Jet Observables, Jet Selection, Jet Modification, and Quasiparticles in QGP

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Disentangling Jet Modification in Jet Simulations and in Z+Jet Data

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Jasmine Brewer, *CERN TH*
Krishna Rajagopal, *MIT*

arXiv:2110.13159 JHEP 02 (2022) 175

Sensitivity of Jet Observables to the Presence of Quasiparticles in the QGP

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Krishna Rajagopal, *MIT*

arXiv:220n.nnnnn

What you can do with, and learn from, a model…

- There are things you can do with a model (in this talk, the Hybrid Model) that you can’t do with experimental data (eg turn physical effects off) …
- But that nevertheless teach us important lessons for how to look at, and learn from, experimental data…
- Both these papers provide examples.
  - On the importance of disentangling jet modification from jet selection…
  - On which jet observables are more sensitive to the presence of quasiparticles in the strongly coupled QGP-soup, and which are more sensitive to the wakes that jets make in the soup.
- But first a *very* brief intro to the Hybrid Model…

Perturbative Shower … Living in Strongly Coupled QGP

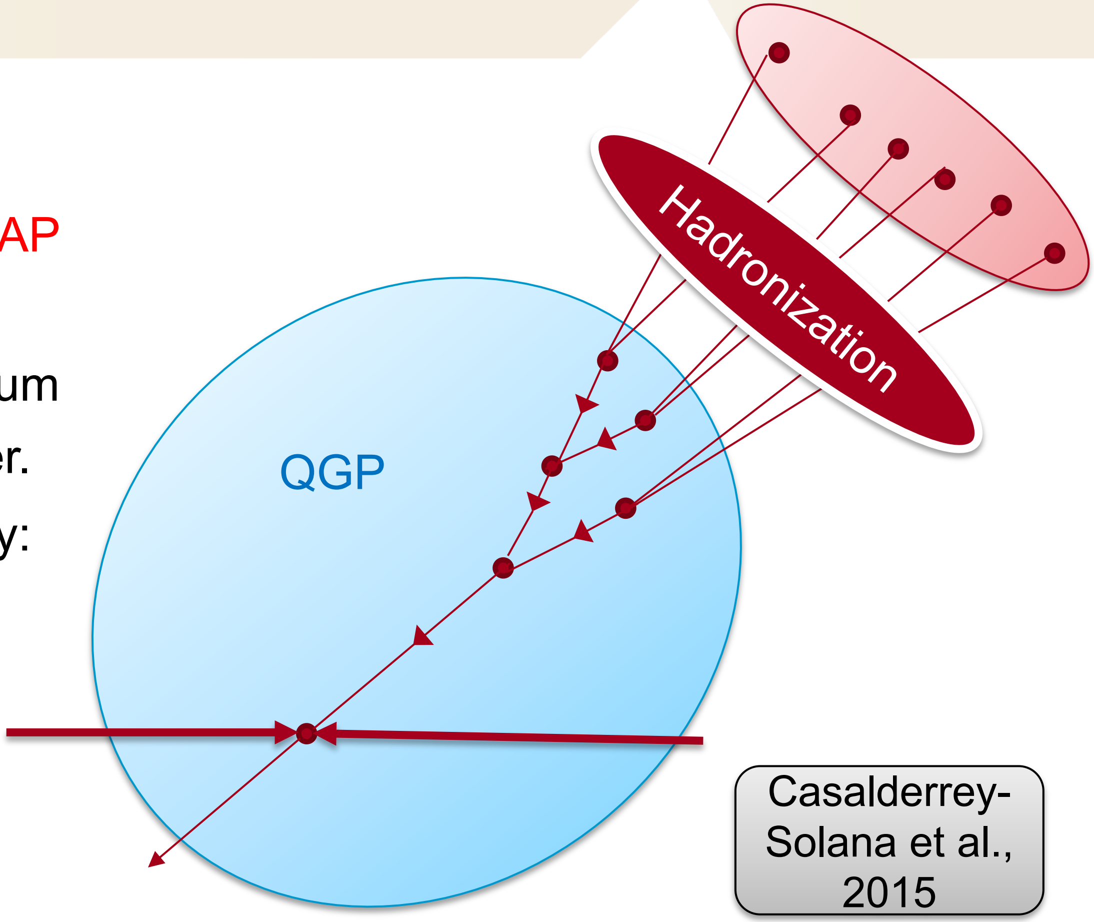
- High Q^2 parton shower up until hadronization described by DGLAP evolution (PYTHIA).
- For QGP with $T \sim \Lambda_{QCD}$, the medium interacts strongly with the shower.
  - Energy loss from holography:

$$\frac{1}{E_{in}}\frac{dE}{dx} = -\frac{4}{\pi}\frac{x^2}{x_{stop}^2}\frac{1}{\sqrt{x_{stop}^2 - x^2}}$$

O(1) fit const.

$$x_{stop} = \frac{1}{2\kappa_{sc}}\frac{E_{in}^{\frac{1}{3}}}{T^{\frac{4}{3}}}$$

$$\tau = \frac{2E}{Q^2}$$



Casalderrey-Solana et al., 2015

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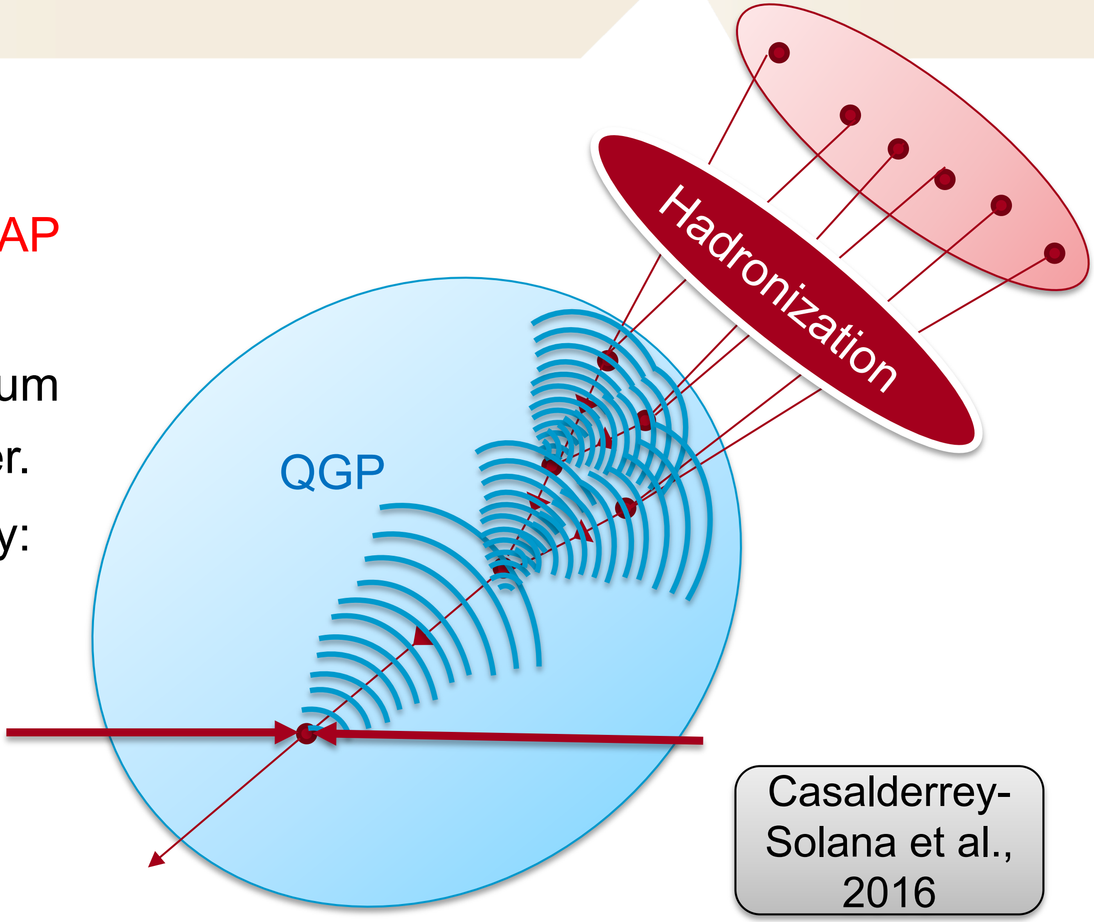

Casalderrey-Solana et al., 2016

Energy and momentum conservation → deposit hydrodynamic wake in QGP liquid

$$\frac{d\Delta N}{p_T dp_T d\phi dy} = \frac{1}{(2\pi)^3}\int \tau dx dy d\eta_s m_T \cosh(y-\eta_s)\left[f\left(\frac{u^\mu p_\mu}{T_f+\delta T}\right) - f\left(\frac{u_0^\mu p_\mu}{T_f}\right)\right]$$

Disentangling Jet Modification in Jet Simulations and in Z+Jet Data

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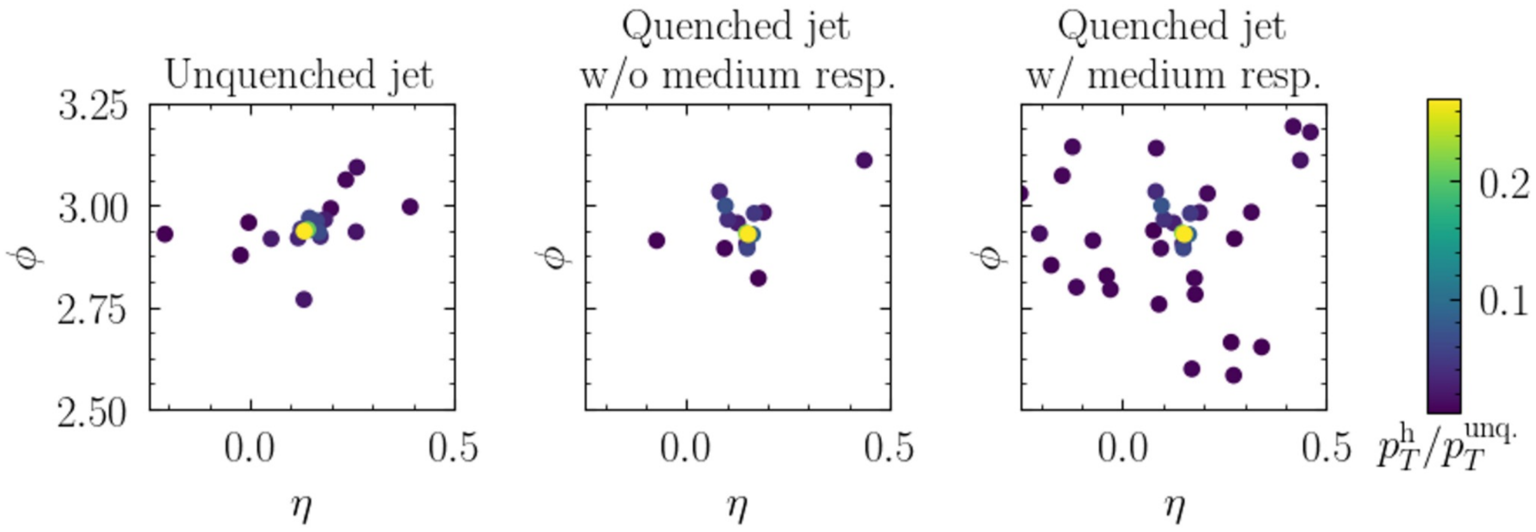
Introduction

- In experiment, you can never know what an individual jet in a PbPb collision would have looked like without quenching
    - How to best to study jet modification, in particular given that selection biases also modify observed distributions?
- Hybrid Model: possible to study a jet as it would evolve in vacuum or in medium.
- Possible to study *the same* jet as it would have been with or without quenching

An Example…

- Matched jets = jets in quenched and unquenched samples at the same (η, ϕ) location
- Furthermore, in quenched jet can identify particles originating from medium response, and can include or exclude them, to isolate their contribution to jet modification.
- Both the above are *impossible* to do with experimental data



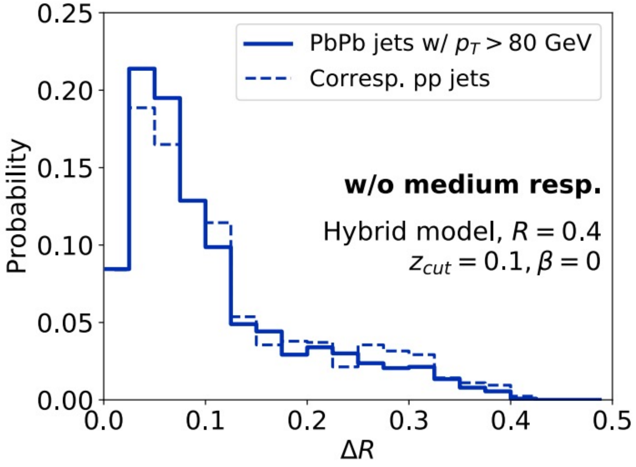
First, inclusive jets, matched…

- Select jets that fall above a $p_T^{cut} = 80\ GeV$, two possible methods:
  - **Quench-then-Select**: in PbPb collisions, select jet with quenched p_T above cut; then find matching pp jet
  - **Select-then-Quench**: select pp jet with unquenched p_T above cut; then find matching PbPb jet
- Study effects of selection bias by comparing distribution of observables in these two differently-selected samples of PbPb jets…
- Blue-selection in PbPb collisions corresponds to inclusive jet sample; orange-selection in PbPb is impossible to do with experimental data
- Look at two observables: Softdrop ΔR and C_1^1 (in this talk, only Softdrop ΔR)
- Recall Softdrop condition: for two constituent particles with transverse momentum $p_{T,1}, p_{T,2}$ in a jet with anti-kt radius R, particles are groomed away unless

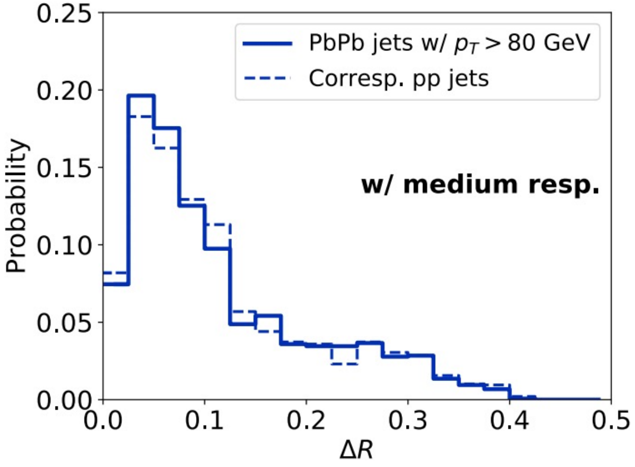
$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut} \left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$

Inclusive jet modification

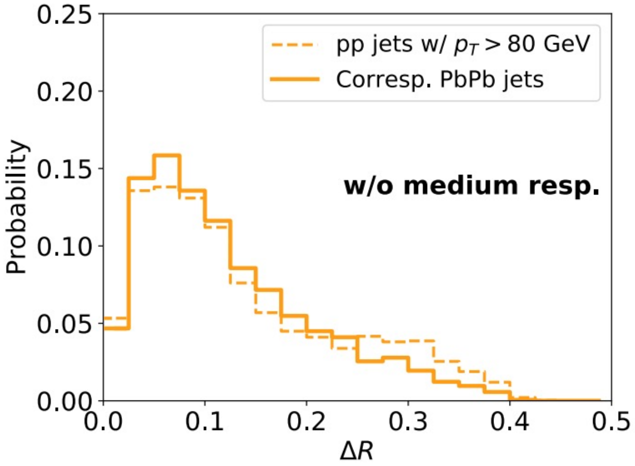
- Blue: reproduce previous result that the distribution of groomed ΔR appears to be unmodified
- Orange: in reality, quenching substantially modifies the ΔR of jets → apparent lack of modification is a selection bias effect.
- Also see that blue-selection favors jets with smaller ΔR
- However, experimentalists cannot replicate these results – cannot look at the same jet before and after quenching
- NB: substantial modification principally originates from medium response



(a)



(b)



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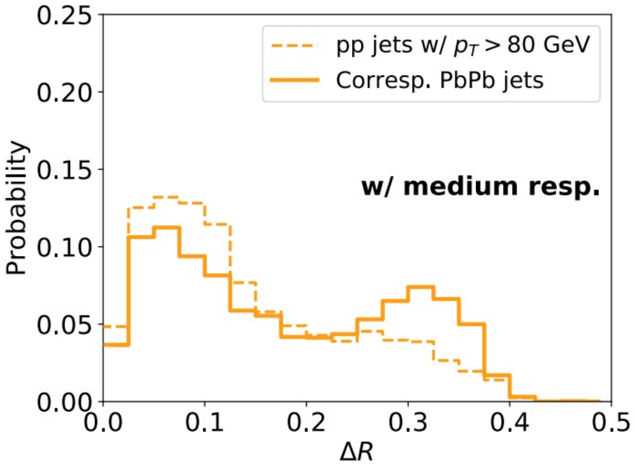
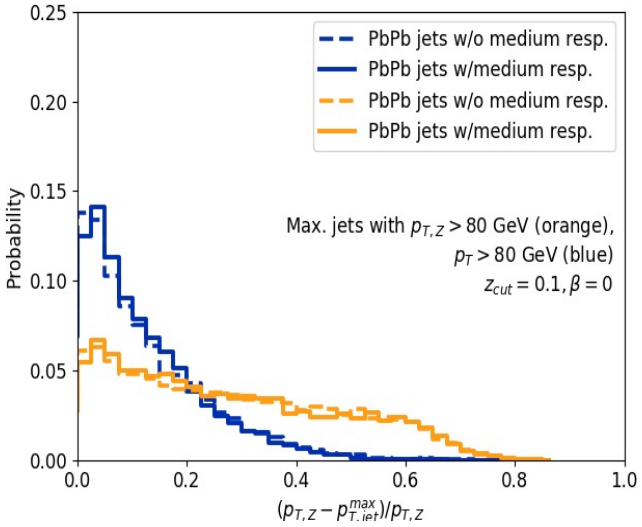


(d)

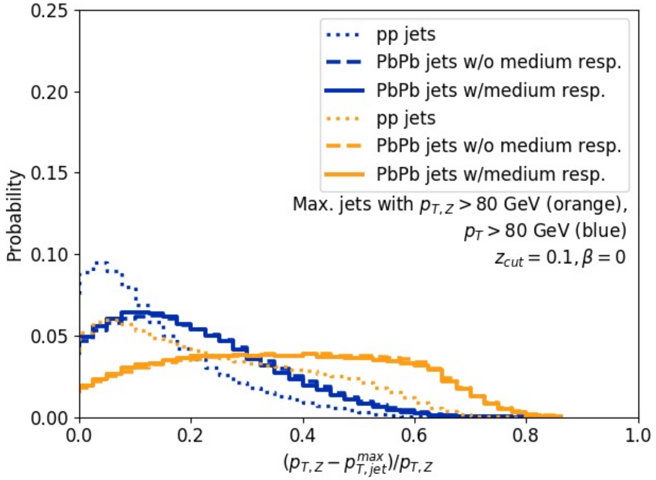
Results – energy loss

- Blue-selection picks jets that lost least energy; “survivor bias”
- What jets are in the excess at large ΔR? Study jets with $\Delta R < 0.2$ and ≥ 0.2.
- The jets whose ΔR became larger as they were quenched are those which lost most energy → they don’t end up in distribution of Quench-then-Select/Select Jet due to its selection bias.
  - Energy loss falls steeply with energy
  - Most heavy ion jets with $p_T > 80$ GeV didn’t lose much energy, and also didn’t have their ΔR much modified

HI sample



Z+jet sample

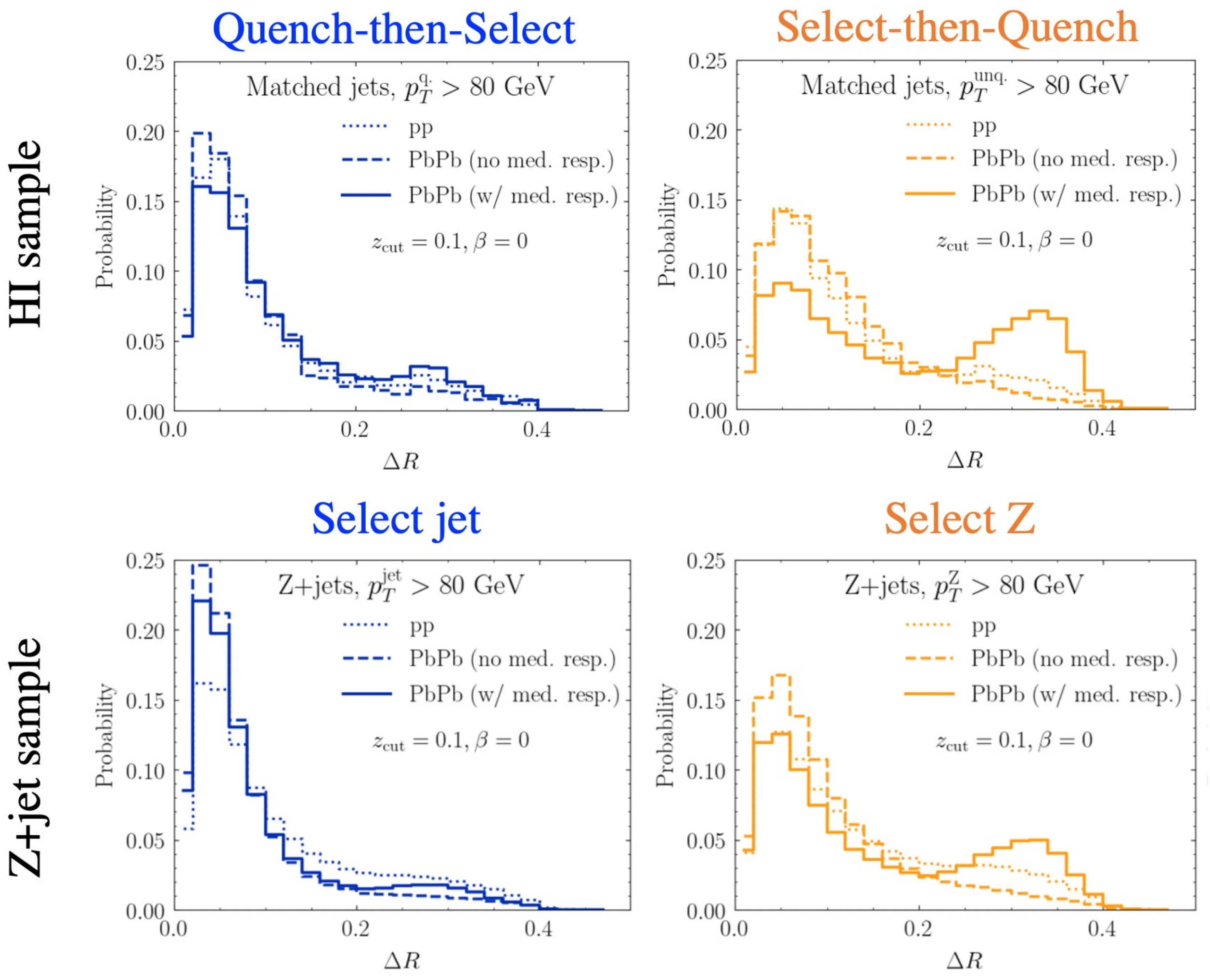


Analogous Z+jet analysis…

- Use Z+jet events; Z and leading jet; no need for matching procedure
- Select objects that fall above a $p_T^{cut} = 80\ GeV$, two possible methods:
  - **Select Jet**: select jets in events with a Z boson where the quenched p_T of the jet is above cut; Z has whatever p_T it has, although we did require it to be above 30 GeV
  - **Select Z**: select Z with p_T^Z above cut; jet has whatever p_T it has, although we did require jet p_T above 30 GeV.
- Can we reproduce previous results using a procedure that experimentalists can follow?
- Blue selection is unusual, but can be realized.
- Orange selection is more standard; important to include jets with p_T well below p_T^{cut}
- Look at two observables: Softdrop ΔR and C_1^1 (again, here show only the first)

Z+jet Results – ΔR

- z-cut = 0.10 and $\beta = 0$, with and without medium response
- Selection bias in Quench-then-Select/Select Jet
    - Most heavy ion jets with $p_T > 80$ GeV didn't lose much energy
    - ΔR distribution appears unmodified
- Select-then-Quench/Select Z does NOT have that selection bias
    - Select based on unquenched pp jet, or Z → heavy ion jets of any p_T are are included
    - ΔR distribution *is* substantially modified by quenching: modification of ΔR on jet-by-jet basis, originates from medium response
    - Note: only using Z as a selection tool; no claim that it tells us jet energy



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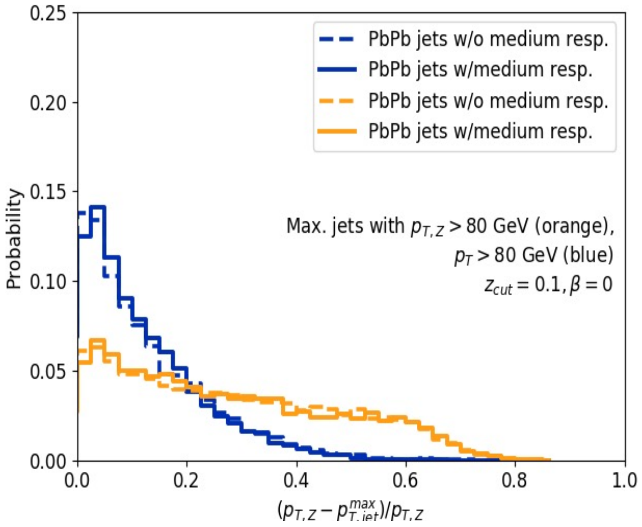
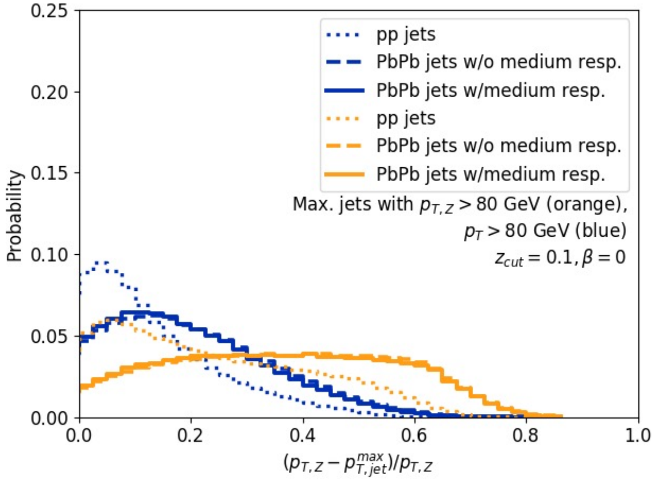


Z+jet sample



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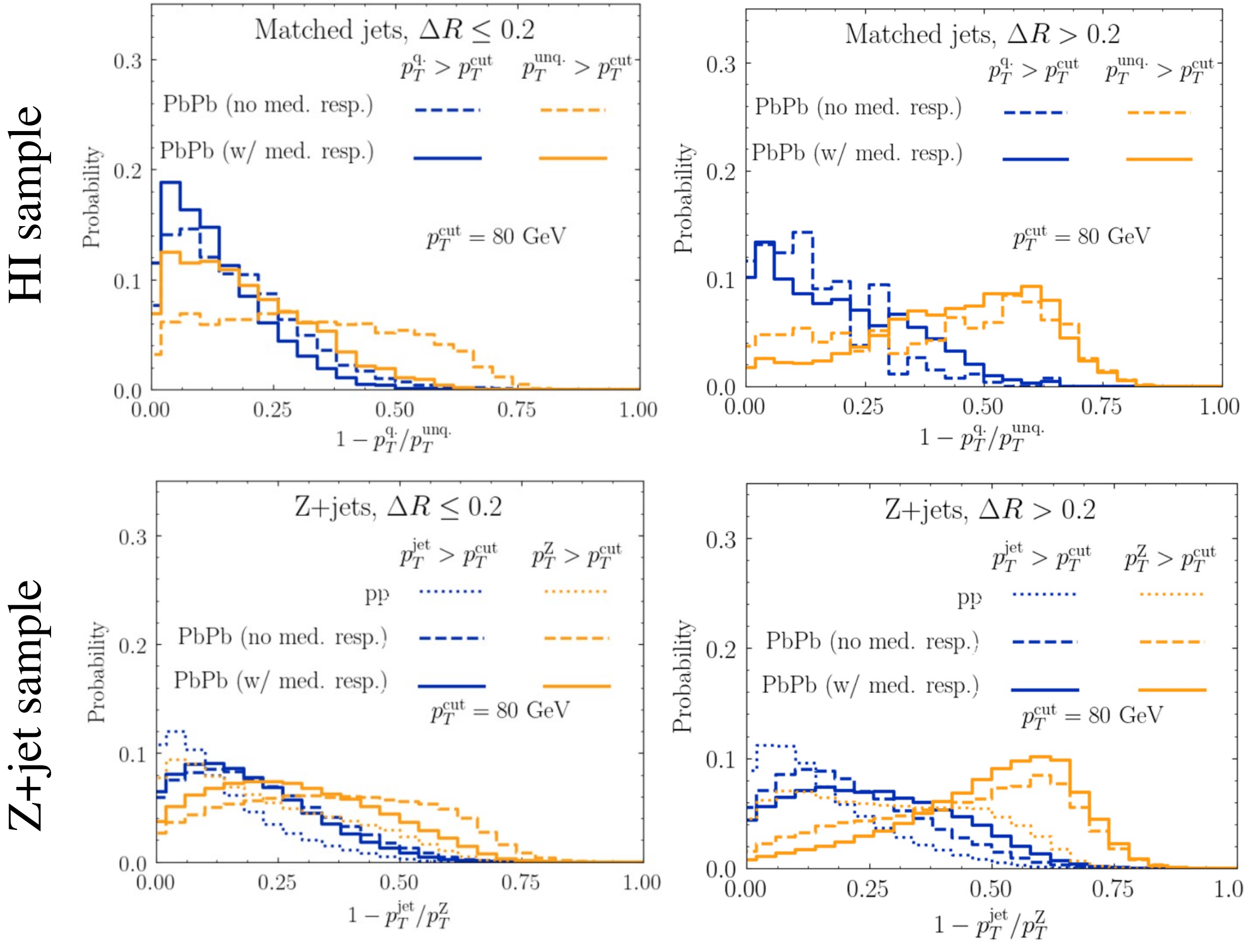
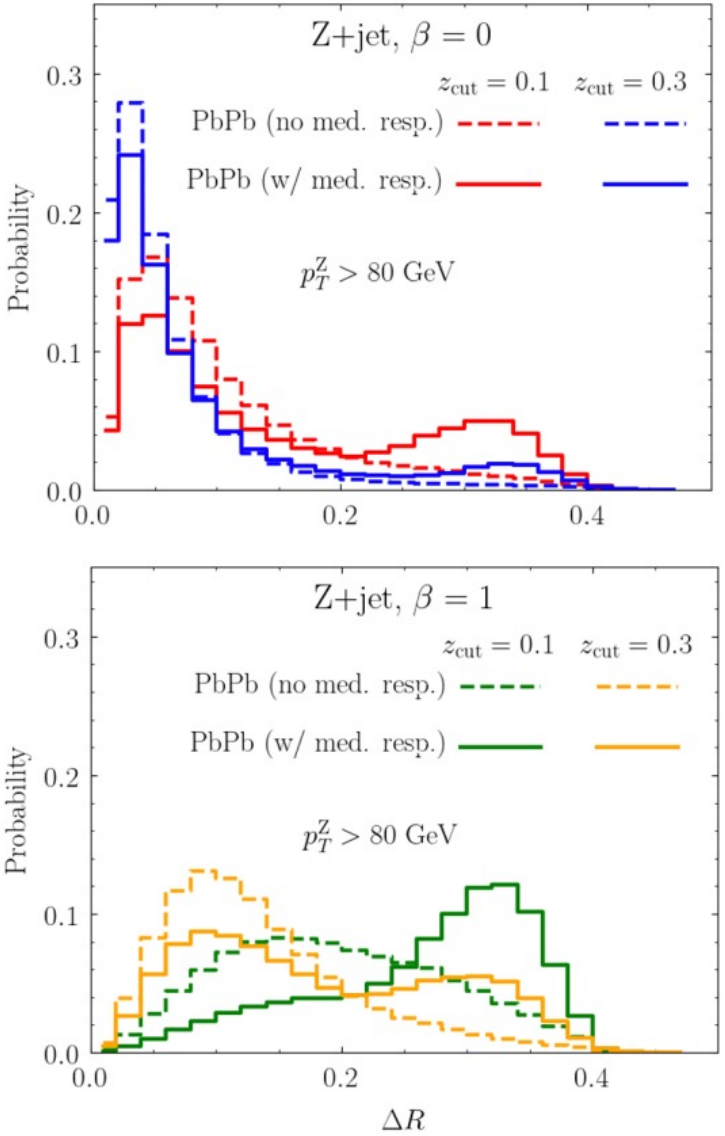


How does bias effect change with grooming?

- Look at Z+jet sample in medium (with or without medium response)
- Recall recursive Softdrop condition: for any two particles in a jet, remove particles unless

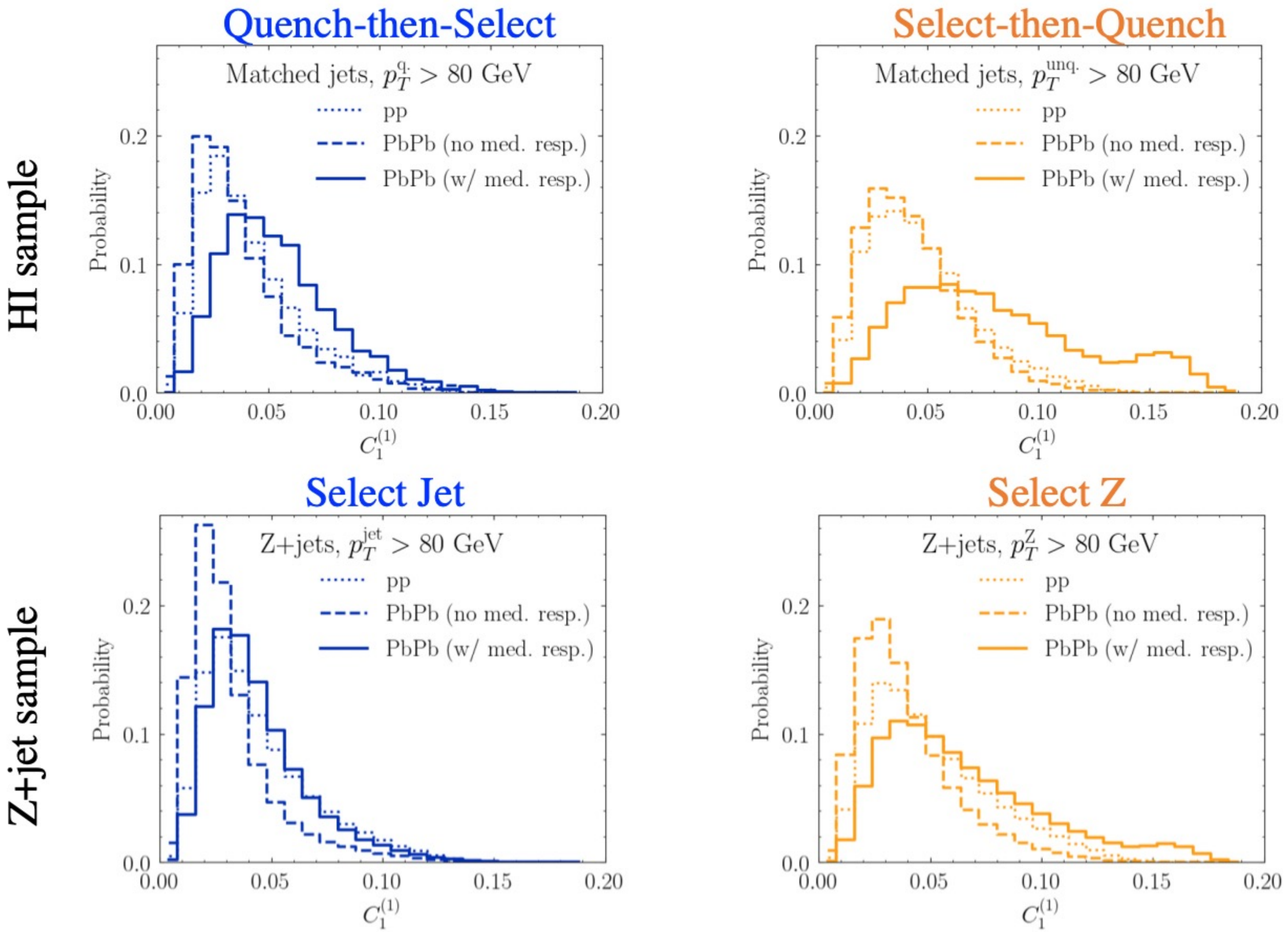
$$\frac{\min(p_{T,1},p_{T,2})}{p_{T,1}+p_{T,2}} > z_{cut}\left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

- Vary $z_{cut} = 0.1, 0.3;\;\; \beta = 0, 1$
- Increase β → increase enhancement at large ΔR
- Increase z_{cut} → decrease enhancement at large ΔR



Is this a Softdrop-dependent effect?

- Study an observable that does not depend on Softdrop parameters
- Observable analogous to jet width – choose C_1^1
- See same effect – enhancement at large jet width for Select-then-Quench/Select Z, absent in Quench-then-Select/Select Jet
- These wide jets are the same jets that lose the most energy



Discussion

- Quenching modifies ΔR of jets in the hybrid model
- The jets whose ΔR is substantially modified are those which lose a large fraction of their energy.
- Selecting a jet sample using a cut on the jet p_T in PbPb collisions creates bias towards jets that had smaller ΔR, lose very little energy, and whose ΔR is not substantially modified.
  - In Monte Carlo study, select jet sample by placing cut on jet p_T in pp collisions → study quenched versions of these jets → removes bias toward less modified jets. ΔR of individual jets is substantially modified in the hybrid model.
- Modification of ΔR distribution is not seen if medium response is excluded.
  - Hybrid model: structure of the parton shower is not modified by quenching except that partons in the shower lose energy; this hardly changes ΔR distribution.
  - Soft partons from wake in the medium (i.e. the "lost" energy) *do* change the ΔR distribution.
- The Select-then-Quench method (for matched inclusive jets) is not feasible in experiment.
- The Select-Z method is one that experimentalists can employ in analyzing Z+jet data

Sensitivity of Jet Observables to the Presence of Quasiparticles in the QGP

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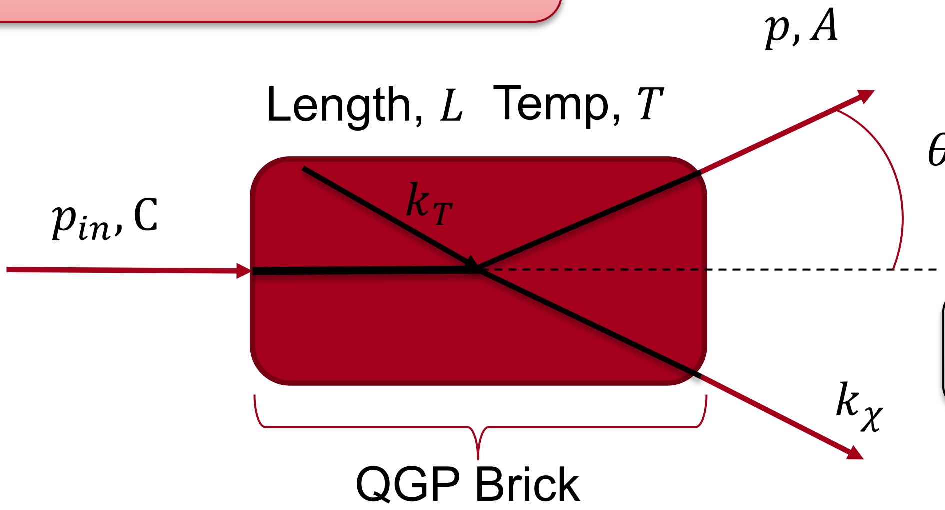
Why Moliere scattering? Why add to Hybrid Model?

- QGP, at length scales of $O(T^{-1})$, including flow and parton energy loss, is well-described as a strongly coupled liquid.
- At shorter length scales, probed at high exchanged-momentum, asymptotic freedom → quasi-particle behavior.
- High energy partons in jet showers have the potential to probe the particulate nature of QGP via power-law-rare, high-momentum-transfer, large-angle, Moliere scattering.
- “Seeing” such scattering is first step to probing microscopic structure of QGP
- What jet observables are sensitive to effects of Moliere scattering?
- To answer, need to turn it off/on. Start from Hybrid Model (Moliere is definitely off!), add it, and look at its effects…

Moliere Scattering in a brick of QGP (D'Eramo, KR, Yin, 2019)

Power-law-rare medium kicks which can probe particle constituents of QGP

In JEWEL, LBT, MARTINI, harder to turn off



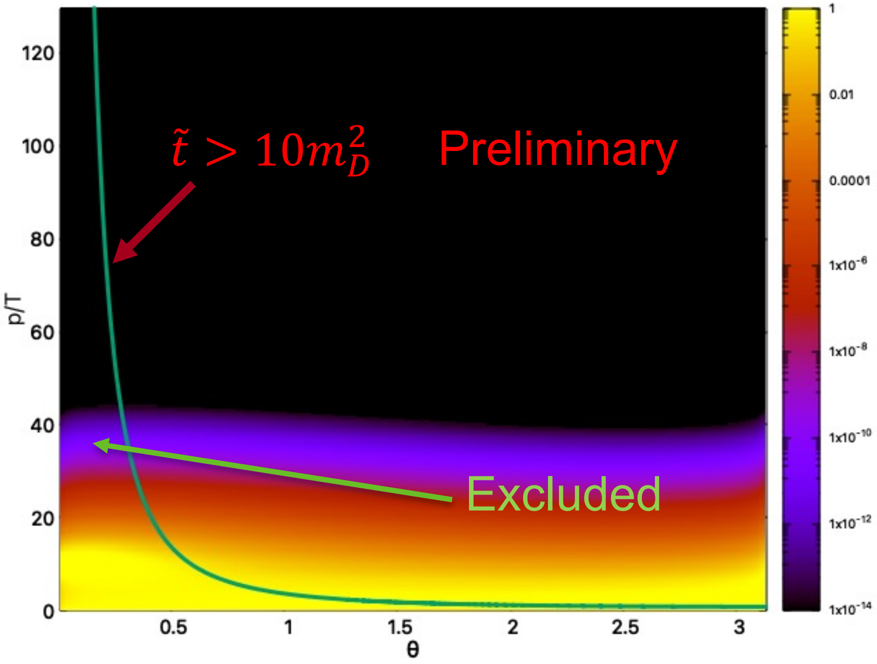
D'Eramo et al., 2019

Tree-Level 2-2 massless scattering amplitudes

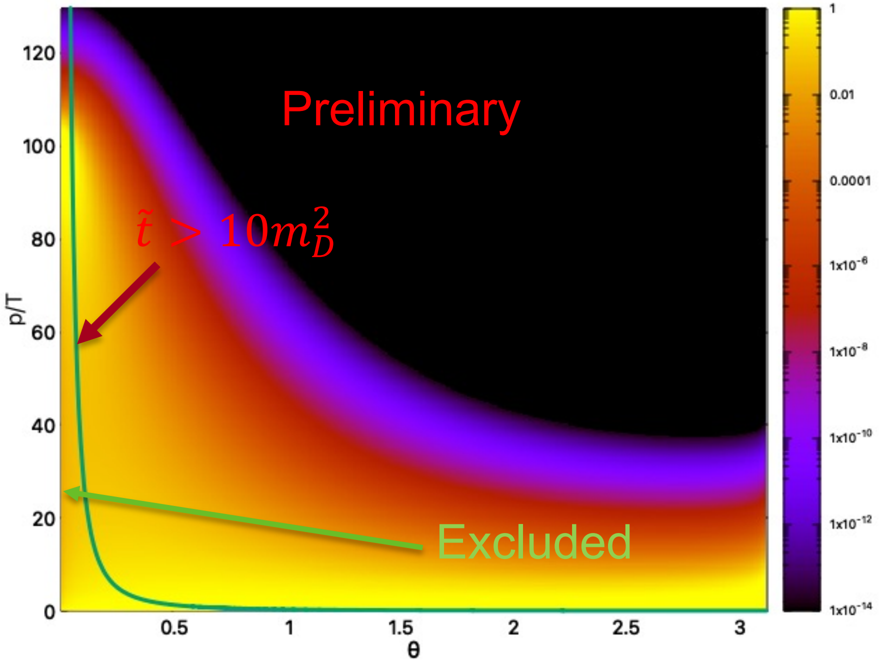
- Sufficiently hard scattering should be perturbative.
- High p_T particle can be deflected, changing its energy and direction.
- Recoiling particle, k_χ, a new particle to be quenched
- Thermal particle, k_T, from BE/FD distribution, removed from medium.

$$F^{C\to A}(p,\theta;p_{in}) = \sum_{nDB} \frac{c_{DBn}^{C\to A}}{2(4\pi)^3}\left(\frac{p\sin(\theta)}{p_{in}|\boldsymbol{p}-\boldsymbol{p_{in}}|T}\right)\int_{k_{min}}^{\infty} dk_T\, n_D(k_T)\left[1 \pm n_B(k_\chi)\right]\int_0^{2\pi}\frac{d\phi}{2\pi}\frac{\left|M^{(n)}\right|^2}{g_s^4}$$

Results (for a QGP brick)



Incoming gluon, $p_{in} = 10T, \mathrm{L} = 15/T$



Incoming gluon, $p_{in} = 100T, \ \mathrm{L} = 15/T$

- Also exclude $\tilde{u} > 10m_D^2$; not a simple curve on this plot
- Restricting to $\tilde{u}, \tilde{t} > 10 \cdot m_D^2$ excludes soft scatterings; justifies assumptions made in amplitudes; avoids double counting
- Analytical results → fast to sample
- Apply at every time step, to every rung, in every shower, in Hybrid Model Monte Carlo…. And, if a scattering happens, two subsequent partons then lose energy a la Hybrid

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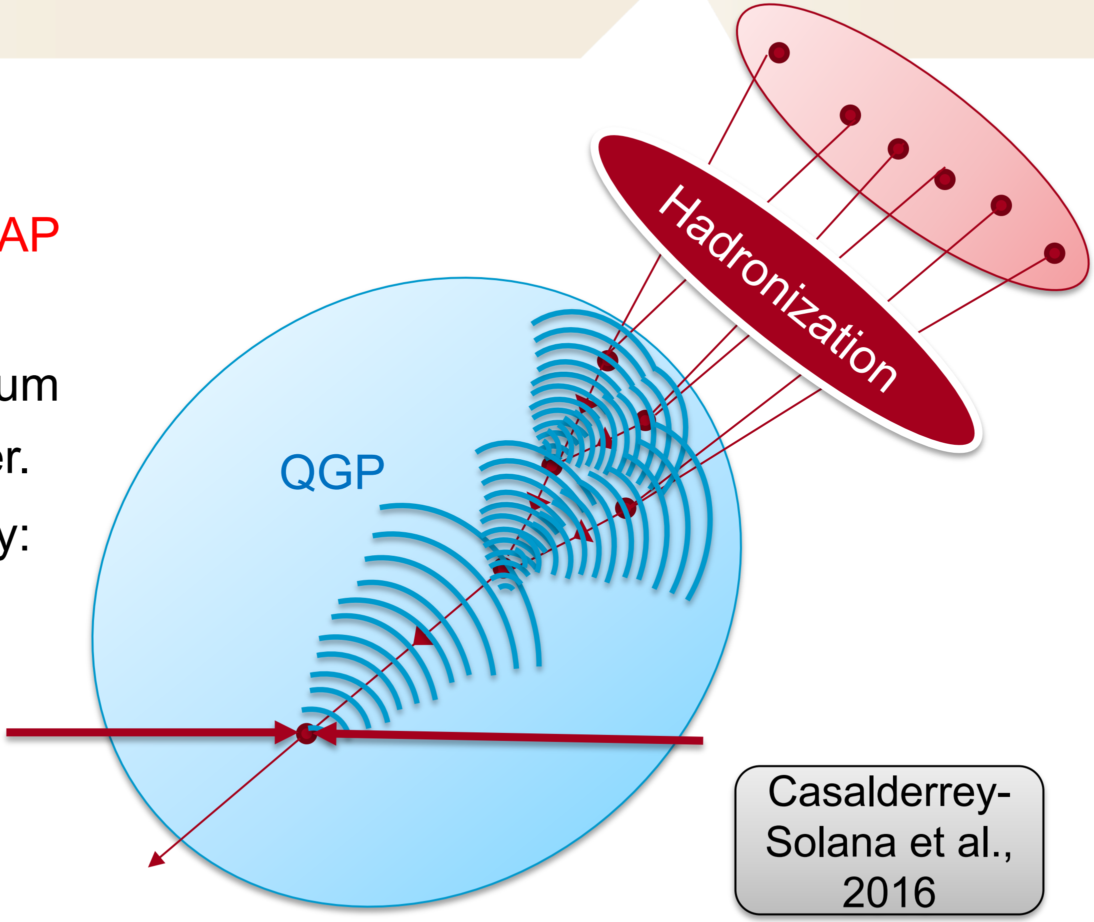

Casalderrey-Solana et al., 2016

Energy and momentum conservation → deposit hydrodynamic wake in QGP liquid

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Adding Moliere Scattering to Hybrid Model

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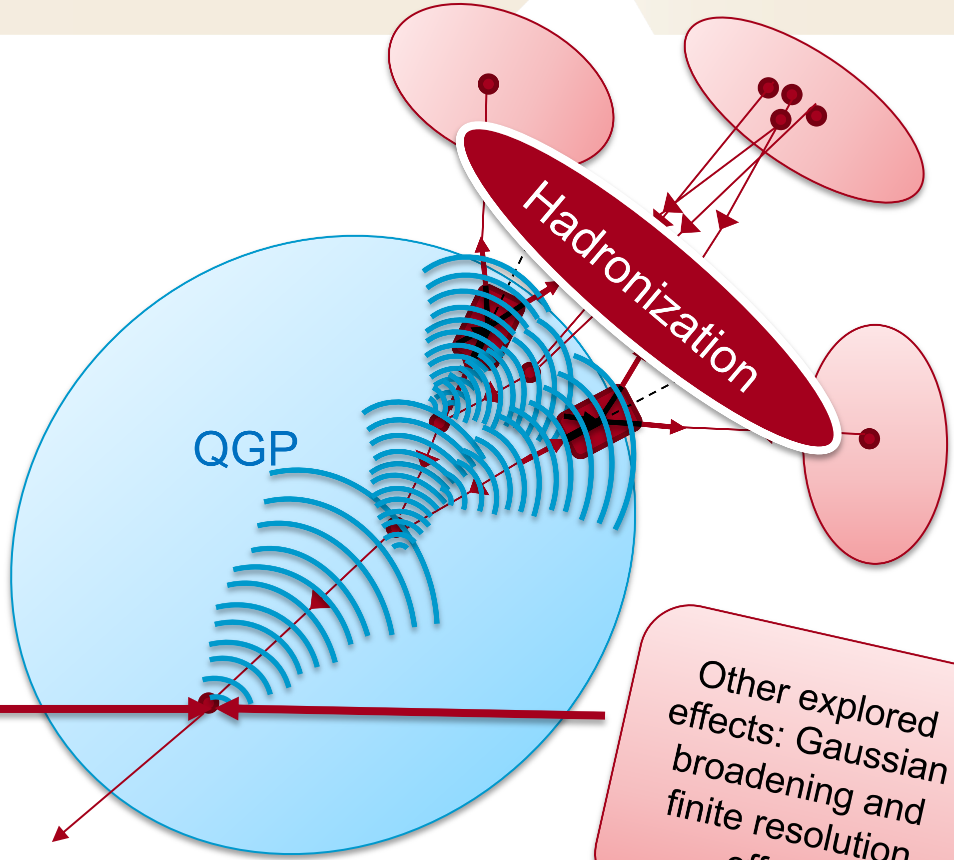

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$$x_{stop} = \frac{1}{2\kappa_{sc}}\frac{E_{in}^{\frac{1}{3}}}{T^{\frac{4}{3}}}$$

$$\tau = \frac{2E}{Q^2}$$

O(1) fit const.

Other explored effects: Gaussian broadening and finite resolution effects

Energy and momentum conservation ⟶ activate hydrodynamic modes of plasma

$$\frac{d\Delta N}{p_T dp_T d\phi dy} = \frac{1}{(2\pi)^3}\int \tau dx dy d\eta_s m_T \cosh(y-\eta_s)\left[f\left(\frac{u^\mu p_\mu}{T_f + \delta T}\right) - f\left(\frac{\mu_0^\mu p_\mu}{T_f}\right)\right]$$

Gaussian Broadening vs Large Angle Scattering

- Elastic scatterings of exchanged momentum $\sim m_D$

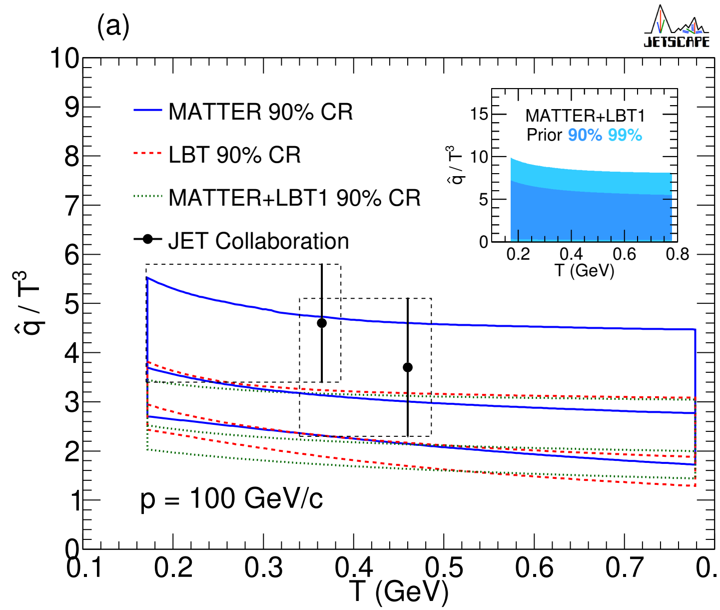
  → Gaussian broadening due to multiple soft scattering

- At strong coupling, holography predicts Gaussian broadening without quasi-particles (ex: N=4 SYM)

$$P(k_\perp) \sim \exp\left(-\frac{\sqrt{2}k_\perp^2}{\hat{q}L^-}\right) \qquad \hat{q} = \frac{\pi^{\frac{3}{2}}\Gamma\left(\frac{3}{4}\right)}{\Gamma\left(\frac{5}{4}\right)}\sqrt{\lambda}T^3$$

- Restrict to momentum exchanges $\gg m_D$

  → perturbative regime with a power law distribution separated from Gaussian broadening



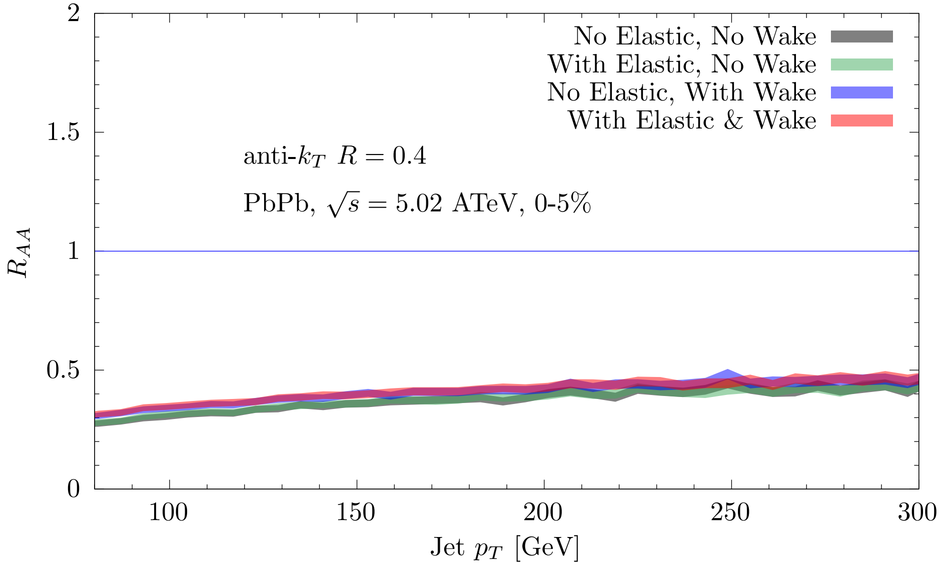
D'Eramo et al., 2011
+
Mehtar-Tani et al., PRD 2021

Jet R_{AA}

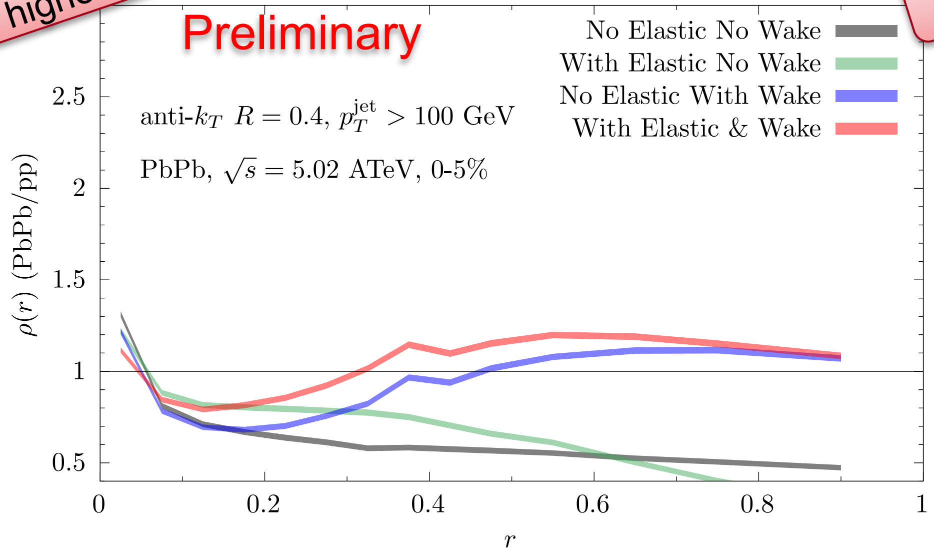
Casalderrey-Solana et al. 2019

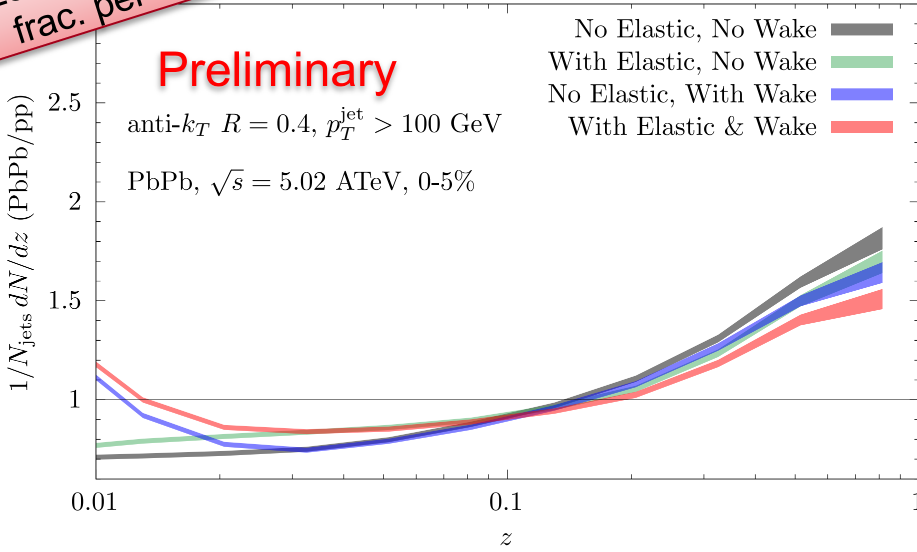
- κ_{sc} previously fit with jet and hadron suppression data from ATLAS+CMS at 2.76+5.02 TeV
- Elastic scatterings lead to slight additional suppression; refit κ_{sc} . That means red is on top of blue in this plot by construction. (Addition of the elastic scatterings yields only small change to value of κ_{sc}.)
- Adding the hadrons from the wake allows the recovery of part of the energy within the jet cone; blue and green slightly below red and blue.
- All results, here on, are Preliminary.

Preliminary



Jet Shapes and Fragmentation Functions


More energy at higher radius


Lower momentum frac. per hadron

→ Elastic scattering effects look very similar to wake effects, but smaller.

- Moliere scattering transfers jet energy to high angle and lower momentum fraction particles. So does energy loss to wake in fluid.
- In these observables, effect of Moliere looks like just a bit more wake.
- In principle sensitive to Moliere, but in practice not at all.
- What if we look at groomed observables? Less sensitive to wake…

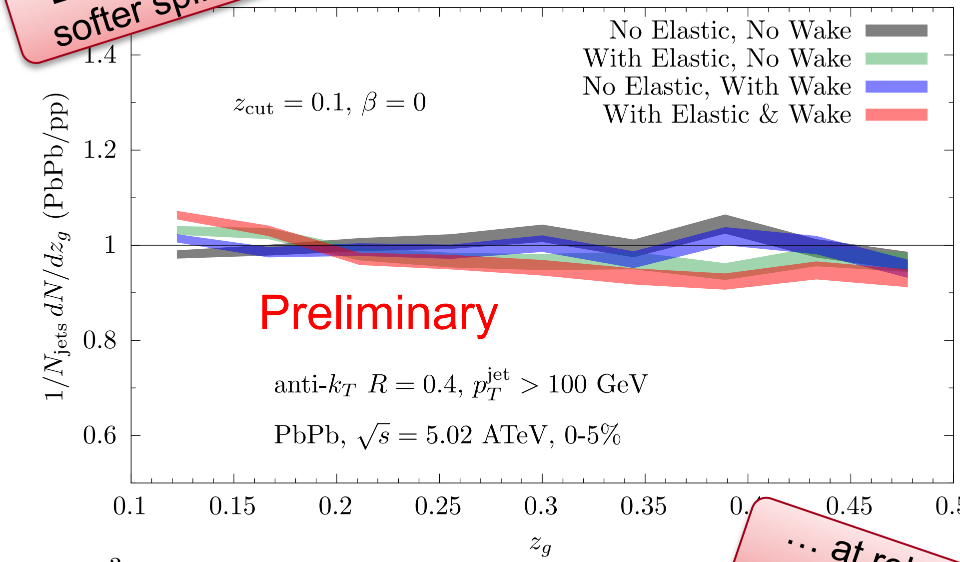
Groomed z_g and R_g

Soft Drop ($\beta = 0$)

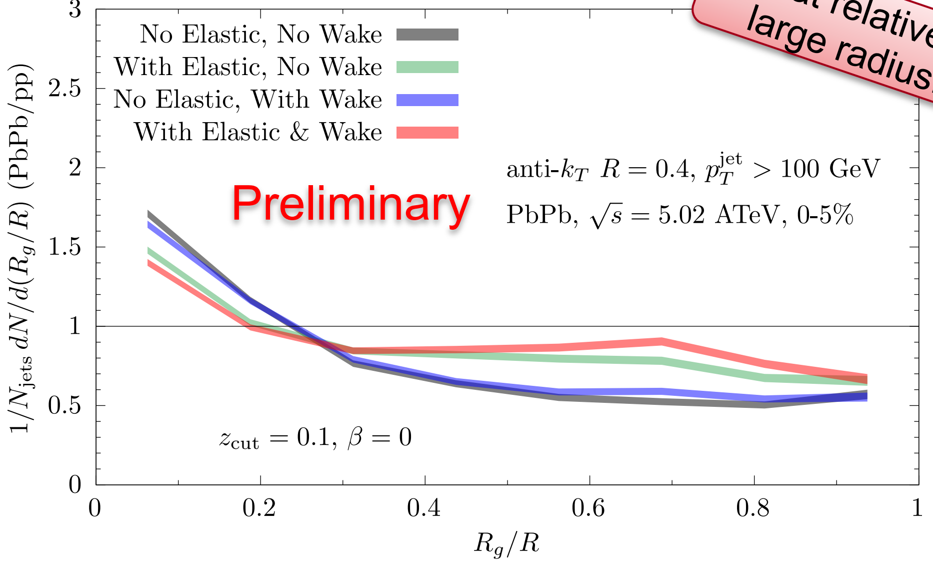
1. Reconstruct jet with anti-k_T
2. Recluster with Cambridge-Aachen
3. Undo last step of 2, resulting in subjets 1 and 2, separated by angle R_g
4. If $\frac{\min(p_{T1}, p_{T2})}{p_{T1}+p_{T2}} \equiv z_g > z_{cut}$, then original jet is the final jet. Otherwise pick the harder of subjets 1 and 2 and repeat

Much less sensitivity to wake; Moliere scattering shows up; effects of Moliere and wake are again similar in shape, but here effects of Moliere are dominant.

Enhancement of softer splittings…



… at relatively large radius.

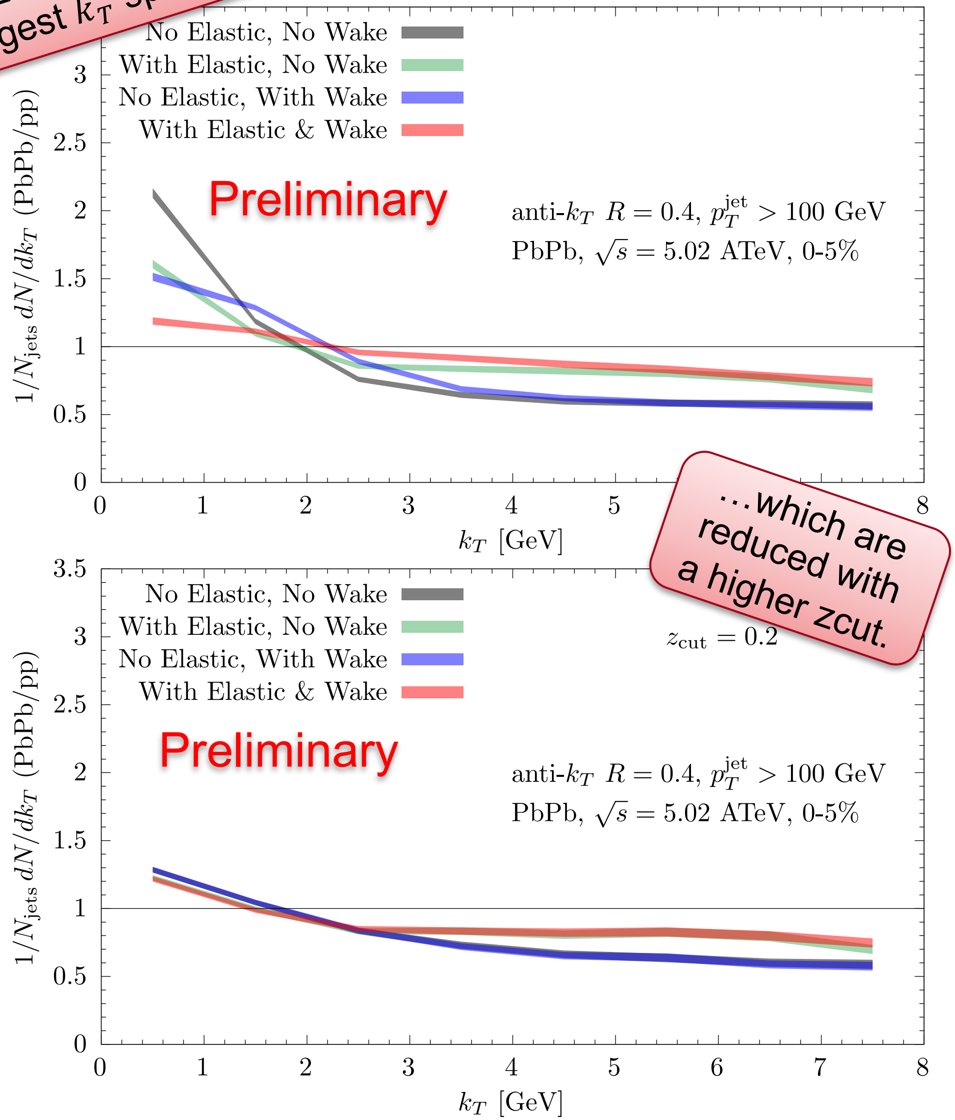


Leading k_T

1. Reconstruct jet with anti-k_T
2. Recluster with Cambridge-Aachen
3. Undo last step of 2, resulting in subjets 1 and 2
4. Note k_T of splitting
5. Follow primary branch until the end.
6. Record largest k_T

$$k_T = \min(p_{T1}, p_{T2}) \sin(R_g)$$

Similar message also for this groomed observable: Moliere scattering effects show up; much larger than wake effects.

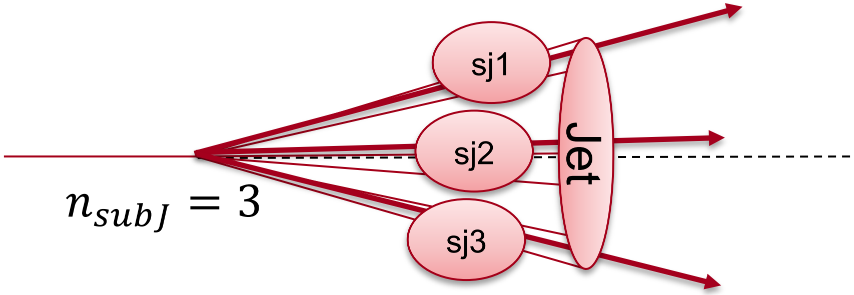


Enhancement of largest k_T splittings…

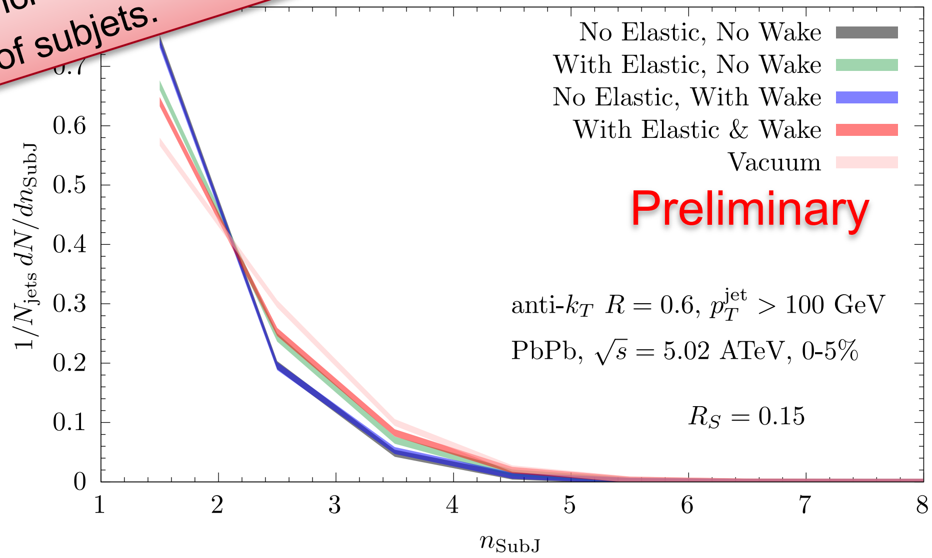
…which are reduced with a higher zcut.

Inclusive Jets within Inclusive Jets: Inclusive Subjets

1. Reconstruct jet with R=0.6
2. Recluster each jet's particle content into subjets with R=0.15



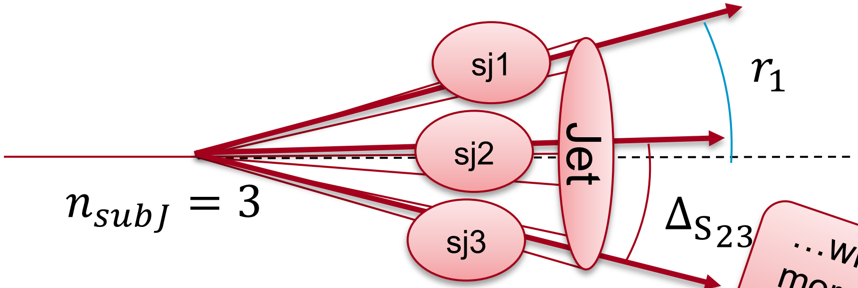
Increase in number of subjets.



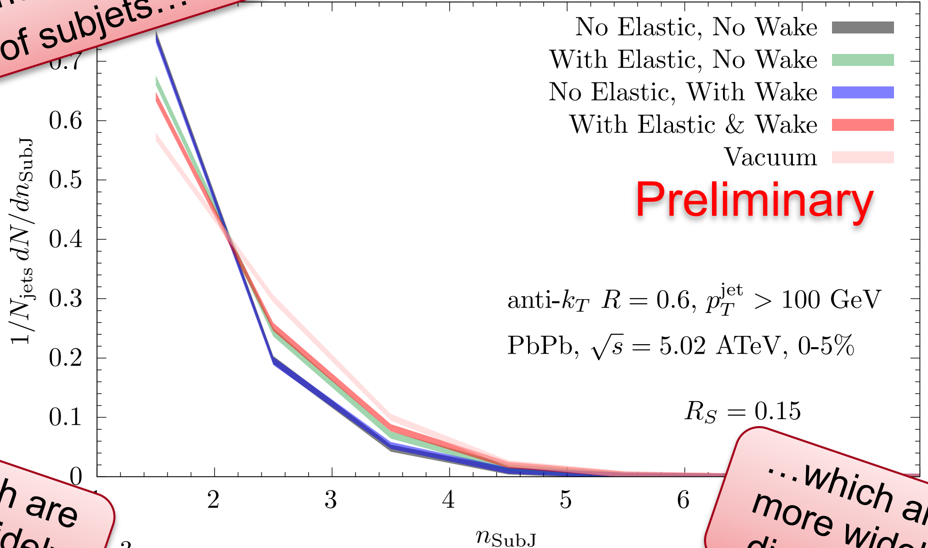
Moliere scattering visible as increase in number of subjets; no such effect coming from wake at all.
Moliere scattering also yields more separated subjets…

Inclusive Subjets

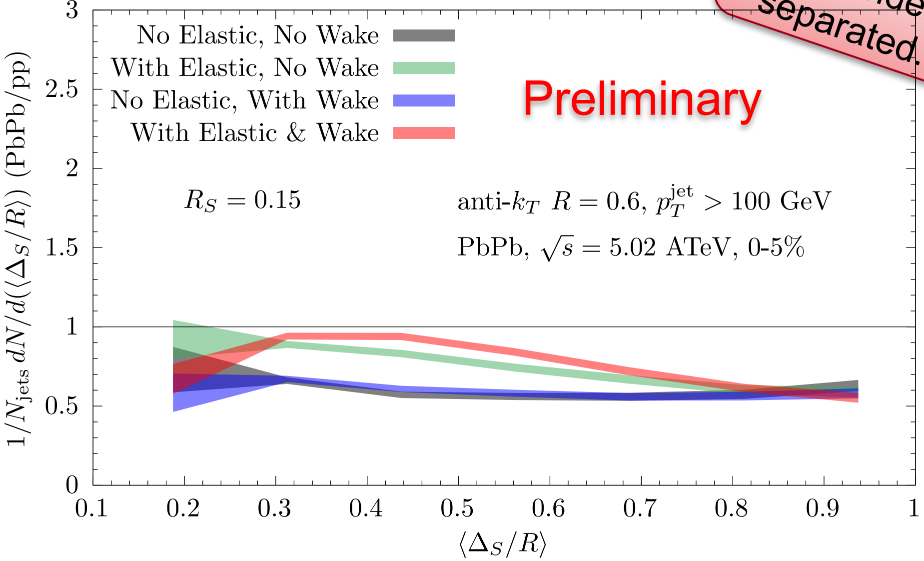
1. Reconstruct jet with R=0.6
2. Recluster each jet's particle content into subjets with R=0.15



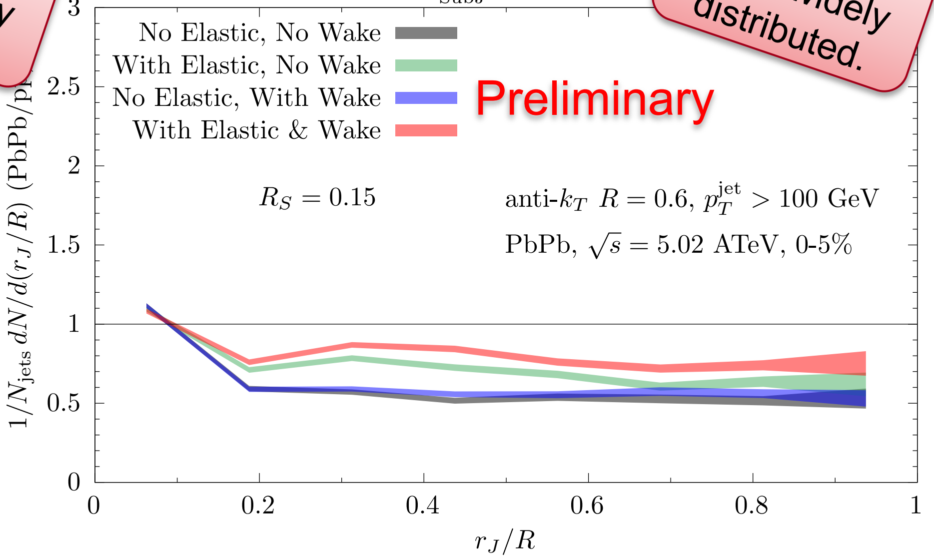
Increase in number of subjets…



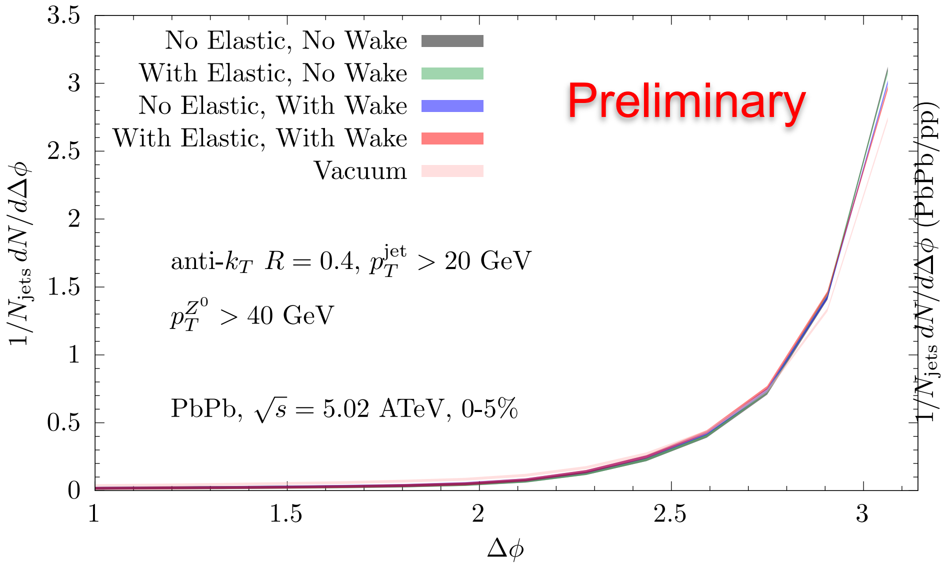
…which are more widely separated.

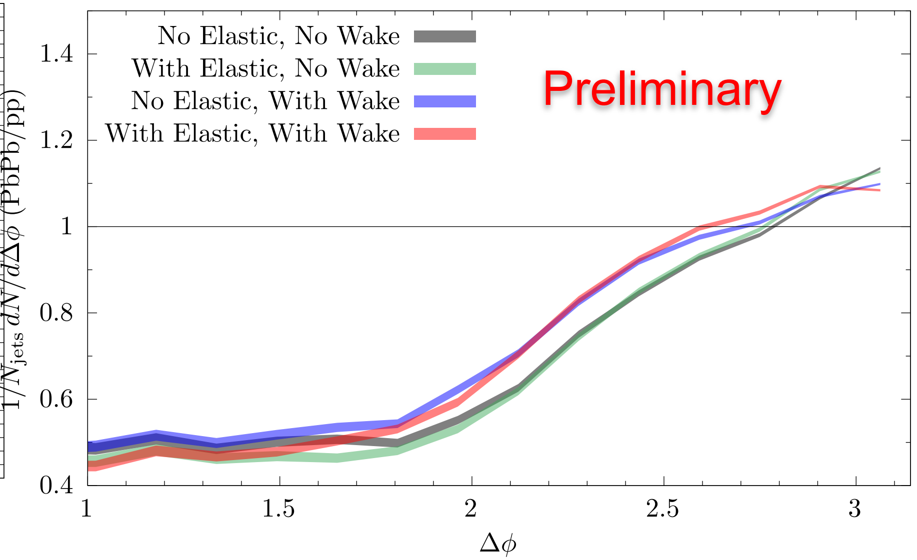


…which are more widely distributed.



Z-Jet Acoplanarity

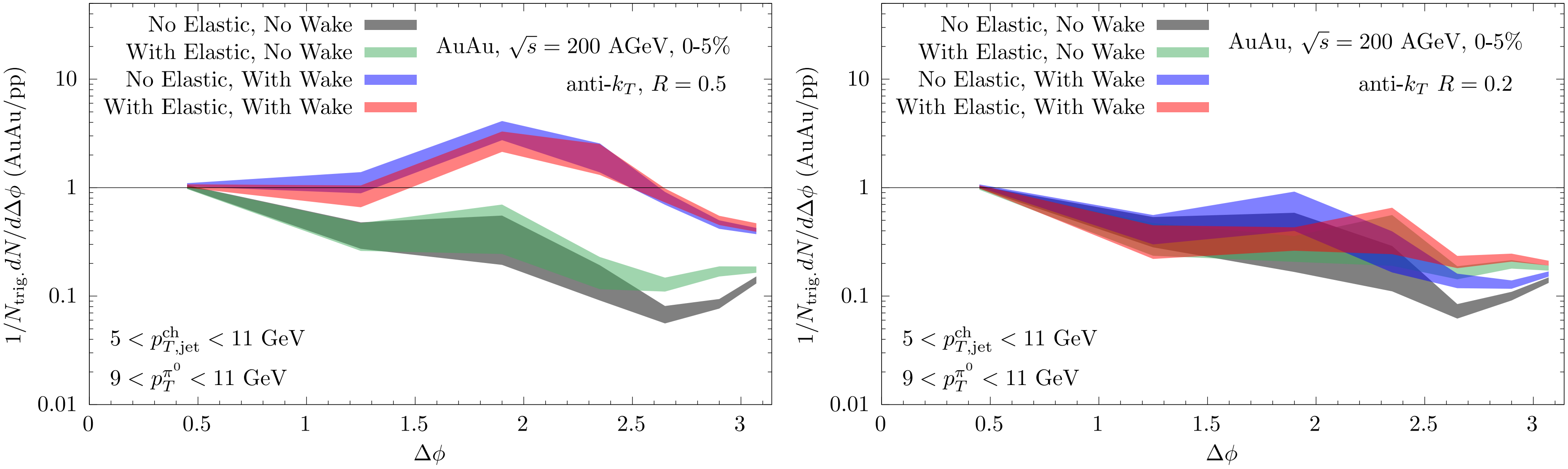




- Study acoplanarity in boson-jet system: Z-jet.
- Very little effect from Moliere scattering; increase in acoplanarity that we see is almost entirely due to the wake.
- Desirable to look into acoplanarities at even lower p_T , perhaps via single hadron correlations. And then also Gamma-D, $D\bar{D}$ correlations….
- Groomed z_g and R_g , leading kT, and in particular inclusive subjet observables all more sensitive to Moliere scattering.
- Moliere scattering: jet sprouts added prongs, not much overall deflection

Hadron-ChargeJet Acoplanarity, RHIC energy

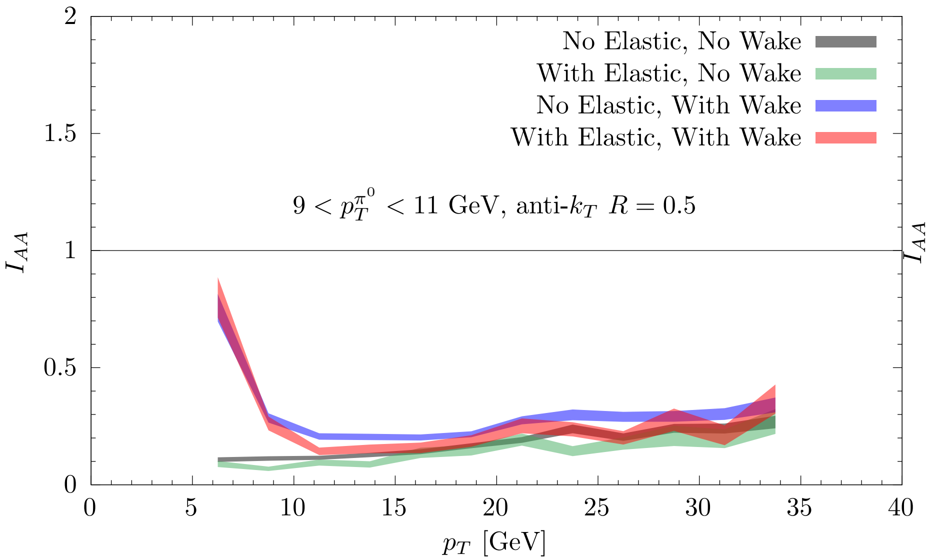
Very Preliminary

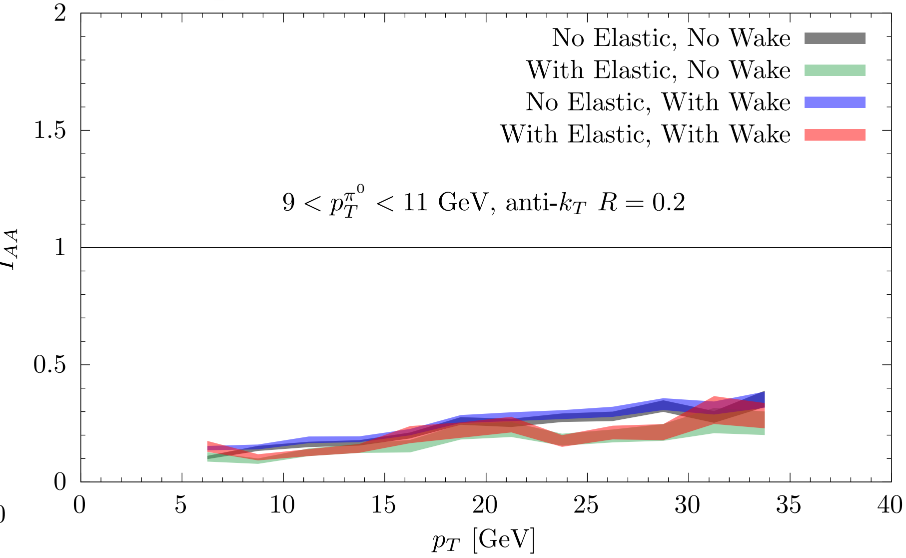


- Study acoplanarity in pi0 - charged jet system.
- Parameters similar to but not same as STAR
- Very little effect from Moliere scattering; increase in acoplanarity that we see is almost entirely due to the wake.
- Significant effect caused by the wake seen for R=0.5 jets, not for R=0.2
- I_{AA} indicates effect of wake enhances number of jets at these p_T
- Moliere scattering: jet sprouts added prongs, not much overall deflection

Hadron-ChargeJet Acoplanarity, RHIC energy

Very Preliminary





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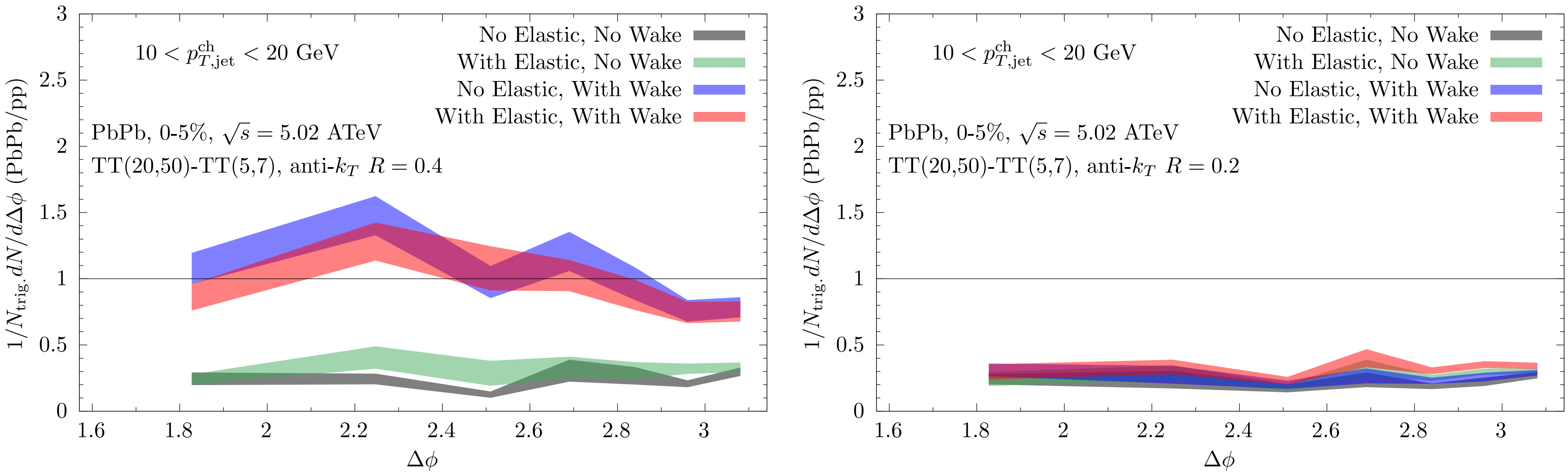
Hadron-ChargeJet Acoplanarity, LHC energy

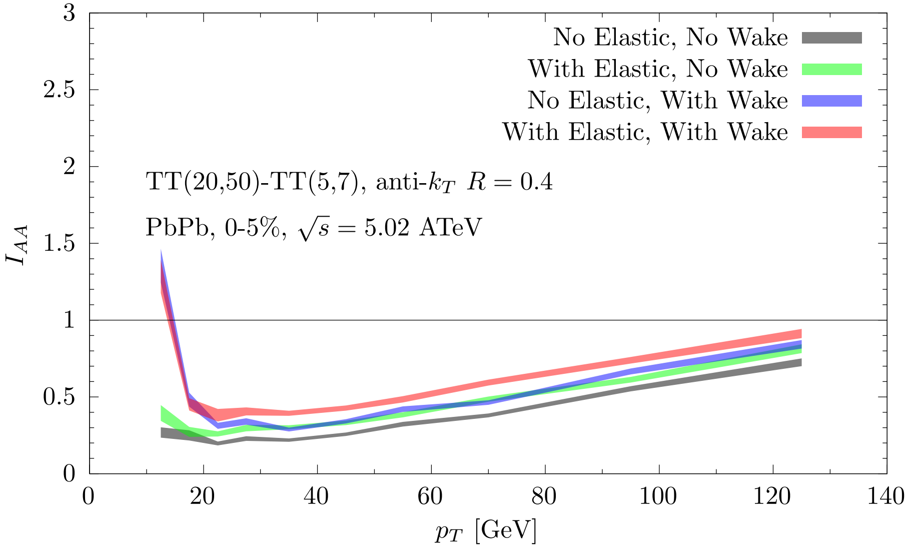
Very Preliminary

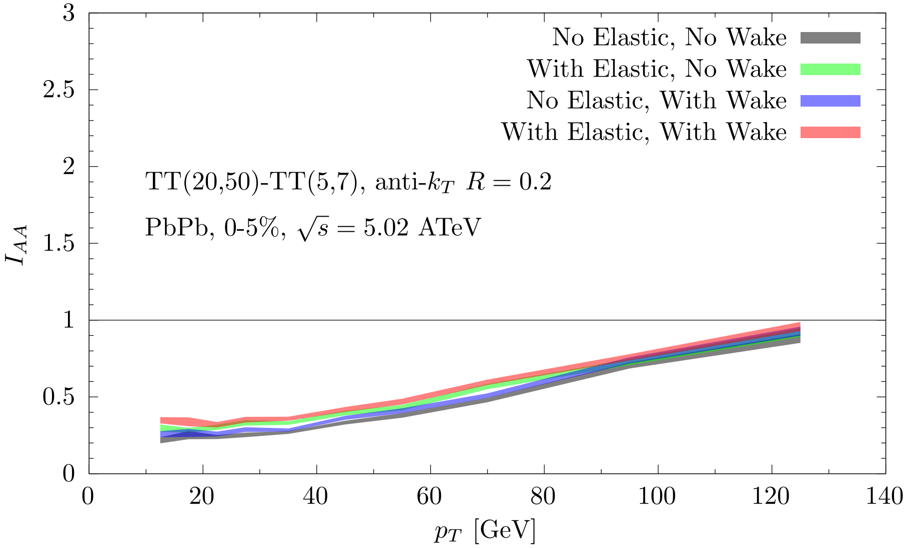


- Study acoplanarity in hadron - charged jet system.
- Parameters similar to ALICE
- Very little effect from Moliere scattering; increase in acoplanarity that we see is almost entirely due to the wake.
- Significant effect caused by the wake seen for R=0.4 jets, not for R=0.2
- I_{AA} indicates effect of wake enhances number of jets at these p_T
- And indeed effect of wake seen only in the lower charged jet p_T bin
- Moliere scattering: jet sprouts added prongs, not much overall deflection

Hadron-ChargeJet Acoplanarity, LHC energy

Very Preliminary





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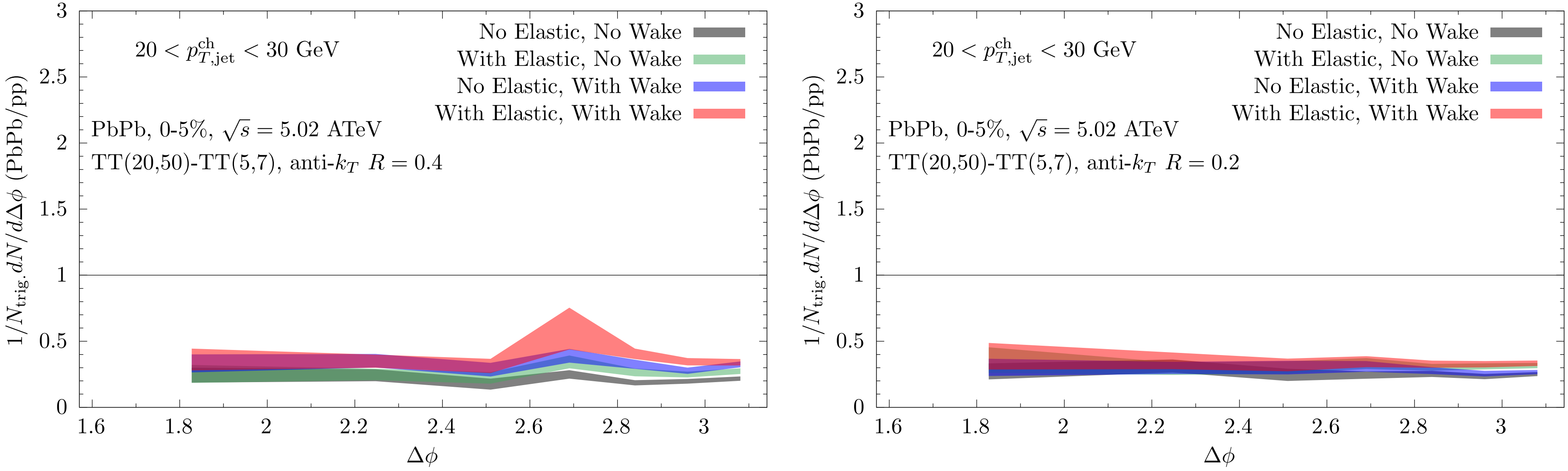
Hadron-ChargeJet Acoplanarity, LHC energy

Very Preliminary



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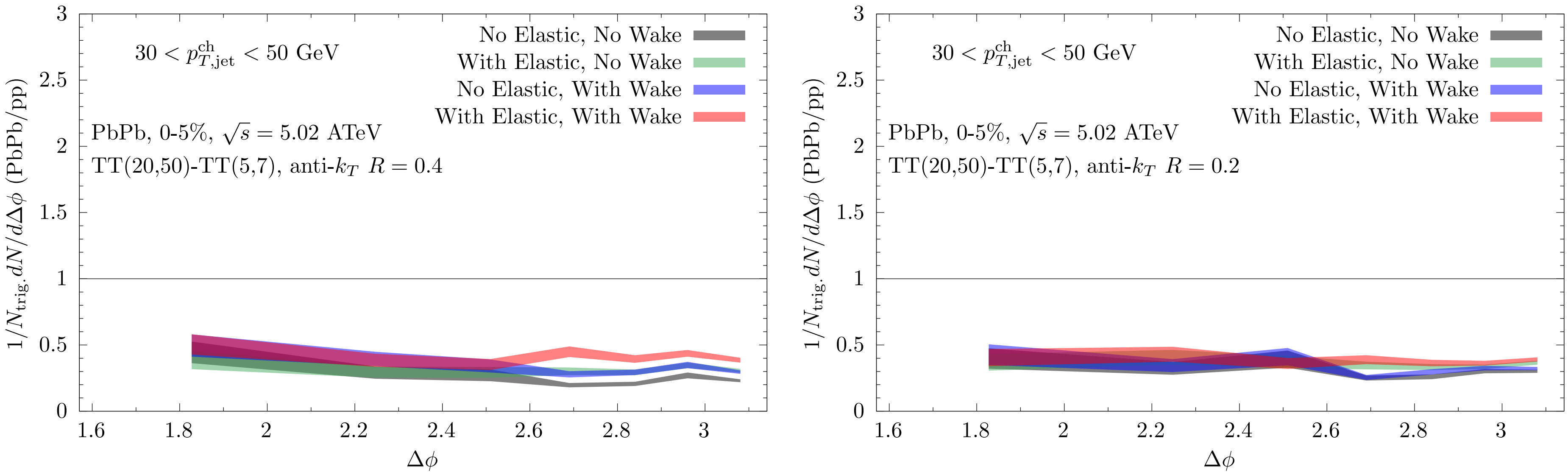
Hadron-ChargeJet Acoplanarity, LHC energy

Very Preliminary



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Conclusions

- Studied the effect of power-law-rare large-angle scattering on jet observables in the perturbative regime.

- Moliere scattering affects many “shape observables”, but for “overall shape observables” (jet shapes; FF) effects are similar to, and smaller than, effects of wake.

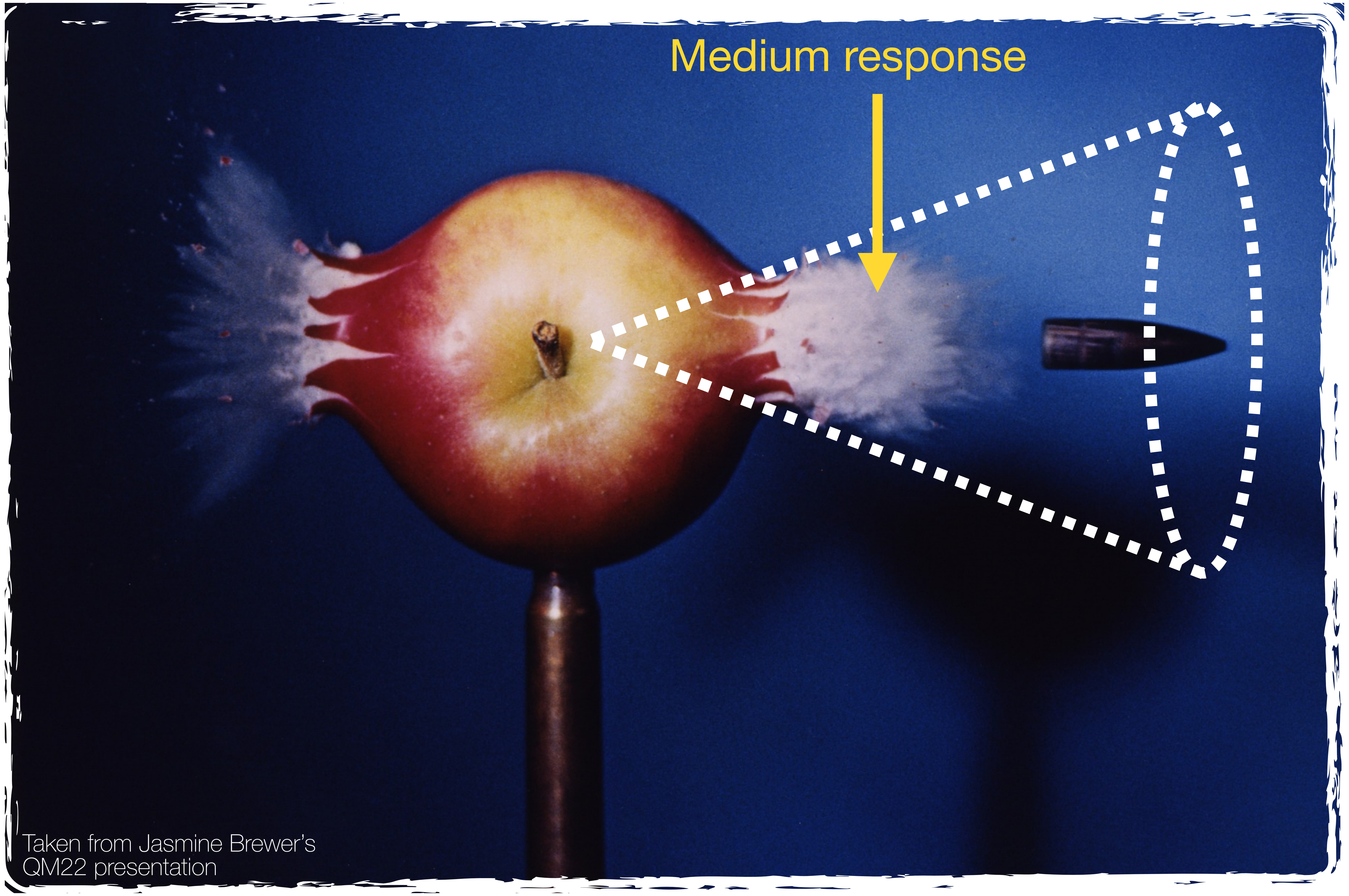
- Grooming helps, by grooming away the soft particles from the wake. Effects of Moliere scattering dominant in modification of several groomed observables.

- Inclusive subjet observables (number, and angular spread, of subjets) are especially sensitive to the presence of Moliere scatterings. These observables are unaffected by the wake.

- Acoplanarity observables that we have investigated to date show little sensitivity to Moliere scattering; significant sensitivity to the wake in some cases.

- Future: studying charm observables (gamma-D, $D\overline{D}$, D within jets …)

Experimental overview of medium-response-sensitive observables



Taken from Jasmine Brewer's QM22 presentation

Rey Cruz-Torres
reynier@lbl.gov

June 15, 2022

BERKELEY LAB

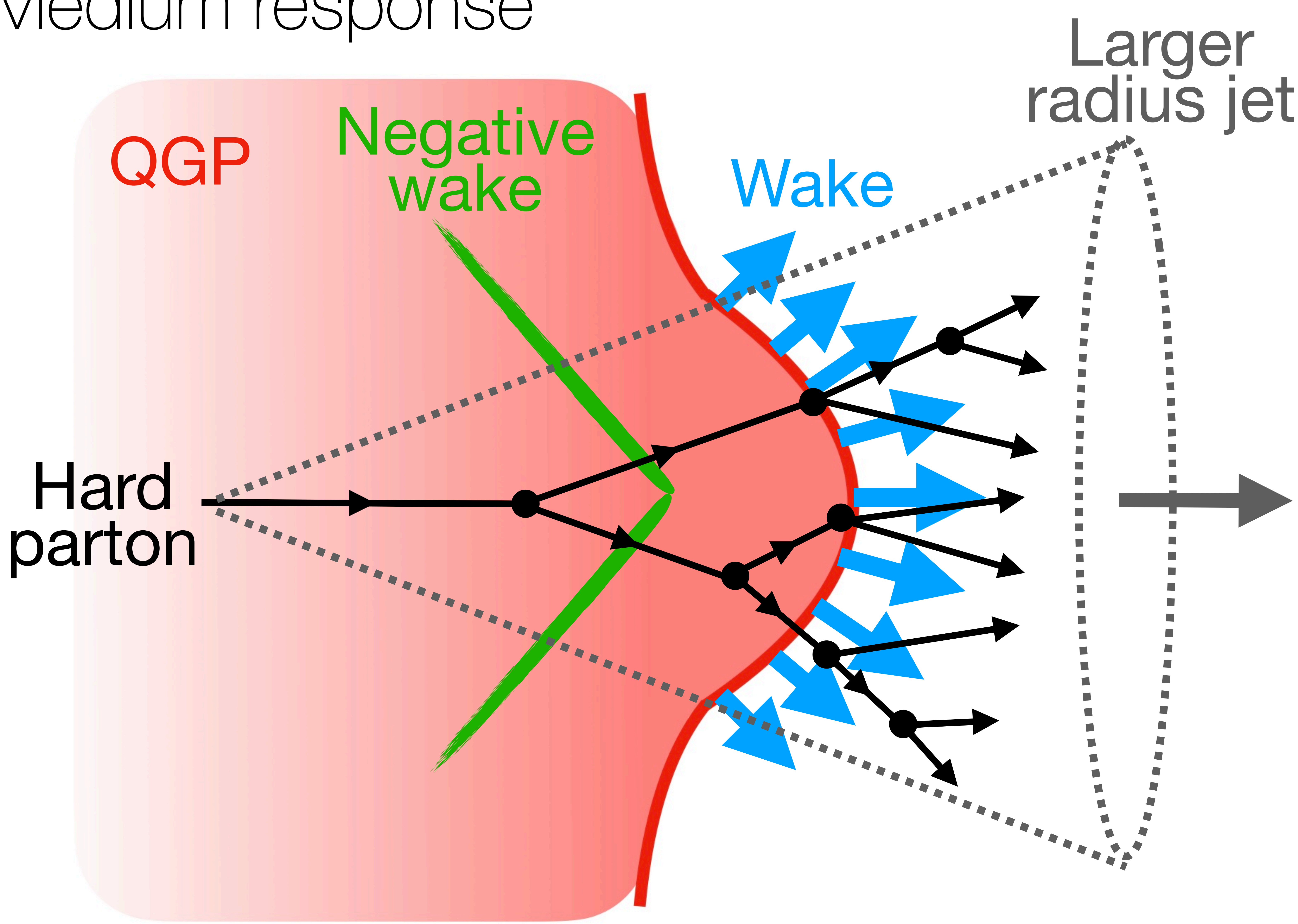
FONDAZIONE BRUNO KESSLER

ECT*
EUROPEAN CENTRE
FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS

Medium response

Finding jets (or knowing their direction) can be used to study medium response

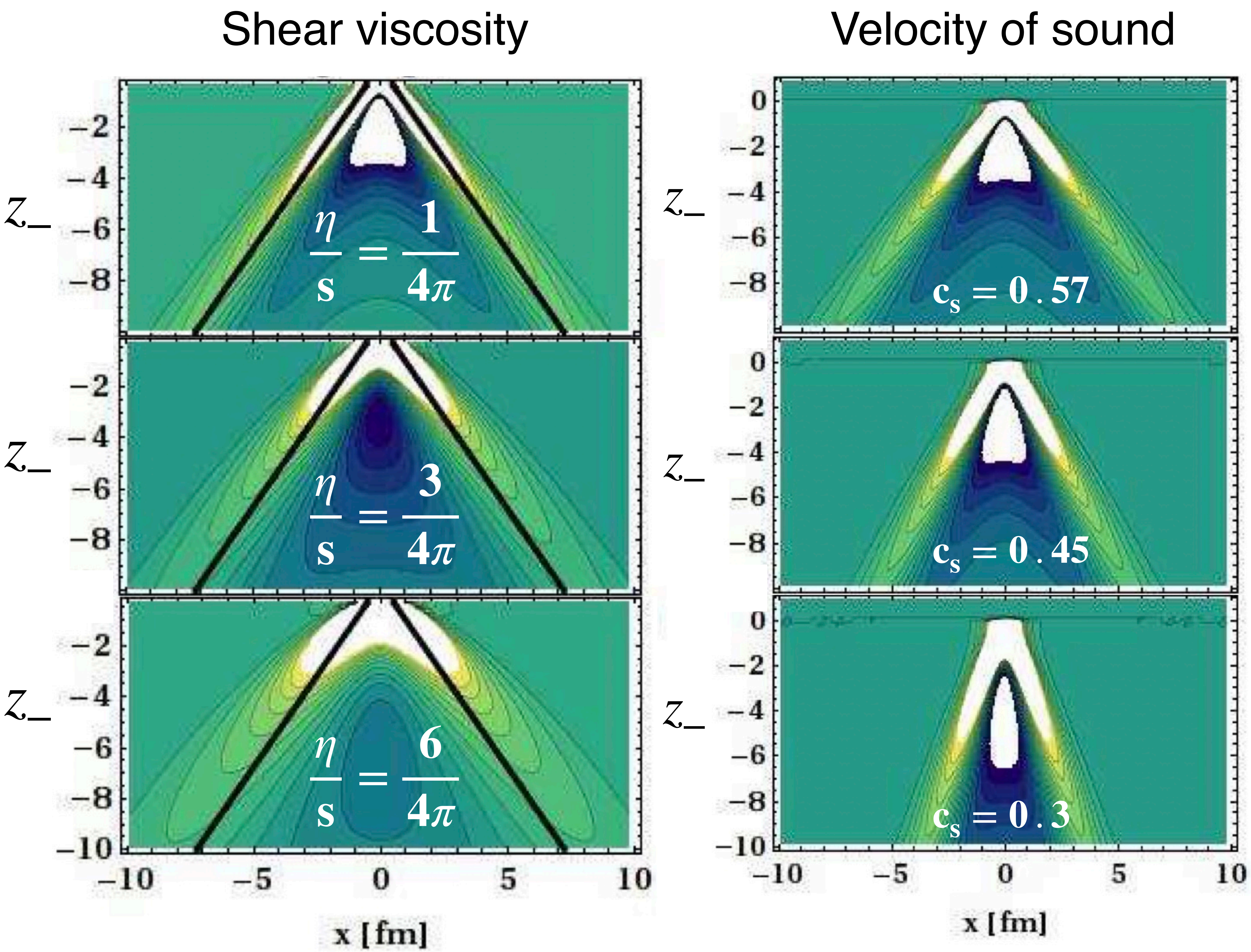
Large-radius jets capture more of this effect



correlated background, medium response, wake, recoils, Mach-cone, jet-induced medium flow, backreaction

Why study medium response?

- Full characterization of QGP
- Better understanding of observables in medium
- QGP bulk properties of the (velocity of sound, viscosities)
- thermalization: how fast is the jet energy is propagated and thermalized with the rest of the QGP?
  See talk by S Schlichting



Shear viscosity

Velocity of sound

PRC 79 (2009) 054909

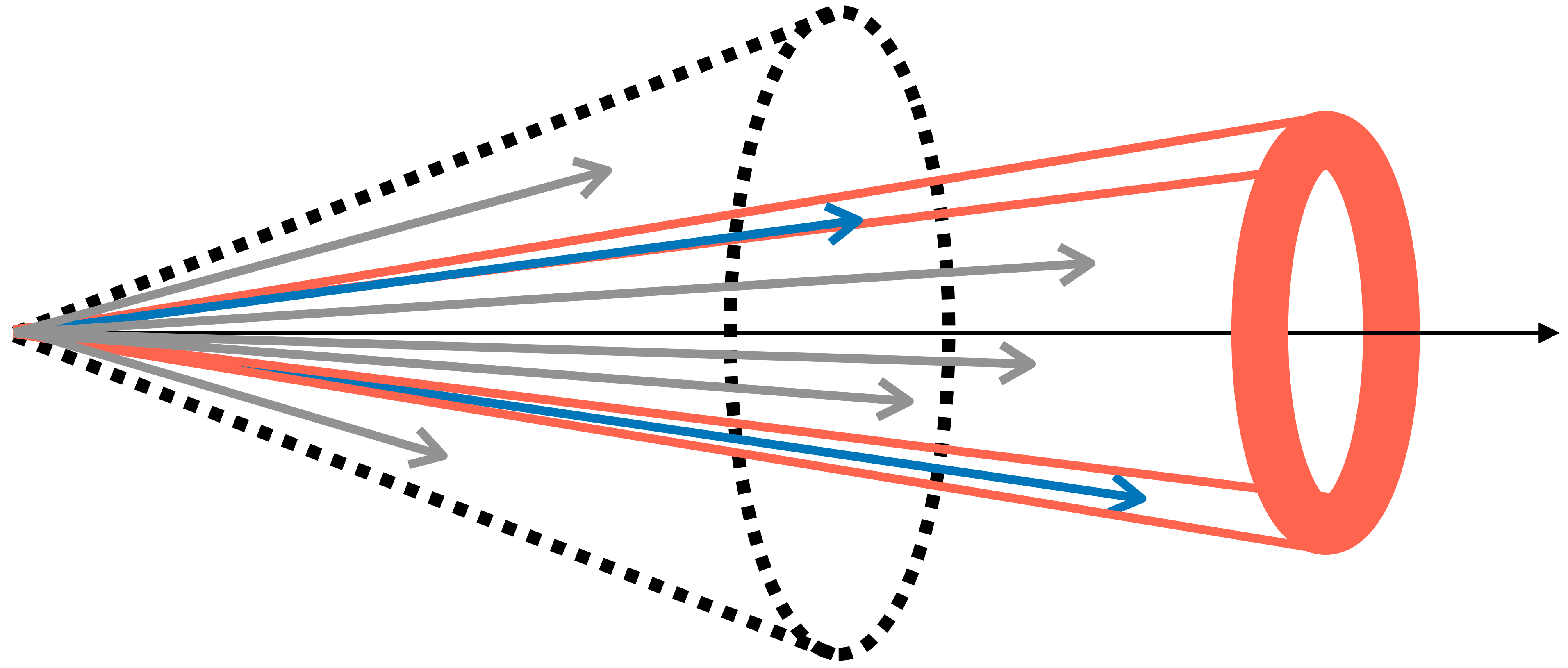
Jet shapes

CMS, PLB 730 (2014) 243

Describes how energy inside (and outside) jets is distributed in the radial direction

$$\rho(r) = \frac{1}{\delta r}\frac{1}{N_{\text{jet}}}\sum_{\text{jets}}\frac{\sum_{\text{tracks}\in[\text{r}_\text{a},\text{r}_\text{b})} p_\text{T}^{\text{track}}}{p_\text{T}^{\text{jet}}}$$

$$\delta r = 0.05$$



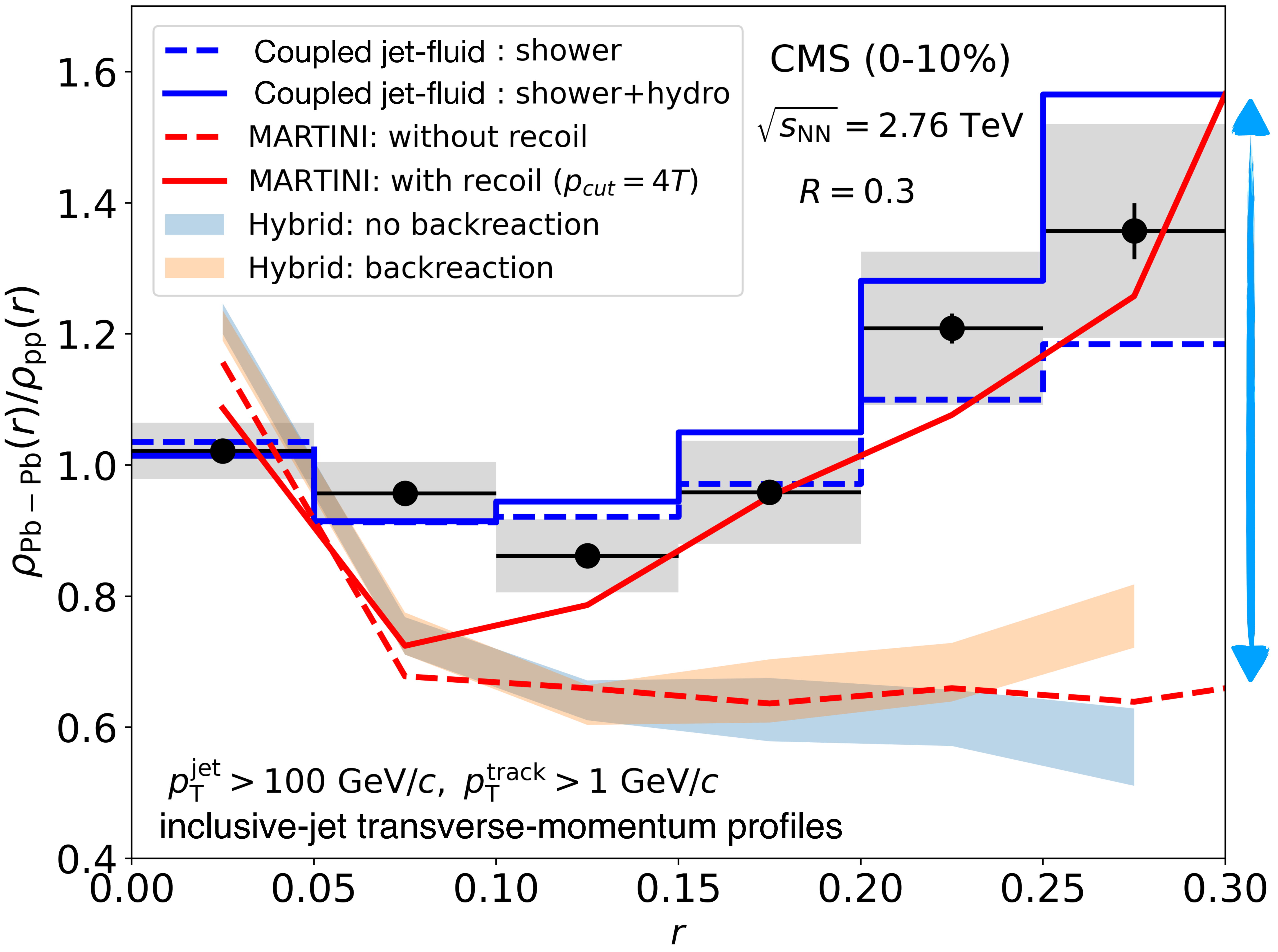
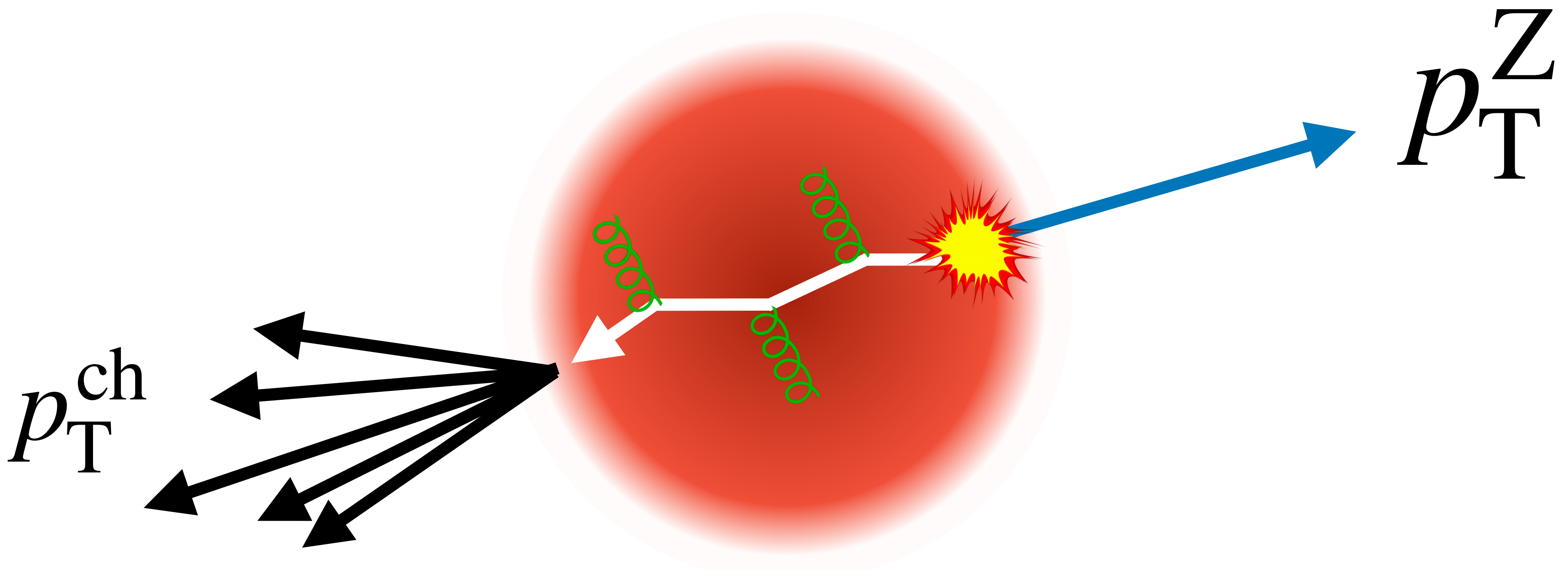


Fig adapted from PRC 95 (2017) 4, 044909, JHEP 03 (2017) 135, & NPA 982 (2019) 643

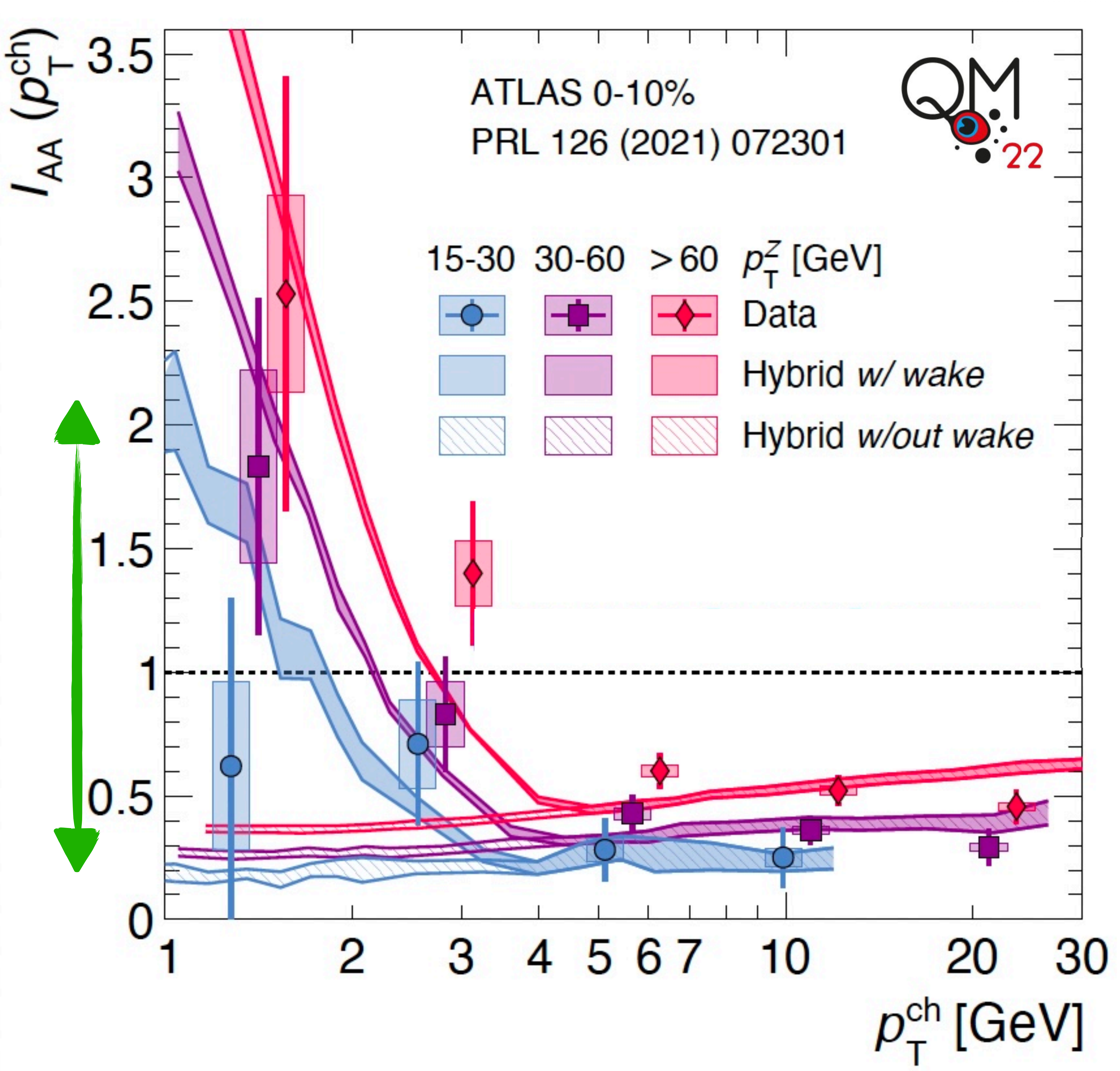
Charged particles recoiling against a Z

$$Y \equiv \frac{1}{N_Z} \frac{d^2 N_{ch}}{dp_T^{ch}\, d\Delta\phi} \qquad I_{AA} = \frac{Y_{Pb-Pb}}{Y_{pp}}$$



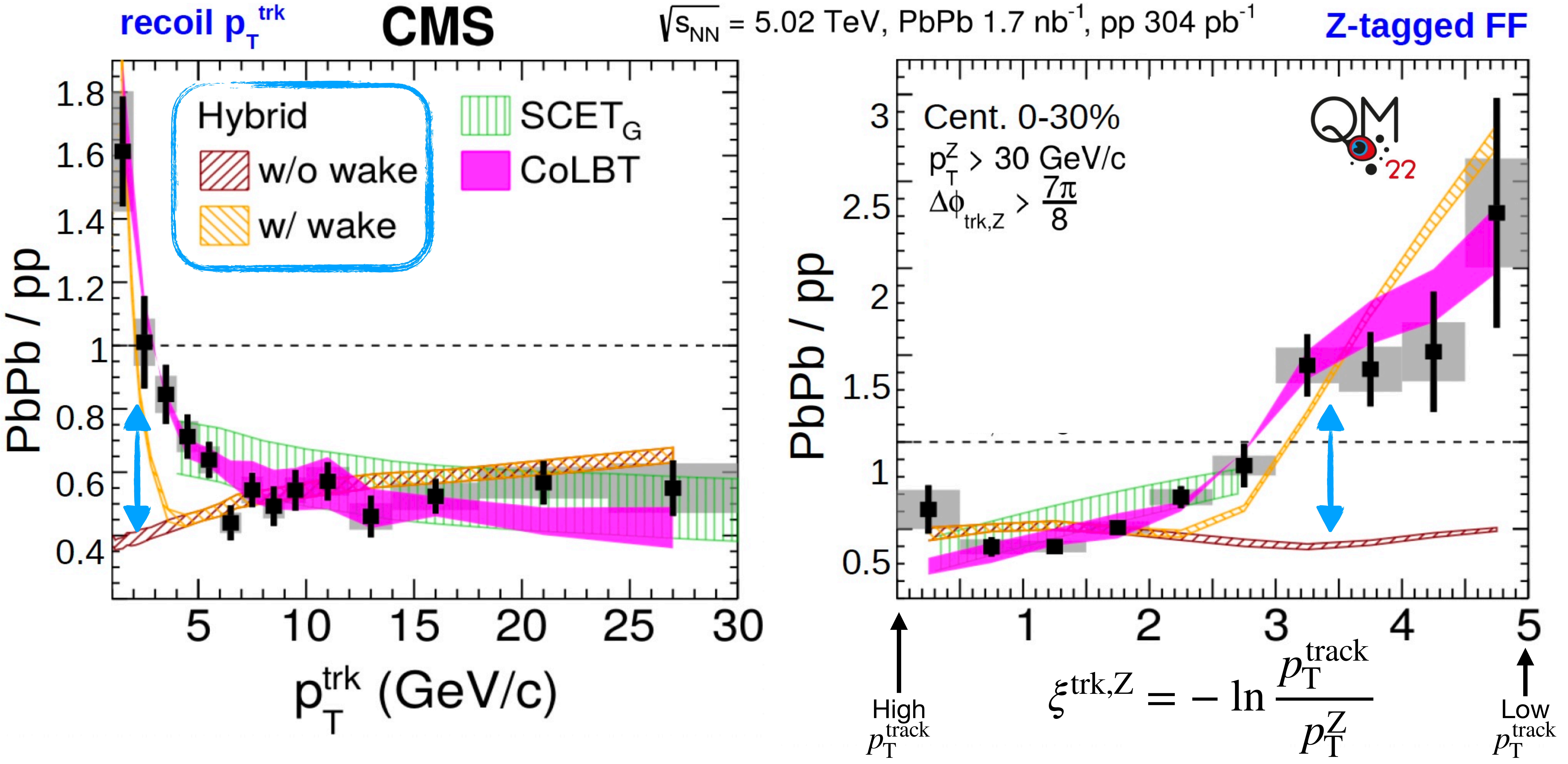
- Hybrid model with wake qualitatively describes rising trend at low p_T^{ch}

- Hybrid model without the wake does not describe the low-p_T^{ch} excess in data



Christopher McGinn's QM22 presentation

Charged particles recoiling against a Z



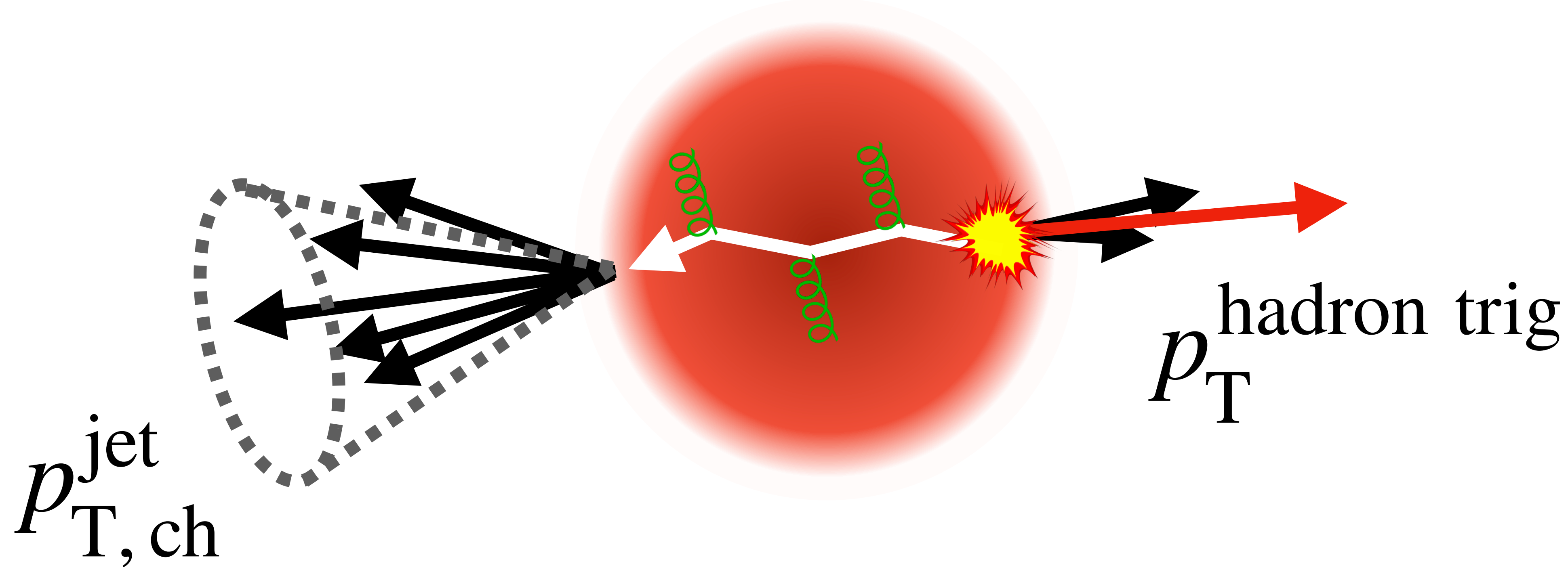
Kaya Tatar's QM22 presentation

Semi-inclusive yield of jets recoiling from high-p_T hadron

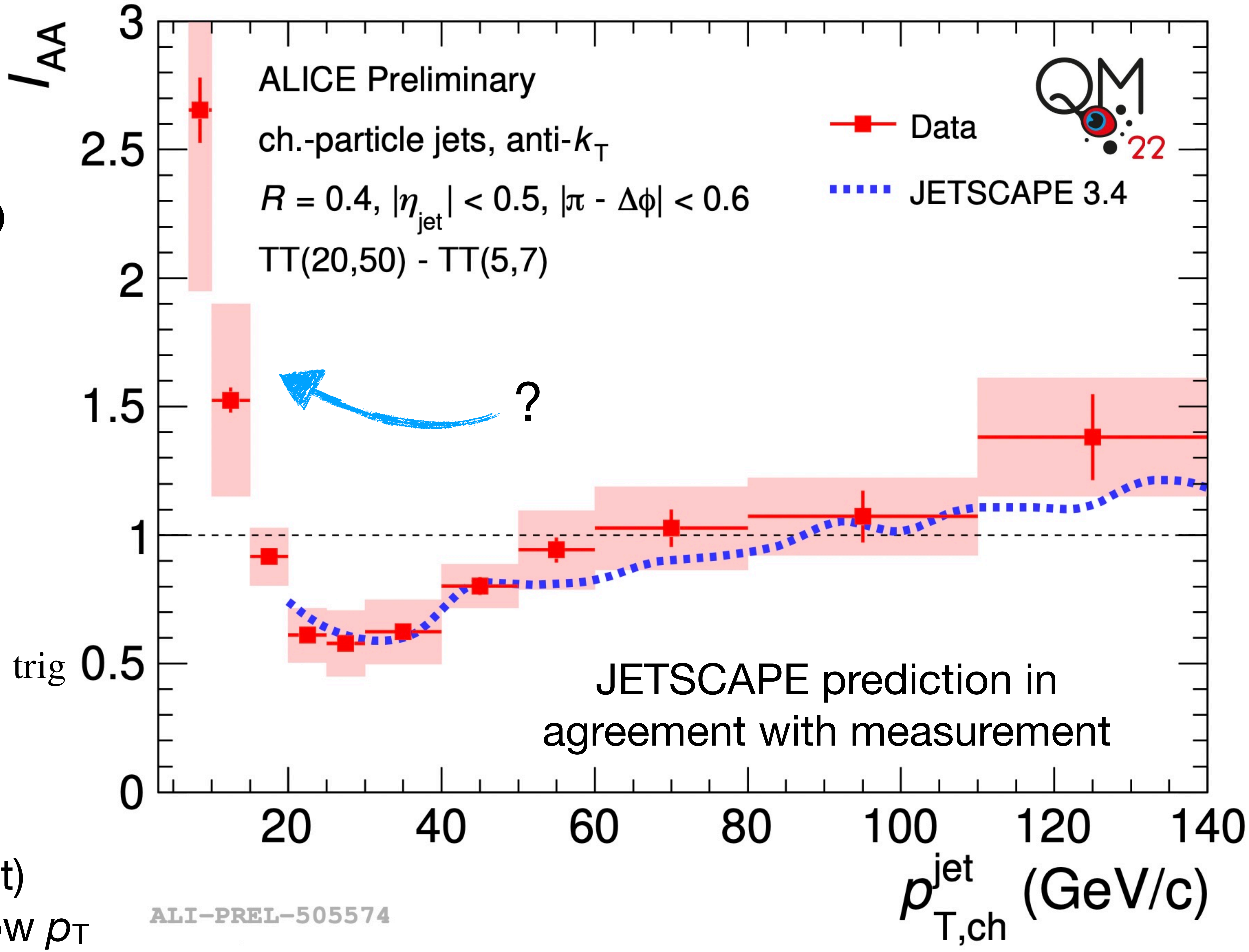
$$n \equiv \frac{1}{N^{AA}_{\mathrm{trig}}} \frac{d^2 N^{AA}_{\mathrm{jet}}}{dp^{\mathrm{jet}}_{\mathrm{T,ch}} d\eta_{\mathrm{jet}}}$$

$$\Delta_{\mathrm{recoil}} = n(\mathrm{TT}_{\mathrm{Sig}}) - c_{\mathrm{Ref}} \cdot n(\mathrm{TT}_{\mathrm{Ref}})$$

$$I_{AA} \equiv \frac{\Delta_{\mathrm{recoil}}(\mathrm{Pb-Pb})}{\Delta_{\mathrm{recoil}}(\mathrm{pp})}$$



Need to compare models with(out) medium-response effects down to low p_T



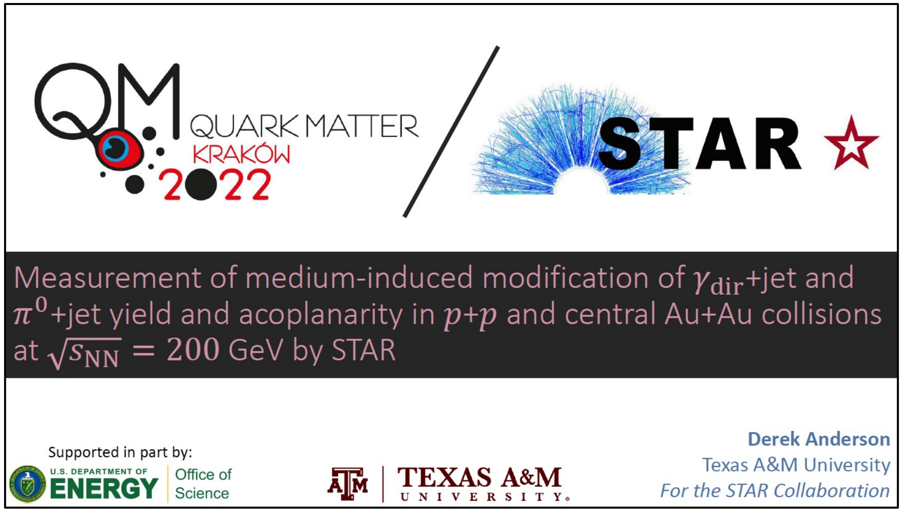
JETSCAPE prediction in agreement with measurement

See talk by P Jacobs

Acoplanarity: new angles on an old idea

Peter Jacobs, LBNL

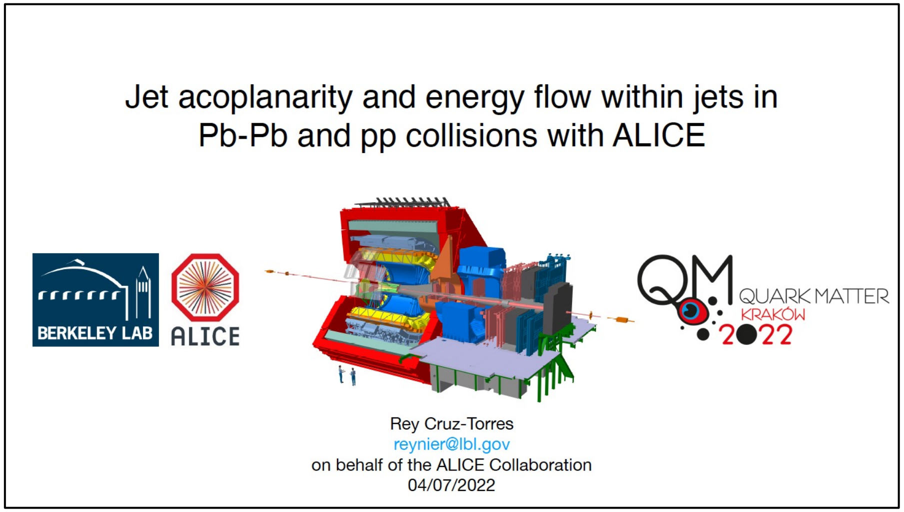
Jet Quenching In The Quark-Gluon Plasma
ECT Trento*
June 16, 2022



Measurement of medium-induced modification of γ_{dir}+jet and π^0+jet yield and acoplanarity in p+p and central Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV by STAR

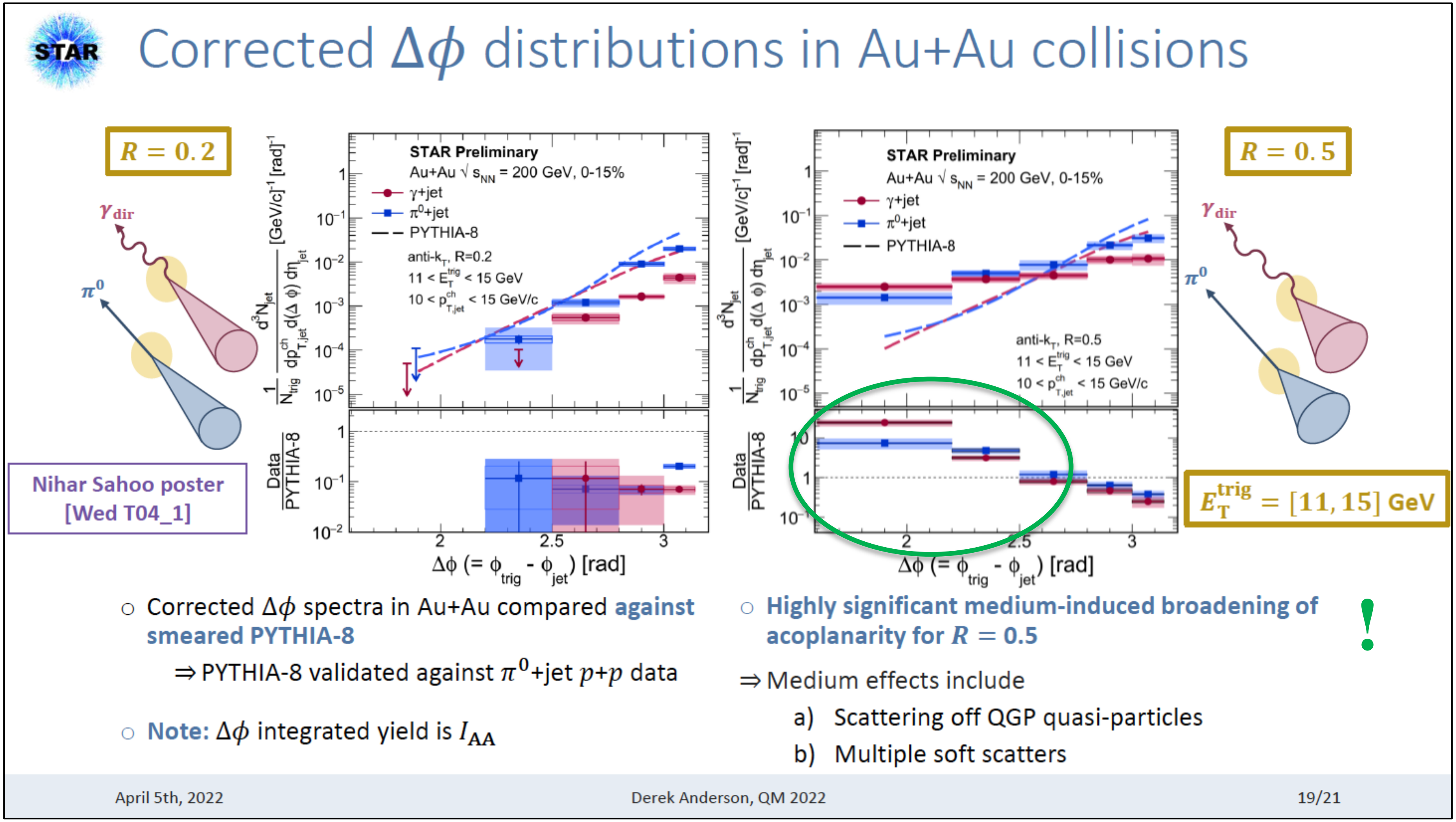
Supported in part by:
U.S. DEPARTMENT OF ENERGY | Office of Science
TEXAS A&M UNIVERSITY

Derek Anderson
Texas A&M University
For the STAR Collaboration



Jet acoplanarity and energy flow within jets in Pb-Pb and pp collisions with ALICE

Rey Cruz-Torres
reynier@lbl.gov
on behalf of the ALICE Collaboration
04/07/2022



Corrected $\Delta\phi$ distributions in Au+Au collisions

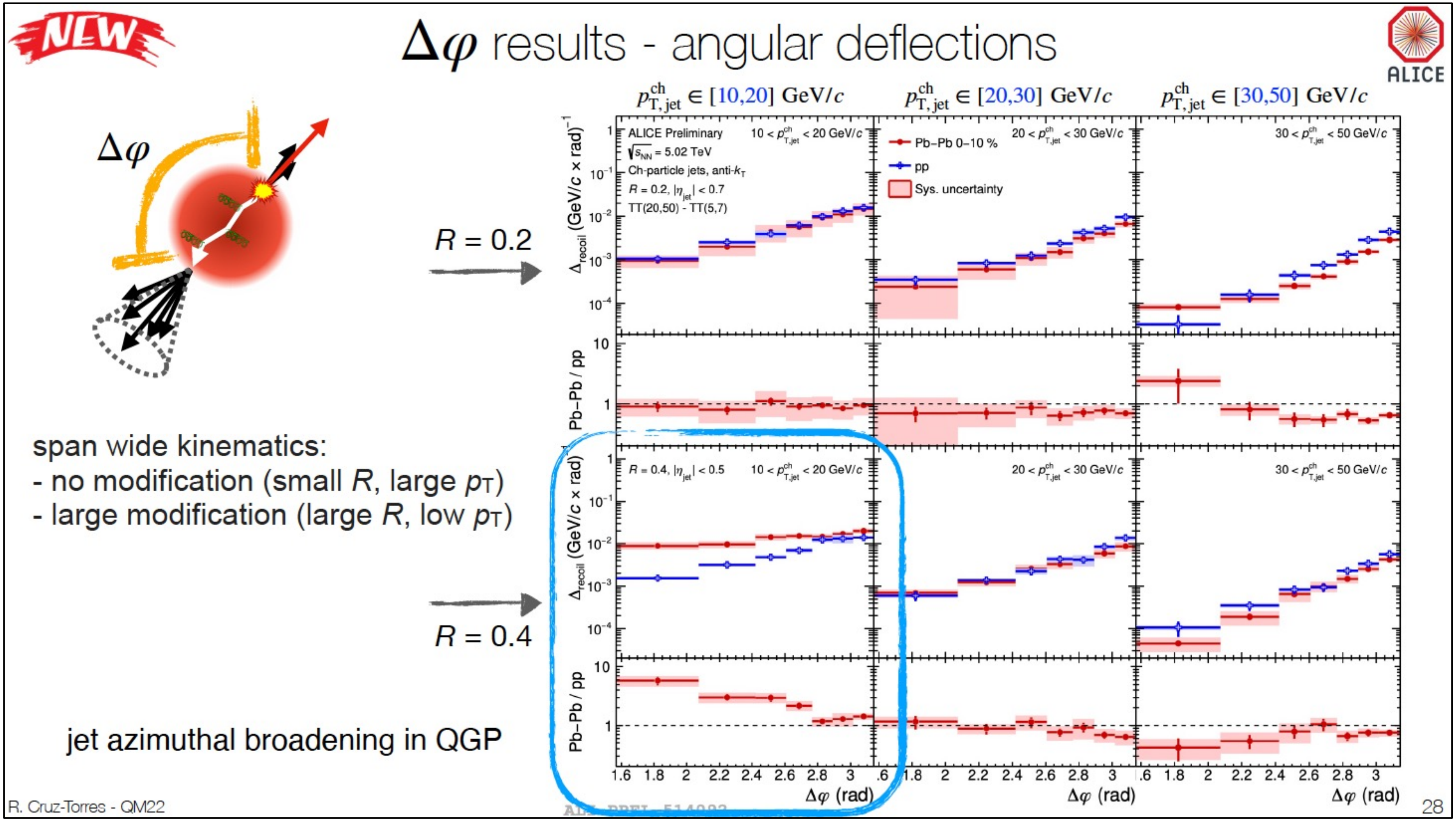
Nihar Sahoo poster
[Wed T04_1]

$E_T^{\text{trig}} = [11, 15]$ GeV

- Corrected $\Delta\phi$ spectra in Au+Au compared **against smeared PYTHIA-8**
  - ⇒ PYTHIA-8 validated against π^0+jet p+p data
- **Note:** $\Delta\phi$ integrated yield is I_{AA}

- **Highly significant medium-induced broadening of acoplanarity for $R = 0.5$** !

⇒ Medium effects include
- a) Scattering off QGP quasi-particles
- b) Multiple soft scatters



Δφ results - angular deflections

R = 0.2

R = 0.4

span wide kinematics:
- no modification (small R, large p_T)
- large modification (large R, low p_T)

jet azimuthal broadening in QGP

R. Cruz-Torres - QM22

28

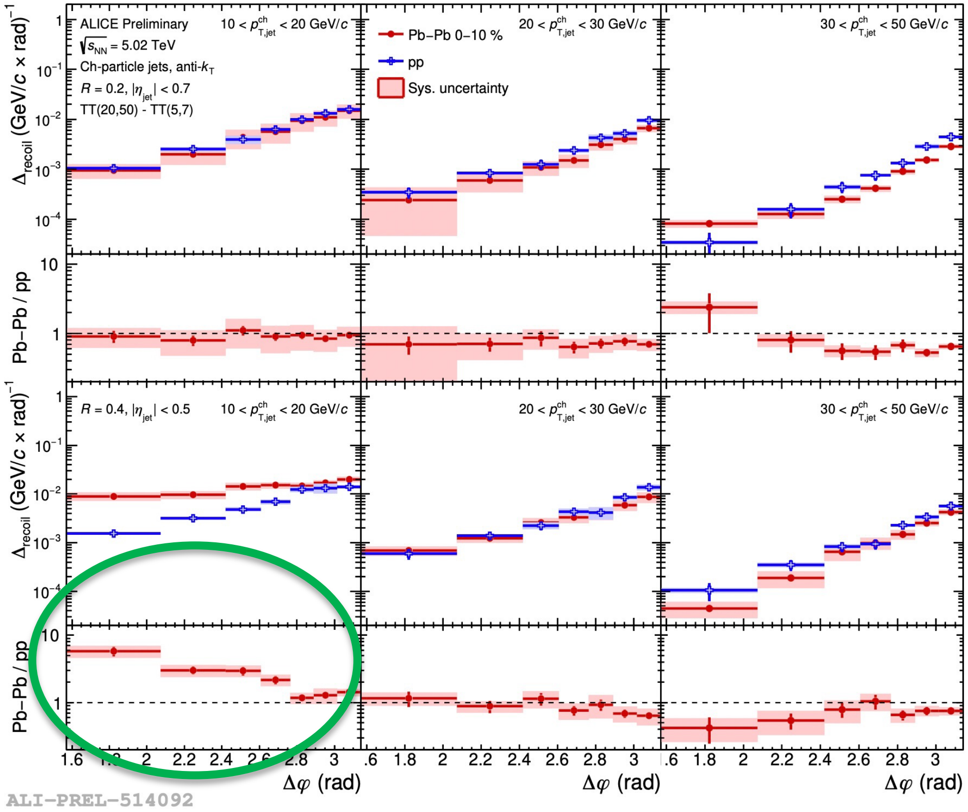
Next steps

$10<p_T^{jet}<20$ $20<p_T^{jet}<30$ $30<p_T^{jet}<50$

R=0.2

Striking dependence on R and p_T^{jet}

R=0.4



Conjecture: enhanced yield at low p_T^{jet} and large R us due to diffuse radiation

- Medium response, jet fragments,...

Then driving parameter to collect 10 GeV is R^2, not R

→ measure jet profile/internal structure of this population

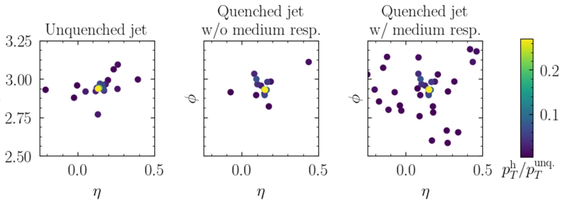
Disentangling Jet Modification in Jet Simulations and in Z+Jet Data

Jasmine Brewer, *CERN Theory*, Quinn Brodsky*, Krishna Rajagopal, *Massachusetts Institute of Technology Department of Physics*

Introduction

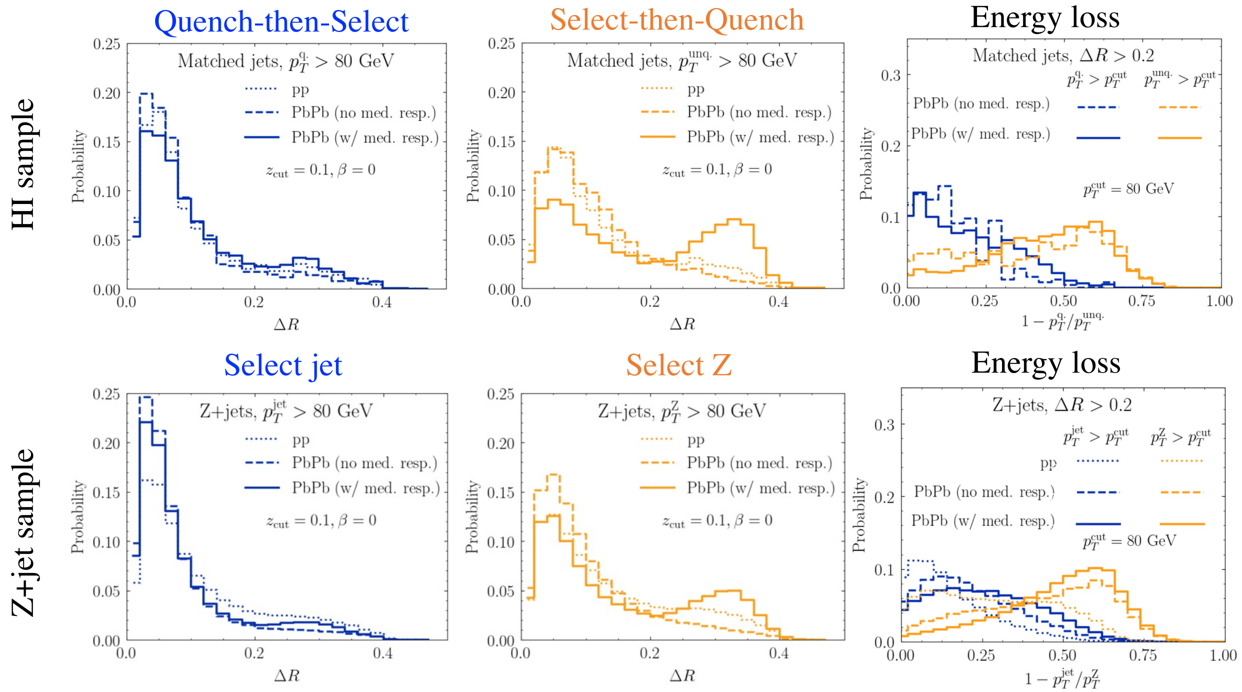
Jet modification in heavy-ion (HI) collisions is an important probe to study the structure of the QGP produced in HI collisions. However, in experiment, one cannot know what a jet would have looked like without quenching, making it difficult to interpret measurements in terms of individual jet modification. The goal of this study is to gain insight into the modification of jet observables using the Monte Carlo-based hybrid model in which it is possible to study a jet as it would evolve in vacuum or in medium. We reproduce previous results in the hybrid model that the distribution of groomed ΔR appears to be unmodified, and we show that there is a substantial modification of the ΔR of individual jets, indicating that this apparent lack of modification is a bias effect. To create an experimentally-verifiable analogy, we show the same analysis holds for Z+jet collisions.

Methods



- Hybrid model: hybrid strong/weak coupling model of jet quenching
- Matched jets = jets in quenched and unquenched samples at the same (η, ϕ) location
- For Z+jet samples, compare observables of Z boson with those of jet with highest recoiling p_T
- **Quench-then-Select/Select Jet**: in HI collisions, select on quenched p_T; in Z+jet collisions, select on p_T of highest-p_T recoiling jet
- **Select-then-Quench/Select Z**: in HI, select on unquenched p_T; in Z+jet, select on p_T^Z

Results



We groomed the jets with a z-cut of 0.10 and $\beta = 0$. The groomed ΔR distributions are shown above for these jets, both with and without medium response.

- Selection Bias in Methods:
  - Selection bias in Quench-then-Select/Select Jet
    - Most heavy ion jets with $p_T > 80$ GeV don't lose much energy
    - This method's results similar to experiment – conclude ΔR remains unmodified
  - Select-then-Quench/Select Z does NOT have that selection bias
    - Select on pp sample → heavy ion jets of any p_T are allowed (if they match)
    - Remove selection bias - conclude ΔR is NOT unmodified: modification of ΔR on jet-by-jet basis
- Effect is not dependent on grooming: can show similar distribution for C_1^1
- In order to understand what jets are in the excess at large ΔR, we looked at two samples of jets which had $\Delta R <$ 0.2 and ≥ 0.2. For these jets, plots of the fractional energy loss show that jets with large ΔR are those which lose most energy, and therefore are the jets that don't end up in distribution of Quench-then-Select/Select Jet due to its selection bias (most heavy ion jets with $p_T > 80$ GeV don't lose much energy)

Discussion

- In the hybrid model, quenching modifies ΔR of jets substantially.
- The jets whose ΔR is substantially modified are those which lose a large fraction of their energy.
- Selecting a jet sample using a cut on the jet p_T in PbPb collisions creates bias towards jets that lose very little energy. These are the jets whose ΔR is not substantially modified. By selecting a jet sample using a cut on the jet p_T in pp collisions and looking at the quenched versions of these jets, we remove the bias toward less modified jets and see that the ΔR of individual jets is substantially modified in the hybrid model.
- Modification of ΔR distribution (see Results) is not seen if medium response is excluded. In the hybrid model, the structure of the parton shower is not modified by quenching except that energy can be redistributed among partons. This suggests that this effect does not substantially modify the ΔR distribution, but medium effects do.
- The methods outlined for the HI sample (particularly, Select-then-Quench) are not feasible in experiment. However, the analysis of Z+jet collisions is an analysis that can be performed on experimental data.

References

Brewer, J., Brodsky, Q. & Rajagopal, K. Disentangling jet modification in jet simulations and in Z+jet data. J. High Energ. Phys. 2022, 175 (2022). https://doi.org/10.1007/JHEP02(2022)175

Analogous Z+jet analysis…

- Use Z+jet events; Z and leading jet; no need for matching procedure
- Select jets that fall above a $p_T^{cut} = 80\ GeV$, two possible methods:
  - **Select Jet**: select jets in events with a Z boson where the quenched p_T of the jet is above cut; Z has whatever p_T it has, although we did require it to be above 30 GeV
  - **Select Z**: select Z with p_T^Z above cut; jet has whatever p_T it has, although we did require jet p_T above 30 GeV.
- Can we reproduce previous results using a procedure that experimentalists can follow?
- Blue selection is unusual, but can be realized.
- Orange selection is more standard; important to include jets with p_T well below p_T^{cut}
- Look at two observables: Softdrop ΔR and C_1^1 (again, here show only the first)