Path-length dependence of energy loss

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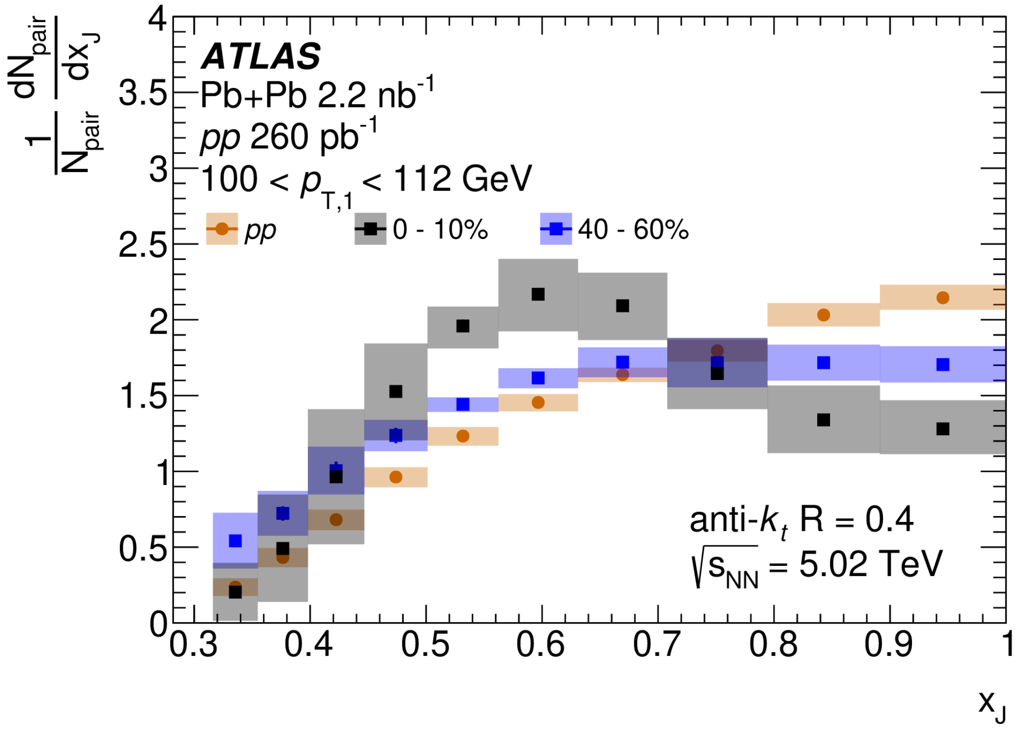
QCD Challenges from pp to AA collisions

Talk content

- Few selected recent **experimental data** on path-length sensitive observables. What can we do better?
- Phenomenological **parametric approach** to jet quenching to extract the path-length dependence of energy loss with minimal assumptions.
- How to **move forward**: a bit of self-criticism.
- (Backup for joint-track: j**et v_2 at high-p_T**)

Dijets in Pb+Pb

- Input to better understand the path-length dependence and the role of fluctuations.
- Dijet energy loss quantified in terms of $x_J = p_{T,\mathrm{leading}} / p_{T,\mathrm{subleading}}$.



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

PRC 107 (2023) 054908

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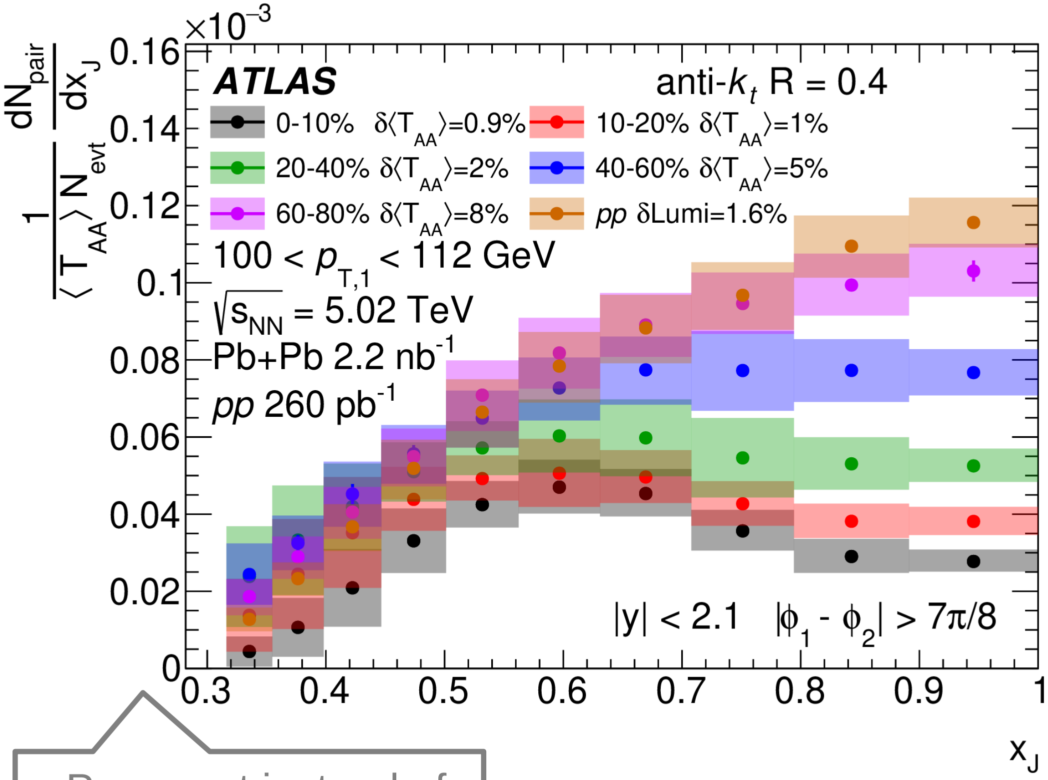

Per-event instead of dijet normalization

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

PRC 107 (2023) 054908

Dijets in Xe+Xe

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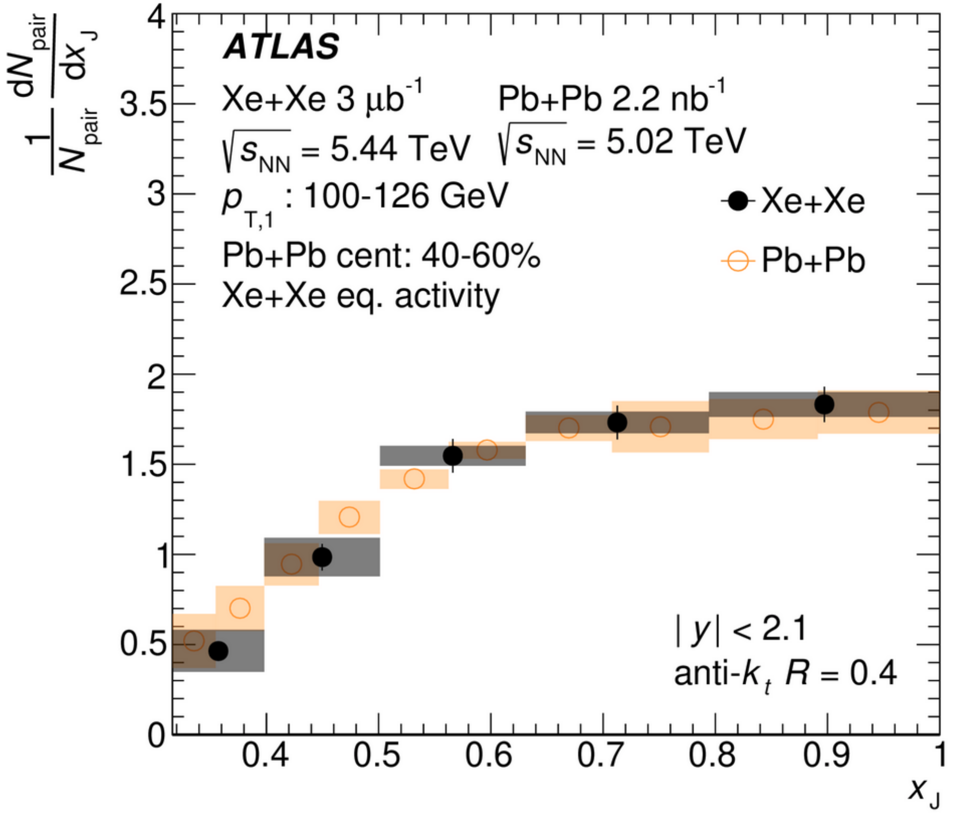


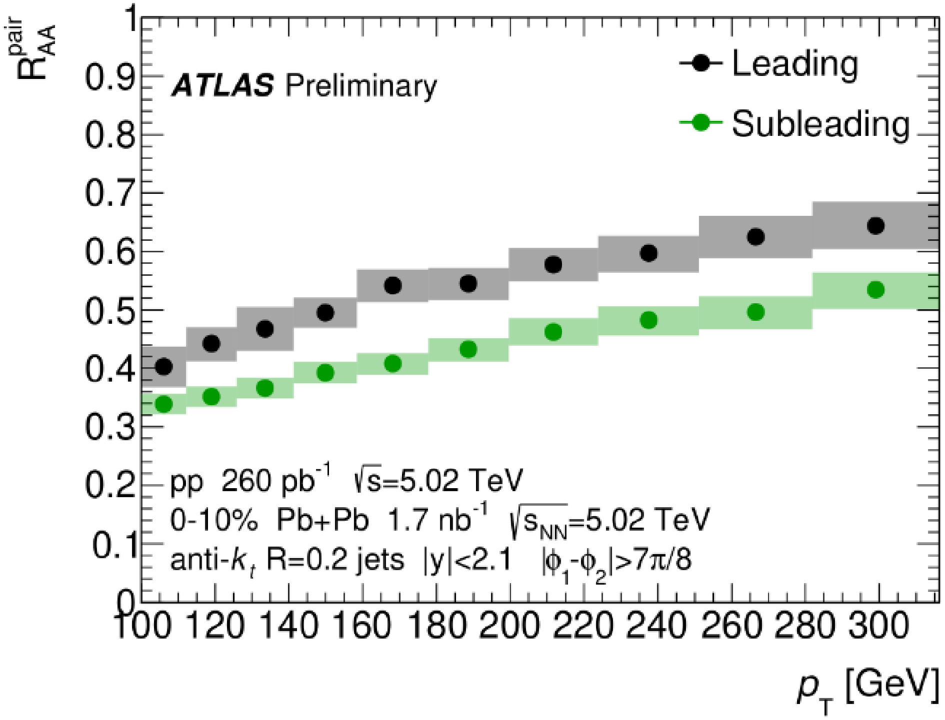
- Significant **dijet imbalance** seen in central heavy ion collisions.
- Studied also **in Xe+Xe** collisions – important to understand the system size dependence of jet quenching … similar level of jet suppression when taking into account differences in geometry and $\sqrt{s_{NN}}$

PRC 108 (2023) 024906

Radius dependence of dijet suppression

$$R_{\mathrm{AA}}^{\mathrm{pair}}(p_{\mathrm{T},1}) = \frac{\frac{1}{N_{\mathrm{evnt}}\langle T_{\mathrm{AA}}\rangle}\int\limits_{0.32\times p_{\mathrm{T},1}}^{p_{\mathrm{T},1}} \frac{\mathrm{d}^2N_{\mathrm{pair}}^{\mathrm{AA}}}{\mathrm{d}p_{\mathrm{T},1}\mathrm{d}p_{\mathrm{T},2}}\,\mathrm{d}p_{\mathrm{T},2}}{\frac{1}{L^{pp}}\int\limits_{0.32\times p_{\mathrm{T},1}}^{p_{\mathrm{T},1}} \frac{\mathrm{d}^2N_{\mathrm{pair}}^{pp}}{\mathrm{d}p_{\mathrm{T},1}\mathrm{d}p_{\mathrm{T},2}}\,\mathrm{d}p_{\mathrm{T},2}}$$

ATLAS-CONF-2023-060

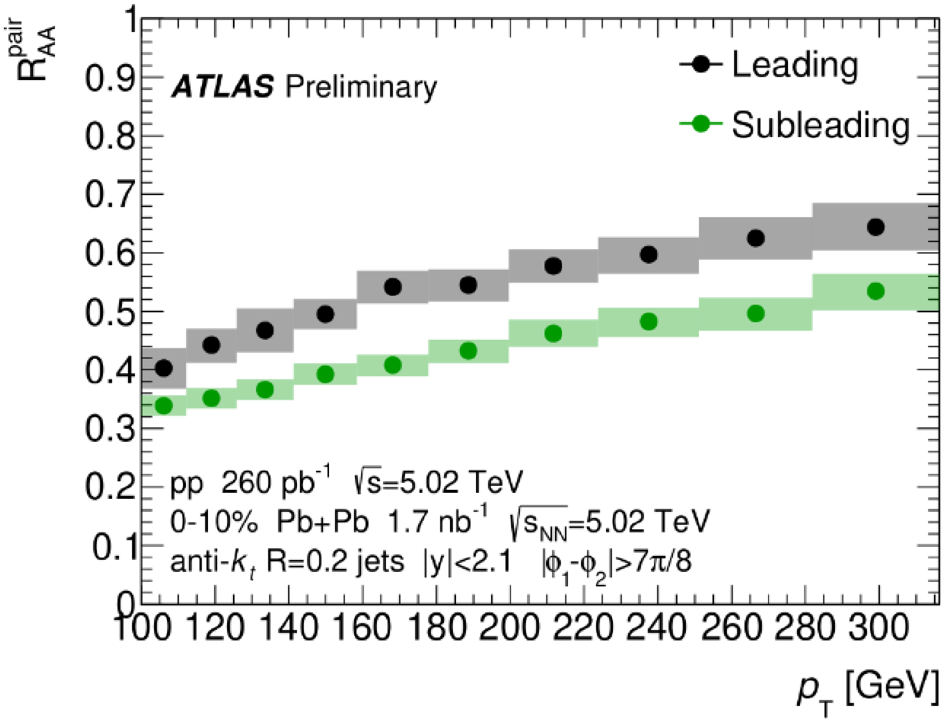


- Sub-leading jets are quenched more than leading jets.

Radius dependence of dijet suppression

$$R_{\mathrm{AA}}^{\mathrm{pair}}(p_{\mathrm{T},2}) = \frac{\dfrac{1}{N_{\mathrm{evnt}}\langle T_{\mathrm{AA}}\rangle}\displaystyle\int_{p_{\mathrm{T},2}}^{p_{\mathrm{T},2}/0.32}\frac{\mathrm{d}^2N_{\mathrm{pair}}^{\mathrm{AA}}}{\mathrm{d}p_{\mathrm{T},1}\mathrm{d}p_{\mathrm{T},2}}\mathrm{d}p_{\mathrm{T},1}}{\dfrac{1}{L^{pp}}\displaystyle\int_{p_{\mathrm{T},2}}^{p_{\mathrm{T},2}/0.32}\frac{\mathrm{d}^2N_{\mathrm{pair}}^{pp}}{\mathrm{d}p_{\mathrm{T},1}\mathrm{d}p_{\mathrm{T},2}}\mathrm{d}p_{\mathrm{T},1}}$$

ATLAS-CONF-2023-060



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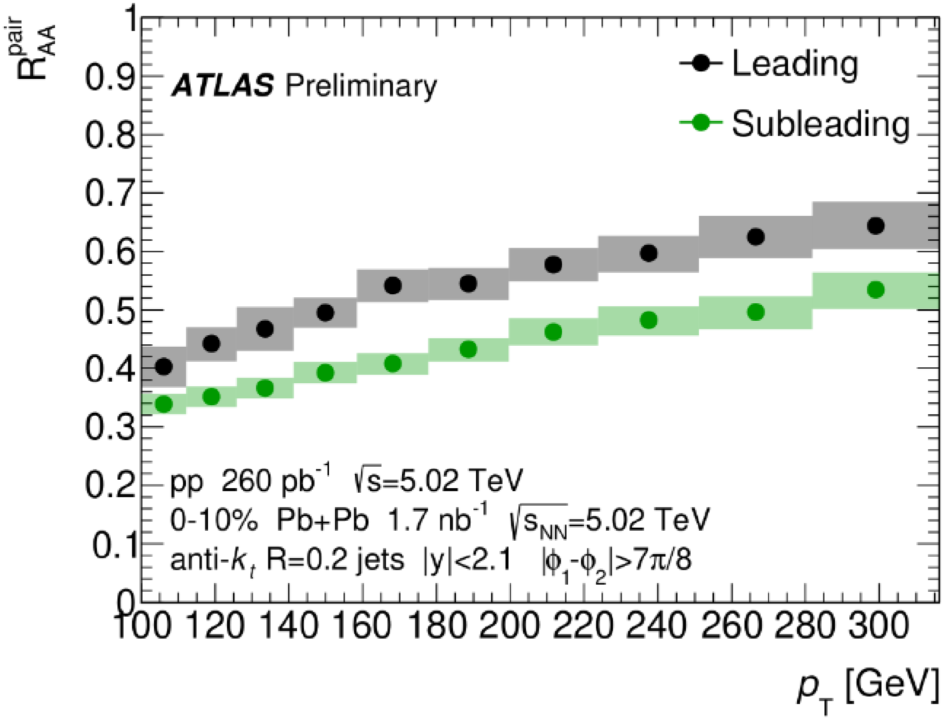
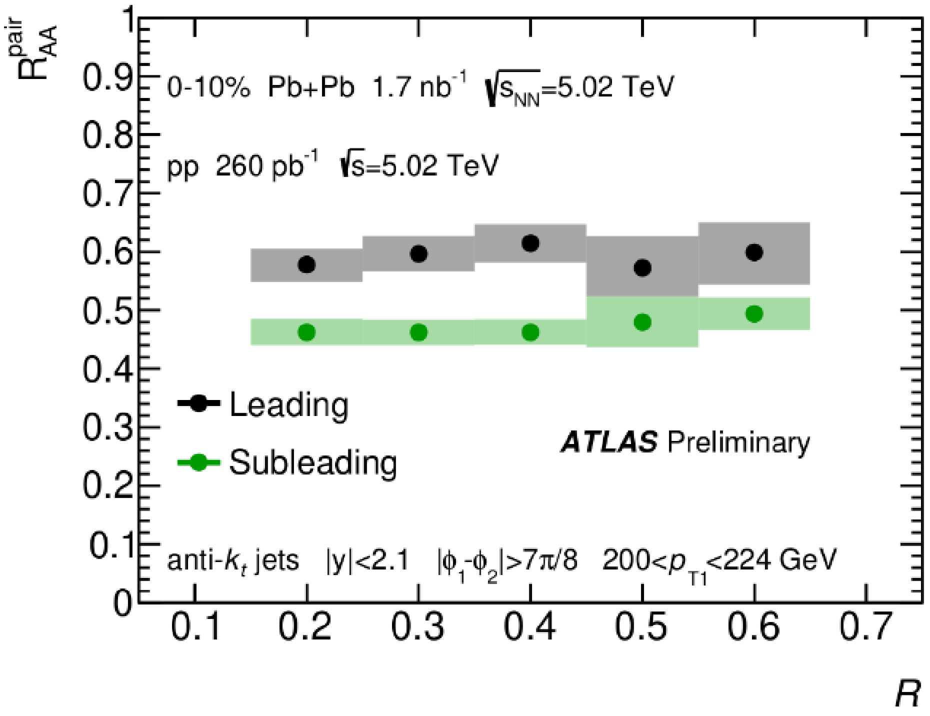
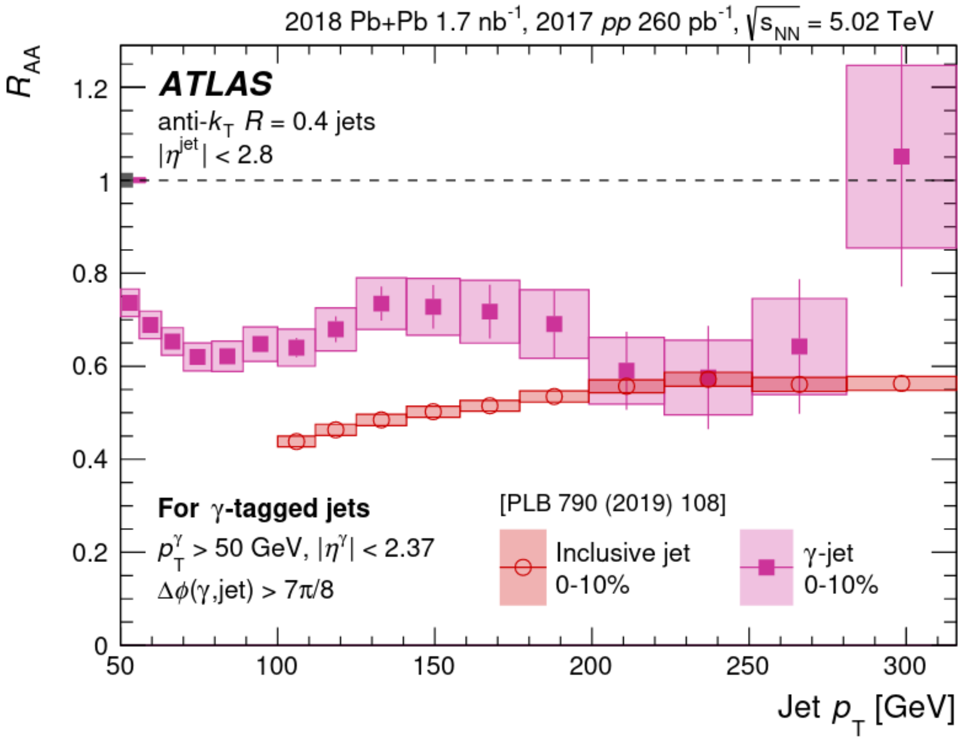
ATLAS-CONF-2023-060





- Sub-leading jets are quenched more than leading jets.
- No significant dependence of suppression on jet radius observed.

Suppression in γ-jet system



- Inclusive jets dominated by gluon-initiated jets.
- γ-jets dominated by **quark-initiated jets** => **less suppression** as expected.

PLB 846 (2023) 138154

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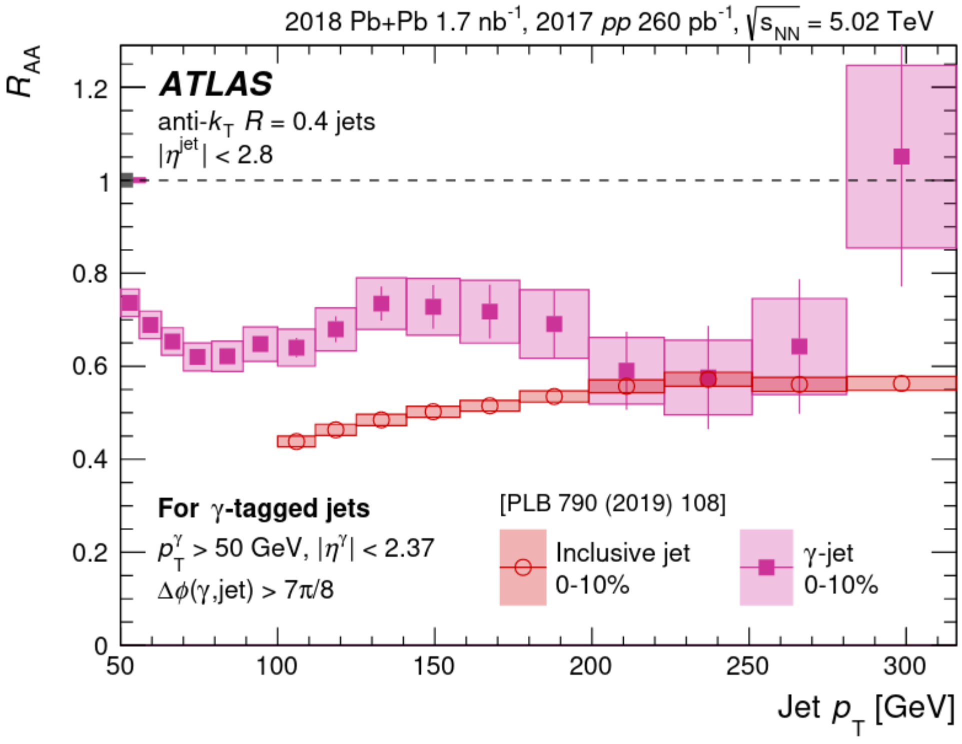
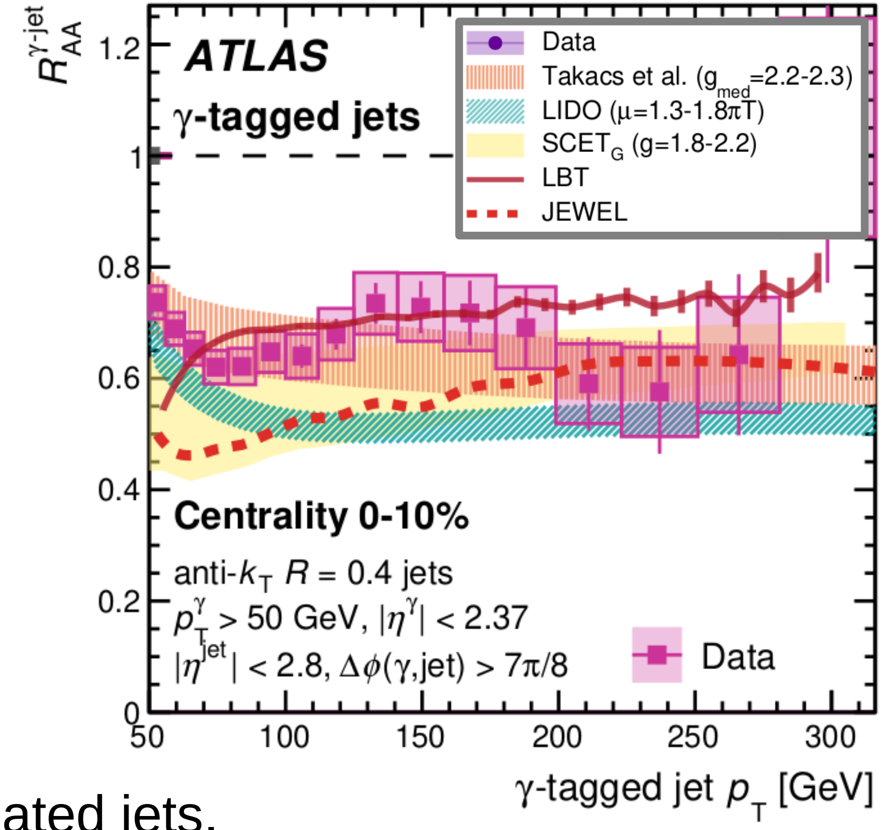




- Inclusive jets dominated by gluon-initiated jets.
- γ-jets dominated by **quark-initiated jets** => **less suppression** as expected.
- All models can be adjusted to reproduce inclusive jet R_{AA}, but none of them fully reproduces the γ-jet R_{AA} (typically **predict larger quenching**)
- Theory: impact of **color charge** & **selection bias**

PLB 846 (2023) 138154

Question 1

- The dijet measurement should have a good discriminative power wrt to path-length, fluctuations, etc. Is that sufficient? Can we improve?
- E.g. how about ratio of dN/dx_J in central and peripheral collisions? Could be less sensitive to absolute energy loss and more sensitive to path-length?
- Very demanding, but how about dijet asymmetry vs jet v_2?
  Or something else?
- What did we learn from gamma-jets?

Parametric modeling

- Jet spectra parameterized by an extended power-law

$$\frac{dN}{dp_{\mathrm{T}}^{\mathrm{jet}}} = A\left[f_{q0}\left(\frac{p_{T0}}{p_{\mathrm{T}}^{\mathrm{jet}}}\right)^{n_q} + (1-f_{q0})\left(\frac{p_{T0}}{p_{\mathrm{T}}^{\mathrm{jet}}}\right)^{n_g}\right]$$

where the exponent is jet pt dependent

$$n_i(p_{\mathrm{T}}^{\mathrm{jet}}) = \sum_{j=0}^{j_{\max}} \beta_j \log^j\left(\frac{p_{\mathrm{T}}^{\mathrm{jet}}}{p_{\mathrm{T}0}}\right)$$

- Average transverse momentum loss modeled using three parameters

$$\langle \Delta p_{\mathrm{T}}^{\mathrm{jet}} \rangle_i = c_{F,i}\ s\ \left(\frac{p_{\mathrm{T}}^{\mathrm{jet}}}{p_{\mathrm{T}0}}\right)^{\alpha}$$

Parametric modeling

- Energy loss is not a delta function but it has certain distribution

$$w(p_{\mathrm{T}}^{\mathrm{jet}}, \Delta p_{\mathrm{T}}^{\mathrm{jet}})$$

which then has an impact on the quenched jet spectra,

$$\frac{dN_Q}{dp_{\mathrm{T}}^{\mathrm{jet}}} = \int d\Delta p_{\mathrm{T}}^{\mathrm{jet}} \frac{dN}{dp_{\mathrm{T}}^{\mathrm{jet}}} w(p_{\mathrm{T}}^{\mathrm{jet}}, \Delta p_{\mathrm{T}}^{\mathrm{jet}})$$

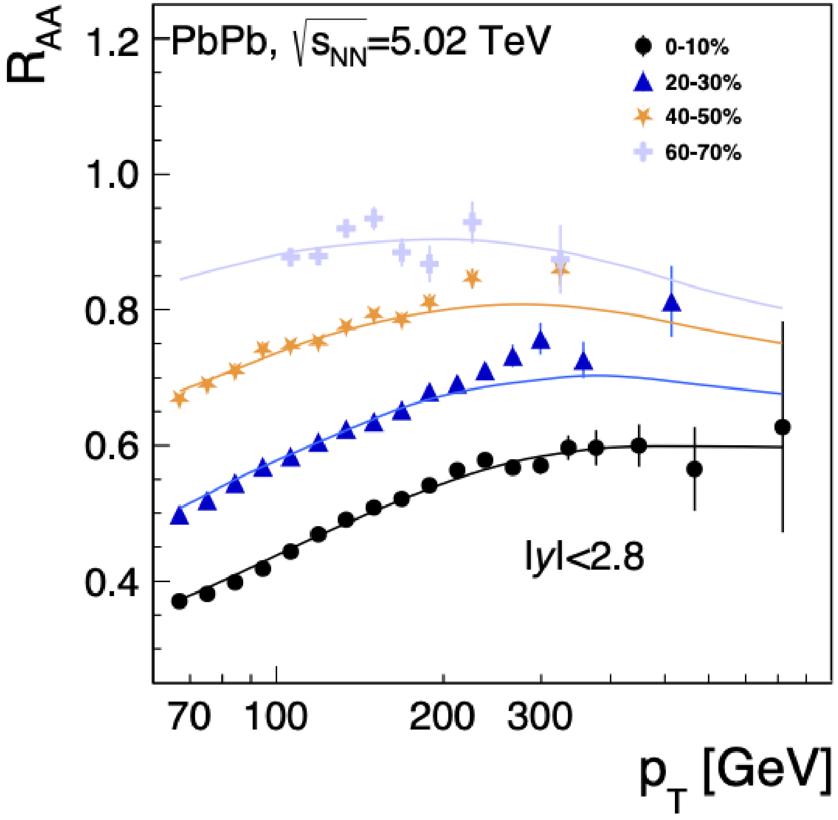
- The average energy loss is then:

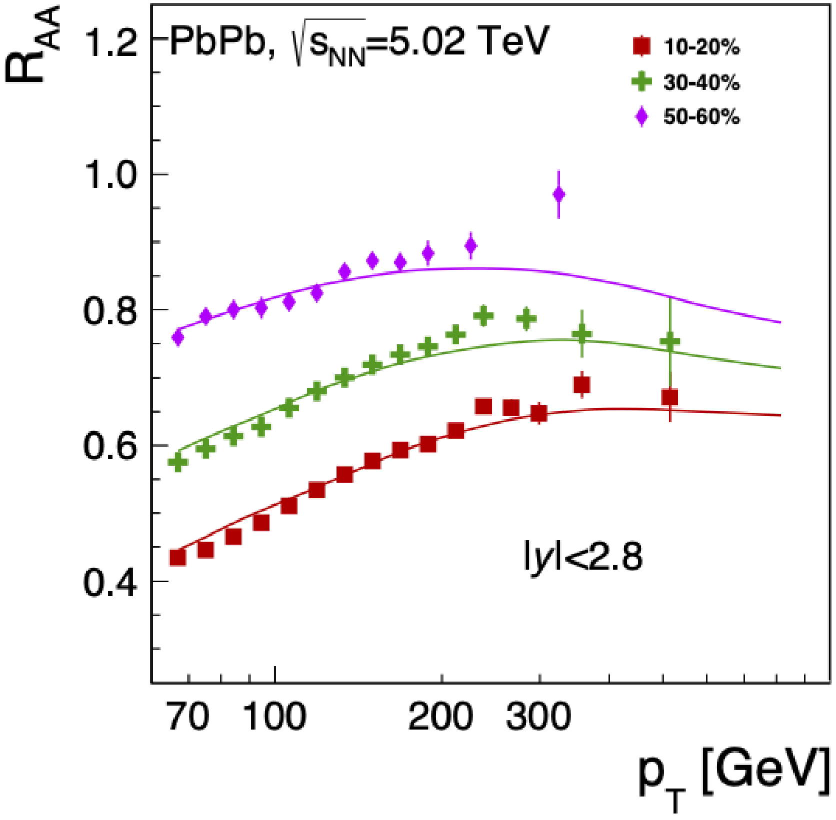
$$\langle \Delta p_{\mathrm{T}}^{\mathrm{jet}} \rangle = \int d\Delta p_{\mathrm{T}}^{\mathrm{jet}} \, \Delta p_{\mathrm{T}}^{\mathrm{jet}} \, w(p_{\mathrm{T}}^{\mathrm{jet}}, \Delta p_{\mathrm{T}}^{\mathrm{jet}})$$

- We assume that energy loss distribution depends only on self-normalized fluctuations, $x \equiv p_{\mathrm{T}}^{\mathrm{jet}} / \langle \Delta p_{\mathrm{T}}^{\mathrm{jet}} \rangle$, see e.g. PRL 122 (2019) 252302.

- Energy loss distribution is parameterized by generalized integrand of gamma function see e.g. LBT papers or work by Brewer et al.

Jet R_{AA}





- Can describe all centrality bins **with single power α=0.27**, c_F=1.78, when including **nPDF effects** and **fluctuations**.

Path-length dependence of energy loss

- Fitted ⟨ΔpT⟩ can be used to **extract path-length** dependence of energy loss.
- Assumption: path-length proportional to **Glauber model** initial conditions.

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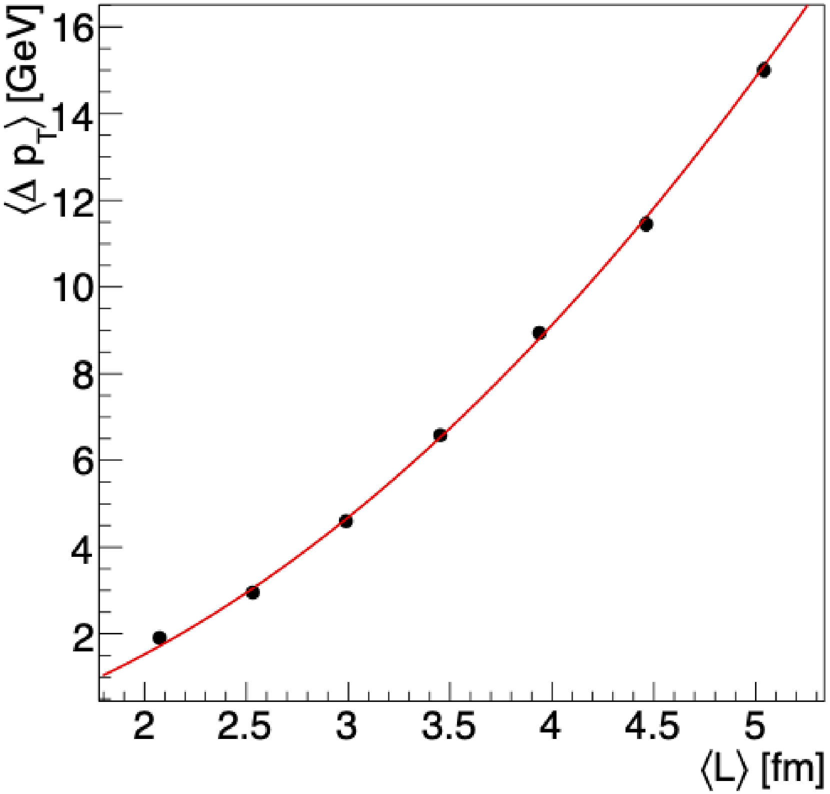

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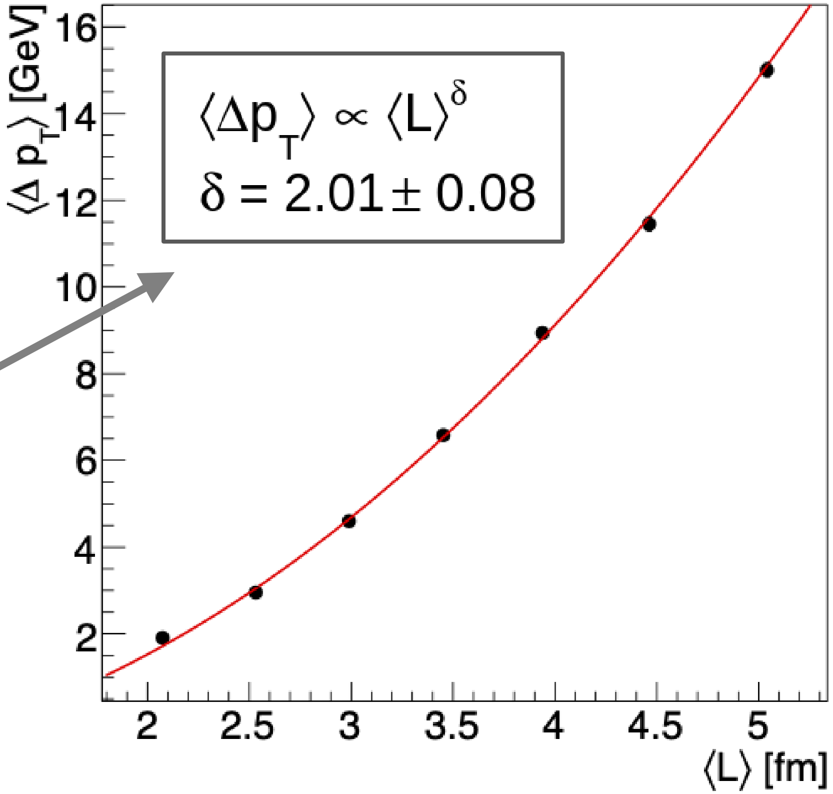
- Fitted ⟨ΔpT⟩ can be used to **extract path-length** dependence of energy loss.
- Assumption: path-length proportional to **Glauber model** initial conditions.
- Fitted exponent strongly supports **quadratic dependence**.
- **Radiative nature** of energy loss under the assumption that expansion does not wash out the original glauber proportionality.



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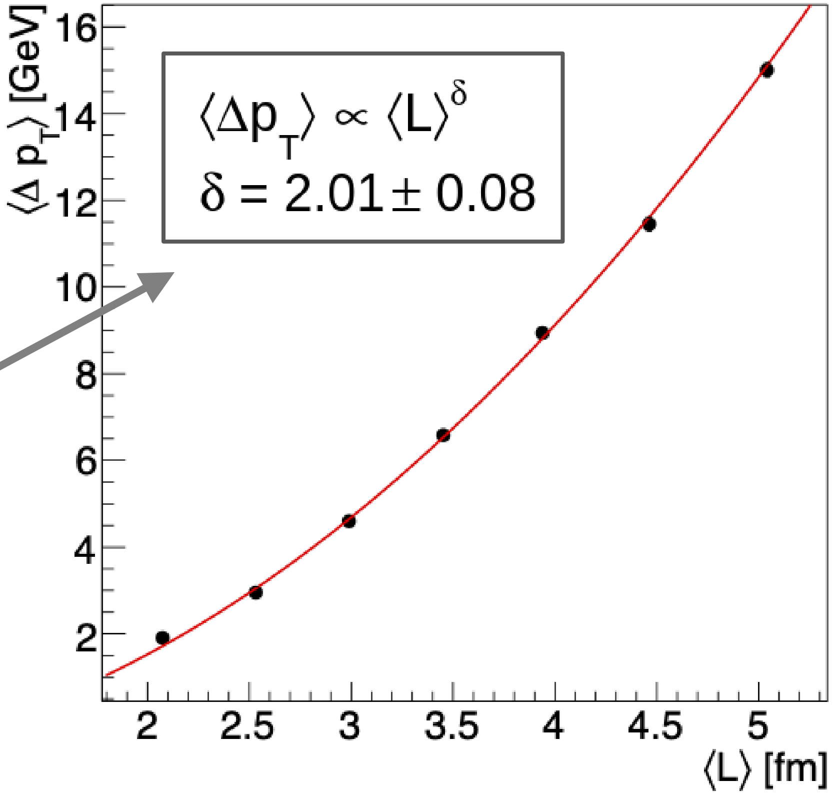
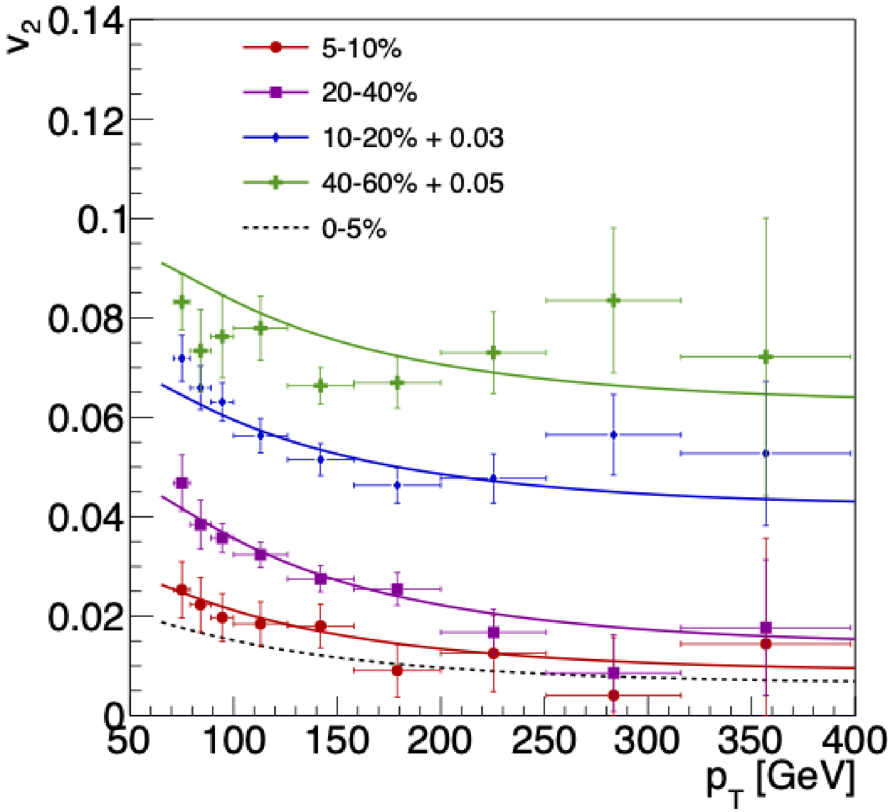


EPJC 82 (2022) 20: For exponential expansion, the difference wrt to static can be fully absorbed to rescaled q-hat

arXiv:2407.11234

Jet v_2



- Can use extracted path-length dependence of energy loss and evaluate **jet v_2**:

$$v_2 \approx \frac{1}{2}\frac{R_{\mathrm{AA}}(L_{in}) - R_{\mathrm{AA}}(L_{out})}{R_{\mathrm{AA}}(L_{in}) + R_{\mathrm{AA}}(L_{out})}$$

$$L_{in} = \langle L \rangle - c \cdot \Delta L_{in}$$
$$L_{out} = \langle L \rangle + c \cdot \Delta L_{out}$$

- Here $\langle L \rangle$, ΔL_{in}, ΔL_{out}, **from Glauber**, *c* is fit constant taking into account **expansion**.
- With *c*=0.35 we can nicely **reproduce all the data** except for 0-5%

=> Consistent picture

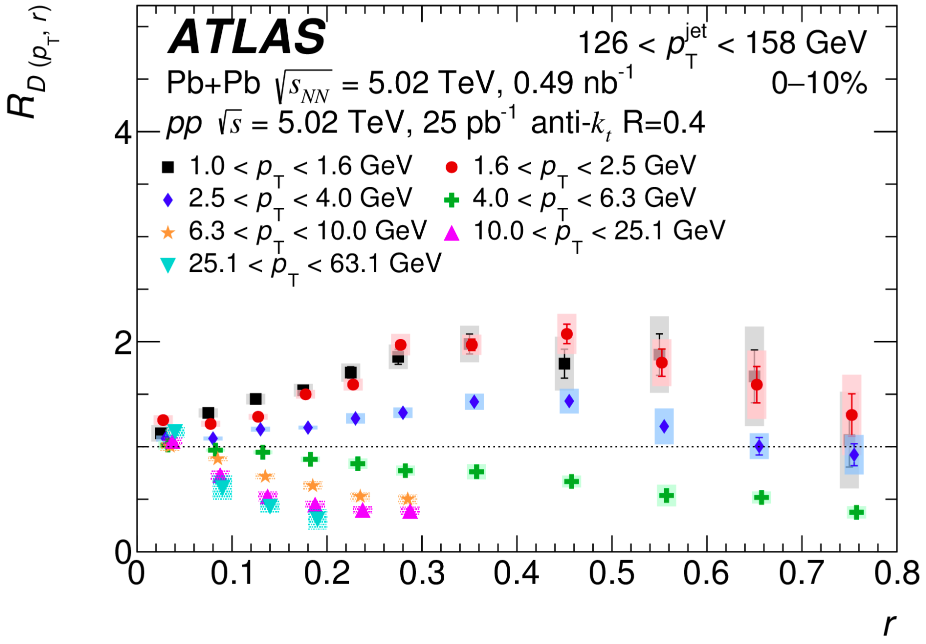
arXiv:2407.11234

Question 2

- Can we repeat the same exercise with quenching MC generators like JEWEL, extract qhat and see how it behaves as a function of Glauber path-length?
- Can we collect more evidence by doing this and establish the overall path-length dependence of energy loss? This should be a “basic question to address” before aiming for more complex questions?

Self criticism

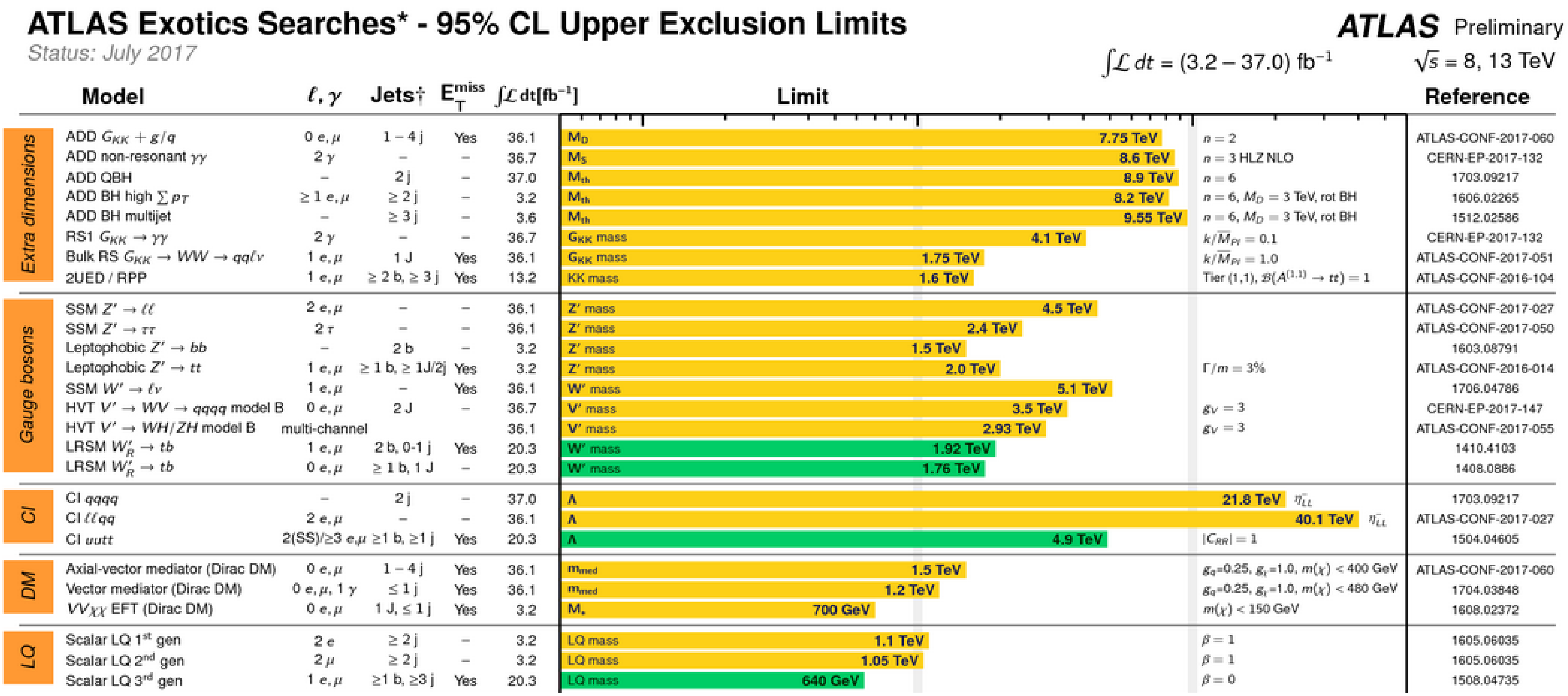
- We published 90+ papers on jet energy loss at the LHC.
- But some of very precise measurements are not used by the theory at all, e.g.:



- Multi-differential jet substructure: differential in centrality, r, particle-pt, jet-pt.
- Published in PRC 100 (2019) 064901 (i.e. 5 years ago).
- Collected nice 41 citations:
  - Experimental work: 10
  - Review: 5
  - Proceedings: 13
  - Theory intro section: 13
  - **Theory results: 0**

- How to avoid that? How to publish that nobody looks? Life-web page with table with models, chi2, and journal reference?

Self criticism



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2017

ATLAS Preliminary

$\int\mathcal{L}\,dt = (3.2 - 37.0)\ \mathrm{fb}^{-1}$

$\sqrt{s} = 8,\ 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Limit			Reference
Extra dimensions	ADD $G_{KK} + g/q$	$0\ e, \mu$	$1-4$ j	Yes	36.1	M_D	7.75 TeV	$n = 2$	ATLAS-CONF-2017-060
	ADD non-resonant $\gamma\gamma$	$2\ \gamma$	–	–	36.7	M_S	8.6 TeV	$n = 3$ HLZ NLO	CERN-EP-2017-132
	ADD QBH	–	2 j	–	37.0	M_{th}	8.9 TeV	$n = 6$	1703.09217
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	3.2	M_{th}	8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th}	9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	$2\ \gamma$	–	–	36.7	G_{KK} mass	4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	CERN-EP-2017-132
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	$1\ e, \mu$	1 J	Yes	36.1	G_{KK} mass	1.75 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2017-051
	2UED / RPP	$1\ e, \mu$	≥ 2 b, ≥ 3 j	Yes	13.2	KK mass	1.6 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	ATLAS-CONF-2016-104
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	36.1	Z' mass	4.5 TeV		ATLAS-CONF-2017-027
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	36.1	Z' mass	2.4 TeV		ATLAS-CONF-2017-050
	Leptophobic $Z' \to bb$	–	2 b	–	3.2	Z' mass	1.5 TeV		1603.08791
	Leptophobic $Z' \to tt$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	3.2	Z' mass	2.0 TeV	$\Gamma/m = 3\%$	ATLAS-CONF-2016-014
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	36.1	W' mass	5.1 TeV		1706.04786
	HVT $V' \to WV \to qqqq$ model B	$0\ e, \mu$	2 J	–	36.7	V' mass	3.5 TeV	$g_V = 3$	CERN-EP-2017-147
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass	2.93 TeV	$g_V = 3$	ATLAS-CONF-2017-055
	LRSM $W'_R \to tb$	$1\ e, \mu$	2 b, 0-1 j	Yes	20.3	W' mass	1.92 TeV		1410.4103
	LRSM $W'_R \to tb$	$0\ e, \mu$	≥ 1 b, 1 J	–	20.3	W' mass	1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	37.0	Λ	21.8 TeV η^-_{LL}		1703.09217
	CI $\ell\ell qq$	$2\ e, \mu$	–	–	36.1	Λ	40.1 TeV η^-_{LL}		ATLAS-CONF-2017-027
	CI $uutt$	2(SS)/$\geq$3 e,μ	$\geq$1 b, $\geq$1 j	Yes	20.3	Λ	4.9 TeV	$\lvert C_{RR}\rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	$0\ e, \mu$	$1-4$ j	Yes	36.1	m_{med}	1.5 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 400$ GeV	ATLAS-CONF-2017-060
	Vector mediator (Dirac DM)	$0\ e, \mu$, $1\ \gamma$	≤ 1 j	Yes	36.1	m_{med}	1.2 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 480$ GeV	1704.03848
	$VV\chi\chi$ EFT (Dirac DM)	$0\ e, \mu$	1 J, ≤ 1 j	Yes	3.2	M_*	700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	$2\ e$	≥ 2 j	–	3.2	LQ mass	1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	$2\ \mu$	≥ 2 j	–	3.2	LQ mass	1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	$1\ e, \mu$	$\geq$1 b, $\geq$3 j	Yes	20.3	LQ mass	640 GeV	$\beta = 0$	1508.04735

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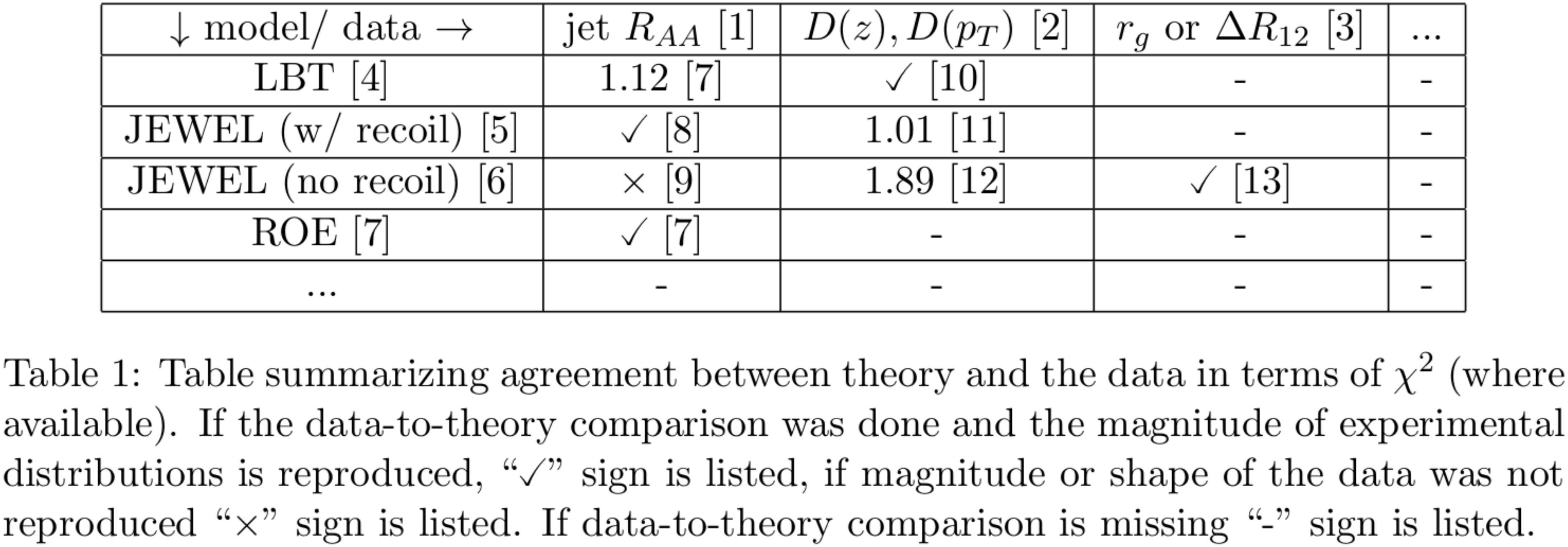
Self criticism



↓ model/ data →	jet R_{AA} [1]	$D(z), D(p_T)$ [2]	r_g or ΔR_{12} [3]	...
LBT [4]	1.12 [7]	✓ [10]	-	-
JEWEL (w/ recoil) [5]	✓ [8]	1.01 [11]	-	-
JEWEL (no recoil) [6]	× [9]	1.89 [12]	✓ [13]	-
ROE [7]	✓ [7]	-	-	-
...	-	-	-	-

Table 1: Table summarizing agreement between theory and the data in terms of χ^2 (where available). If the data-to-theory comparison was done and the magnitude of experimental distributions is reproduced, "✓" sign is listed, if magnitude or shape of the data was not reproduced "×" sign is listed. If data-to-theory comparison is missing "-" sign is listed.

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- We keep publishing new stuff. And keep forgetting the old one.

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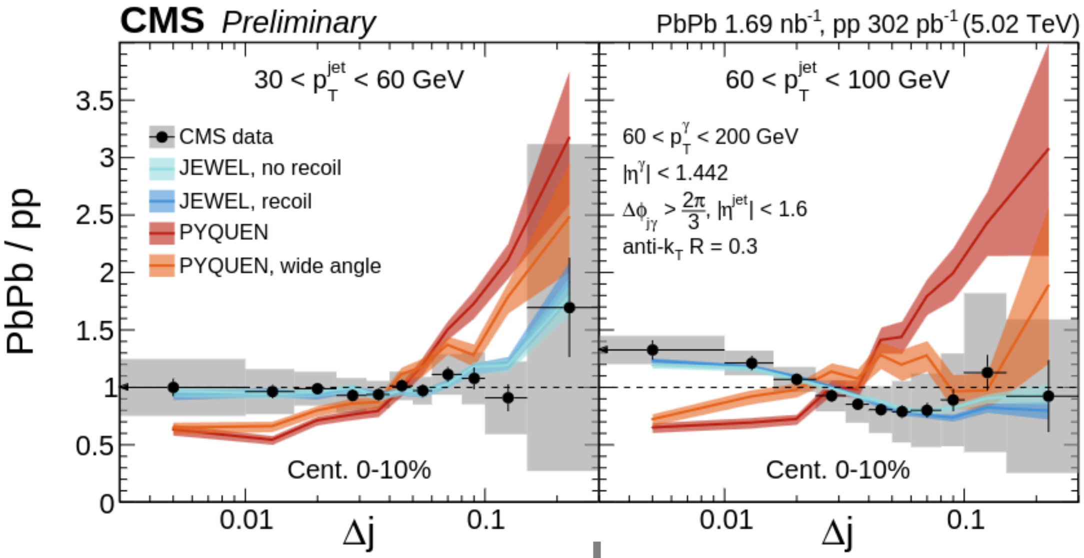

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CMS-PAS-HIN-21-019

Why the difference between WTA and E-scheme axes is a better observable than any of previously studied substructure observables or full fragmentation functions that directly quantify large angle scattering effects?

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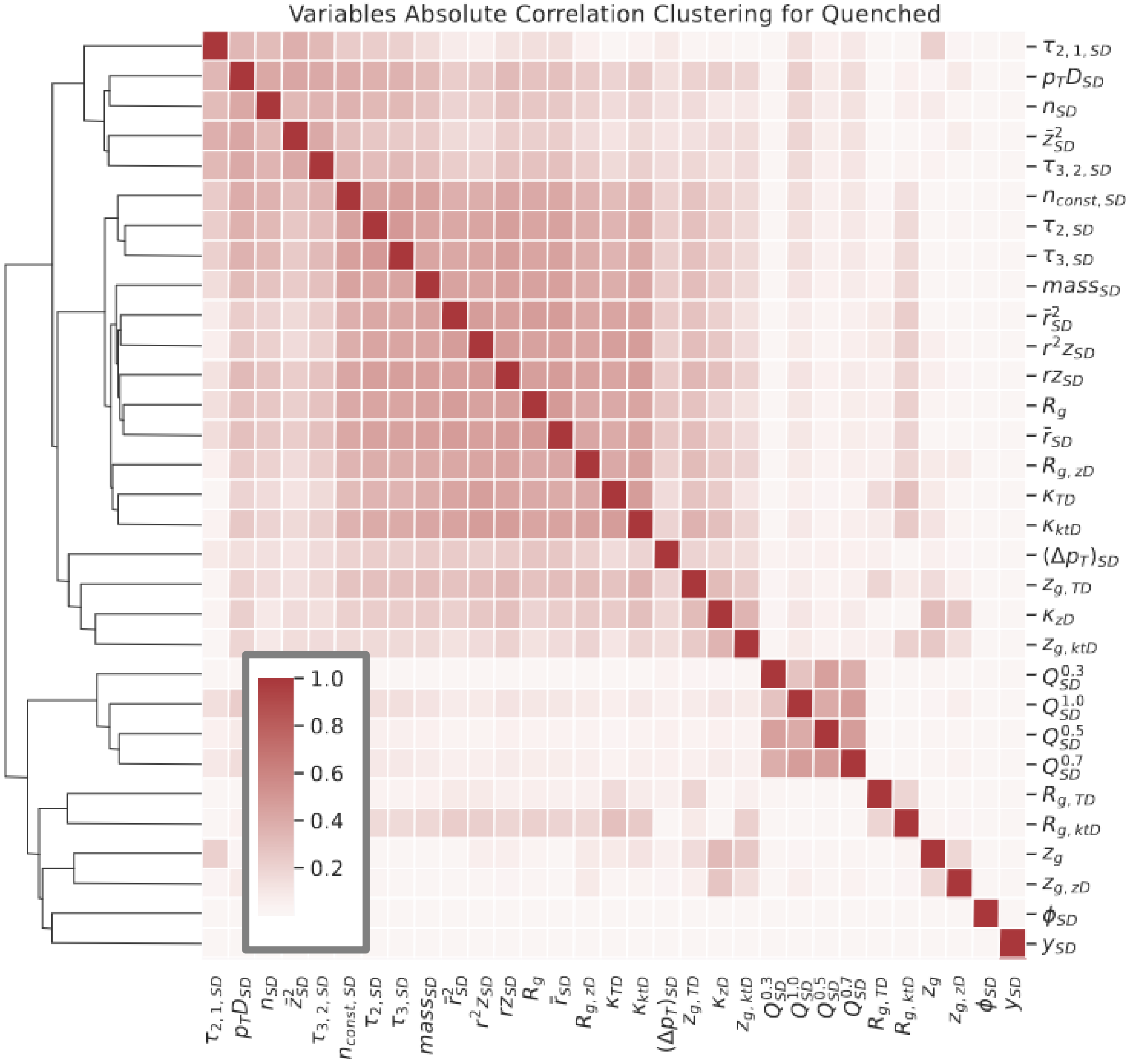

Variables Absolute Correlation Clustering for Quenched

- We keep publishing new stuff. And keep forgetting the old one.
- Also, quite a lot of observables (esp. substructure observables) are correlated (see SciPost Phys. 16 (2024) 015)
- Question: How to avoid running in circles? Perhaps we should keep evaluating correlations for each new observable (web page?).

Summary of questions

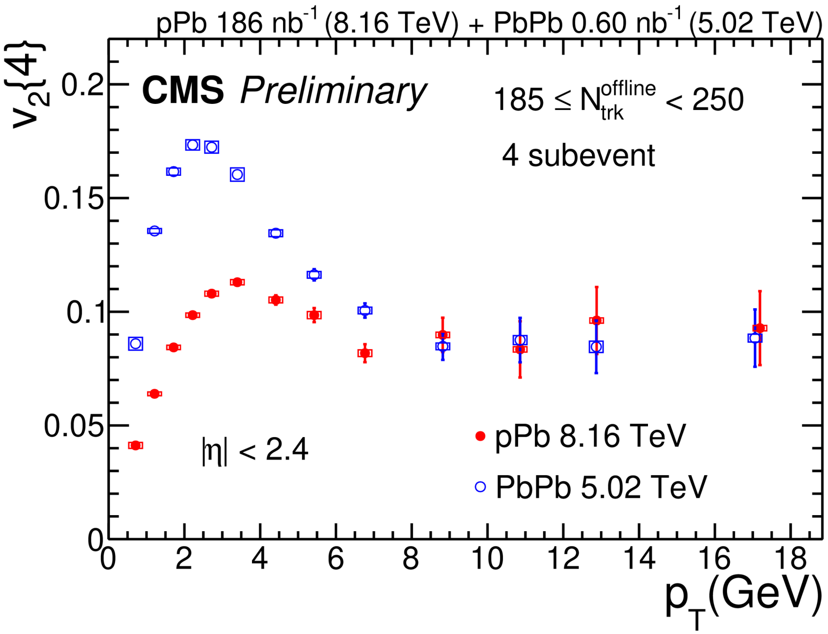
- The dijet measurement and path-length sensitive observables: **what new do we need to measure**? Some quantities proposed.
- Can we collect more evidence for L^2 dependence of energy loss by repeating the evaluation of ⟨ΔpT⟩(L) **with quenching MC generators** like JEWEL?
- How to avoid that theory keeps ignoring some of precise experimental data? **Life-web page with table with models**, chi2, and journal reference?
- How to avoid running in circles in the experiment? Perhaps we should keep evaluating correlations for each new observable. Again, some live web page?

This work was supported by ERC-CZ grant LL2327

Backup

High-pt v2 and energy loss

CMS-PAS-HIN-23-002

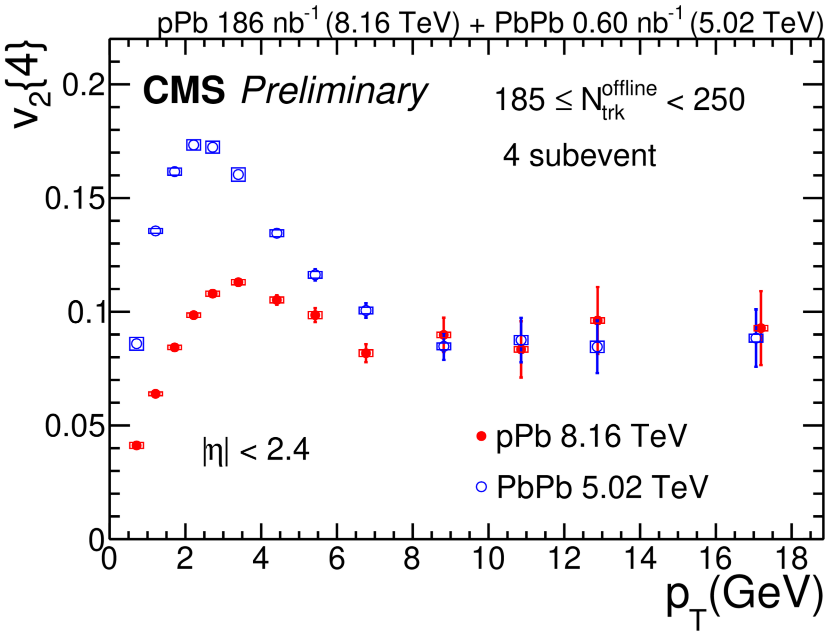


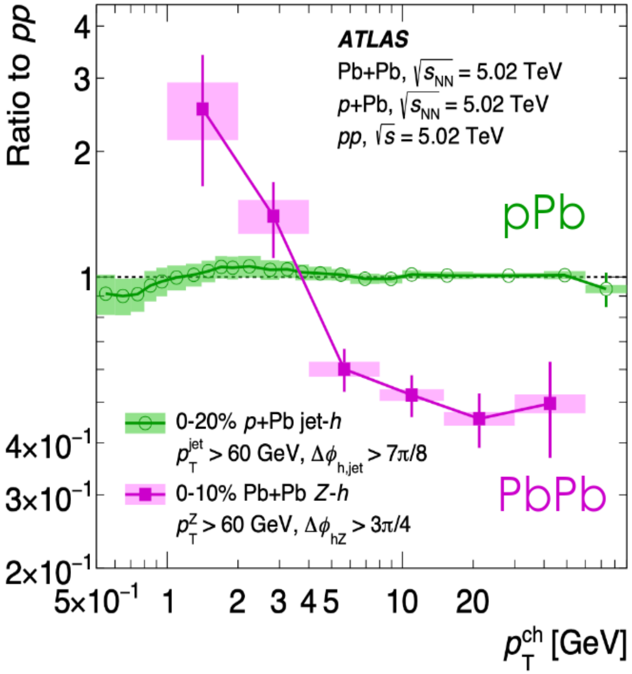
- **Charged particle v2** at high-pt consistent between p+Pb and Pb+Pb, but no energy loss seen in p+Pb => puzzle?

High-pt v2 and energy loss

CMS-PAS-HIN-23-002

PRL 131 (2023) 072301





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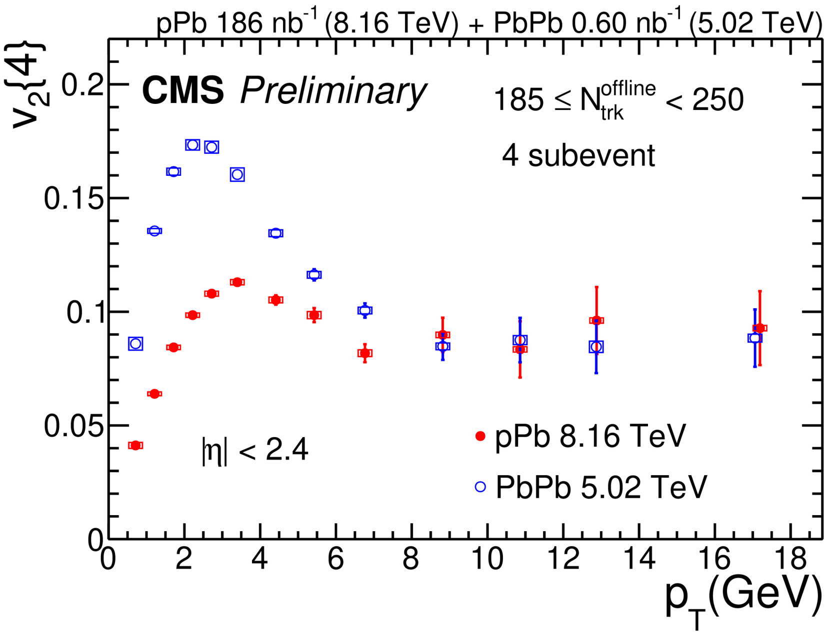
Measured p+Pb to pp ratio of **yields of hadrons** produced opposite the jet.

High-pt v2 and energy loss

CMS-PAS-HIN-23-002



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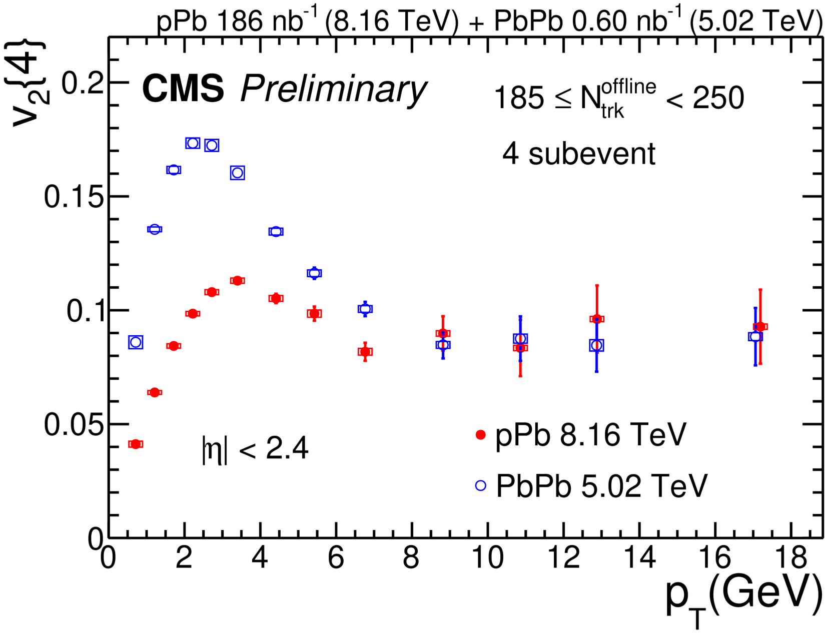
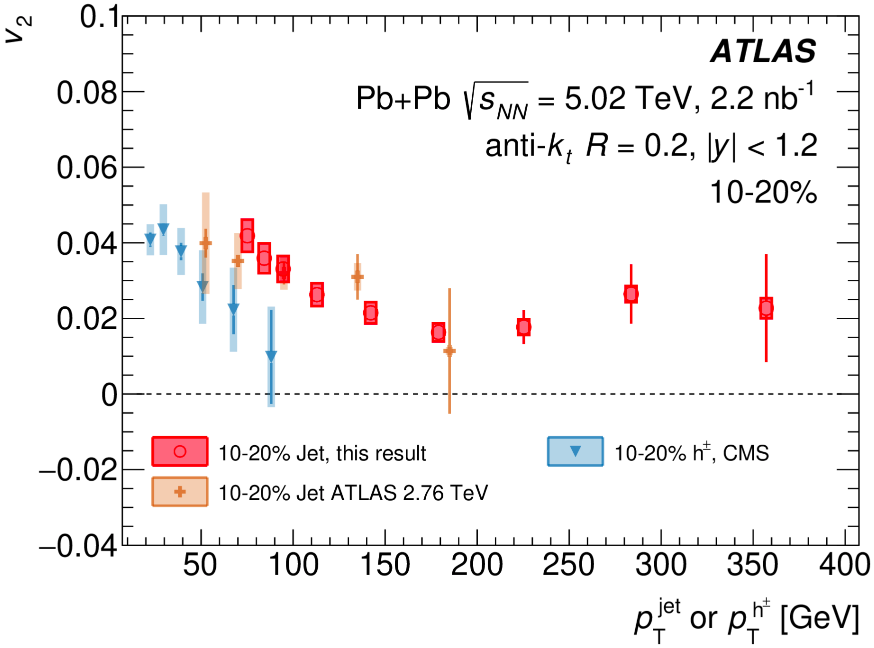
High-pt v2 and energy loss

CMS-PAS-HIN-23-002



PRC 105 (2022) 064903



- **Charged particle v2** at high-pt consistent between p+Pb and Pb+Pb, but no energy loss seen in p+Pb => puzzle?
- Non-zero **jet v2** measured **up to high jet pt** in Pb+Pb => natural would be to measure jet v2 in p+Pb as well … but biases by soft-hard correlations?

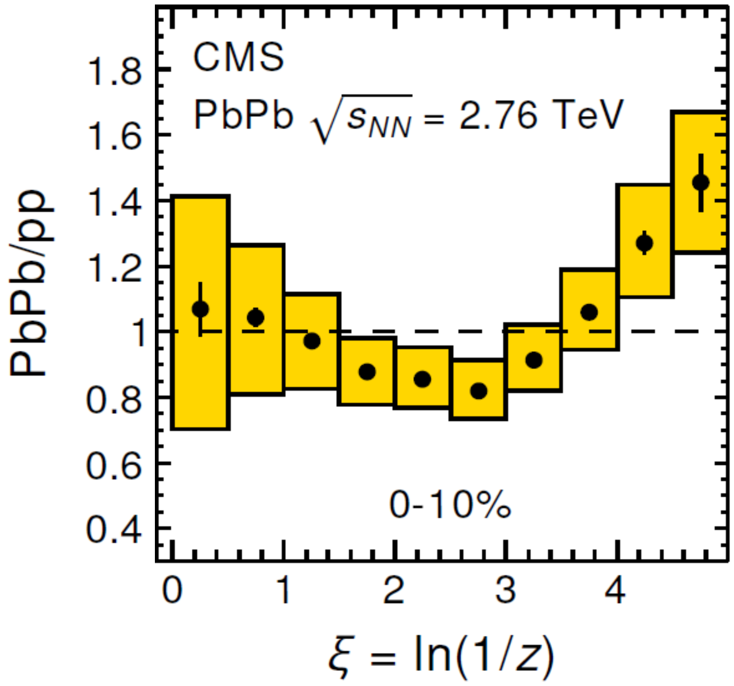
Question

- Can we learn something more from MC here?
  Is there any MC that would allow us to study various aspects of this difference?

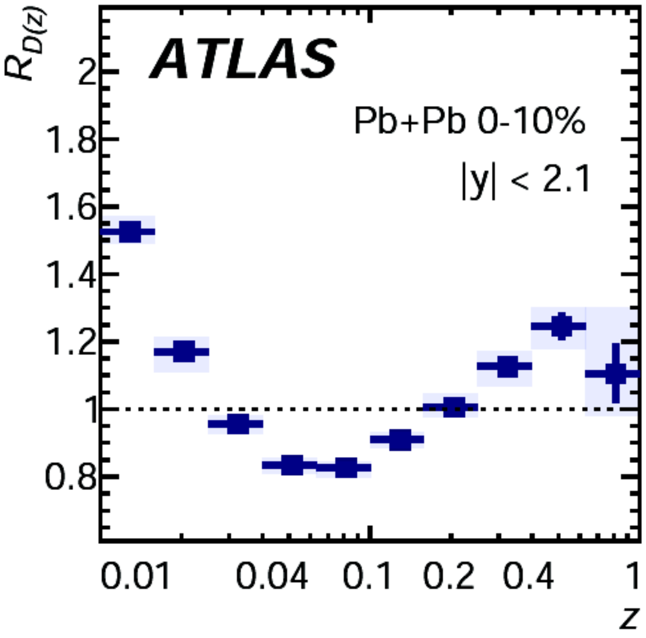
Backup II.

Color coherence: evidence in data?

- Early fuzzy evidence for color coherence: Significant suppression of jet production seen, but jet fragmentation was not drastically modified ...



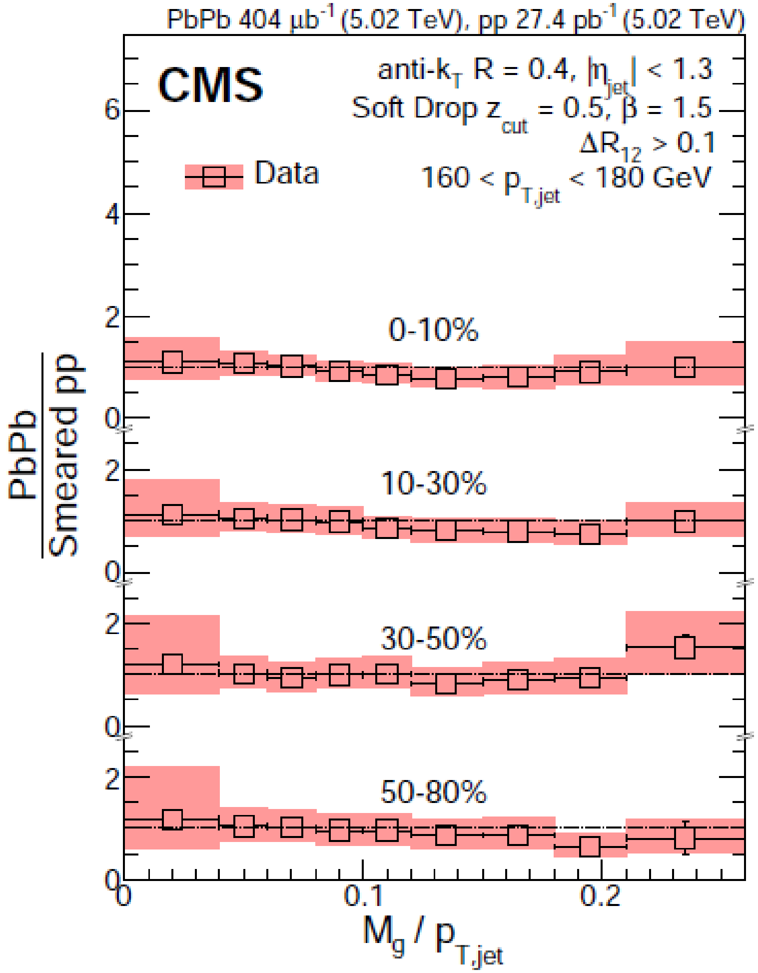
PRC 90 (2014) 024908



EPJC 77 (2017) 379
PRC C 98 (2018) 024908

Color coherence: evidence in data?

- Groomed **jet mass** measurement.
- Jet mass is sensitive to the angular structure of jets.
- When removing large angle soft radiation by grooming, **no modifications** are seen.
- (More on mass later)



JHEP 10 (2018) 161

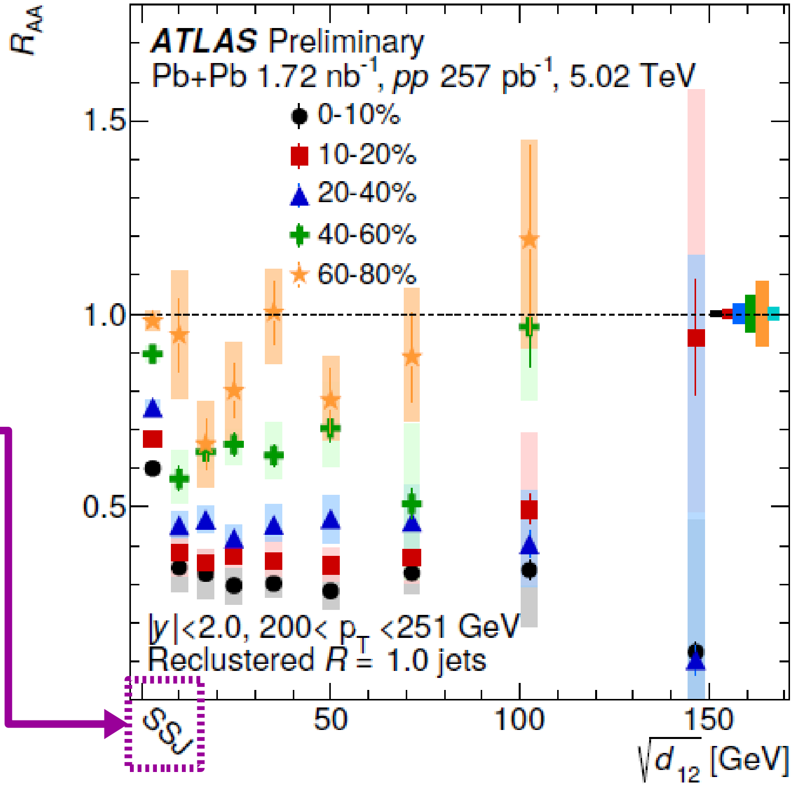
Color coherence: evidence in data?

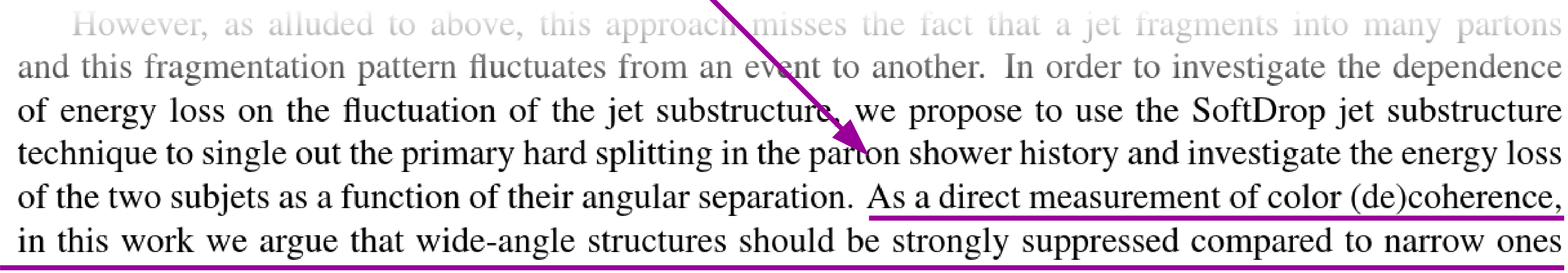
ATLAS-CONF-2019-056

- Measurement of large-*R* jets reclustered from *R*=0.2 jets.
- Measurement done as a function of **splitting scale**,

$$\sqrt{d_{12}} = \min(p_{T,1}, p_{T,2}) \cdot \Delta R_{12}$$

- Jets with **one prong** structure clearly less suppressed than the rest.
- An effect expected due to color coherence (see NPA 967 (2017) 564).





However, as alluded to above, this approach misses the fact that a jet fragments into many partons and this fragmentation pattern fluctuates from an event to another. In order to investigate the dependence of energy loss on the fluctuation of the jet substructure, we propose to use the SoftDrop jet substructure technique to single out the primary hard splitting in the parton shower history and investigate the energy loss of the two subjets as a function of their angular separation. As a direct measurement of color (de)coherence, in this work we argue that wide-angle structures should be strongly suppressed compared to narrow ones

Color coherence: evidence in data?

ATLAS-CONF-2019-056

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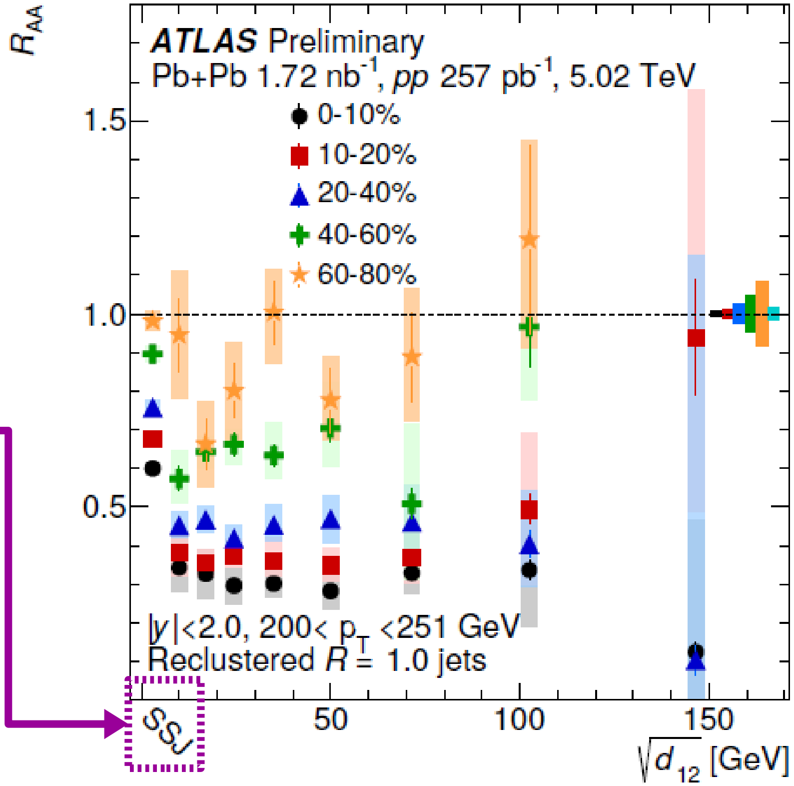
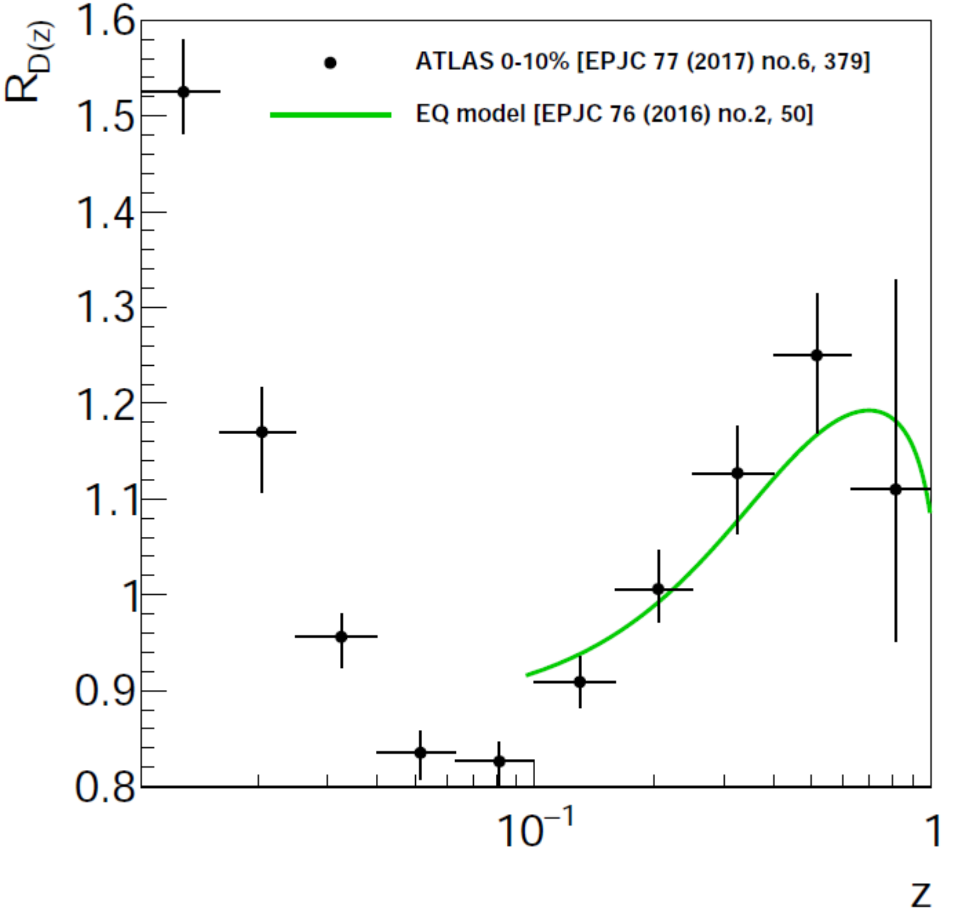
- … but not the only interpretation.



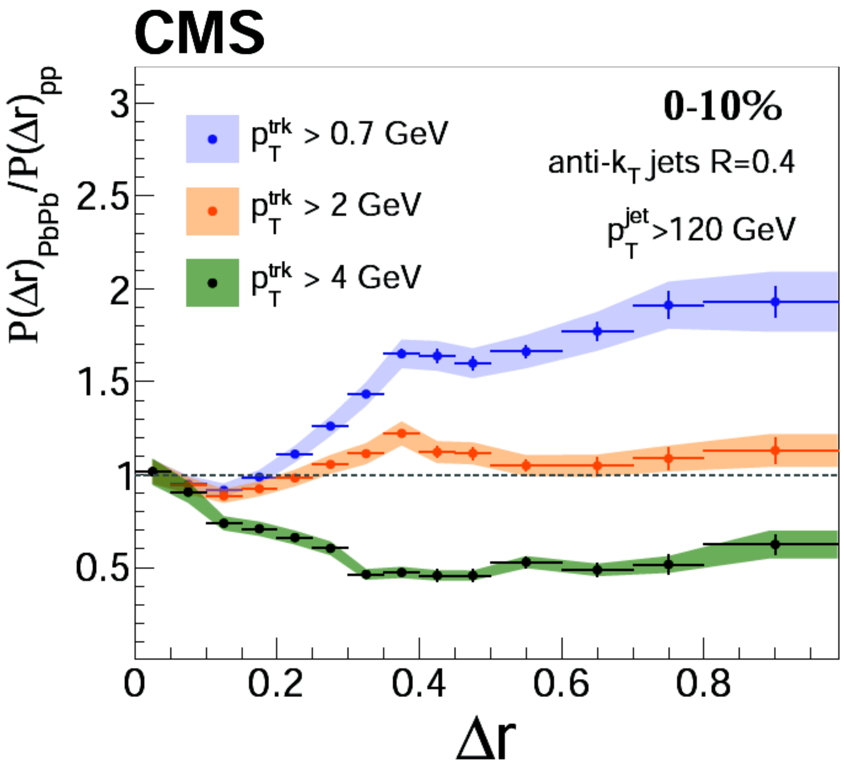
Color coherence: evidence in data?

- **Longitudinal** jet structure – fragmentation functions.
- Enhancement at **large *z*** and depletion at **intermediate *z*** can be largely explained as a consequence of color charge dependent coherent energy loss.
- … but again not the only explanation.

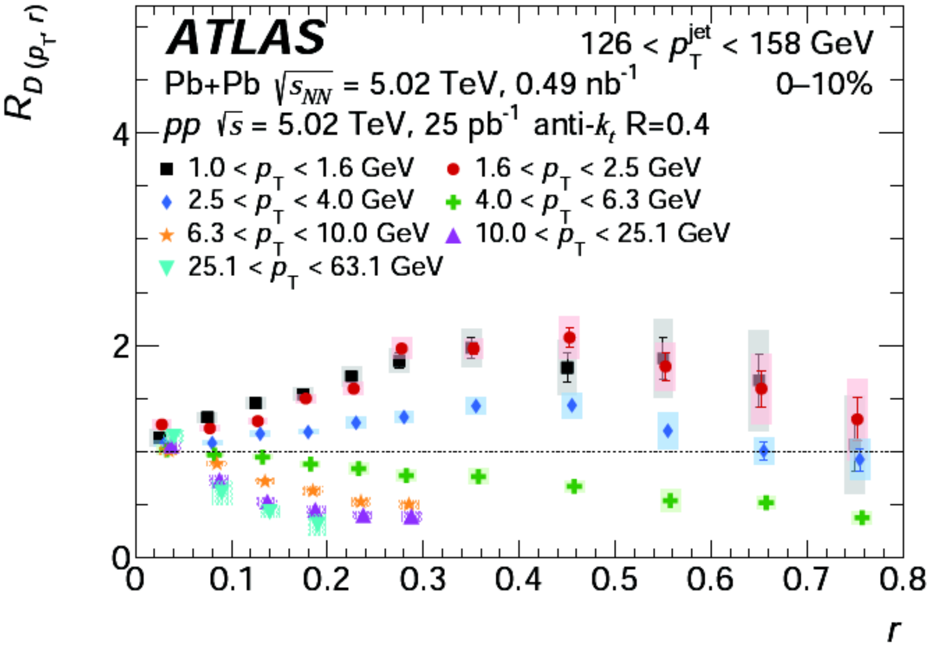


Color coherence: evidence in data?

- **Transverse** structure of jet – jet shape (cf. PRL 69 (1992) 3615).
- Data seem to suggest that the coherence angle is small, $\theta_0 \sim 0.1$, although some part of structures may be due to different energy loss of q/g.



JHEP 05 (2018) 006



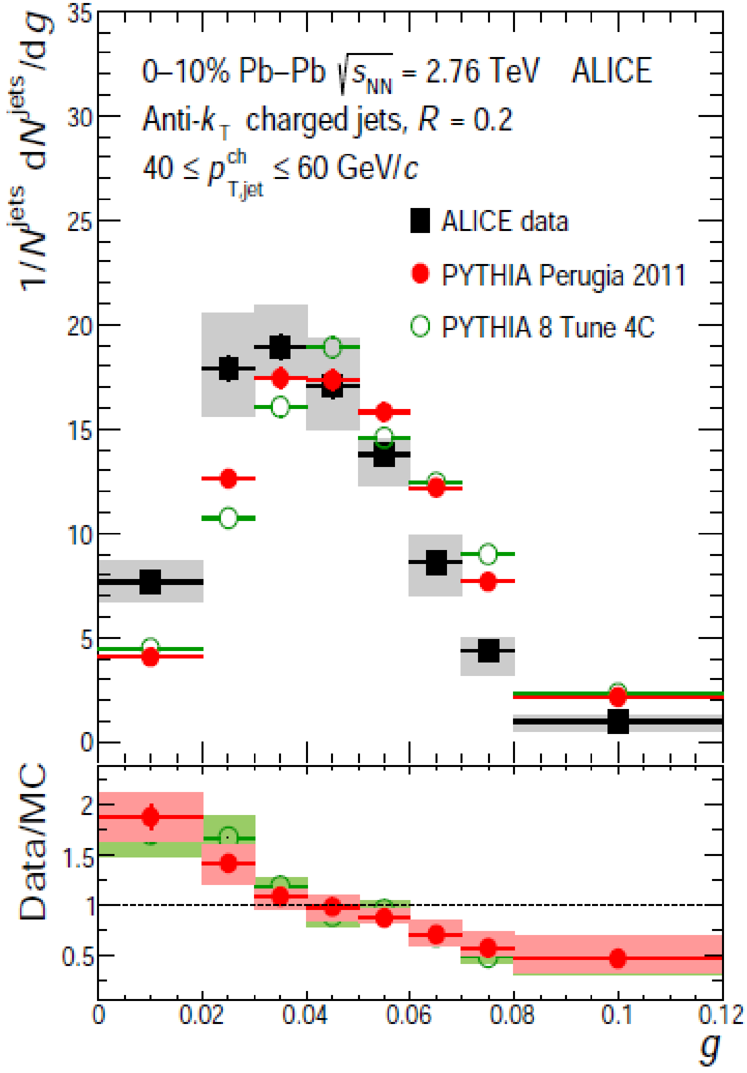
PRC 100 (2019) 064901

Color coherence: evidence **against** in data?

- Groomed jet mass unmodifed, but other substructure observables show significant modifications.
- One example is **girth** = first moment of previously discussed jet shape:

$$g = \sum_{i \in \mathrm{jet}} \frac{p_{\mathrm{T},i}}{p_{\mathrm{T,jet}}} \Delta R_{\mathrm{jet},i}$$

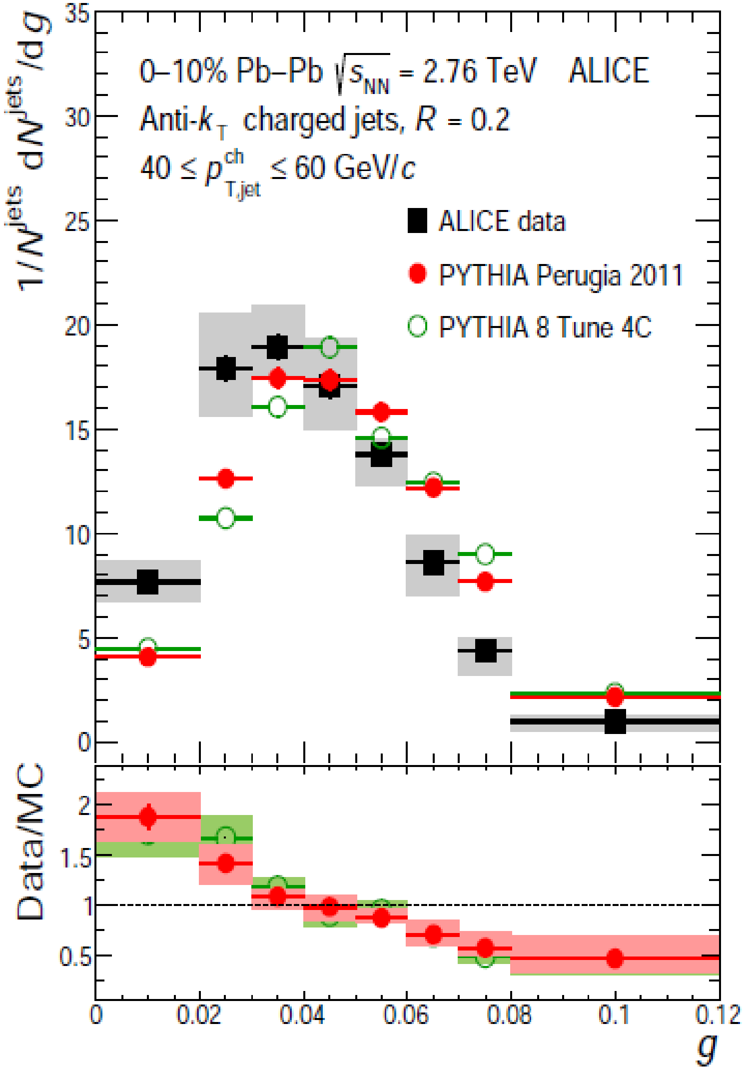
- **Narrowing** of jets is observed.
- **Qualitative** arguments in JHEP 10 (2018) 161 say that data speaks against the coherent energy loss – but difficult...



JHEP 10 (2018) 161

Color coherence: evidence **against** in data?

- Qualitative arguments are difficult because:
  - **Observables evolve** with jet p_T and depend on initial parton **color charge** => in general ratios cannot be expected to be unity.
  - Some observables are sensitive to enhancement of **soft particles** present due to quenching
  - Some observables **simplify** the complex structure too much, e.g. girth is just a 1^{st} moment of jet shape. Then important details may be averaged out (we already know the full jet shape distribution).
- => Interpretation requires deeper analysis taking various effects into account **quantitatively**.



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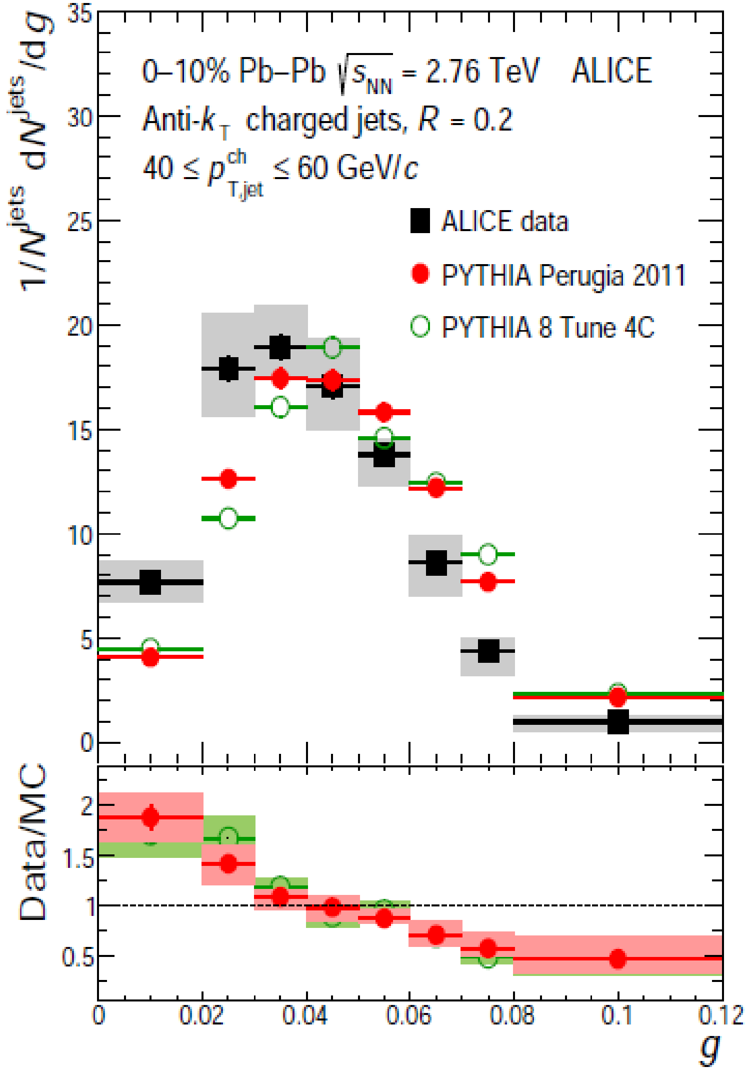
Why to interpret first moment when we have the full energy flow distribution available?



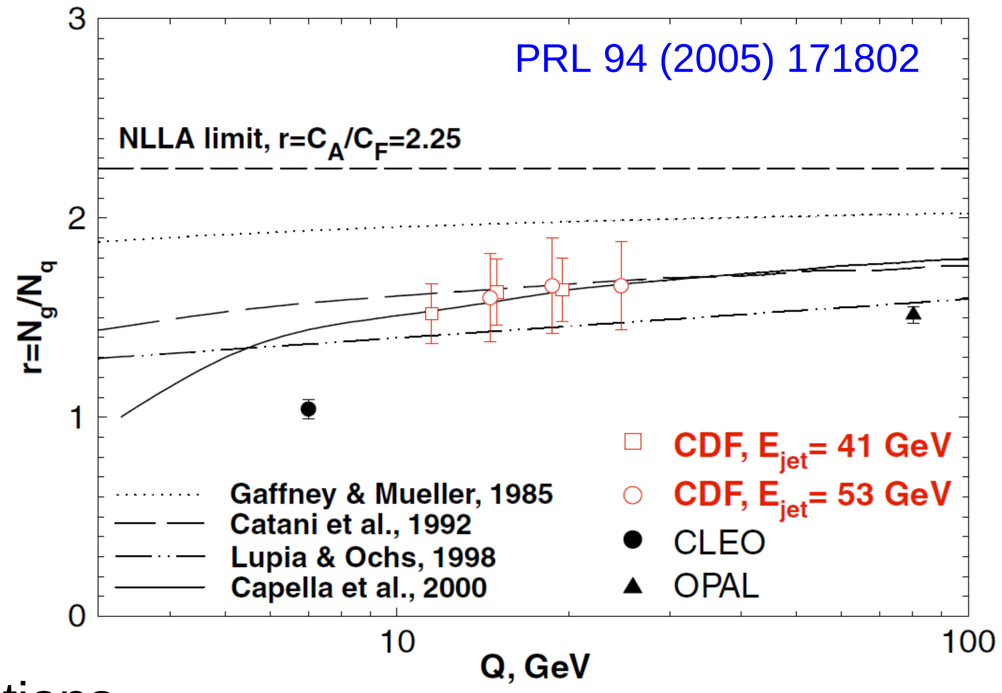
JHEP 10 (2018) 161

Color coherence: summary

- Evidence for color coherence seems to be present in the data ...
  - But radiation is not *fully* coherent.
  - Data give estimate on coherence angle, $\theta_0 \sim 0.1$, at $p_T \sim 100$ GeV.
- Direct interpretation of substructure observables is diffcult, since:
  - Some observables are sensitive to initial-parton p_T, color-factor and soft enhancement which can make ratio different from 1 even for fully coherent energy loss.
  - Some observables “oversimplify” the complex structure.
- Way forward ?
  - Have color coherence as a regime available in MC generators.
  - Test color coherence against a large set of existing data and:
    - report where it fails,
    - estimate kinematic range where it works.
  - Understand the sensitivity of a observables to above mentioned effects.

Role of color-factor

- Difference between radiation of quark-initiated and gluon-initiated showers quantified in vacuum
- Ratio of multiplicities = = “color factor”, here c_F.
- In vacuum, c_F is equal to:
  - $C_A/C_F = 2.25$ from NLLA
  - ~ 1.7 from measurement
  - ~ 1.7-1.8 from 3NLO calculations



- In medium:
  - Often C_A/C_F value used for c_F
  - Extracted in PLB 767 (2017) 10 to be $c_F = 1.78 \pm 0.12$
  - Extracted in EPJC 80 (2020) 6, 586 to be $c_F = 1.6\text{-}1.7$ (with small p_T dependence)

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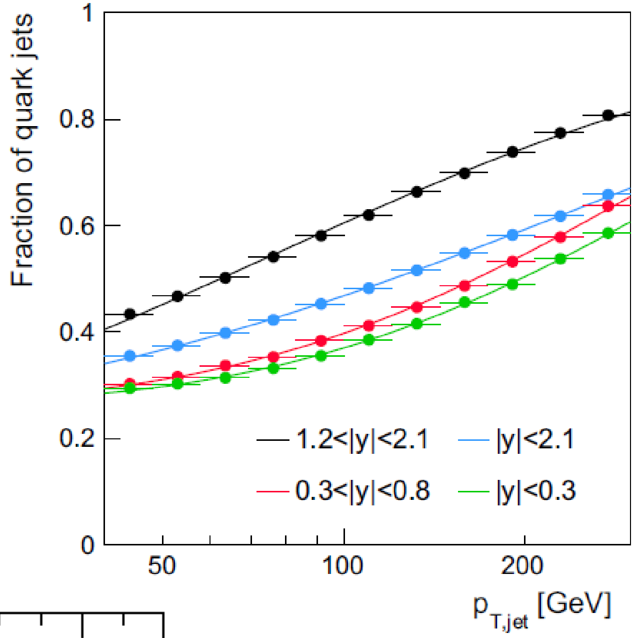
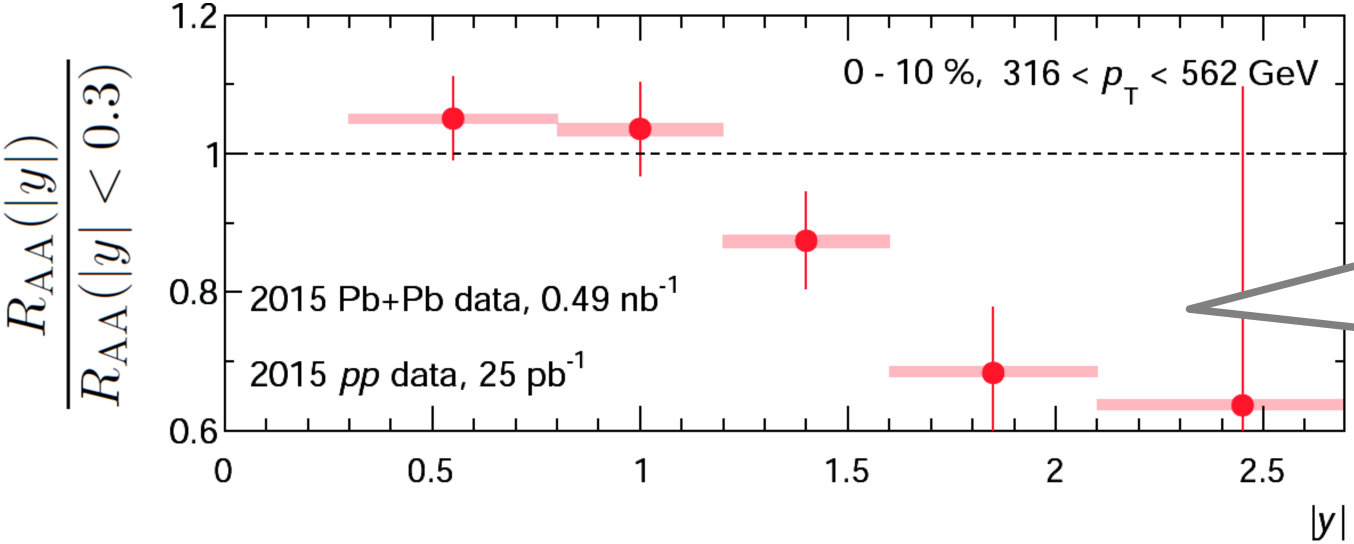
Two different analyses arrived at the same value which is consistent with the in-vacuum calculations

Evidence for **color factor** in data?

- q/g fraction as well as steepness of the spectra evolve significantly with rapidity
- R_{AA} is sensitive to c_F value (c.f. analysis in EPJC 76 (2016) 2, 50)
- In particular sensitive should be the R_{AA} in the forward region which shows trends expected from c_F != 1.

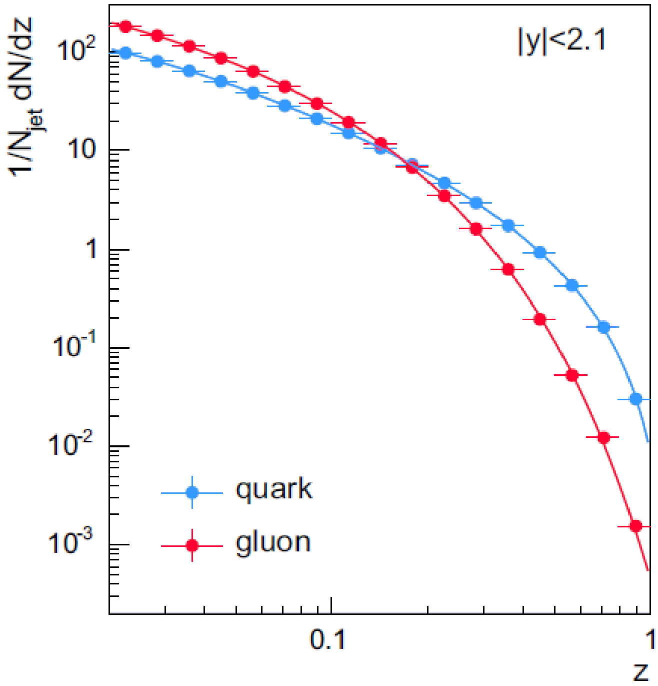


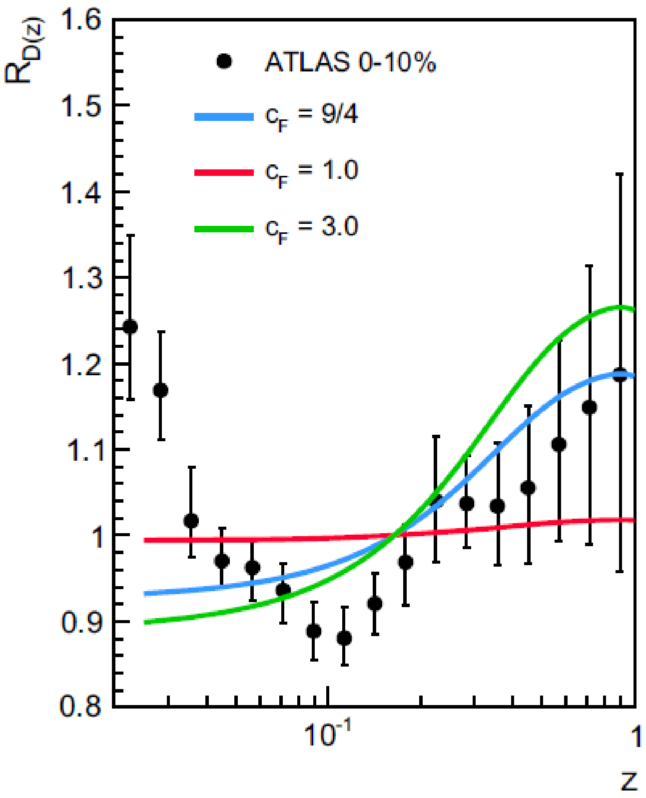


At high p_T, decreasing R_{AA} in the forward region

Evidence for **color factor** in data?

- Fragmentation functions different for q/g jets + q/g fractions evolve with p_T.

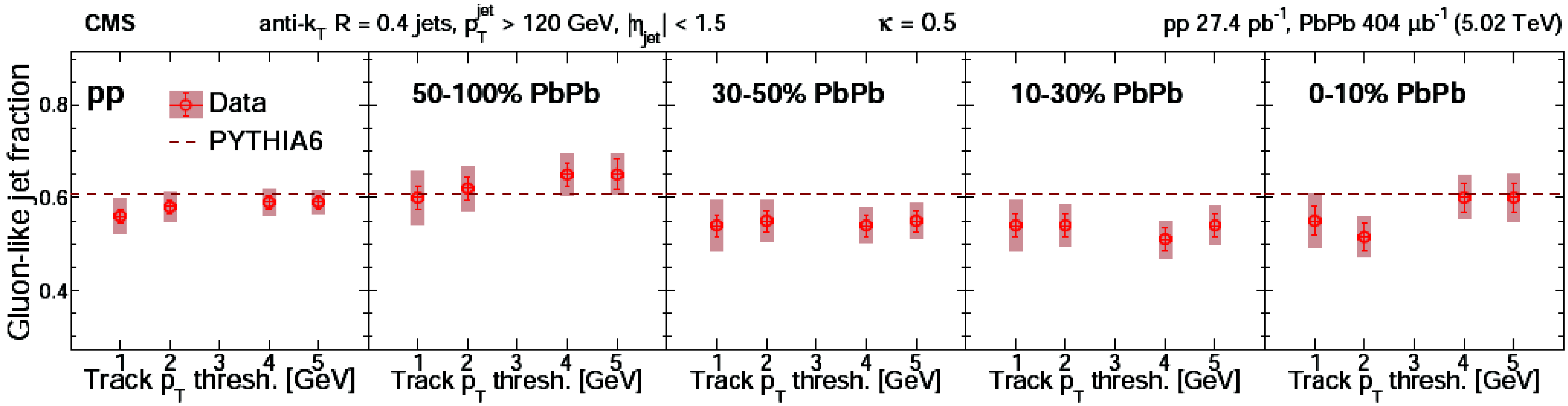




- High-z enhancement can be naturally explained as a consequence of different radiation of q and g jets
- … but not the only explanation

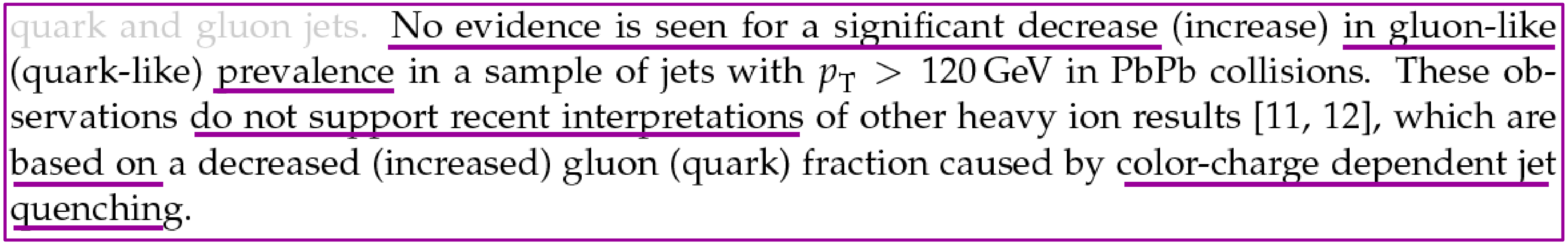
EPJC 76 (2016) 2, 50

Evidence **against** **color factor** in data?



- Jet charge $$Q^\kappa = \frac{1}{(p_{\mathrm{T}}^{\mathrm{jet}})^\kappa} \sum_{i\in \mathrm{jet}} q_i {p_{\mathrm{T},i}}^\kappa$$ JHEP 07 (2020) 115

  and **gluon-like jet fraction** extracted from the data … **data match PYTHIA**.
- Conclusion from the paper:

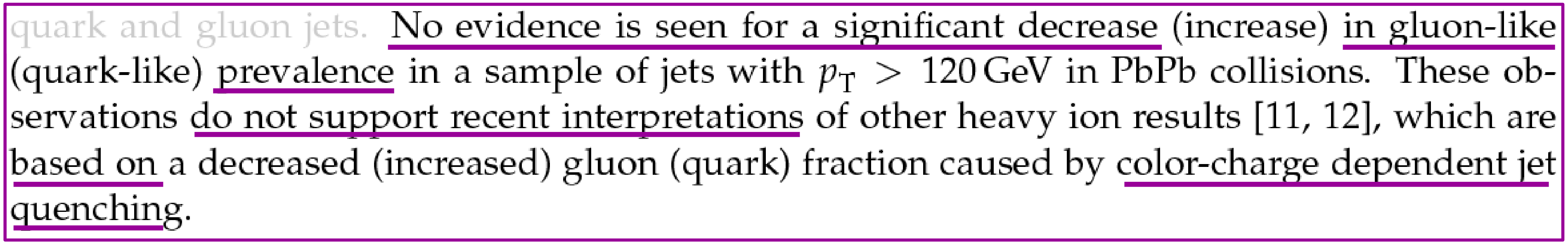

quark and gluon jets. No evidence is seen for a significant decrease (increase) in gluon-like (quark-like) prevalence in a sample of jets with $p_{\mathrm{T}} > 120\,\mathrm{GeV}$ in PbPb collisions. These observations do not support recent interpretations of other heavy ion results [11, 12], which are based on a decreased (increased) gluon (quark) fraction caused by color-charge dependent jet quenching.

Evidence **against** **color factor** in data?

Perhaps too strong statement since it is not quantitative.
We know that:

- q/g fraction evolves only slowly with p_T (slide 16)
- c_F is < C_A/C_F and it is the same in pp and Pb+Pb (slide 15)

=> More quantitative analyses are needed to understand the sensitivity of the jet charge



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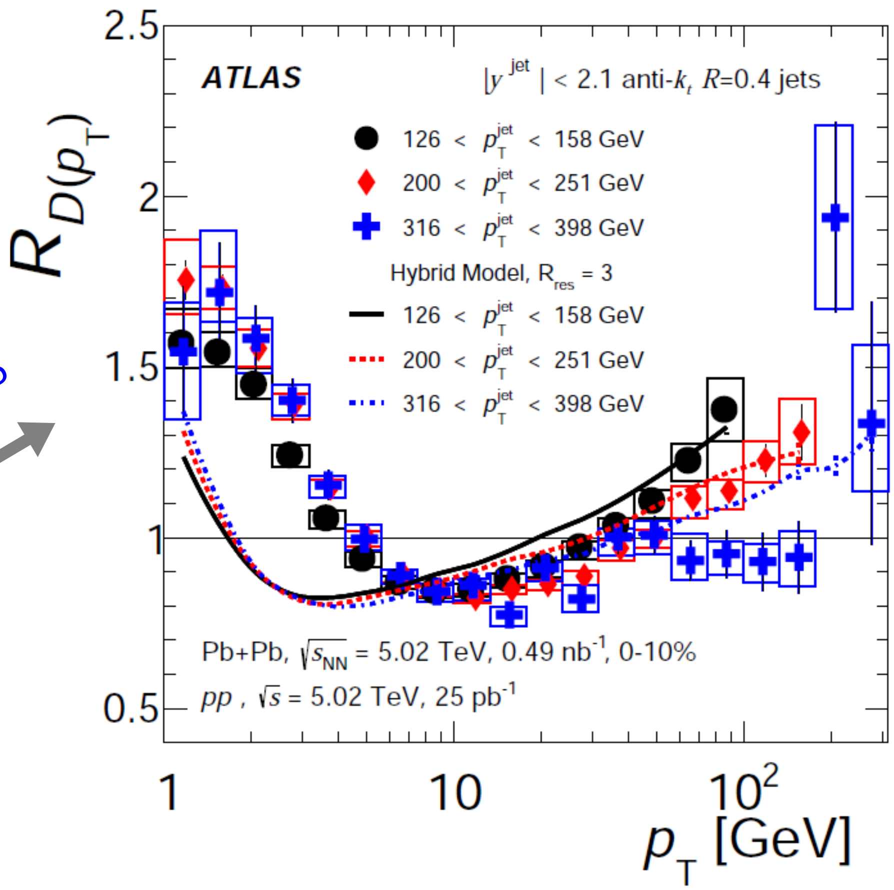
Color factor: summary

- Phenomenological analyses suggest that the Casimir scaling (c_F=2.25) is broken and c_F is ~ 1.7 which is similar to the value reported in the vacuum case.
- Data on R_{AA} and fragmentation seem to support these findings.
- Data on jet charge may contradict this picture, but more detailed analysis is needed to draw a quantitative conclusion
- What we could do?
  - Test theory against forward jet R_{AA} and e.g. FF simultaneously.
  - Test theory against recent jet charge measurement.
  - Measure jet charge in gamma-jet or Z-jet system.

Color vs width

- Many times it was said „this is not the only interpretation“ ...
- Basic questions: What is driving modifications of jet internal structure – color factor or a width of jet?
  - That is: „**Gluon-initiated jets** lose more energy.“
    vs.
    „**Wider jets** lose more energy.“
- Color coherence is surely not the only mechanism behind jet quenching
  => likely both are important, depending on the kinematic regime, fluctuations, etc.
- For example, the **Hybrid model** also successful in describing high-z excess seen in the fragmentation functions.
- => How to **distinguish** between width vs color?

Color vs width

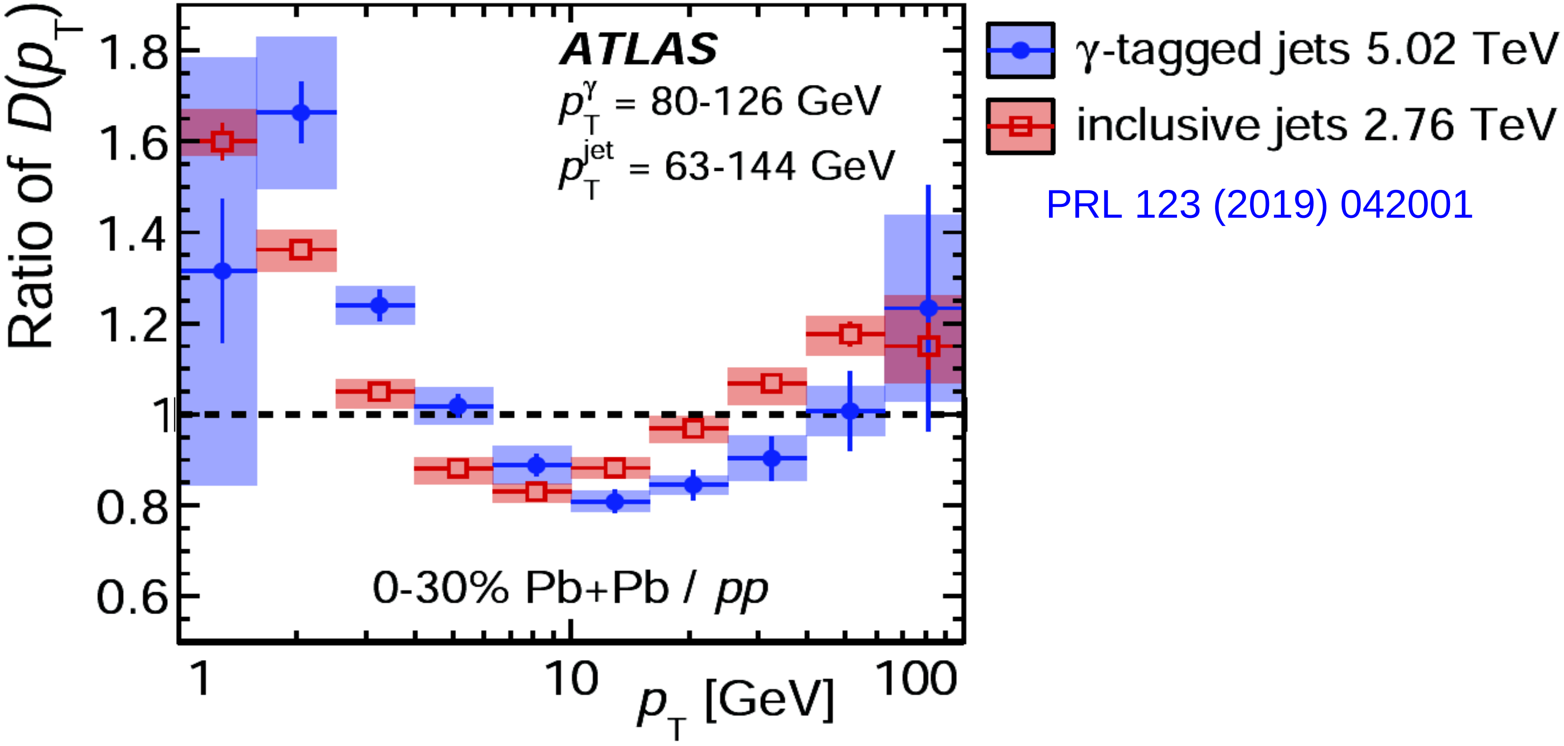


see e.g. JHEP 03 (2017) 135

- For example, the **Hybrid model** also successful in describing high-z excess seen in the fragmentation functions.
- => How to **distinguish** between width vs color?

Color vs width: how to distinguish?

- One may think about comparing inclusive jet and gamma-tagged jet measurements, such as the measurement of FF:

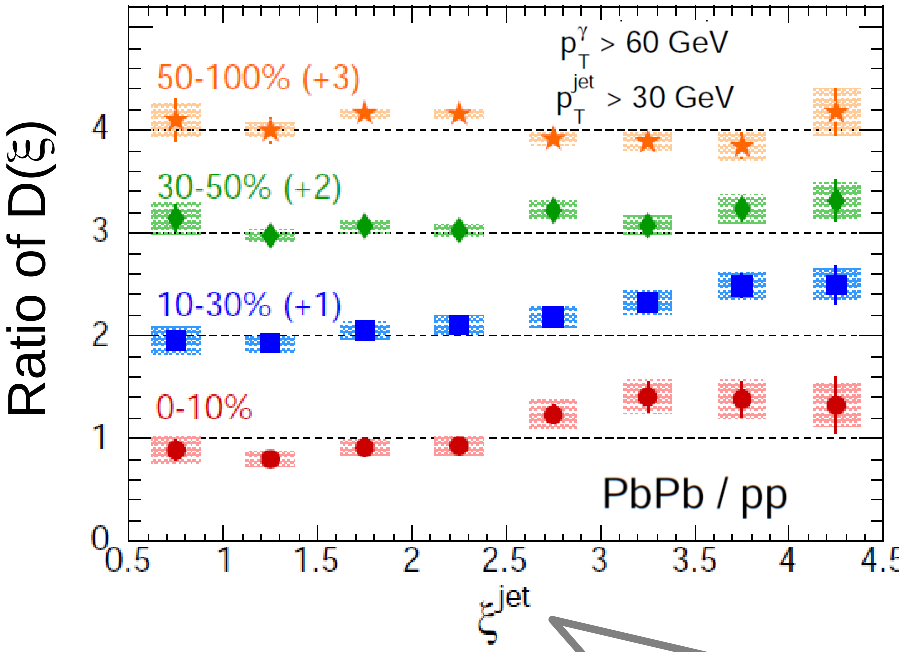


PRL 123 (2019) 042001

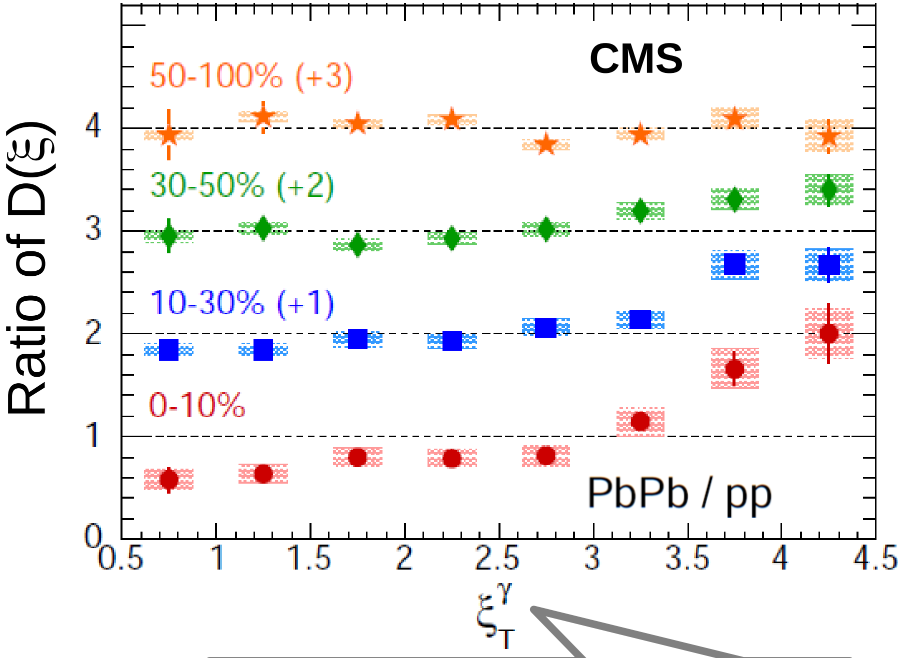
- … but path-length effects (“surface bias”) can be more important than q/g effects …

Color vs width: how to distinguish?

PRL 121 (2018) 242301



ξ wrt **jet** momentum

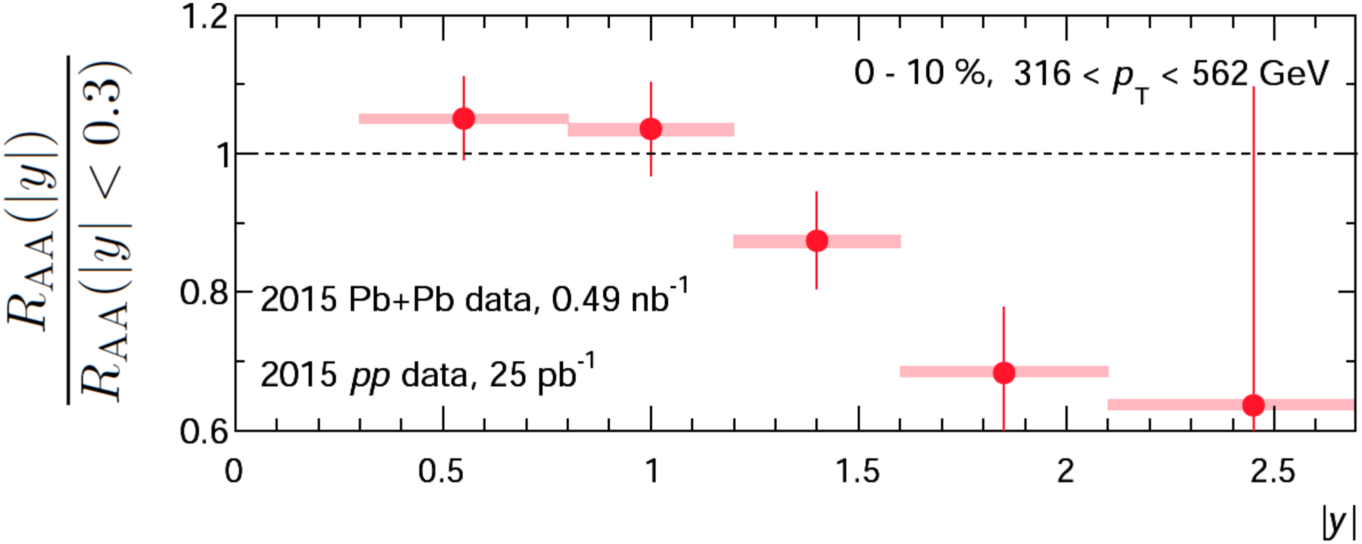


ξ wrt **photon** momentum

- … evident from this measurement of PbPb/pp ratio of D(ξ)
- Both the position of crossing 1 and the shape depend on the **initial parton kinematics** (=> on how much the jet is quenched)
- => gamma-jet observables are not that straightforward tools

Color vs width:
how to distinguish?

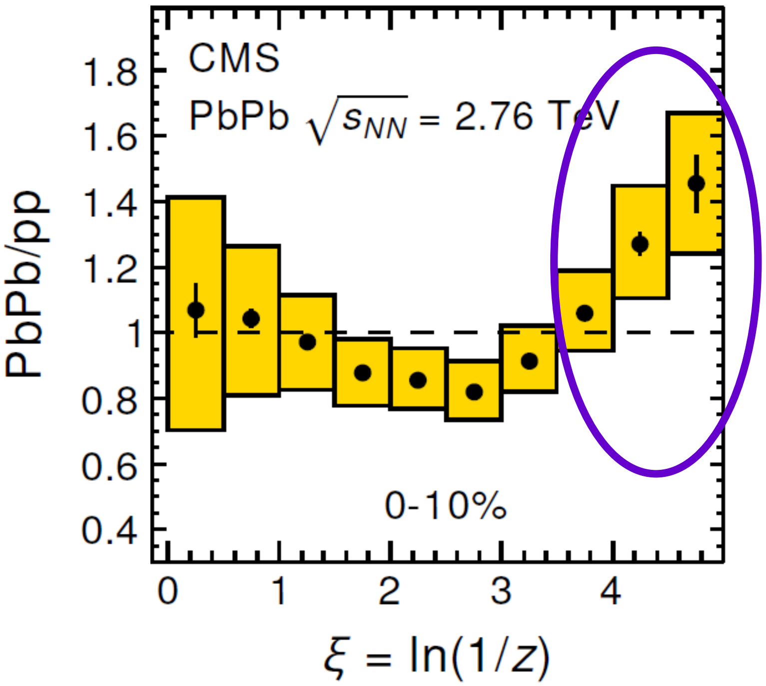
- We can try to measure **q/g sensitive** observables **as a function of jet width** observables. E.g. measure the ratio of <jet charge> at mid-rapidity and forward rapidity for the same <jet width>?
  - May sound complicated but should be doable (ratio largely cancels systematics, pt does not need to be unfolded due to similar JER effects)
  - Requires testing of sensitivity of observables prior the measurement.
- Theory can try to predict / reproduce *various* g/q sensitive observables. E.g.:



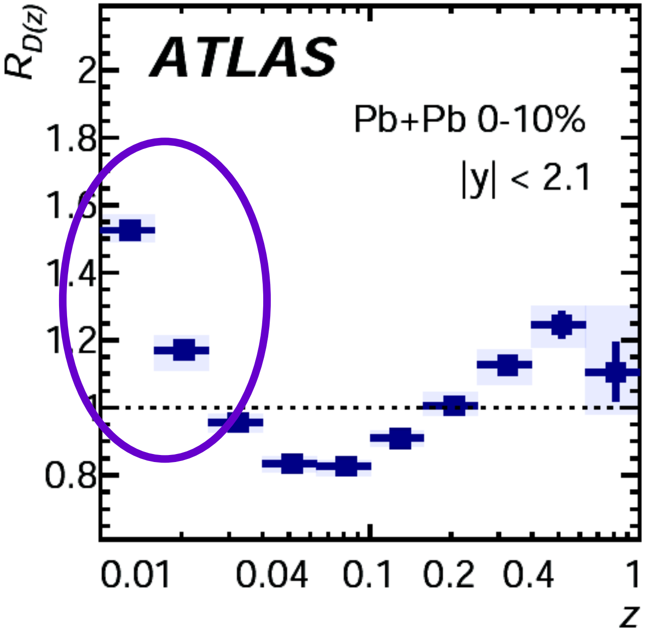
PLB 790 (2019) 108

Soft enhancement

- What is driving the enhancemement of soft particles inside the jet?
- How much energy is in soft particles?



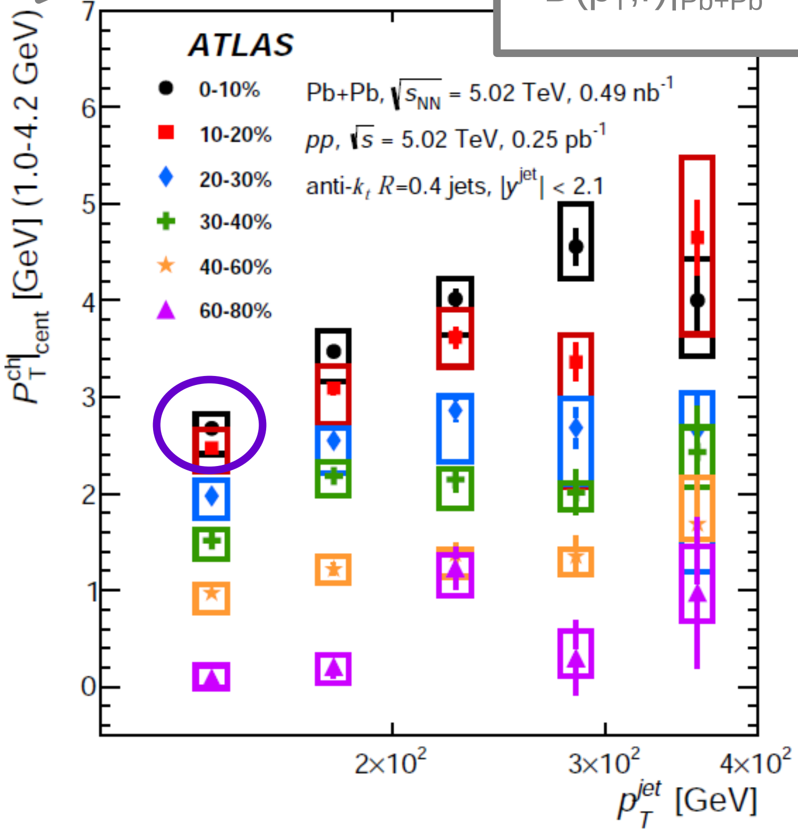
PRC 90 (2014) 024908



EPJC 77 (2017) 379
PRC C 98 (2018) 024908

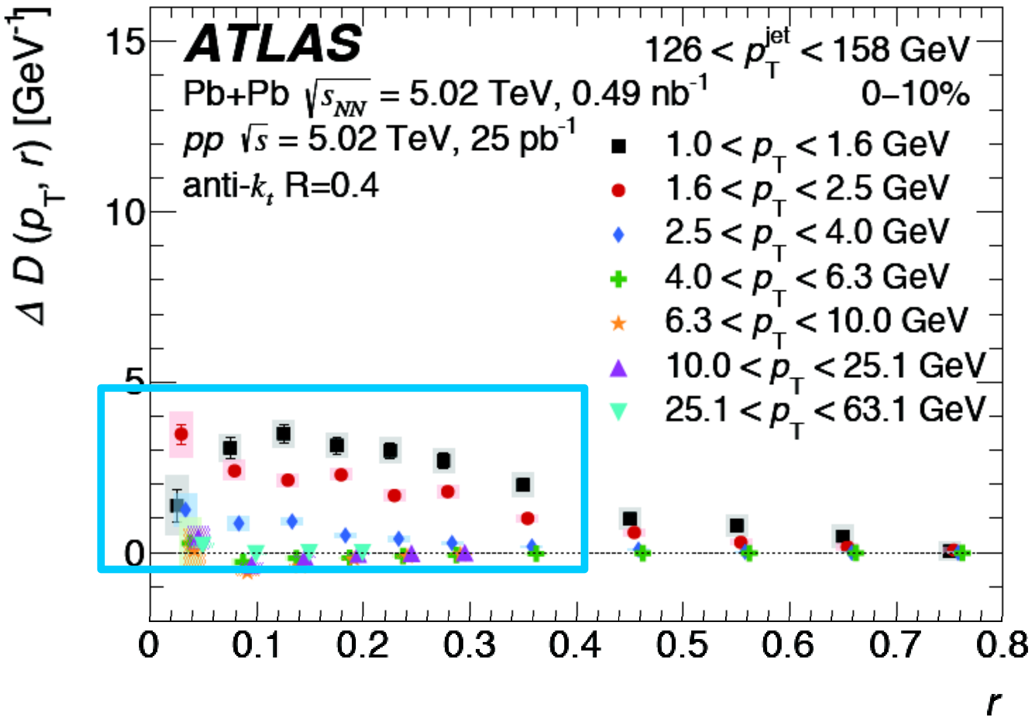
Quantifying soft enhancement

First moment of D(p_T) distribution



D(p_T,r)|$_{Pb+Pb}$ – D(p_T,r)|$_{pp}$

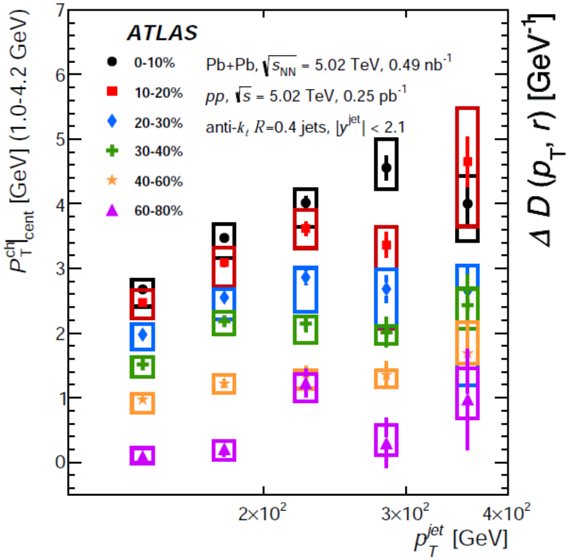
$$D(p_T, r) = \frac{1}{N_{jet}} \frac{1}{2\pi r\, dr} \frac{dn_{ch}(p_T, r)}{dp_T}$$



- In 0-10%, jet with p_T ~ 140 GeV has about 2.5 GeV in soft particles with p_T=1–4 GeV within the jet cone.

- For p_T=1–4 GeV 80% of energy inside the jet cone, 20% outside.
- Quantified for different jet p_T.

Quantifying soft enhancement



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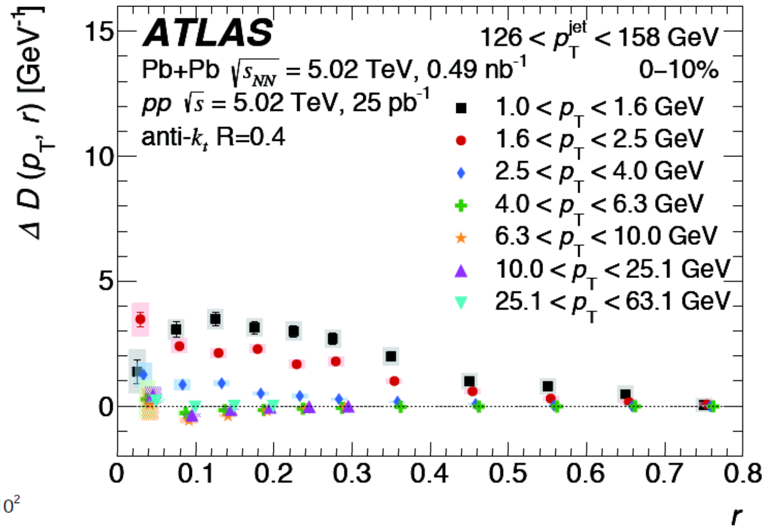
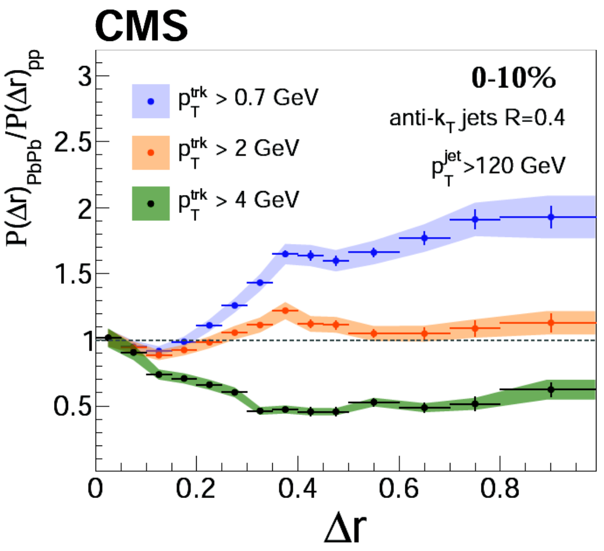


PRC 100 (2019) 064901 *



JHEP 05 (2018) 006

- Supplemented by jet-hadron correlation measurements (PLB 796 (2019) 204, JHEP 09 (2015) 170, PRL 119 (2017) 102301, PRC 96 (2017) 034904, JHEP 1602 (2016) 156).
- Energy flow inside and outside the jet **quantified in great detail**.
- This is a lot of input information for theory comparisons!
- But e.g. detailed measurement in * has only 3 citations from theory papers, none of them use the data directly or compares with data …

Soft enhancement – impact on other observables

- Soft enhancement implies that: $p_{\mathrm{T,jet}}^{\mathrm{measured}} = p_{\mathrm{T,jet}}^{\mathrm{quenched}} + p_{\mathrm{T}}^{\mathrm{soft}}$
- => using only inclusive jet R_{AA} will give biased estimate of magnitude of quenching. The average **energy loss is larger** (shift formalism + fragmentation data say it is 10-20% effect).

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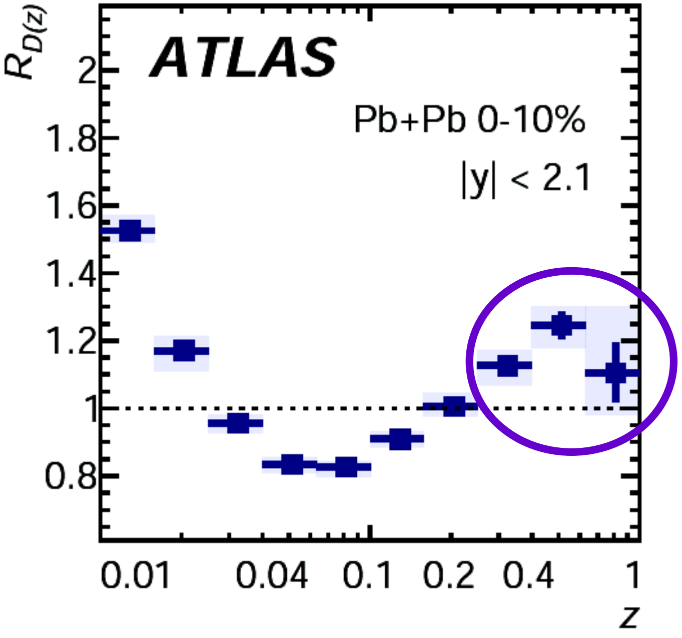
- => using only inclusive jet R_{AA} will give biased estimate of magnitude of quenching. The average **energy loss is larger** (shift formalism + fragmentation data say it is 10-20% effect).
- Other observables may also exhibit unexpected impact from the soft enhancement. E.g. **depletion of high-z** fragments, since

$$z \propto \frac{p_{\mathrm{T,particle}}}{p_{\mathrm{T,jet}}^{\mathrm{measured}}}$$

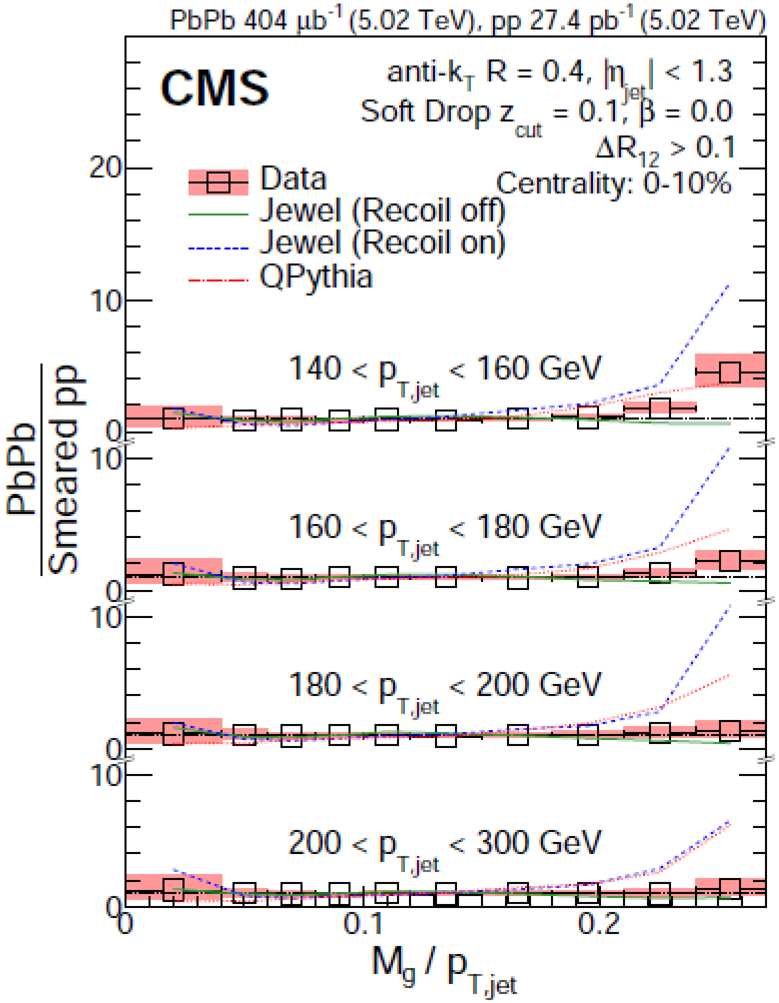
(cf. discussion in EPJC 76 (2016) 2, 50)

  - may help to better understand the origin of soft enhancement (in future data)
  - may be one of sources of difference between low-ξ CMS and high-*z* ATLAS data (this + unfolding)



Soft enhancement

- Clear an well known impact seen in non-groomed substructure observables.
- One example: jet mass.
- When using less restrictive soft-drop settings a modest **enhancement** at large M/p_T is present.
- Seems **tricky for models** ...



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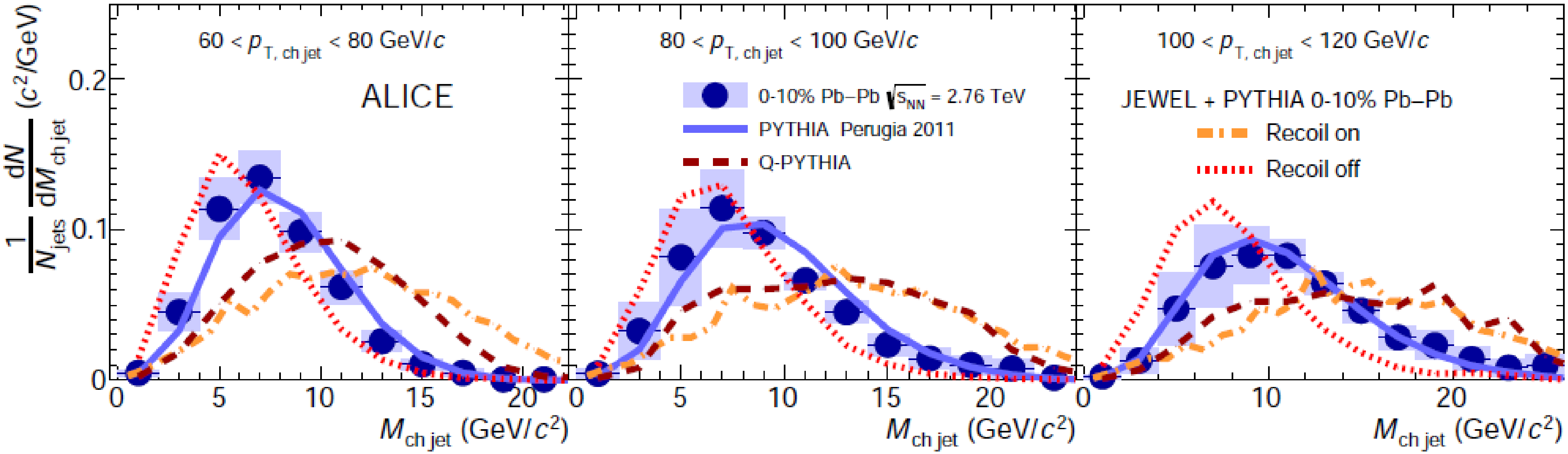
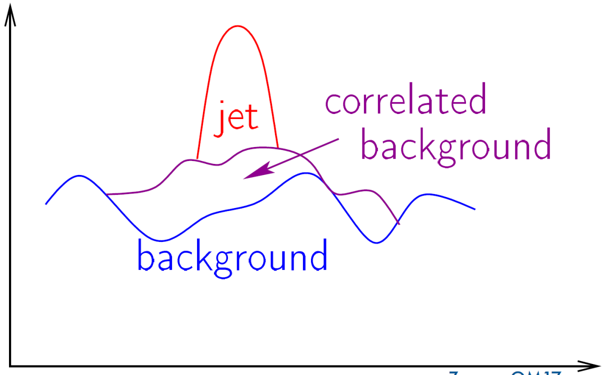
Soft enhancement



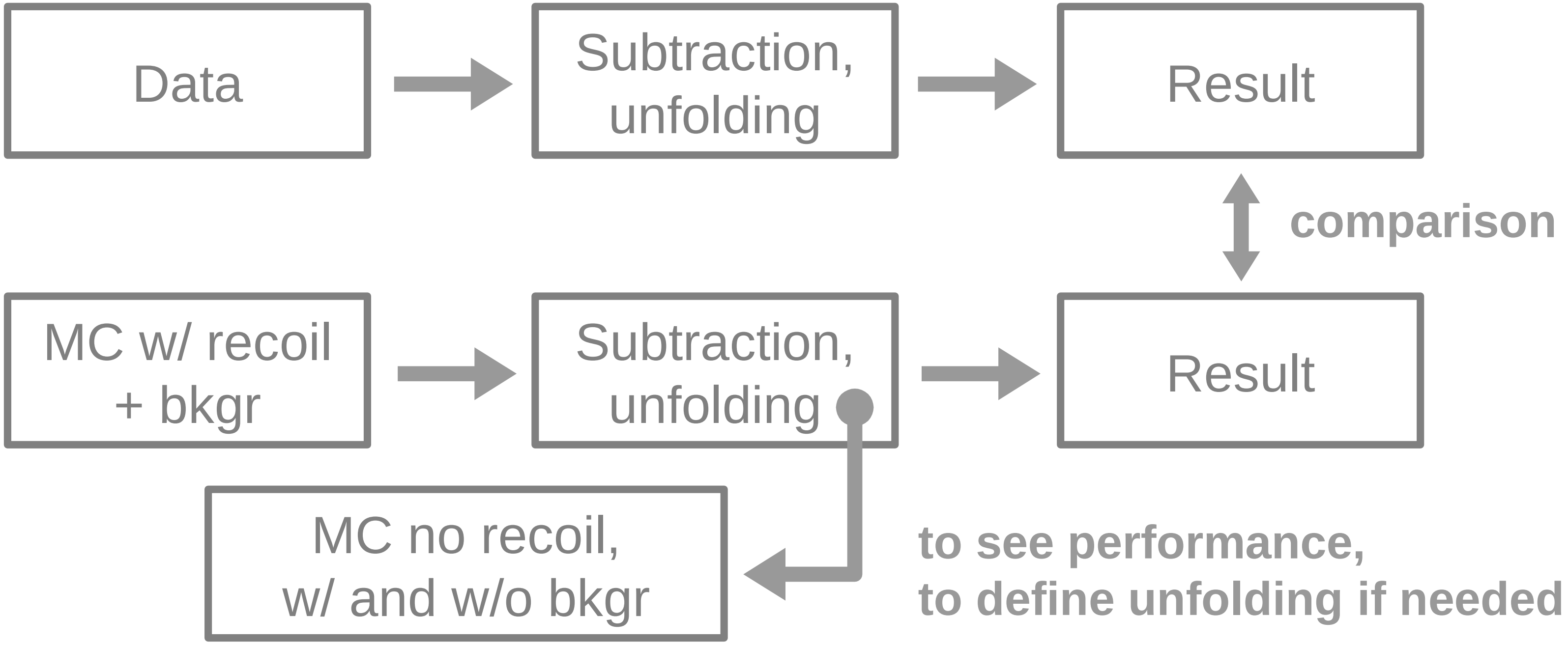
- Seems **tricky for models** … low p_T enhancement my be a mix of in-cone radiation and back-reaction.
- But how to find out **what is what** if it mixes with the background?



Zapp :: QM17

Proposal

- Do the same as in MC as in the experiment:
  - have well defined uncorrelated background as a source of partons for the recoil in MC
  - subtract the background using the same methods as applied in the experiment



Data

Subtraction, unfolding

Result

comparison

MC w/ recoil + bkgr

Subtraction, unfolding

Result

MC no recoil, w/ and w/o bkgr

to see performance,
to define unfolding if needed

Soft enhancement: Summary

- To quantify the amount of lost energy one needs to take into account **both**, the measurements of the inclusive jet suppression and measurements of jet fragmentation which quantify the soft enhancement.
- Treating the MC in the same way **as the data** may help to improve the ability to understand the soft enhancement.
- A lot of information about soft enhancement **already published by experiments** which should allow detailed comparisons with theory.
- My view: it is at least equally important to have a **detailed confrontation** of theory with various existing measurements as to develop new strategies and new observables.