
# Jet results in heavy ion collisions with the ATLAS experiment at the LHC

Dennis V. Perepelitsa
for the ATLAS Collaboration
Brookhaven National Laboratory

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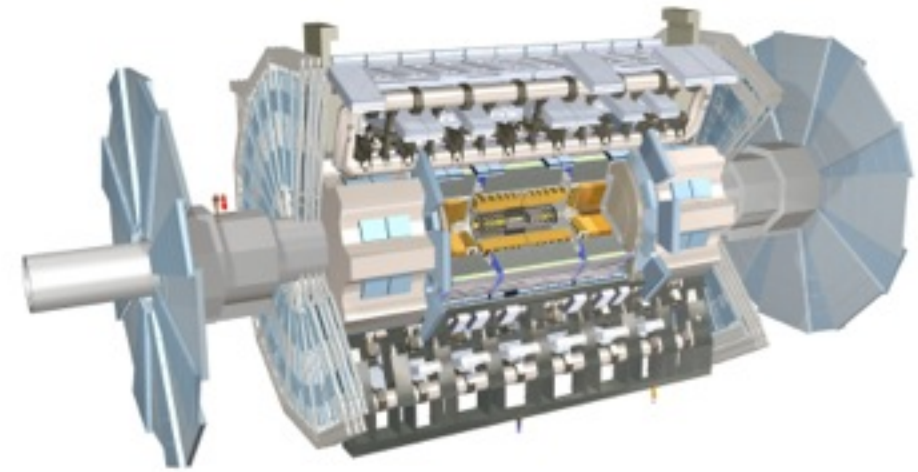
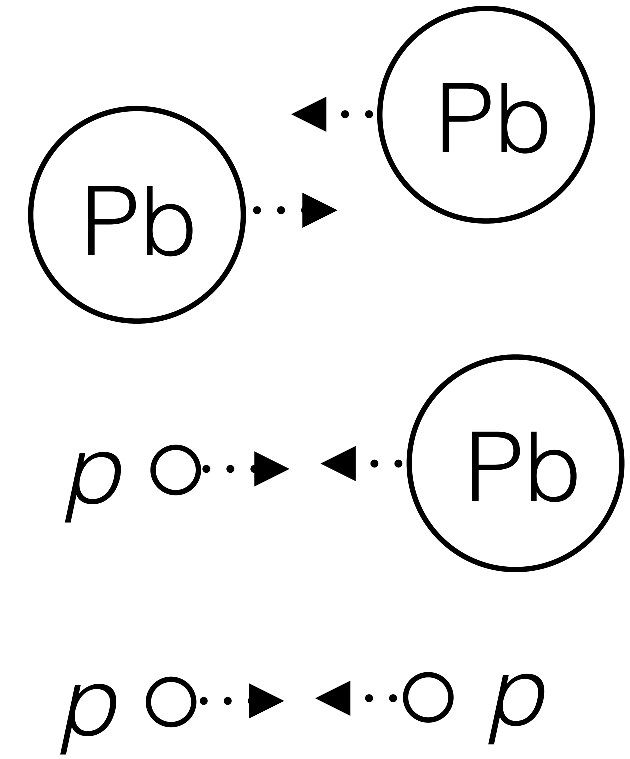
BROOKHAVEN NATIONAL LABORATORY

ATLAS EXPERIMENT

# Jet probes of hot and cold nuclear matter



- LHC Run I heavy ion data sets:
  - Pb+Pb @ 2.76 TeV, $\int\mathcal{L}dt$ = 140 μb$^{-1}$ in 2011
  - *p*+Pb @ 5.02 TeV, $\int\mathcal{L}dt$ = 28 nb$^{-1}$ in 2013
  - *pp* @ 2.76 TeV, $\int\mathcal{L}dt$ = 4.0 pb$^{-1}$ in 2013



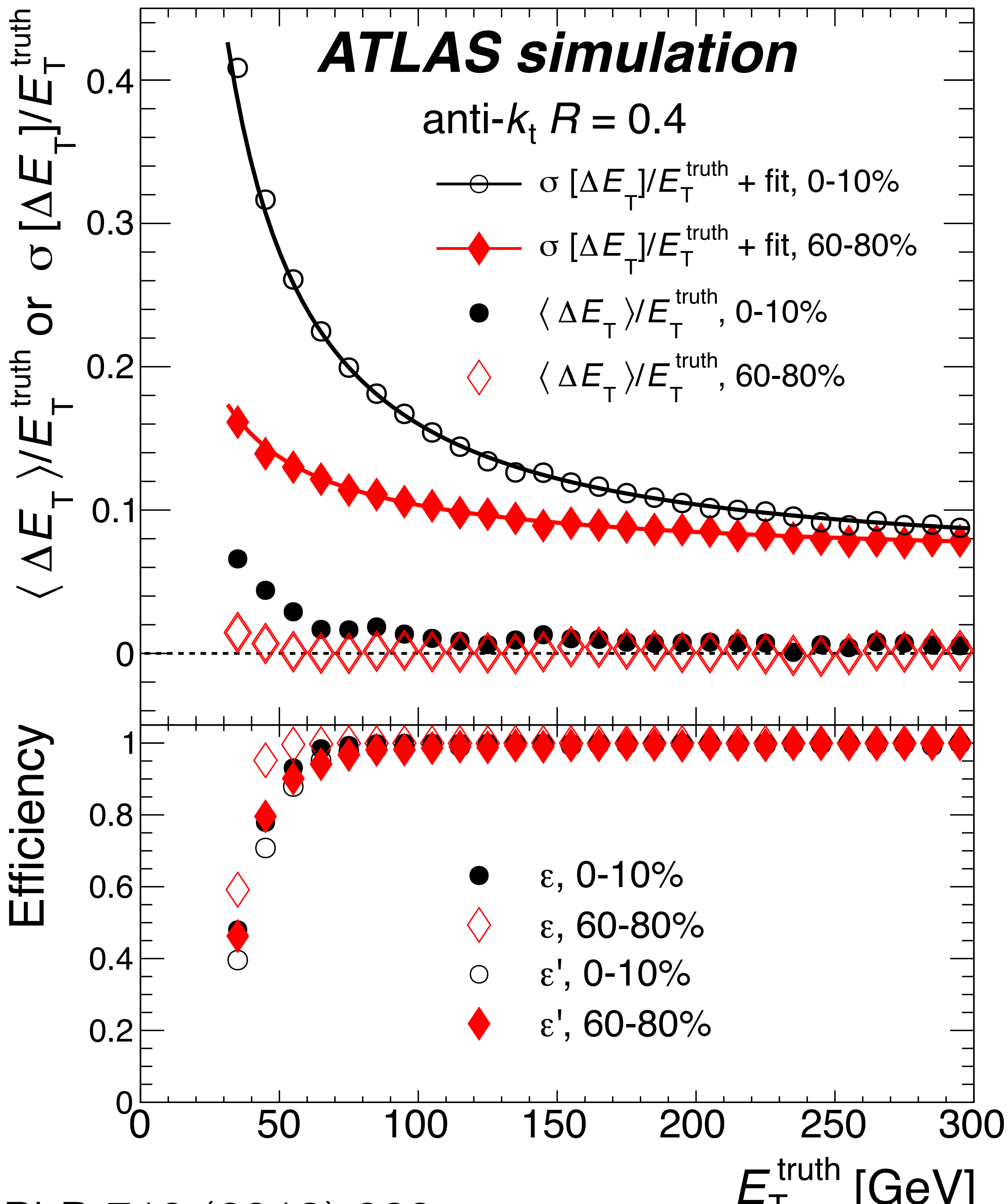

- I will highlight some of the **latest jet results** (<1 year)
- For more information (and electroweak boson, single hadron, heavy flavor, quarkonia, flow and correlation measurements), see:

⇒ https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults ⇐

# Jets in hot nuclear matter

- How does **jet reconstruction** perform in a heavy ion environment?
  - ➡ technical note on jet energy scale uncertainty
    *ATLAS-CONF-2015-016*
- What can Run I data teach us about **inclusive jet suppression**?
  - ➡ measurement of jet $R_{\mathrm{AA}}$ vs. $p_{\mathrm{T}}$, rapidity, centrality
    *PRL 114 (2015) 072302*
- Do we understand the **path length dependence** of energy loss?
  - ➡ measurement of dijet asymmetry vs. reaction plane
    *ATLAS-CONF-2015-021*
  - ➡ measurement of multi-jet production
    *hep-ph/1506.08656*

# Jet measurements in ATLAS



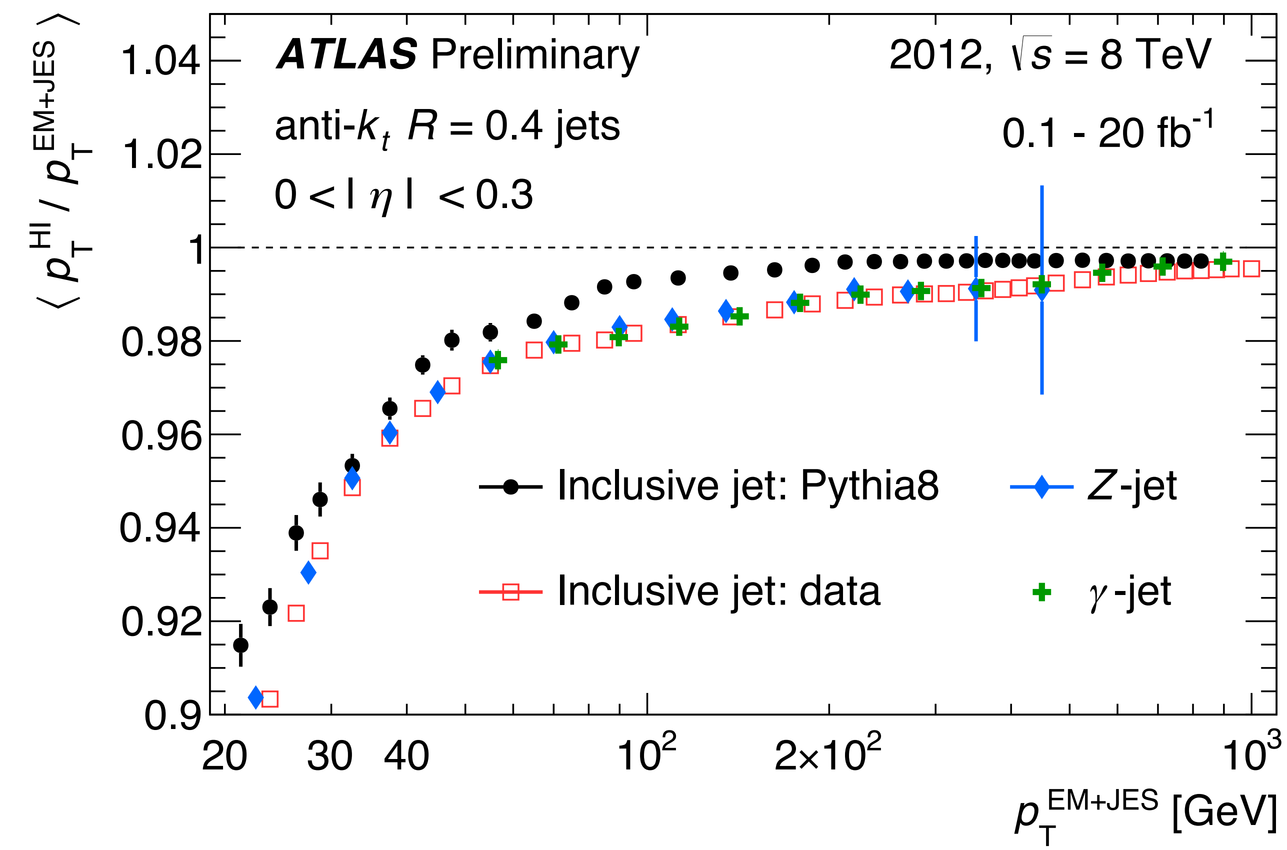

PLB 719 (2013) 220

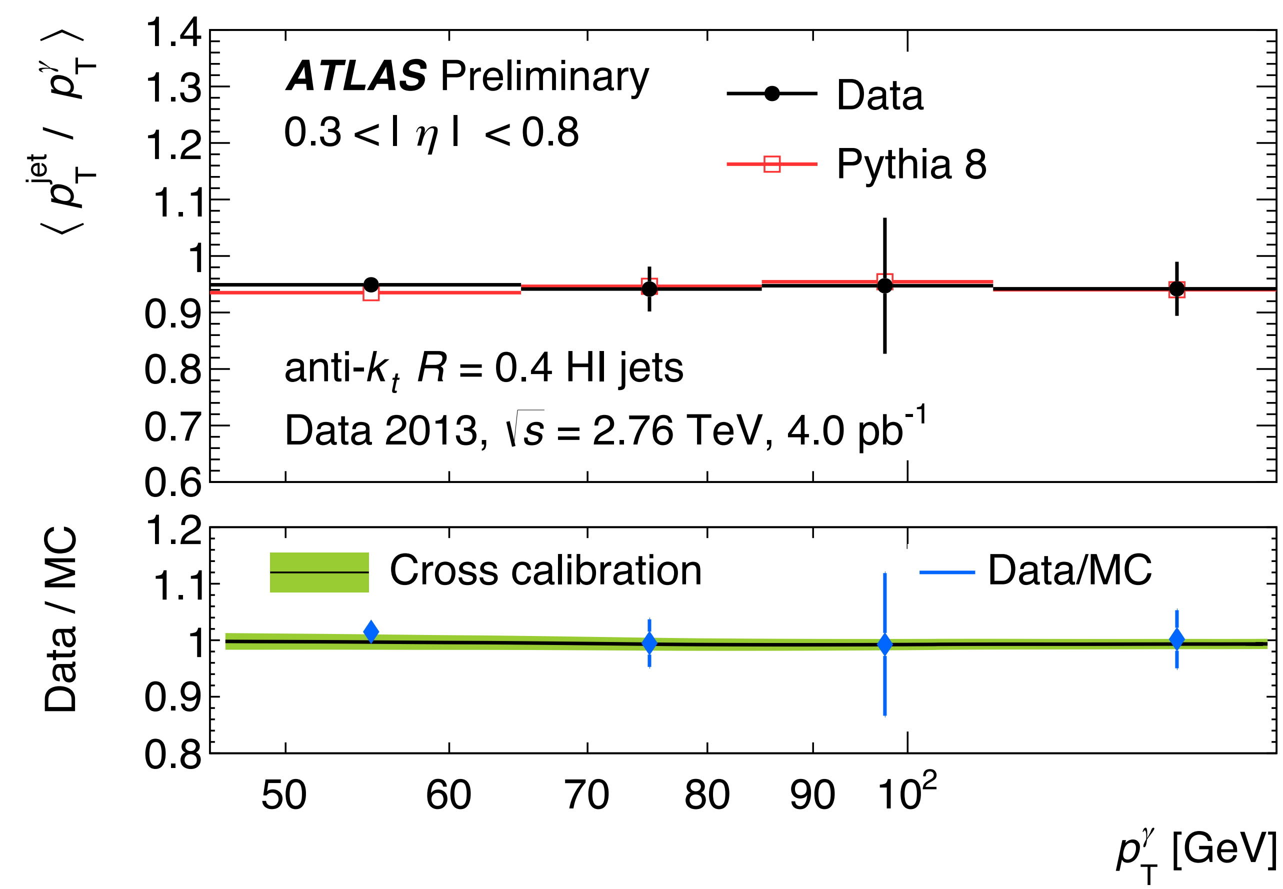
- Jets are built with the anti-$k_t$ algorithm from 0.1×0.1 towers in the EM+HCals
- Estimate & subtract correlated, η-dependent, underlying event
  ➡ and <u>reject "fake jets"</u> arising from localized UE fluctuations
- Early performance in Pb+Pb collisions
  ➡ experimental control of $R$=0.4 spectrum <u>down to 40 GeV</u>
  ➡ but without rigorously determined JES uncertainty

NEW

ATLAS-CONF-2014-016

- First, establish control in *pp* collisions at √s = 8 TeV:
  - ➡ fix <u>Heavy Ion</u>-style jet E-scale to the <u>Standard Model</u>-style jet E-scale
  - ➡ derive “cross-calibration” factor to inherit effects of *in situ* corrections
- To constrain flavor dependence, study HI vs. SM scale in ɣ-jet and Z-jet events
  - ➡ and *in situ* ɣ-jet at lower √s



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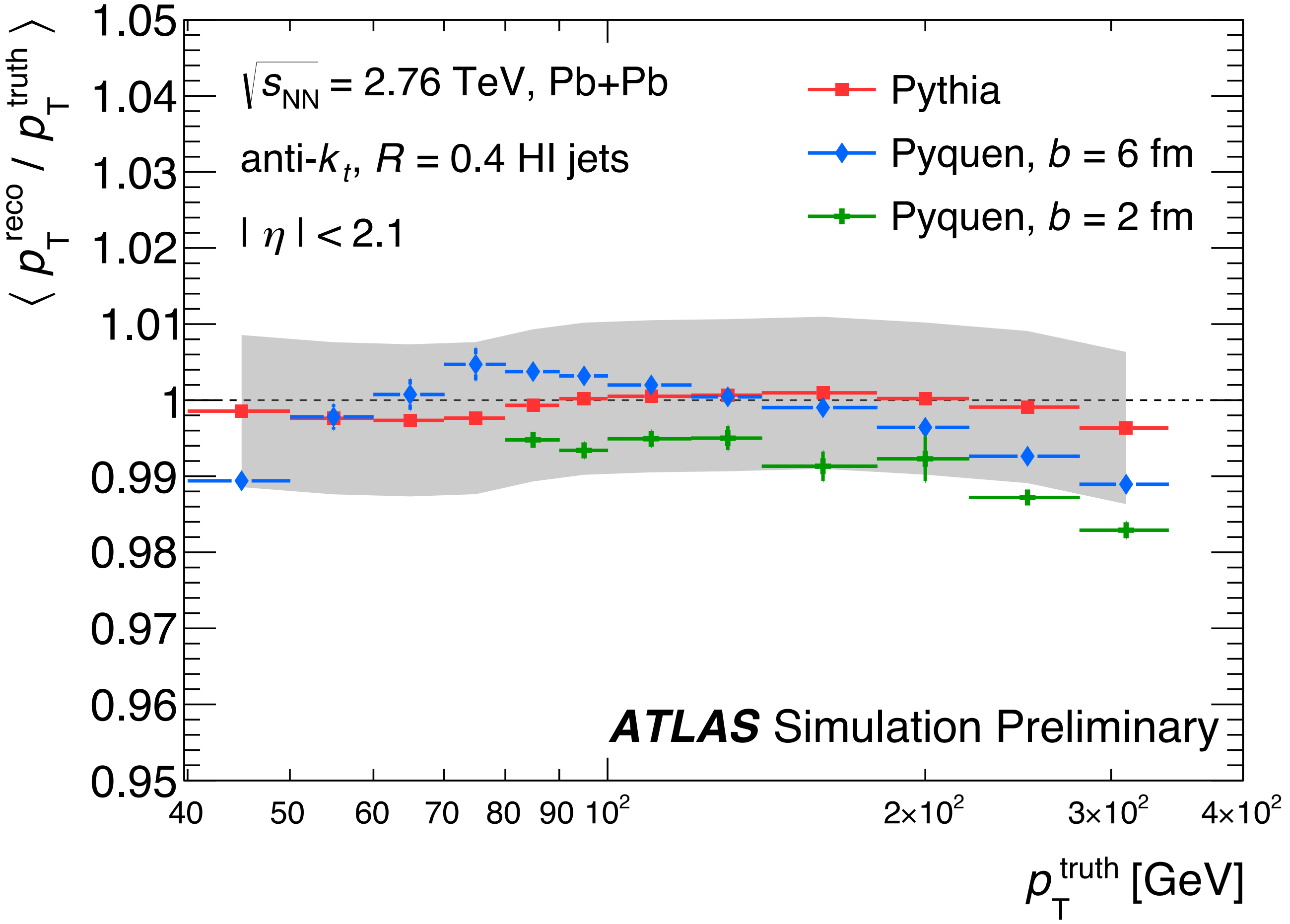
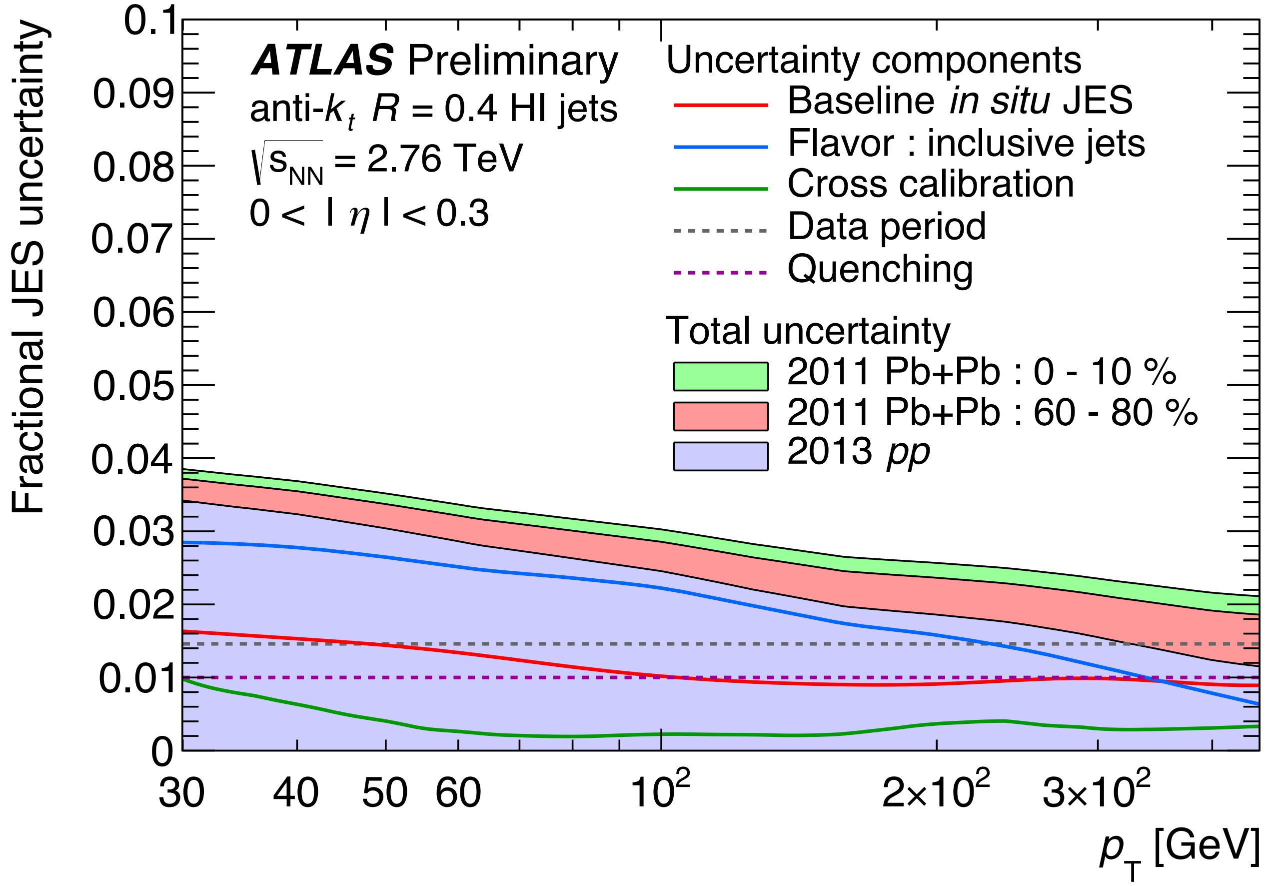


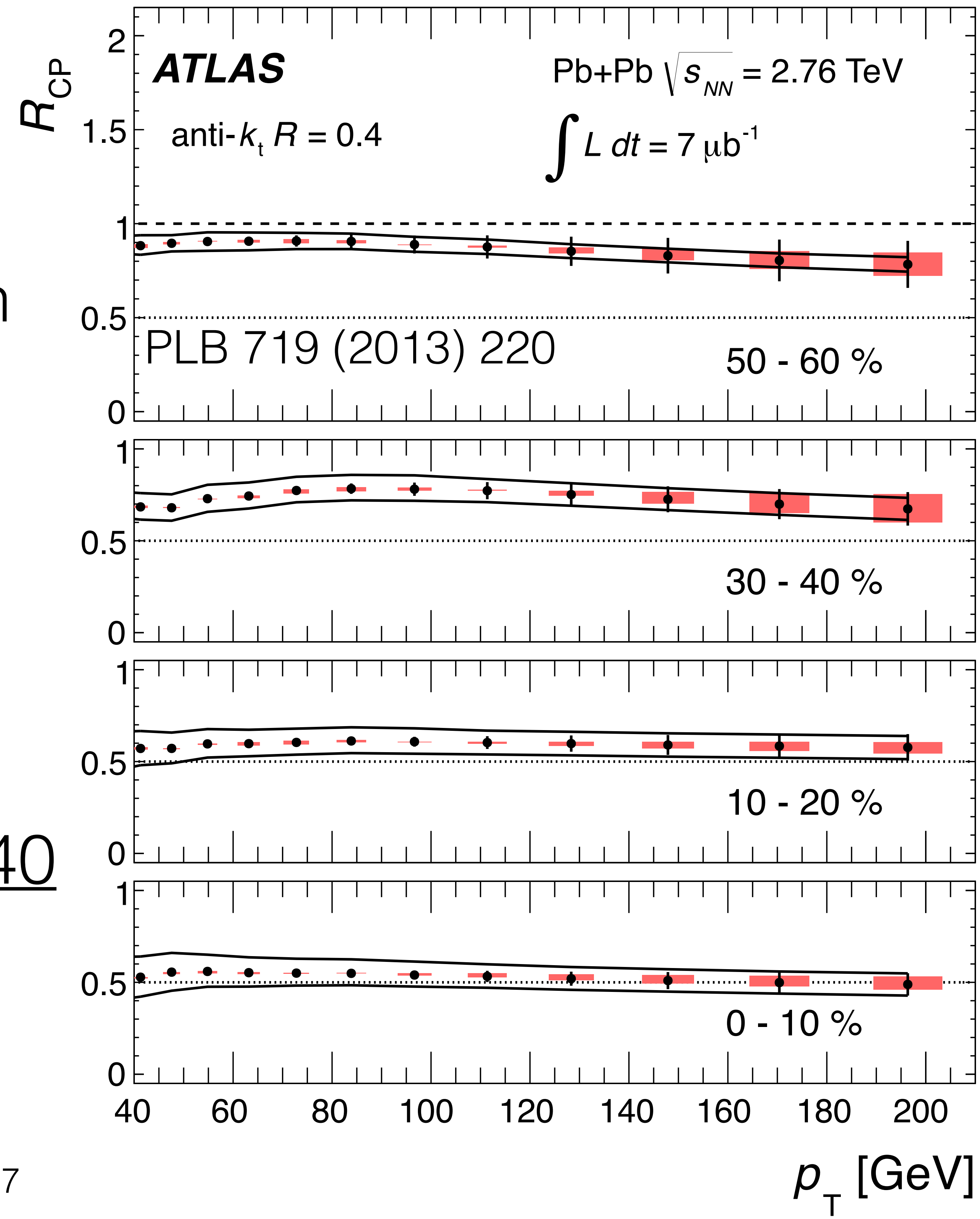

- Response to quenched jets constrained via:
  - ➡ simulations tuned to reproduce quenching observables
  - ➡ calo-jet/track-jet energy scale check, after correcting for effects of modified fragmentation function
- $p_T$-, η-, centrality-dependent jet energy scale uncertainty for *pp*, *p*+Pb, Pb+Pb collisions — state of the art!

# Inclusive jet suppression ca. 2013

- Fully corrected $R_{CP}$ for $R$=0.4 jets, relative to the 60-80% bin

$$R_{CP} = \frac{dN^{\textit{cent.}}/dp_T\,/\,<T_{AA}{}^{\textit{cent.}}>}{dN^{\textit{peri.}}/dp_T\,/\,<T_{AA}{}^{\textit{peri.}}>}$$

- Factor of 2 suppression in central events
- weak $p_T$ dependence from <u>40 to 200 GeV</u>, within <u>|y*| < 2.1</u>



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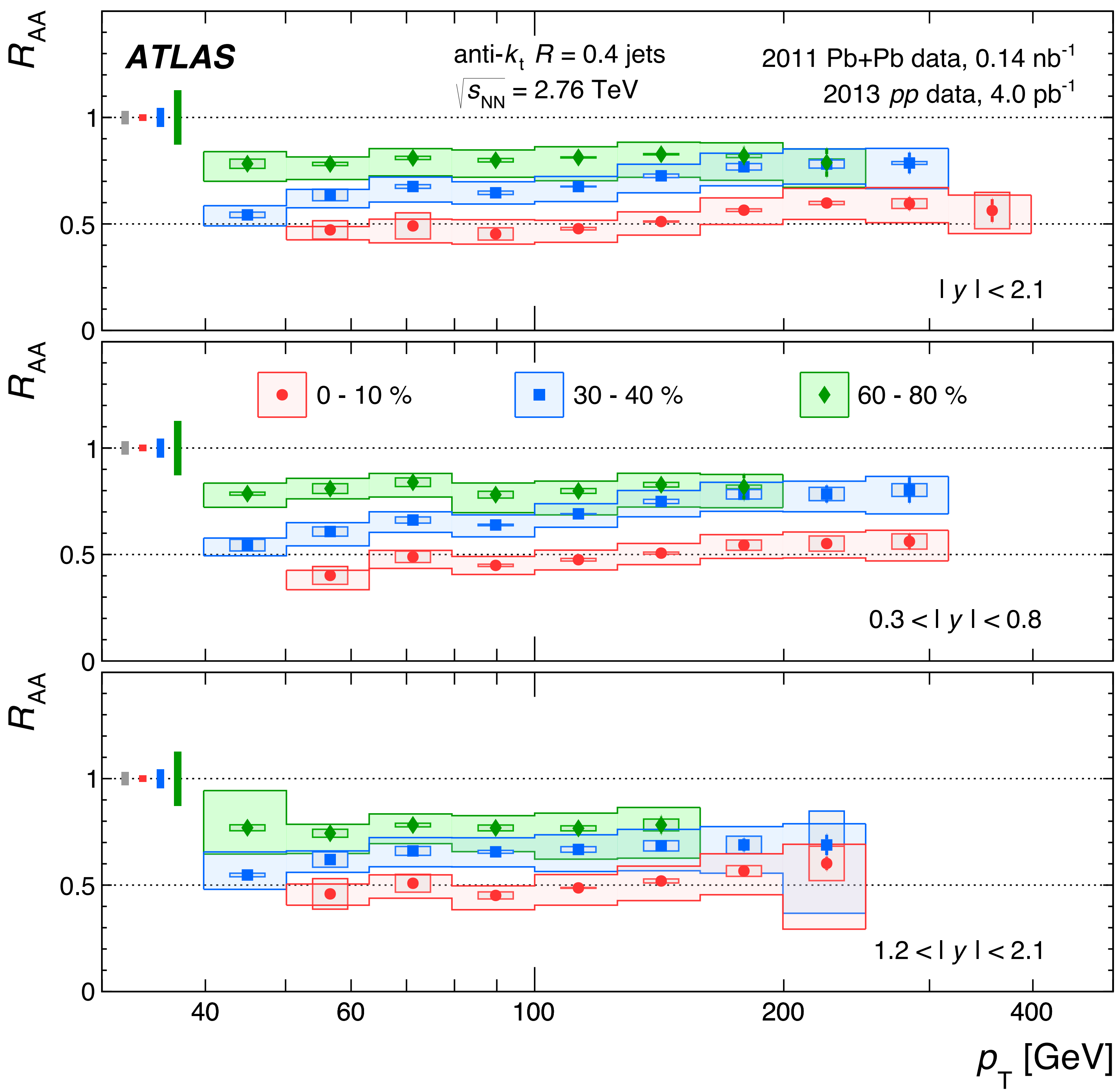
- High statistics *pp* data & JES uncertainty allows for measurement of the: $R_{AA} = \dfrac{dN^{cent.}/dp_T}{\langle T_{AA}^{cent.}\rangle \, d\sigma^{pp}/dp_T}$

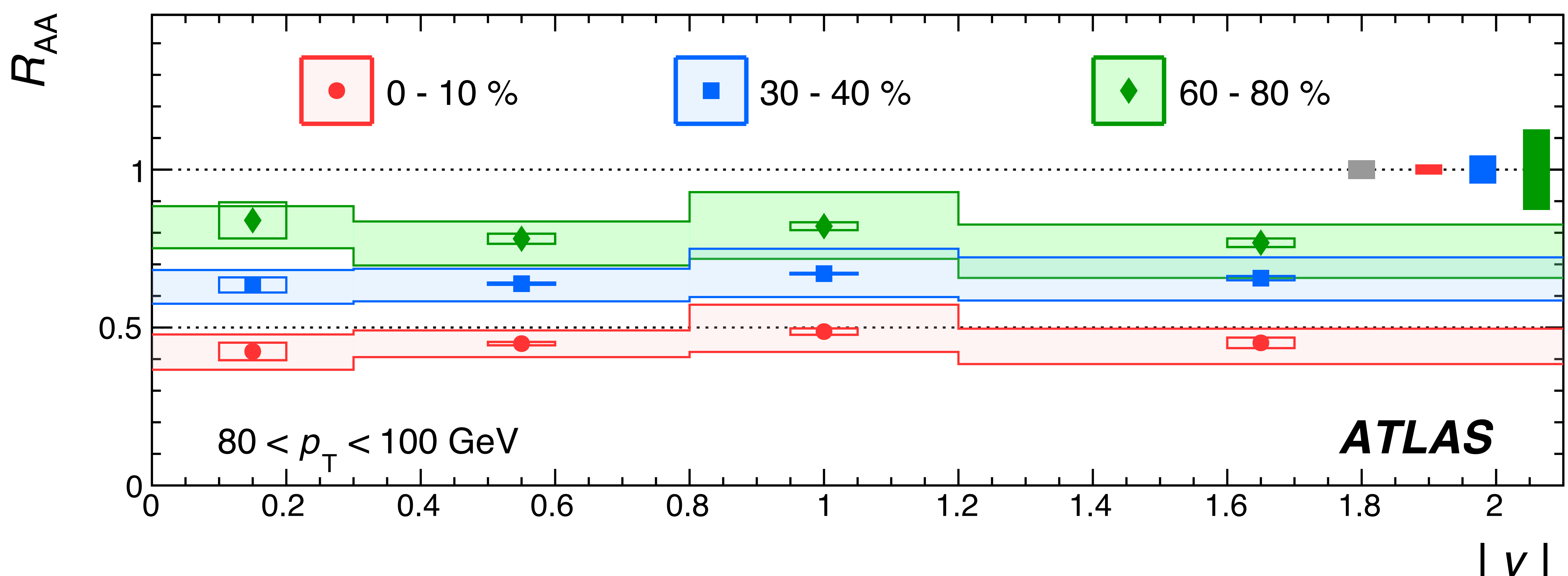



- 40-400 GeV
- differential in rapidity
  - ➡ legacy measurement for Run I!
- centrality-dependent suppression, with modest $p_T$ dependence

NEW

PRL 114 (2015) 072302

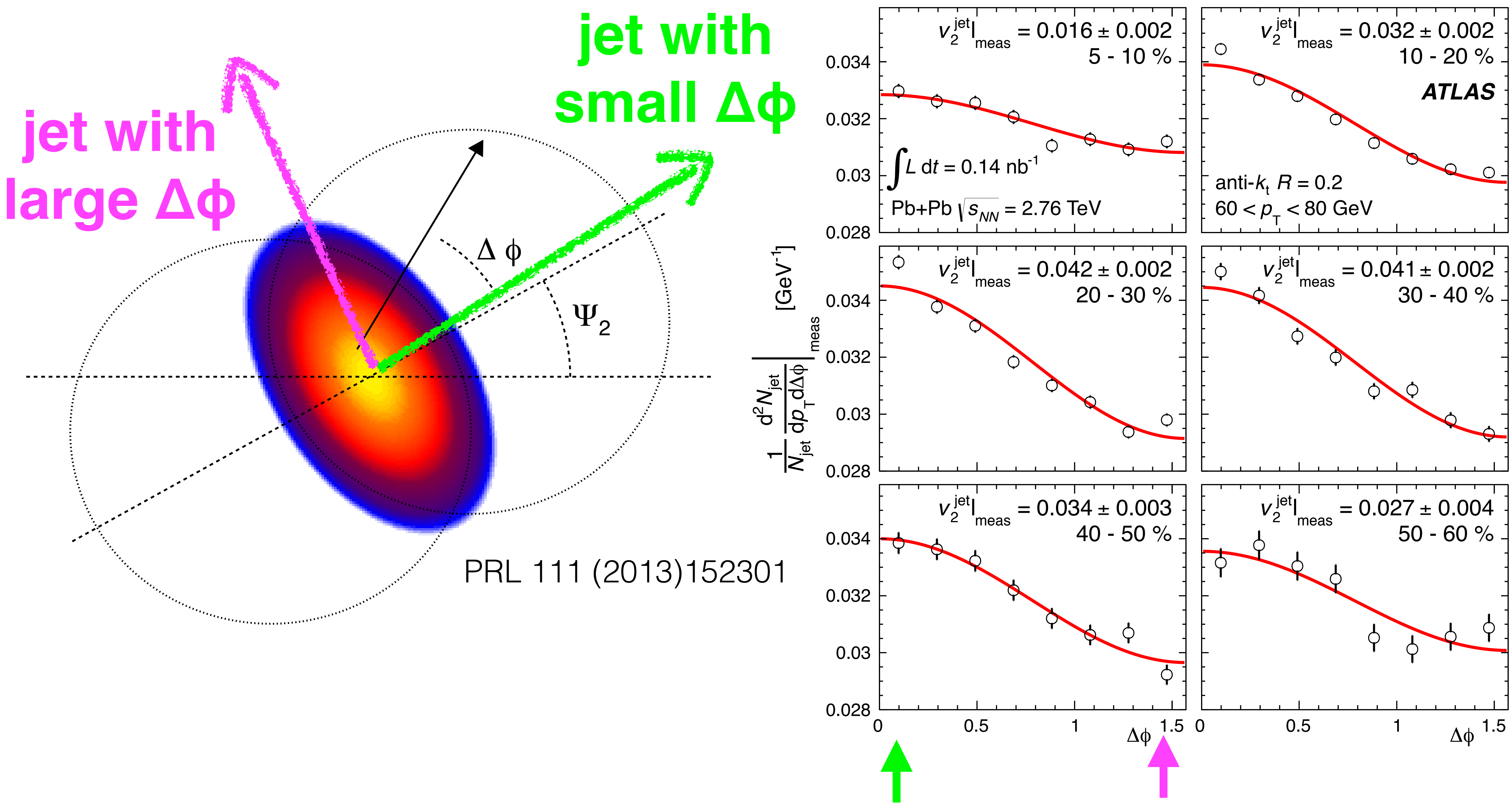
- Substantial insight from a rapidity-differential measurement:
  - ➡ different shape of initial jet spectrum before quenching
  - ➡ different quark/gluon mixture at fixed $p_T$
  - ➡ different path length seen by jets




- Intriguingly, $R_{AA}$ shows little dependence on $y$
  - ➡ should we expect this? which models can explain this?

hep-ex/1411.2357

# Path length dependence of quenching




- Previous studies of jet yield vs. $\Delta\phi = \phi^{jet} - \Psi_2$, and jet $v_2$
  - ➡ energy loss has modest but non-zero dependence on path length
  - ➡ two new ATLAS measurements to elucidate this…

NEW

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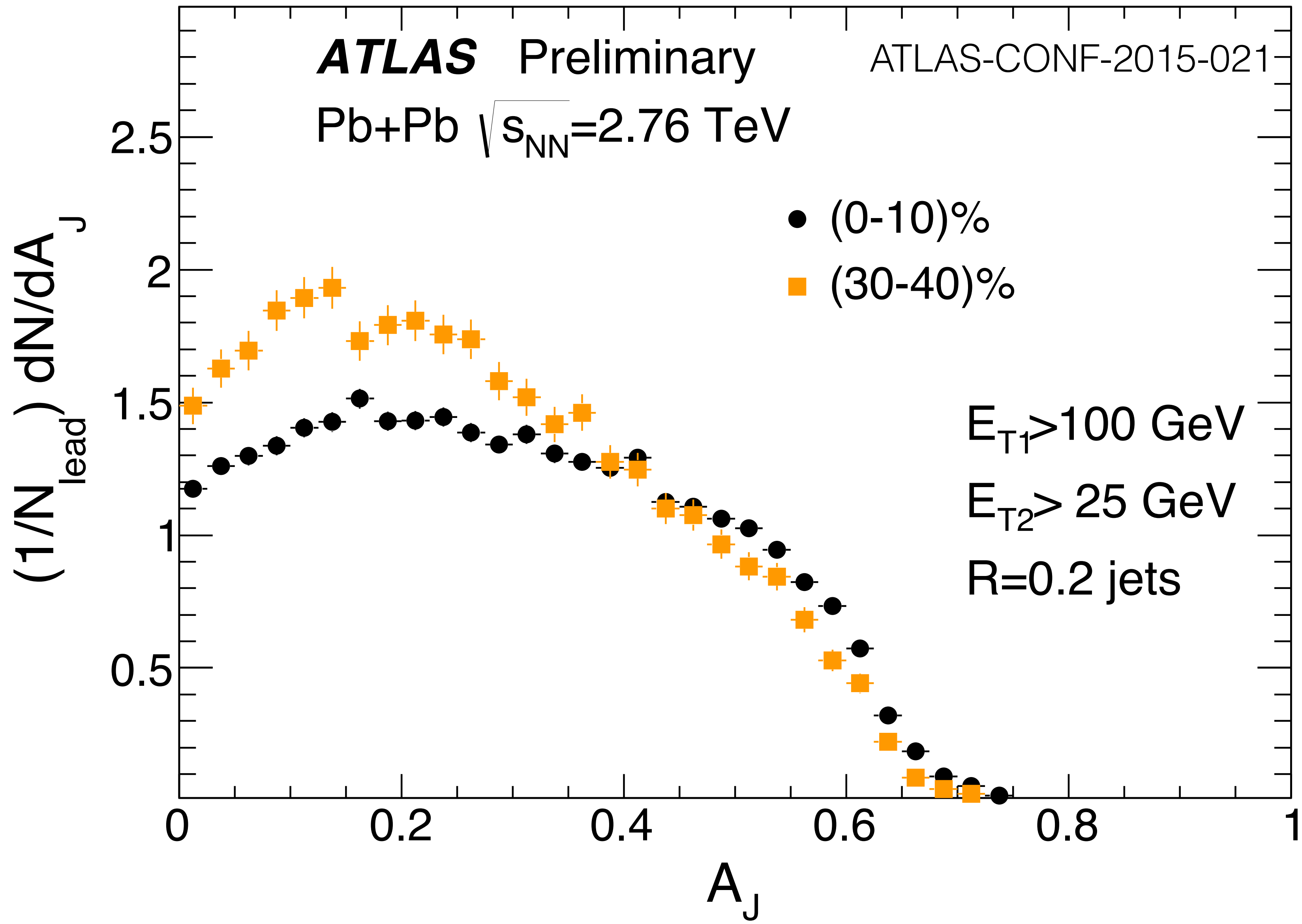
# Dijet asymmetry vs. event-plane

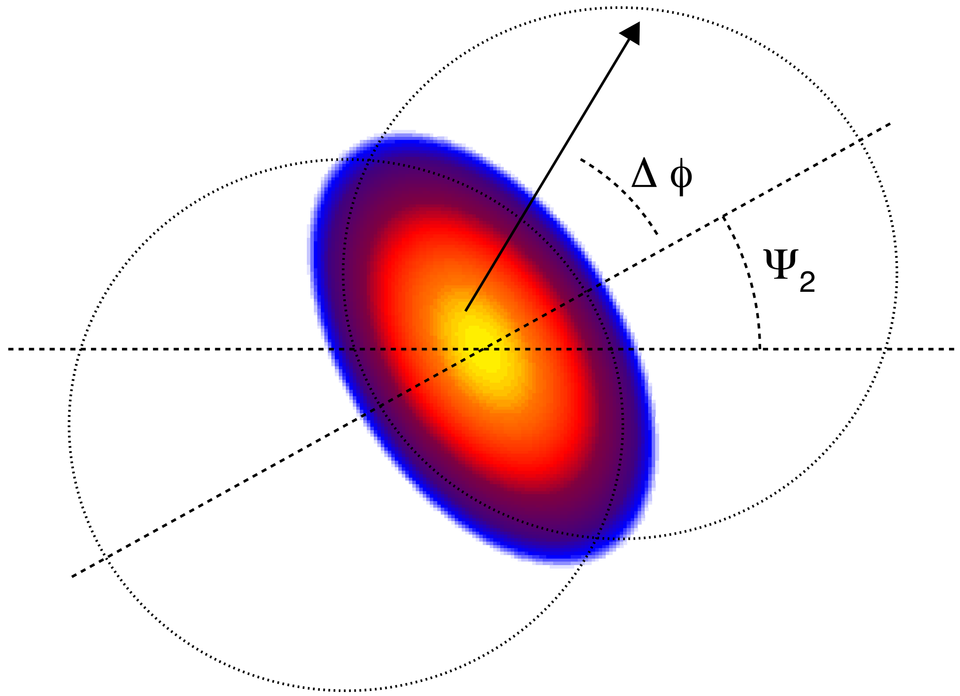


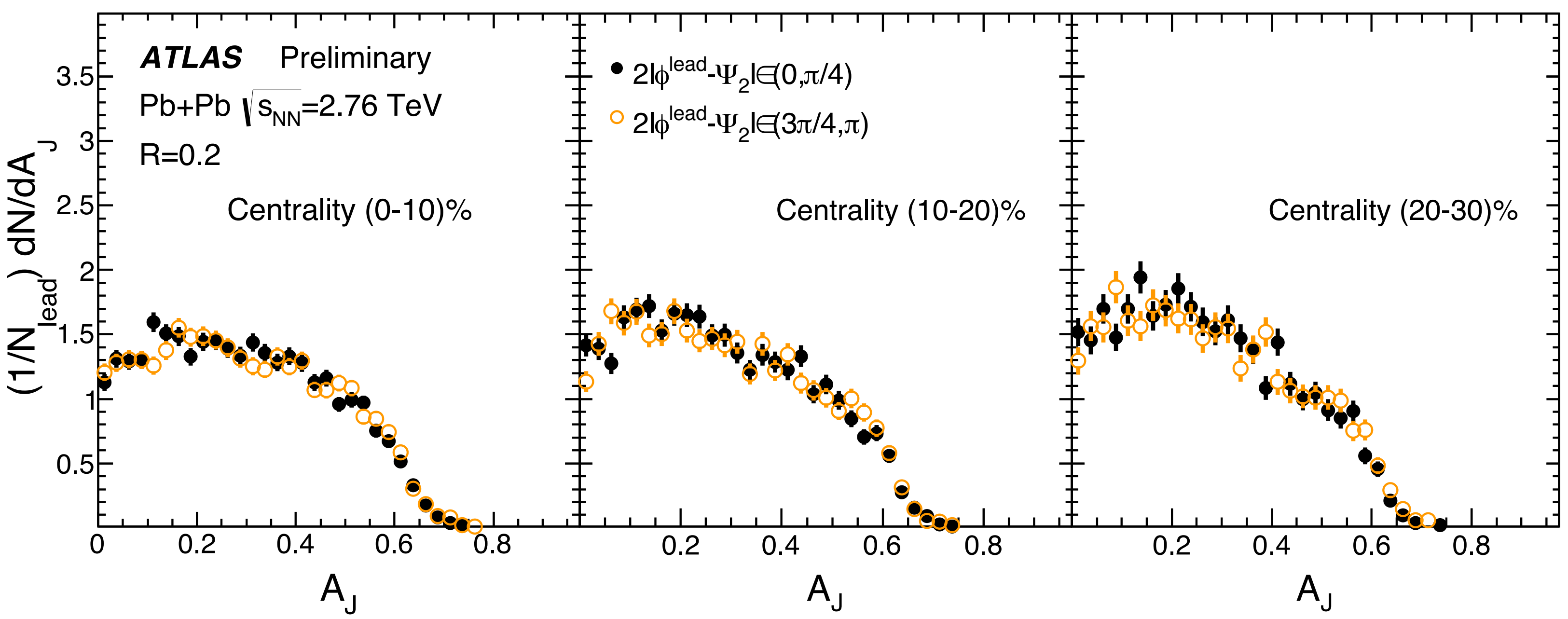

(statistical uncertainties only)

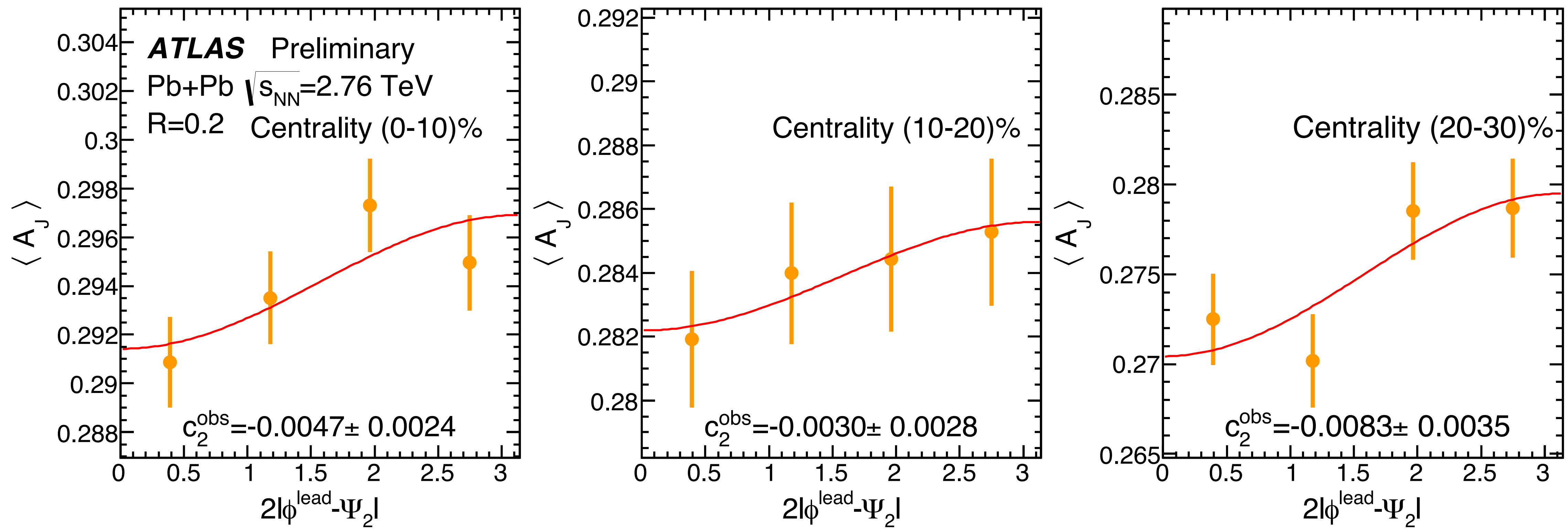
- Dijet asymmetry $A_J = (E_{T,1} - E_{T,2}) / (E_{T,1} + E_{T,2})$
  - ➡ sensitive to path length differences event-by-event
  - ➡ certainly sensitive to centrality, but how about $\Delta\phi$?

ATLAS-CONF-2015-021

# Dijet asymmetry vs. event-plane



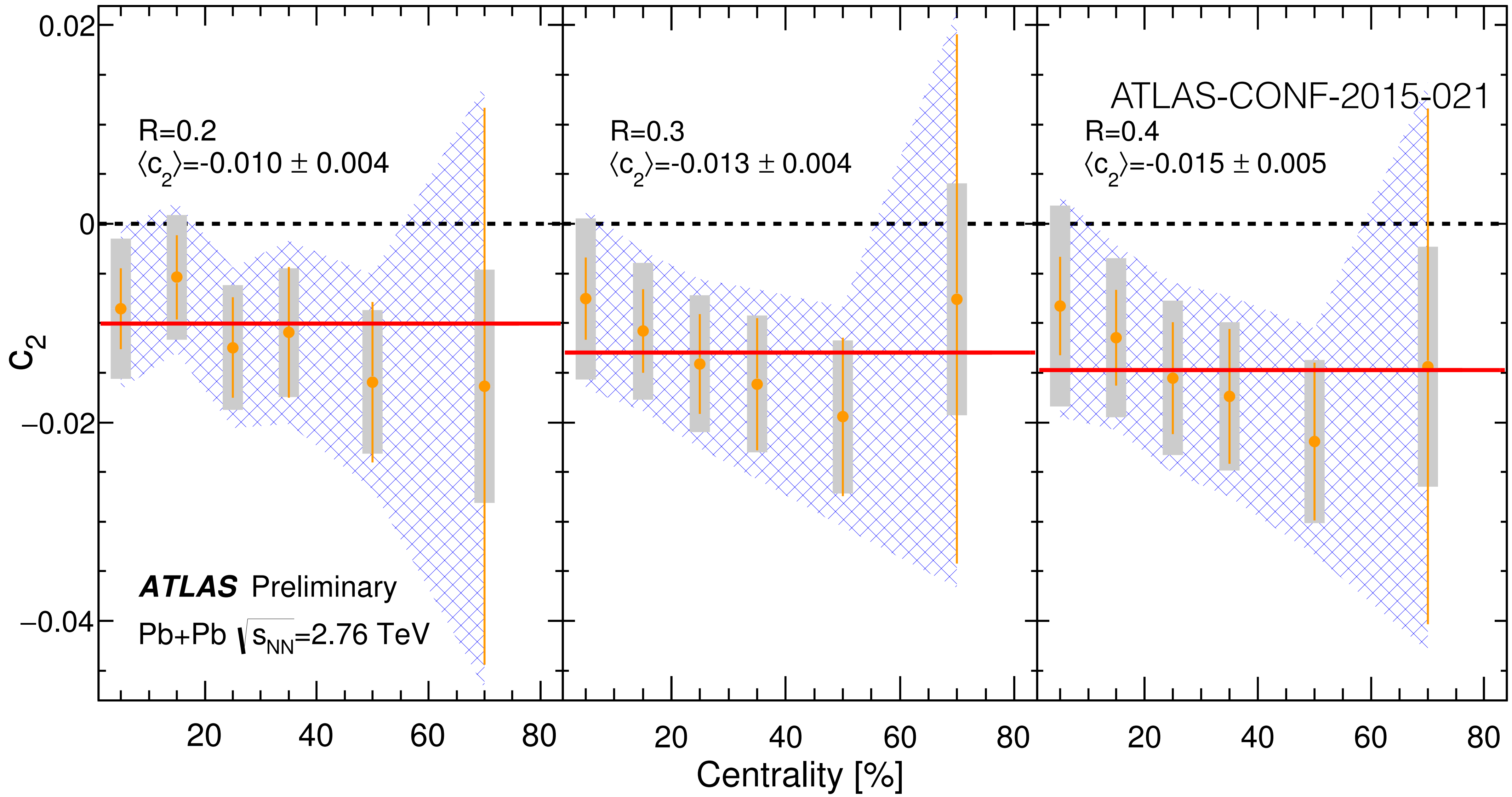




➡ $\langle A_J \rangle$ systematically increases with $\Delta\phi$

NEW



# Dijet asymmetry vs. event-plane




- Extract reaction plane dependence via $\mathbf{c_2}$ where $\langle A_J \rangle(\Delta\phi) = \langle A_J \rangle_0 (1 + 2\boldsymbol{c_2}\cos(2\Delta\phi))$
- Shown here vs. centrality for three choices of cone size $R$
  - ➡ c2 is negative, and reaches a maximum for 40-60% collisions

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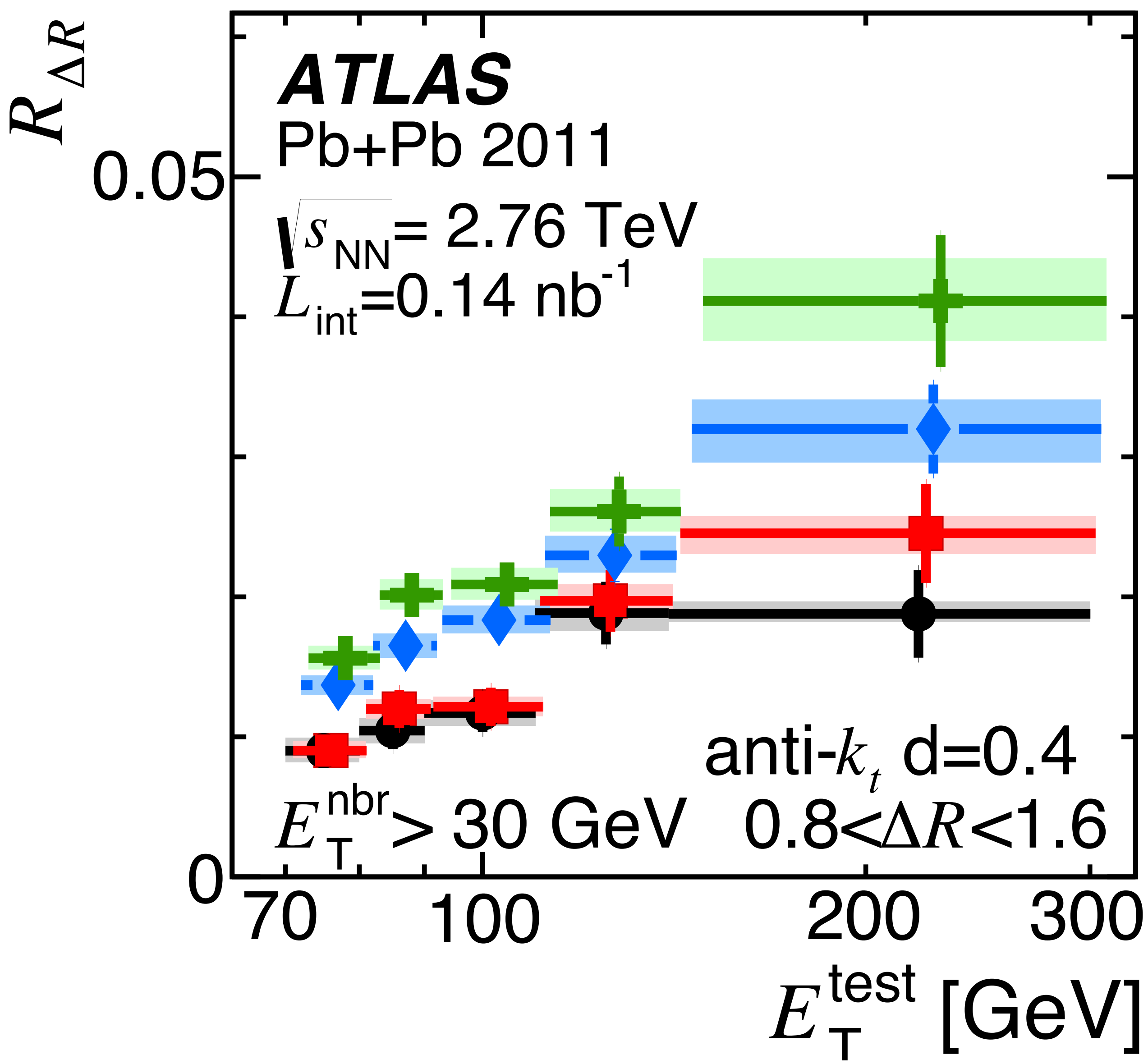
hep-ph/1506.08656

# Nearby jet production

- Nearby jets arise from hard radiation early in a parton shower
  - ➡ their production is an intriguing test of path length dependence




- Observable inspired from, e.g. D0 measurements of nearby jet production to infer $\alpha_s$

- Given a "test" jet with $\boldsymbol{E_T^{test}}$, what is the probability to have a "neighboring" jet with some $\boldsymbol{E_T^{nbr}}$?
  - ➡ different colors show different centralities

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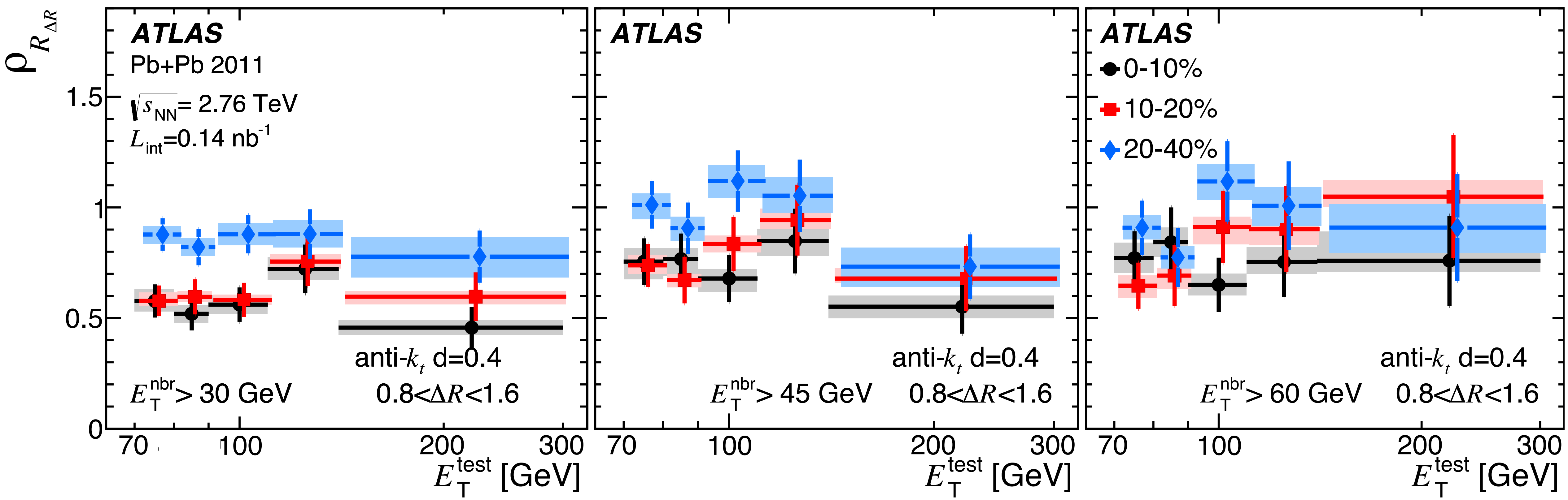
# Nearby jet production




- Plot central/peripheral ratio as a function of **test jet $E_T^{test}$**
- This quantity is suppressed below unity and is independent of $E_T^{test}$

➡ qualitatively similar to the suppression of inclusive jet production

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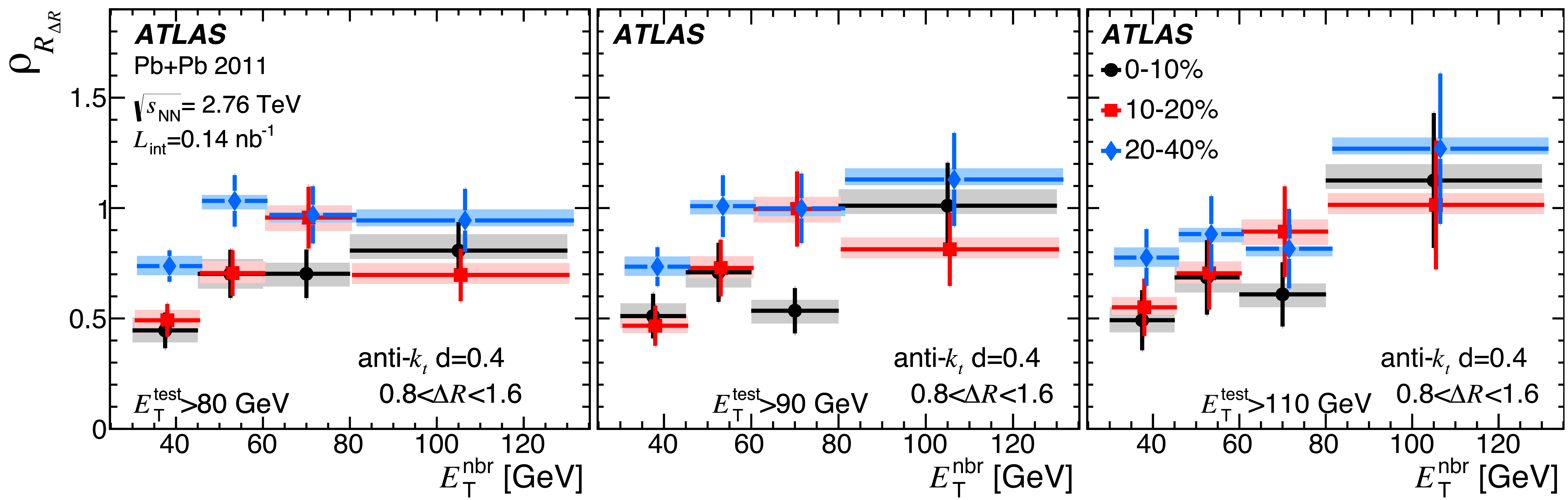
# Nearby jet production

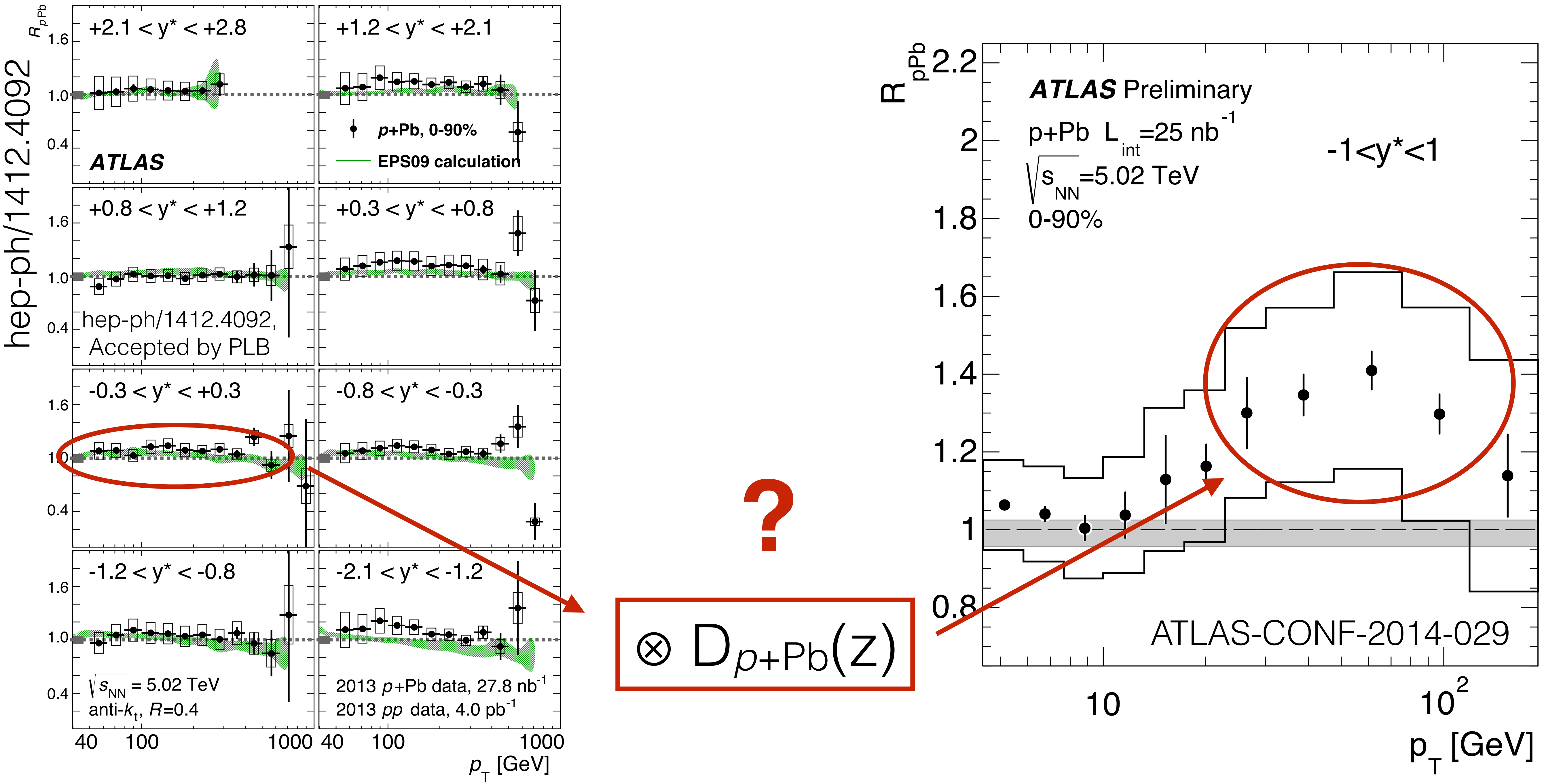



- Now plot central/peripheral ratio as a function of **nearby jet $E_T^{nbr}$**
- This quantity rises and reaches unity when $E_T^{test} \approx E_T^{nbr}$
  - ➡ suggesting that jets with the same "unquenched" $p_T$ and path length are quenched in the same way

# Jets in cold nuclear matter

- Are rates of jet and hadron production modified in the **cold nuclear environment**?
    - ➡ measurement of the *p*+Pb jet fragmentation function
      *ATLAS-CONF-2015-022*
- What is the correlation between **hard scattering and soft production** in *pp* collisions?
    - ➡ forward energy production in *pp* collisions
      *ATLAS-CONF-2015-019*

# Jet and hadron production




- Unmodified jet $R_{pPb}$ but possible enhancement in hadron $R_{pPb}$
  ➡ notably outside of what global nPDF fits can accommodate
- Necessitates measurement of the **fragmentation function**

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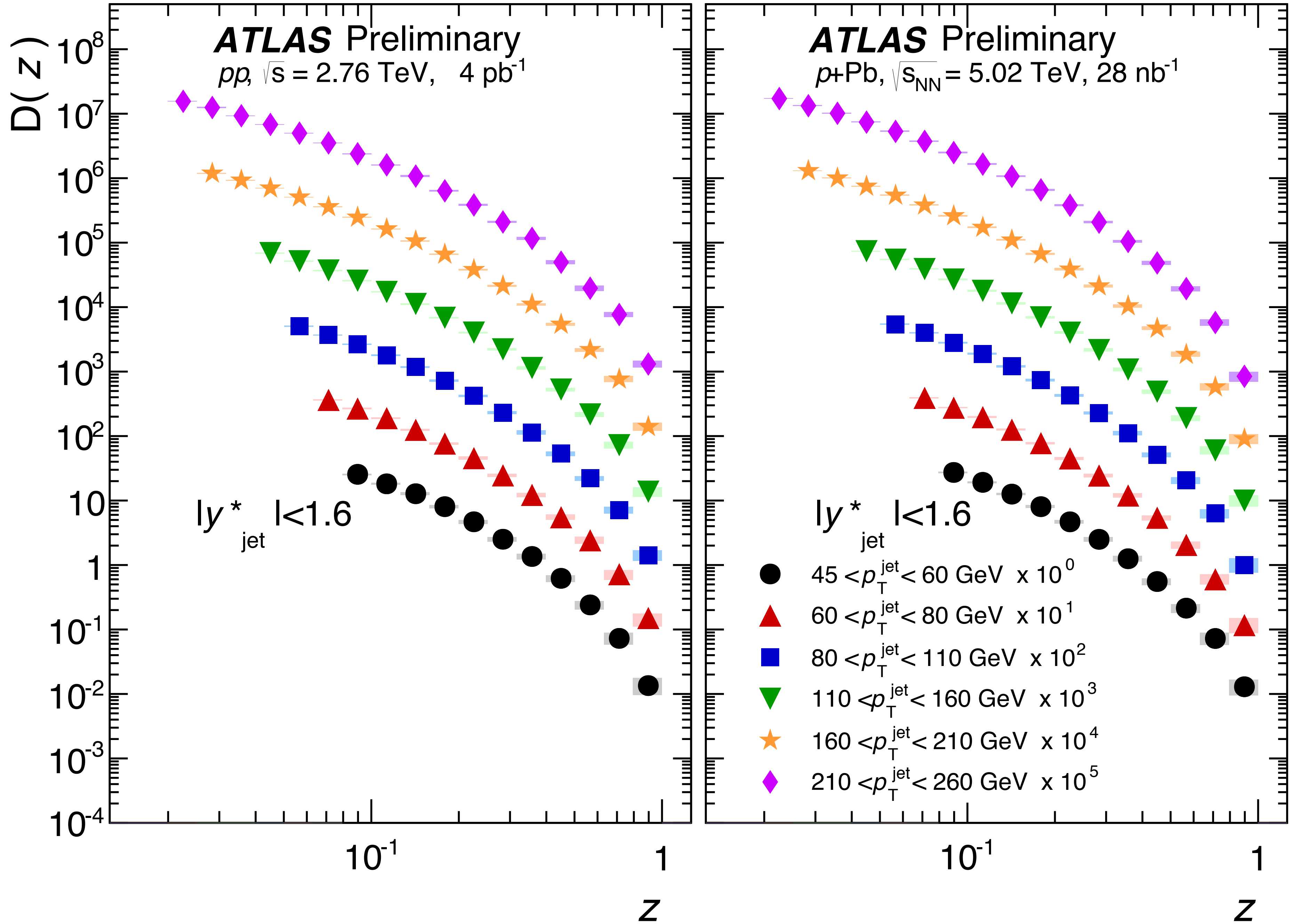


- D($z$), $z = p_T^{track} / p_T^{jet}$, for $p_T$ > 3 GeV charged hadrons
  - ➡ measured in 5.02 TeV *p*+Pb and 2.76 TeV *pp* collisions,
  - ➡ differentially vs. jet $p_T$

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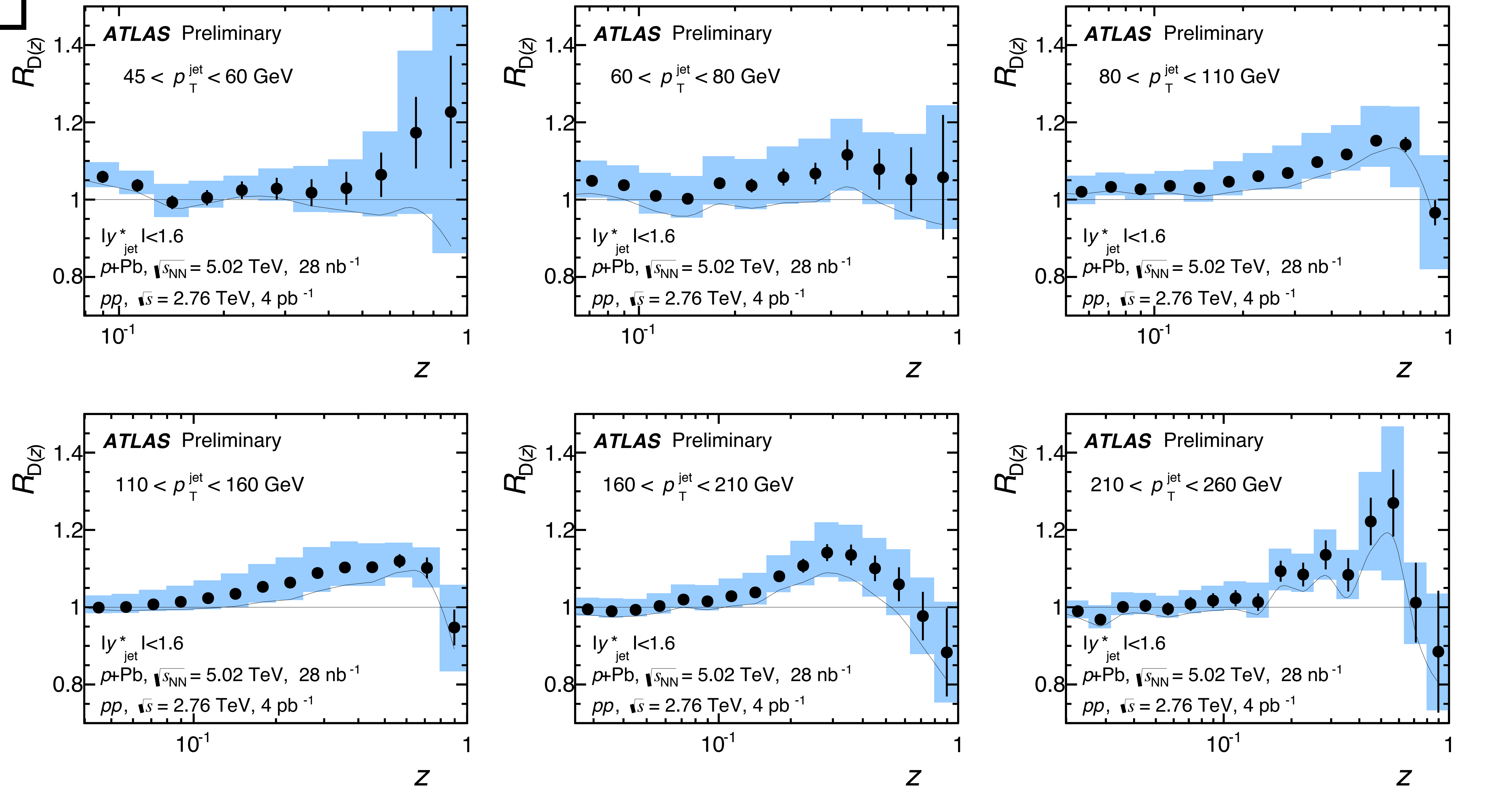
ATLAS-CONF-2015-022

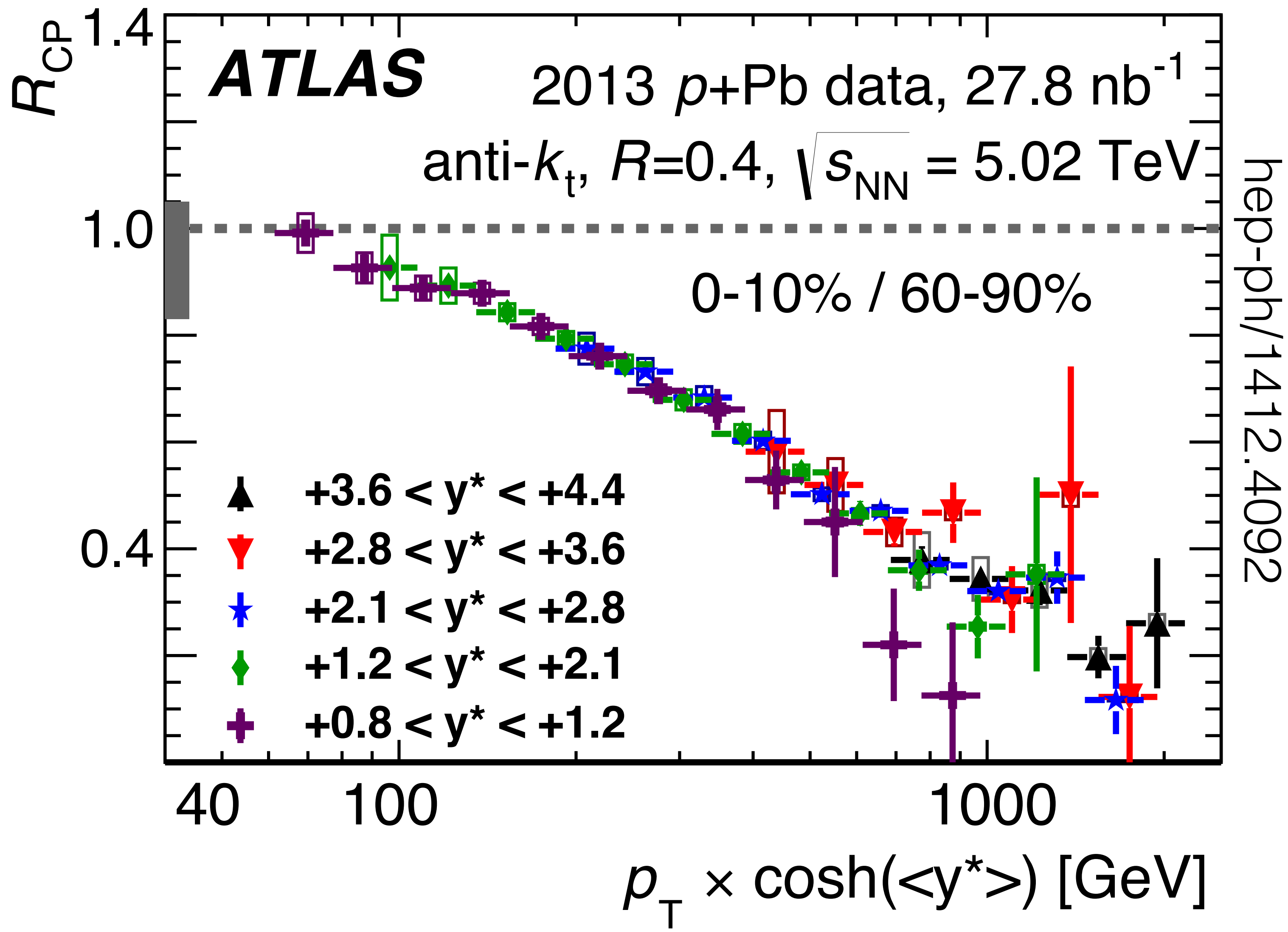



- MC-based extrapolation used to transform 2.76 TeV data to 5.02 TeV

$$R_{D(z)} = D(z;\,5\text{ TeV})_{p+Pb} \,/\, D(z;\,2.76\text{ TeV})_{pp} \times \underline{[D(z;\,2.76\text{ TeV})_{PYTHIA} \,/\, D(z;\,5\text{ TeV})_{PYTHIA}]}$$

- This initial study does not exclude a possible z-dependent excess
  - ➡ 5 TeV *pp* reference data in Run 2 crucial to have the full story

# Understanding centrality-dependence of jet production in *p*+Pb




- Suppressed $R_{CP}$ (**centrality** characterized with $\Sigma E_T$ at Pb-going pseudorapidity) and forward (*p*-going) **jet production**

➡ single trend as a function of $p_T \times \cosh(y^*) \approx x_p / (\sqrt{s} / 2)$

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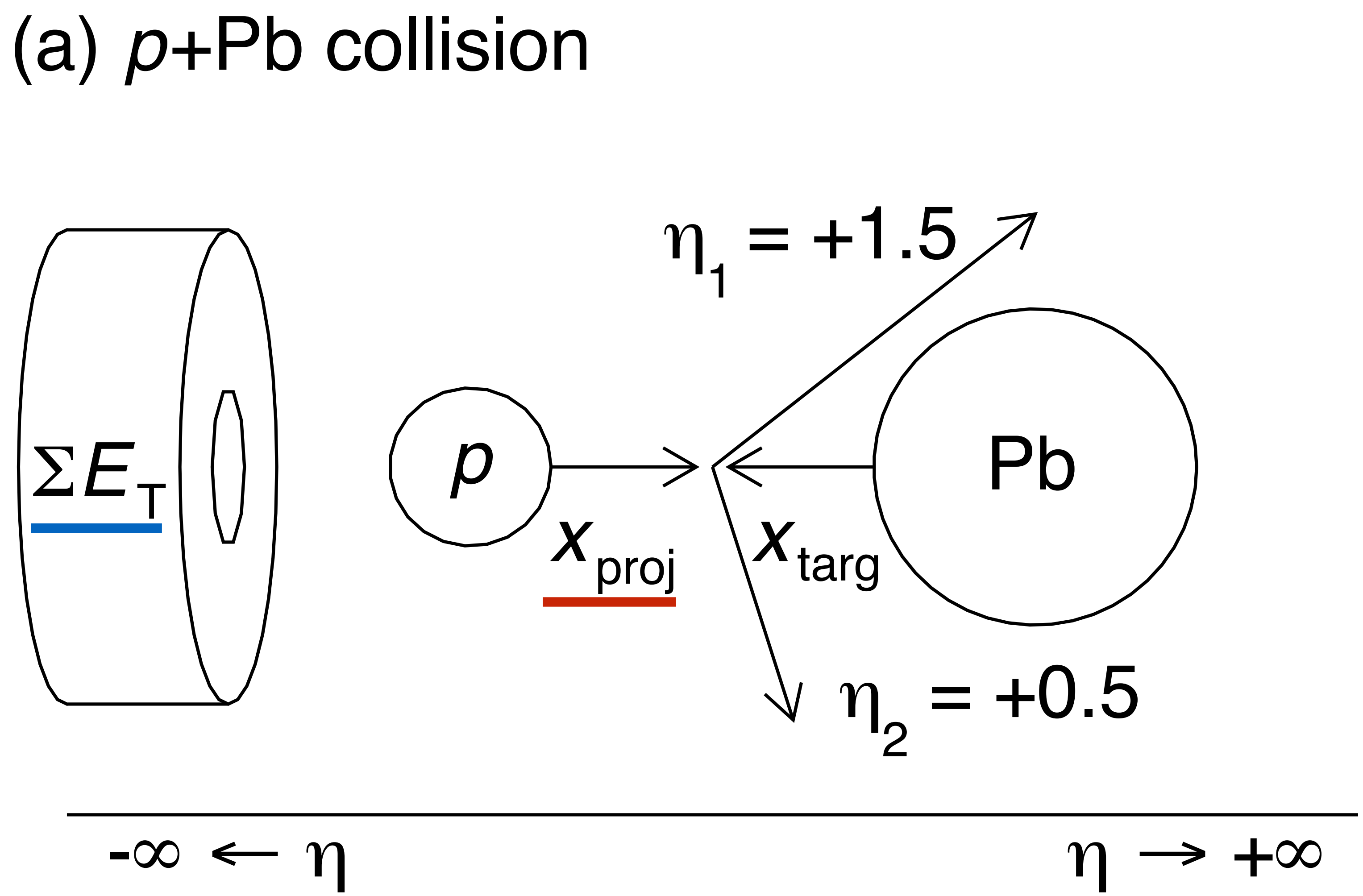


- Experimental signature in $p$+Pb: decreasing $\Sigma E_{\mathrm{T}}$ with increasing proton $x$
  - ➡ does this just arise from a feature of $pp$ collisions?

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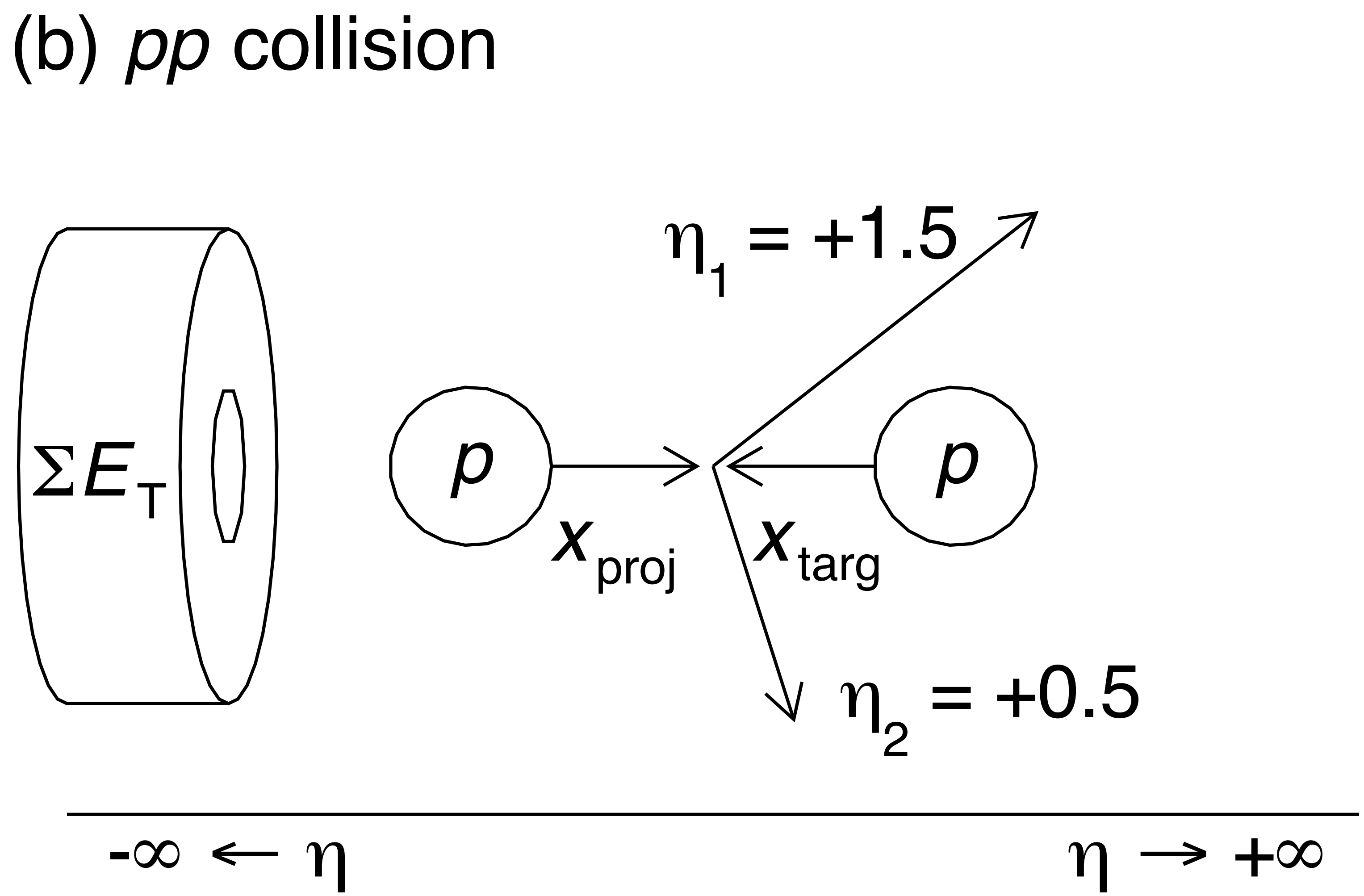


- Measure $\Sigma E_T$ at large pseudorapidity as a function of:
  - ➡ $x_{proj}$ (e.g. in the proton moving *away* from $\Sigma E_T$ region)
  - ➡ $x_{targ}$ (e.g. in the proton moving *towards* $\Sigma E_T$ region)
- Reconstruct event-by-event e.g. $x_{proj} = p_T\,(\exp(+\eta_1) + \exp(+\eta_2)) / \sqrt{s}$

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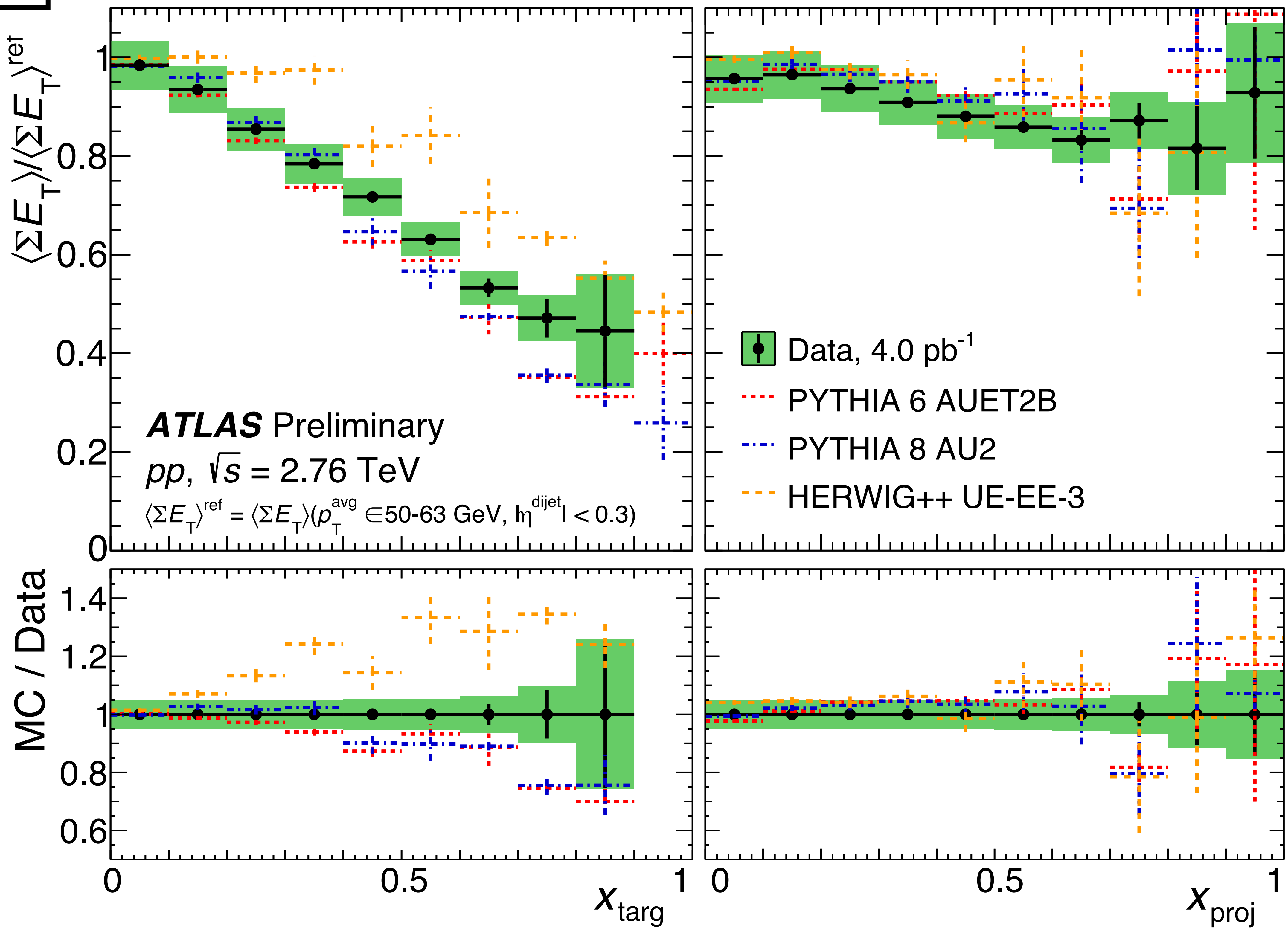


- In *pp* collisions, <Σ$E_T$> falls with $x_{targ}$, mostly insensitive to $x_{proj}$
  - ➡ so the ***p*+Pb effect** does not obviously reflect something in ***pp***

NEW

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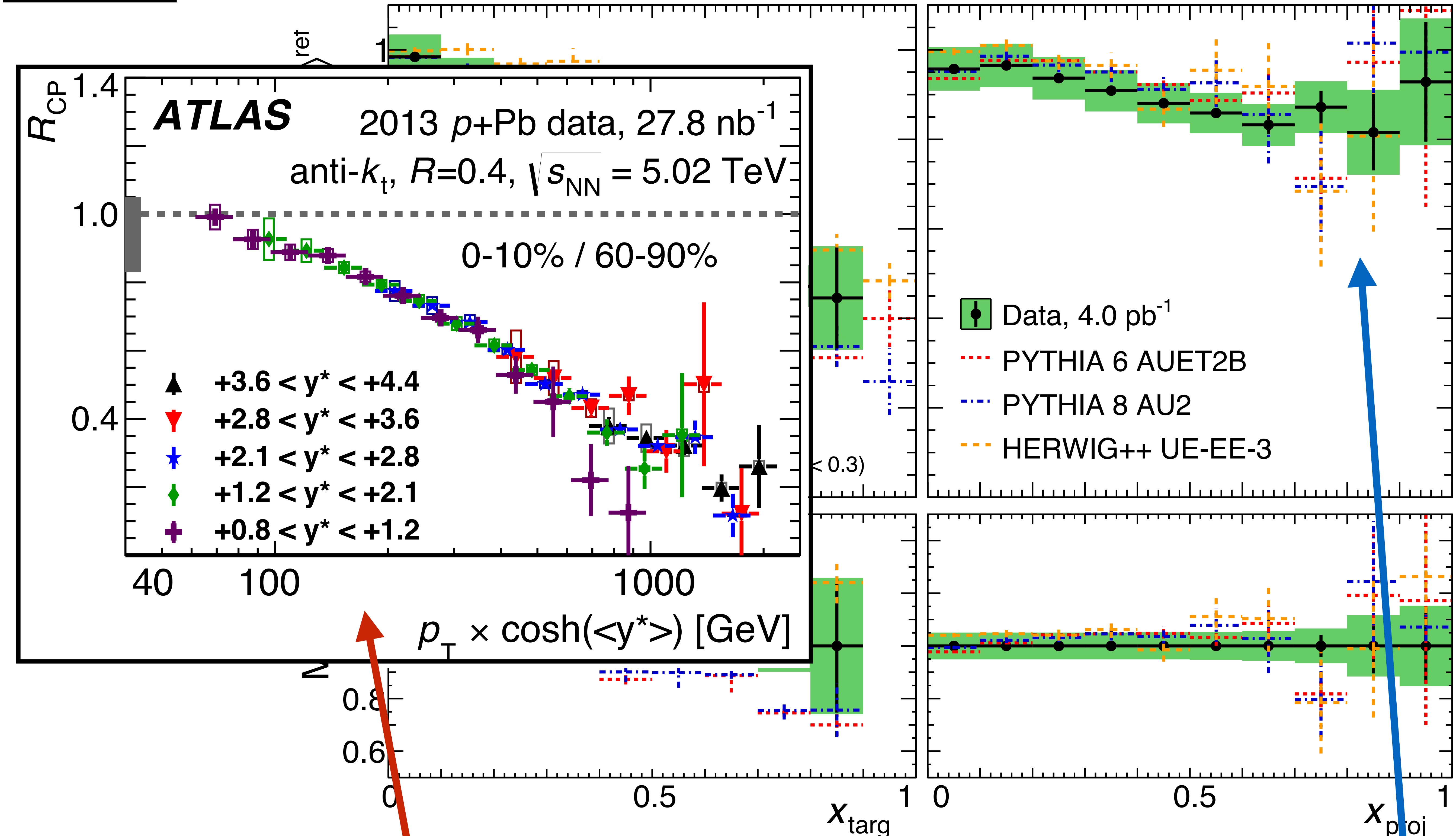


- In *pp* collisions, <$\Sigma E_T$> falls with $x_{\text{targ}}$, mostly insensitive to $x_{\text{proj}}$
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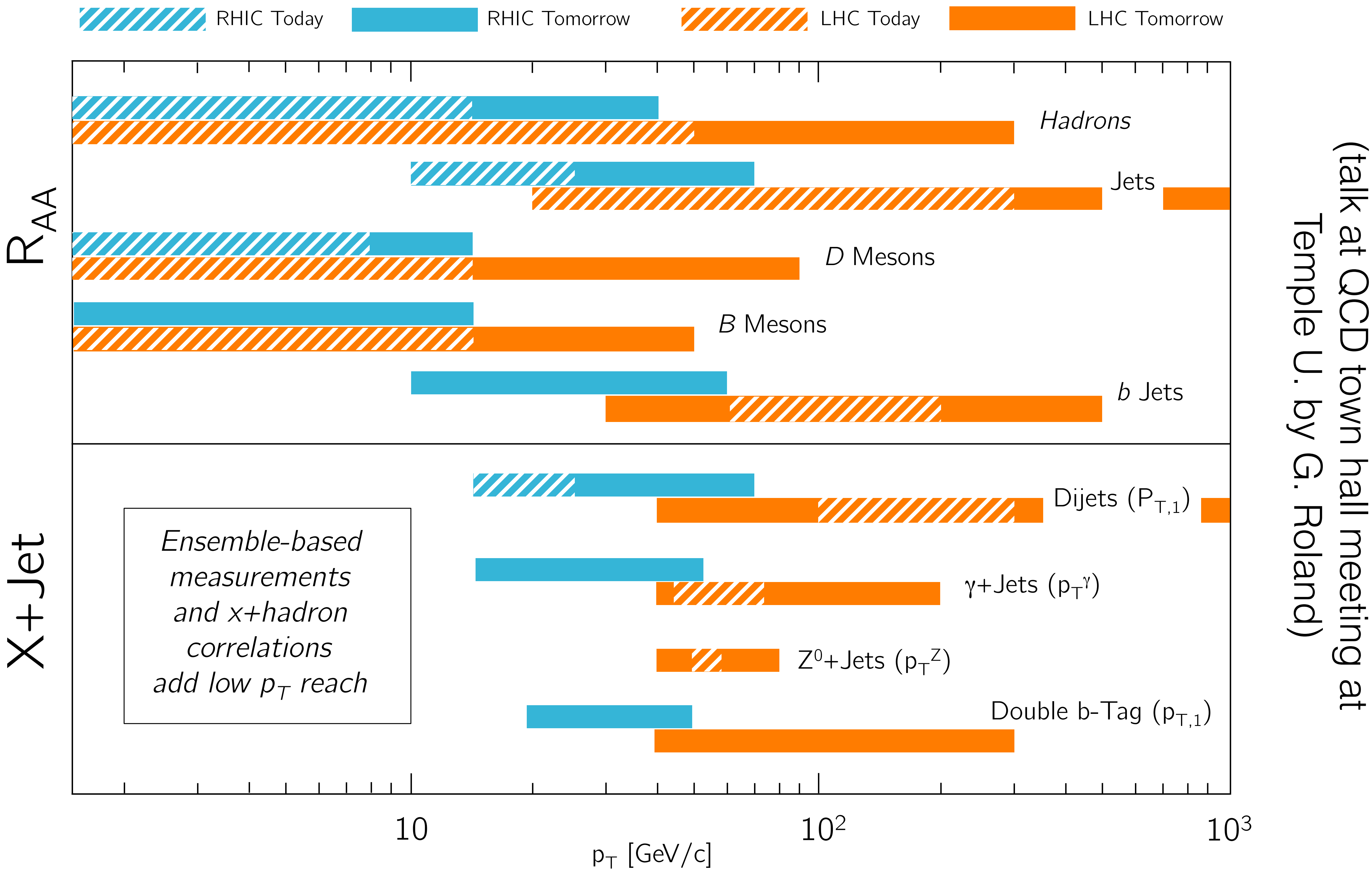
# Jet measurements in LHC Run 2




- 5 TeV Pb+Pb collisions, Nov. 2015: 30x the hard probe rate in Run I
- Differential looks at Run I quantities and entirely new Run 2 observables

# Outlook

- Jet probes of heavy ion collisions in ATLAS are providing detailed information about the physics of jet quenching
  - ➡ producing “legacy” Run I results (e.g. inclusive jet suppression)
  - ➡ while still exploring imaginative new measurements (e.g. reaction plane dependent asymmetries)
- Jet probes of small collision systems are revealing unexpected phenomena
- Imminent Run II data (Pb+Pb and *pp*) will substantially increase our knowledge of both systems

⇒ *https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults* ⇐