Experimental results of jet physics in heavy-ion collisions

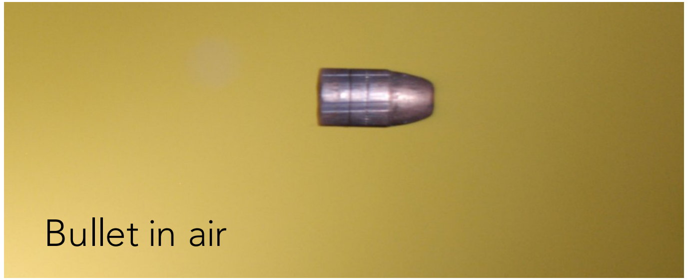
The 8th Asian Triangle Heavy-Ion Conference (ATHIC 2021)

Invited Session 4: Hard Probes

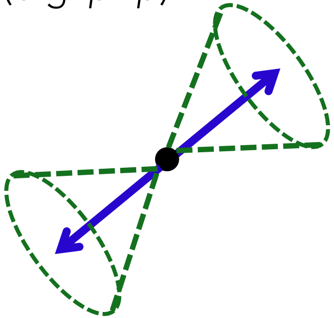
November 7, 2021

Saehanseul Oh (LBNL)

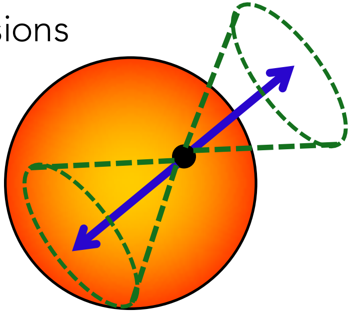
Jets in QCD matter



In vacuum (e.g. p+p)



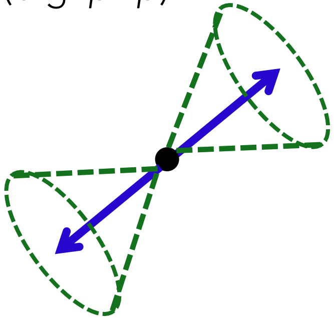
In A+A collisions



Jets in QCD matter

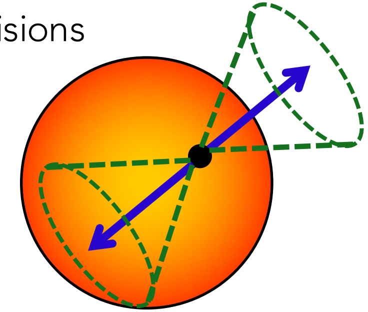
- **Jets in vacuum**
  - Hard-scattered parton fragments into final state particles → Algorithmic recombination into a **Jet**
  - Jets in vacuum are well understood in pQCD framework

In vacuum (e.g. $p+p$)



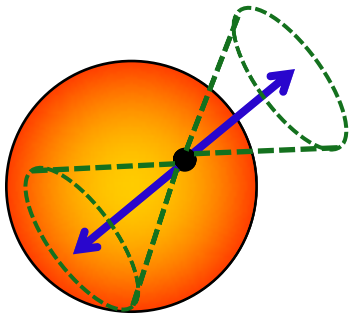
- **Jets in heavy-ion collisions**
  - Hard-scattered partons are produced at the very early stages of collisions → Interact with QGP as they traverse it
  - Any modifications to jet observables are due to the interaction with the QCD medium → **Jet quenching**

In A+A collisions



Jets in QCD matter

- What questions are we trying to answer?
  - How does QGP respond to the external out-of-equilibrium probe, e.g. jets?
  - How can we use jets to probe the microstructure of the QGP?
  - What is the resolution scale of the medium? How can we measure that?
  - What can we learn from the mass dependence of jet quenching?
  - …



Jets in QCD matter

➢ What questions are we trying to answer?

- How does QGP respond to the external out-of-equilibrium probe, e.g. jets?
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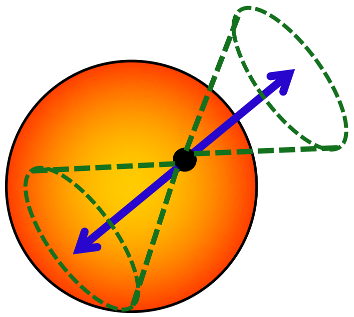
- What is the resolution scale of the medium? How can we measure that?
- What can we learn from the mass dependence of jet quenching?
- …

➢ Jet observables

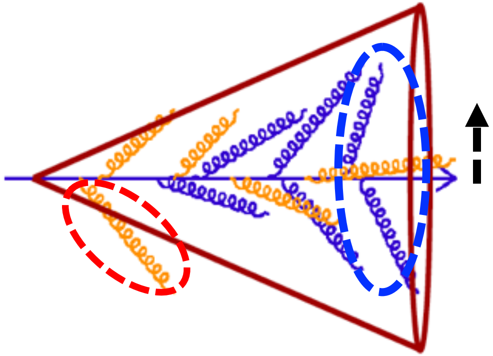
- Each jet observable is connected to one or multiple questions – We can probe different aspects of jet quenching
- We measure the same physics in multiple ways – Consistency



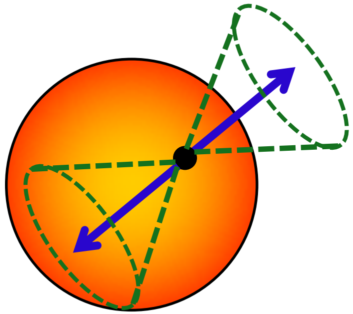
Jets in QCD matter

- What que
  - How d … brium probe, e.g. jets?
  - How c … he QGP?
  - What i … we measure that?
  - How t … QCD properties?
  - What … quenching?
  - …
- Jet observ
  - Each je … uestions
    – We c
  - We me … sistency?

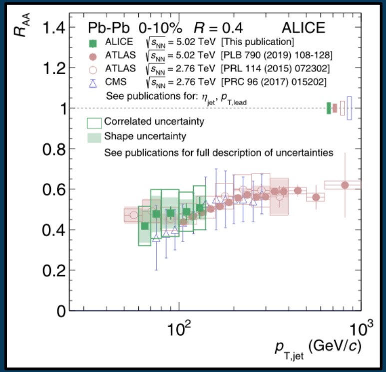
What have we found so far?



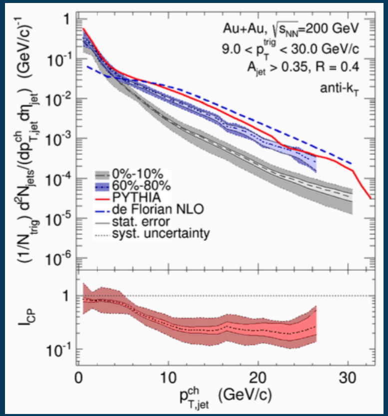
- Jet energy loss
- Jet substructure modification
- Jet deflection



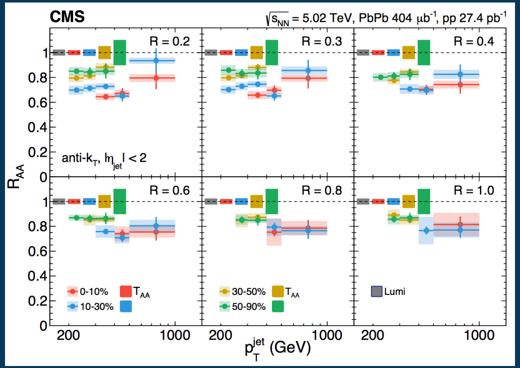
Jet spectra



Pb-Pb 0-10% R = 0.4 ALICE
ALICE √sNN = 5.02 TeV [This publication]
ATLAS √sNN = 5.02 TeV [PLB 790 (2019) 108-128]
ATLAS √sNN = 2.76 TeV [PRL 114 (2015) 072302]
CMS √sNN = 2.76 TeV [PRC 96 (2017) 015202]
See publications for: ηjet, pT,lead
Correlated uncertainty
Shape uncertainty
See publications for full description of uncertainties
RAA
pT,jet (GeV/c)



Au+Au, √sNN=200 GeV
9.0 < pTtrig < 30.0 GeV/c
Ajet > 0.35, R = 0.4
anti-kT
0%-10%
60%-80%
PYTHIA
de Florian NLO
stat. error
syst. uncertainty
ICP
pT,jetch (GeV/c)

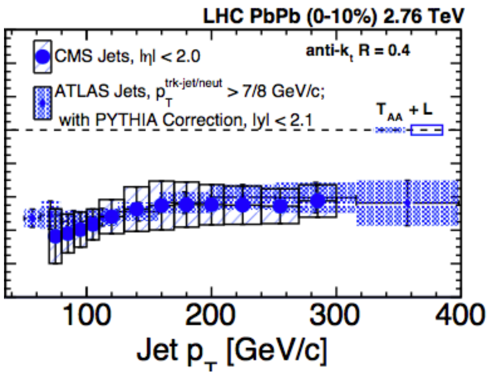


CMS
√sNN = 5.02 TeV, PbPb 404 μb-1, pp 27.4 pb-1
R = 0.2
R = 0.3
R = 0.4
R = 0.6
R = 0.8
R = 1.0
anti-kT, |ηjet| < 2
RAA
0-10%
10-30%
TAA
30-50%
50-90%
Lumi
pTjet (GeV)

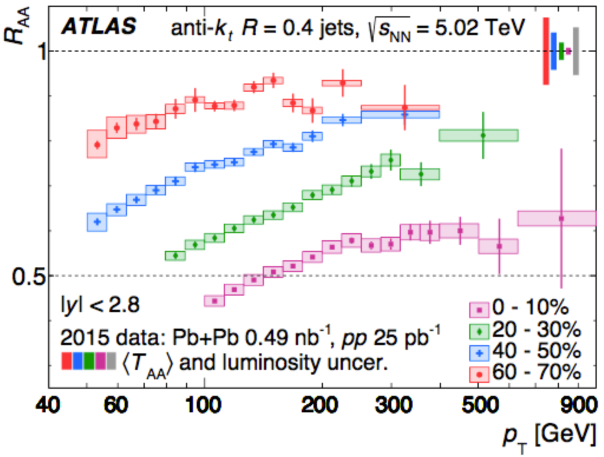
Inclusive jet spectra

- Jet $R_{AA} = \frac{\frac{1}{N_{\mathrm{event}}} \frac{\mathrm{d}^2 N}{\mathrm{d}p_{\mathrm{T,jet}} \mathrm{d}\eta_{\mathrm{jet}}}\Big|_{AA}}{\langle T_{AA} \rangle \frac{\mathrm{d}^2 \sigma}{\mathrm{d}p_{\mathrm{T,jet}} \mathrm{d}\eta_{\mathrm{jet}}}\Big|_{pp}}$ → Basic measurements of jet yield suppression

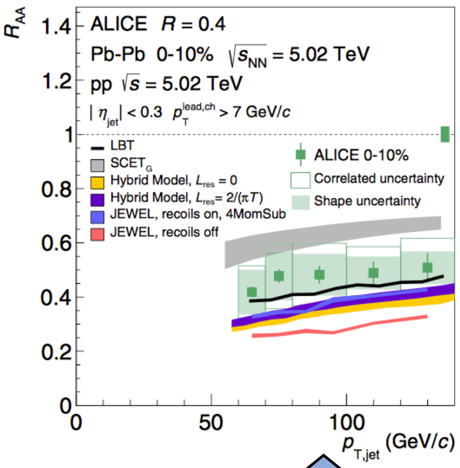
CMS, 2.76 TeV, PRC 96 (2017) 015202



ATLAS, 5.02 TeV, PLB 790 (2019) 108-128



ALICE, 5.02 TeV, PRC 101 (2020) 034911

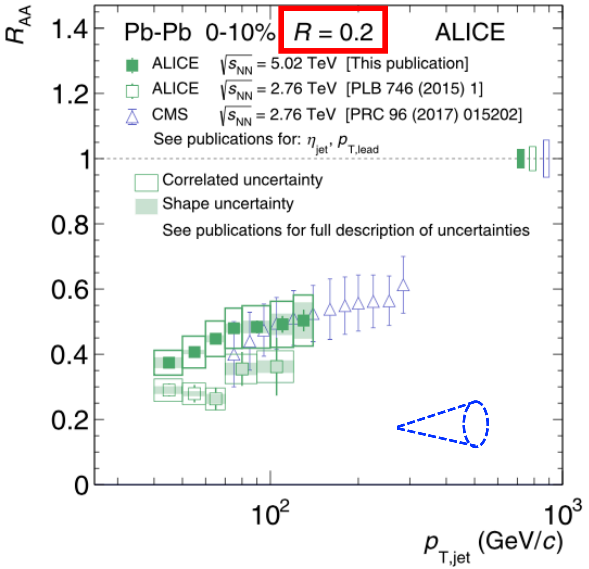


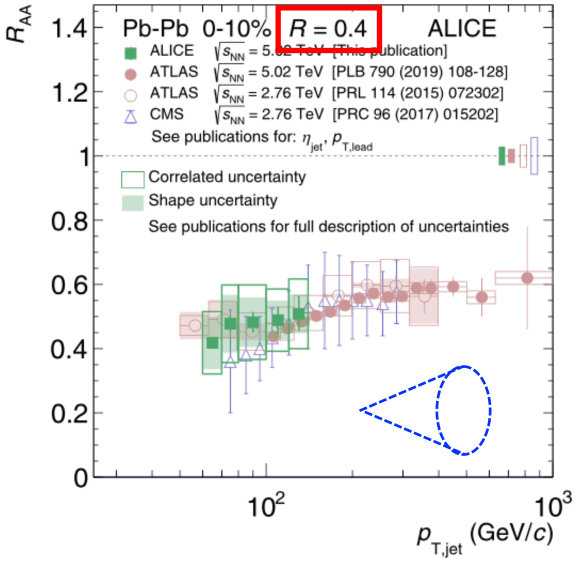
- Most models reasonably describe data – more differential measurements needed

Inclusive jet spectra

- Jet $R_{AA} = \frac{\frac{1}{N_{\mathrm{event}}} \frac{\mathrm{d}^2 N}{\mathrm{d}p_{\mathrm{T,jet}} \mathrm{d}\eta_{\mathrm{jet}}}\Big|_{\mathrm{AA}}}{\langle T_{\mathrm{AA}} \rangle \frac{\mathrm{d}^2 \sigma}{\mathrm{d}p_{\mathrm{T,jet}} \mathrm{d}\eta_{\mathrm{jet}}}\Big|_{pp}}$

ALICE, 5.02 TeV, PRC 101 (2020) 034911



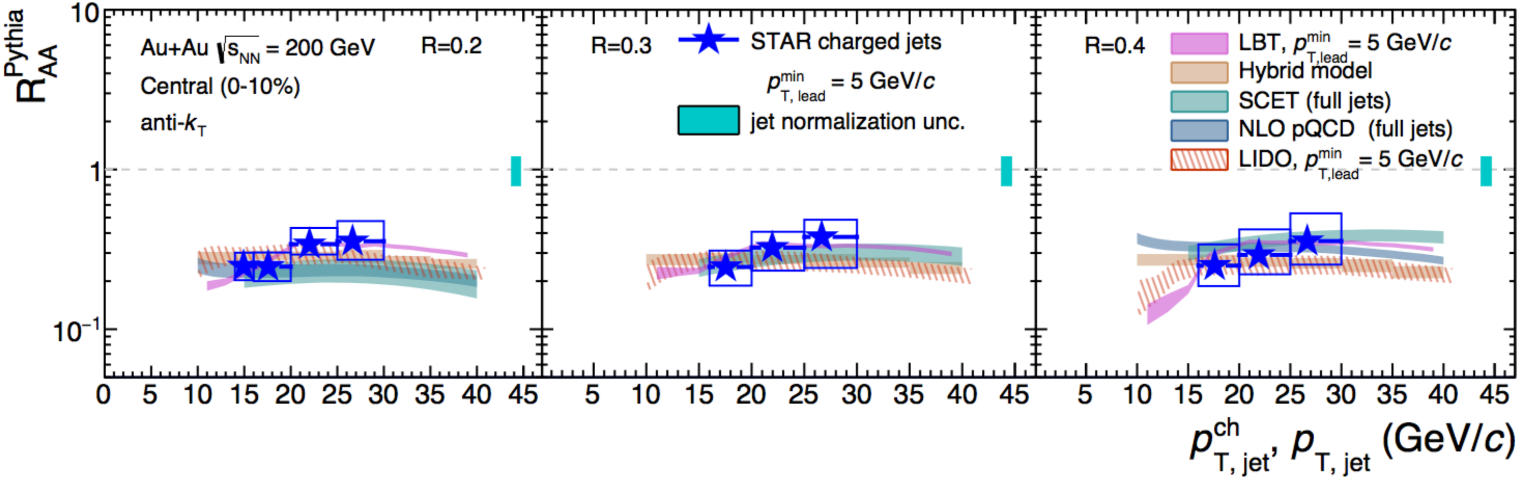


- No clear *R* dependence or collision energy dependence at the LHC at standard *R*
- Consistent R_{AA} values from different collaborations (Different η_{jet}, systematics)
- What about at RHIC energies?

Inclusive jet spectra

➢ Jet $R_{AA} = \frac{\frac{1}{N_{event}} \frac{d^2 N}{dp_{T,jet} d\eta_{jet}}\Big|_{AA}}{\langle T_{AA}\rangle \frac{d^2\sigma}{dp_{T,jet} d\eta_{jet}}\Big|_{pp}}$

STAR, 0.2 TeV, PRC 102 (2020) 054913

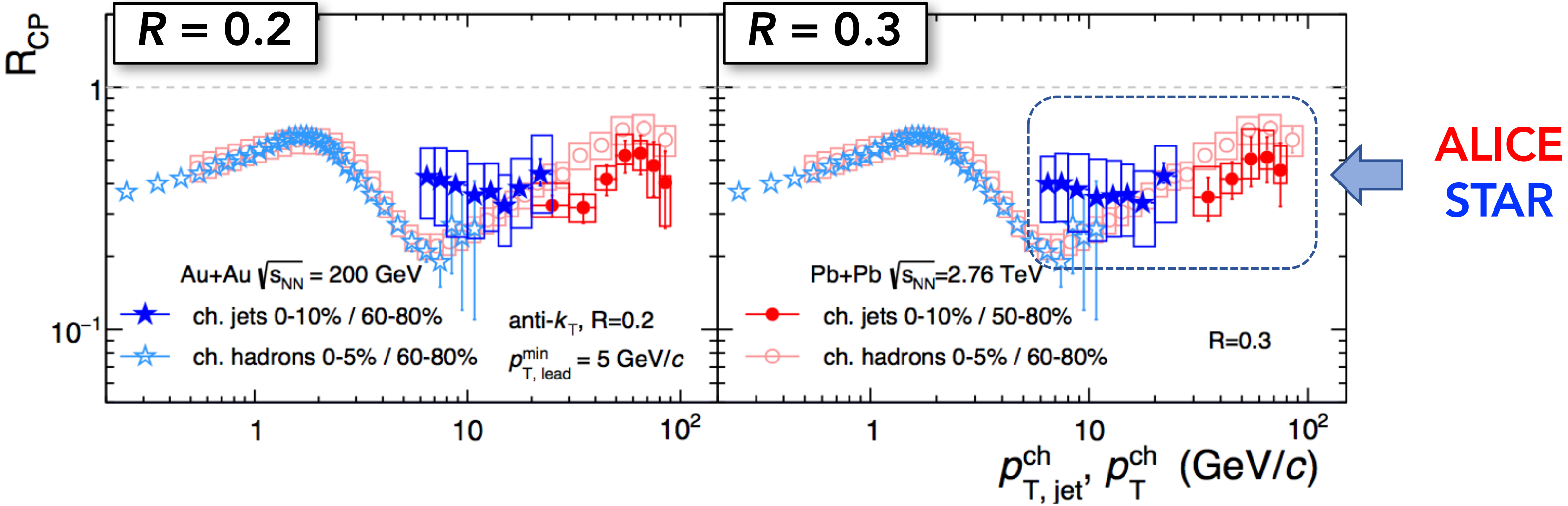


- Inclusive charged-particle jet spectra at 200 GeV Au+Au collisions with respect to PYTHIA

Inclusive jet spectra

- Jet R_{CP} – Comparison between central and peripheral collisions

STAR, 0.2 TeV, PRC 102 (2020) 054913

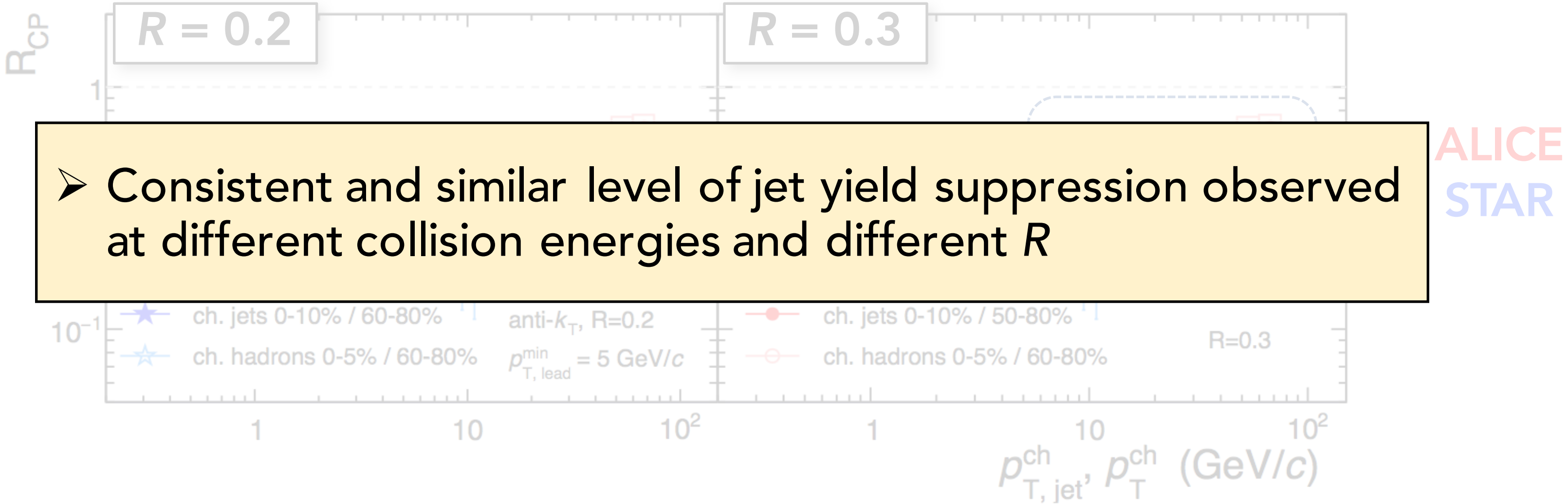


- Similar level of suppression between 200 GeV and 2.76 TeV, although their spectrum shapes are different

Inclusive jet spectra

- Jet R_{CP} – Comparison between central and peripheral collisions

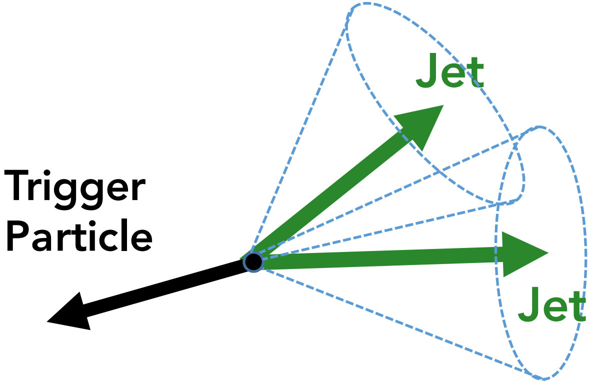
STAR, 0.2 TeV, PRC 102 (2020) 054913



- Consistent and similar level of jet yield suppression observed at different collision energies and different *R*

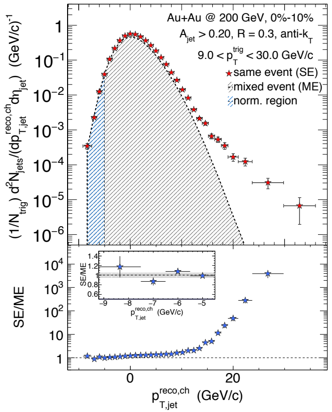
- Similar level of suppression between 200 GeV and 2.76 TeV, although their spectrum shapes are different

Semi-inclusive jet spectra



- Semi-inclusive jet measurements
  - Jets in the recoil region of high-p_T trigger particles
  - Correlated vs. uncorrelated contributions with respect to the trigger particle → Effective removal of the latter
  - Capability to access lower $p_{T,jet}$

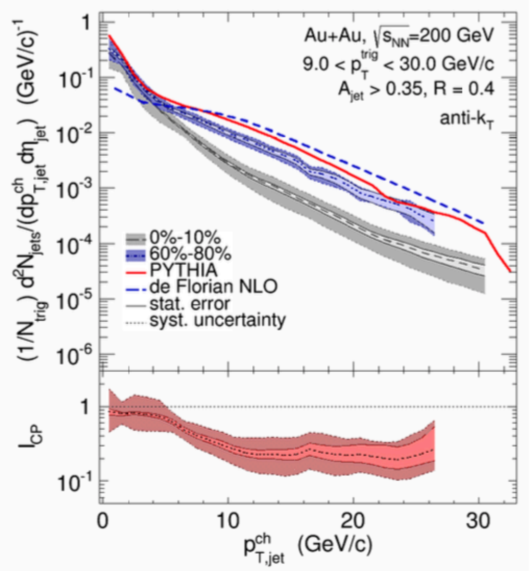
STAR, Phys. Rev. C 96 (2017) 24905



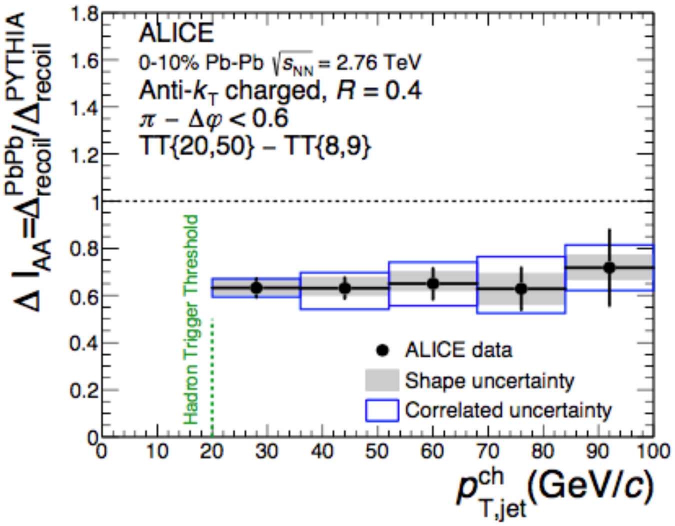
Removal of uncorrelated contributions with a Mixed-event technique

Semi-inclusive jet spectra

STAR, Phys. Rev. C 96 (2017) 24905



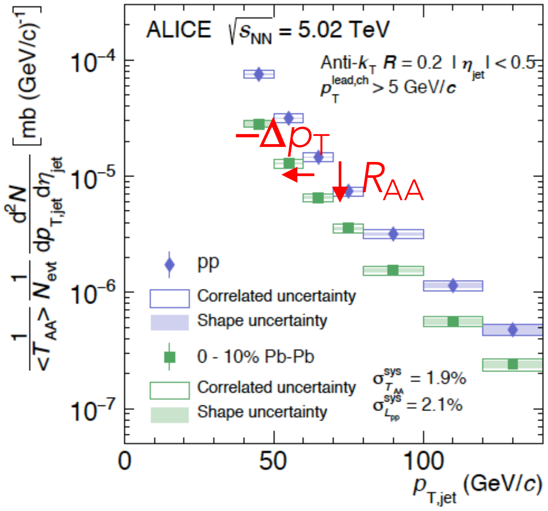
ALICE, JHEP 09 (2015) 170



- I_{CP} , I_{AA}= The ratio of recoil jet yields in central to peripheral or *pp* distributions

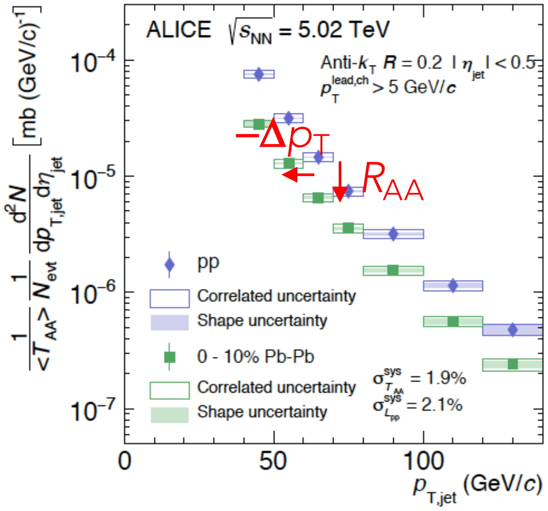
- Similar level of suppression via I_{CP} to charged-particle jet R_{CP} at 200 GeV

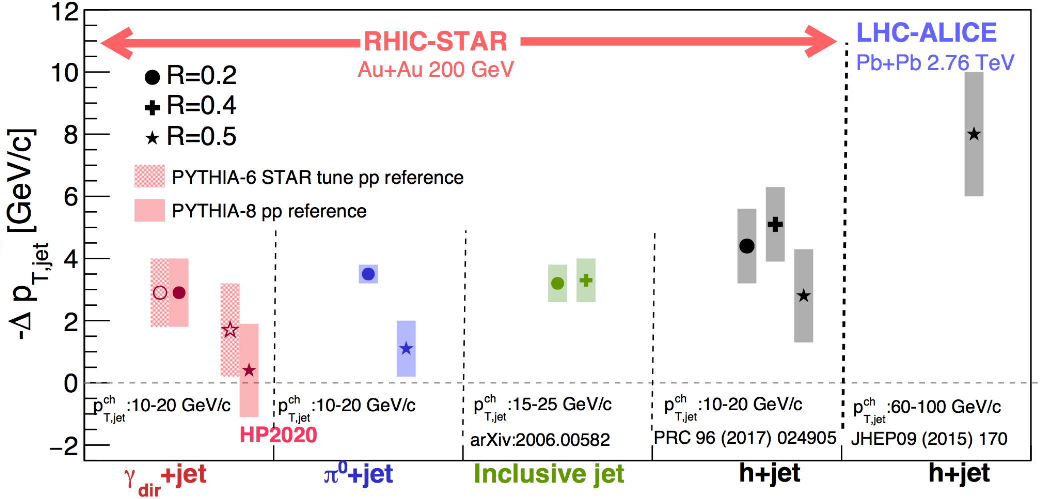
Inclusive and semi-inclusive jet spectra



- In addition to R_{AA} or $I_{AA,}$ jet yield suppression can be quantified with $-\Delta p_T$

Inclusive and semi-inclusive jet spectra





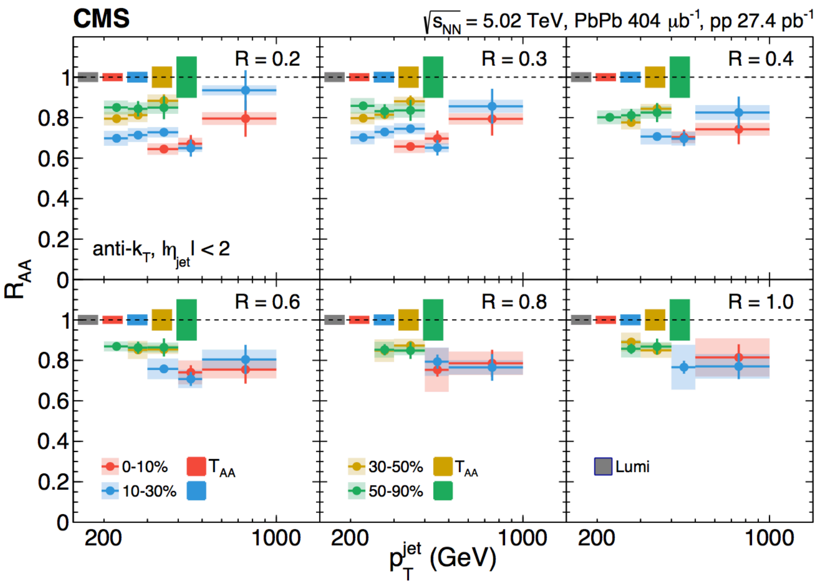
- In addition to R_{AA} or I_{AA}, jet yield suppression can be quantified with $-\Delta p_T$

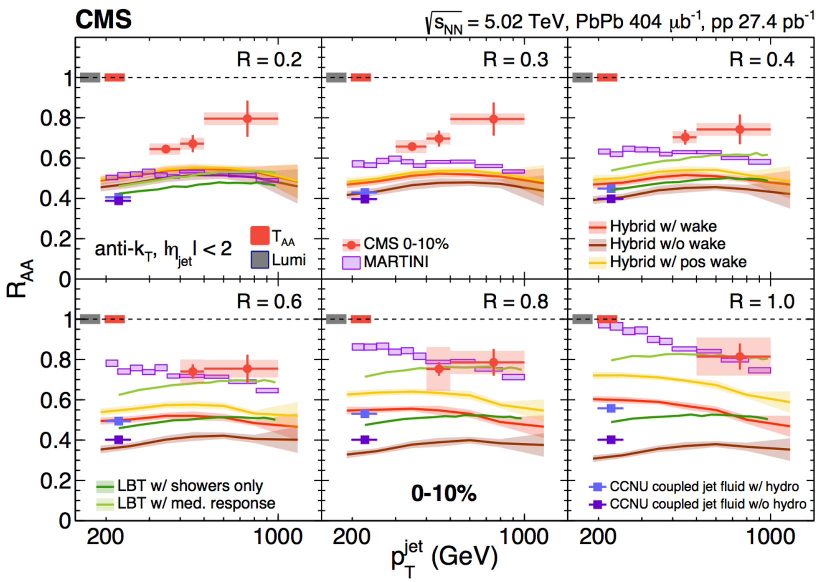
- At RHIC, similar energy loss for different channels of measurements
- **At the LHC with higher $p_{T,jet}$, indication of larger energy loss than RHIC for h+jet measurements**
- Further $-\Delta p_T$ quantification for other spectrum measurements is needed

Inclusive jet spectra at larger jet *R*

➢ Jet R_{AA} at higher jet *R* – Wider jets more suppressed? Quenched energy toward larger *R*?

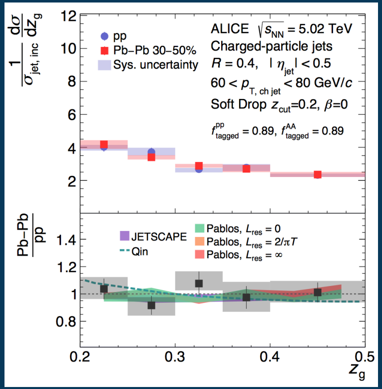
CMS – 5.02 TeV, JHEP 05 (2021) 284

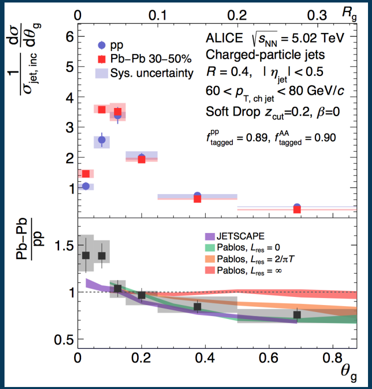


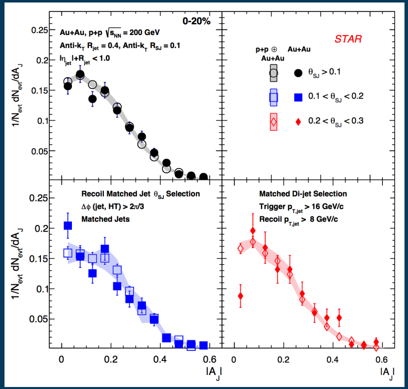


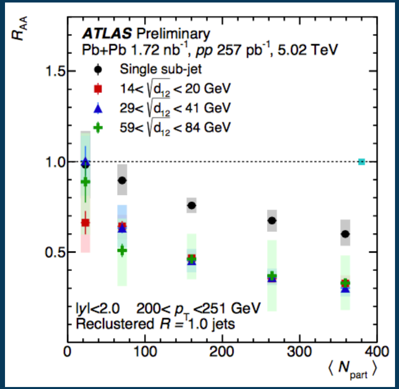
- No strong dependence on jet radius persists at large *R* (=1.0) and high $p_{T,jet}$ (1 TeV/*c*)
- Significant tension between models – Further constraints on the underlying jet quenching mechanisms

Jet substructure observables



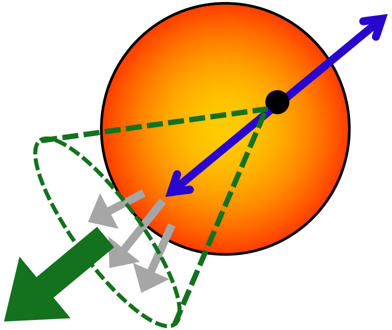


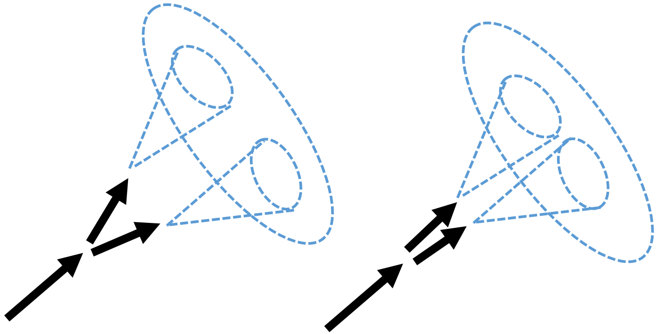




Jet substructure observables

- Given the jet energy loss in the medium, how is the shower modified when a jet traverses the medium?

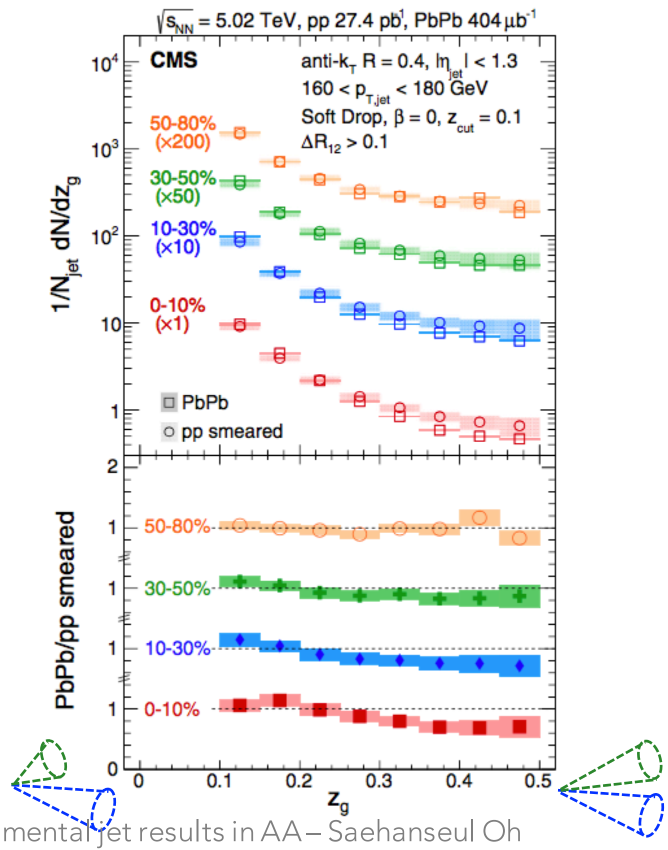




- Do these jets quench differently in QCD medium? What is the resolution scale of the medium?

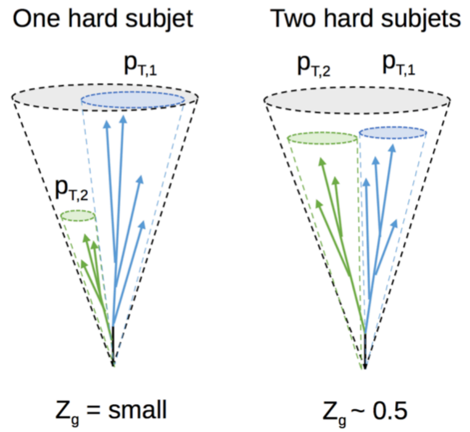
Groomed jet substructure

CMS, PRL 120 (2018) 142302



- Jet grooming via SoftDrop : $\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1}+p_{T,2}} > z_{cut}\left(\frac{\Delta R}{R}\right)^{\beta}$

$$z_g = \frac{p_{T,2}}{p_{T,1}+p_{T,2}}$$



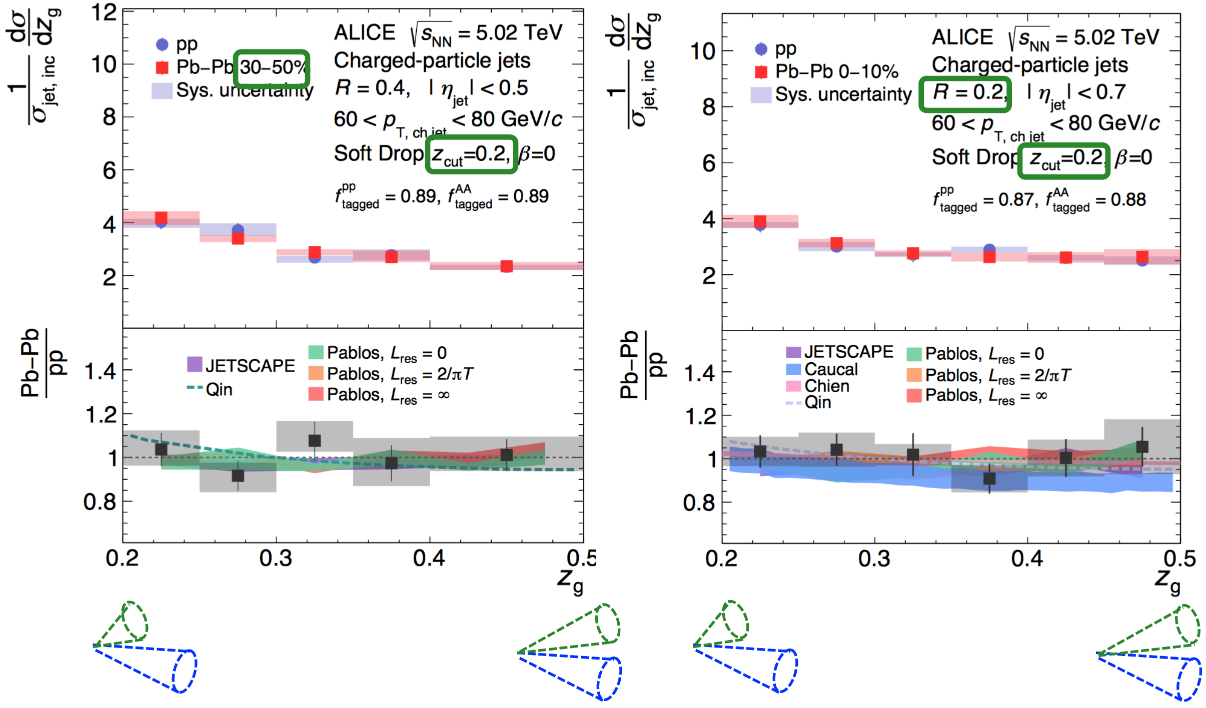
- Comparison between A+A and smeared *pp* results
- Steeper z_g distributions in central Pb+Pb collisions – parton splitting process is modified by the medium

Groomed jet substructure

- Background fluctuations in heavy-ion environment result in an incorrect splitting being identified by the grooming algorithm
- Smaller R jets, increased z_{cut} in SD, using semi-central collisions

- z_g distributions in Pb+Pb collisions are consistent with those of pp collisions within experimental uncertainties

ALICE, arXiv:2107.12984

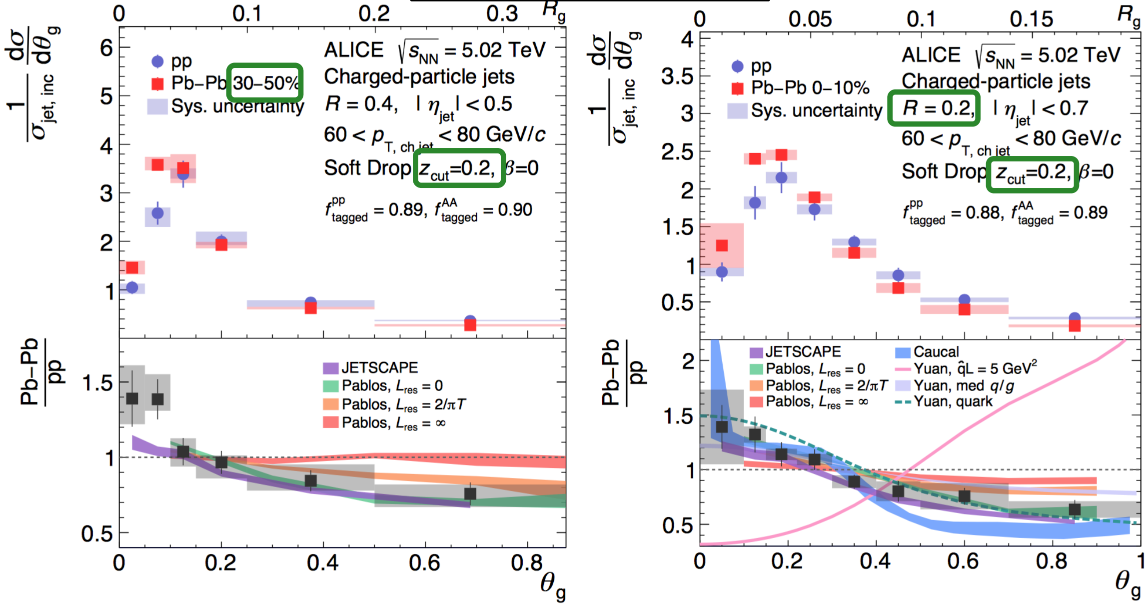


Groomed jet substructure

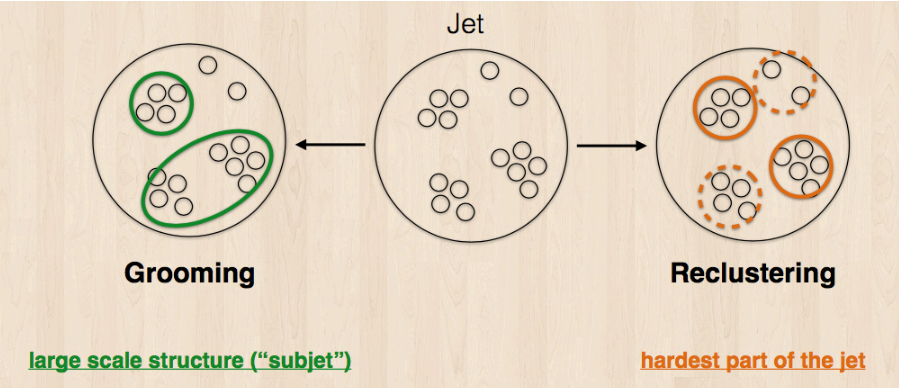
- Background fluctuations in heavy-ion environment result in an incorrect splitting being identified by the grooming algorithm
- Smaller R jets, increased z_{cut} in SD, using semi-central collisions

- Suppression (enhancement) of large (small) angles – Qualitative description by models

ALICE, arXiv:2107.12984

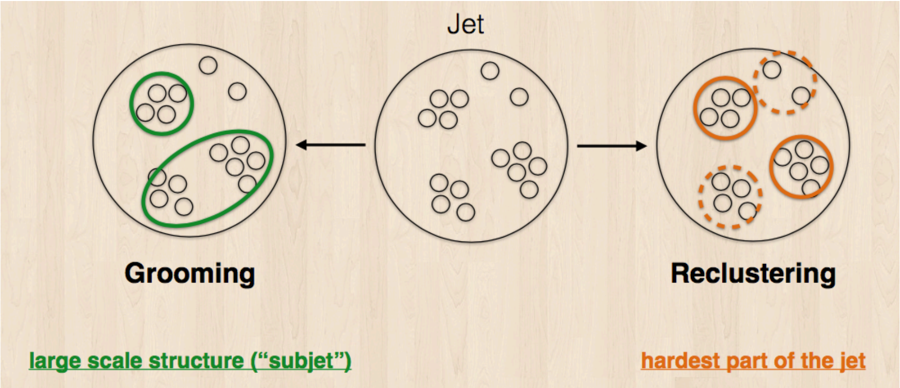


Jet substructure with subjets



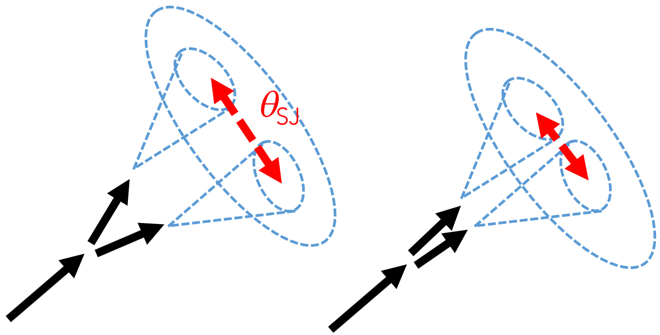
- Reclustering jets with smaller resolution parameter ($r < R$) with the original jet constituents
- Subjets are proxy for the hardest shower splitting

Jet substructure with subjets



- Reclustering jets with smaller resolution parameter ($r < R$) with the original jet constituents
- Subjets are proxy for the hardest shower splitting

θ_{SJ} = Distance between two hardest subjets

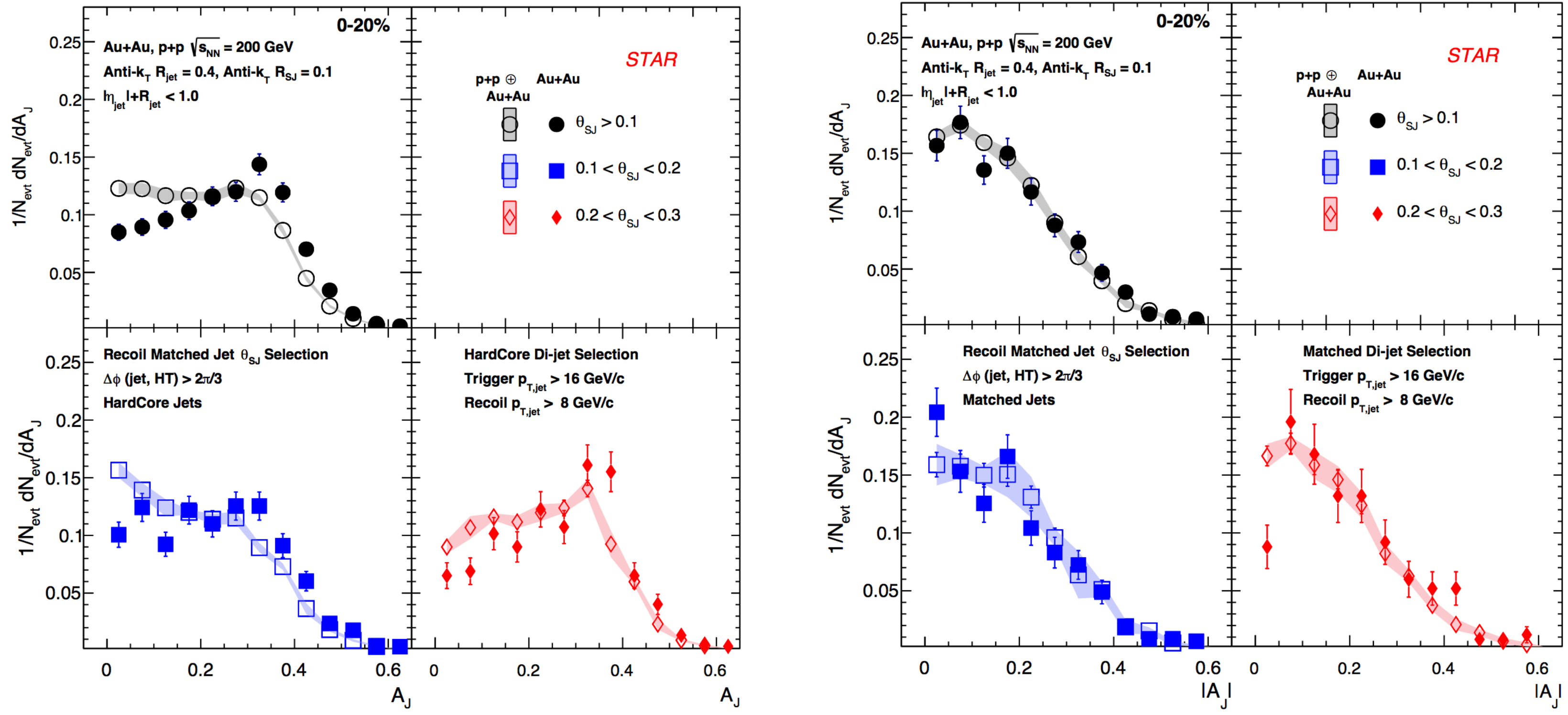


Is jet quenching different for two θ_{SJ} classes?

Jet substructure with subjets

$$A_J = \frac{p_T^{Lead} - p_T^{SubLead}}{p_T^{Lead} + p_T^{SubLead}}$$

STAR, arXiv:2109.09793

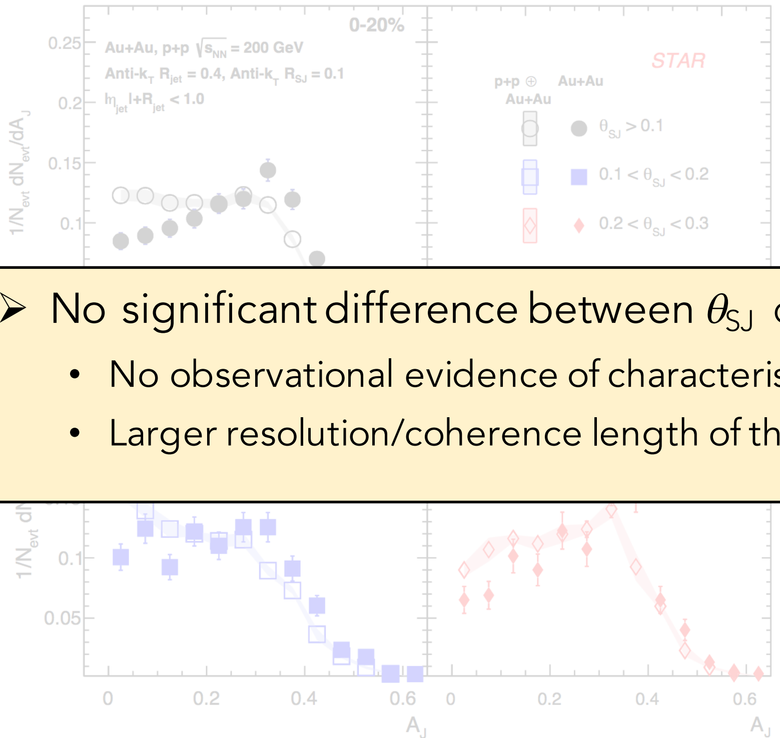


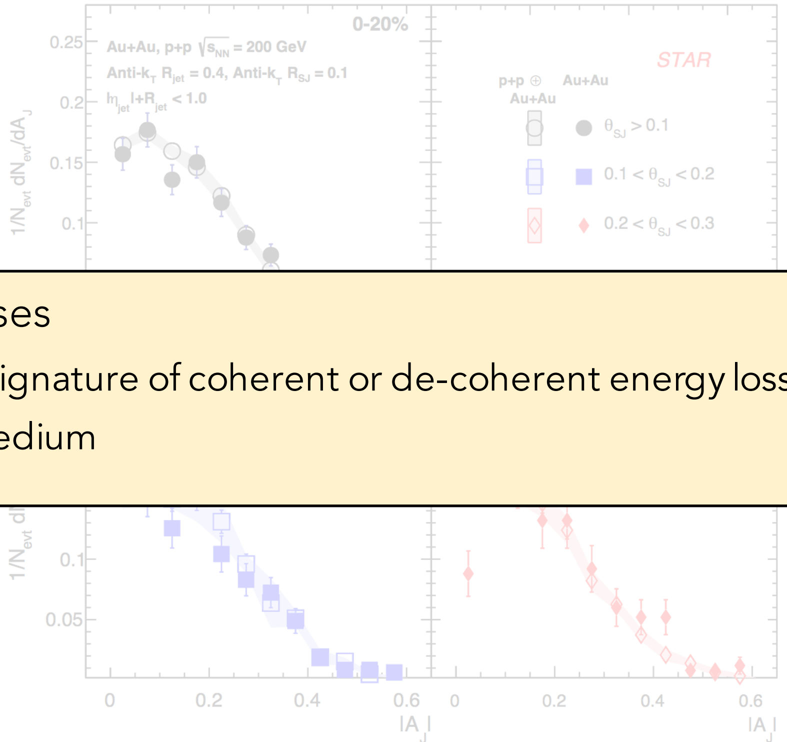
Jet substructure with subjets

HardCore jets

STAR, arXiv:2109.09793

Matched jets



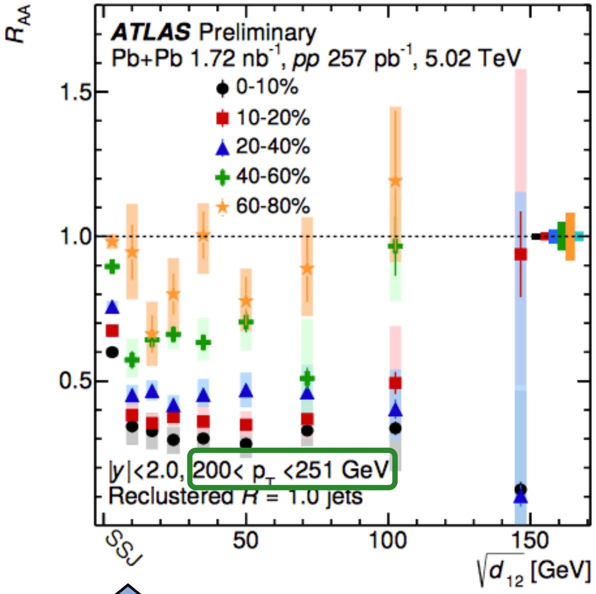


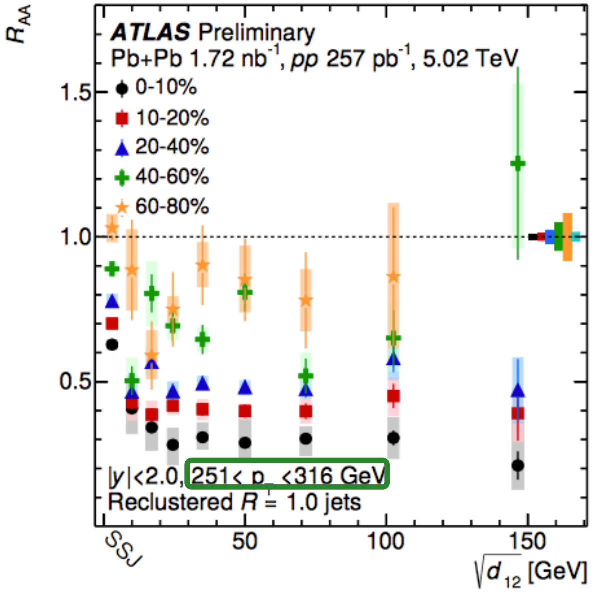
- ➢ No significant difference between θ_{SJ} classes
  - No observational evidence of characteristic signature of coherent or de-coherent energy loss
  - Larger resolution/coherence length of the medium

Jet substructure with subjets

ATLAS, 5.02 TeV

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

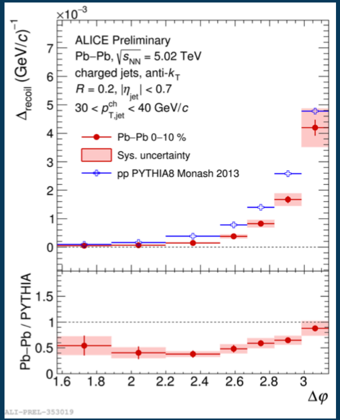


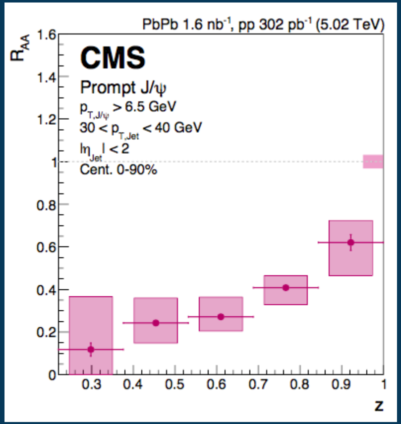


$\sqrt{d_{12}} = 0$ → Single isolated subjet

- Small $\sqrt{d_{12}}$ dependence for jets with a complex substructure, i.e. $\sqrt{d_{12}} > 0$ jets
- Significant difference in jet quenching between jets with a single subjet and jets with multi-prong structure

Other jet observables





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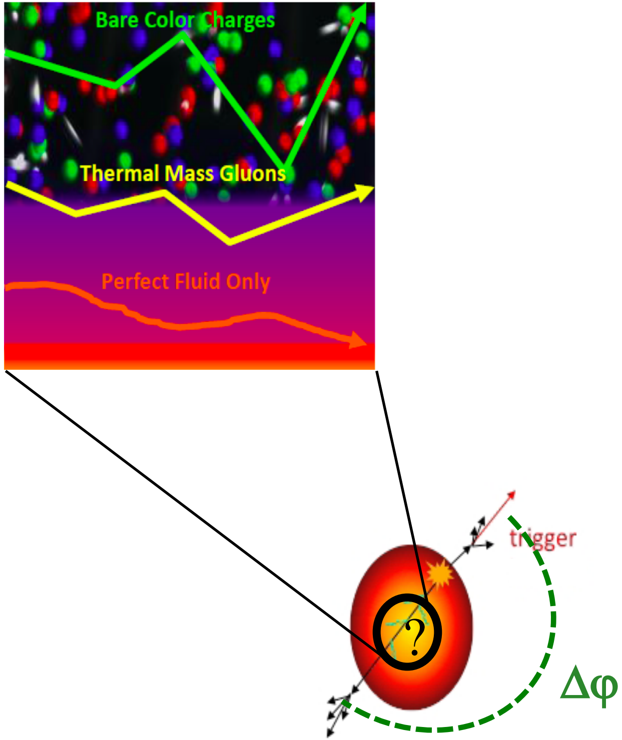
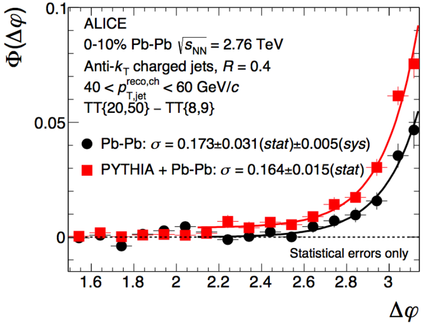
Jet acoplanarity

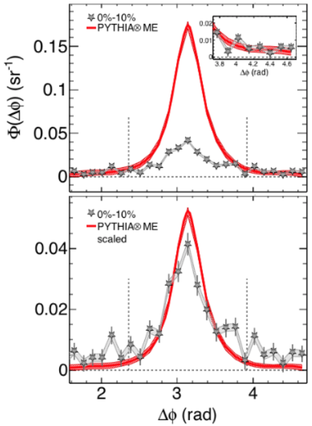


➢ Angular decorrelations between a trigger particle and its recoil jet – Are we seeing <u>discrete scattering centers</u> or <u>effectively continuous medium</u>?

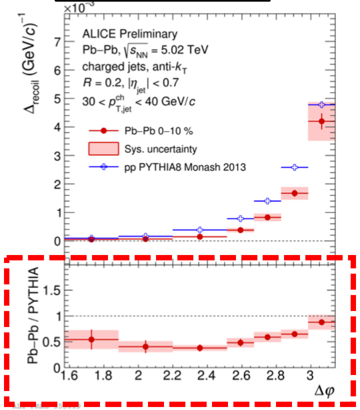
ALICE, JHEP 09 (2015) 170



STAR, Phys. Rev. C 96 (2017) 24905



ALICE, 5.02 TeV

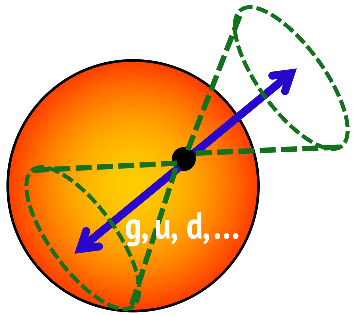


- Narrowing in central Pb+Pb collisions ← due to negative radiative correction to $\langle p_T^2 \rangle$? (Zakharov, EPJC 81 (2021) 57)

J/ψ in jets

CMS, arXiv:2106.13235

STAR, 0.5 TeV, *pp*

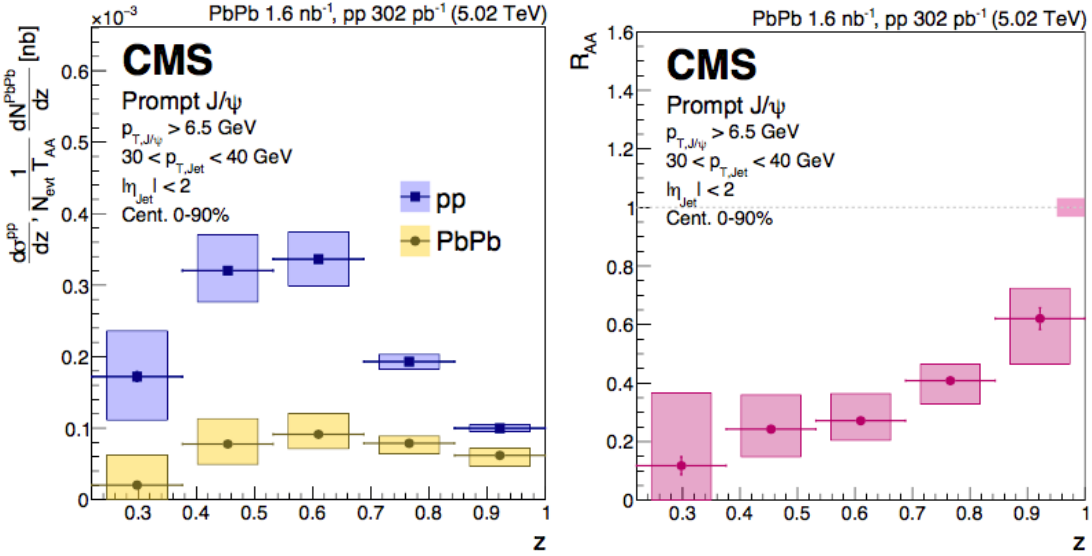


Does jet quenching depend on the flavor of the parton?

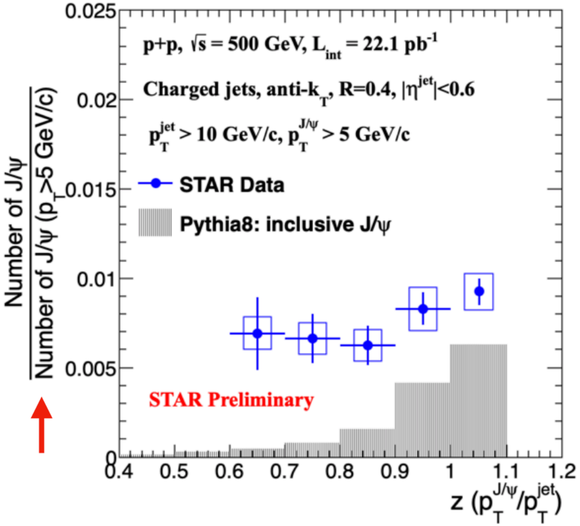
- Jets contai…
  - J/ψ proc… …re more suppressed – Need to incorporate Jet quenching + J/ψ suppression?
  - Further results coming at RHIC energies

J/ψ in jets

CMS, arXiv:2106.13235

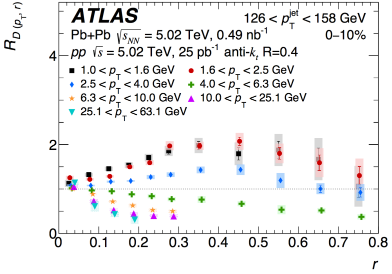


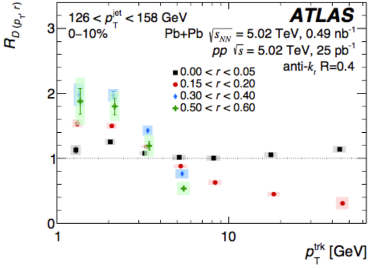
STAR, 0.5 TeV, *pp*

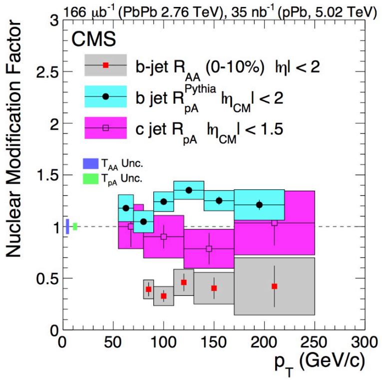


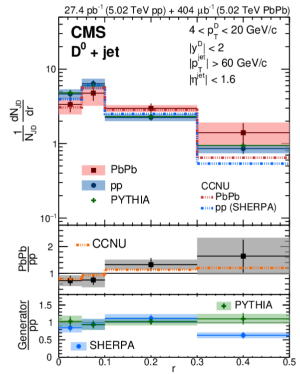
- Jets containing a prompt (or inclusive) J/ψ
  - J/ψ produced with a larger degree of surrounding jet activity are more suppressed – Need to incorporate Jet quenching + J/ψ suppression?
  - Further results coming at RHIC energies

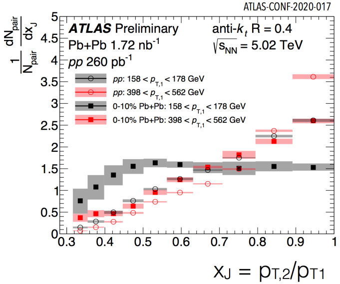
Other observables

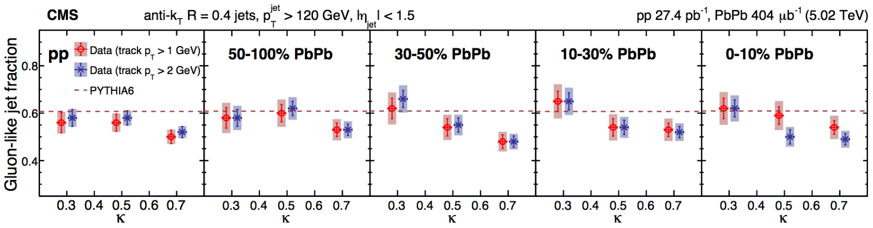


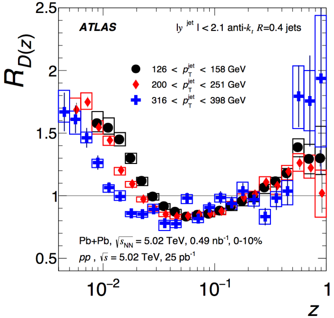


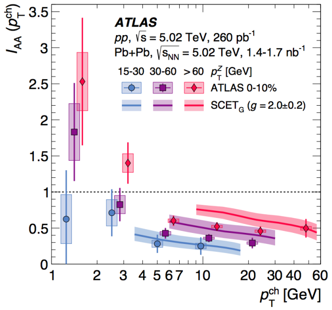












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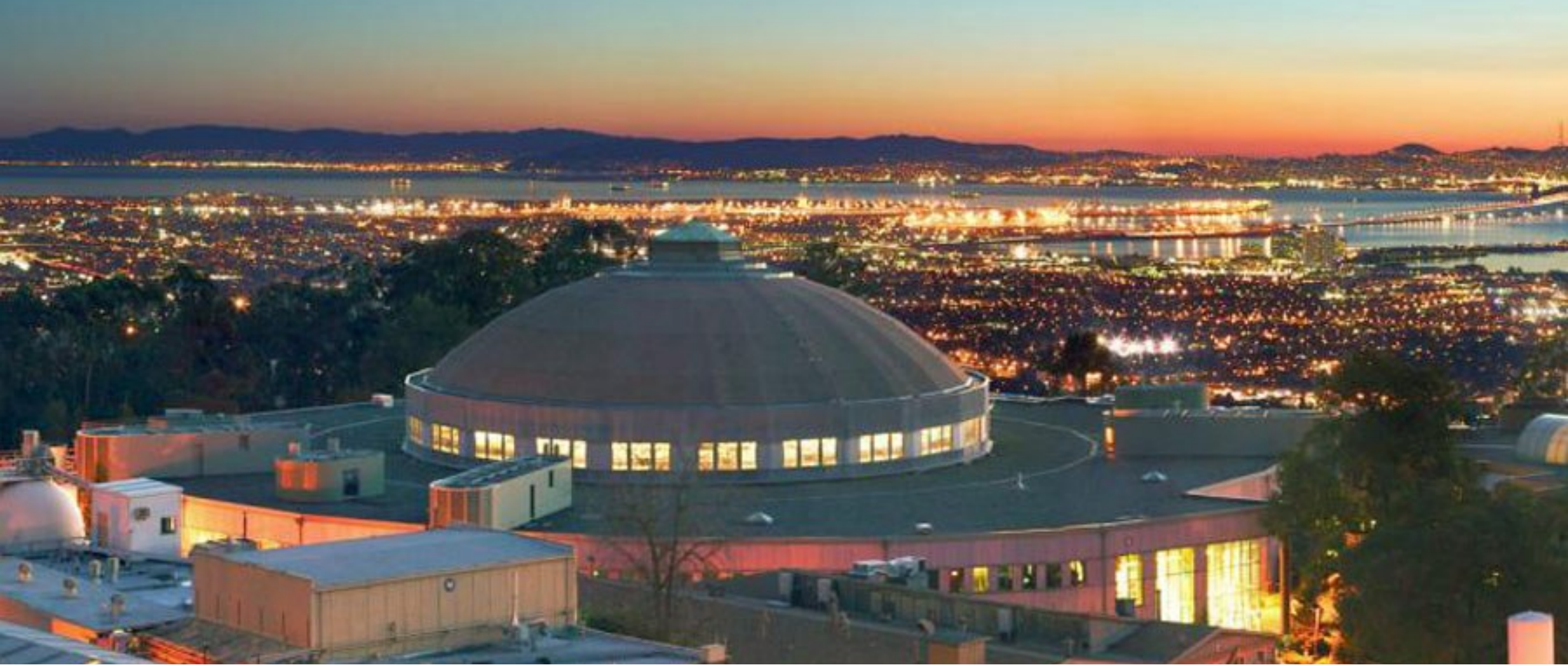
➢ There are more results deserved to be mentioned…

Summary

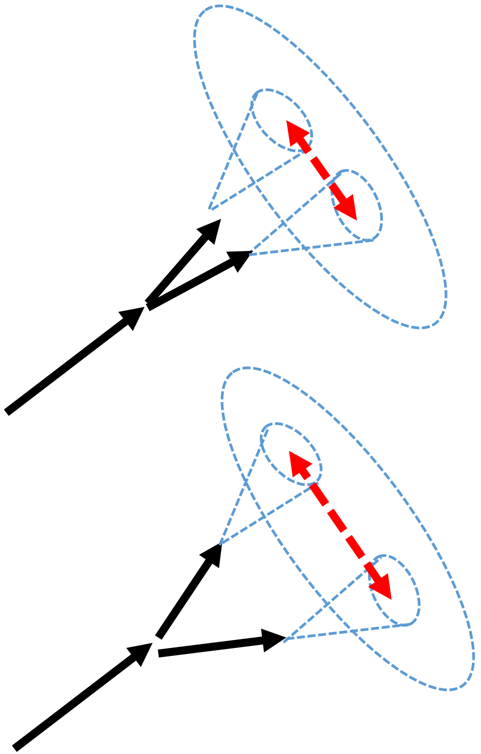
- Jets provide unique tools to study hot dense QCD medium
  - Jets in vacuum and in-medium: theoretically well controlled in many aspects (but not all)
  - Broad kinematic reach: probe the medium over a wide range in scale
  - Complex structure: many complementary observables that probe similar physics – require consistent picture

- Experimental jet results
  - Jet R_{AA} and I_{AA} show consistent values for different R and collision energy
  - Parton splitting process is modified by the medium
  - Jet classification based on subjet distance can shed light on medium resolution scale
  - Further results expected to be presented at QM 2022, and more data coming with LHC Run 3, and RHIC 2023-2025 run with advanced detectors



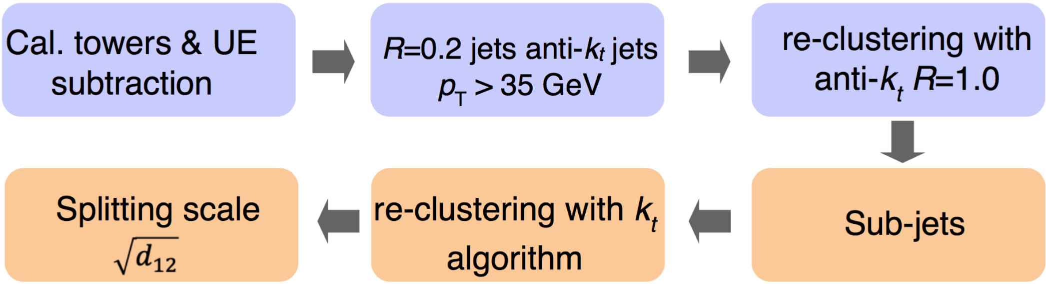
Thank you!

Jet substructure with subjets



ATLAS, 5.02 TeV

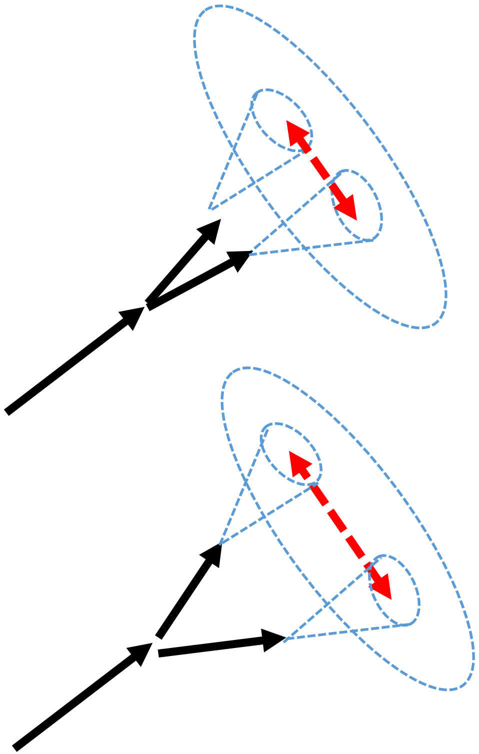
- ATLAS measurements using reclustered large-R jets



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

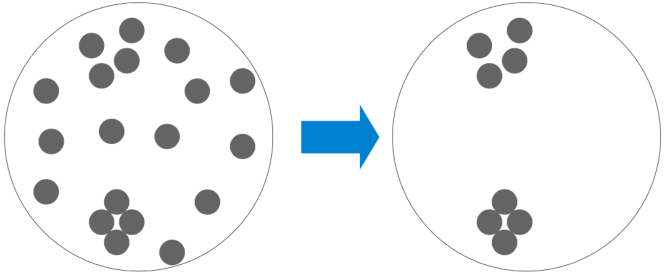
with two jets before the final clustering step

Jet substructure with subjets



ATLAS, 5.02 TeV

- ATLAS measurements using reclustered large-*R* jets

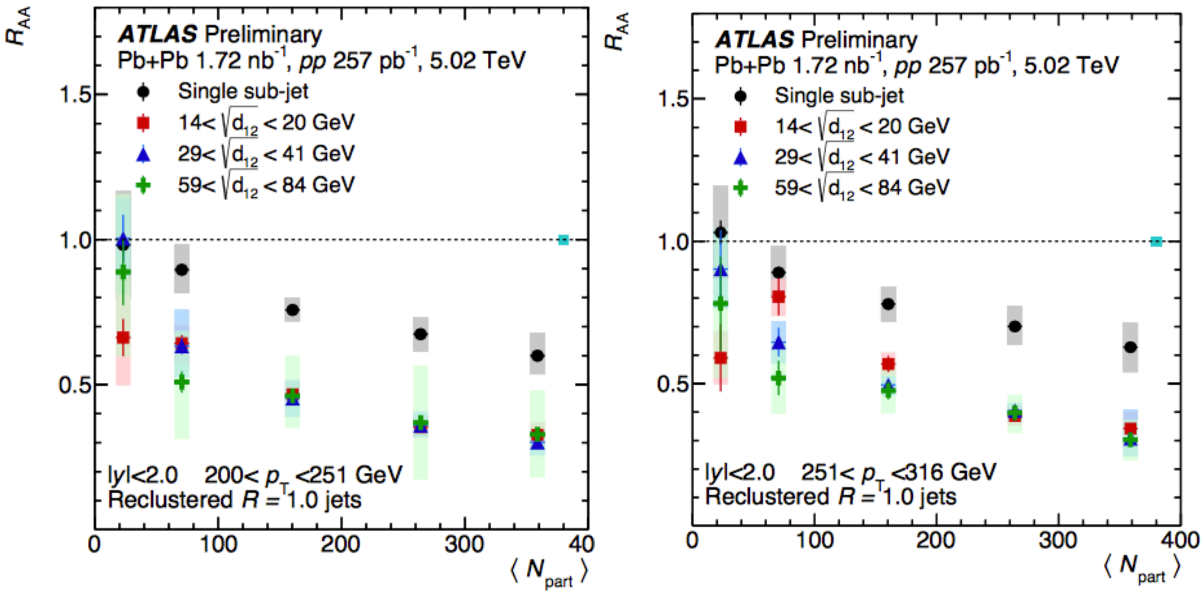


- Reclustered jets are different to the conventional R = 1.0 jets
- Trimming and 35 GeV/c threshold remove soft components

Jet substructure with subjets

Utilizing subjets, i.e. reclustering

ATLAS, 5.02 TeV



- Small $\sqrt{d_{12}}$ dependence for jets with a complex substructure, i.e. $\sqrt{d_{12}} > 0$ jets
- Significant difference in jet quenching between jets with a single subjet and jets with multi-prong structure