Recent results on heavy ion collisions from the ATLAS experiment

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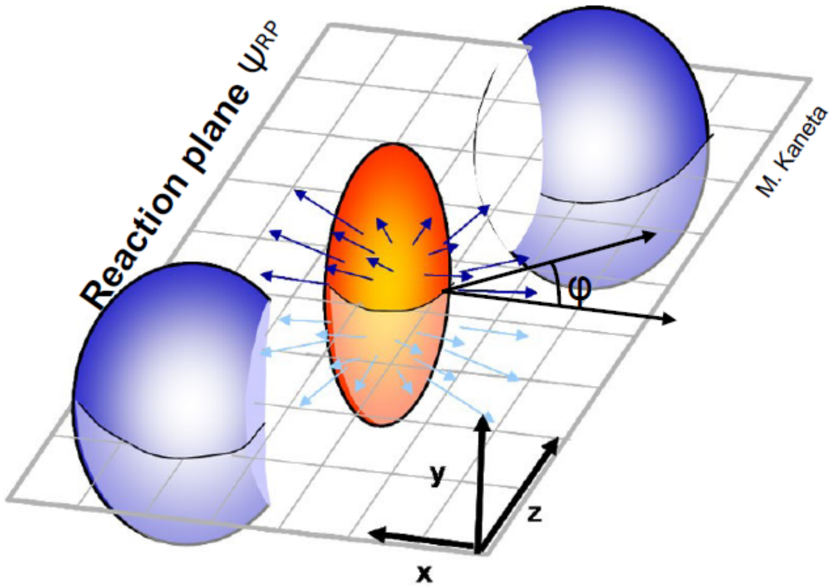
Three topics and some of related questions

- Flow phenomenon:
  - What is the origin of the flow at high-p_T?
  - What is the origin of the flow in small systems such as *pp*?
  - Is there a universality of flow / particle production among collision systems?
- Penetrating probes of Quark Gluon Plasma:
  - What is the mechanisms of the suppression of hadrons?
  - How do the particles radiate when going trough the plasma?
  - What are the properties of the plasma?
- Photon physics:
  - Can measure g-2 for tau leptons?
  - Can we study nuclear structure with photons?

Flow phenomenon: basic picture



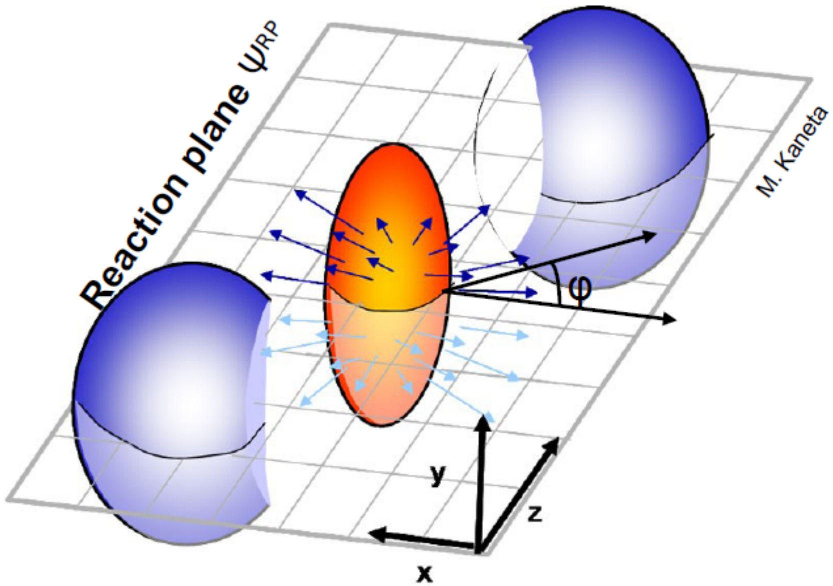
- Pressure gradients in the fireball of the overlapping region lead to the **azimuthal anisotropy**. At the lowest order:

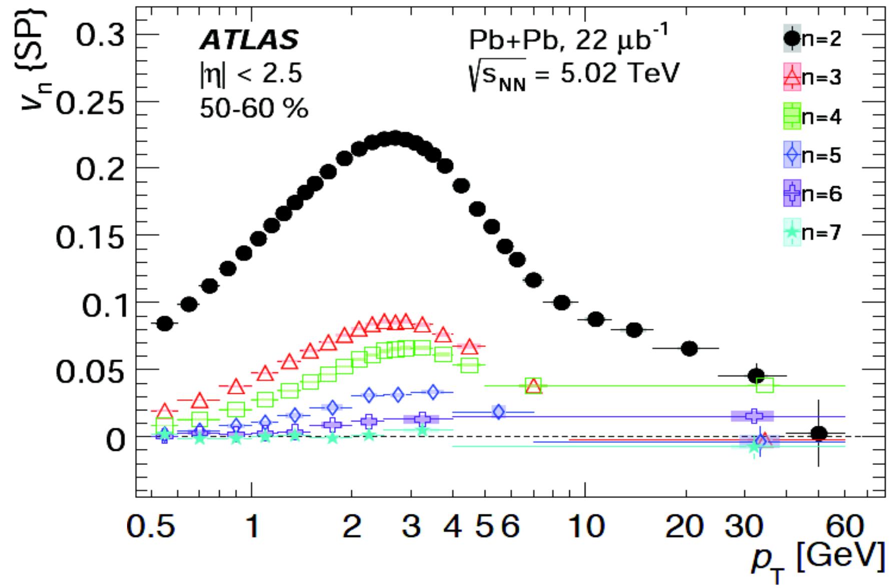
$$\frac{\mathrm{d}N}{\mathrm{d}\phi} = N_0\Big(1 + 2v_2\cos 2(\phi - \Phi^{RP})\Big) \qquad v_2 = \Big\langle \cos 2(\phi - \Phi^{RP})\Big\rangle$$

- …v_2 is the elliptic flow. Elliptic flow – one of the main signatures for a presence of hot and dense deconfined matter – quark gluon plasma.

Flow phenomenon: basic picture

EPJC 78 (2018) 997





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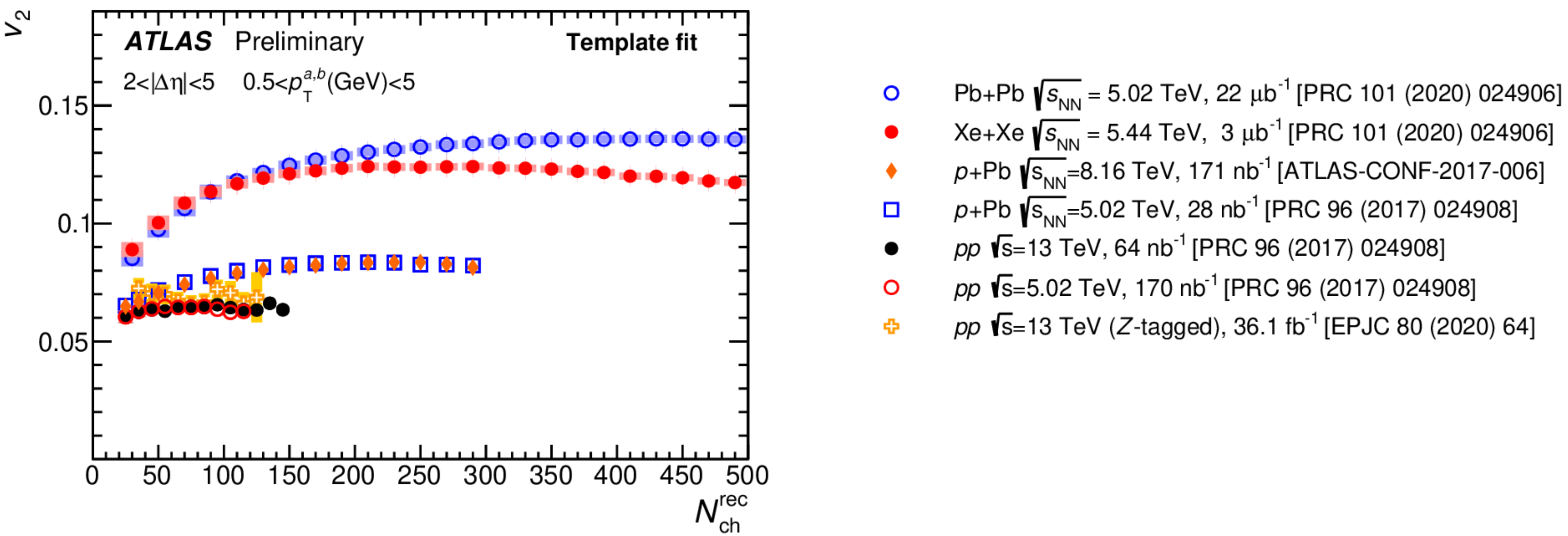
- …v_2 is the elliptic flow. Elliptic flow – one of the main signatures for a presence of hot and dense deconfined matter – quark gluon plasma.
- Precision measurements reaching high p_T and higher v_n available.

Flow – in small systems

- Flow seen not only in Pb+Pb, but also in high multiplicity pp and p+Pb collisions. What is the origin of that? Is the deconfined matter formed there?



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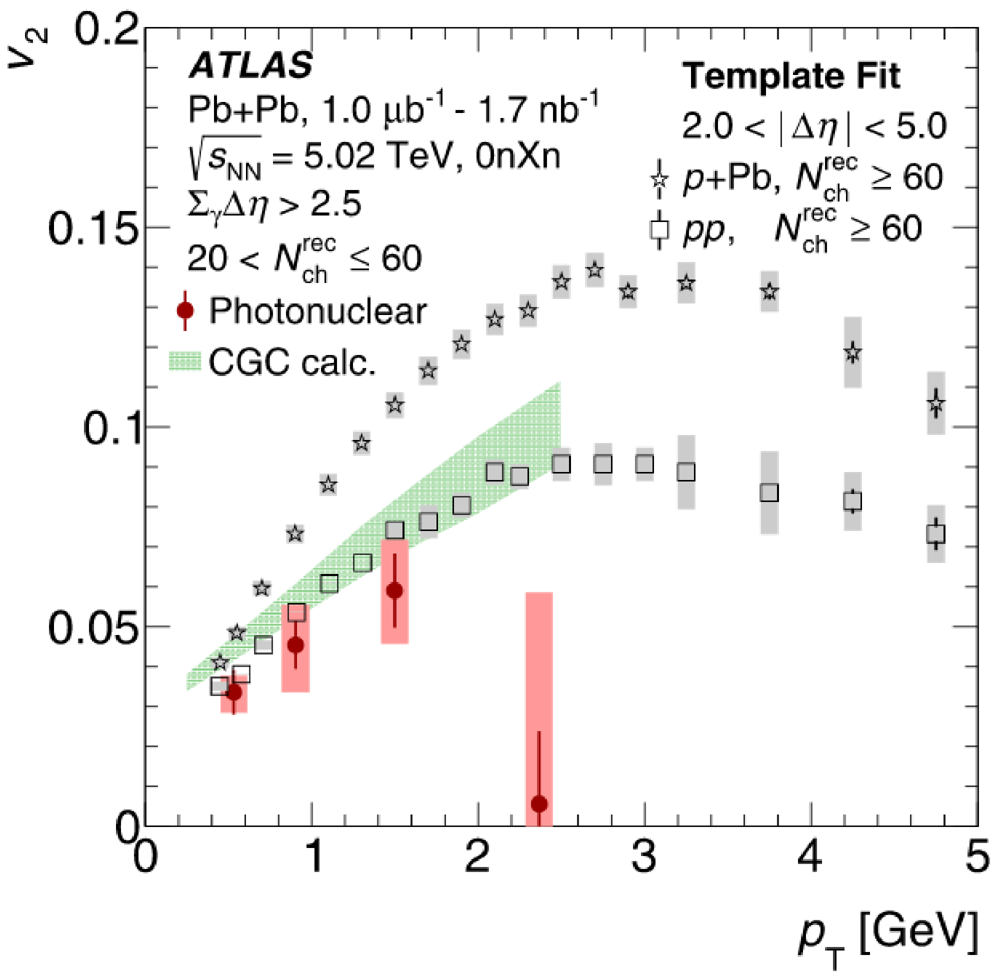

- Flow observed also **in γ-Pb collisions**!
- In vector meson dominance view, the γ-Pb collisions can be interpreted as ρ-Pb collisions.
- In general, it is important to understand the initial conditions => e.g. studies of flow de-correlations (see ATLAS-CONF-2022-020)

PRC 104 (2021) 014903

Flow – tool for nuclear structure studies

- Correlations between v_n and p_T (ρ_n)– information about the nuclear geometry.
- ϱ_n reflects correlation in initial state between size and eccentricities => sensitivity to the **nuclear deformations**

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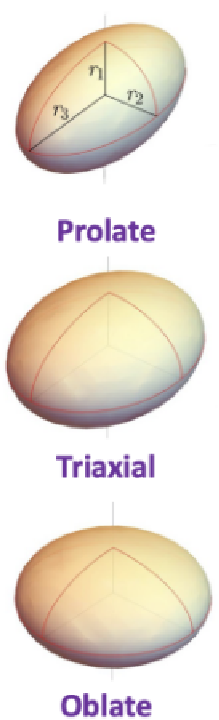
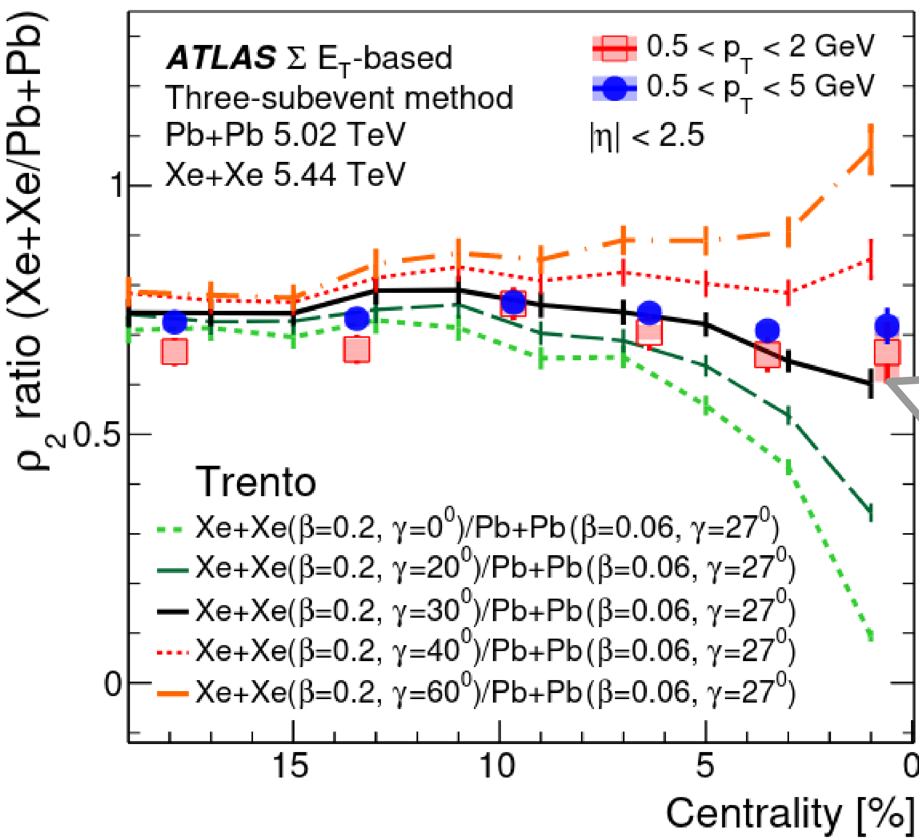




Modeling of initial state using Trento favors γ=30° – evidence that Xe[129] is highly **deformed triaxial nucleus**

arXiv:2205.00039

Jet quenching

Nuclear modification factor

$$R_{AA} = \frac{\boxed{\left.\frac{1}{N_{\mathrm{evnt}}}\frac{\mathrm{d}^2 N_{\mathrm{jet}}^{PbPb}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}\right|_{\mathrm{cent}}}}{\boxed{\langle T_{\mathrm{AA}}\rangle_{\mathrm{cent}}} \times \boxed{\frac{\mathrm{d}^2\sigma_{\mathrm{jet}}^{pp}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}}}$$

Jet yield in heavy-ion collisions

Nuclear thickness function

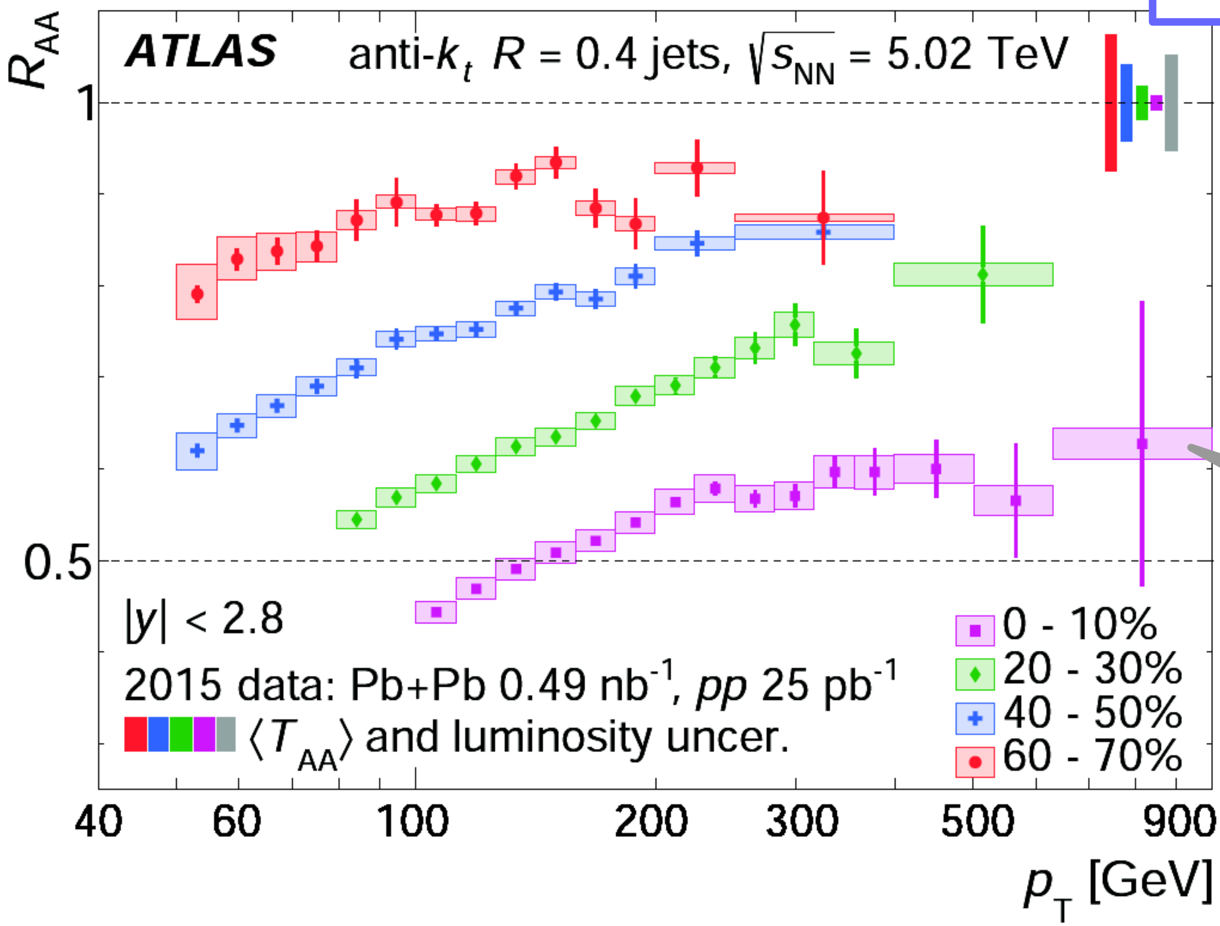
Jet cross-section in *pp* collisions

Number of expected jets per event of a given centrality

- Large **suppression of jets** seen in Pb+Pb collisions with respect to p+p collisions quantified by the nuclear modification factor, R_{AA}.
- If there was no modification of the jet yield in heavy-ion collision, then $R_{AA} = 1$.

Jet quenching

PLB 790 (2019) 108

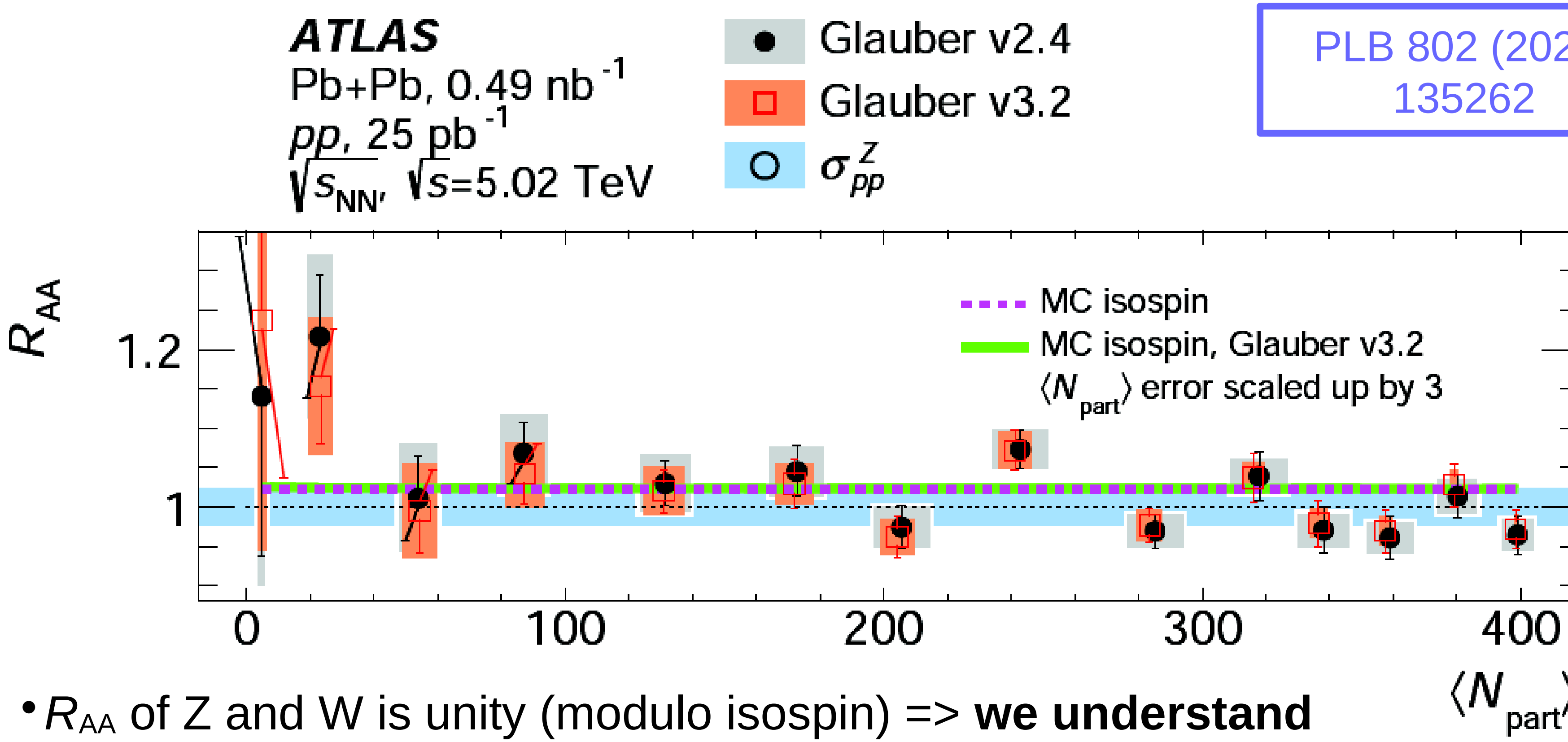


Suppression seen up to 1 TeV!

- Jet quenching – significant phenomenon, present also at the TeV scale!

Electroweak bosons

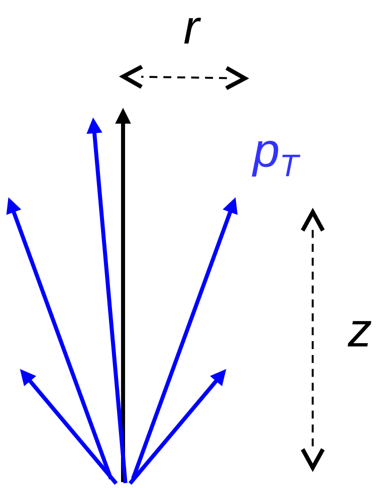
PLB 802 (2020) 135262

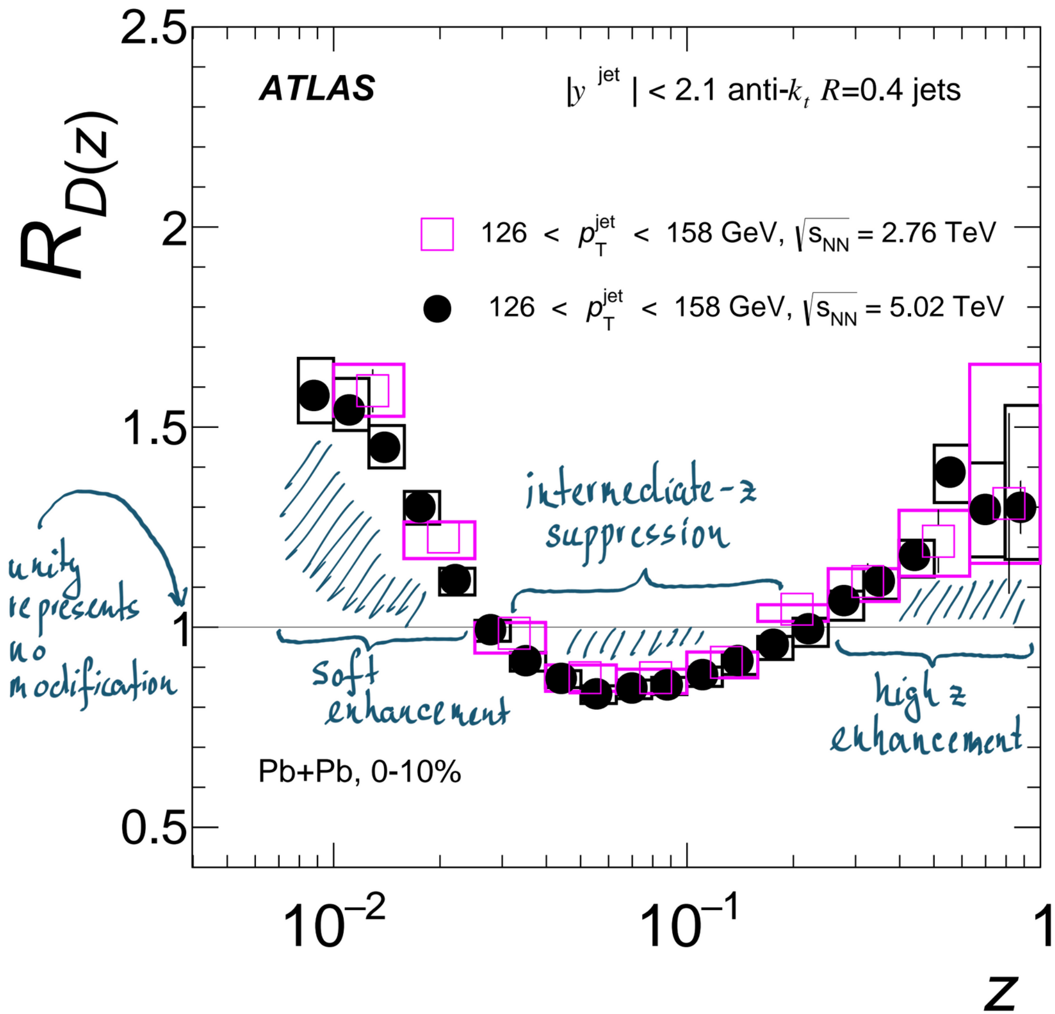


- R_{AA} of Z and W is unity (modulo isospin) => **we understand the geometry** of Pb+Pb collision.
- Some small deviation from unity => information about high-energy nuclear structure: **nuclear-PDFs**, **neutron skin-effect**, …
- Jet quenching – result of **final state interaction** of parton shower with deconfined medium.

… back to jets

- Jet structure is also significantly modified ...





PRC 98 (2018) 024908

EPJC 77 (2017) 379

Modification of jet structure

- How does the modification depend on parton color charge?
- How does it look at lower jet energies?
- How do the color coherence effect contribute?

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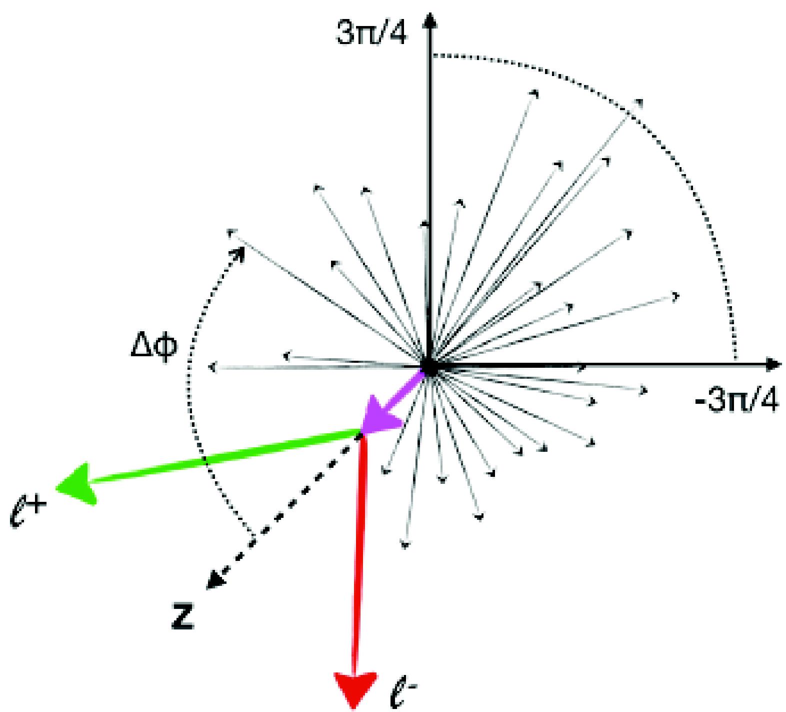
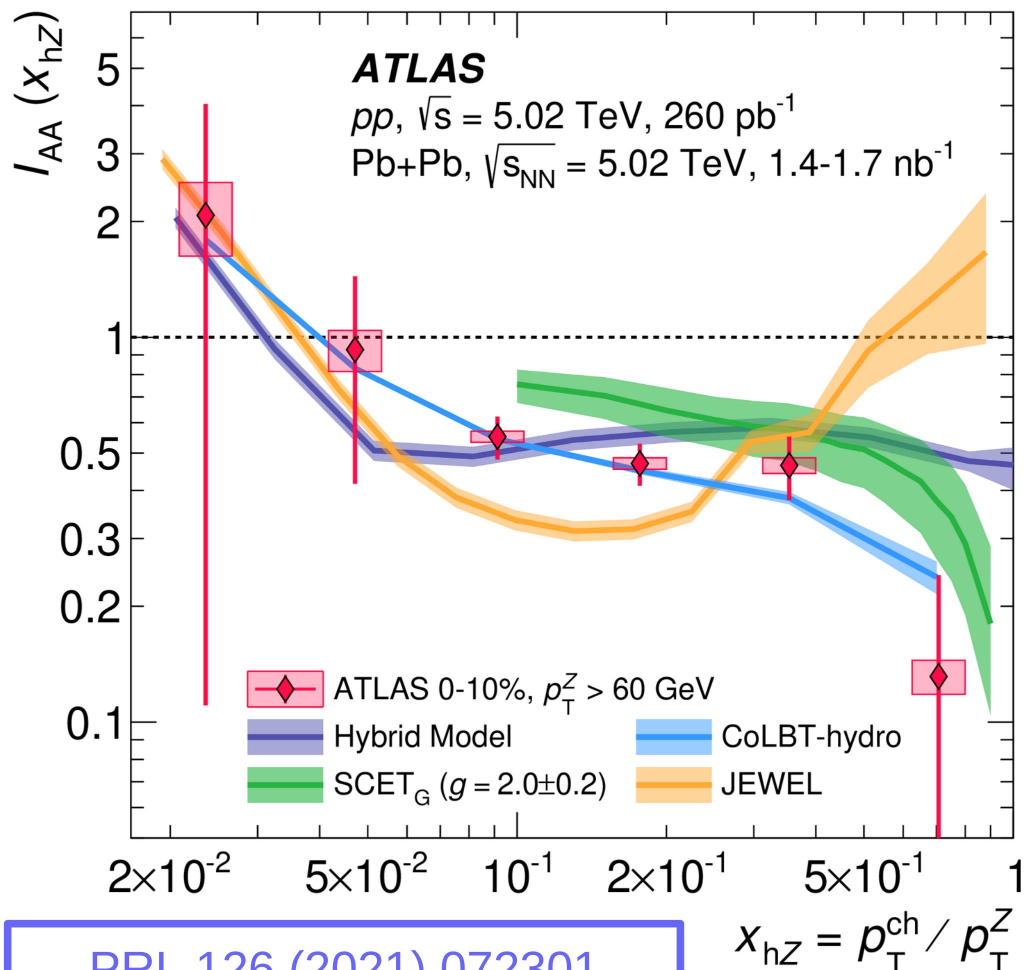


- … measure the yield of charged particles opposite the Z boson.

Modification of jet structure



PRL 126 (2021) 072301

- … measure the yield of charged particles opposite the Z boson.
- I_{AA} is Pb+Pb to *pp* ratio of these yields.
- Z tagging implies dominate **quark jet** contribution (=> helps understanding the role of color charge).
- Using I_{AA} one can probe **lower energies**.
- Amplitude of modification is larger compared to jet fragmentation functions

Modification of jet structure

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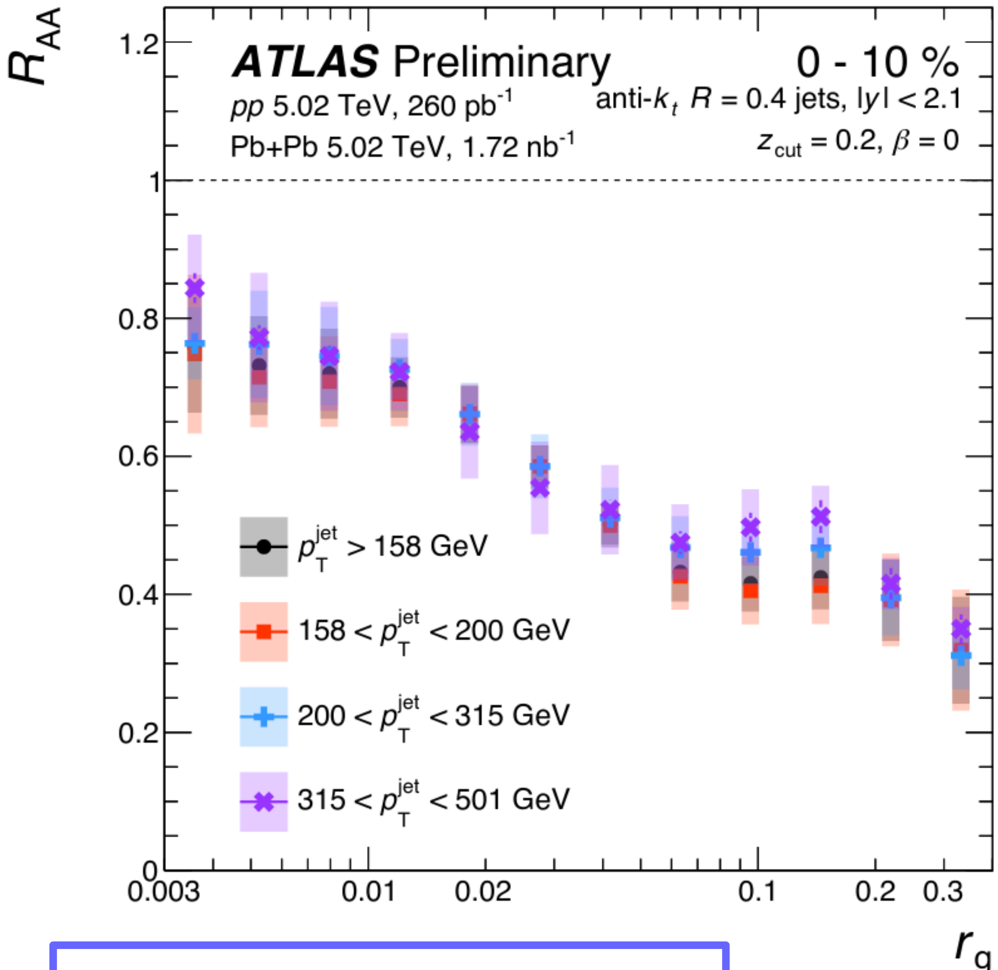
Modification of jet structure

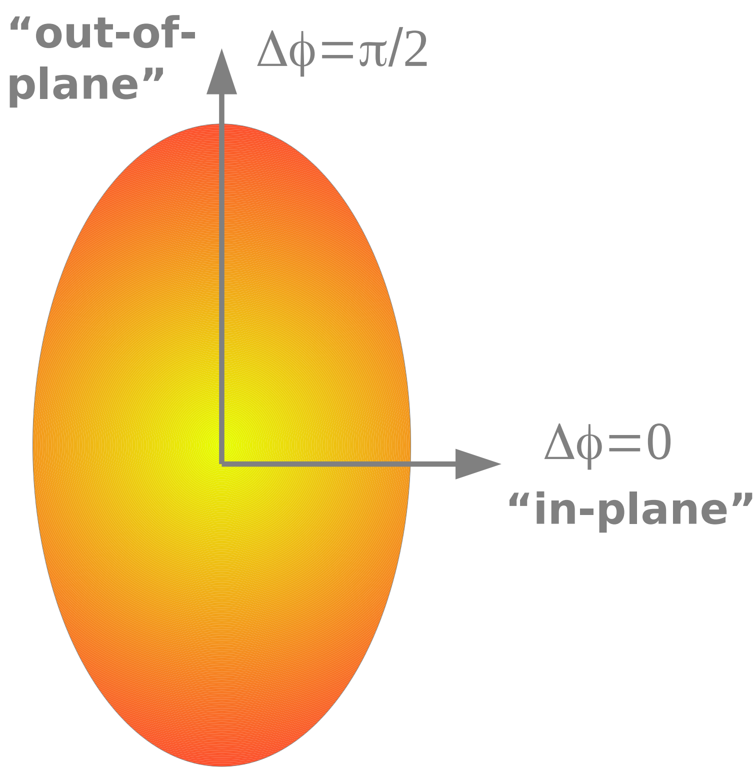


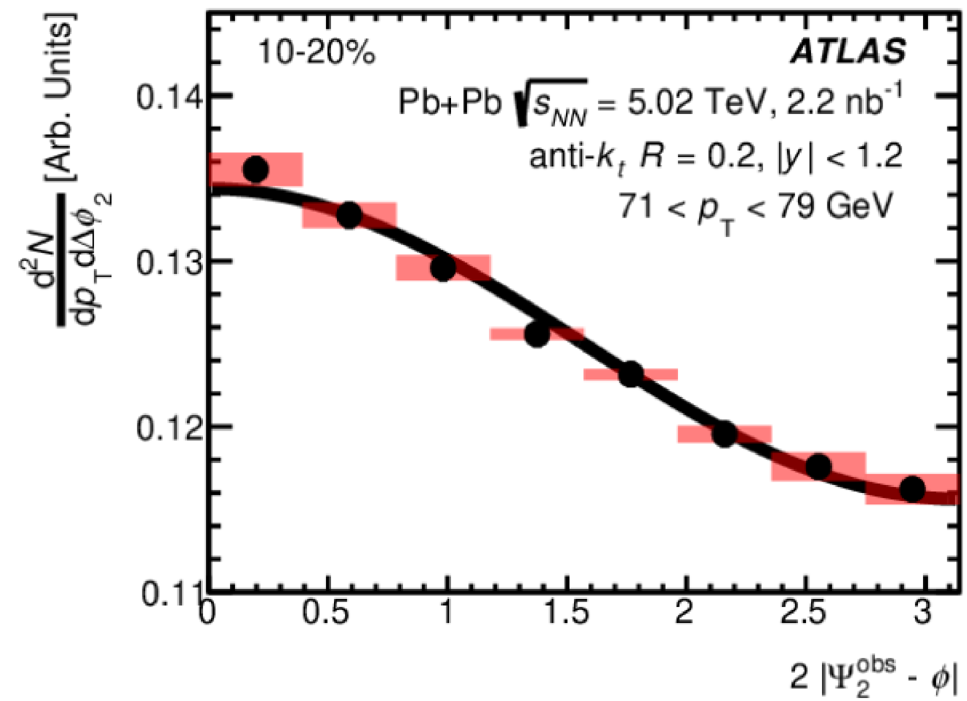
ATLAS-CONF-2022-026

- R_{AA} measured as a function of r_g – distance between two hardest splittings in the groomed jet
- Smaller r_g => more compact jets => smaller suppression **due to color coherence** effect (jet lose the energy coherently)

What is the path-length dependence of jet quenching?

- Measure the jet yield with respect to the event plane ...





- … expand in cosine series => obtain v_2 (magnitude of first order modulation)

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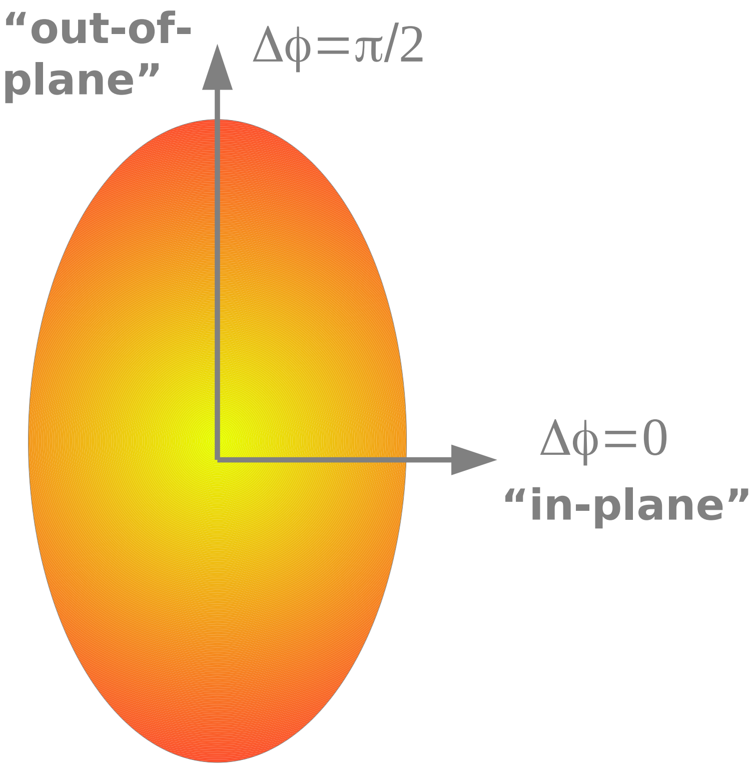
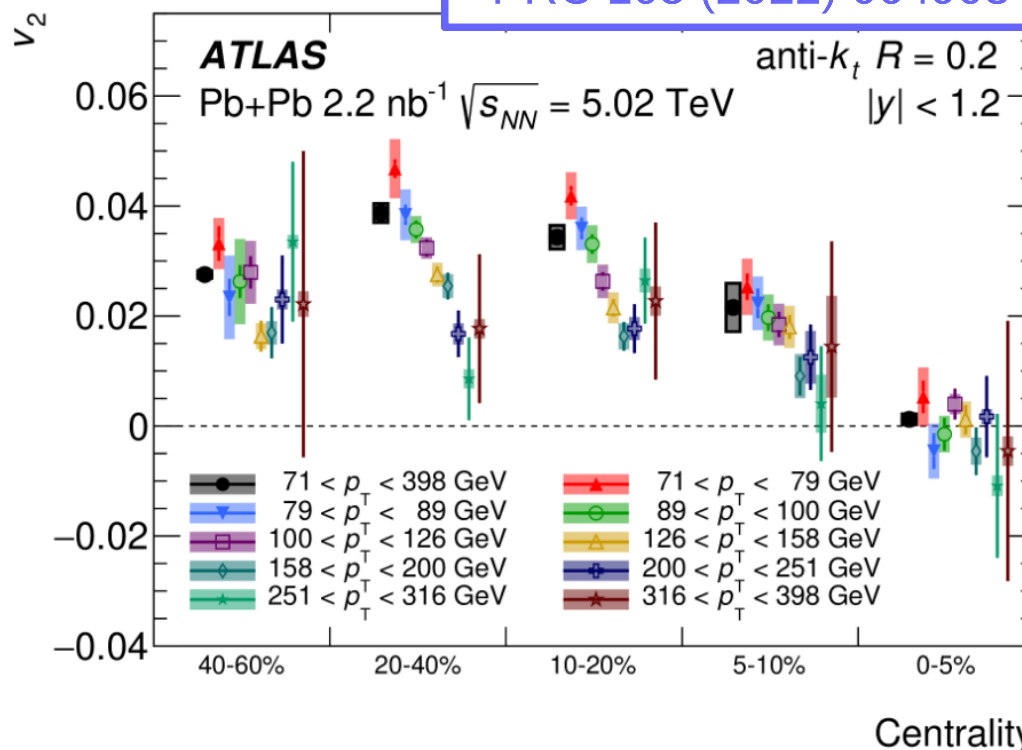
PRC 105 (2022) 064903

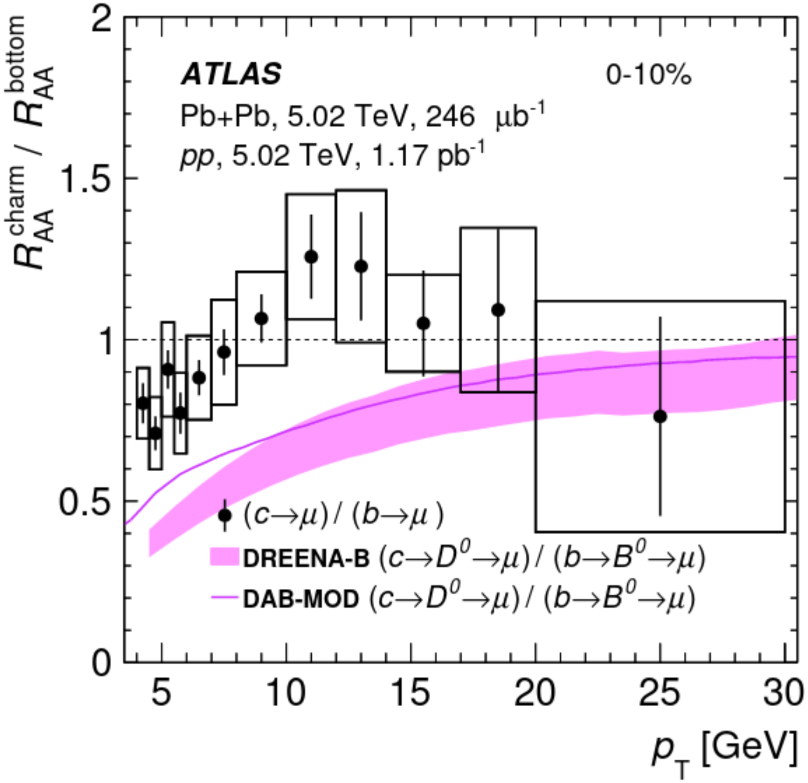


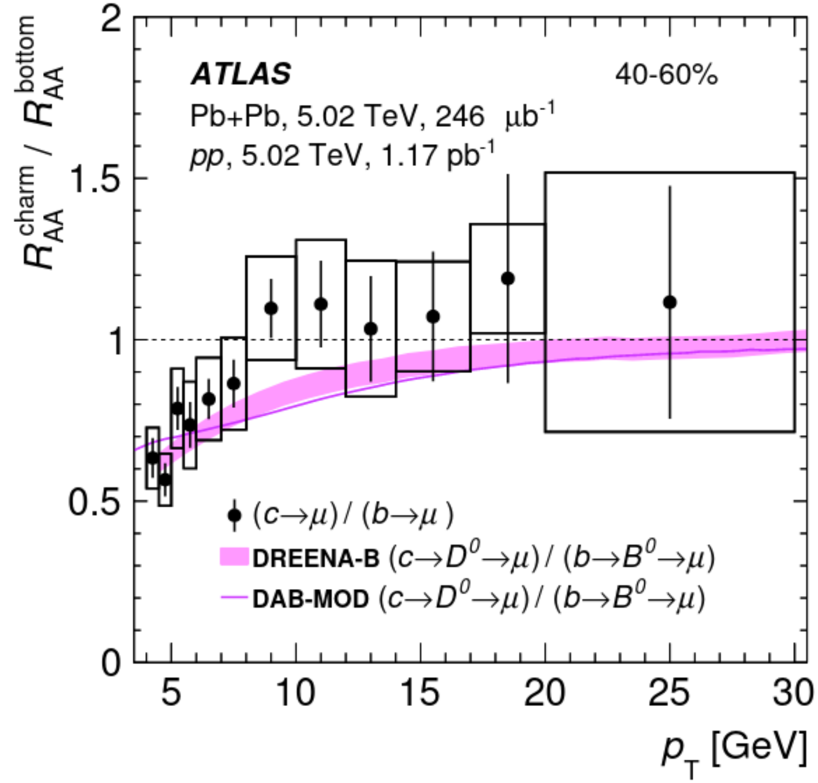


- … expand in cosine series => obtain v_2 (magnitude of first order modulation)
- Significant v_2 => **significant path-length dependence**

Is the suppression different for heavy quarks?

0-10% **40-60%**

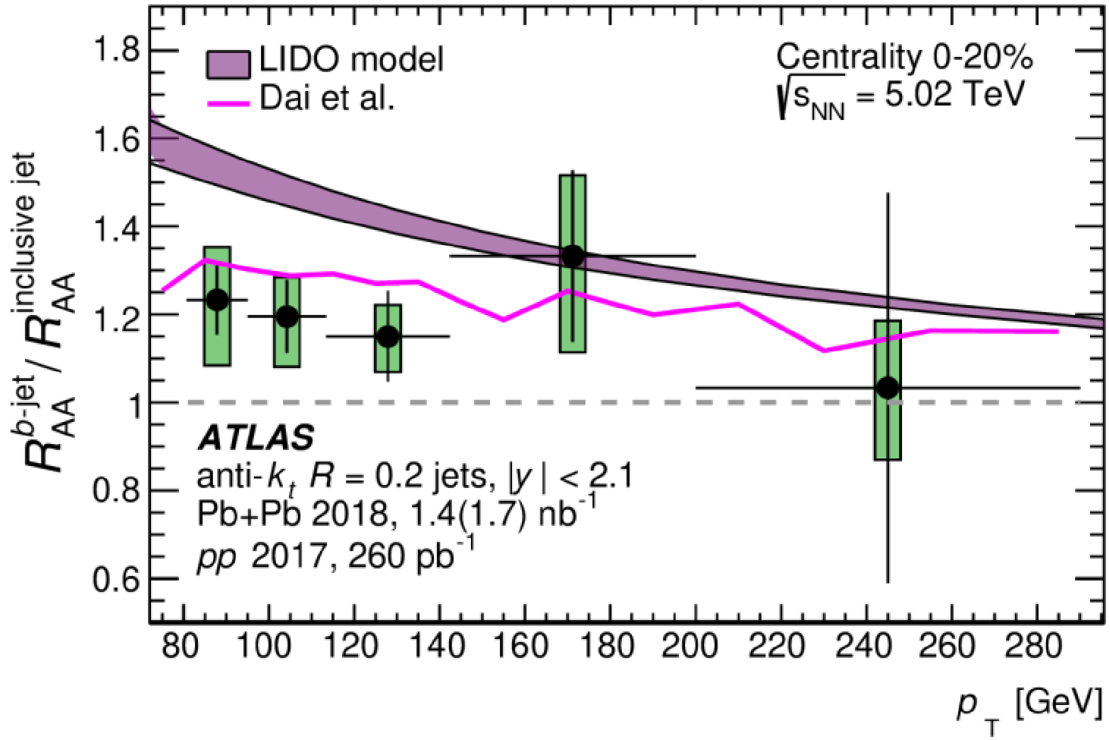




- Measuring R_{AA} of muons from semileptonic decays of HF hadrons
- Order of double ratio consistent with expectation from the **radiative energy loss** involving the dead-cone effect.

PLB 829 (2022) 137077

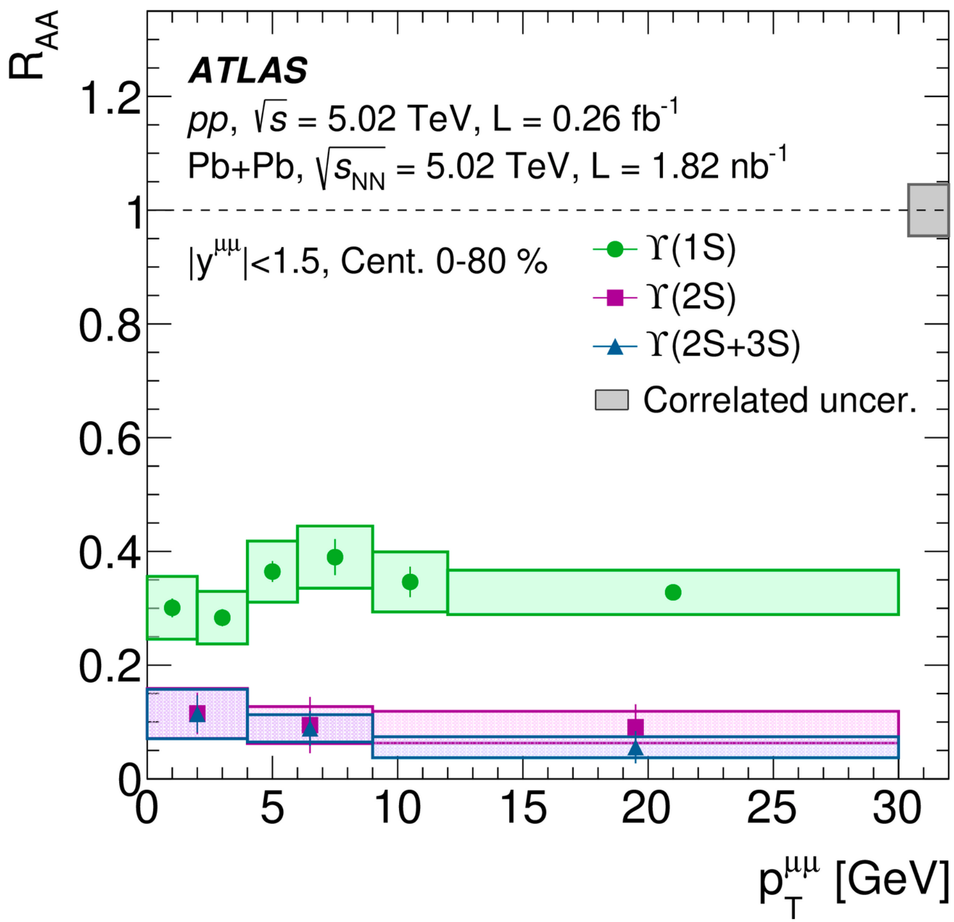
Is the suppression different for heavy quarks?



- Measuring the R_{AA} of b-jets.
- Significantly **smaller suppression** of b-jets compared to inclusive jets.
- Here the dead cone effect less important than **color** (inclusive jets are mixture of quark-initiated and gluon-initiated jets).

arXiv:2204.13530

How does it look at lower energies?

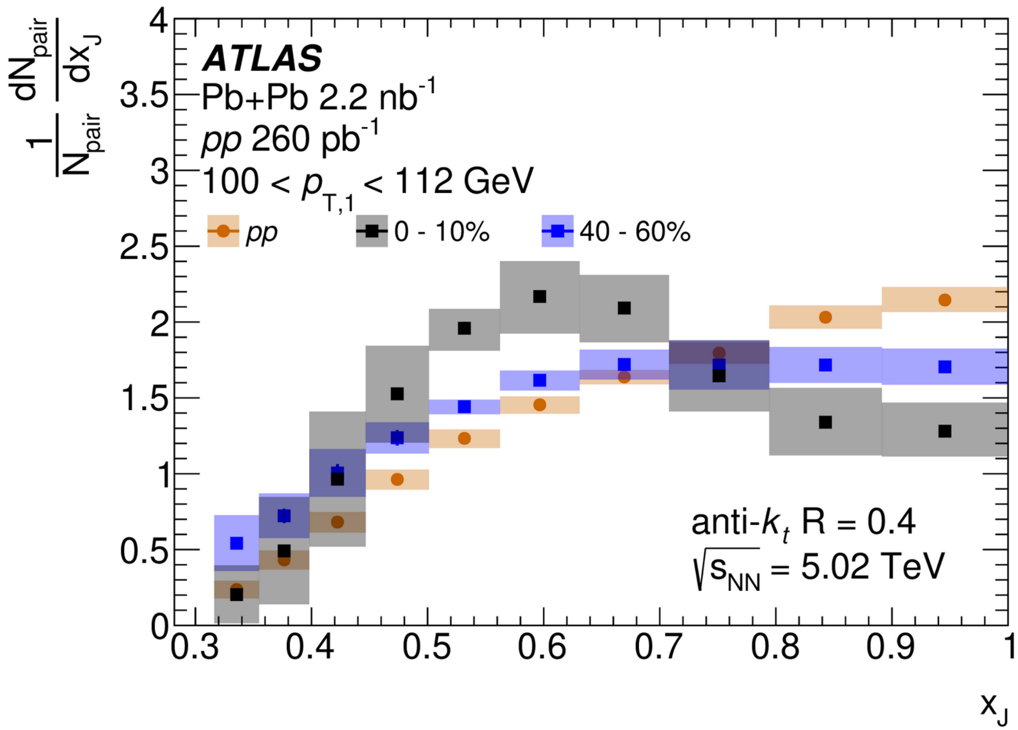


- At lower energies, e.g. a **strong suppression** of Upsilon family measured.
- In models, sequential suppression is sensitive to the **temperature** of QGP
- **Various mechanisms** inducing the suppression may contribute, radiative energy likely one of them at higher p_T

arXiv:2205.03042

Dijet studies

- Measuring dijets allows to also study the path-length dependence and the role of fluctuations.
- Dijet energy loss quantified in terms of $x_J = p_{T,leading} / p_{T,subleading}$.



- Significant **dijet imbalance** seen in central heavy ion collisions.

arXiv:2205.00682

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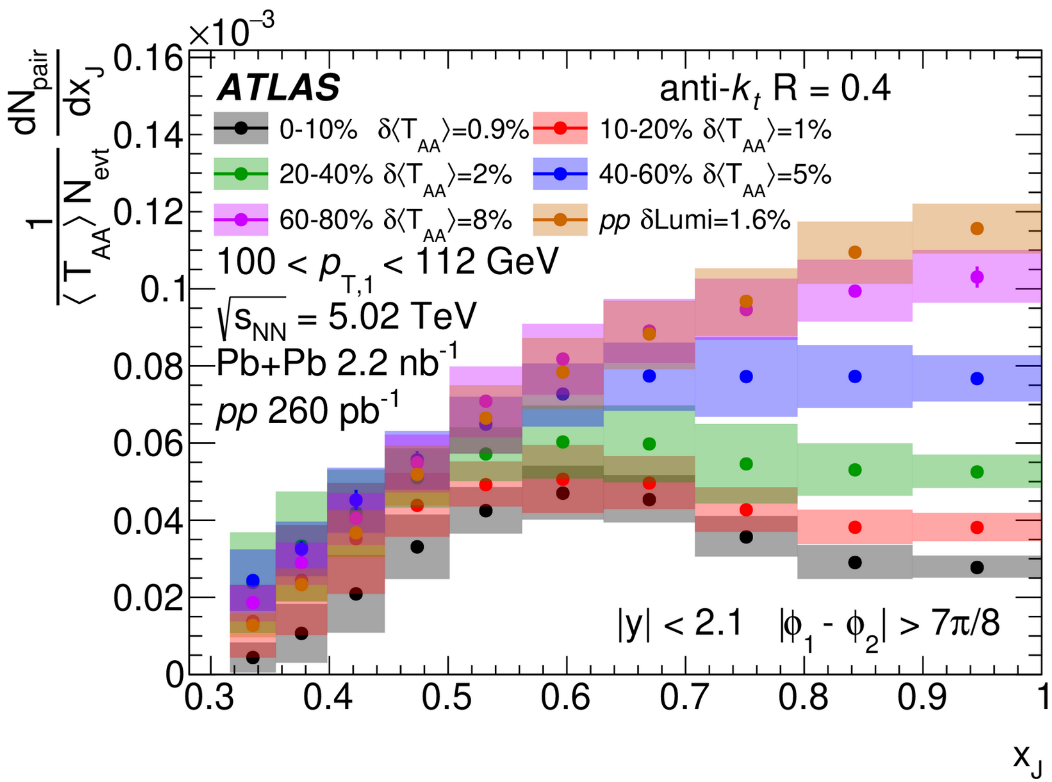
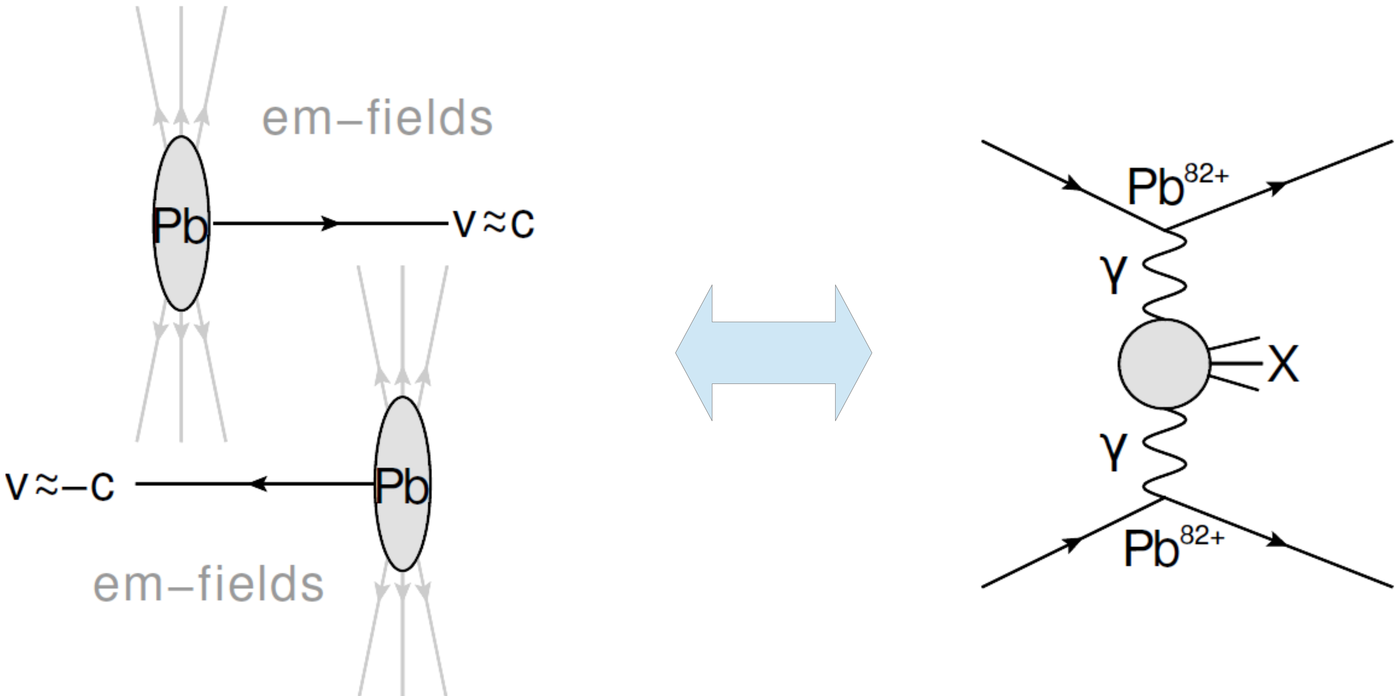


- Significant **dijet imbalance** seen in central heavy ion collisions.
- This imbalance is shown to be due to a **suppression of balanced** dijet topologies rather than enhancement in imbalanced topologies

arXiv:2205.00682

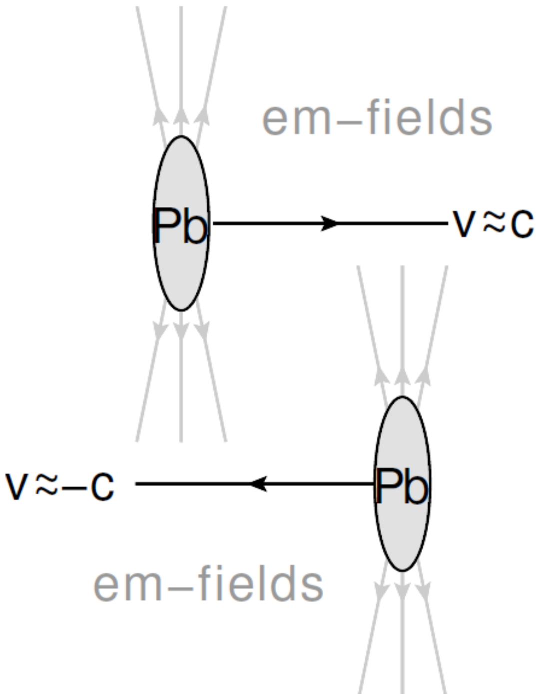
Ultra-peripheral collisions

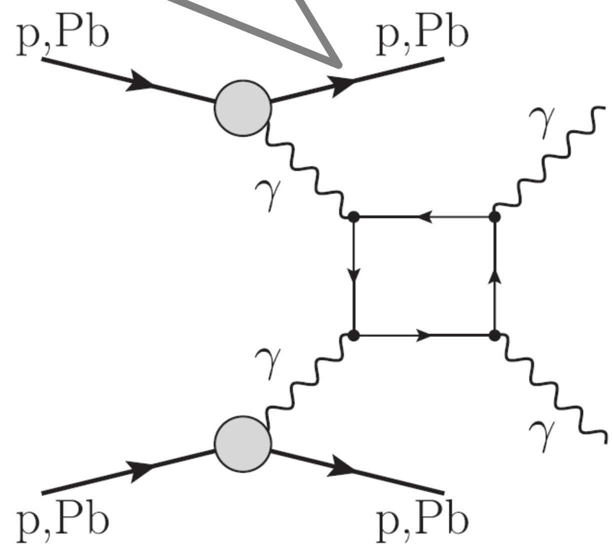


- Boosted nuclei: source of photons of small virtuality
  => **EM interactions** dominate at large impact parameters.
- Magnified by a factor of 82^4 in Pb+Pb compared to *pp*
  => allows to turn the LHC into a **photon-photon collider**!

Ultra-peripheral collisions

Example:
light-by-light scattering





JHEP 03 (2021) 243

PRL 123 (2019) 052001

Nat. Phys. 13 (2017) 852

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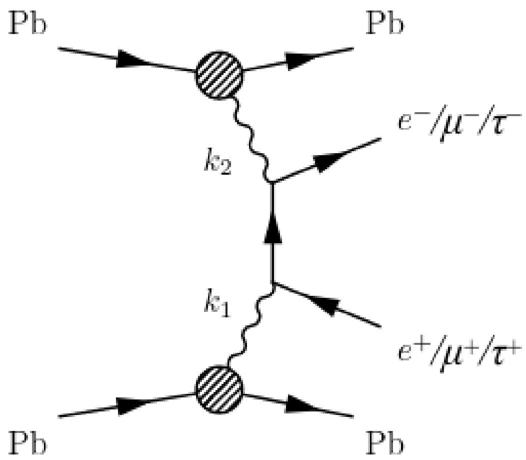
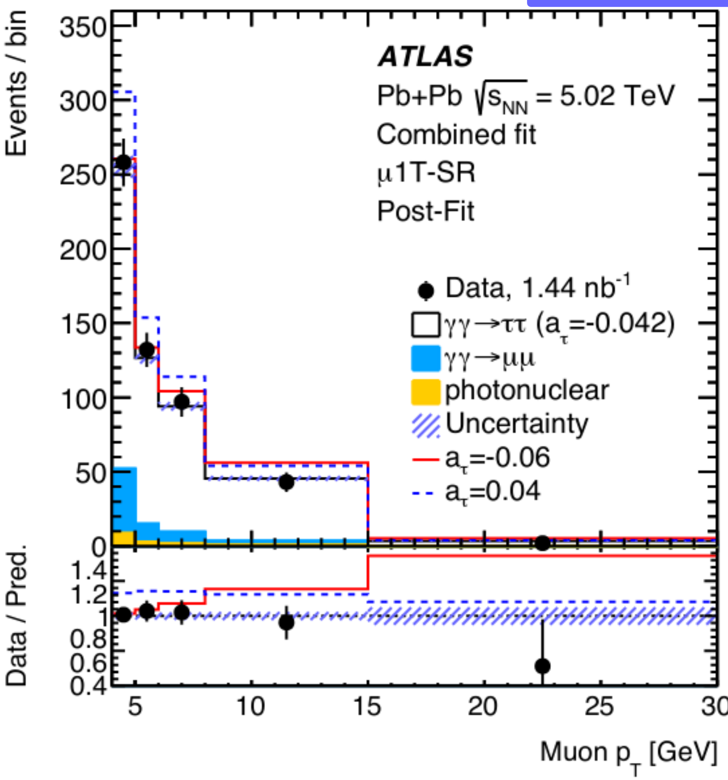
Dileptons in UPC

arXiv:2204.13478





arXiv:2207.12781

arXiv:2206.12594

PRC 104 (2021) 024906

- Measuring dileptons: di-electrons, dimuons, di-taus.
- Di-taus clearly observed …

Dileptons in UPC

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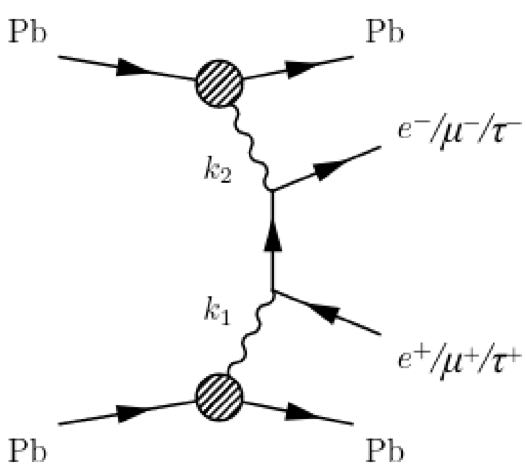
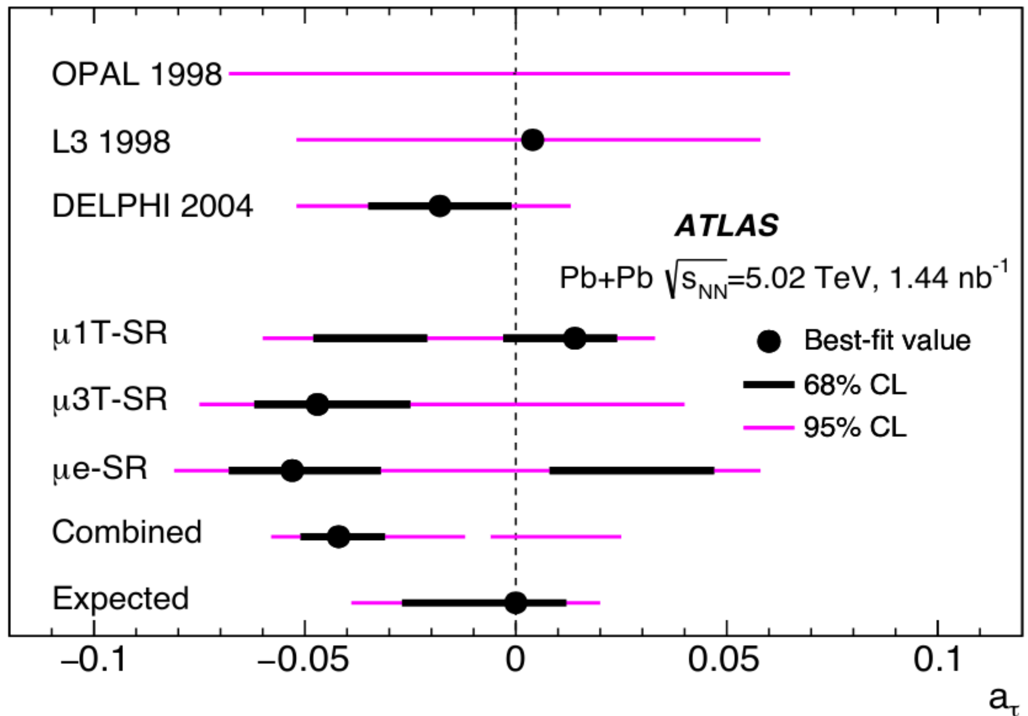
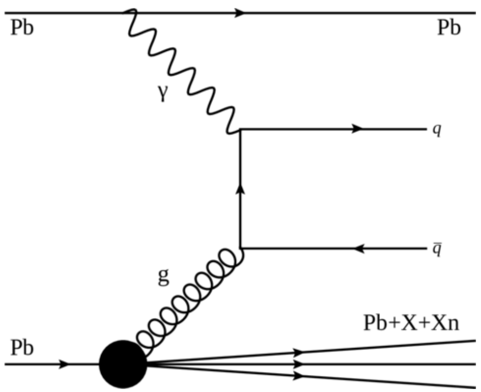


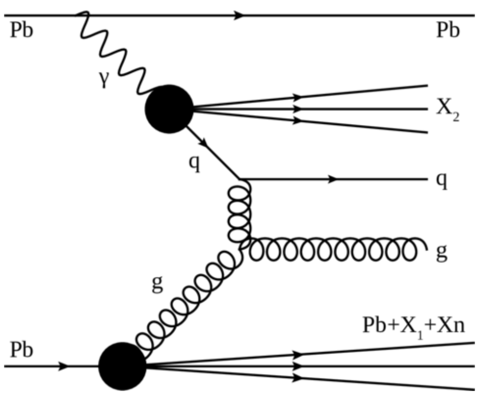


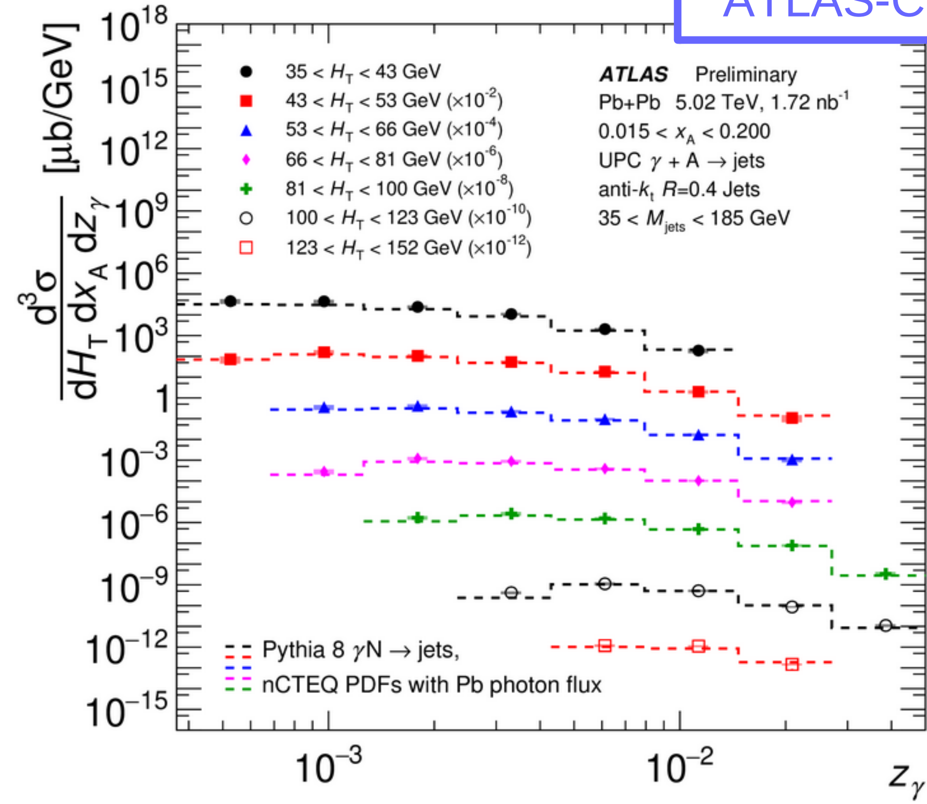
- Measuring dileptons: di-electrons, dimuons, di-taus.
- Di-taus clearly observed …
- ... and allowed to measure the **anomalous magnetic moment of τ.**
- Constrains similar to those by DELPHI.

Jets in UPC

ATLAS-CONF-2022-021







- Triple differencial cross-section measured for dijets in terms of:

$$H_T \equiv \sum_i p_{T\,i} \qquad z_\gamma \equiv \frac{M_{\text{jets}}}{\sqrt{s}} e^{+y_{\text{jets}}} \qquad x_A \equiv \frac{M_{\text{jets}}}{\sqrt{s}} e^{-y_{\text{jets}}}$$

- May allow to put new constraints on **nuclear PDFs**.

Summary

- Flow measurements allow to:
  - constraints nuclear deformation of Xe
  - constraints initial conditions of small systems and help to understand the origin of flow in small systems
- Suppression of jets and hadrons is very significant, we are on path to better understand:
  - Role of parton color (quark vs gluon)
  - Role of parton mass (light quarks vs heavy quarks)
  - Path length dependence
  - Color coherence effects
- Photon induced process allows to:
  - Measure tau g-2
  - Constrain nPDFs

All results available from:

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

Backup slides