A closer look at quark-gluon plasma: Recent results on hard processes in heavy-ion collisions with ATLAS

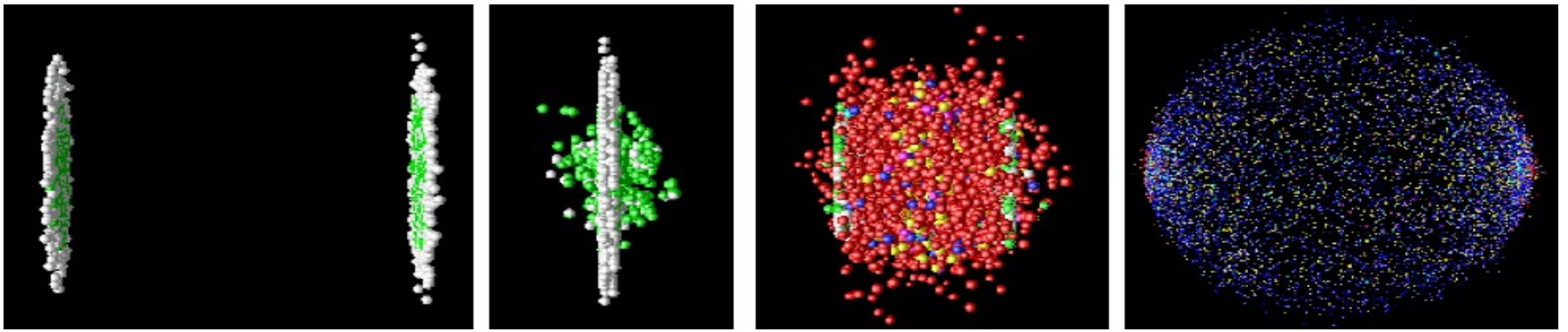
Martin Rybar
for the ATLAS collaboration

CERN-LHC seminar

November 6, 2018

QCD matter at high temperatures

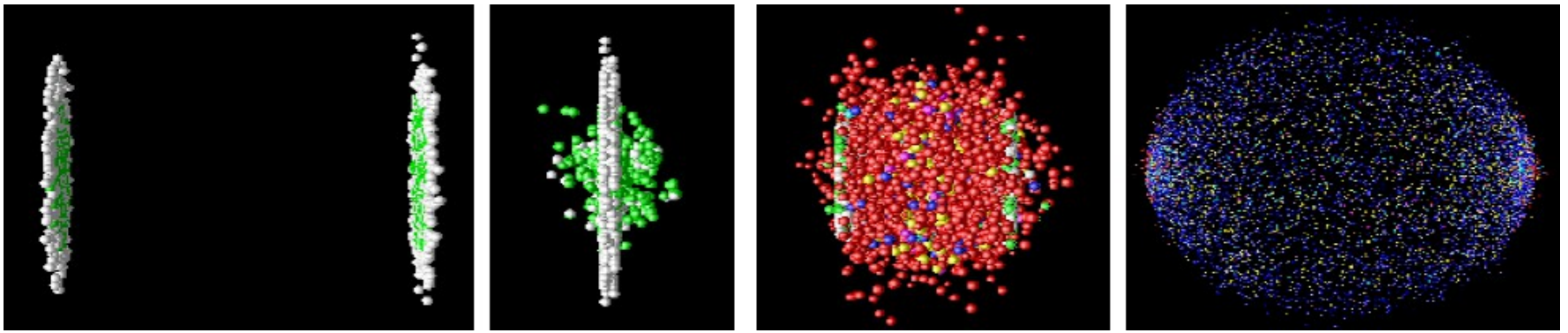
- What are the properties of medium created in heavy ion collisions?
- HI collisions produce deconfined medium: Quark Gluon Plasma
- We want to:
  - Study parton dynamics underlying QGP properties.
  - Characterize macroscopic long-wavelength QGP properties.
  - Understand particle production mechanism both in small and larger systems.
- How can we achieve that?



QCD matter at high temperatures

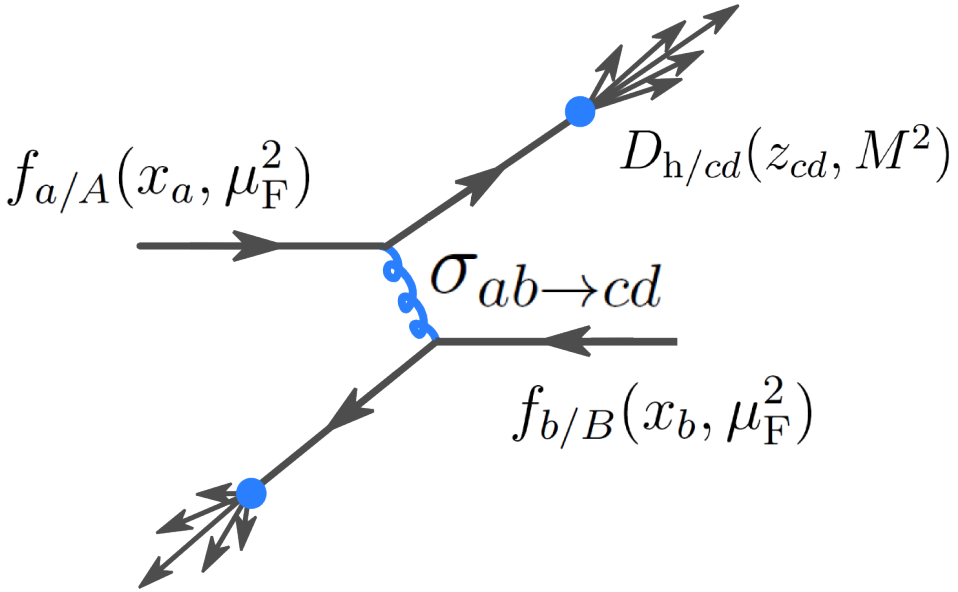
- What are the properties of medium created in heavy ion collisions?
- HI collisions produce deconfined medium: Quark Gluon Plasma
- We want to:
  - Study parton dynamics underlying QGP properties.
  - Characterize macroscopic long-wavelength QGP properties.
  - Understand particle production mechanism both in small and larger systems.
- How can we achieve that?

  by using (hard) probes of different scales...



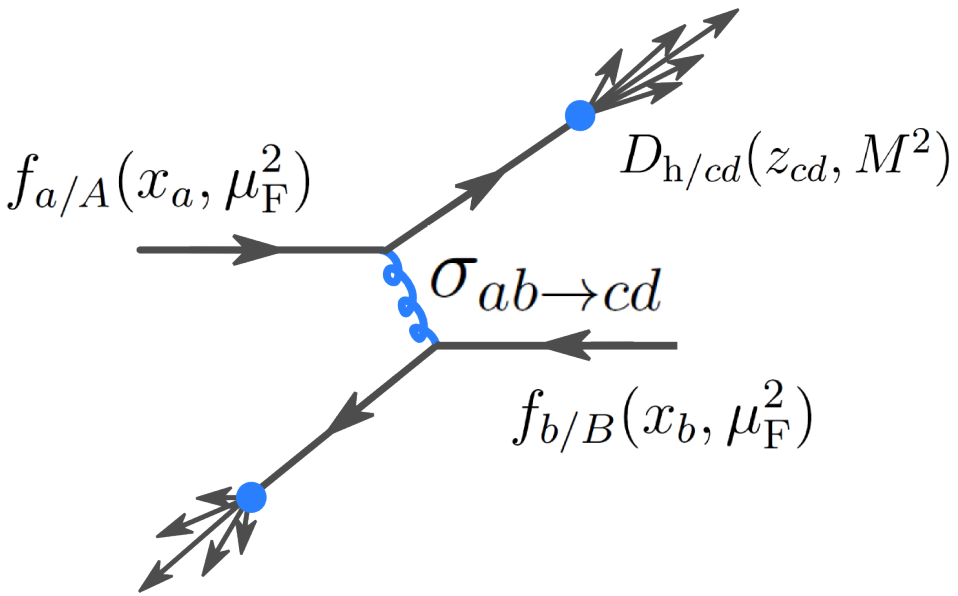
Hard probes

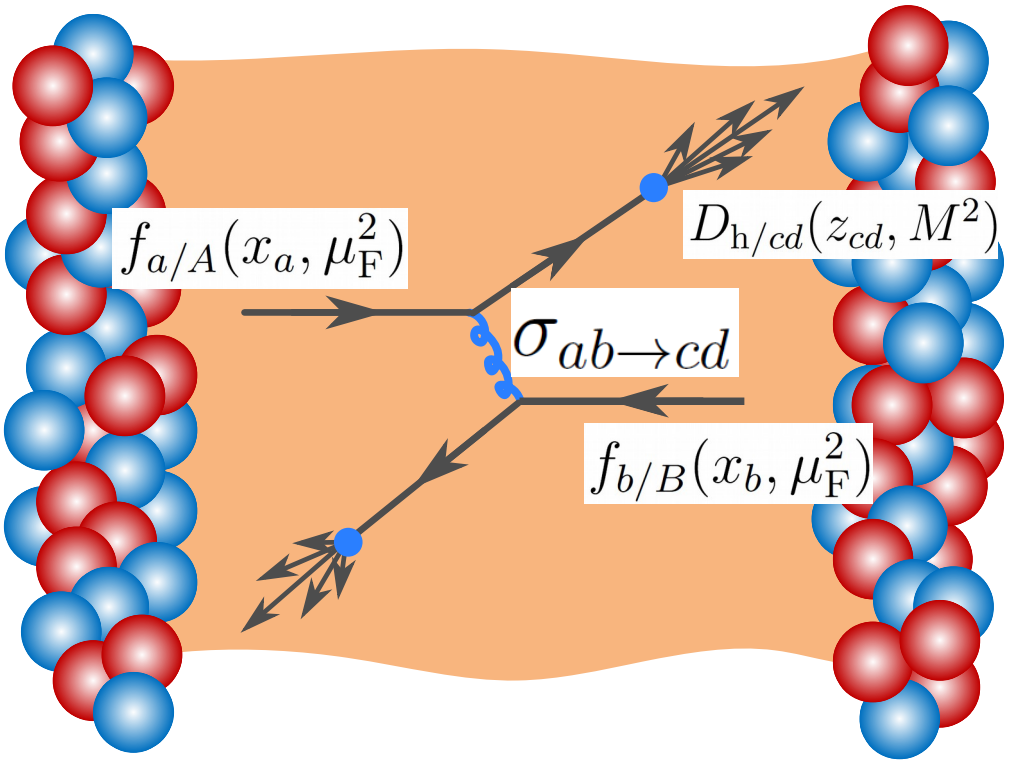
- Description is complex even in *pp* collisions.
- But we can factorize it...



Hard probes in quark-gluon plasma

- Description is complex even in *pp* collisions.
- But we can factorize it...

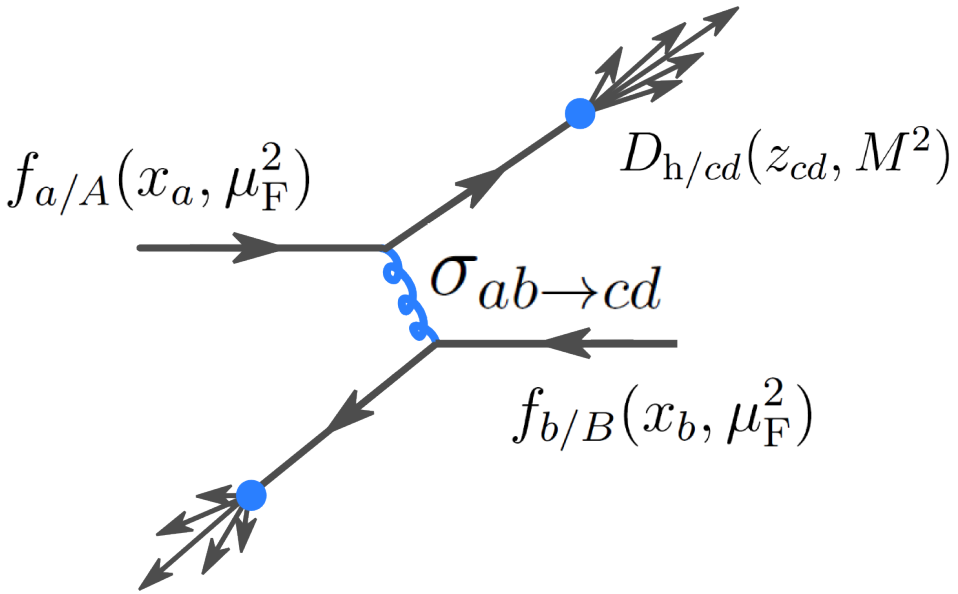


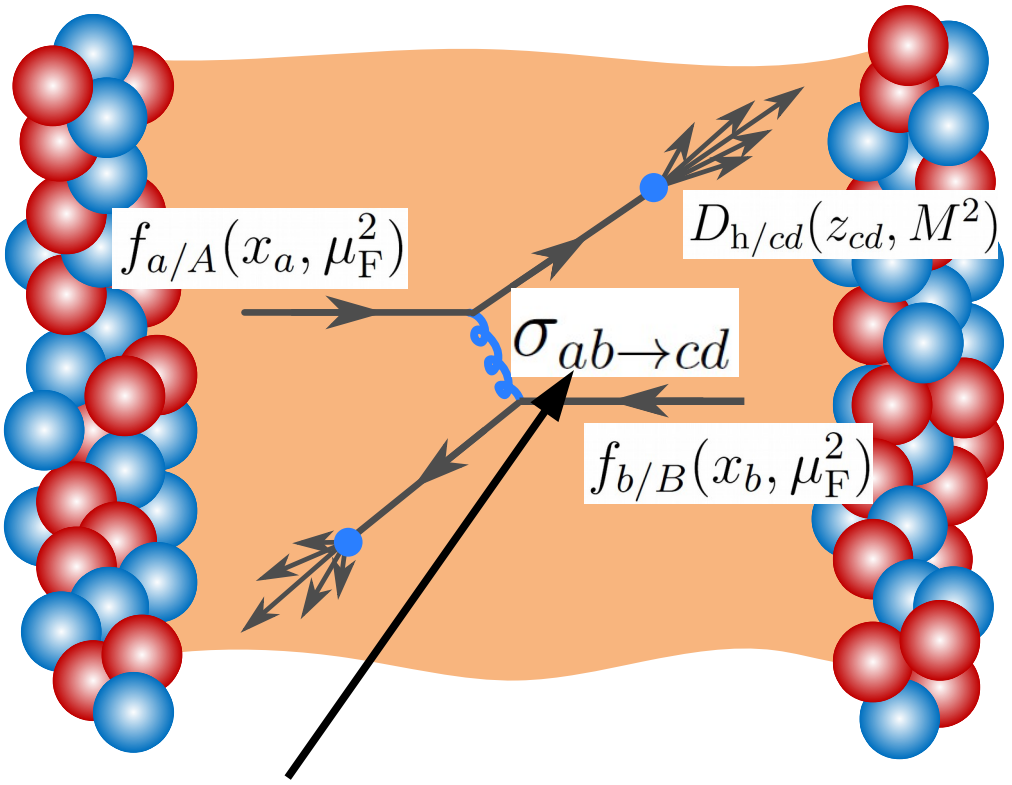


- In Heavy Ion (HI) collision?

Hard probes in quark-gluon plasma

- Description is complex even in *pp* collisions.
- But we can factorize it...



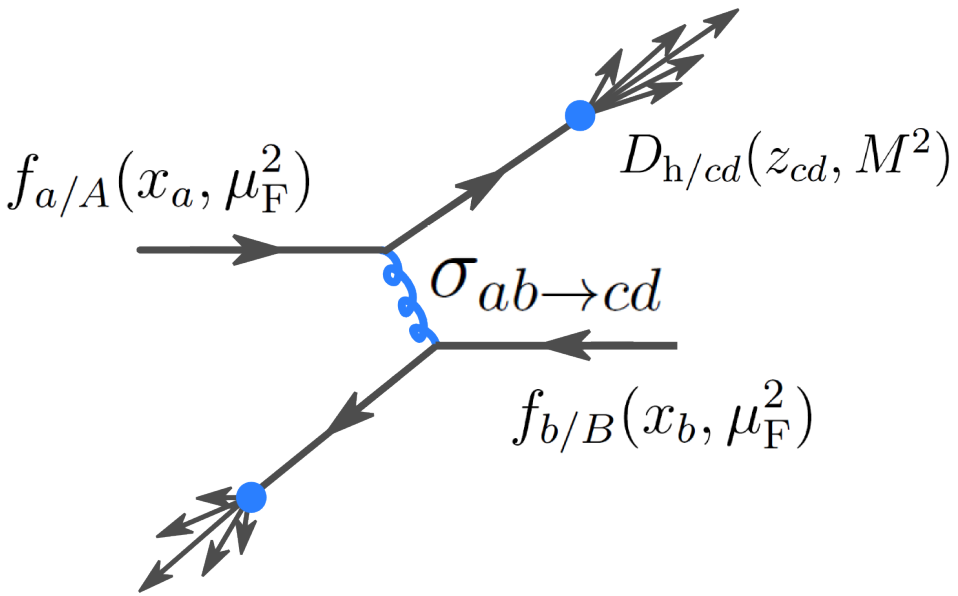


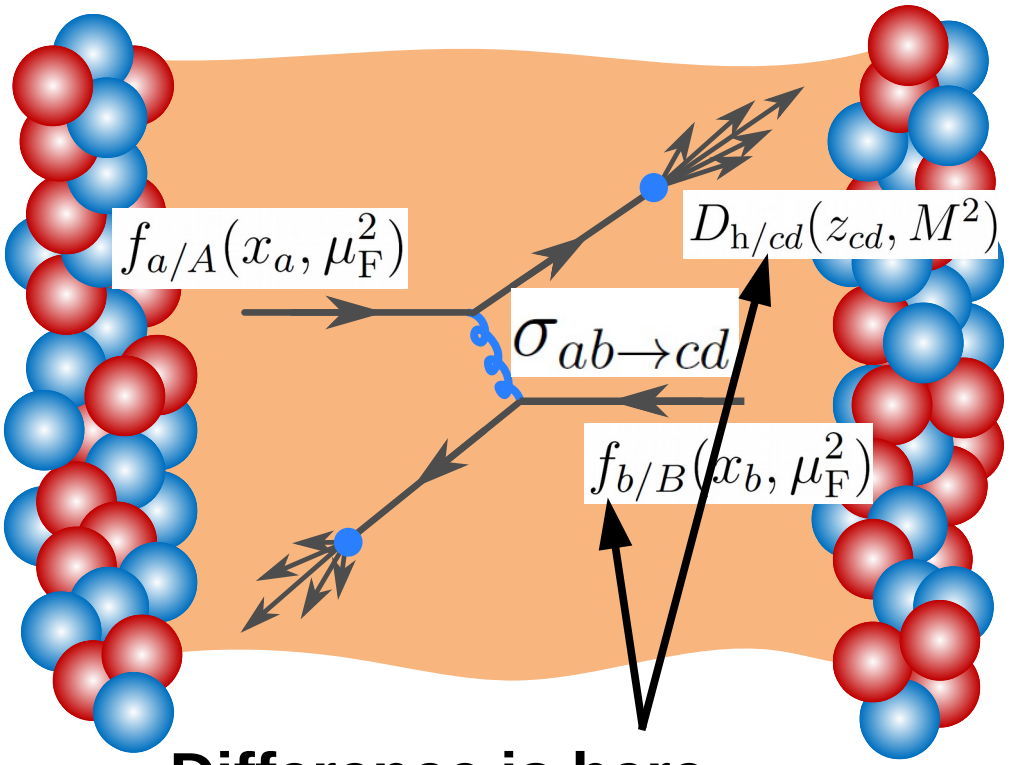
- In Heavy Ion (HI) collision:
  - Hard probes (HP) are produced early in the collision.
  - Initial cross-section unchanged by presence of medium.

➡ pQCD calculable.

Hard probes in quark-gluon plasma

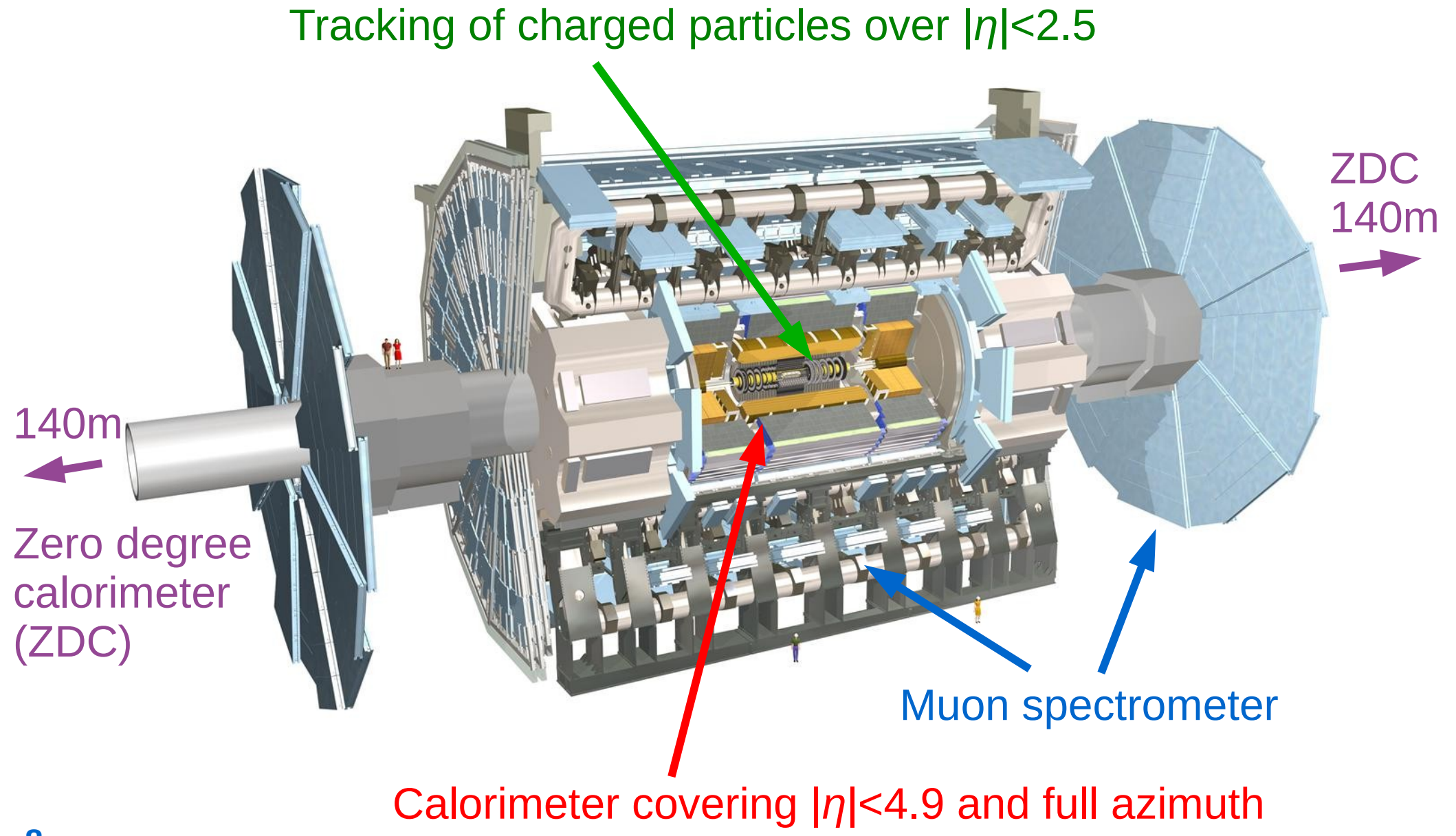
- Description is complex even in *pp* collisions.
- But we can factorize it...



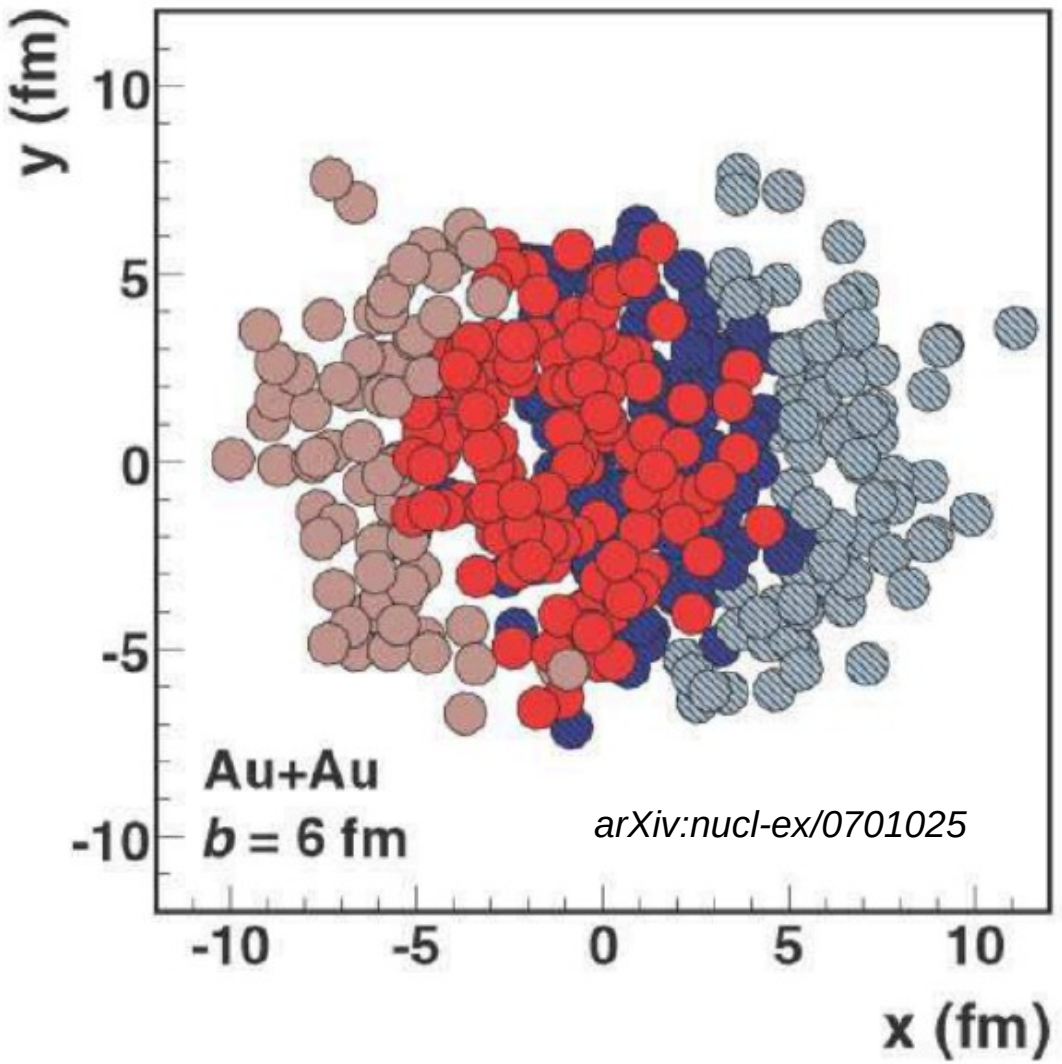


- In Heavy Ion (HI) collision: **Difference is here...**
  - How much modification is from different initial state like nPDFs?
  - Parton shower is affected by the medium.

ATLAS detector



Centrality

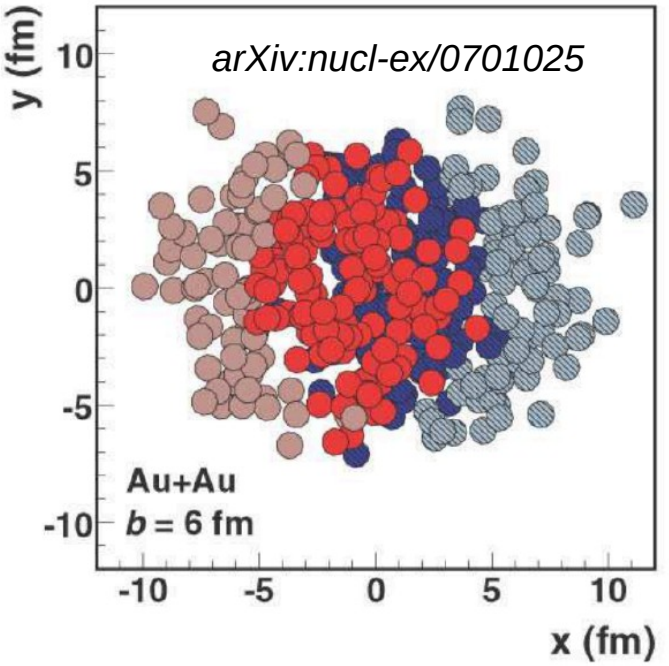


Centrality

- Yields of hard processes in HI collisions are expected to scale with number of binary nucleon-nucleon collisions, N_{coll}.
- The N_{coll} depends on centrality of collision.

Peripheral collisions **Central collisions**

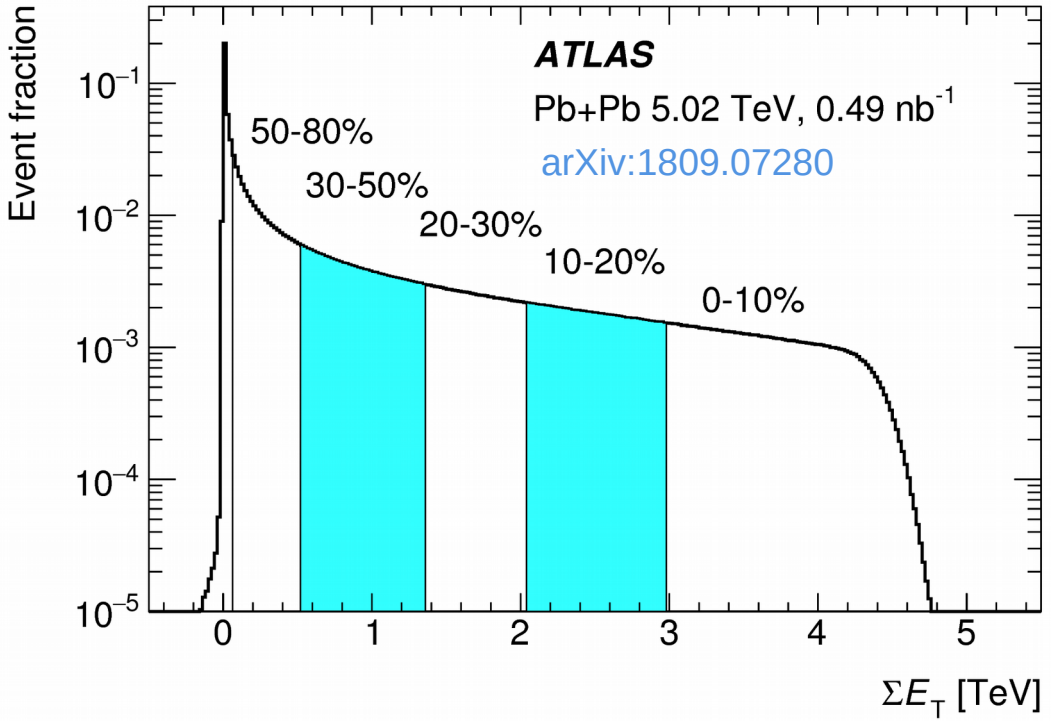
Small overlap	Large overlap
Low number of N_{coll}	High number of N_{coll}
Low number of participating nucleons, N_{part}	High number of participating nucleons, N_{part}



Centrality

- Yields of hard processes in HI collisions are expected to scale with number of binary nucleon-nucleon collisions, N_{coll}.
- The N_{coll} depends on centrality of collision.

Peripheral collisions **Central collisions**



Characterized by transverse energy in forward calorimeters.

Correlated with number of participants/collisions.

HI data sets

Run 1 (2010-2013)

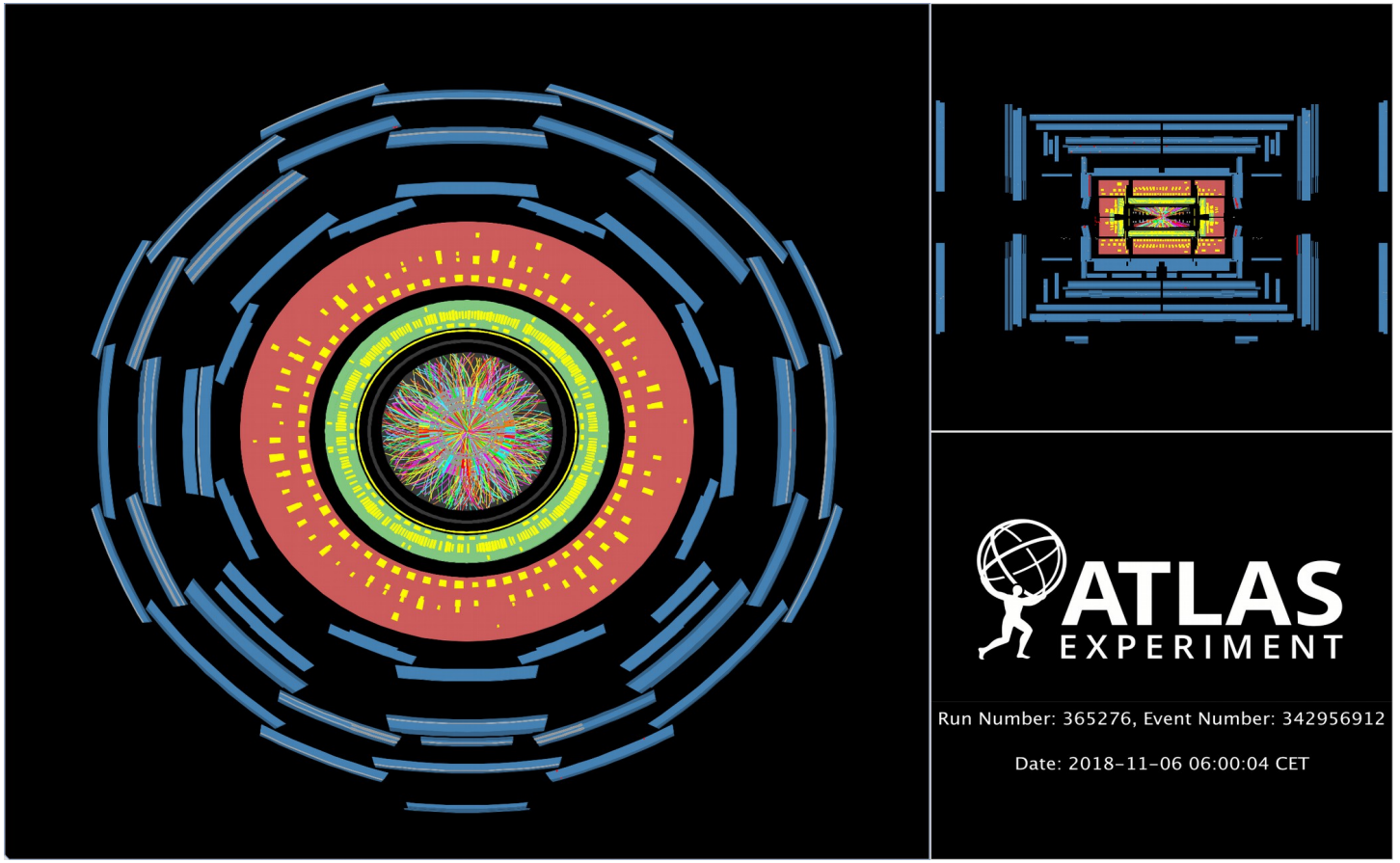
- *p*+Pb (5.02 TeV) and Pb+Pb (2.76 TeV) systems
- + *pp* reference (2.76 TeV)

Run 2 (2015-present)

- center-of-mass energy almost doubled:
  - Pb+Pb@5.02 TeV and p+Pb@8.16
  - + *pp* reference (5.02 TeV)
- factor of 3.5 more integrated luminosity of Pb+Pb and 5.5 for *p*+Pb.
- Test run with lighter Xe ions recorded.
  - 8h of data-taking → ~40% of the 2010 Pb+Pb run.

- 2018 Pb+Pb data taking is about to start!

HI data sets



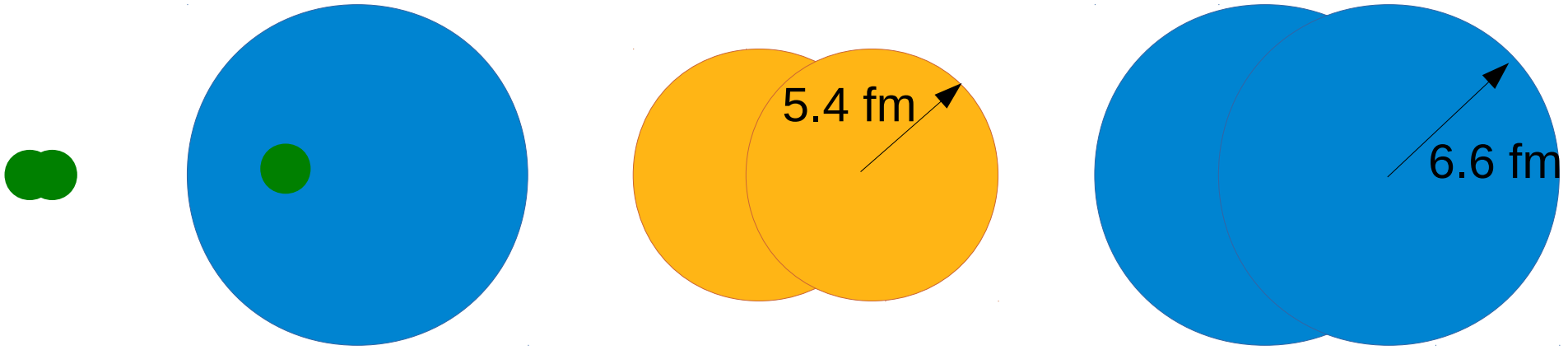
- 2018 Pb+Pb data taking is about to start!
  - Same collision energy as in 2015.
  - ***Up-to factor of ~4 increase in the integrated luminosity compared to 2015.***

Comparing collision systems

- Different collision systems provided by LHC.

➡ *pp*, *p*+Pb, Xe+Xe, Pb+Pb …at different energies.

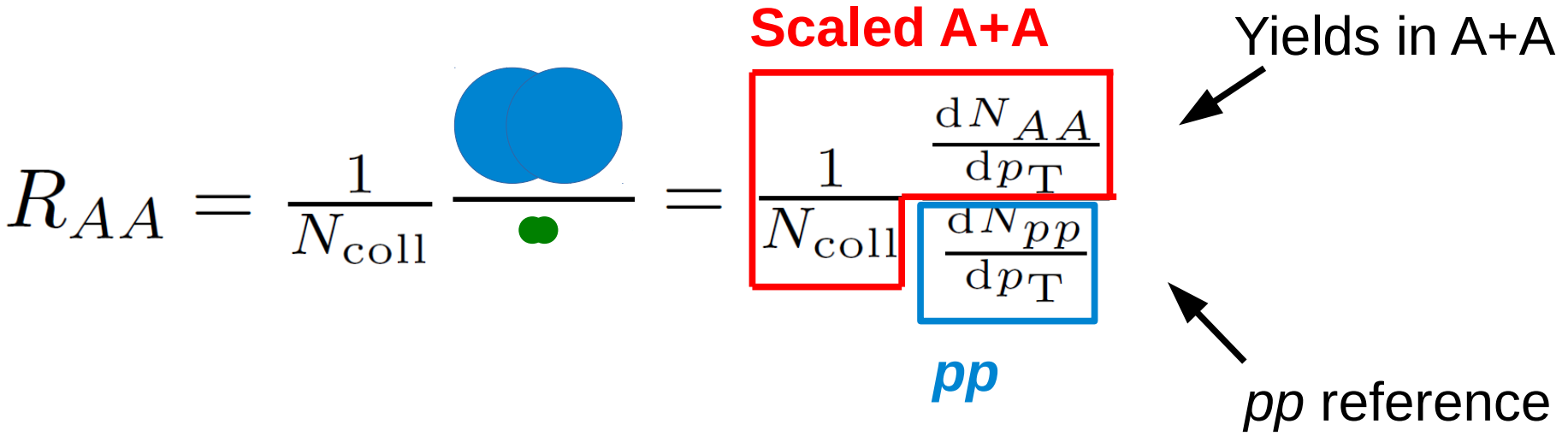
- Higher collision energy → higher temperature
  → larger cross-section
  → harder shape of the spectrum
- Larger nucleus → higher density
  → larger path-lengths at same centrality interval
  → different geometry for the same system size
  → different systematic related to the UE.



pp *p*+Pb Xe+Xe Pb+Pb

Measure of modifications: Nuclear modification factor

- Observable: nuclear modification factor.



- Compares HI and pp collisions and removes the geometrical scaling.

Measure of modifications: Nuclear modification factor

- Obser

R_{AA}

s in A+A

eference

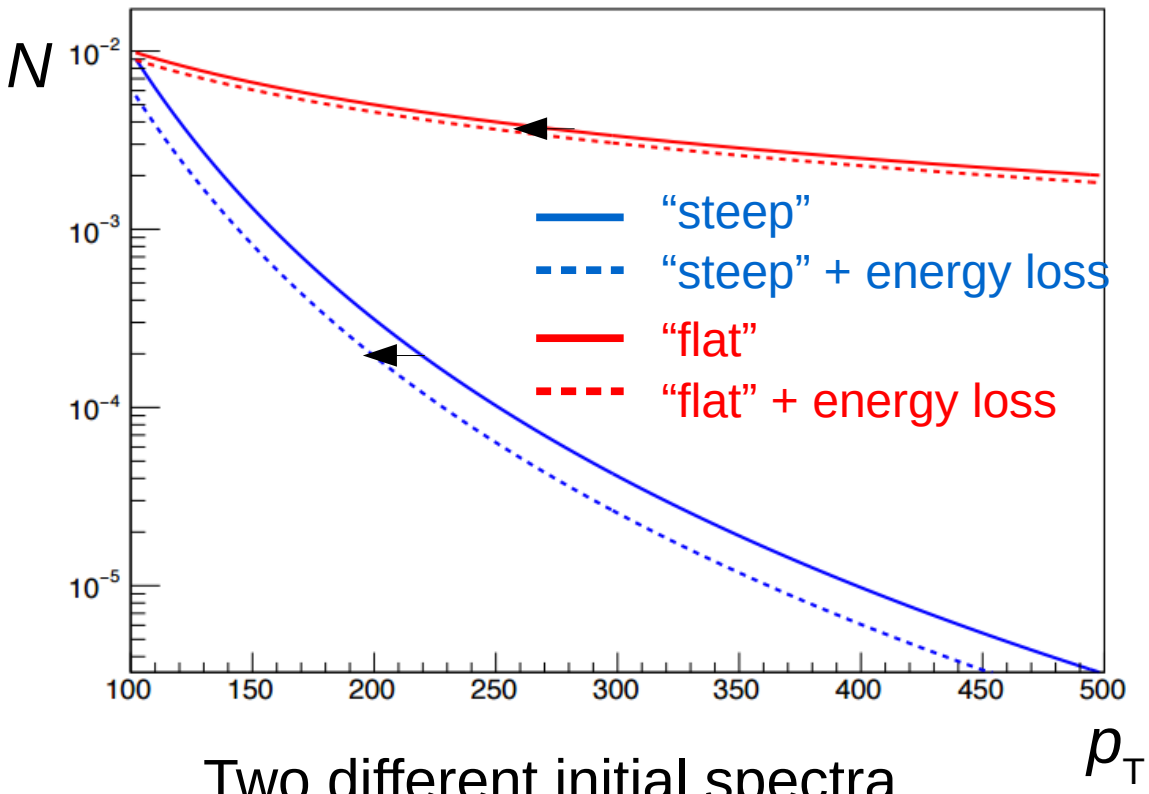
- Comp

trical

scalin

Caveats on R_{AA}:

Sensitive to shapes of p_T spectra



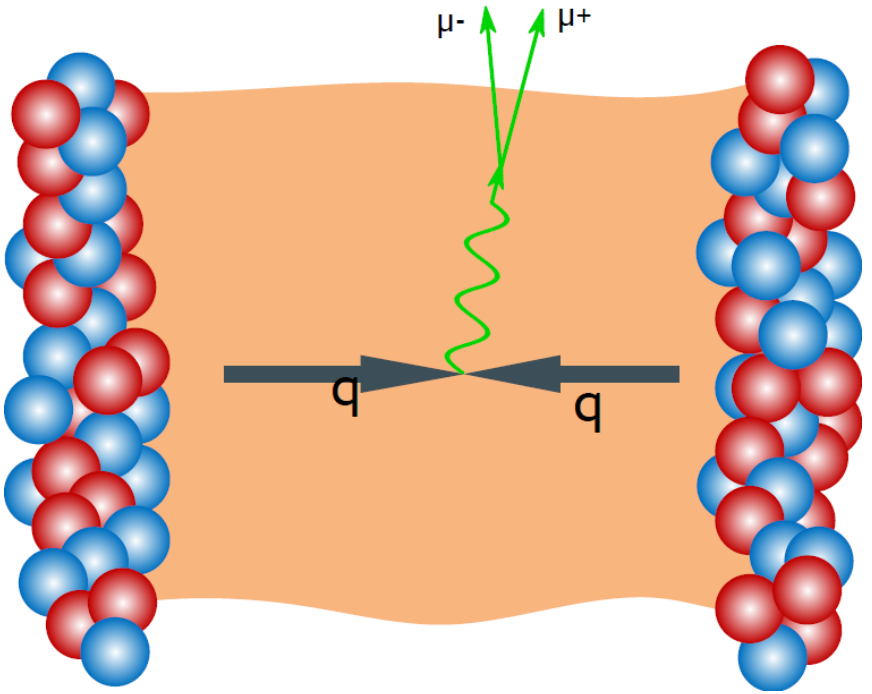
Two different initial spectra

10% fractional energy loss

different R_{AA} for blue and red

Vector bosons

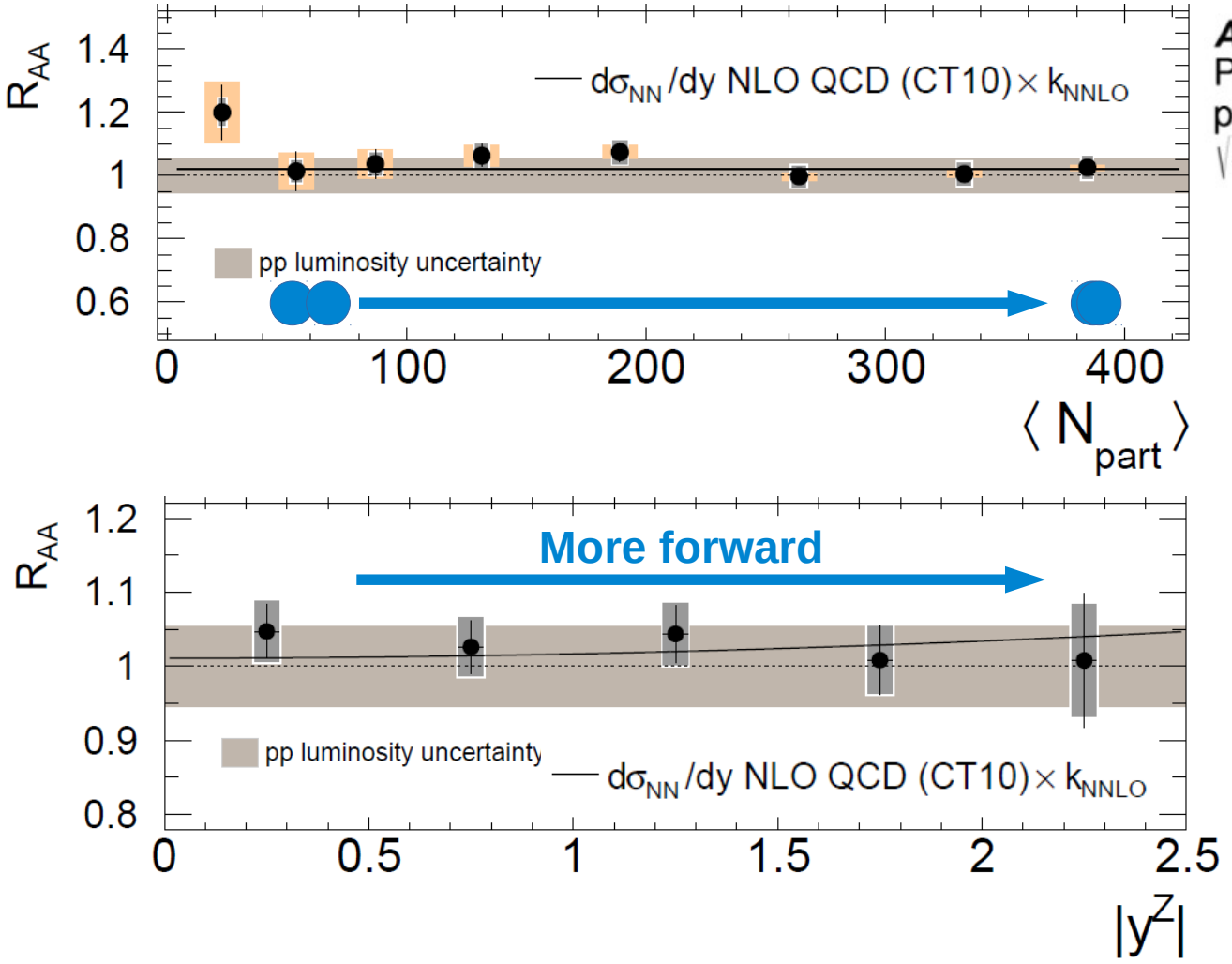
- Different hard probes interact with medium differently.



- Measurements of photons, Z and W bosons.
- Interact differently with the medium.
- No medium effect is expected.
- Sensitive to initial state → nuclear PDFs.

EW boson production

Z bosons:

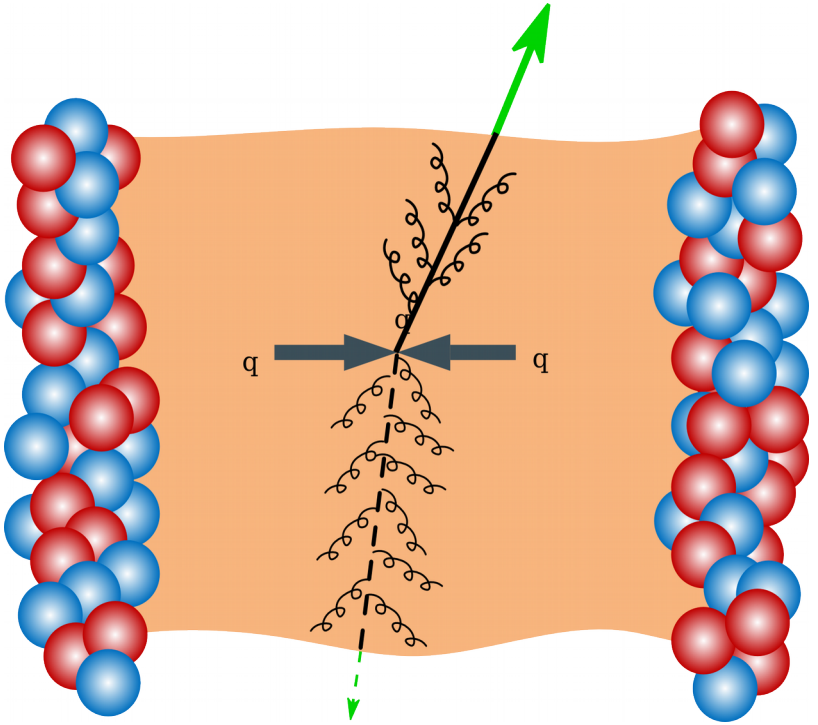


- No deviation from N_{coll} scaling.
- Z bosons starts to compete with the Glauber model accuracy.

ATLAS-CONF-2017-10

Jets

- Different hard probes interact with medium differently.



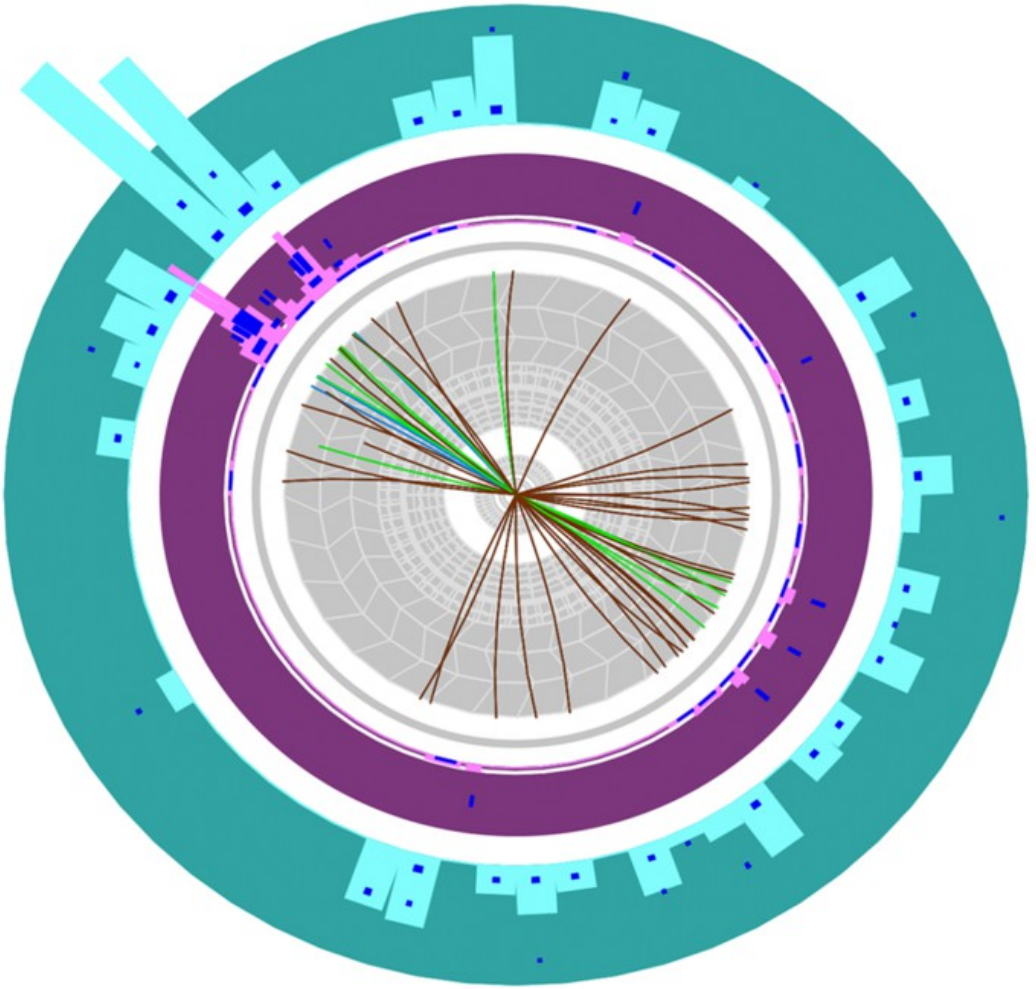
- Interactions of medium and colored probe.
  - elastic scattering, medium induced radiation or “drag force” in strong coupling picture.

➡ fast partons lose energy ➡ jet quenching

- Jets are multi-scale probes of QGP.

Jet quenching measurement

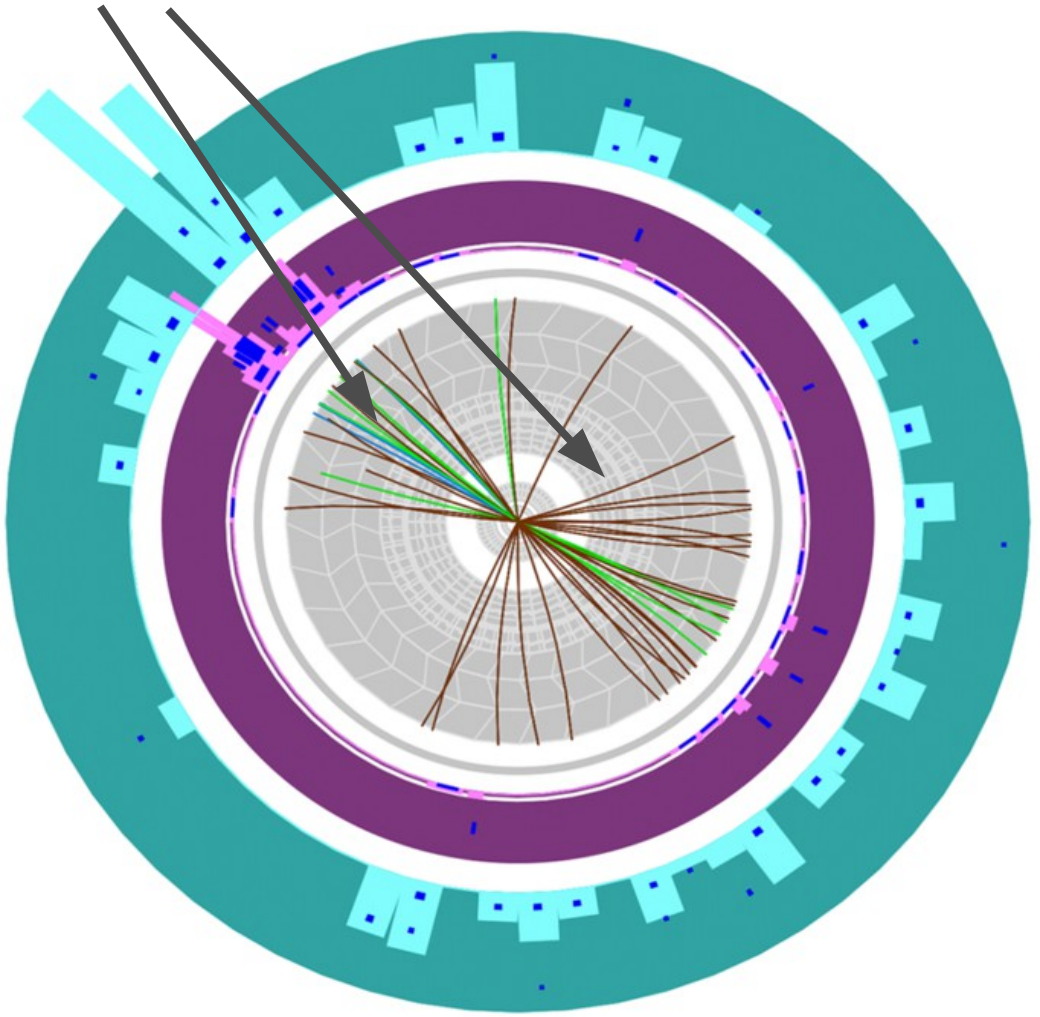
Many different observables….



….each observable is sensitive to different aspects of energy loss.

Jet quenching measurement

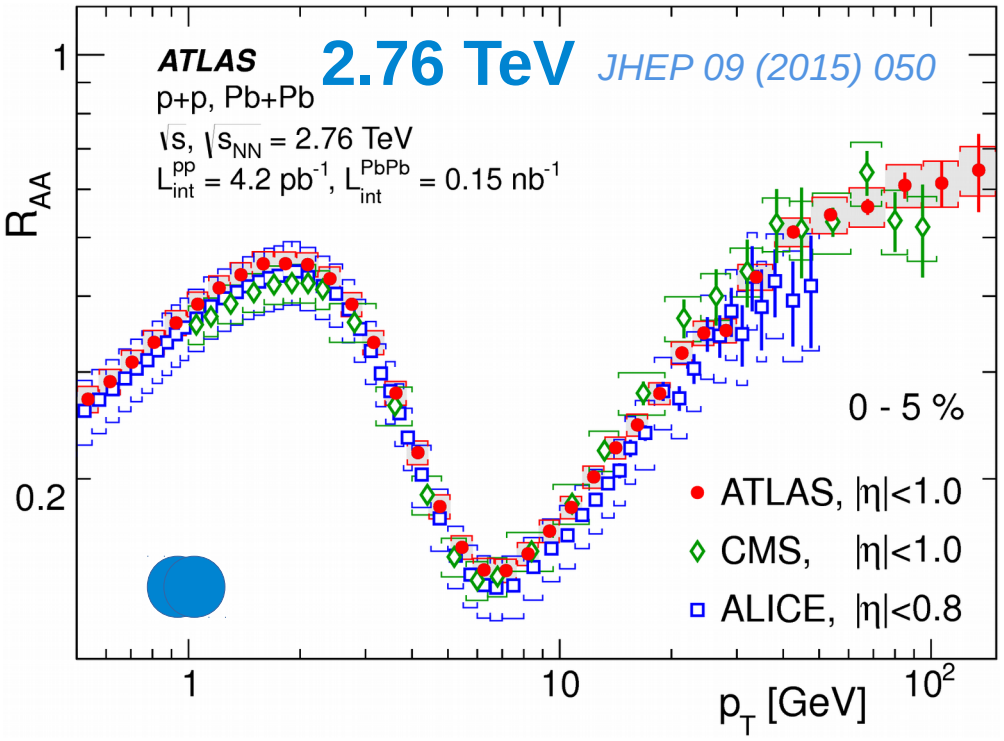
Single charged hadron spectra



The “easiest” way to study jet quenching.

Charged hadrons

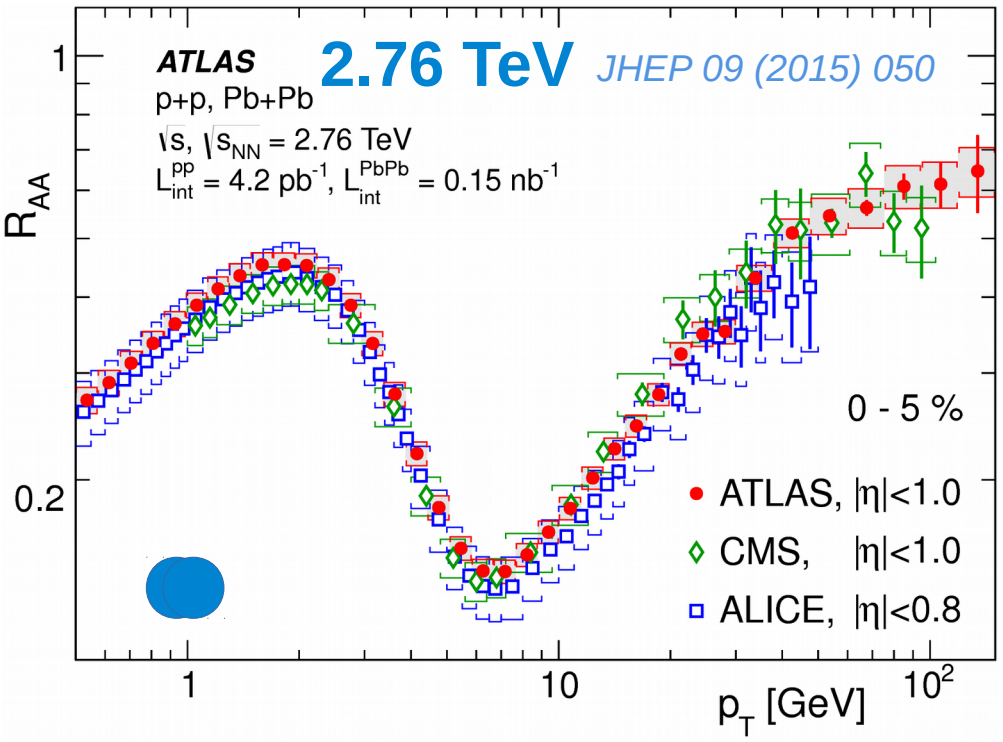
- Does not sample the full parton energy.

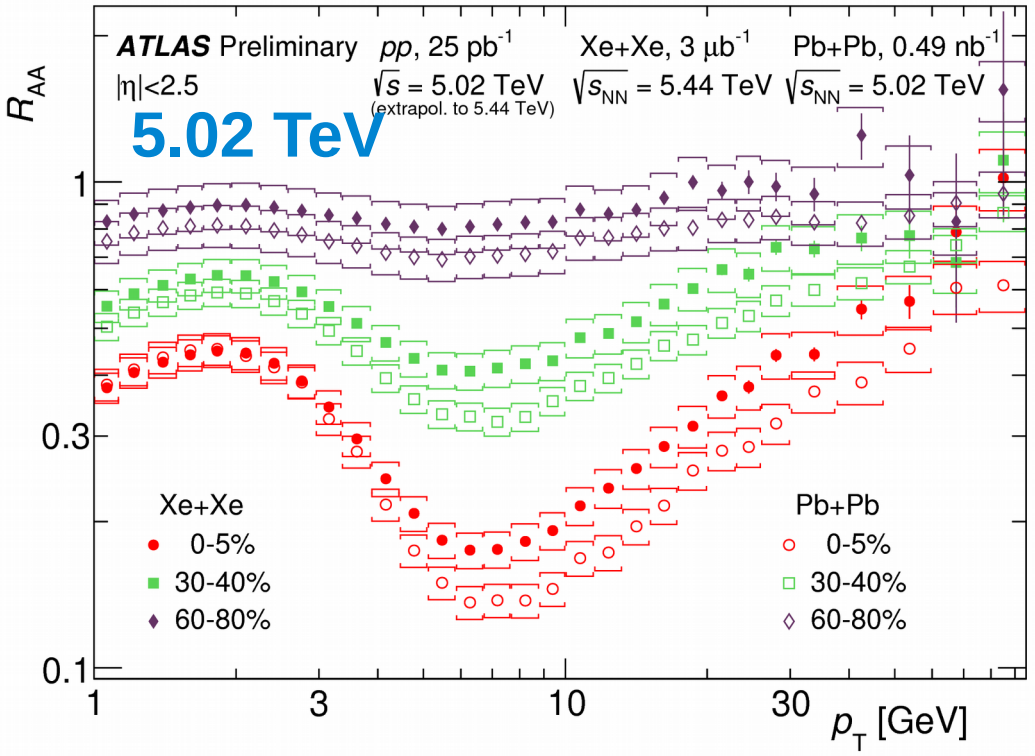


- Very good agreement between experiments.
- Sign of flattening of R_{AA} at very high p_T.

Charged hadrons

- Does not sample the full parton energy.



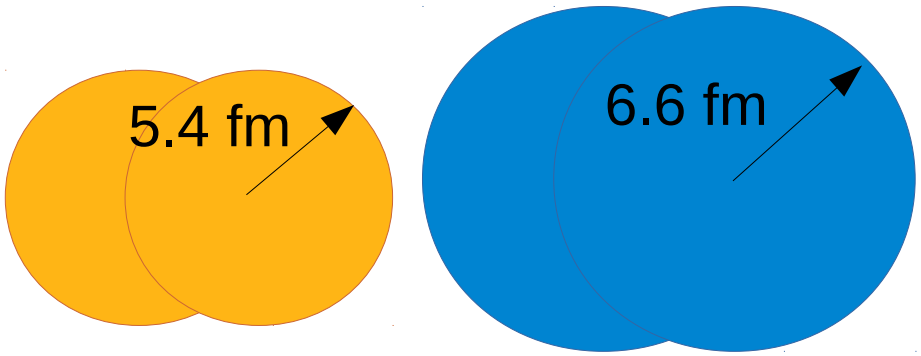


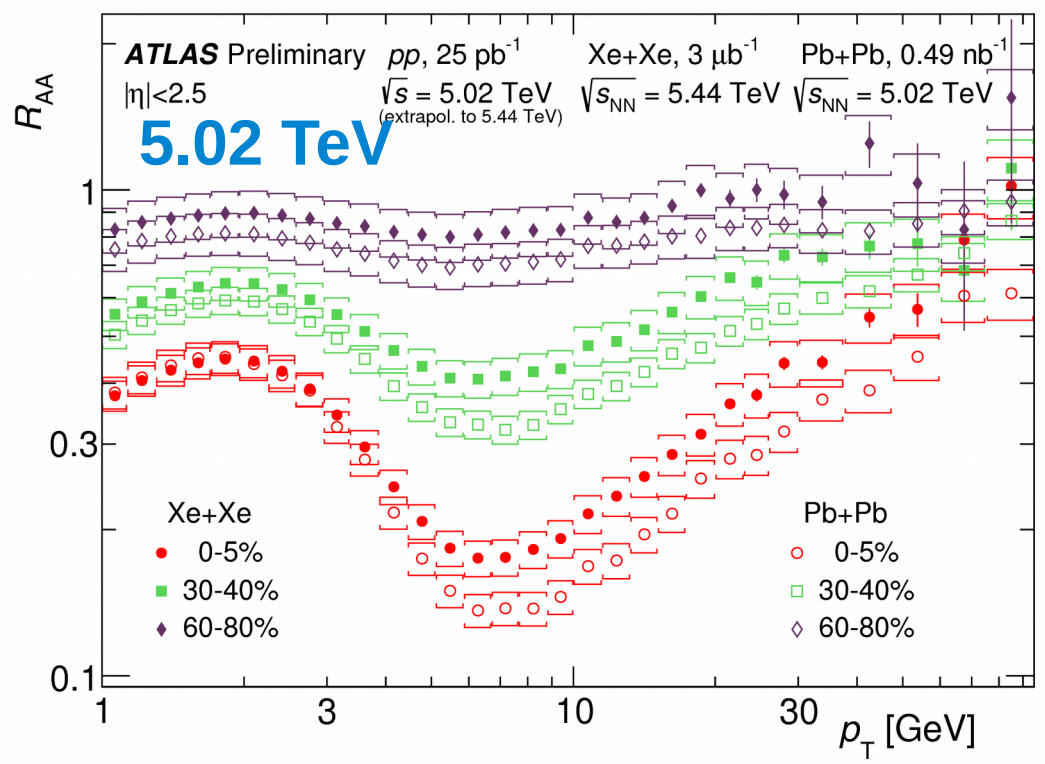
- Pb+Pb: agreement between 2.76 TeV and 5.02 TeV.
- Xe+Xe: less suppressed than Pb+Pb at the same centrality.

ATLAS-CONF-2018-007

Charged hadrons

- Does not sample the full parton energy.



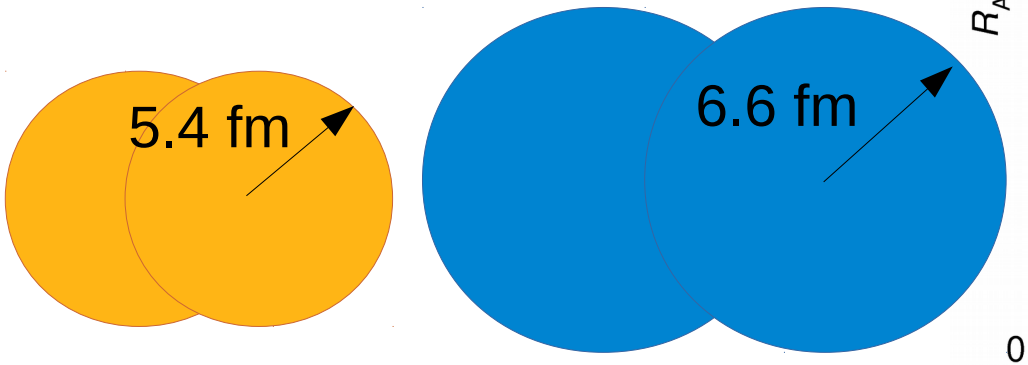


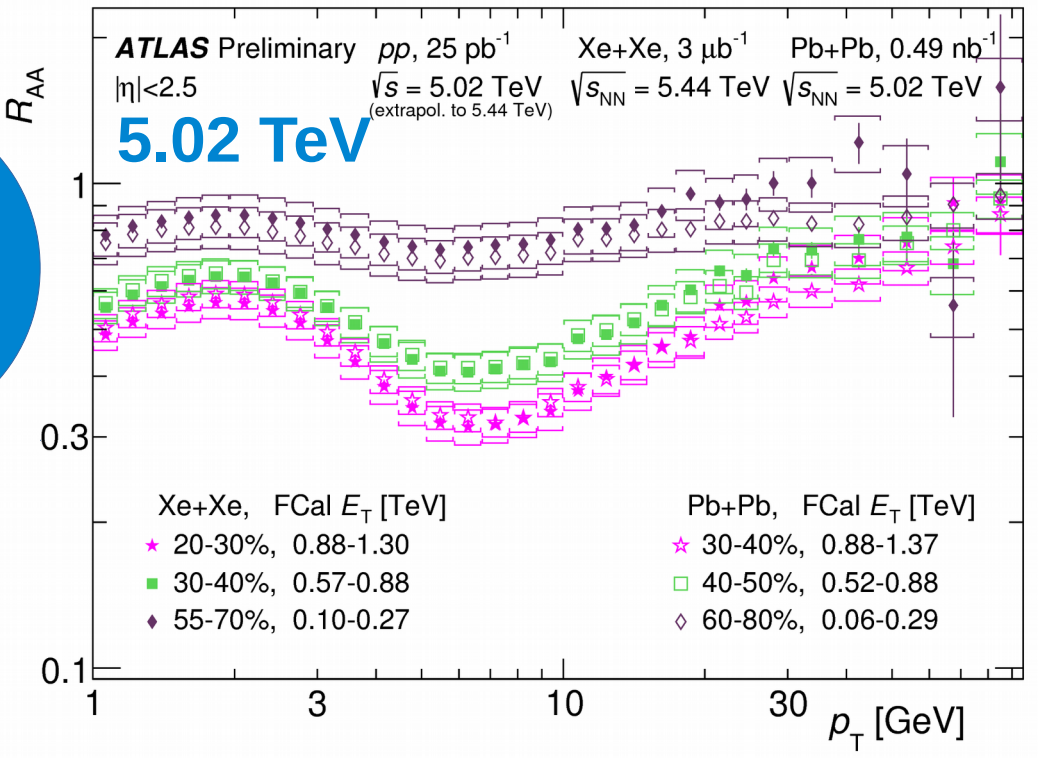
- Qualitative and quantitative agreement between the two energies.
- Xe+Xe less suppressed than Pb+Pb at the same centrality.

ATLAS-CONF-2018-007

Charged hadrons

- Does not sample the full parton energy.

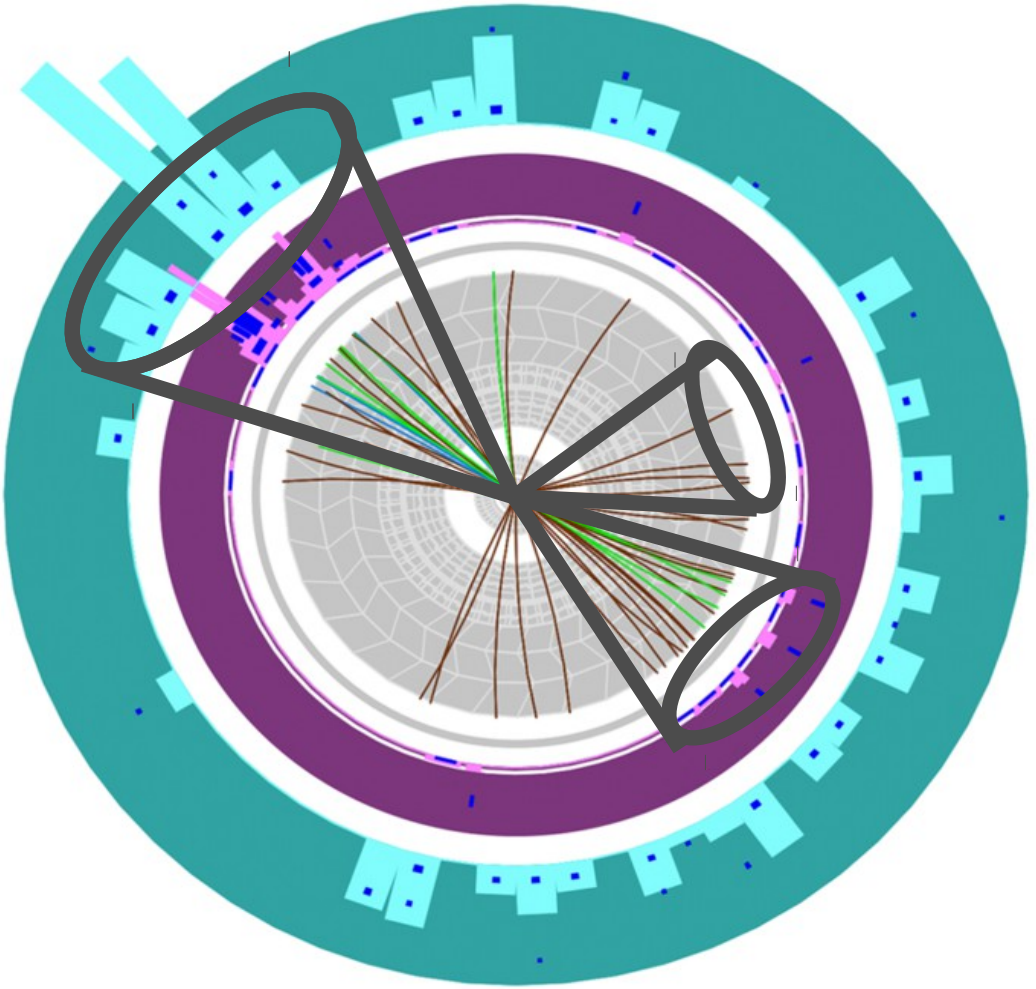




- Xe+Xe and Pb+Pb comparable when the final system has the same size.

ATLAS-CONF-2018-007

Jet measurement

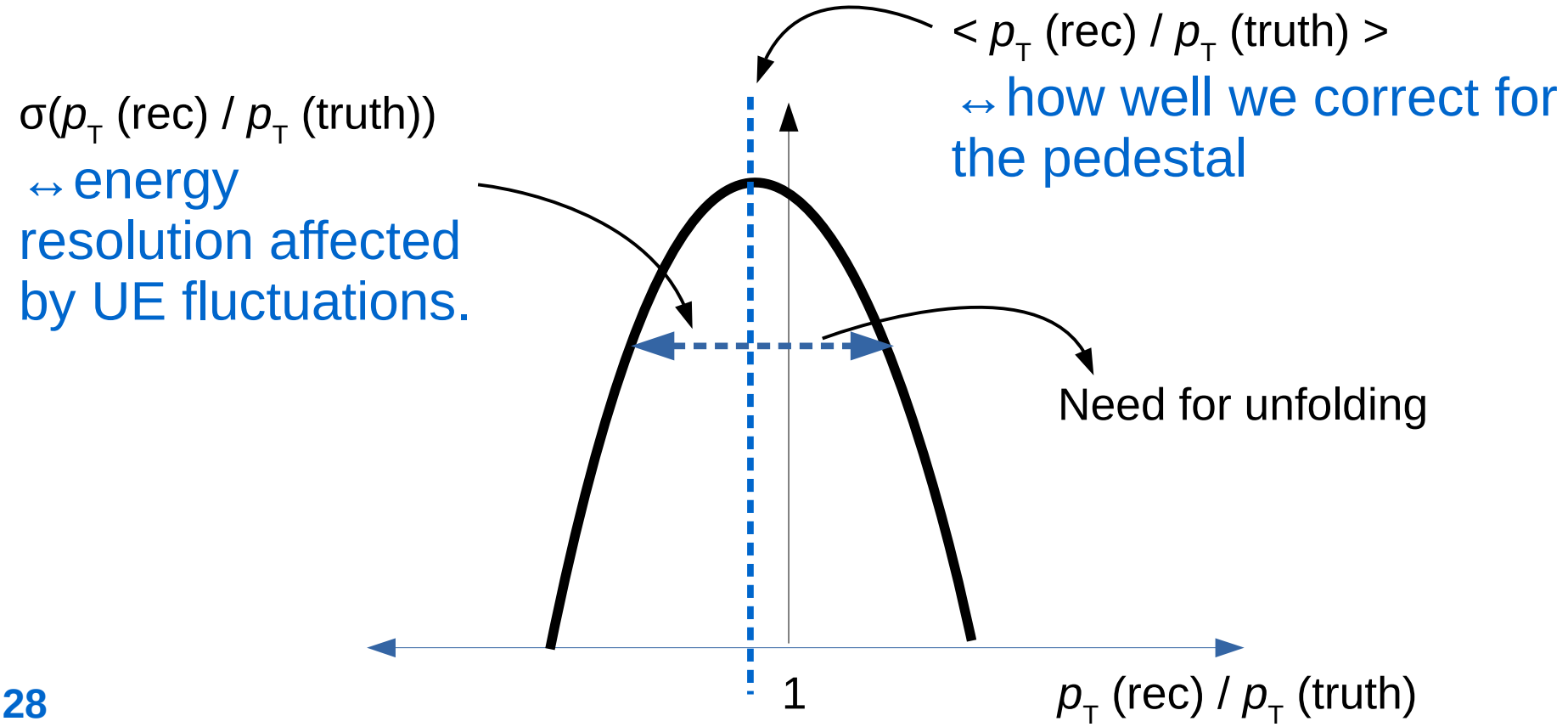


Jet reconstruction

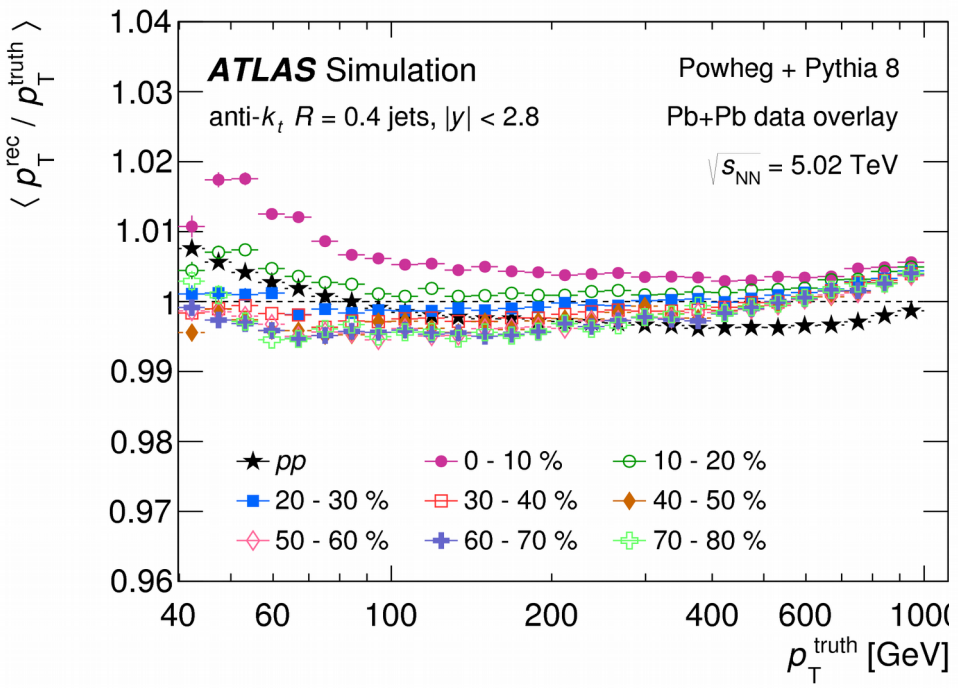
- Jets reconstructed with Anti-k_t with R=0.4 and underlying event (UE) subtraction.
- Mean UE, up to 150 GeV for 0.4 jet, estimated event-by-event as a function of pseudorapidity.

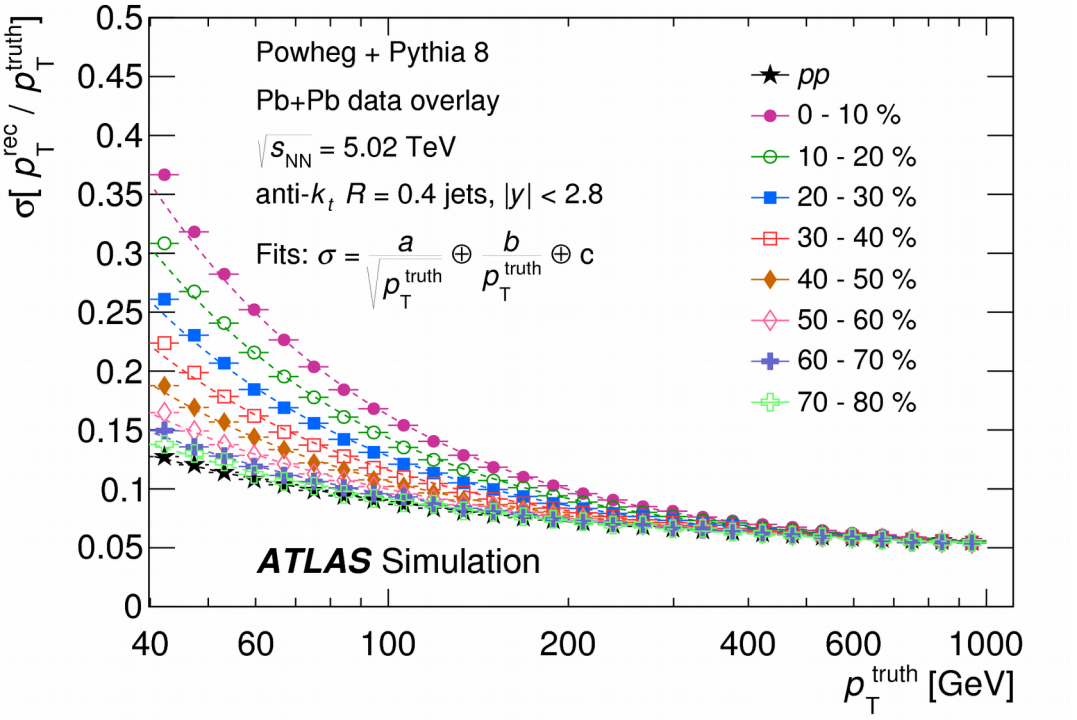
Jet reconstruction

- Jets reconstructed with Anti-k_t with R=0.4 and underlying event (UE) subtraction.
- Mean UE, up to 150 GeV for 0.4 jet, estimated event-by-event as a function of pseudorapidity.



Jet reconstruction





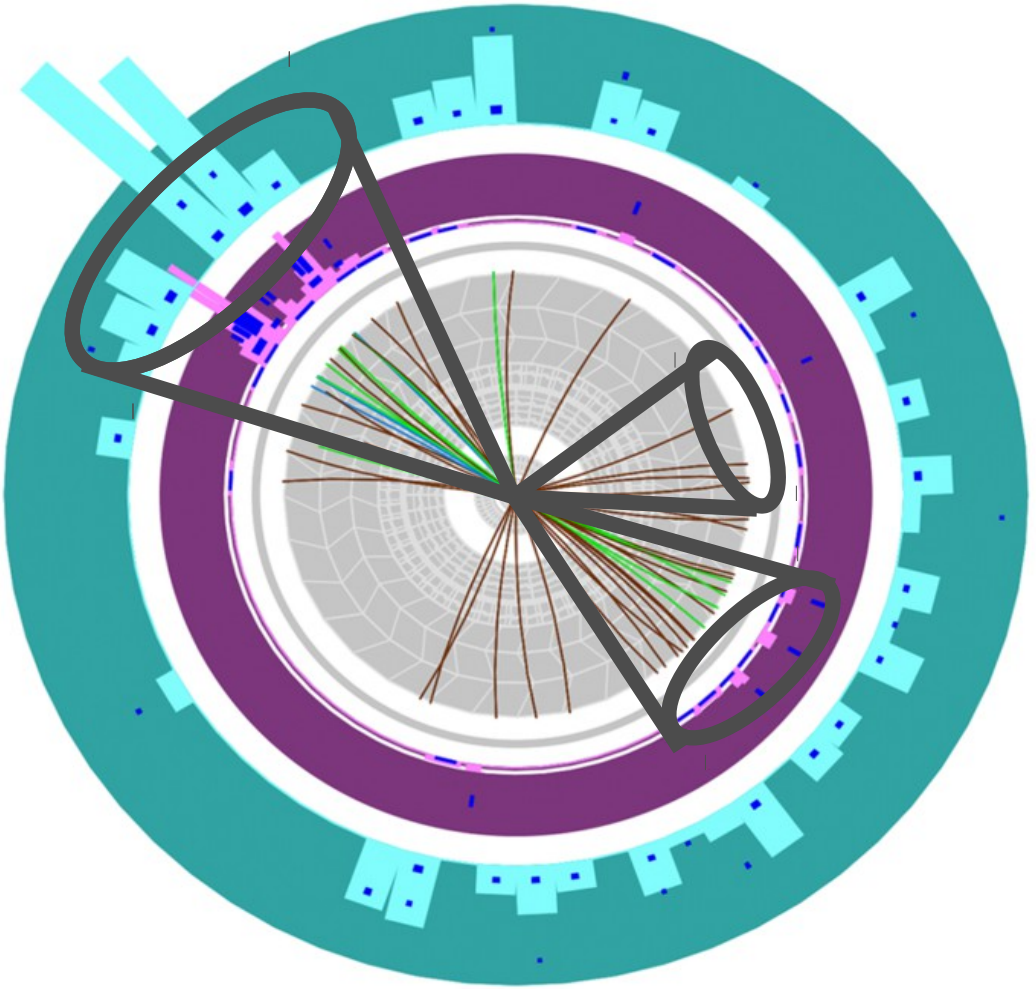
Average responses within 1% from unity almost independent of centrality.

Jet energy resolution dominated by UE fluctuations.

arXiv:1805.05635

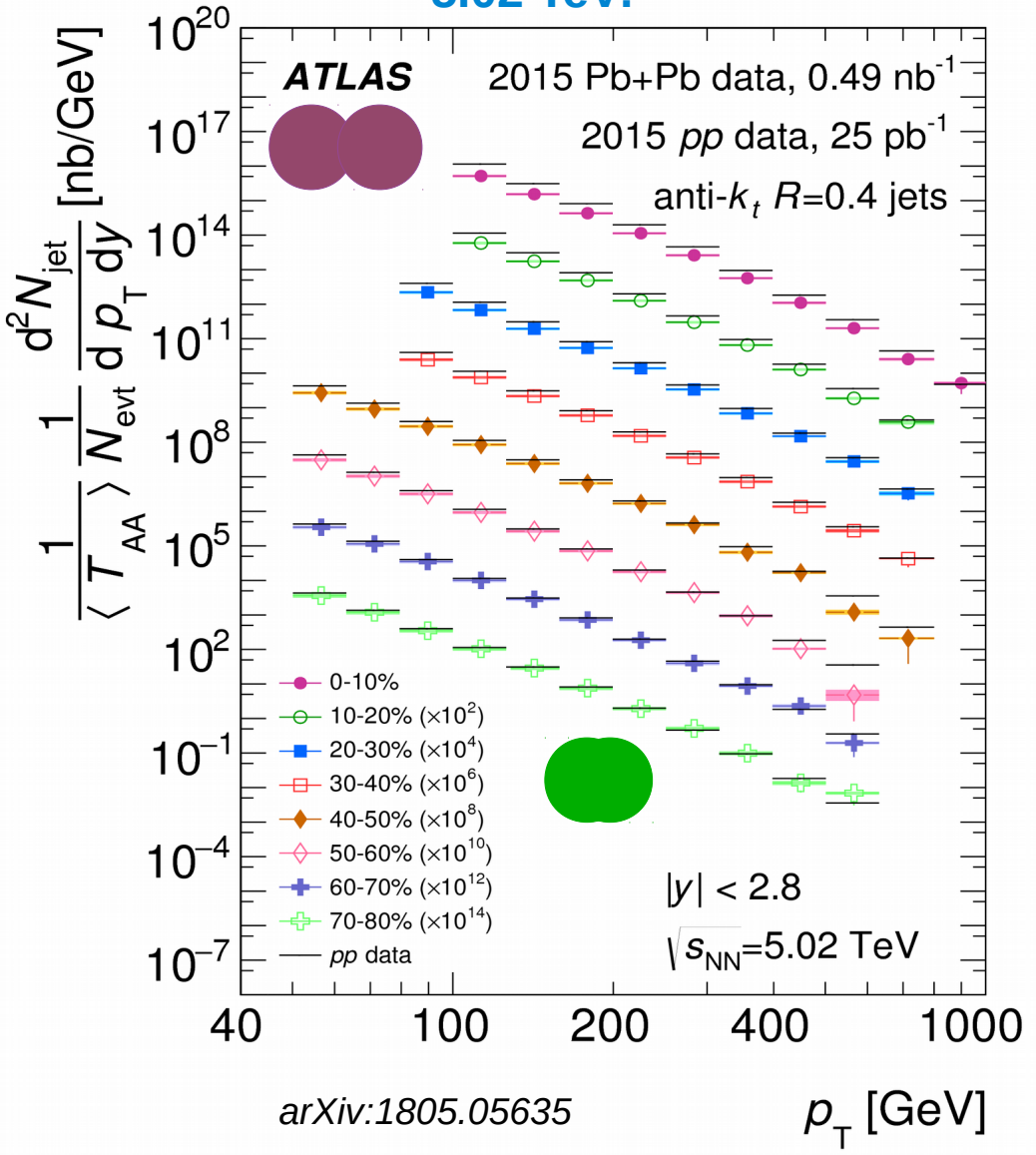
Jet quenching measurement

Inclusive jet spectra



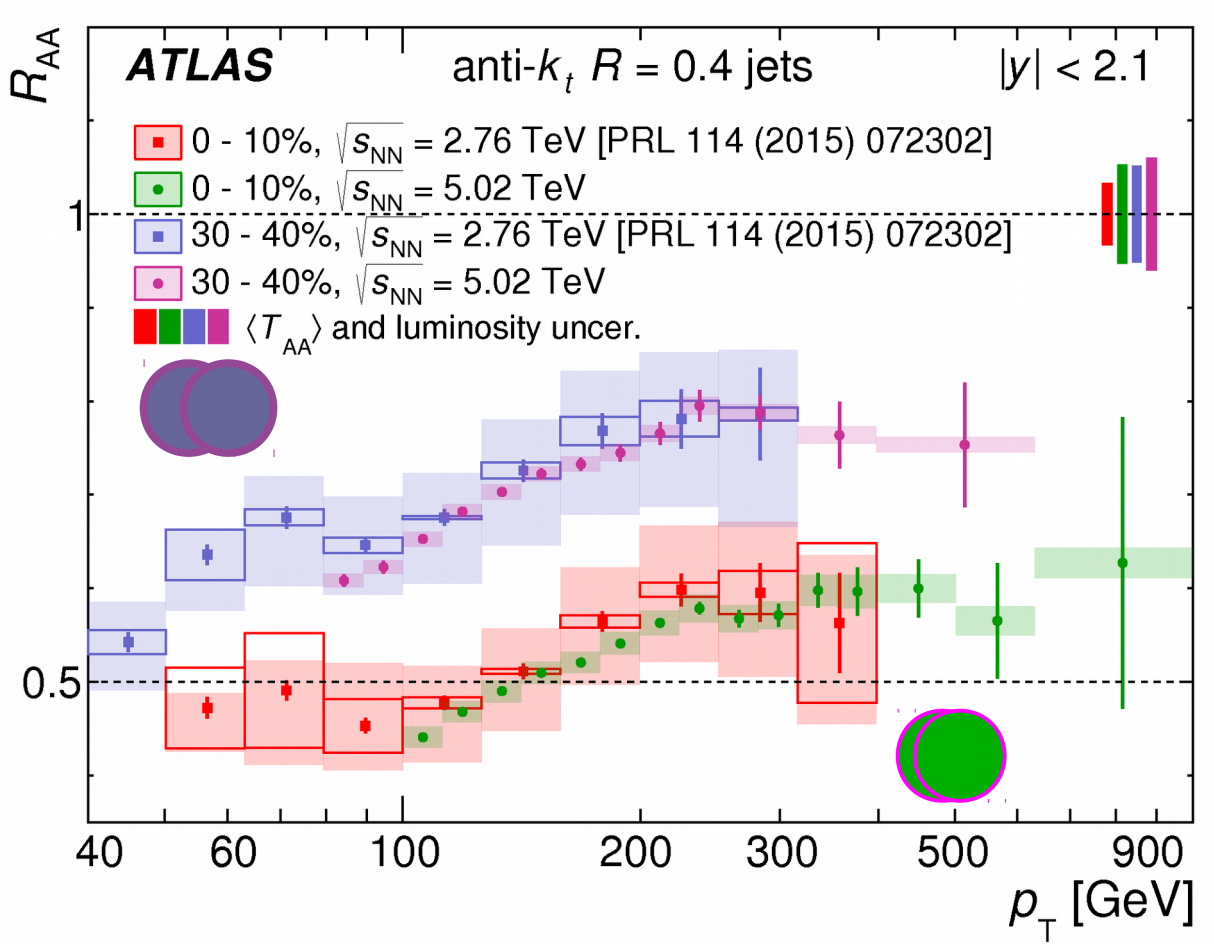
Inclusive jet spectra in *pp* and Pb+Pb collisions

5.02 TeV:



arXiv:1805.05635

Suppression of single jet spectra

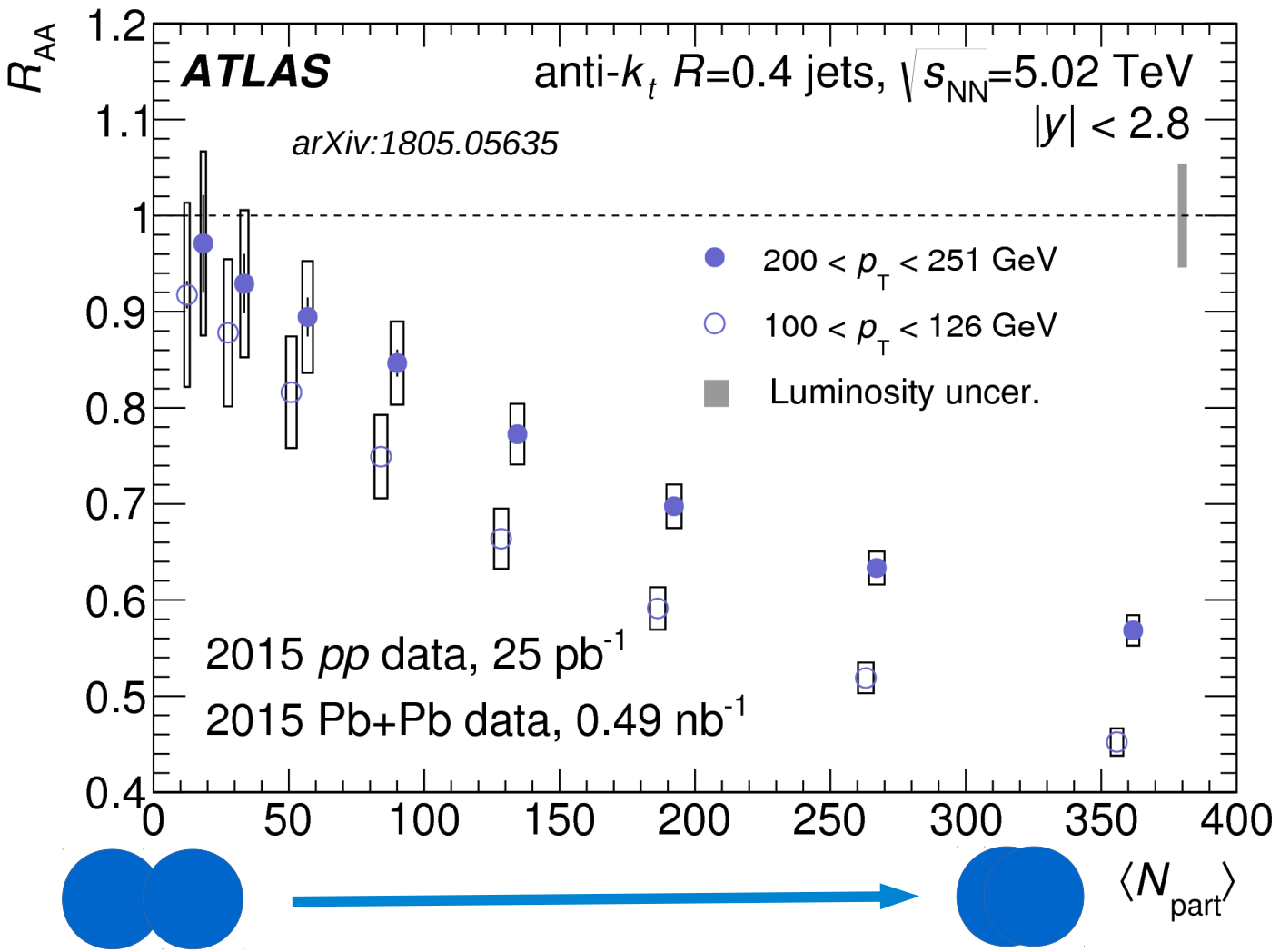


- R_{AA} exhibits weak p_T dependence.
- Same magnitude of R_{AA} seen between 2.76 TeV and 5.02 TeV.
- Access to jet p_T up to 1 TeV and improved systematic uncertainties at 5.02TeV.

arXiv:1805.05635

Suppression of single jet spectra

R_{AA}@5.02 TeV:



- Increasing suppression w.r.t. pp reference with increasing centrality.

What about rapidity dependence?

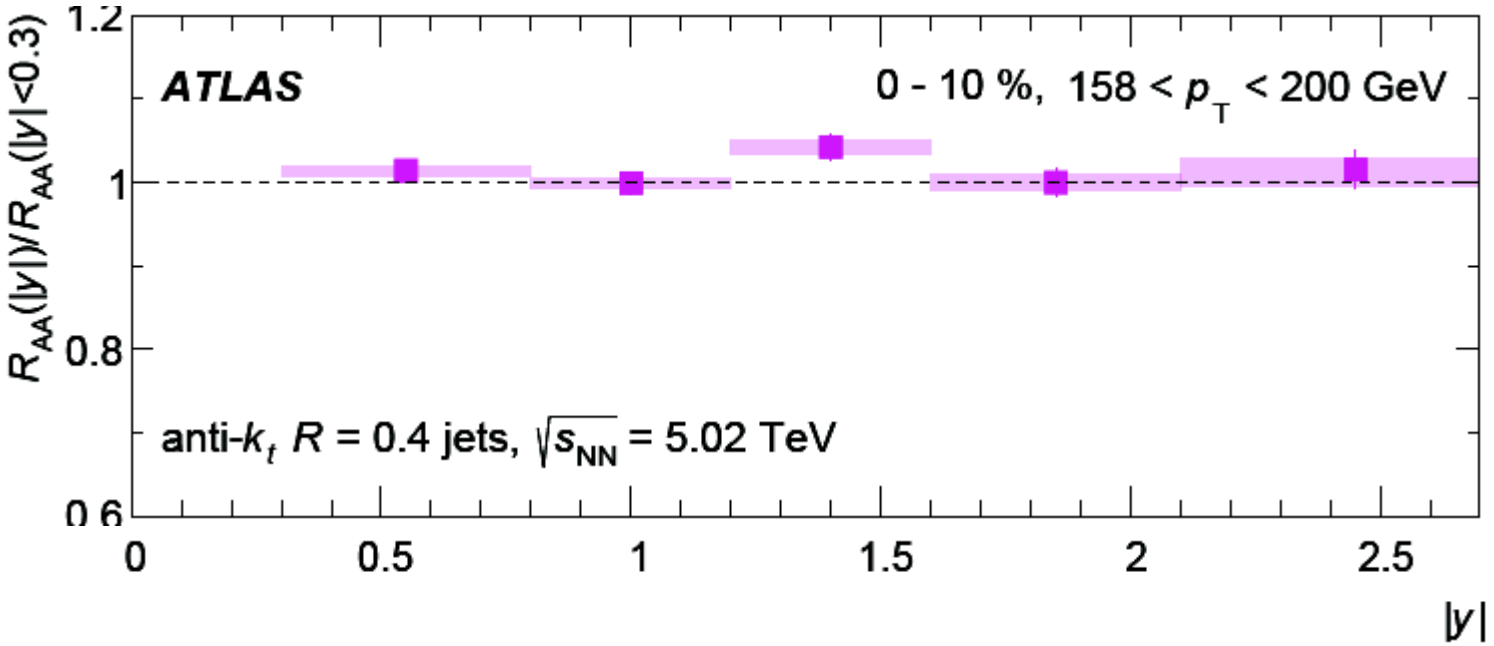
Two competing effects:

- Increasing rapidity ➡ steeper spectrum ➡ decrease of R_{AA}
- Increasing rapidity ➡ higher quark fraction ➡ increase of R_{AA}

What about rapidity dependence?

Two competing effects:

- Increasing rapidity ➡ steeper spectrum ➡ decrease of R_{AA}
- Increasing rapidity ➡ higher quark fraction ➡ increase of R_{AA}



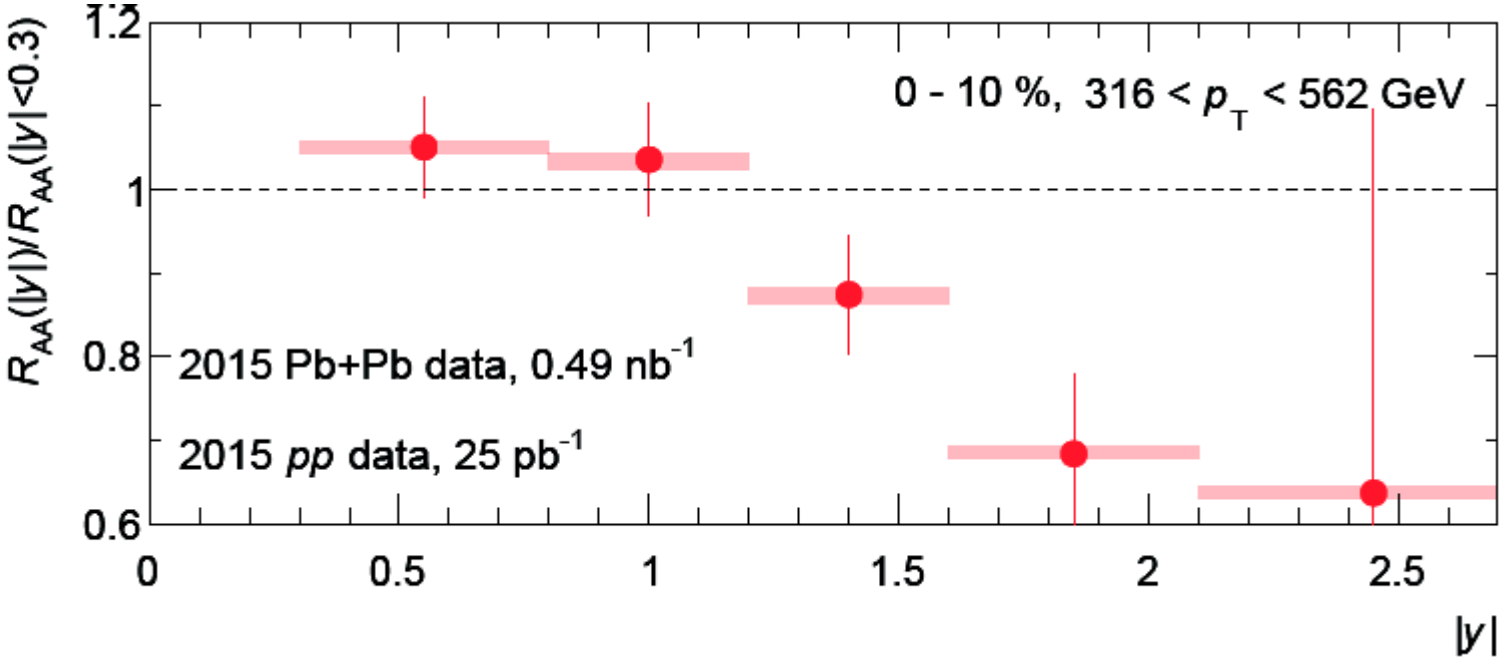
➡ Effects seems to cancel at low and intermediate p_T.

arXiv:1805.05635

What about rapidity dependence?

Two competing effects:

- Increasing rapidity ➡ steeper spectrum ➡ decrease of R_{AA}
- Increasing rapidity ➡ higher quark fraction ➡ increase of R_{AA}



➡ Larger suppression in forward region at high p_T likely dominated by steepness of spectra.

arXiv:1805.05635

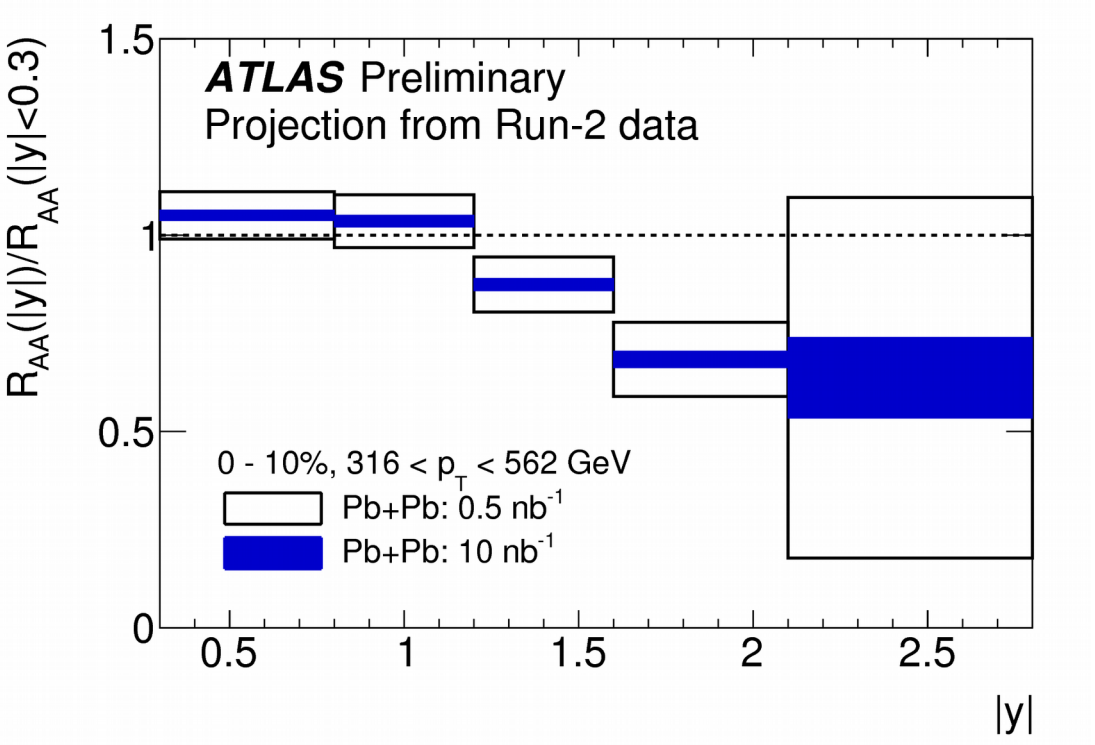
What about rapidity dependence?

Two competing effects:

- Increasing rapidity ➡ steeper spectrum ➡ decrease of R_{AA}
- Incre… …se of R_{AA}

➡ L…
d…

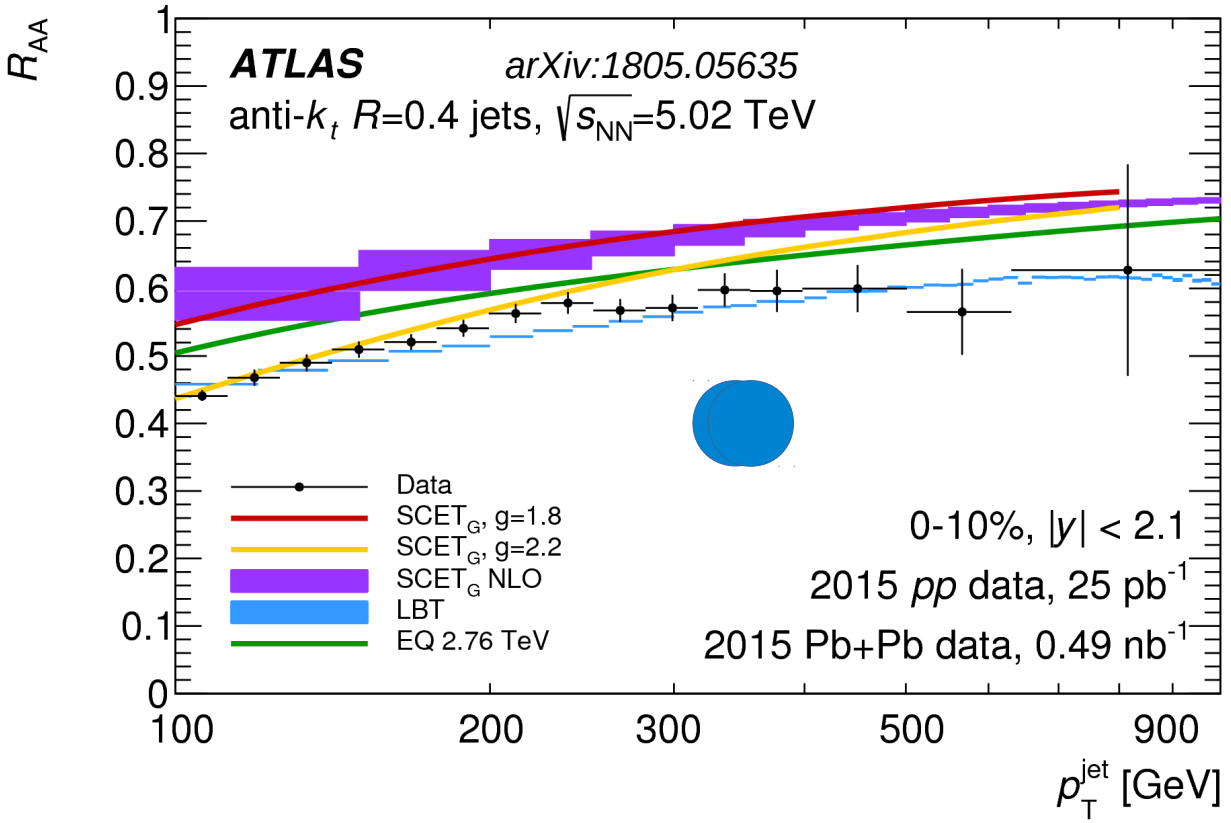
Benefit from Run3 + Run4



ATL-PHYS-PUB-2018-019

arXiv:1805.05635

Theoretical descriptions

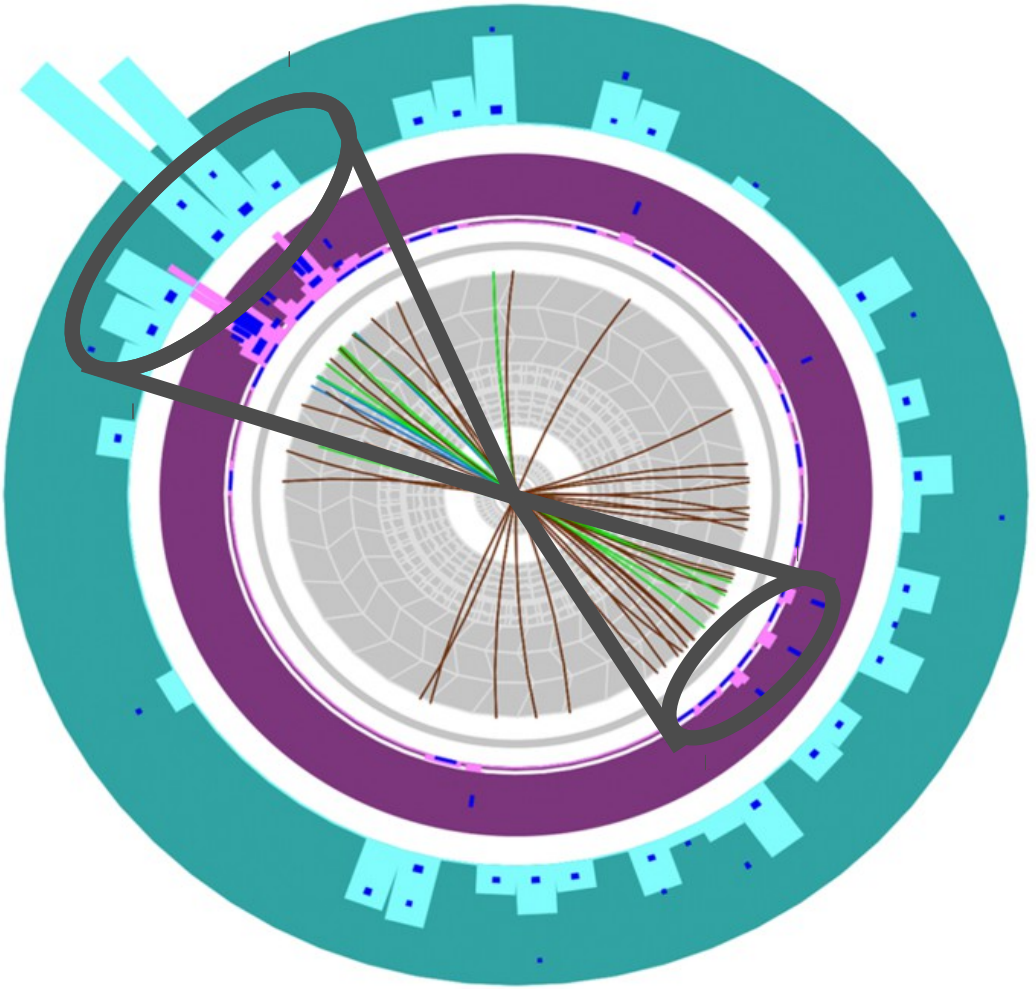


Lorentz Boltzmann Transport (LBT) model (arXiv:1503.03313)
Soft Collinear Effective Field Theory (SCETg) (arXiv:1509.02936)
Effective Quenching (EQ) model (arXiv:1504.05169)

- Models are able to describe trends in the data.

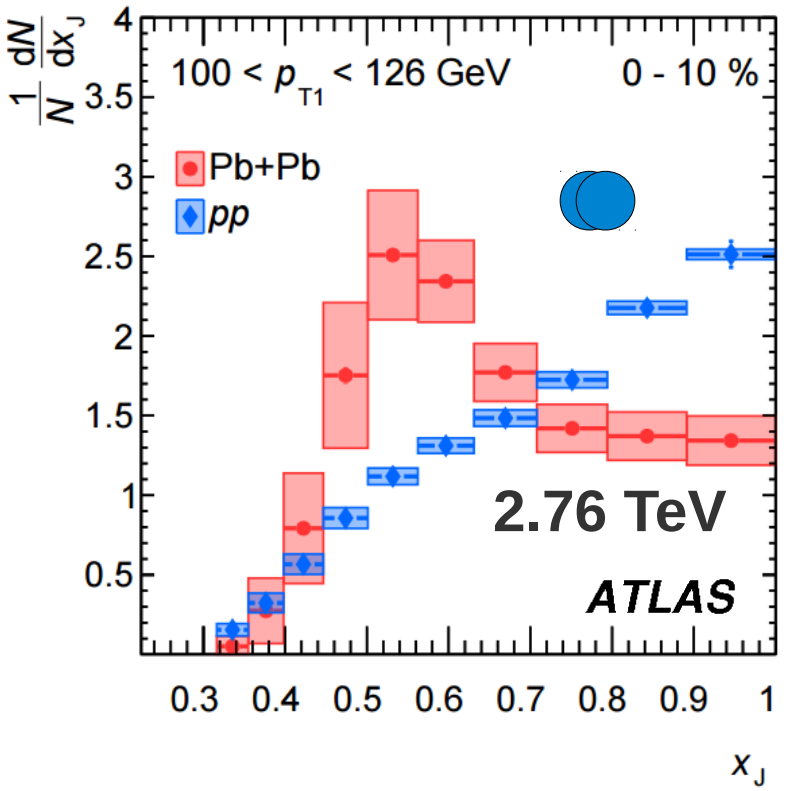
Jet quenching measurement

Dijet asymmetry



Dijet p_T correlation

- ATLAS fully unfolded dijet p_T correlations distributions



$$x_J \equiv p_{T_2}/p_{T_1}$$

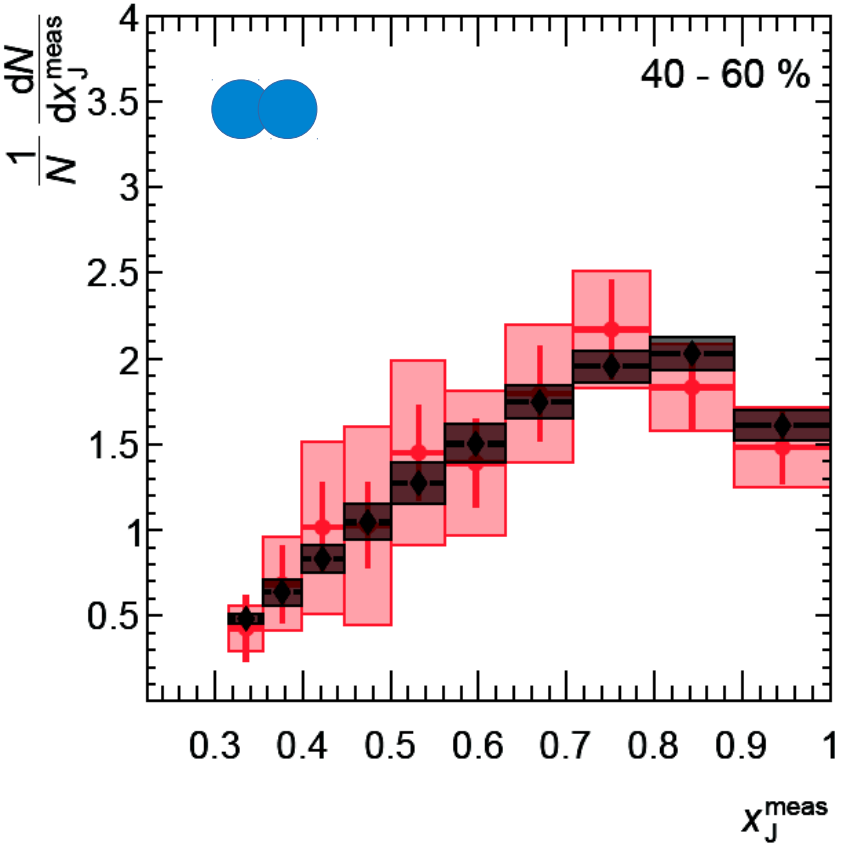
Unfolding restores features smeared out by the detector resolution.

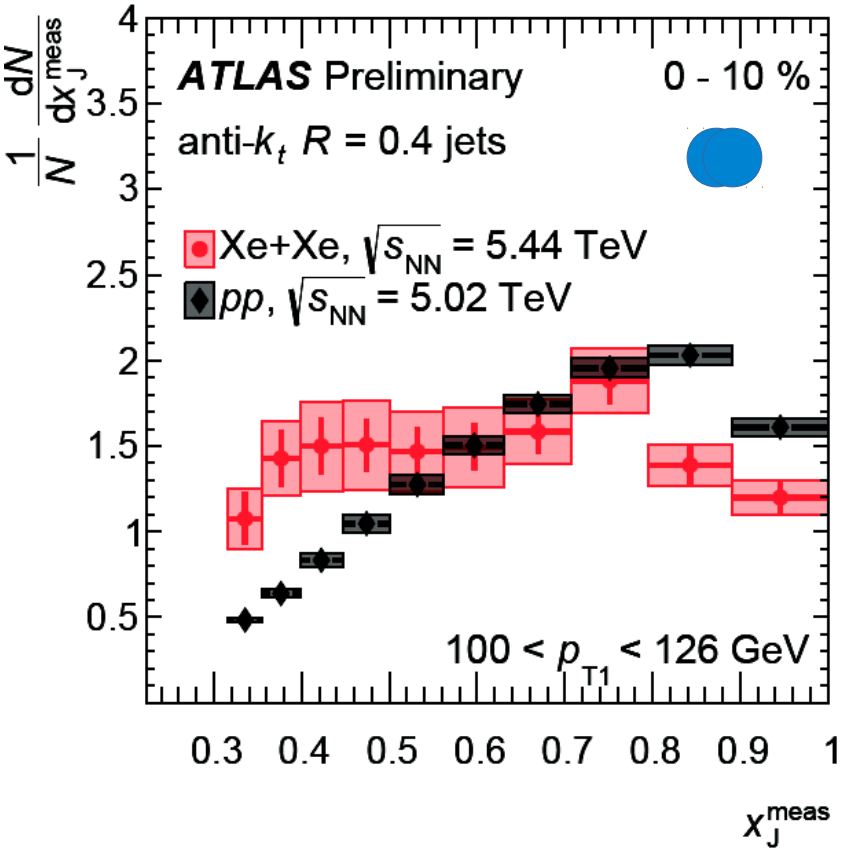
- Significant shift toward imbalanced dijets in central HI collisions w.r.t. *pp* reference.
  - Role of fluctuations in energy loss?
  - Quark/gluon fraction?

PLB 774 (2017) 379

Jet quenching in lighter nuclei

- Dijet p_T correlation in Xe+Xe.



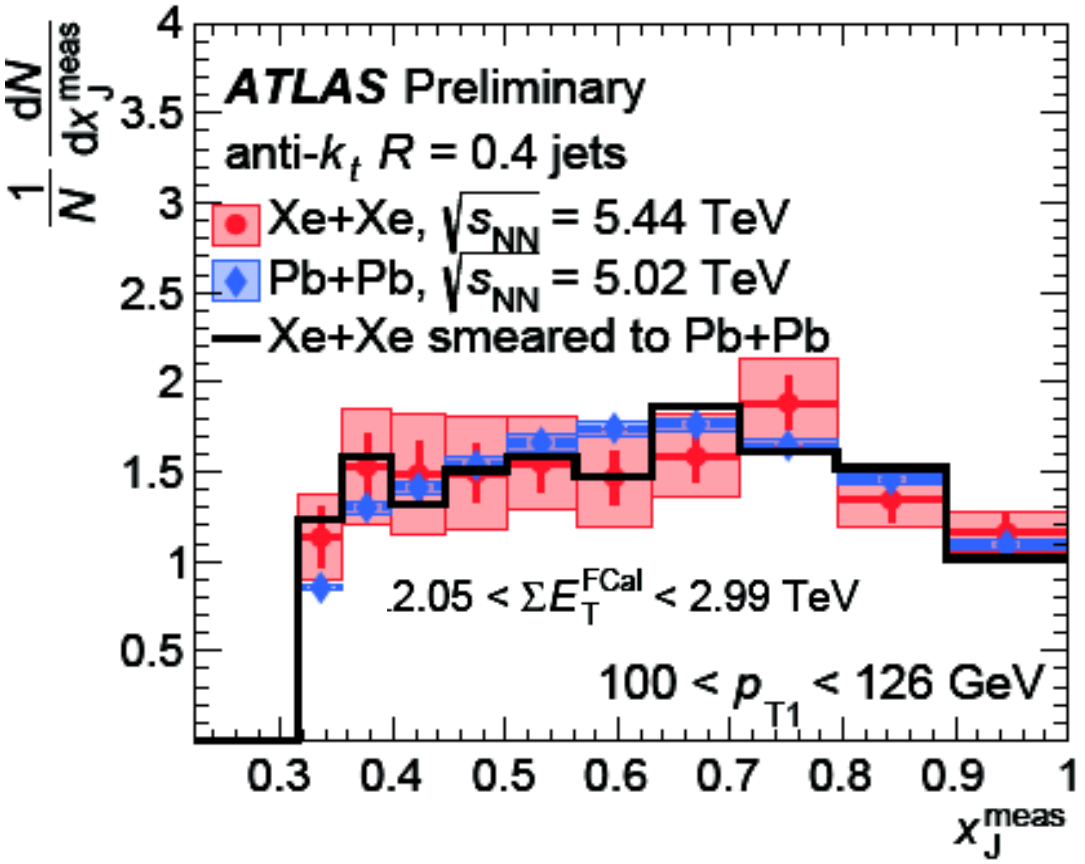


- Significant imbalance in central Xe+Xe collisions.
- How does it compare to Pb+Pb?

ATLAS-CONF-2018-007

Lighter versus heavier nuclei

Xe+Xe and Pb+Pb comparison in events with the same event activity:

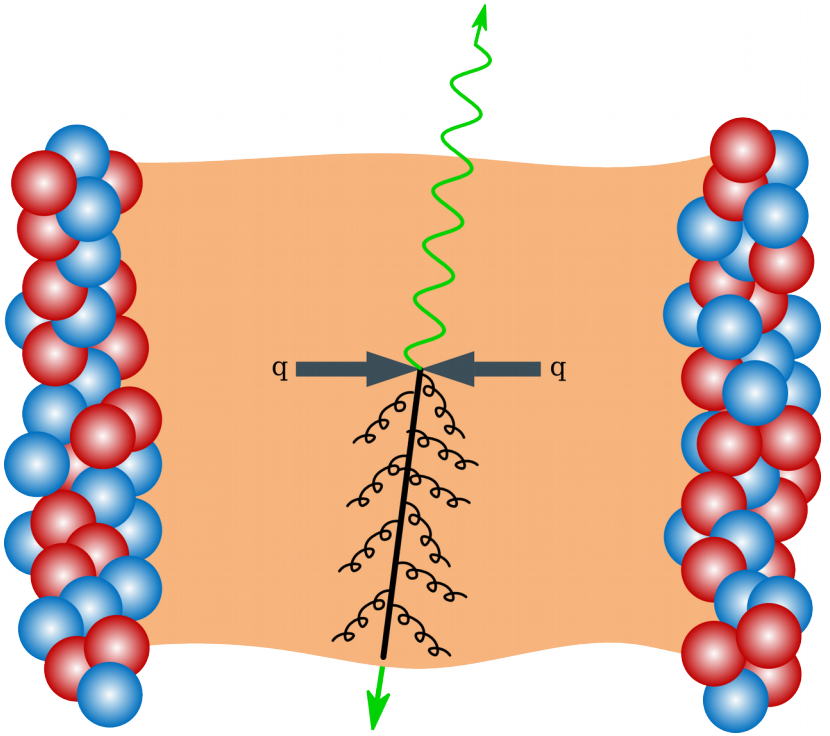


- No difference within uncertainties between the two systems.

ATLAS-CONF-2018-007

Jets + vector bosons

- Different hard probes interact with medium differently.

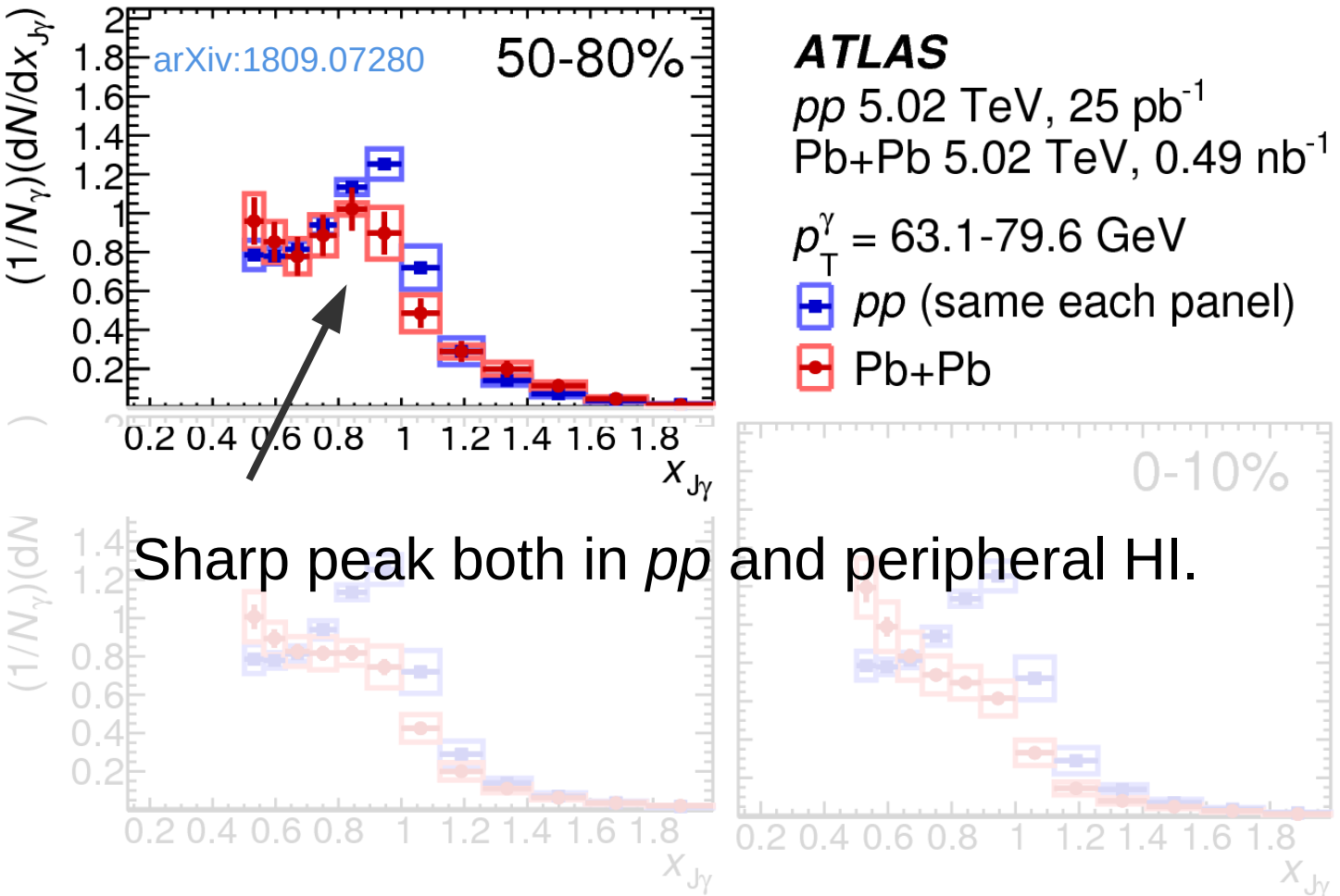


- Photons and Z's calibrate the parton energy.
- Flavor fraction differs compared to di-jets.

Photon-jet correlations

- What is the absolute amount of energy lost in QGP?

➡ Measurement of balance in photon-jet system $x_{J\gamma} = p_T^{jet} / p_T^{\gamma}$



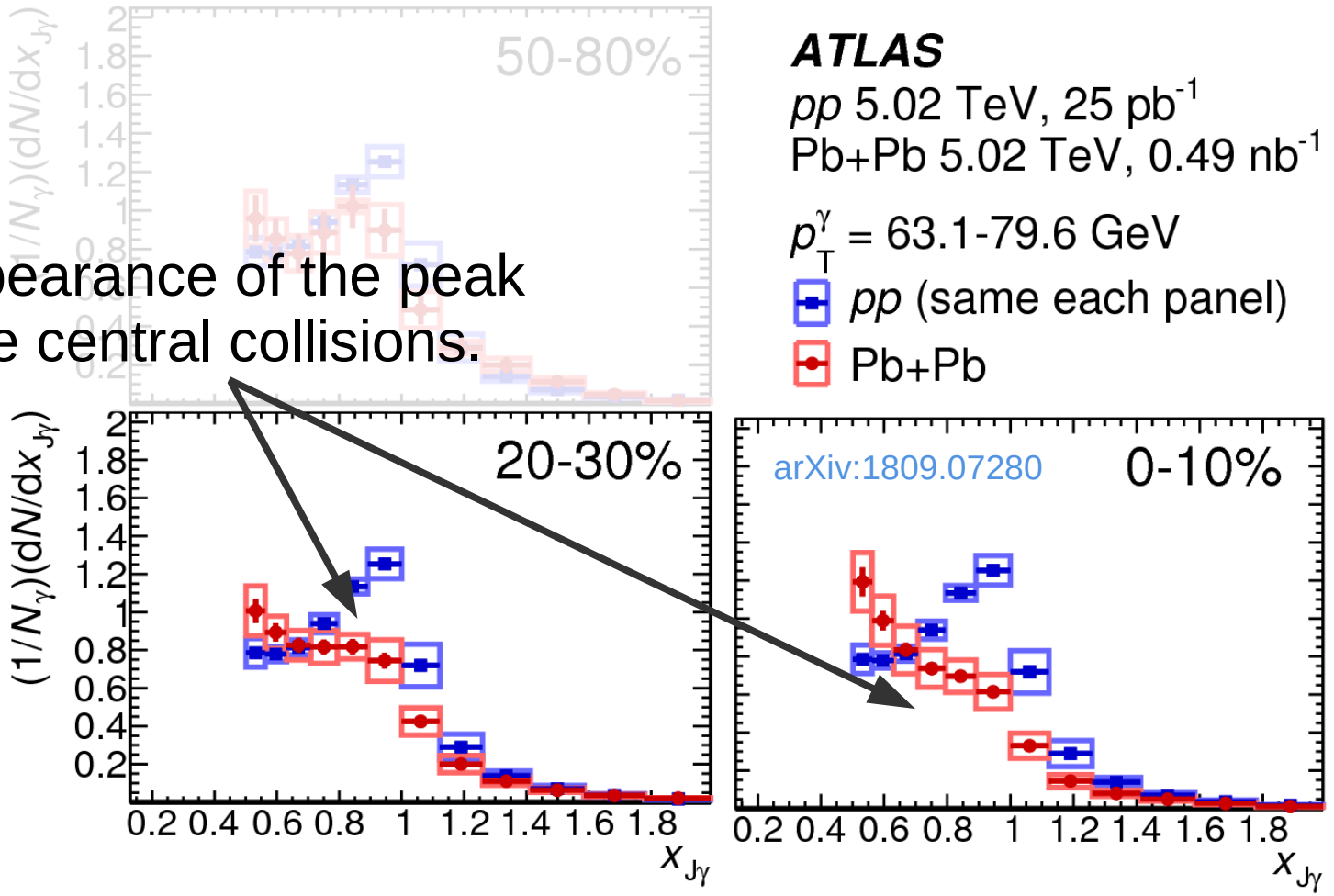
Sharp peak both in *pp* and peripheral HI.

Photon-jet correlations

- What is the absolute amount of energy lost in QGP?

➡ Measurement of balance in photon-jet system $x_{J\gamma} = p_T^{jet} / p_T^{\gamma}$

Disappearance of the peak
in more central collisions.

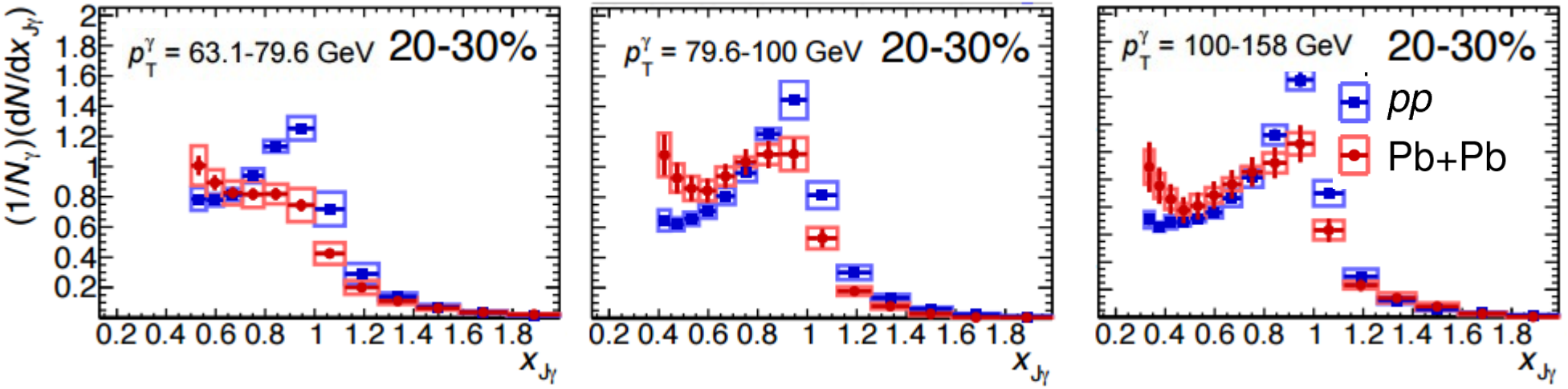


Photon-jet correlations

- What is the absolute amount of energy lost in QGP?

➡ Measurement of balance in photon-jet system $x_{J\gamma} = p_T^{jet} / p_T^{\gamma}$

Increasing photon p_T

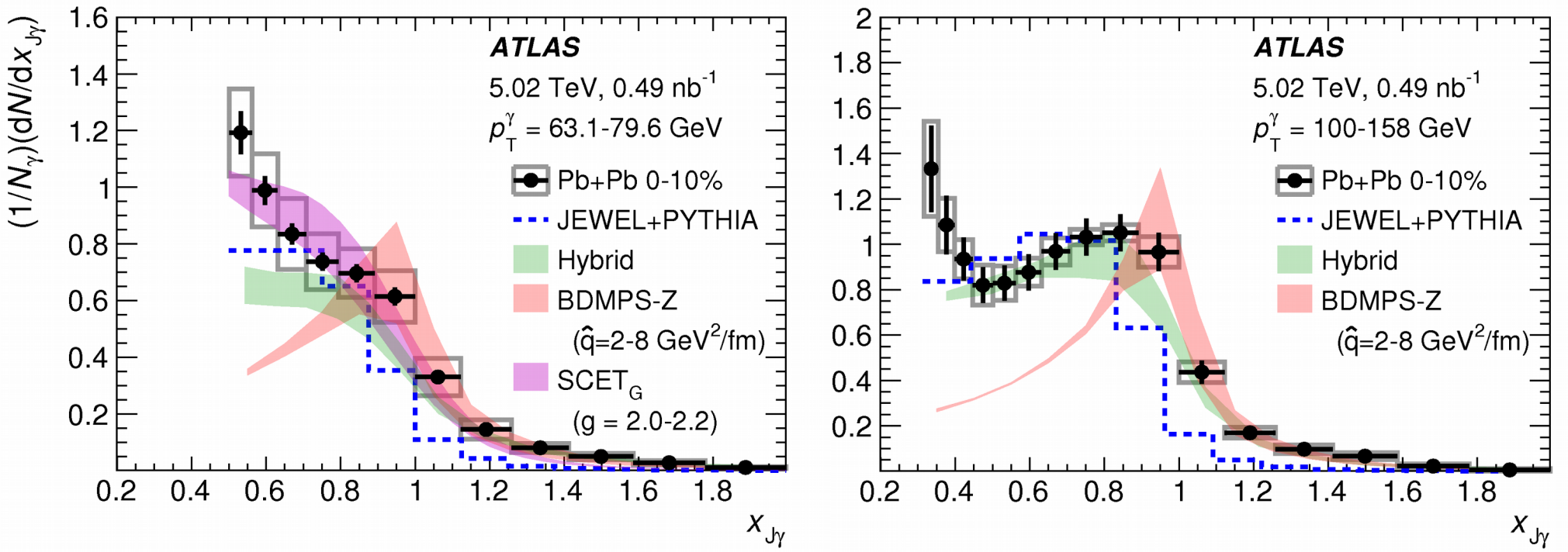


- Peak reappears at higher p_T.
- Contribution from jets without energy loss?

arXiv:1809.07280

Can theory describe observed trends?

Increasing photon p_T

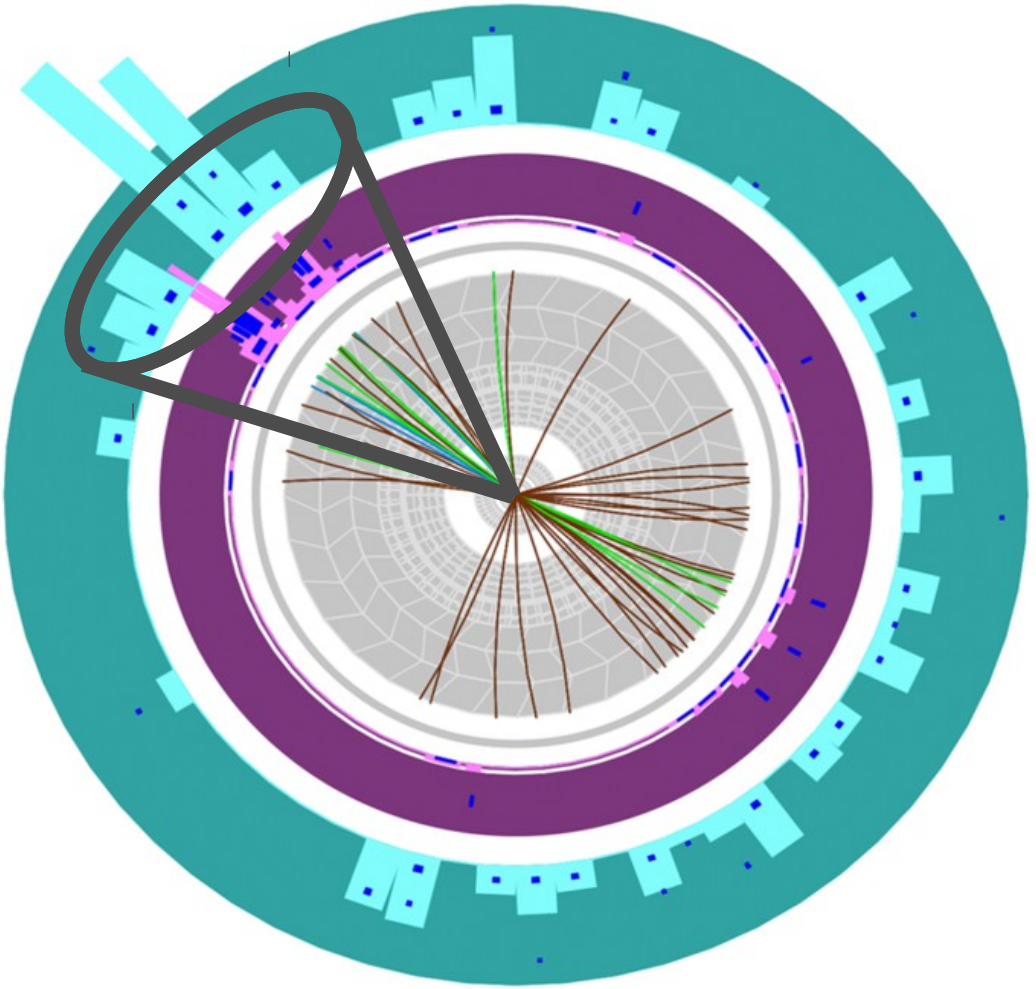


- Comparison to SCETg, Hybrid model, BDMPS-Z (arXiv1803.10533), and JEWEL MC (arXiv:1608.03099)
- Some models able to describe basic features.
- Difficult to describe the detailed behavior of the distribution.

arXiv:1809.07280

Jet quenching measurement

Jet structure



How much is the jet structure modified in Pb+Pb?

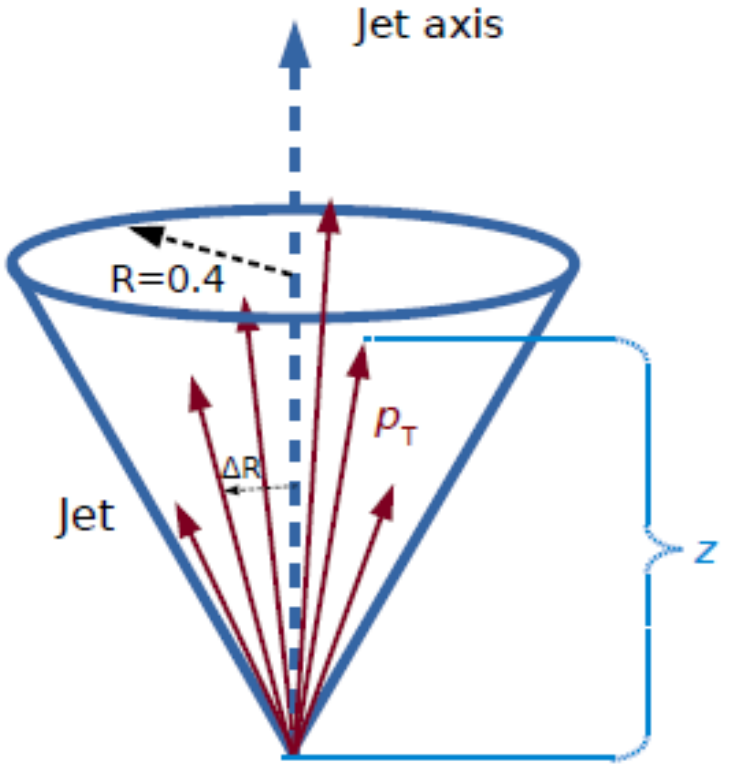
- Measurement of fragmentation functions

$$D(p_{\mathrm{T}}) \equiv \frac{1}{N_{\mathrm{jet}}} \frac{\mathrm{d}n_{\mathrm{ch}}}{\mathrm{d}p_{\mathrm{T}}} \qquad D(z) \equiv \frac{1}{N_{\mathrm{jet}}} \frac{\mathrm{d}n_{\mathrm{ch}}}{\mathrm{d}z}$$, where $z \equiv p_{\mathrm{T}} \cos \Delta R \; / \; p_{\mathrm{T}}^{\mathrm{jet}}$

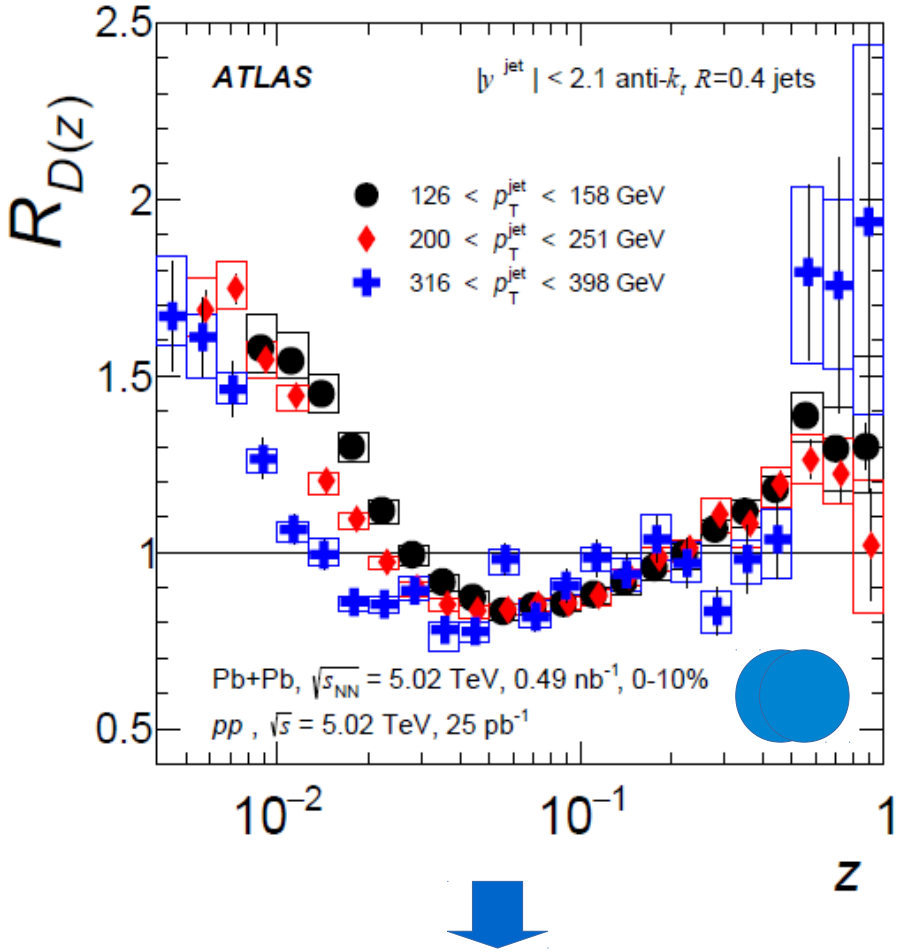
$$R_{D(z)} \equiv \frac{D(z)_{\mathrm{PbPb}}}{D(z)_{pp}}$$

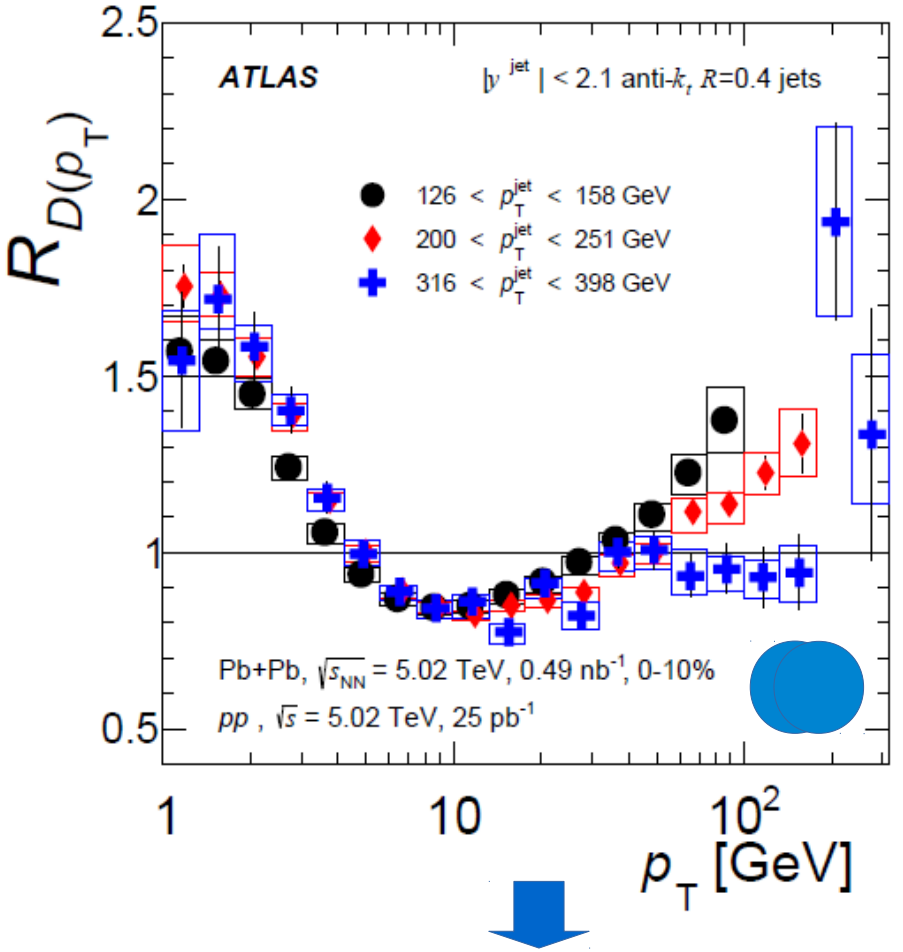
Shower in medium

Shower in vacuum



Modification in central collisions





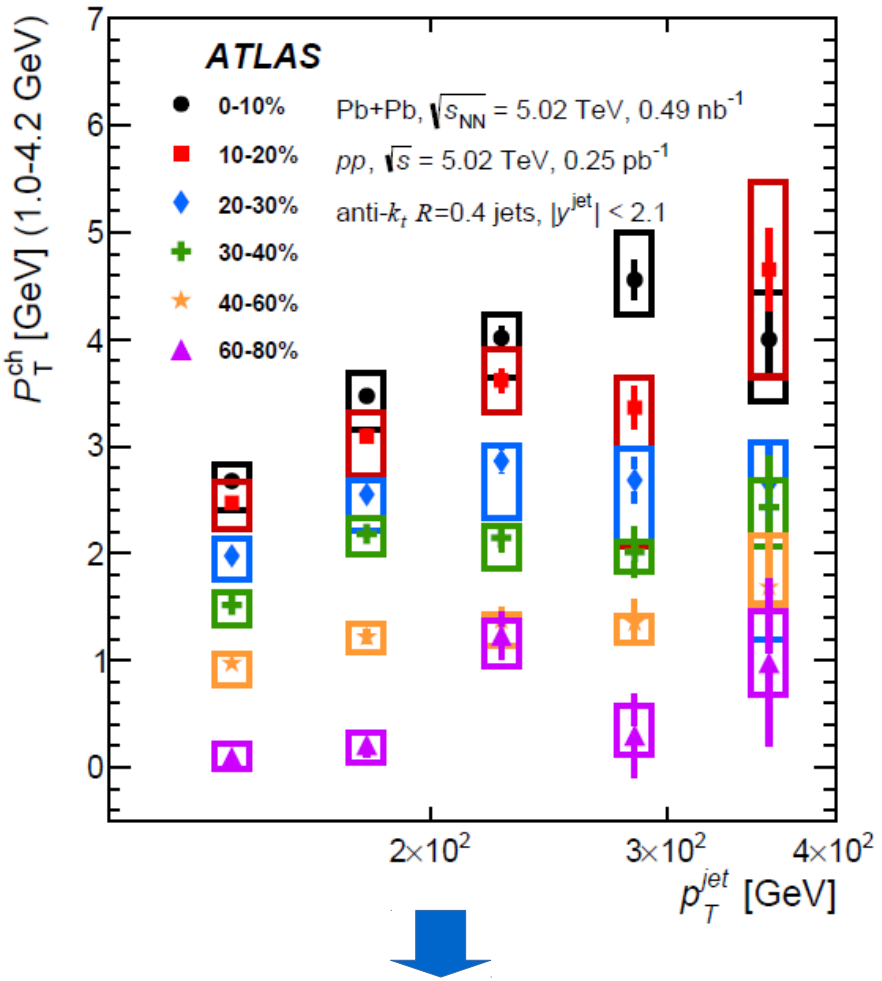
Enhancement of hard fragments.

Enhancement of soft fragments.

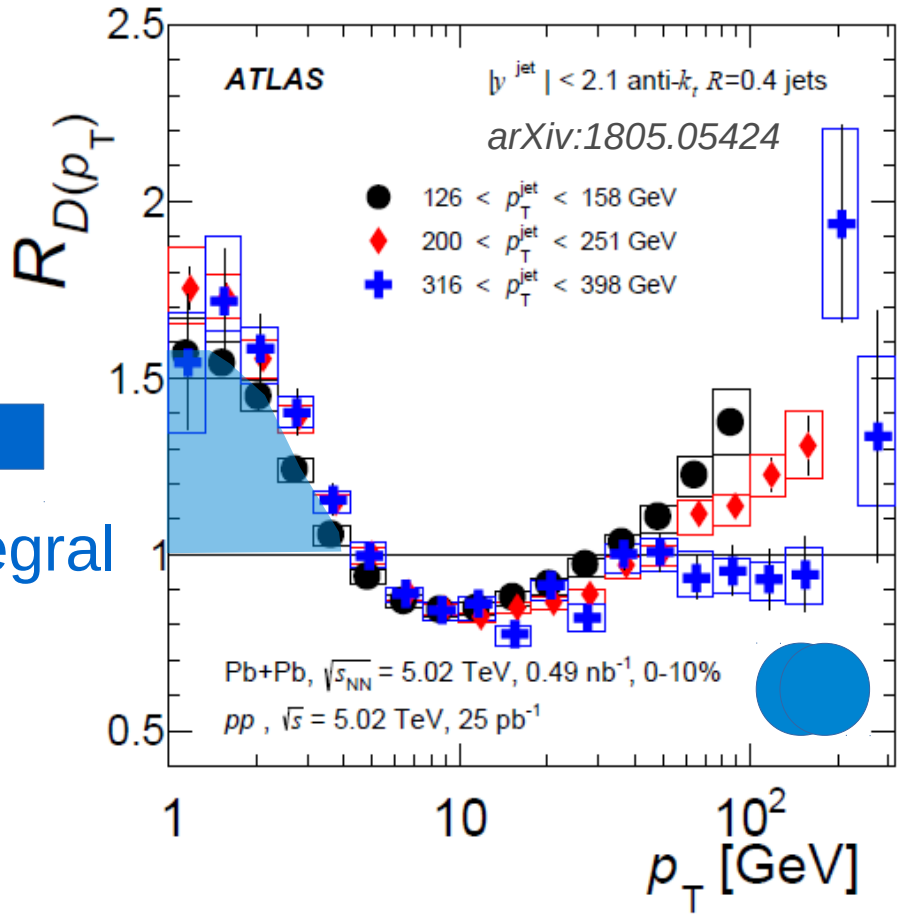
No dependence on jet p_T observed at high z for jets up to 400 GeV.

Phys. Rev. C 98 (2018) 024908

Modification in central collisions



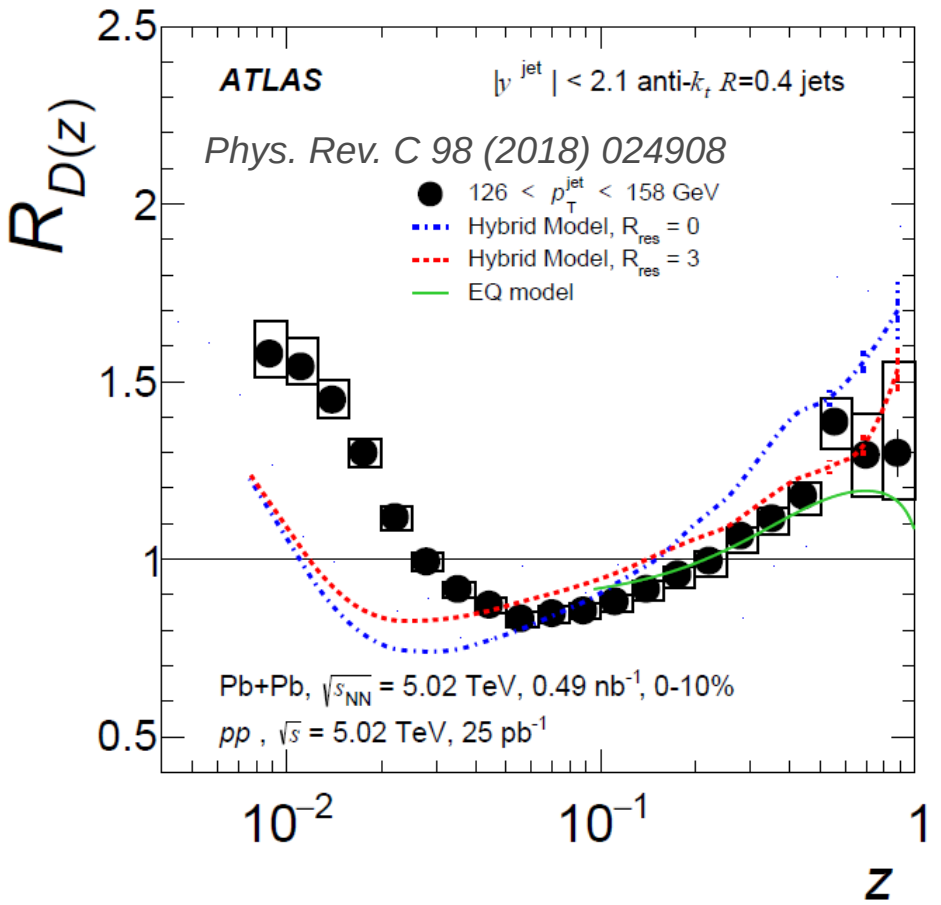
Integral

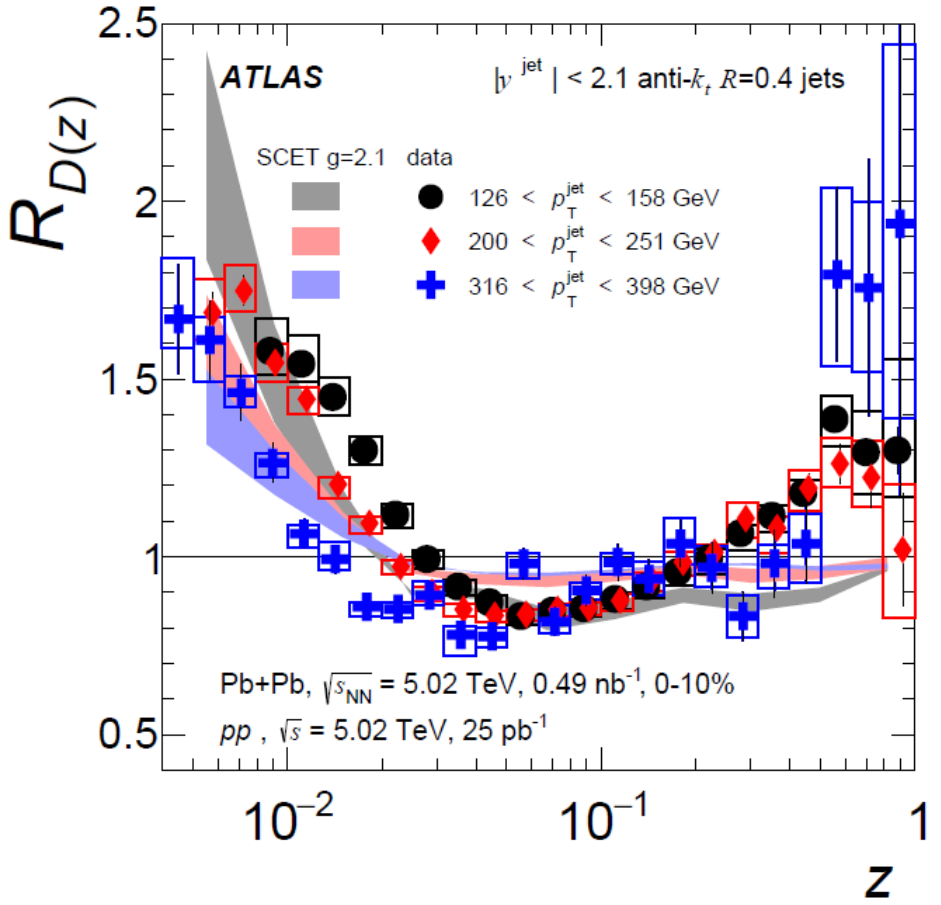


- Jet p_T dependence to the enhancement.
- Response of the medium to the high-p_T parton?

Phys. Rev. C 98 (2018) 024908

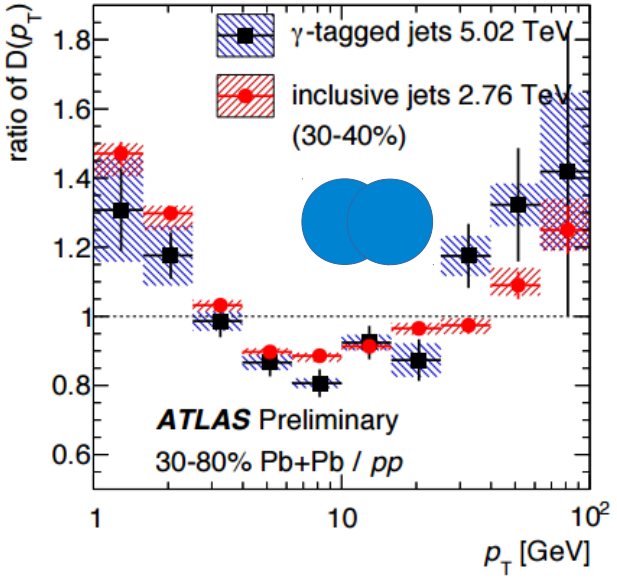
Can theory describe measurement?

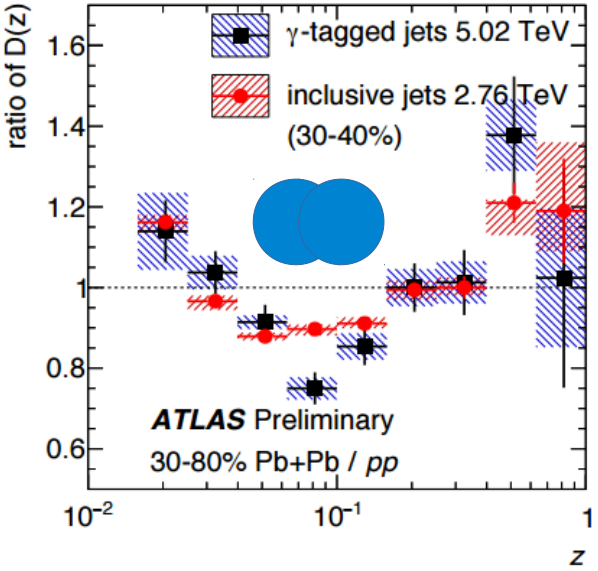




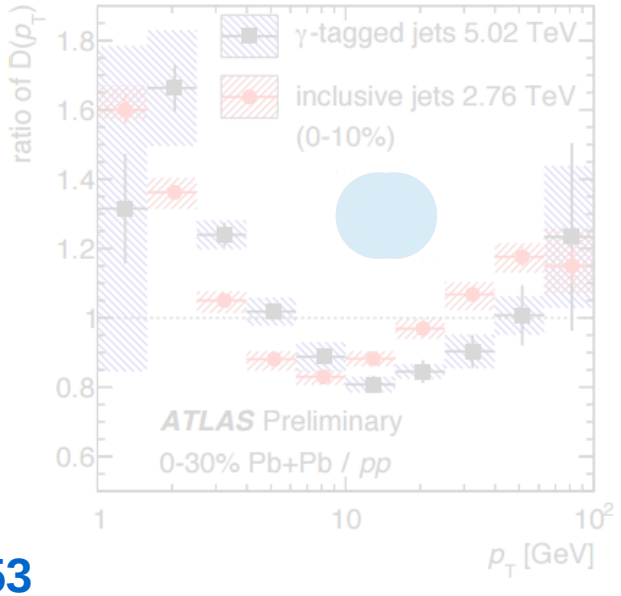
- Hybrid model (arXiv:1707.05245) consistent at high *z*, disagreement at low z due to simplistic medium response modeling.
- EQ model is able to describe the high-*z* excess.
- SCETg model is able to qualitatively described the low-*z* excess.

Photon-tagged jet fragmentation



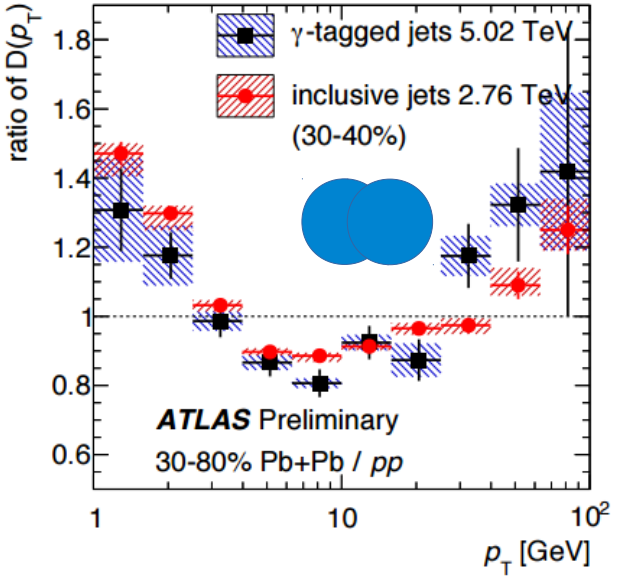


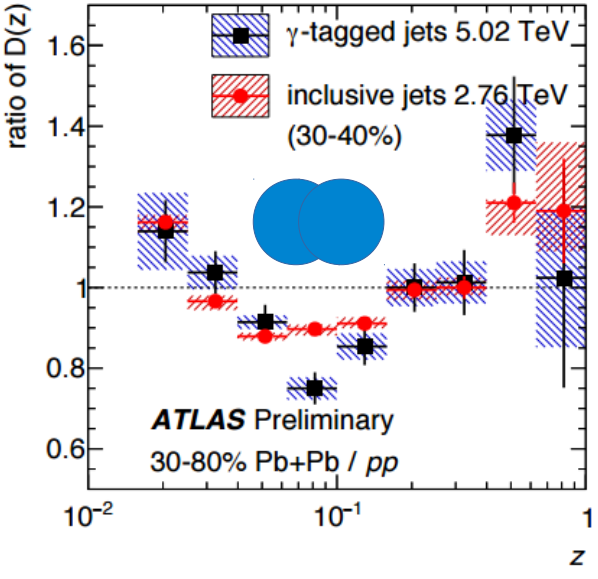
- Statistically limited.
- Same pattern as for inclusive jets.
- Ratios similar in peripheral collisions.

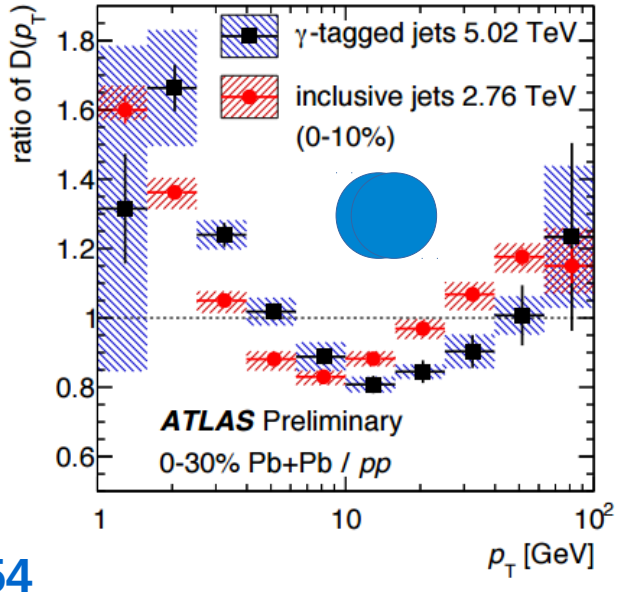


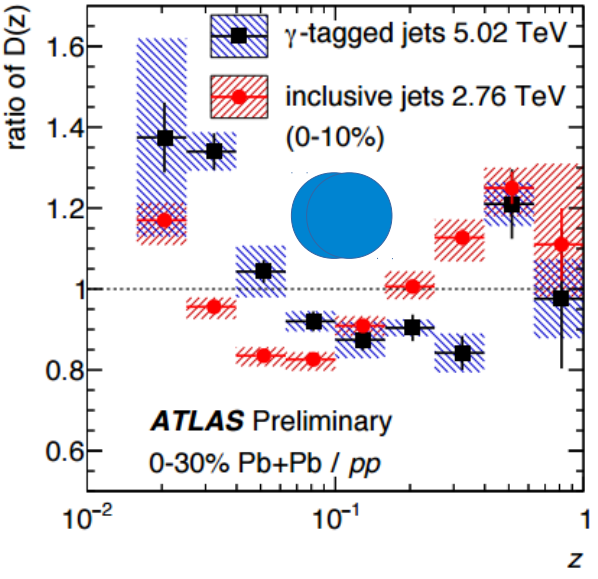
ATLAS-CONF-2017-074

Photon-tagged jet fragmentation





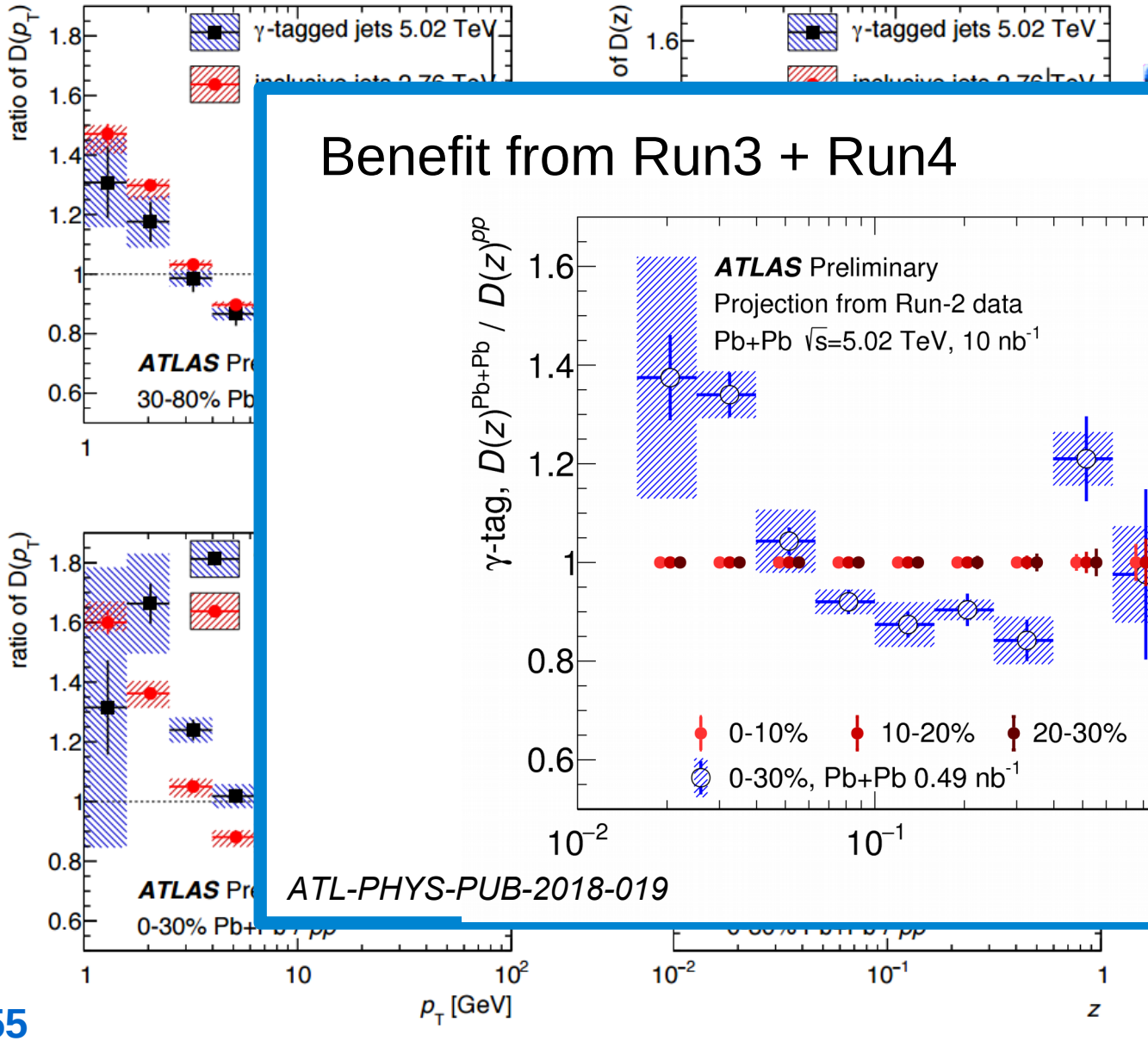




- Statistically limited.
- Same pattern as for inclusive jets.
- Ratios similar in peripheral collisions.
- Extra enhancement/suppr-ession seen in photon-tagged FF in central collisions.

ATLAS-CONF-2017-074

Photon-tagged jet fragmentation



Benefit from Run3 + Run4

ATL-PHYS-PUB-2018-019

Statistically limited.

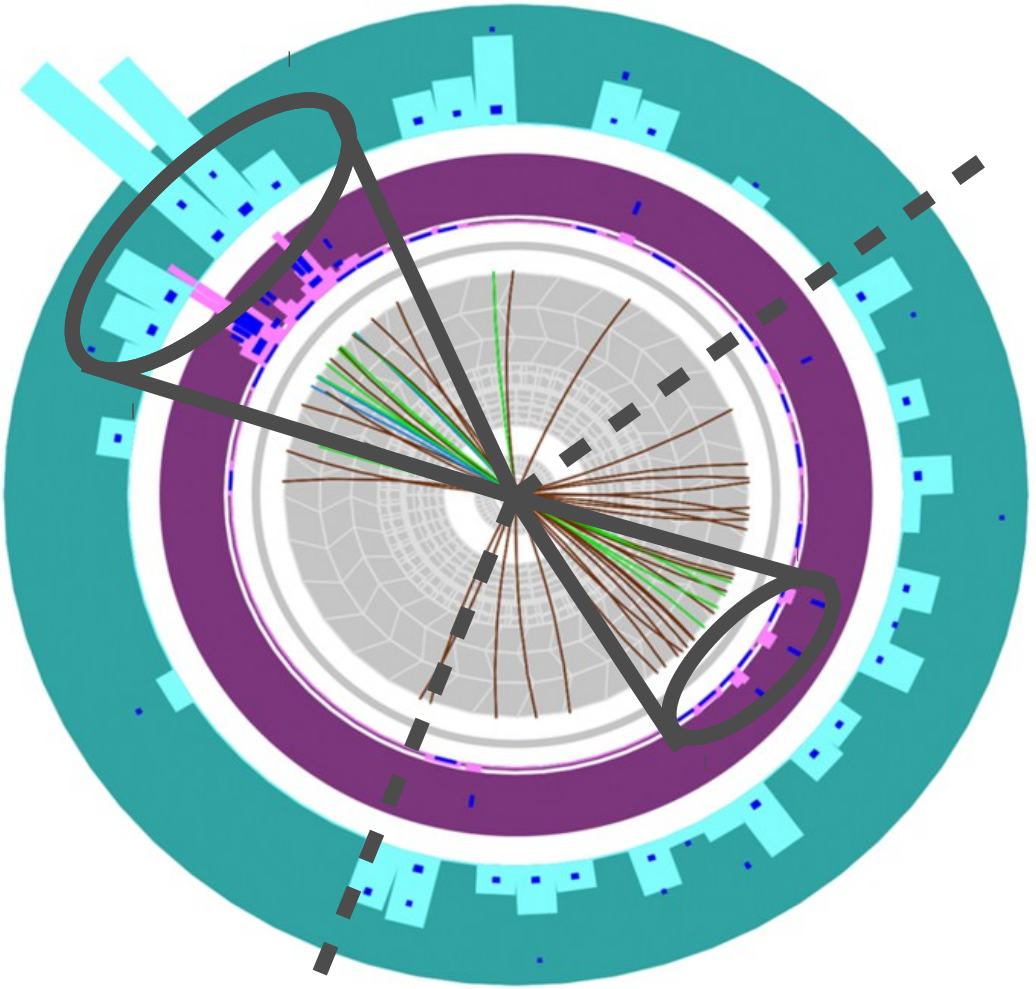
ttern as for
e jets.

milar in
ripheral
s.

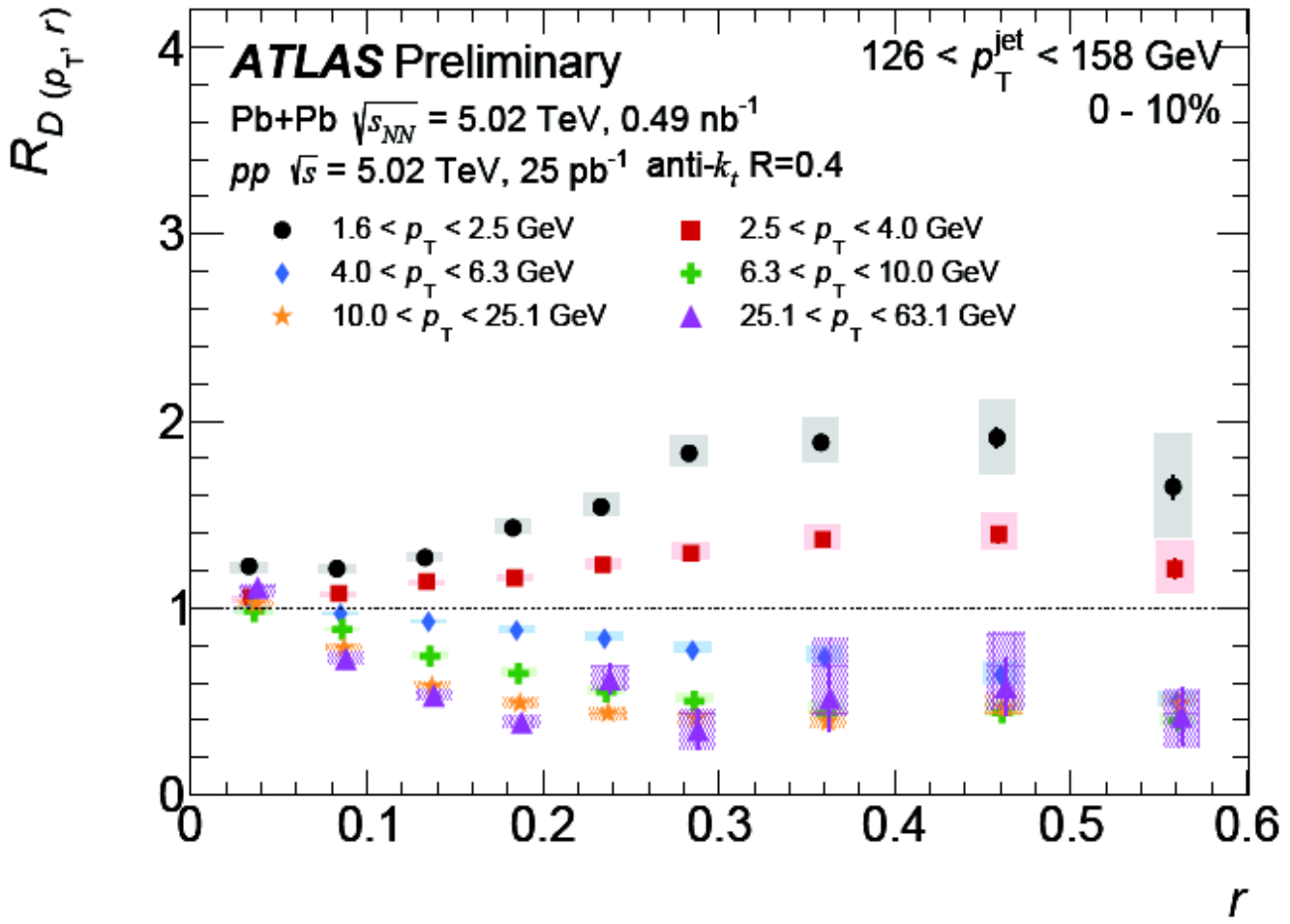
ment/suppr
een in
tagged FF in
collisions.

Jet quenching measurement

Track-jet correlations at large angles

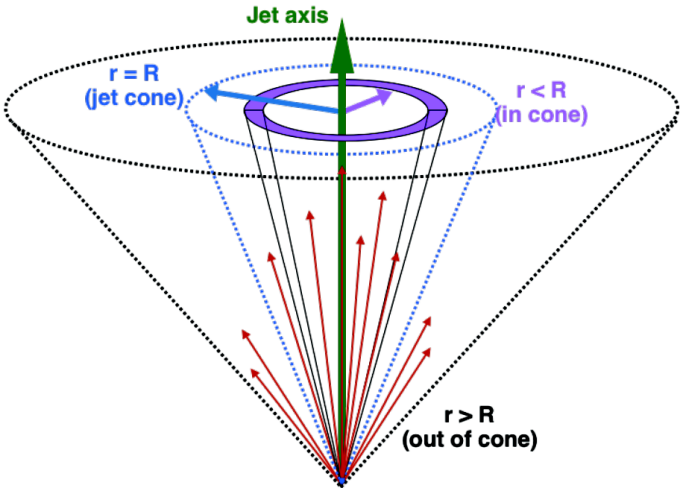


Let's look around jet….



$$D(p_{\mathrm{T}}, r) = \frac{1}{N_{\mathrm{jet}}} \frac{1}{2\pi r} \frac{\mathrm{d}^2 n_{\mathrm{ch}}(r)}{\mathrm{d}r \mathrm{d}p_{\mathrm{T}}}$$

where $r < 0.6$

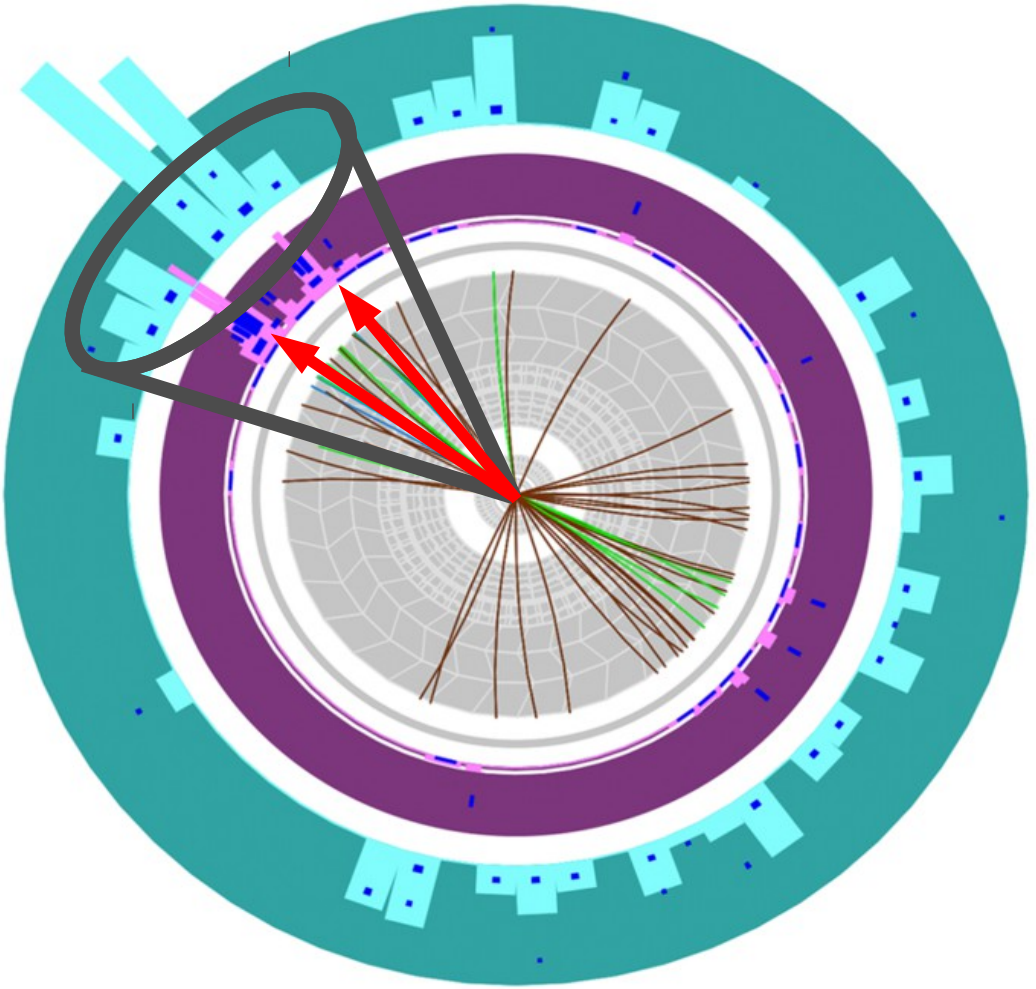


- Jets are broader in central collisions compared to *pp*.
  - But decrease of yields of intermediate p_T particles with r.
- Smallest modification seen in the jet core.

ATLAS-CONF-2018-010

Jet quenching measurement

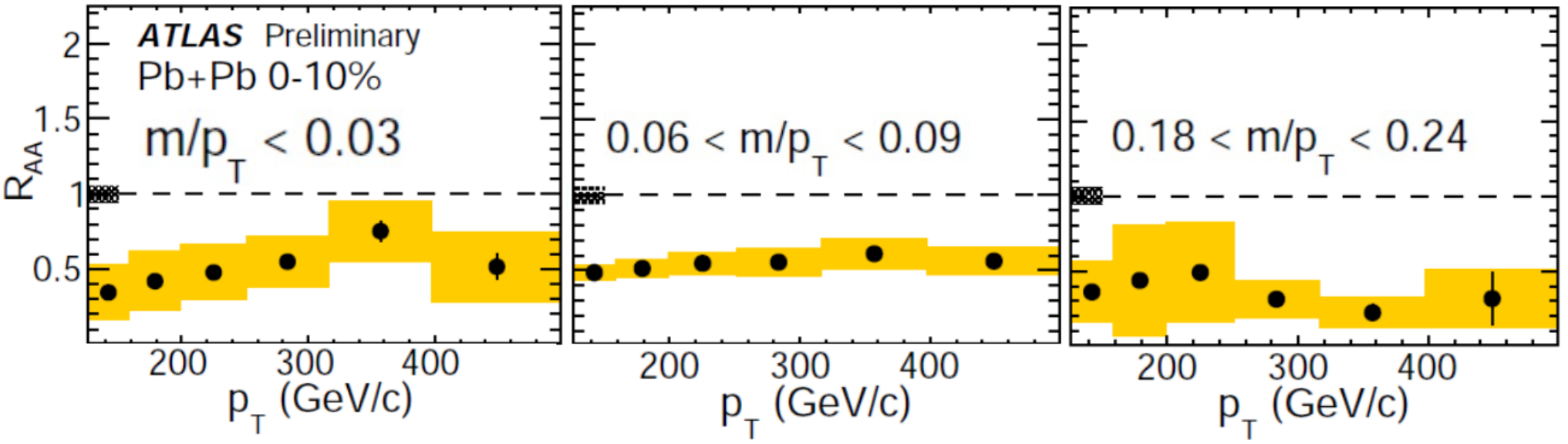
Jet substructure



Jet substructure in HI collisions

- Does the jet suppression depend on jet structure?
- Jet mass carries information about transverse structure of jet.
  - connection to virtuality of initial parton.

Increasing m/p_T

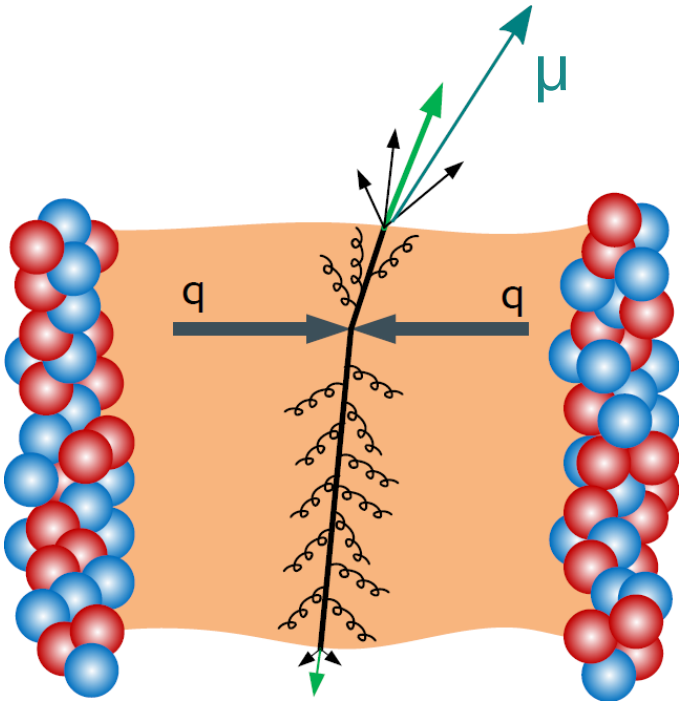


- No significant change of R_{AA} with mass
  → consistent with inclusive jet R_{AA}.

ATLAS-CONF-2018-014

Open heavy flavor

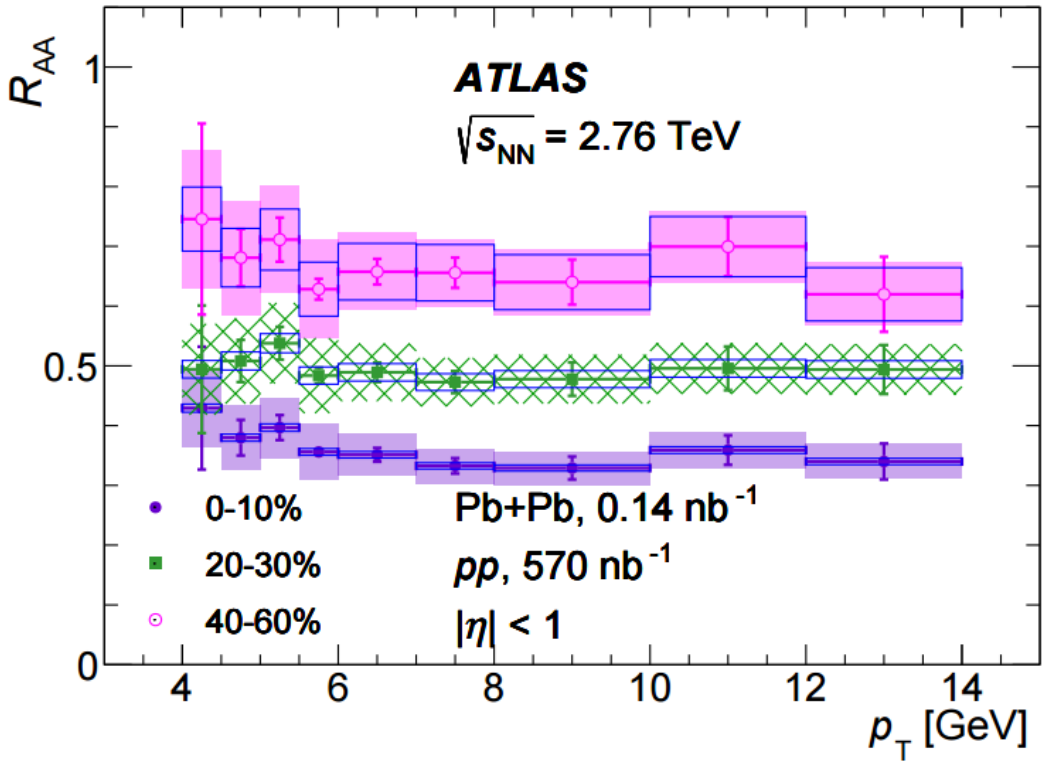
- Different hard probes interact with medium differently.



- Mass of heavy quarks as additional relevant scale.
- Short formation time.
- Small thermal production rate.
- Energy loss depends on:
  - Color charge $\Delta E_g > \Delta E_{u,d,s}$
  - Parton mass $\Delta E_{u,d,s} > \Delta E_c > \Delta E_b$

Heavy flavor muons

- Single muons from HF decays

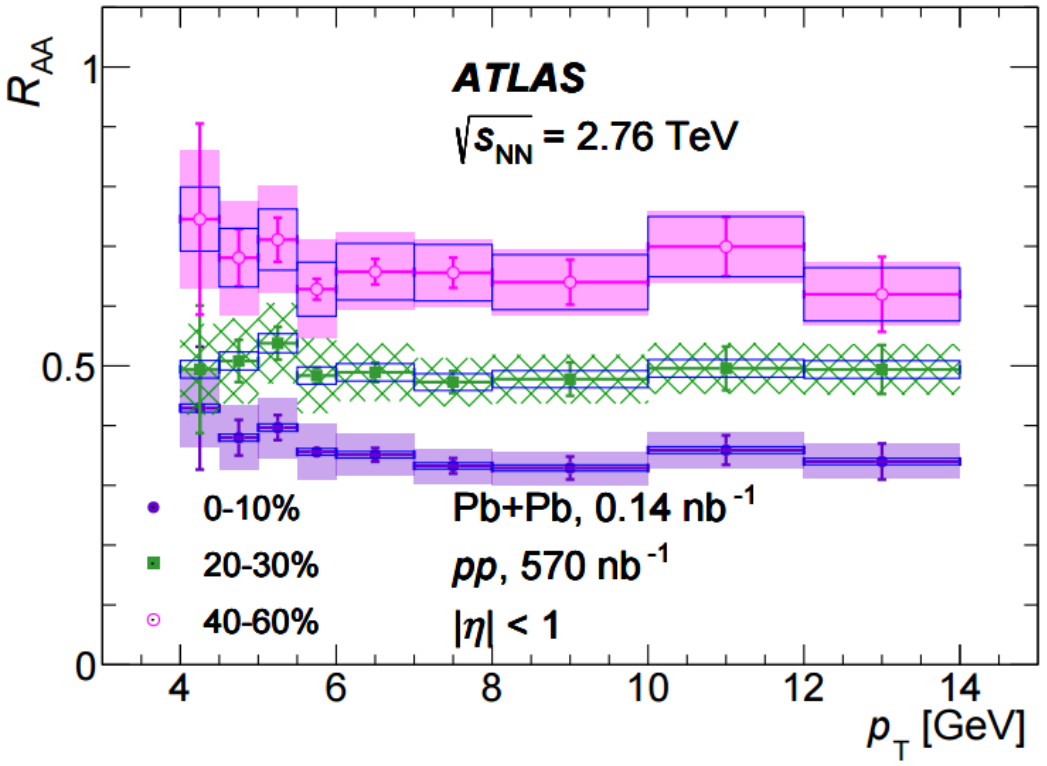


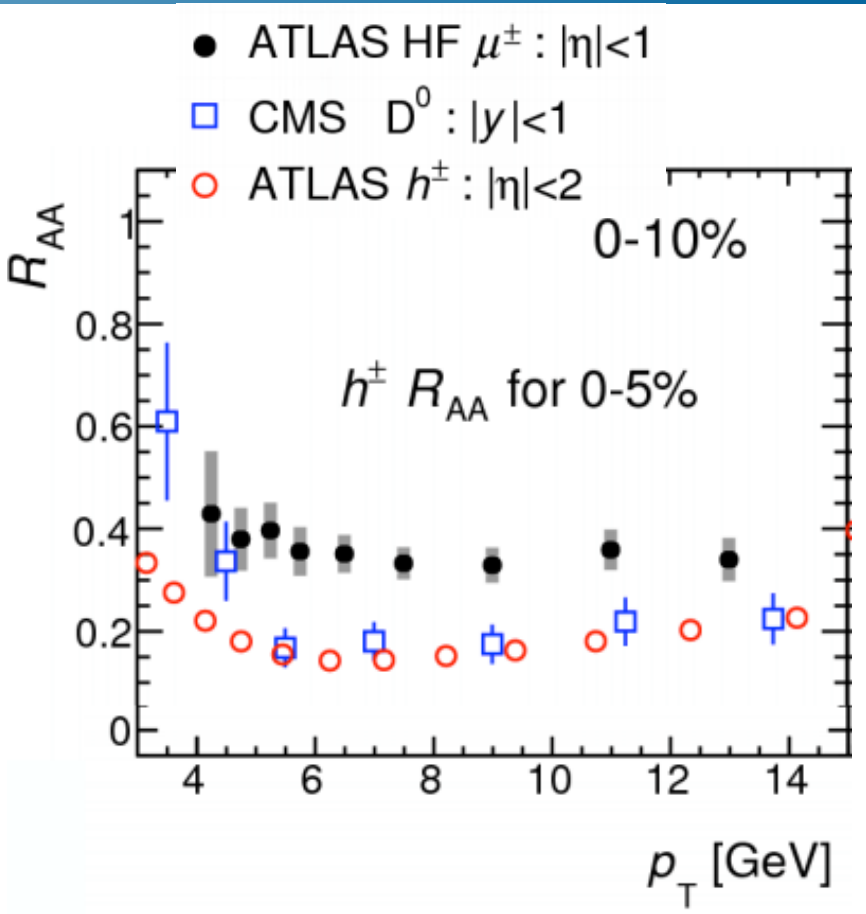
- Suppression factor down to ~0.35 with week p_T dependence.
- How does it compare to hadron suppression?

Phys. Rev. C 98 (2018) 044905

Heavy flavor muons

- Single muons from HF decays



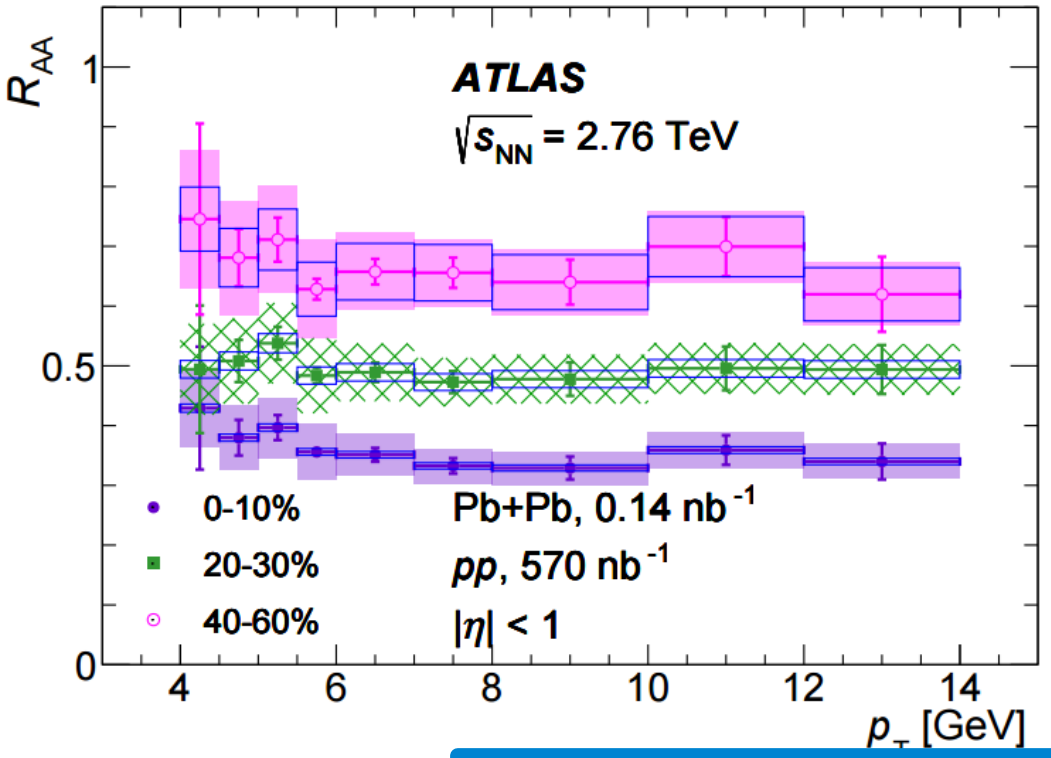


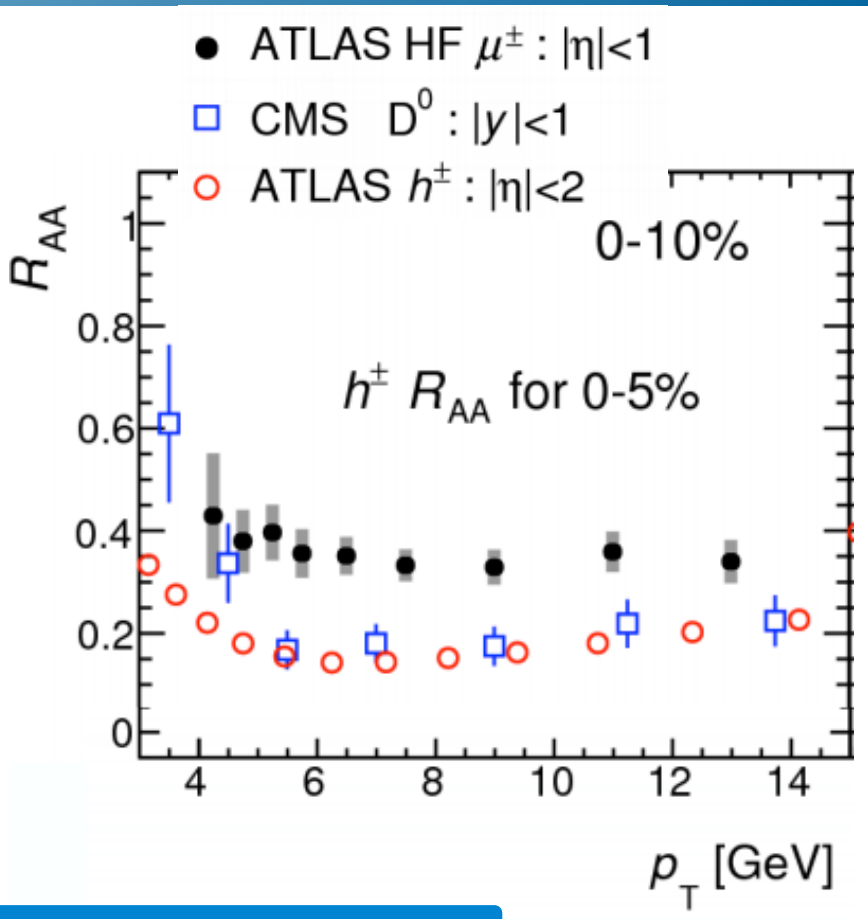
- HF muons less suppressed

Phys. Rev. C 98 (2018) 044905

Heavy flavor muons

- Single muons from HF decays





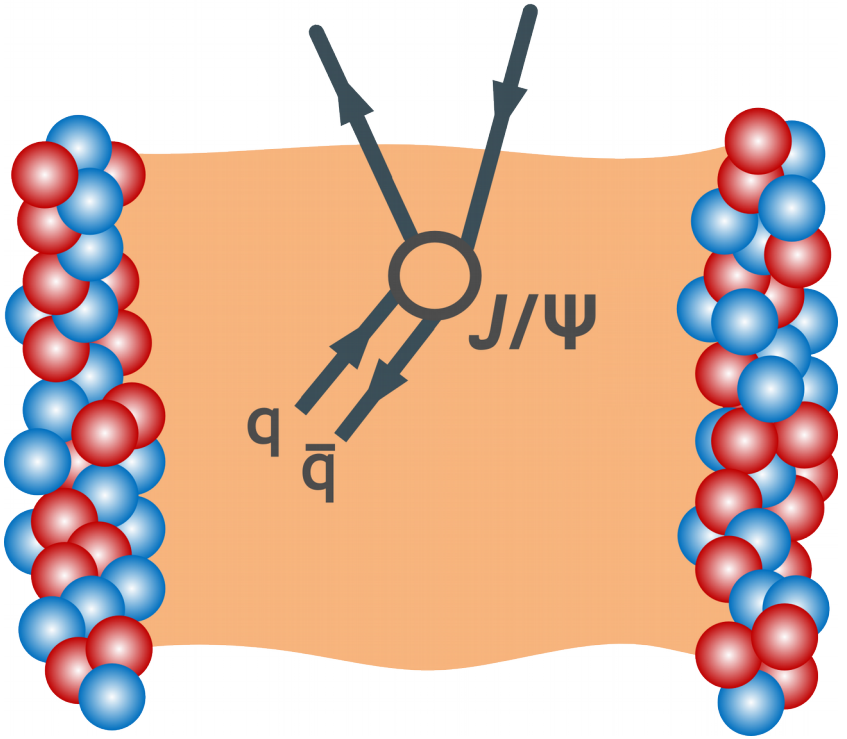
- HF muons

Caveats on R_{AA}:
Different shapes of parton p_T spectra
Different fragmentation

Phys. Rev. C 98 (2018) 044905

Quarkonia

- Different hard probes interact with medium differently .

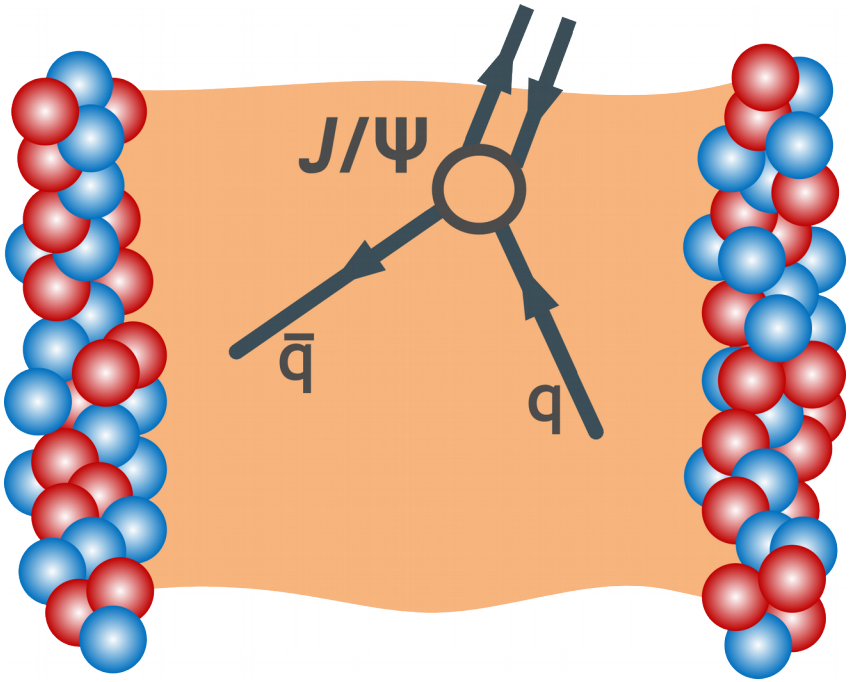


- Dissociation in the medium due to the color screening.
- ➡ Differences in the quarkonium binding energy.
- ➡ Sequential melting with increasing temperature.
- Other effects?

$$\tau^{Q\bar{Q}}_{\text{formation}} \lesssim \tau^{\text{QGP}}_{\text{formation}} < \tau^{\text{QGP}}_{\text{life}} < \tau^{\text{quarkonia}}_{\text{life}}$$

Quarkonia

- Different hard probes interact with medium differently



- Dissociation in the medium due to the color screening.

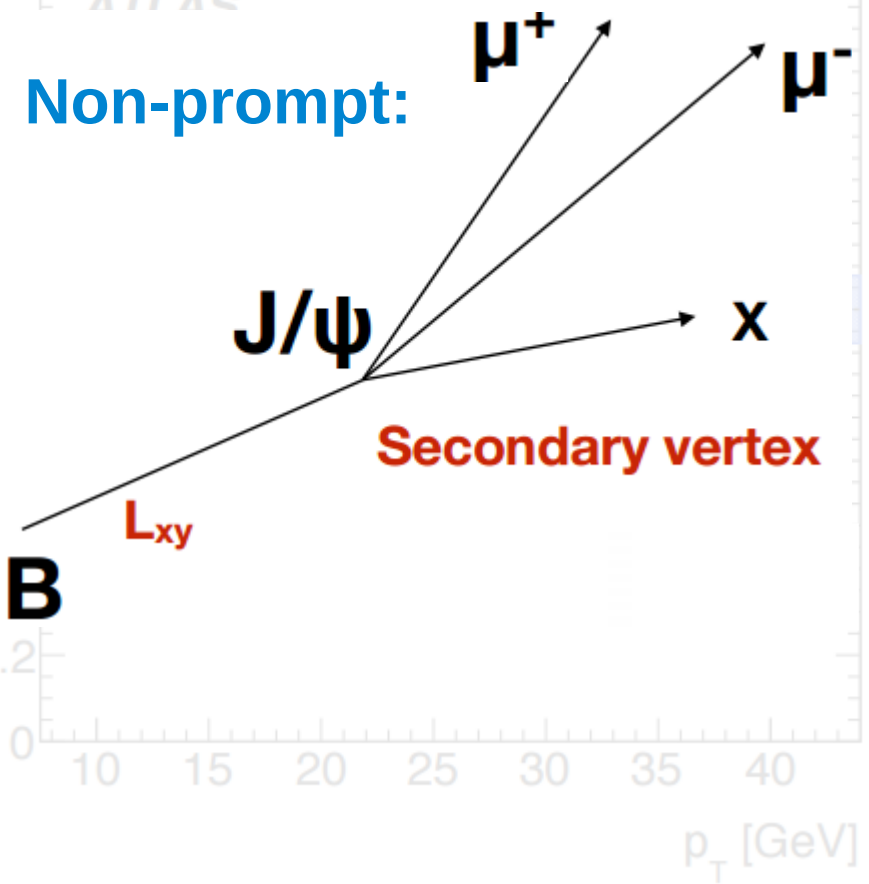
➡ Differences in the quarkonium binding energy.

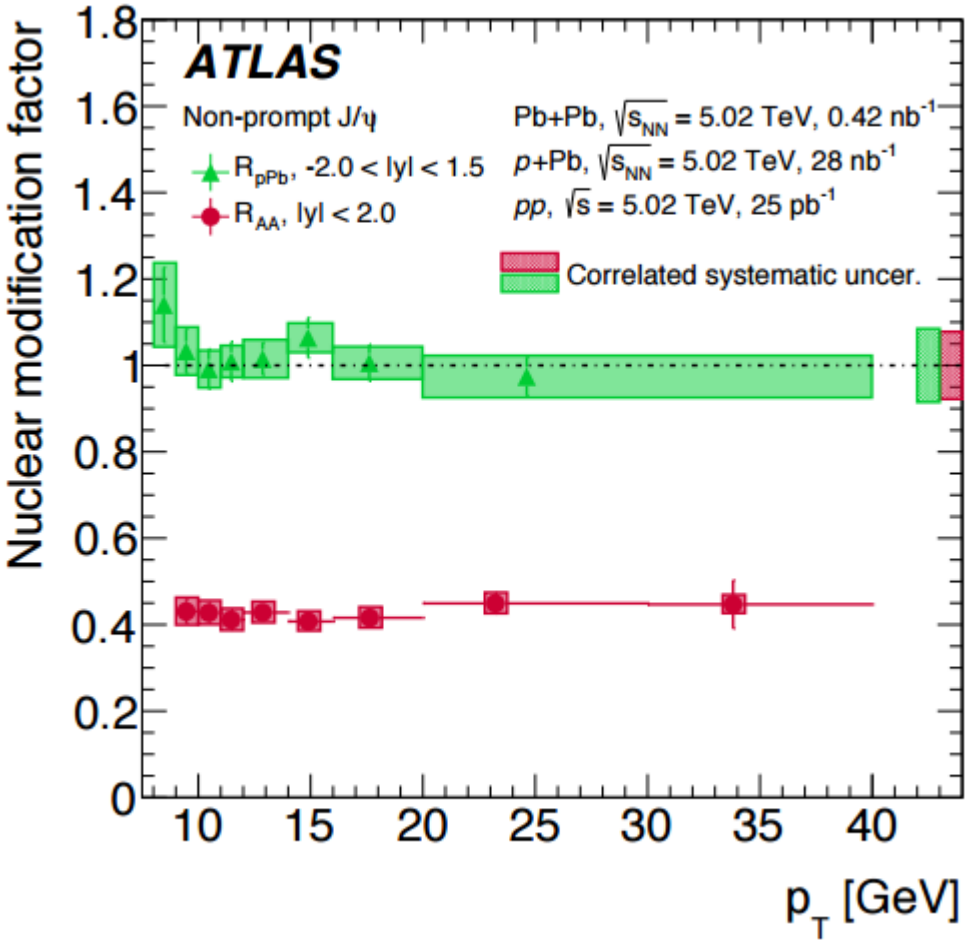
➡ Sequential melting with increasing temperature

...or can we see a recombination?

...may also be sensitive to energy loss.

J/ψ production in HI collisions

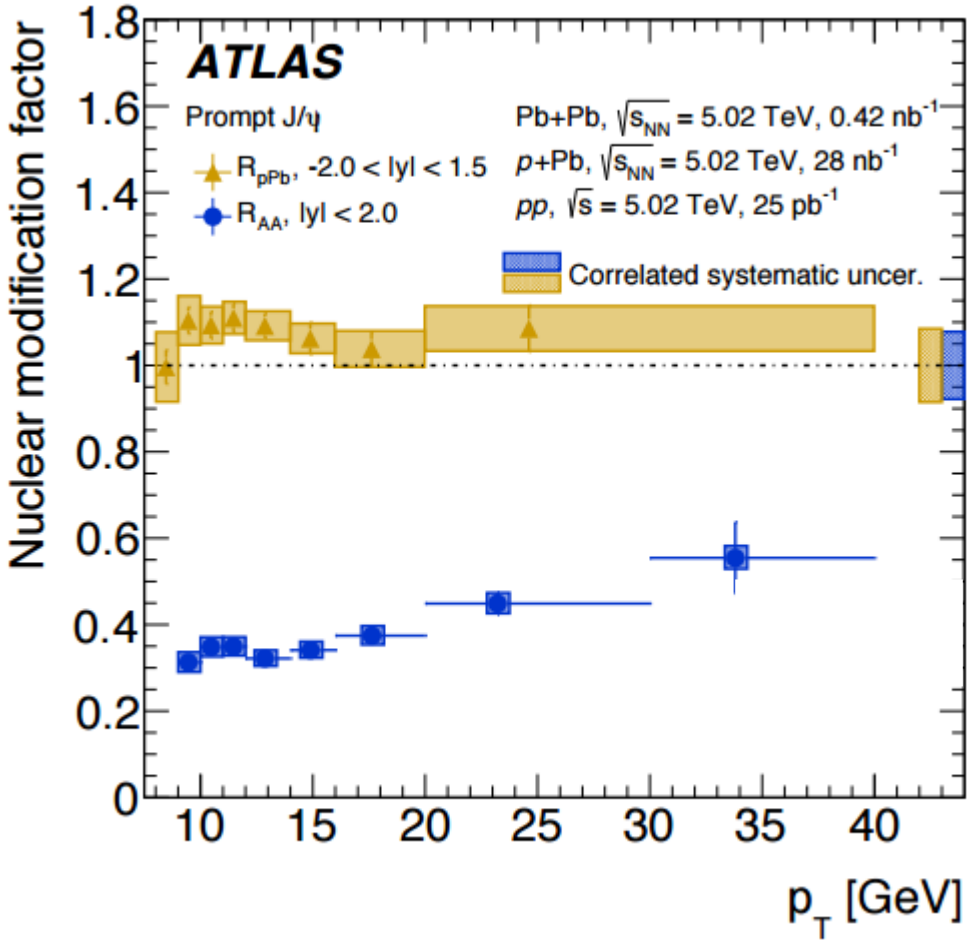


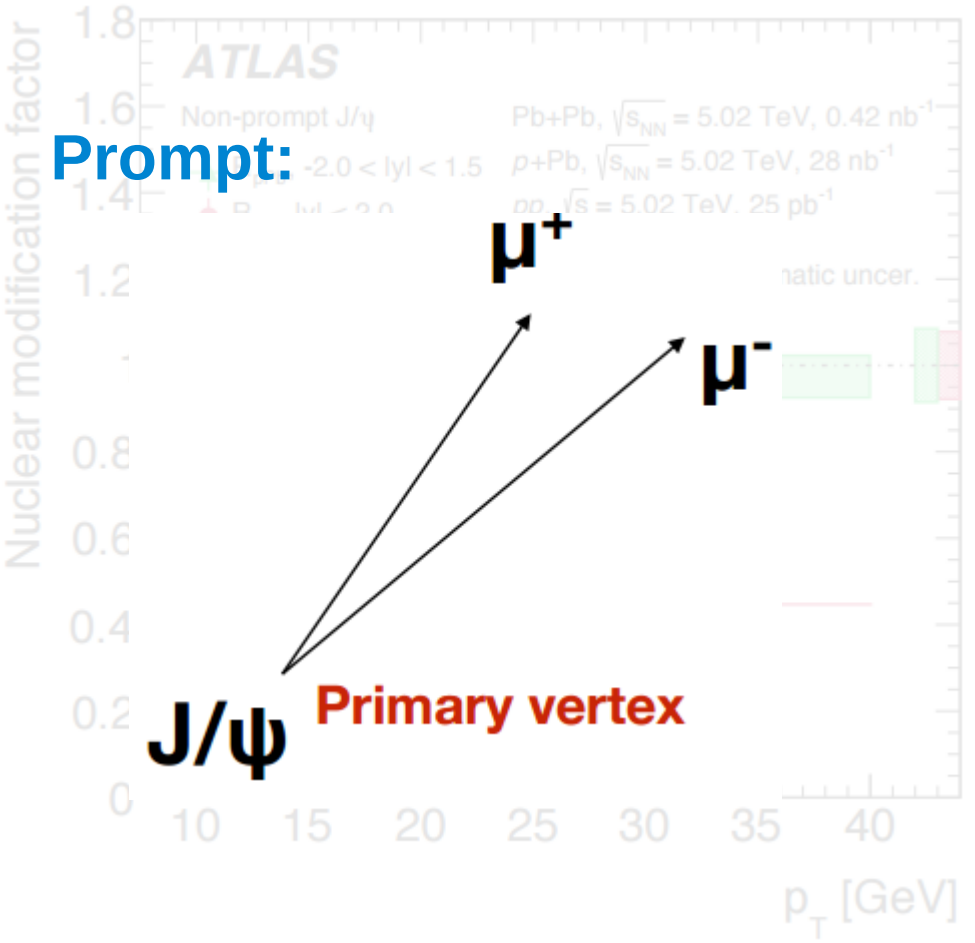


- Sensitive to energy loss of b-quarks in the medium

Eur. Phys. J. C 78 (2018) 762

J/ψ production in HI collisions



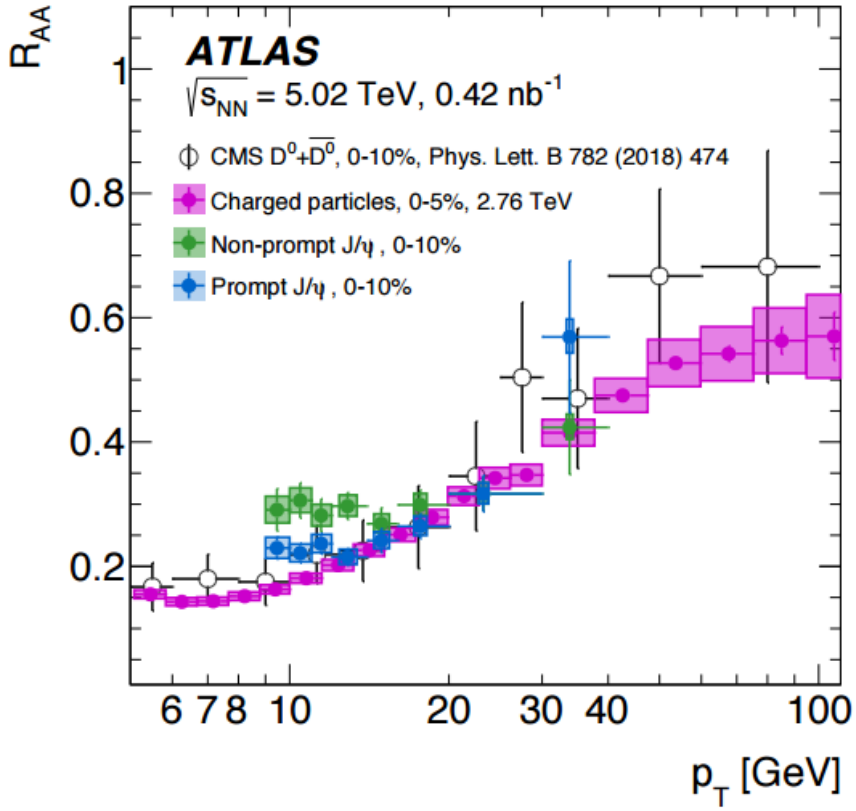


- Sensitive to screening, regeneration, and potentially energy loss.

Eur. Phys. J. C 78 (2018) 762

J/ψ production in HI collisions

Direct comparison to charged hadrons



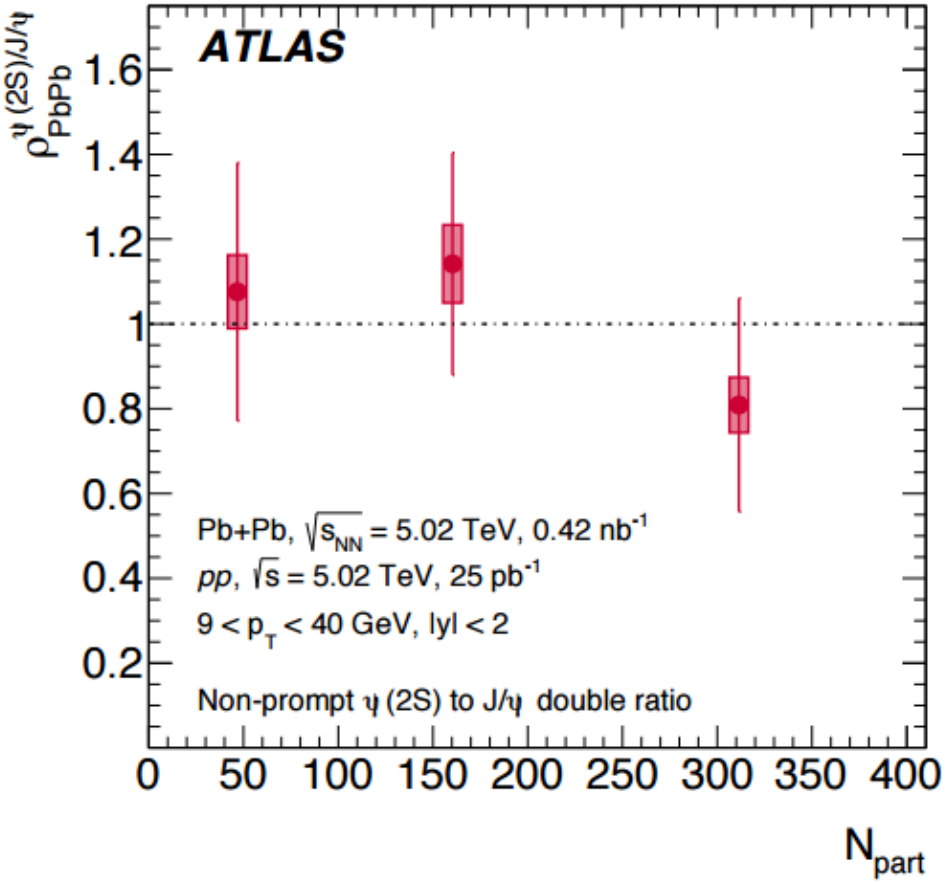
Eur. Phys. J. C 78 (2018) 762

J/ψ and ψ(2s) production

- Comparison of suppression of J/ψ and ψ(2s).

$$\rho_{\mathrm{PbPb}}^{\psi(2\mathrm{S})/J/\psi} = R_{\mathrm{AA}}^{\psi(2\mathrm{S})} / R_{\mathrm{AA}}^{J/\psi}$$

Non-prompt:



R_{AA} (J/ψ) = R_{AA}(ψ(2s))

- No difference is expected as both are coming from B decays outside the QGP.

Eur. Phys. J. C 78 (2018) 762

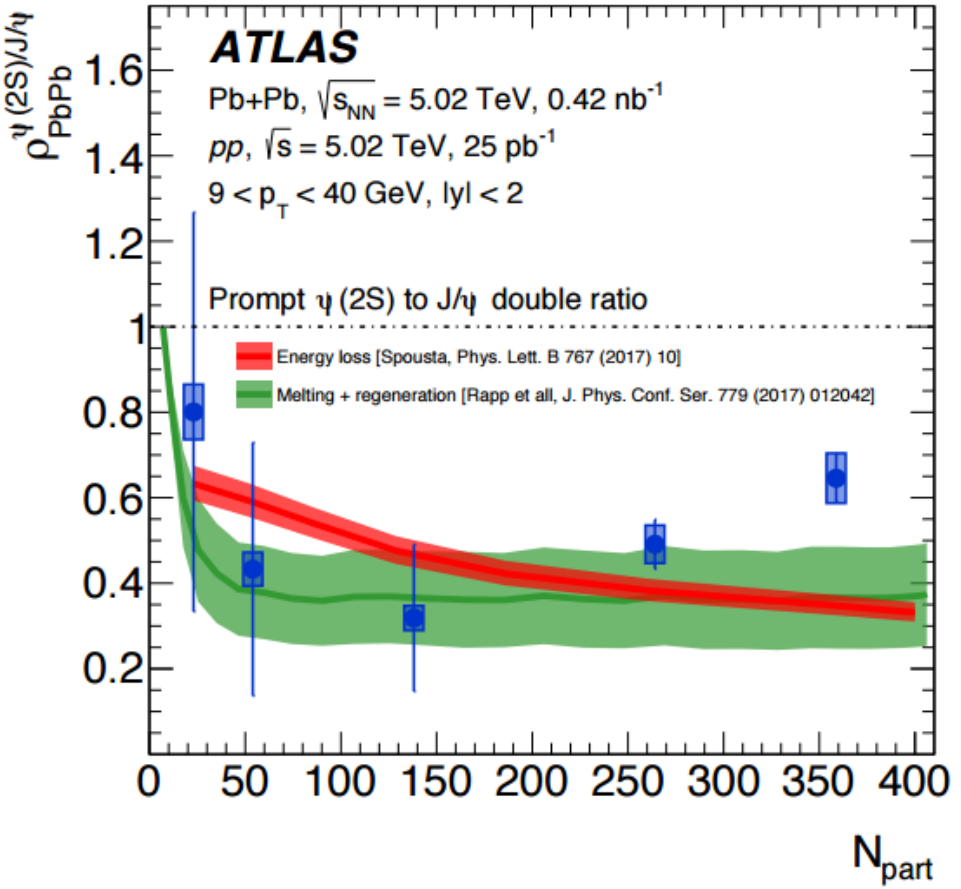
J/ψ and ψ(2s) production

- Comparison of suppression of J/ψ and ψ(2s).

$$\rho_{\mathrm{PbPb}}^{\psi(2\mathrm{S})/J/\psi} = R_{\mathrm{AA}}^{\psi(2\mathrm{S})} / R_{\mathrm{AA}}^{J/\psi}$$

Prompt:

R_{AA} (J/ψ) > R_{AA}(ψ(2s))

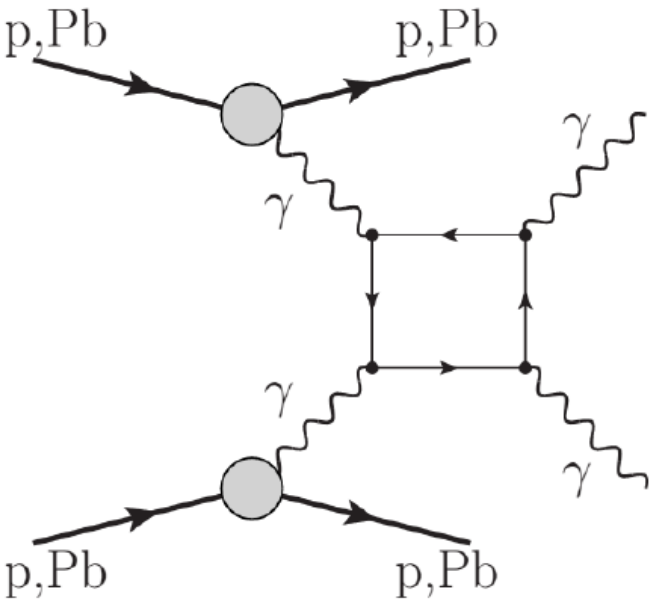


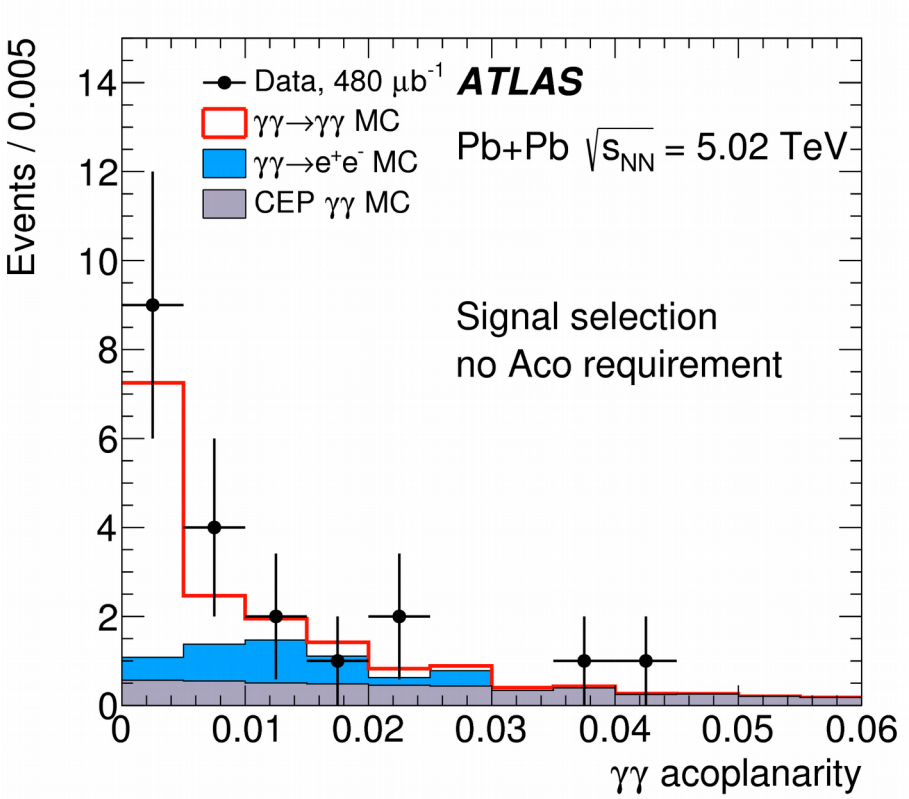
- Consistent with both sequential **melting + recombination** as well as **energy loss.**

Eur. Phys. J. C 78 (2018) 762

New probes

- Large electromagnetic fields accompanying the nuclei.
- Flux of coherently emitted γ by whole nucleus enhanced by Z^2
- Allows measurement processes like Light-by-Light scattering

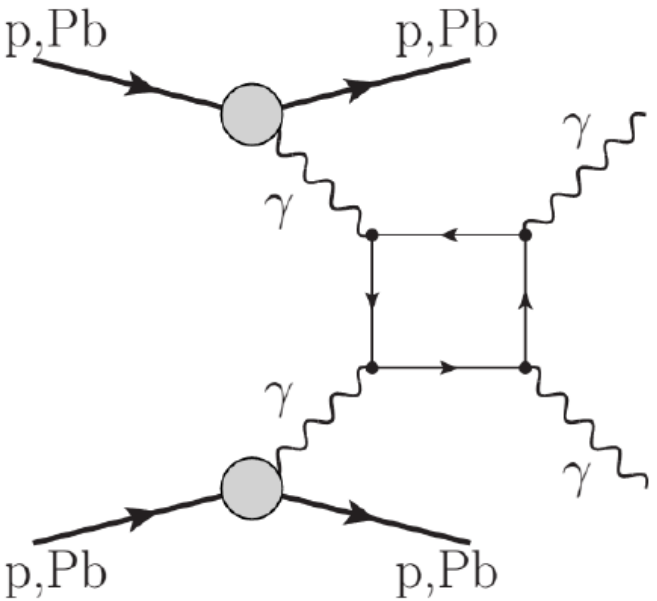


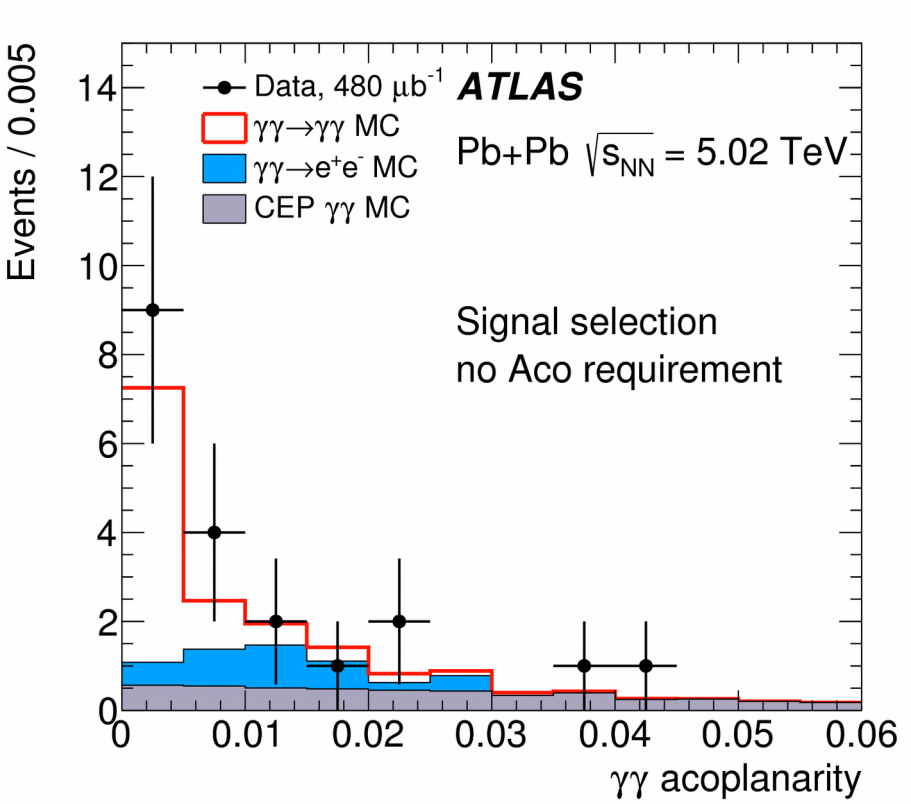


Nature Physics 13 (2017) 852

New probes

- Large electromagnetic fields accompanying the nuclei.
- Flux of coherently emitted γ by whole nucleus enhanced by Z^2
- Allows to measure e.g. light-by-light scattering.

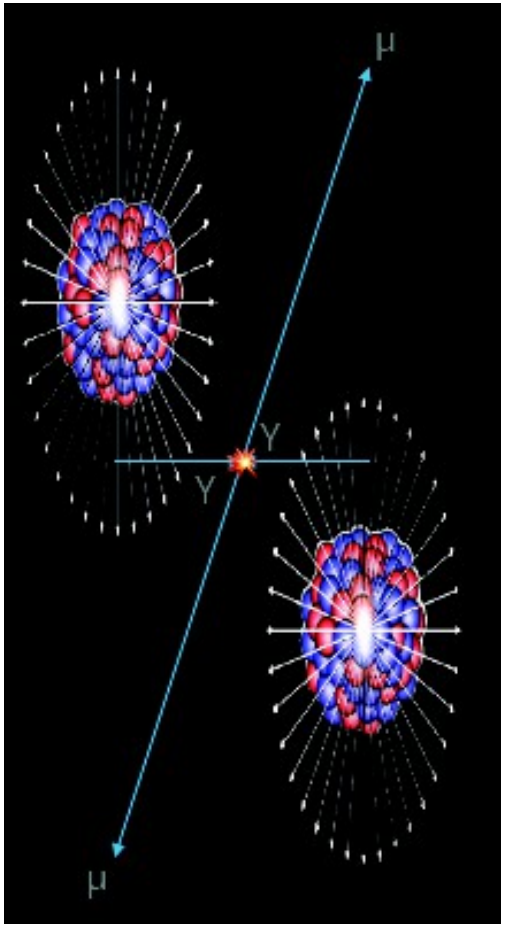




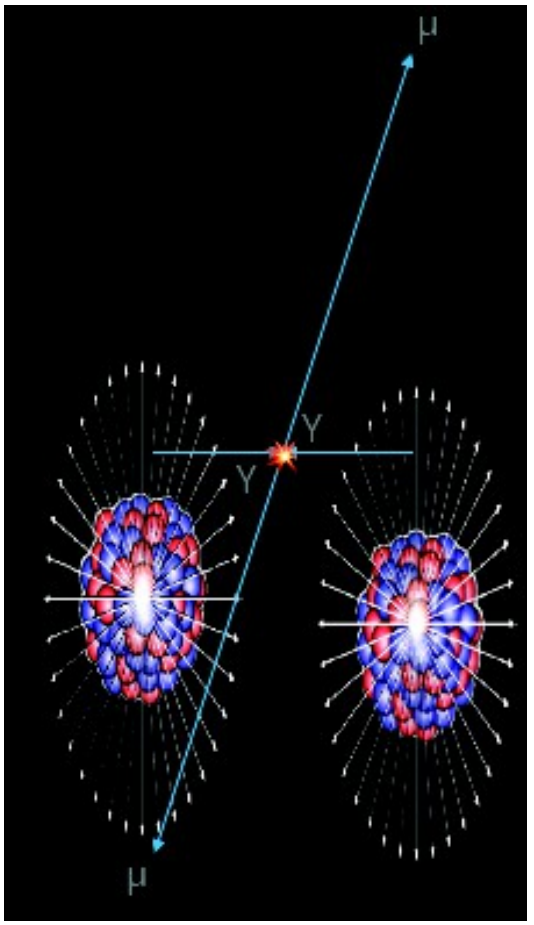
Can we use quasi real photon-photon collisions to probe QGP?

Nature Physics 13 (2017) 852

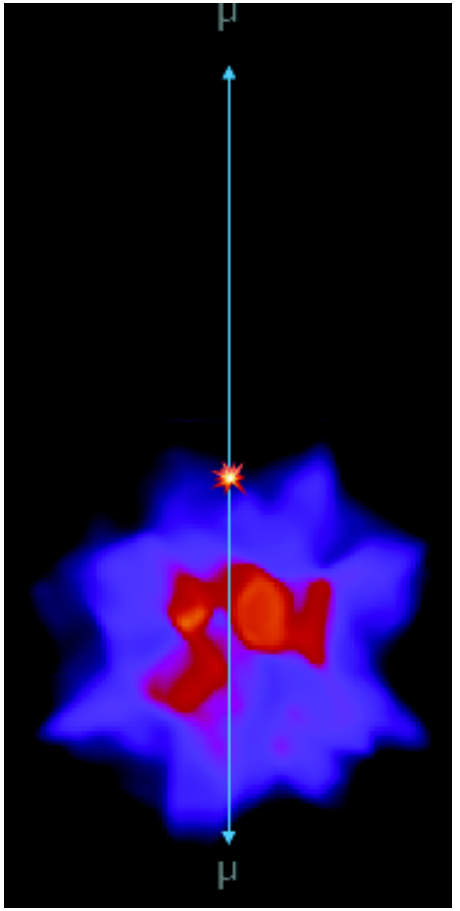
UPC dimuons in non-UPC events



UPC event



non-UPC event



UPC muon in non-UPC event probing QGP

UPC dimuons in non-UPC events

- Low p_T of the photons

  → muons produced nearly back-to-back in azimuth

- → nearly identical transverse momenta.
- What happens to azimuthal correlation and balance in central collisions?

$$\alpha \equiv 1 - \frac{|\phi^+ - \phi^-|}{\pi} \qquad A \equiv \left| \frac{p_T^+ - p_T^-}{p_T^+ + p_T^-} \right|$$

Acoplanarity *Asymmetry*

- Background from semileptonic decays of heavy-flavor hadrons is subtracted.

UPC dimuons in non-UPC events

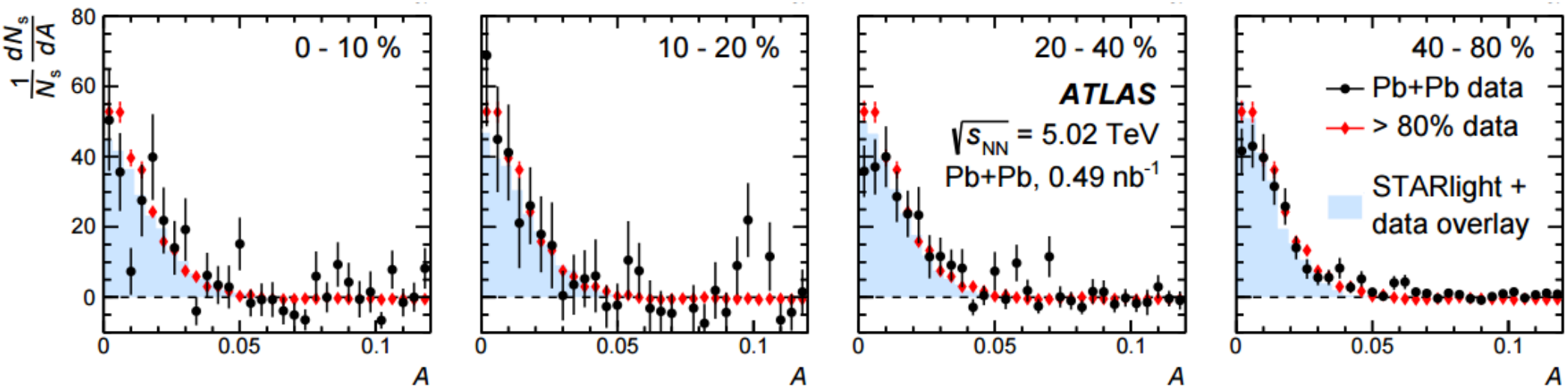
- Low p_T of the photons

  → muons produced nearly back-to-back in azimuth

  → nearly identical transverse momenta.

- What happens to azimuthal correlation and balance in central collisions?

decreasing centrality



No modification

arXiv:1806.08708

UPC dimuons in non-UPC events

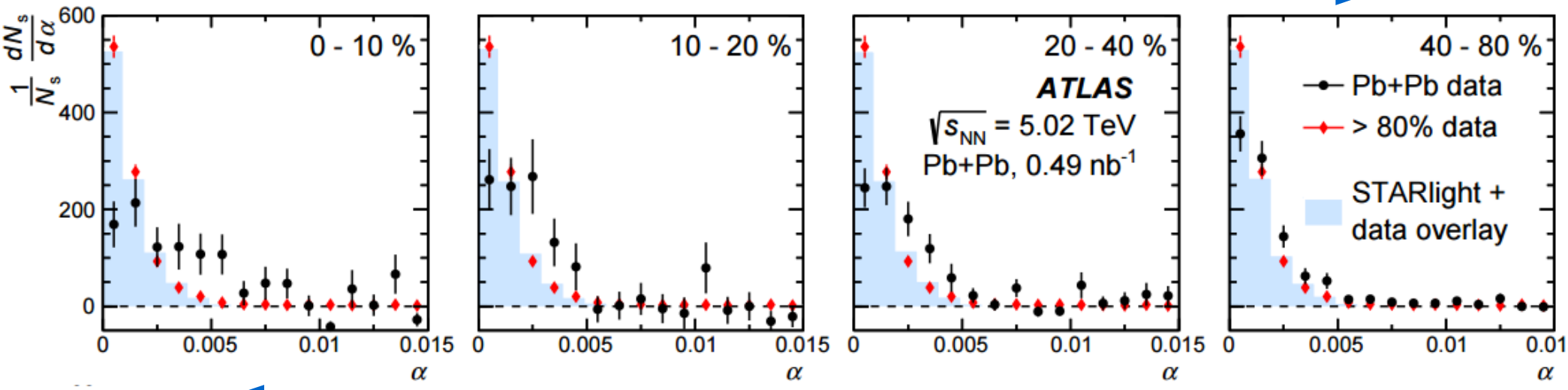
- Low p_T of the photons

  → muons produced nearly back-to-back in azimuth

  → nearly identical transverse momenta.

- What happens to azimuthal correlation and balance in central collisions?

decreasing centrality

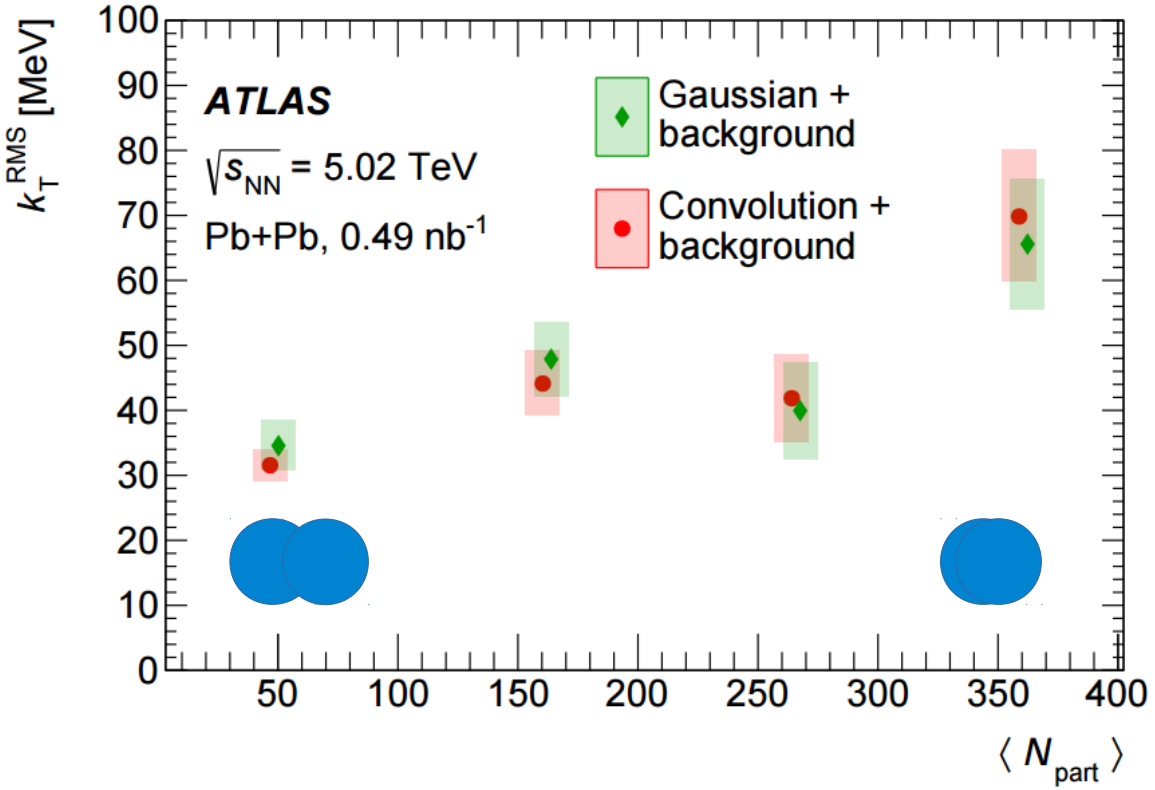


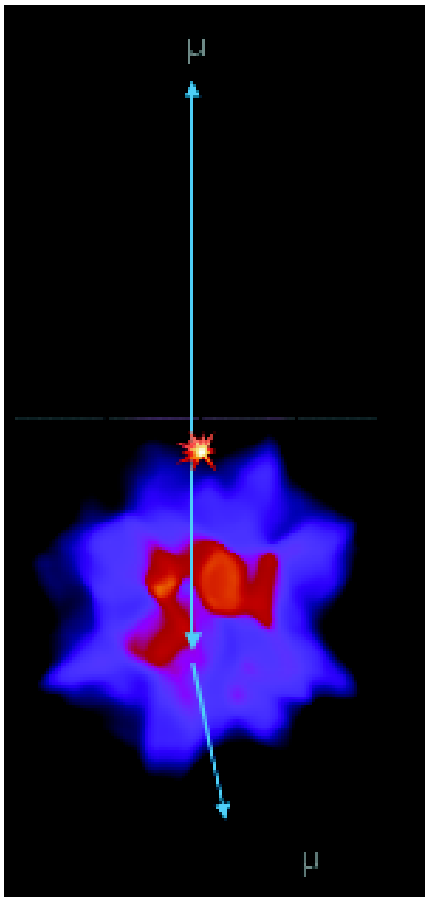
broadening increases

arXiv:1806.08708

Do we see interaction with QGP?

- Assume broadening as resulting from a physical process.
  → transfers a small amount of $\langle k_T \rangle$
  - Extracted from measured distributions.





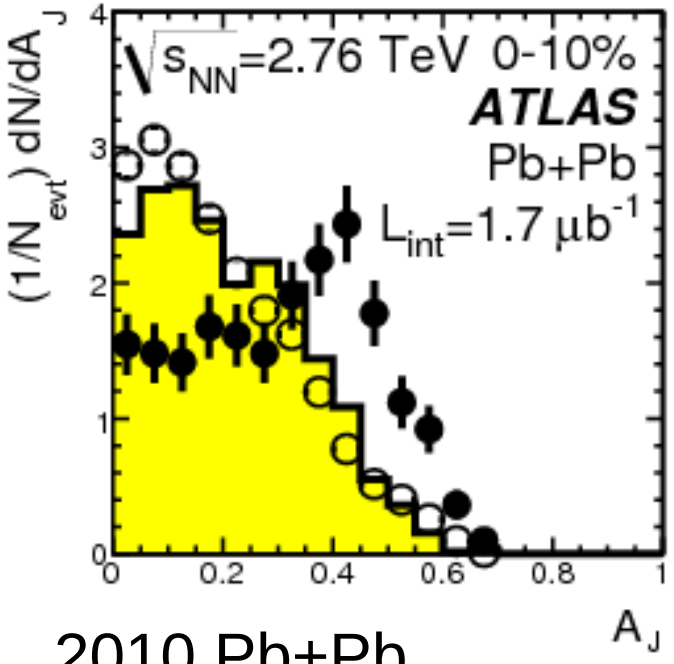
- Qualitatively consistent with re-scattering of muons in the QGP.

arXiv:1806.08708

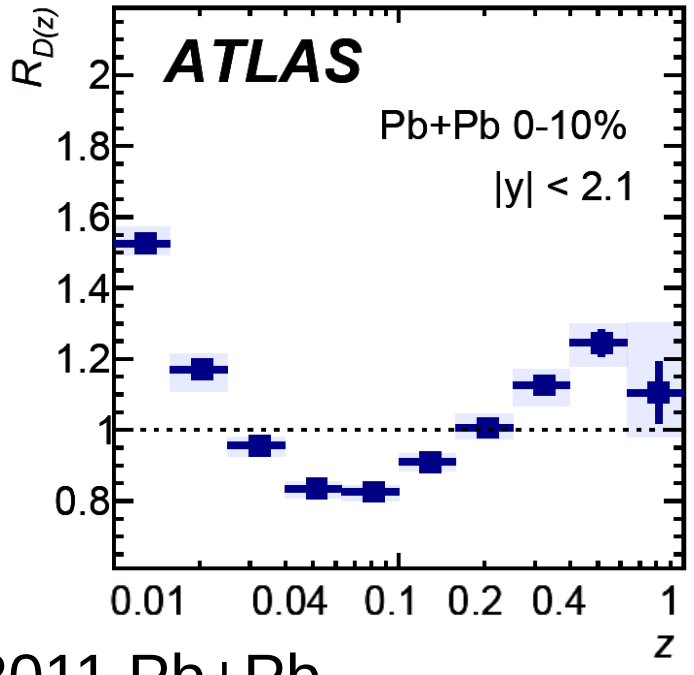
Summary

- Using high statistics LHC data and new techniques bring us to era of precise measurements in heavy-ion collisions
  - Strong constraints on theoretical models.
- We still need new measurements
  - Each observable is sensitive to different aspect of probing the QGP.
  - New probes like EM-induced processes give new perspective on QED, QCD, and QGP

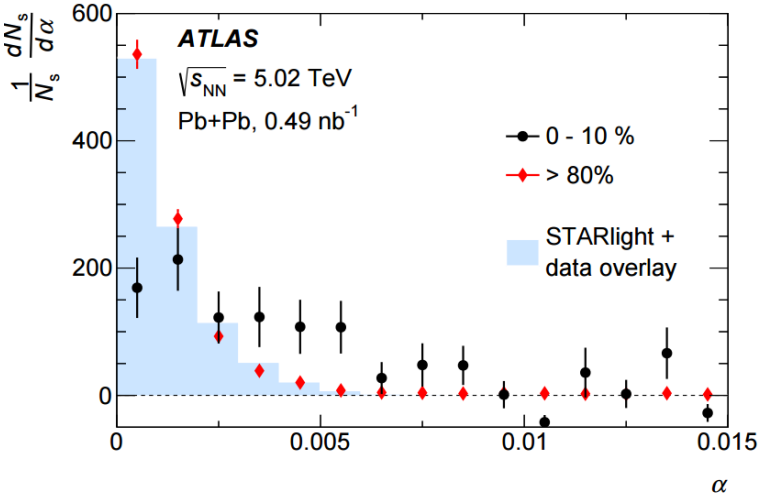
All ATLAS Heavy Ion public results:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults



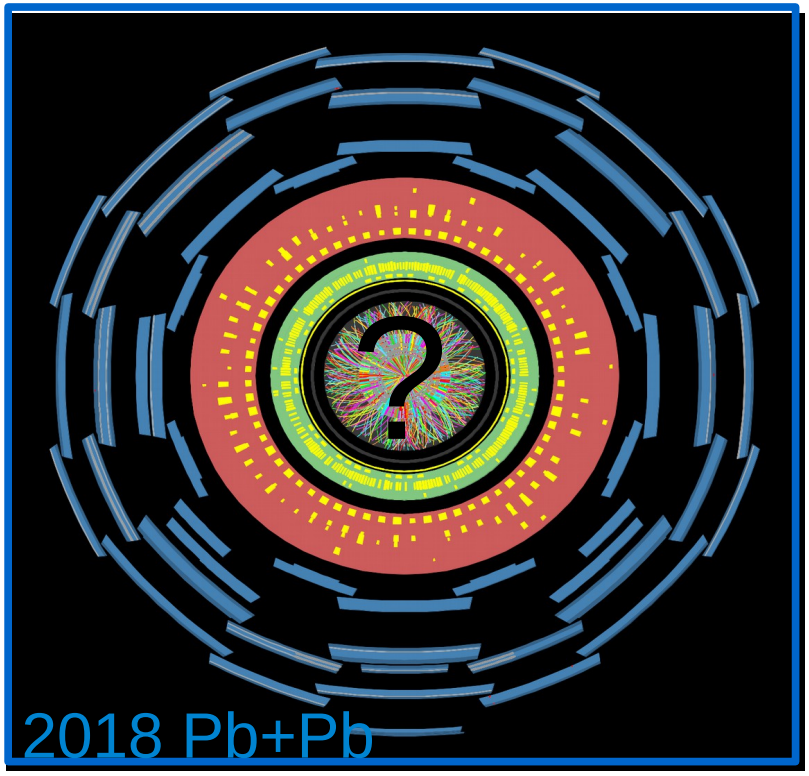
2010 Pb+Pb



2011 Pb+Pb



2015 Pb+Pb



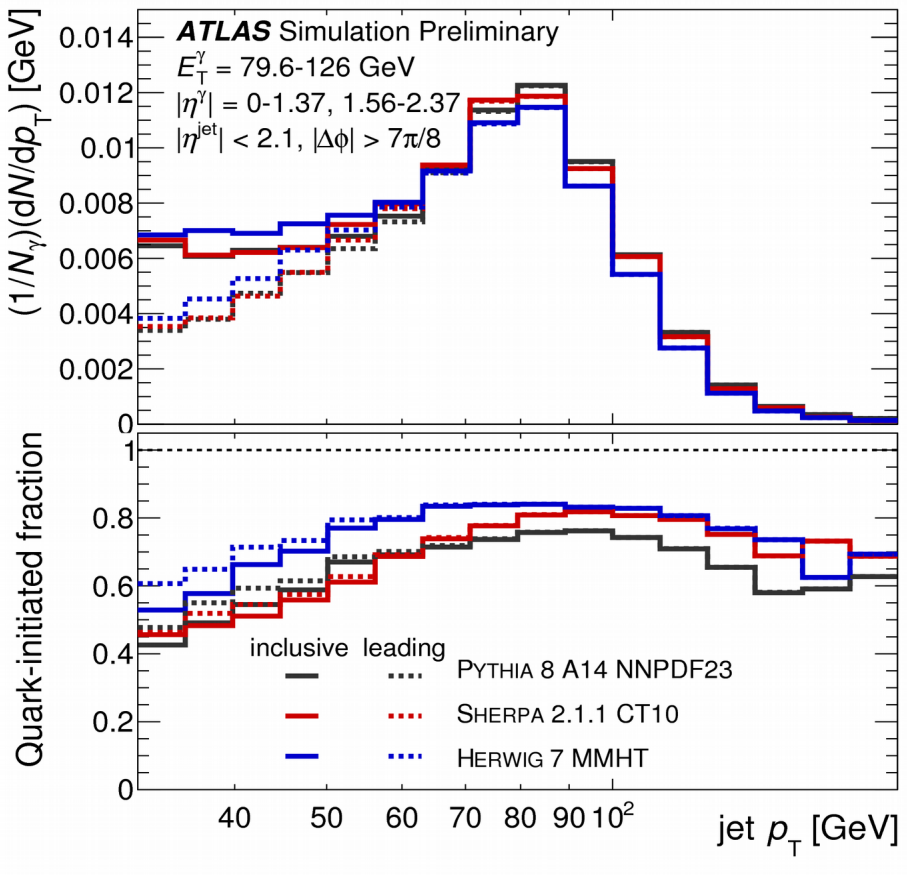
2018 Pb+Pb

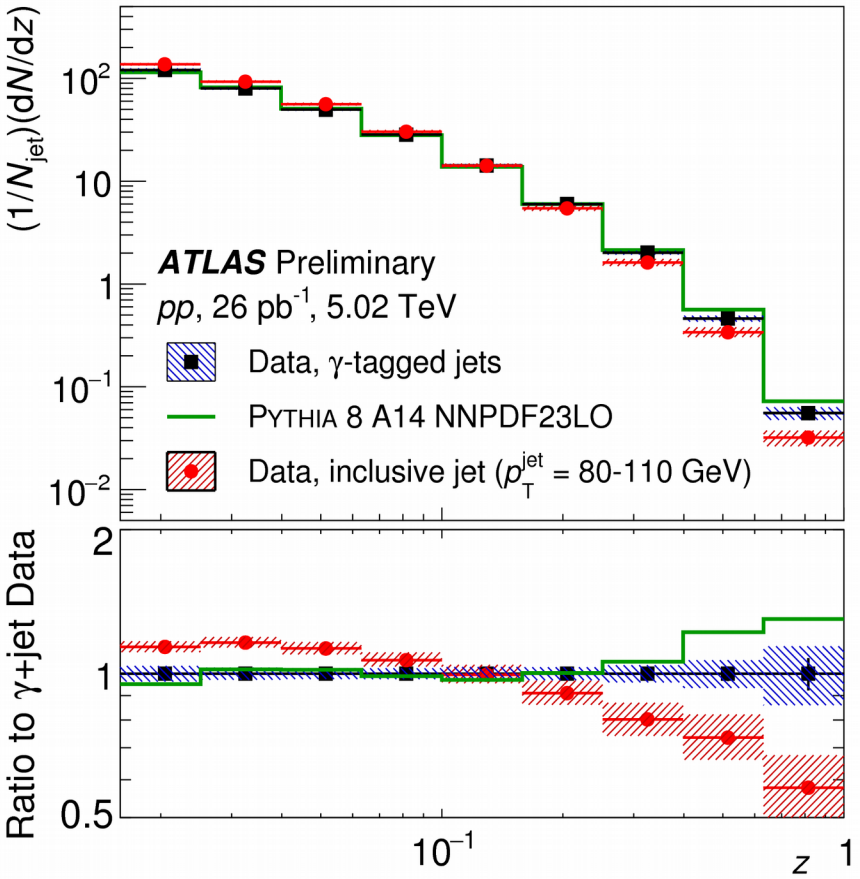
Backup

Photon-tagged jet fragmentation

- Enhanced quark jet contribution compared to inclusive jets.

➡ flavor dependence of quenching.

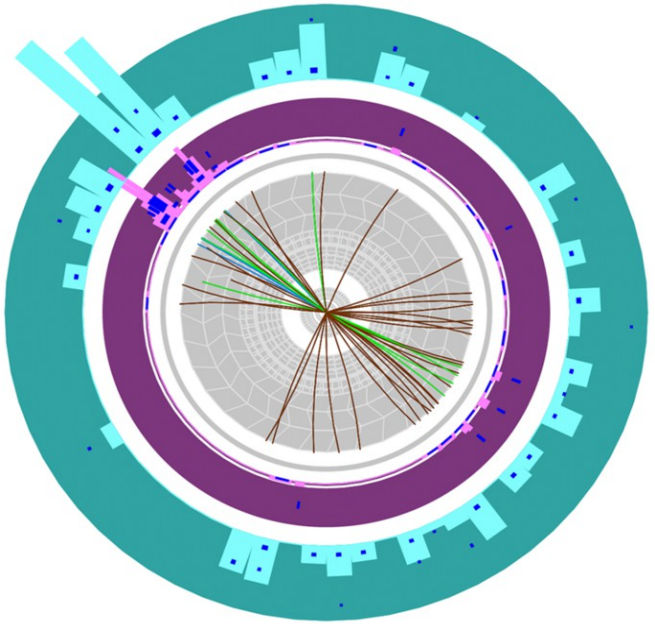


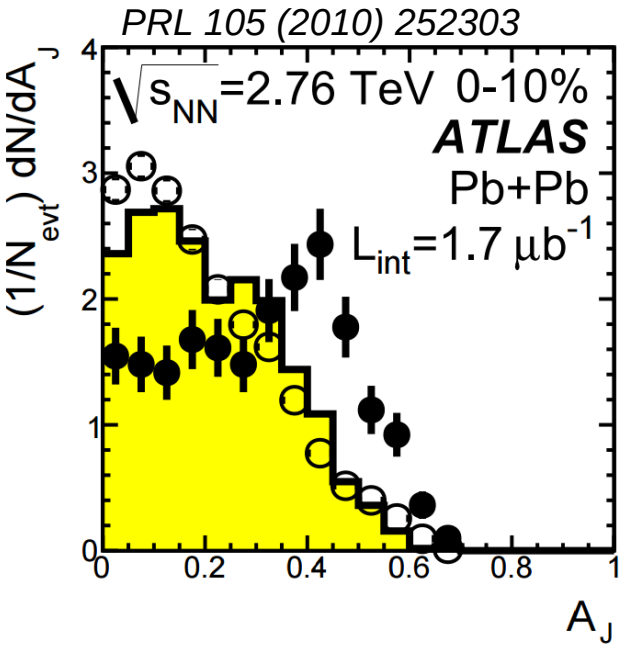


➡ Steeper FF in photon-tagged jets.

ATLAS-CONF-2017-074

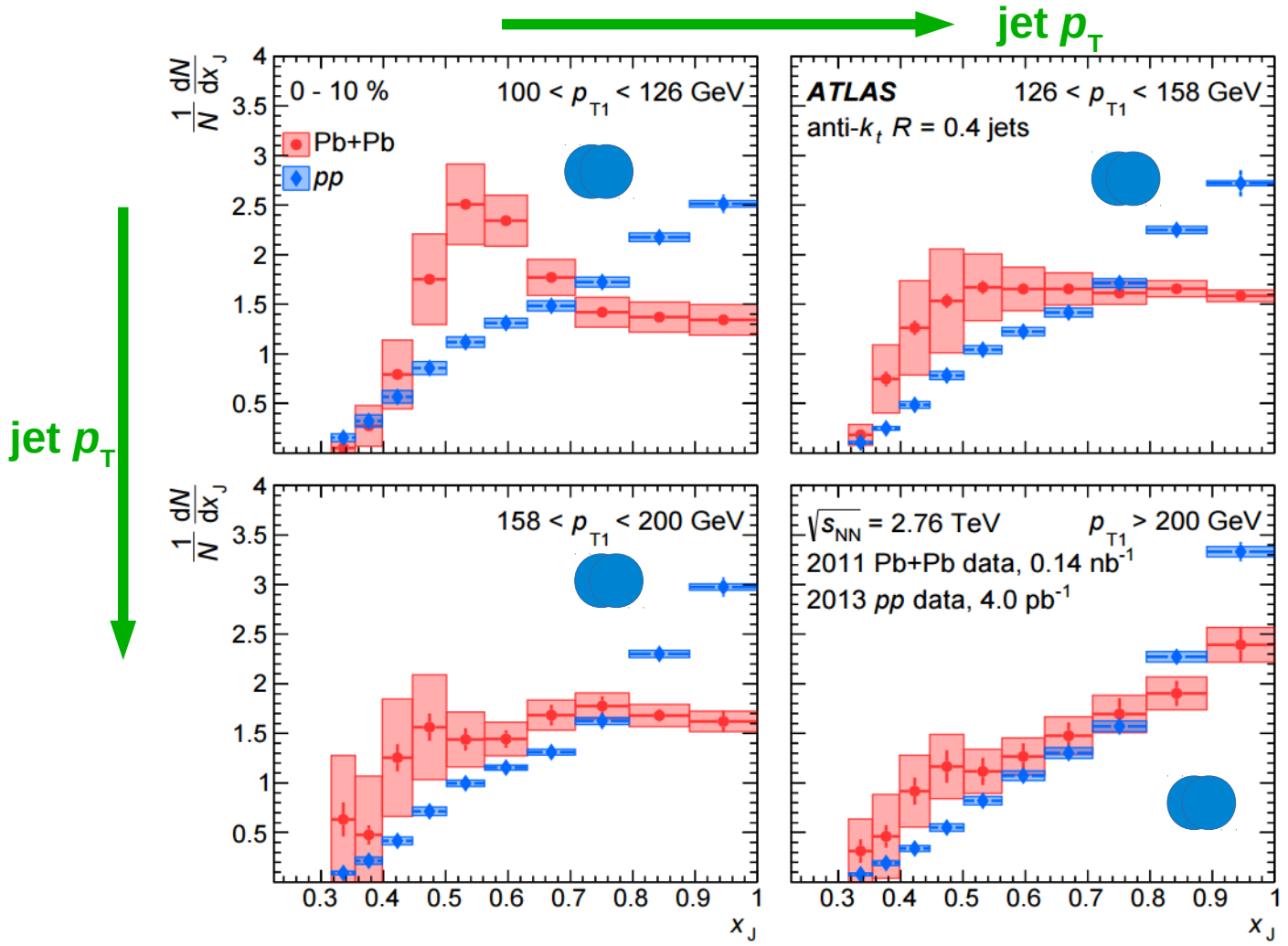
Jets and charged hadrons





- A significant modification of di-jets and suppression of inclusive jet spectra is observed in central HI collisions.
  - Is the energy redistributed to the medium out of the jet cone?
  - Does the energy remain inside the jet but redistributed among fragments?
  - How much modification is coming from initial nPDF effects?
- Understanding modification of parton showers is essential for understanding of properties of medium.

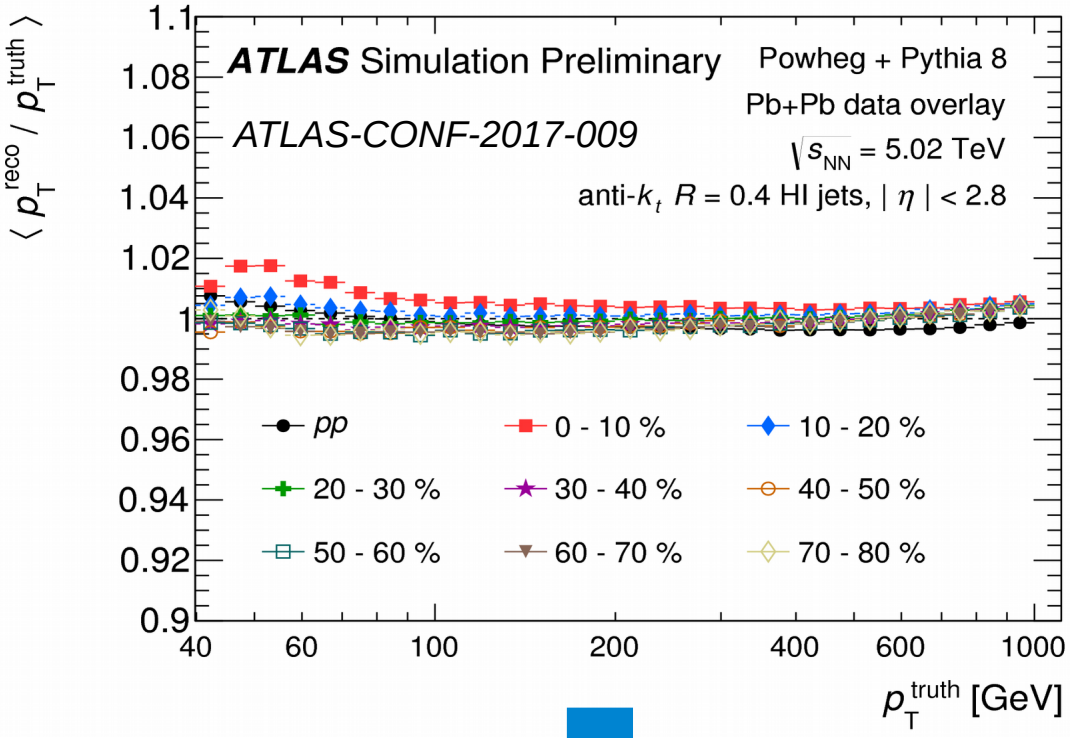
Di-jet asymmetry

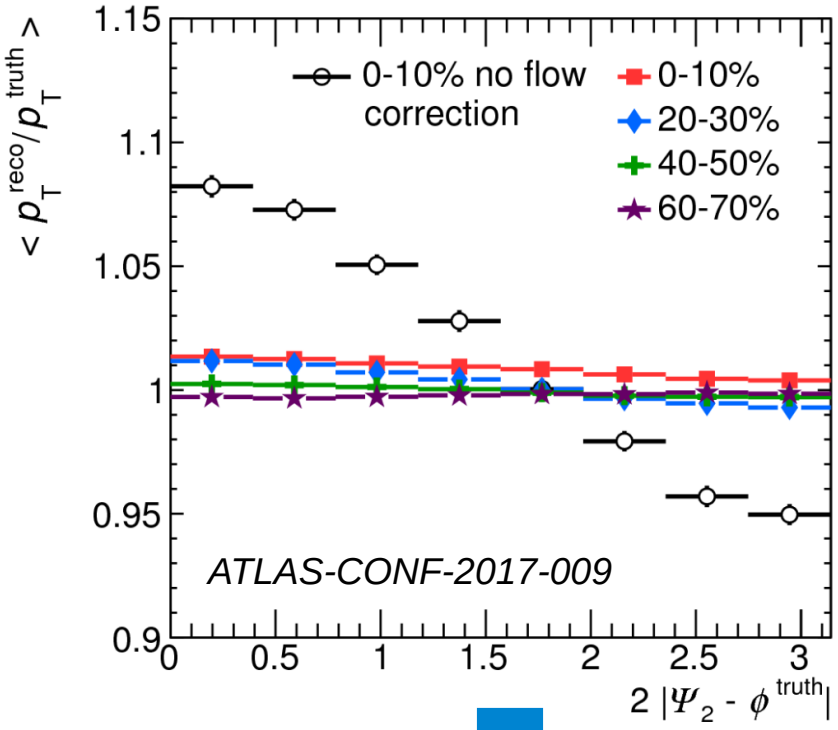


- Much less modification at high p_T.

PLB 774 (2017) 379

Performance of jet reconstruction

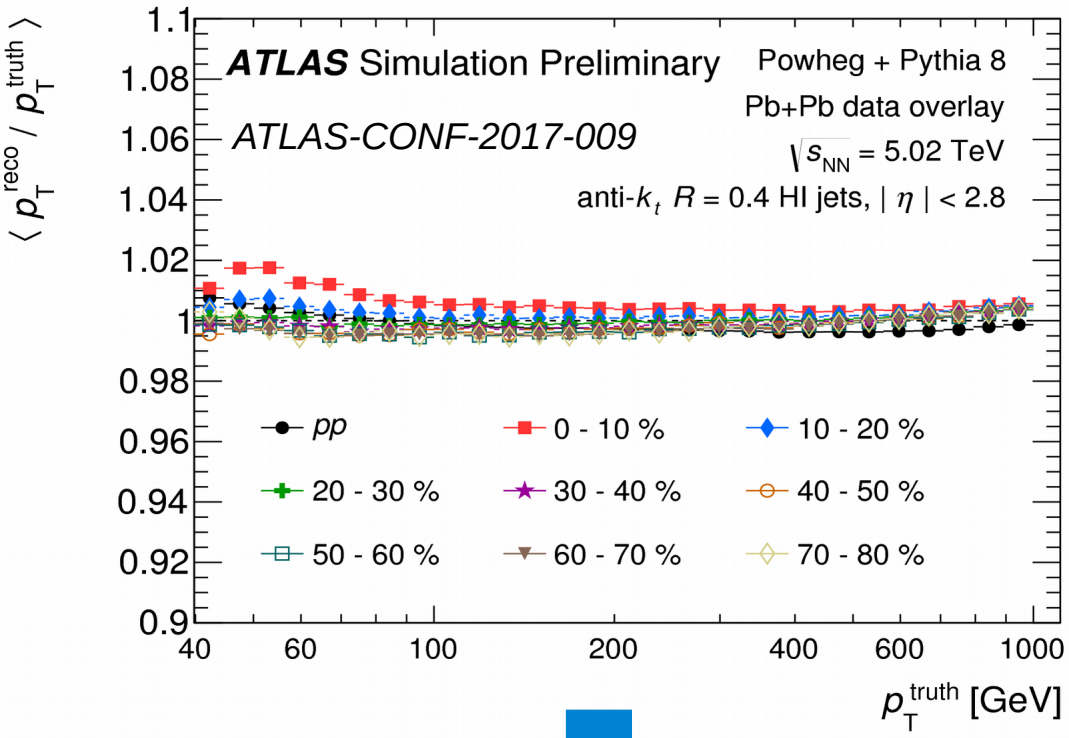


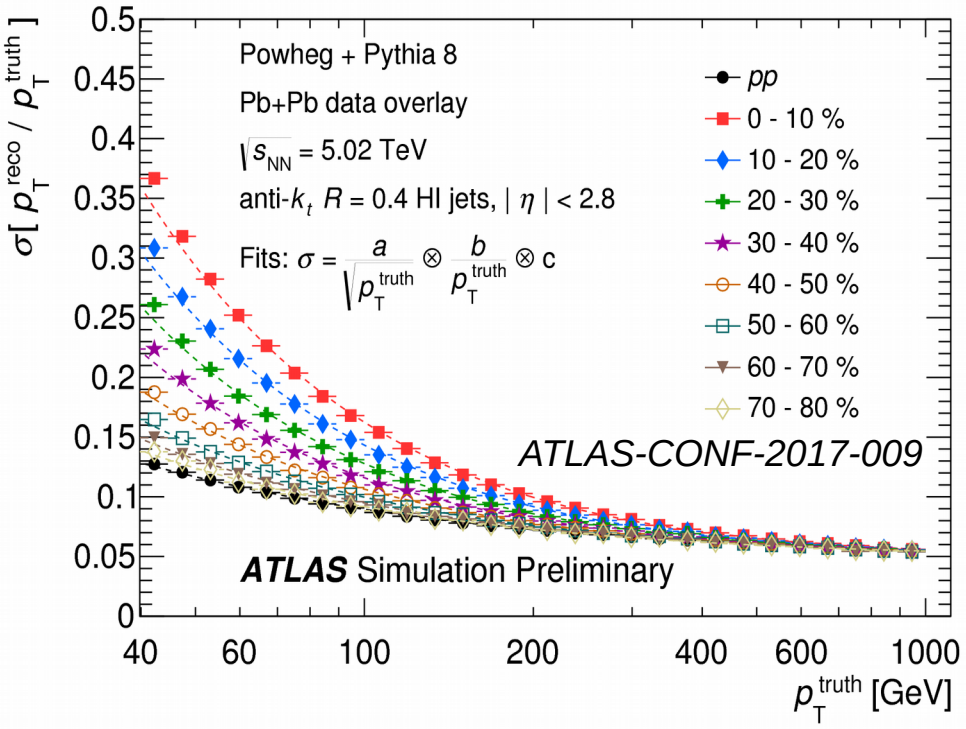


Average responses within 1% of unity.

Response w.r.t. reaction plane
Significant improvement with the flow correction.

Performance of jet reconstruction

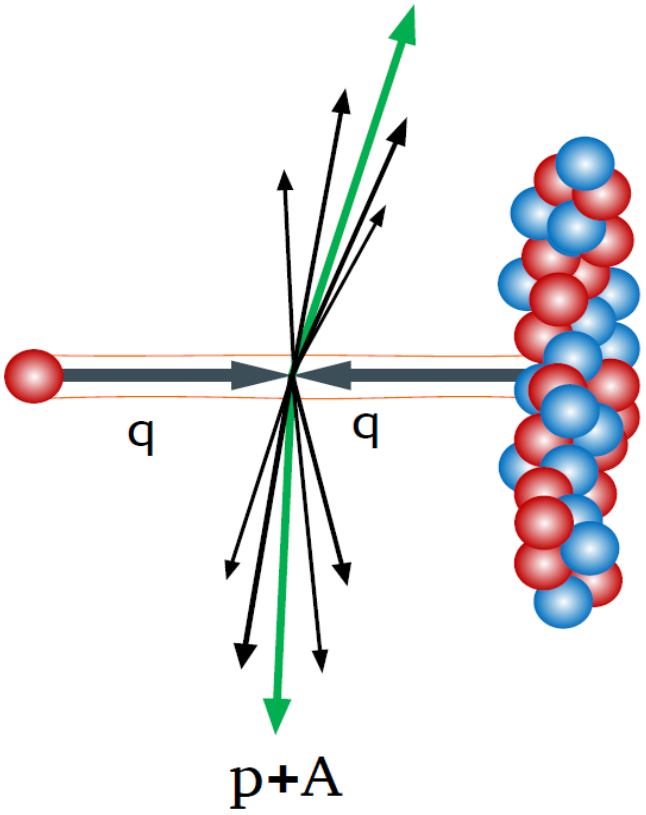


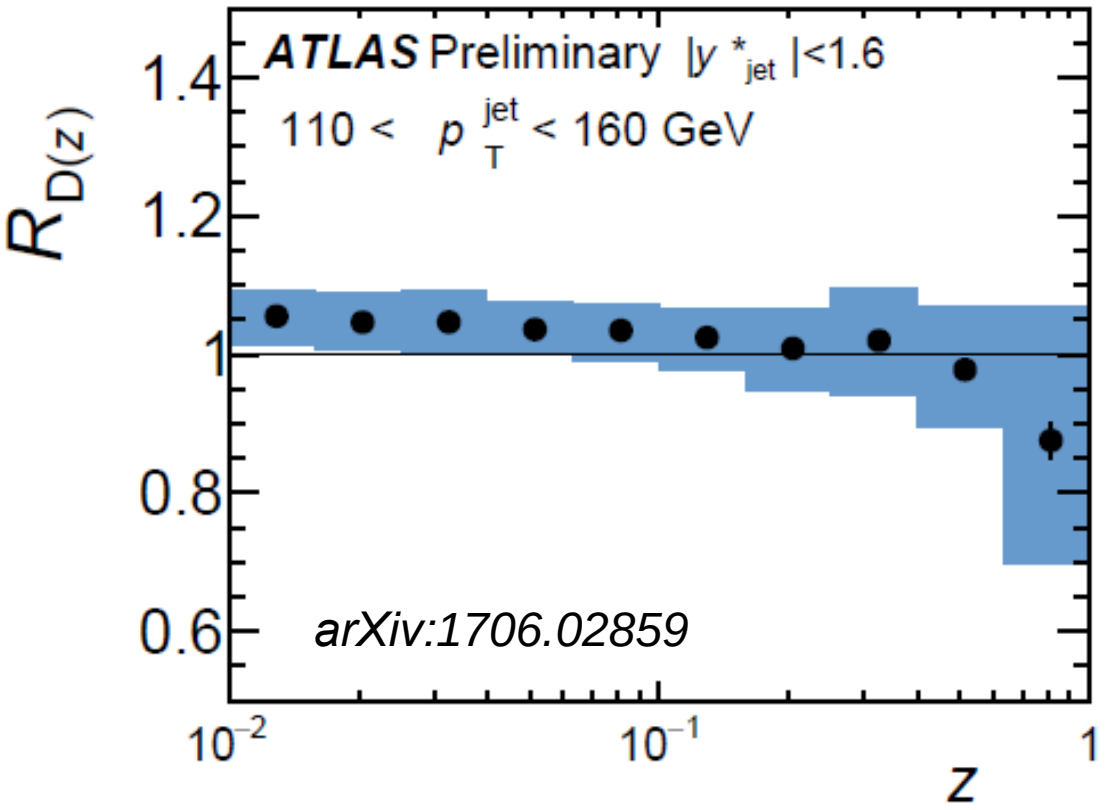


Average responses within 1% of unity.

Jet energy resolution improved b the flow correction.

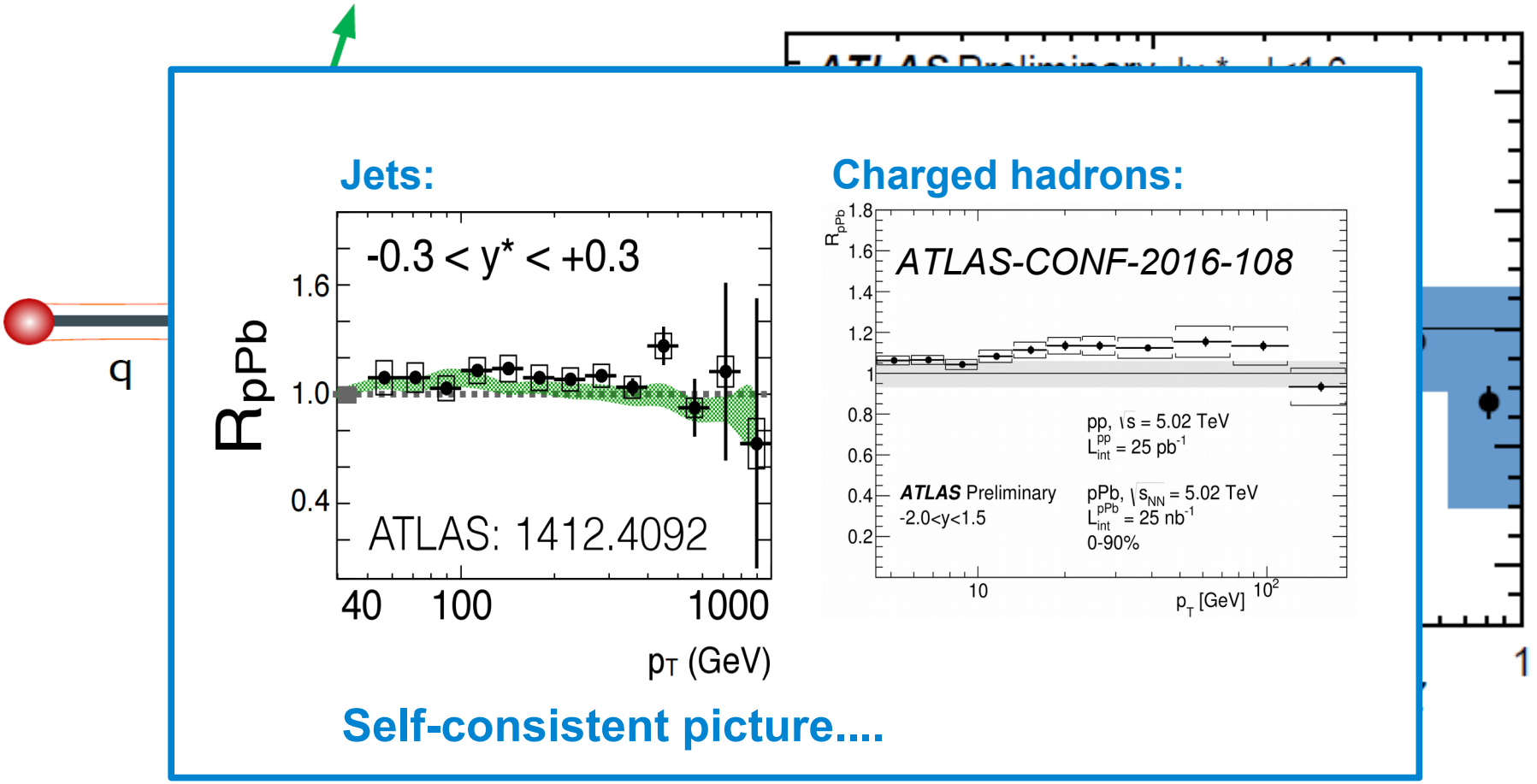
Do we see some modifications of jet structure in *p*+Pb collisions?





- **No modification of jet internal structure is observed in *p*+Pb system.**

Do we see some modifications of jet structure in *p*+Pb collisions?

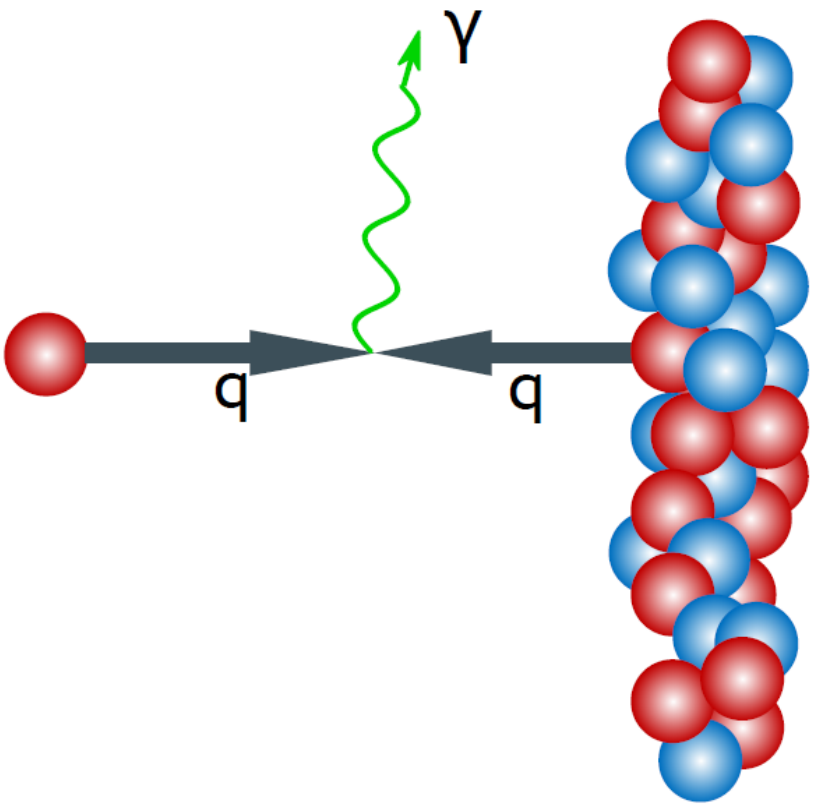


- **No modification of jet internal structure is observed in *p*+Pb system.**

EW bosons production

- More sensitivity to nPDF effects in ***p*+Pb collisions**

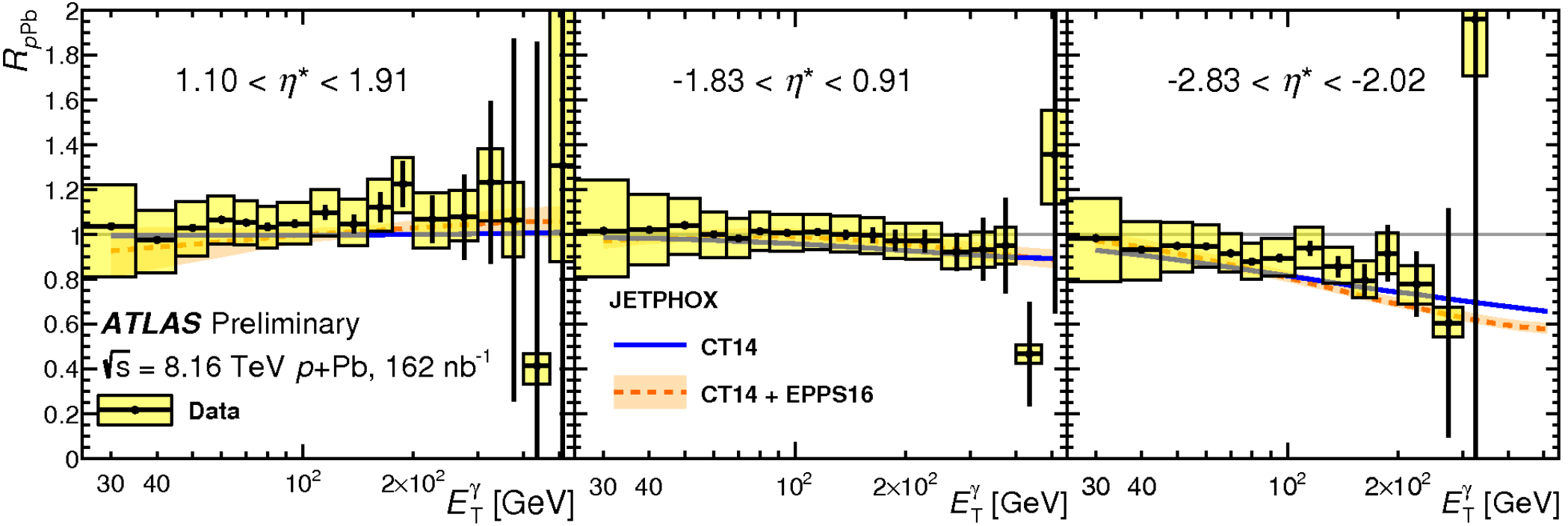
Prompt photons:



EW bosons production

- More sensitivity to nPDF effects in ***p*+Pb collisions**

Prompt photons:



- Isospin effect in “backward” direction.
- Measurement tests the energy loss of parton incoming to the hard scattering.
- Results use in global nPDF analysis.

ATLAS-CONF-2017-072