Hard probes of the QGP

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on behalf of the ALICE, ATLAS, and CMS collaborations

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Wright Laboratory

Yale

Hard probes in heavy-ion collisions

- Hard (high p_T) probes: high Q2 processes that are well understood in pQCD

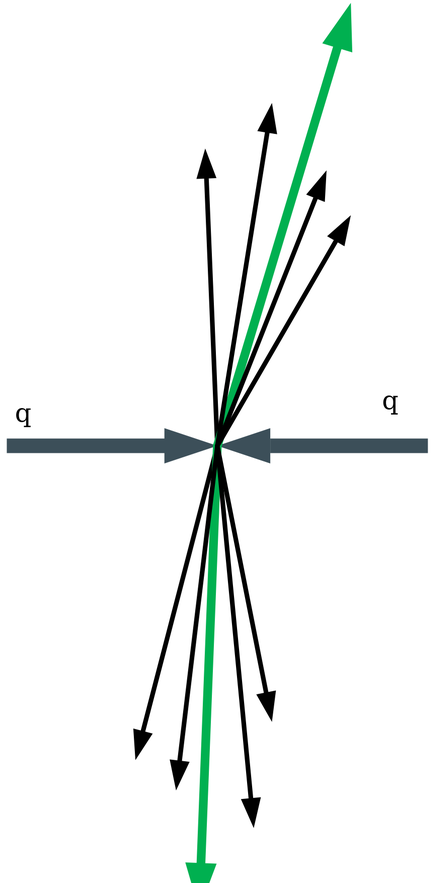
➡Electroweak bosons, jets/high p_T hadrons, and **heavy flavor/quarkonia***

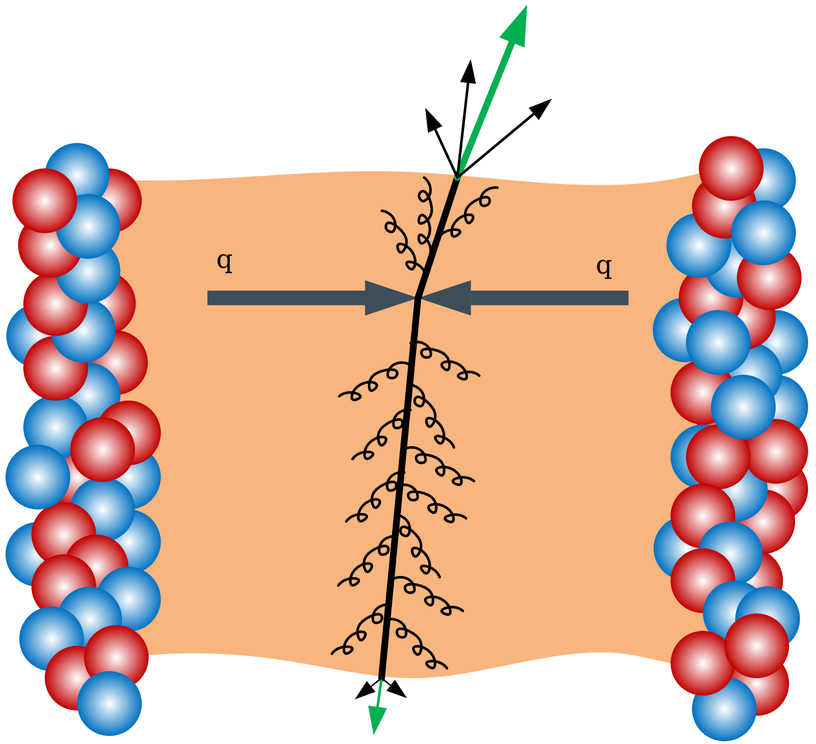
➡Learn about QCD at high temperatures through medium interactions

➡p-Pb and pp collisions used to understand initial and final state effects not from medium interactions

  - Recent questions of QGP formation in small systems?

*See next talk from Sebastian Tapia Araya





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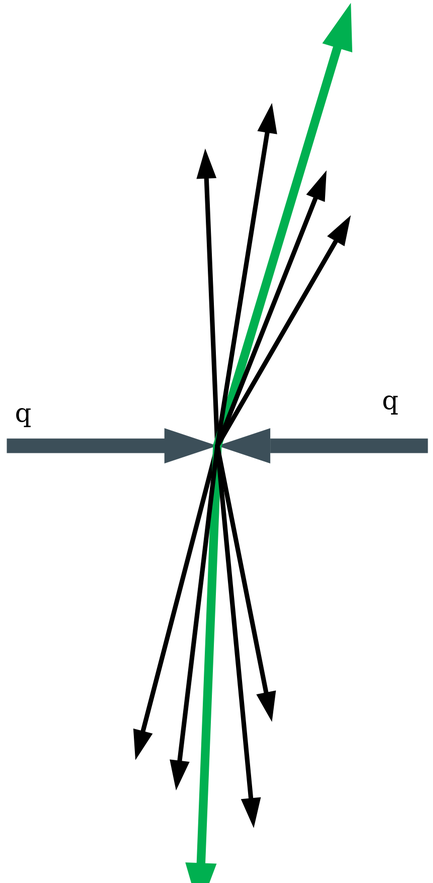
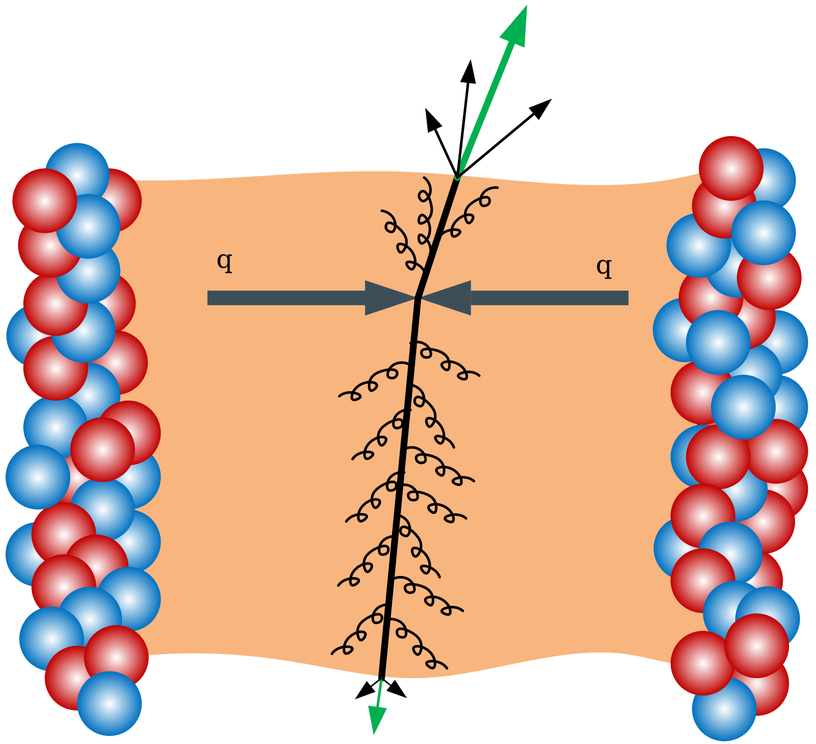
- Jets/high p_T hadrons: colored probes from partons that interact strongly with medium





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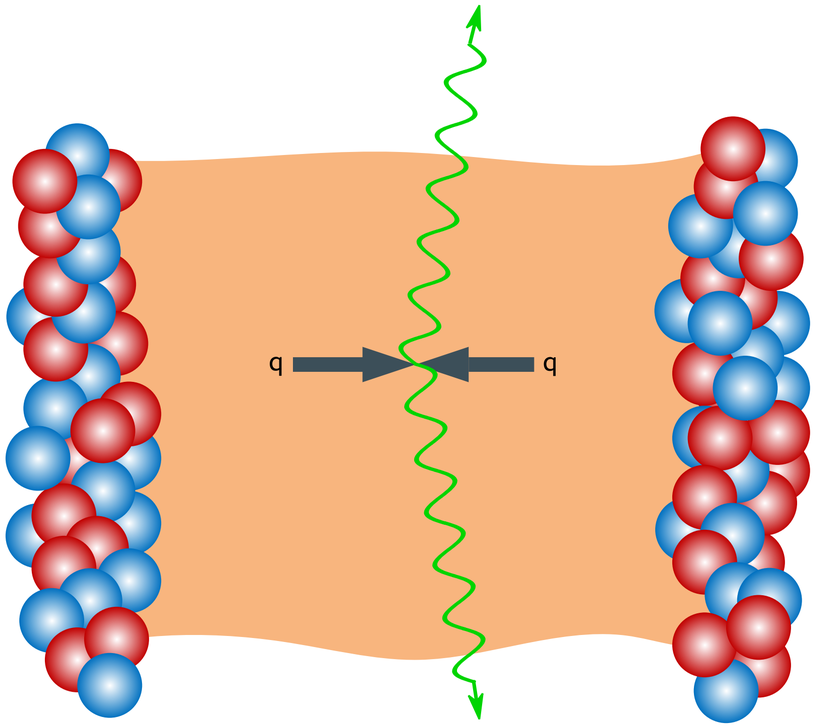
  - Recent questions of QGP formation in small systems?

- EW bosons: colorless probes that do not strongly interact with medium

➡ initial state and geometry

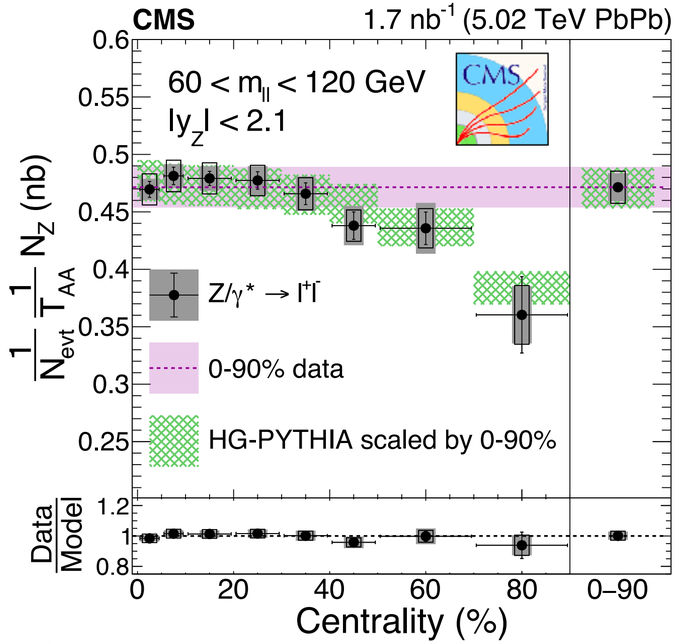


High precision EW bosons

$$R_{AA} = \frac{\text{Pb-Pb}}{\text{scaled} \otimes \text{pp}}$$

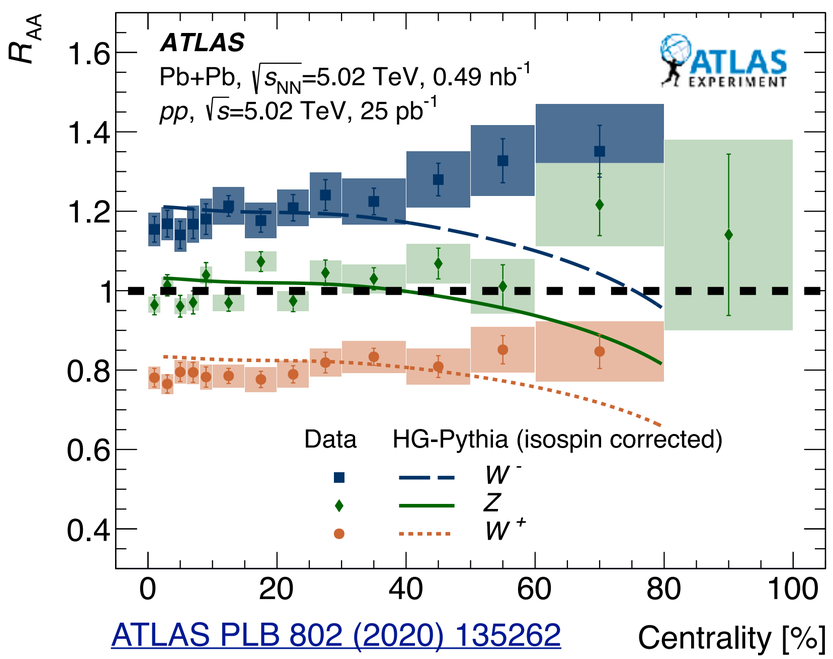
- Constraints on nPDFs, collision geometry, centrality

Z



CMS arXiv:2103.14089

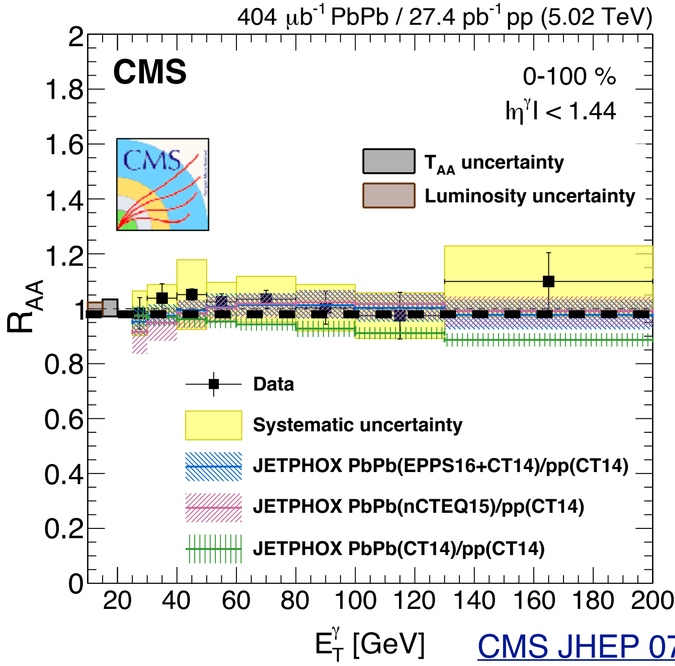
W$^{+/-}$/Z



ATLAS PLB 802 (2020) 135262

ATLAS EPJC 79 (2019) 935

Direct photons



CMS JHEP 07 (2020) 116

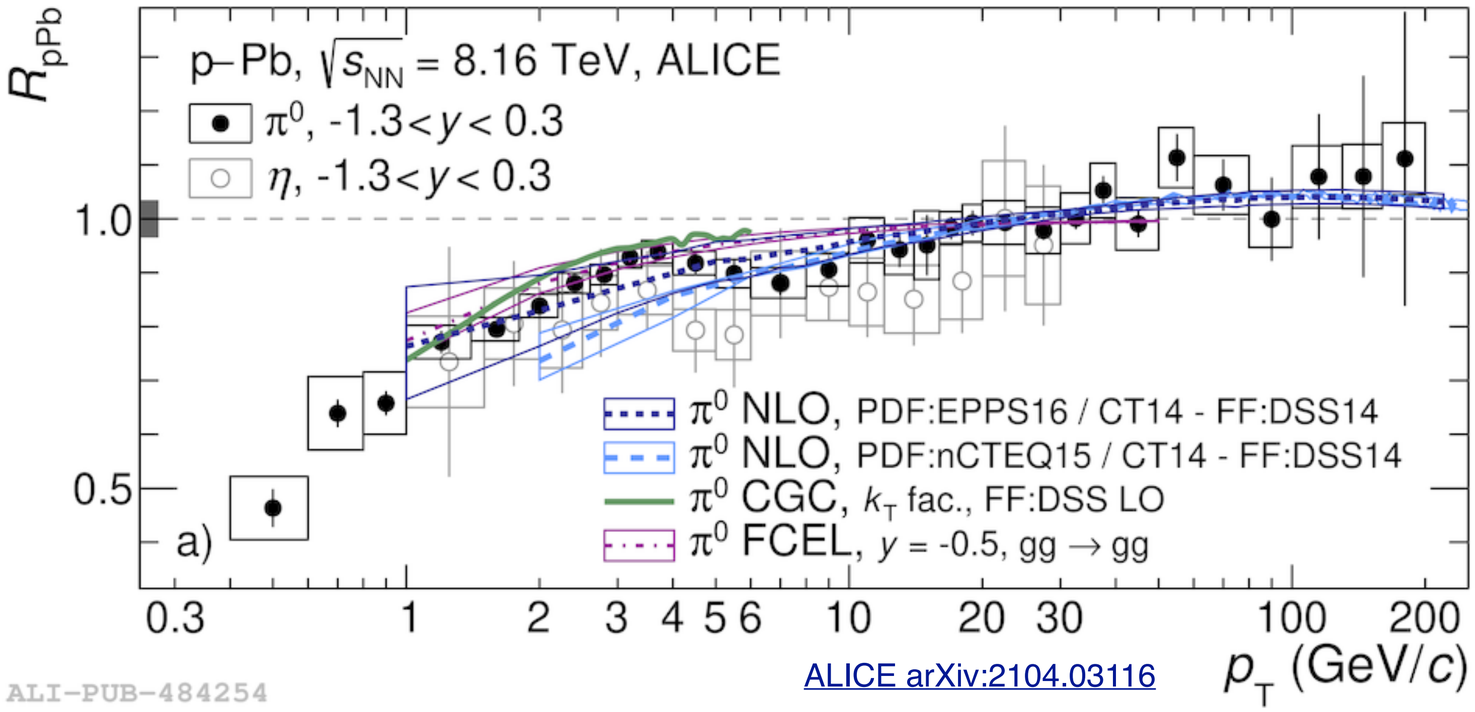
- Consistent with the expectation of no modification of boson yields in the QGP

Cold nuclear matter effects with p-Pb

- Look for modifications in p-Pb to pp collisions probes initial and final state effects
  - Cold nuclear matter effects: (anti) shadowing, gluon saturation (CGC), energy loss, p_T-broadening (Cronin)

$$R_{\mathrm{pA}} = \frac{\text{p-Pb}}{\text{scaled}\otimes\text{pp}}$$

- Measure the R_{pPb} for π^0 and η mesons at $\sqrt{s_{\mathrm{NN}}}$ = 8.16 TeV
- Order of magnitude higher p_T (200 GeV) than previous results!
  - No modification p_T > 10 GeV/c
  - New constraints on nPDFs



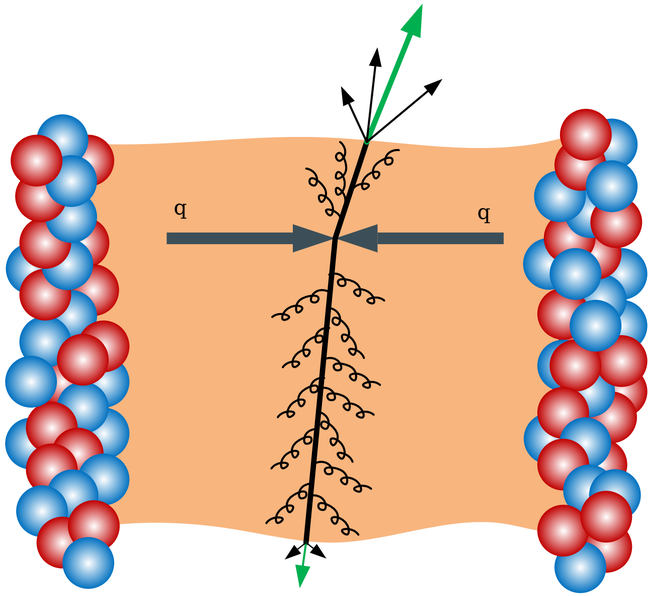
ALICE arXiv:2104.03116

Jets in heavy-ion collisions

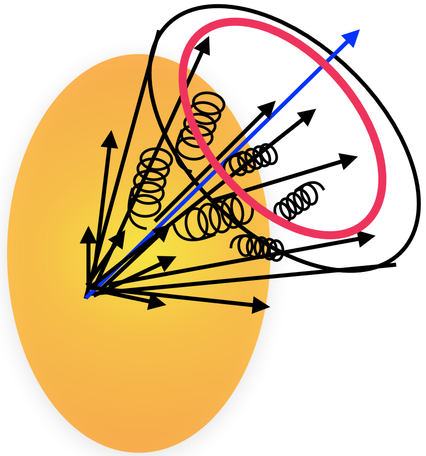
- Jet quenching: partons in heavy-ion (HI) collisions interact with the medium to produce:
  - ➡jet energy loss
  - ➡jet substructure modification

Depends on the path traveled in the medium

Flavor dependence

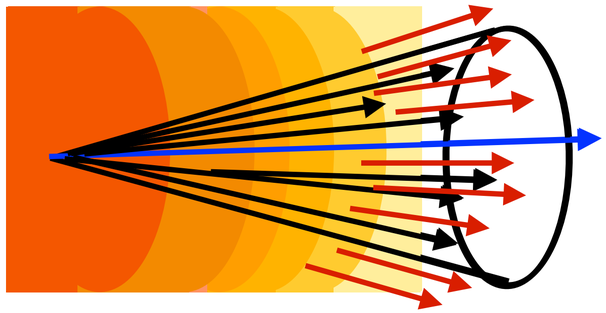


- Jet-medium interactions:



➡Momentum broadening
- widens the jet
- *E*-loss outside jet cone

➡Wide-angle deflection

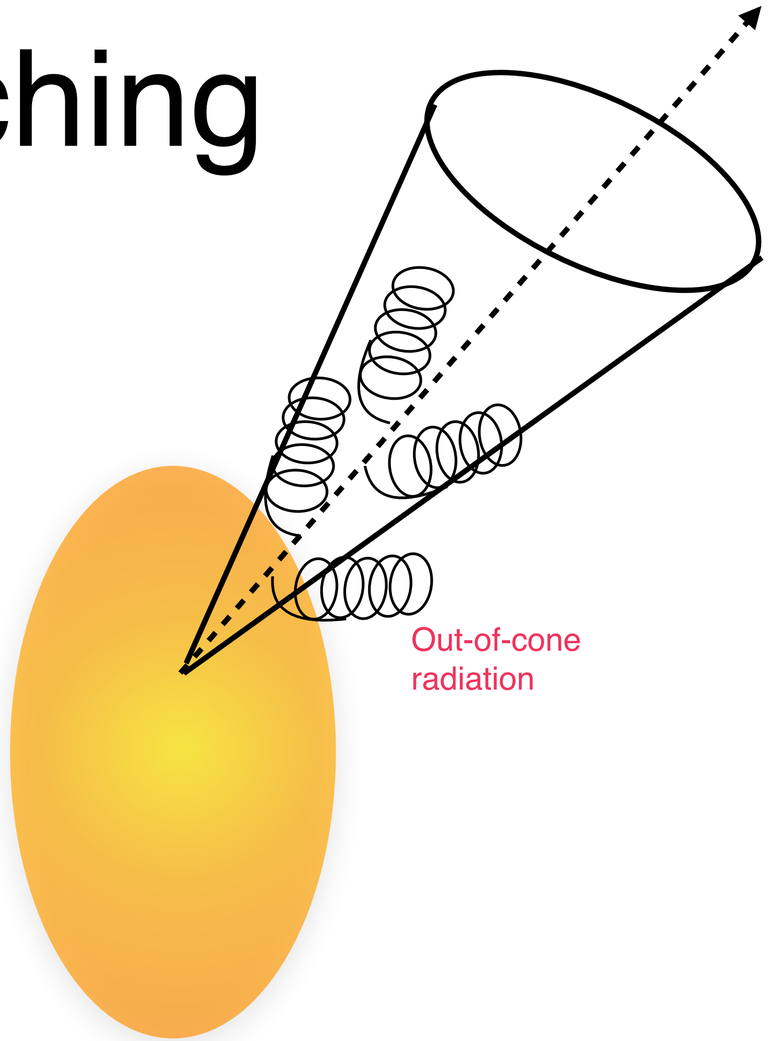


➡Medium response pushes soft particles back inside jet

Measuring jet quenching

- Measuring jet quenching includes:

  ➡ Energy loss through the suppression of high-p_T jet yields



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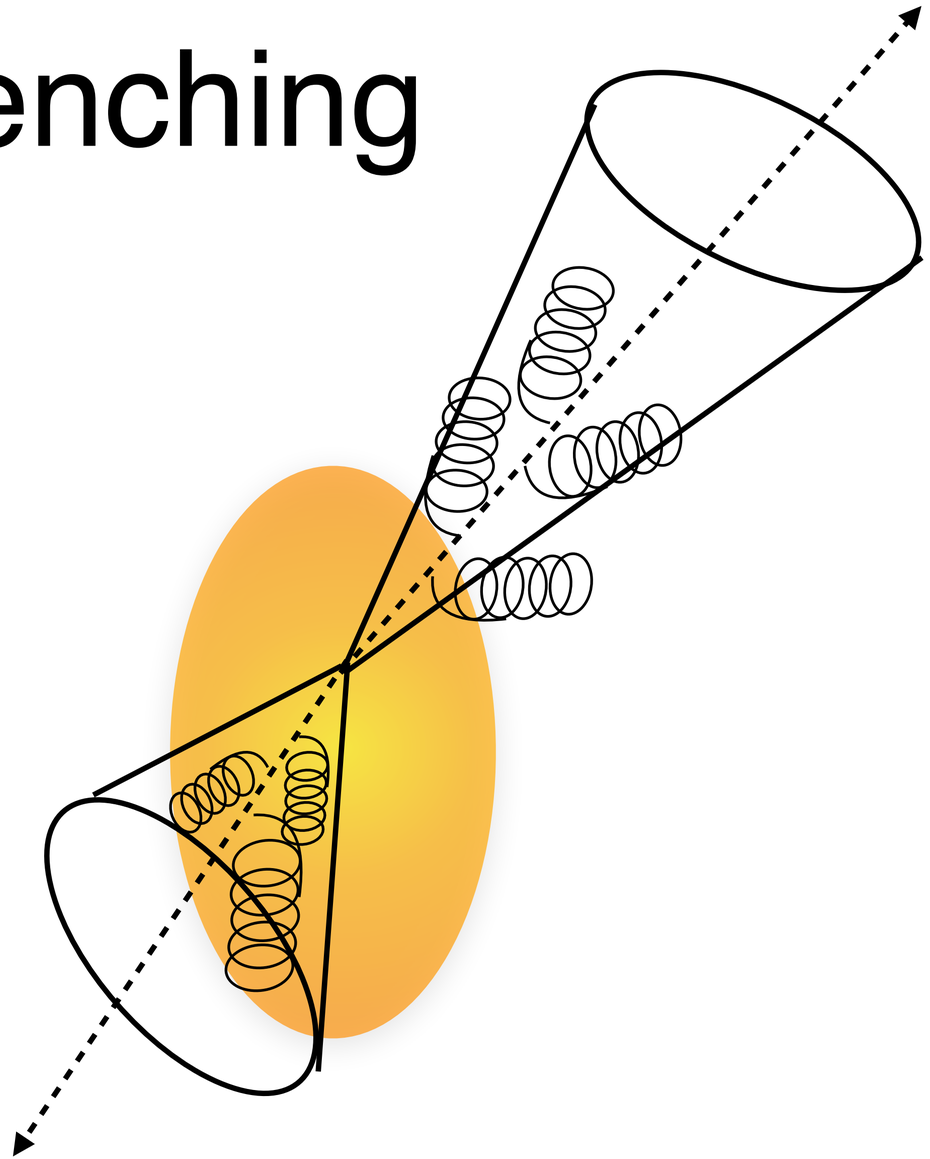

Measuring jet quenching

- Measuring jet quenching includes:

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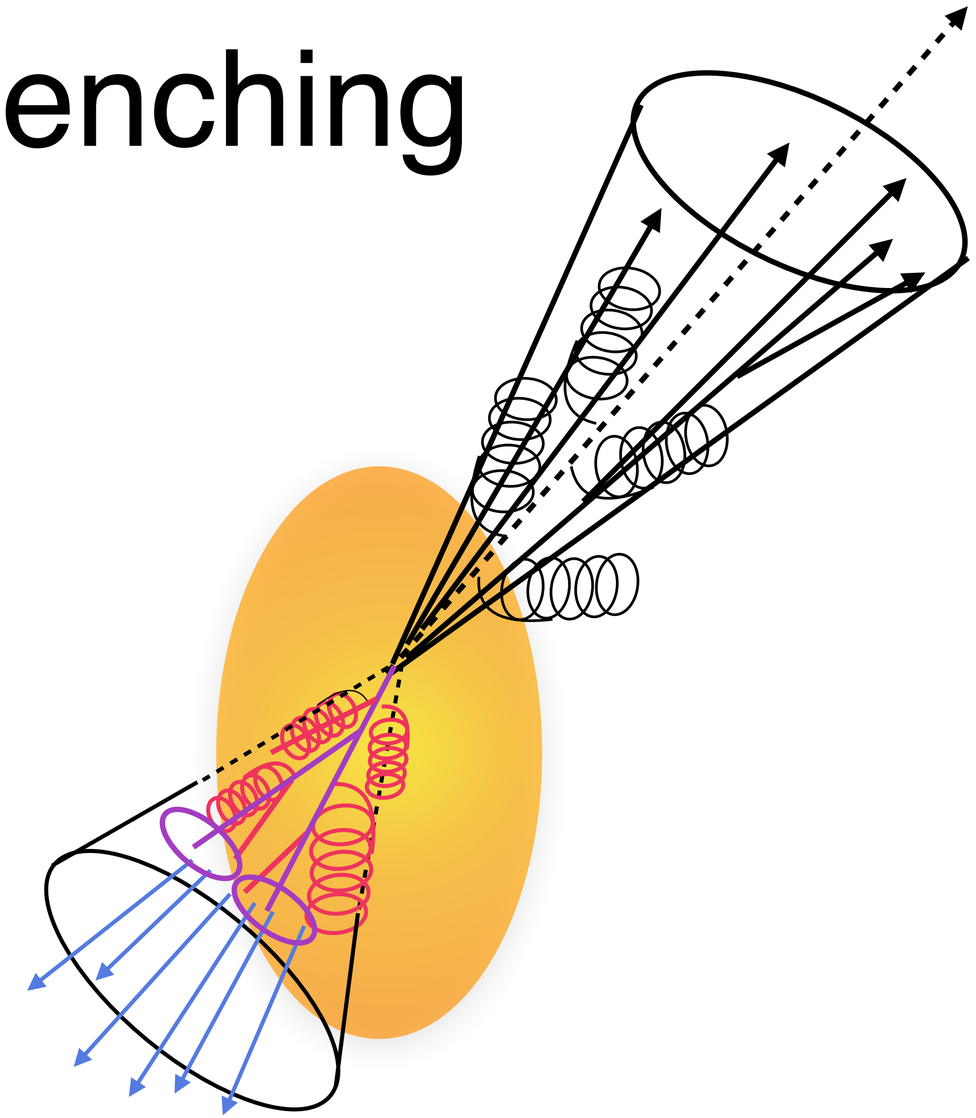
  ➡ Intra-jet modifications by measuring jet structure and substructure



Desire to measure over a large range of scales including jet p_T and radii

- *New results include correlations between observables to better isolate medium effects*

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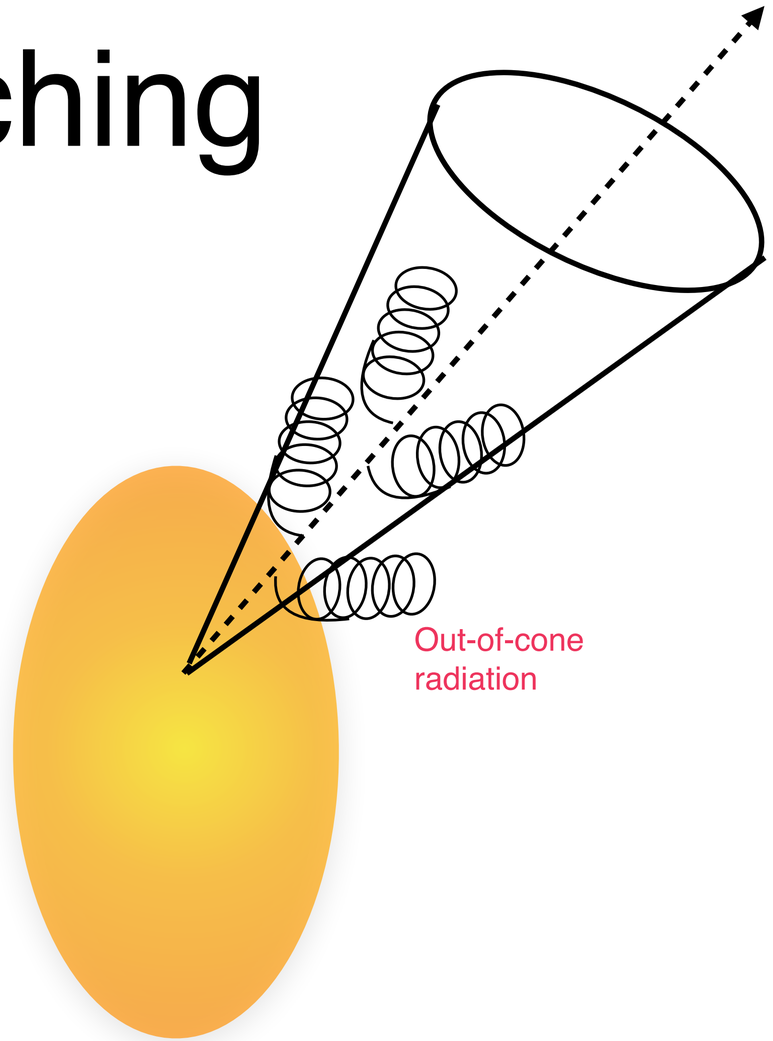

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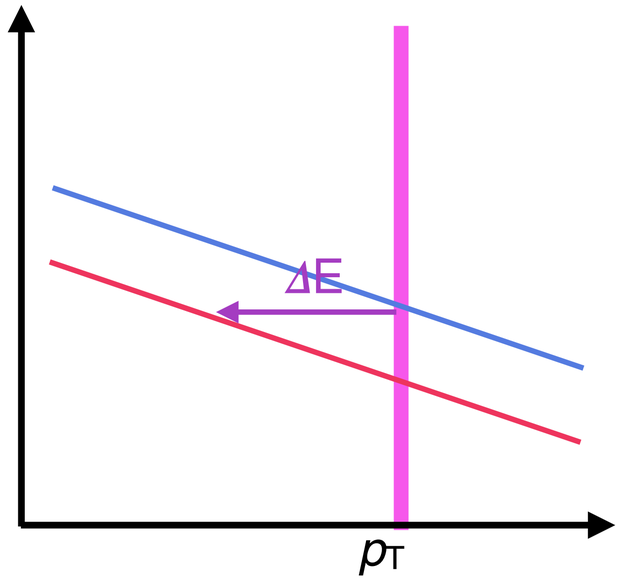
Inclusive jet suppression

- Inclusive jet suppression over a large jet p_T range

$$R_{AA} = \frac{\text{Pb-Pb}}{\text{scaled} \otimes \text{pp}}$$



Inclusive jet suppression

- Inclusive jet suppression over a large jet p_T range

➡ HI underlying event constrains larger R and lower p_T and ability to unfold to compare to jet quenching models

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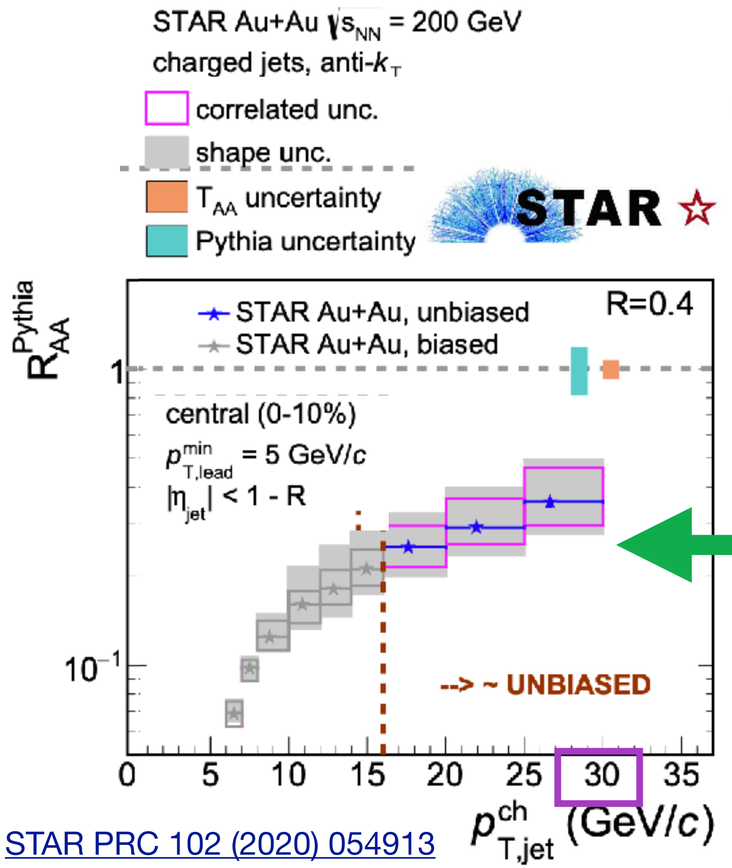
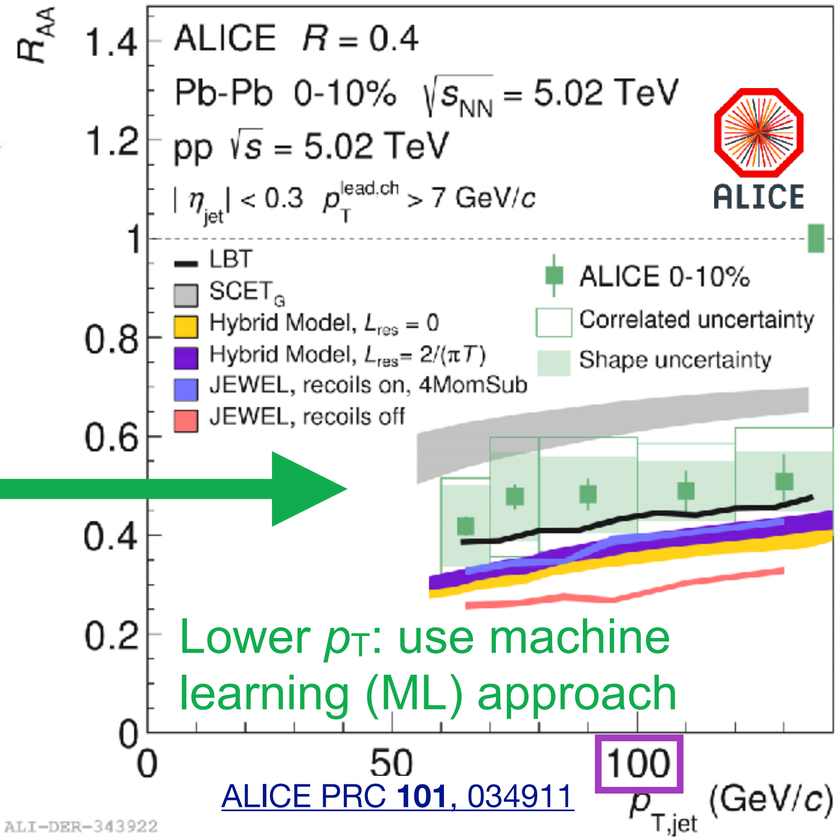
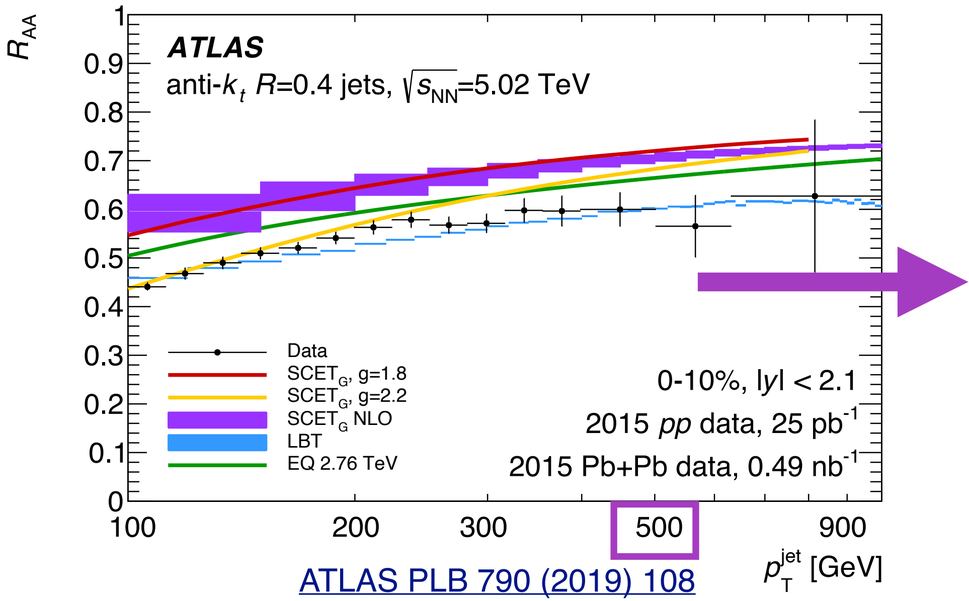




Lower p_T: use machine learning (ML) approach

Larger R: use higher p_T



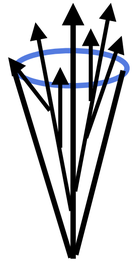
STAR PRC 102 (2020) 054913

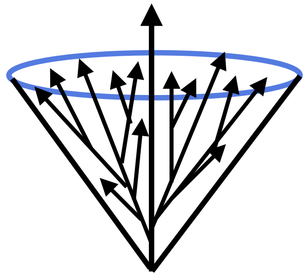
ALICE PRC **101**, 034911

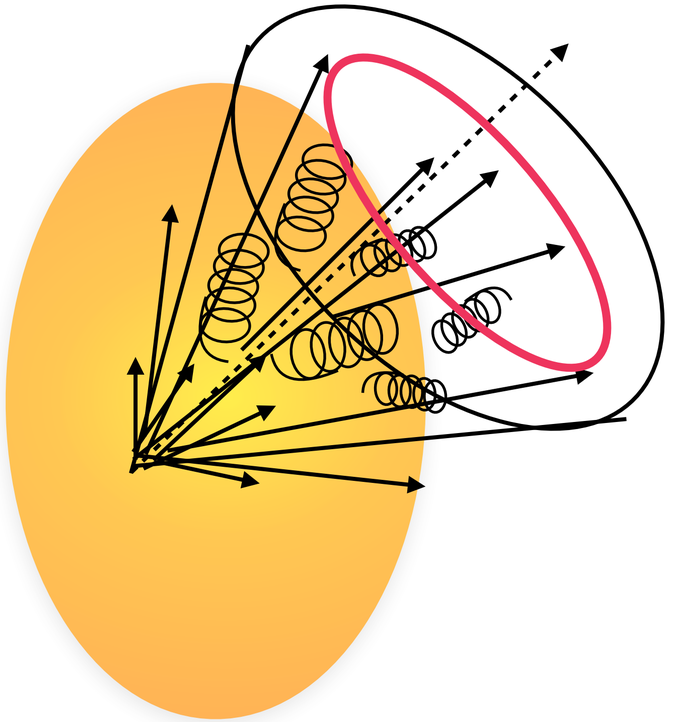
ATLAS PLB 790 (2019) 108

Large R/low p_T motivation

- Larger radii
  - ➡ Possible recovery of the jet energy because of out-of-cone radiation
  - ➡ Possible difference in modification for larger jets





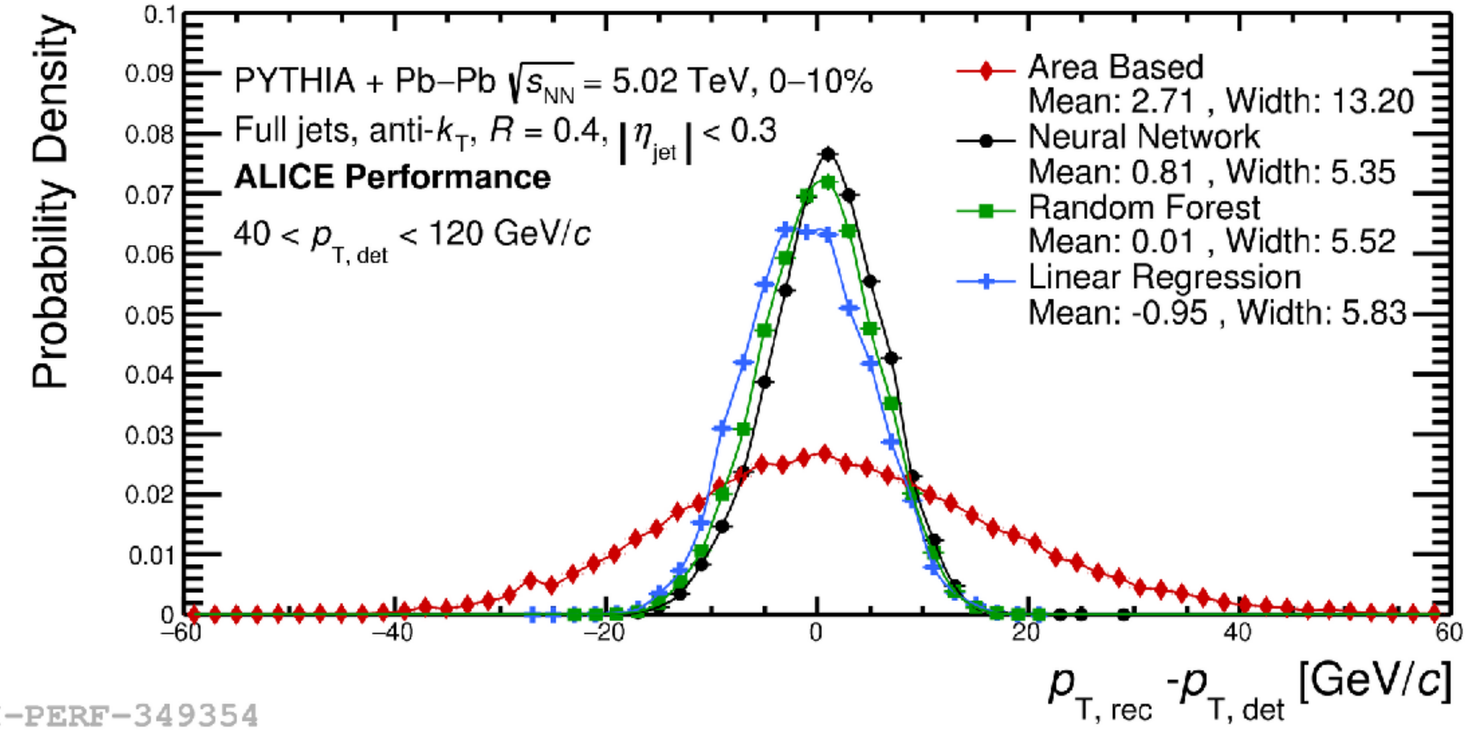


- Lower jet p_T
  - ➡ Connection to RHIC
  - ➡ Probes different scales and modification expected to be different
  - ➡ Quark and gluon fractions vary

Inclusive jet suppression: low p_T

- ML method reduces residual fluctuations
  -> unfold to lower p_T

Haake, Loizides PRC 99, 064904 (2019)



Inclusive jet suppression: low p_T

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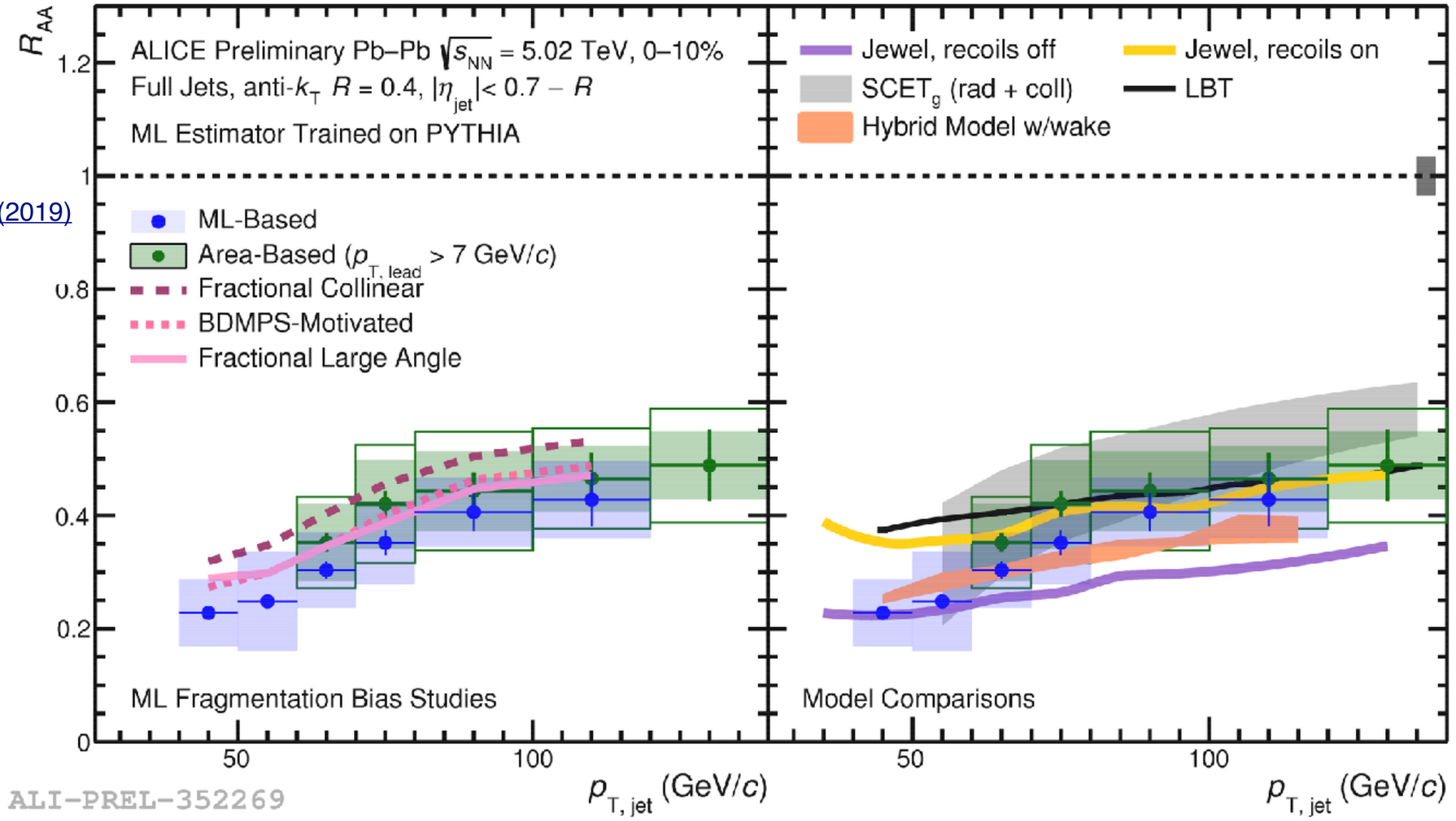
- ML-based and area-based method with a leading track bias are consistent with each other, fragmentation bias explored!

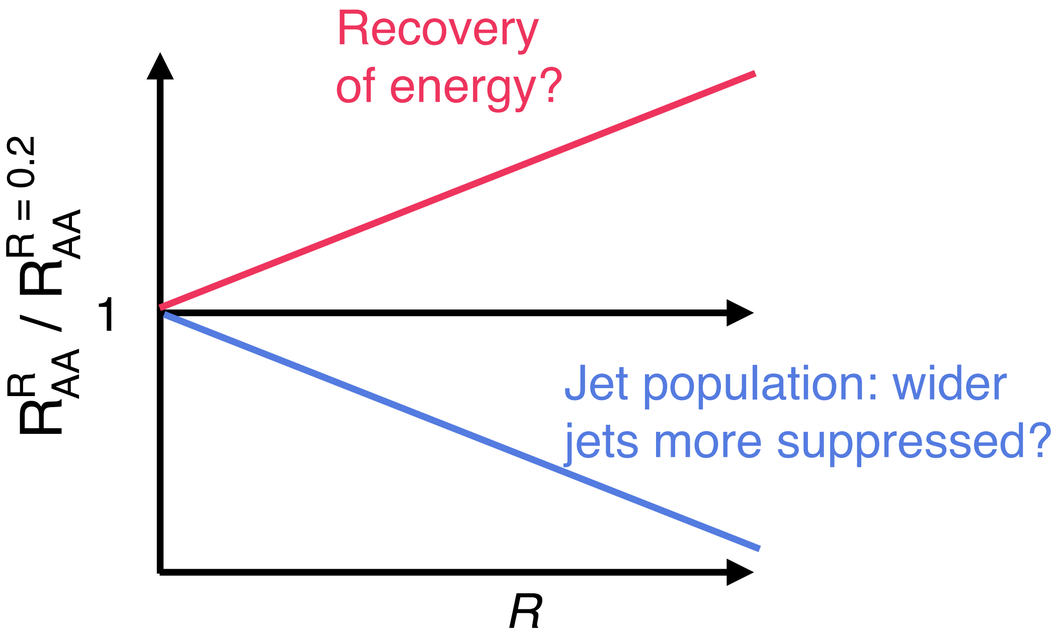


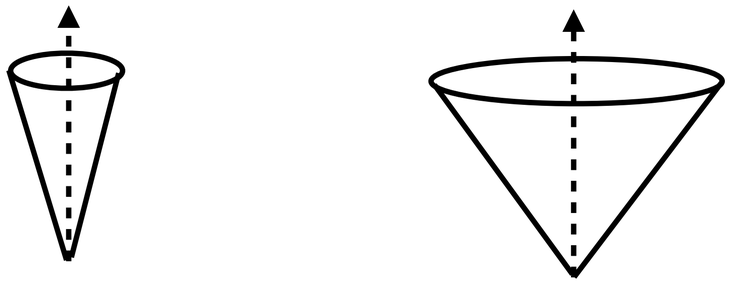
p_T reach extended to 40 GeV/c

- Constrains models at low p_T

Inclusive jet suppression: large R

- Compare R_{AA} at larger R to R_{AA} at R=0.2 as a function of R at high p_T
  - Scanning R=0.2 to 1.0!





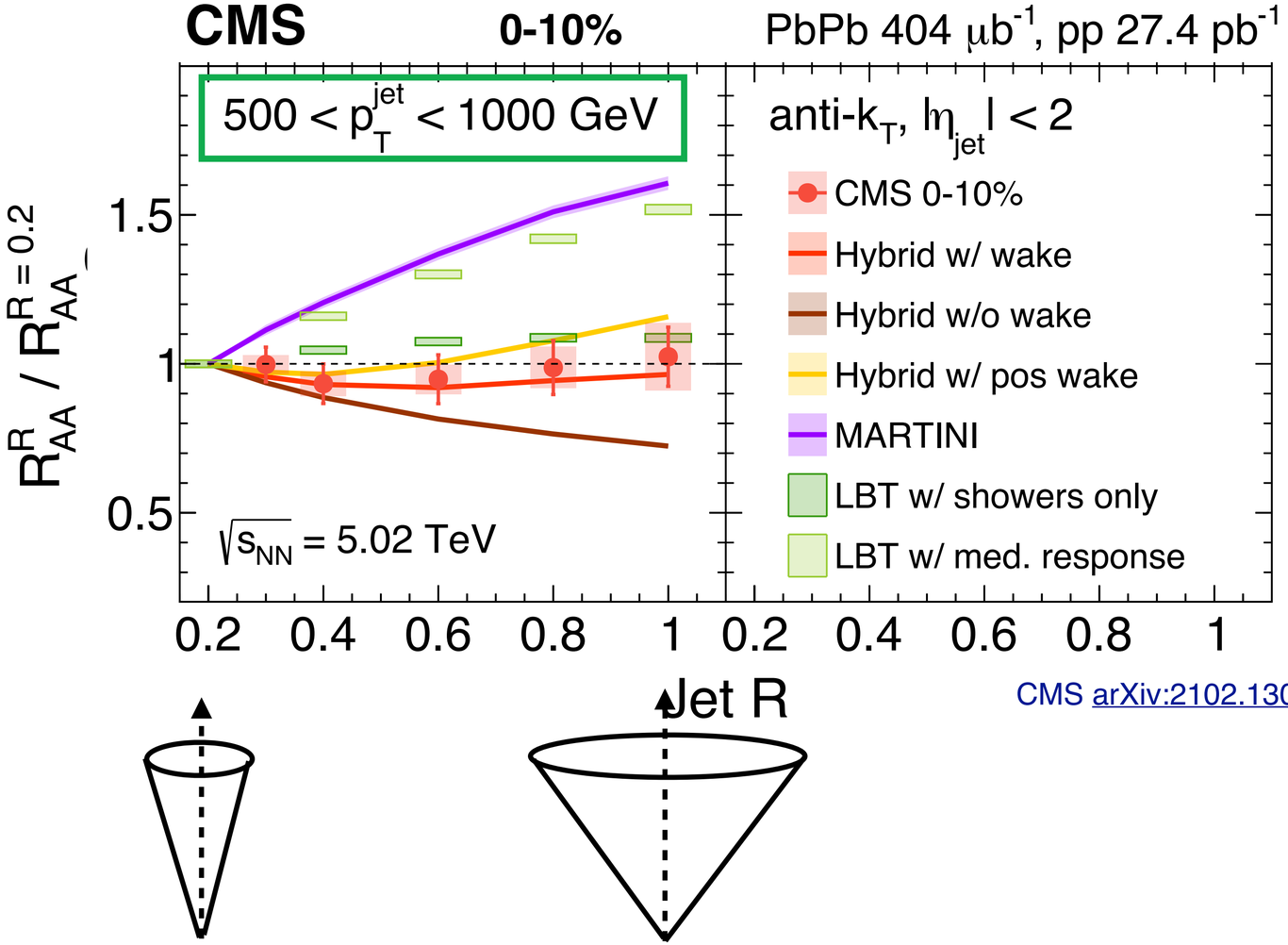
CMS arXiv:2102.13080

Inclusive jet suppression: large *R*

- Compare R_{AA} at larger *R* to R_{AA} at *R*=0.2 as a function of *R* at high p_T
  - Scanning *R*=0.2 to 1.0!

- *See suppression at large R and no significant radial dependence*
  - Not seeing energy recovered at large *R*?
  - Different jet populations?
  - Challenges our energy loss picture?

- Discriminating power for models and the physics mechanisms at play



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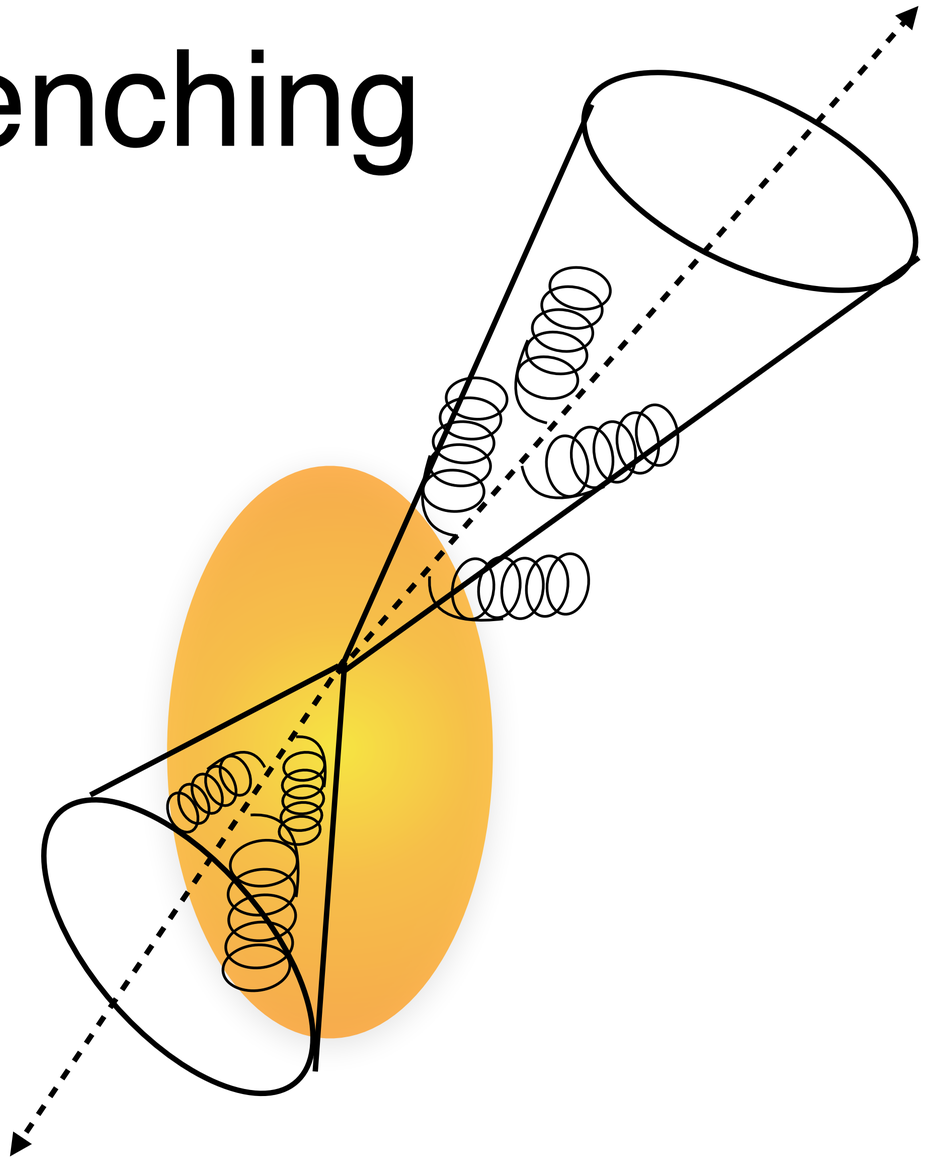
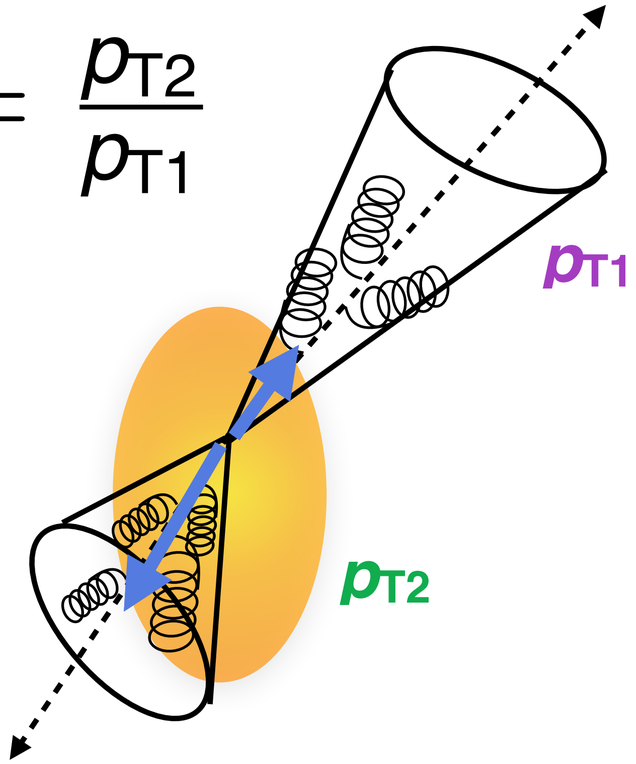


Desire to measure over a large range of scales including jet p_T and radii

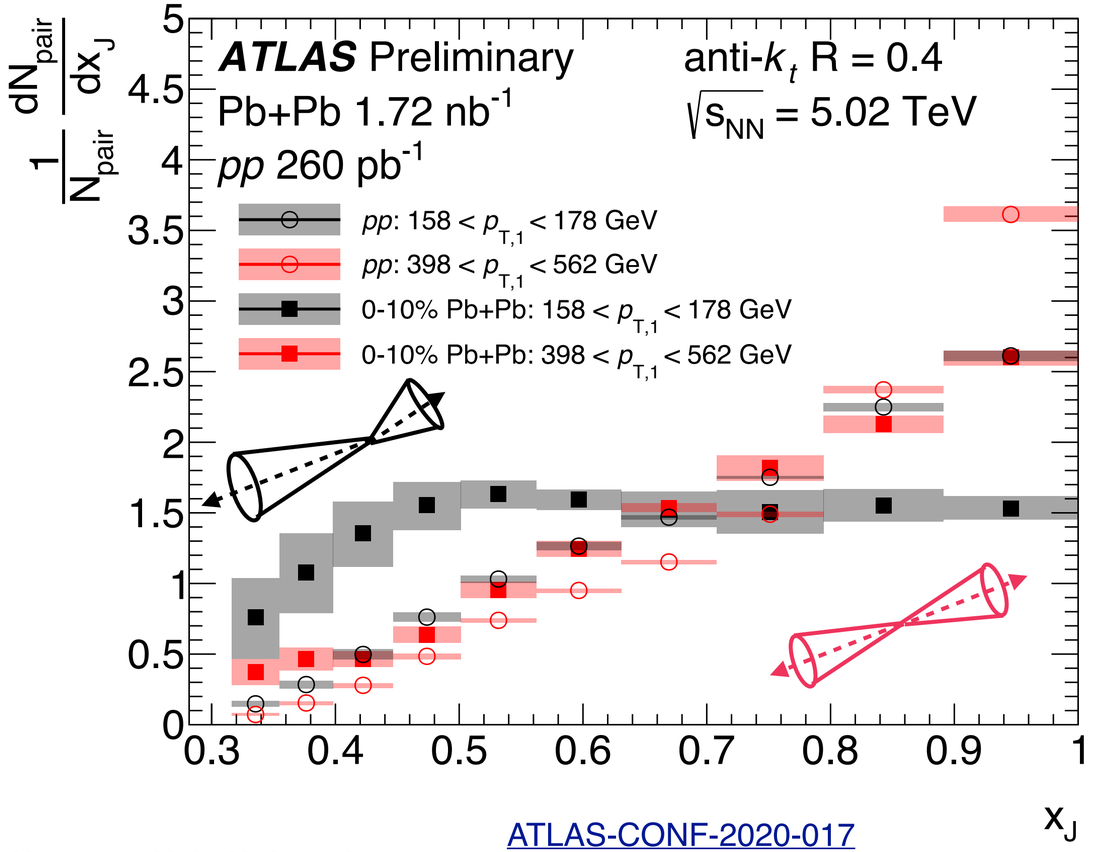
- *New measurements transcend these categories to better isolate medium effects*

Dijet asymmetry

$$x_J = \frac{p_{T2}}{p_{T1}}$$



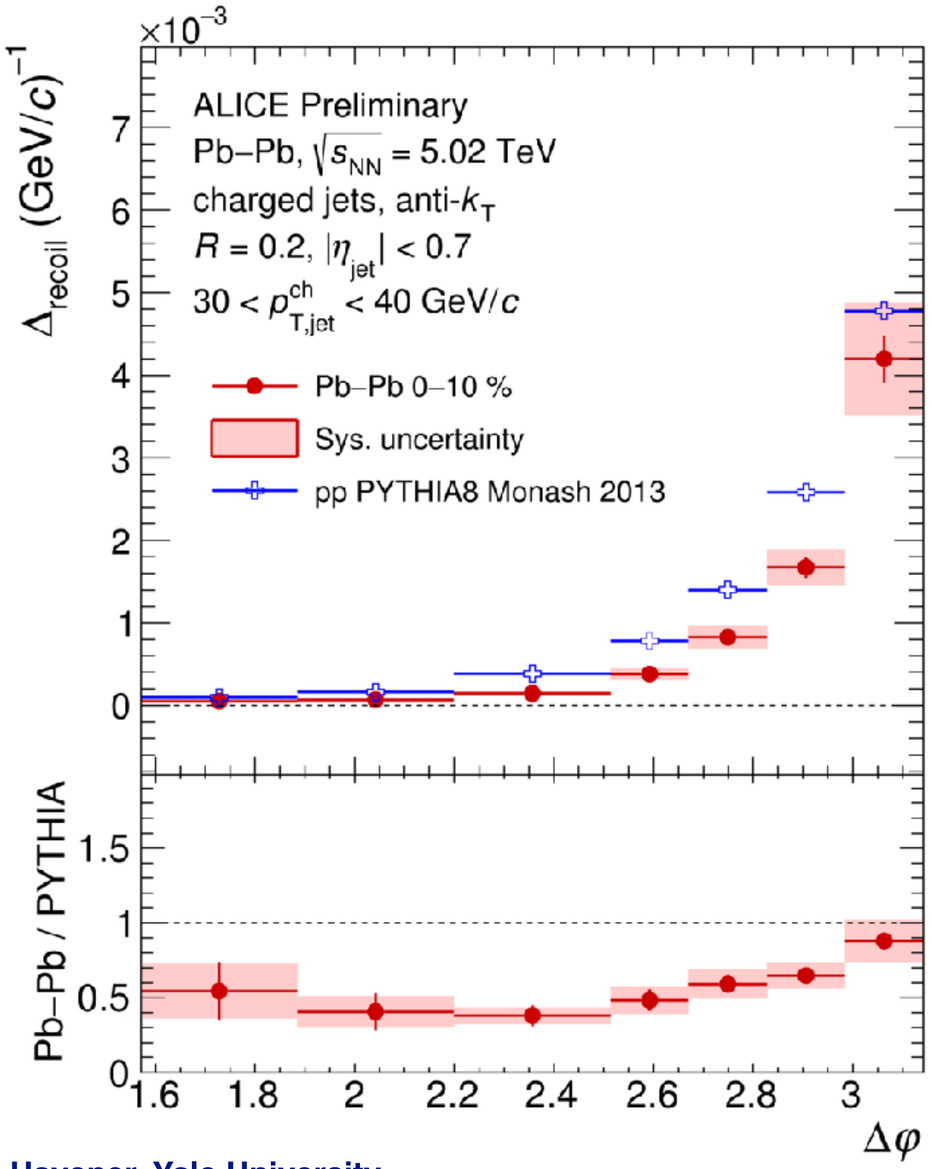
- Two jets in the pair lose different amounts of energy
  - Travel different paths
  - Jet-by-jet fluctuations in the energy loss



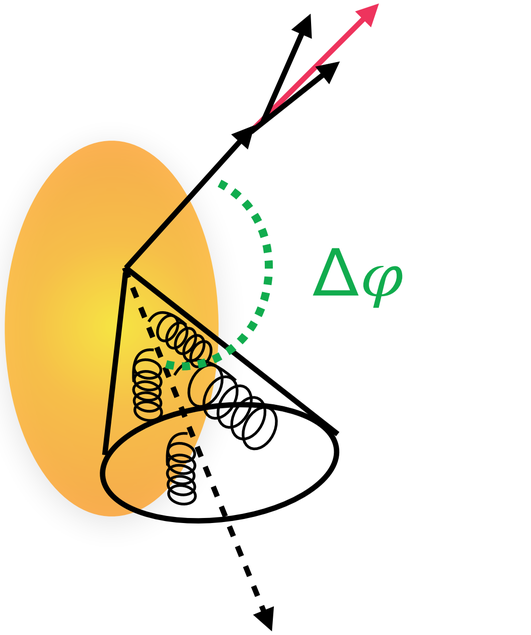
ATLAS-CONF-2020-017

- See significant asymmetry for HI dijets at lower p_T
- Less difference between Pb-Pb and pp at higher p_T -> higher p_T dijets experience same amount of energy loss?

Jet acoplanarity



- Measure opening angle ($\Delta\varphi$) of the jet with respect to a hadron trigger
  - In search of multiple soft scatterings (broadening) in the medium and large-angle deflection (enhancement)



- Corrected central Pb-Pb compared to PYTHIA8
  - Jet yields *suppressed* and $\Delta\varphi$ distribution *narrowed*? Quantum interference? Zakharov arXiv:2003.10182

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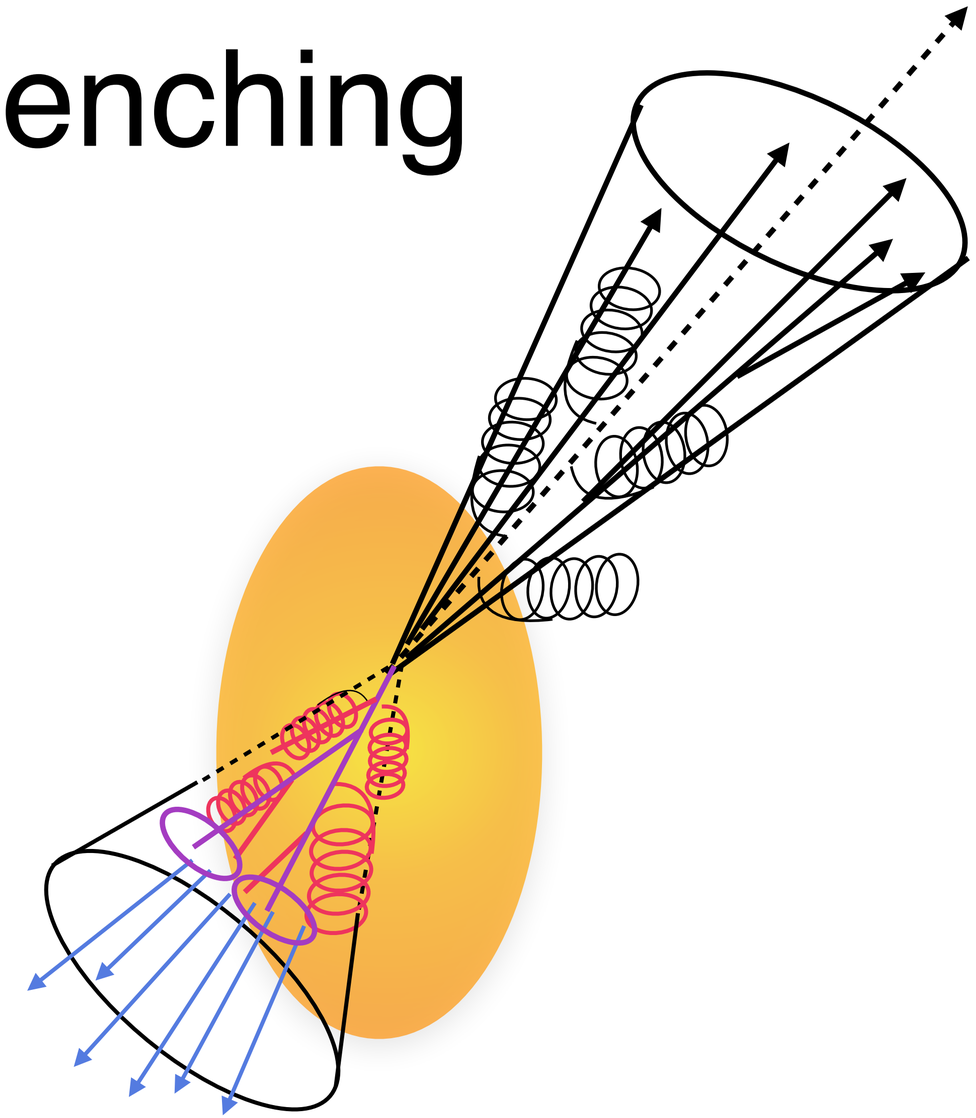

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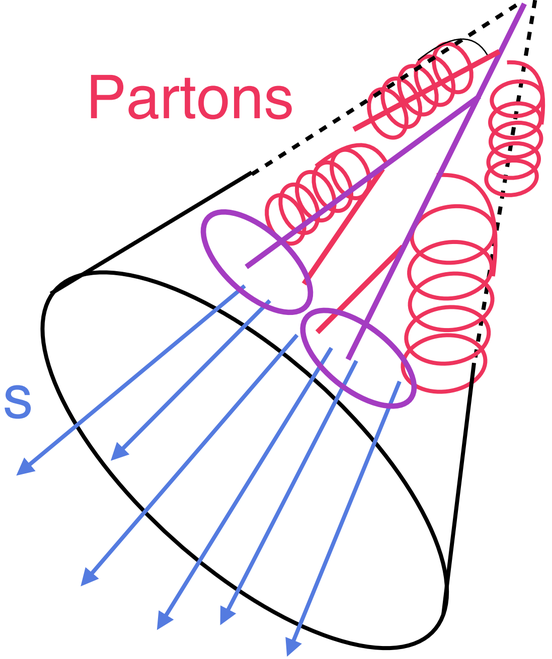
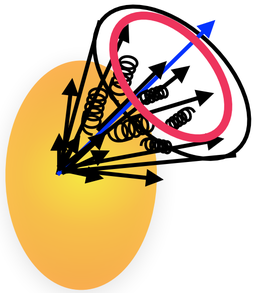
Jet internal structure



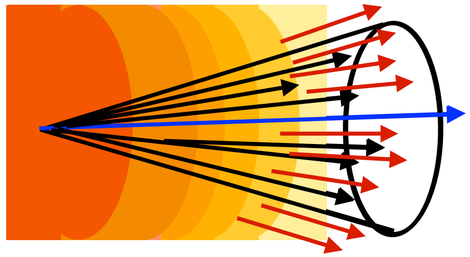
- Different variables probe a different aspect of jet structure modification

➡ Distribution of charged hadrons inside the jet

Momentum broadening



Medium response



➡ Subjets from hard parton splittings

Separate out soft signal from softening of constituents and medium response

Also, see talk by Helena Santos

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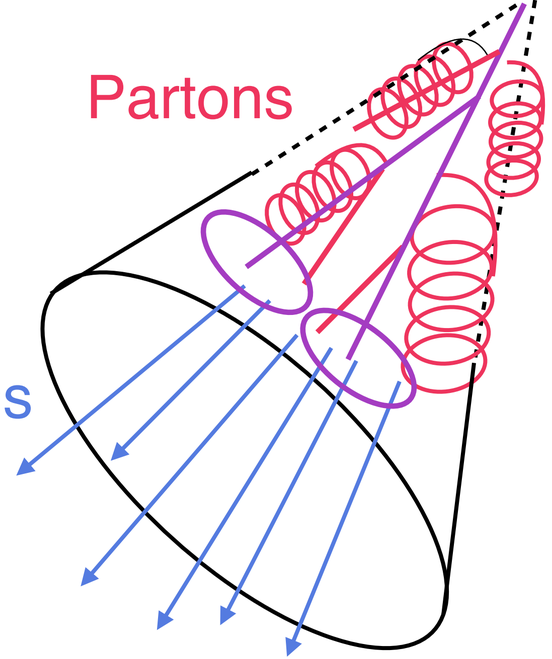

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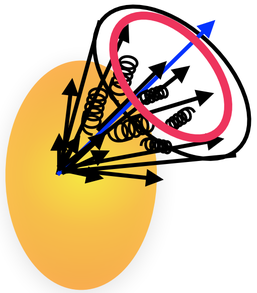

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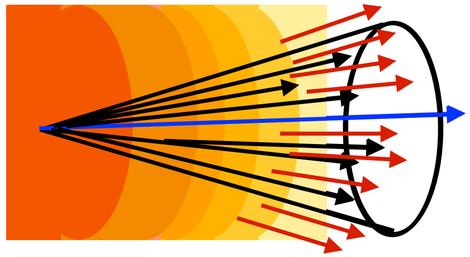

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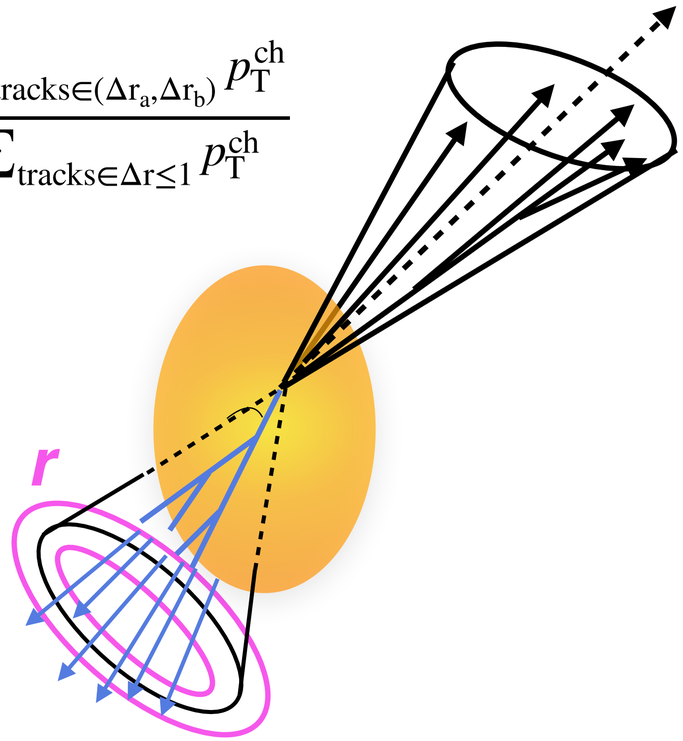
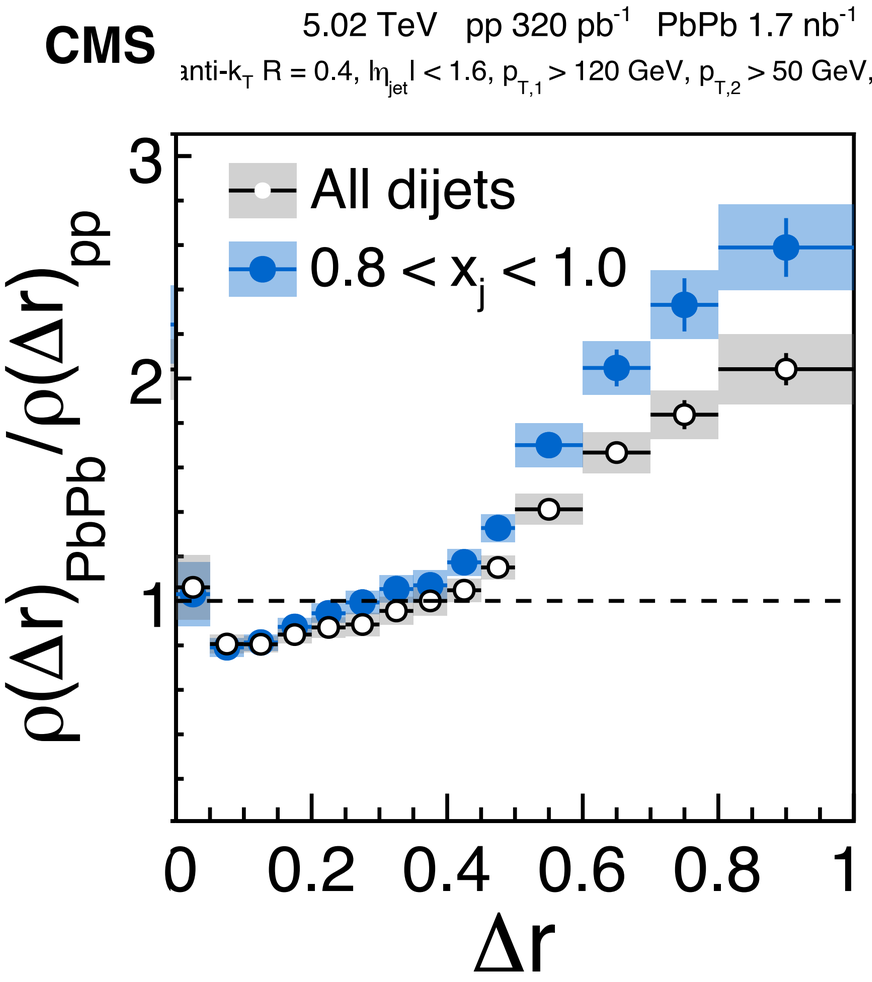
Dijet shapes

$$\rho(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{\text{jets}}}\frac{\sum_{\text{jets}}\sum_{\text{tracks}\in(\Delta r_a,\Delta r_b)} p_{\text{T}}^{\text{ch}}}{\sum_{\text{jets}}\sum_{\text{tracks}\in\Delta r\leq 1} p_{\text{T}}^{\text{ch}}}$$



- Jet shape: radial profile of charged particles in a jet

  Energy transferred to soft particles at large angles



CMS JHEP 05 (2021) 116

Dijet shapes

$$\rho(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{\text{jets}}}\frac{\sum_{\text{jets}}\sum_{\text{tracks}\in(\Delta r_a,\Delta r_b)} p_{\text{T}}^{\text{ch}}}{\sum_{\text{jets}}\sum_{\text{tracks}\in\Delta r\le 1} p_{\text{T}}^{\text{ch}}}$$

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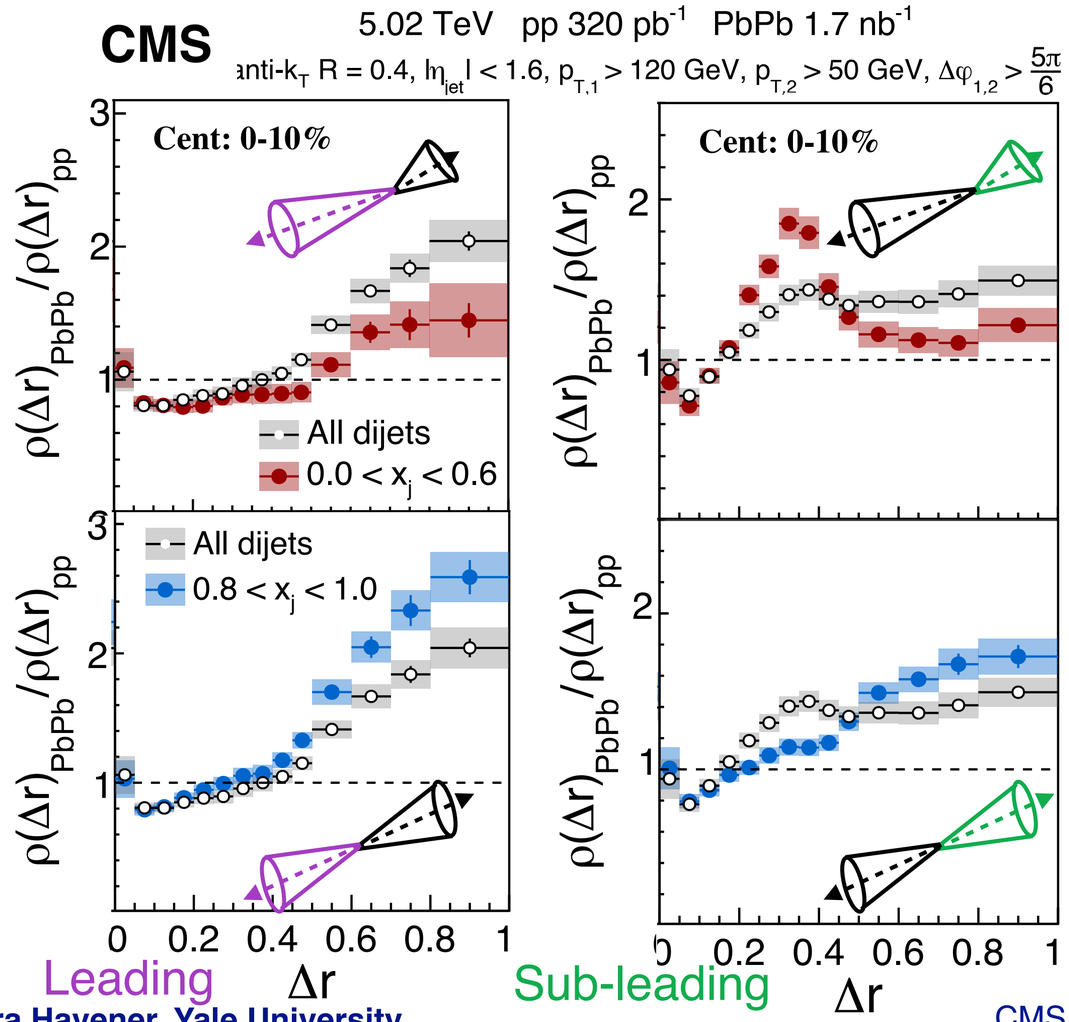
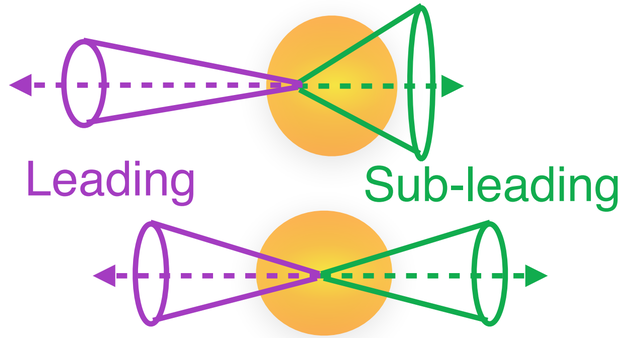
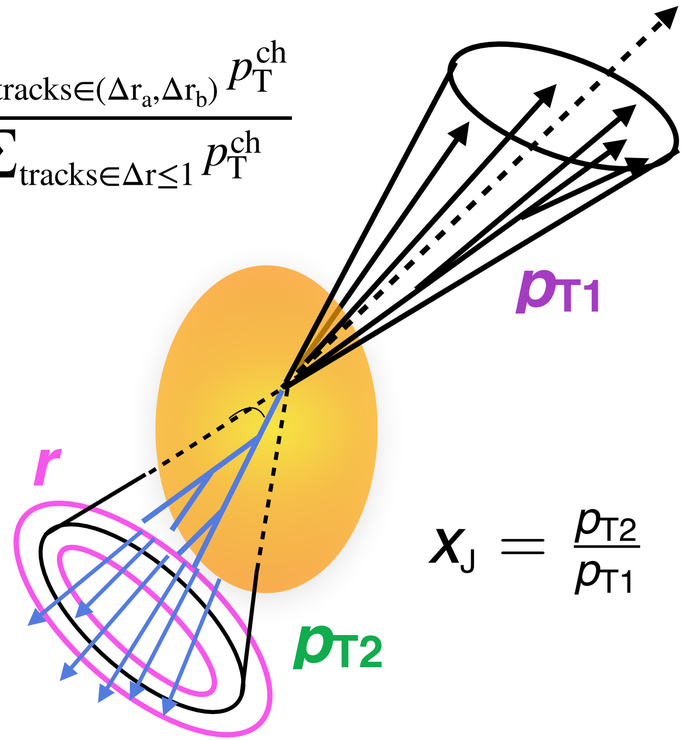






$$x_J = \frac{p_{T2}}{p_{T1}}$$

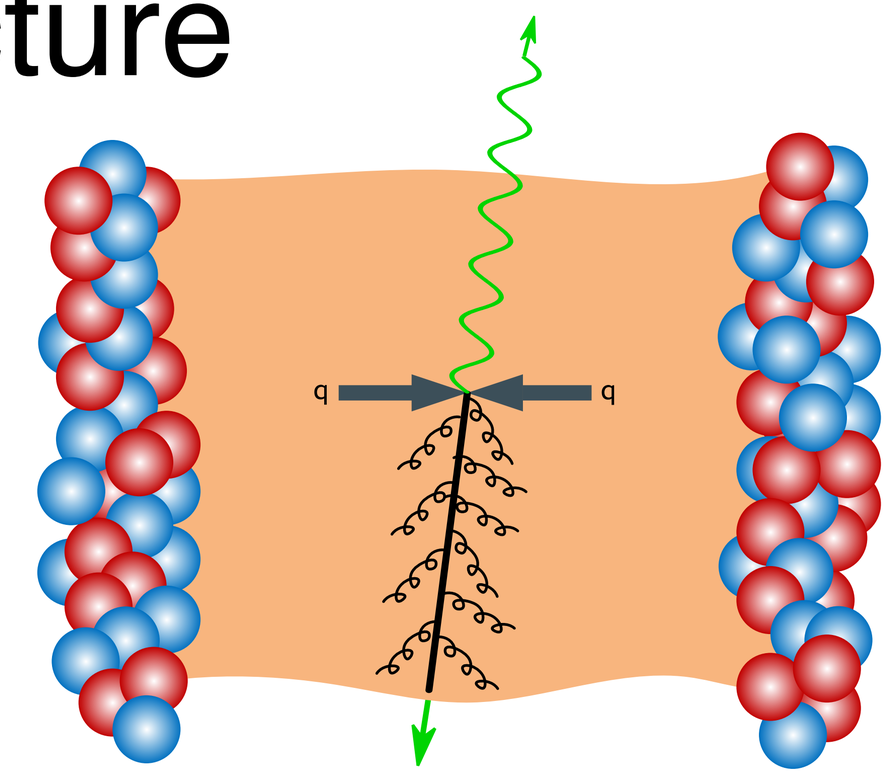
Select balanced and unbalanced dijets pairs whose jets could've traversed different paths

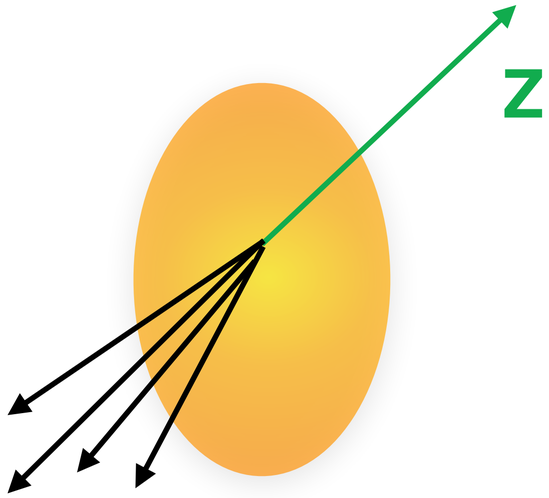
- Leading jets more modified for balanced configurations
- Sub-leading jets more modified for unbalanced configurations

CMS JHEP 05 (2021) 116

Boson-tagged jet structure

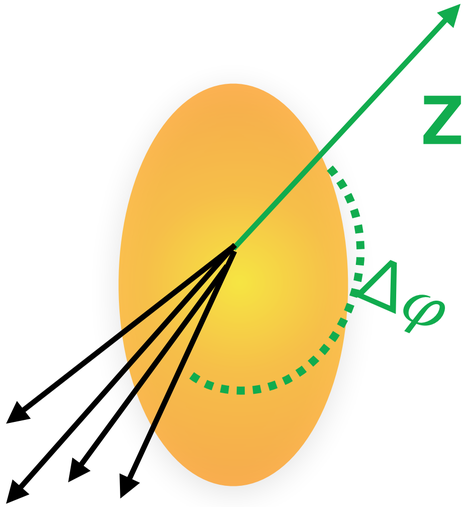
- Boson-jets dominated by quark jets
- Boson tag provides approximate initial momentum of jet (no energy loss)



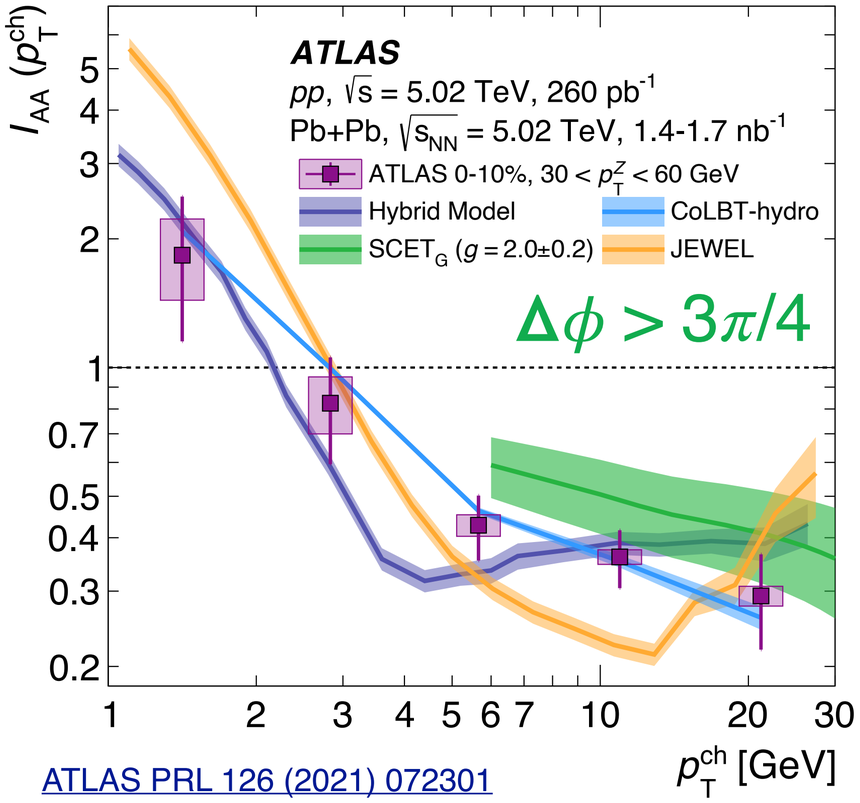


- Z-tag allows access to lower momentum than photons because of less background
- Z-tagged particles not biased by jet -> possibly access to larger jet quenching effects

Z-tagged particles



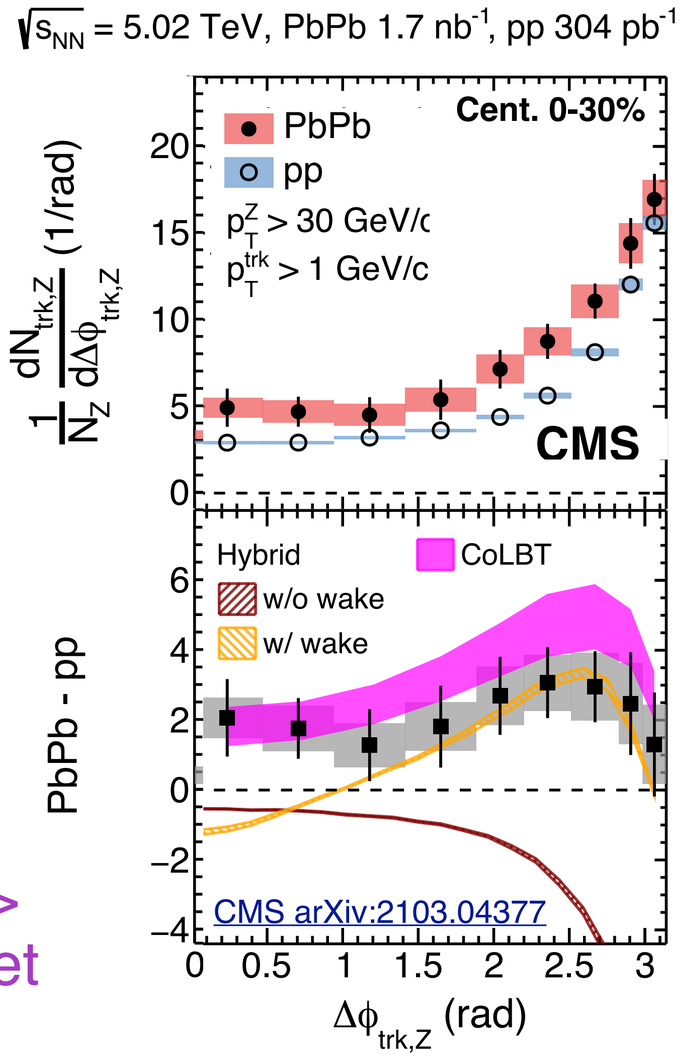
I_{AA}: yields in Pb-Pb/pp



ATLAS PRL 126 (2021) 072301

- Enhancement of soft particles -> similar to inclusive and photon jet

Δφ between Z and hadrons



- Excess of charged particles at all Δφ

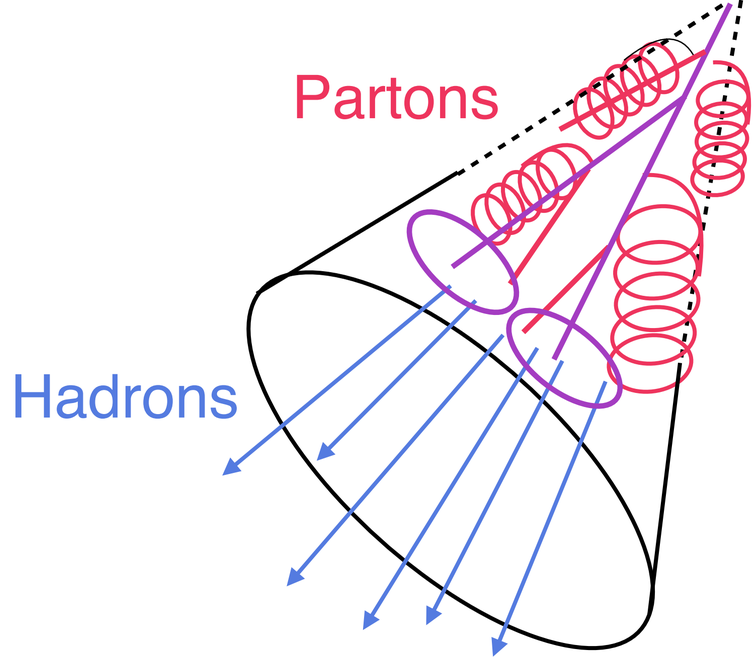
Away side excess expected from momentum broadening

Medium response could cause excess at all Δφ or possible MPI effects?

Zhong arXiv:2101.05422

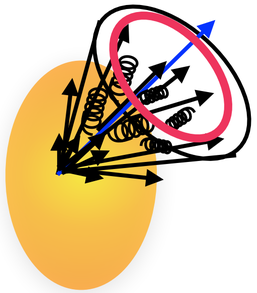
Jet internal structure

- Different variables probe a different aspect of jet structure modification

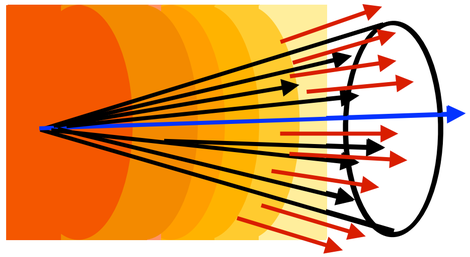


➡ Distribution of charged hadrons inside the jet

Momentum broadening



Medium response

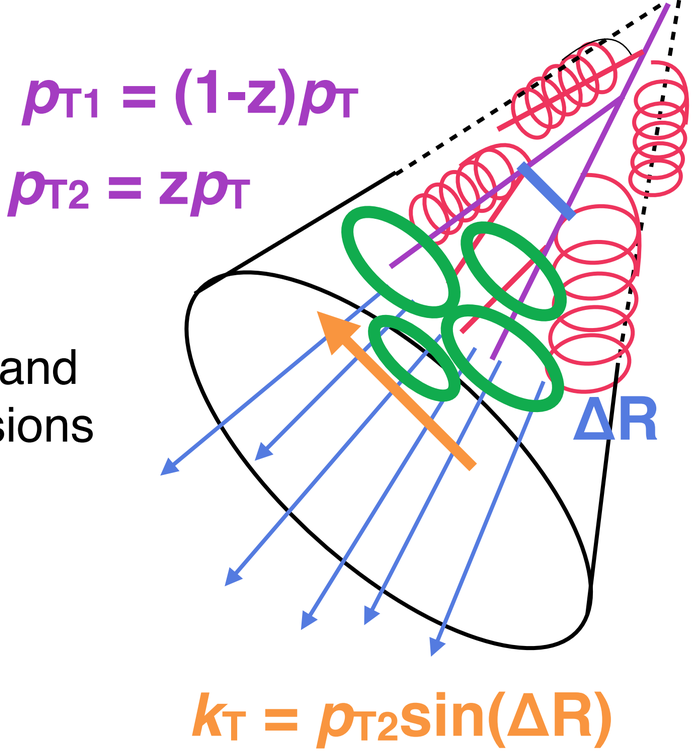


➡ **Subjets from hard parton splittings**

Separate out soft signal from softening of constituents and medium response

Also, see talk by Helena Santos

Jet splitting tools



- Methods from pp select on harder splittings inside the jet to remove the soft contribution

See plenary by Leticia Cunqueiro and QCD jet substructure parallel sessions

z: shared momentum fraction between subjets (asymmetry)

ΔR: opening angle between subjets (width)

k_T: relative transverse momentum of subjets (hardness)

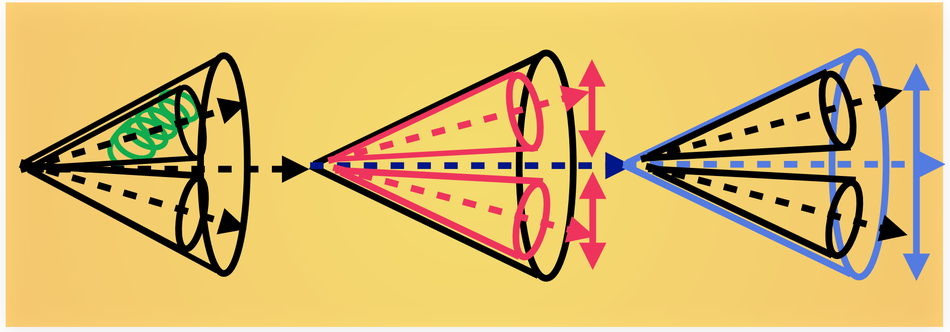
Multiple subjets within a jet:

- Subjet fragmentation: distribution of subjets within a jet
- Nsubjettiness: how many subjets are within the jet

- In-medium: did the medium resolve the splitting? how was it modified?

Probe medium-induced splittings and coherence vs. decoherence

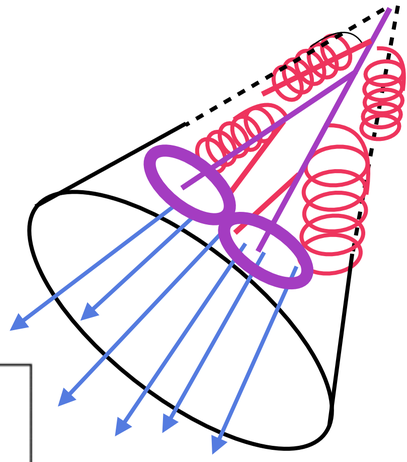
Resolved splitting-> more energy loss



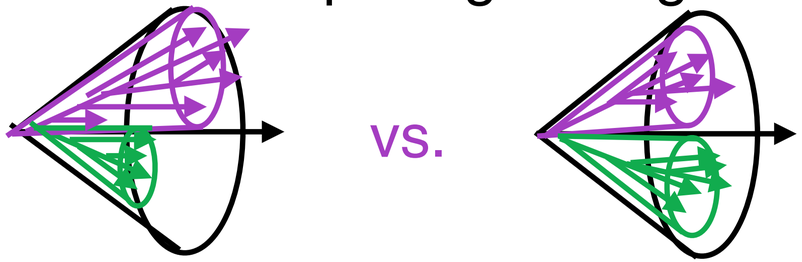
Casalderrey-Solana et al PLB 725 (2013) 447

Jet splittings: z_g

$$z_g = \frac{\min(p_{Ti}, p_{Tj})}{p_{Ti} + p_{Tj}}$$



- Select hard splittings using Soft Drop



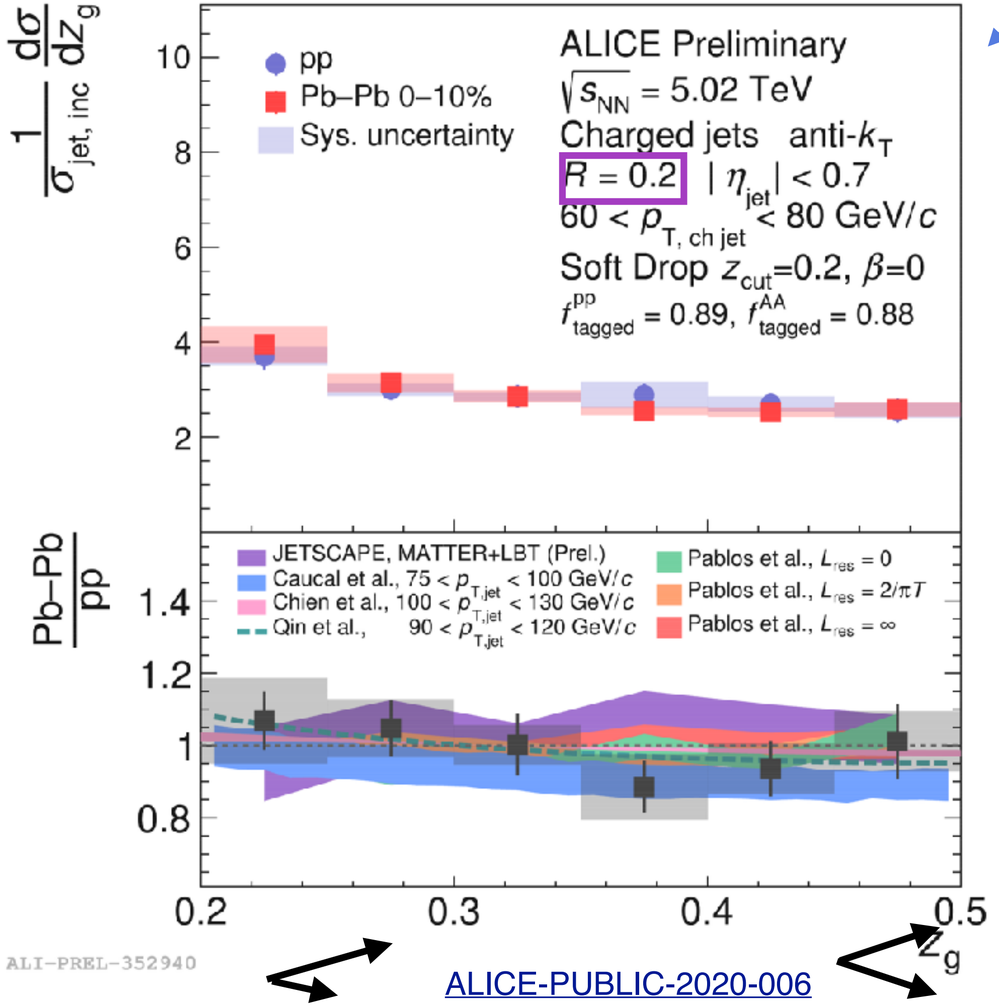
vs.

Modification of splitting function?

- Fully corrected Pb-Pb and pp compared to models:

Smaller R at lower p_T

- *No significant modification, mostly consistent with models*

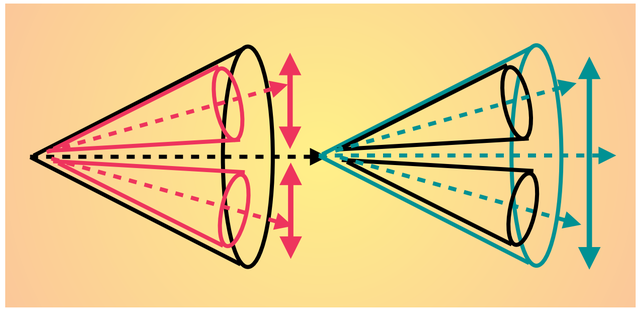


ALICE-PUBLIC-2020-006

Jet splittings: R_g

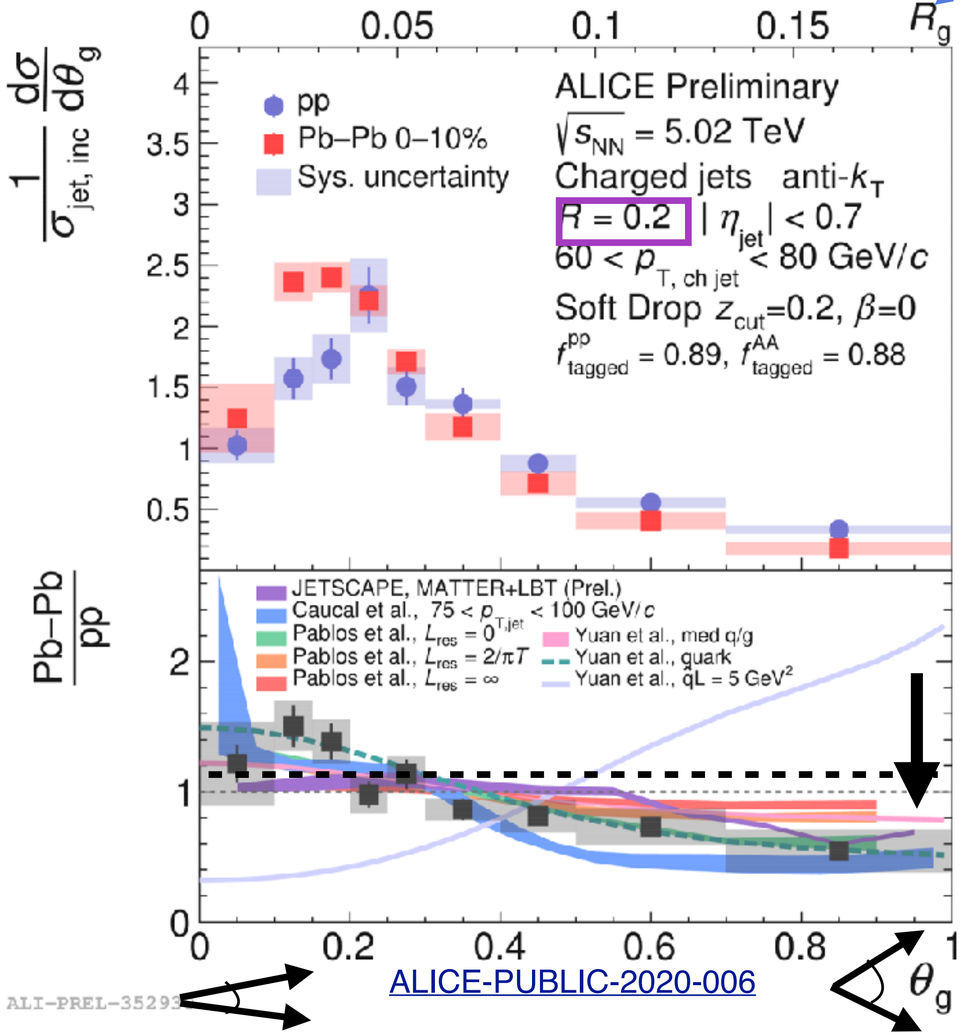
Resolution length of QGP?

- *Modification with large angle suppression (narrowing)*
- Favored by model with incoherent energy loss or coherent energy loss with a high quark fraction



Pablos et al
JHEP (2020) 044

Yuan et al
arXiv:1907.12541



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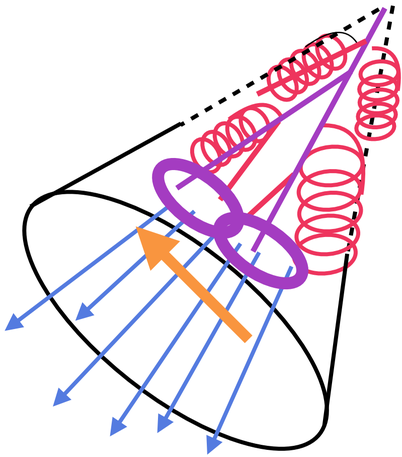
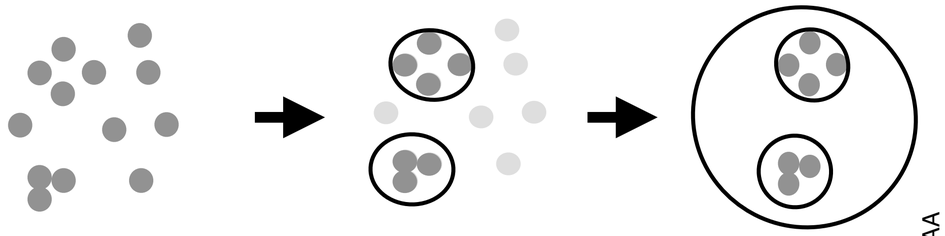
Jet splittings: large R

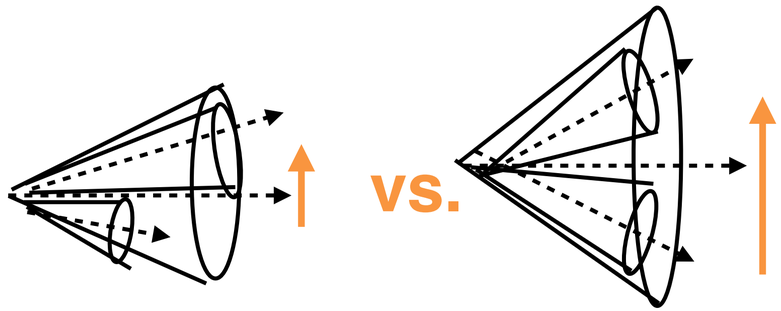


- Combining R=0.2 into R=1.0 jets removes energy radiated between subjets

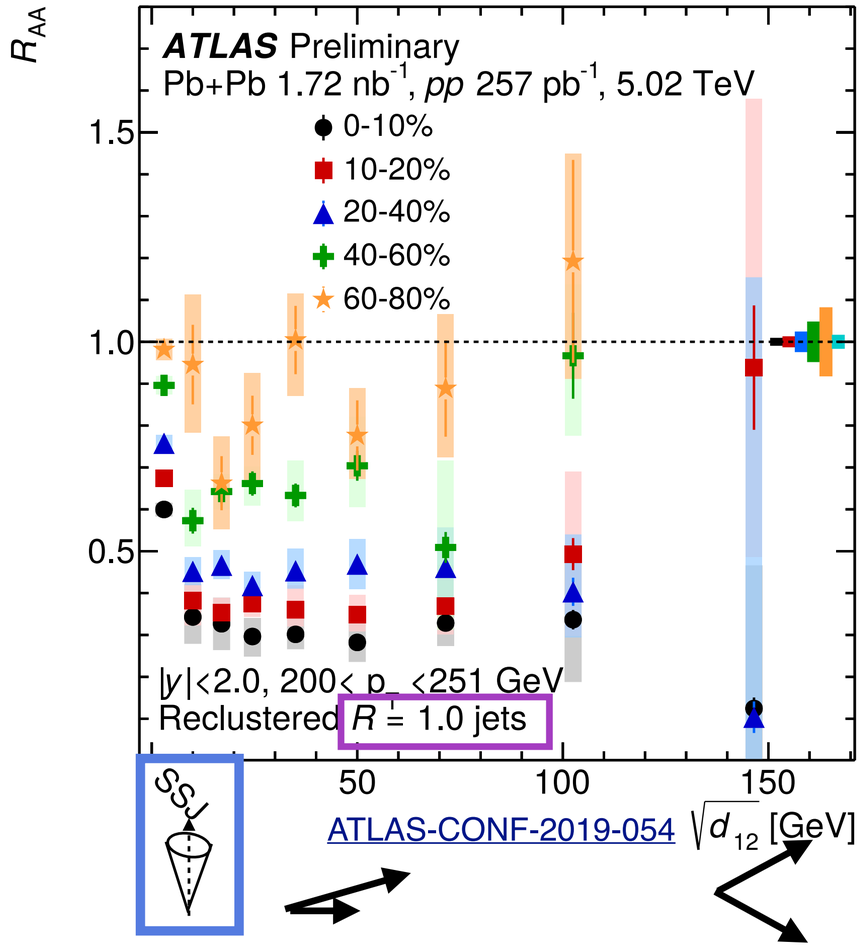


Recluster with k_T algorithm to access k_T

How hard is the resolved splitting?



$$\sqrt{d_{12}} = p_{T2}\Delta R_{12}$$

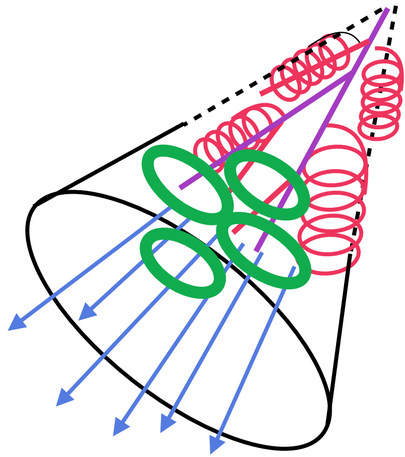


- Fully corrected R_{AA} vs. d_{12}: jets with a substructure more suppressed than jets without (single subjets SSJ)

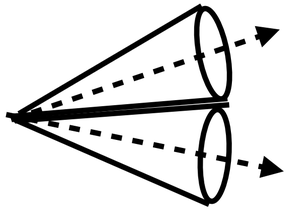
Larger R at higher p_T

N-subjettiness

$$\tau_N = \frac{\sum_{i \in \text{jet}} p_{T,i} \min \Delta R_{i,1}, \Delta R_{i,2}, \ldots, \Delta R_{i,N}}{R p_{T,\text{jet}}}$$

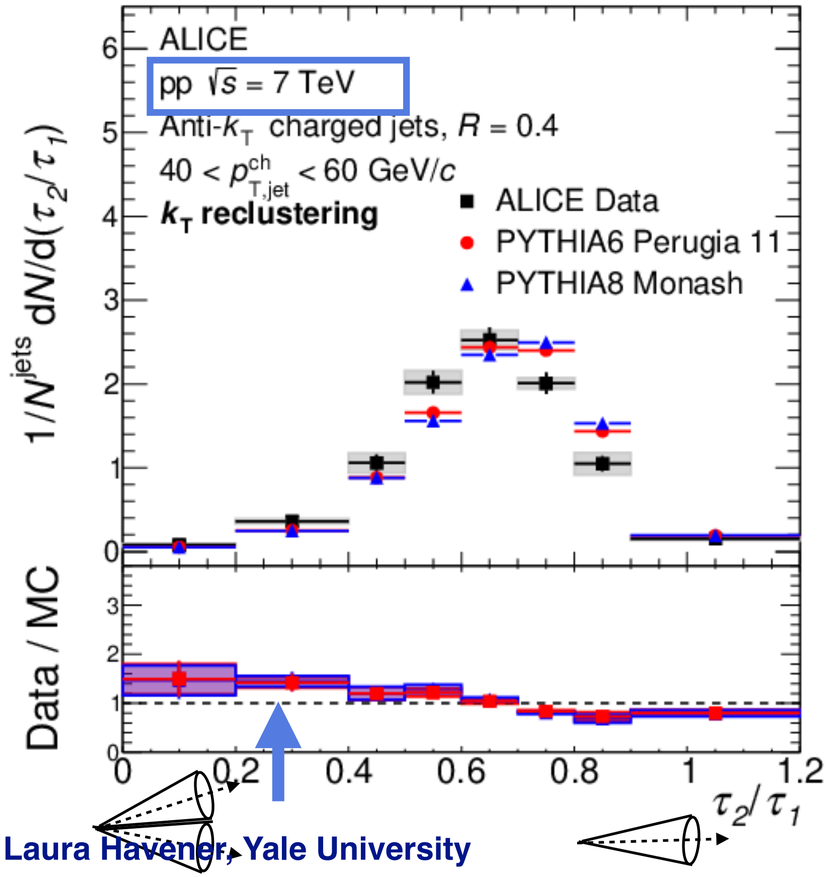


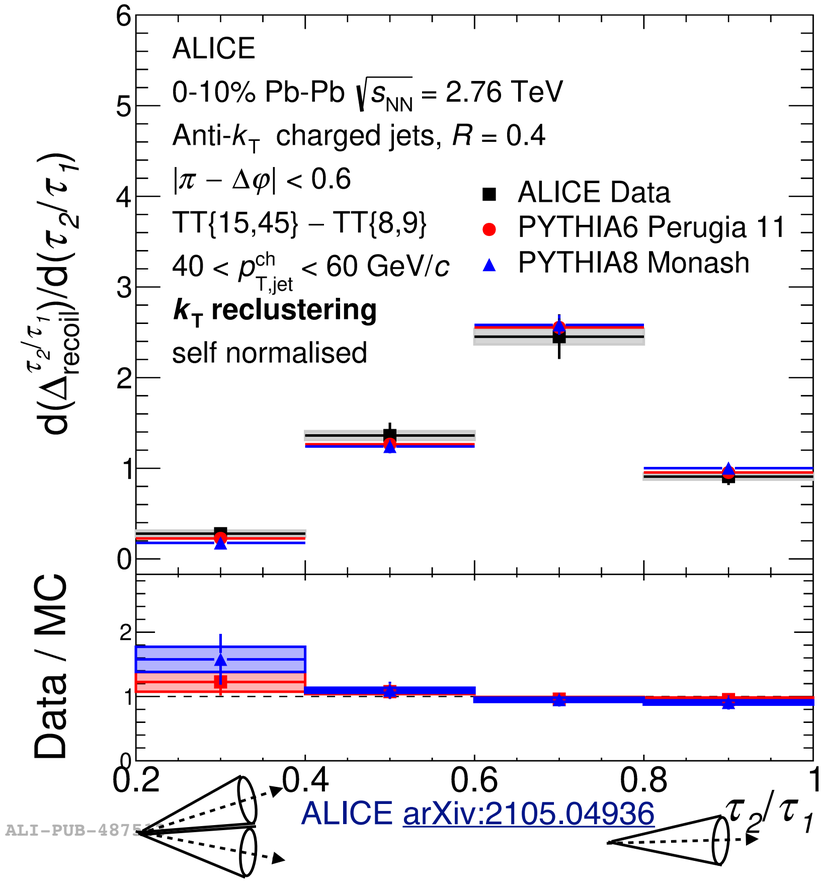
- k_T reclustering selects hard subjets



$\tau_2/\tau_1 -> 0$
Jet has 2 prongs

Are the prongs resolved by the medium?





ALICE arXiv:2105.04936

- Fully corrected τ_2/τ_1 in pp and Pb-Pb data compared to PYTHIA

p/MC > 1 Pb-Pb/MC ~ 1

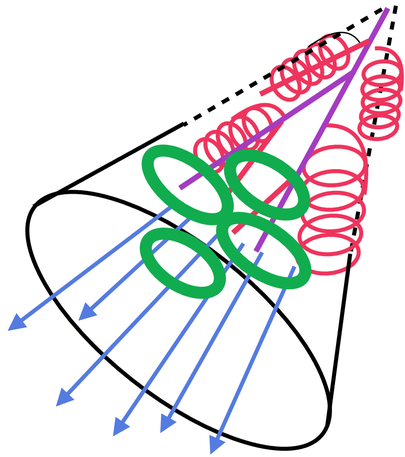
Pb-Pb/pp < 1

Hint of suppression of 2-prongness in HIs

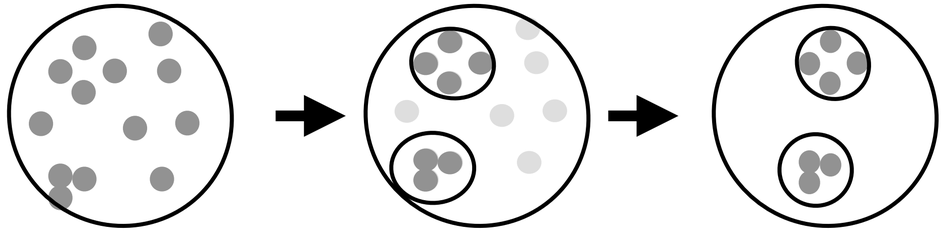
Subjet fragmentation

$$F(z_r) = \frac{1}{N_{\text{jet}}} \frac{dN}{dz_r}$$

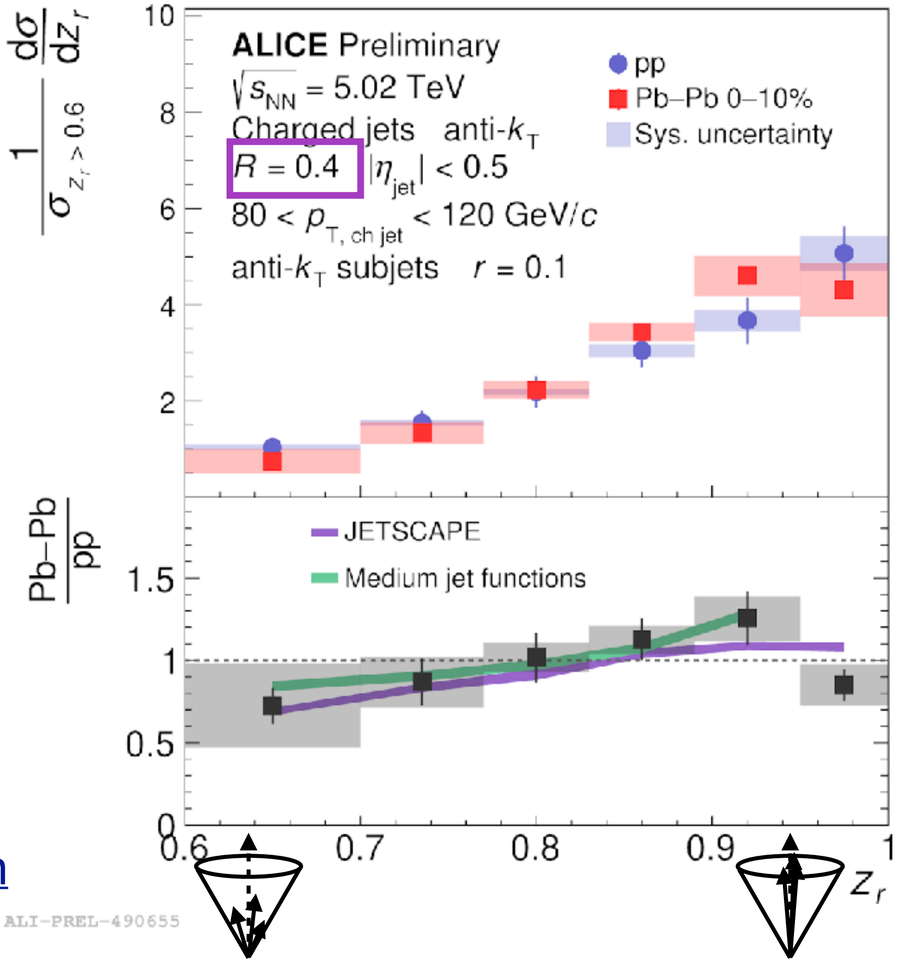
$$z_r = \frac{p_T^{\text{ch subjet}}}{p_T^{\text{ch jet}}}$$



- Recluster constituents of R=0.4 jets into r=0.1 jets



- Compare to fragmentation at hadron level
- Fully corrected Pb-Pb data compared to pp
  - Possible hardening at intermediate z -> similar to R_g and hadron fragmentation
  - Hint of suppression as z -> 1, energy loss of pure quarks?

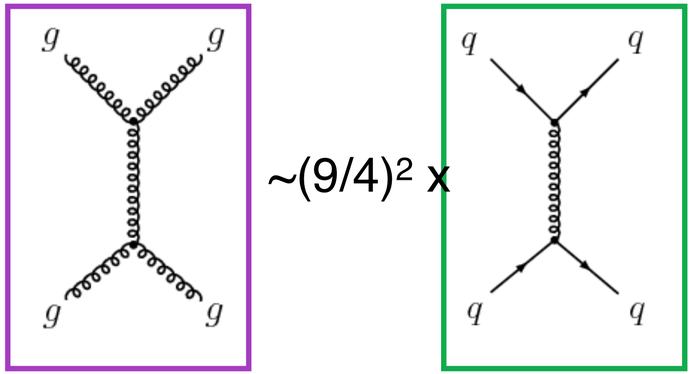


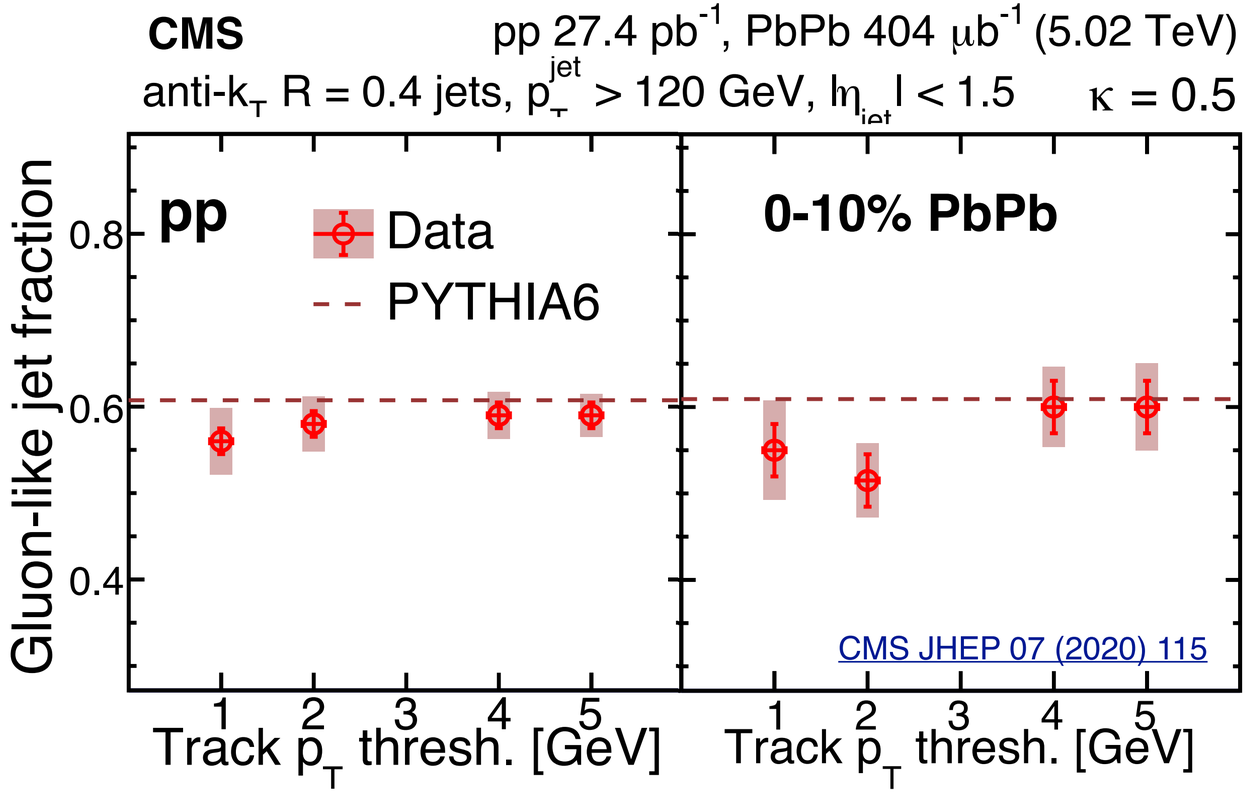
See talk by James Mulligan for more details

Jet charge

- The energy loss by quarks is predicted to be less than the energy loss by gluons
- Jet charge sensitive to electric charge of initial parton
- PYTHIA template fits to extract q/g fractions from fully corrected jet charge

$$Q^k = \frac{1}{p_{\mathrm{T}}^{\mathrm{jet}}} \sum_{i \in \mathrm{jet}} q_i p_{\mathrm{T,i}}^k$$



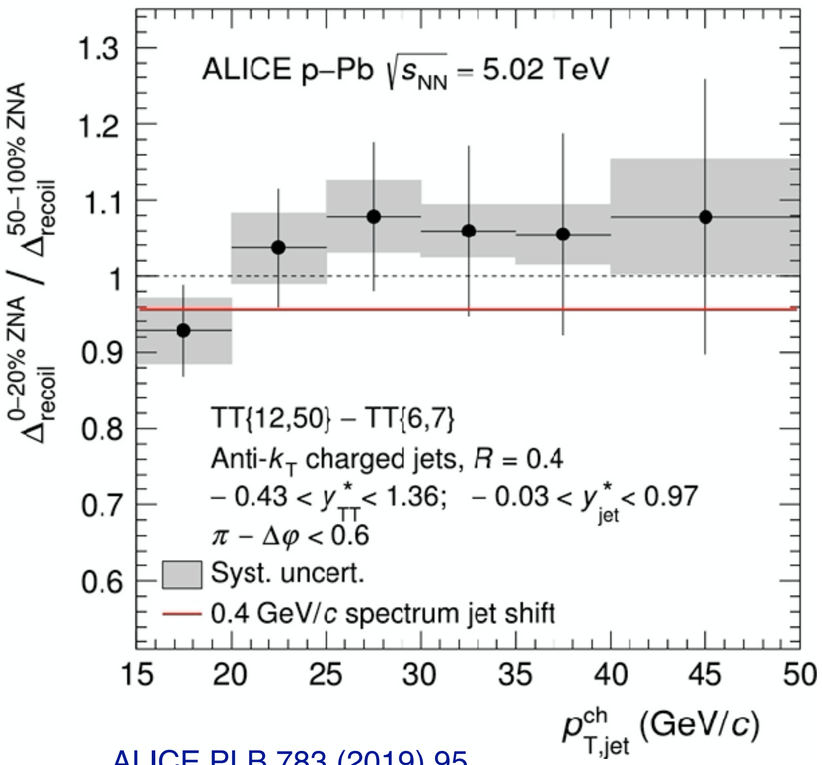


- Fractions in pp and Pb-Pb similar -> no modification of gluon fraction?

Caveat: templates fits have a PYTHIA fragmentations bias

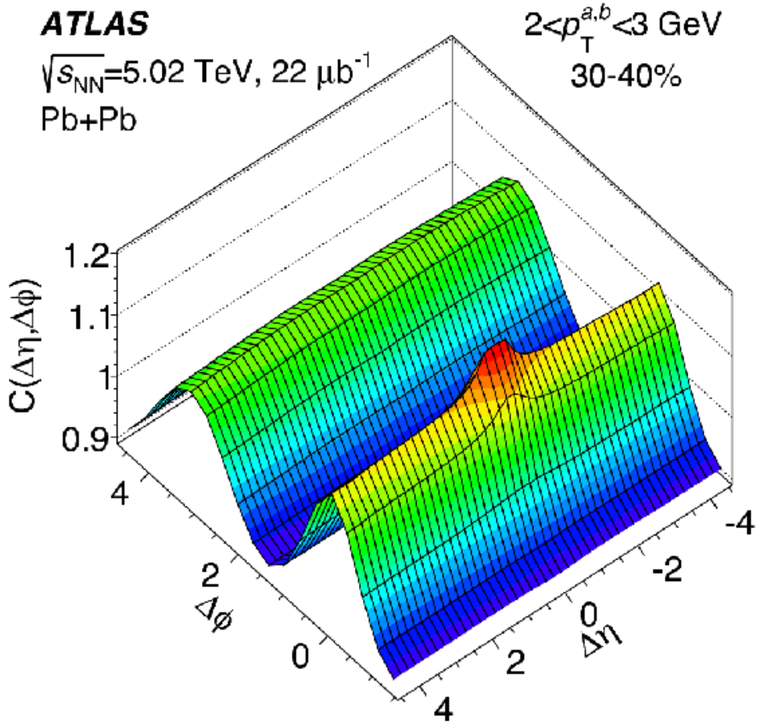
Jets and hadrons in small systems

- Signature of QGP formation in AA: flow of two-particle correlations



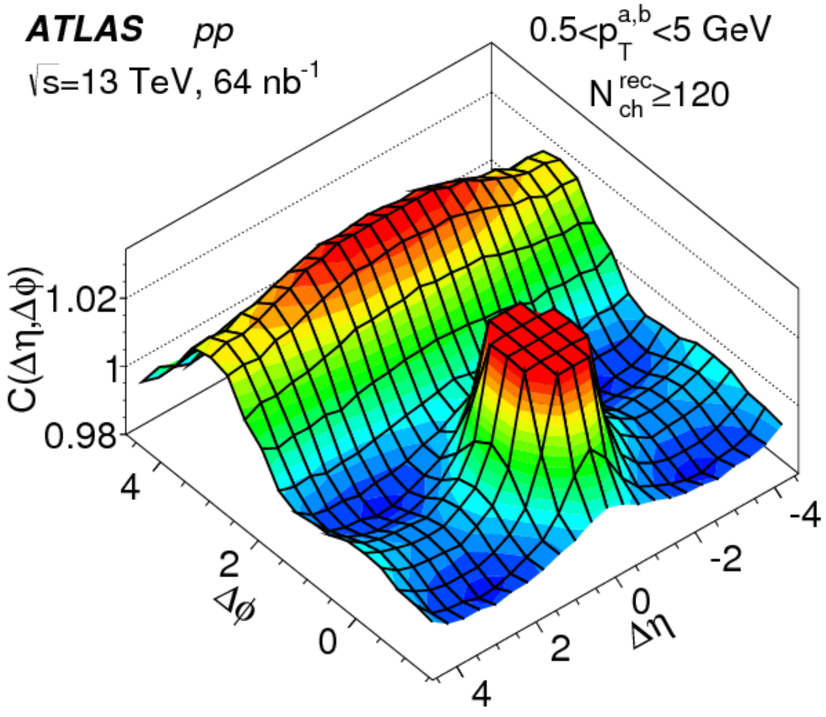
ALICE PLB 783 (2019) 95

Semicentral Pb-Pb



ATLAS EPJ. C 78 (2018) 997

High multiplicity pp

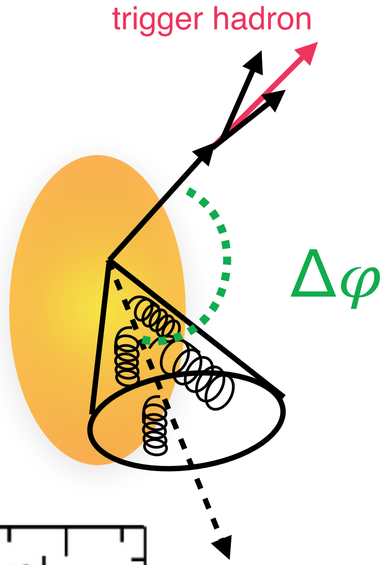


ATLAS PRC 96 (2017) 024908

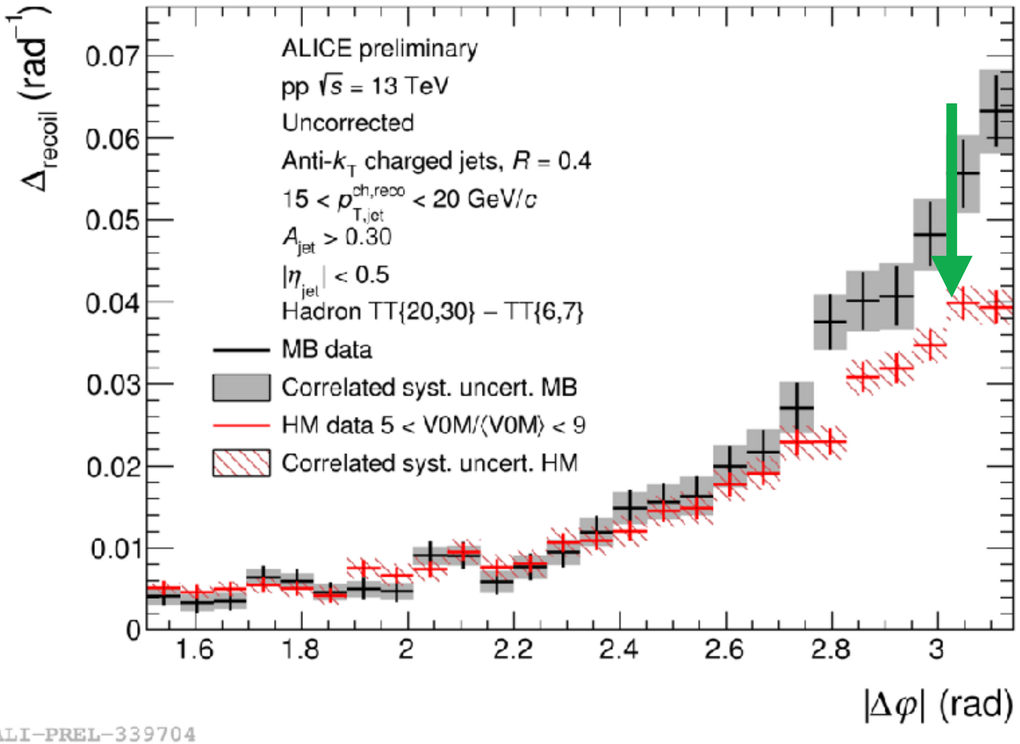
- Also seen in small systems: high multiplicity (HM) p-Pb and pp collisions
- Jet quenching in small collision systems?

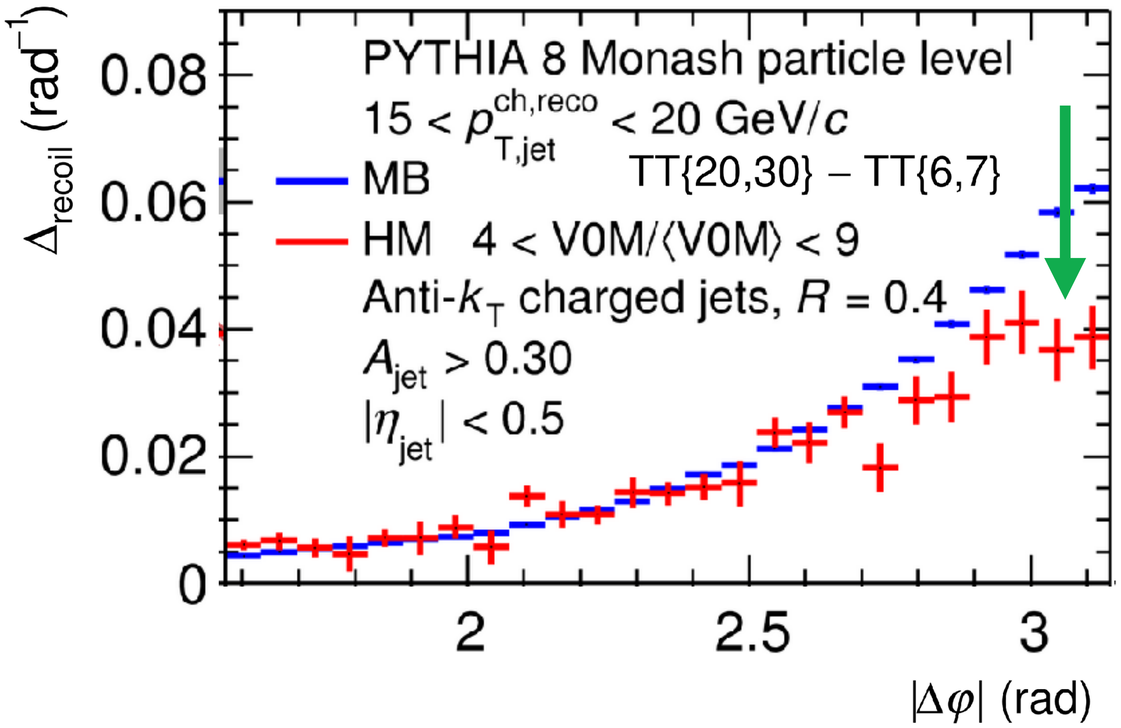
Energy loss limit in p-Pb of 400 MeV (90% CL)

Jet quenching in pp collisions?



- Jet acoplanarity in **HM** compared to **MB** pp collisions
  - Suppression of HM compared to MB → jet quenching?
  - Similar effect in PYTHIA! What's happening?



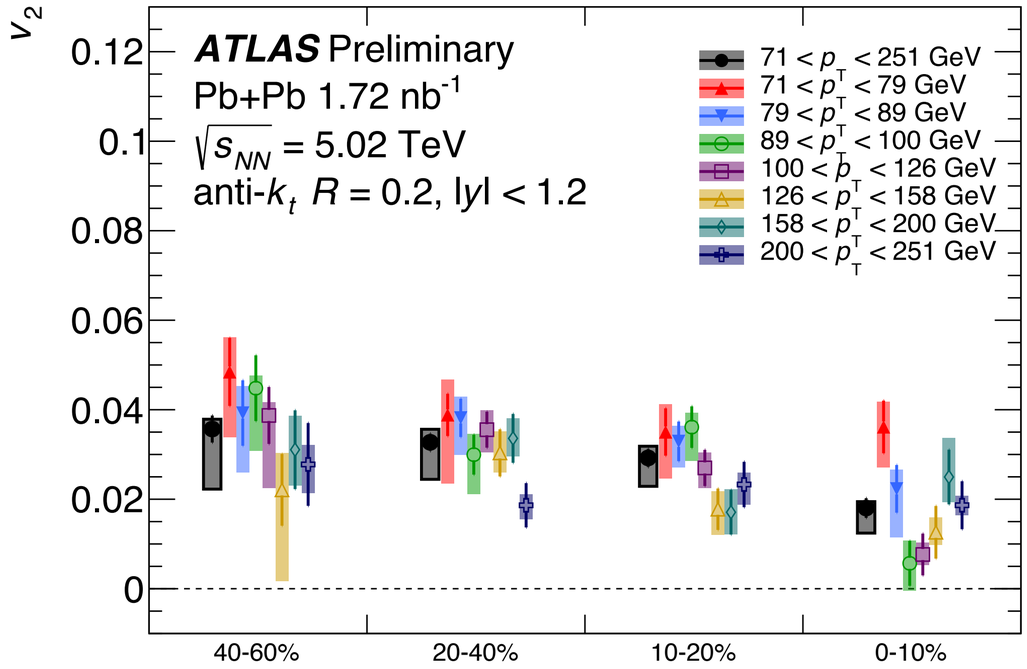


- *HM trigger biases towards multi-jet events in small systems → important for all studies of HM in small systems!*

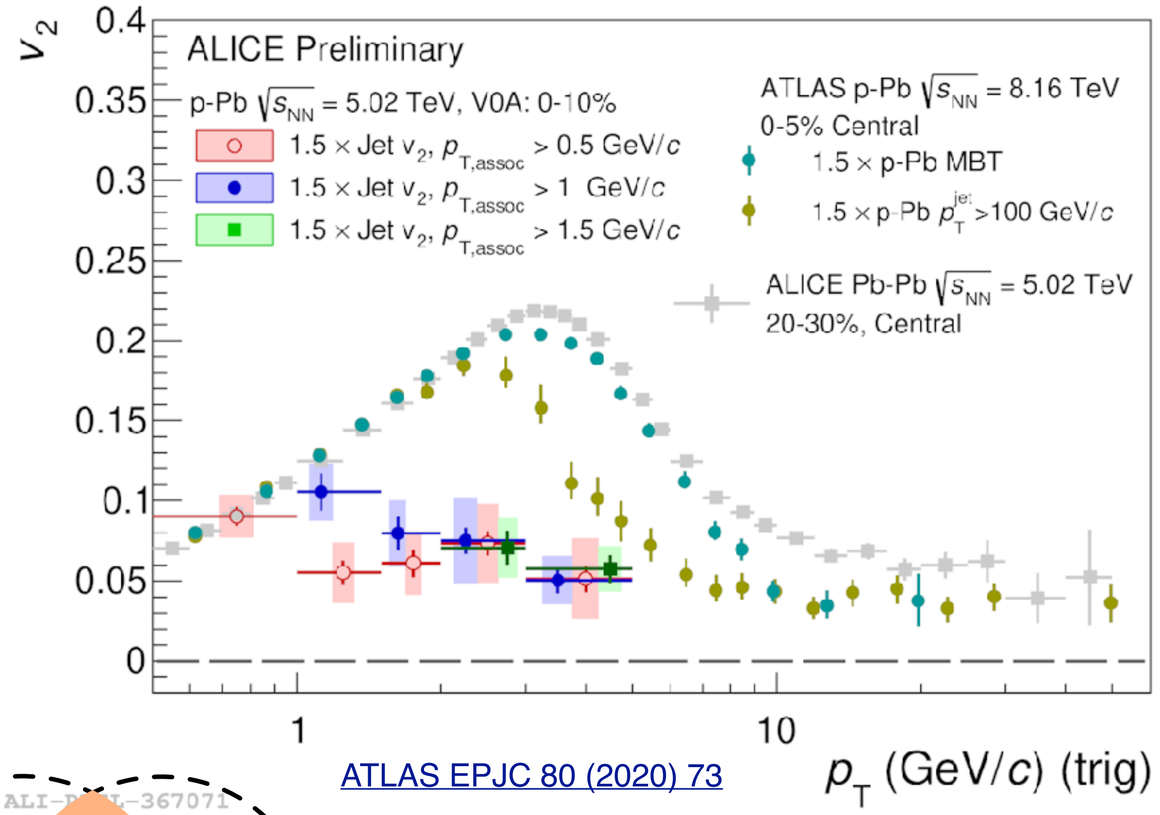
High p_T v_n in p-Pb?

$$\frac{dN}{d\phi} = N_0(1 + 2\sum_{n=1} v_n \cos n(\phi - \psi_n))$$

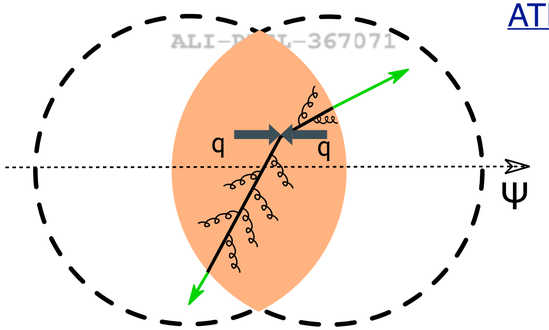
- Positive v_n seen in p-Pb collisions at high p_T
- In Pb-Pb this is usually attributed to path length dependence from jet quenching as seen in jet v_n at high p_T



ATLAS-CONF-2020-019



ATLAS EPJC 80 (2020) 73



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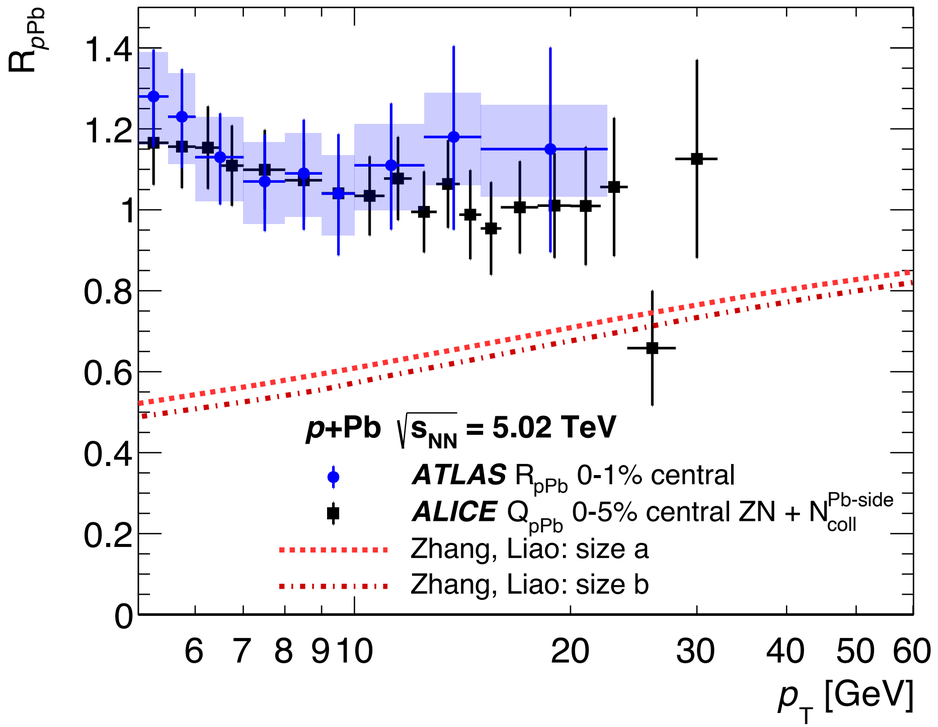

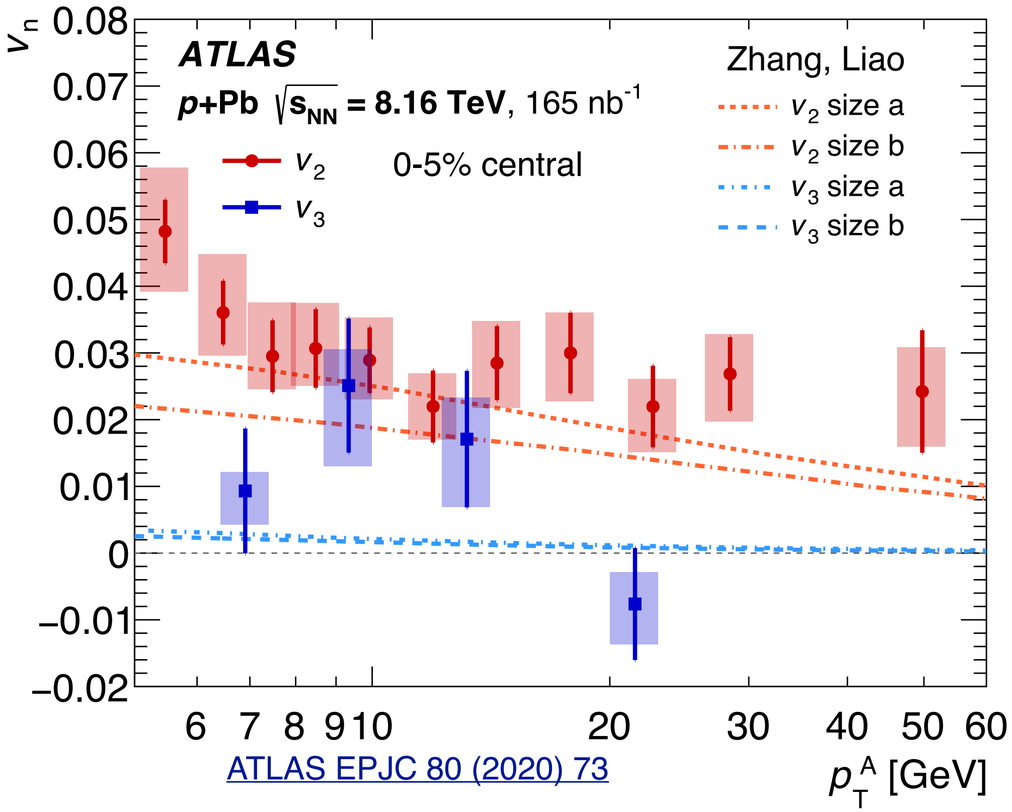

ATLAS EPJC 80 (2020) 73

- Reproduced by jet quenching model
- But this model predicts suppression for R_{pPb} that is not seen in data?

Conclusion

- LHC has an array of new results on jet quenching in heavy-ion collisions:
  - Remaining questions:
    - No recovery of energy at large R?
    - Unexpected narrowing in jet accoplanarity?
    - No flavor dependence in jet charge?
    - Best way to probe coherence with jet substructure?
    - Jet quenching in small systems?
- How can we use jet quenching measurements to learn about the QGP?
- Jet quenching effects tangled in different observables, how do we best isolate effects of flavor, path length, coherence, and medium response?
- Higher statistics datasets in Run 3 will allow for precise measurements more differentially and with rarer probes like bosons or heavy flavor

Thank you!

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