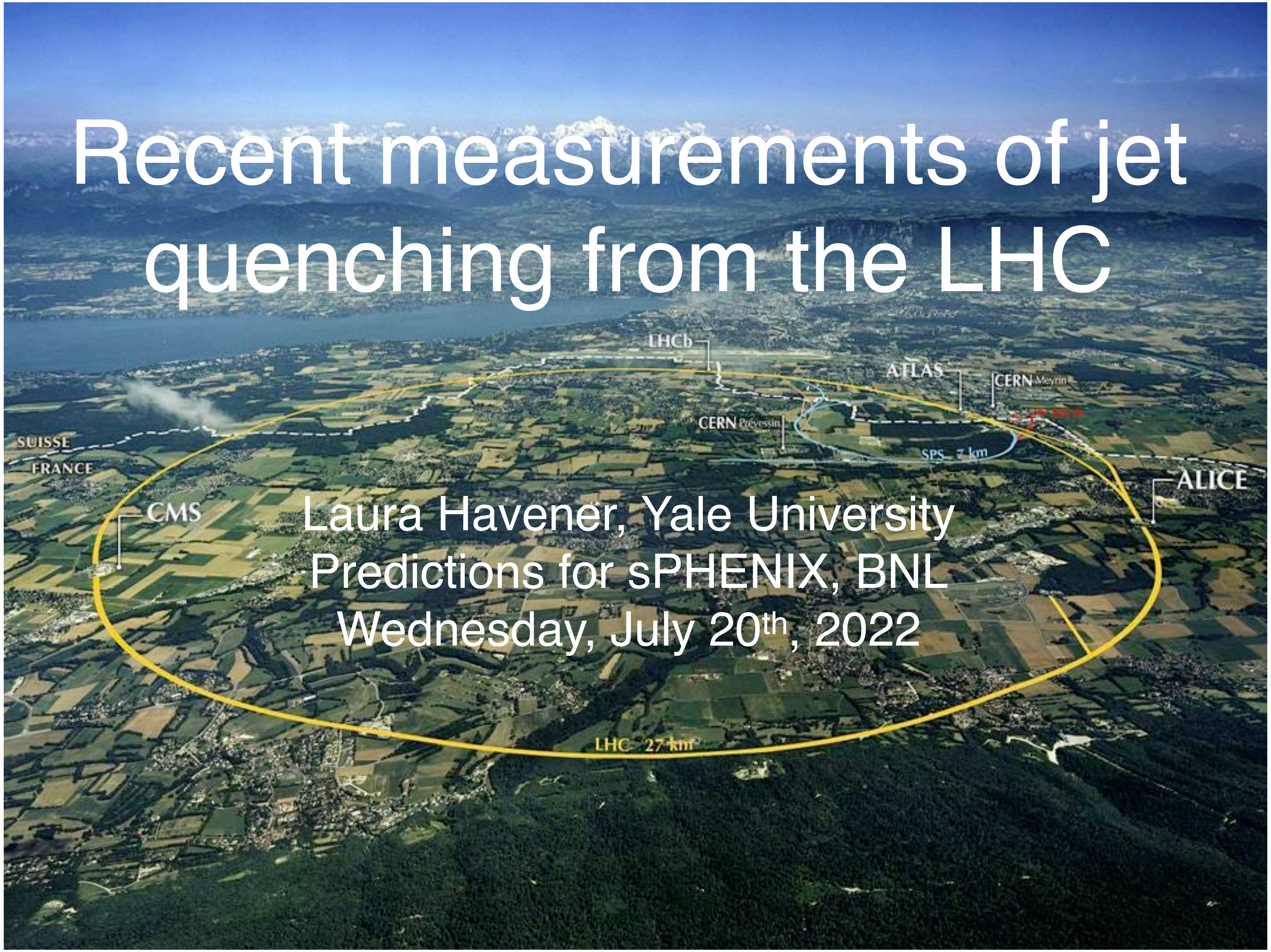
Recent measurements of jet quenching from the LHC

Laura Havener, Yale University
Predictions for sPHENIX, BNL
Wednesday, July 20th, 2022



Wright Laboratory

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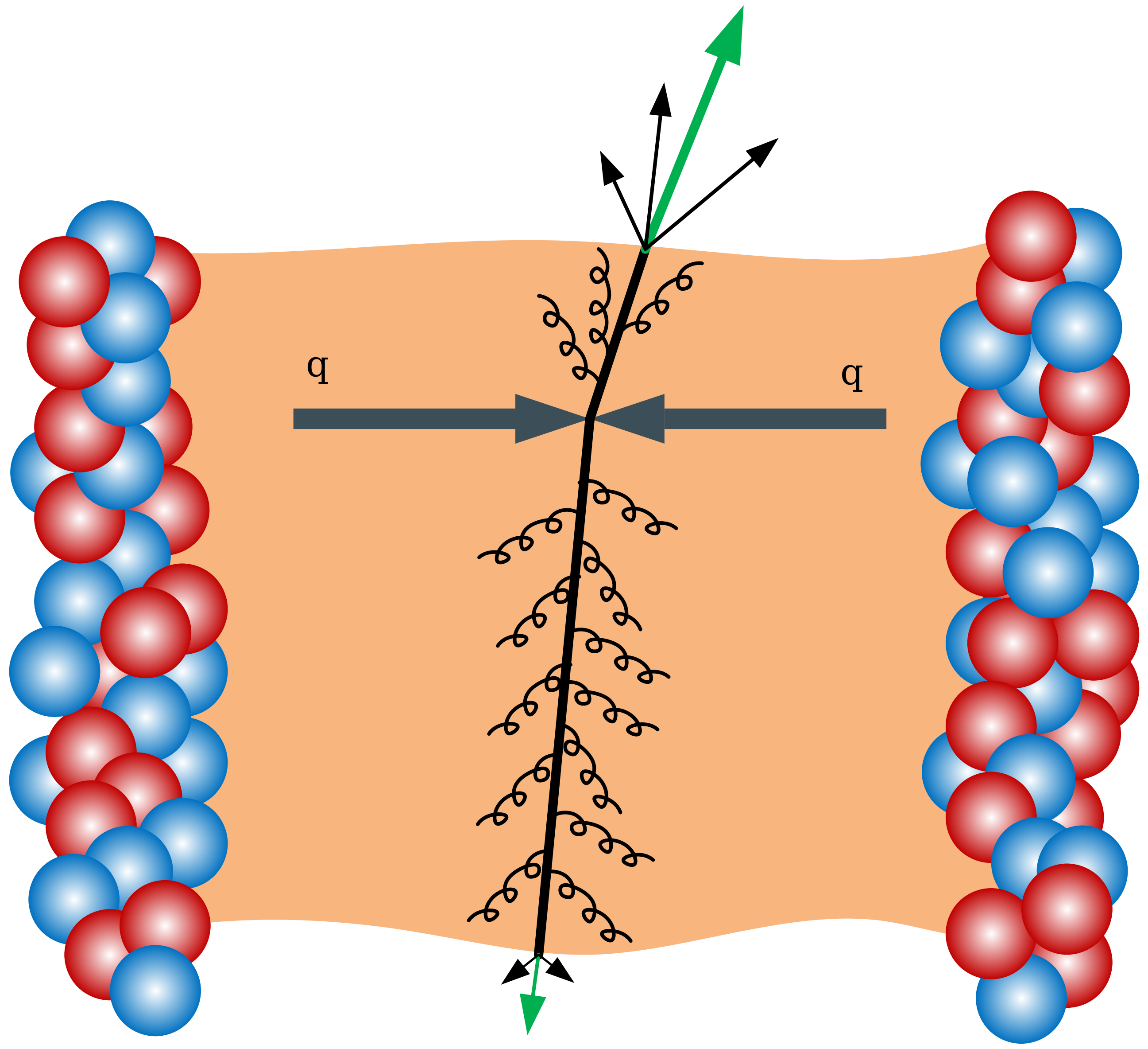
Jet quenching expectations

- Jet quenching: partons in heavy-ion (HI) collisions interact with the medium to produce:
  - ➡jet energy loss
  - ➡jet substructure modification



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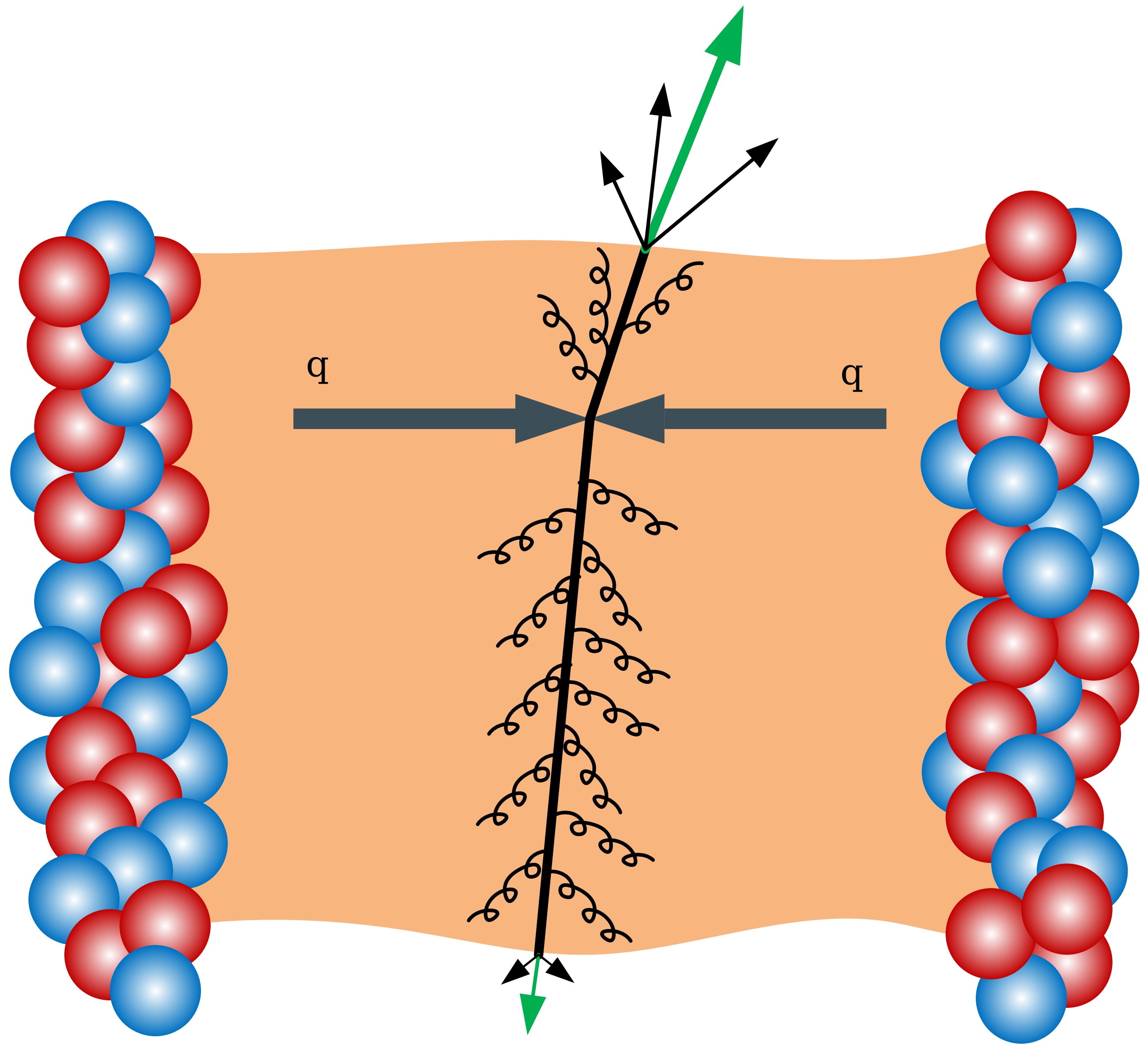
Depends on the path traveled in the medium

Flavor dependence



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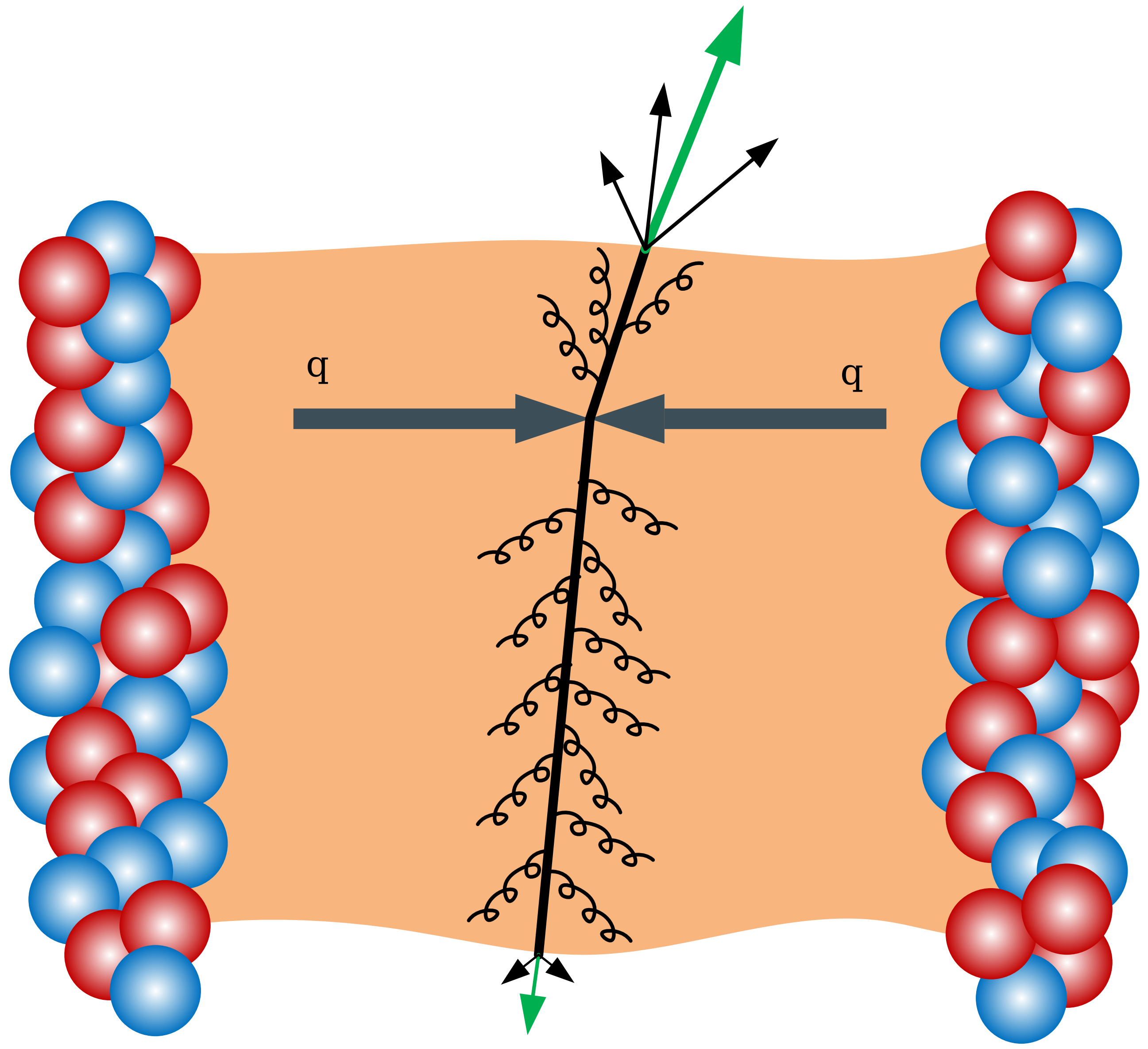

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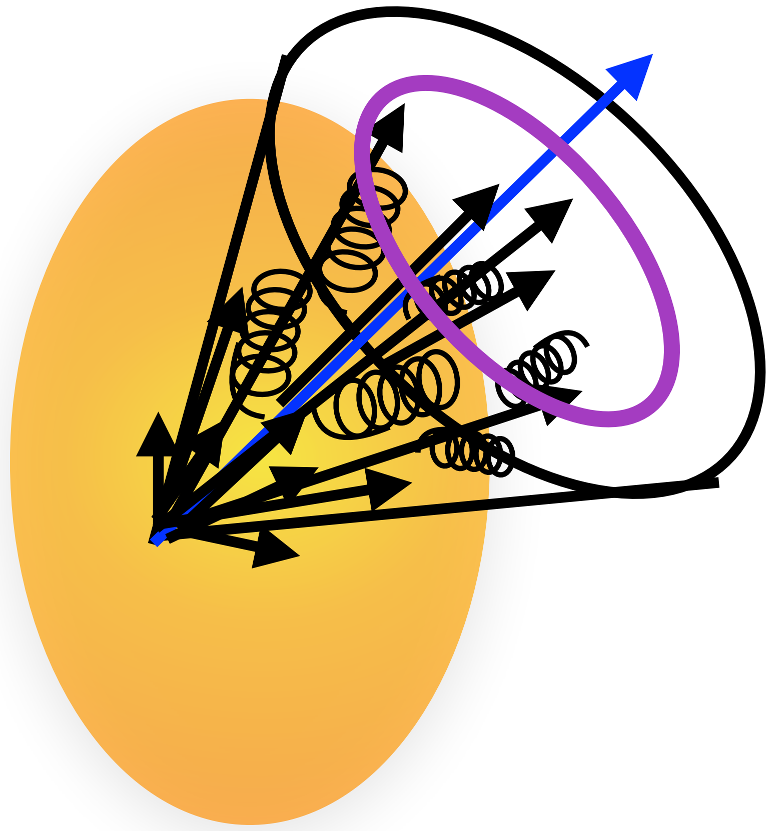
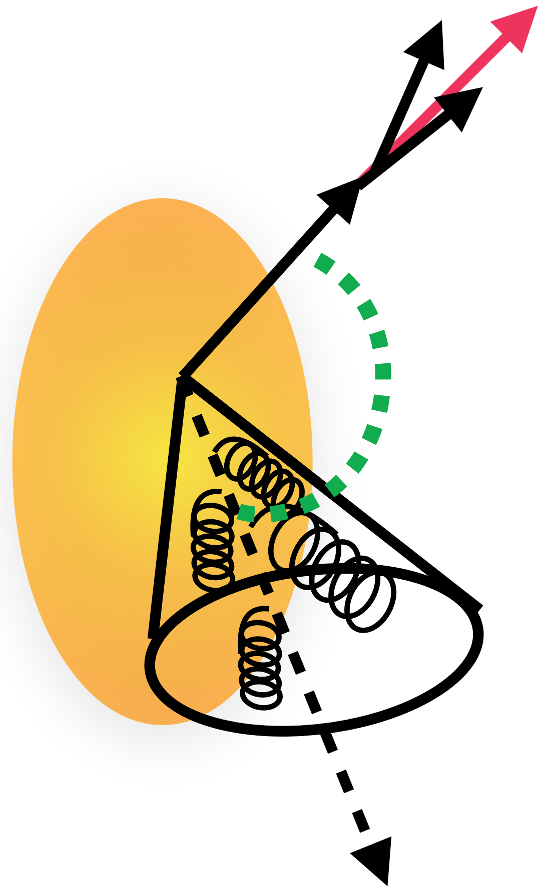
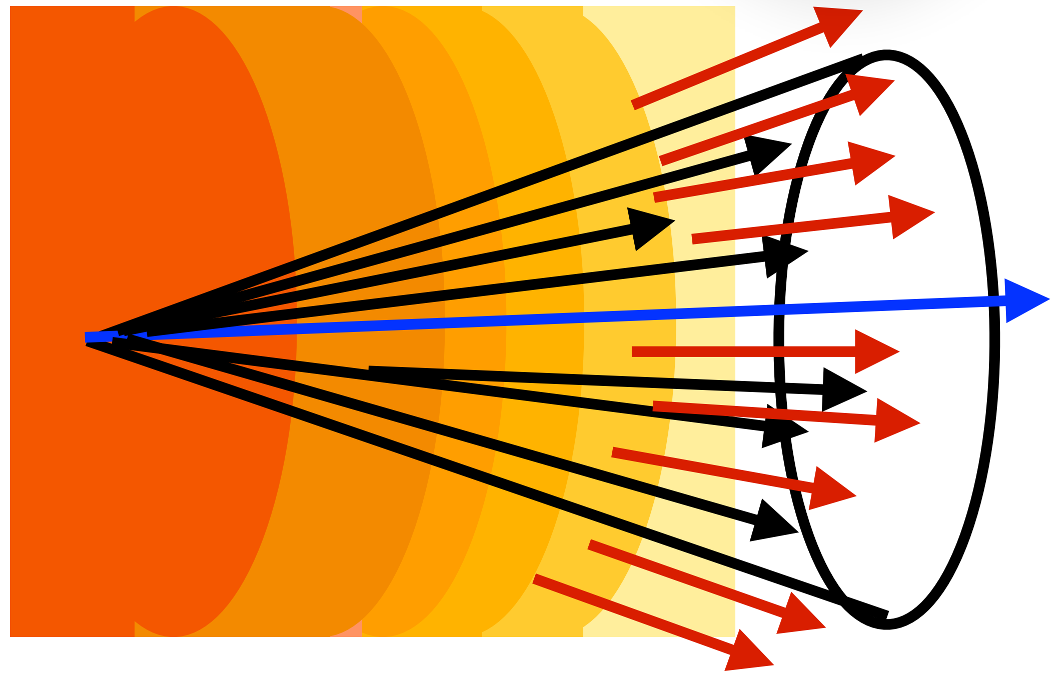
- Jet-medium interactions:



➡ Momentum broadening widens jet

➡ Wide-angle deflection



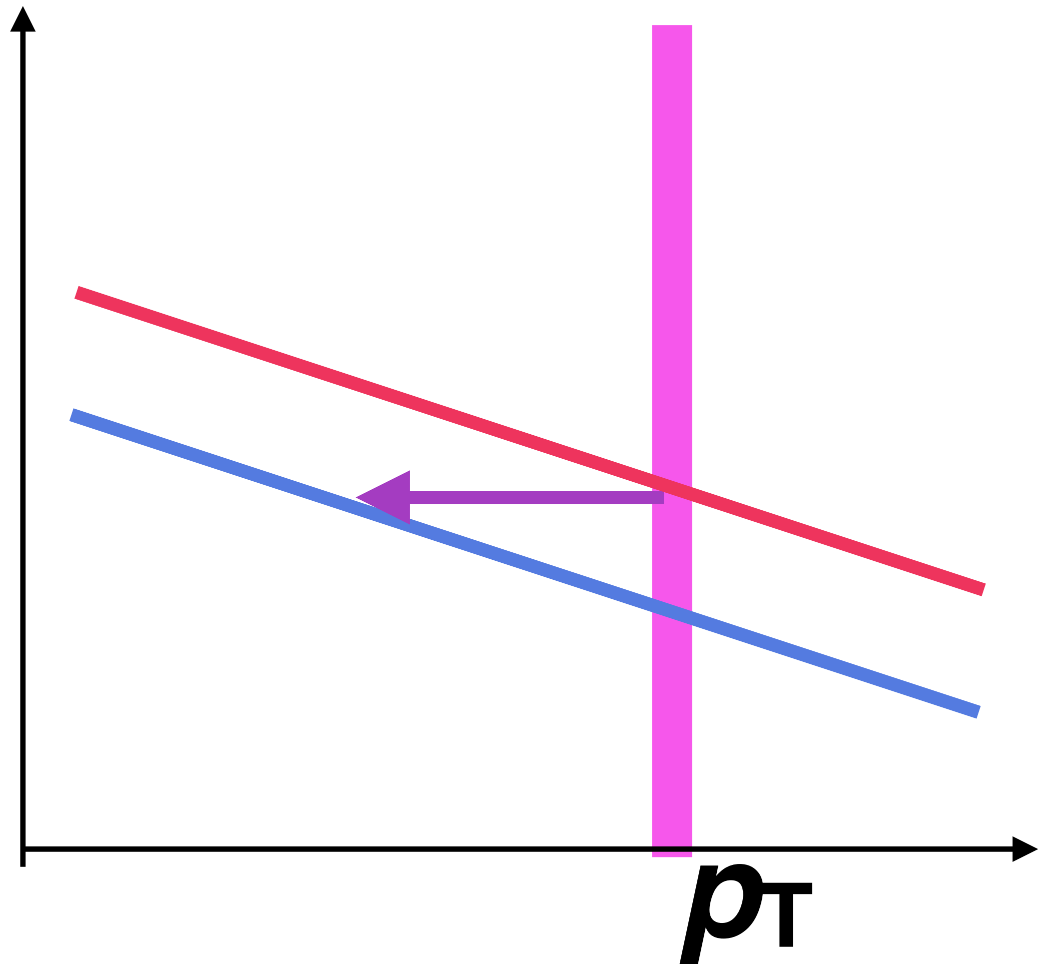


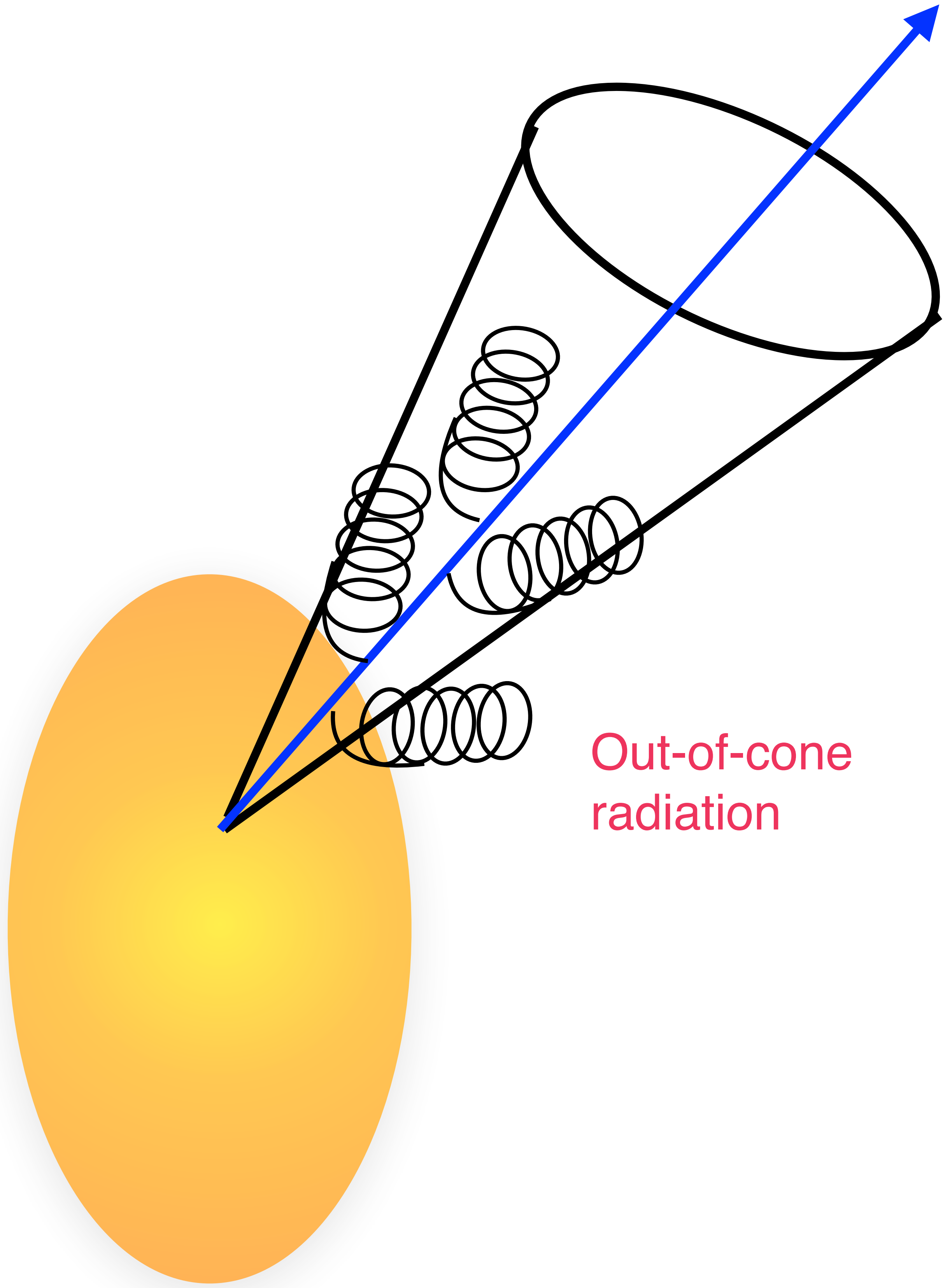
➡ Medium response, causing a wake of soft particles

Measuring jet quenching

- Measuring jet quenching includes:

➡ Energy loss through the suppression of high-p_T jet yields





Measuring jet quenching

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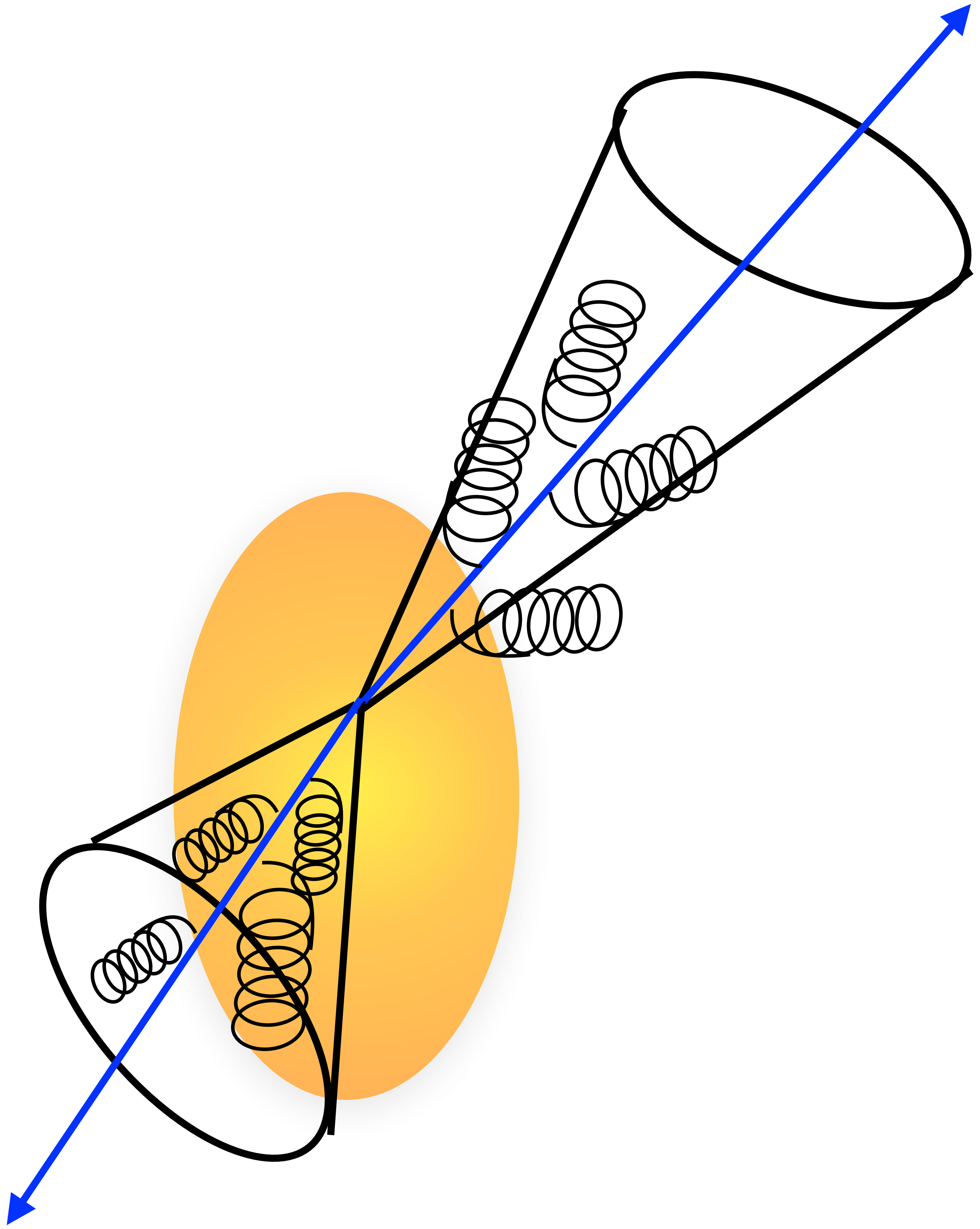


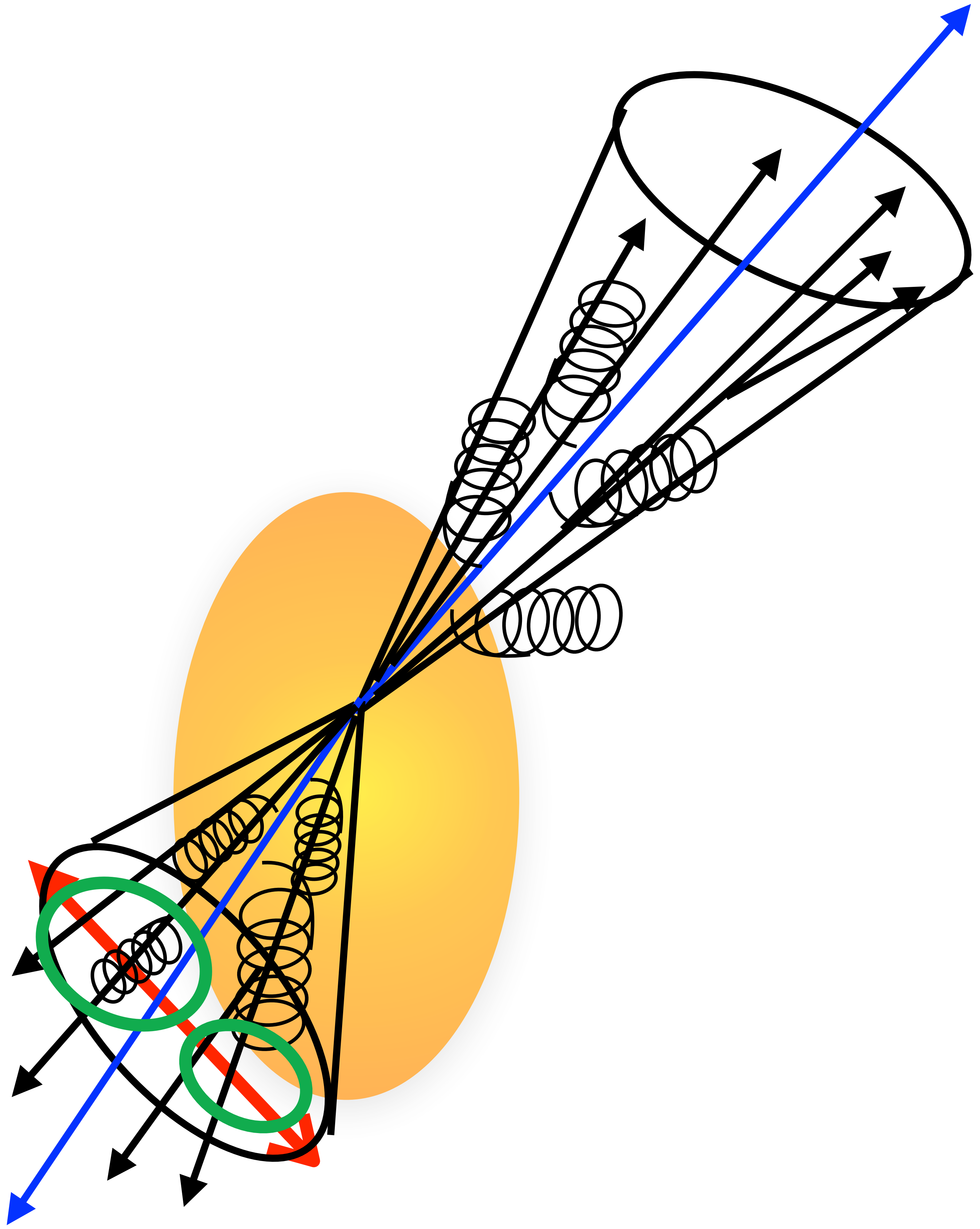
Measuring jet quenching

- Measuring jet quenching includes:

➡ Energy loss through the suppression of high-p_T jet yields

➡ Angular deflections and path length dependence through jet correlations

➡ Intra-jet modifications by measuring jet structure and substructure



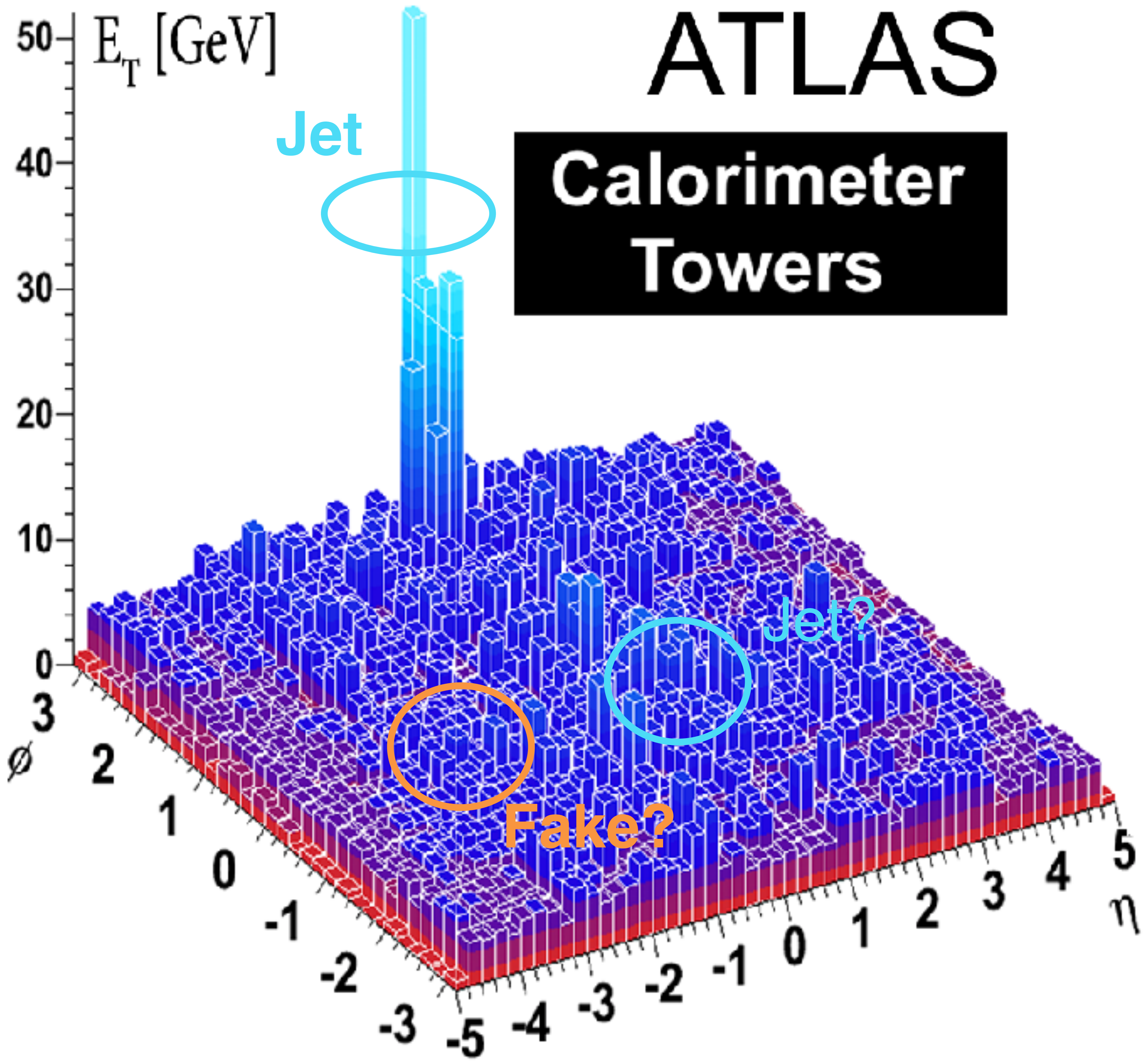
Desire to measure over a large range of scales including jet p_T and radii

Measuring jets in HIs

- Large uncorrelated background due to underlying event (UE) fluctuations can be of the order of the jet energy itself

➡ Be careful with fake jets from upward UE fluctuations (prohibits unfolding)

- Remove the background from inside the jets and then unfold to remove remaining residual fluctuations
    - Also, need to remove the fake jets



➡ Constrains how large in R and low in p_T jets can be measured and how well measurements can be unfolded for background effects

Jets at RHIC vs. LHC

- Keep in mind: not a direct comparison, kinematics and QGP medium different!

QGP at LHC hotter, denser, and longer lived than RHIC!

	RHIC	**LHC**
Center-of-Mass (√s)	3-510 GeV	2.76-5.02 TeV
Collision systems	Many species	Pb, Xe, p
Effective temperature	~220 MeV PHENIX: PRL 104 (2010) 132301	~300 MeV ALICE: PLB 754 (2016) 235-248
Detectors	STAR, PHENIX, sPHENIX	ALICE, ATLAS, CMS, LHCb

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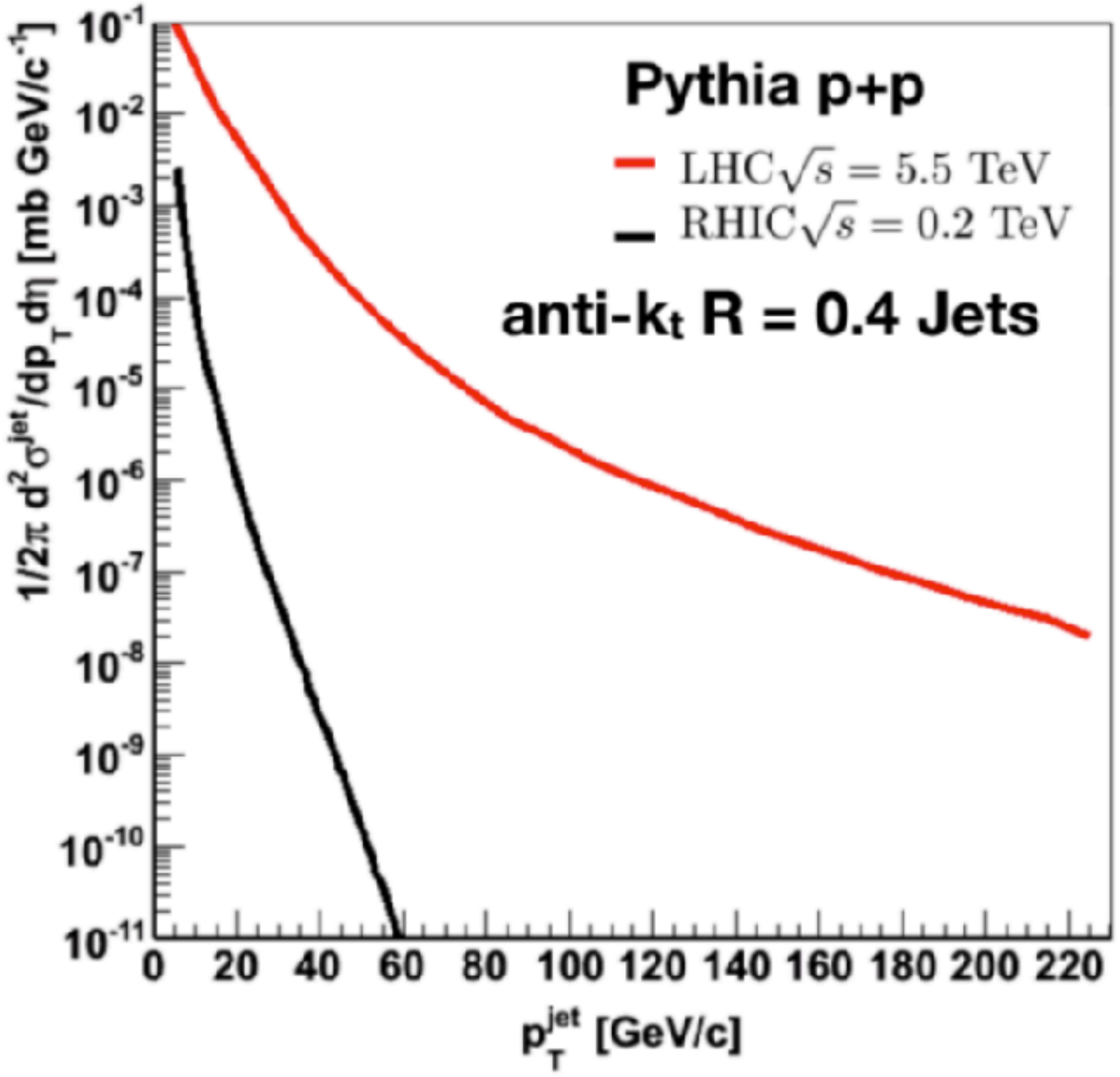

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Jet spectra at RHIC is steeper and contains a higher quark fraction at the same p_T.

Measuring jet quenching

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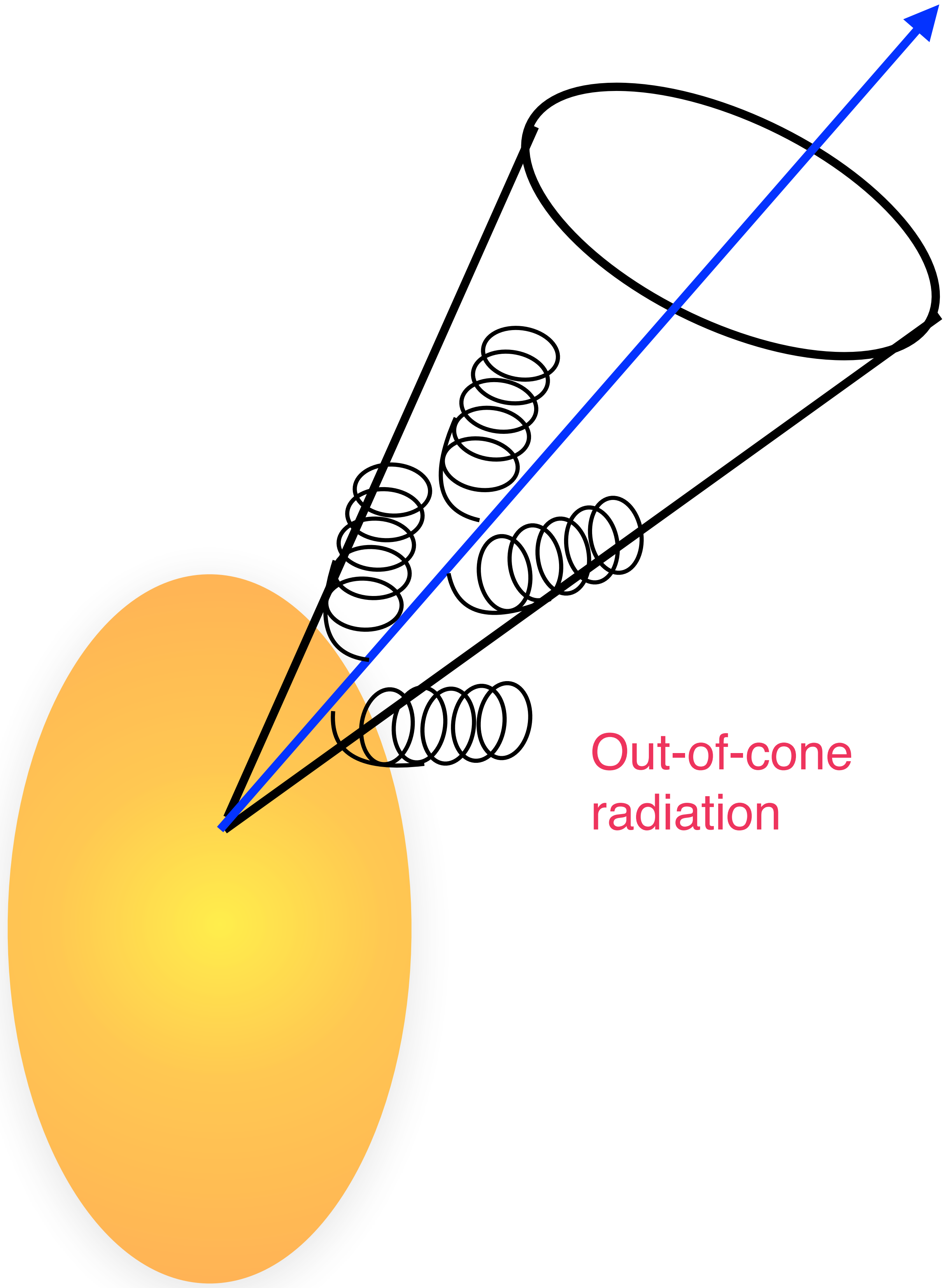

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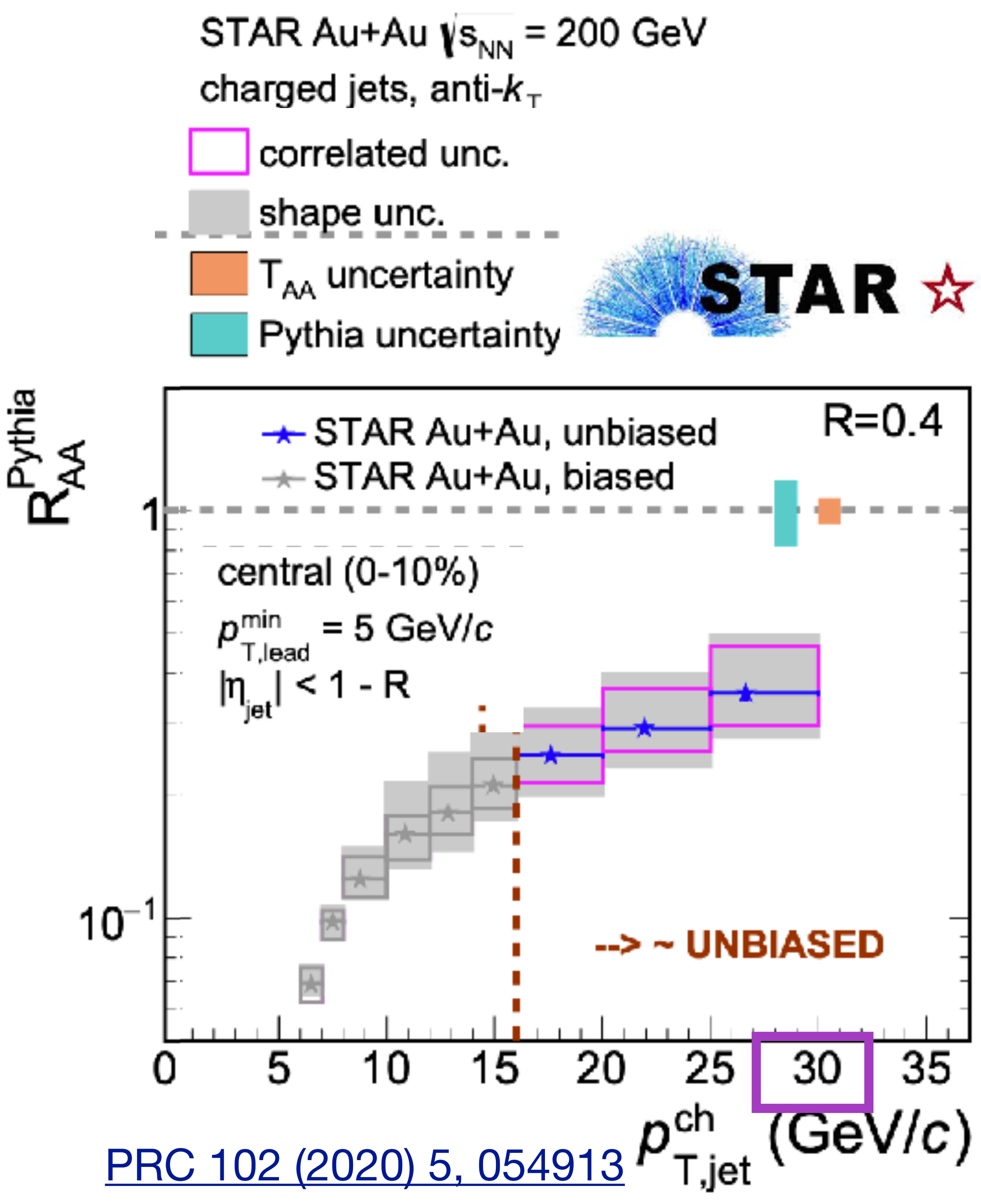
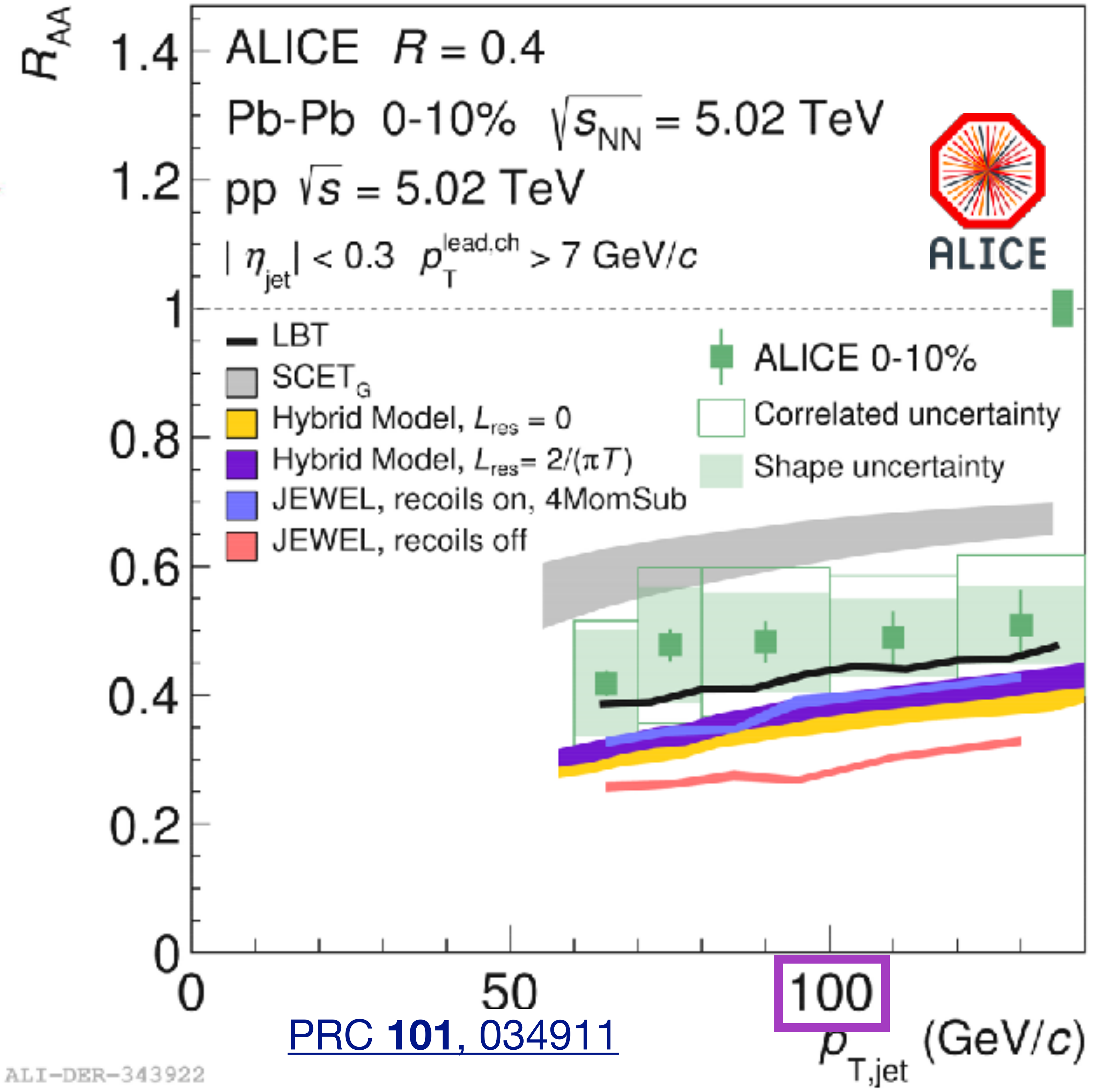
Inclusive jet suppression

- Inclusive jet suppression over a large jet p_T range

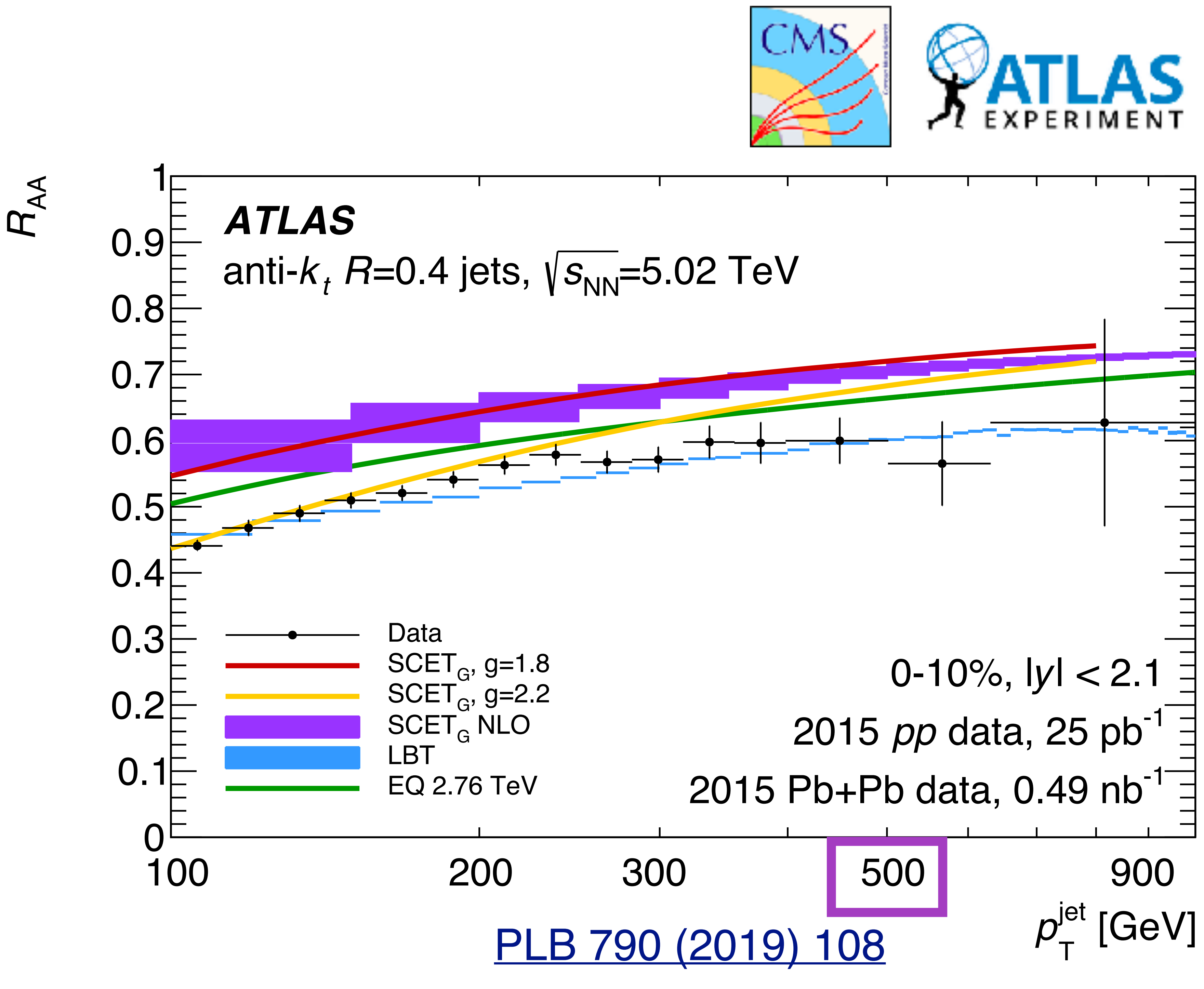
$$R_{AA} = \frac{\text{Pb-Pb}}{\text{scaled}\otimes\text{pp}}$$



PRC 102 (2020) 5, 054913



PRC **101**, 034911



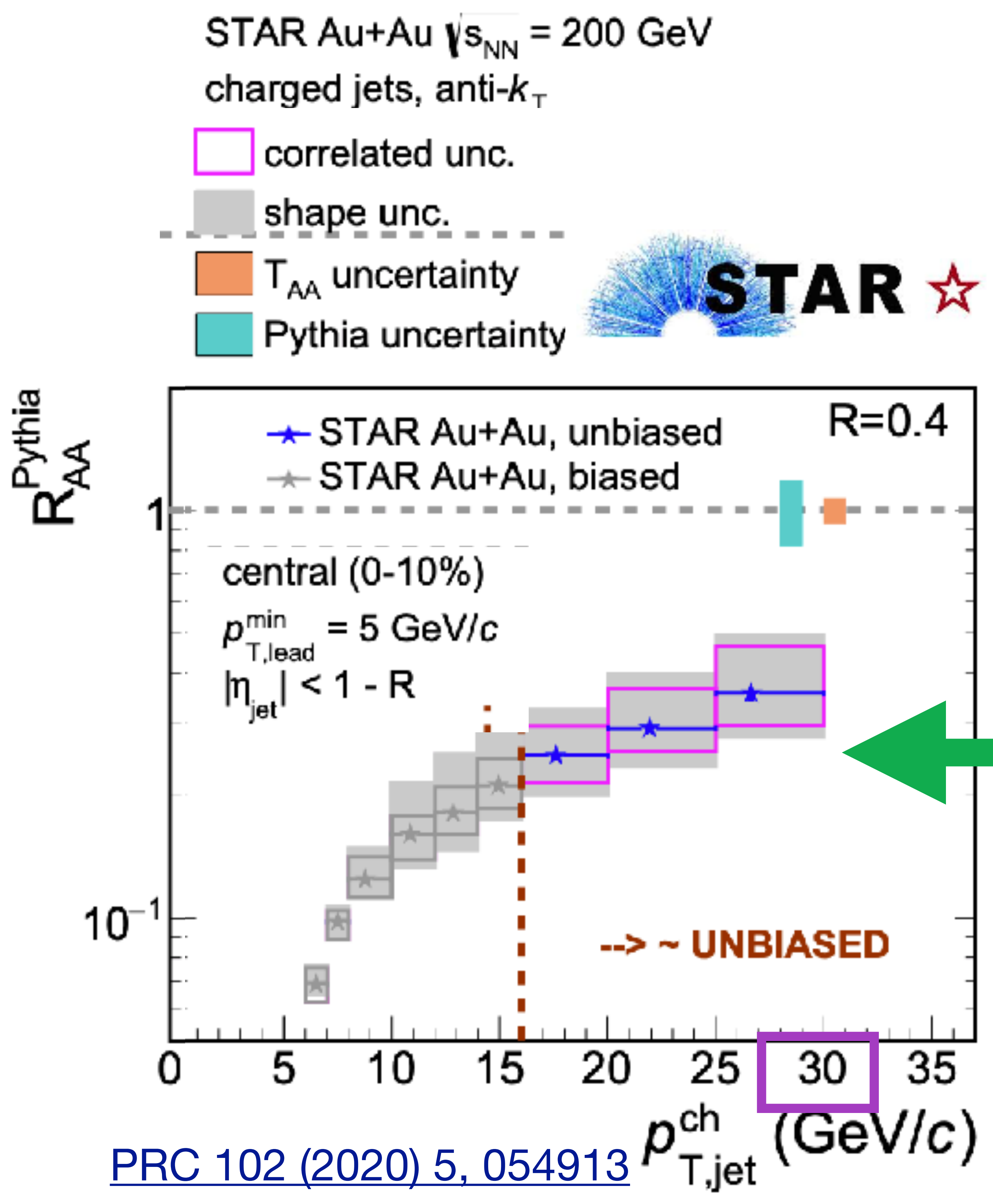
PLB 790 (2019) 108

Inclusive jet suppression

- Inclusive jet suppression over a large jet p_T range

➡HI underlying event constrains measurements at larger *R* and lower p_T

$$R_{AA} = \frac{\text{Pb-Pb}}{\text{scaled}\otimes\text{pp}}$$



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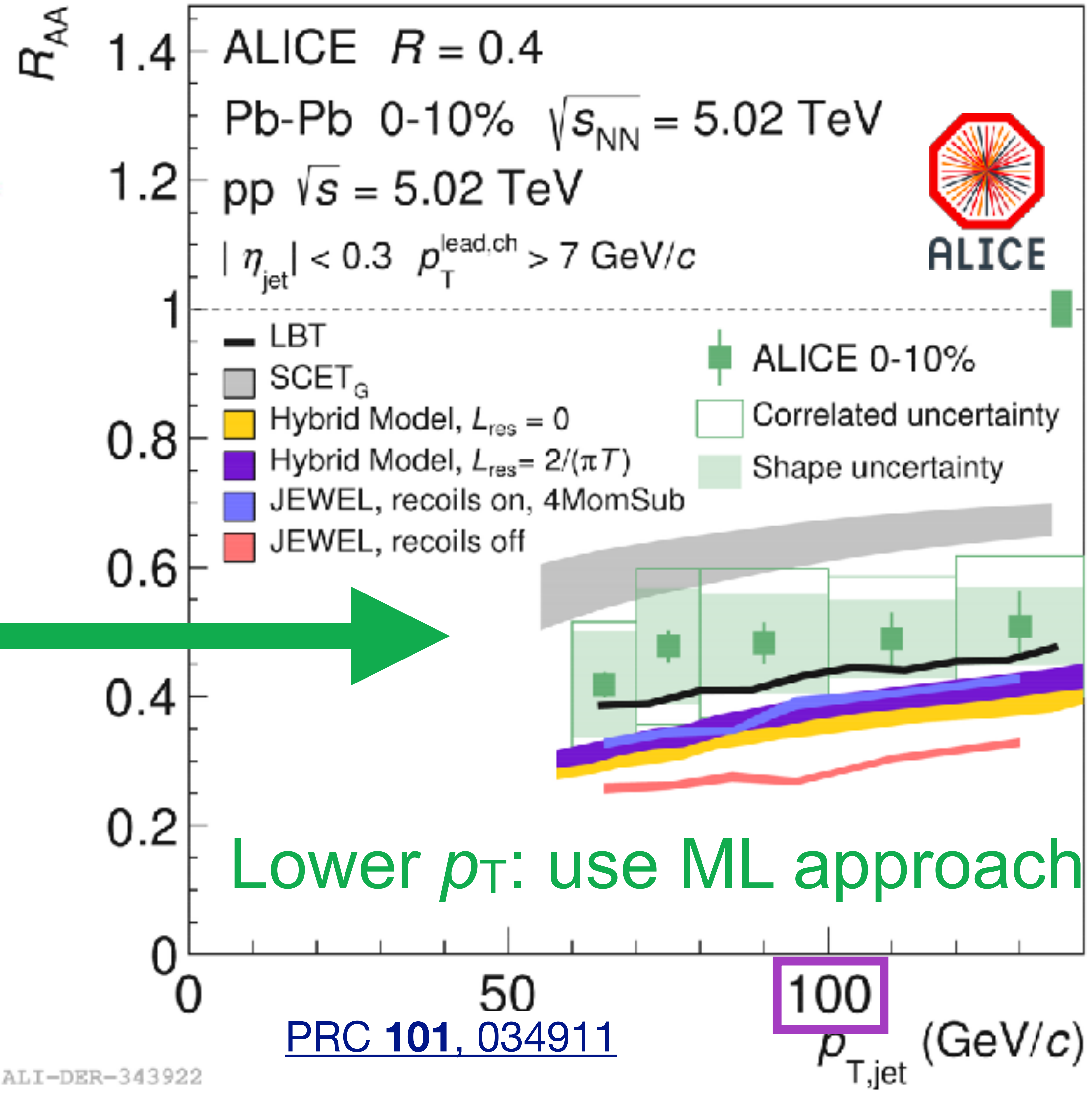
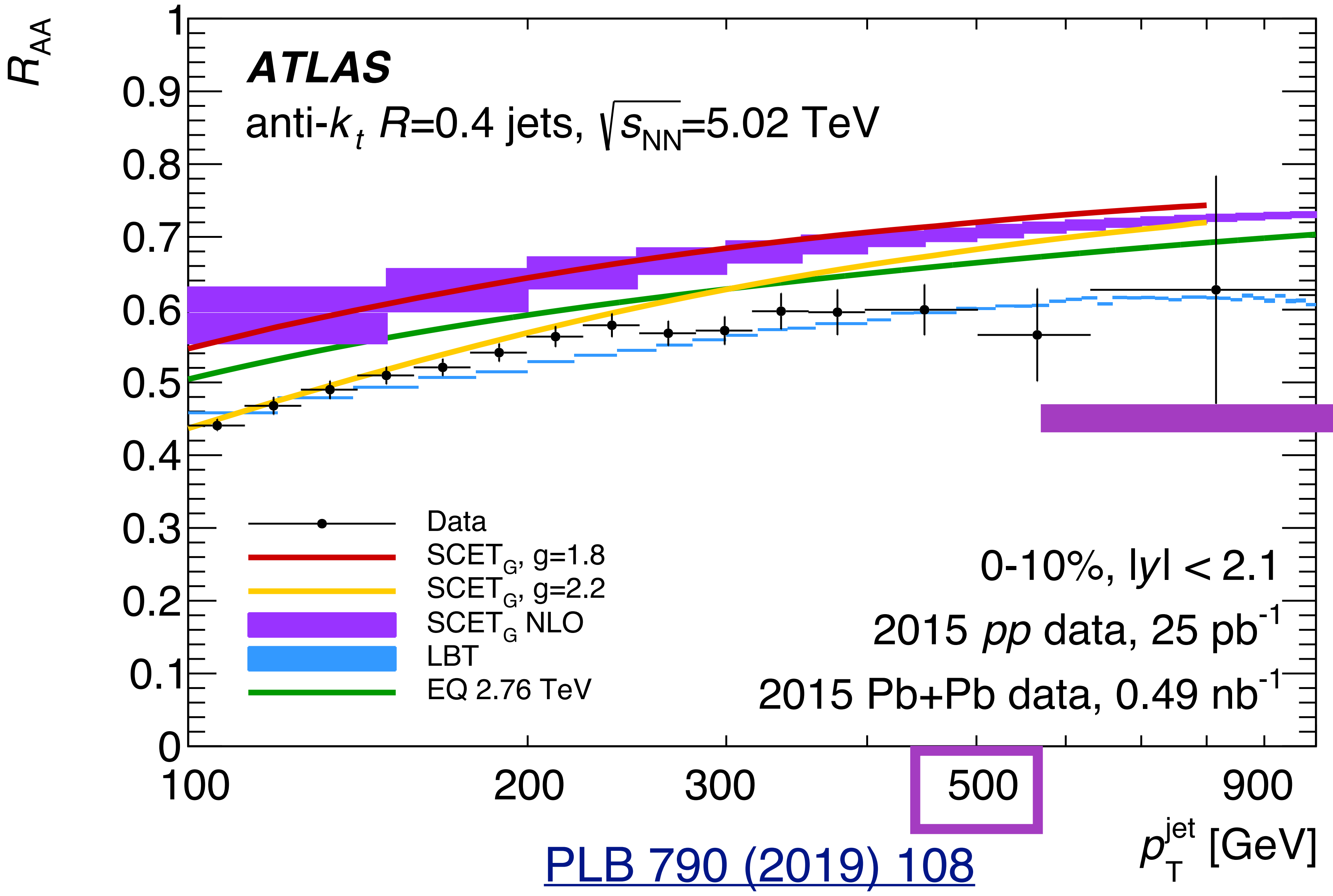


Lower p_T: use ML approach

PRC **101**, 034911

Larger R: use higher p_T



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Inclusive jet suppression

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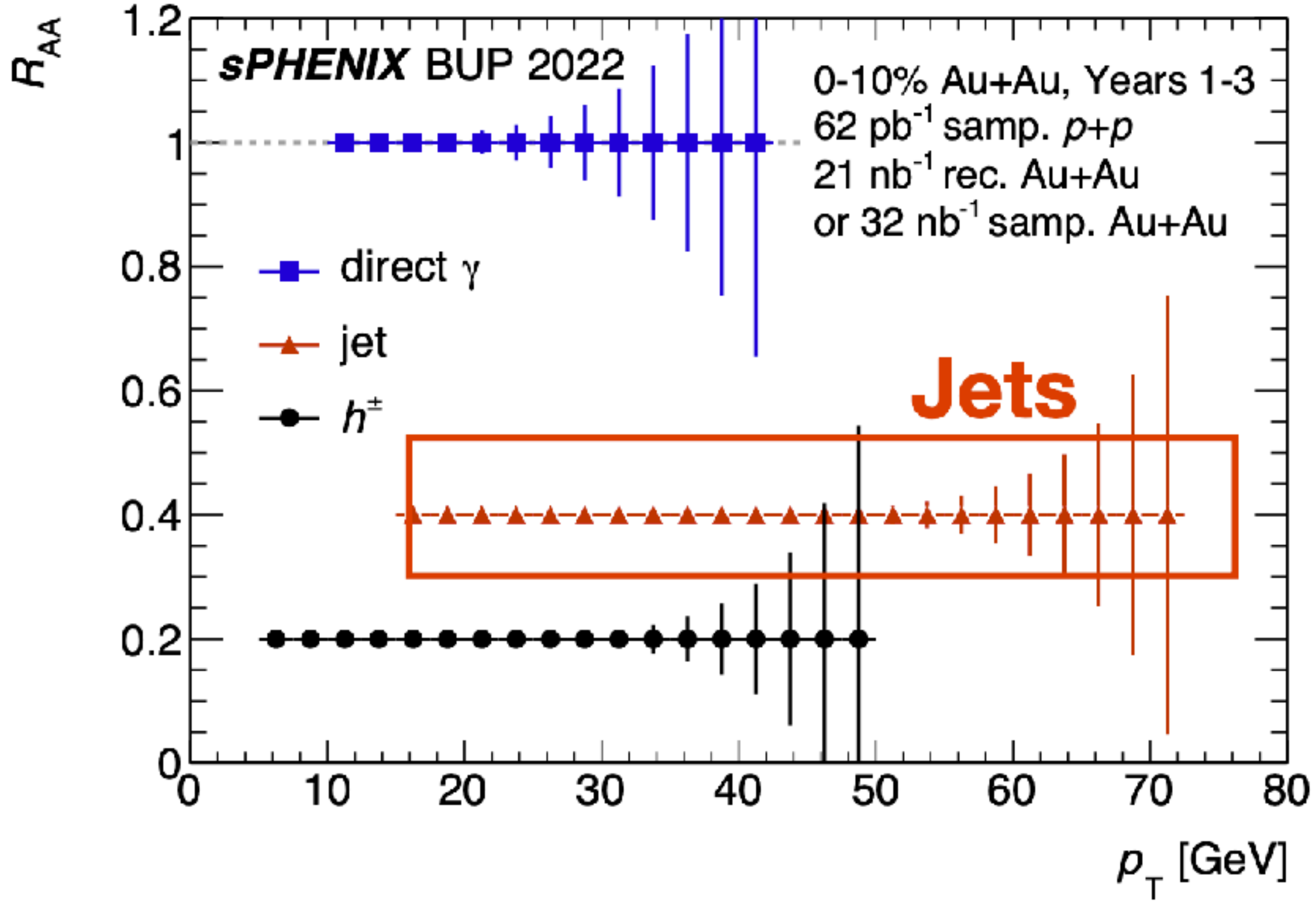
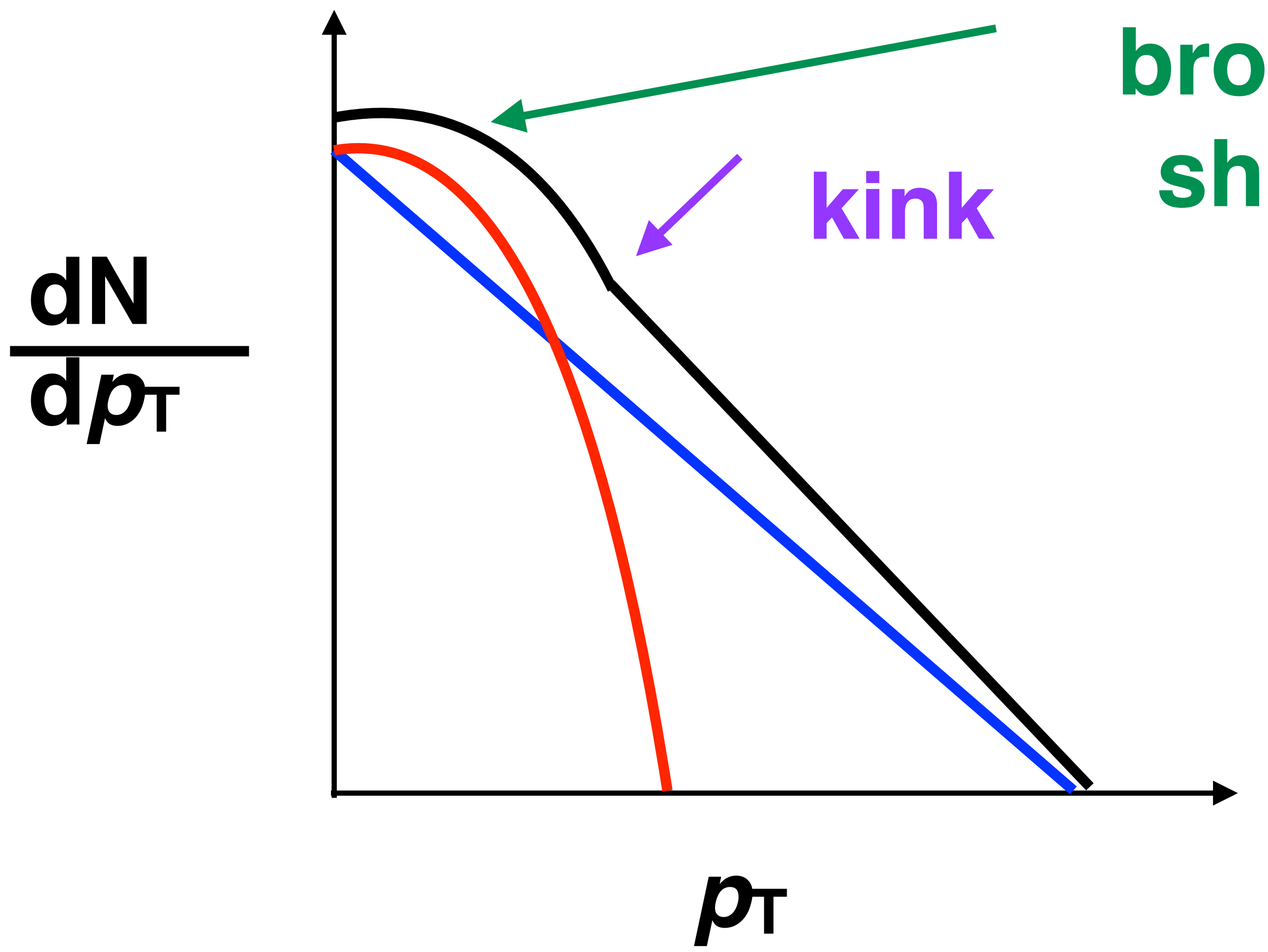


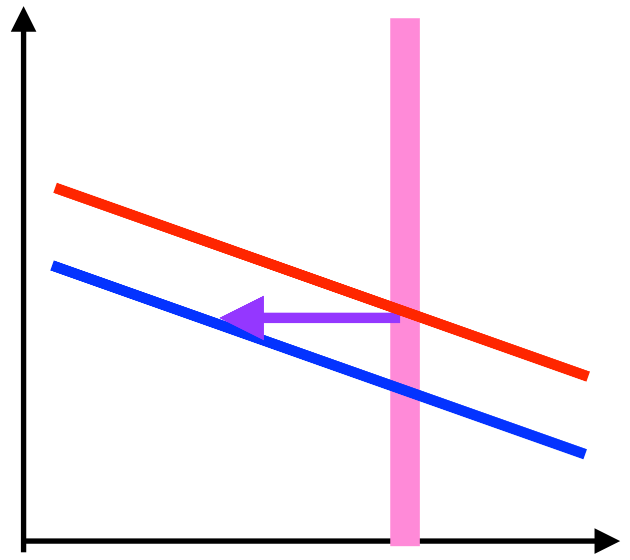
Overlap between ~50-70 GeV/c

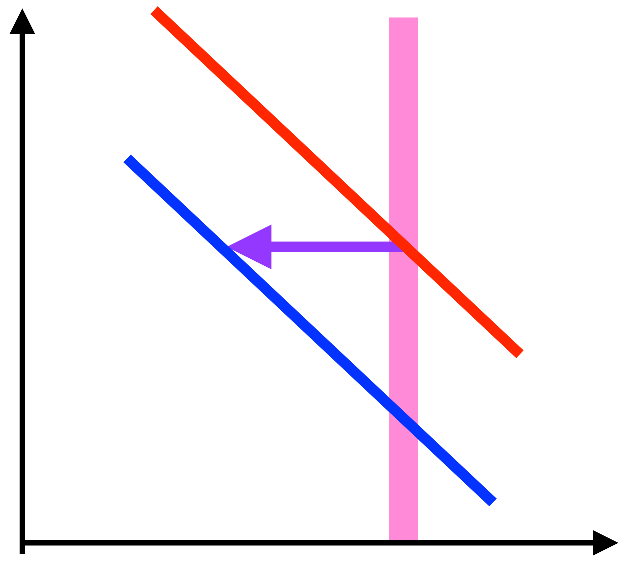
Signal/background higher in this region at LHC than RHIC

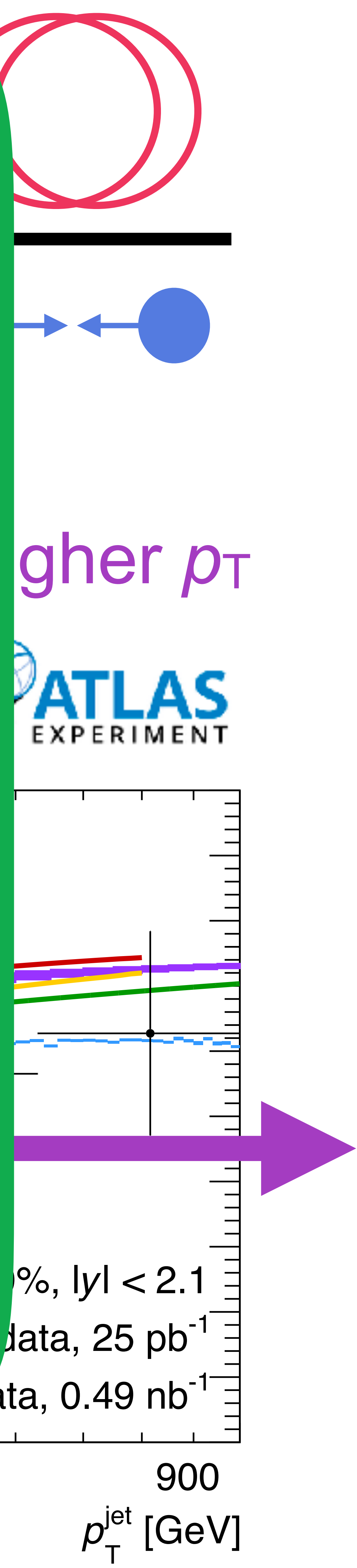
data = fake+real

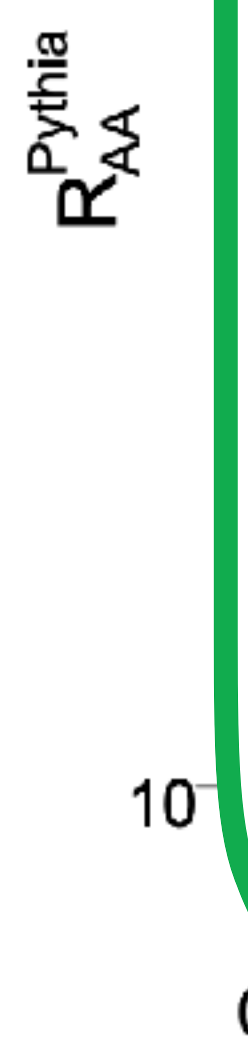


Steeper spectra at RHIC: same amount of e-loss-> lower R_{AA}









$p^{ch}_{T,jet}$ (GeV/c) 0 50 100 $p_{T,jet}$ (GeV/c)

ALI-DER-343922

PRC 102 (2020) 5, 054913

PRC **101**, 034911

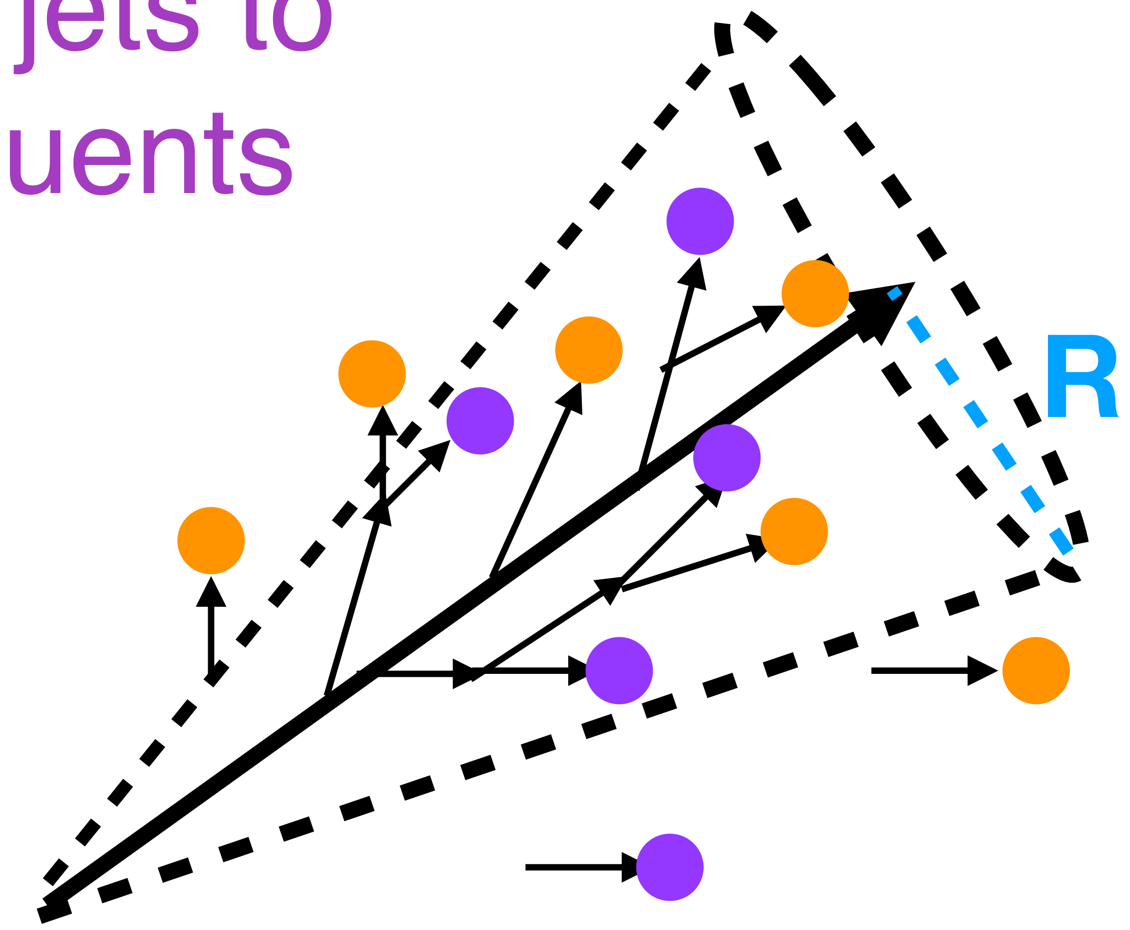
PLB 790 (2019) 108

Haake, Loizides PRC 99, 064904 (2019)

Machine learning approach

- Conventional approach: area-based method removes average pedestal background with leading track bias to suppress fakes
- ML approach: learns on PYTHIA jets to correct the jet p_T using jet constituents

Introduces a fragmentation bias: systematic uncertainty



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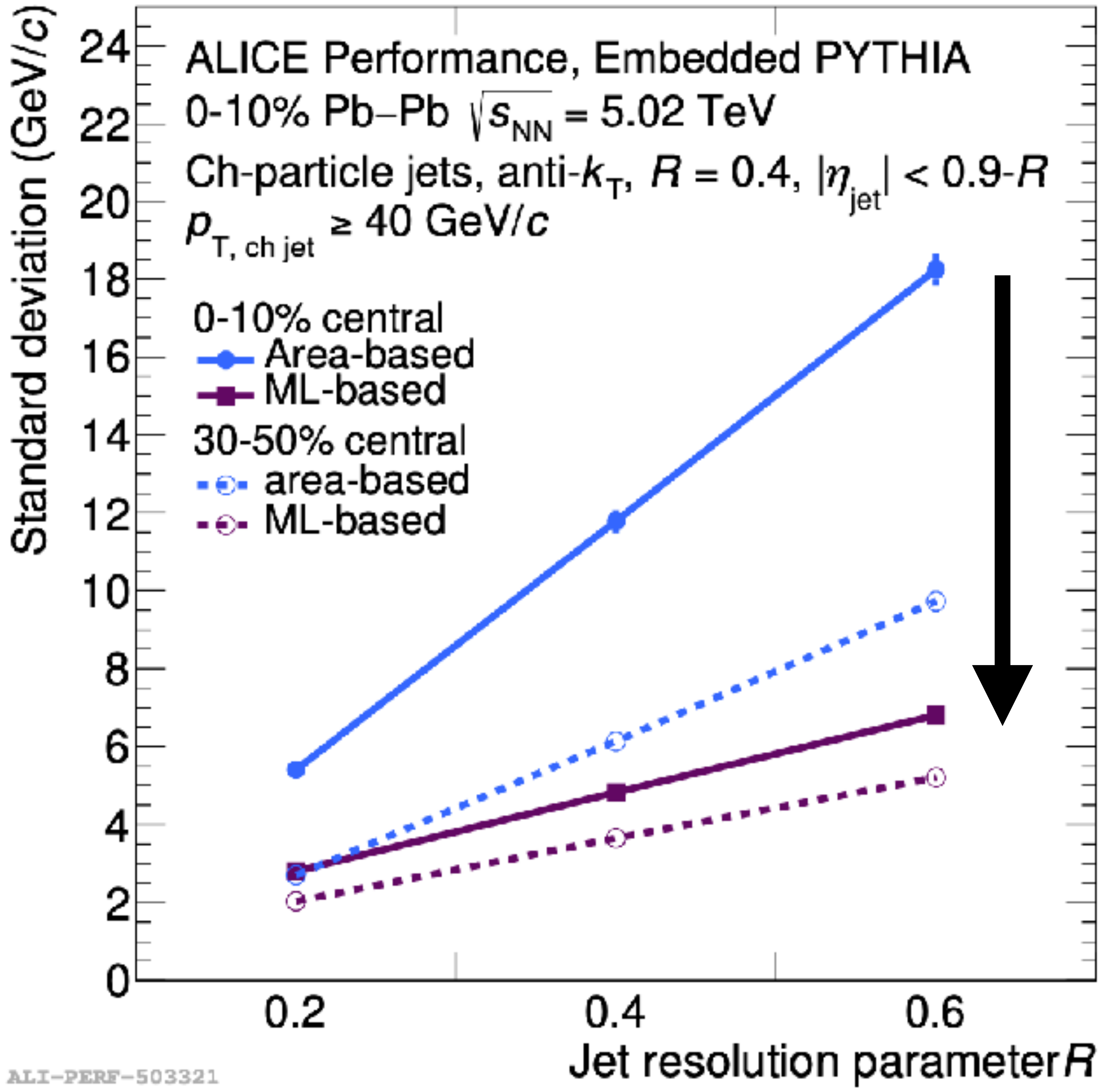

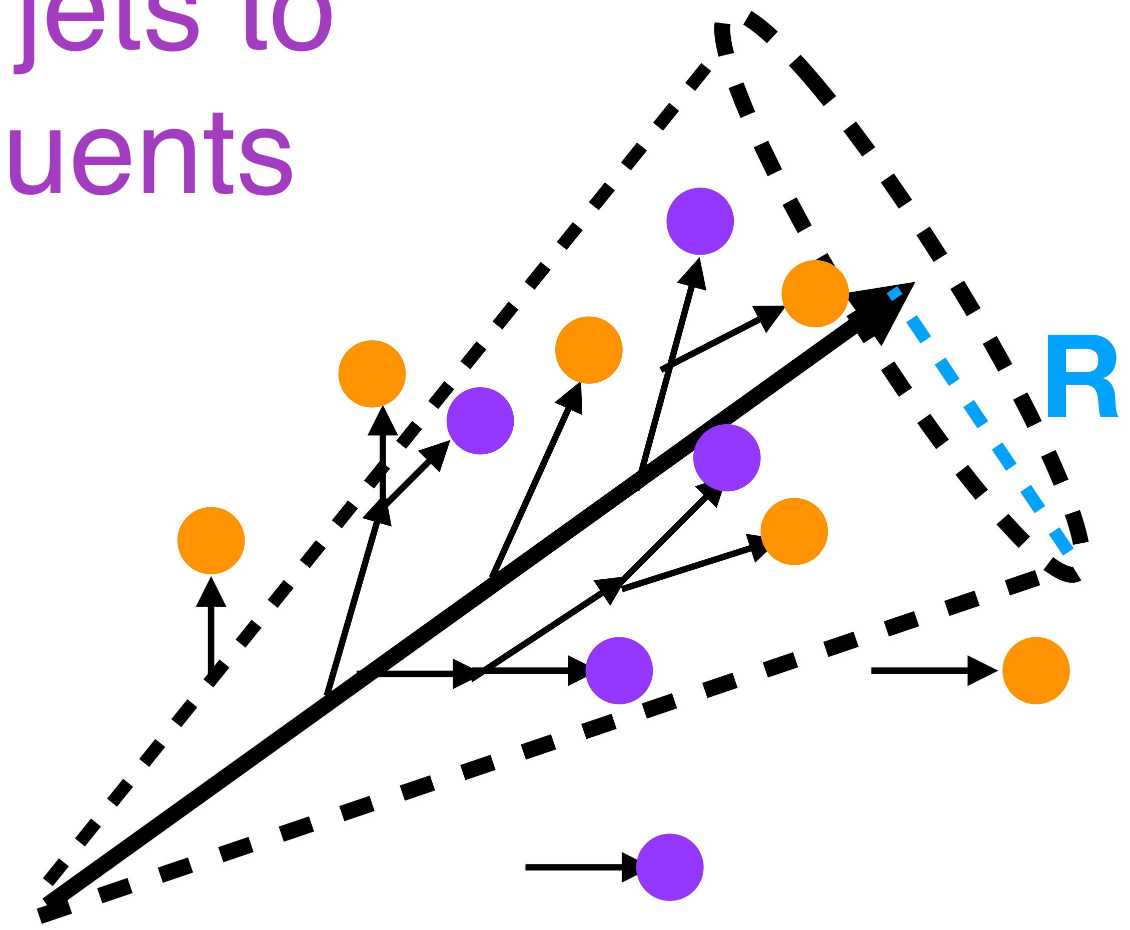

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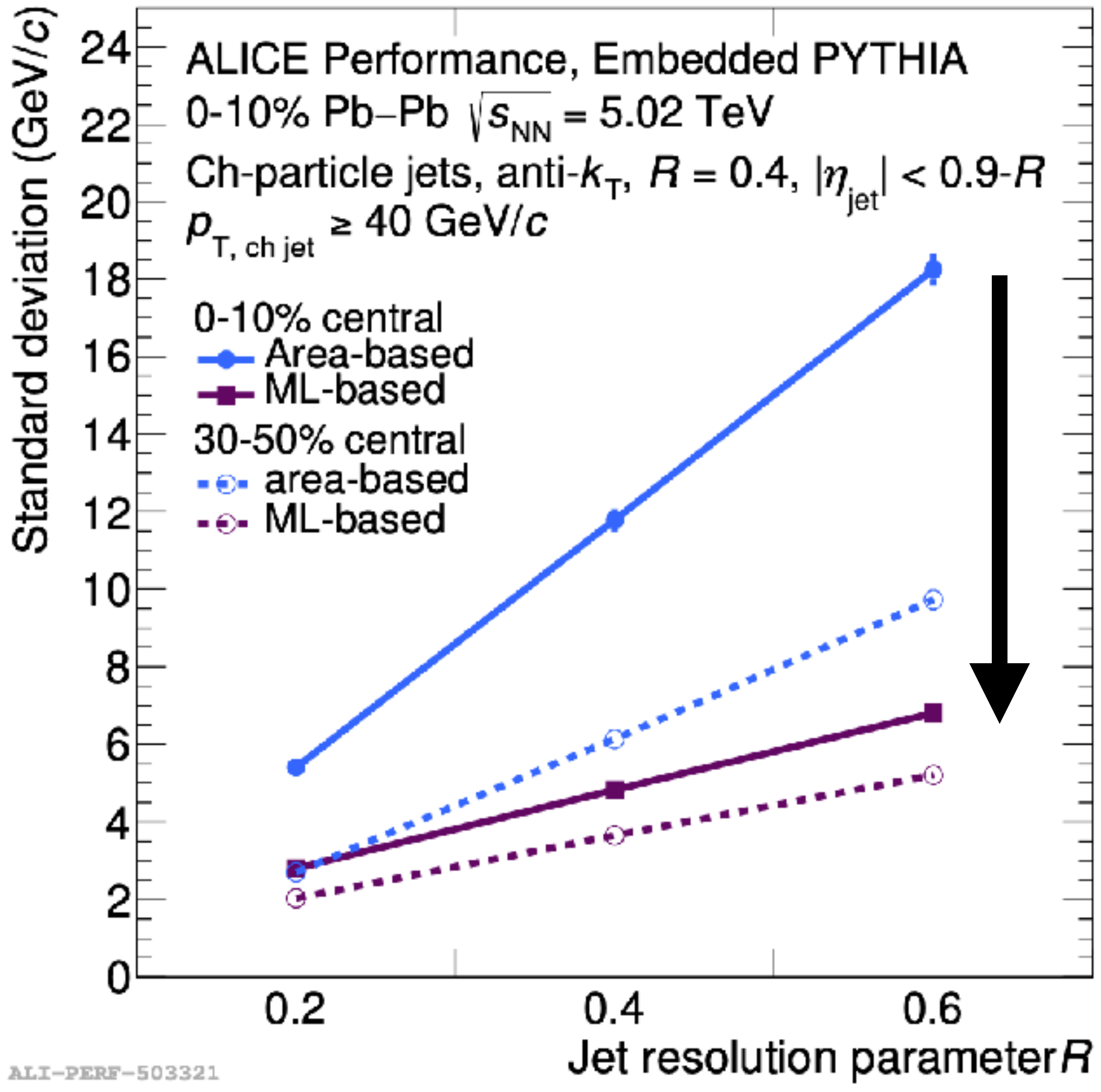
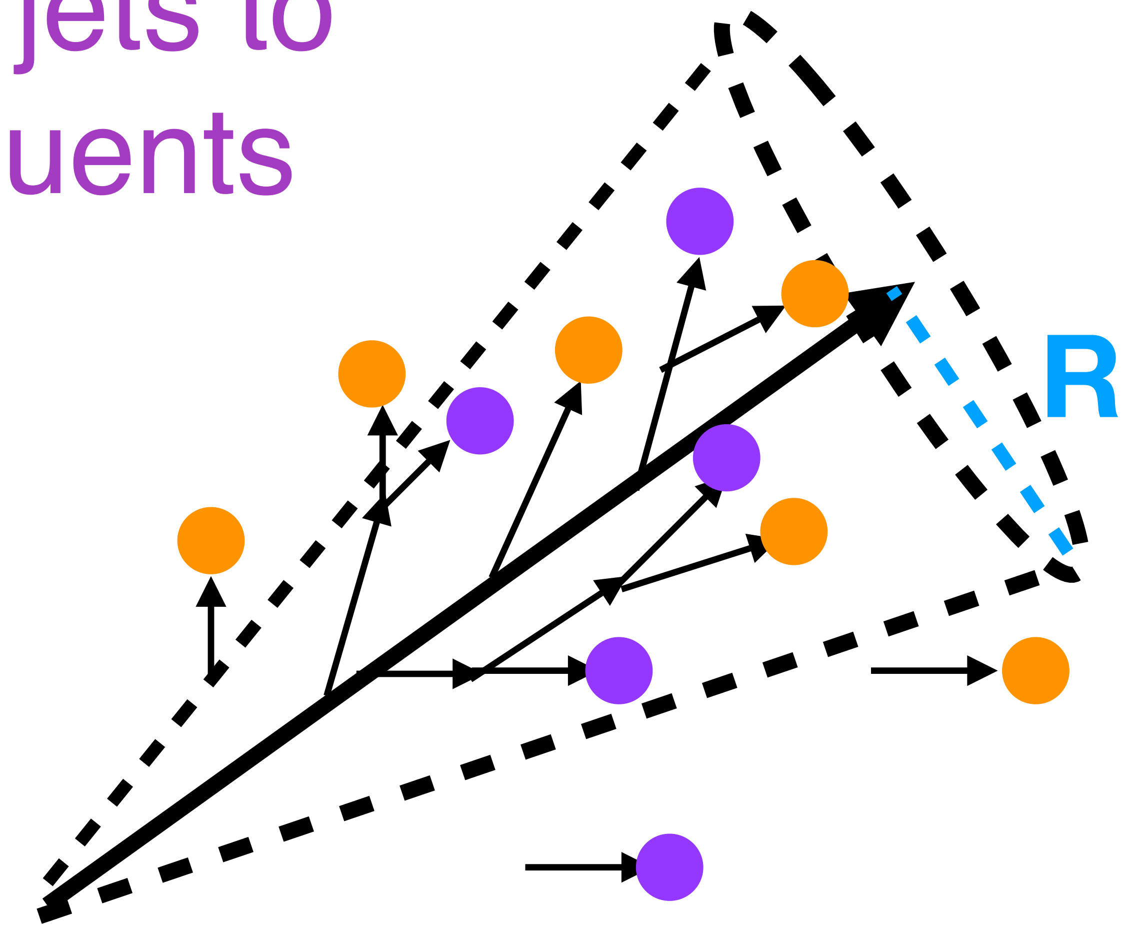
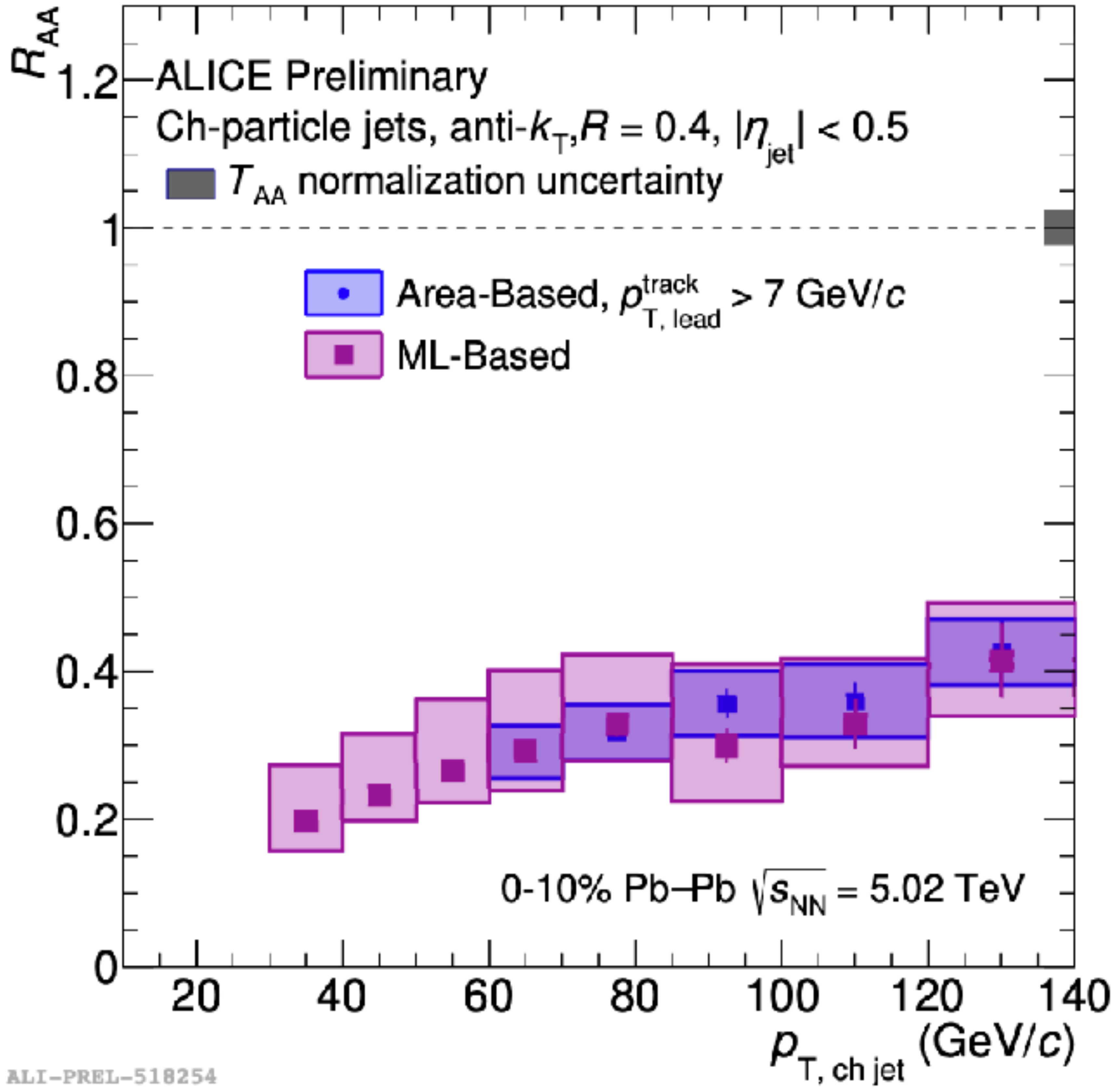


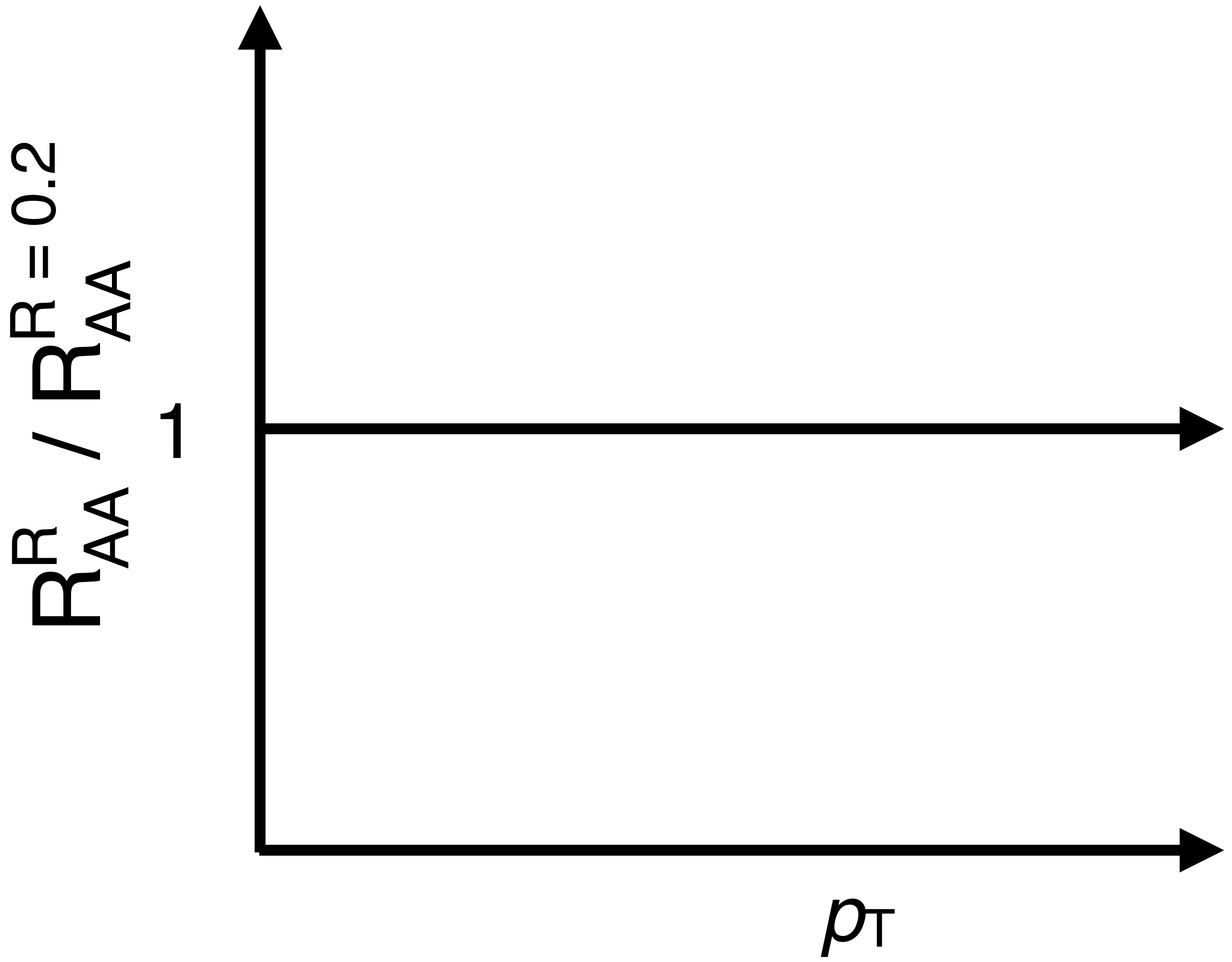


- ML-based and AB-method are consistent



R-dependence of jet suppression

- Compare R_{AA} at larger R to R_{AA} at R=0.2
  - Scanning R=0.2 to 0.6!



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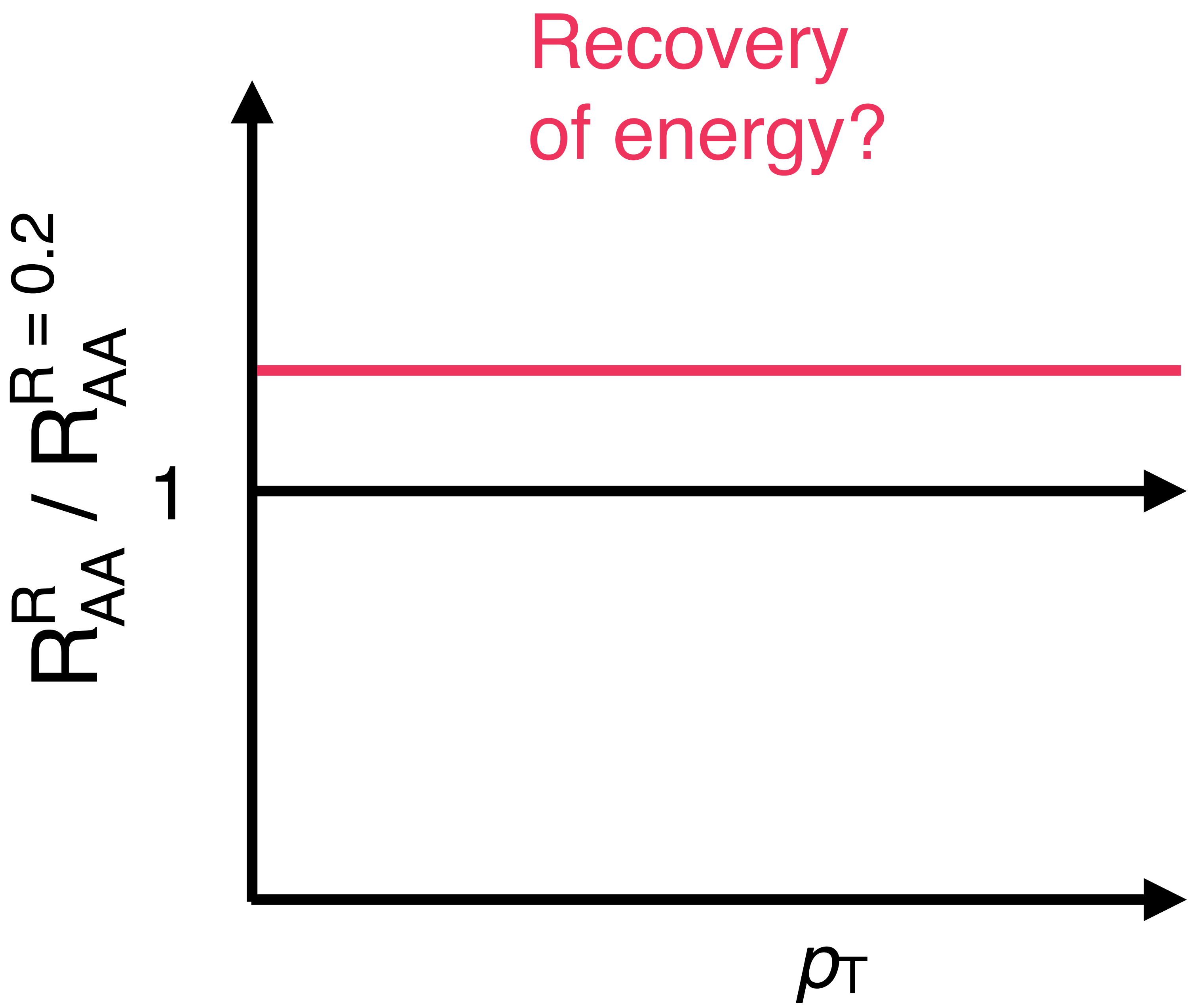

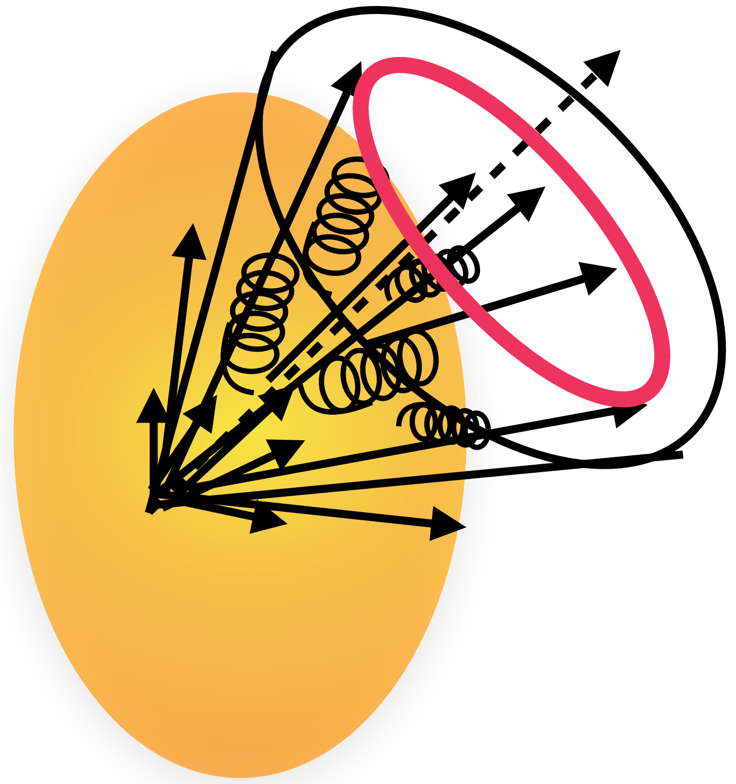

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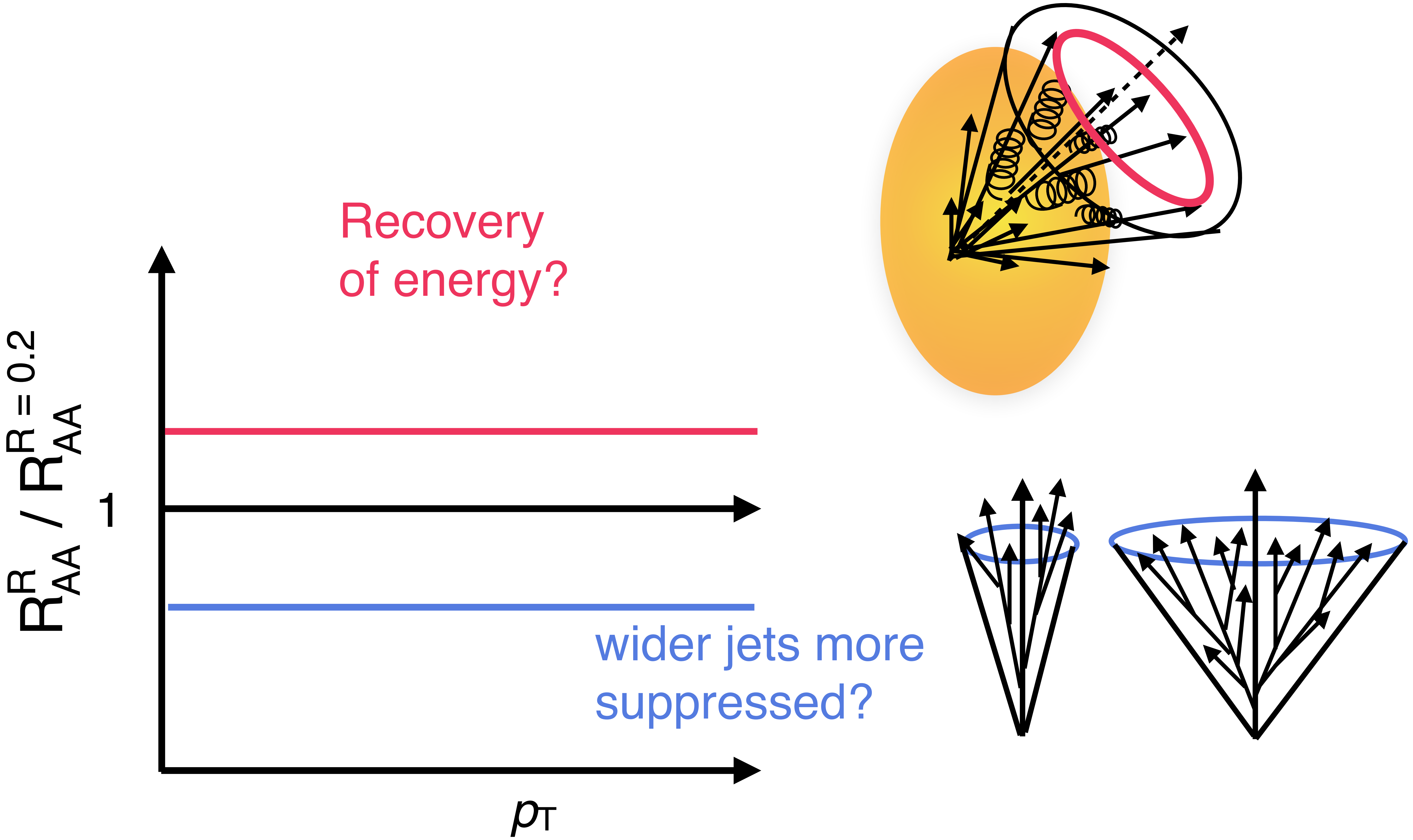

Recovery of energy?

wider jets more suppressed?

R-dependence of jet suppression

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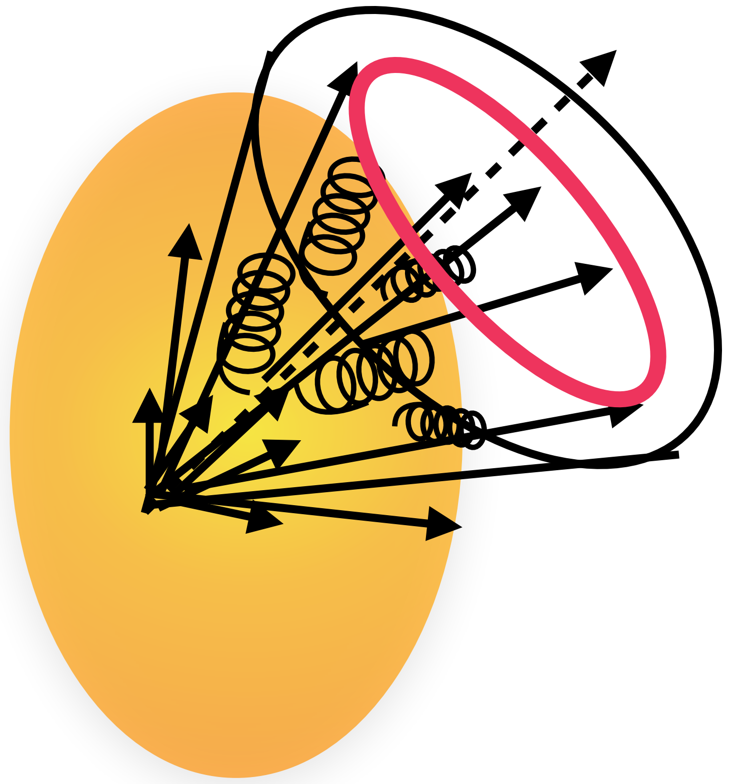

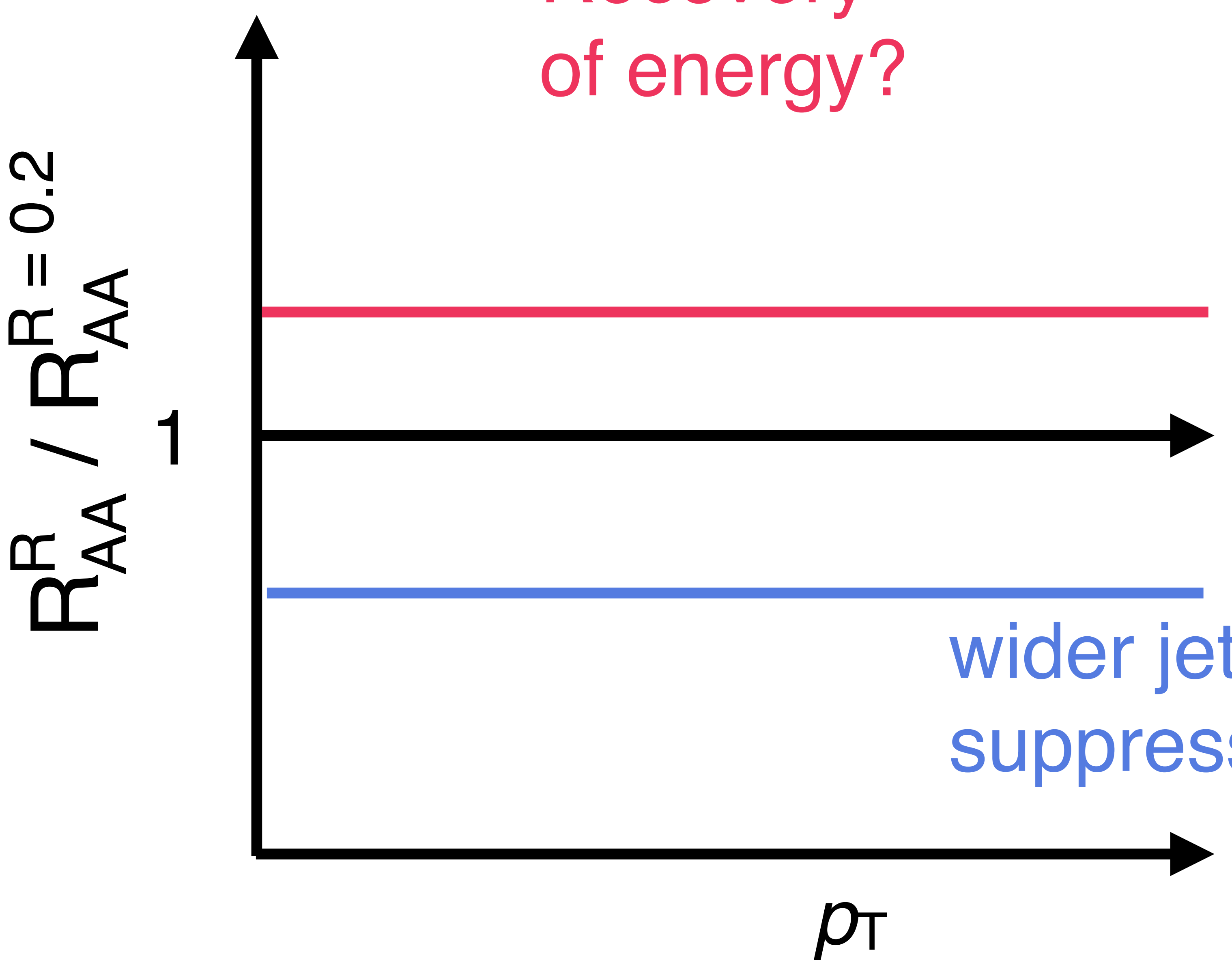

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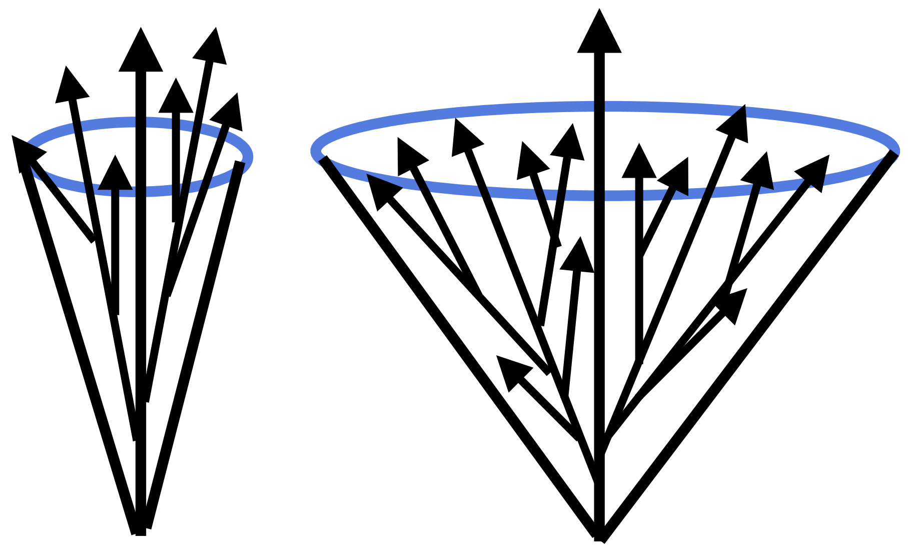
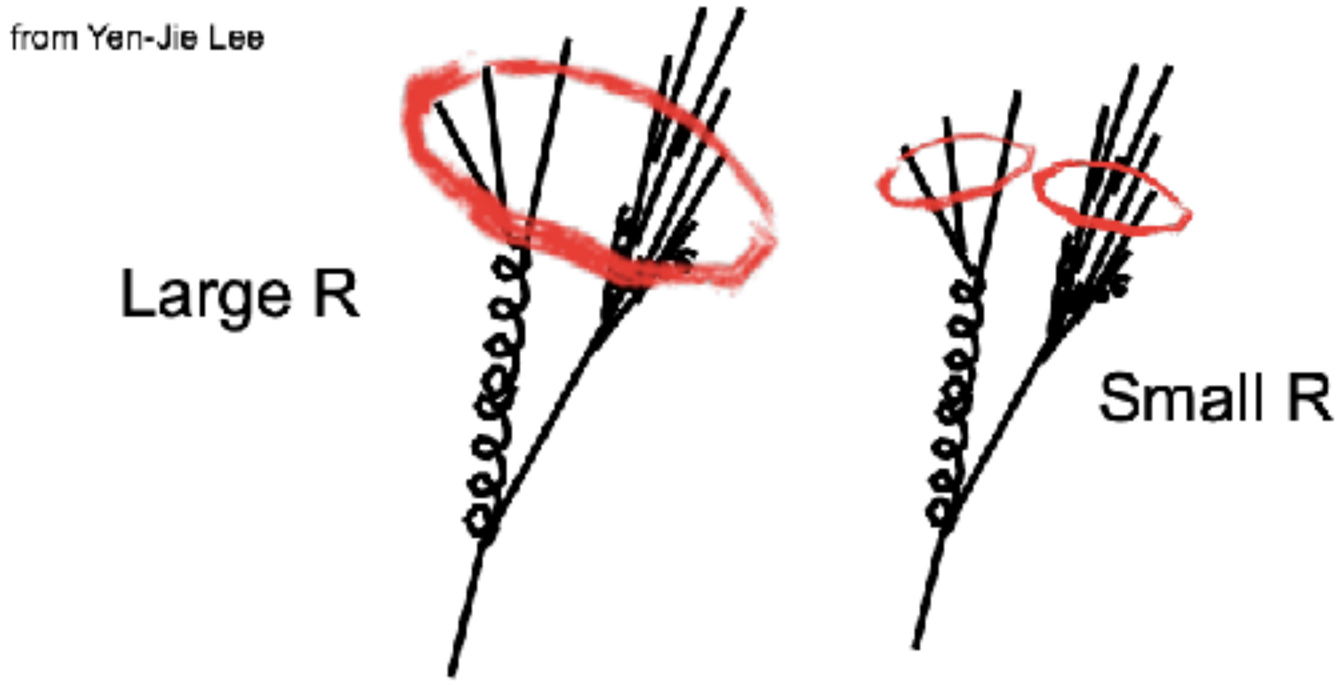
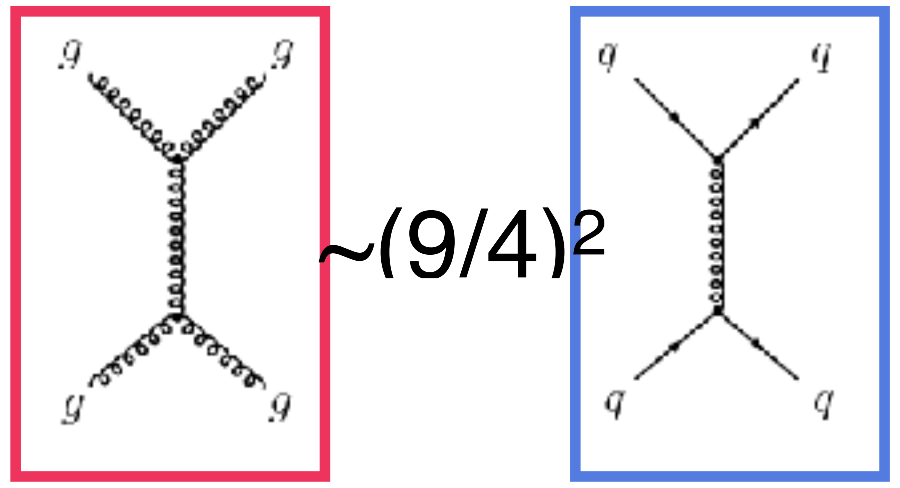


wider jets more suppressed?

Different jet populations?

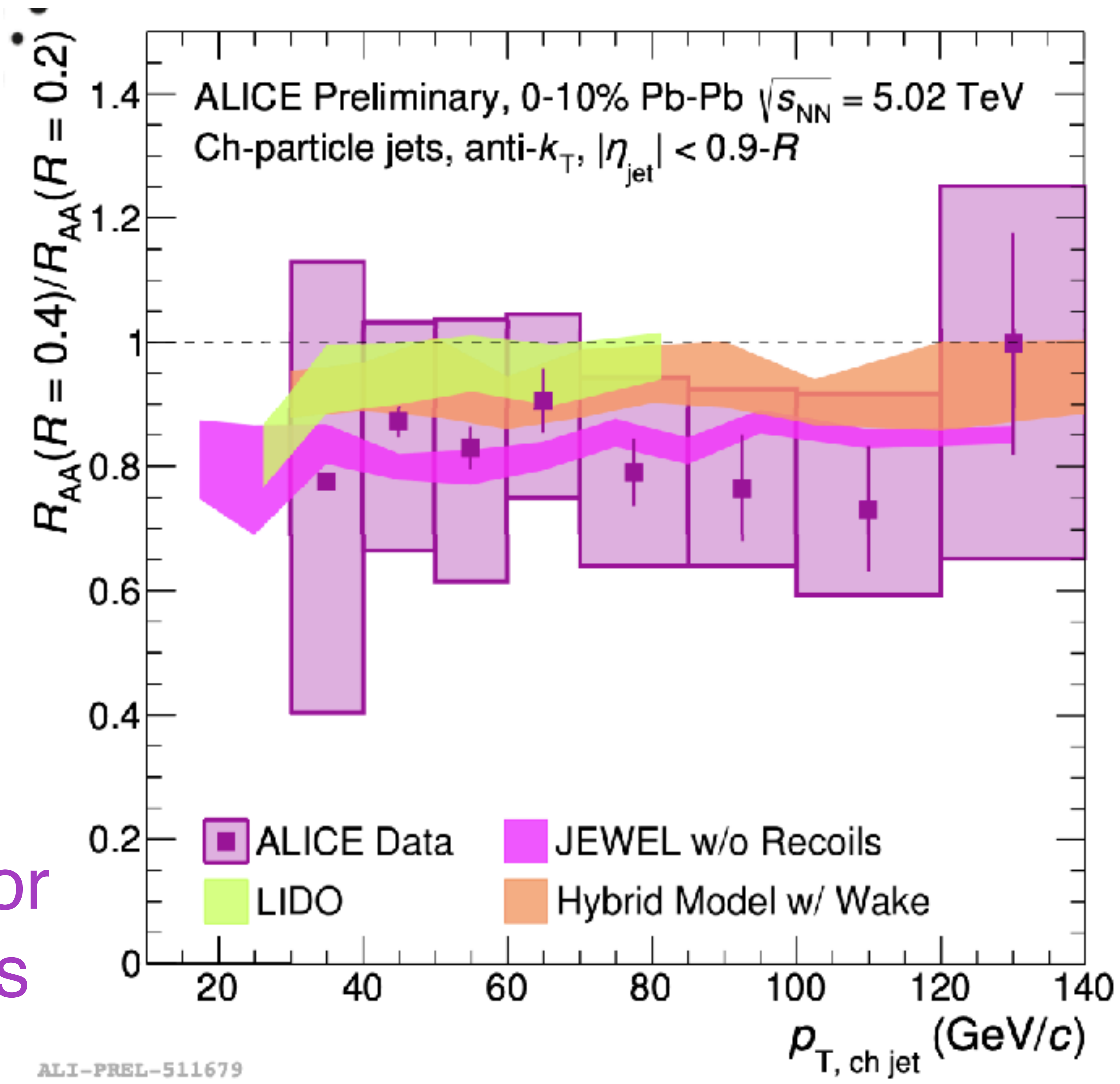


Increase in gluon fraction at larger *R*?



R-dependence of jet suppression

- Compare R_{AA} at larger R to R_{AA} at R=0.2
  - R=0.6 jets more suppressed the R=0.2 jets
- Discriminating power for models and the physics mechanisms at play



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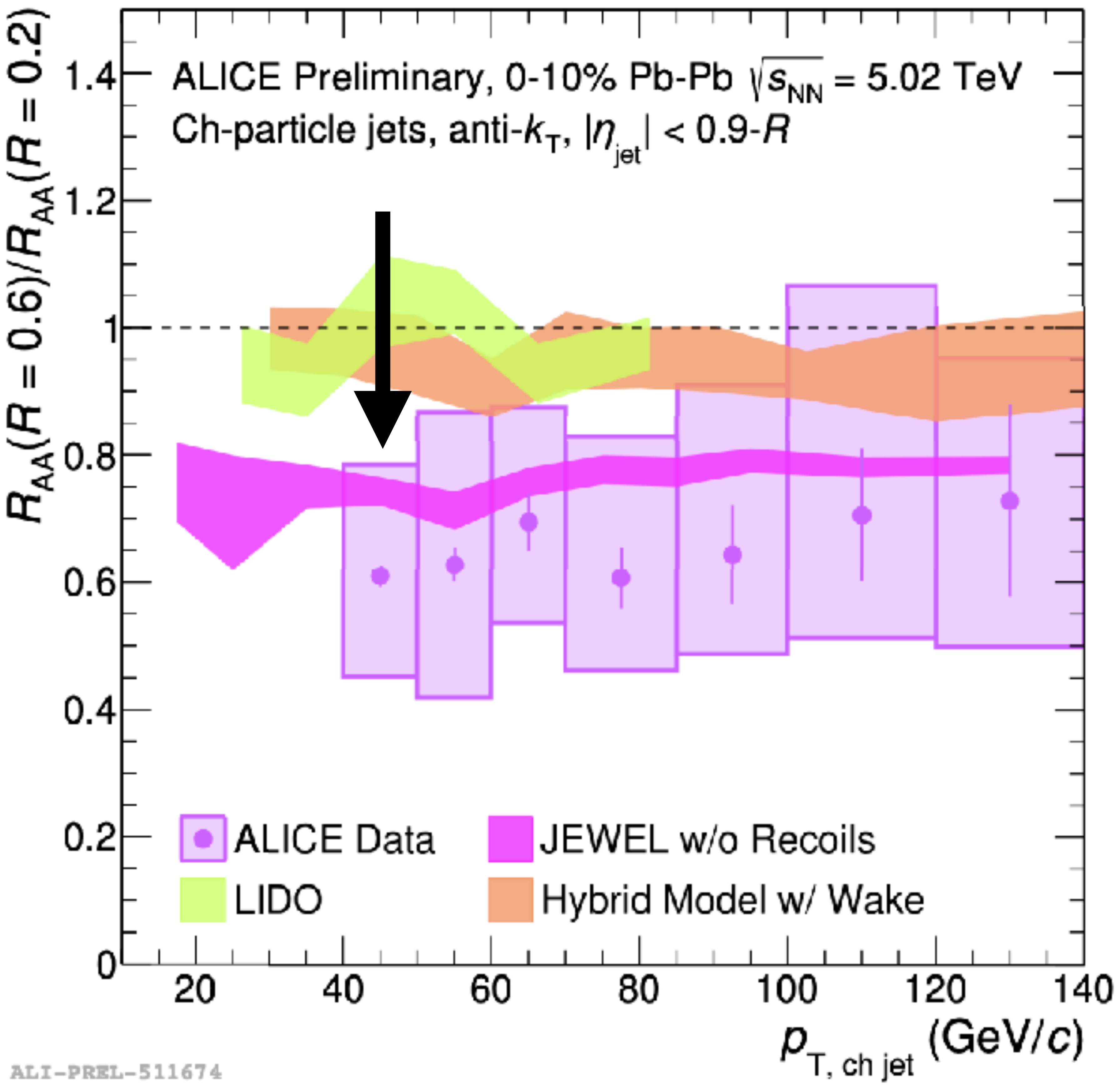
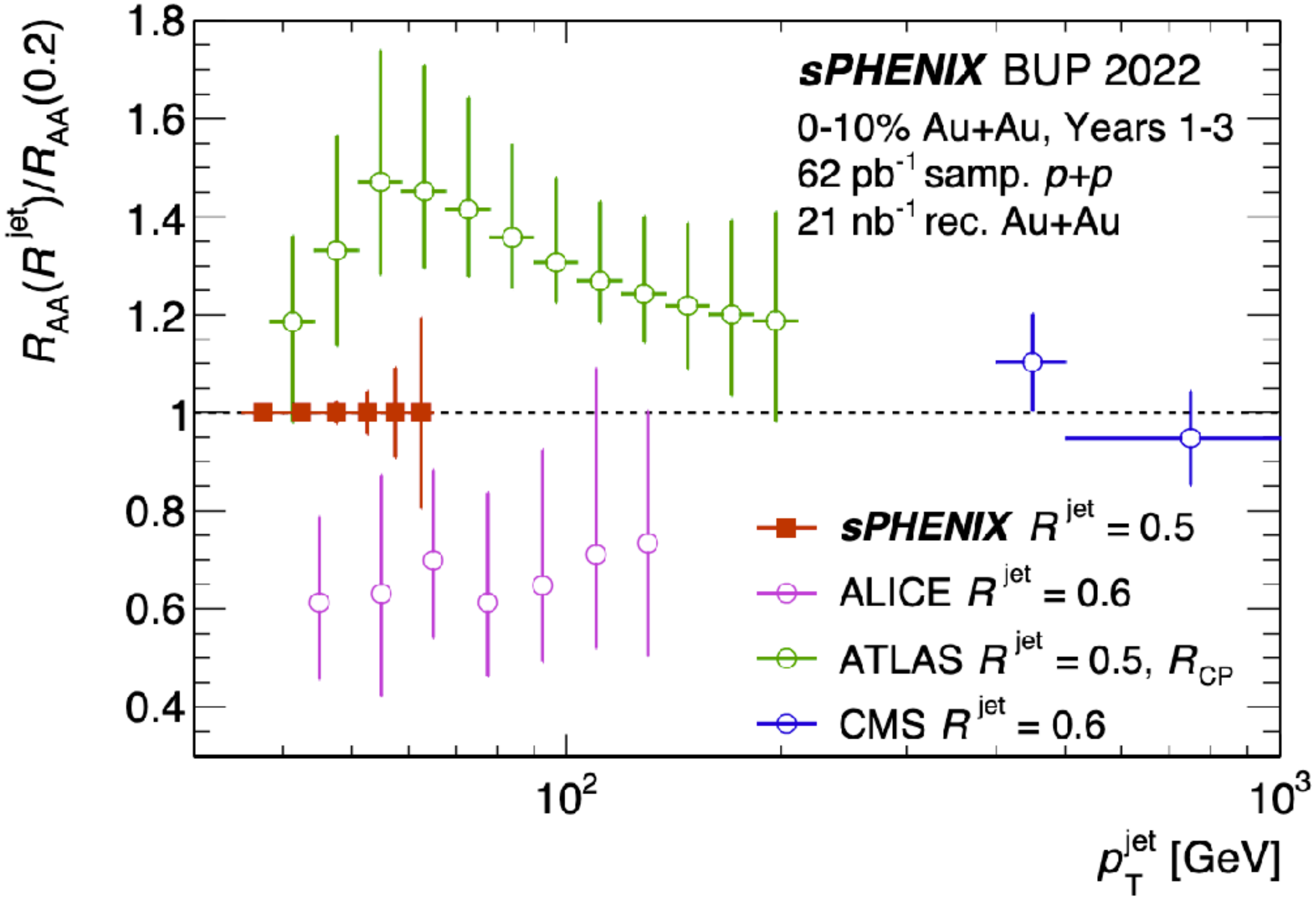


ALI-PREL-511674

R-dependence of jet suppression

- Tension at low p_T with ATLAS result at 2.76 TeV Phys. Lett. B 719 (2013) 220-241
  - Converge to CMS result at high p_T CMS arXiv:2102.13080
- Differences:
  - R_{CP} vs. R_{AA} Center-of-mass, rapidity, charged vs. full jet
  - ALICE track p_T above 150 GeV, ATLAS calorimeter towers from tracks about ~700 GeV
  - Background subtraction: region with large HI background is challenging!

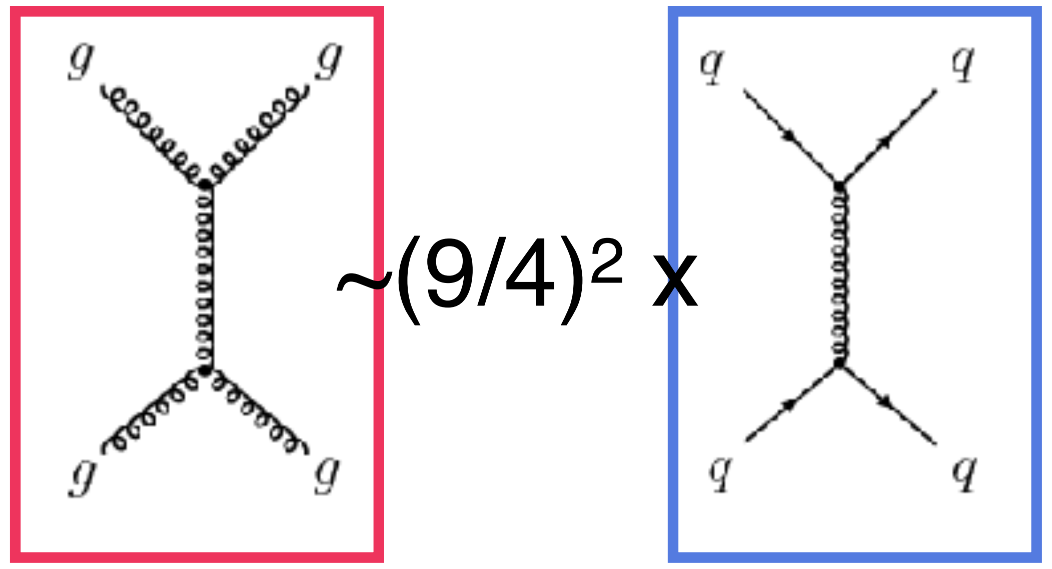
From G. Roland ECT* slides



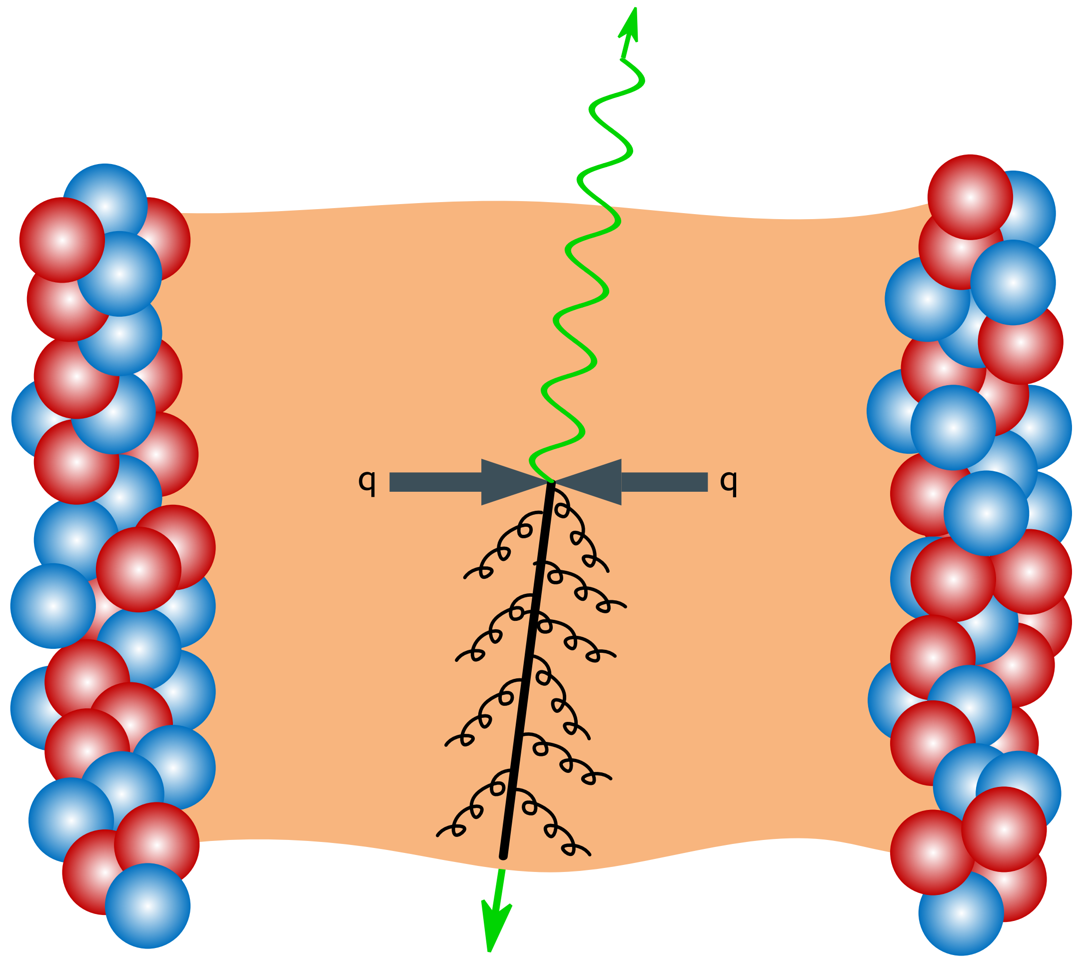
- sPhenix will measure this region and be less background dominated

Photon-jet suppression

- The energy loss by quarks is predicted to be less than the energy loss by gluons



- Photon provides initial energy of jet (less selection bias!)



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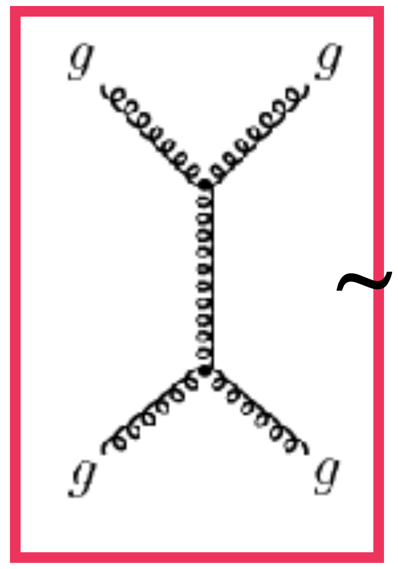
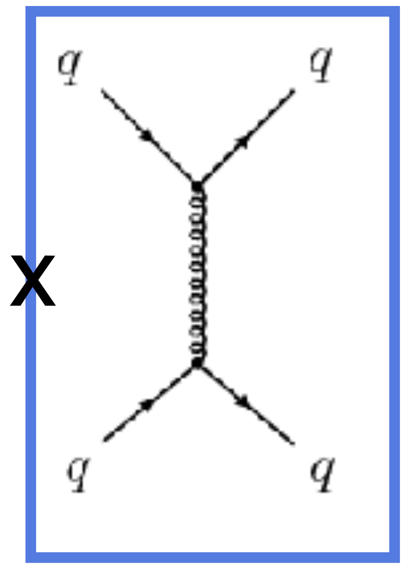


~$(9/4)^2$ x



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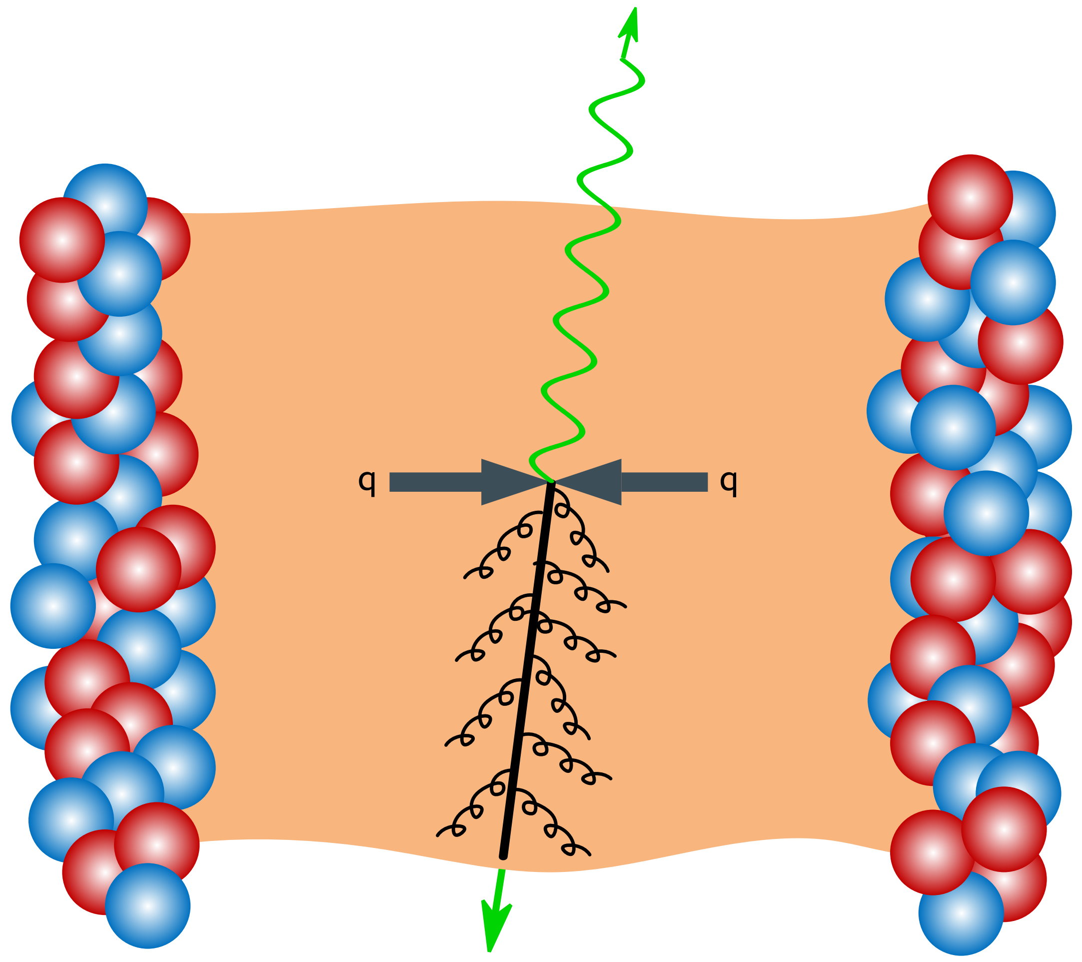

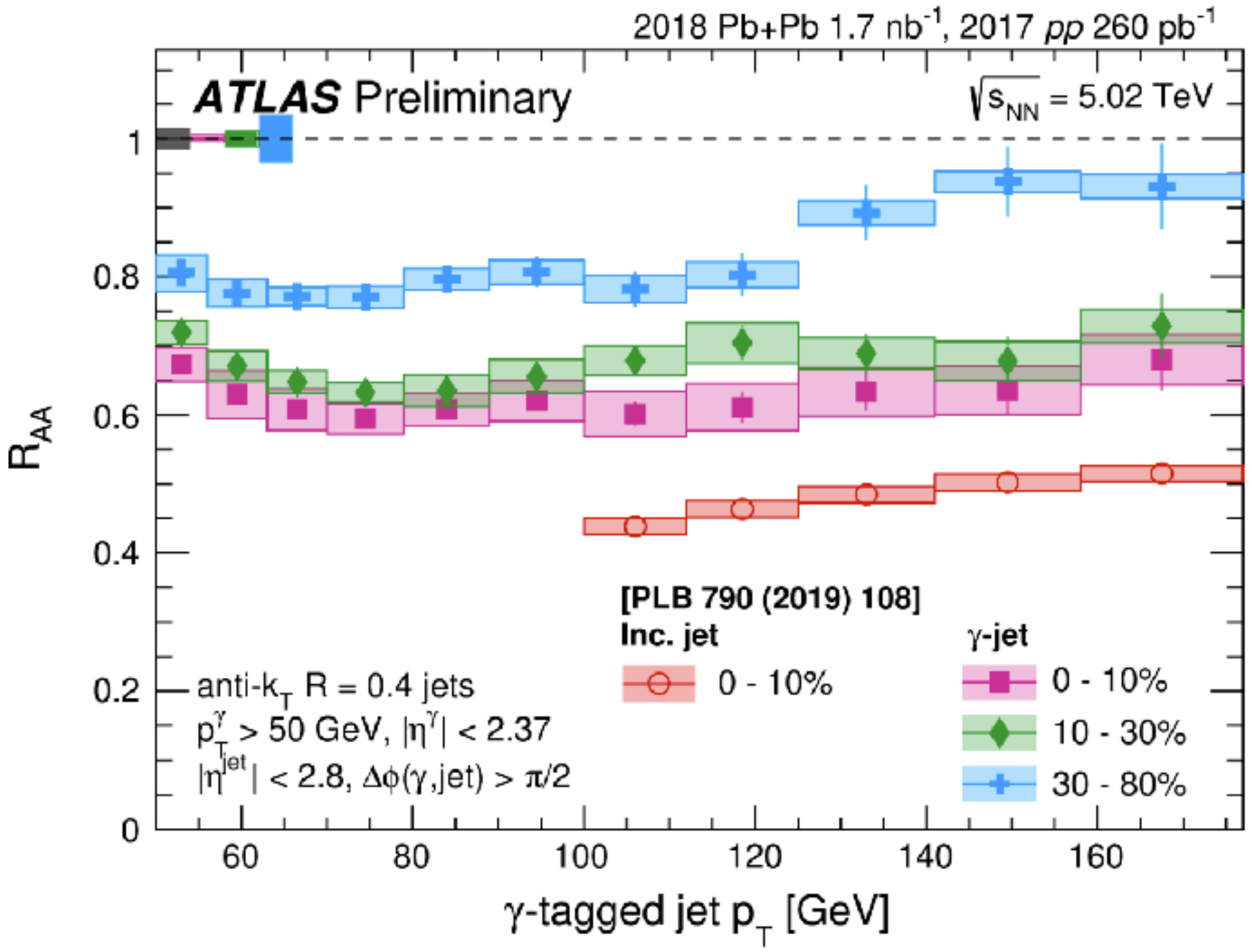

ATLAS-CONF-2022-019

- Confirmed photon-tagged jets less suppressed than inclusive jets!
- Less background allows measurements to lower p_T
- Photon-tagged jets to be measured with sPHENIX using full calorimeter
  - Measurements to even lower p_T
  - More direct comparison to LHC with quarks

Measuring jet quenching

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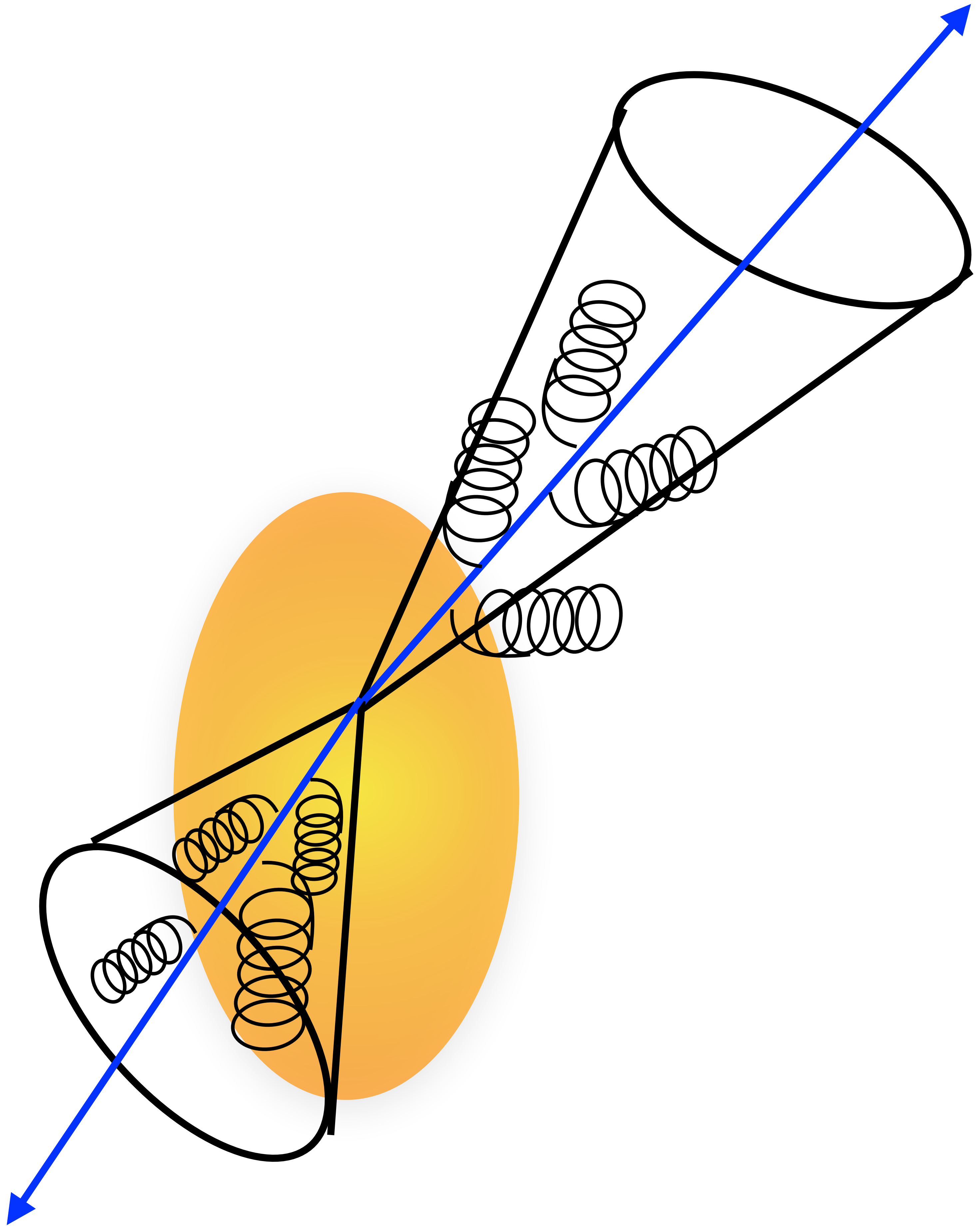
  - ➡ Angular deflections and path length dependence through jet correlations
  - ➡ Intra-jet modifications by measuring jet structure and substructure



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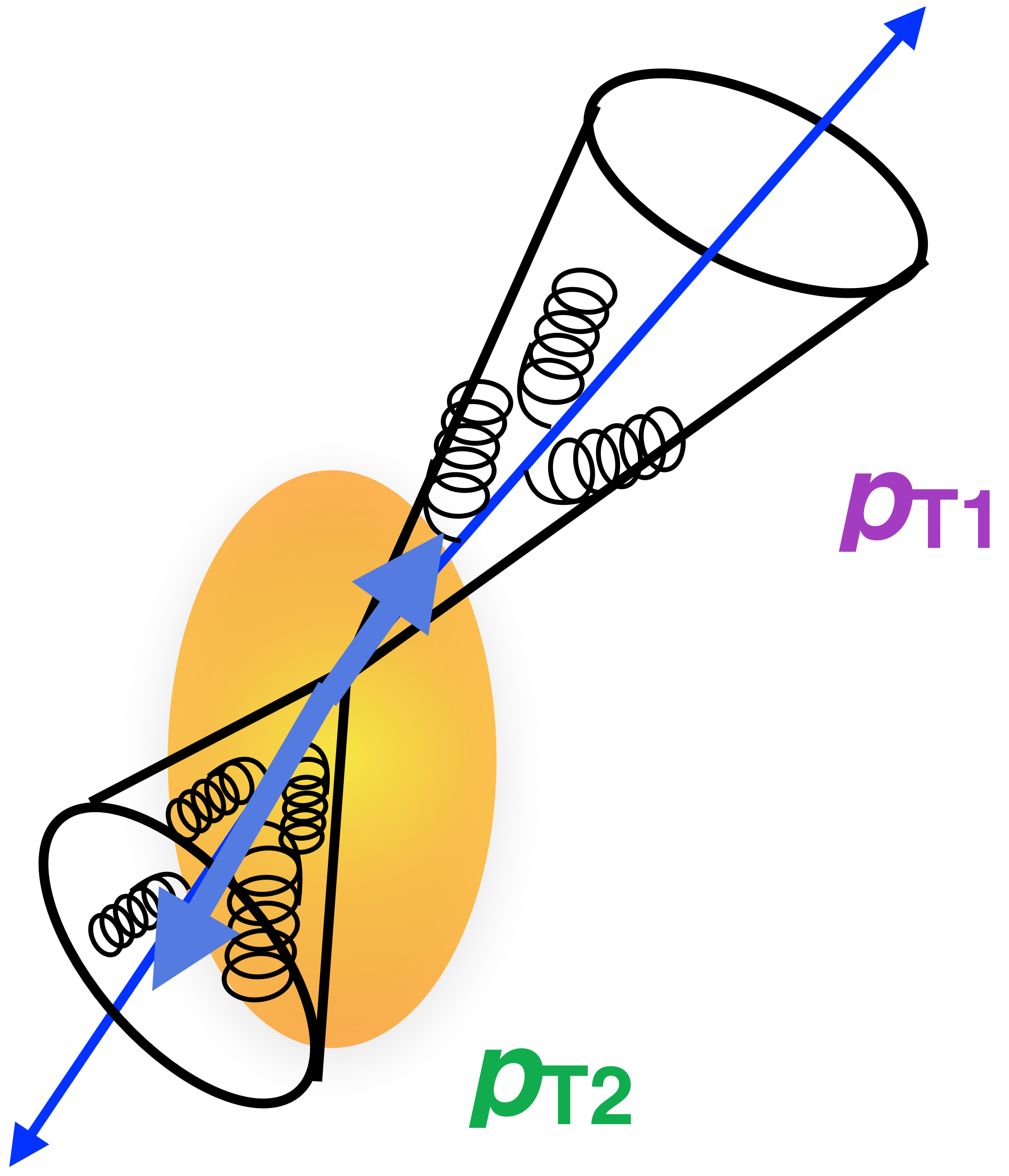
Dijet asymmetry

$$x_J = \frac{p_{T2}}{p_{T1}}$$

- Two jets in the pair lose different amounts of energy
  - Travel different paths
  - Jet-by-jet fluctuations in the energy loss



arXiv:2205.00682

Dijet asymmetry

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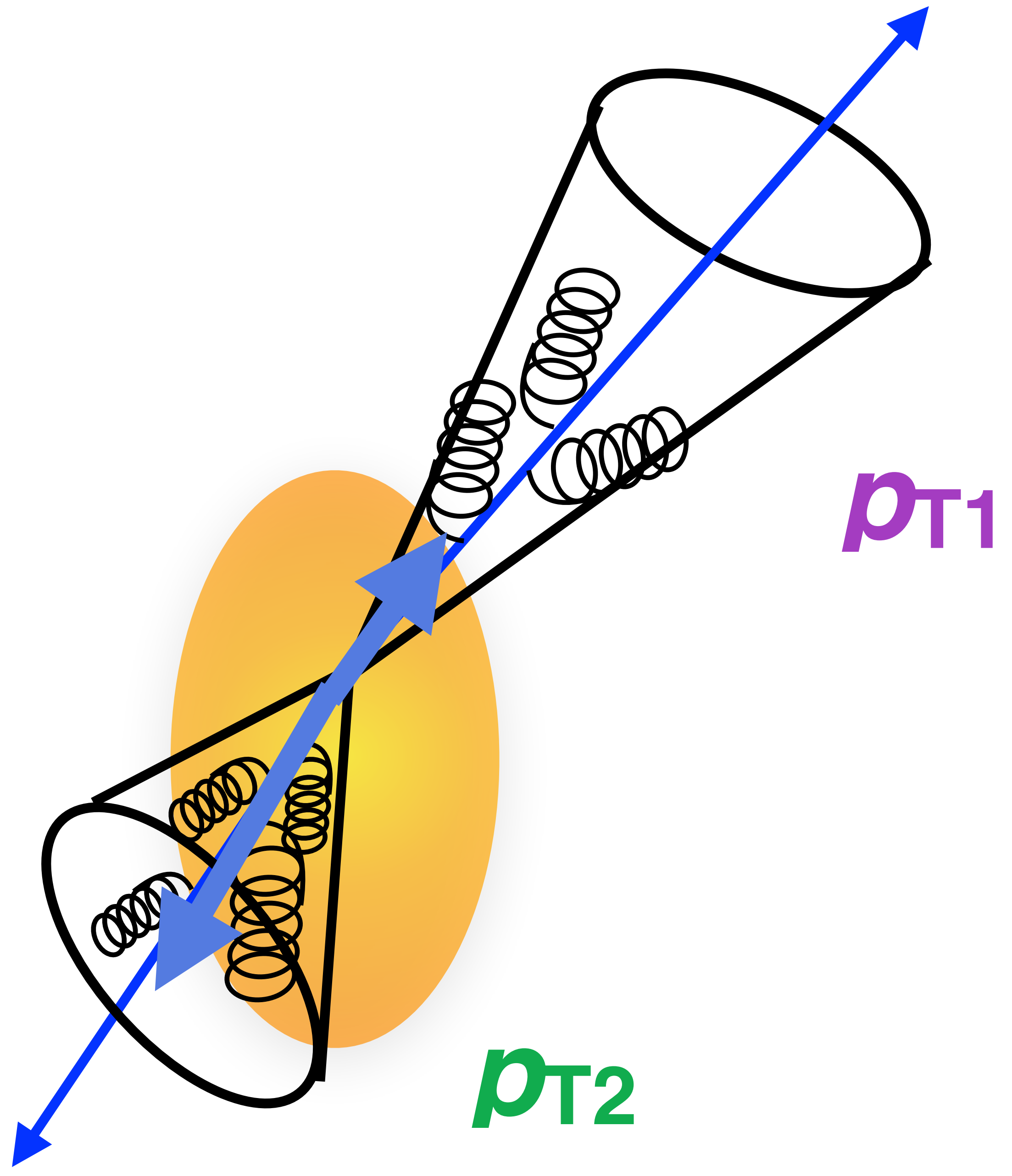

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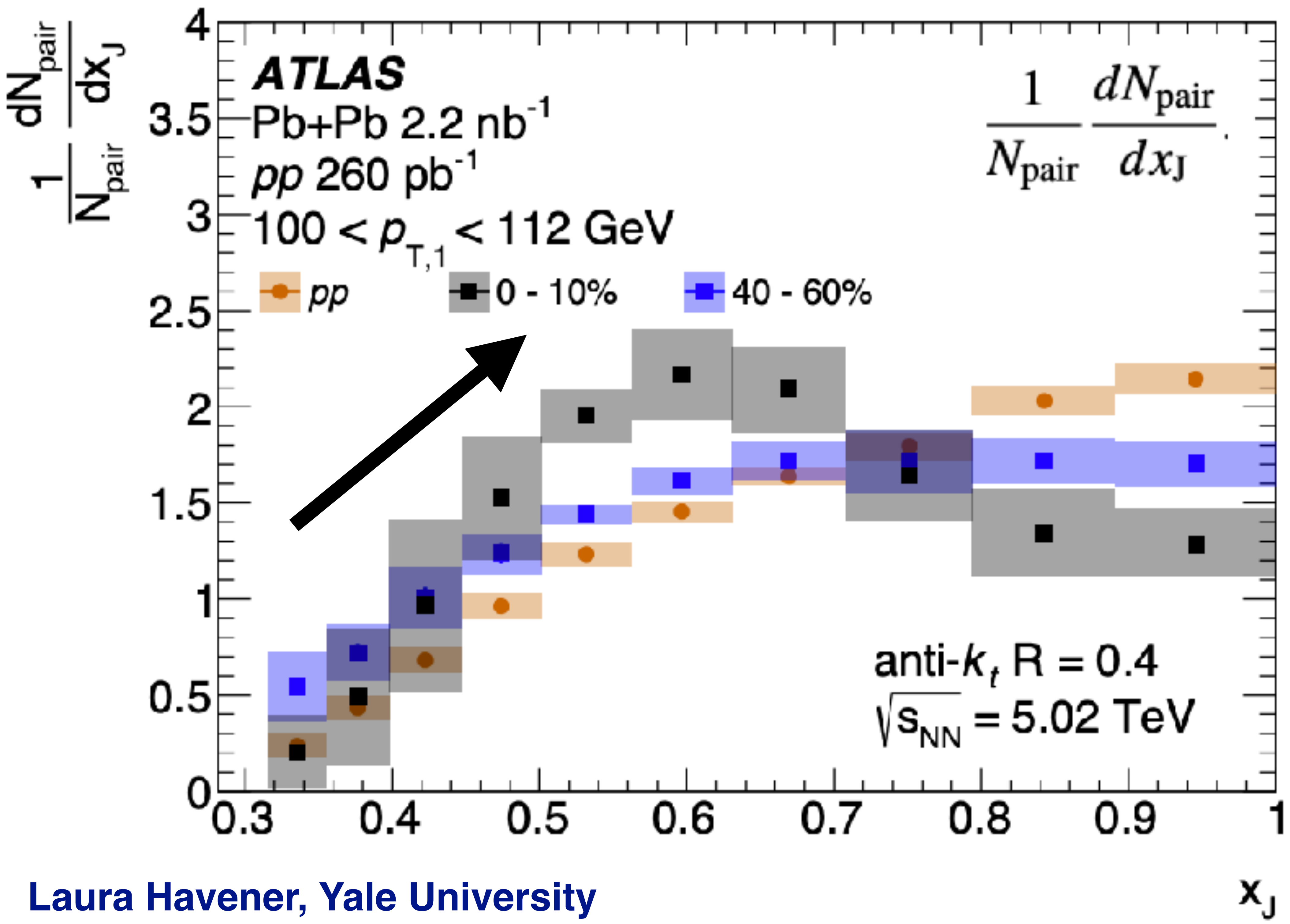
    - Jet-by-jet fluctuations in the energy loss

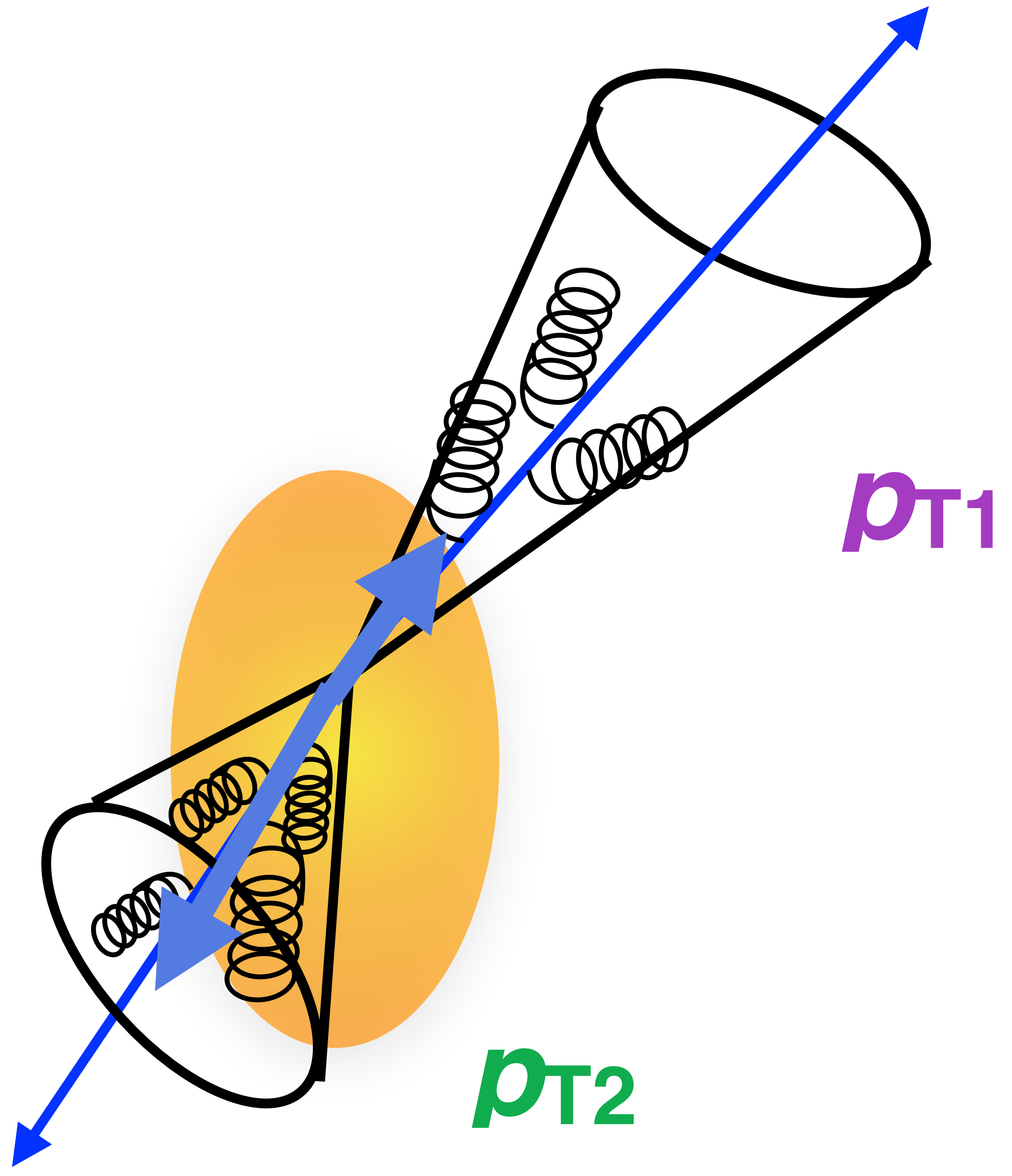
- See significant asymmetry for HI dijets



arXiv:2205.00682

Dijet asymmetry

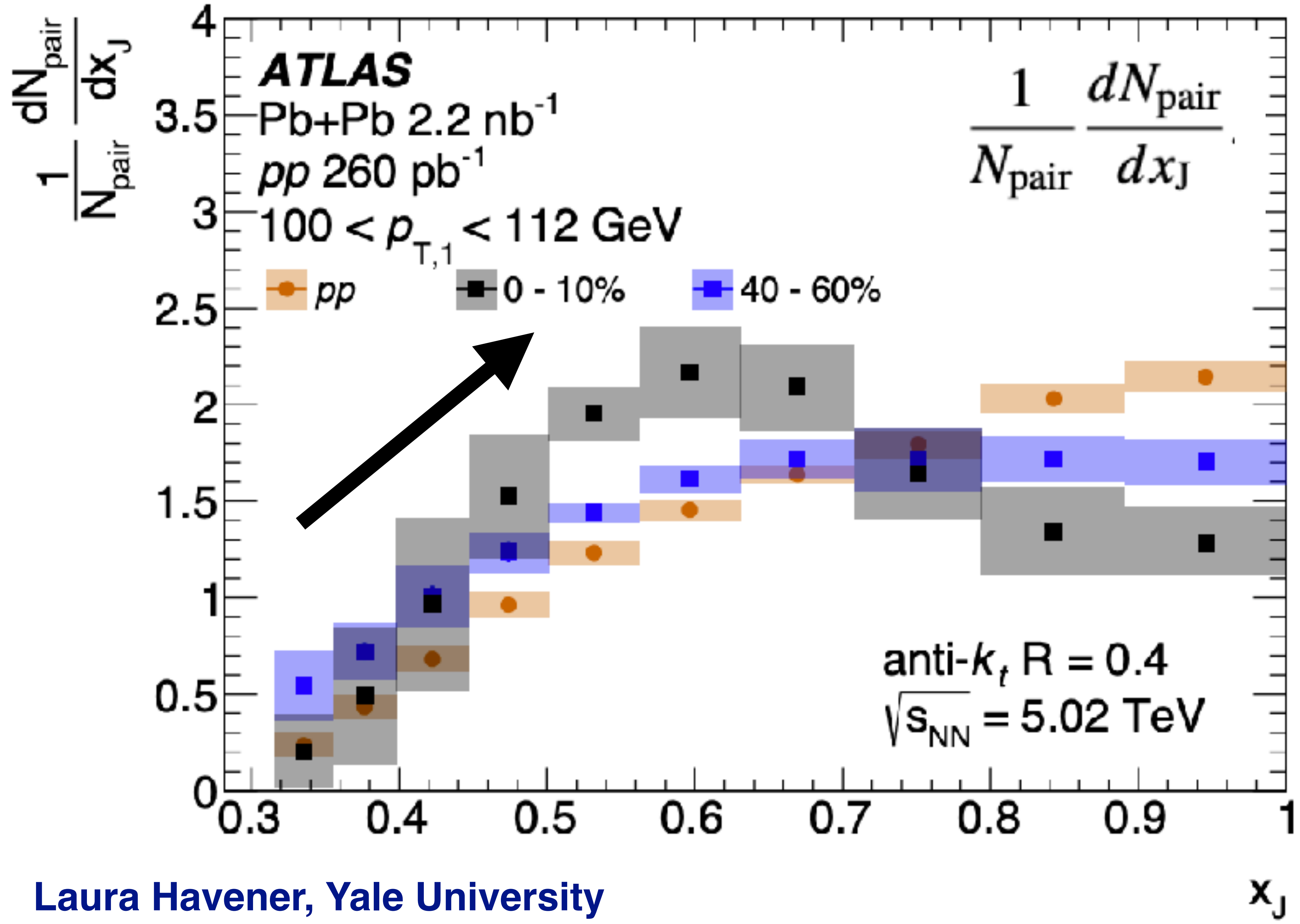
$$x_J = \frac{p_{T2}}{p_{T1}}$$

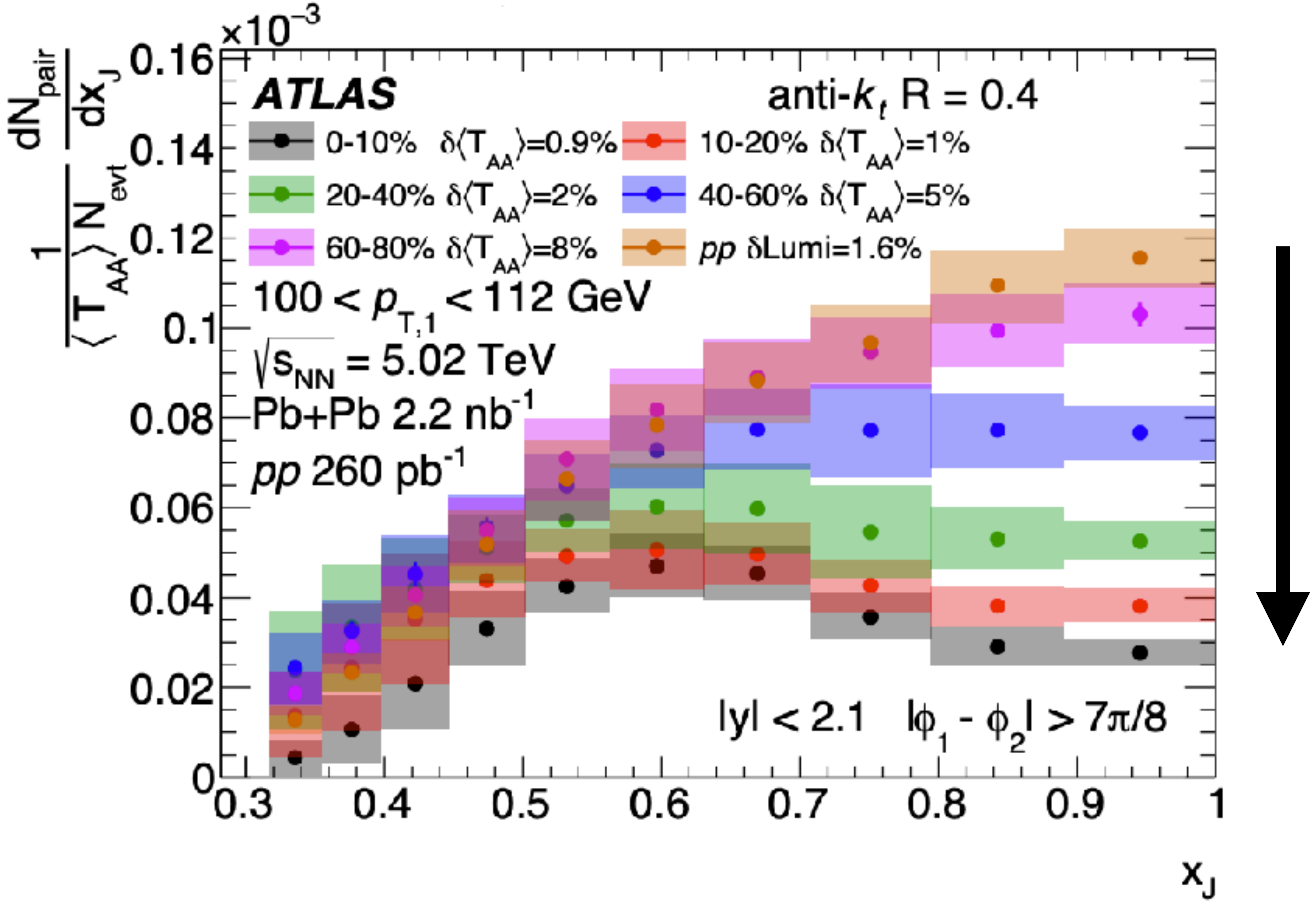


- Two jets in the pair lose different amounts of energy
  - Travel different paths
  - Jet-by-jet fluctuations in the energy loss

- See significant asymmetry for HI dijets caused by a suppression of balanced dijets

$$\frac{1}{\langle T_{AA}\rangle N_{evt}^{AA}} \frac{dN_{pair}^{AA}}{dx_J}$$





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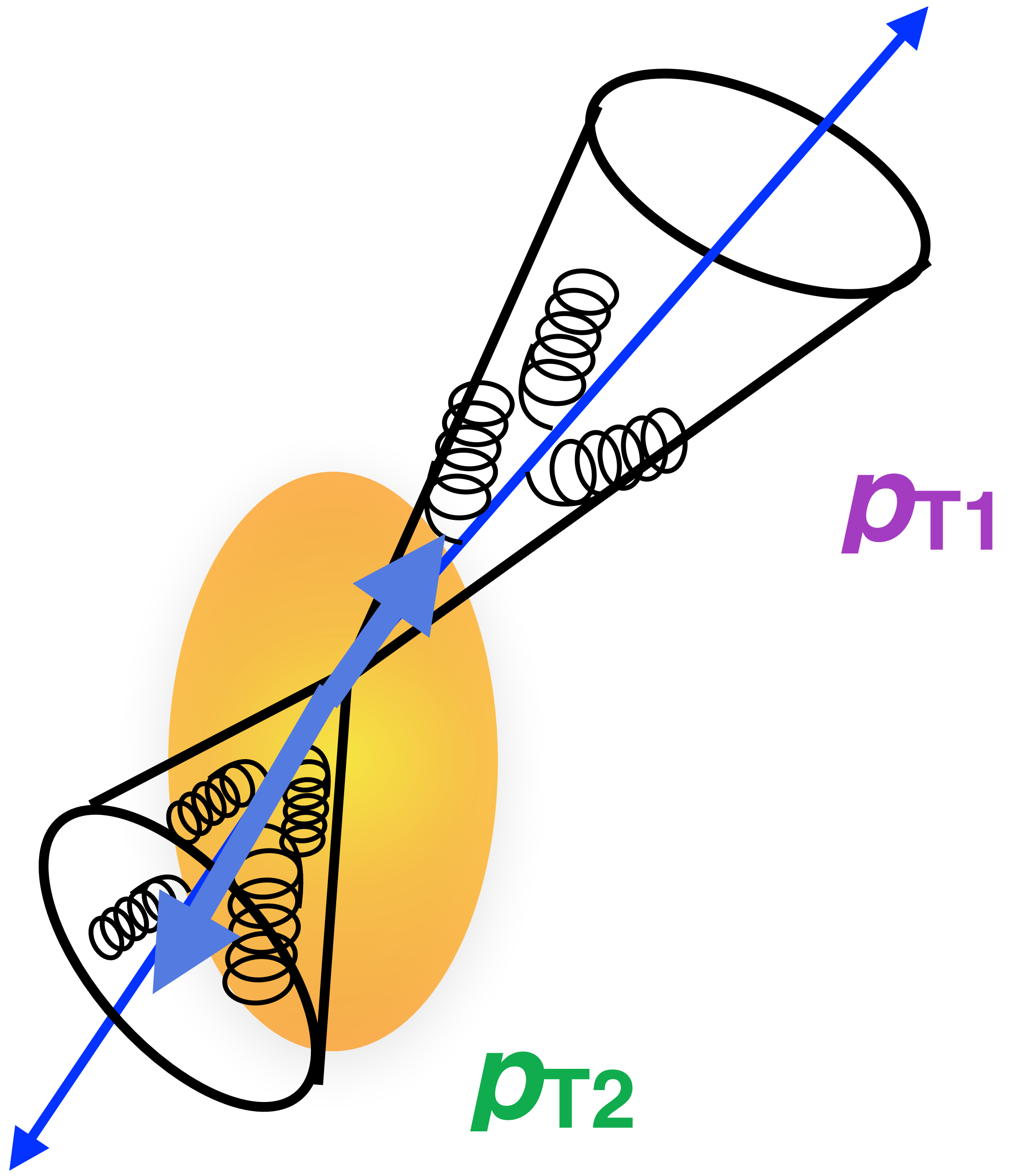

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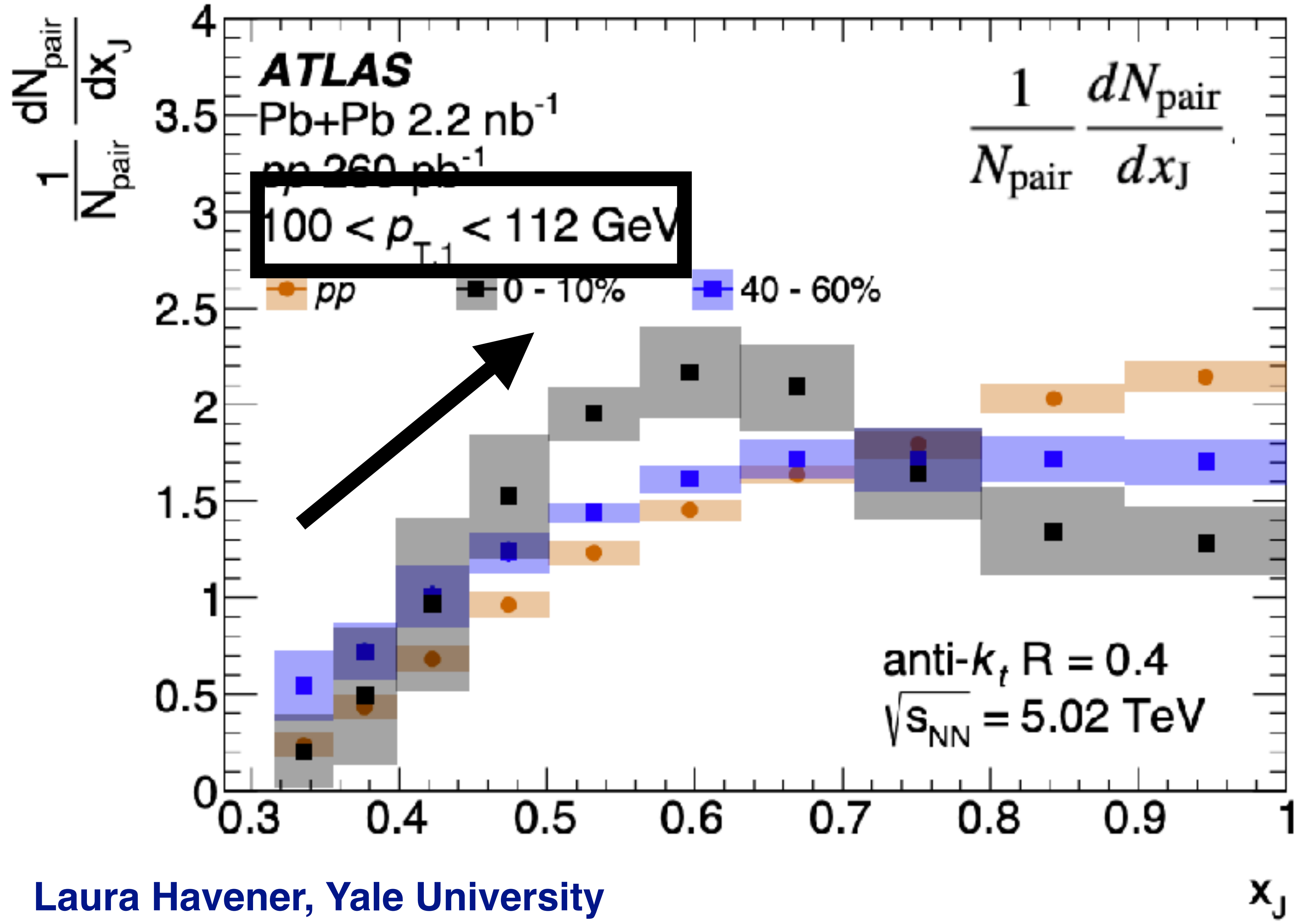

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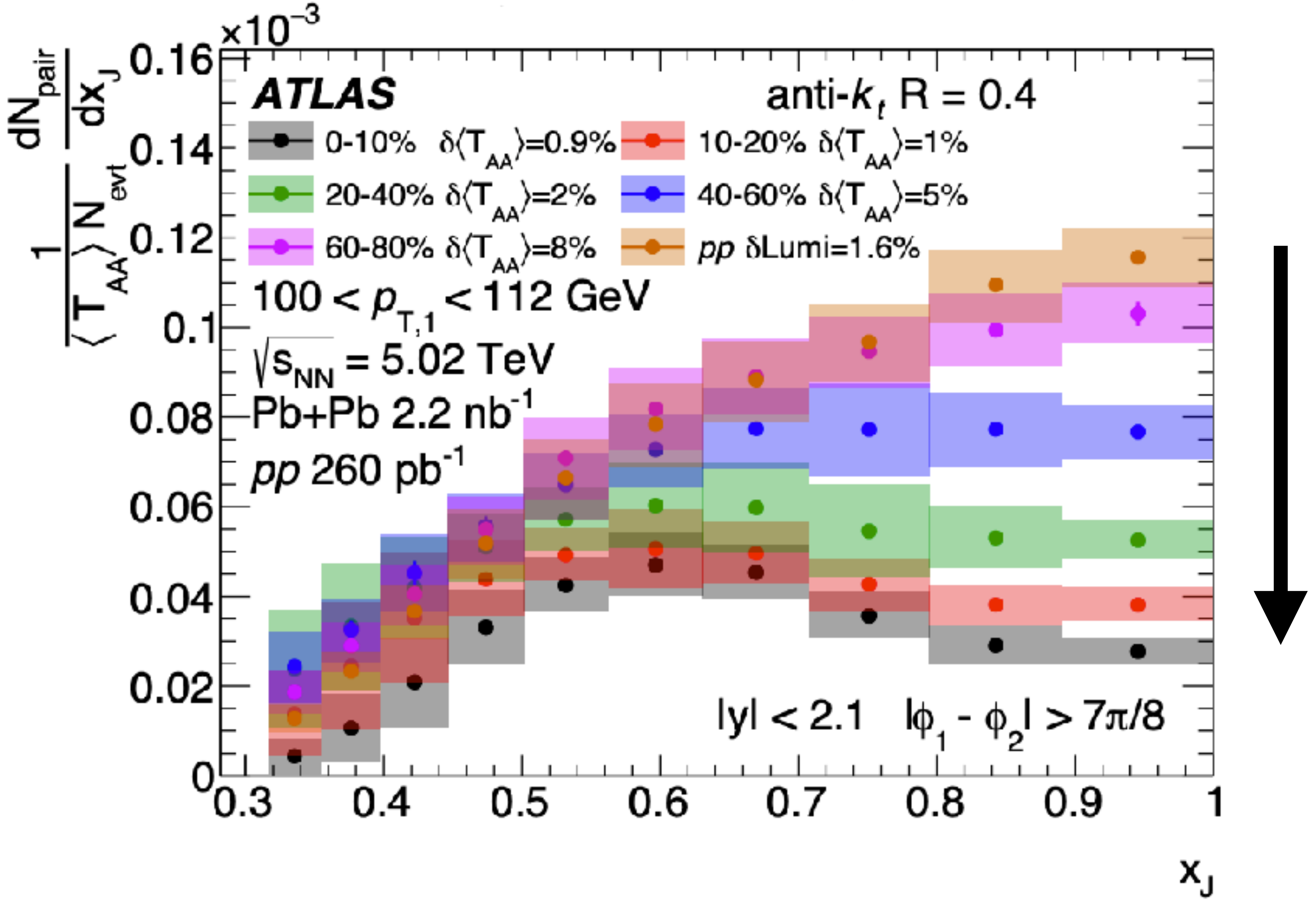
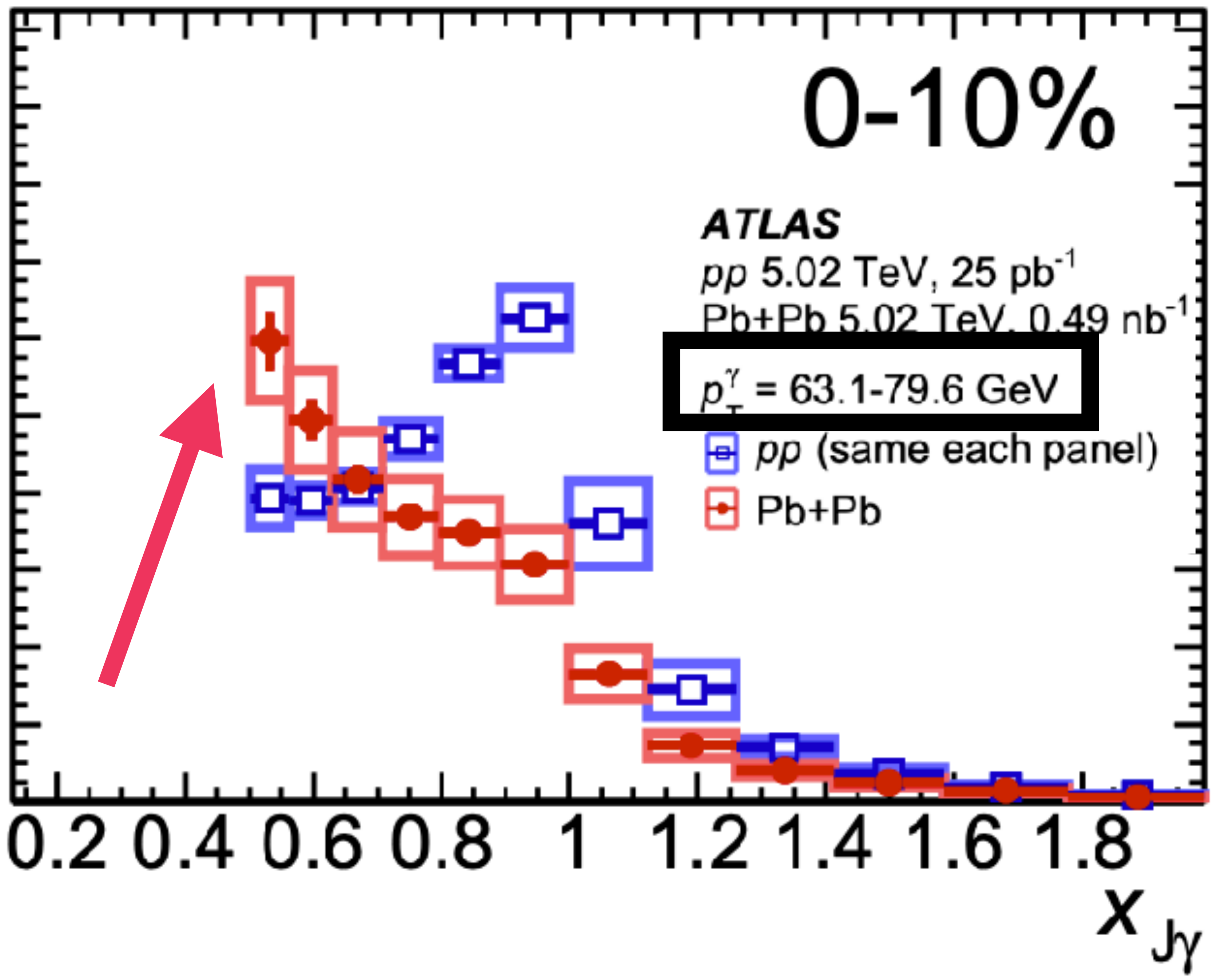
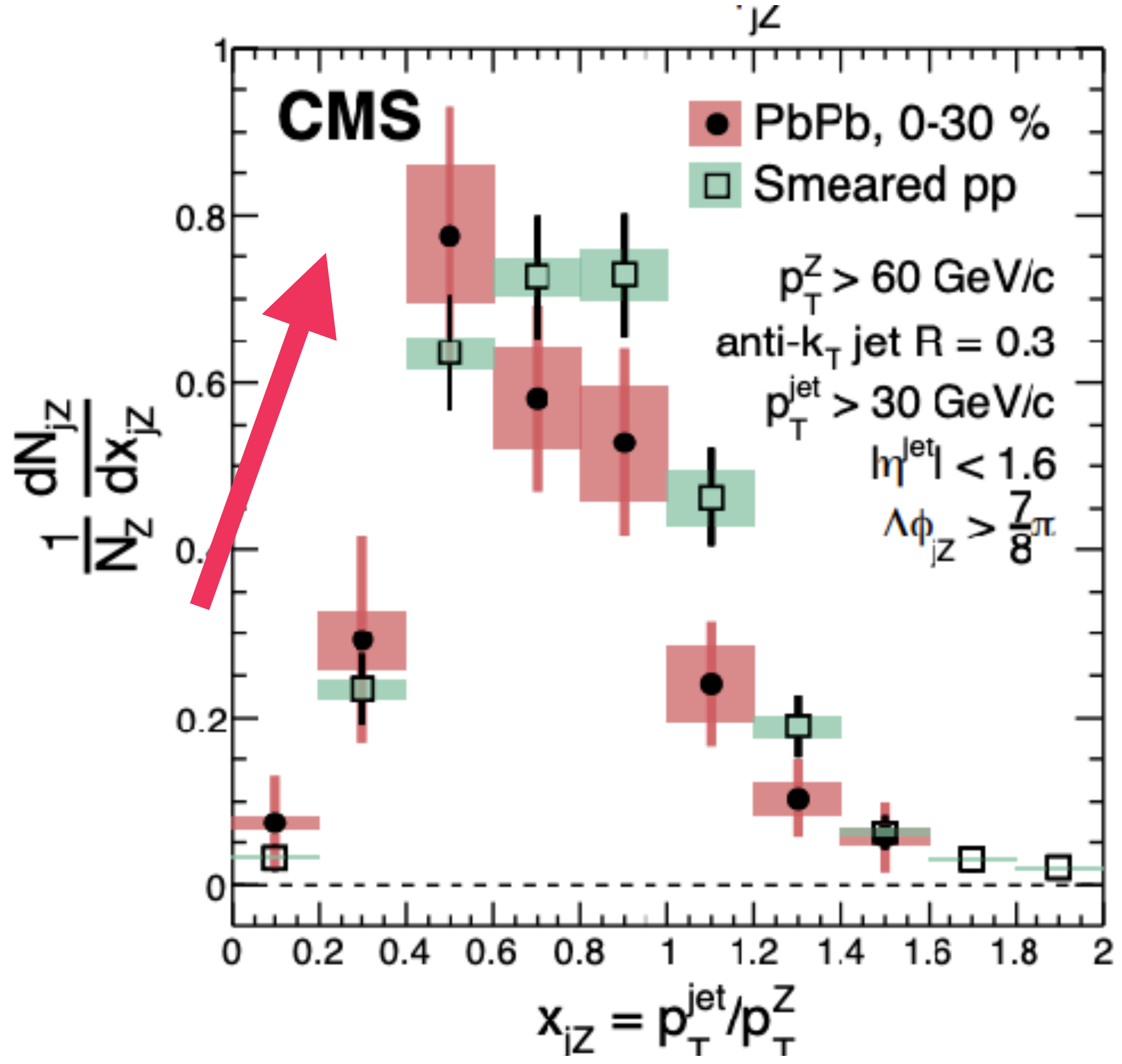


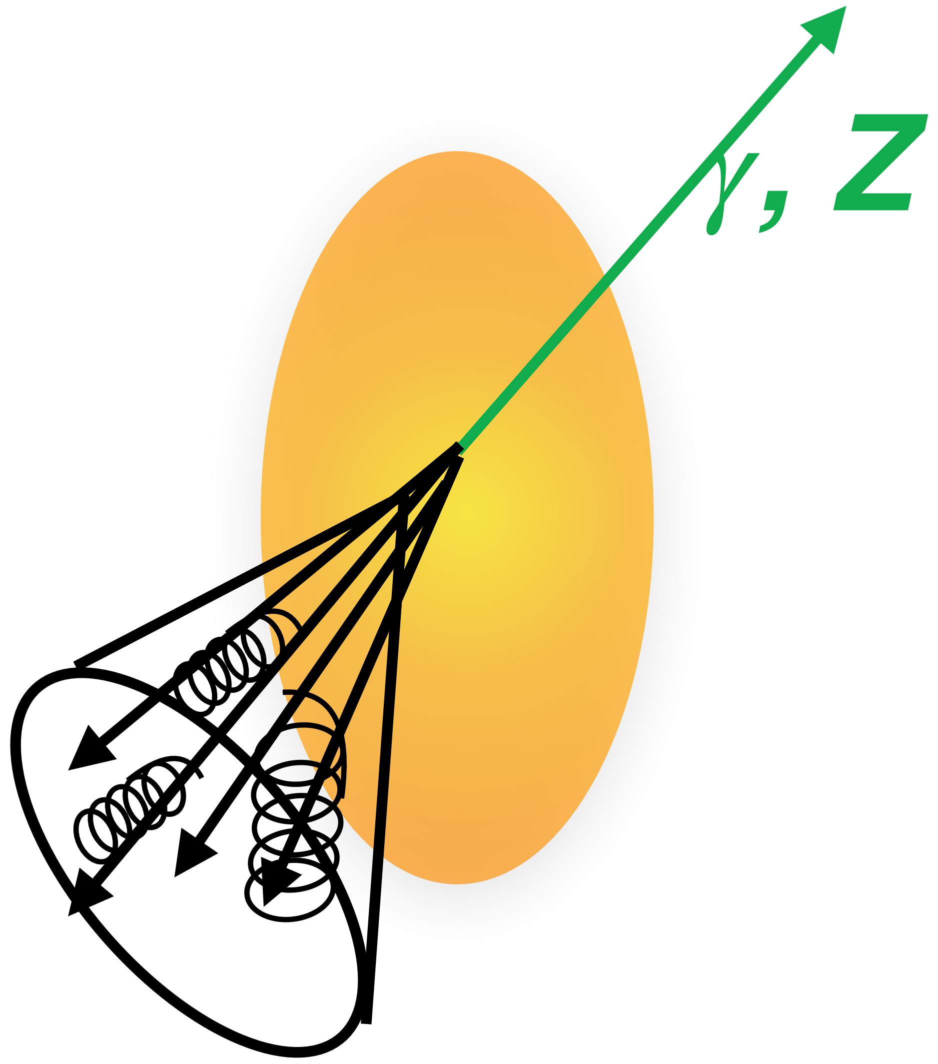
Boson-tagged asymmetry

Phys. Lett. B 789 (2019) 167

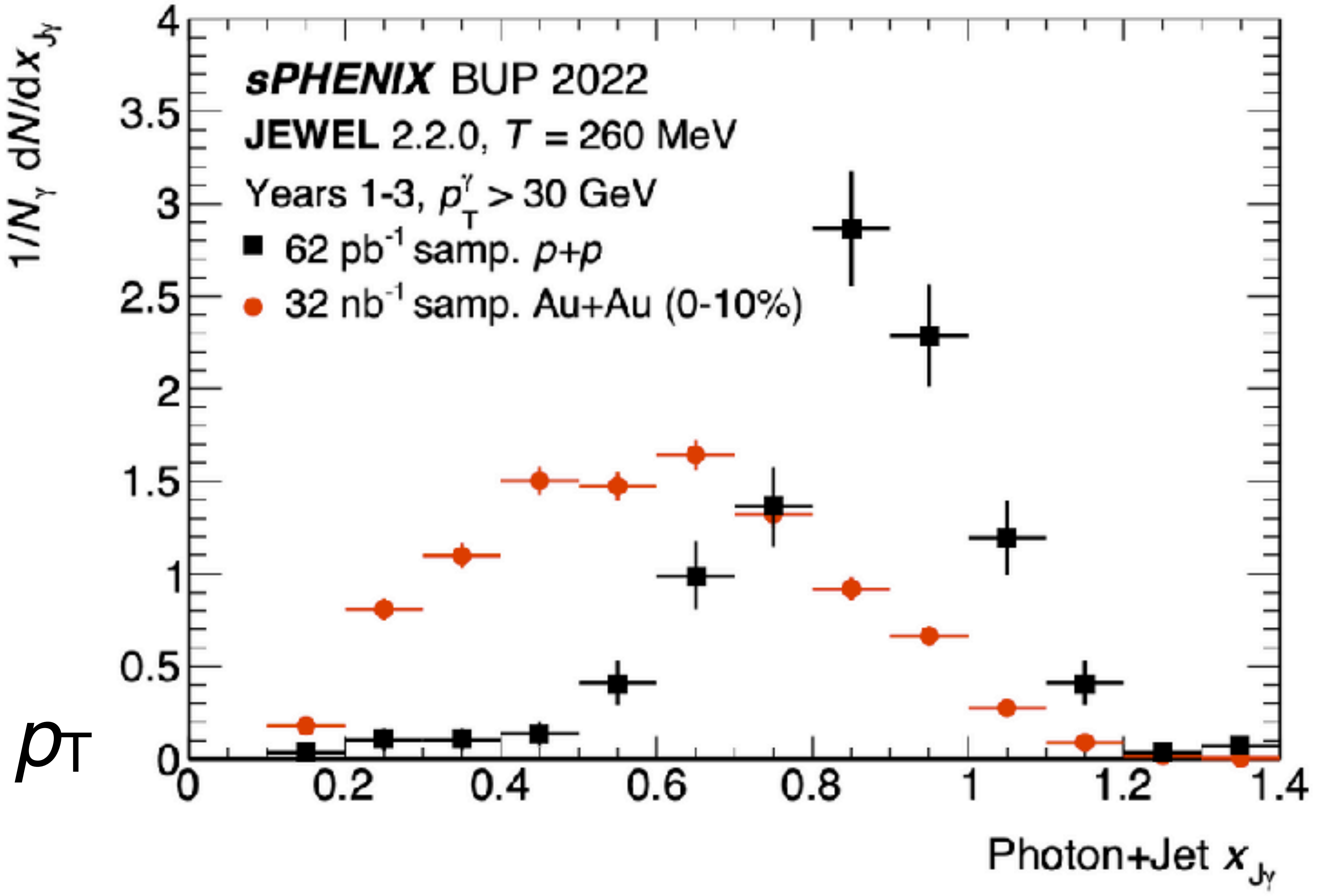


Phys. Rev. Lett. 119, 082301 (2017)





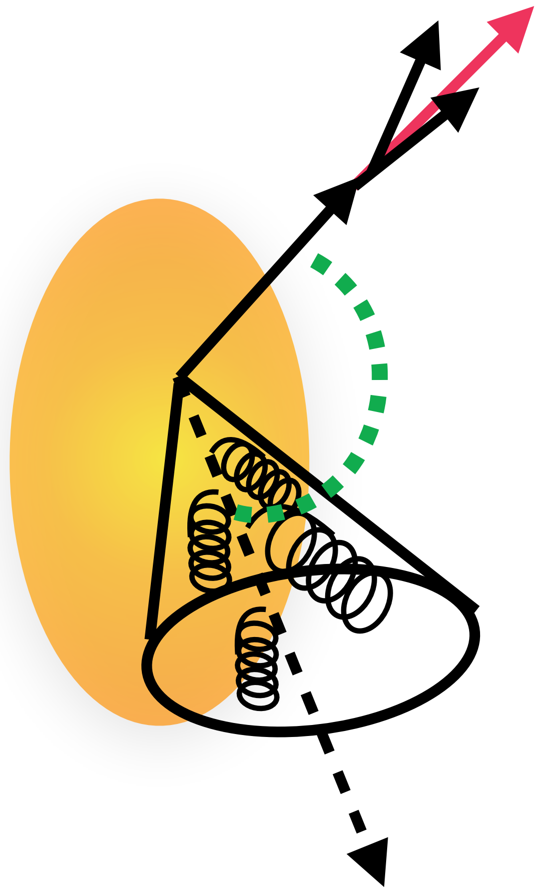
- Access initial parton momentum and lower p_T
  - See asymmetry for Z and photon-tagged jets compared to pp



- sPhenix will access lower p_T

Jet acoplanarity

- Measure the opening angle ($\Delta\varphi$) of the jet with respect to a hadron trigger
    - Multiple soft scatterings or in-medium Moliere scattering?



Jet acoplanarity

$$\Delta_{\mathrm{recoil}} = \frac{1}{N^{\mathrm{AA}}_{\mathrm{trig}}} \frac{\mathrm{d}^3 N^{\mathrm{AA}}_{\mathrm{jet}}}{\mathrm{d}p^{\mathrm{ch}}_{\mathrm{T,jet}}\,\mathrm{d}\Delta\varphi\,\mathrm{d}\eta_{\mathrm{jet}}}\Bigg|_{p_{\mathrm{T,trig}}\in \mathrm{TT}_{\mathrm{Sig}}} - c_{\mathrm{ref}} \cdot \frac{1}{N^{\mathrm{AA}}_{\mathrm{trig}}} \frac{\mathrm{d}^3 N^{\mathrm{AA}}_{\mathrm{jet}}}{\mathrm{d}p^{\mathrm{ch}}_{\mathrm{T,jet}}\,\mathrm{d}\Delta\varphi\,\mathrm{d}\eta_{\mathrm{jet}}}\Bigg|_{p_{\mathrm{T,trig}}\in \mathrm{TT}_{\mathrm{Ref}}}$$

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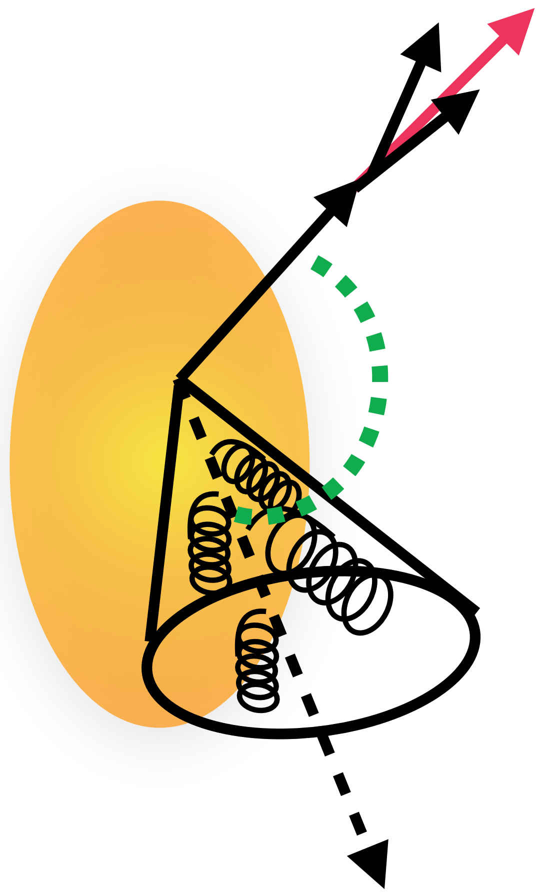

- Data-driven subtraction of recoil jet spectra in exclusive trigger p_{T} bins -> recoil jets at low (10 GeV!) p_{T}

Jet acoplanarity

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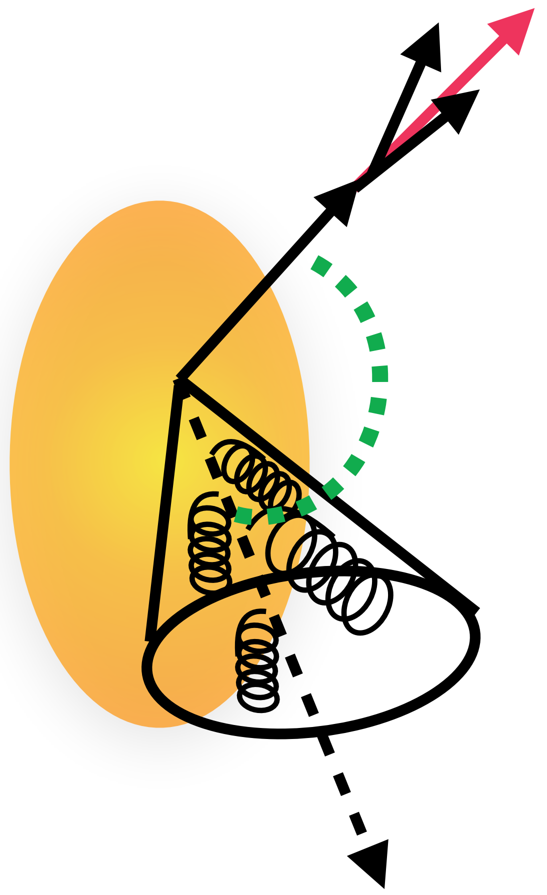
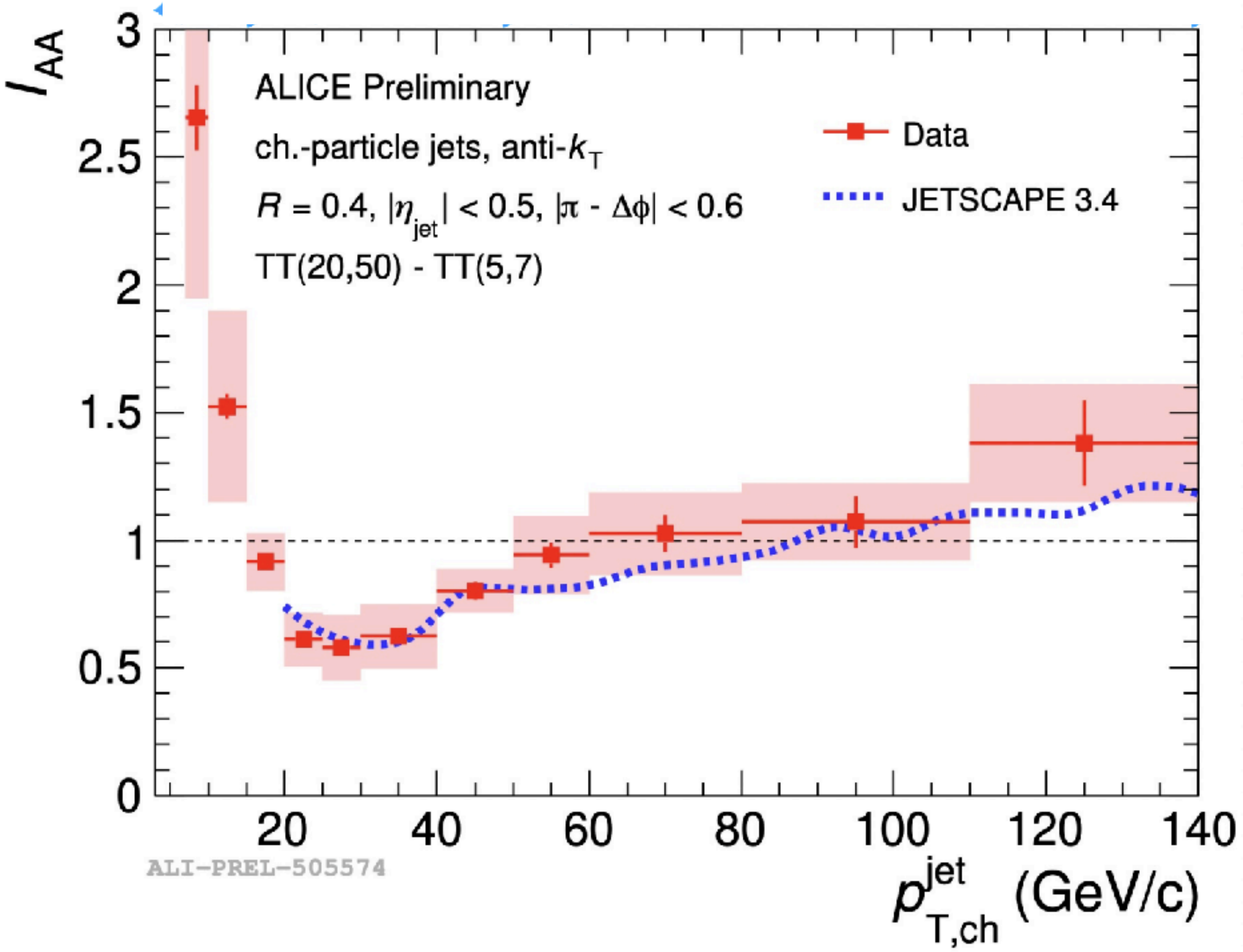


$$I_{\rm AA} \equiv \frac{\Delta_{\rm recoil}(\rm Pb-Pb)}{\Delta_{\rm recoil}(\rm pp)}$$

$I_{\rm AA} \equiv$



- Data-driven subtraction of recoil jet spectra in exclusive trigger $p_{\rm T}$ bins -> recoil jets at low (10 GeV!) $p_{\rm T}$

Jet acoplanarity

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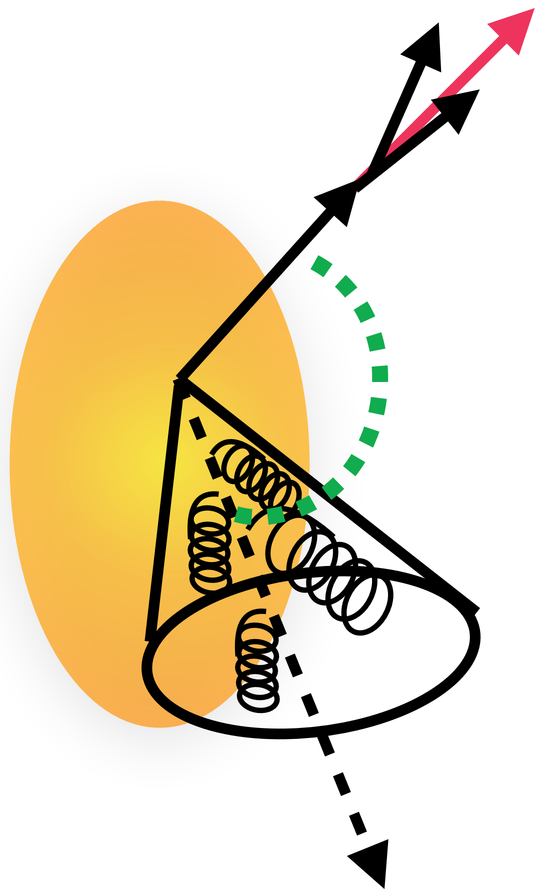

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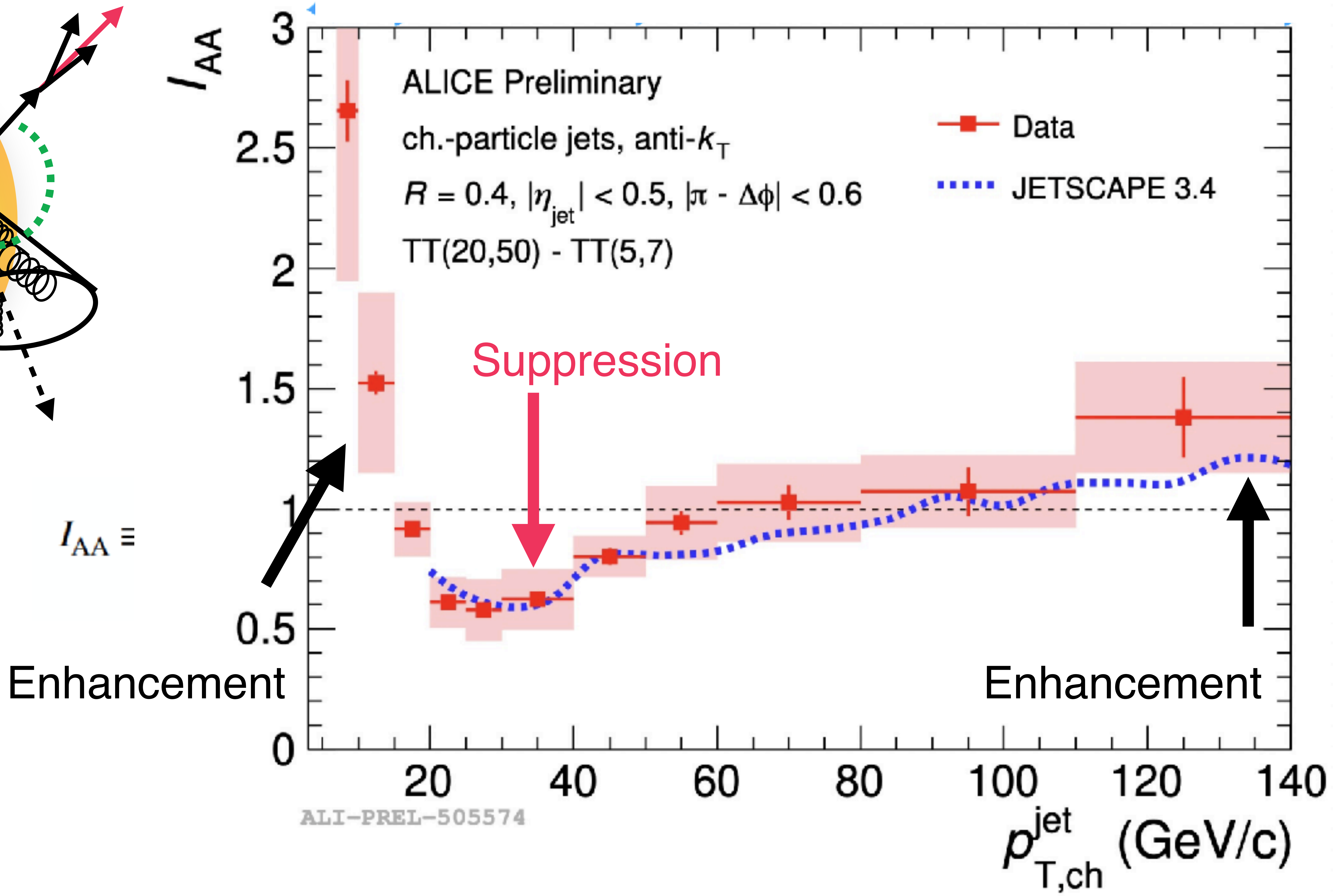

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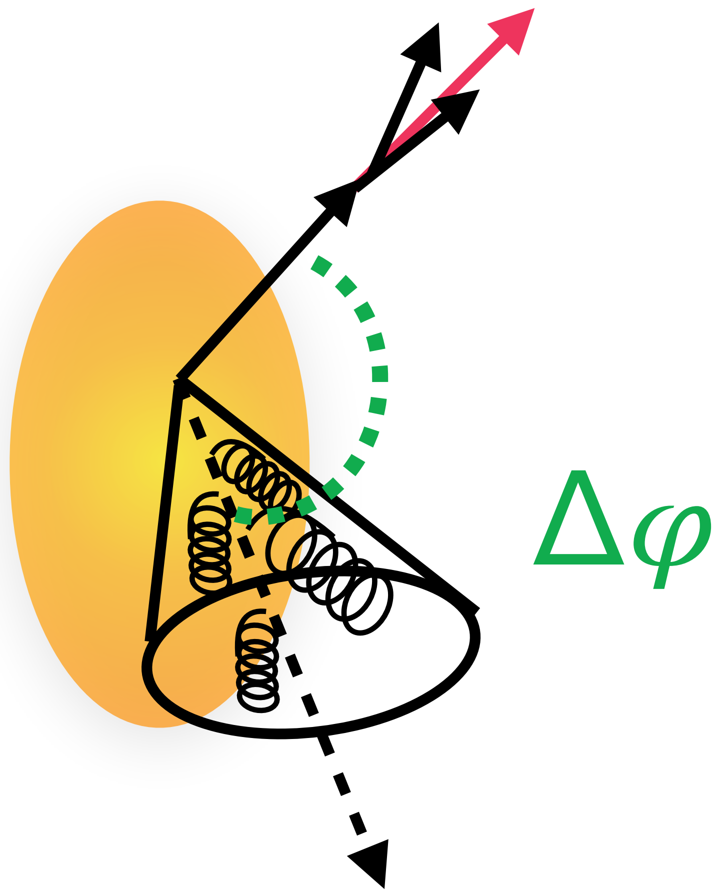
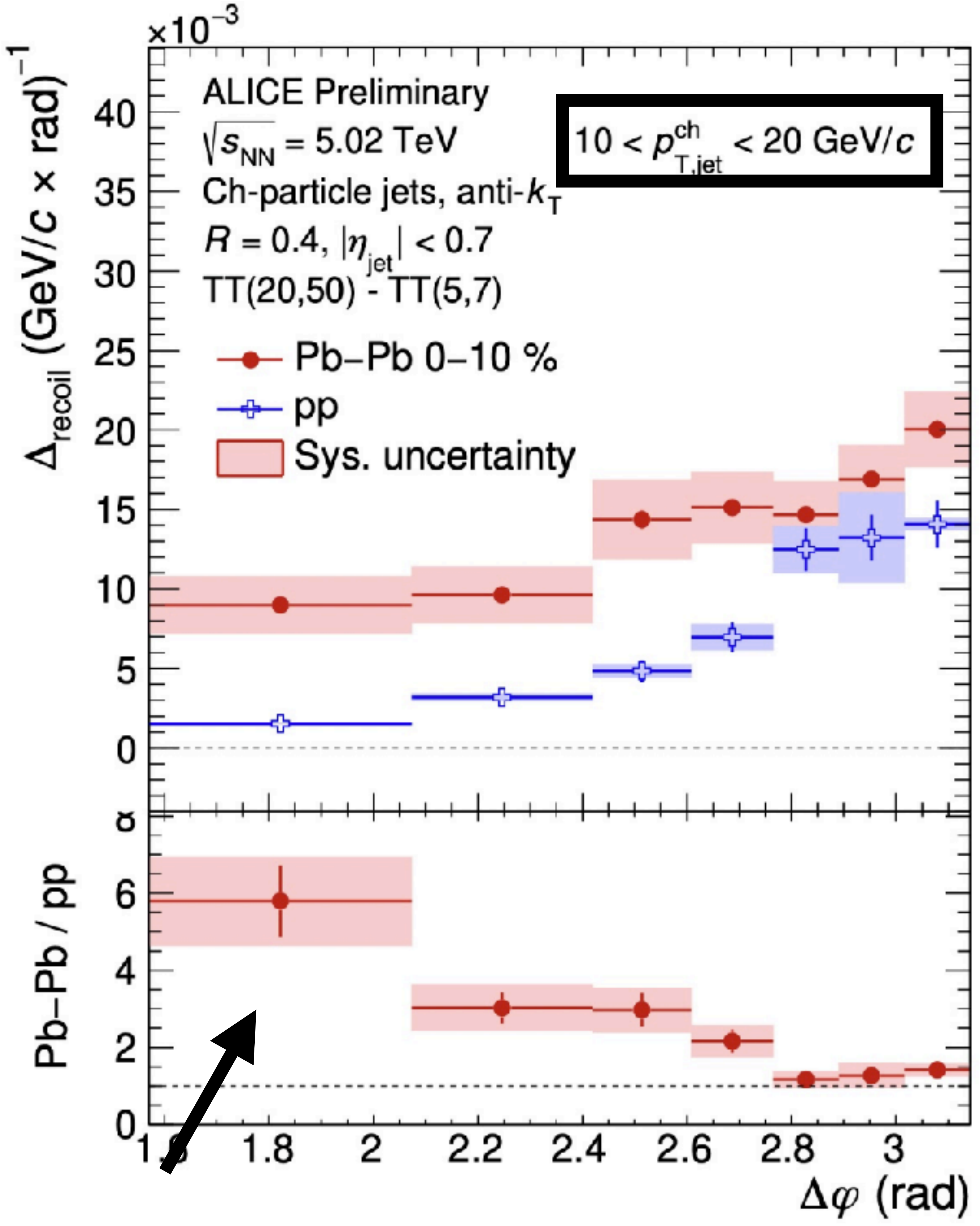


- Signature of jet azimuthal broadening!



ALI-PREL-505599

Jet acoplanarity

$$\Delta_{\rm recoil} = \frac{1}{N^{\rm AA}_{\rm trig}} \frac{{\rm d}^3 N^{\rm AA}_{\rm jet}}{{\rm d}p^{\rm ch}_{\rm T,jet}\,{\rm d}\Delta\varphi\,{\rm d}\eta_{\rm jet}}\Bigg|_{p_{\rm T,trig}\in {\rm TT}_{\rm Sig}} - c_{\rm ref}\cdot \frac{1}{N^{\rm AA}_{\rm trig}} \frac{{\rm d}^3 N^{\rm AA}_{\rm jet}}{{\rm d}p^{\rm ch}_{\rm T,jet}\,{\rm d}\Delta\varphi\,{\rm d}\eta_{\rm jet}}\Bigg|_{p_{\rm T,trig}\in {\rm TT}_{\rm Ref}}$$

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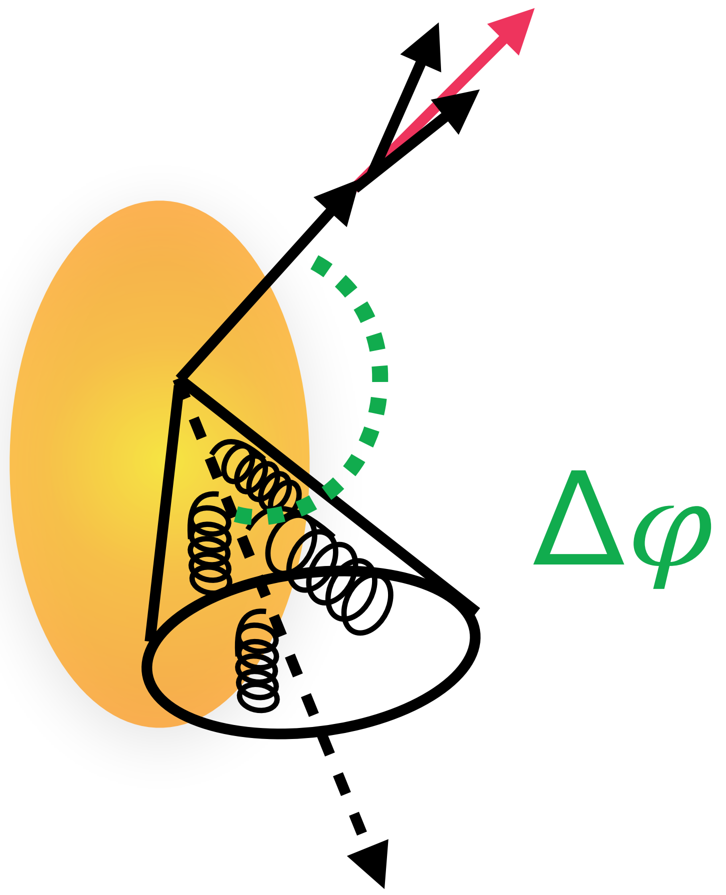
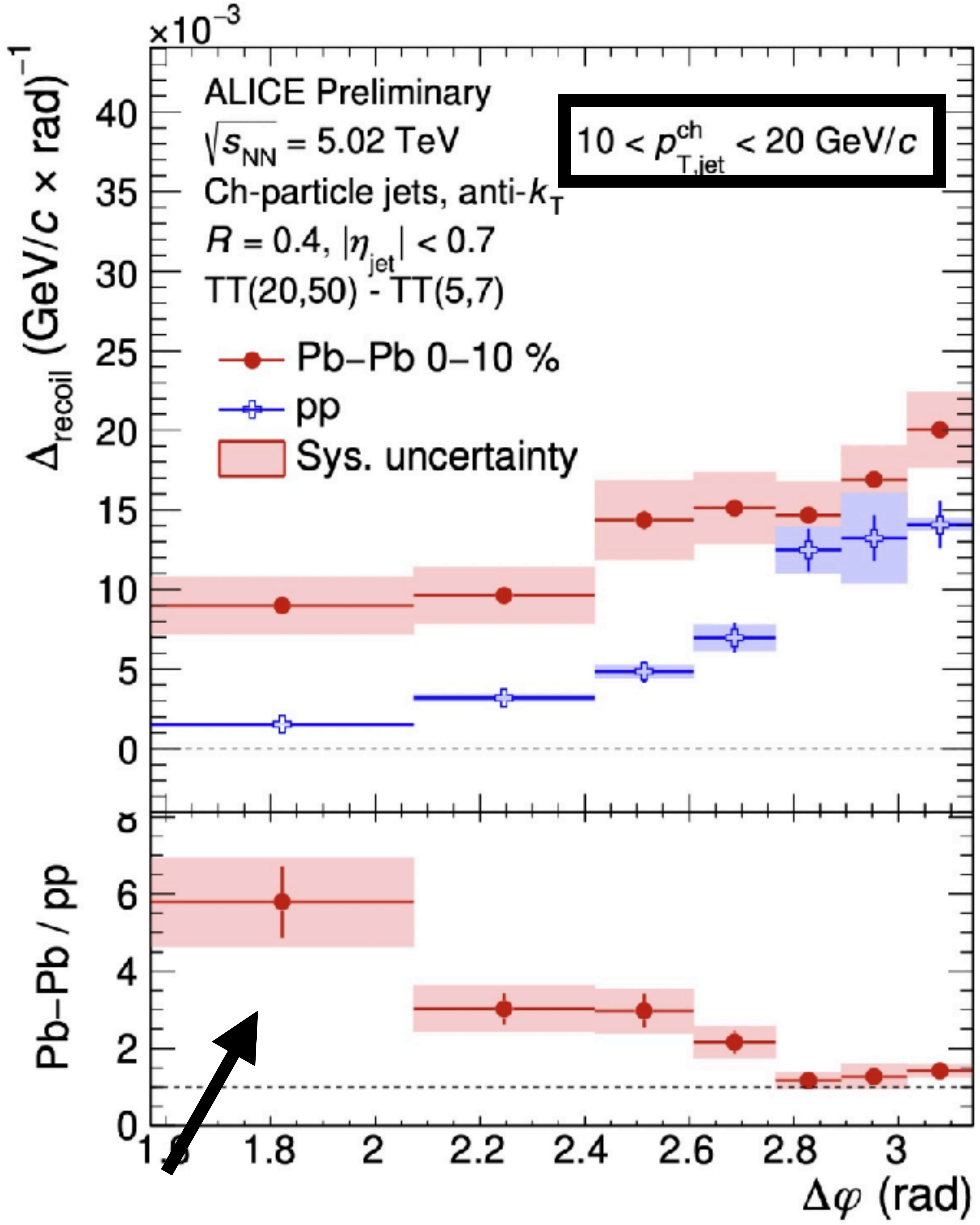
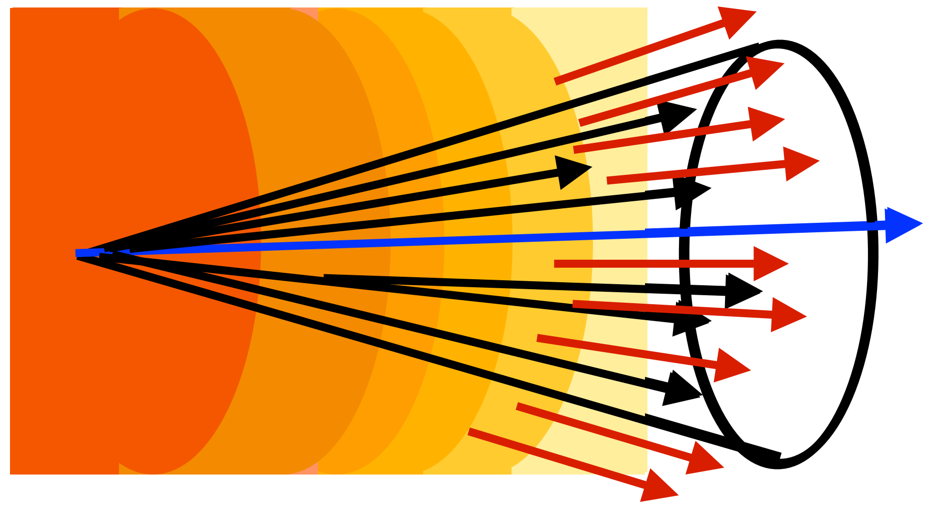




ALI-PREL-505599

- Signature of jet azimuthal broadening!

- Preliminary results from hybrid model show wake is dominant effect!



See talk by K. Rajagopal at ECT* workshop

Jet acoplanarity

$$\Delta_{\rm recoil} = \frac{1}{N^{\rm AA}_{\rm trig}} \frac{{\rm d}^3N^{\rm AA}_{\rm jet}}{{\rm d}p^{\rm ch}_{\rm T,jet}\,{\rm d}\Delta\varphi\,{\rm d}\eta_{\rm jet}}\Bigg|_{p_{\rm T,trig}\in{\rm TT_{Sig}}} - c_{\rm ref}\cdot\frac{1}{N^{\rm AA}_{\rm trig}} \frac{{\rm d}^3N^{\rm AA}_{\rm jet}}{{\rm d}p^{\rm ch}_{\rm T,jet}\,{\rm d}\Delta\varphi\,{\rm d}\eta_{\rm jet}}\Bigg|_{p_{\rm T,trig}\in{\rm TT_{Ref}}}$$

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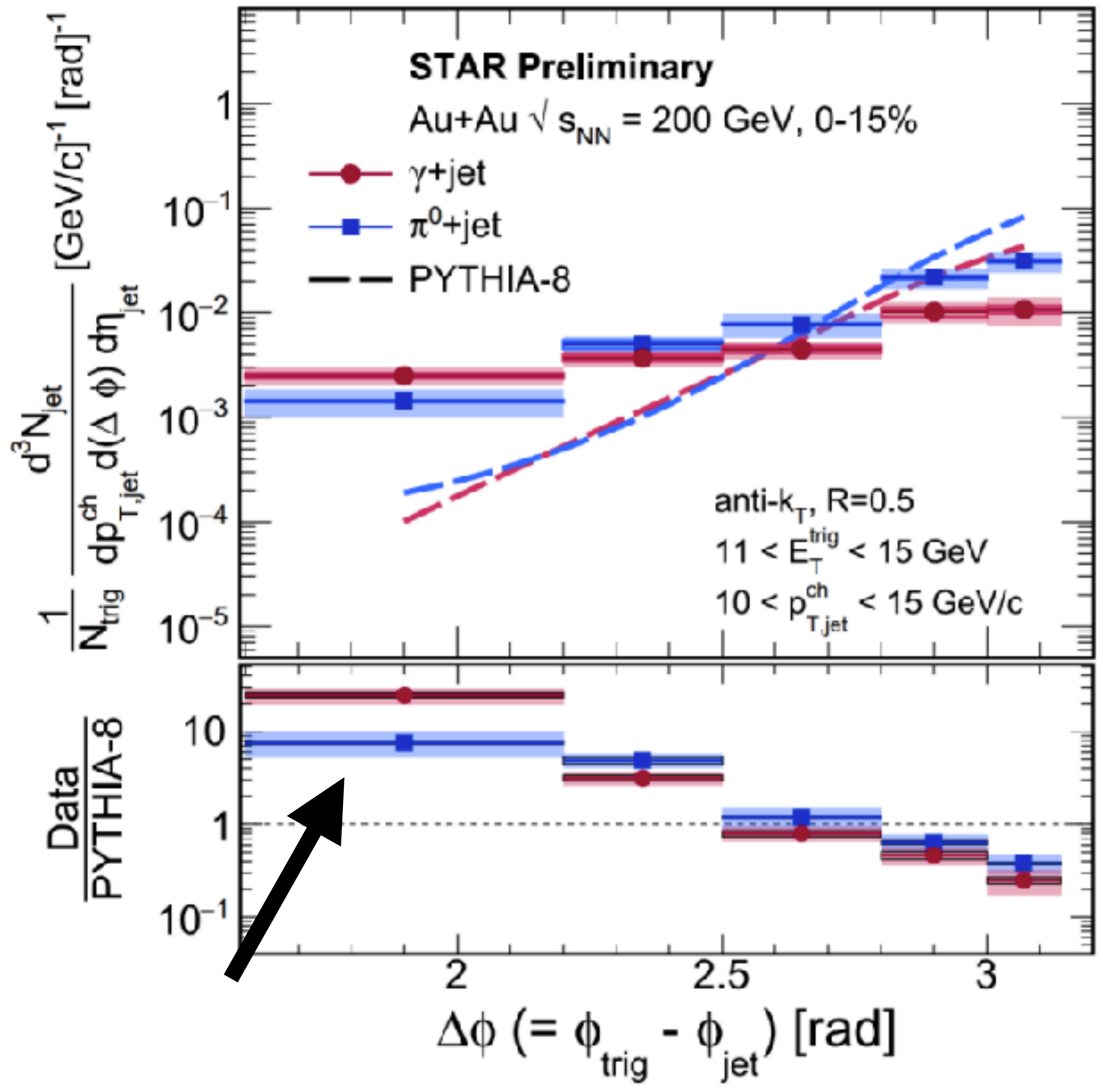
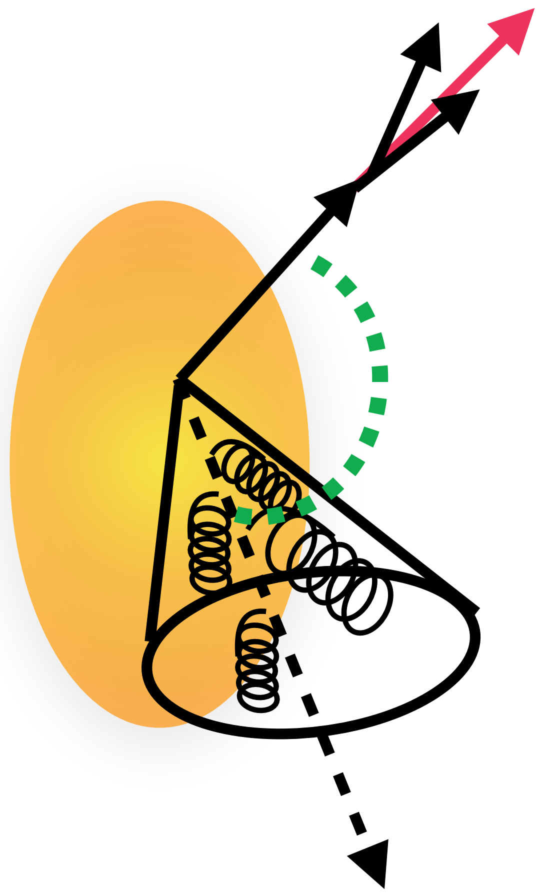
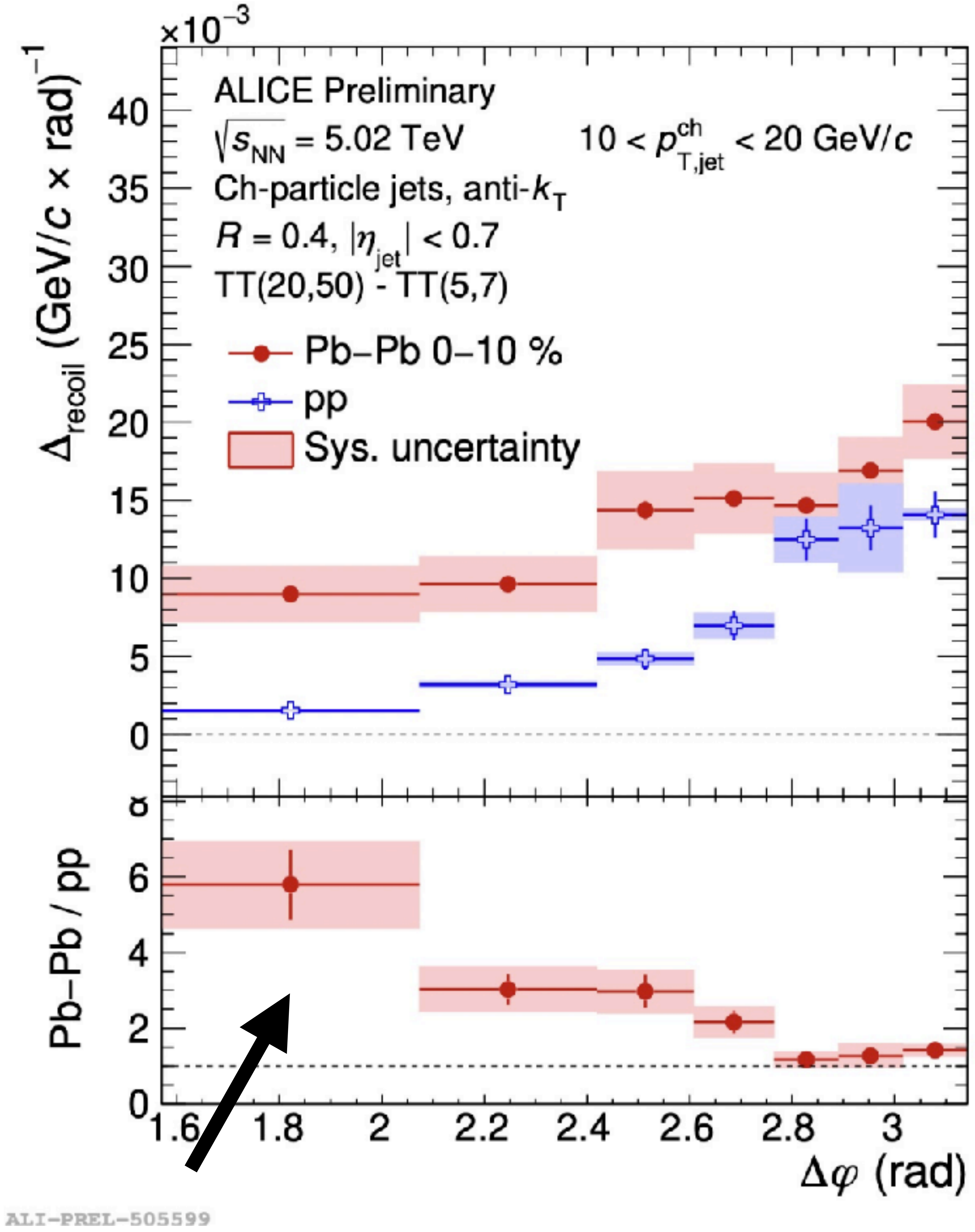




$\Delta\varphi$

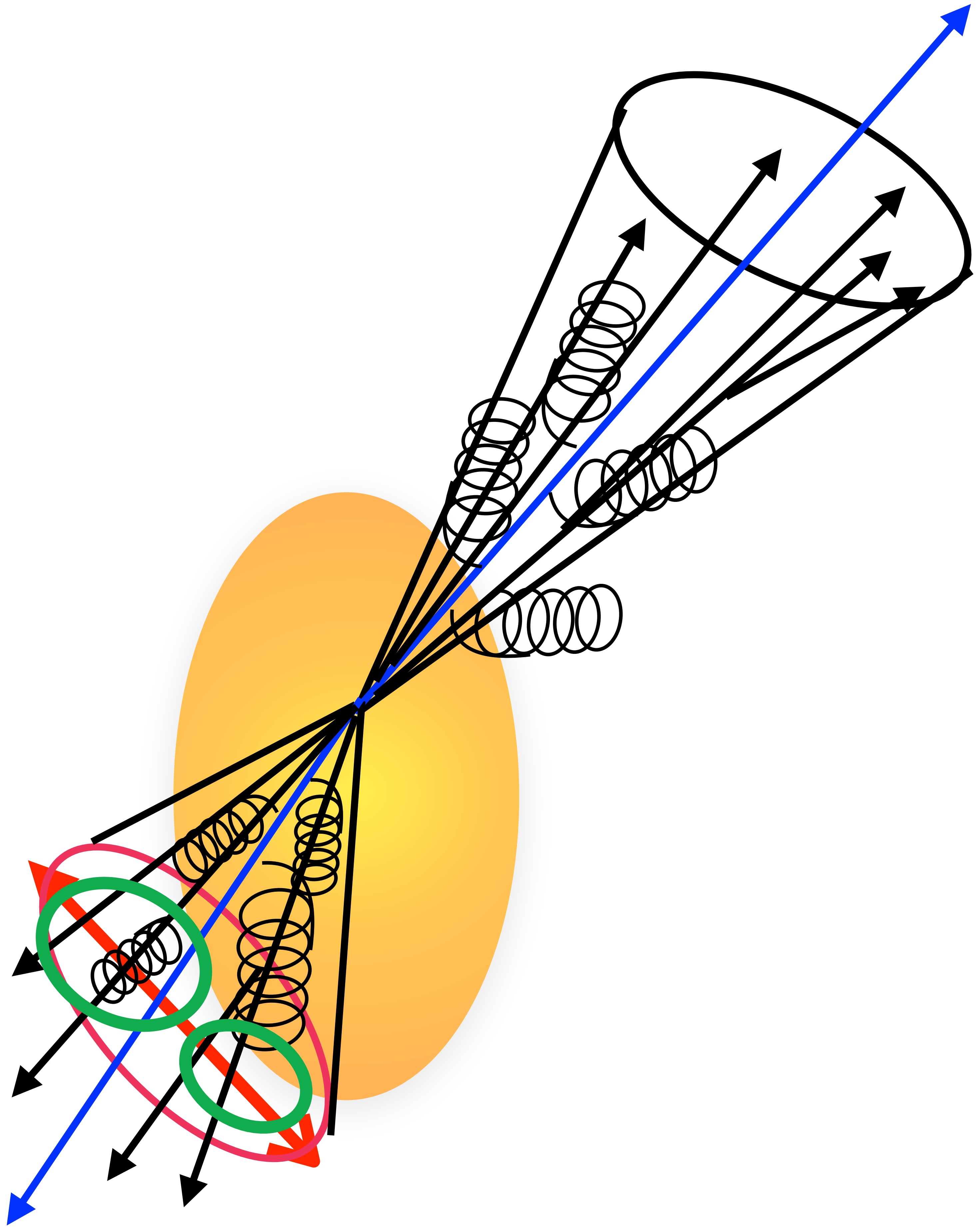
- Signature of jet azimuthal broadening!



- Already see similar effect at RHIC energies with STAR!

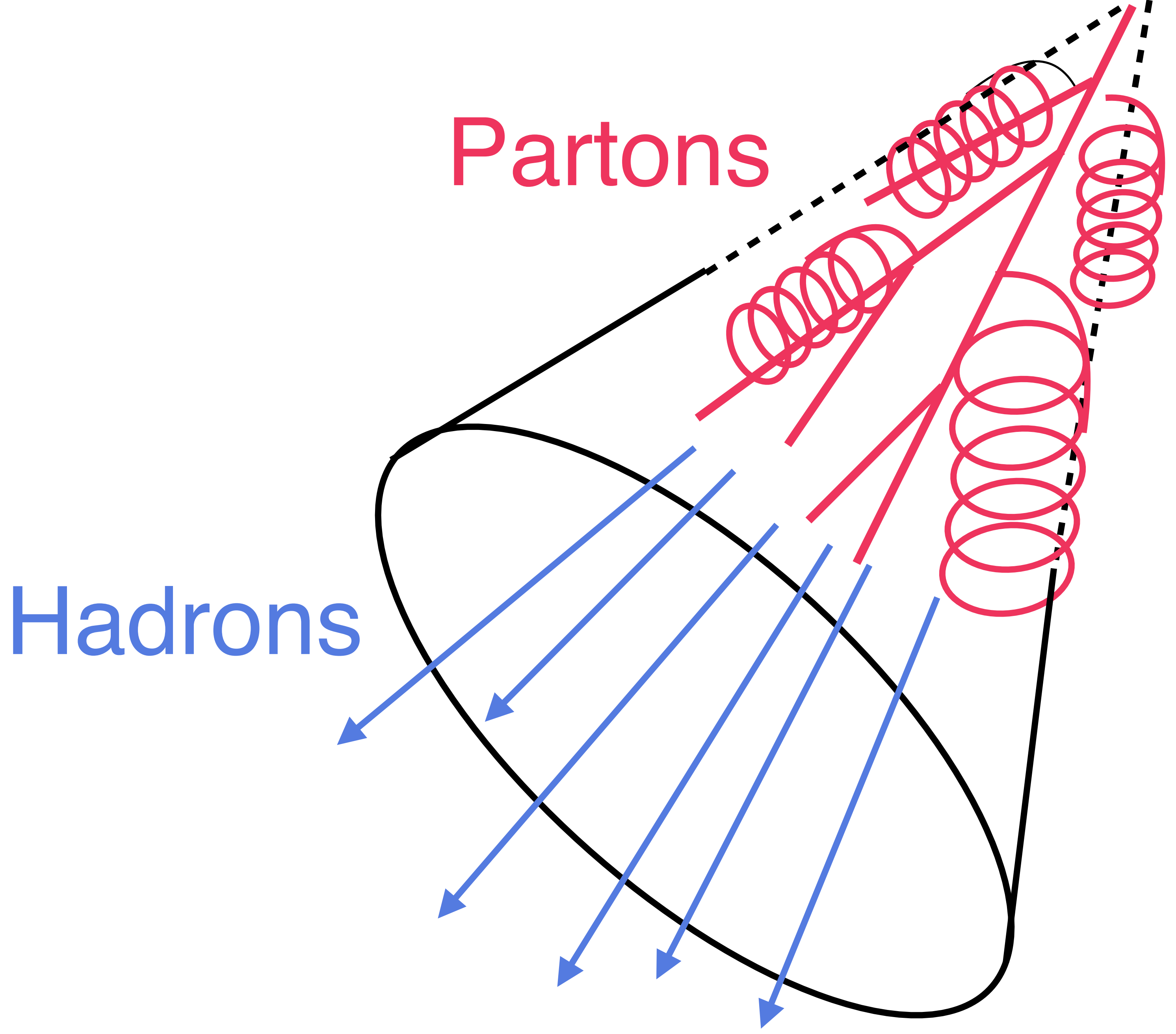
Measuring jet quenching

- Measuring jet quenching includes:
  - ➡ Energy loss through the suppression of high-p_T jet yields
  - ➡ Angular deflections and path length dependence through jet correlations
  - ➡ Intra-jet modifications by measuring jet structure and substructure



Desire to measure over a large range of scales including jet p_T and radii

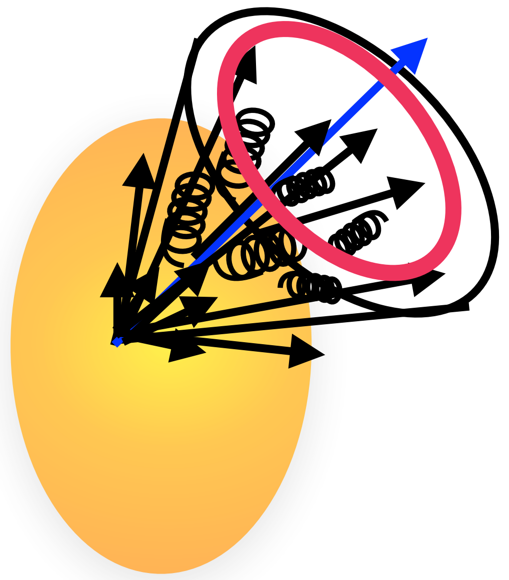
Jet internal structure



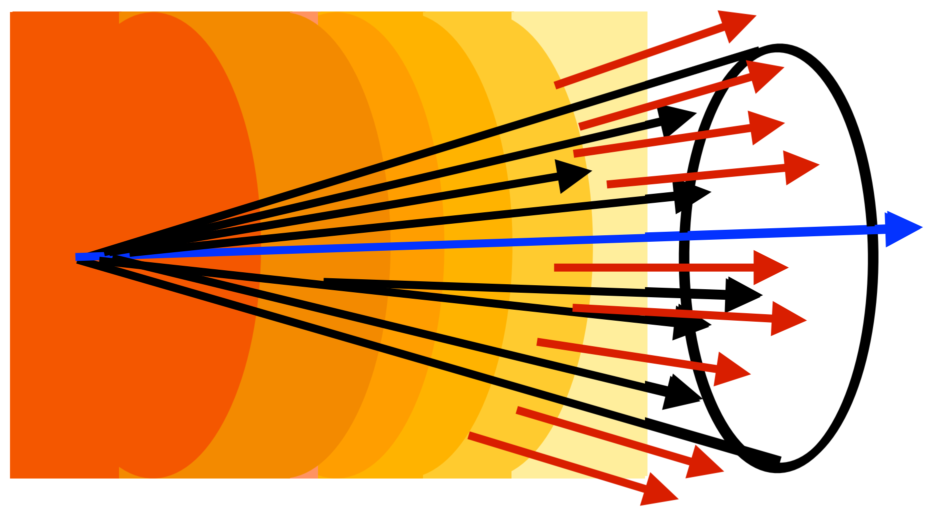
- Different variables probe a different aspect of jet structure modification

➡ Distribution of charged hadrons inside the jet

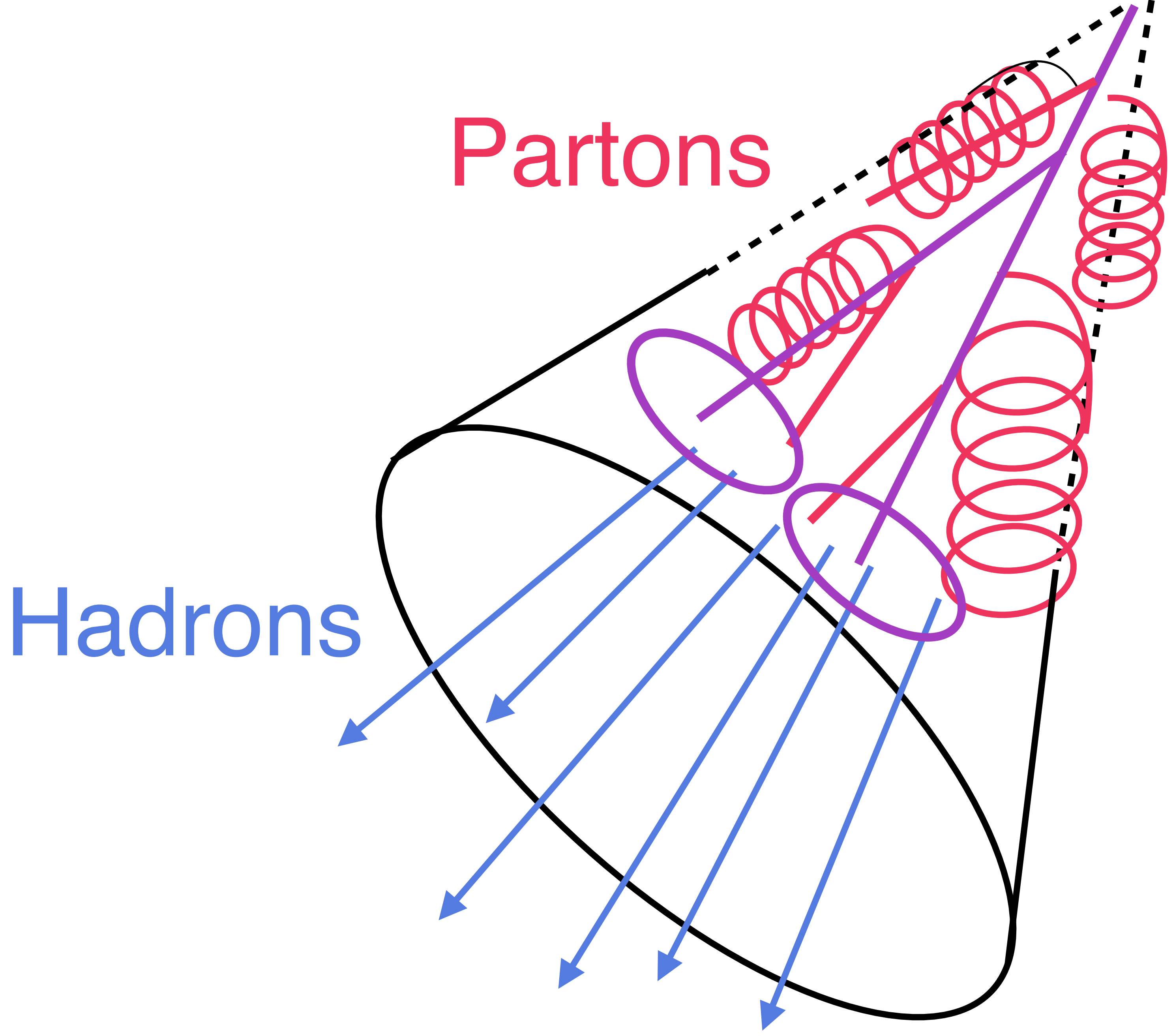
Momentum broadening



Medium response



Jet internal structure



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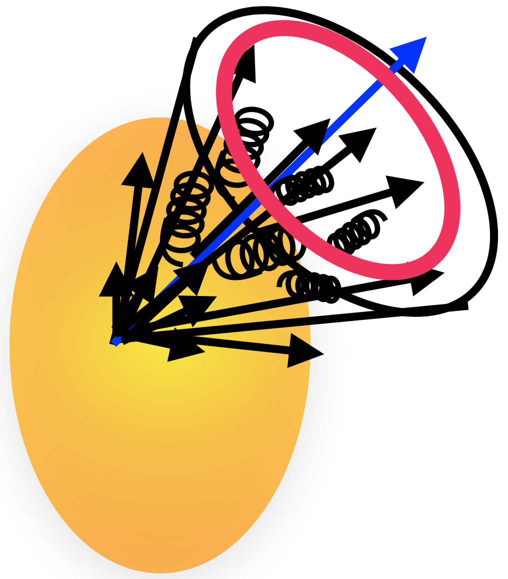

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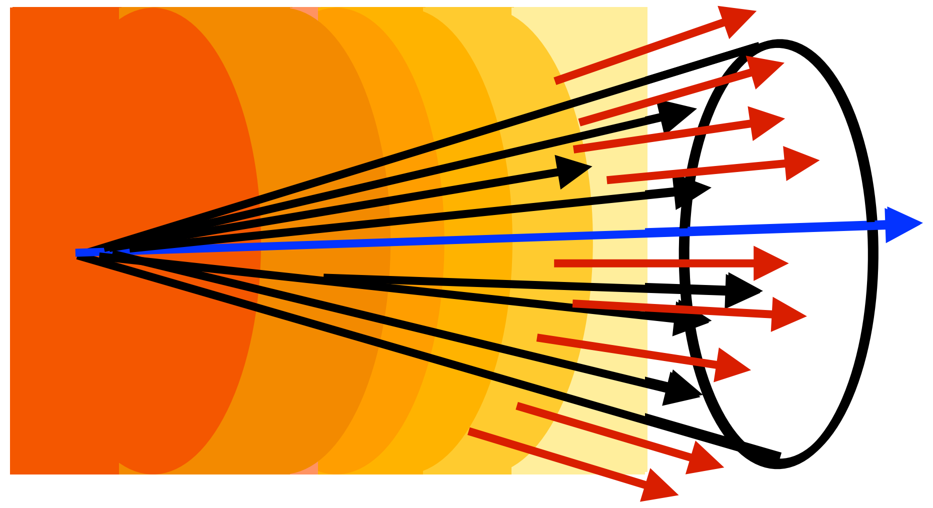
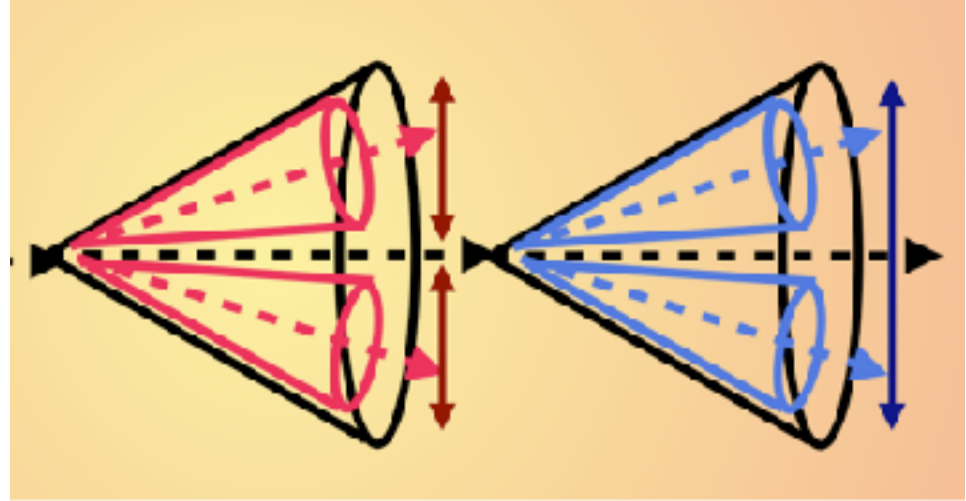


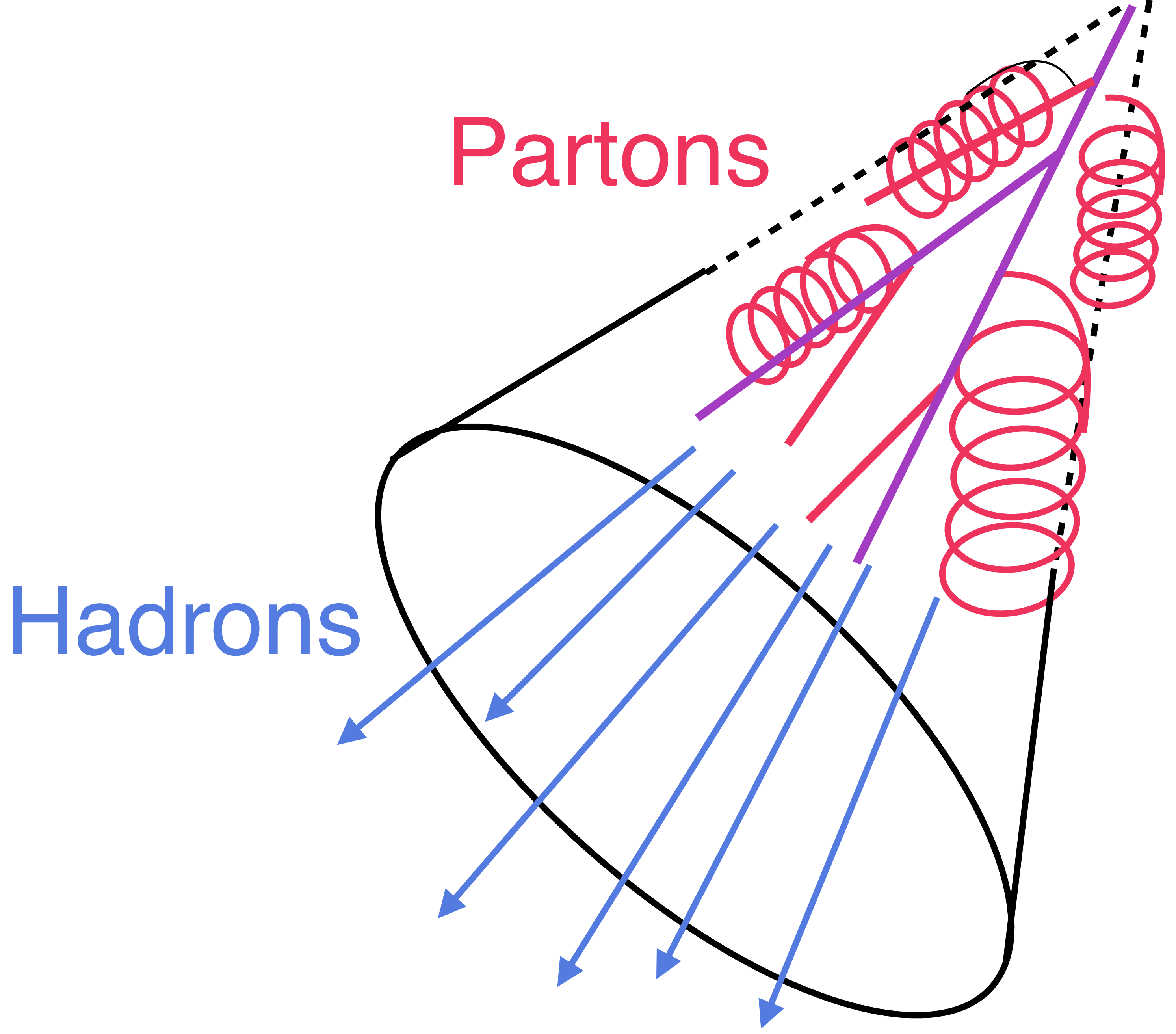
➡ Subjets from hard parton splittings

Separate out soft signal from softening of constituents and medium response to focus on modification of hard core



Resolution length of QGP?

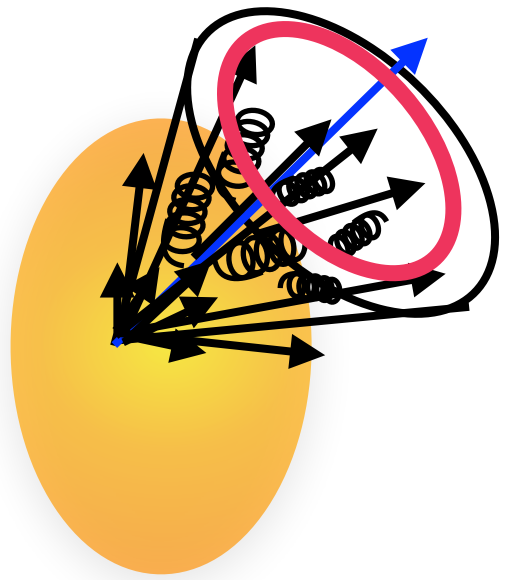
Jet internal structure



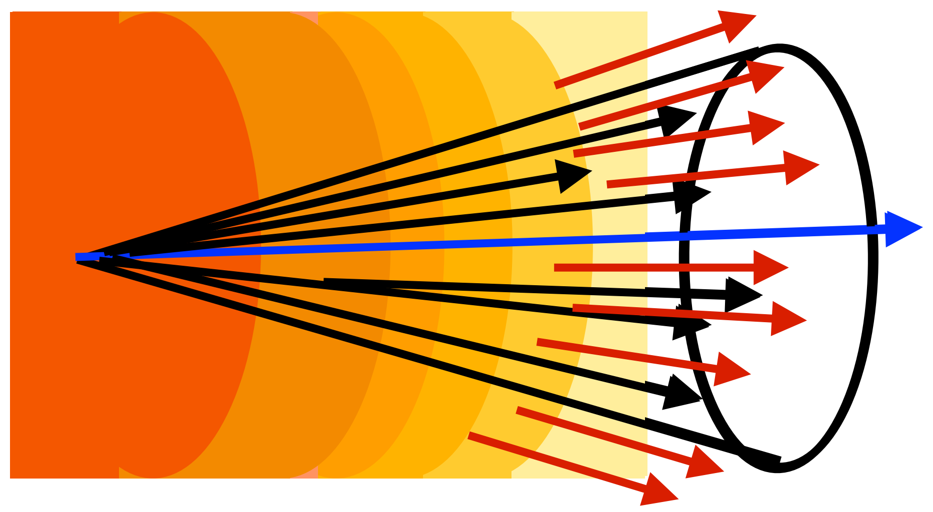
- Different variables probe a different aspect of jet structure modification

➡ **Distribution of charged hadrons inside the jet**

Momentum broadening



Medium response



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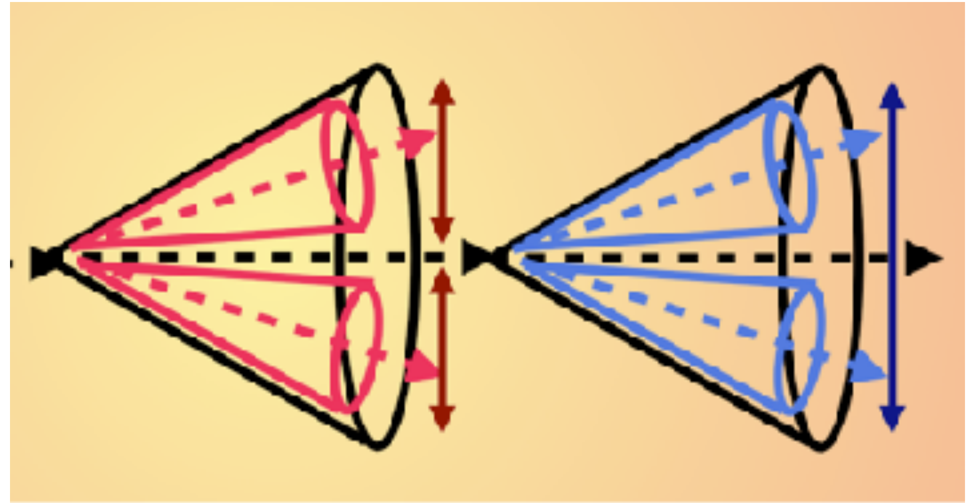
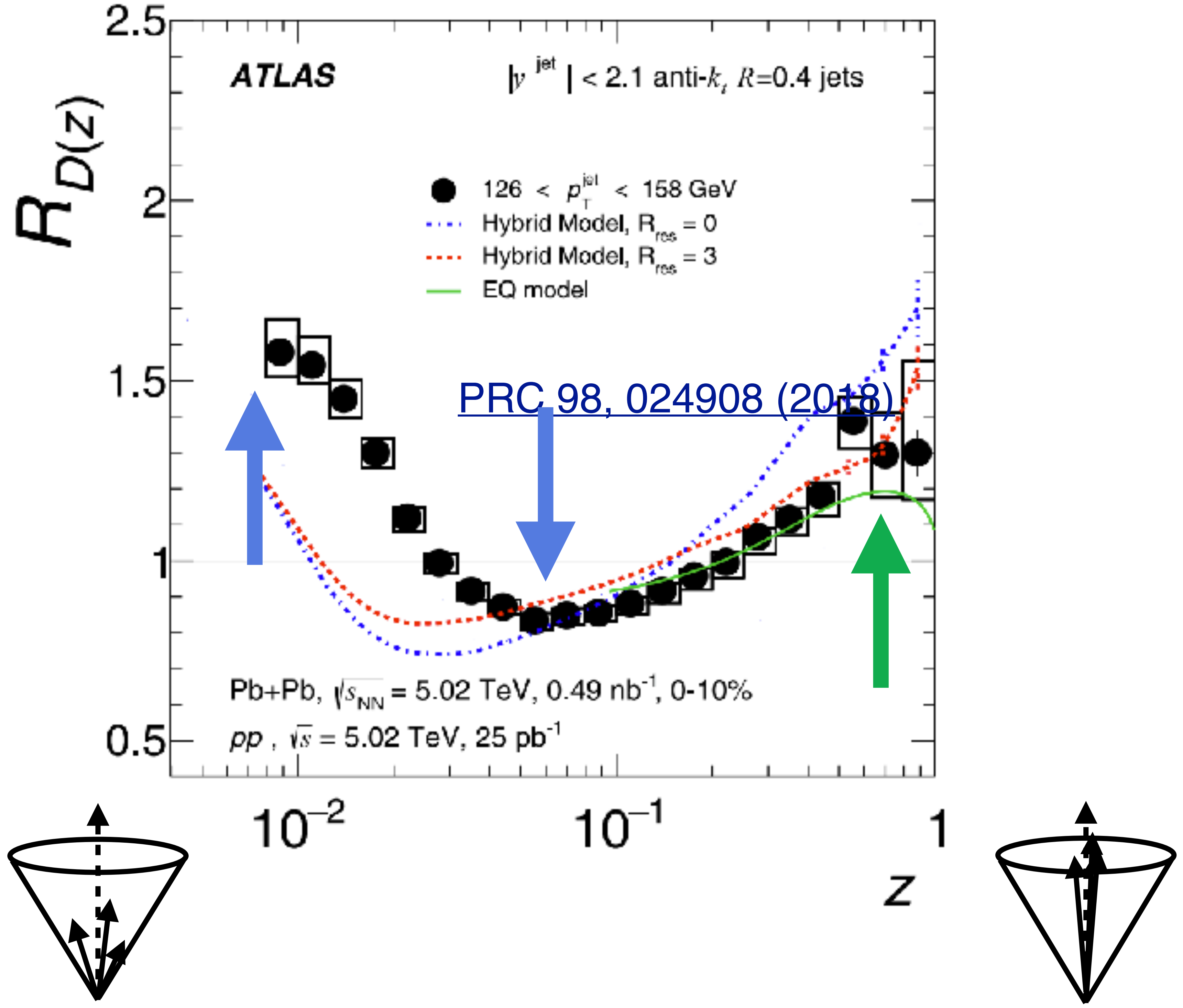


Jet shapes and fragmentation

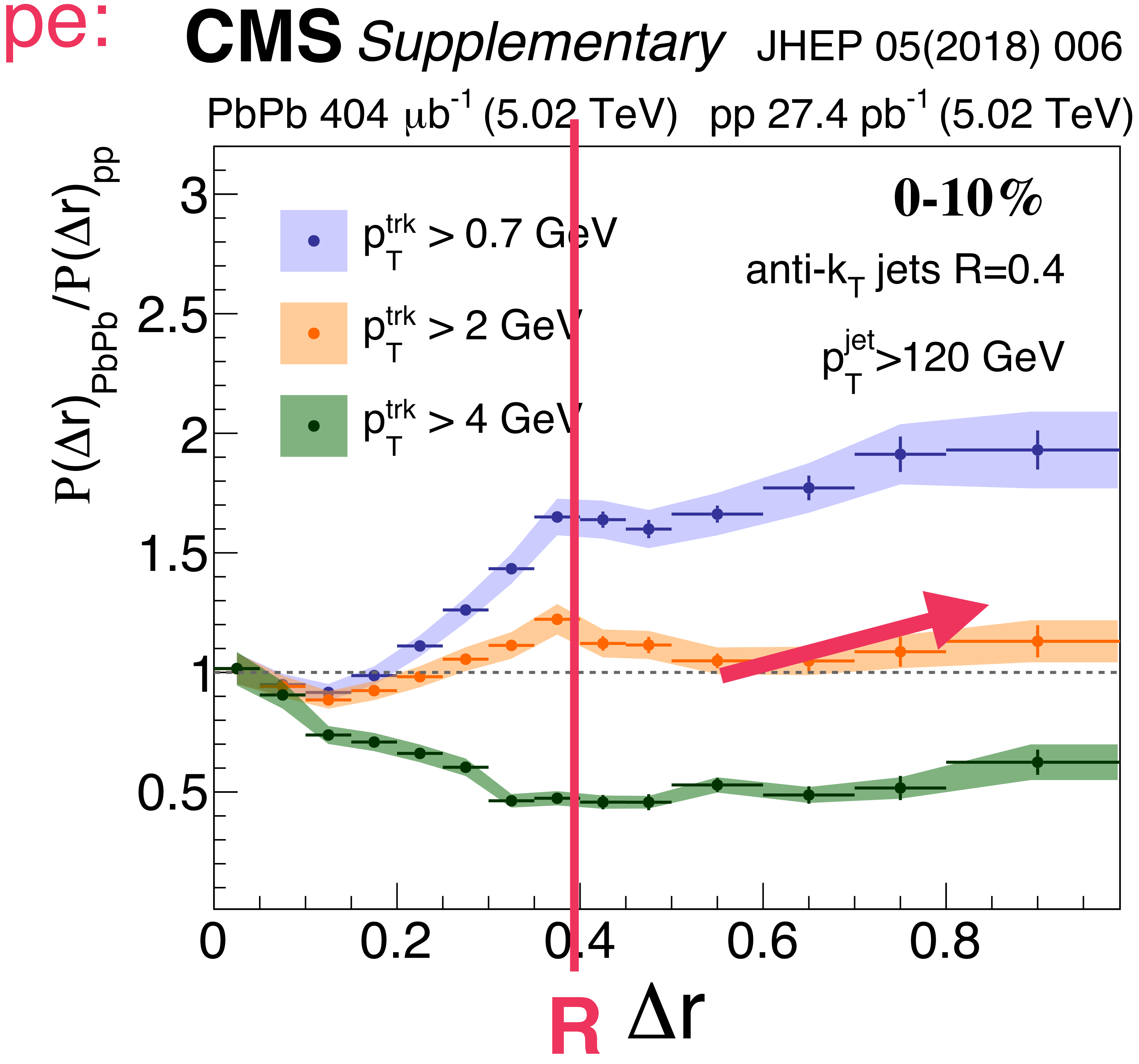
- Jet fragmentation:



Energy transferred to soft particles inside the jet

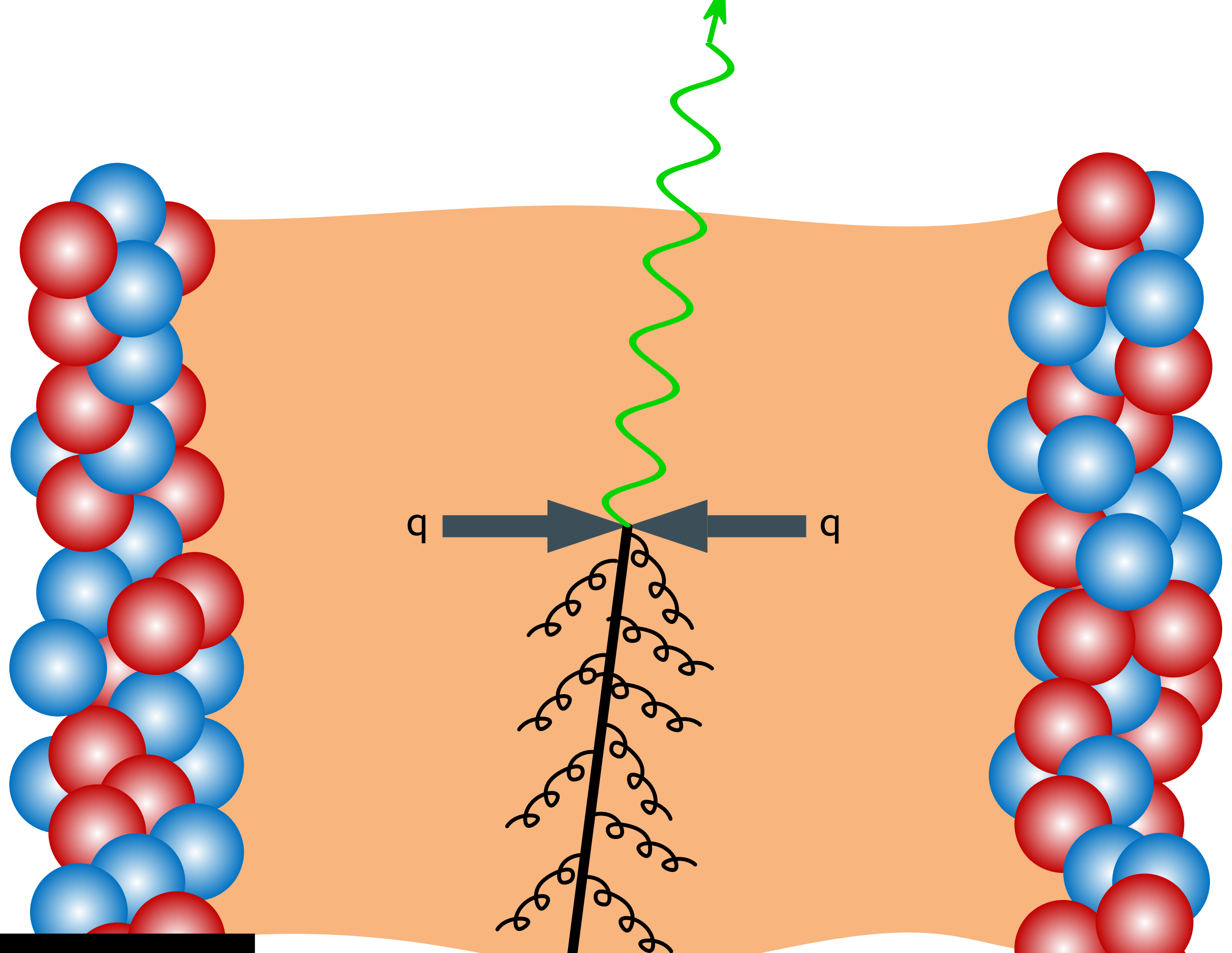
Hardening of core: high z enhancement from quark vs. gluons?

- Jet shape:



Soft particles are at large angles from jet axis

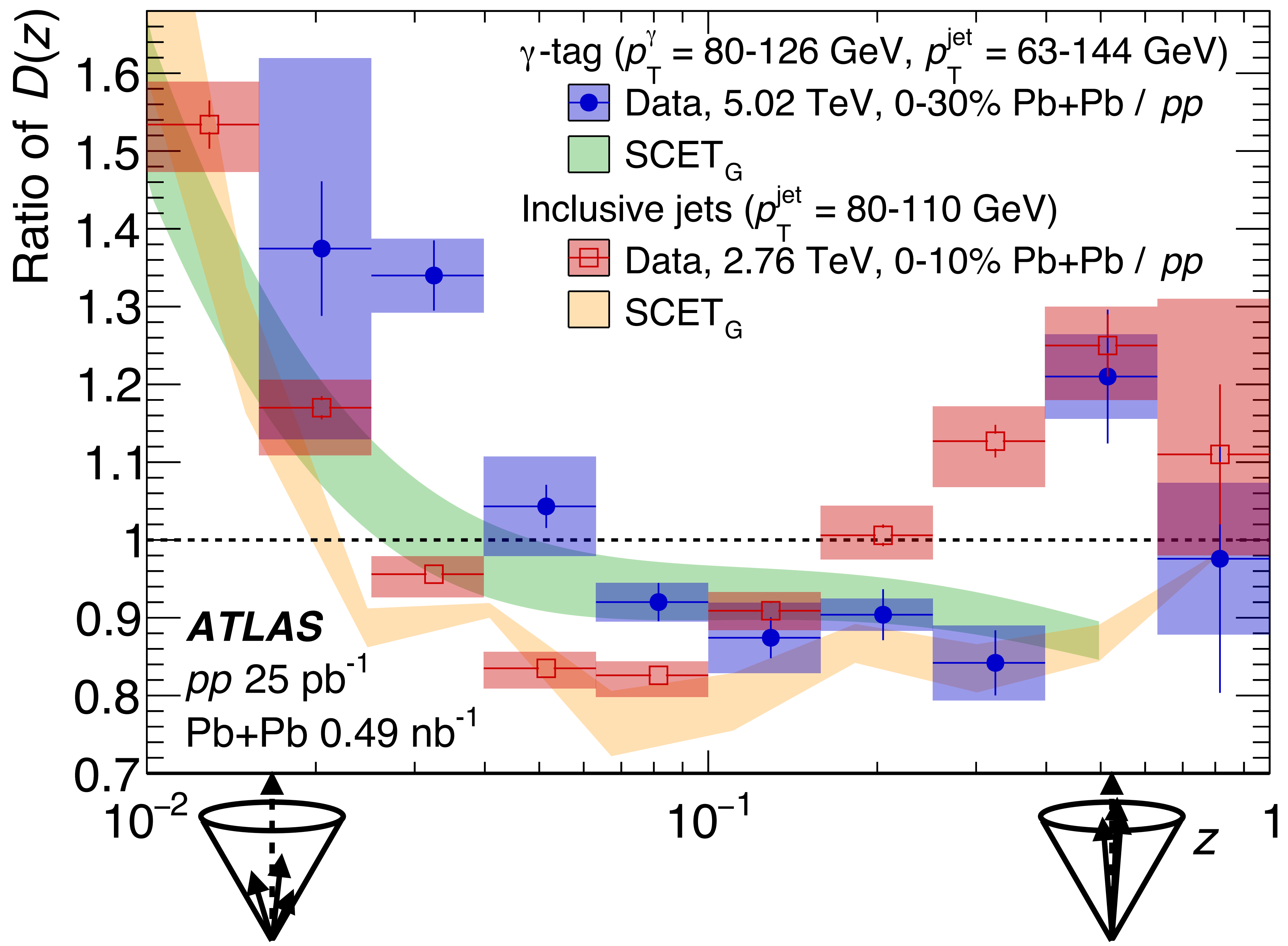
Boson-tagged jet structure



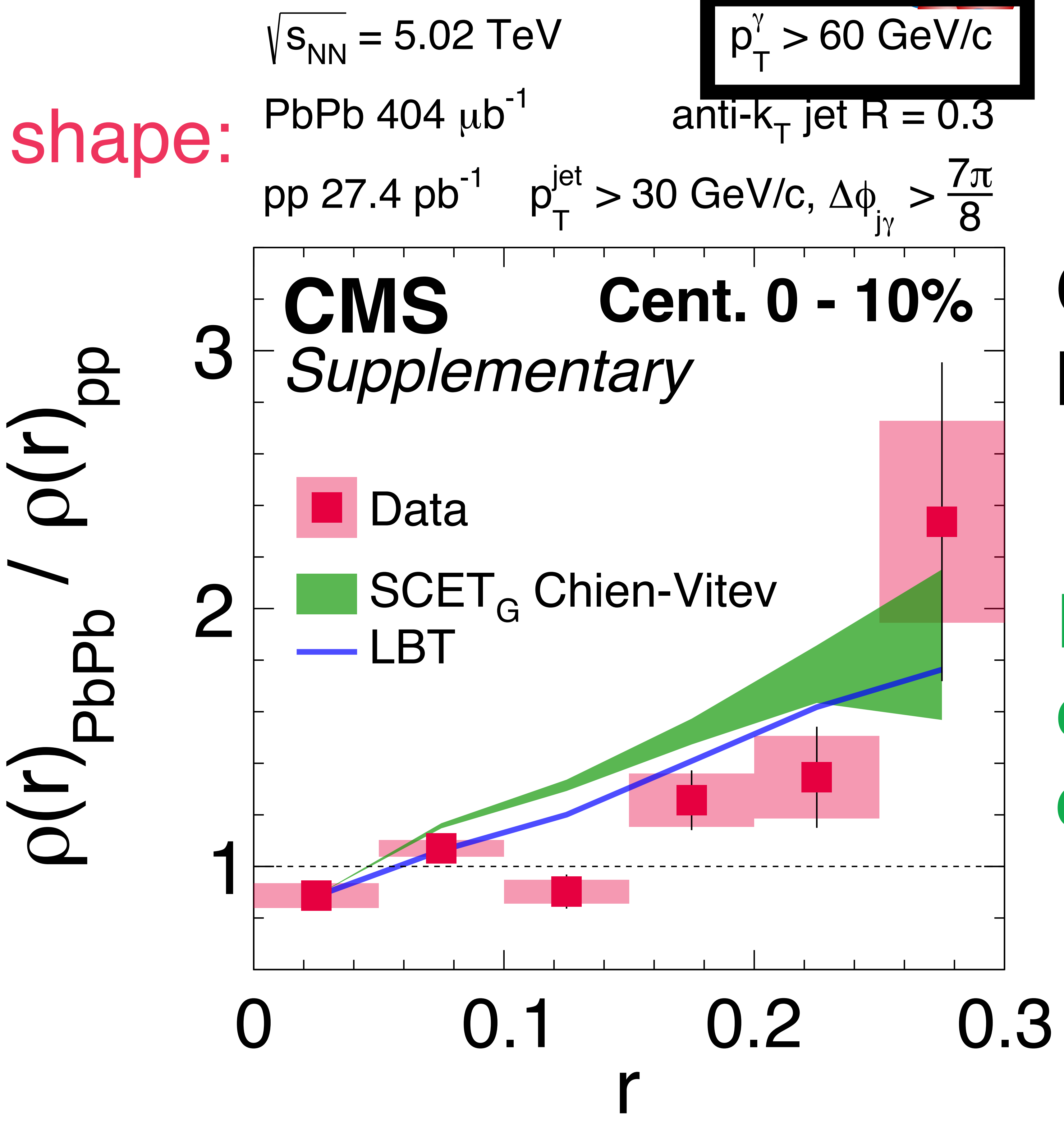
- Boson-jets dominated by quark jets
- Boson tag provides approximate initial momentum of jet (no energy loss)

- Photon-jet fragmentation

PRL 123 (2019) 042001



- Photon-jet shape:

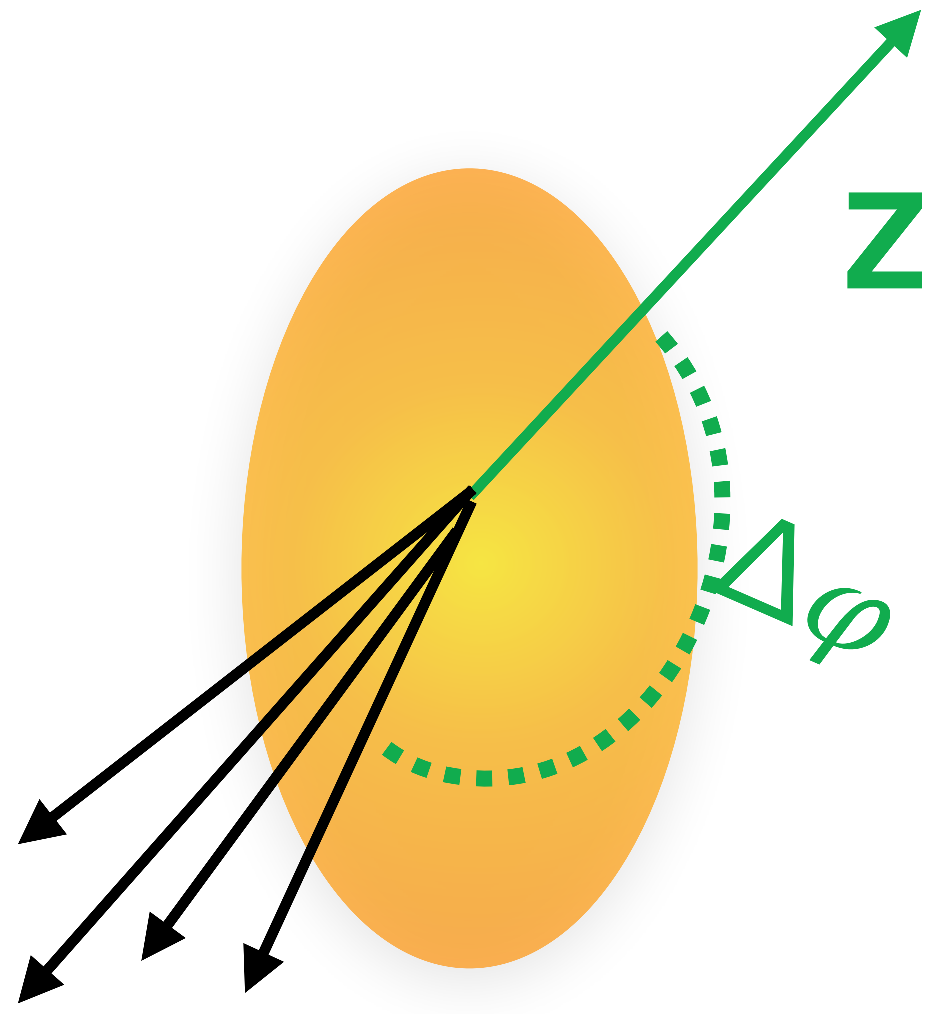


Qualitatively similar behavior to inclusive

Except high z enhancement disappears?

PRL 122 (2019) 1520

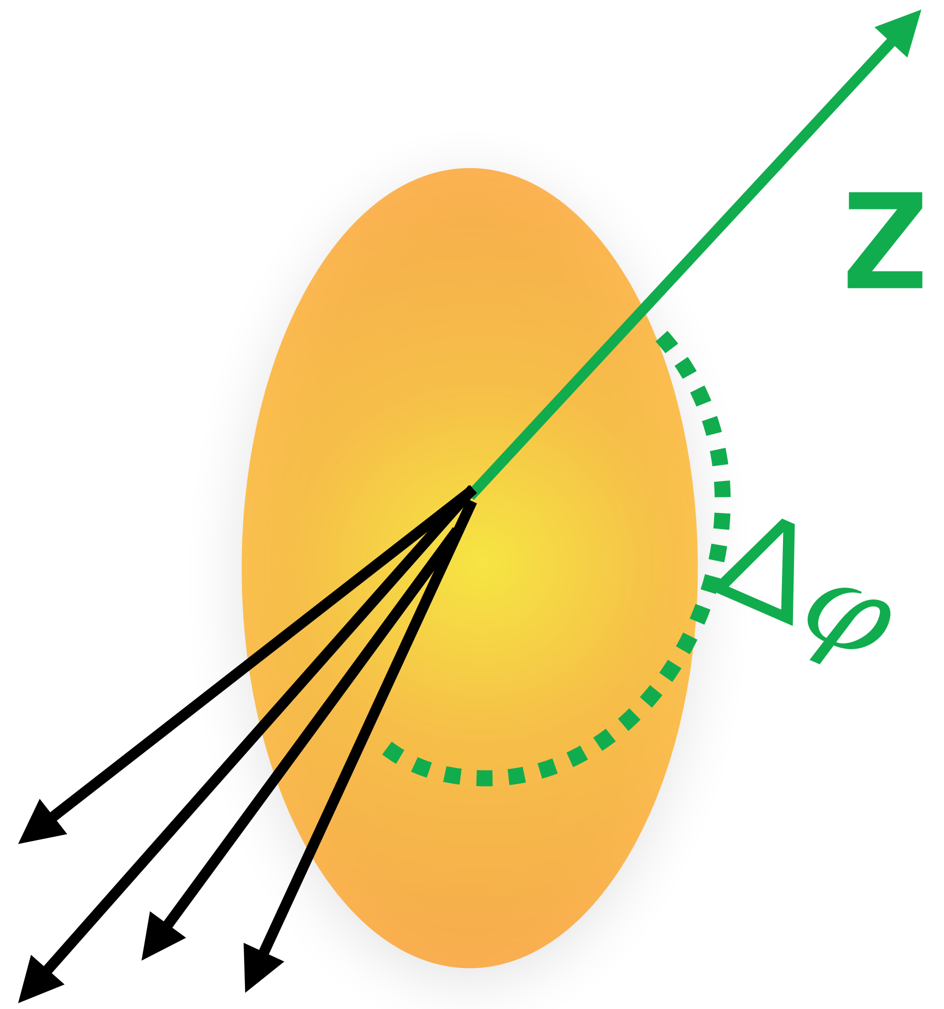
Z-tagged particles



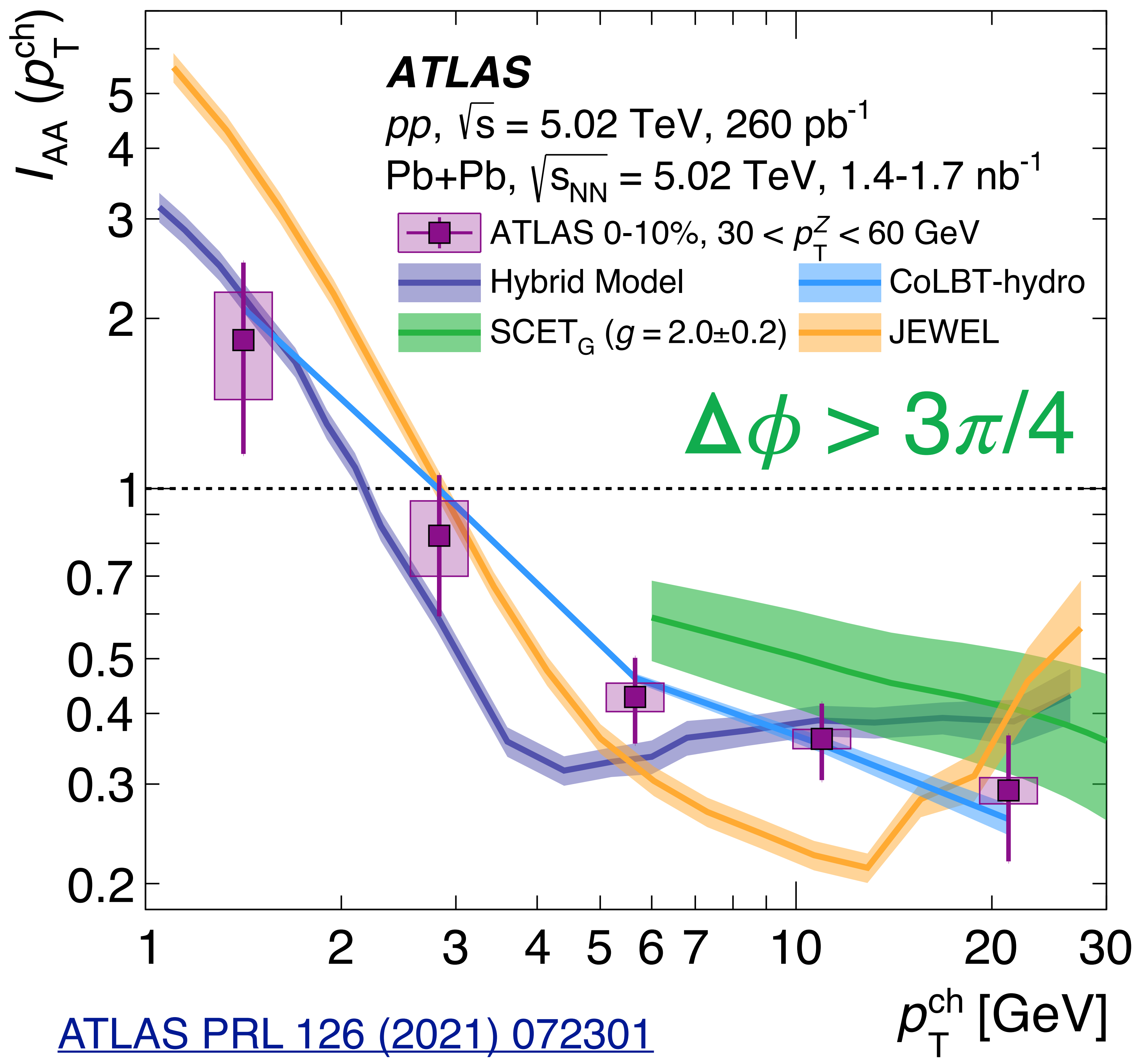
- Z-tag allows access to lower momentum than photons because of less background

- Z-tagged particles not biased by jet -> possibly access to larger jet quenching effects

Z-tagged particles



I_{AA}: yields in Pb-Pb/pp



ATLAS PRL 126 (2021) 072301

- Enhancement of soft particles -> similar to inclusive, photon, and hadron-jet

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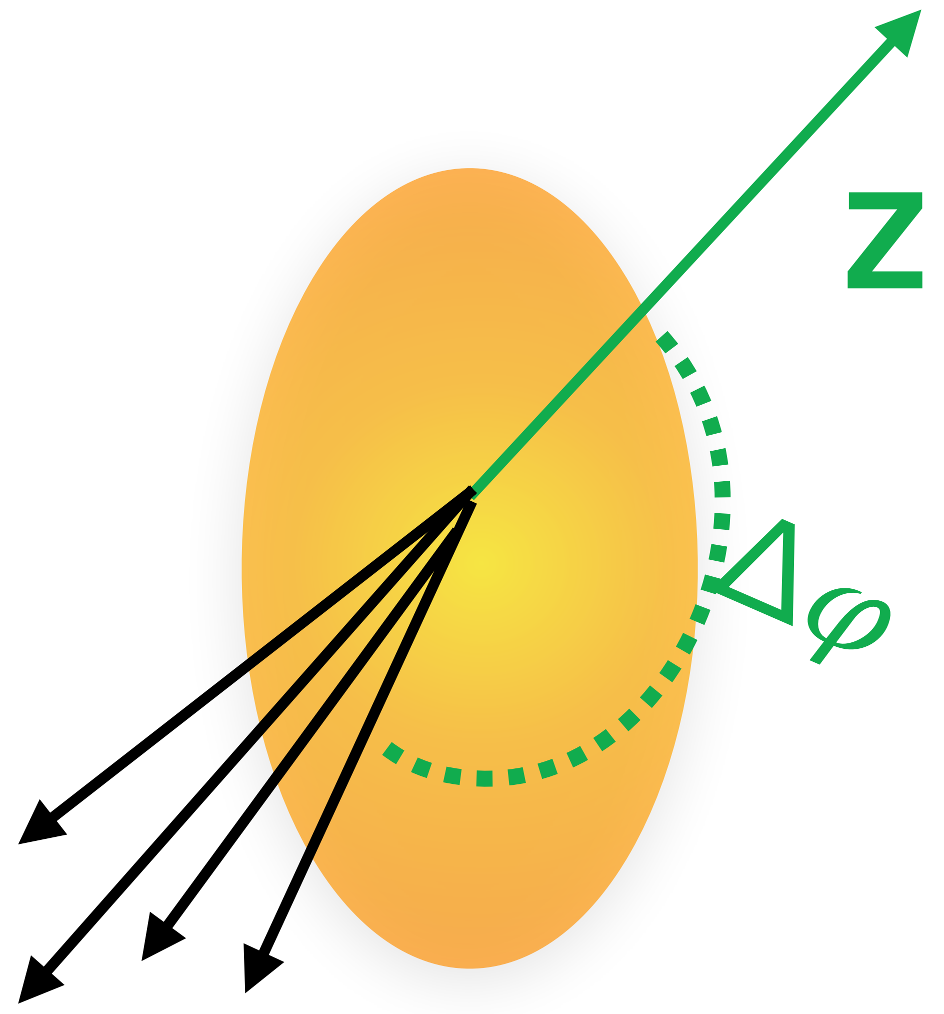
Z-tagged particles



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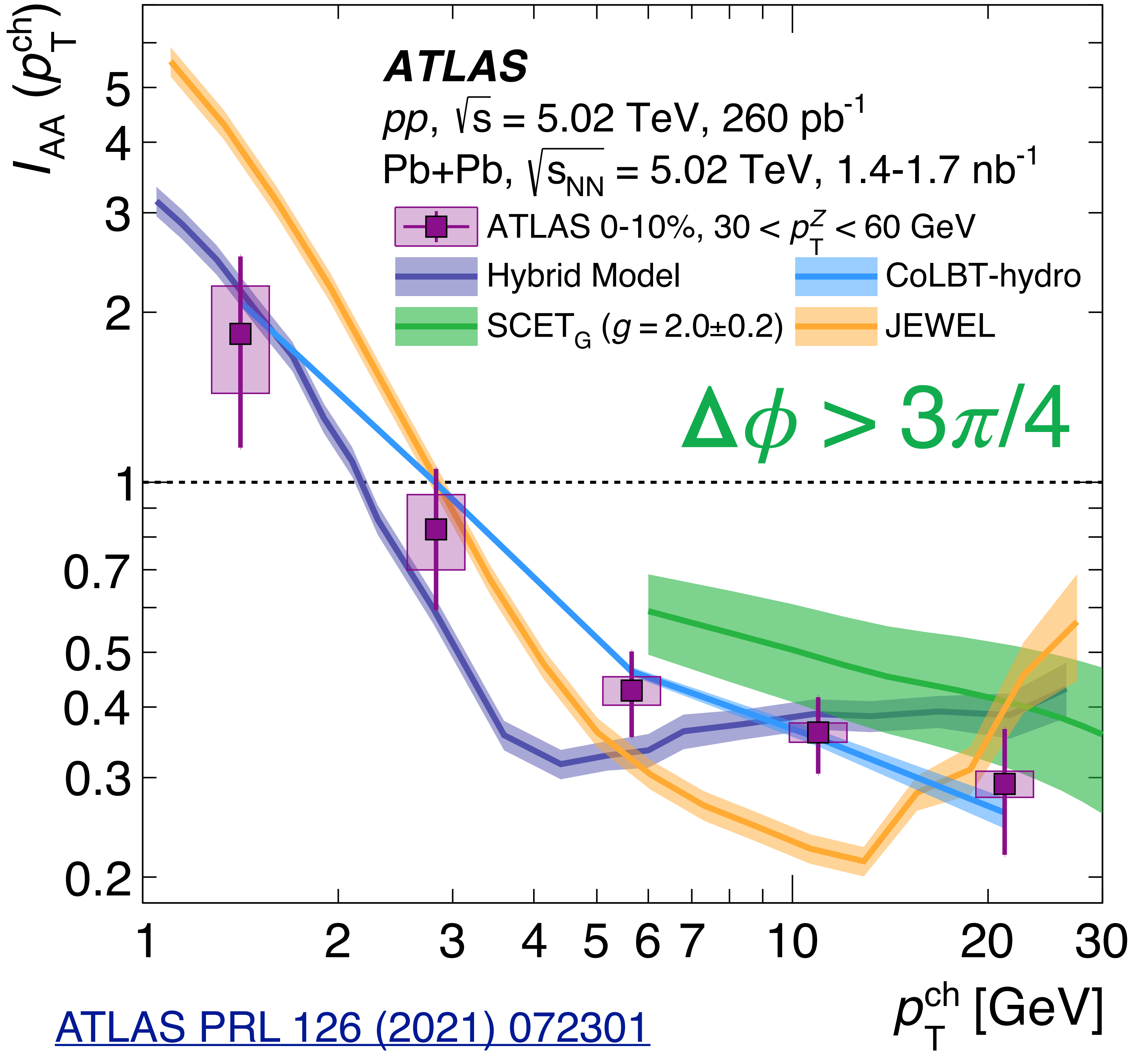

ATLAS PRL 126 (2021) 072301

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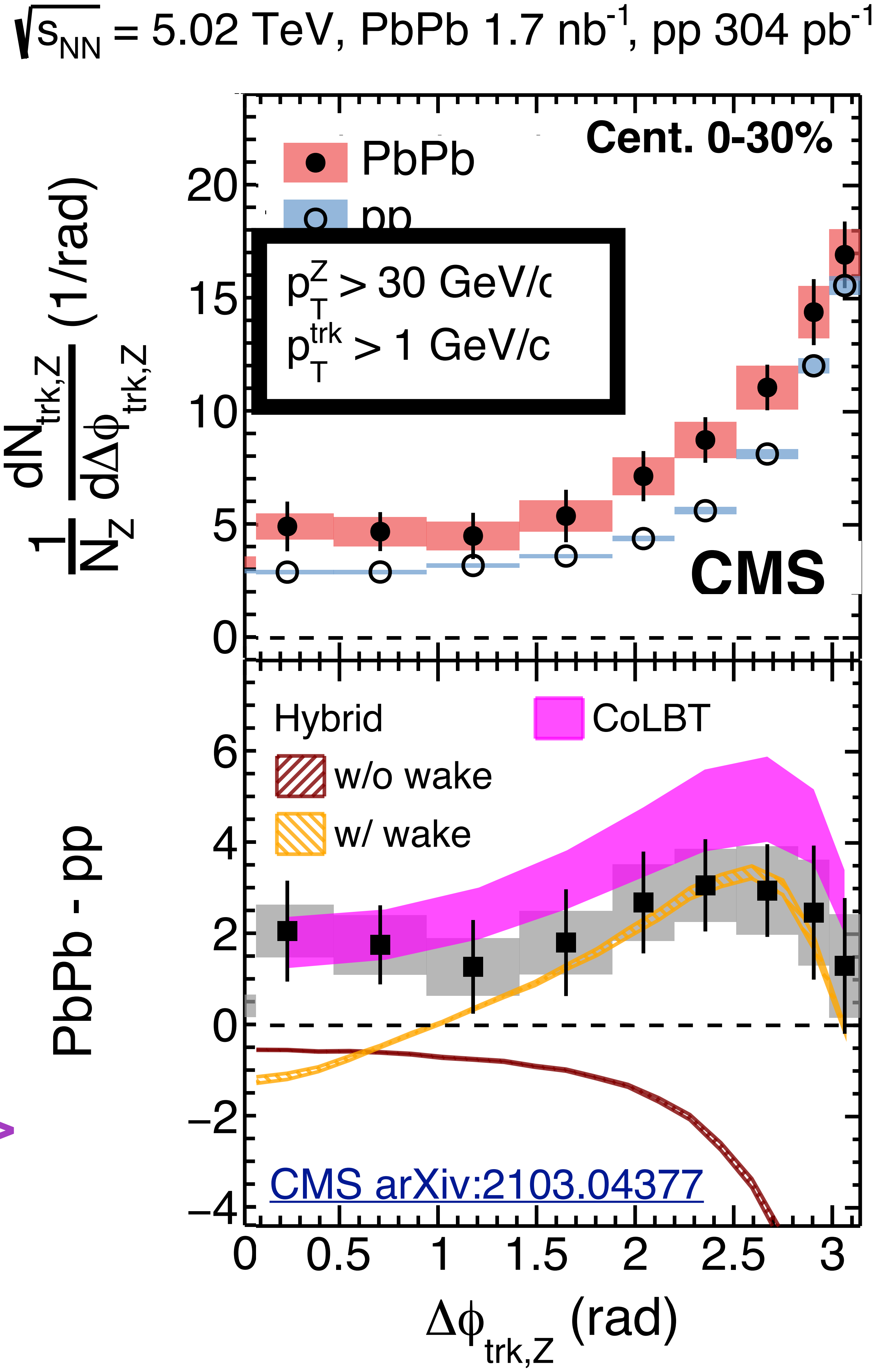
Δϕ between Z and hadrons



CMS arXiv:2103.04377

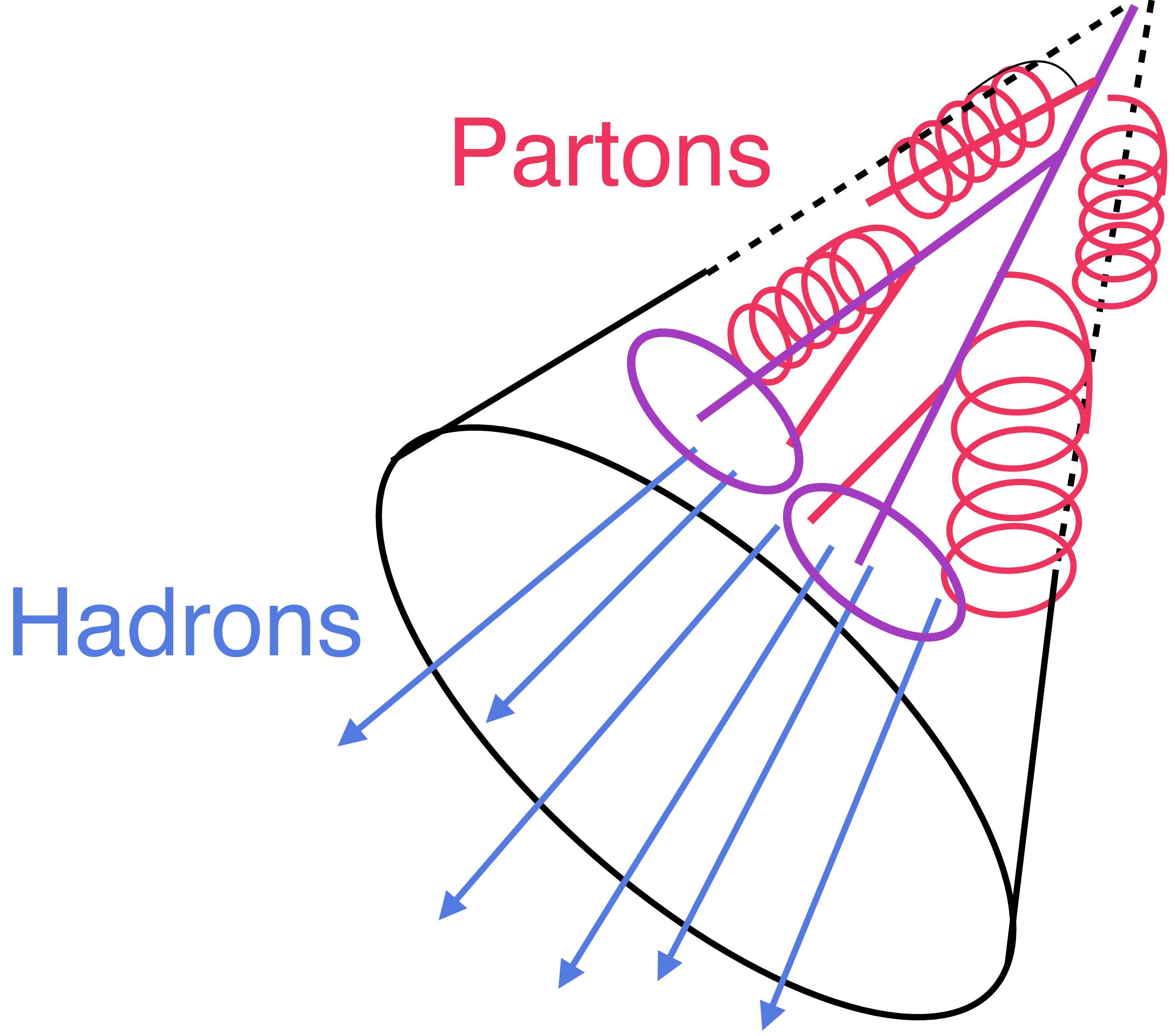
- Excess of charged particles at all Δϕ

Away side excess expected from momentum broadening

Medium response could cause excess at all Δϕ or possible MPI effects?

Zhong arXiv:2101.05422

Jet internal structure



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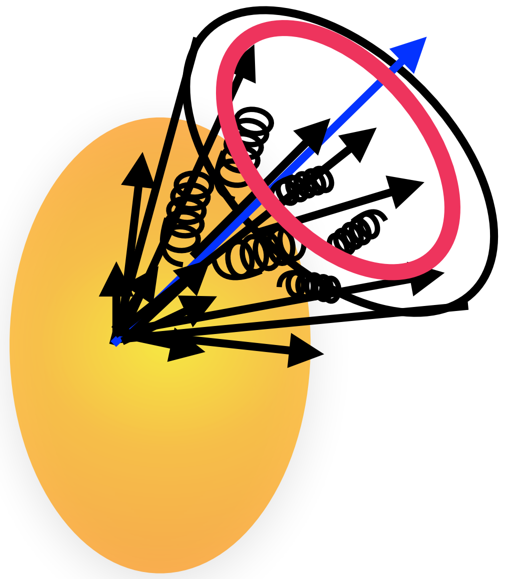
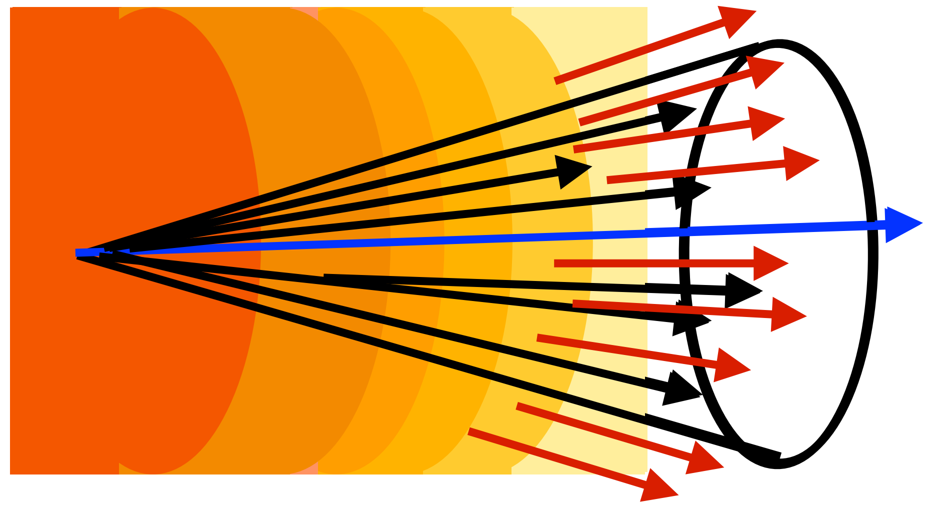


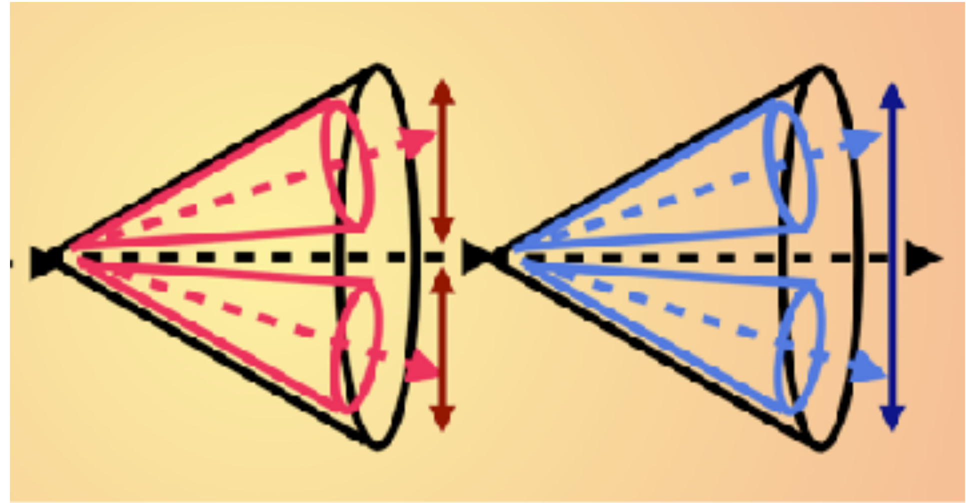
Medium response



➡**Subjets from hard parton splittings**

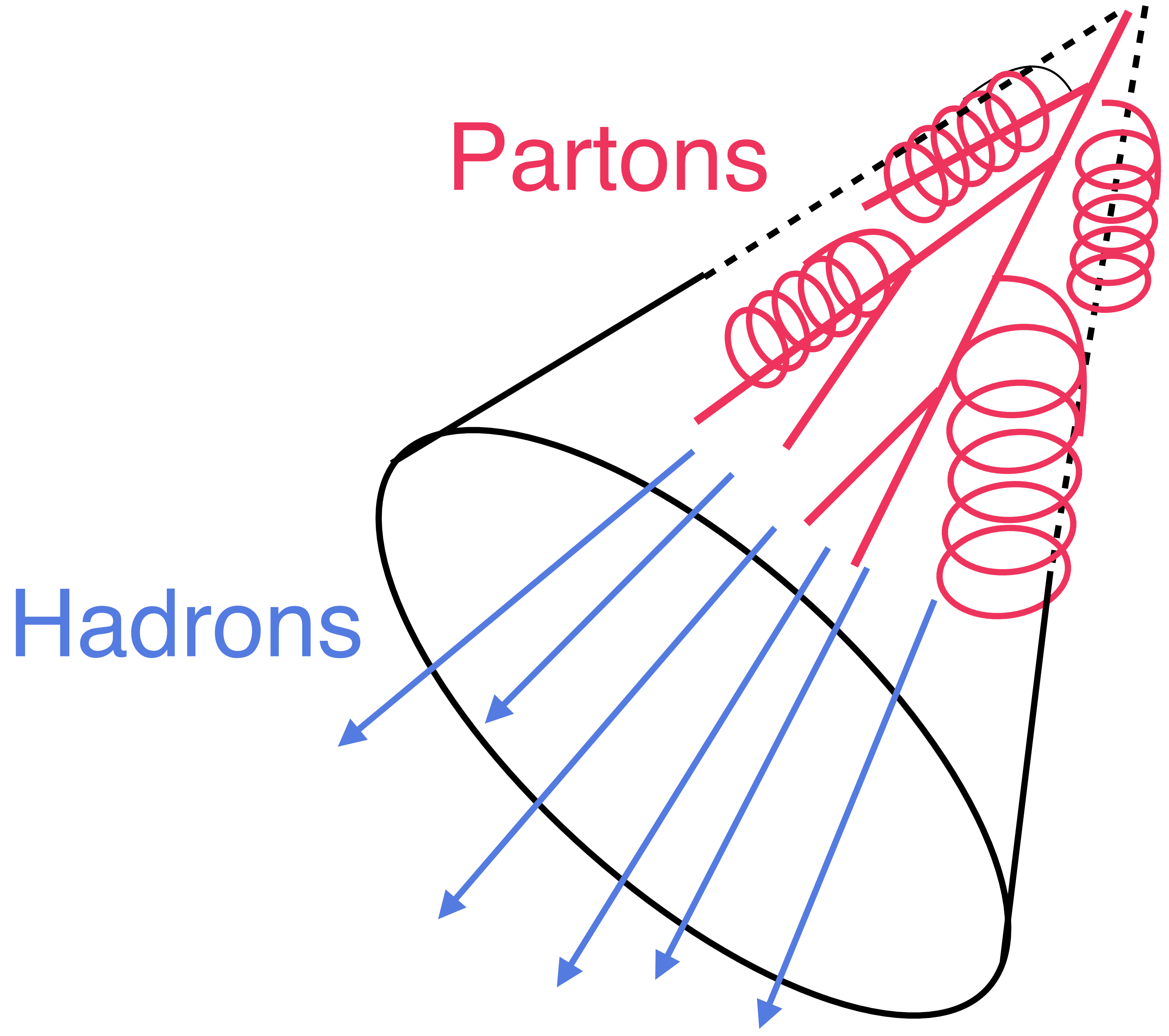
Separate out soft signal from softening of constituents and medium response to focus on modification of hard core

Resolution length of QGP?



Experimentally probing medium resolution

New tool: jet splittings



Experimentally probing medium resolution

New tool: jet splittings

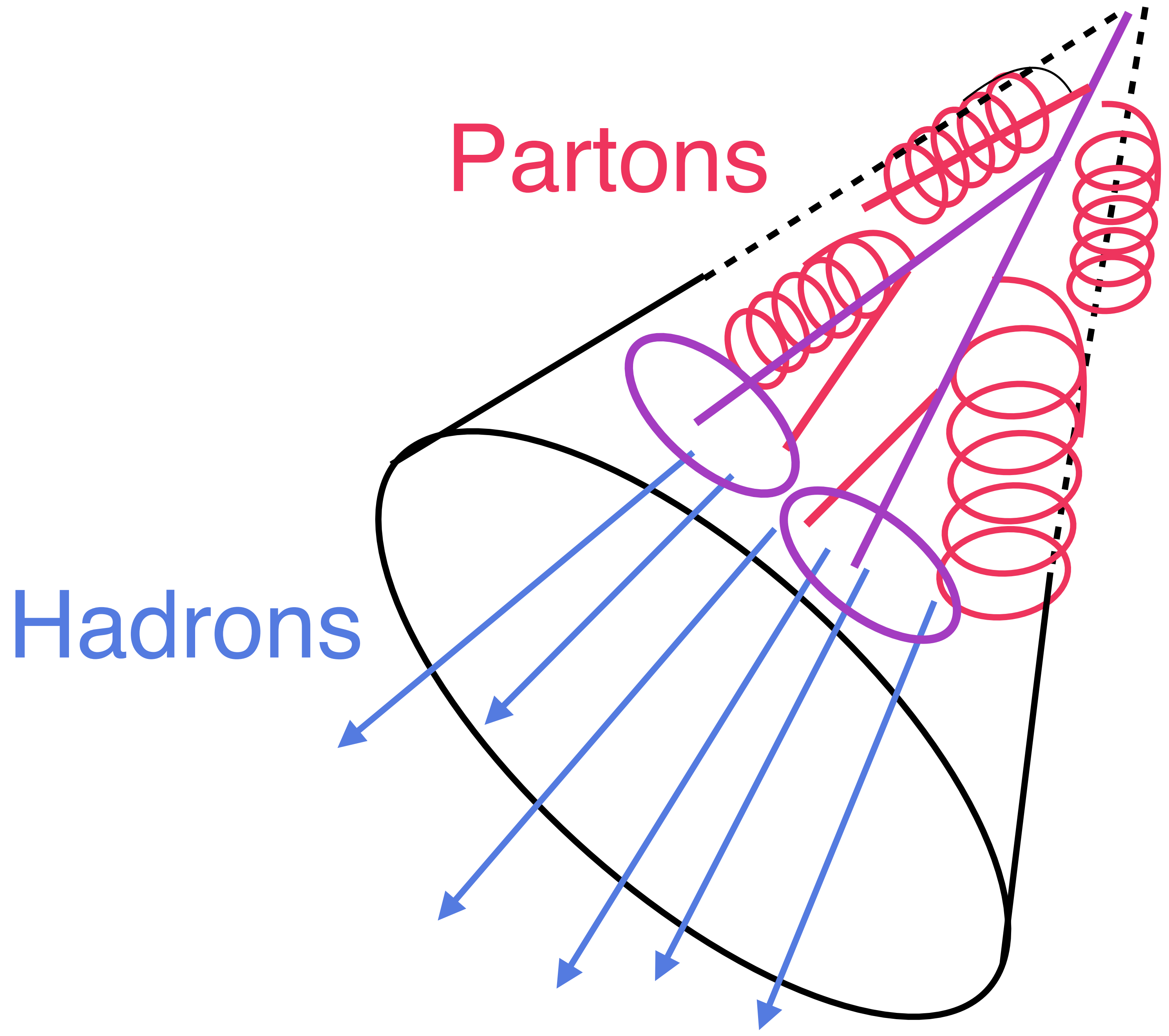
- Soft drop grooming: selects on harder parton splittings inside the jet to remove the soft contribution JHEP 1405 (2014) 146

$$z_g > z_{\mathrm{cut}}\theta^{\beta} \qquad \theta = \frac{\Delta R}{R} \qquad z = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$$

Removes non-perturbative effects

Perturbative regime under better theoretical control

Advantage: less sensitive to HI background



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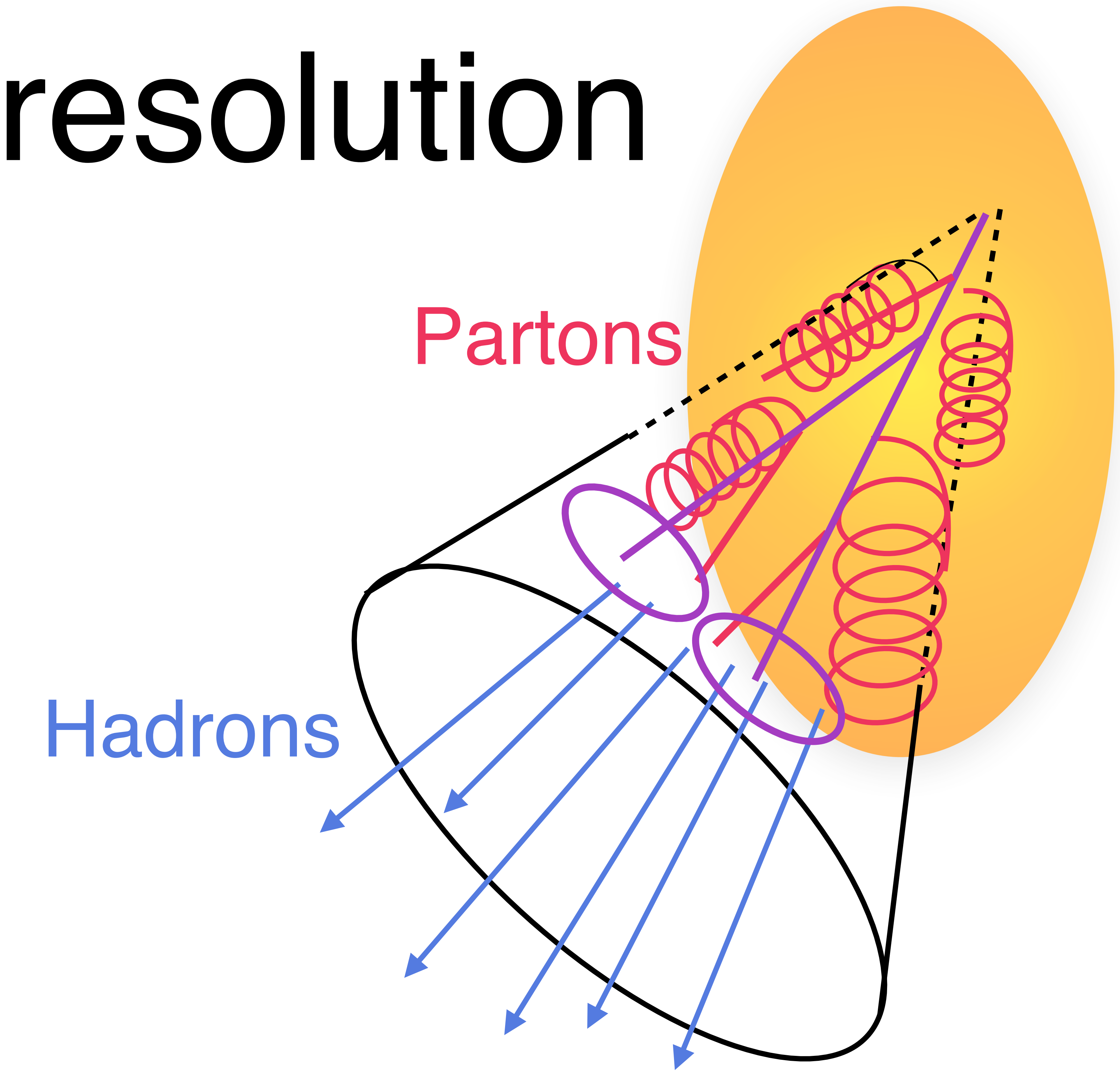

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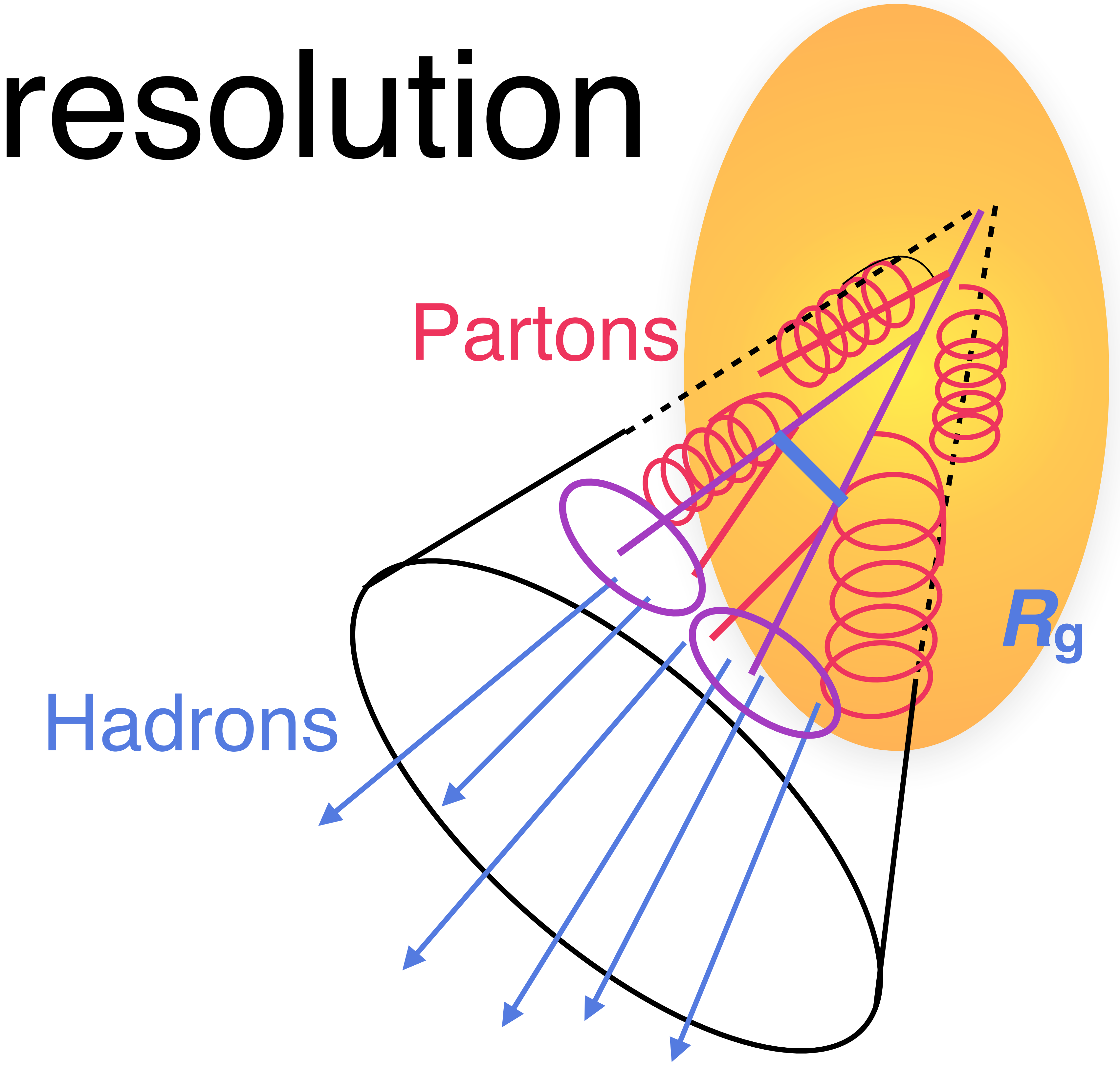

Removes non-perturbative effects

Perturbative regime under better theoretical control

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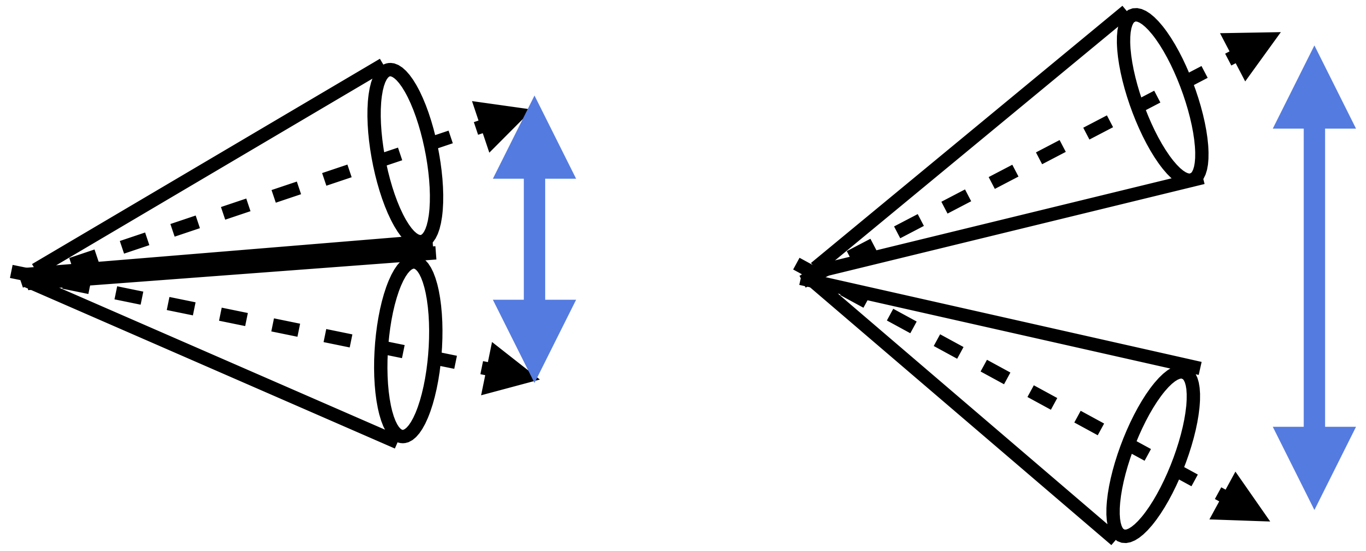
Resolution length of QGP?

➡ R_g: distance between subjets

$$R_g = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

How far apart are the subjets?



Jet splittings: R_g

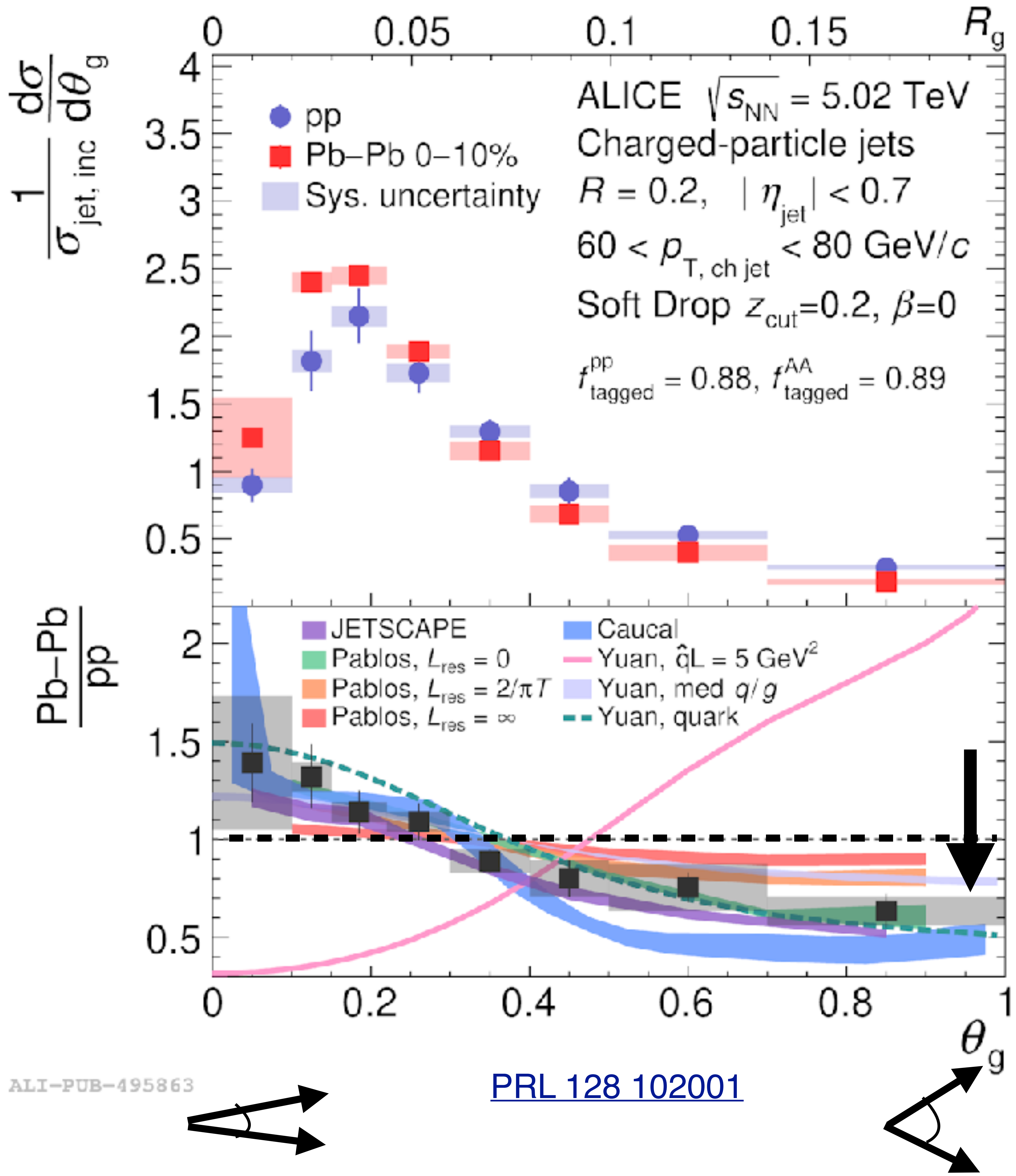
Resolution length of QGP?

Jet splittings: R_g

Resolution length of QGP?

- *Modification with large angle suppression (narrowing)*
- *Consistent picture with ALICE R-dependent R_{AA} ATLAS R_g result at higher p_T*

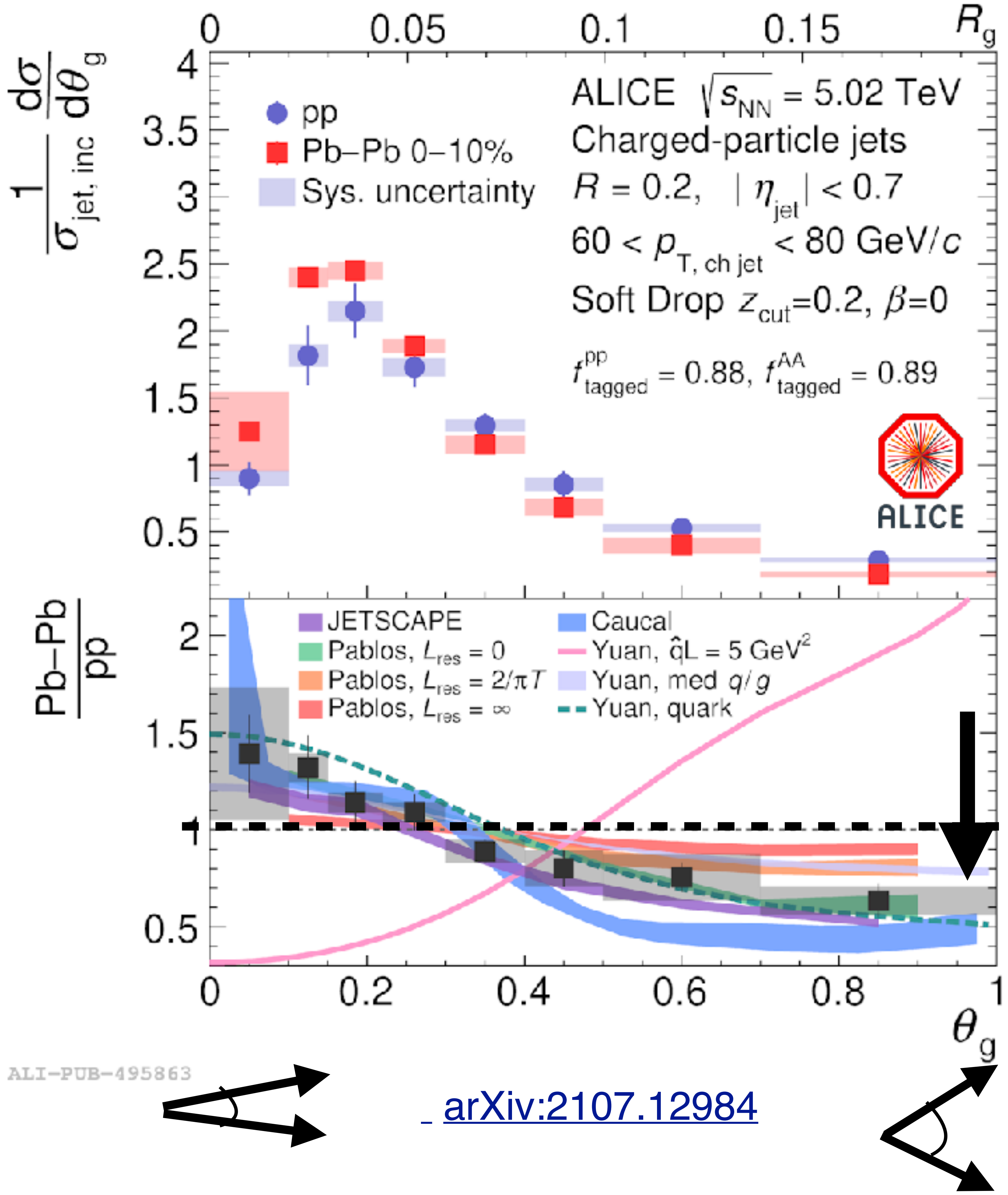
ATLAS-CONF-2022-026



PRL 128 102001

Jet splittings: narrowing?

- *Narrowing reproduced by models with different implementations of jet-medium interactions*



arXiv:2107.12984

Jet splittings: narrowing?

- *Narrowing reproduced by models with different implementations of jet-medium interactions*

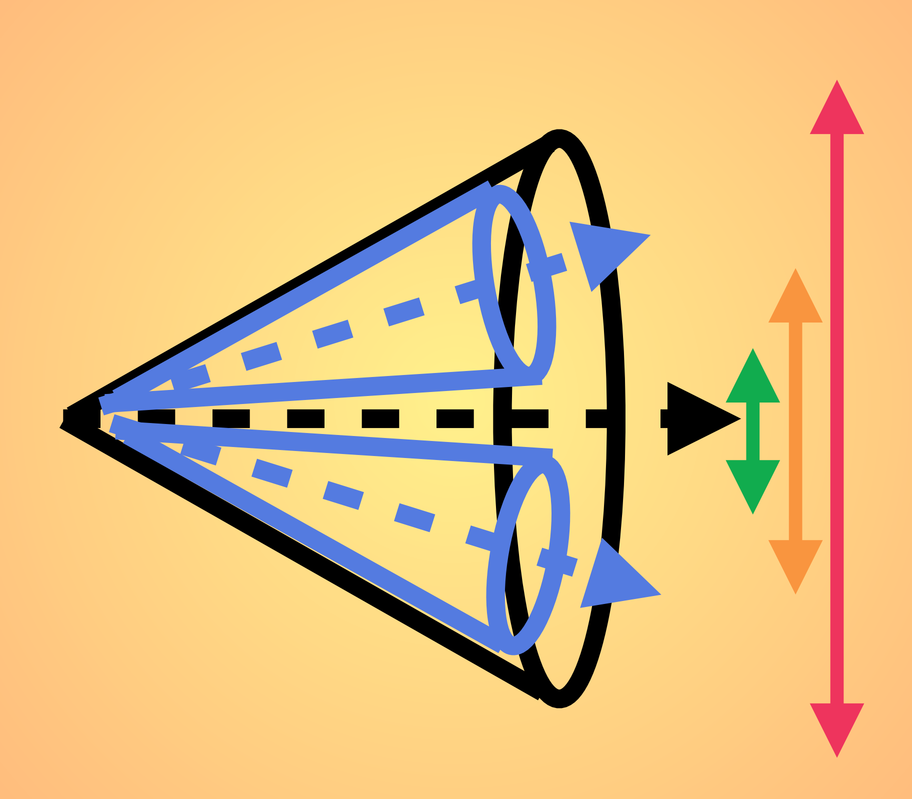
- Model 1: role of color coherence?

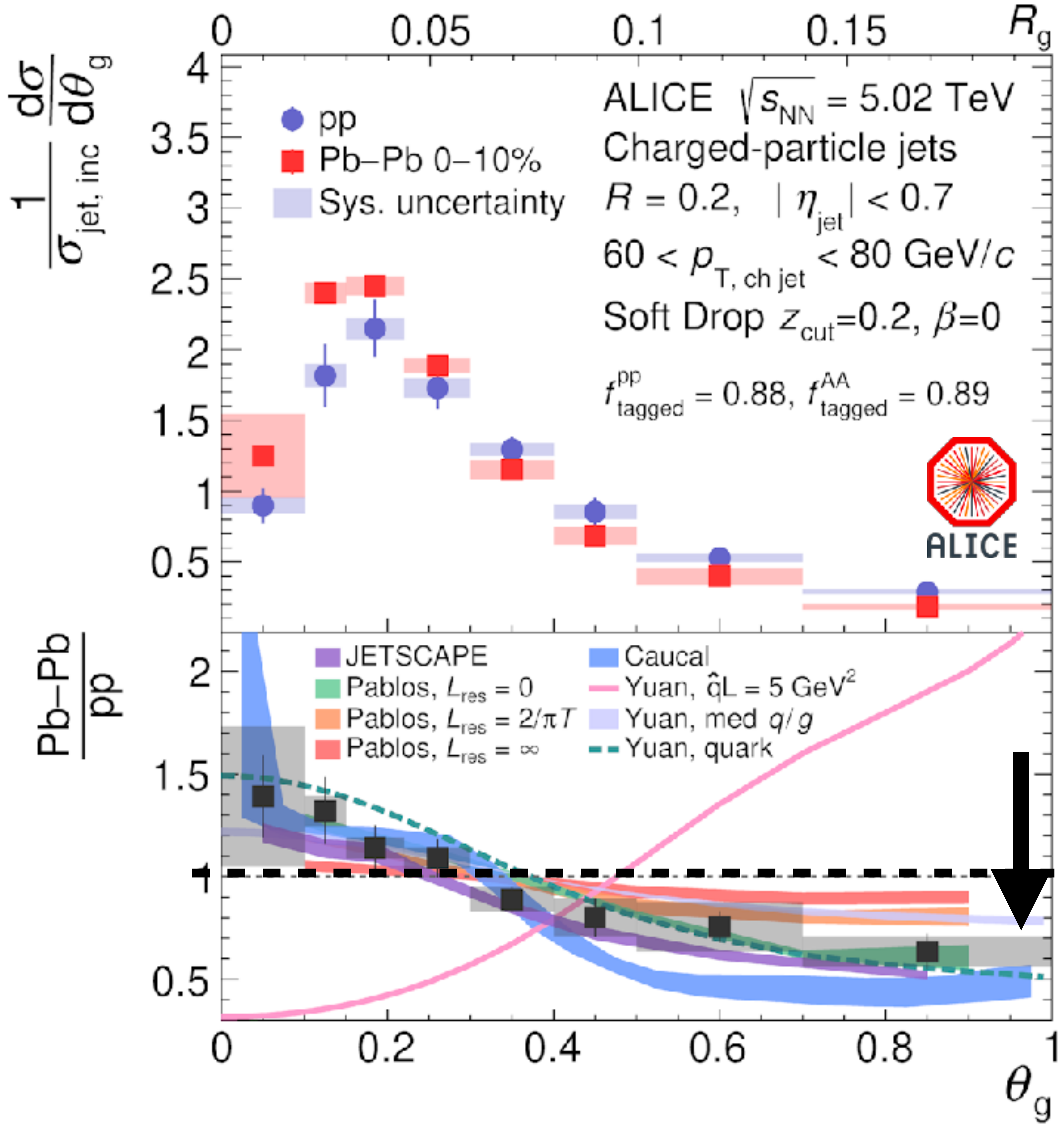
Pablos et al JHEP (2020) 044

-$L_{\mathrm{res}} = 2/\pi T$

-$L_{\mathrm{res}} = \infty$, coherence

-$L_{\mathrm{res}} = 0$, decoherence





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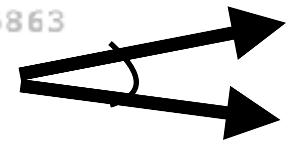
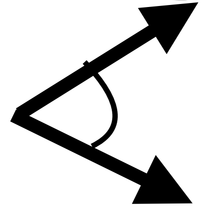


arXiv:2107.12984



Jet splittings: narrowing?

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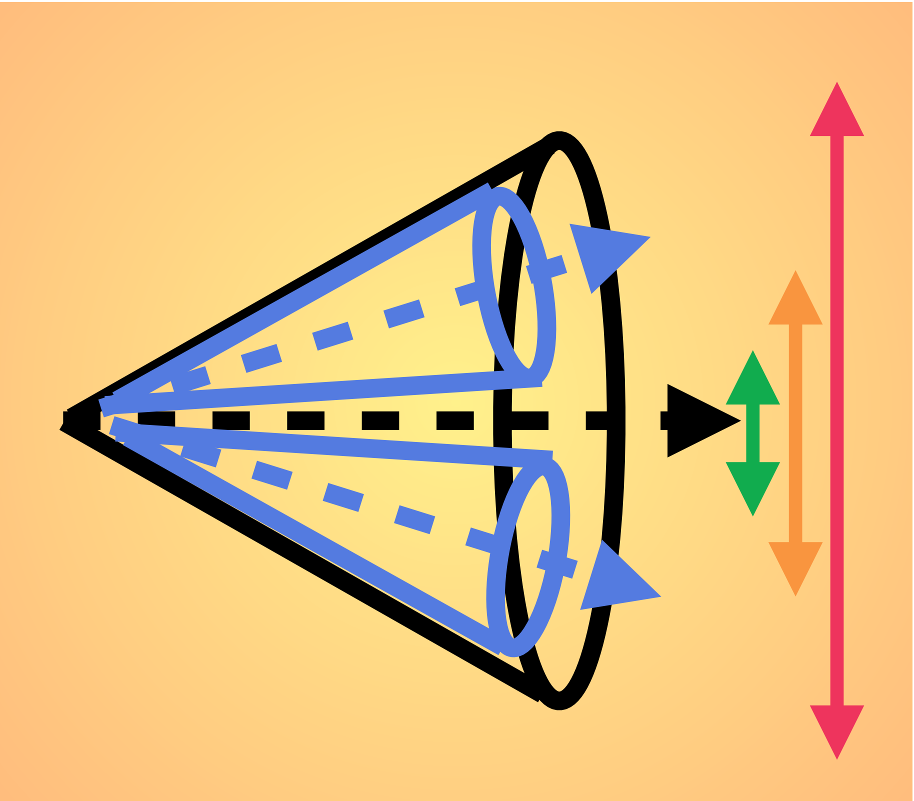
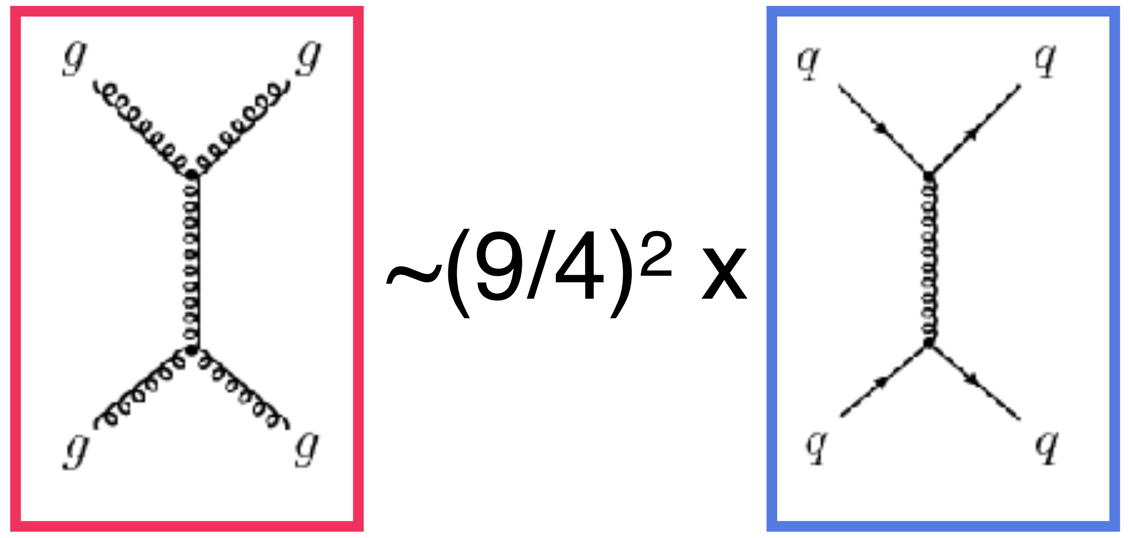


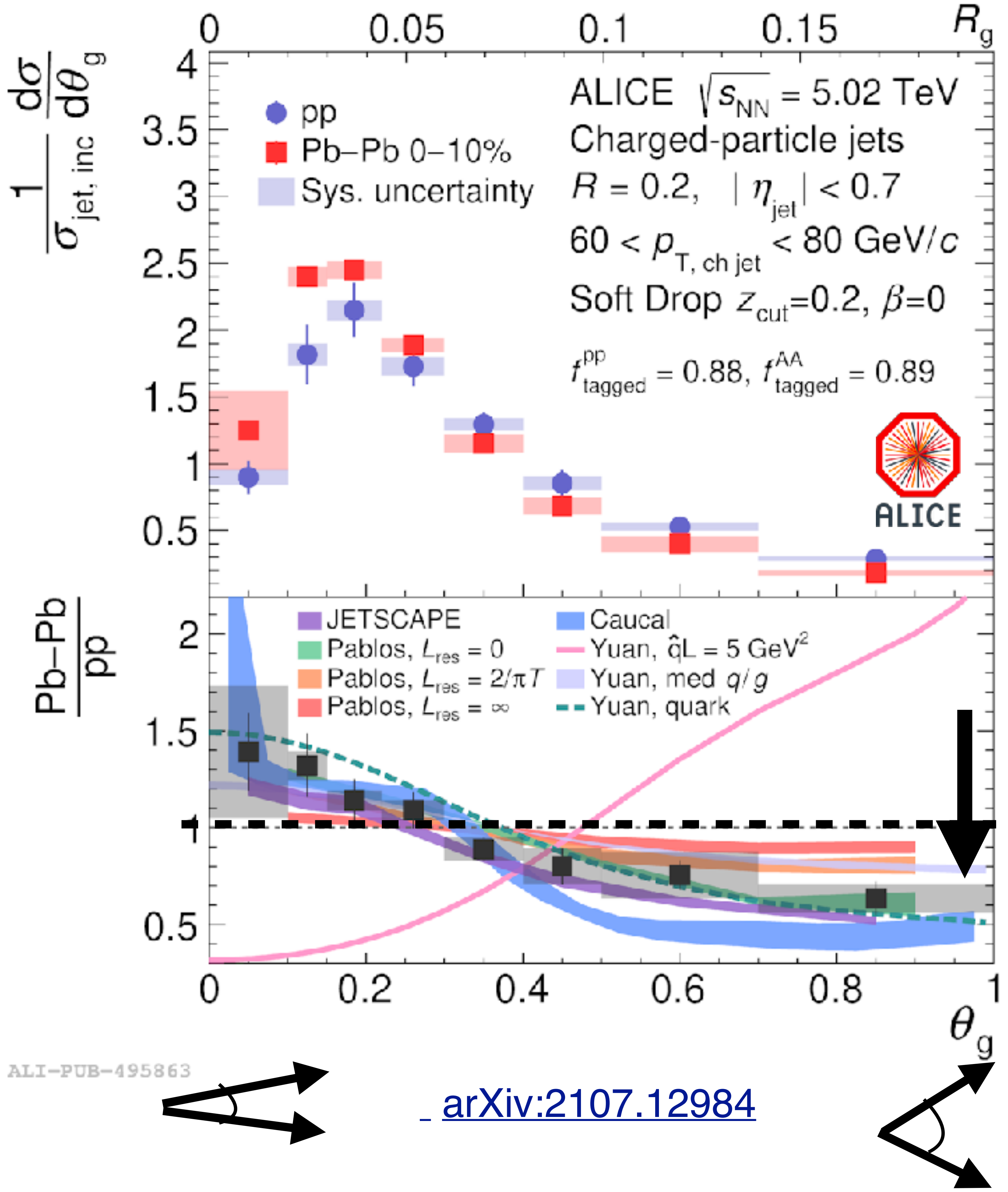
- Model 2: coherence with changing q/g fractions? Yuan et al arXiv:1907.12541

-quark only

-medium q/g



~$(9/4)^2$ x



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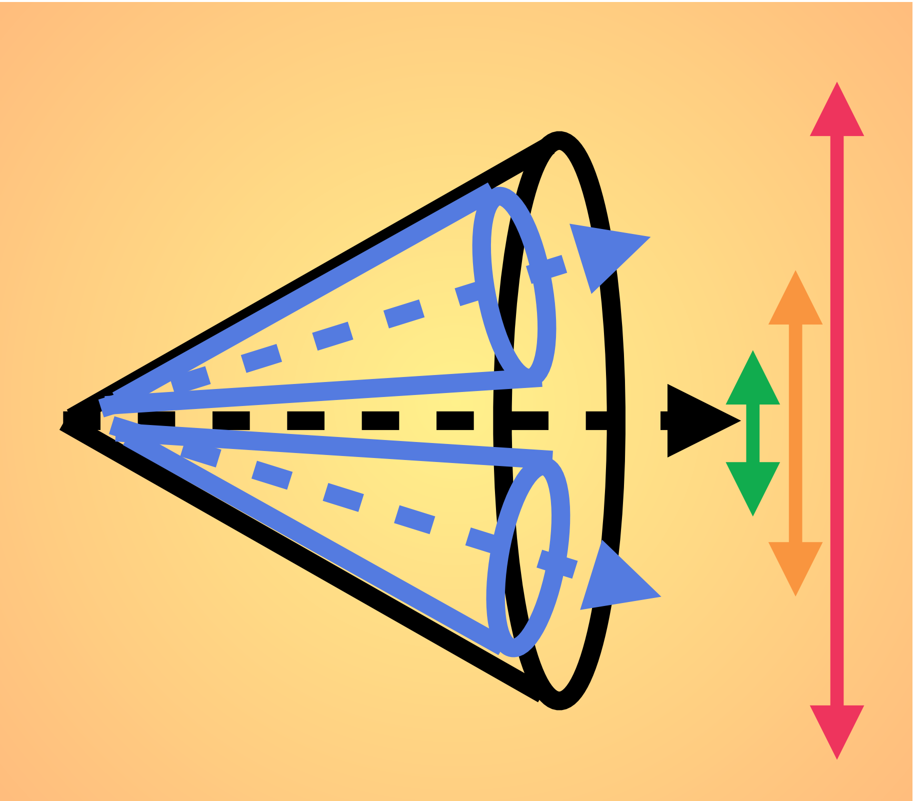

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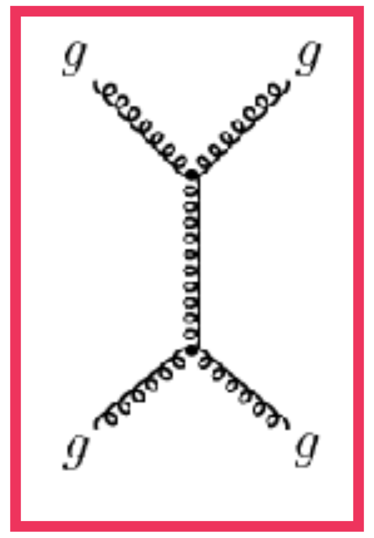

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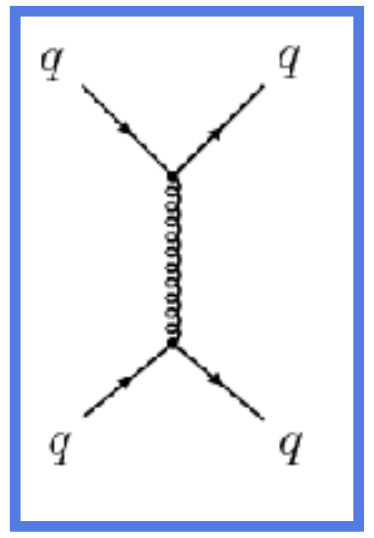

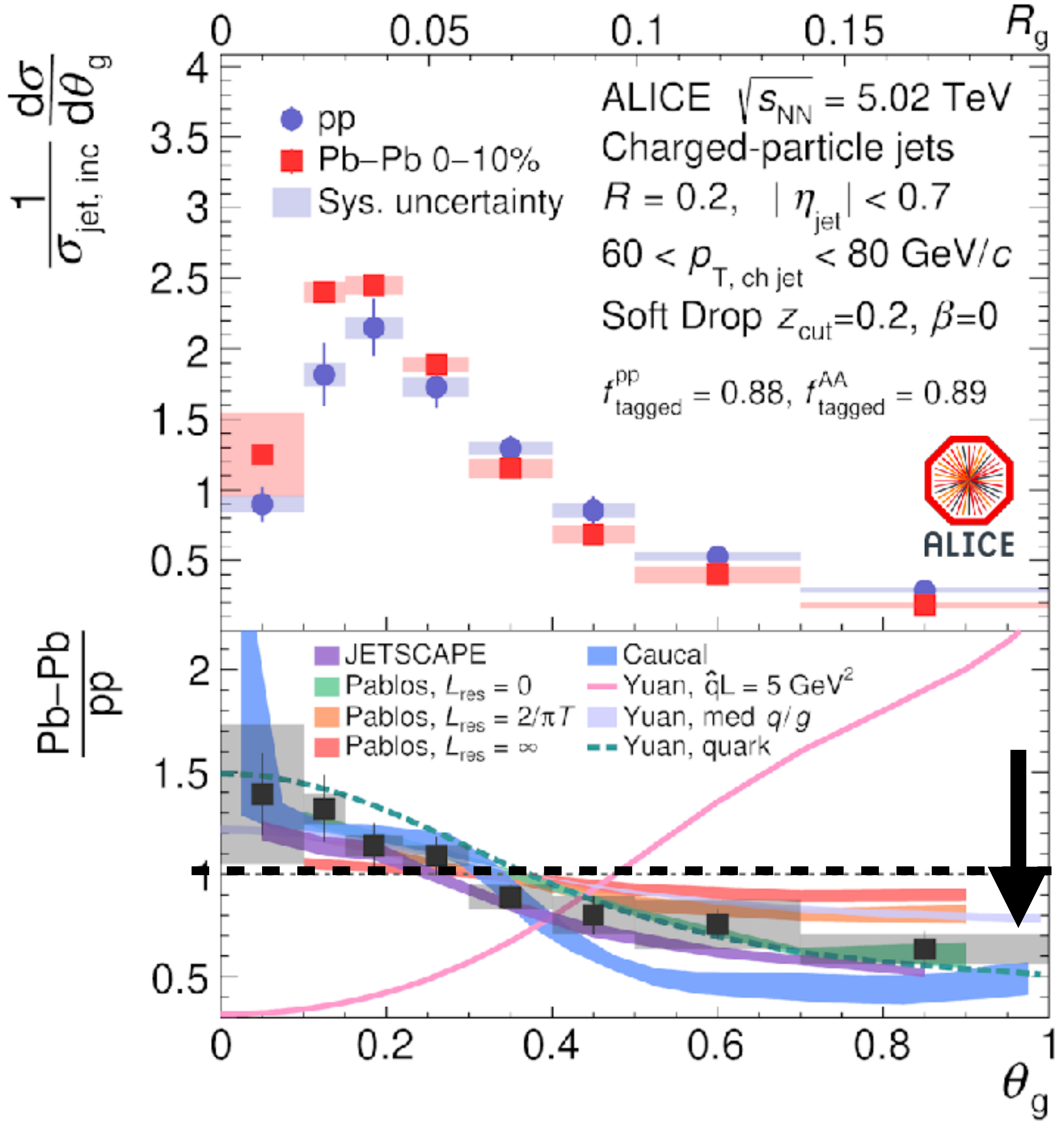

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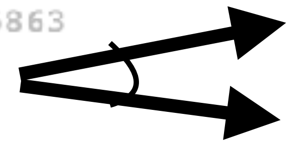
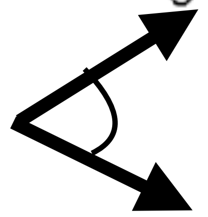


arXiv:2107.12984

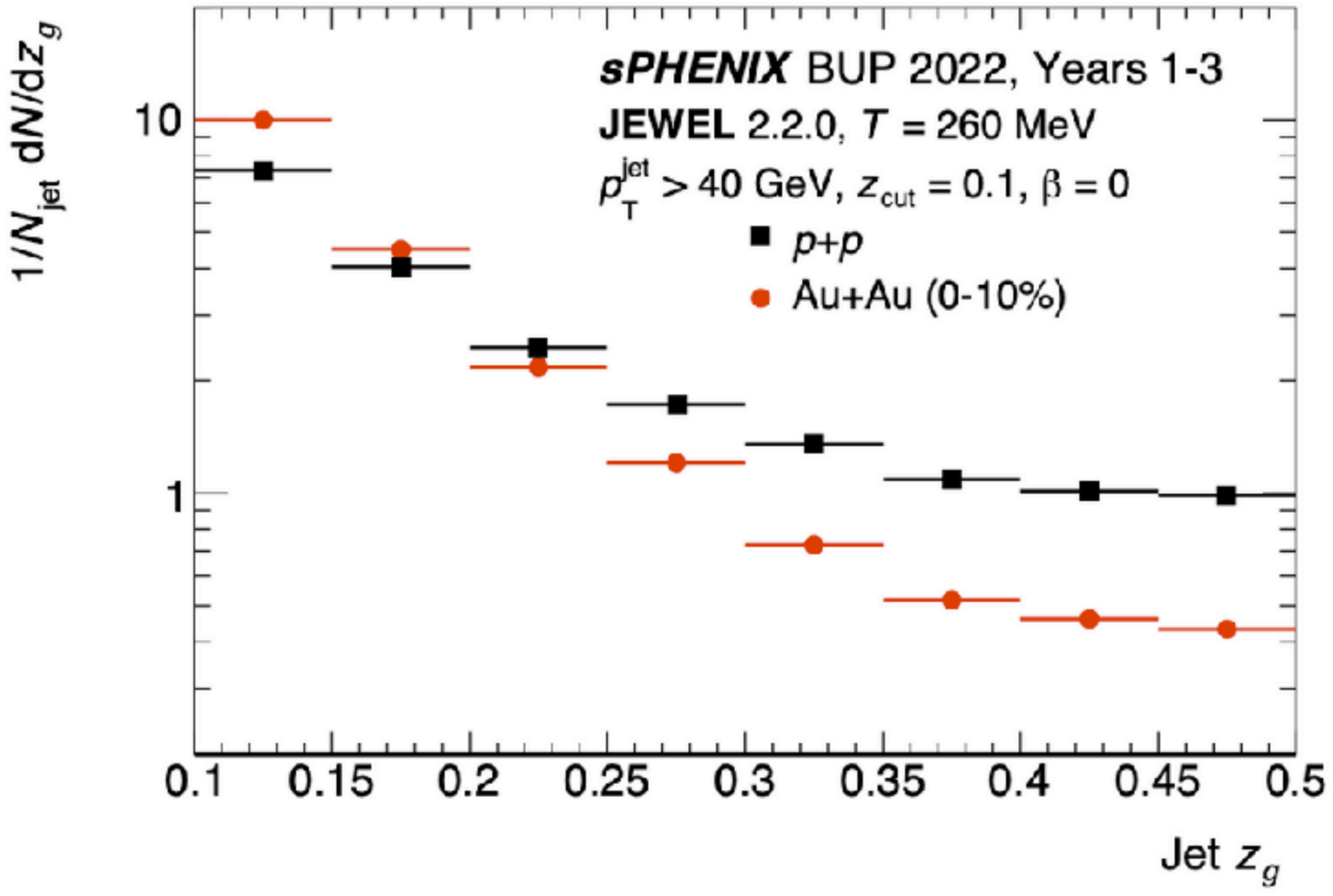


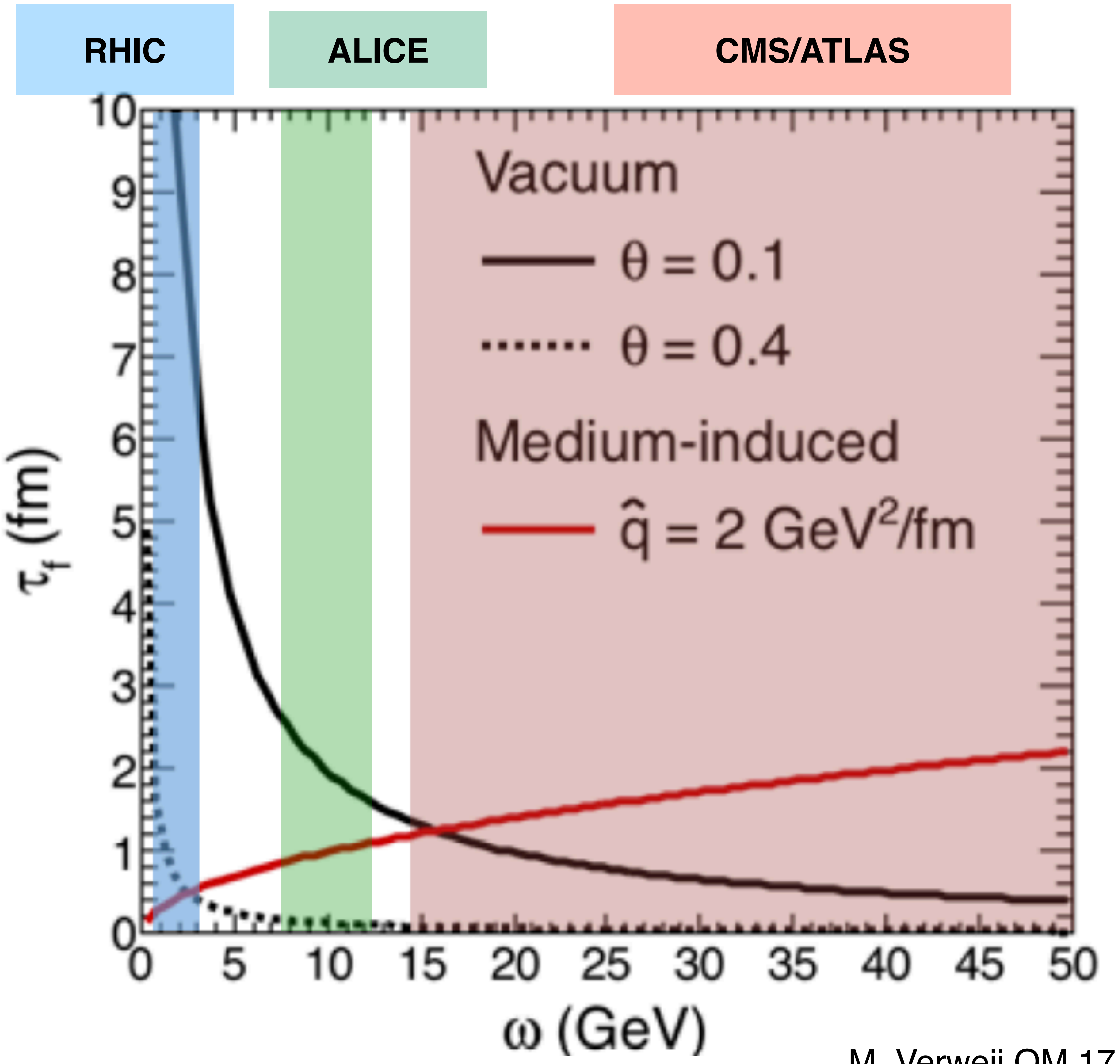
Jet splittings at RHIC

- Higher quark fraction could help resolve question about the selection bias and gluon suppression

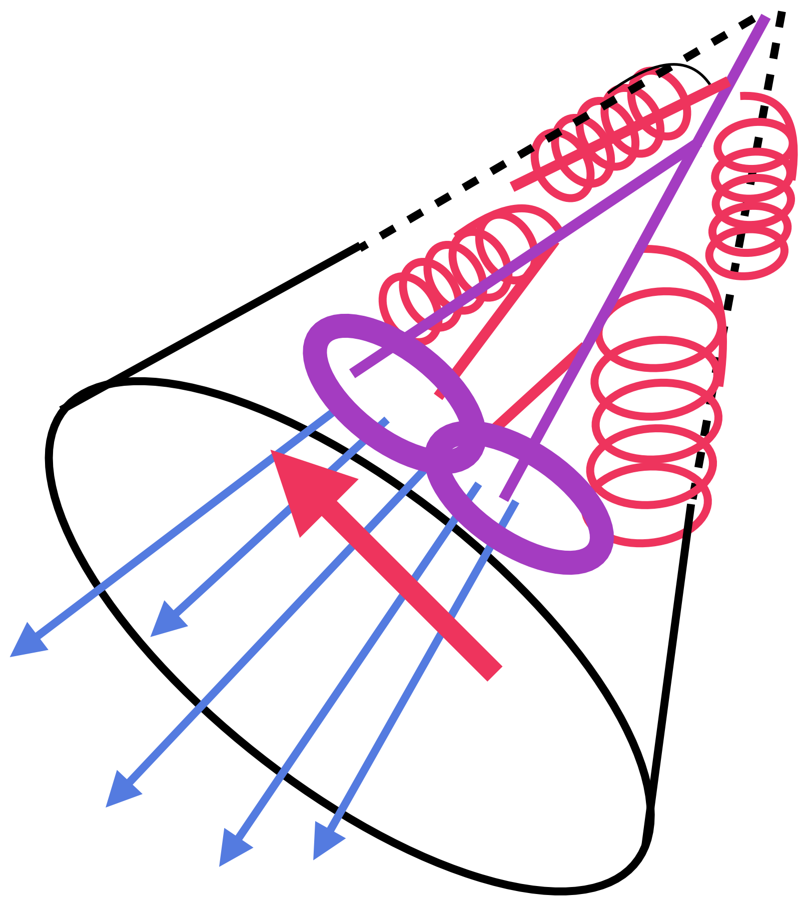
- Lower jet pT will allow us to study different phase space

- Caveat: RHIC later formation times outside of medium?

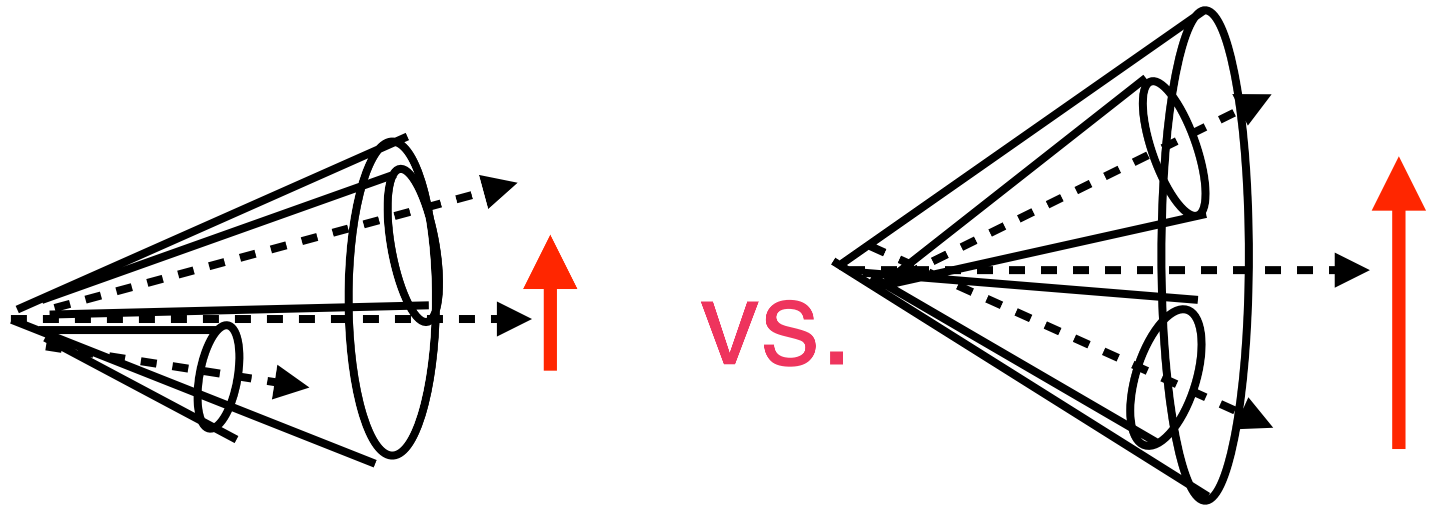




M. Verweij QM 17

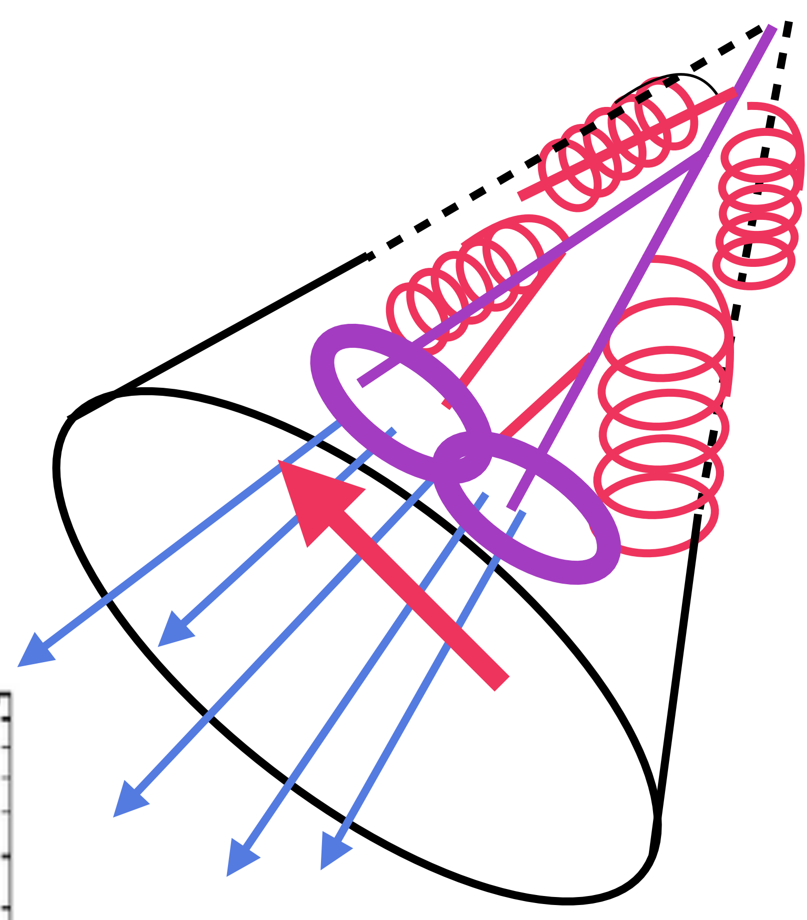


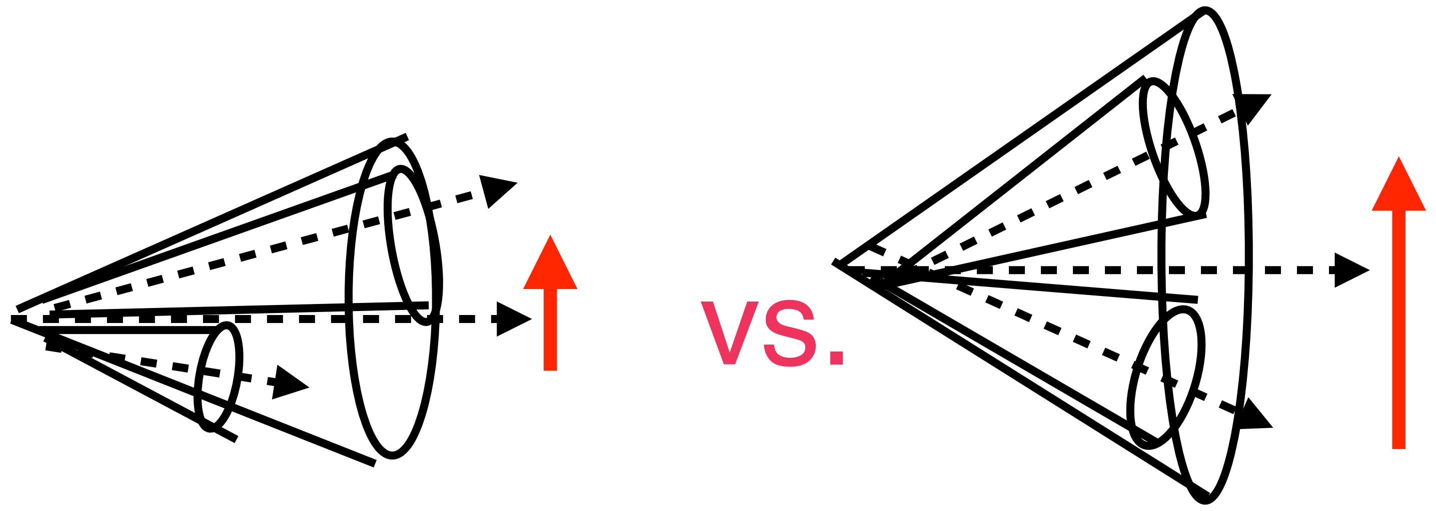
Jet splittings: hardest k_{Tg}



Quasi-particle nature of QGP?

Jet splittings: hardest k_{Tg}





Quasi-particle nature of QGP?

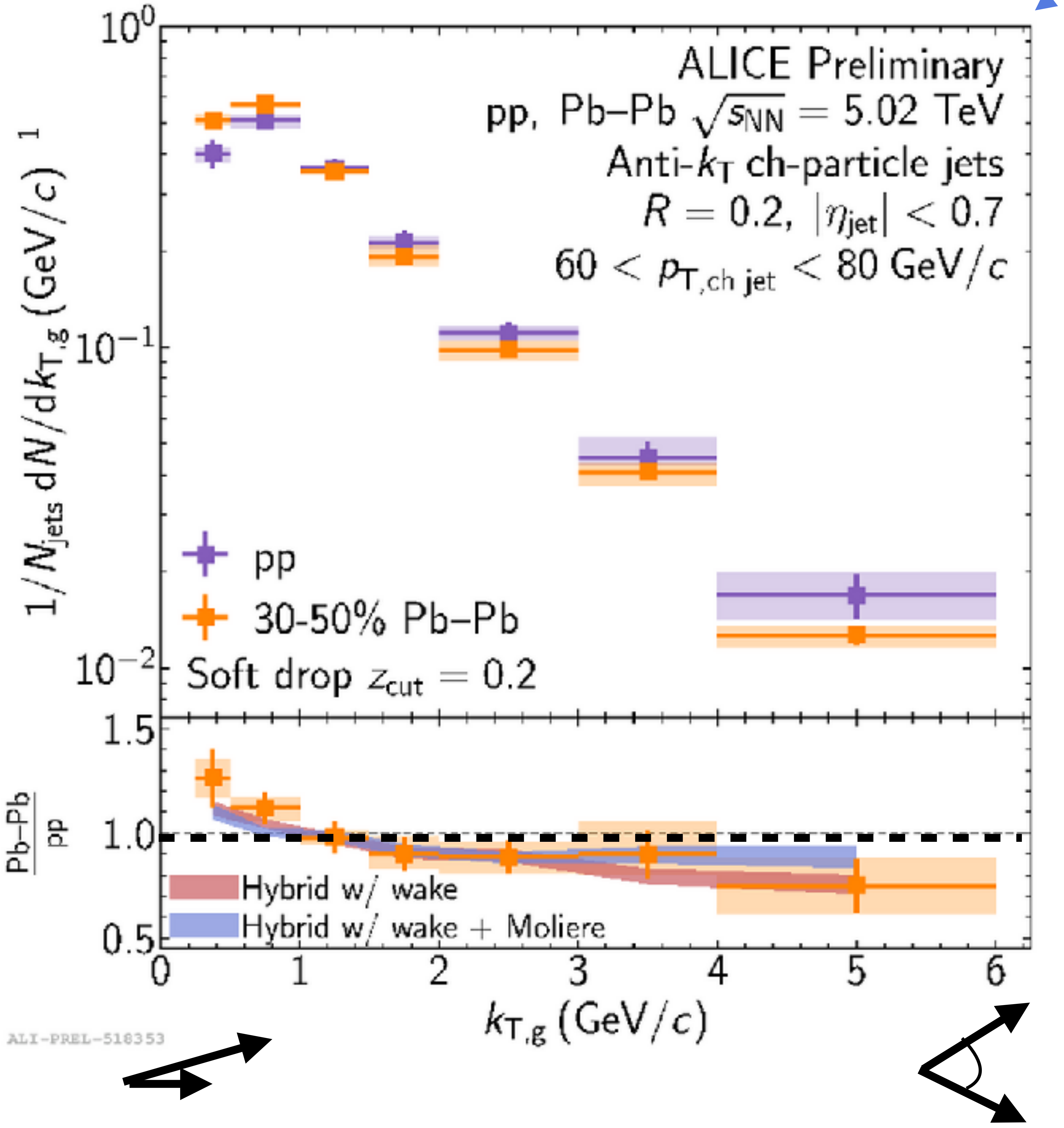
- Hybrid model: role of Moliere scattering?

  -without Moliere

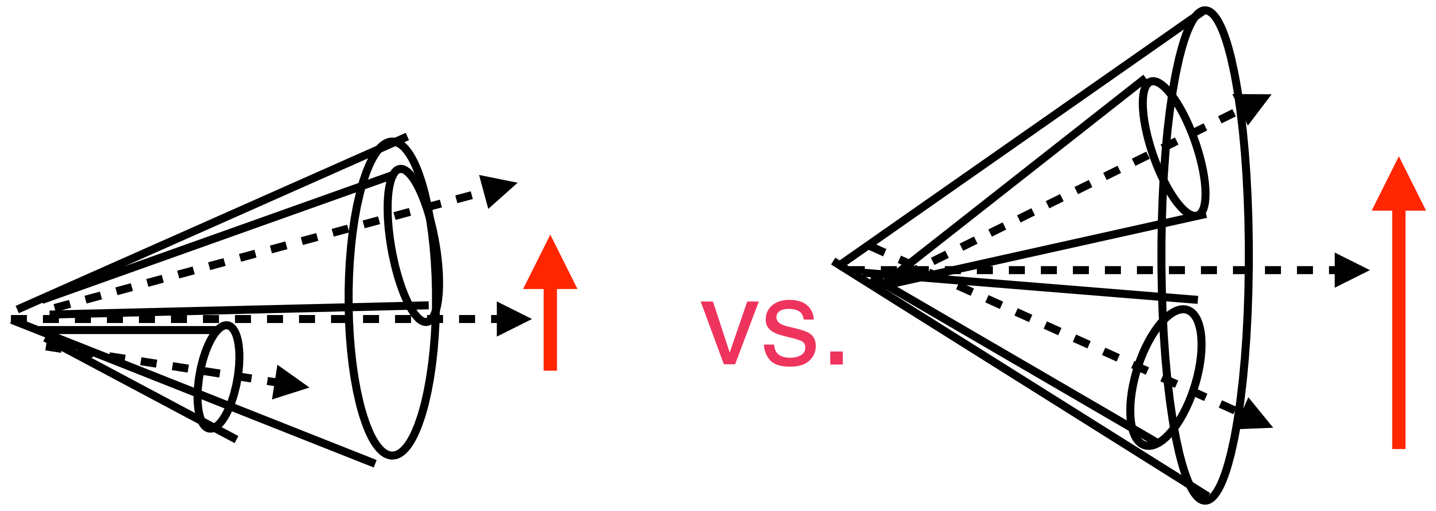
  -with Moliere

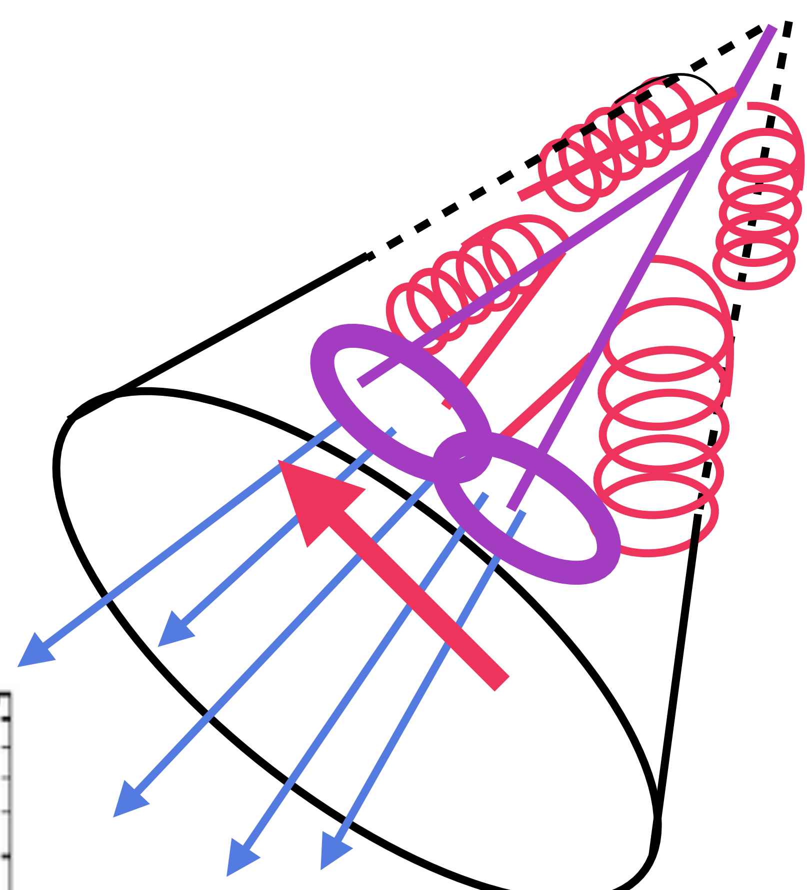
Pablos et al JHEP (2020) 044

- *Not sensitive enough to distinguish models yet*



Jet splittings: hardest k_{Tg}





Quasi-particle nature of QGP?

- Hybrid model: role of Moliere scattering?

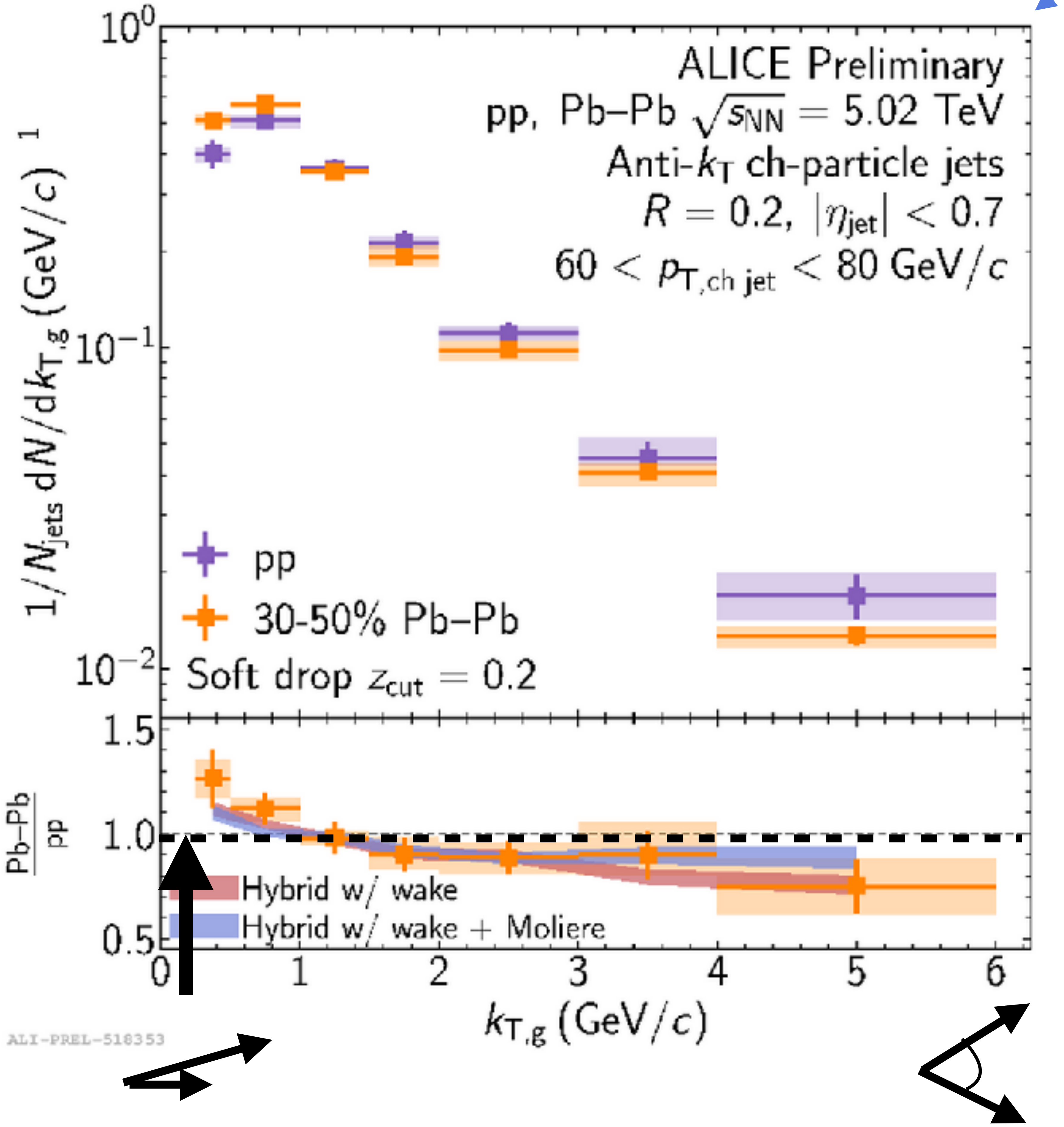
  -without Moliere

  -with Moliere

  Pablos et al JHEP (2020) 044

  - *Not sensitive enough to distinguish models yet*

- *Hint of enhancement at small k_{Tg}-> consistent with narrowing picture?*



Conclusion

- LHC has an array of results on jet quenching in heavy-ion collisions:
  - Remaining questions:
    - No recovery of energy at large R despite energy distribution to large angles?
    - Enhancement of soft particles and jets in coincidence measurements?
    - Where is the narrowing effect coming from?
    - No definitive sensitivity to Moliere scattering?
    - Not discussed: jet quenching in small systems?
    - Heavy flavor jets: see talk later today by Jing Wang
- How can we use jet quenching measurements to learn about the QGP?
- Jet quenching effects tangled in different observables, how do we best isolate effects of flavor, path length, coherence, and medium response?
- Higher statistics datasets in Run 3 will allow for precise measurements more differentially and with rarer probes like bosons or heavy flavor

Outlook: Run 3 and beyond

- Run 3 began this month! Exciting times ahead!
- Pb-Pb collisions in November!

The third run of the Large Hadron Collider has successfully started

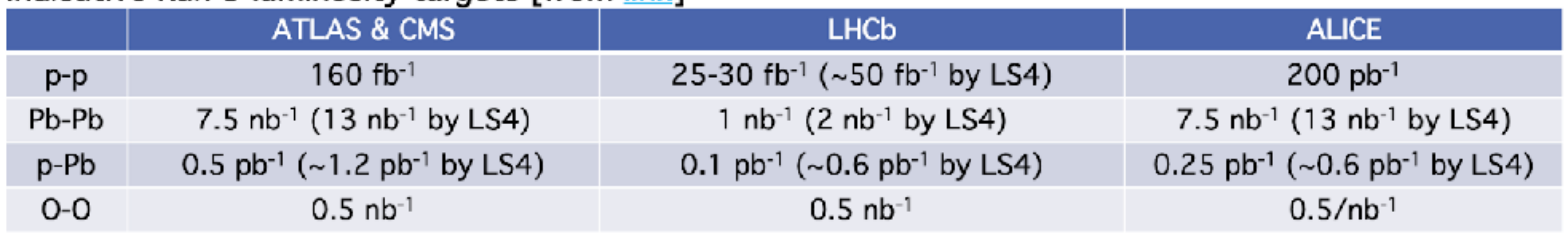
A round of applause broke out in the CERN Control Centre on 5 July at 4.47 p.m. CEST when the Large Hadron Collider (LHC) detectors started recording high-energy collisions at the unprecedented energy of 13.6 TeV

CERN press release: pictures and videos from live stream!

Outlook: Run 3 and beyond

arXiv:1812.06772

Indicative Run 3 luminosity targets [from link]

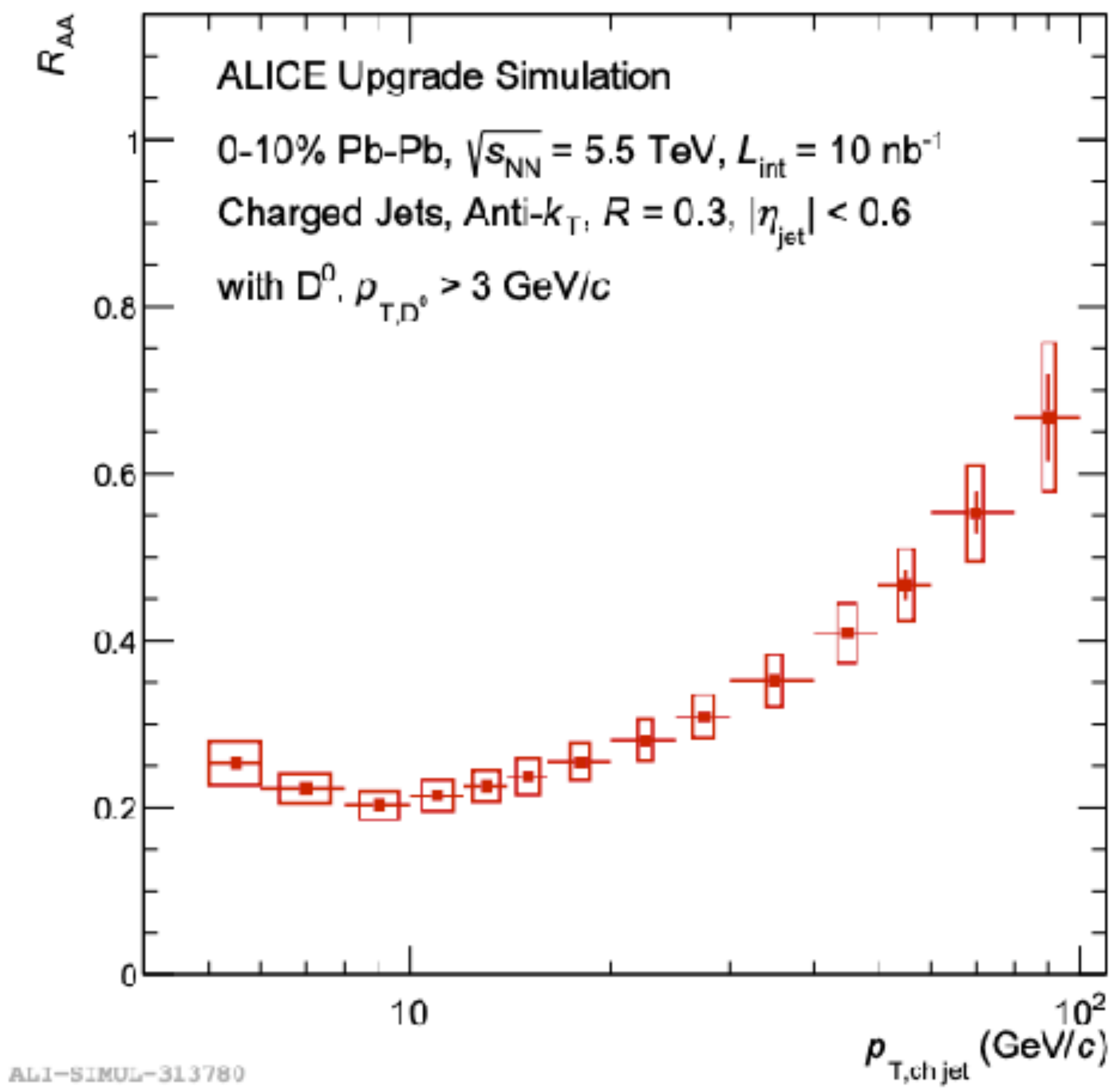


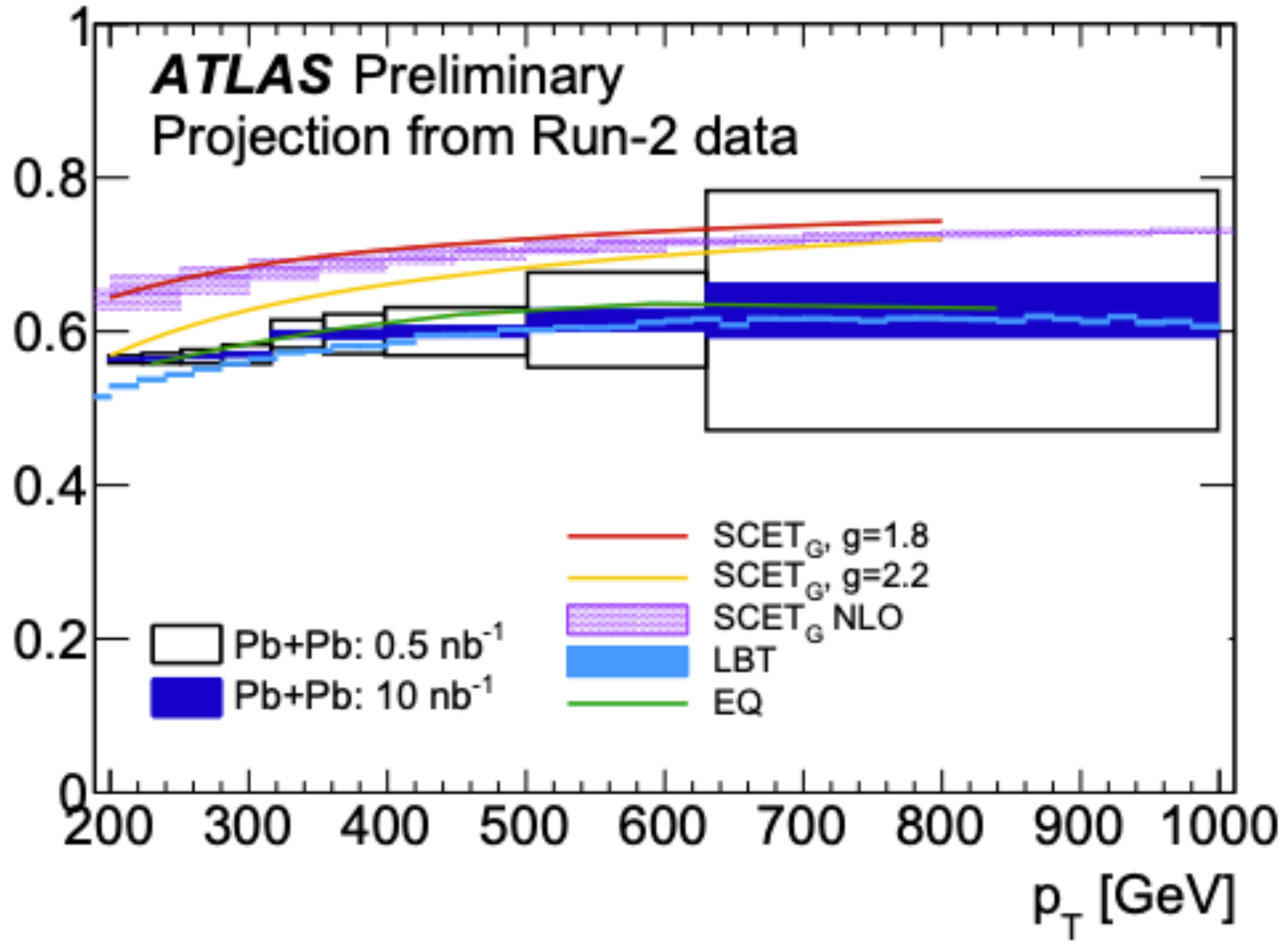
	ATLAS & CMS	LHCb	ALICE
p-p	160 fb^{-1}	25-30 fb^{-1} (~50 fb^{-1} by LS4)	200 pb^{-1}
Pb-Pb	7.5 nb^{-1} (13 nb^{-1} by LS4)	1 nb^{-1} (2 nb^{-1} by LS4)	7.5 nb^{-1} (13 nb^{-1} by LS4)
p-Pb	0.5 pb^{-1} (~1.2 pb^{-1} by LS4)	0.1 pb^{-1} (~0.6 pb^{-1} by LS4)	0.25 pb^{-1} (~0.6 pb^{-1} by LS4)
O-O	0.5 nb^{-1}	0.5 nb^{-1}	0.5/nb^{-1}

N.B.: pp reference data at 5.x TeV will also be collected

- ATLAS and CMS: high precision and statistics for jet measurements at high p_T including heavy flavor, boson-tagged, and many substructure measurements

- ALICE: ~100 times more jets than in Run 2
  - Precision for D0 jets and limited statistics for B jets in Pb-Pb
  - HI physics at LHCb!
  - Smaller system: O+O





- *High luminosity LHC Runs 5-6: more upgrades, statistics, ALICE 3, etc.*

Outlook: RHIC and LHC

- Complementary, parallel programs at RHIC and LHC will help to answer remaining questions about jet quenching and more!

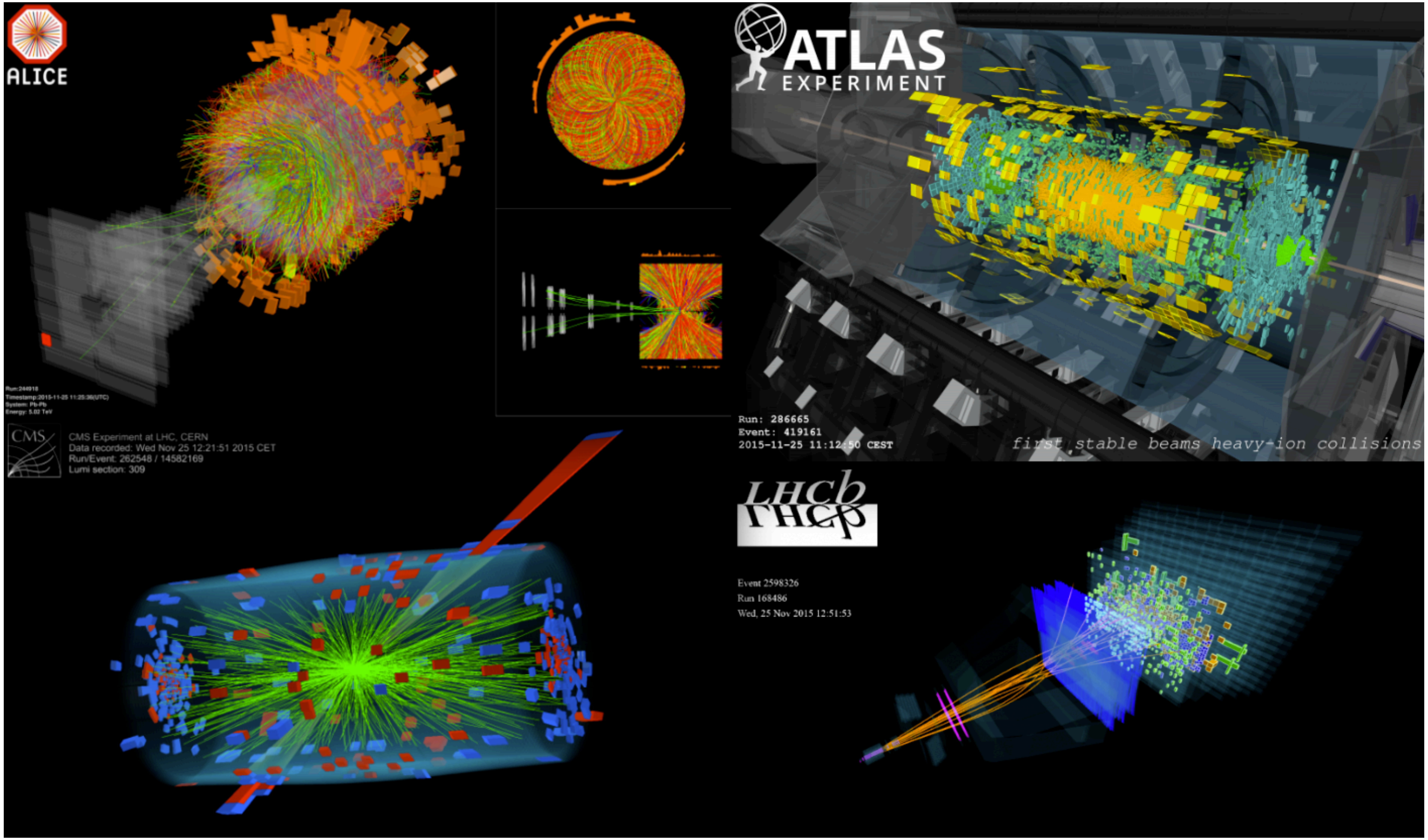
RHIC

- sPHENIX turning on next year!
- Au+Au, pp, and p+Au planned
- High statistics data at lower energies near QGP transition
- Full hadronic calorimeter to measure jets at lower momentum
  - Rare probes: photons and HF
- STAR upgrades -> increased stats and more jet measurements

LHC

- Run 3 started this month, HI data coming soon!
- Smaller systems: pp, O+O, etc.
- High statistics data at highest energies for precision measurements at very high momentum
  - Rare probes: bosons and HF

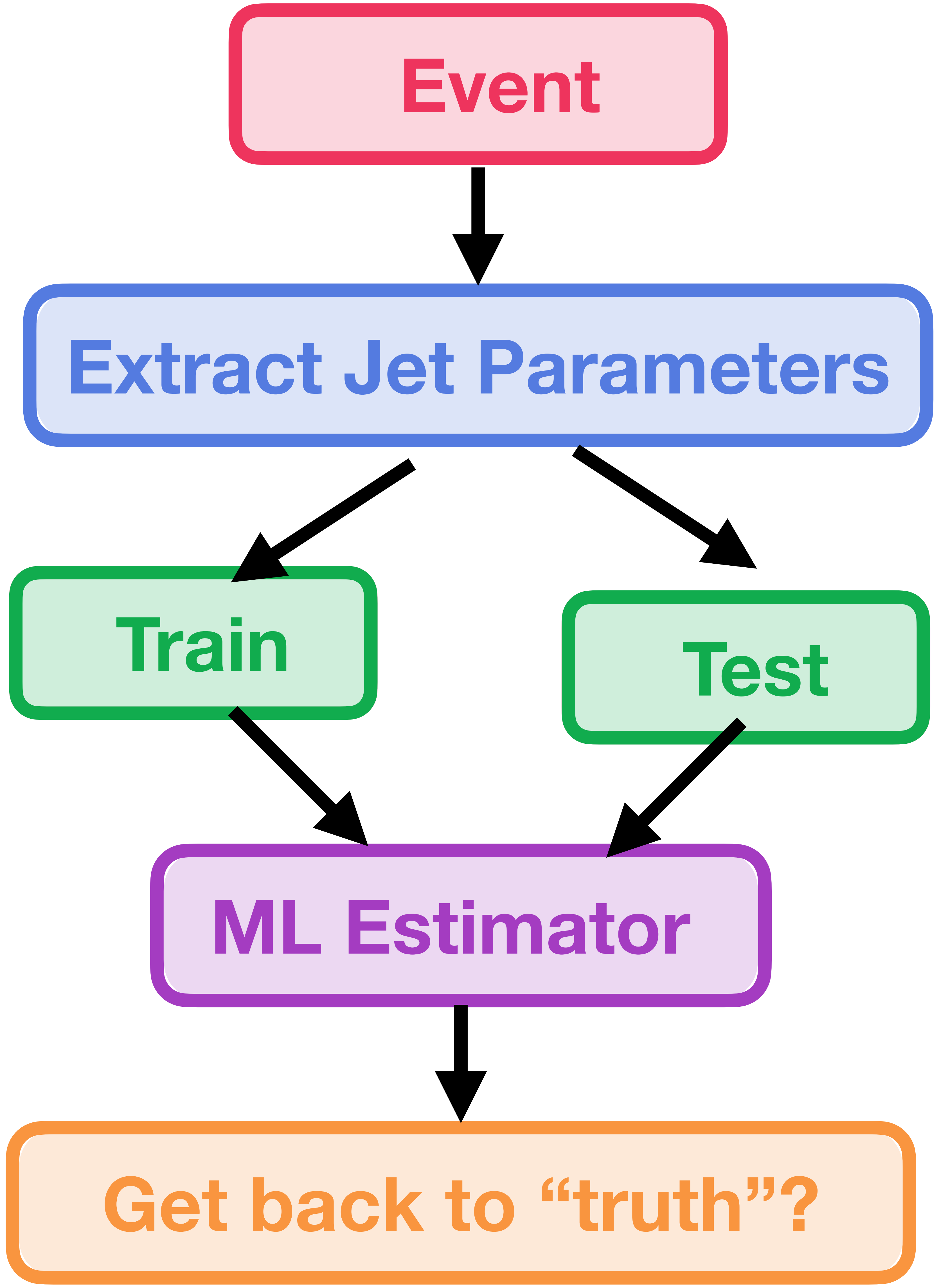
Thank you!



Laura Havener, Yale University

Backup

ML approach: method



Event

Extract Jet Parameters

Train

Test

ML Estimator

Get back to “truth”?

- Embedding pp PYTHIA events into real Pb-Pb data

- Optimized for method performance and how important/correlated they are
  - Area-based corrected
  - jet angularity
  - 12 leading constituents
  - number of constituents

  - 10% train
  - 90% test

  - shallow neural network (100, 100, 50)
  - random forest
  - linear regression

- Regression task to predict the corrected jet p_T
  - “truth” = detector level PYTHIA jet p_T

ML configurations

- Regression task that is prioritizing a simple model
- Implemented in scikit-learn with defaults unless otherwise specified

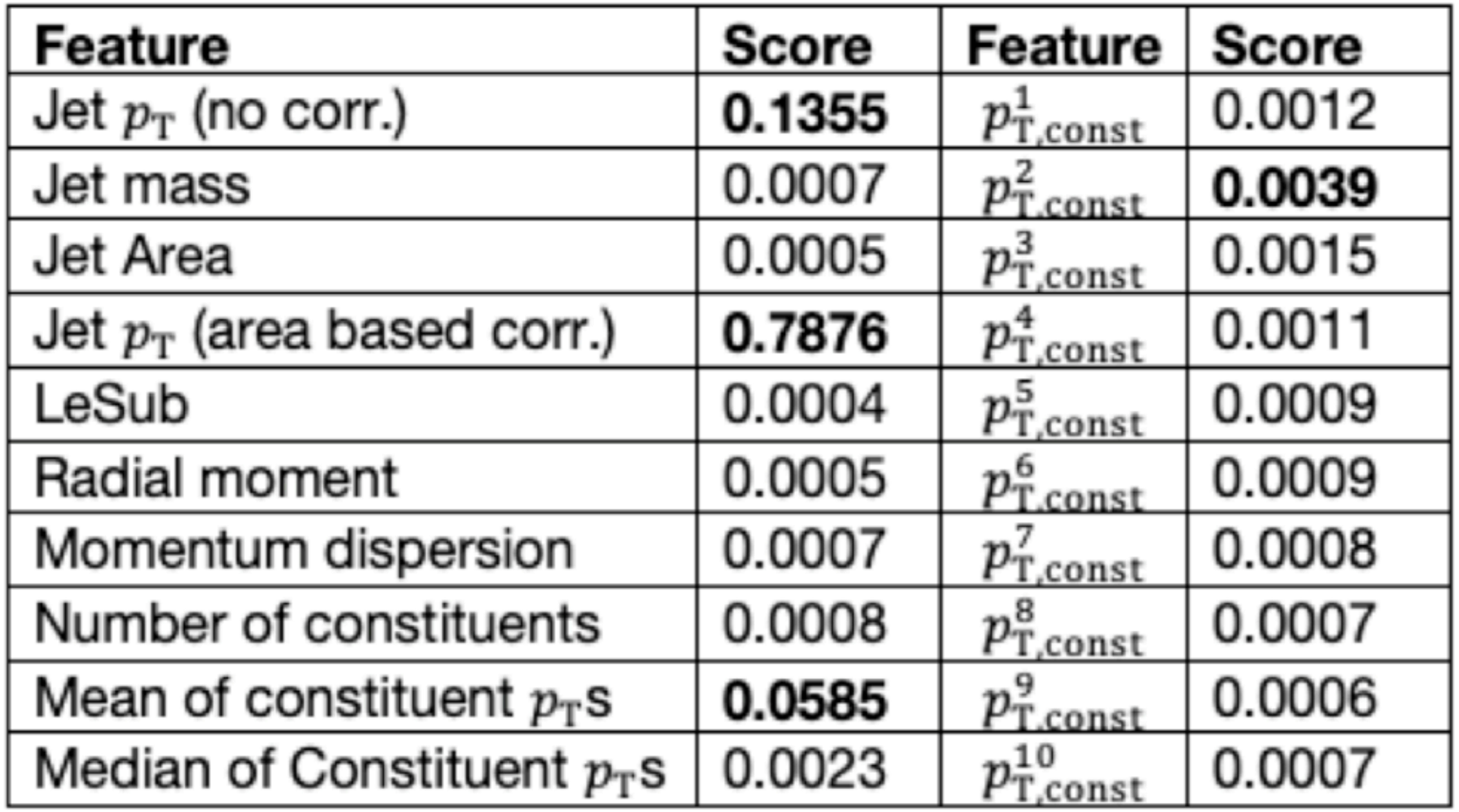
1. Shallow neural network
   - Shallow, three-layer network with [100, 100, 50] nodes
   - ADAM optimizer, stochastic gradient descent algorithm
   - Nodes/neutrons activated by a ReLU activation function
2. Linear regression
   - Normalization set to the default
3. Random Forest
   - Ensemble of 30 decision trees
   - Maximum number of features set to 15

ML: features for training

- In order to determine the features for training, ask two questions:

1. How important is the feature in this model? -> feature score
    - Higher score, more often it is used in training
2. How correlated is the feature with other features?

Charged Particle Jets

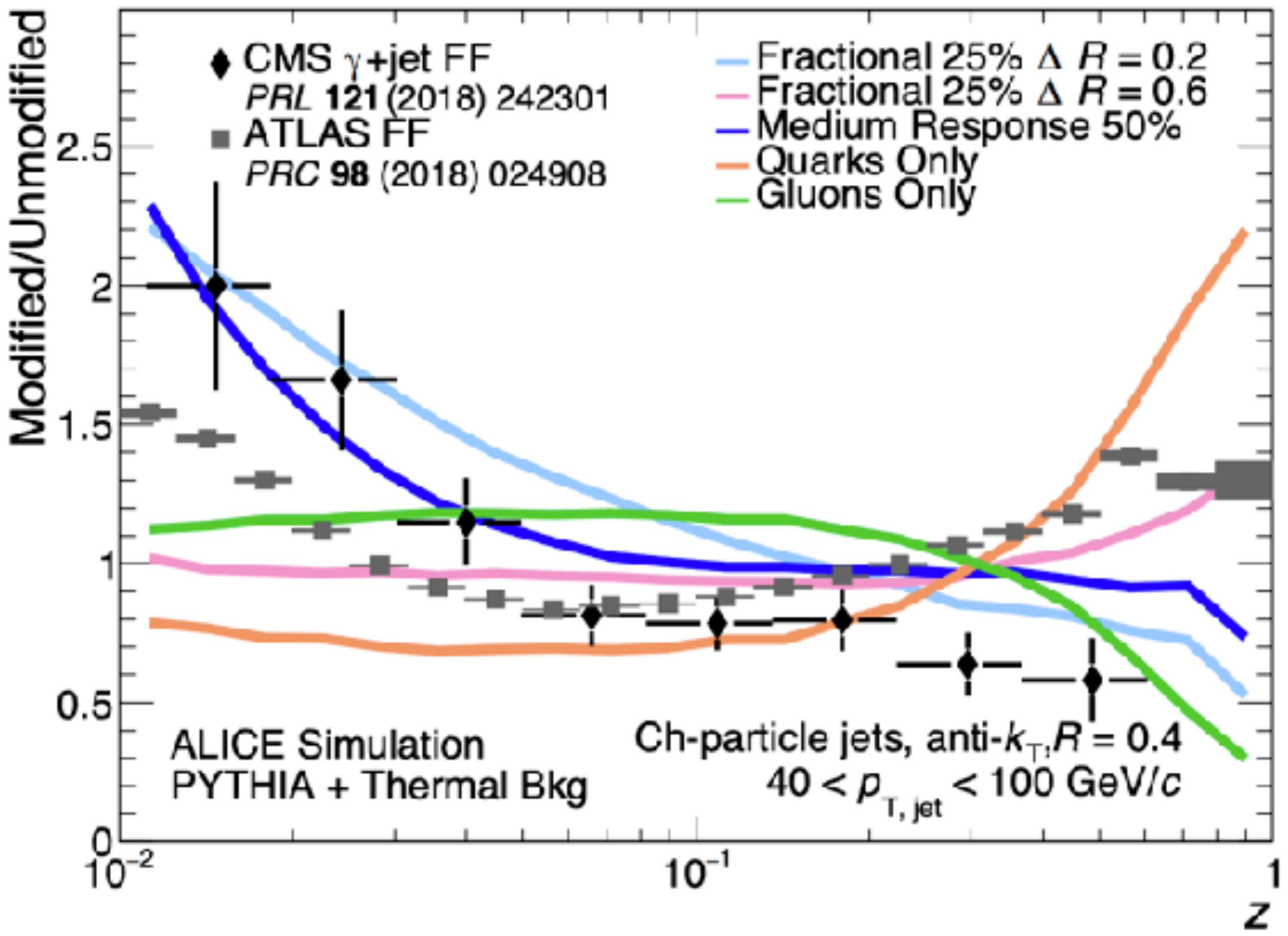


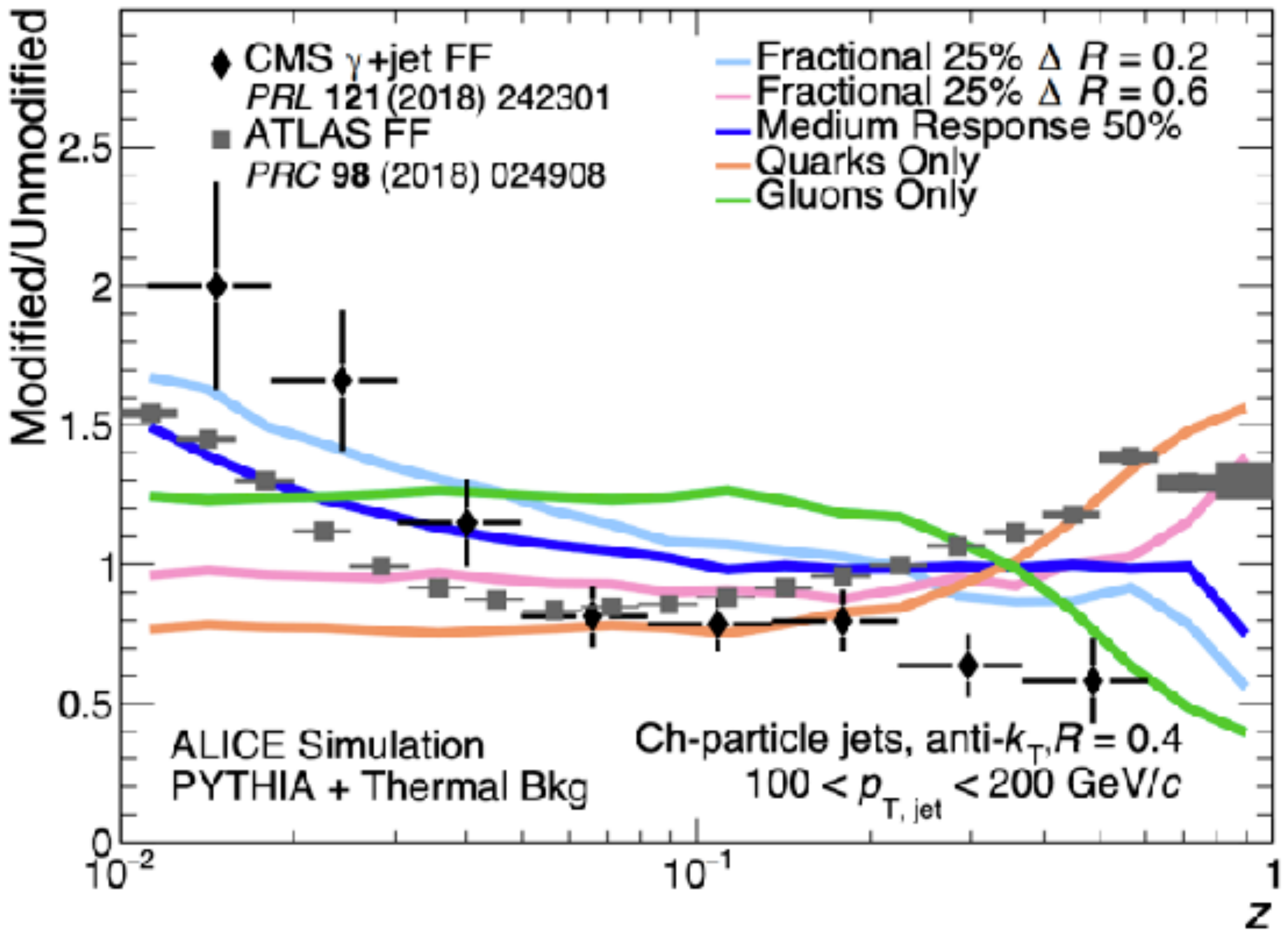
Feature	Score	Feature	Score
Jet p_{T} (no corr.)	**0.1355**	$p_{\mathrm{T,const}}^{1}$	0.0012
Jet mass	0.0007	$p_{\mathrm{T,const}}^{2}$	**0.0039**
Jet Area	0.0005	$p_{\mathrm{T,const}}^{3}$	0.0015
Jet p_{T} (area based corr.)	**0.7876**	$p_{\mathrm{T,const}}^{4}$	0.0011
LeSub	0.0004	$p_{\mathrm{T,const}}^{5}$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

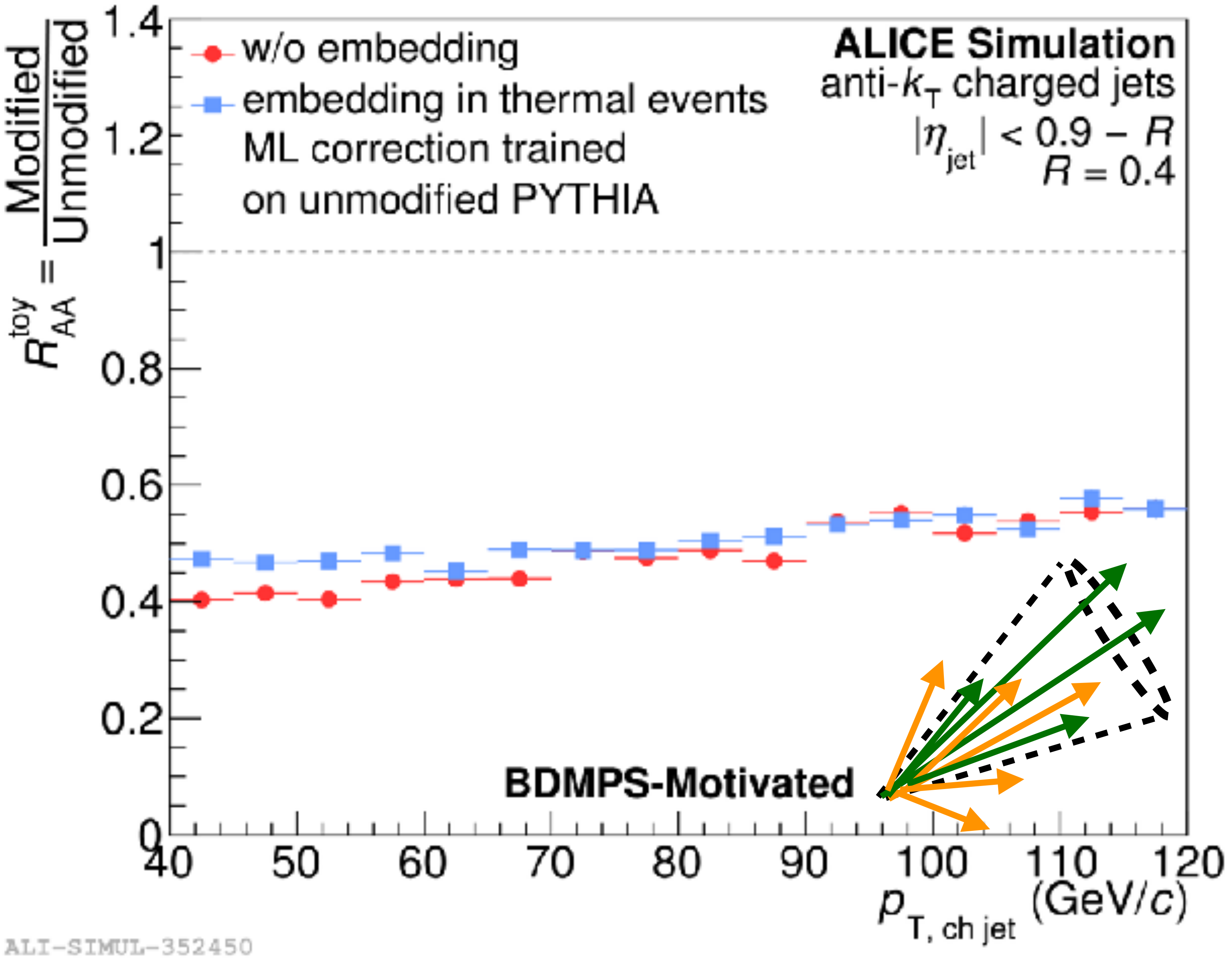
Phys. Rev. C 99, 064904 (2019)

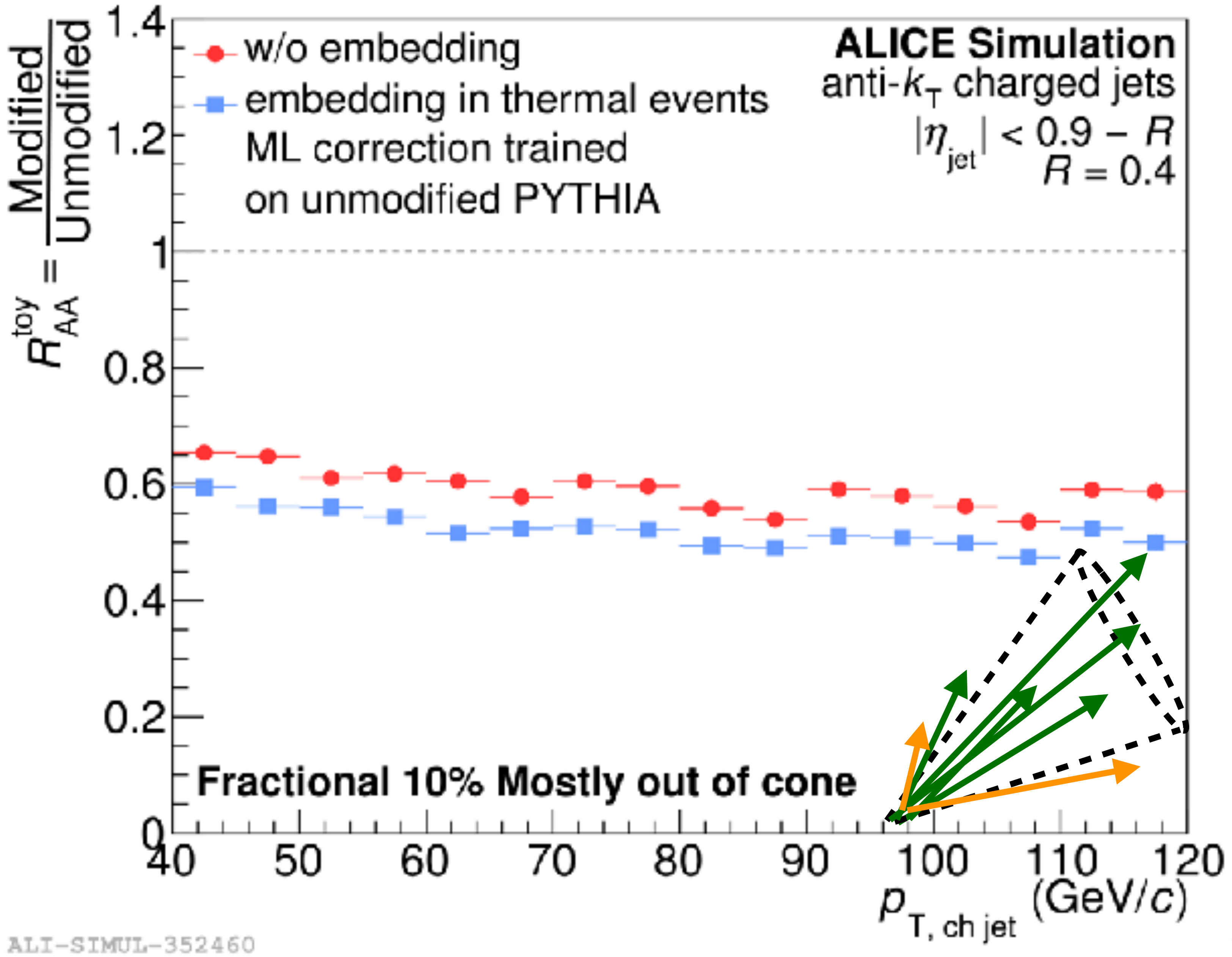
▸ Iteratively remove unimportant and/or highly correlated feature!

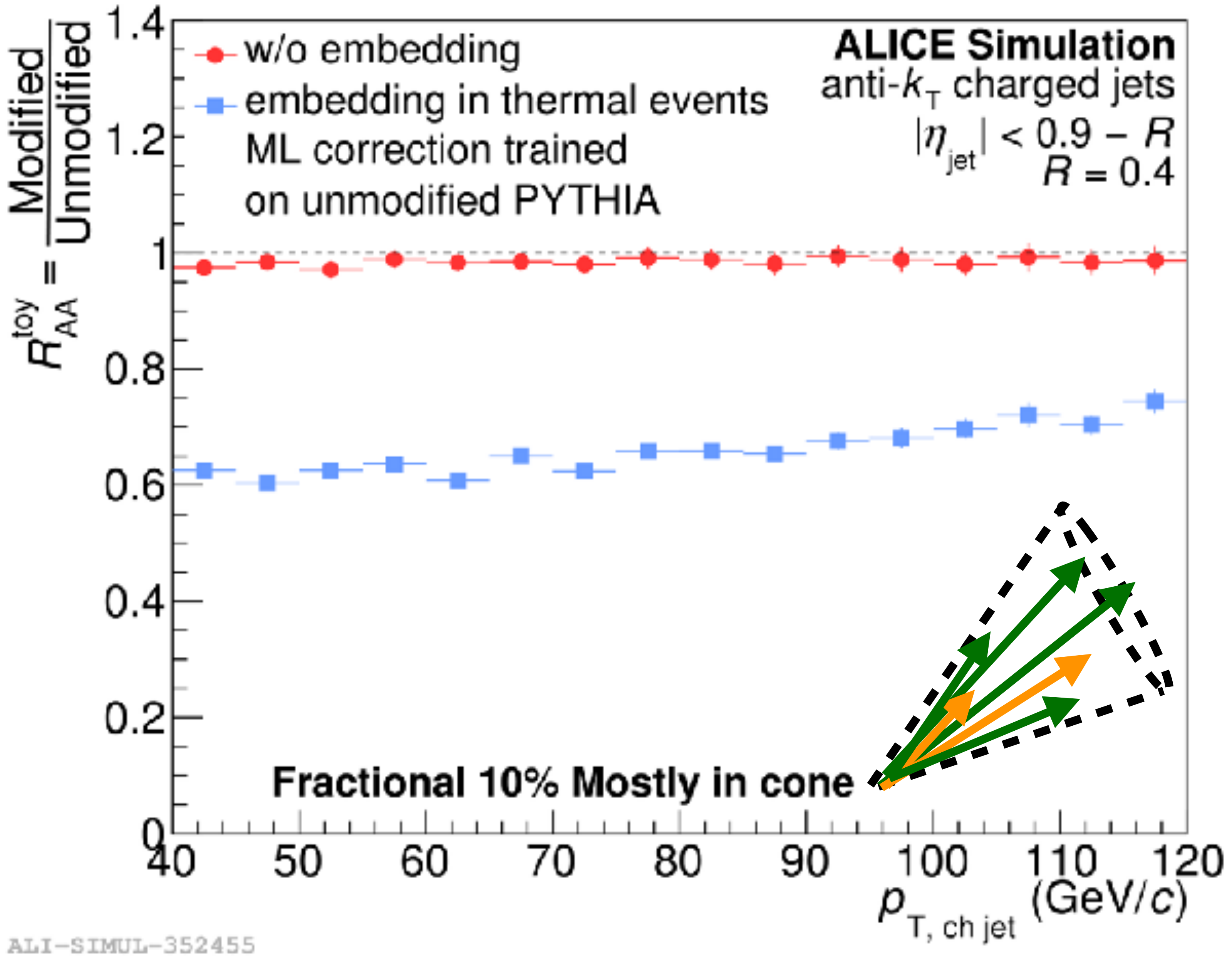
ML approach: fragmentation



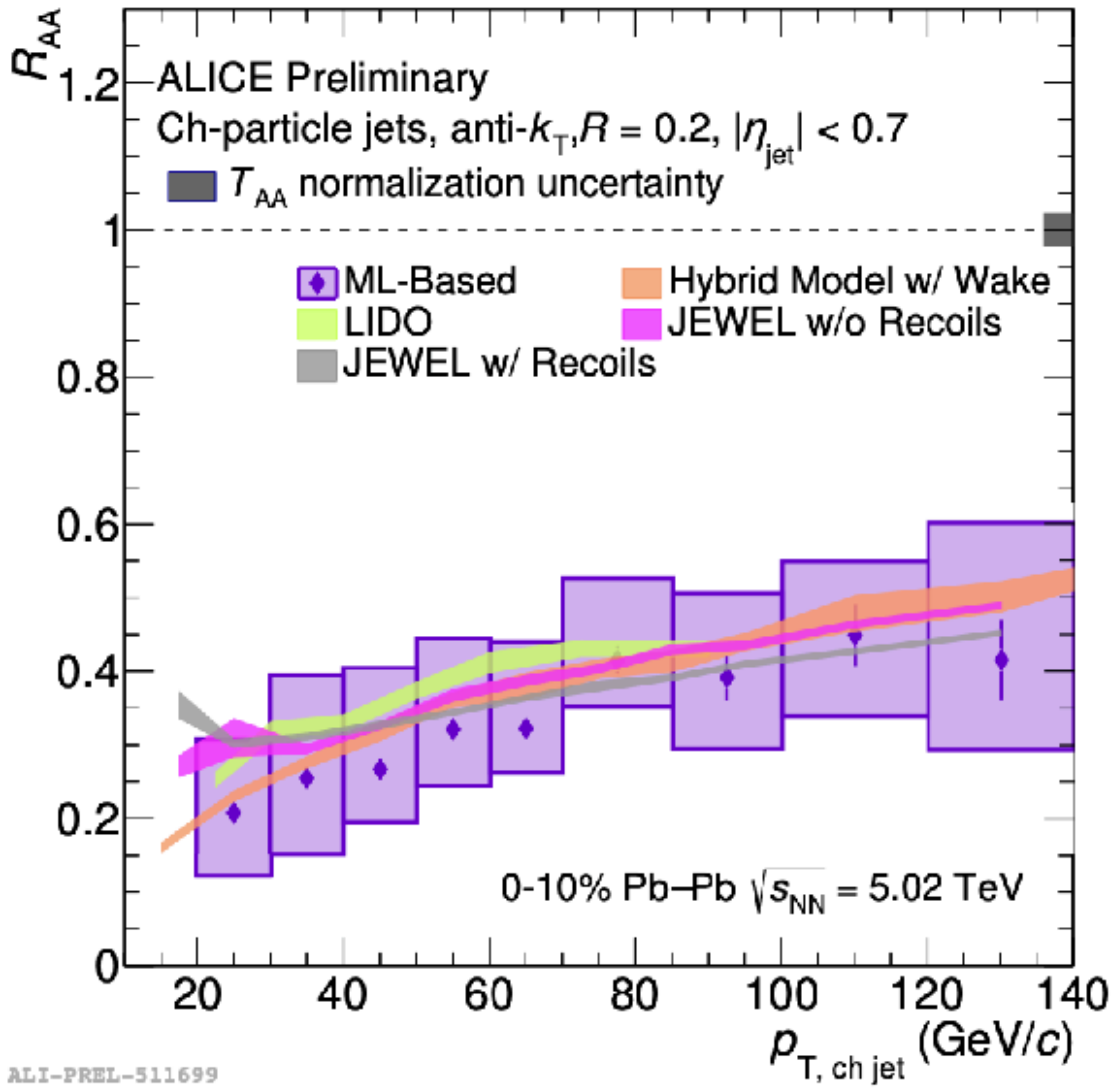








ML approach: Raa



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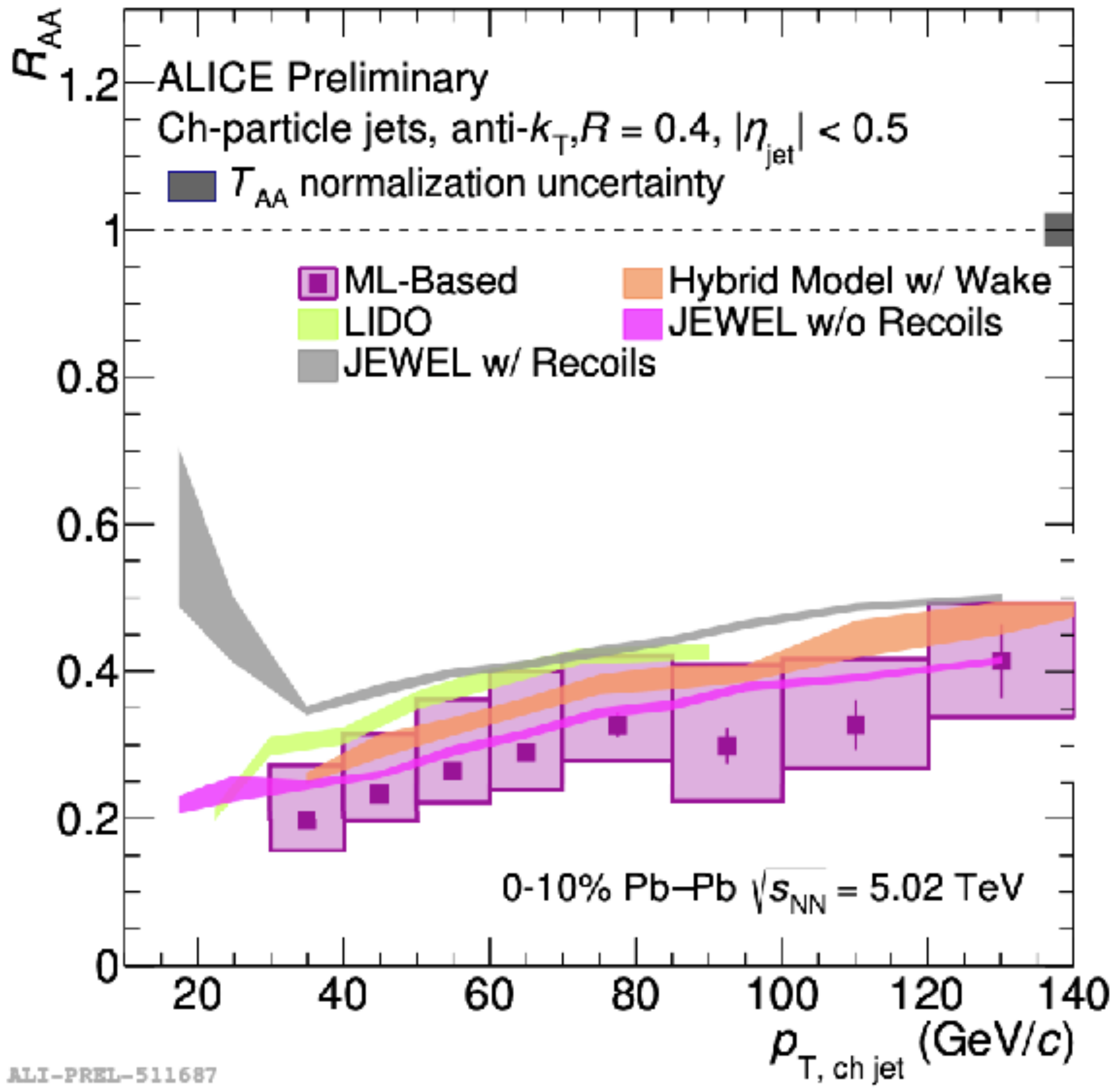
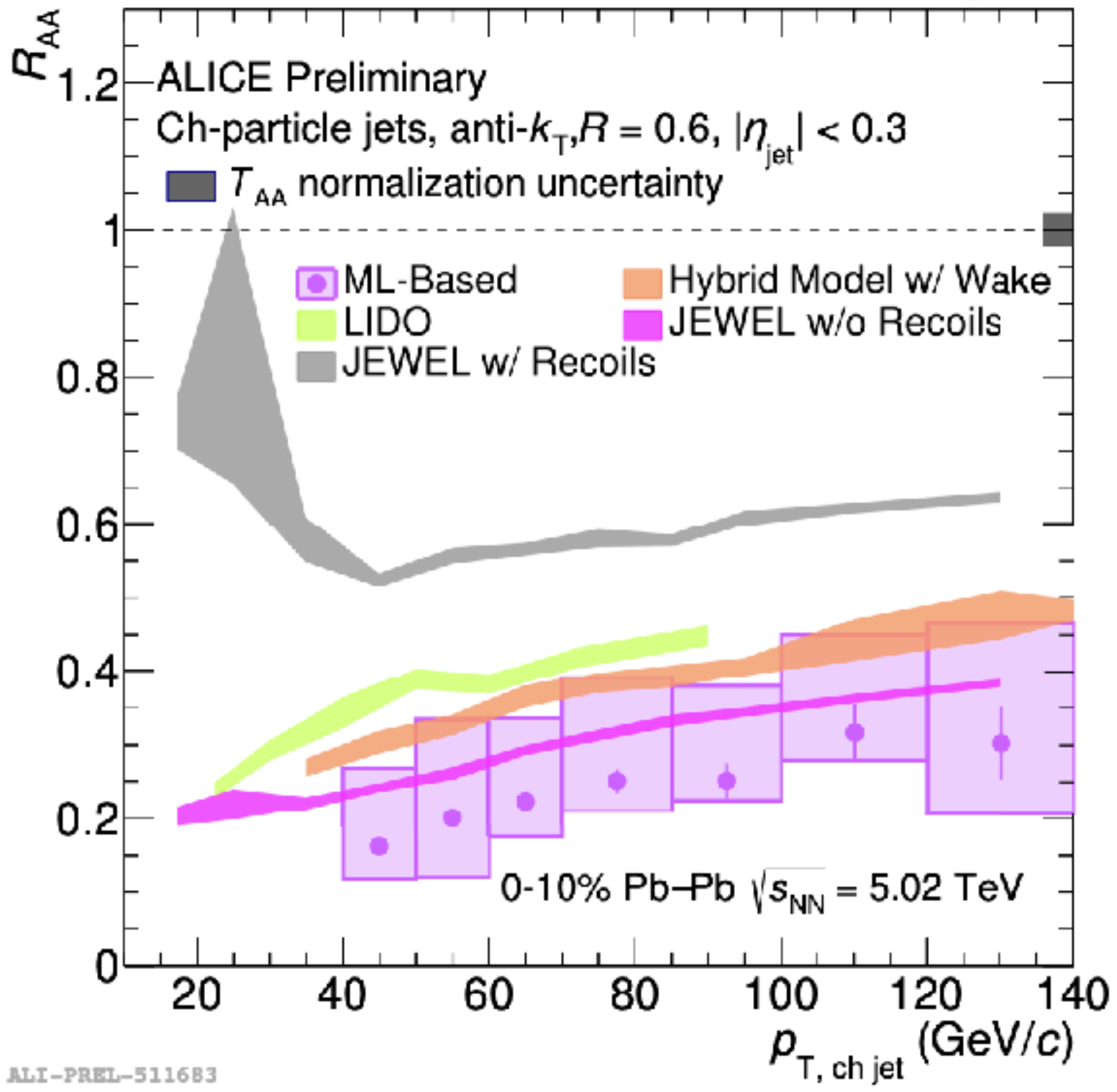


ALI-PREL-511687

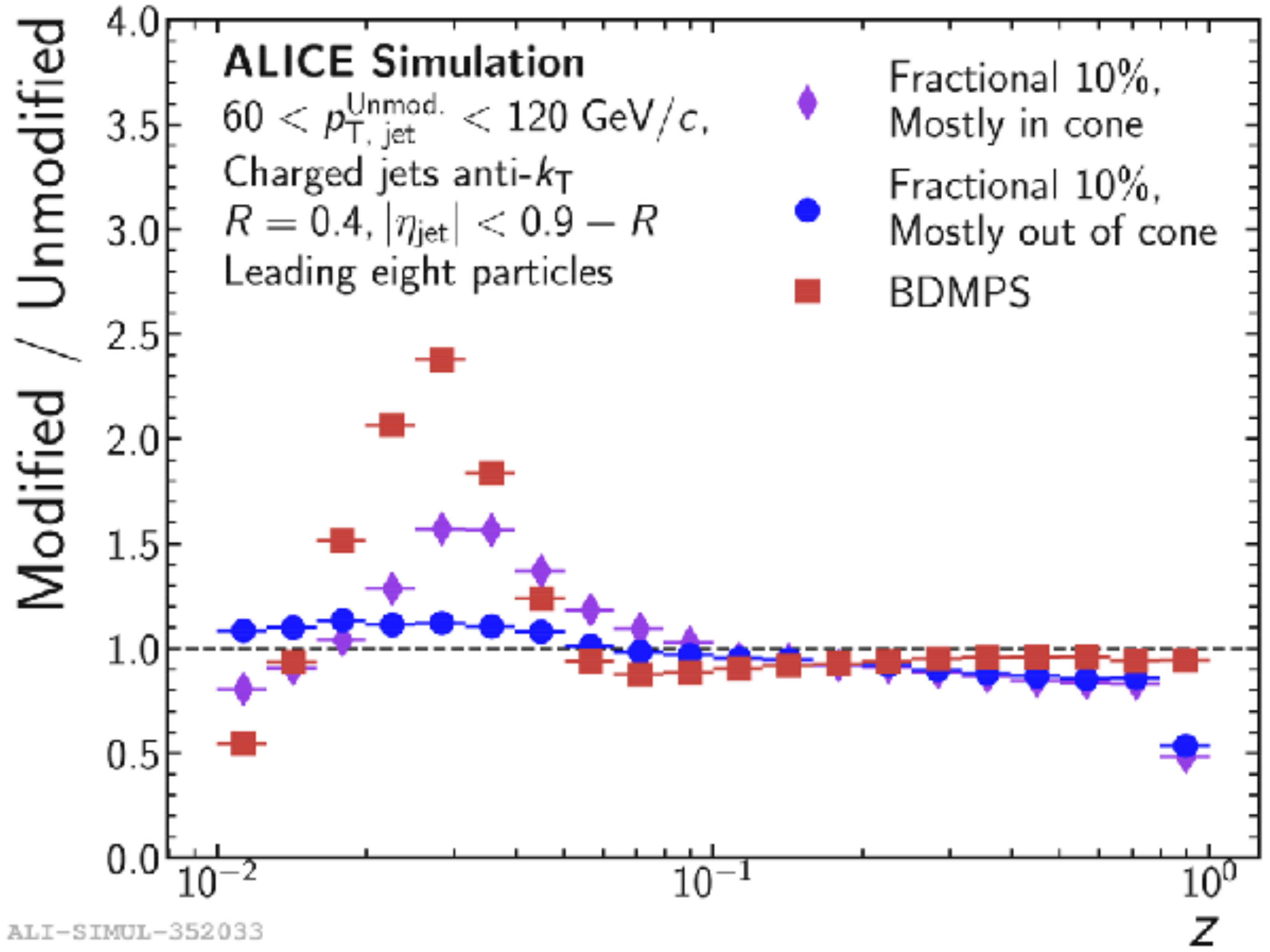


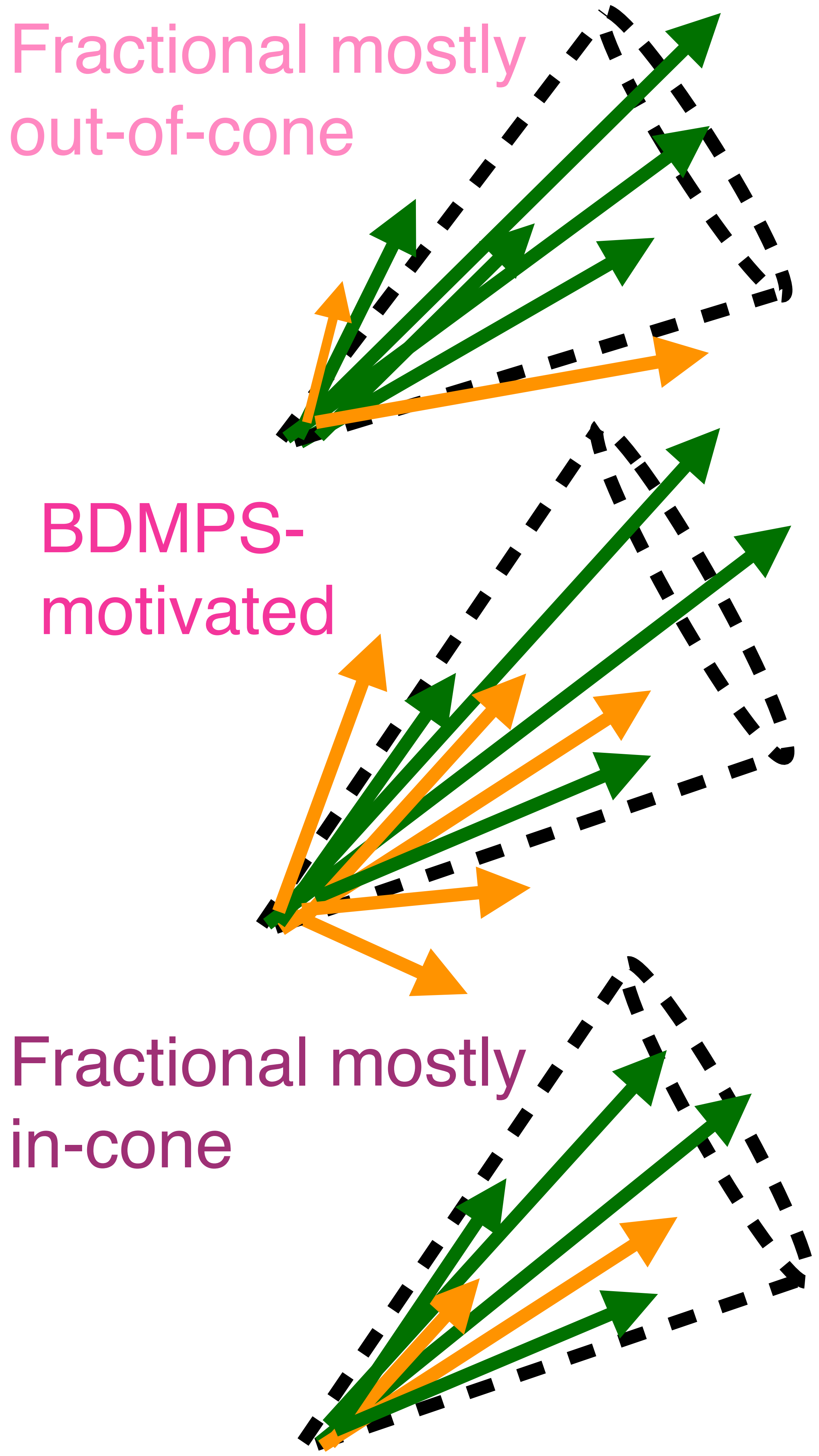
ALI-PREL-511683

ML approach: jet fragmentation bias

- Jets in HI collisions have a different fragmentation than jets in a vacuum

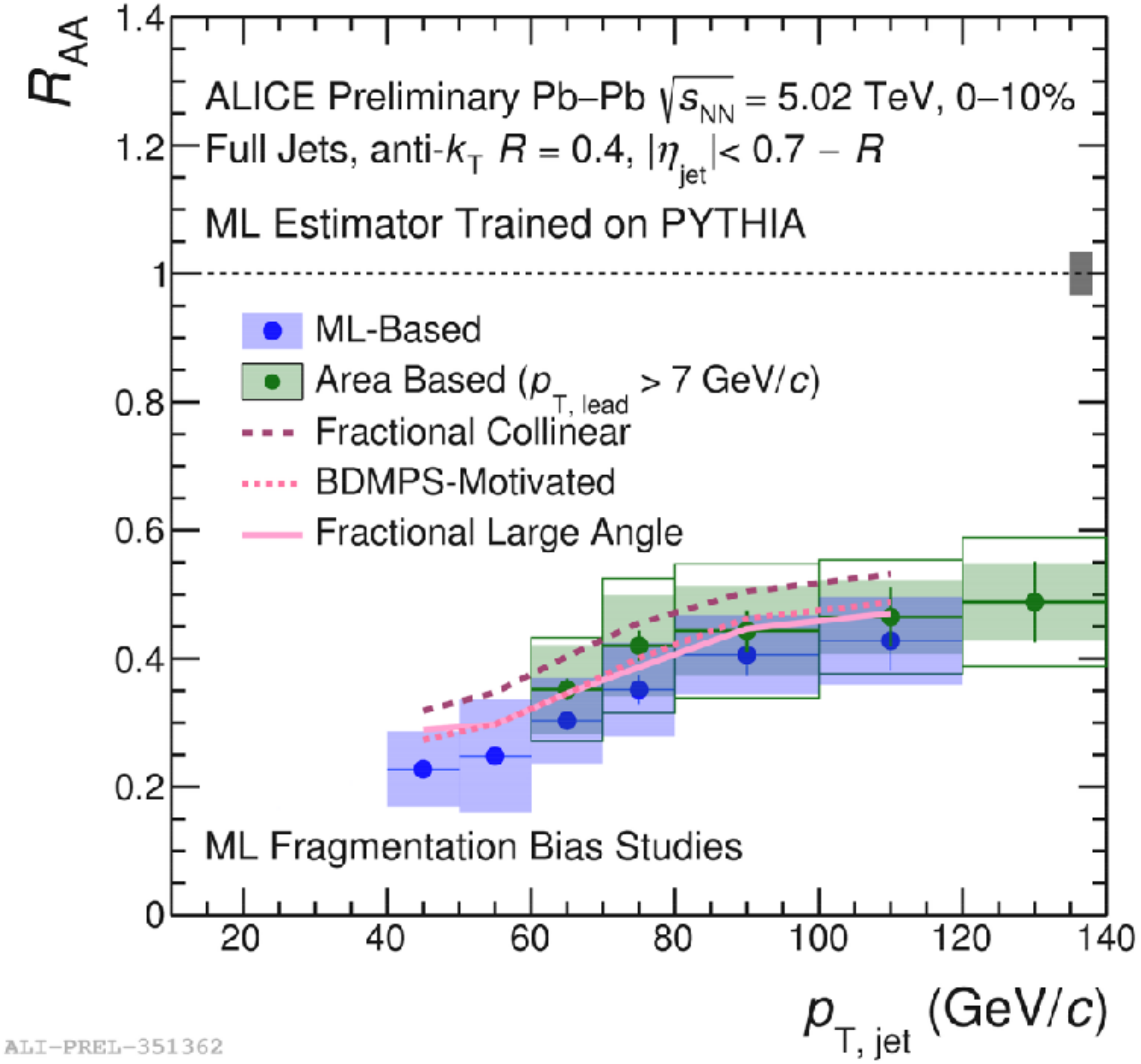
- Study jet fragmentation bias from learning on PYTHIA by training on samples with varied fragmentations




Fractional mostly out-of-cone

BDMPS-motivated

Fractional mostly in-cone



- ▸ Bias is similar in magnitude to other systematic uncertainties

ML approach: model comparisons

JEWEL: collisional and radiative energy loss

-with medium recoil

-without medium recoil

Elayavalli, Zapp JHEP 1707 (2017) 141

SCETg: interactions of medium with Glauber gluon exchange

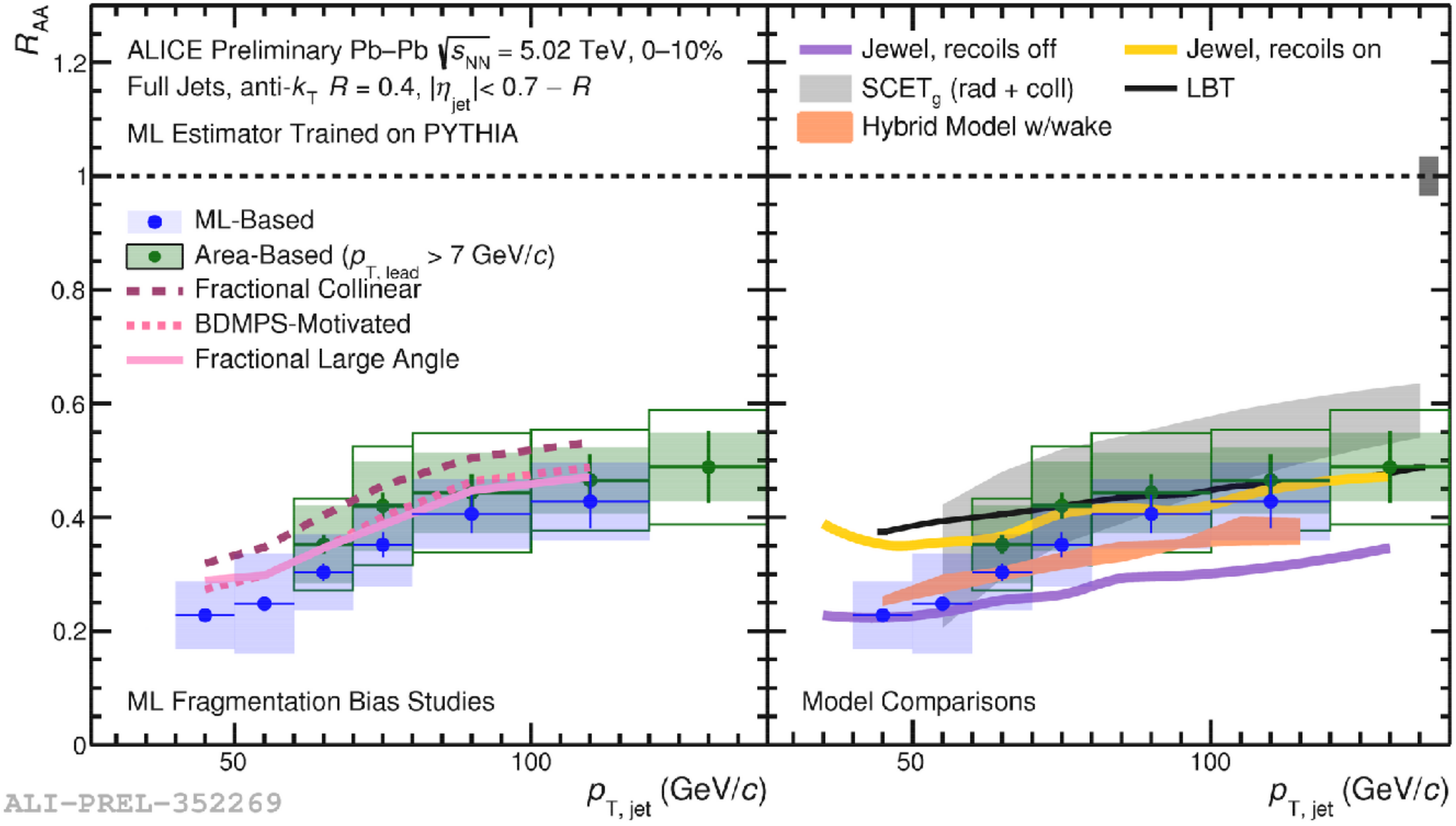
Li, Vitev JHEP 07 (2019) 148

Hybrid model: non-perturbative energy loss via AdS/CFT, medium response with wake

Pablos PRL 124, 052301

LBT: jet-medium interactions with recoil and hydrodynamical medium

He et al PRC 99 (2019) 054911



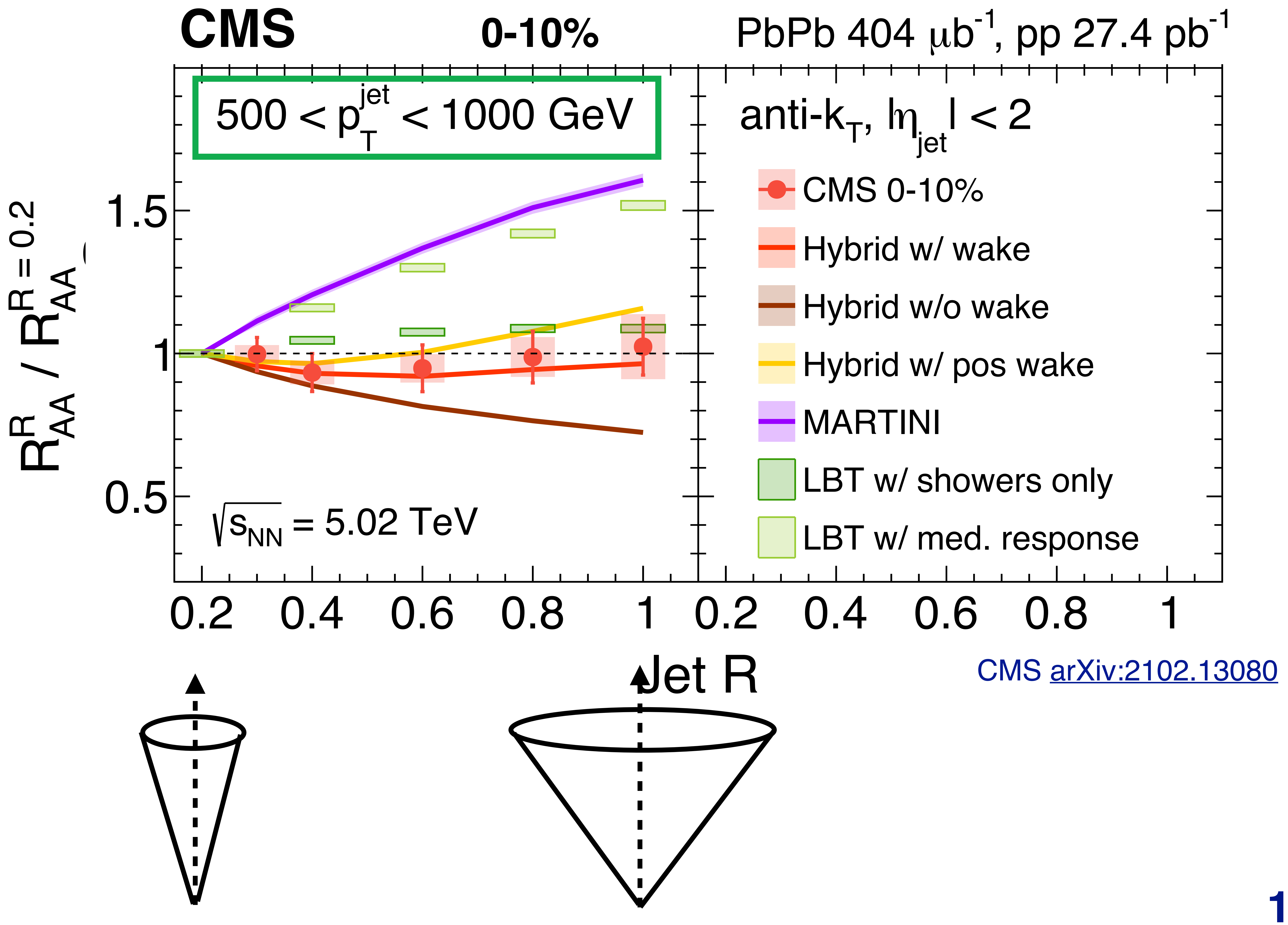
- Constrains models at low p_T

Inclusive jet suppression: large *R*

- Compare R_{AA} at larger *R* to R_{AA} at *R*=0.2 as a function of *R* at high p_T
  - Scanning *R*=0.2 to 1.0!

- *See suppression at large R and no significant radial dependence*
  - Not seeing energy recovered at large *R*?
  - Convolution of effects?

- Discriminating power for models and the physics mechanisms at play



CMS arXiv:2102.13080

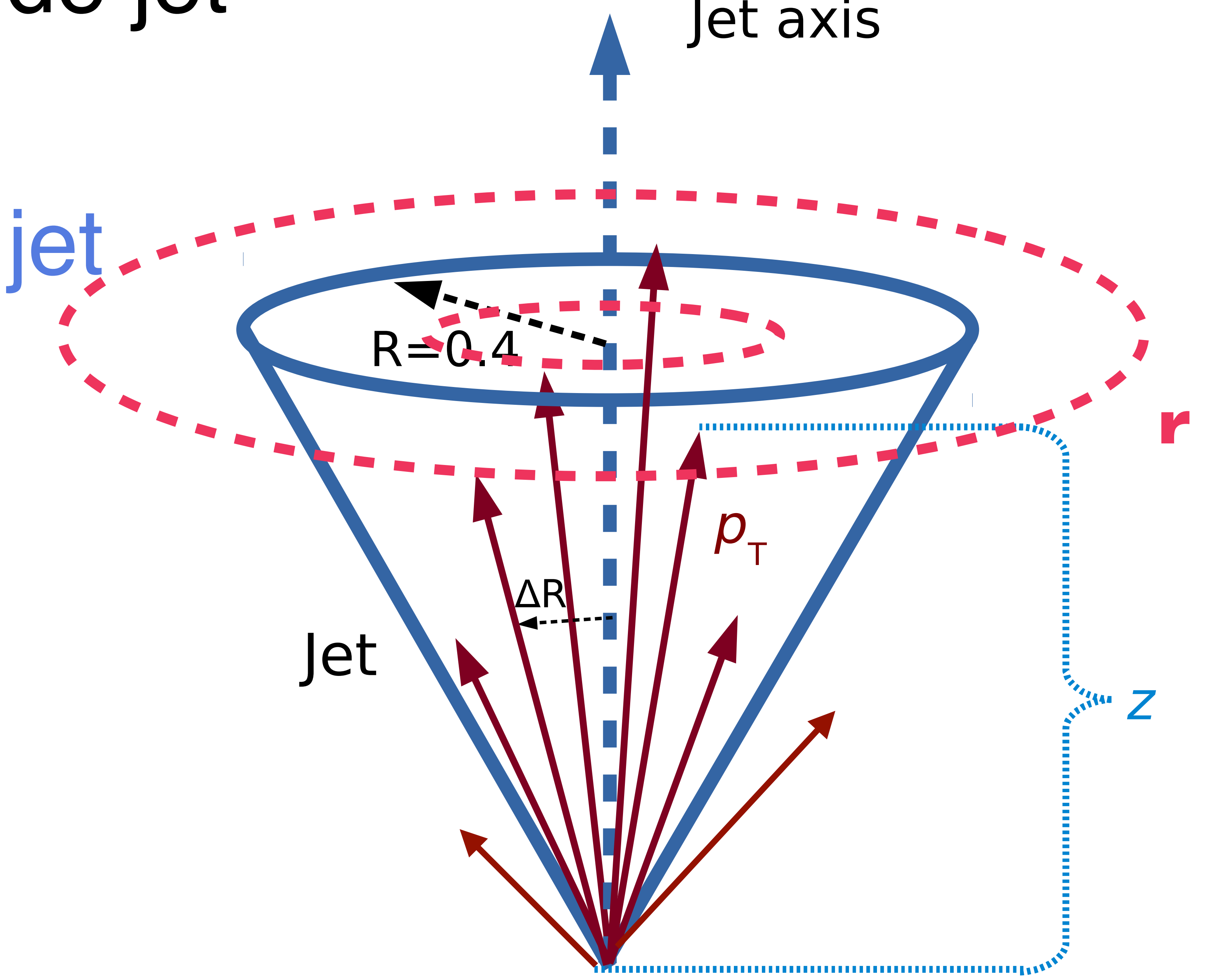
Hadron-level observables

- Distributions of particles inside jet

Jet fragmentation: longitudinal profile of charged particles in a jet

$$D(z) = \frac{1}{N_{\text{jet}}}\frac{dN_{ch}}{dz}$$

$$z = \frac{p_{\text{T}} \cos \Delta R}{p_{\text{T}}^{\text{jet}}}$$

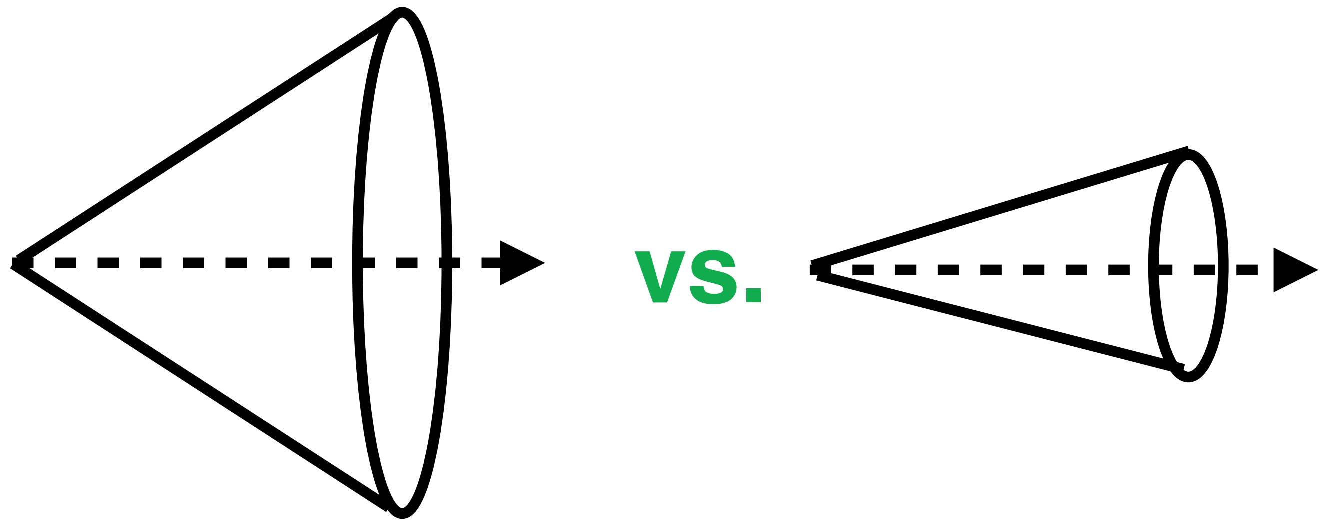


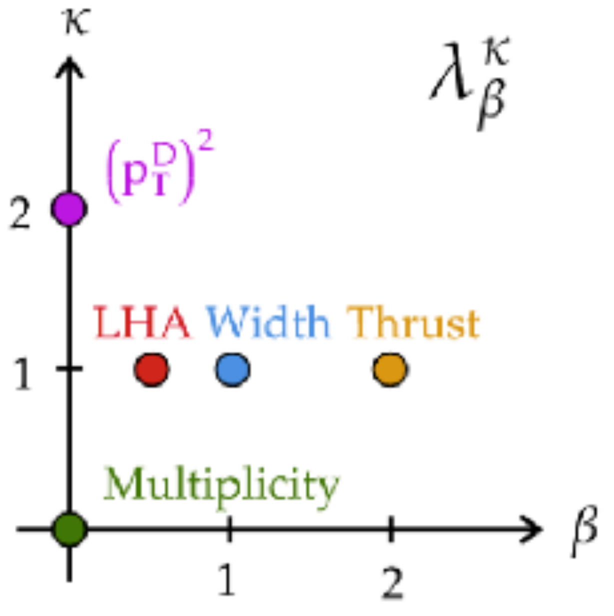
Jet shape: radial profile of charged particles in a jet

$$\rho(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{\text{jets}}}\frac{\sum_{\text{jets}}\sum_{\text{tracks}\in(\Delta r_a,\Delta r_b)} p_{\text{T}}^{\text{ch}}}{\sum_{\text{jets}}\sum_{\text{tracks}\in\Delta r\leq 1} p_{\text{T}}^{\text{ch}}}$$

- Properties of the jet (generalized angularities)

How wide are the jets?

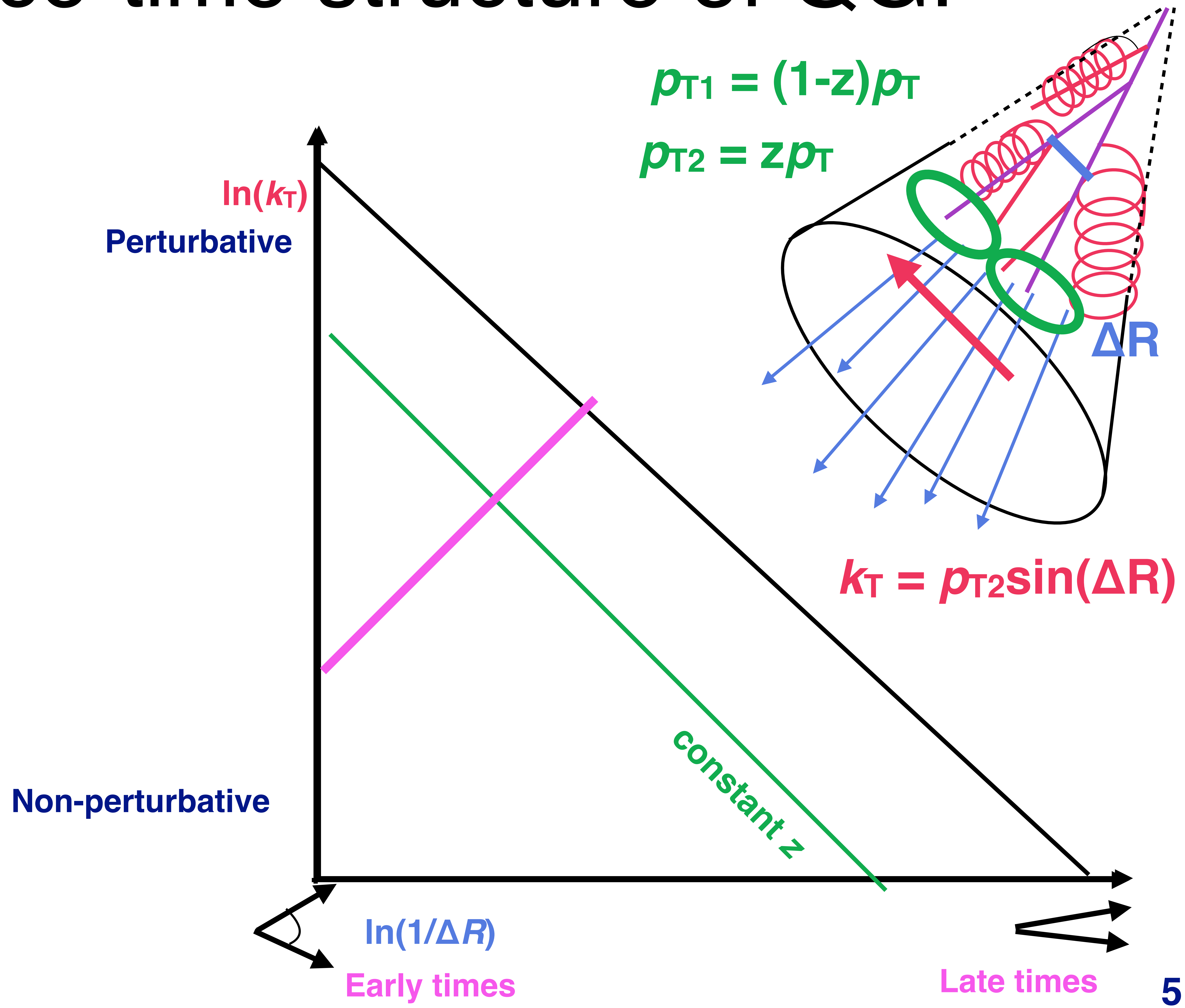




$$\lambda_\beta^\kappa = \sum_{i\in \text{jet}} z_i^\kappa \left(\frac{\Delta R_i}{R}\right)^\beta$$

Related to jet shapes:
Angularity (girth) g α=1
~Mass α=2

Lund Plane: space-time structure of QGP



- Formation time:

$$t_\mathrm{f} = \frac{1}{(1-z)k_\mathrm{T}\Delta R}$$

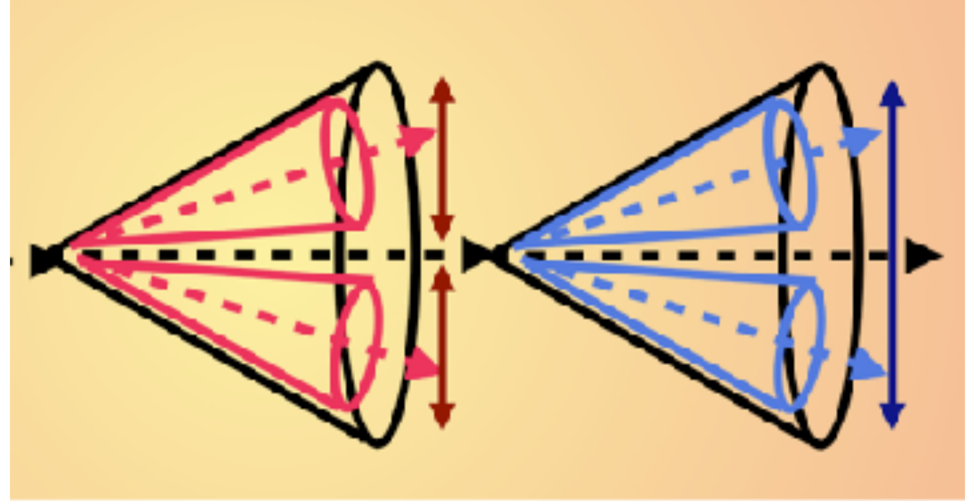
Y. L. Dokshitzer, et.al.

Lund Plane: space-time structure of QGP

1: Outside of medium

2: Decoherence

3: Coherence



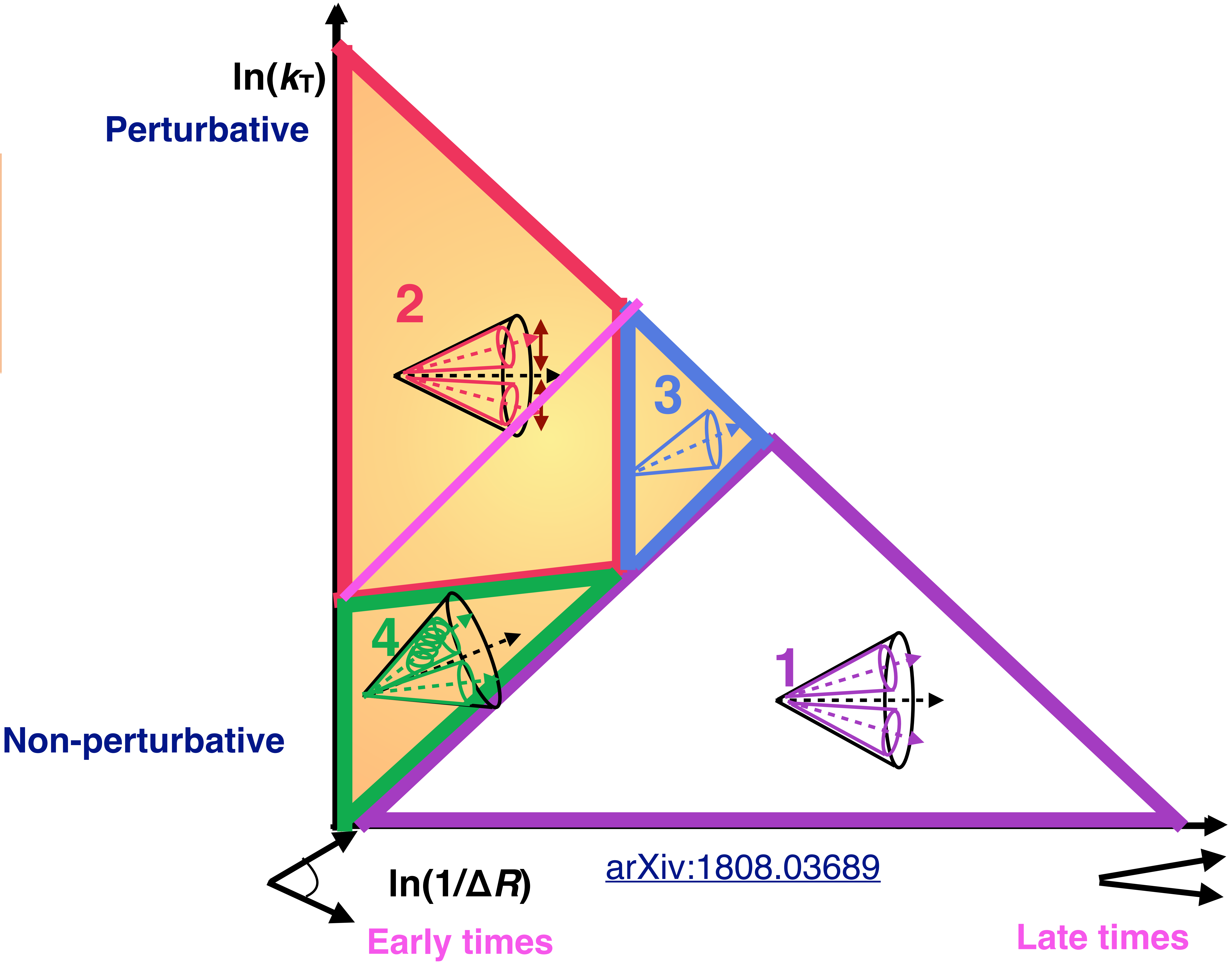
4: Medium-induced splittings

- Formation time: wider jets formed earlier experience more medium

See Liliana's talk today

Y. L. Dokshitzer, et.al.

$$t_{\mathrm{f}} = \frac{1}{(1-z)k_{\mathrm{T}}\Delta R}$$



arXiv:1808.03689

Soft drop grooming: in-medium

- Recluster jets with C/A*

*JHEP 9708:001,1997

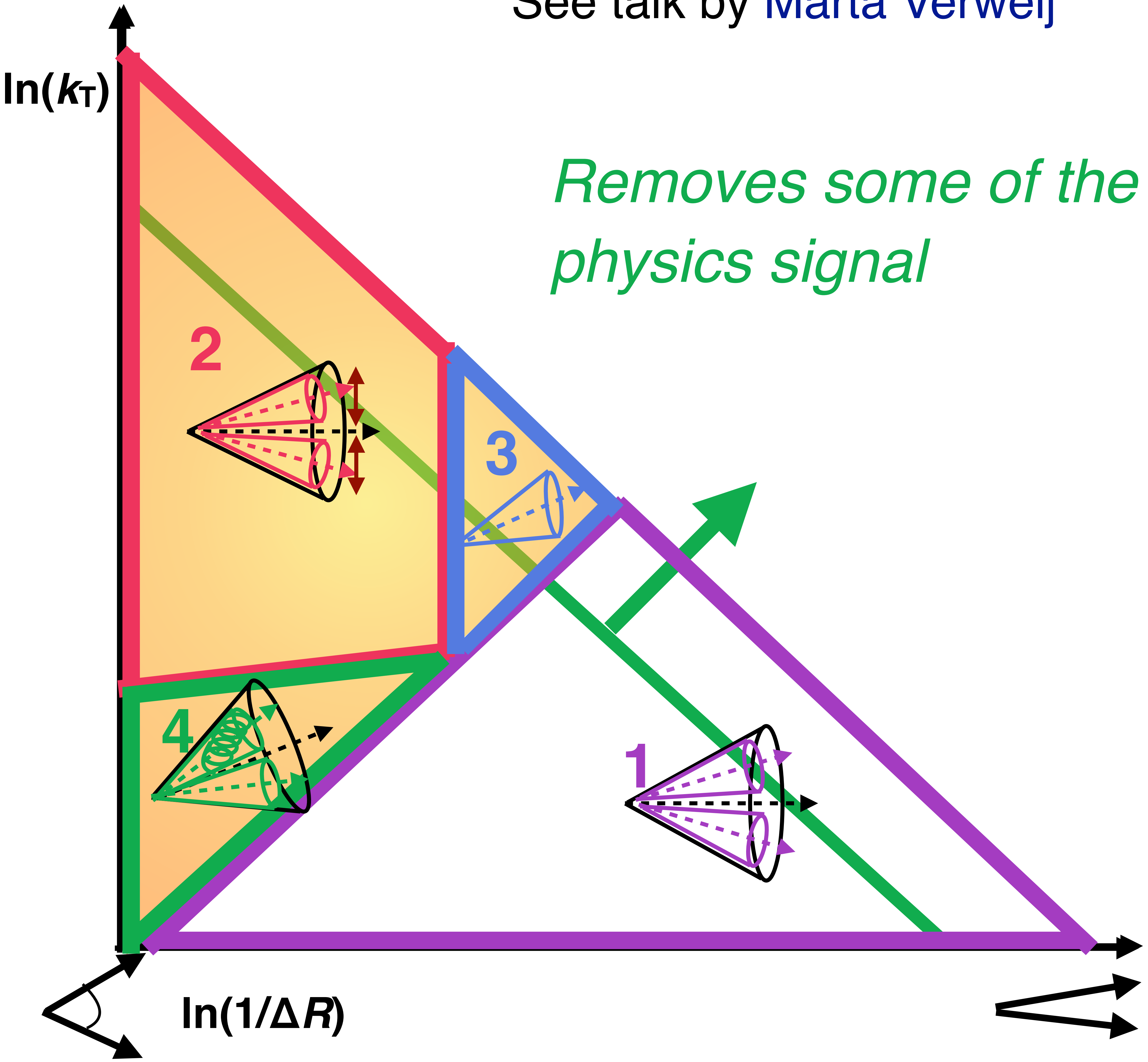
- Apply grooming to access first hard splitting

$$z_{\mathrm{g}} > z_{\mathrm{cut}}\,\theta^{\beta}$$

$$\theta = \frac{\Delta R}{R}$$

- Helps remove soft background for UE in HI collisions
- Removes soft signal from softening of jet constituents and medium response to focus on hard structure modification

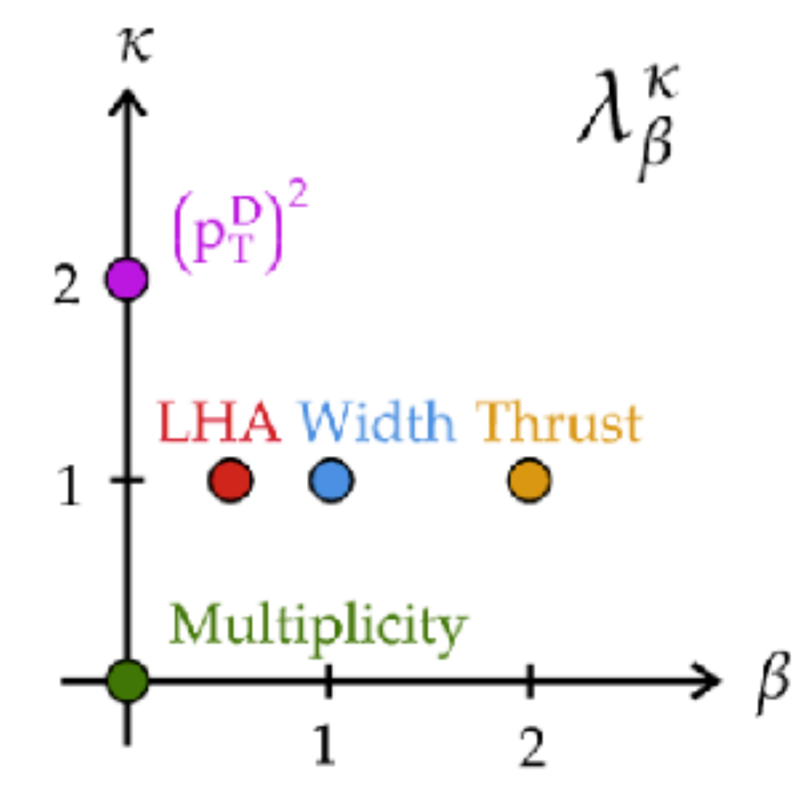
See talk by Marta Verweij



Removes some of the physics signal

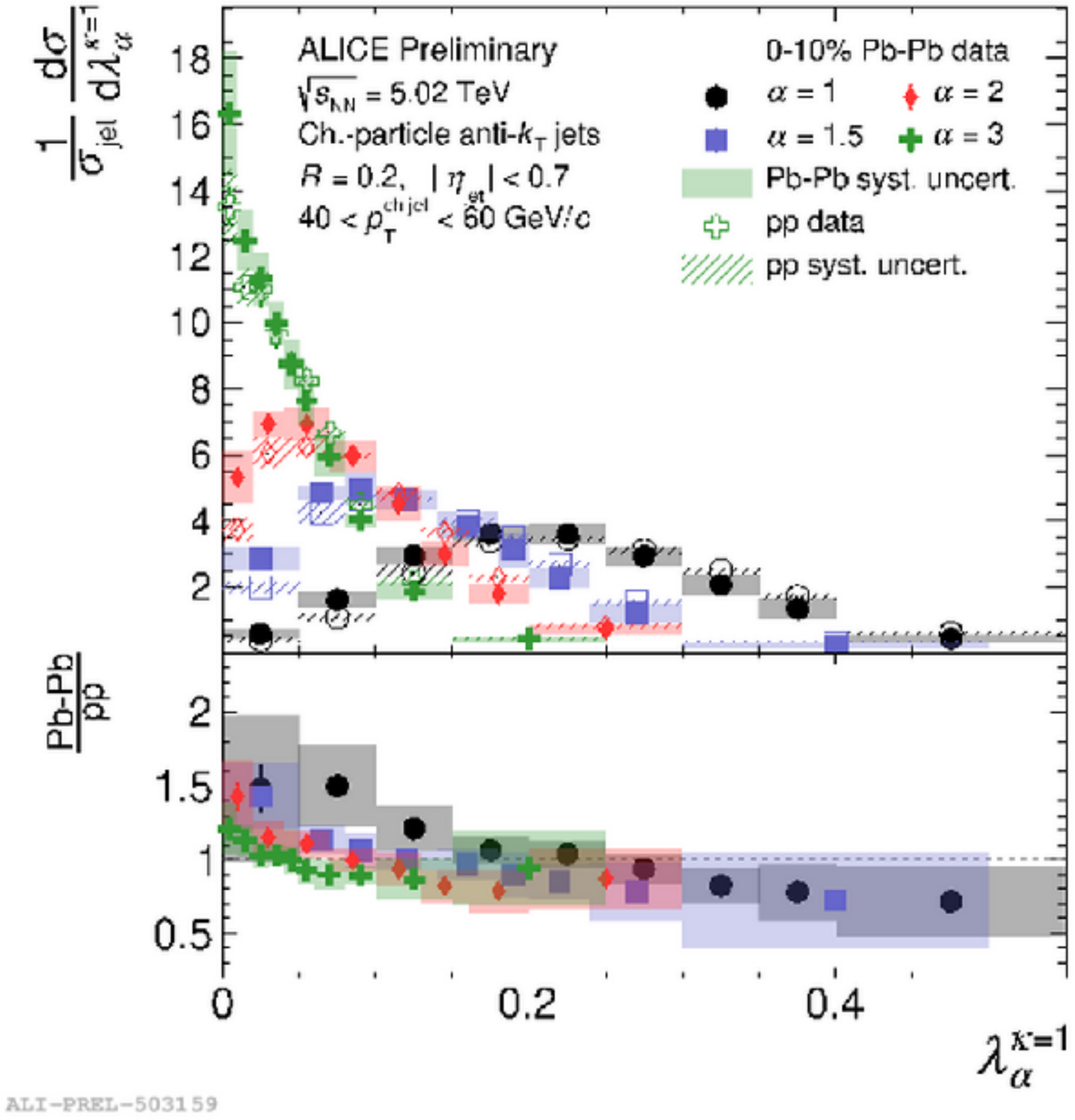
Groomed jet angularities

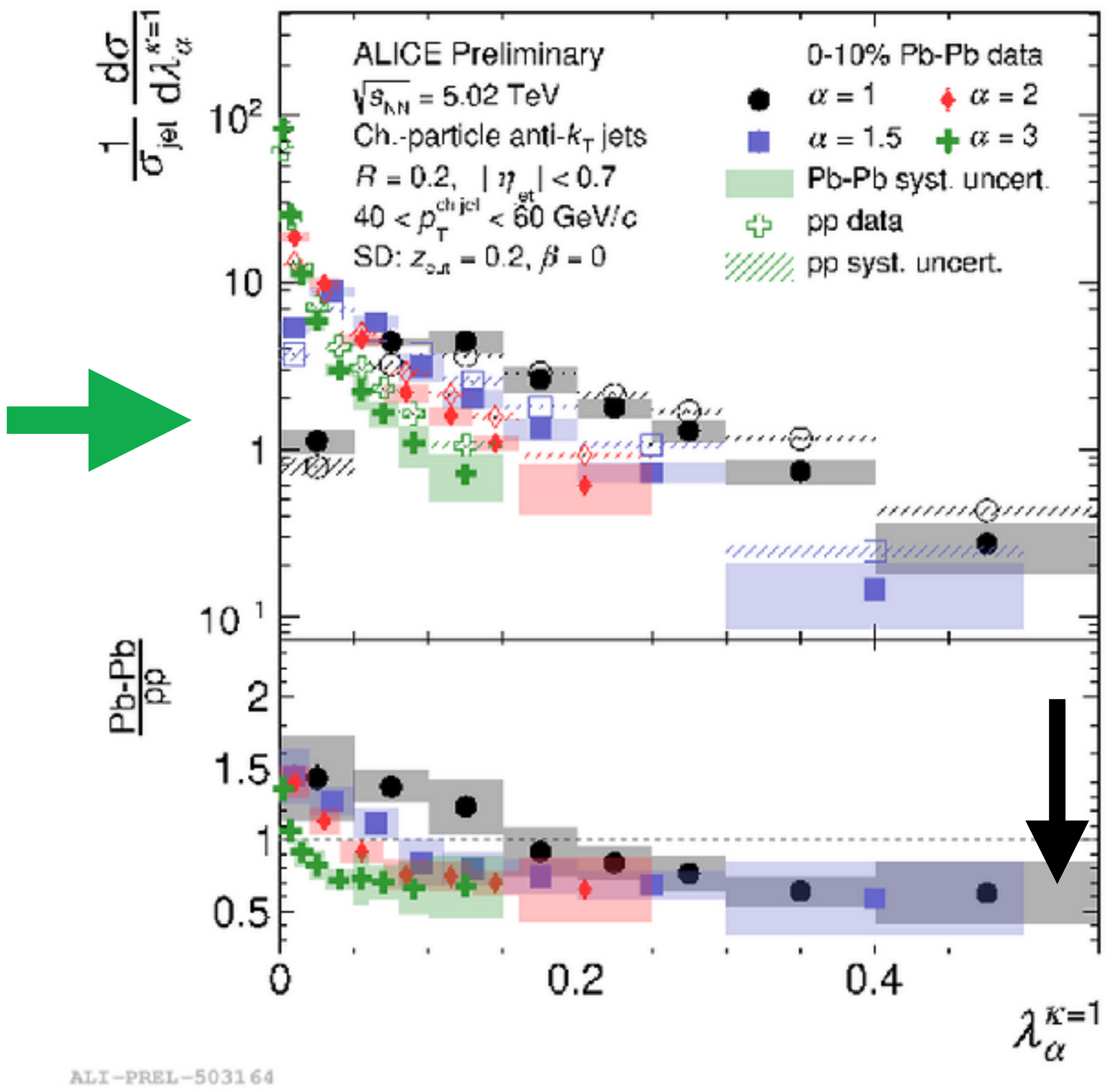
- Class of IRC-safe observables to summarize all substructure



$$\lambda_\beta^\kappa = \sum_{\mathrm{i}\in\mathrm{jet}} z_\mathrm{i}^\kappa \left(\frac{\Delta R_\mathrm{i}}{R}\right)^\beta$$

Related to jet shapes:
Angularity (girth) g α=1
~Mass α=2

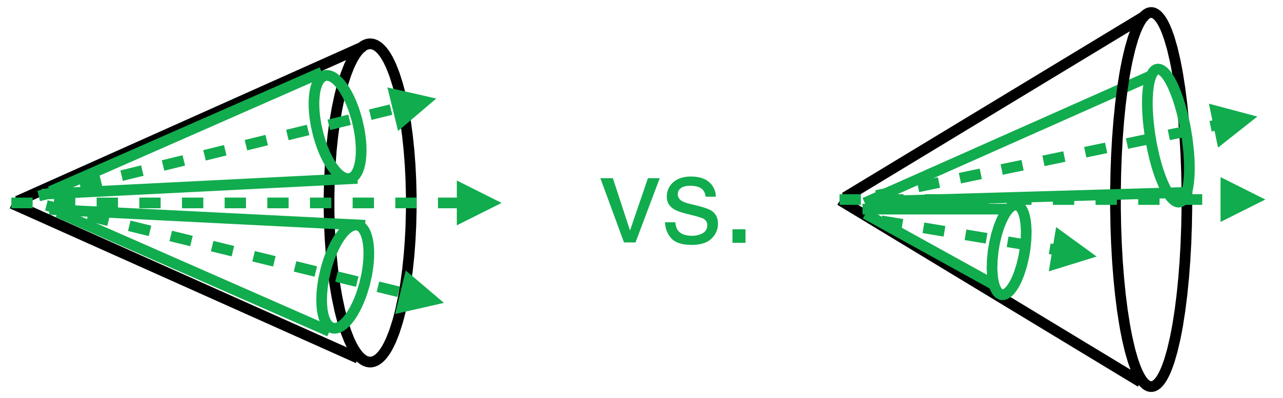




- Grooming reduces systematics and reveals narrowing feature
  - *Grooming reduces intra-jet broadening and recoil effects*

SD grooming variables

Modifications to splitting function?



vs.

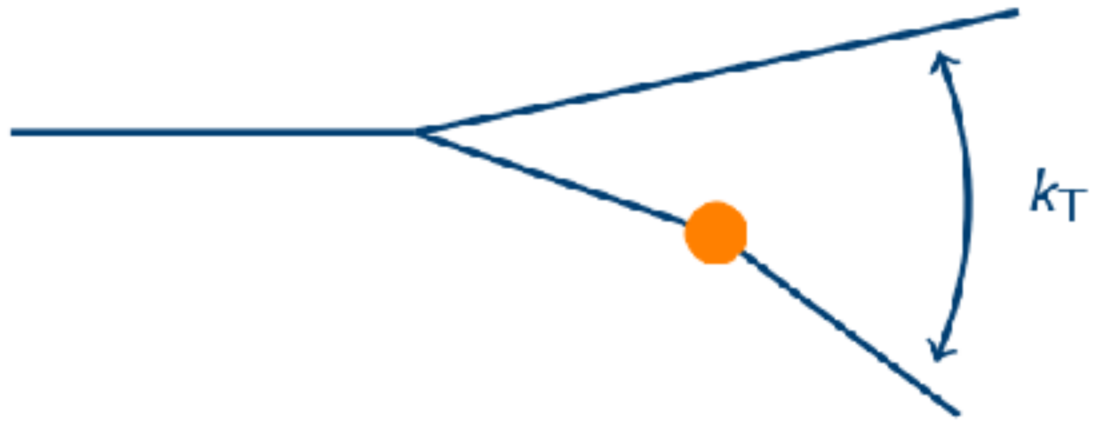
$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$$

Resolution length of the QGP?

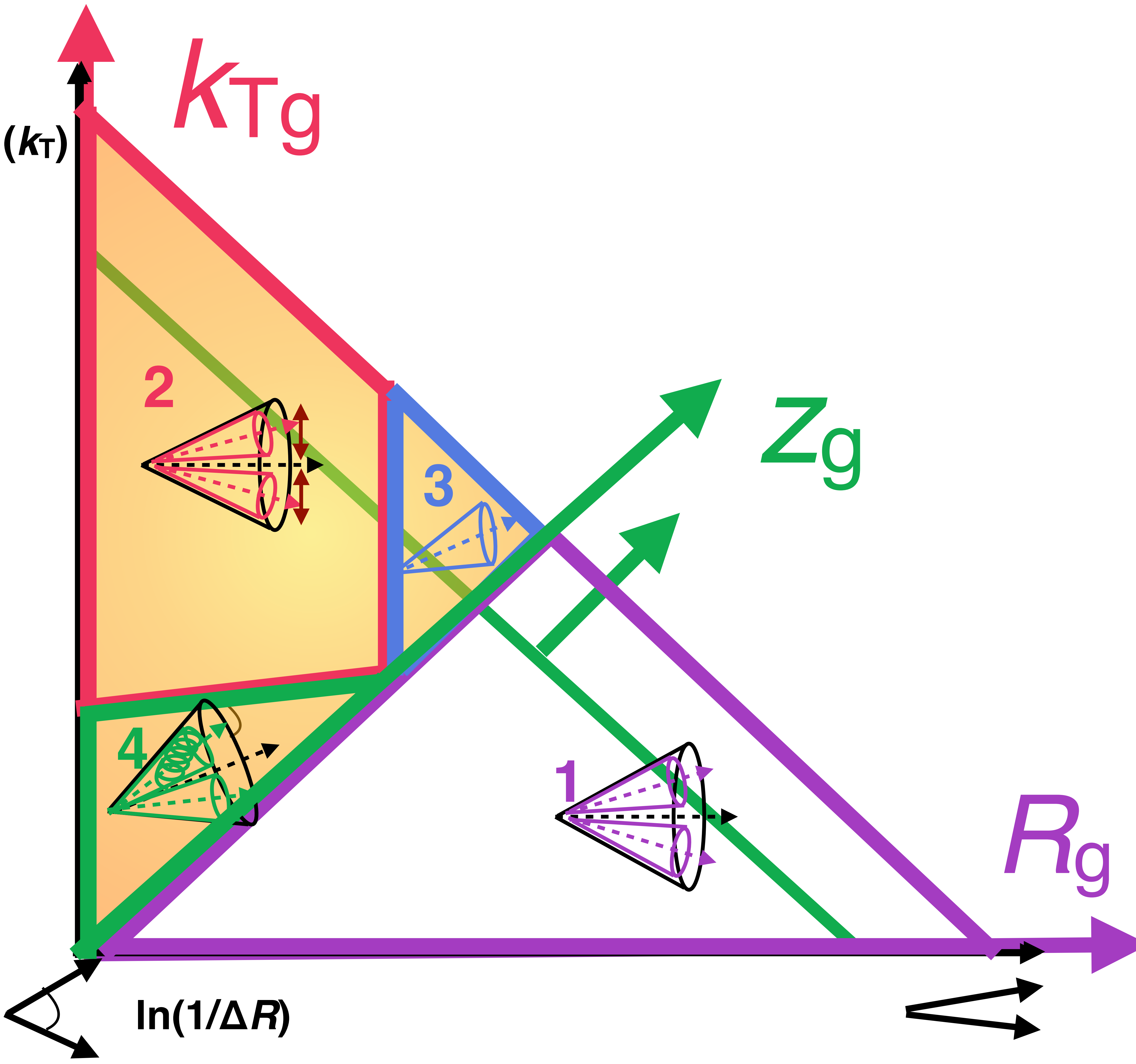
vs.

$$R_g = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

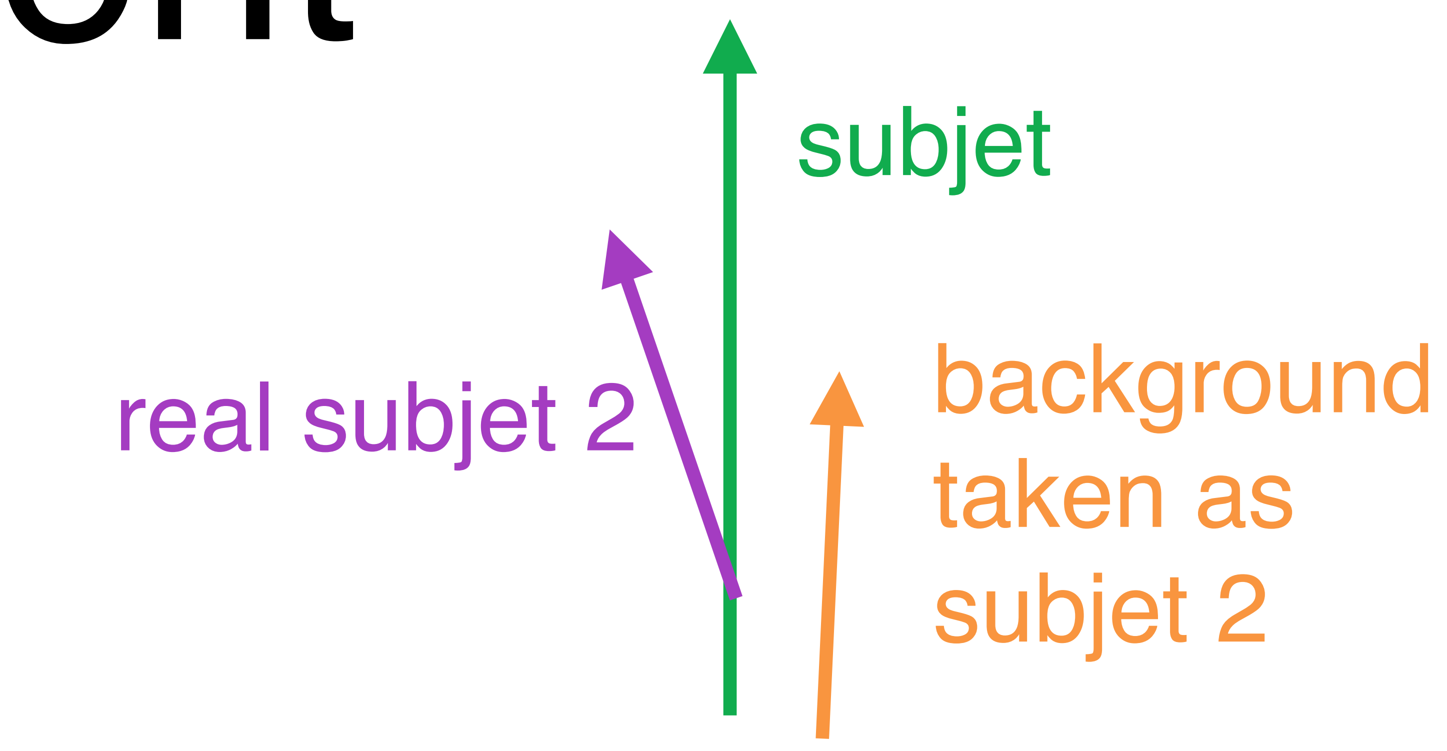
In-medium Moliere scattering?



$k_{Tg} \sim z_g p_T R_g$



Background treatment



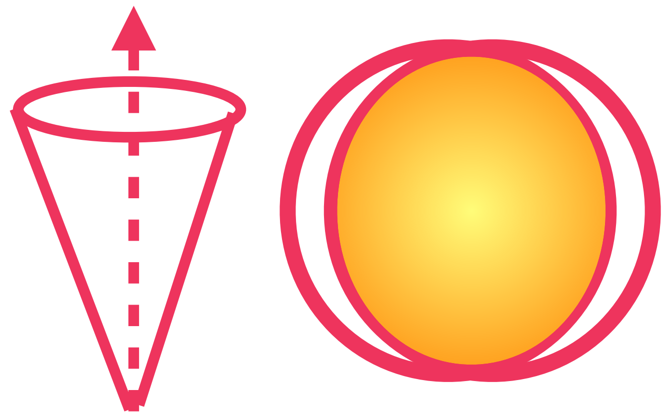
subjet

real subjet 2

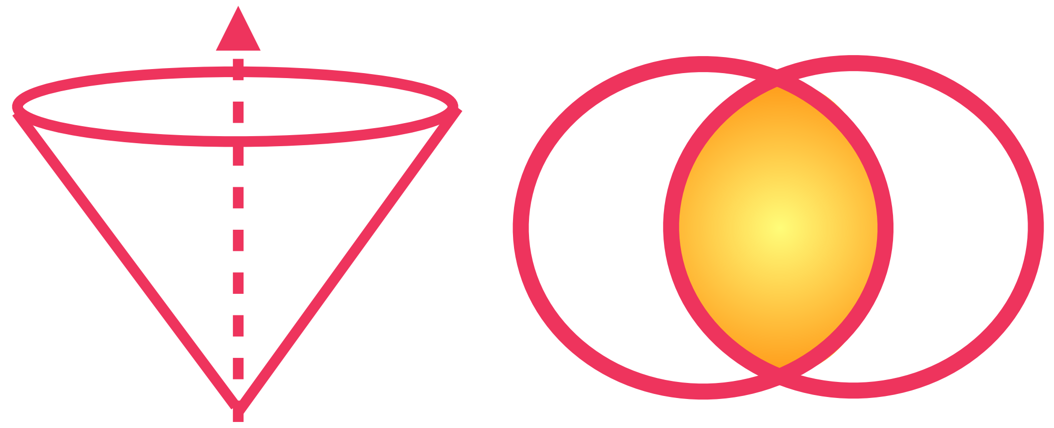
background taken as subjet 2

- Uncorrelated background leads to incorrect splittings
- Solutions:

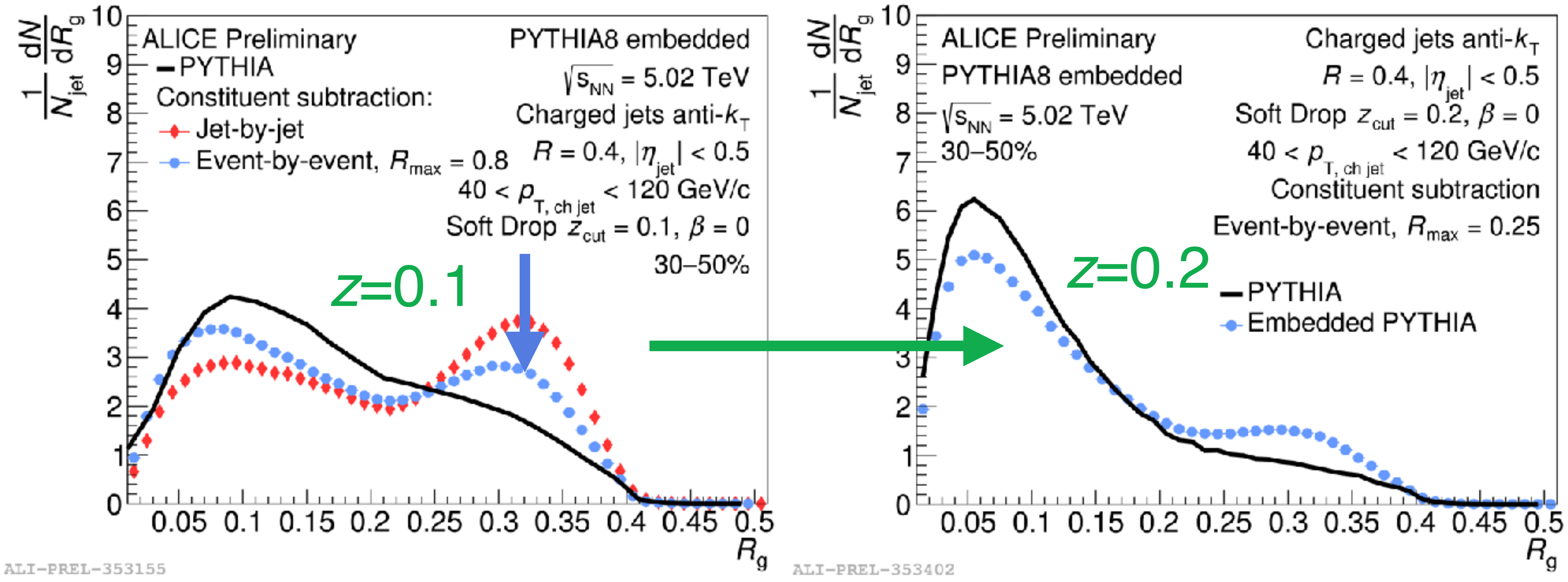
1. smaller jet radii



or semi-central collisions



2. tighter SD condition



z=0.1

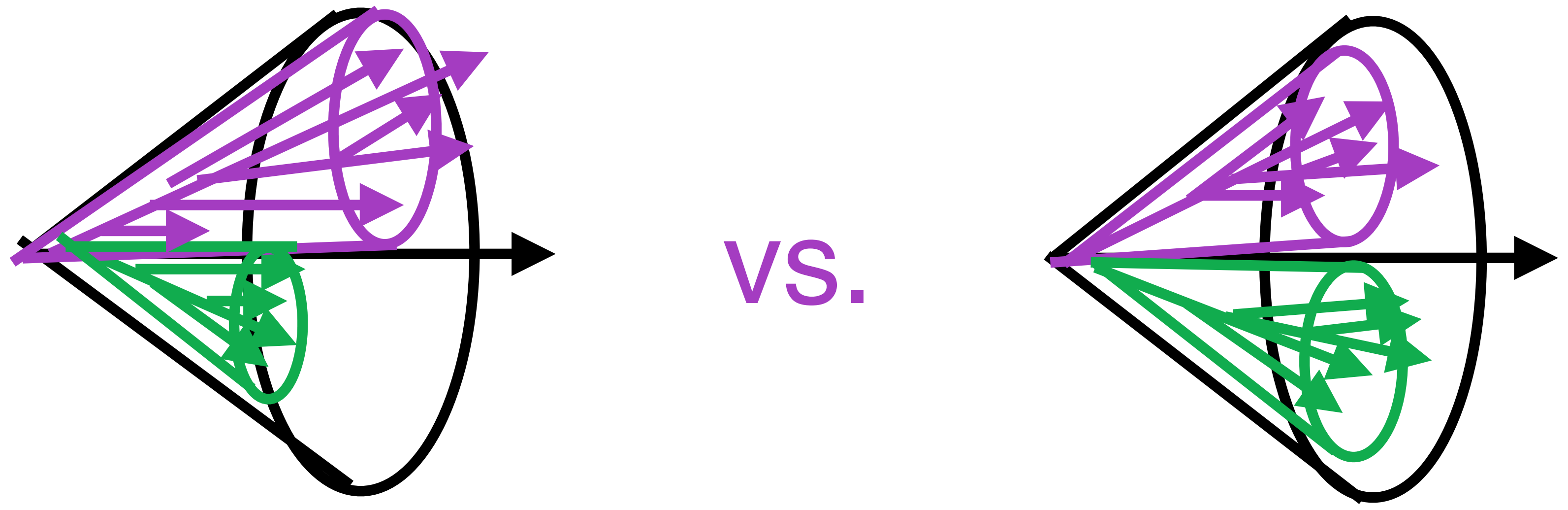
z=0.2

ALI-PREL-353155

ALI-PREL-353402

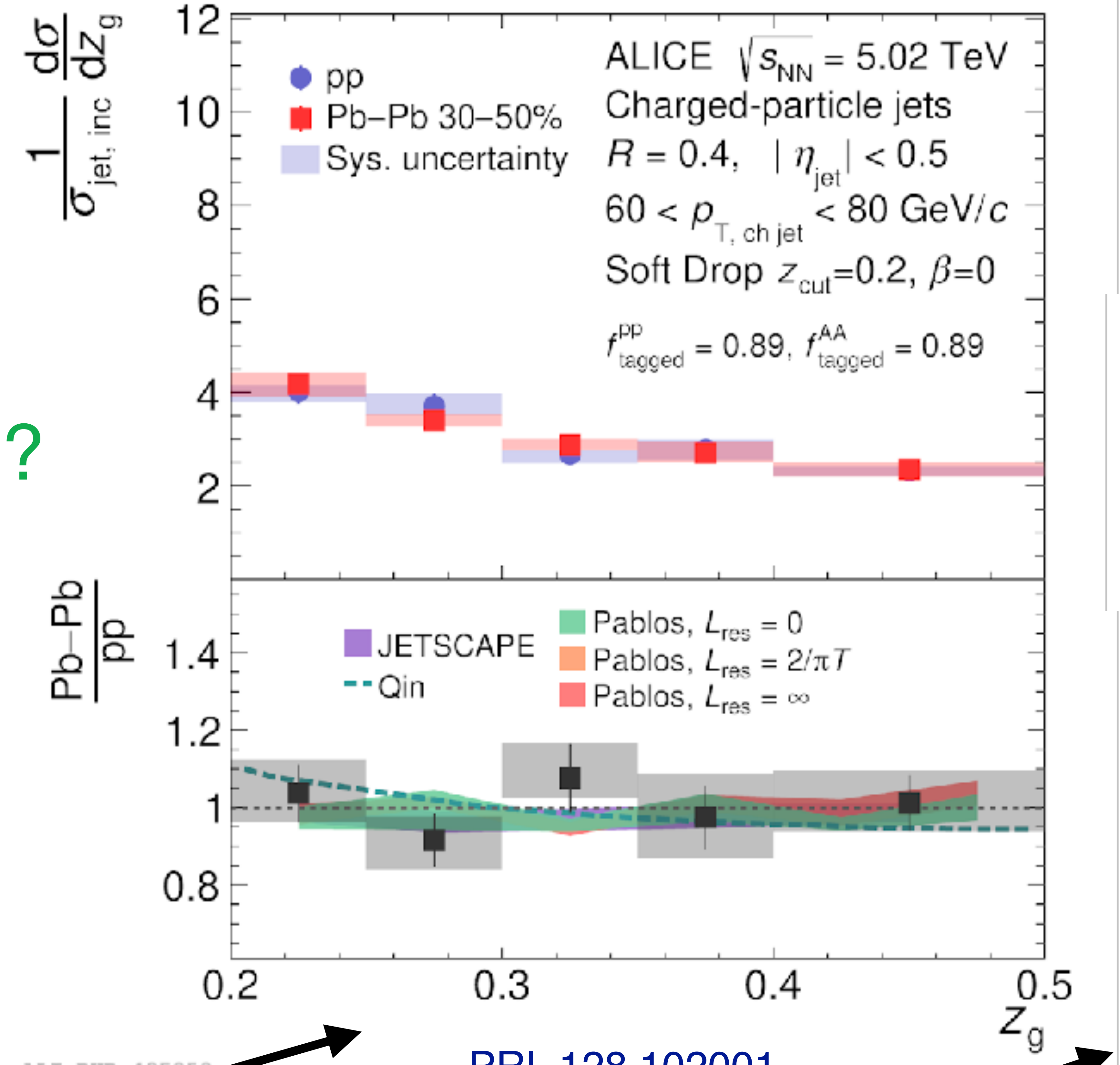
Jet splittings: z_g

$$z_g = \frac{\min(p_{\mathrm{Ti}}, p_{\mathrm{Tj}})}{p_{\mathrm{Ti}} + p_{\mathrm{Tj}}}$$

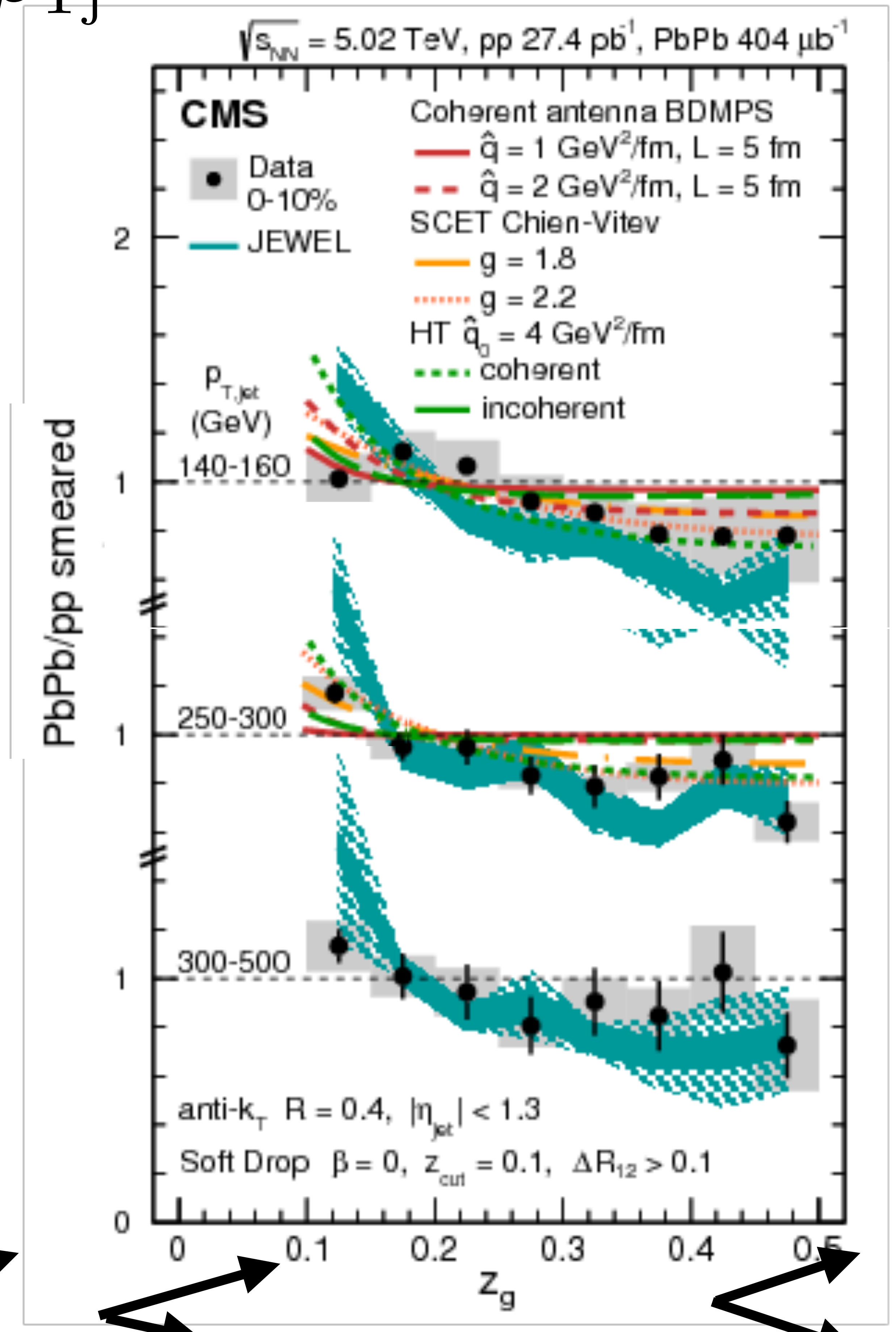


Modification of splitting function?

- *Low p_T: no significant modification, mostly consistent with models*
- *High p_T: hint of suppression at high z_g*



PRL 128 102001

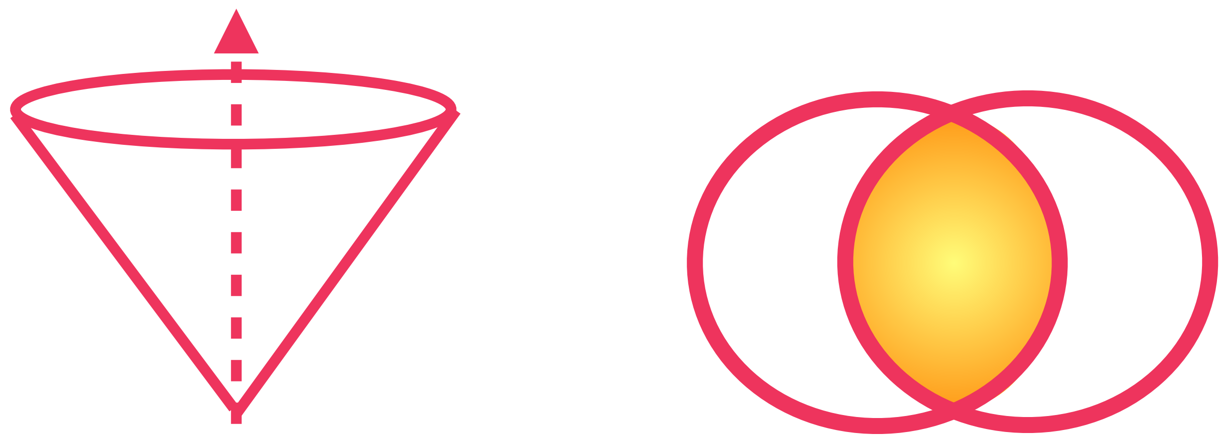


PRL 120, 142302 (2018)

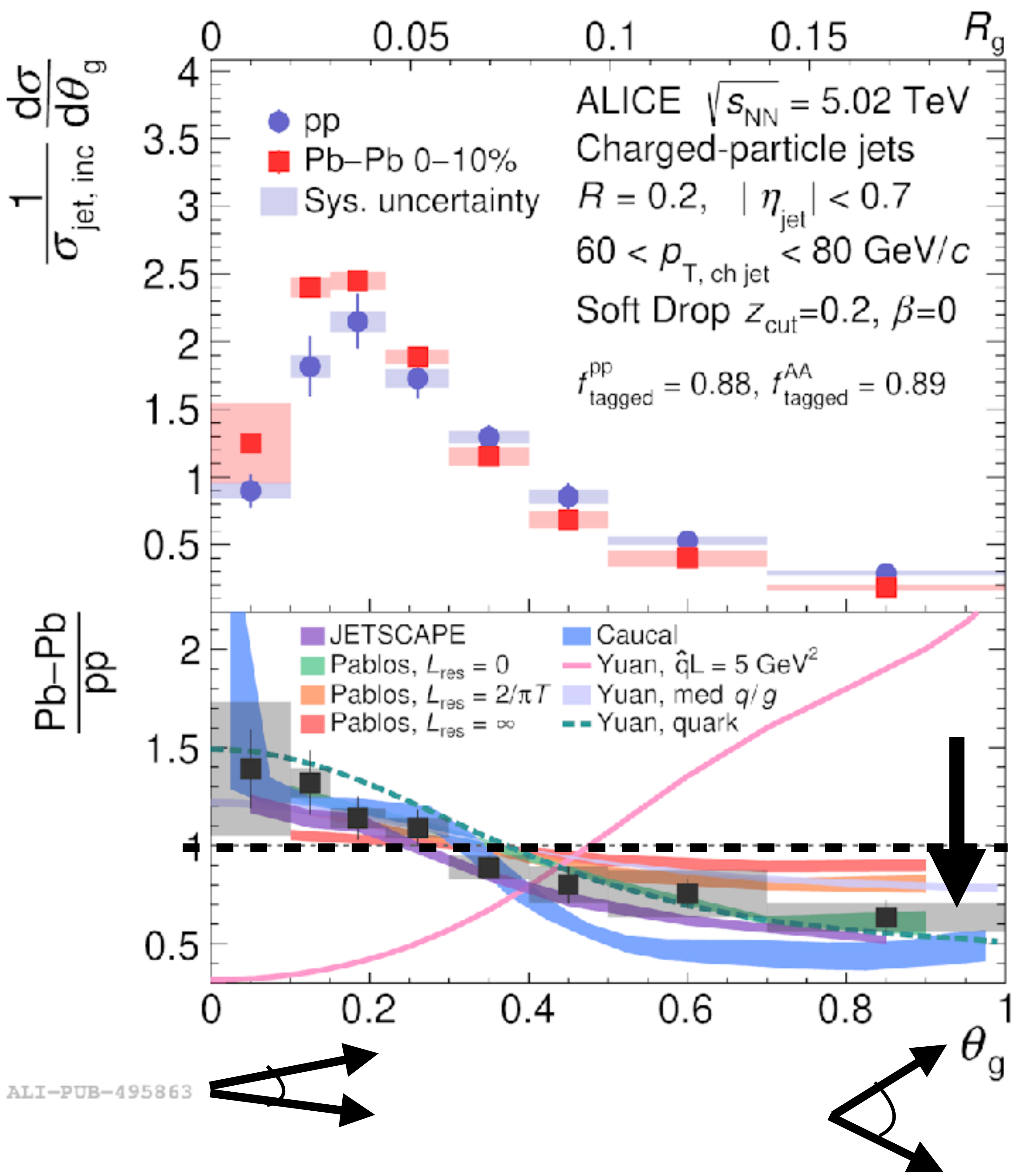
ALICE: low p_T, z_{cut}=0.2, unfolded

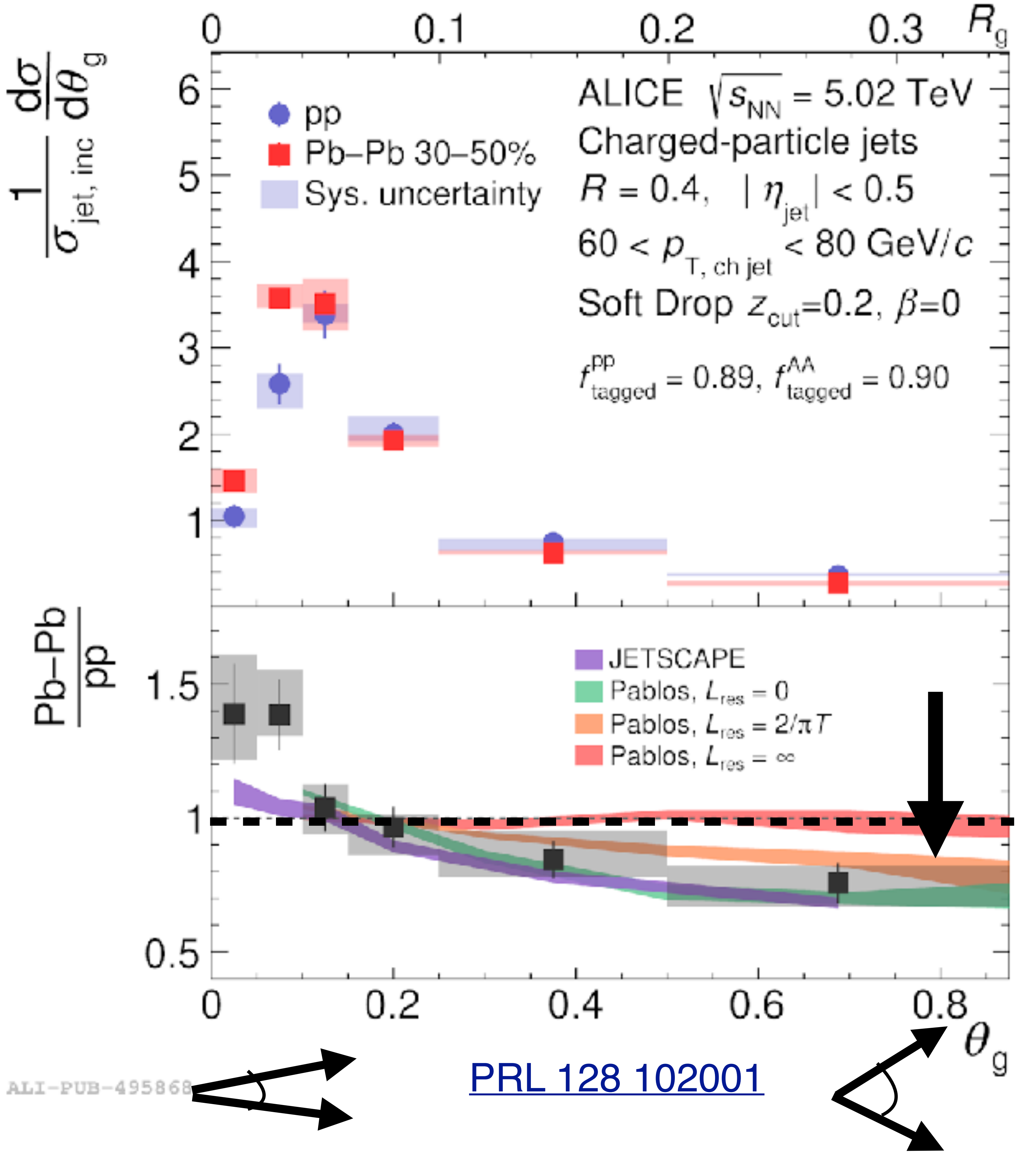
CMS: high p_T, z_{cut}=0.1, smeared

Jet splittings: R_g larger R



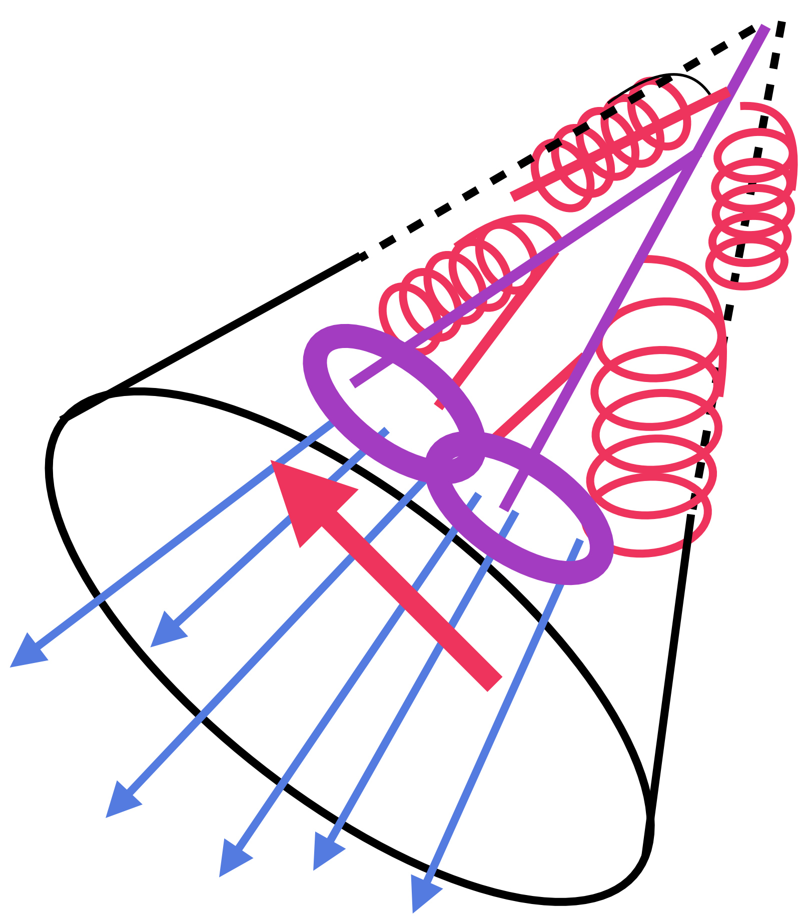
- *Narrowing remains for larger R in more semi-central collisions*



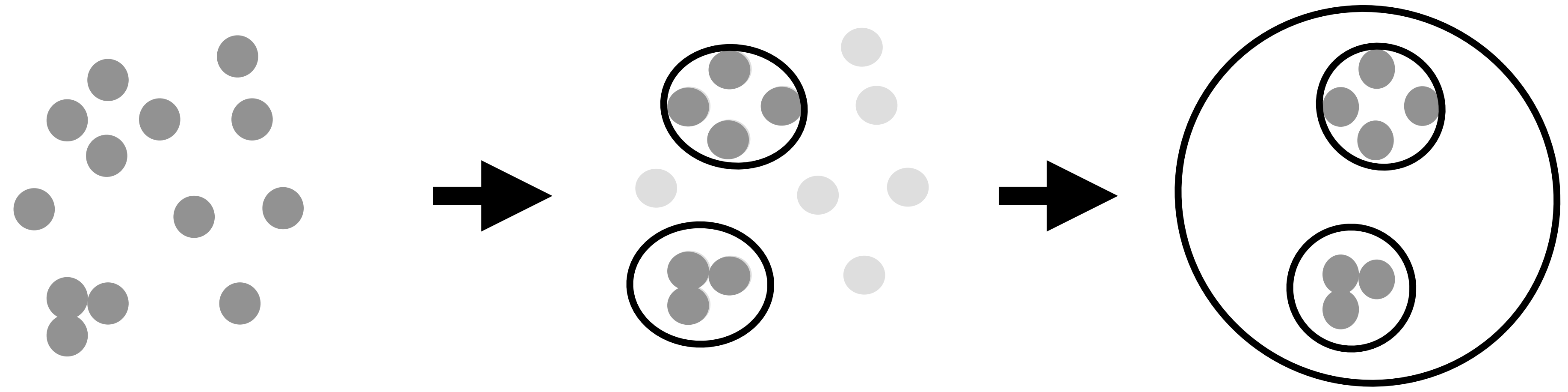


PRL 128 102001

Jet splittings: large R trimming

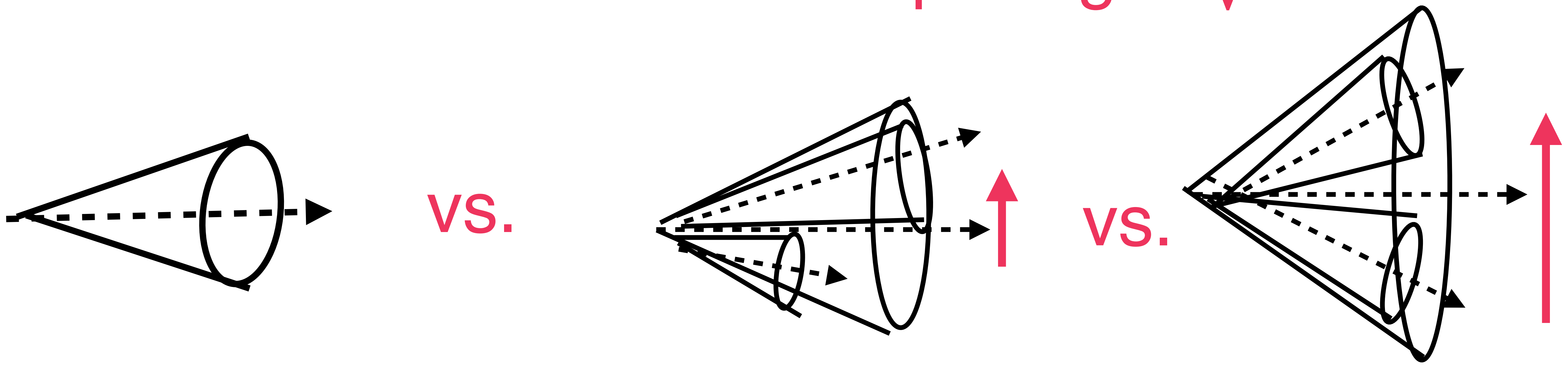


- Combining R=0.2 into R=1.0 jets removes energy radiated between subjets



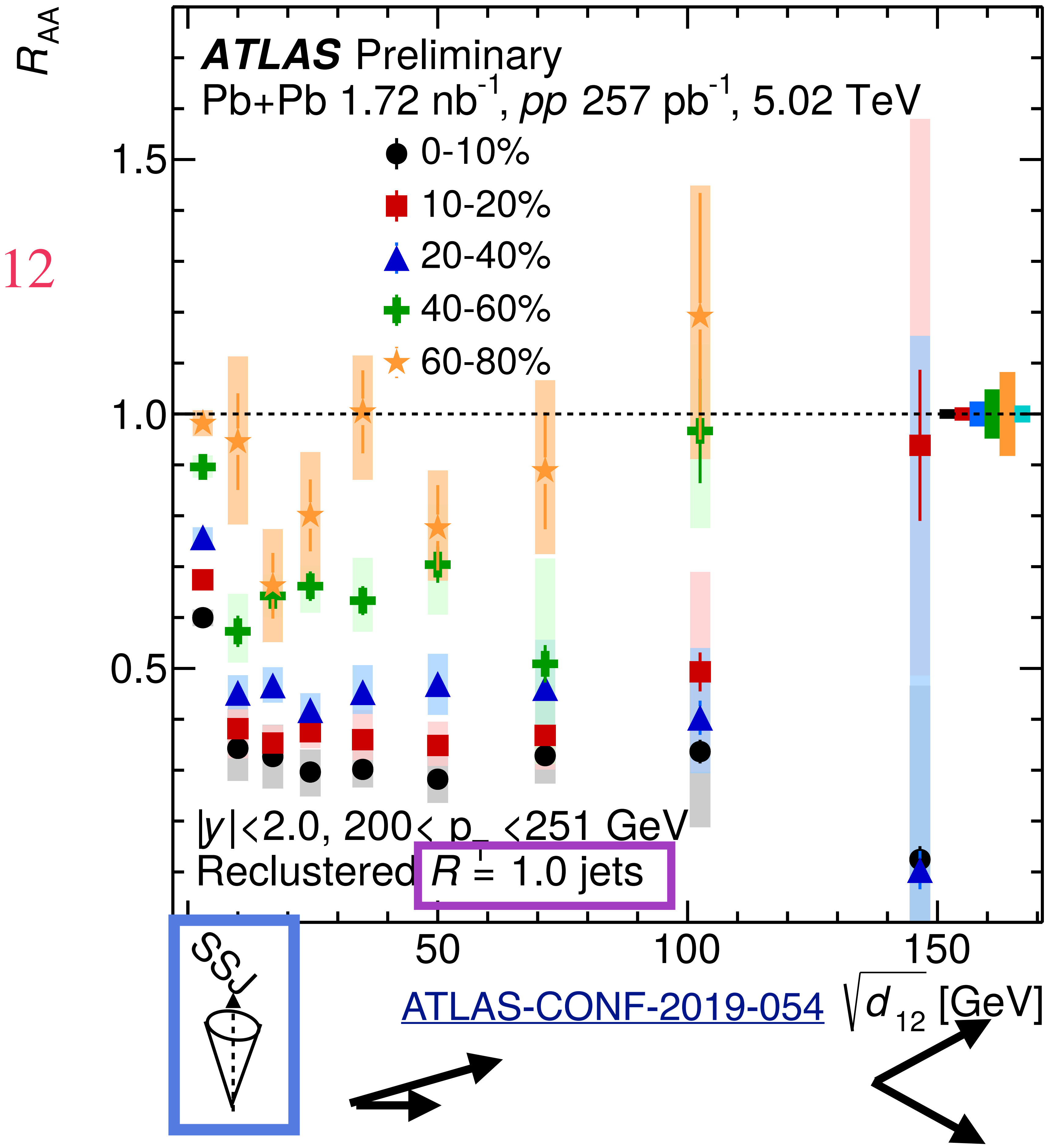
Recluster with k_T algorithm to access k_T

How hard is the resolved splitting? $\sqrt{d_{12}} = p_{T2}\Delta R_{12}$



- Jets with a substructure more suppressed than jets without (single subjets SSJ)

Is the medium resolving the splittings?

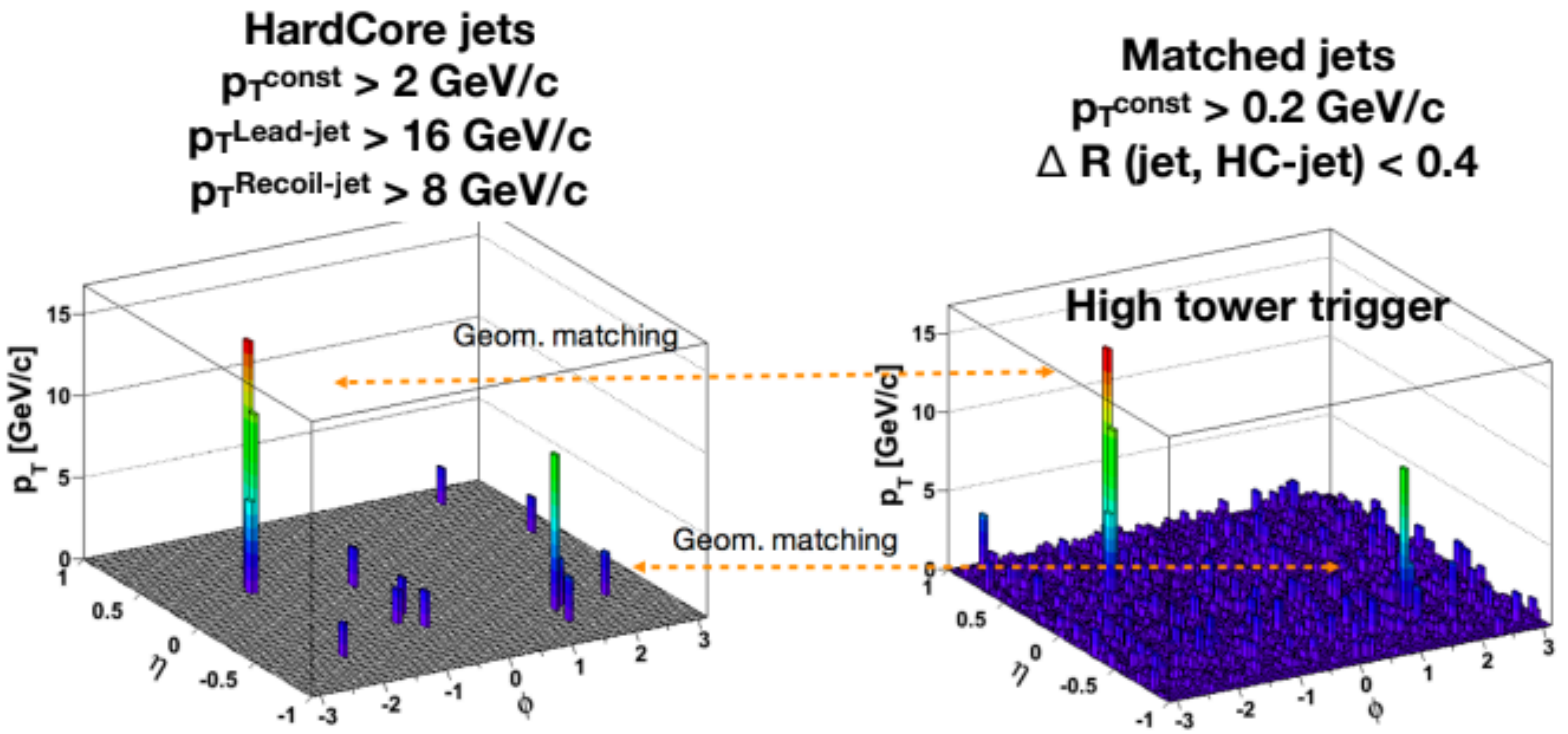


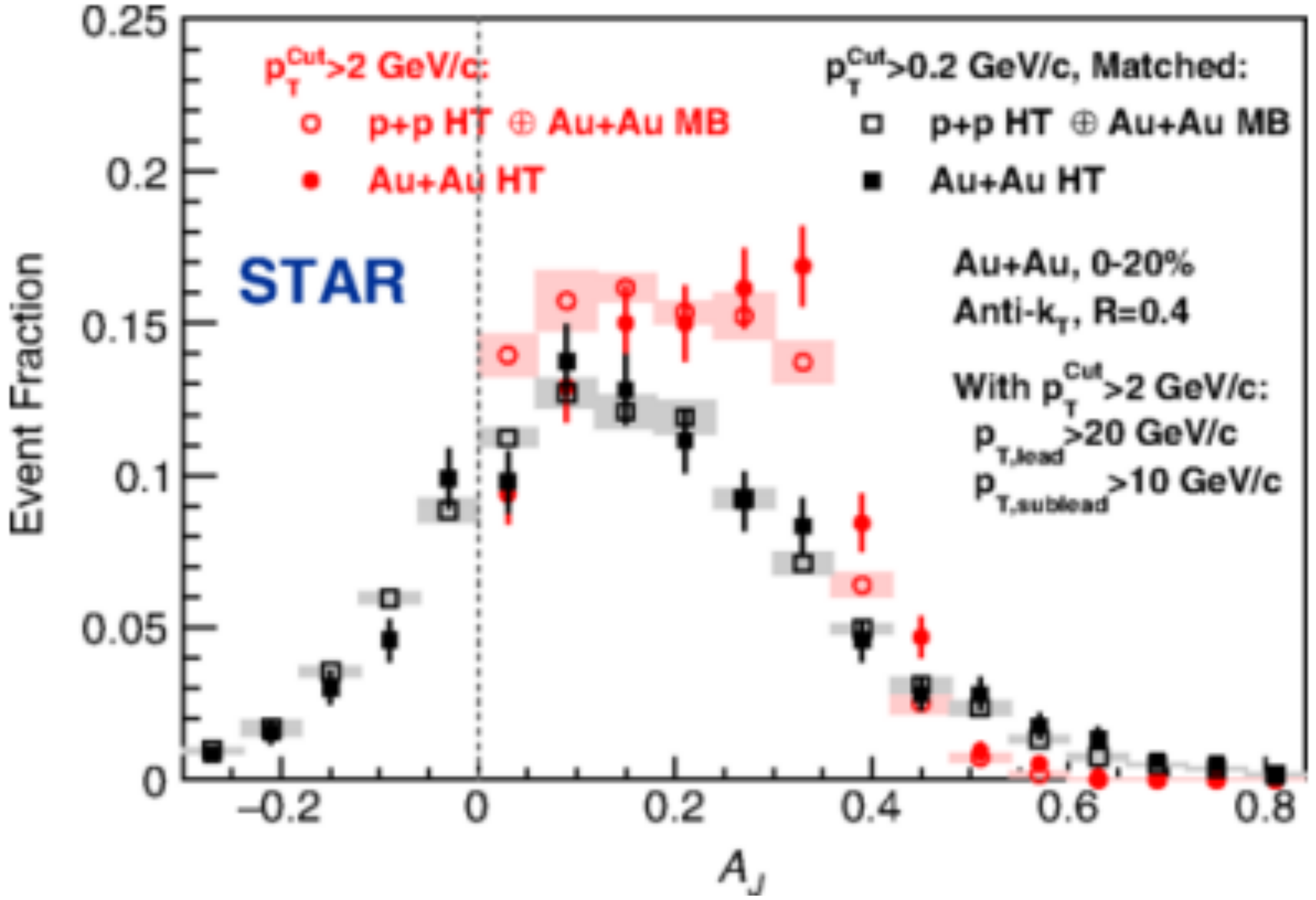
ATLAS-CONF-2019-054

Jet substructure at RHIC

- STAR uses a HardCore selection to suppress the background

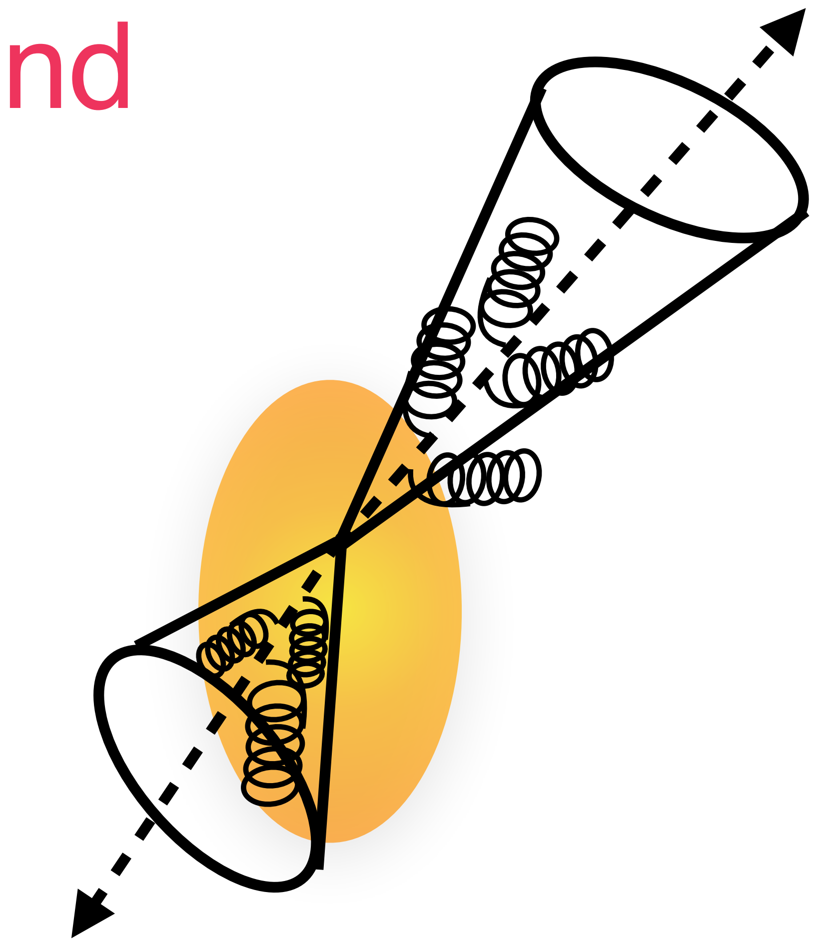
- Then matches to original jet to recover constituents





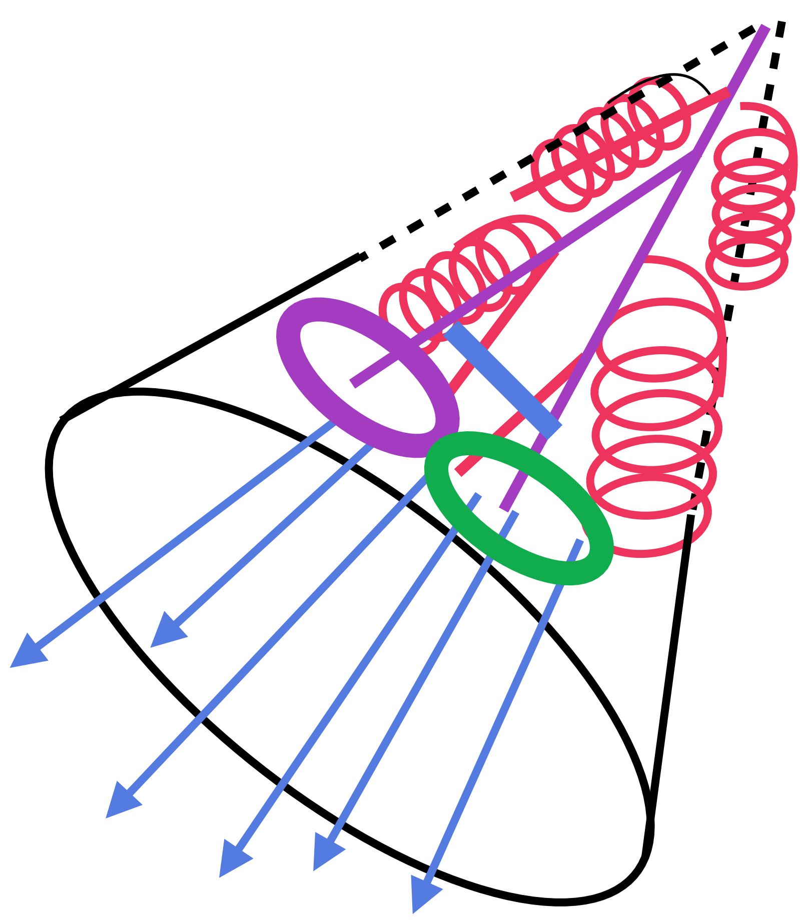
- HardCore jets are imbalanced and matched jets are balanced

$$A_J = \frac{p_{T1} - p_{T2}}{p_{T1} + p_{T2}}$$



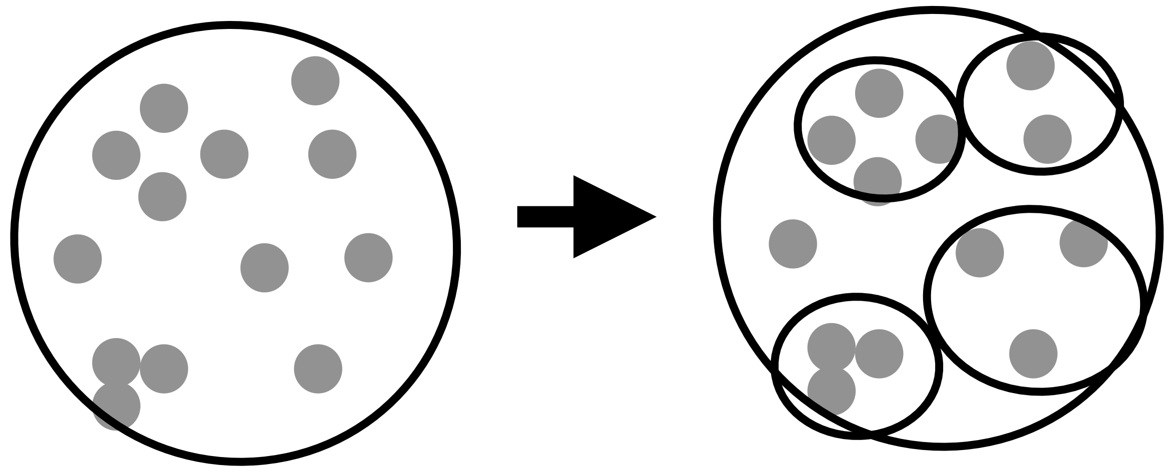
STAR, PRL 119 062301 (2017)

Substructure with subjets

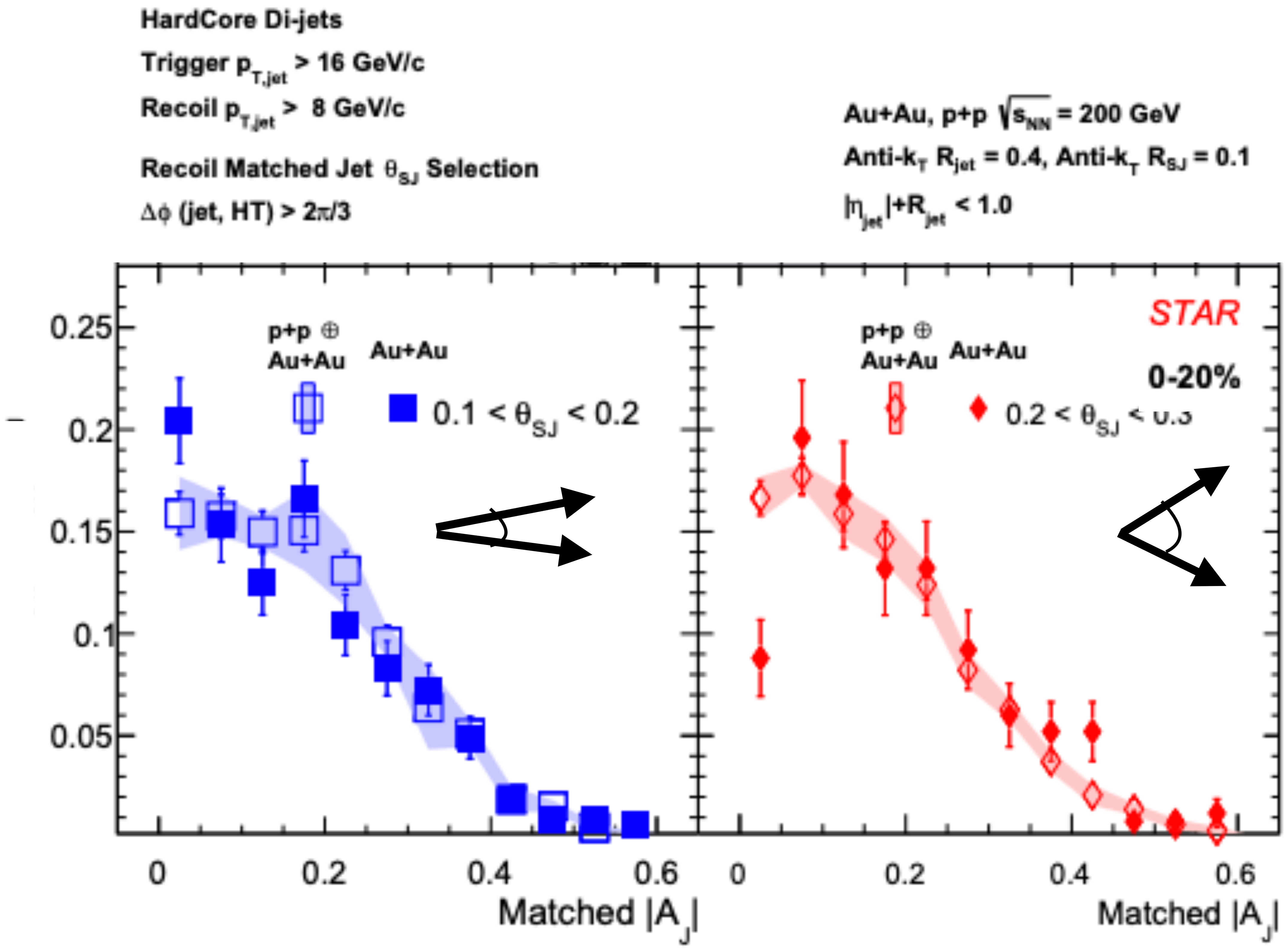


- Recluster constituents of R=0.4 jets into r=0.1 jets

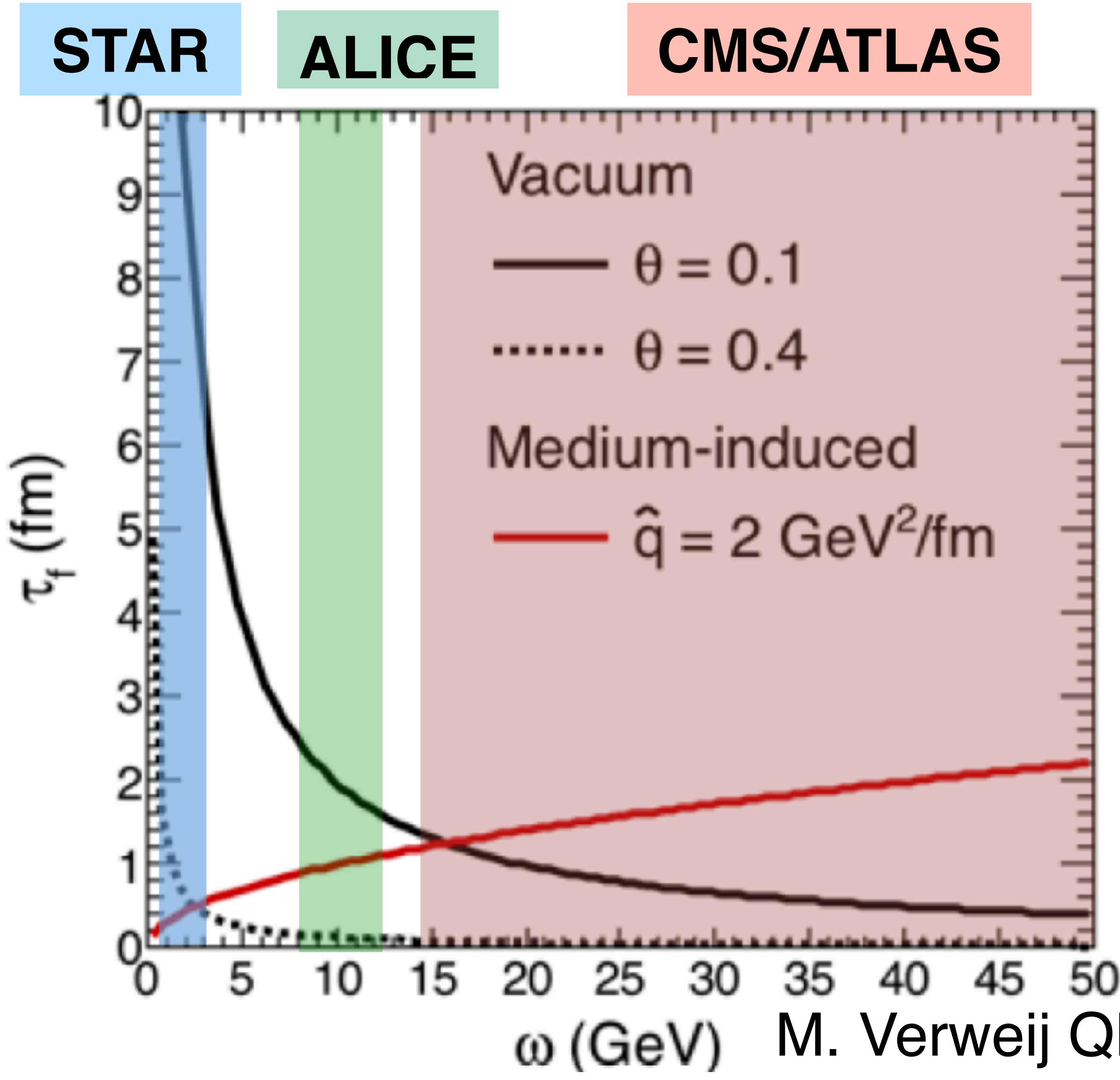
$$\theta_{\mathrm{SJ}} = \Delta R_{1,2}$$



- Find the leading (1) and subleading (2) jet
- No modification with angle



- Contradiction with R_g
  - RHIC later formation times outside of medium?



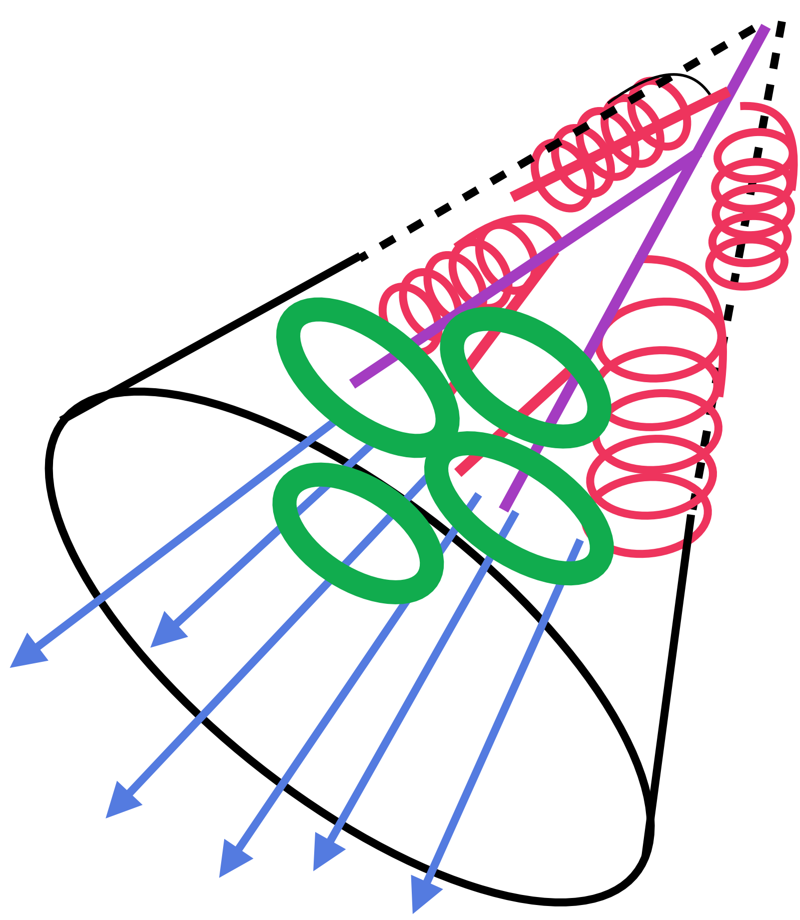
M. Verweij QM 17

arXiv:2109.09793

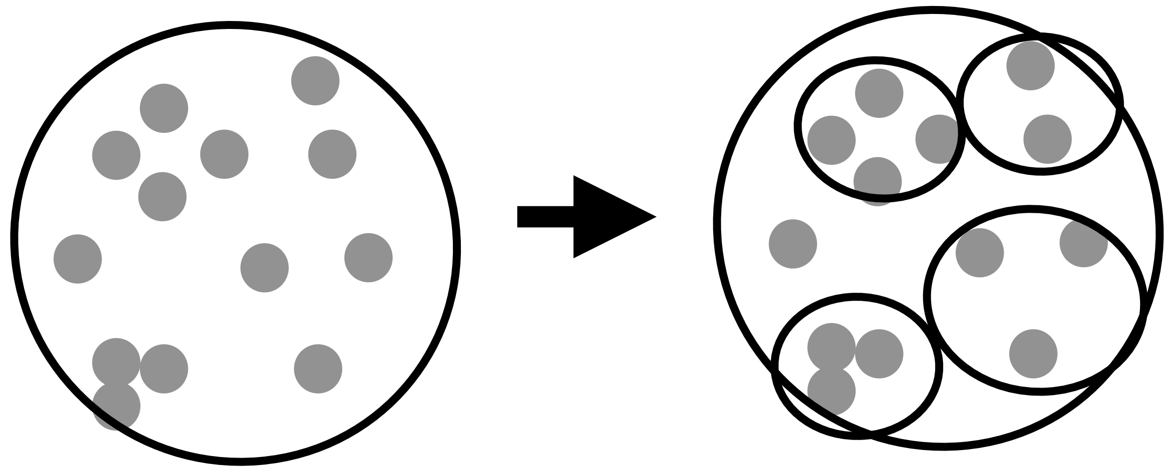
Subjet fragmentation

$$F\left(z_r\right) = \frac{1}{N_{\text{jet}}}\frac{dN}{dz_r}$$

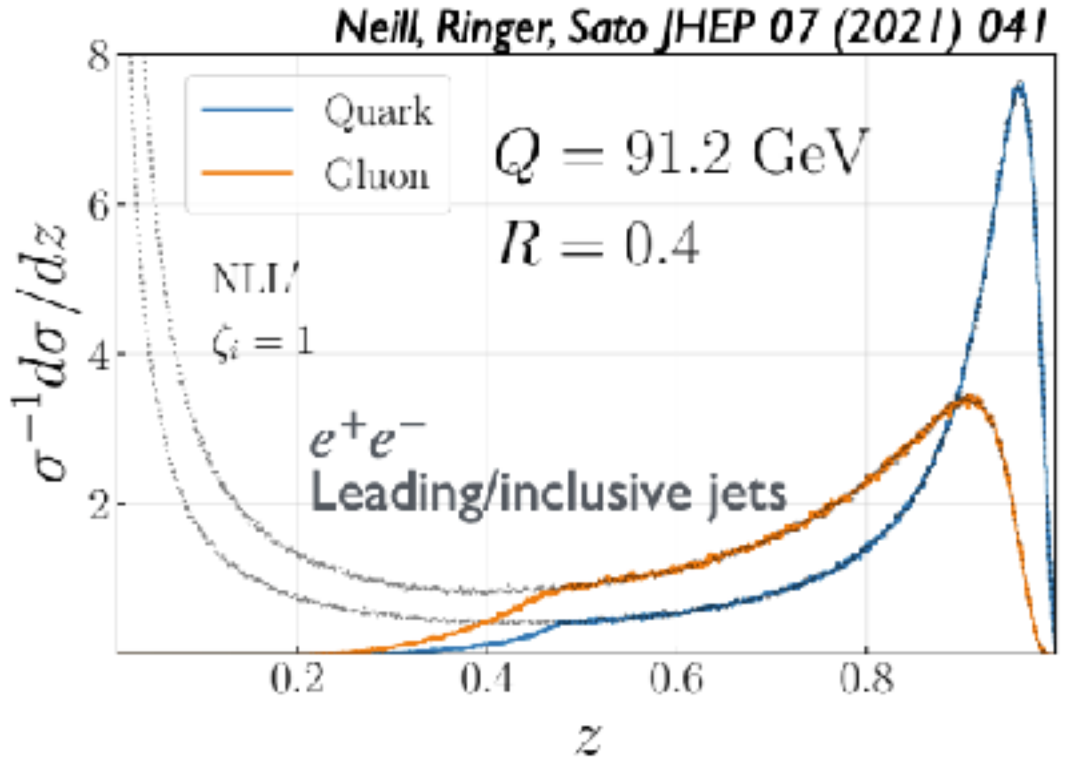
$$z_r = \frac{p_{\mathrm{T}}^{\text{ch subjet}}}{p_{\mathrm{T}}^{\text{ch jet}}}$$

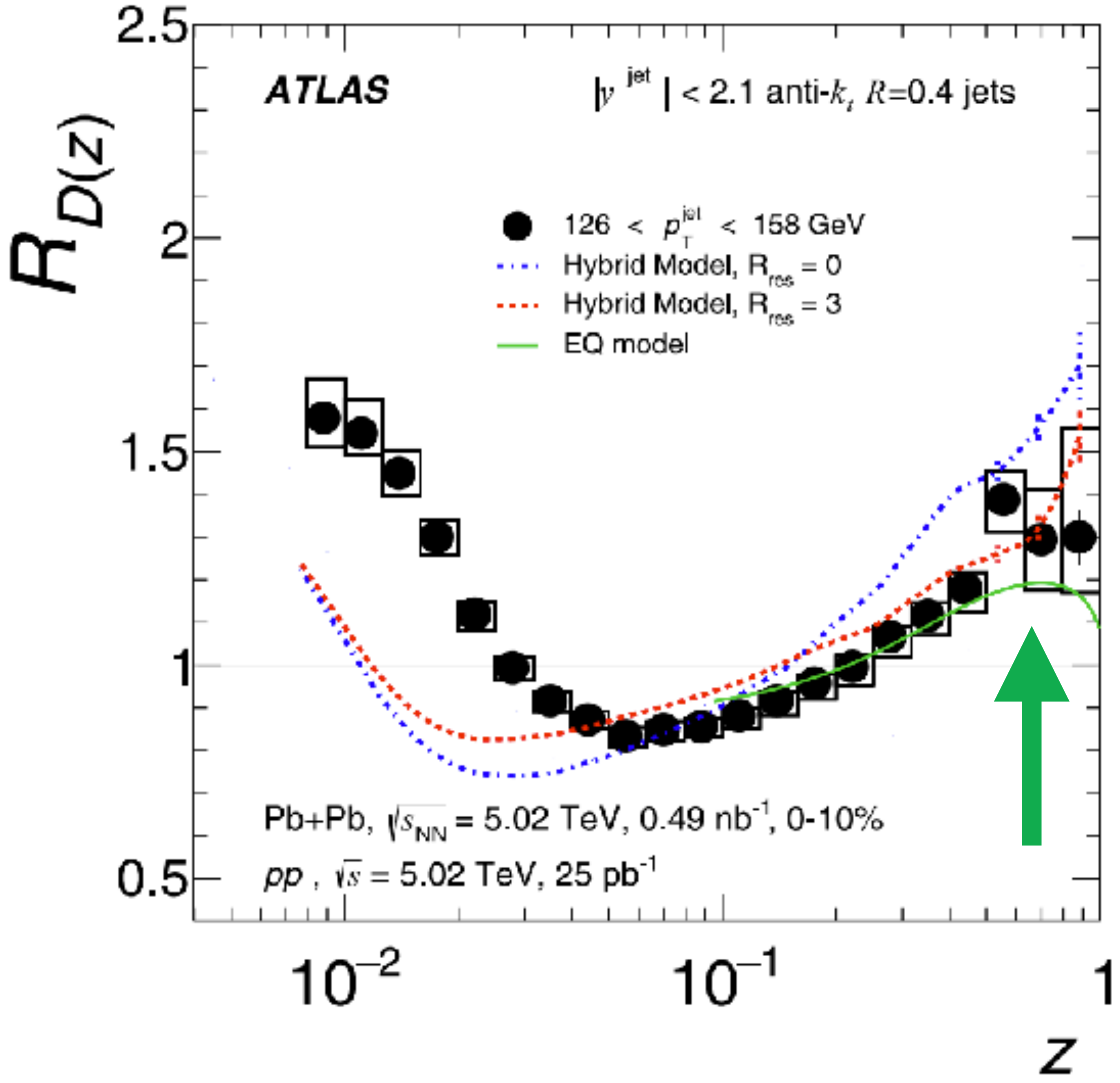


- Recluster constituents of R=0.4 jets into r=0.1 jets

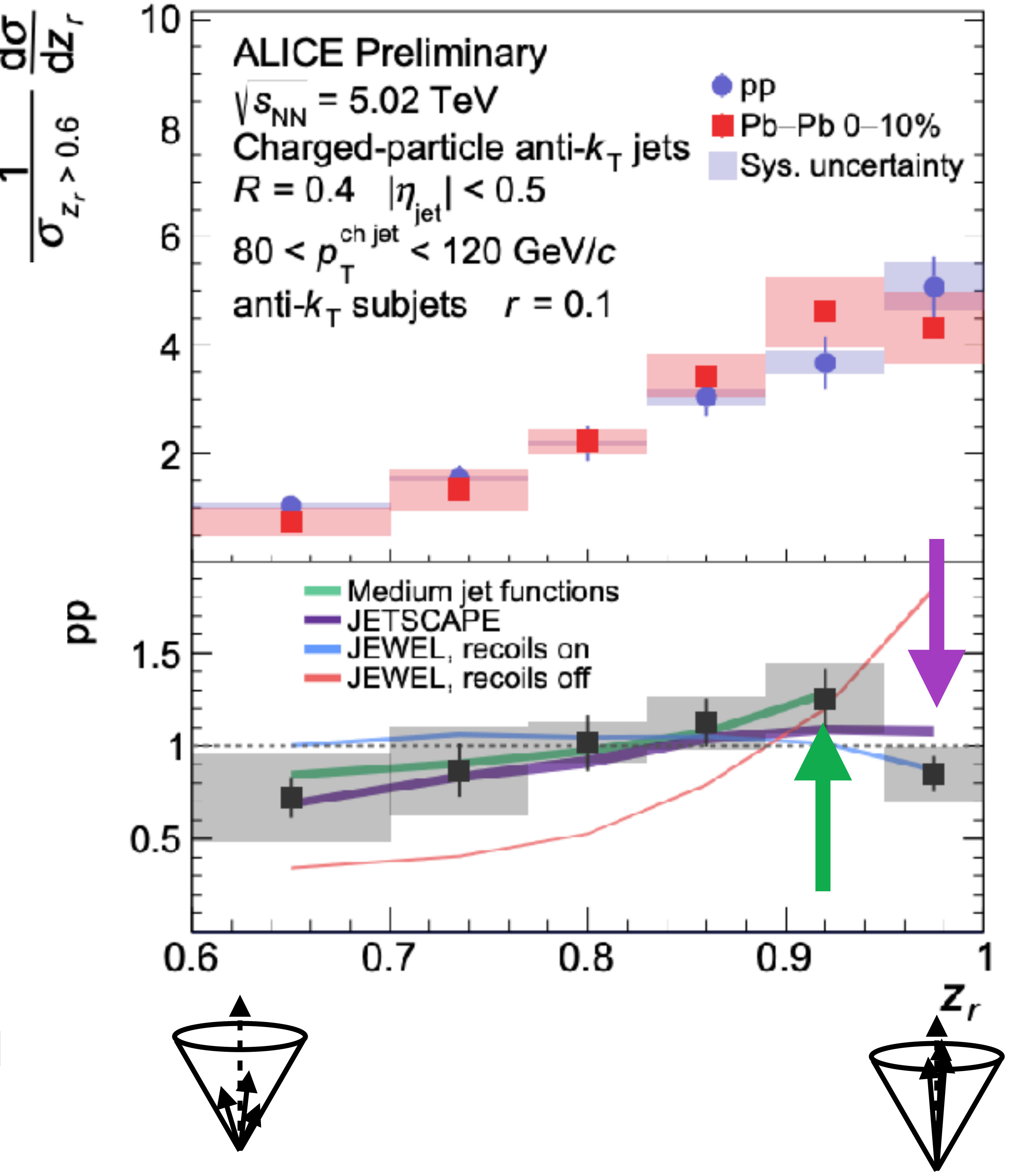


▸ Hint of hardening at intermediate z -> similar to R_g and hadron FF





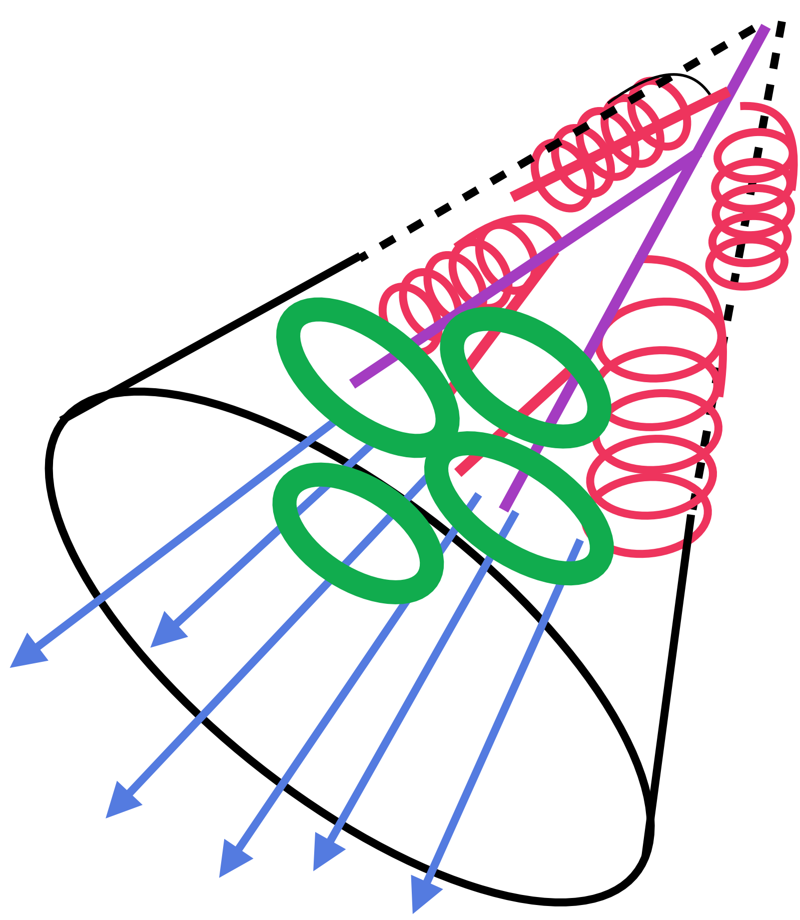
ALICE-PUBLIC-2022-016



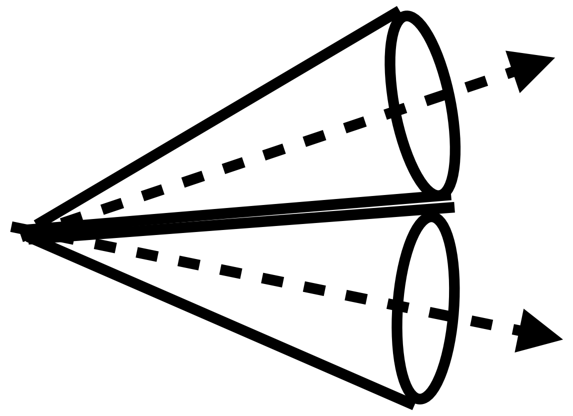
▸ Hint of suppression as z -> 1, energy loss of pure quarks?

N-subjettiness

$$\tau_N = \frac{\sum_{i\in\mathrm{jet}} p_{T,i} \min \Delta R_{i,1}, \Delta R_{i,2}, \ldots, \Delta R_{i,N}}{R p_{T,\mathrm{jet}}}$$

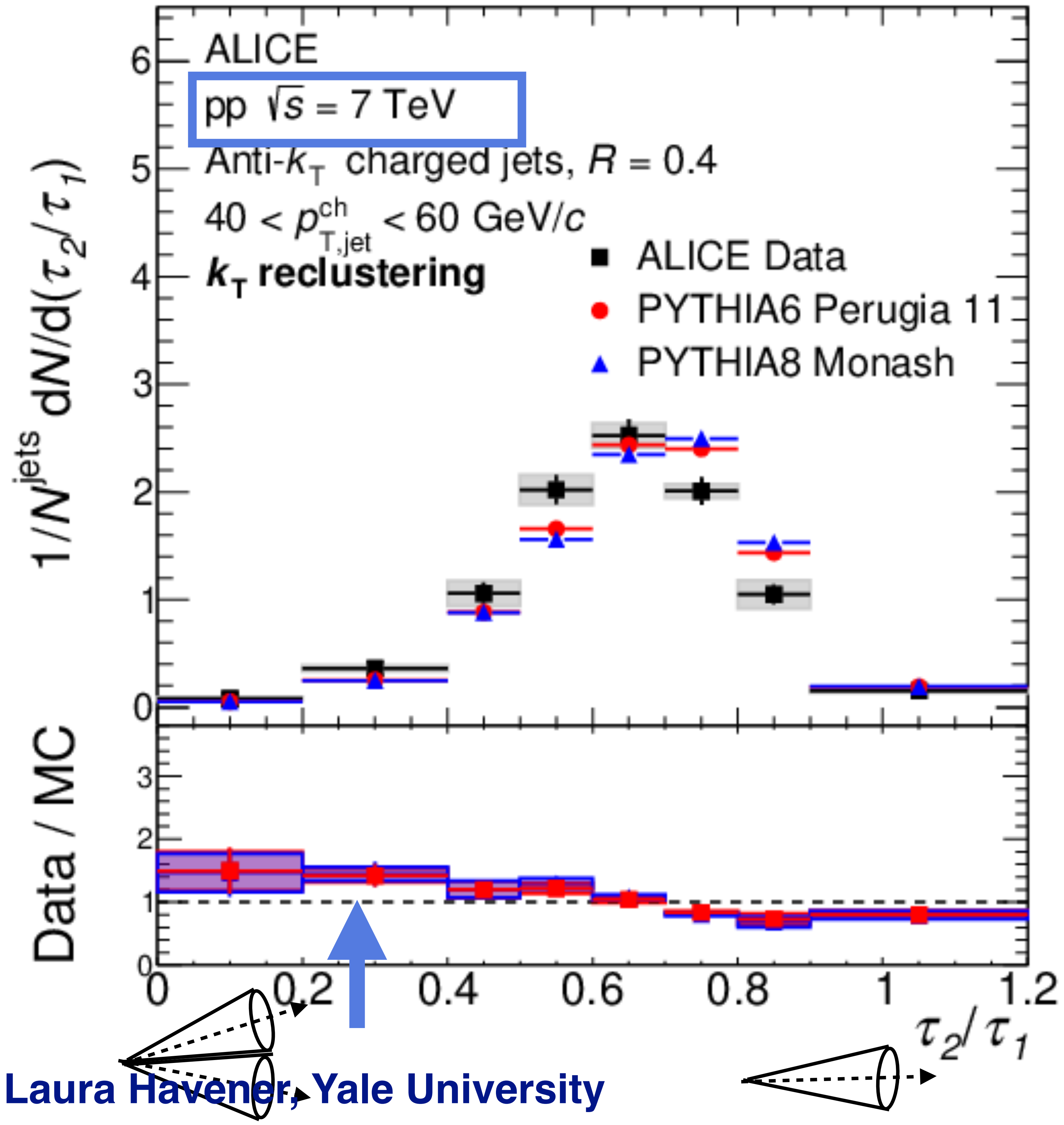


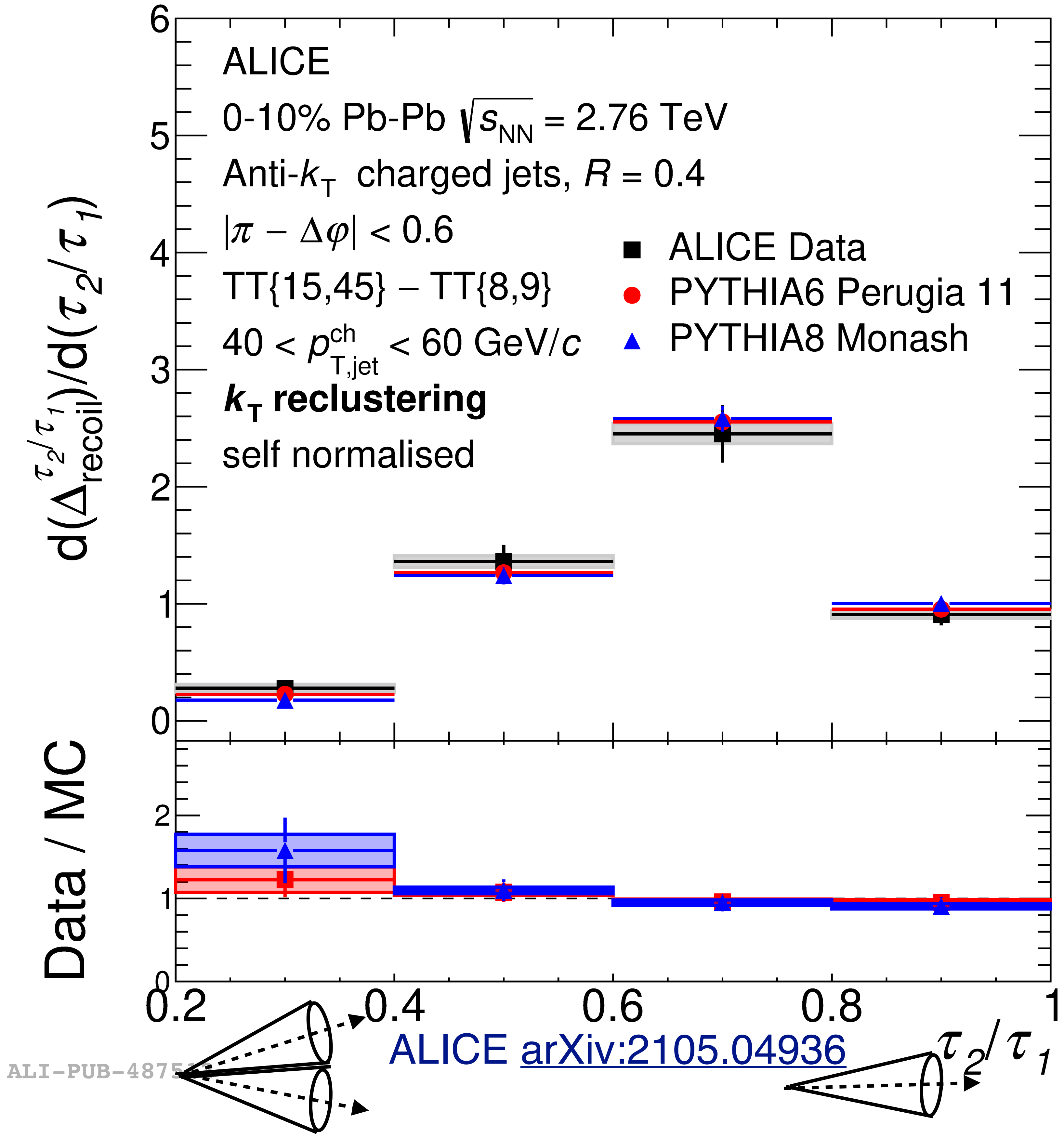
- k_T reclustering selects hard subjets



$\tau_2/\tau_1 -> 0$
Jet has 2 prongs

Are the prongs resolved by the medium?





ALICE arXiv:2105.04936

- Fully corrected τ_2/τ_1 in pp and Pb-Pb data compared to PYTHIA

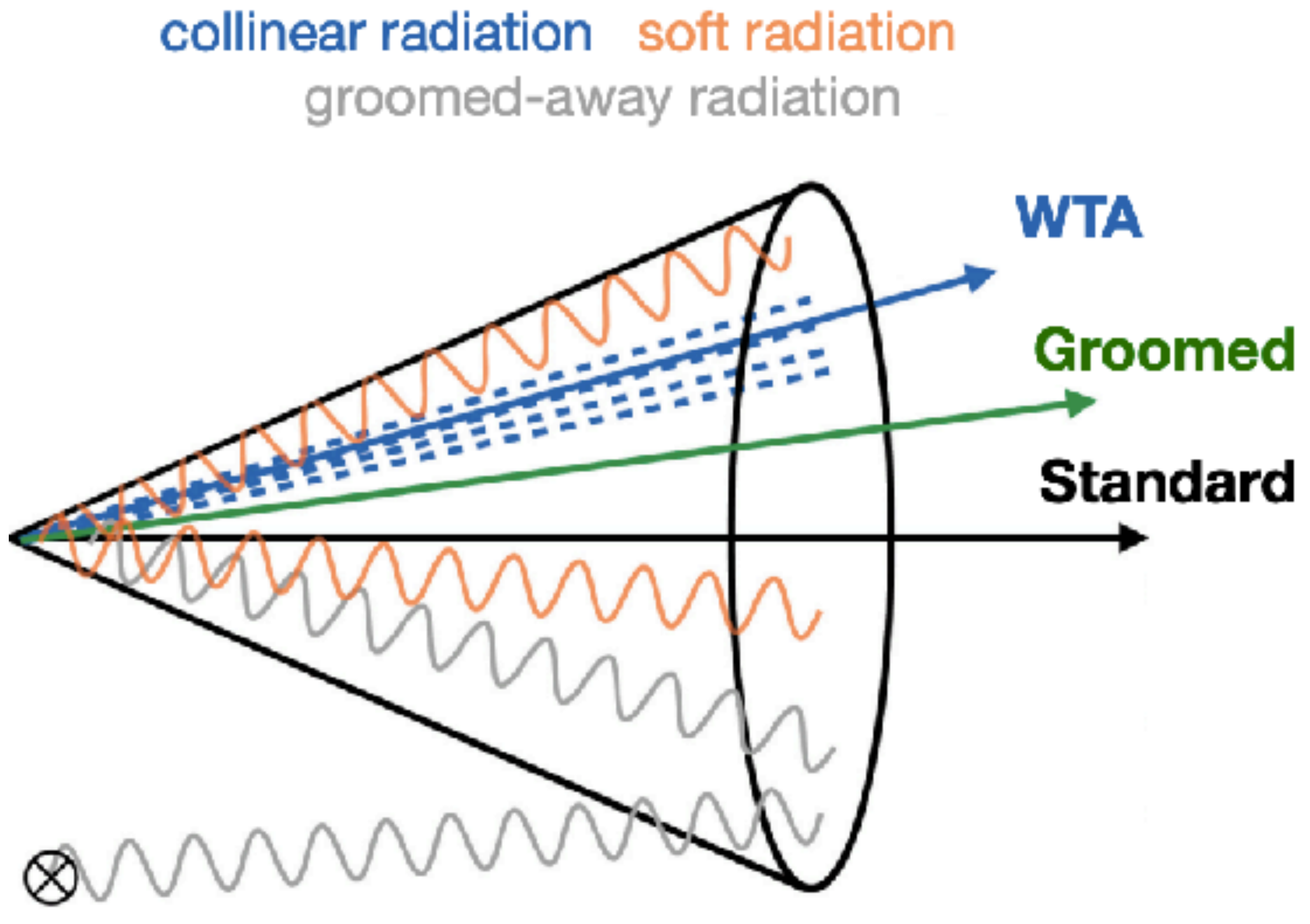
p/MC > 1

Pb-Pb/MC ~ 1

Pb-Pb/pp < 1

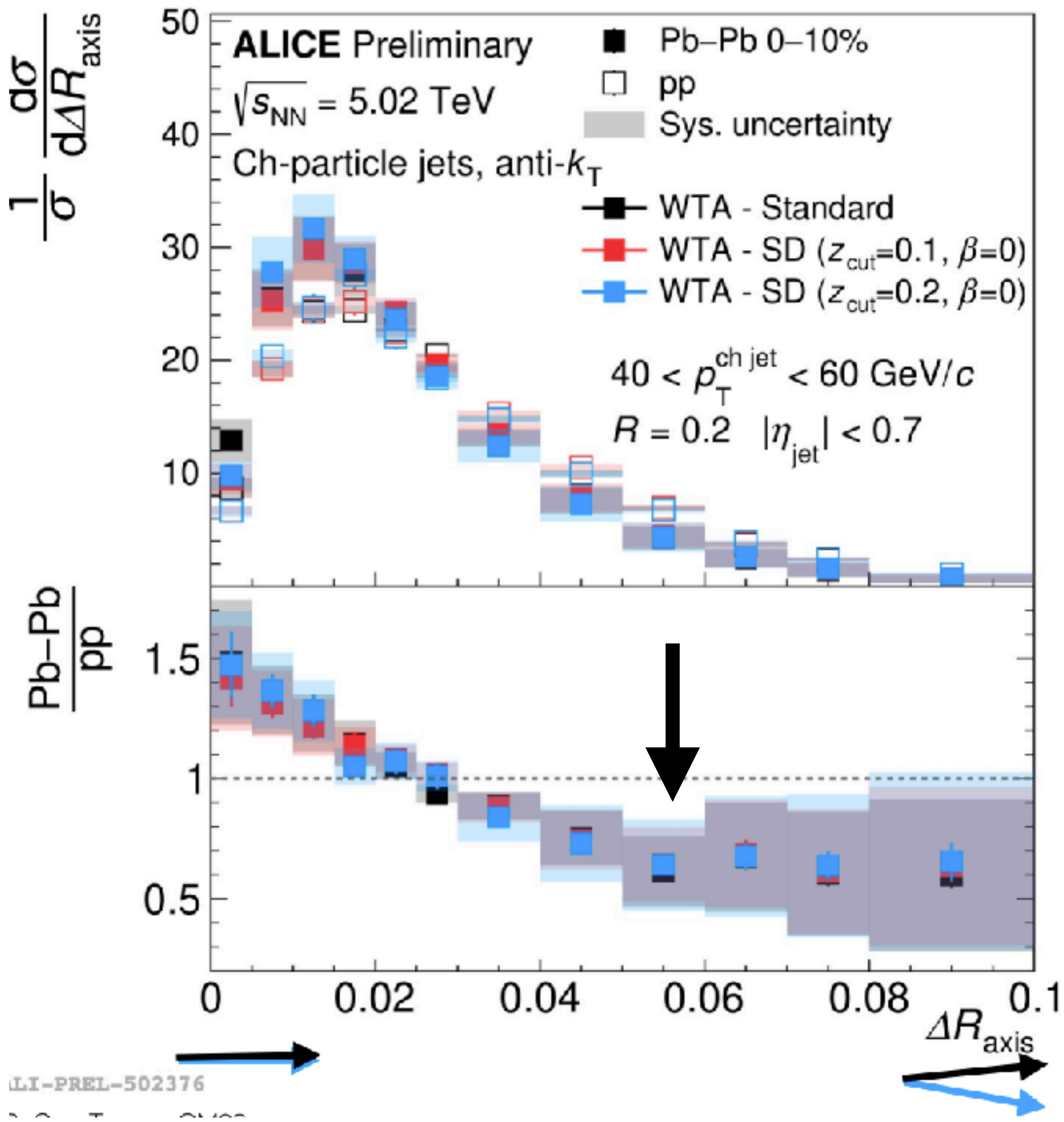
Hint of suppression of 2-prongness in HIs

Jet axis



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

: $\Delta R_{\text{axis}} = \sqrt{(y_2 - y_1)^2 + (\varphi_2 - \varphi_1)^2}$



- *See narrowing effect*
- Not sensitive to grooming: does not change jet direction

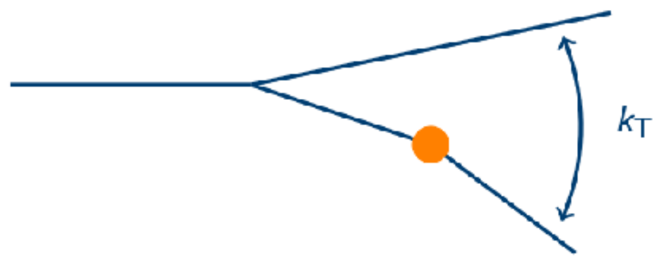
Jet axis: model comparisons

- Hybrid model: role of Moliere scattering?

  -without Moliere

  -with Moliere

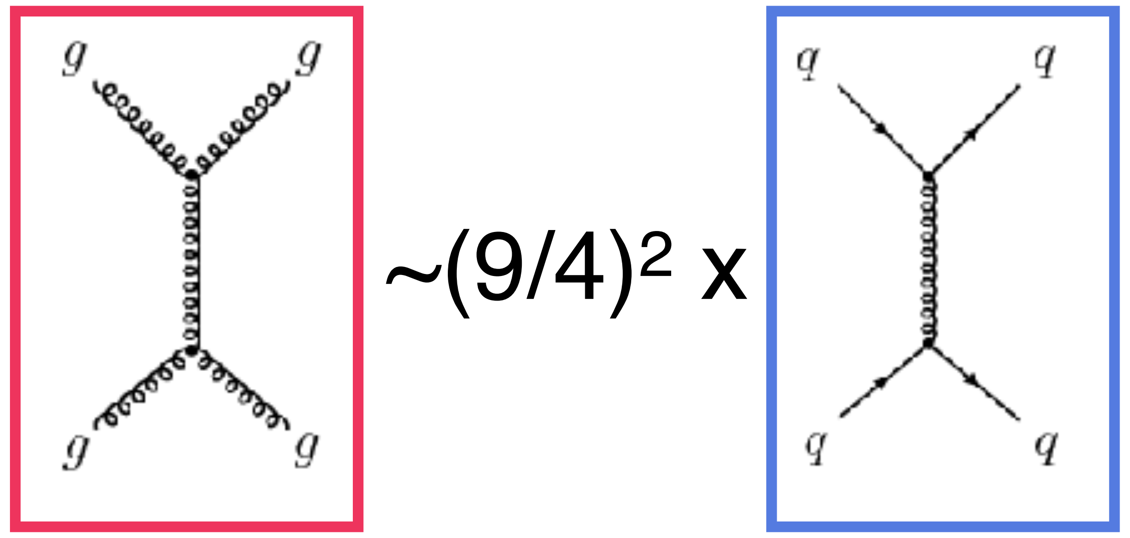
Pablos et al [JHEP (2020) 044]

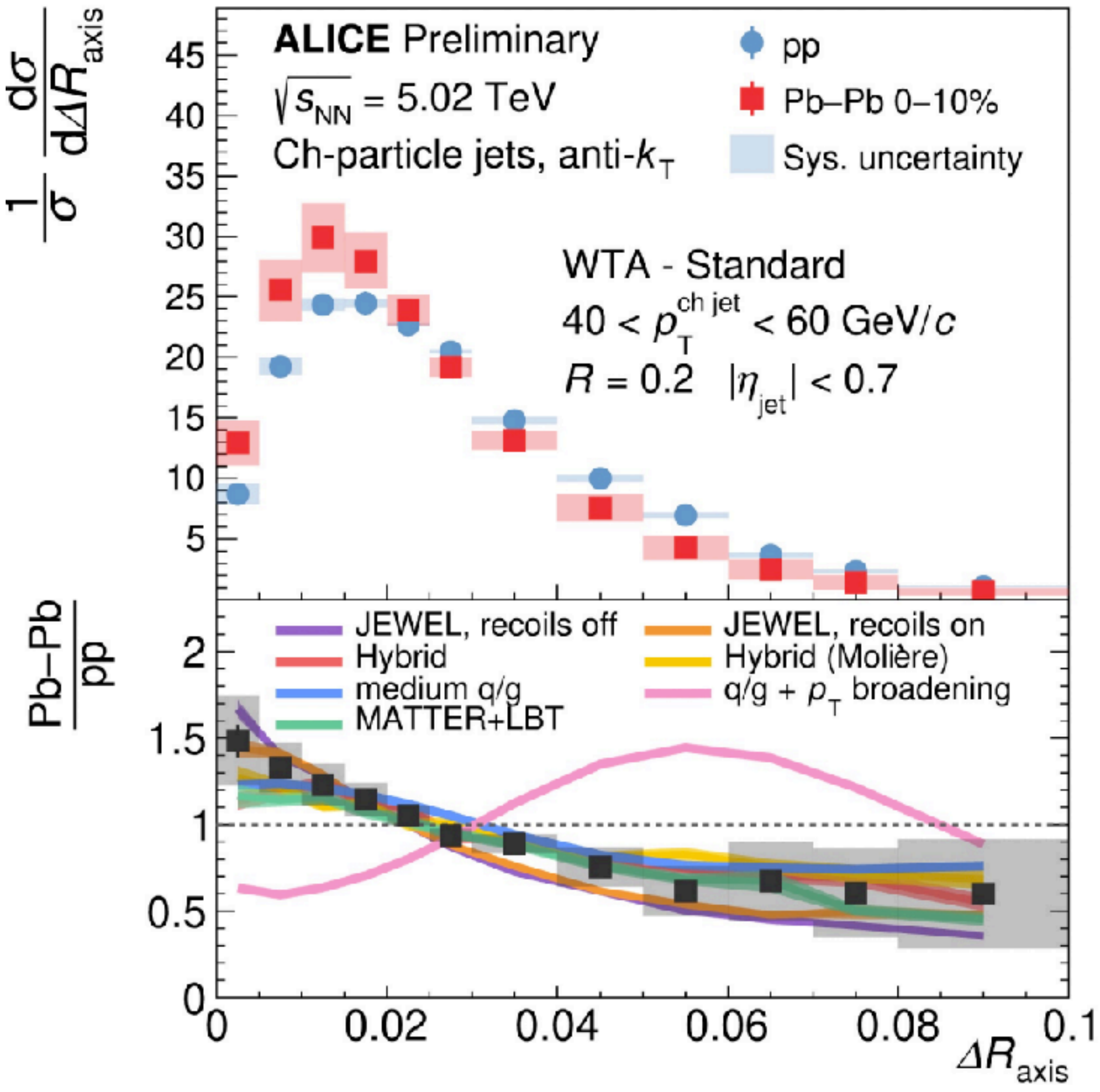


- Model: coherence with changing q/g fractions?

  -medium q/g

Yuan et al arXiv:1907.12541



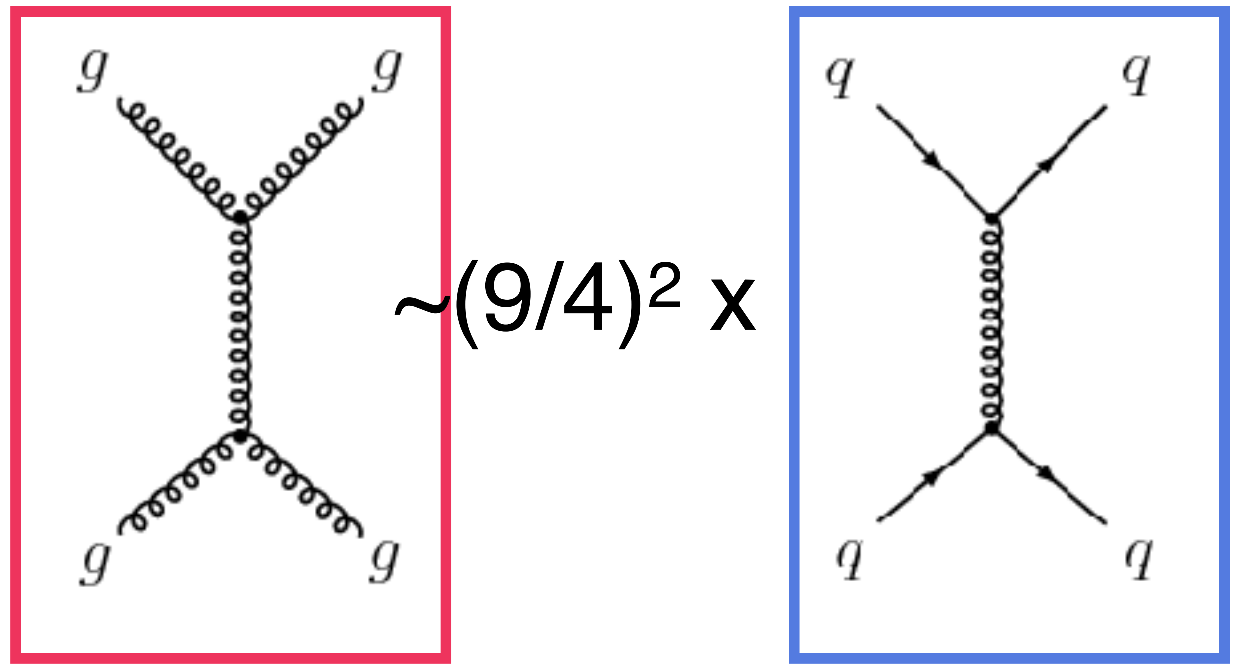


Jet charge: q/g fraction modification?

- Jet charge sensitive to electric charge of initial parton

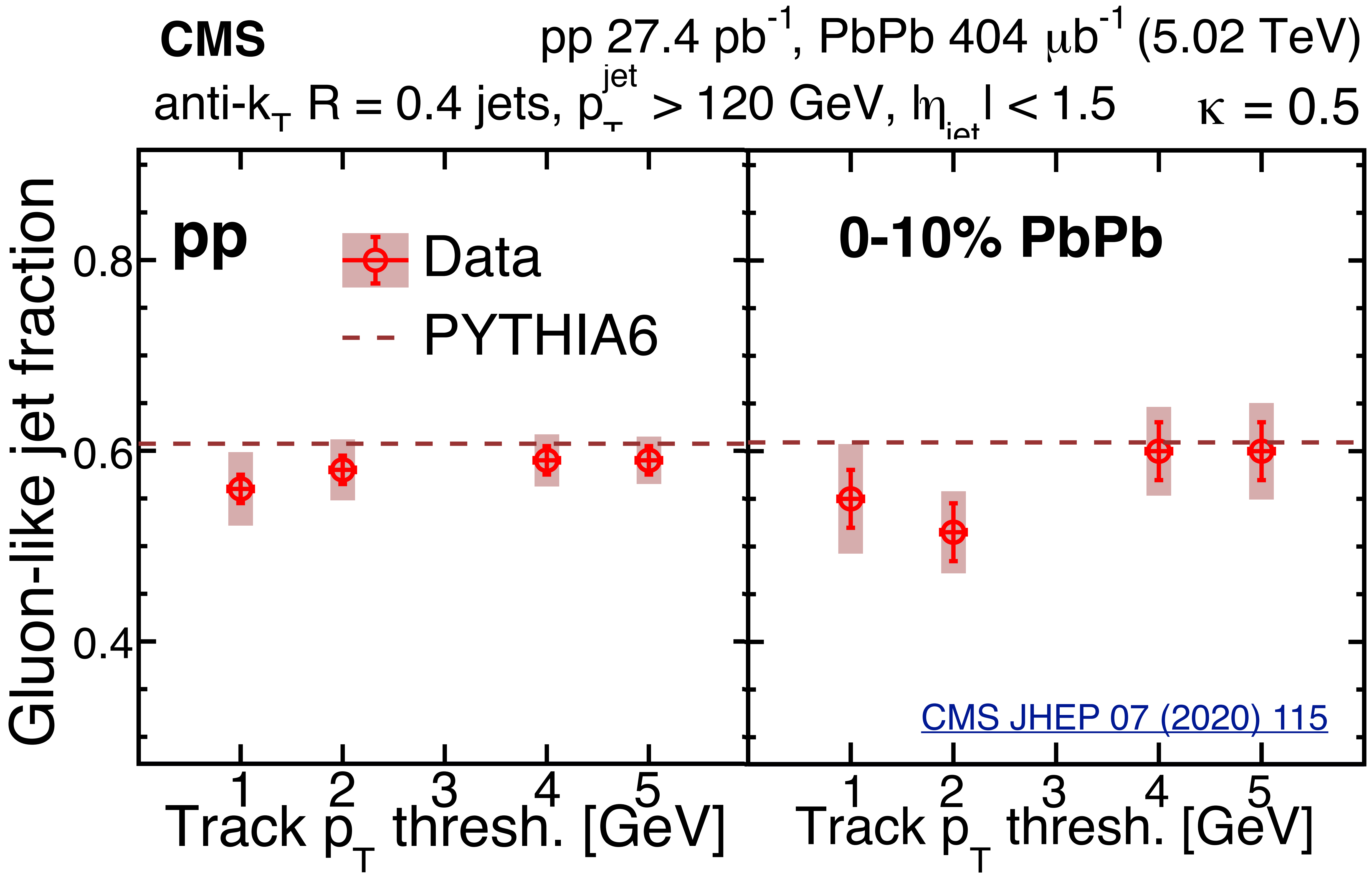
- Fractions in pp and Pb-Pb similar -> no modification of gluon fraction?

$$Q^k = \frac{1}{p_{\mathrm{T}}^{\mathrm{jet}}} \sum_{i\in\mathrm{jet}} q_i p_{\mathrm{T,i}}^k$$



- *Possibly indicates that narrowing is due to decoherence effects!*

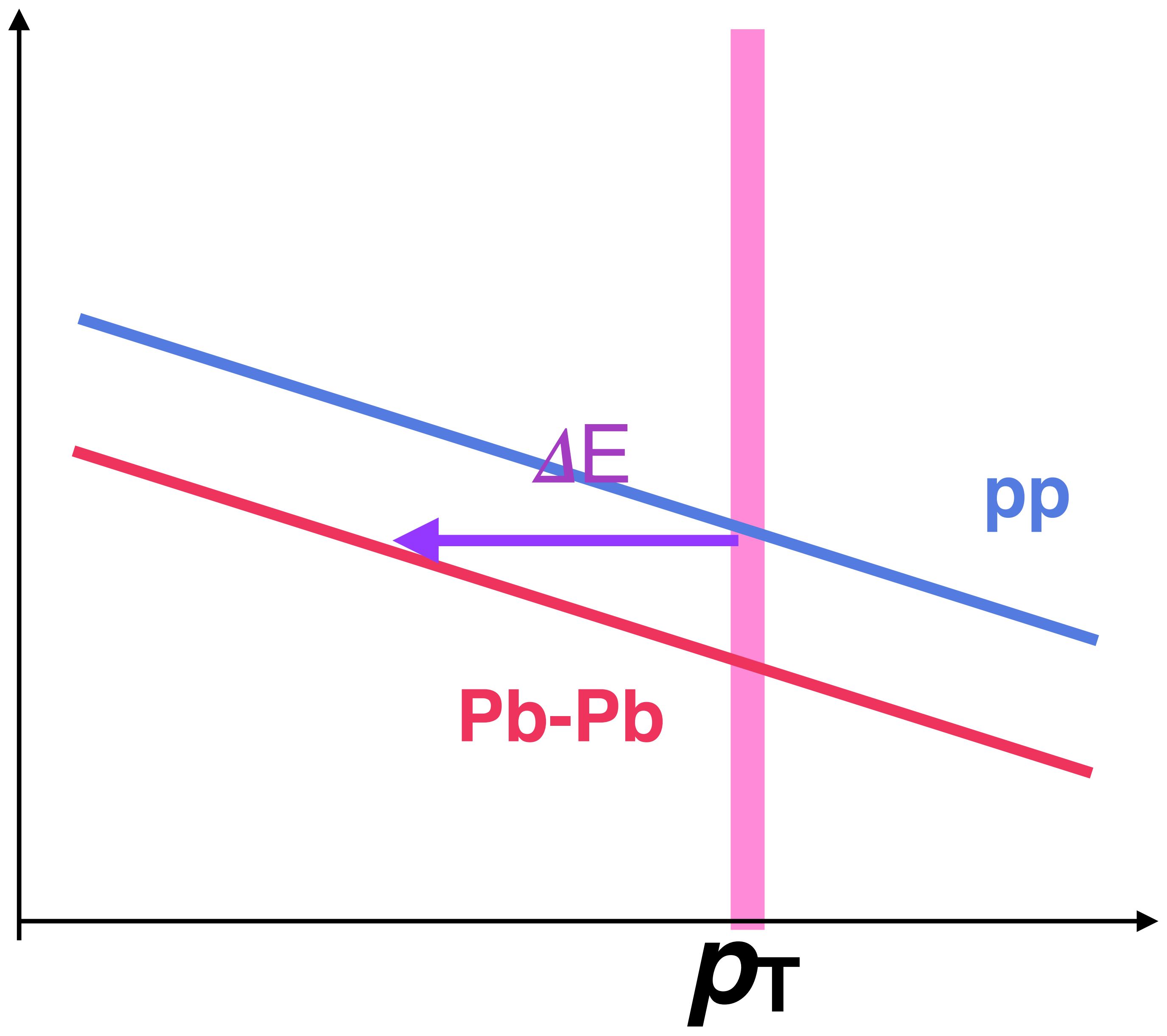
- Is this measurement sensitive to same effects as jet mass?



CMS JHEP 07 (2020) 115

“Survivor Bias”

C. Nattrass recent talk at INT



Comparing final modified Pb-Pb jet to unmodified pp jets instead of comparing the initial unmodified jets

“Survivor bias” where at a fixed p_T bin we are left with less quenched narrower jets

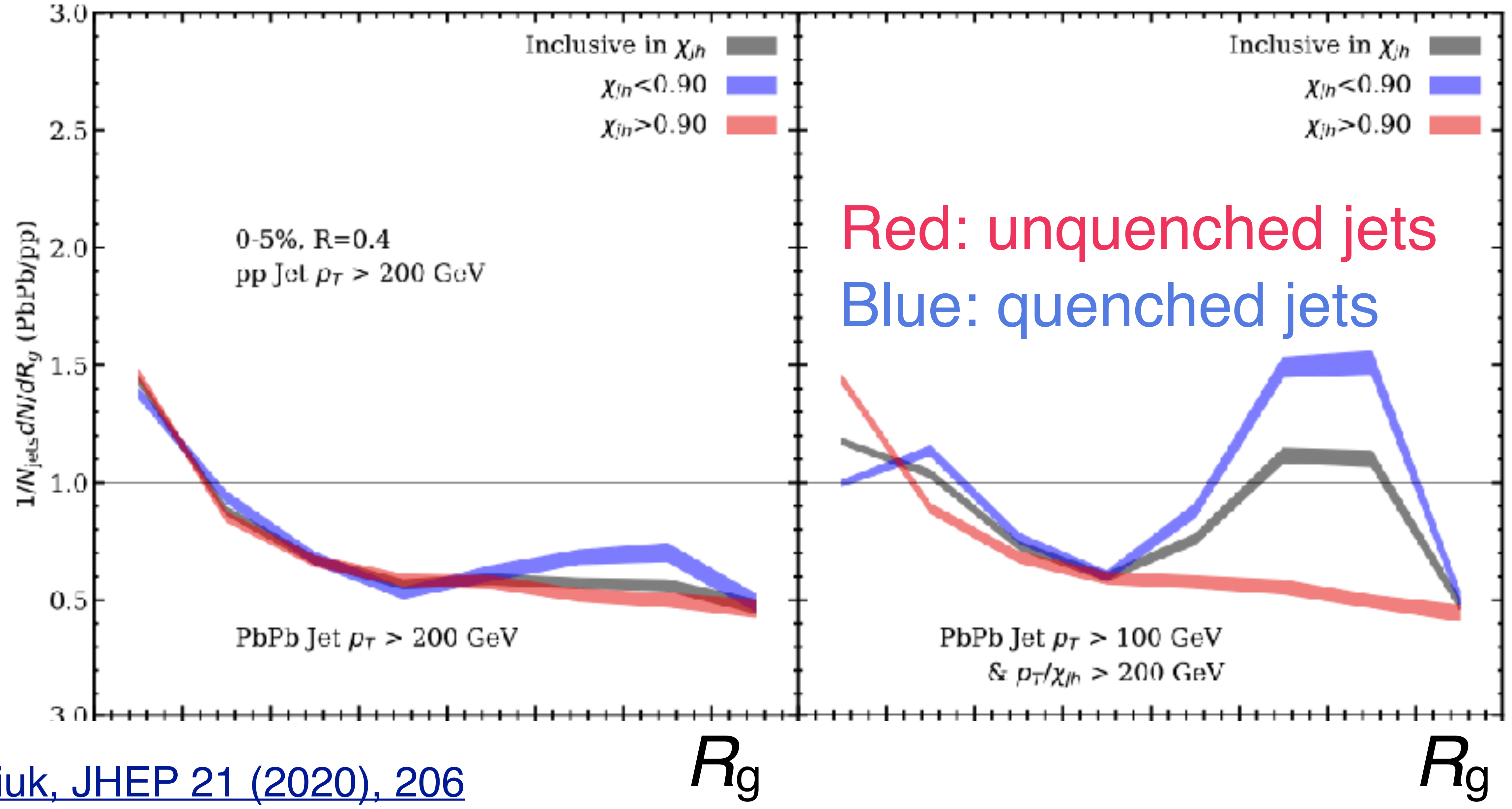
[Cole, Spousta EPJ C76 (2016) 50](#)
[Caucal et al *JHEP* **2020,** 204 (2020)](#)

[Brewer, et al PRL **122**, 222301](#)
[Brodsky et al arXiv:2009.03316](#)

- Selection on the initial instead of final energy removes narrowing effect for more quenched jets in hybrid model

Final energy selection

Initial energy selection

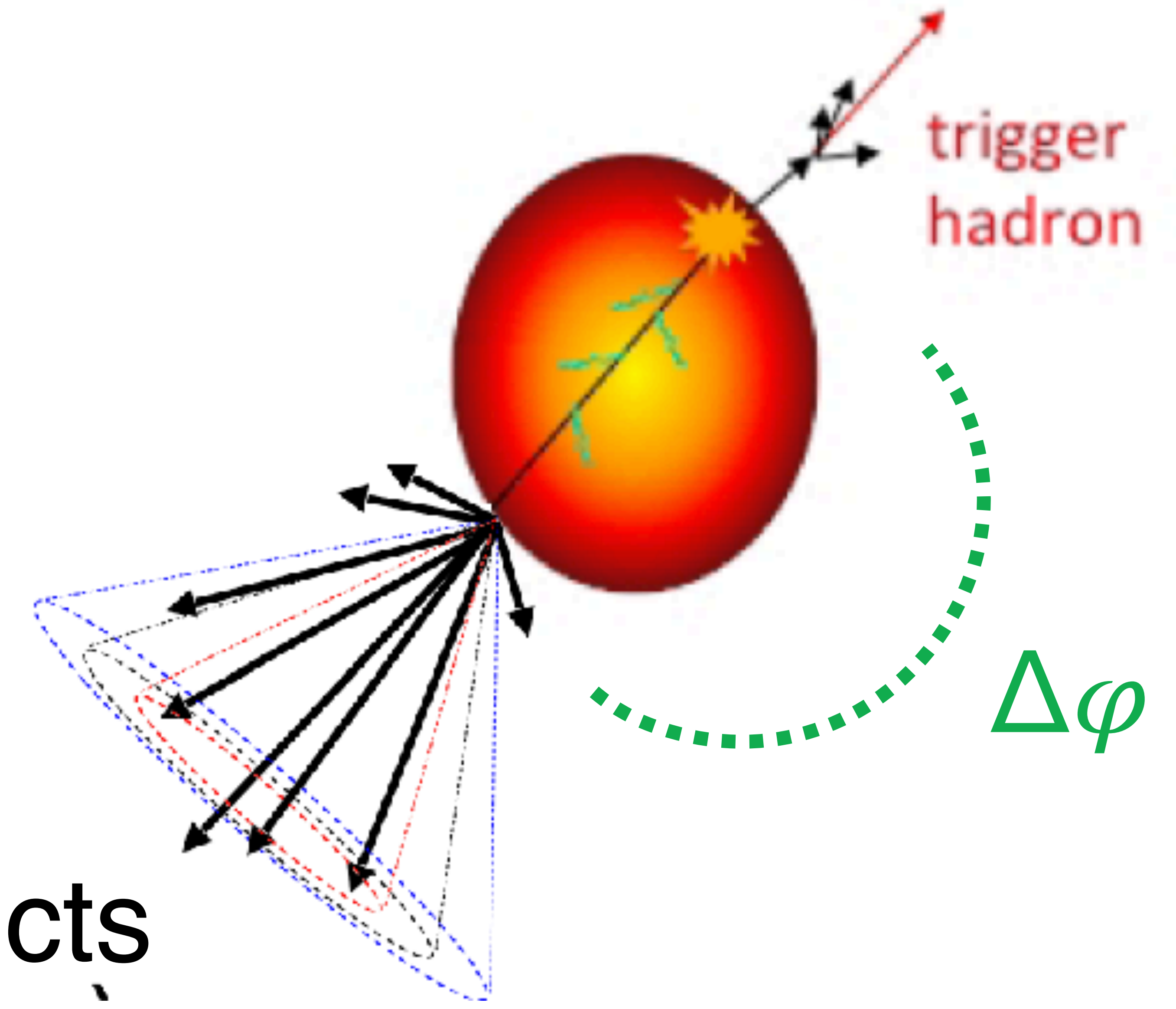


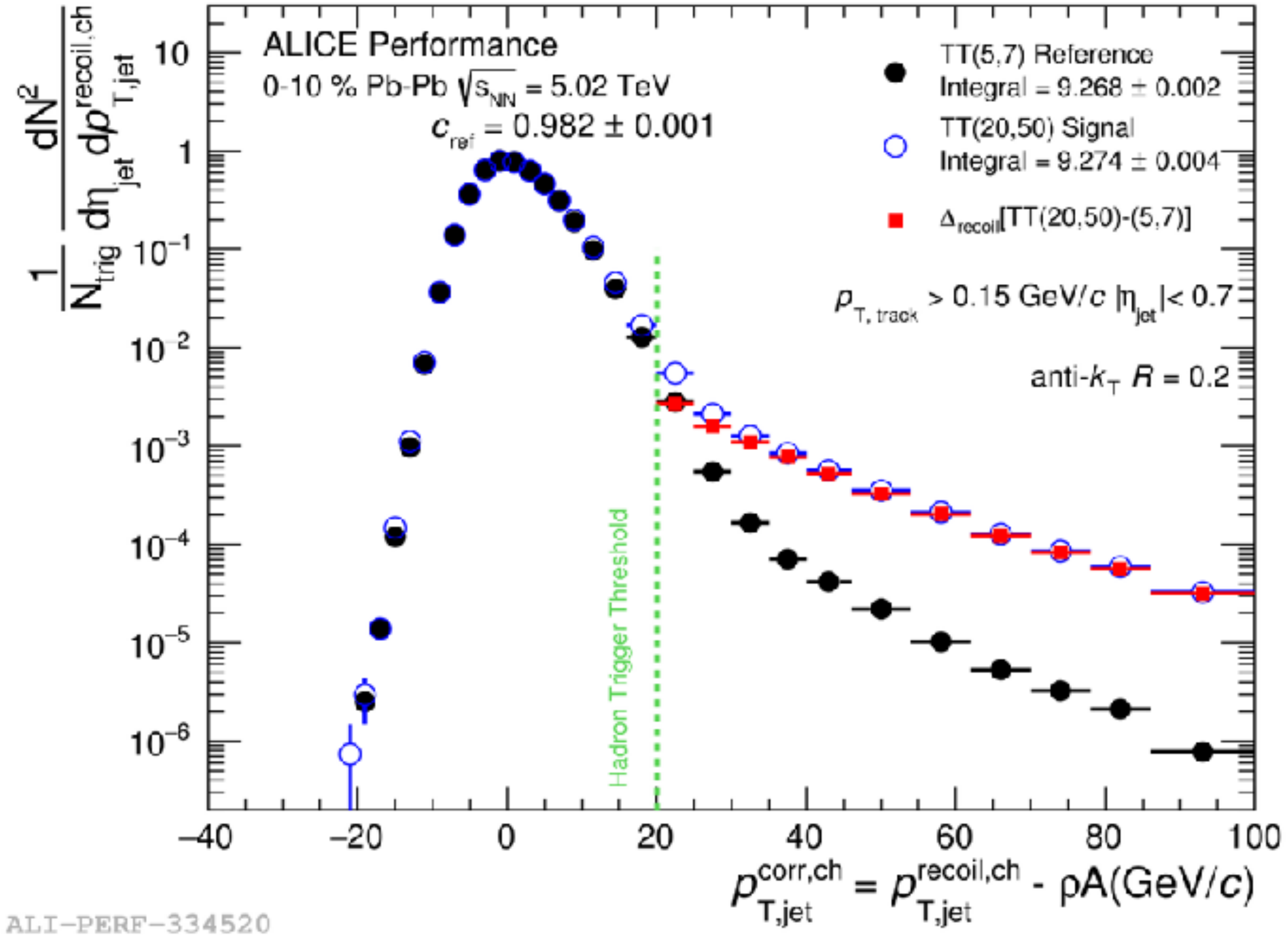
Red: unquenched jets
Blue: quenched jets

[Du, Pablos, Tywoniuk, JHEP 21 (2020), 206](#)

Jet acoplanarity

- Measure the opening angle ($\Delta\varphi$) of the jet with respect to a hadron trigger
    - In search of multiple soft scatterings in the medium and large-angle deflection
    - Low-p_T/larger-R jets are most sensitive to these effects





ALI-PERF-334520

- Subtracting the reference in different trigger regions allows for recoil jets to be measured to low p_T

signal
TT 20-50 GeV/c

reference
TT 5-7 GeV/c

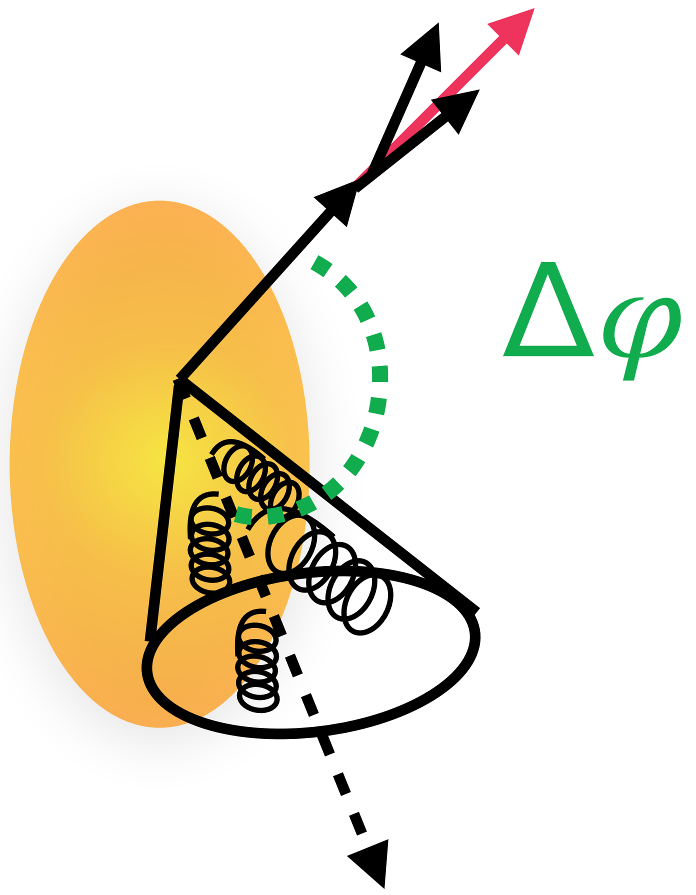
$$\boxed{\Delta_{\mathrm{recoil}}} = \boxed{\frac{1}{N_{\mathrm{trig}}^{\mathrm{AA}}}\frac{\mathrm{d}^3N_{\mathrm{jet}}^{\mathrm{AA}}}{\mathrm{d}p_{\mathrm{T,jet}}^{\mathrm{ch}}\,\mathrm{d}\Delta\varphi\,\mathrm{d}\eta_{\mathrm{jet}}}\Bigg|_{p_{\mathrm{T,trig}}\in\mathrm{TT}_{\mathrm{Sig}}}} - c_{\mathrm{ref}}\cdot\boxed{\frac{1}{N_{\mathrm{trig}}^{\mathrm{AA}}}\frac{\mathrm{d}^3N_{\mathrm{jet}}^{\mathrm{AA}}}{\mathrm{d}p_{\mathrm{T,jet}}^{\mathrm{ch}}\,\mathrm{d}\Delta\varphi\,\mathrm{d}\eta_{\mathrm{jet}}}\Bigg|_{p_{\mathrm{T,trig}}\in\mathrm{TT}_{\mathrm{Ref}}}}$$

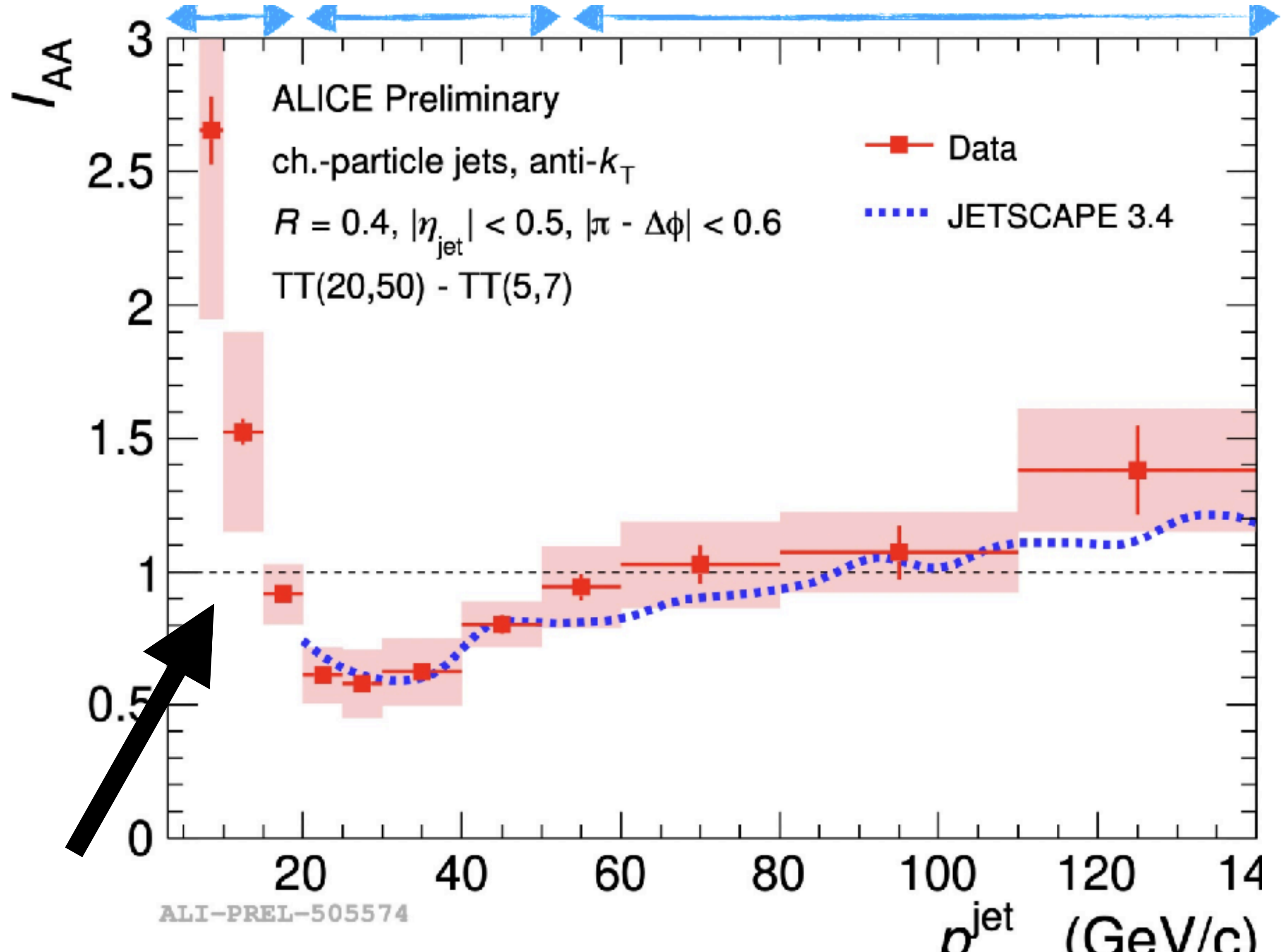
- Data driven subtraction of uncorrelated background

Jet acoplanarity

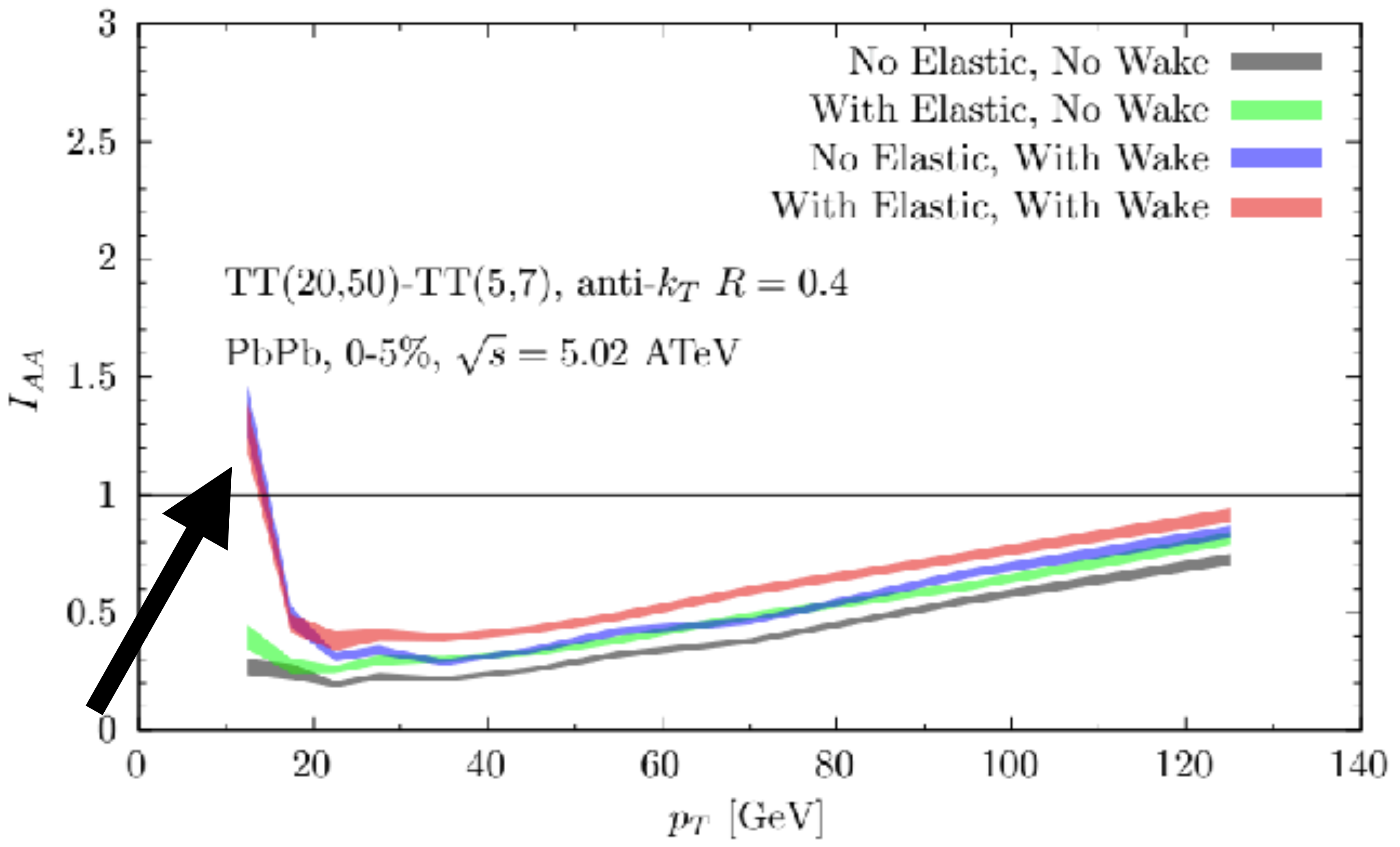
$$\Delta_{\rm recoil} = \frac{1}{N_{\rm trig}^{\rm AA}}\frac{{\rm d}^3N_{\rm jet}^{\rm AA}}{{\rm d}p_{\rm T,jet}^{\rm ch}{\rm d}\Delta\varphi {\rm d}\eta_{\rm jet}}\Bigg|_{p_{\rm T,trig}\in {\rm TT_{Sig}}} - c_{\rm ref}\cdot \frac{1}{N_{\rm trig}^{\rm AA}}\frac{{\rm d}^3N_{\rm jet}^{\rm AA}}{{\rm d}p_{\rm T,jet}^{\rm ch}{\rm d}\Delta\varphi {\rm d}\eta_{\rm jet}}\Bigg|_{p_{\rm T,trig}\in {\rm TT_{Ref}}}$$

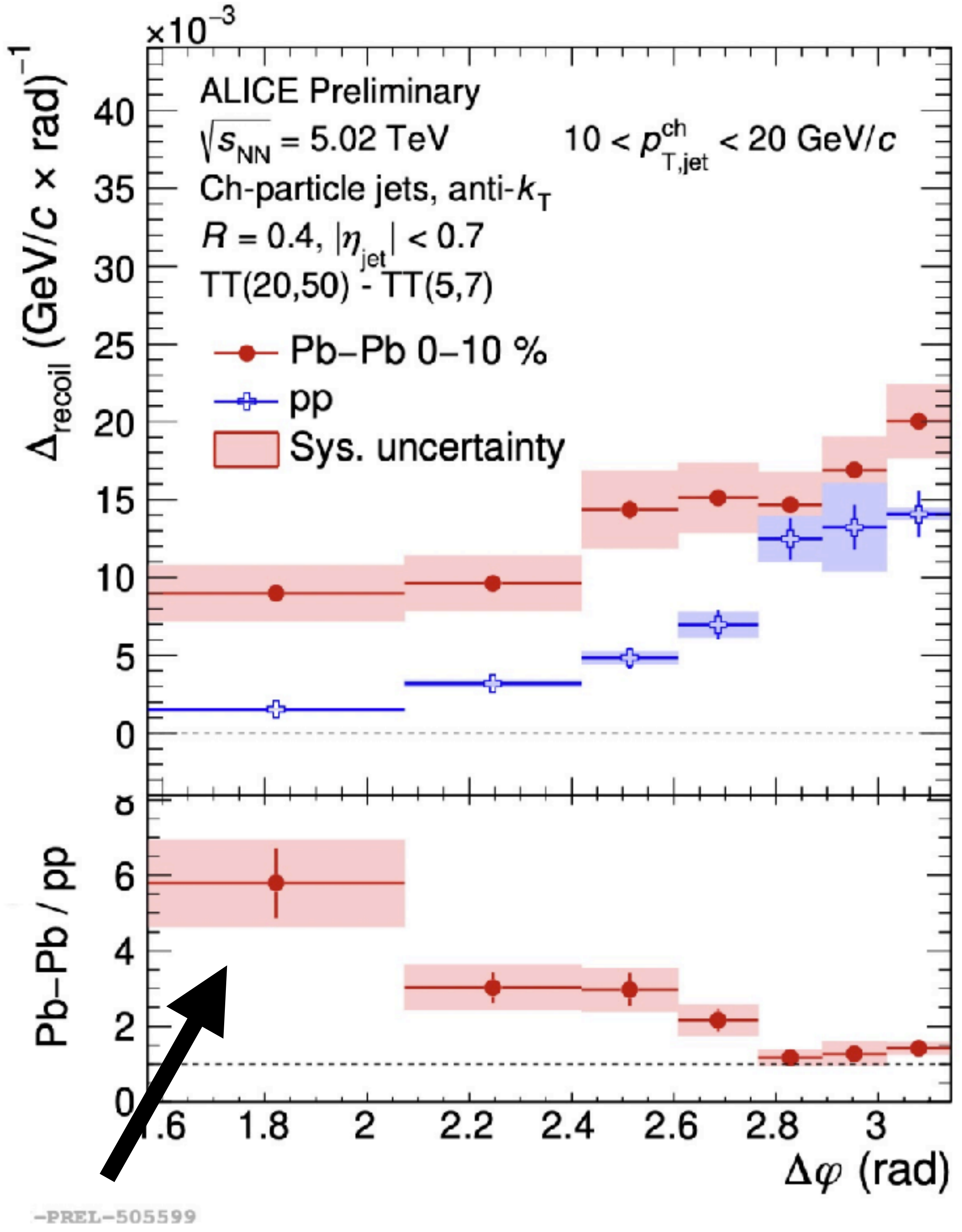
- Measure the opening angle ($\Delta\varphi$) of the jet with respect to a hadron trigger
    - Multiple soft scatterings or in-medium Moliere scattering?





ay between hadron vs jet energy loss?

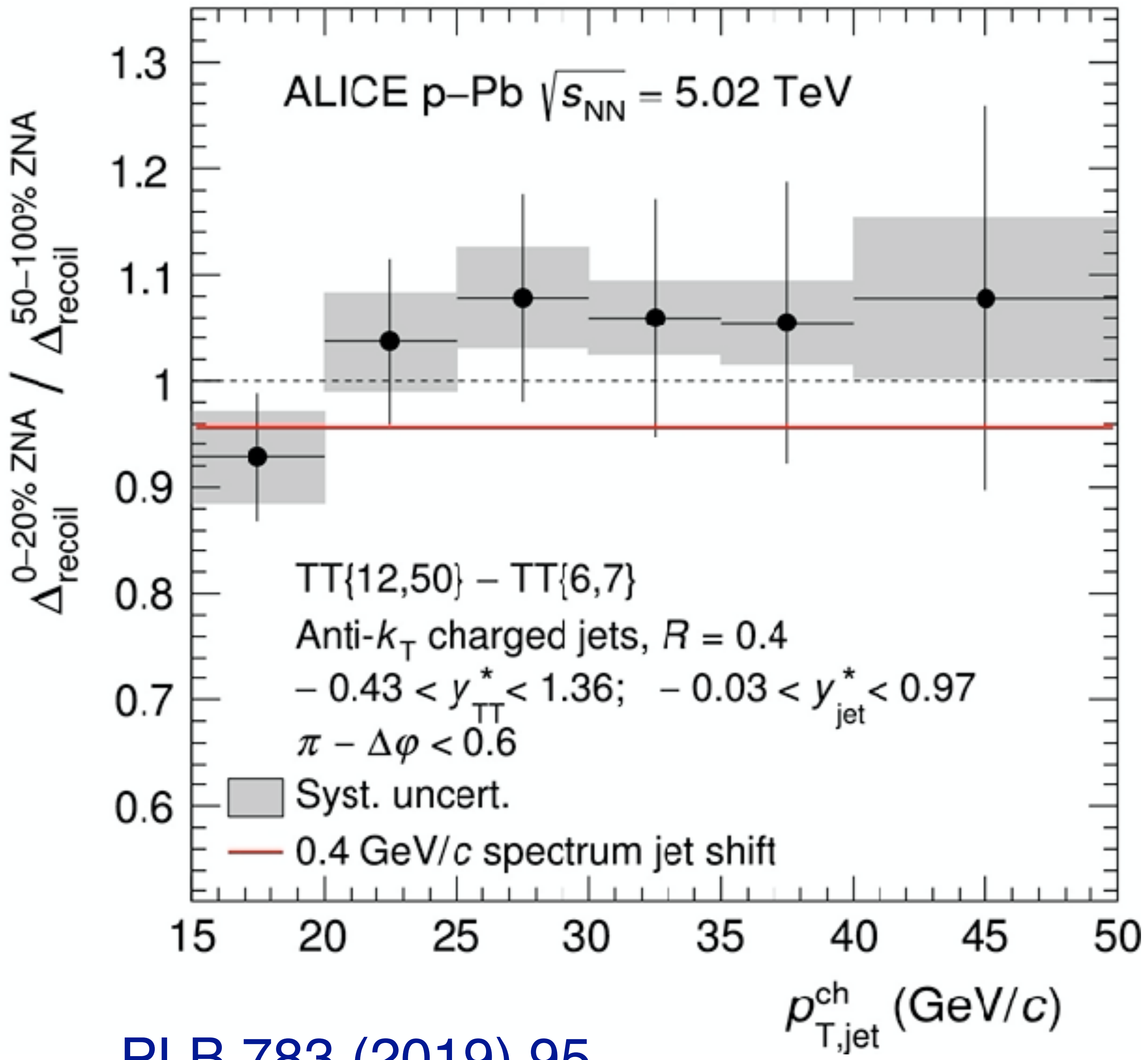




- Preliminary results from hybrid model show wake is dominant effect!

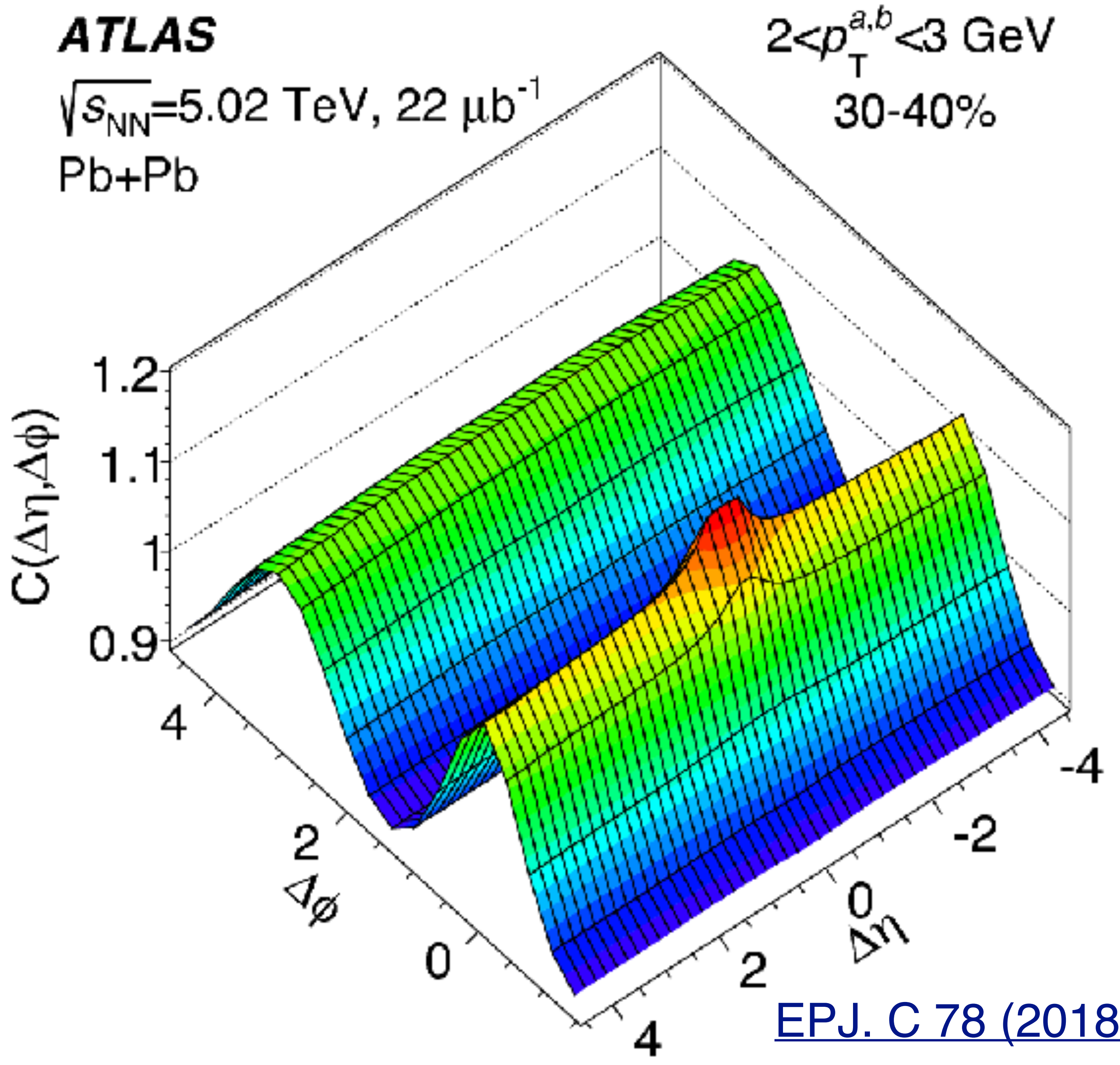
Jets and hadrons in small systems

- Another signature of QGP formation in AA is flow in two-particle correlations



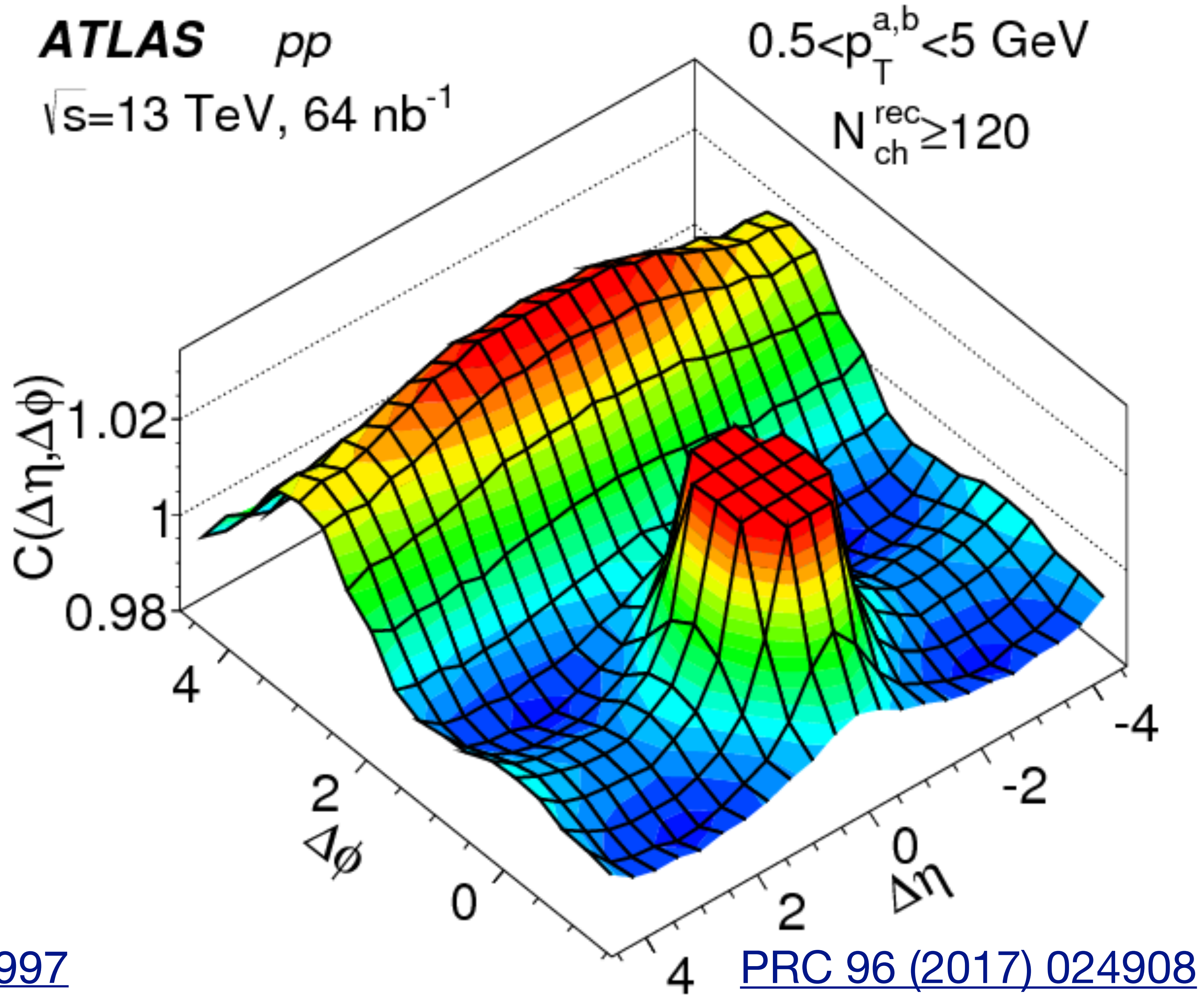
PLB 783 (2019) 95

Semi-central Pb-Pb



EPJ. C 78 (2018) 997

High multiplicity pp

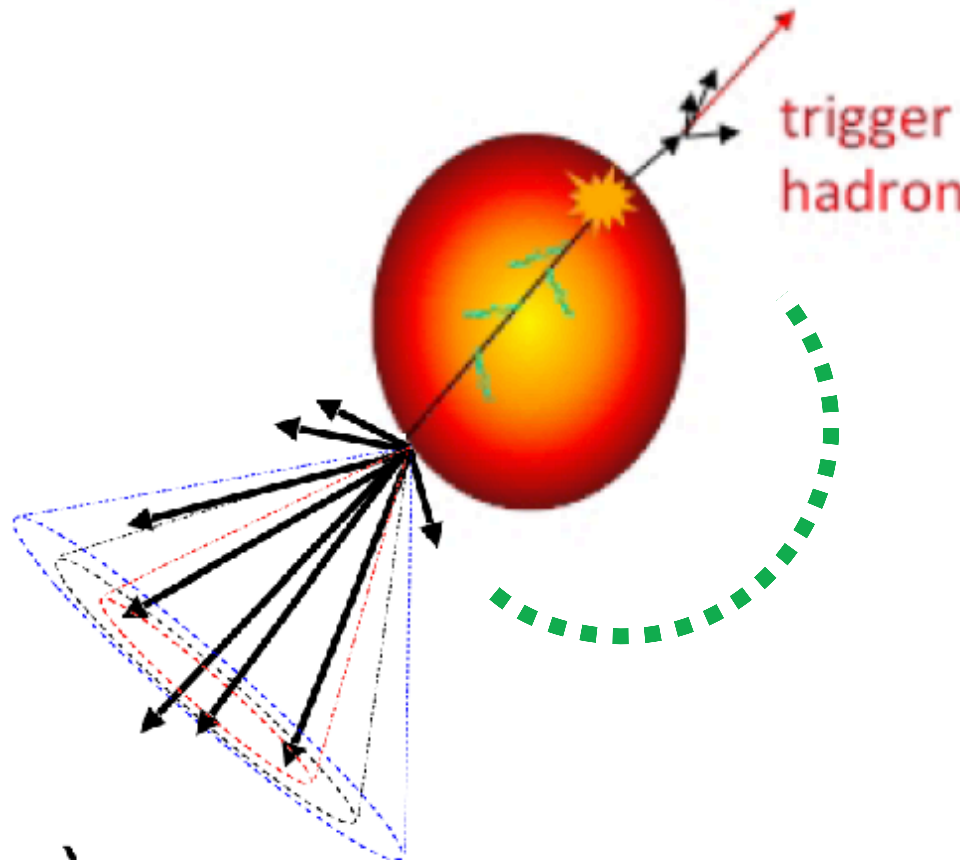


PRC 96 (2017) 024908

- ▸ Also seen in small collisions systems: p-Pb and high multiplicity (HM) pp collisions
- Jet quenching in small collision systems?

Energy loss limit in p-Pb of 400 MeV with 90% CL

Jet quenching in pp collisions?

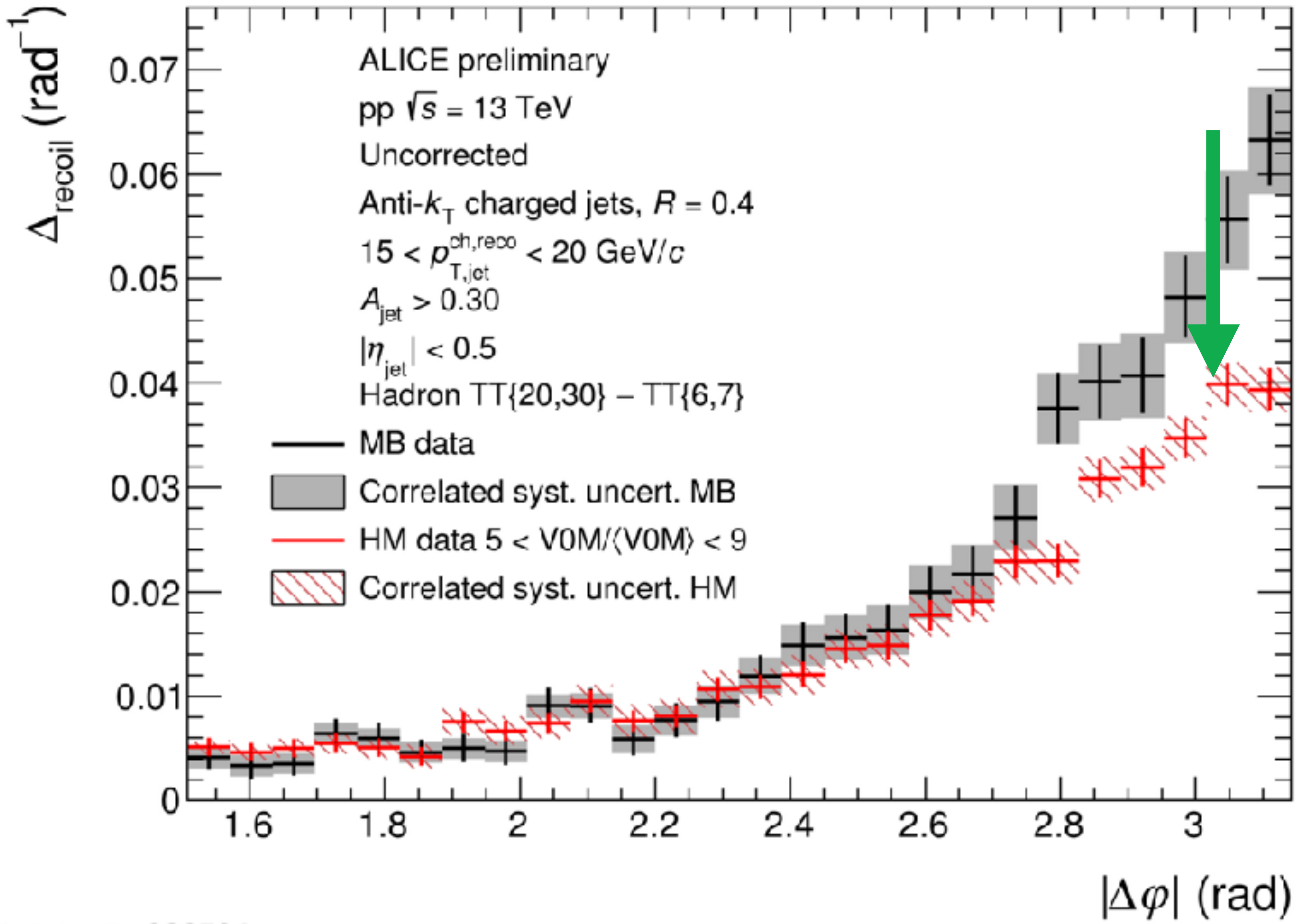


- Look at jet acoplanarity in **HM** compared to **MB** pp collisions

HM: 5 < (V0M/⟨V0M⟩) < 9

V0M is the number of charged, final state particles in forward and backward η

- ▸ Significant suppression of HM compared to MB → jet quenching?



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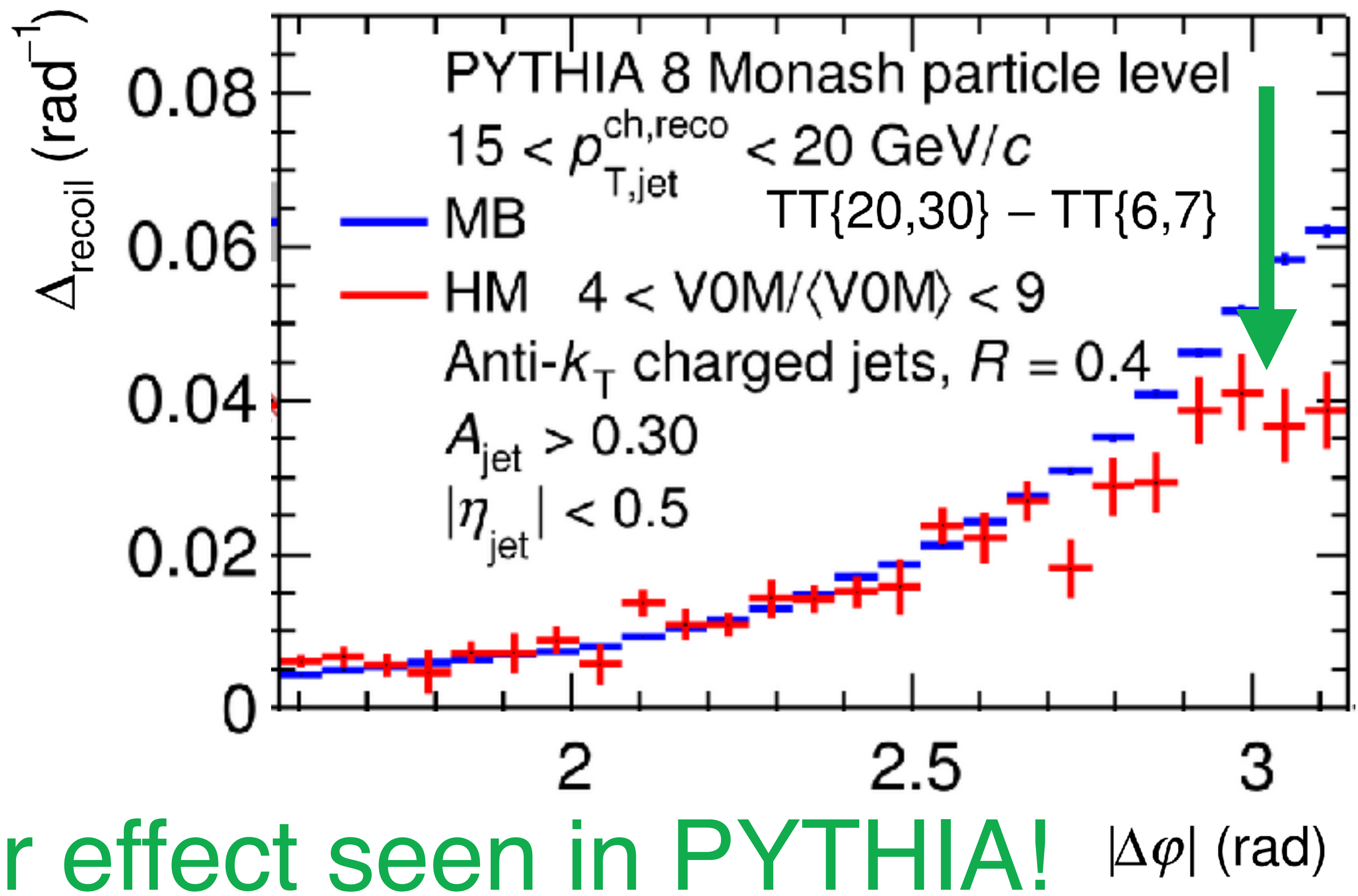


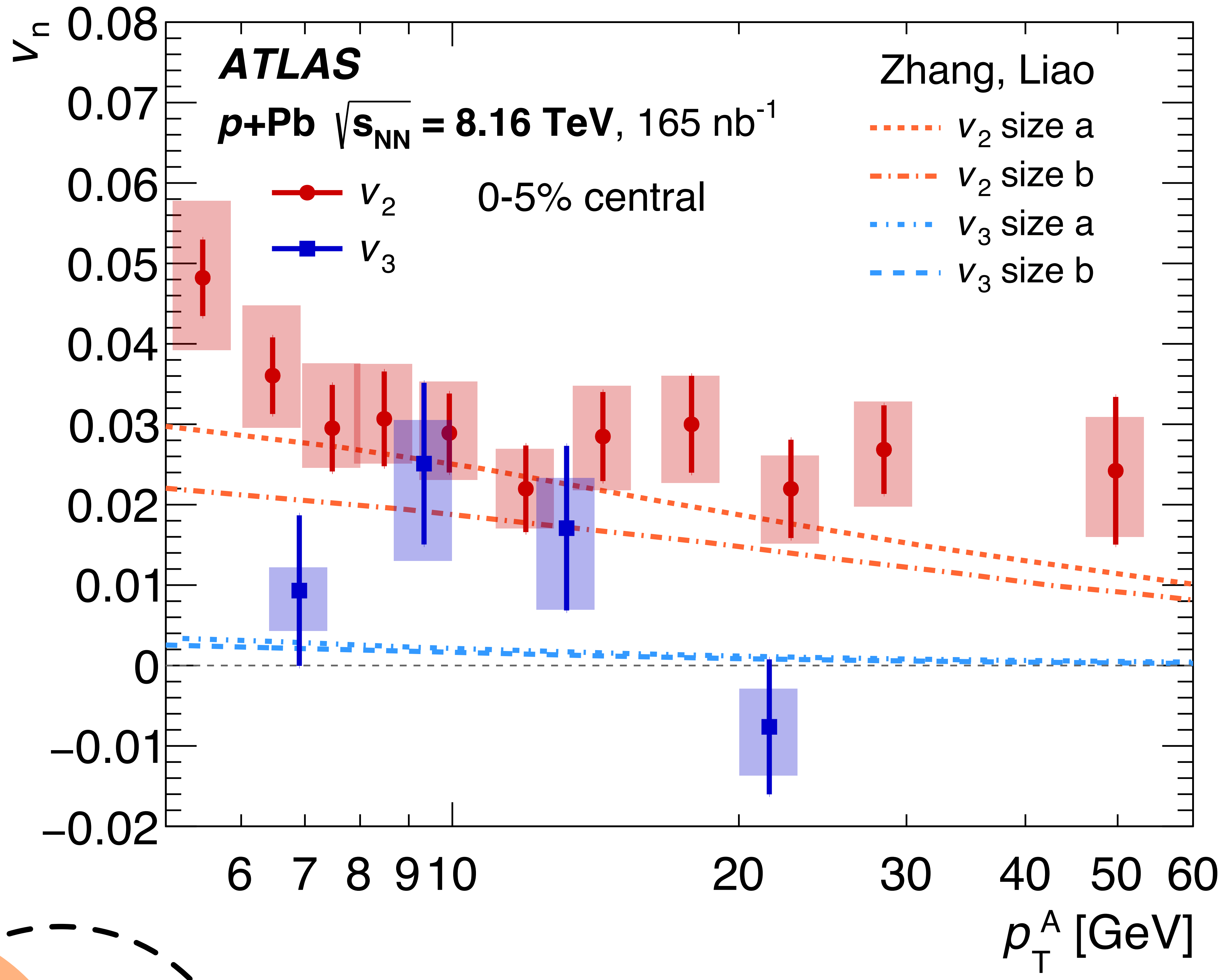
- ▸ Similar effect seen in PYTHIA! What's happening?

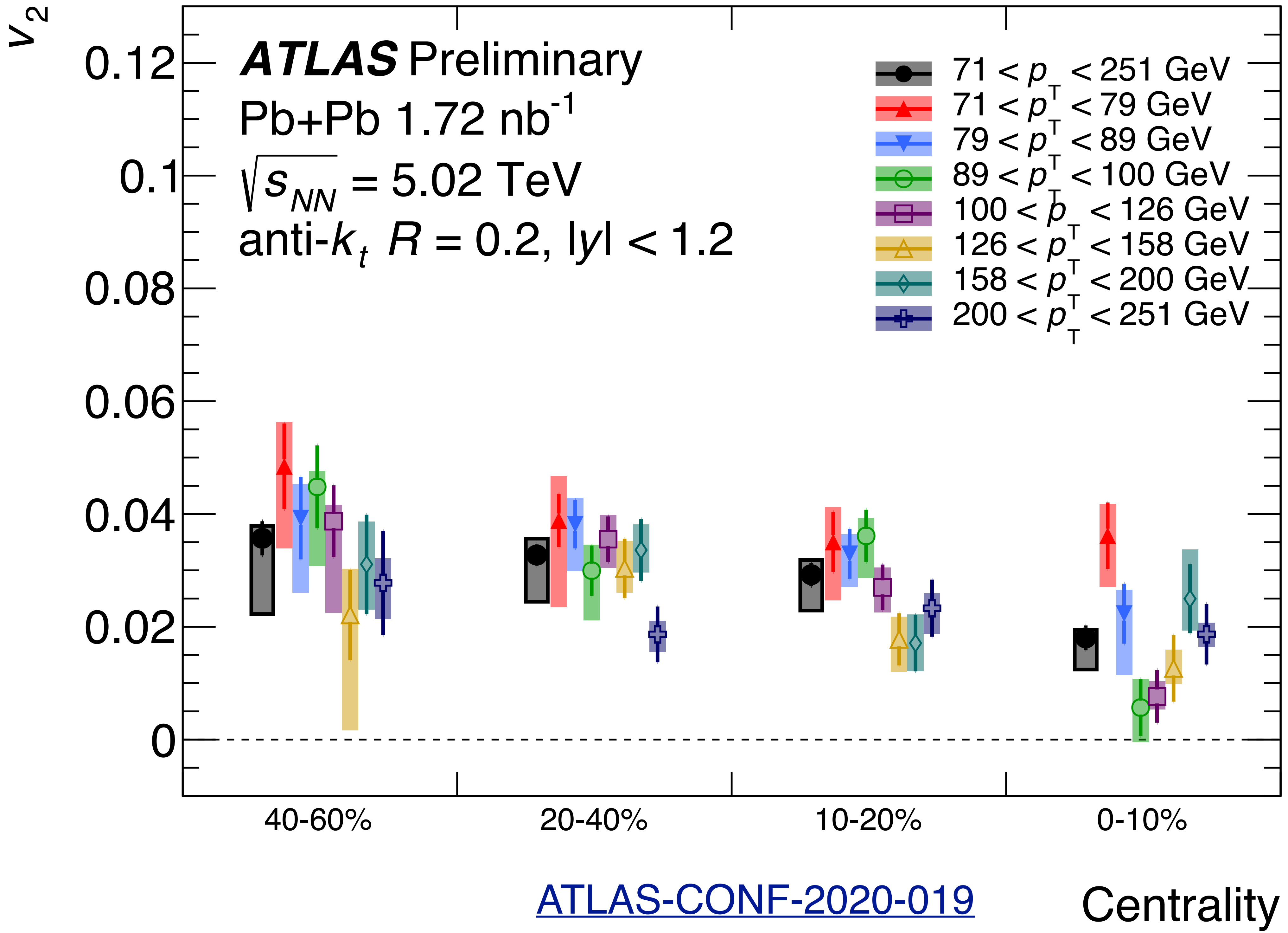
- ▸ *HM trigger biases towards multi-jet events in small systems → important for all studies of HM in small systems!*

High p_T v_n in p-Pb?

$$\frac{dN}{d\phi} = N_0\left(1 + 2\sum_{n=1} v_n \cos n(\phi - \psi_n)\right)$$

- Positive v_n seen in p-Pb collisions at high p_T
- In Pb-Pb this is usually attributed to path length dependence from jet quenching as seen in jet v_n at high p_T





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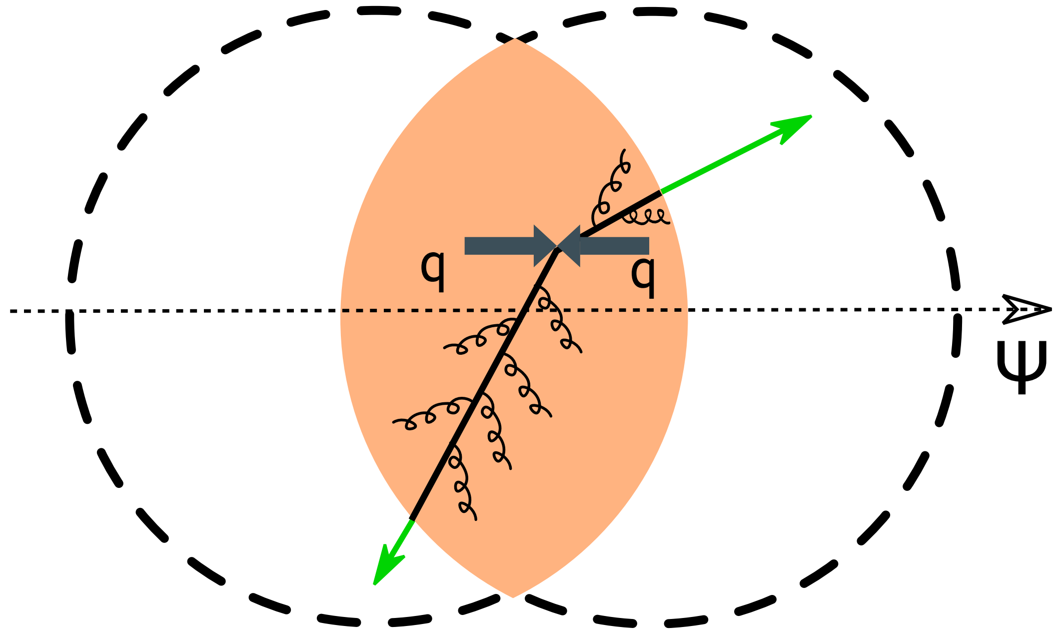

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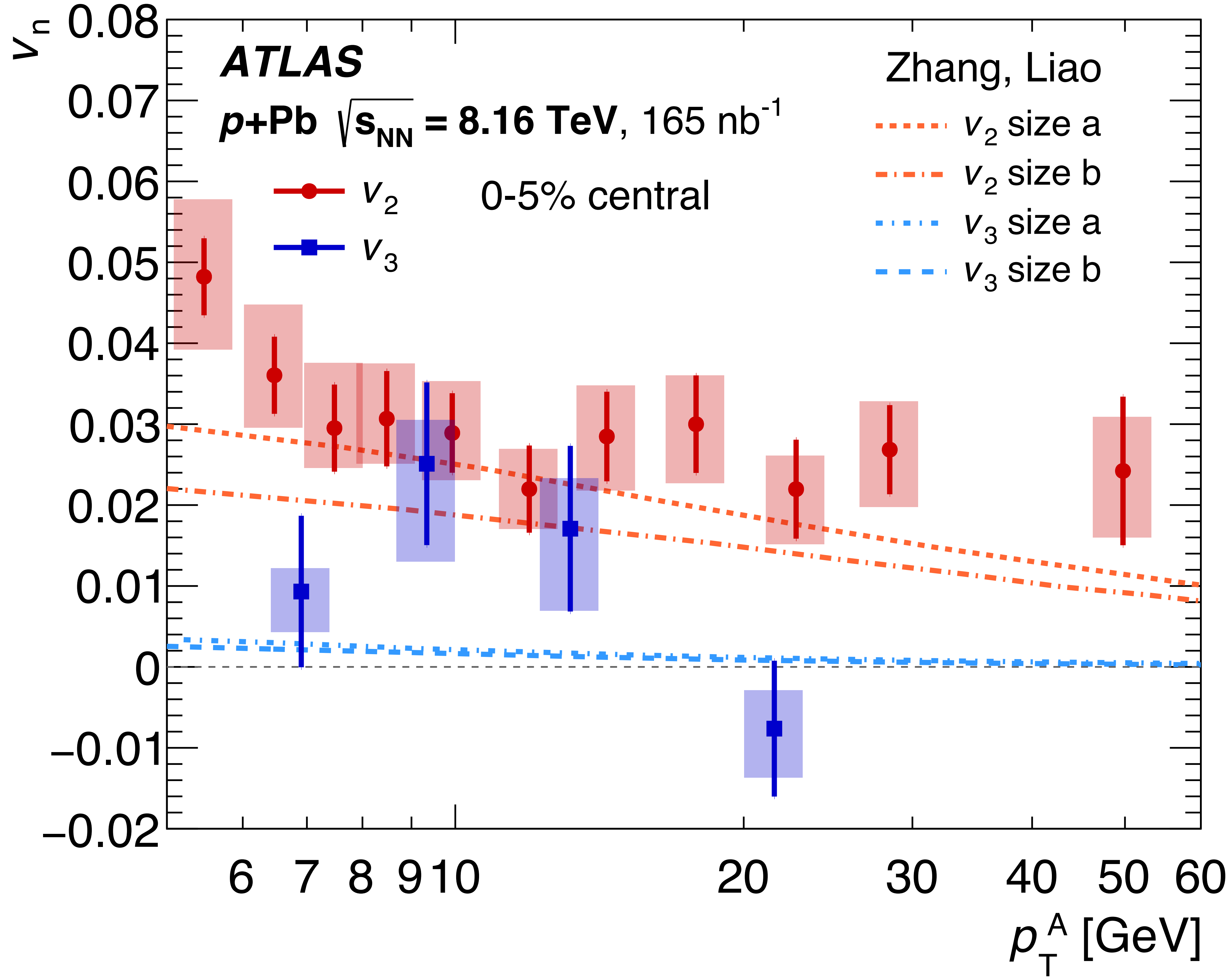
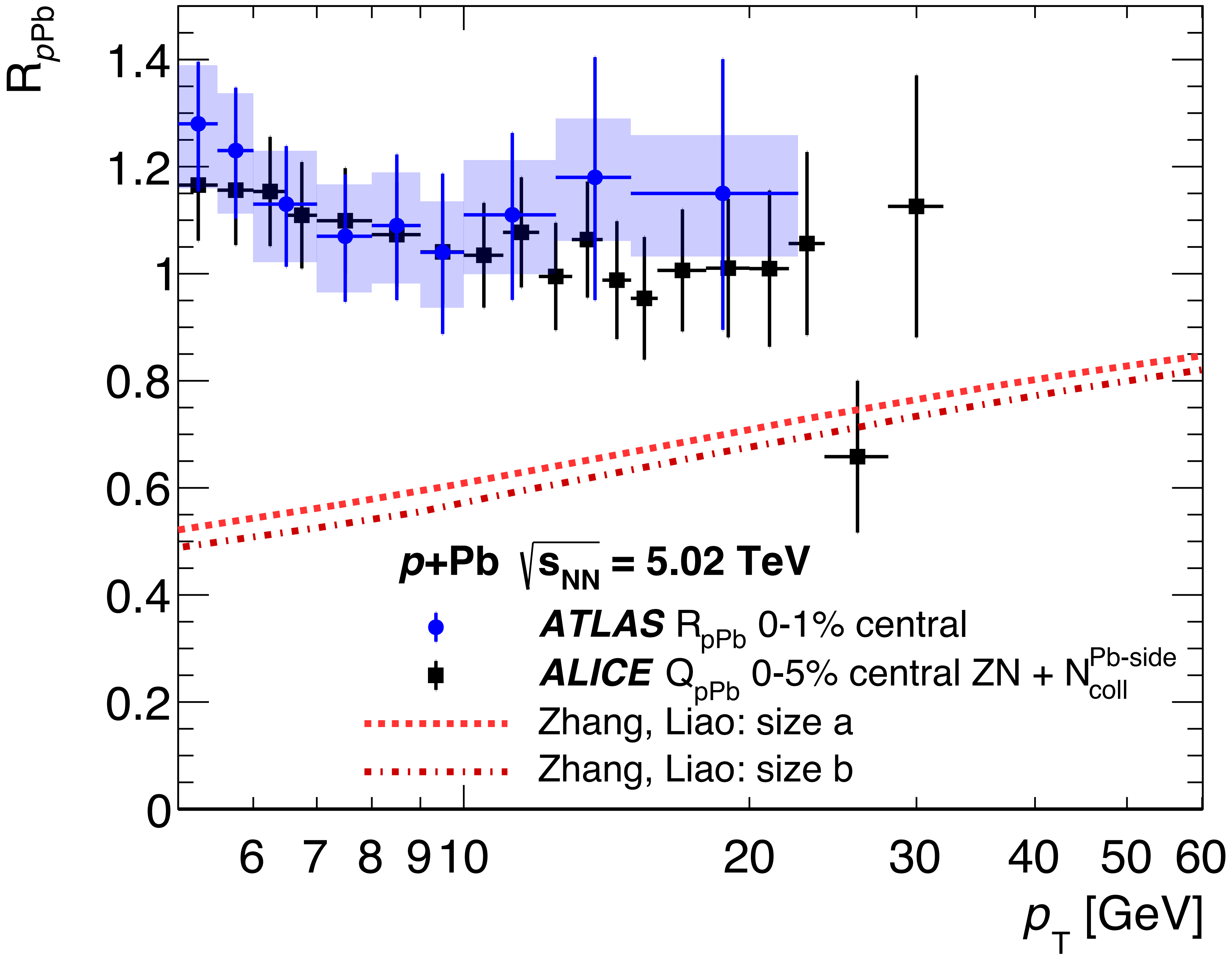
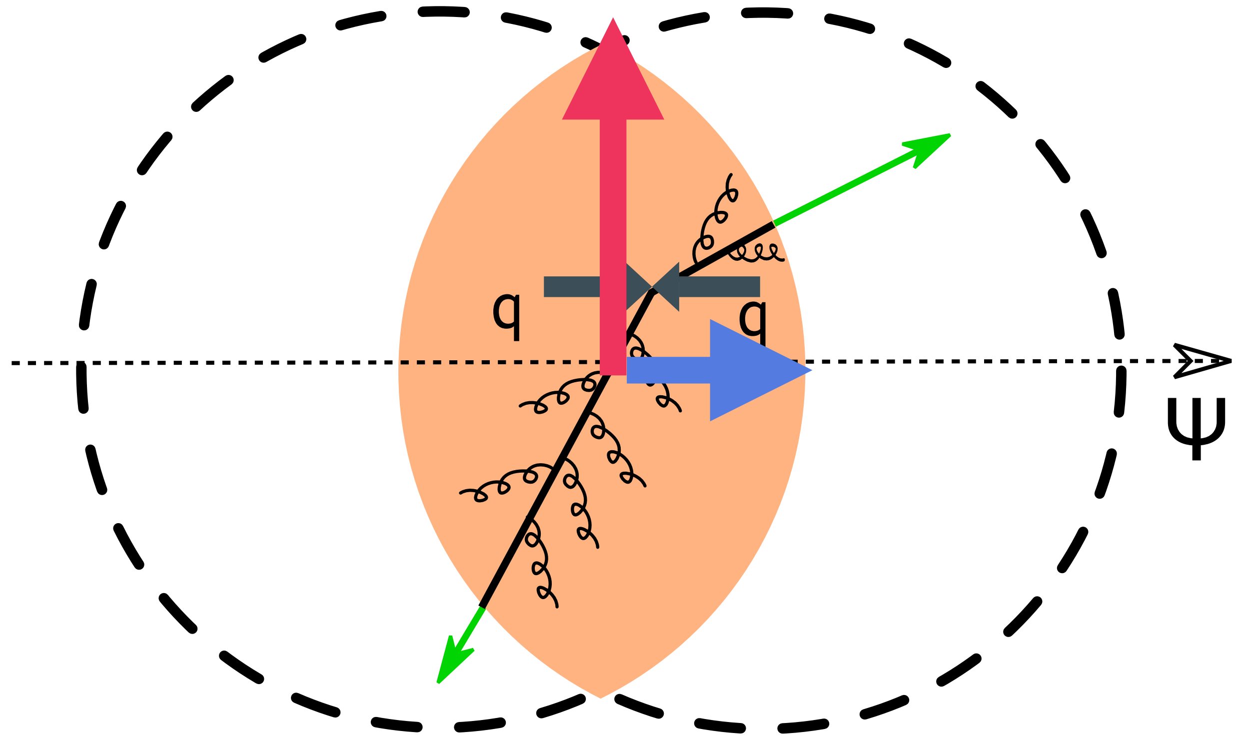




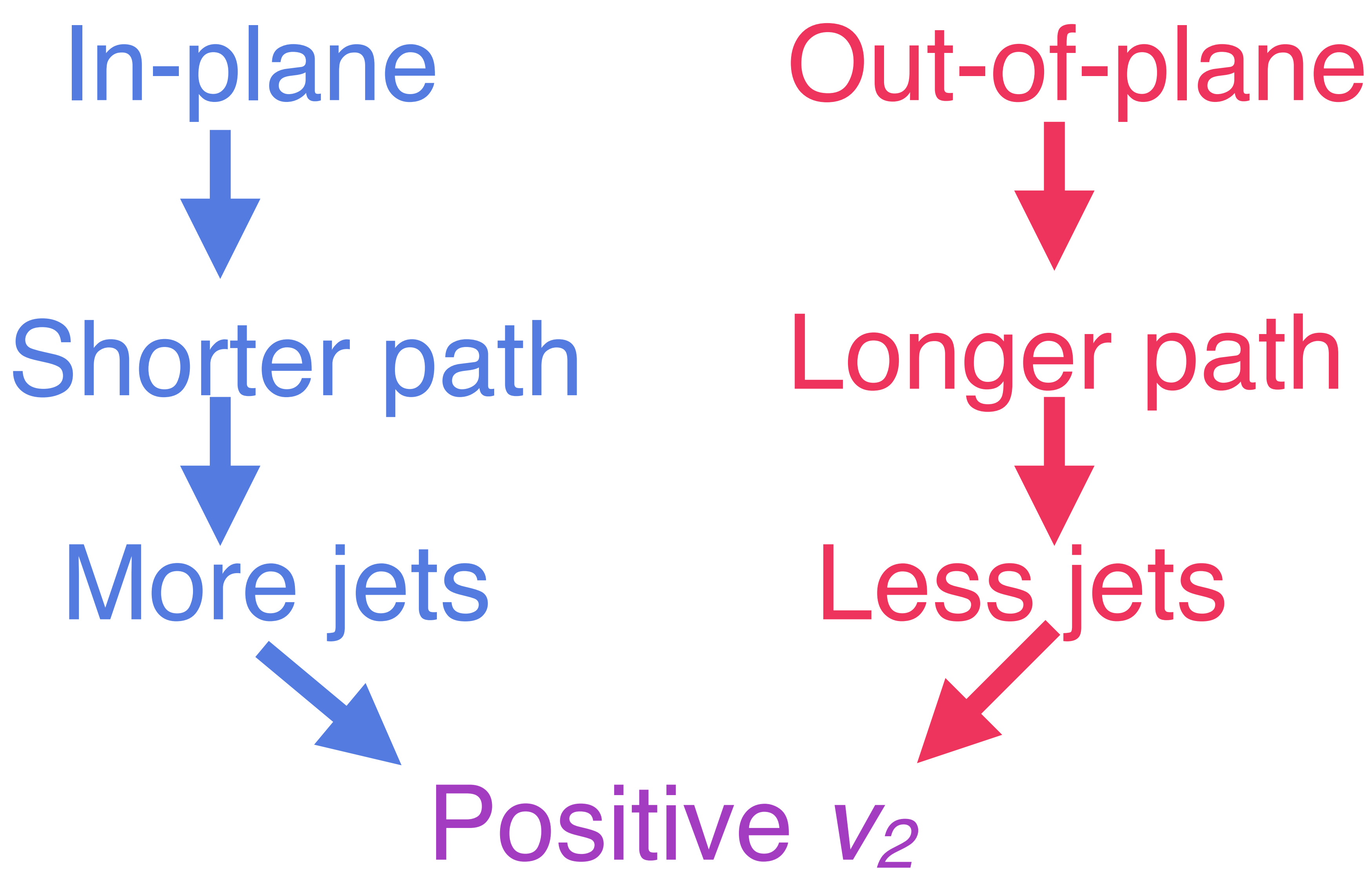
- Reproduced by jet quenching model
- But this model predicts suppression for R_{pPb} that is not seen in data?

Jet v_n

$$\frac{dN}{d\phi} = N_0\left(1 + 2\sum_{n=1} v_n \cos n(\phi - \psi_n)\right)$$



- Measure jet yields with respect to the event plane angle
  - Probes path length dependence since the jets can travel in vs. out of plane

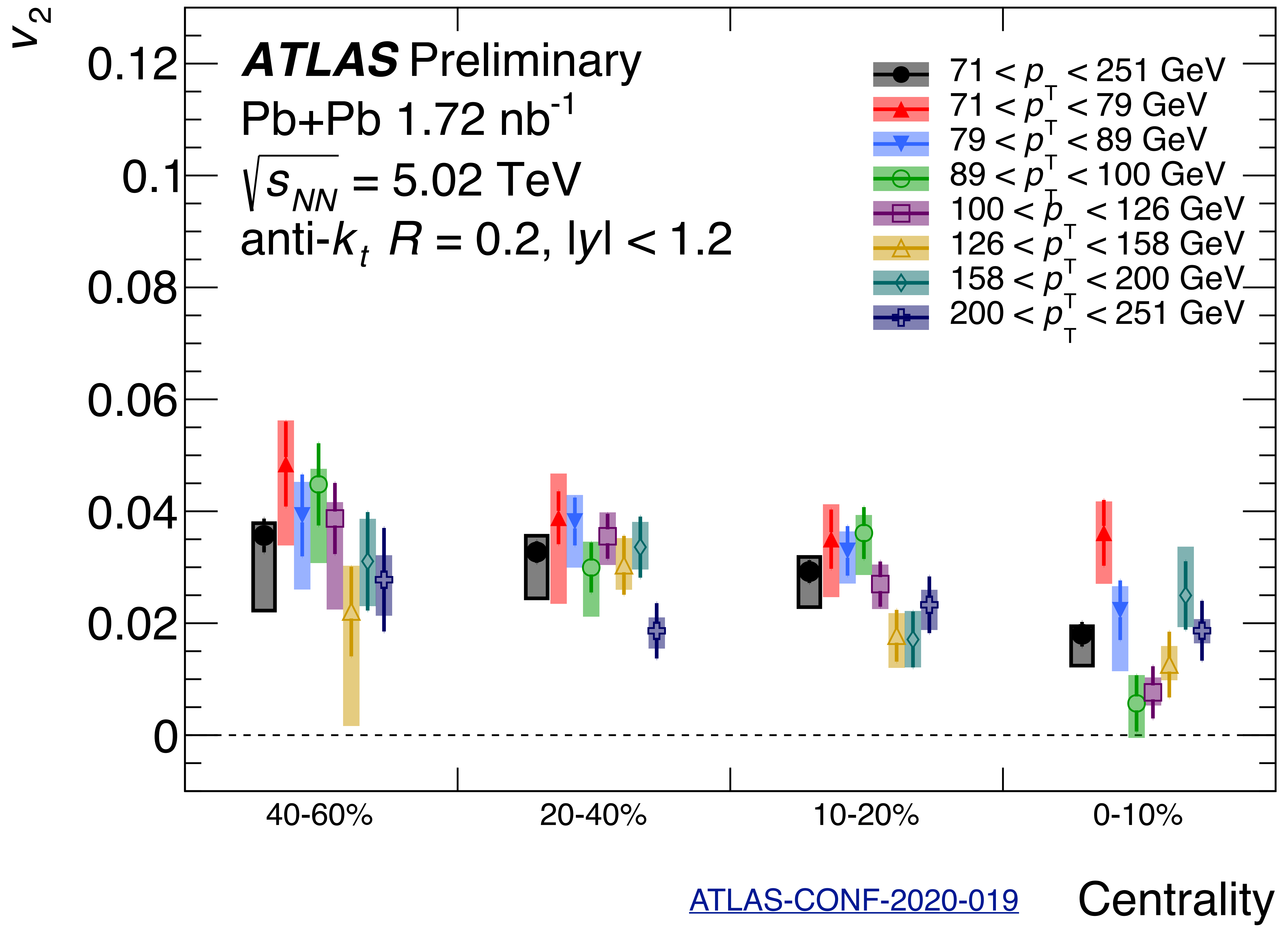


In-plane → Shorter path → More jets

Out-of-plane → Longer path → Less jets

Positive v_2

- *See a significant positive v_2*



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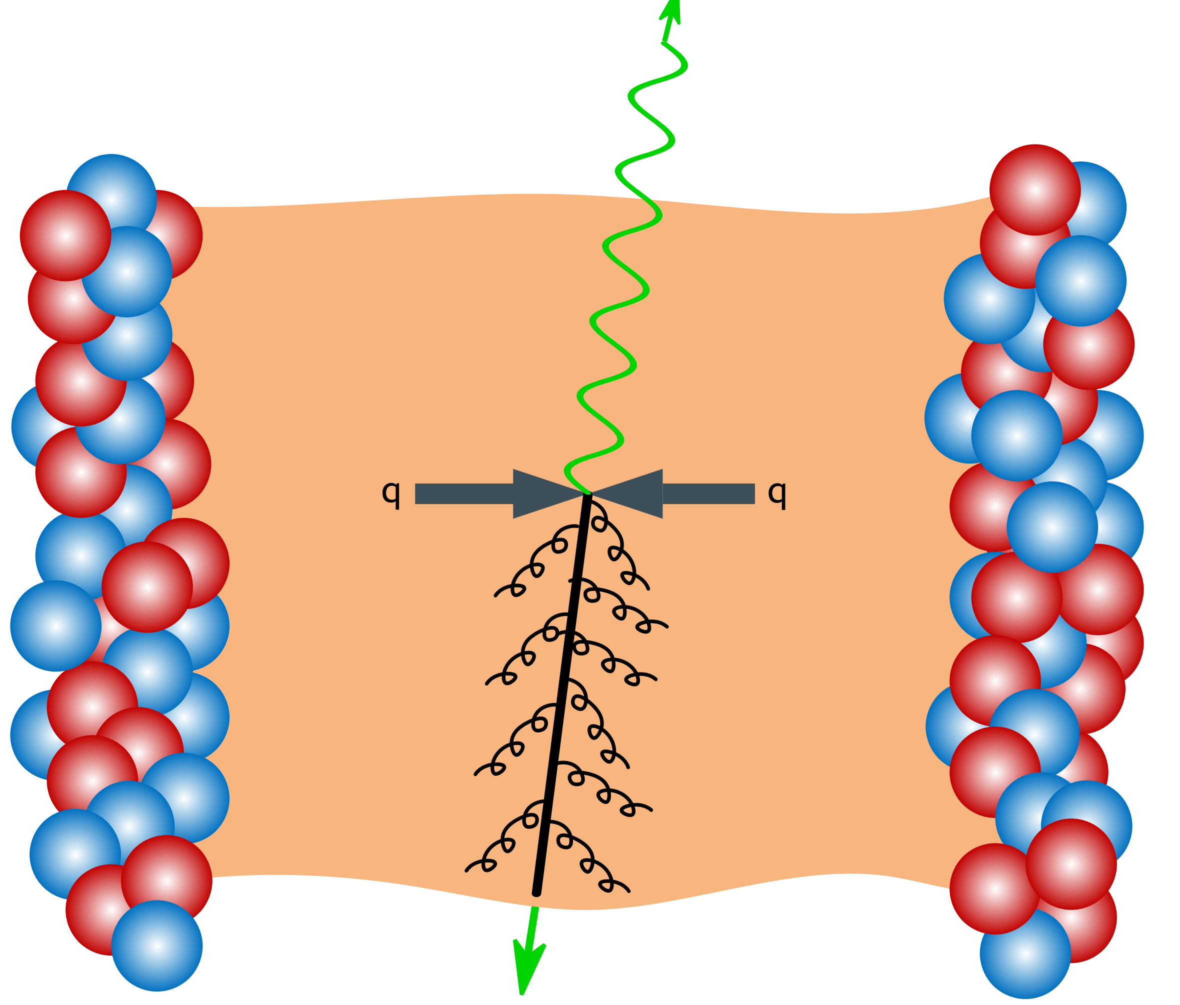
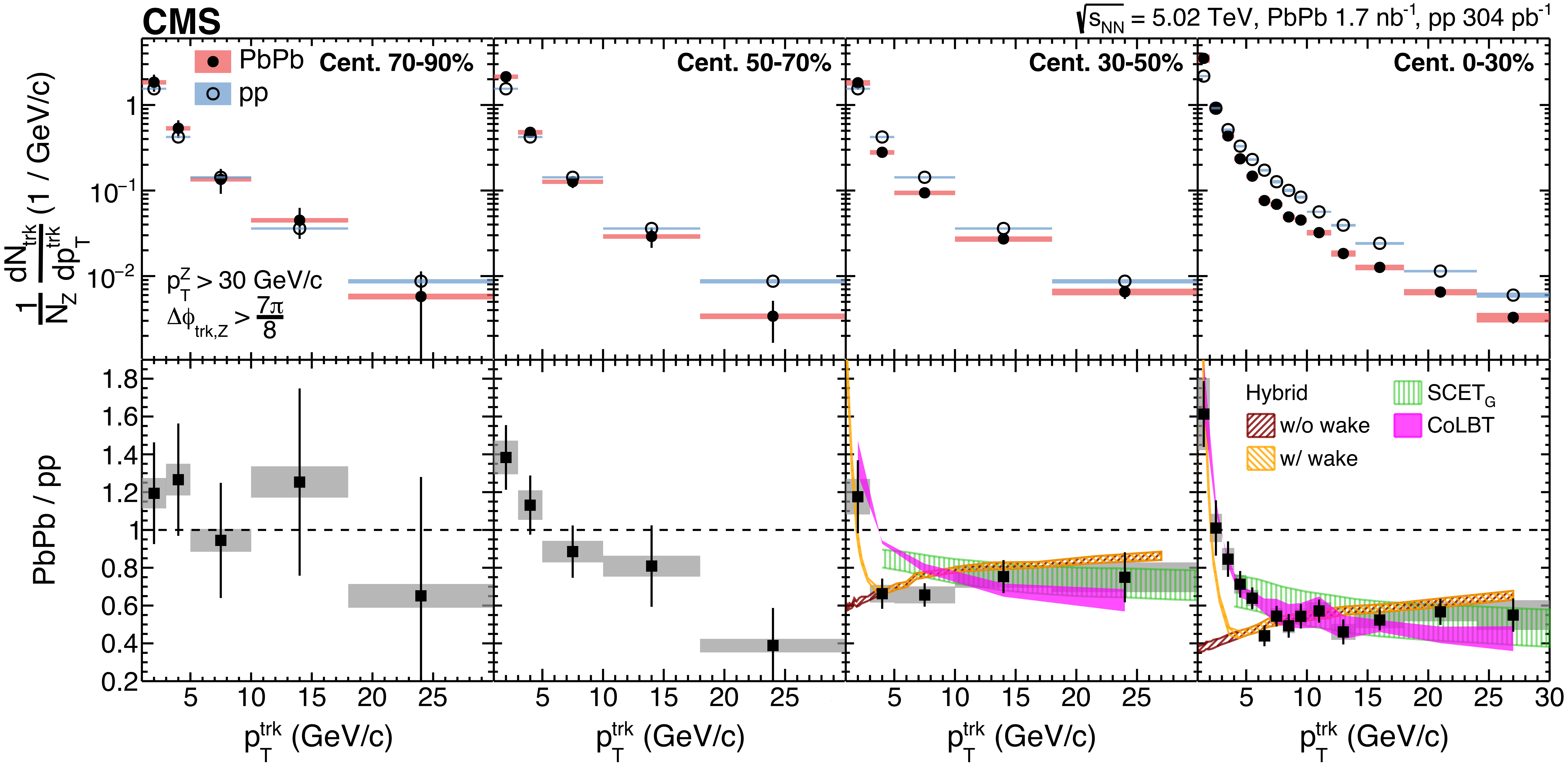
Z-tagged particles





Constituent subtraction (CS)

- Estimate background density in each jet or event

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

$$\rho_m = \mathrm{med}\left(\frac{m_i}{A_{\mathrm{jet}}^{\mathrm{i}}}\right)$$

- Add infinitesimally small ghosts to the event
- Set the p_T for each ghost to negative values

$$p_{\mathrm{T,g}} = A_{\mathrm{g}}\rho$$

$$m_{\mathrm{g}} = A_{\mathrm{g}}\rho_m$$

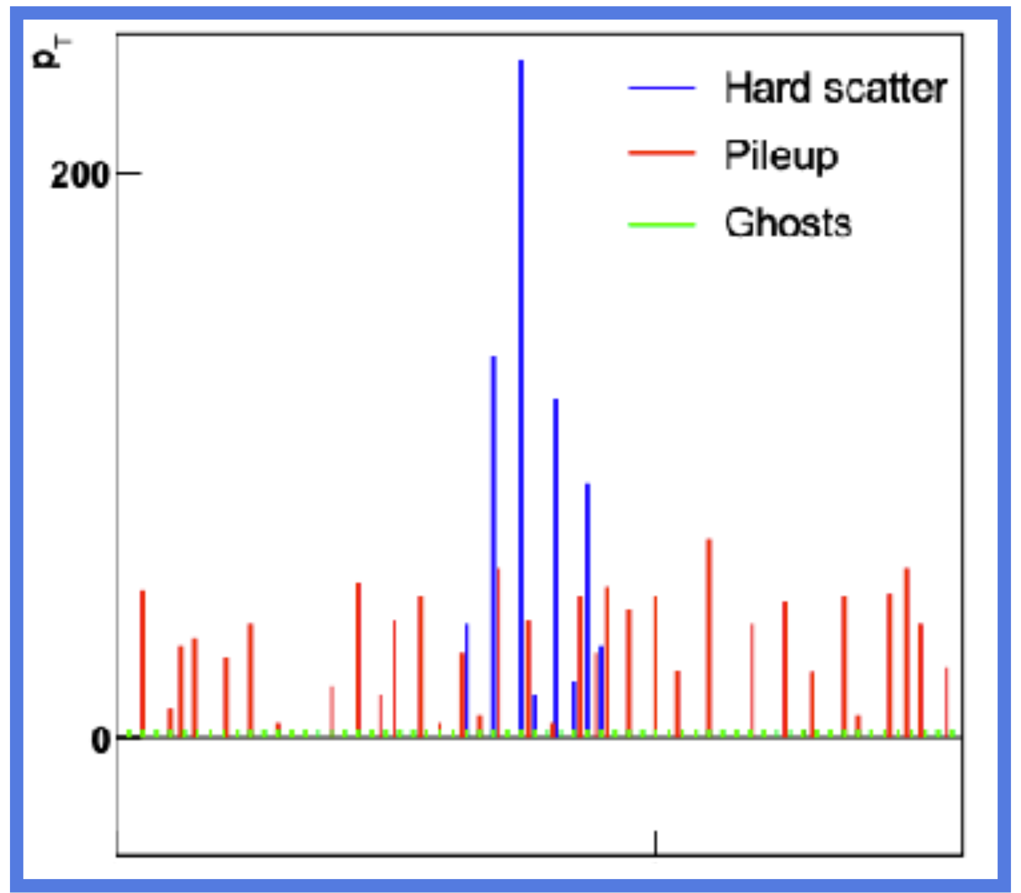
- Calculate distance between each particle and ghost for each pair and sort in ascending order
- Iteratively change the momentum and mass of each ghost/particle until no more pairs remain

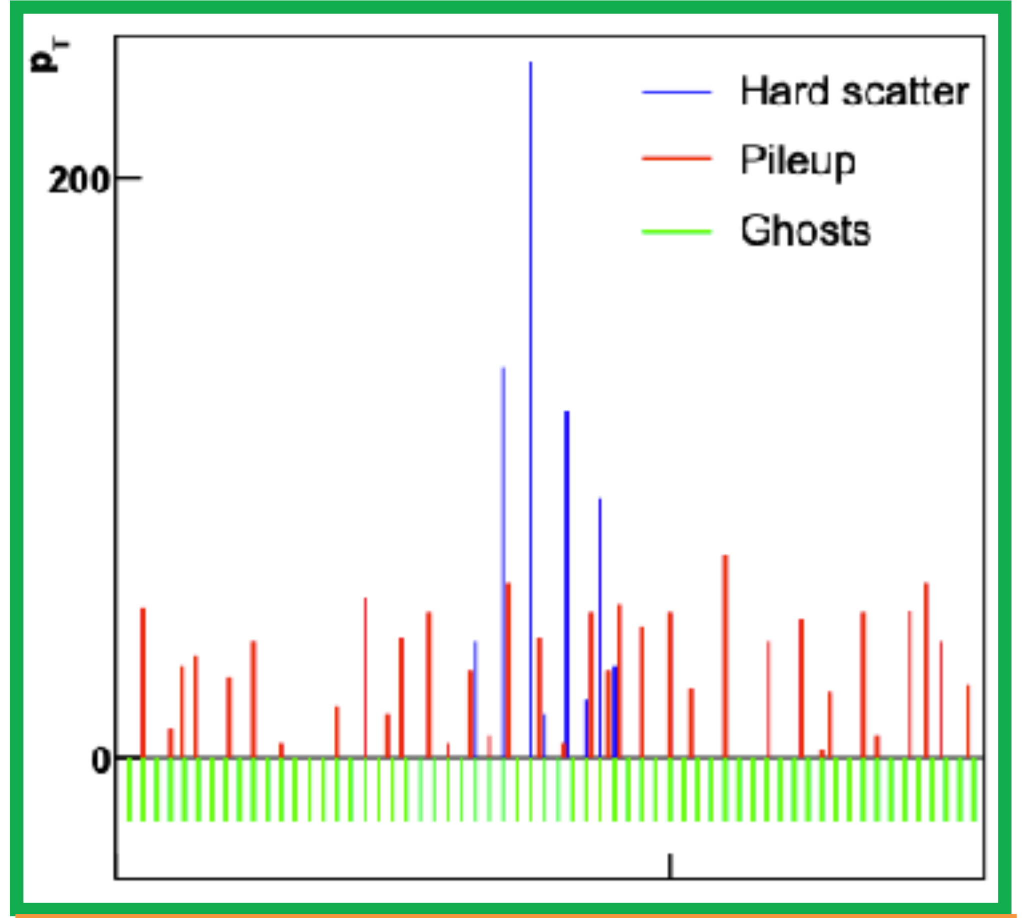
if ($p_T > p_T^g$) $p_T = p_T - p_T^g$ $\quad p_T^g = p_T^g - p_T$

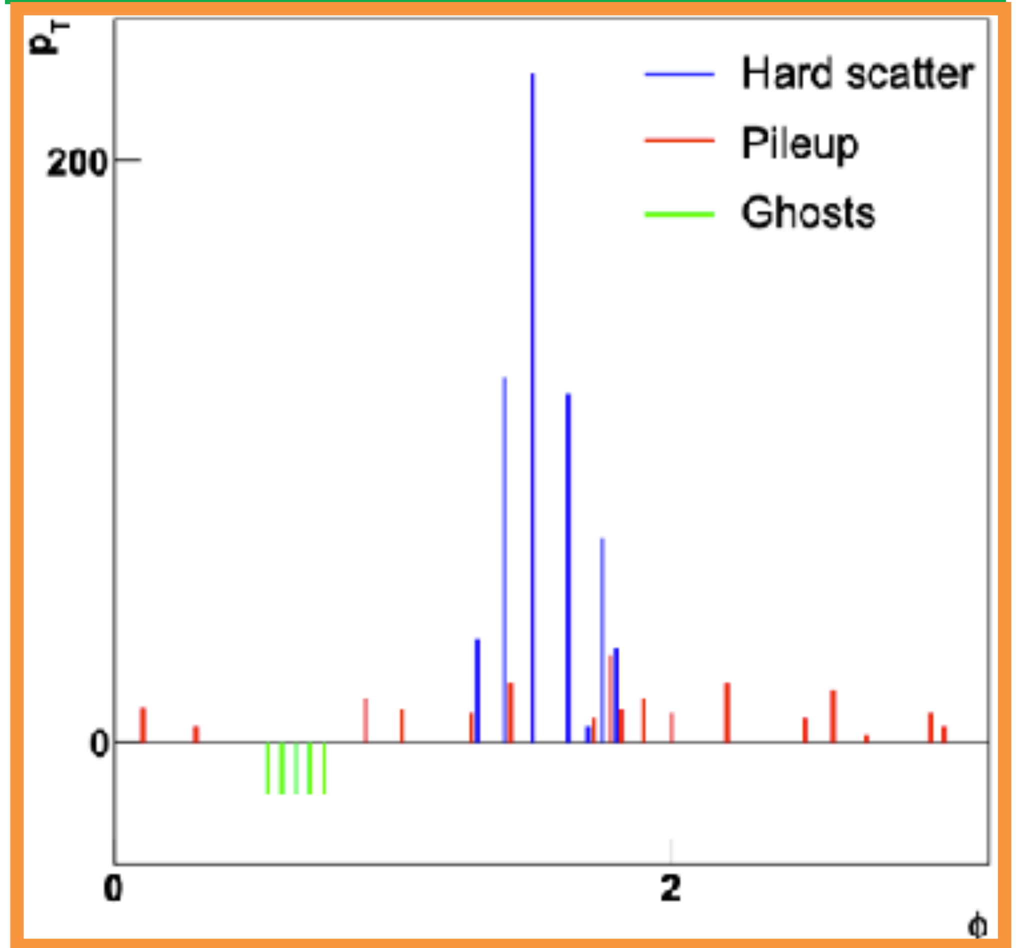
$p_T^g = 0 \quad p_T = 0$

- Discard particles with 0 momentum

JHEP 1908 (2019) 175

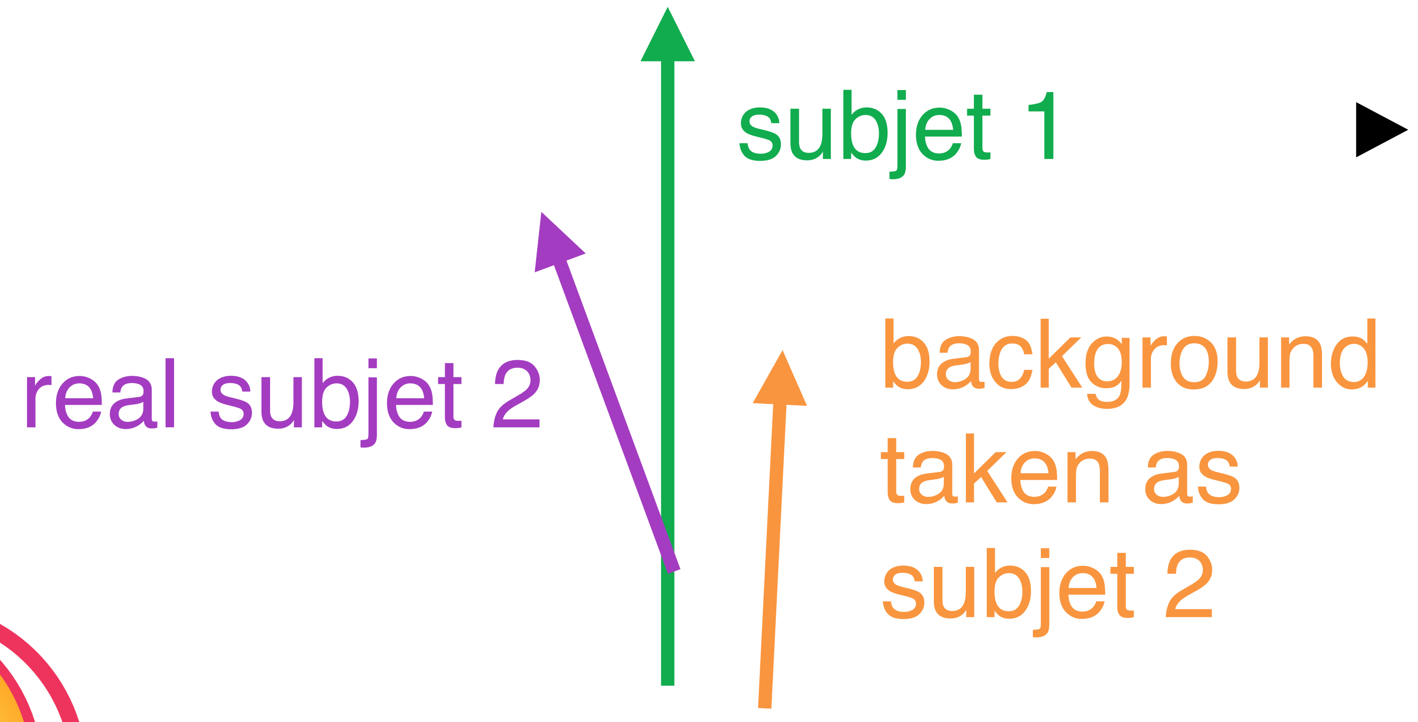






Background treatment

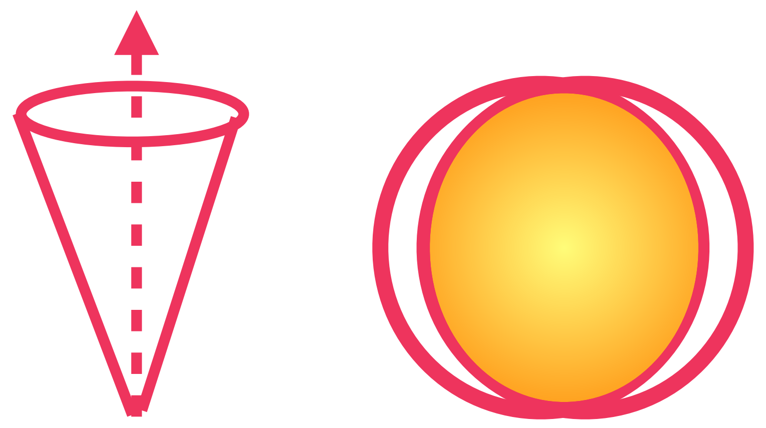
- Uncorrelated background leads to incorrect splittings



- Need to suppress the background in order to unfold

- Solutions:

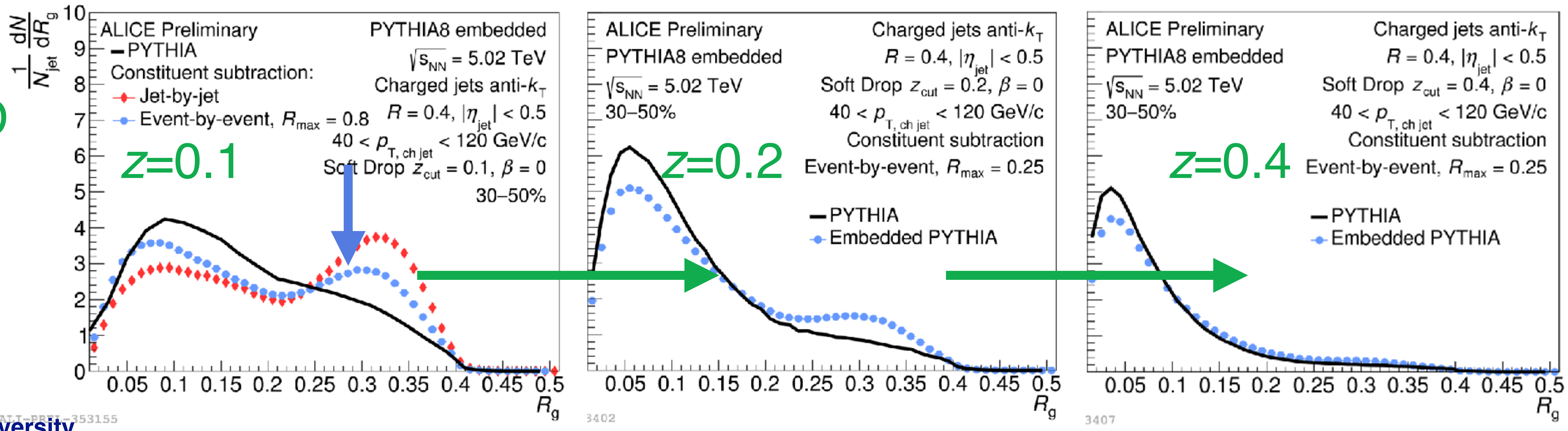
1. smaller jet radii



or semi-central collisions

2. event-by-event constituent subtraction instead of jet-by-jet

3. tighter SD condition

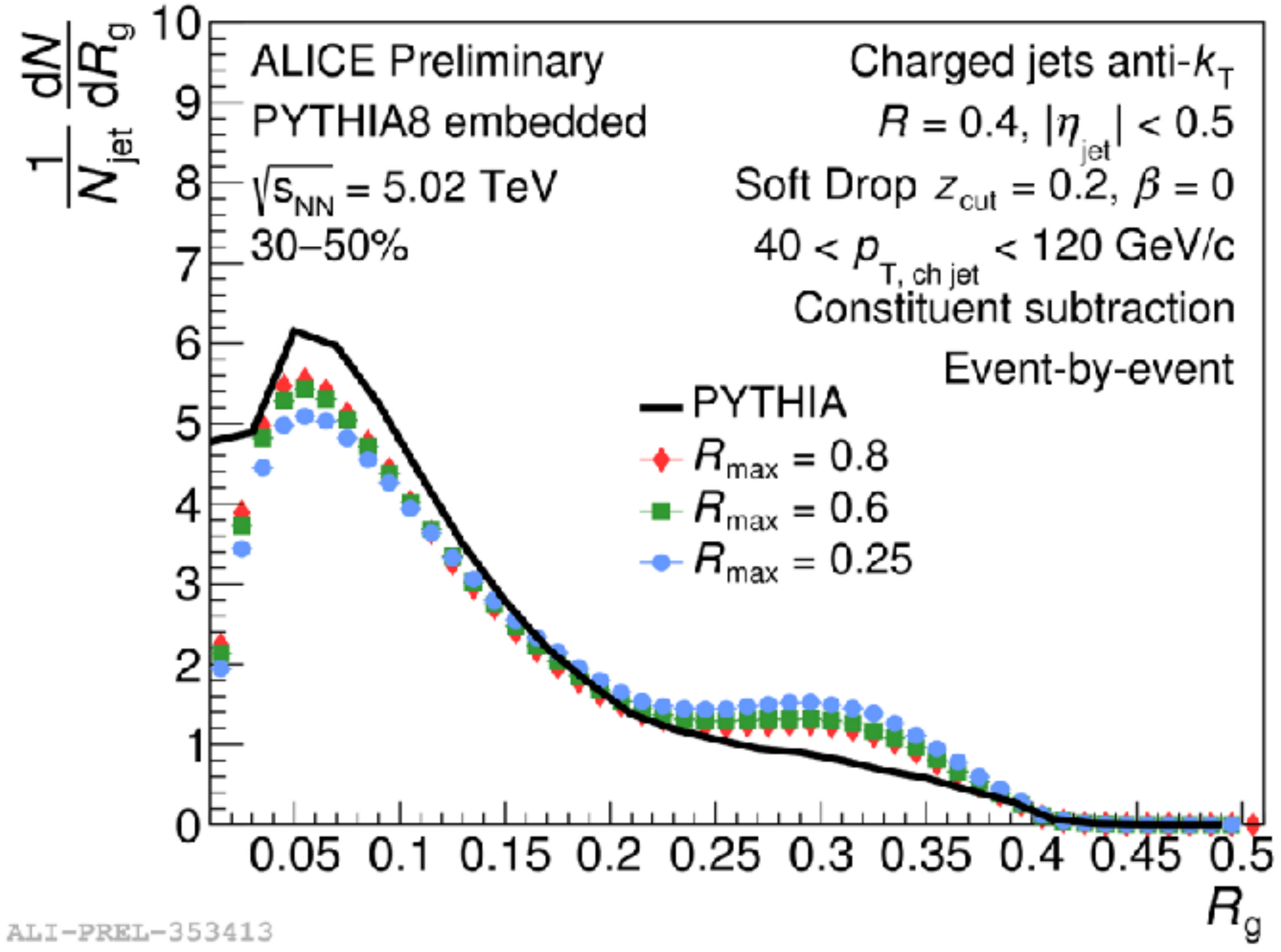


Interesting study of the background:
Mulligan, Ploskon
arXiv:2006.01812

Event-by-event CS

$60 < p_{T}^{ch} < 80$ GeV

JHEP 1908 (2019) 175



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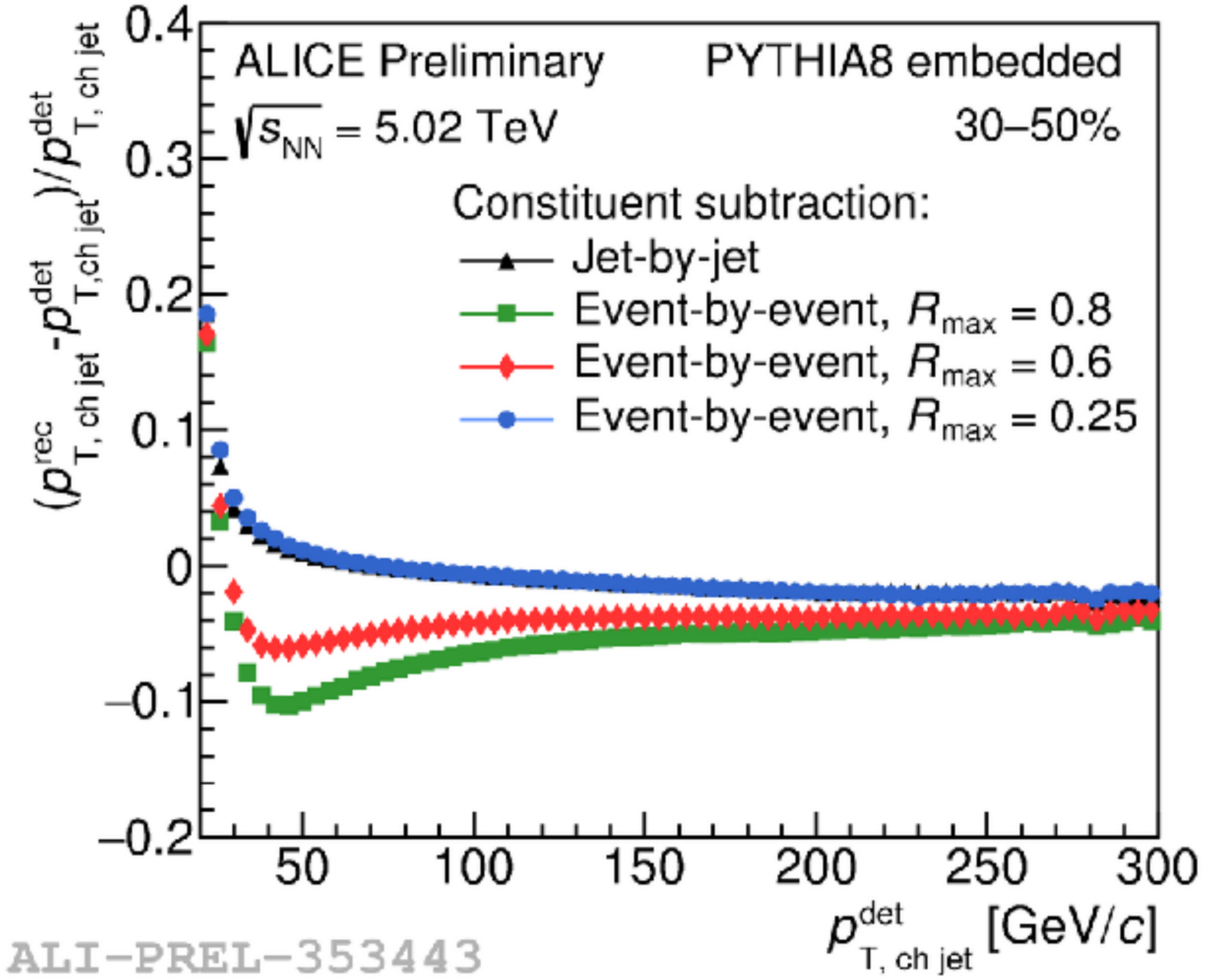

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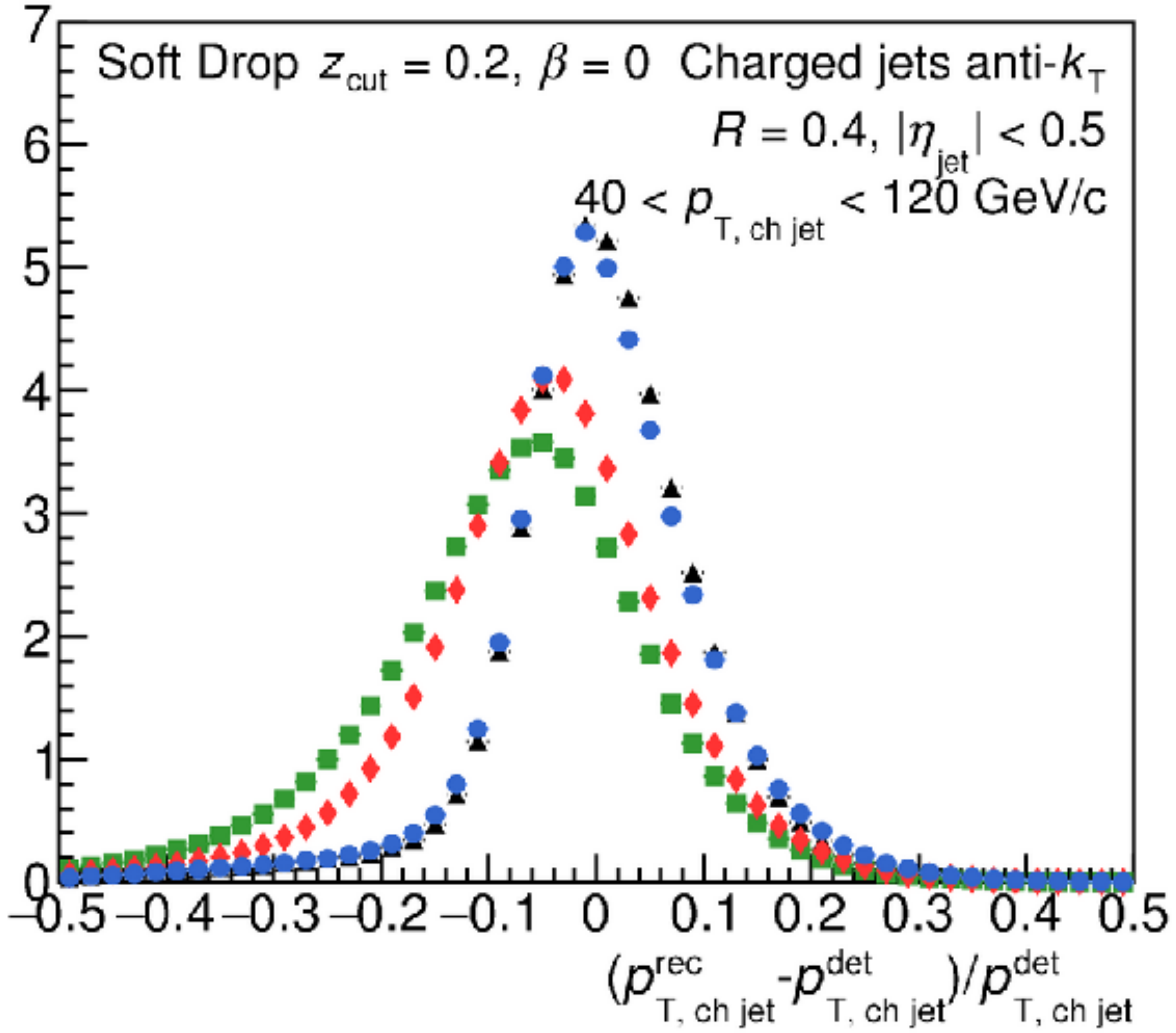
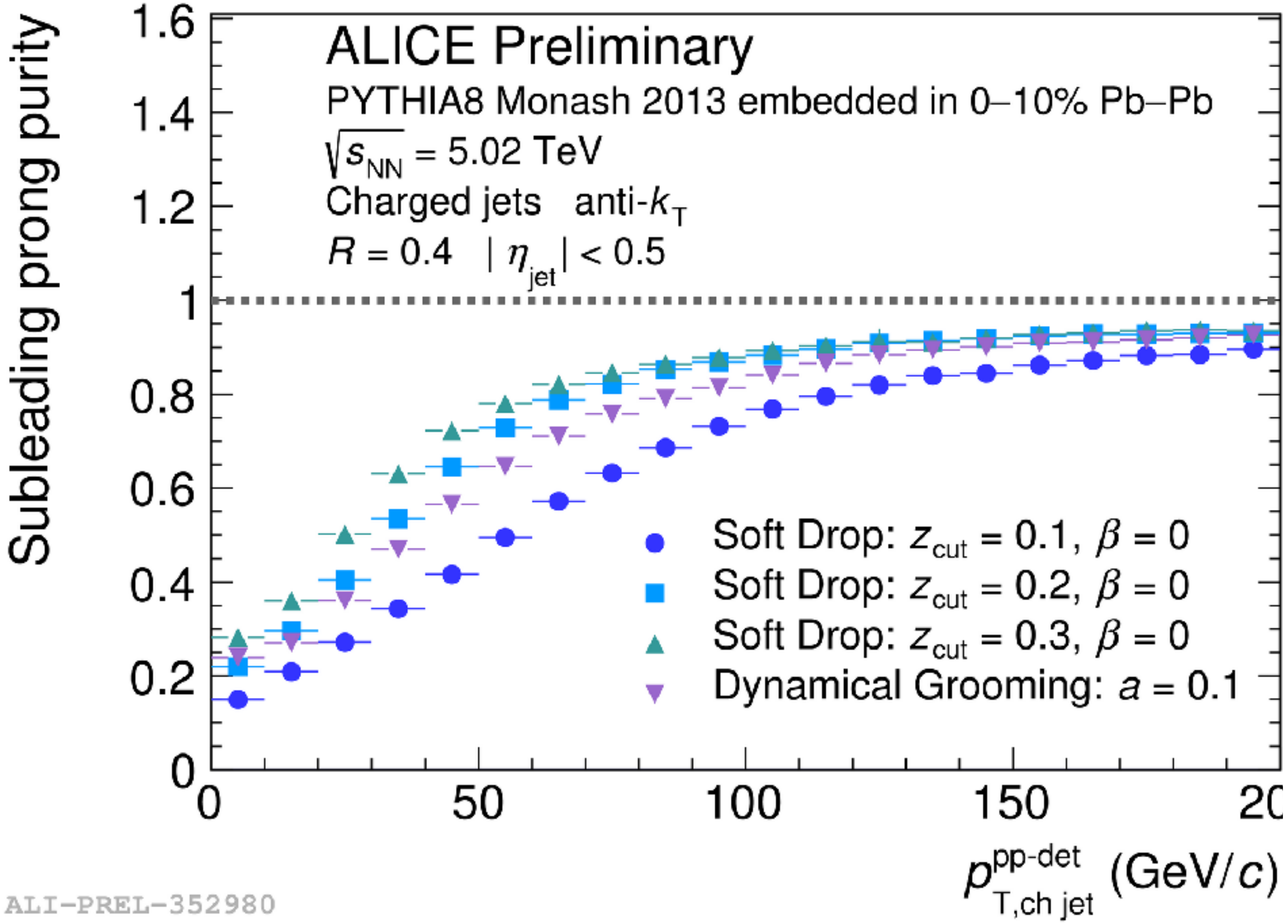


Background treatment

$60 < p_{\mathrm{T}}^{\mathrm{ch}} < 80$ GeV



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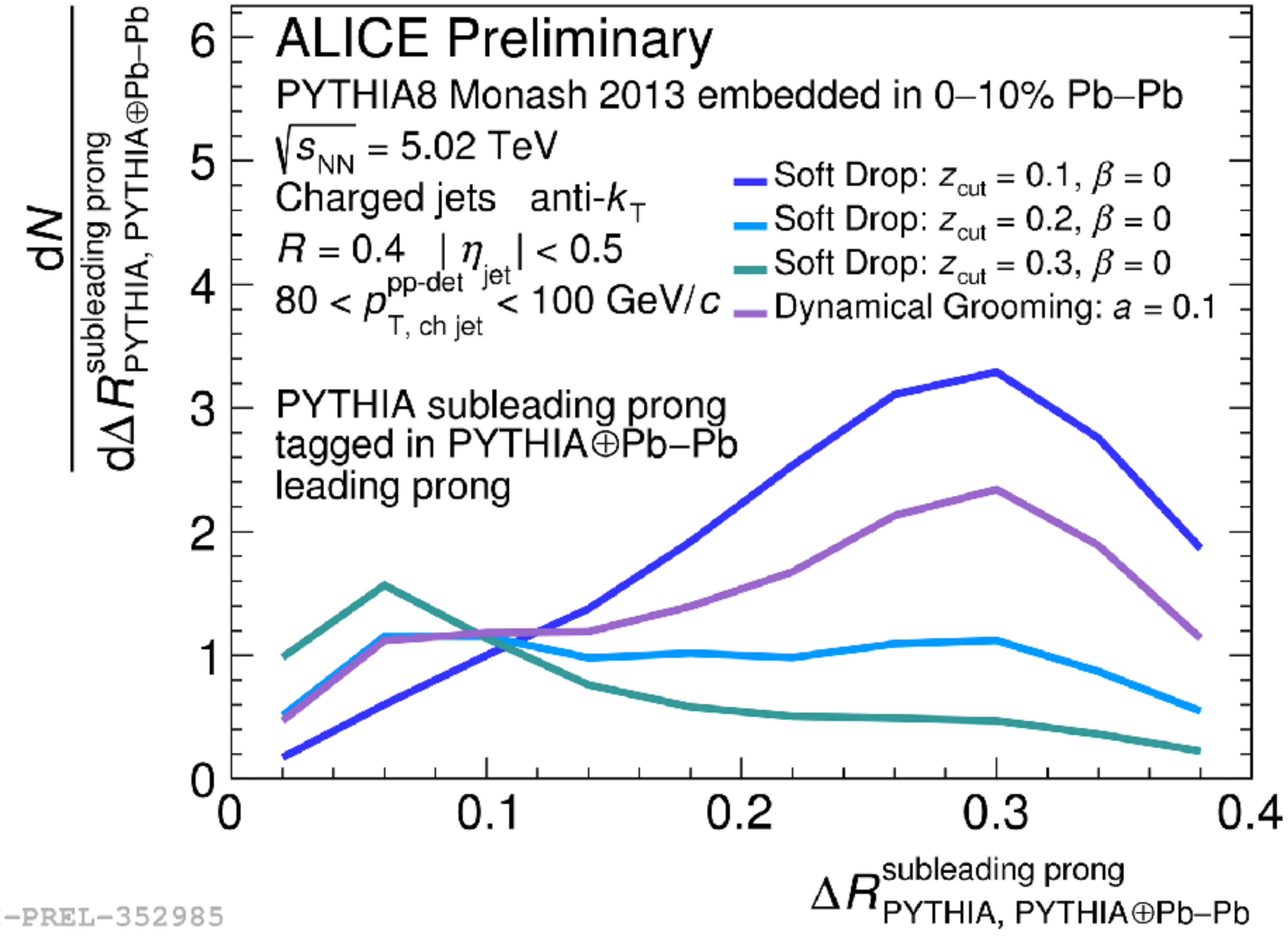

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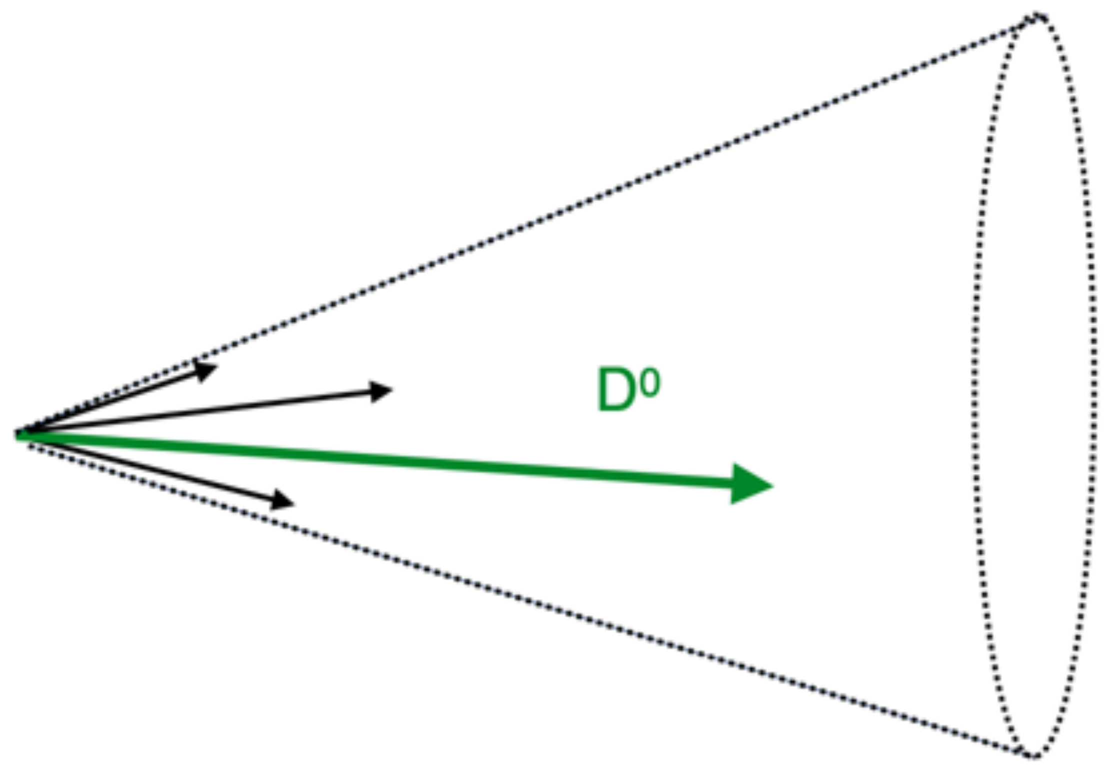
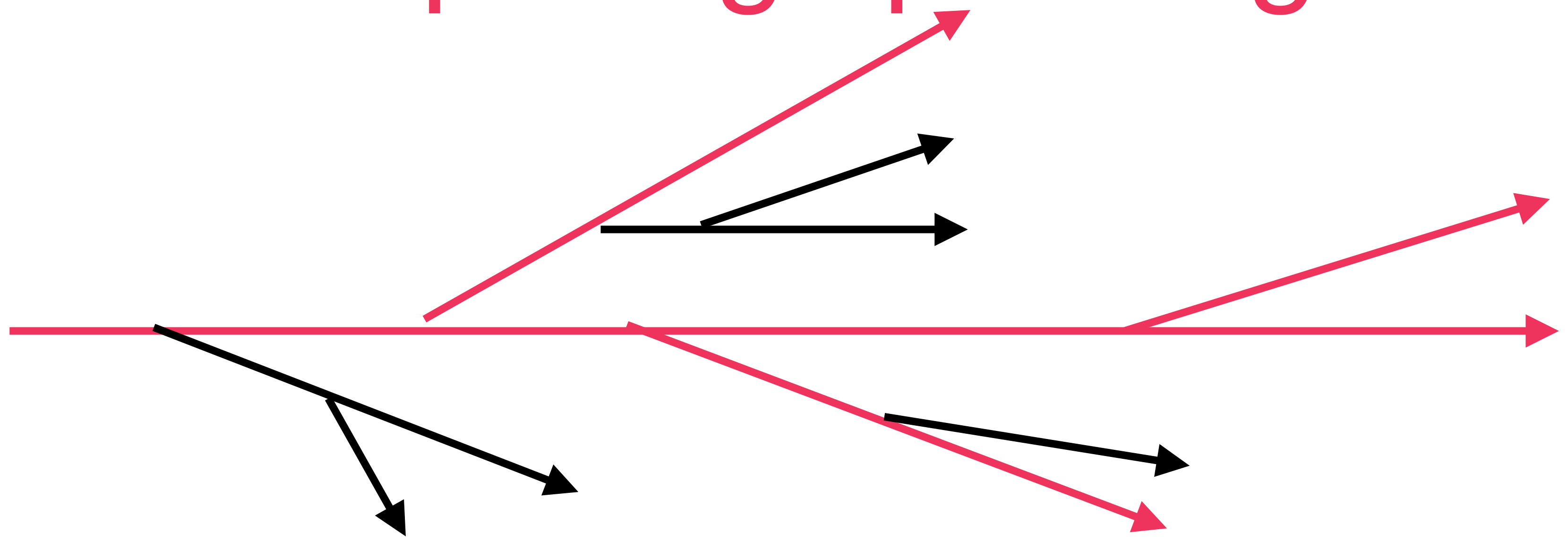
Heavy-flavor jet substructure in pp

ALICE-PUBLIC-2020-002

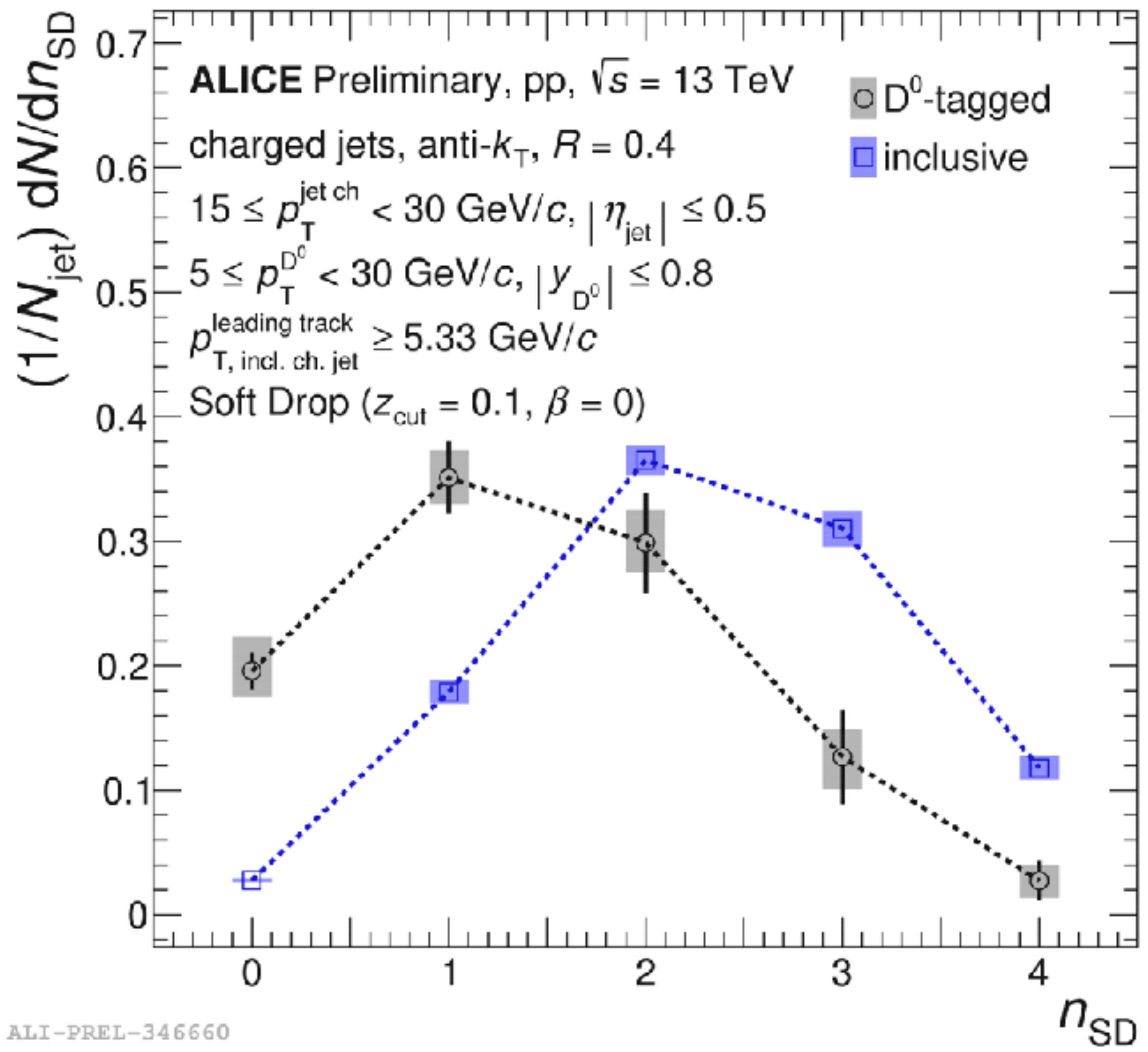
- Measure groomed jet substructure for D^0-tagged jets compared to inclusive jets to compare quark jets (i.e. charm) with inclusive jets
  - ▸ quarks should have a harder fragmentation and be more collimated



➡ n_{SD}: number of splittings passing SD

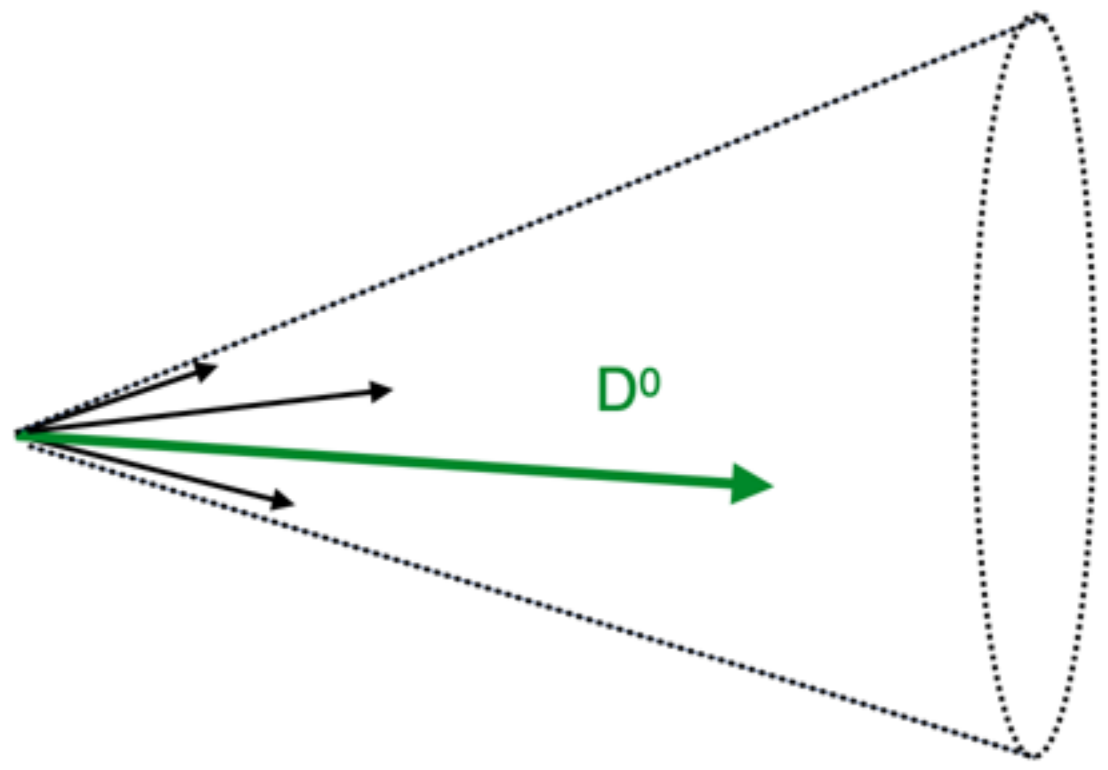


- Flavor dependence observed: harder fragment of charm quarks vs. inclusive jets



Heavy-flavor jet substructure in pp

ALICE-PUBLIC-2020-002



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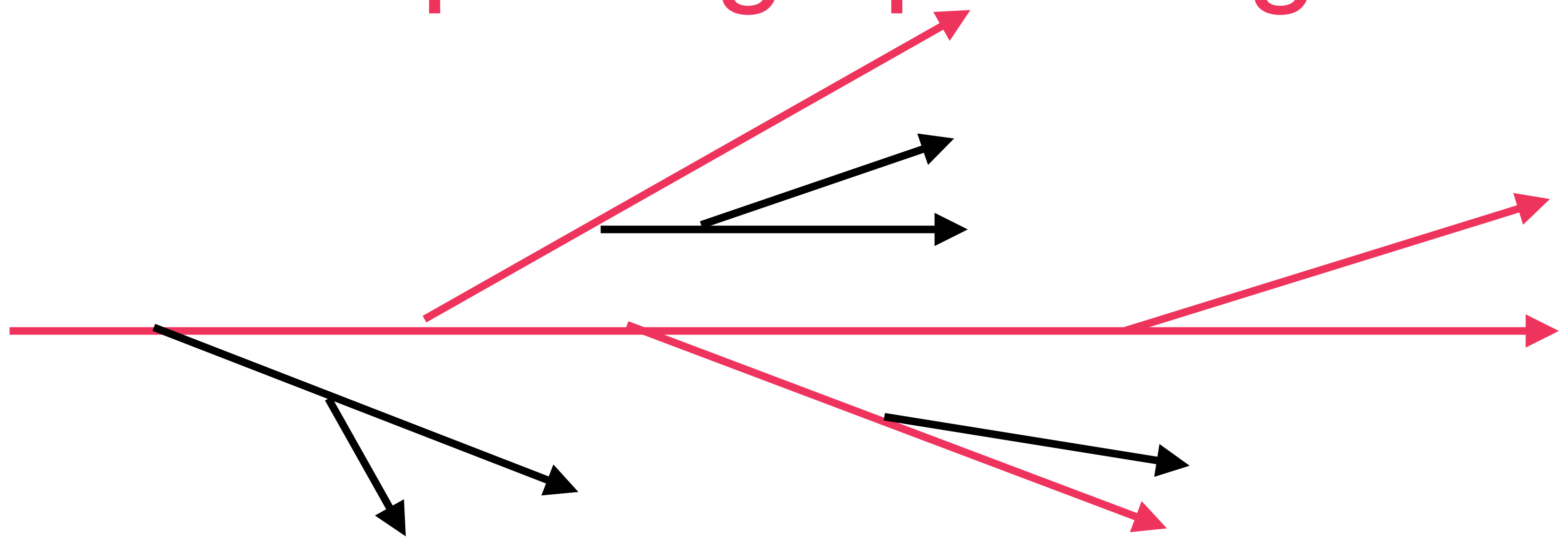
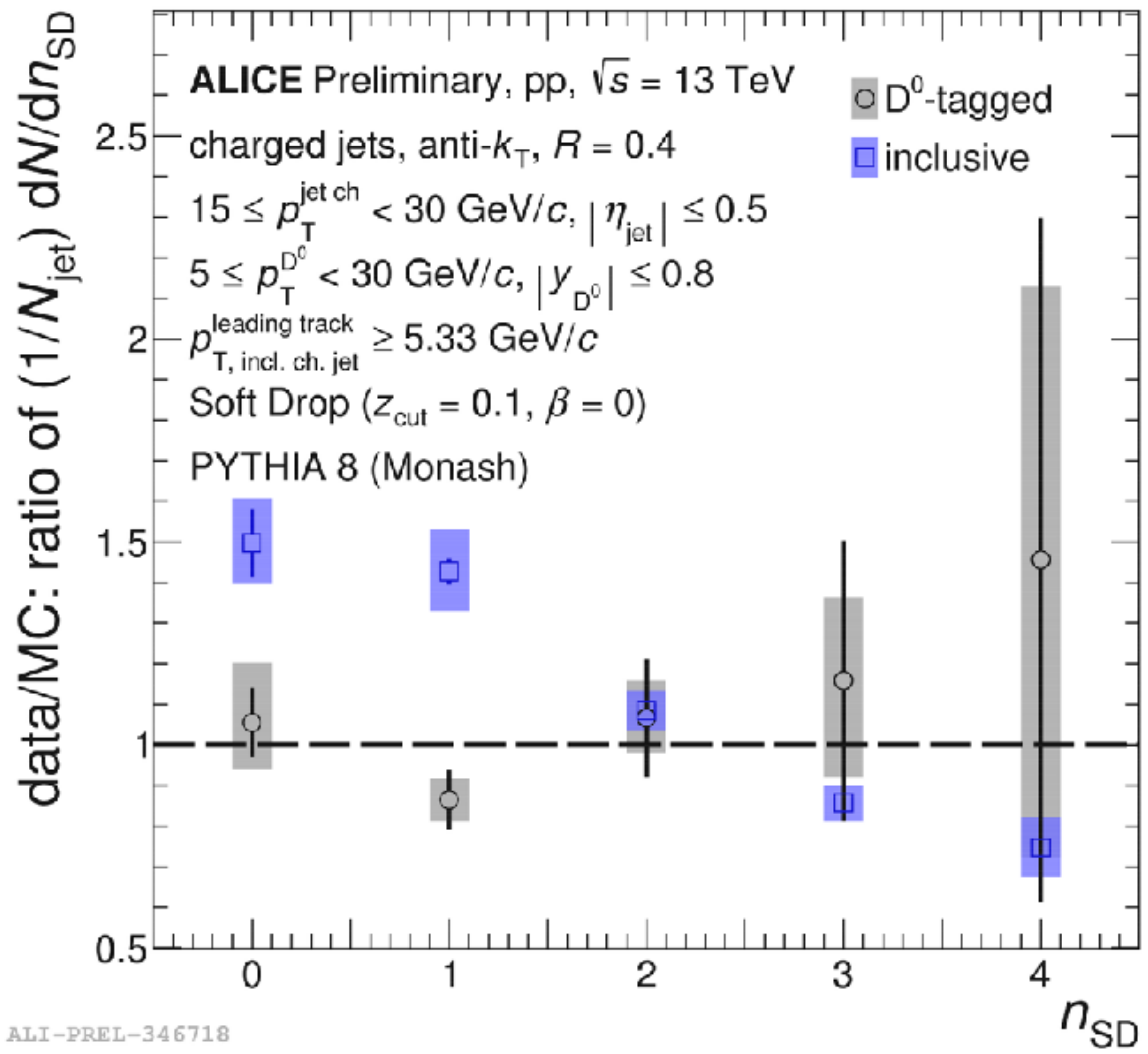


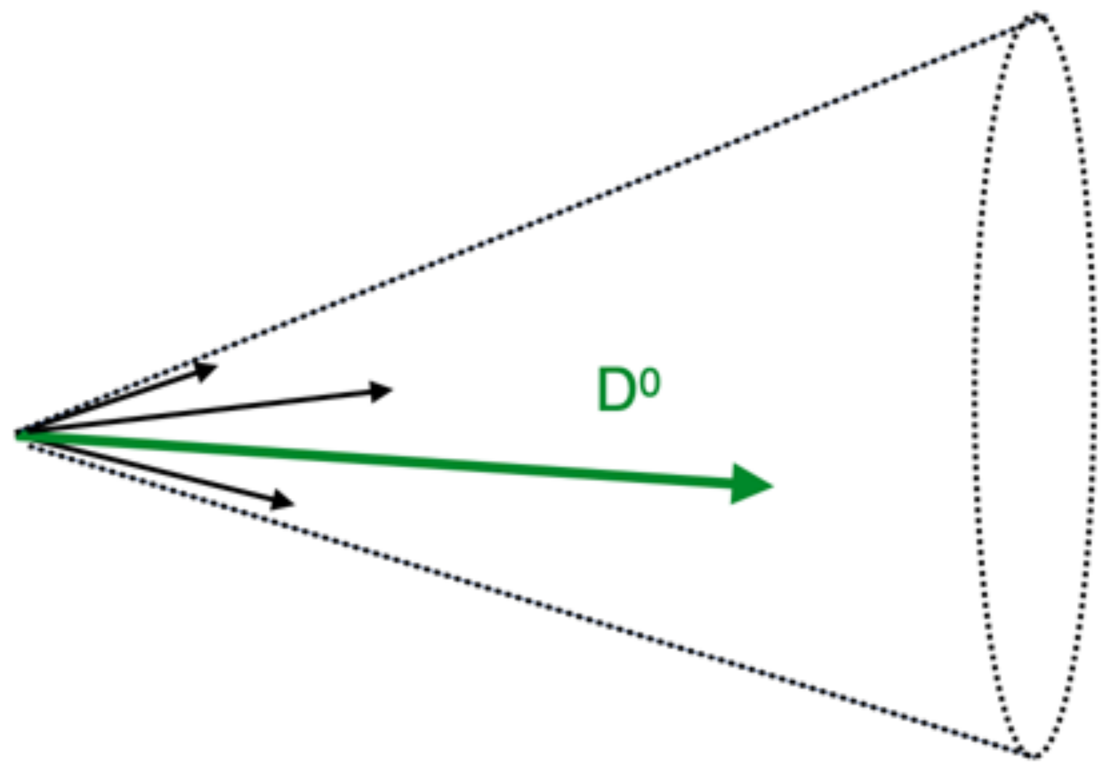
- Flavor dependence observed: harder fragment of charm quarks vs. inclusive jets
- PYTHIA mostly describes D^0-tagged but not inclusive



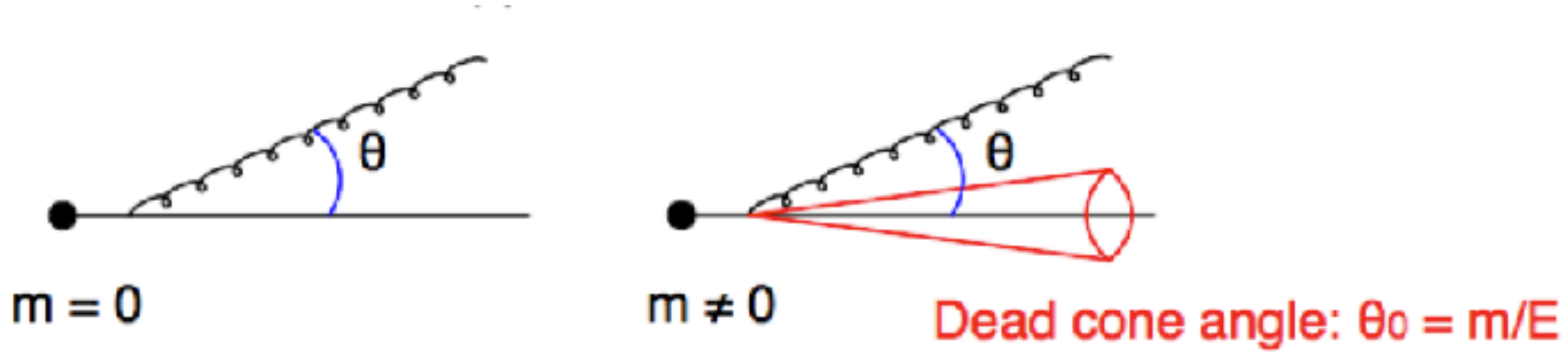
ALI-PREL-346718

Heavy-flavor jet substructure in pp

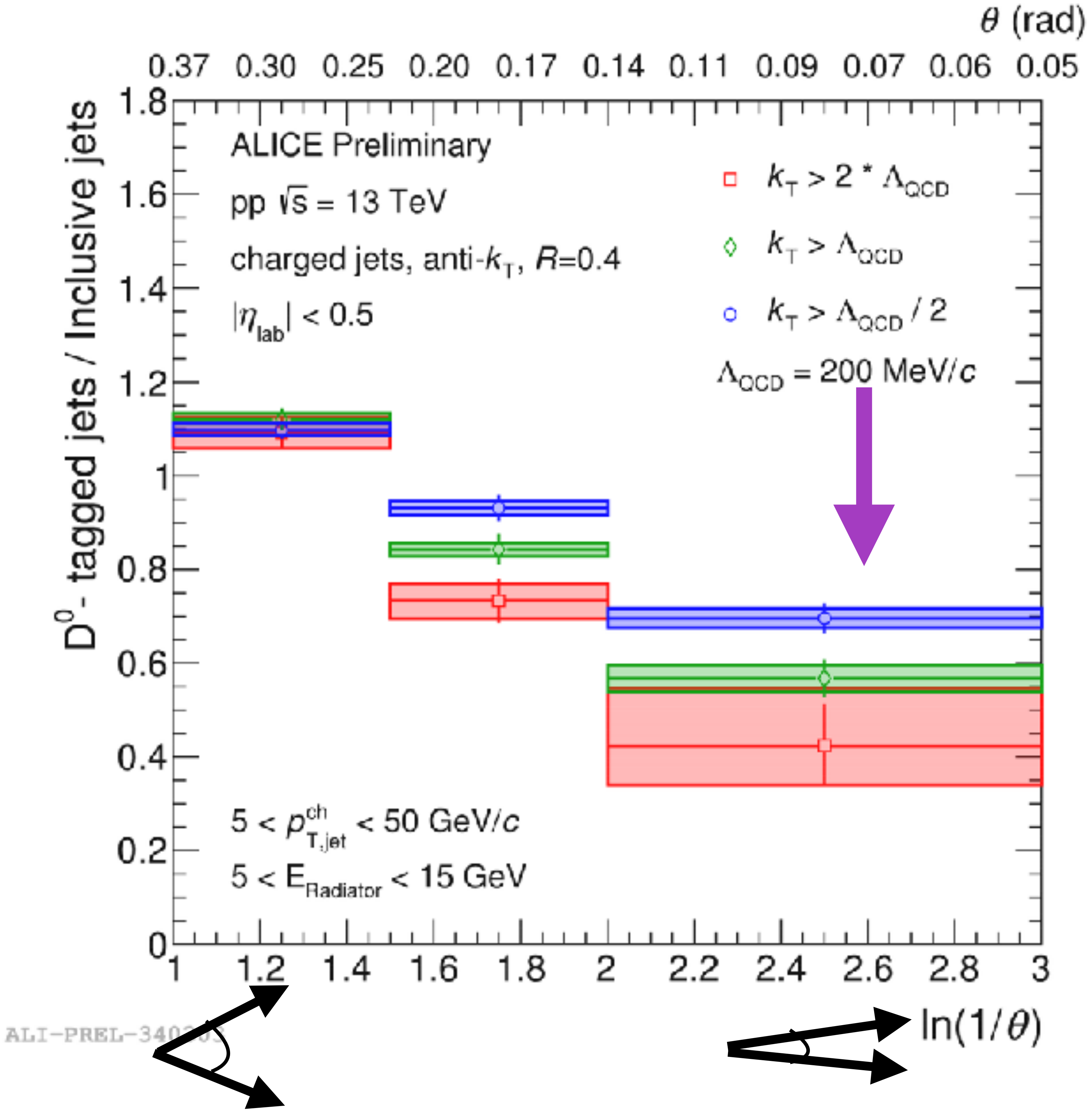
- Measure groomed jet substructure for D⁰-tagged jets compared to inclusive jets to compare quark jets (i.e. charm) with inclusive jets



- Dead cone effect: suppression of emissions from a radiator (quark) with, $\theta < \frac{m_q}{E_q}$



- Comparing projections of the Lund plane should see a suppression at small angles for heavy quarks   Cunqueiro, Ploskon PRD 99, 074027
  - Significant suppression at small angles!

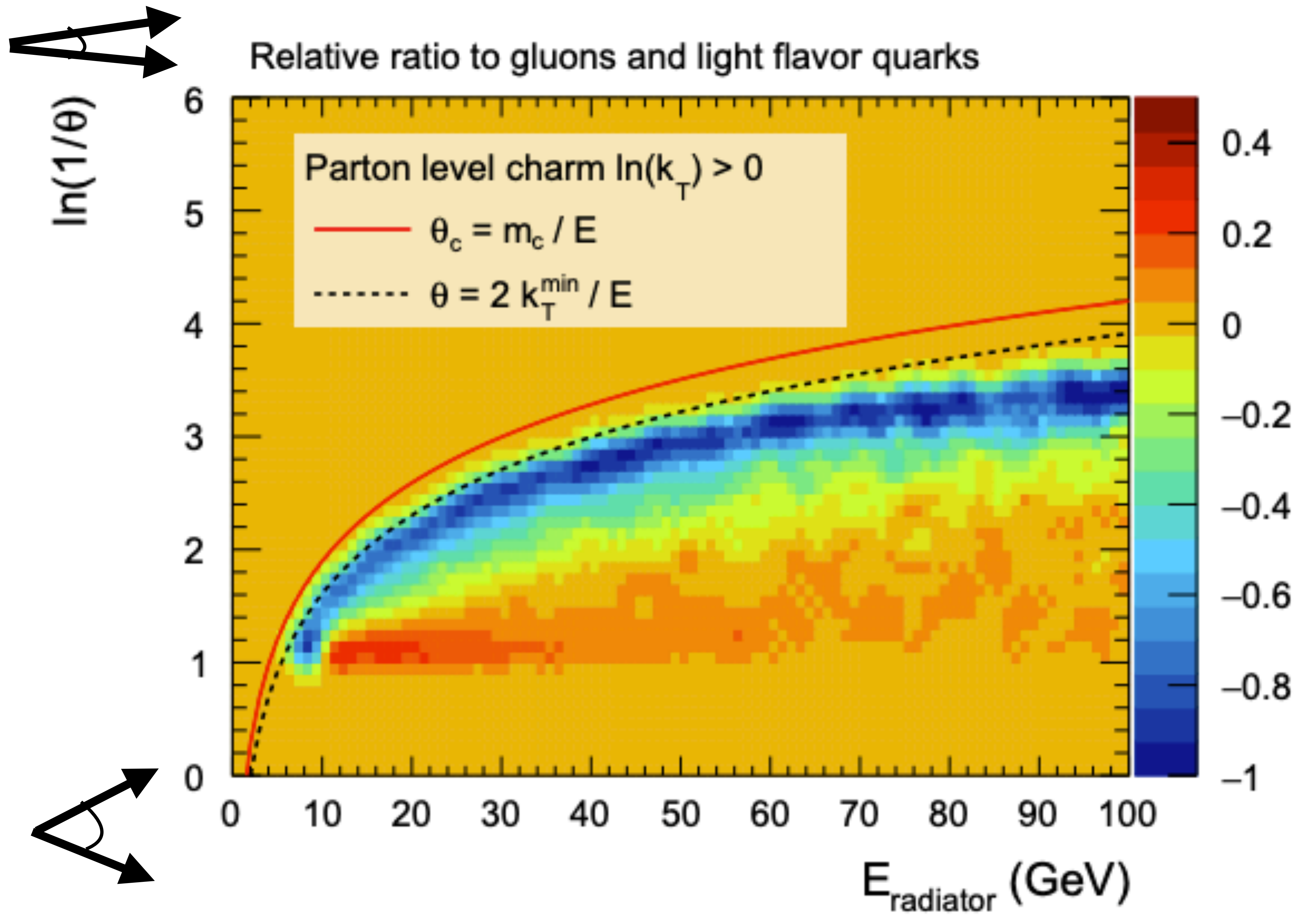


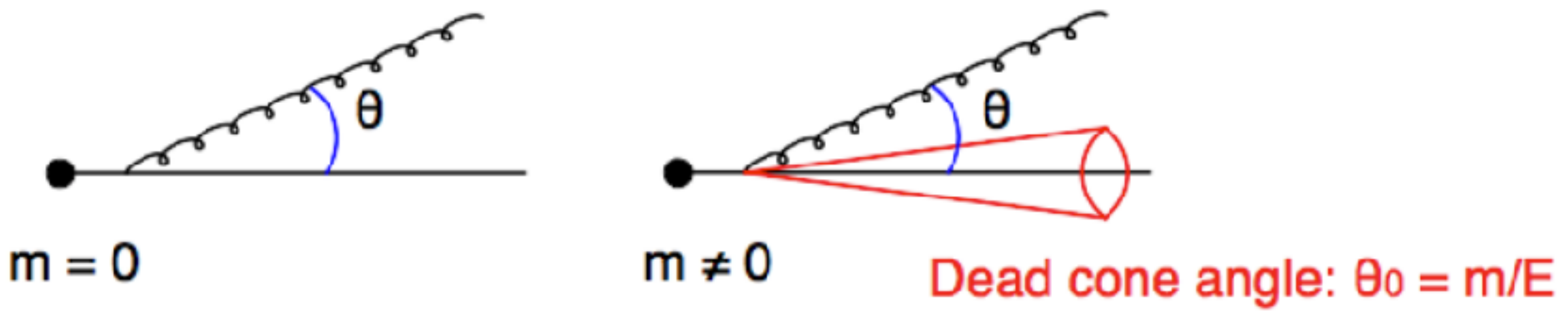
Heavy-flavor jet tagged Lund plane

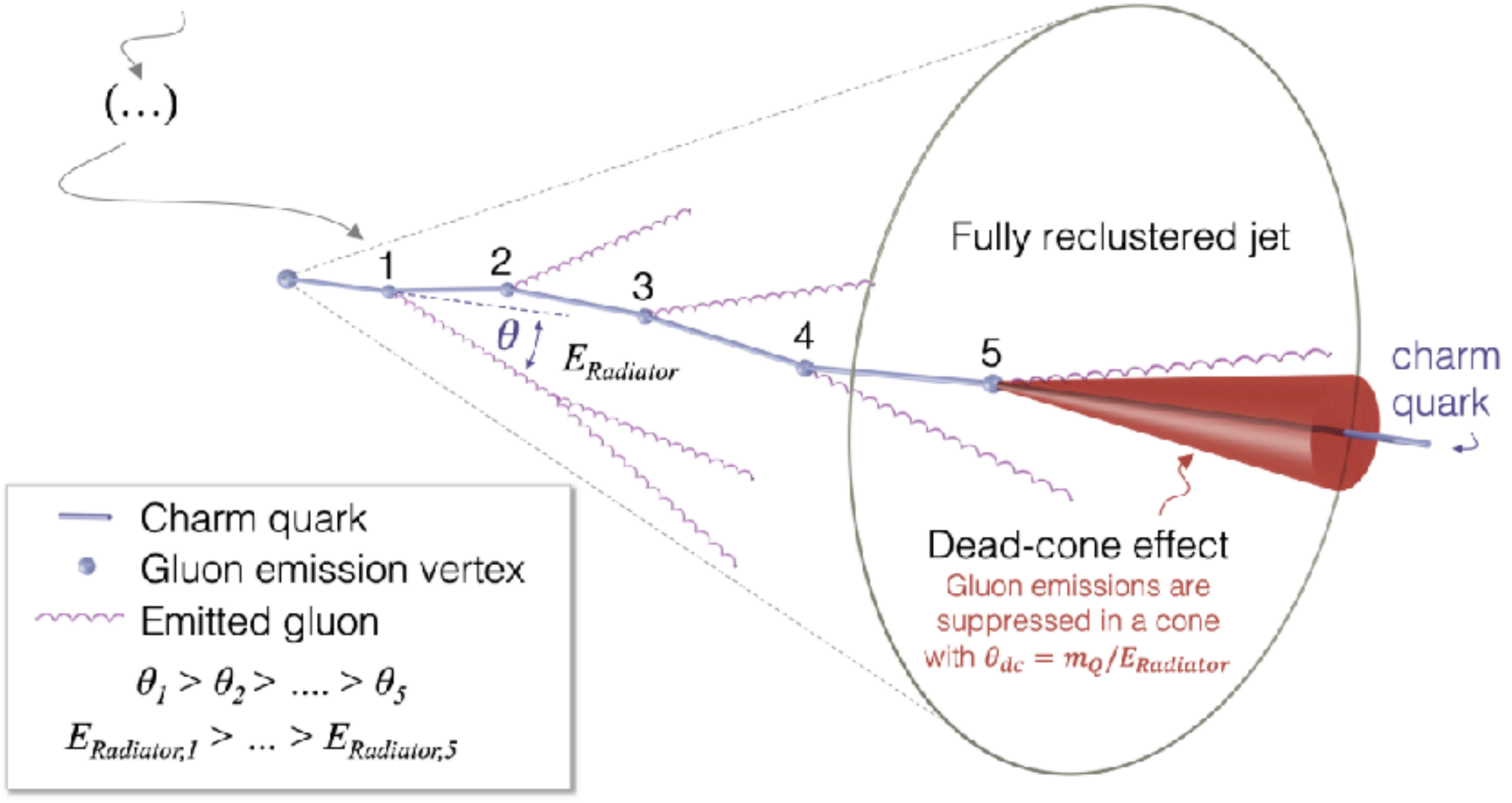
- Lund plane for D⁰-tagged (charm) jets compared to inclusive jets
- Dead cone effect: suppression of emissions from a radiator (quark) with,

$$\theta < \frac{m_q}{E_q}$$

Cunqueiro, Ploskon PRD 99, 074027





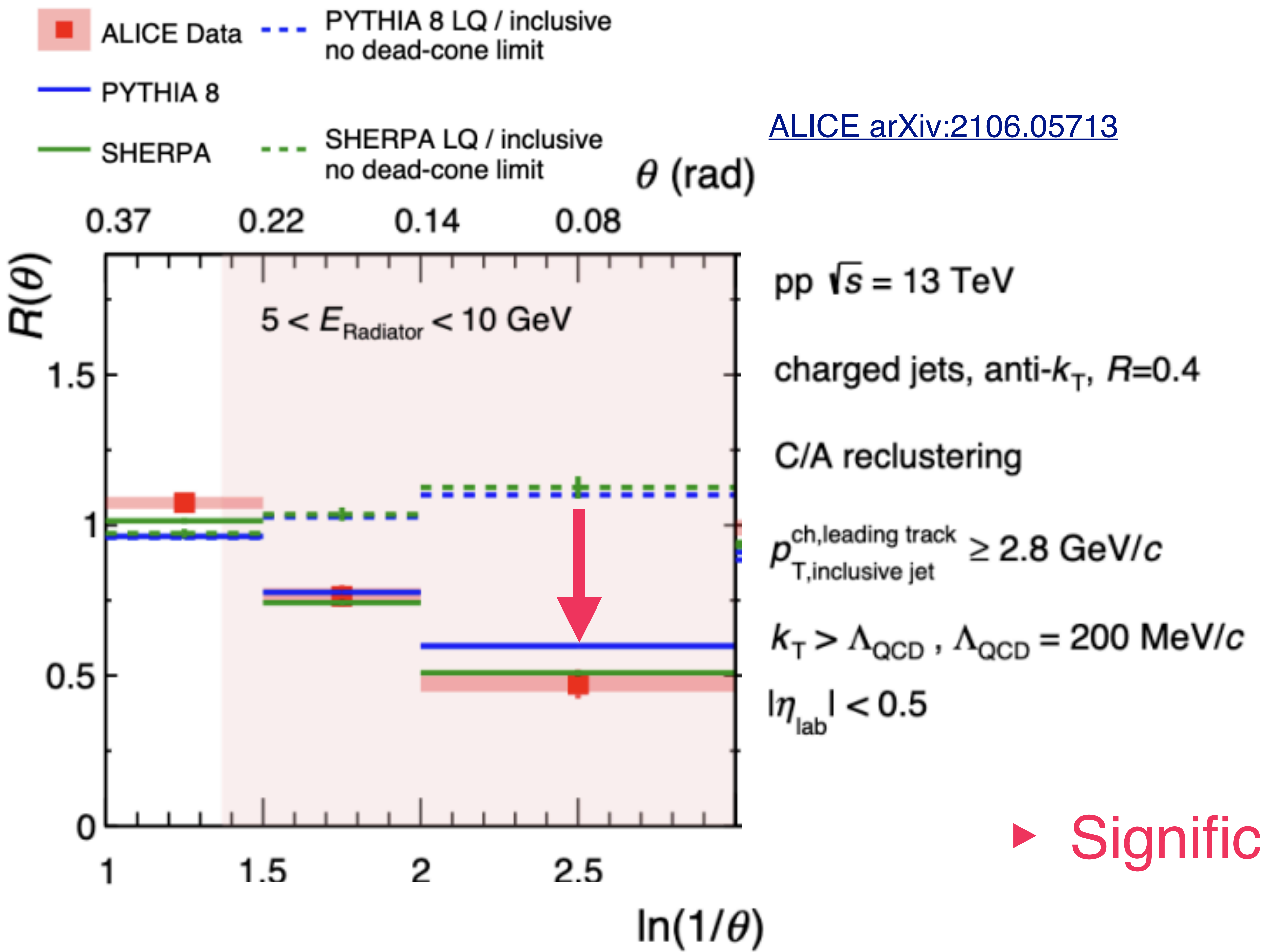


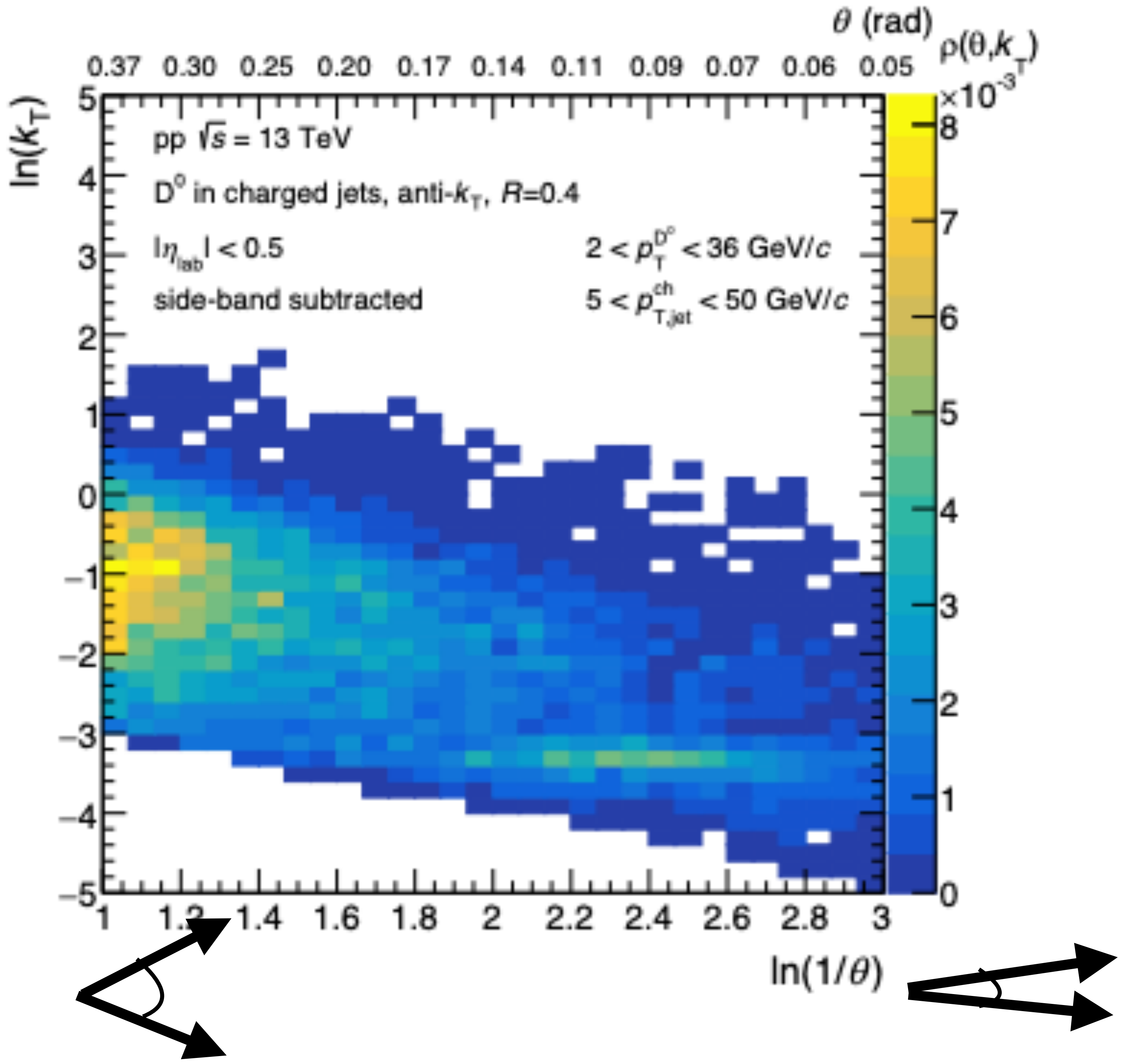
- Expect a suppression at small angles for heavy quarks

Lund plane: dead cone effect

- Lund plane for D⁰-tagged (charm) jets compared to inclusive jets

ALICE arXiv:2106.05713

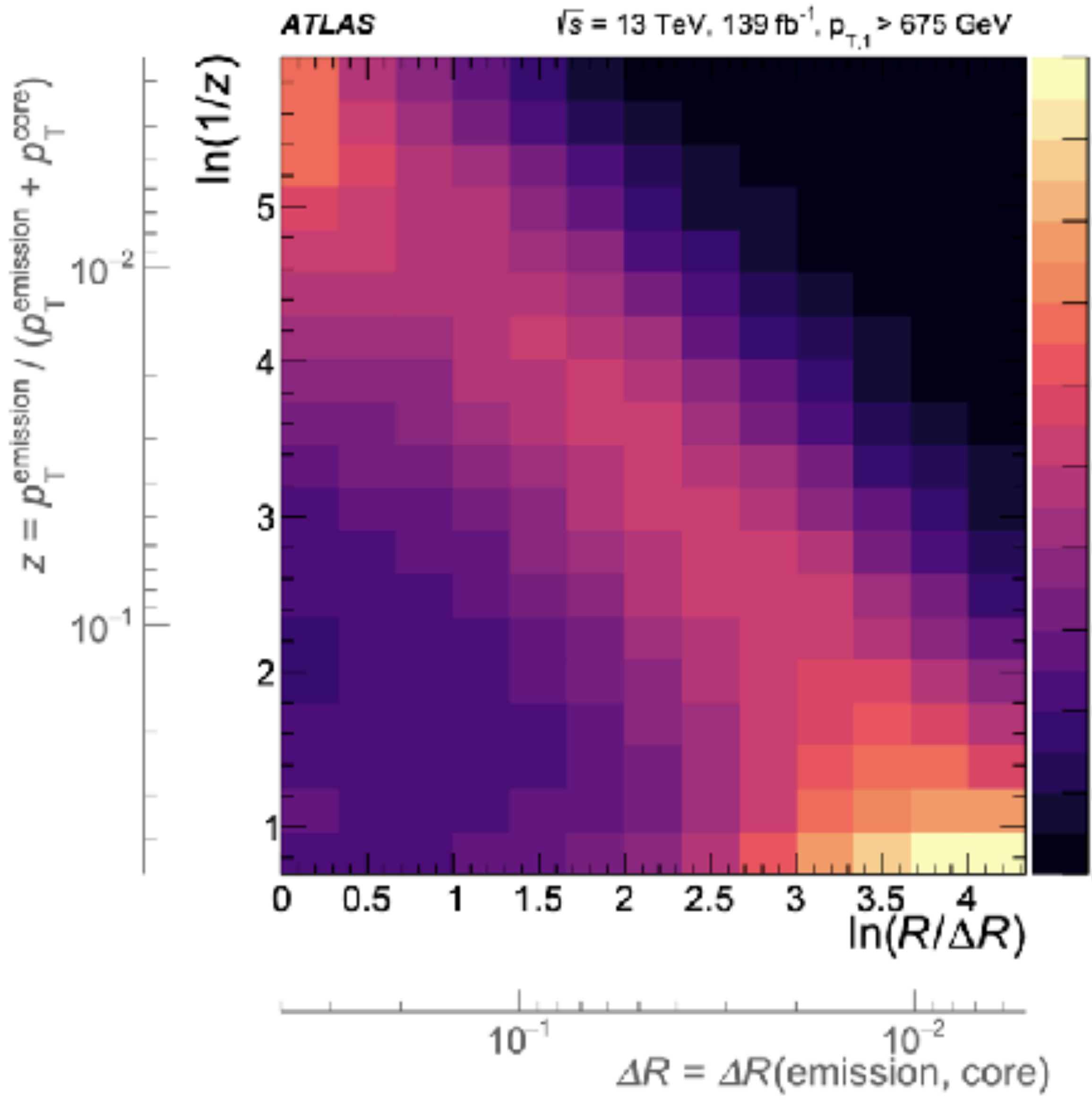


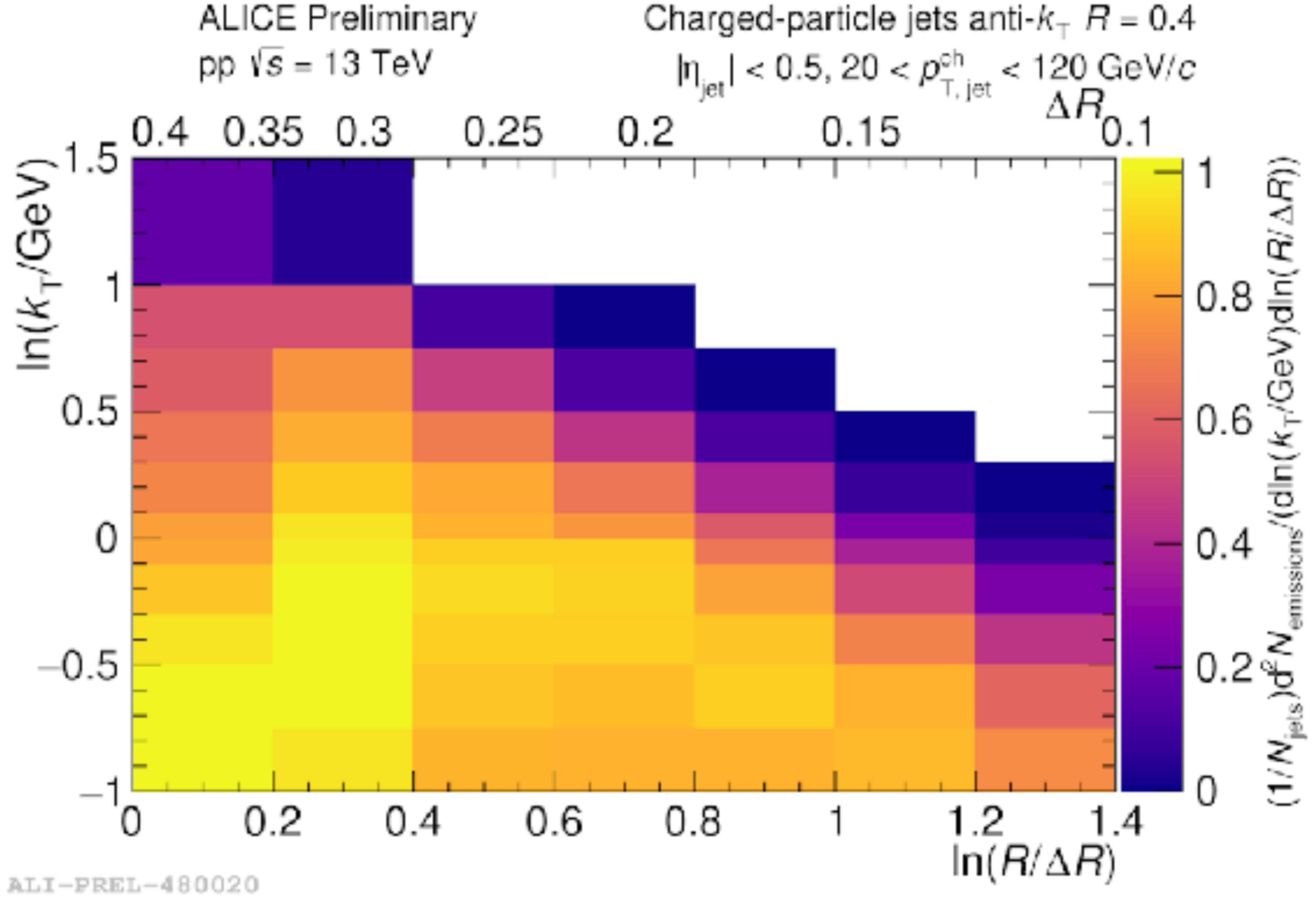


- Significant suppression at small angles!

Lund plane density: pp collisions

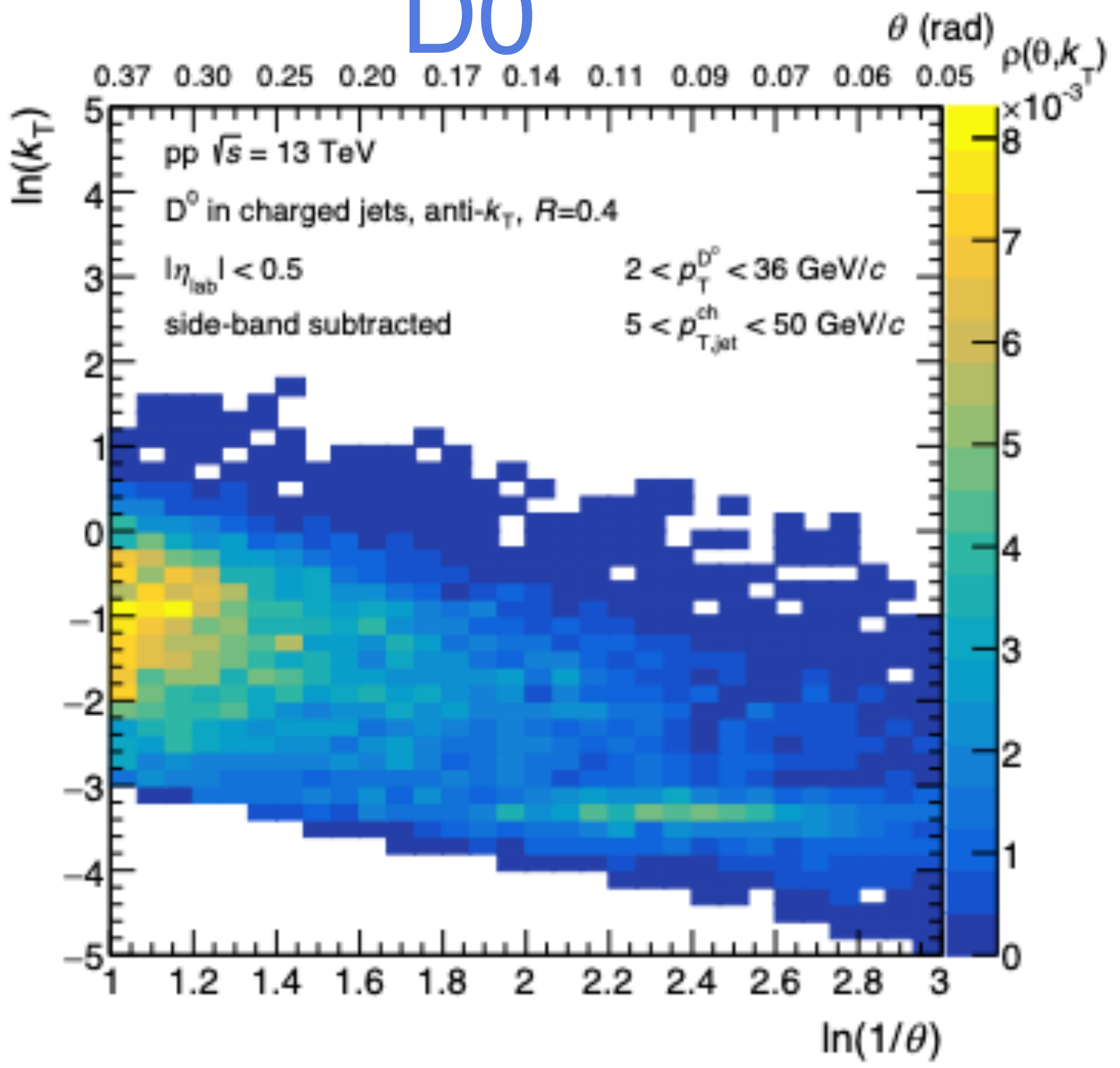
Inclusive





ATLAS PRL 124 (2020) ALICE-PUBLIC-2021-002

D0



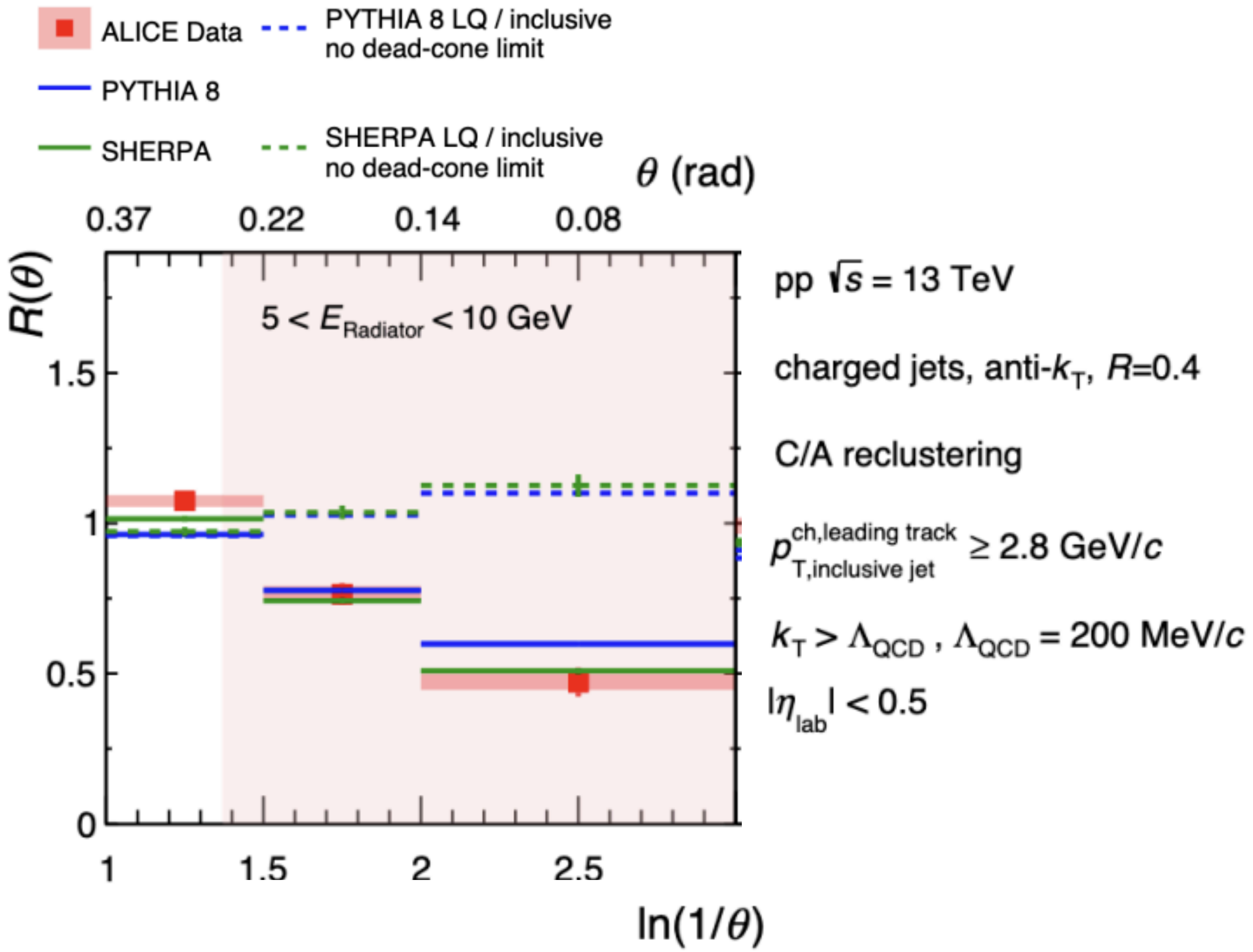
3D Lund plane (p_T, ln(k_T), ln(R/ΔR)) unfolded in ATLAS and ALICE (intermediate and high p_T!)

Requires high statistics and excellent angular resolution: unfolding in multi-dimensions with omnifold?

Λc, B+, etc. in ALICE 3?

D0-tagged Lund plane: direct observation of dead cone effect at small angles!

Nature 605 (2022) 440-446



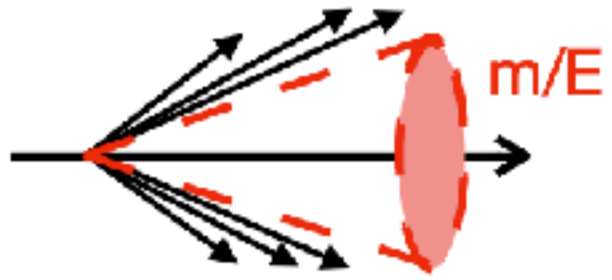
Heavy-flavor jet substructure in HIs

Grooming selects hardest split and suppresses HI background

- Inclusive substructure in Pb-Pb and D0-tagged HF jet substructure measurements in pp already underway

- Can this be measured in HIs?
  - Goal for Run 3 but with substantial gains in S/B purities for D0 and B this will be more precise at low p_T in ALICE 3

- Access dead-cone effects in HIs
  - Is the substructure of the jet less modified because of the dead-cone?



- Study background subtraction in HIs for subjets: explore small angles since dead cone signal is at small angles where background impact is smaller

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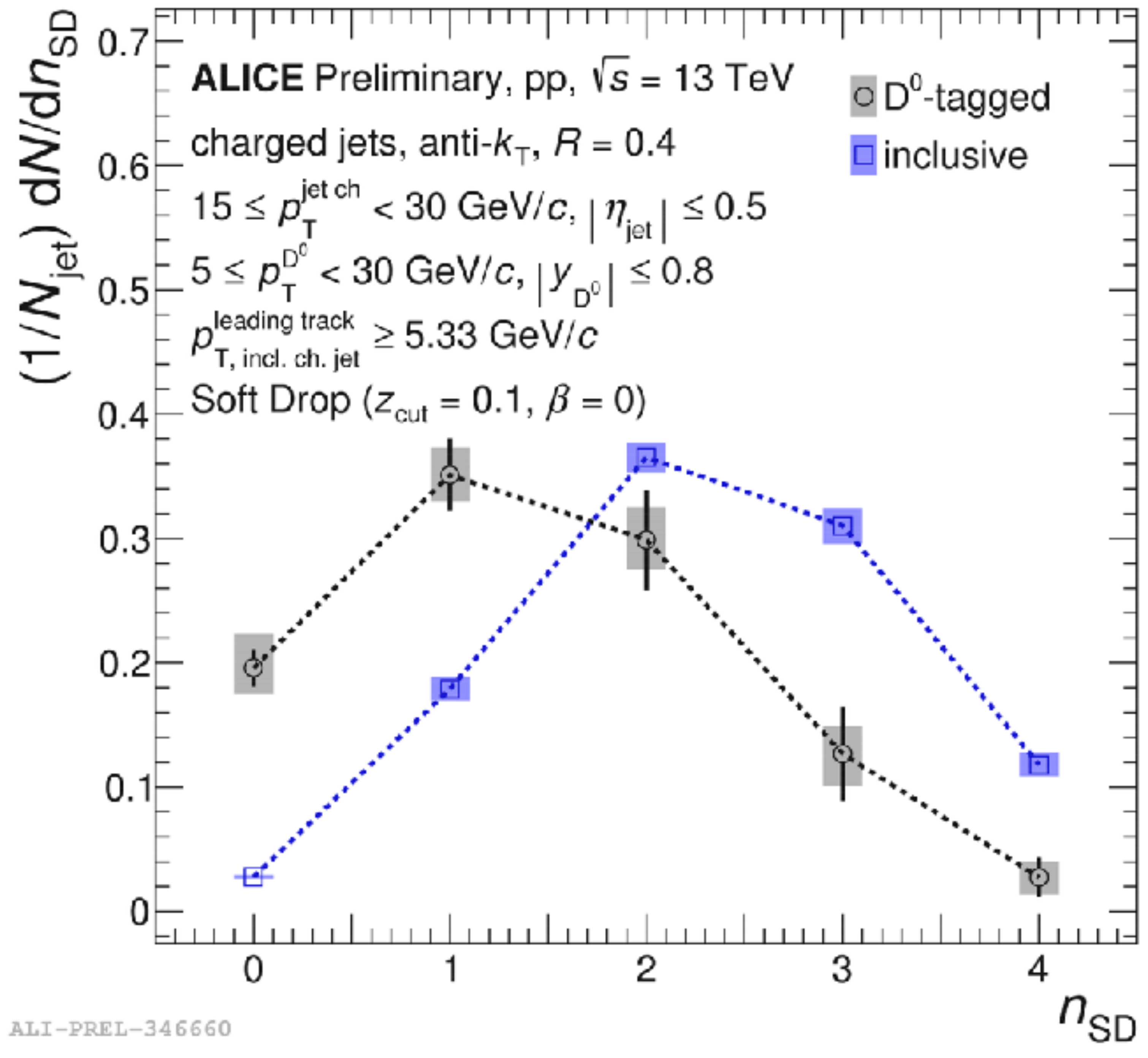

n_{SD}: number of splittings passing SD