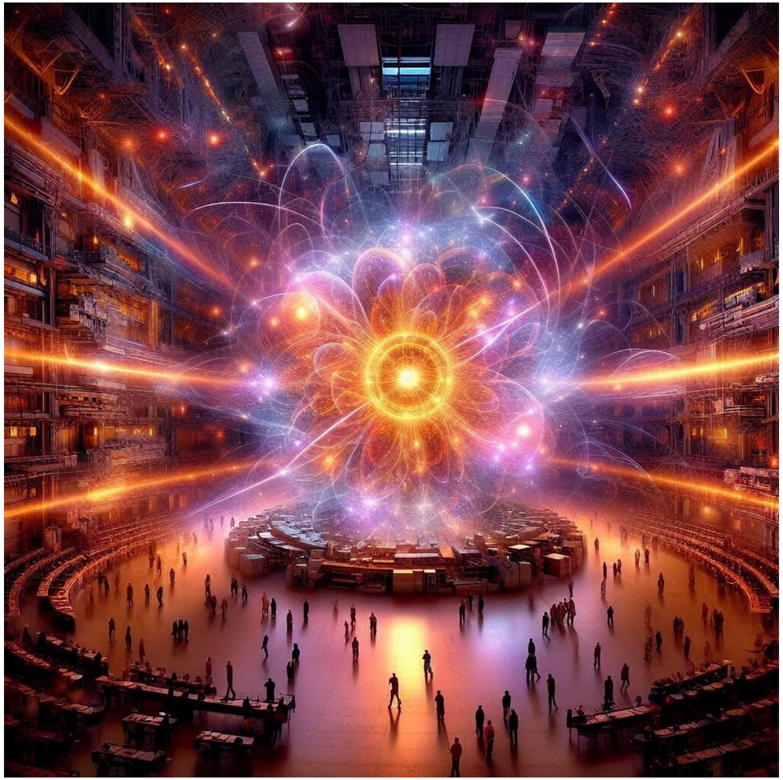
Jet Tomography:
Unveiling the Secrets of QCD Matter

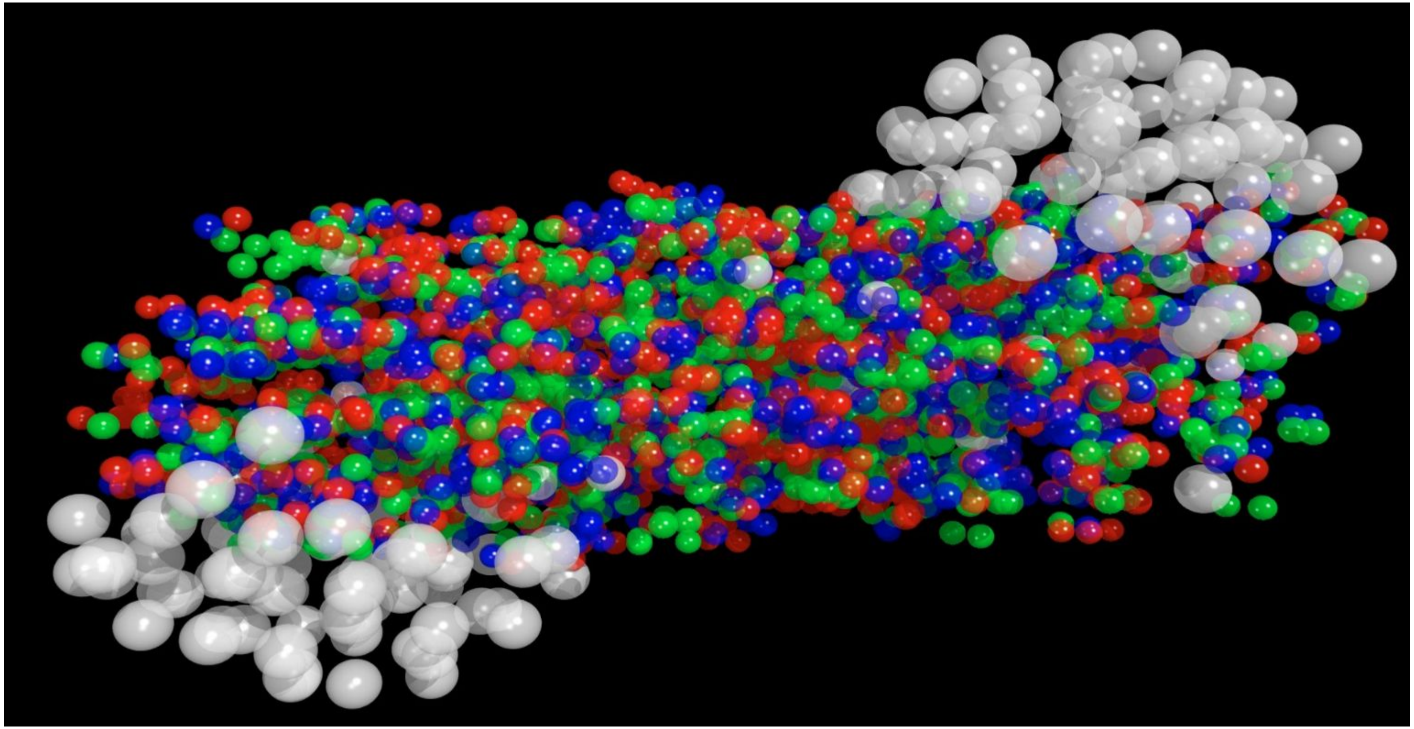


Martin Rybar

AGH seminar

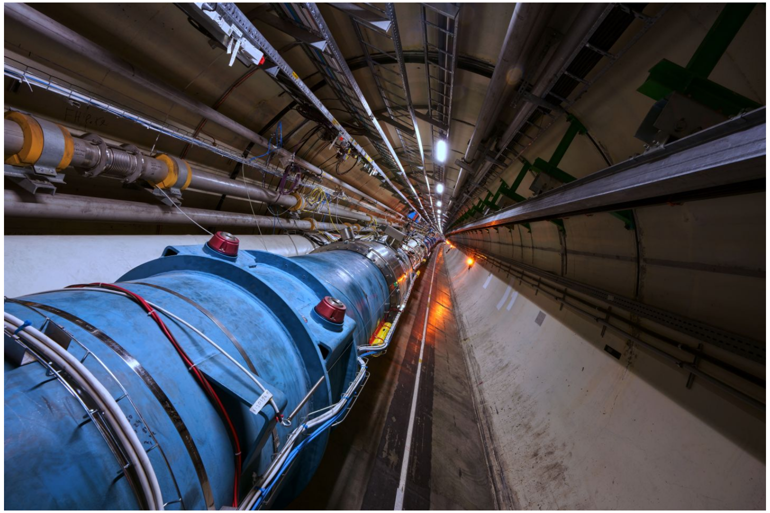
February 7, 2025

Physics of HI collisions



Study of the nature&properties of hot and dense QCD matter
⇒ QCD laboratory

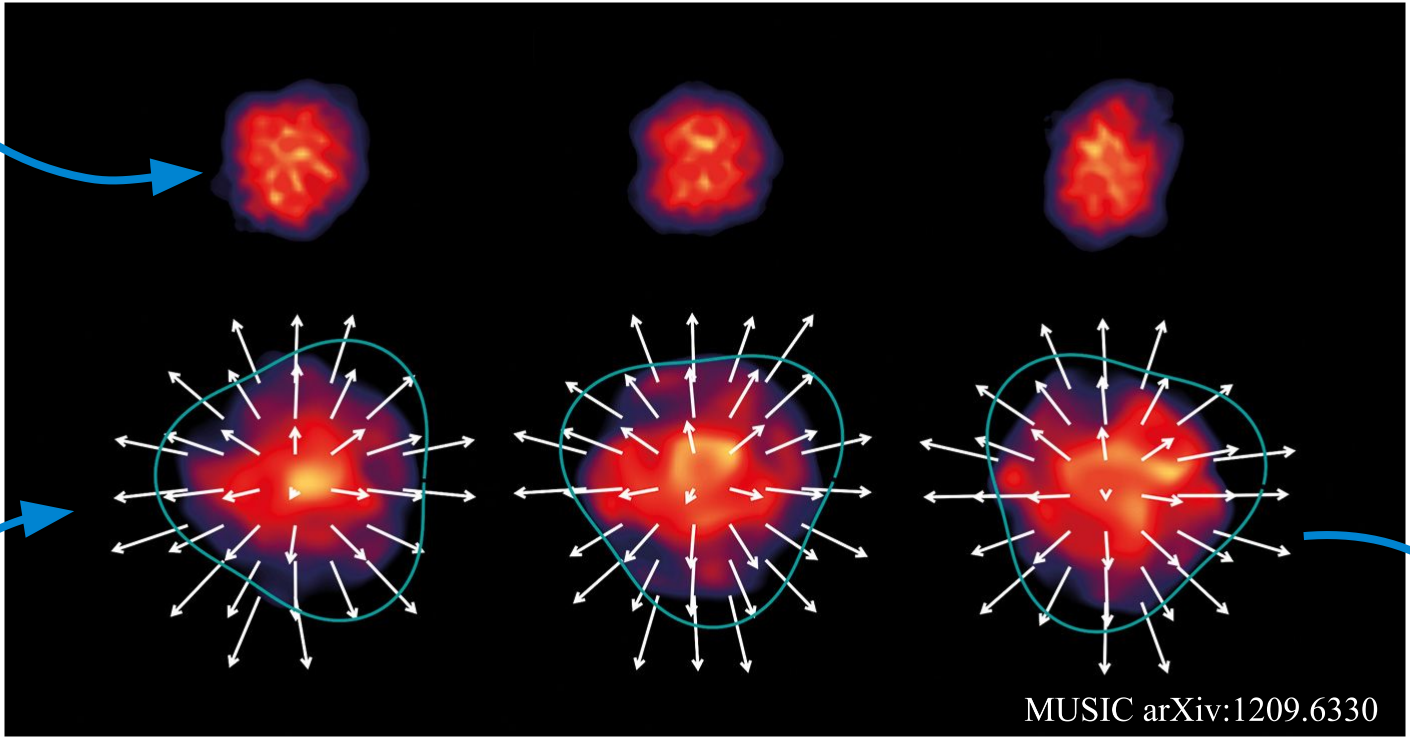
Heavy Ion Collisions at LHC



- **LHC provides collision of heavy-ions since 2010**
  - Pb+Pb, Xe+Xe, p+Pb (O+O and p+O expected in 24/25)
  - CME from 2.76 TeV to 5.36 TeV for Pb+Pb and 5.44 TeV for Xe+Xe

What do we measure?

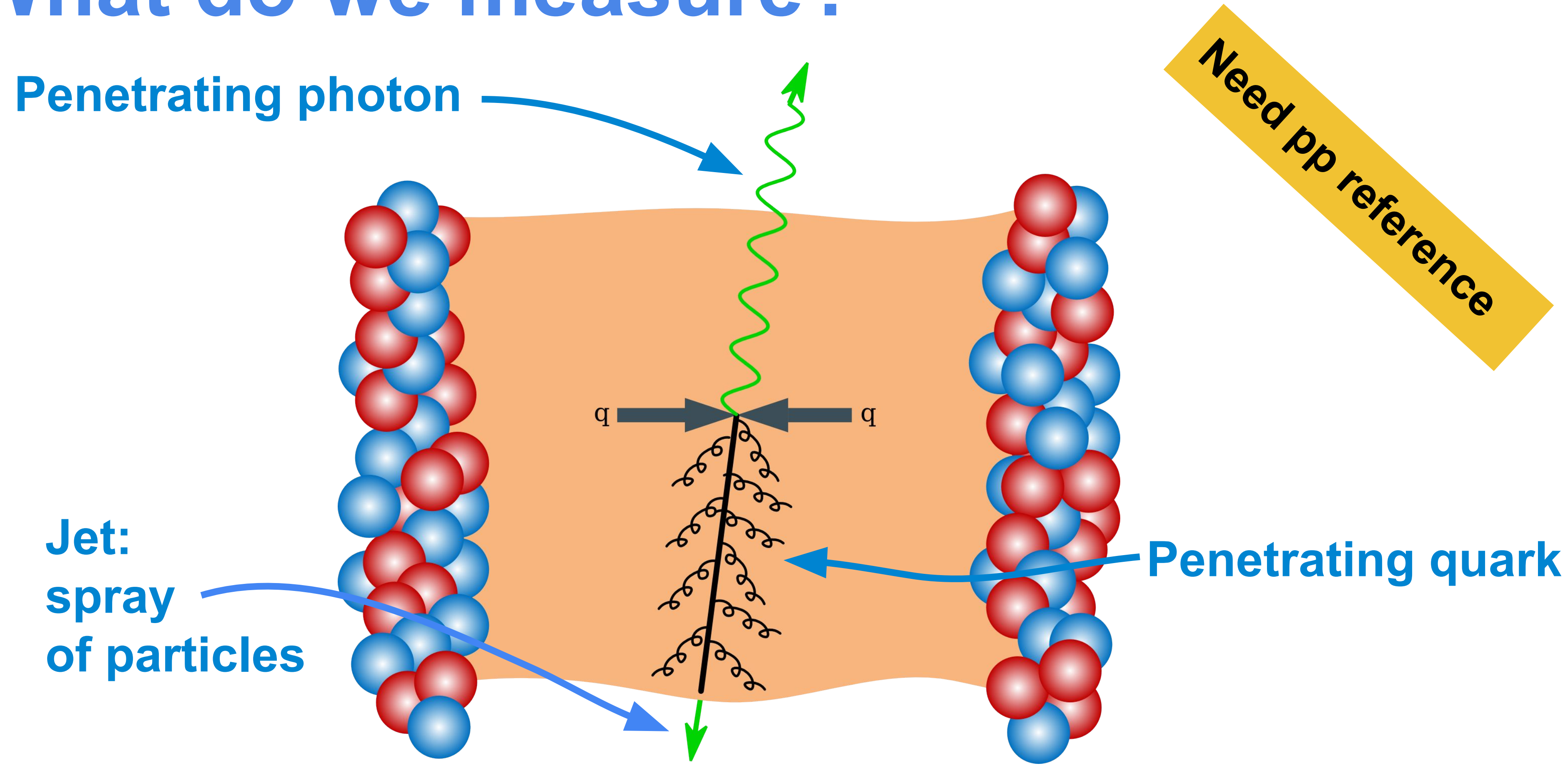
Anisotropy in shape of plasma



Translates to anisotropies in particle production

Properties of Quark-gluon plasma

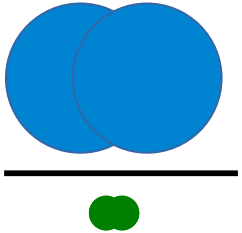
What do we measure?



Are they affected? ⇒ microscopic properties of plasma & study of strong force

Proton-Proton reference

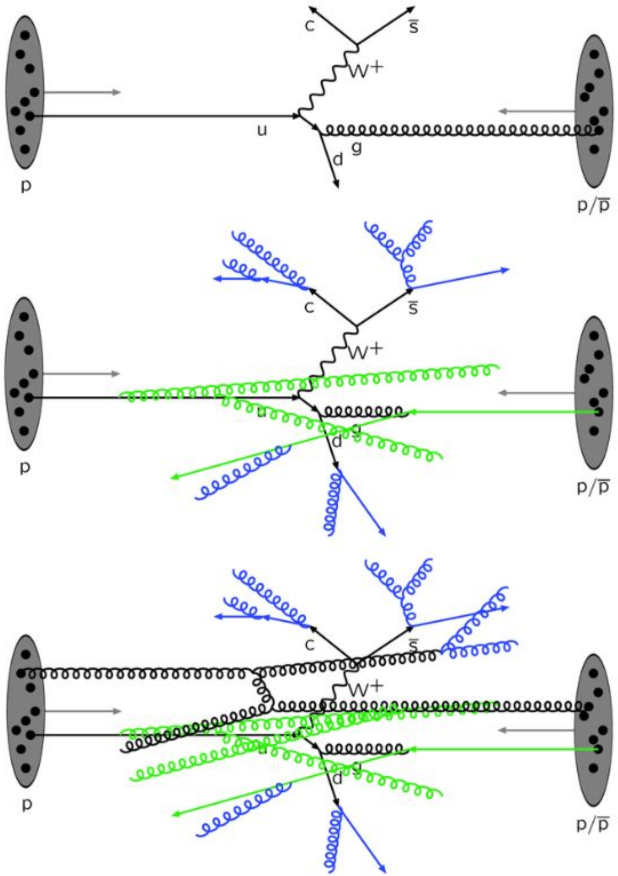
We need reference, “standard candles” for our measurements.

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

Heavy ion physicists love ratios!

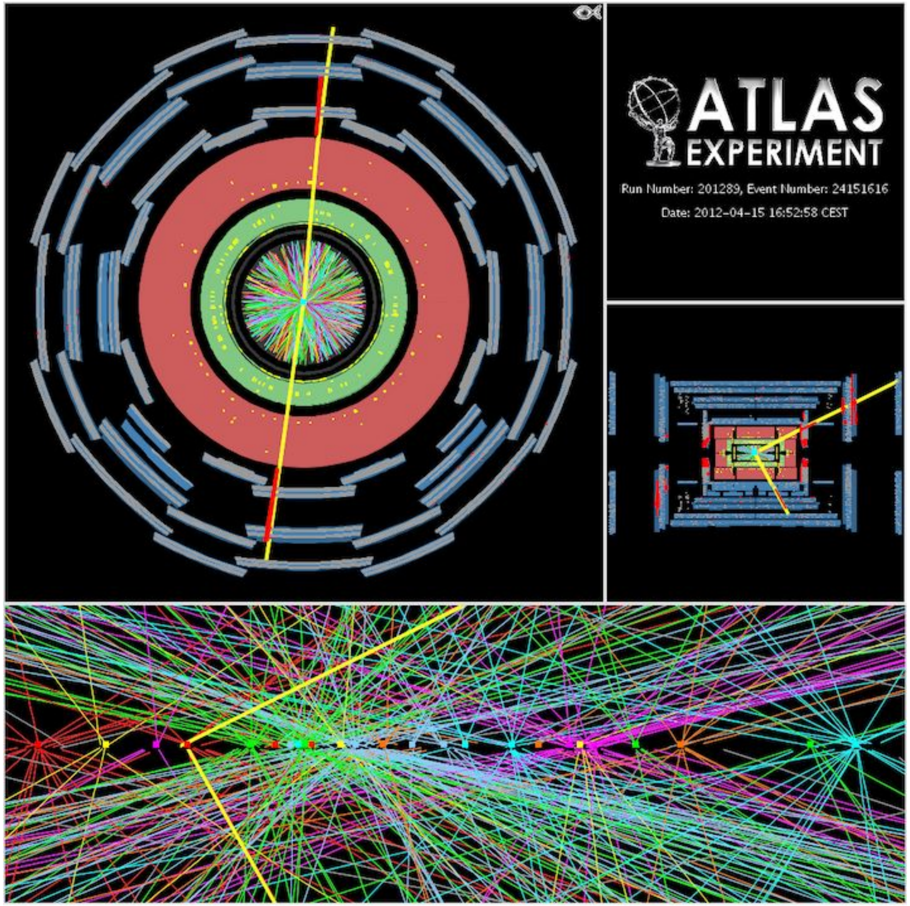
⇒ recording also proton-proton collisions at the same collision energy as Pb+Pb

Busy LHC collisions: *pp*

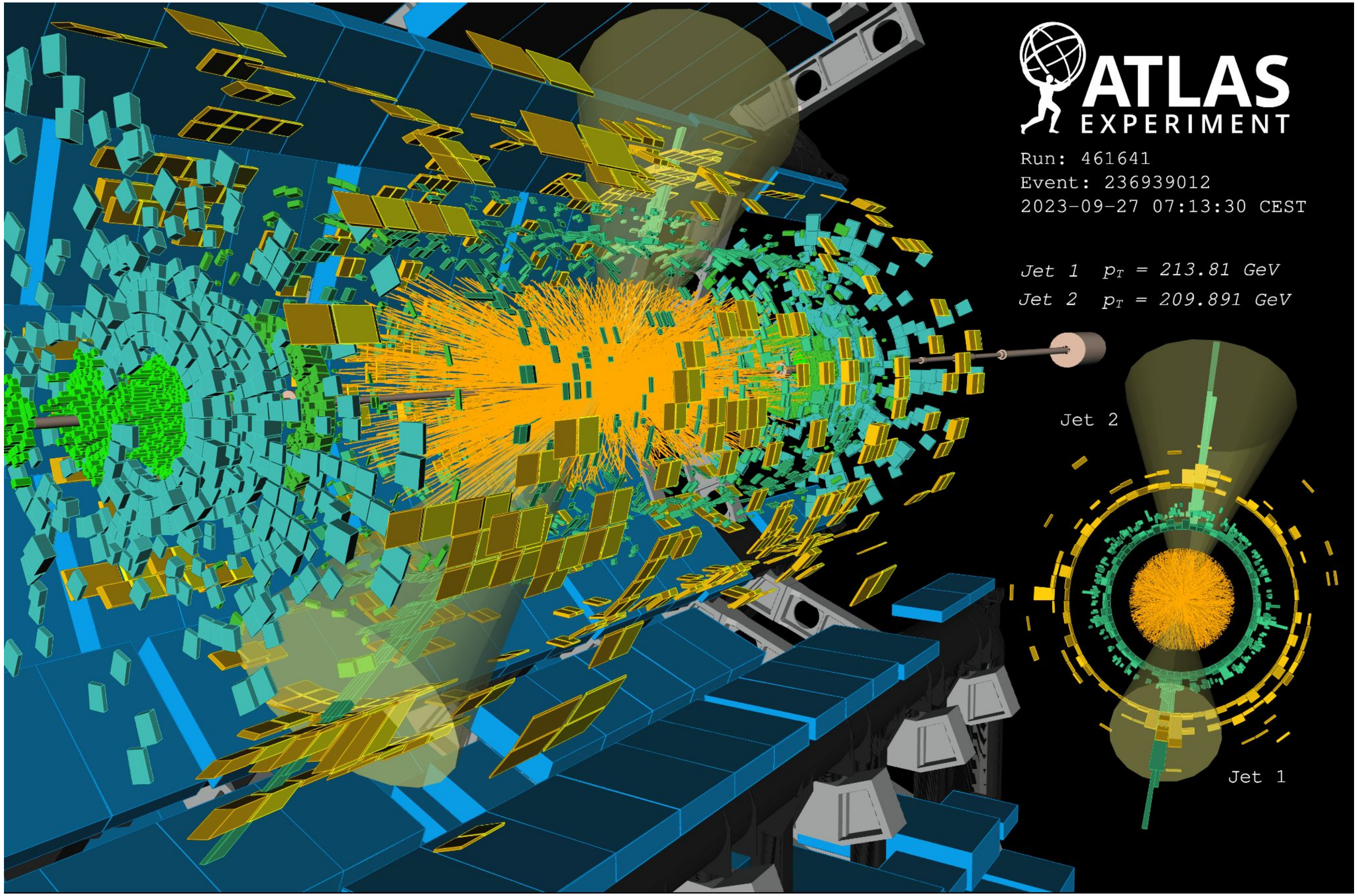


by Florian Bechtel and Peter Schleper

Busy LHC collisions: pileup

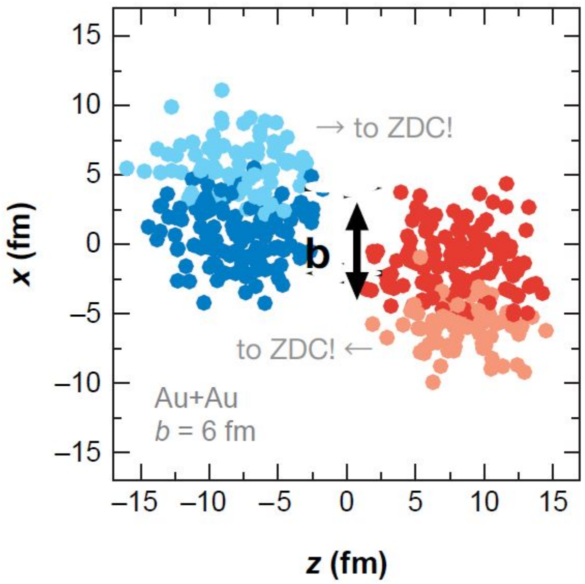


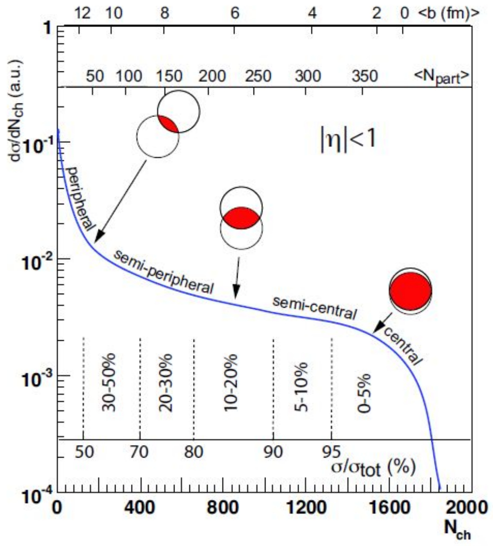
Busy LHC collisions: Pb+Pb



Geometry of HI collision

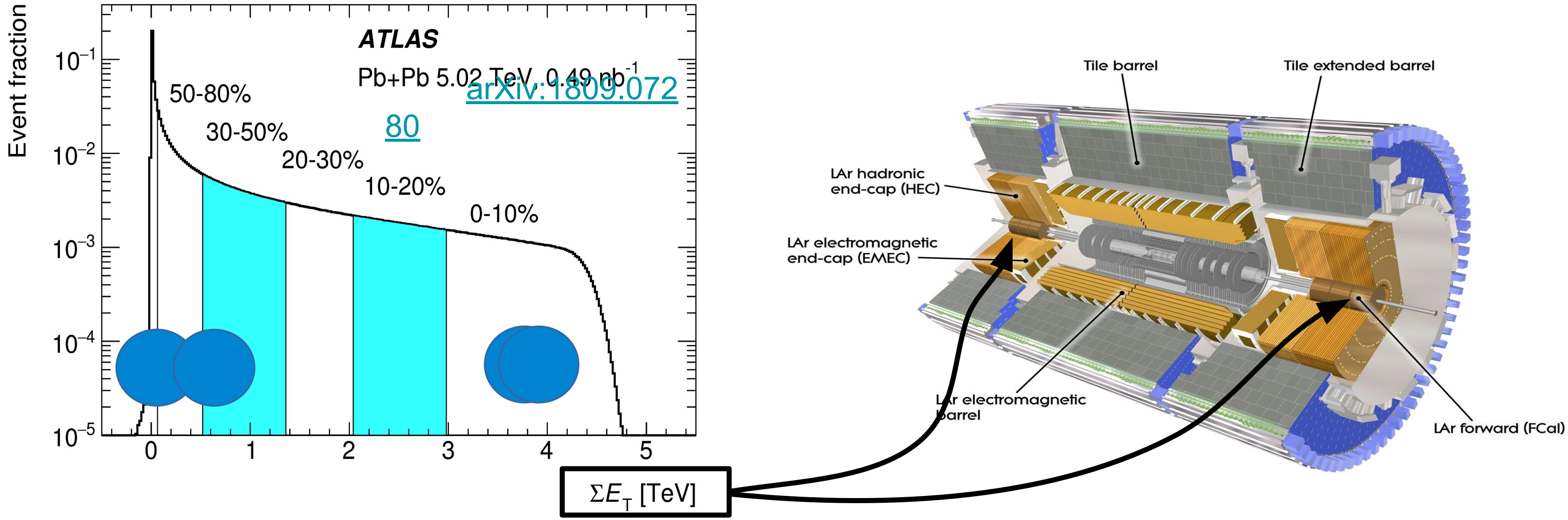
- Particle production is expected to scale with number of binary nucleon-nucleon collisions.
  - Soft processes scales with #participants
  - Hard processes with #binary collisions



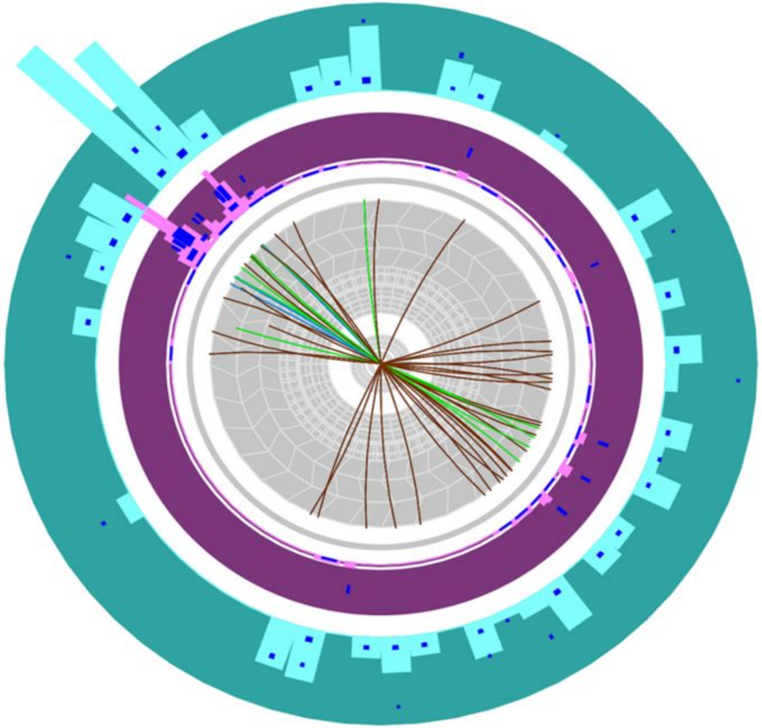


Geometry of HI collision

- Collision centrality is measured using transverse energy deposited in forward calorimeters.

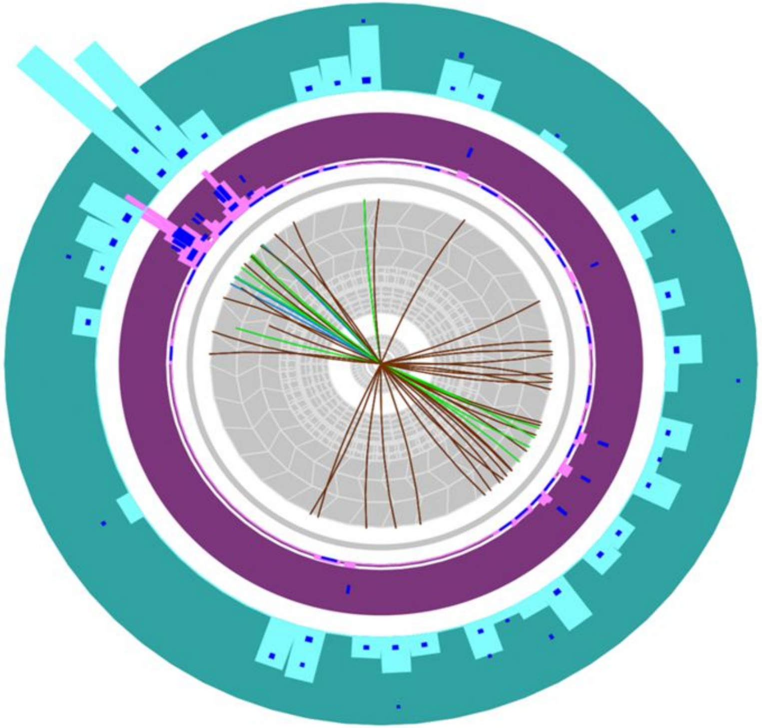


Jets in HI



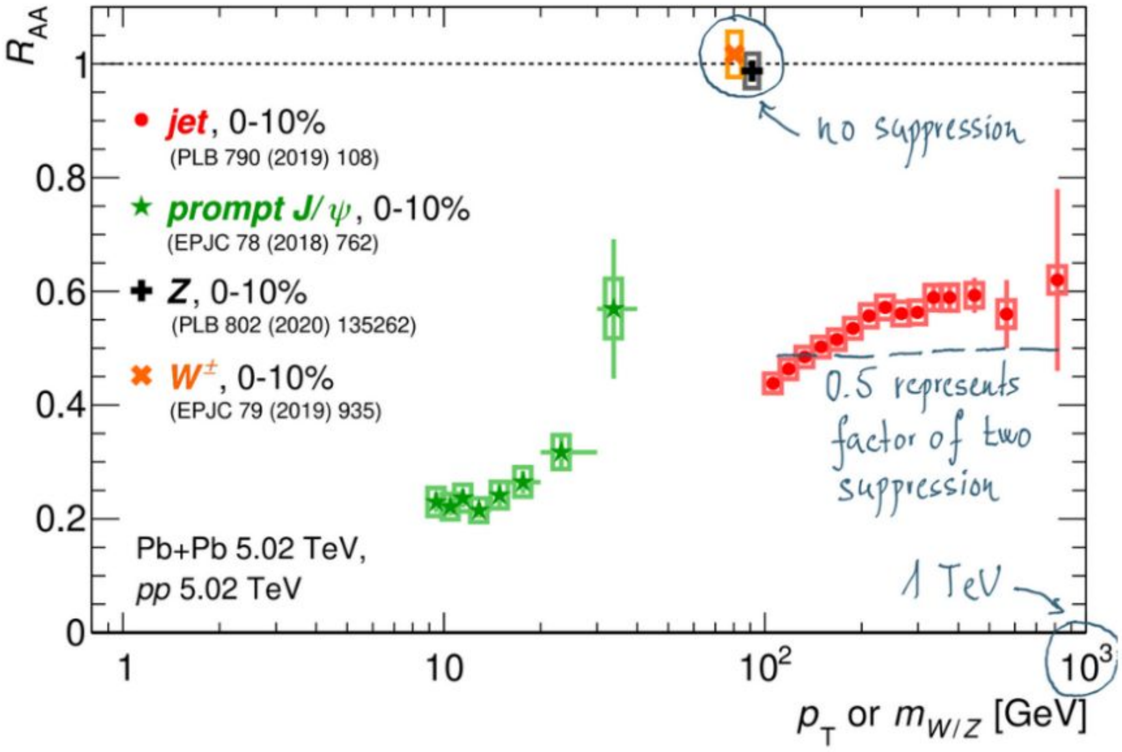
Specific reconstructions to deal with large background.

Jets in HI



Many different observables ⇔ each observable is sensitive to different aspects of energy loss.

Inclusive Jet Suppression



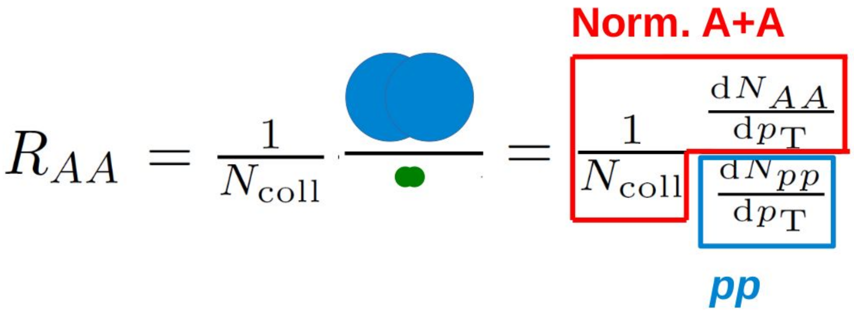
Courtesy of Martin S.

Norm. A+A

$$R_{AA} = \frac{1}{N_{\mathrm{coll}}} \frac{}{} = \frac{\boxed{\frac{1}{N_{\mathrm{coll}}} \frac{\mathrm{d}N_{AA}}{\mathrm{d}p_{\mathrm{T}}}}}{\boxed{\frac{\mathrm{d}N_{pp}}{\mathrm{d}p_{\mathrm{T}}}}}$$

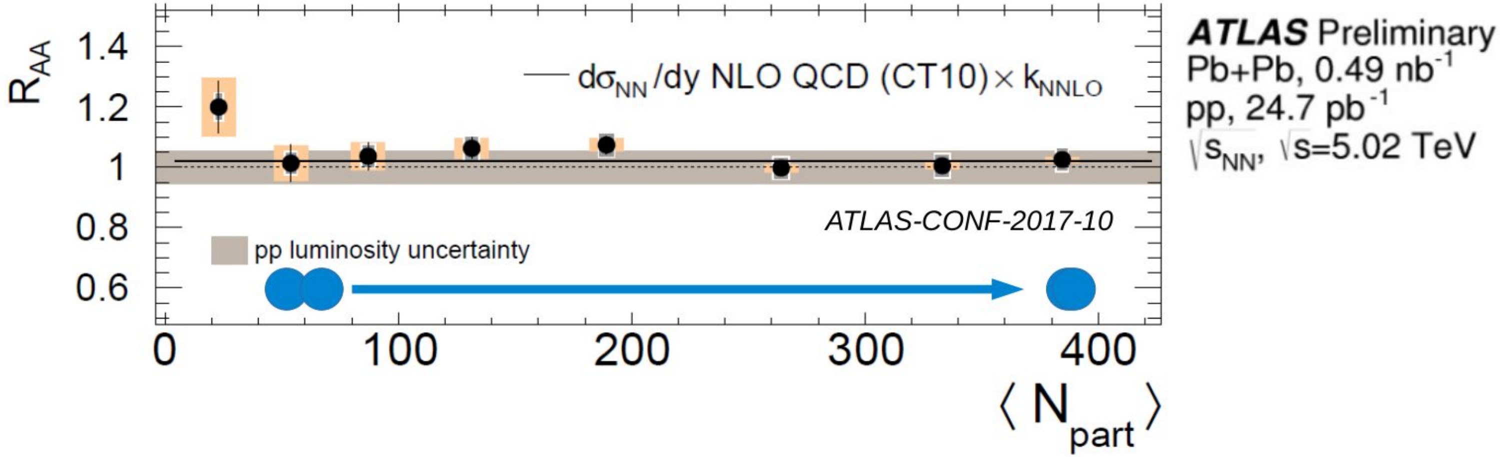
pp

Do we understand the geometry?



$$R_{AA} = \frac{1}{N_{\rm coll}} \frac{\bullet\bullet}{\bullet} = \frac{1}{N_{\rm coll}} \frac{\frac{dN_{AA}}{dp_T}}{\frac{dN_{pp}}{dp_T}}$$

Z bosons:



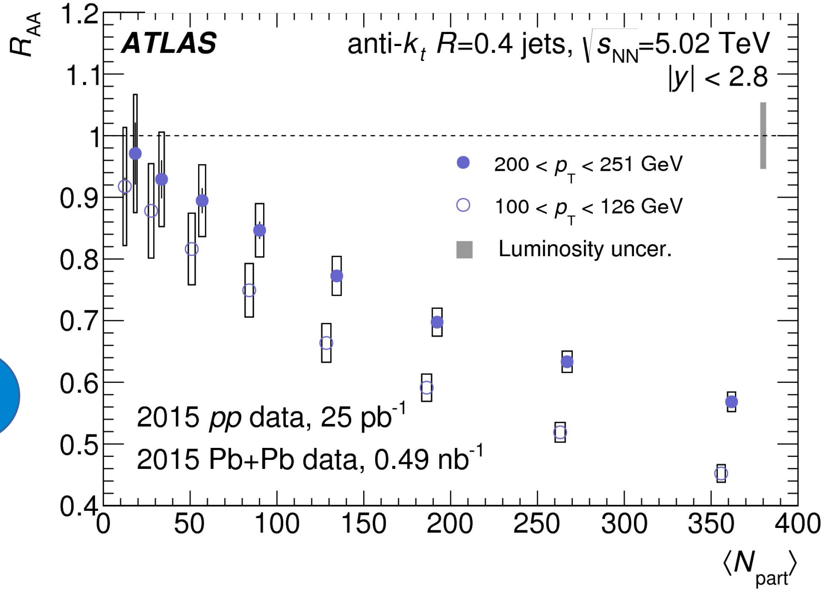
Inclusive supresion

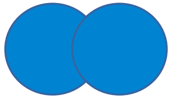
Norm. A+A

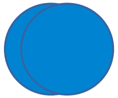
$$R_{AA} = \frac{1}{N_{\mathrm{coll}}} \cdot \frac{}{} = \frac{\boxed{\frac{1}{N_{\mathrm{coll}}} \frac{\mathrm{d}N_{AA}}{\mathrm{d}p_{\mathrm{T}}}}}{\boxed{\frac{\mathrm{d}N_{pp}}{\mathrm{d}p_{\mathrm{T}}}}}$$

pp

Jets:







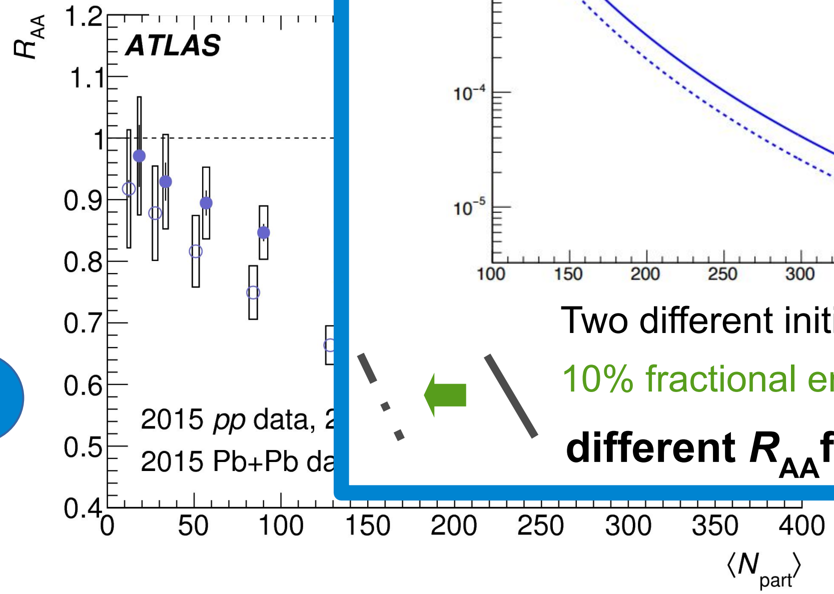
Energy loss in QCD medium

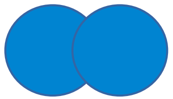
arXiv:1805.05635

Inclusive supresion

$$R_{AA} =$$

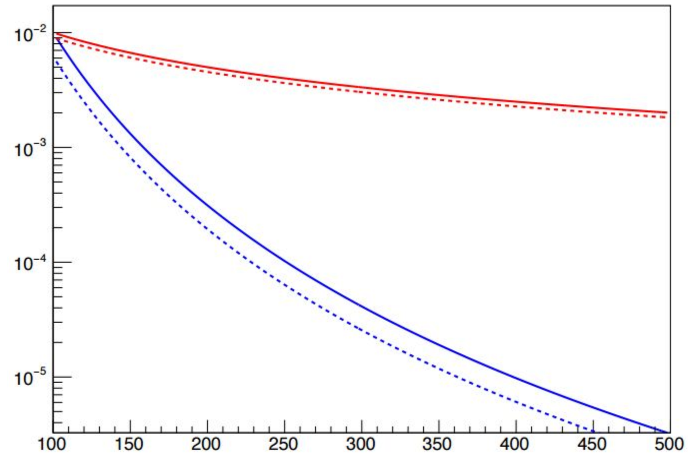
Jets:





Caveats on R_{AA}:

Sensitive to shapes of p_T spectra



Two different initial spectra

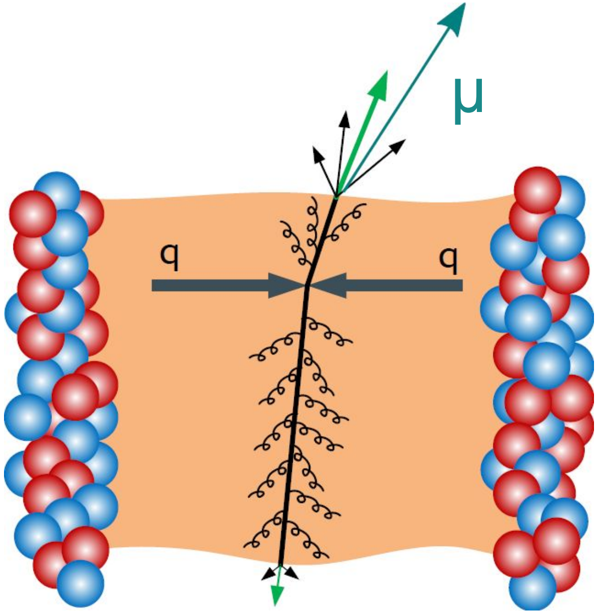
10% fractional energy loss

different R_{AA} for blue and red

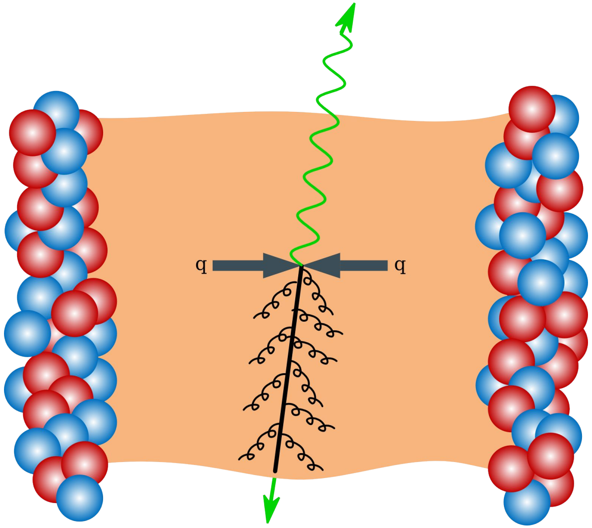
Energy loss in QCD medium

arXiv:1805.05635

Role of flavour in quenching



Mass of heavy quarks as additional relevant scale.

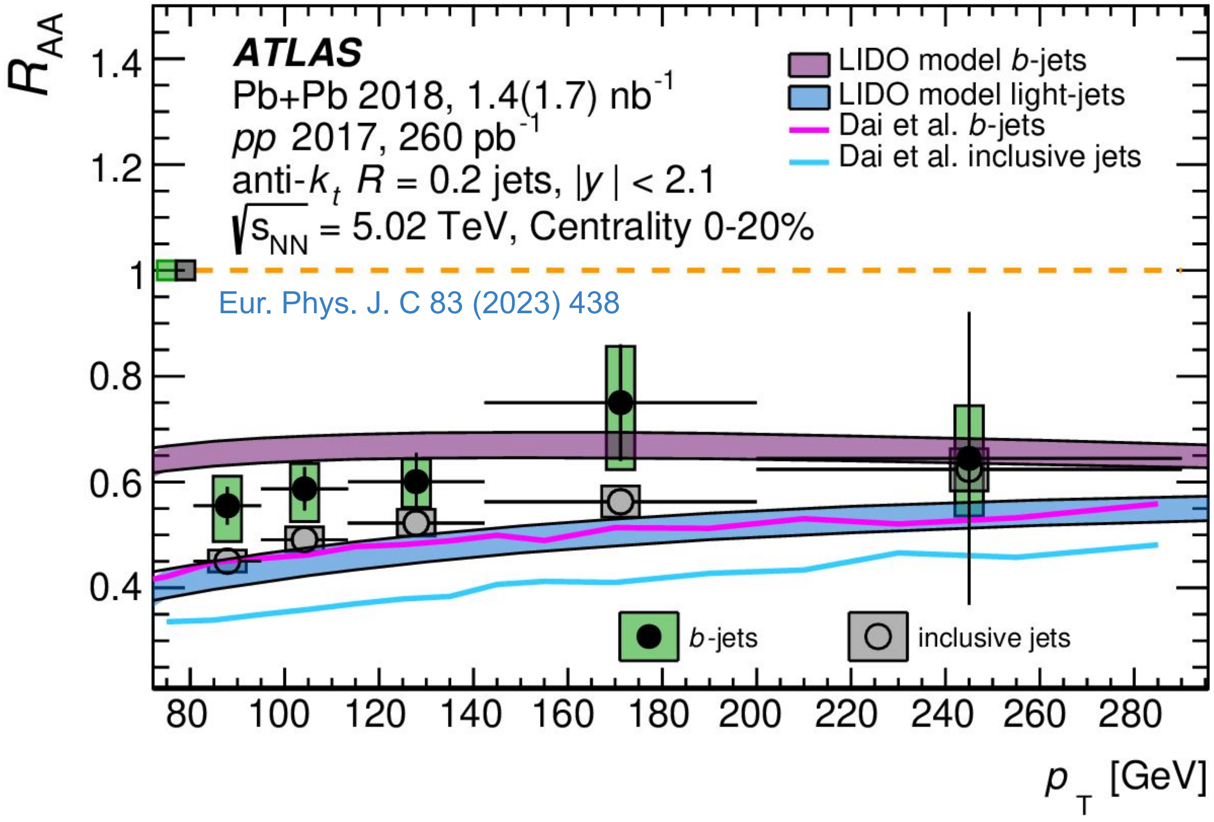


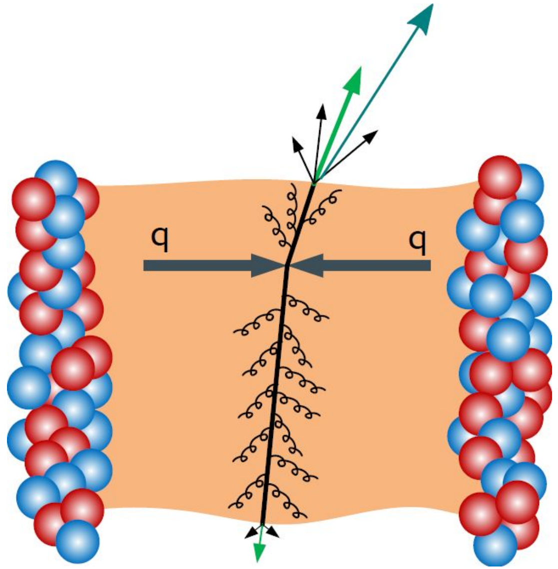
Quark vs. Gluon color factor Different fragmentation

Parton mass: $\Delta E_{u,d,s} > \Delta E_c > \Delta E_b$

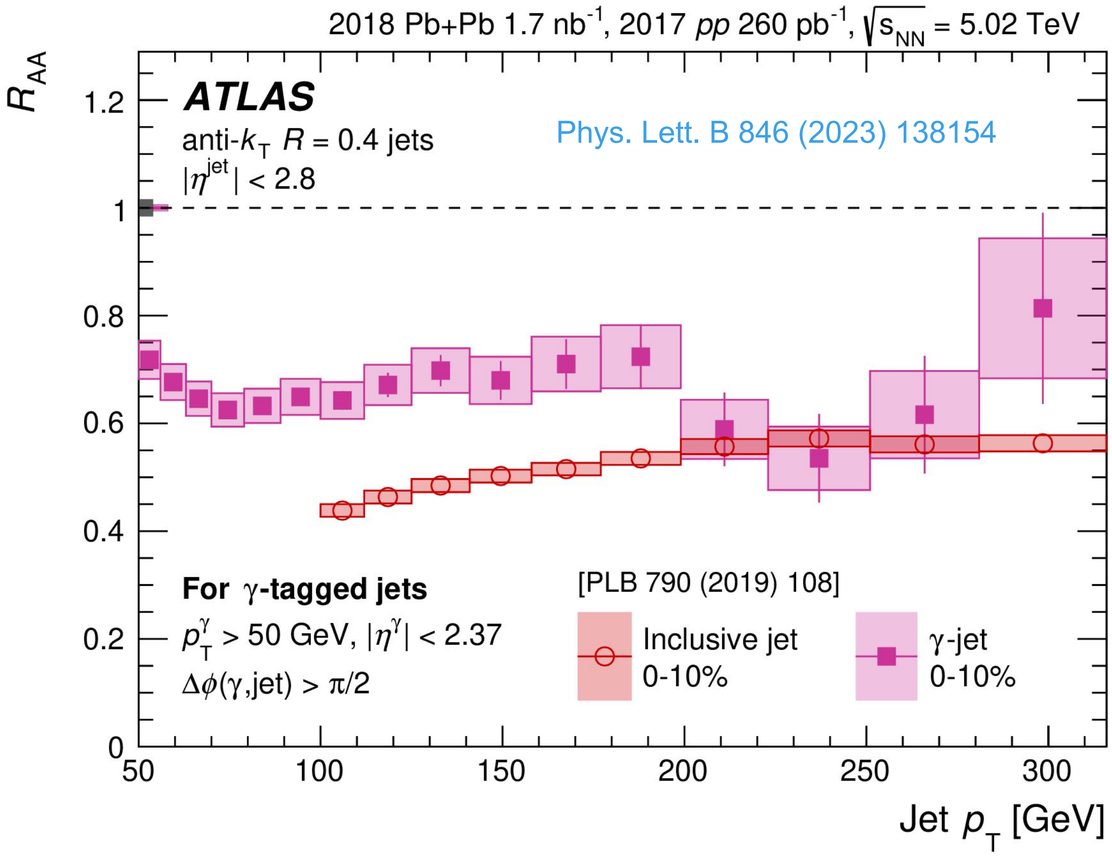
Color charge: $\Delta E_g > \Delta E_{u,d,s}$

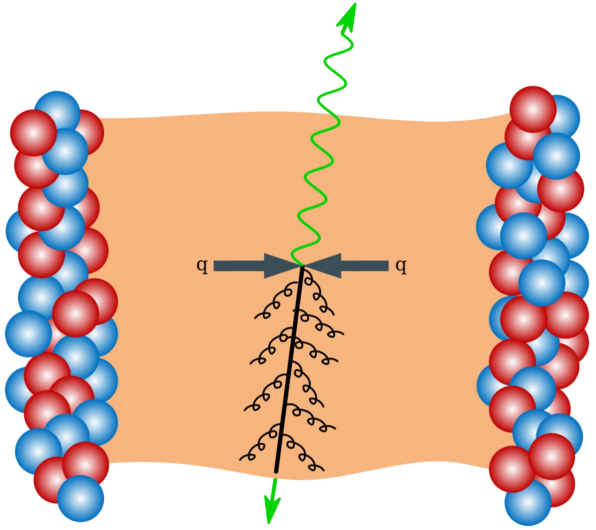
Role of flavour in quenching





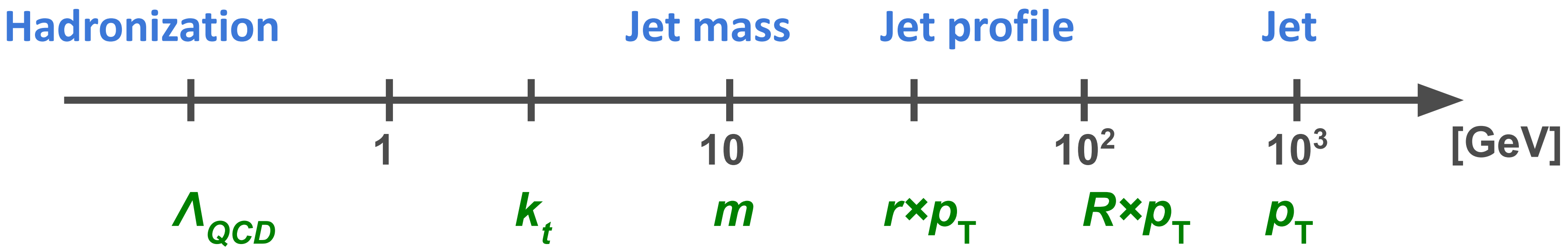
Role of flavour in quenching





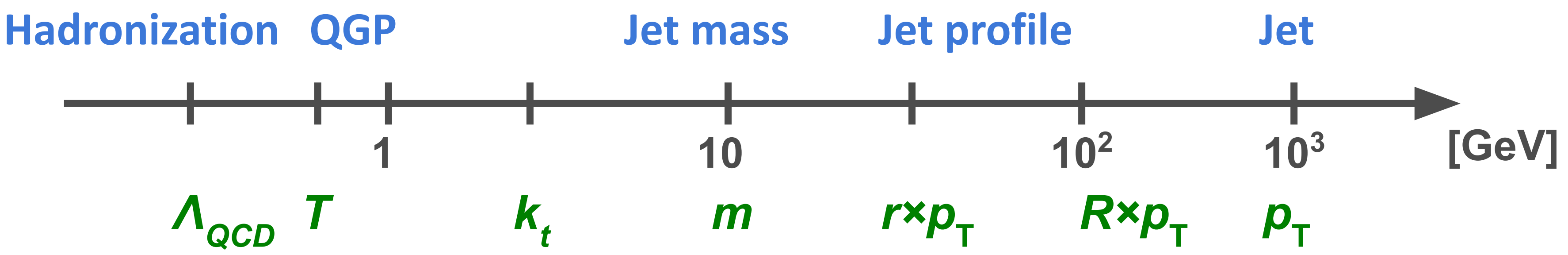
Why jet substructure?

- Jets are not point-like but complex & multiscale objects.



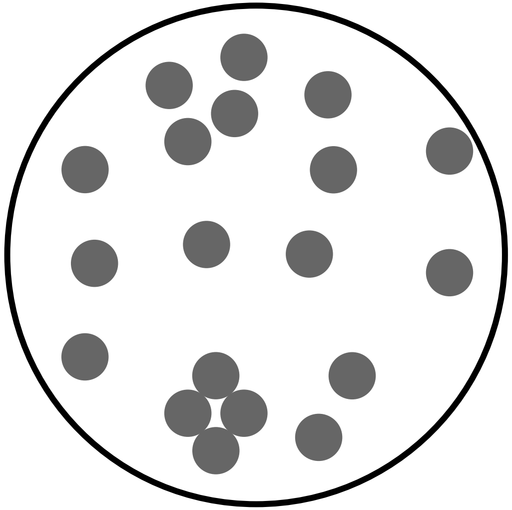
Why jet substructure in HI?

- Jets are not point-like but complex & multiscale objects.



- We can use various jet substructure observables to probe different regimes.
  - What are the properties and degrees of freedom of QGP at length scales between point-like partons and hydrodynamic modes?
  - How does the color charge interact and lose energy?
  - What are the effective scales of the interactions determining the energy loss?

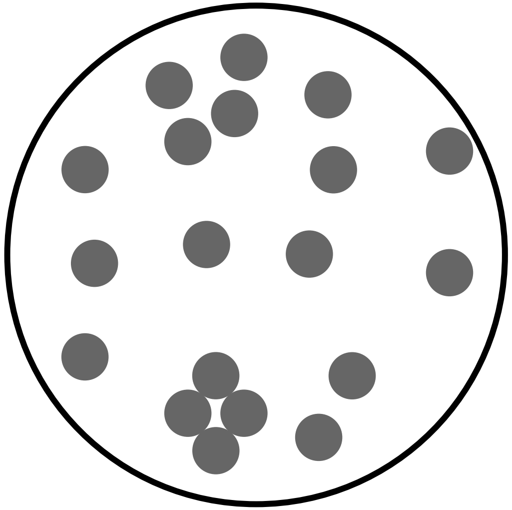
Jet definition & substructure

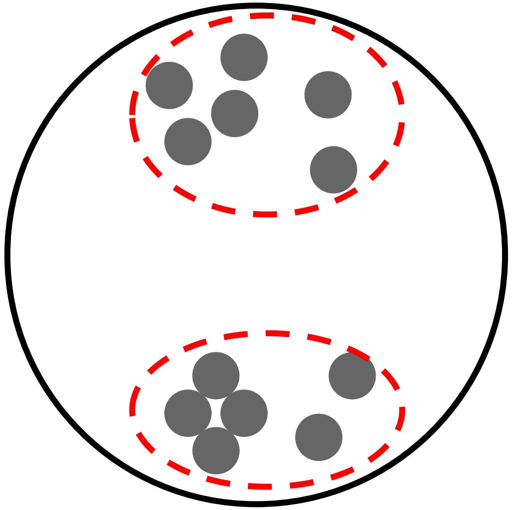


"Conventional" jet made of particles/tracks/towers/clusters

Fragmentation functions, track-jet correlations and jet shapes (can be extended to large angles).

Jet definition & substructure





"Conventional" jet made of particles/tracks/towers/clusters

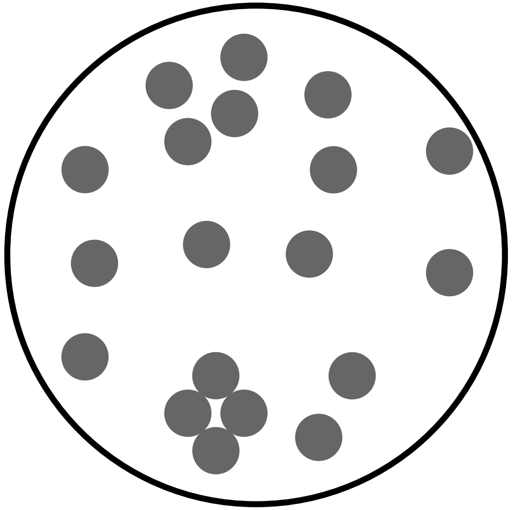
De-clustered & groomed jet with SoftDrop

Focusing on hard substructure…

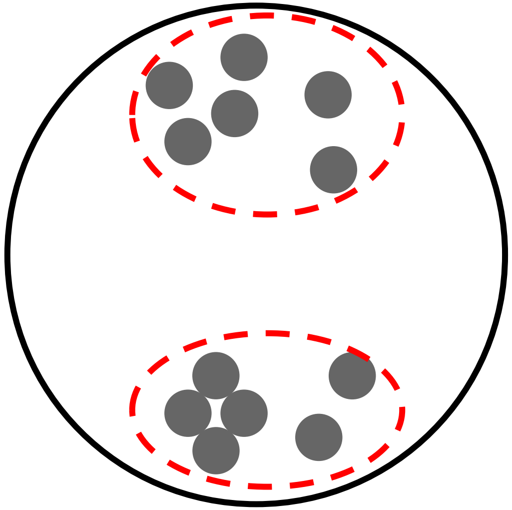
Fragmentation functions, track-jet correlations and jet shapes (can be extended to large angles).

Declustering follow the splitting evolution; grooming parameters ⇔ affects physics.

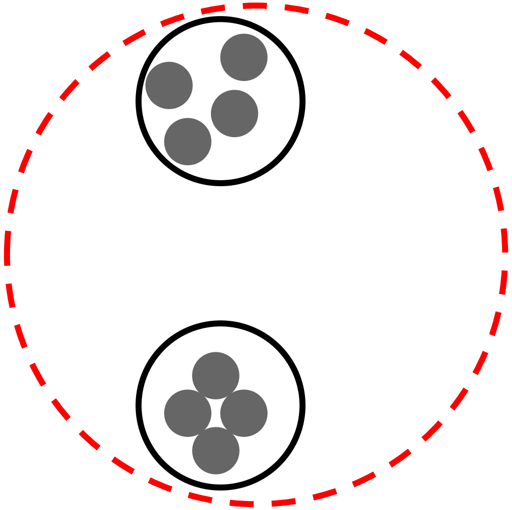
Jet definition & substructure



"Conventional" jet made of particles/tracks/towers/clusters



De-clustered & groomed jet with SoftDrop



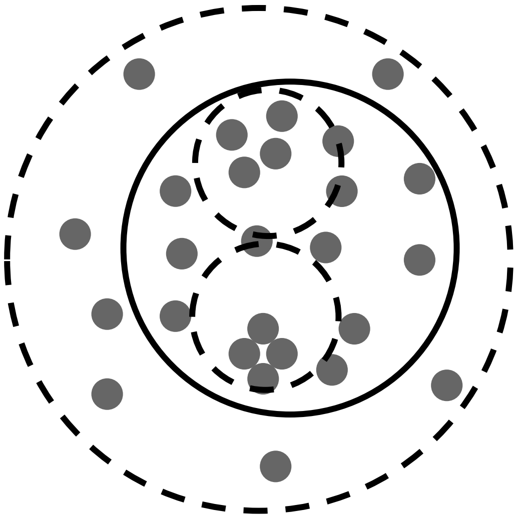
Re-clustered jet from smaller jets

Fragmentation functions, track-jet correlations and jet shapes

Declustering follow the splitting evolution; grooming parameters ⇔ affects physics.

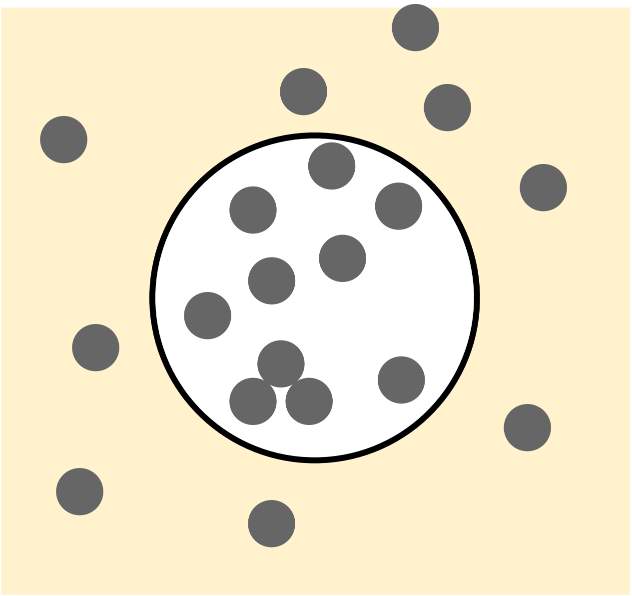
Large-R jets designed for boosted W/Z/t; focus on hard structure; sub-jets.

Jet definition & substructure



"Conventional" jet made of particles/tracks/towers/clusters

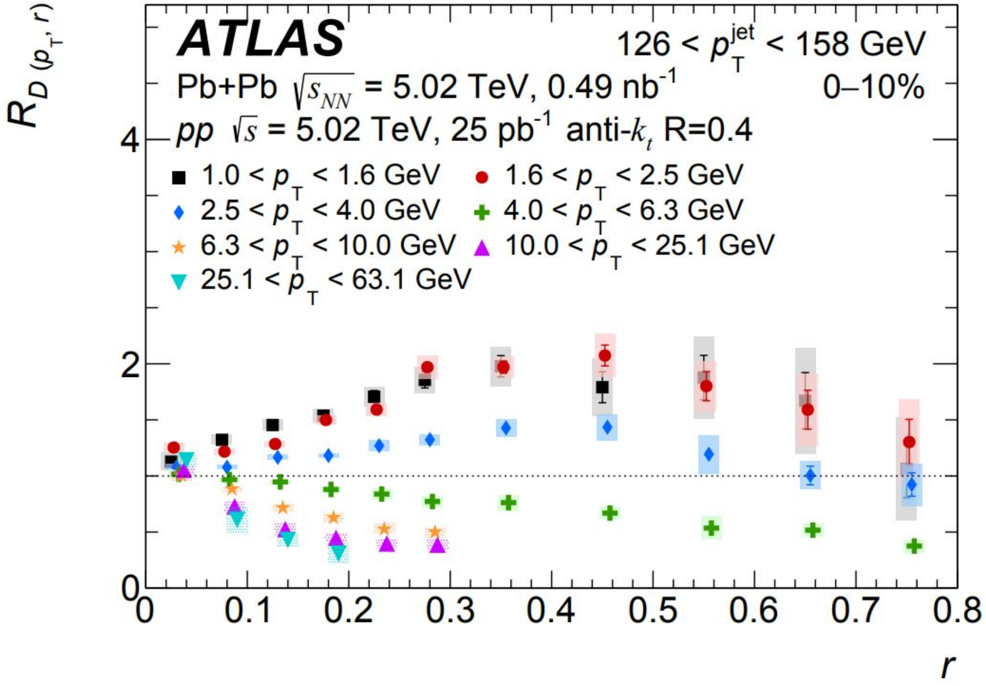
Radius dependence of dijet momentum balance



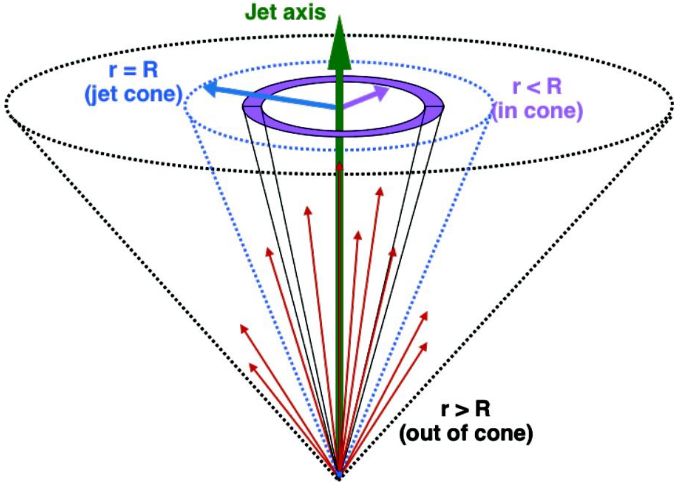
jet and some global event property

Missing transverse momentum calculculated in jet events.

Modification of Radial Profile



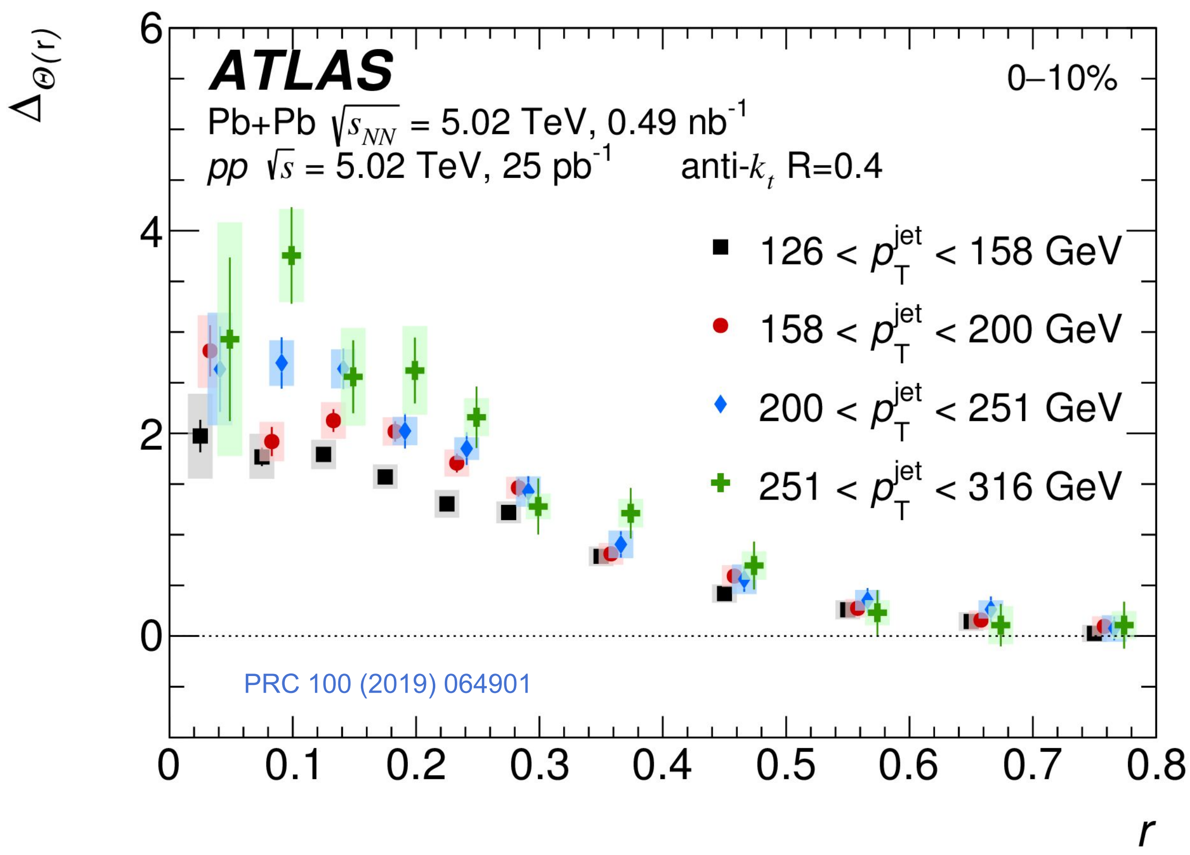
$$D(p_T, r) = \frac{1}{N_{jet}^{unfolded}} \frac{1}{2\pi r dr} \frac{dn_{ch}^{unfolded}(p_T^{ch}, r)}{dp_T}$$



- Jets are broader in more central collisions at low p_T.
- Significant suppression of yields of particles p_T > 4 GeV outside the jet core.

arXiv:1908.05264

Radial profile



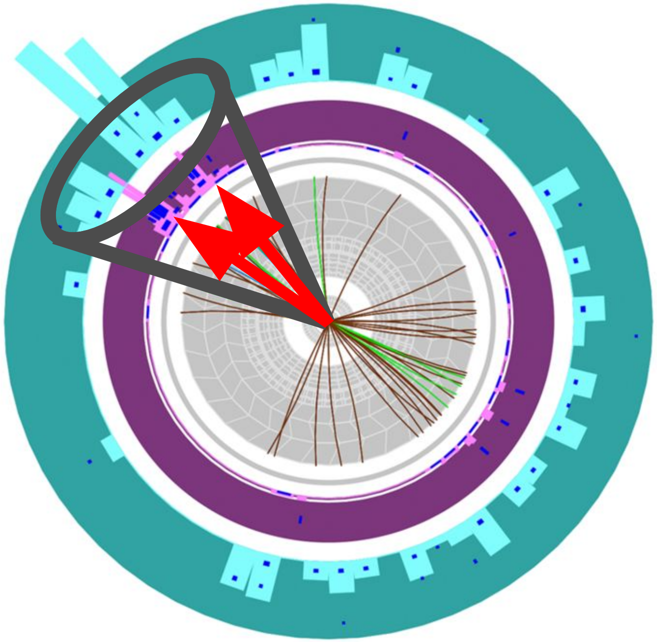
$$\Theta(r) = \int_{1\ \text{GeV}}^{4\ \text{GeV}} D(p_T, r) dp_T$$

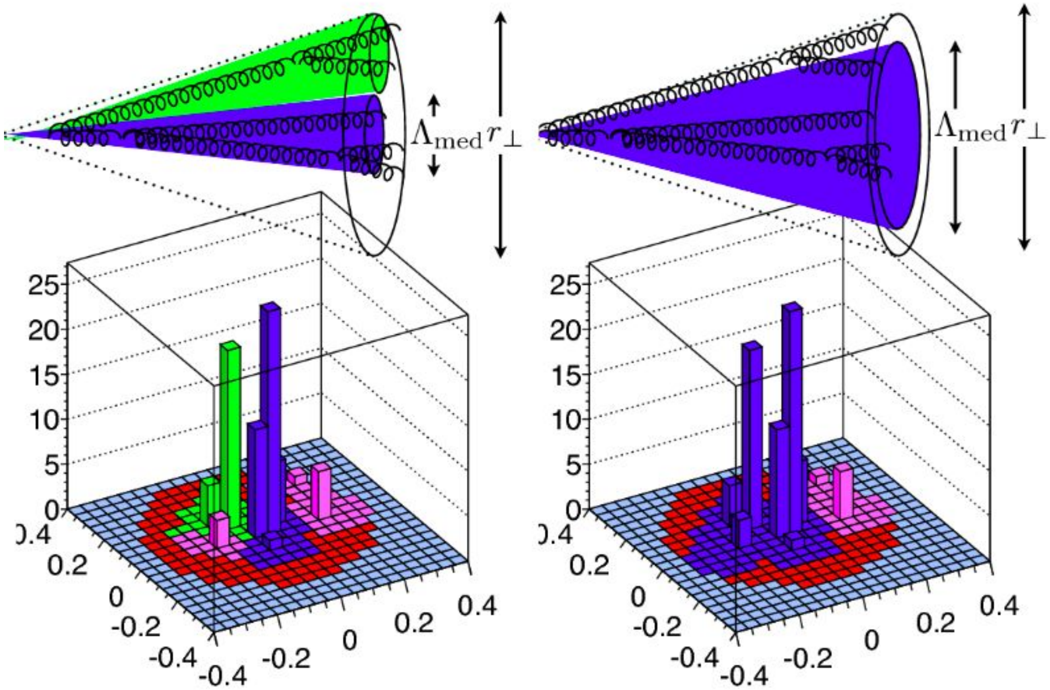
$$\Delta_{\Theta(r)} = \Theta(r)_{\text{Pb+Pb}} - \Theta(r)_{pp}$$

The absolute difference (#low p_T particles) is the highest inside the jet.

Can we see medium response in the jet p_T dependence?

Dependence of suppression on jet structure?



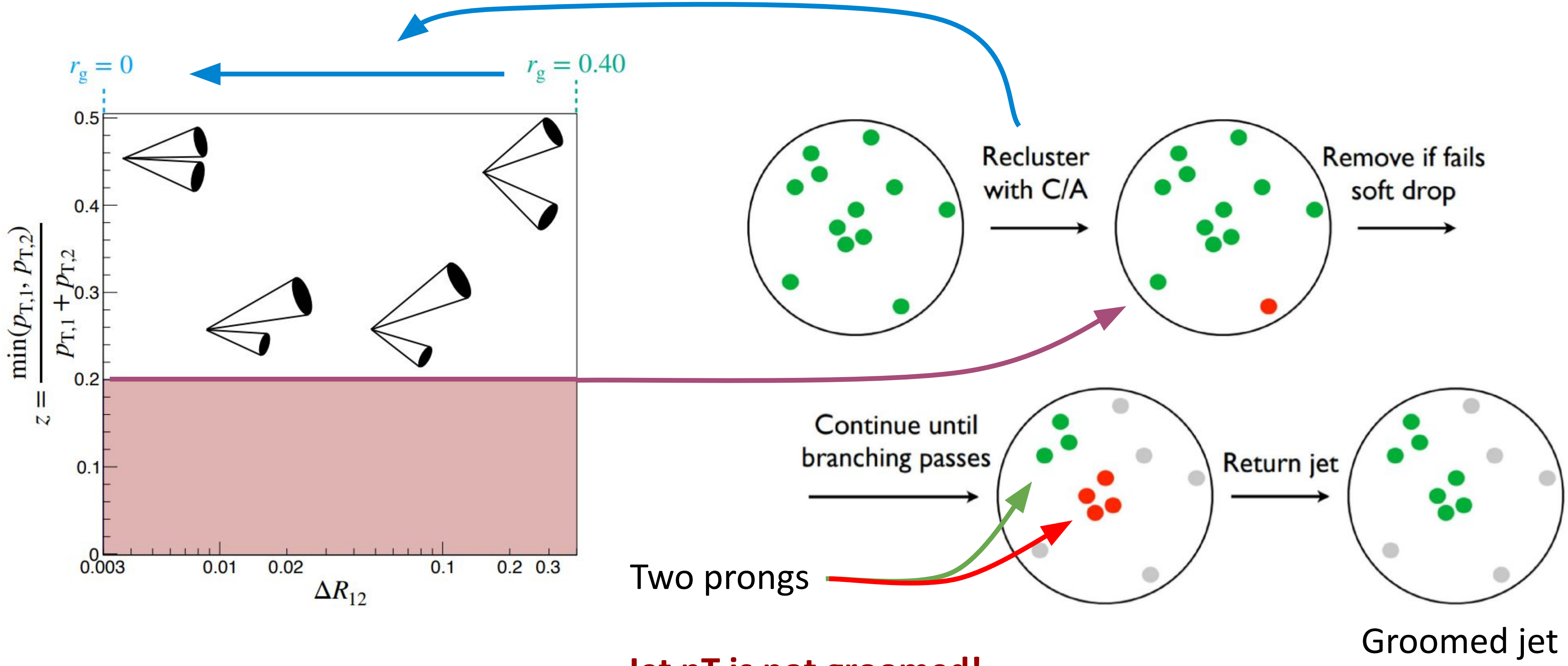


J. Casalderrey-Solana, Y. Mehtar-Tani, C. A. Salgado, K. Tywoniuk, Phys. Lett. B725 (2013) 357

Can be addressed by measurement of jet R_{AA} as a function of their sub-structure.

Classifying parton splittings with Soft-Drop

- Classifying R =0.4 jets using angular separation of the hardest splitting

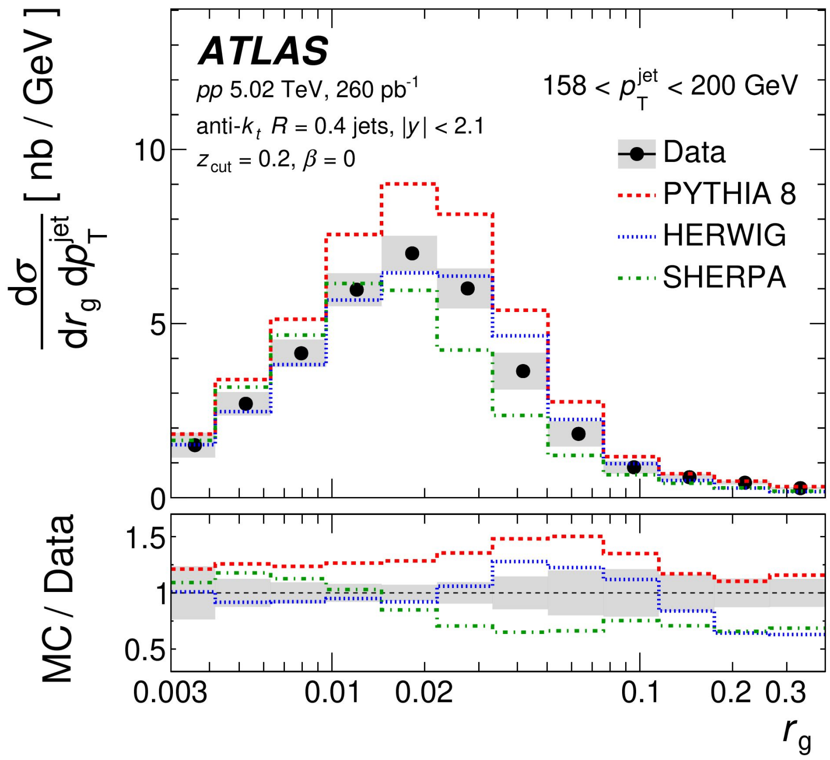


Drawing by Dhanush Hangal

Jet pT is not groomed!

Classifying parton splittings with Soft-Drop

- Fully corrected & absolutely normalized cross-sections & yields.

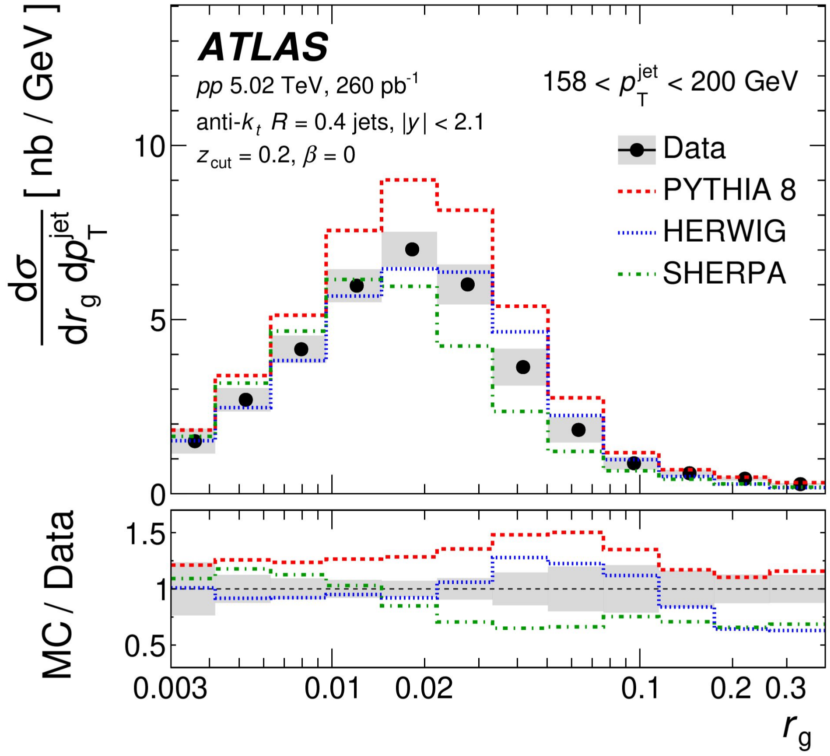


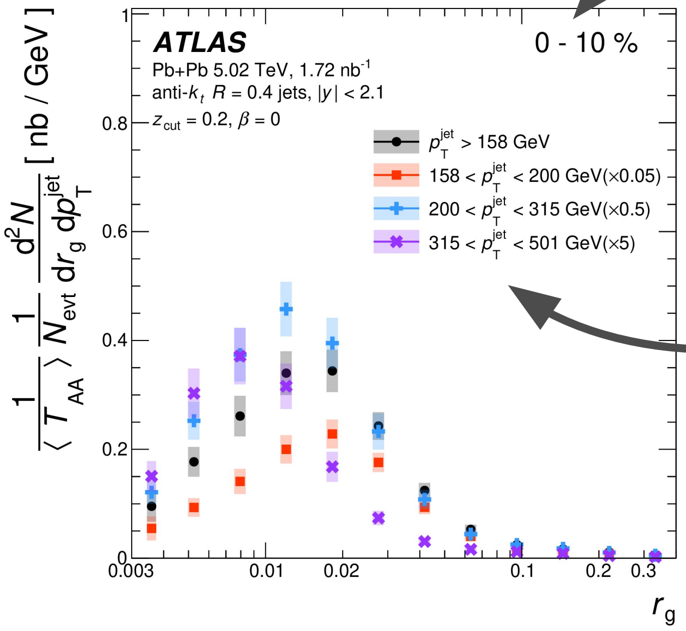
Reference measurement in pp collisions at 5.02 TeV

arXiv:2211.11470

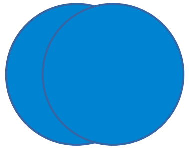
Classifying parton splittings with Soft-Drop

- Fully corrected & absolutely normalized cross-sections & yields.





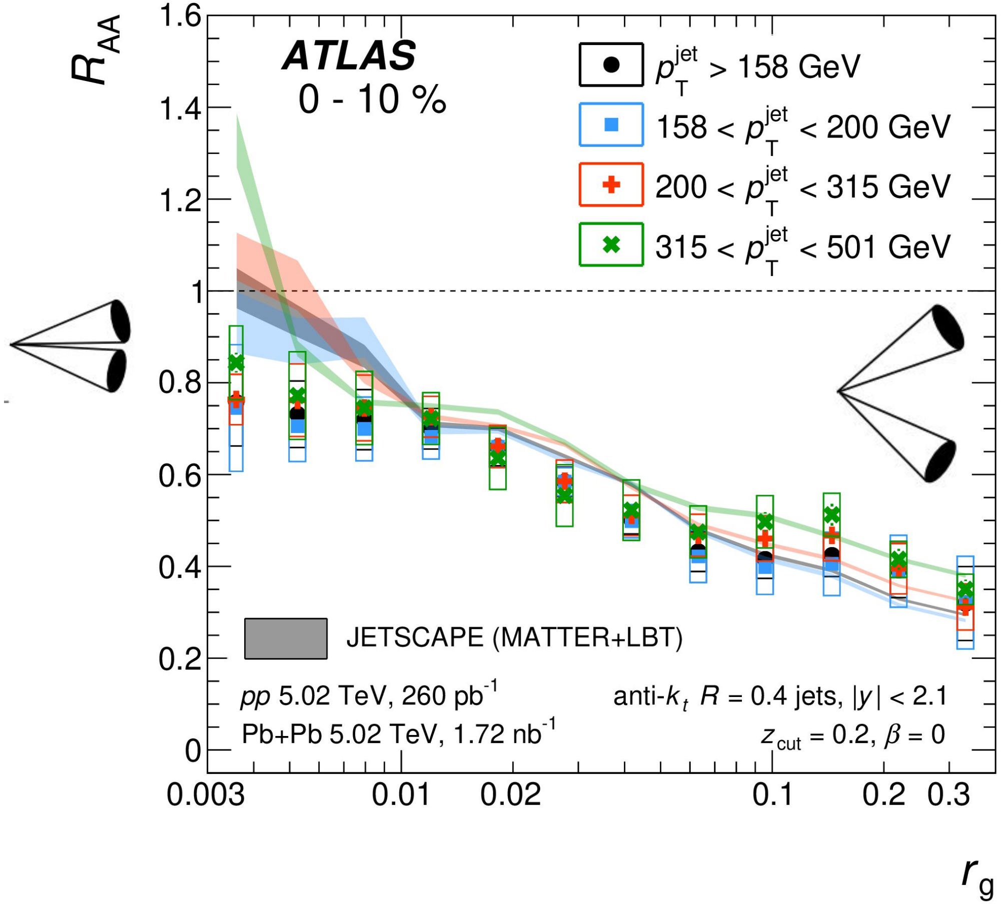
Central "0-10%" Pb+Pb

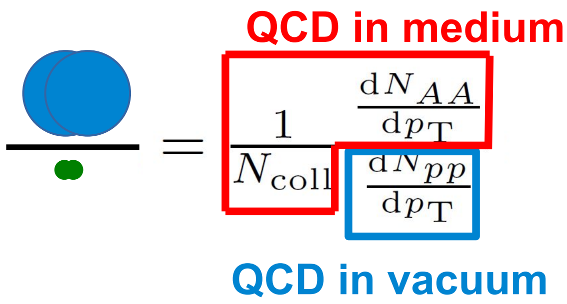


Differential in jet p_T

arXiv:2211.11470

Suppression vs parton splittings





$$R_{AA} = \frac{1}{N_{coll}} \frac{\frac{dN_{AA}}{dp_T}}{\frac{dN_{pp}}{dp_T}}$$

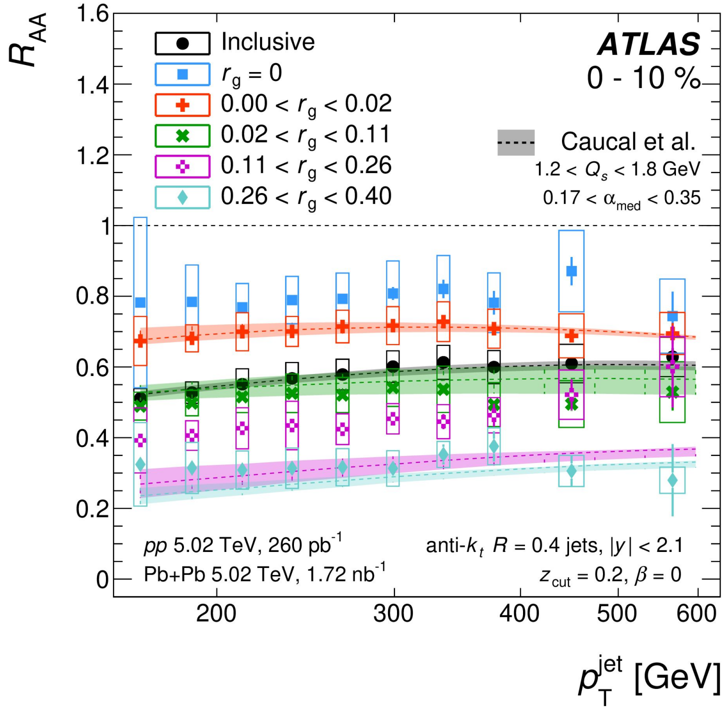
Strong dependence of jet suppression
on r_g.

How can we understand the r_g vs p_T dependence?

arXiv:2211.11470

Jet p_T dependence of the suppression

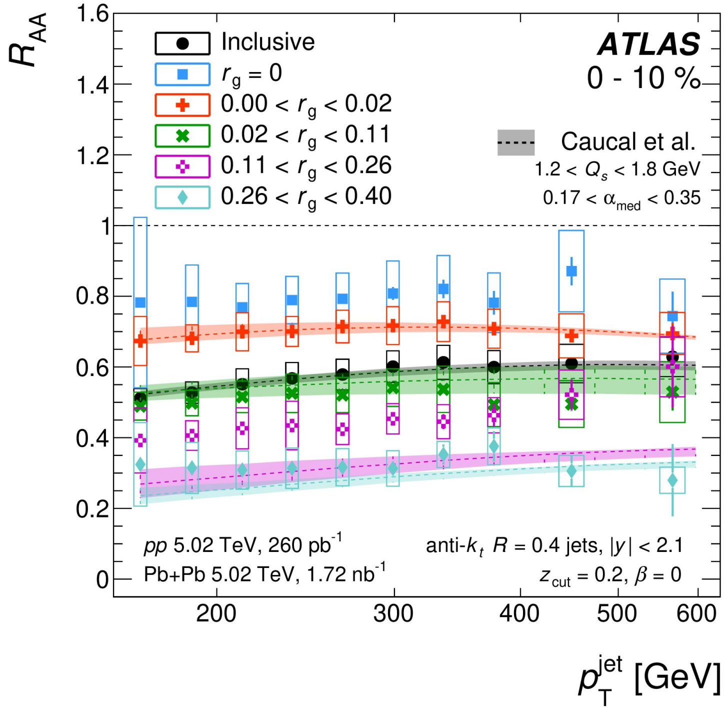
arXiv:2211.11470

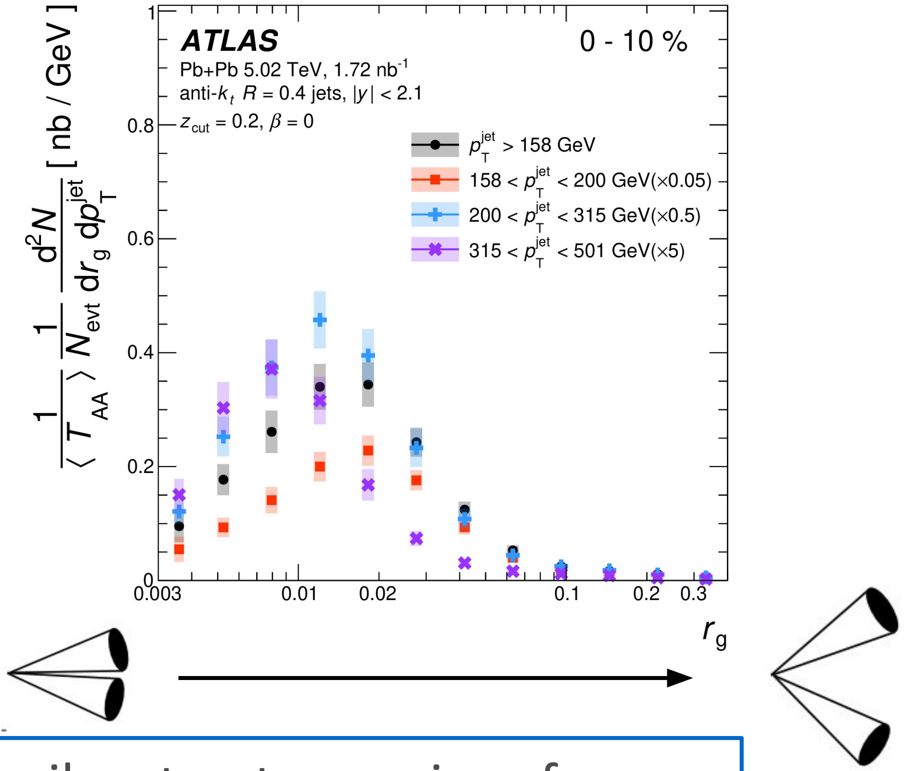


Lack of p_T dependence of R_{AA} for jets with similar structure

Jet p_T dependence of the suppression

arXiv:2211.11470





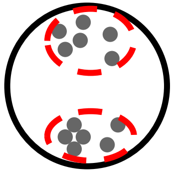
Lack of p_T dependence of R_{AA} for jets with similar structure + rise of inclusive R_{AA} ⇔ p_T dependence to r$_g$.

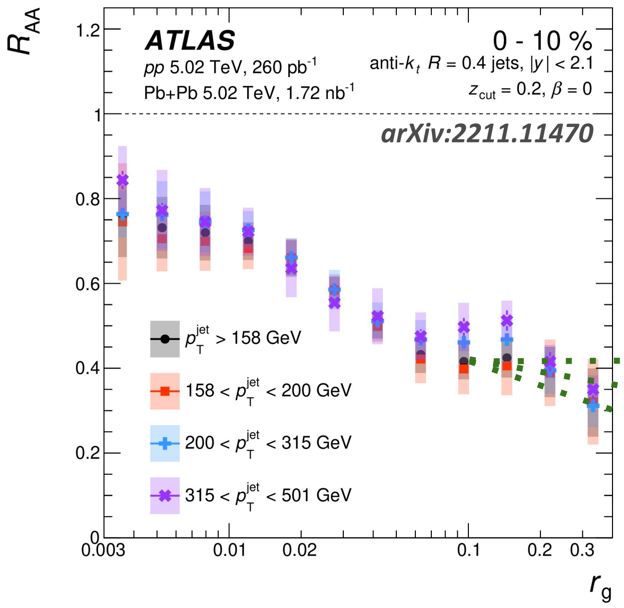
Full picture: small & large jets

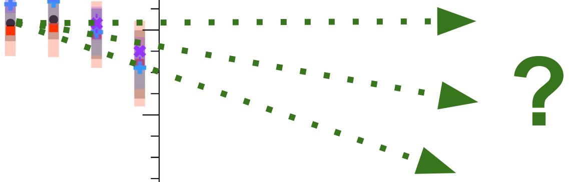
- Addressing transition from color-coherence to decoherence…

r_g

***R*=0.4**







arXiv:2301.05606

Re-clustered large-R jets

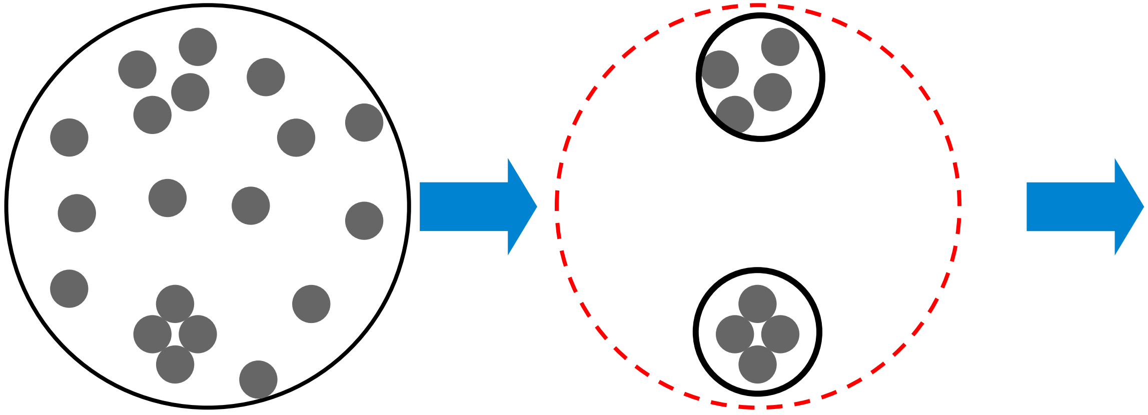
R=0.2 jets
p_T > 35 GeV

→ re-clustering with anti-k_t R=1.0

→ Sub-jets

→ re-clustering with k_t algorithm

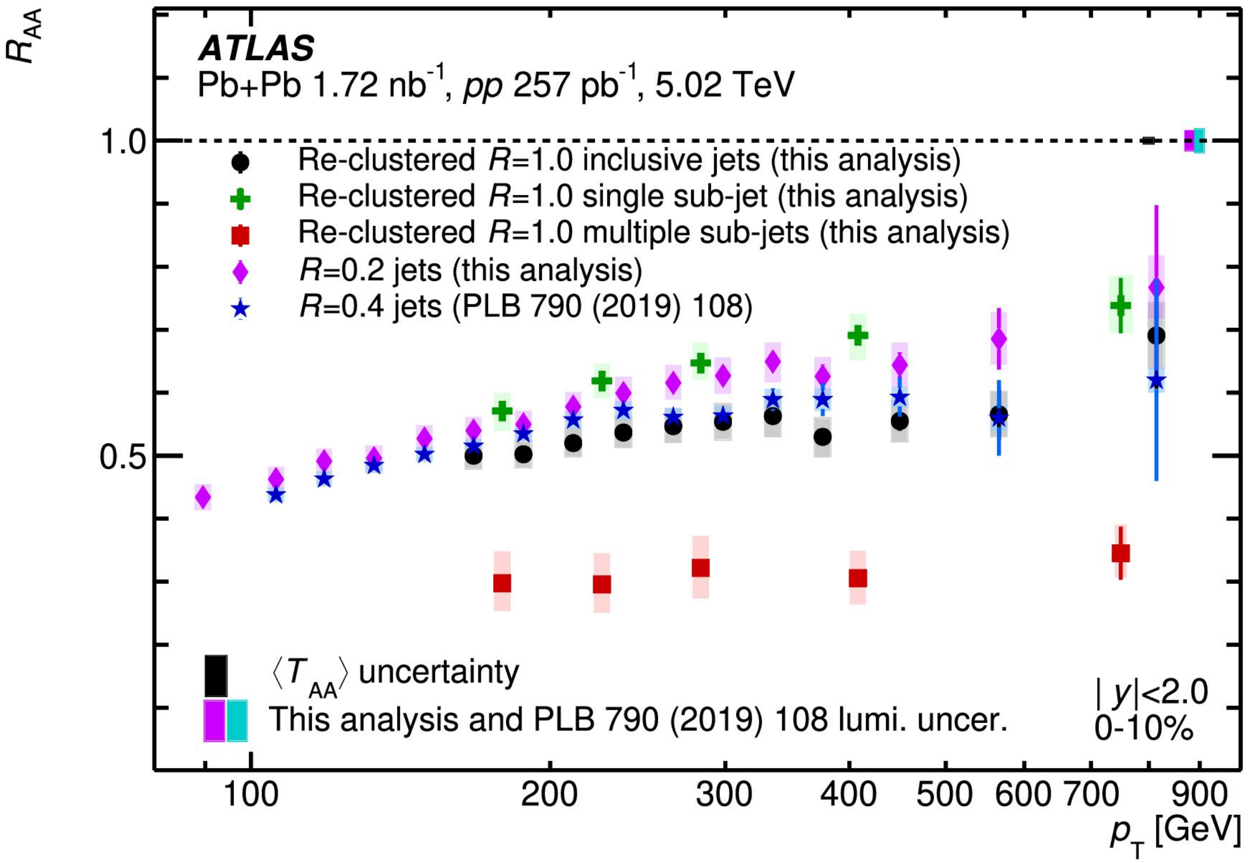
→ $\sqrt{d_{12}}$ and ΔR_{12}



"Conventional" jet   Re-clustered jet

Different jets than the conventional R=1.0.
35 GeV threshold remove the soft component.

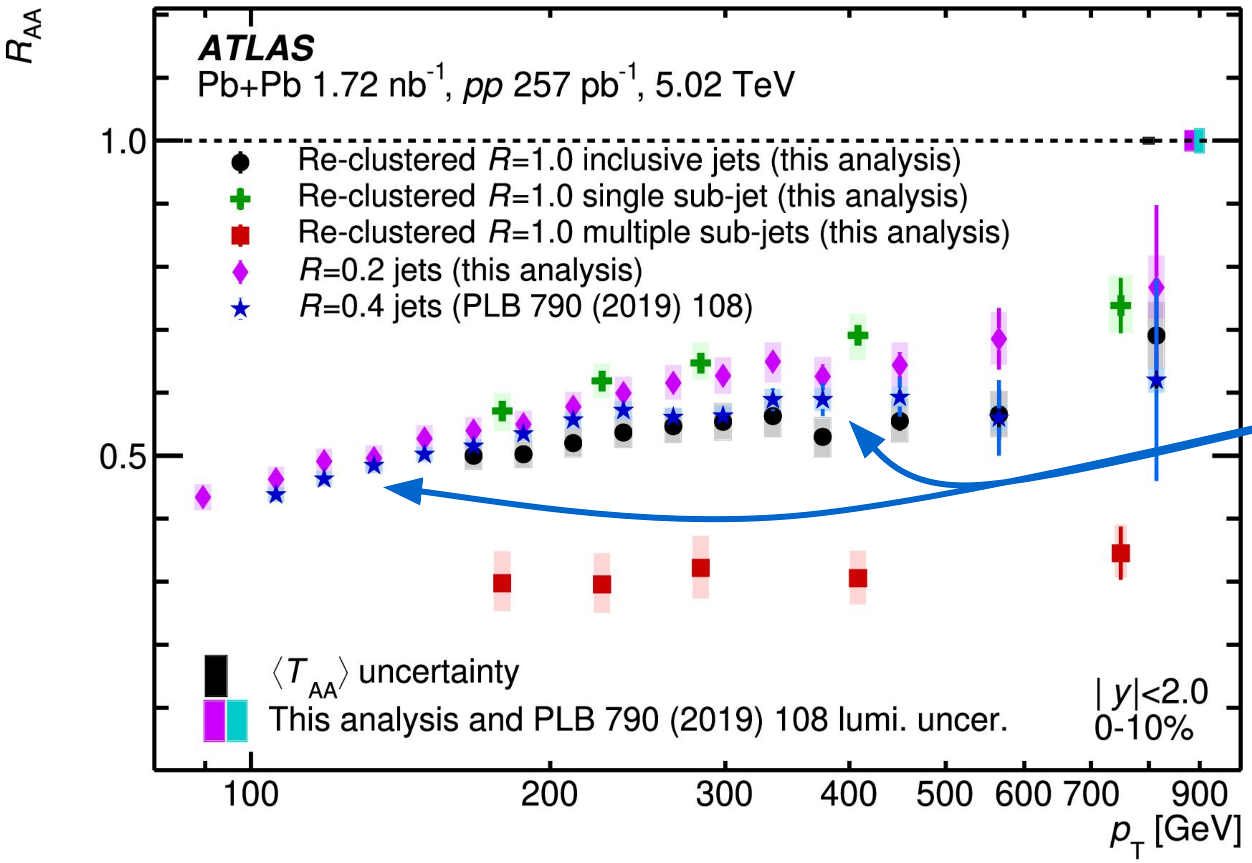
Jet suppression for different jet type



- Overall jets are suppressed in by factor ~2 (except red points) in central Pb+Pb.

arXiv:2301.05606

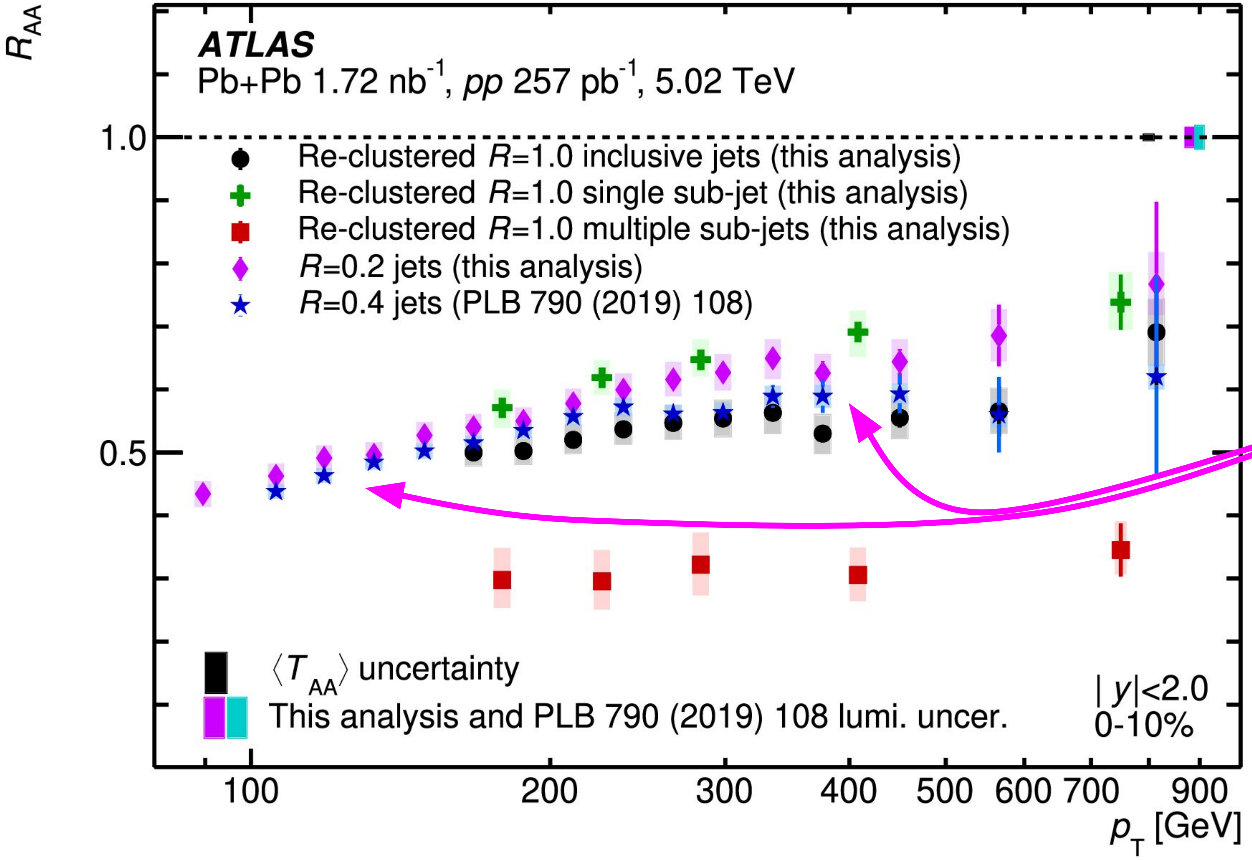
Jet suppression for different jet type



Inclusive R = 0.4 jets

arXiv:2301.05606

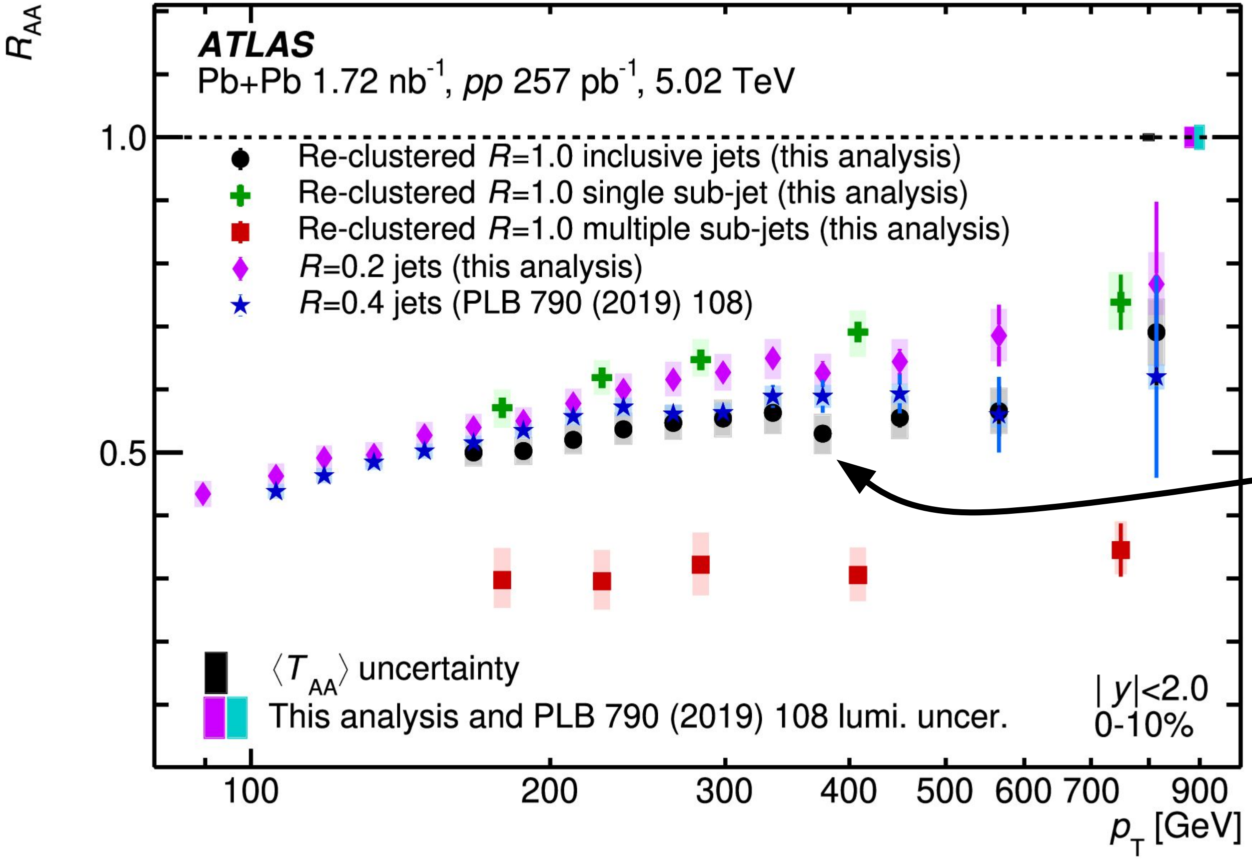
Jet suppression for different jet type



Inclusive R = 0.2 jets suppressed by a few % less wrt R = 0.4

arXiv:2301.05606

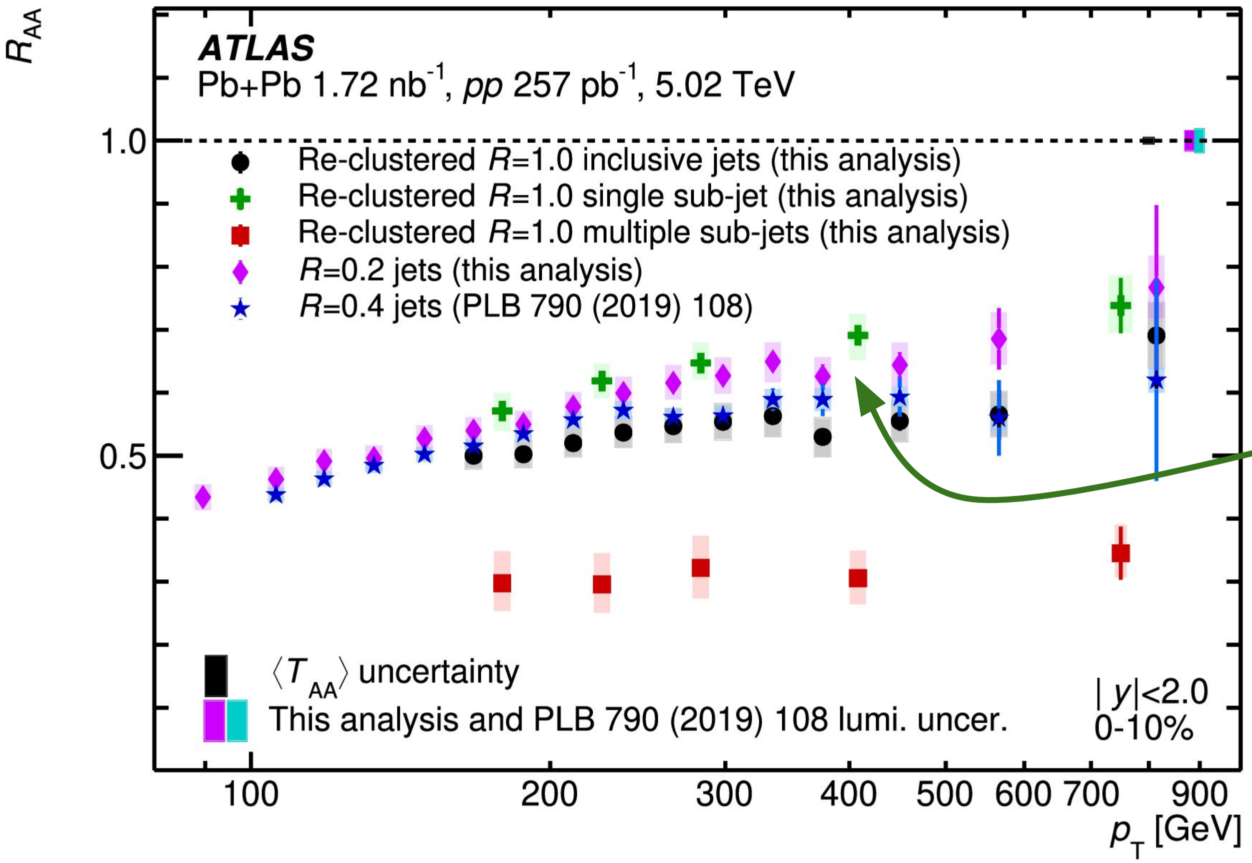
Jet suppression for different jet type



Inclusive re-clustered R=1.0 jets suppressed even more

arXiv:2301.05606

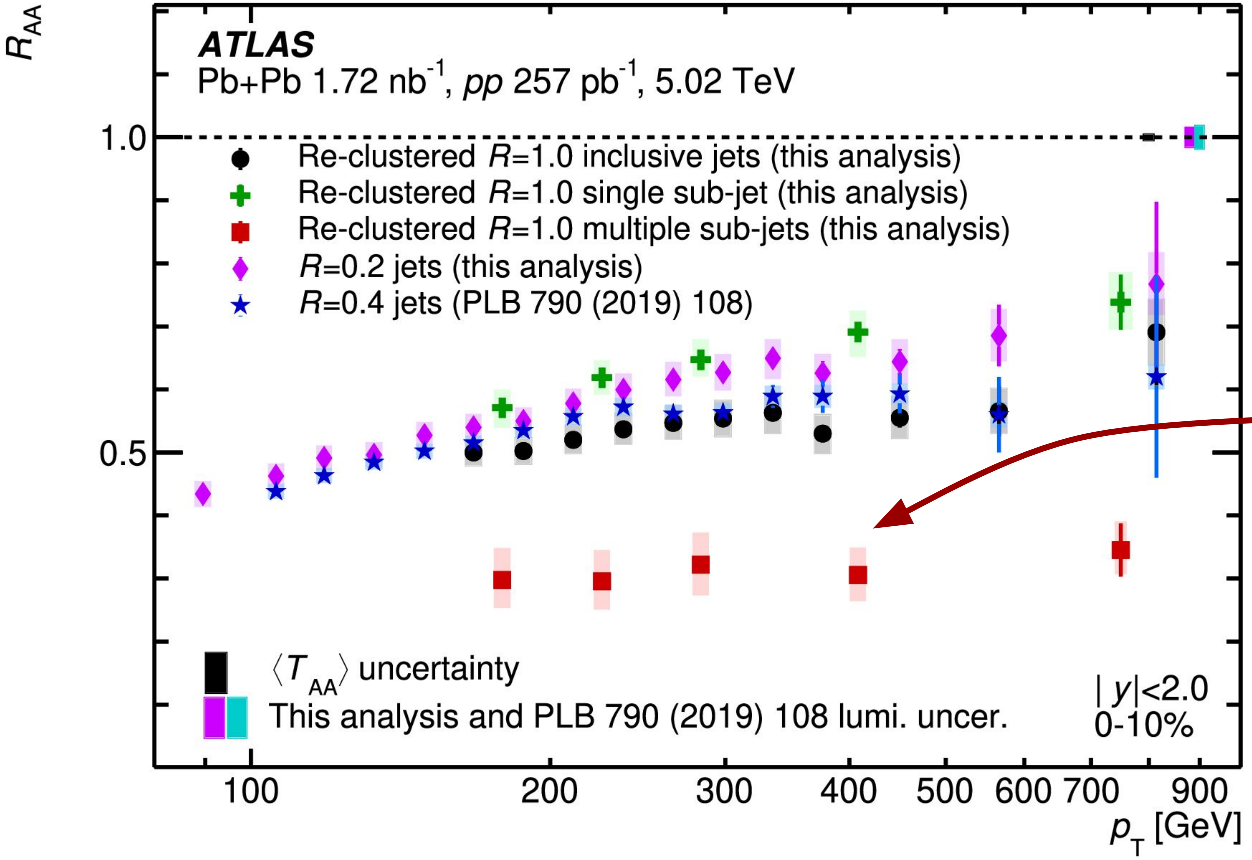
Jet suppression for different jet type



Two components:
single sub-jet R=1.0
suppressed the least

arXiv:2301.05606

Jet suppression for different jet type



Two components:
multiple sub-jet *R*=1.0
suppressed of the largest suppression

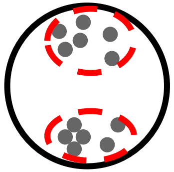
arXiv:2301.05606

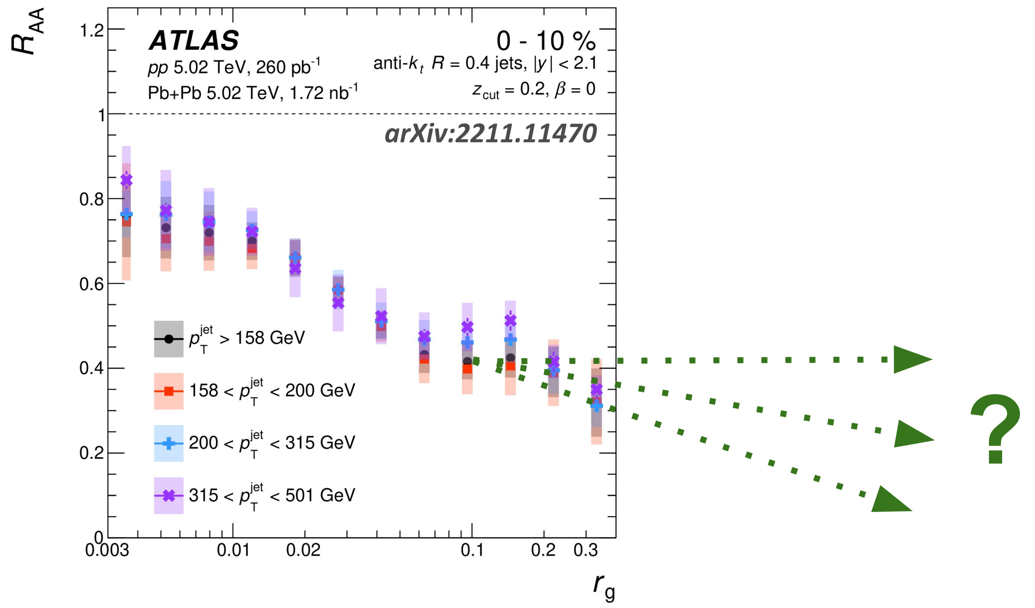
Full picture: small & large jets

- Addressing transition from color-coherence to decoherence…

r_g

***R*=0.4**



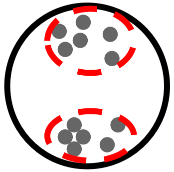


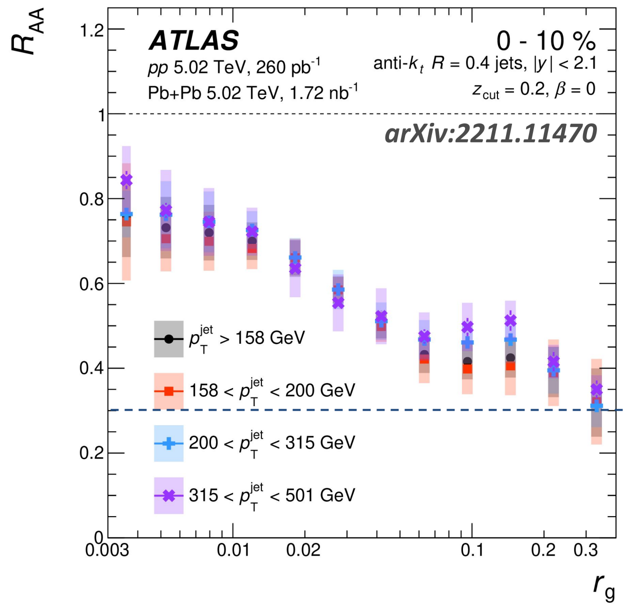
Full picture: small & large jets

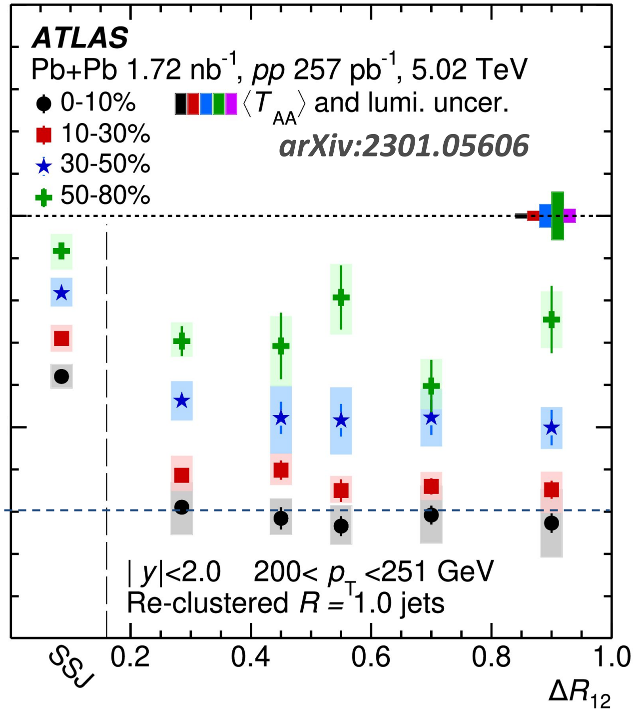
- Addressing transition from color-coherence to decoherence…

r_g

R=0.4

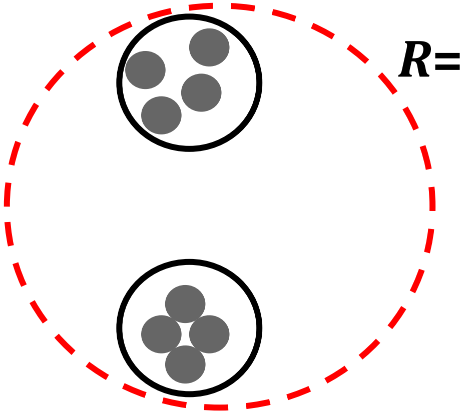






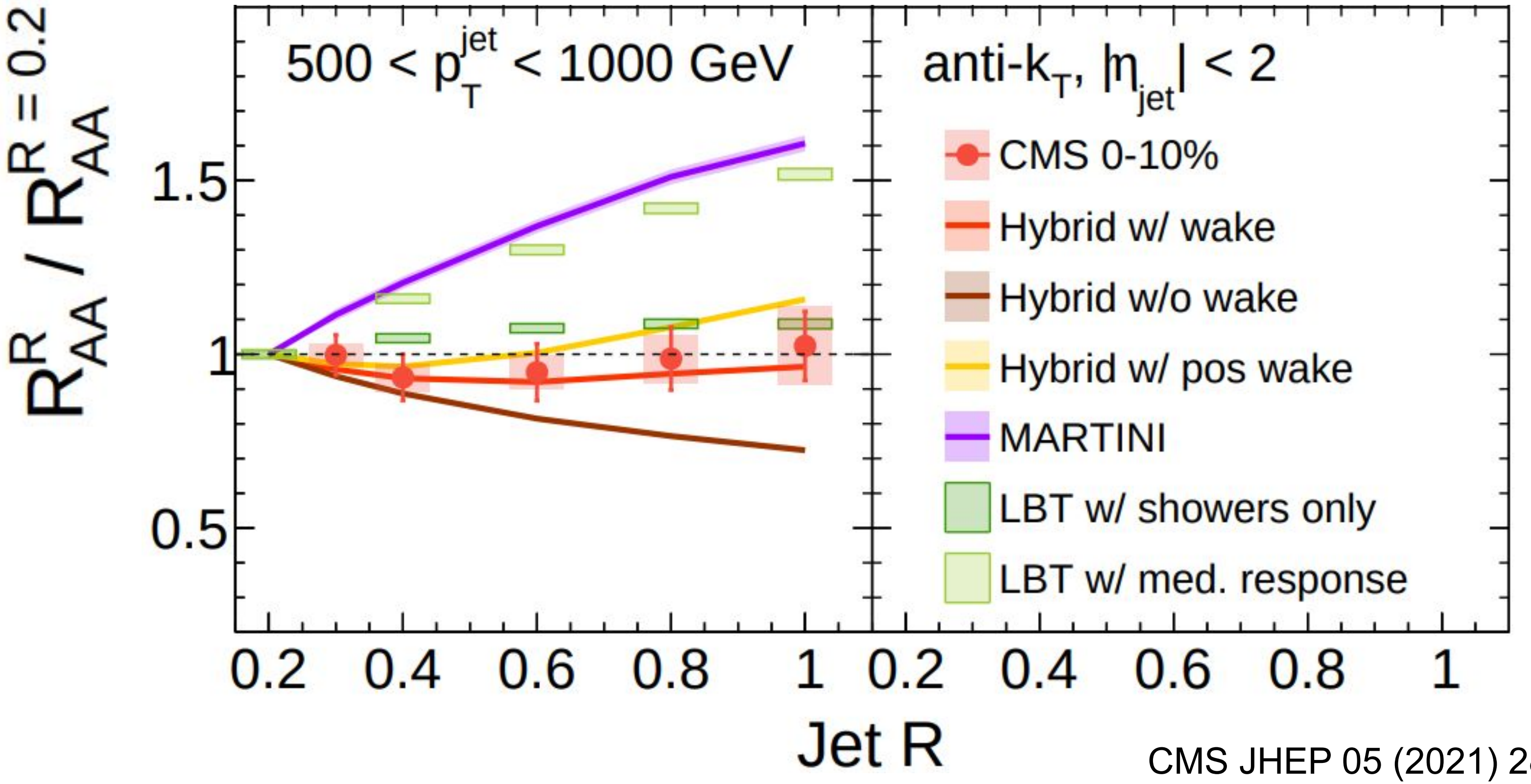
$$\Delta R_{12} = \sqrt{\Delta y_{12}^2 + \Delta\phi_{12}^2}$$

R=1.0



Radial scan

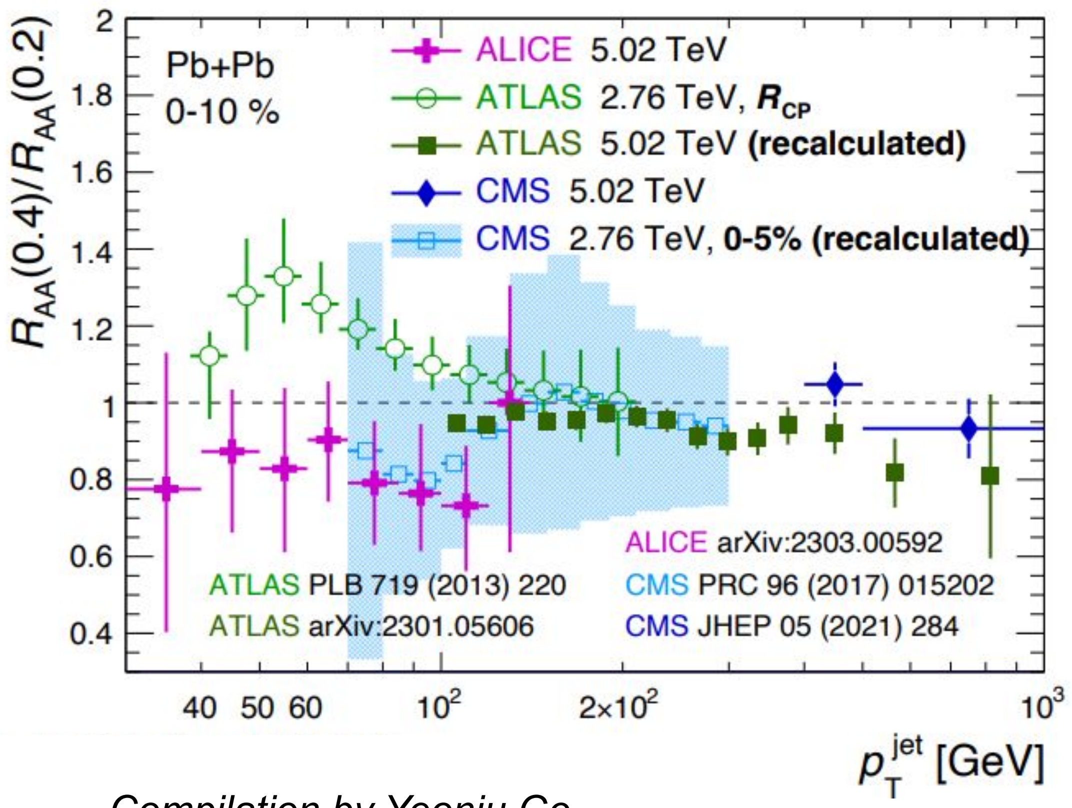
- Comparison of inclusive jets for different jet radii ⟶ recovery + medium response vs flavour fraction + more resolved structure.



CMS JHEP 05 (2021) 284

Radial scan

- Comparison of inclusive jets from different experiments.



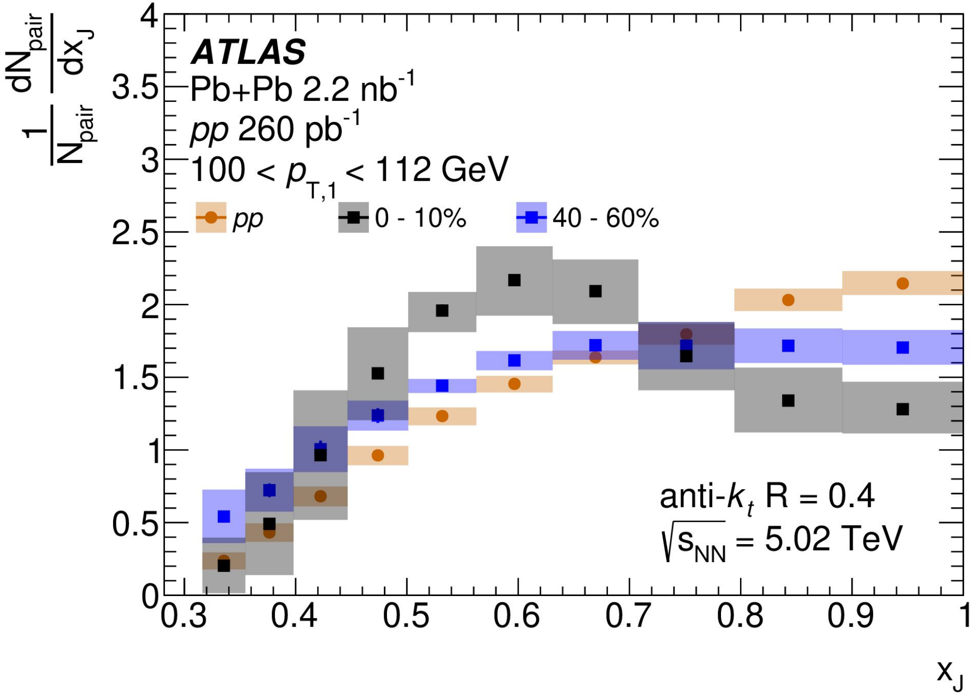
Compilation by Yeonju Go

Tension between result…

- Larger systematics
- Charged vs full jet?
- 2.76 TeV vs 5.02 TeV & slightly different phase-space can not explain the difference.
- Lower-level details & comparison is needed.

Dijet imbalance

$$\frac{1}{N_{\text{pair}}}\frac{dN_{\text{pair}}}{dx_J}$$ Self-normalized measurement



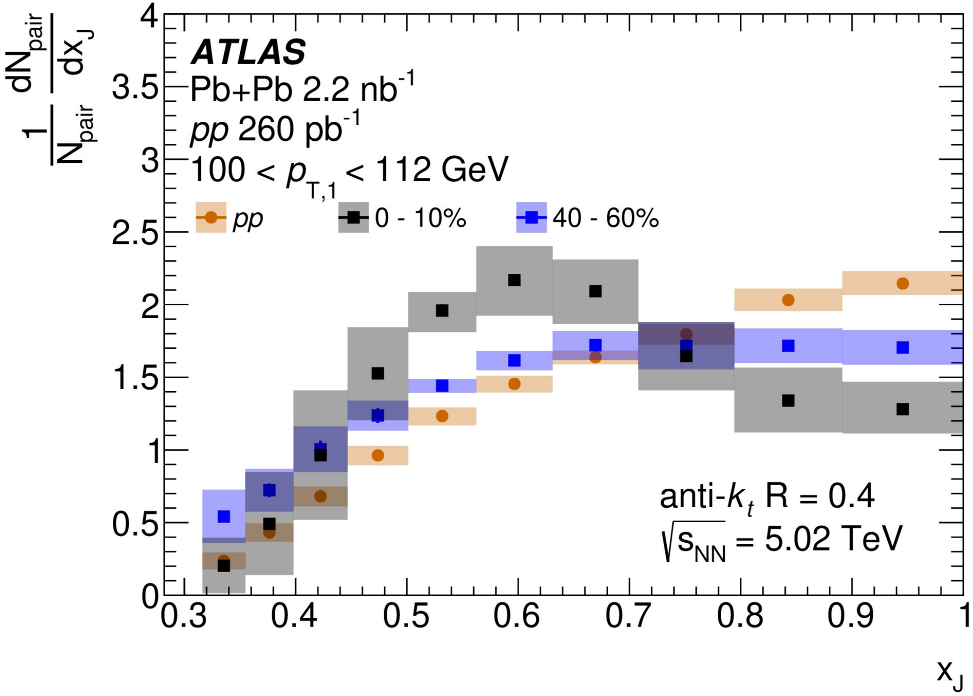
$x_J = p_{T2} / p_{T1}$

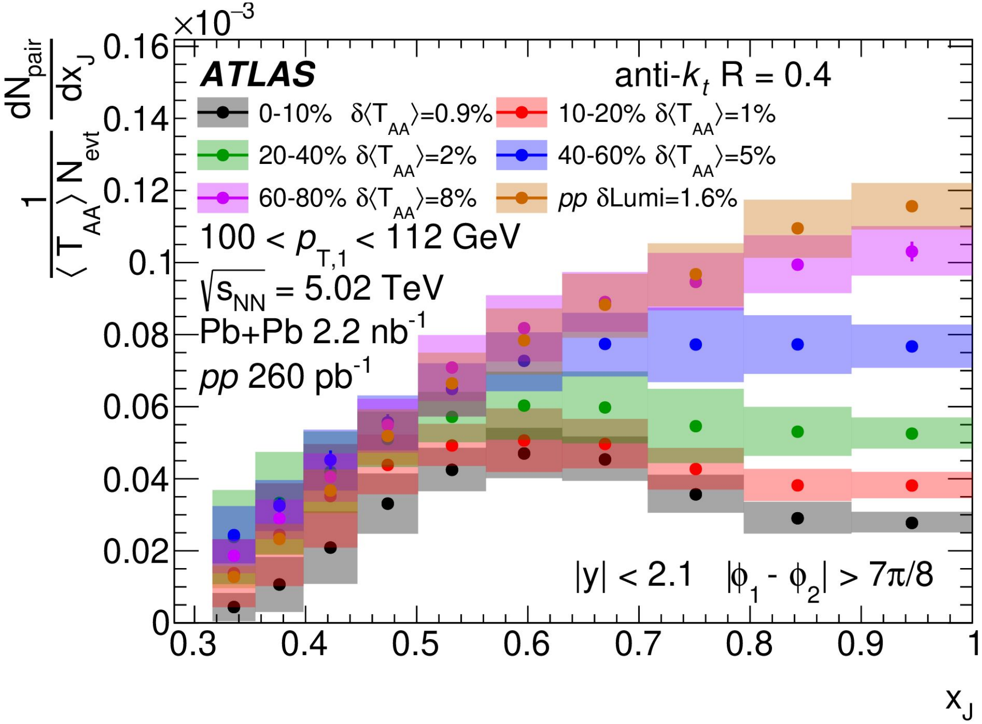
Phys. Rev. C 107 (2023) 054908

Dijet imbalance

$$\frac{1}{N_{\rm pair}}\frac{dN_{\rm pair}}{dx_{\rm J}}$$ Self-normalized measurement

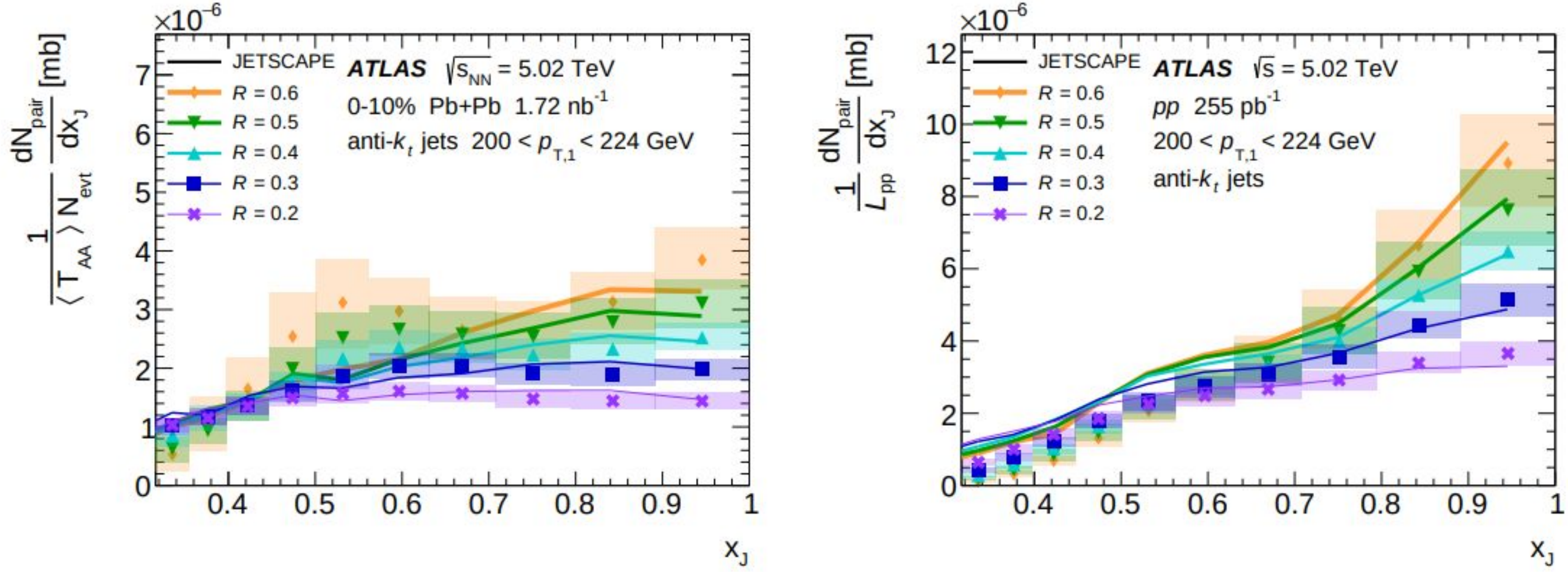
$$\frac{1}{\langle T_{\rm AA}\rangle N_{\rm evt}^{\rm AA}}\frac{dN_{\rm pair}^{\rm AA}}{dx_{\rm J}}$$ absolute-normalized measurement





Phys. Rev. C 107 (2023) 054908

R-dependence of dijet imbalance



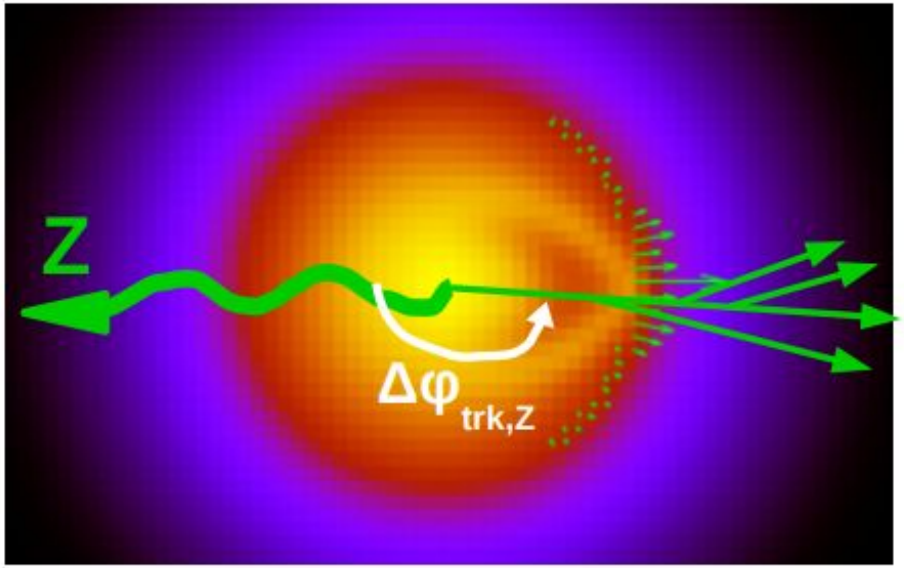
- Larger dijets are more balanced in p_T.
- R-dependent suppression only seen mainly for low-xJ values.

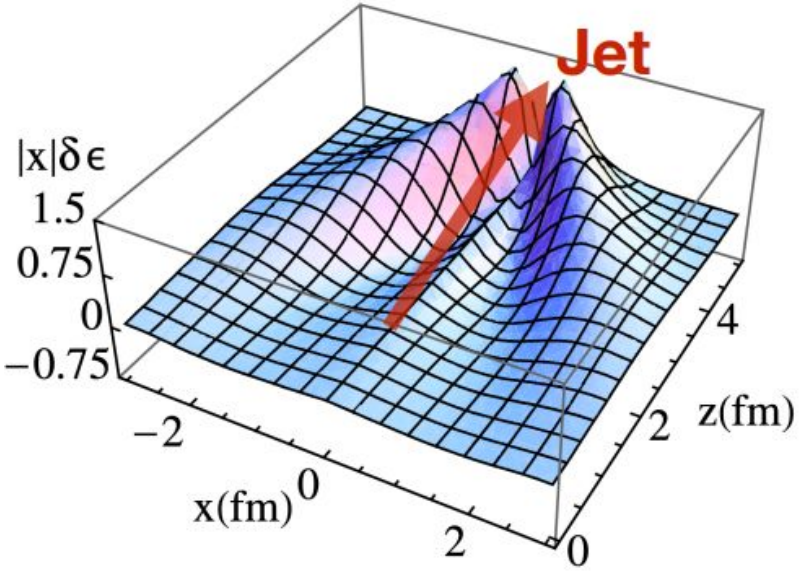
arXiv:2407.18796

Angular scan using EW boson tagged "jets"

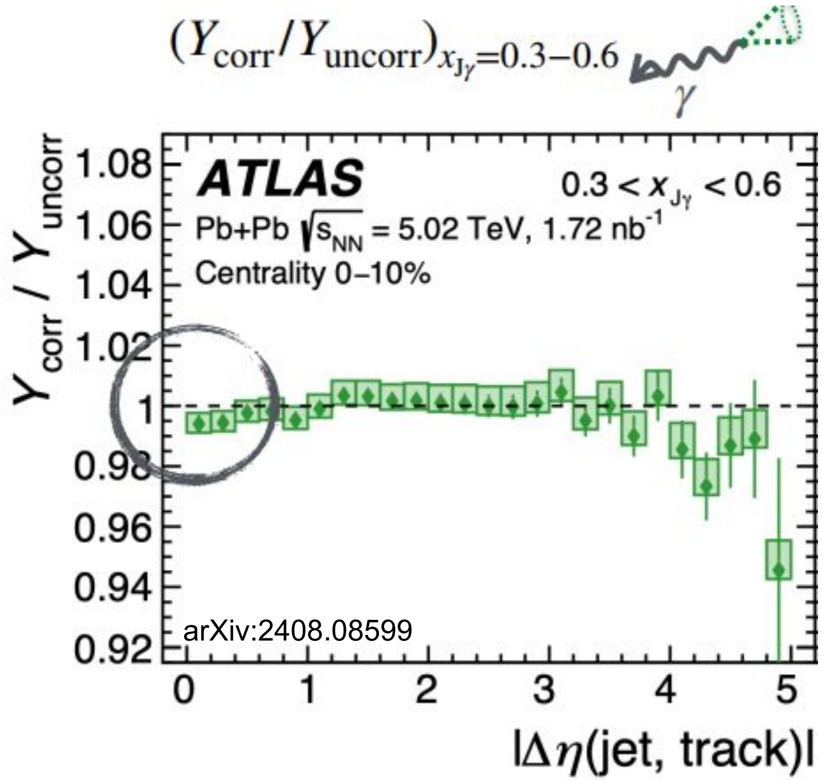
- EW bosons tag the parton kinematics and flavour.
- Way to understand medium response.
- **Wake & diffusion Wake are hot topics**

PRL 103, 152303 (2009)

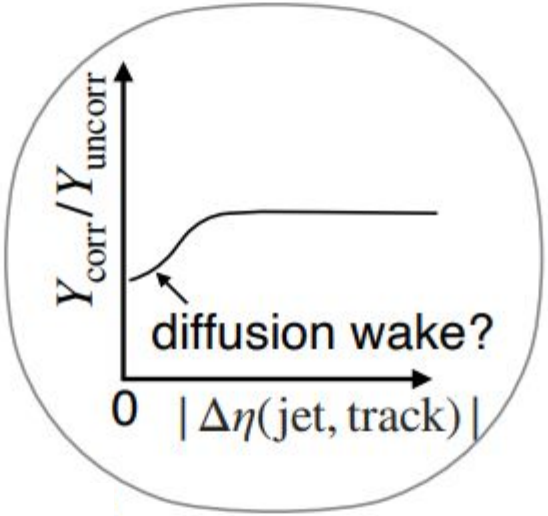




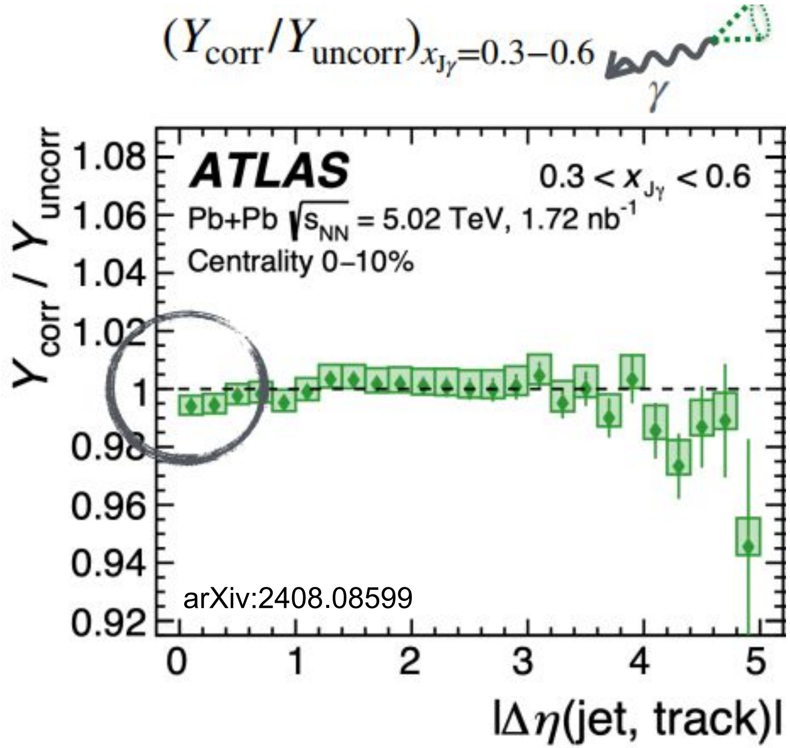
Angular scan using EW boson tagged "jets"



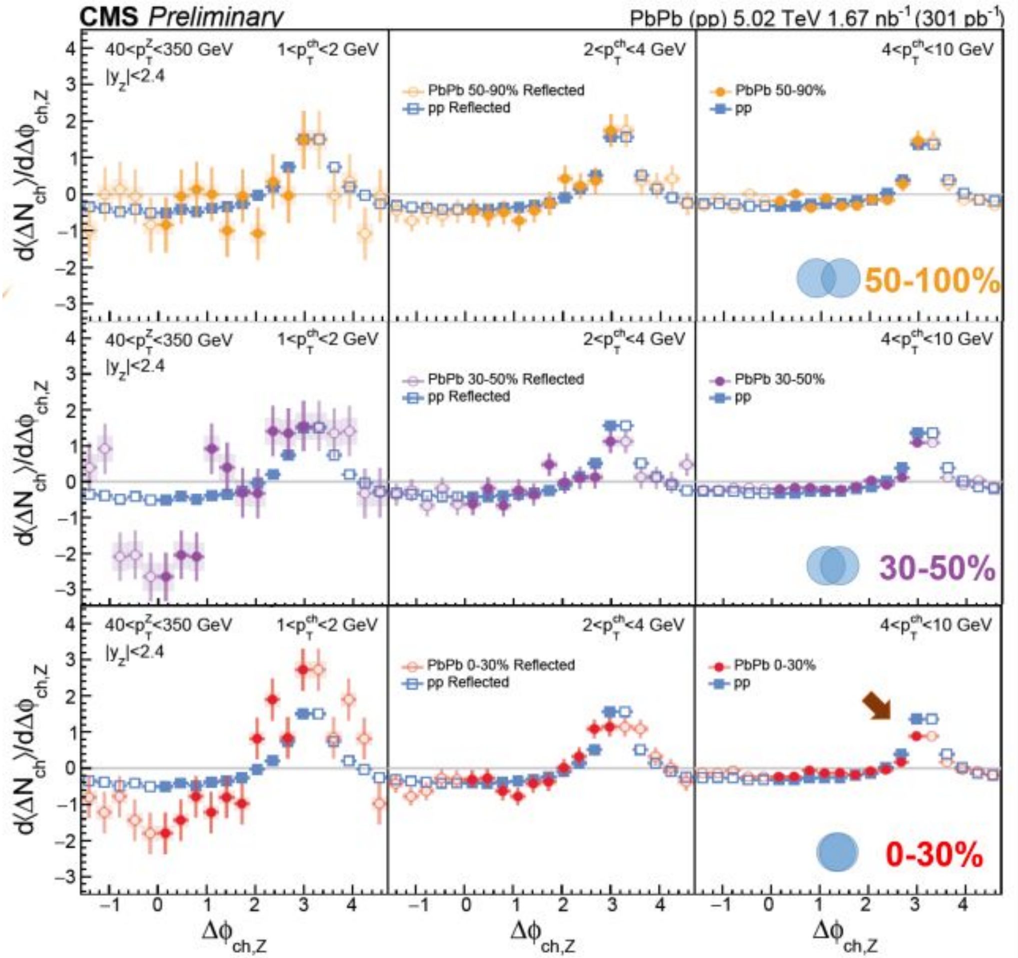
Courtesy of Yeonju Go



Angular scan using EW boson tagged "jets"



Courtesy of Yeonju Go



Where are we?

We know:

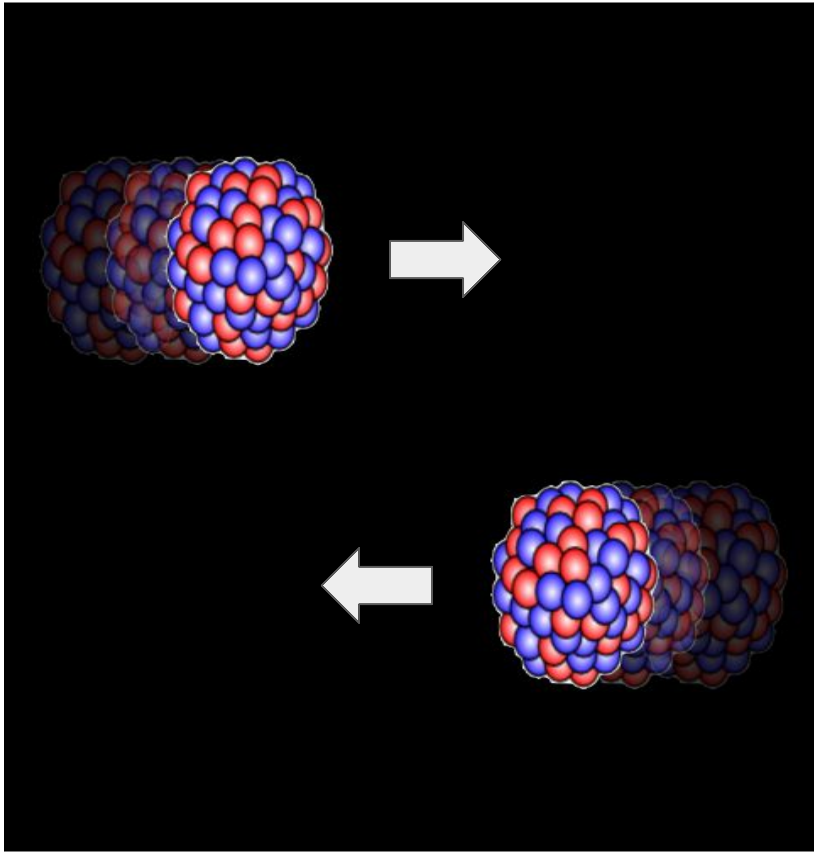
- Medium-induced gluon radiation ⇒ soft particle production at large angles.
- Energy loss: 100 GeV gluon jet ~ 15 GeV & q~2 GeV^2/fm
- Color coherence is important
- Initial parton color charge is important

We want to know:

- Quantitative understanding of color coherence phenomena and medium response
- Better understanding of space-time structure of radiative processes.
- Understand limits in applicability of certain descriptions.
- Better understand specific aspects of hadron formation.

Backup

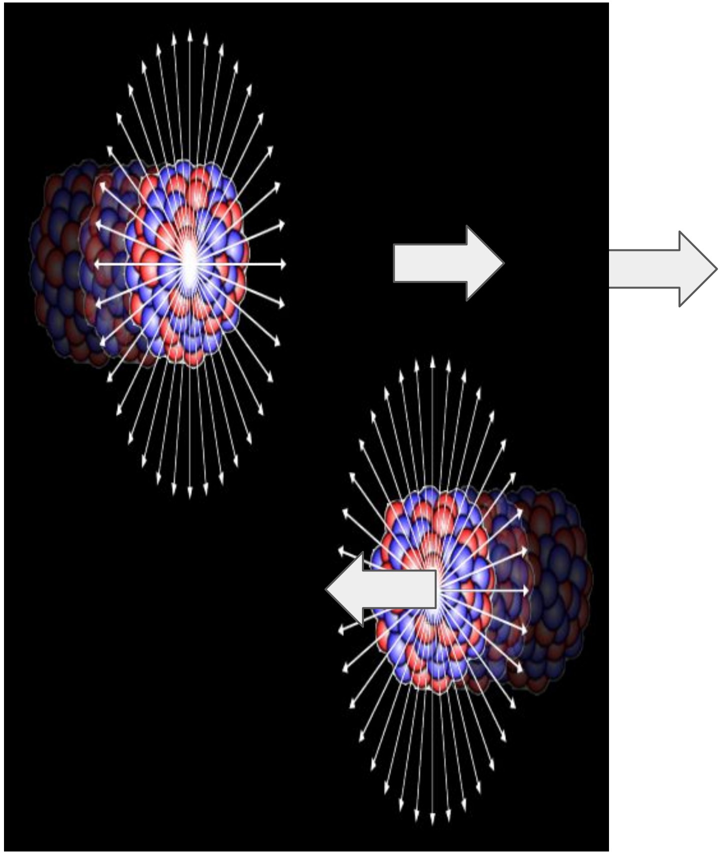
No nuclear overlap



P. Steinberg

What will happen?

Ultra peripheral collisions



P. Steinberg

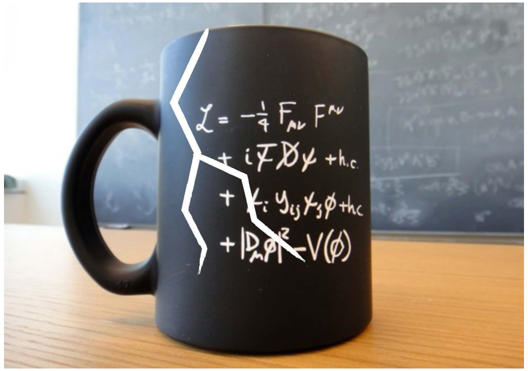
Nucleus with Z of 82 traveling at ultra relativistic speeds ⇒ lorentz contracted

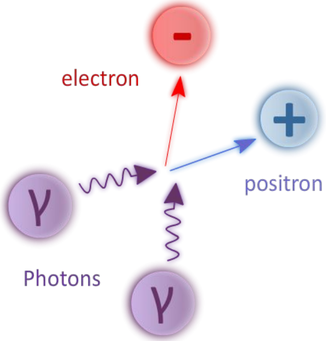
Very strong EM fields: B~O(10^{15} T)

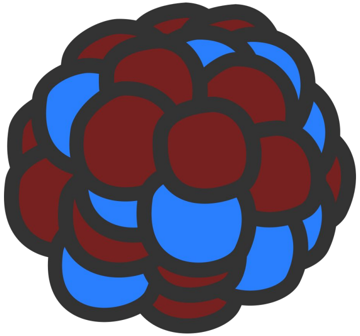
⇒ source of nearly-real high energy photons

⇒ powerful QED laboratory & precision QCD & BSM searches

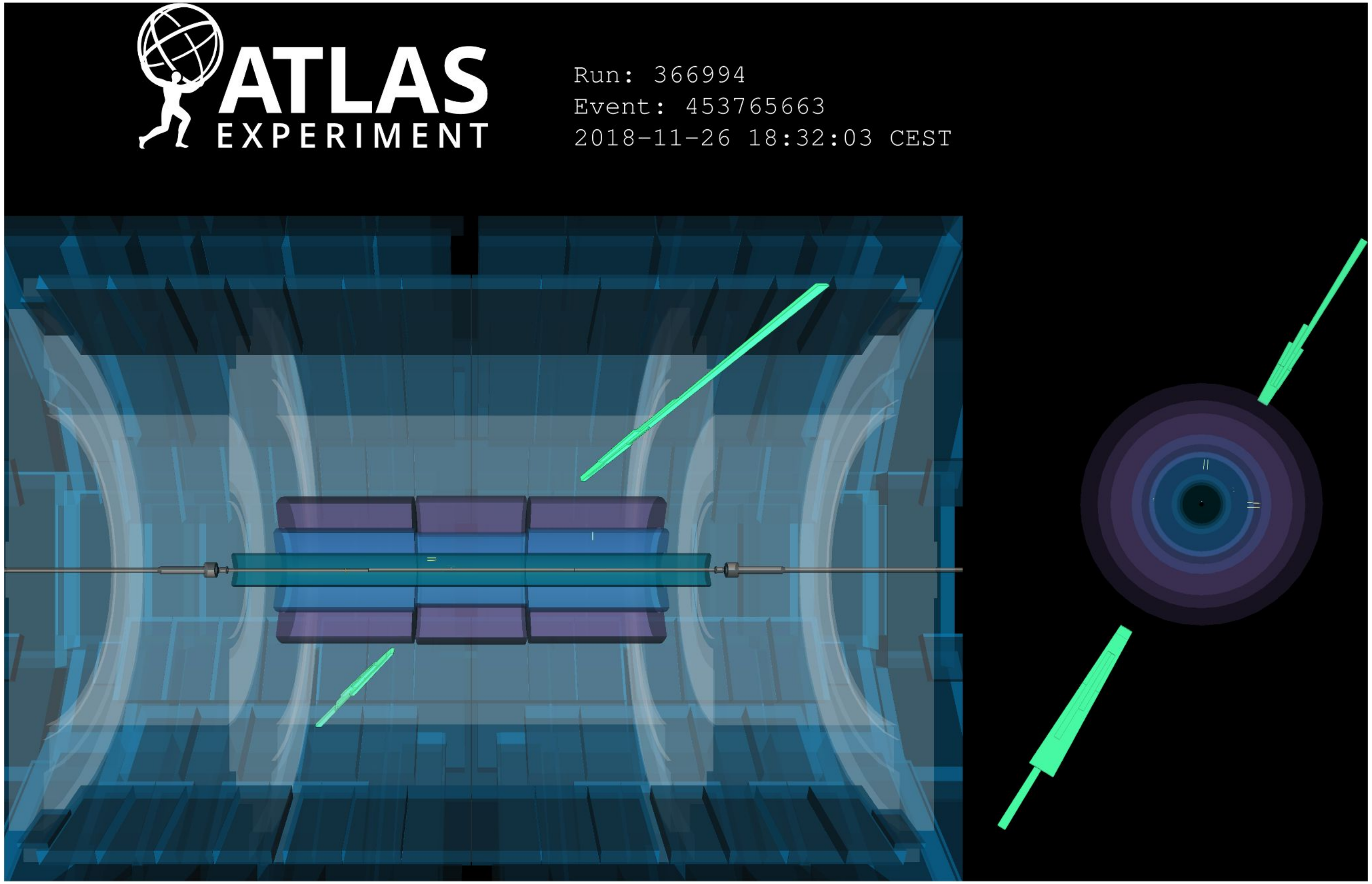
Why is scattering of light interesting?





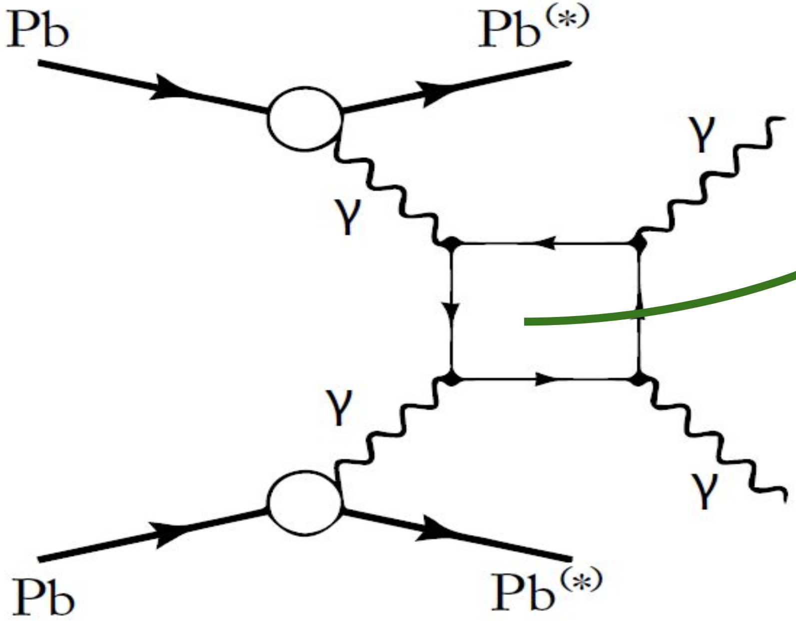


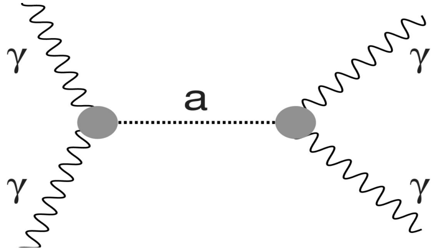
Light-by-light scattering



Light-by-light scattering

- Not allowed classically, but possible in QED
- Very rare process $O(\alpha^4)$ → not observed in laser experiments



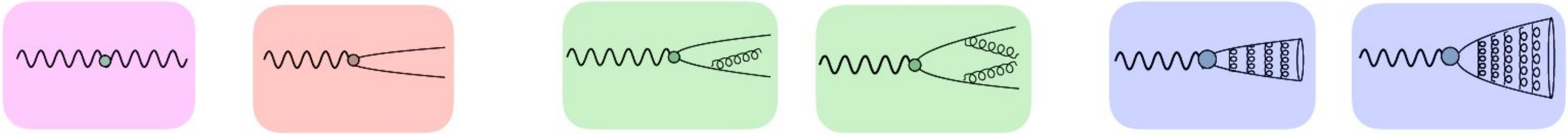


Sensitive to BSM

Imaging the nucleon and nuclei

Photon has significant hadronic component

$$|\gamma\rangle \equiv \sqrt{Z}\,|\gamma\rangle_{\rm direct} + \sum_{\ell=e,\,\mu,\,\tau} \frac{e}{f_{\ell\ell}}\,|\ell^+\ell^-\rangle + \sum_{q} \frac{e}{f_{q\bar{q}}}\,|q\bar{q}\rangle + \cdots + \sum_{V} \frac{e}{f_V}\,|V\rangle$$



Point-like photon

Dipole

Multi-parton configurations

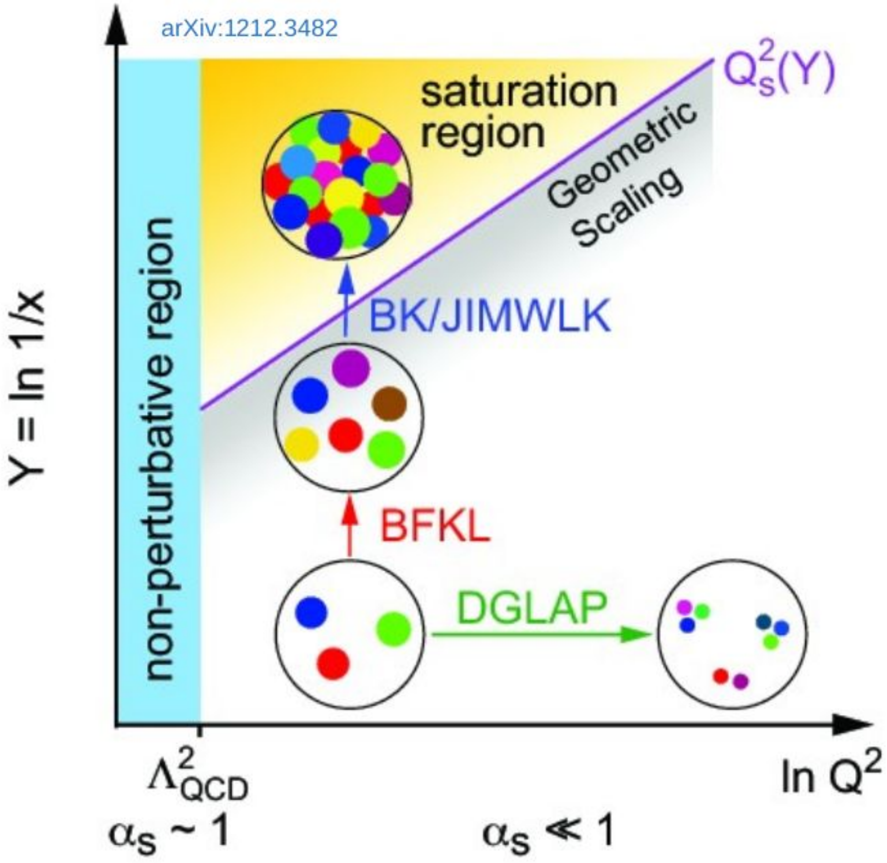
Vector mesons

Increasing size/interaction strength →

Courtesy of A. Angerami

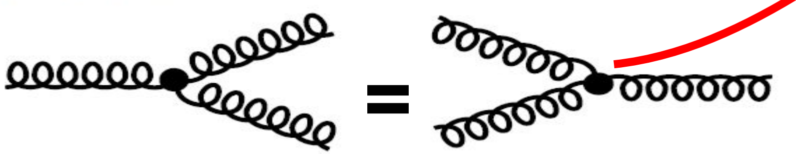
Imaging the nucleon and nuclei

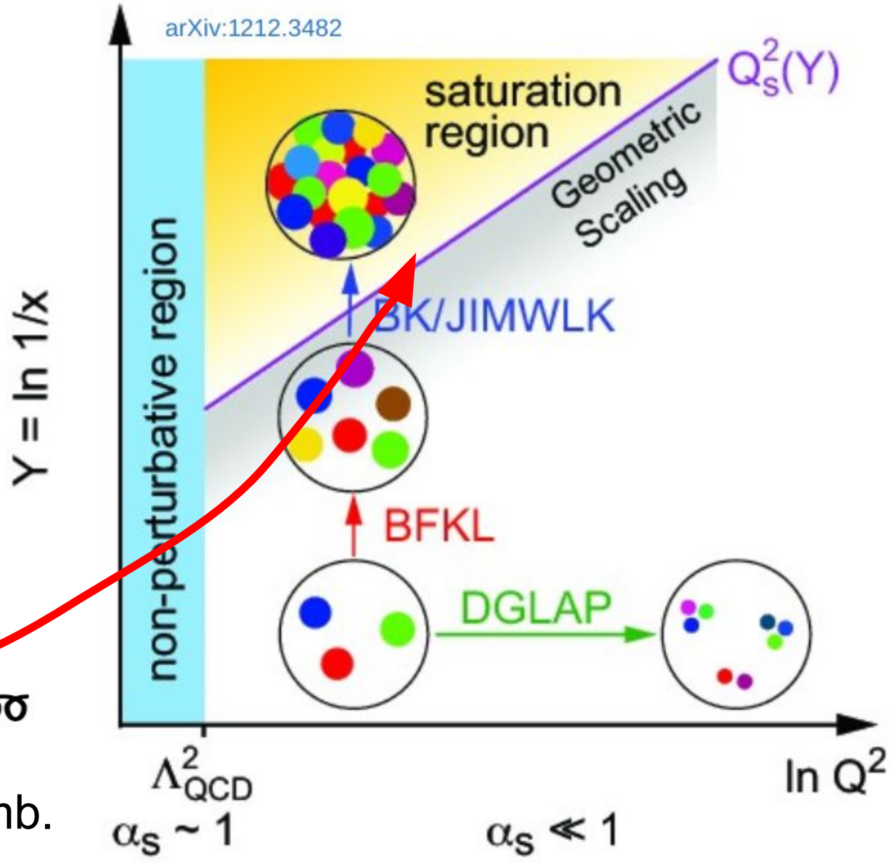
- What is the size of modification of the PDF for nucleons inside nuclei?



Imaging the nucleon and nuclei

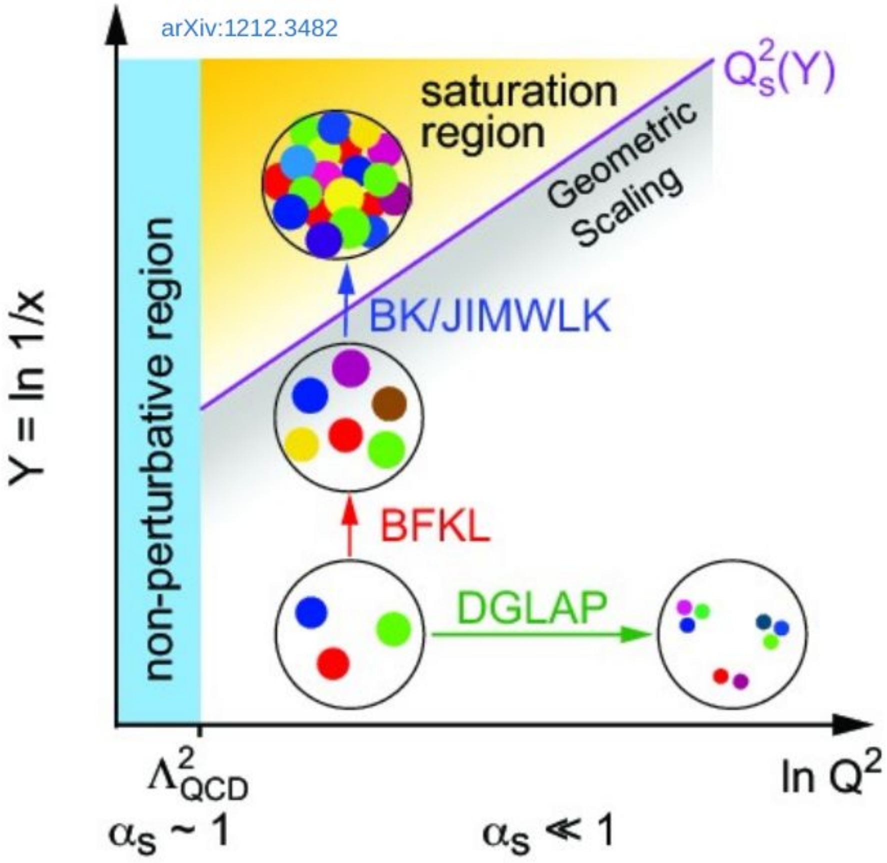
- What is the size of modification of the PDF for nucleons inside nuclei?
- Can we see onset of gluon saturation or non-linear QCD effects?





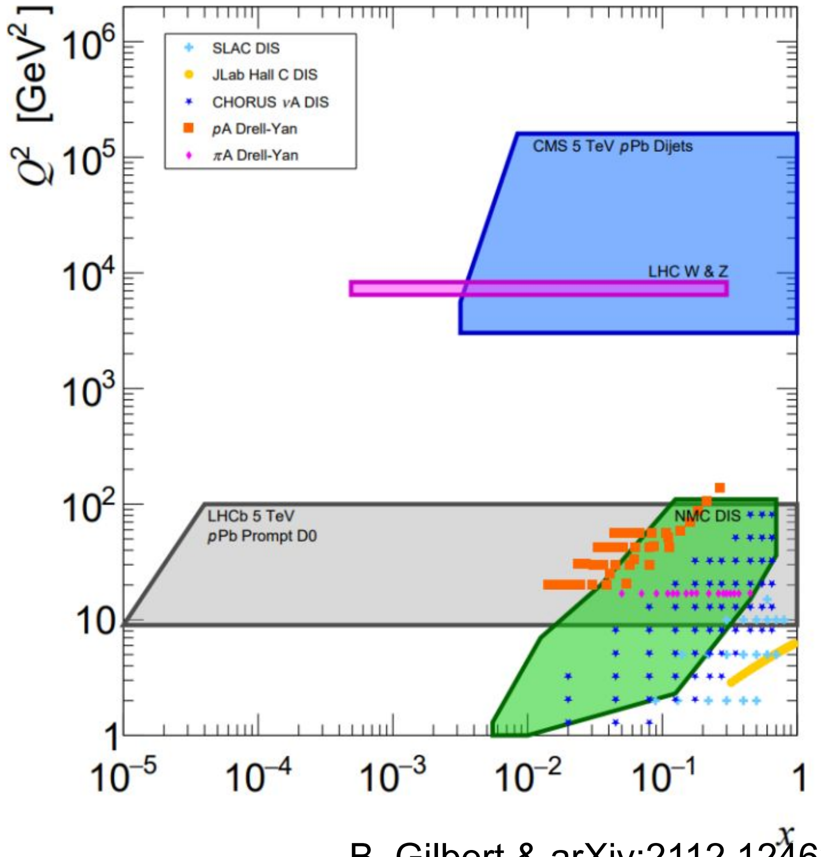
Imaging the nucleon and nuclei

- Can we see onset of gluon saturation or non-linear QCD effects?
- What is the size of modification of the PDF for nucleons inside nuclei?
- **Pb+p ⇒ γ+p interactions**



Photonuclear Jet Production

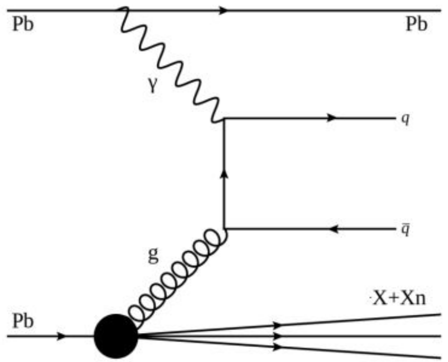
- Significant gaps in our knowledge of nuclear PDFs.

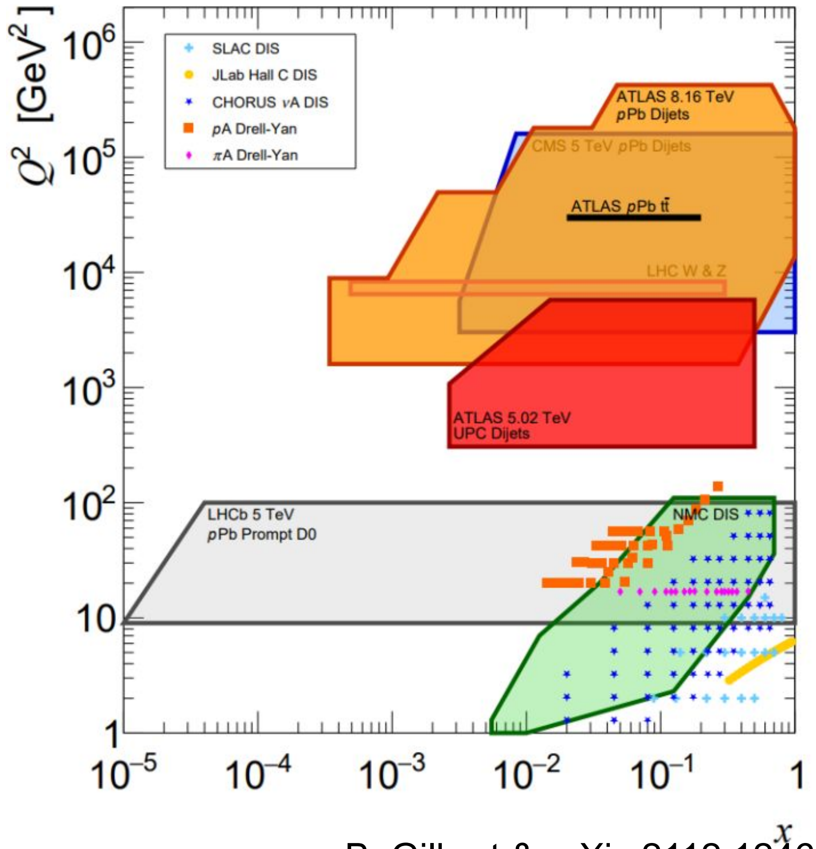


B. Gilbert & arXiv:2112.12462

Photonuclear Jet Production

- Significant gaps in our knowledge of nuclear PDFs.
- Three recent ATLAS measurements will help to fill the gap.
- Dijets and ttbar in p+Pb and in dijets in UPC.





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Photonuclear Jet Production

- Significant gaps in our knowledge of nuclear PDFs.
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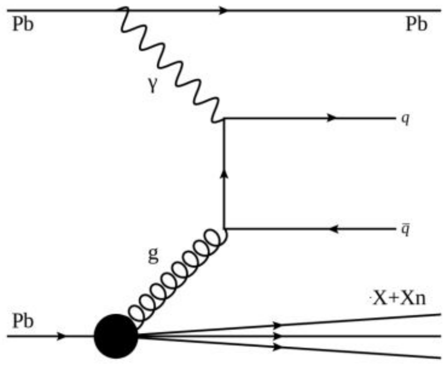
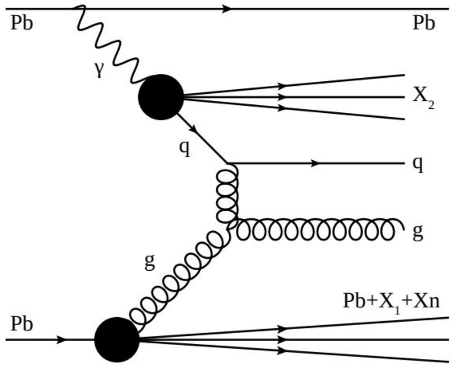
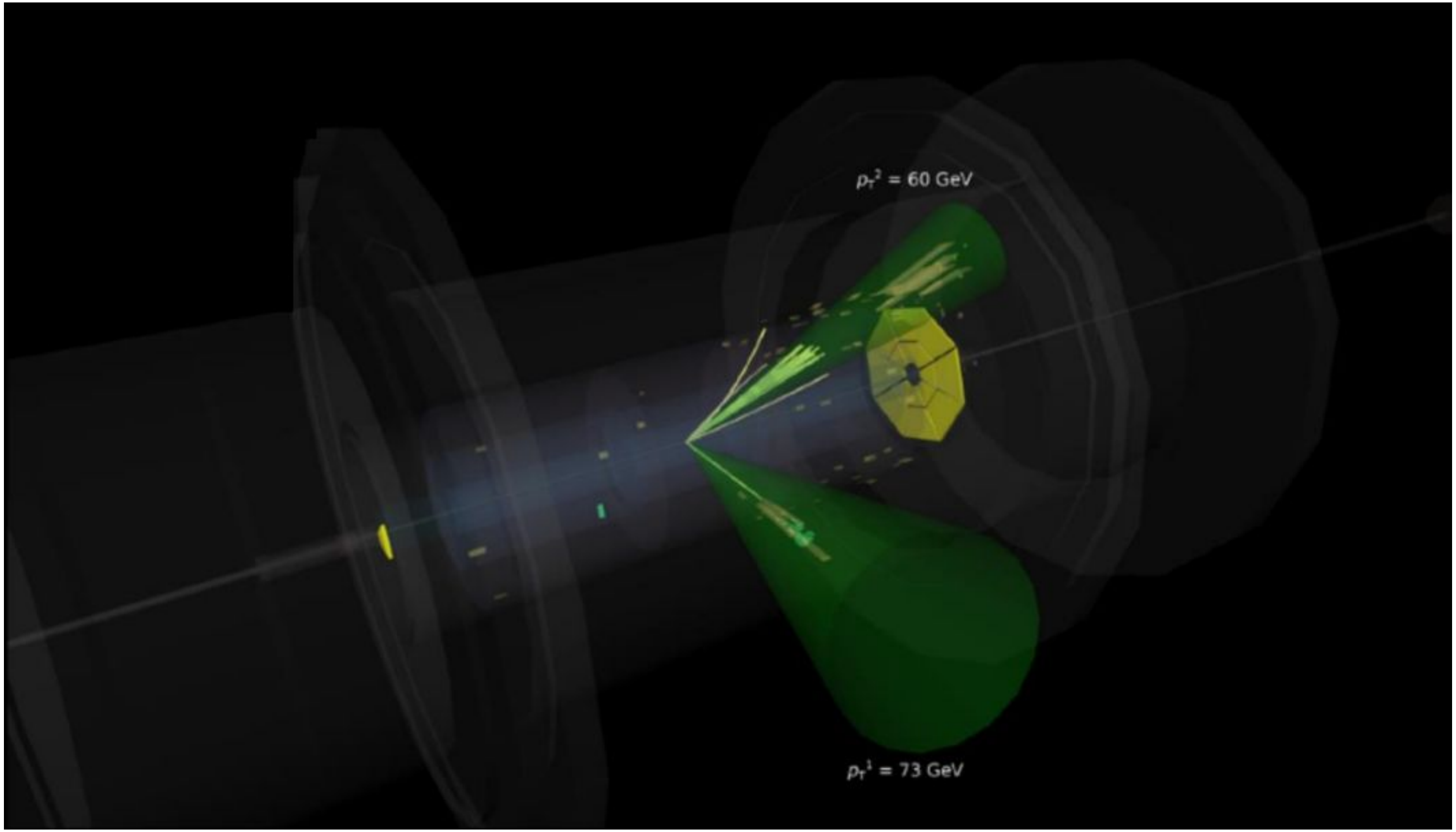
- Dijets and ttbar in p+Pb and in dijets in UPC.

Photon fluctuates into a hadronic state ⇒ "Resolved" contribution





Photonuclear Jet Production



Photonuclear Jet Production

Proxy for Q^2

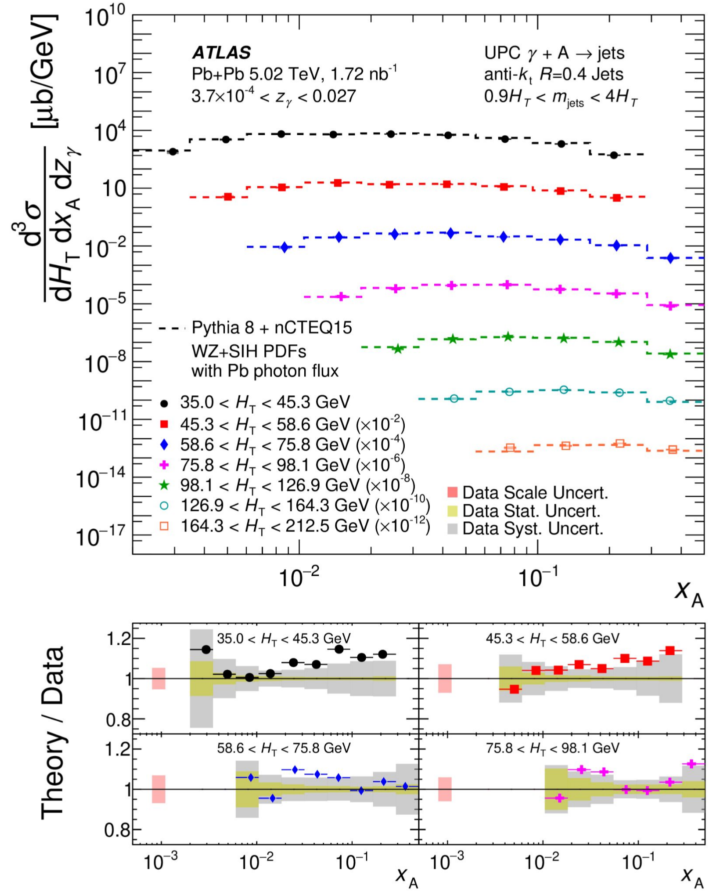
$$\boxed{H_T = \sum_i p_T^i}$$

$$\boxed{z_\gamma = \frac{M_{jets} e^{+y_{jets}}}{\sqrt{s_{NN}}}}$$

$$\boxed{x_A = \frac{M_{jets} e^{-y_{jets}}}{\sqrt{s_{NN}}}}$$

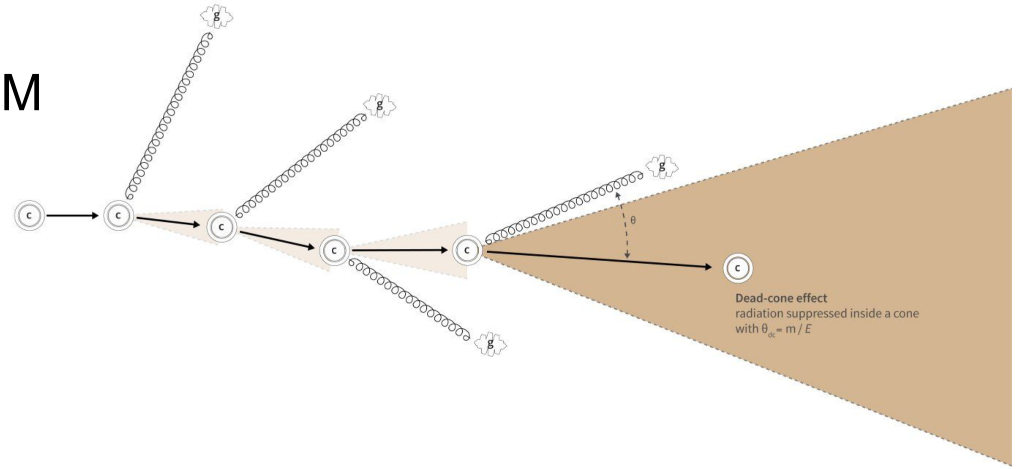
~photon energy fraction

~target energy fraction



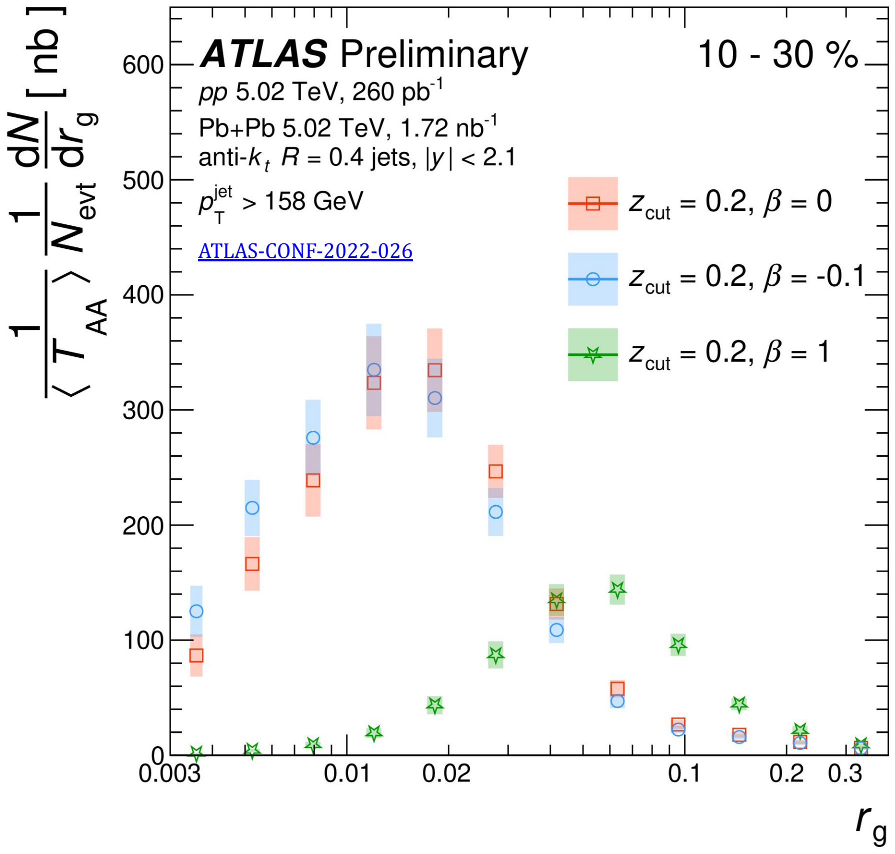
Photonuclear Jet Production: Prospects

- Large systematic uncertainties ⇔ not competitive
  ⇒ work on significant improvements
- Almost pure quark jet sample
  - Allow for precision measurement of jet structure
- Flavour tagging
  - Heavy flavour jets will help to constrain nPDFs
  - Study of dead cone effect
  - Cross-section sensitive to BSM



Challenges in jet structure measurements

- **Push towards larger phase space: lower energy and various/larger radius.**
- Large UE contribution from soft particles.
- Combinatorial background from independent hard scatterings.
- For calorimetric measurement:
  - Jet energy calibration and uncertainties for every new jet “collection”.... different radius, subjects, and constituents.
- Role of ISR@FSR
- Choice of setting in grooming…
  - Sensitive to modeling and subtraction.
  - Need to understand biases we introduce.

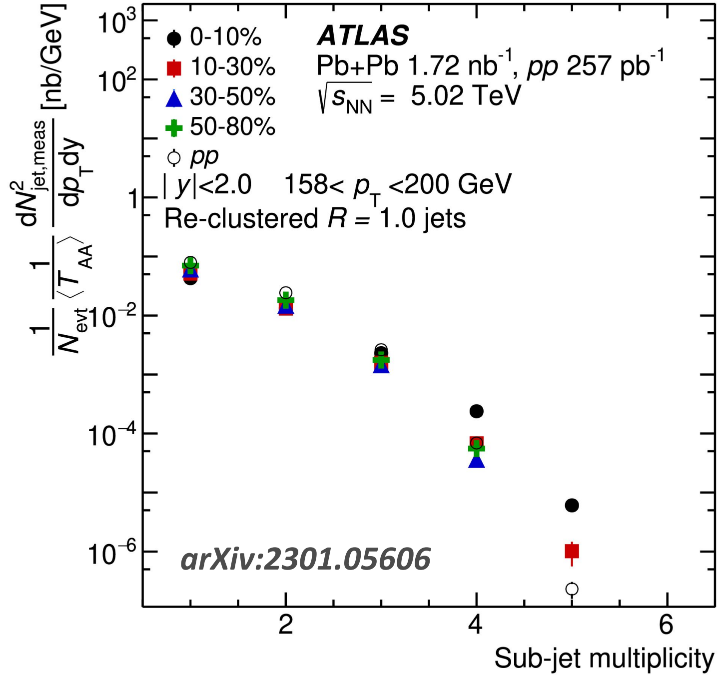


Observables and analysis procedure

- Measurement of yields of re-clustered R=1.0 jets as function of p_T, angular separation, and k_t splitting scale:

$$\Delta R_{12} = \sqrt{\Delta y_{12}^2 + \Delta\phi_{12}^2},\ \sqrt{d_{12}} = \min(p_{T1}, p_{T2}) \times \Delta R_{12}$$

- Jet suppression is evaluated using modification factor R_{AA}.



Raw sub-jet multiplicity

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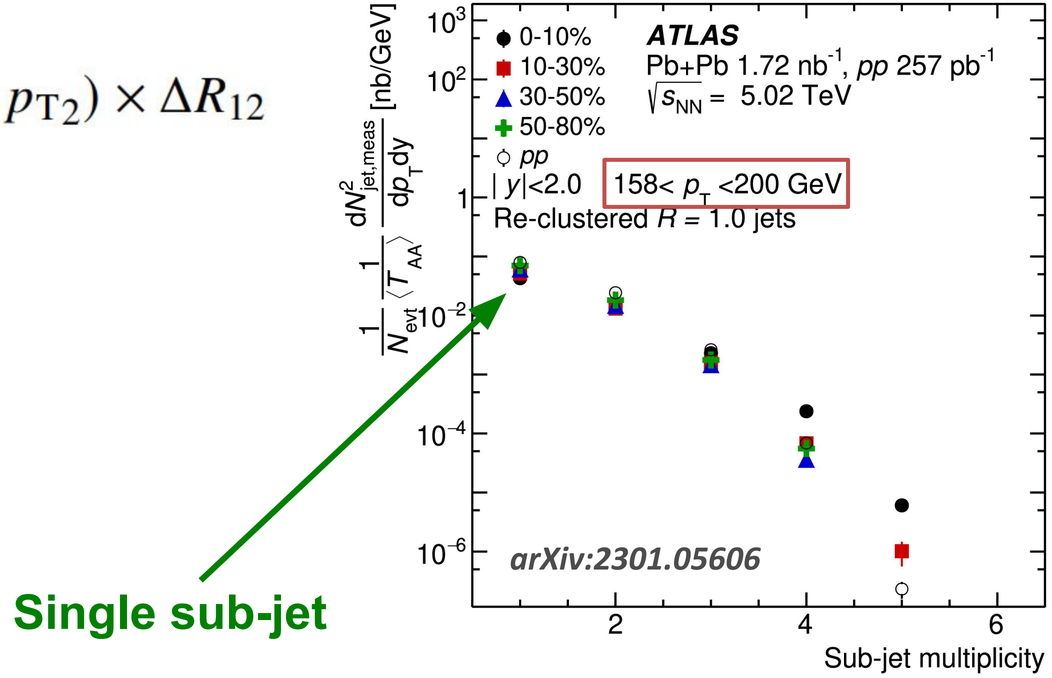

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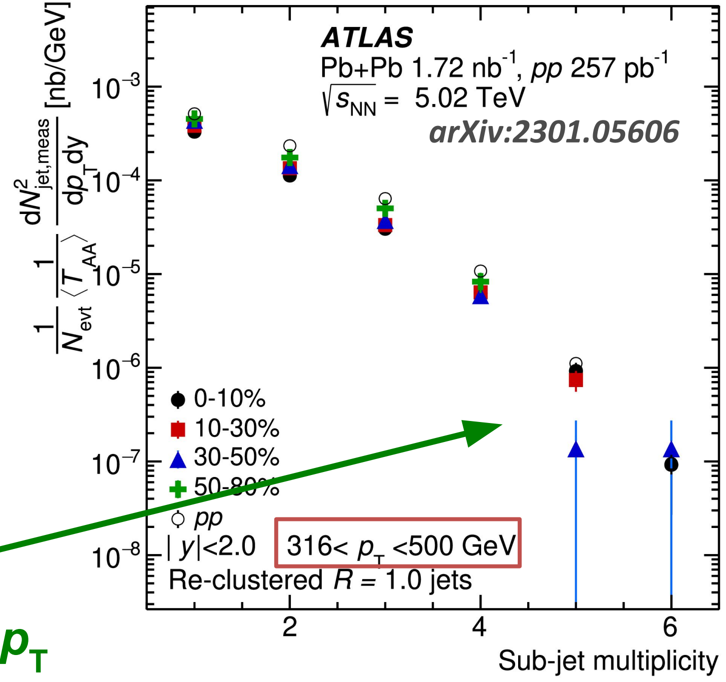
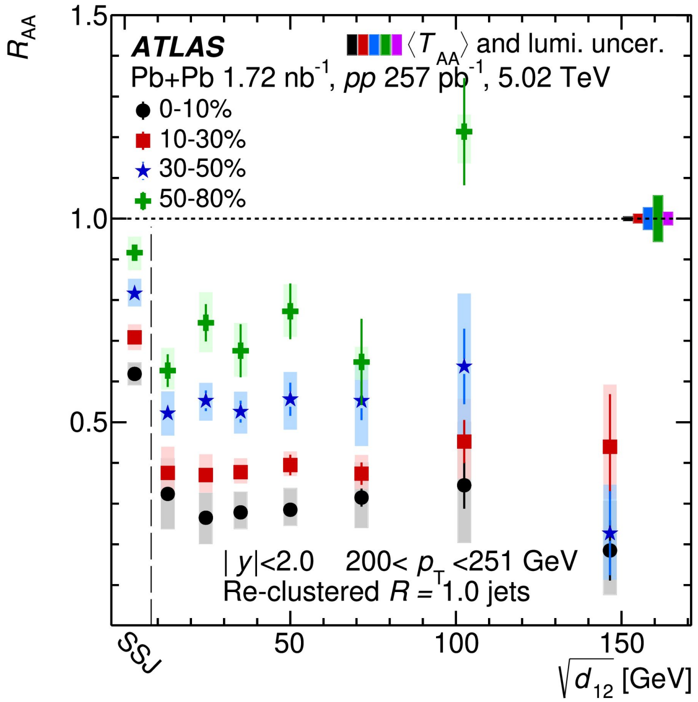


Increasing multiplicity with p_T

Raw sub-jet multiplicity

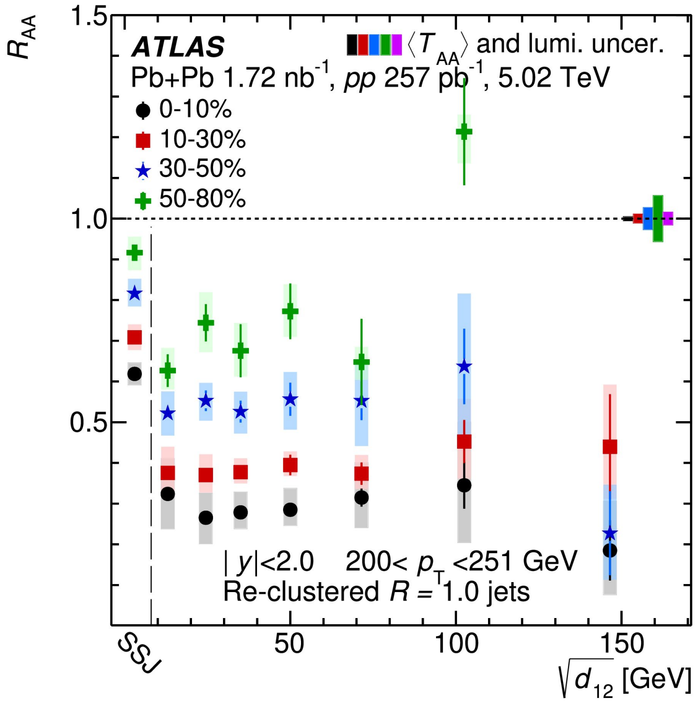
Re-clustered jets vs substructure

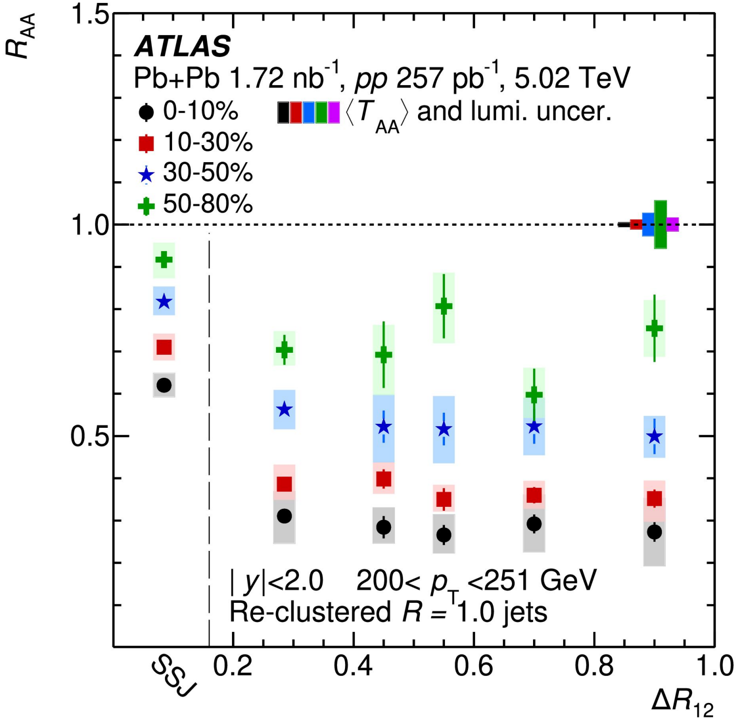


- Significant change of the R_{AA} magnitude between jets with single sub-jet and and those with more complex substructure.
- The R_{AA} sharply decreases followed by flattening.

arXiv:2301.05606

Re-clustered jets vs substructure





- The R_{AA} sharply decreases followed by flattening.
- Similar observation for suppression as function of angular separation.

arXiv:2301.05606

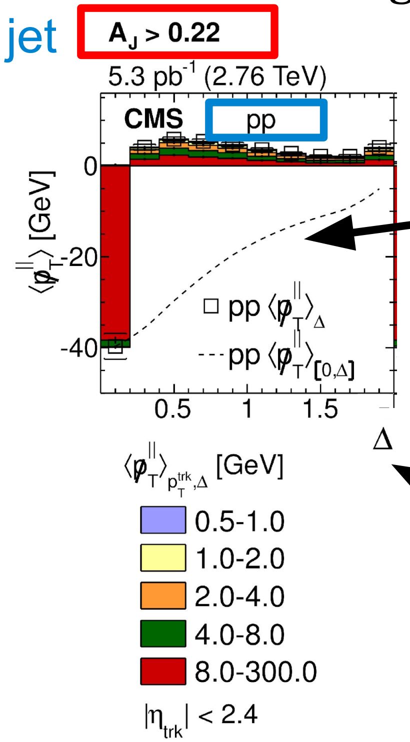
Where does the energy flows?

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

Subleading jet direction

Missing p_T projection

Leading jet direction



Cumulative energy

Angular distance from jet axis

JHEP 01 (2016) 006

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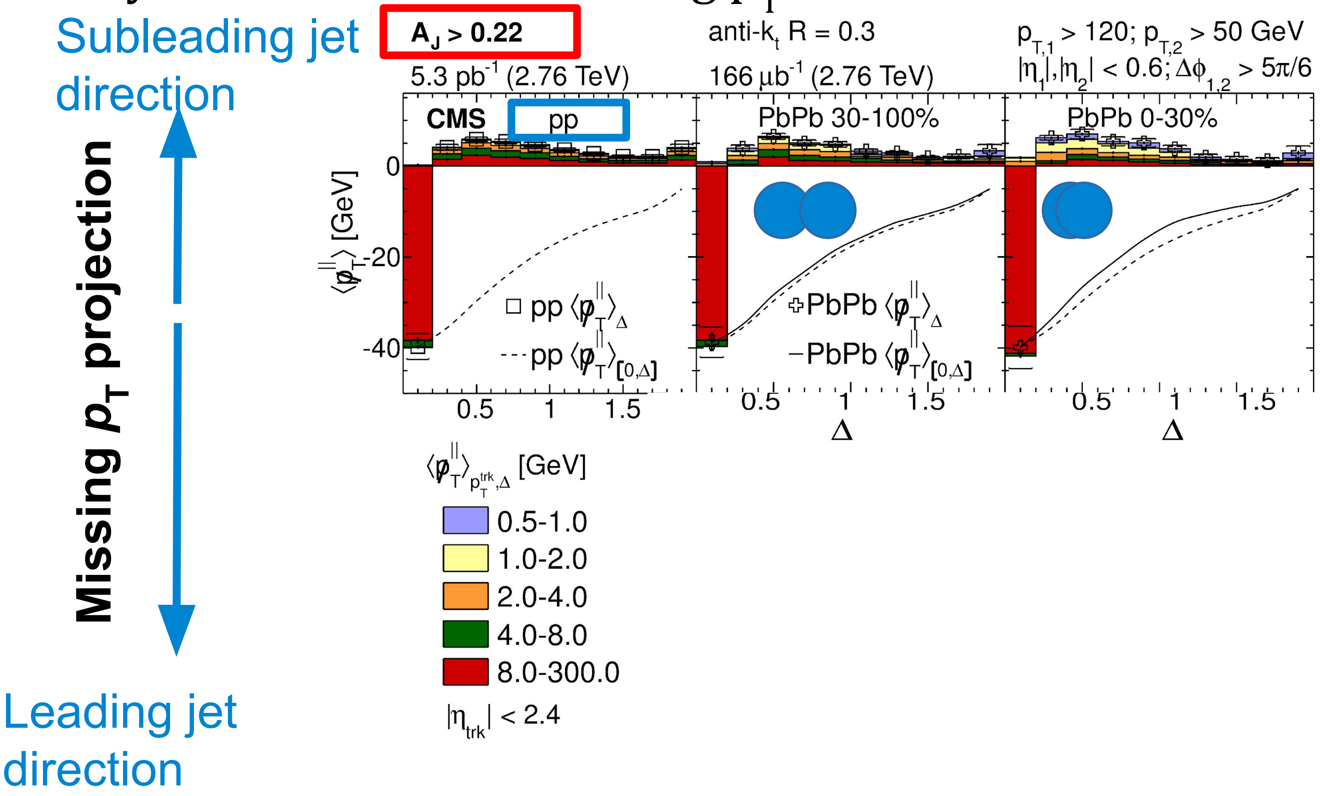
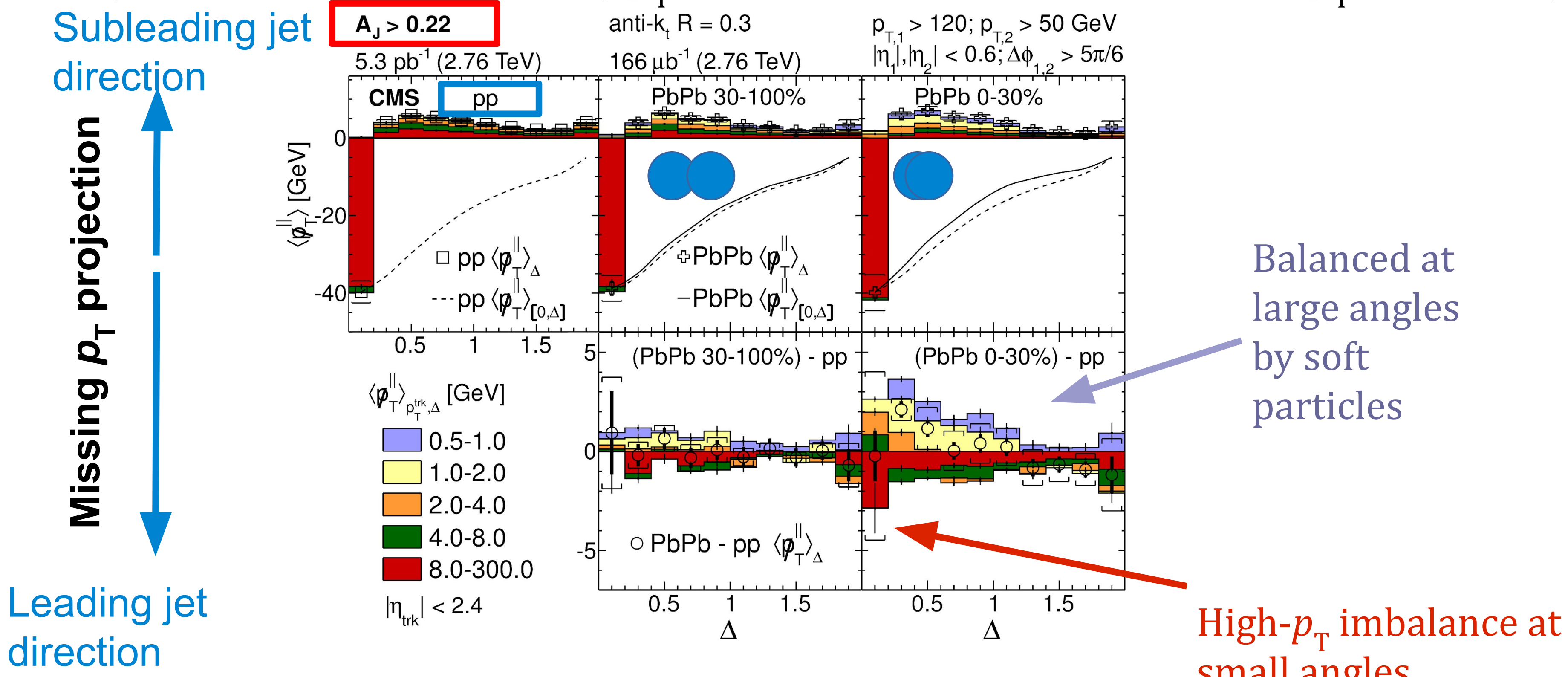
- Study of correlation of missing p_T evaluated with tracks in various p_T bins with jets.



JHEP 01 (2016) 006

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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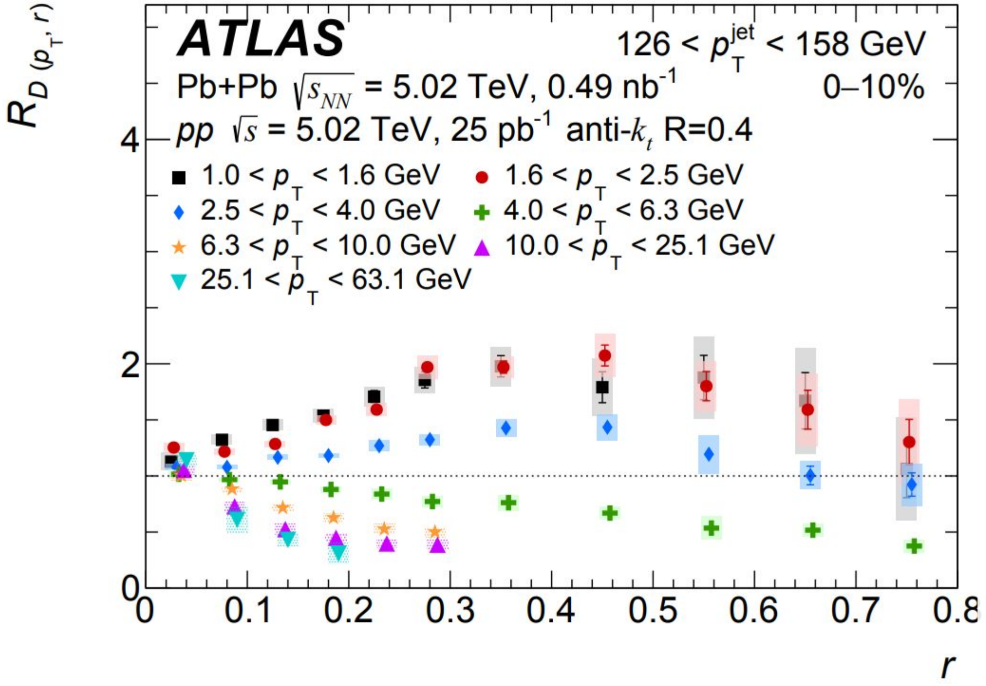
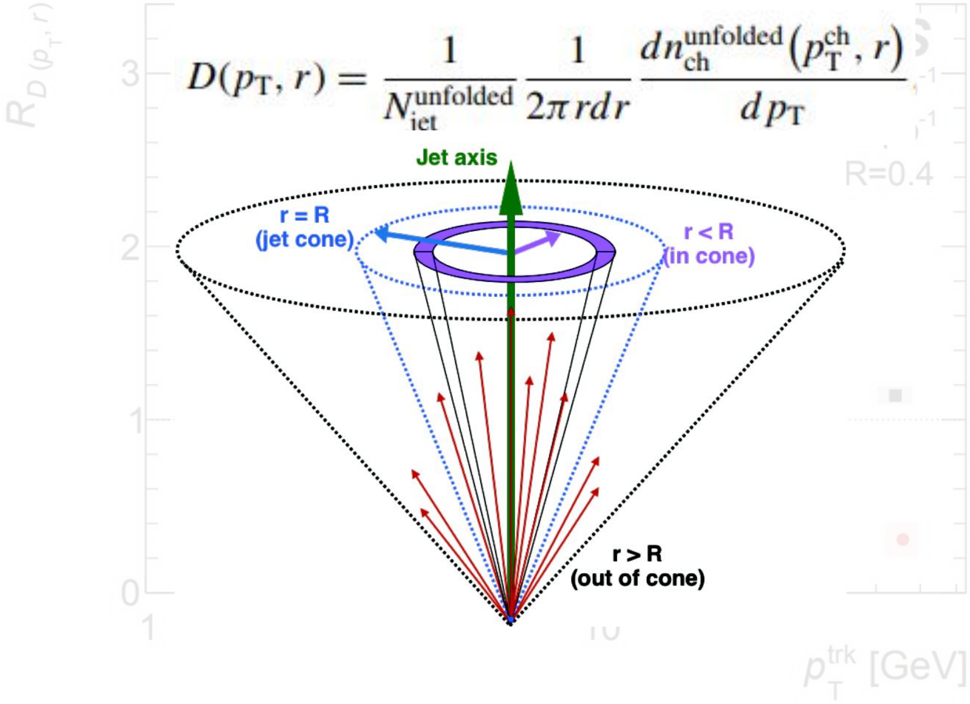
Modification of Radial Profile

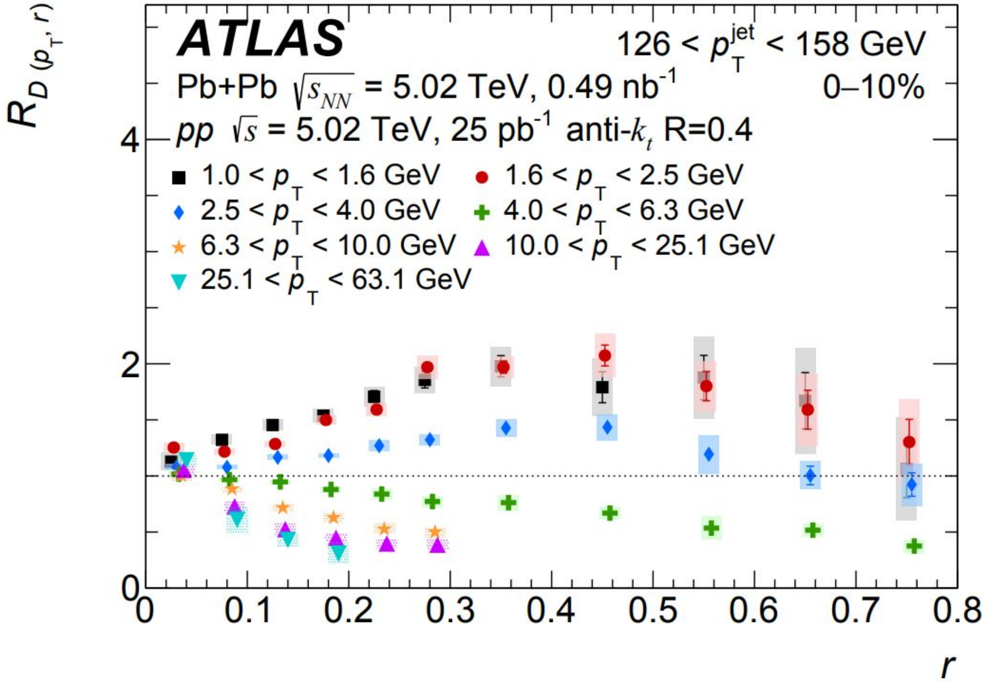


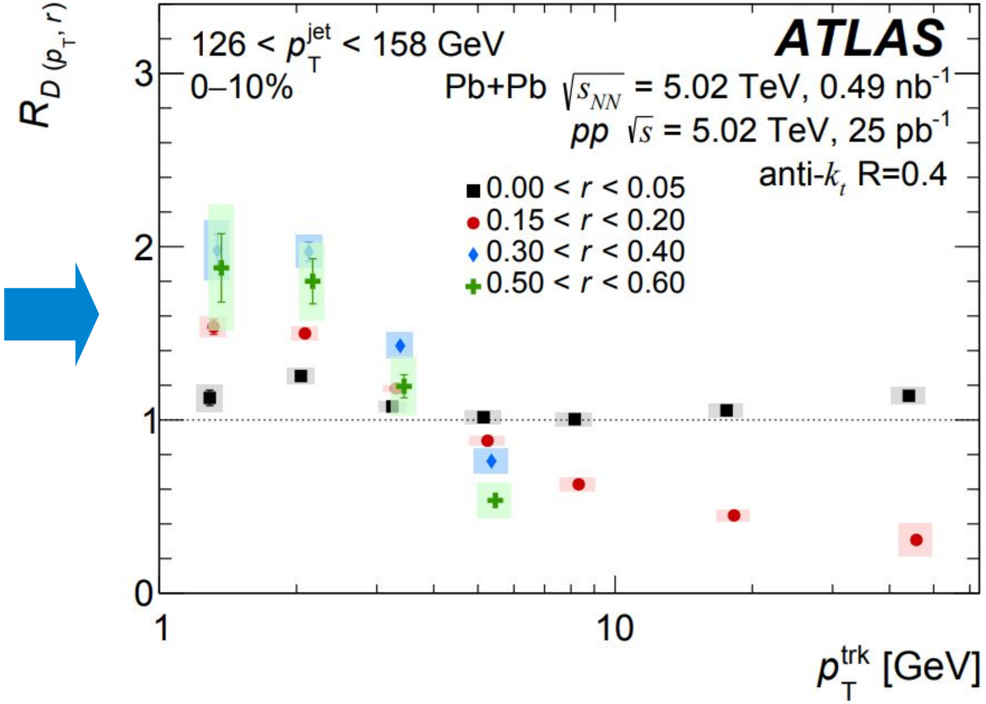


- Jets are broader in more central collisions at low p_T.
- Significant suppression of yields of particles p_T > 4 GeV outside the jet core.

arXiv:1908.05264

Modification of Radial Profile

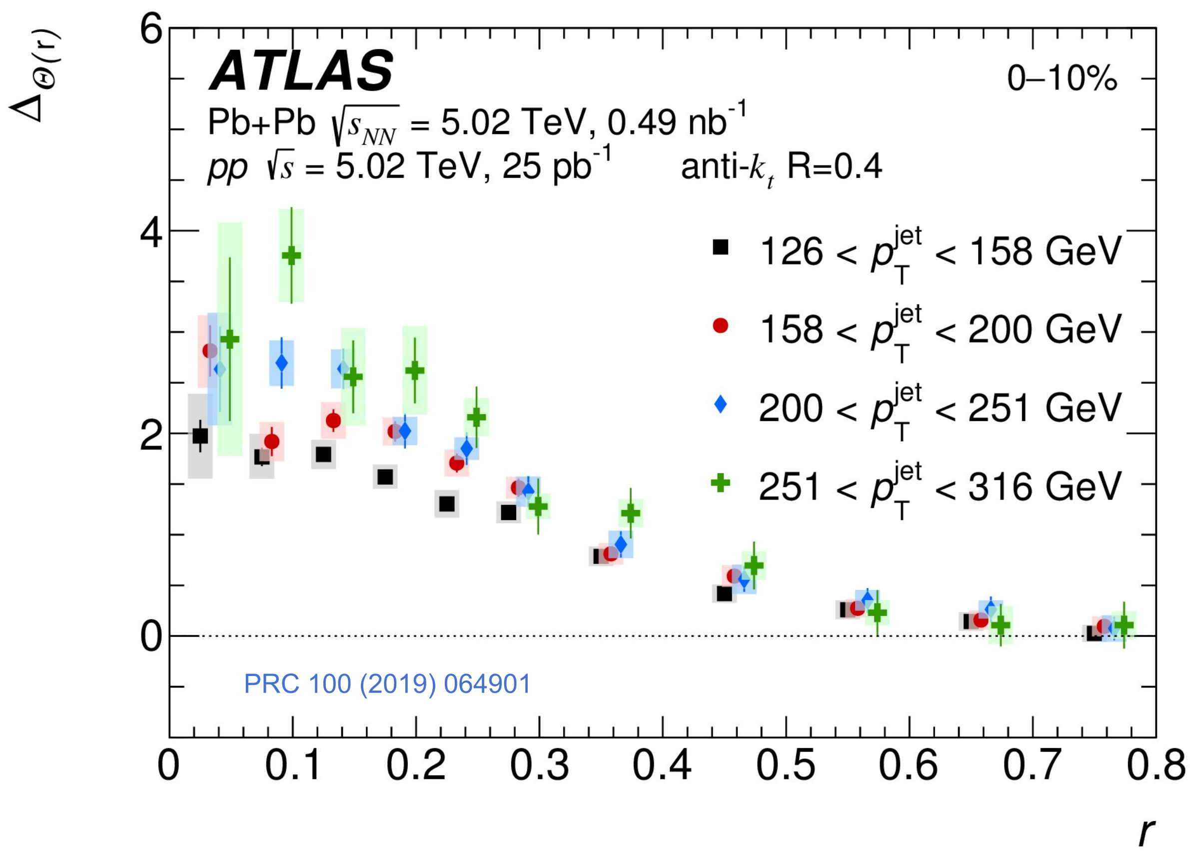




- Smallest modification seen in the jet core.
- The enhancement increases with decreasing p_T.

arXiv:1908.05264

Radial profile



$$\Theta(r) = \int_{1\ \text{GeV}}^{4\ \text{GeV}} D(p_T, r)dp_T$$

$$\Delta_{\Theta(r)} = \Theta(r)_{\text{Pb+Pb}} - \Theta(r)_{pp}$$

The absolute difference (#low p_T particles) is the highest inside the jet.

Can we see medium response in the jet p_T dependence?

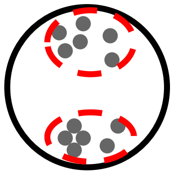
Full picture: small & large jets

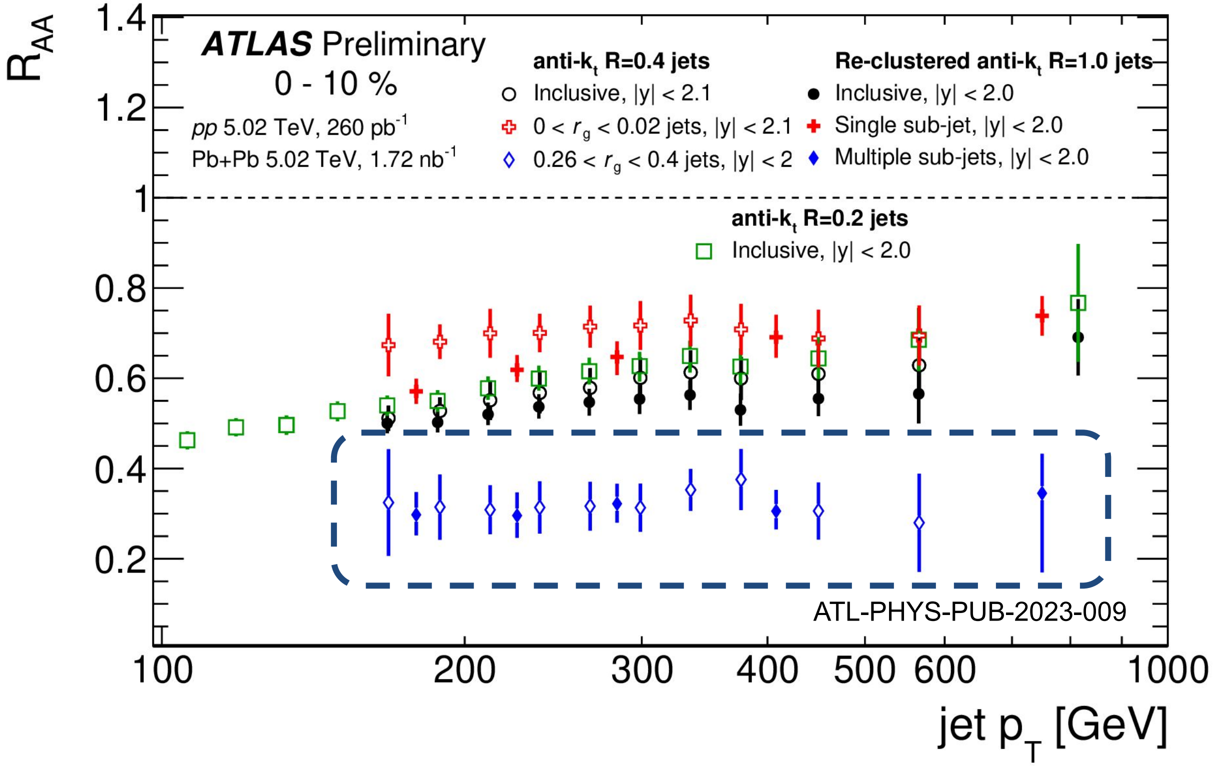
- Addressing transition from color-coherence to decoherence…

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

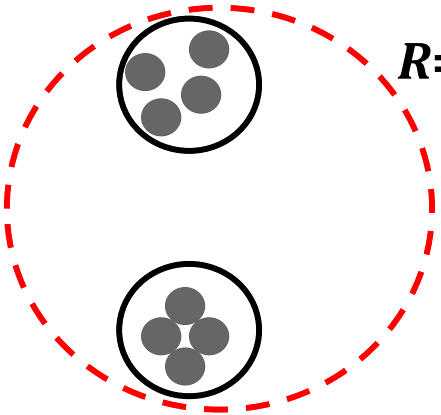
r_g

***R*=0.4**





***R*=1.0**

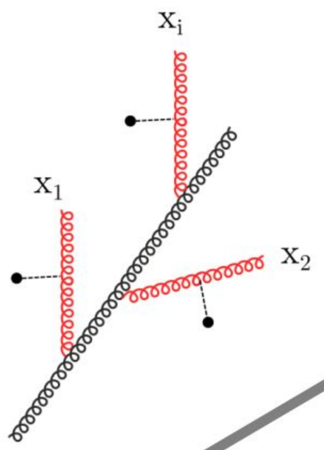


Example of description

Splitting rate

$$\mathcal{K}(z,\tau) \equiv \frac{\mathrm{d}I}{\mathrm{d}z\,\mathrm{d}\tau}$$

Gluon emission spectra



Evolution equation

$$\frac{\partial D(x,\tau)}{\partial \tau} = \int_0^1 \mathrm{d}z\, \mathcal{K}(z,\tau) \left[\sqrt{\frac{z}{x}} D\left(\frac{x}{z},\tau\right) \Theta(z-x) - \frac{z}{\sqrt{x}} D(x,\tau) \right]$$

$$\frac{\mathrm{d}\sigma_{\mathrm{AA}}}{\mathrm{d}p_T} = \int_0^\infty \mathrm{d}p'_T \int_0^1 \mathrm{d}x\, \delta(p_T - x p'_T) D\left(x, \tau \equiv \sqrt{\hat{q}_0/p'_T}\, L\right) \frac{\mathrm{d}\sigma_0}{\mathrm{d}p'_T}$$

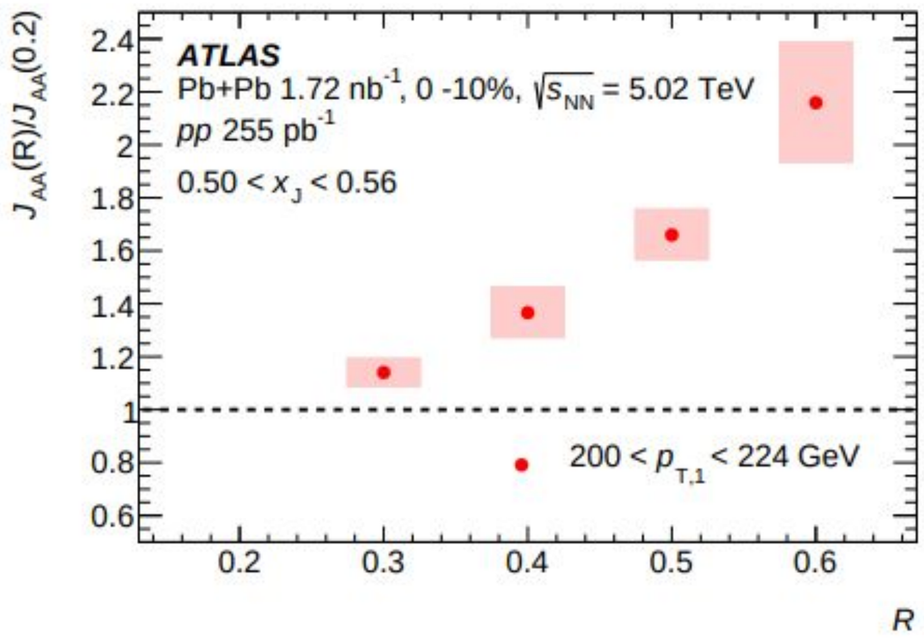
$$Q_{\mathrm{AA}}(p_T) = \int_0^1 \mathrm{d}x\, x^{n-1} D(x, \sqrt{x}\tau)$$

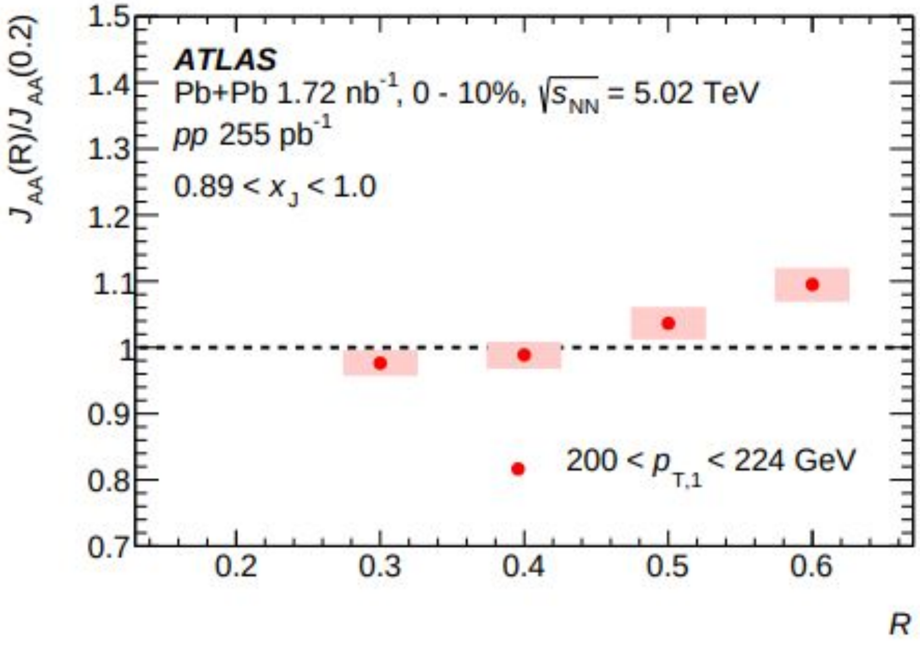
Suppression factor of jets

Courtesy of Martin S.

R-dependence of dijet imbalance

$$J_{\mathrm{AA}} \equiv \frac{1}{\langle T_{\mathrm{AA}}\rangle N_{\mathrm{evt}}^{\mathrm{AA}}} \frac{\mathrm{d}N_{\mathrm{pair}}^{\mathrm{AA}}}{\mathrm{d}x_{\mathrm{J}}} \Bigg/ \left(\frac{1}{L_{pp}} \frac{\mathrm{d}N_{\mathrm{pair}}^{pp}}{\mathrm{d}x_{\mathrm{J}}}\right)$$





- R-dependent suppression only seen mainly for low-x_J values.

arXiv:2407.18796