Hard probes in heavy ion collisions

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Probing trillion degree QCD matter

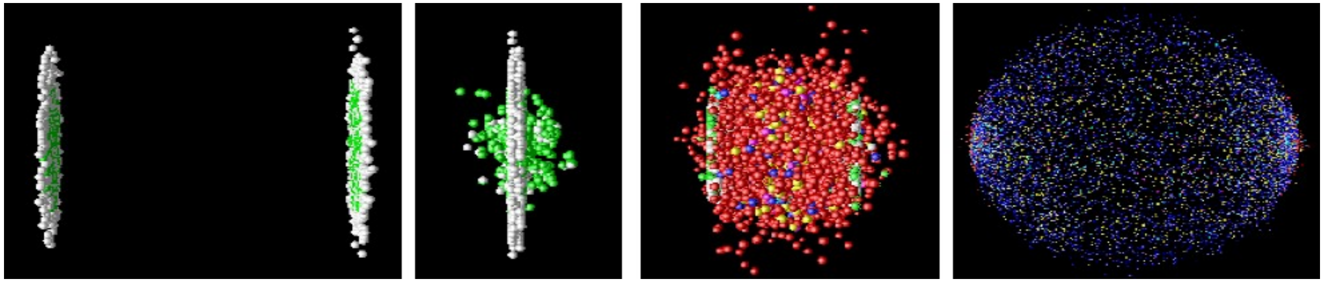
- What are the properties of medium created in heavy ion collisions?
- Heavy ions collisions produce deconfined medium:

  quark gluon plasma (QGP)

  ➡ study of QCD phase diagram.

  ➡ understanding of the QCD in the limit of high densities and temperatures.
- How we can study details of properties of the medium?

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



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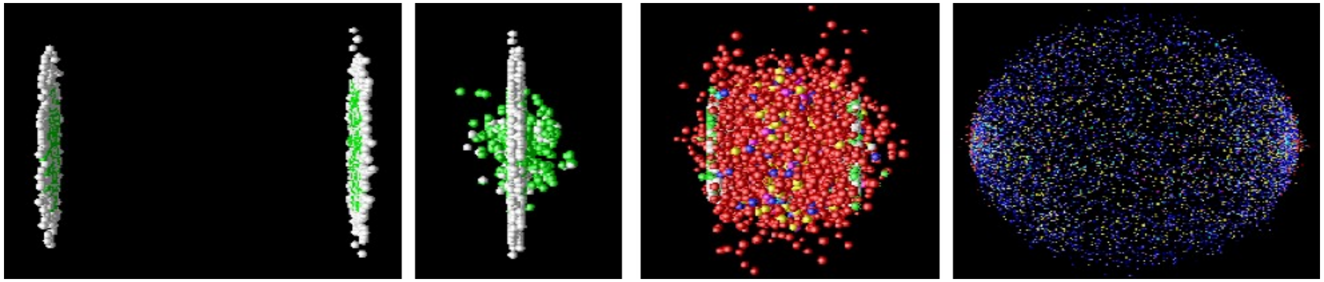
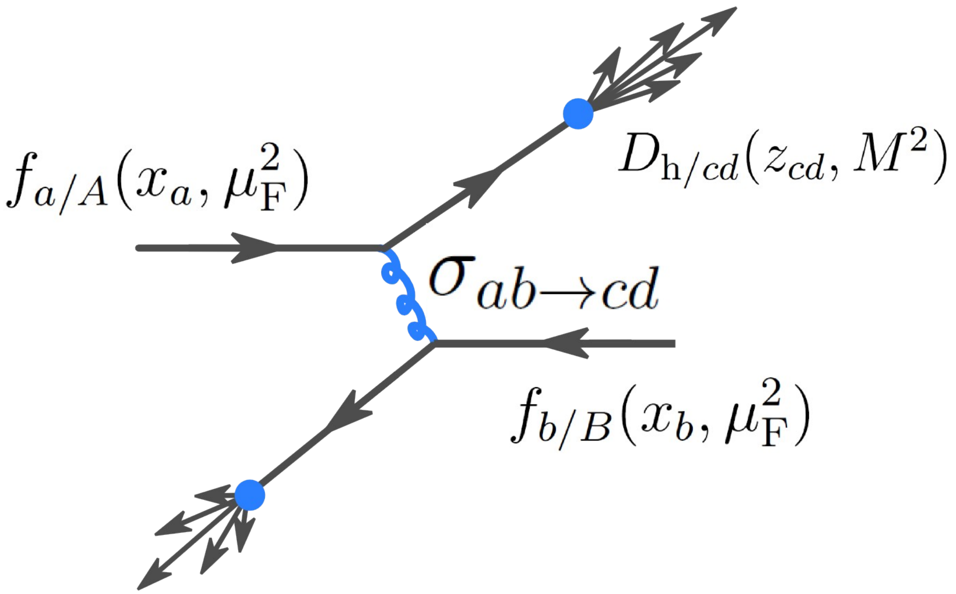
- **How these properties emerge from QCD?**



Hard probes

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



Hard probes in quark-gluon plasma

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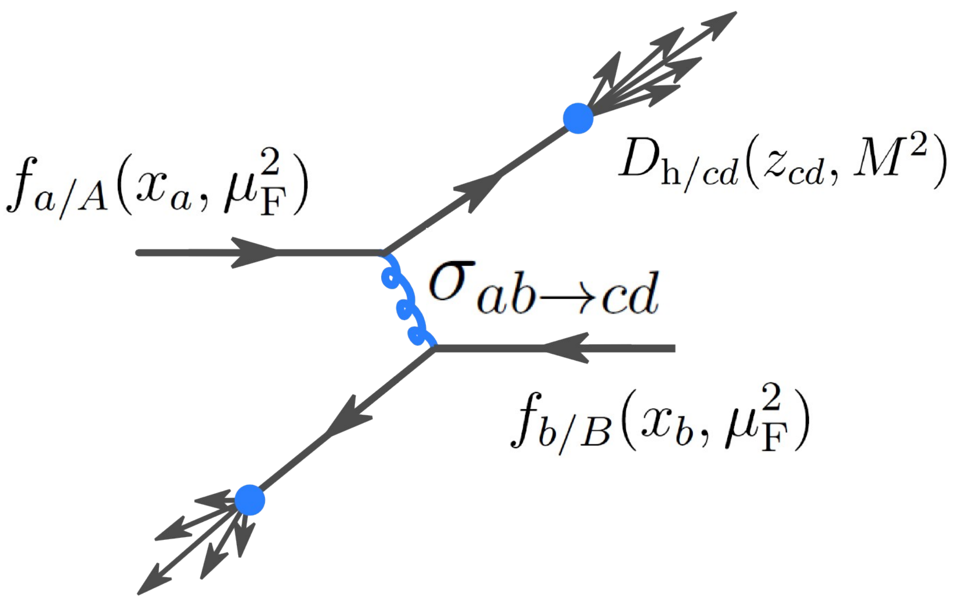
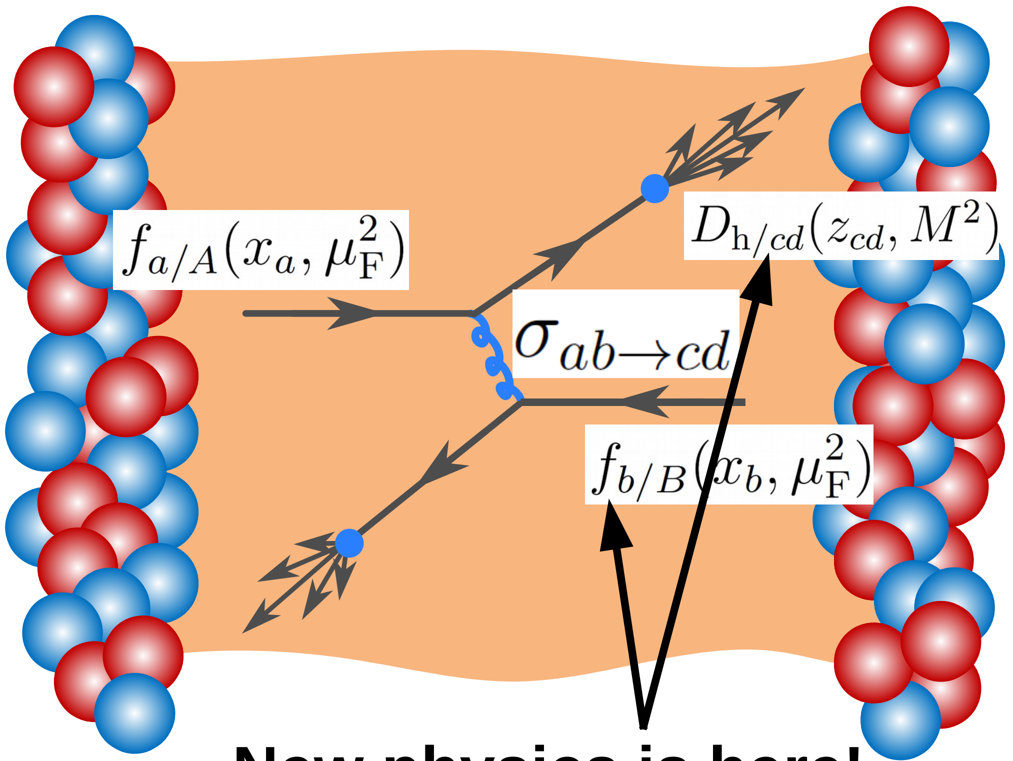




New physics is here!

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

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.
- Measurement of impact parameter is not possible.
  - ➡ Centrality is typically characterized by activity in forward detectors.

Peripheral collisions **Central collisions**

Small overlap

"0-10% bin"

Low number of N_{coll}

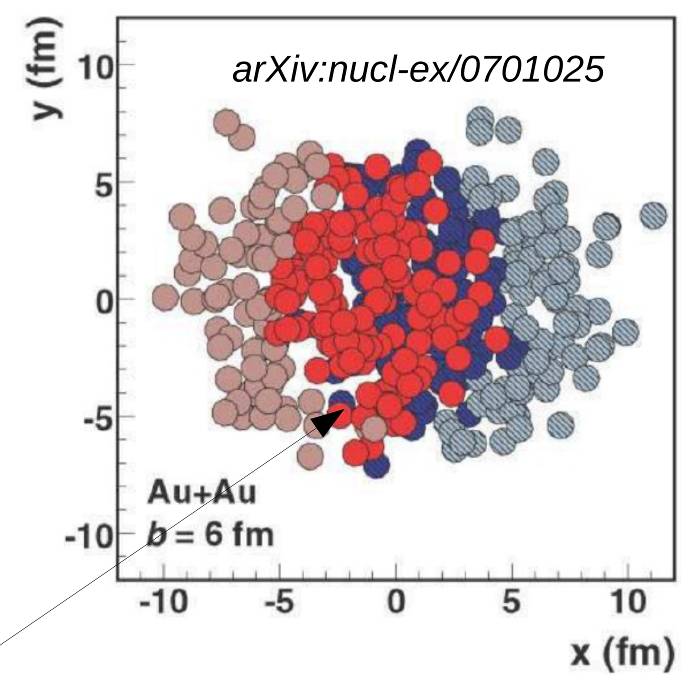
Low number of participating nucleons N_{part}

Large overlap

"90-100% bin"

High number of N_{coll}

High number of participating nucleons N_{part}



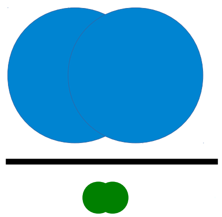
Nuclear modification factor

- Typical observable: nuclear modification factor.

QCD in medium

Yields in A+A

$$R_{AA} = \frac{1}{N_{\mathrm{coll}}}$$



$$= \frac{1}{N_{\mathrm{coll}}} \frac{\frac{\mathrm{d}N_{AA}}{\mathrm{d}p_{\mathrm{T}}}}{\frac{\mathrm{d}N_{pp}}{\mathrm{d}p_{\mathrm{T}}}} = \frac{1}{T_{AA}} \frac{\frac{\mathrm{d}N_{AA}}{\mathrm{d}p_{\mathrm{T}}}}{\frac{\mathrm{d}\sigma_{pp}}{\mathrm{d}p_{\mathrm{T}}}}$$

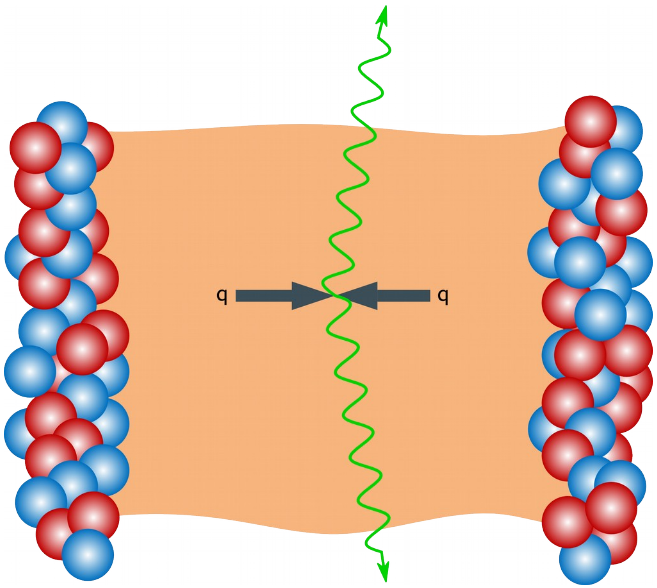
QCD in vacuum

pp reference

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

Hard probes gallery

- Different hard probes interact with medium differently.



Vector bosons

- Measurements of photons, Z and W bosons.

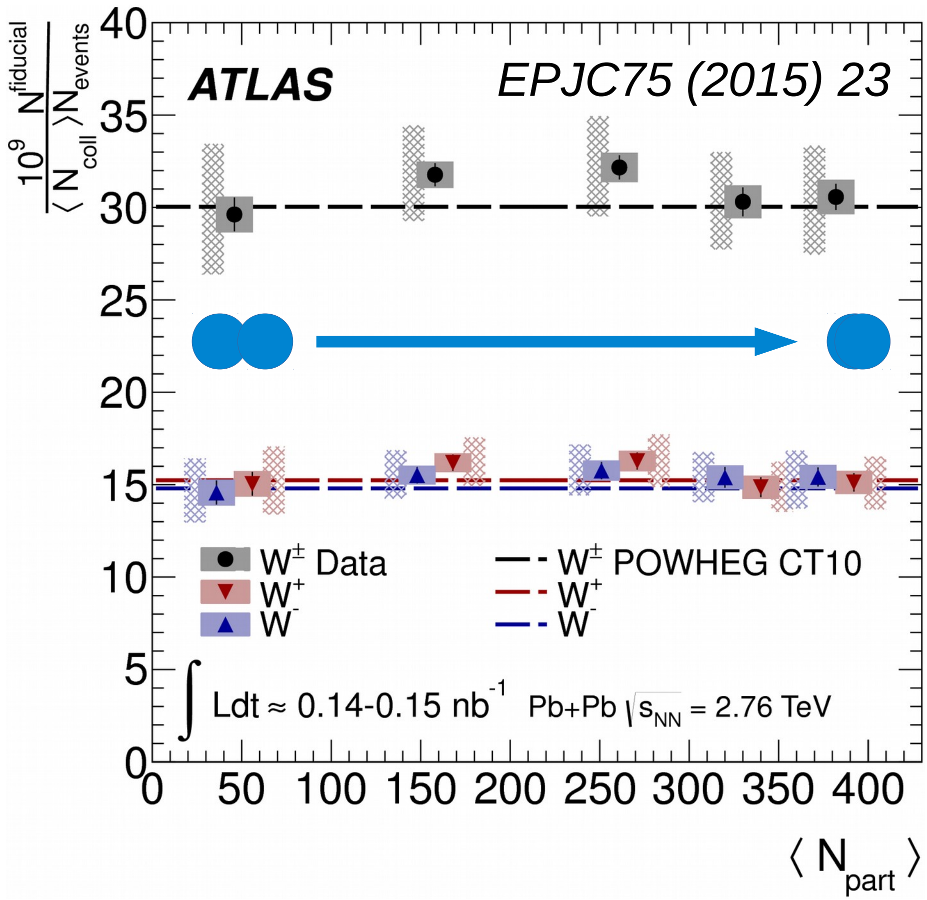
➡ Do not interact strongly.

- No medium effect is expected.
- Provide information about the initial state → nuclear PDFs.

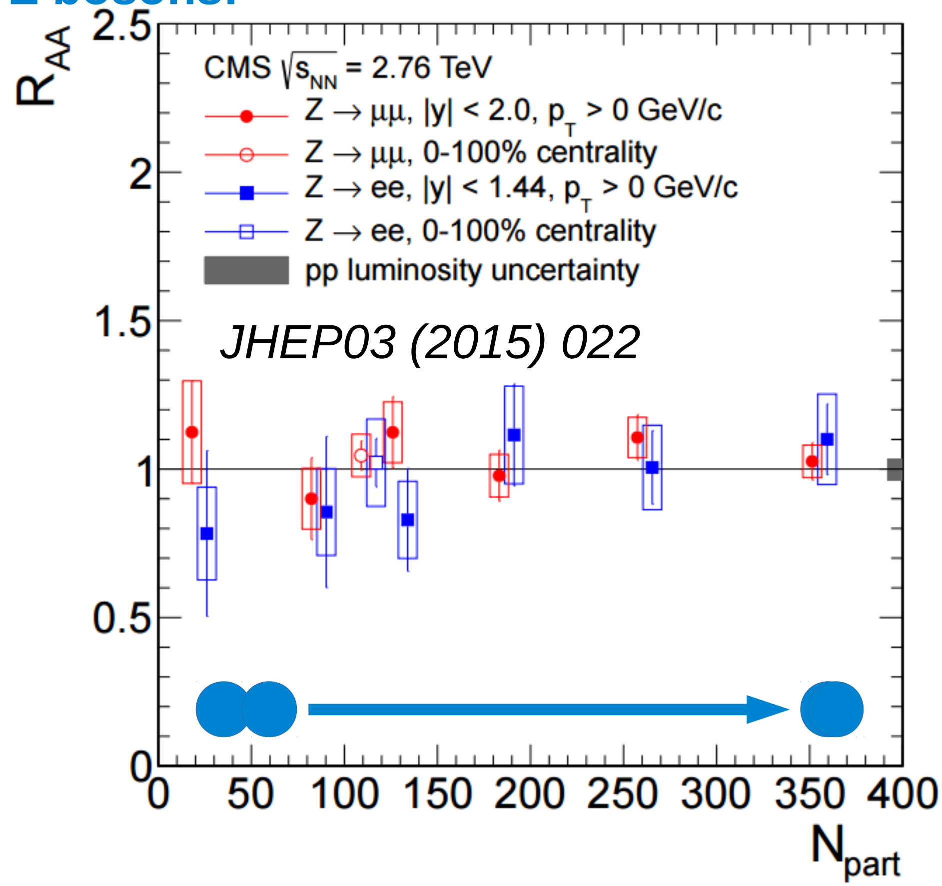
EW bosons production

- Similarly to prompt photons do not interact with QGP.

W bosons:



Z bosons:



- No deviation from N_{coll} scaling.

Hard probes gallery

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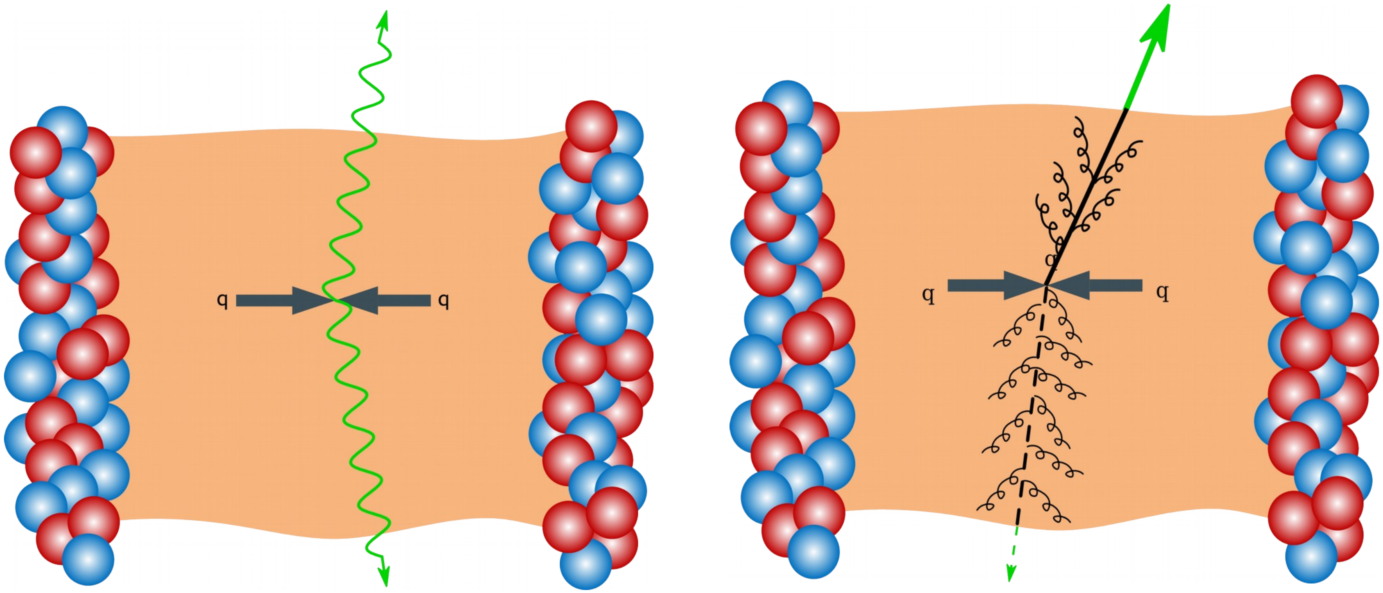


Vector bosons

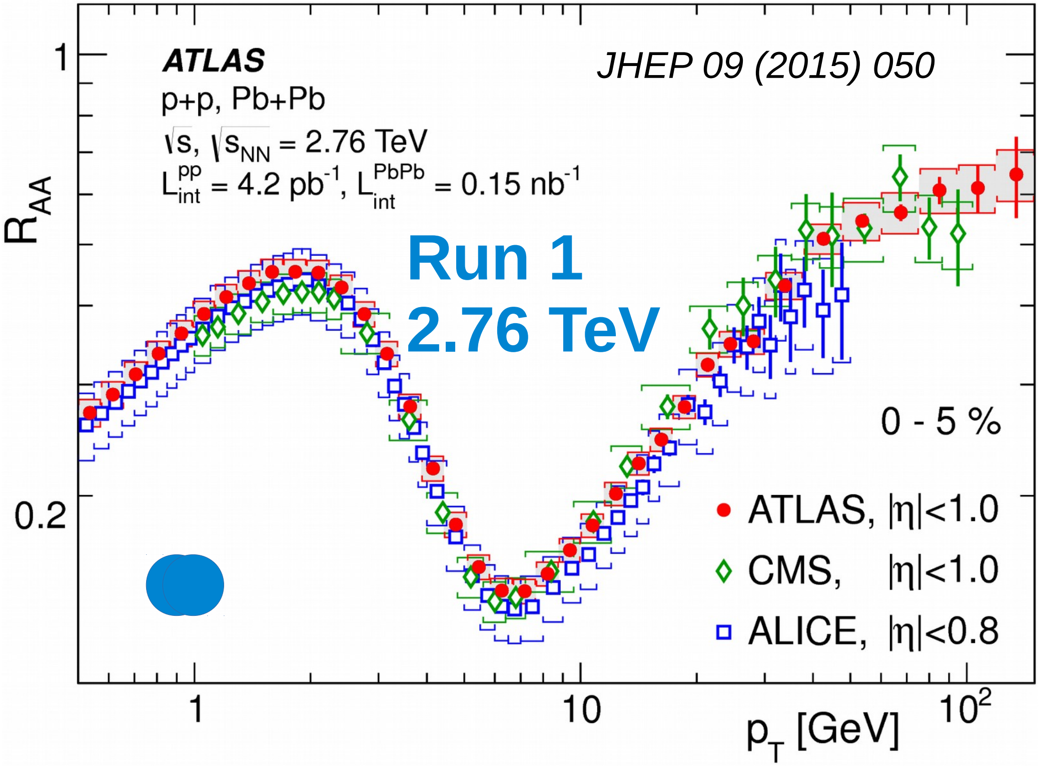
Jets

- Interactions of medium and colored probe.
  - elastic scattering.
  - induced radiation.

➡ fast partons loose energy ➡ jet quenching

Charged hadrons

- The easiest way how to study jet quenching.
- However does not sample the full parton energy.



- Final Run 1 results.
- Very good agreement between experiments.
- Sign of flattening of R_{AA} at very high p_T.

Charged hadrons high-p_T spectra

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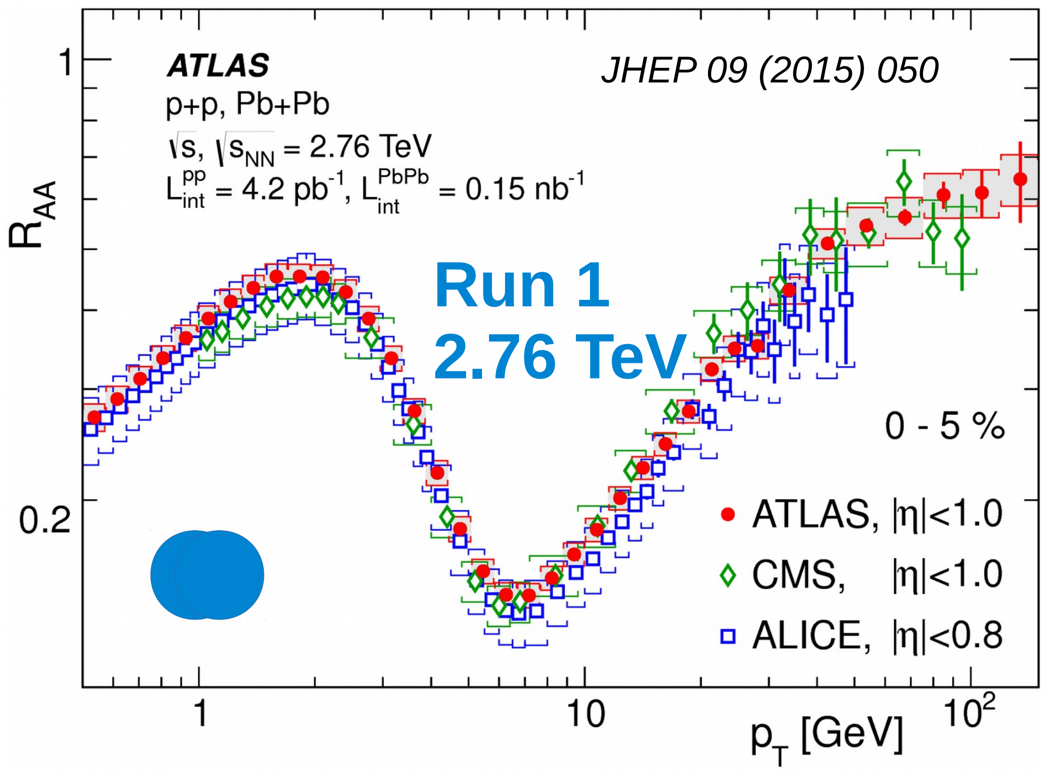
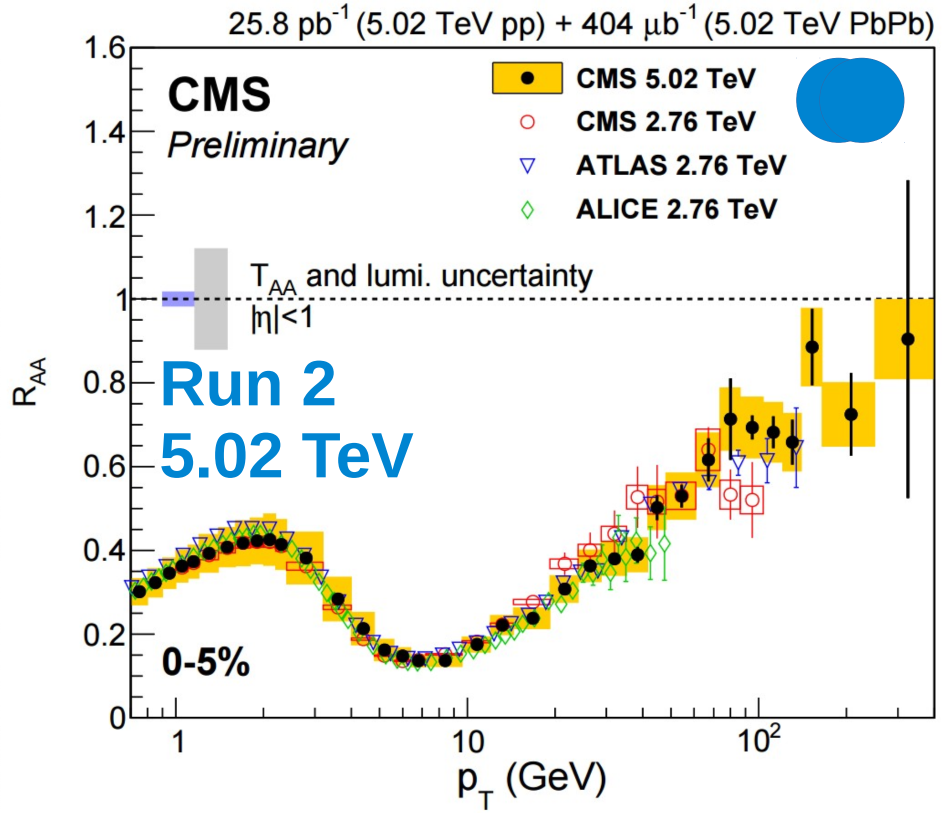
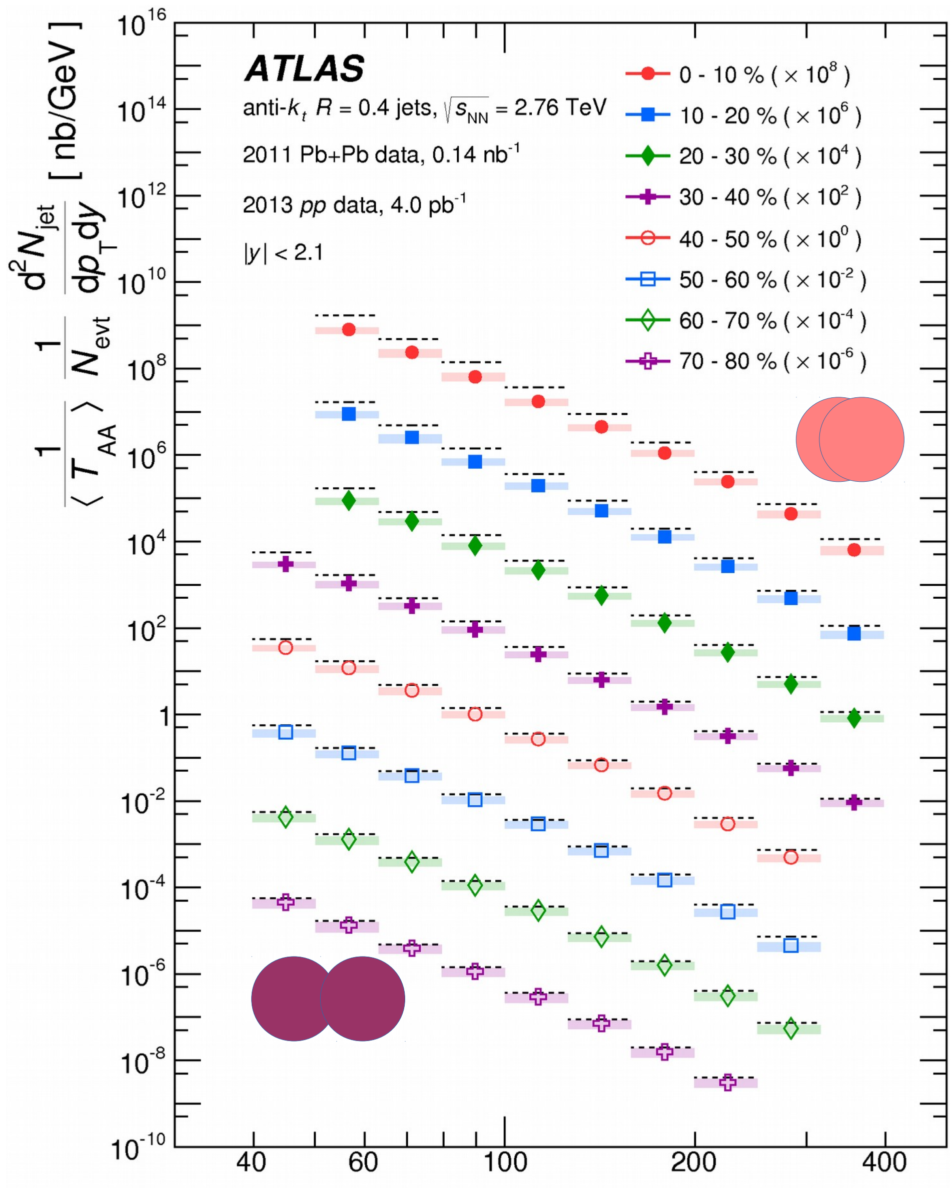




- No significant increase of the suppression from 2.76 to 5.02 TeV.

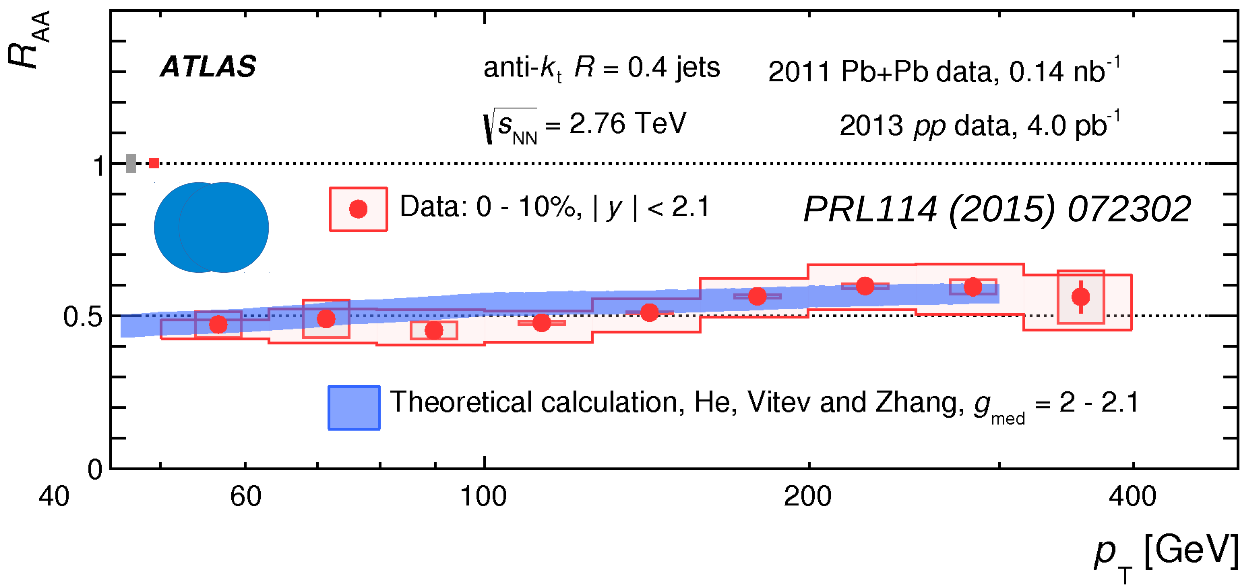
Single jet spectra

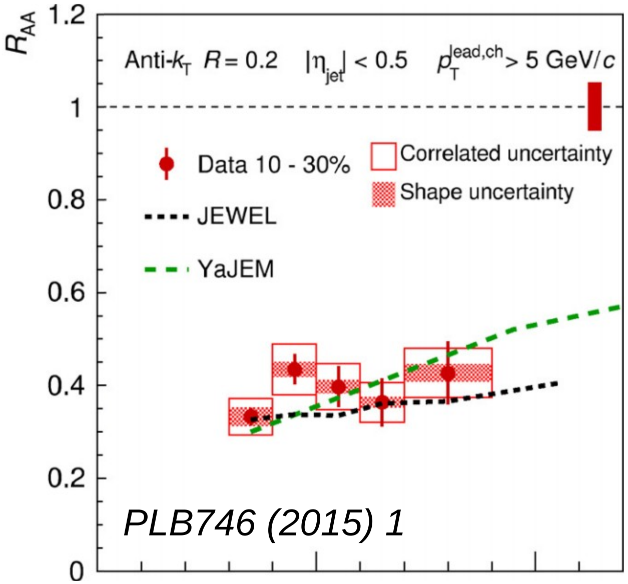


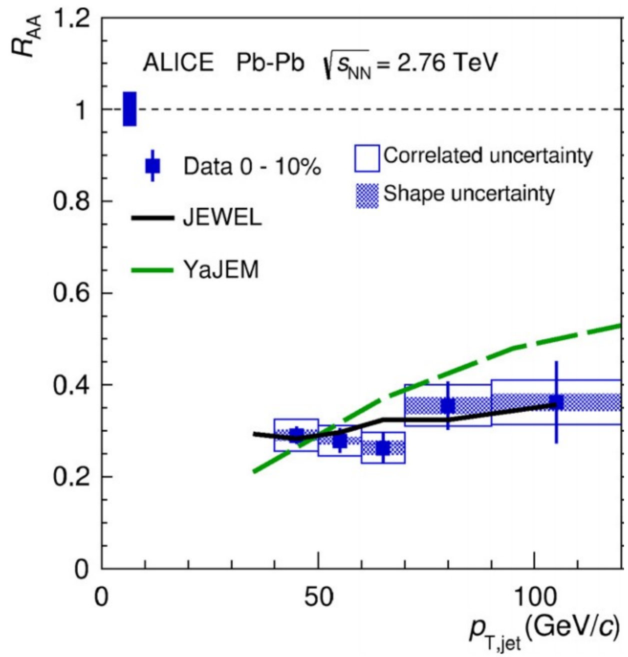
PRL114 (2015) 072302

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

Single jet spectra

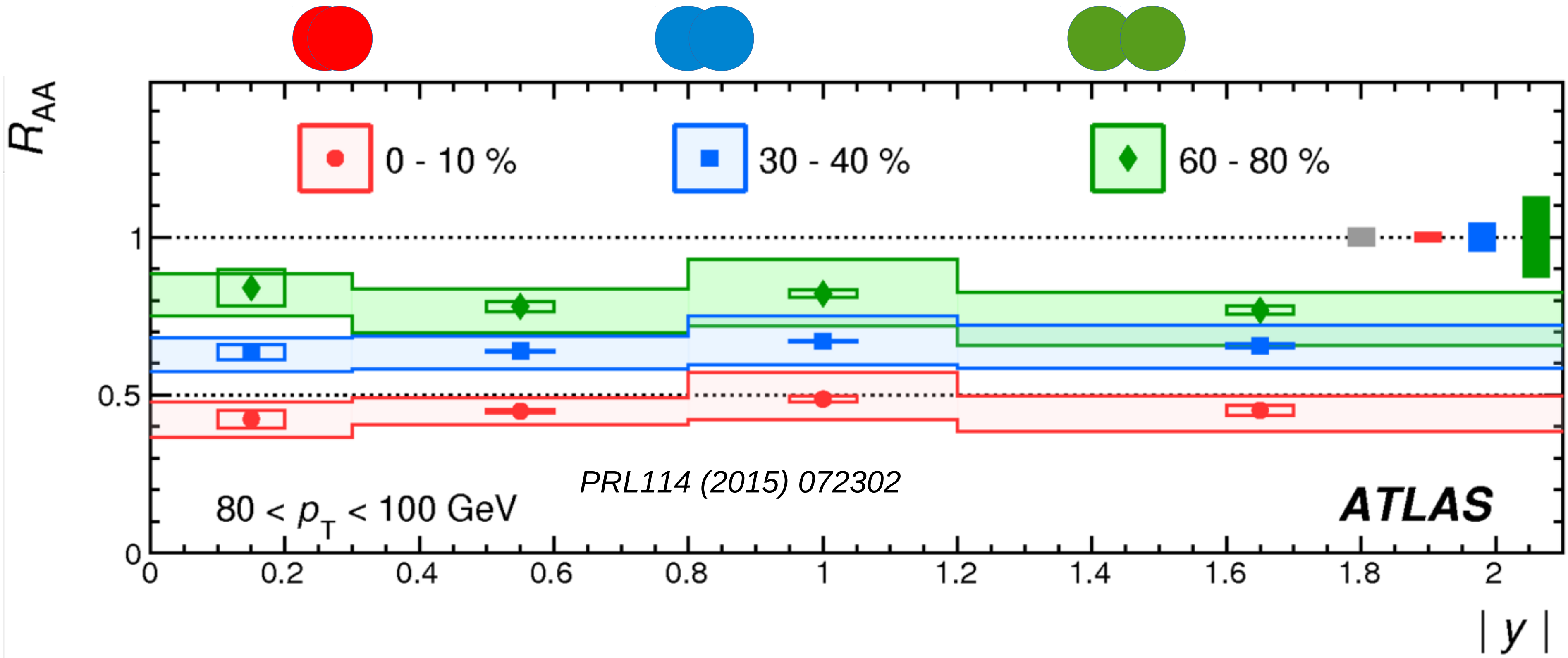






- R_{AA} exhibits very weak p_T dependence.
- Good description by models.

What about pseudorapidity dependence?



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

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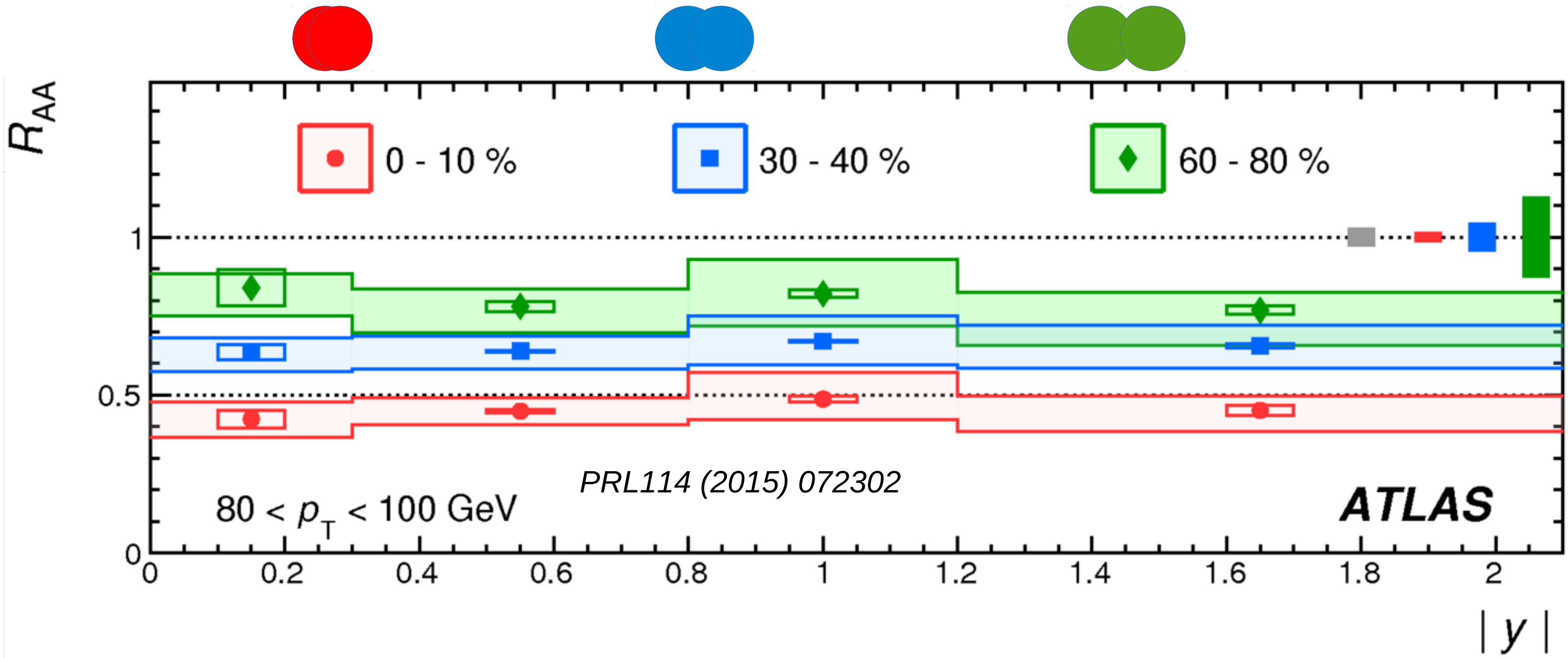

- Increasing rapidity ➡ steeper spectrum ➡ decrease of R_{AA}
- Increasing rapidity ➡ higher quark fraction ➡ increase of R_{AA}

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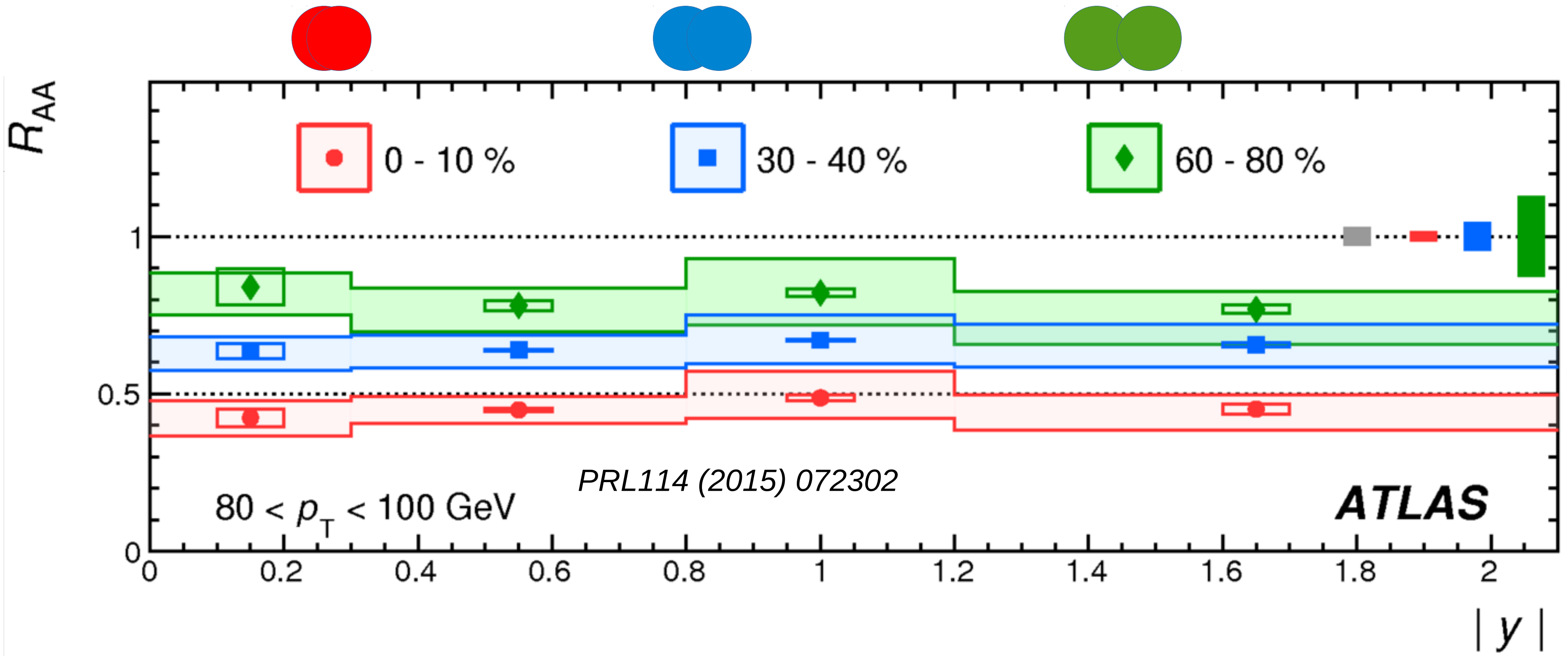
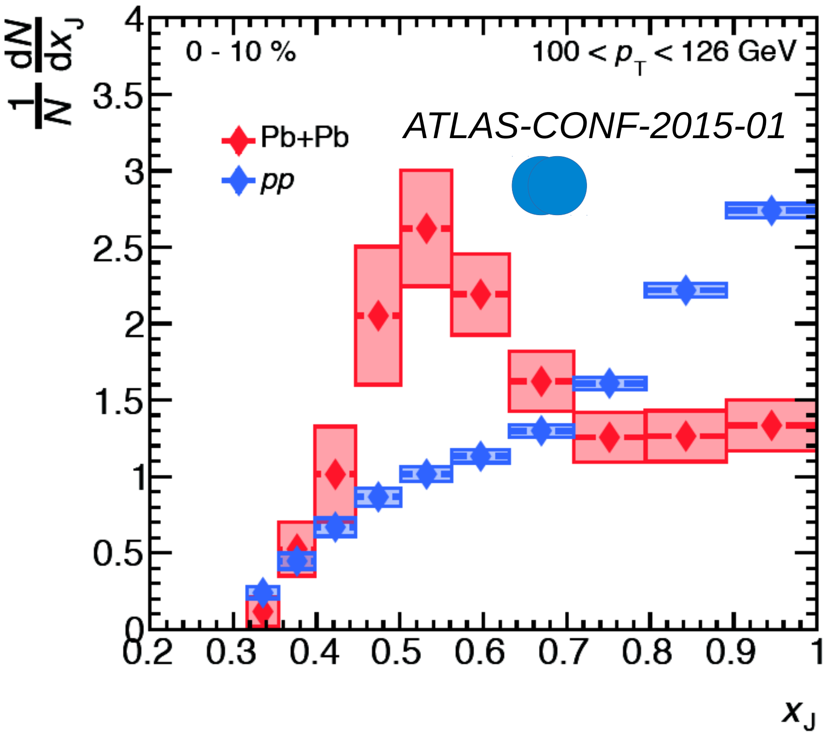
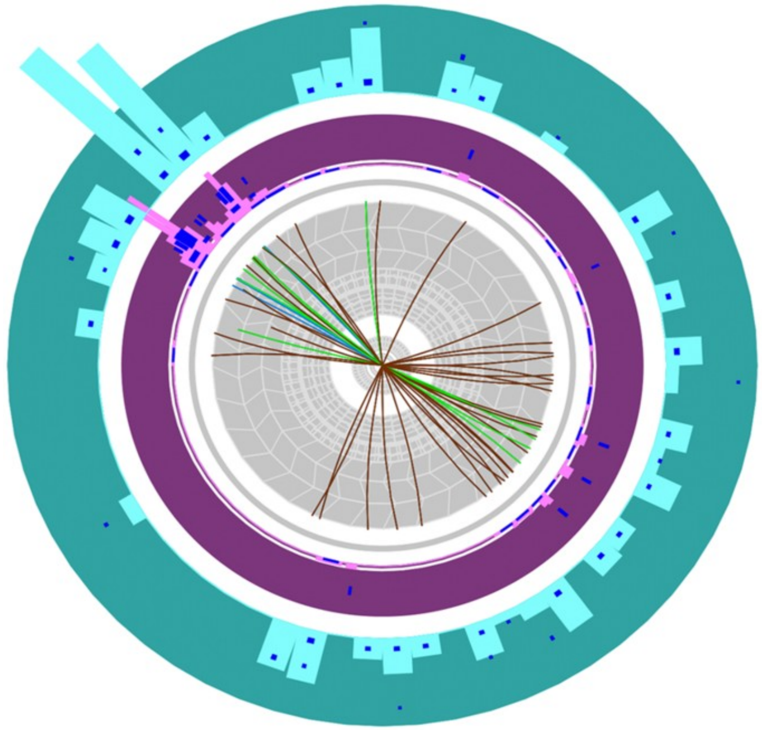


- Increasing rapidity ➡ steeper spectrum ➡ decrease of R_{AA}
- Increasing rapidity ➡ higher quark fraction ➡ increase of R_{AA}
- R_{AA} is completely flat with rapidity! ➡ Cancellation?
- We look forward to see this measurement at 5 TeV whether the different shape of spectra remove the cancelation.

Update on di-jet asymmetry

- ATLAS fully unfolded di-jet asymmetry distributions $x_{\mathrm{J}} \equiv p_{\mathrm{T}_2}/p_{\mathrm{T}_1}$





- Significant shift toward large di-jet asymmetry in central HI collisions w.r.t. *pp* reference.

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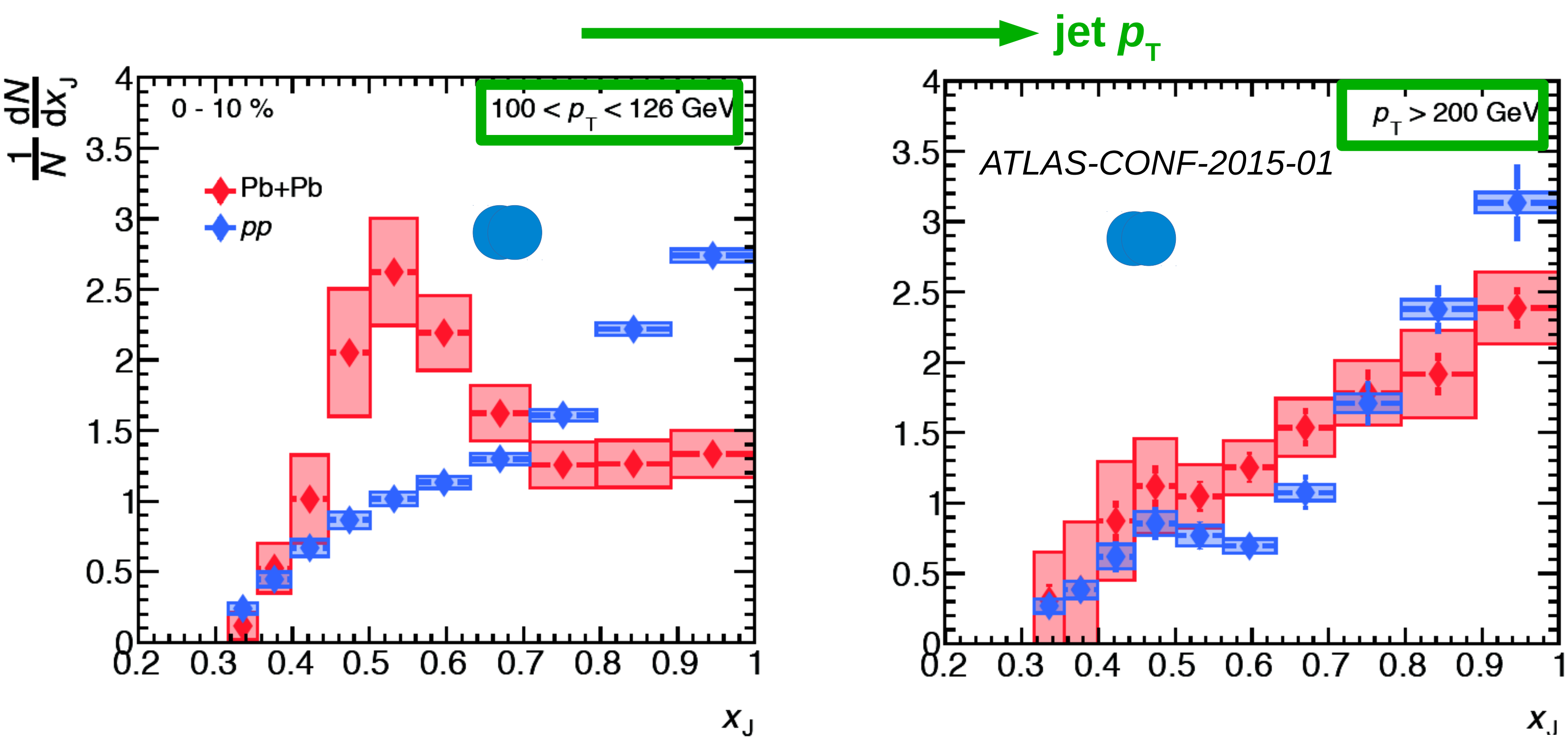
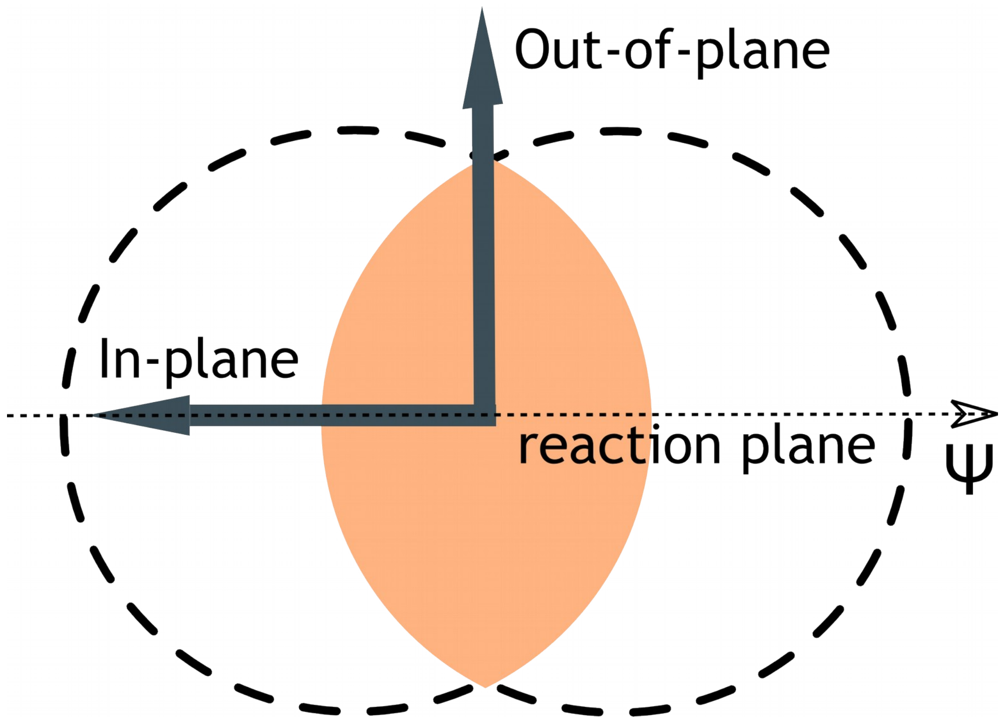


- Much less modification at high pT.
  - per jet fluctuations of quenching?
  - Change in the flavor compositions?

More differential study of jet quenching

- We can study path length dependence dependence of quenching.

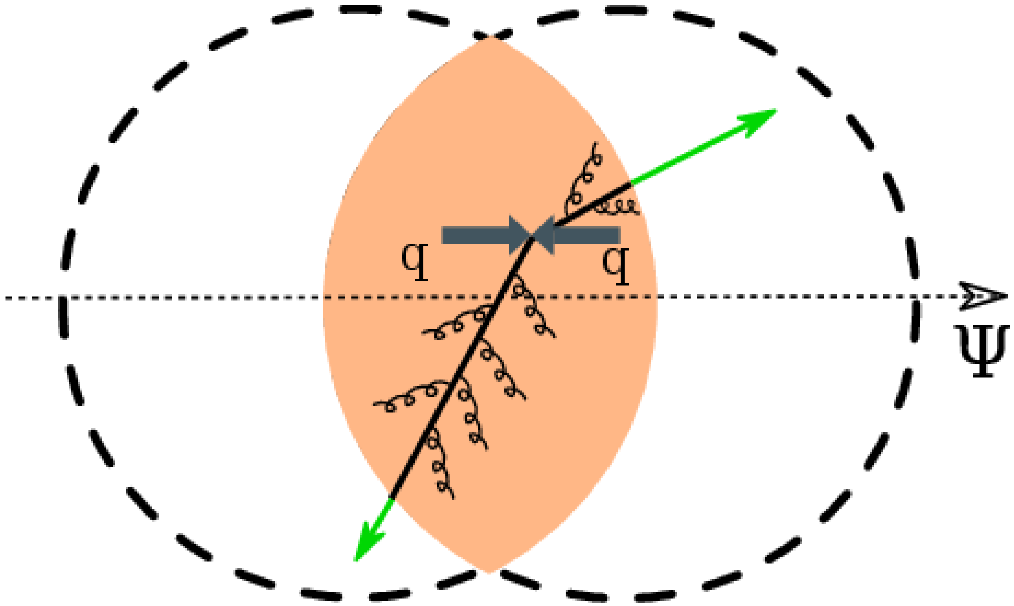


In-plane: shorter path length in the medium.

Out-of-plane: shorter path length in the medium.

More differential study of jet quenching

- We can study path length dependence dependence of quenching by measuring our probes differentially w.r.t. reaction plane.



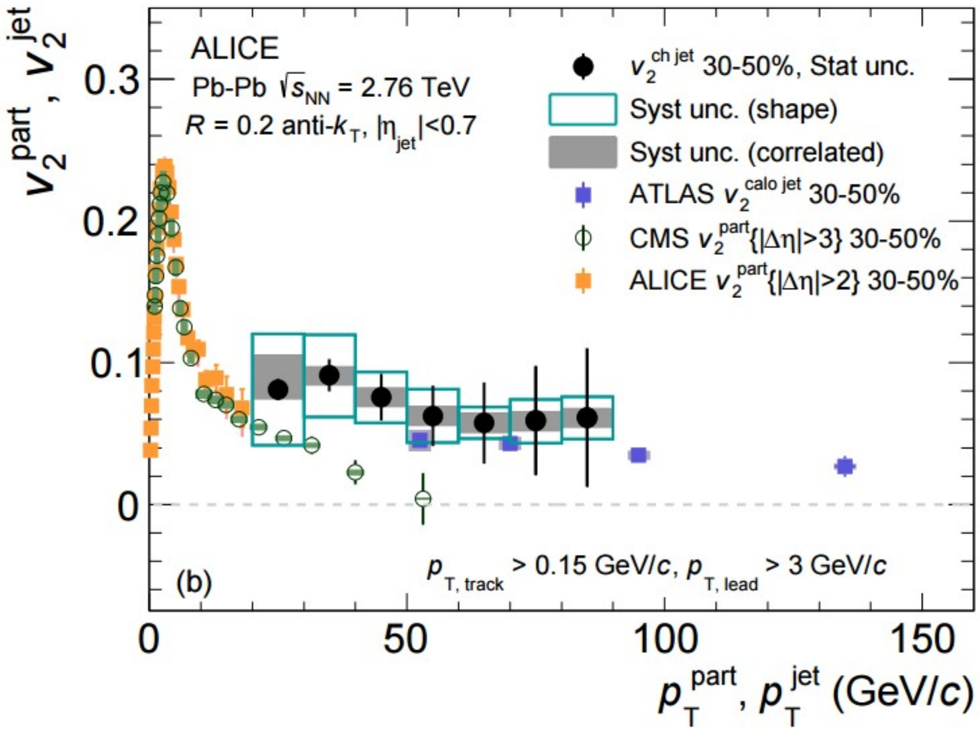
In-plane: shorter path length in the medium ➡ less suppression

Out-of-plane: shorter path length in the medium ➡ more suppression

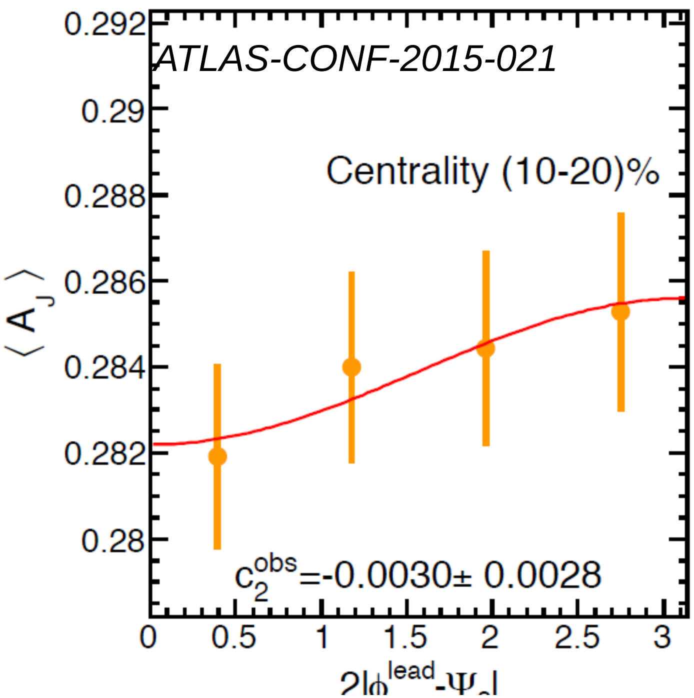
More differential study of jet quenching

- We can study path length dependence dependence of quenching.

Jet yields versus angular distance to reaction plane



Di-jet asymmetry versus angular distance to reaction plane

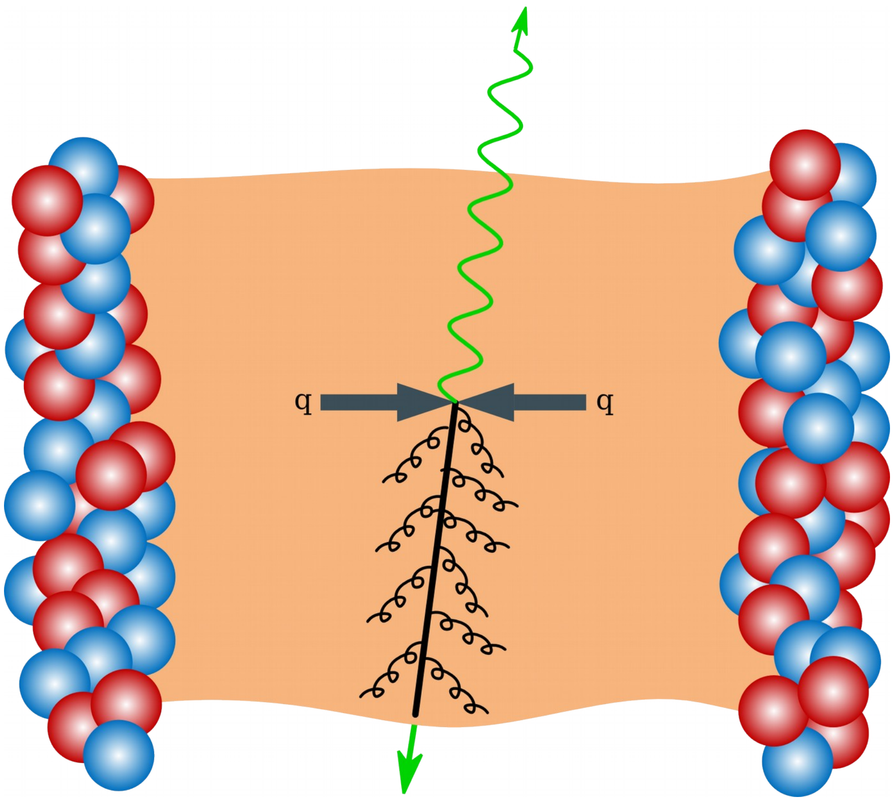


- Up to 10% variation of jets yields in-plane and out-of-plane.
- Contrary to small variation of asymmetry.
- Such a results is not unexpected but comparison to models is needed.

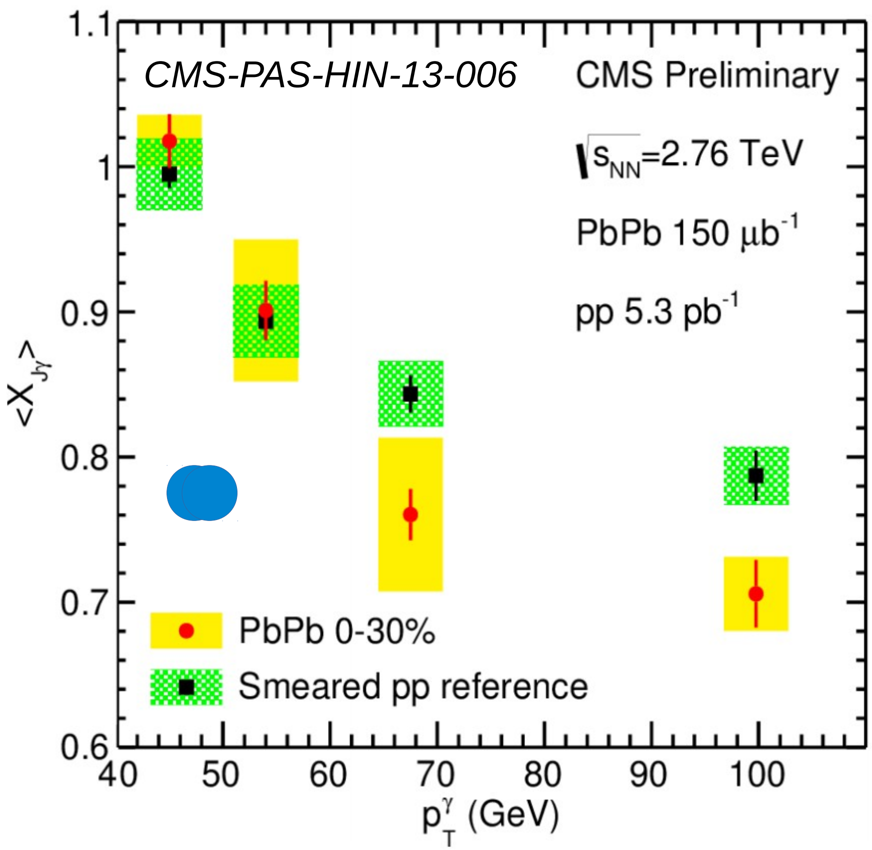
Vector boson-jet correlations

- Photons and Z's tagged the parton energy.
- Flavor fraction differs compared to di-jets.
- Low Z-jet cross section → limitation in Run1.

$$x_{J\gamma} = p_{\mathrm{T}}^{\mathrm{Jet}} / p_{\mathrm{T}}^{\gamma}$$



photon-jet balance (Run 1)

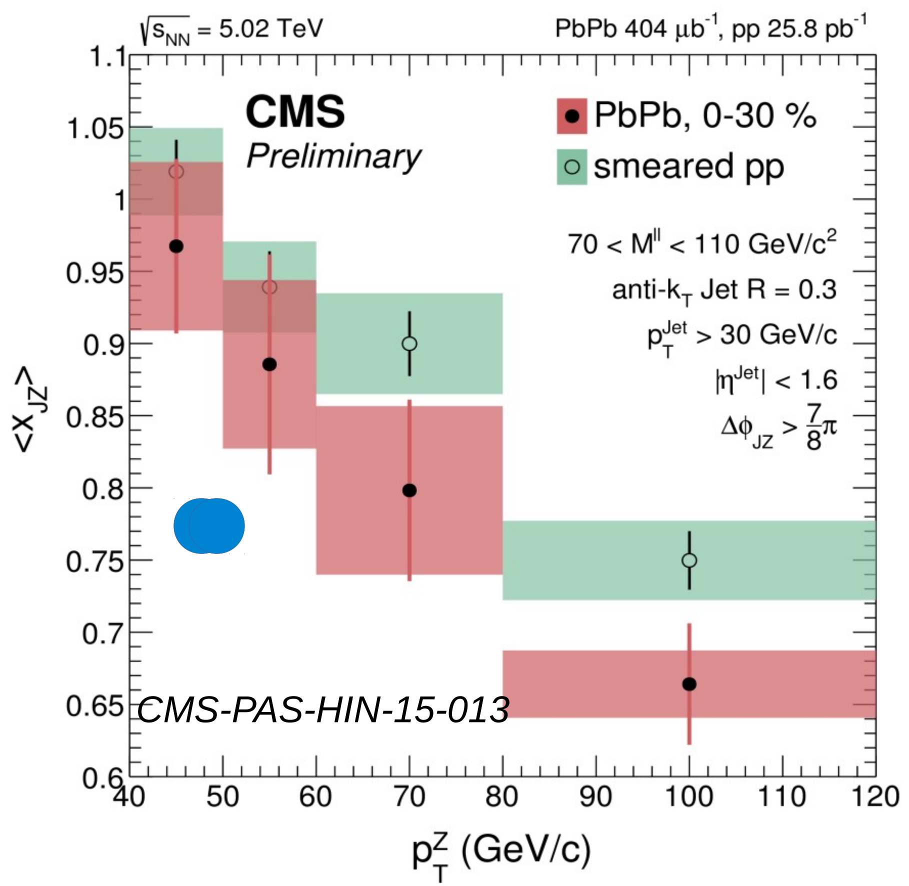


Vector boson-jet correlations

- Photons and Z's tagged the parton energy.
- Flavor fraction differs compared to di-jets.
- Low Z-jet cross section → limitation in Run1.
  - New CMS measurement benefits from Run2 luminosity and $\sqrt{s}$.

$$x_{JZ} = \frac{p_T^{Jet}}{p_T^{Z}}$$

Z-jet balance (Run 2)



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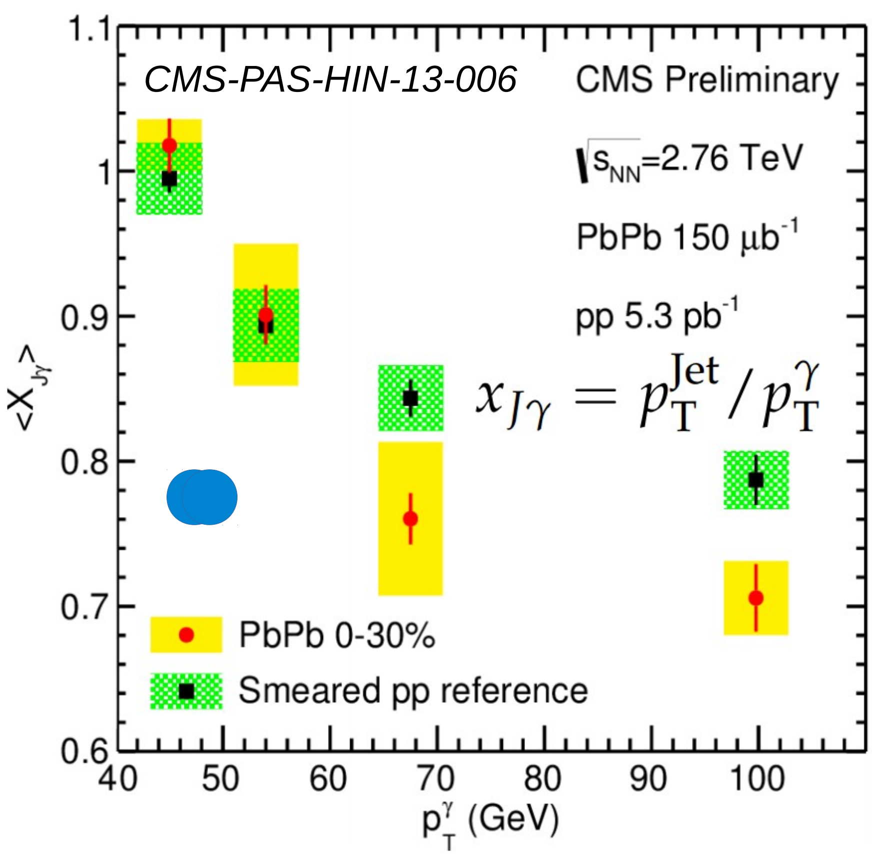
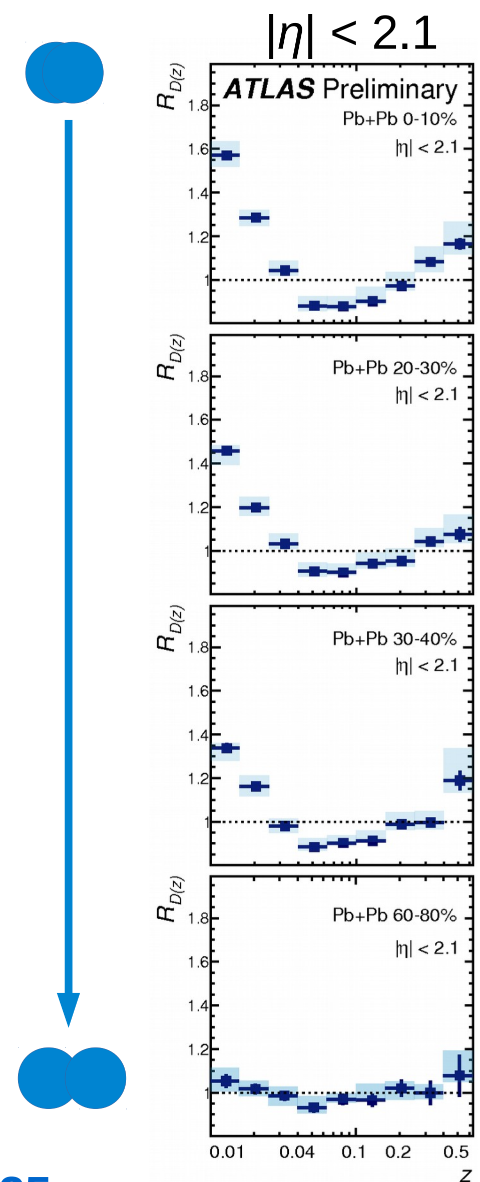


How much is the jet structure modified?

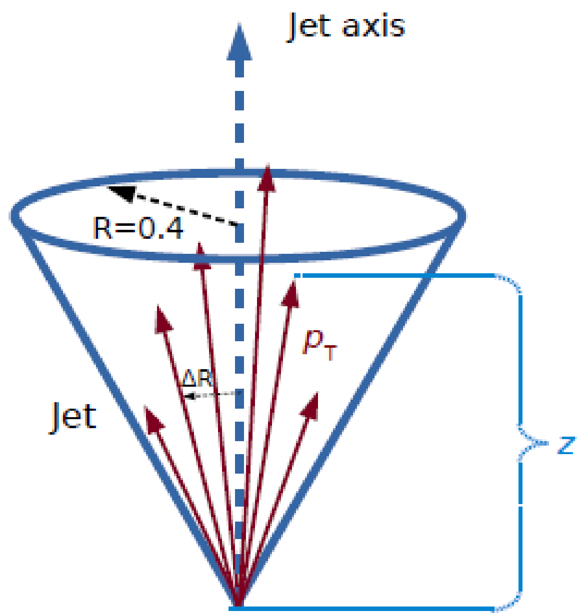


ATLAS-CONF-2015-055

- Measurement of fragmentation functions:

$$D(z) \equiv \frac{1}{N_{\rm jet}} \frac{dN_{\rm ch}}{dz}$$

$$z = p_{\rm T}^{\rm ch} / p_{\rm T}^{\rm jet} \cos \Delta R$$



Centrality dependence:

- Enhancement at low and high *z*.
- Suppression at intermediate *z*.
- No significant dependence on jet p_T.

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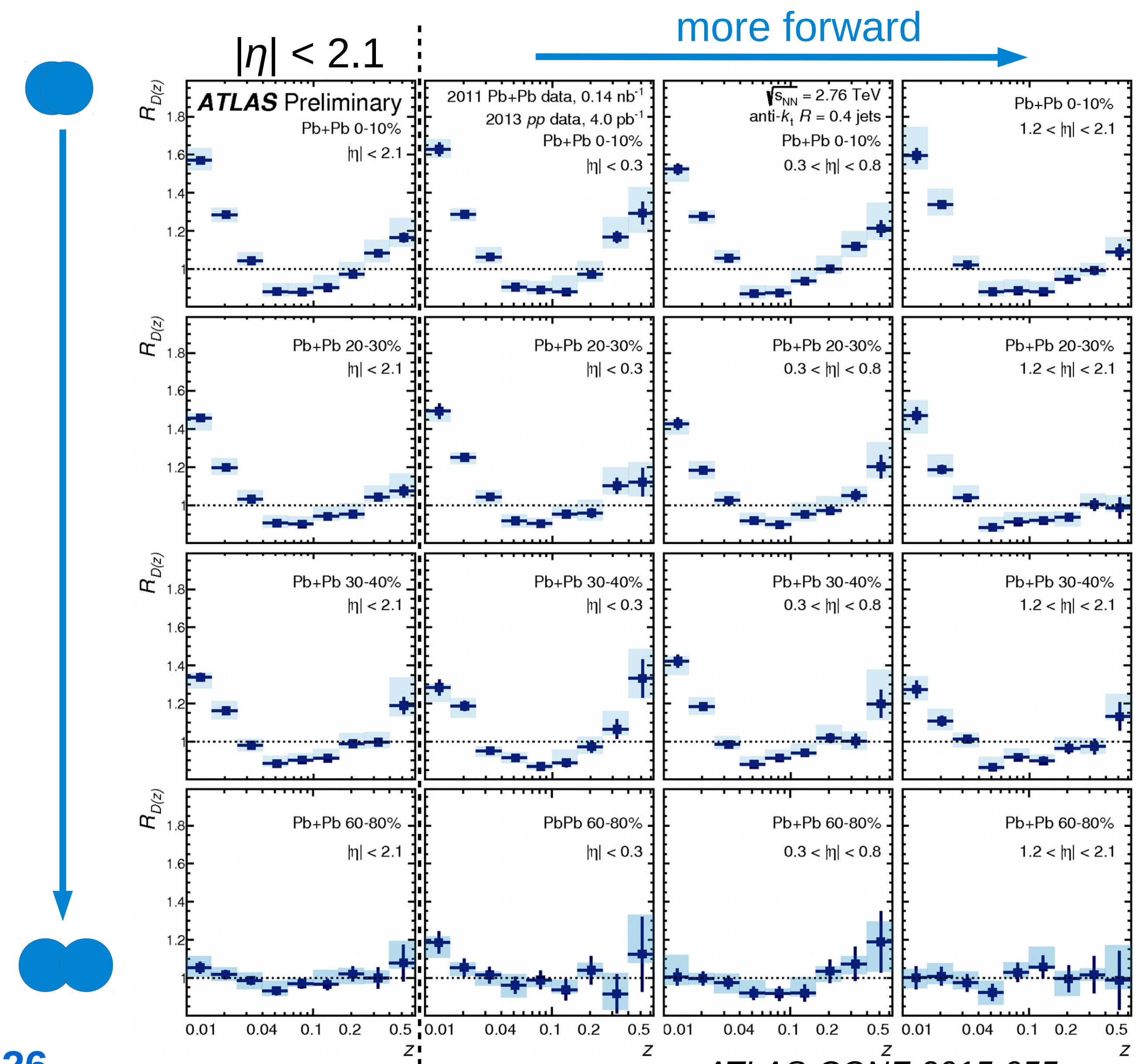

ATLAS-CONF-2015-055

Centrality dependence:

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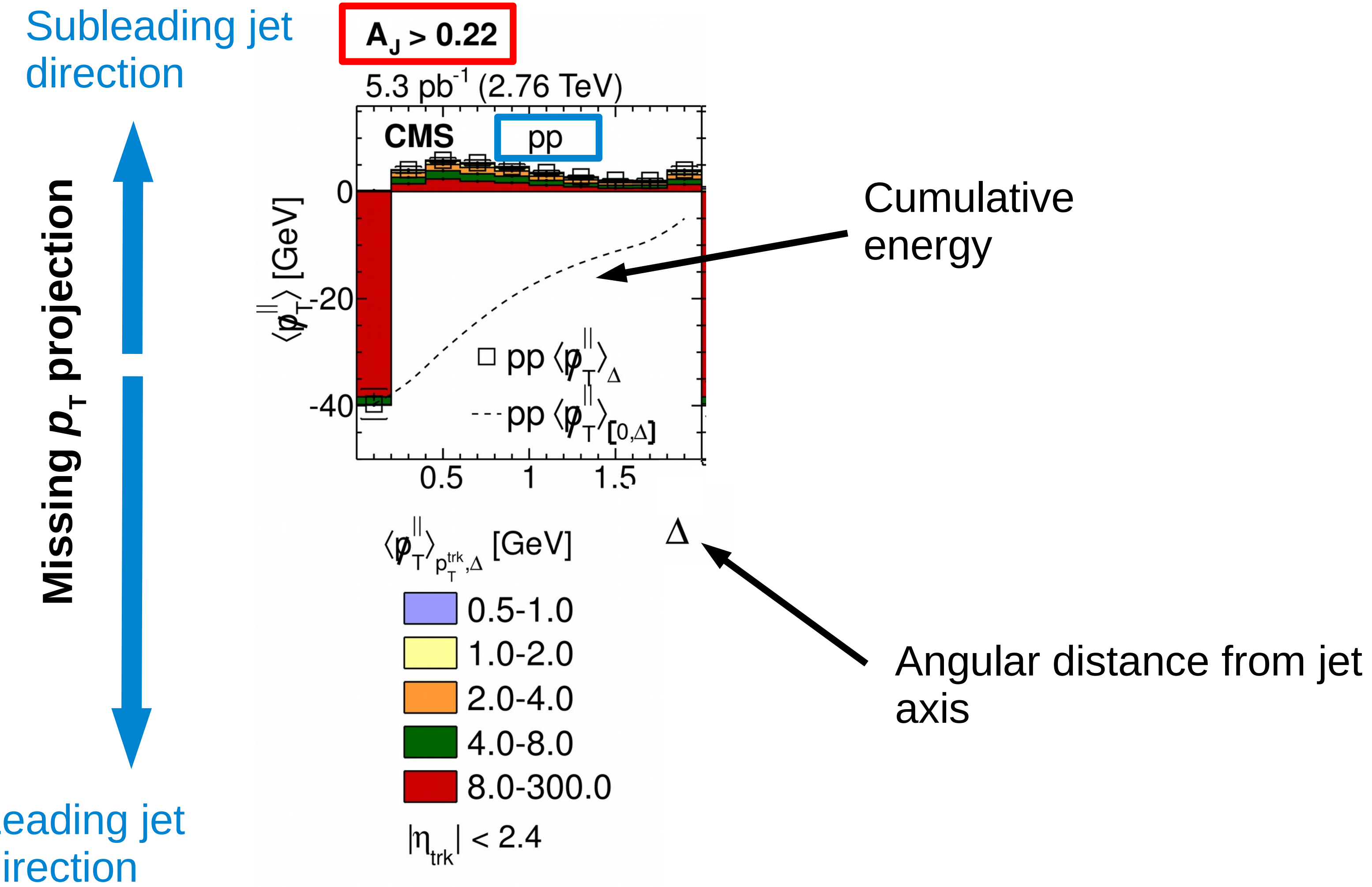
Pseudorapidity dependence:

- Hint of pseudorapidity dependence:
- Consistent with change of flavor composition as suggested in *ArXiv:1504.05169.*

Where does the energy flows?

- Study of correlation of missing p_T evaluated with tracks in various p_T bins with jets.



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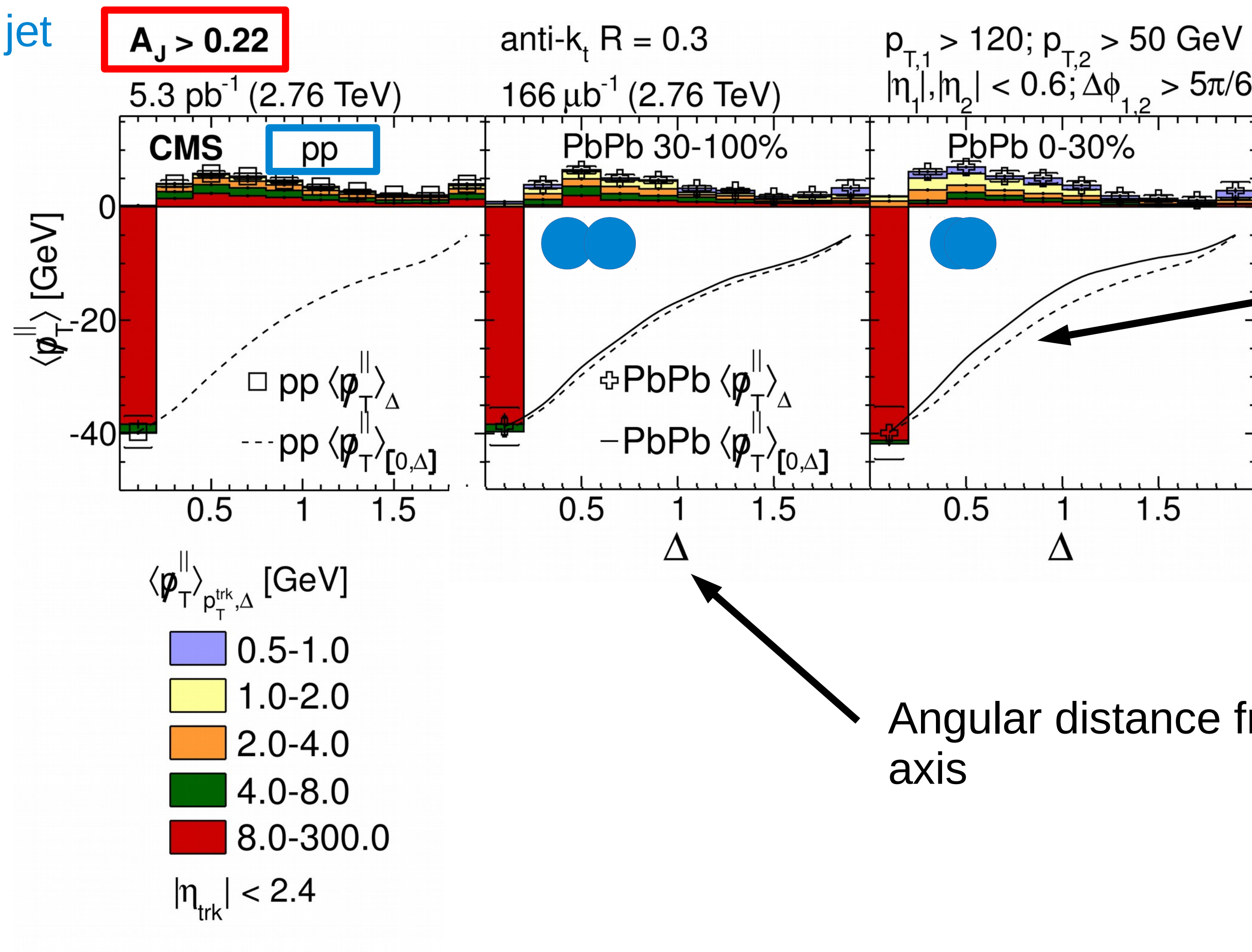
Subleading jet direction

Missing p_T projection

Leading jet direction



Cumulative energy (*pp* and Pb+Pb)

Angular distance from jet axis

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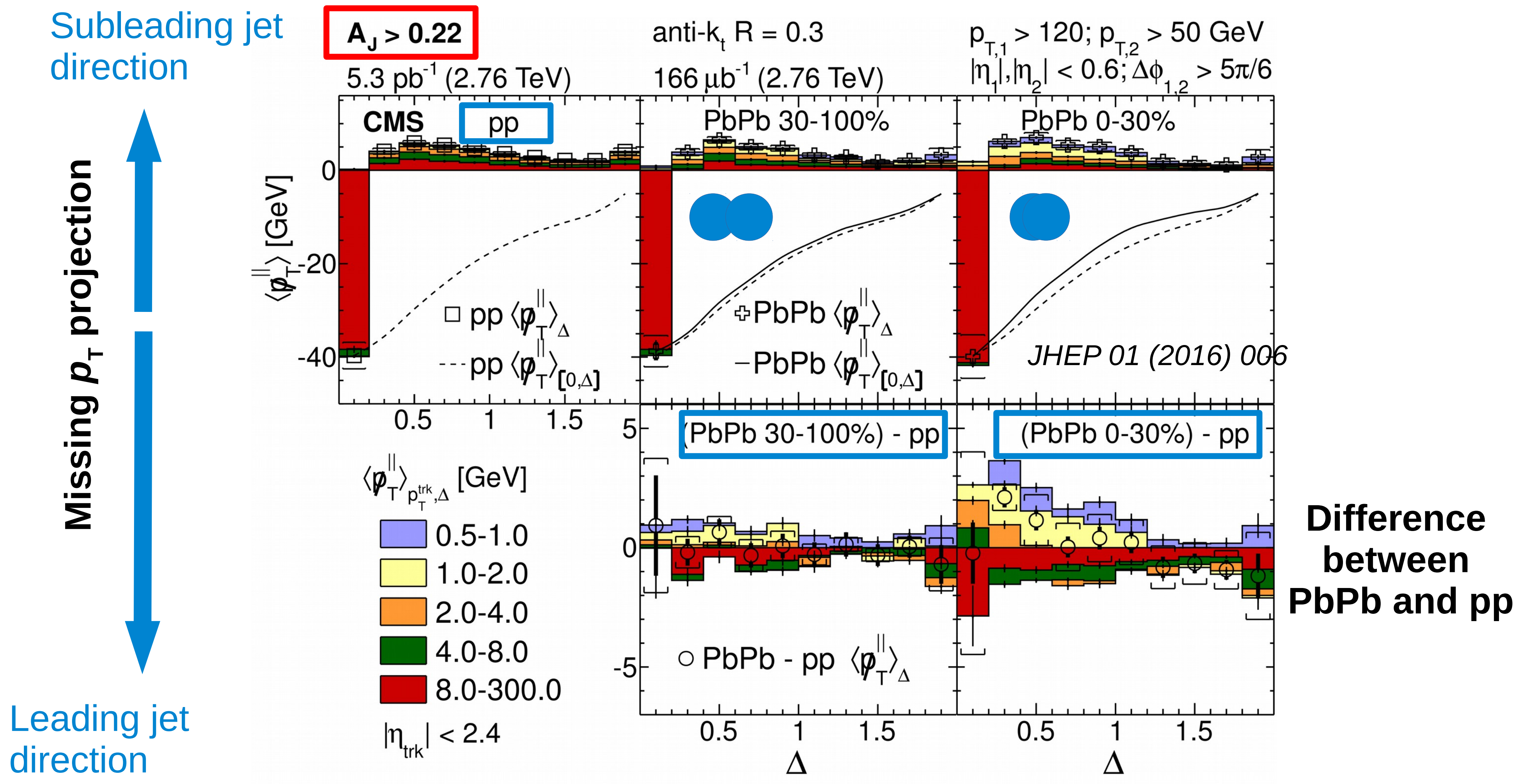

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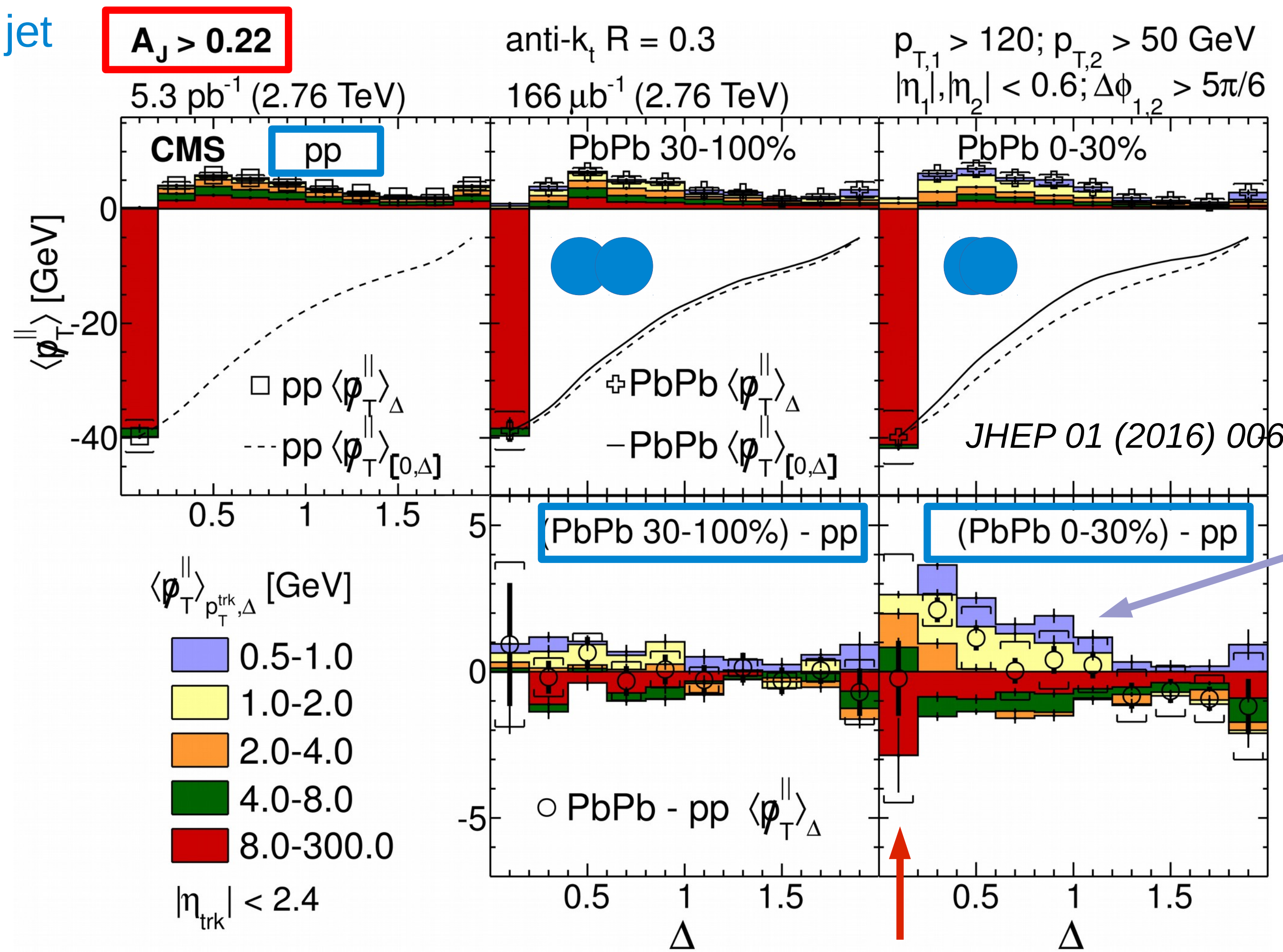
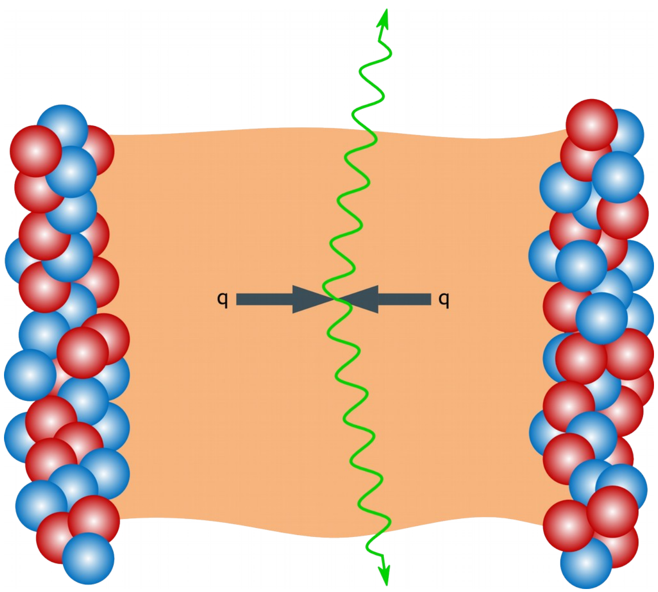


Balanced at large angles by soft particles

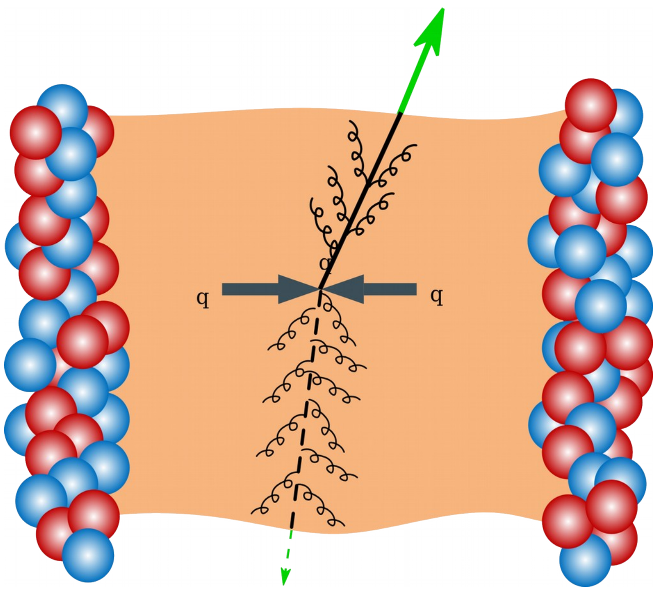
High-p_T imbalance at small angles

Hard probes gallery

- Different hard probes interact with medium differently.



Vector bosons



Open heavy flavor

- 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 $\Delta E_{u,d,s} > \Delta E_{c} > \Delta E_{b}$

Hard probes gallery

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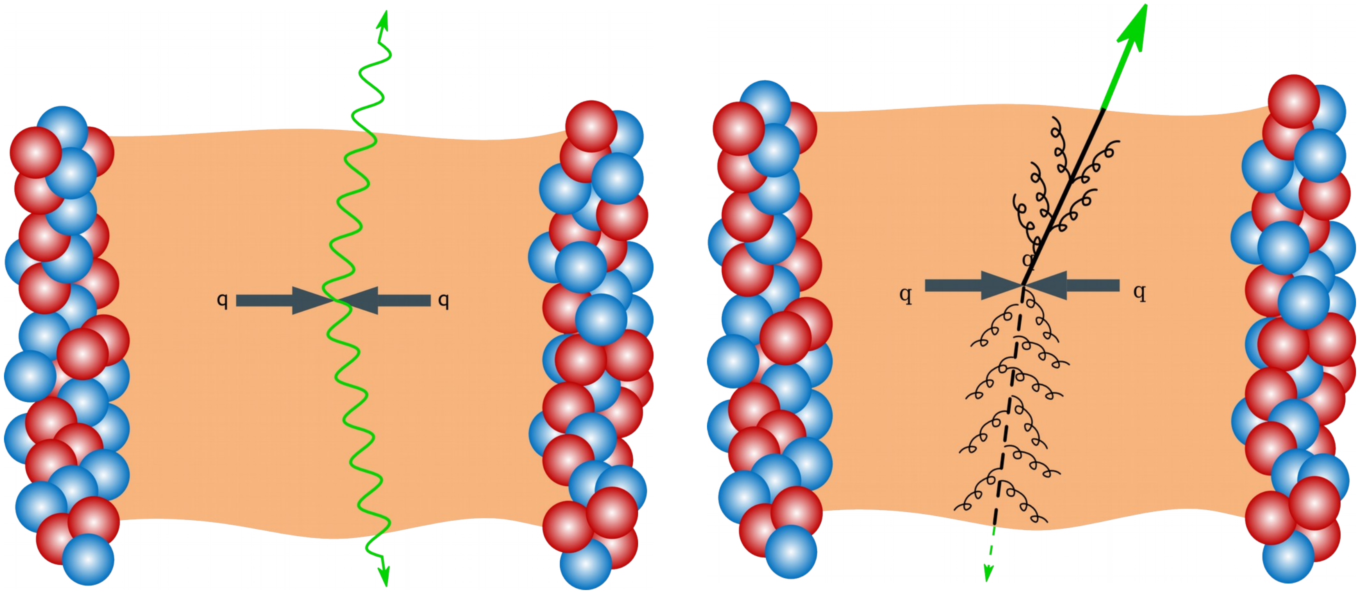

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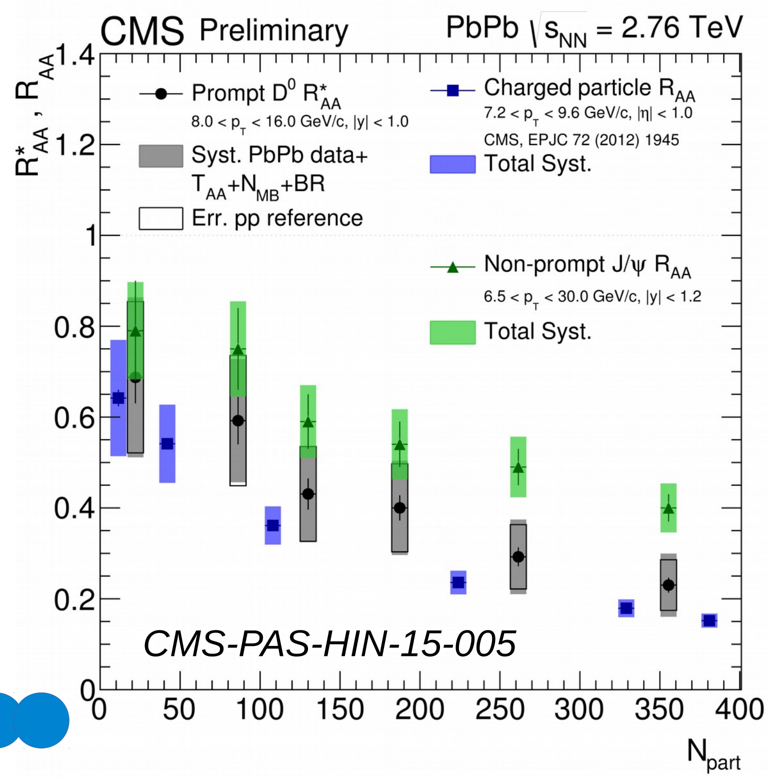
Caveats on R_{AA}:

Different shapes of parton p_T spectra

Different fragmentation

Open heavy flavor production

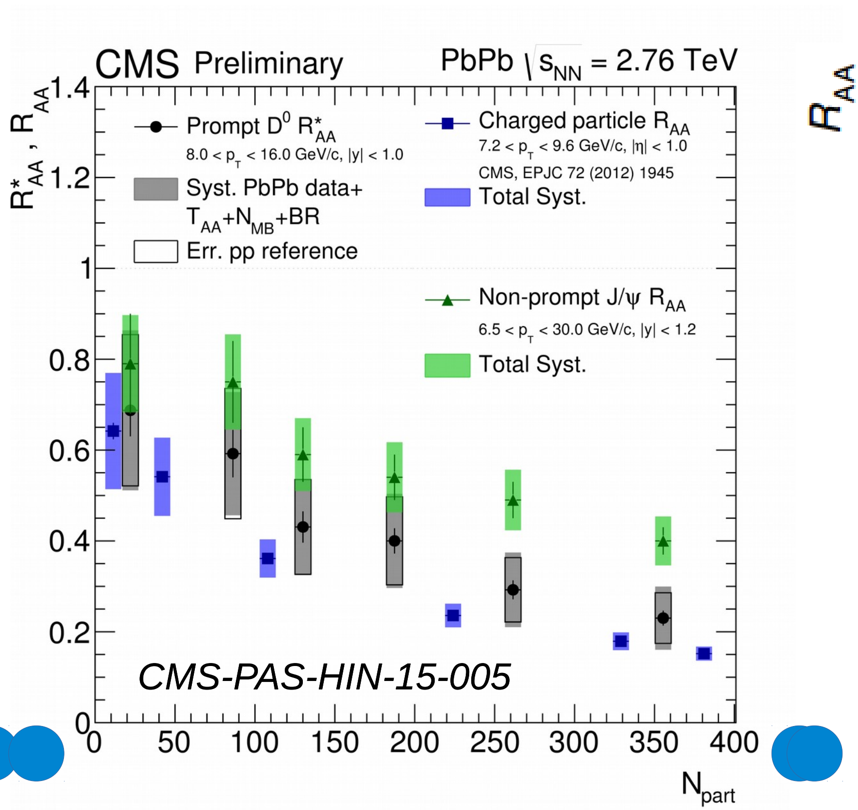
- D^0, D^+, D^{*+}, D_s^+ mesons measured by ALICE and CMS

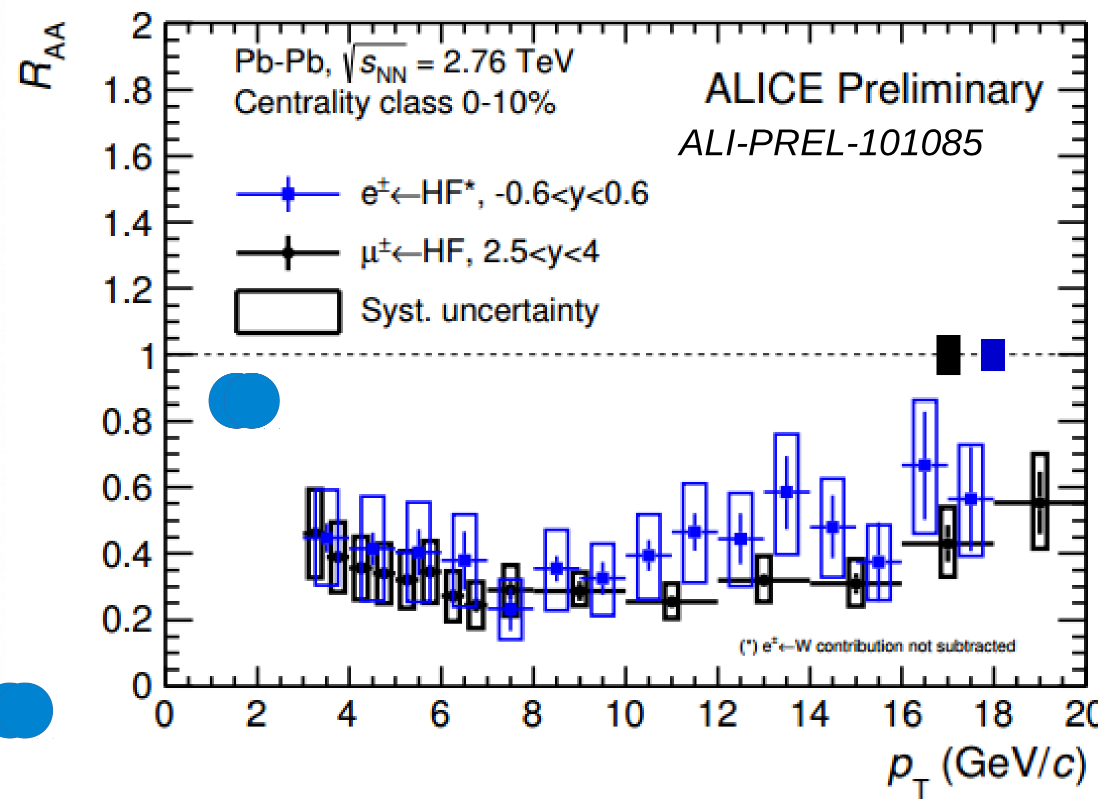


- Suppression in central Pb+Pb collisions relative to FONLL reference.
- Prompt D^0 suppressed more than non-prompt J/ψ from B decays.
  - Consistent with our expectations of flavor dependence energy loss.

Open heavy flavor production

- Lepton production from decays of B and C hadrons by ATLAS and ALCIE.





- Higher R_{AA} than inclusive charged hadrons at the same p_T.

Hard probes gallery

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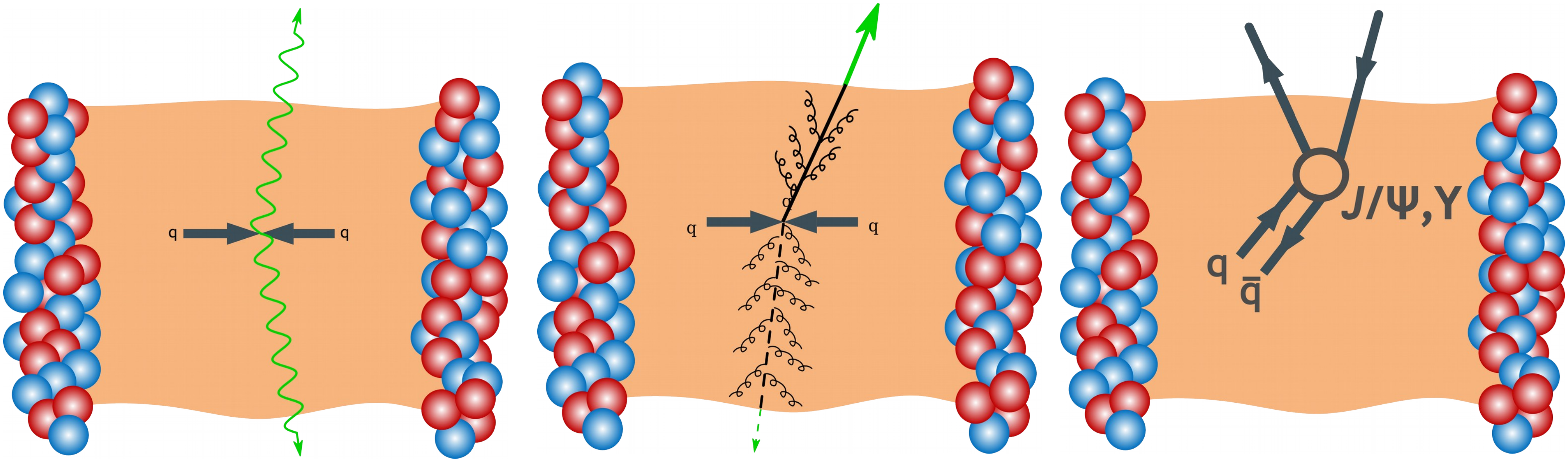


Vector bosons | Open heavy flavor/ jets | **Quarkonia**

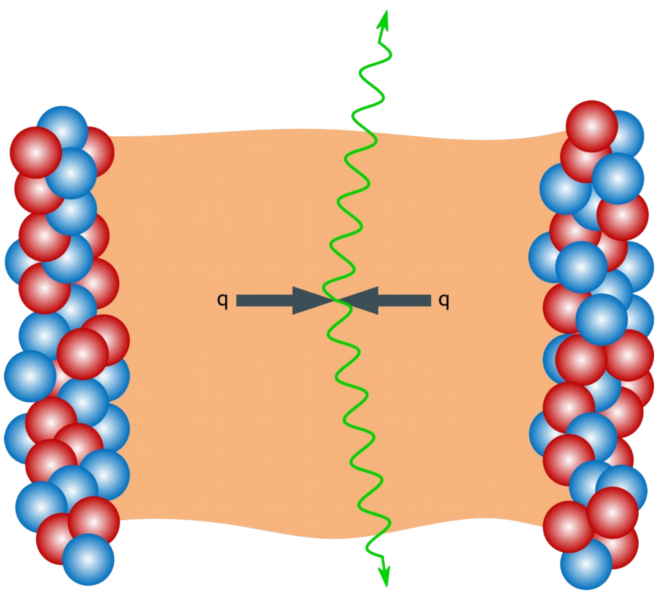
- Dissociation in the medium due to the color screening.

➡ Differences in the quarkonium binding energy.

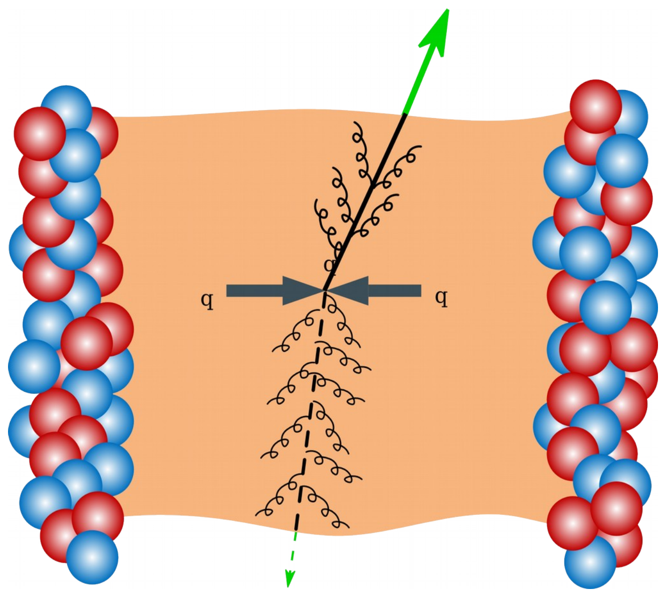
➡ Sequential melting with increasing temperature

Hard probes gallery

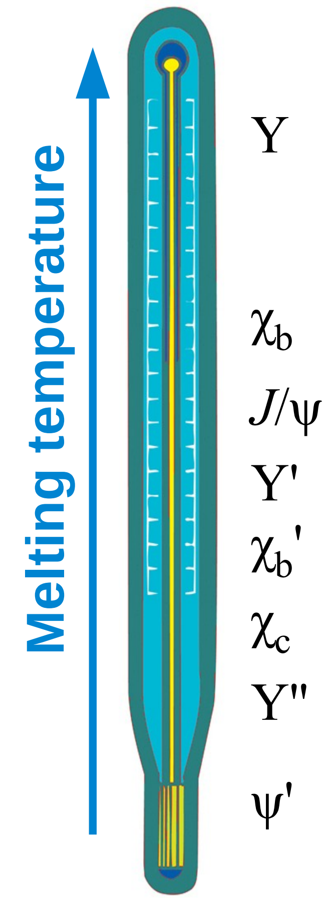
- Different hard probes interact with medium differently



Vector bosons



Open heavy flavor/ jets



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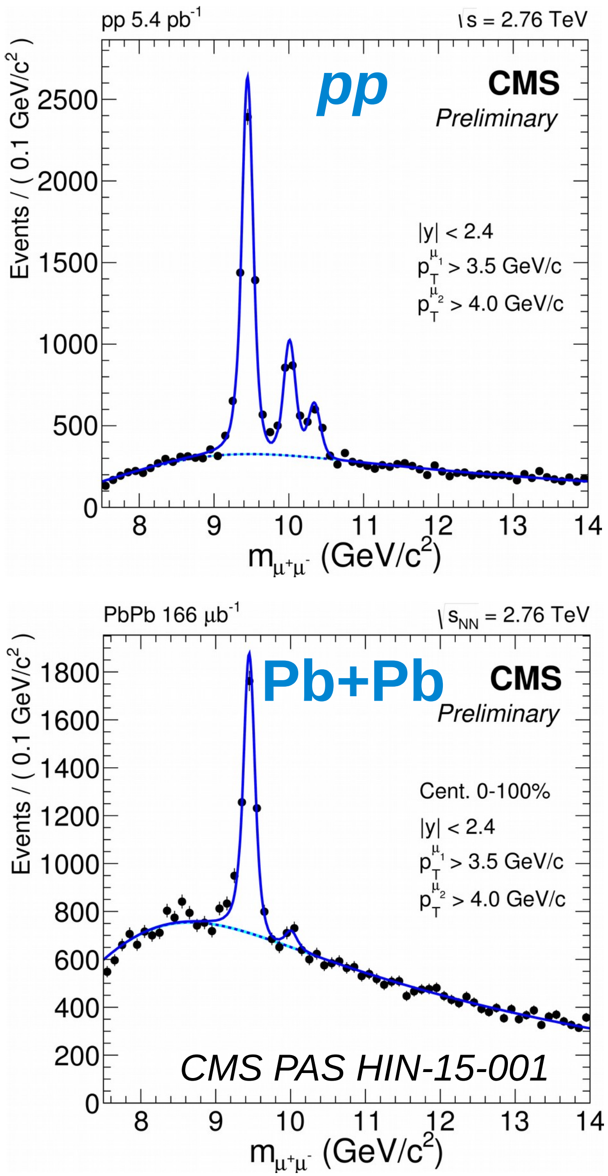
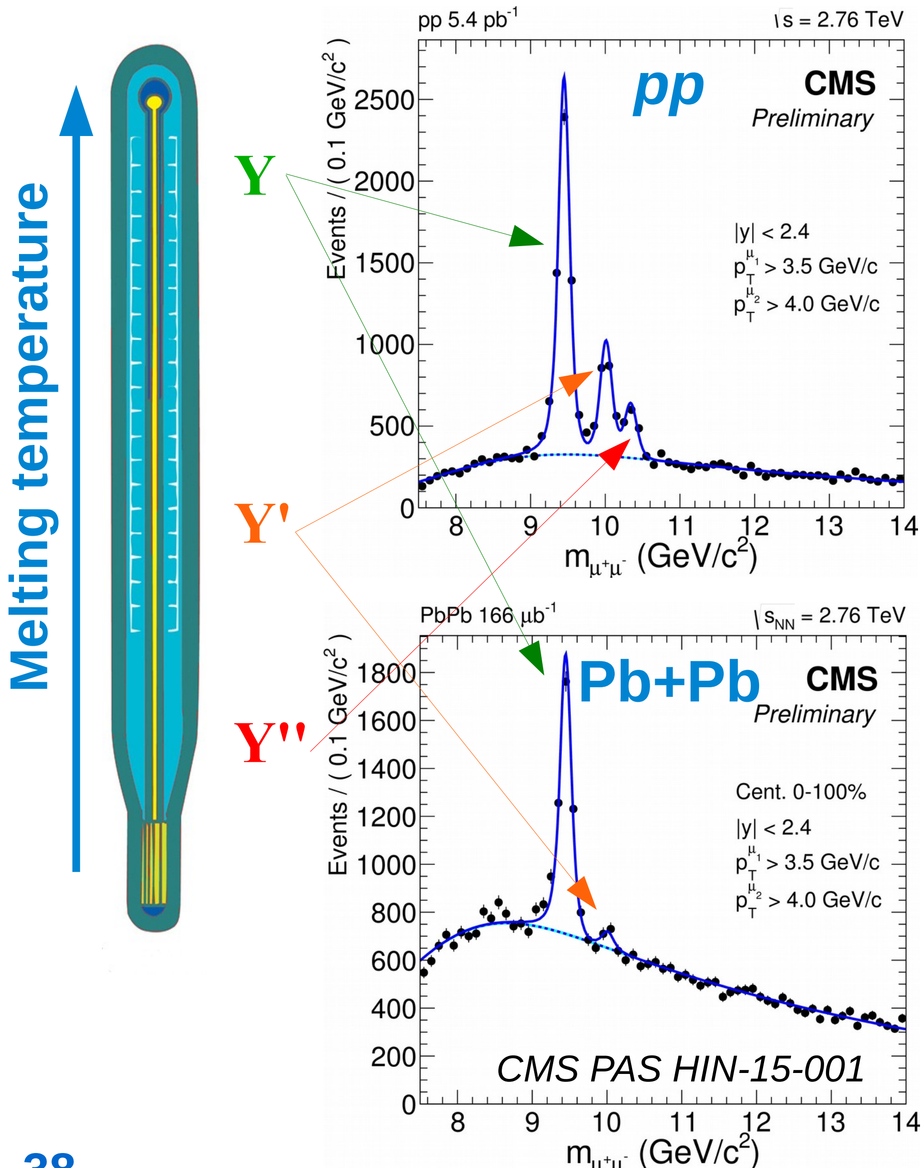
Quarkonia serve as thermometer of the medium.

Upsilon production



- Reanalysis of 2011 CMS data + high statistic *pp* reference.

Upsilon production



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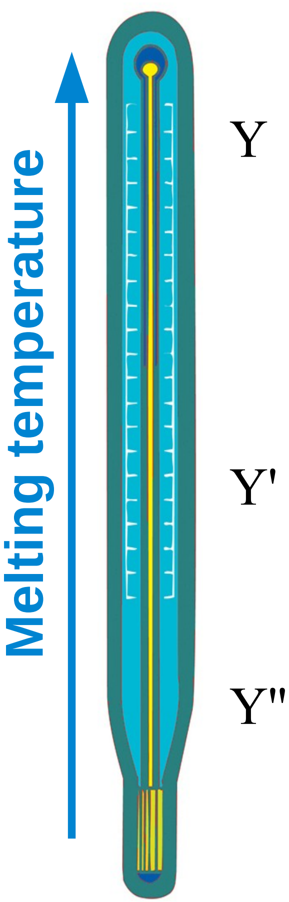
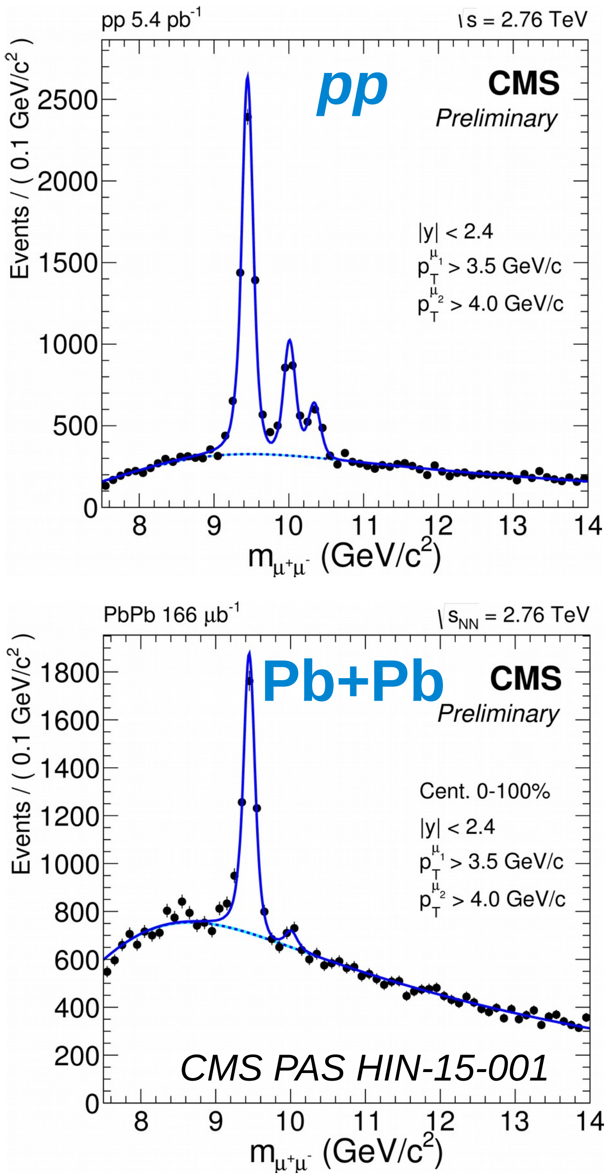
Upsilon production





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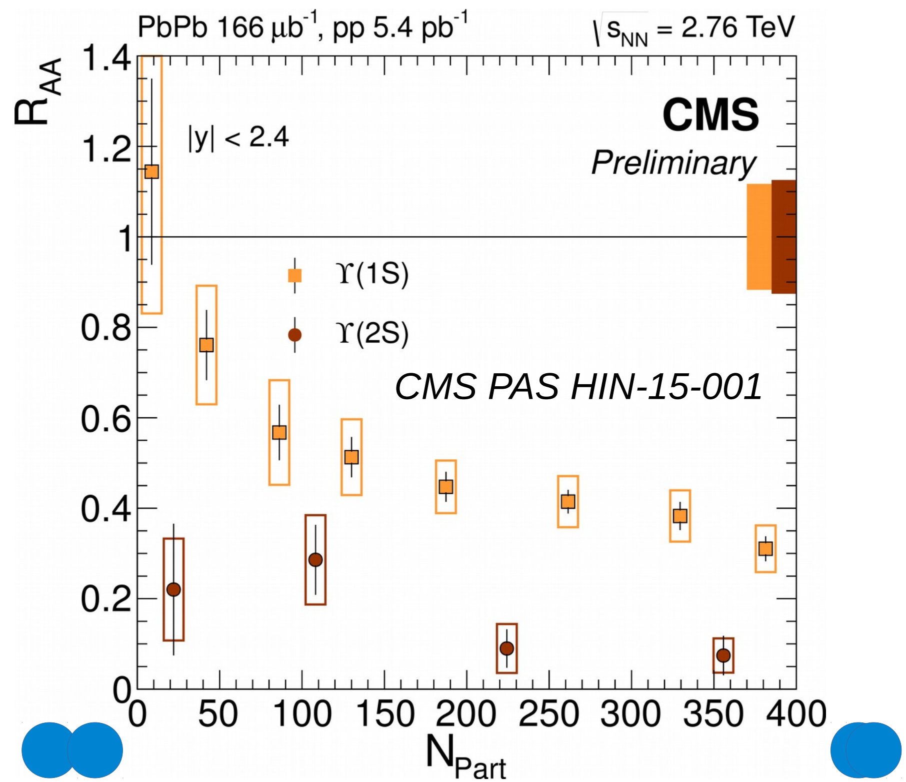
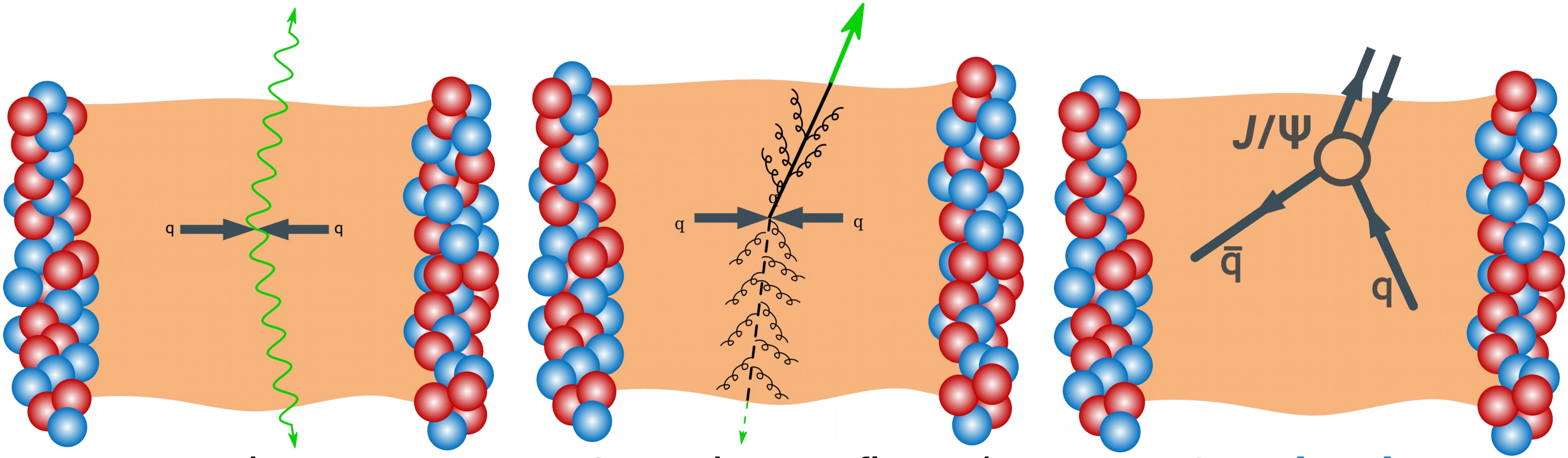


- Centrality dependent suppression for Y(1s) and Y(2s).
- Sequential melting:
  R_{AA} (Y(3s)) < R_{AA}(Y(2s)) < R_{AA}(Y(1s))

Hard probes gallery

- Different hard probes interact with medium differently



Vector bosons | Open heavy flavor/ jets | Quarkonia

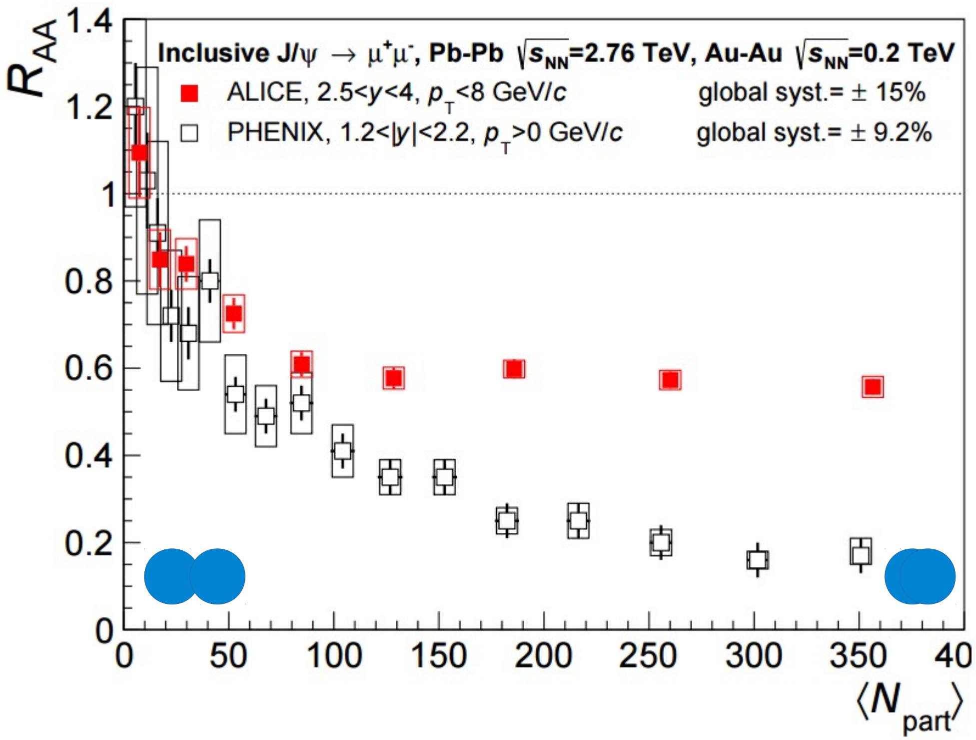
- Dissociation in the medium due to the color screening.

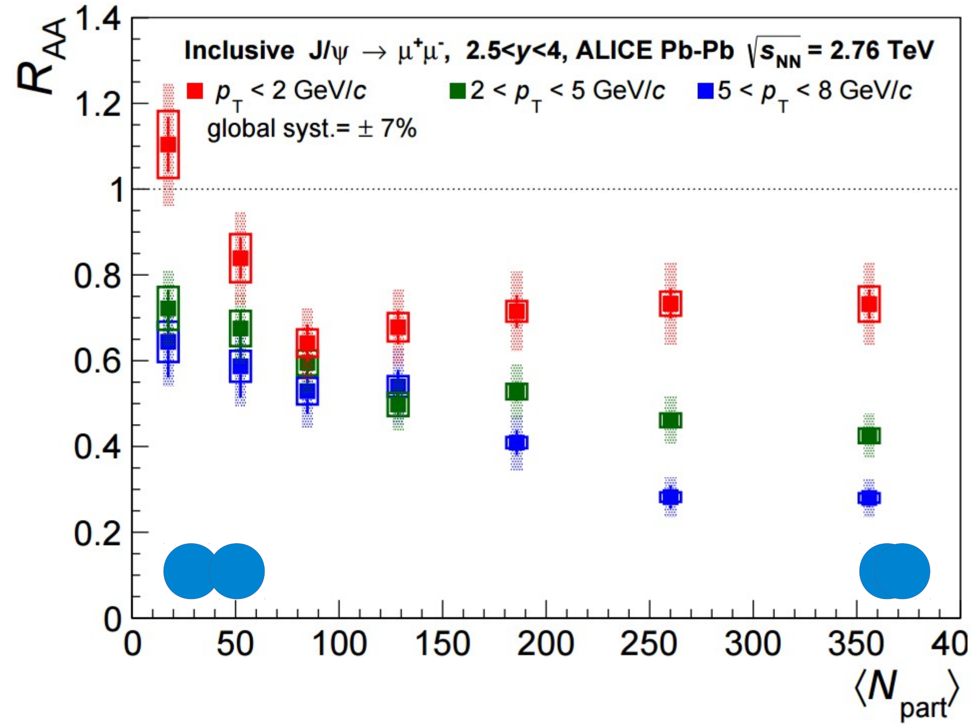
➡ Differences in the quarkonium binding energy.

➡ Sequential melting with increasing temperature

...or can we see a recombination in the high collision energy?

Evidence for recombination...





- Higher suppression for low pT J/ψ at RHIC despite the smaller energy density.
- Different behavior is observed at higher p_T.
- Do we see recombination of $c\bar{c}$ pairs at LHC?

Summary

- Medium created in HI collisions is opaque to energetic colored particles.
  - High p_T partons lose energy in the deconfined medium.
  - Lost energy is transported to soft particles at large angles.
  - Parton mass is additional relevant scale.

- The formation of quarkonium bound states is affected by the medium.
- Different mechanisms through which their production is affected.

- Non-trivial theoretical problem
- Field is mostly driven by experimental measurements.
- **New exciting results expected from Run2 data!**

Summary

- Medium created in HI collisions is opaque to energetic colored particles.
  - High p_T partons lose energy in the deconfined medium.
  - Lost energy is transported to soft particles at large angles.

More details in the dedicated parallel section on Hard probes in HI collisions tomorrow morning.

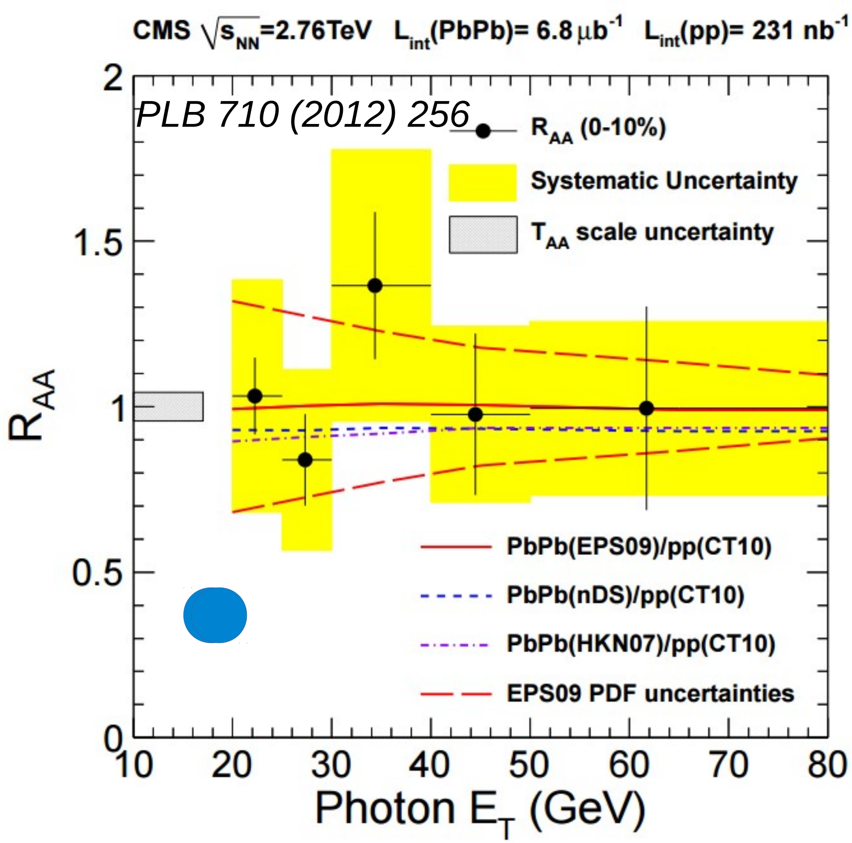
- Different mechanisms through which their production is affected.

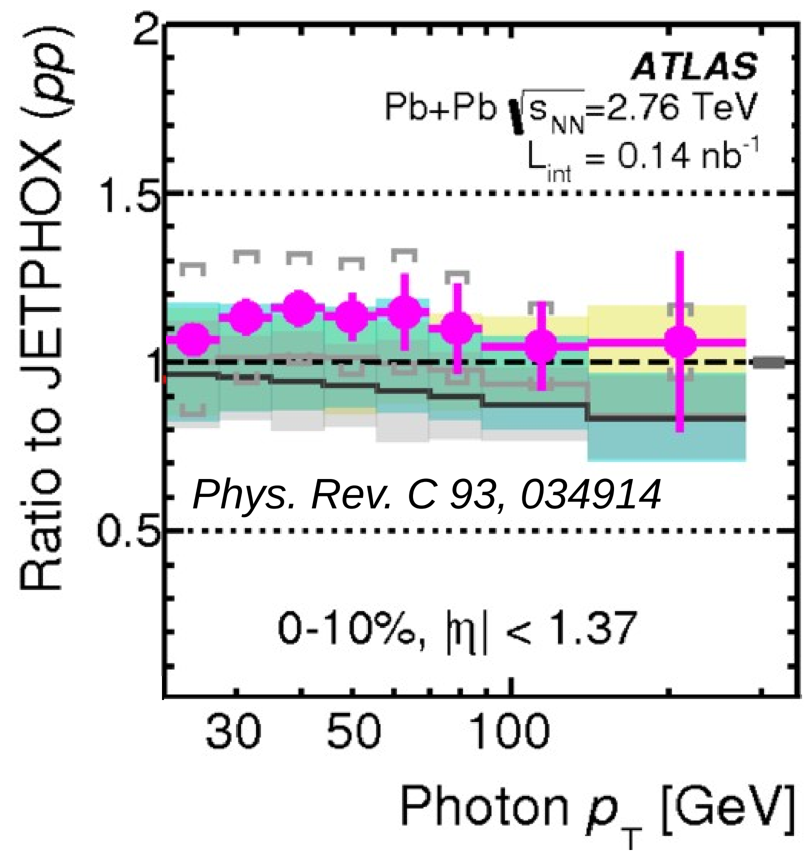
- Non-trivial theoretical problem
- Field is mostly driven by experimental measurements.
- **New exciting results expected from Run2 data!**

Backup

Prompt photons production

- Promtp photons are sensitive only to initial state effects.





- CMS: comparison to *pp* collisions.
- ATLAS: comparison to NLO pQCD (JETPHOX MC)

➡ No medium effects, yields consistent with N_{coll} scaling.

Jets and charged hadrons

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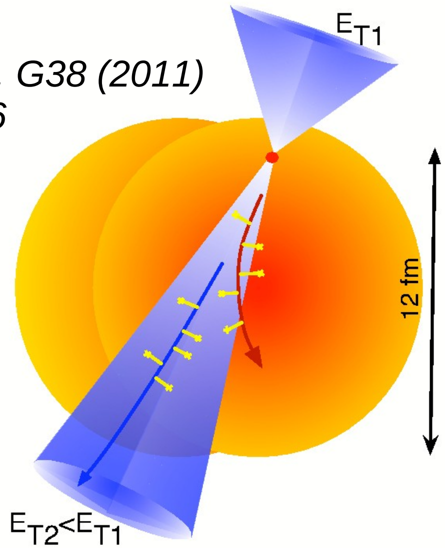

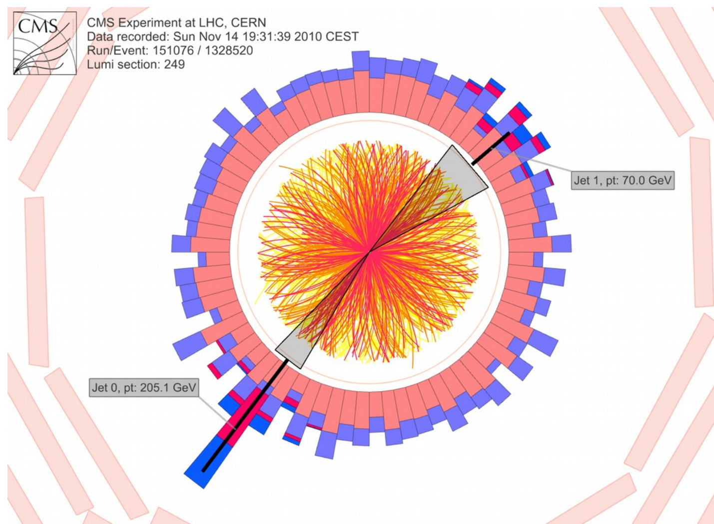

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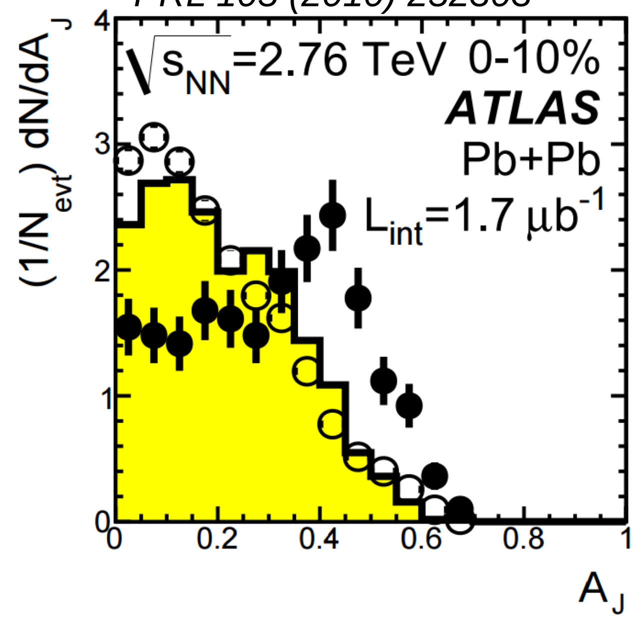
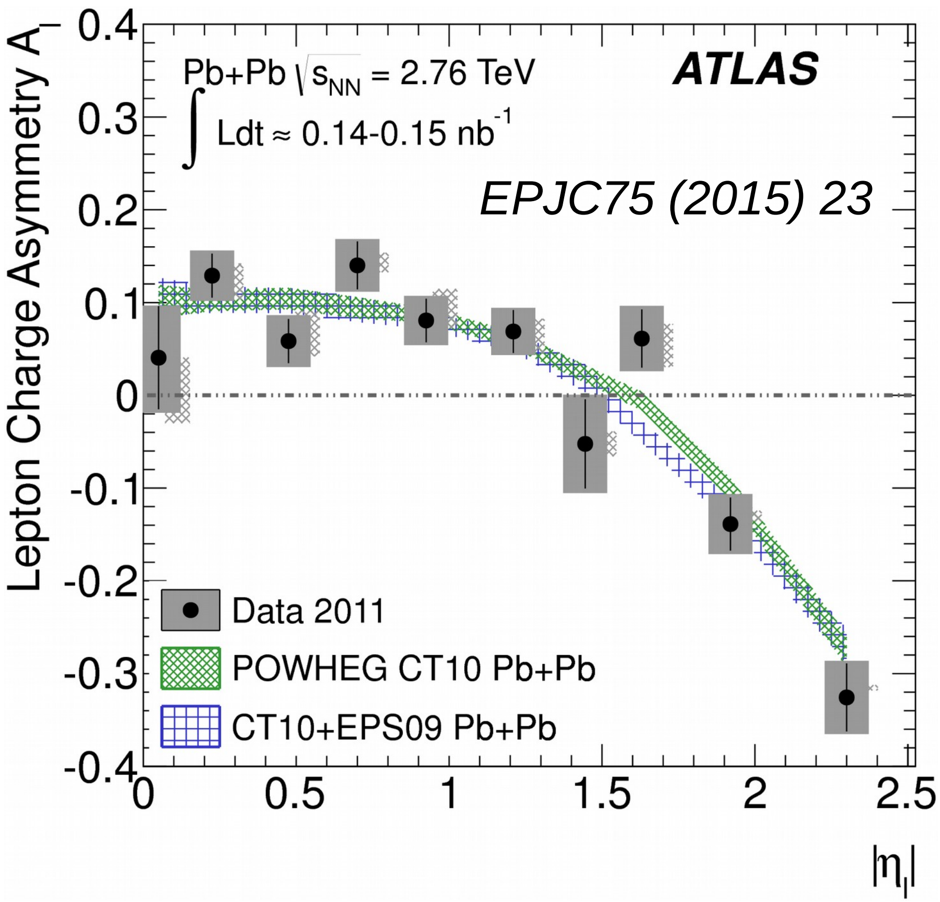
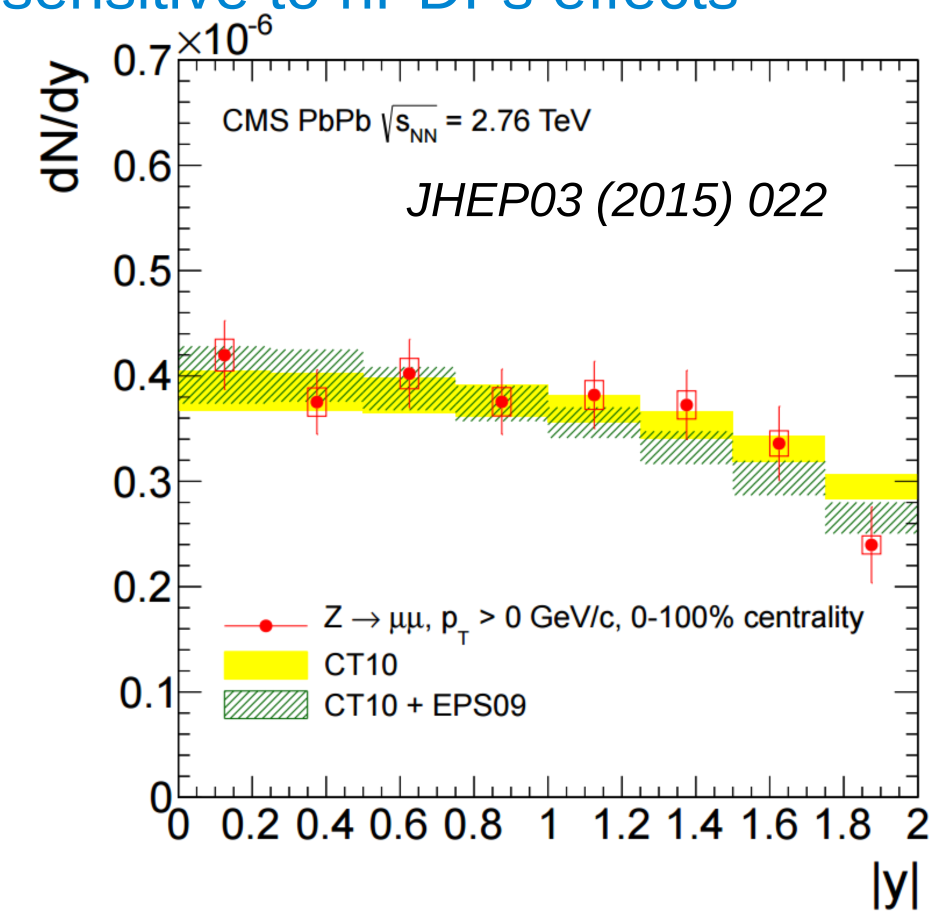


- A significant modification of di-jets and suppression of inclusive jet spectra is observed in central HI collisions.
  - Is the energy redistributed to the medium out of the jet cone?
  - Does the energy remain inside the jet but redistributed among fragments?
  - How much modification is coming from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

EW bosons production

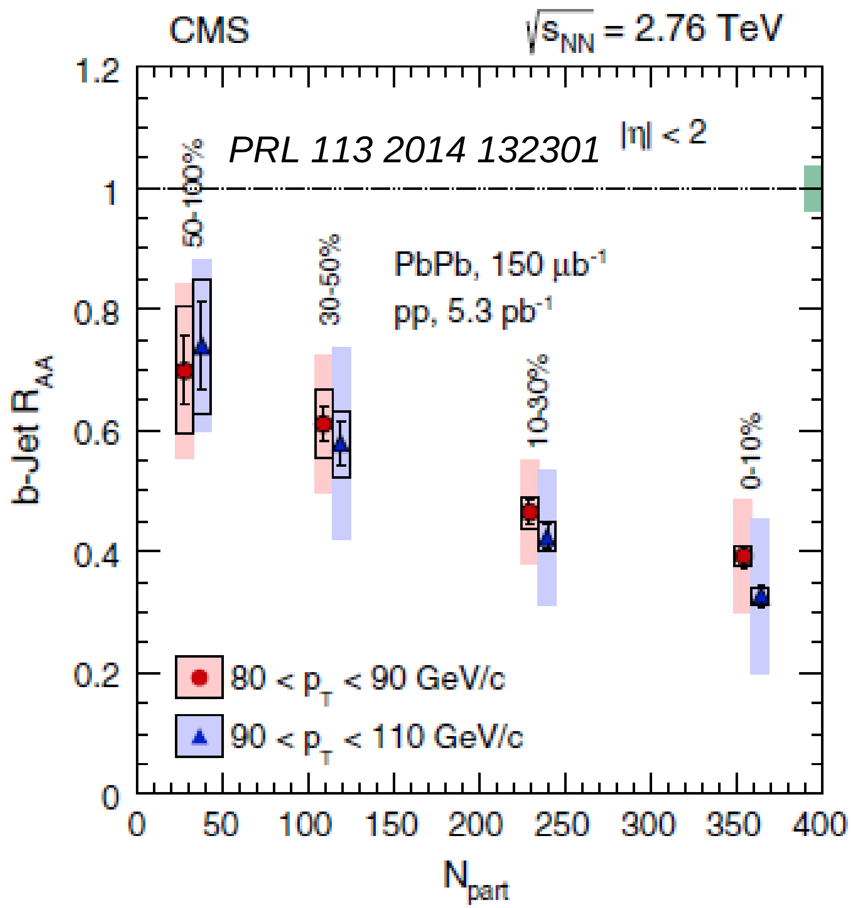
- Similarly to prompt photons do not interact with QGP
- Produced in $q\bar{q}$ annihilation ➡ sensitive to nPDFs effects

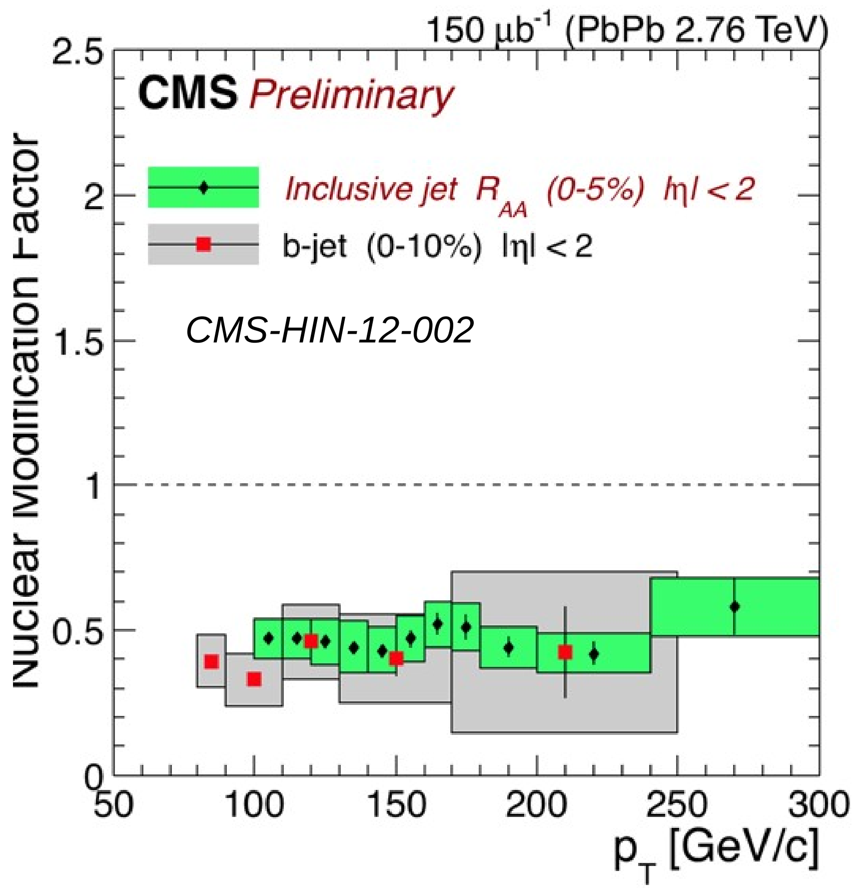




- Observables sensitive to initial state and spin conservation
- Not enough sensitivity to nPDFs effects (isospin and shadowing).

b-jet suppresion

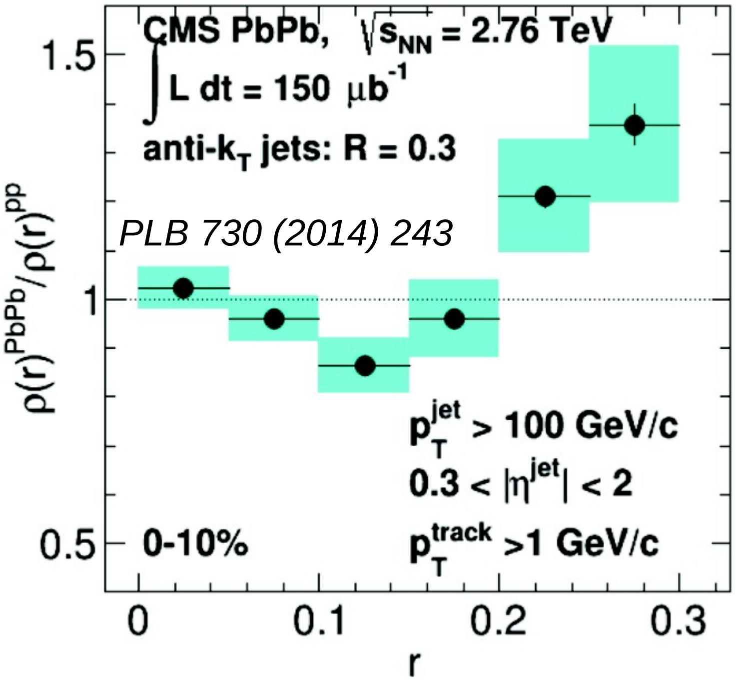


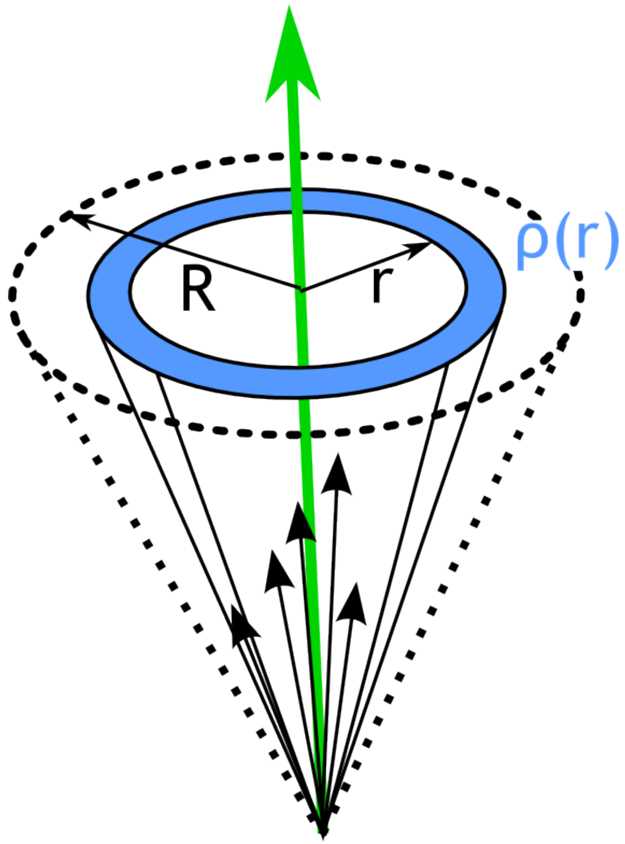


- B-jet production is suppressed by a similar factor as inclusive jets.

What is the shape of jets?

Jet shape: $\rho(r) = \frac{1}{\delta r}\frac{1}{N_{\mathrm{jet}}}\sum_{\mathrm{jets}}\frac{\sum_{\mathrm{tracks}\in[r_a,r_b)} p_T^{\mathrm{track}}}{p_T^{\mathrm{jet}}}$





- CMS measurement:
  - Modest modification of jet structure at small angles.
  - Excess at large angles (and low p_T).

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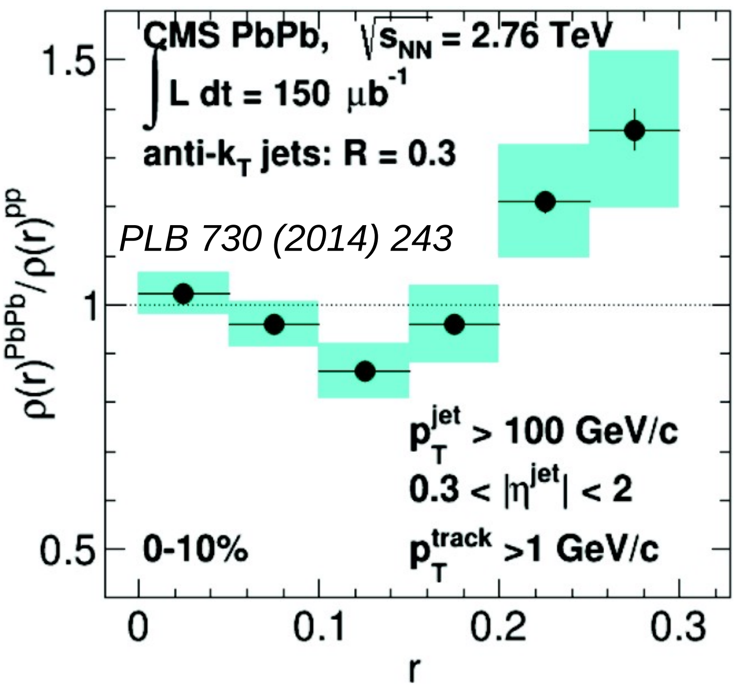
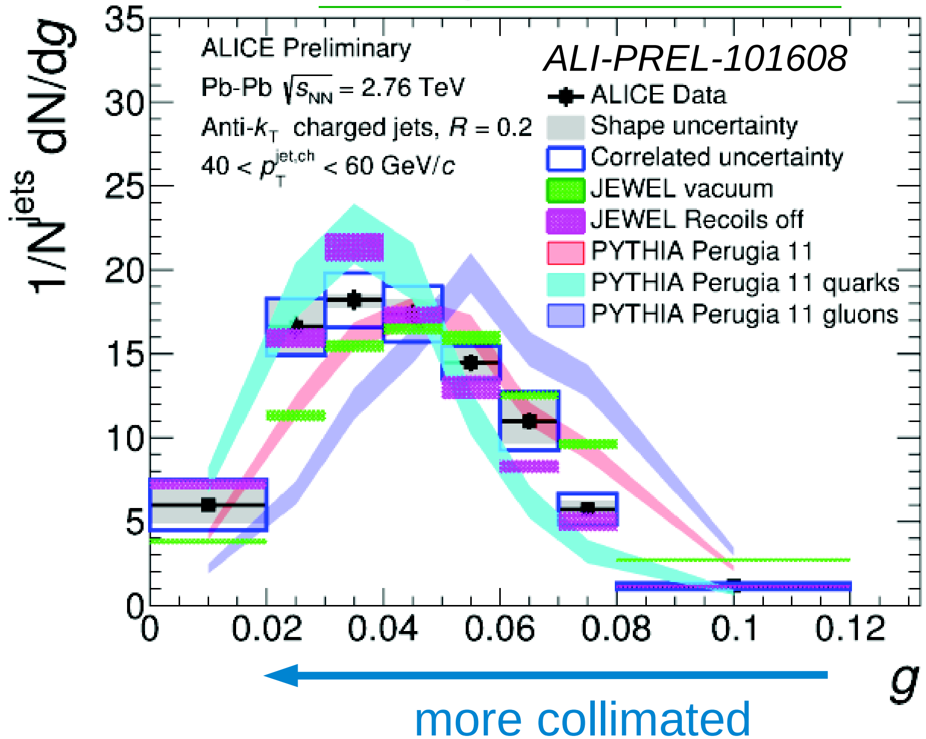
Radial moment: $g = \sum_{i\in jet}\frac{p_T^i}{p_{T,jet}}|\Delta R_{ijet}|$

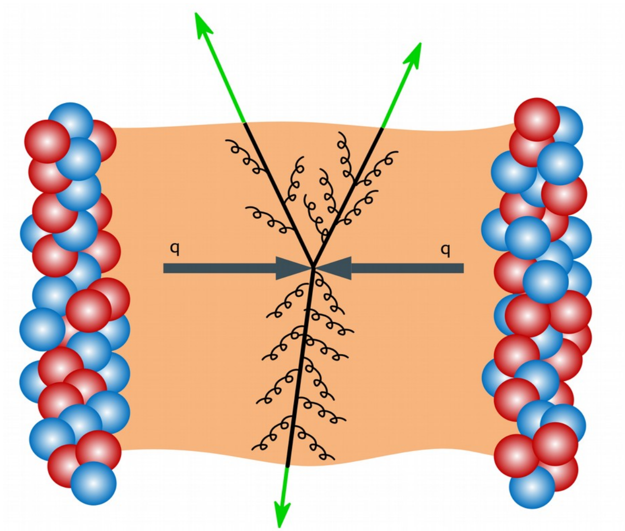


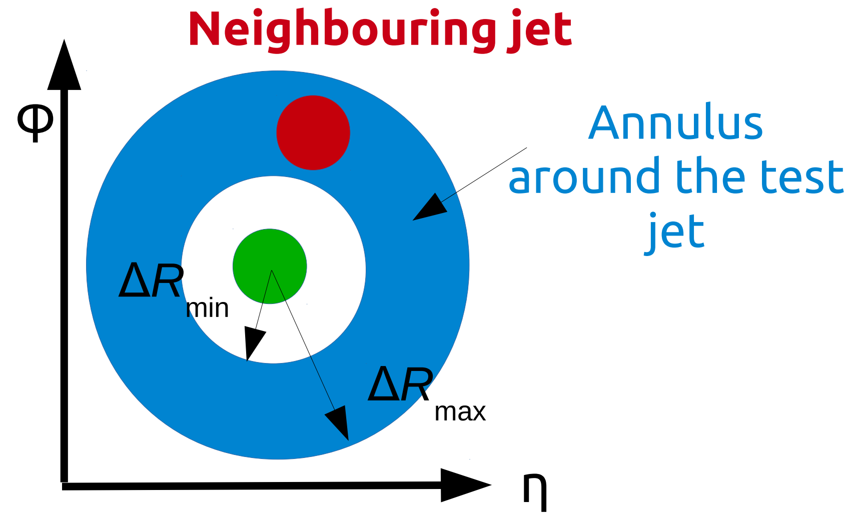


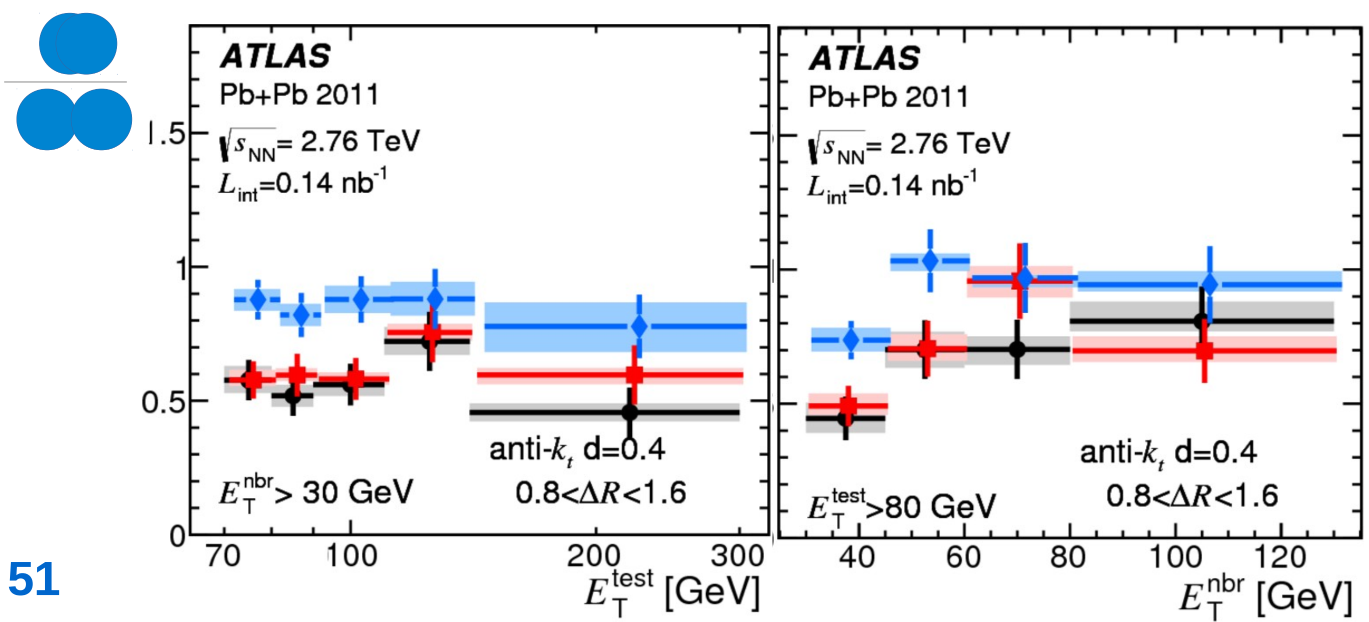
- CMS measurement:
  - Modest modification of jet structure at small angles.
  - Excess at large angles (and low p_T).
- ALICE study of jet core:
  - Core of jet more collimated ⟺ gluon quenching?

Production of neighbouring jets

- First multi-jet measurement in HI: rate of neighbouring jets.



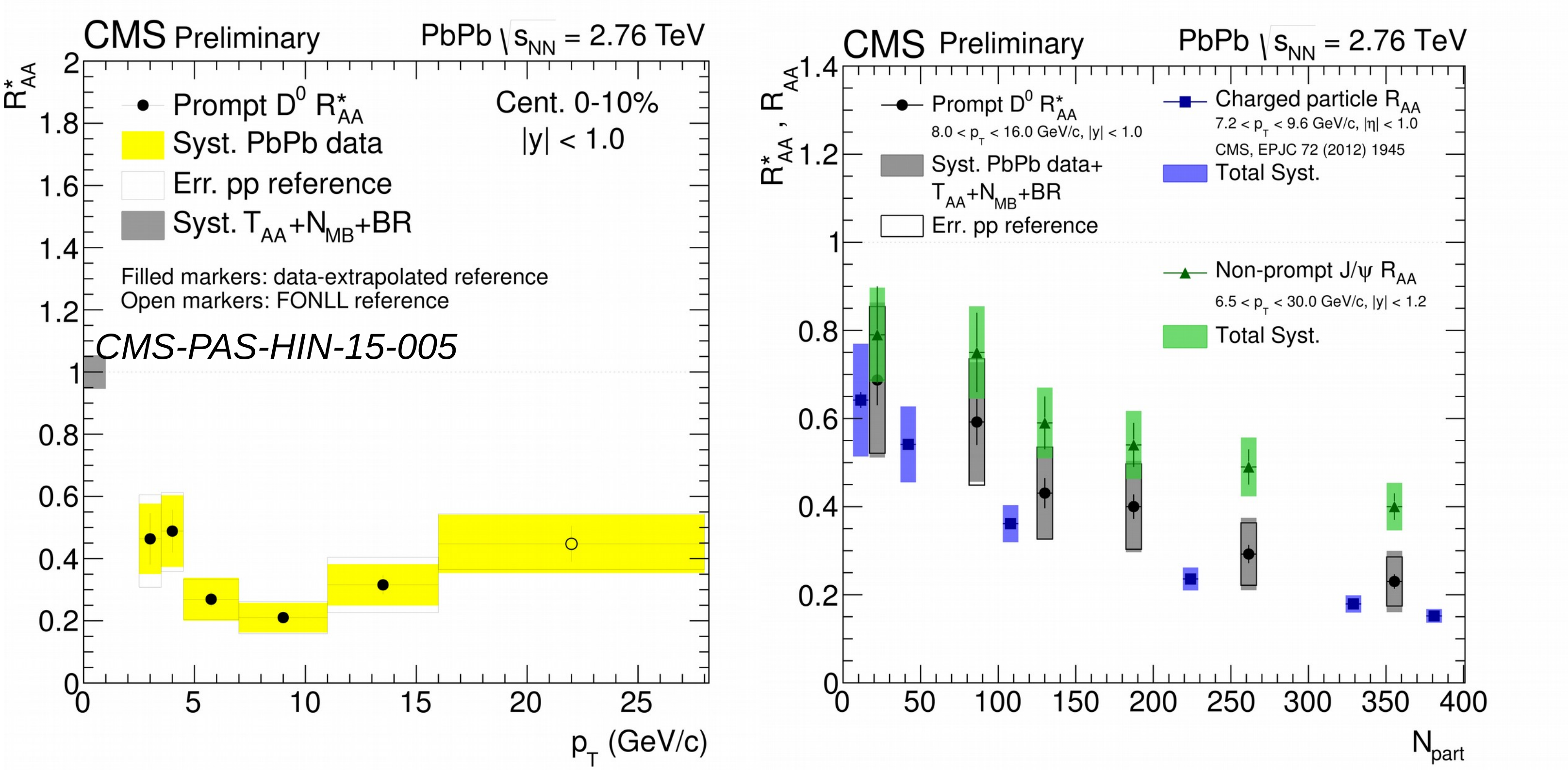




- Study of relative quenching in neighbouring jet pair.
- Hint of a decrease of suppression when energy of two jets is similar.

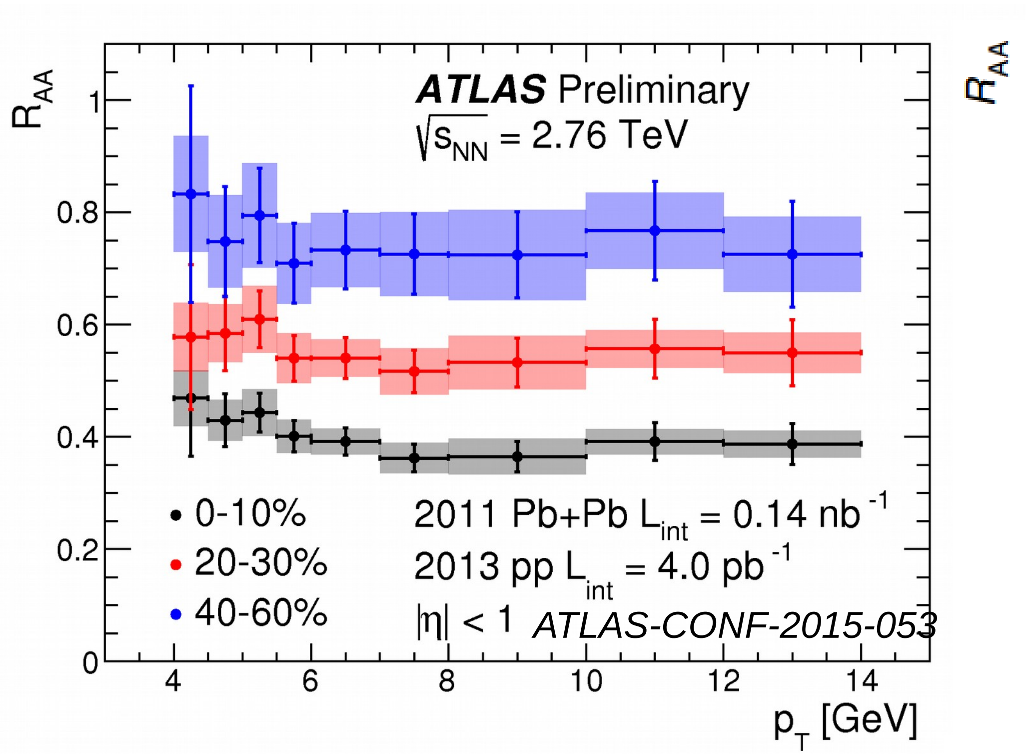
Promt D^0 production

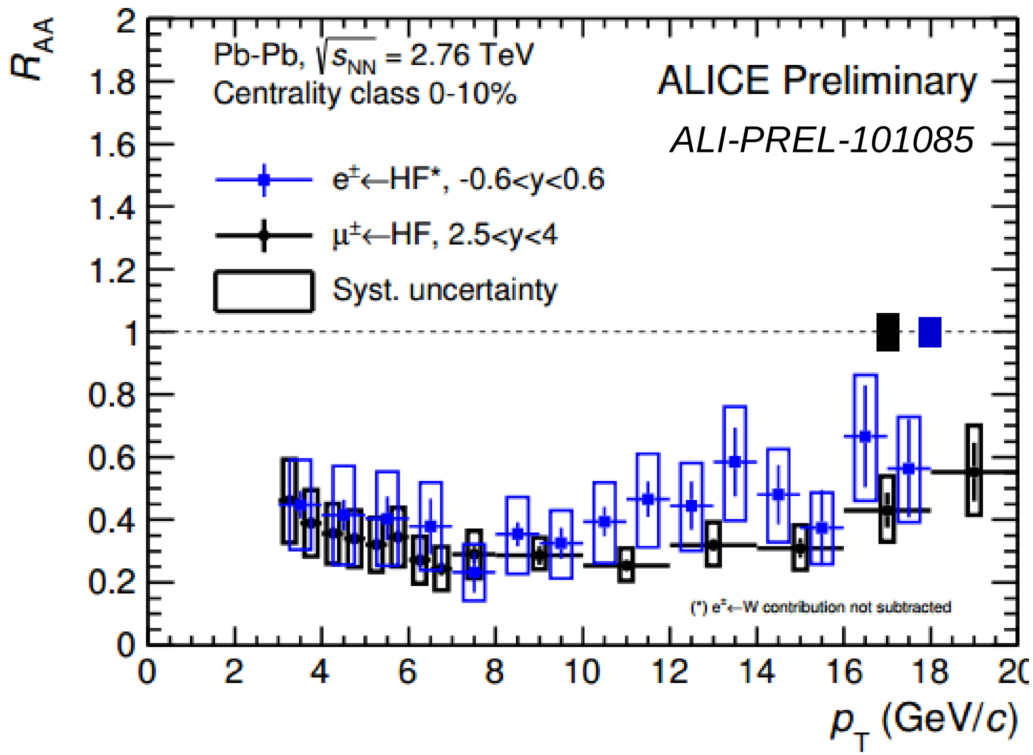
- D^0, D^+, D^{*+}, D_s^+ mesons measured by ALICE
- D^0 measured by CMS:



- R_{AA} shows suppression in central Pb+Pb collisions relative to FONLL reference.
- Prompt D^0 suppressed more than non-prompt J/ψ from B decays

Open heavy flavor





- Lepton production suppressed in the p_T region dominated by decays of B and C hadrons.
- Higher R_{AA} than inclusive charged hadrons at the same p_T.
- Radial flow affects the low p_T part.