Jets in heavy-ion collisions

- Introductory lecture from a experimental jet physicist

High energy nuclear physics school for young physicists 2022

Inha University, Incheon, South Korea

November 19th, 2022

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Announcement

- ➢ This lecture will be given in Korean/English
- ➢ You can ask questions whenever you want to. (You are encouraged to do so!)

Outline

- What is a jet?
- How to find jets?
- What have we done with/about jets?

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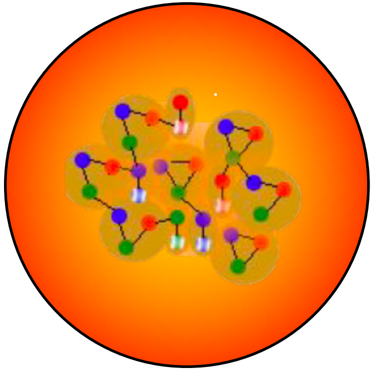
Quark-Gluon Plasma



- Quark-Gluon Plasma created from heavy-ion collisions
- How can we measure the properties of the QGP?

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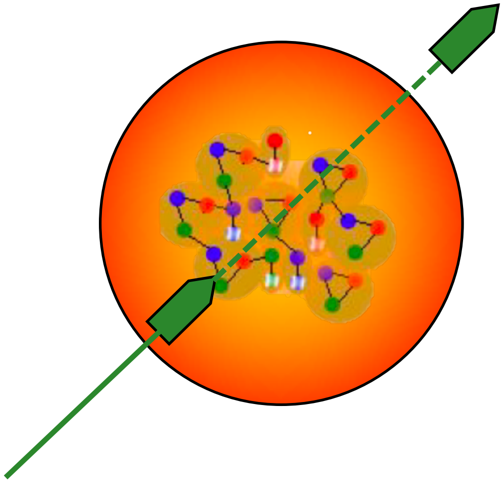

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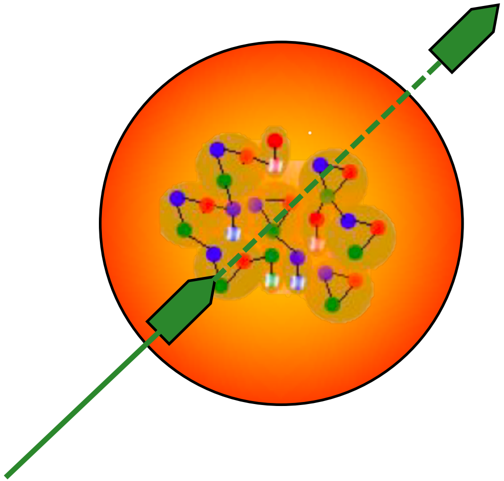

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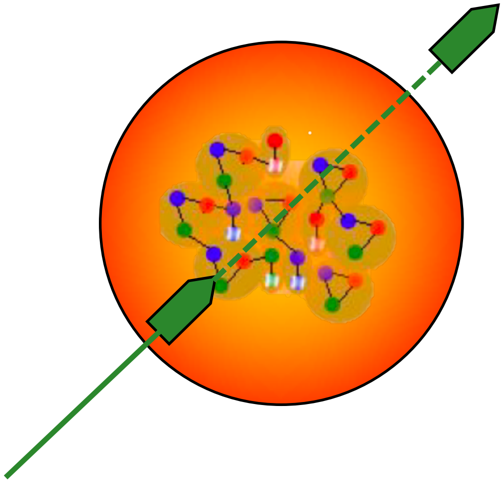
Bullet in water

Do we have external particles that can work as a bullet in water? **No**

Quark-Gluon Plasma



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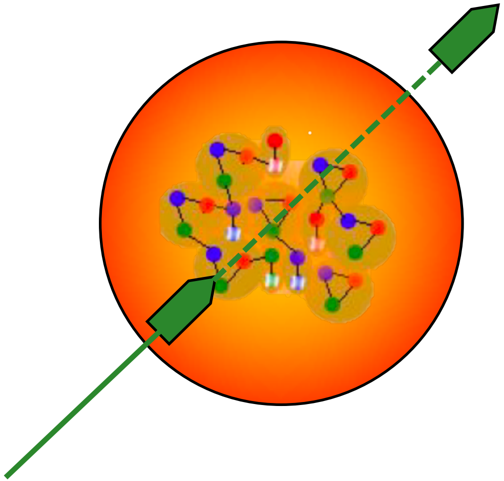
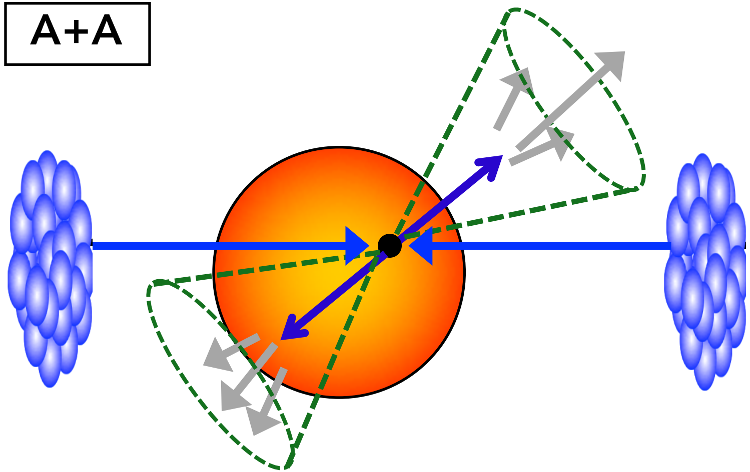
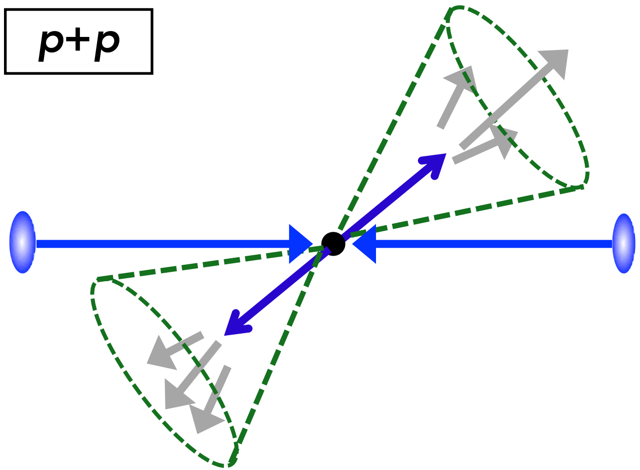


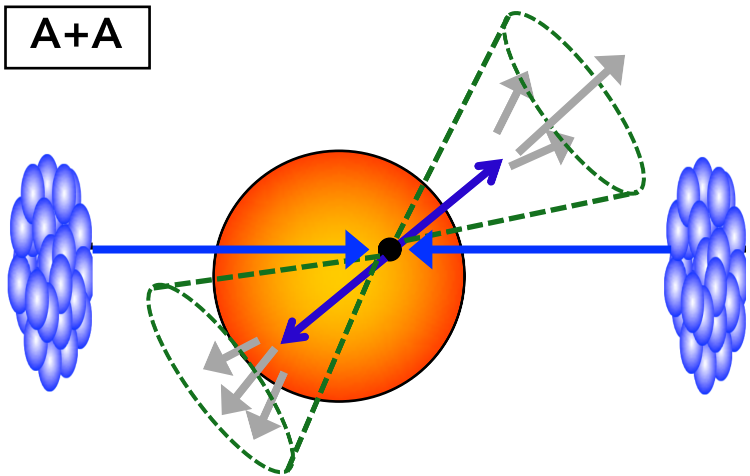


- Hard-scattered partons are produced at the very early stages of collisions → Interact with QGP as they traverse it

Quark-Gluon Plasma

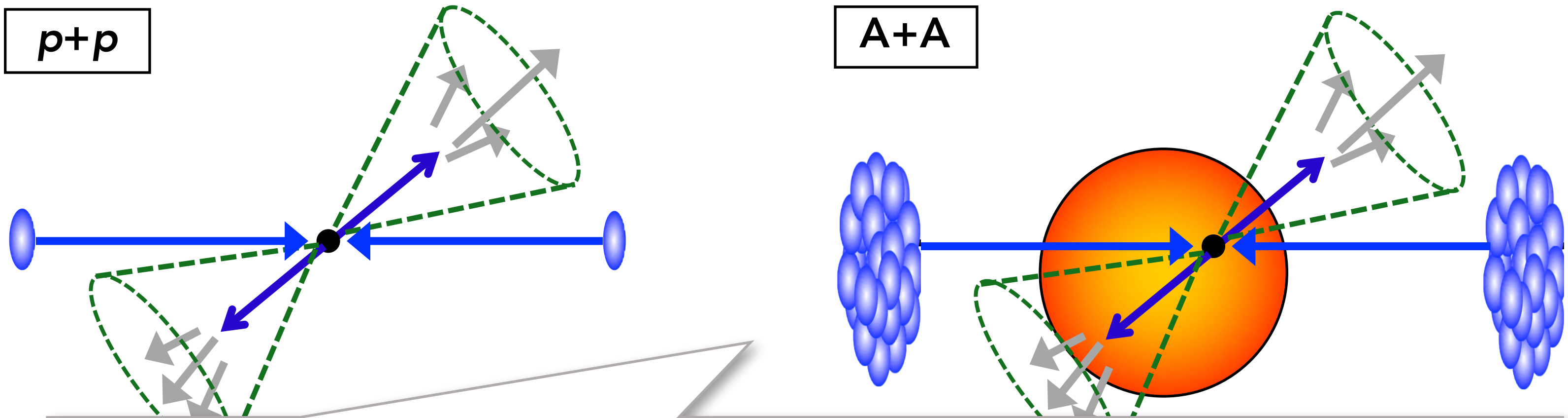


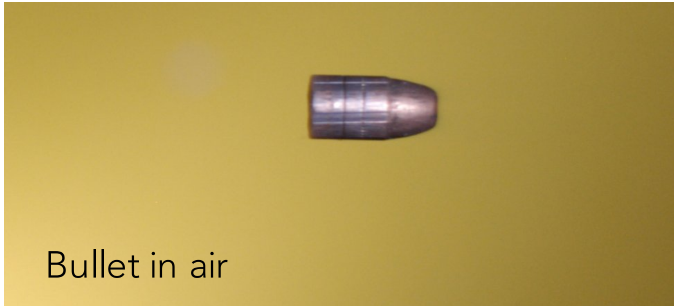
(This is well understood in the pQCD framework)



- 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

Quark-Gluon Plasma





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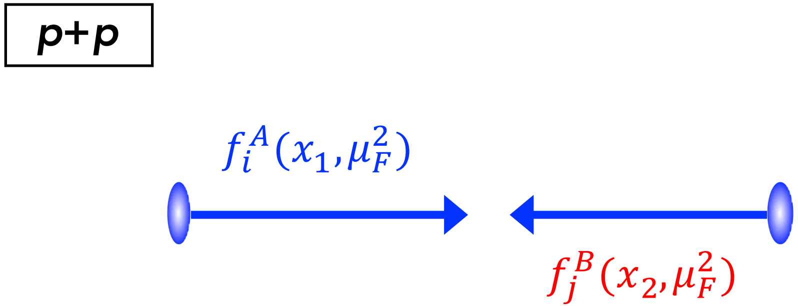
Factorization

$$\sigma^{AB\to kl} \sim f_i^A(x_1,\mu_F^2) \otimes f_j^B(x_2,\mu_F^2) \otimes \hat{\sigma}^{ij\to kl}$$

Parton Distribution Function (PDF)



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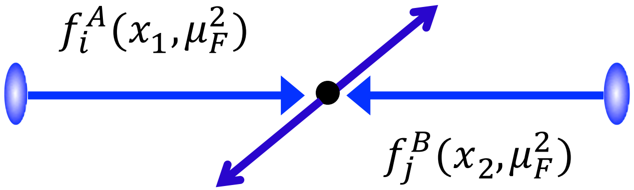
Parton Distribution Function (PDF)

Cross section of 2 →2 process

p+p

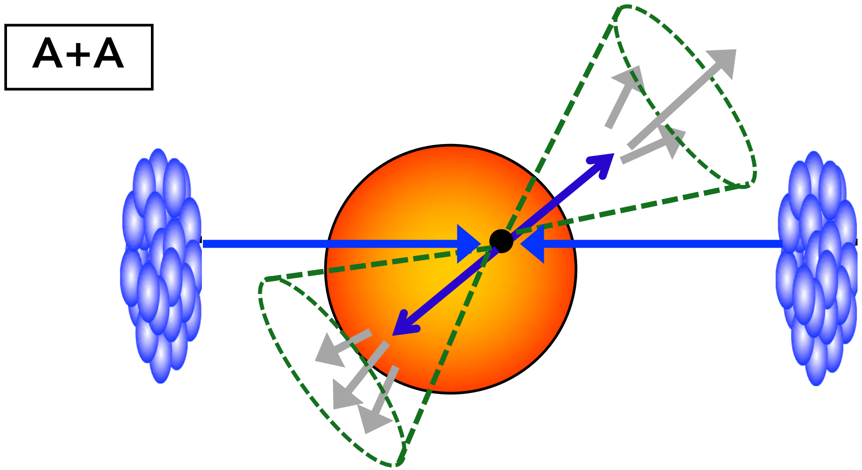


Factorization

$$\sigma^{AB\to kl} \sim f_i^A(x_1, \mu_F^2) \otimes f_j^B(x_2, \mu_F^2) \otimes \hat{\sigma}^{ij\to kl}$$

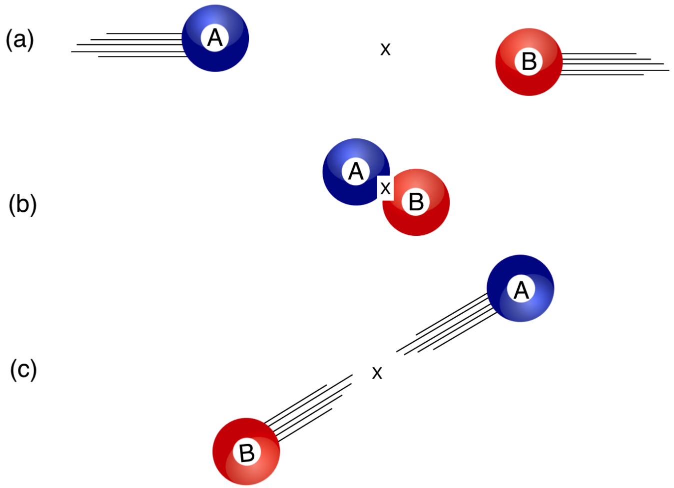
Nuclear Parton Distribution Function (nPDF)

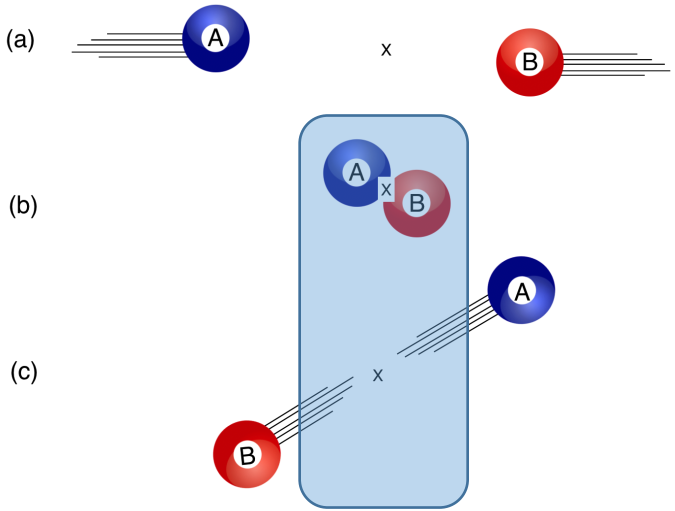
Cross section of 2 →2 process



Comparison between p+p and A+A data enables us to extract the medium effect

Classical mechanics





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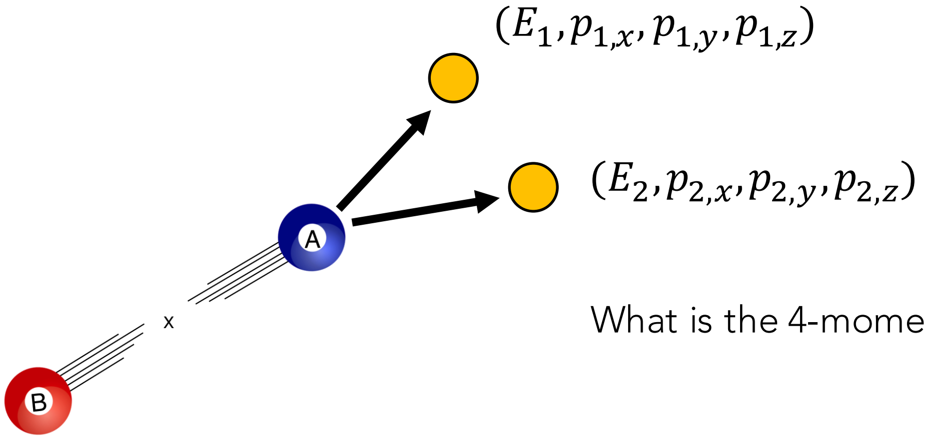
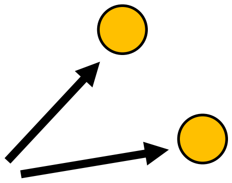


What is the 4-momentum of particle A?

Classical mechanics

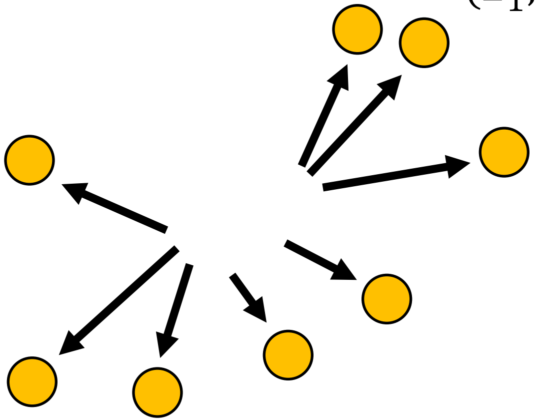


What is the 4-momentum of particle A?

What if we can only see particle 1 and 2?

Classical mechanics

$(E_1, p_{1,x}, p_{1,y}, p_{1,z})$



$(E_2, p_{2,x}, p_{2,y}, p_{2,z})$

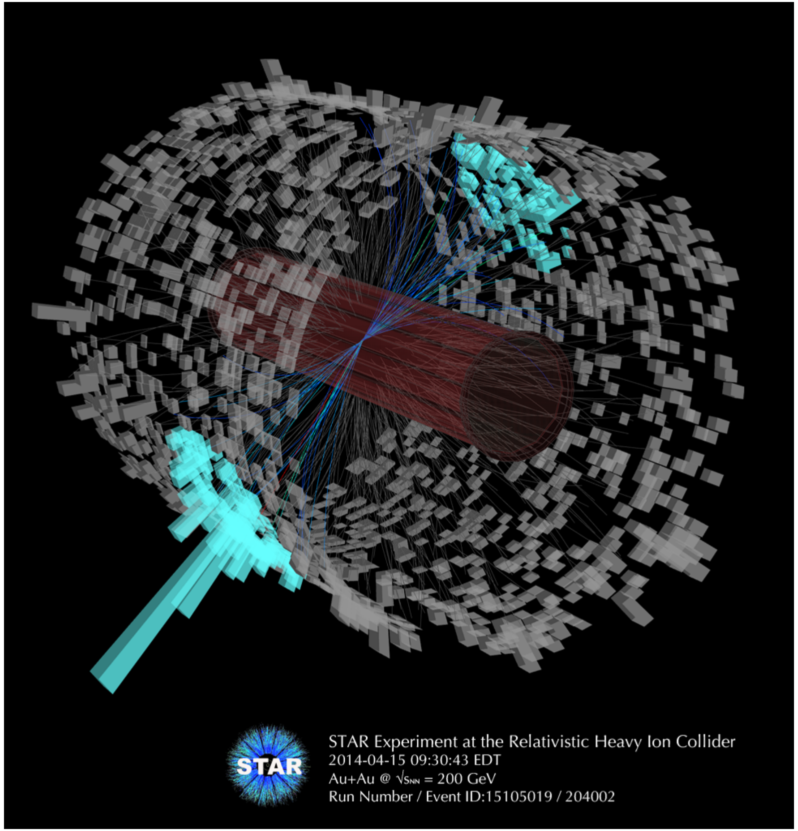
What is the 4-momentum of particle A?

What if we can only see particle 1 and 2?

What if there are more particles?

Can we always get back to particle A?

Jet

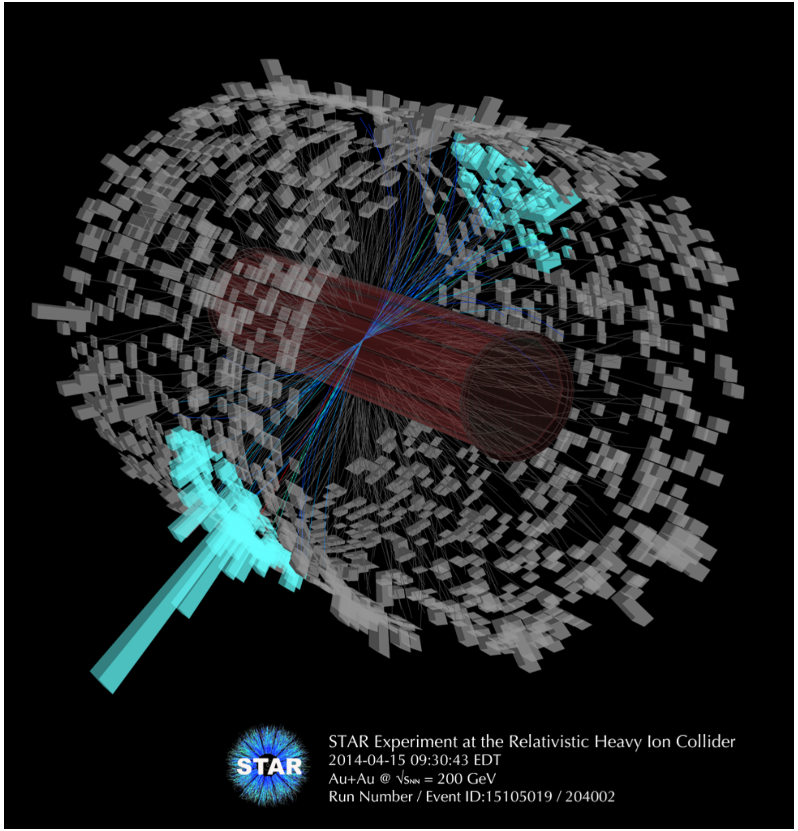


- Jets are collimated bunches of stable hadrons, originating from **partons** after **fragmentation** and **hadronization**
- Jets are the observable objects to relate experimental observations to theoretical predictions formulated in terms of quarks and gluons
- Momenta of final state particles → Momenta of a certain number of jets
  - ✓ It reduces the complexity of the final state (Many hadrons → simpler objects, jets)
- How can we find jets? Jet finding is an approximate attempt to reverse the quantum-mechanical processes of fragmentation and hadronization. Is it unique?

Outline

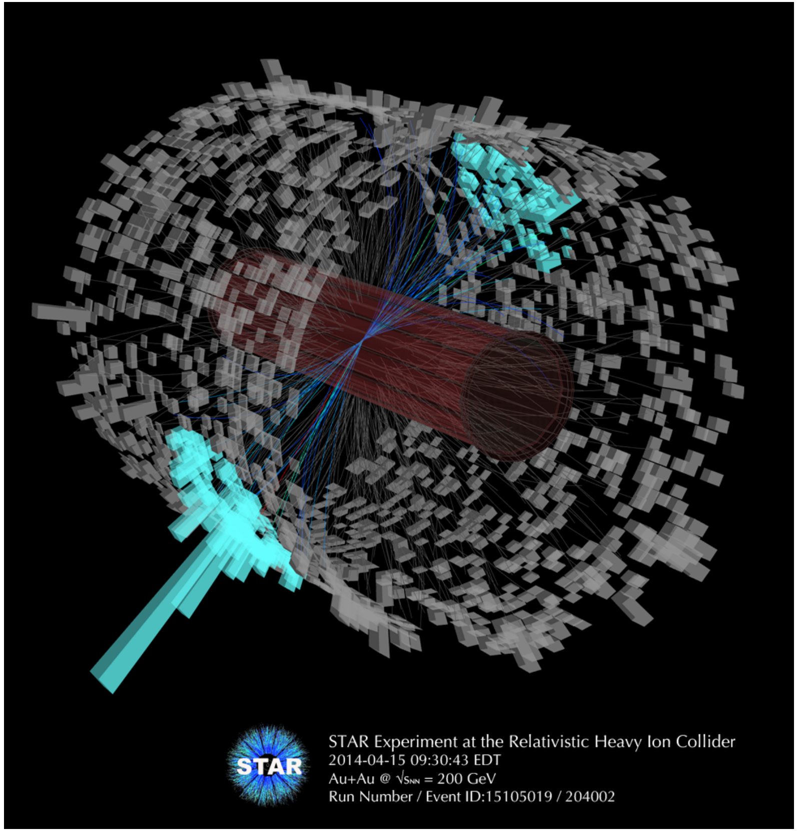
- What is a jet?
- How to find jets?
- What have we done with/about jets?

First attempt



- Can we just cluster collimated-looking bunches by looking at particle distribution in each event?

First attempt



- Can we just cluster collimated-looking bunches by looking at particle distribution in each event?
  - ✓ What if we have millions of events?
  - ✓ How can we connect them to theoretical predictions?

- We need a certain clustering algorithm

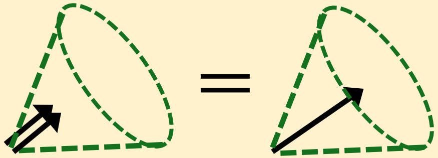
Jet clustering algorithms

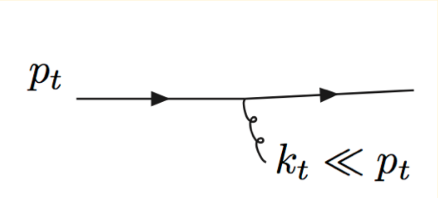
- **Sequential recombination algorithms** (1990s)
  - Bottom-up approach: combine particles starting from closes ones
  - Define the distance between particles, iterate recombination until few objects left, call them jets
  - Jade, k_T, Cambridge/Aachen, Anti-k_T, …

- **Cone algorithms** (1970s)
  - Top-down approach: Find coarse regions of energy flow
  - Find stable cones
  - JetClu, MidPoint, SISCone, …

Jet clustering algorithms

- Requirements for jet clustering algorithms at RHIC and the LHC
  - Collinear and infrared safety
    - ✓ Collinear splitting should not change jets
    - ✓ Soft emissions should not change jets
    - ✓ Cancellation of real and virtual divergences in higher order calculations – comparison with the higher-order calculation





Jet clustering algorithms

- Requirements for jet clustering algorithms at RHIC and the LHC
  - Collinear and infrared safety
    - ✓ Collinear splitting should not change jets
    - ✓ Soft emissions should not change jets
    - ✓ Cancellation of real and virtual divergences in higher order calculations – comparison with the higher-order calculation
  - Computationally fast
  - Background (underlying event and pileup) can be handled

Jet clustering algorithms

- **Sequential recombination algorithms** (1990s)
  - Bottom-up approach: combine particles starting from closes ones
  - Define the distance between particles, iterate recombination until few objects left, call them jets
  - Jade, k_T, Cambridge/Aachen, Anti-k_T, …
  - Infrared and collinear safe, favored by theorists
  - Computational performance / Background susceptibility later significantly improved
- **Cone algorithms** (1970s)
  - Top-down approach: Find coarse regions of energy flow
  - Find stable cones
  - JetClu, MidPoint, SISCone, …
  - Typically not infrared and collinear safe, several non-physical parameters needed
  - Disfavored by theorists

k_T algorithm and siblings

$$\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2}$$

$$d_{iB} = k_{ti}^{2p}$$

Distance between entities i and j

Transverse momentum

Distance between entity i and beam (B)

- Identify the smallest of the distance. If it is a d_{ij}, recombine entities i and j into a pseudojet. If it is d_{iB} , call i a jet and remove it from the list of entities
- Repeat the procedure until no entities are left

$p = 1$: **k_T algorithm**

$p = 0$: **Cambridge/Aachen algorithm**

$p = -1$: **Anti-k_T algorithm**

k_T algorithm and siblings – IRC safety

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p})\frac{\Delta_{ij}^2}{R^2}$$

$$d_{iB} = k_{ti}^{2p}$$

- $p > 0$
  - New soft particles ($k_t \to 0$) → $d \to 0$ → Clustered first, no effect on jets
  - New collinear particle particle ($\Delta^2 \to 0$) → $d \to 0$ → Clustered first, no effect on jets
- $p = 0$
  - New soft particles ($k_t \to 0$) → New jet of 0 momentum → No effect on other jets
  - New collinear particle particle ($\Delta^2 \to 0$) → $d \to 0$ → clustered first, no effect on jets
- $p < 0$
  - New soft particles ($k_t \to 0$) → $d \to \infty$ → clustered last, no effect on hard jets
  - New collinear particle particle ($\Delta^2 \to 0$) → $d \to 0$ → clustered first, no effect on jets

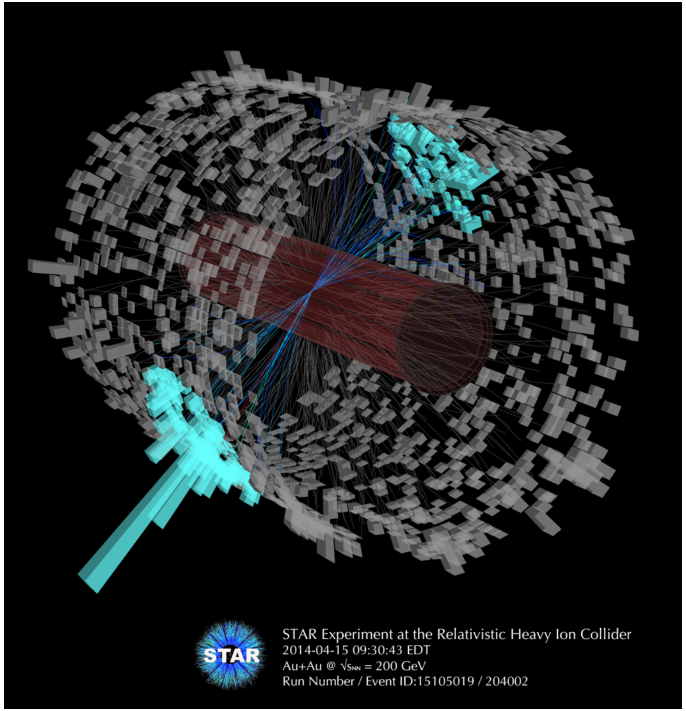
In practice

- Jets are modified by the background (pile-up and underlying event)
- Anti-k_T jets are more resilient (less changed in a background) than others, as well as easier to correct for detector-related effects – thus preferred in general these days

- FastJet package
  - ✓ C++ library providing implementation of jet finding algorithms + others
  - ✓ http://fastjet.fr

Nothing to do with this…

Jets in a background



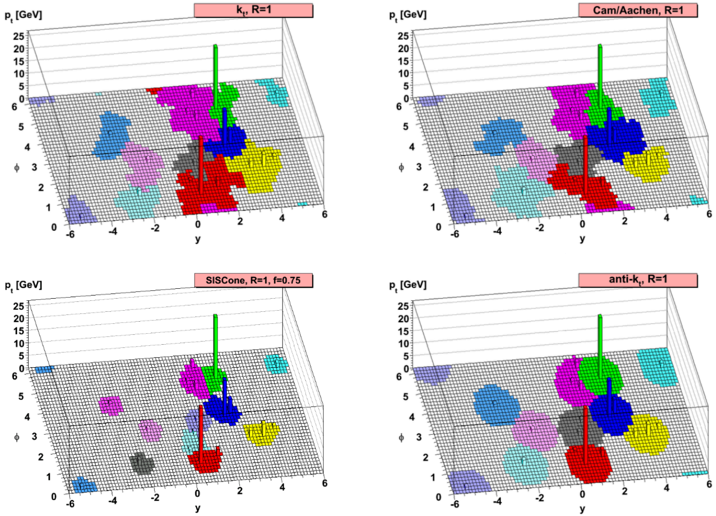
- Jets are modified by the background
- Common way to correct jet p_T

$$\rho = \mathrm{median}\left\{ \frac{p_{\mathrm{T,jet}}^{\mathrm{raw,i}}}{A_{\mathrm{jet}}^{\mathrm{i}}} \right\}$$

$$p_{\mathrm{T,jet}}^{\mathrm{reco,i}} = p_{\mathrm{T,jet}}^{\mathrm{raw,i}} - \rho \cdot A_{\mathrm{jet}}^{\mathrm{i}}$$

Jets in a background

- Jet area is defined as the size of the region where infinitesimally soft particles (=ghost particles) get clustered into the jet in the jet finding process



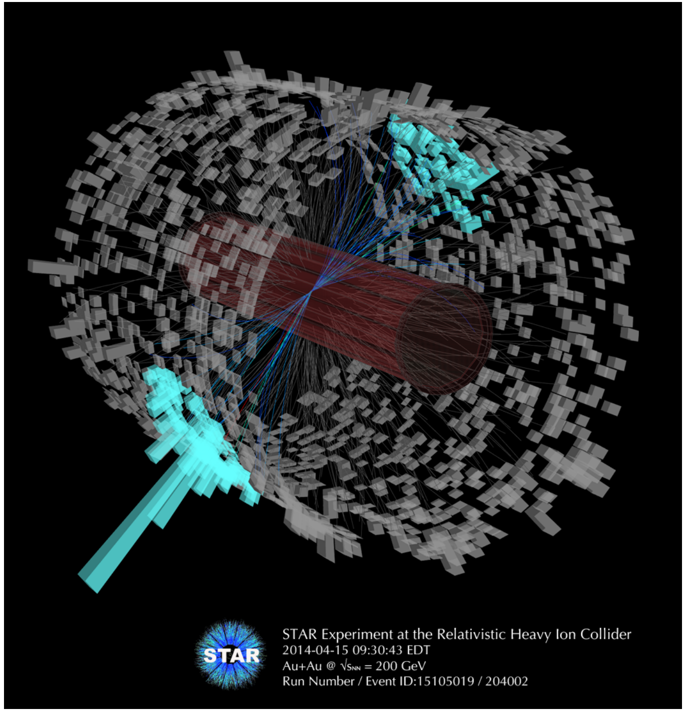
d by the background

correct jet p_T

$$n \left\{ \frac{p_{\mathrm{T,jet}}^{\mathrm{raw,i}}}{A_{\mathrm{jet}}^{\mathrm{i}}} \right\}$$

$$^{\mathrm{i}} = p_{\mathrm{T,jet}}^{\mathrm{raw,i}} - \rho \cdot A_{\mathrm{jet}}^{\mathrm{i}}$$

Jets in a background



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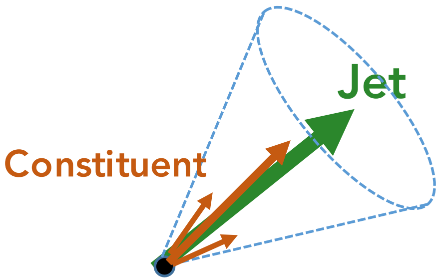
- There are other methods as well
  - ✓ Particle-based method: constituent subtraction method, …
  - ✓ Machine-learning based method

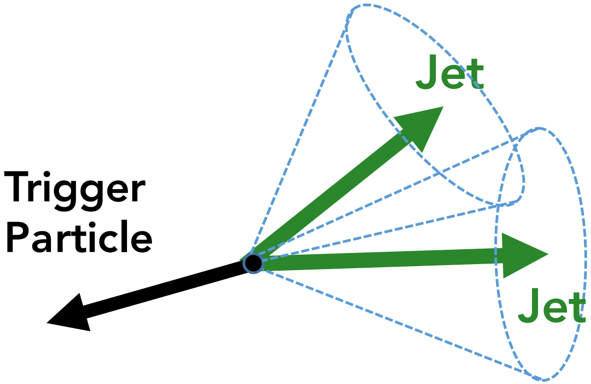
Jets in a background

- Further techniques developed/utilized for low momentum jets, where there are many combinatorial jets

- Requiring **a high-p_T constituent** (STAR, Phys. Rev. C 102 (2020) 054913) or reconstruct **jets only with high-p_T constituents** (STAR, Phys. Rev. Lett. 119 (2017) 062301) then matched to jets reconstructed with all constituents



- **Semi-inclusive approach** – jets in the recoil region of a high-p_T trigger particle (STAR, Phys. Rev. C 96 (2017) 24905)



Outline

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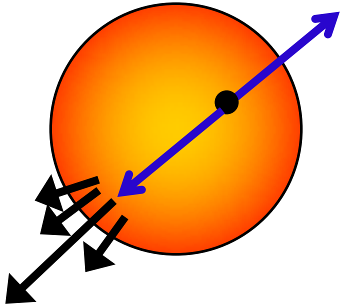
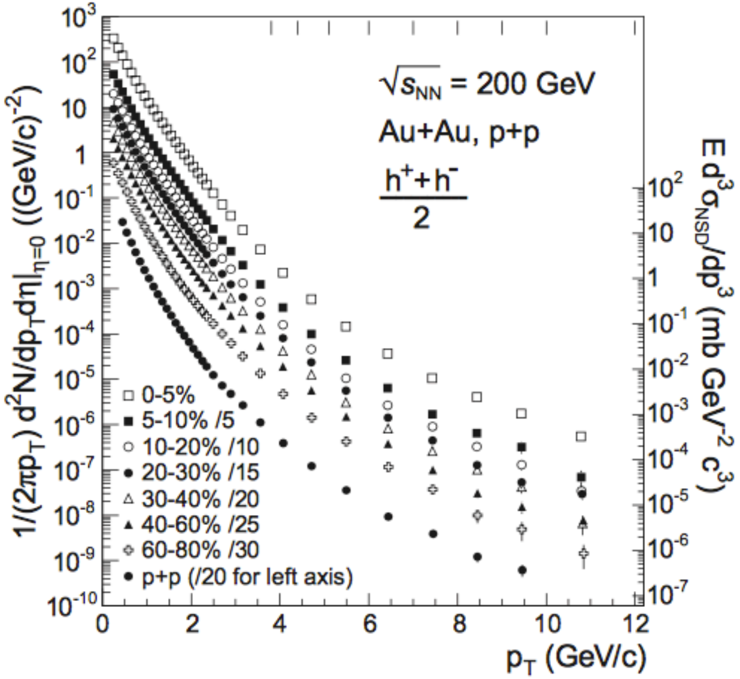
- How to find jets?
- What have we done with/about jets?

High p_T charged hadron yield



- High p_T particles – Proxy of hard-scattered parton
- Number of high p_T particles produced in heavy-ion collisions compared to that in $p+p$ collisions?

STAR, Phys. Rev. Lett. 91 (2003) 172302



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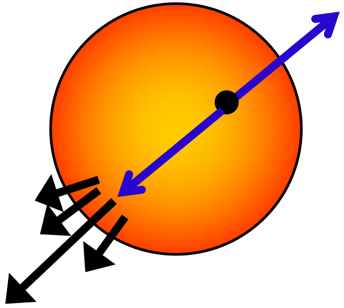
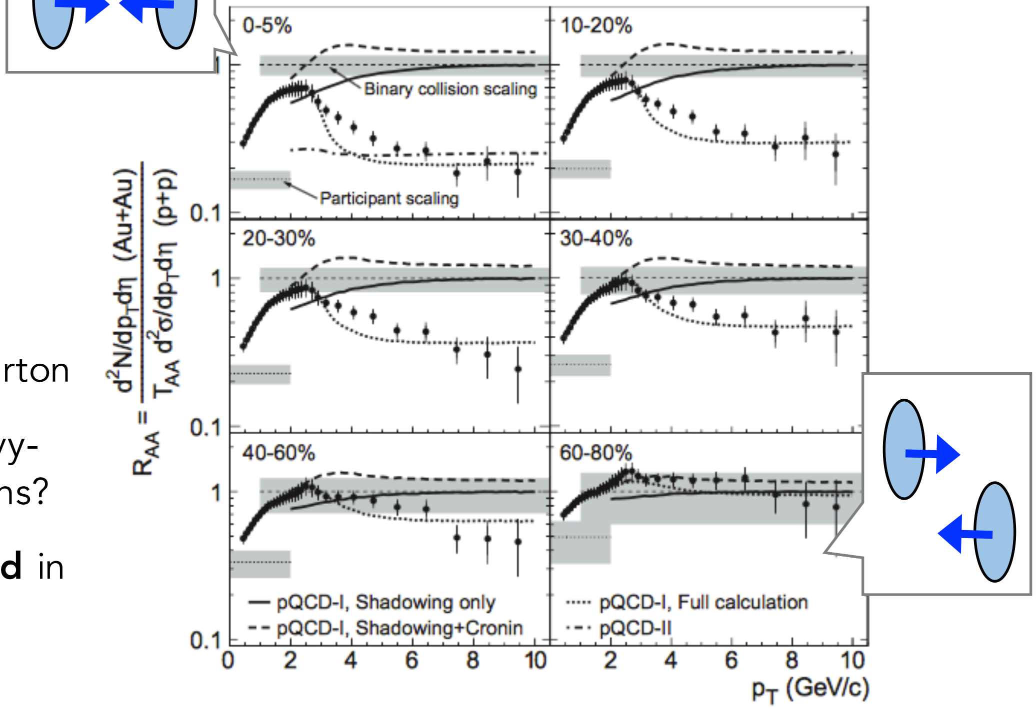
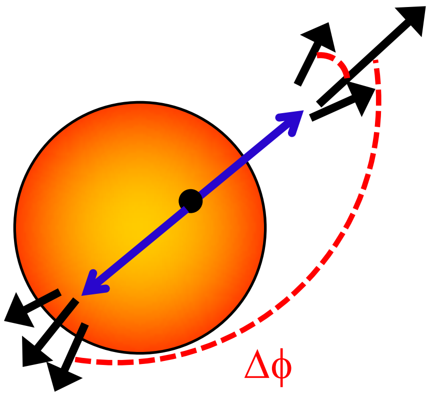


- High p_T particles – Proxy of hard-scattered parton
- Number of high p_T particles produced in heavy-ion collisions compared to that in p+p collisions?
- High p_T charged particle yields are **suppressed** in central heavy-ion collisions

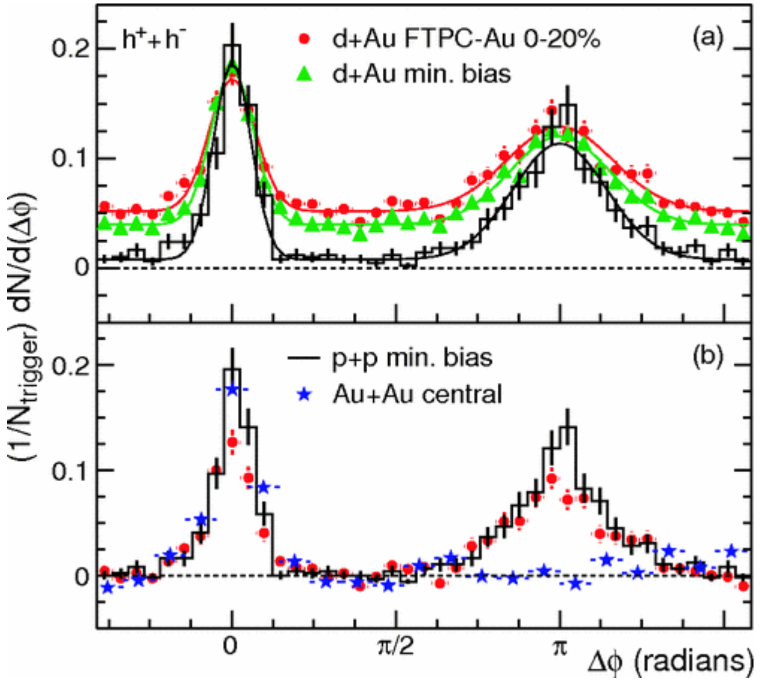
STAR, Phys. Rev. Lett. 91 (2003) 172302



Two-particle angular correlations

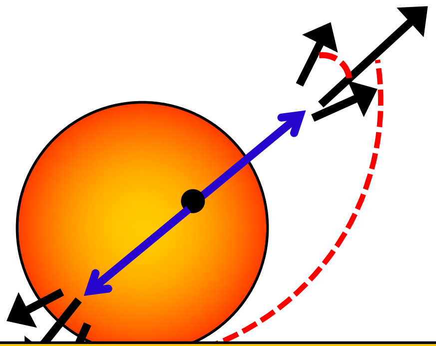


STAR, Phys. Rev. Lett. 91 (2003) 072304



- Two-particle angular correlations between high-p_T trigger particles and lower-p_T associated particles
- Suppression of back-to-back correlations in central Au+Au collisions

Two-particle angular correlations



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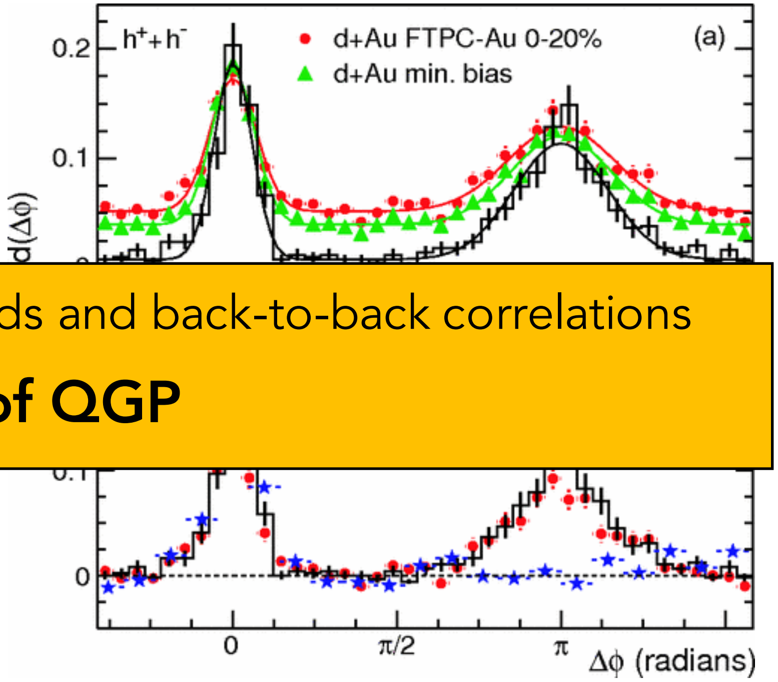
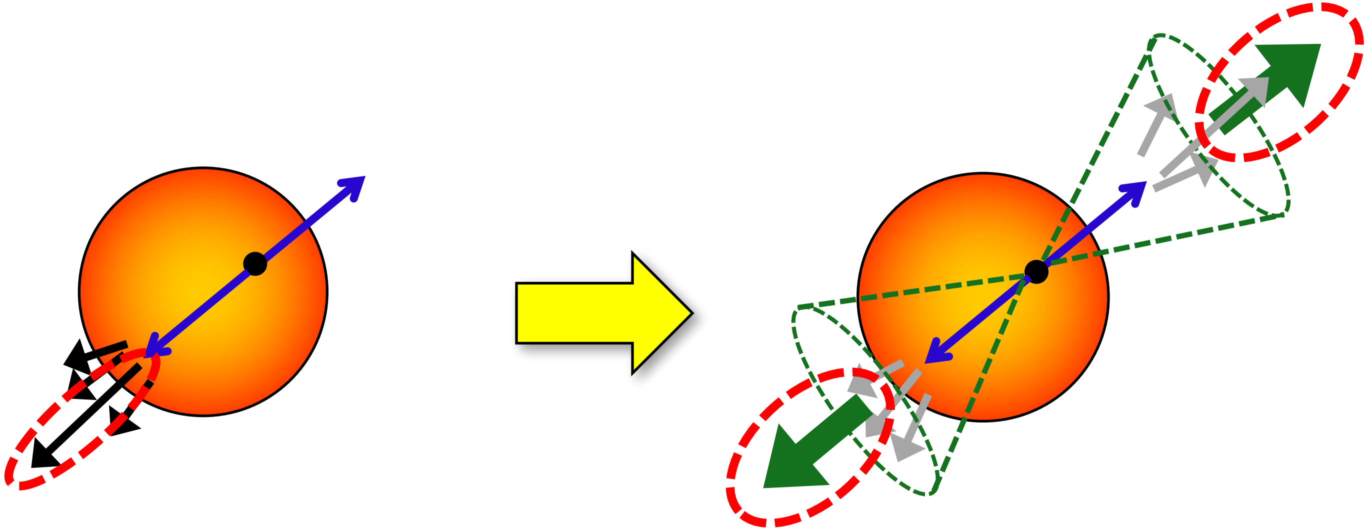


Suppression of both high-p_T particle yields and back-to-back correlations

→ Evidence of QGP

- trigger particles and lower-p_T associated particles
- Suppression of back-to-back correlations in central Au+Au collisions

Jets in QCD matter



Using high-p_T particles

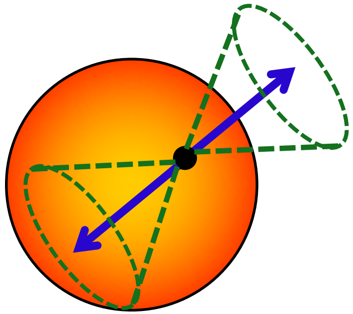
Using jets

- Better proxy of hard-scattered partons
- It reduces the complexity of the final state

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

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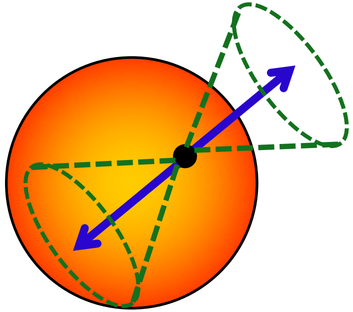
  - How can we use jets to probe the microstructure of the QGP?
  - What is the resolution scale of the medium? How can we measure that?
  - What can we learn from the mass dependence of jet quenching?
  - …

- 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

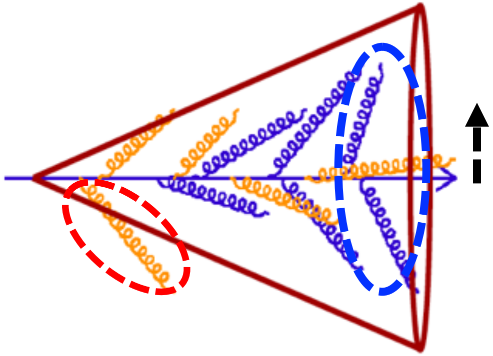


Jets in QCD matter

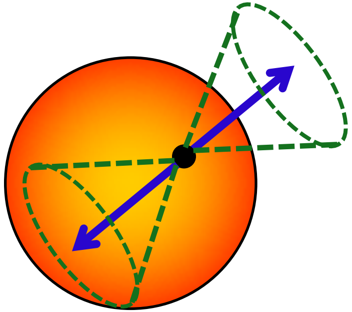
➢ What que…
- How d… …brium probe, e.g. jets?
- How c… …he QGP?
- What i… …we measure that?
- How t… …QCD properties?
- What … …quenching?
- …

➢ Jet observ…
- Each je… …uestions
  – We ca…
- We me… …sistency?

What have we found so far?



- Jet energy loss
- Jet substructure modification
- Jet deflection



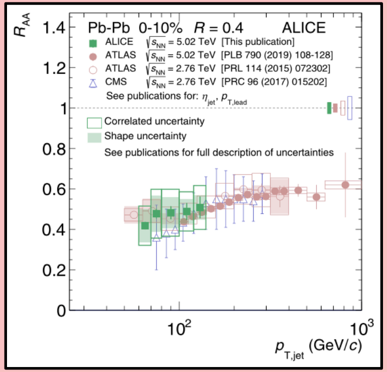
Jet measurement summary

pp, pA (dA), AA

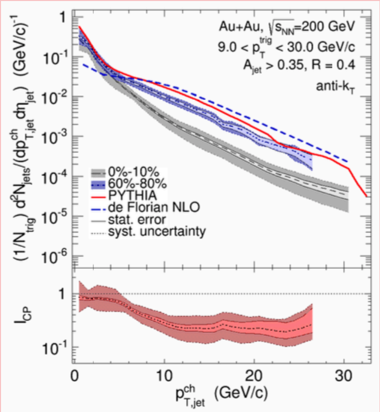
	Inclusive spectra (R_{AA}, R_{pA}, R_{dA})	Semi-inclu. spectra	A_J	Triggered-jet momentum ratio (x_J)	Fragmentation Function	Jet shape	HF tagged jet	Substructure	Etc.
CMS	R_{pPb}, 5.02 R_{AA}, 2.76 Large R R_{AA}, 5.02		A_J, 2.76 A_J, 2.76	$x_{J\gamma}$, 2.76 x_{JZ}, 5.02 $x_{J\gamma}$, 2.76 x_J, b-jet 5.02	FF(ξ), 2.76 FF(ξ), 2.76 γ-jet FF(ξ), 5.02	ρ(r), 2.76 J-h 2PC, 2.76 J-h 2PC, 2.76 J-h 2PC, 5.02 γ-jet ρ(r), 2.76 γ-jet ρ(r), 5.02 b-jet shape, 5.02	b-jet, 7 b-jet, 2.76 b-jet, 5.02 c-jet, 5.02 b-jet x_J, 5.02 D^0-jet, 5.02 c-jet, 5.02 J/ψ-jet, 5.02 b-jet, 5.02	Jet mass, 7 Groomed mass, 5.02	Di-jet momentum balance, η, 5.02 Missing momentum, 2.76 Jet charge, 5.02
ATLAS	R_{AA}, 2.76 R_{AA}, 5.02		A_J, 2.76	x_J, 2.76 $x_{J\gamma}$, 5.02	D(z), 2.76 D(z), 2.76 D(z) D(p_T), 2.76 D(z) D(p_T), 5.02 D(z) D(p_T), 5.02 γ-jet D(z), 5.02	Track profile, 5.02	D^*-jet, 7 b-jet, 5.02	Jet mass, 7 Groomed mass, 13	Neighboring jet $R_{\Delta R}$, 2.76 Jet v_n, 5.02
ALICE	Spectra, 2.76 R_{CP}, 2.76 Spectra, 7 R_{AA}, 2.76 R_{pPb}, 5.02 Q_{pPb}, 5.02 Spectra, 5.02 R_{AA}, 5.02 Spectra, 13	h-jet, 2.76 h-jet, 5.02			D(z), 7 j_T, 5.02 D(z), 5.02	Shape, 2.76 Radial profile, 2.76 EP j-h, 2.76	D^0-jet, 7 b-jet, 5.02 D^0-jet, 5.02	Jet mass, 2.76, 5.02 SoftDrop z_g, 7, 2.76 z_g and R_g, 5.02 c-jet subtructure, 13 z_g, R_g, 5.02	Jet background fluctuation, 2.76 Di-jet acoplanarity, 5.02 Jet v_2, 2.76 Jet angularity, 5.02 L and K^0_s in jet, 5.02, 7 Jet axes, 5.02
STAR	R_{AA}, 0.2	h-jet, 0.2	A_J, 0.2			J-h 2PC, 0.2		z_g and R_g, 0.2 Jet mass, 0.2 Opening angle, 0.2	
PHENIX	R_{dAu}, 0.2								

- Preliminary results are not included
- Results with jet reconstruction only

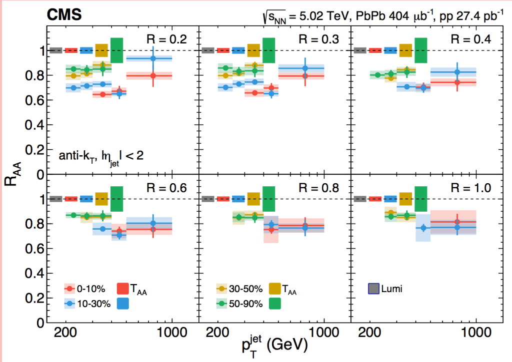
Jet spectra



R_{AA}
Pb-Pb 0-10% R = 0.4 ALICE
ALICE $\sqrt{s_{NN}}$ = 5.02 TeV [This publication]
ATLAS $\sqrt{s_{NN}}$ = 5.02 TeV [PLB 790 (2019) 108-128]
ATLAS $\sqrt{s_{NN}}$ = 2.76 TeV [PRL 114 (2015) 072302]
CMS $\sqrt{s_{NN}}$ = 2.76 TeV [PRC 96 (2017) 015202]
See publications for: η_{jet}, $p_{T,lead}$
Correlated uncertainty
Shape uncertainty
See publications for full description of uncertainties
$p_{T,jet}$ (GeV/c)



Au+Au, $\sqrt{s_{NN}}$=200 GeV
9.0 < p_T^{trig} < 30.0 GeV/c
A_{jet} > 0.35, R = 0.4
anti-k_T
0%-10%
60%-80%
PYTHIA
de Florian NLO
stat. error
syst. uncertainty
$(1/N_{trig})\ d^2N_{jets}/(dp^{ch}_{T,jet}\ d\eta_{jet})$ $(GeV/c)^{-1}$
I_{CP}
$p^{ch}_{T,jet}$ (GeV/c)

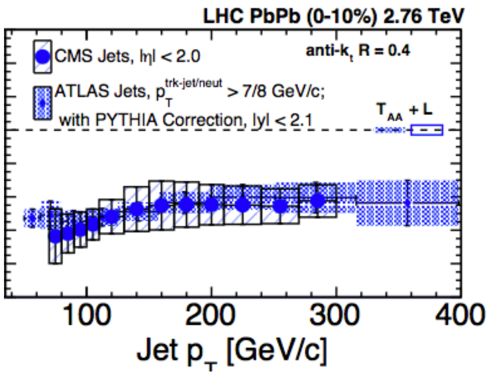


CMS
$\sqrt{s_{NN}}$ = 5.02 TeV, PbPb 404 μb^{-1}, pp 27.4 pb^{-1}
R = 0.2
R = 0.3
R = 0.4
R = 0.6
R = 0.8
R = 1.0
anti-k_T, $|\eta_{jet}|$ < 2
R_{AA}
0-10%
10-30%
T_{AA}
30-50%
50-90%
Lumi
p_T^{jet} (GeV)

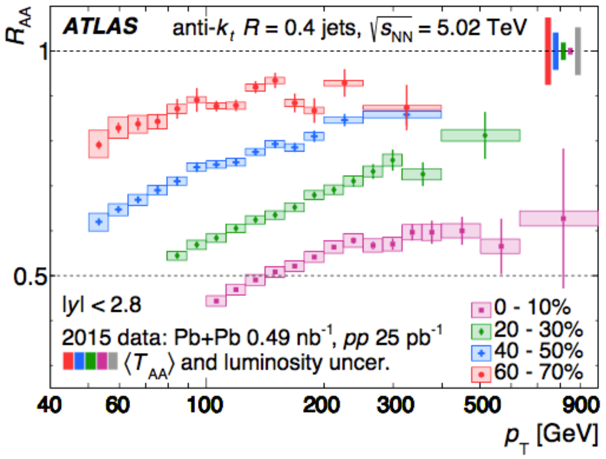
Inclusive jet spectra

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

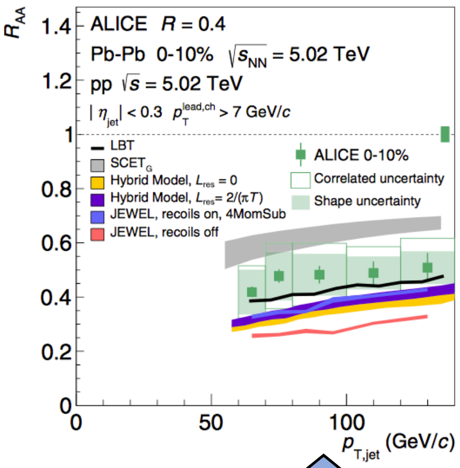
CMS, 2.76 TeV, PRC 96 (2017) 015202



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



ALICE, 5.02 TeV, PRC 101 (2020) 034911

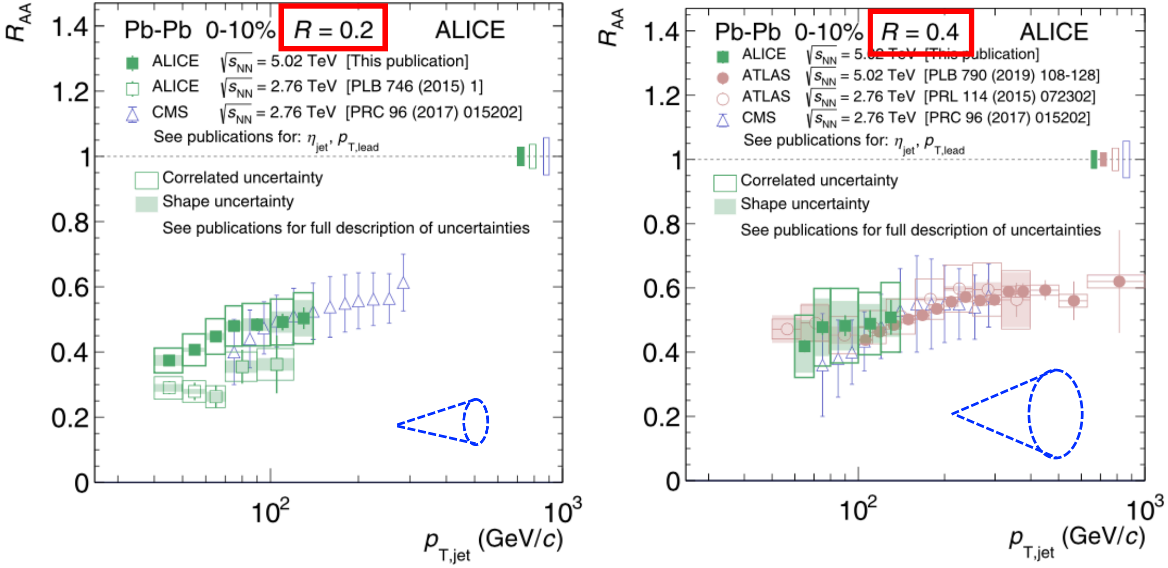


- Most models reasonably describe data – more differential measurements needed

Inclusive jet spectra

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

ALICE, 5.02 TeV, PRC 101 (2020) 034911

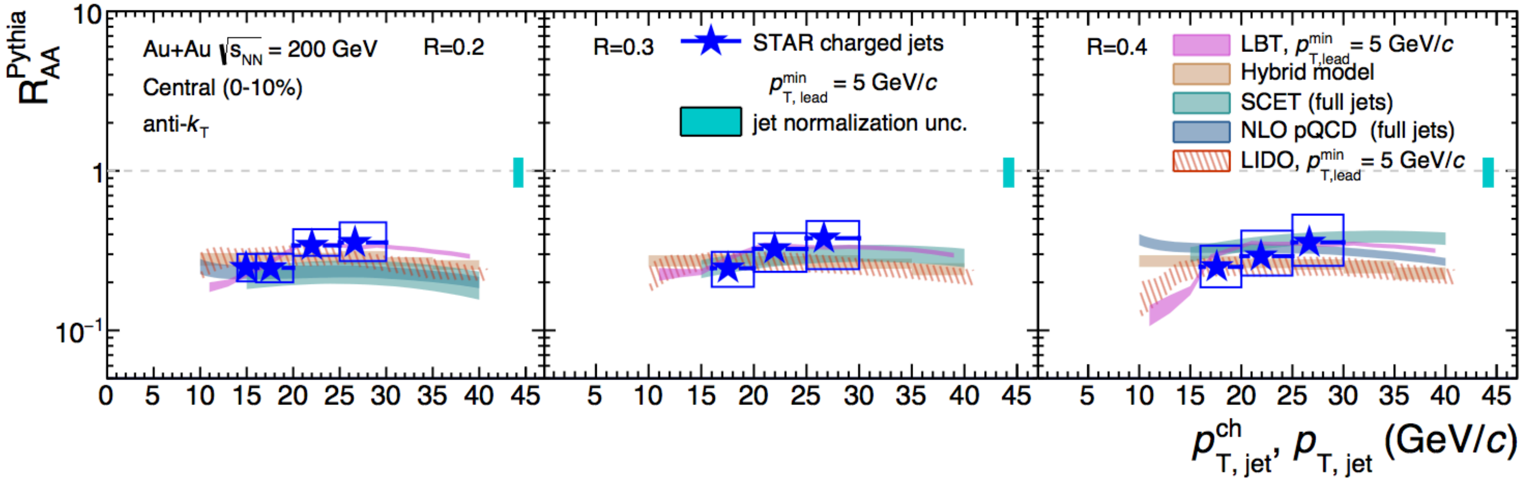


- No clear R dependence or collision energy dependence at the LHC at standard R
- Consistent R_{AA} values from different collaborations (Different η_{jet}, systematics)
- What about at RHIC energies?

Inclusive jet spectra

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

STAR, 0.2 TeV, PRC 102 (2020) 054913

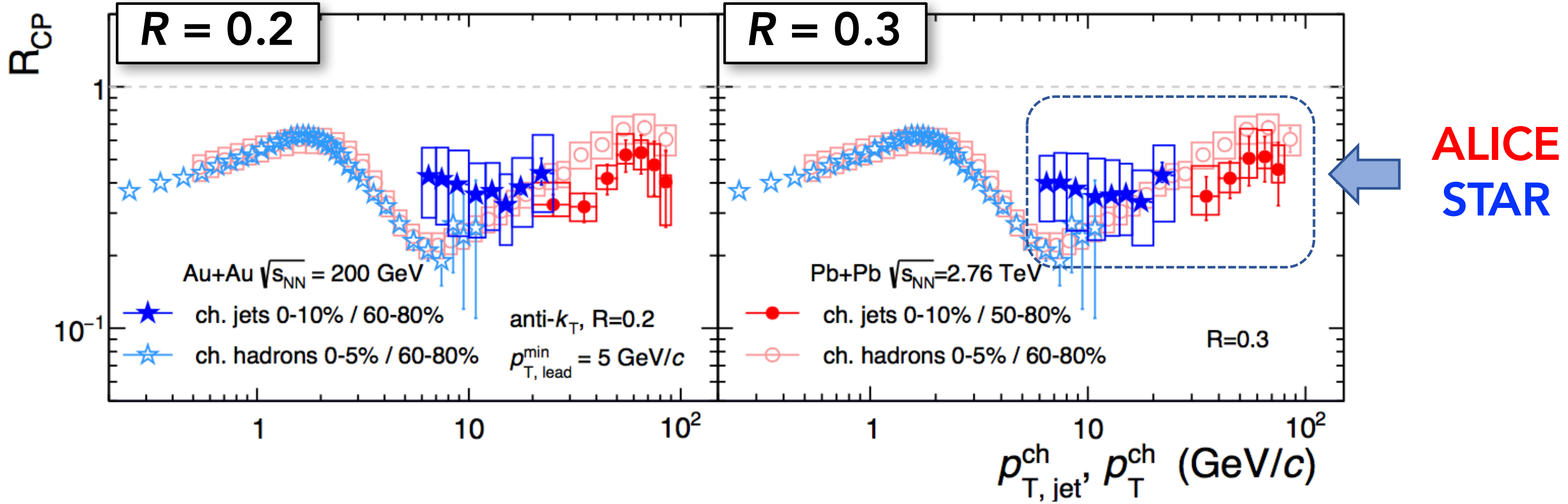


- Inclusive charged-particle jet spectra at 200 GeV Au+Au collisions with respect to PYTHIA

Inclusive jet spectra

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

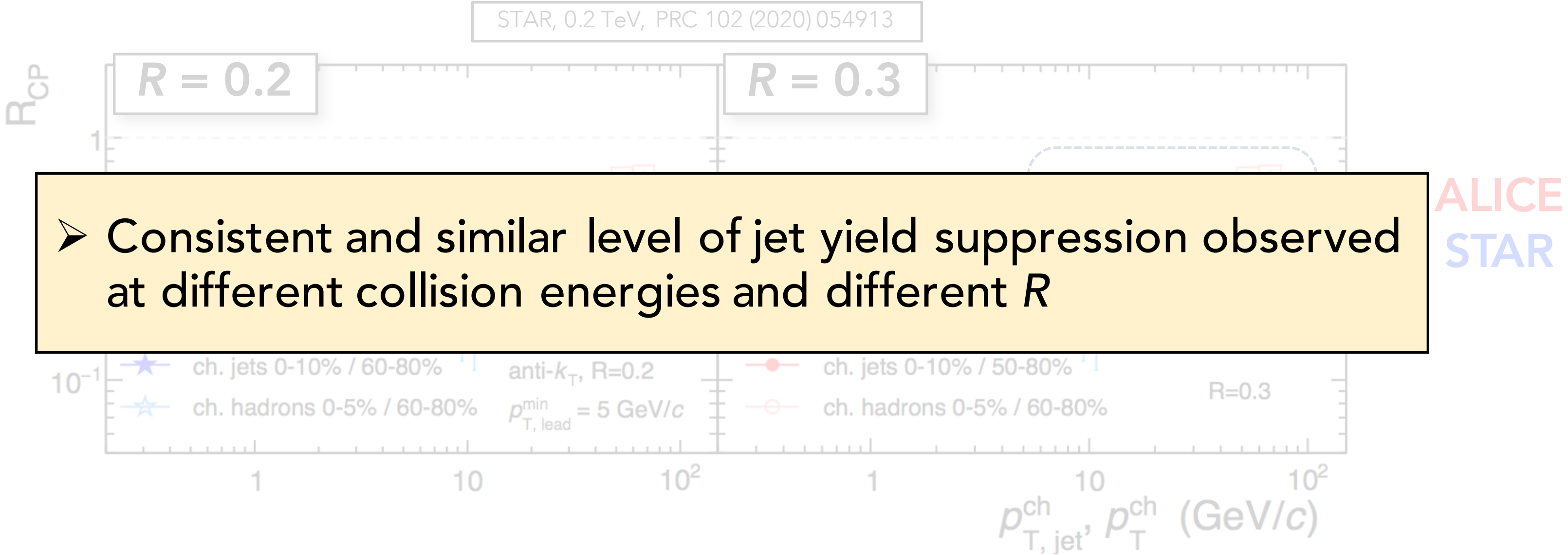
STAR, 0.2 TeV, PRC 102 (2020) 054913



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

Inclusive jet spectra

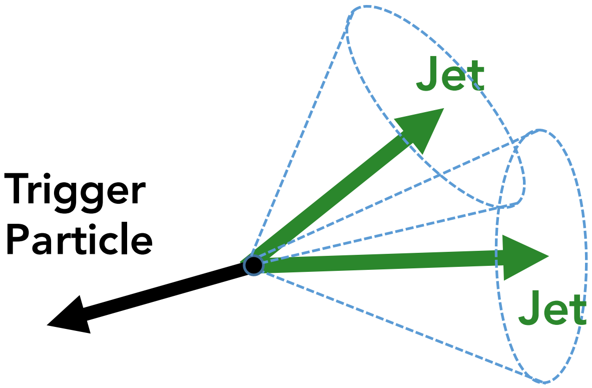
- Jet R_{CP} – Comparison between central and peripheral collisions



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

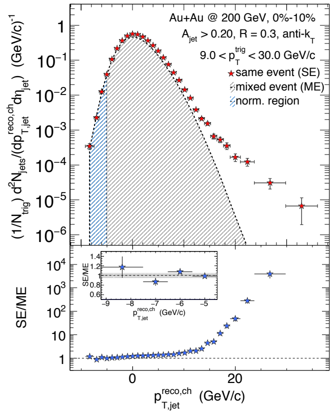
- Similar level of suppression between 200 GeV and 2.76 TeV, although their spectrum shapes are different

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 $p_{T,jet}$

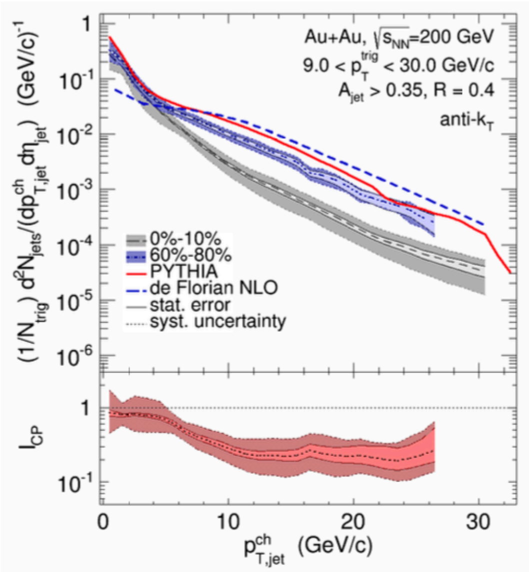
STAR, Phys. Rev. C 96 (2017) 24905



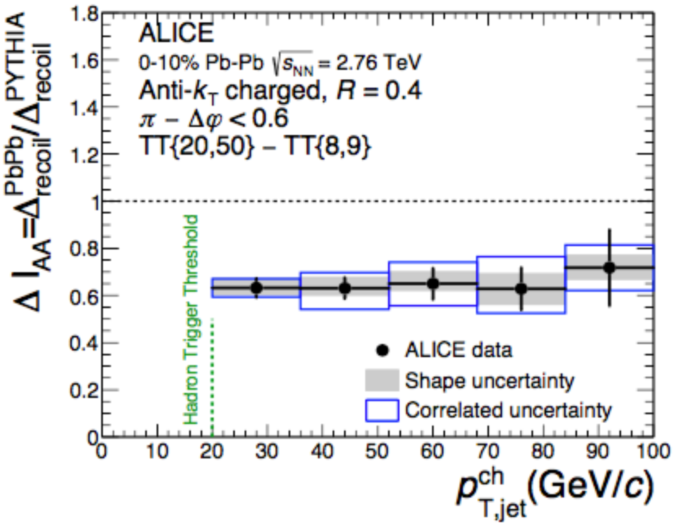
Removal of uncorrelated contributions with a Mixed-event technique

Semi-inclusive jet spectra

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



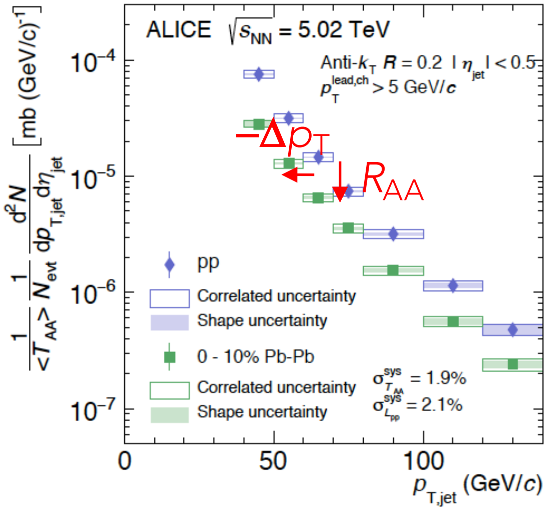
ALICE, JHEP 09 (2015) 170



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

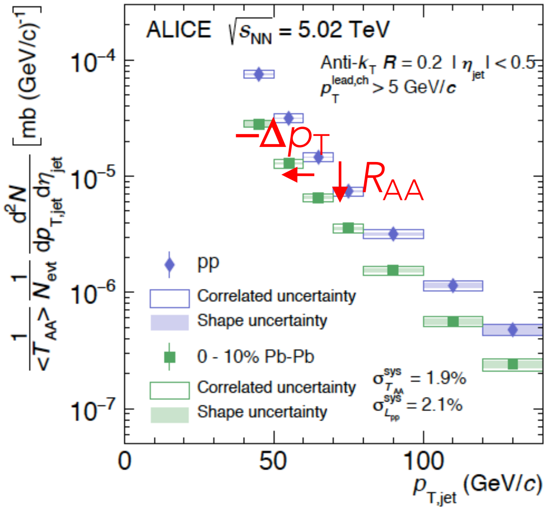
- Similar level of suppression via I_{CP} to charged-particle jet R_{CP} at 200 GeV

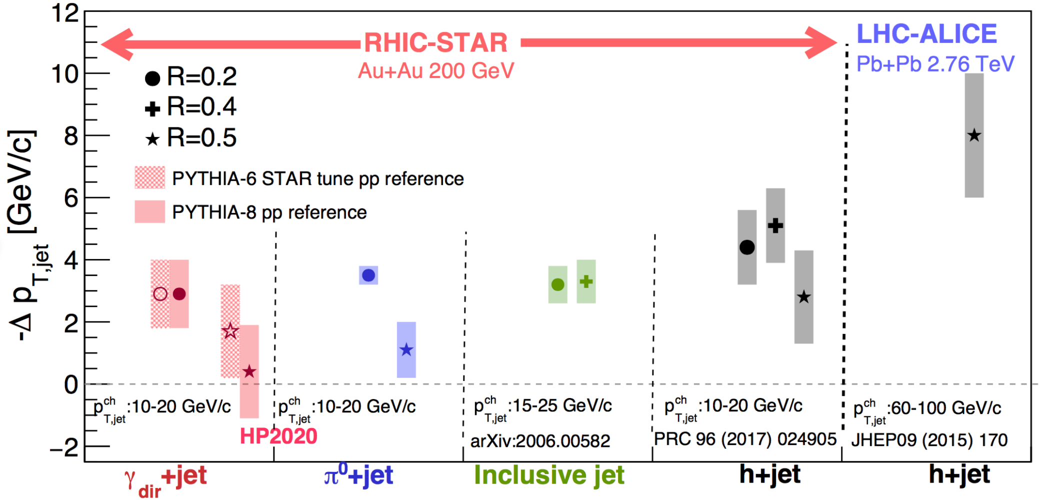
Inclusive and semi-inclusive jet spectra



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

Inclusive and semi-inclusive jet spectra





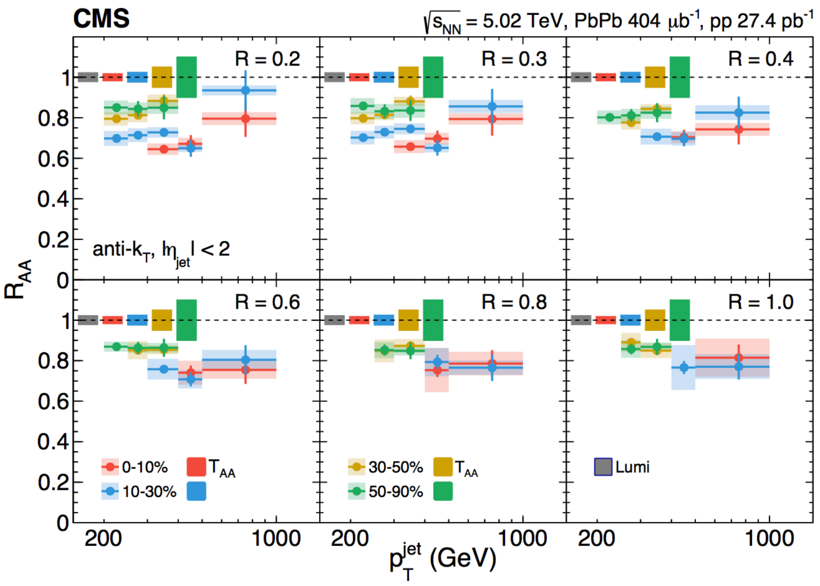
- In addition to R_{AA} or $I_{AA,}$ jet yield suppression can be quantified with $-\Delta p_T$

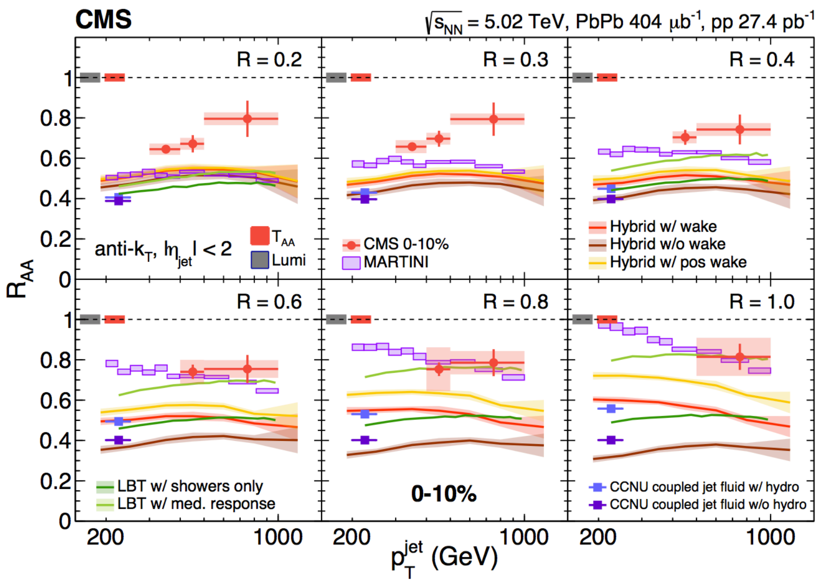
- At RHIC, similar energy loss for different channels of measurements
- **At the LHC with higher $p_{T,jet}$, indication of larger energy loss than RHIC for h+jet measurements**
- Further $-\Delta p_T$ quantification for other spectrum measurements is needed

Inclusive jet spectra at larger jet *R*

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

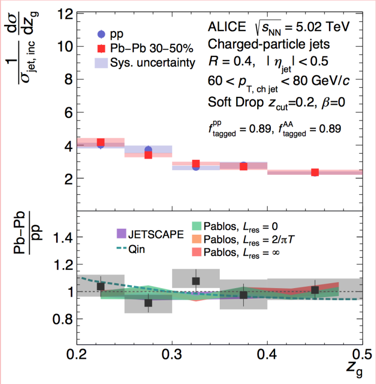
CMS – 5.02 TeV, JHEP 05 (2021) 284

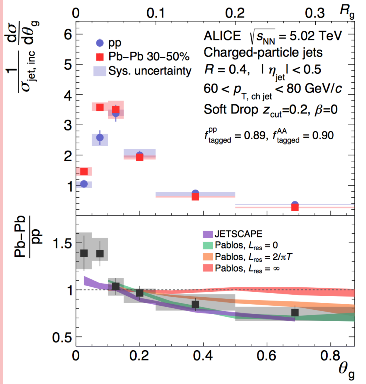


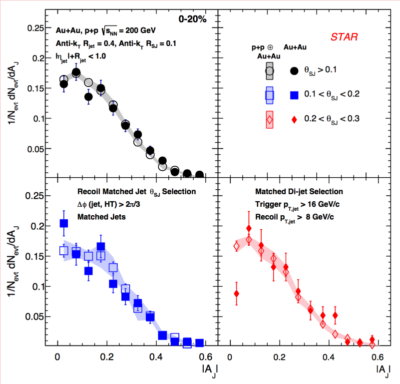


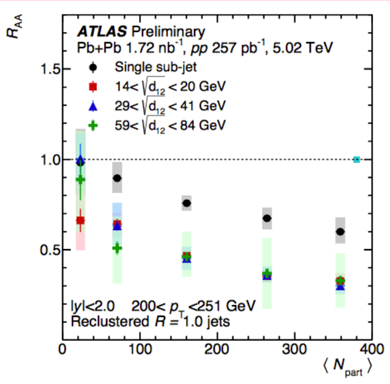
- No strong dependence on jet radius persists at large R (=1.0) and high $p_{T,jet}$ (1 TeV/c)
- Significant tension between models – Further constraints on the underlying jet quenching mechanisms

Jet substructure observables



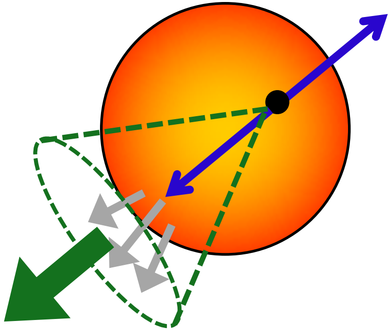


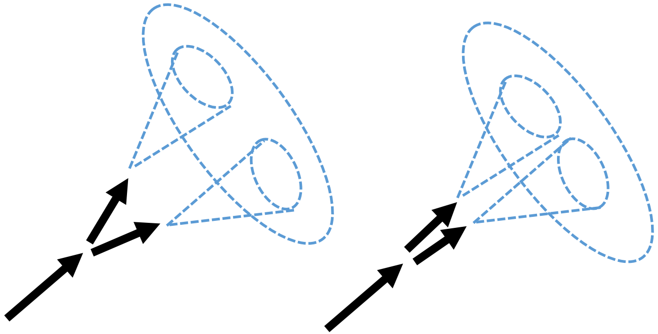




Jet substructure observables

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

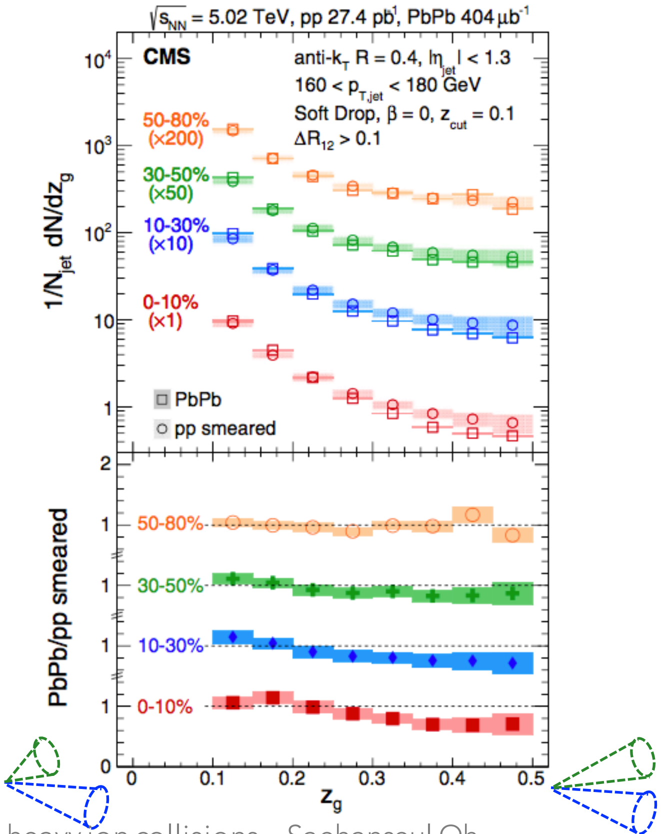




- Do these jets quench differently in QCD medium? What is the resolution scale of the medium?

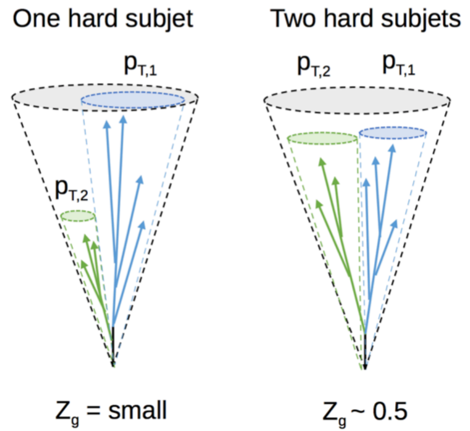
Groomed jet substructure

CMS, PRL 120 (2018) 142302



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

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

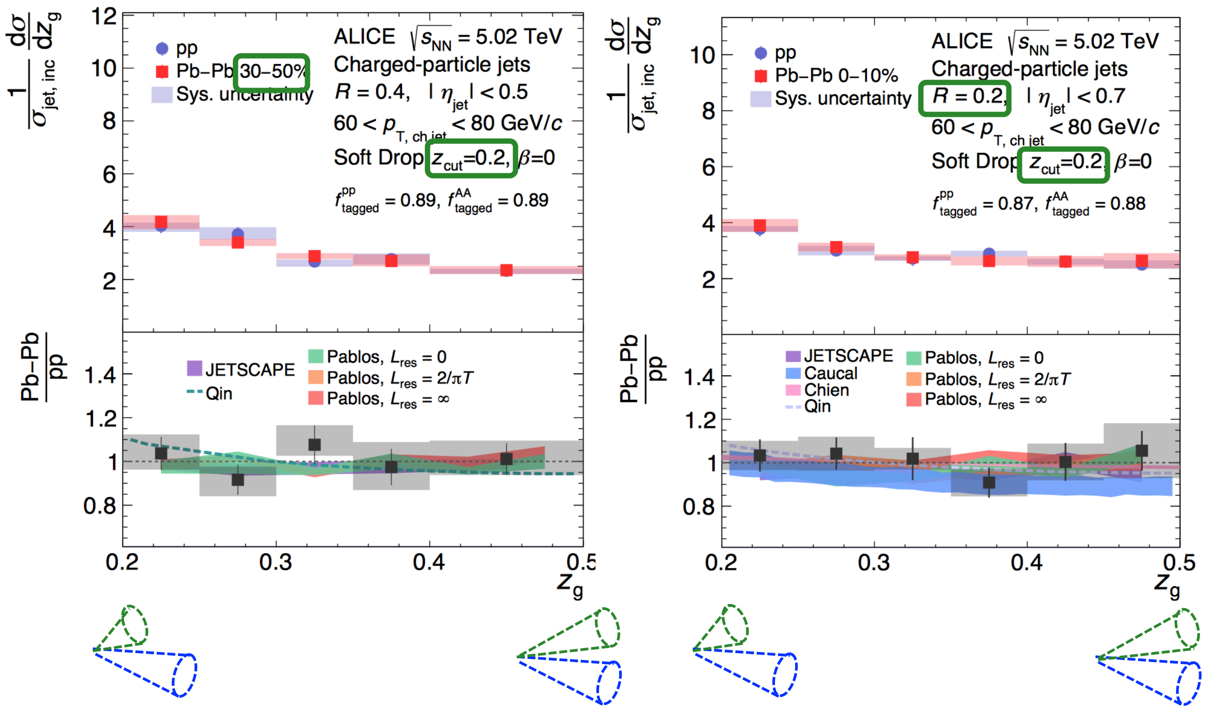


- Comparison between A+A and smeared *pp* results
- Steeper z_g distributions in central Pb+Pb collisions – parton splitting process is modified by the medium

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

ALICE, arXiv:2107.12984



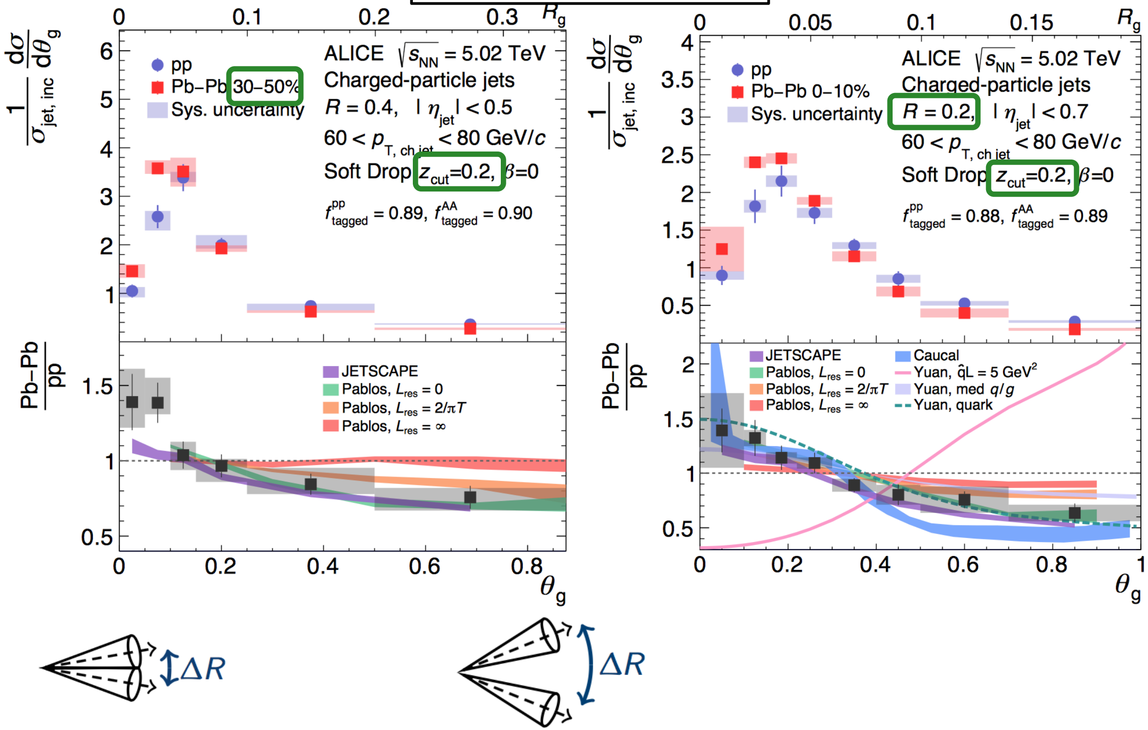
- z_g distributions in Pb+Pb collisions are consistent with those of pp collisions within experimental uncertainties

Groomed jet substructure

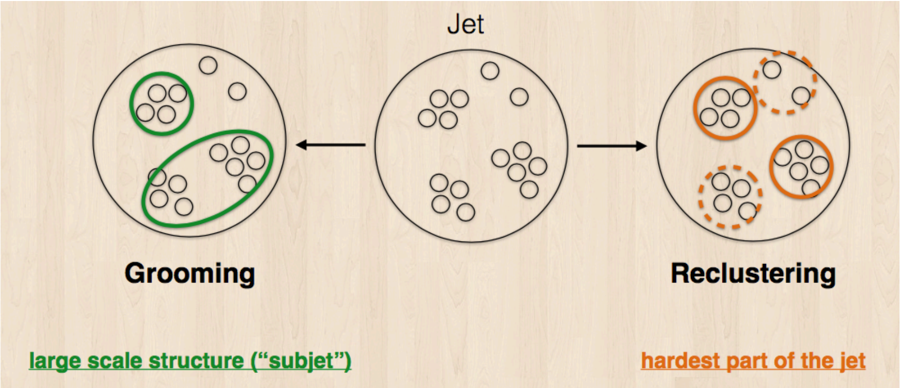
- Background fluctuations in heavy-ion environment result in an incorrect splitting being identified by the grooming algorithm
- Smaller R jets, increased z_{cut} in SD, using semi-central collisions

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

ALICE, arXiv:2107.12984

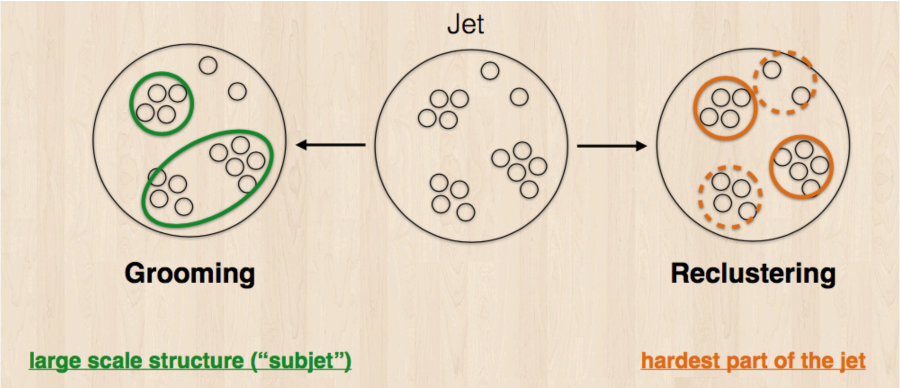


Jet substructure with subjets



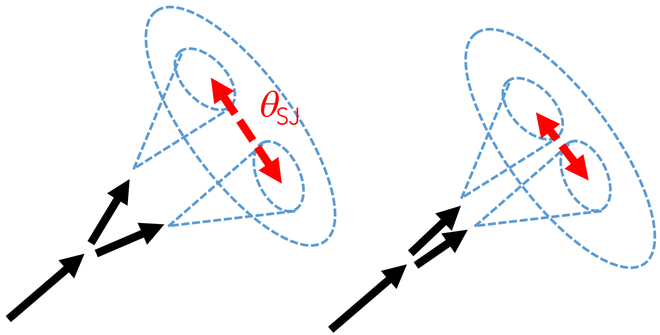
- Reclustering jets with smaller resolution parameter ($r < R$) with the original jet constituents
- Subjets are proxy for the hardest shower splitting

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

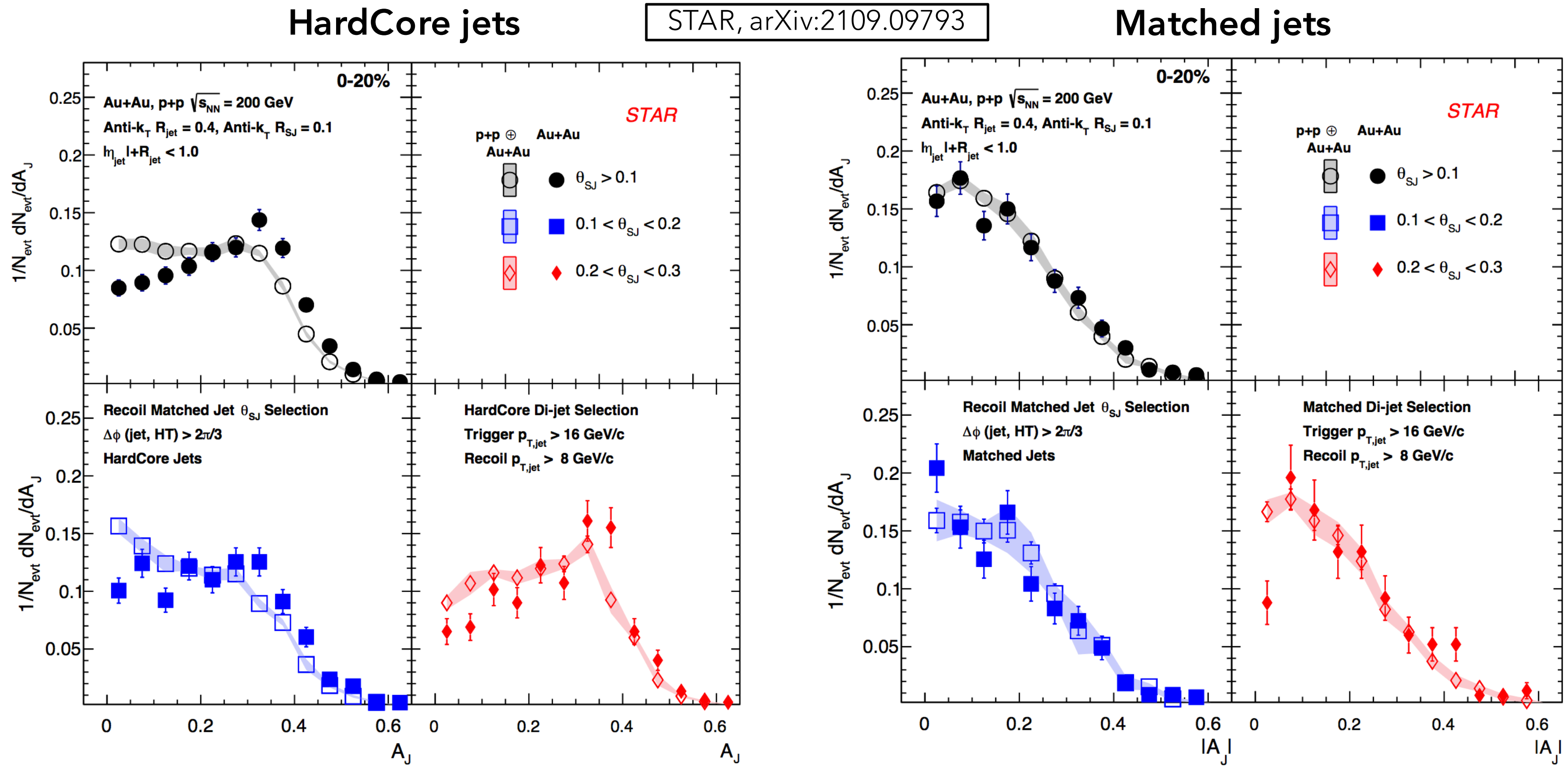


Is jet quenching different for two θ_{SJ} classes?

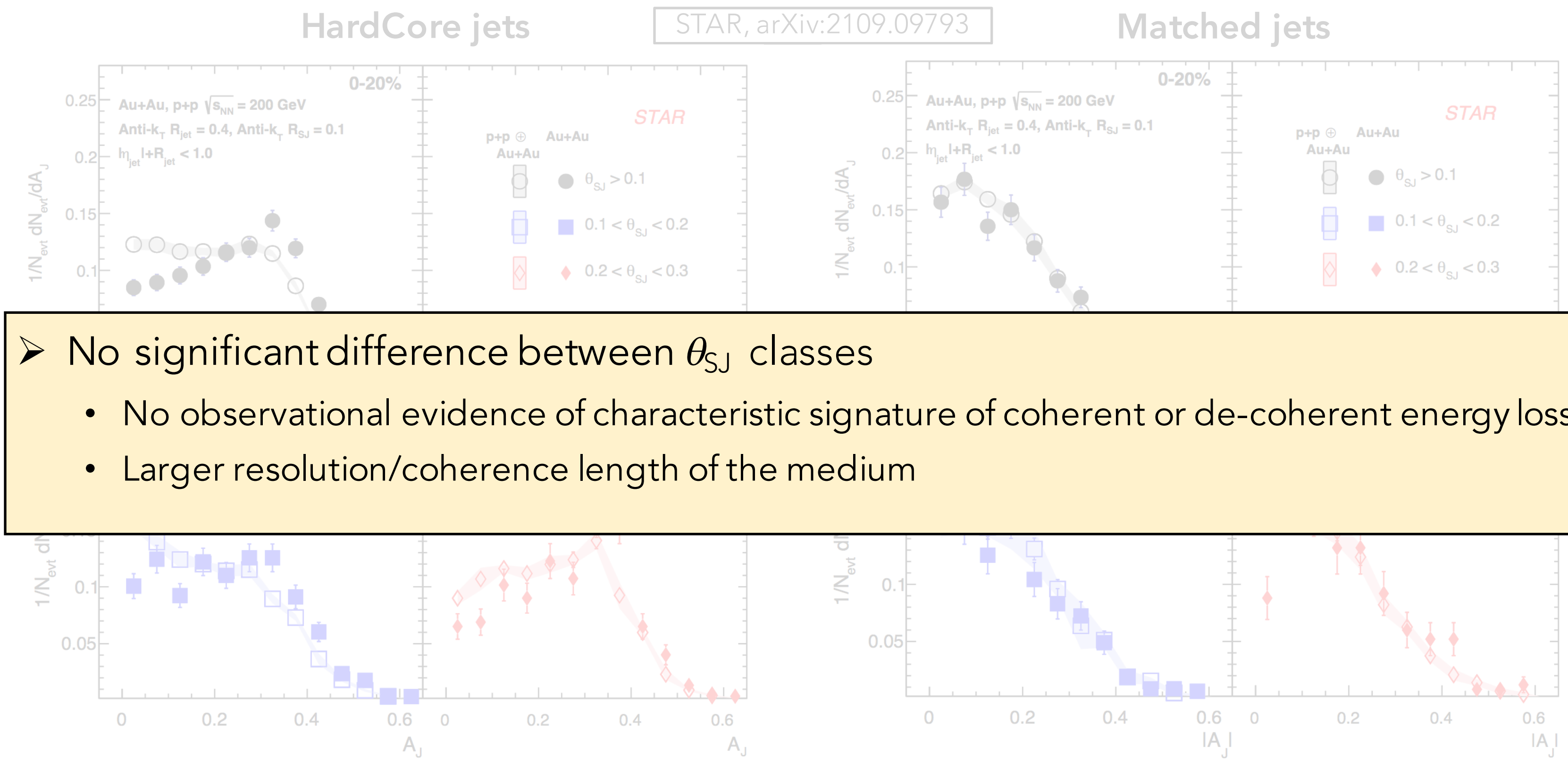
Jet substructure with subjets

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

STAR, arXiv:2109.09793



Jet substructure with subjets

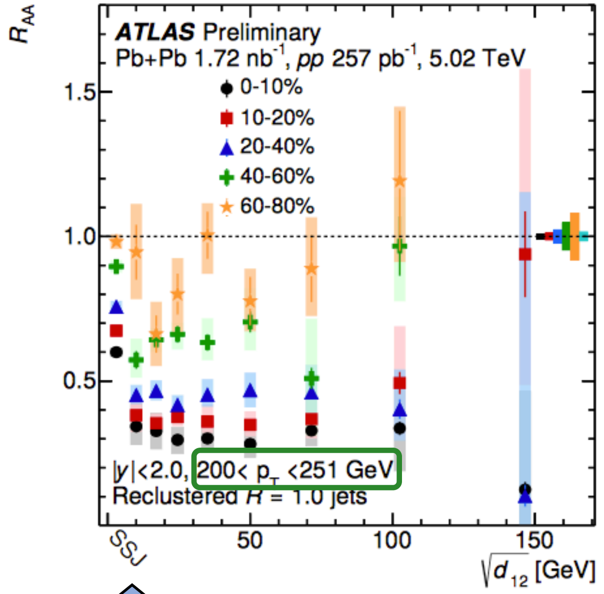


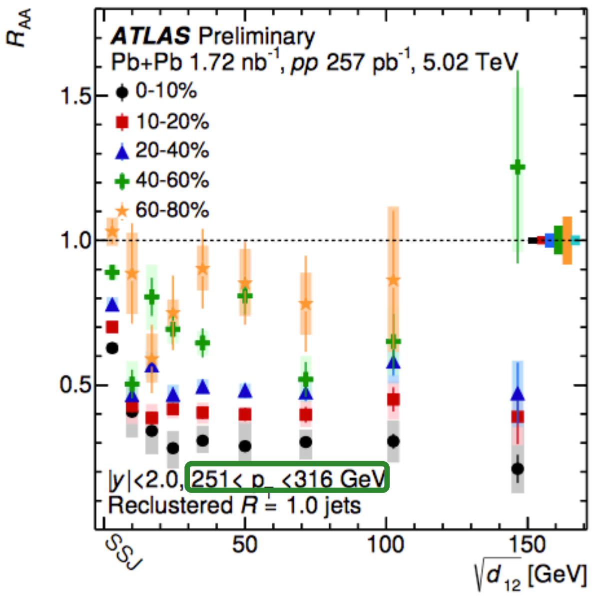
- ➢ No significant difference between θ_{SJ} classes
  - No observational evidence of characteristic signature of coherent or de-coherent energy loss
  - Larger resolution/coherence length of the medium

Jet substructure with subjets

ATLAS, 5.02 TeV

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

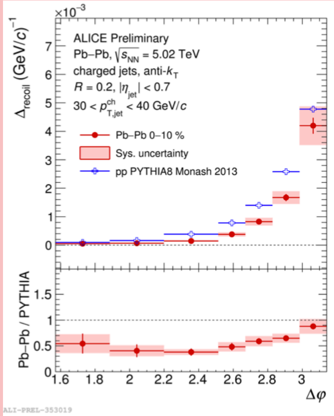


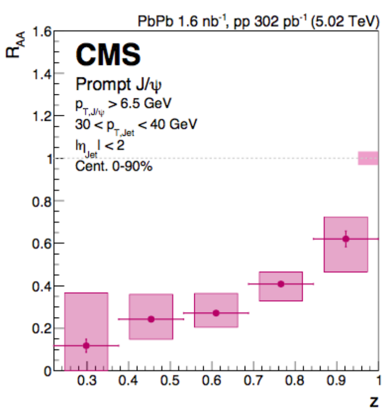


$\sqrt{d_{12}} = 0$ → Single isolated subjet

- 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

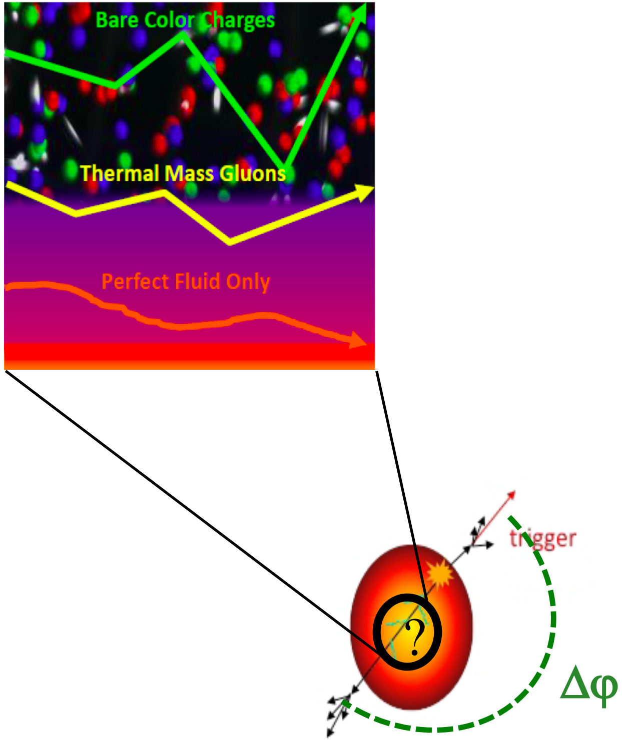
Other jet observables





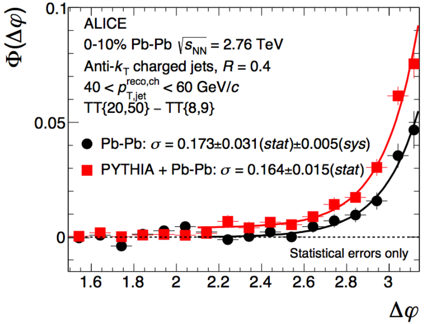
…

Jet acoplanarity

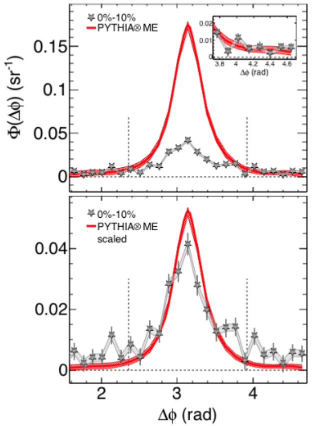


- Angular decorrelations between a trigger particle and its recoil jet – Are we seeing <u>discrete scattering centers</u> or <u>effectively continuous medium</u>?

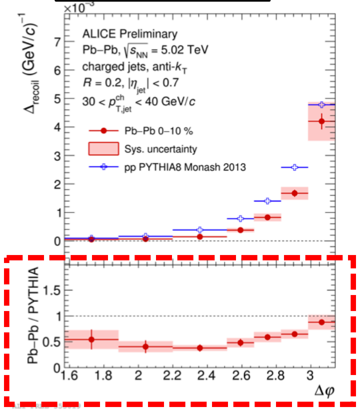
ALICE, JHEP 09 (2015) 170



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



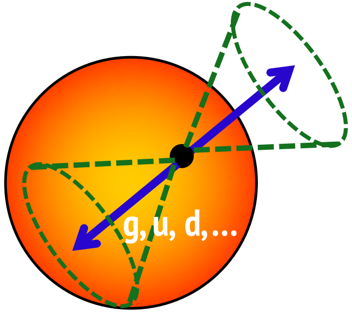
ALICE, 5.02 TeV



- 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



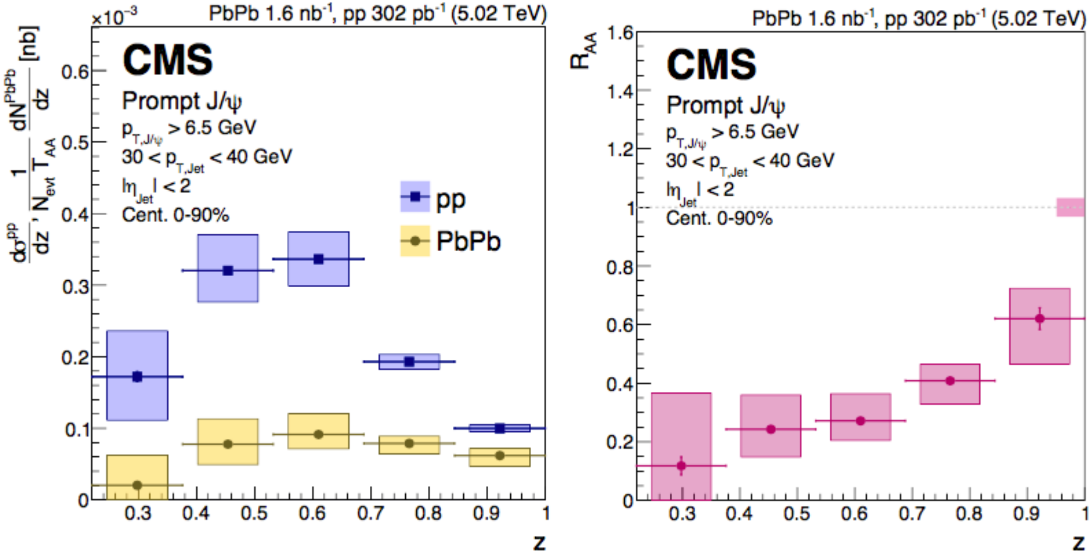
Does jet quenching depend on the flavor of the parton?

STAR, 0.5 TeV, *pp*

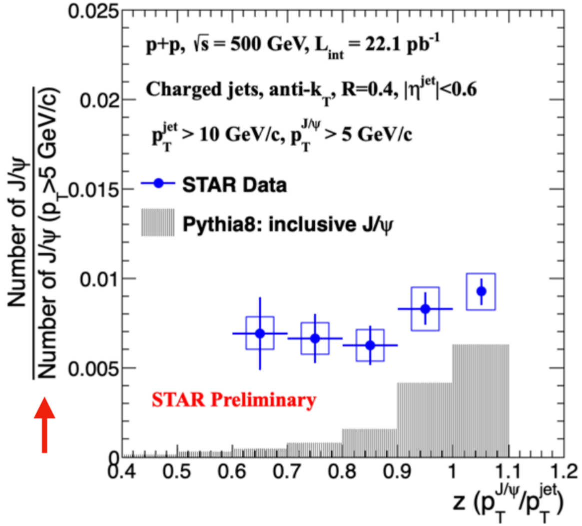
- Jets contai…
  - J/ψ proc… …re more suppressed – Need to incorporate Jet quenching + J/ψ suppression?
  - Further results coming at RHIC energies

J/ψ in jets

CMS, arXiv:2106.13235

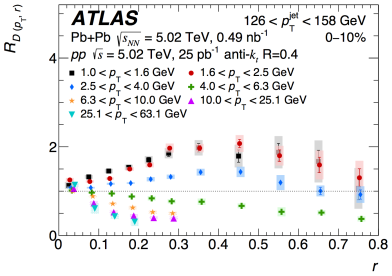


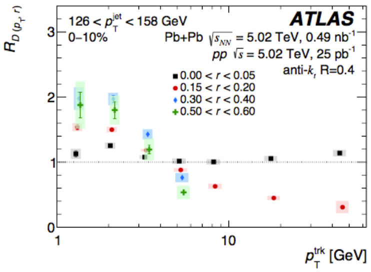
STAR, 0.5 TeV, *pp*

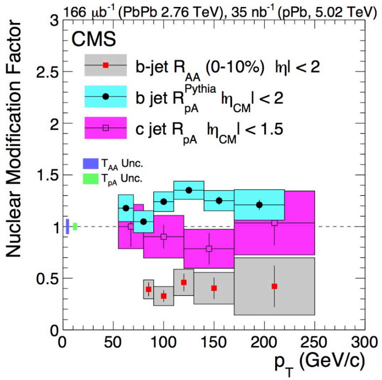


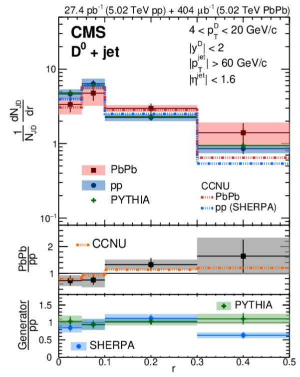
- Jets containing a prompt (or inclusive) J/ψ
  - J/ψ produced with a larger degree of surrounding jet activity are more suppressed – Need to incorporate Jet quenching + J/ψ suppression?
  - Further results coming at RHIC energies

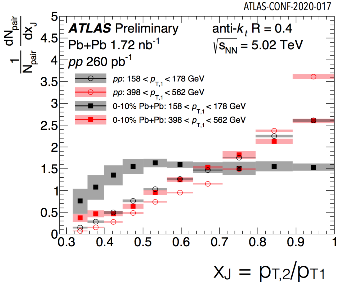
Other observables

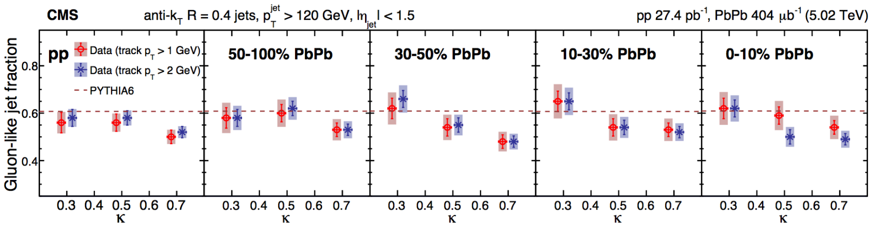


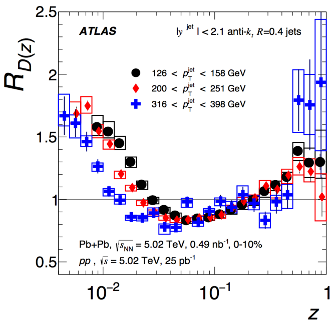


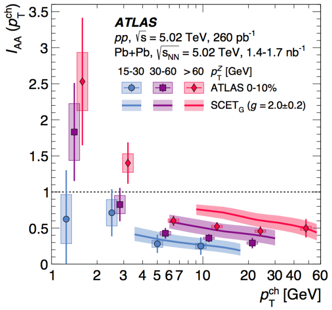












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➢ There are more results deserved to be mentioned…

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