Jet Quenching from Light to Dense Systems

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LIP

TÉCNICO LISBOA

February 8th 2021

Opportunities of OO and pO collisions at the LHC, CERN (Remote)

QGP in dense systems

- PbPb and AuAu presents consistent signatures of a QGP formation:
  - Azimuthal anisotropy in n-particle correlations (collective flow)
  - Increase of strange hadrons yields (strangeness enhancement)
  - Suppression of single hadron spectra (energy loss)

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[STAR: Phys. Rev. Lett. 89 (2002) 202301]
[PHENIX: Phys.Rev.Lett. 88 (2002) 022301]

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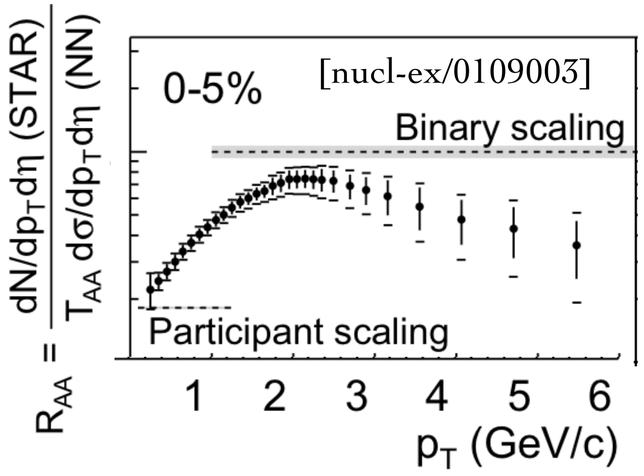
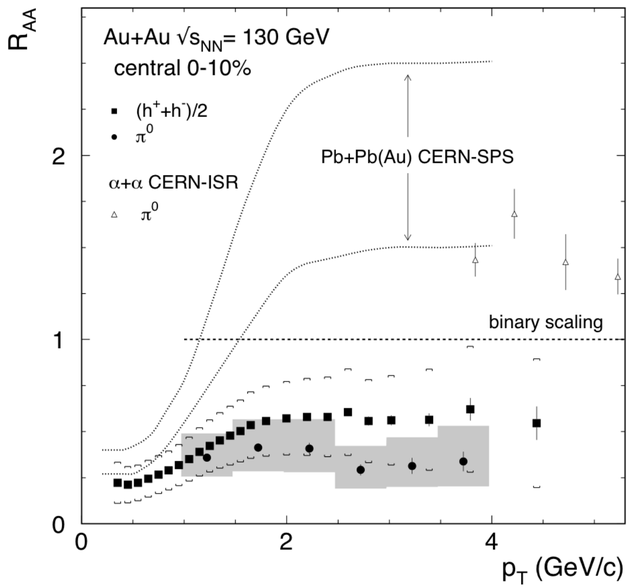


[nucl-ex/0109003]



QGP in dense systems

[ATLAS: JHEP 09 (2015) 050]

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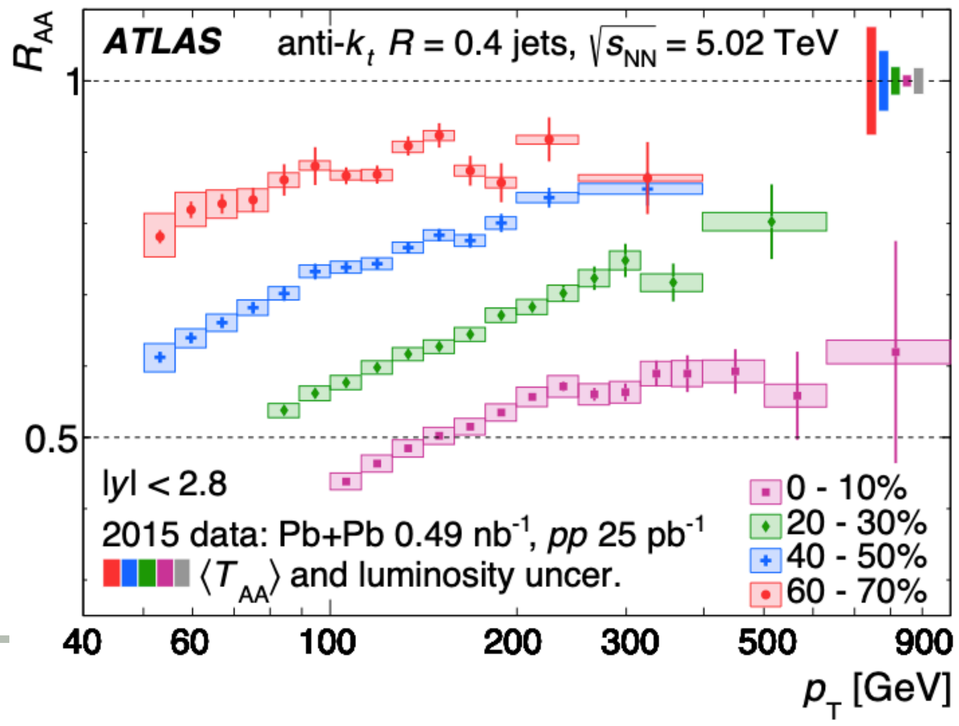
  - Suppression of jet spectra (energy loss) ✓

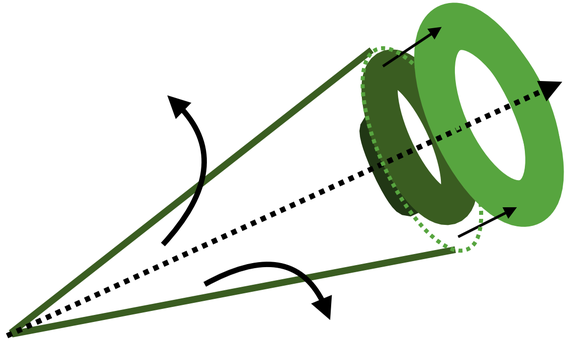
[arXiv:1504.04337]



[CMS: Phys. Rev. Lett. 121 (2018) 242301]
[CMS: PRL 122 (2019) 152001]

QGP in dense systems

[Adapted from: K. Zapp]



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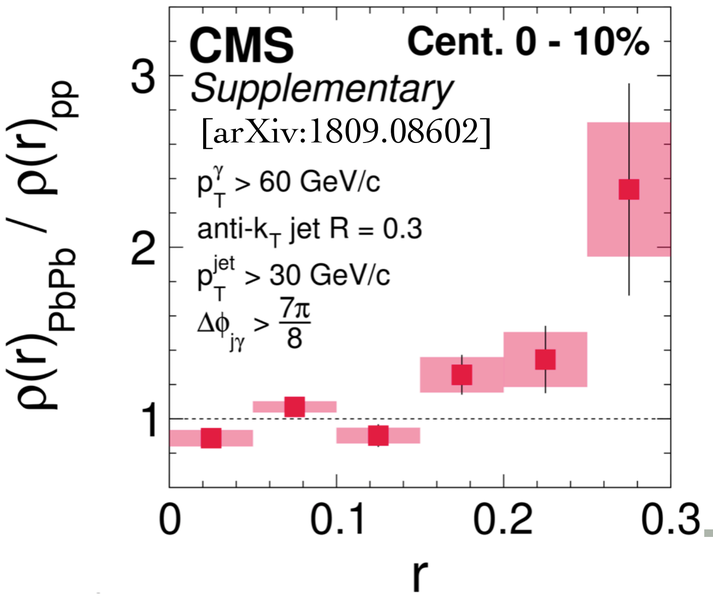
  - Suppression of single hadron spectra (energy loss) ✓
  - Suppression of jet spectra (energy loss) ✓
    - Modification of jet substructure ✓

$p_T^{trk} > 1$ GeV/c, anti-k_T jet R = 0.3

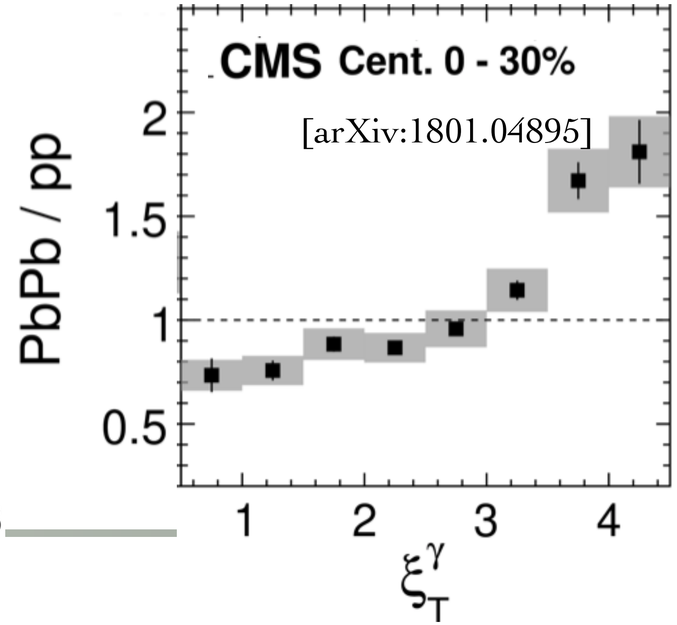
$p_T^{jet} > 30$ GeV/c, $|\eta^{jet}| < 1.6$

$p_T^{\gamma} > 60$ GeV/c, $|\eta^{\gamma}| < 1.44$, $\Delta\phi_{j\gamma} > \frac{7\pi}{8}$

Jet radial profile (PbPb/pp)



Fraction of energy of jet fragments (PbPb/pp)



QGP in XeXe

- Short run of XeXe allowed to pin down the same effects:
  - $\sqrt{s}$ = 5.44 TeV, $\mathscr{L}_{int} \simeq 3\ \mu b^{-1}$
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collective flow ✓

[CMS: JHEP 08 (2011) 141]

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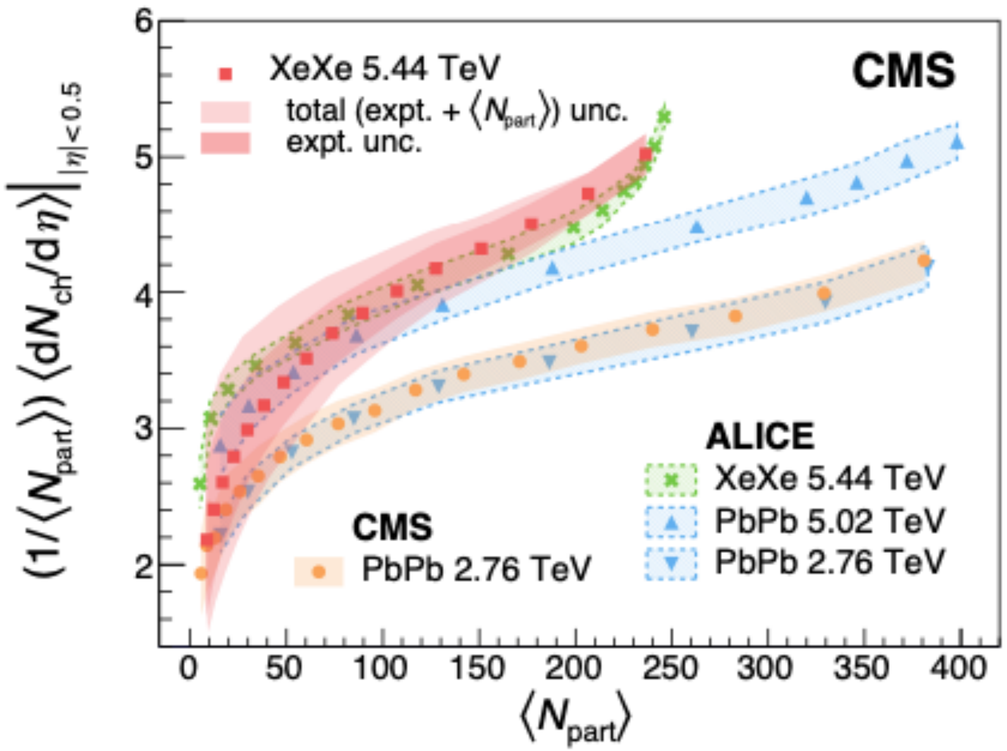

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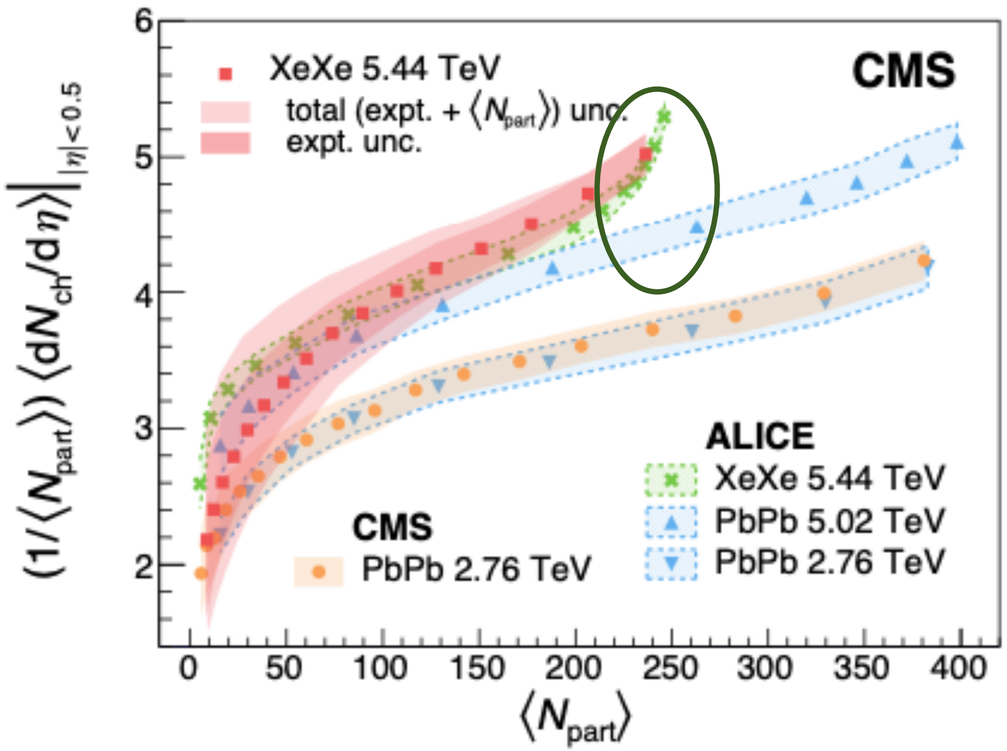

XeXe > PbPb at same <N_{part}>?

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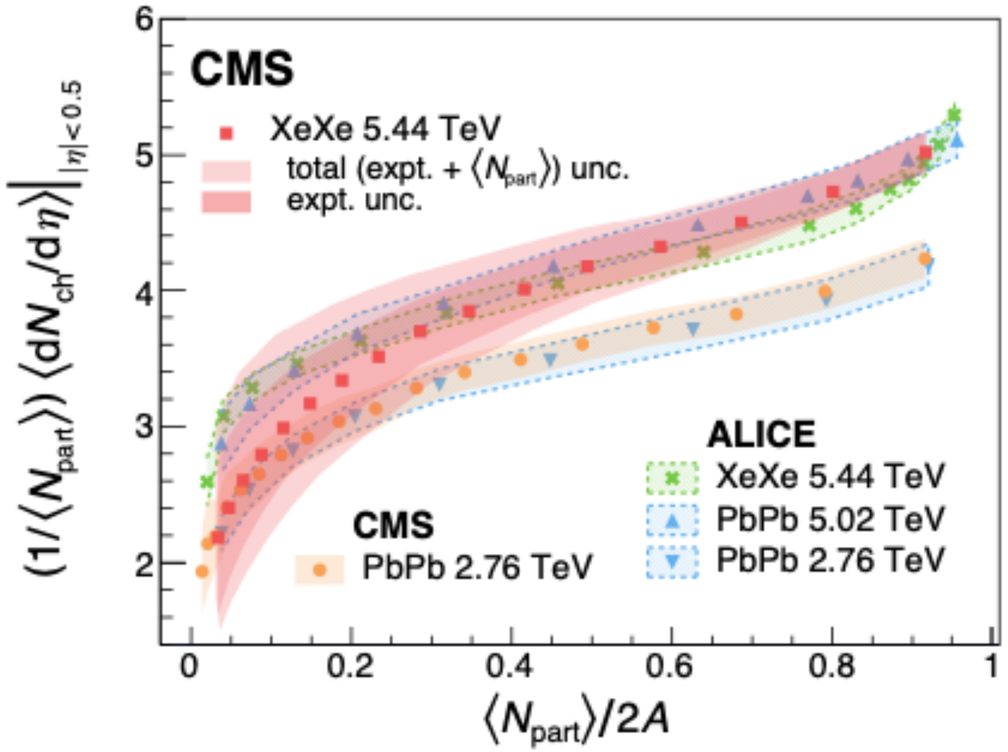


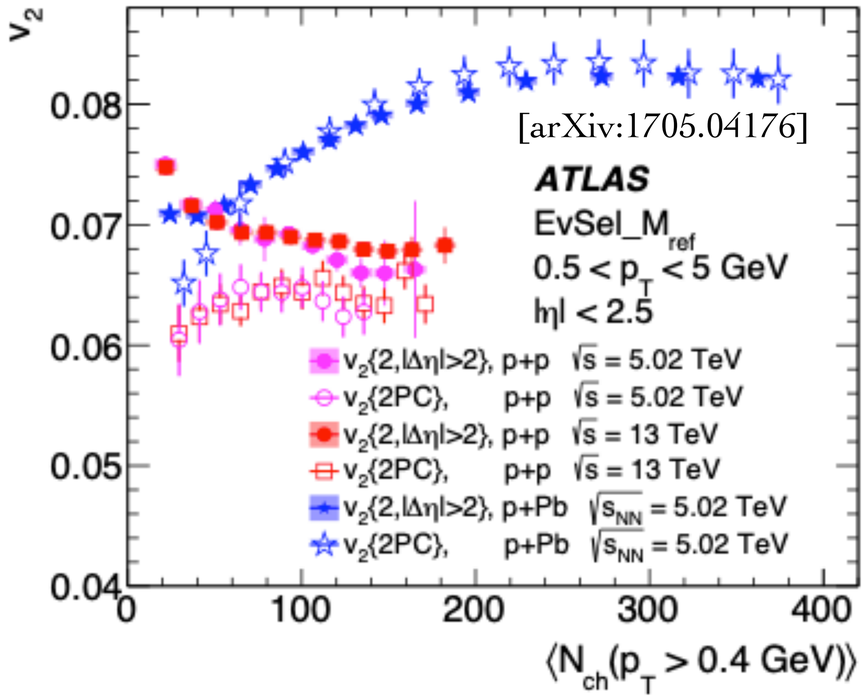
No scaling with same <Npart>
(different centralities)…

Scaling with per-participant charged-hadron multiplicity!

QGP in pA ?

[ATLAS: Eur.Phys.J.C 77 (2017) 6, 428]

- Collectivity signatures ✓



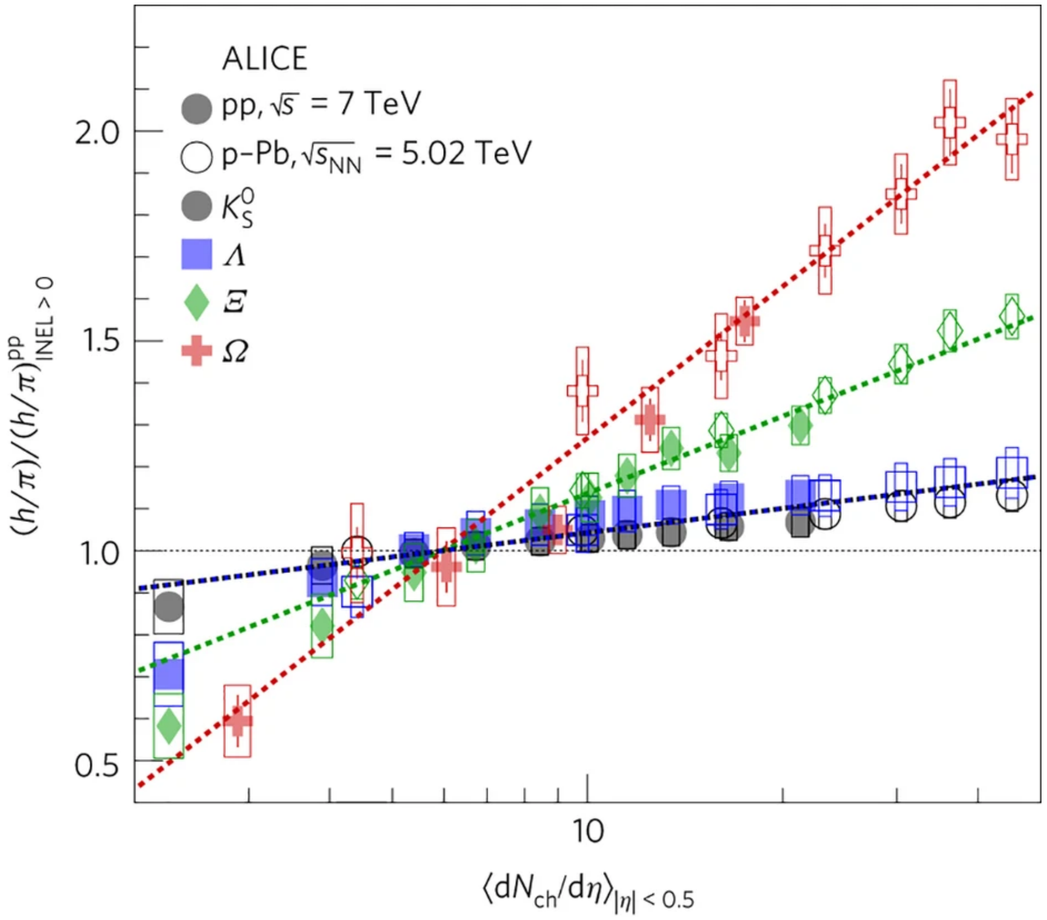
non-negligible flow harmonics

QGP in pA ?

[ALICE: Nature Physics 13 (2017) 535-539]

- Collectivity signatures ✓
- Strangeness enhancement ✓

hyperon-to-pion ratios is driven by strangeness content

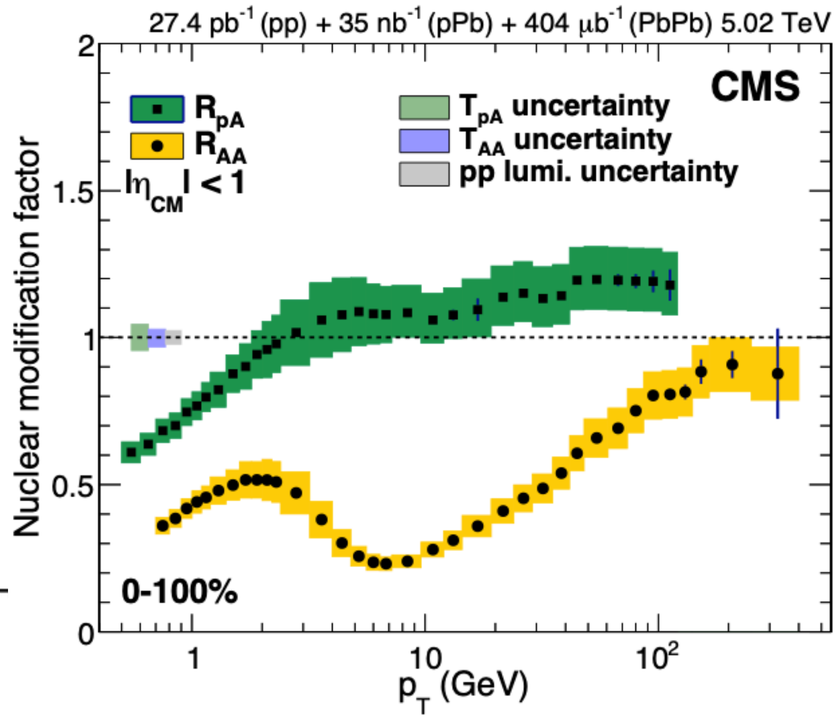


QGP in pA ?

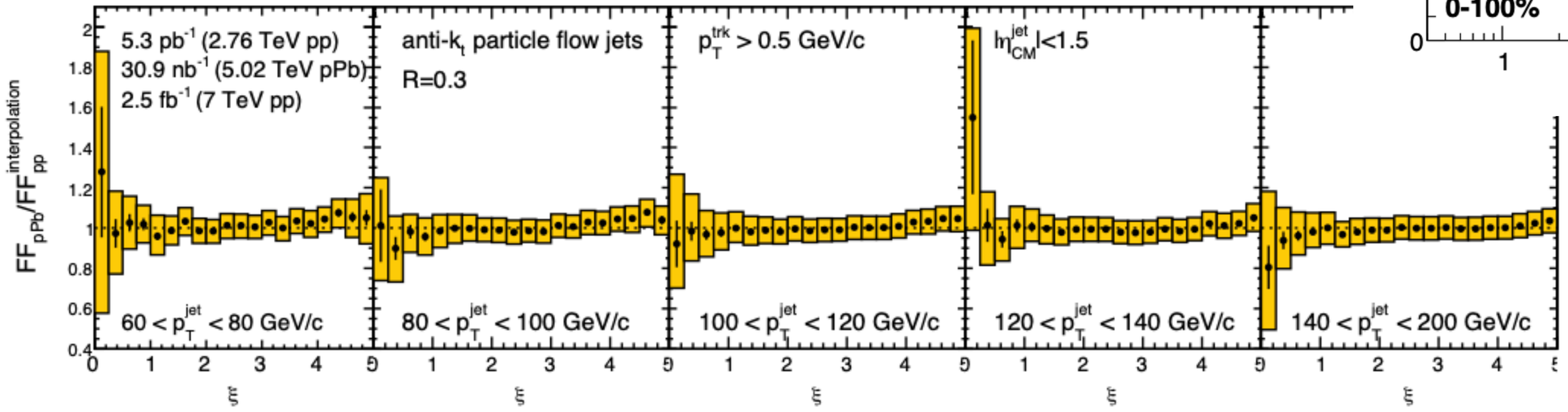
[CMS: JHEP 04 (2017) 039]

[arXiv:1611.01664]

- Collectivity signatures ✓
- Strangeness enhancement ✓
- No modifications on hard probes ✗



[CMS: HIN-15-004-pas]



QGP in pA ?

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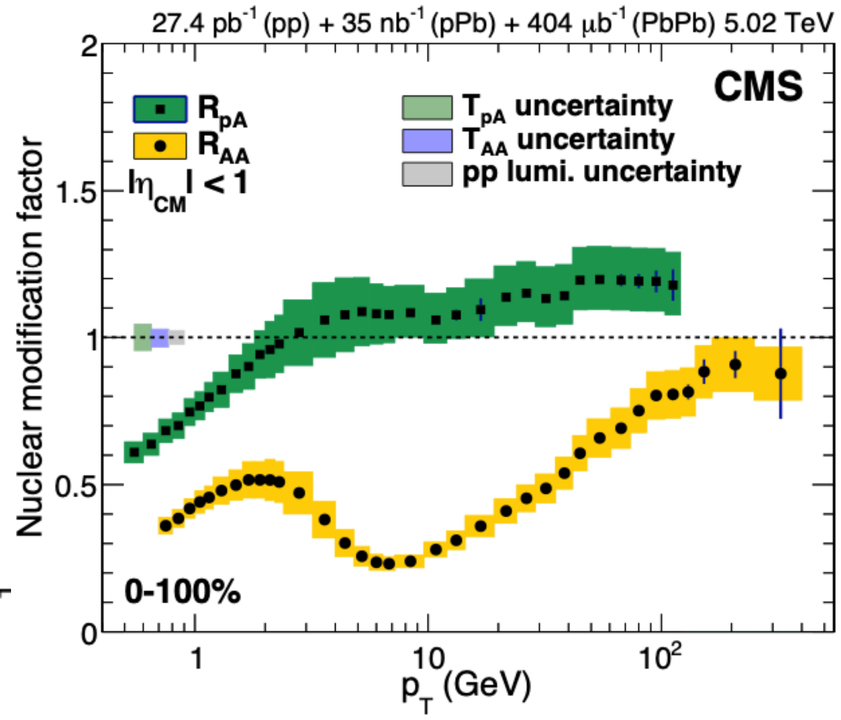
- Collectivity signatures ✓
- Strangeness enhancement ✓
- No modifications on hard probes ✗ Incoherent picture…

Need more limits on JQ description!



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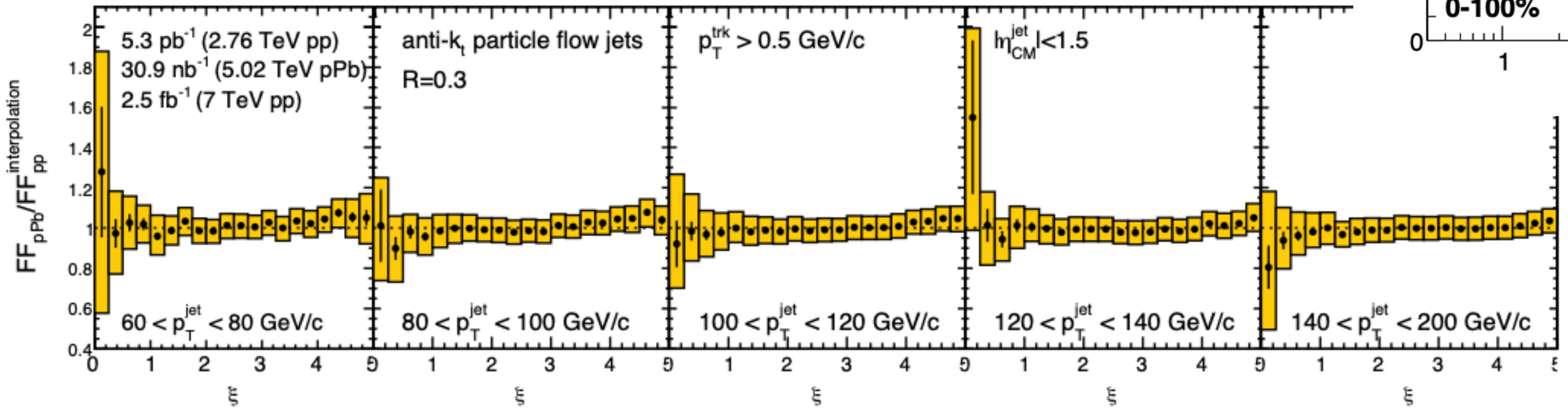
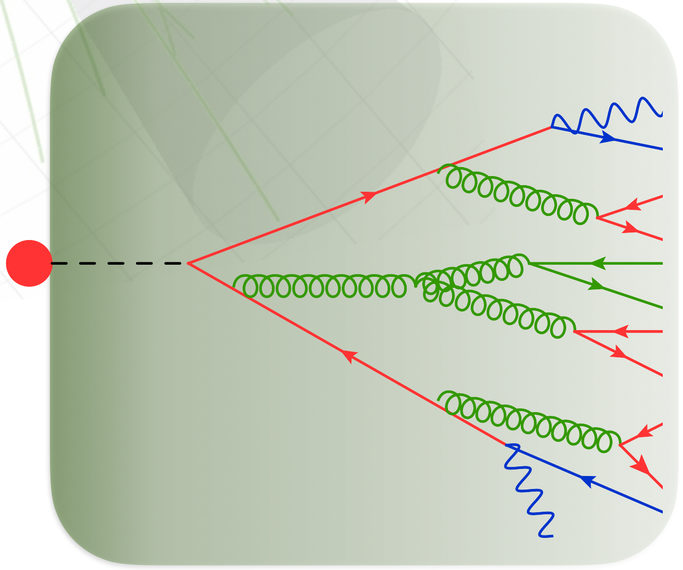


Jet quenching

- Modifications of the parton shower induced by the interaction with a deconfined state of matter:



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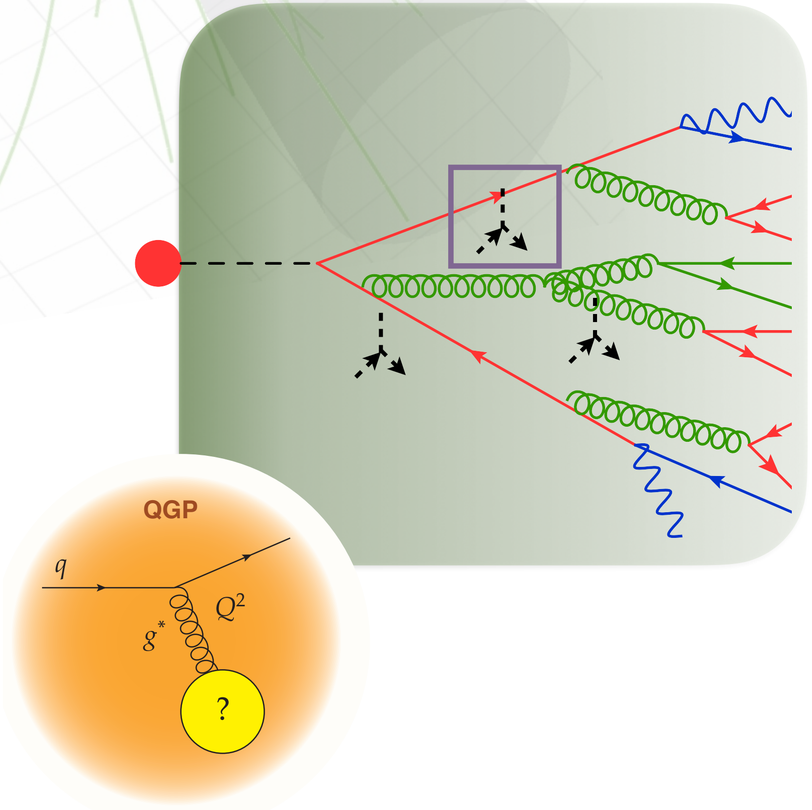
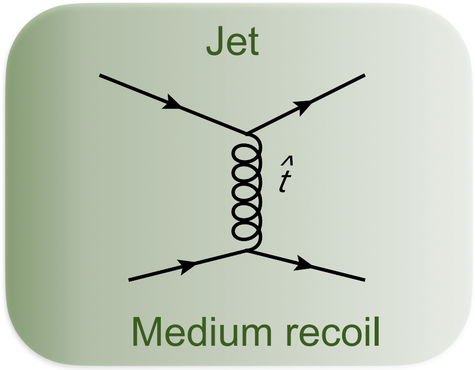


Elastic scattering processes:



From: PHENIX Collab (15)

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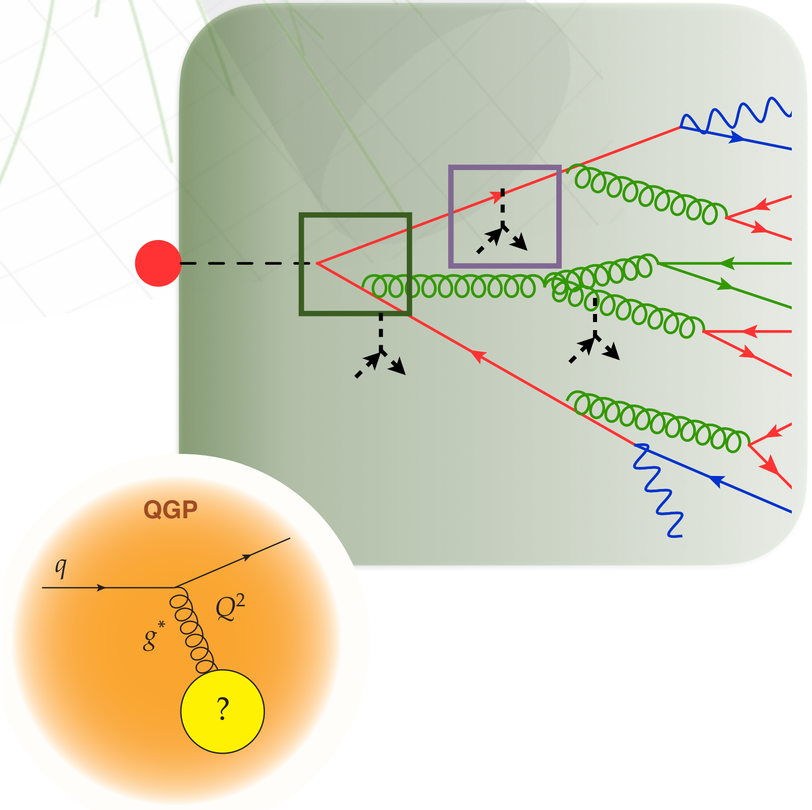

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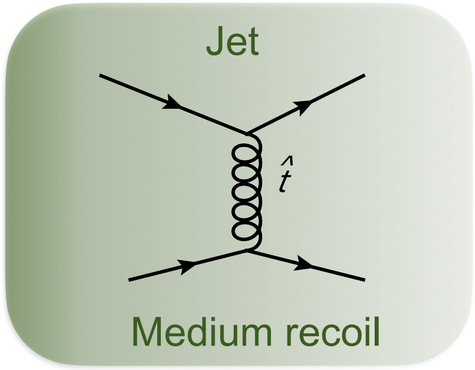

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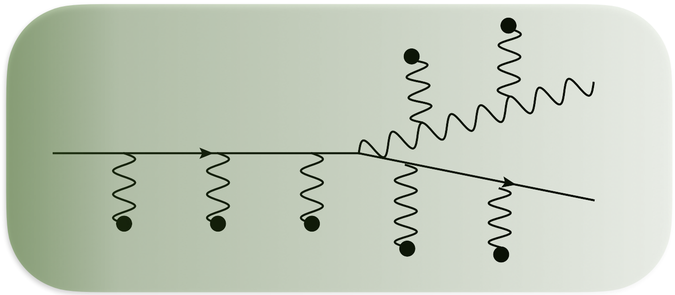

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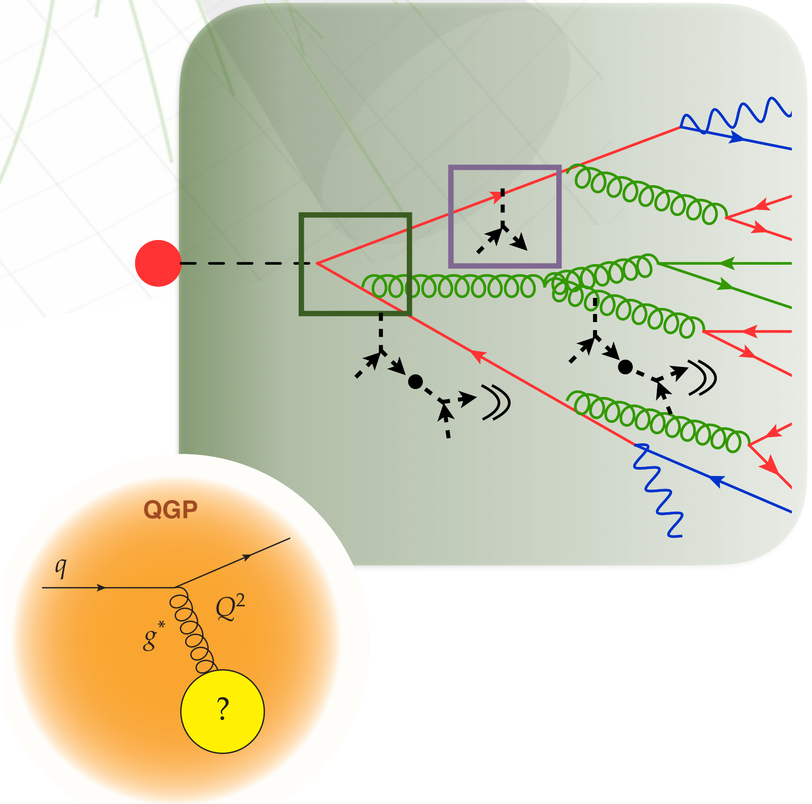

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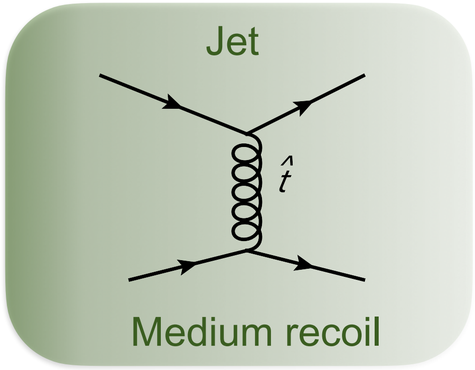

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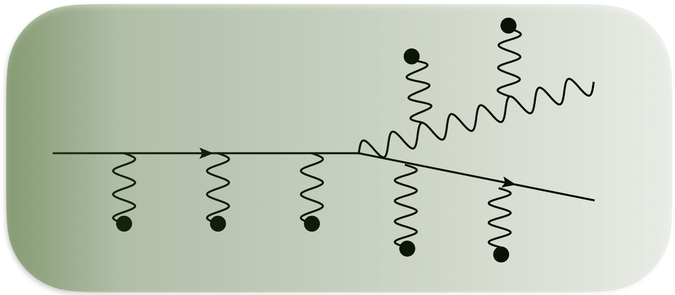

Medium-induced response

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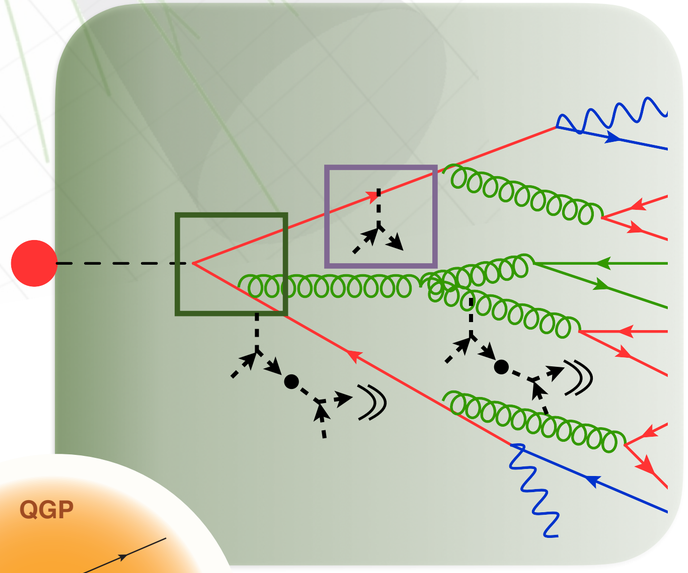

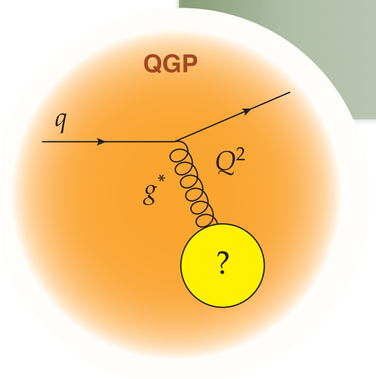

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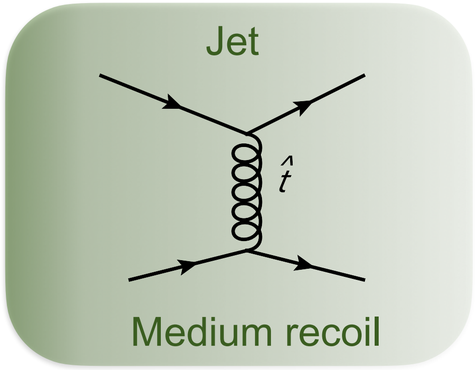

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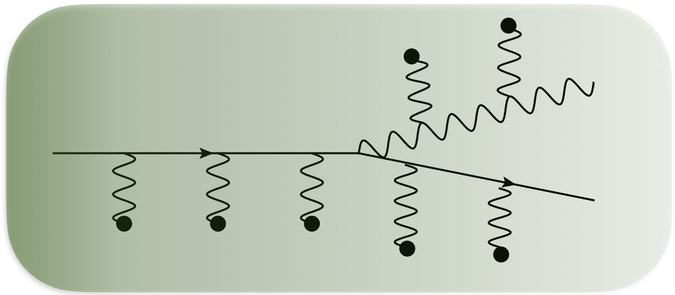

Medium-induced response

- Resulting effects: energy loss, modification of jet substructure, medium-induced acoplanarity

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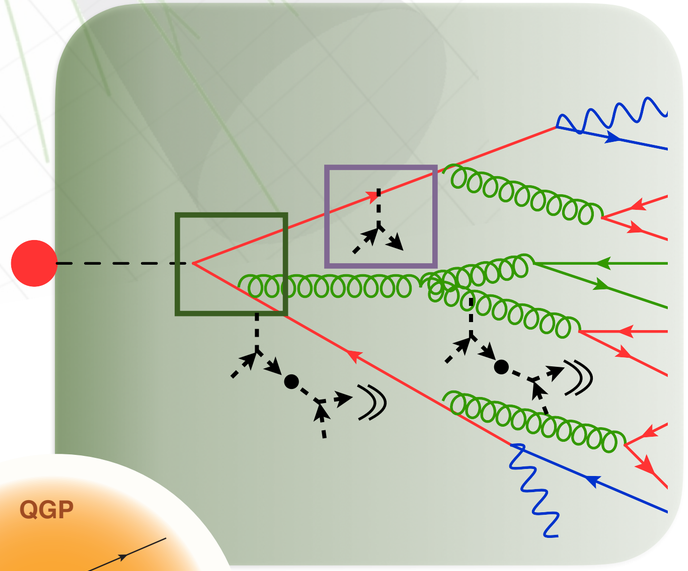

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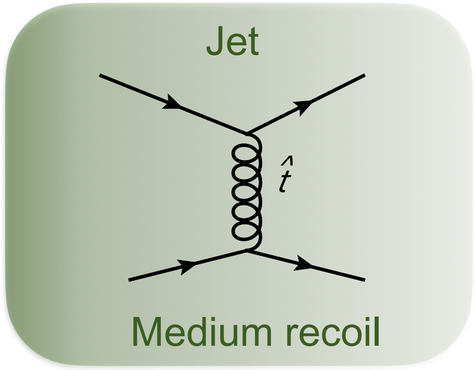

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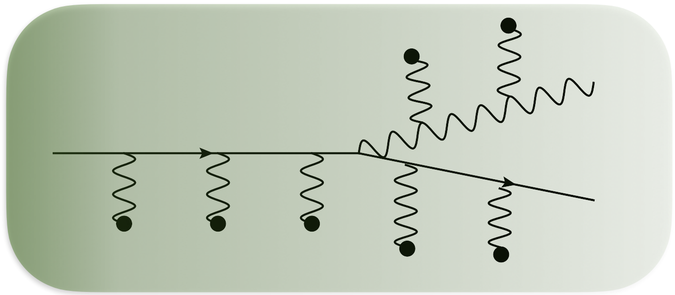

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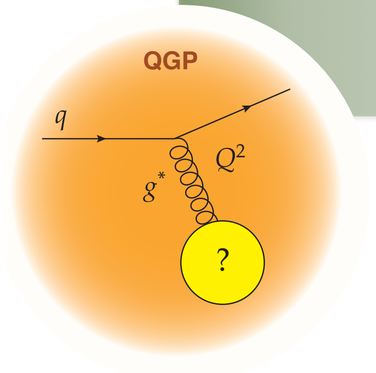

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Which observables are most sensitive to each quenching effect?

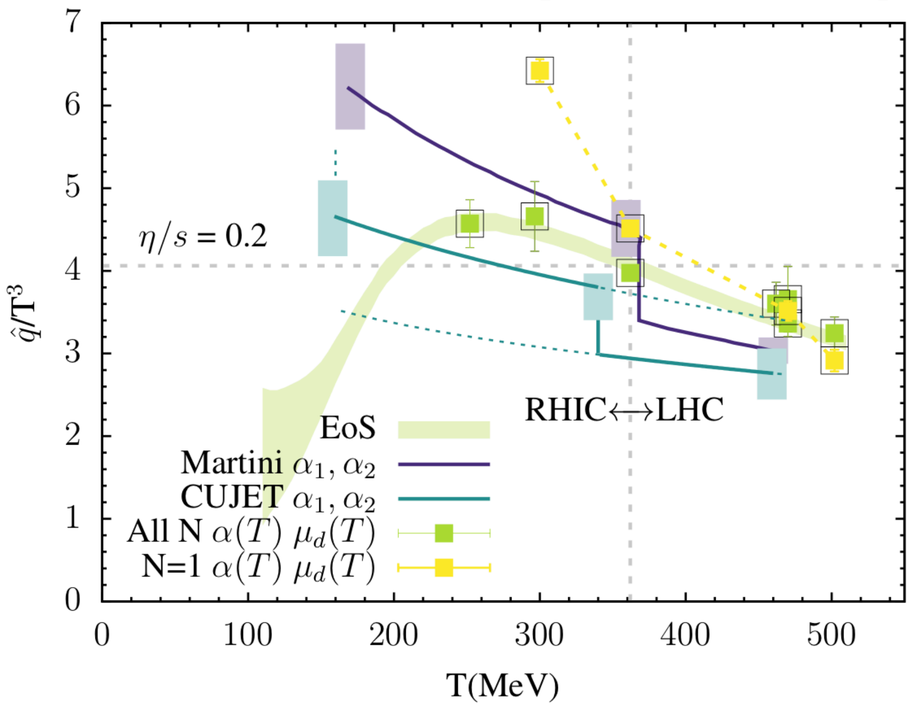
[Feal, Salgado, Vasquez (19), Andrés, LA, Dominguez (20)]

[Heavy-quarks: S. Cao et al (19)]

Energy Loss

- Towards an accurate determination of QGP characteristics:
  - Transparency to the passage of a high momentum particle (Eg:transport coefficient, qhat)
  - Consistent description of single hard and multiple soft scattering regime

[Feal et al: 1911.01309]



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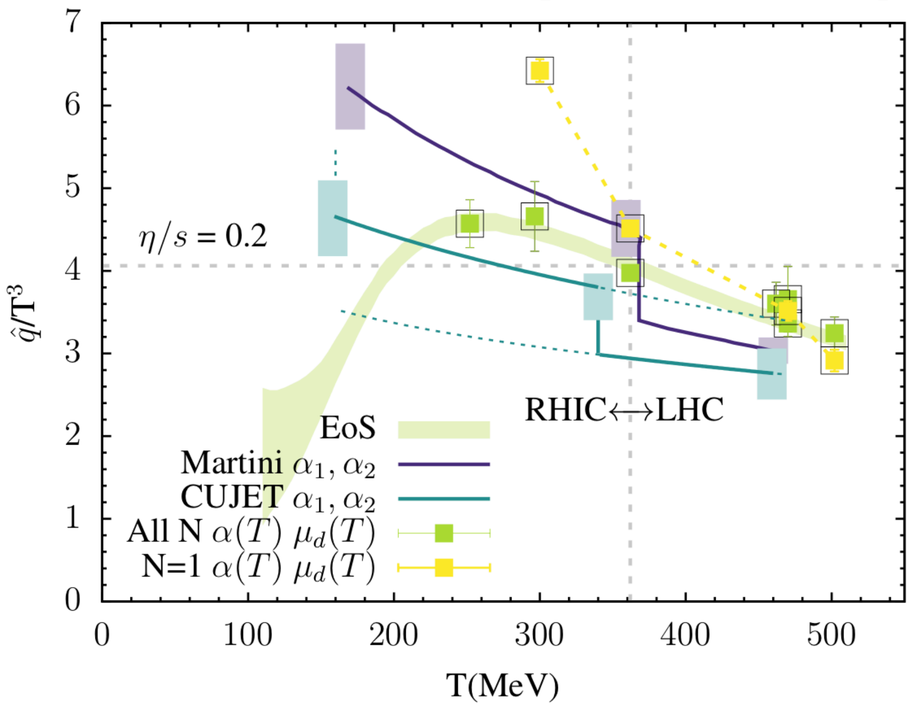

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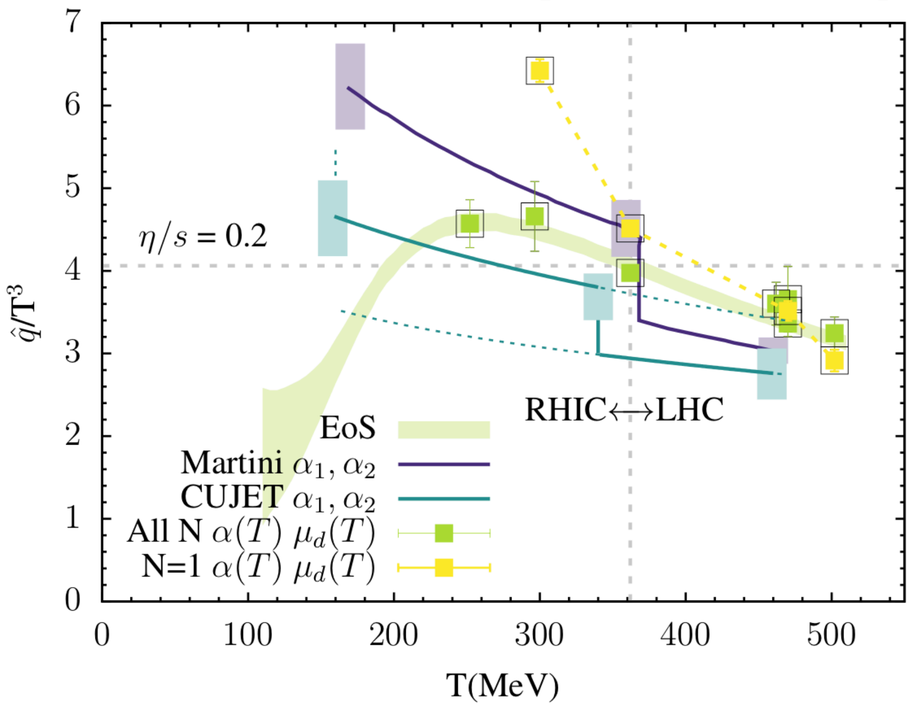


Model-dependent parameters: qhat, debye mass?

Evolution with fast expanding medium?

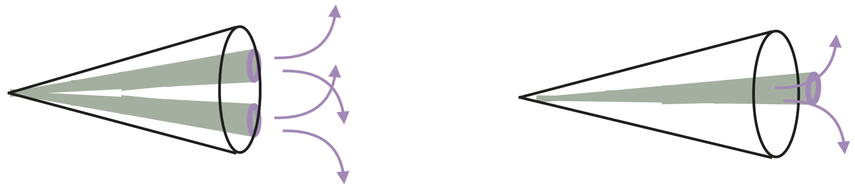
[Salgado, Wiedemann (02, 03), Zakharov (07)]

[Caucal, Iancu, Soyez (21), Adhya, Salgado, Spousta, Tywoniuk (20)]

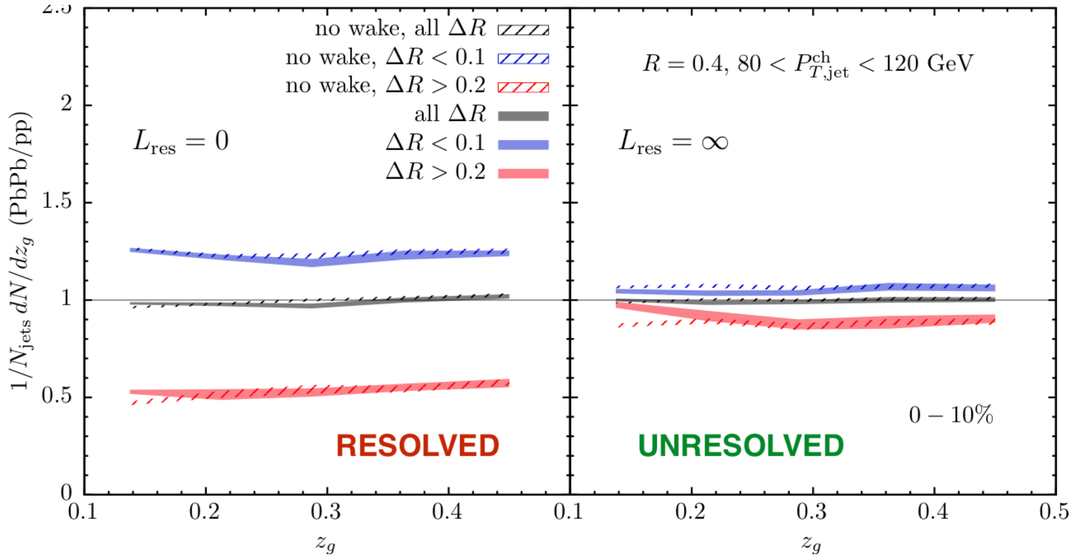
[ALICE PLB 802 (2020) 135227]
[Casalderrey-Solana et al (10)]

Jet Substructure

- Towards a consistent treatment of multi-gluon emission process
  - Identification of in-medium modifications of QCD parton shower



[arXiv:1905.02512]



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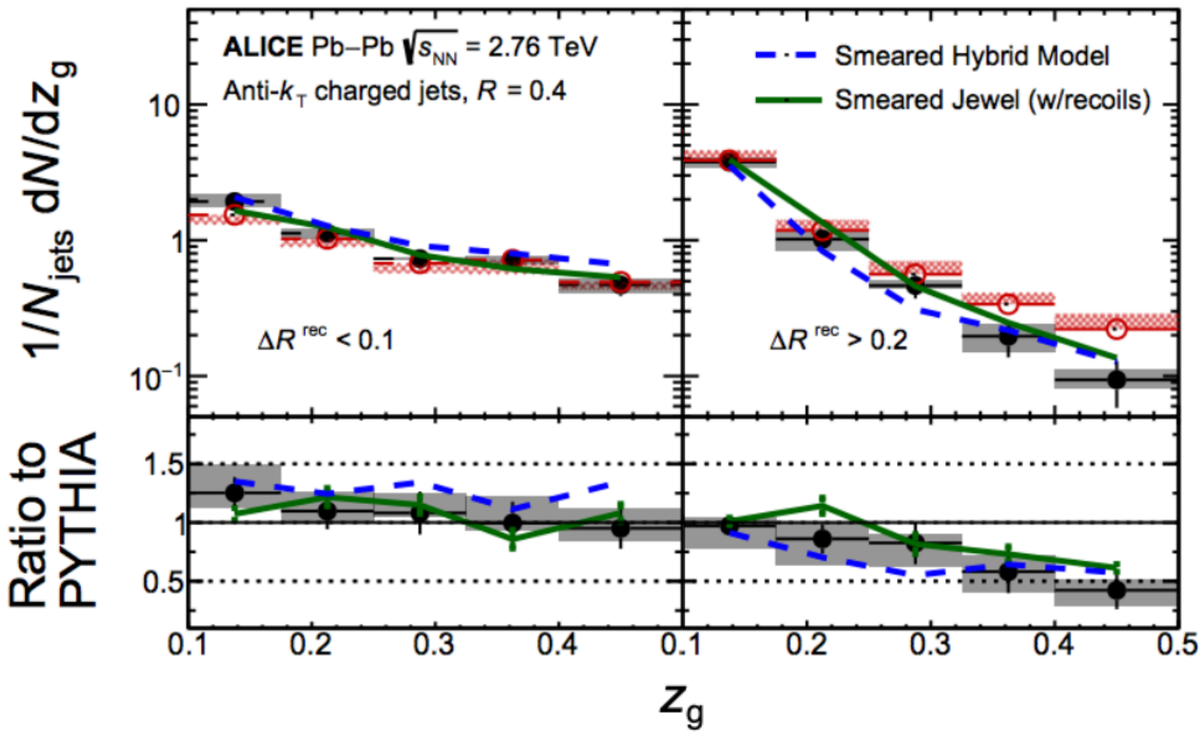

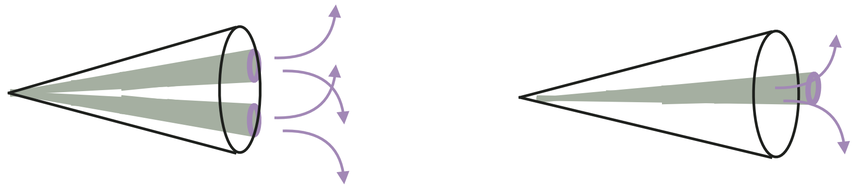

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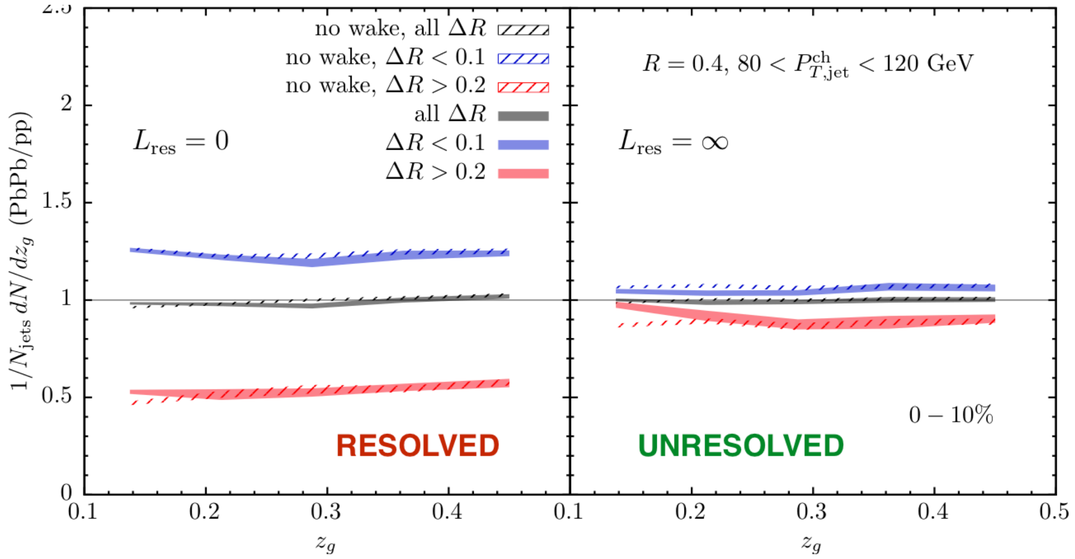

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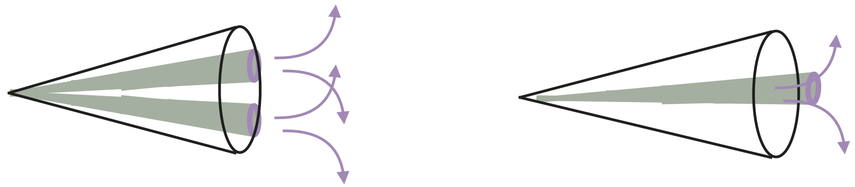
No significant difference between models that account or not for coherence effects…



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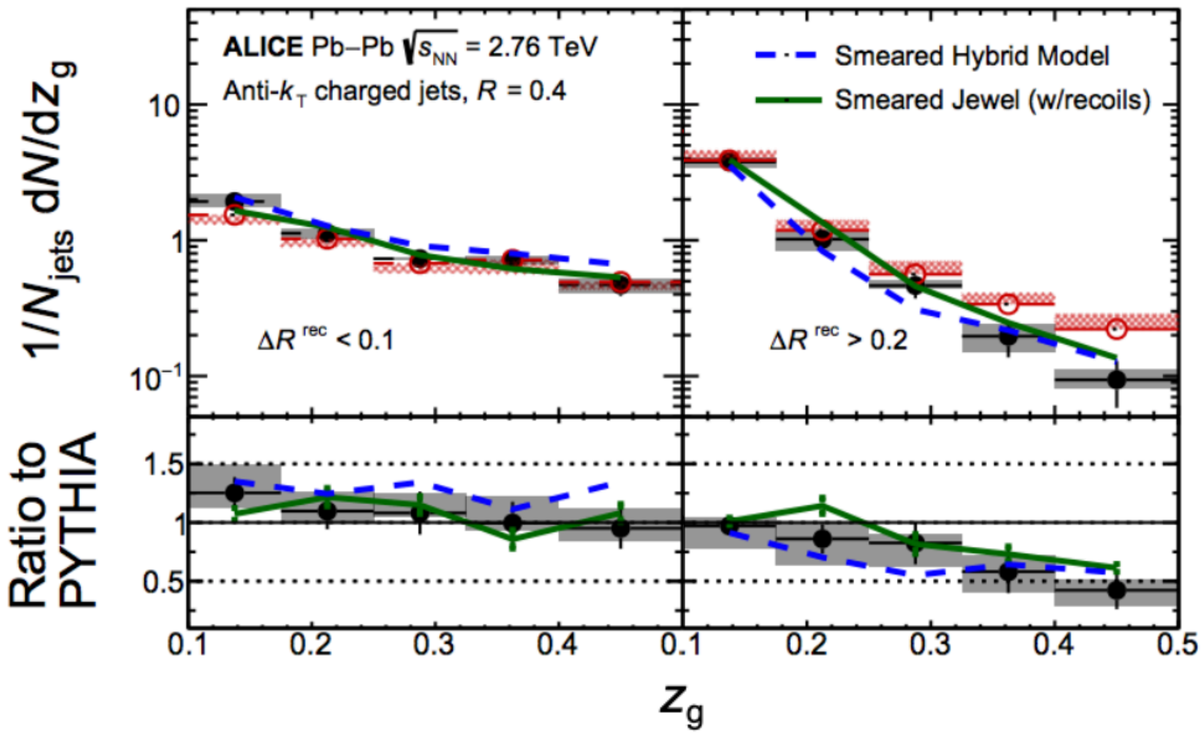

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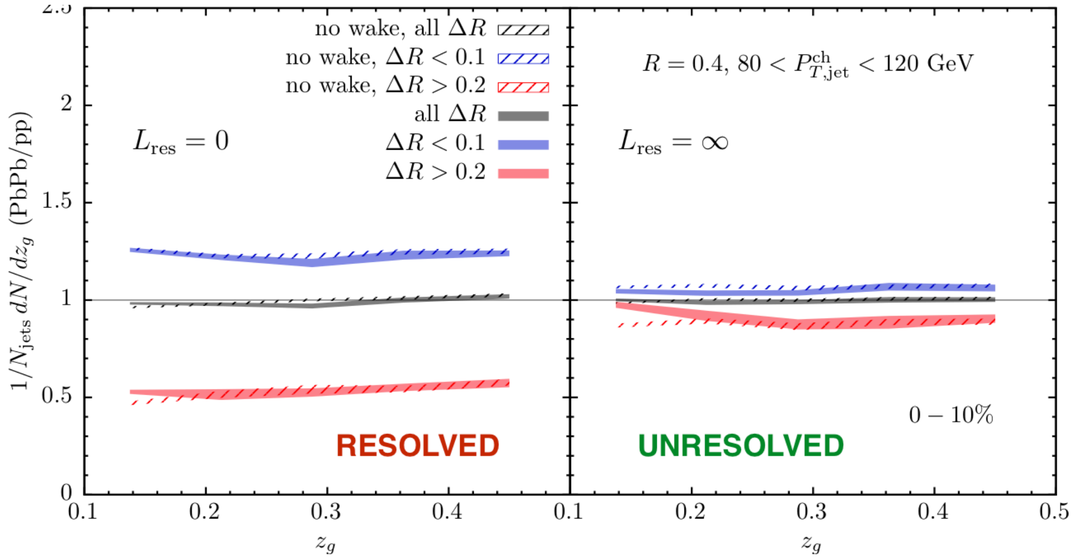
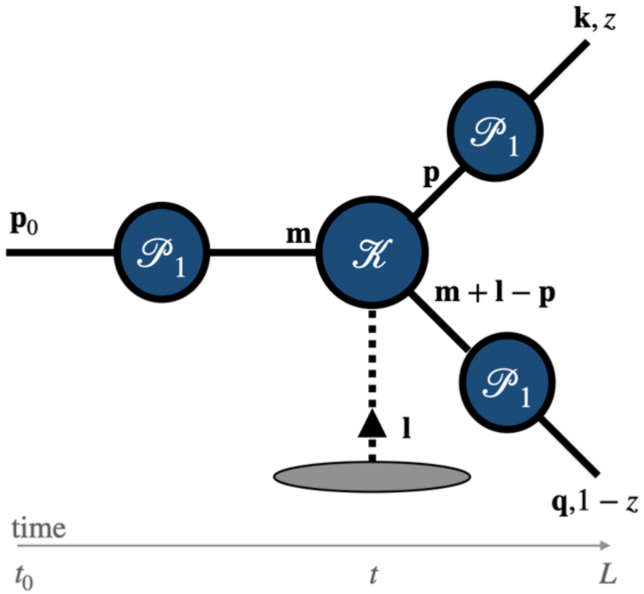


[Domíngez, et al (20)]
[Barata, Domínguez, Salgado, Vila (21)]

Jet Substructure

- Towards a consistent treatment of multi-gluon emission process
  - Identification of in-medium modifications of QCD parton shower
  - QCD evolution equations that include corrections due to the interference of subsequent emitters.



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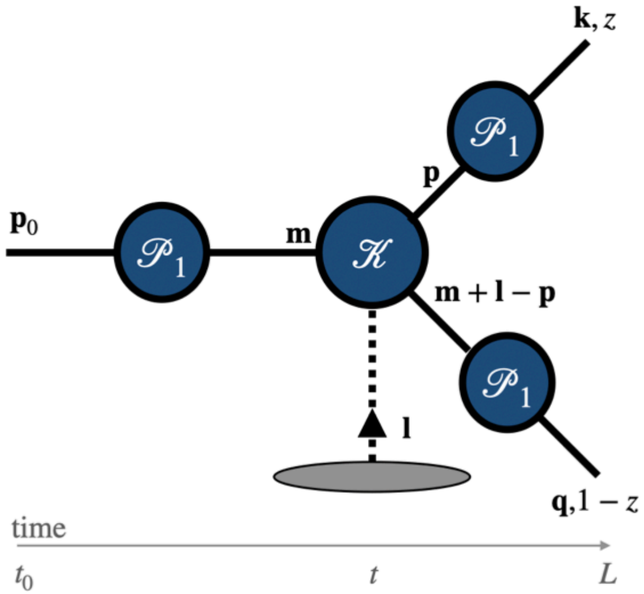


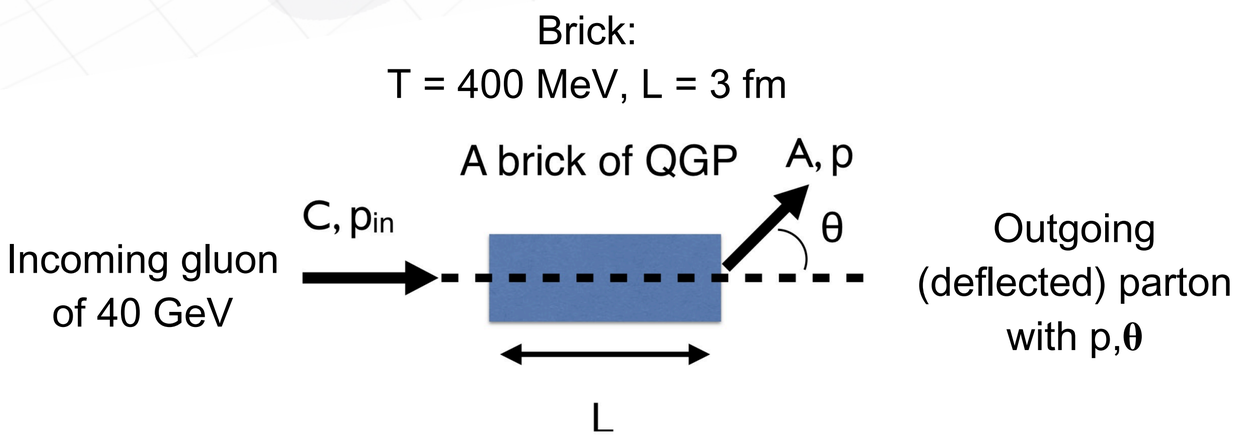
What is the phenomenological manifestation?

[Chen et al (17)]

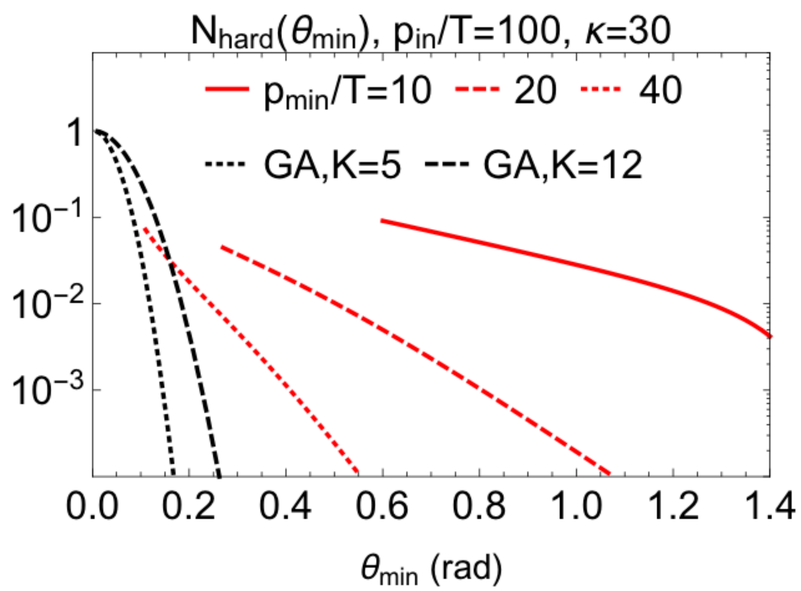
[D'Eramo, et al (13), D'Eramo, et al (19)]

Acoplanarity

- Jet broadening linked to energy loss processes
  - But is also intrinsic to QCD vacuum radiation…



[D'Eramo et al: 1808.03250]



Probability of finding a parton with p_{min}/T above an angle θ_{min}

[CMS (20), ALICE JHEP 09 (2015)]
[STAR Phys.Rev.C 96 (2017) 2, 024905]

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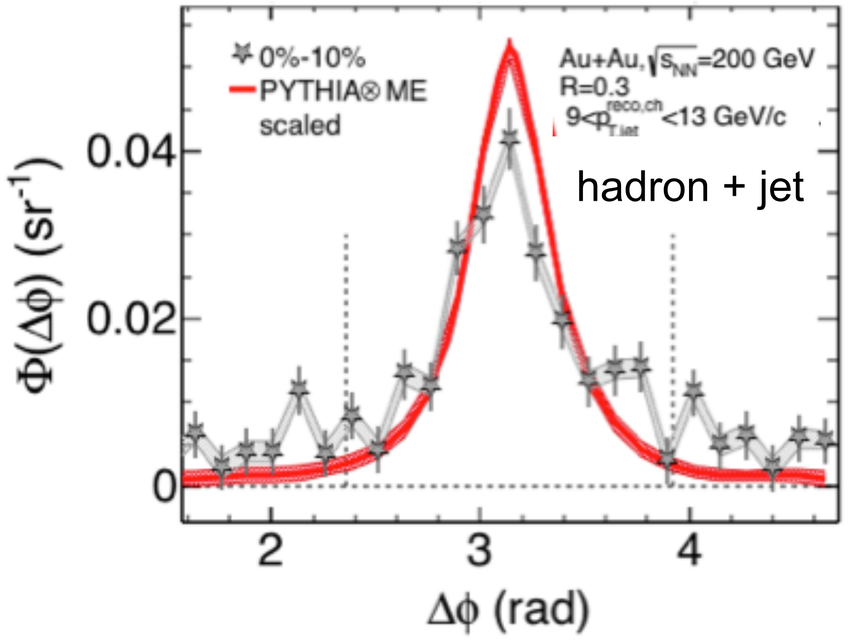
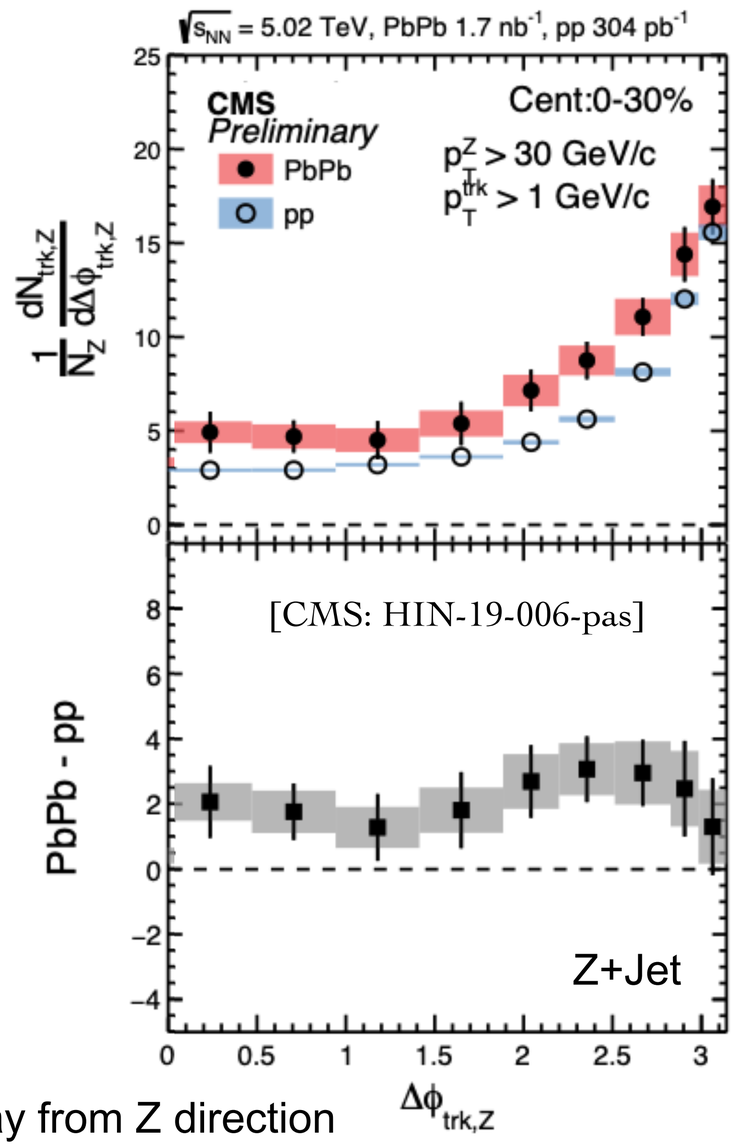
[STAR: 1702.01108]



distribution of recoil jets



charged particles away from Z direction

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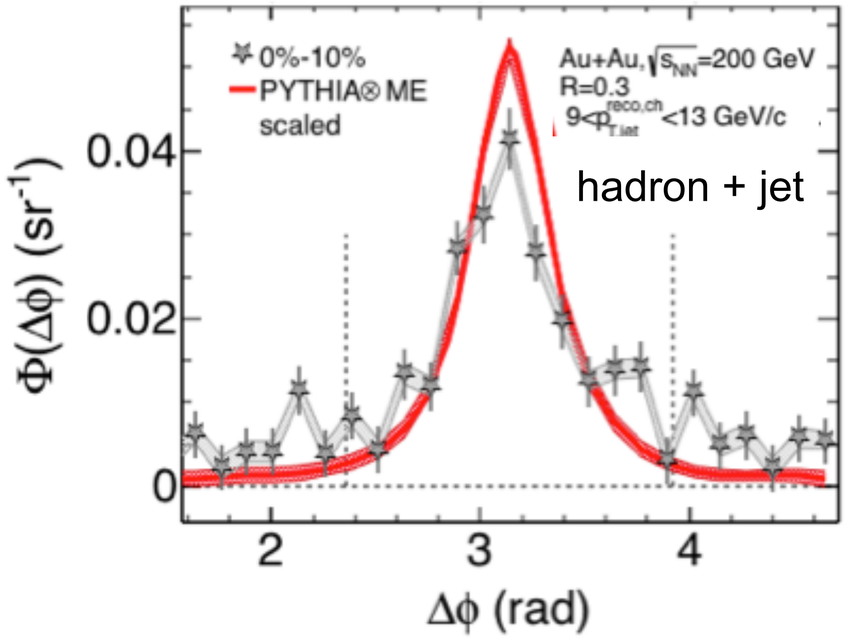
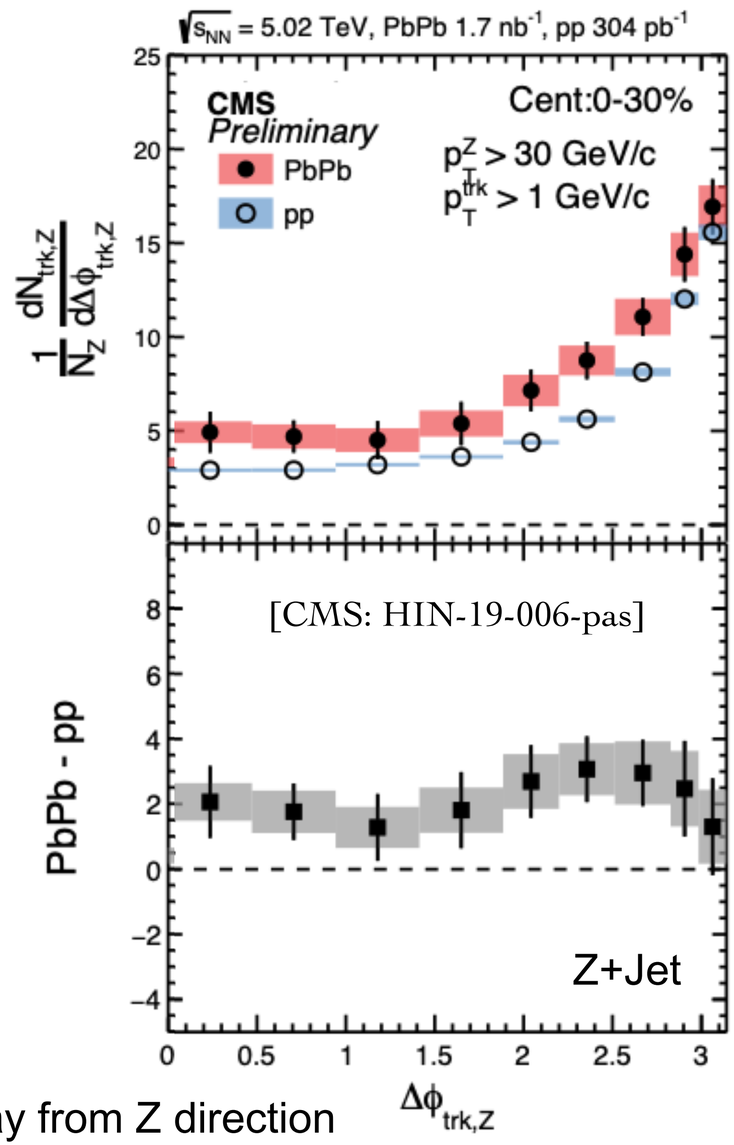


distribution of recoil jets

First hints of jet broadening physics?



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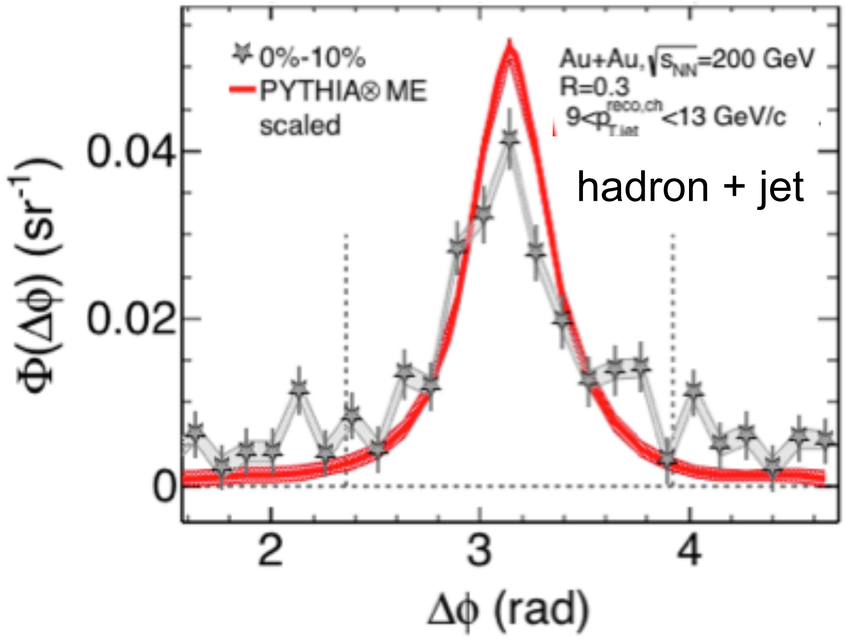
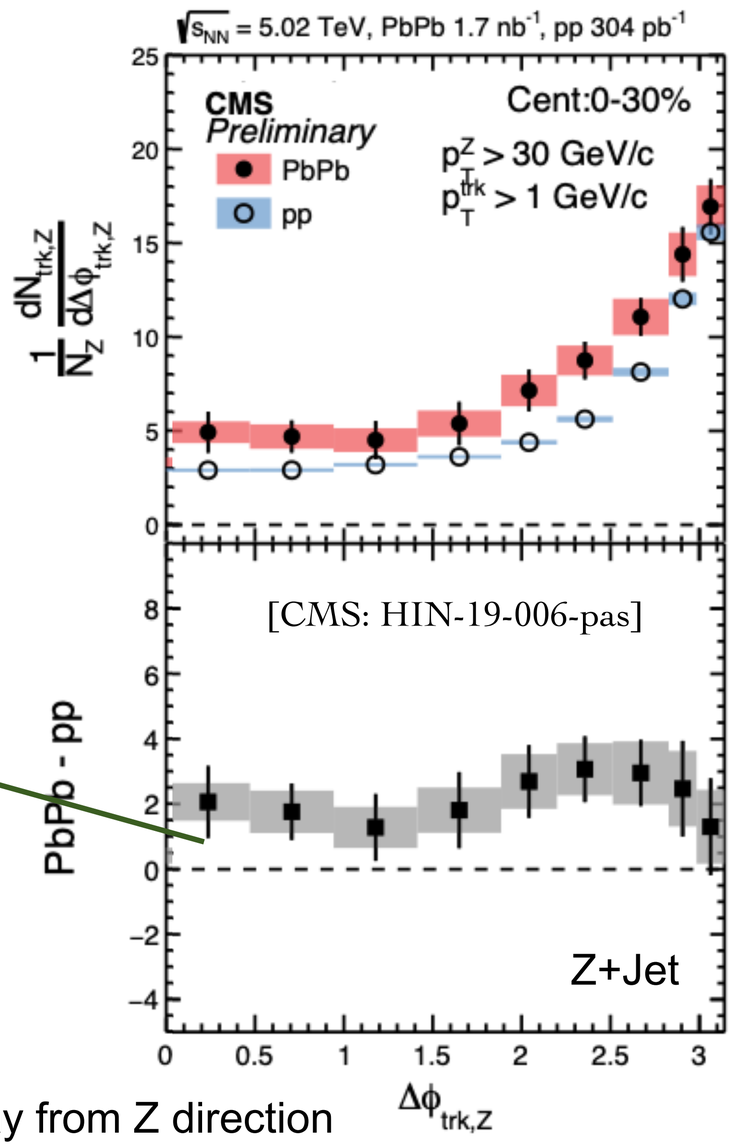


distribution of recoil jets

First hints of jet broadening physics?

Or MPI + medium response?

[Chen et al (21)]



charged particles away from Z direction

QGP onset scale

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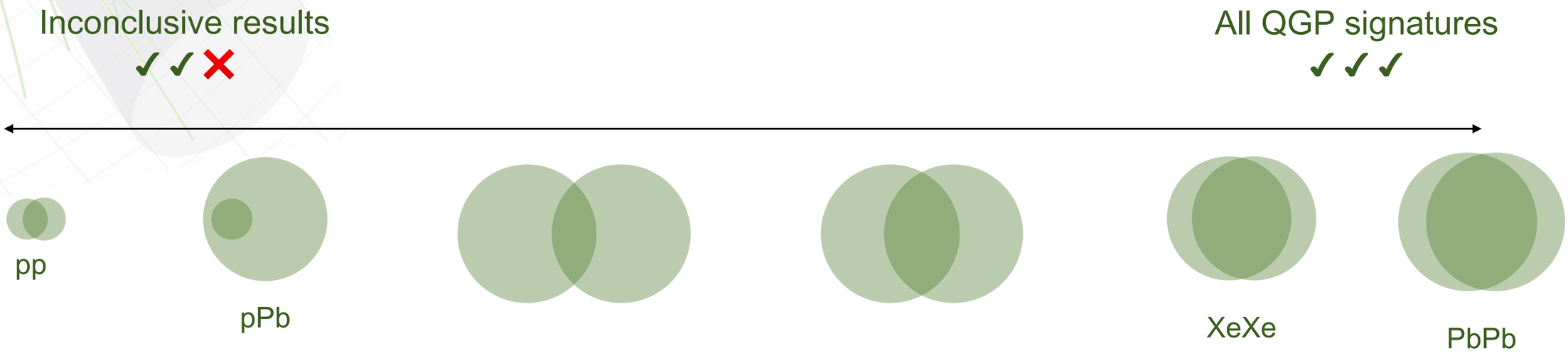
Is there jet quenching in light systems?

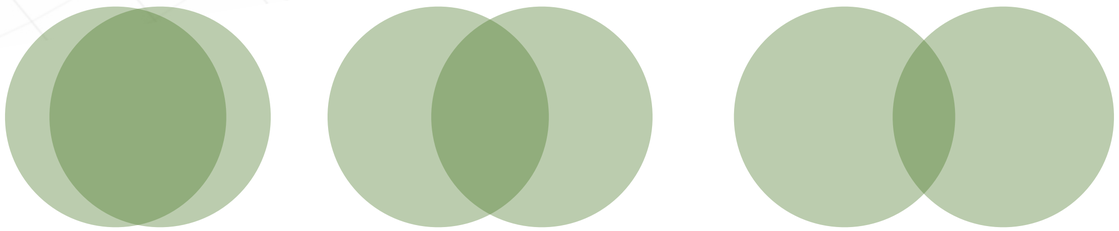
QGP onset scale



Is there jet quenching in light systems?

Light Systems

- Magnitude of Jet quenching depends on system size:
  - Peripheral collisions: expected some energy loss



Pb Pb Pb

Studies of System Size dependence

[JEWEL: Zapp (14)]

[Citron, Dainese et al (19)]

Light Systems

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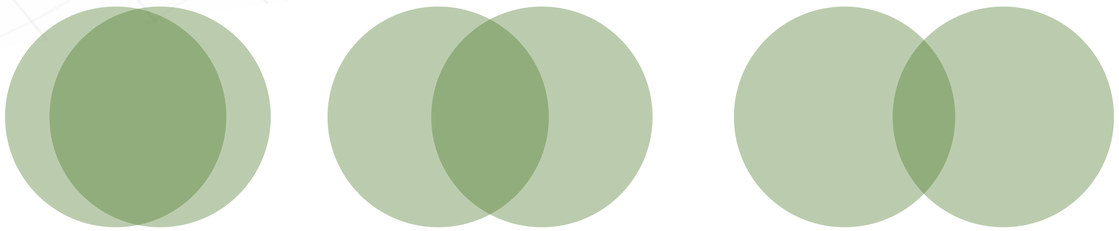
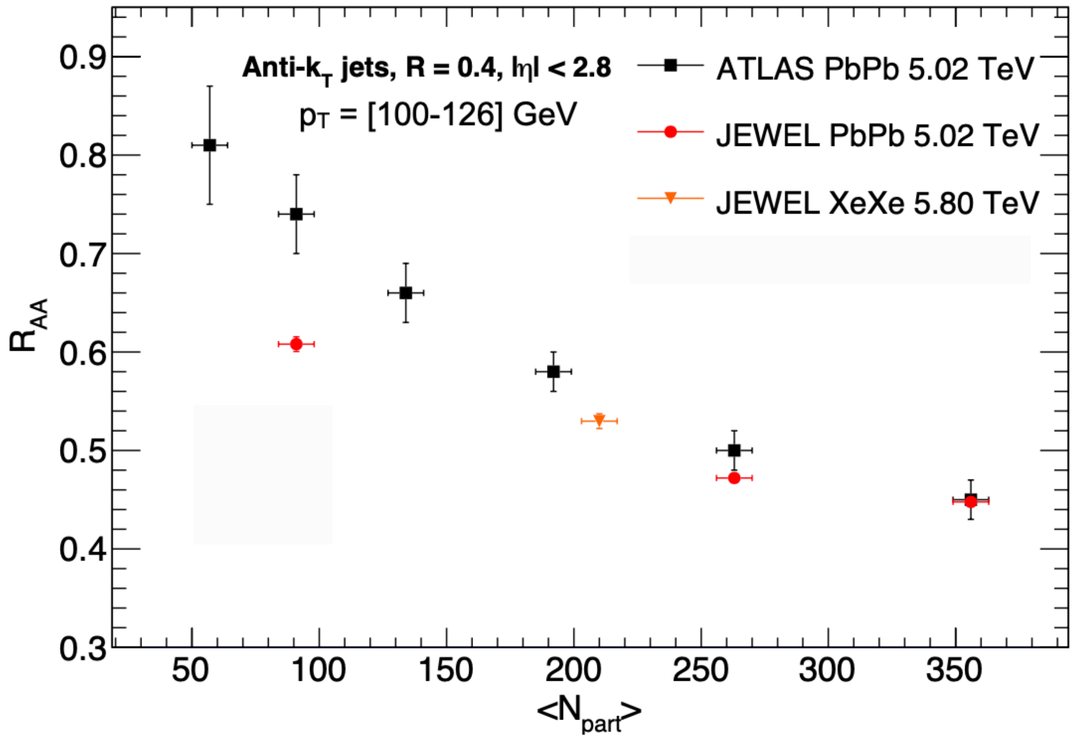
Several changes at the same time: energy loss, nuclear overlap,…

(too many variables)



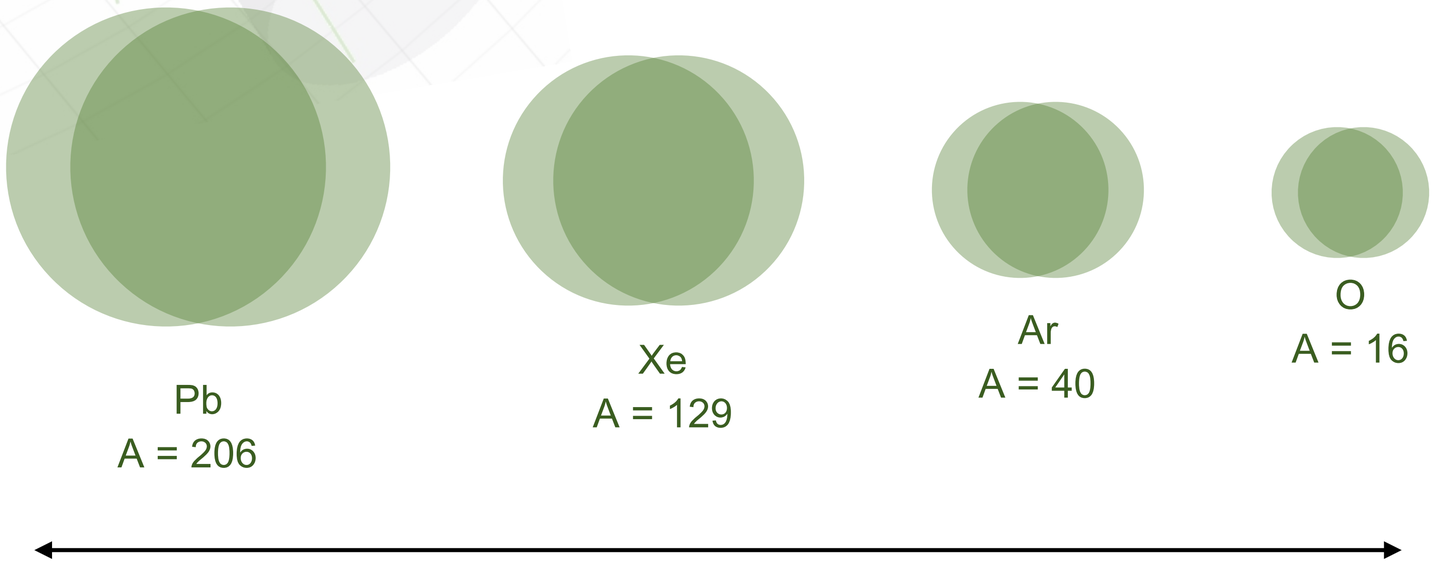
Studies of System Size dependence

[arXiv: 1812.06772]



Light Systems

- Magnitude of Jet quenching depends on system size:
  - Lighter nuclei allow to fix geometry



Studies of System Size dependence
(always fixing geometry - [0-10]%)

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[Huss, Kurkela, Mazeliauskas, Paatelainen, Van der Schee, Widemann (20)]

[arXiv:2007.13754]

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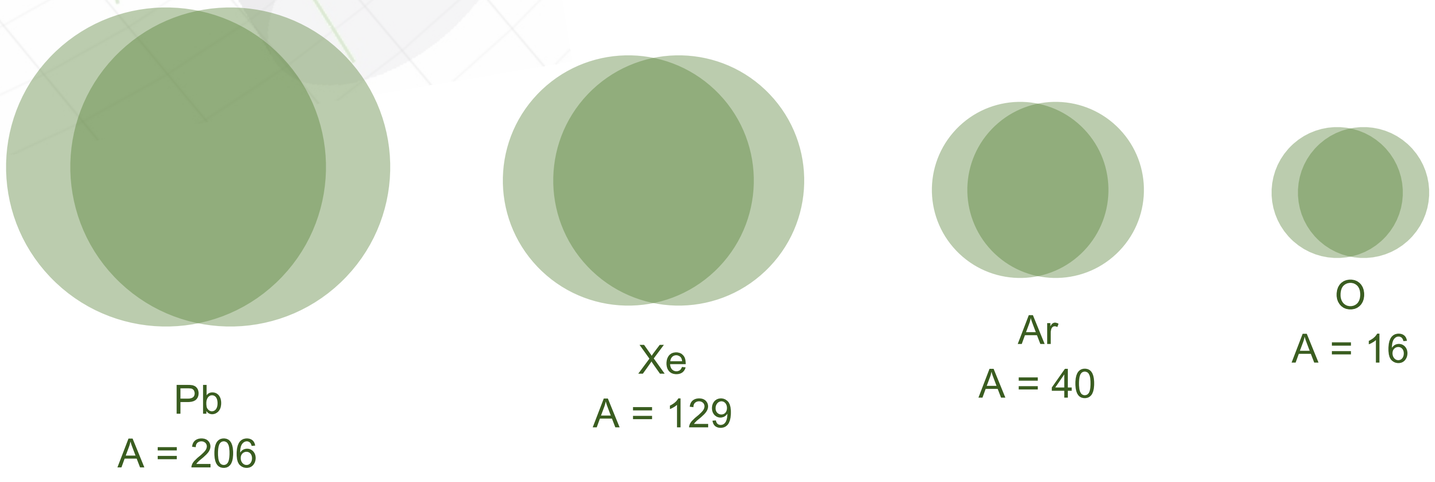

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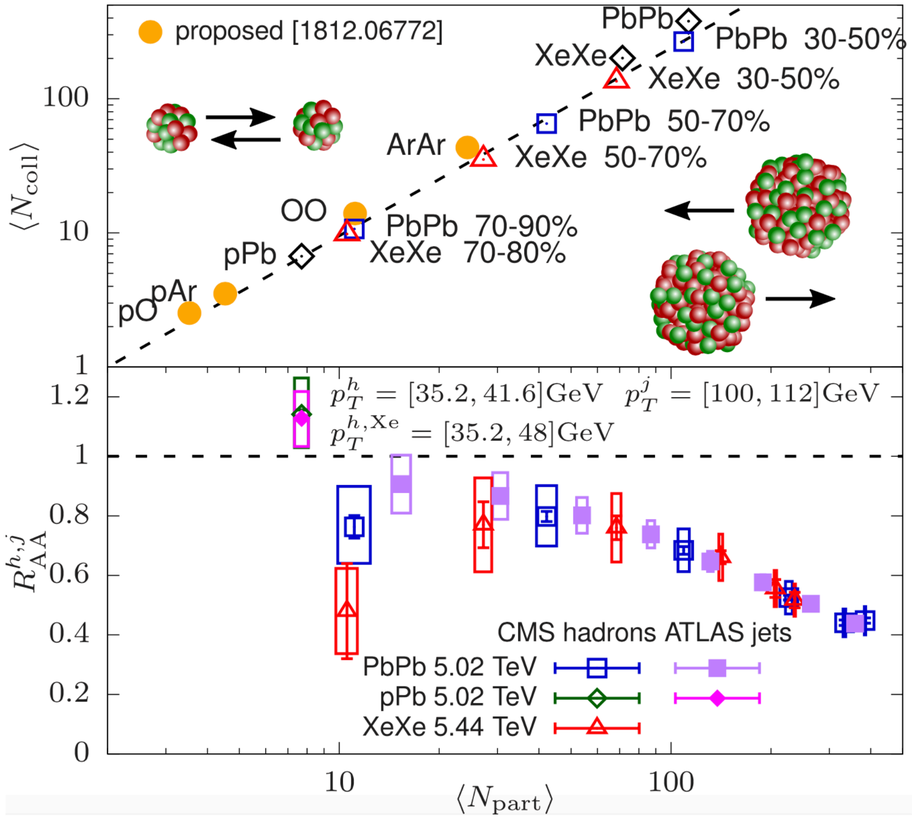

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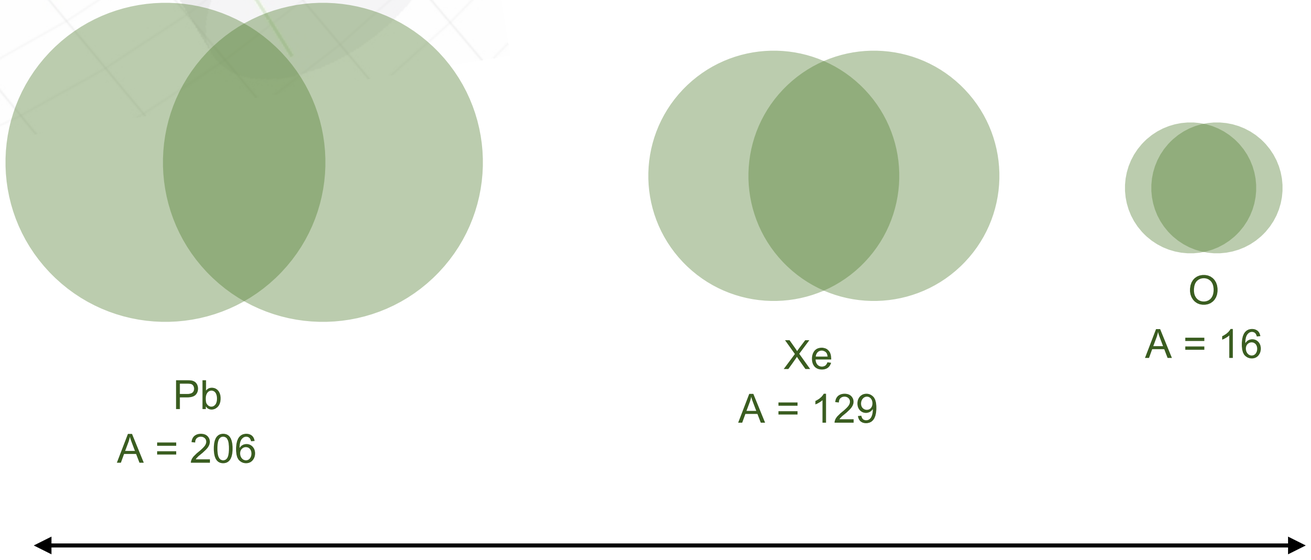

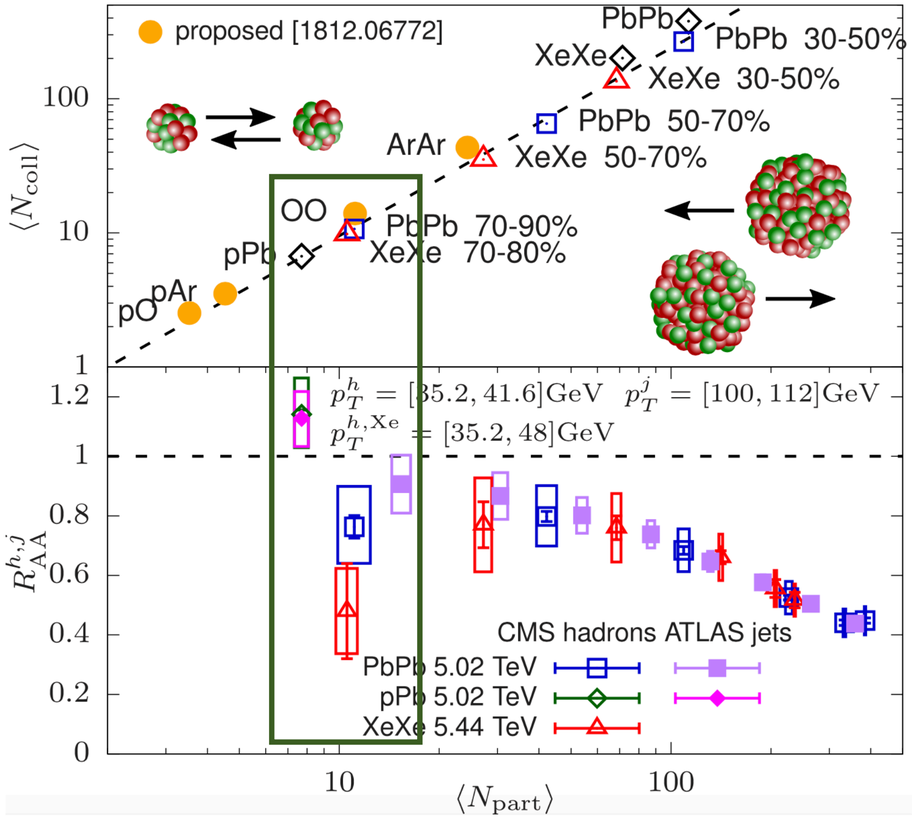

Energy Loss in OO

- Inclusive jet yield independent of nuclear overlap:

$$R_{AA}^{h,j}(p_T, y) = \frac{1}{\langle T_{AA} \rangle} \frac{(1/N_{ev}) dN_{AA}^{h,j}/dp_T dy}{d\sigma_{pp}^{h,j}/dp_T dy}$$

Energy Loss in OO

[Huss, Kurkela, Mazeliauskas, Paatelainen, Van der Schee, Widemann (20)]

See Huss's talk

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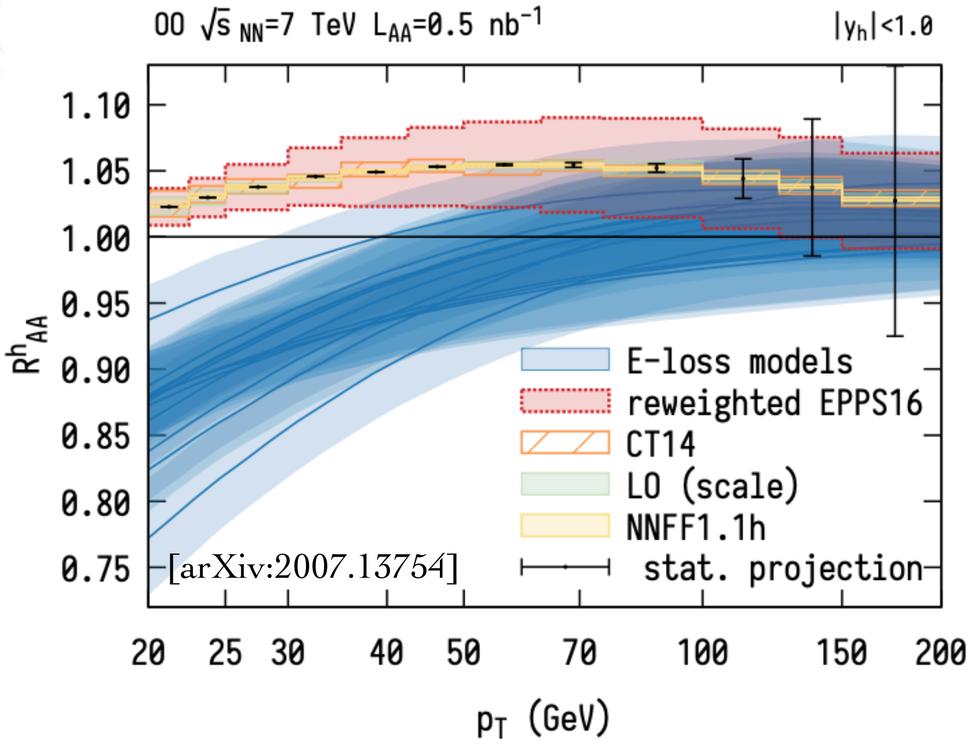

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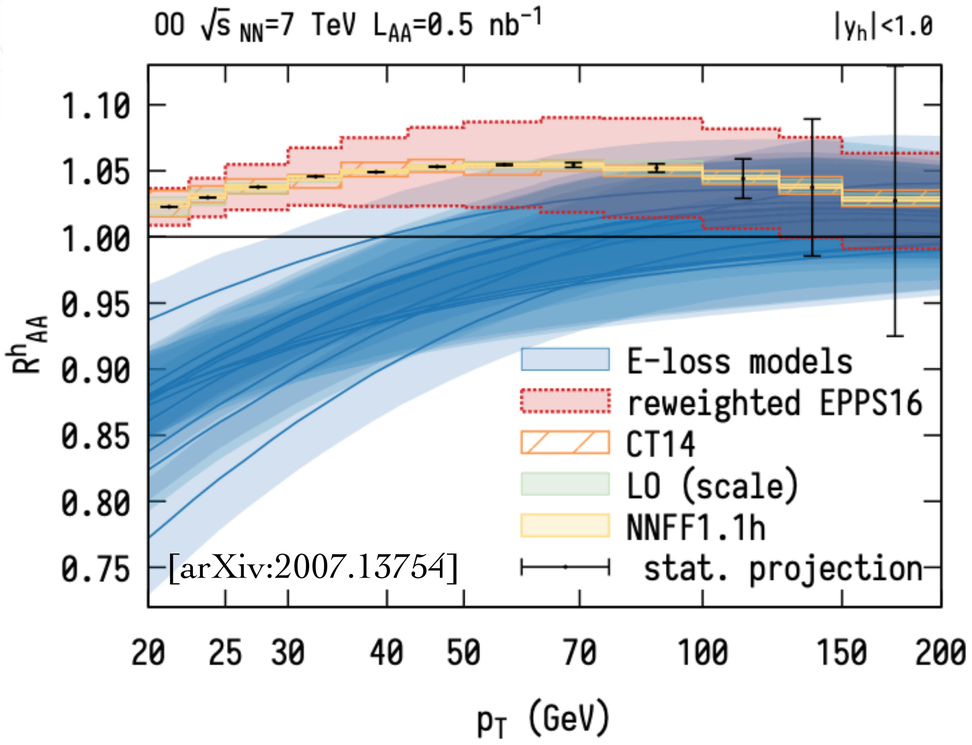


nPDFs play an important role when assessing small jet quenching effects!

(see Paakkinen's talk)

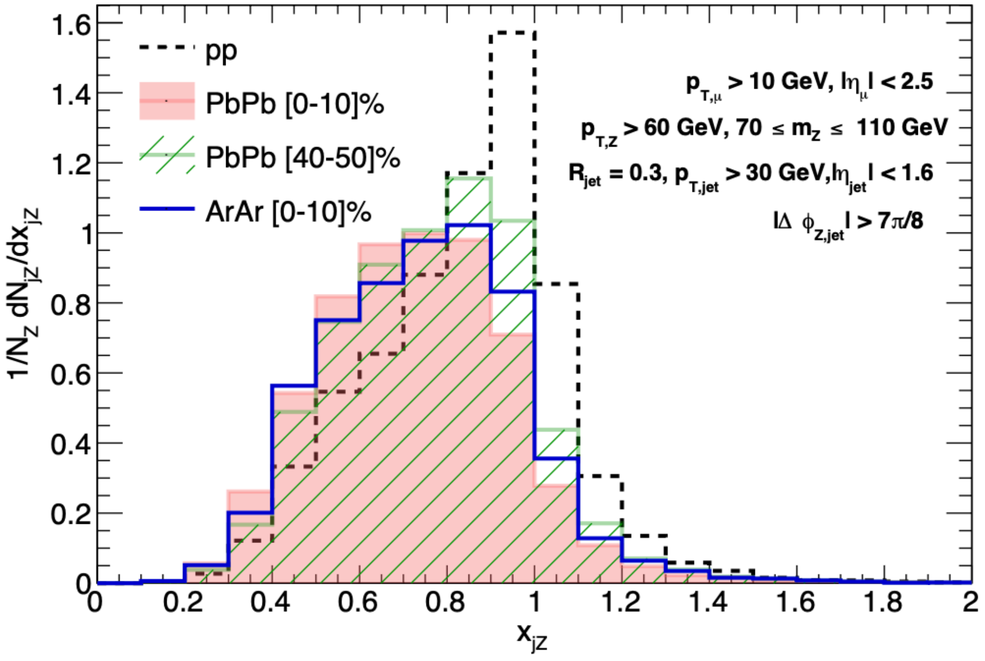
[JEWEL: Zapp (14)]

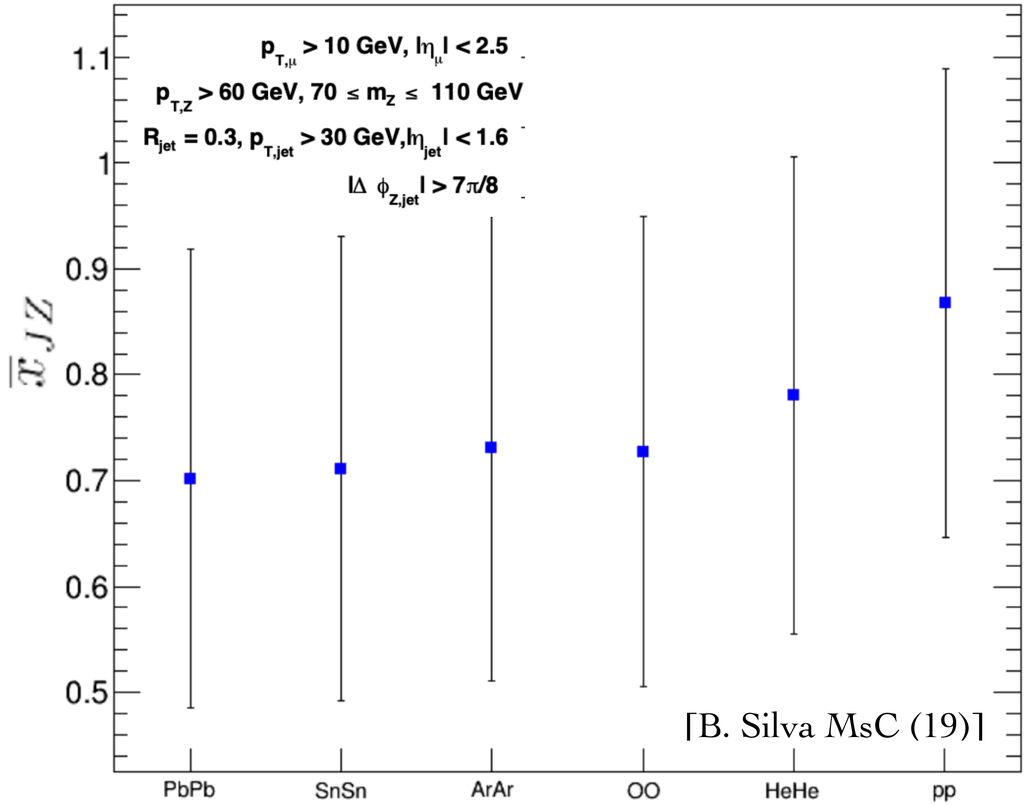
[Citron, Dainese et al (19)]

Jet Coincidences

- Signatures of energy loss in Z + jet coincidences?

[arXiv: 1812.06772]





[B. Silva MsC (19)]

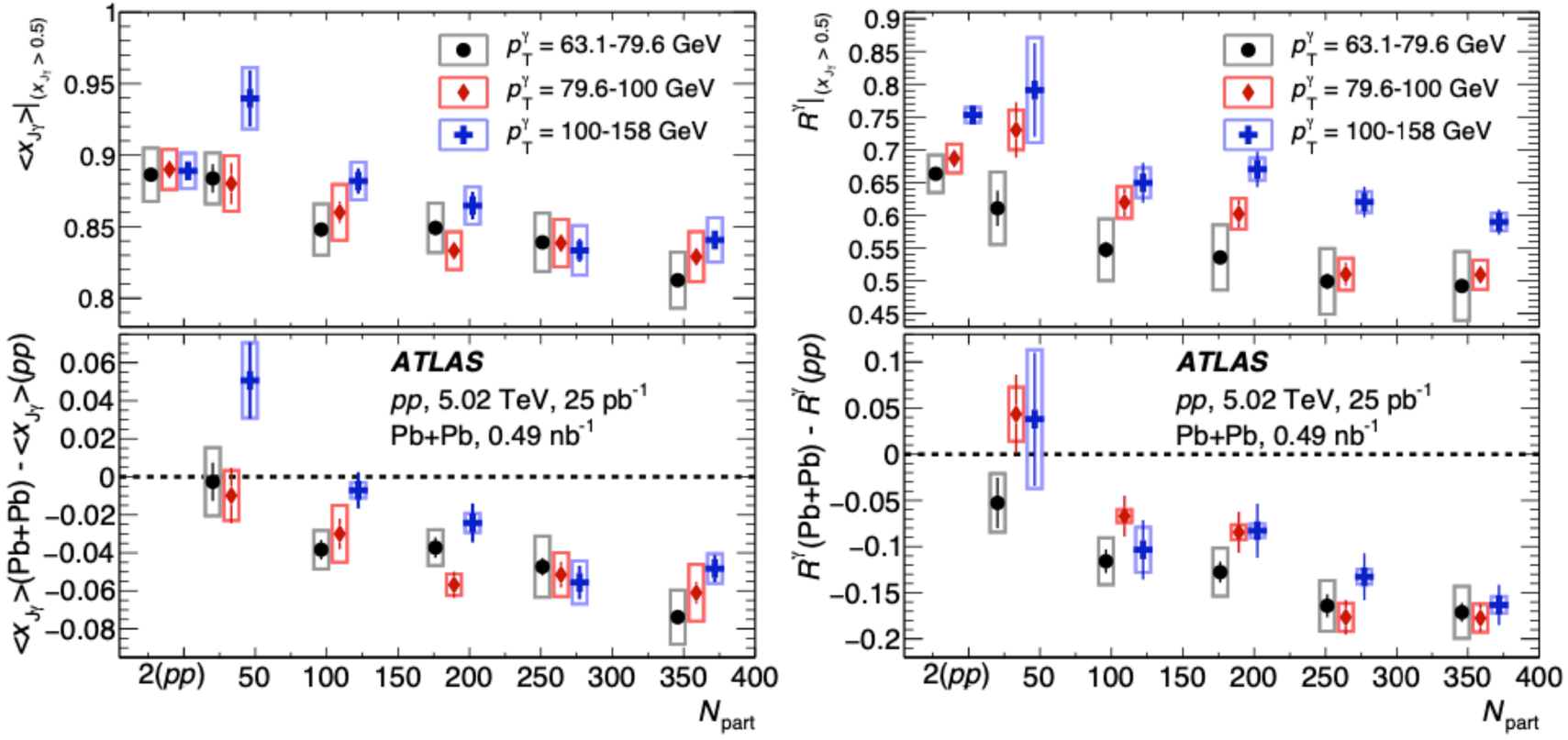
JEWEL (no recoils) + Bjorken Expansion + Stefan-Boltzmann limit

Jet Coincidences

[ATLAS: Phys.Lett.B 789 (2019) 167-190]

- Signatures of energy loss in γ + jet coincidences?

[arXiv: 1809.07280]



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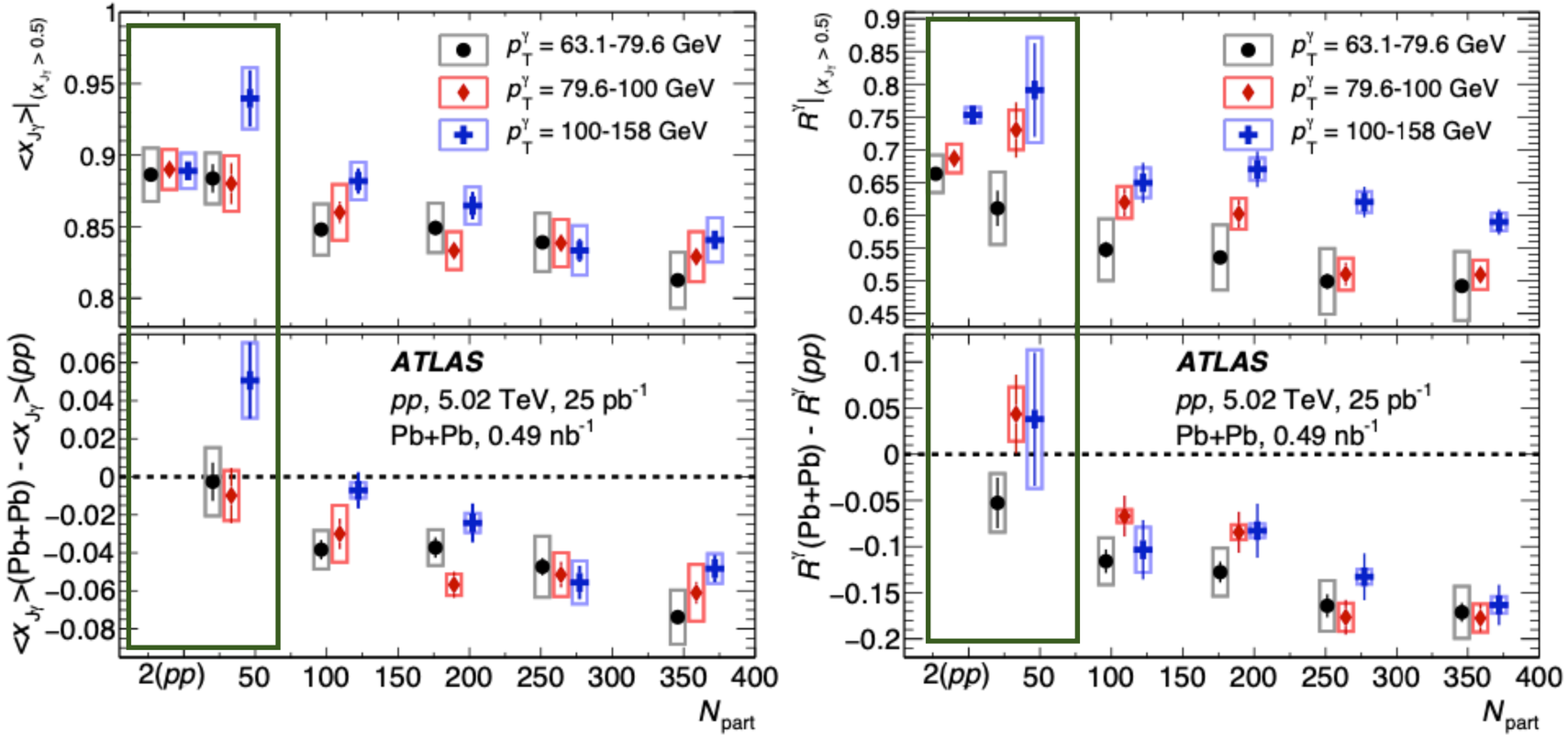


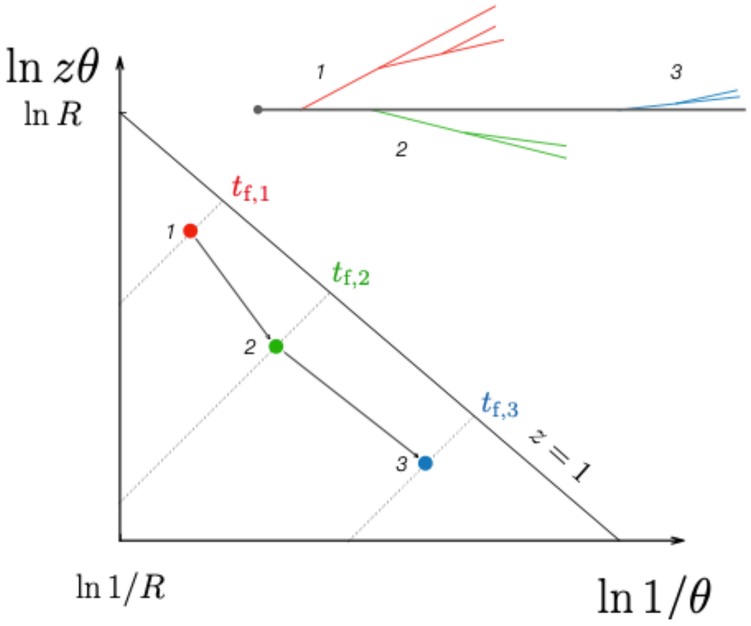
Possibility for OO run (requires statistics)…

Jet substructure

[Andrews et al (20)]

- Looking inside of jets intrinsic constitution
  - Allows to select regions of phase space where medium effects are enhanced

[Andrews et al: 1808.03689]



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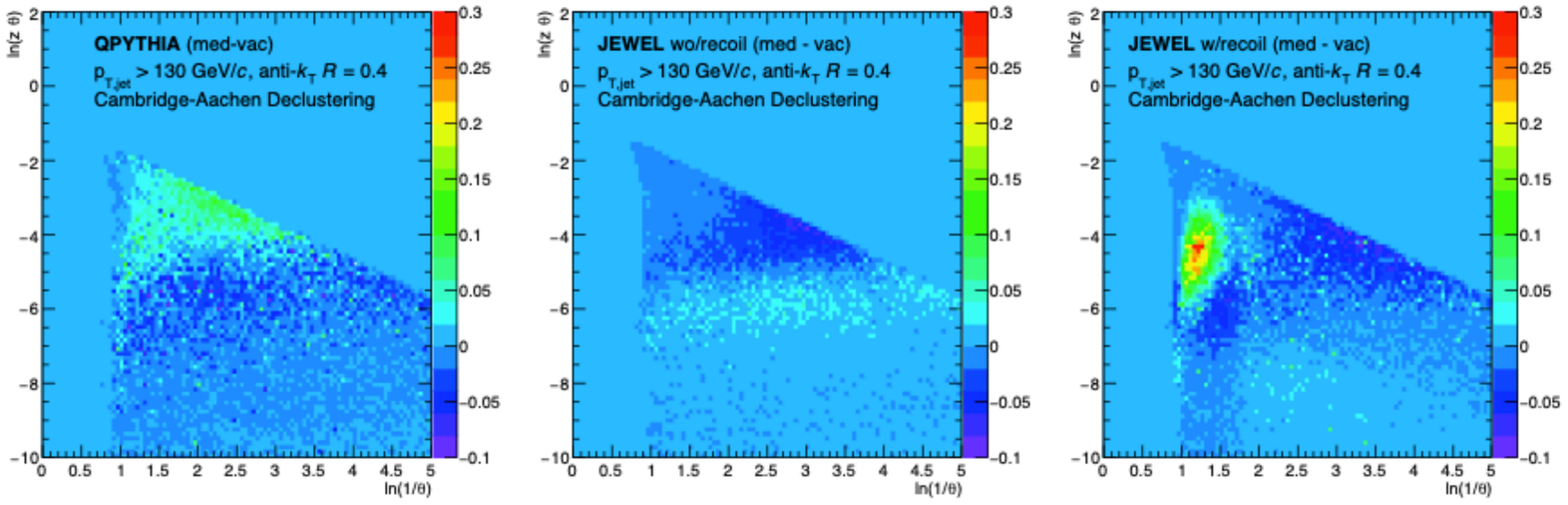

[Dominguez et al (20), Caucal et al (18), Caucal, Iancu, Soyez (20)]

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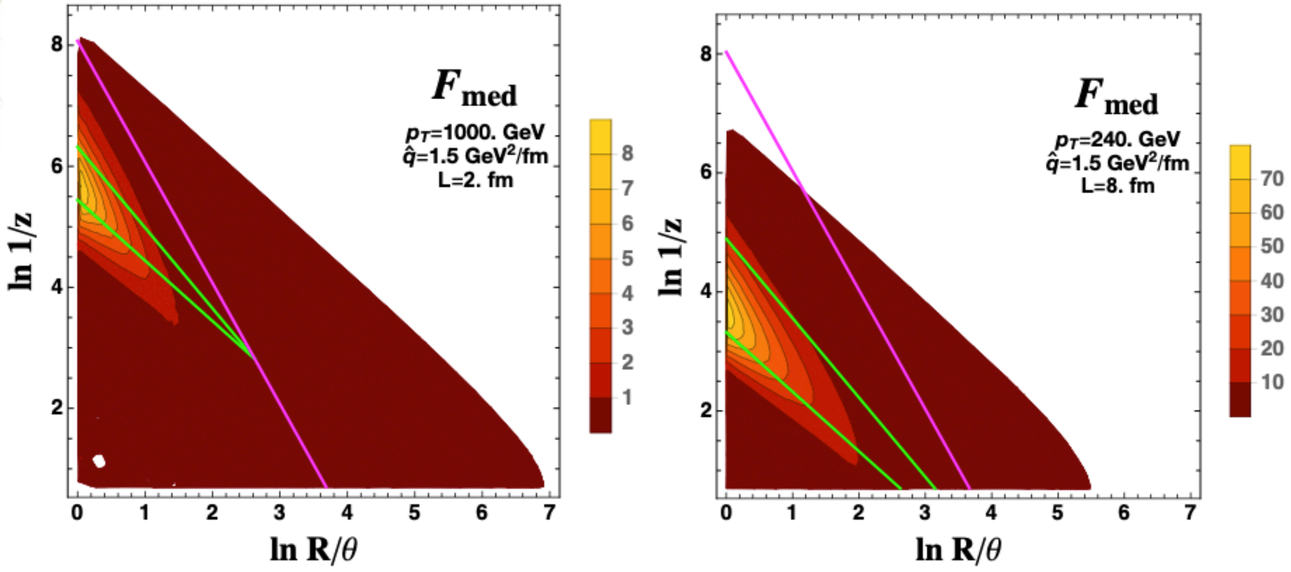
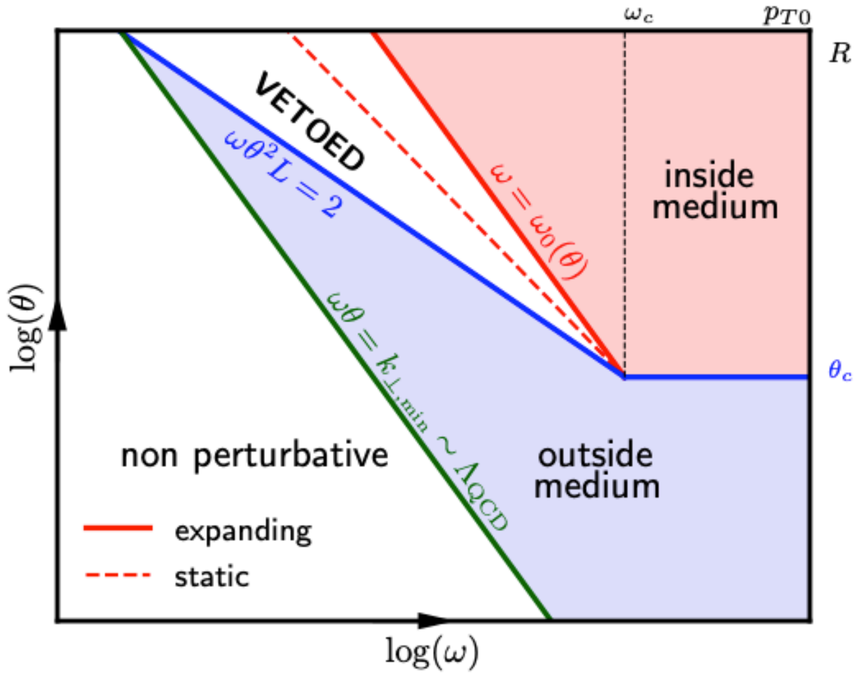


Medium modification factor

[Caucal et al: 2012.01457]



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[ALICE: Nucl.Phys.A 1005 (2021) 121906]

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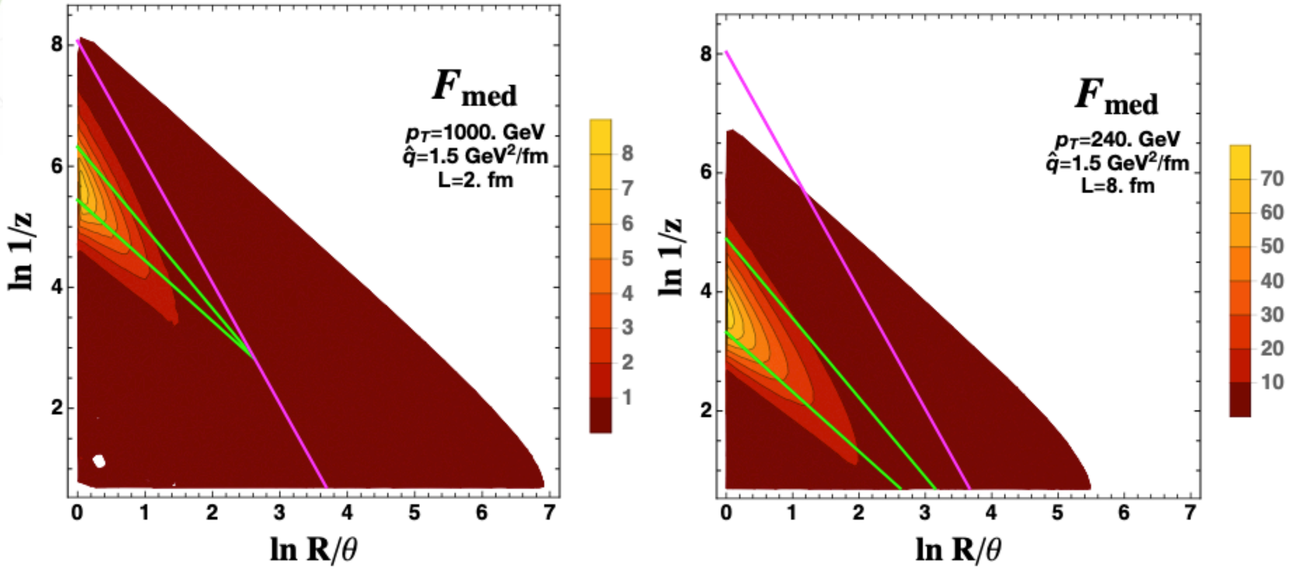

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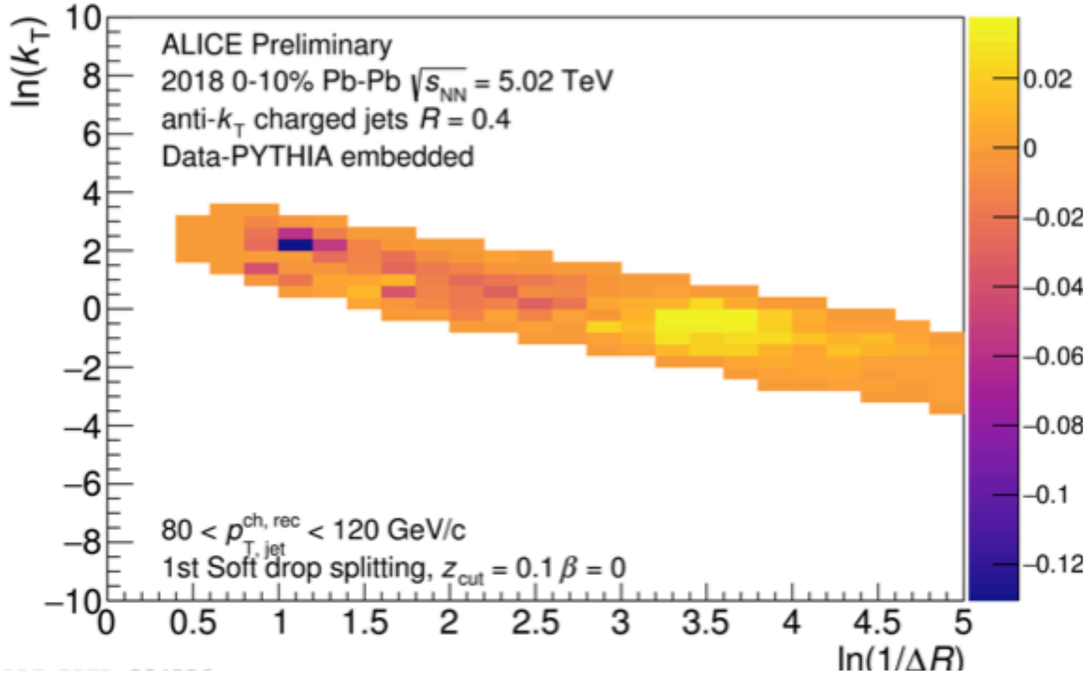

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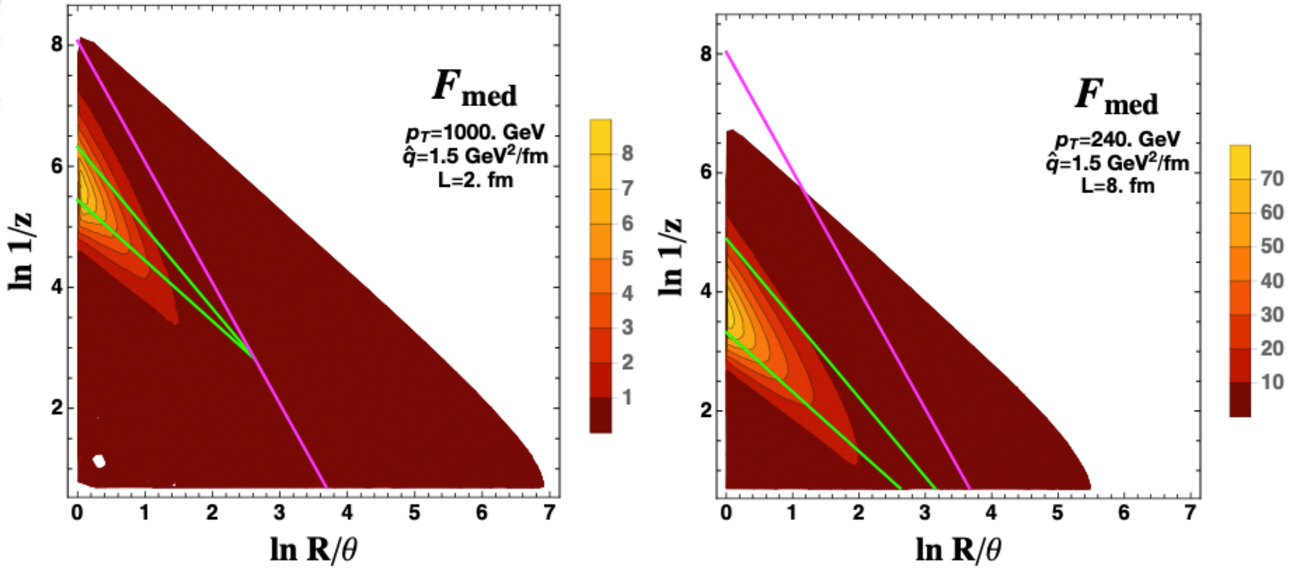

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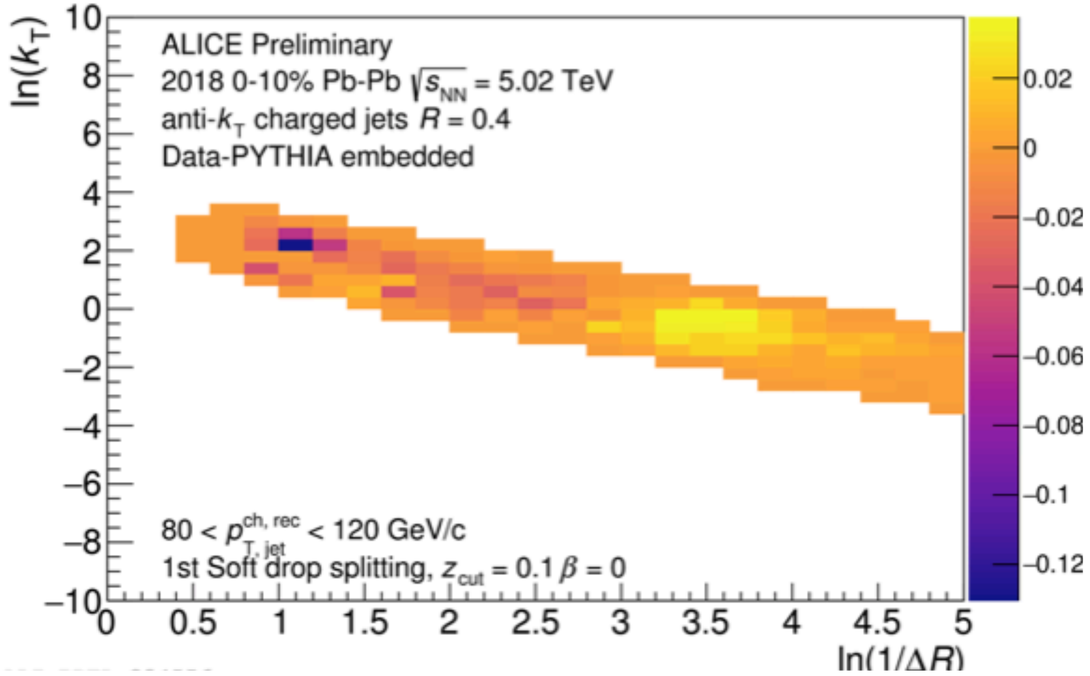
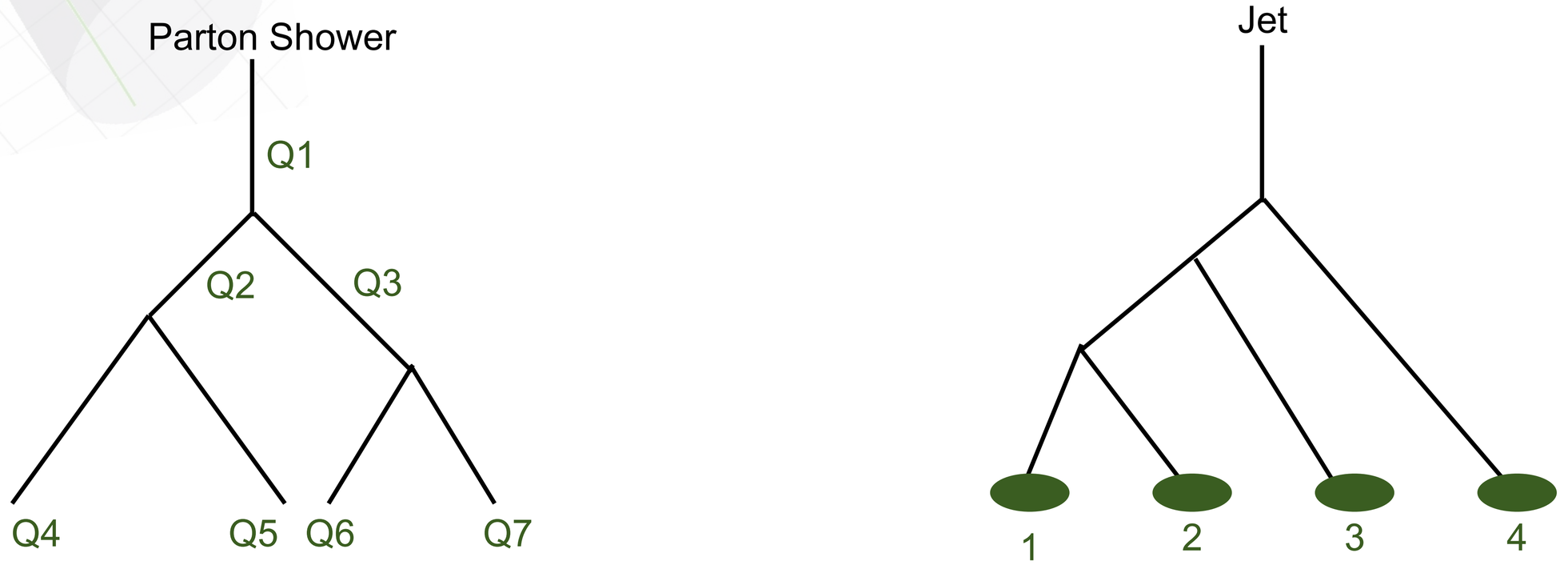


Increase precision to study medium-induced effects

Jet spacetime structure

- Inclusive jet spectra is always a mixture of different magnitudes of quenching
  - Possibility to select jets whose parton shower initiated at early stages (strongly modified)?



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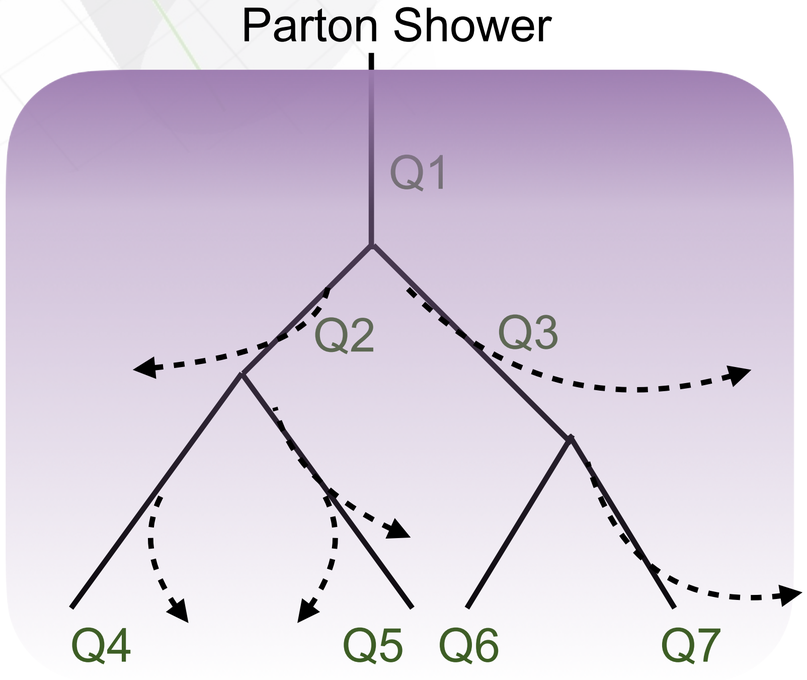
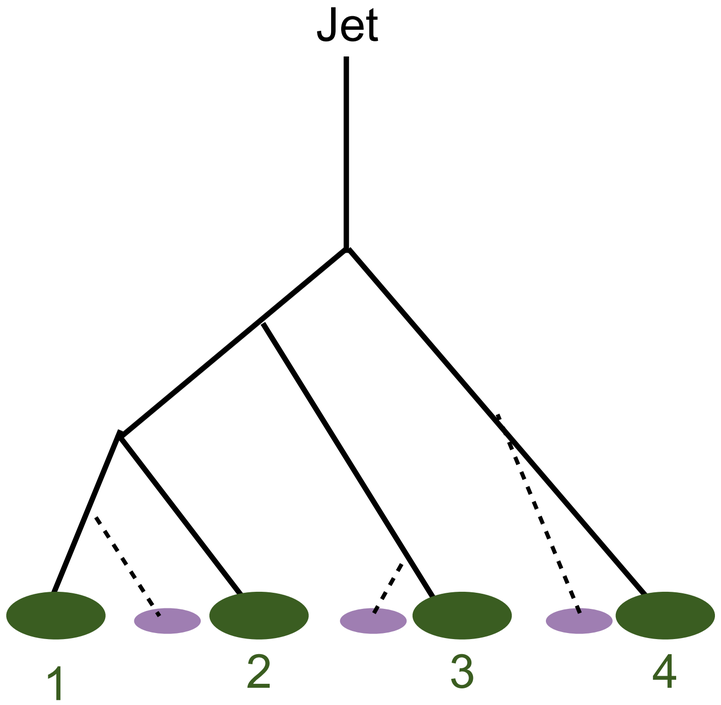


Fast Expanding medium
Medium-induced radiation



Additional particles to be clustered in the jet history

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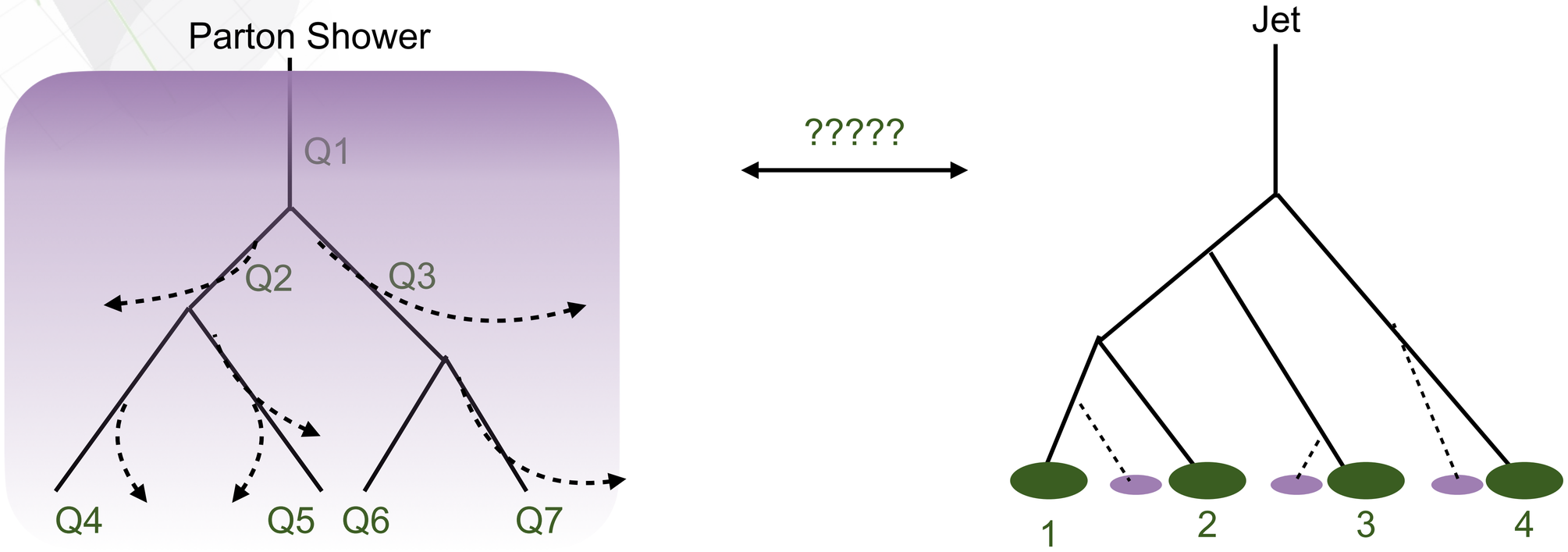

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[LA, Cordeiro, Zapp (20)]

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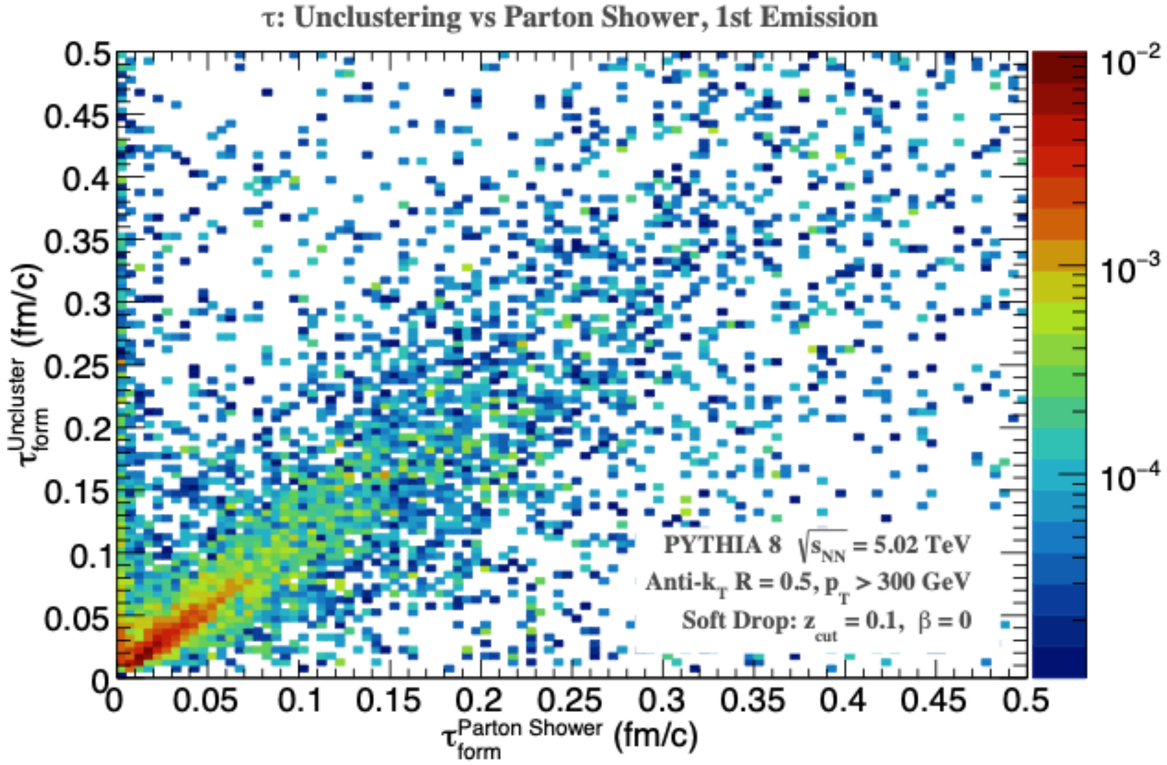
[arXiv. 2012.02199]

$$d_{ij} = \min(p_{t,i}^{2p}, p_{t,j}^{2p}) \frac{\Delta R_{ij}^2}{R^2} \qquad d_{iB} = p_{t,i}^{2p}$$

$$d_{ij} \sim p_{T,i} \frac{\Delta R_{ij}^2}{R^2} \sim p_T \theta^2 \sim \frac{1}{\tau_{form}}$$

p = 0.5 (τ)

$$\tau_{form} \approx \frac{E}{Q^2} \approx \frac{1}{2Ez(1-z)(1-\cos\theta_{12})}$$



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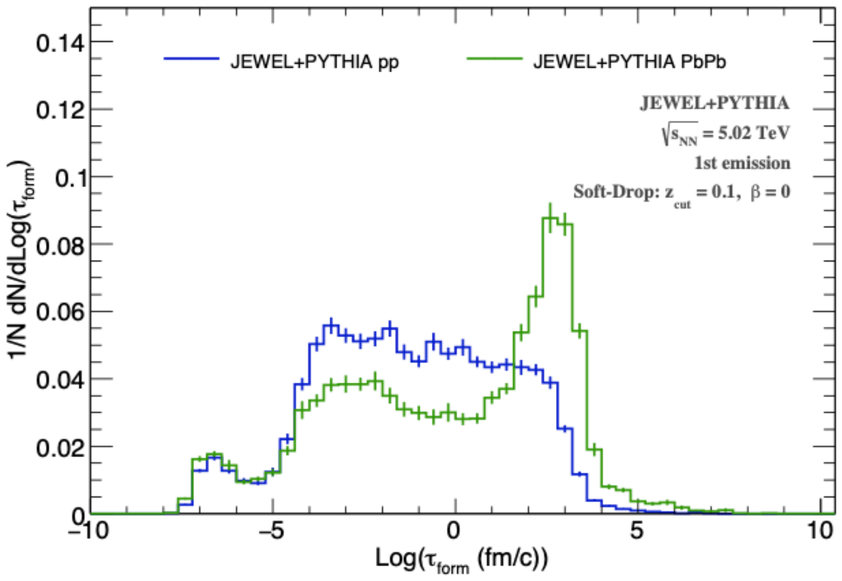

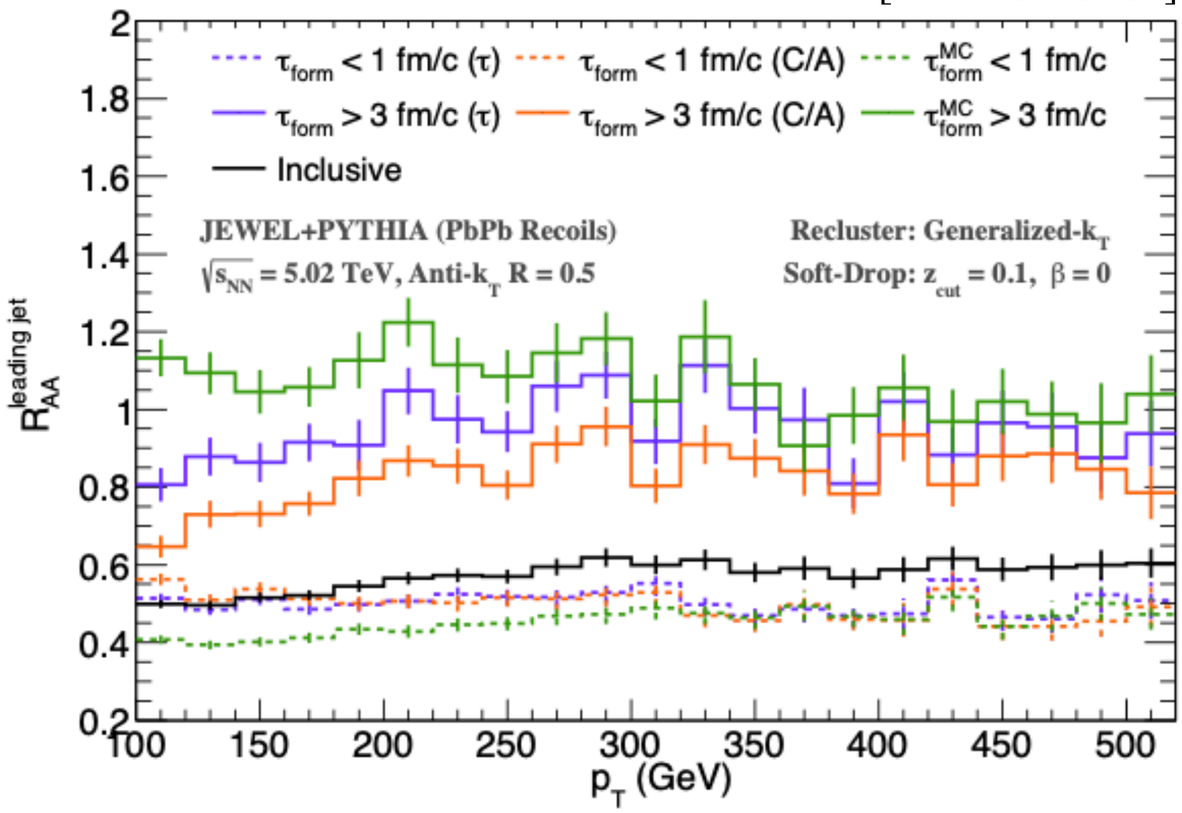

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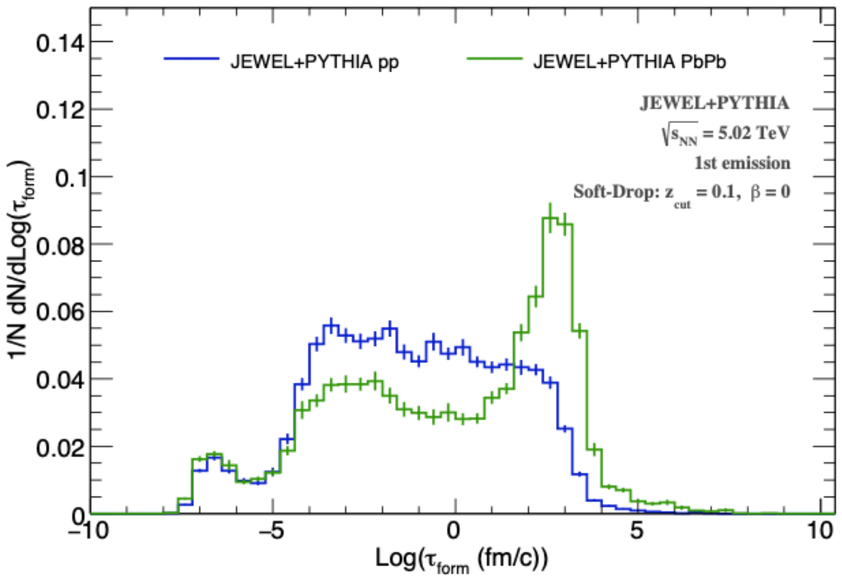
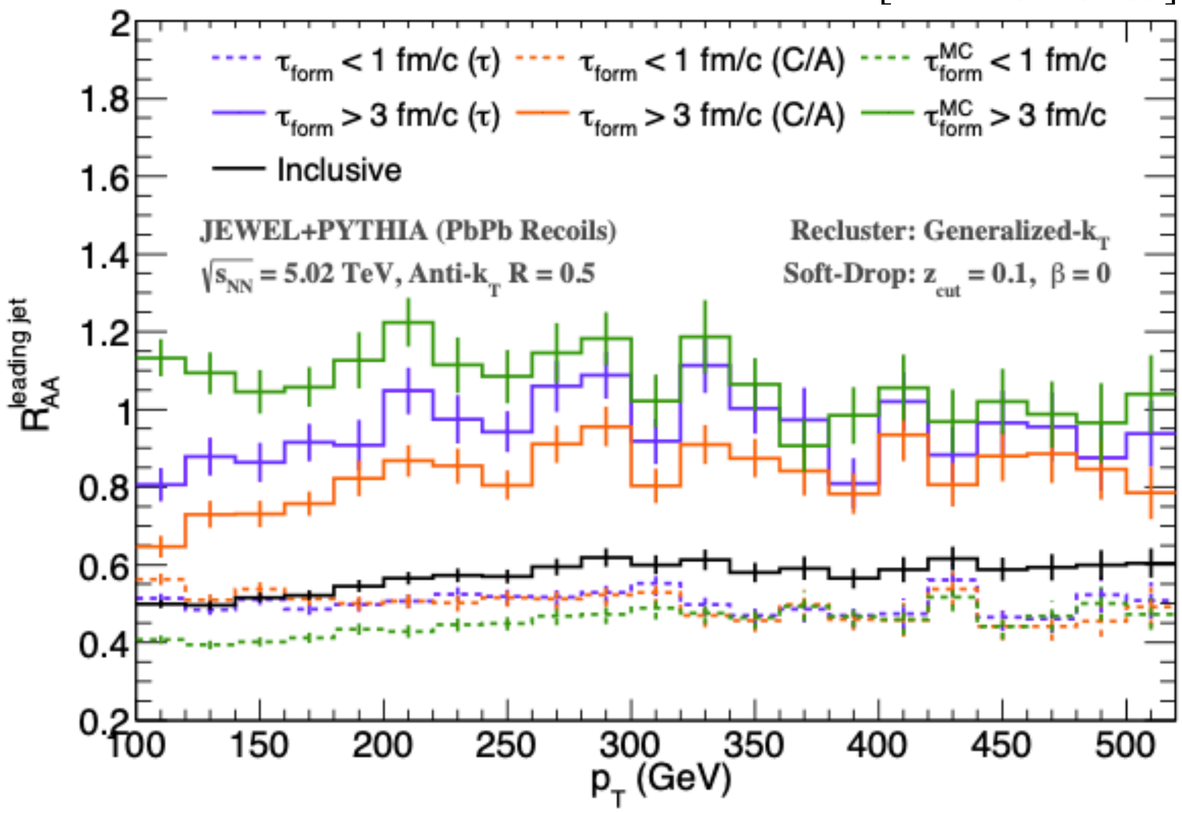




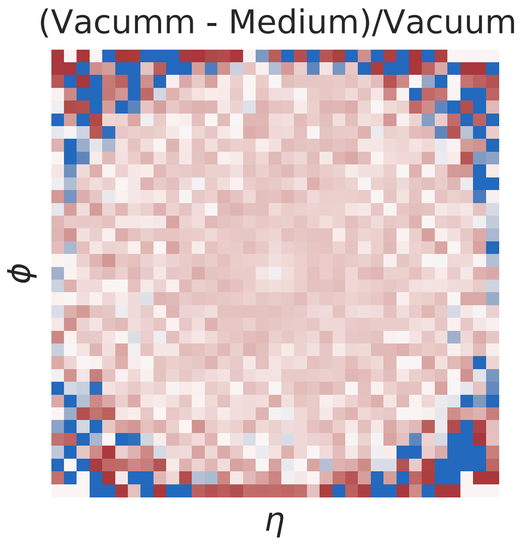
Choosing a better proxy enhances precision and allows to select different jet classes (based on quenching magnitude)

[LA, Castro, Crispim, Milhano, Pedro, Peres (under preparation)]

[Du, Pablos, Tywoniuk (20)]

Machine Learning

- Machine learning techniques might also help to select strongly modified jets
  - Ex: calorimetric jet images
    - Jewel Z Boson (muons) + Jet @ 5.02 TeV (no recoils)
      - Z pt >= 90
      - R = 0.5 recoiling jet (7/8 π) and pt > 30



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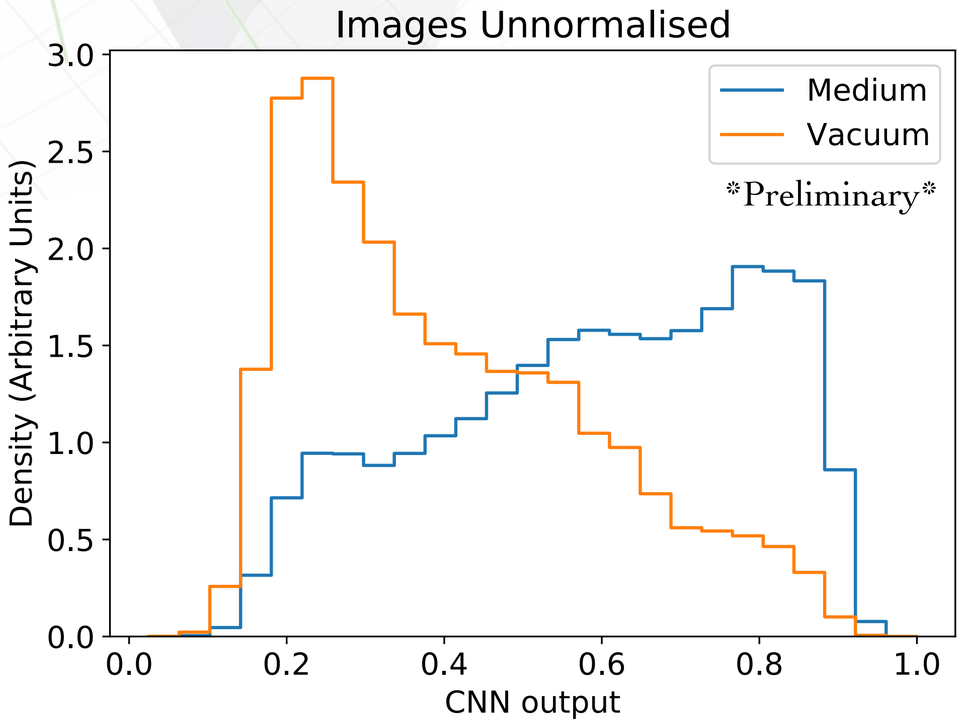

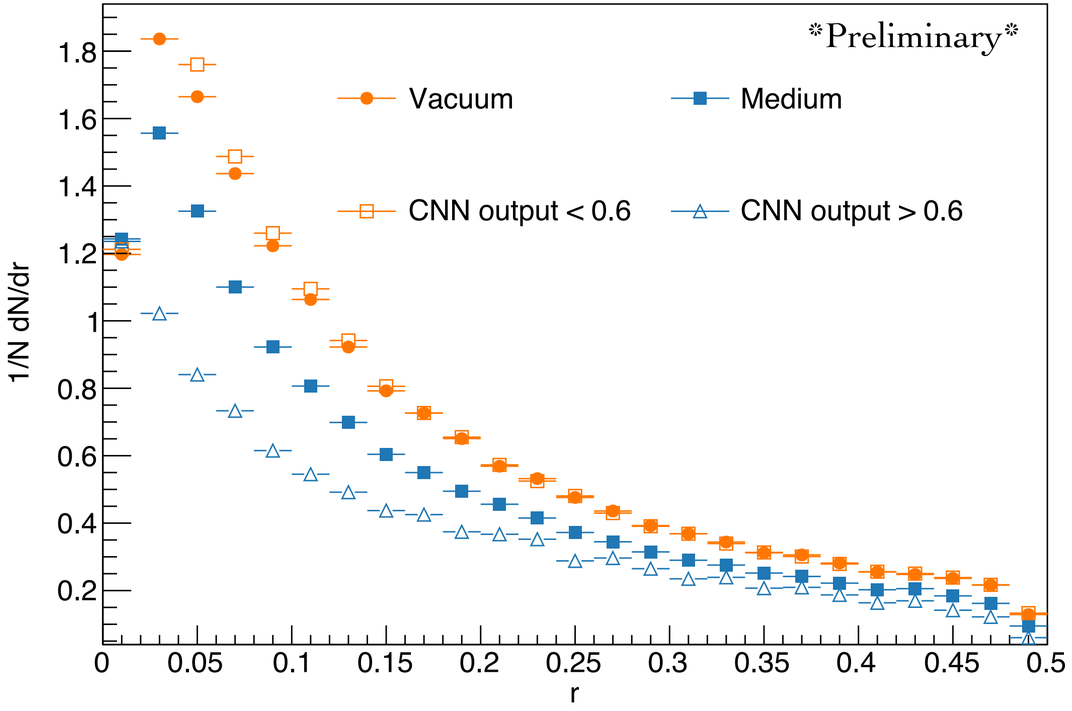

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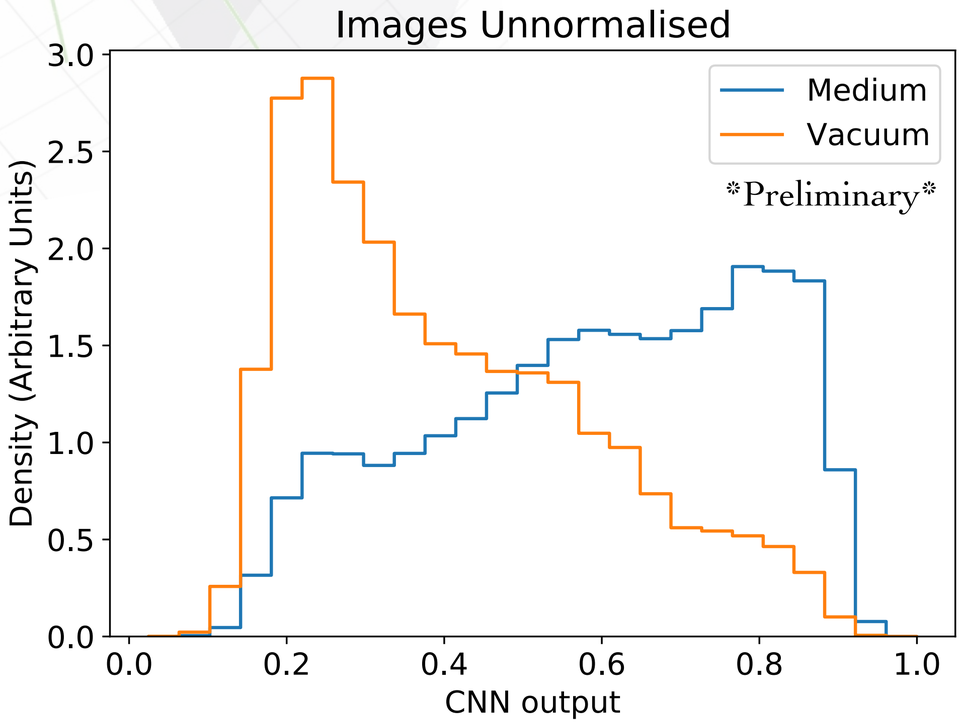
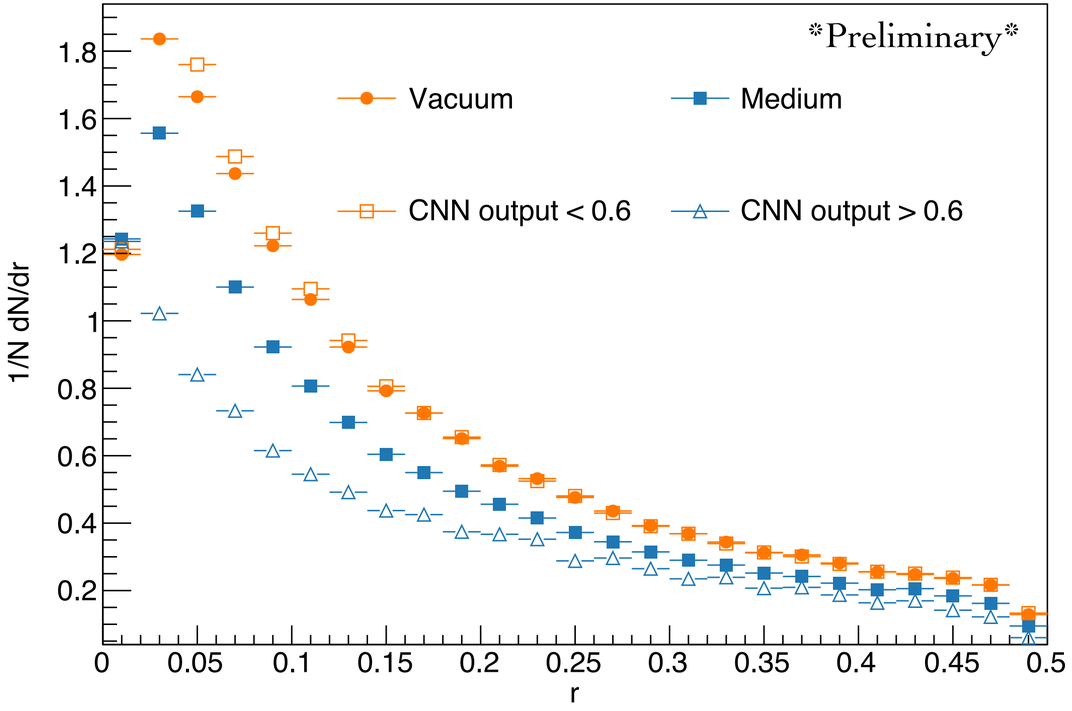




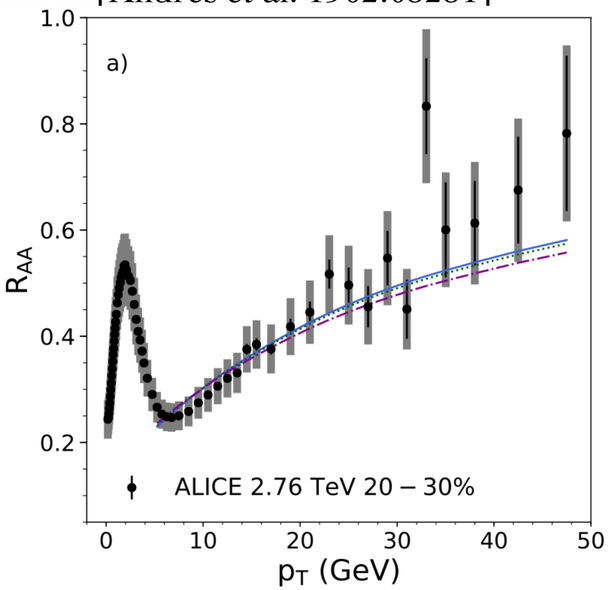
Promising selection of medium-modified jets (trained on model dependent features…)

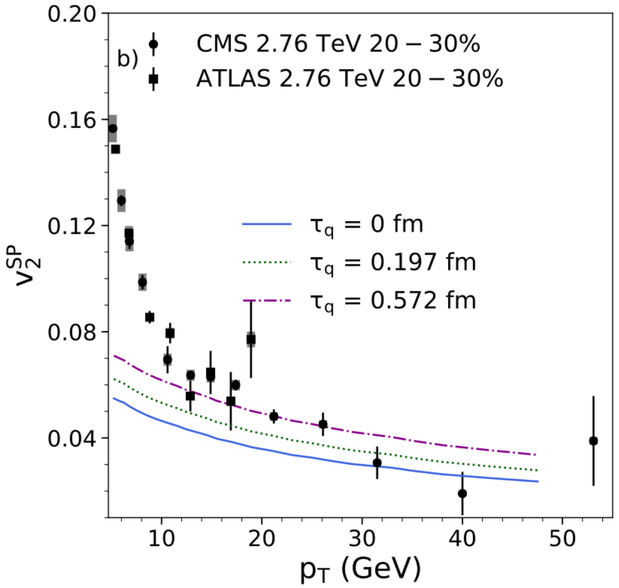
[Andrés, Armesto, Niemi, Paatelainen, Salgado(19)]

Soft and Hard Scales

- QGP-like effects in small systems:
  - Are they all related to the same phenomena?
    - Flow and strangeness from non-QGP physics?

[Andrés et al: 1902.03231]





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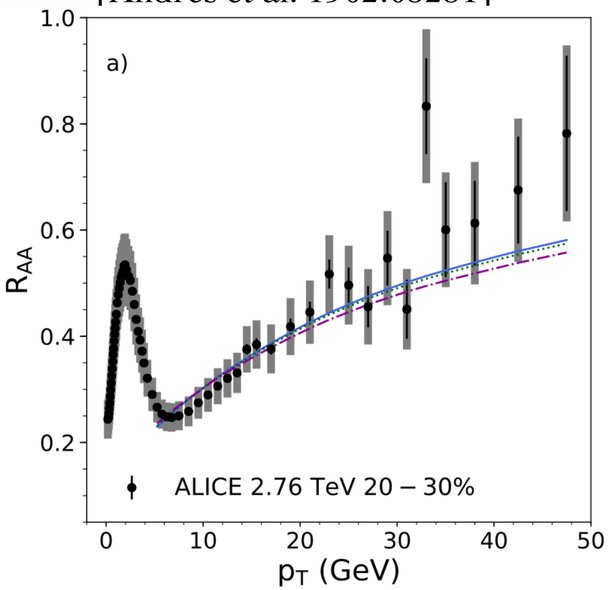

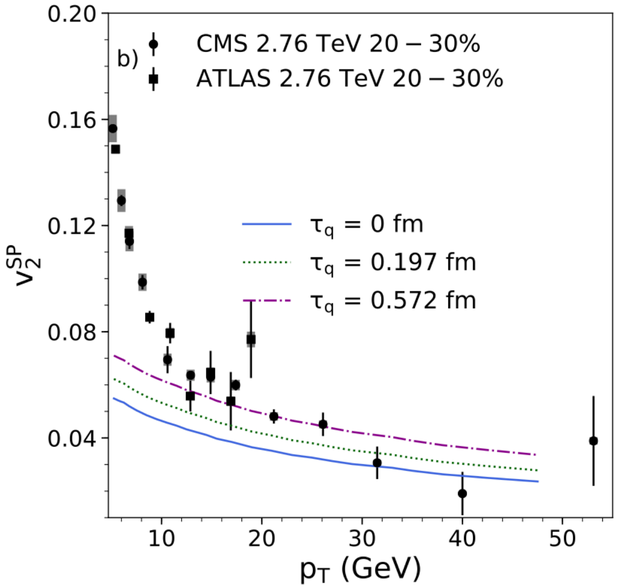

[Andrés, Armesto, Niemi, Paatelainen, Salgado(19)]
[Katz, Prado, Noronha-Hostler, Suaide (20)]

Soft and Hard Scales

See Noronha-Hostler's talk

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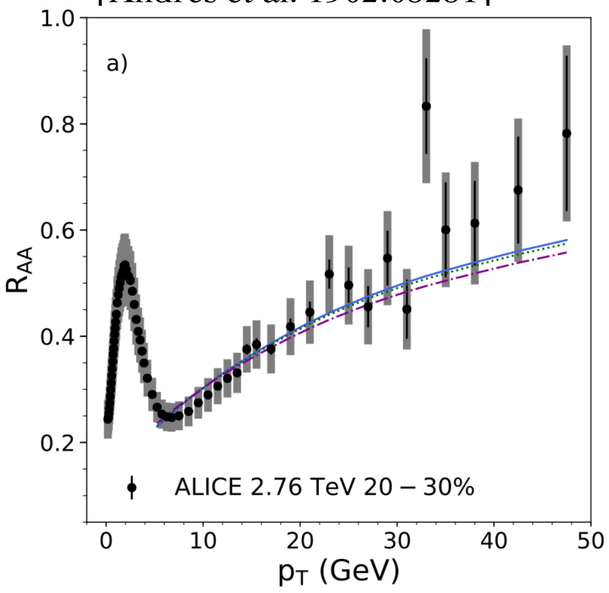
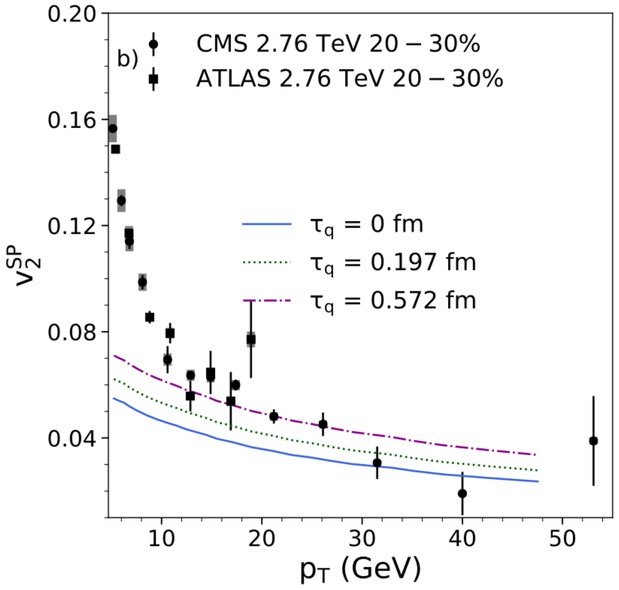
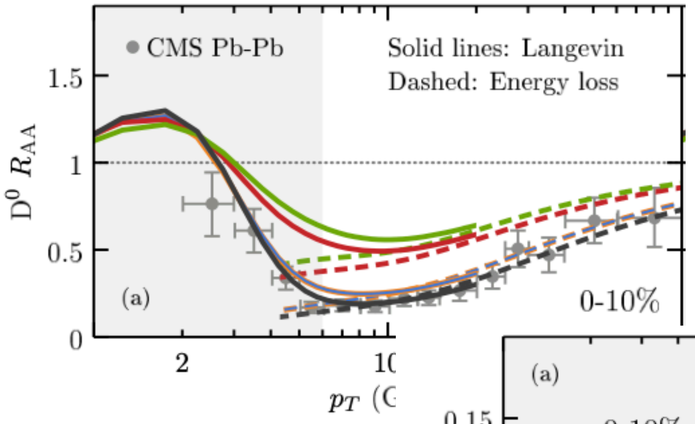
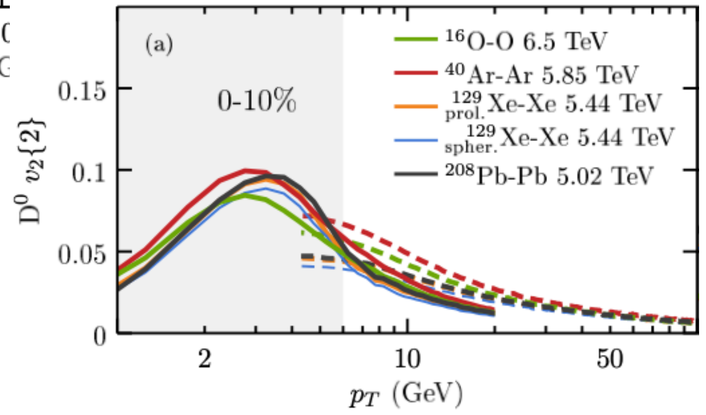




[Katz et al: 1907.03308]





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  - Geometry in light systems vs geometry in pPb?

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Thank you!

Acknowledgements

REPÚBLICA PORTUGUESA

FCT
Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

LIP

TÉCNICO LISBOA

Backup slides

QGP in dense systems

- PbPb and AuAu presents consistent signatures of a QGP formation:

[ATLAS: Eur.Phys.J.C 78 (2018) 12, 997]

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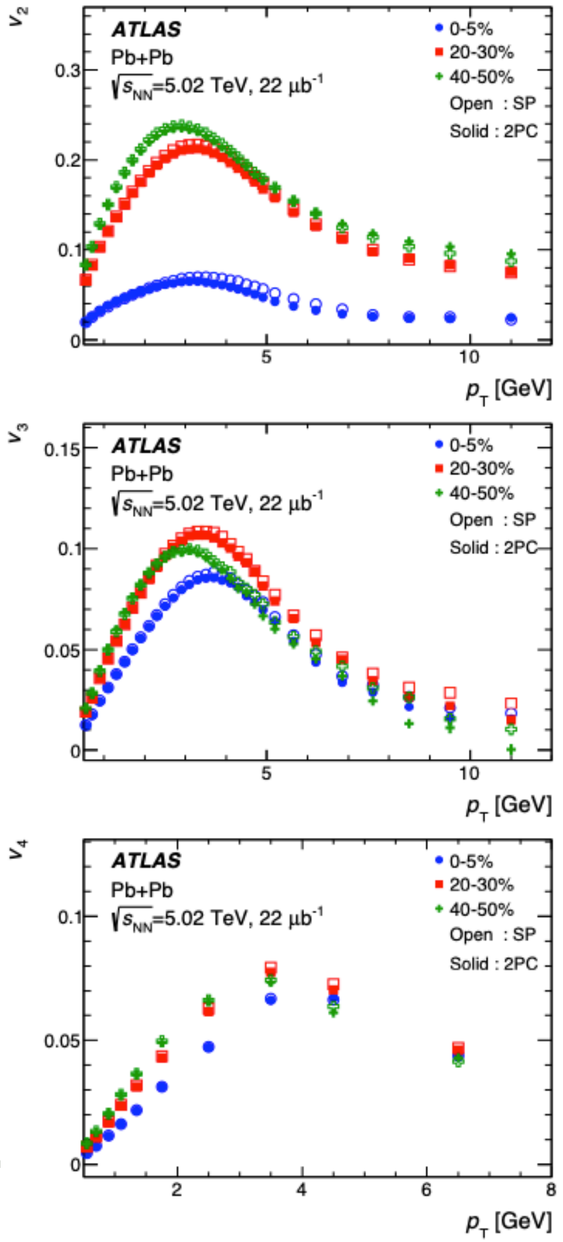
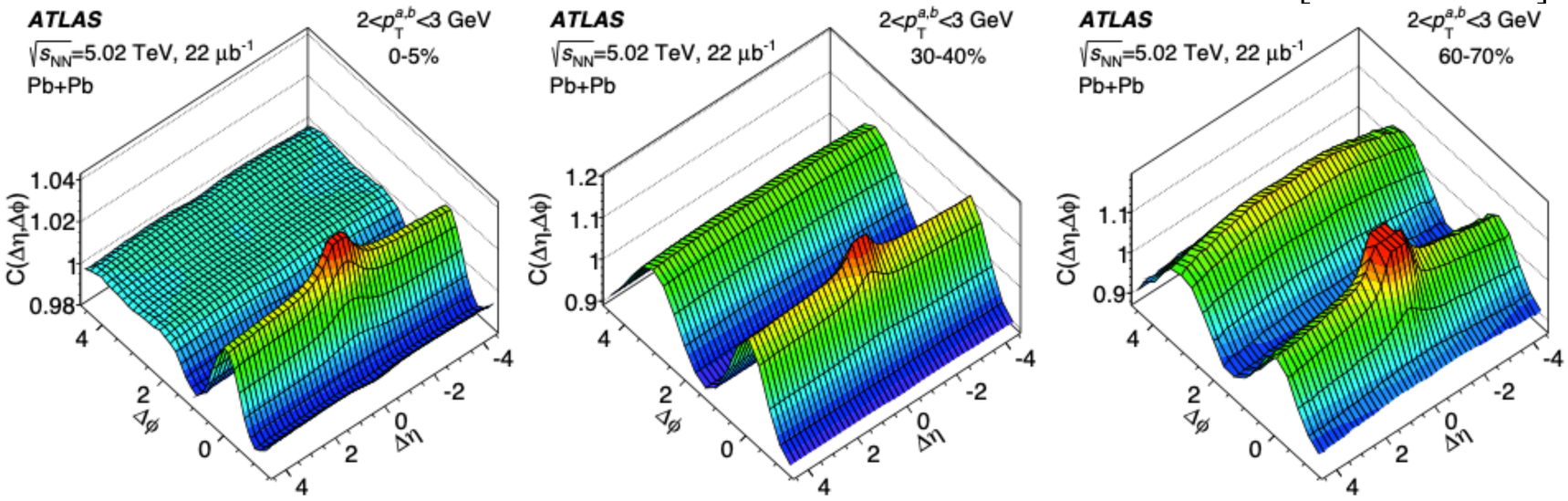


[arXiv:1808.0395]



[ALICE: Phys.Lett.B 734 (2014) 409-410]

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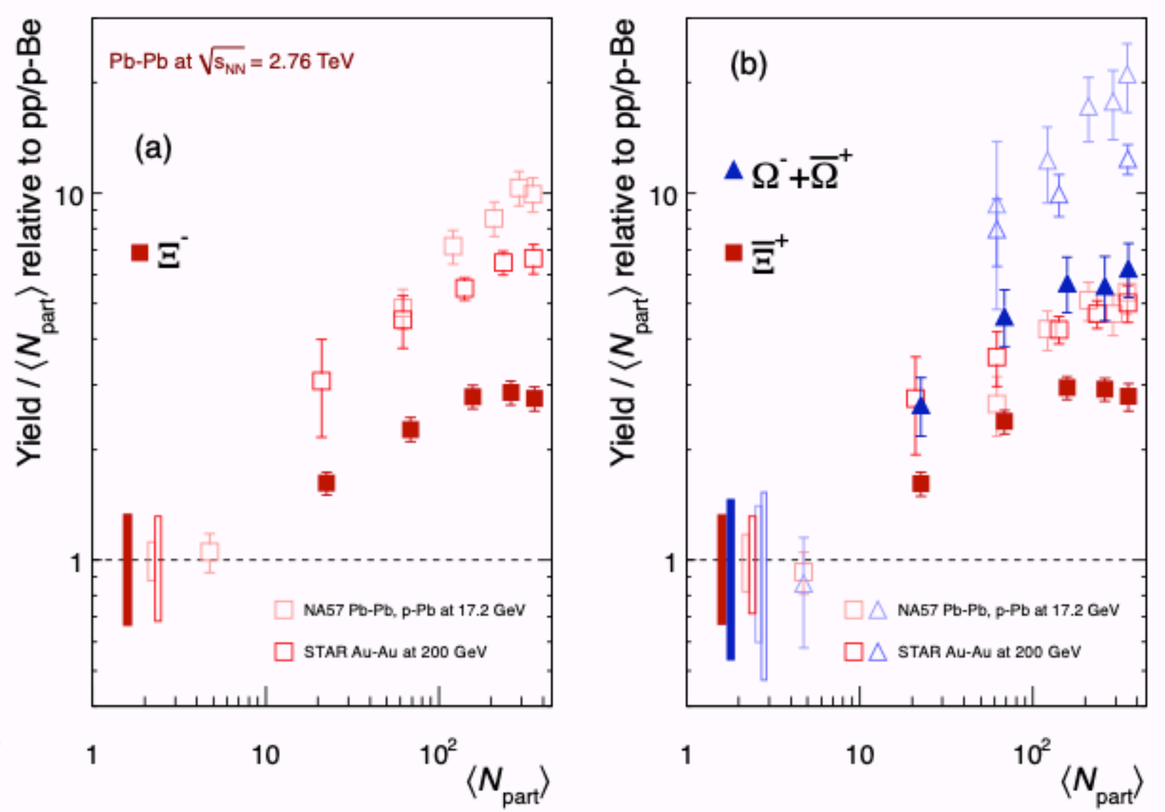
[arXiv:1307.5543]



[STAR: Phys. Rev. Lett. 89 (2002) 202301]
[PHENIX: Phys.Rev.Lett. 88 (2002) 022301]

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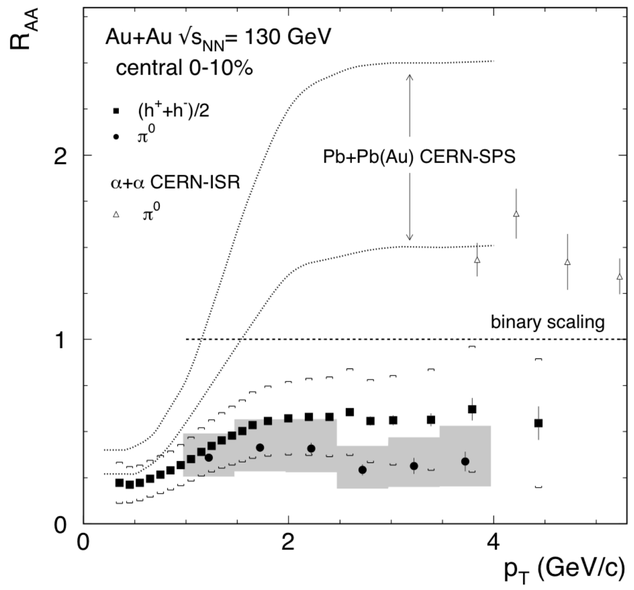
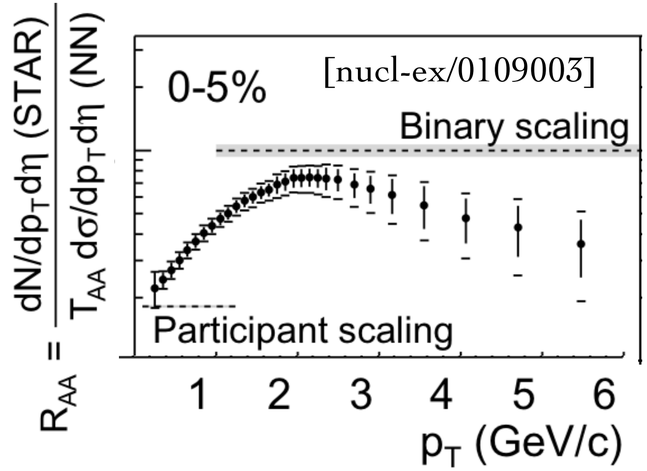
[nucl-ex/0109003]





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[ATLAS: JHEP 09 (2015) 050]

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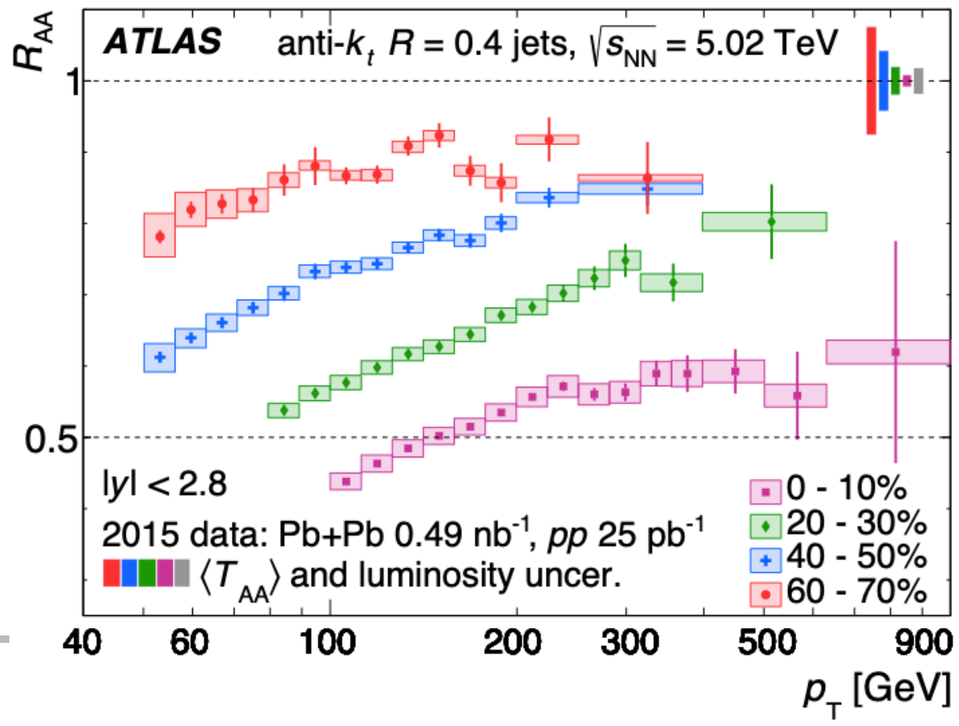
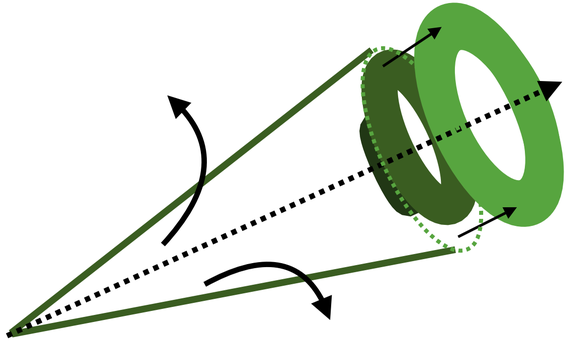
[arXiv:1504.04337]



[CMS: Phys. Rev. Lett. 121 (2018) 242301]
[CMS: PRL 122 (2019) 152001]

QGP in dense systems

[Adapted from: K. Zapp]



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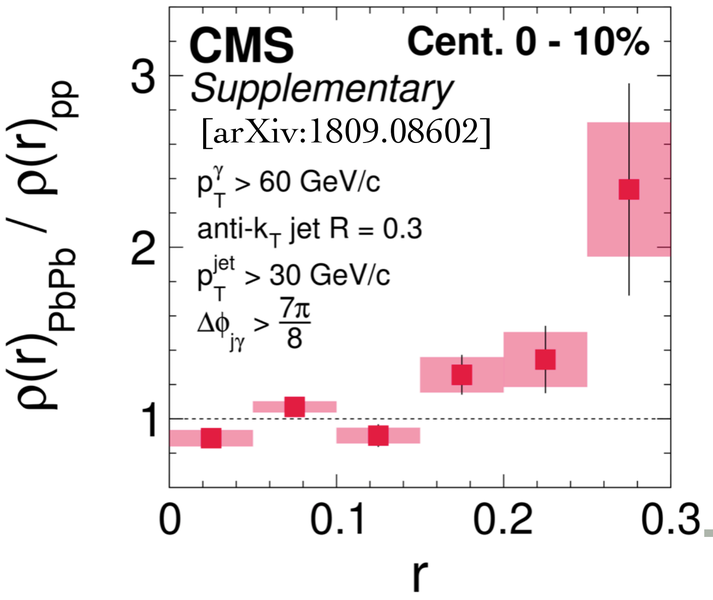
  - Suppression of jet spectra (energy loss) ✓
    - Modification of jet substructure ✓

$p_T^{trk} > 1$ GeV/c, anti-k_T jet R = 0.3

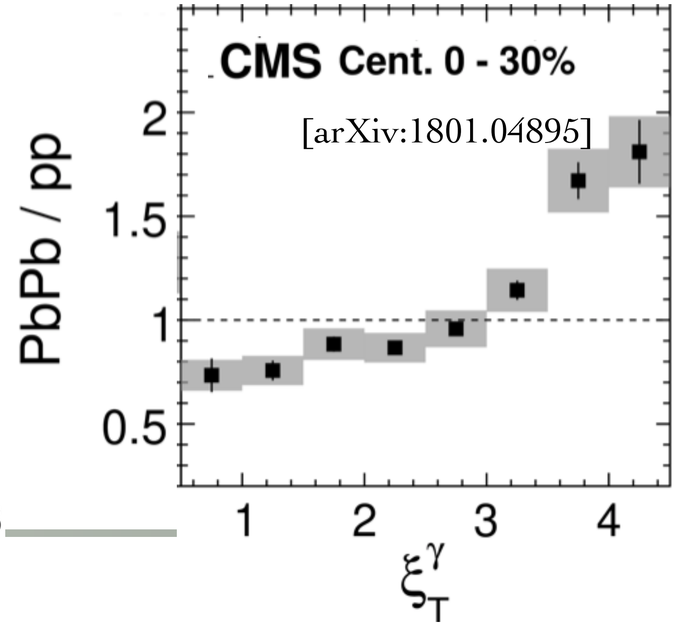
$p_T^{jet} > 30$ GeV/c, $|\eta^{jet}| < 1.6$

$p_T^{\gamma} > 60$ GeV/c, $|\eta^{\gamma}| < 1.44$, $\Delta\phi_{j\gamma} > \frac{7\pi}{8}$

Jet radial profile (PbPb/pp)



Fraction of energy of jet fragments (PbPb/pp)



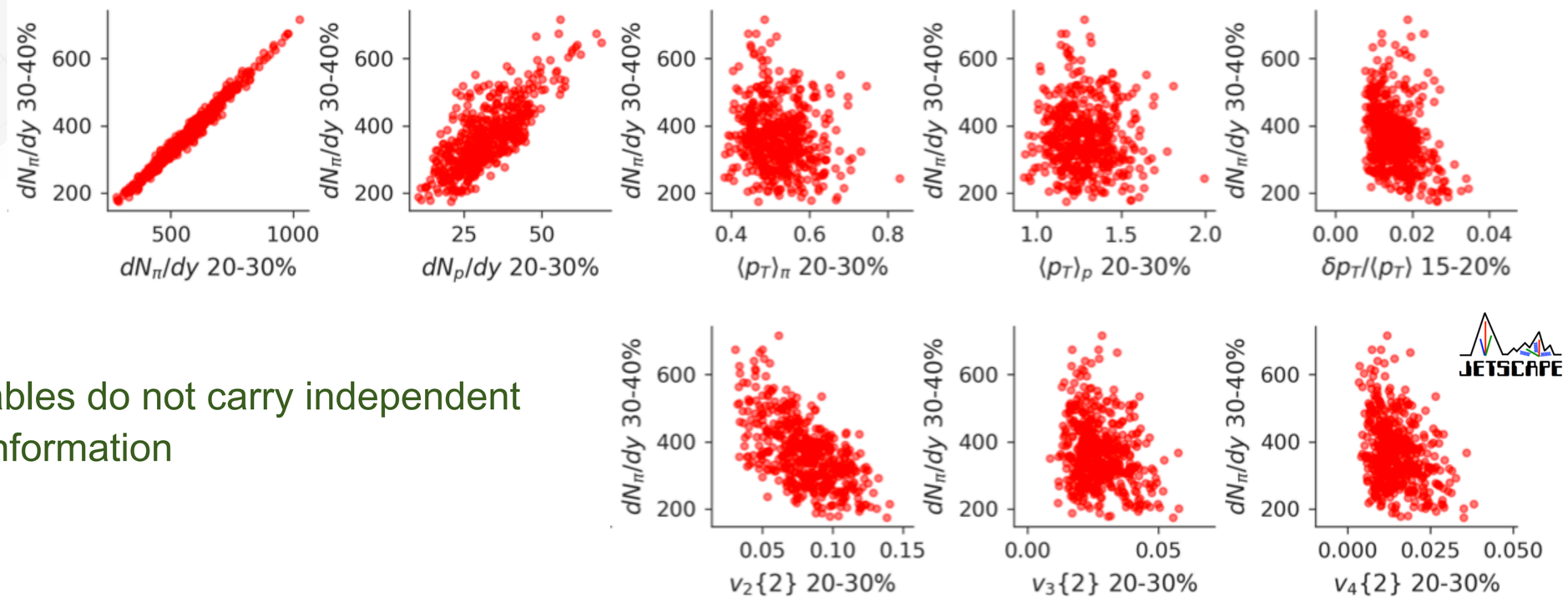
[STRONG 2020 - NA3 (on-going)]

[JETSCAPE (20,21)]

Multibayesian approach

- Identification of reduced set of observables that are most discriminant

[arXiv:2011.01430]



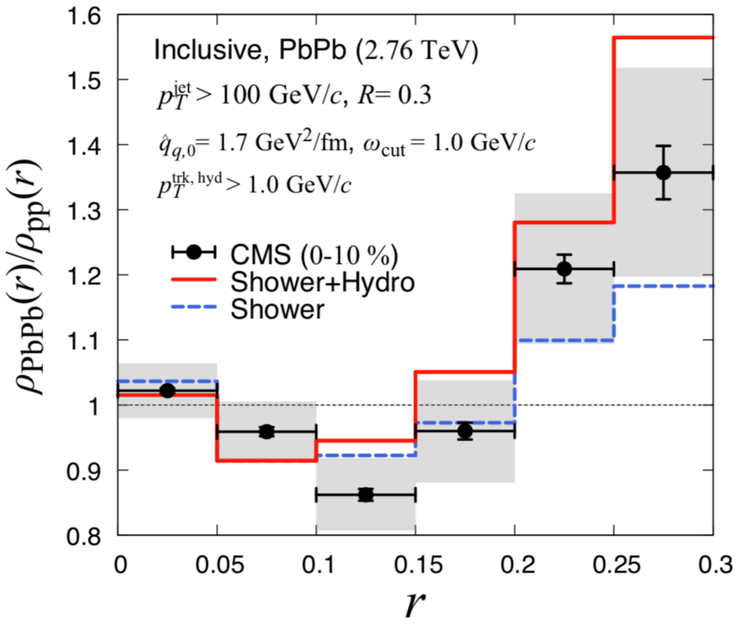
Some pair of observables do not carry independent information

[Tachibana, Chang, Qin (17)]
[Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal (14;17)]
[Park, Jeon, Gale (18)]

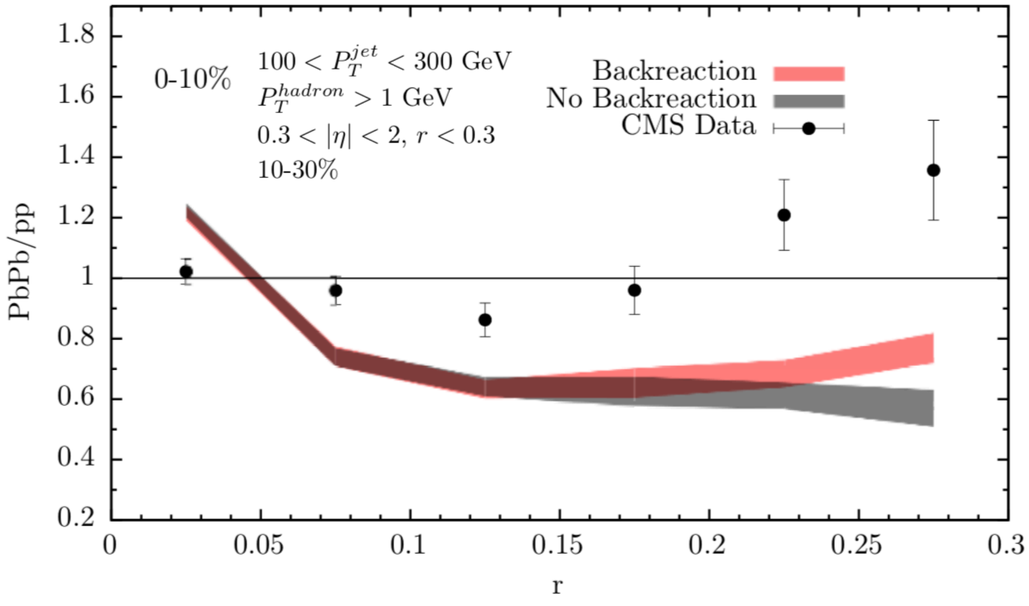
Medium Response

- Mostly seen in jet radial profile but signatures of each approach is very different:

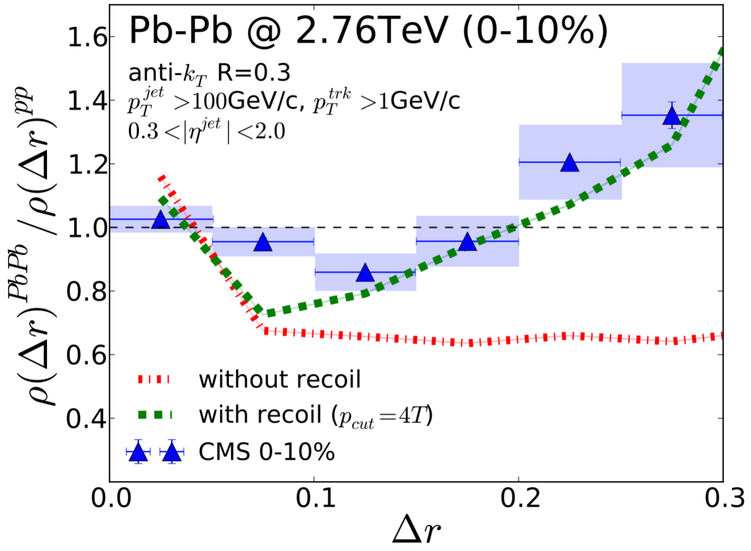
[Coupled Jet-Fluid: 1701.07951]



[Hybrid: 1609.05842]



[MARTINI:1807.06550]



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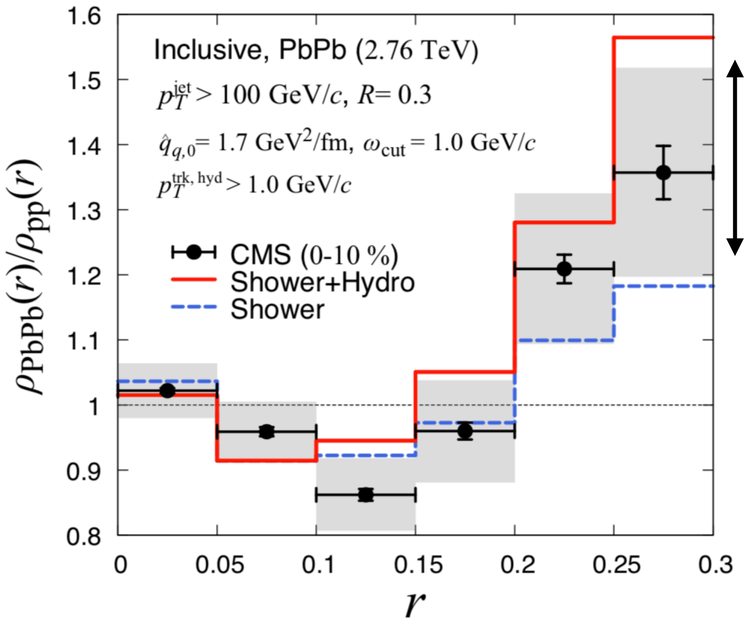

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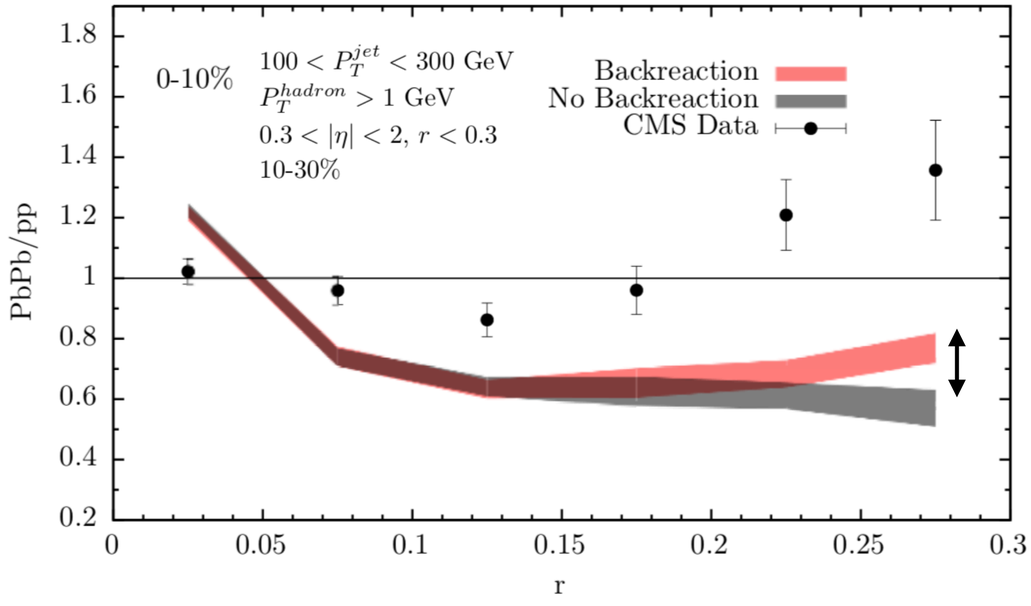

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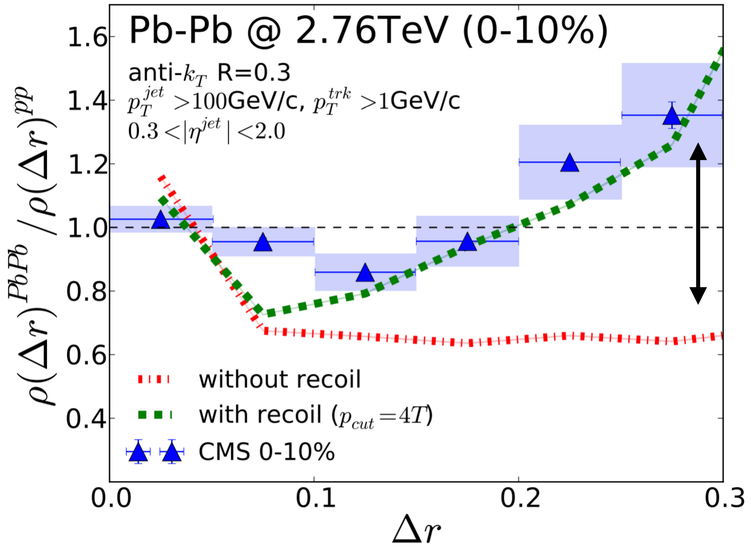

Several uncertainties… But seems to be necessary to describe excess of particles at large angles…

Medium response

- However :
  - Large contribution of medium response leads to a large R dependence on jet RAA
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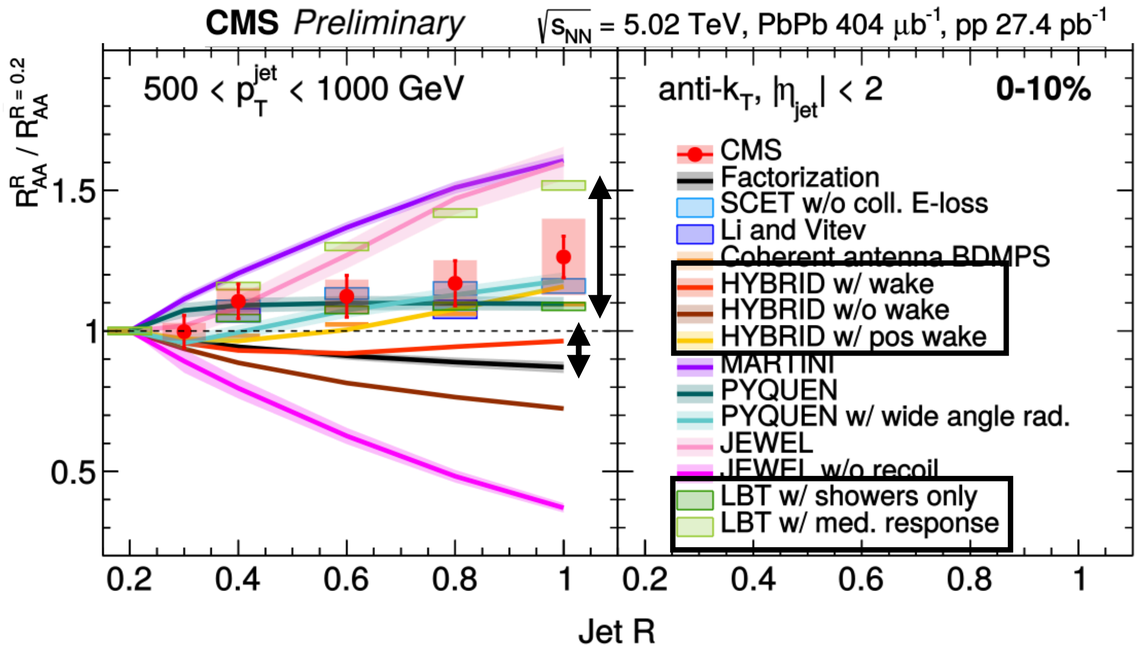

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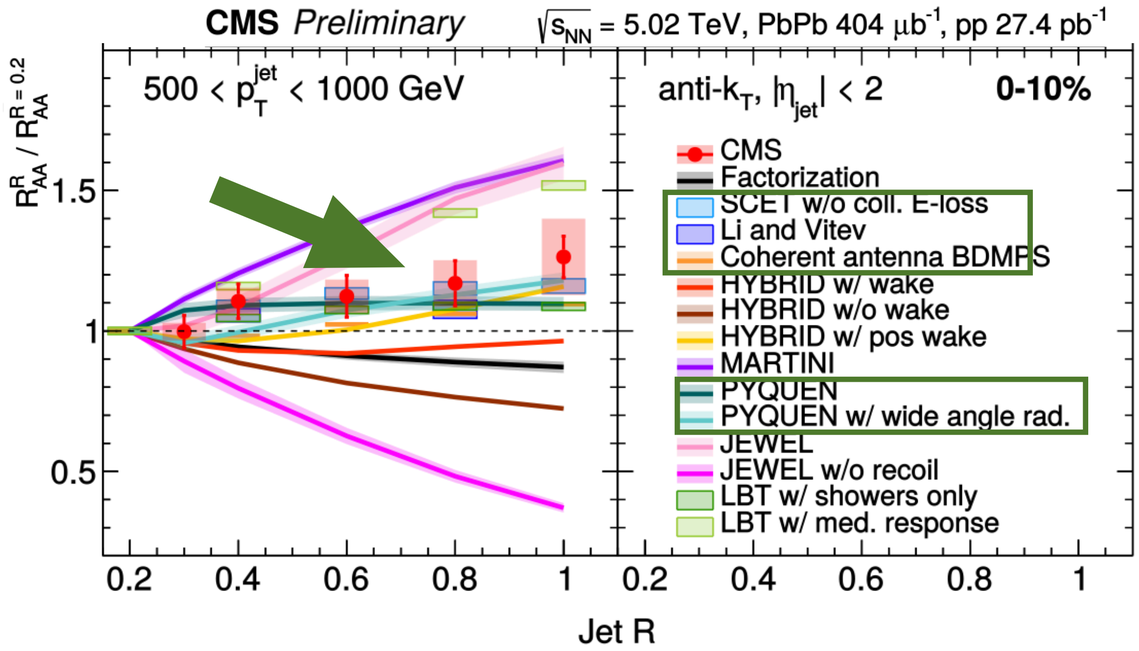

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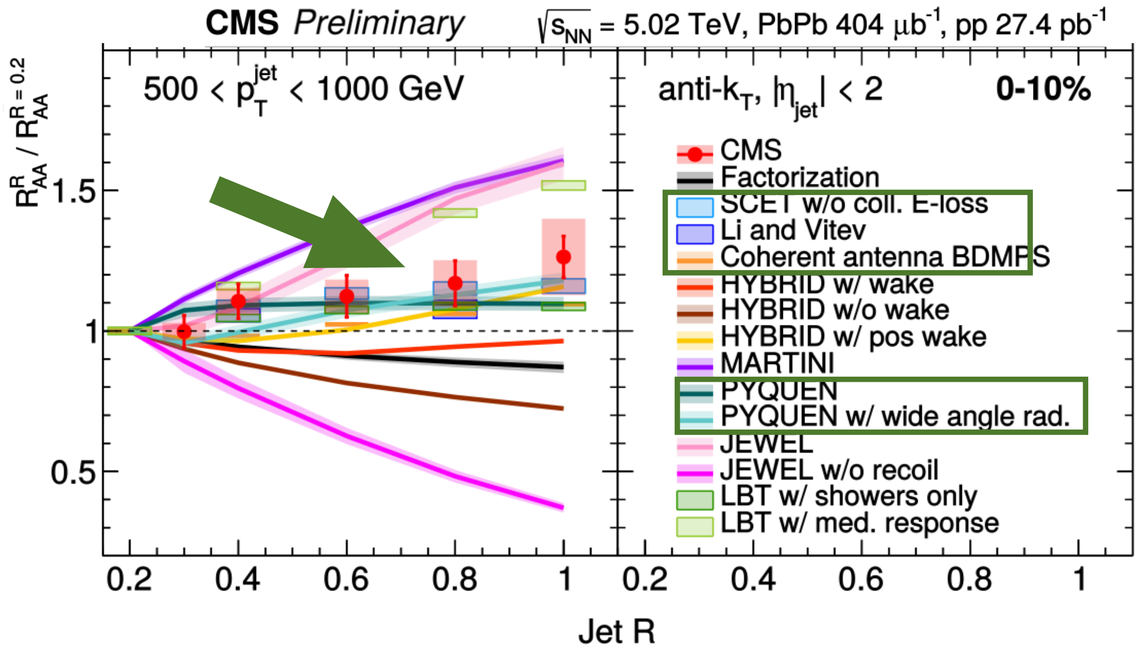
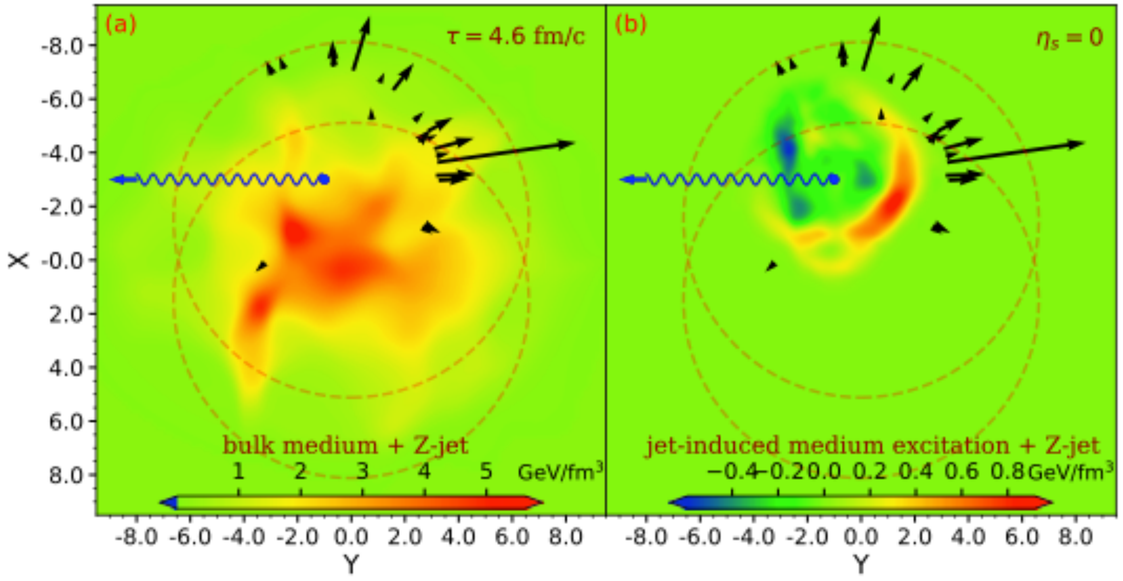
- Jet Radial profile vs Jet RAA
  - Put severe constrains on the jet-induced component

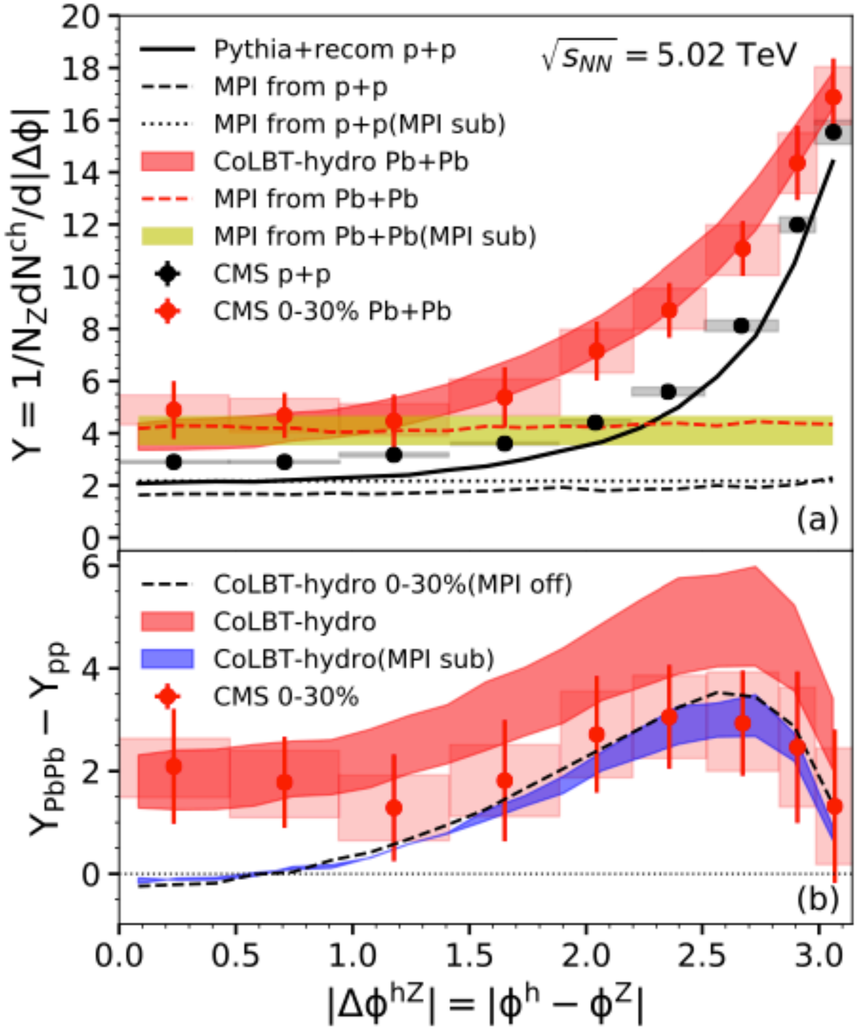


(We also have: missing pT, ρ(r) with pT bin information, 2-particle correlations,…)

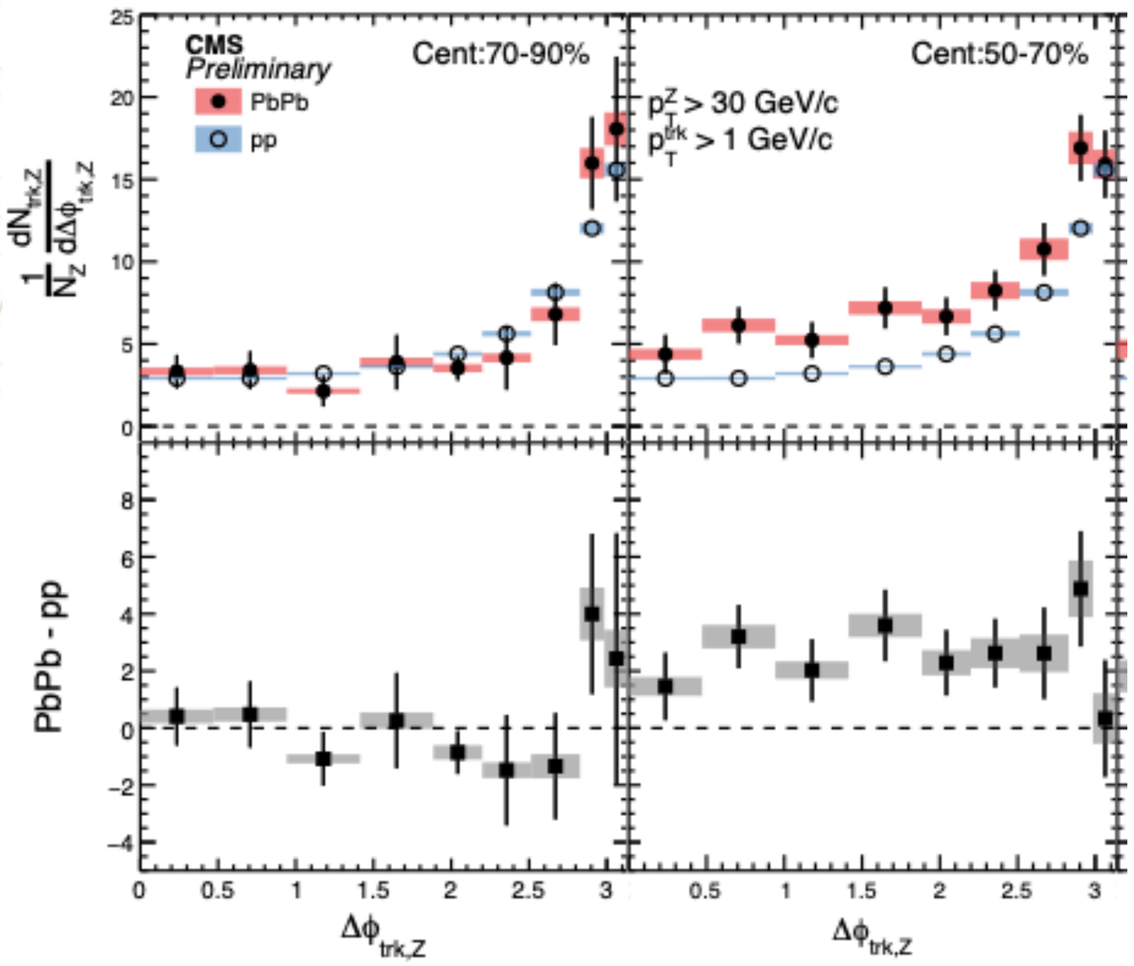
Medium response

- Might also appear in the near-size Z-hadron correlation

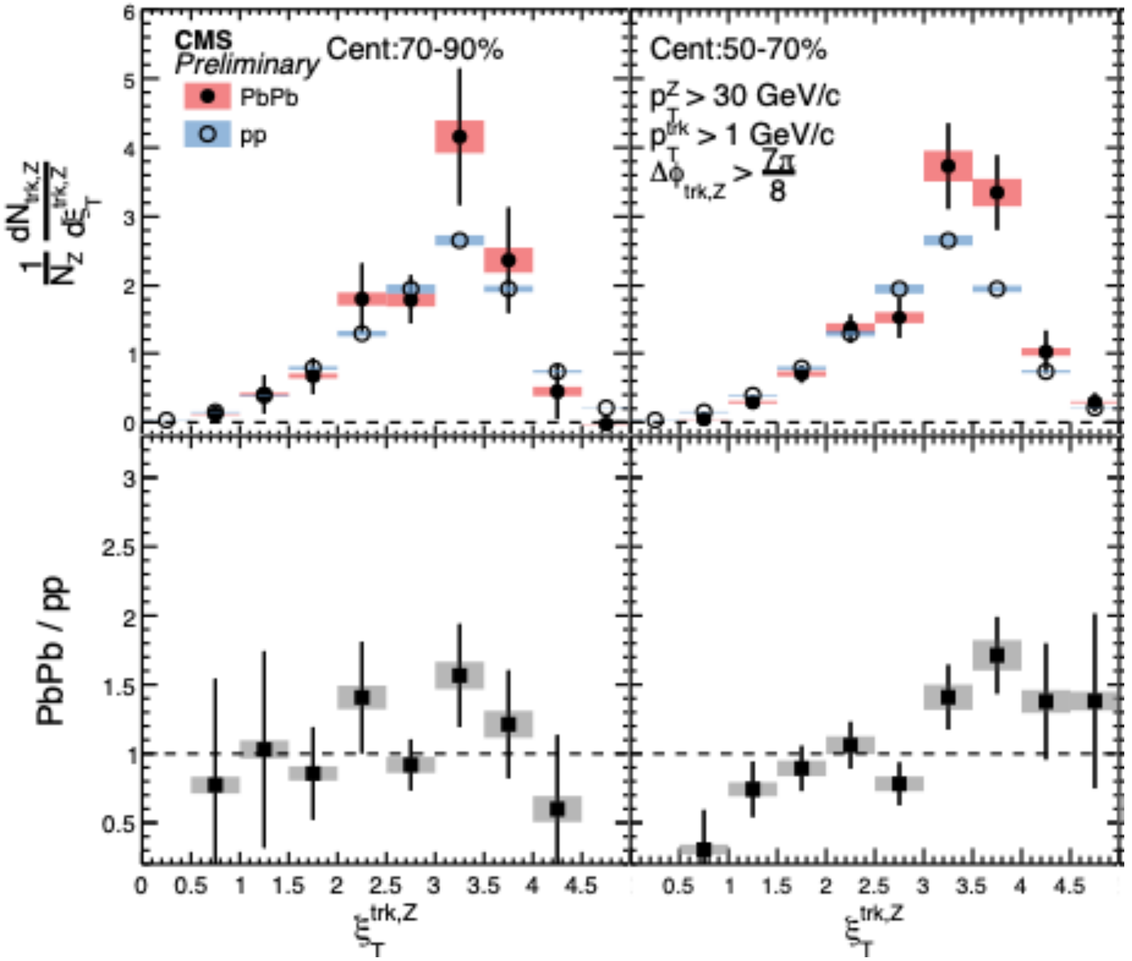




PbPb Peripheral



Recoiling charged particles



Recoiling jet FF

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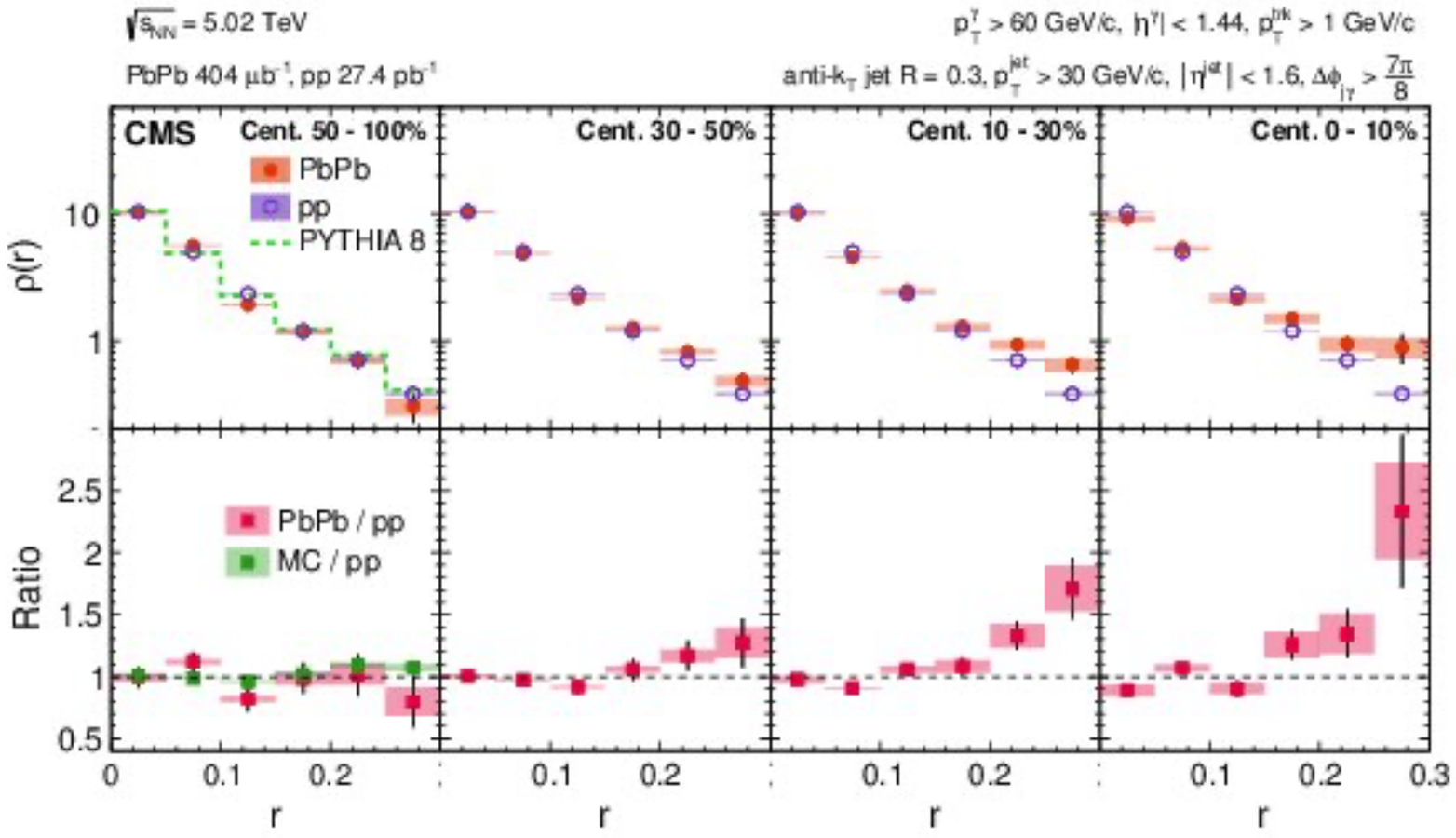

Recoiling Jet Transverse Profile