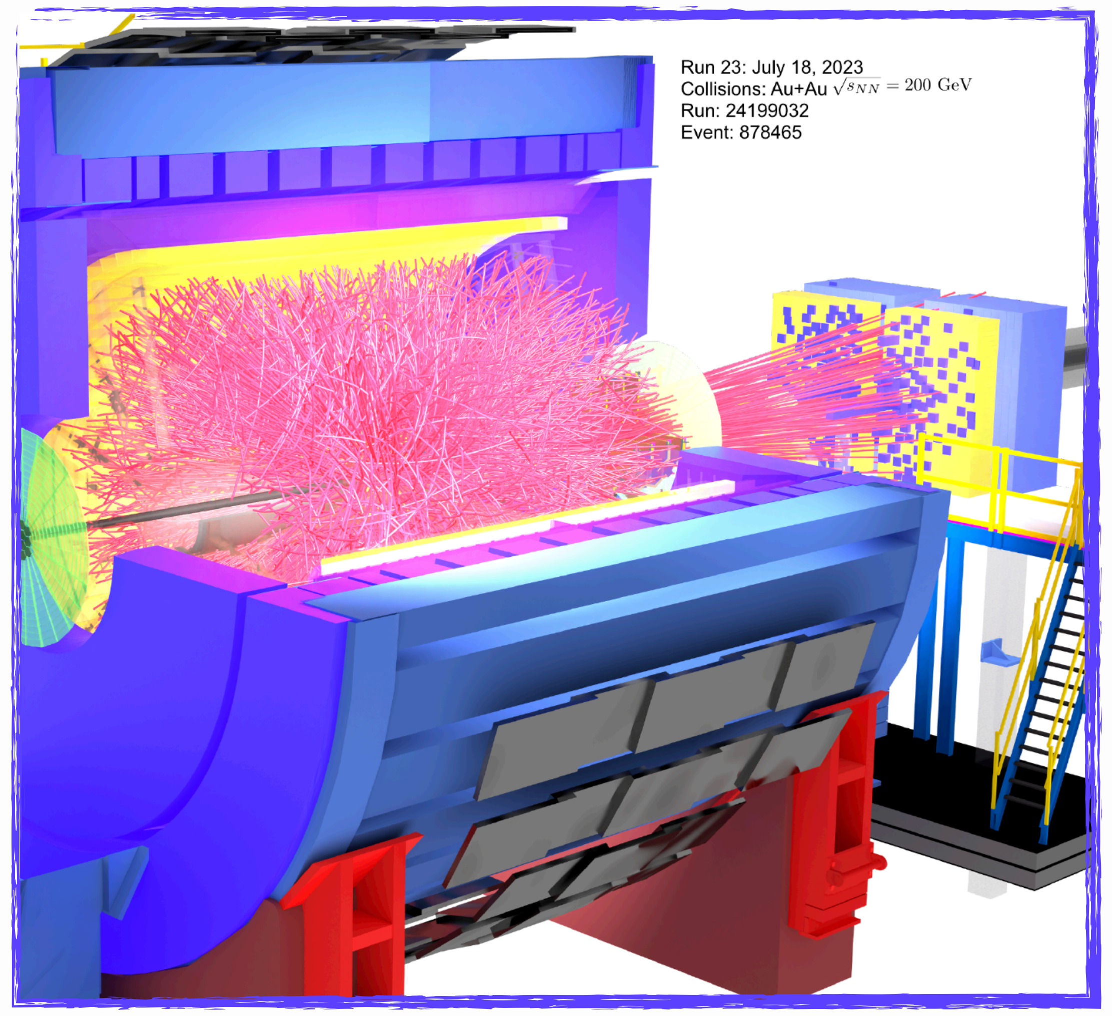
- This means ~30 years without the possibility to have new HI data taking @ high-energy
- **It is essential to plan the data collection for the next 15 years with foresight…**

A last, and personal, opinion ….



After outstanding efforts, sPHENIX is now shining!





STAR Forward Upgrade is a major leap in the experiment capabilities for p+A

- Jets @ RHIC have very different q/g mixing compared to LHC
  → Ideal to **study parton energy loss in a complementary regime**
- Great opportunities are available for cold nuclear matter studies, color-fluctuations measurements, low-x investigations in **p+Au… it would be invaluable to have a p+Au run before RHIC shutdown!**
- **I am firmly convinced we would regret not taking this opportunity**

Summary

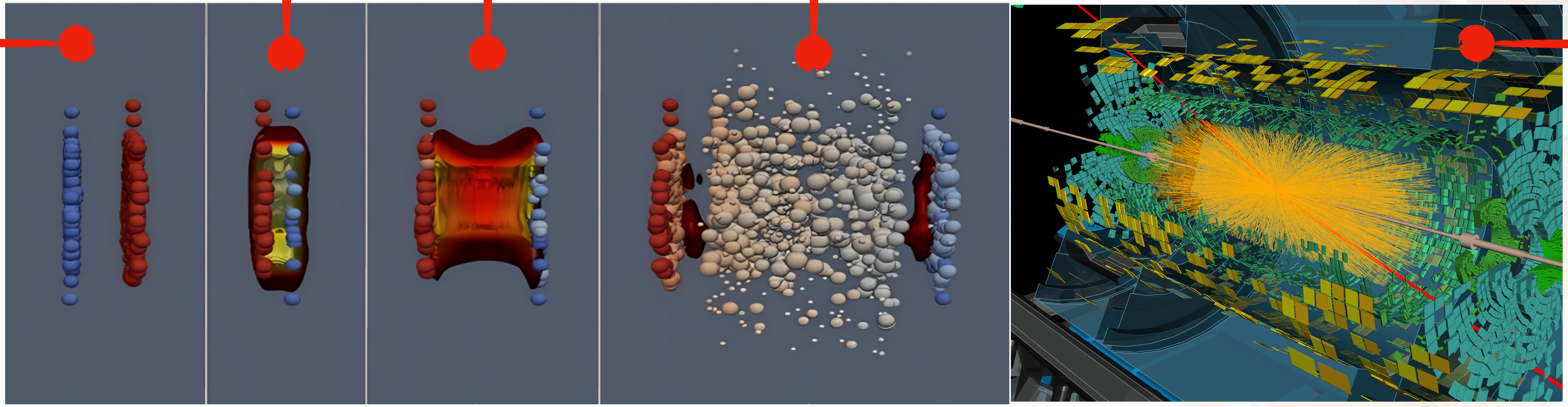
- Jets at the LHC are and will be a fundamental tool to advance our understanding of QCD in extreme temperature regimes
- Steady progress in advancing our understanding of the QGP
- Still a long way to go… but no evidence that the field is running out of ideas!
- Crucial to leverage synergies/complementarities between different facilities

Summary

- HI @ LHC are currently approved until Run 4 (2032) – critical to confirm Run 5 to extend HI data-taking life until the end of HL-LHC
- Dijet studies to investigate initial state and cold nuclear matter effects @ LHC have strong synergies with the EIC
- sPHENIX and STAR data taken ~now will be unique for a long time, critical to ensure the legacy of the data

Backup

One question to rule them all



Temperature

Time

τ = 0 τ ~1 fm/c ~10^{-23} s τ ~ 10 fm/c ~10^{-22} s τ > 10 cm/c ~10^{-11} s

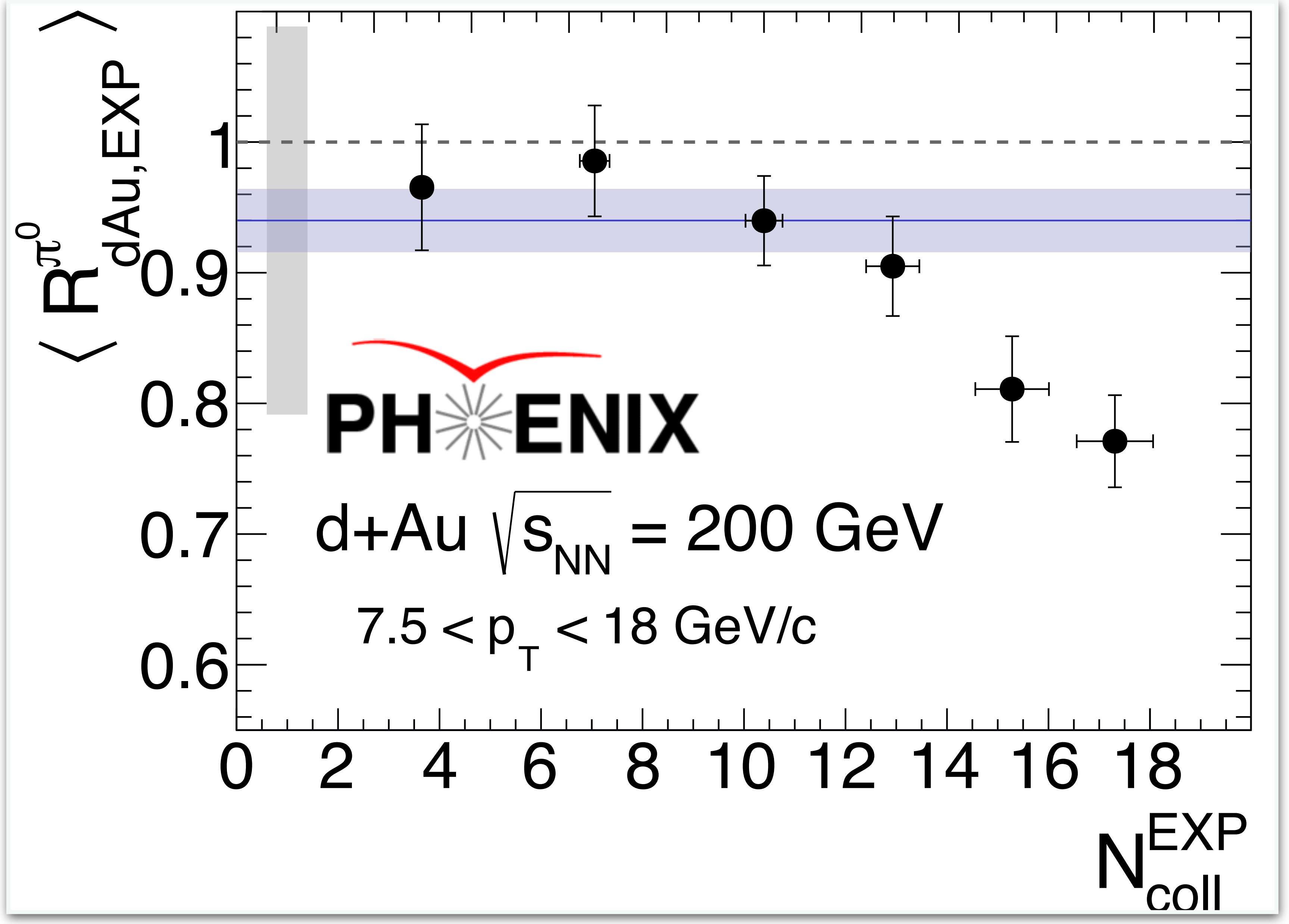
System Size

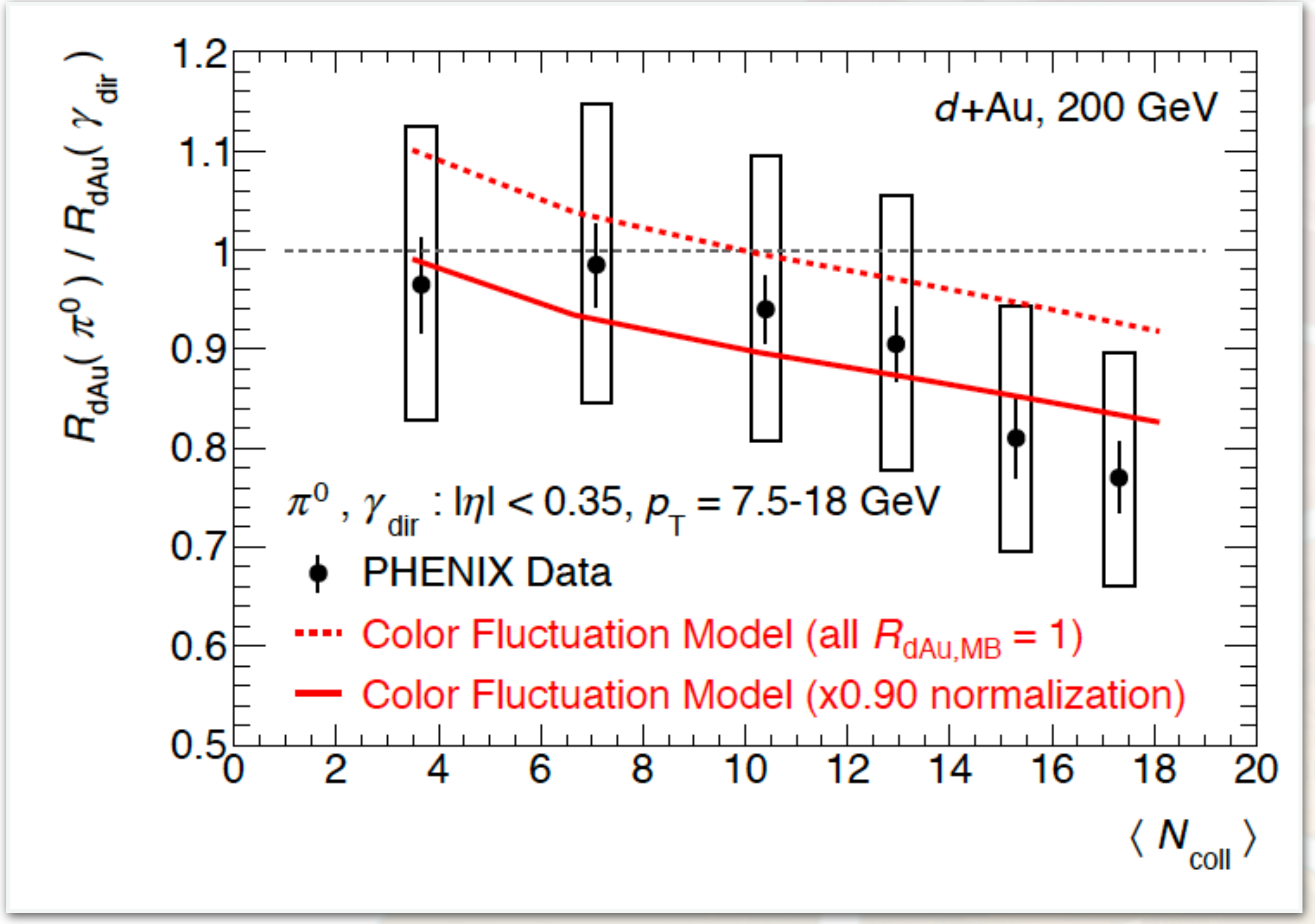
Femtoscale O(100m)

How can we pair the microscopic behavior of the QGP - built up from the interaction of color charges that we understand very well in vacuum - with the long-range collective behavior that we observe as a result of the hydrodynamical evolution of the QGP?

Importance of color fluctuations at RHIC

$$R^{\pi^0}_{\mathrm{dAu,EXP}} = \frac{Y^{\pi^0}_{\mathrm{dAu}}/Y^{\pi^0}_{pp}}{Y^{\gamma^{\mathrm{dir}}}_{\mathrm{dAu}}/Y^{\gamma^{\mathrm{dir}}}_{pp}}$$

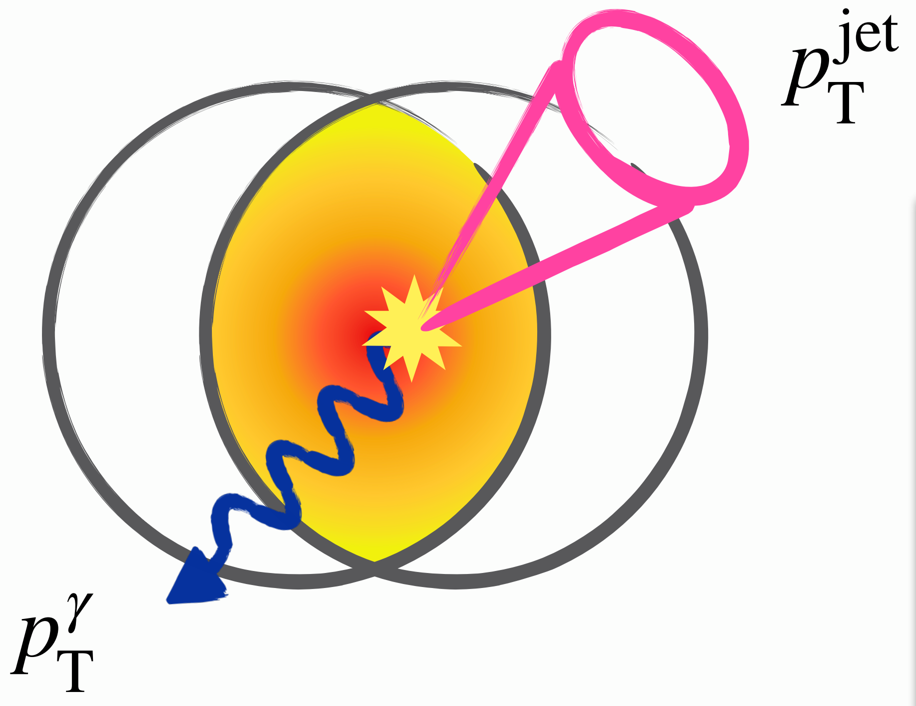




- Relative yield of π^0 to γ^{dir} under the argument both are subject to the same centrality bias (**PRL 134, 022302 (2025)**)
- Evidence of jet quenching? (At odds w/ several other measurements at both RHIC and LHC)

- Same kinematic cuts but π^0 & γ^{dir} have **different x_d distributions**
- Results can be explained w/ color fluctuation model (**D.Perepelitsa, PRC 110, L011901**)

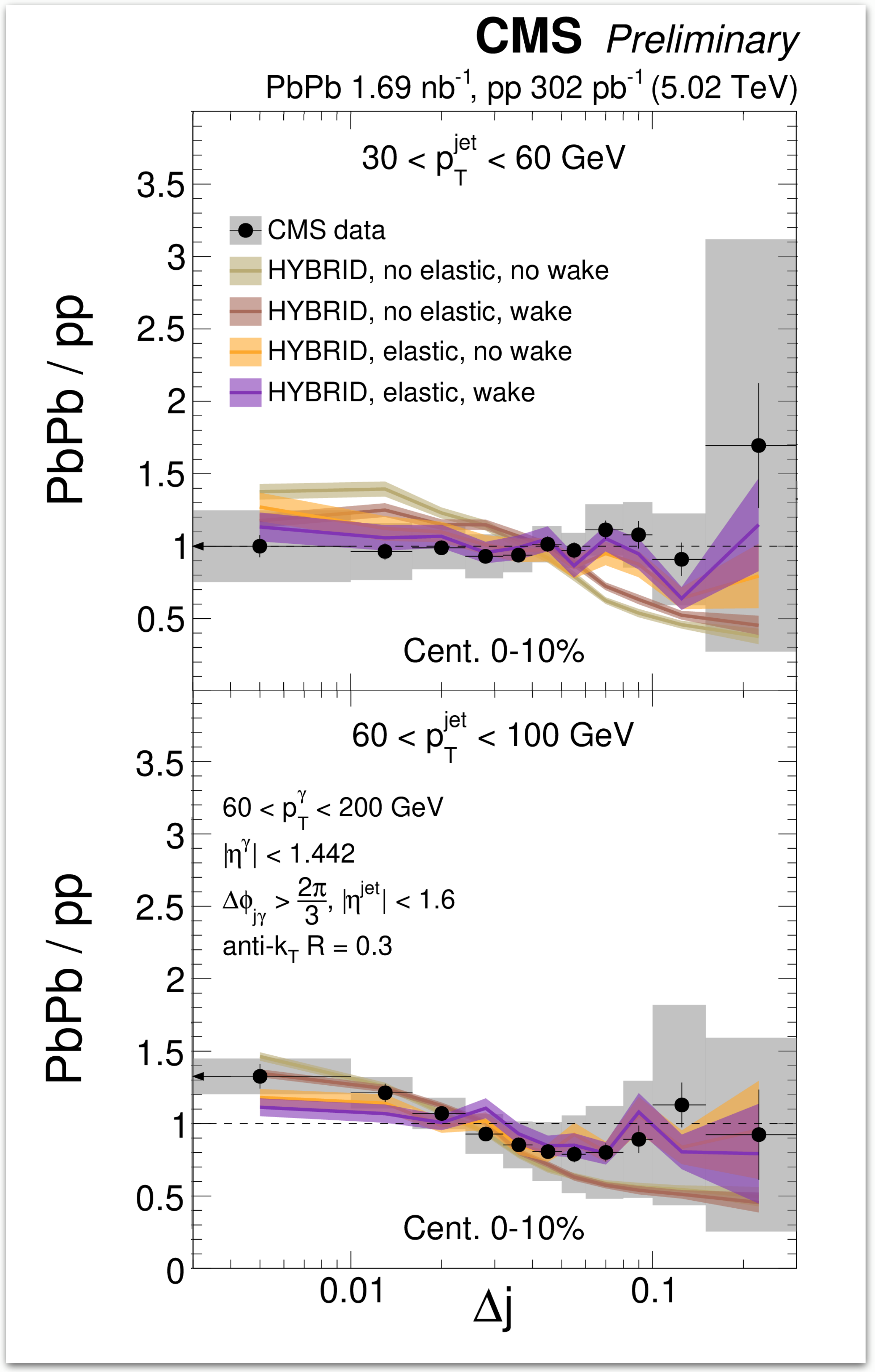
Another example: jet-axis decorrelation



CMS γ-tagged jets:

- Ratio ~1 for more quenched selections (lower jet p_T)
- Narrowing observed for higher p_T (less quenched) selections

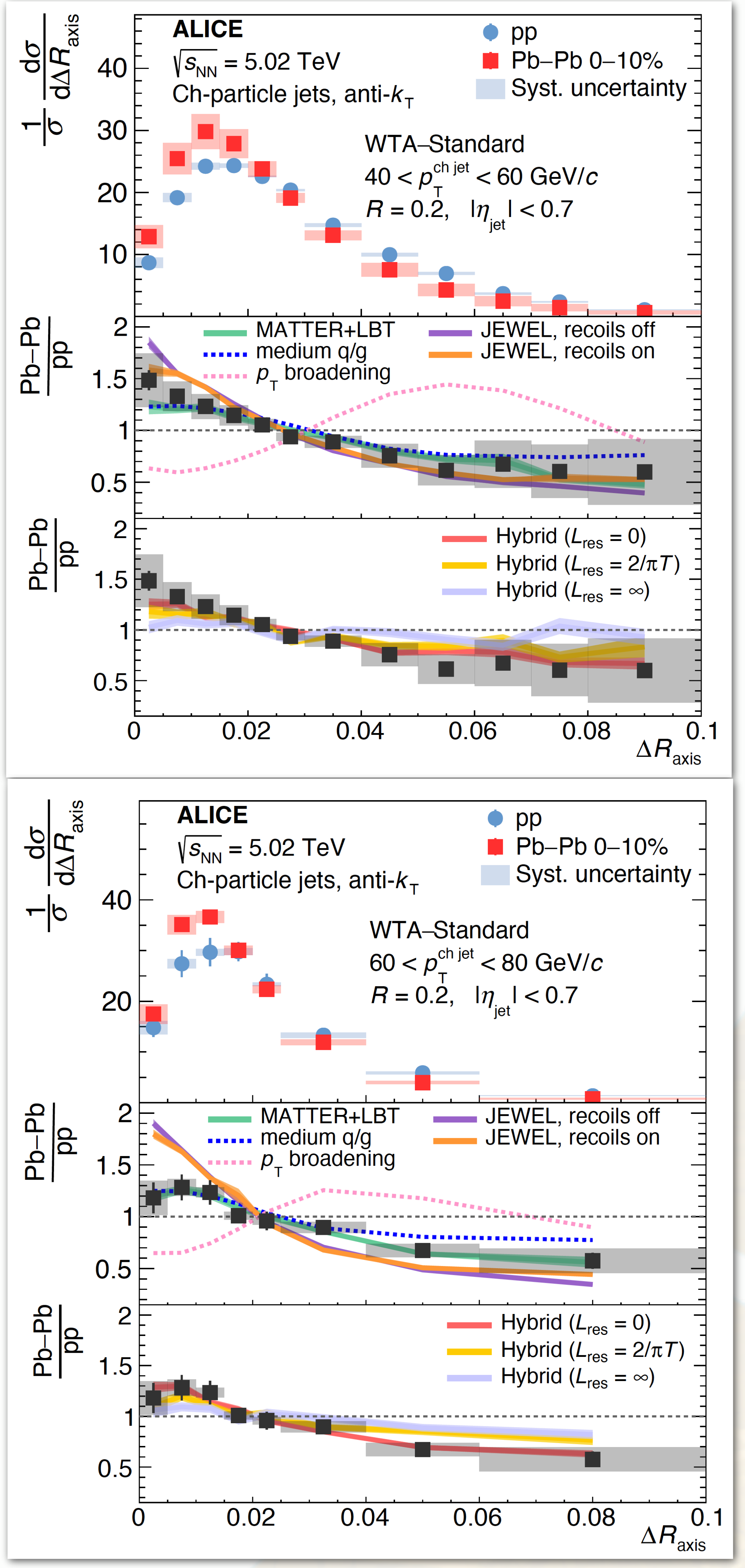
CMS PAS HIN-21-019

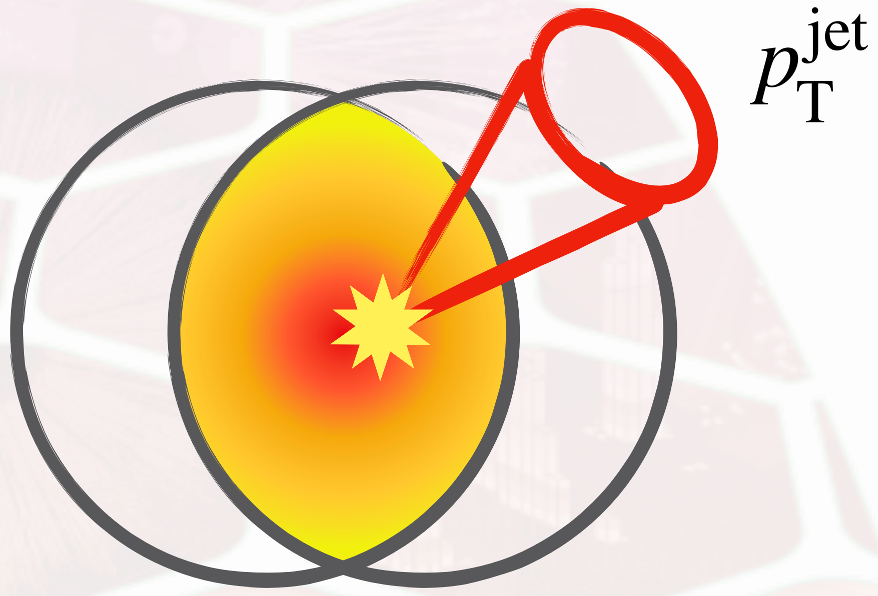


Jet axis decorrelation

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

arXiv:2303.13347



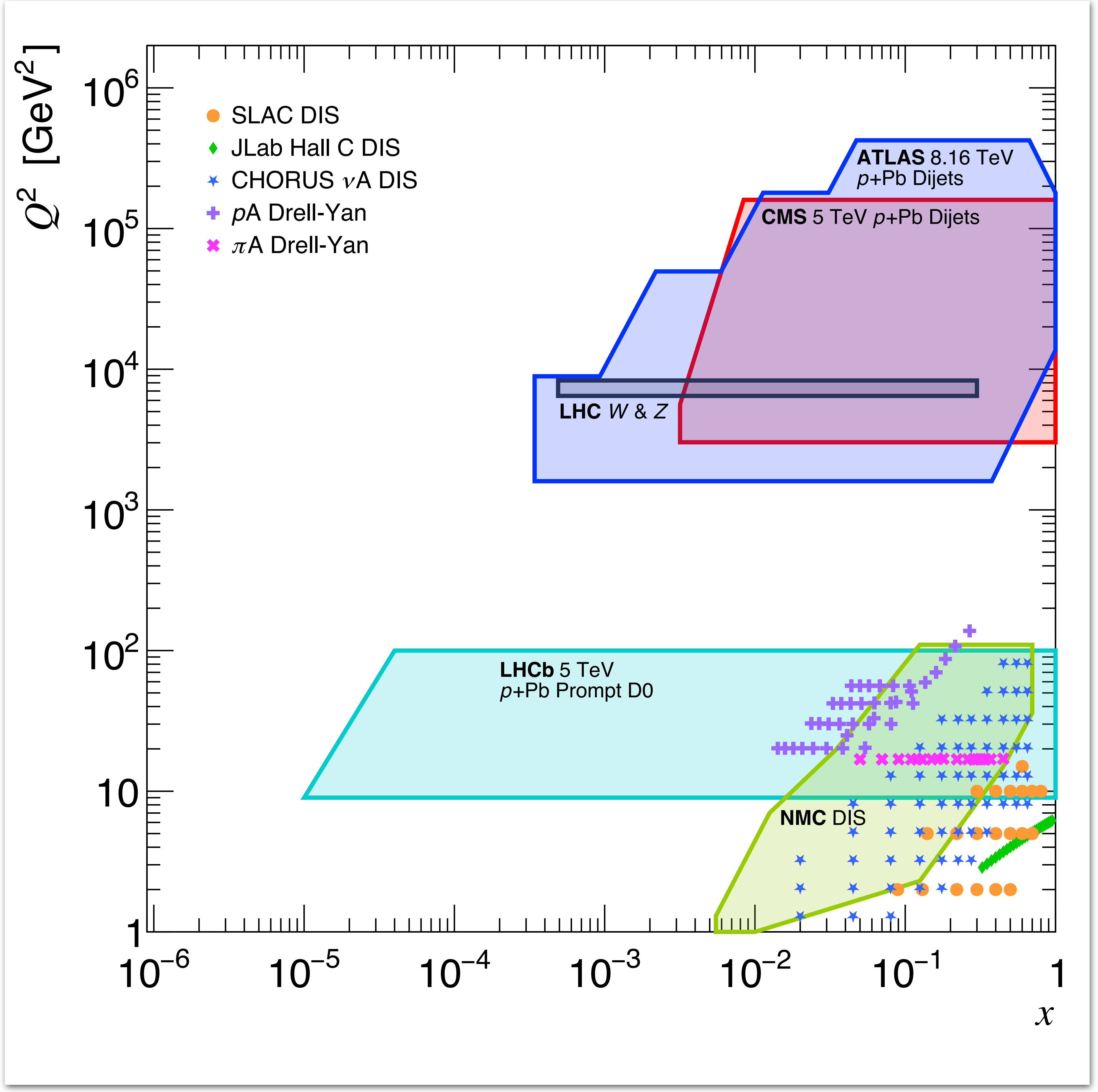


ALICE inclusive jets:

- Narrowing observed in each p_T^{jet} selection (no control on quenching)
- Different jet collections & rapidity coverage, as well as calorimeter vs track jets

CMS new dijet in p+Pb @ 8.16 TeV

The last few years have marked a **golden age of dijet measurements** at the **LHC**



Data included in EPPS21 (Eur.Phys.J.C 82 (2022) 5, 413)

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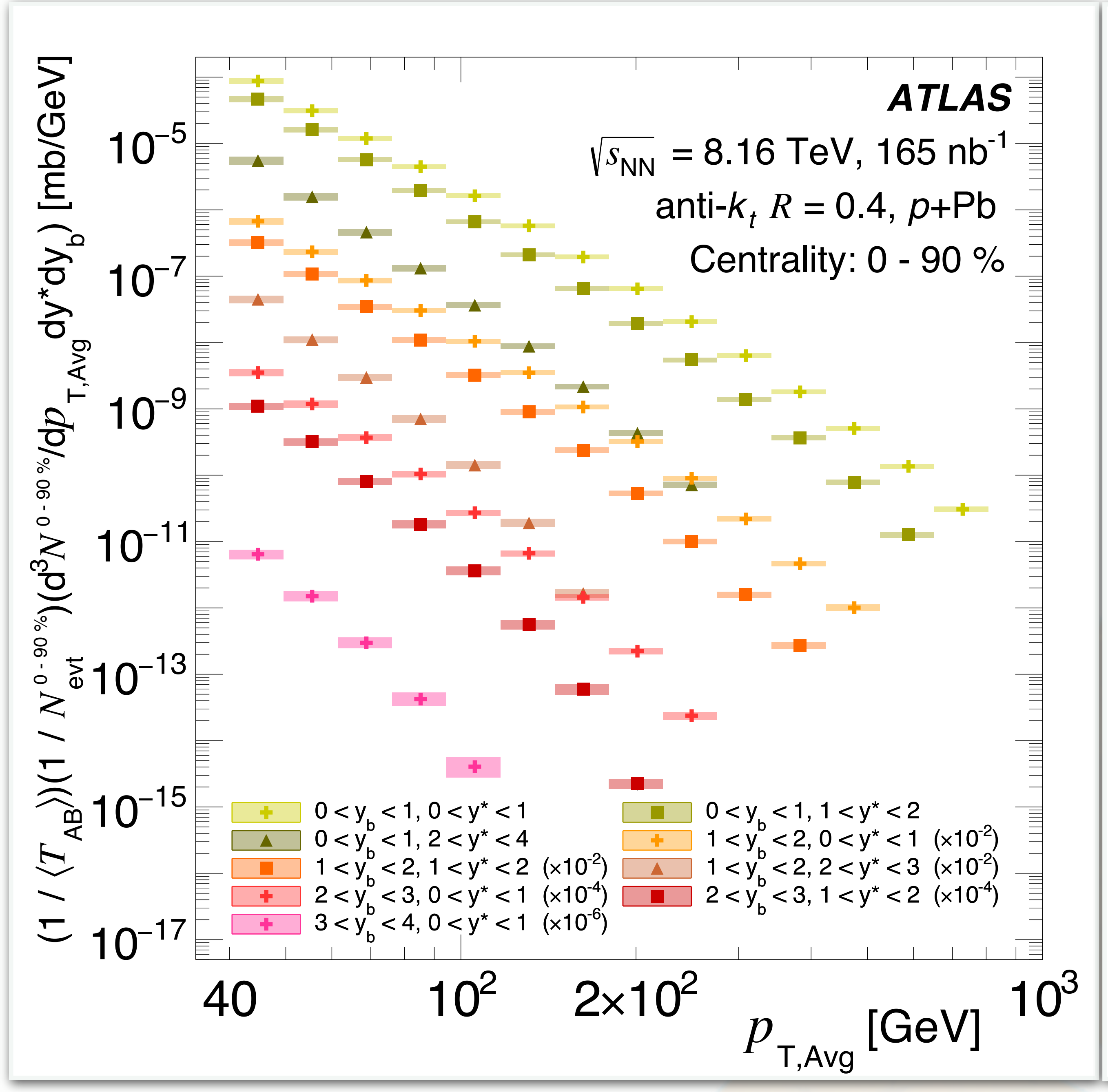

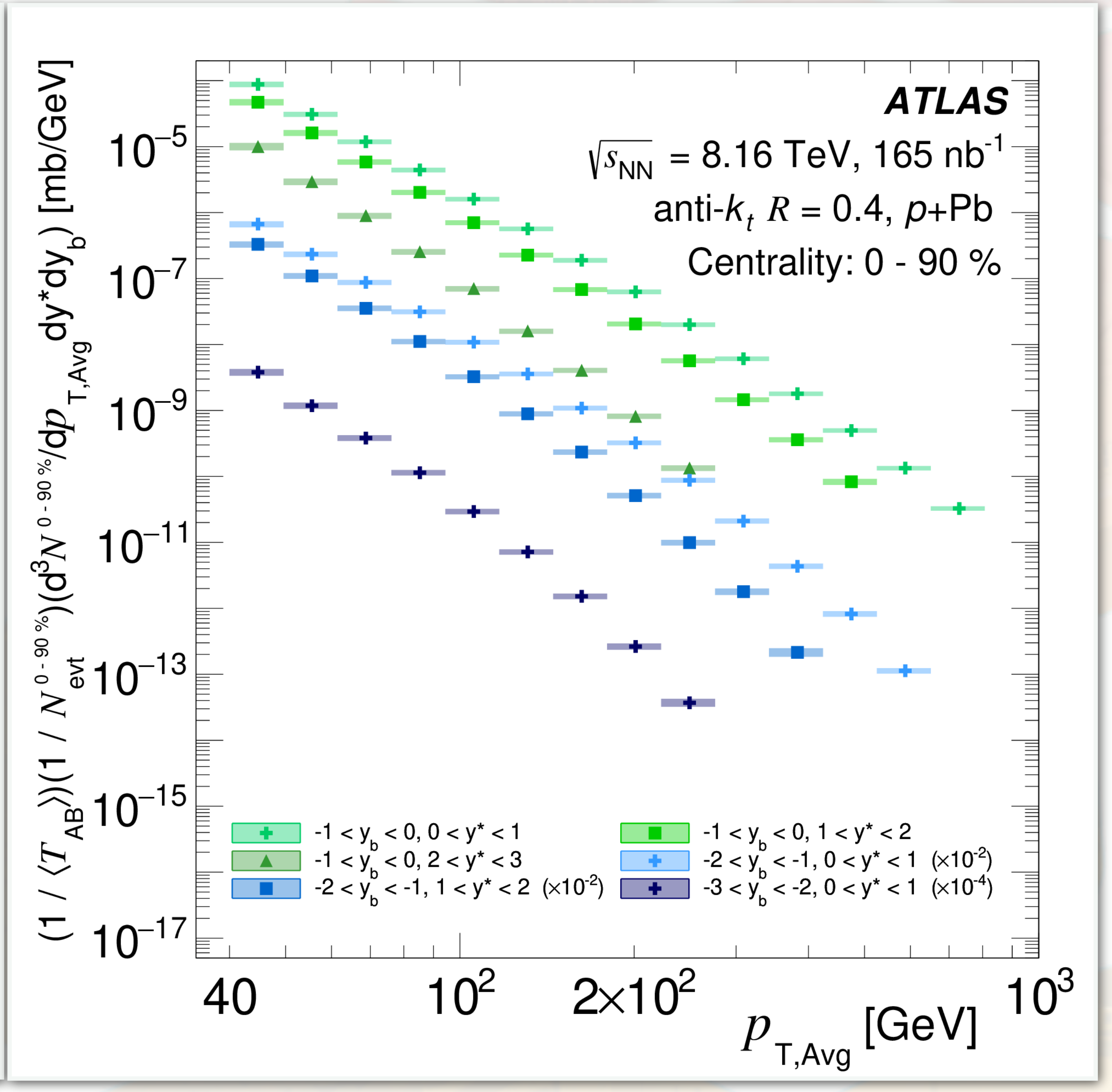

Dijets in p+Pb @ 8.16 TeV per-event yields, x-section studies underway

CMS new dijet in p+Pb @ 8.16 TeV

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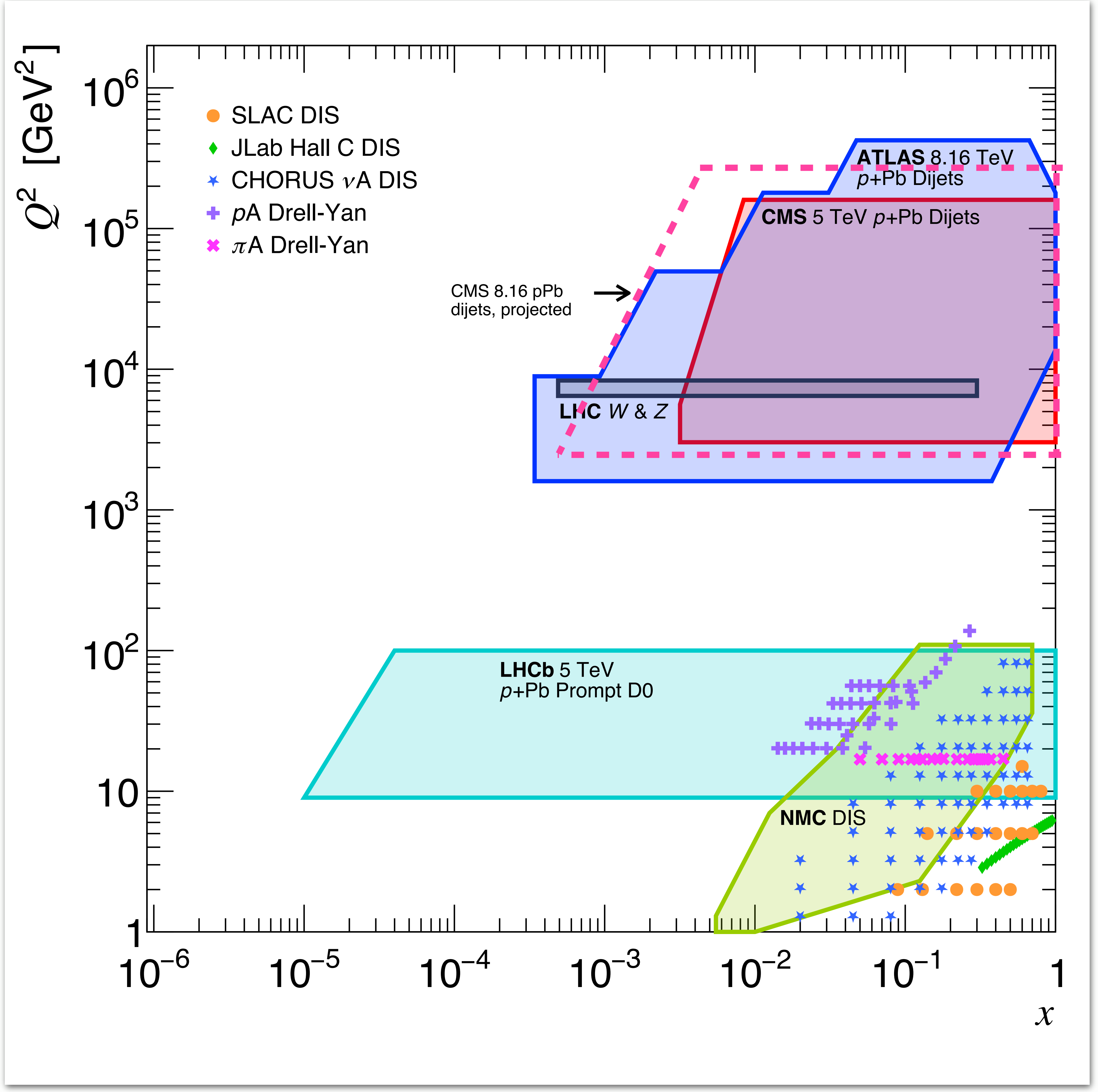

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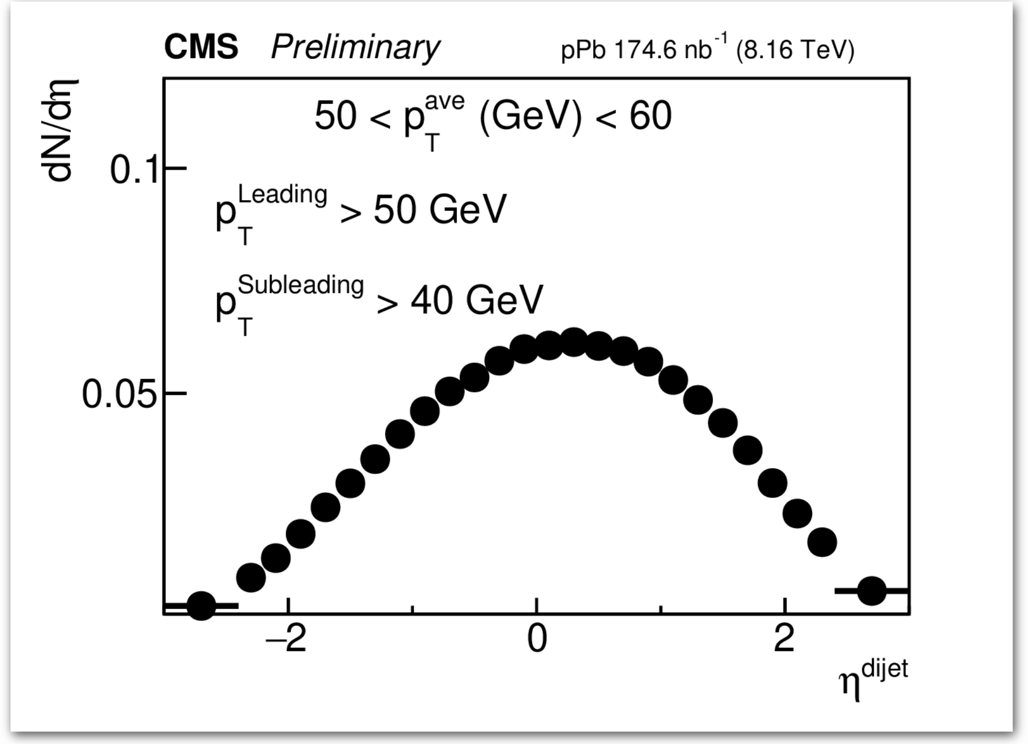
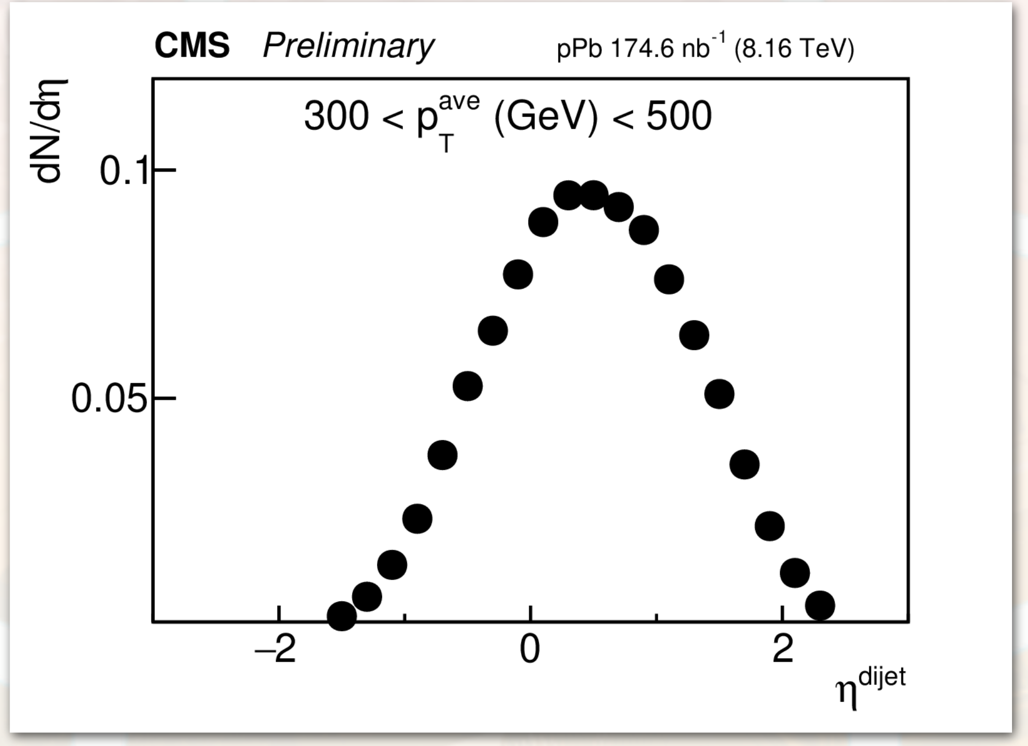
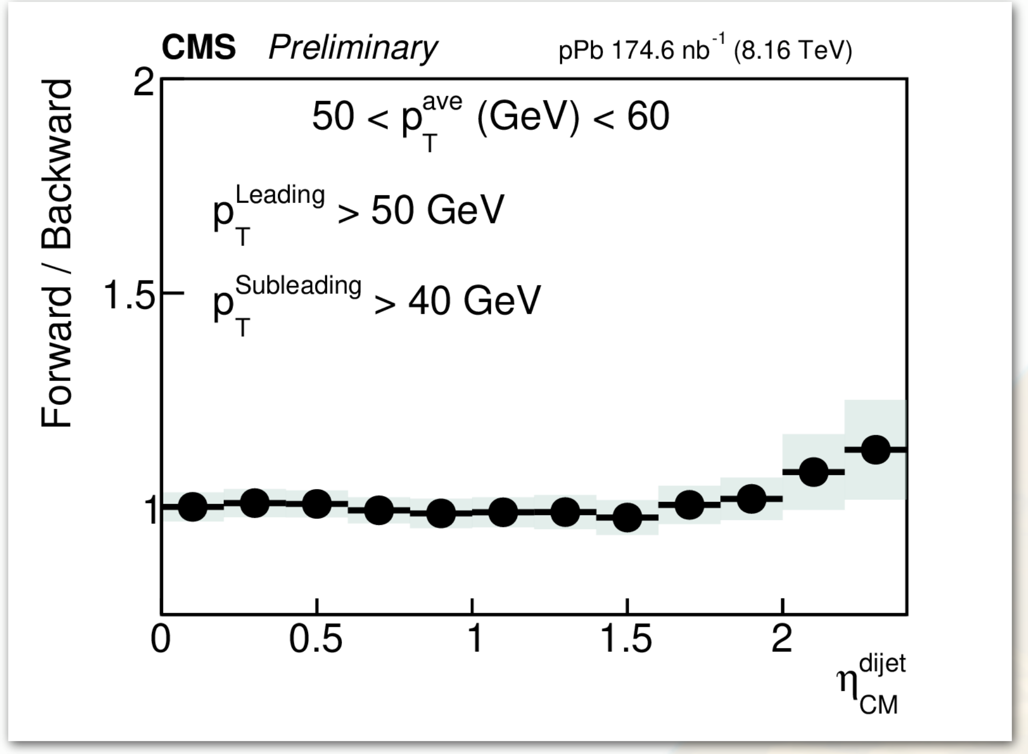


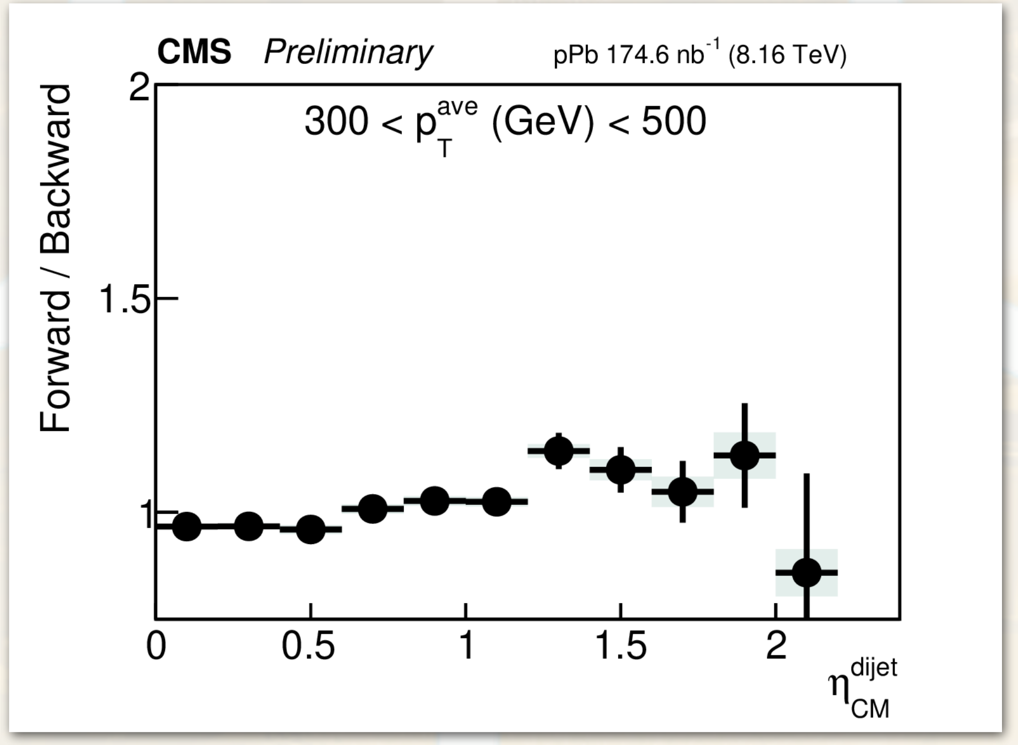


Dijet pseudorapidity distributions

$\cdots$14 p_T^{ave} bins$\cdots$

Dijet forward to backward ratio





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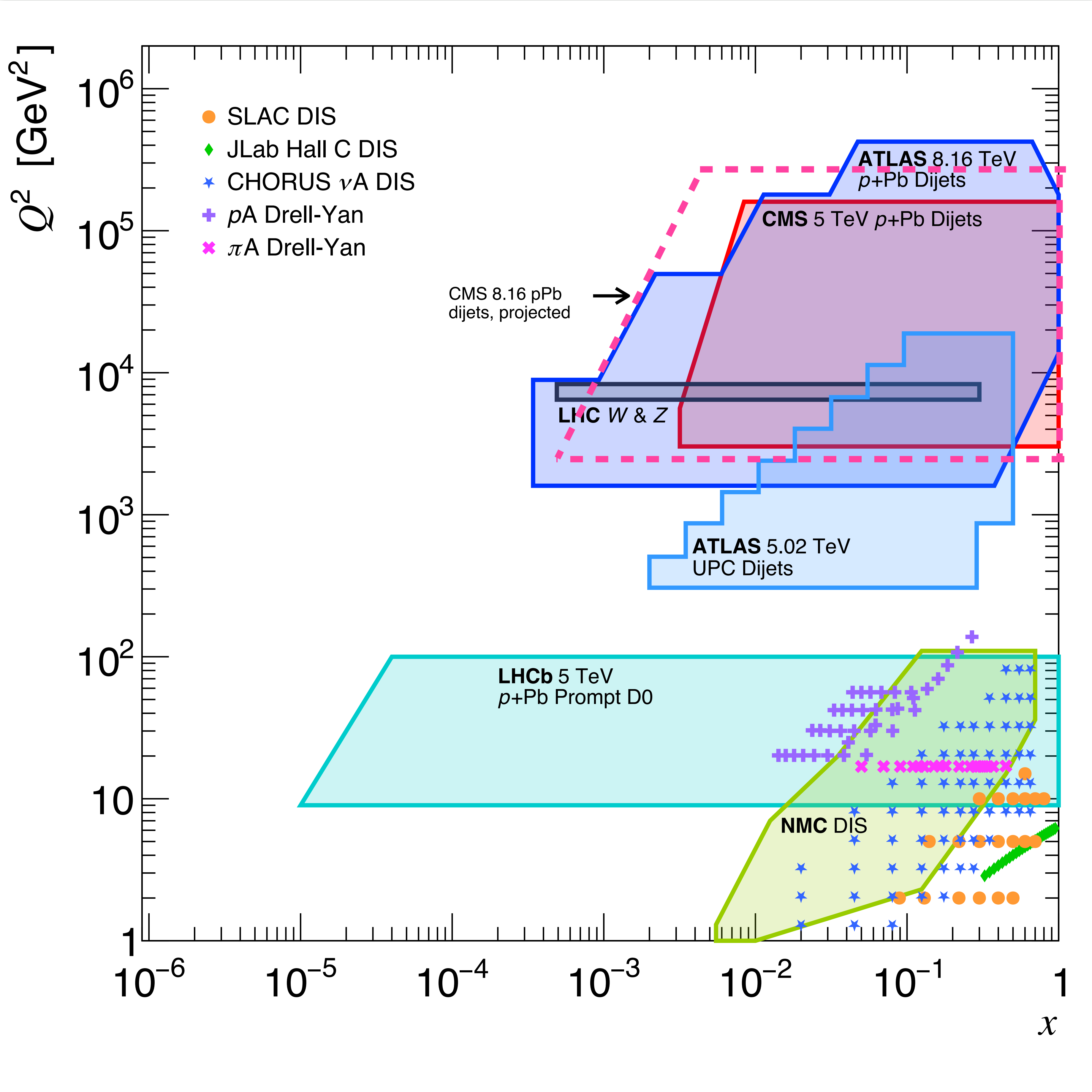

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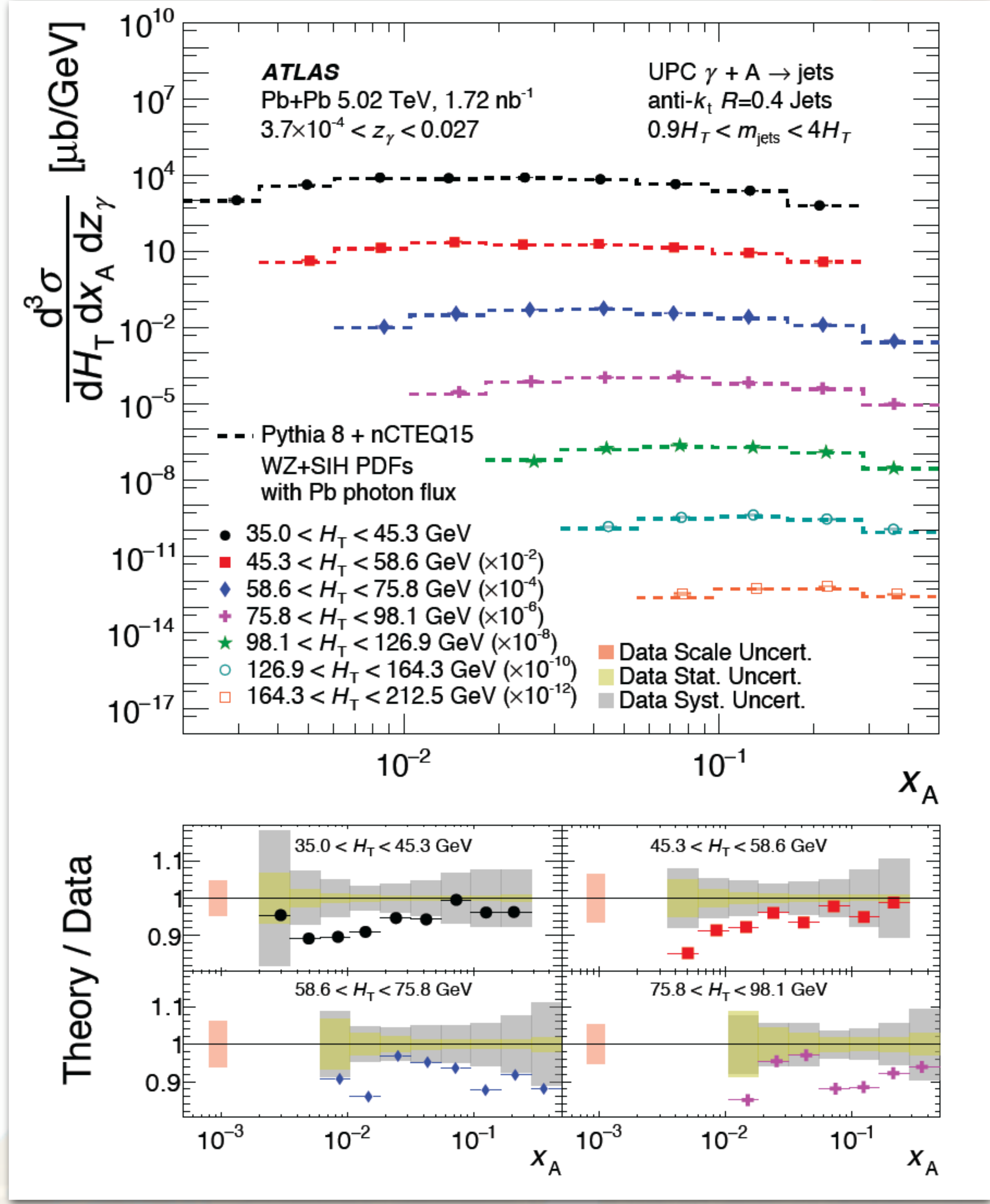

3D unfolded extraction of **UPC dijet cross-section**

hard-scale, $\mathbf{H_T}$,

photon resolution power, $\mathbf{z_\gamma}$,

parton momentum fraction in the Pb, $\mathbf{x_A}$

unique (x,Q$_2$) phase space covered thanks to the photon energy

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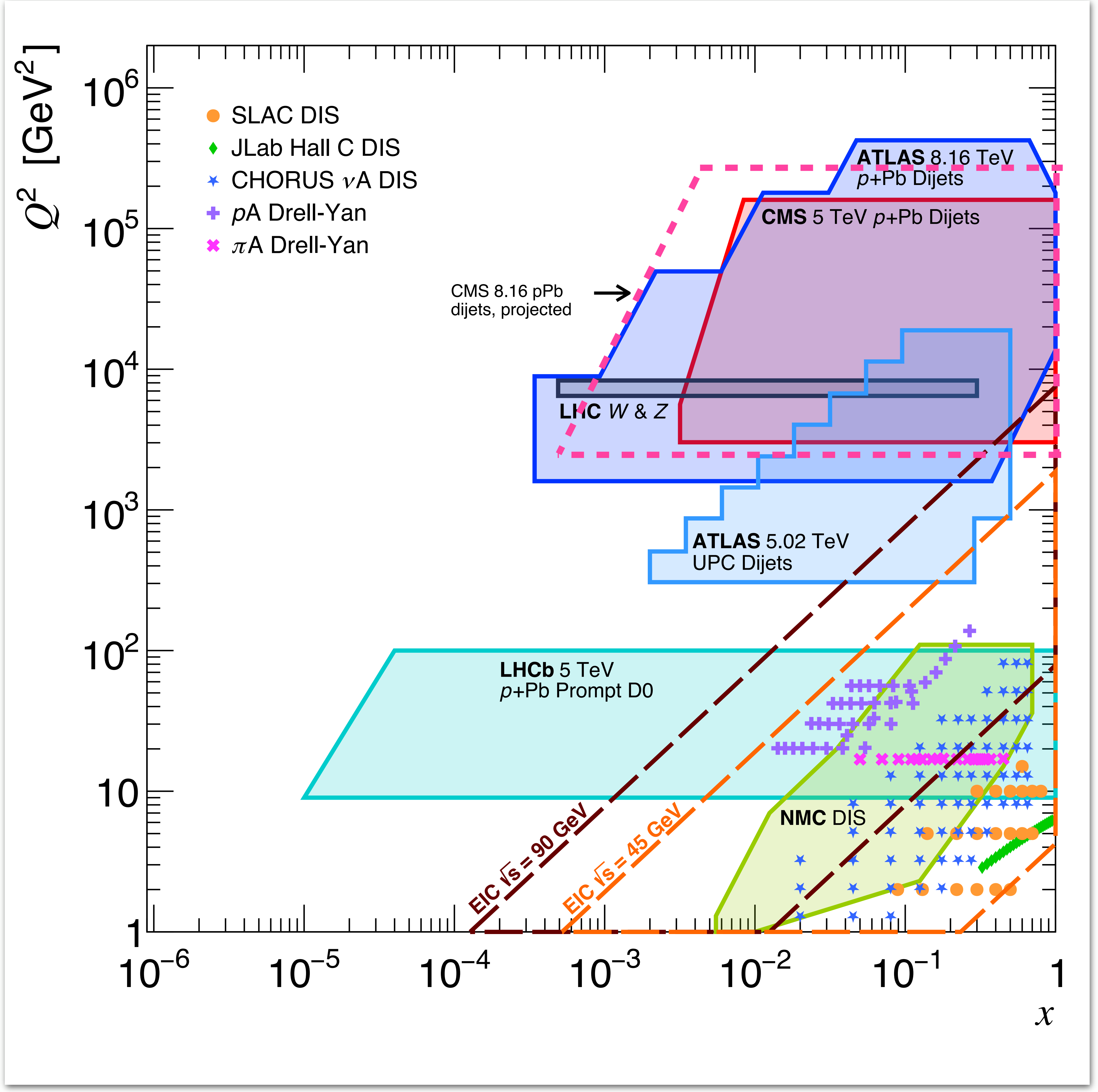

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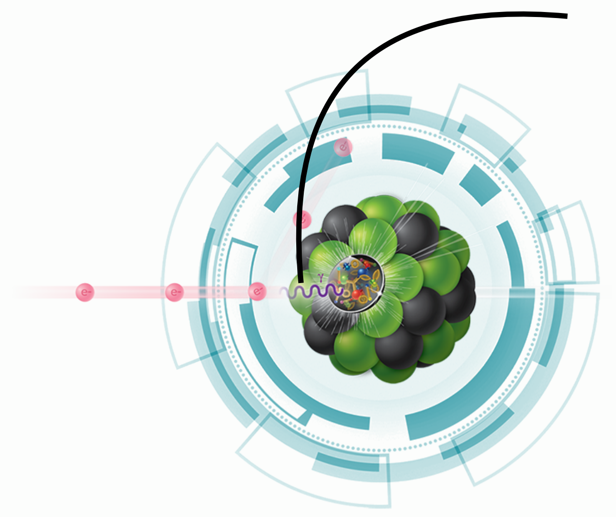
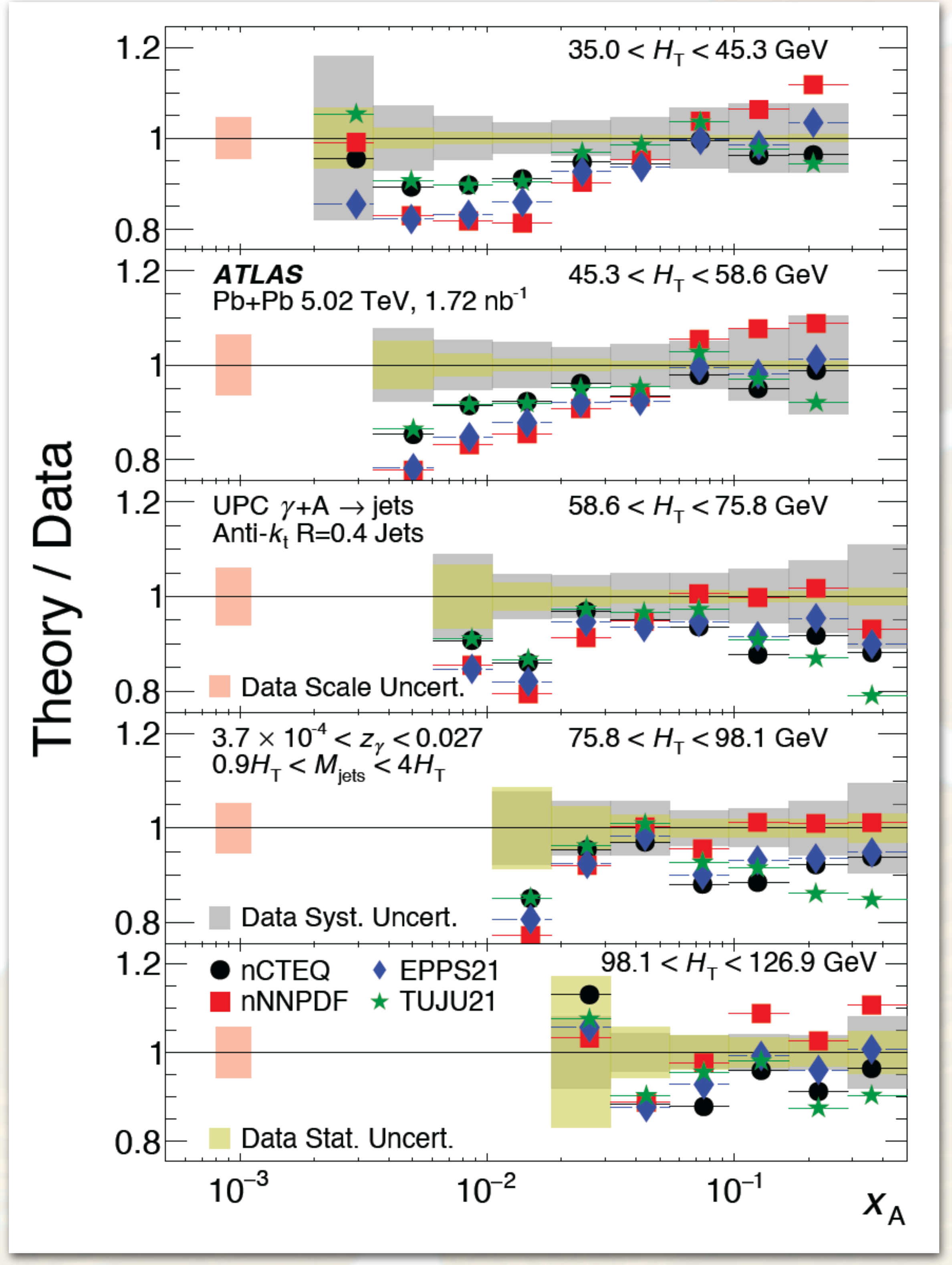


Direct bridge to the EIC phase space!

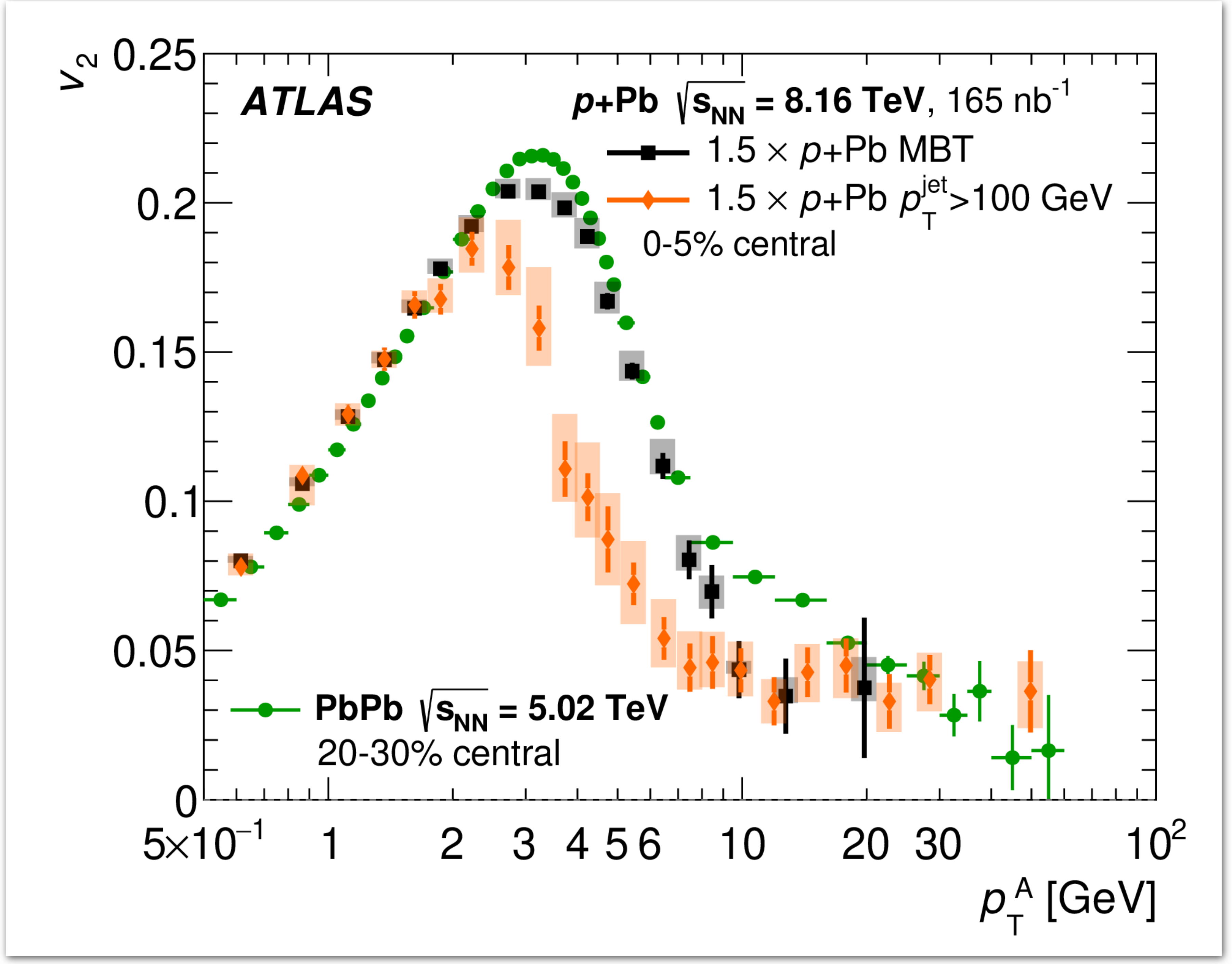


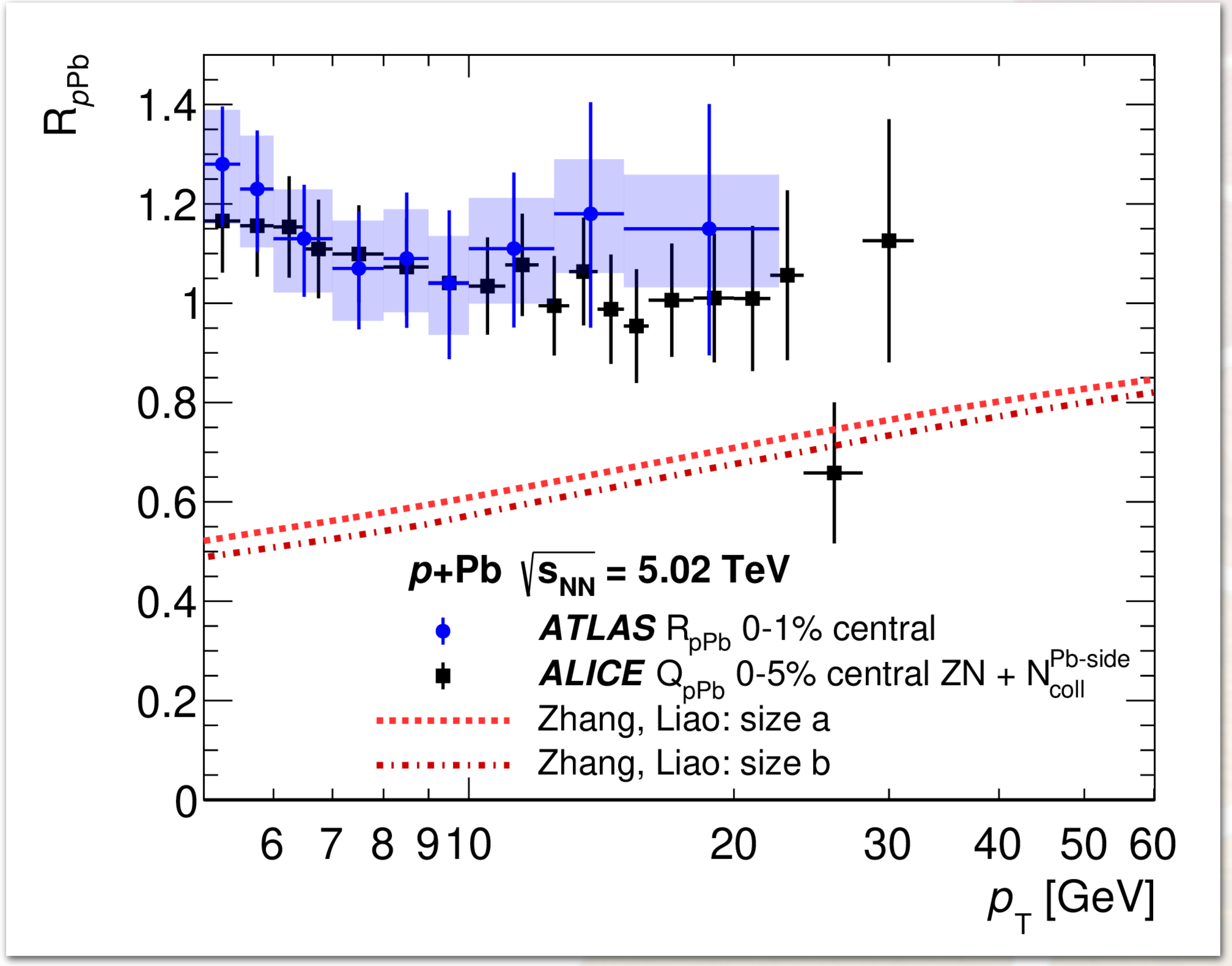
Comparison to different nPDF sets

unique (x,Q2) phase space covered thanks to the photon energy

From AA to pA: the high p_T puzzle

Eur. Phys. J. C 80 (2020) 73





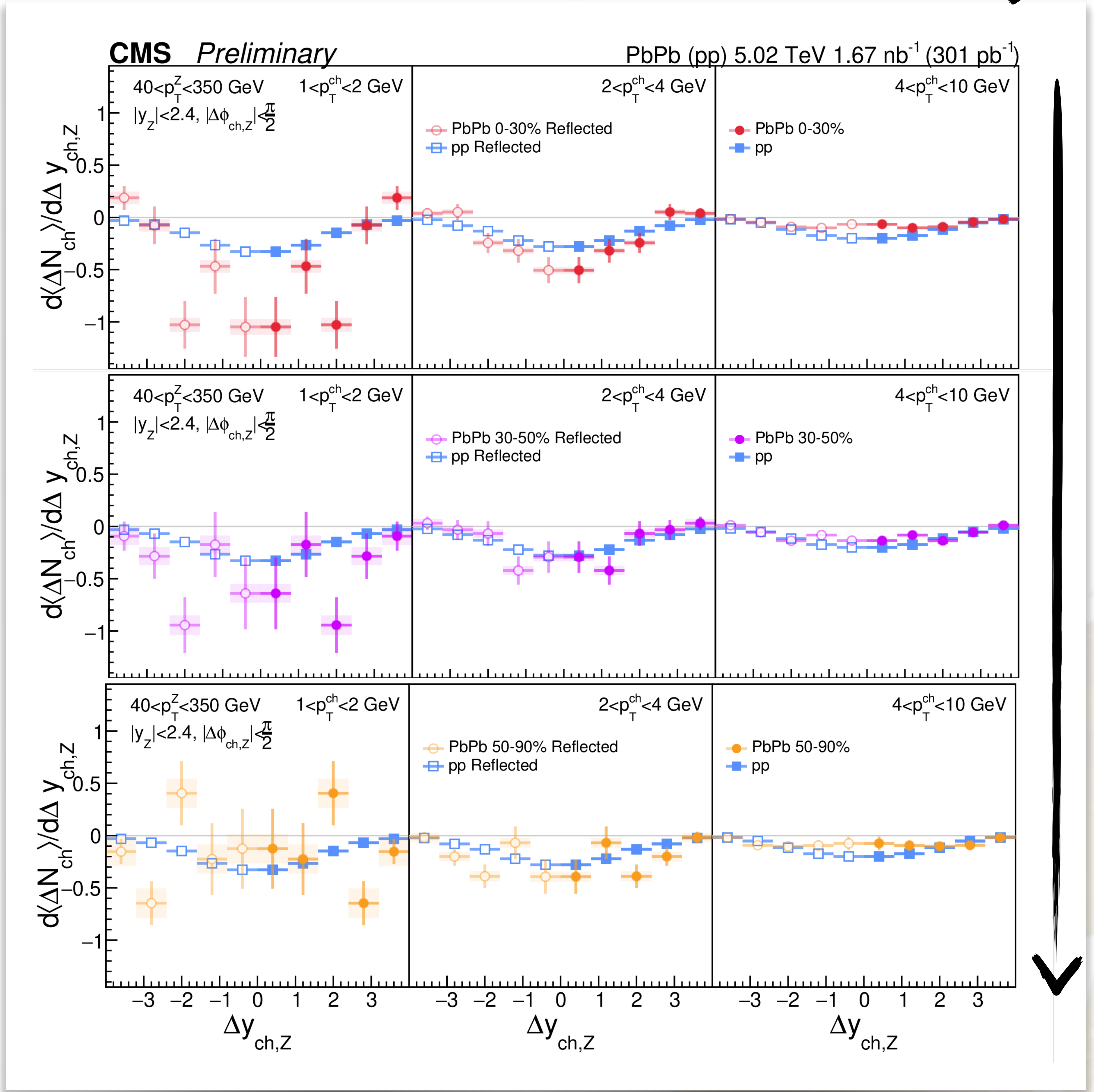
High p_T 'puzzle' in p+Pb

- No jet quenching
- Clear v_2 signal – similar to mid-central Pb-Pb
- Models that predict collective behavior largely overestimate R_{pPb} suppression

Diffusion wake: CMS Z+h results - Δy

CMS-PAS-HIN-23-006

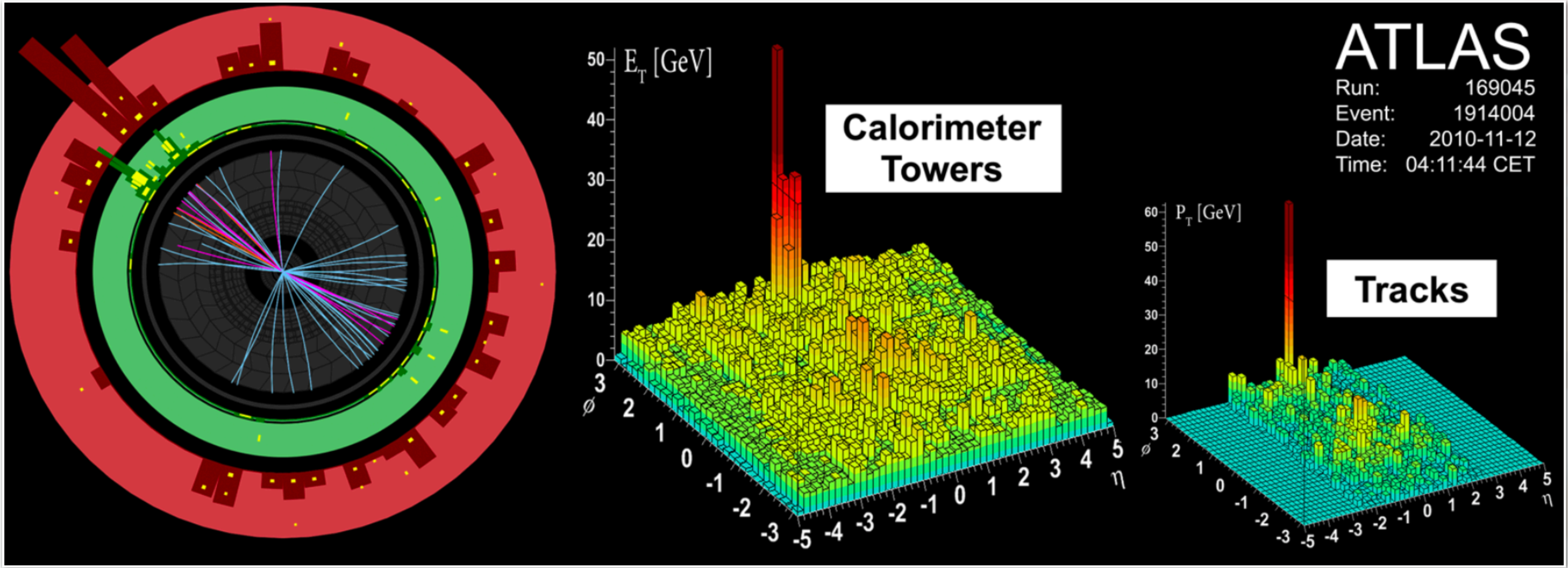
Hadron p_T selection



Centrality

Hot QCD: a long way still ahead of us…

“We have not yet figured out how to measure or quantify what your eye can see in this one event…" – B.Cole - HI & QGP Town Meeting @ CERN - 2025



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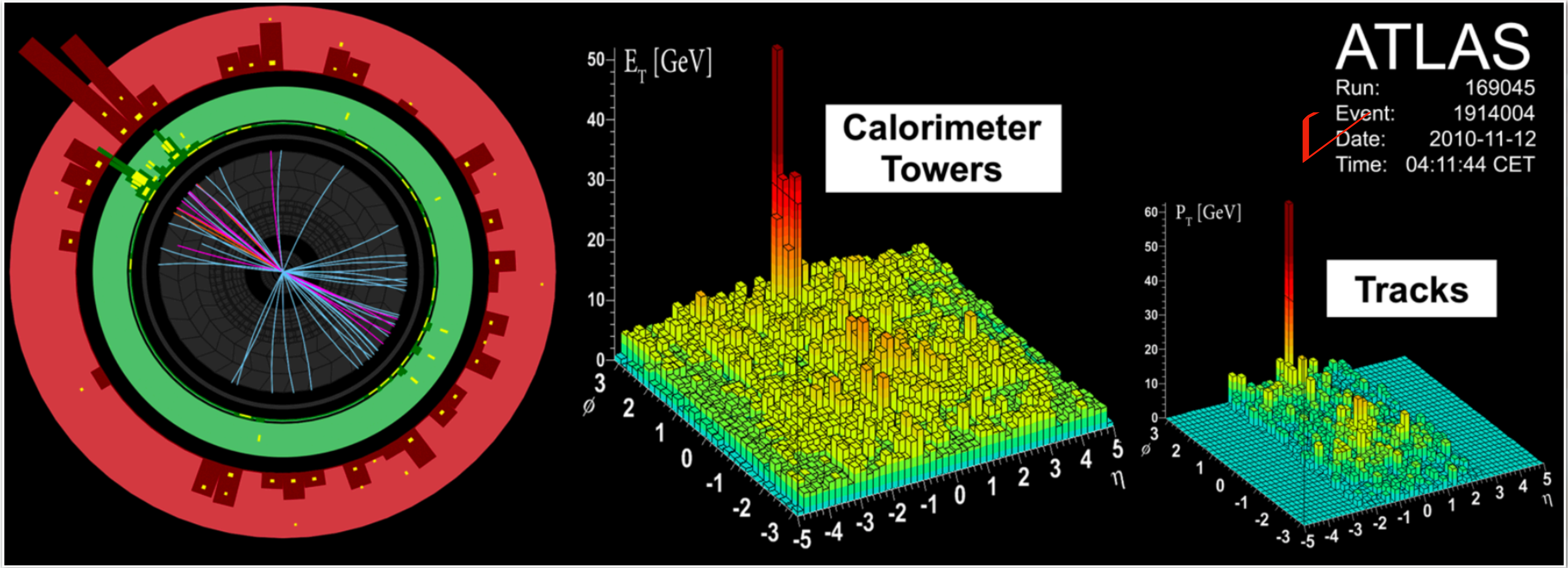
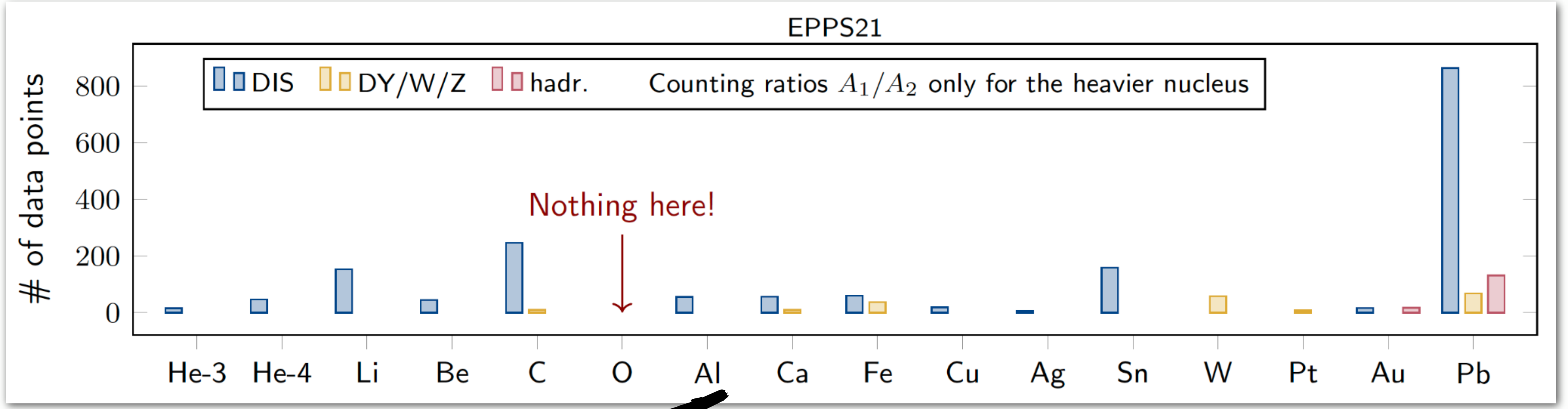


Date: 2010-11-12

To set the time scale, in 2010 I was a 2nd year Physics Undergrad...

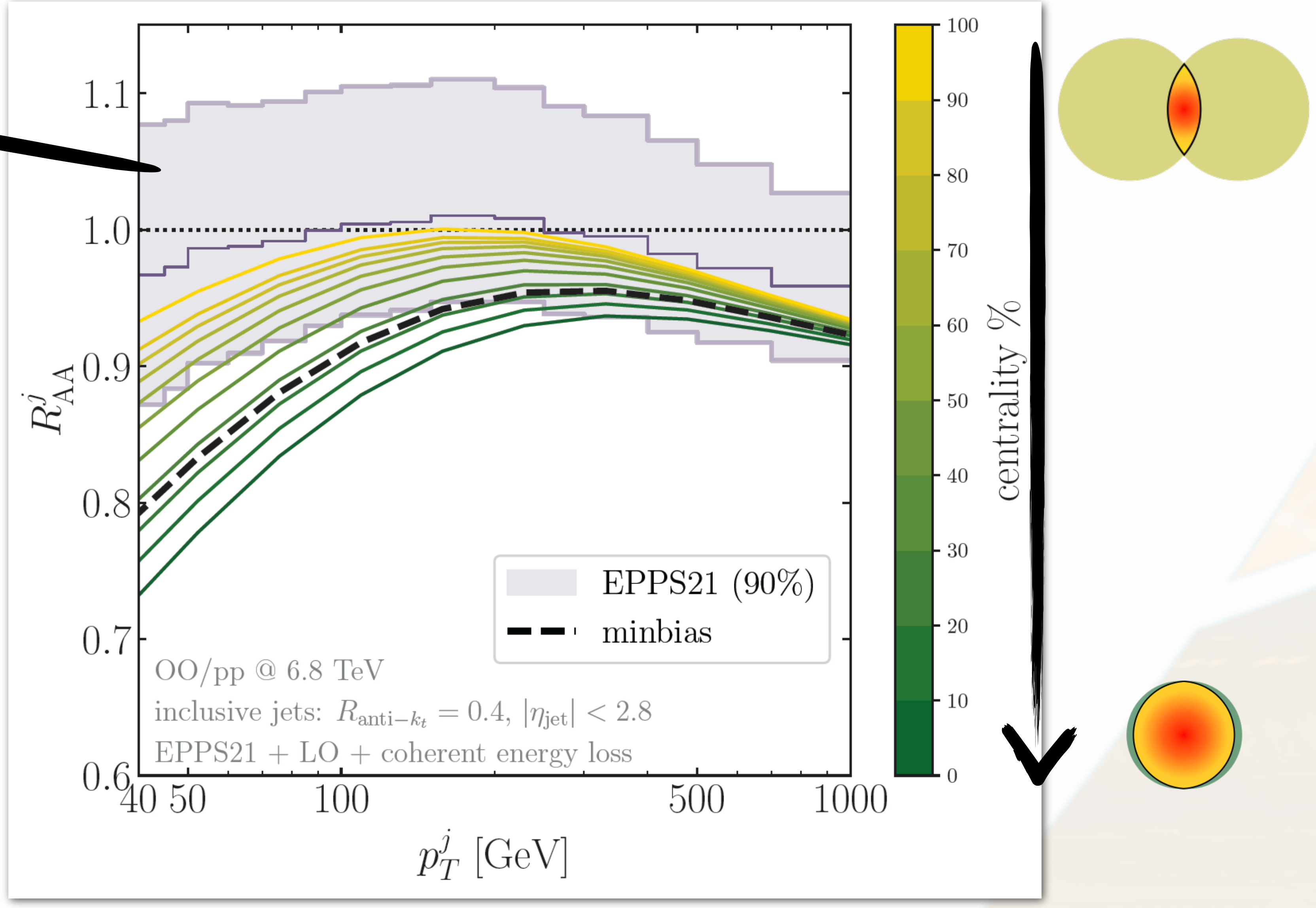
Opportunities at the LHC p+O run



Nuclear PDF uncertainties are particularly relevant

Currently, **no** existing **data** to constrain **Oxygen** nuclear PDFs

P.Paakkinen - Light Ion Workshop 2024 @ CERN



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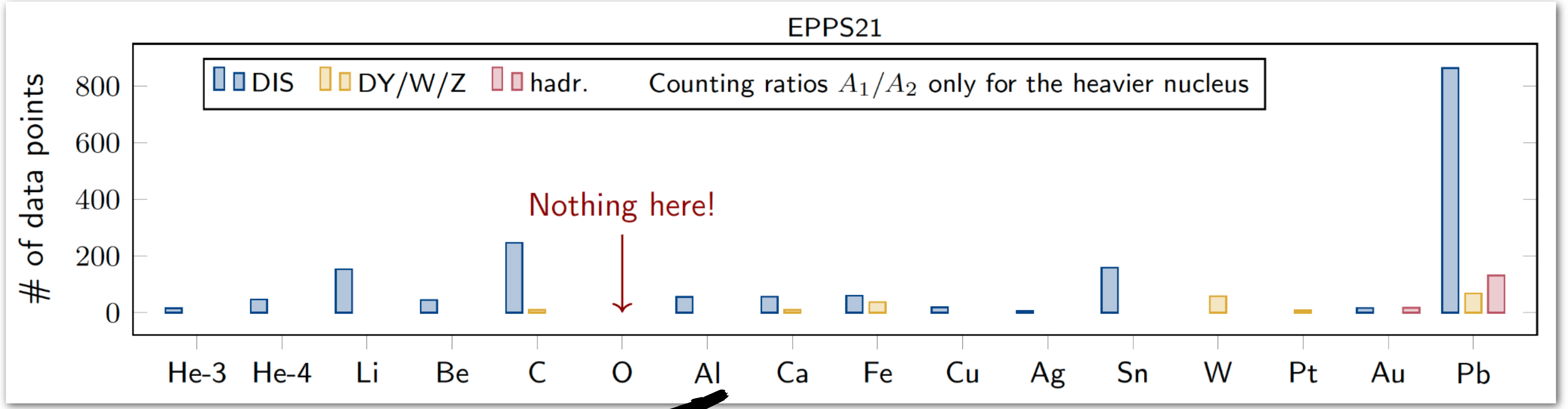

Nuclear PDF uncertainties are particularly relevant

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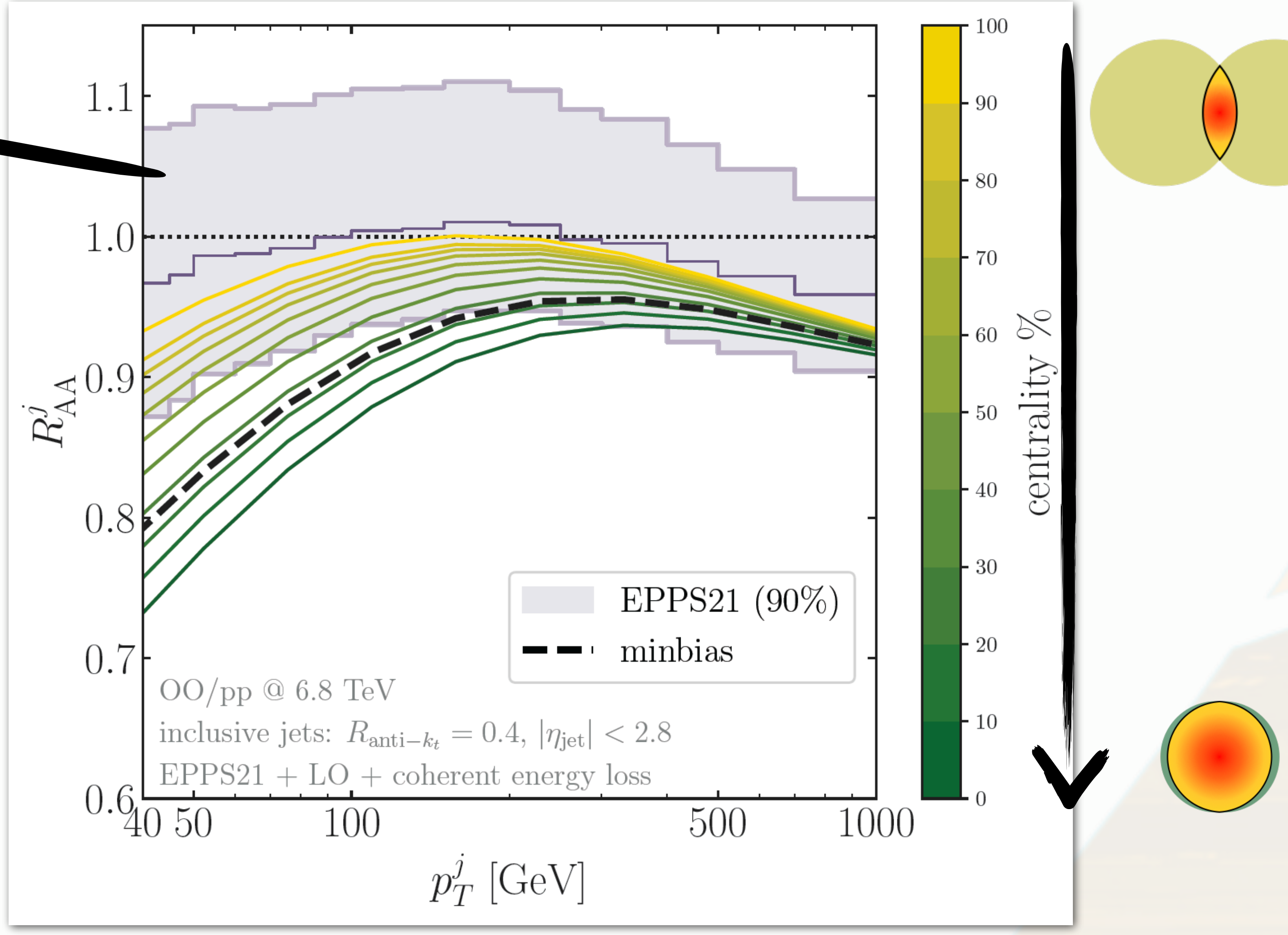
P.Paakkinen - Light Ion Workshop 2024 @ CERN

Dijet measurements in **p+O critical to inform nPDF** parameterizations and reduce uncertainties on the R_{AA}!



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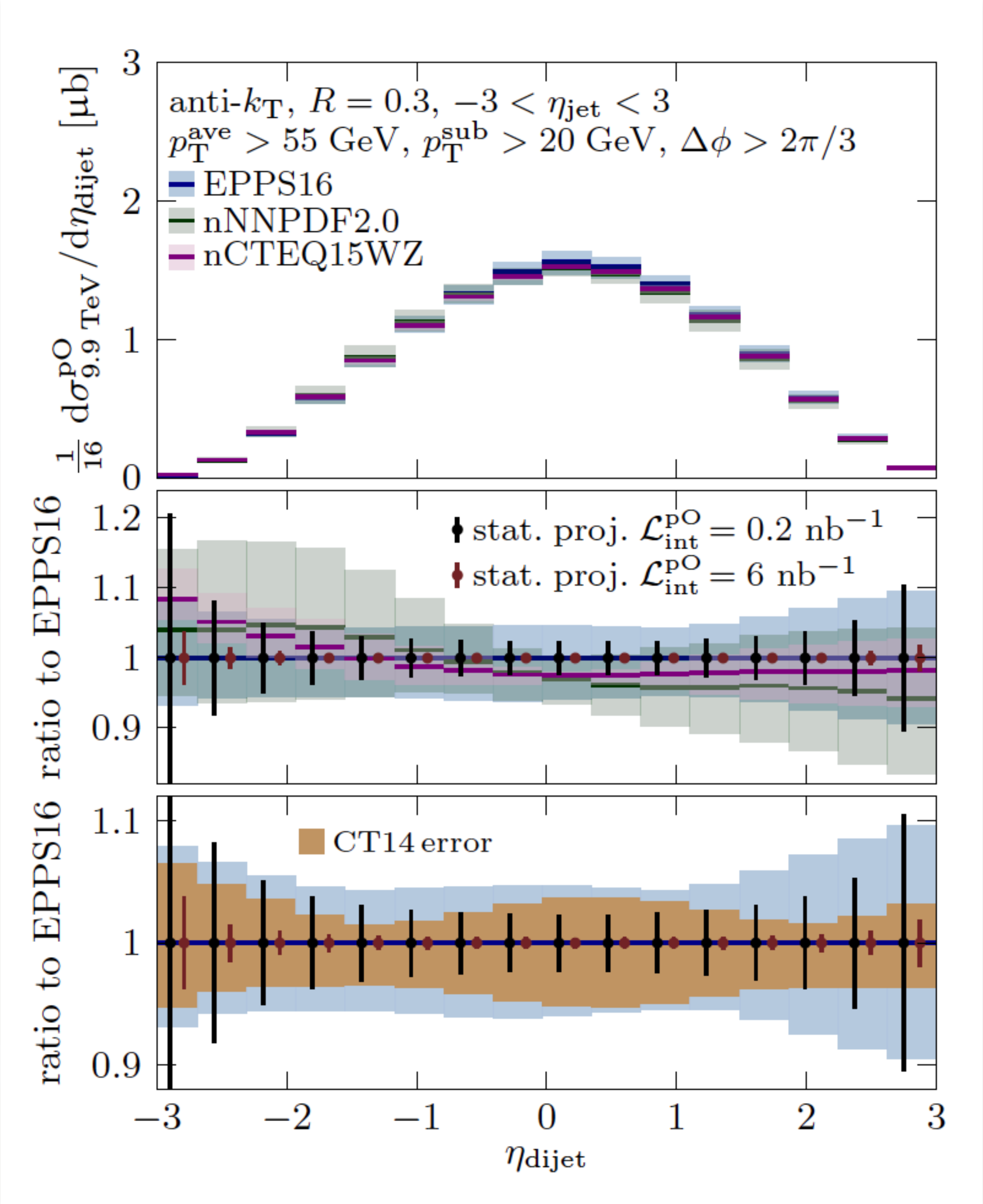

P.Paakkinen, PRD 105, L031504 (2022)