Jet fragmentation and radial distribution of charged particles within and around jets in Pb+Pb collisions with ATLAS

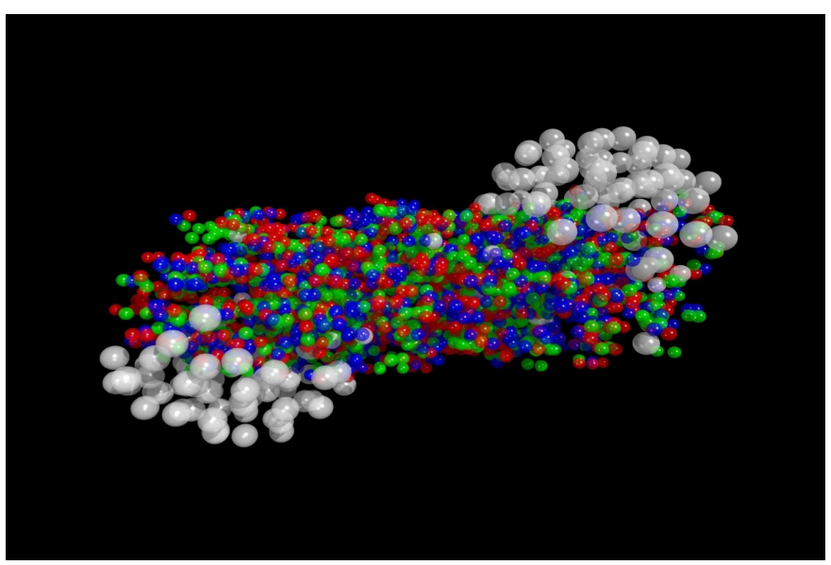
Akshat Puri
for the ATLAS Collaboration

October 25, 2018

Overview

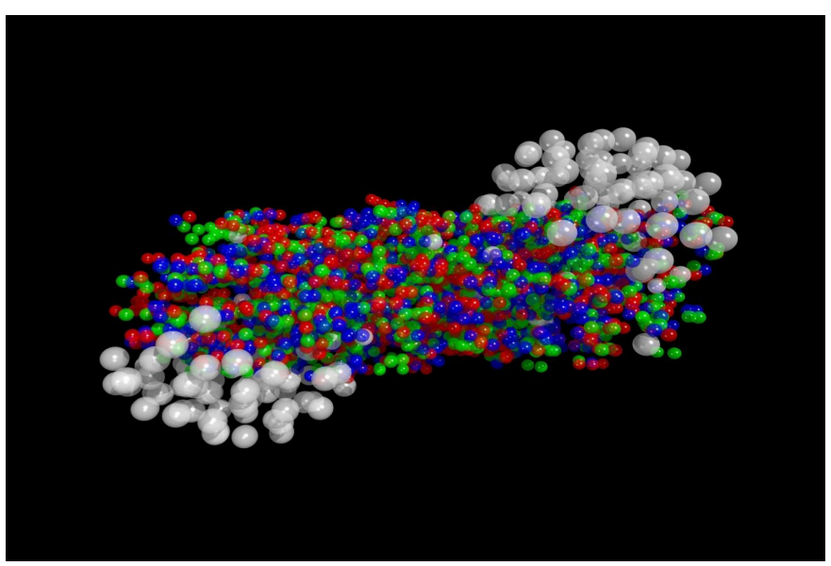
Overview

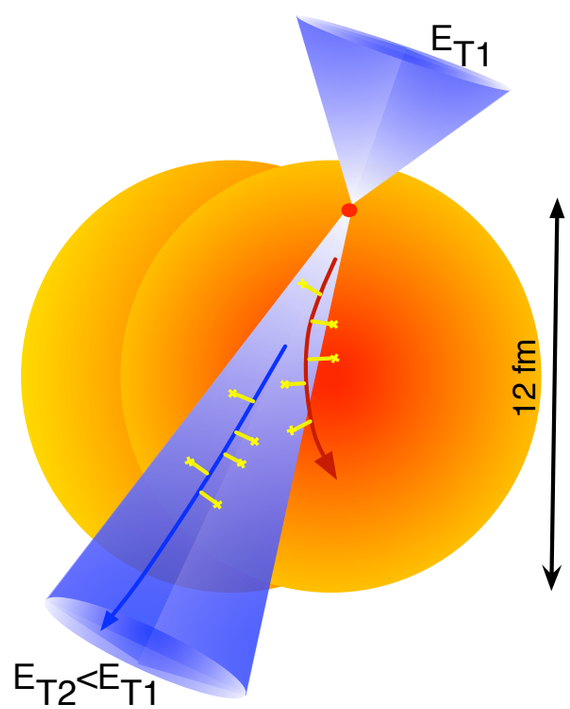
- The Quark Gluon Plasma



Overview

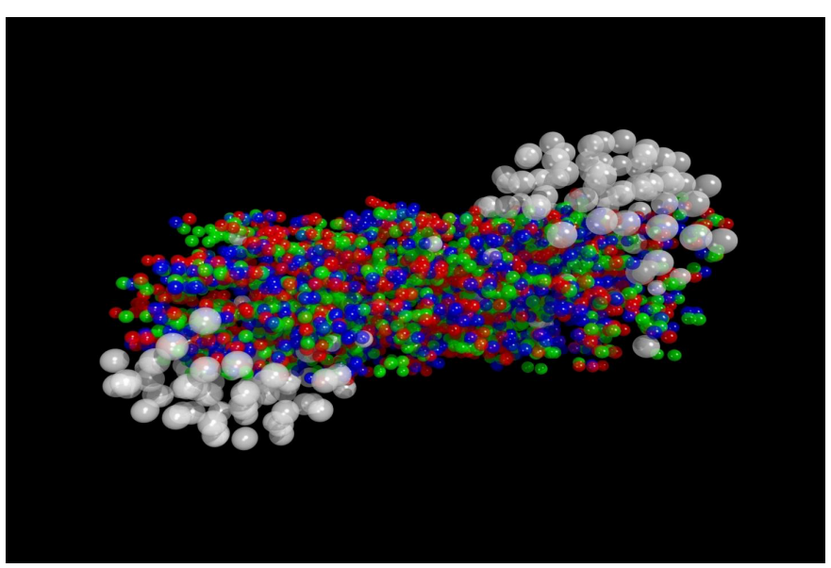
- The Quark Gluon Plasma
- Jets and jet energy loss

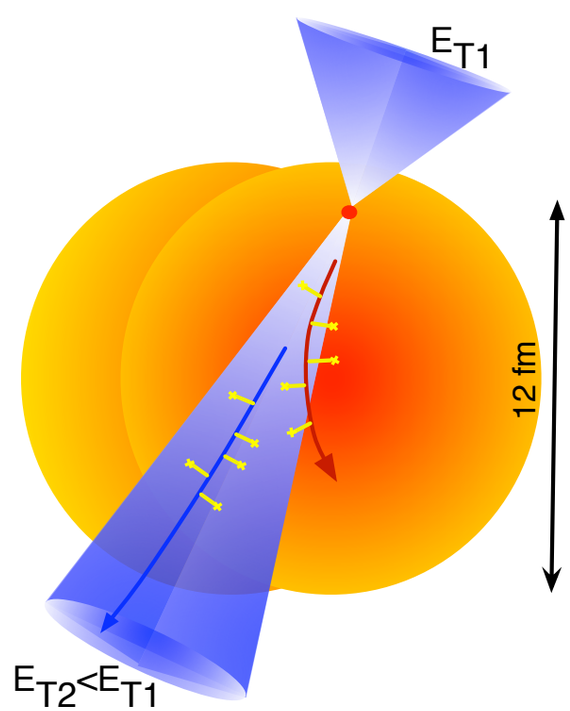


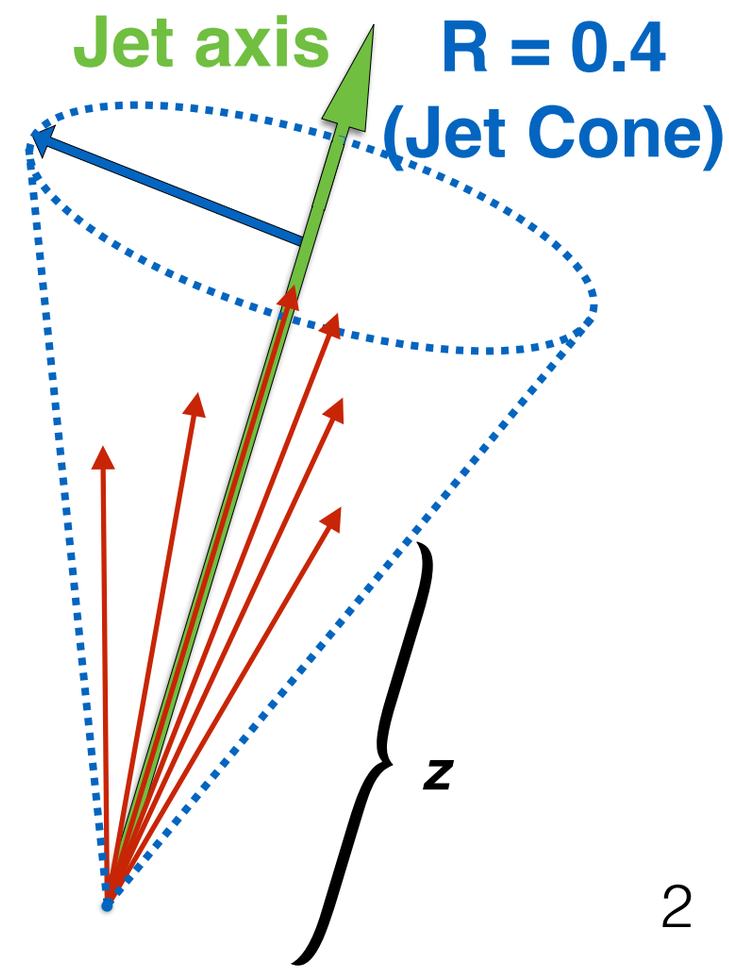


Overview

- The Quark Gluon Plasma
- Jets and jet energy loss
- Fragmentation Functions

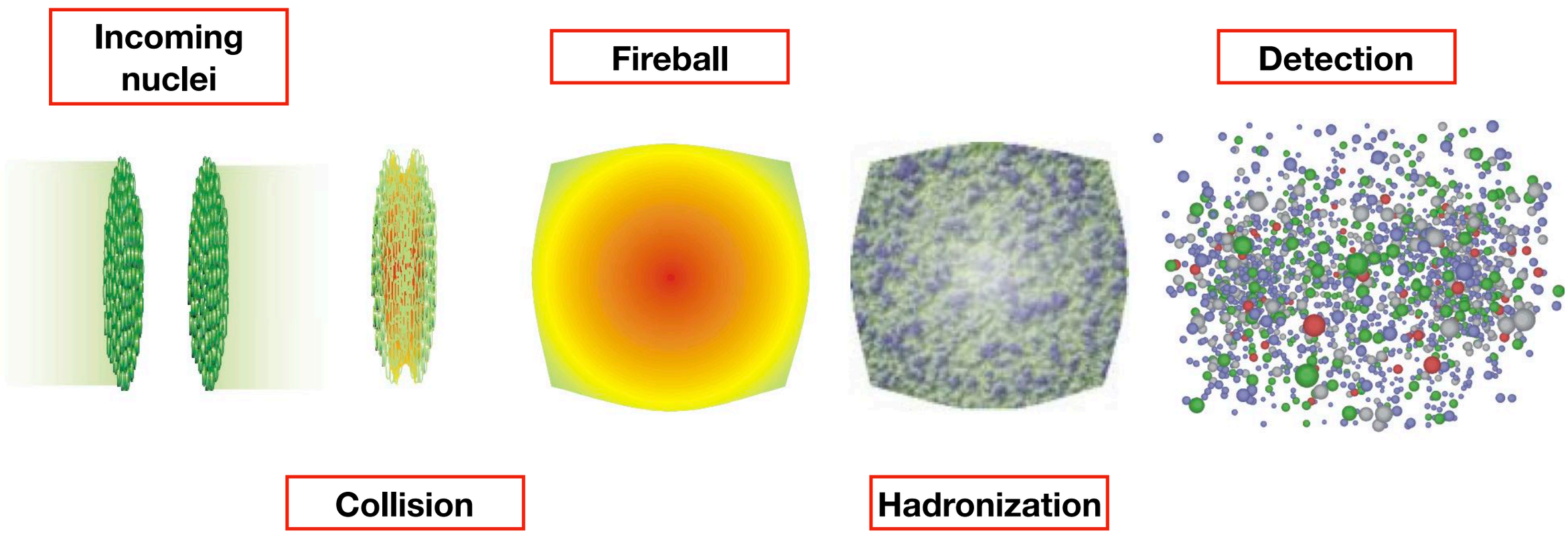






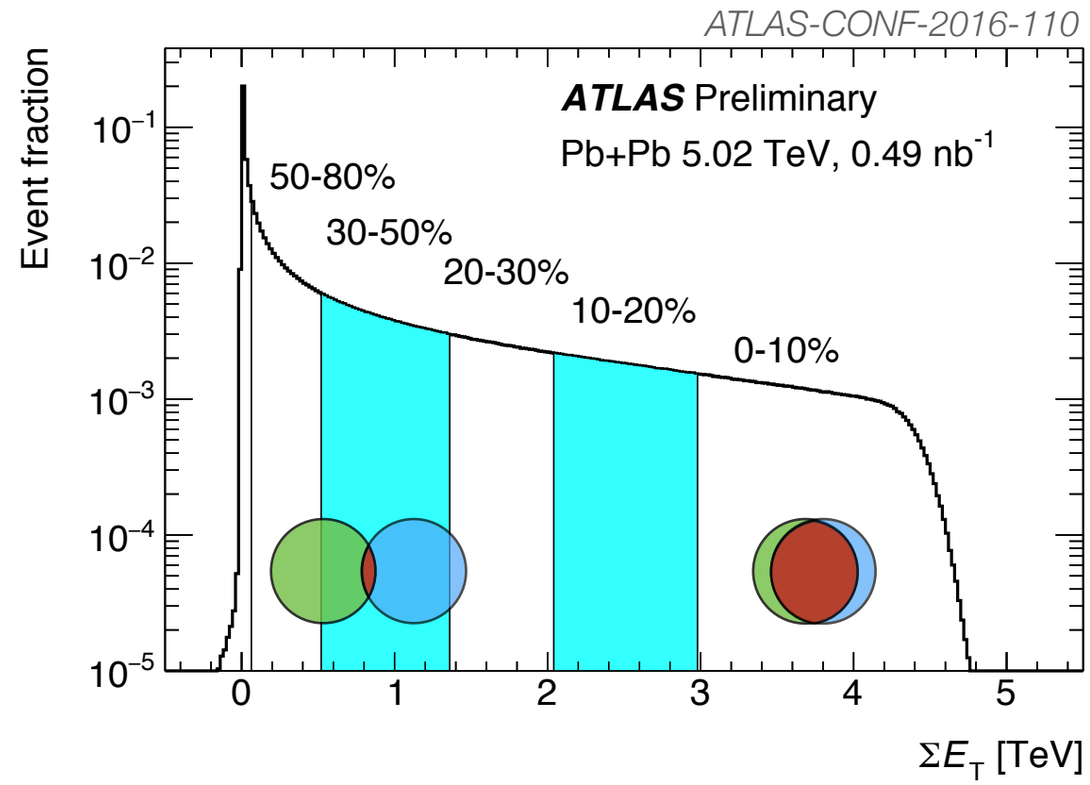
Quark Gluon Plasma (QGP)

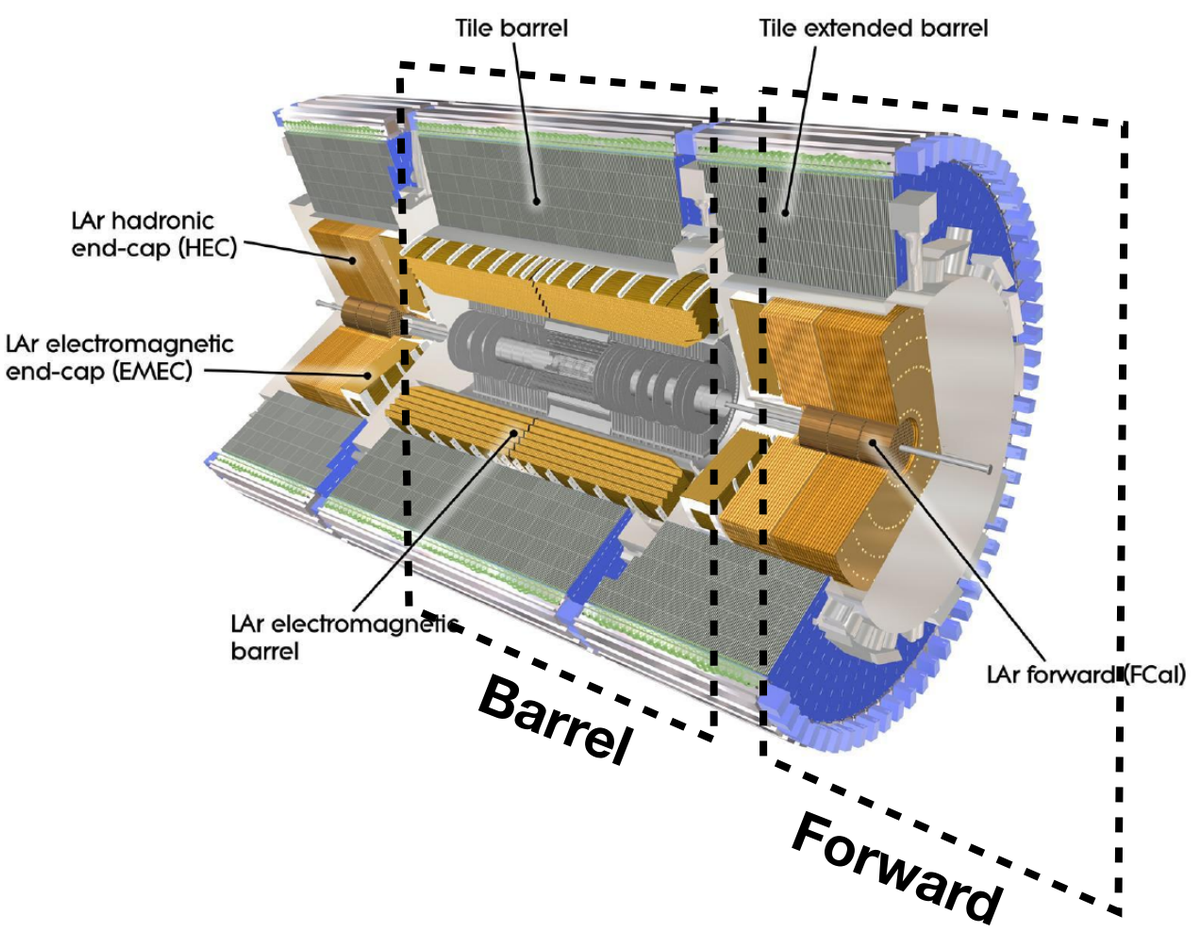
- This is formed in relativistic heavy ion collisions
  - Deconfined medium
  - 500 MeV temperature

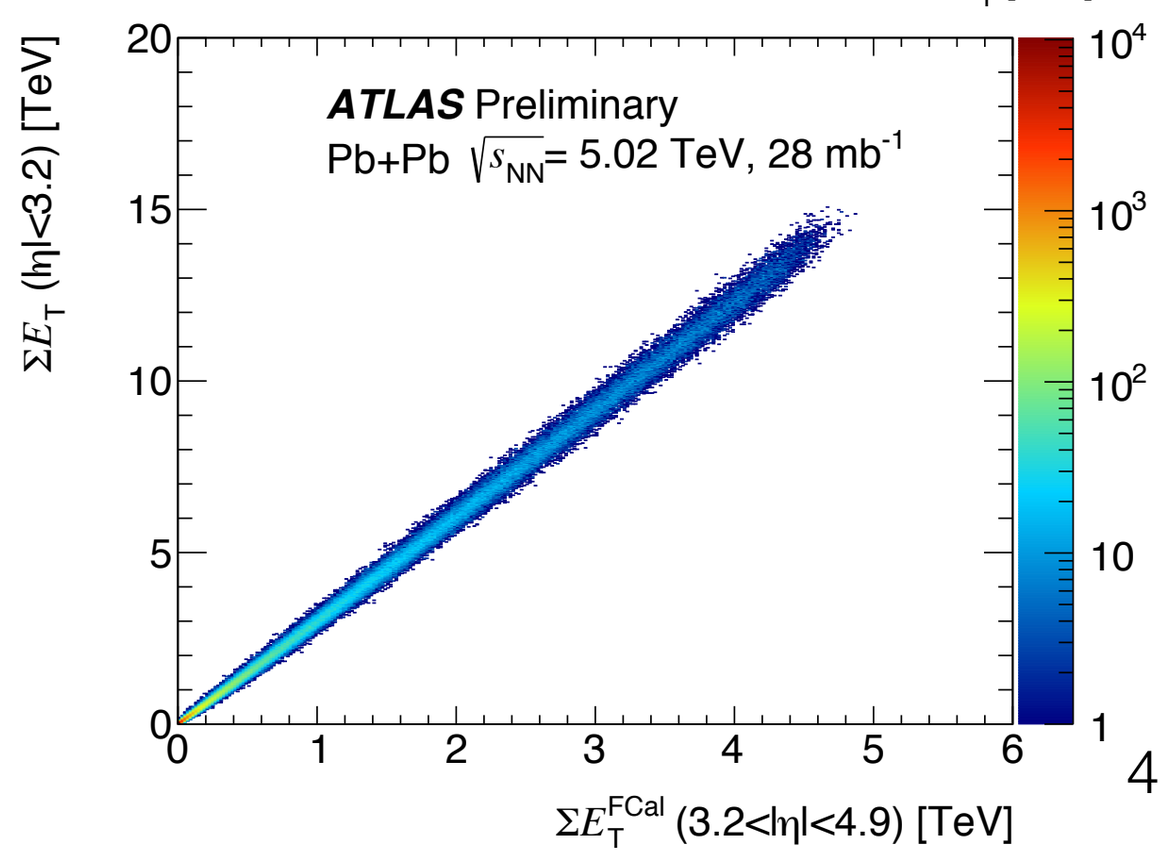


Centrality

- Proxy for the impact parameter
- Quantified by activity in forward detector $\sum FCalE_T$

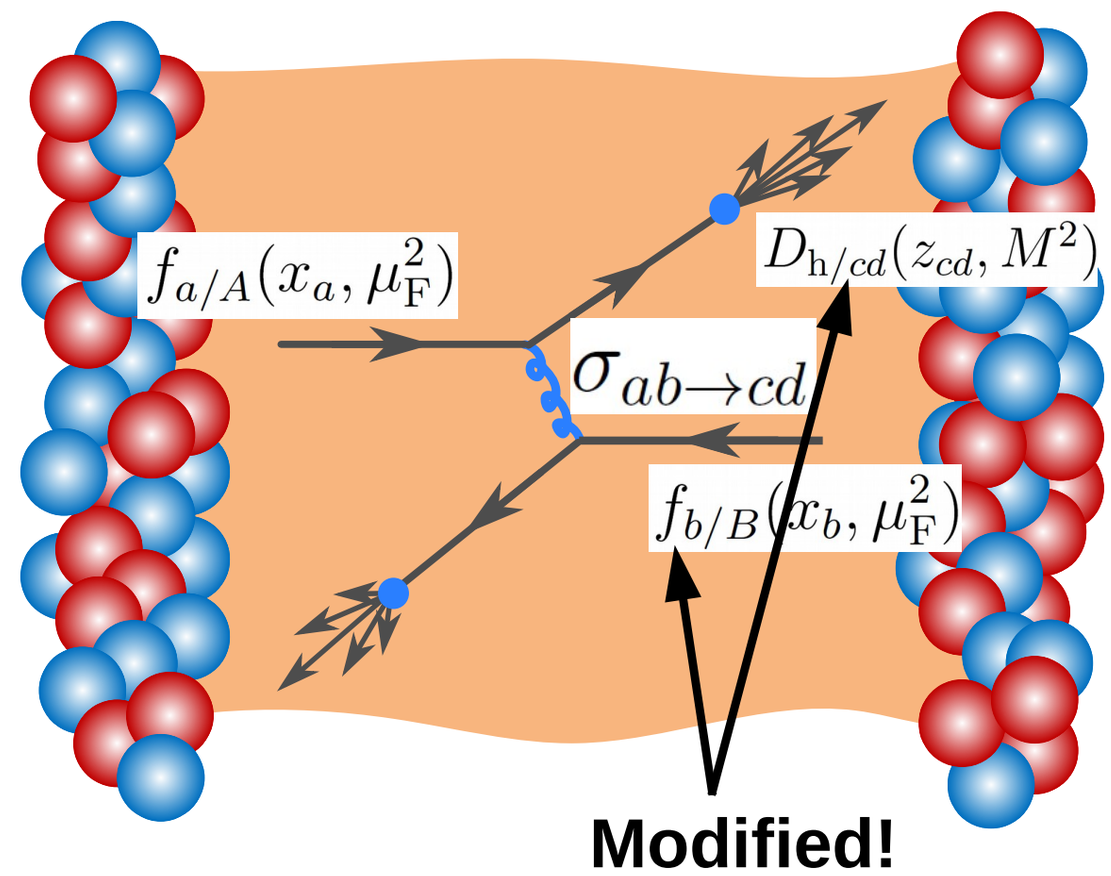




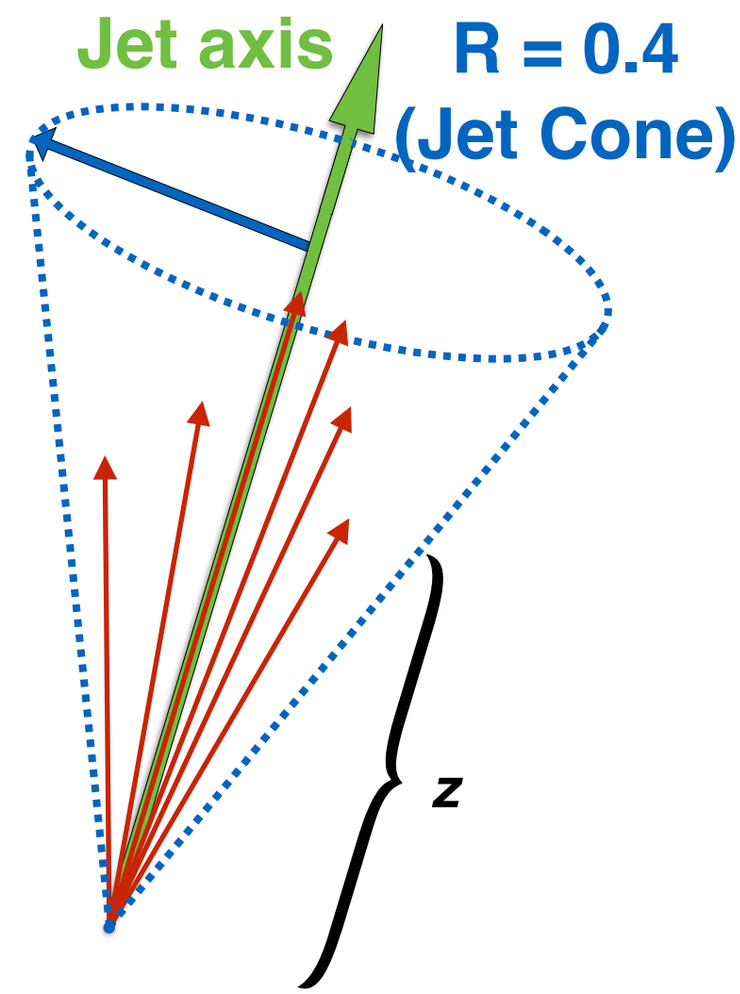


Jets

- Jets can be used as probes of the QGP
- Produced early in collisions
  - Initial cross section unchanged
- Have to go through the QGP
  - Modified PDFs and final state

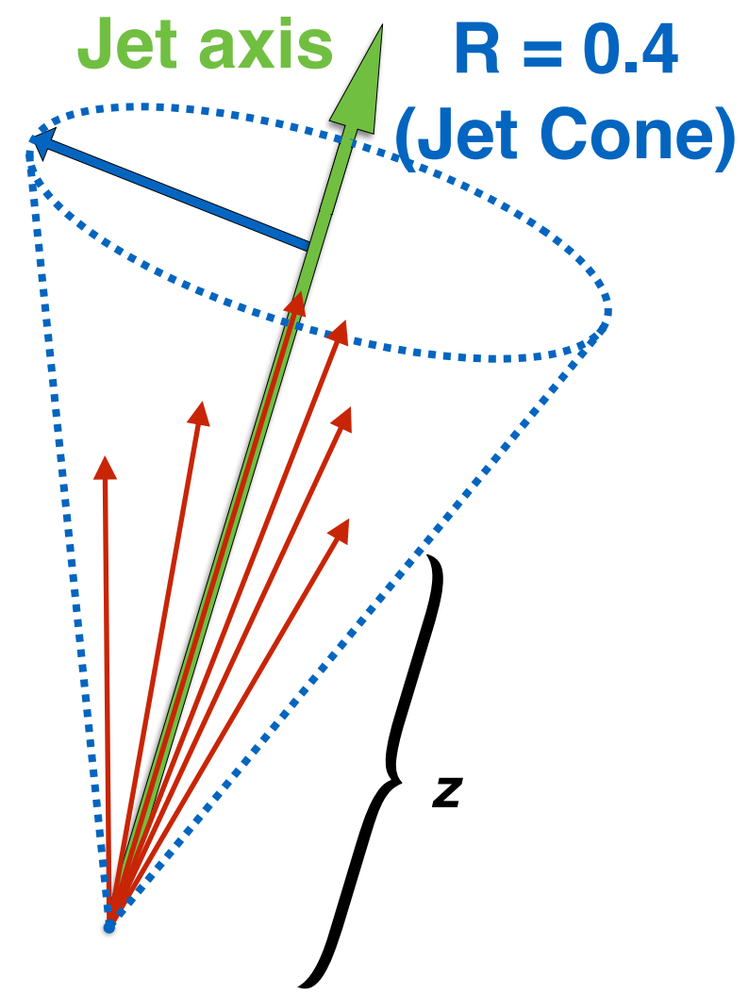


Observables



Observables

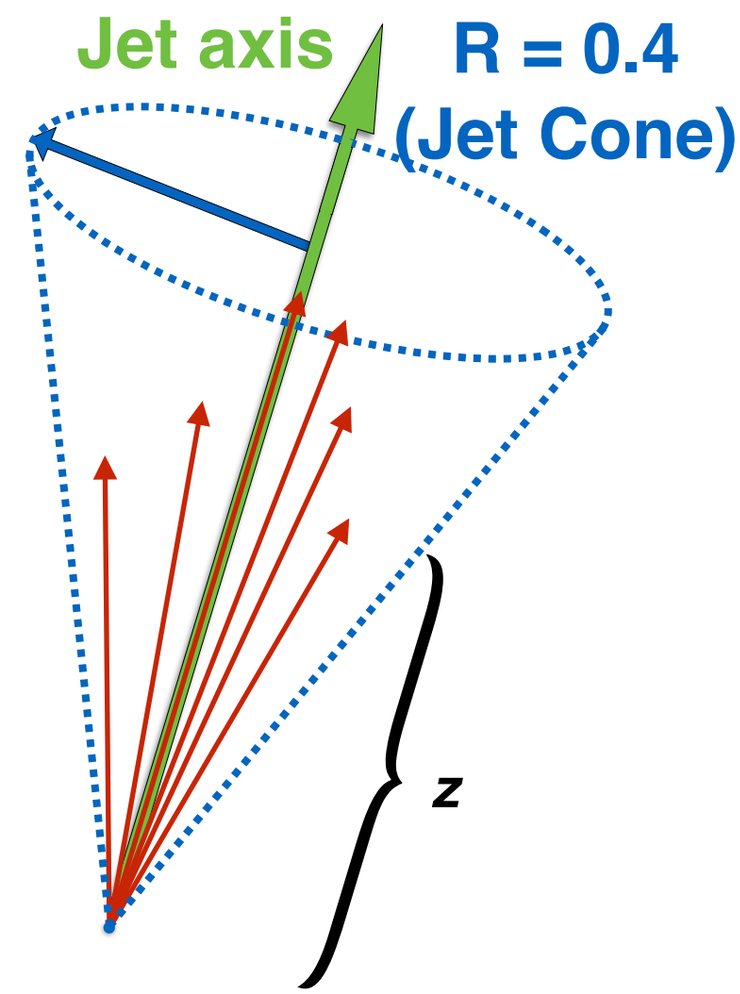
- Fragmentation functions:



Observables

- Fragmentation functions:

$$D(p_{\mathrm{T}}) \equiv \frac{1}{N_{\mathrm{jet}}} \frac{\mathrm{d}n_{\mathrm{ch}}}{dp_{\mathrm{T}}}$$



Observables

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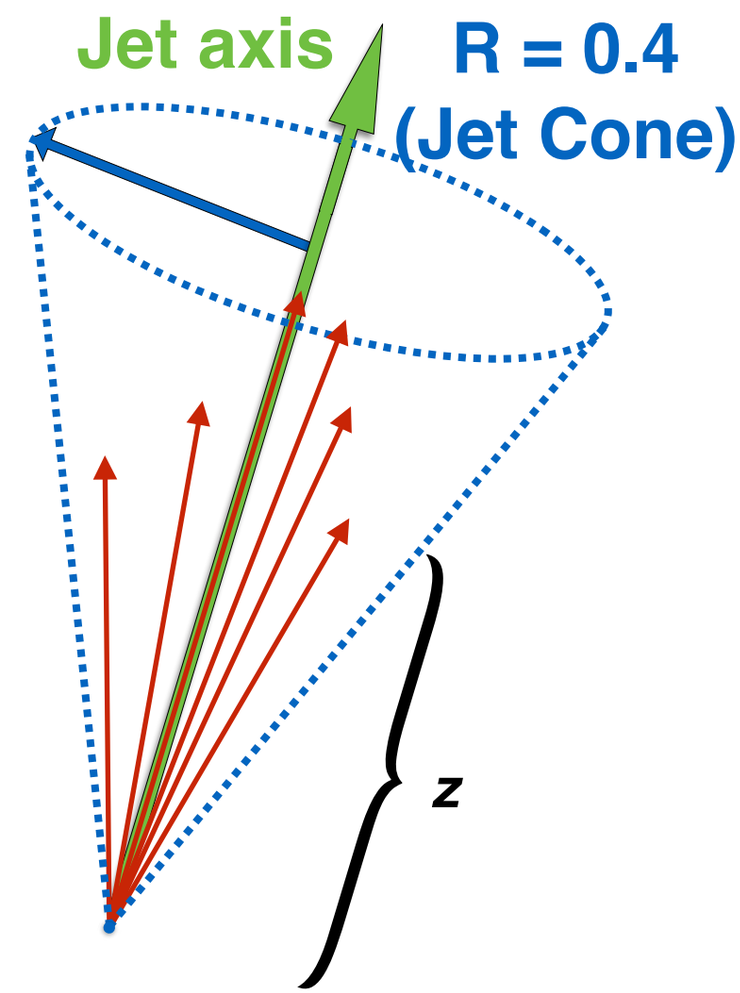
$$D(p_{\mathrm{T}}) \equiv \frac{1}{N_{\mathrm{jet}}} \frac{\mathrm{d}n_{\mathrm{ch}}}{dp_{\mathrm{T}}}$$

$$D(z) \equiv \frac{1}{N_{\mathrm{jet}}} \frac{\mathrm{d}n_{\mathrm{ch}}}{dz} \quad [z \equiv p_{\mathrm{T}} \cos(\Delta R)/p_{\mathrm{T}}^{\mathrm{jet}}]$$



- Comparison between *pp* and Pb+Pb

Observables

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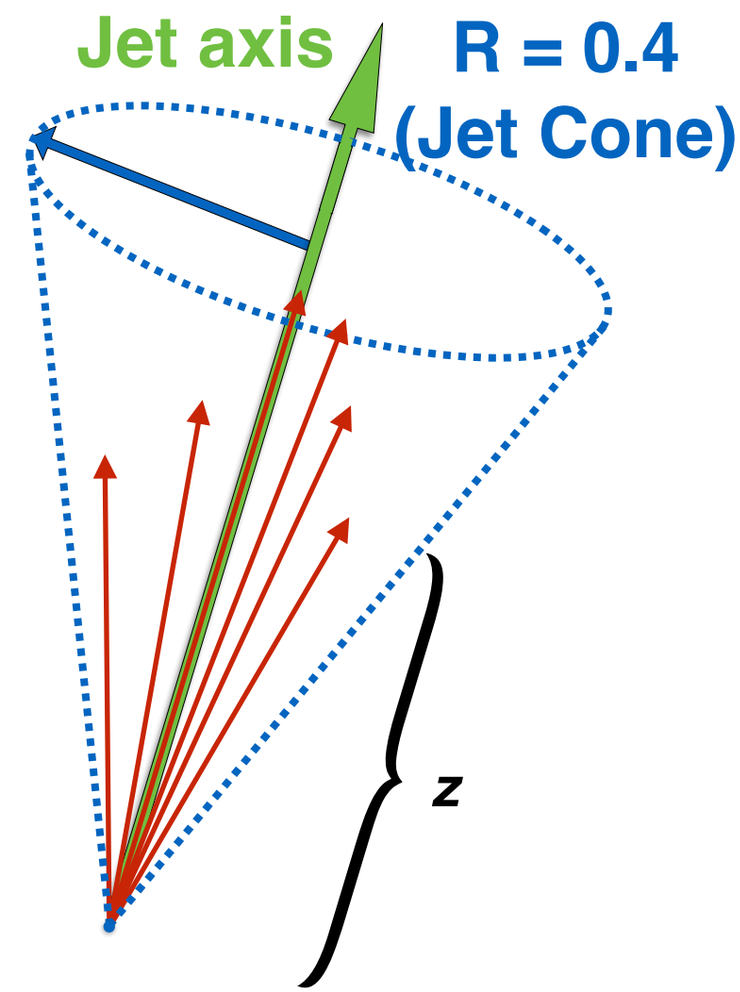
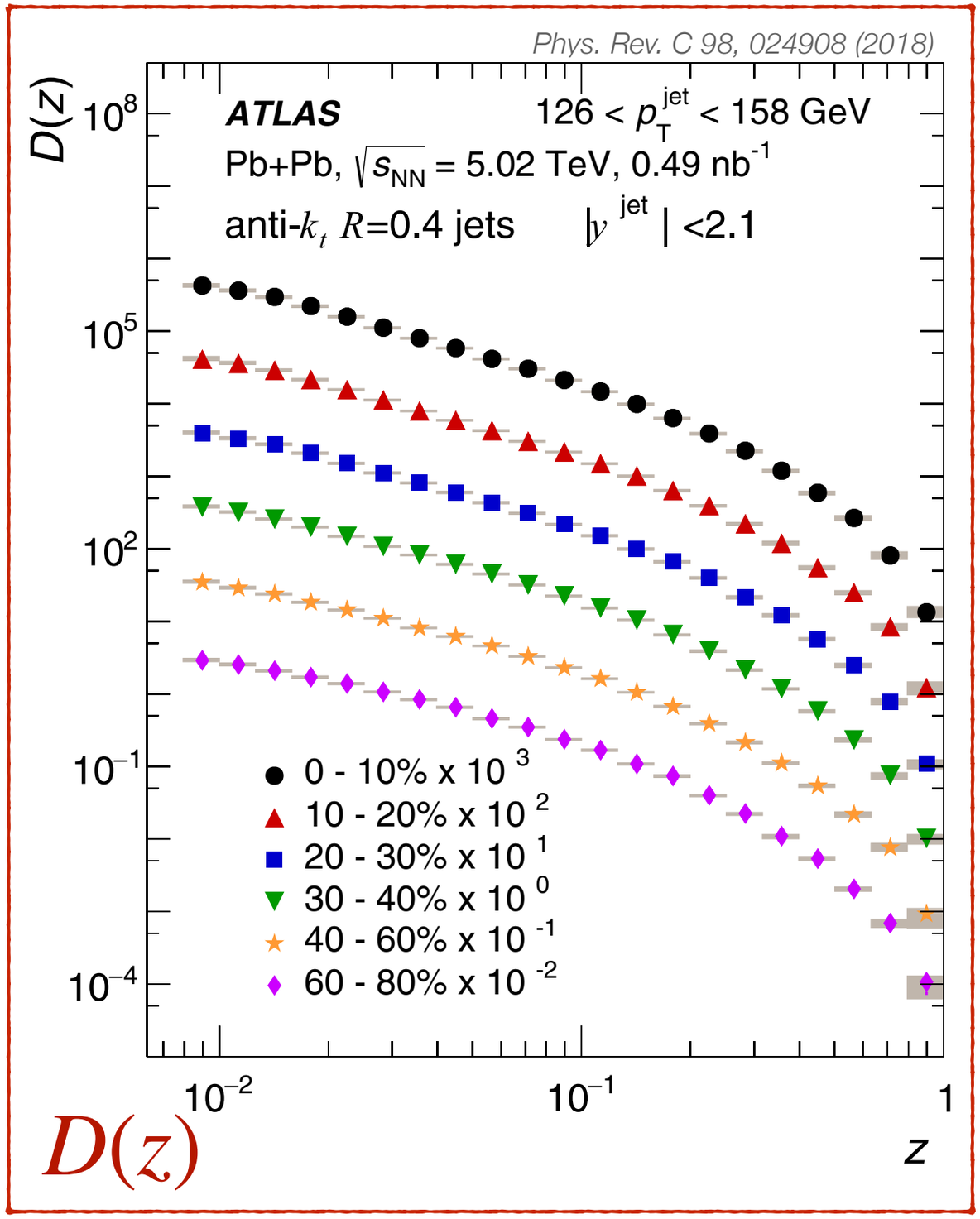
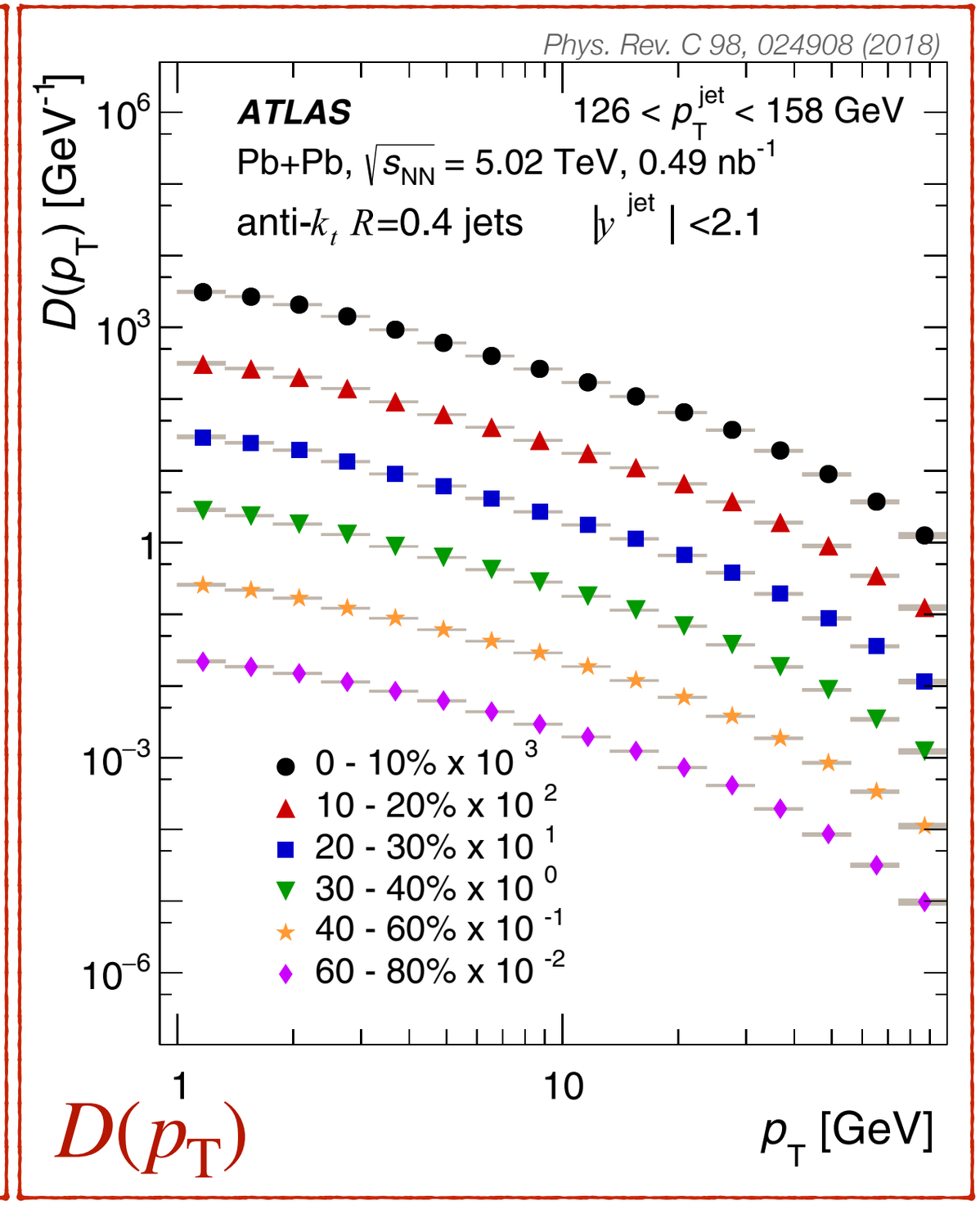


- Comparison between *pp* and Pb+Pb

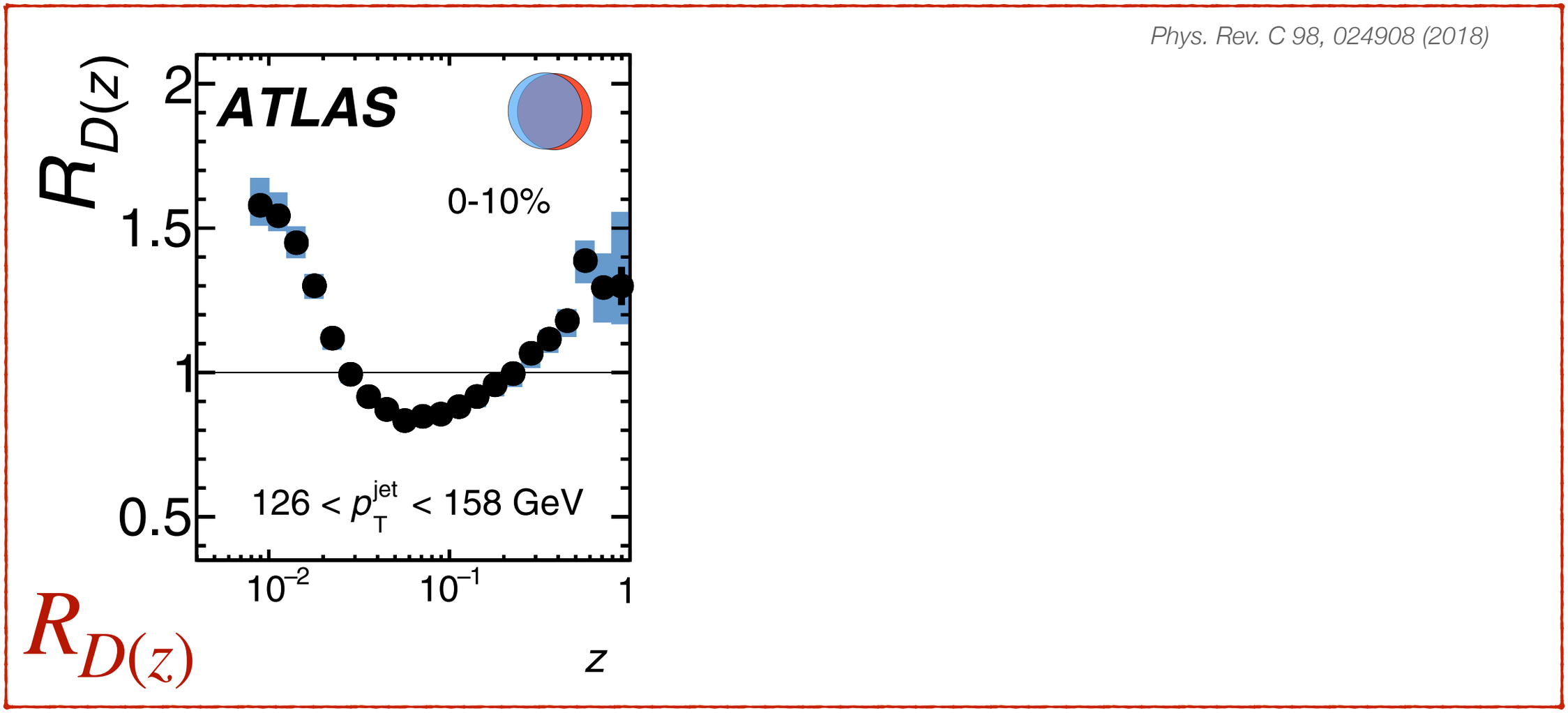
$$R_{D(p_{\mathrm{T}})} \equiv \frac{D(p_{\mathrm{T}})_{\mathrm{PbPb}}}{D(p_{\mathrm{T}})_{\mathrm{pp}}} \quad R_{D(z)} \equiv \frac{D(z)_{\mathrm{PbPb}}}{D(z)_{\mathrm{pp}}}$$

Fragmentation Functions



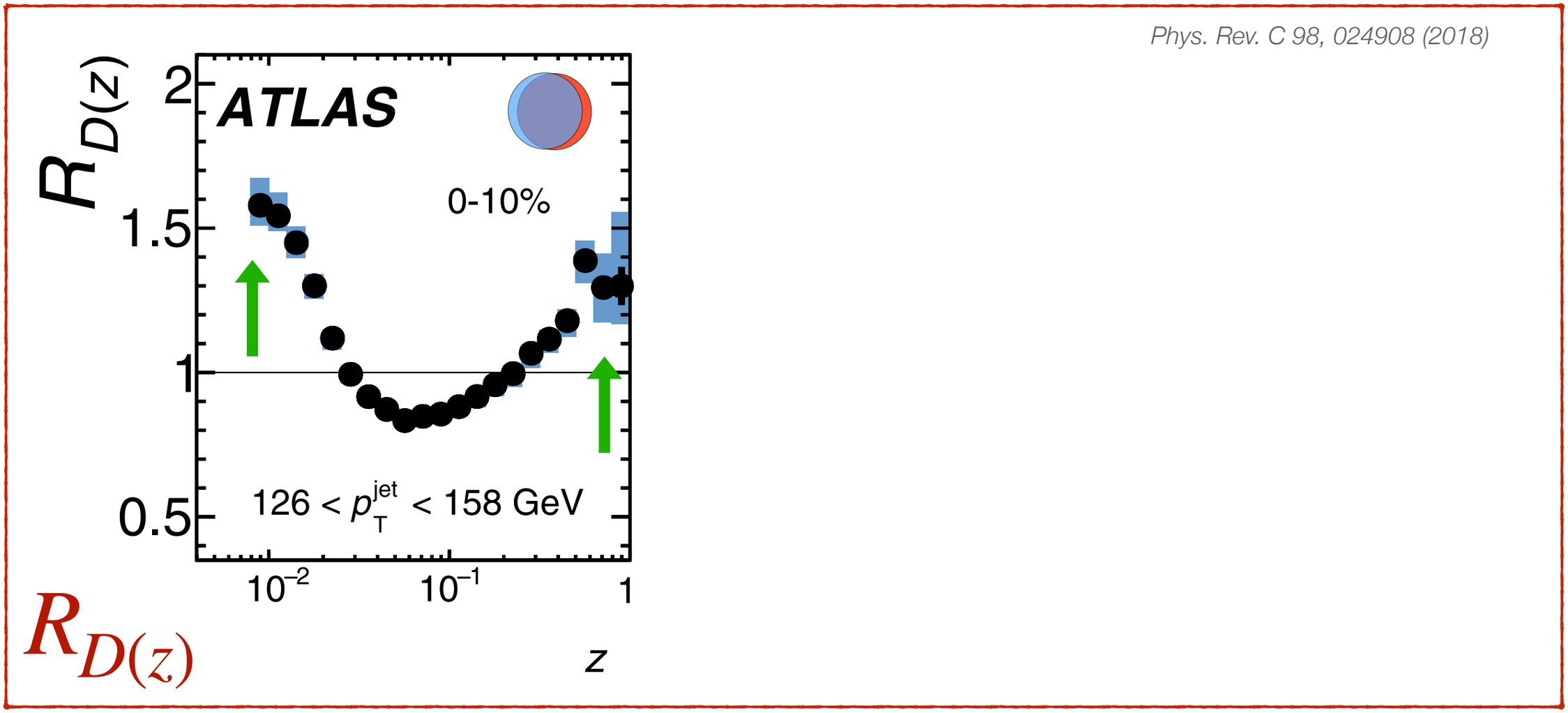


Modification



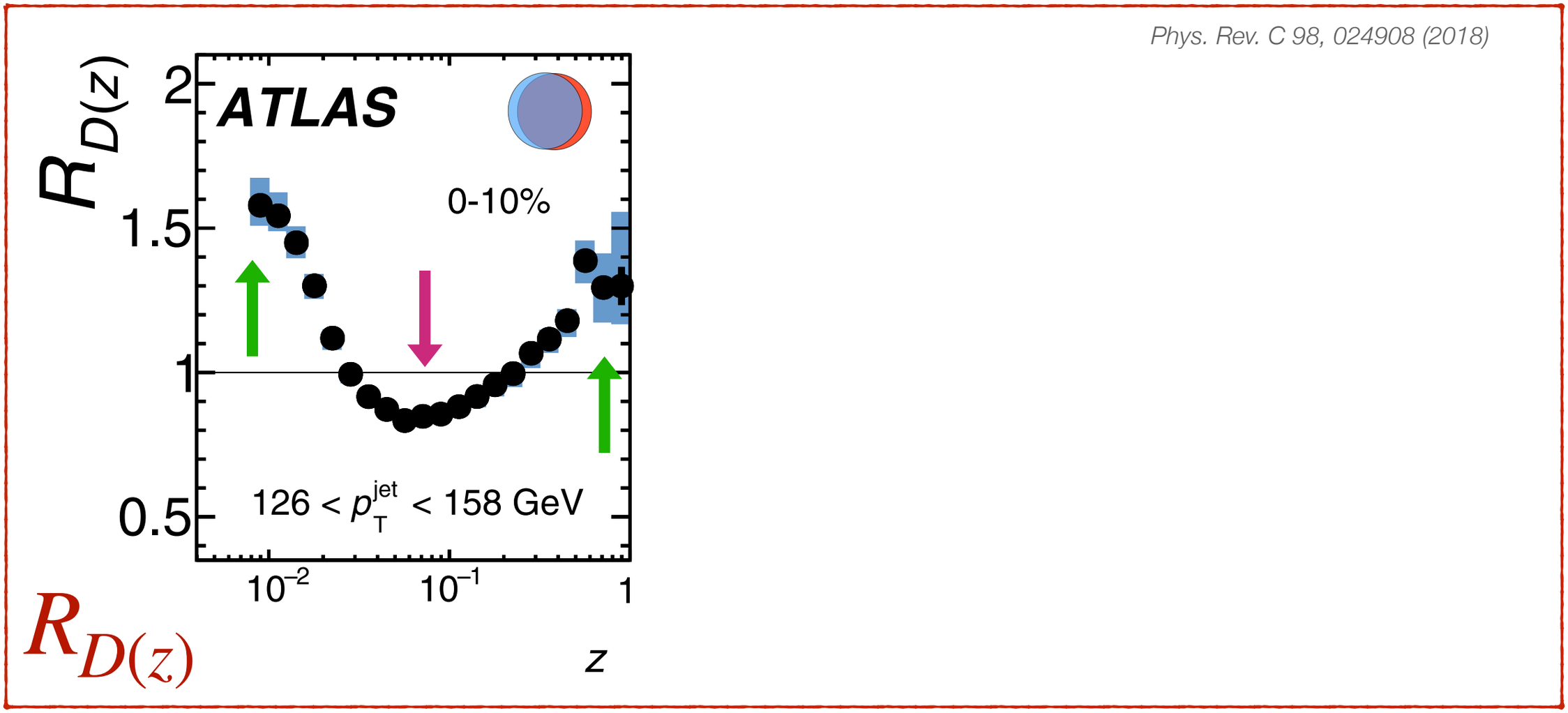
Modification

- Enhancement of yields of hard and soft fragments



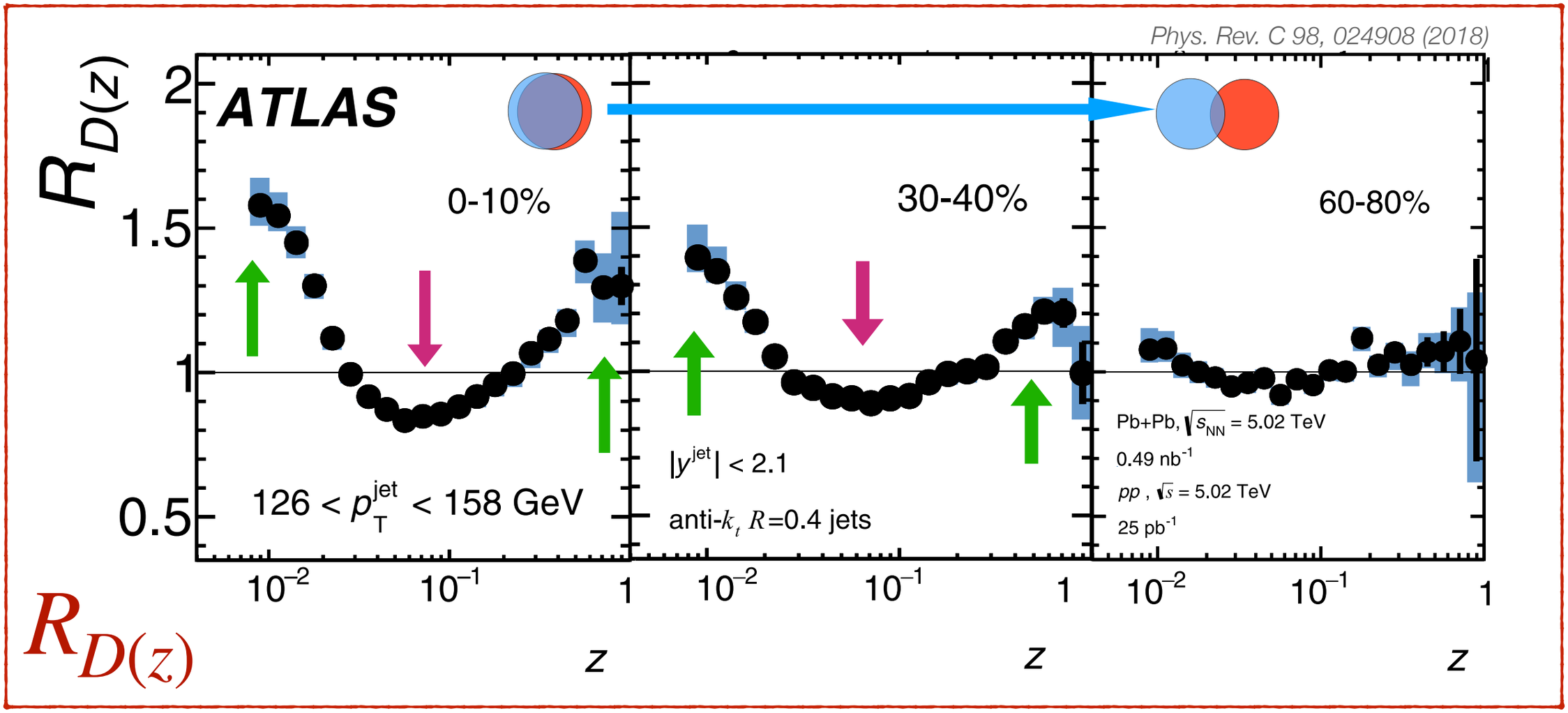
Modification

- Enhancement of yields of hard and soft fragments
- Depletion at mid z, p_T



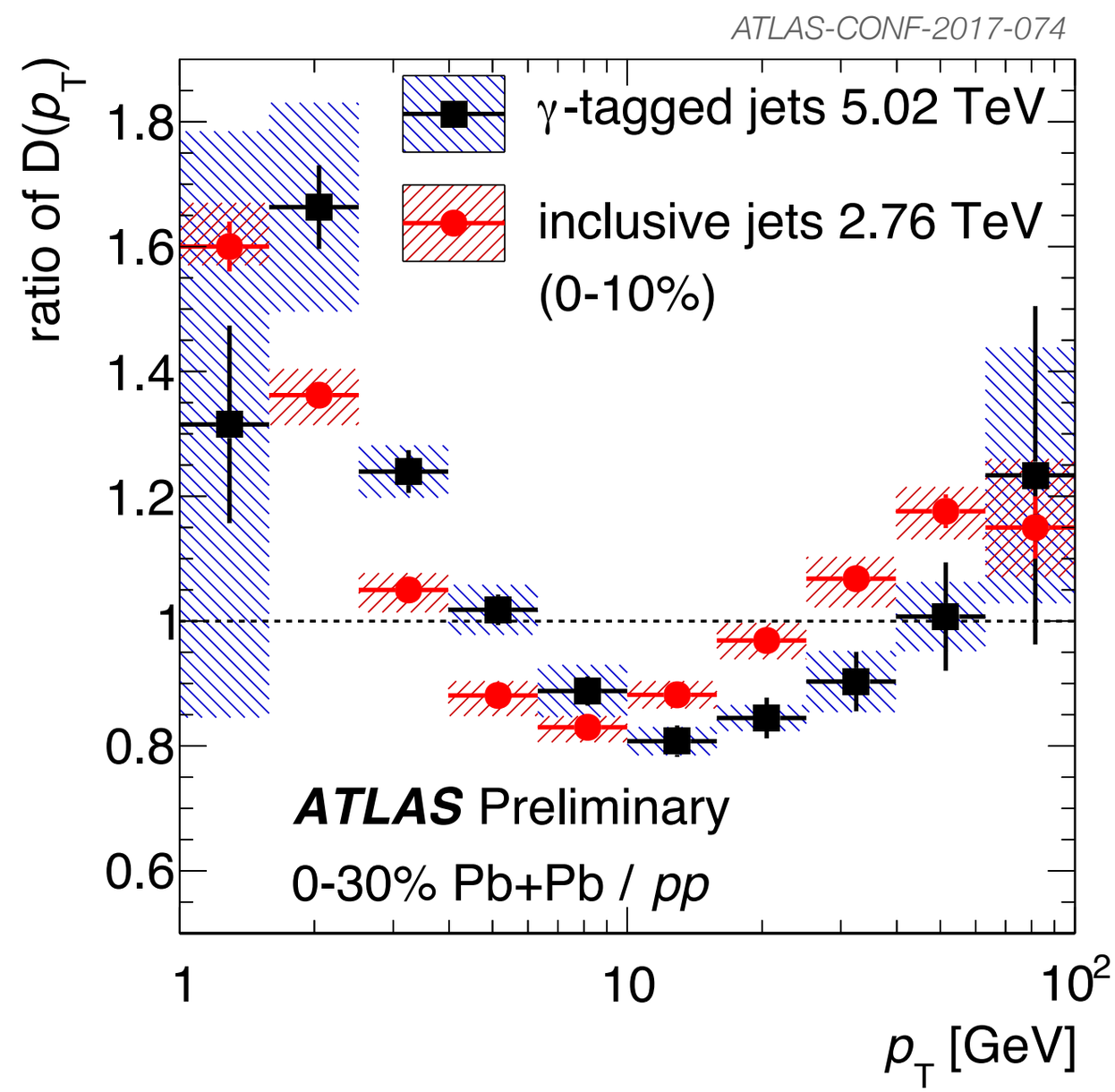
Modification

- Enhancement of yields of hard and soft fragments
- Depletion at mid z, p_T
- Increasing modification as a function of centrality



Flavor dependence (?)

- γ-jet fragmentation functions
  - Comparison to inclusive jet fragmentation functions
  - Additional relative suppression at high z, p_T



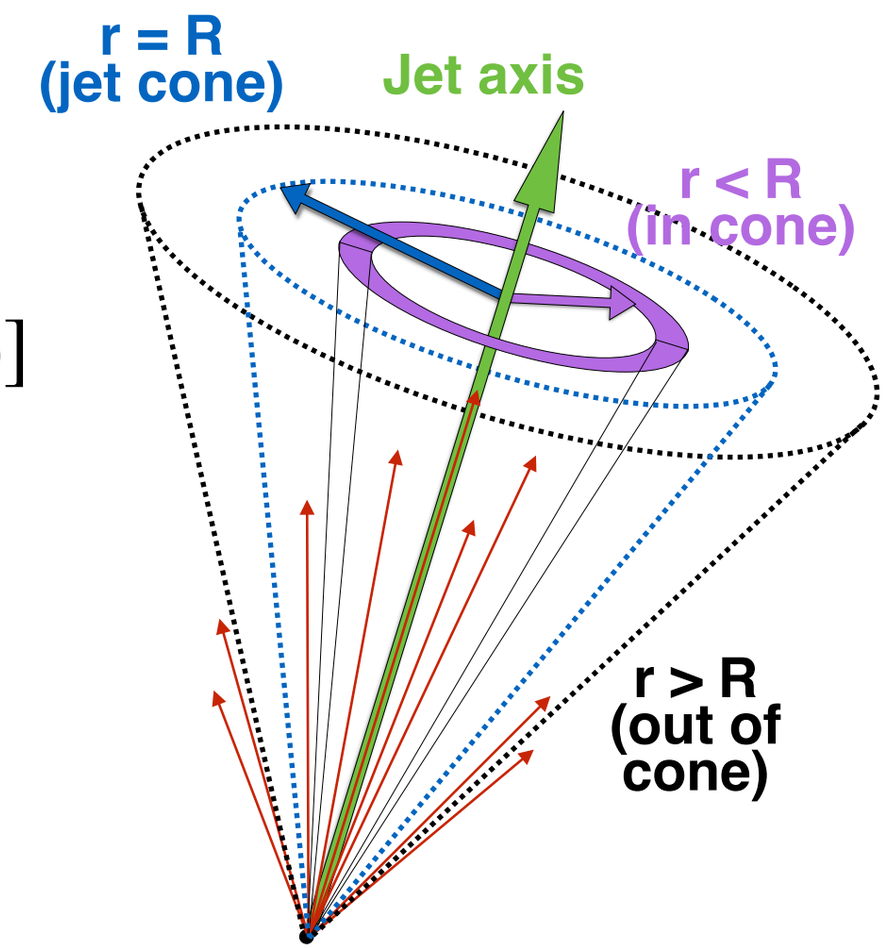
Radial dependence

- Radial distribution (r < 0.6)

$$D(p_{\mathrm{T}}, r) \equiv \frac{1}{N_{\mathrm{jet}}} \frac{1}{2\pi r} \frac{\mathrm{d}^2 n_{\mathrm{ch}}(r)}{dr dp_{\mathrm{T}}} \qquad [r < 0.6]$$

- Comparison to pp at 5 TeV

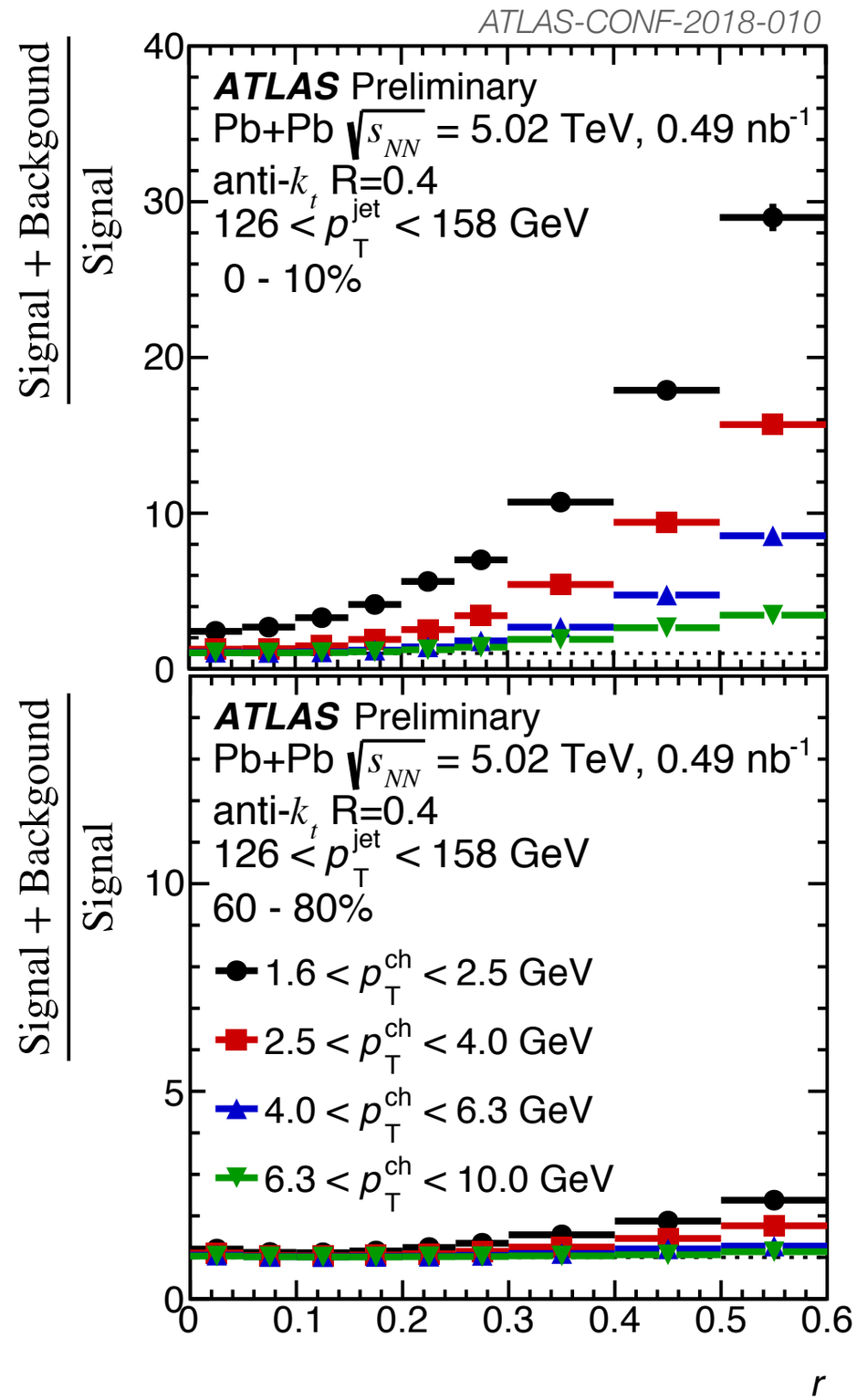
$$R_{D(p_{\mathrm{T}},r)} \equiv \frac{D(p_{\mathrm{T}}, r)_{\mathrm{PbPb}}}{D(p_{\mathrm{T}}, r)_{\mathrm{pp}}}$$



ATLAS-CONF-2018-010

Challenges

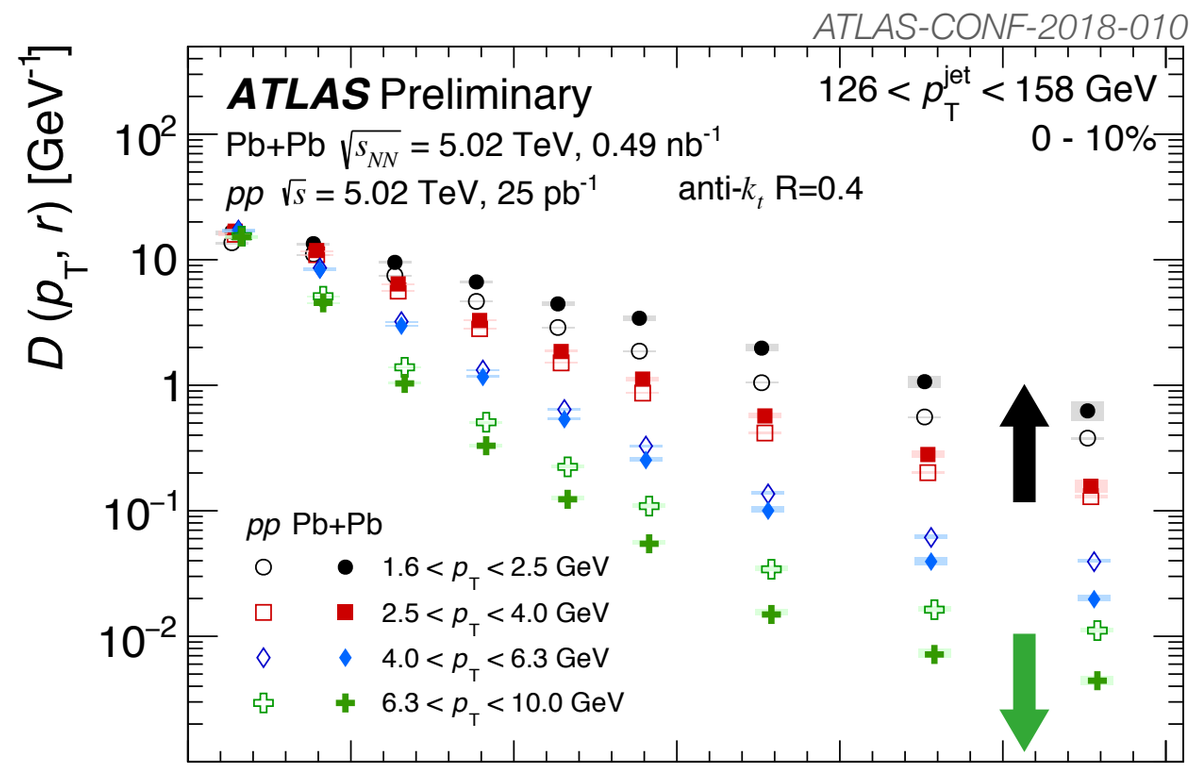
- Large underlying event
- Strongly dependent on, centrality, track p_T, distance from jet axis, eta and flow
- Determined using minimum bias events in the same centrality class with no jet



Radial Distribution

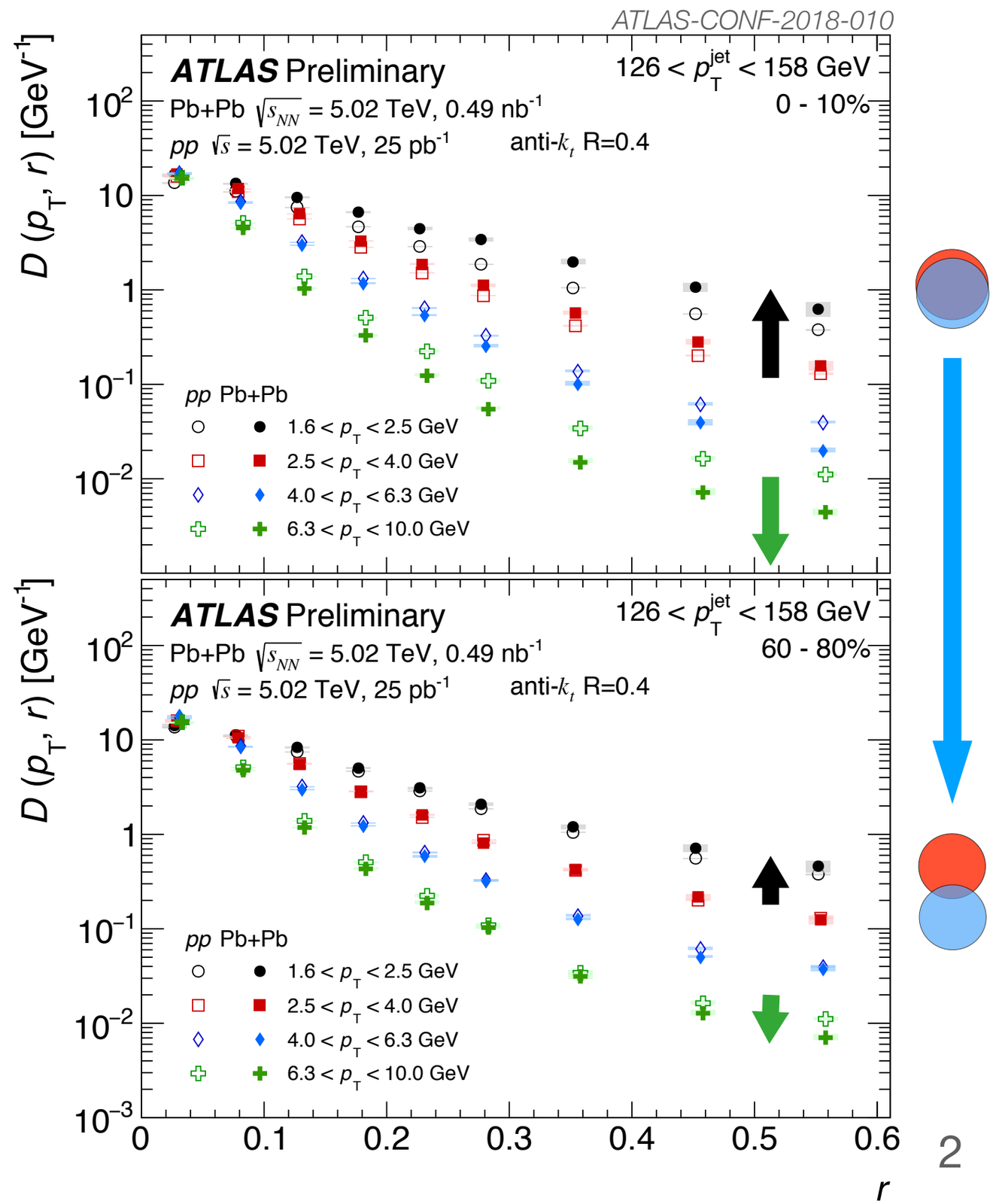
Radial Distribution

- **Broadening** for low p_T particles, **narrowing** for high p_T particles



Radial Distribution

- **Broadening** for low p_T particles, **narrowing** for high p_T particles
- Persists for peripheral collisions, magnitude of modification reduced



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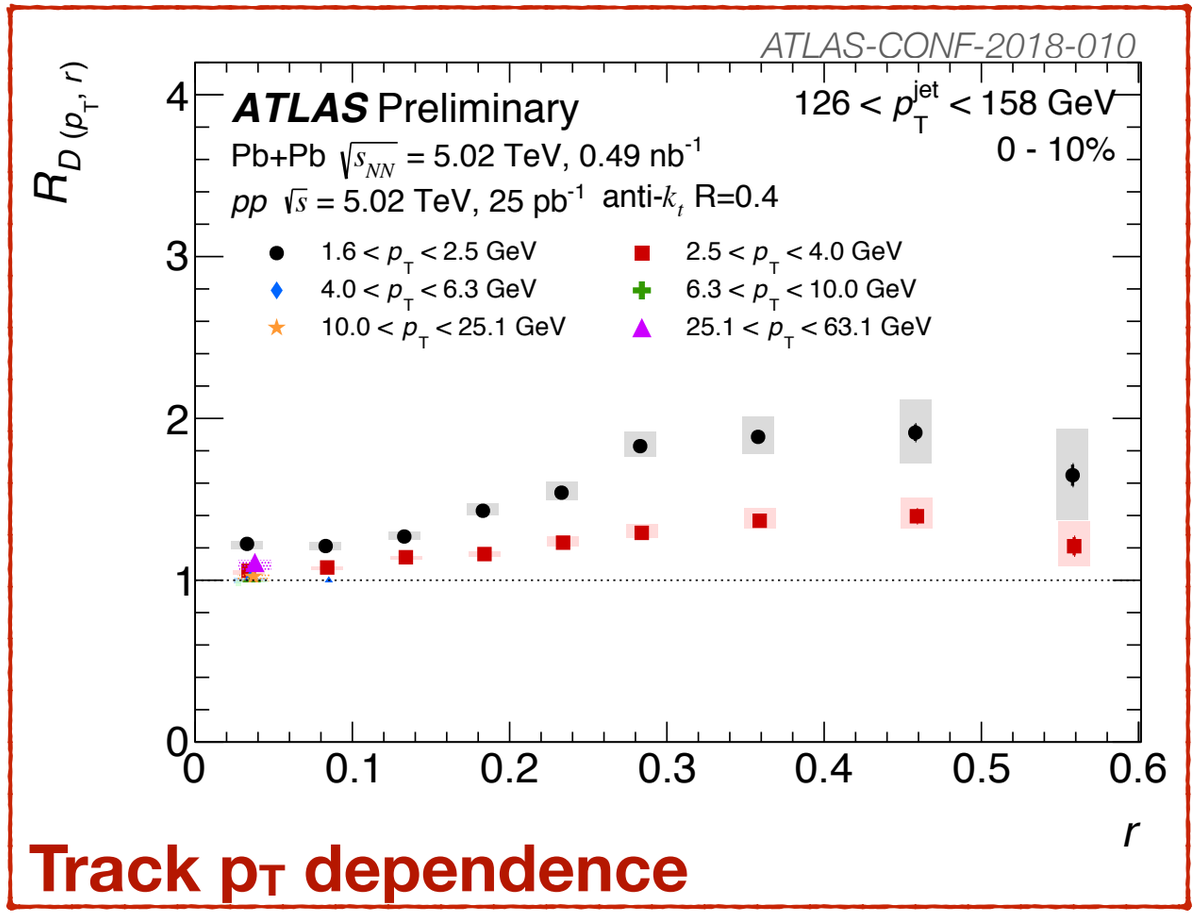
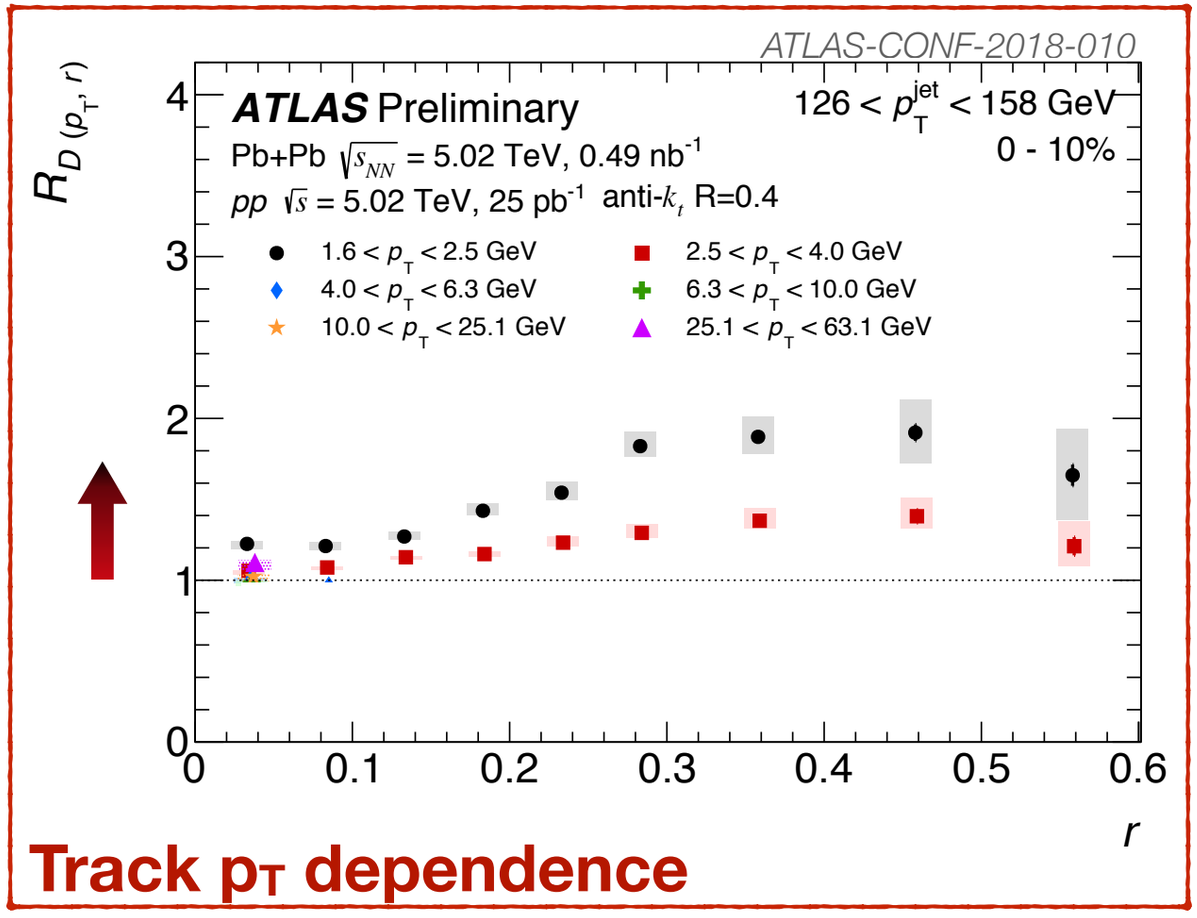


Track p_T dependence

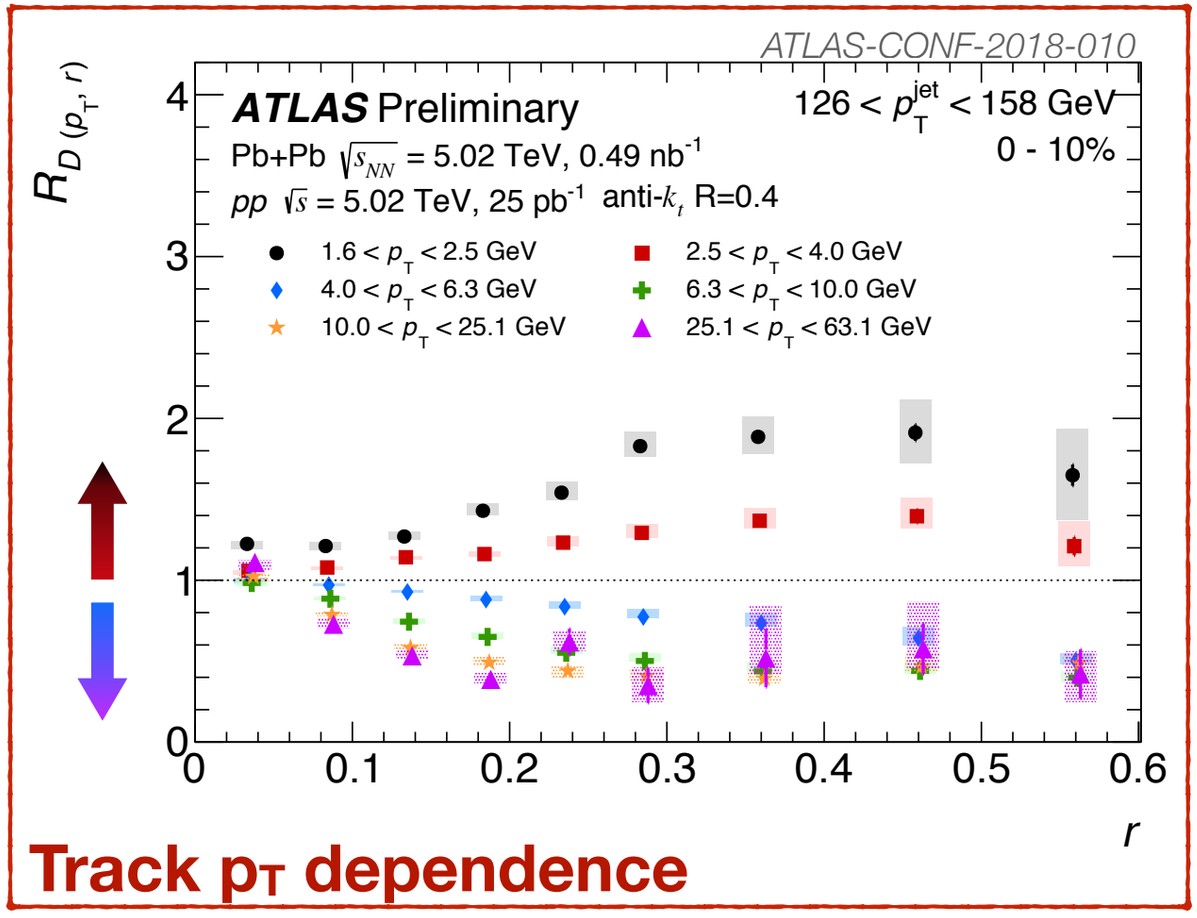
Modification

- Enhancement for particles with $p_T < 4$ GeV



Modification

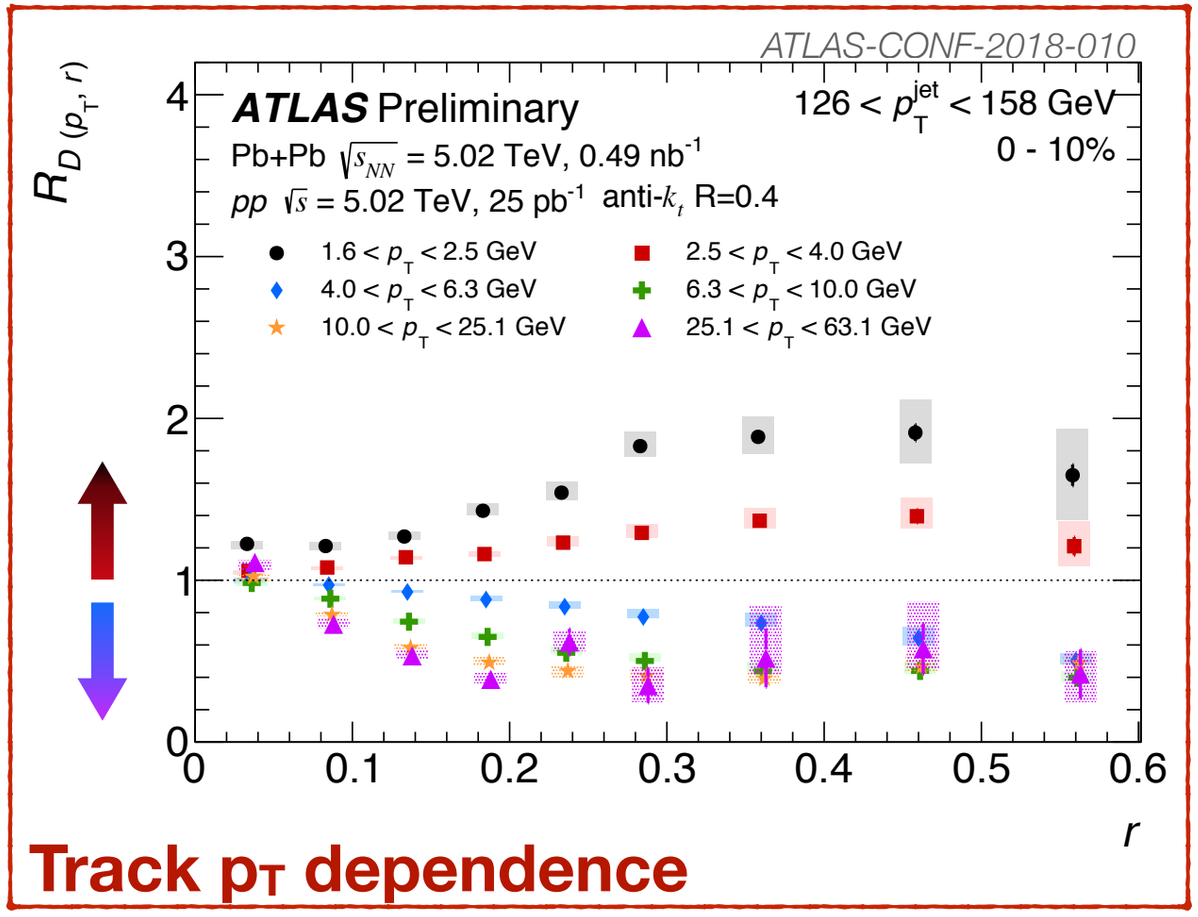
- Enhancement for particles with $p_T < 4$ GeV
- Depletion for particles with $4 < p_T < 63$ GeV



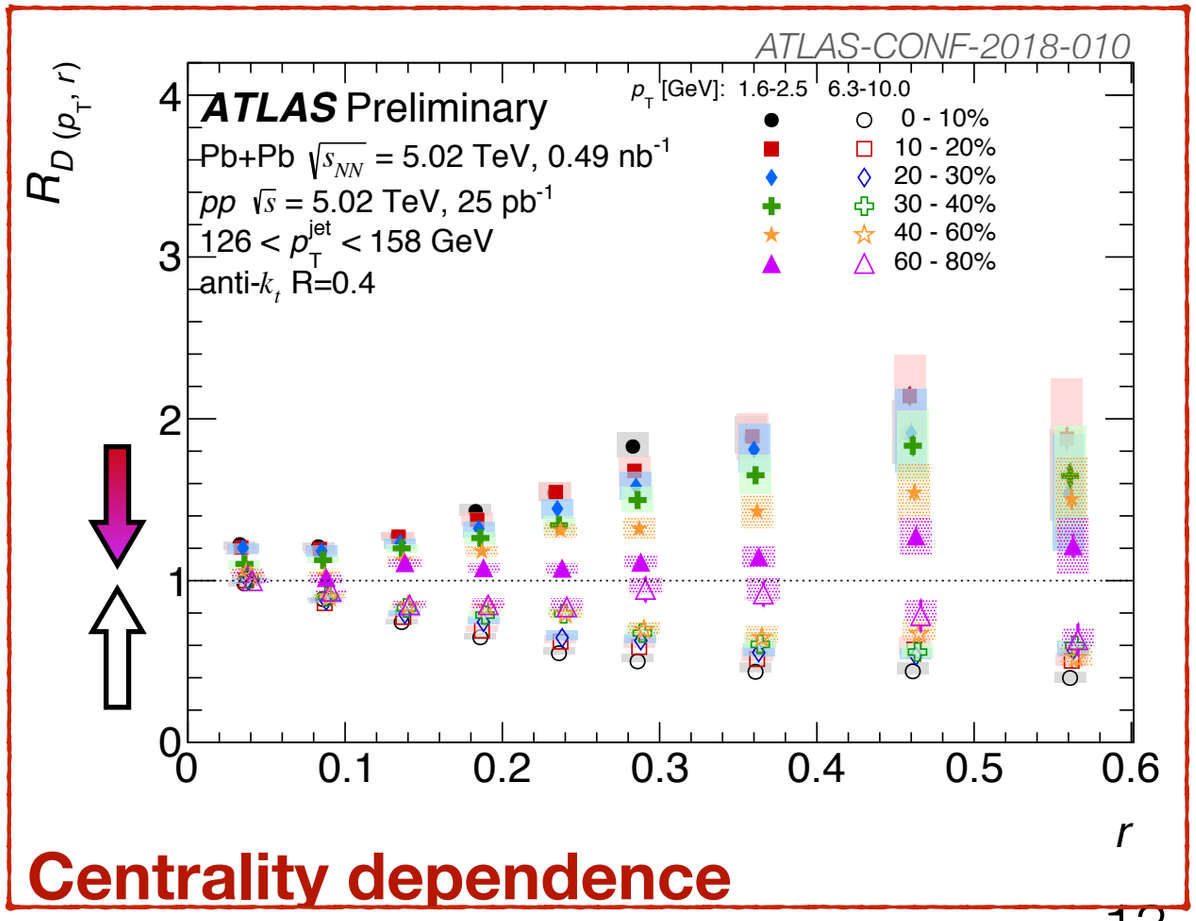
Track p_T dependence

Modification

- Enhancement for particles with $p_T < 4$ GeV
- Depletion for particles with $4 < p_T < 63$ GeV
- Smooth centrality dependence



Track p_T dependence



Centrality dependence

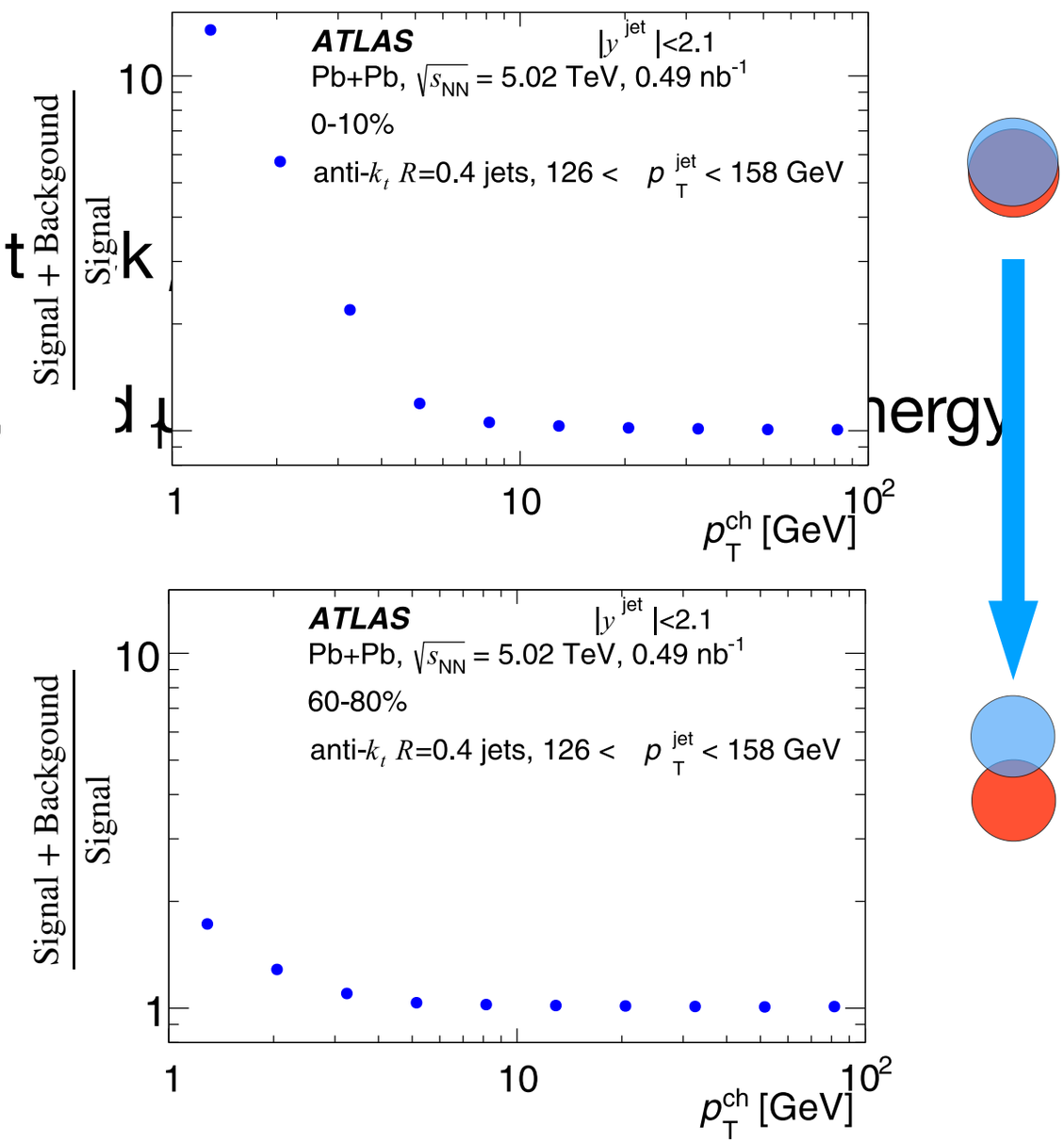
Conclusions

- Comprehensive ATLAS Jet Physics program to constrain the physics of jet energy loss
  - Fully unfolded measurements of jet fragmentation
- Looking forward to the run next month, and are excited to measure the larger Pb+Pb dataset
- <u>Public ATLAS Heavy Ion Results</u>

Backup

Challenges at low p_T

- Shown here as (Signal+Background)/Signal
- Up to 0.05 at low p_T
- Strongly dependent on centrality and t k
- Corrections for flow, eta dependence, d p nergy resolution correlation



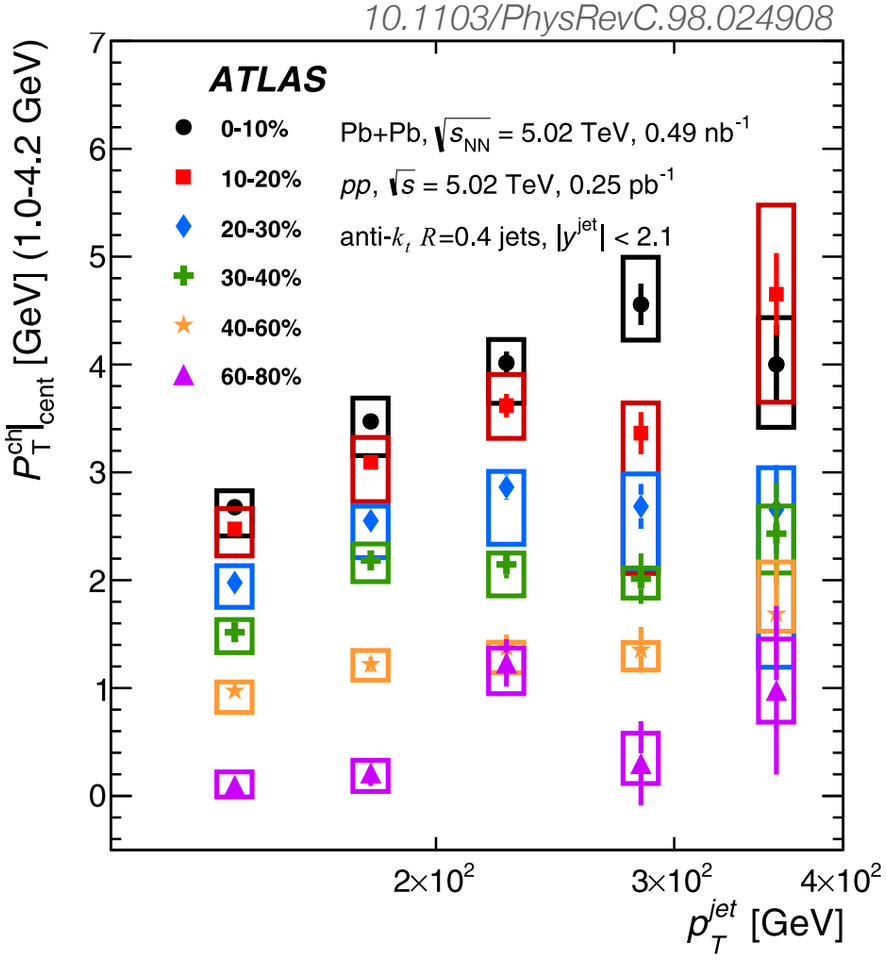
Integrating D(p_T)

- Enhancement is dependent on the Jet p_T

$$P_T^{ch}|_{cent} \equiv \int_{p_{T,min}}^{p_{T,max}} [D(p_T)|_{cent} - D(p_T)|_{pp}] p_T d p_T$$

- Medium response to the high p_T parton?

10.1103/PhysRevC.98.024908



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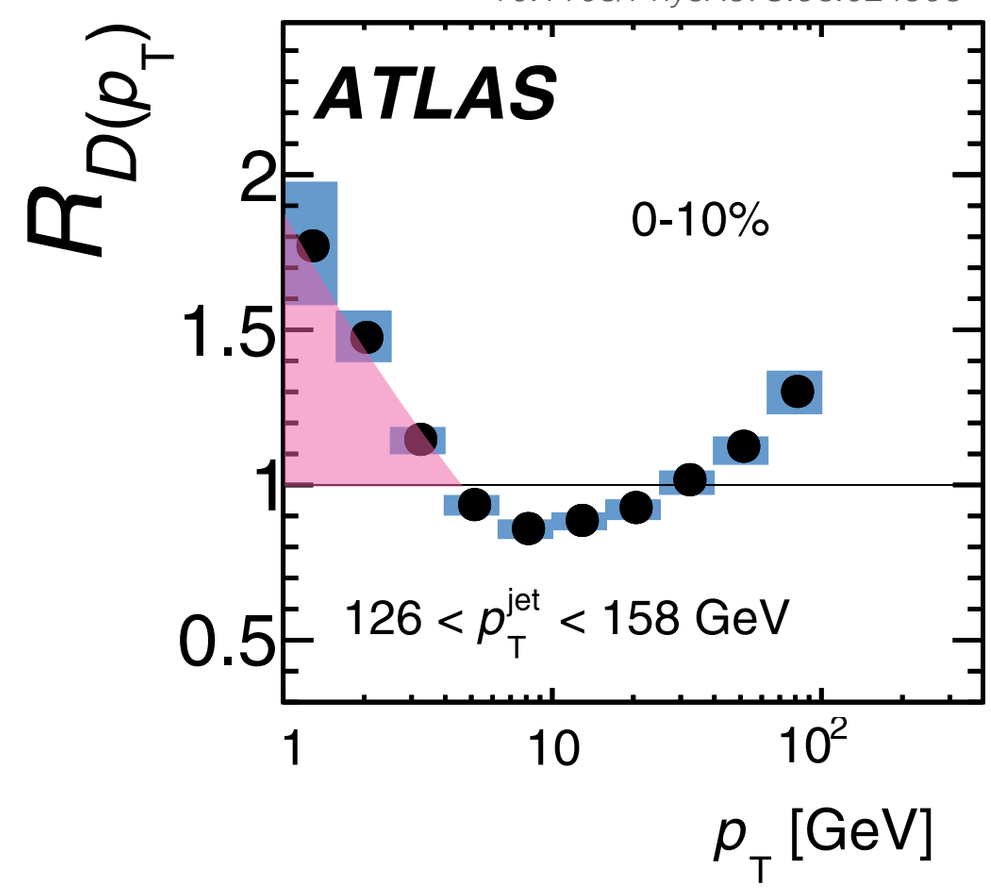

Jet p_T Dependence

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- Low p_T particles show enhancement of yields with increasing jet p_T
- Intermediate p_T particle yield is independent of jet p_T

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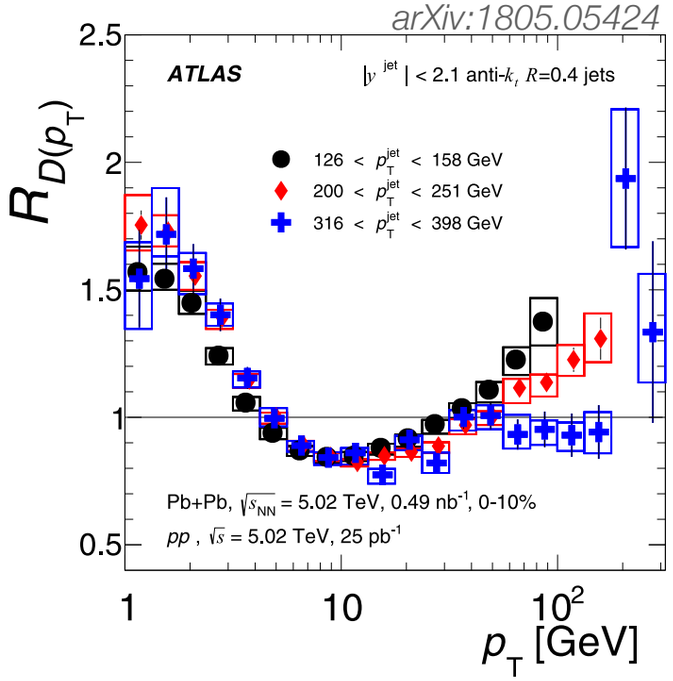
arXiv:1805.05424



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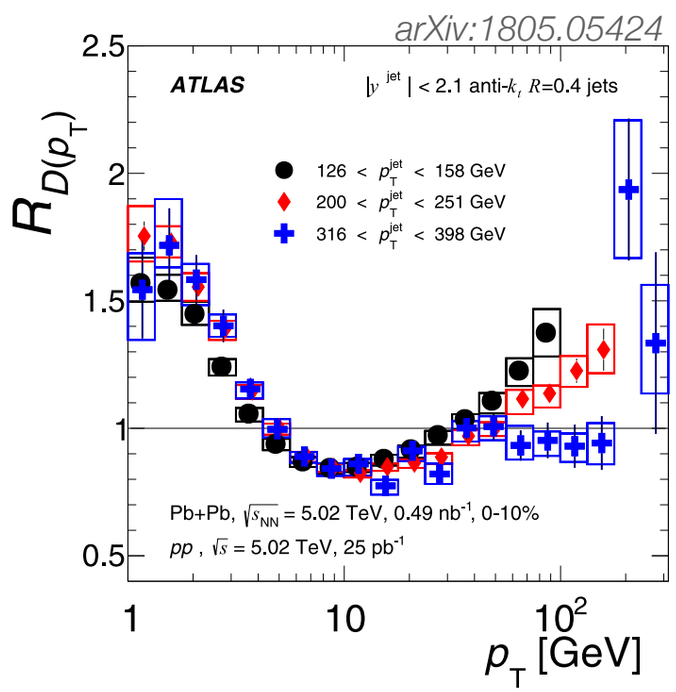
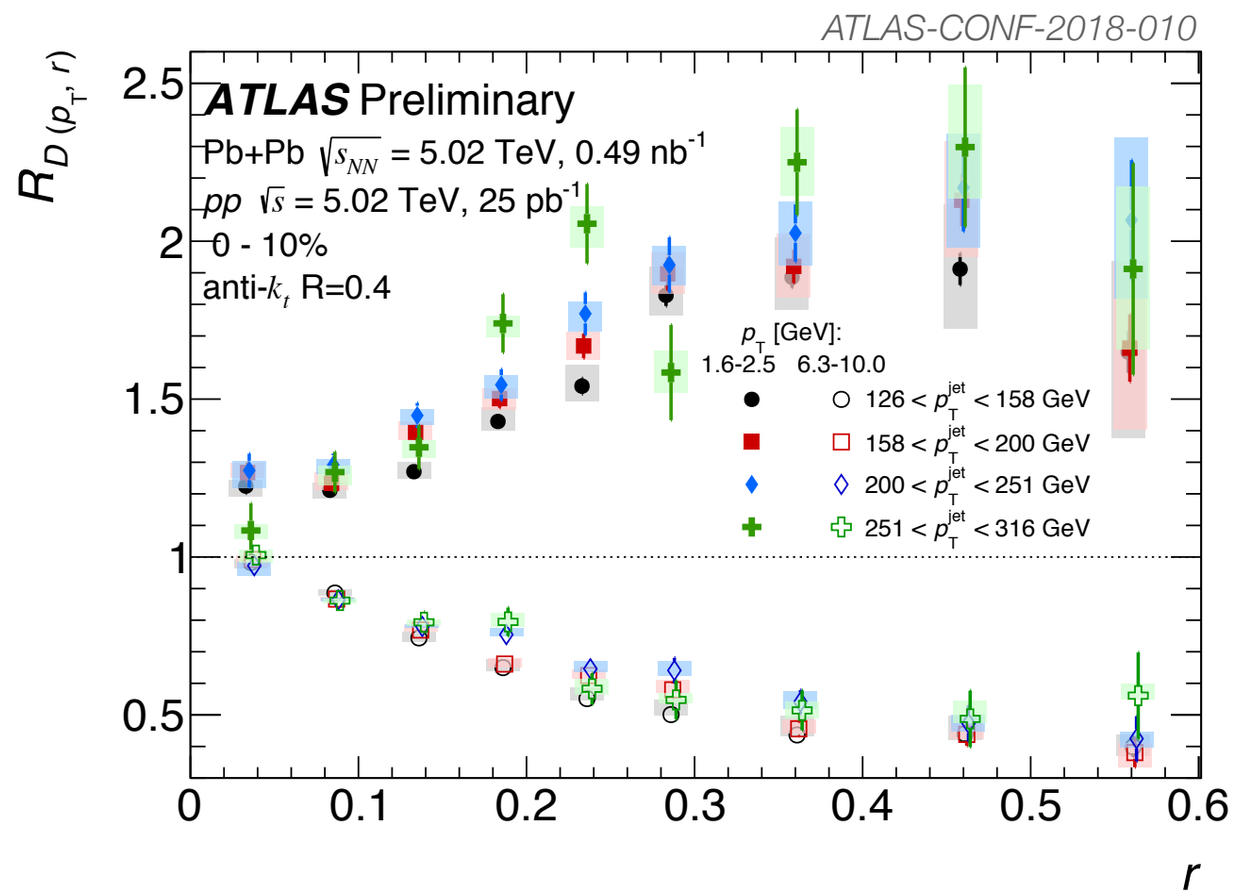
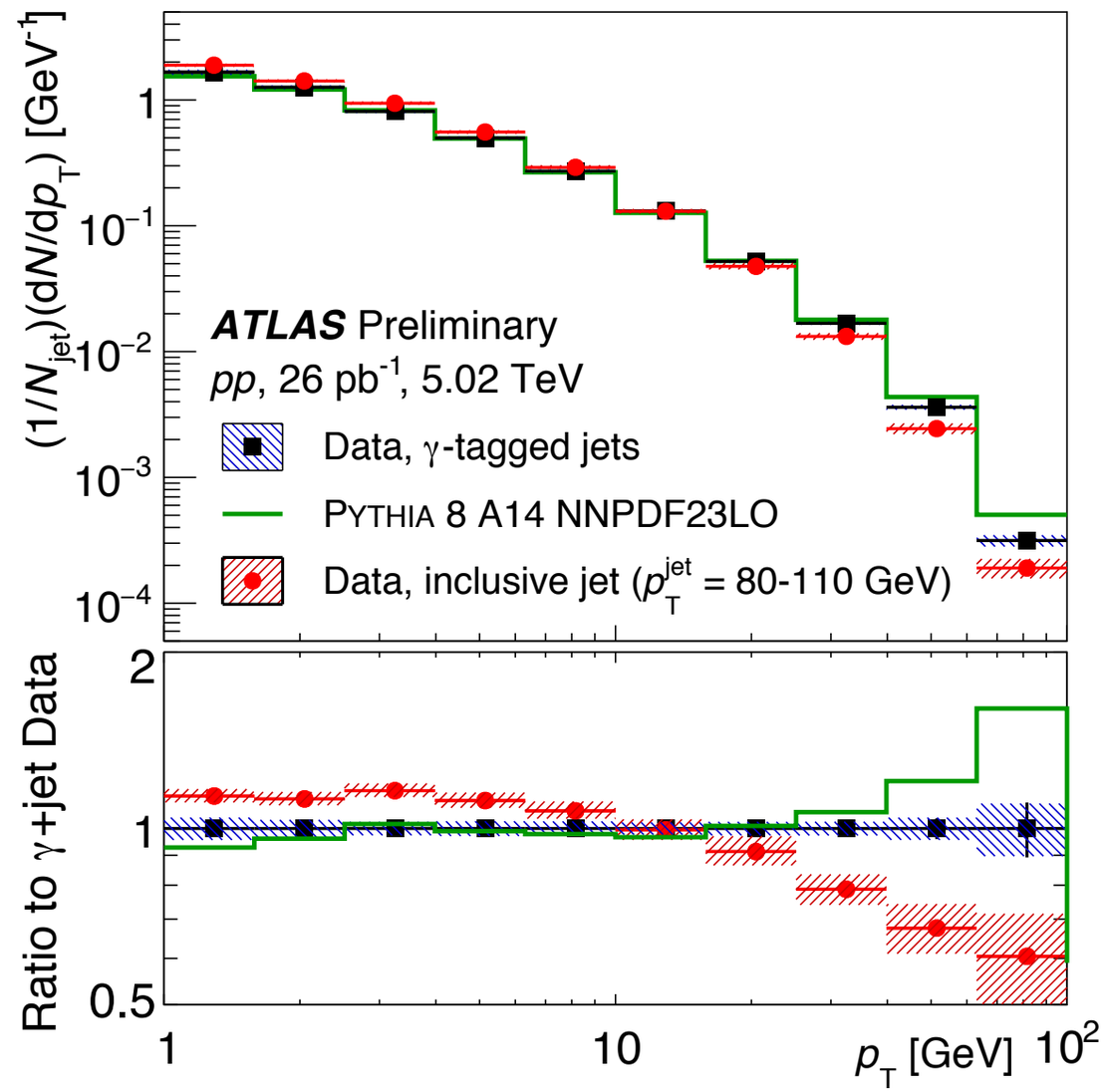




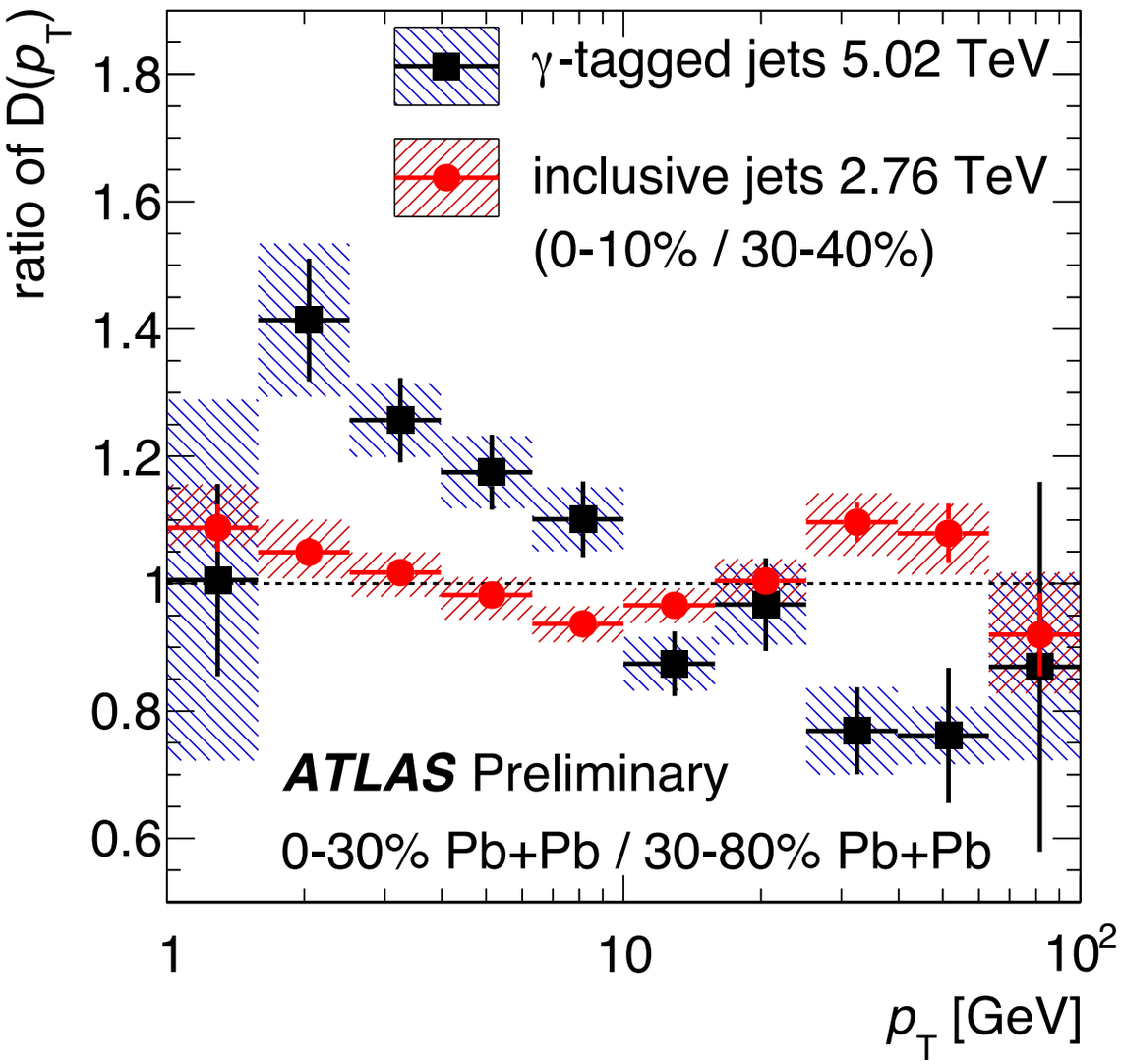
Comparing photon tagged to inclusive

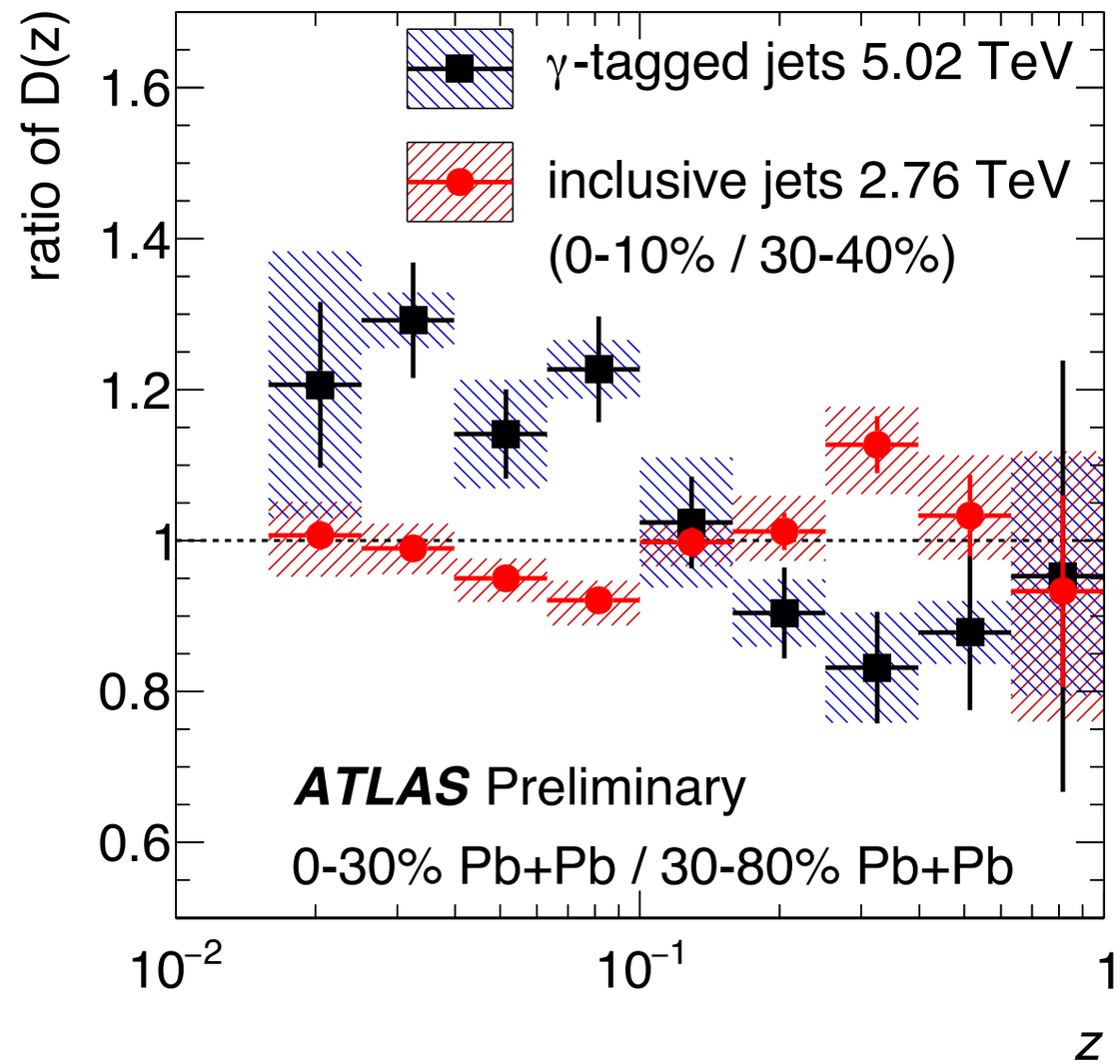
- Difference in shapes in the pp distributions between inclusive and photon tagged
  - Gamma tagged jets fragment hard



Harder fragmentation for q - jets in central collisions

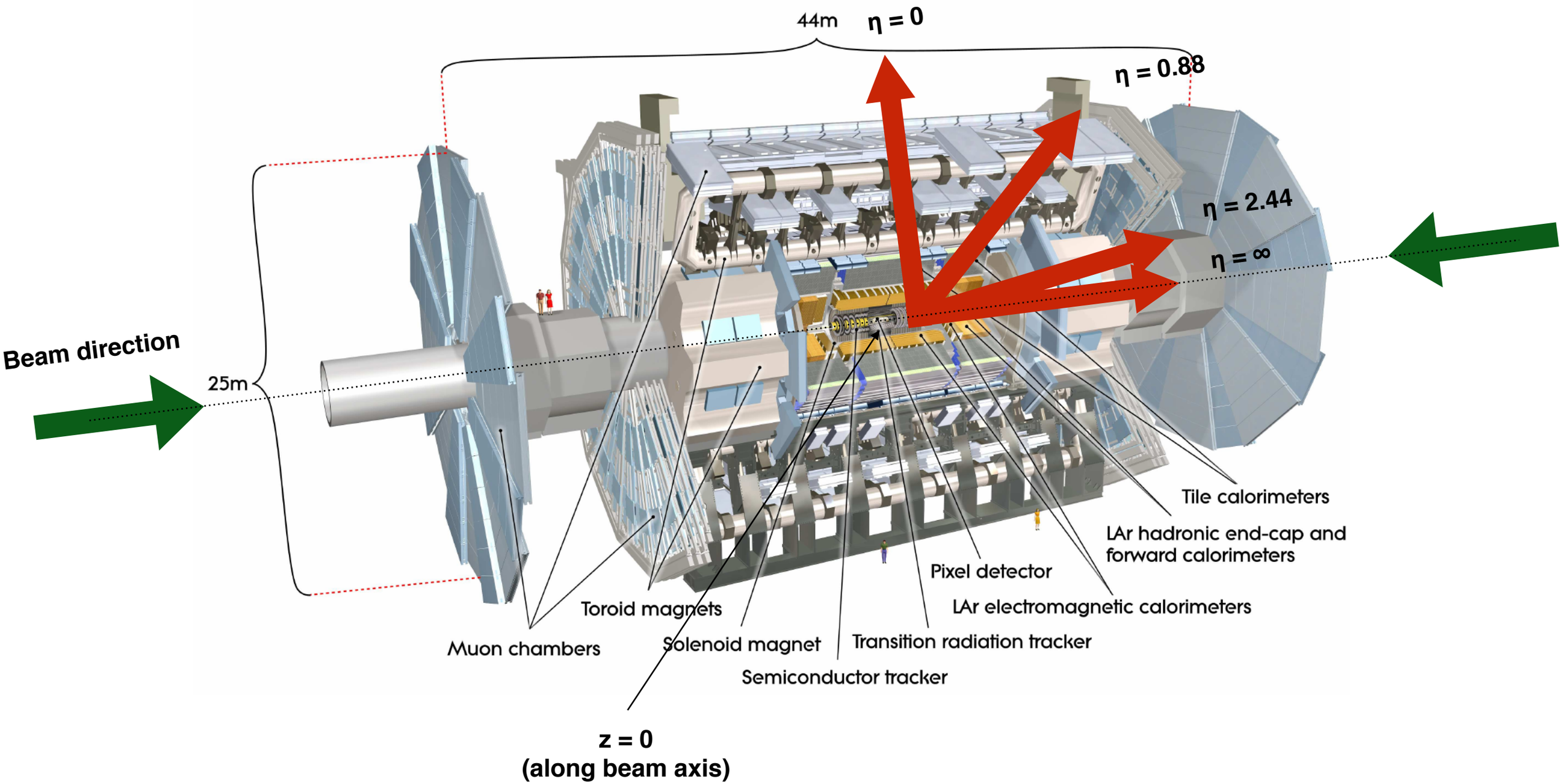
- $R_{CP(Dz),\ D(pT)}$ for photon tagged vs inclusive jets





The ATLAS Detector

$$\eta = -\ln\tan(\theta/2)$$

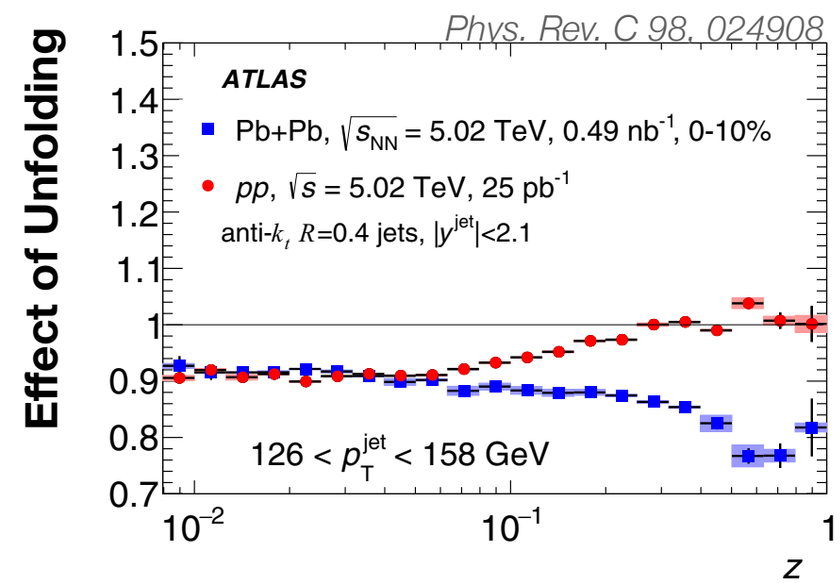


JINST 3 (2008) S08003

Unfolding

Unfolding

- Unfolding has up to a 20% effect



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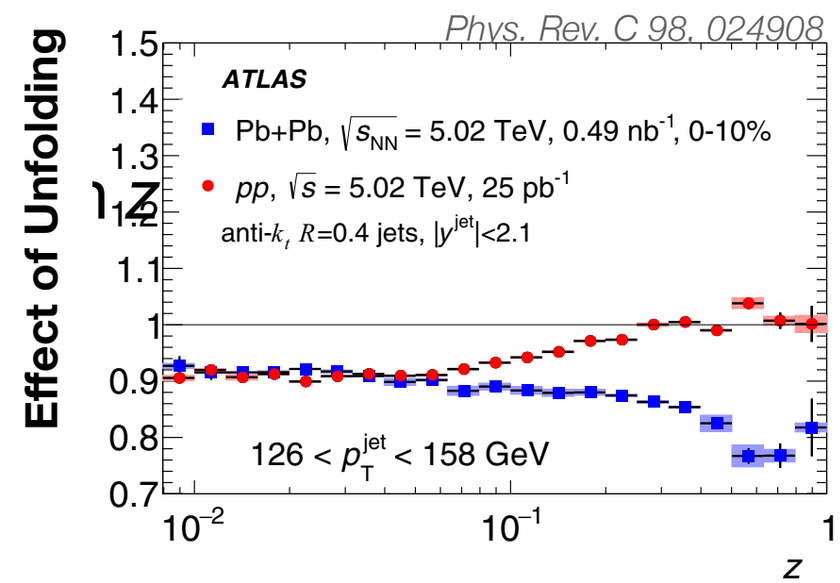
- Corrects for
  - Steeply falling distributions at large p_T, z



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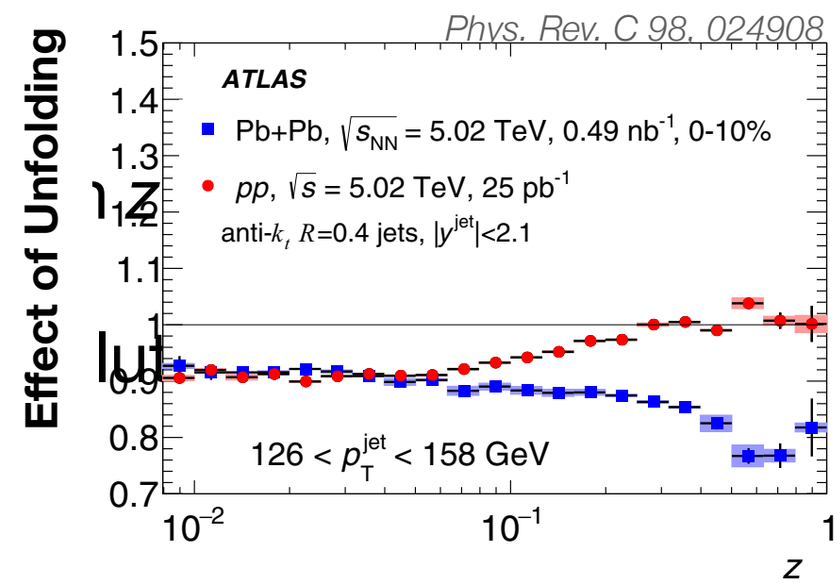
  - Finite jet energy and track momentum r



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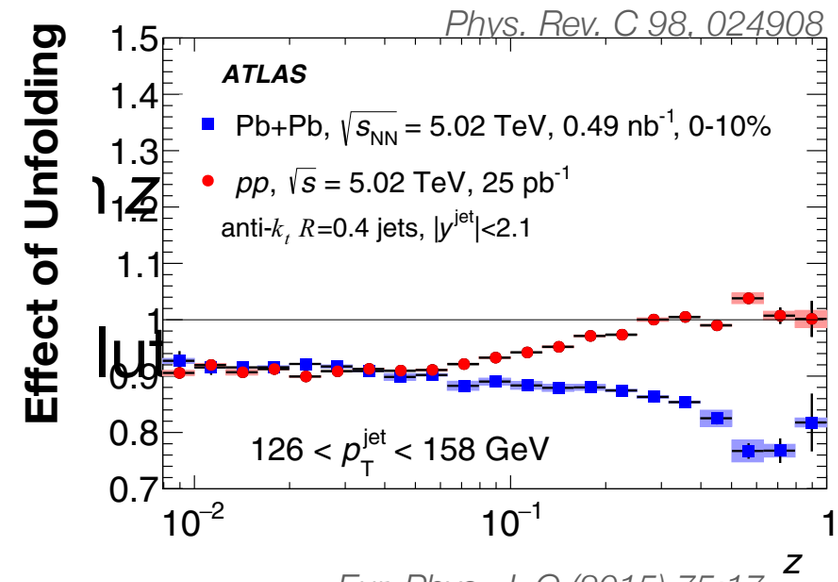
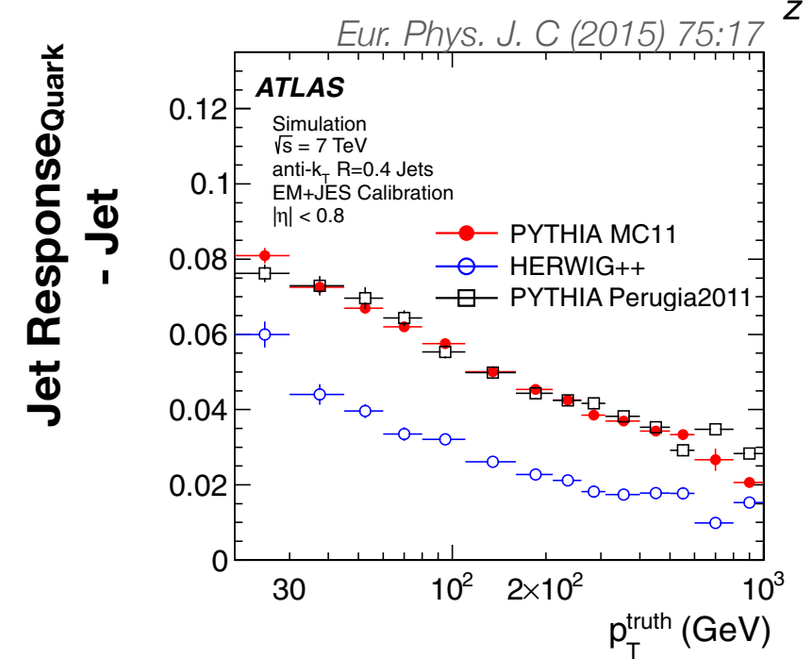
  - Parton flavor dependent jet response





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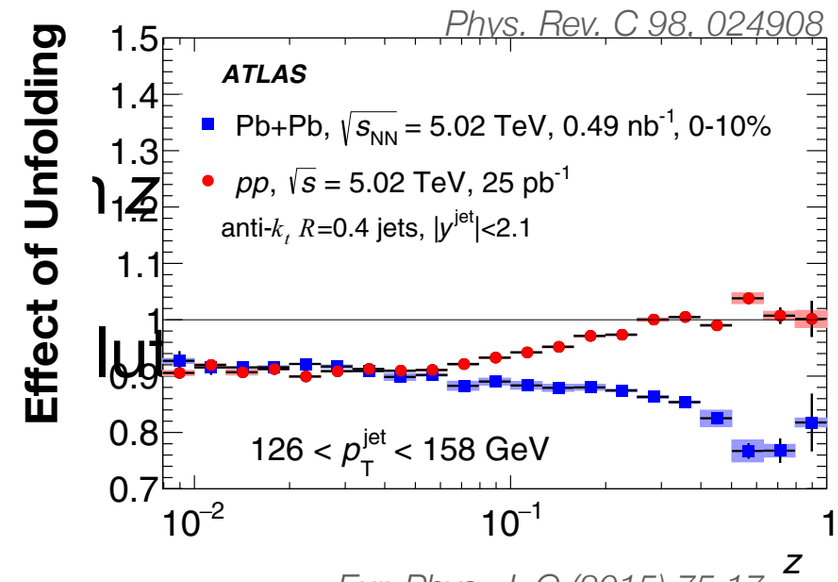
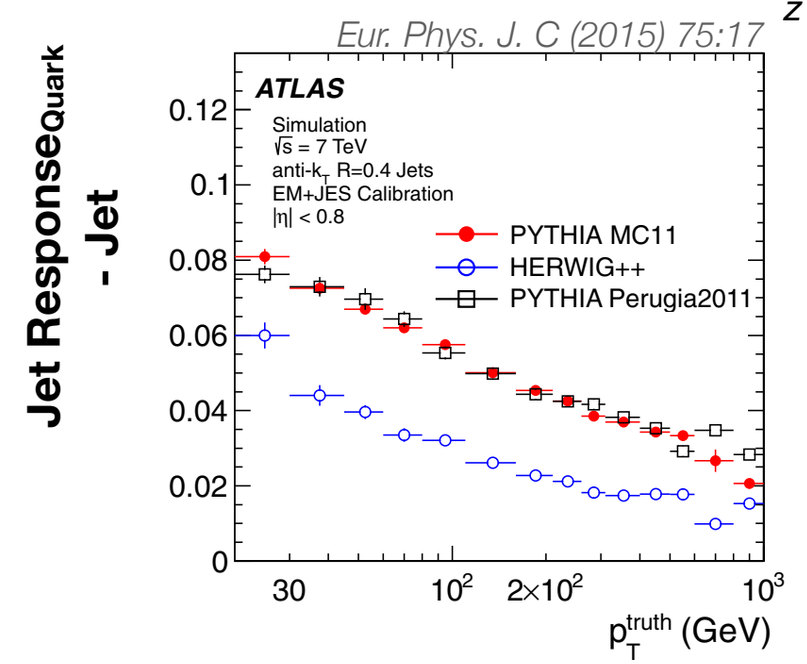
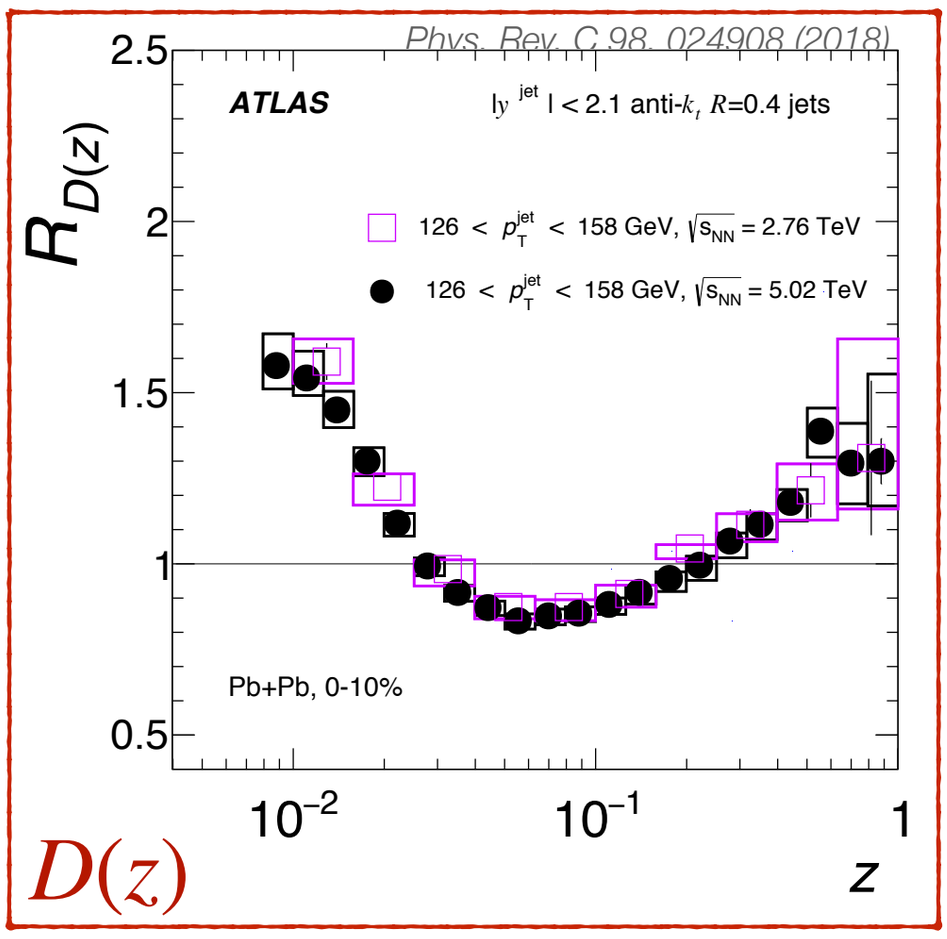


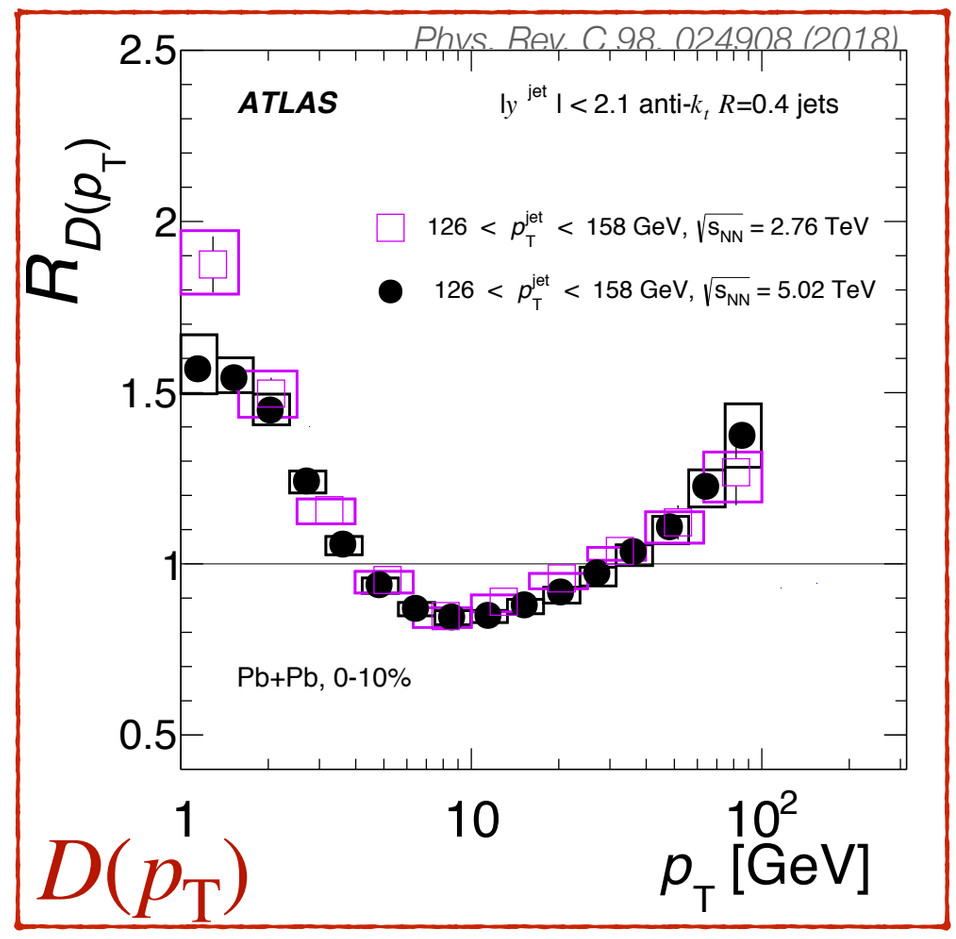


Unfolding enables direct comparison to theoretical models as well as other measurements

Collision energy dependence

- Comparing to lower collision energy
  - 5.02 TeV Phys. Rev. C 98, 024908 (2018) vs 2.76 TeV Eur. Phys. J. C 77 (2017) 379)





Jet p_T dependence

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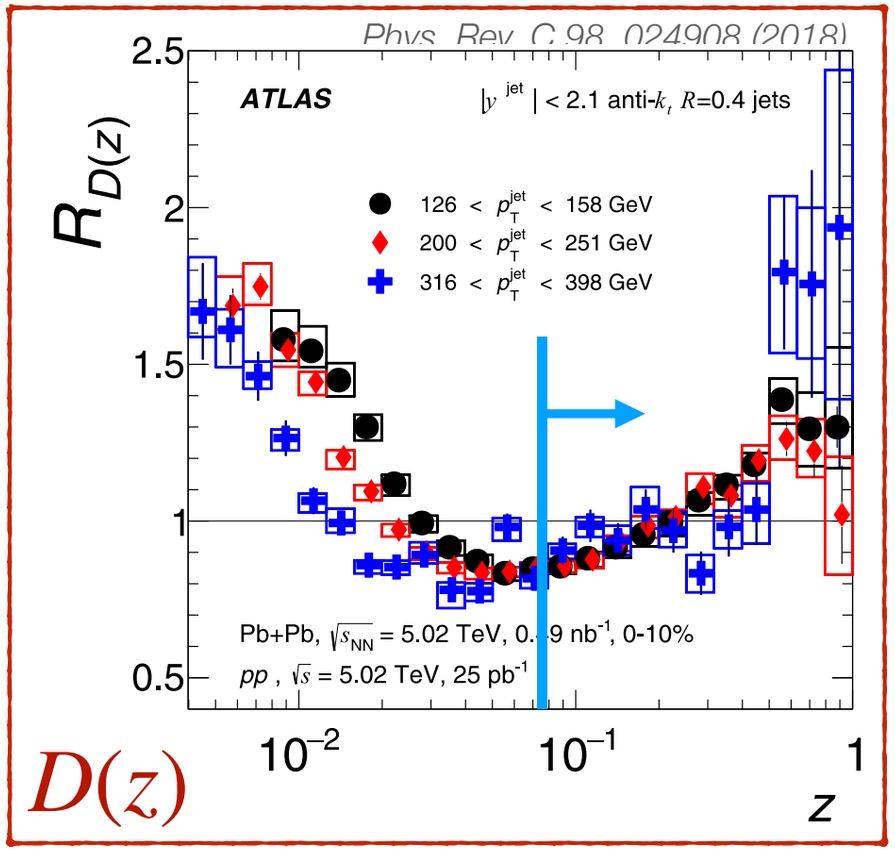
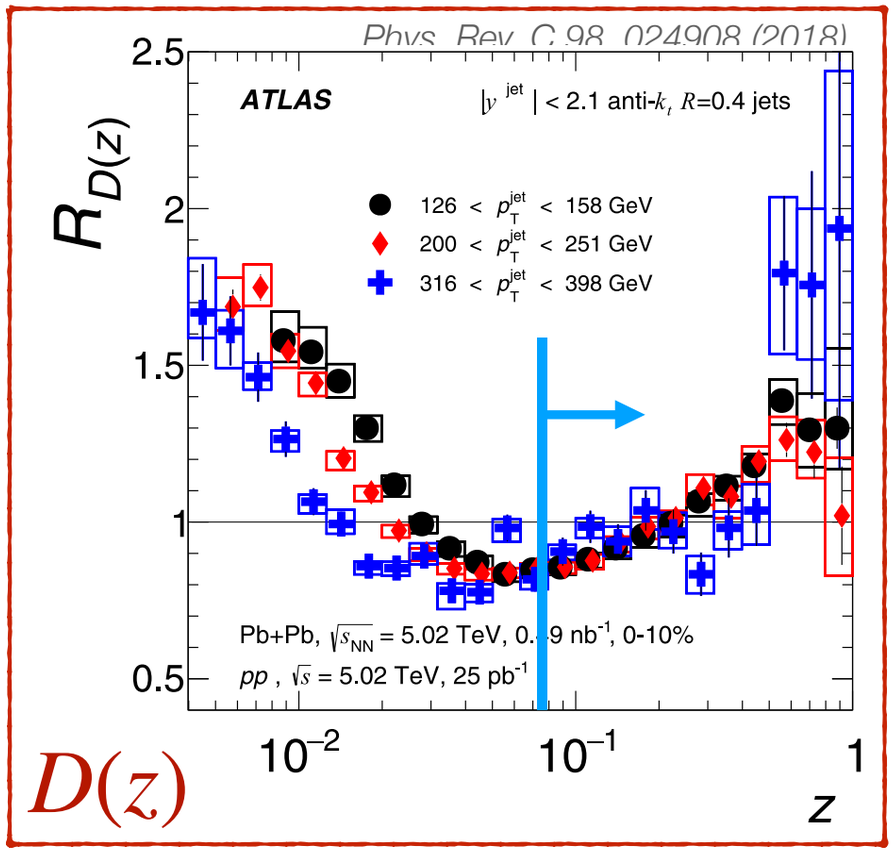
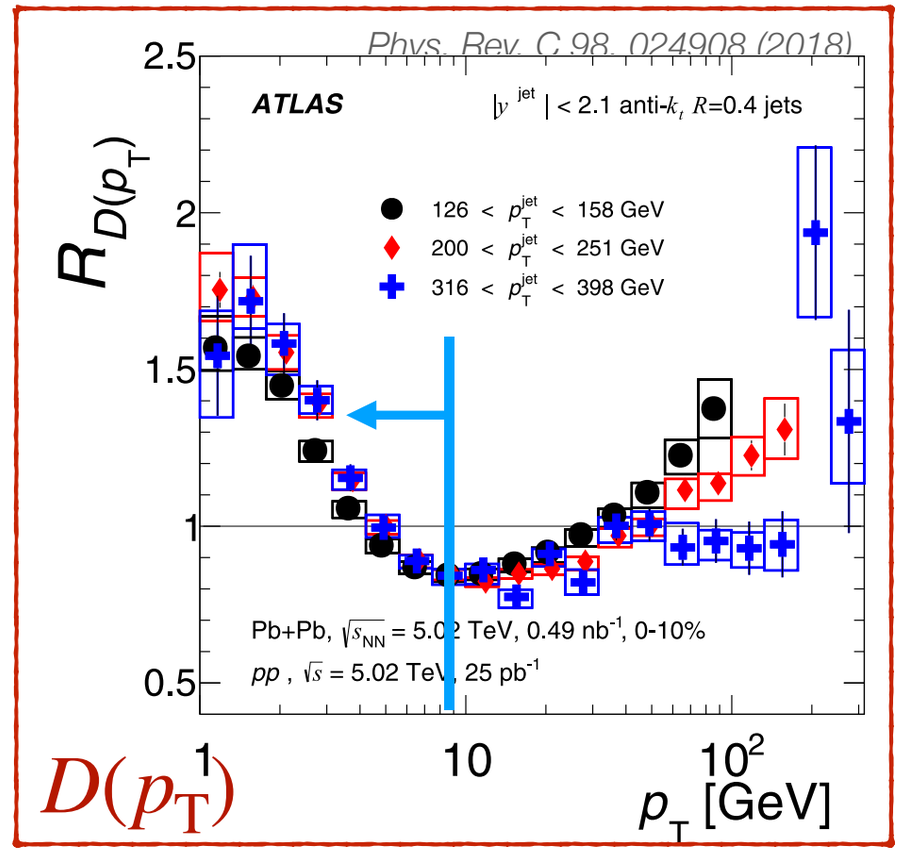


Jet p_T dependence

- Scaling with z: Fragmentation effects; scaling with p_T: medium response effects
  - No jet p_T dependence observed at high z for jets with p_T up to 400 GeV
  - Greater enhancement of soft fragments for high p_T jets





Quantifying soft excess

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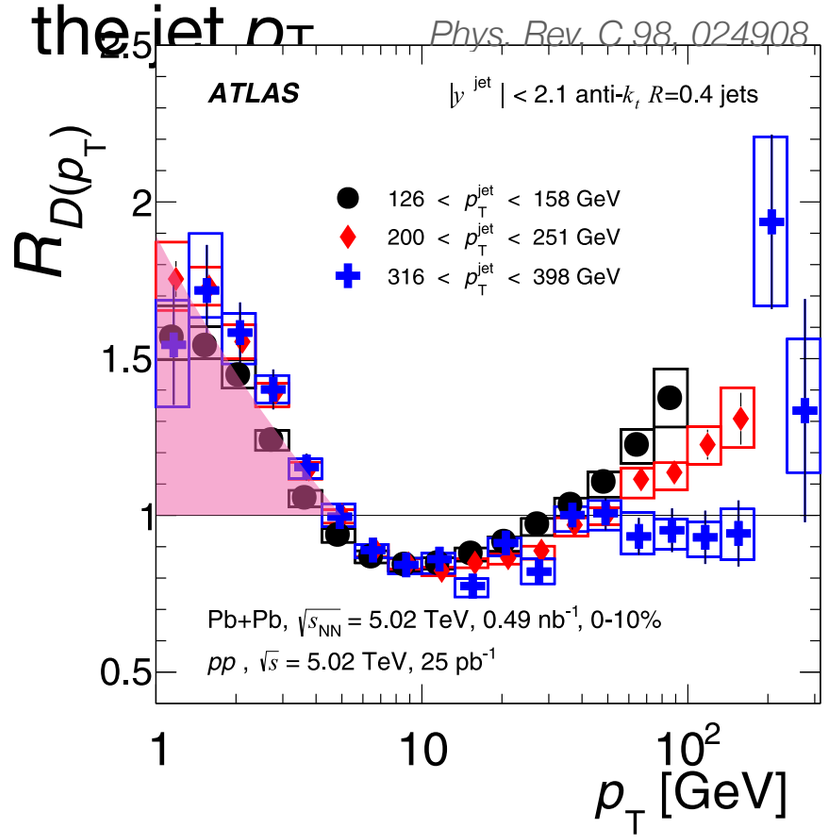

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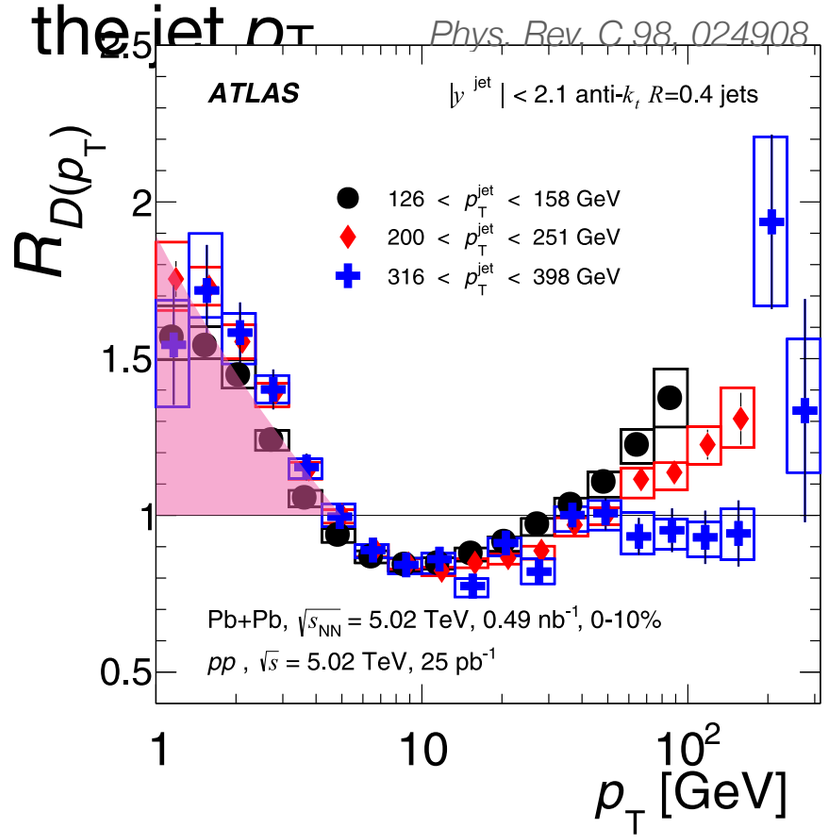

$$N^{\mathrm{ch}}|_{\mathrm{cent}} \equiv \int_{p_{\mathrm{T,min}}}^{p_{\mathrm{T,max}}} [D(p_{\mathrm{T}})|_{\mathrm{cent}} - D(p_{\mathrm{T}})|_{pp}] d\, p_{\mathrm{T}}$$

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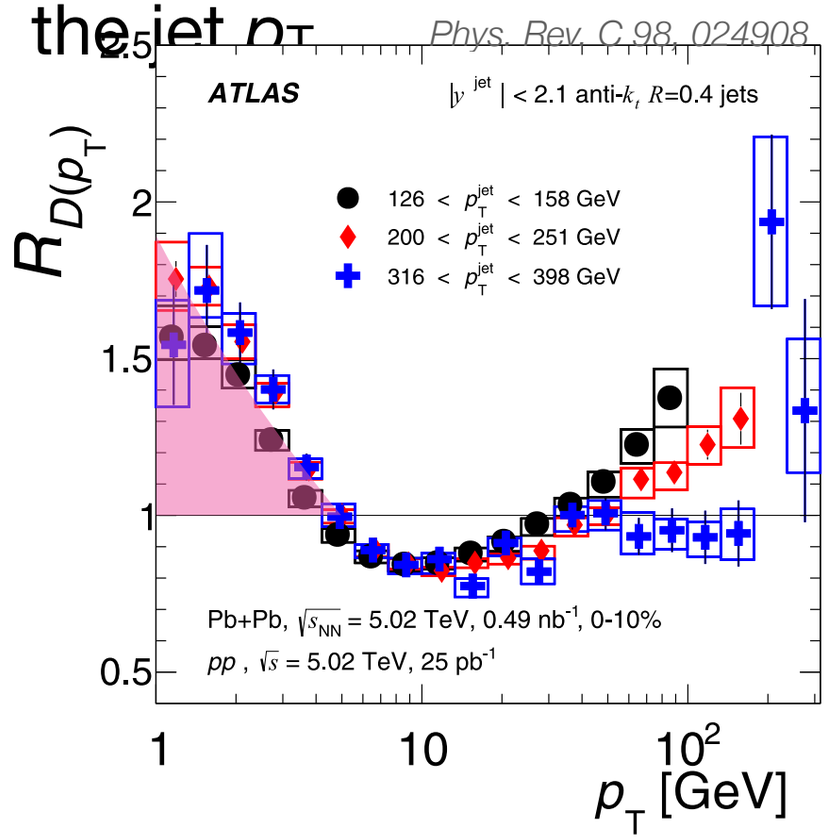

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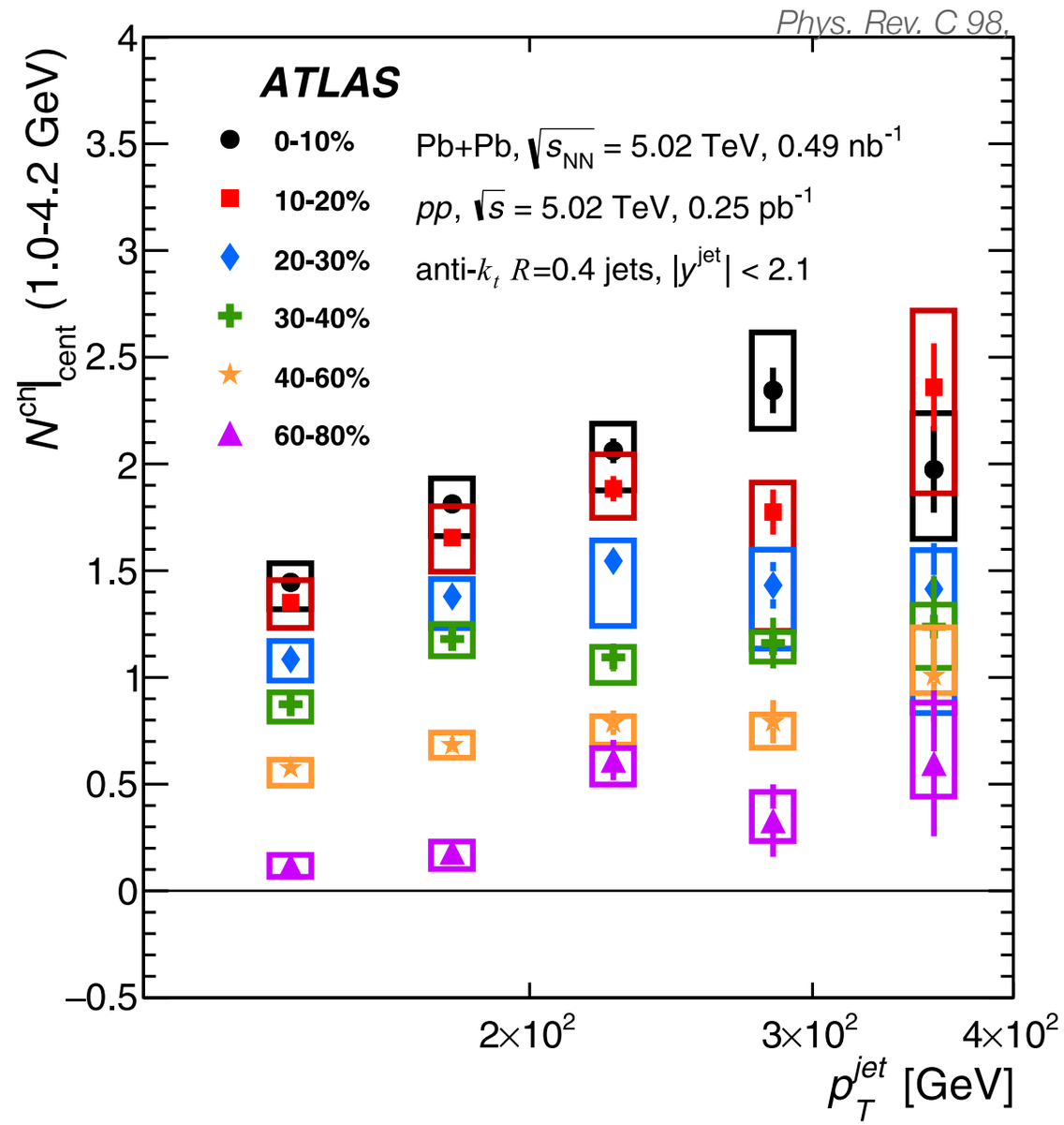

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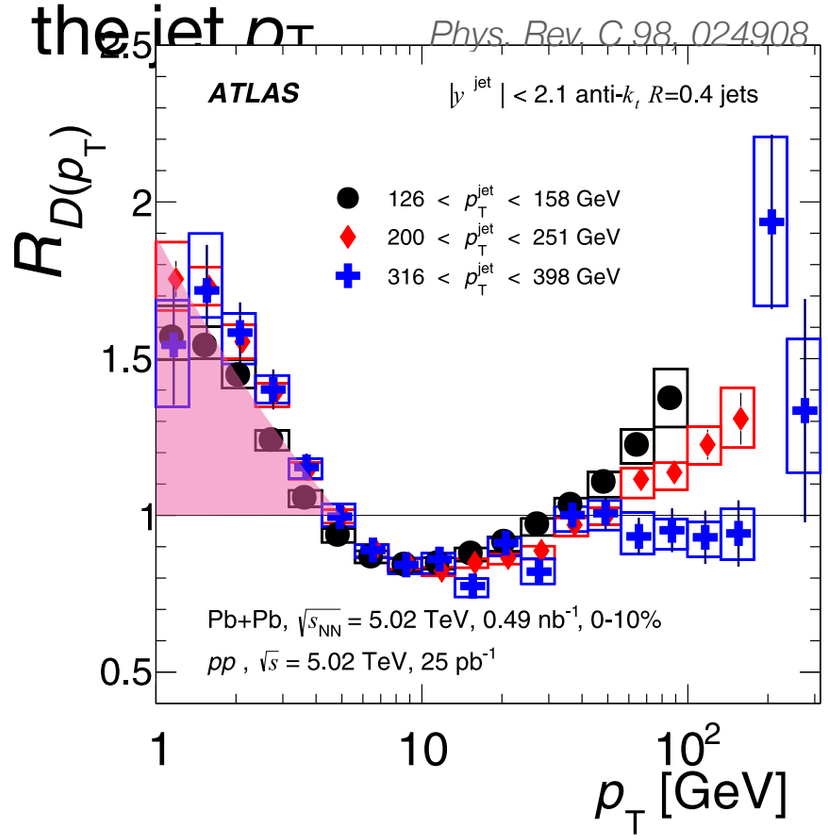

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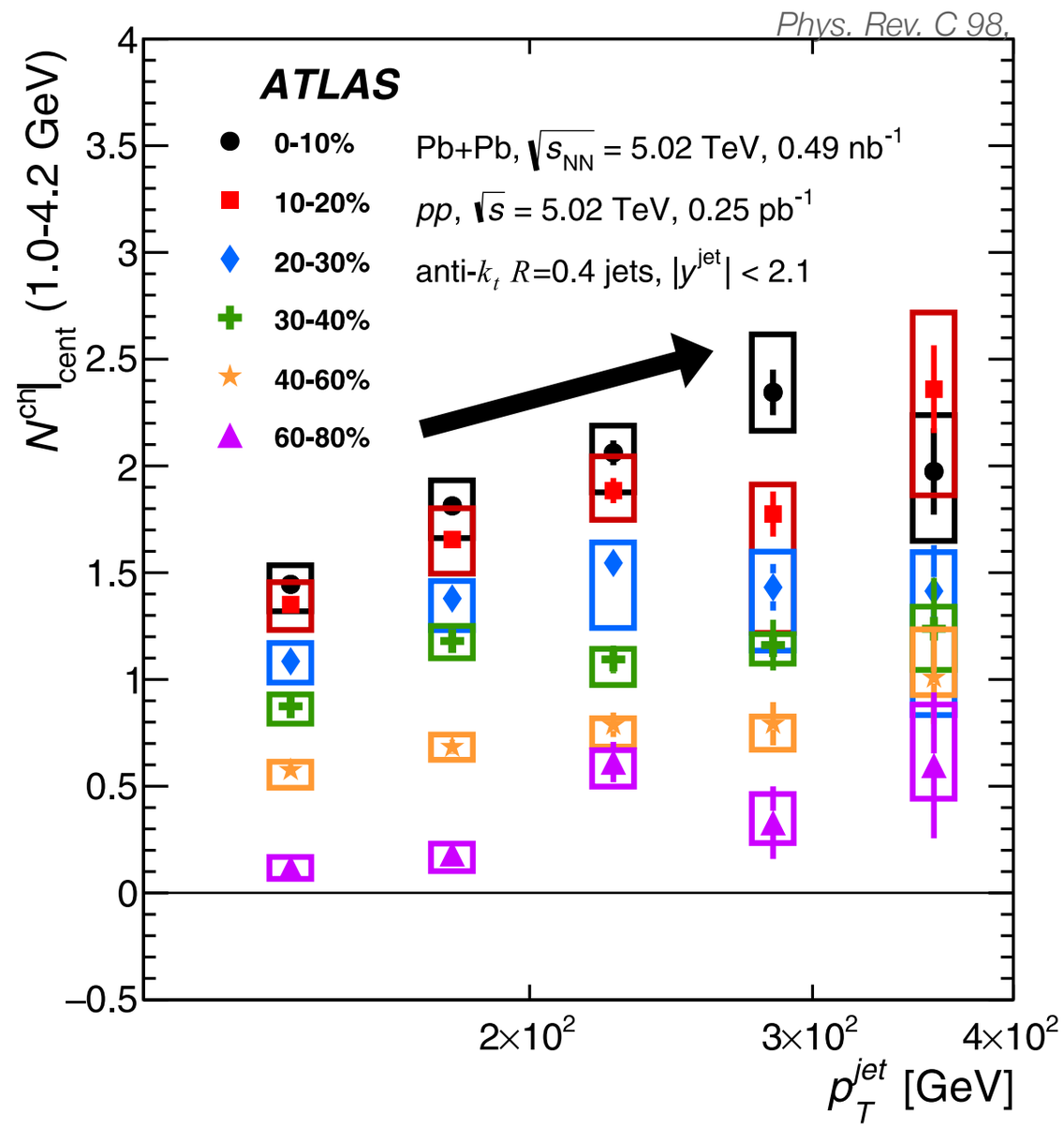

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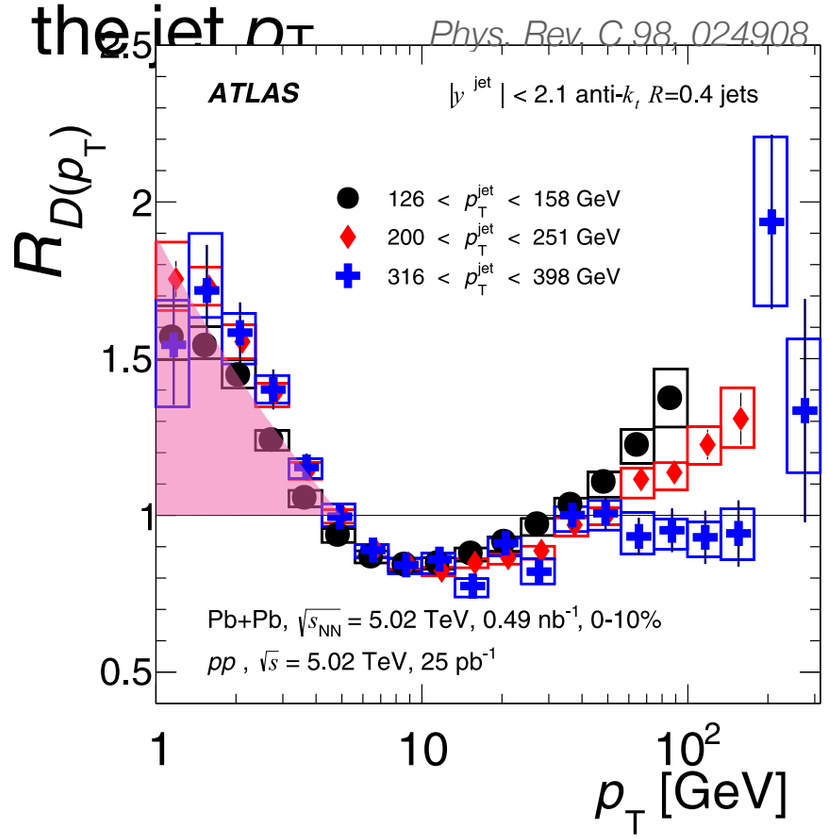

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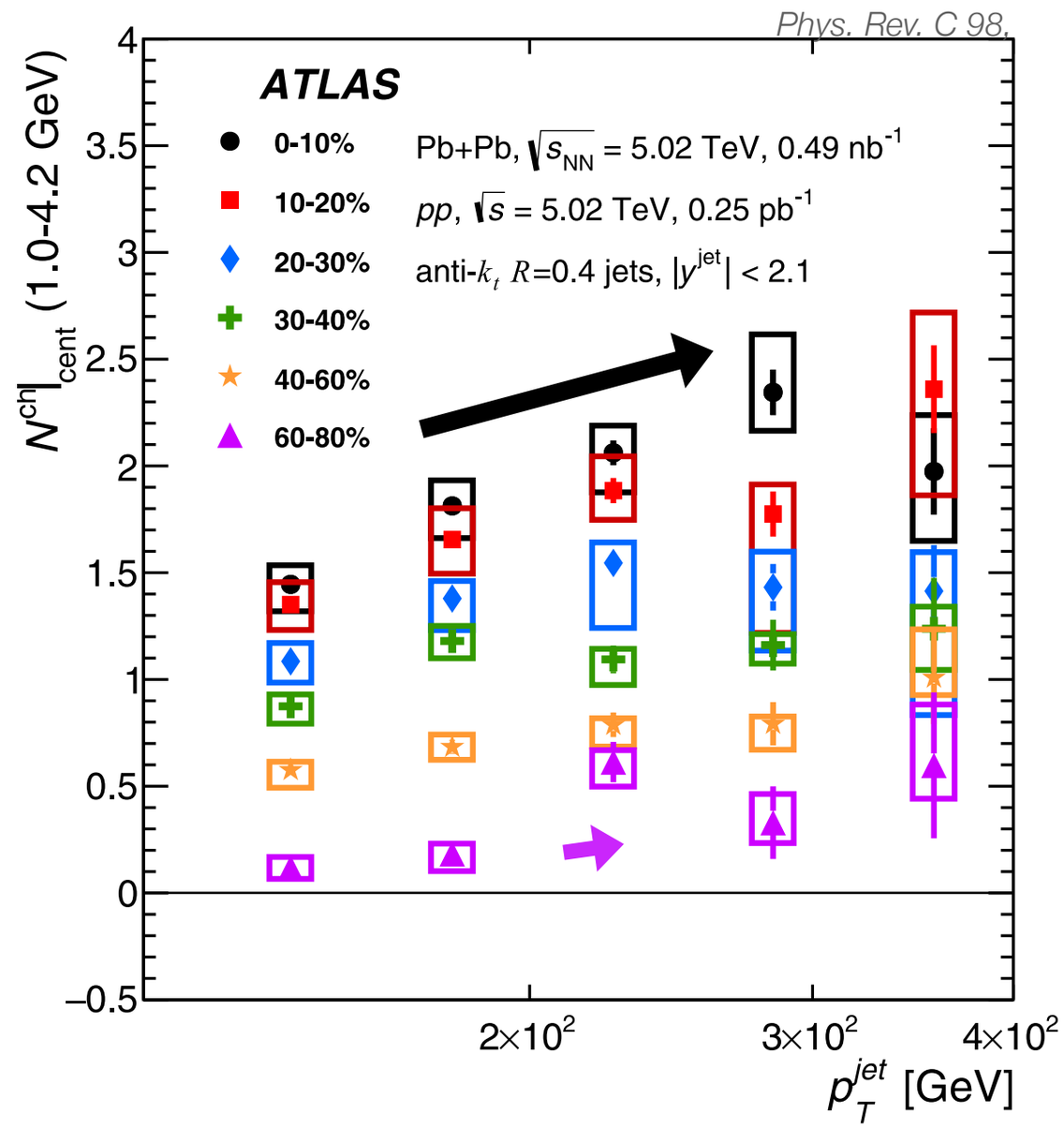
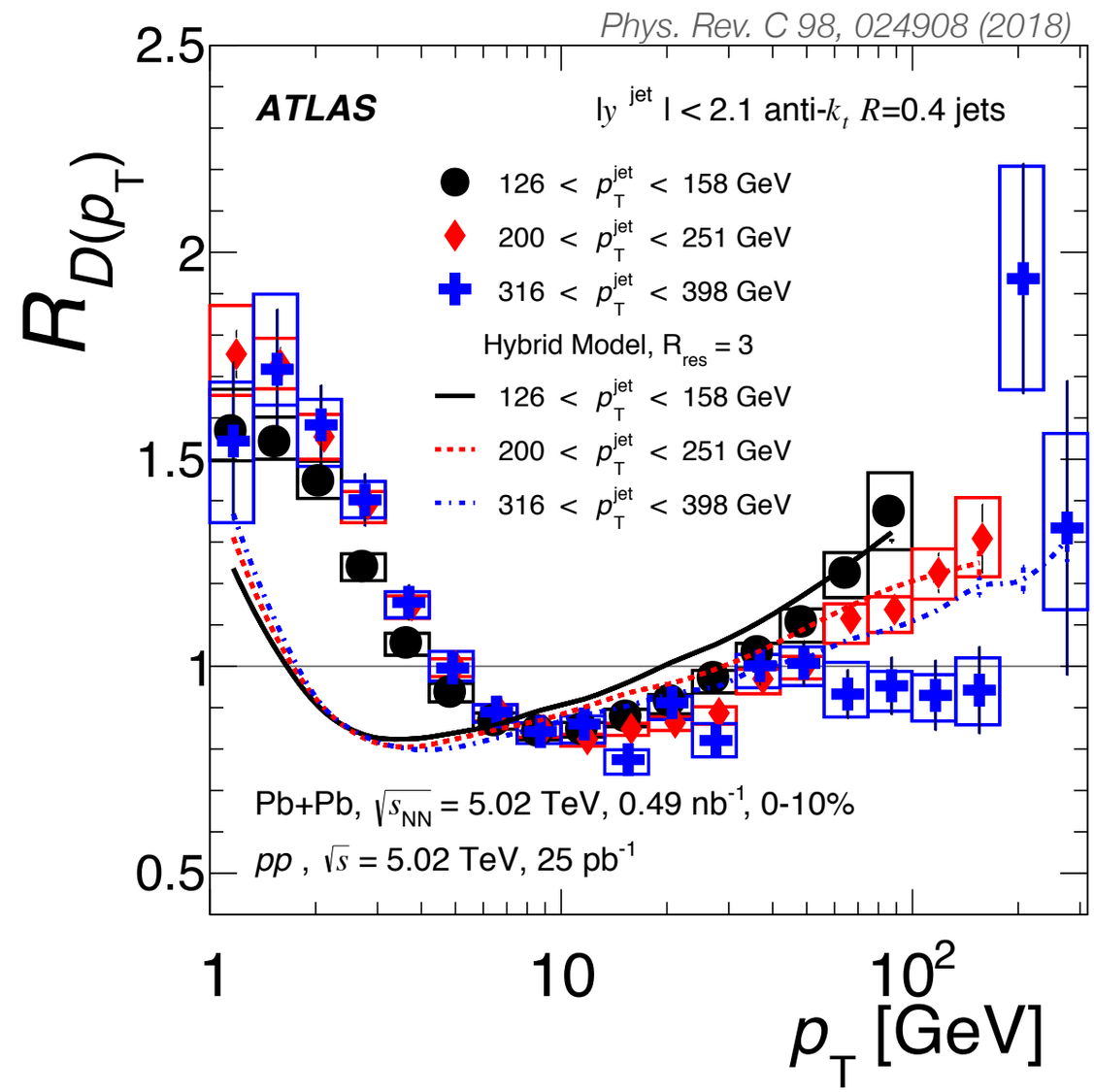


Comparing to theory

- Hybrid Model JHEP03(2018)010
  - Agreement at high p_T
  - Low p_T behavior not described well

Resolution effects in the hybrid strong/weak coupling model

Zachary Hulcher,[a] Daniel Pablos[b] and Krishna Rajagopal[a]

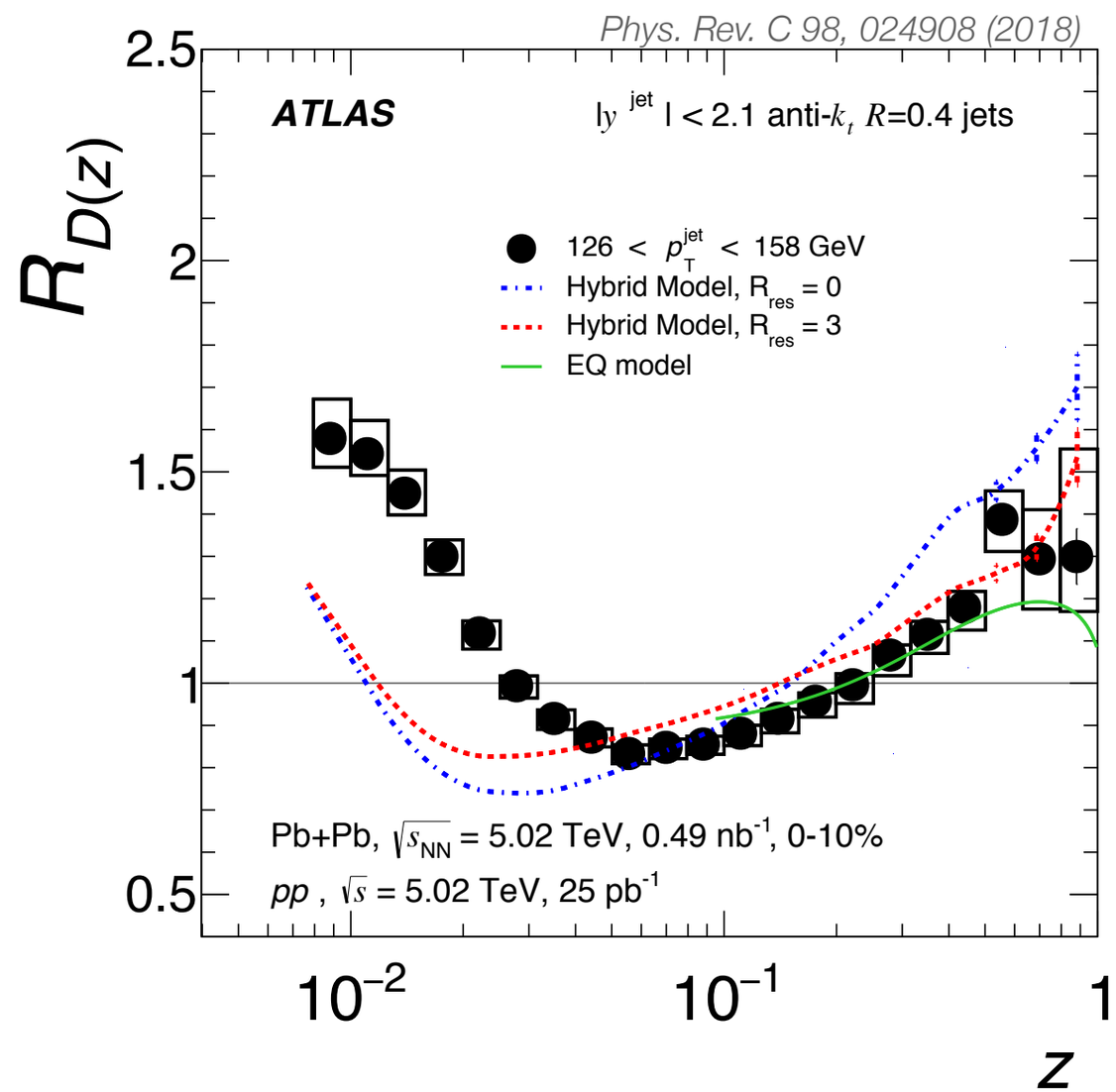


Comparing to theory

- Effective Quenching (EQ) Eur.Phys.J. C76 (2016) 50
  - Agreement at high *z*
  - Low *z* behavior not part of EQ

Interpreting single jet measurements in Pb+Pb collisions at the LHC

Martin Spousta[1,a], Brian Cole[2,b]

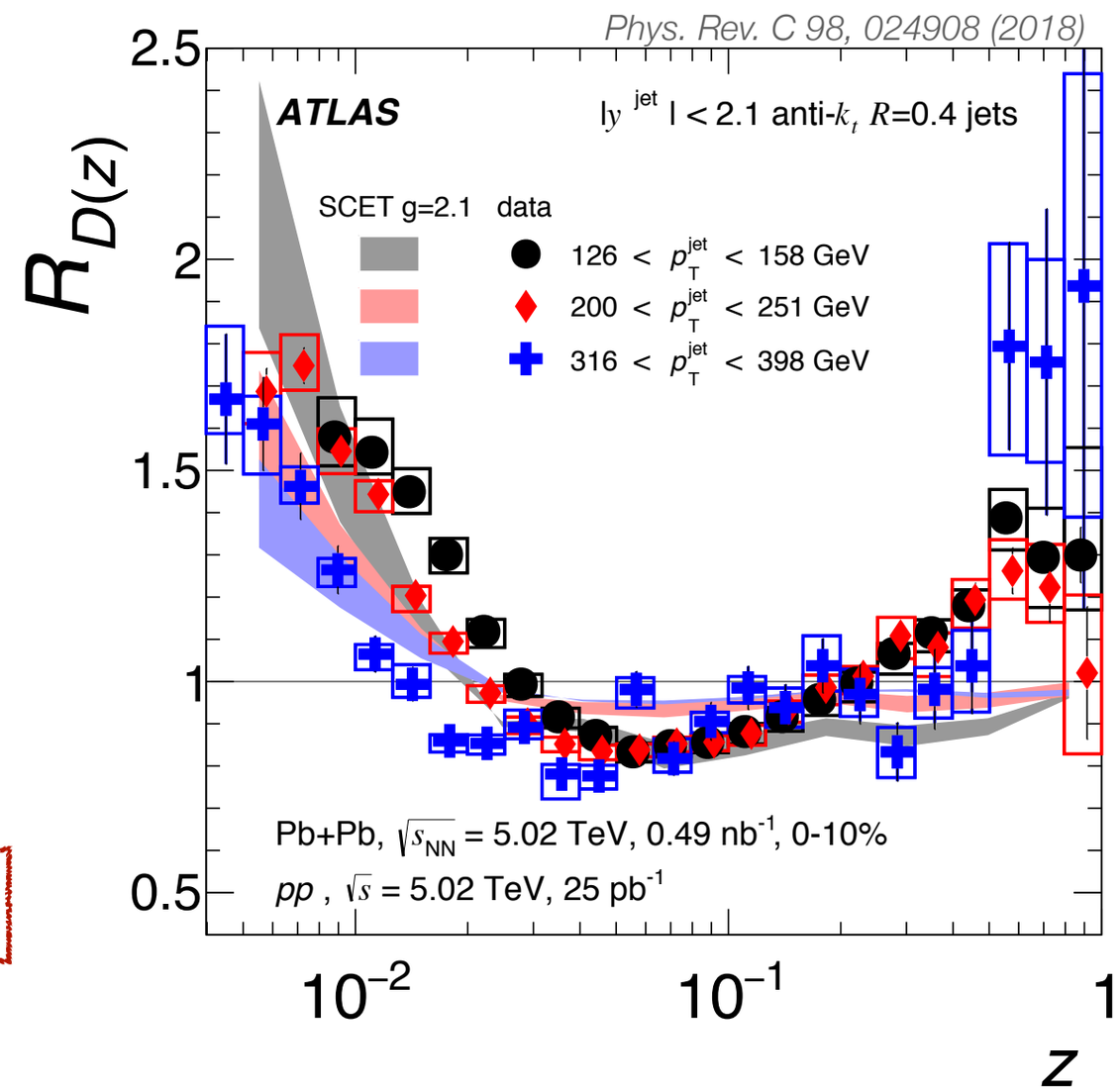


Comparing to theory

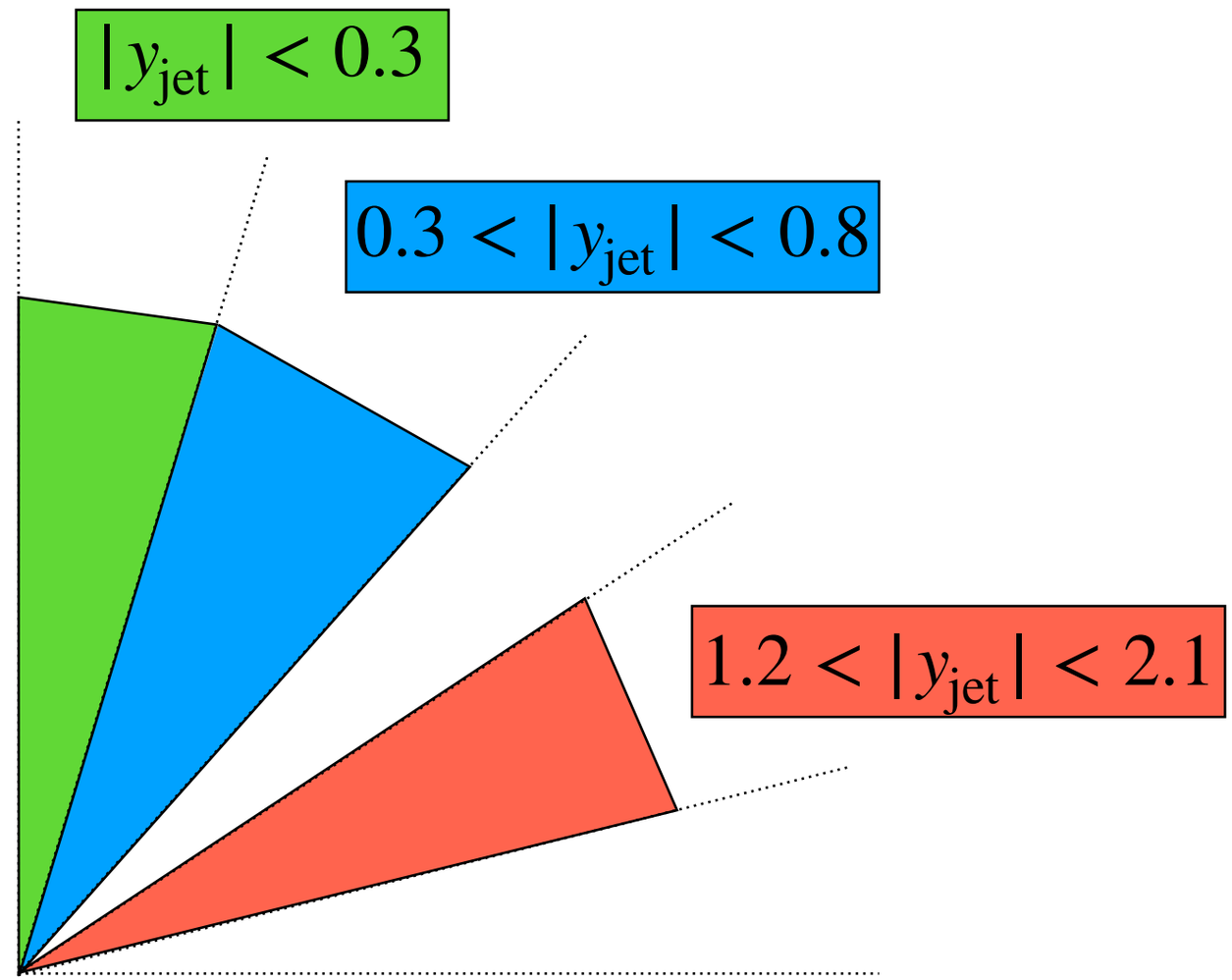
- Soft Collinear Effective Theory Phys. Rev. D 93, 074030 (2016)
  - Agreement at low *z*
  - High *z* excess is not described
- Hybrid model, EQ, and SCET can be used to describe other measurements:
  - ɣ-jet balance: arXiv:1809.07280
  - ɣ-jet fragmentation: ATLAS-CONF-2017-074
  - jet R_{AA}: arXiv:1805.05635

Jet quenching from QCD evolution

Yang-Ting Chien,[1,*] Alexander Emerman,[2,†] Zhong-Bo Kang,[1,‡] Grigory Ovanesyan,[3,§] and Ivan Vitev[1,¶]



Rapidity Dependence



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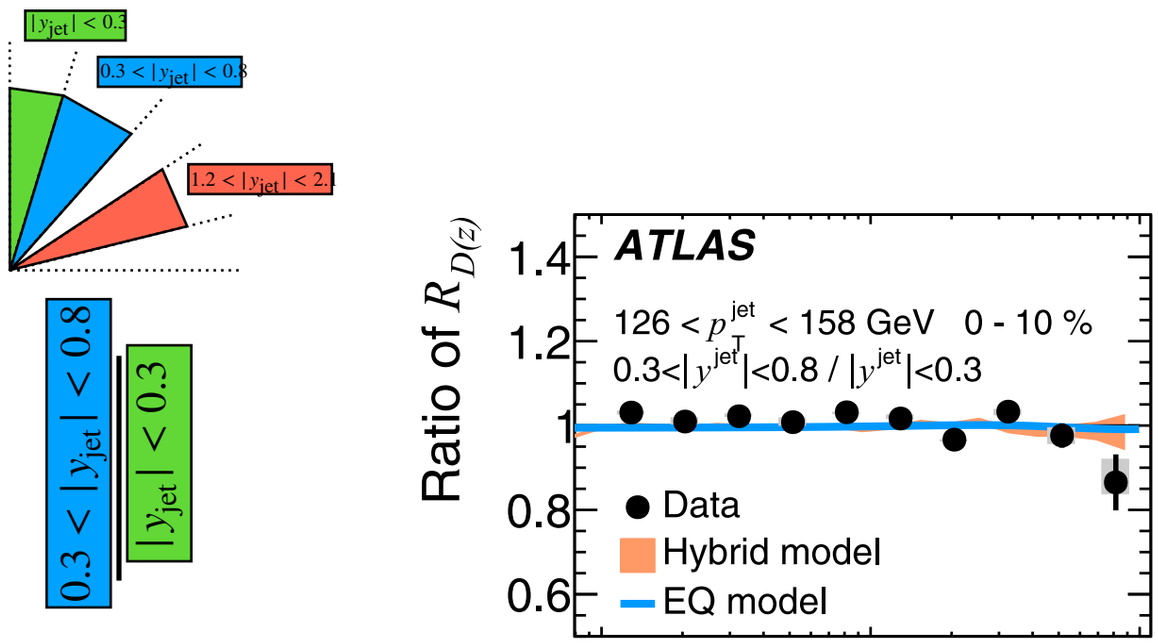
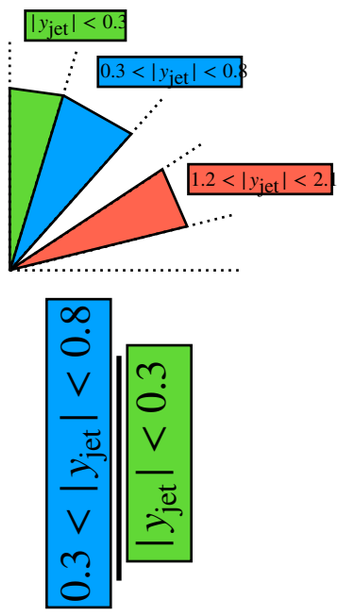
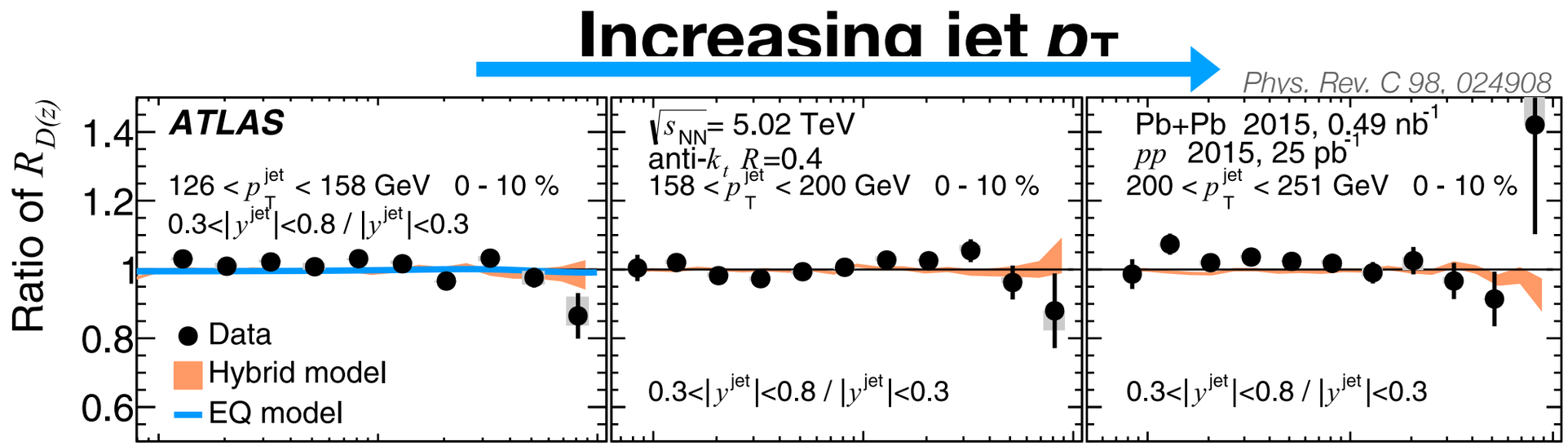


Rapidity Dependence





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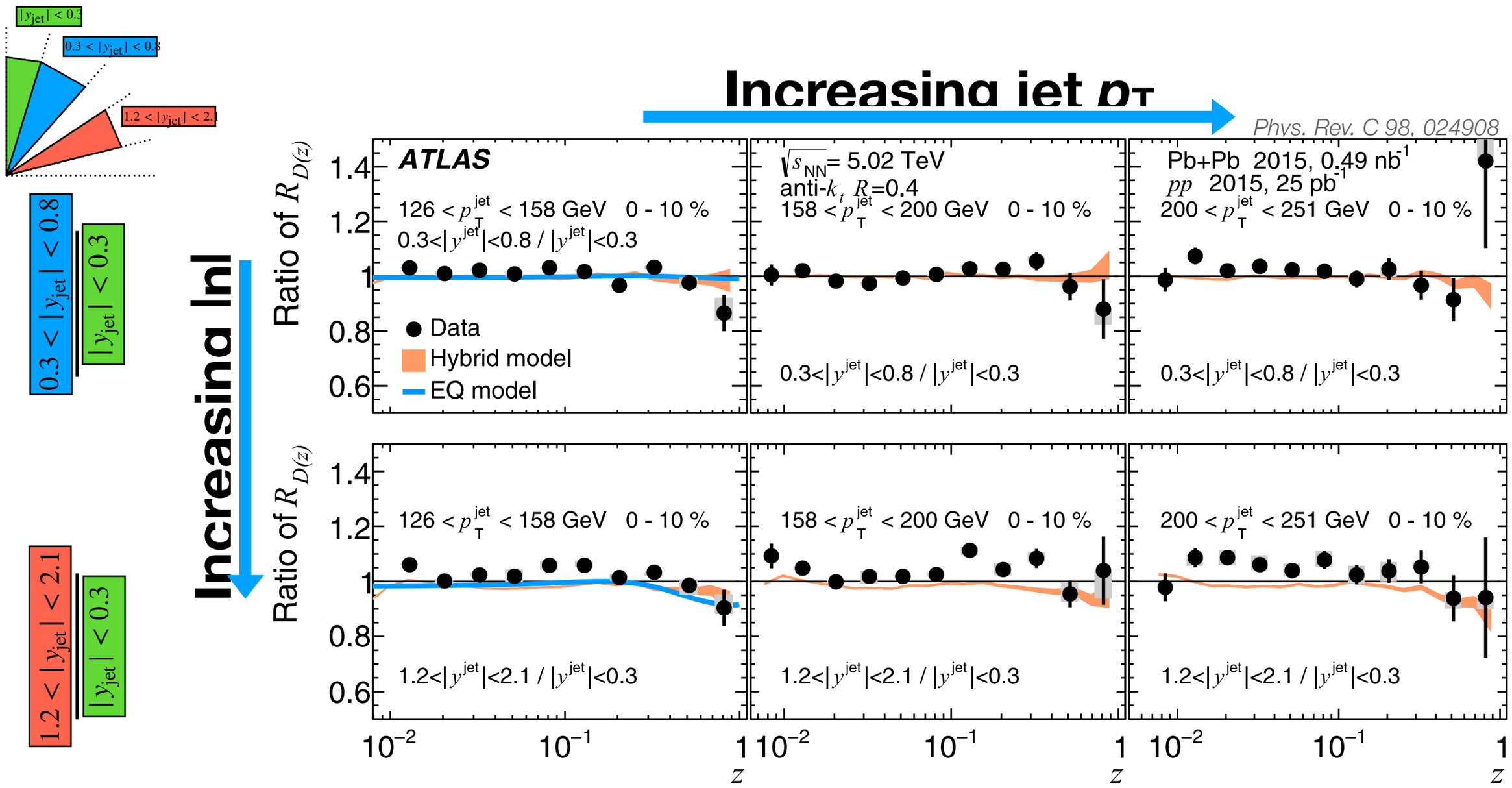

Modification of radial distribution

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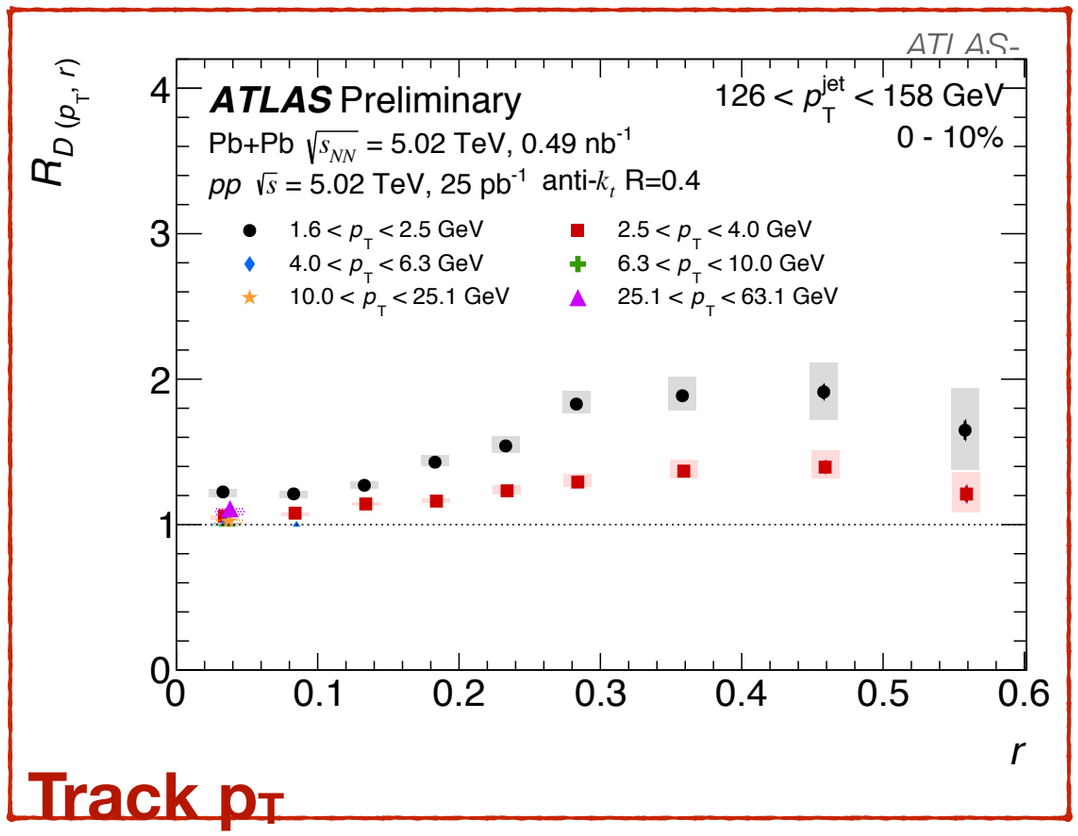
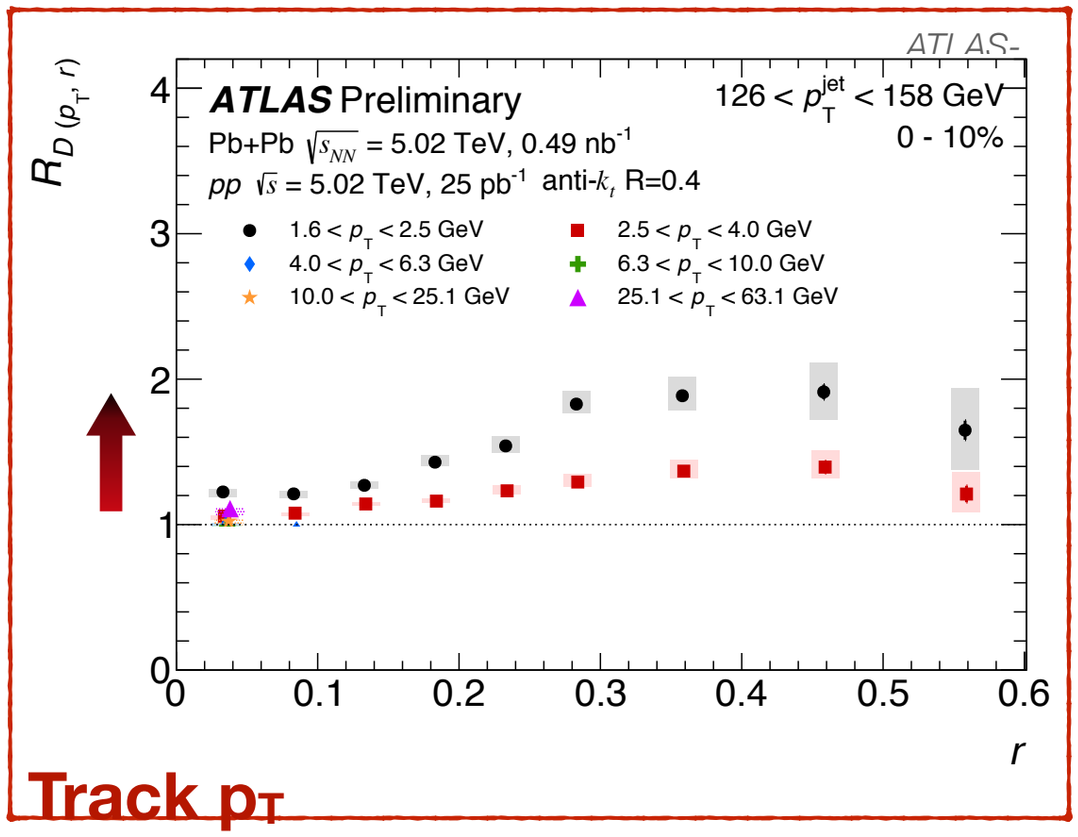


Track p_T

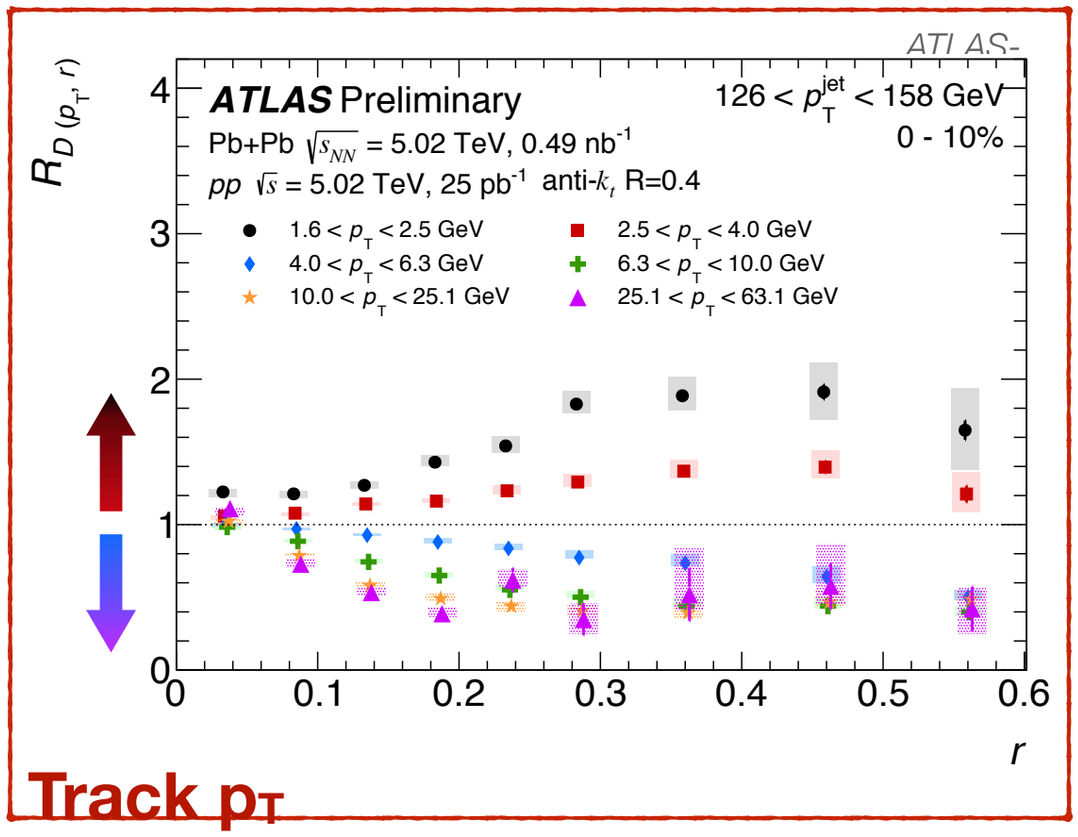
Modification of radial distribution

- Enhancement for particles with p_T < 4 GeV



Modification of radial distribution

- Enhancement for particles with $p_T < 4$ GeV
- Depletion for particles with $4 < p_T < 63$ GeV



Modification of radial distribution

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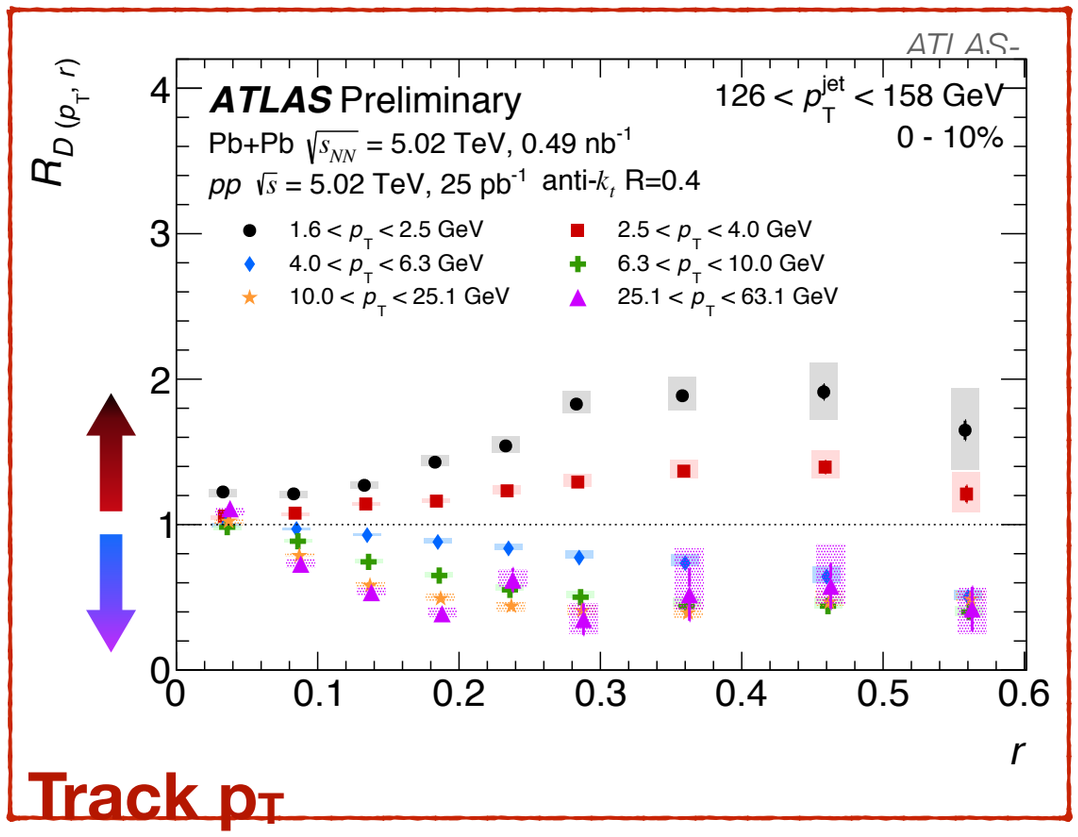

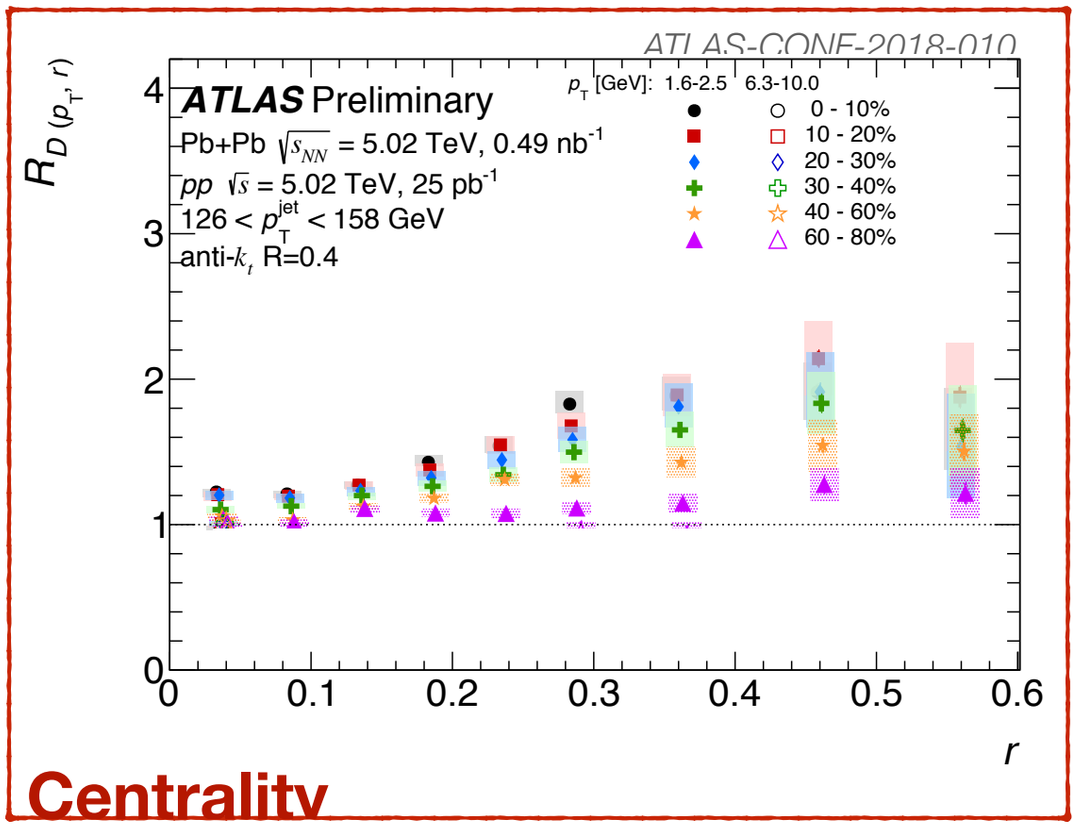

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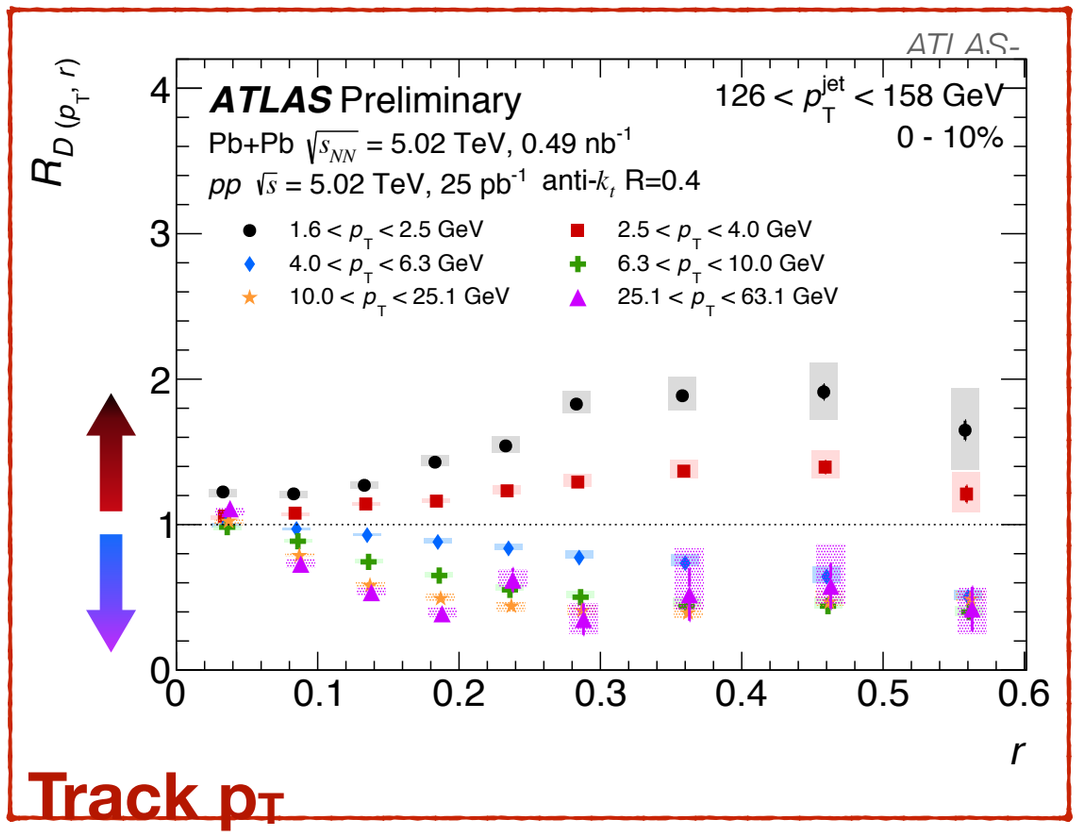

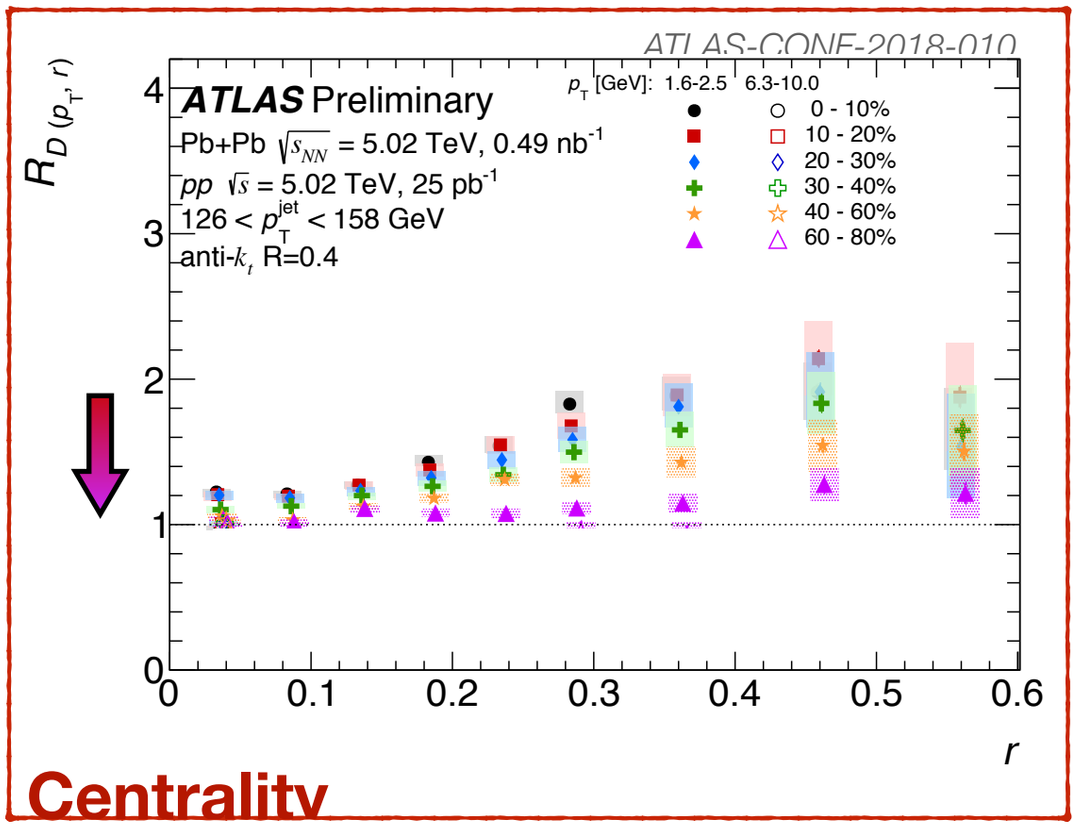

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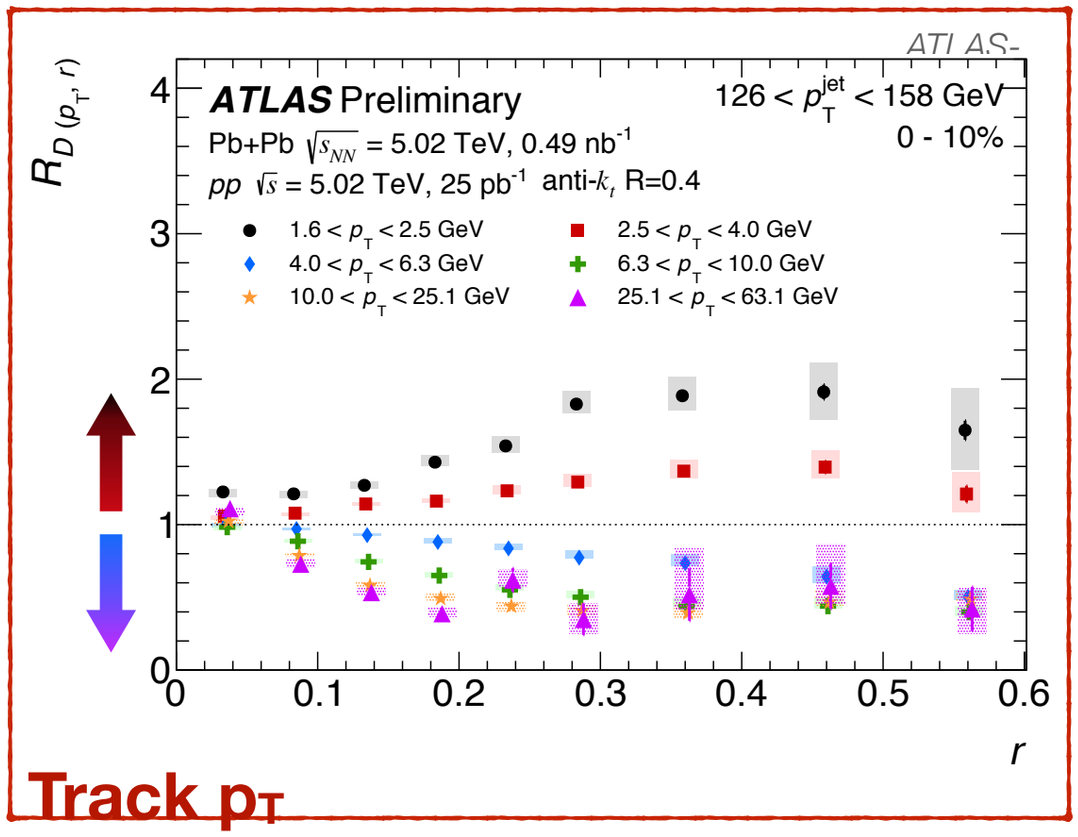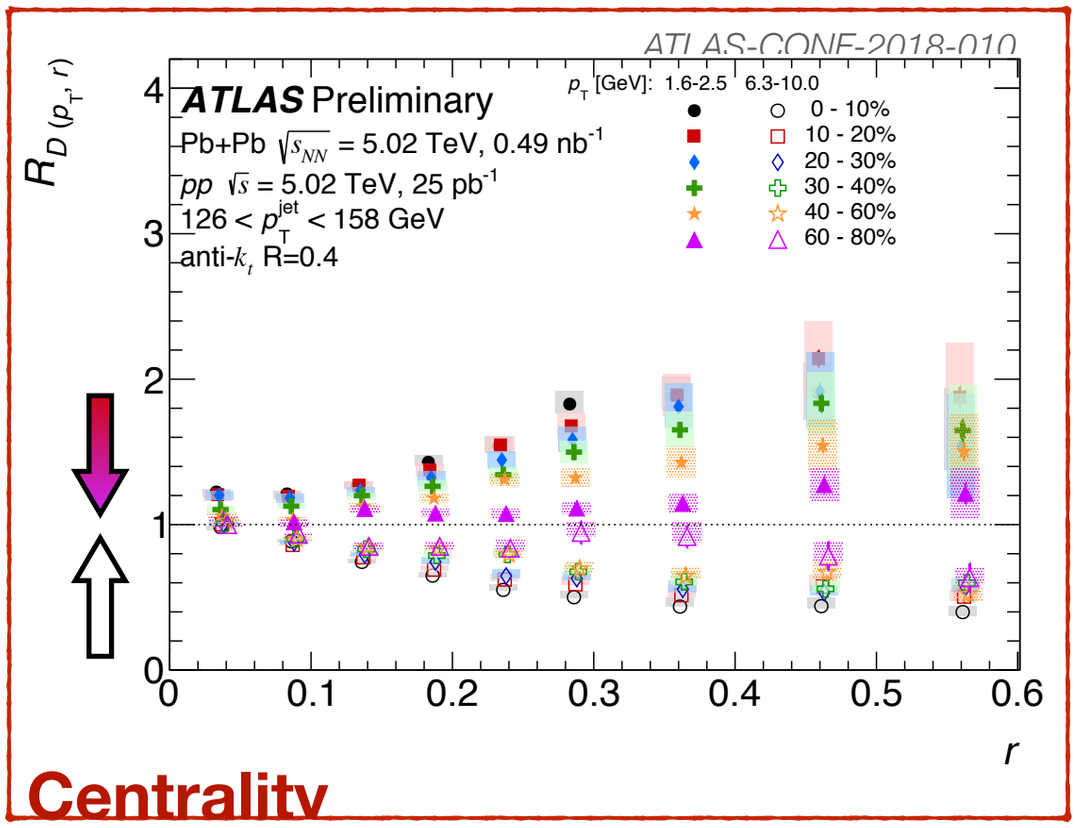
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