Measurement of the *R*-dependence of inclusive jet suppression in Pb—Pb collisions with ALICE

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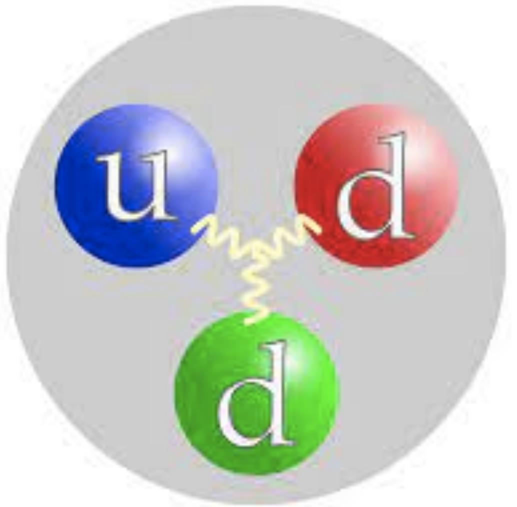
Nuclear Physics Seminar at BNL

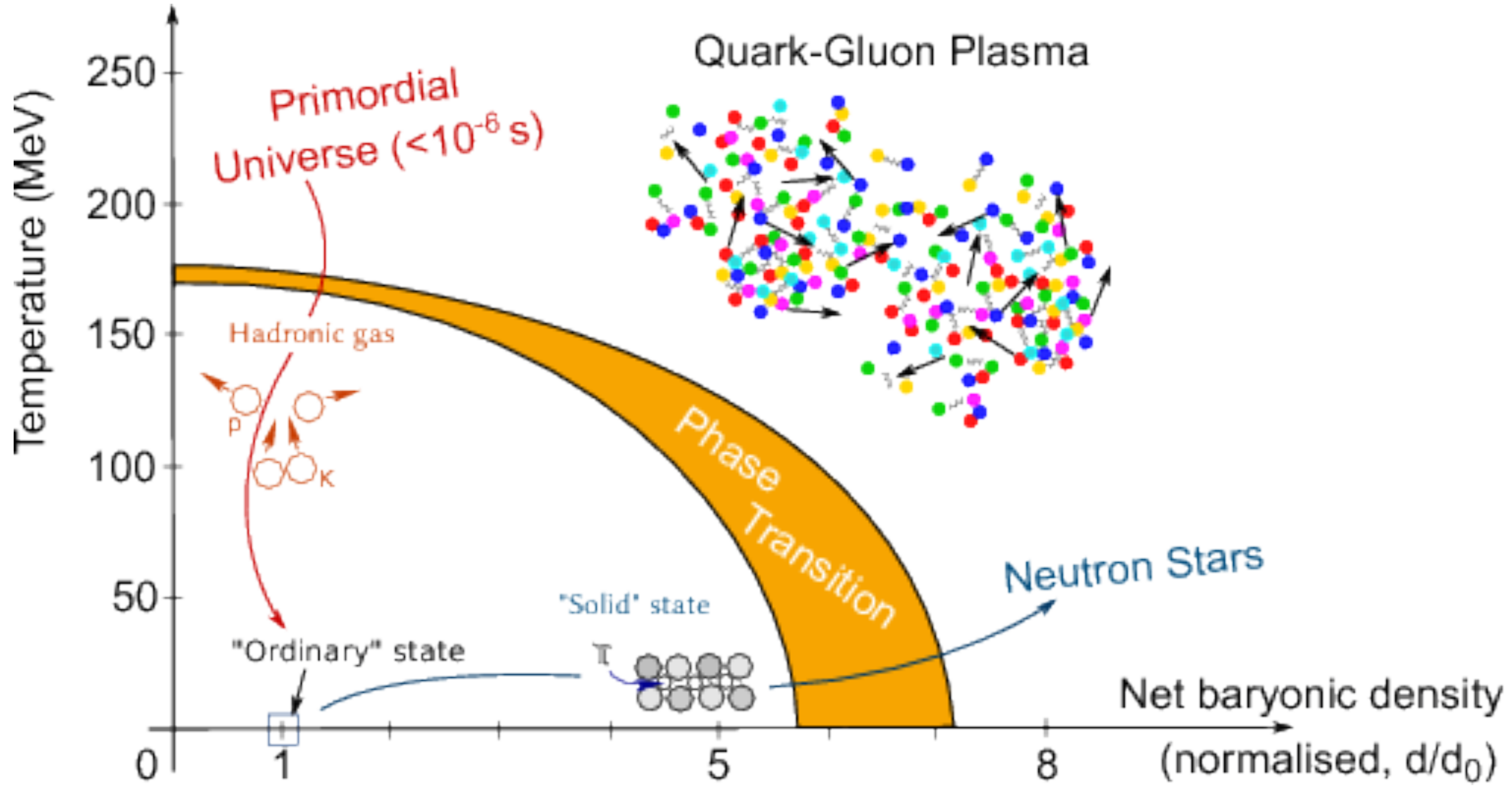
May 12th, 2022

Brookhaven National Lab

QCD at high temperatures



- At low temperatures, QCD matter is confined inside colorless hadrons.
- At sufficiently high temperatures QCD matter becomes a hot and dense deconfined medium known as the **Quark Gluon Plasma (QGP)** in which quarks and gluons are asymptotically “free”.



Phase Diagram for Strongly Interacting Matter

- In nature, a QGP at extremely high temperatures and low baryon density existed $\sim 10\mu s$ after the Big Bang.
- QGP at low temperatures and high baryon density speculated to exist in the core of neutron stars.

Experimentally recreating the QGP

→ Hot and dense QGP medium can be experimentally recreated through the collisions of relativistic heavy-ions.

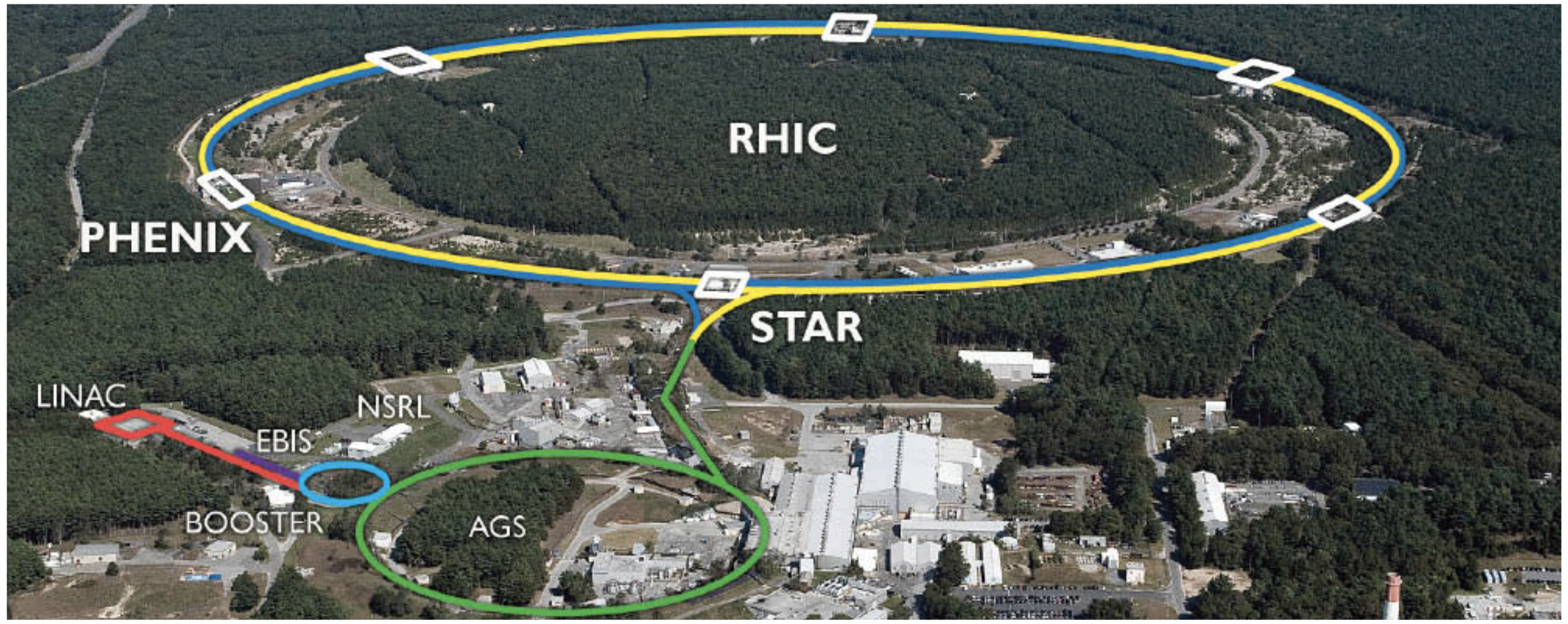
Relativistic Heavy-Ion Collider (RHIC)

(Many species, many energies)

Au—Au, $\sqrt{s_{NN}} = 200$ GeV

Brookhaven National Lab (Long Island)

Future home of the electron-ion collider!



PHENIX STAR

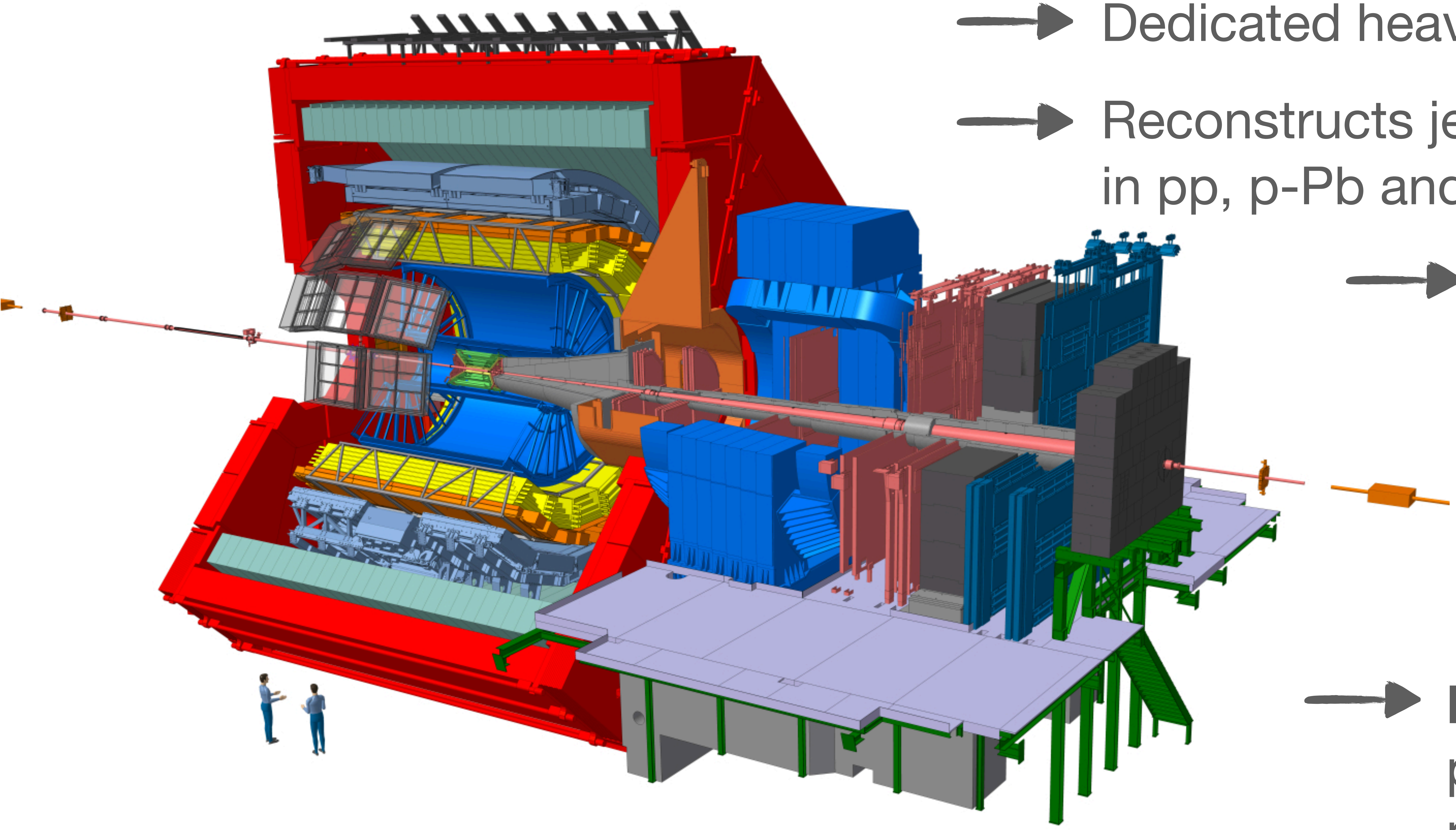
Large Hadron Collider (LHC)

Pb—Pb $\sqrt{s_{NN}} = 5.02$ TeV

CERN (Geneva, Switzerland)

CMS LHCb ATLAS EXPERIMENT ALICE

The ALICE Detector

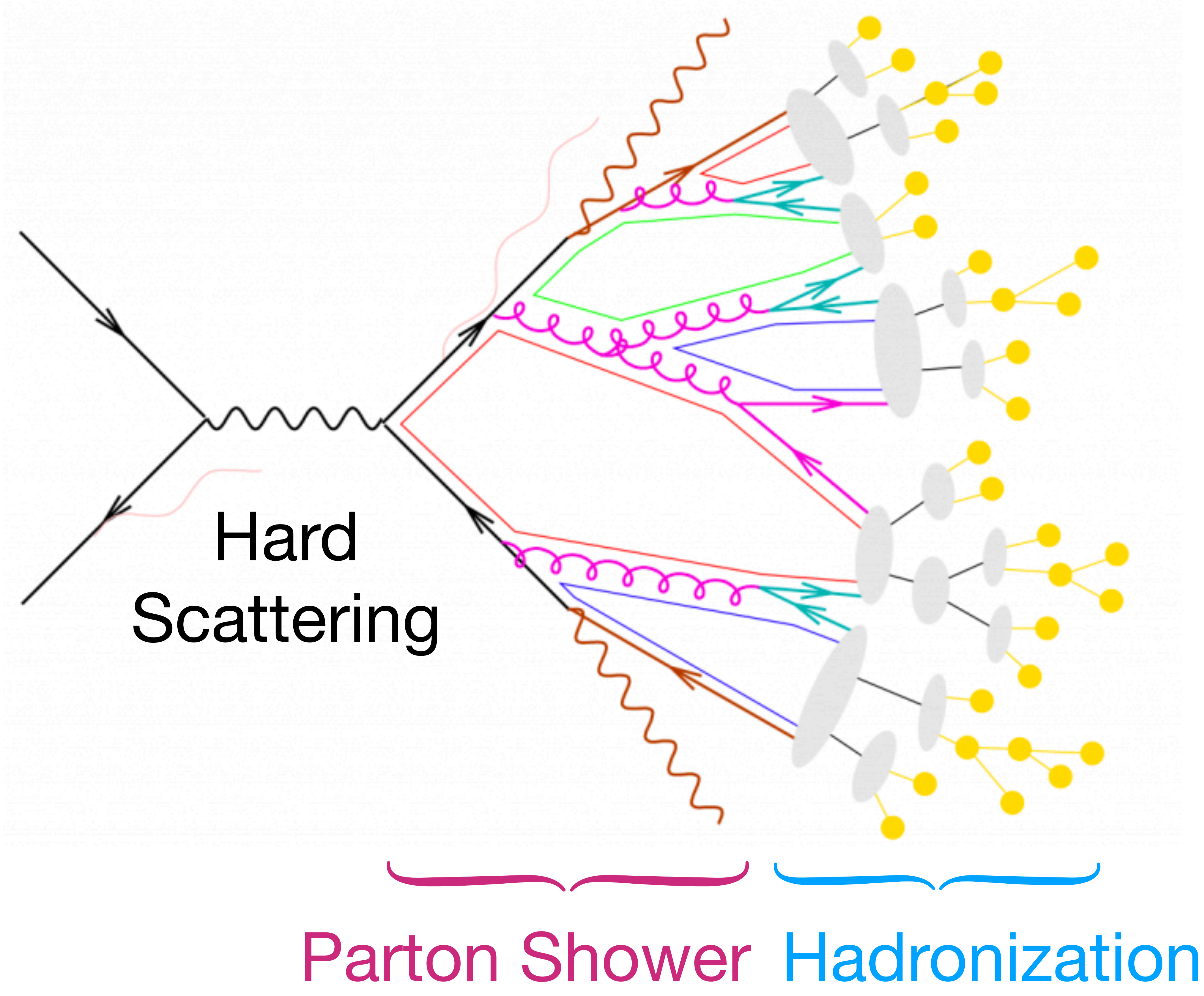


- Dedicated heavy-ion experiment at the LHC.
- Reconstructs jets at mid-rapidity ($|\eta| < 0.7$) in pp, p-Pb and Pb—Pb collisions.
- Utilizes high precision tracking detectors (Inner Tracking System and Time Projection Chamber) to measure **charged-particle jets**** over a wide range in jet p_{T}.
- **Full jets** combine charged particle information with neutral particle information measured in the electromagnetic calorimeter.

ALICE is great for jet measurements, especially measurements of jet substructure!

**In this talk (unless otherwise specified) assume charged jets!

What is a jet?

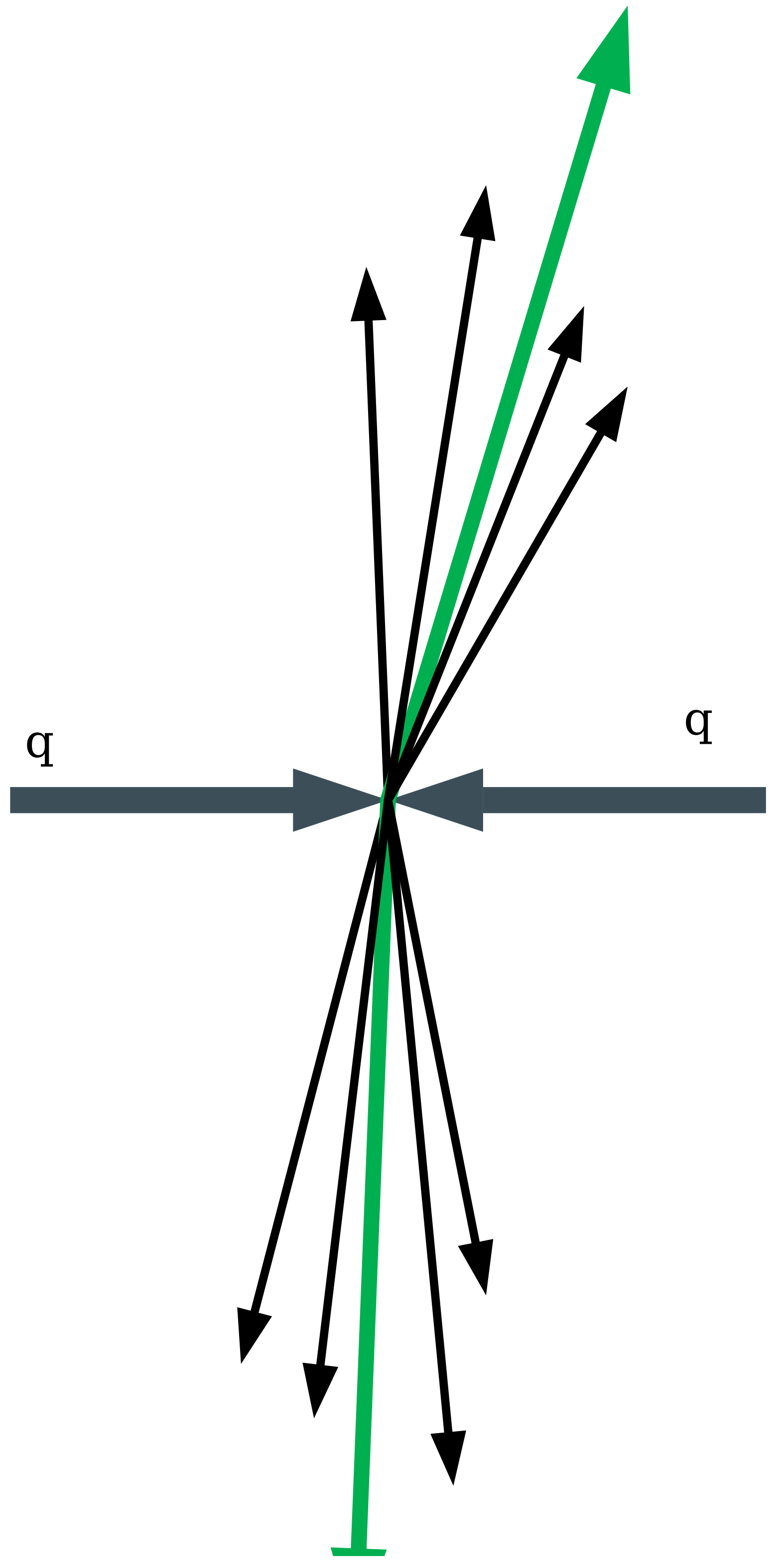


→ In hard scatterings, partons scatter off of one another with a high momentum transfer.

→ A jet is the spray of particles that results from the fragmentation and hadronization of a parton.

Jets are sensitive to physics information from many physics scales → great object to study these different processes!

Jets in Vacuum



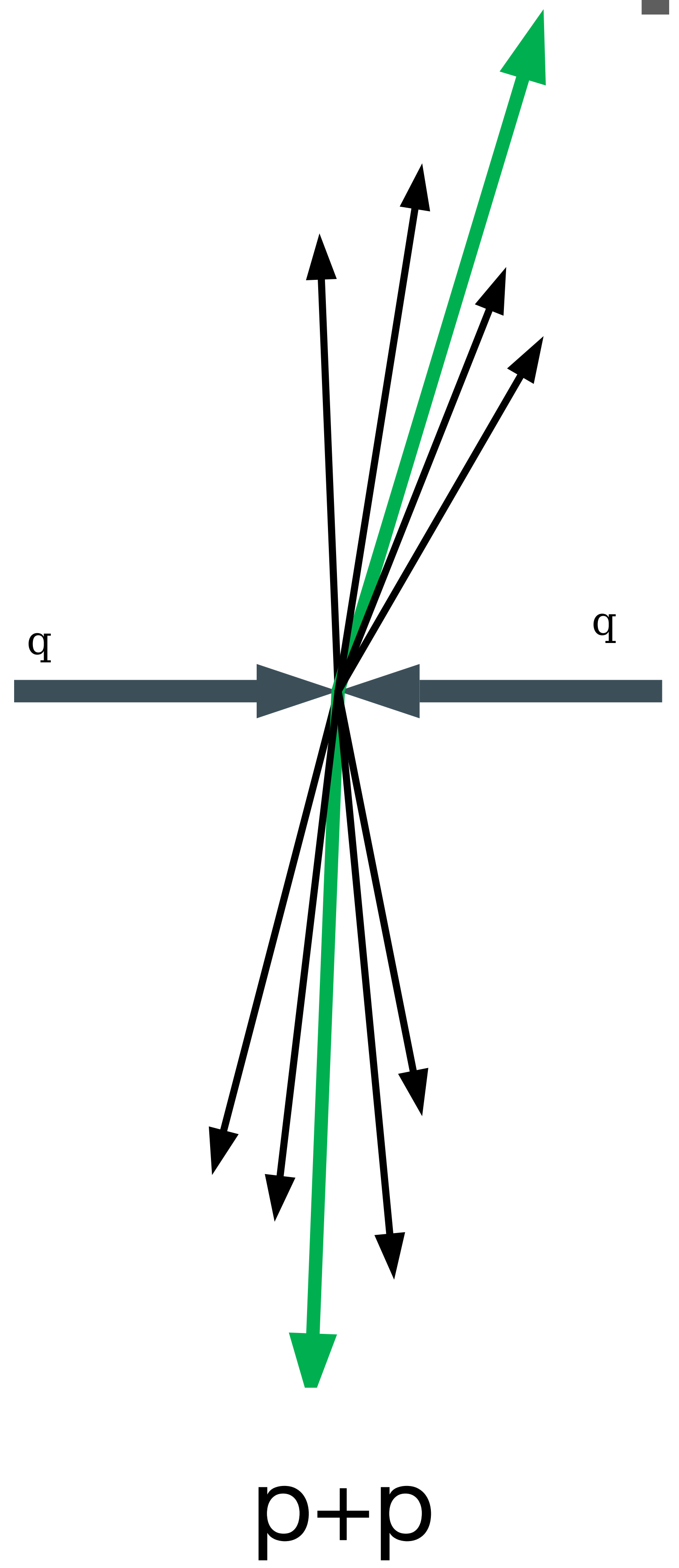
p+p

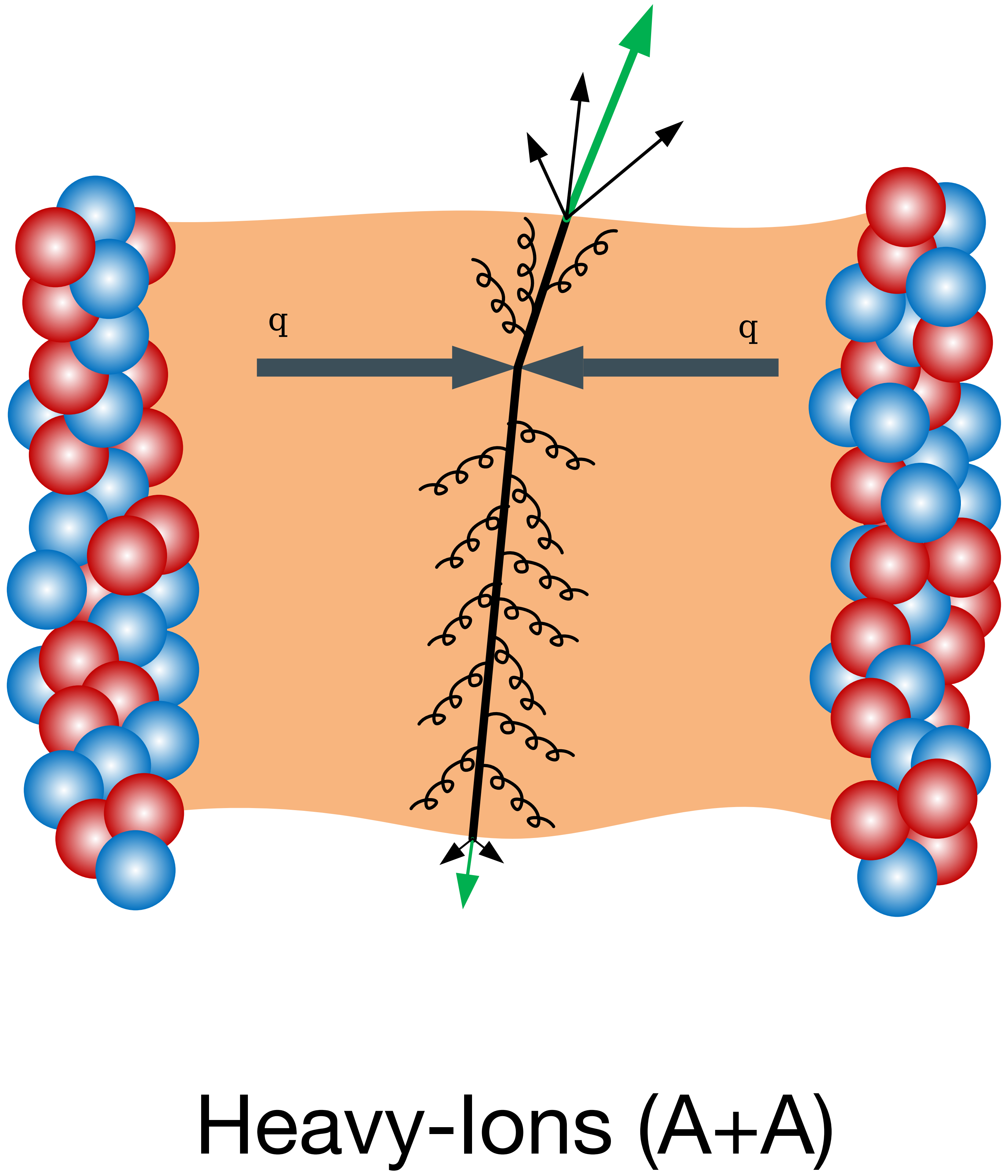
- In vacuum a majority of hard scatterings are 2→2, resulting in high transverse momentum (p_{T}) partons traveling back to back in the transverse plane.

- Production of partons calculable in perturbative QCD (pQCD).
  - Jets in vacuum useful for testing fundamental QCD properties.

What about jets in heavy-ion collisions??

Jets as a probe of the QGP





High p_T parton is expected to lose energy in interactions with the hot and dense medium in heavy-ion collisions (**jet quenching**).

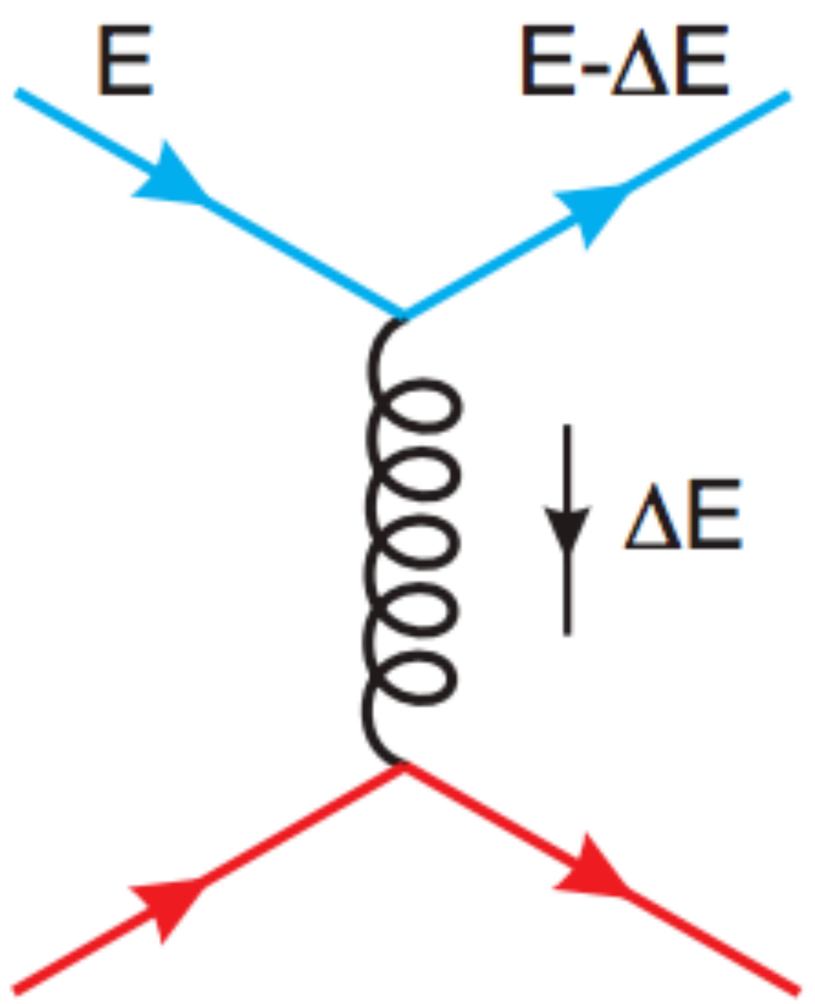
Jets are an excellent probe of the QGP as they experience its full evolution!

Use pp, where jets are measured in vacuum, as a reference for no QGP.

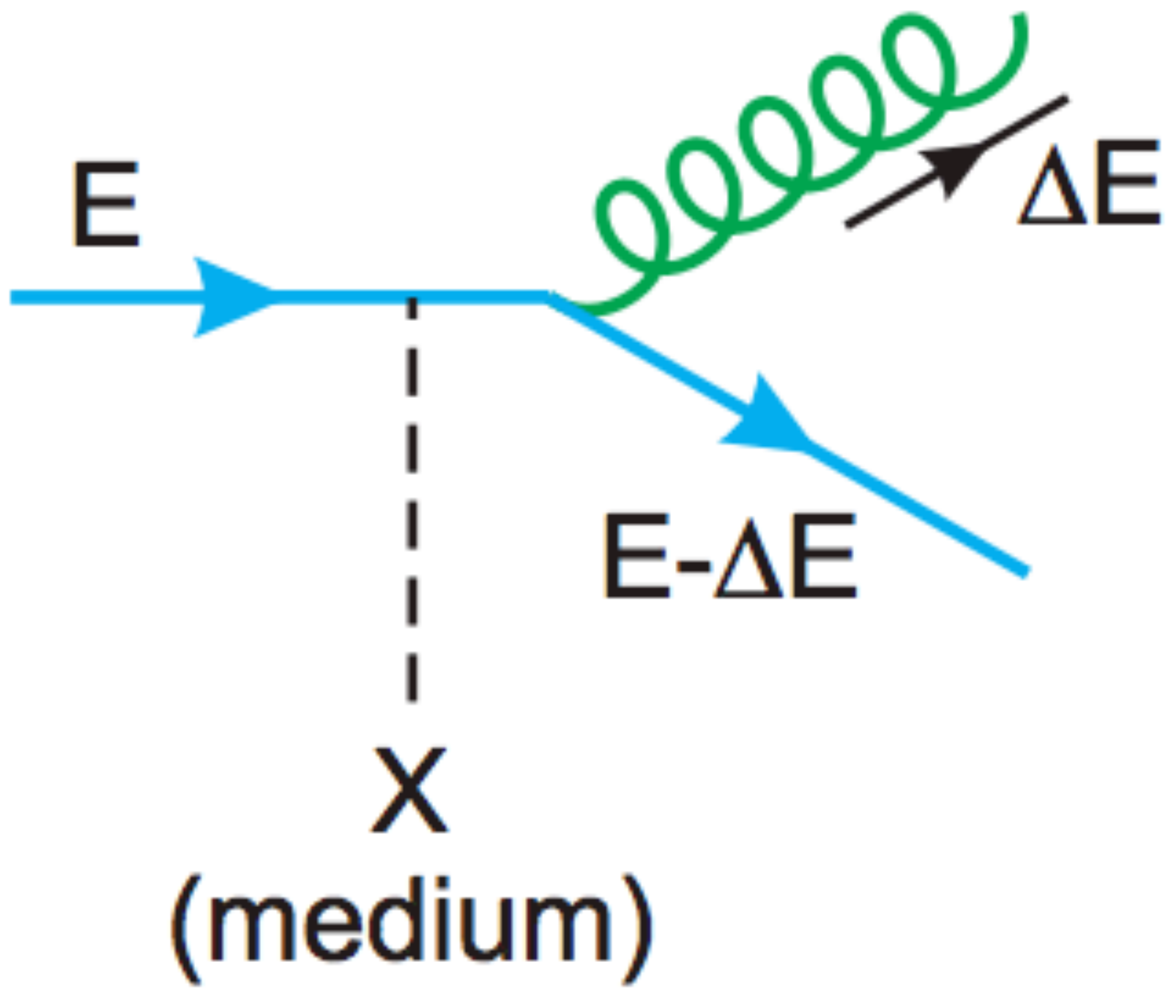
Modeling Jet Energy Loss

- Jets could interact with the medium (and lose energy) in a variety of ways.
- Amount of energy loss can depend on the path length through the medium (*L*), density of the medium and the flavor of the parton.

Weakly-Coupled Limit

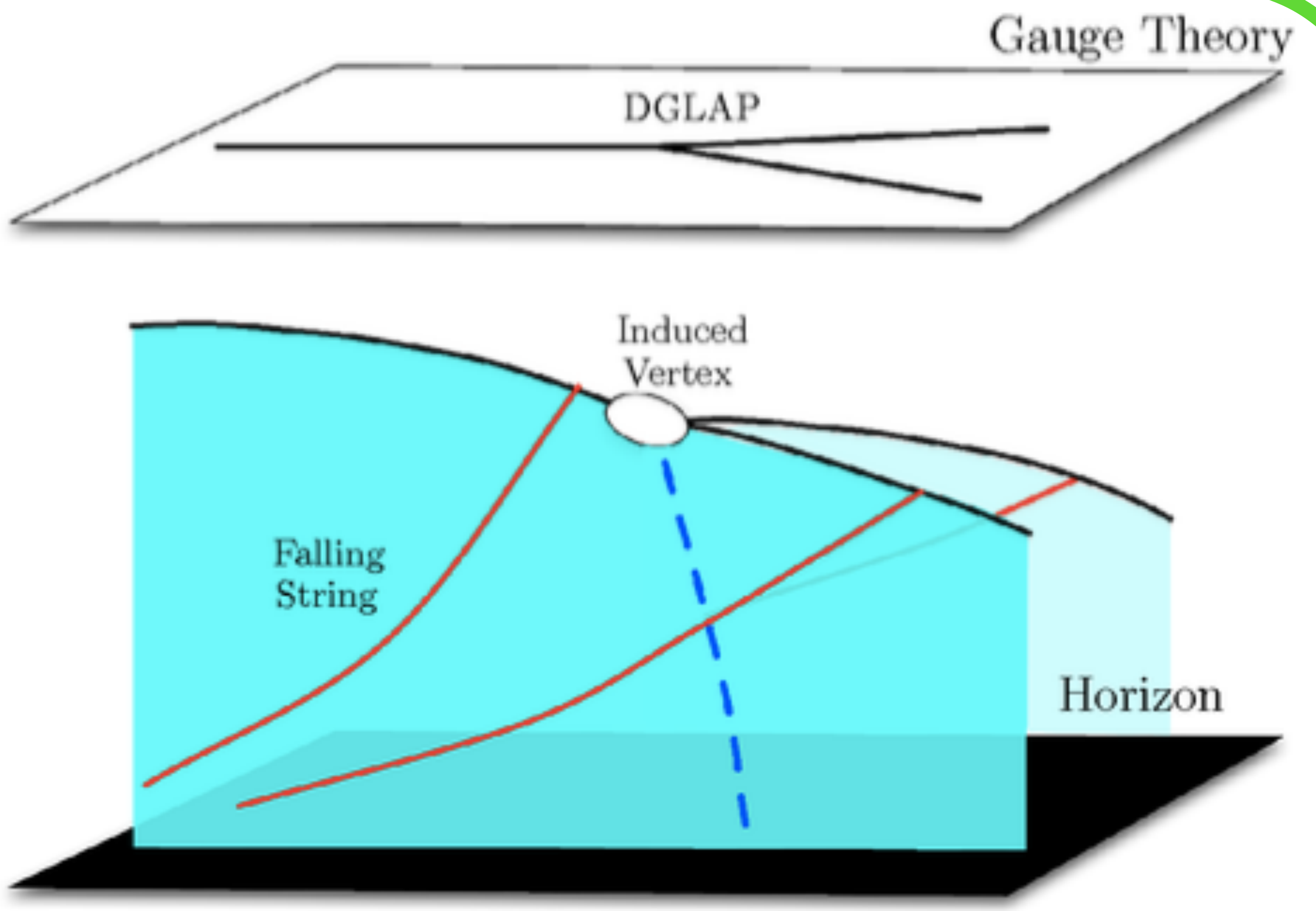


Collisional (L)



Radiative (L^2)

Strongly-Coupled Limit

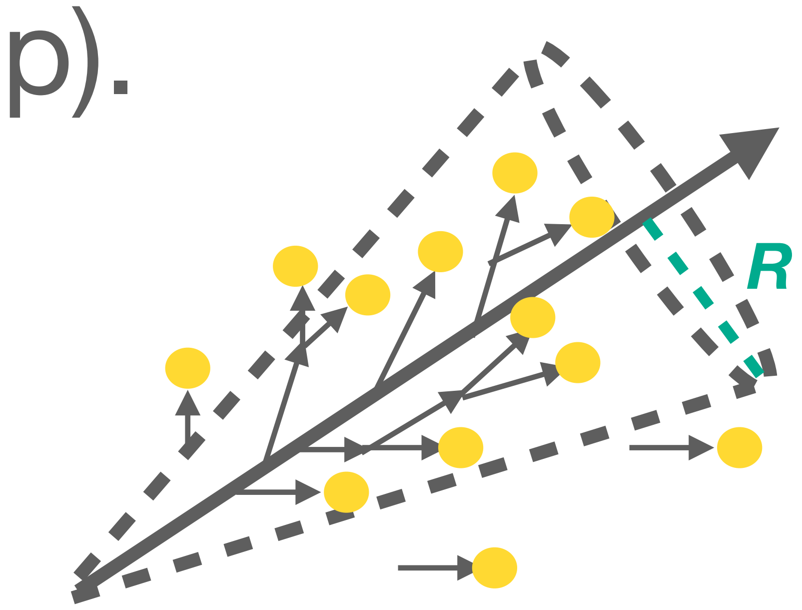


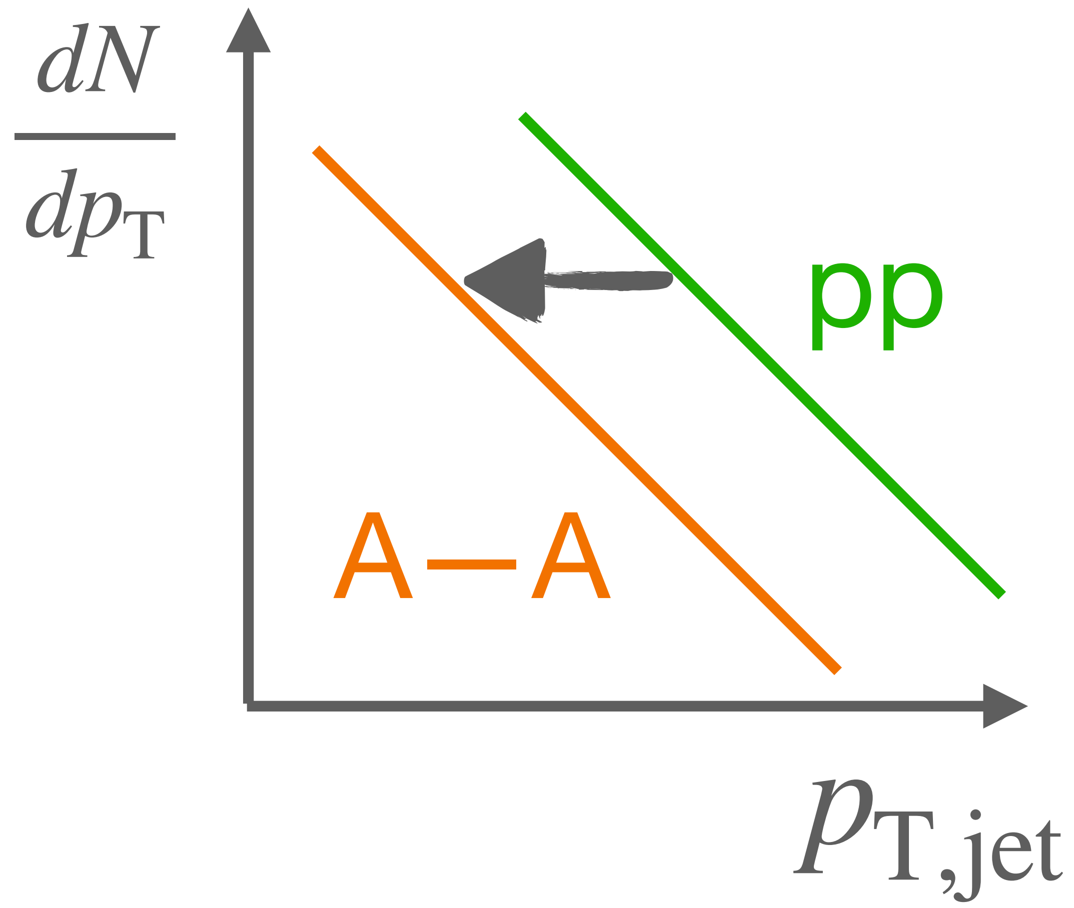
AdS/CFT “drag force” (L^3)

JHEP 10 (2014) 019

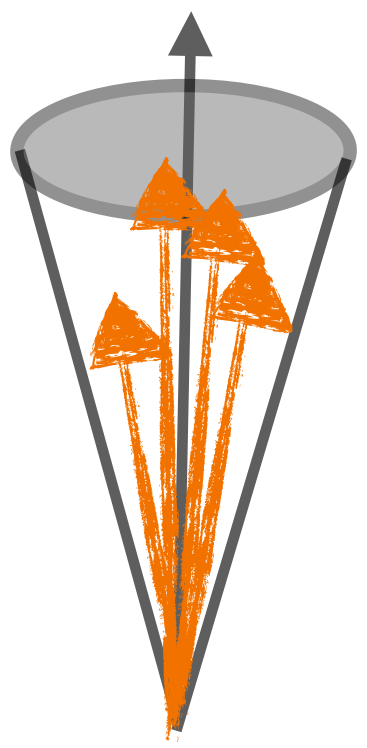
Expectations of jet quenching (1/2)

1. Parton energy loss leading to a suppression of jet yields in heavy-ions (A—A) in comparison to vacuum (pp).

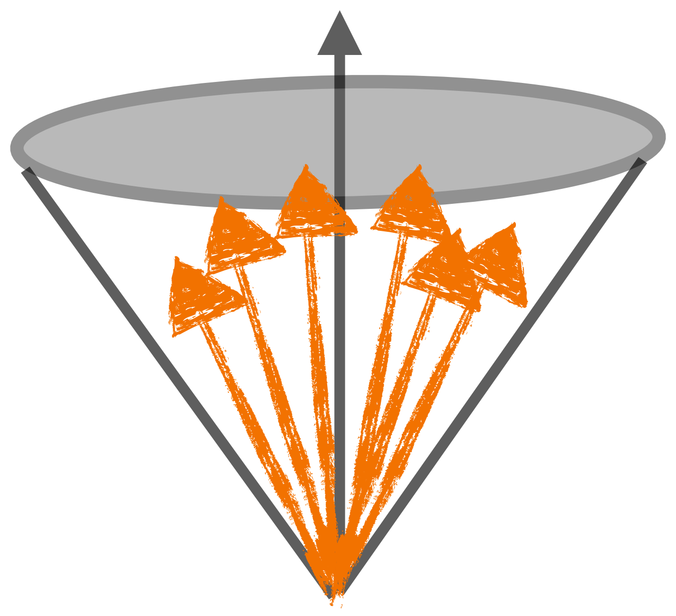




2. Internal structure modification due to…



Vacuum jet



Jet in Medium

Momentum broadening

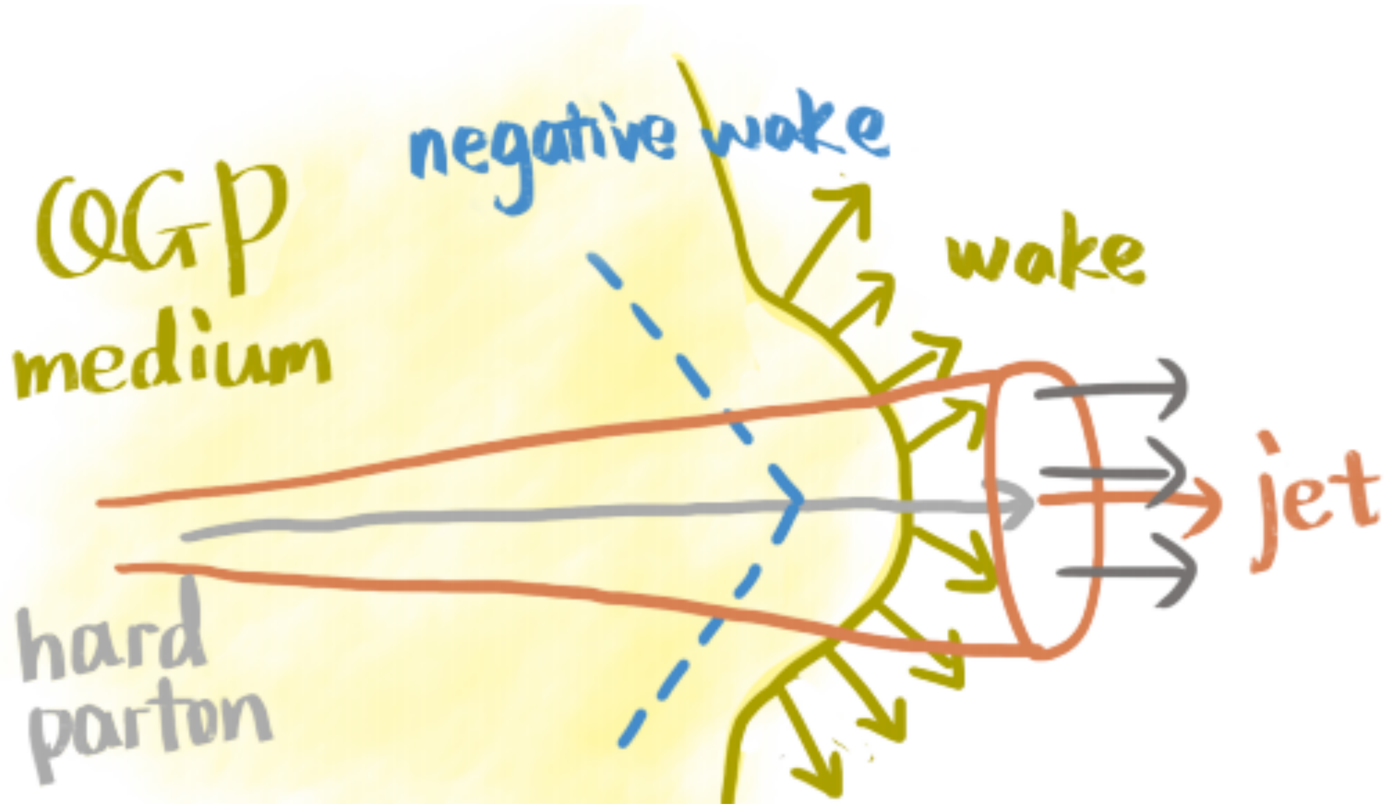
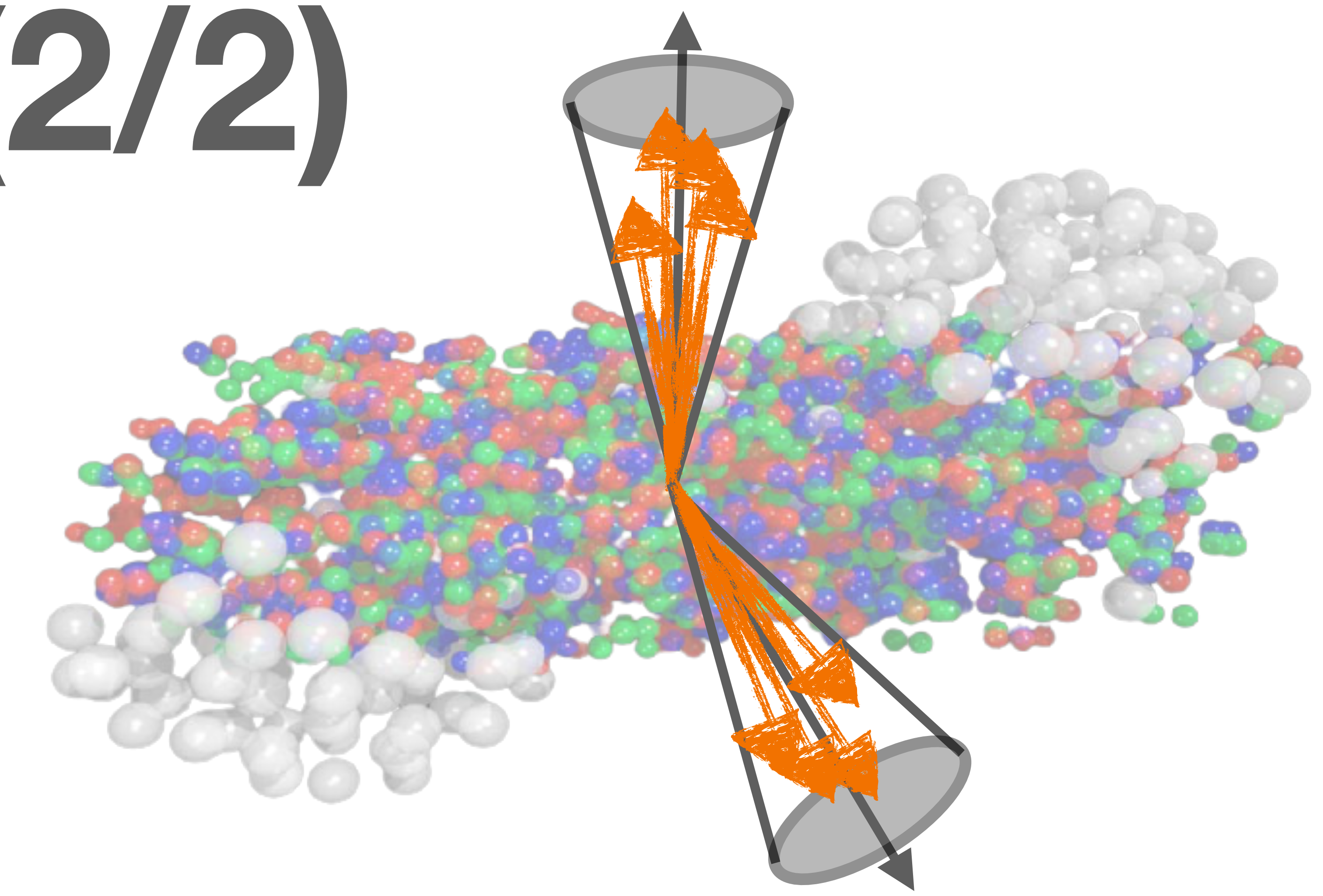


Image Credit:Jing Wang

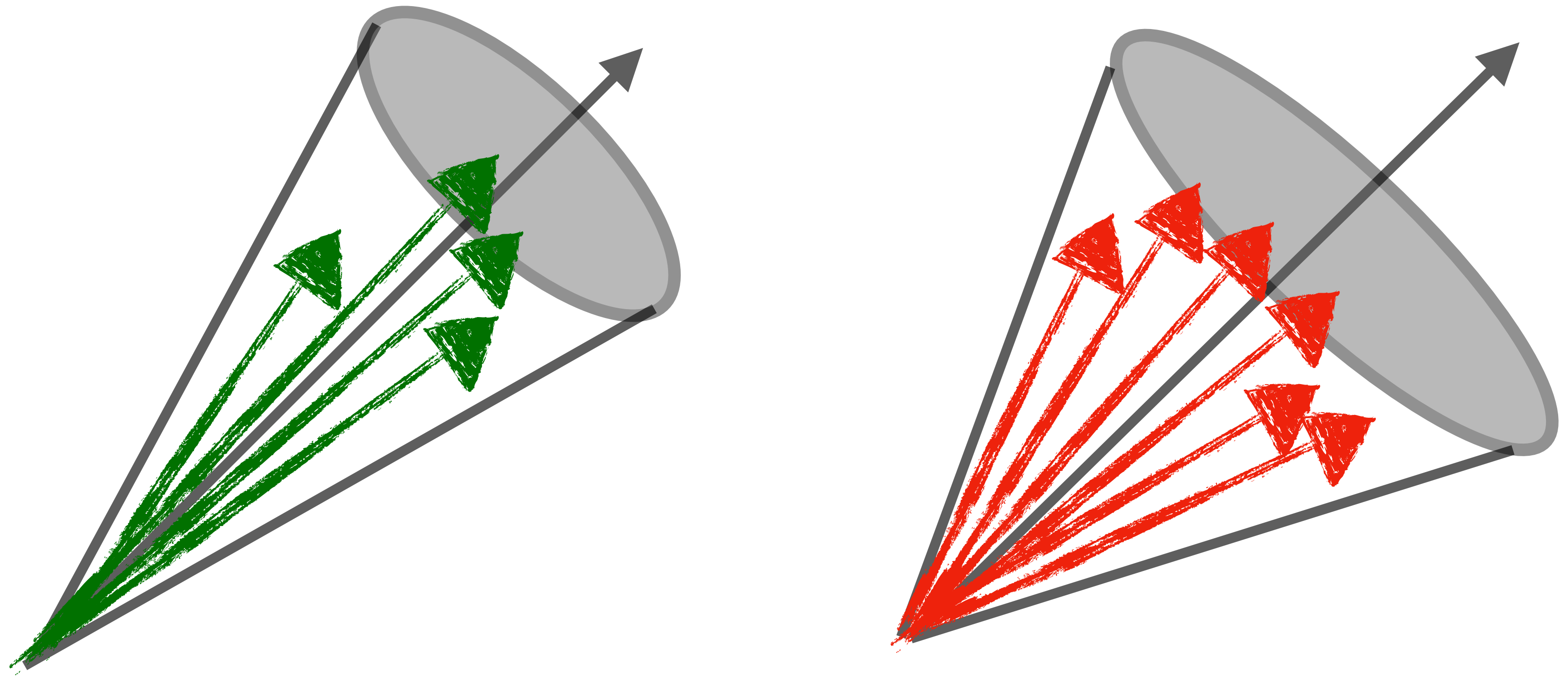
Medium-induced wake

Expectations of jet quenching (2/2)



③ Deflection of the jet centroid due to multiple soft scatterings or scatterings with QGP quasi-particles.

④ Different jets with different partonic structures, flavors, transverse momenta, path lengths through the medium, etc. lose energy differently.

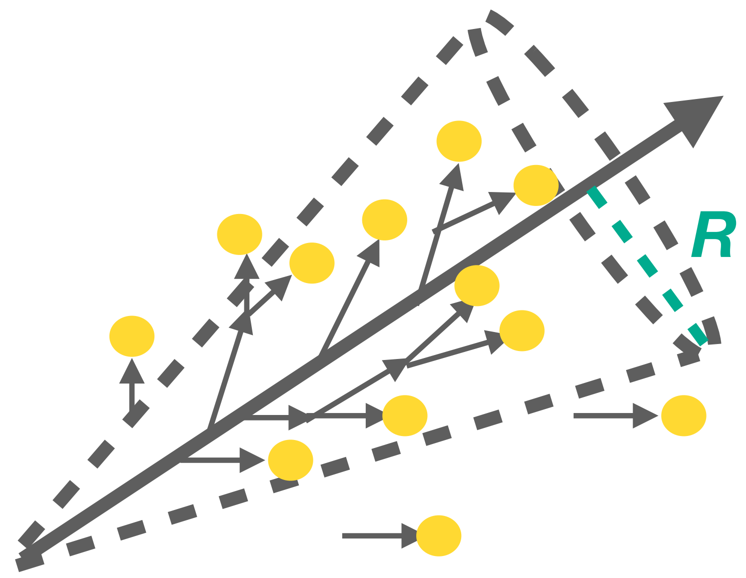


→ The same jets can lose energy differently due to fluctuations in jet-medium interactions.

→ *Isolating the same jet population can be challenging, but useful for disentangling energy loss mechanisms! → Differential jet measurements!*

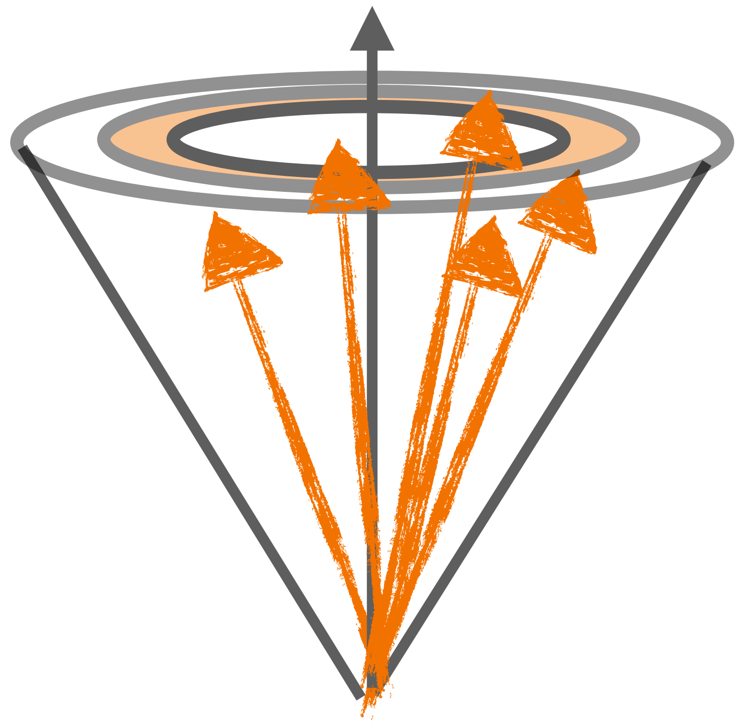
Jet quenching observables

→ Different observables designed to probe different expectations!

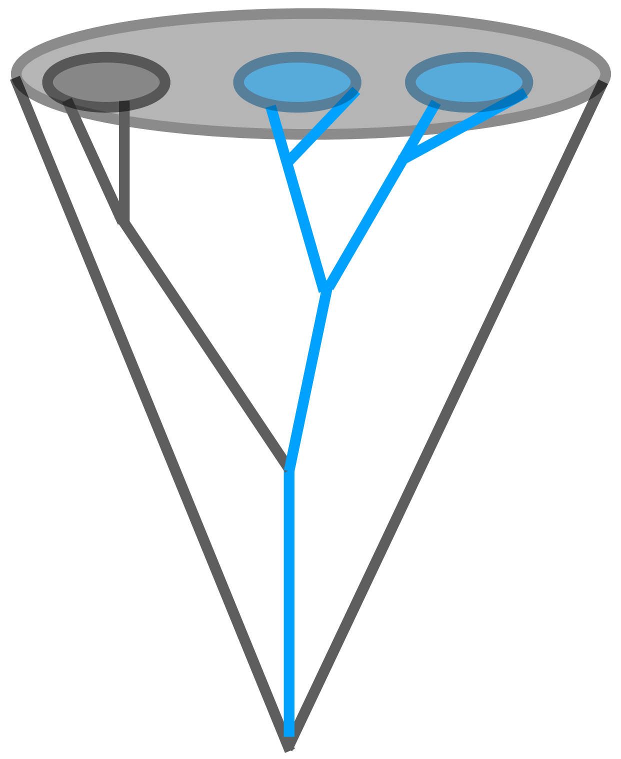


1. Parton energy loss → **inclusive jet yields** (more on this later)

2. Internal structure modification



Jet structure → distribution of radiation in the jet.

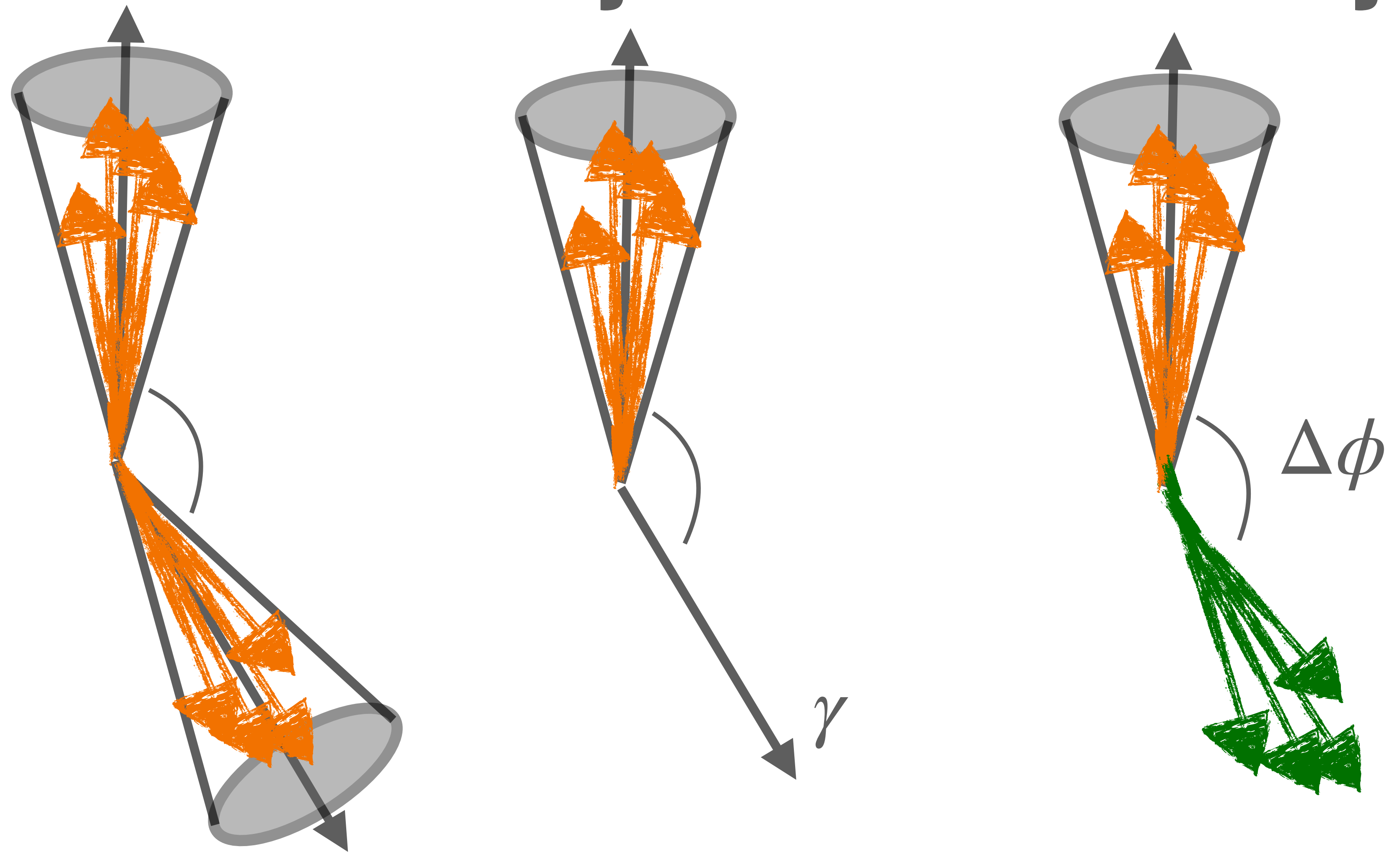


Jet substructure → partonic splittings in the jet.

3. Jet deflection

4. Path length dependence

Correlations of jets w/ other objects

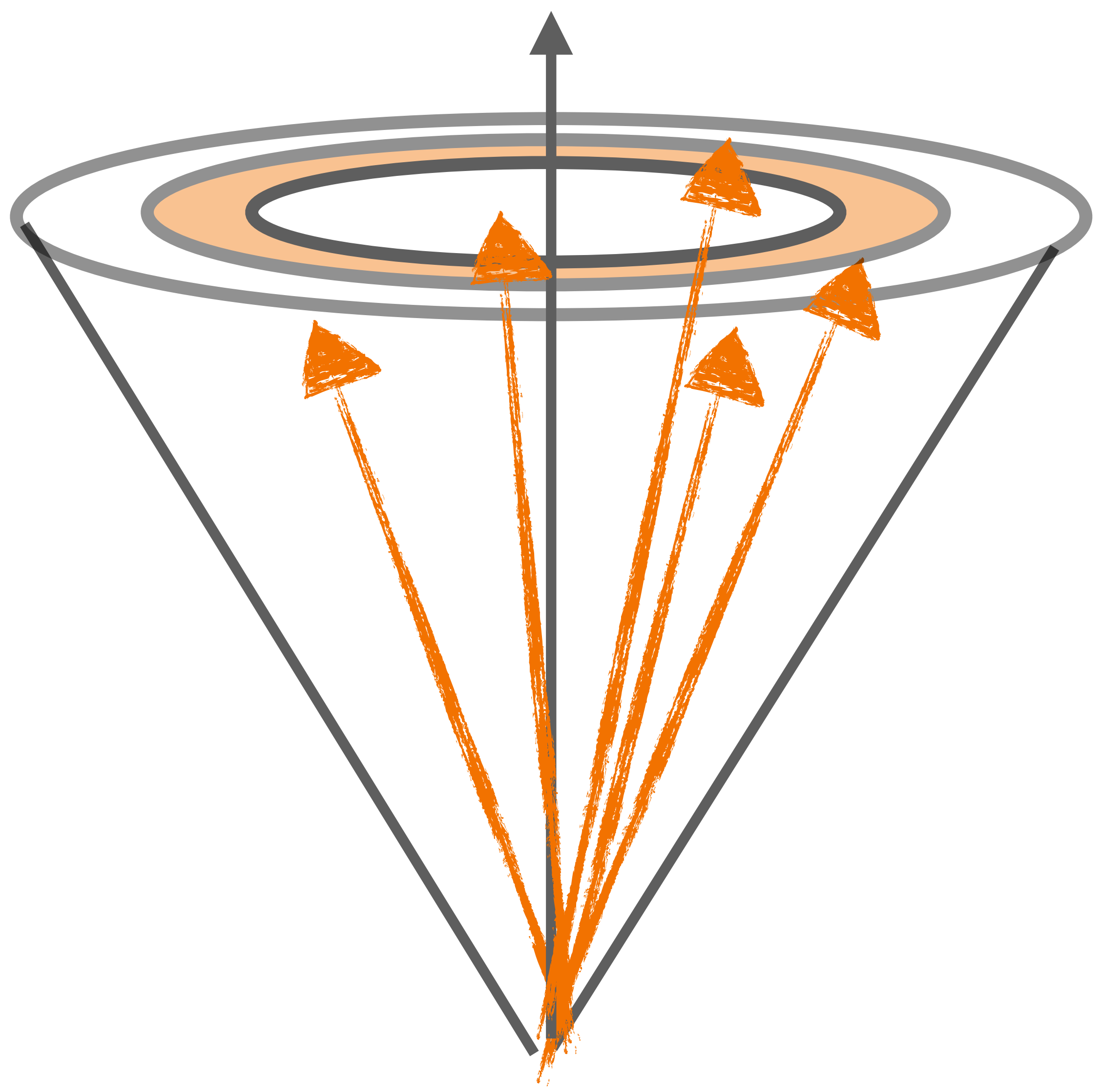


Jet-Jet γ-Jet   Jet-Hadron

What we witness in experiment is actually a convolution of these effects!

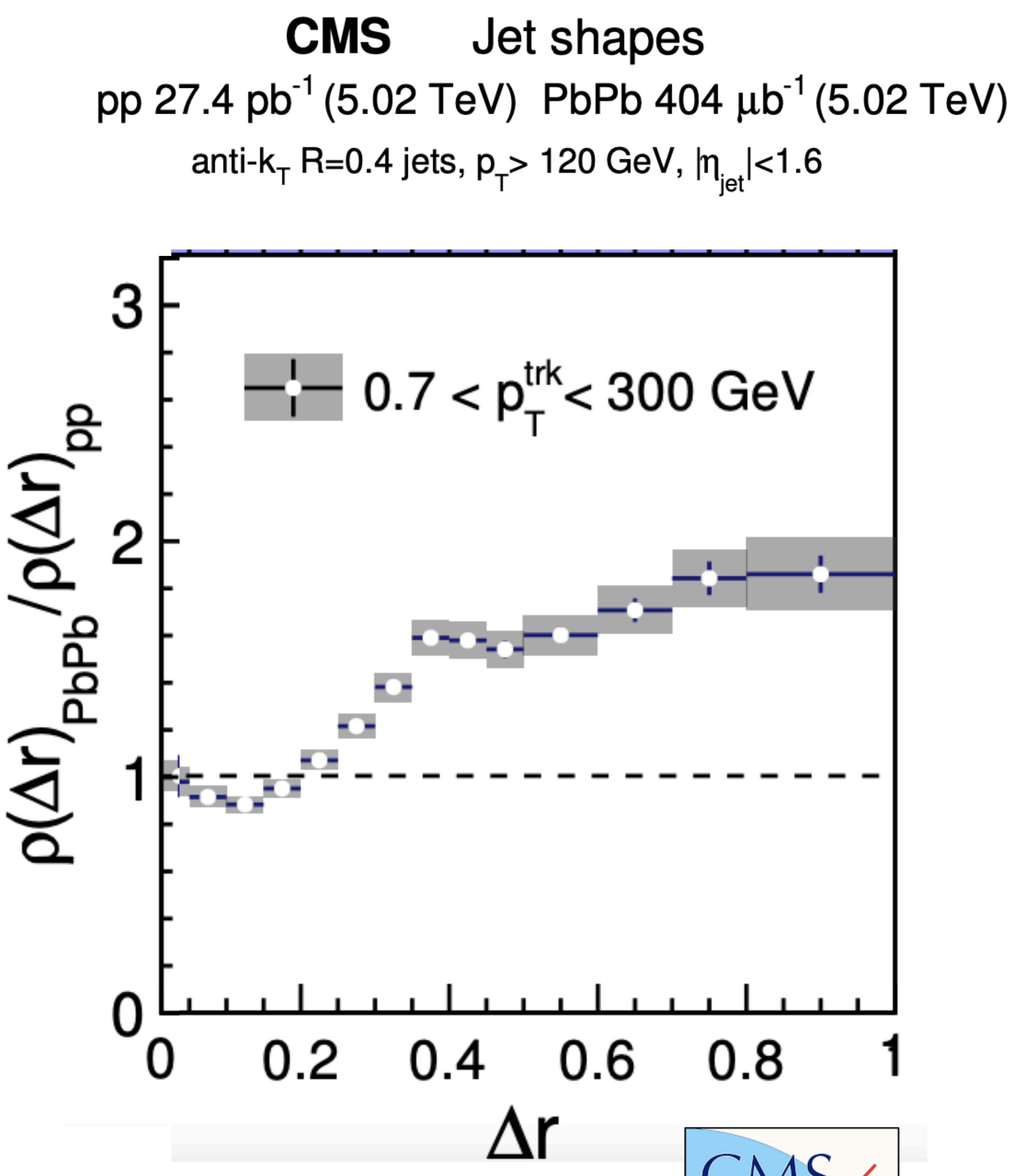
Radial profile

- Look at $\rho(\Delta r)$ which probes the p_{T} density of constituents in a specified radial ring.



- When we compare these distributions between heavy-ions and pp, we see a large excess of wide angle particles.

- Largest excess is outside of the jet radius.

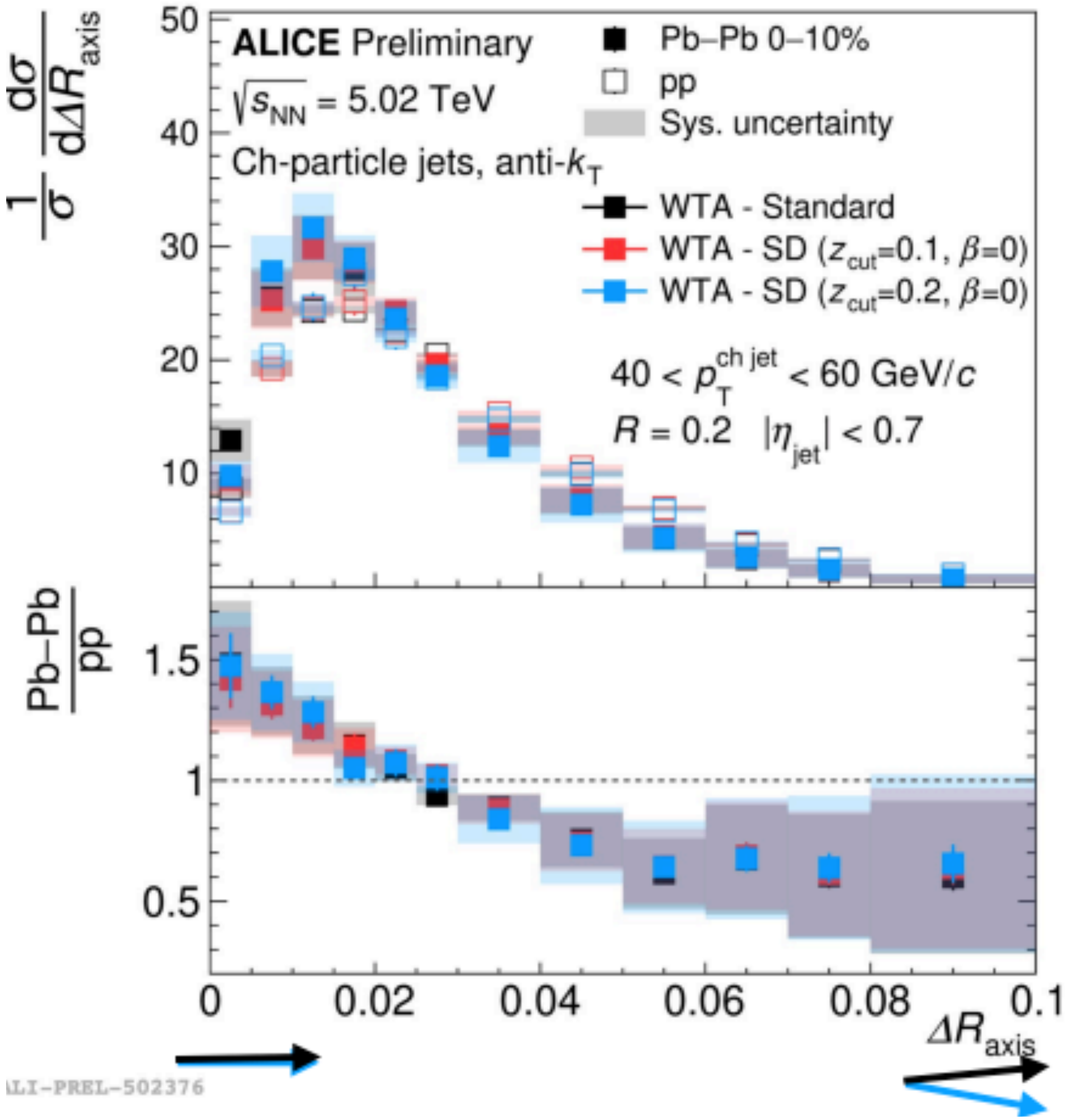


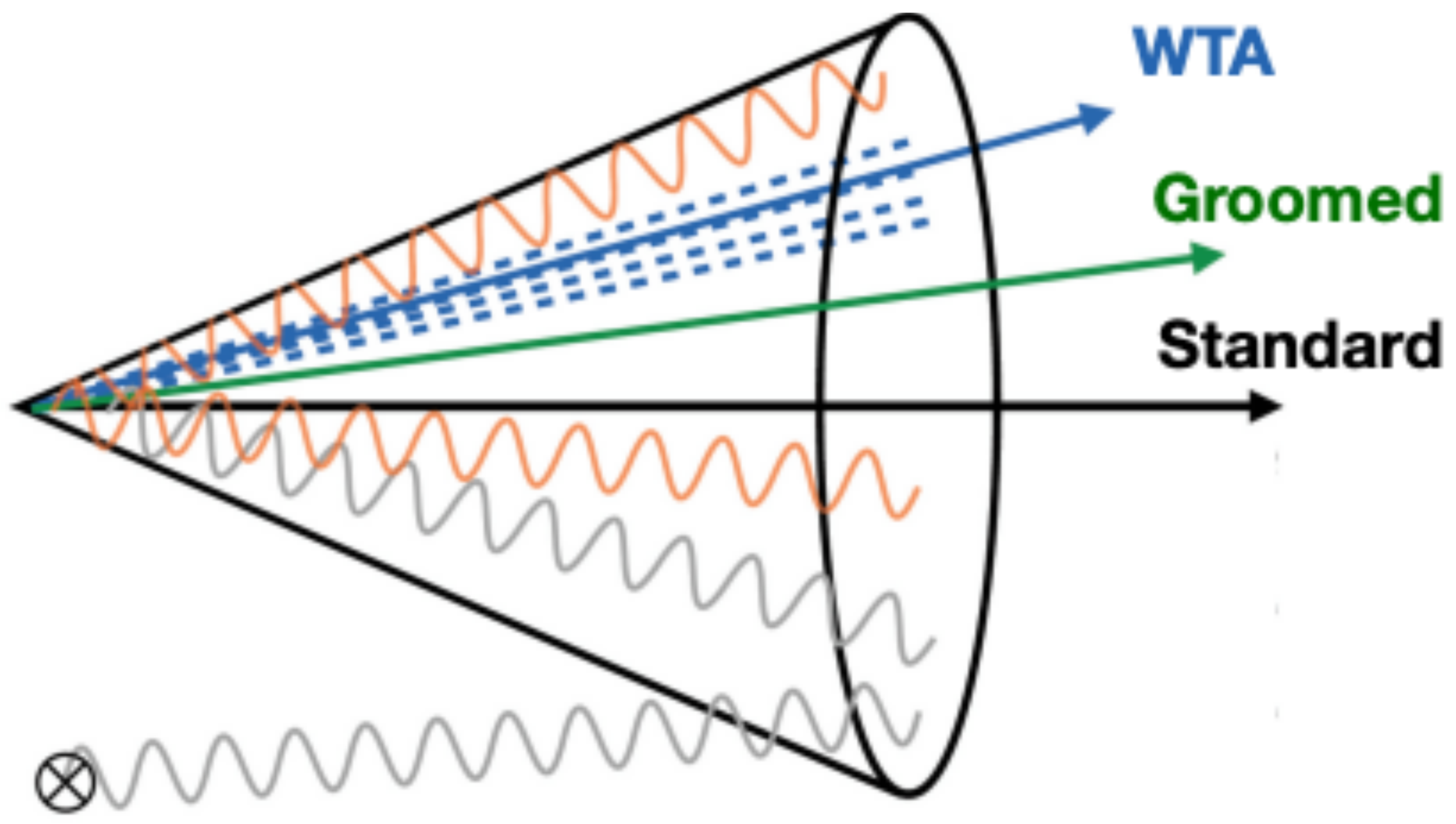
- Consistent with out of cone radiation via momentum broadening.

Would we at some point recover the energy lost via out-of-cone radiation?

JHEP05(2018)006.

Jet axis differences





Substructure observable looking at the difference between jet axis definitions.

P. Cal et. al, JHEP 04 (2020) 211

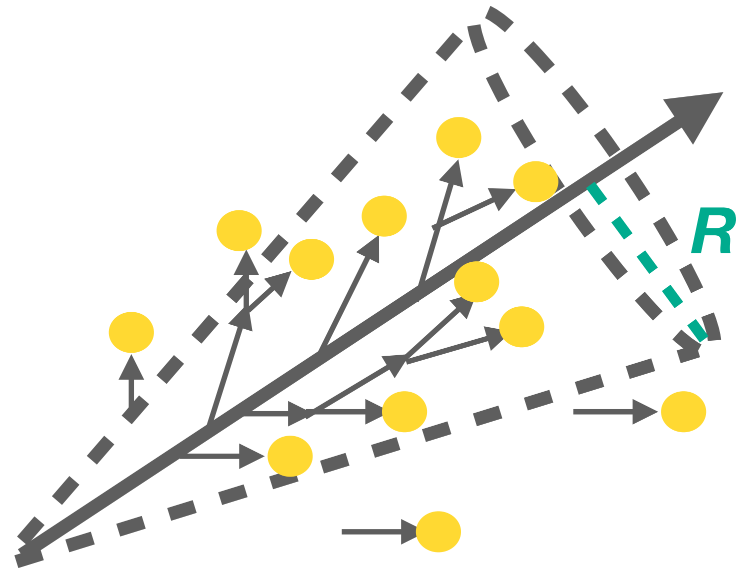
Standard: axis of anti-k_T E-scheme jet.

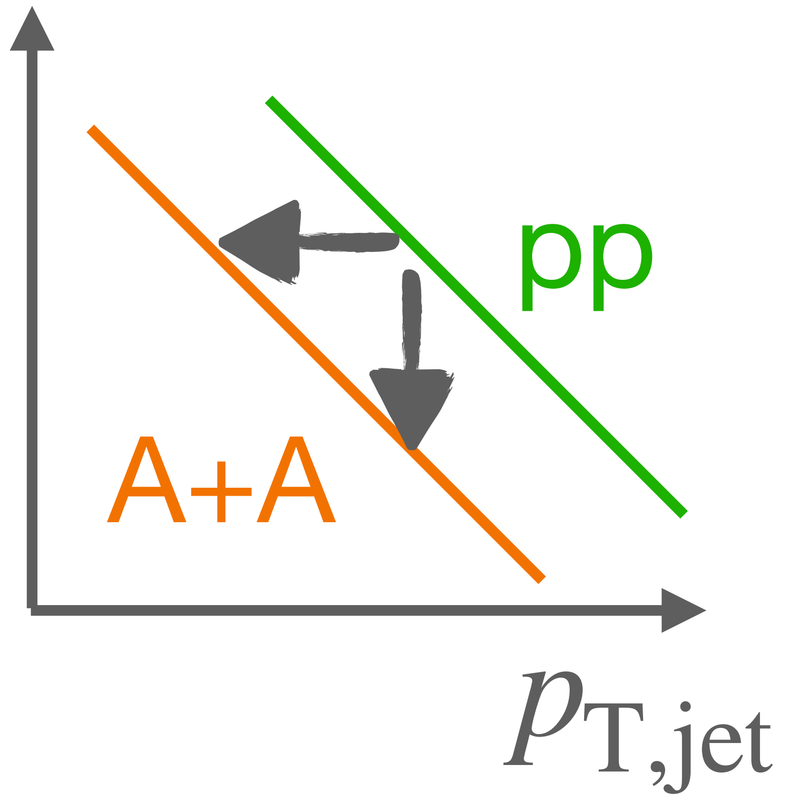
Groomed: soft drop groomed axis.

Winner Take All: hardest prong of reclustered C/A jet.

Suppression of large ΔR_{axis} in Pb—Pb, consistent with a narrowing of jets in Pb—Pb.

The Nuclear Modification Factor (R_{AA})



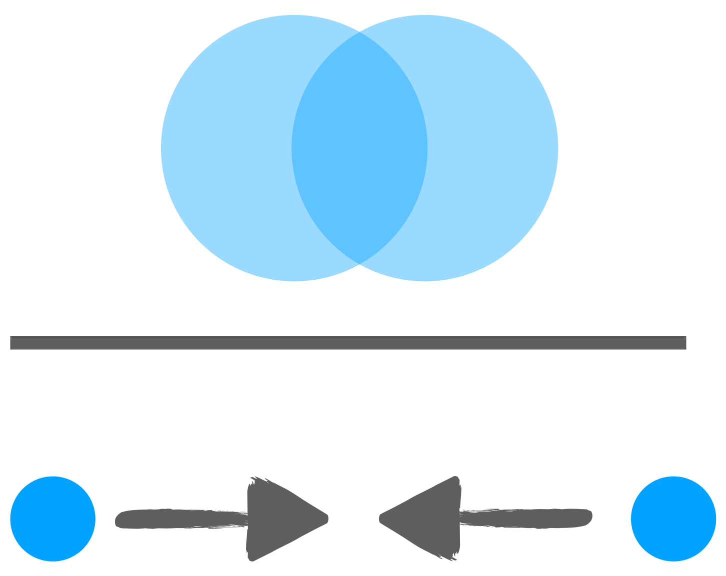


① Parton energy loss will lead to a suppression of jet yields in heavy-ions (A+A) in comparison to vacuum (pp).

→ We use the R_{AA} to probe this expectation.

→ Ratio of the jet yield in Pb—Pb compared to the expected yield if no hot or dense medium was present.

$$R_{\mathrm{AA}} = \frac{\left.\frac{1}{N_{\mathrm{event}}}\frac{d^2N^{\mathrm{PbPb}}_{\mathrm{jet}}}{dp_{\mathrm{T}}dy}\right|_{\mathrm{cent}}}{\langle T_{\mathrm{AA}}\rangle \frac{d^2\sigma^{\mathrm{pp}}_{\mathrm{jet}}}{dp_{T}dy}} =$$



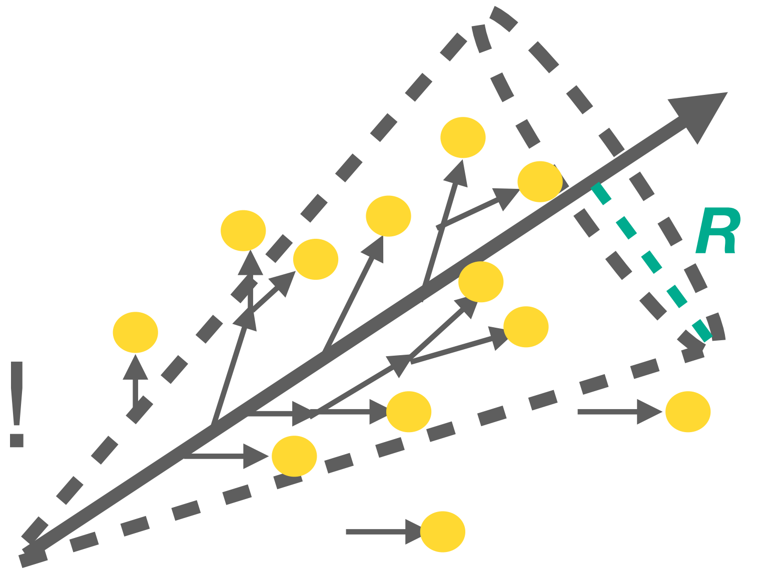
$R_{\mathrm{AA}} > 1 \rightarrow$ Enhancement

$R_{\mathrm{AA}} = 1 \rightarrow$ No modification

$R_{\mathrm{AA}} < 1 \rightarrow$ Suppression

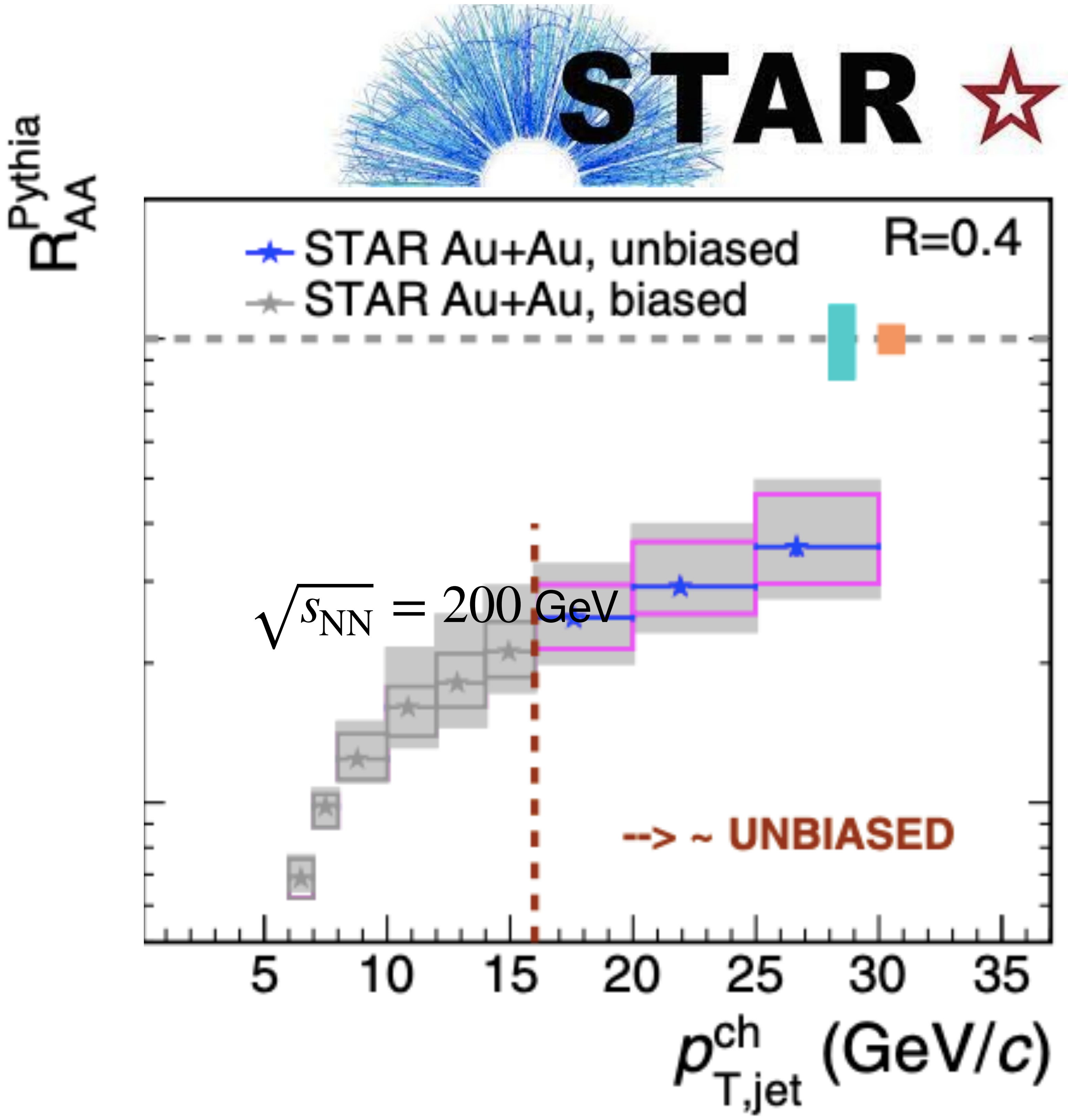
Suppression (as measured via the R_{AA}) is a key observable of QGP formation!

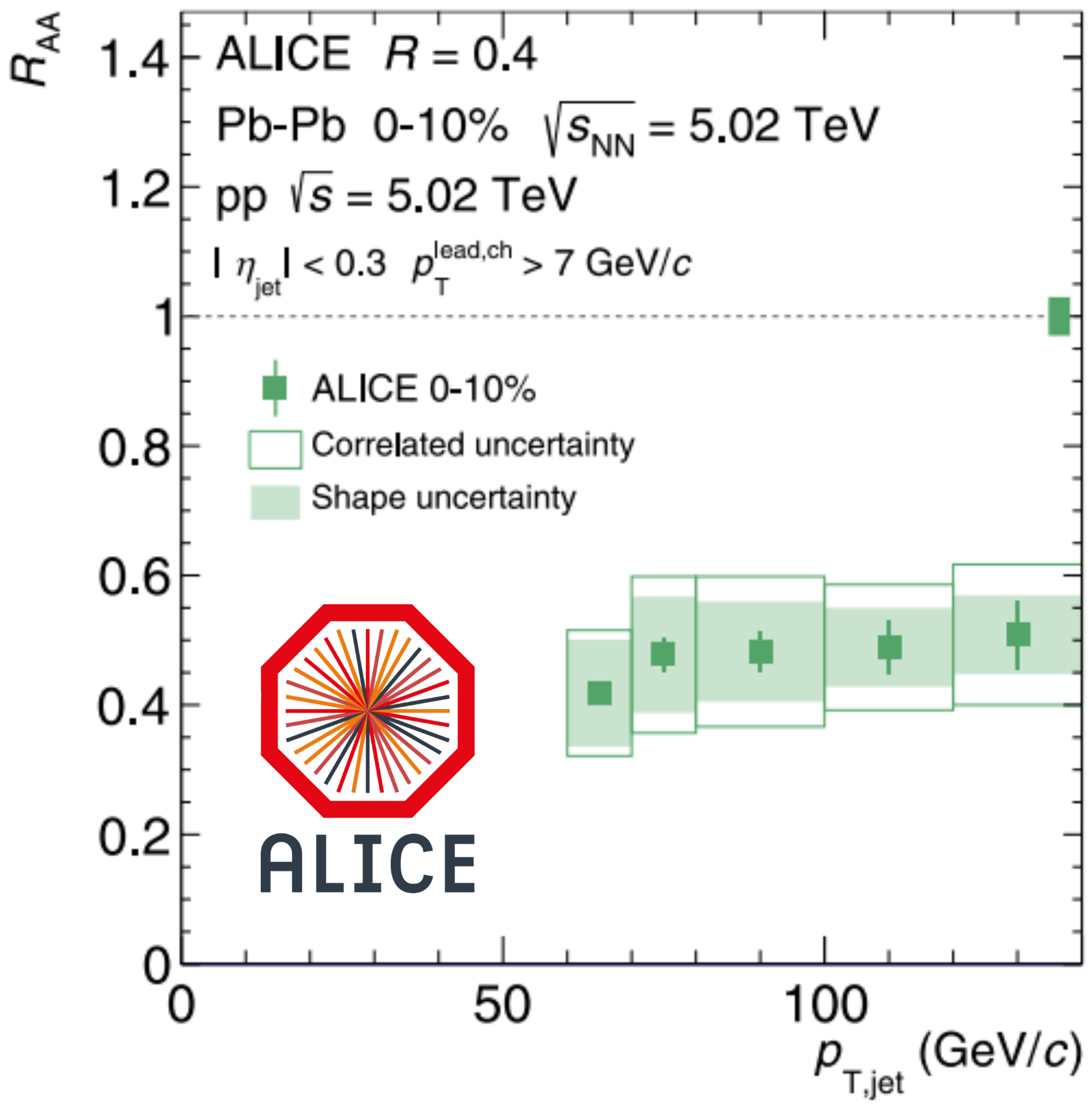
Experimental measurements of the R_{AA}

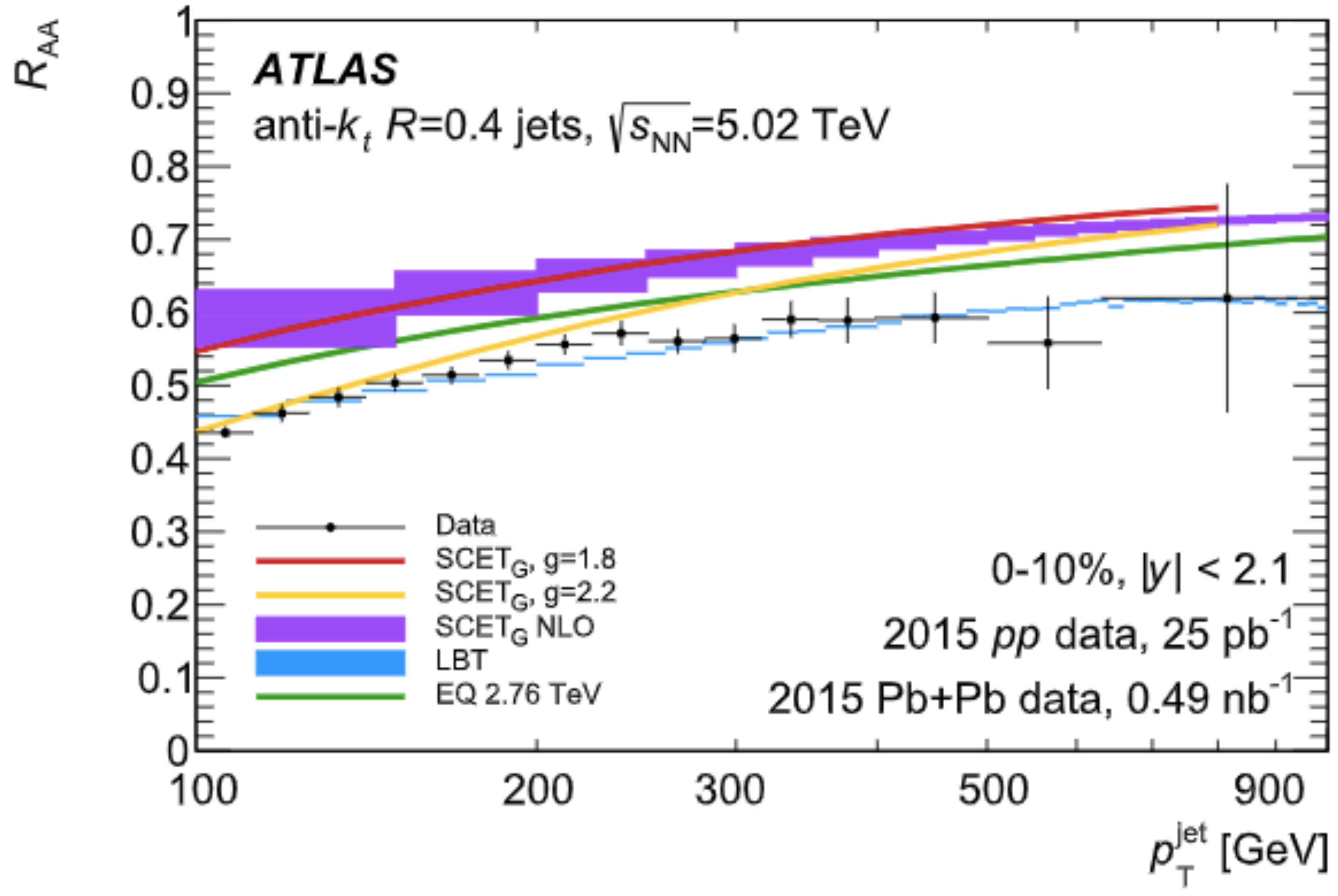


→ Clear evidence of suppression at many different p_T scales for R = 0.4 jets!

Key signature of QGP formation!





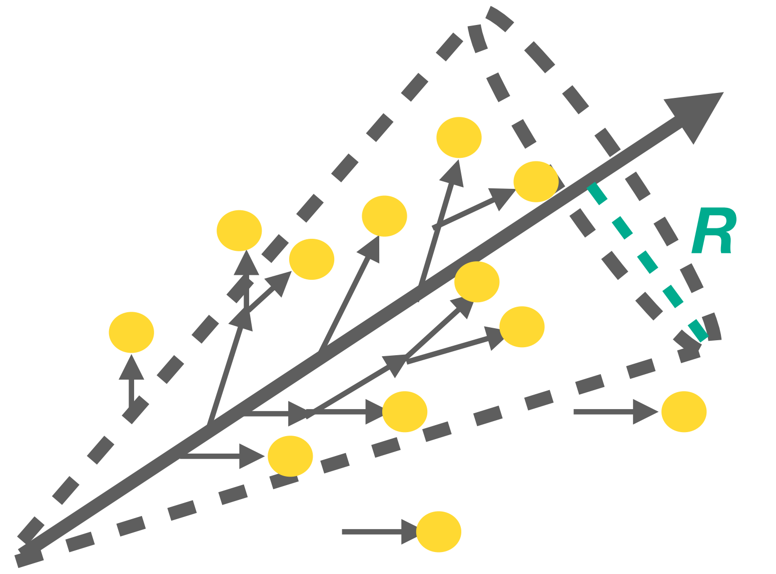


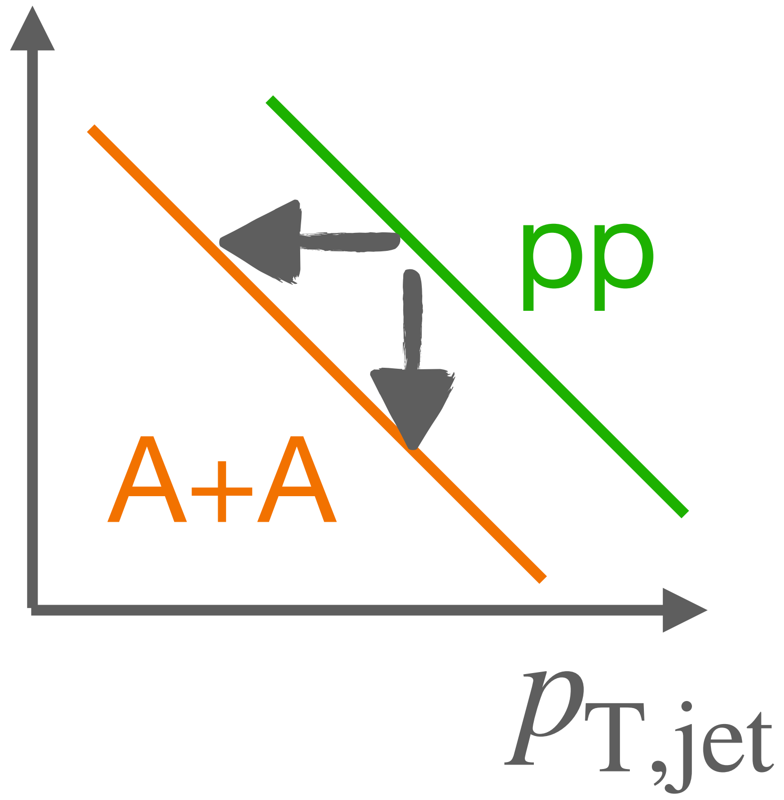
Phys. Rev. C. 102, 054913 | Phys. Rev. C 101, 034911 | Phys. Lett. B 790 (2019) 108

Low p_T ←→ **High p_T**

New view of suppression

→ We are entering a new era of jet suppression measurements!





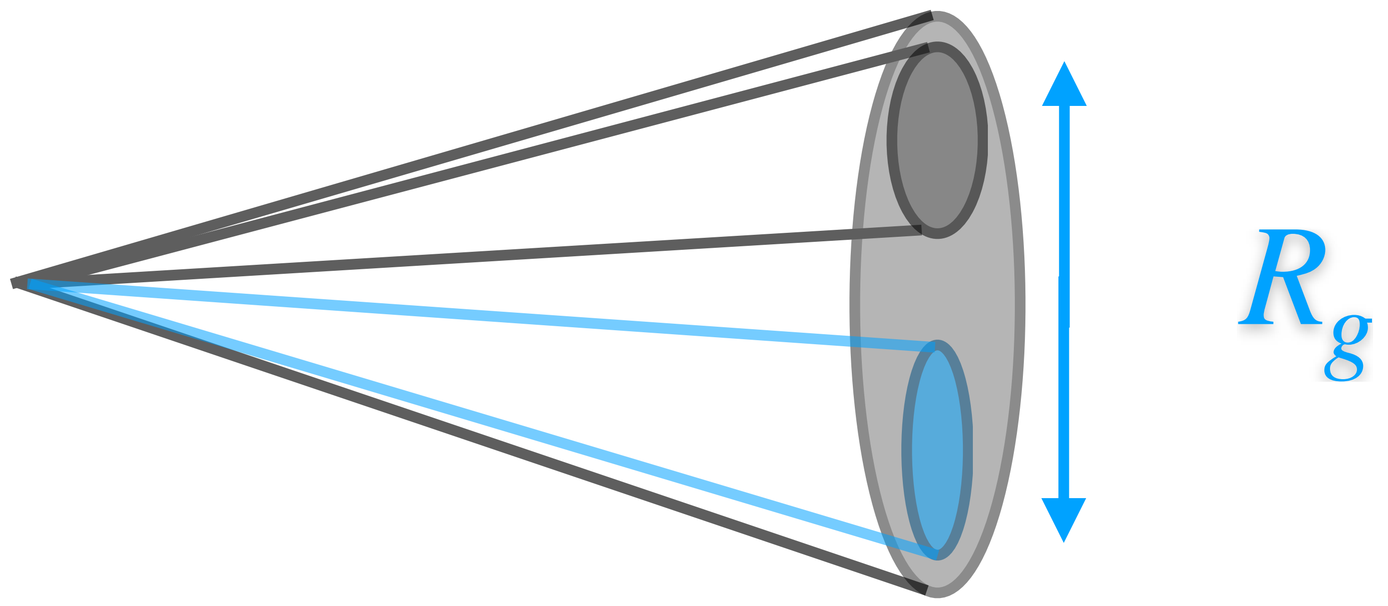
Classic view: Jet suppression measurements offer evidence of QGP formation.

New view: Differential measurements of suppression can bridge the gap between different experimental expectations of jet quenching and offer new insights into the QGP and its properties!

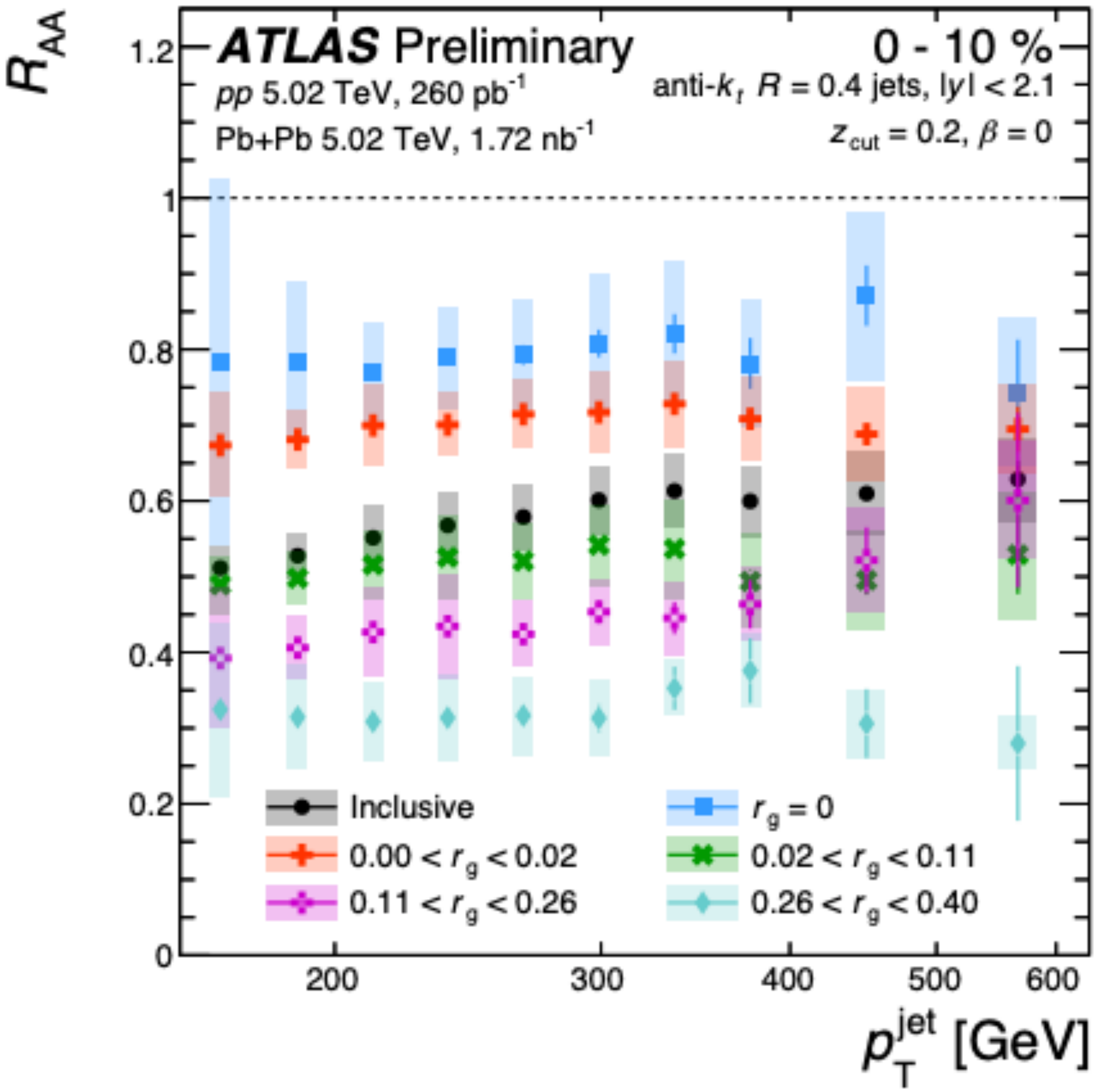
→ Let's take a look at some of these measurements!

Suppression as a function of R_g

- Look at the substructure dependent R_{AA} to combine expectations (1) and (2).



- Look at the R_{AA} as a function of R_g, the angle between subjets.



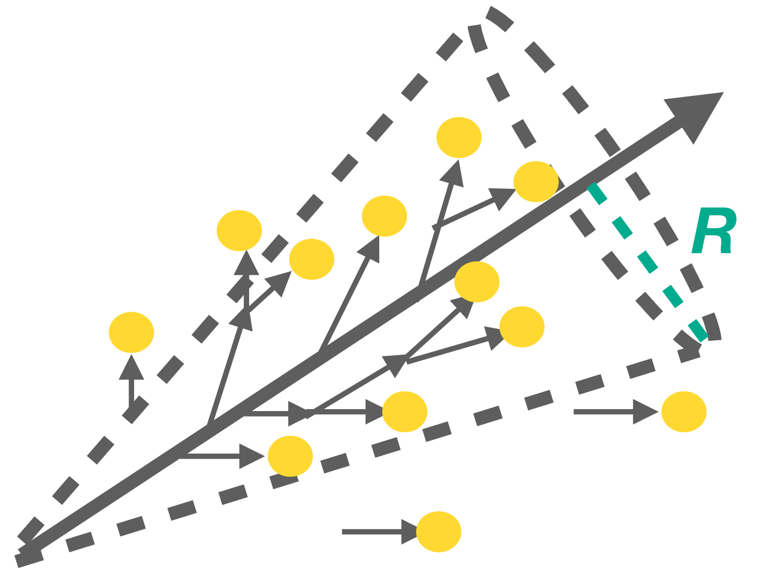
- See that wider jets are more suppressed independently of jet p_T!
- Substructure seems to be a key factor in amount of energy loss.
- What are some other examples of differential measurements of jet suppression?

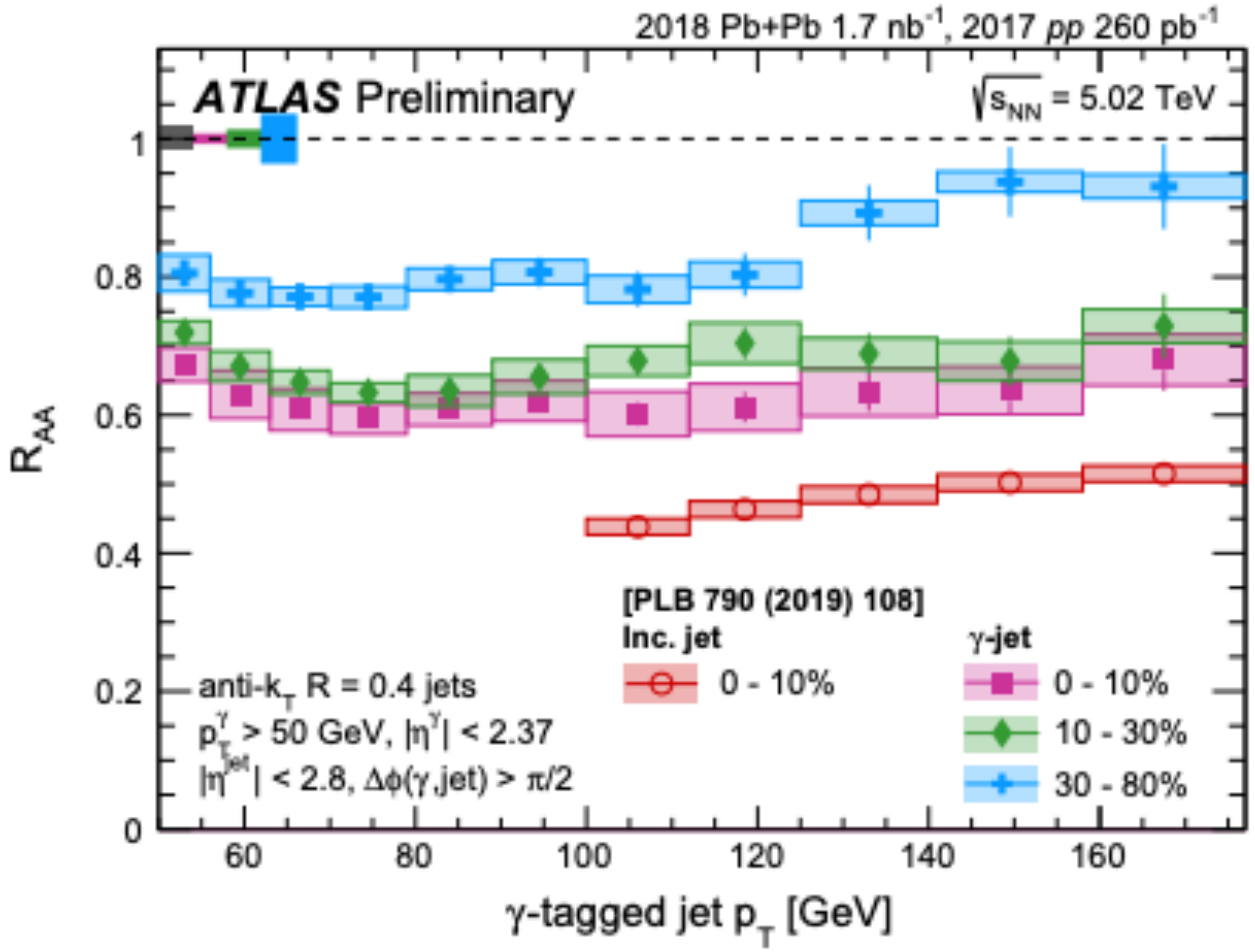
ATLAS EXPERIMENT

ATLAS-CONF-2022-026

Photon-tagged R_{AA}

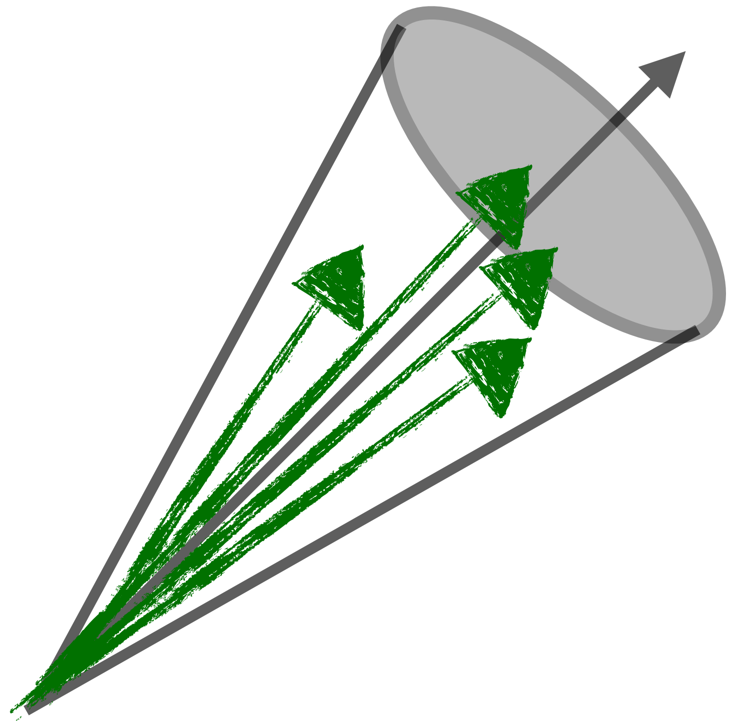
→ Look at the photon tagged R_{AA} to combine expectations (1) and (4).



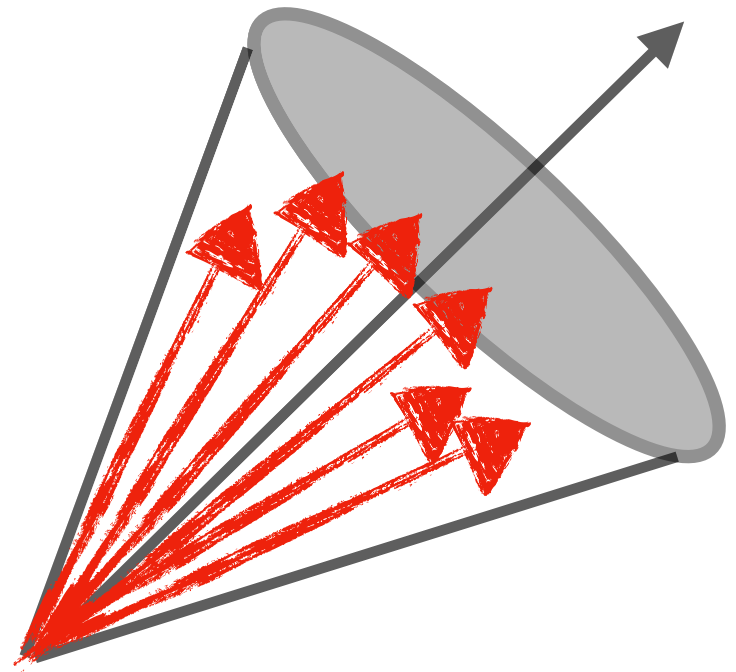


→ Inclusive jets lose more energy than photon-tagged jets (quark dominated).

→ Gluon jets expected to lose more energy than quark jets due to color factors.



$$C_{\mathrm{F}} = \frac{4}{3} < C_{\mathrm{A}} = 3$$



Quark jet

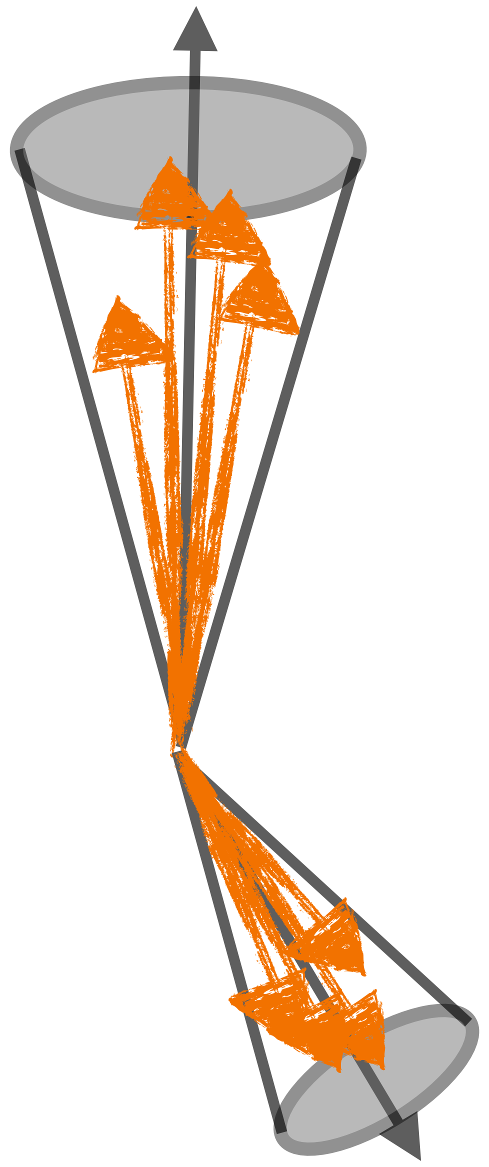
Gluon jet

ATLAS EXPERIMENT

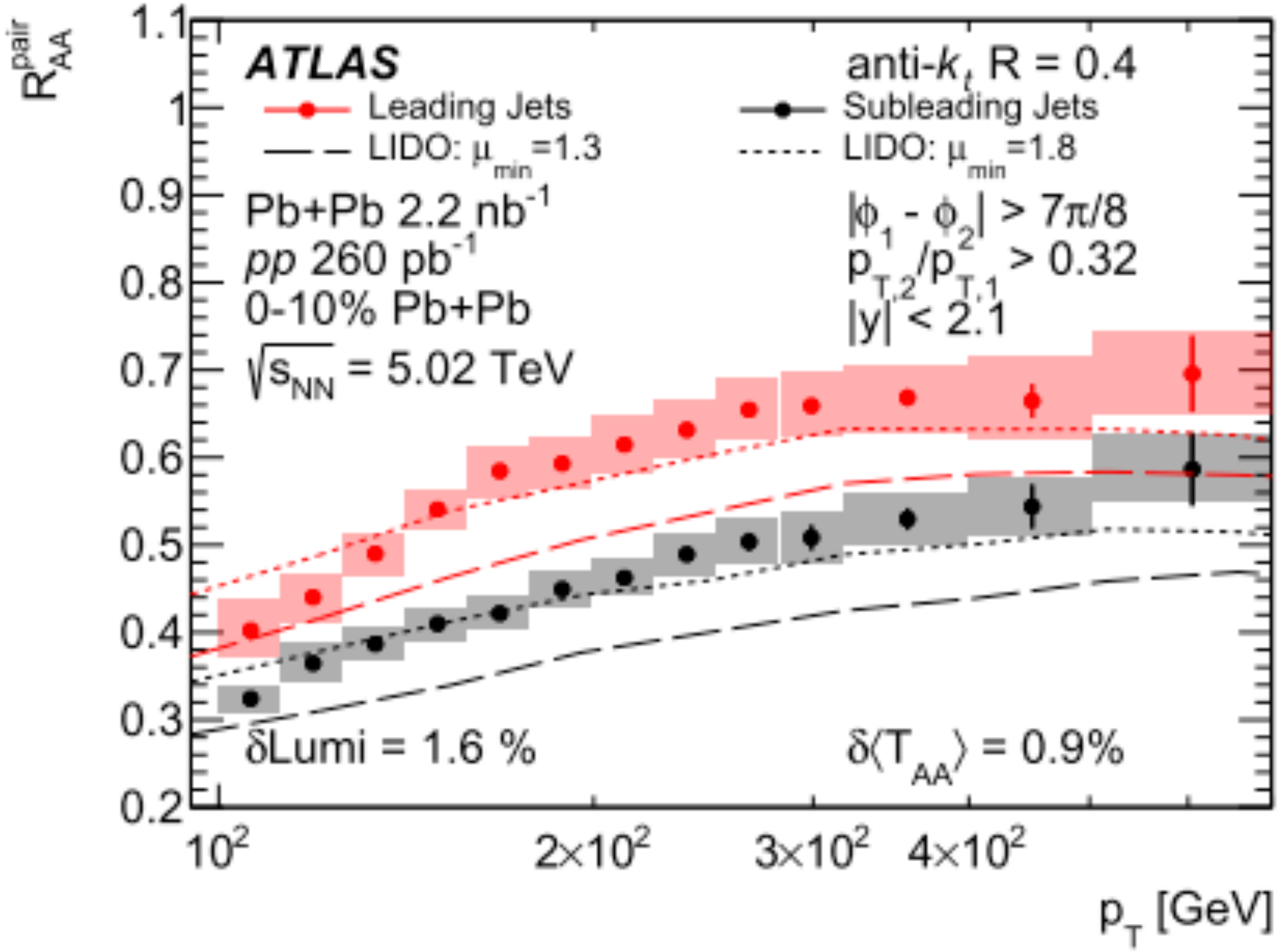
ATLAS-CONF-2022-019

Relative suppression of dijets

- Compare R_{AA} of leading and subleading jets to probe expectations (1) and (4).
- Dijet asymmetry sensitive to path length dependence and fluctuations in energy loss.



Jet-Jet



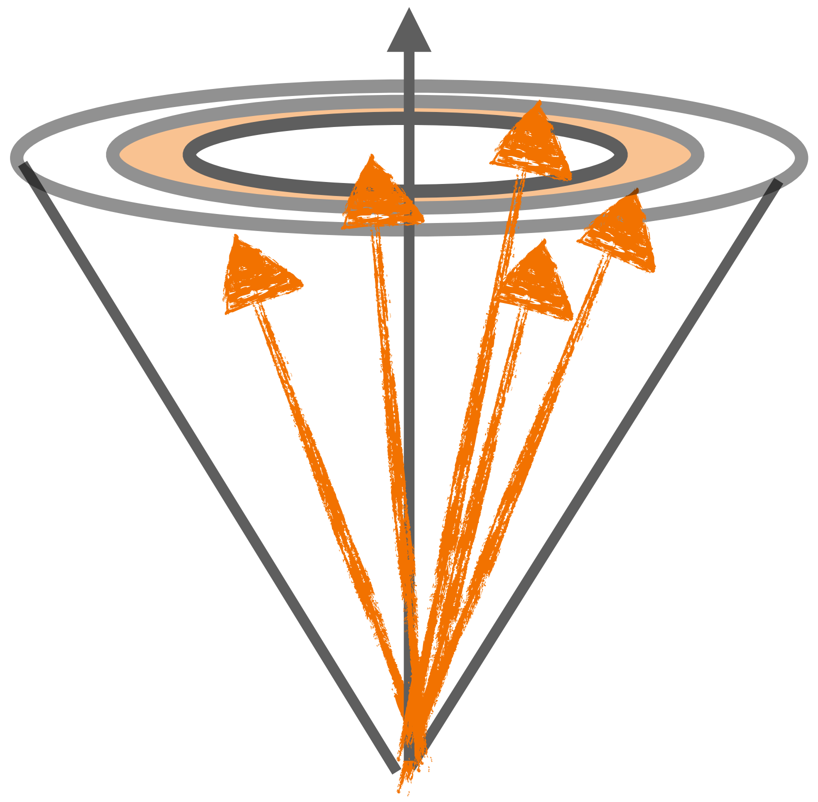
- Subleading jets more suppressed than leading jets.

ATLAS EXPERIMENT

arXiv: 2205.00682

R-dependence of the R_{AA}

- *R*-dependence of the R_{AA} is another way to disentangle energy loss mechanisms.



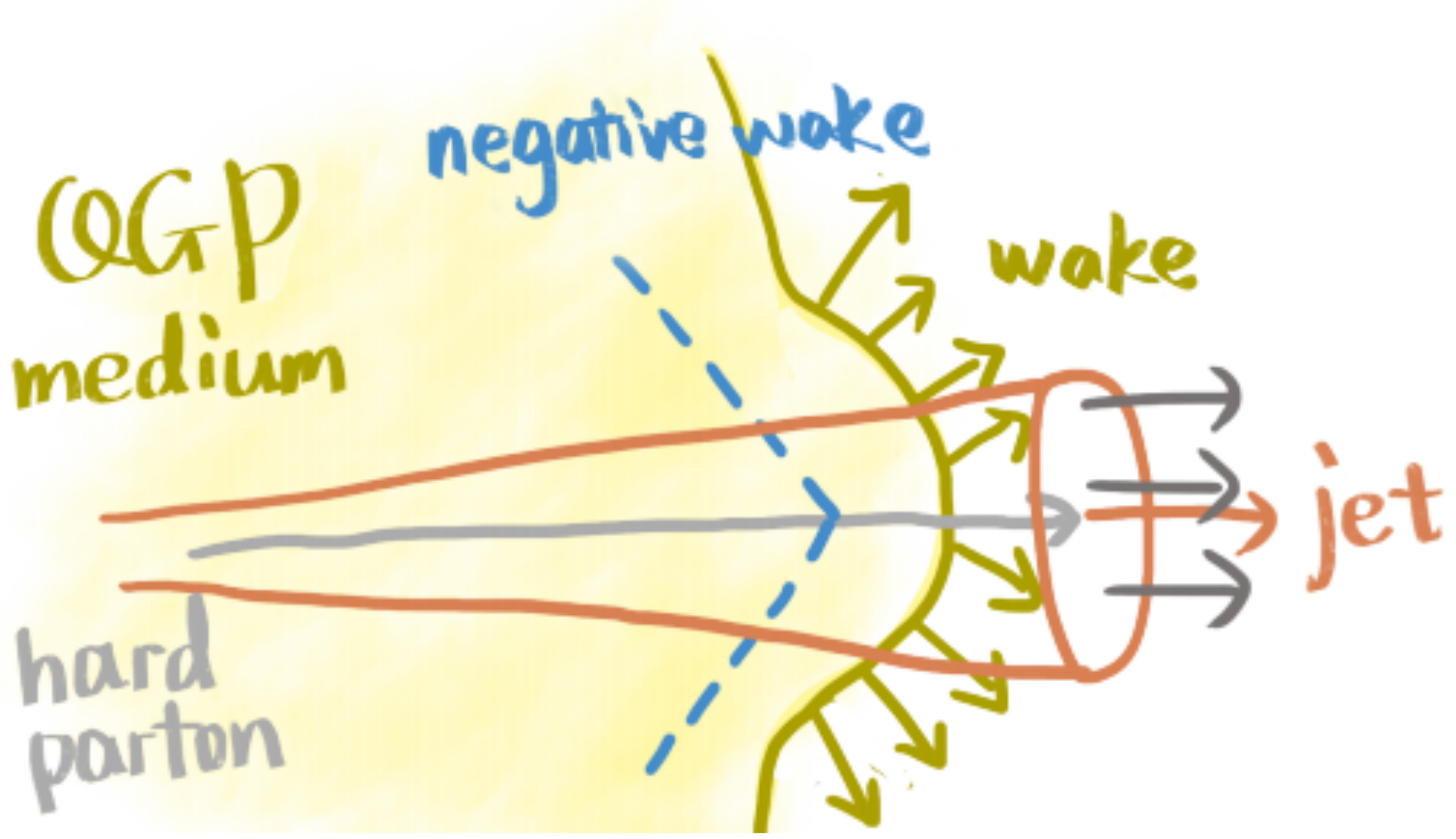


Image Credit:Jing Wang

- Recovery of wide angle radiation $R_{\mathrm{AA}} \nearrow$
- Medium response adds energy to the jet cone $R_{\mathrm{AA}} \nearrow$
- Large *R* jets have more effective energy loss sources, therefore could experience more quenching. $R_{\mathrm{AA}} \searrow$
- Increase gluon to quark ratio at fixed p_{T}, gluons lose more energy $R_{\mathrm{AA}} \searrow$

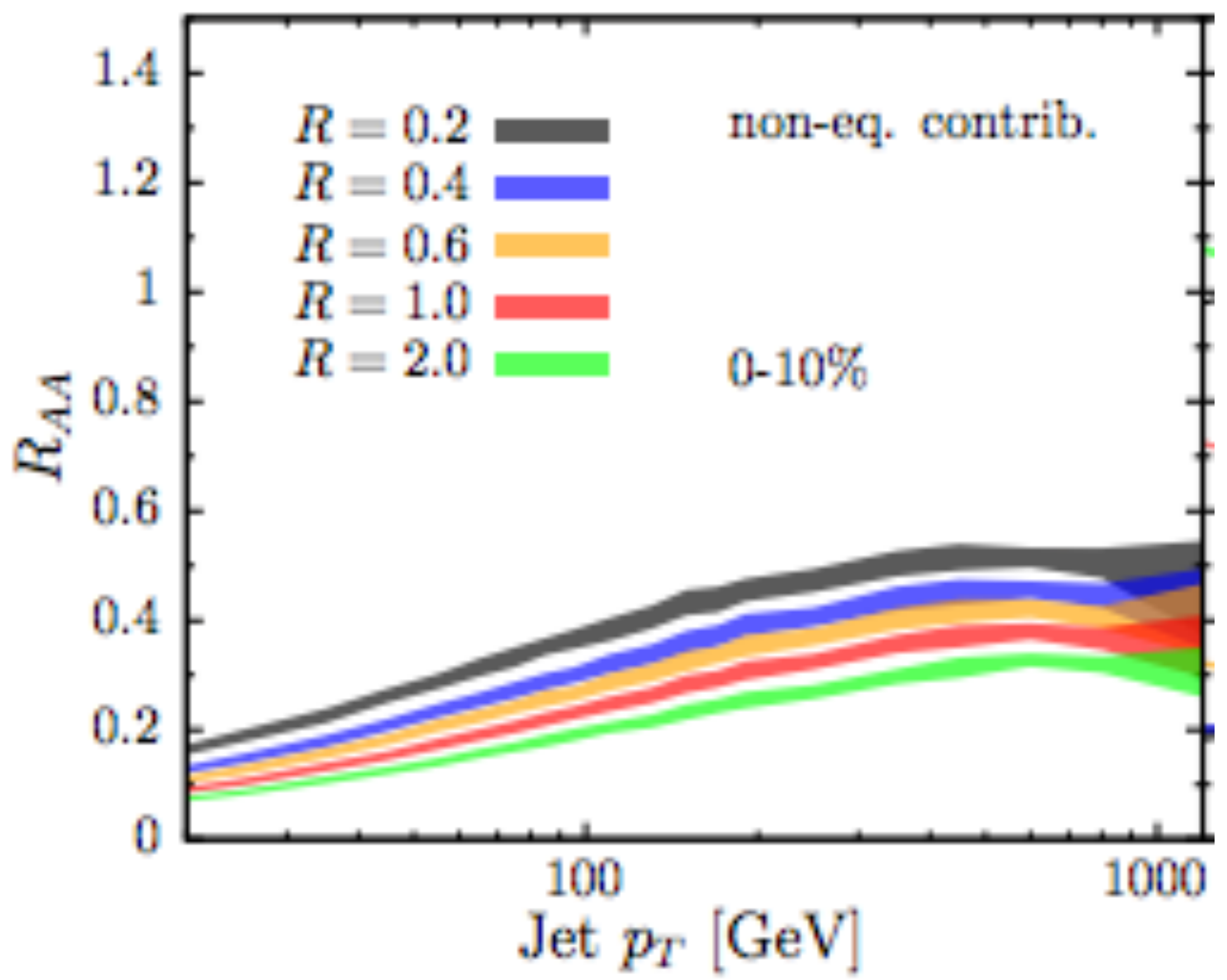
- These measurements rely on ability to measure large range in *R* and p_{T}!

What does theory say? (1/3)

→ Some models have R_{AA} decreasing with R, reflects increased gluon to quark ratio and wider jets losing more energy.

Hybrid Model with No Medium Effects

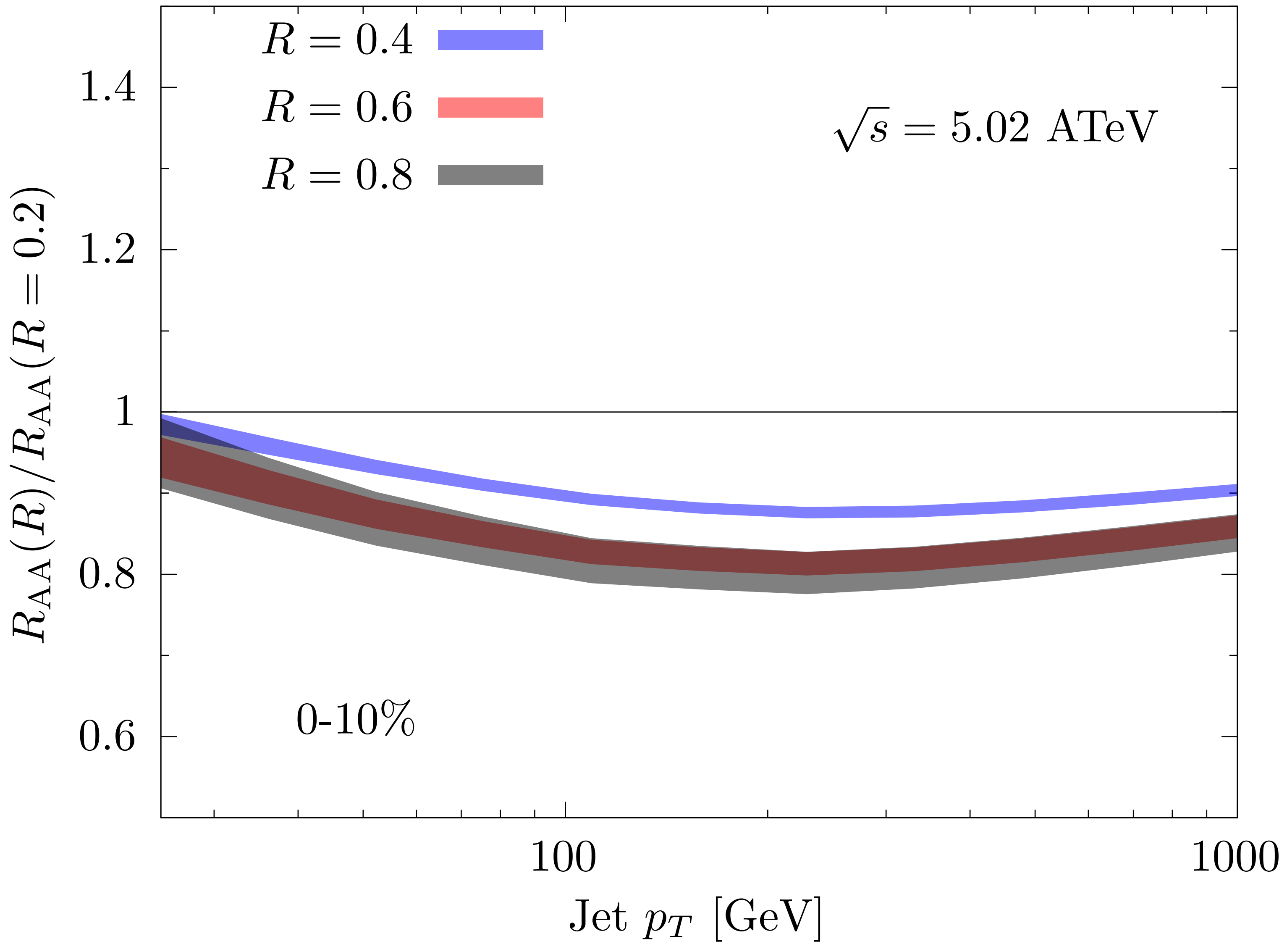
AdS/CFT non-pert. regime.



Phys. Rev. Lett. 124, 052301 (2020)

Mehtar-Tani et. al

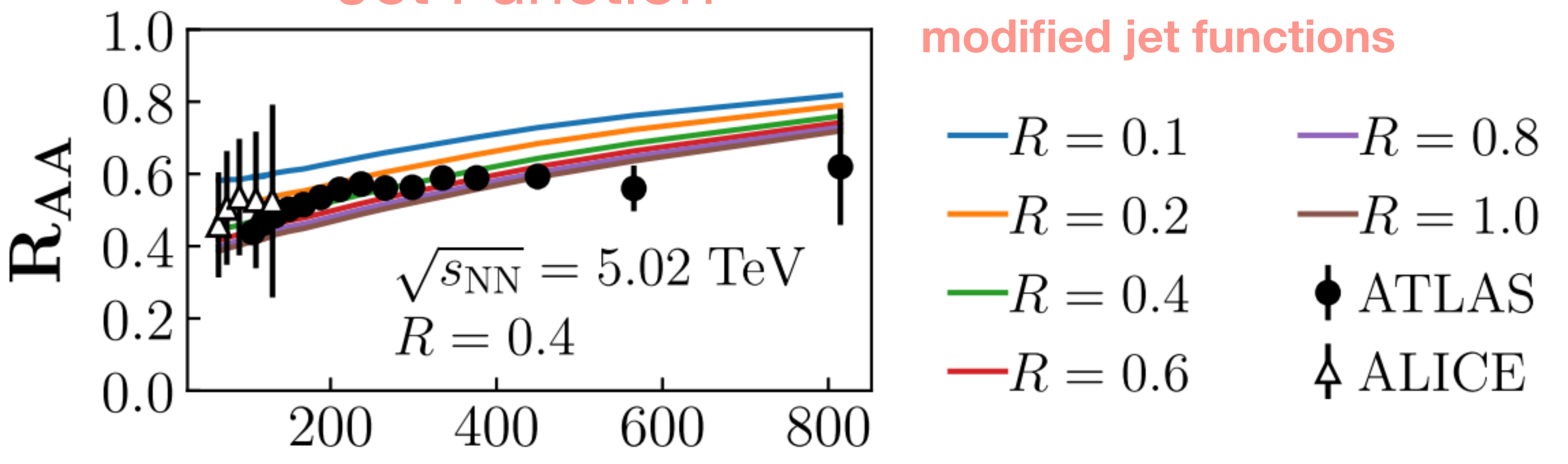
Analytical calculation with resummation of energy loss from vacuum-like emissions includes soft energy flow and recovery.



Phys. Rev. Lett. 127, 252301 (2021)

Jet Function

Factorization formalism with medium-modified jet functions



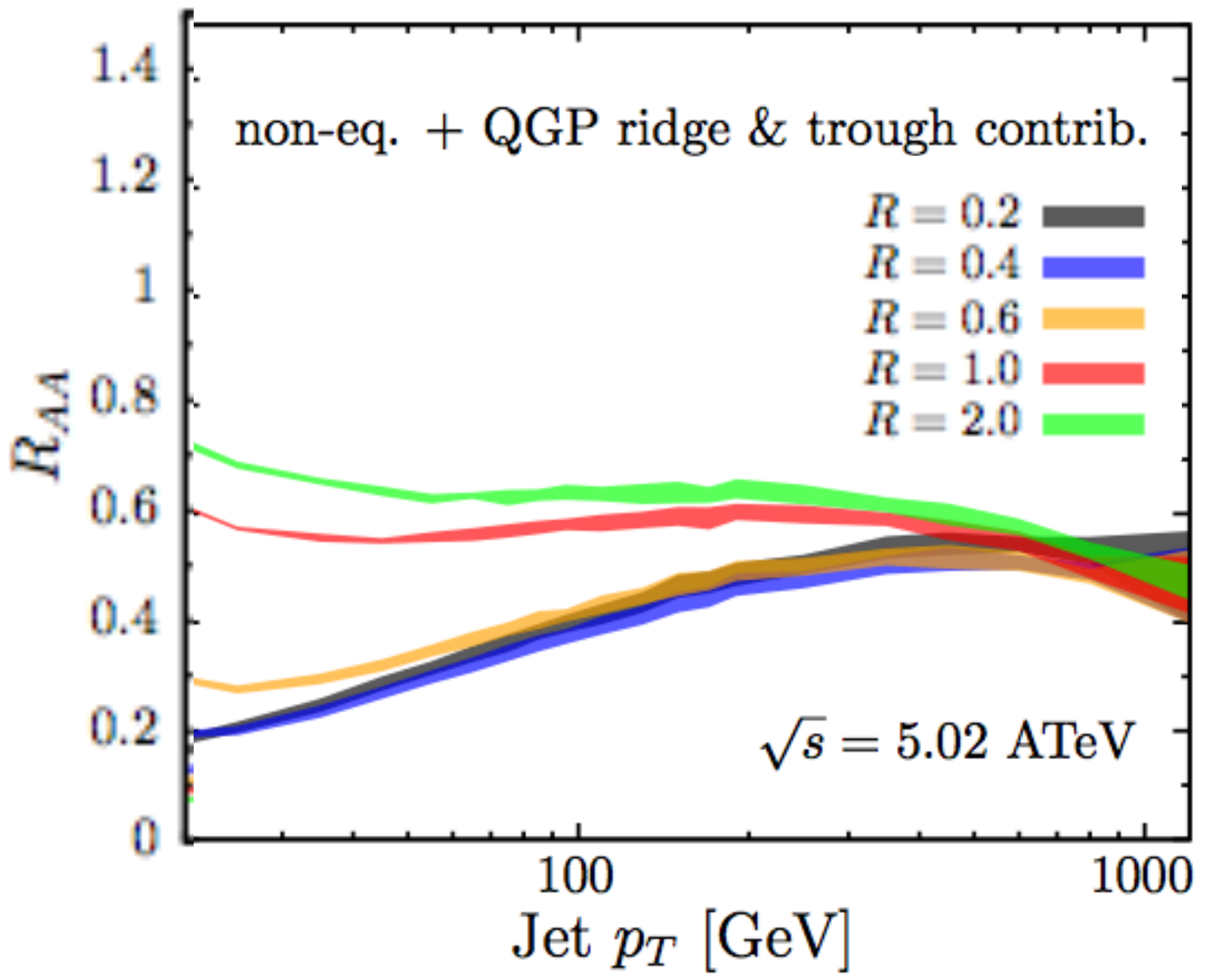
Phys.Rev. Lett. 122, 252301 (2019)

What does theory say? (2/3)

→ Some models have R_{AA} increasing with R, reflects increased recovery of energy and influence of the medium response.

Hybrid Model with Medium Effects

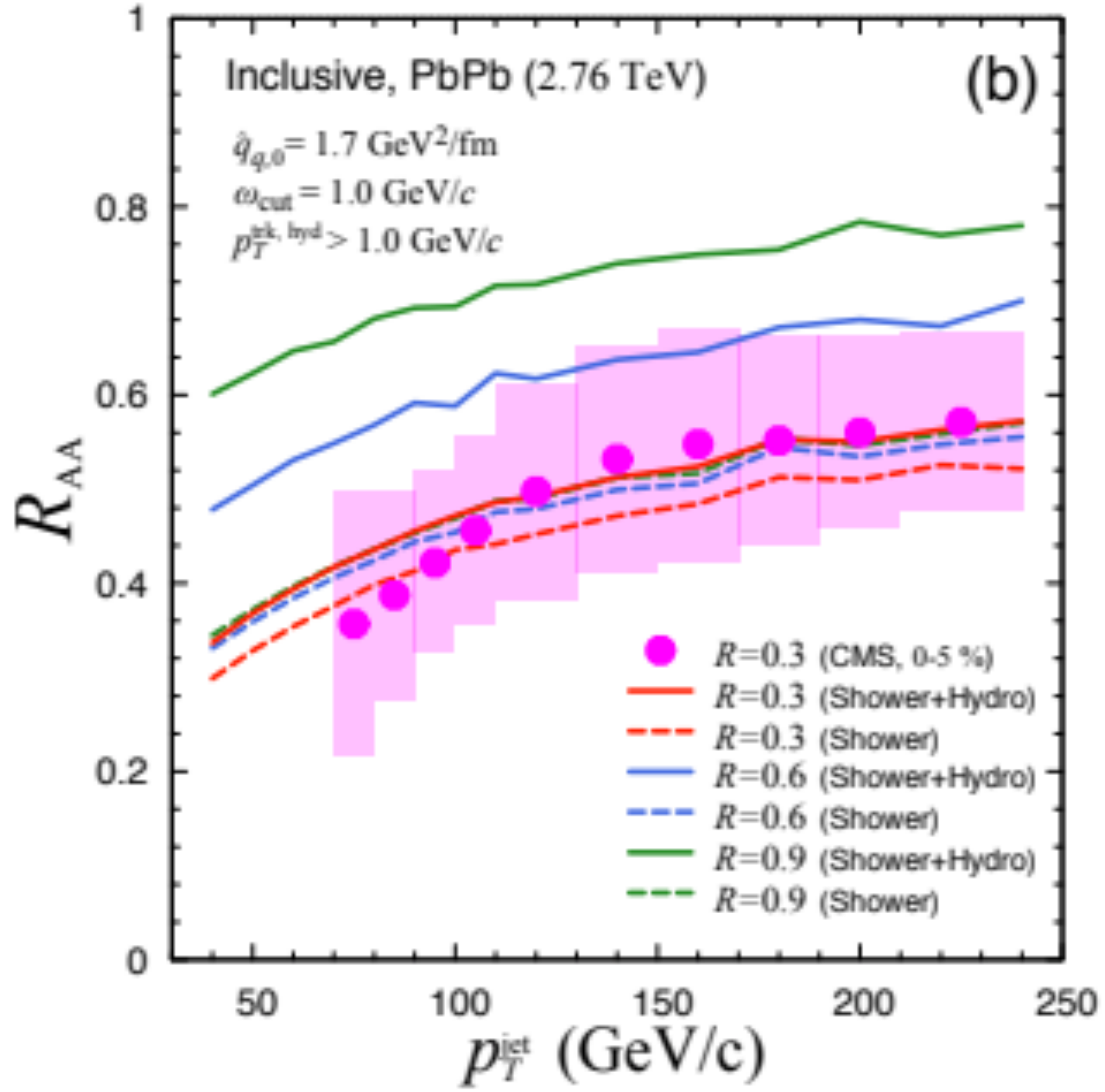
Medium response via wake. AdS/CFT non-pert. regime.



Phys. Rev. Lett. 124, 052301 (2020)

CCNU

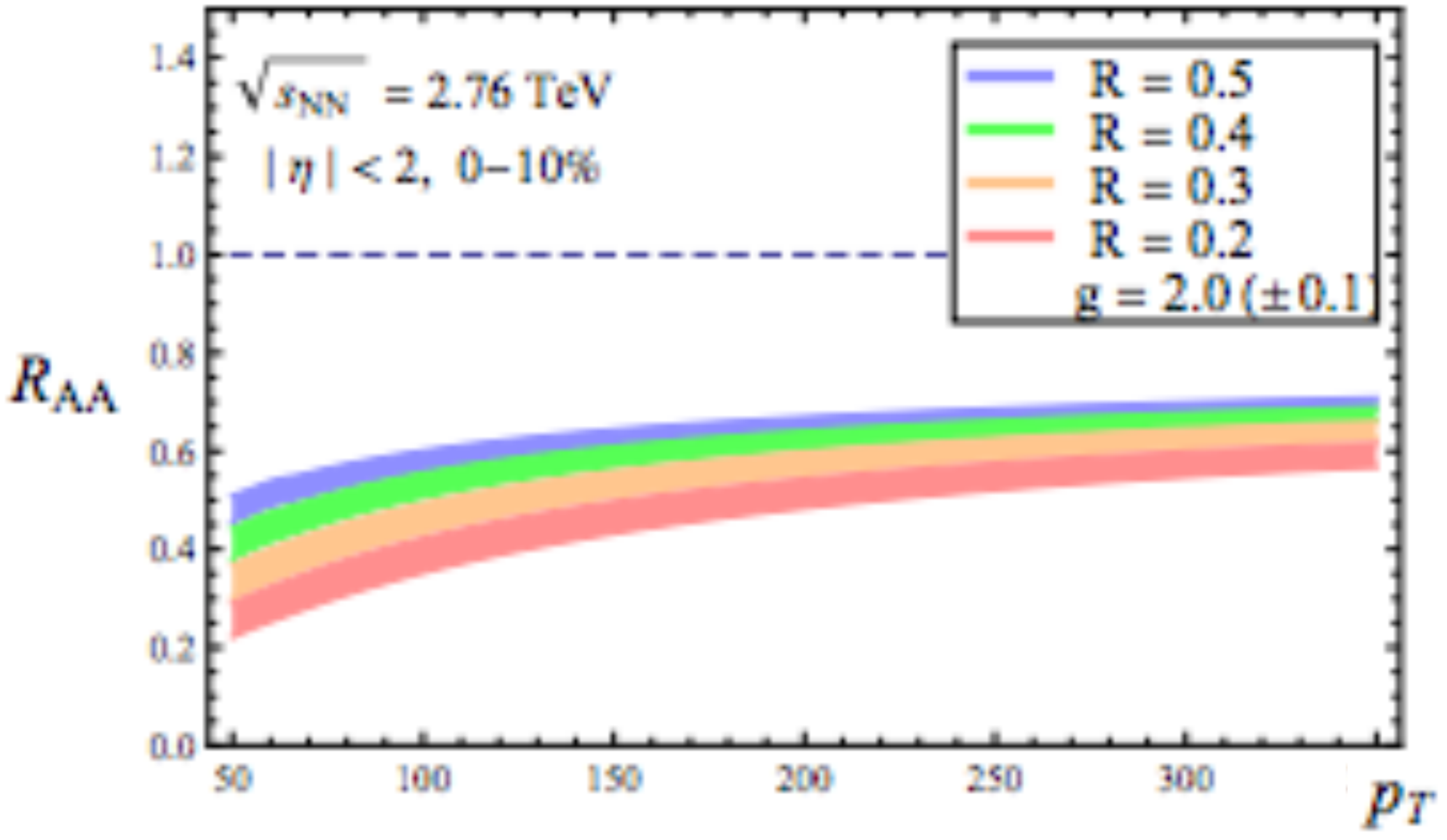
Jet-fluid model with jet transport and relativistic hydrodynamics.



Phys. Rev. C 95, 044909 (2017)

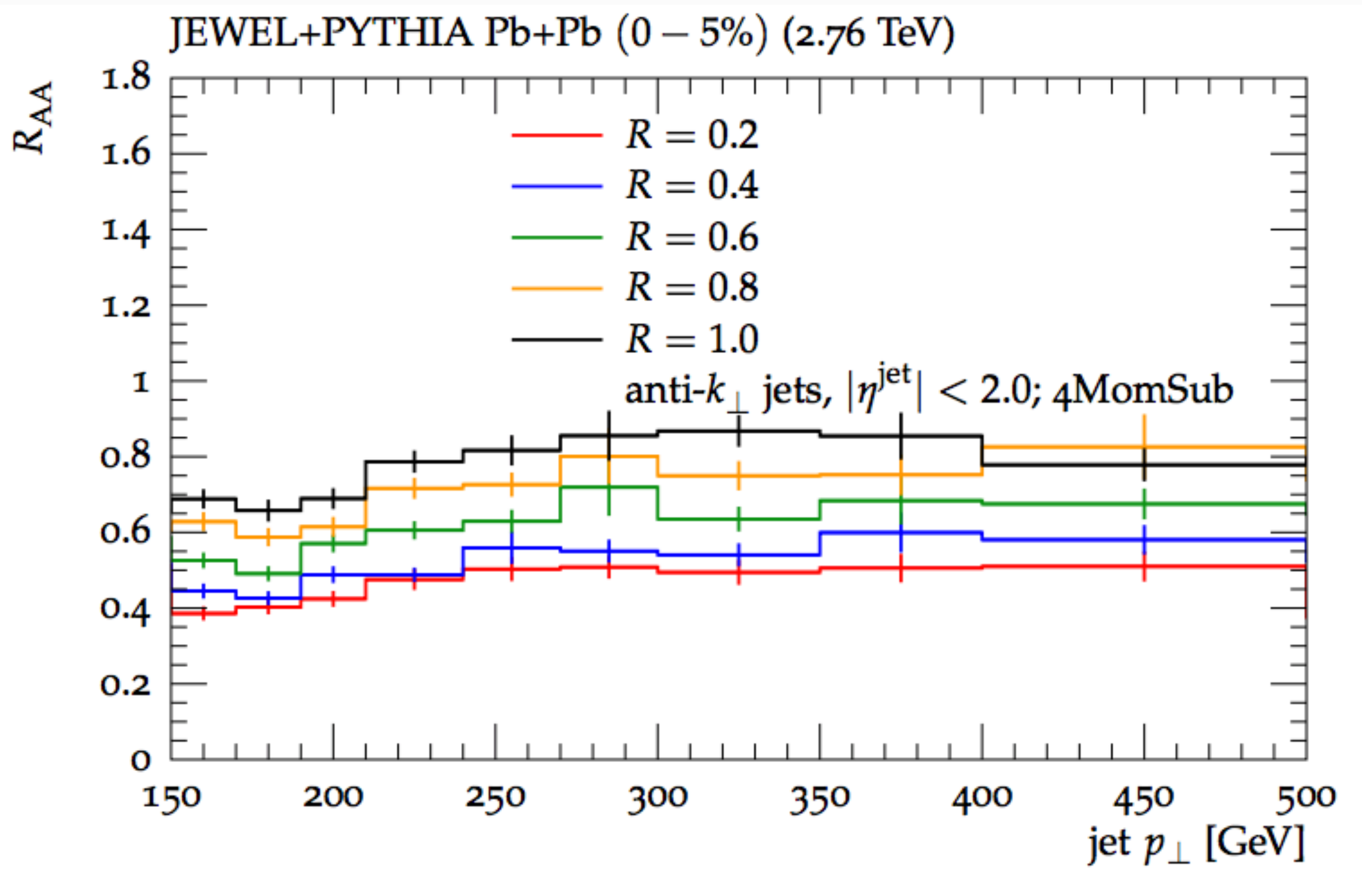
SCETg JHEP05(2016)023

Medium interactions mediated by Glauber gluon exchange.



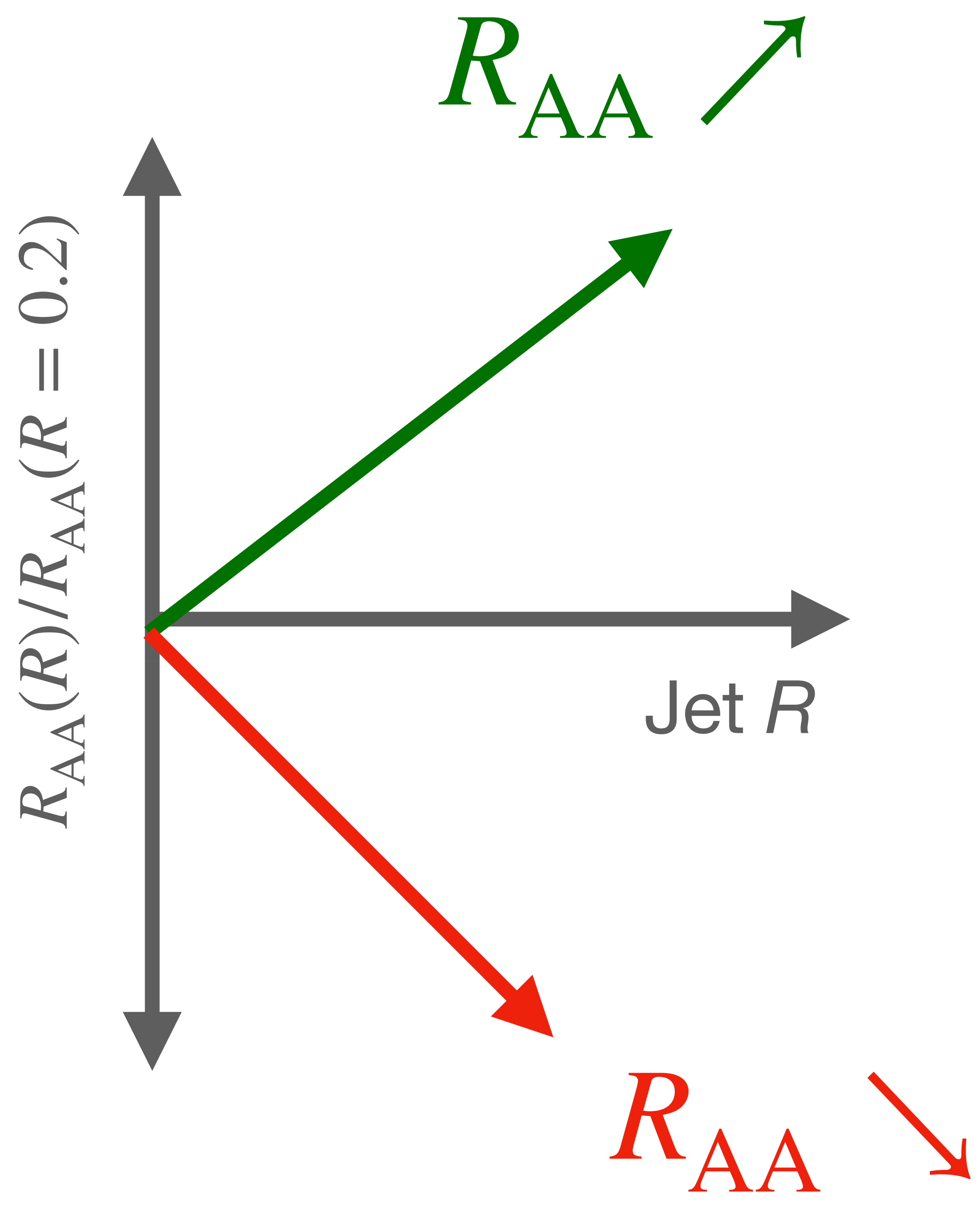
JEWEL JHEP 1707 (2017) 141

Scattering and radiative energy loss with and without recoiling medium.



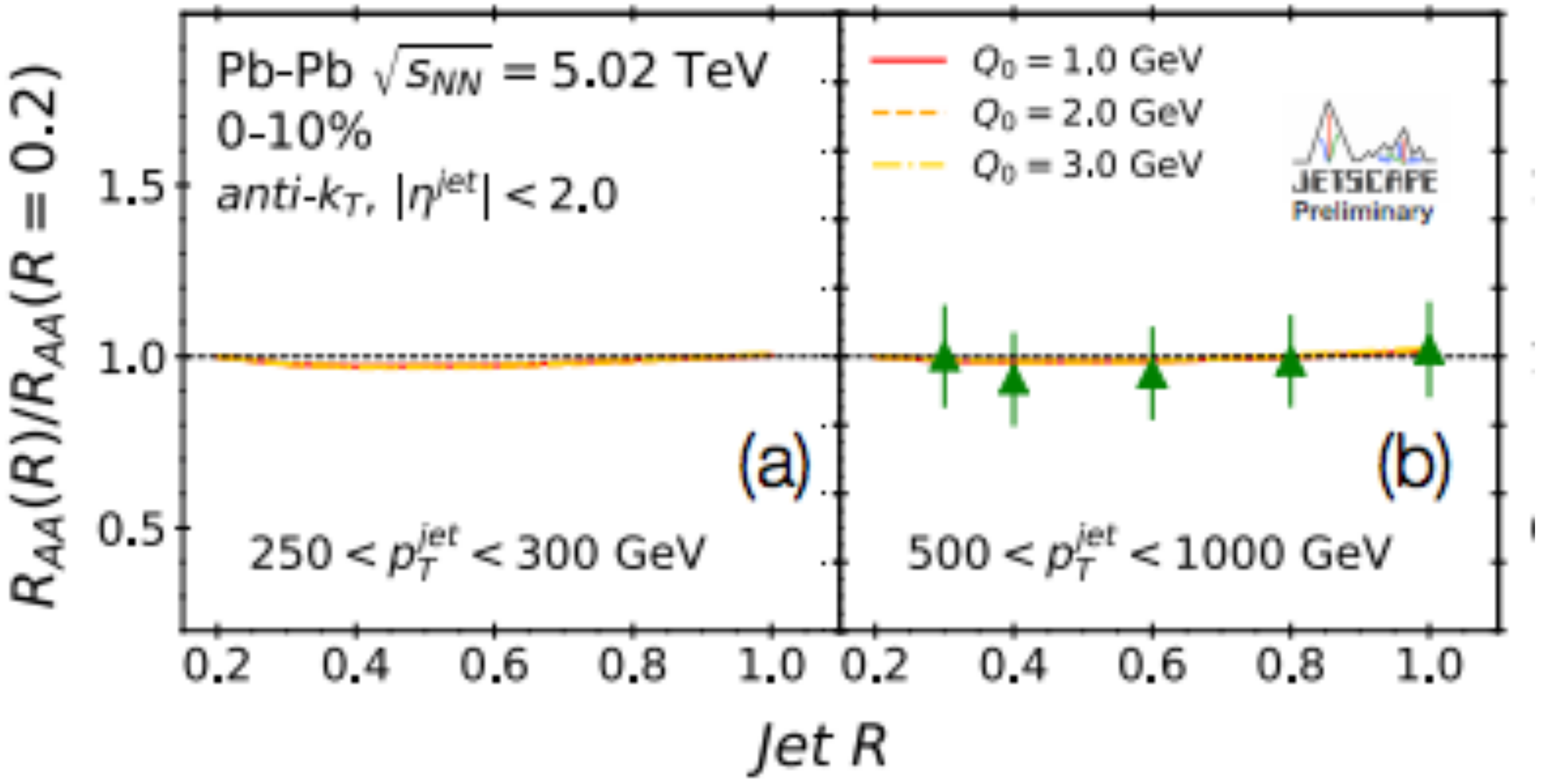
What does theory say? (3/3)

→ Some models have R_{AA} constant with R, reflects some cancellation of effects.



JETSCAPE

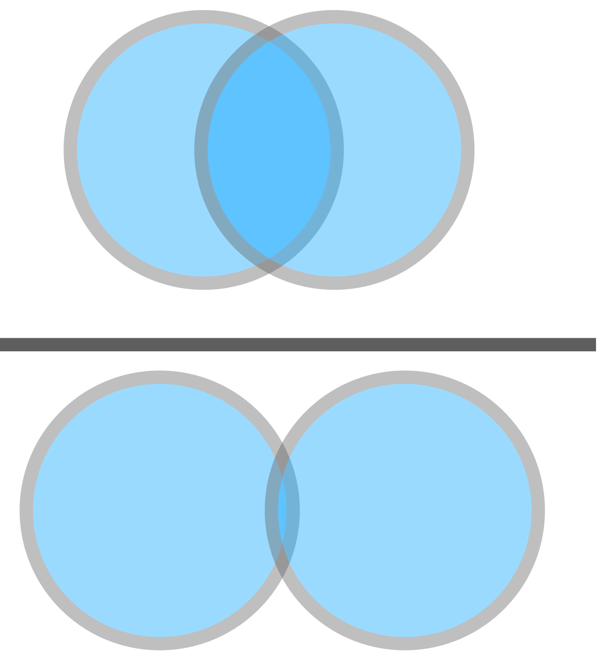
(MATTER + LBT) $\hat{q}(E,T,Q^2)$



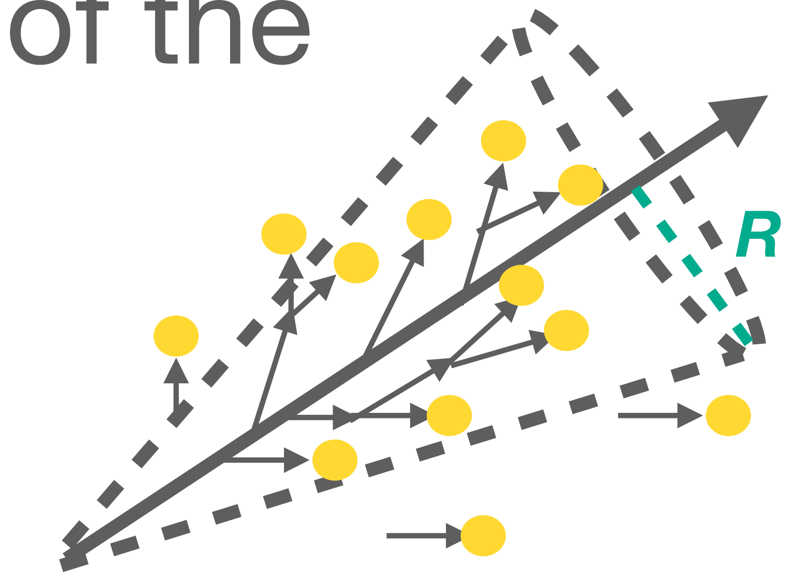
Theory is undecided (very discriminative observable) - what does experiment say?

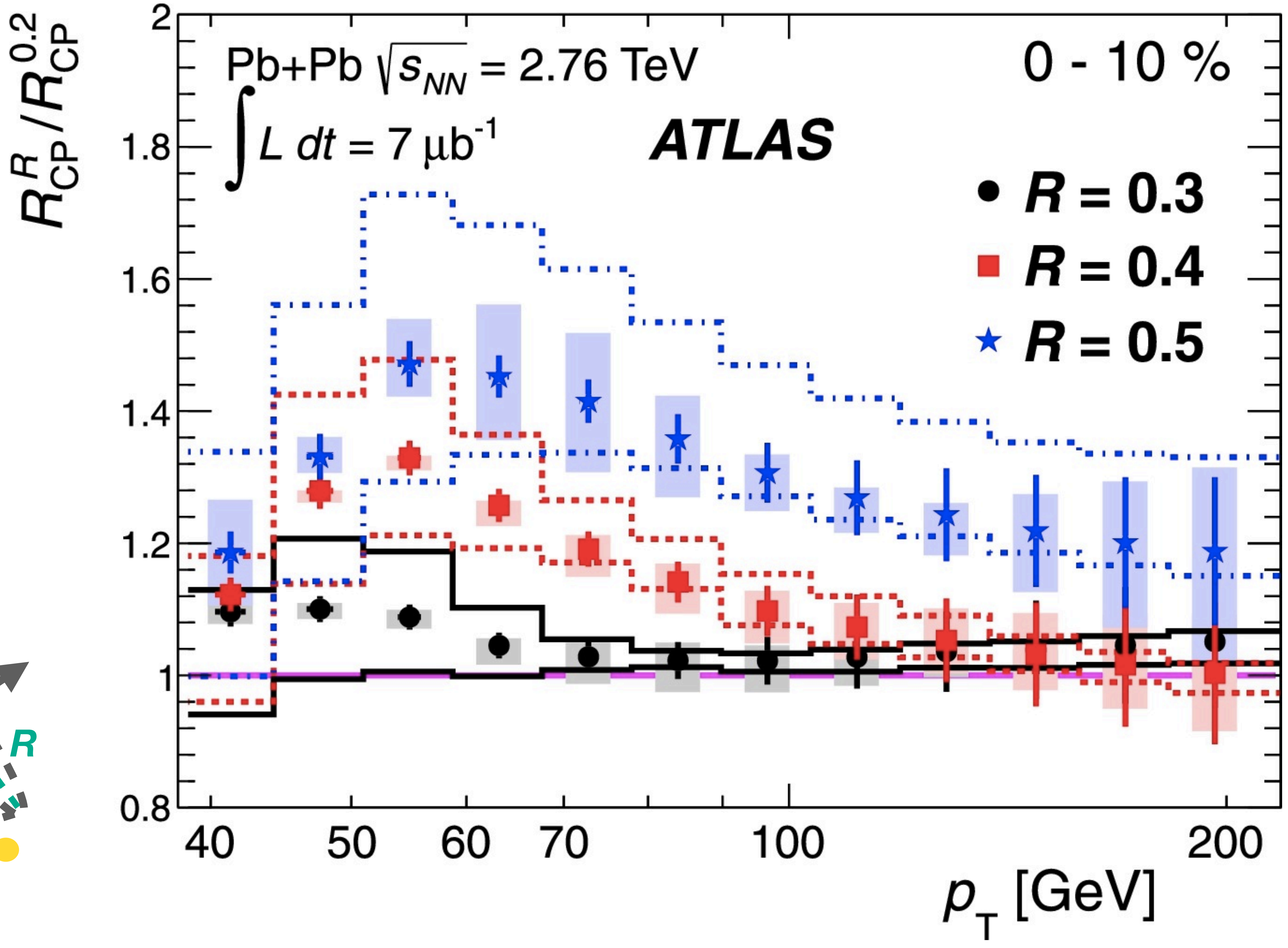
ATLAS *R*-Dependence of the R_{cp}

$R_{cp} =$



- ATLAS has a measurement of the *R*-dependence of the R_{cp} at 2.76 TeV.
- Not exactly quantitatively comparable to the R_{AA}, but qualitatively another important measurement of suppression.
- Shows an increase in the R_{cp} with increasing *R*, reflects recovery of energy and increased influence of the medium response.



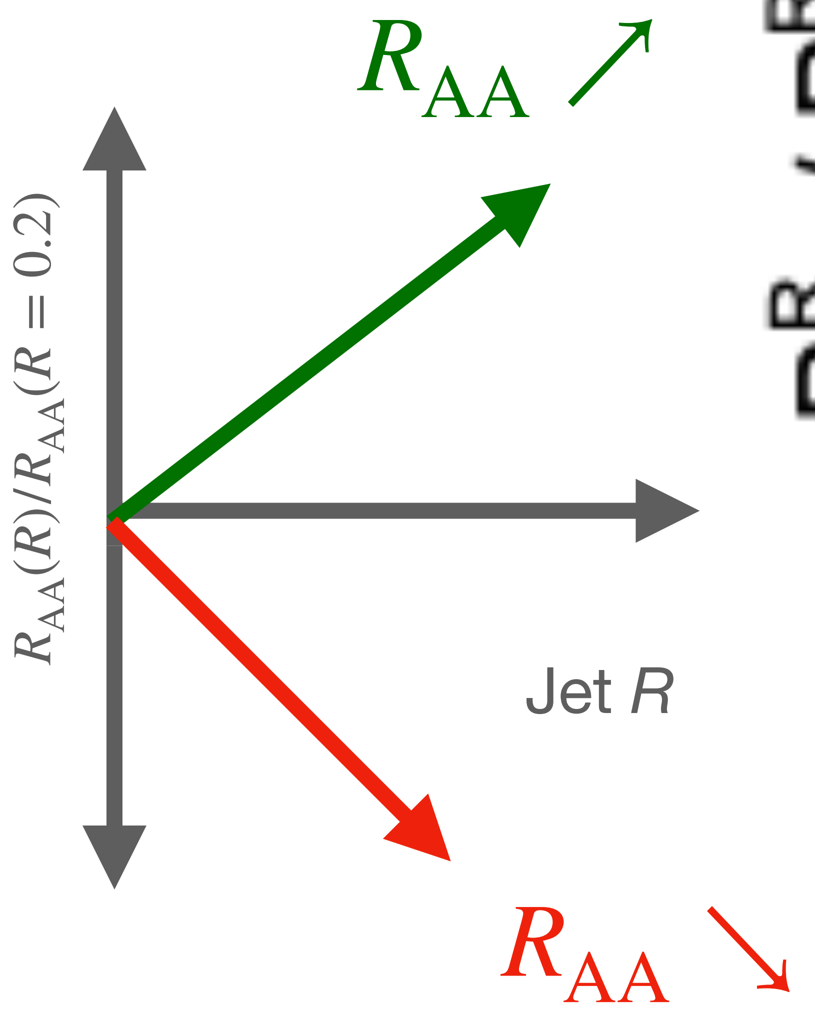


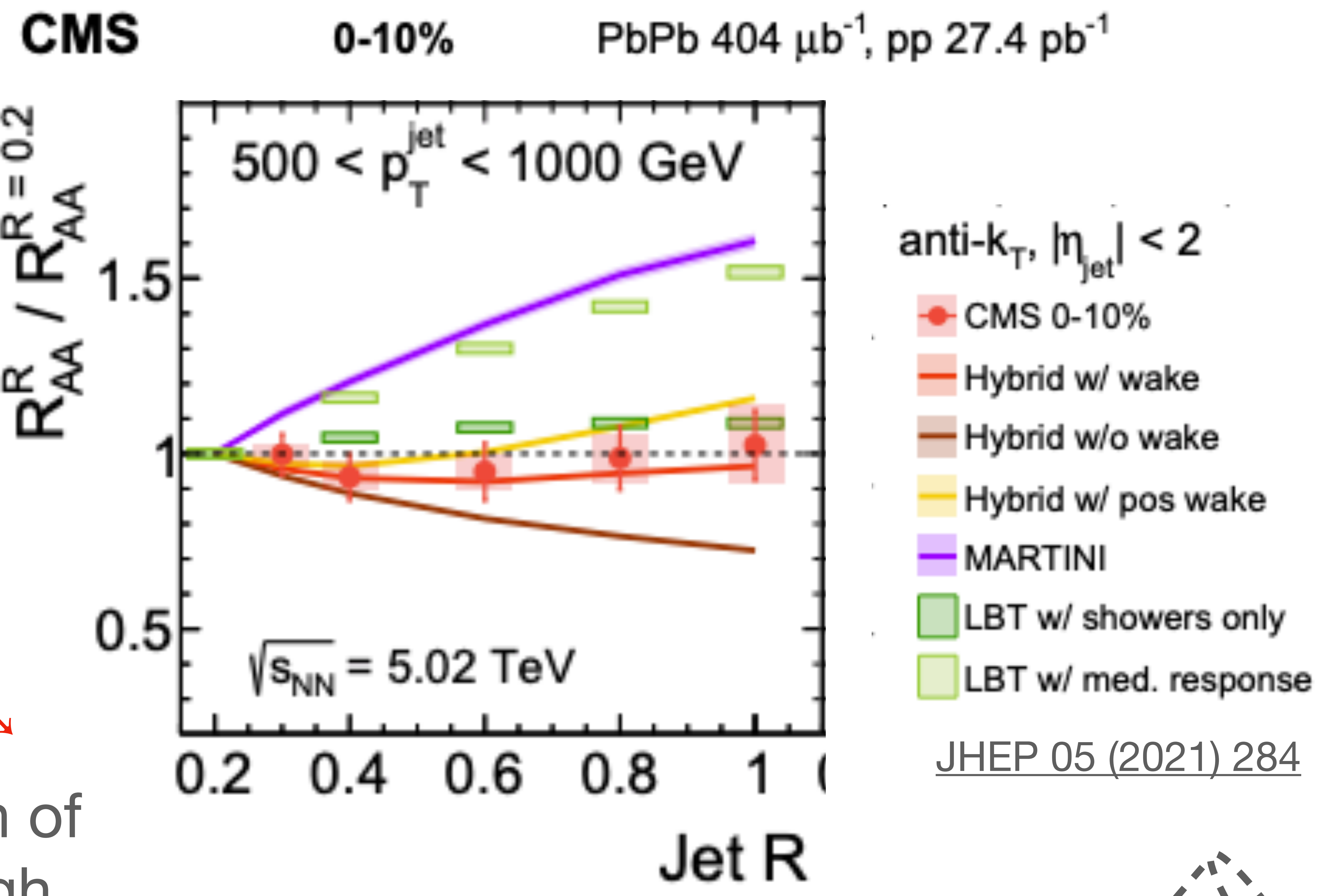
Phys. Lett. B 719 (2013) 220-241

CMS *R*-Dependence of the R_{AA}

- The CMS experiment was able to measure out to R = 1.0 by measuring jets at very high p_T, where the background has less of an effect.

- **No visible *R*-dependence,** consistent with the cancellation of effects.





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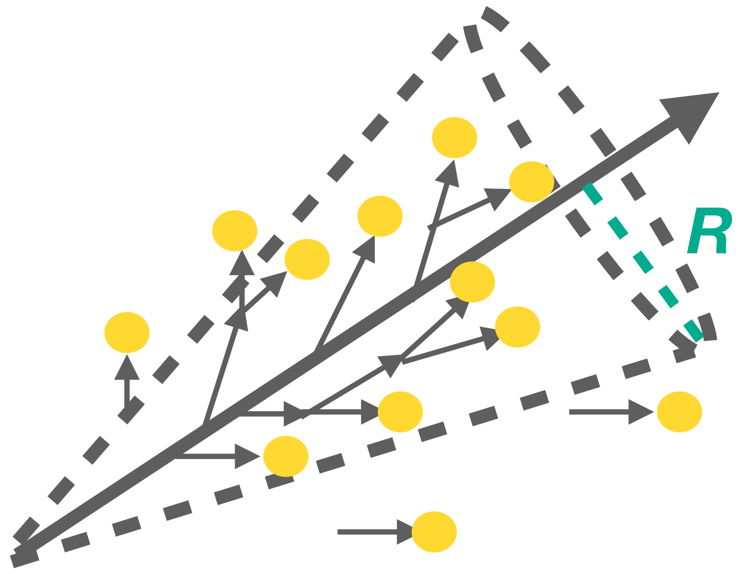
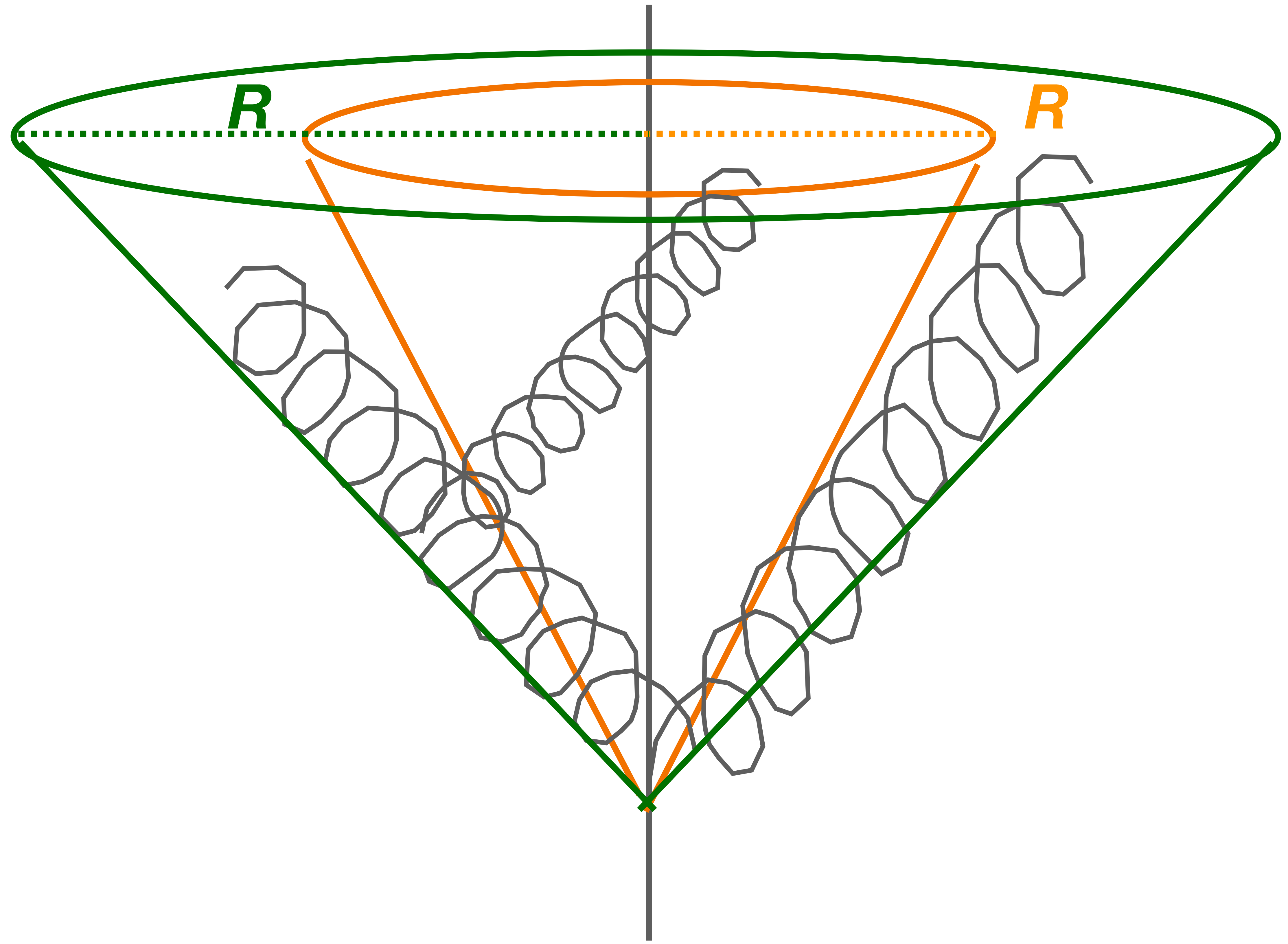
- Because models vary in their prediction of the *R*-dependence, this variable has high discriminating power!

What does lower p_T indicate? Could we measure this with ALICE?



Measuring large *R* jets at low p_T

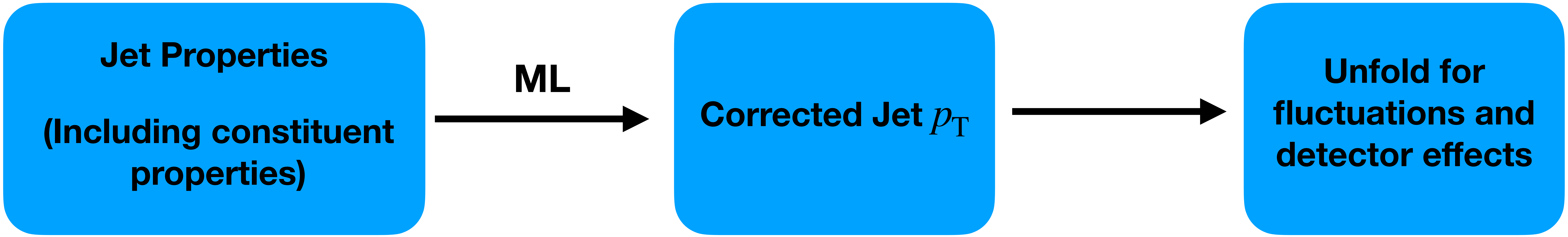


- Large *R* jets are expected to recover radiation that occurs outside of the small *R* jet cone.
- Large *R* jets have a more complex substructure and could lose more energy.
- These jets are difficult to measure due to the larger background! (Proportional to R^2)

- This is especially true at lower p_T where the background can be on the order of the jet p_T itself! Need new techniques to make these measurements in ALICE!

ML background estimator

- **ML approach:** Use ML to construct the mapping between measured and corrected jet.



- Keep the models simple from an ML-perspective (shallow NNs, minimal set of variables), for transparency and to reduce biases on the training sample.

Goal is to use ML to reduce the residual fluctuations remaining after background subtraction, making measurements at large R and low p_T possible.

R.Haake, C. Loizides Phys. Rev. C 99, 064904 (2019)

Features for training

Ask ourselves two questions

How important is the feature to the model? → Feature Scores

Higher the feature score, more often variable is used in training.

How correlated is the feature with other features?

Feature	Score	Feature	Score
Jet p_{T} (no corr.)	**0.1355**	$p^1_{\mathrm{T,const}}$	0.0012
Jet mass	0.0007	$p^2_{\mathrm{T,const}}$	**0.0039**
Jet Area	0.0005	$p^3_{\mathrm{T,const}}$	0.0015
Jet p_{T} (area based corr.)	**0.7876**	$p^4_{\mathrm{T,const}}$	0.0011
LeSub	0.0004	$p^5_{\mathrm{T,const}}$	0.0009
Radial moment	0.0005	$p^6_{\mathrm{T,const}}$	0.0009
Momentum dispersion	0.0007	$p^7_{\mathrm{T,const}}$	0.0008
Number of constituents	0.0008	$p^8_{\mathrm{T,const}}$	0.0007
Mean of constituent p_{T}s	**0.0585**	$p^9_{\mathrm{T,const}}$	0.0006
Median of Constituent p_{T}s	0.0023	$p^{10}_{\mathrm{T,const}}$	0.0007

Iteratively remove unimportant or highly correlated features!

R.Haake, C. Loizides Phys. Rev. C 99, 064904 (2019)

Process

Training

Train on "hybrid event" created by embedding jets from simulation (PYTHIA) into Pb-Pb Background

Shallow neural network

Testing

Apply ML estimator to events not used in training.

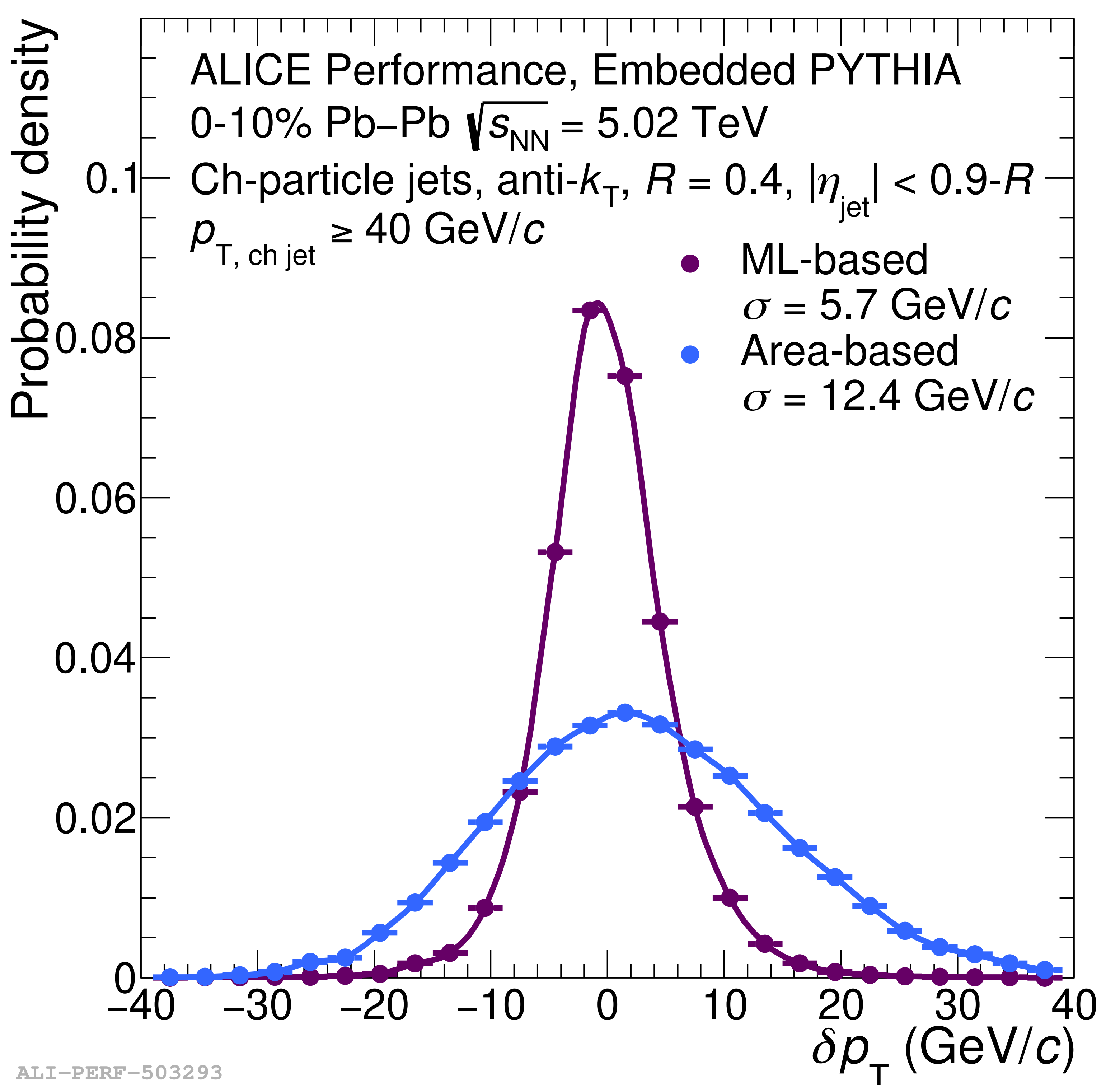
Key is that this background is *realistic.*

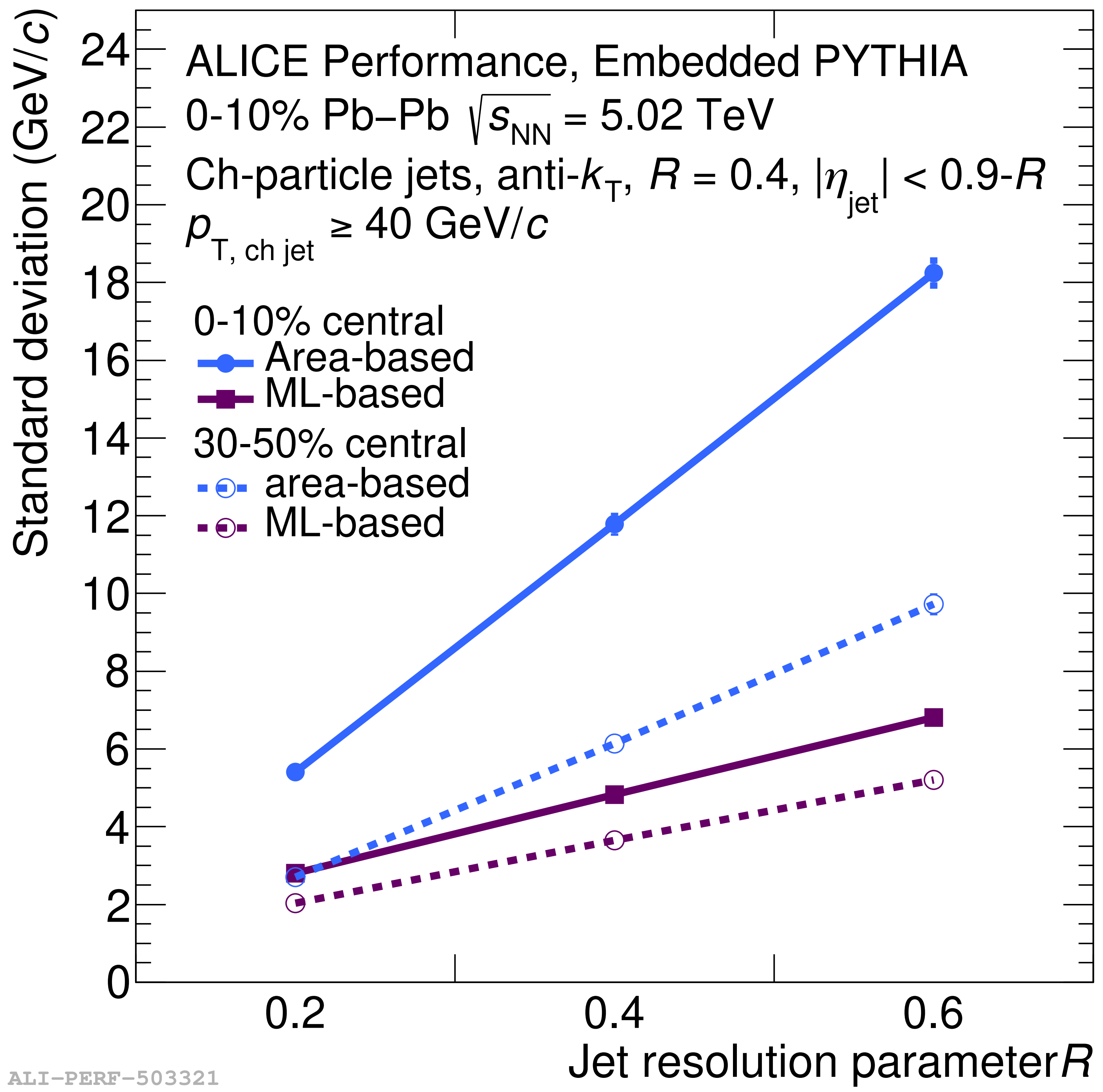
Do we get back the signal we put in?

Testing performance

→ Test if we are getting closer to the "truth"(PYTHIA detector level jet p_T) with

$$\delta p_T = p_{T,rec} - p_{T,true}$$



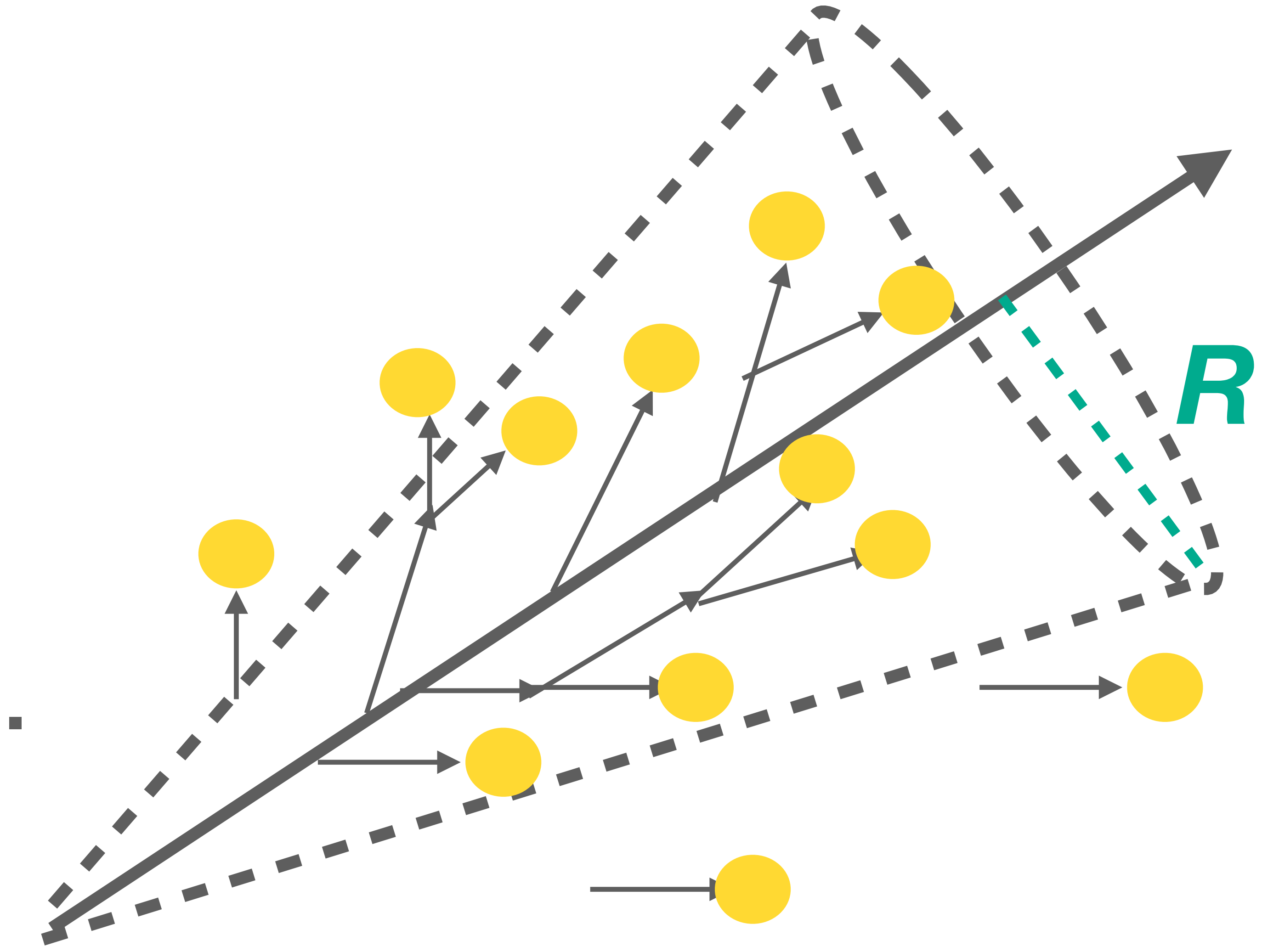


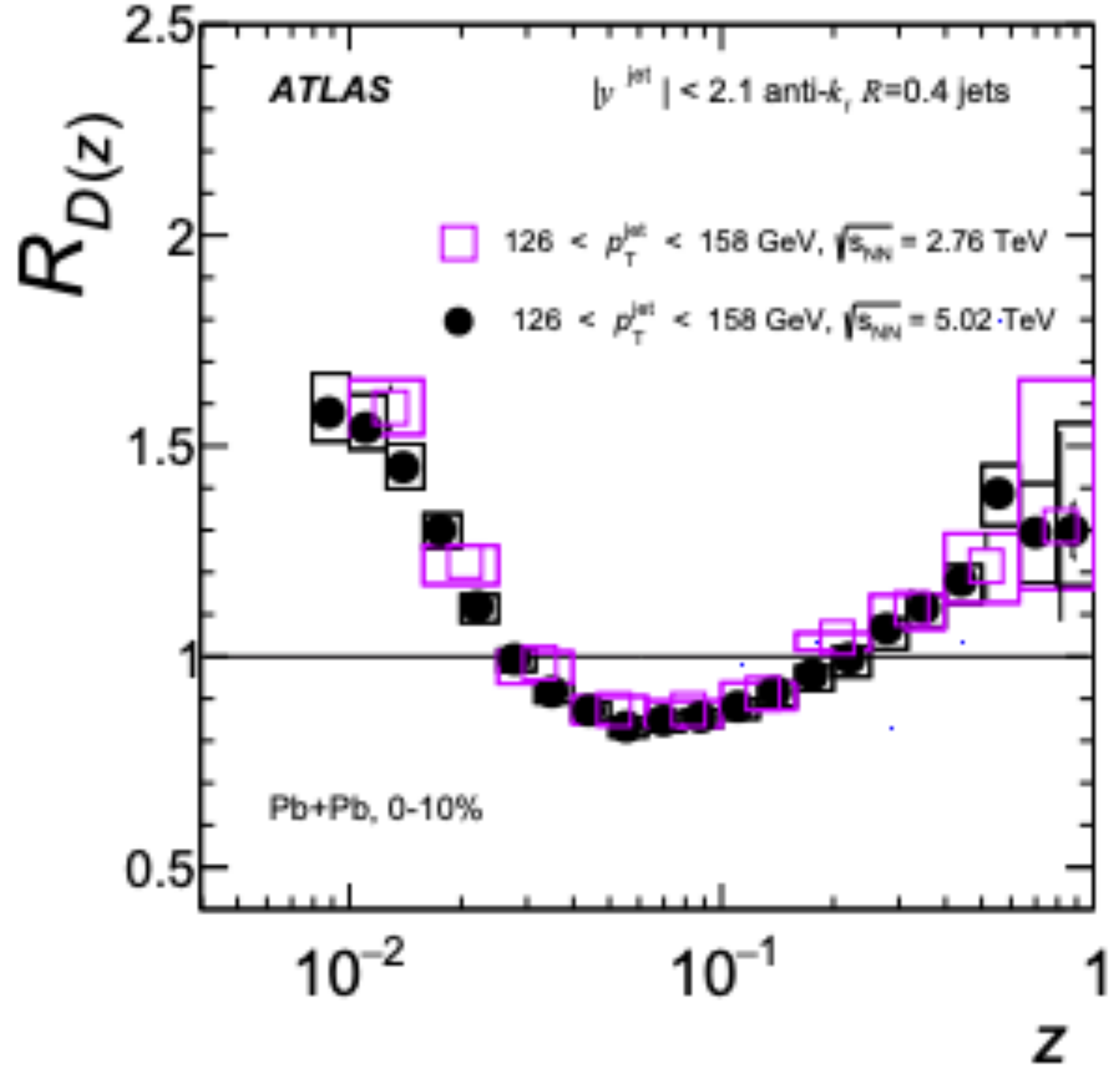
→ Narrowing of this distribution corresponds to a reduction of residual fluctuations.

ML based method has significantly reduced residual fluctuations as compared to the area-based method!

Fragmentation bias

- Learning on constituent information in training creates a dependence on how those constituents are distributed in the jet (fragmentation).
- We train on PYTHIA fragmentation (no QGP effects).





- We know that the fragmentation is modified by the presence of the medium.
- We want to investigate how this impacts the final result that we get with ML!

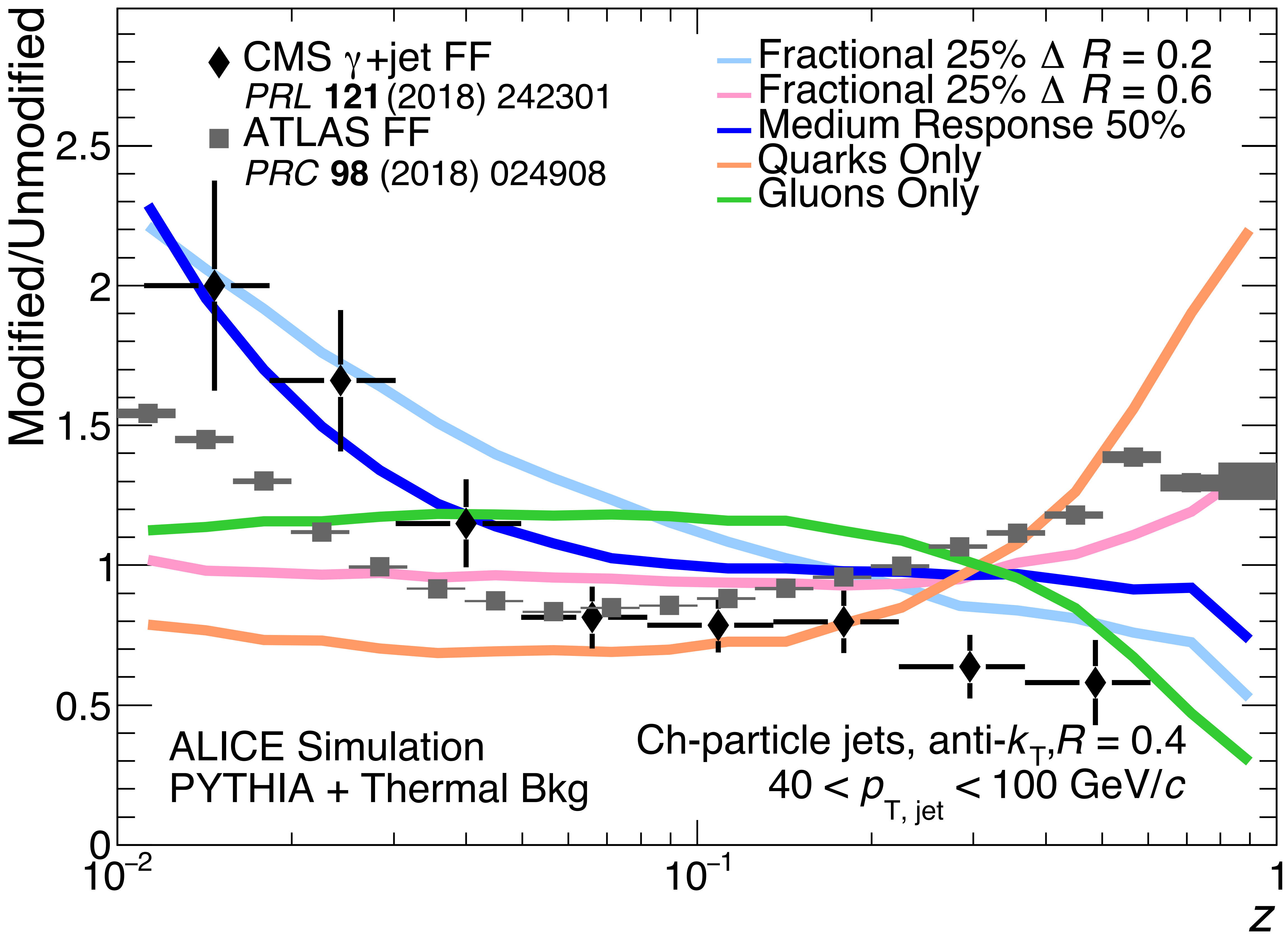
Phys. Rev. C 98, 024908 (2018)

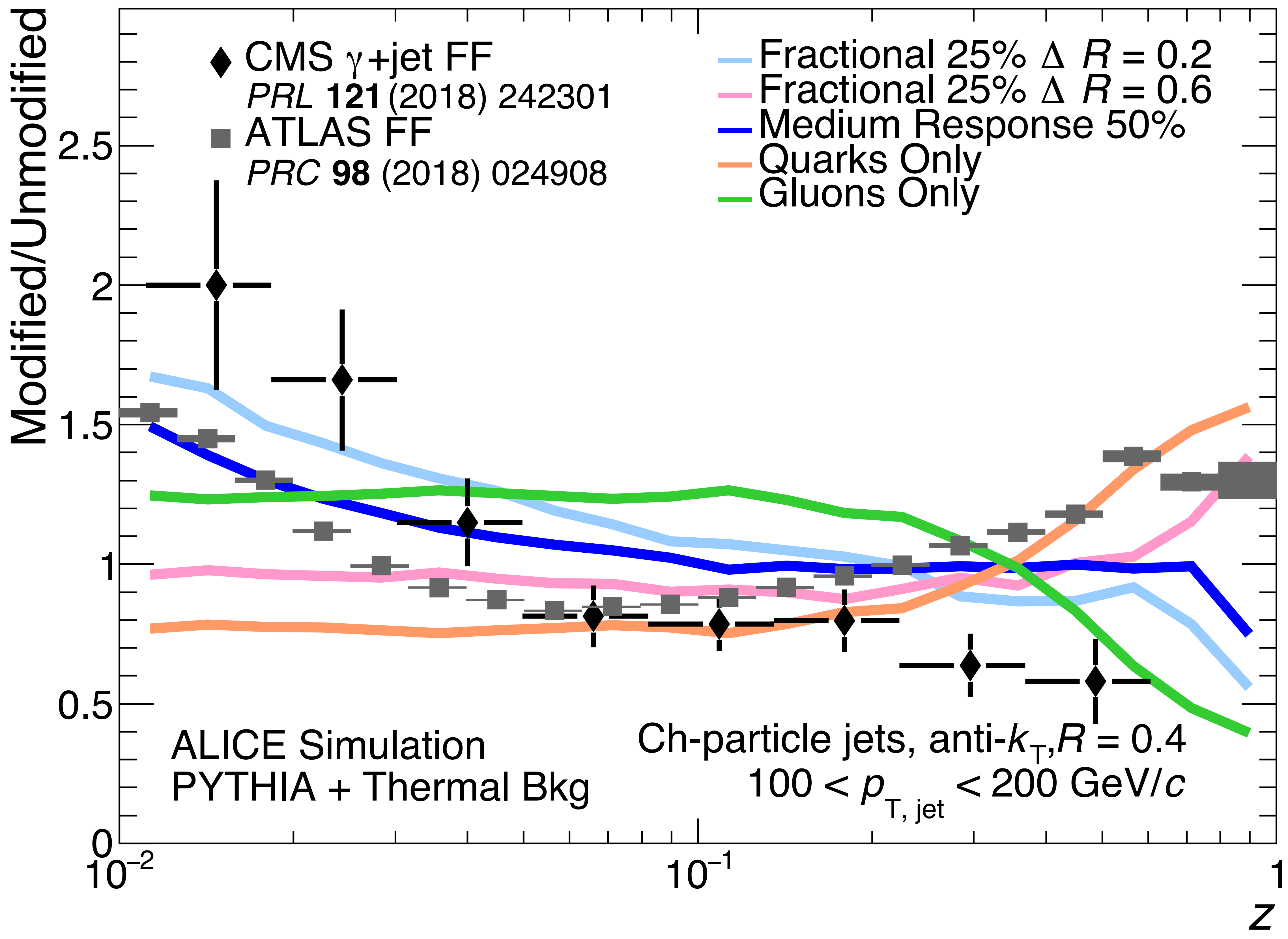
Fragmentation toy modifications

We also study a toy model with three different ways to alter constituents of the jet, changing the fragmentation to generate a different training set.

Also use this varied fragmentation to fill the response - use systematic to check the whole procedure! This systematic (along with tracking) are largest.

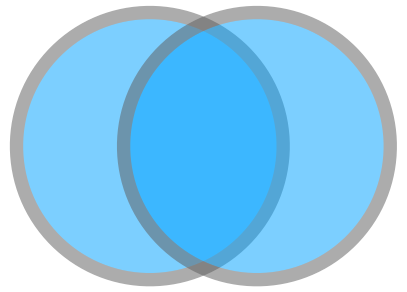
Fragmentation of toy compared to data





- Our fragmentation variations qualitatively cover the data in different regions of phase space.
- Toy model parameters motivated by experimental data: JHEP 05 (2018) 006

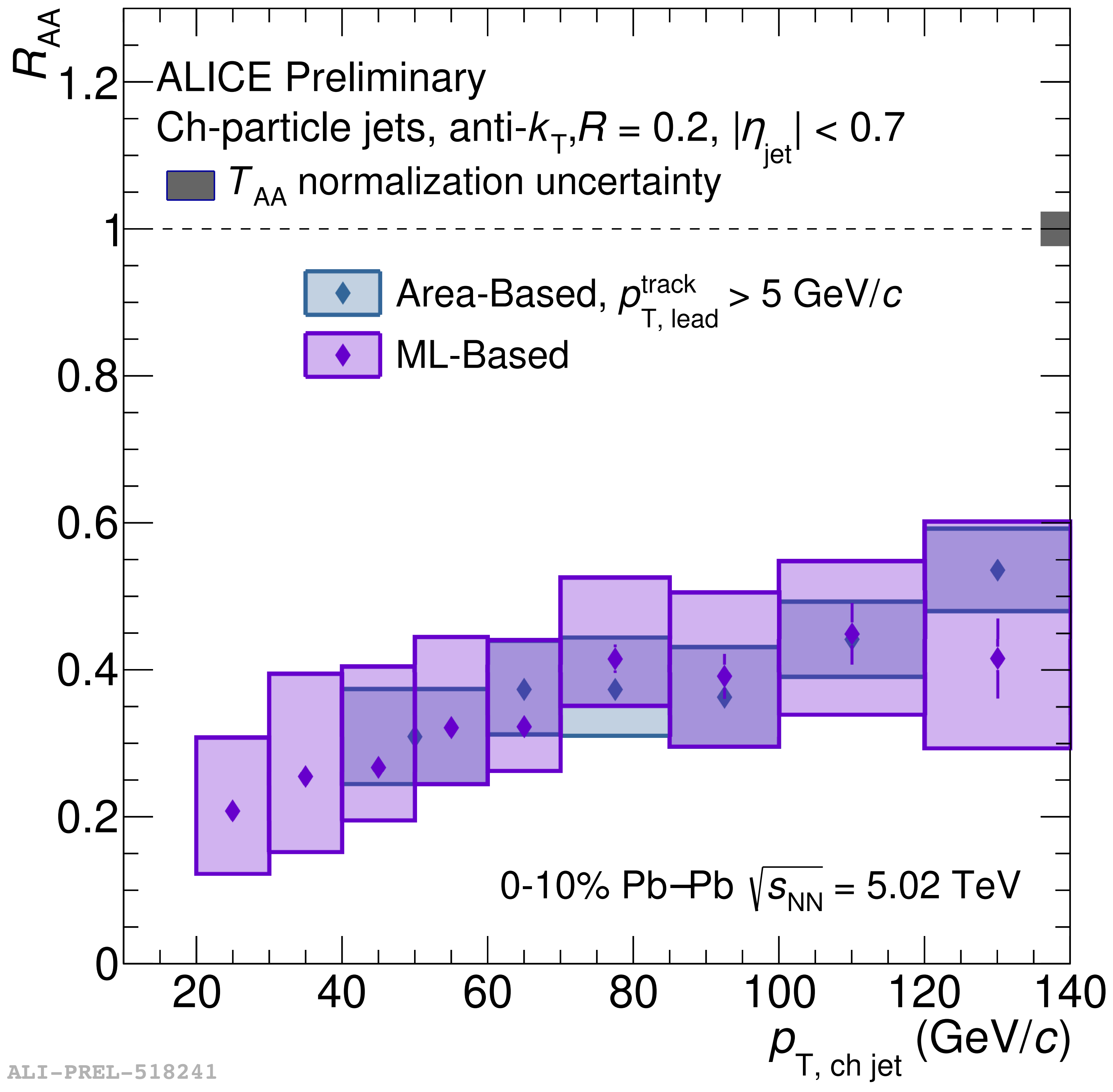
Area-based comparisons (0-10%)



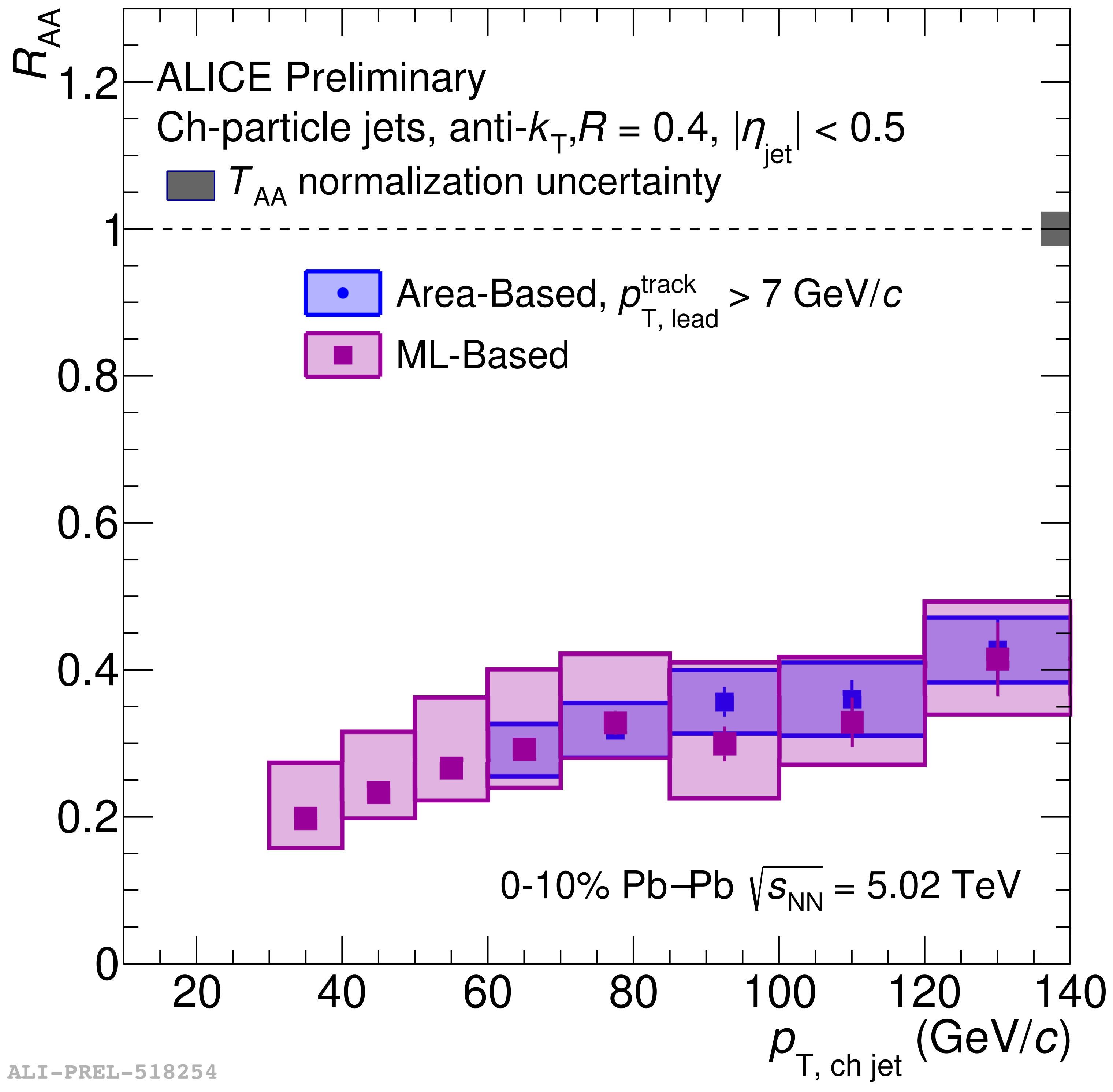
Central (0-10%)

→ Let's first take a look at our results in comparison to the standard (area-based pedestal subtraction of the background).

R = 0.2



R = 0.4



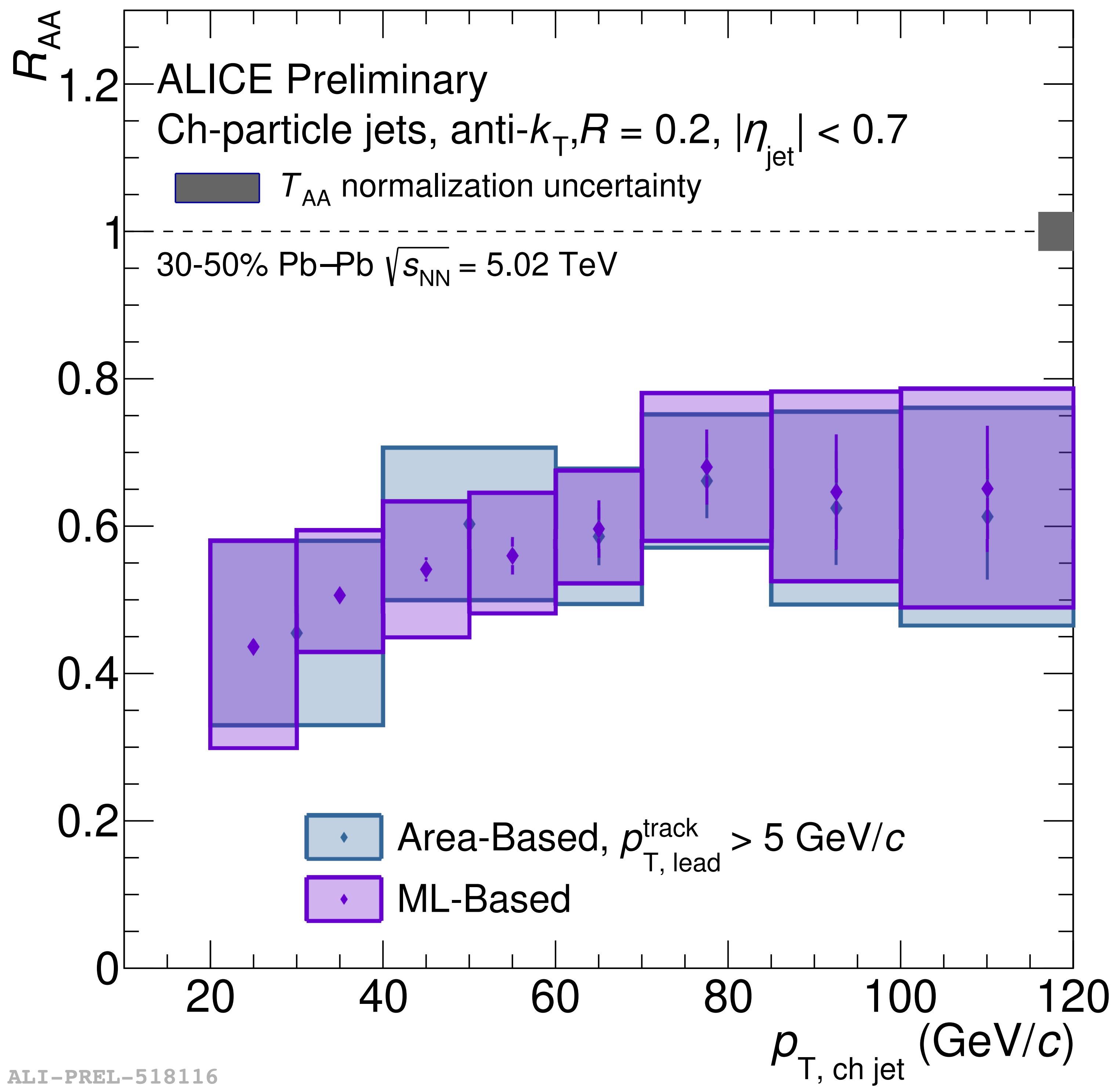
→ Good agreement in regions of phase space where we can measure!

→ ML allows for the extension of measurement to lower in p_T.

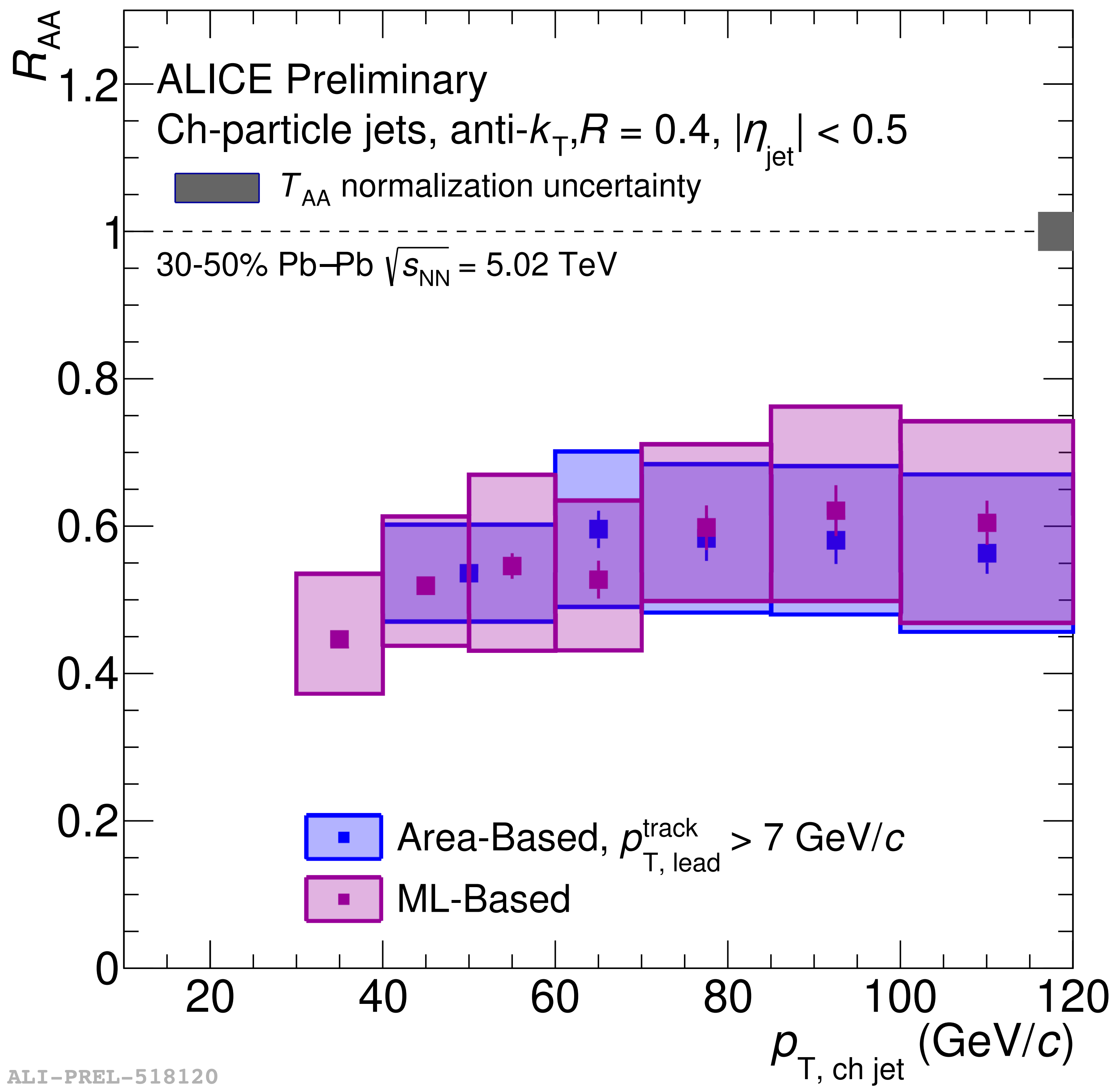
→ Measurements at large R not possible in central collisions due to the background.

Area-based comparisons (30-50%)

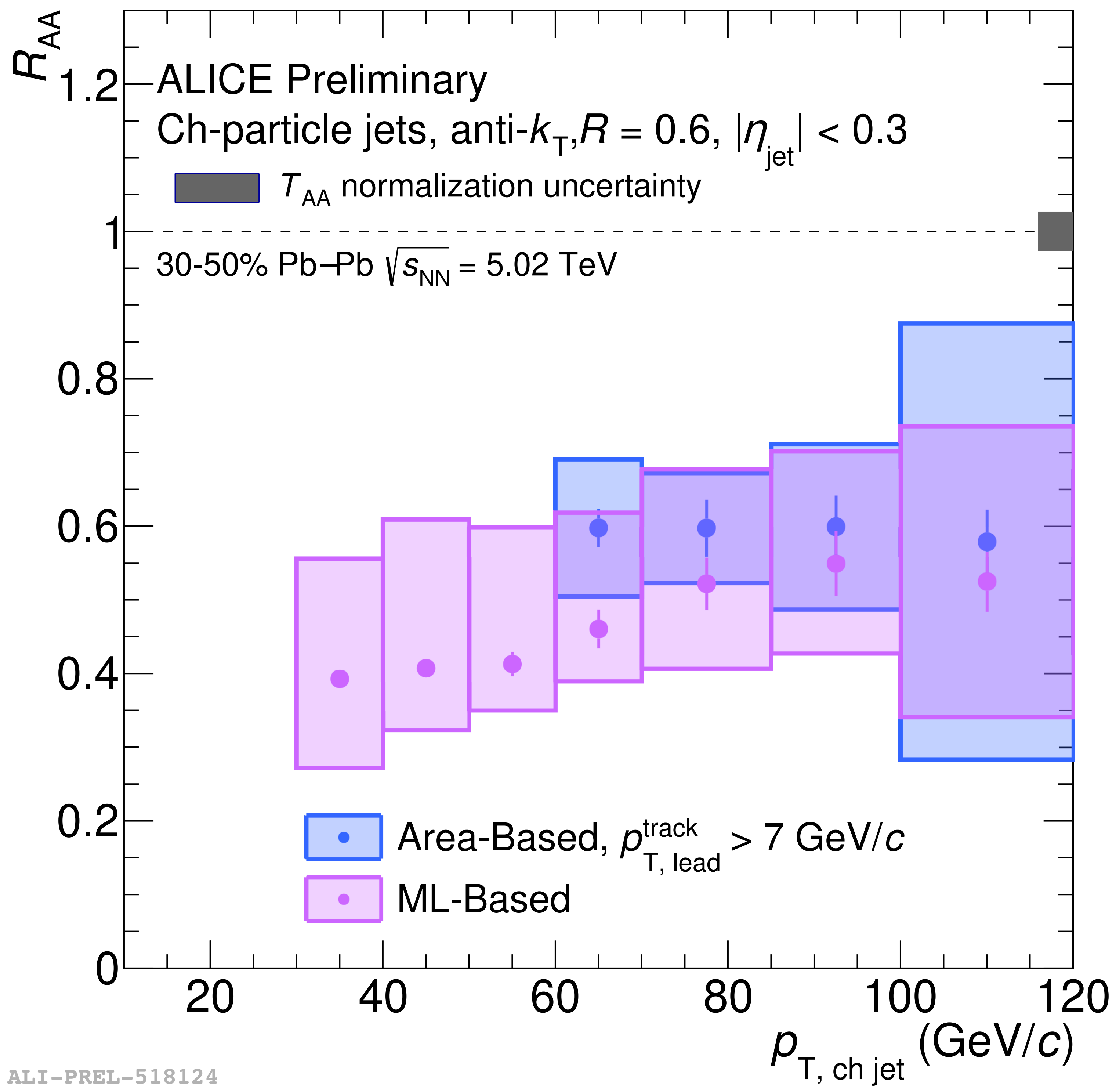
$R = 0.2$



$R = 0.4$



$R = 0.6$



→ Good agreement in regions of phase space where we can measure!

→ Very differential measurement of jet suppression!

Nuclear modification factors (0-10%)

LIDO: JHEP 05 (2021) 041

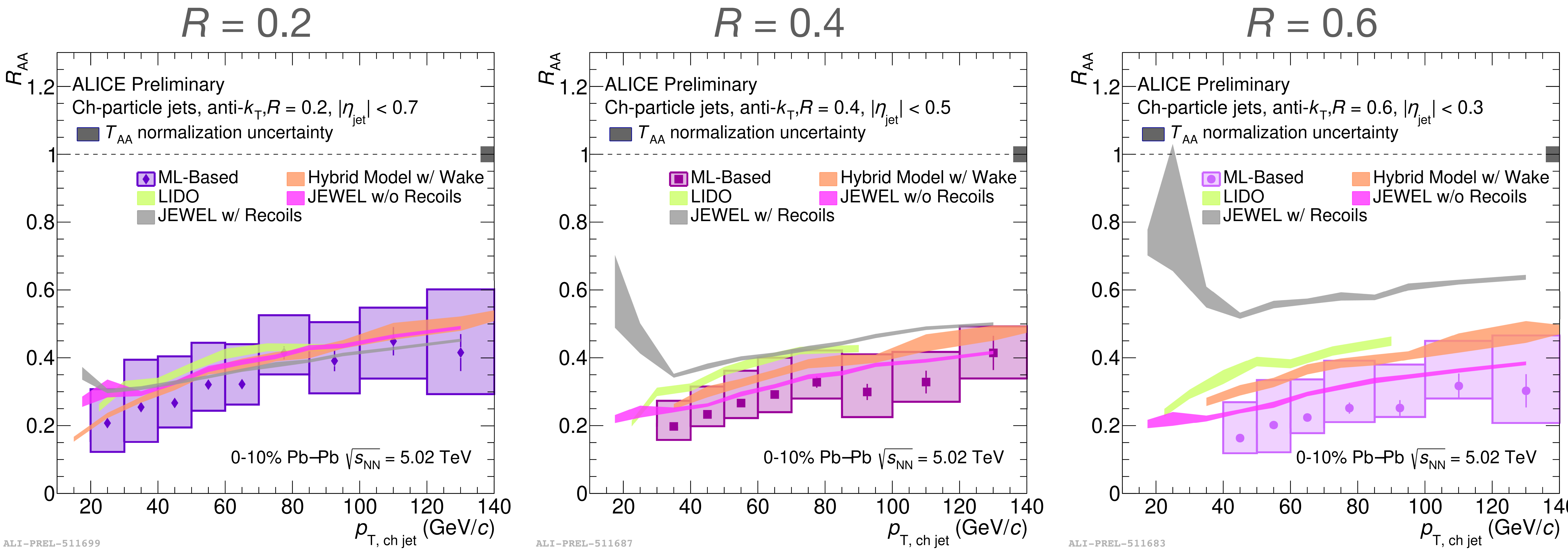
Linearized transport for jet-medium interactions, includes jet-induced hydrodynamic medium response.

JEWEL: JHEP 1707 (2017) 141

Scattering and radiative energy loss with and without recoiling medium.

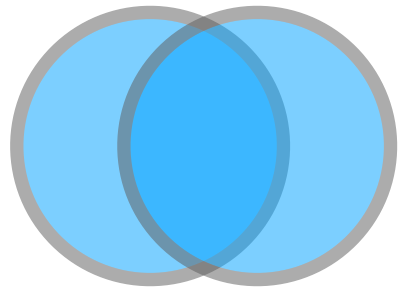
Hybrid Model: Phys. Rev. Lett. 124, 052301 (2020)

Medium response via wake. AdS/CFT non-pert. regime.



→ Measuring down to lower p_T and larger R than ever before in heavy-ions at the LHC!

R-dependence via R_{AA} ratios

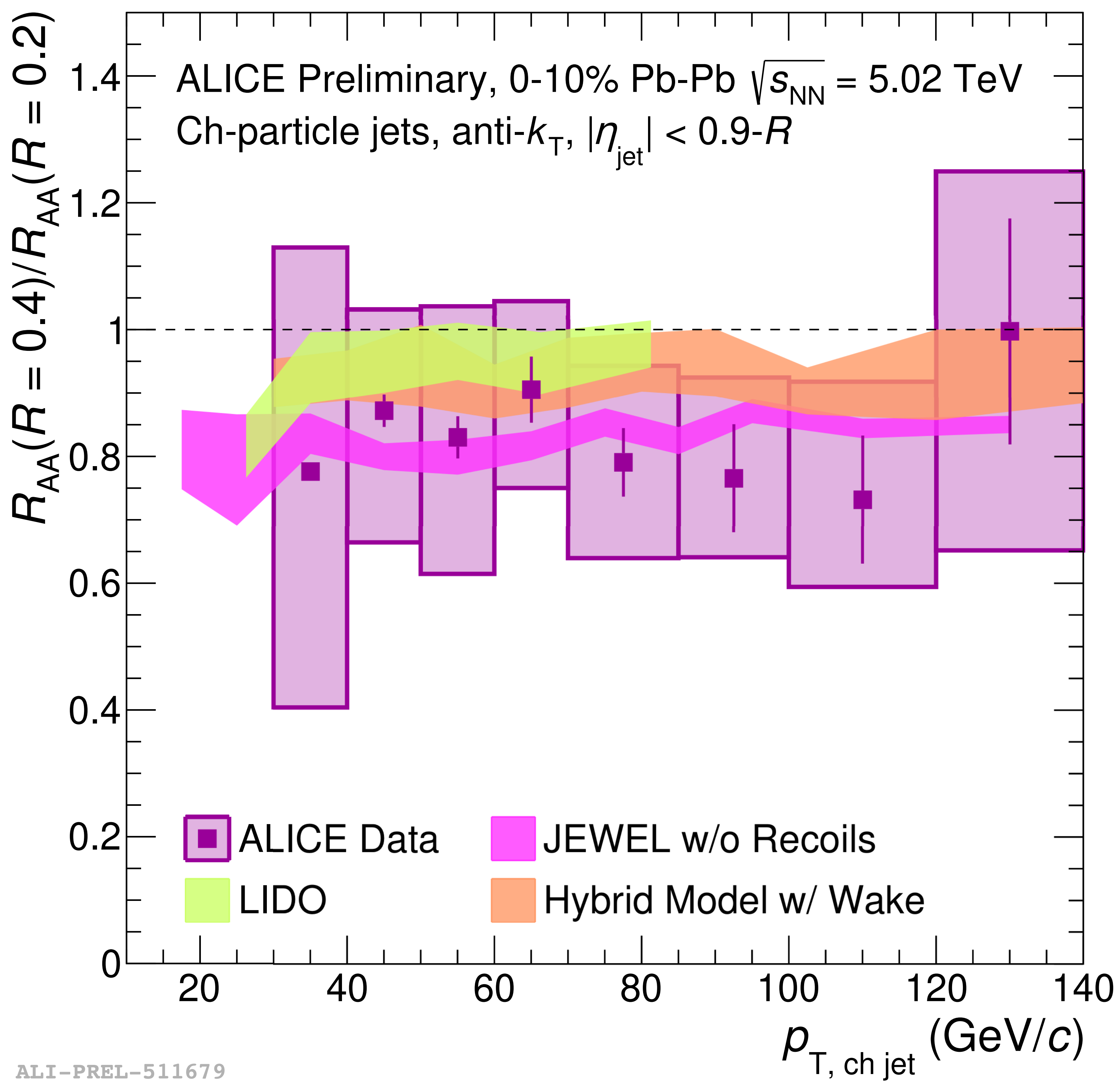


Central (0-10%)

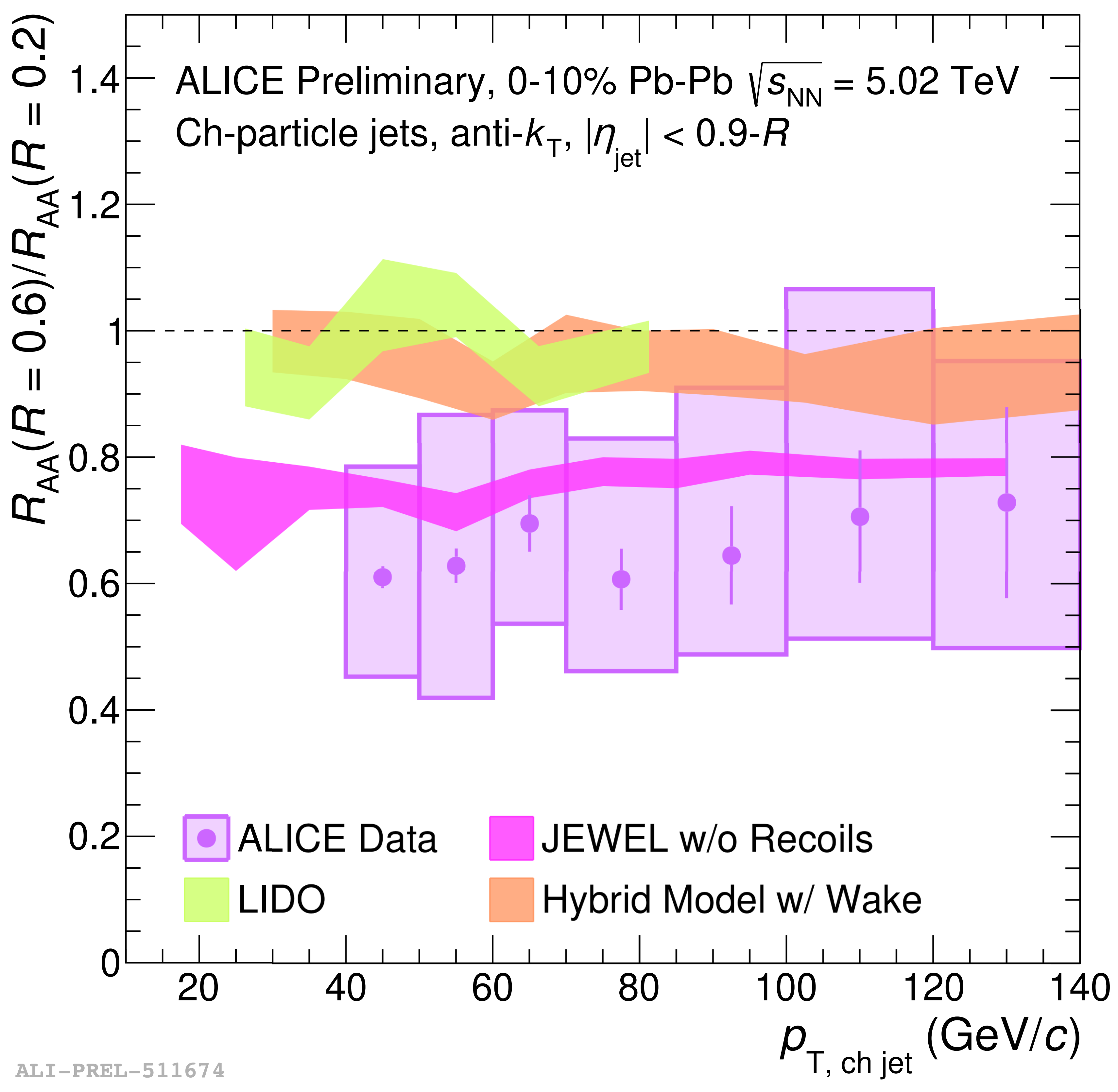
→ No evidence of *R*-dependence between *R* = 0.2 and *R* = 0.4.

→ ***R* = 0.6 jets appear more suppressed than *R* = 0.2 jets, suggesting an *R*-dependence.**

R = 0.4 / *R* = 0.2

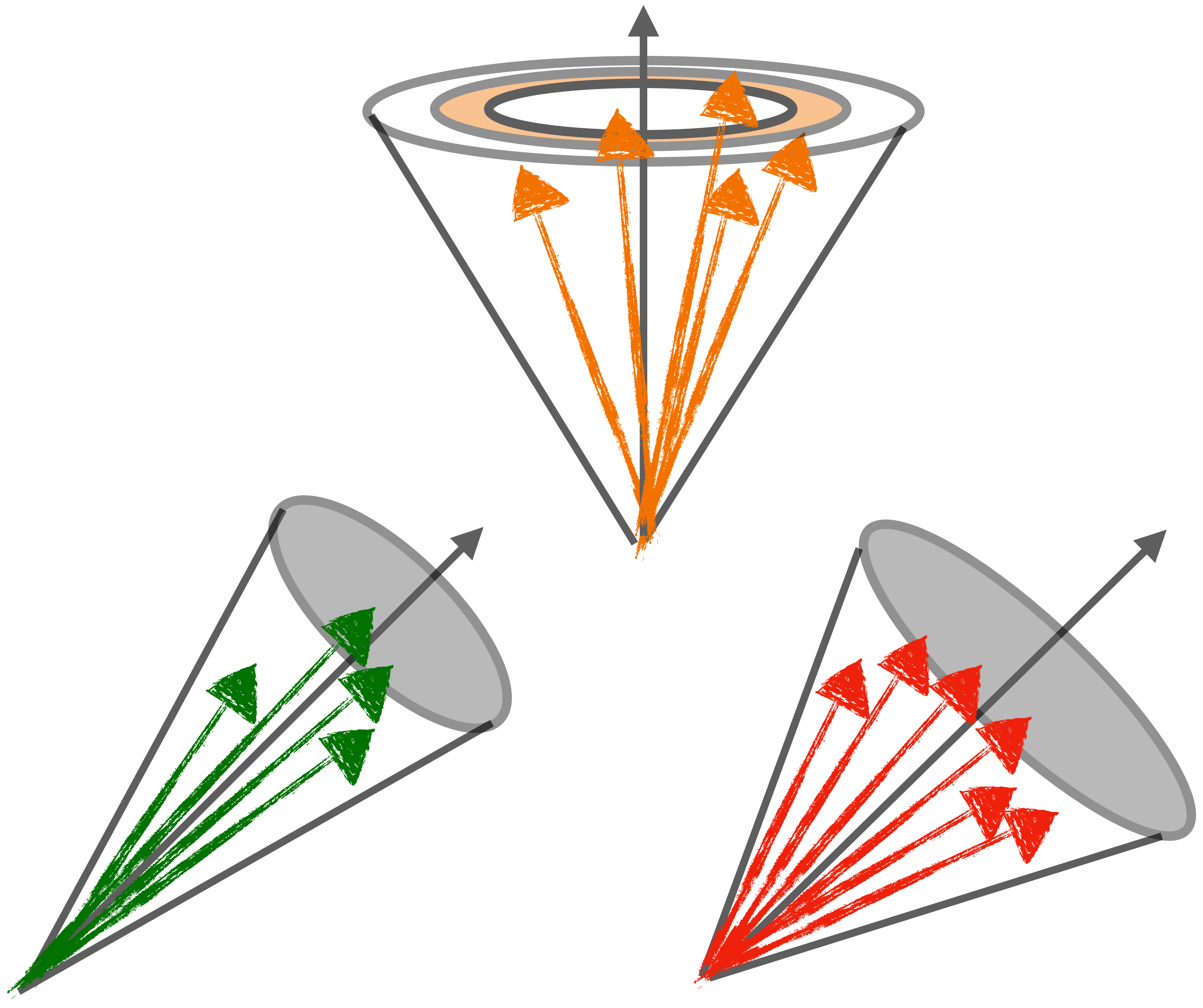


R = 0.6 / *R* = 0.2



R-dependence of the R_{AA}

→ R-dependence of the R_{AA} is another way to disentangle energy loss mechanisms.



Quark jet

Gluon jet

Our results favor larger influence of these effects!

→ Recovery of wide angle radiation $R_{\mathrm{AA}} \nearrow$

→ Medium response adds energy to the jet cone $R_{\mathrm{AA}} \nearrow$

→ Large R jets have more effective energy loss sources, therefore could experience more quenching. $R_{\mathrm{AA}} \searrow$

→ Increase gluon to quark ratio at fixed p_{T}, gluons lose more energy $R_{\mathrm{AA}} \searrow$

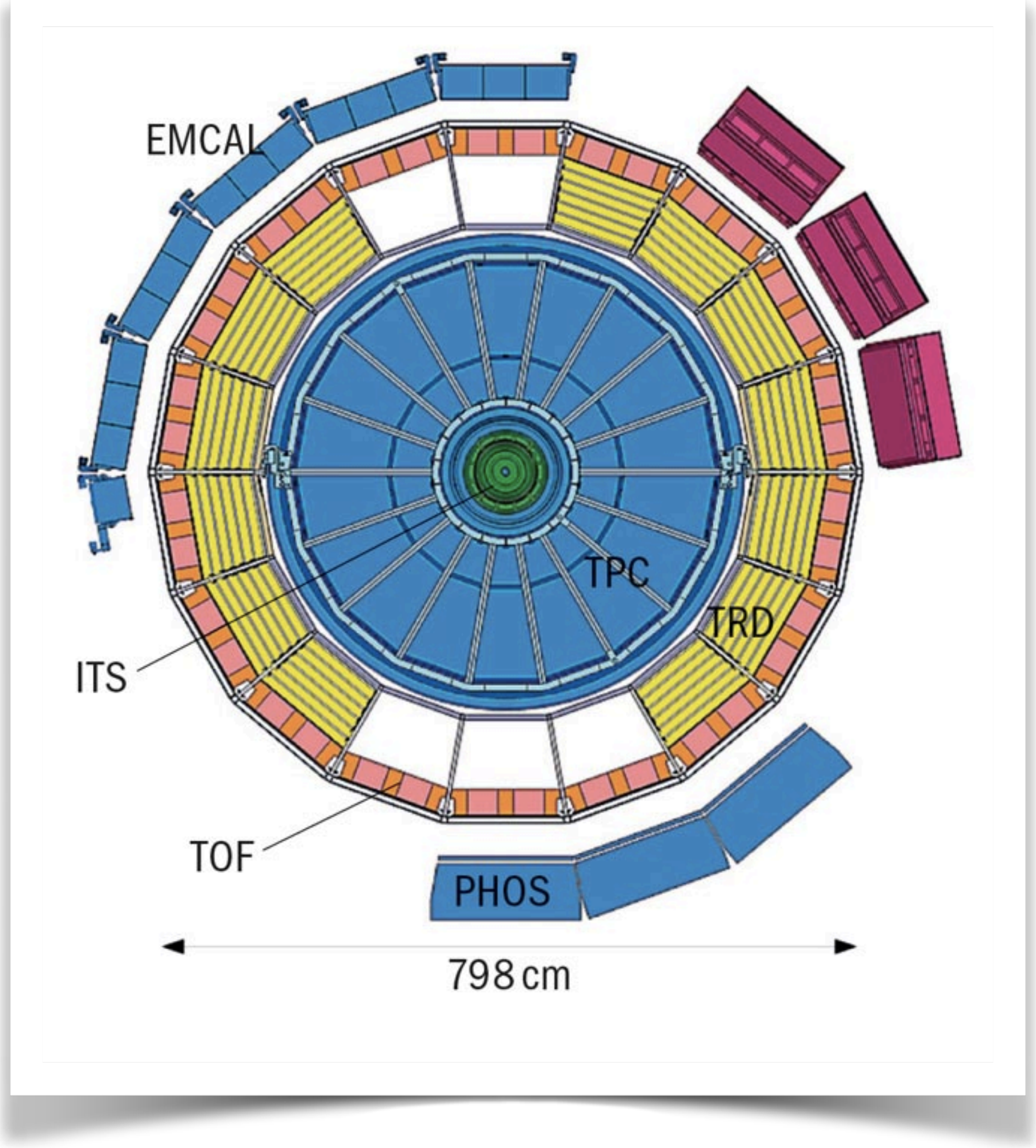
Conclusions

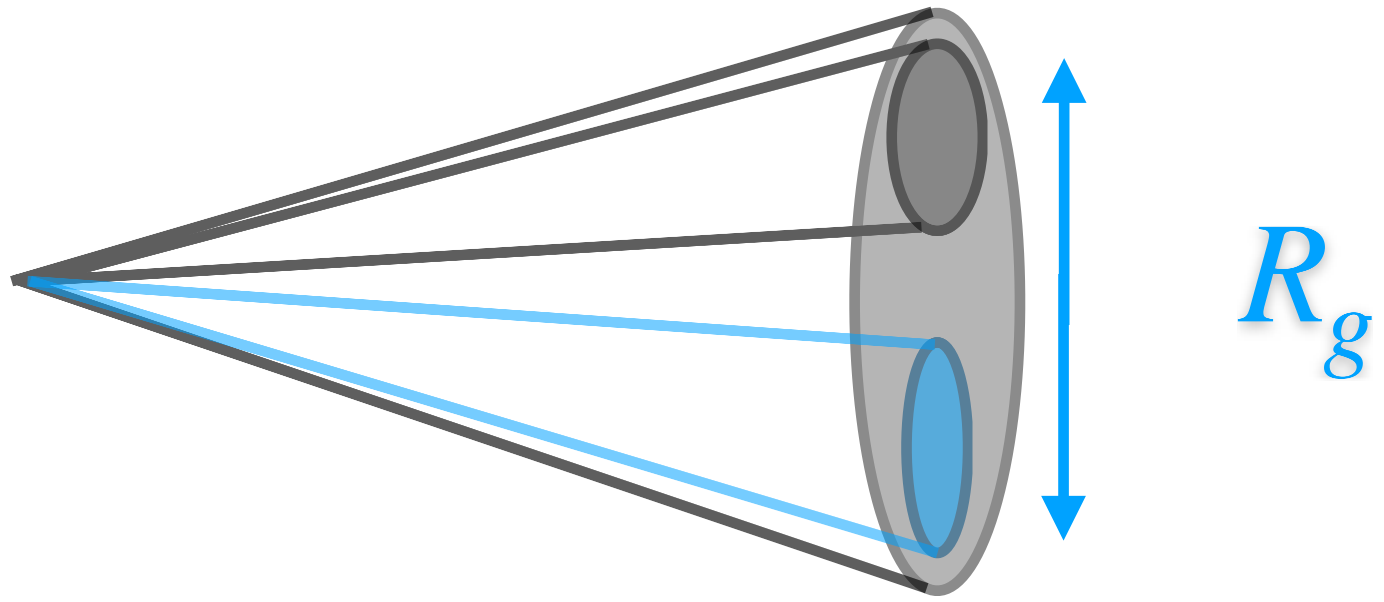
- Quantifying jet quenching effects can be a difficult task as many different effects impact the amount of energy lost.
- Differential measurements of jet suppression serve as one promising path to overcome these difficulties!
- We looked at one differential measurement made using a novel ML-based correction method, measuring the dependence of the R_{AA} on the jet radius *R* down to the lowest ever inclusive jet p_{T}'s measured at the LHC.
- We see that wider jets are more quenched, could be due to more effective energy loss sources, changing q/g fractions or different jet populations? More studies needed!

What's next?

Extensions of ML Method in ALICE

- Want to repeat the R-dependent studies with full jets.
  - Can use EMCal triggers to go to higher p_{T}.
  - This will be more comparable with measurements at ATLAS/CMS.
  - Full jets are limited in R by the acceptance of the calorimeter.

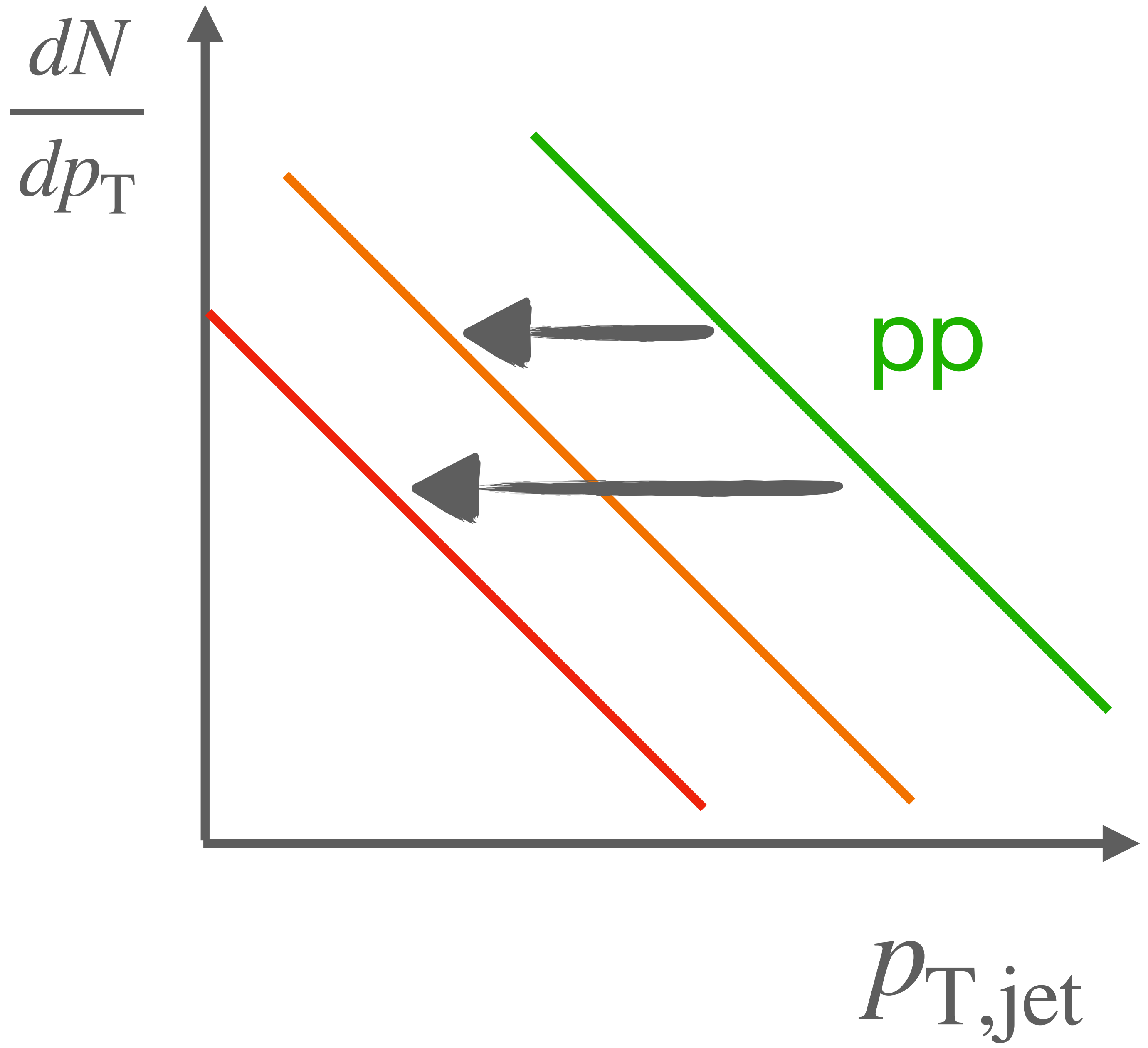




- Can we also use the same ML techniques for measurements of jet substructure! Stay tuned!

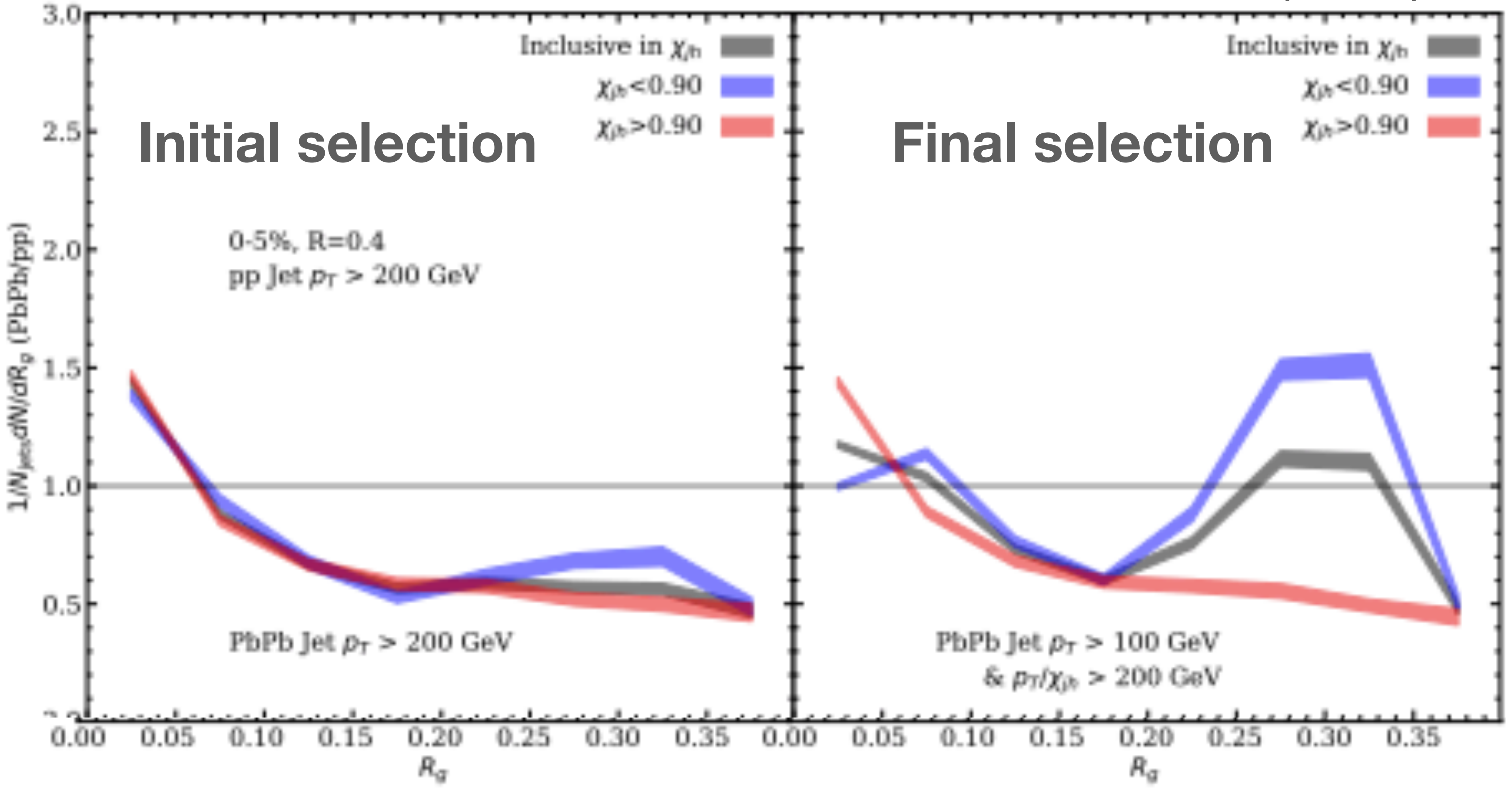
Survivor bias

Brewer et. al: Phys. Rev. Lett.122.222301



- If some populations lose more energy than others, we will see a suppression purely from the selection bias by measuring modified jets at a fixed p_T.
- Selecting on the initial energy removes narrowing for more quenched jets.

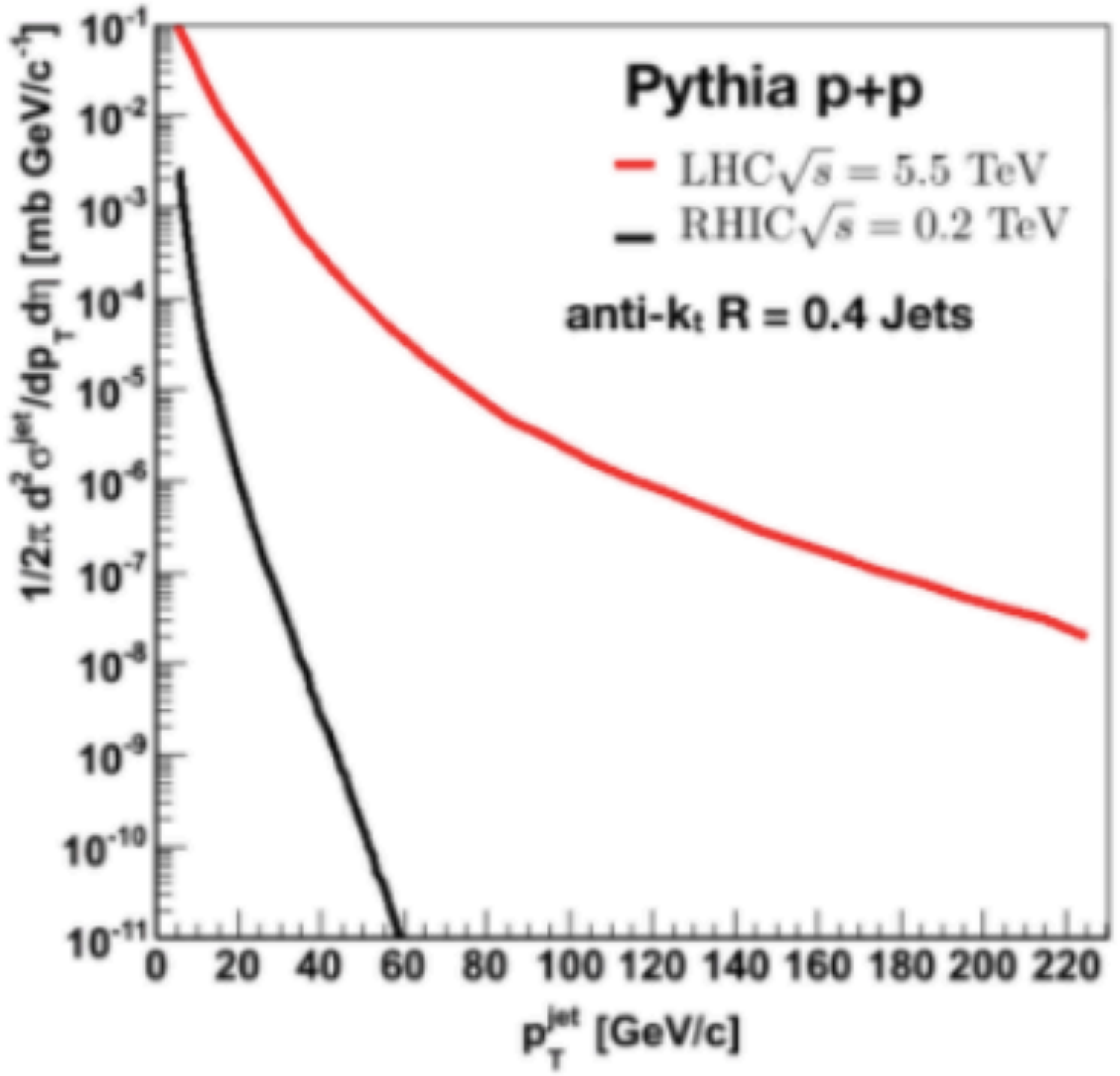
JHEP. 2021, 206 (2021)

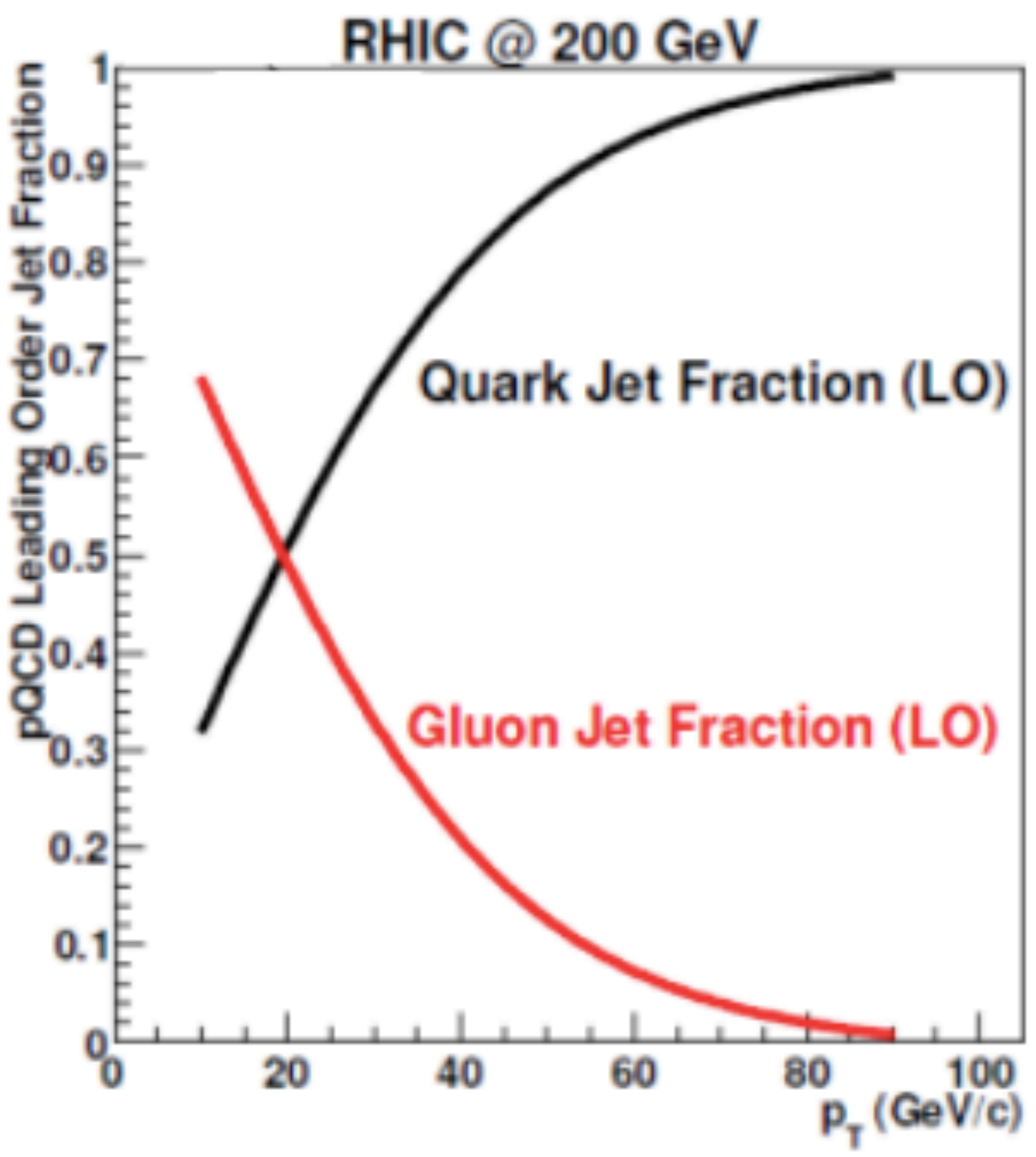


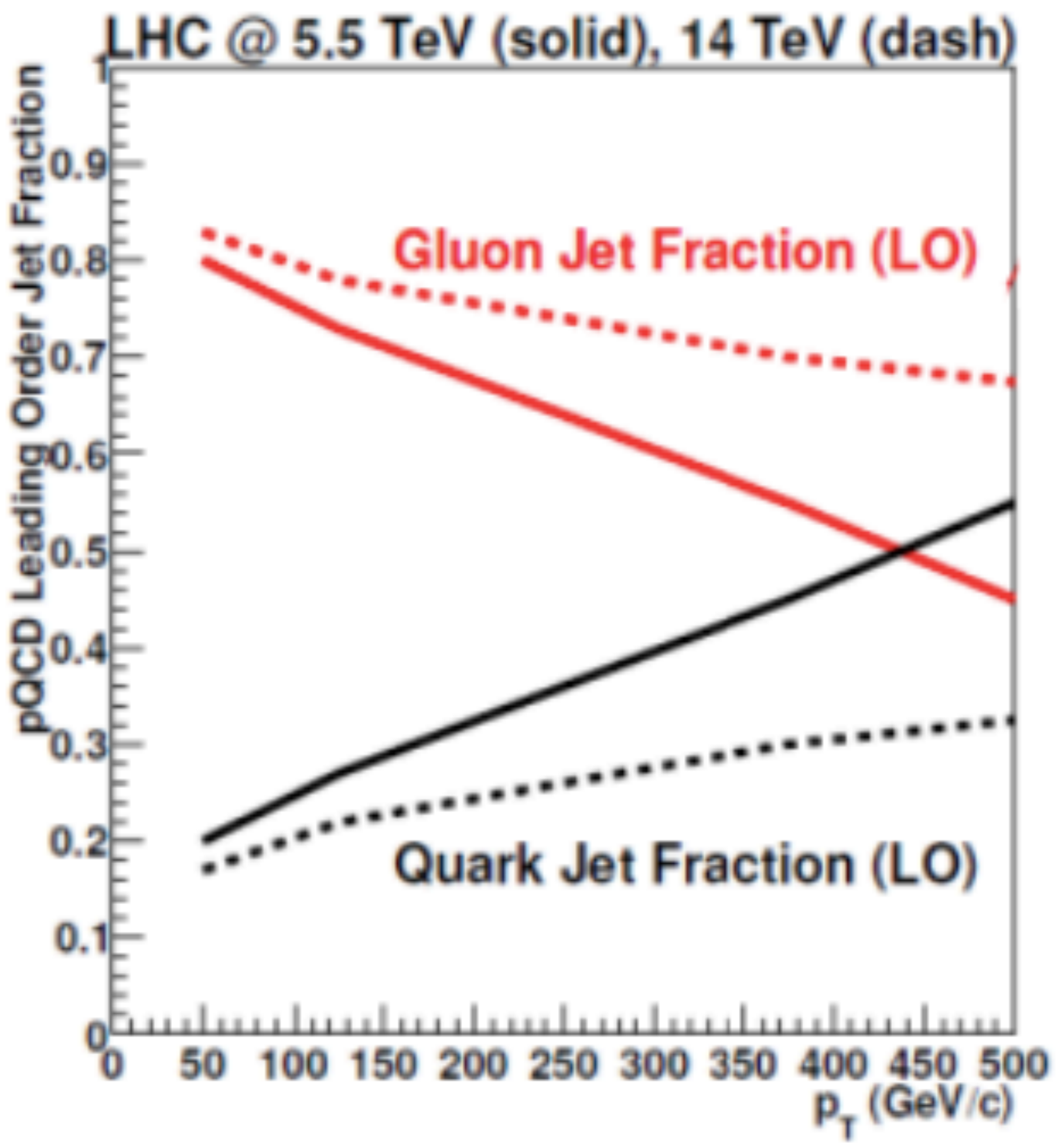
- So far, no reliable way to measure the initial p_T of the jet itself in experiment. ML techniques are promising.
- Can use γ-tagged measurements to probe similar effects.

sPHENIX and other developments @RHIC

- RHIC is a fantastic environment to study these effects as well, especially with the addition of sPHENIX!
- Spectrum much steeper, much lower jet momenta
- Different q/g fractions (much more quarks)







Many new opportunities on the horizon! Stay tuned!

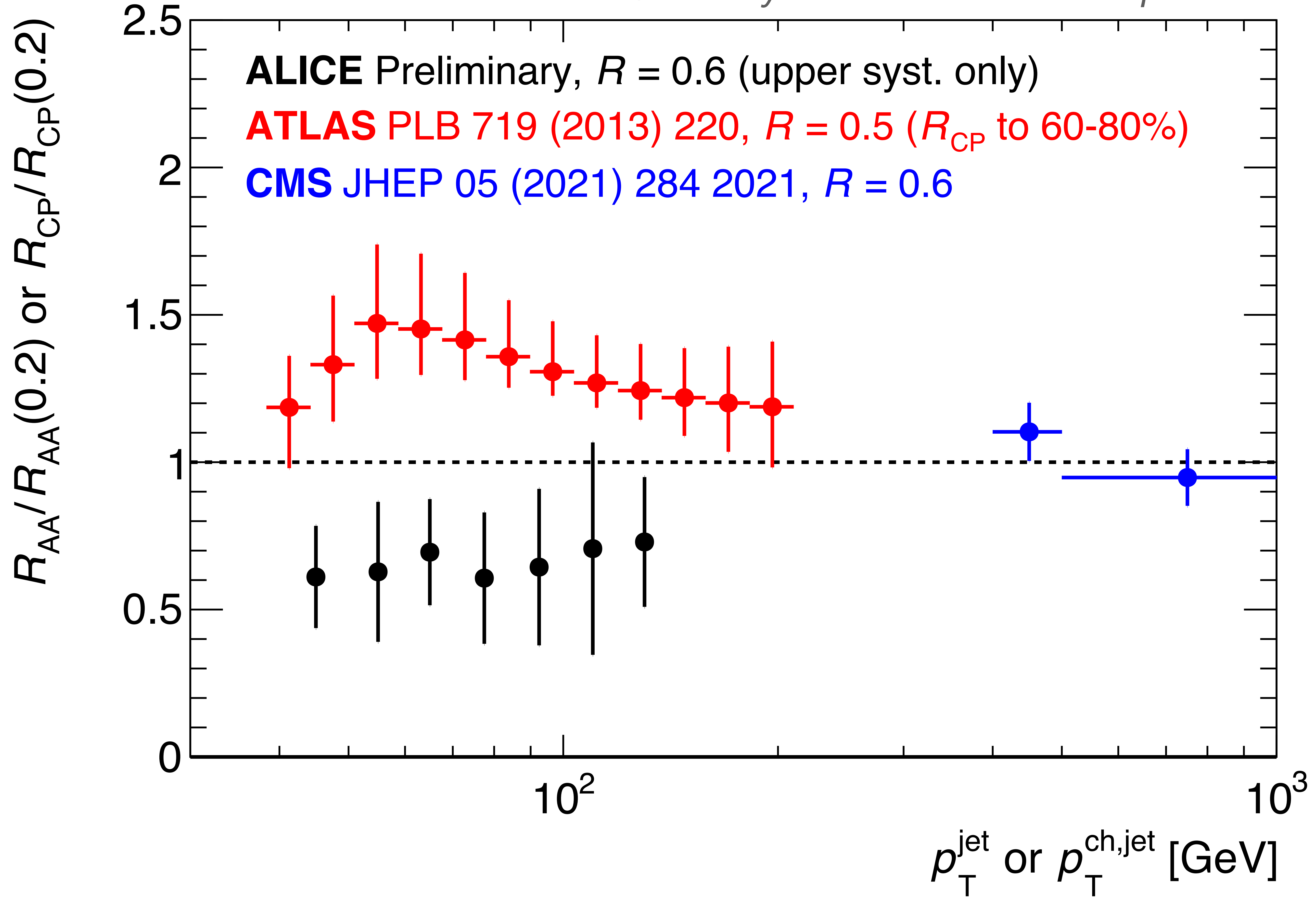
Thanks!

Backup

Large *R* Comparisons w/ ATLAS & CMS

- We know these show different qualitative trends, but here is a quantitative comparison.

Courtesy of Prof. Dennis Perepelitsa

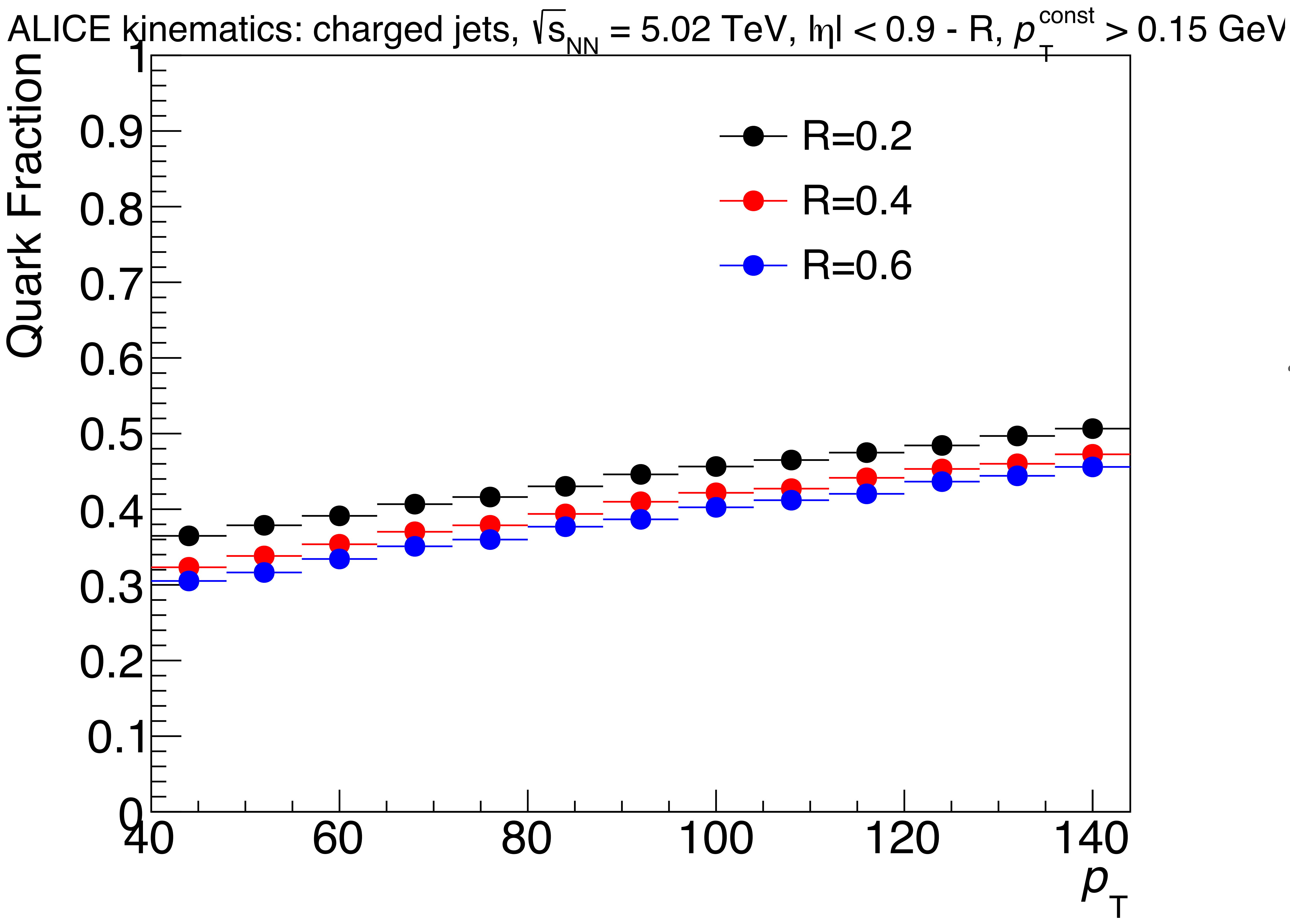


Caveats:

- ALICE measures charged jets while ATLAS/CMS measure full jets.
- Different rapidities: ALICE ($|\eta| < 0.7$), ATLAS ($|\eta| < 2.1$), CMS ($|\eta| < 2$)
- Different center of mass energies (ALICE & CMS - 5.02 TeV, ATLAS - 2.76 TeV)
- Different observable (ALICE & CMS R_{AA}, ATLAS R_{cp})

- Different *R* (ALICE & CMS $R = 0.6$, ATLAS $R = 0.5$)

Quark/gluon fractions as a function of R

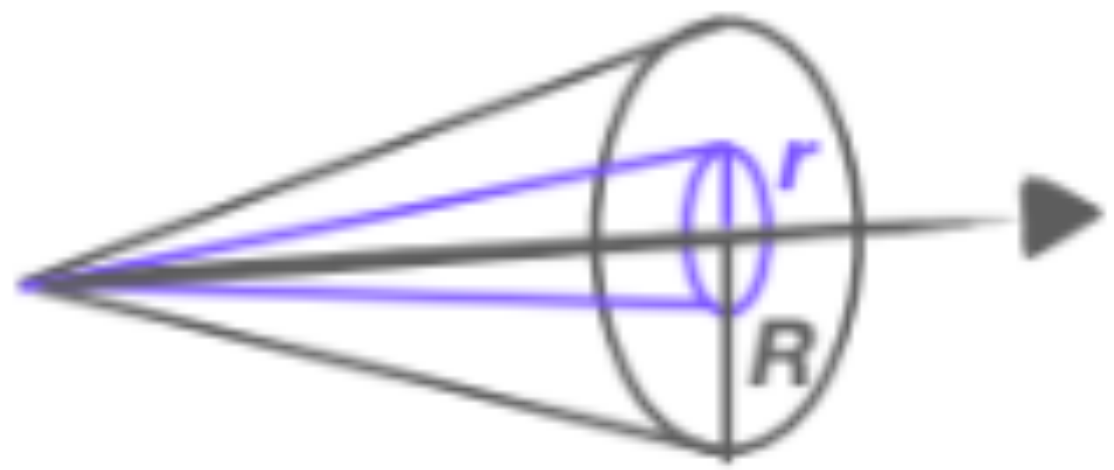


- The q/g fractions in PYTHIA have an *R*-dependence!
- Smaller radii have more quark jets.

Jet Subjet Fragmentation

→ Cluster jets with radius *R* and subjets with radius *r* < *R*. Look at the fragmentation of the subjet.

$$z_r = \frac{p_{\mathrm{T,subjet}}}{p_{\mathrm{T,jet}}}$$



→ Hint of hardening at intermediate z_r with a hint of modification as $z_r \rightarrow 1$.

→ In this region, the sample is closer to a purely quark-jet sample.

→ Could this be due to modification of the q/g fraction?

Technical Details of the ML

Regression task where the regression target is the detector level jet p_{T}.

Here we are prioritizing a simple model!

Training sample 10%, testing sample 90%.

Implemented in *scikit-learn*. Default parameters used unless otherwise specified.

Shallow Neural Network

Shallow, 3 layers with [100, 100, 50] nodes

ADAM optimizer, stochastic gradient descent algorithm.

Nodes/neurons activated by a ReLU activation function.

Linear Regression

Normalization set to true by default.

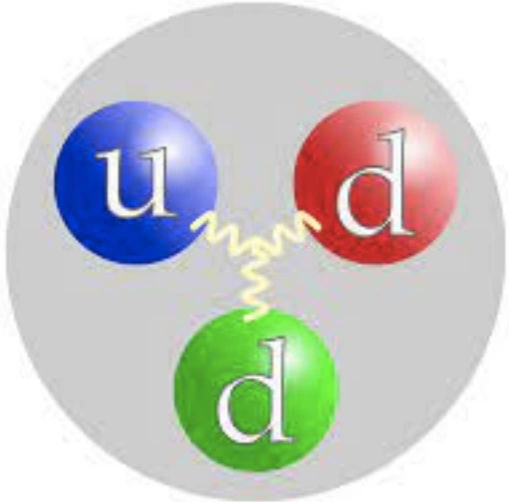
Random Forest

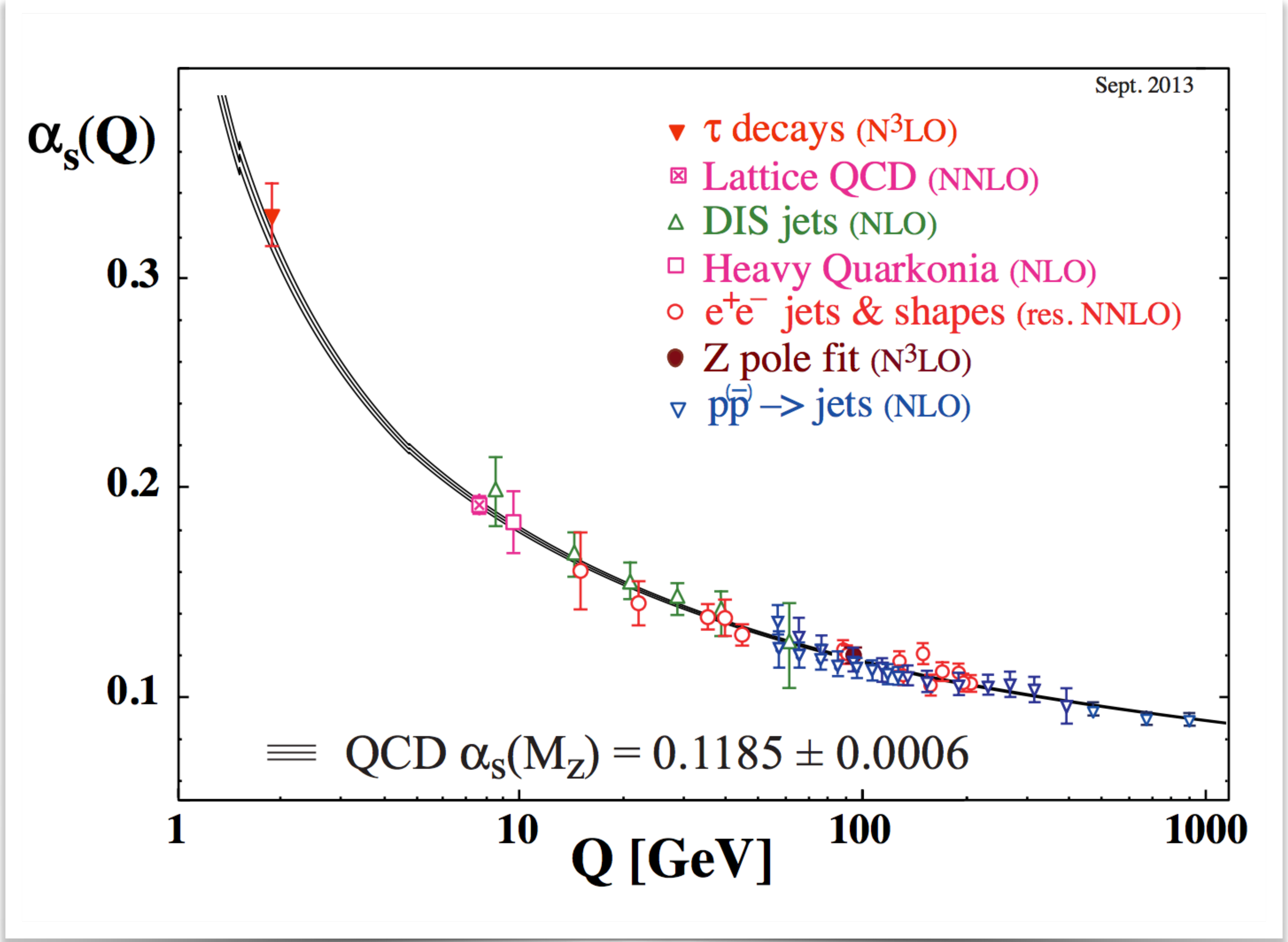
Ensemble of 30 decision trees.

Maximum number of features set to 15.

Quantum chromodynamics (QCD)

→ Quantum Chromodynamics (QCD) is the theory of the strong force that mediates the interactions between partons (quarks and gluons)





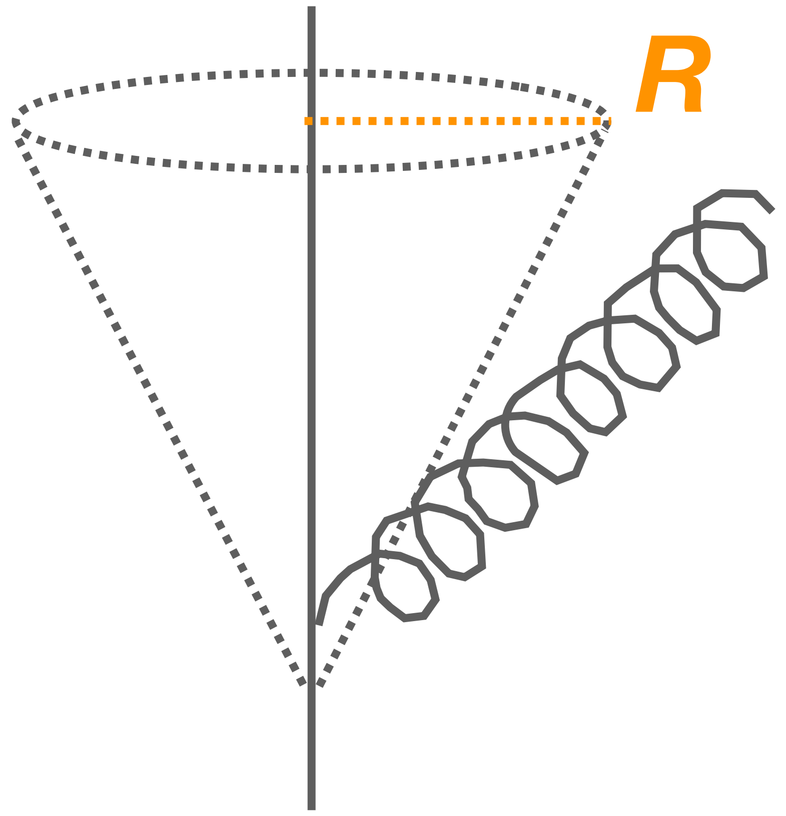
Two distinguishing features

1. ***Asymptotic freedom:*** Coupling constant α_s decreases at high energies (high Q)

2. ***Color confinement:*** Colored partons have never been observed in isolation

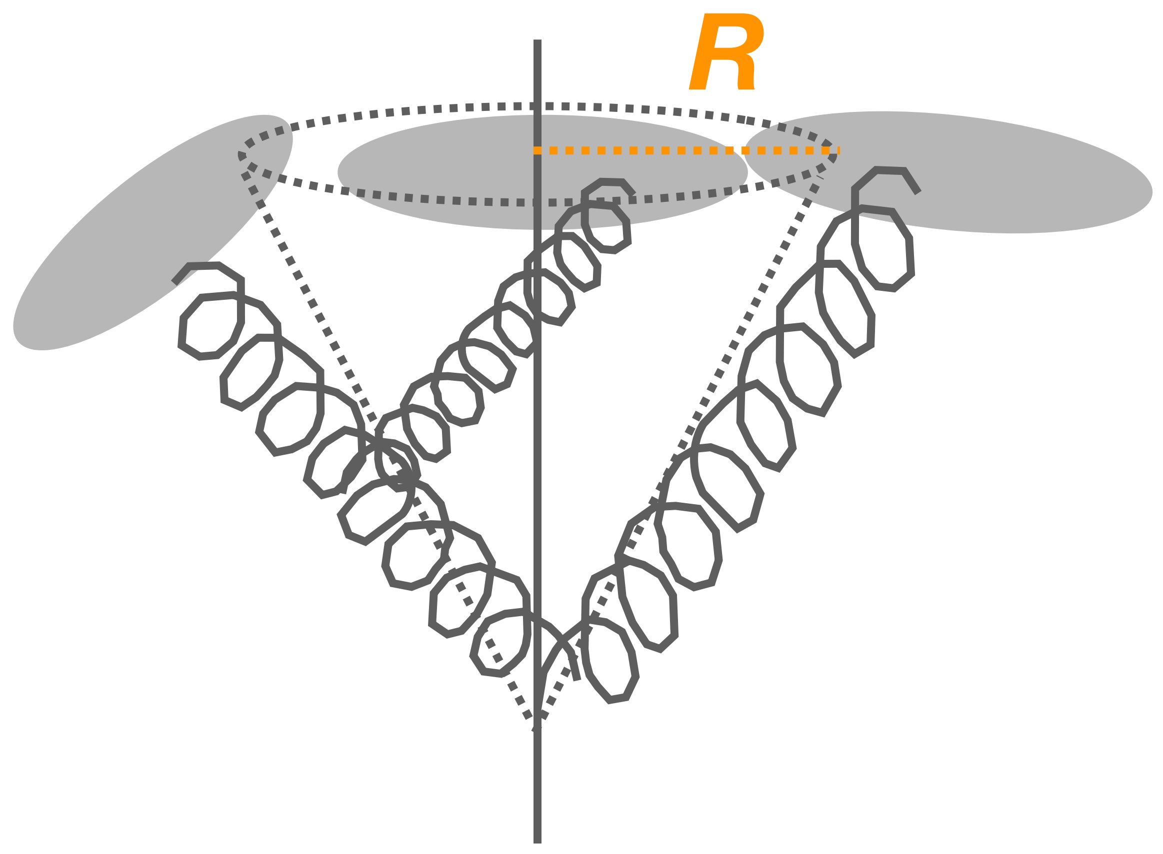
Exact scalings as a function of *R*

Parton Shower



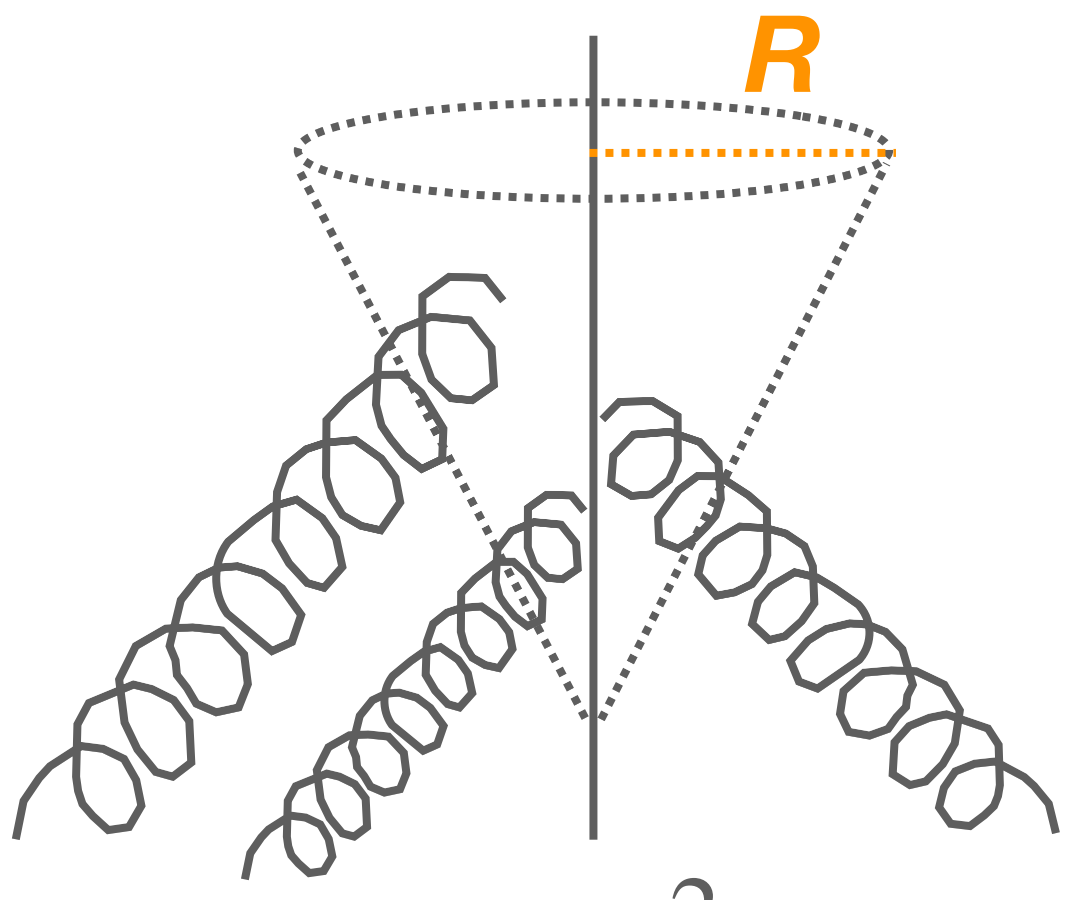
$\sim ln(1/R)$

Hadronization



$\sim 1/R$

Underlying Event



$\sim R^2$

$$(\delta p_T)_q = -C_F \frac{\alpha_S p_T}{\pi} \ln\left(\frac{1}{R}\right)\left(2\ln 2 - \frac{3}{8}\right) + \mathcal{O}(\alpha_S).$$

$$(\delta p_T)_g = -\frac{\alpha_S p_T}{\pi} \ln\left(\frac{1}{R}\right)\left[C_A\left(2\ln 2 - \frac{43}{96}\right) + T_R n_f \frac{7}{48}\right] + \mathcal{O}(\alpha_S),$$

From QCD splitting function at LO

$$(\delta p_T)_{had} \simeq -\frac{2C\mathcal{A}(\mu_1)}{\pi R} + \mathcal{O}(R)$$

Parameterization derived by taking $\alpha_s(\mu) = \mu_1 \delta(\mu - \mu_1)$ where μ_1 corresponds to scale at which α_s is infinite (Landau pole)

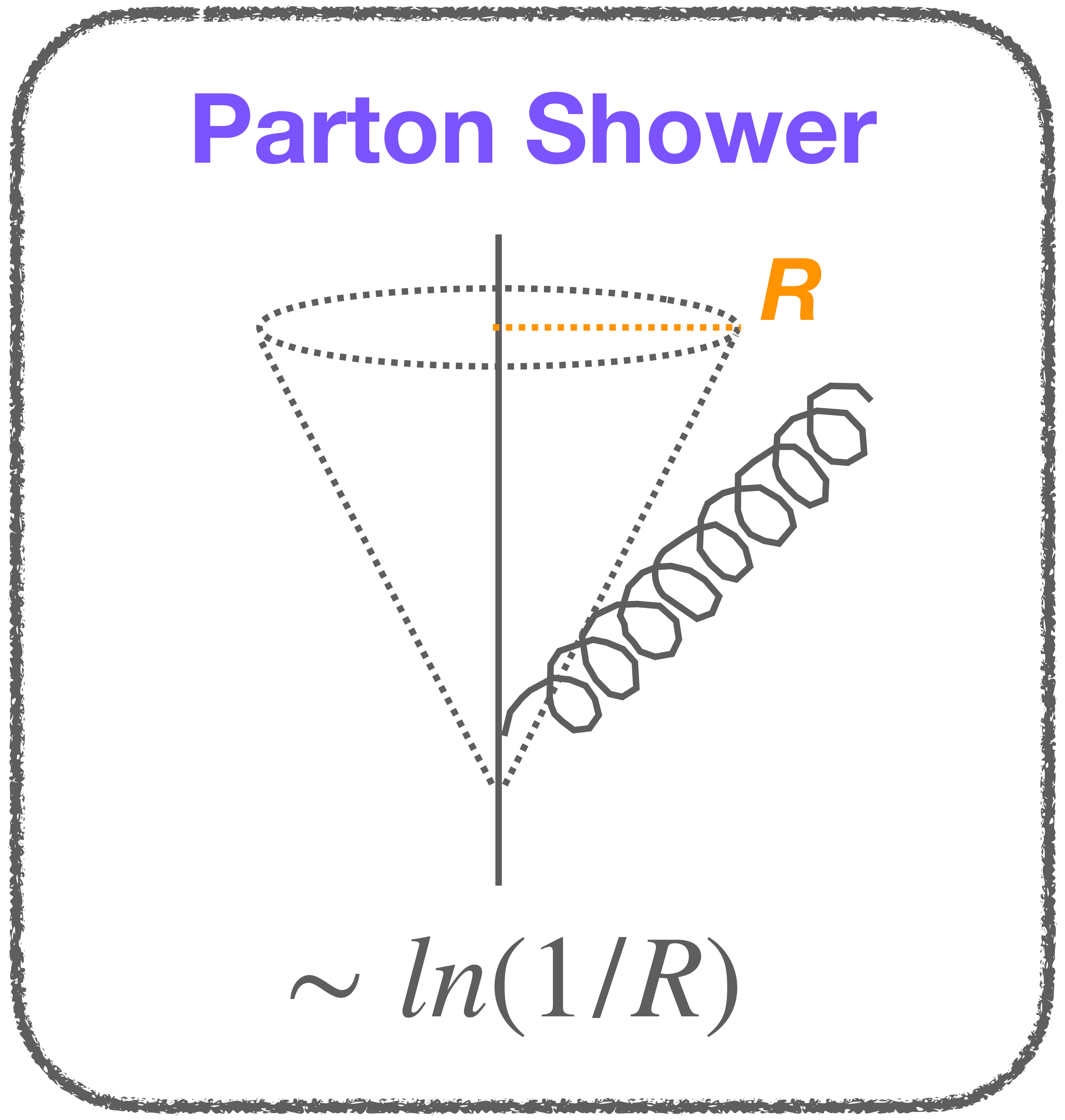
$$(\delta p_T)_{UE} \simeq \frac{1}{2} \Lambda_{UE} R^2$$

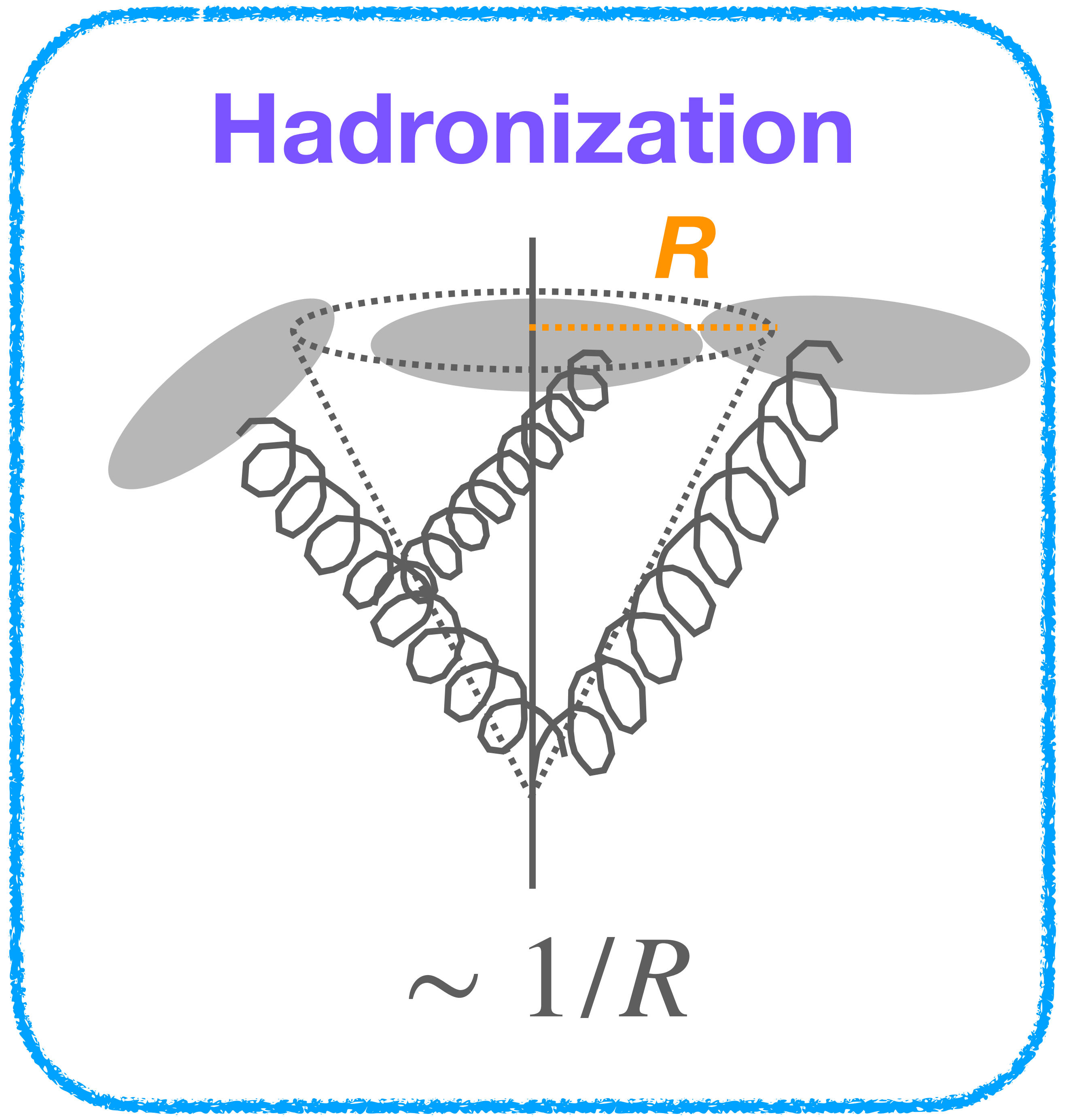
Energy density per unit rapidity

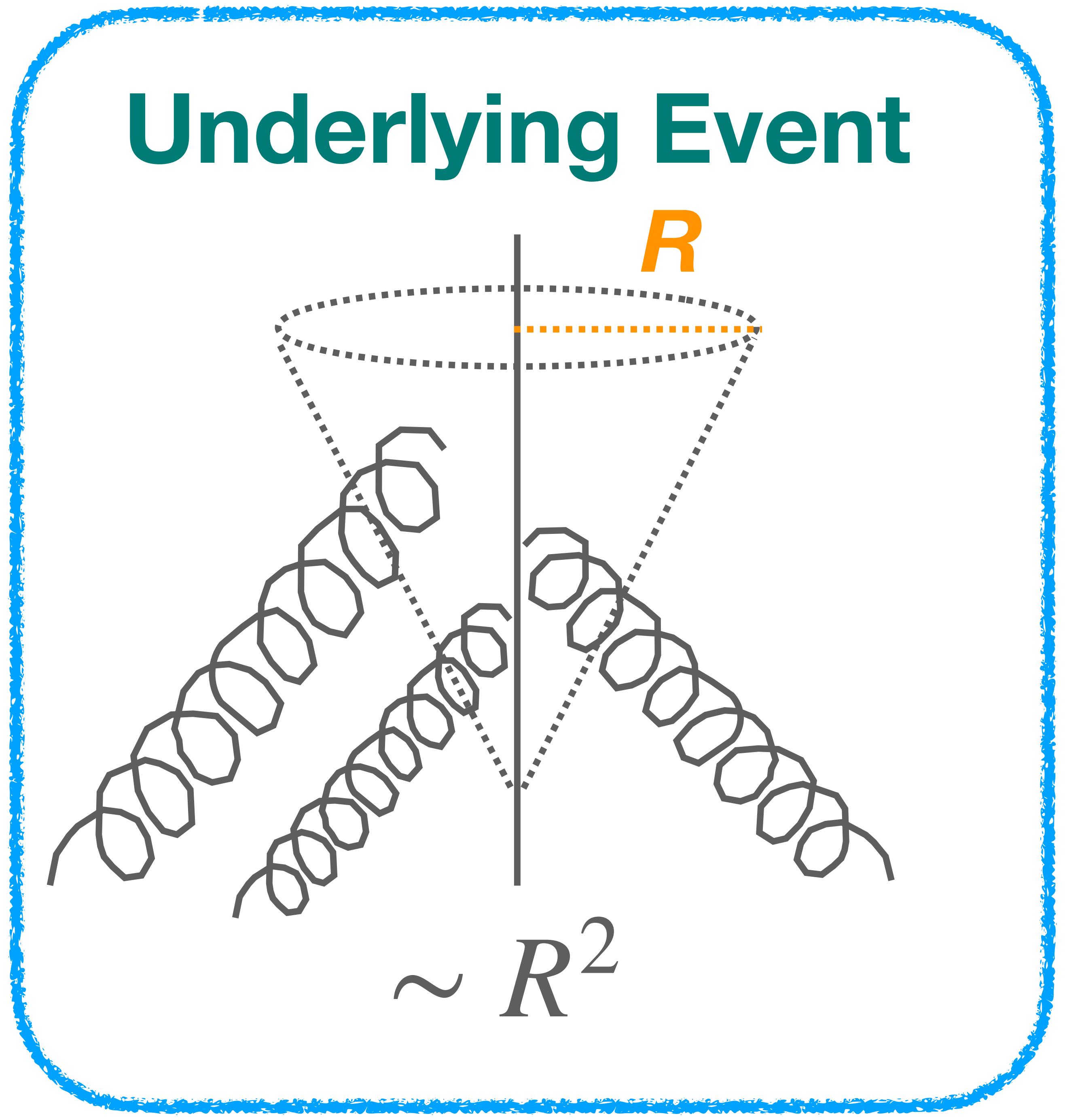
Jets in experiment

Experimental jets are not a *perfect* proxy for the dynamics of the parent parton.

→Different physics effects can move energy **into** or **outside** of the experimental jet cone.







Effects such as hadronization and the underlying event are non-perturbative.

Each of these effects scales differently with the cone radius *R*, jets can be used to study these effects!