Learning about the Quark-Gluon Plasma using jet measurements

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for the ALICE, ATLAS, and CMS collaborations

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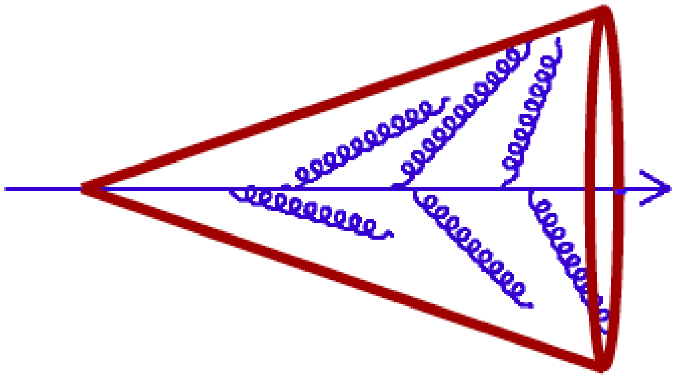
Jet quenching in QCD matter, in one slide

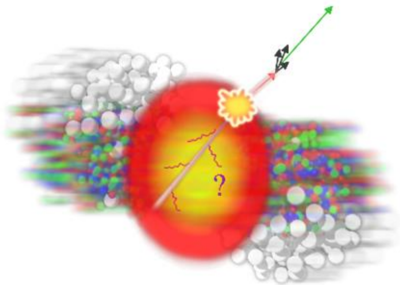
Jet shower in vacuum

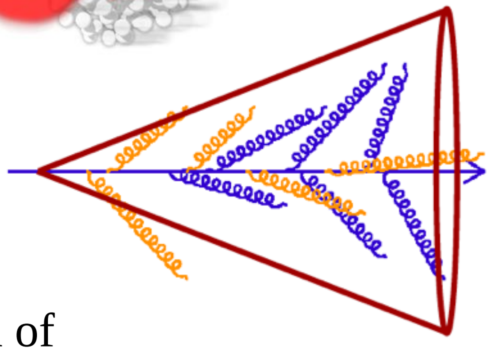


Evolution of a highly virtual parton via gluon radiation

Quantum interference → angular ordering
- hardest radiation is most collinear with jet axis
- Precise understanding in pQCD
- Accurately calculable with QCD-based Monte Carlo models

Jet shower in-medium





Superposition of
- vacuum shower
- medium-induced gluon emission

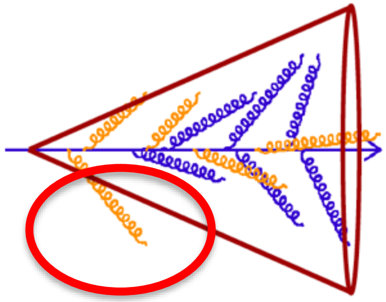
These processes happen simultaneously and interfere

Angle-ordering is modified or destroyed

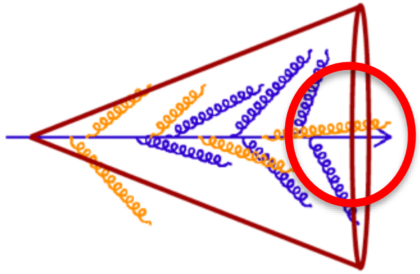
Jet quenching: redistribution of jet shower

Jet quenching: observable consequences

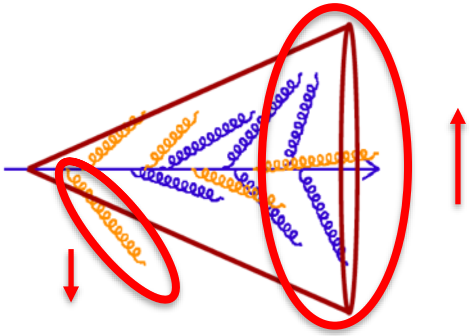
1. Energy loss



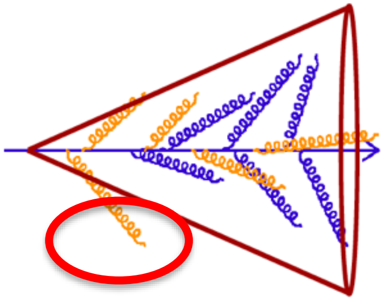
2. Modification of
jet substructure



3. Jet deflection

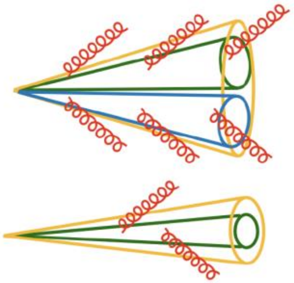


4. Recovery of
large-angle radiation



What can jet modification tell us about the QGP? This talk:

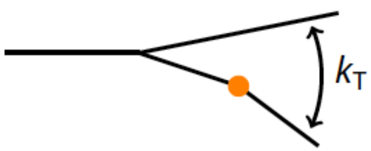
Color coherence: does the jet see the QGP as a coherent scattering target or as multiple targets?



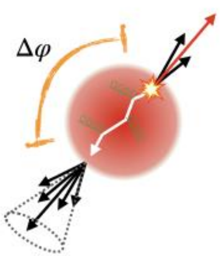
→ resolve the color coherence length of the QGP

Can we detect the scattering of jets off QGP quasi-particles? Or jet excitation of the QGP fluid? Are these experimentally distinct?

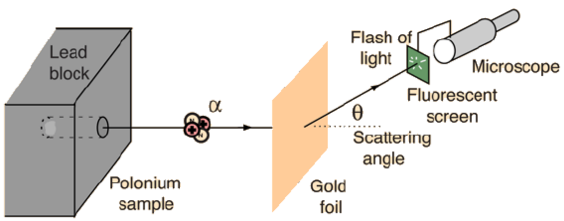
Substructure broadening

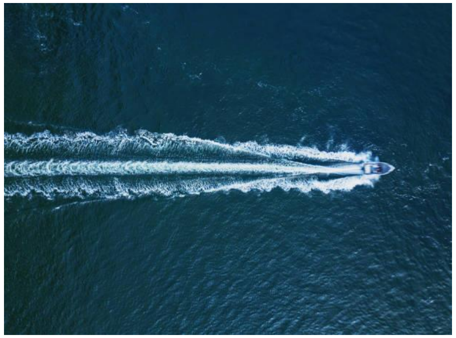


Acoplanarity broadening



Quasi-particles or medium excitation?

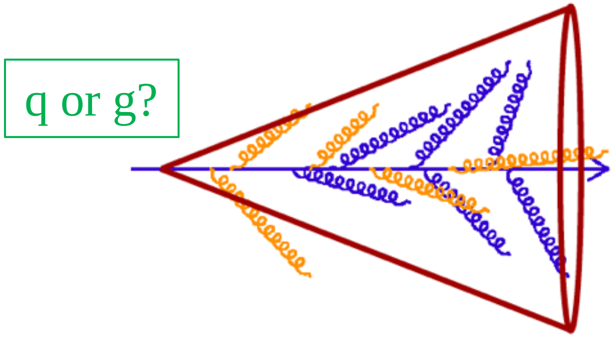




Some questions arising along the way

Jet-initiating partons can be a quark or a gluon, with different color charges (Casimir factor ratio C_A/C_F=9/4)

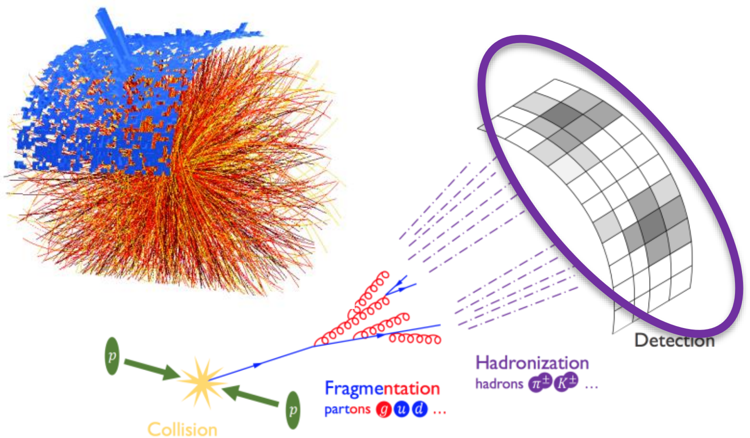
Do q and g interact differently with the QGP?



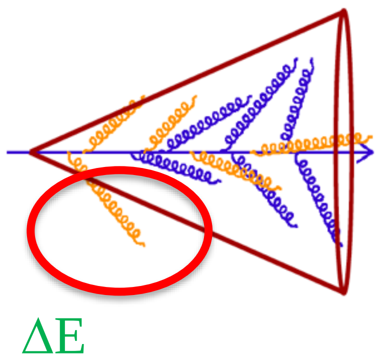
Jets are complex objects observed as a multi-hadronic correlation with a vast range in p_T scale

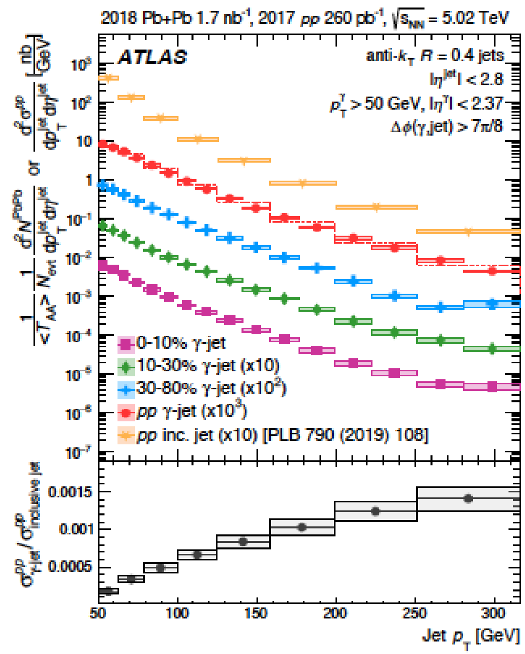
Heavy ion collisions generate complex background

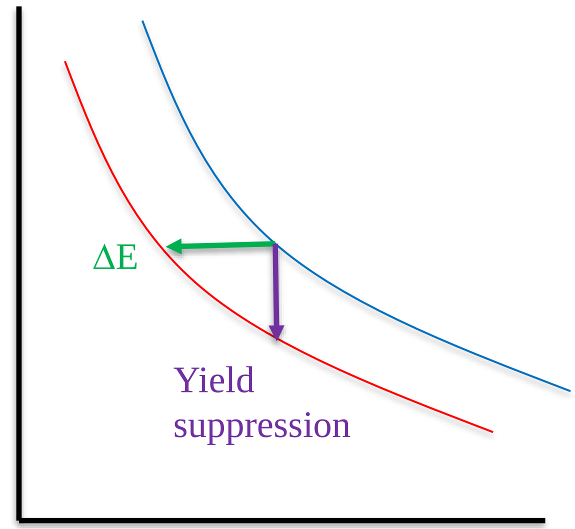
Do we understand jet measurement biases, and can we control them?



Jet yield energy loss → yield suppression





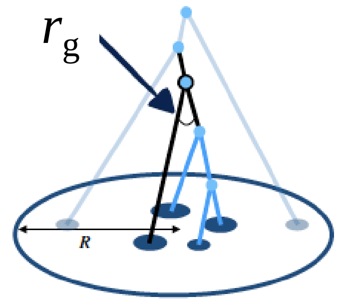


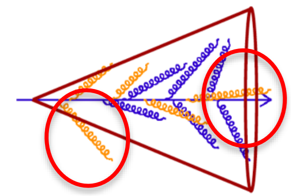
Energy loss ↔ Yield suppression

$$R_{\mathrm{AA}} = \frac{\text{Yield in PbPb}}{\text{Geometric factor x Yield in pp}}$$

Measurement of substructure-dependent jet suppression in Pb+Pb collisions at 5.02 TeV with the ATLAS detector

Phys. Rev. C 107 (2023) 054909
DOI: 10.1103/PhysRevC.107.054909
arXiv:2211.11470





Apply jet grooming

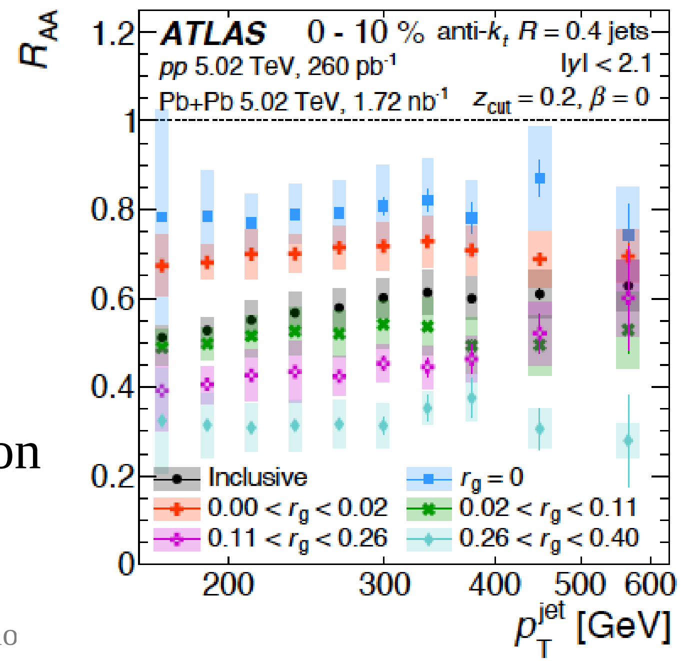
r_g= angular opening between two hardest subjets

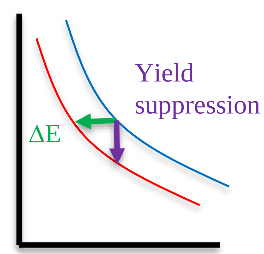
Hard radiation happens early
- before jet interacts with QGP?

→ classify jets based on r_g

$$R_{AA} = \frac{\text{Yield in PbPb}}{\text{Geometric factor x Yield in pp}}$$

Larger r_g → wider opening angle
- greater yield suppression
- greater energy loss

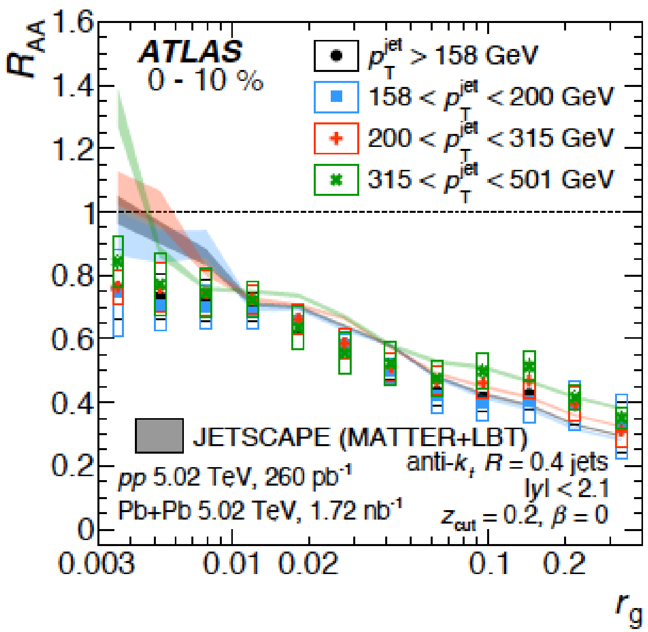




Evidence that jet-medium interaction probes color coherence

r_g-tagged suppression: model comparisons

JETSCAPE MC

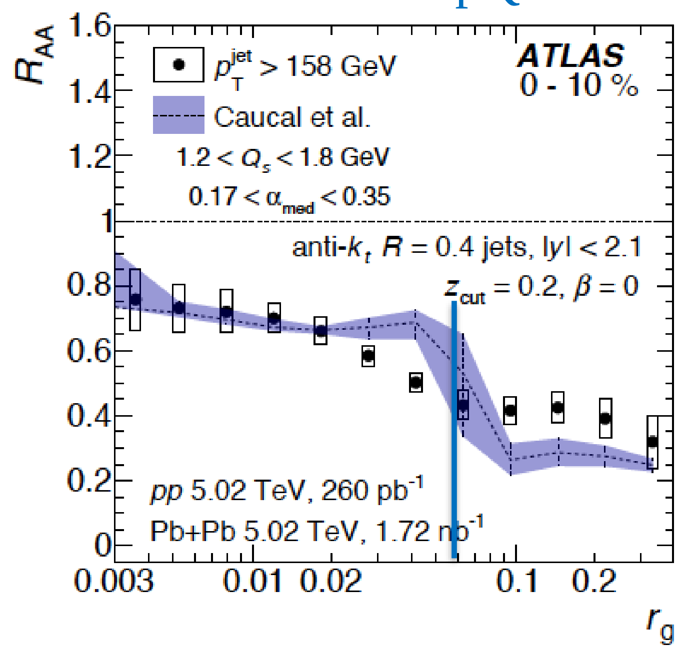


Quenching model:

- Hard Thermal Loop (HTL) formalism
- Multi-stage as fn of jet virtuality (MATTER+LBT)

Coherence model: jet-medium interaction decreases at higher jet virtuality

Caucal et al. pQCD



Quenching model:

- BDMPS (soft mult scat.) formalism
- Partonic only

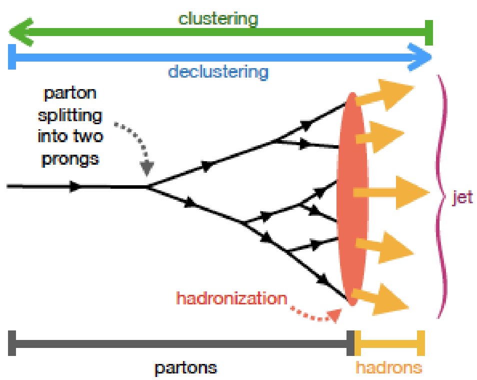
Coherence model: critical angle separates coherent and incoherent energy loss

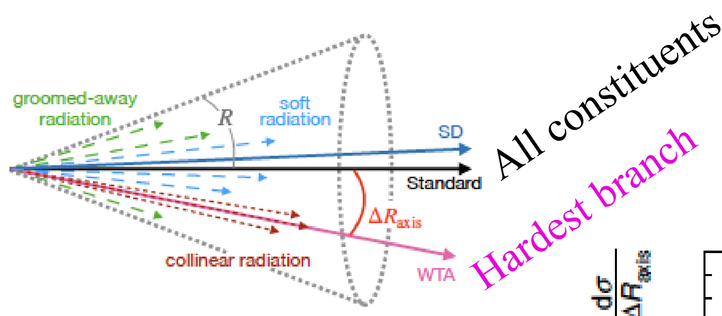
Models capture gross features of data; miss details

- additional support for color coherence driving energy loss
- more accurate modeling needed for quantitative analysis

Measurement of the angle between jet axes in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

arXiv:2303.13347





ΔR_{axis} = angular difference between Std and WTA axes

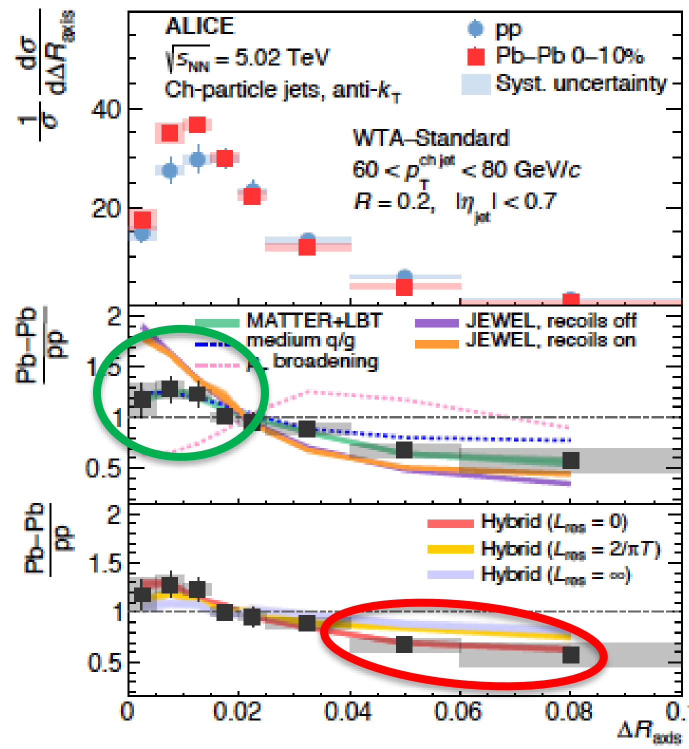
Characterizes redistribution of soft relative to hard radiation due to quenching

Medium-induced narrowing of axis correlation

Selection bias: gluon-induced jets preferentially suppressed…?

Model comparison prefers incoherent e-loss (L_{res}=0)

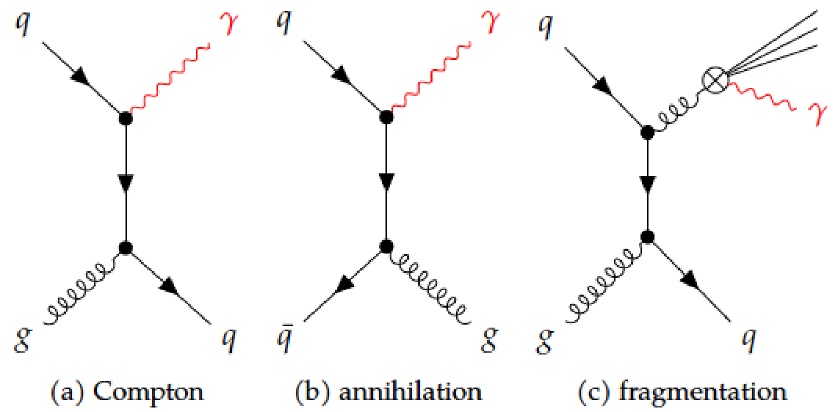
- contrast ATLAS r_g-tagged



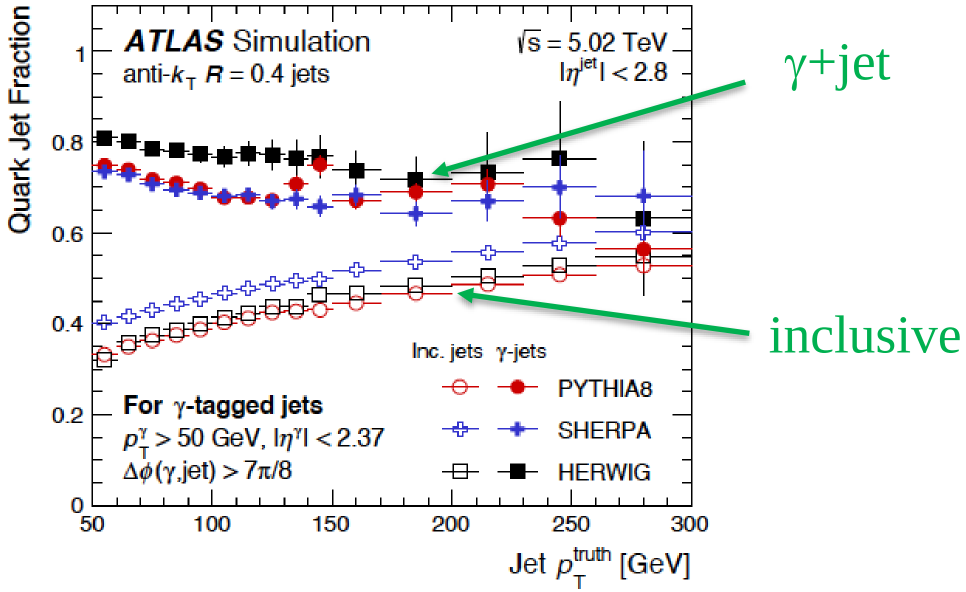
ΔR_{axis}

Coincidence channel: γ+jet

Measure jet recoiling from prompt photon



Quark-initiated fraction of recoil jets



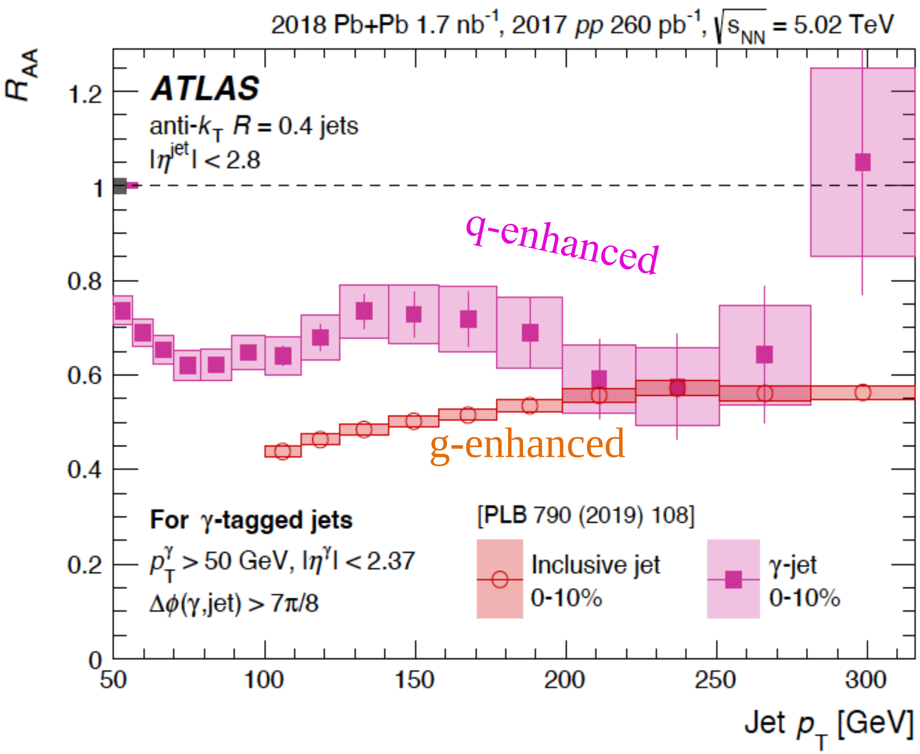
γ–tagged: bias towards recoil quark jets

Comparison of inclusive and photon-tagged jet suppression in 5.02 TeV Pb+Pb collisions with ATLAS

ATLAS EXPERIMENT

Phys. Lett. B 846 (2023) 138154
DOI: 10.1016/j.physletb.2023.138154

$$R_{\mathrm{AA}} = \frac{\text{Yield in PbPb}}{\text{Geometric factor x Yield in pp}}$$



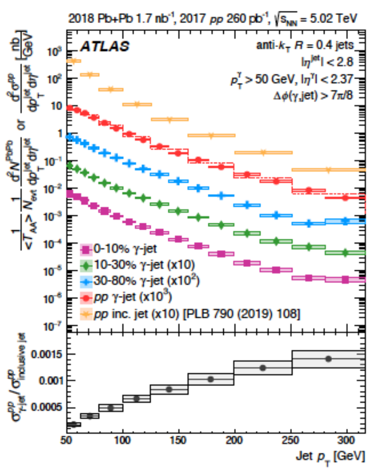
Larger suppression for gluon-enhanced population

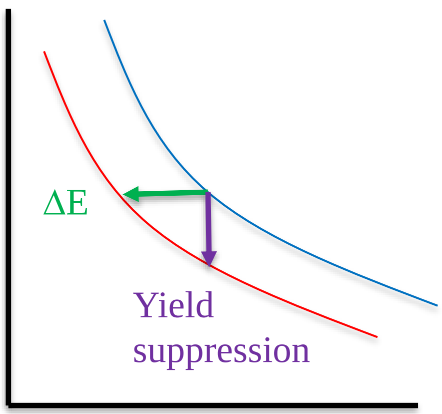
Color-charge dependence of jet quenching?

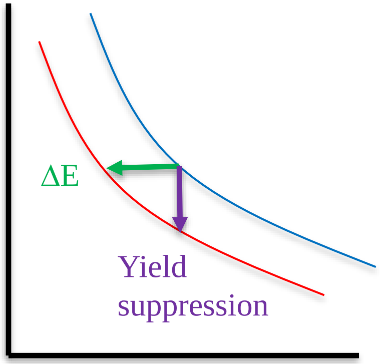
- Casimir factor $C_A/C_F=9/4$

But yield suppression is a convolution:

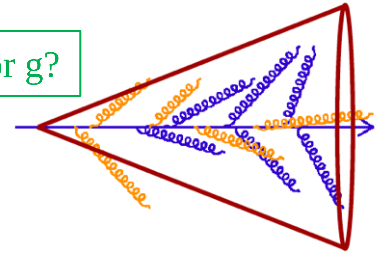
- spectrum shape ⊗ energy loss





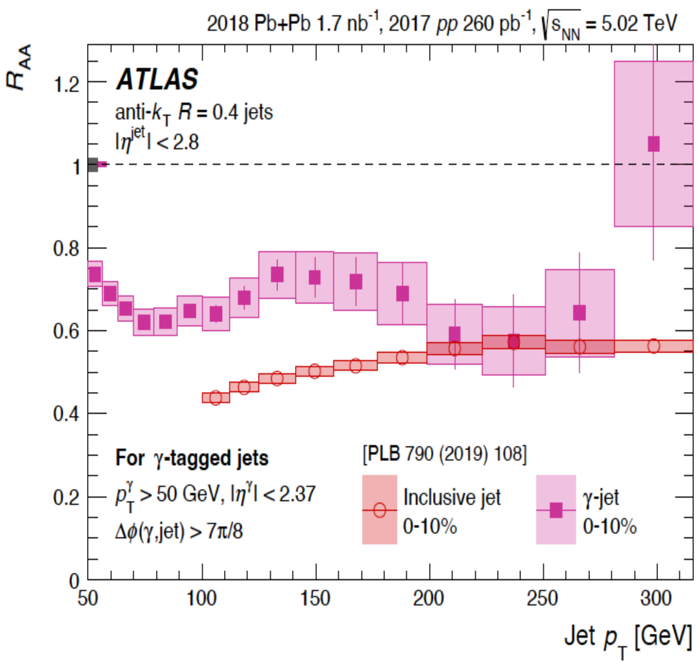


q or g?

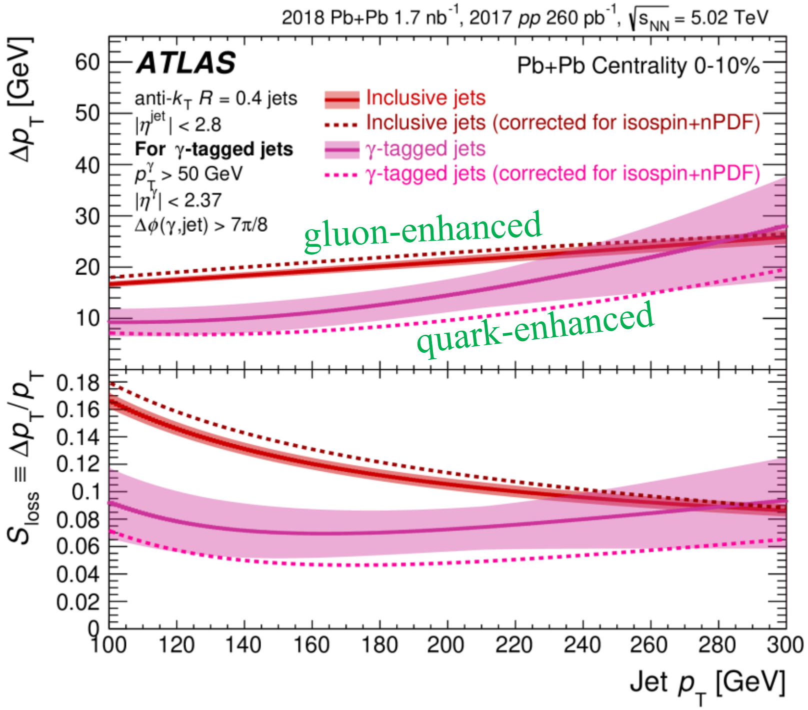


Phys. Lett. B 846 (2023) 138154
DOI: 10.1016/j.physletb.2023.138154

Estimated energy loss



deconvolute



Larger e-loss for gluons than quarks

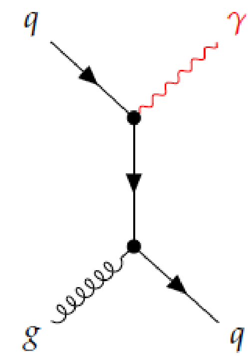
- consistent with relative Casimir factors

γ+jet kinematic balance

$$x_{J\gamma} = \frac{p_T^{\text{jet}}}{p_T^{\gamma}}$$

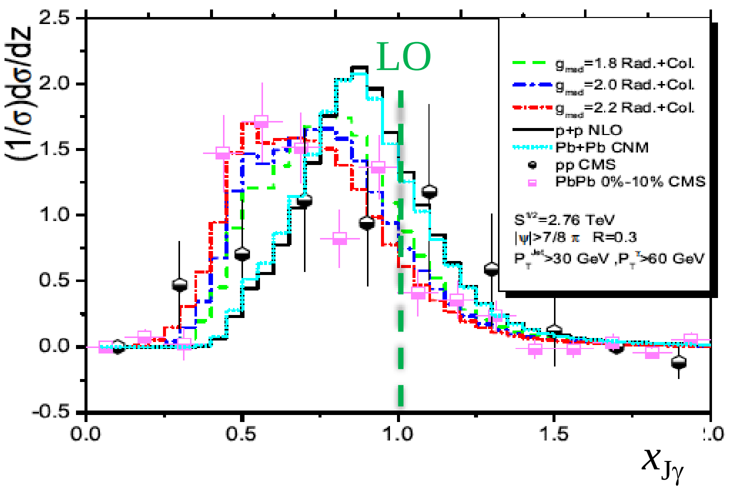
Naïve LO:

- recoil jet is azimuthally back-to-back, $x_{J\gamma}$=1
- γ doesn't interact in QGP
  - enery loss → $x_{J\gamma}$<1



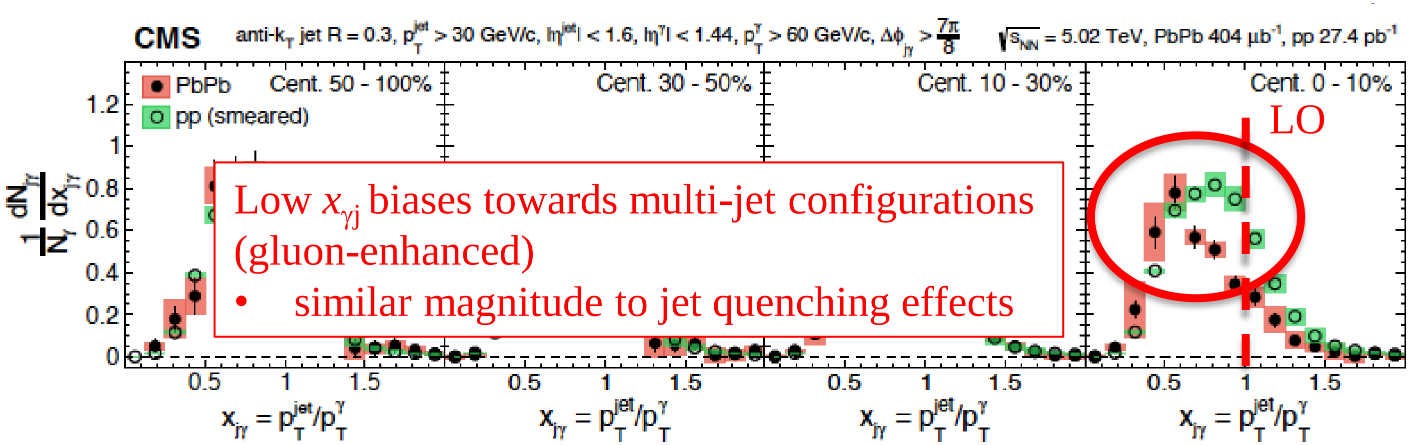
But QCD is not so kind.

NLO: significant broadening



Dai, Vitev and Zhang
PRL 110, 142001 (2013)
arXiv:1207.5177

Data: also broadened



Low $x_{\gamma j}$ biases towards multi-jet configurations (gluon-enhanced)

- similar magnitude to jet quenching effects

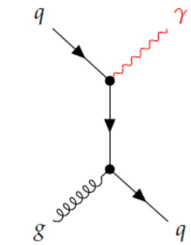
CMS
PhysLett B785, 14 (2018)
arXiv:1711.09738

Girth and groomed radius of jets recoiling against isolated photons in lead-lead and proton-proton collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

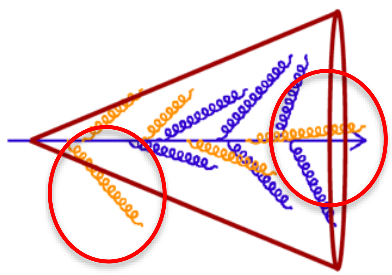
arXiv:2405.02737

Select recoil jet populations for comparison:

- $x_{J\gamma} > 0.4$: more inclusive
- $x_{J\gamma} > 0.8$: bias against e-loss, multi-jet configurations

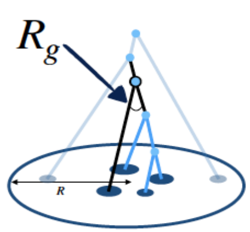


$$x_{J\gamma} = \frac{p_{\mathrm{T}}^{\mathrm{jet}}}{p_{\mathrm{T}}^{\gamma}}$$



Substructure observables:

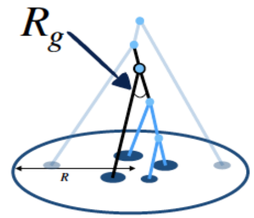
- Groomed subjet separation R_g
- Ungroomed girth g



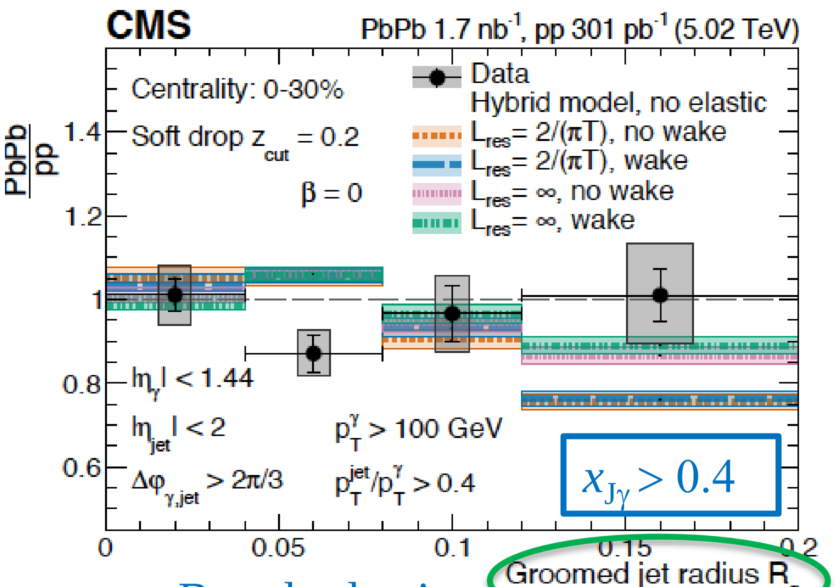
$$g = \frac{1}{p_{\mathrm{T}}^{\mathrm{jet}}} \sum_i p_{\mathrm{T}}^i \Delta R_{i,\mathrm{jet}}$$

Jet shape dependence on γ+jet p_T-balance

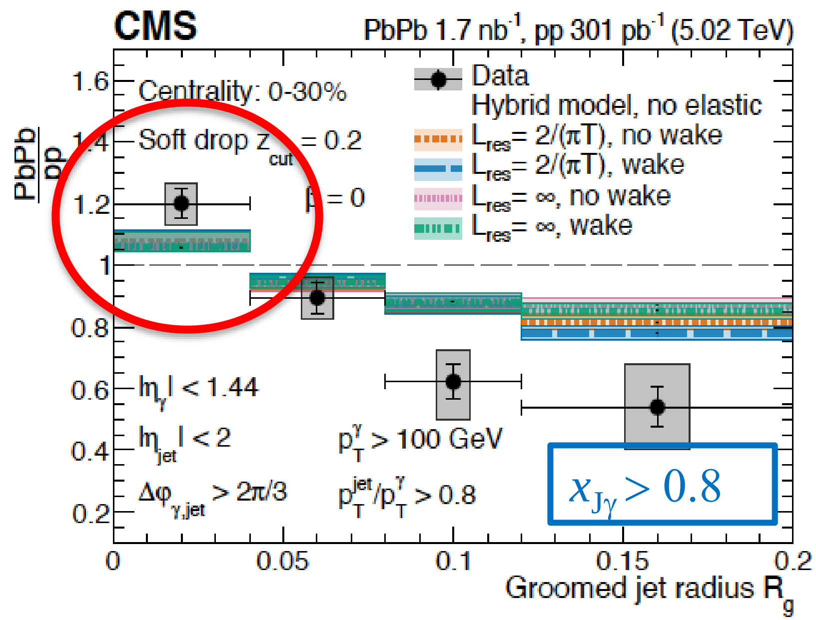
$$x_{J\gamma} = \frac{p_T^{\rm jet}}{p_T^{\gamma}}$$



arXiv:2405.02737



Broad selection

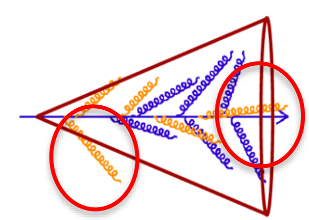


Suppress e-loss + mult-jet config.

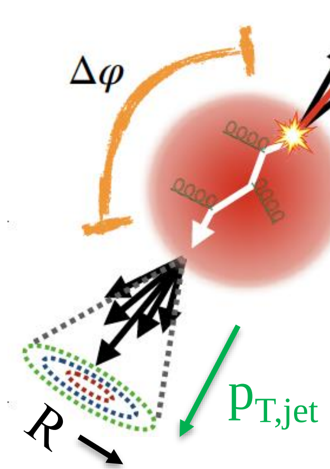
$x_{J\gamma} > 0.8$ narrows jet shape

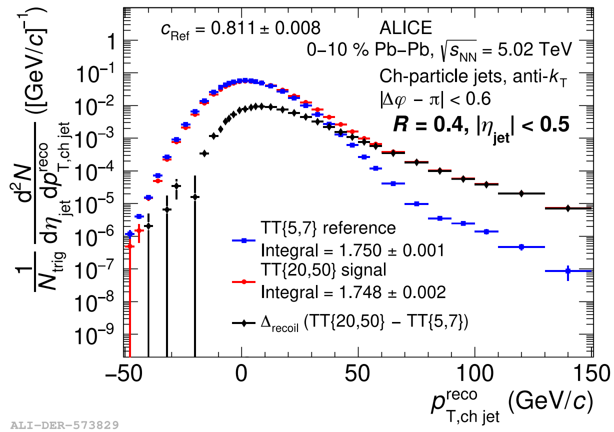
- selection bias due to p_T cut (q-enhanced)
- similar bias to inclusive jet
- not reproduced by quenching models…?

Compare ATLAS e-loss/r_g correlation



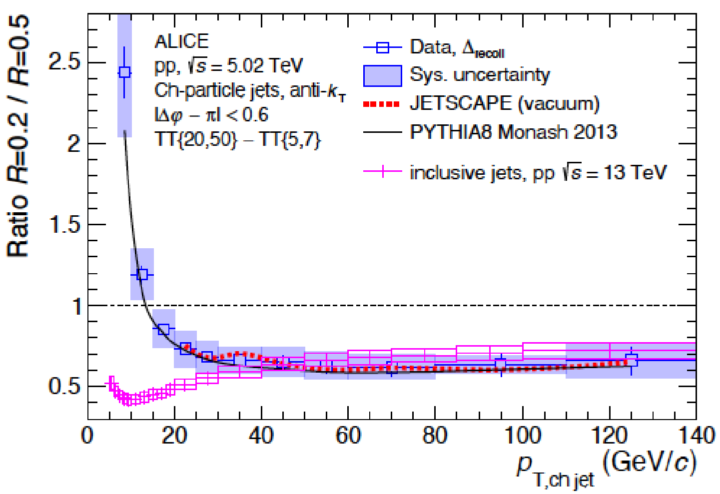
Measurements of jet quenching using semi-inclusive hadron+jet distributions in pp and central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

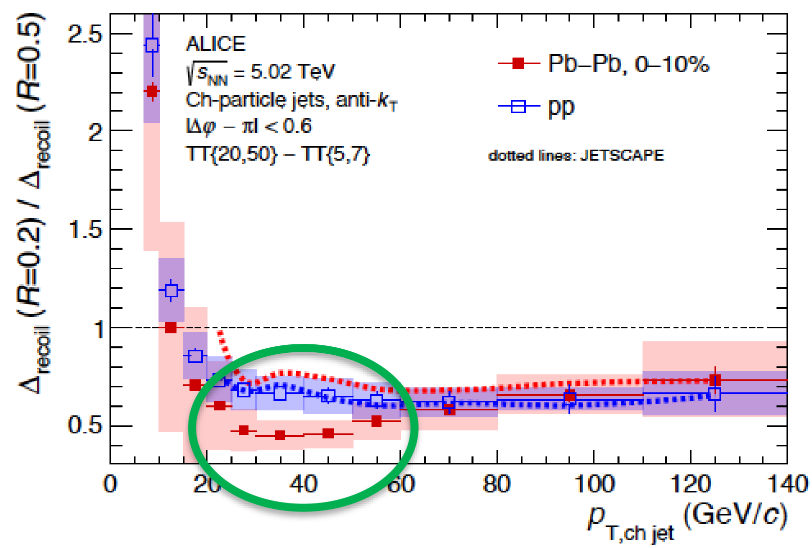




PRC in press
arXiv:2308.16128

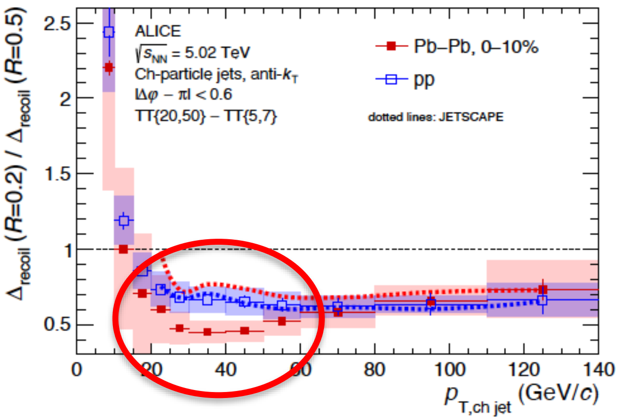
Statistical treatment of background → unbiased recoil jet measurement at low p_T, large R



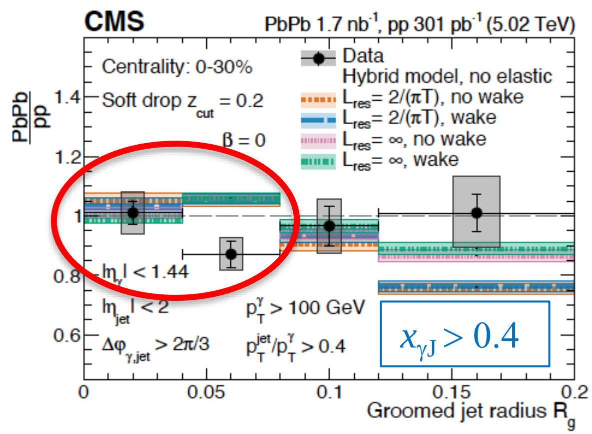


Robust jet shape observable: ratio of semi-incl. yield for R=0.2/R=0.5
→ medium-induced jet shape broadening

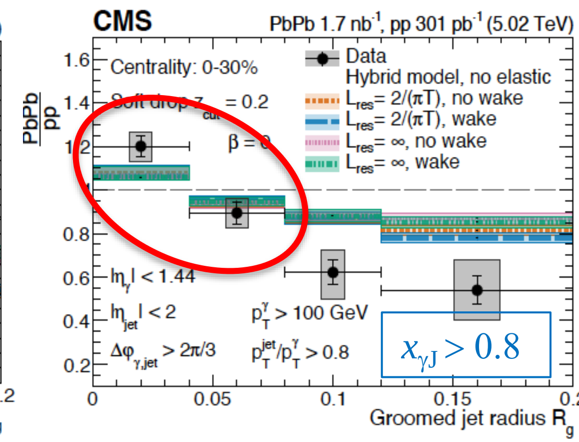
Compare jet shape observables with different bias



No p_T bound → no selection bias
- medium-induced jet broadening



Moderate bias
- no shape change



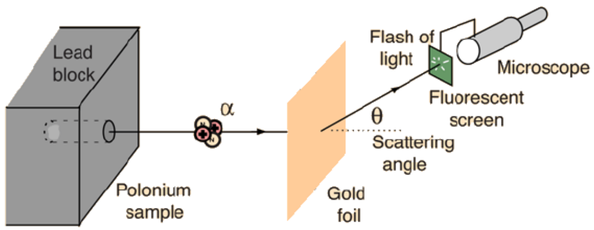
Strong bias
- jet shape narrowing

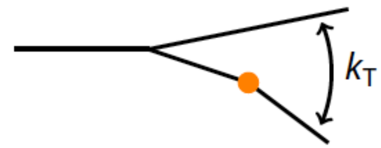
Take-home message:
- jet shape measurements are sensitive to p_T-cut selection bias
- needs to be taken into account in theory/data comparisons

Search for quasi-particle scattering in the quark-gluon plasma with jet splittings in pp and Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

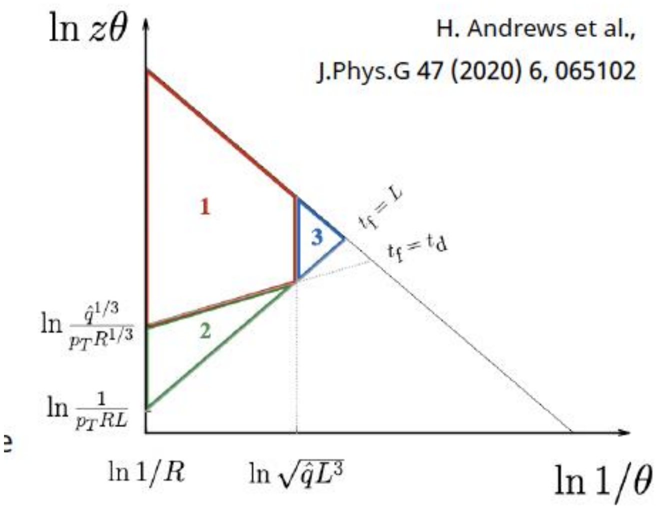
ALICE
preliminary

Raymond Ehlers talk @ INT-21r-2b

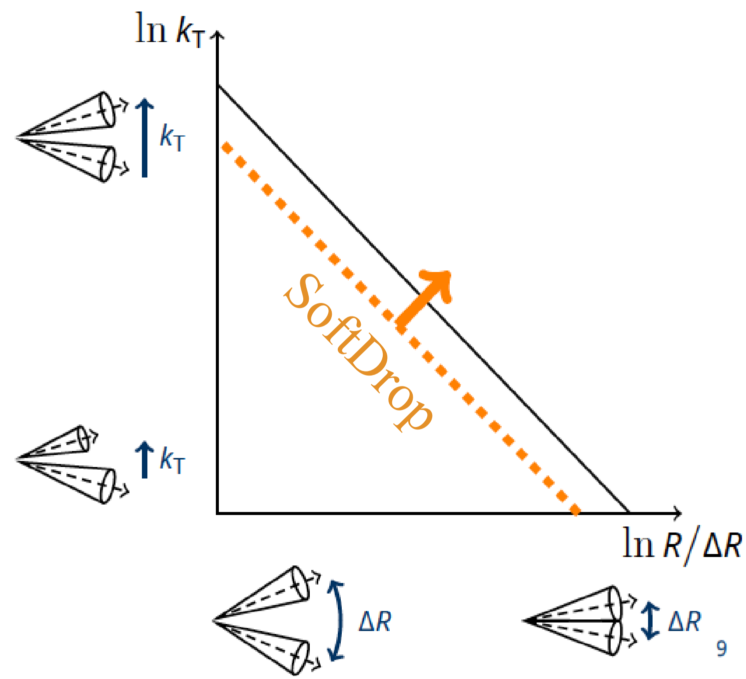


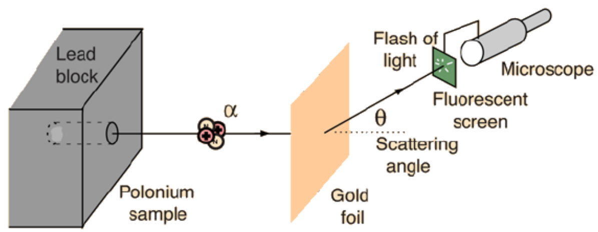


Use jet grooming to isolate hard k_T splittings
→ enhanced rate in Pb+Pb?

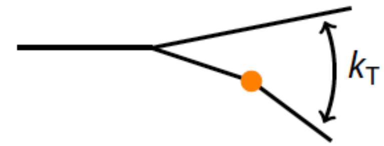


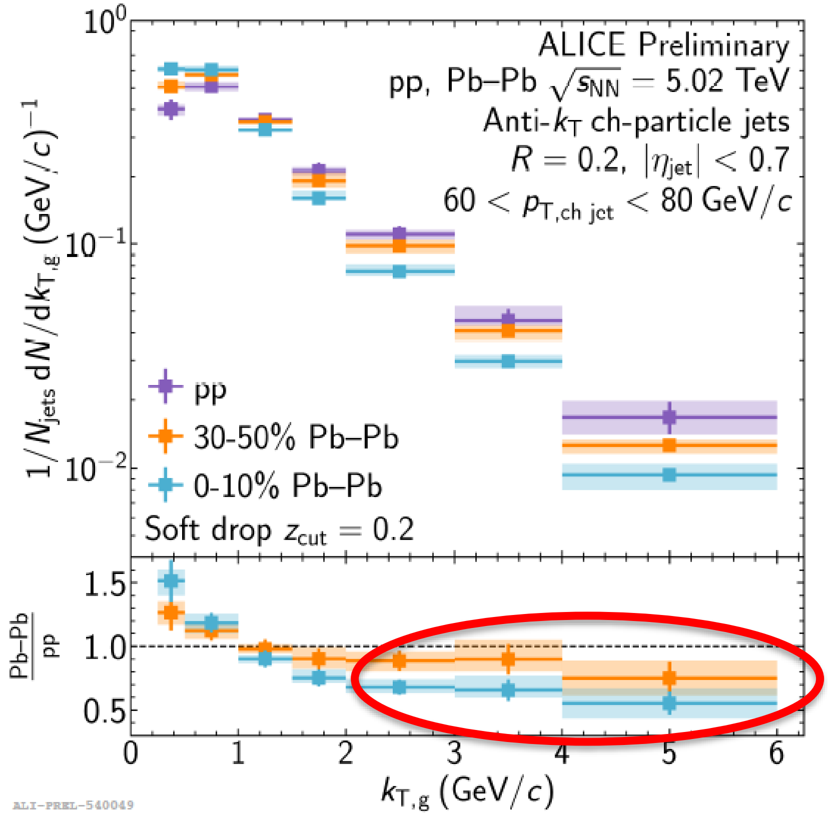
groom

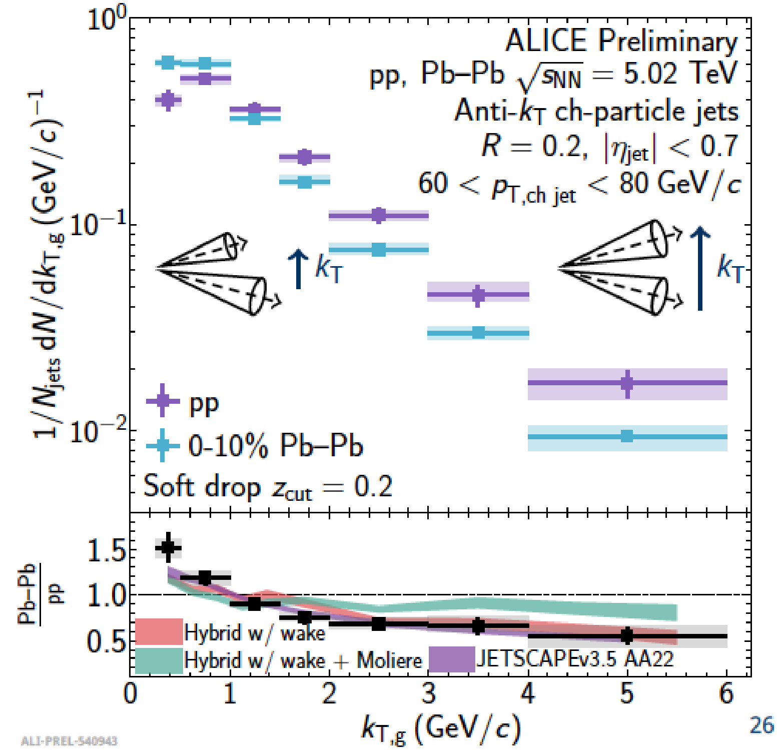




Quasi-particle scattering: enhancement in high-k_T splitting rate



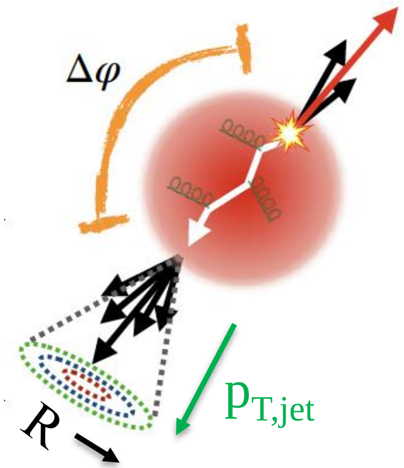


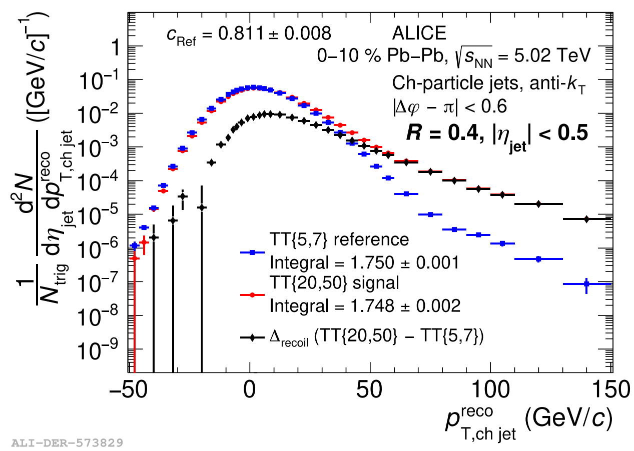


Suppression, not enhancement, is observed at high k_T

Not well-described by model calculation including Moliere scattering

Observation of medium-induced yield enhancement and acoplanarity broadening of low-p_T jets from measurements in pp and central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV



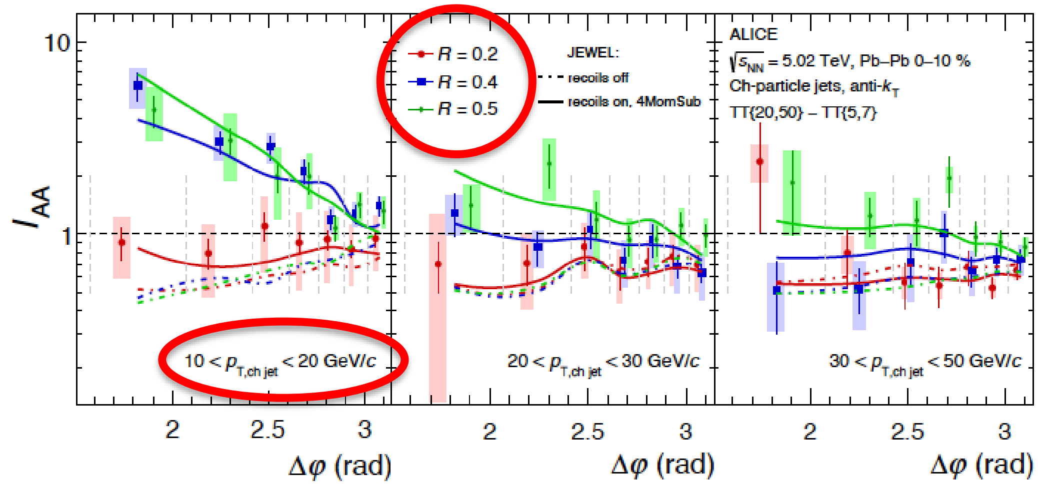


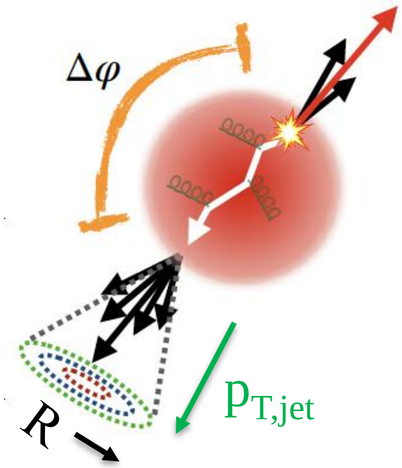
PRL in press
arXiv:2308.16131
PRC in press
arXiv:2308.16128

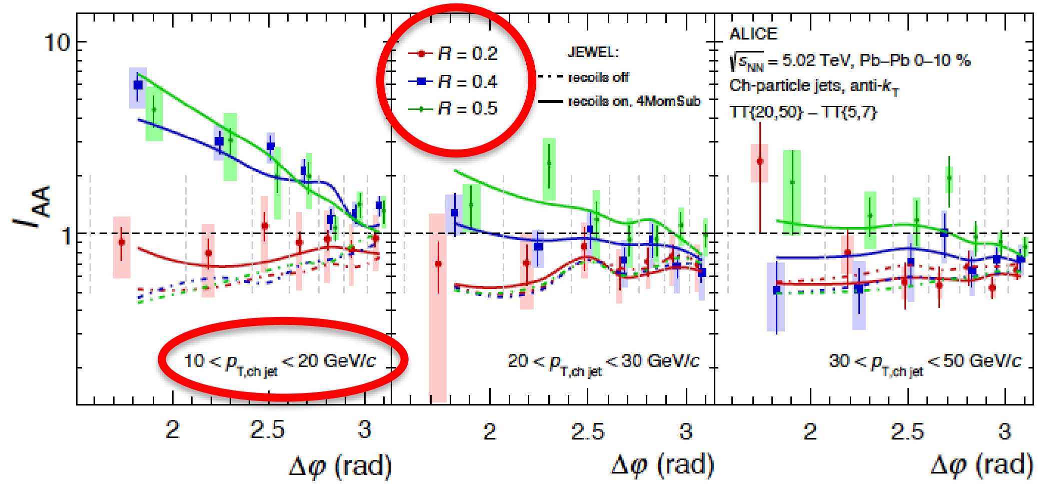
Acoplanarity distribution $\Delta\varphi$: search for in-medium scattering

I_{AA} = ratio of recoil yields PbPb/pp

Striking acoplanarity broadening …only at low p_T and only for large R!



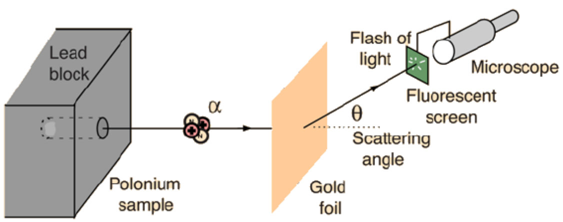


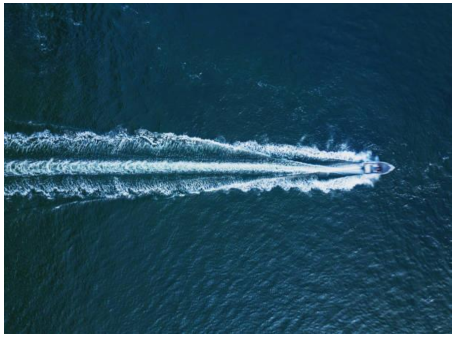


Striking acoplanarity broadening …only at low p_T and only for large R!

Quasi-particle scattering?

QGP medium response (a.k.a. "wake")





Disfavored by strong R-dependence

Currently the favored interpretation

- Run 3 analyses under way for more detailed study

Outlook

Jet quenching as a probe of the QGP was proposed by Bjorken four decades ago

- vast experimental efforts at multiple facilities have amassed a rich dataset
- vast theory effort

But jets are complex multi-hadron objects governed by QCD at multiple scales

→ understanding the effects of the QGP on jets, and in turn understanding what we learn about the QGP from jet quenching, is ongoing

This talk discussed recent progress based on mature LHC data and creative analysis techniques:

- role of coherence in jet quenching → measure color coherence scale of QGP?
- q vs g energy loss; correspondence with Casimir factors
- elucidation of selection bias in measurements of substructure, especially jet broadening
- search for QGP quasi-particle scattering, which revealed the wake instead

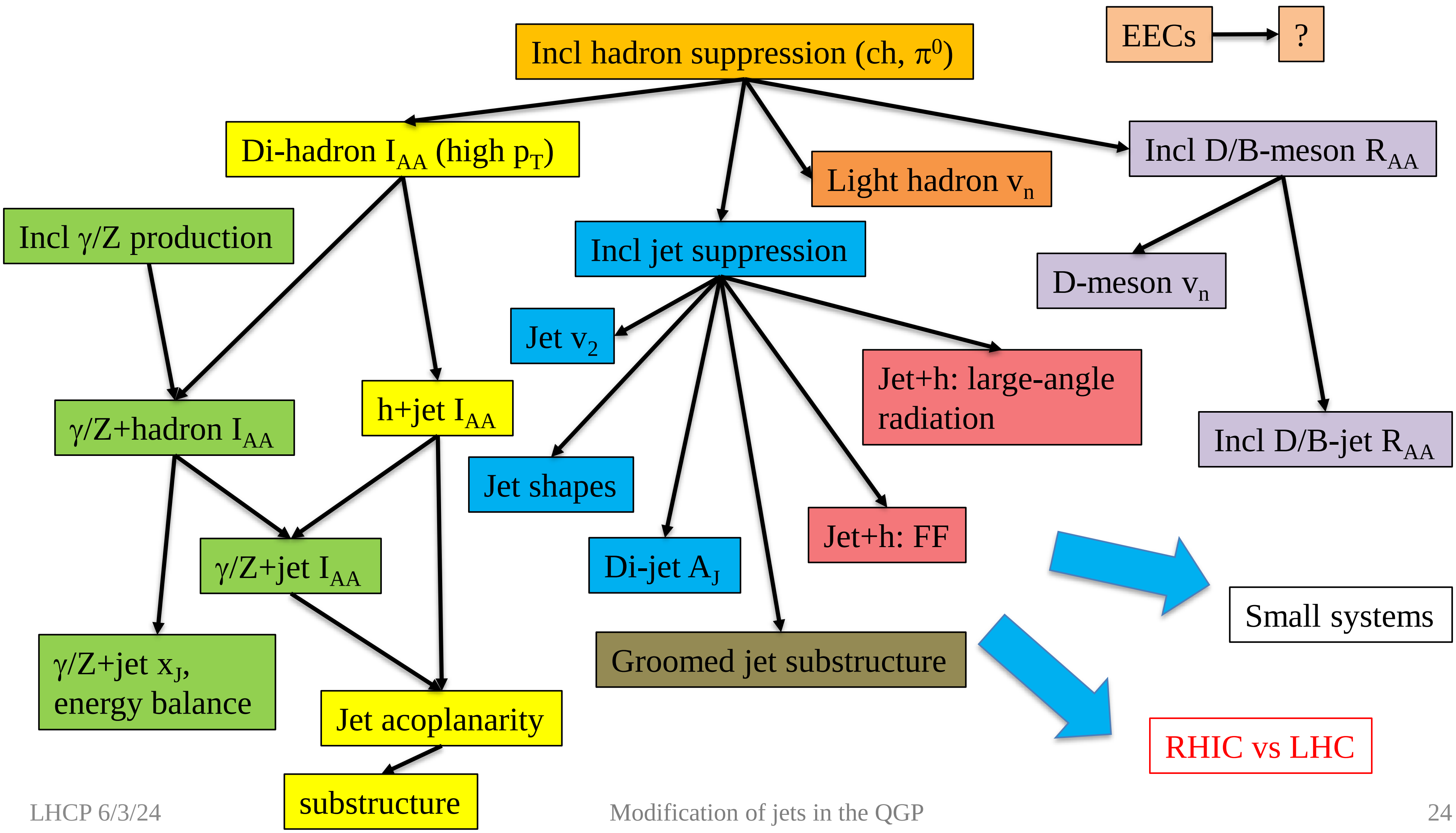
Future:

- LHC Run 3+4; STAR/sPHENIX@RHIC: mature, highly differential measurements
- Ultimate theory/data comparison: multi-observable Bayesian Inference

Extra slides

Taxonomy of current jet quenching measurements

Driven by experimental considerations: arrows connect observables with just one thing changed



Lots of measurements!
How to understand what they are telling us?

Ask targeted questions and go systematically

This talk: focus on recent measurements of jet substructure and correlations…