Recent results on jets and high-p_T hadrons with ALICE

Laura Havener, Yale University
CERN EP LHC Seminar
Tuesday, June 30th, 2020

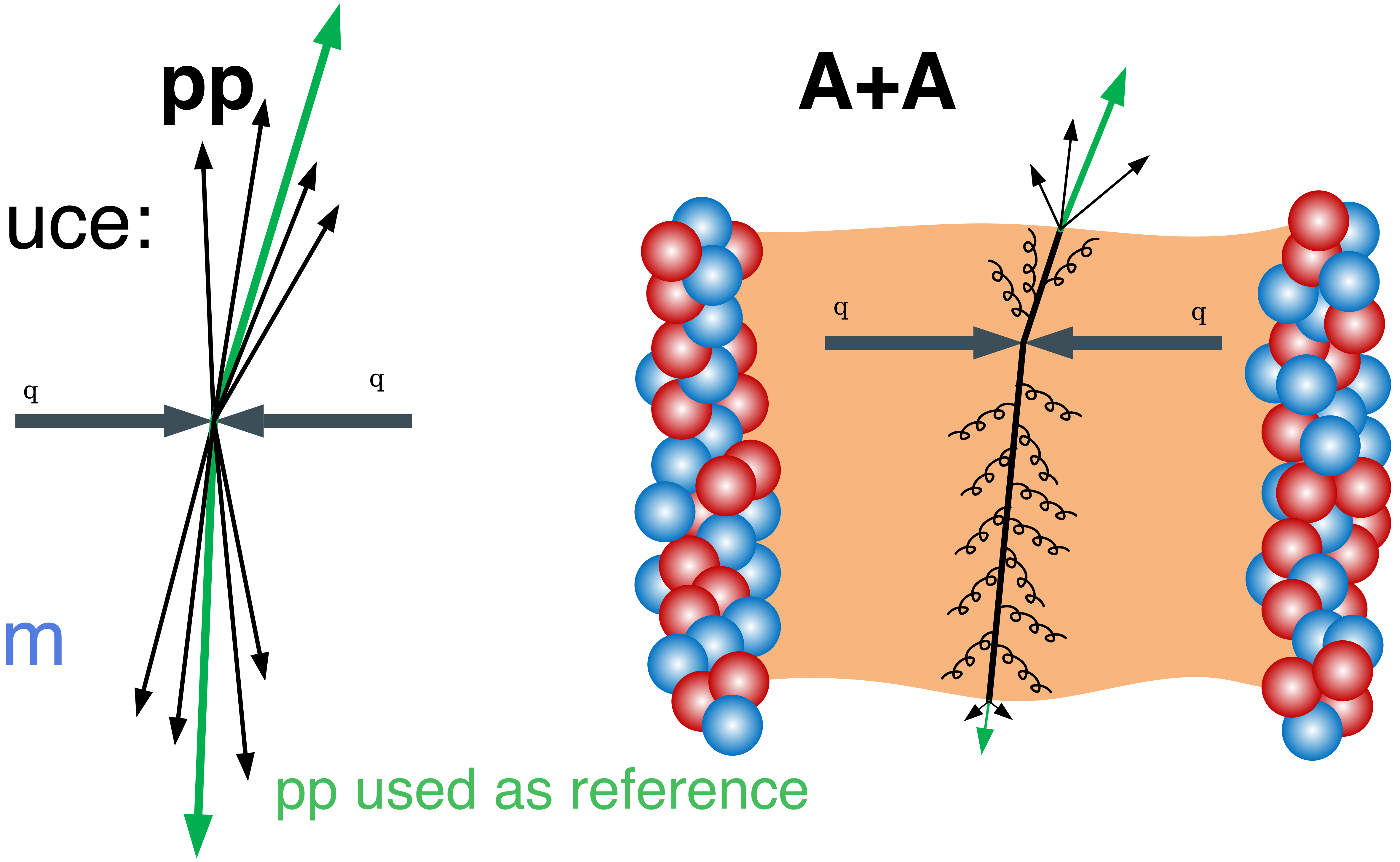
Jets in heavy-ion collisions

- Jet quenching: partons in heavy-ion (HI) collisions interact with the medium to produce:

➡jet energy loss

➡jet substructure modification

Depends on the path traveled in the medium



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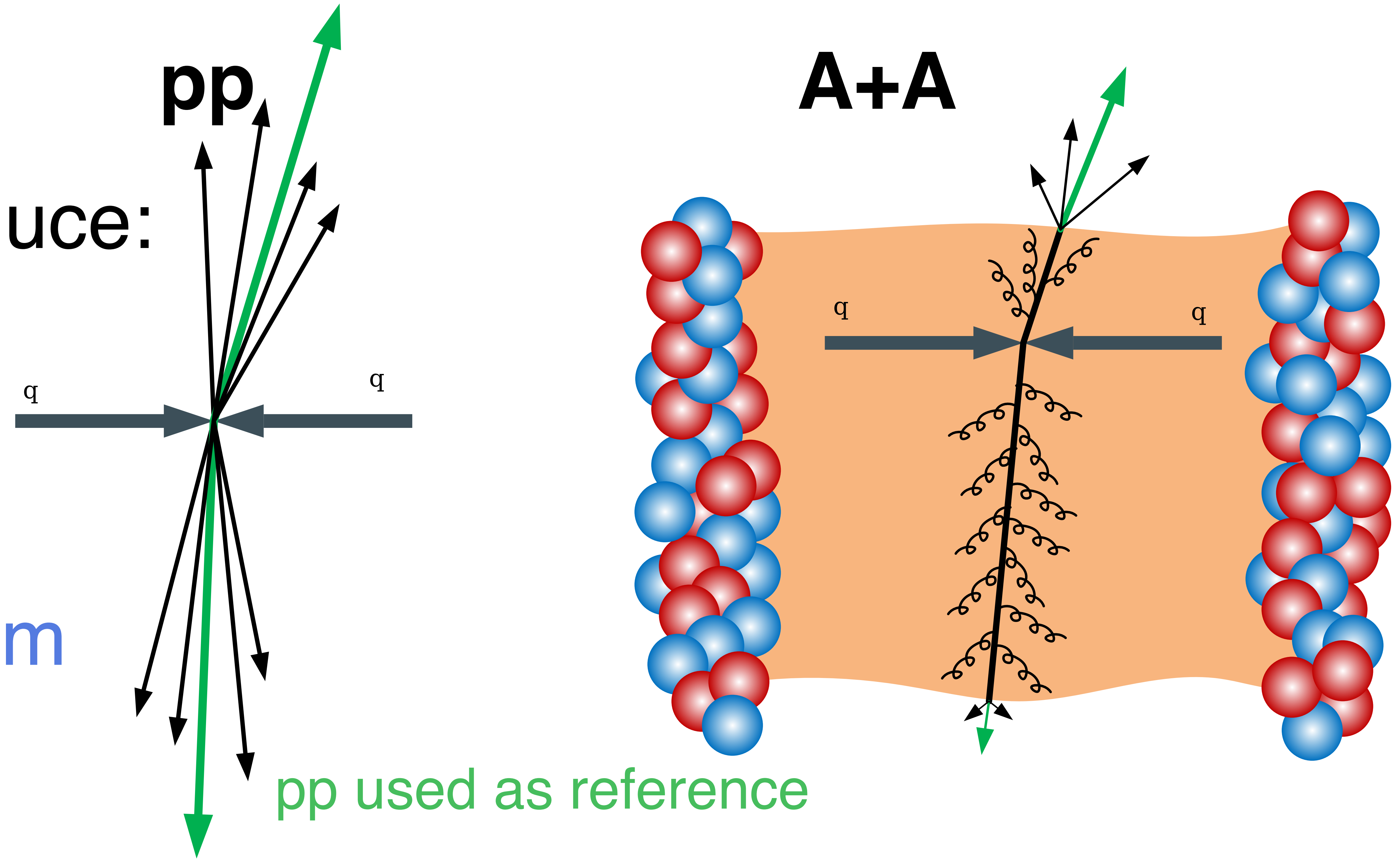
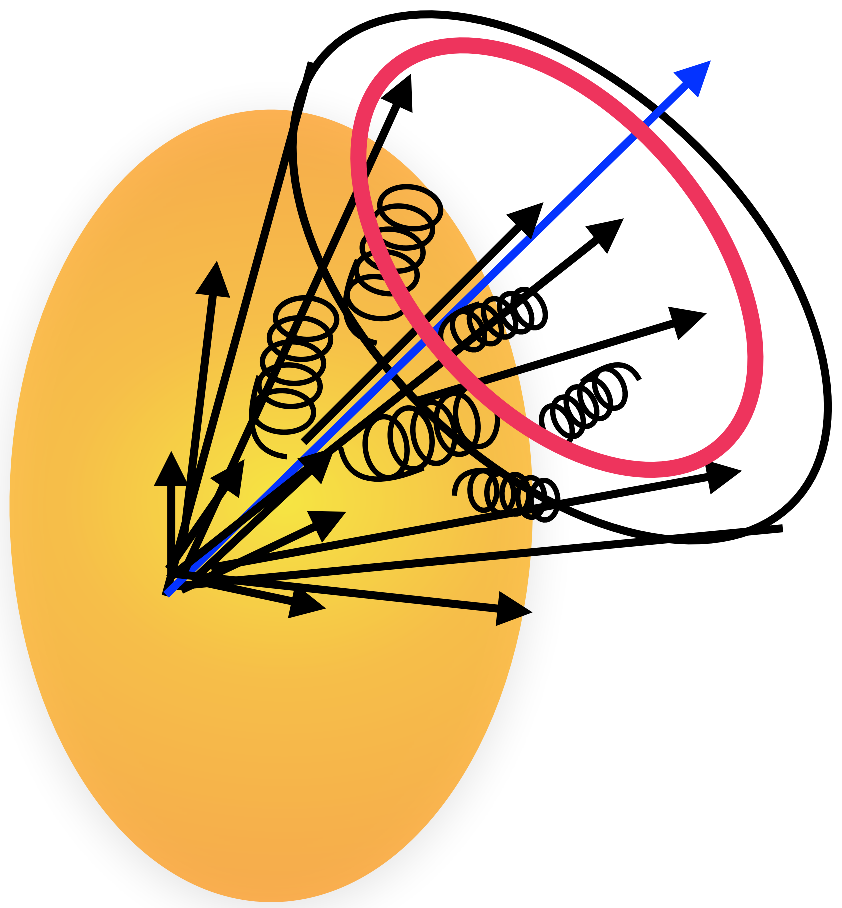


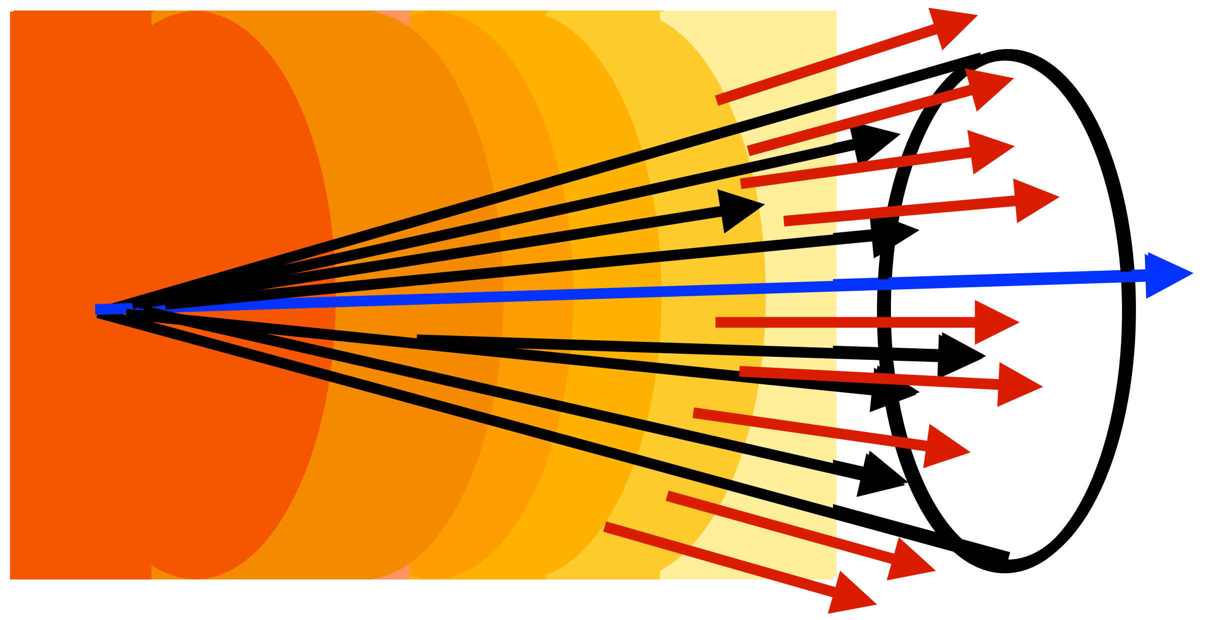
pp used as reference

- Jet-medium interactions:



➡Momentum broadening
- widens the jet
- e-loss outside jet cone

➡Wide-angle deflection

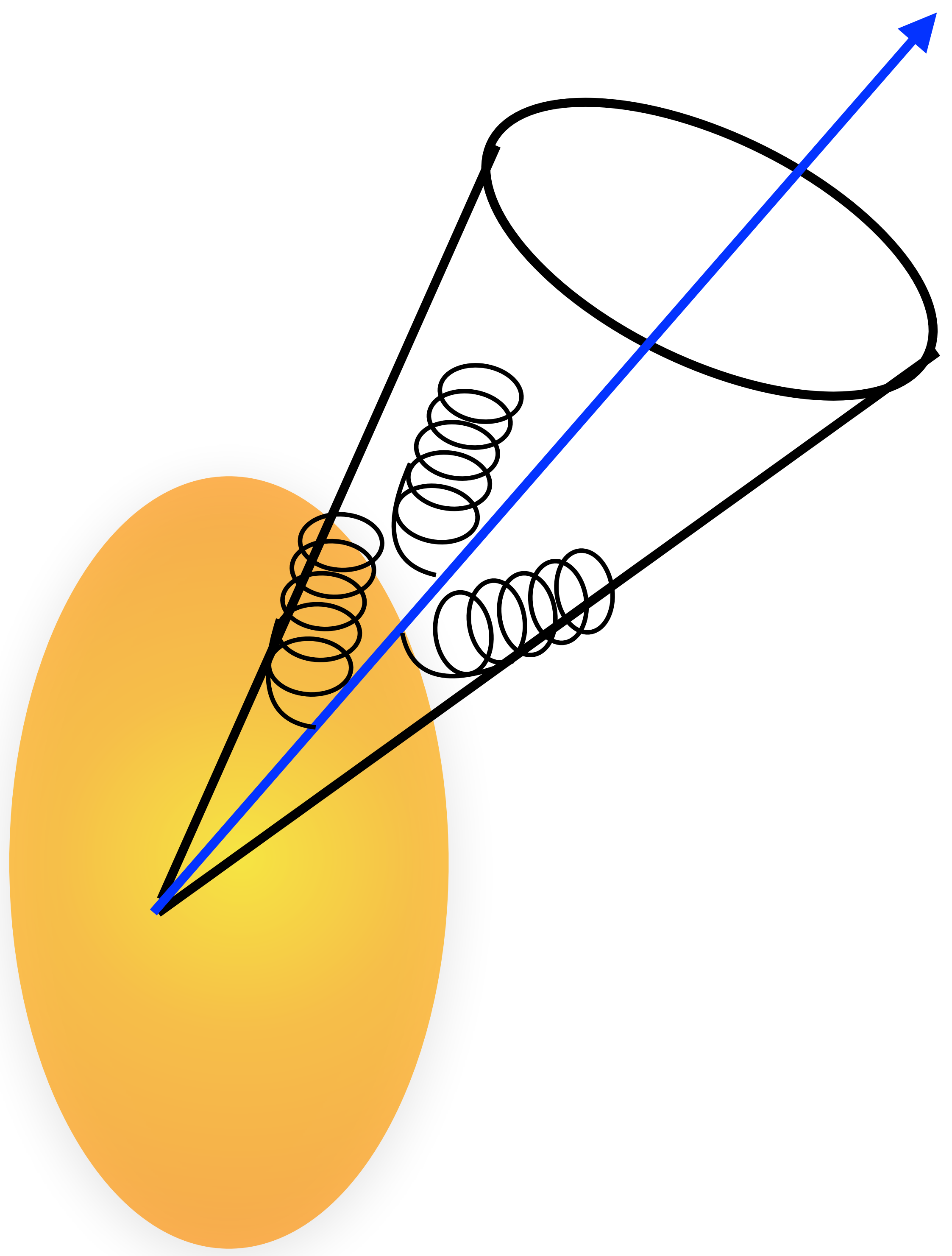


➡Medium response pushes soft particles back inside jet

Measuring jet quenching

- Measuring jet quenching includes:

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



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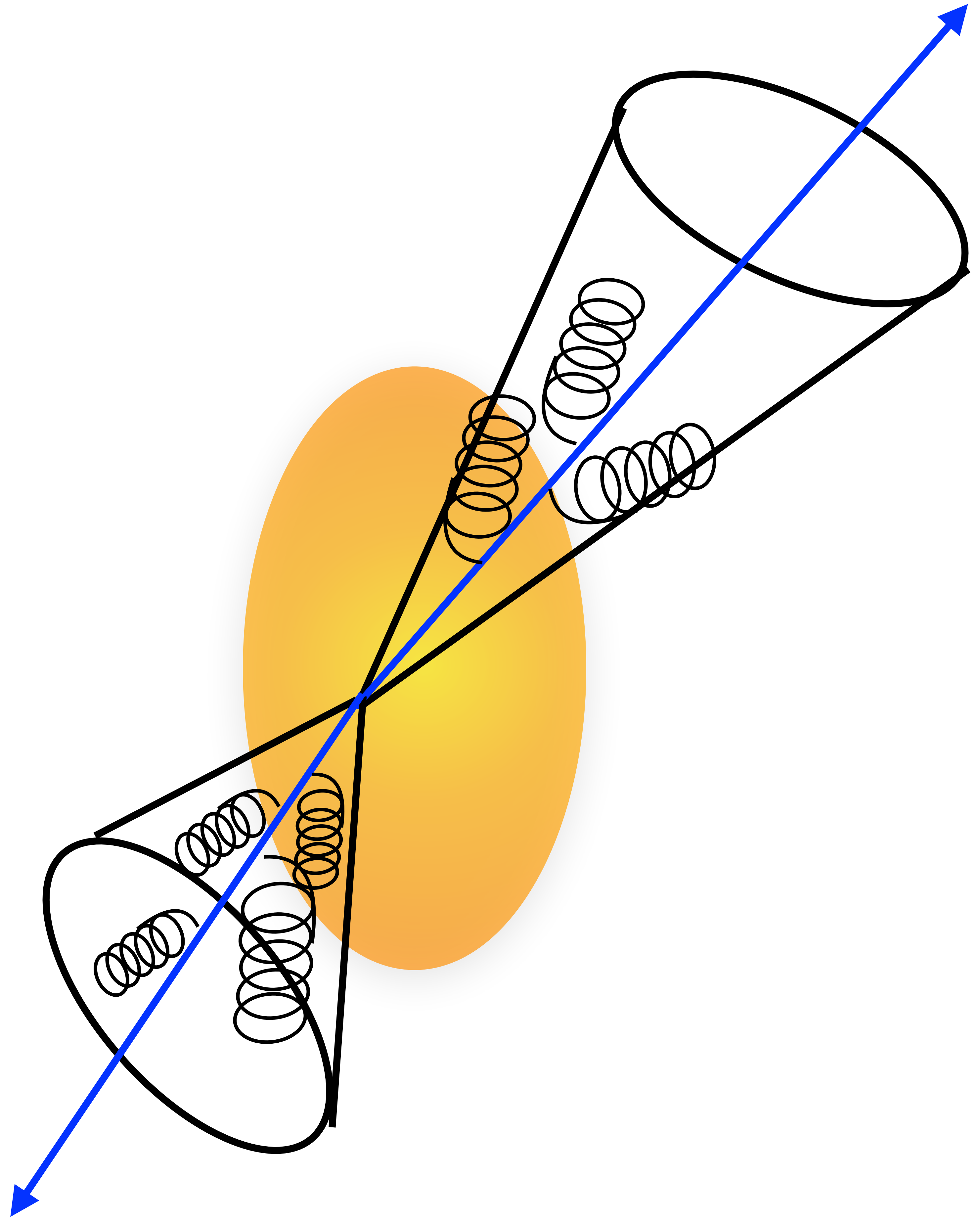

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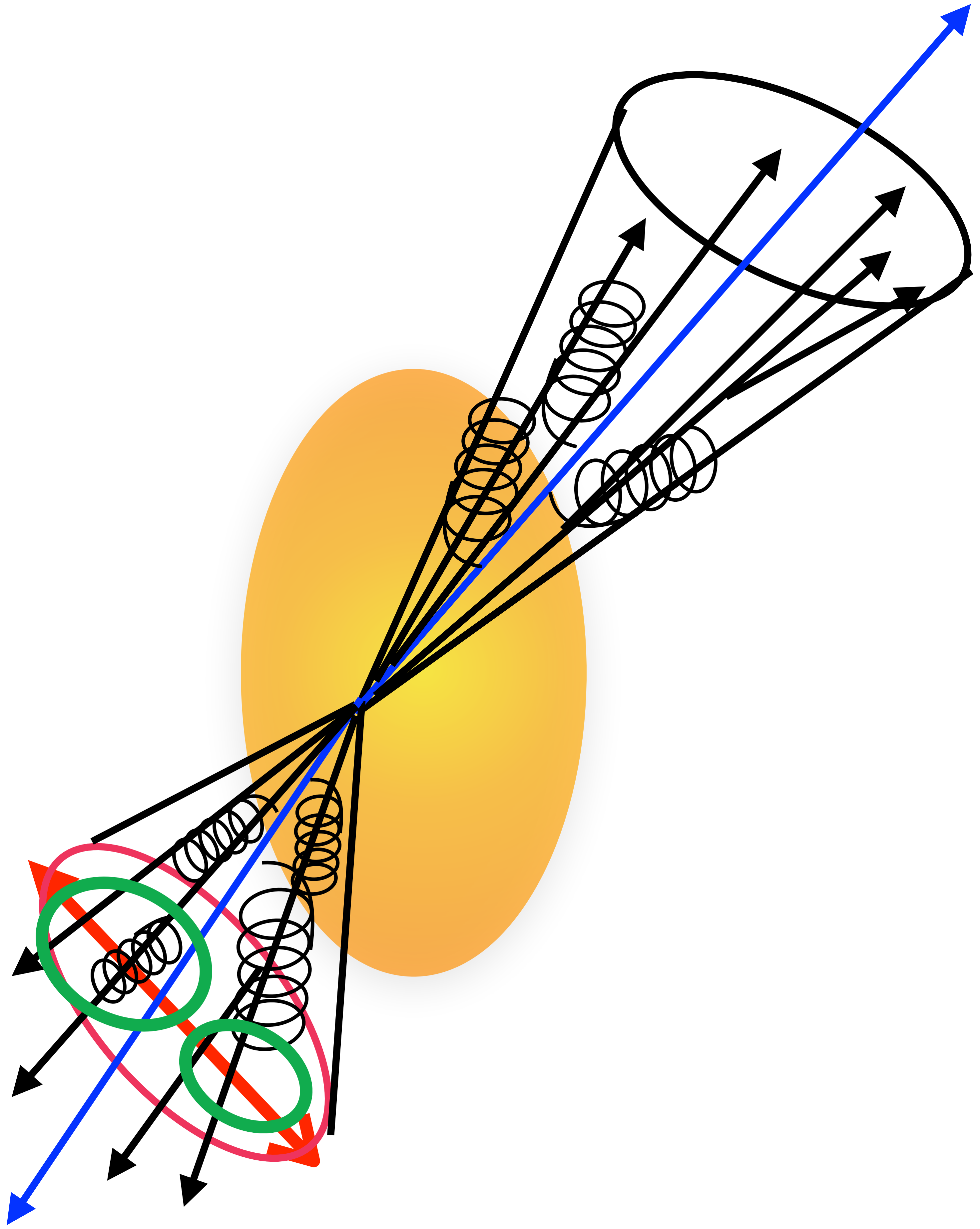

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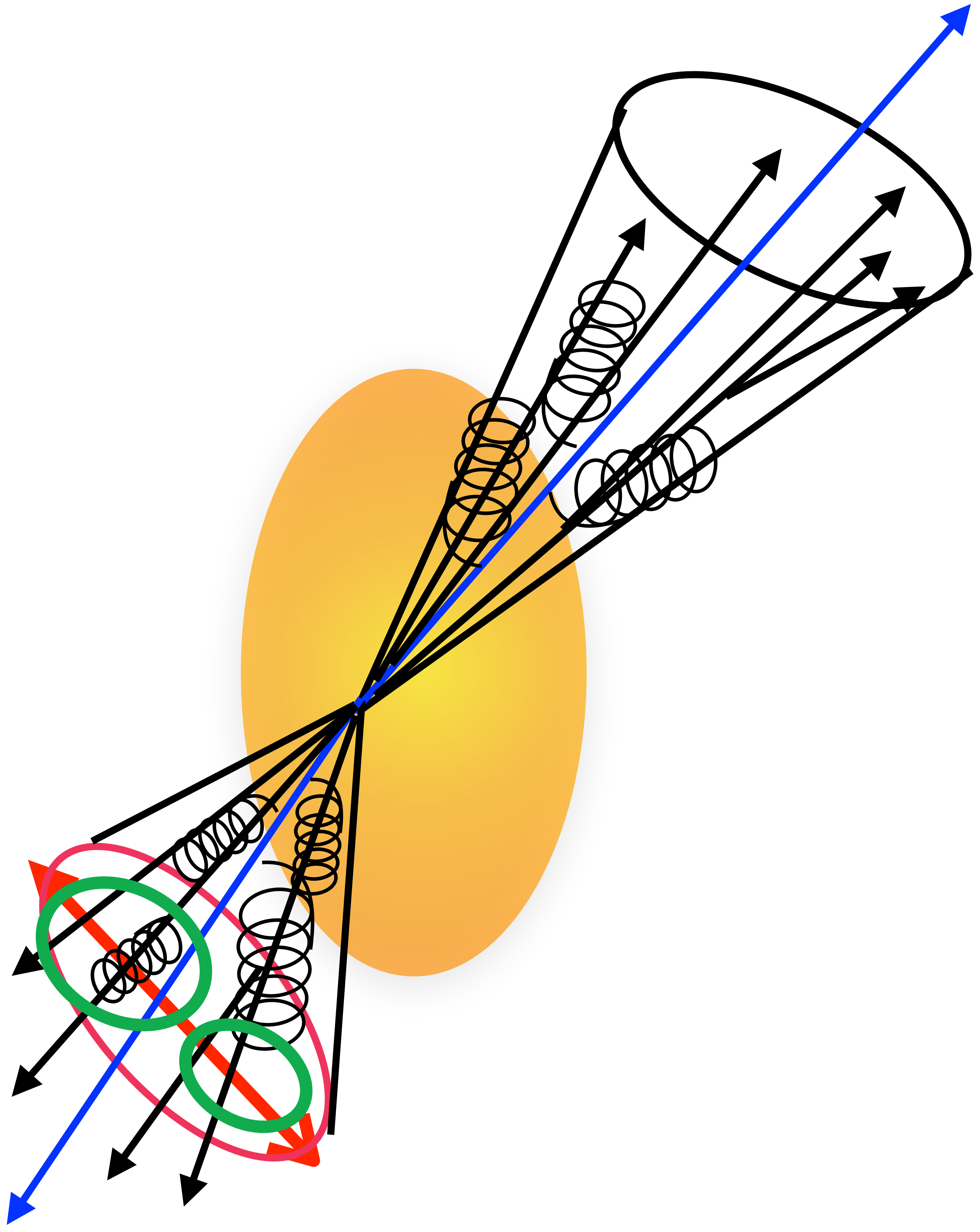


Desire to measure over a large range of scales including jet p_T and radii

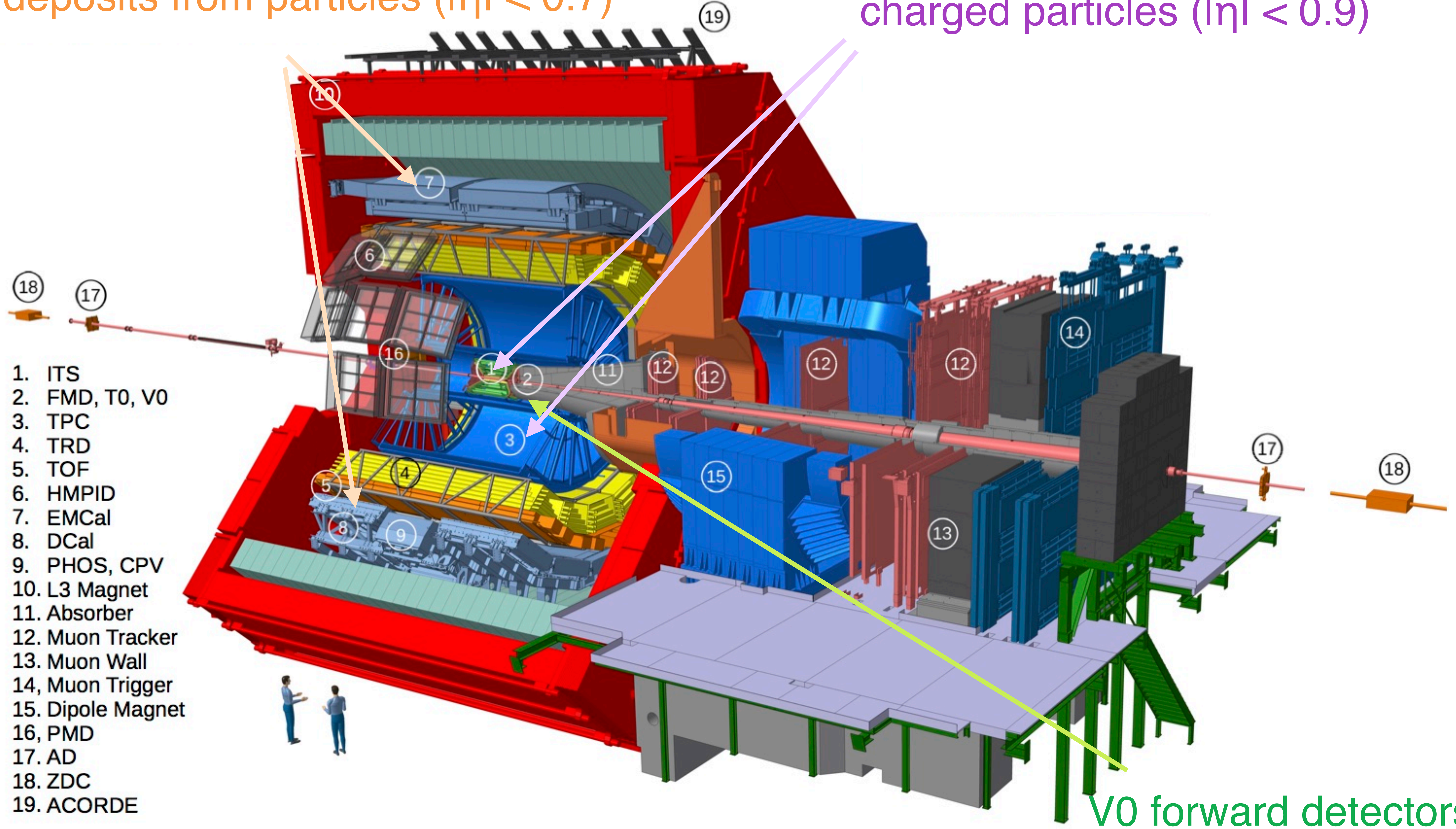
▸ *Need to understand initial and final state effects not from jet quenching*

ALICE detector

Electromagnetic calorimeters (EMCal and DCal) measure clusters of energy deposits from particles (|η| < 0.7)

Time projection chamber (TPC) and ITS measures charged particles (|η| < 0.9)

Charged particle jets from tracks contain only the charged component of the jet



Full jets use tracks and clusters and contain both charged and neutral components

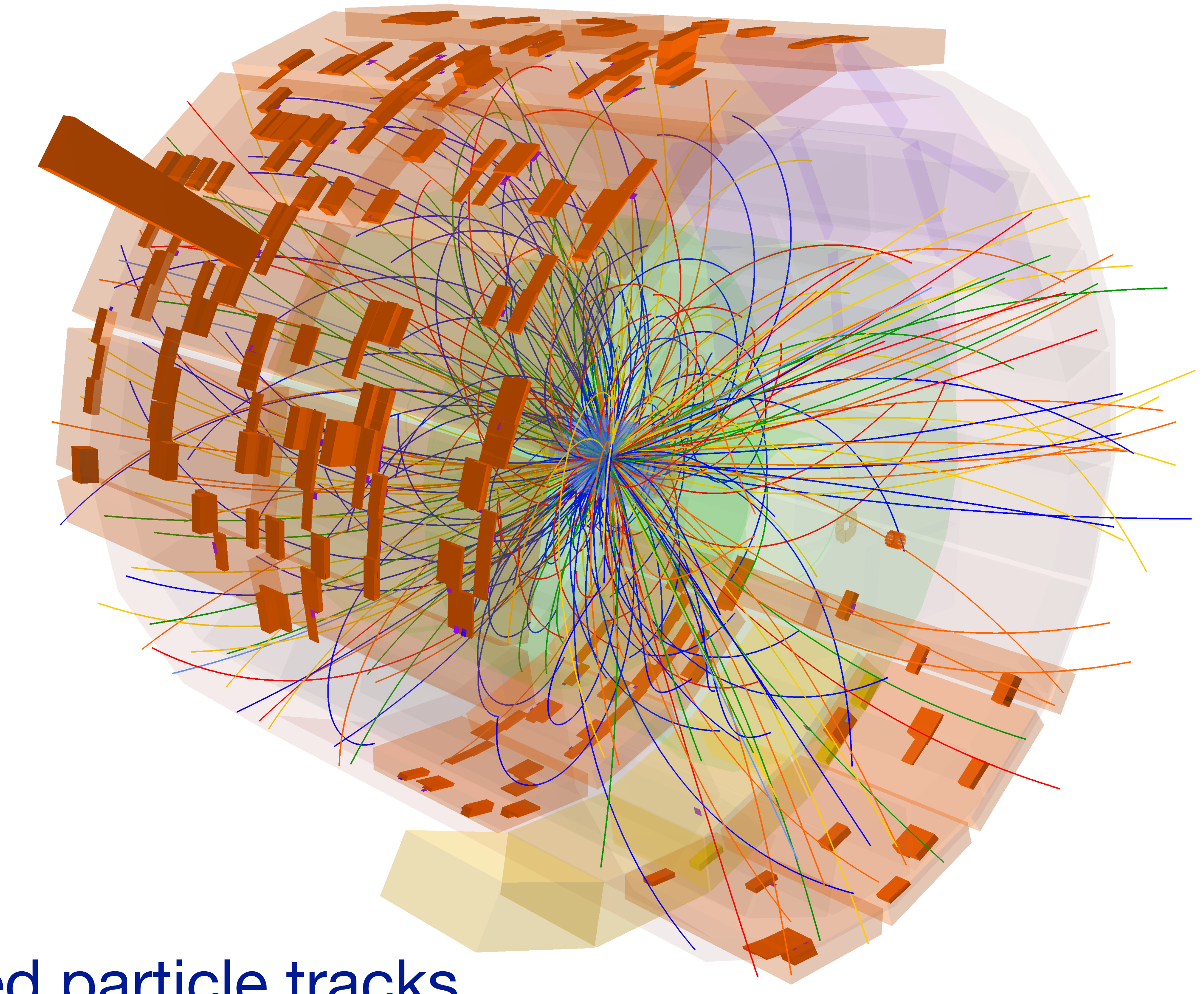
V0 forward detectors used for centrality

Datasets

- New results ALICE results using data from Run 2 at the LHC
  - ➡ 2015 Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, L = 250 μb^{-1}
  - ➡ 2018 Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, L = 0.12 nb^{-1}
  - ➡ 2016 p-Pb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV, L = 0.12 nb^{-1}
  - ➡ 2015 pp collisions at $\sqrt{s}$ = 5.02 TeV, L = 160 nb^{-1}
  - ➡ 2016-2018 pp collisions at $\sqrt{s}$ = 13 TeV, minimum bias L = 0.098 pb^{-1} and high particle multiplicity L = 13 pb^{-1}
- Jets are reconstructed with the anti-k_T jets with various jet resolution parameters and centralities

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 (and splittings) from upward UE fluctuations (prohibits unfolding)



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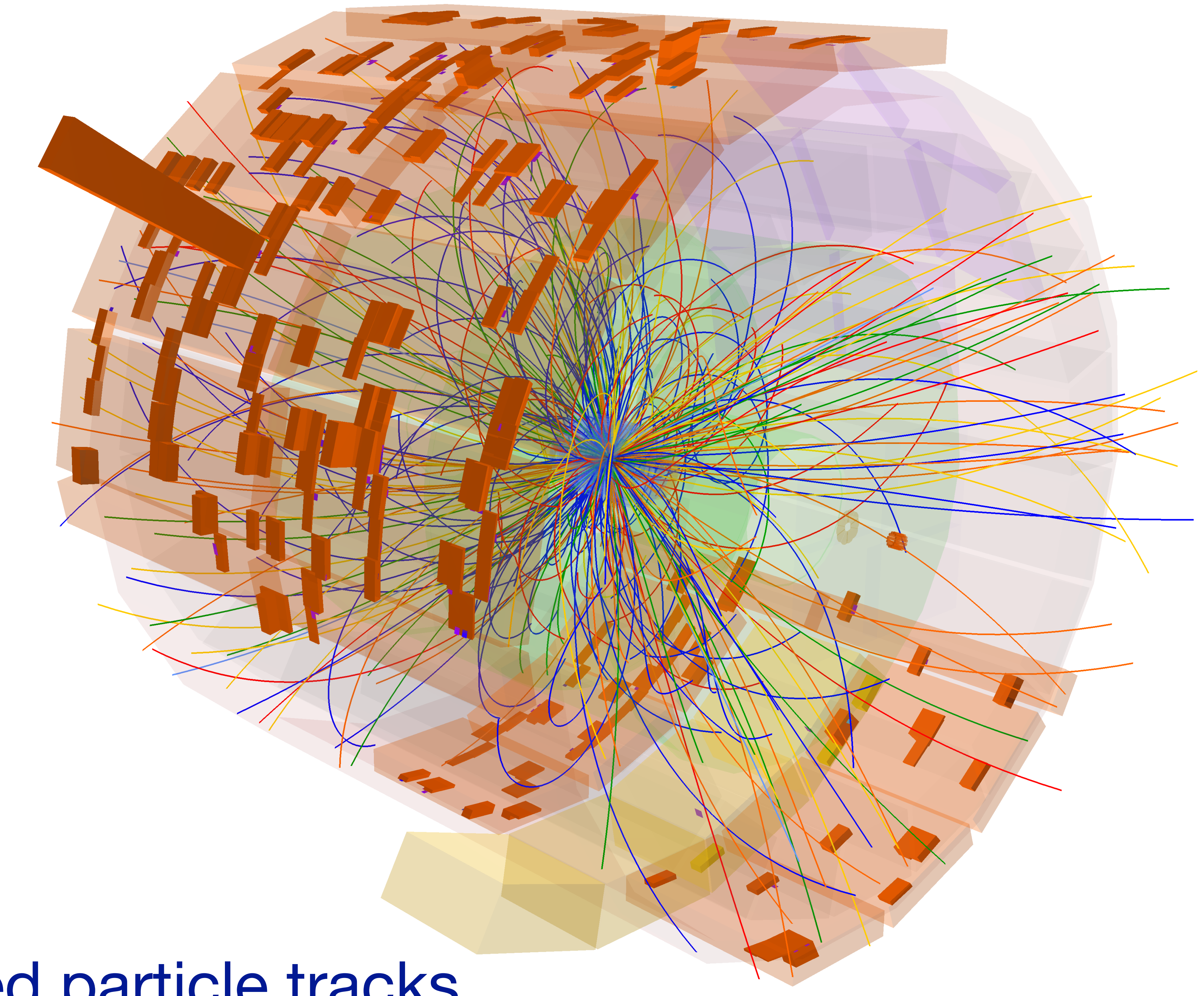

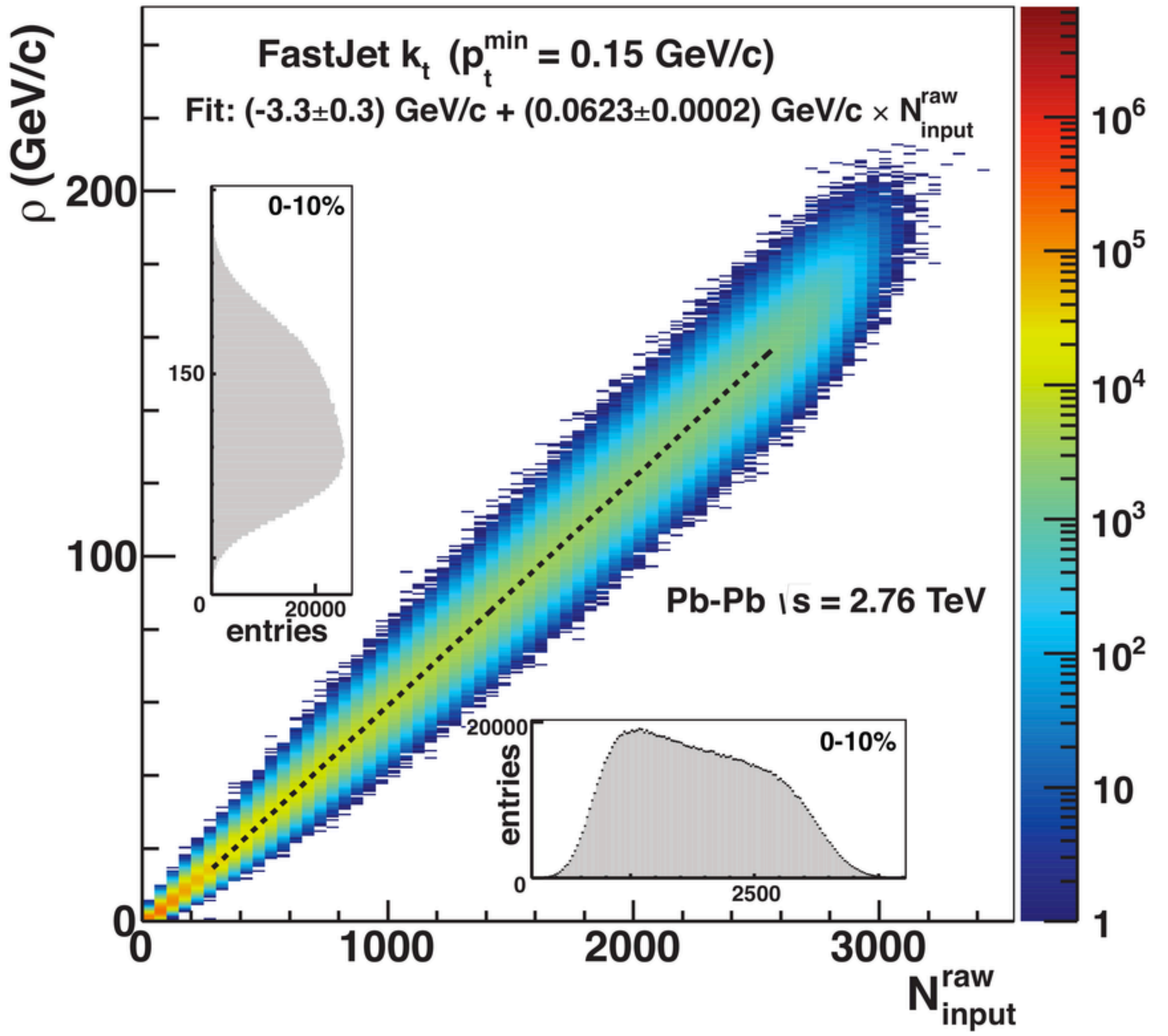

- Remove the background from inside the jets using the area-based method* and then unfold to remove remaining residual fluctuations
- Also, need to remove the fake jets

*PRL **110**, 162001

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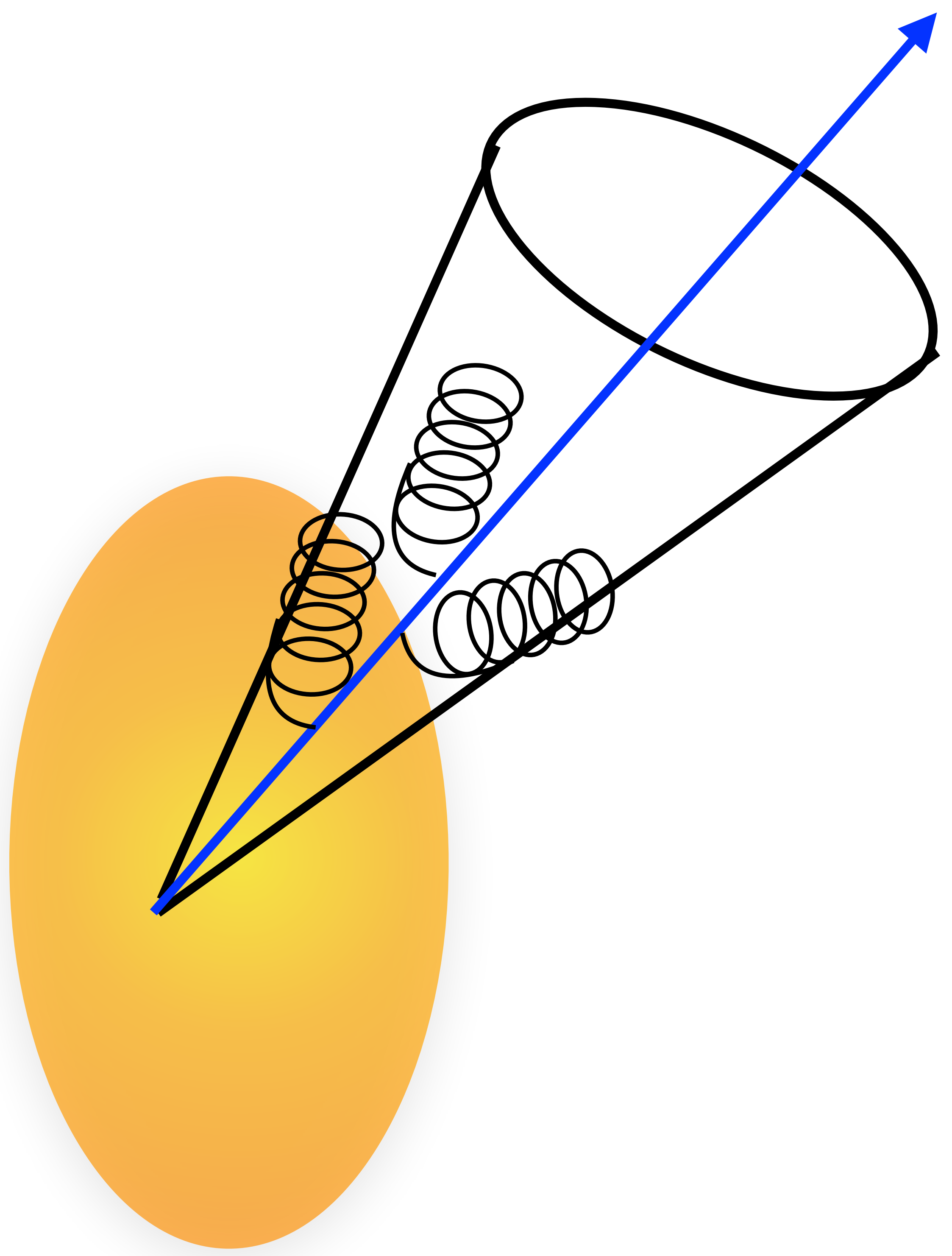

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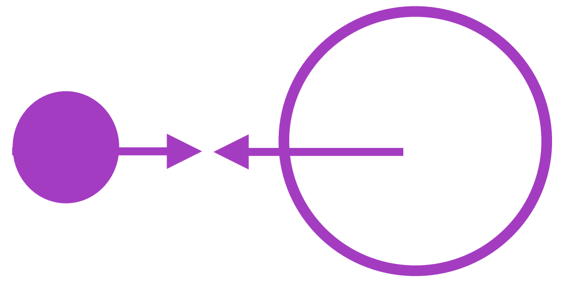
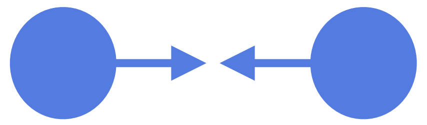
Light meson nuclear modification factor

- Look for modifications in p-Pb to pp collisions probes initial and final state effects
    - Cold nuclear matter effects: (anti) shadowing, gluon saturation (CGC), energy loss, p_T-broadening (Cronin)

$$R_{\mathrm{pA}} = \frac{\text{p-Pb}}{\text{geometry}\otimes\text{pp}}$$





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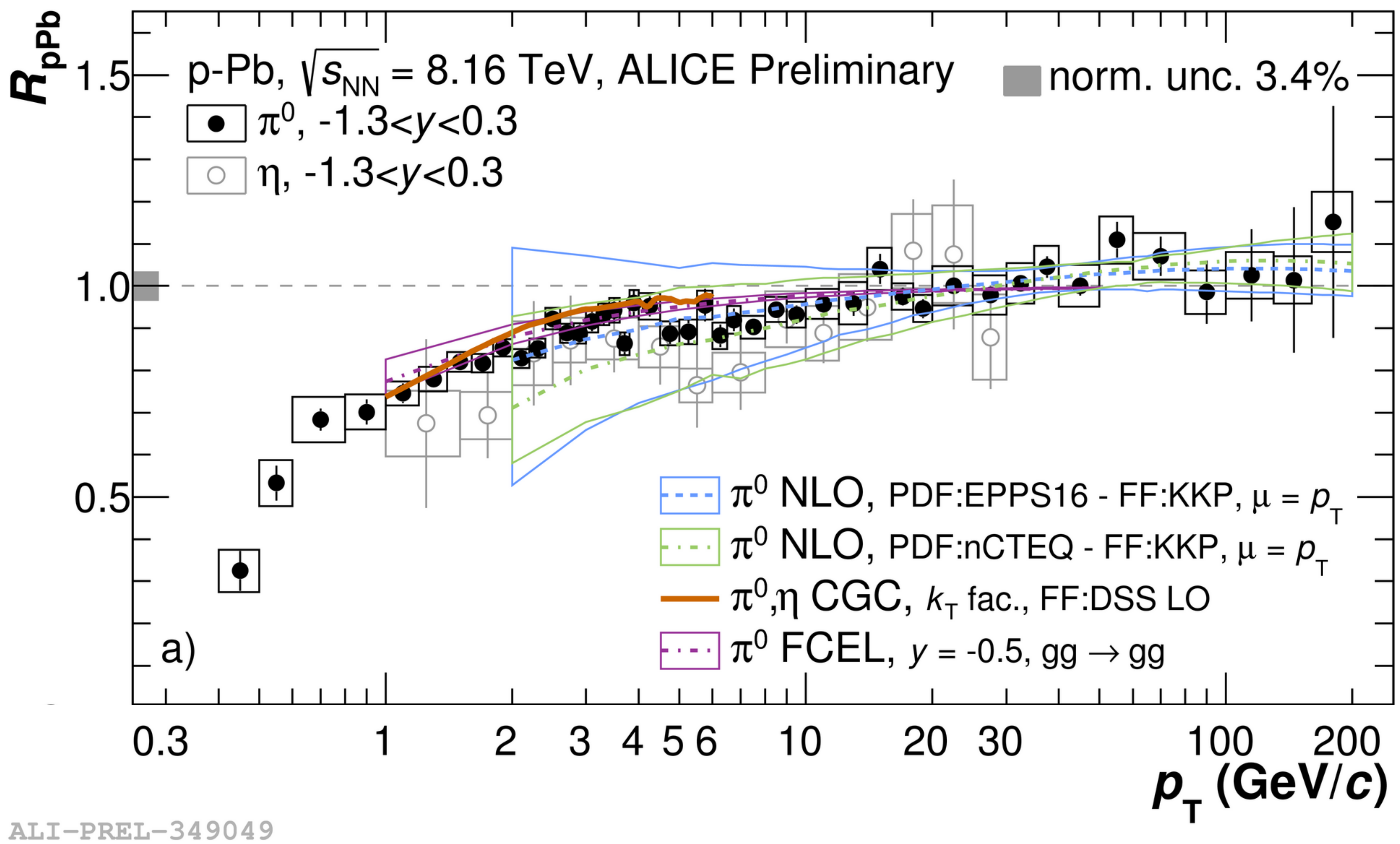
  - Low p_T consistent with CGC and energy loss calculations (FCEL)



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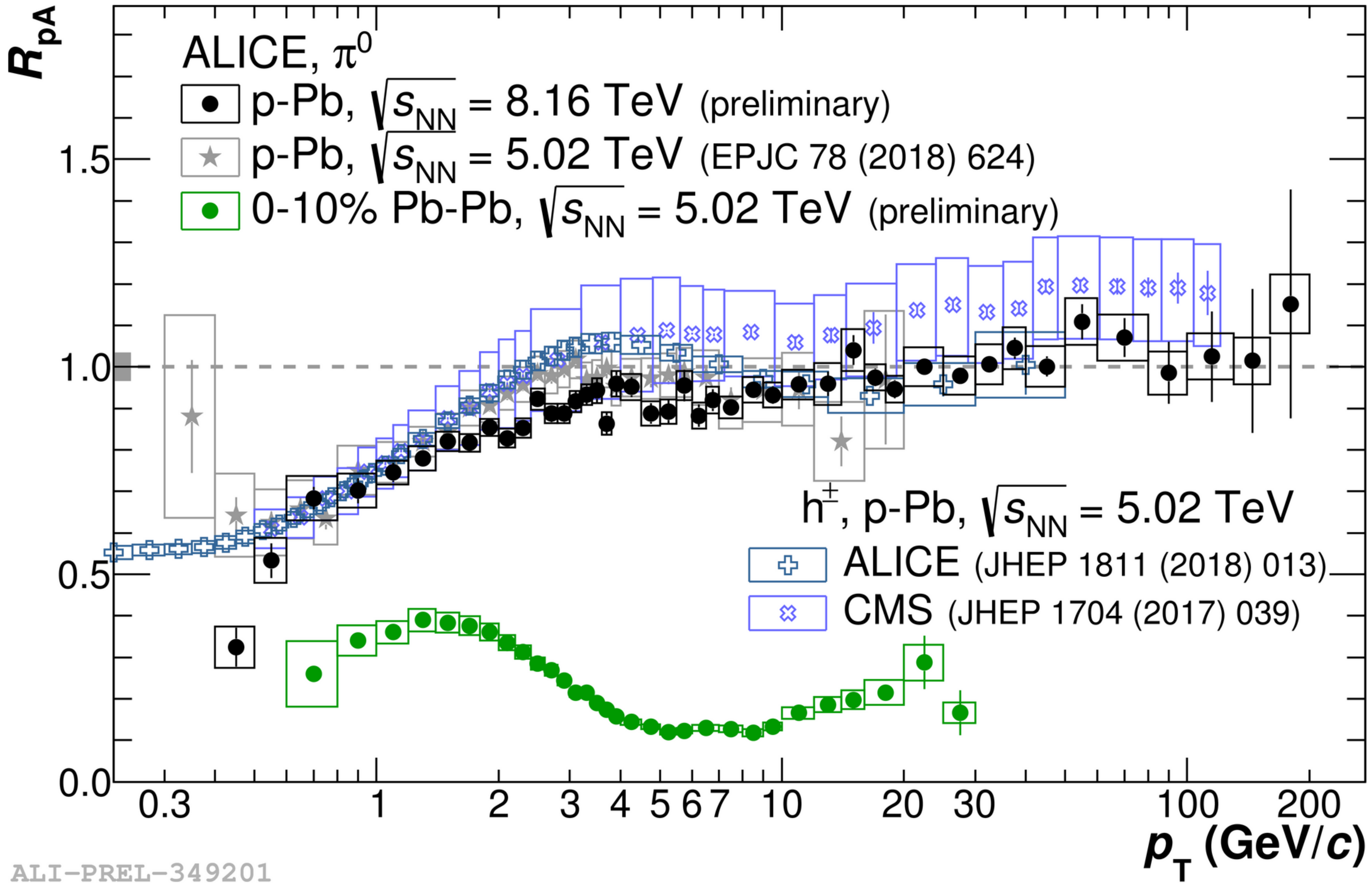
  - New constraints on nPDFs



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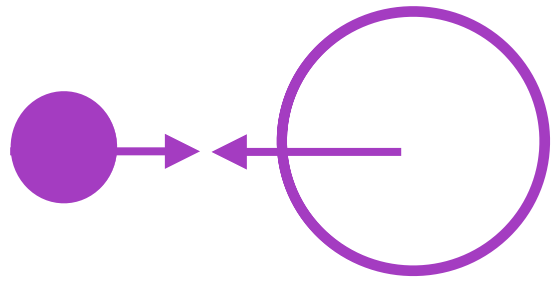
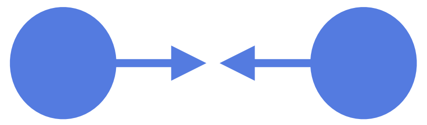

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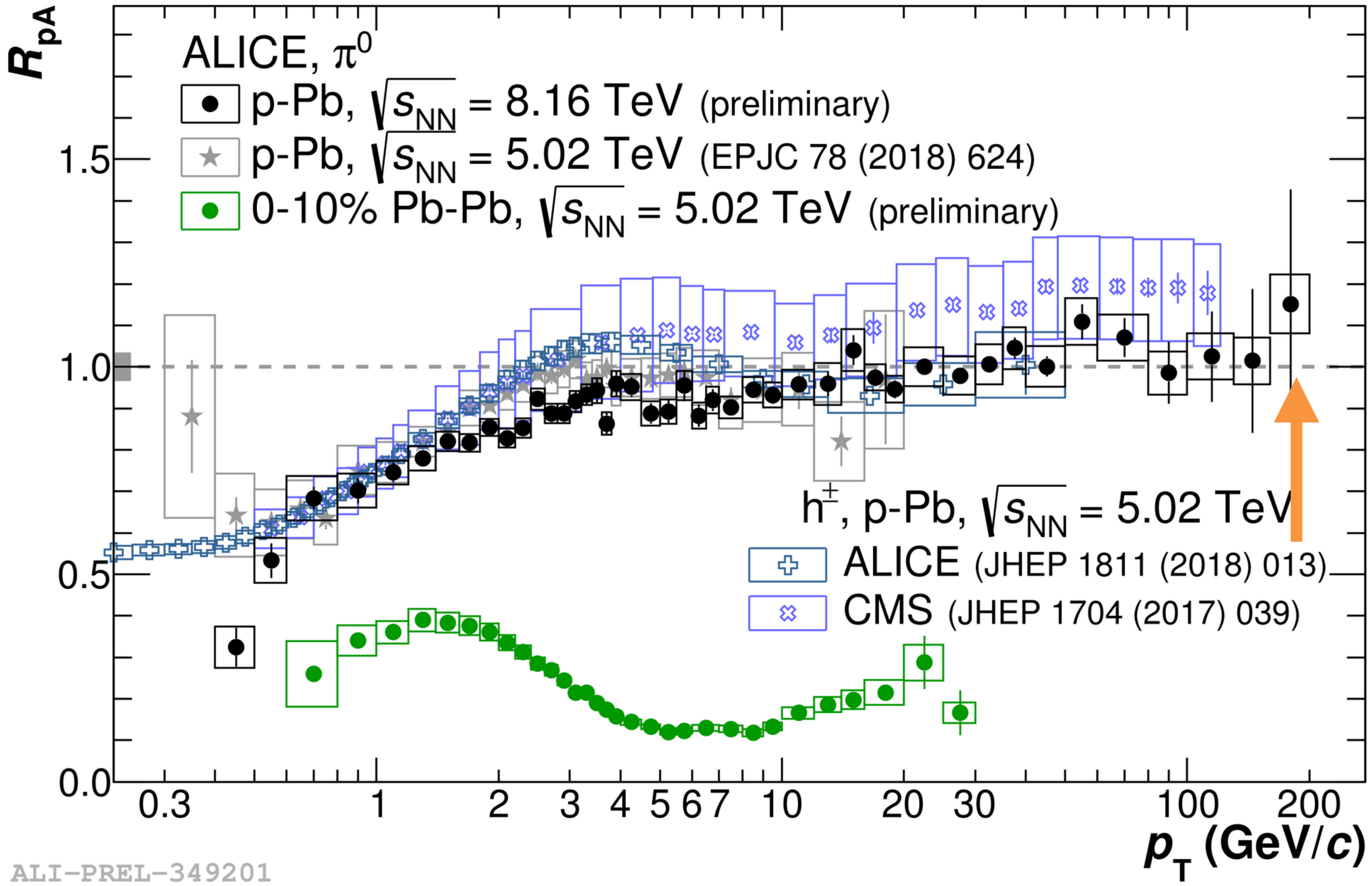
  - New constraints on nPDFs
- Order of magnitude higher p_T (200 GeV) than previous results!



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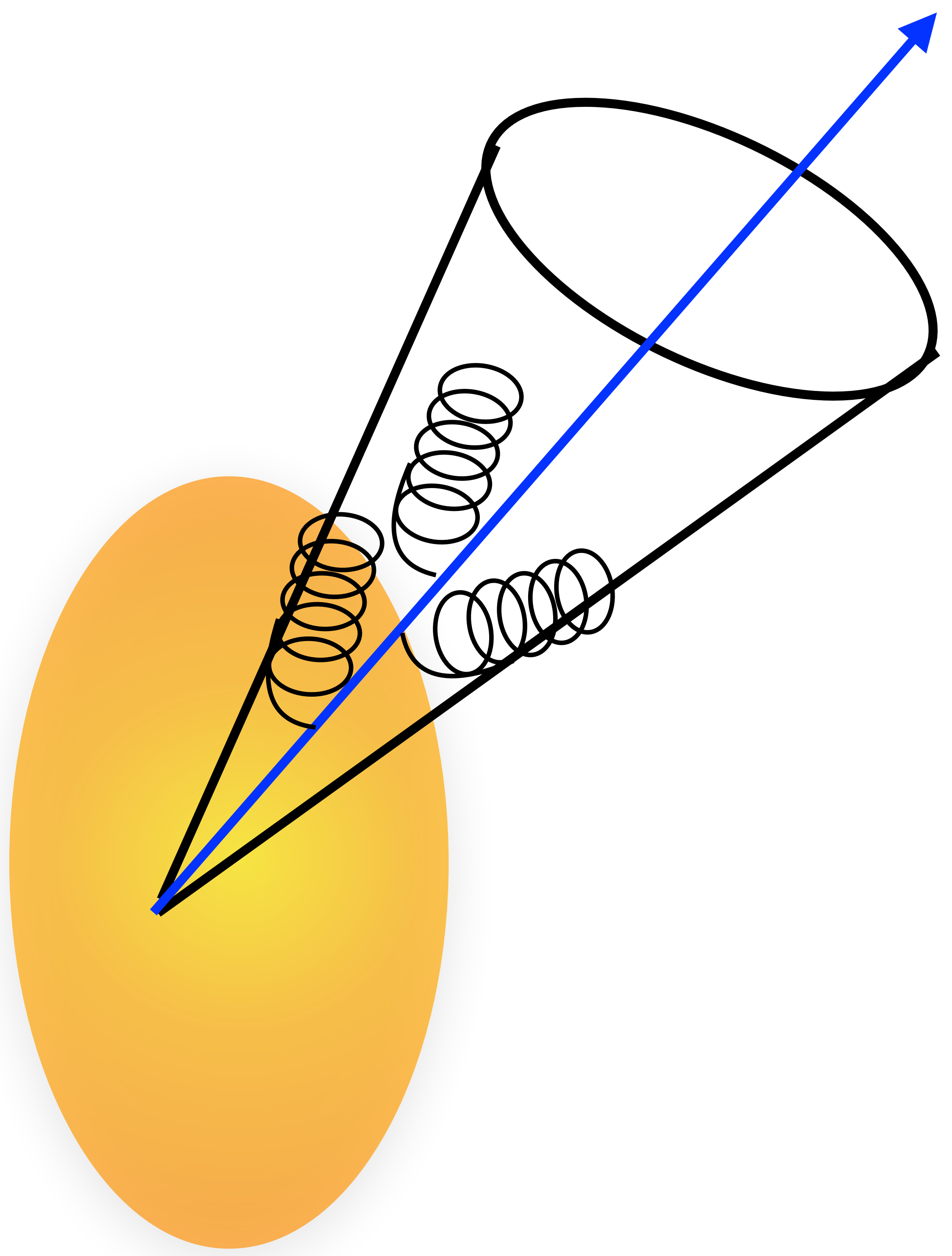

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Inclusive jet suppression

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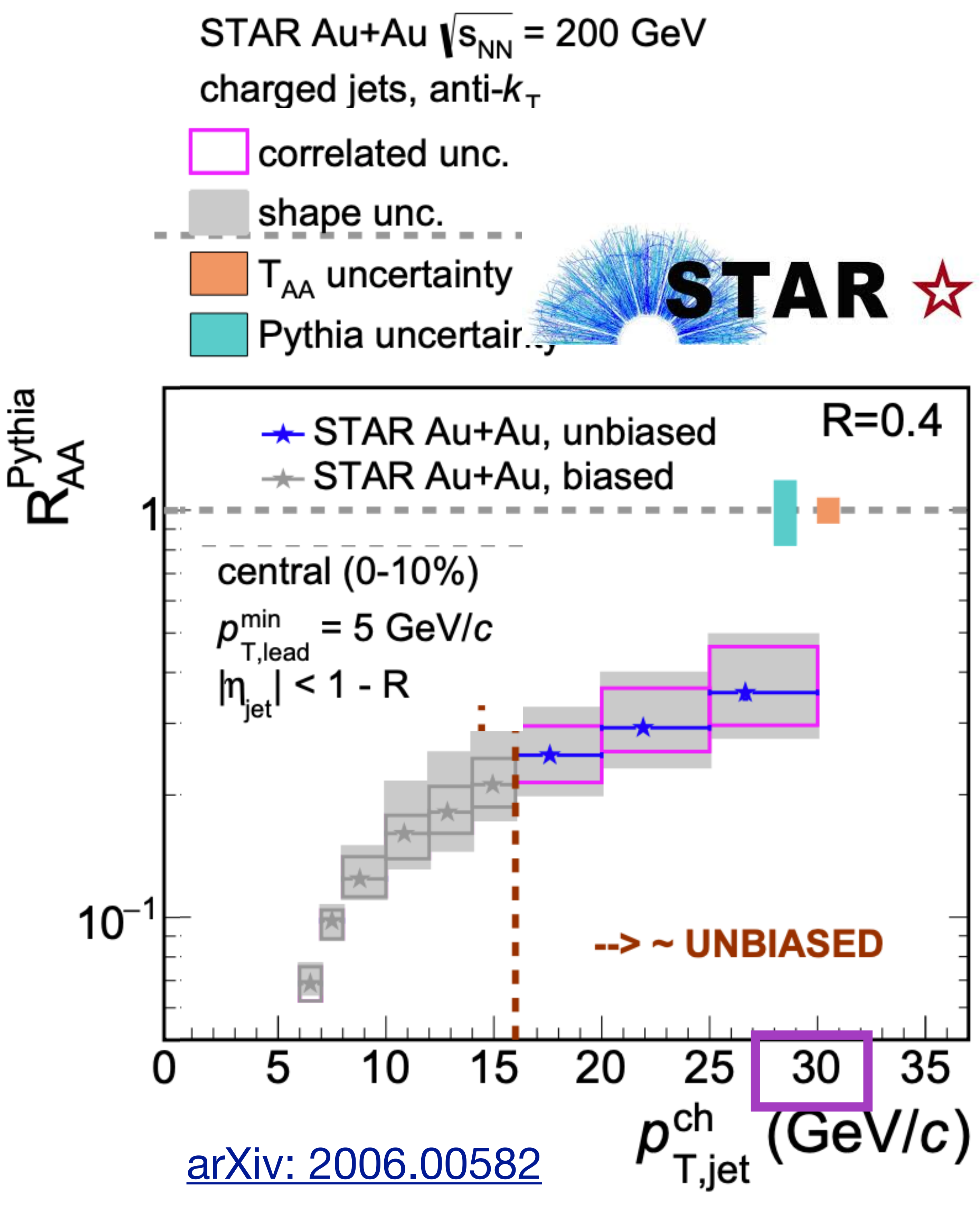
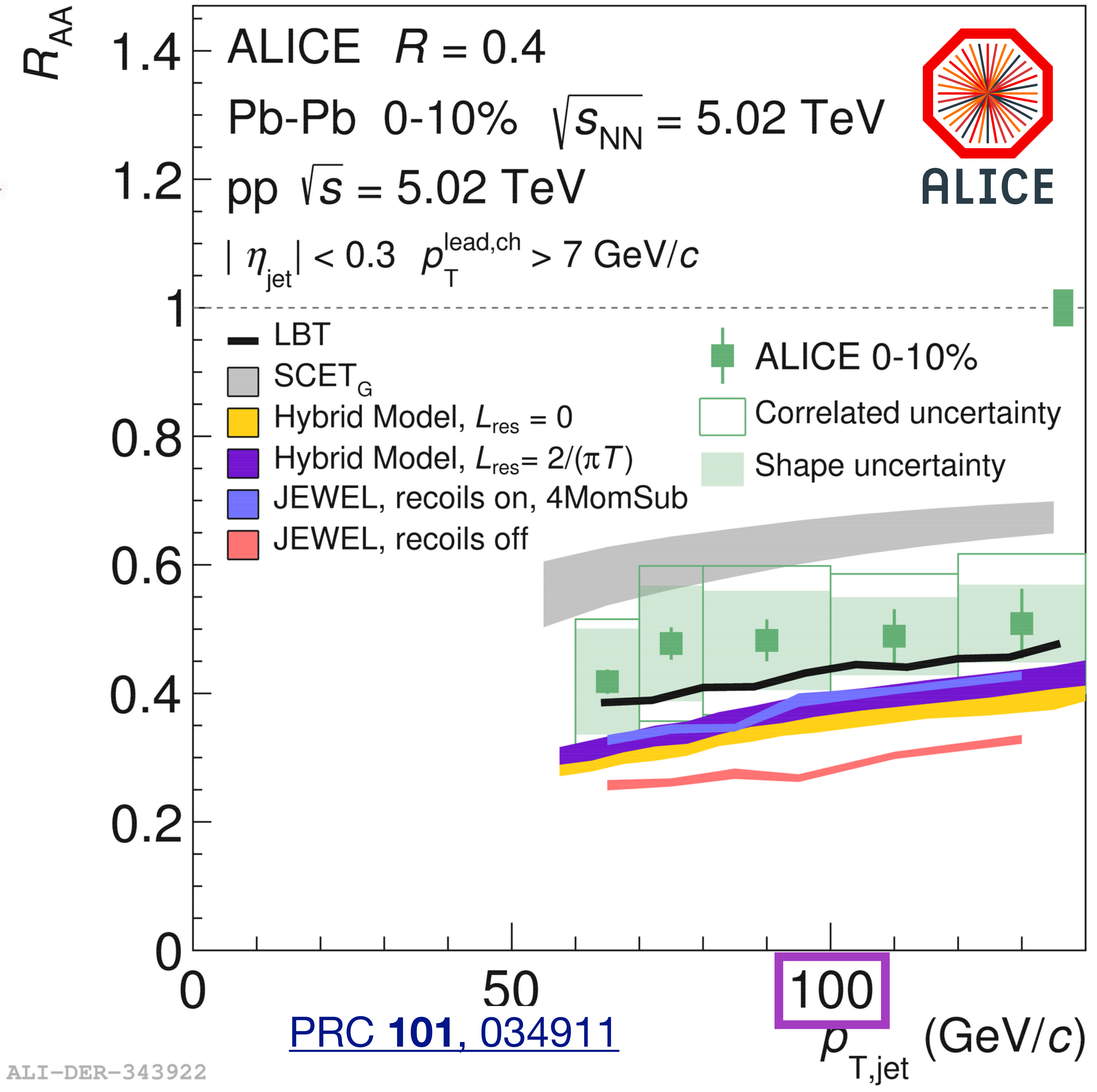
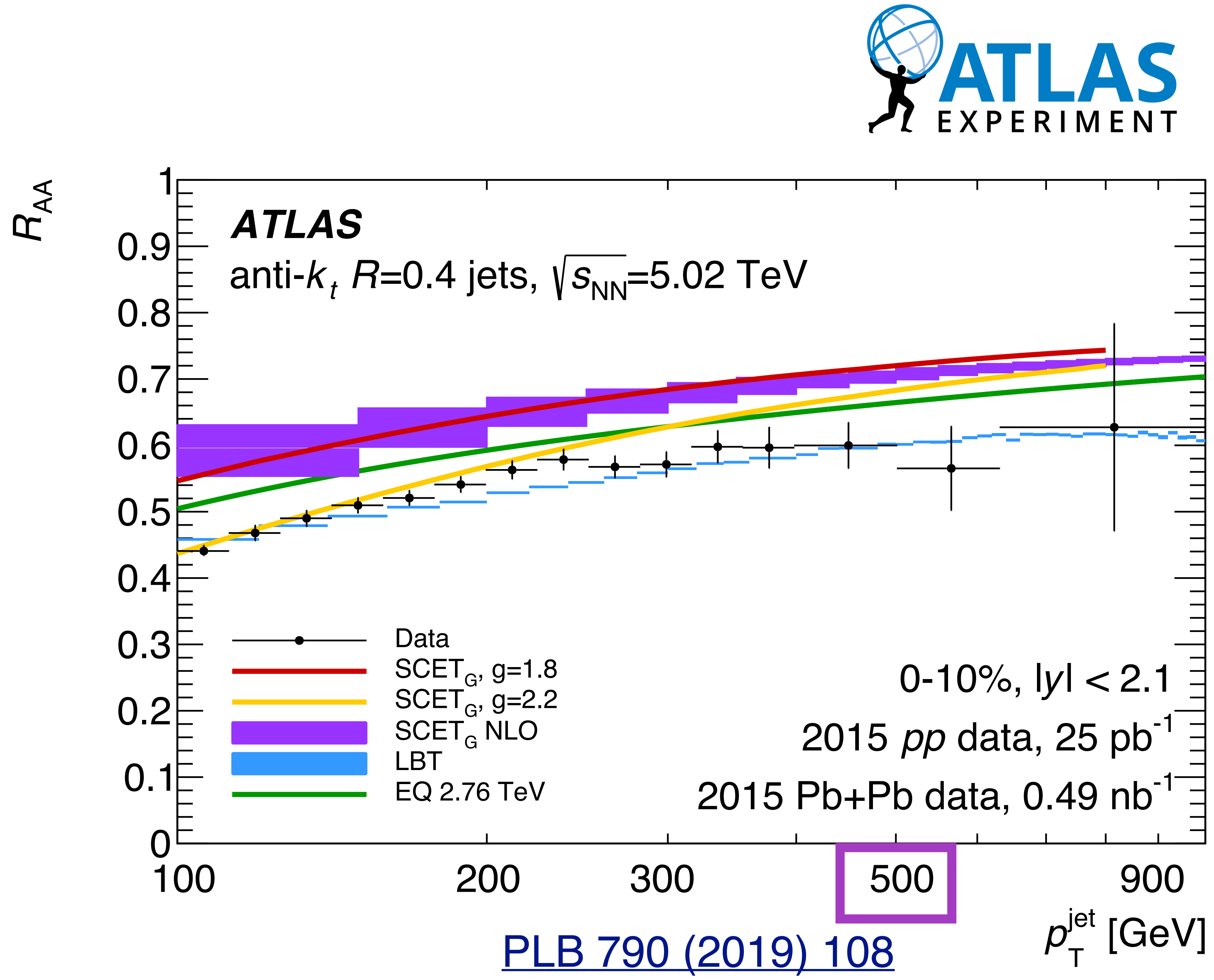


arXiv: 2006.00582



PRC **101**, 034911



PLB 790 (2019) 108

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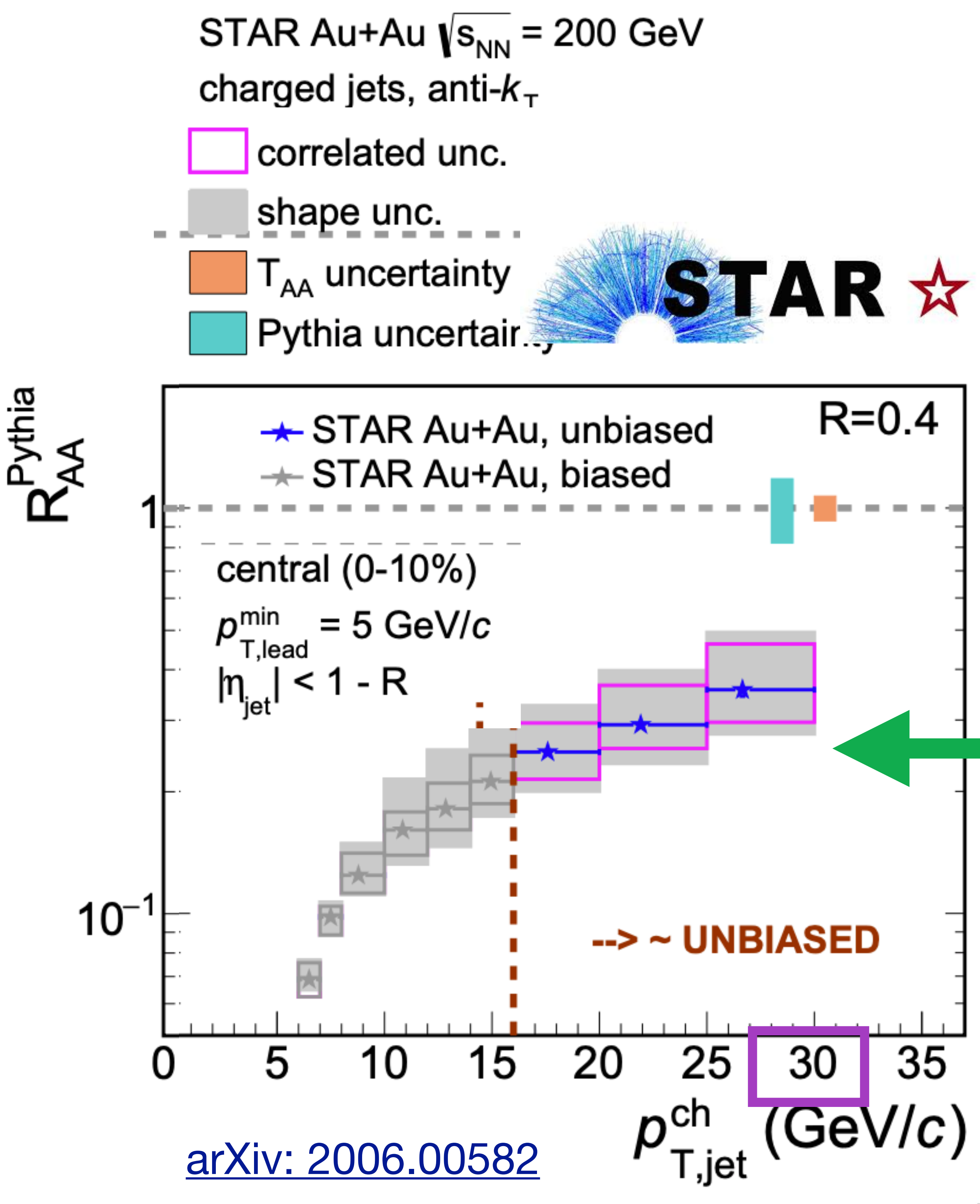

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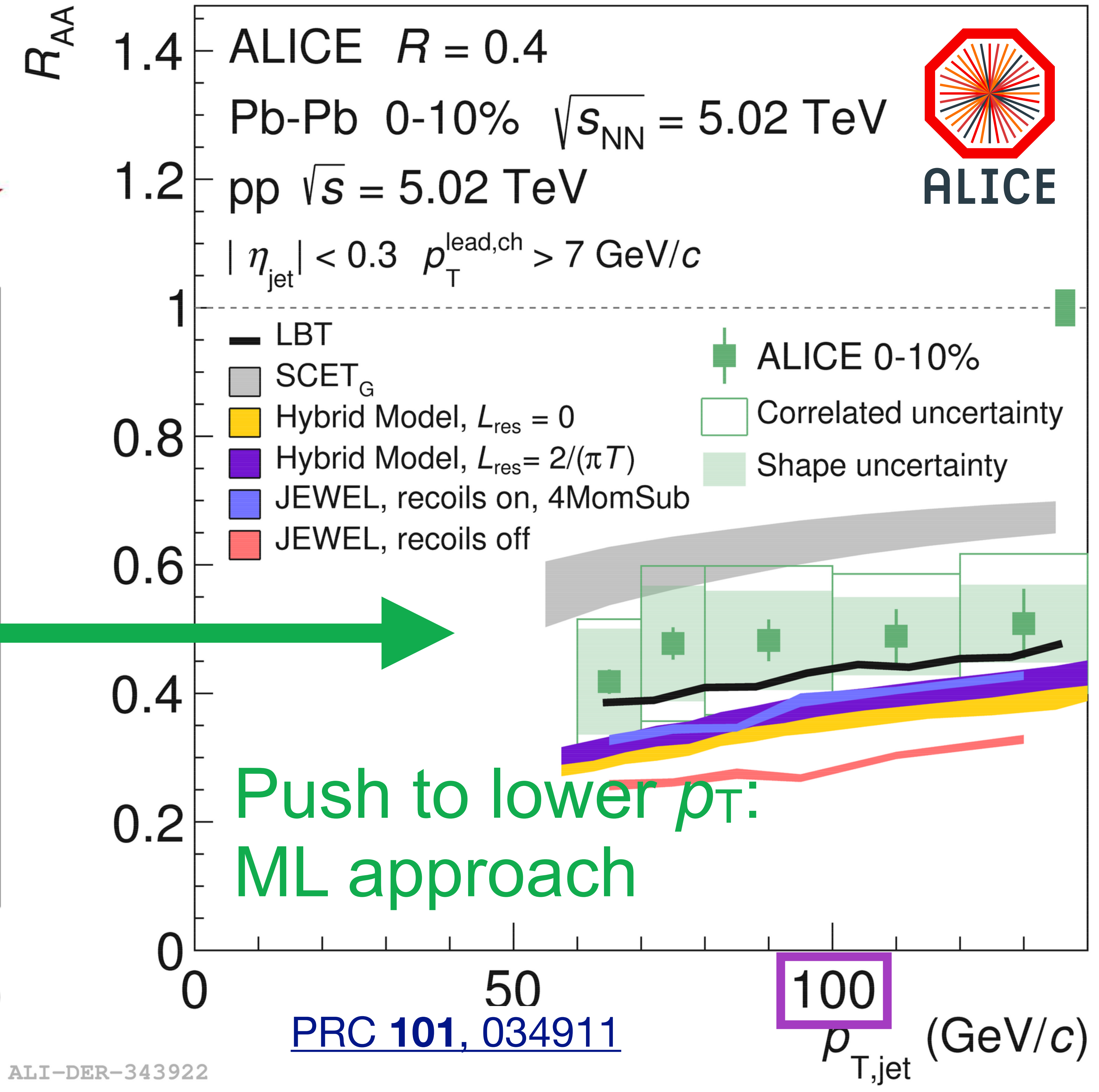

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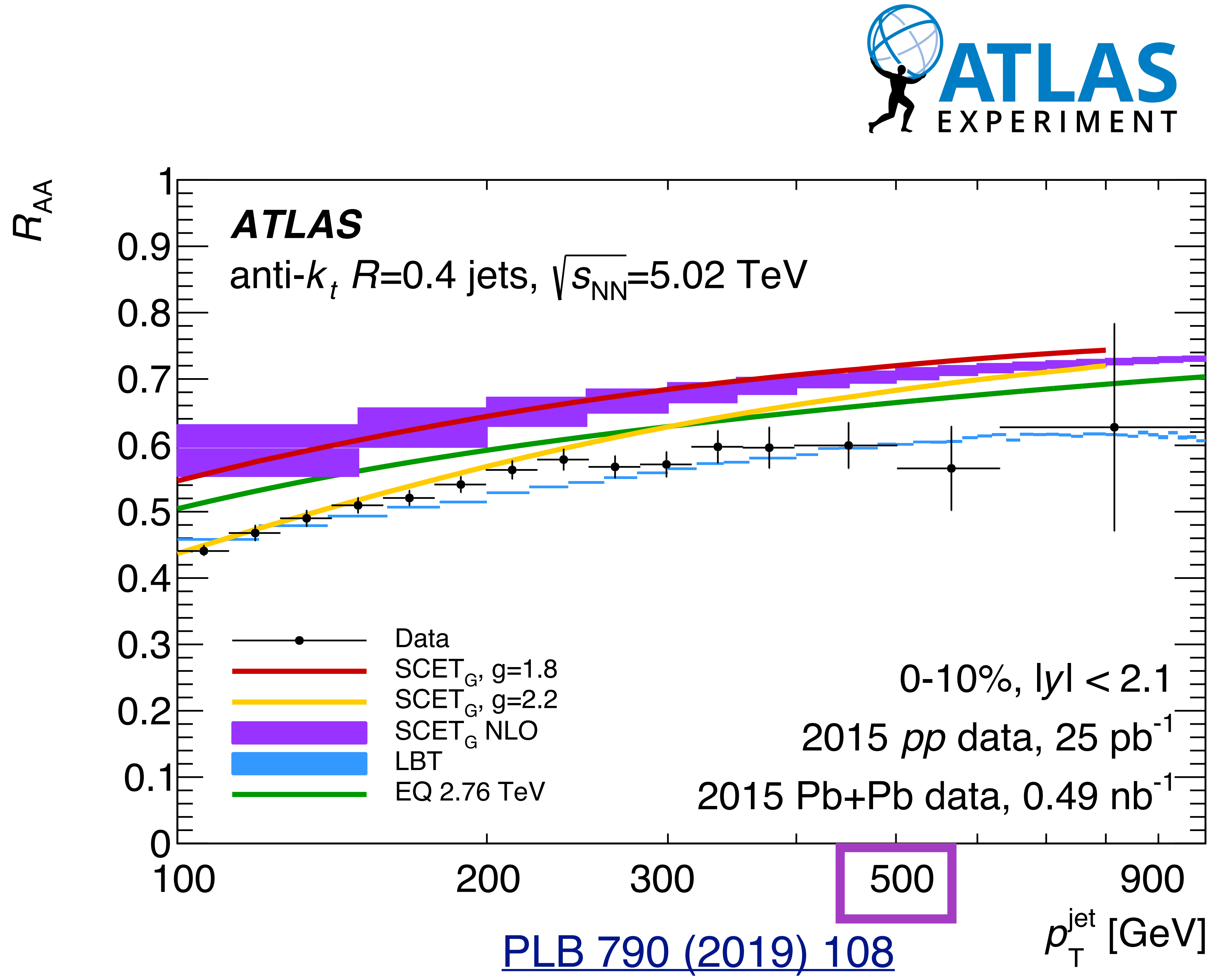

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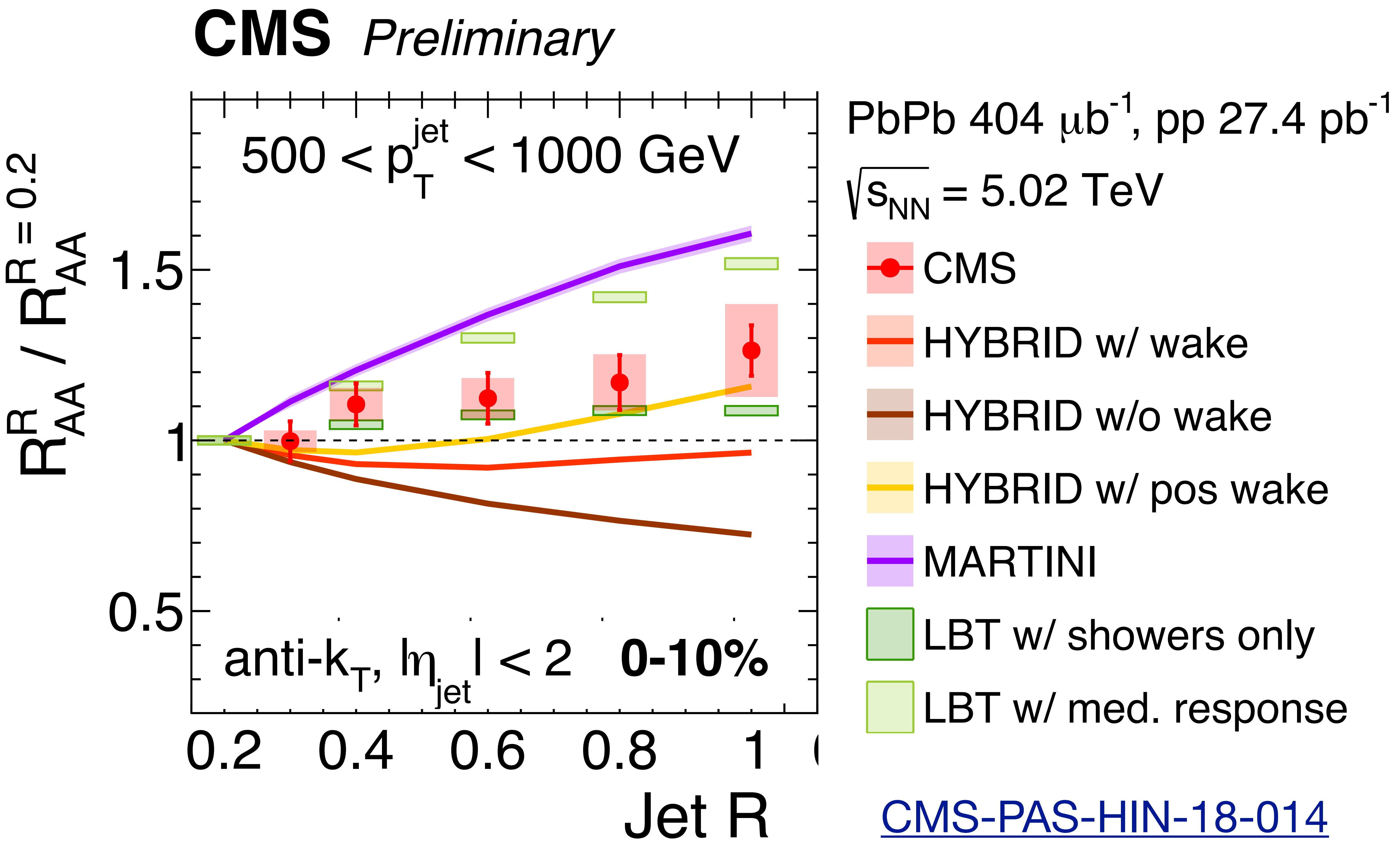
Large *R*/low p_T motivation

- Larger radii jets
  - ➡ Possible recovery of energy from out-of-cone radiation and medium response
- CMS measured large-*R* jets at high p_T



CMS-PAS-HIN-18-014

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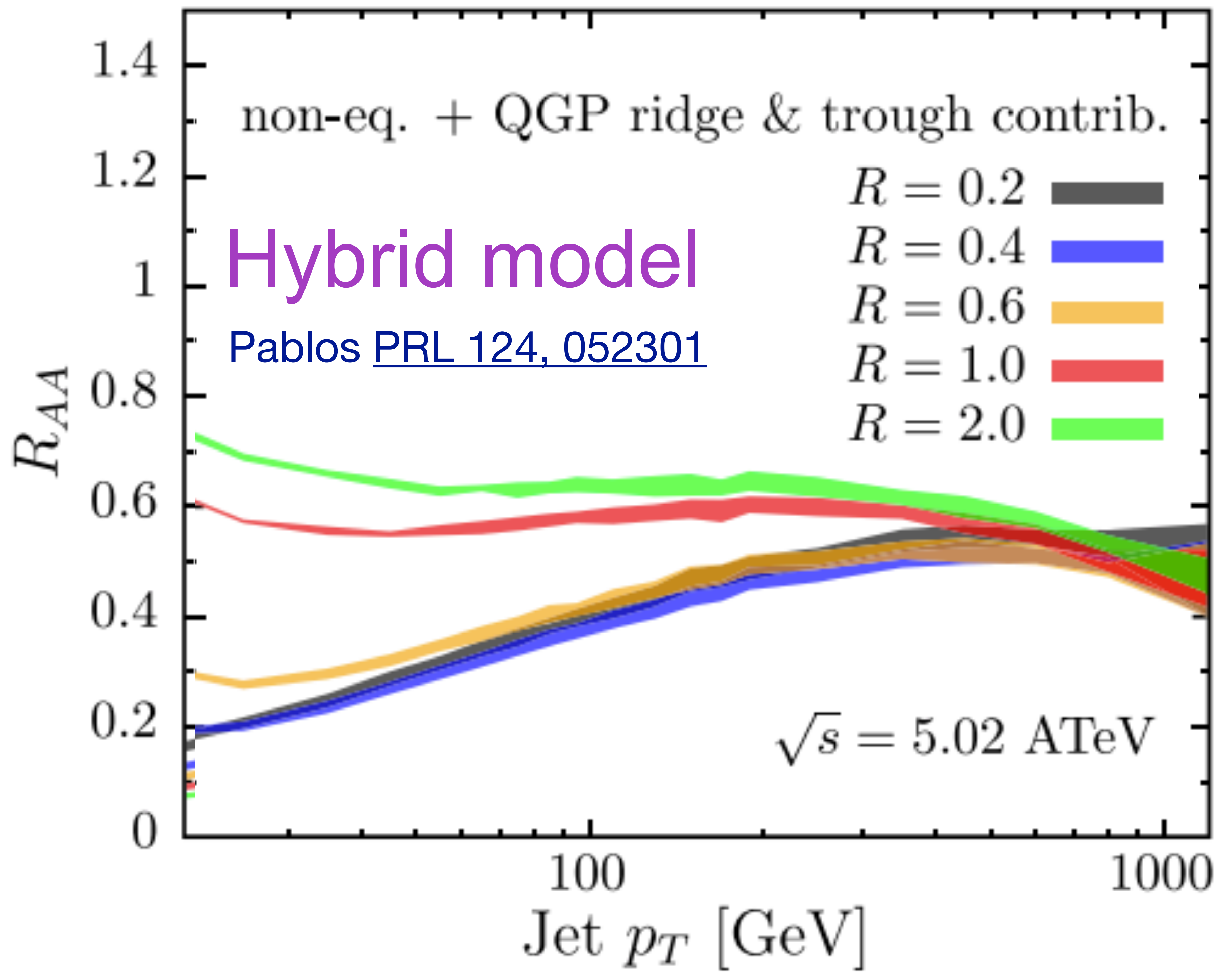
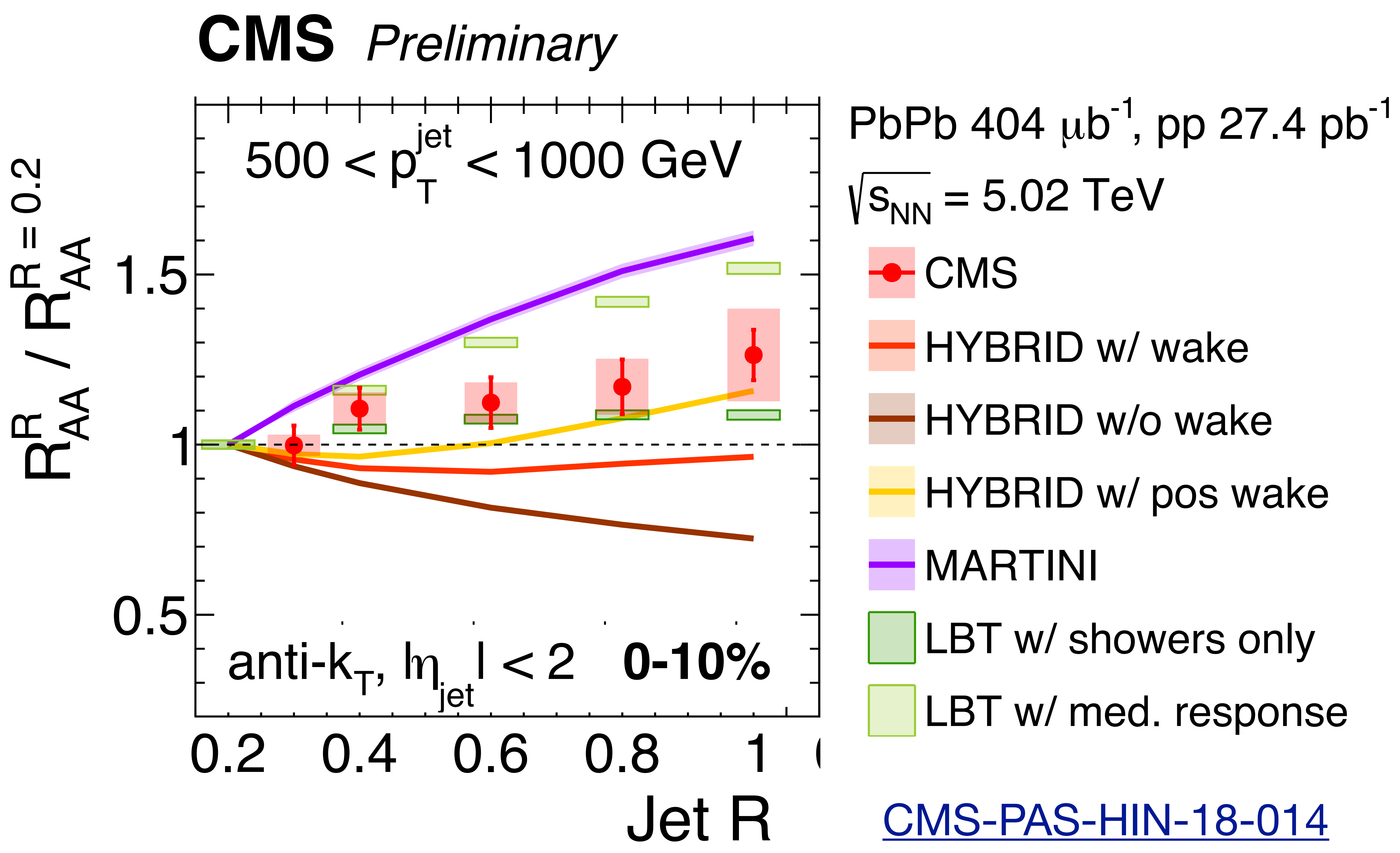




CMS-PAS-HIN-18-014

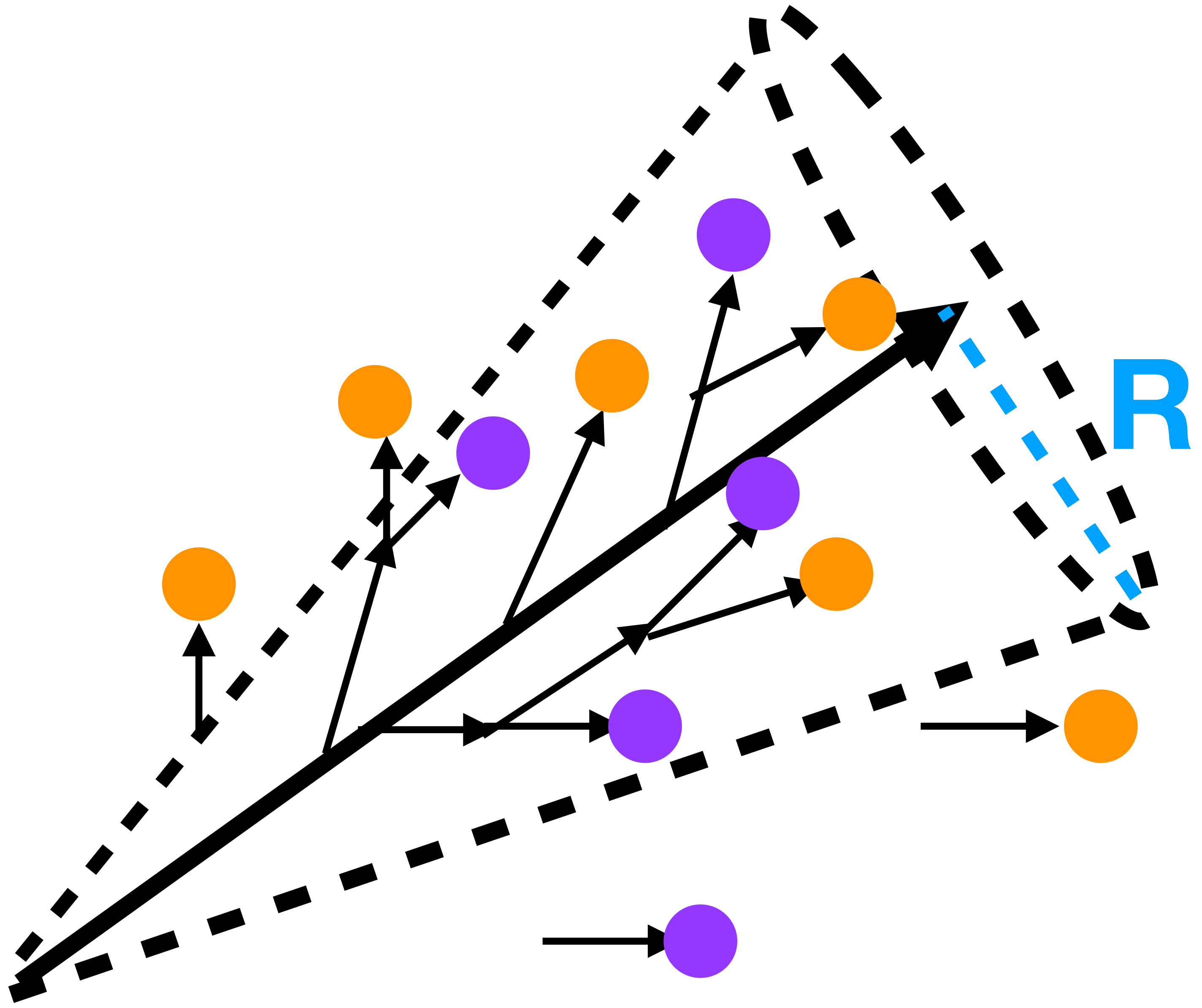
- Lower jet p_T
  - ➡ Varies quark/gluon
  - ➡ Difference between jet radii could be larger at lower p_T

Machine learning approach

- Standard area-based subtraction method is unbiased but residual fluctuations are large

Fakes jets suppressed with a leading track bias

- ML technique learns on PYTHIA jets to correct the jet p_T by exploiting the difference between the signal jets and the background



Introduces a potential fragmentation bias

Haake, Loizides PRC 99, 064904 (2019)

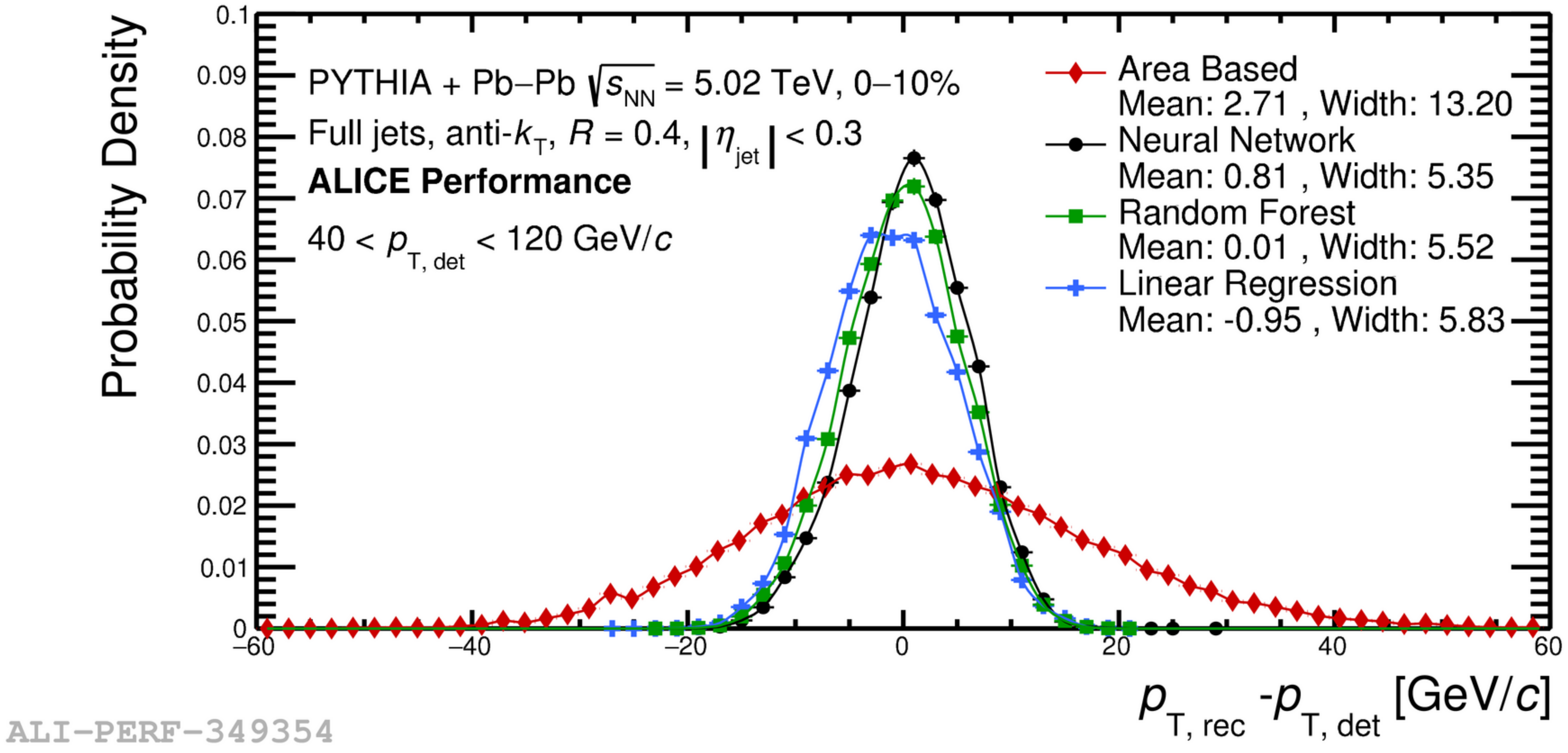
Jet properties including standard corrected p_T and jet constituents

ML

Corrected jet p_T

- Applied to charged or full jets (contain charged tracks and neutral clusters, measured in the TPC and EMCal, respectively)

ML approach: low p_T inclusive jets



- ML method reduces residual fluctuations -> unfold to lower p_T

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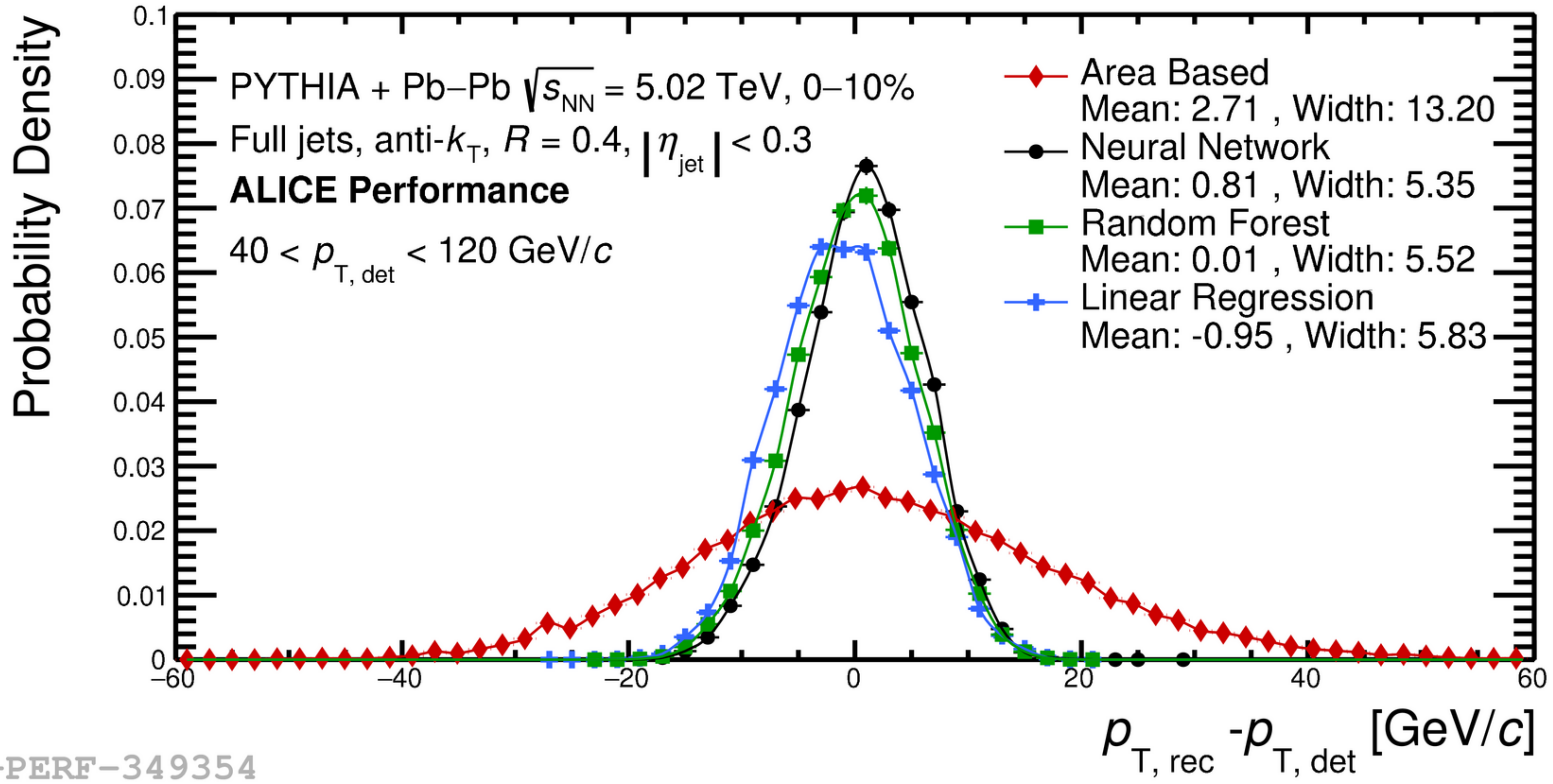

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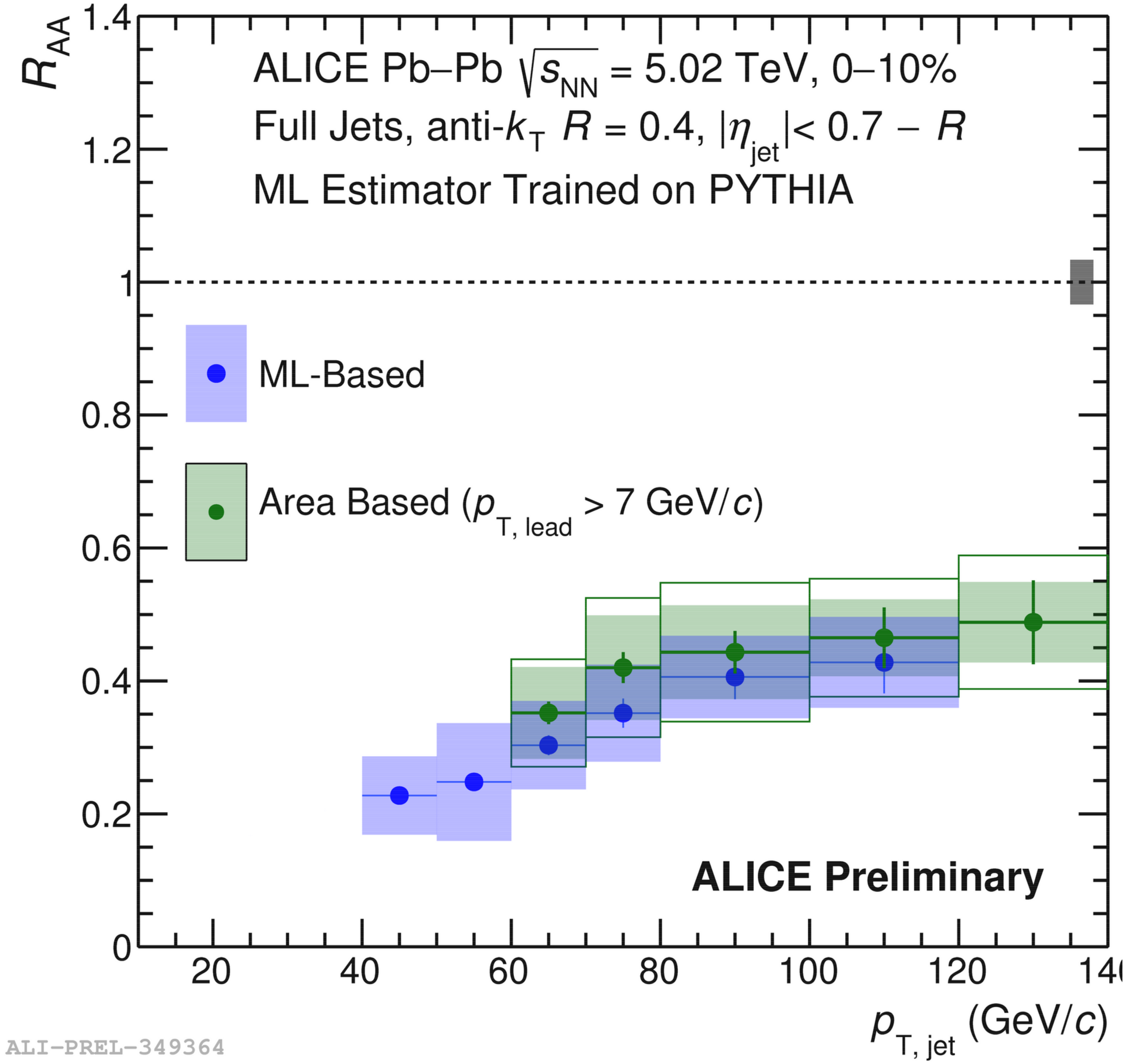
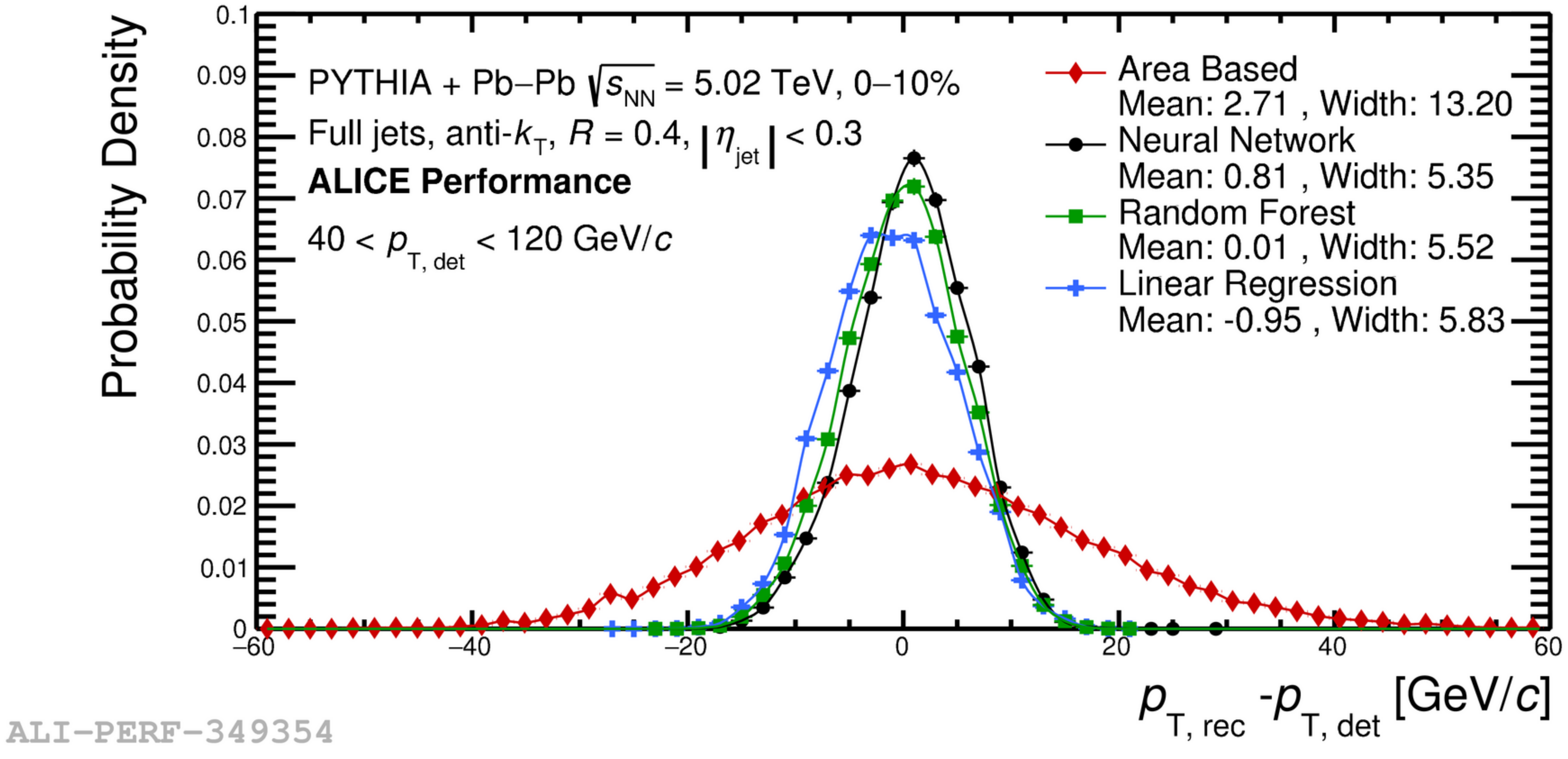


- ML-based and area-based method with a leading track bias are consistent with shift in central values, explore bias!

p_T reach extended to 40 GeV/c with reduced uncertainties

ML approach: low p_T inclusive jets



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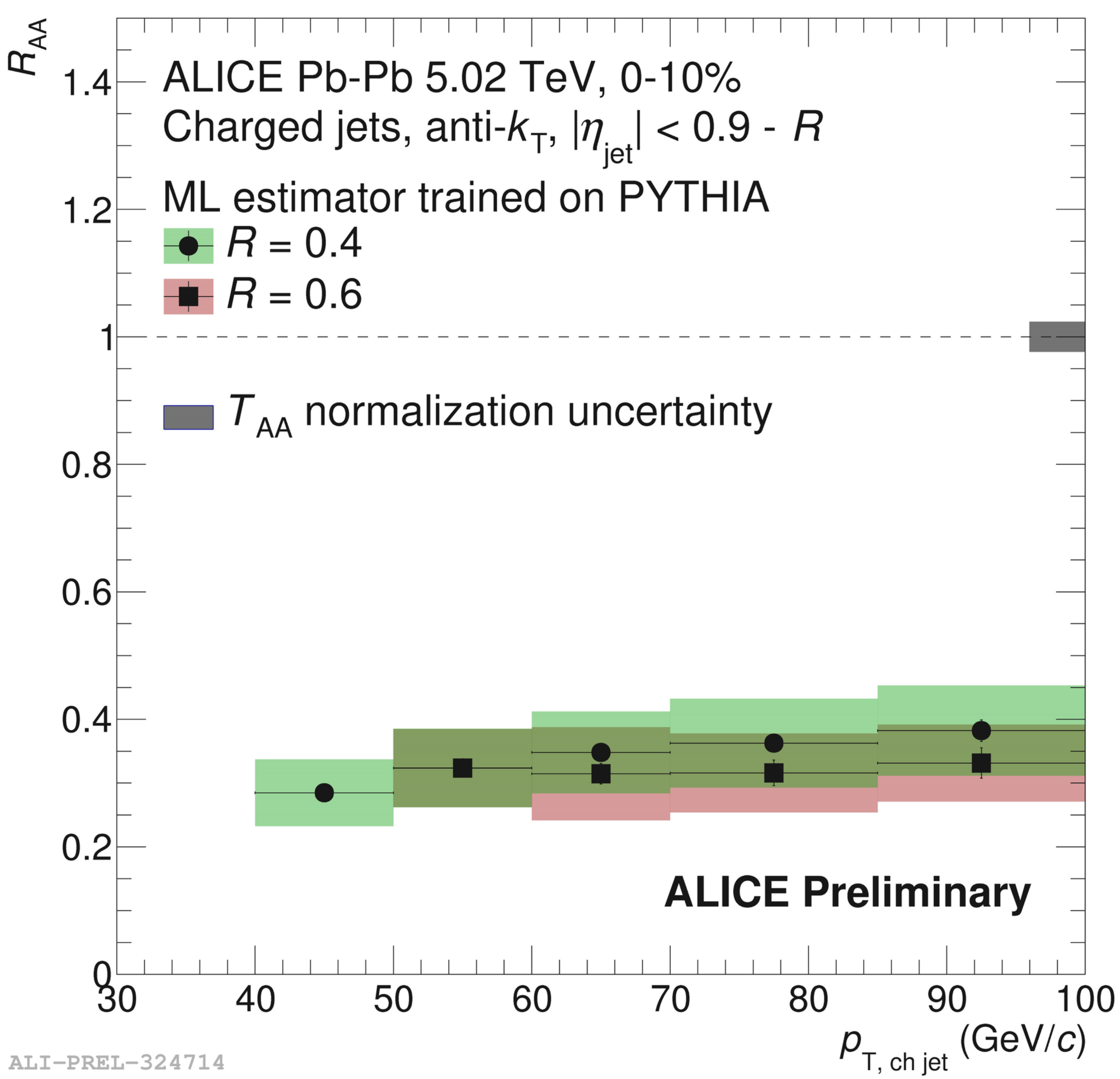


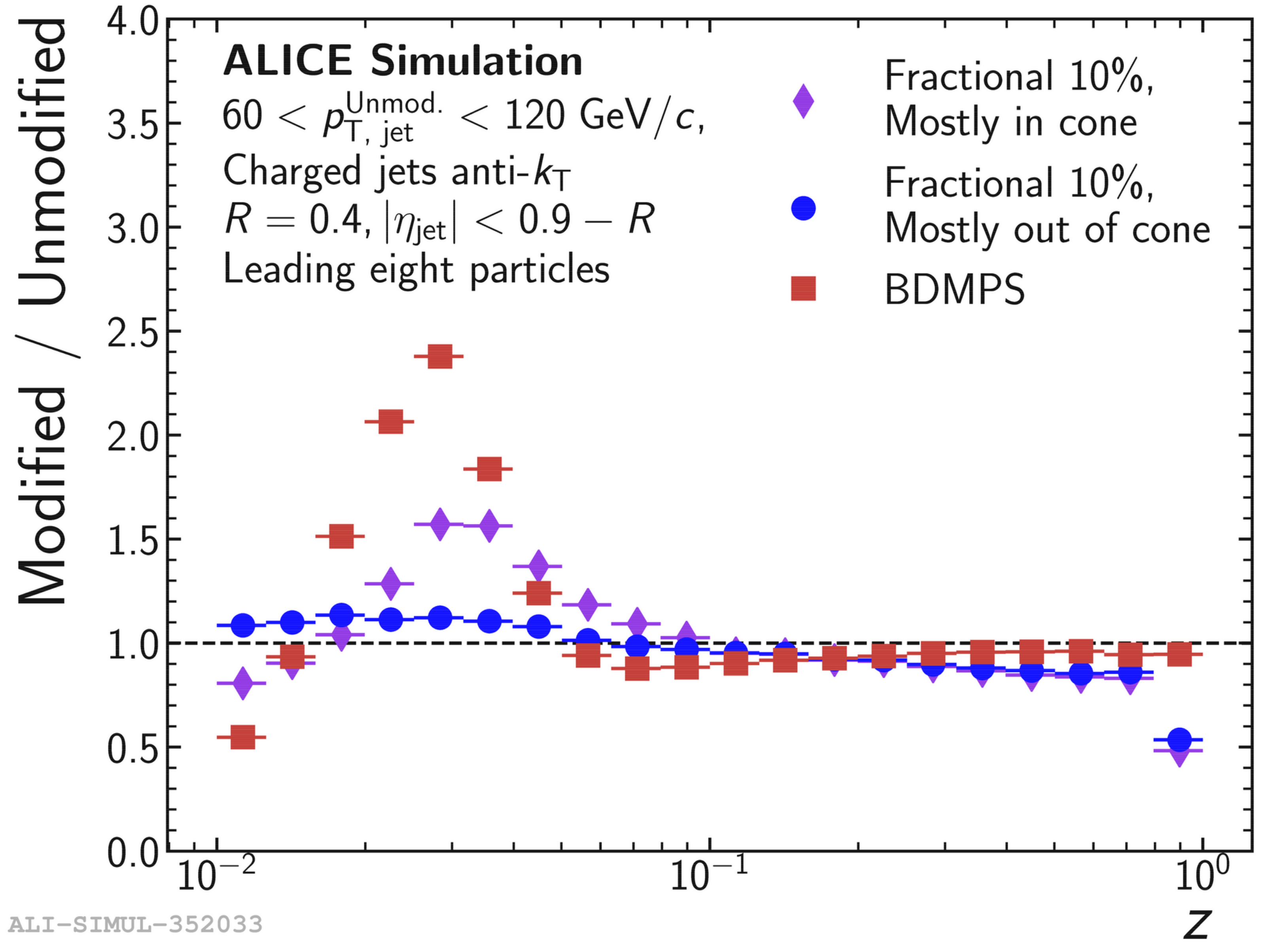
- Using charged particle jets, ALICE was able to push to larger R

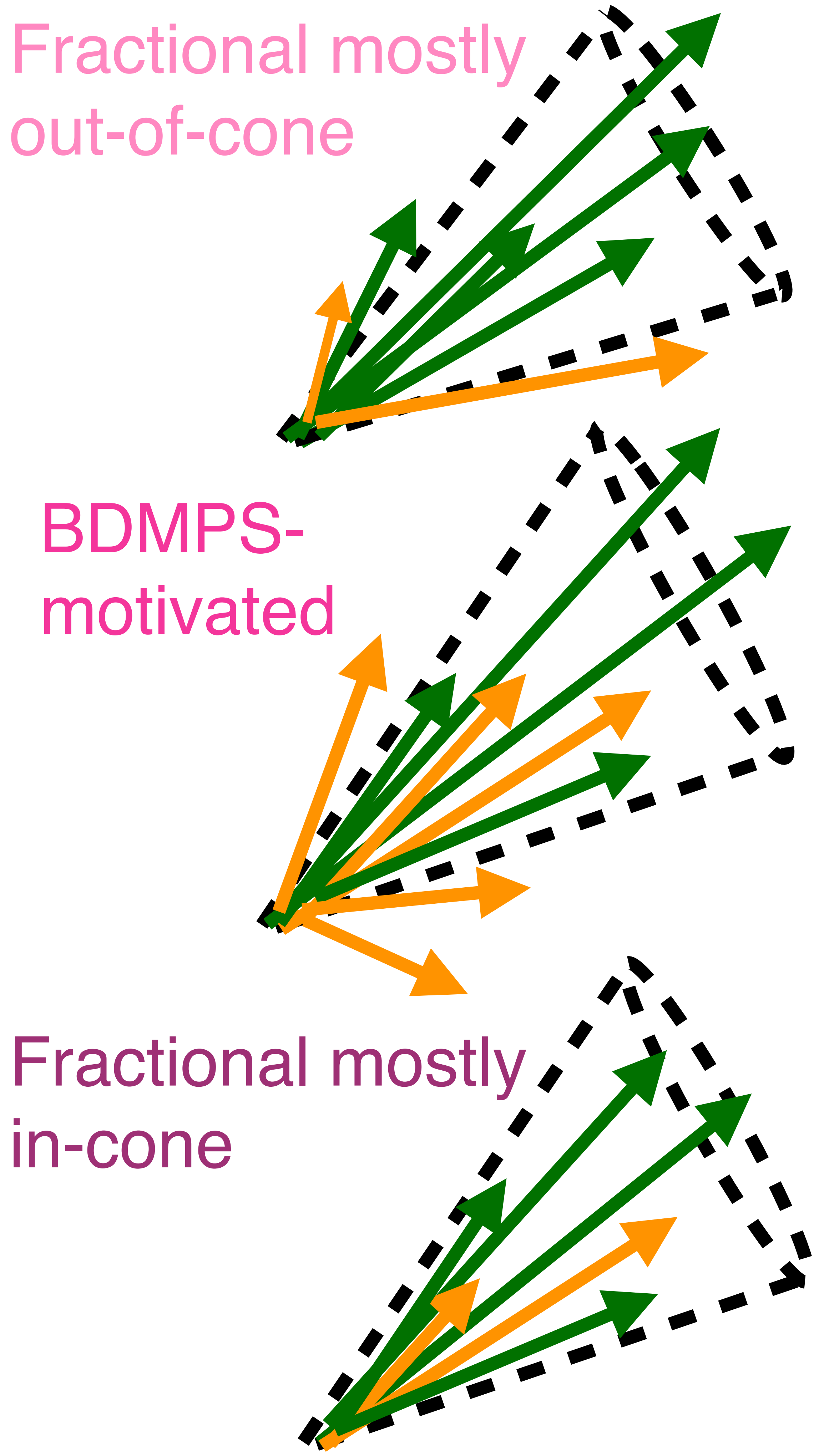
R = 0.6 jets measured down to 60 GeV/c

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





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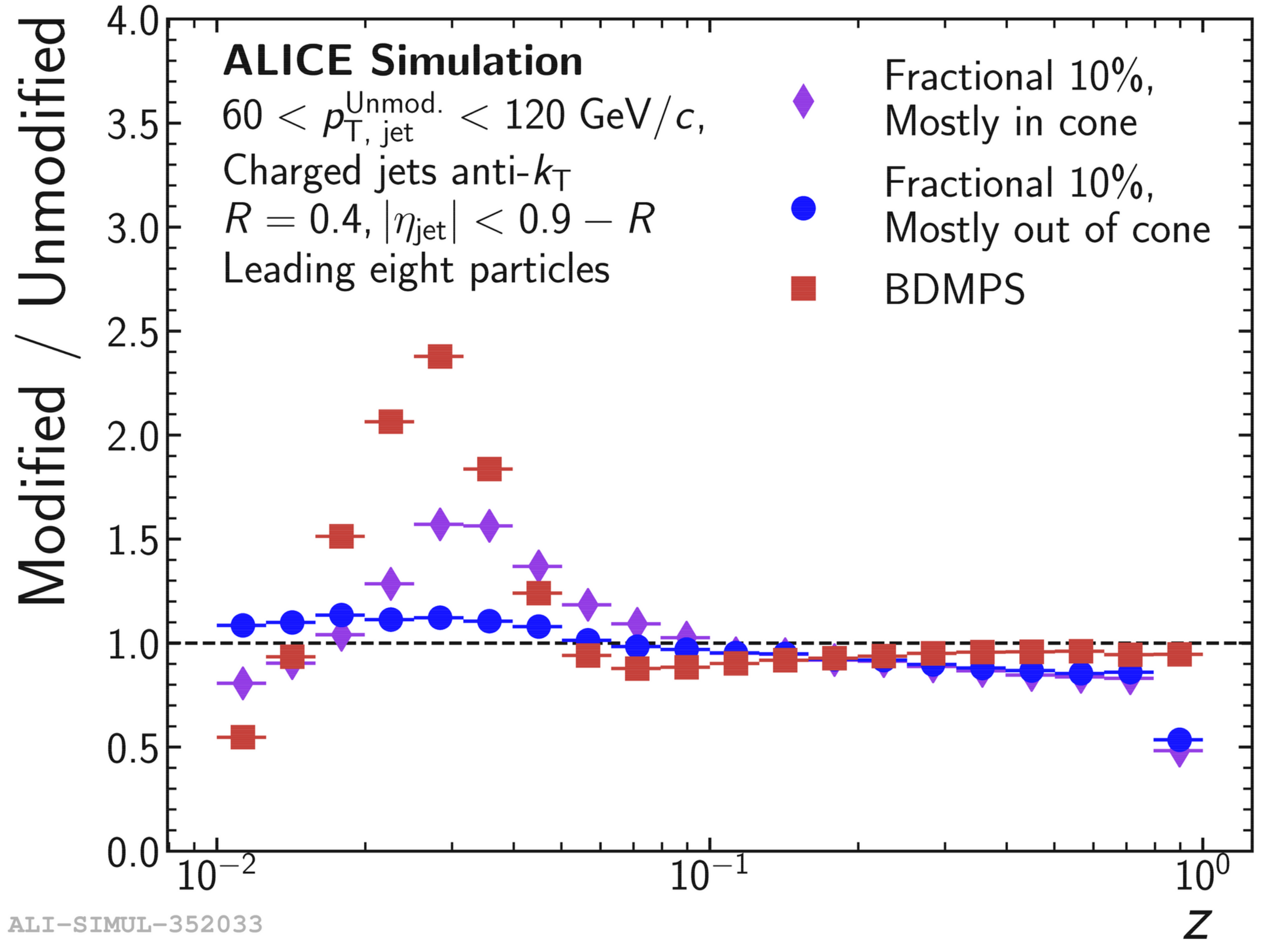
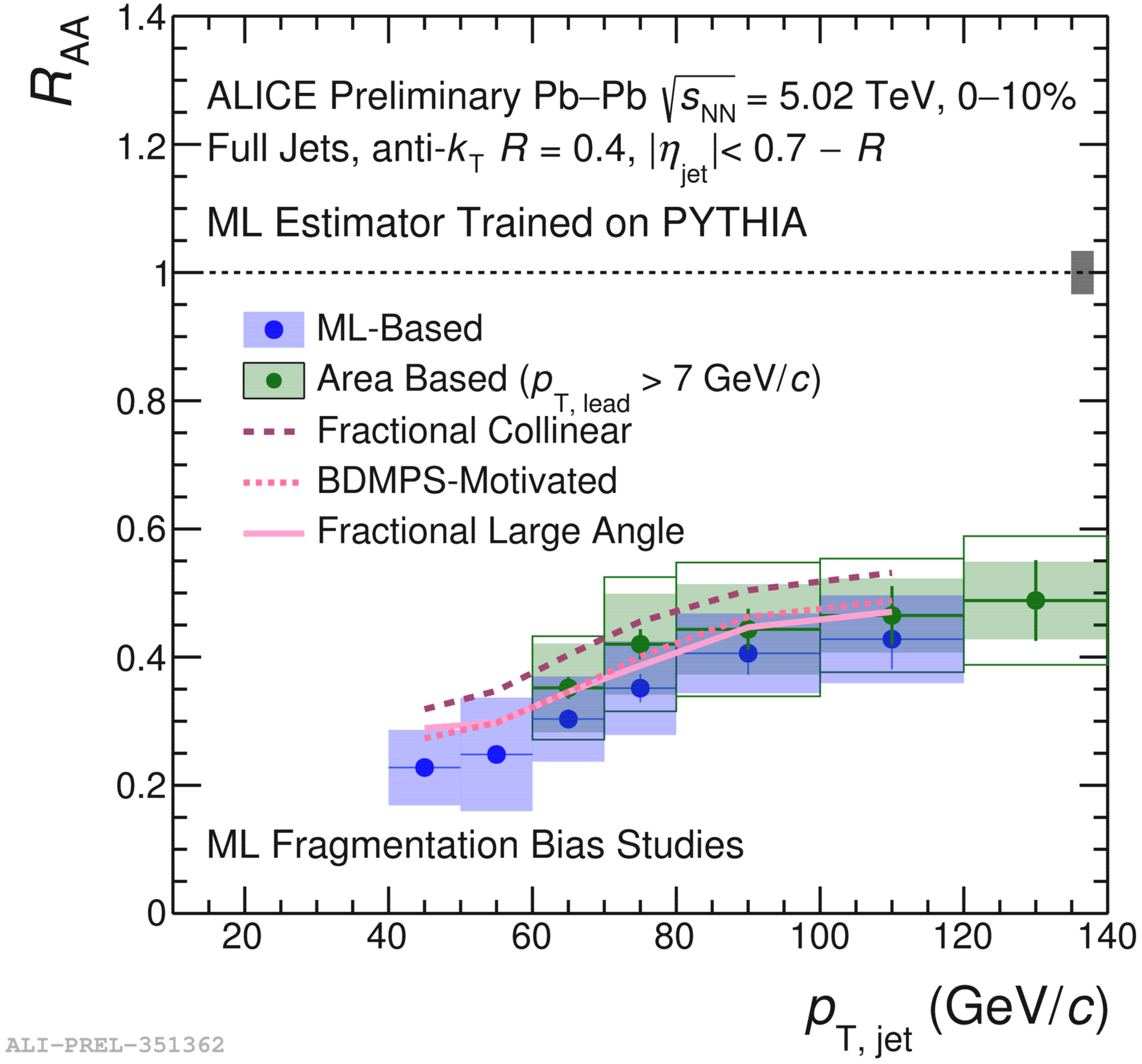




▸ Bias is similar in magnitude to other systematic uncertainties

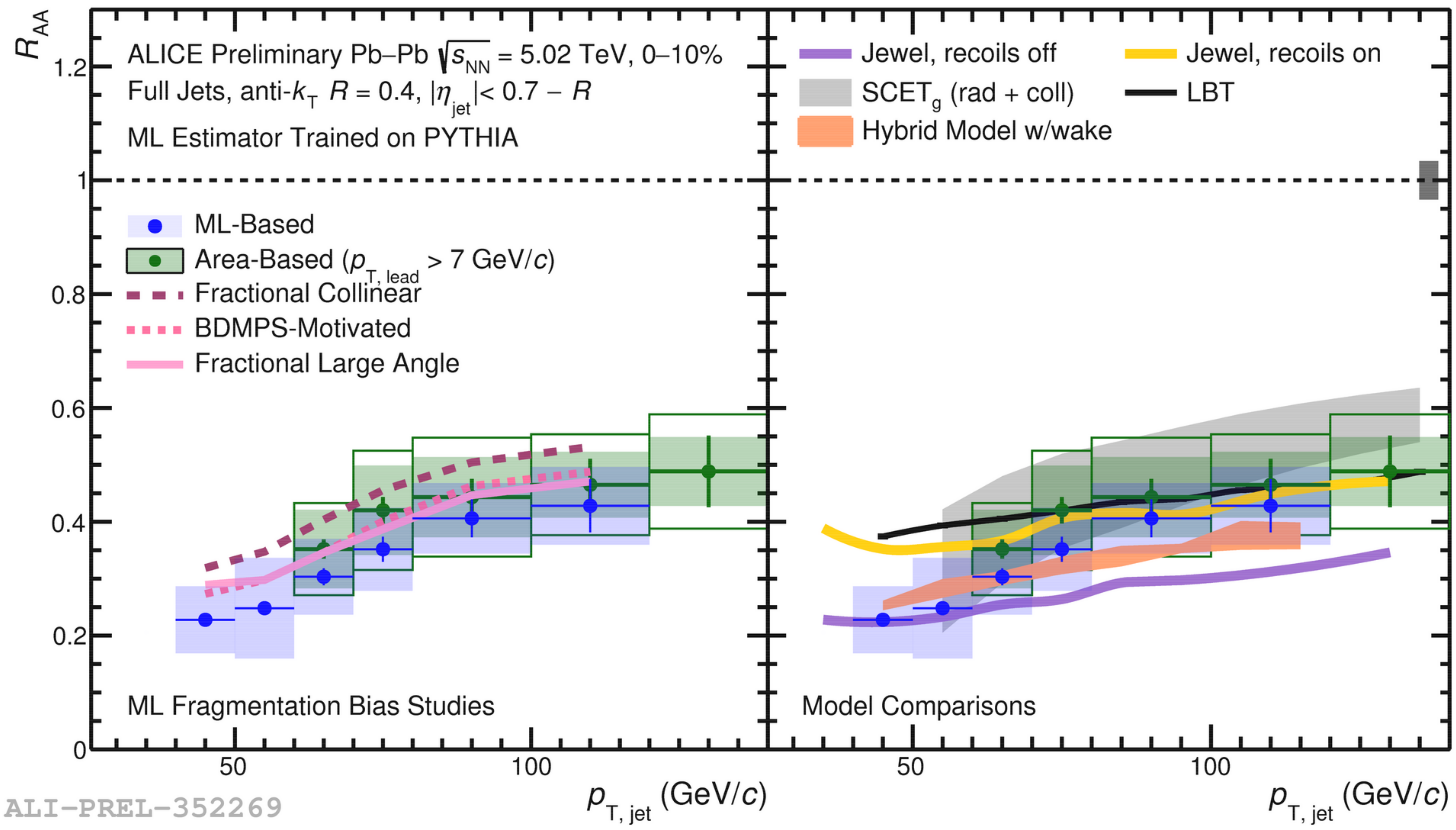
ML approach: model comparisons

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

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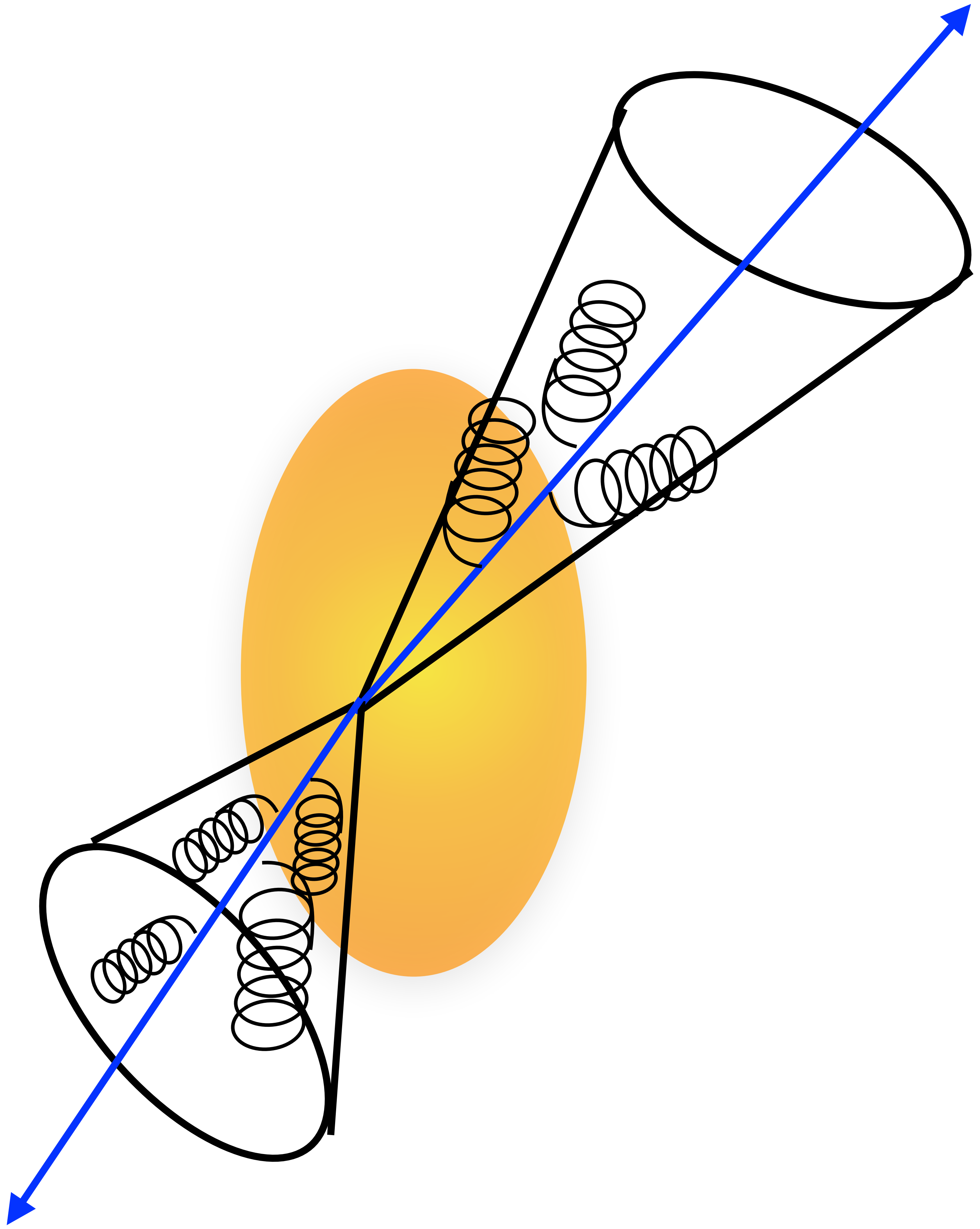

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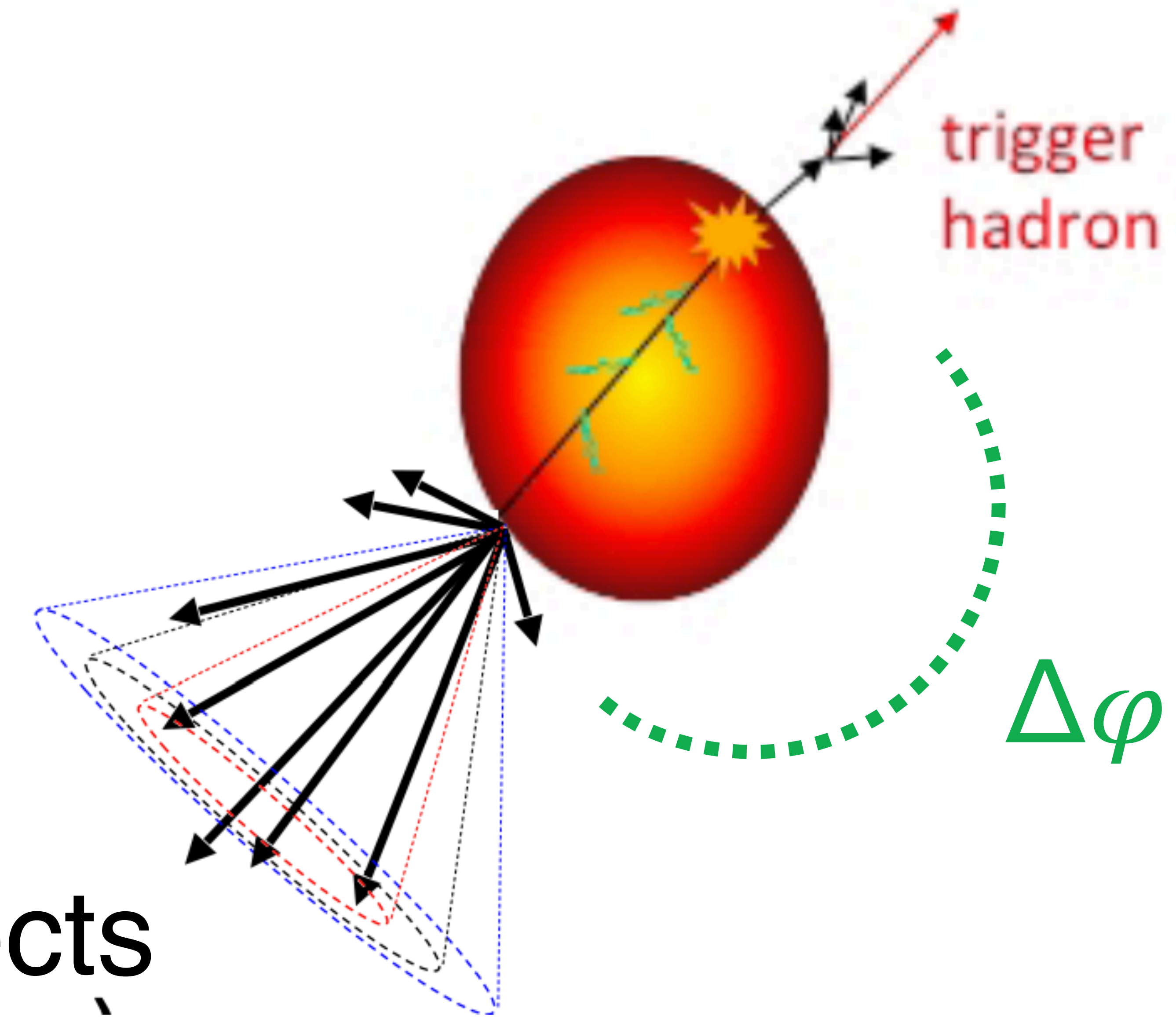
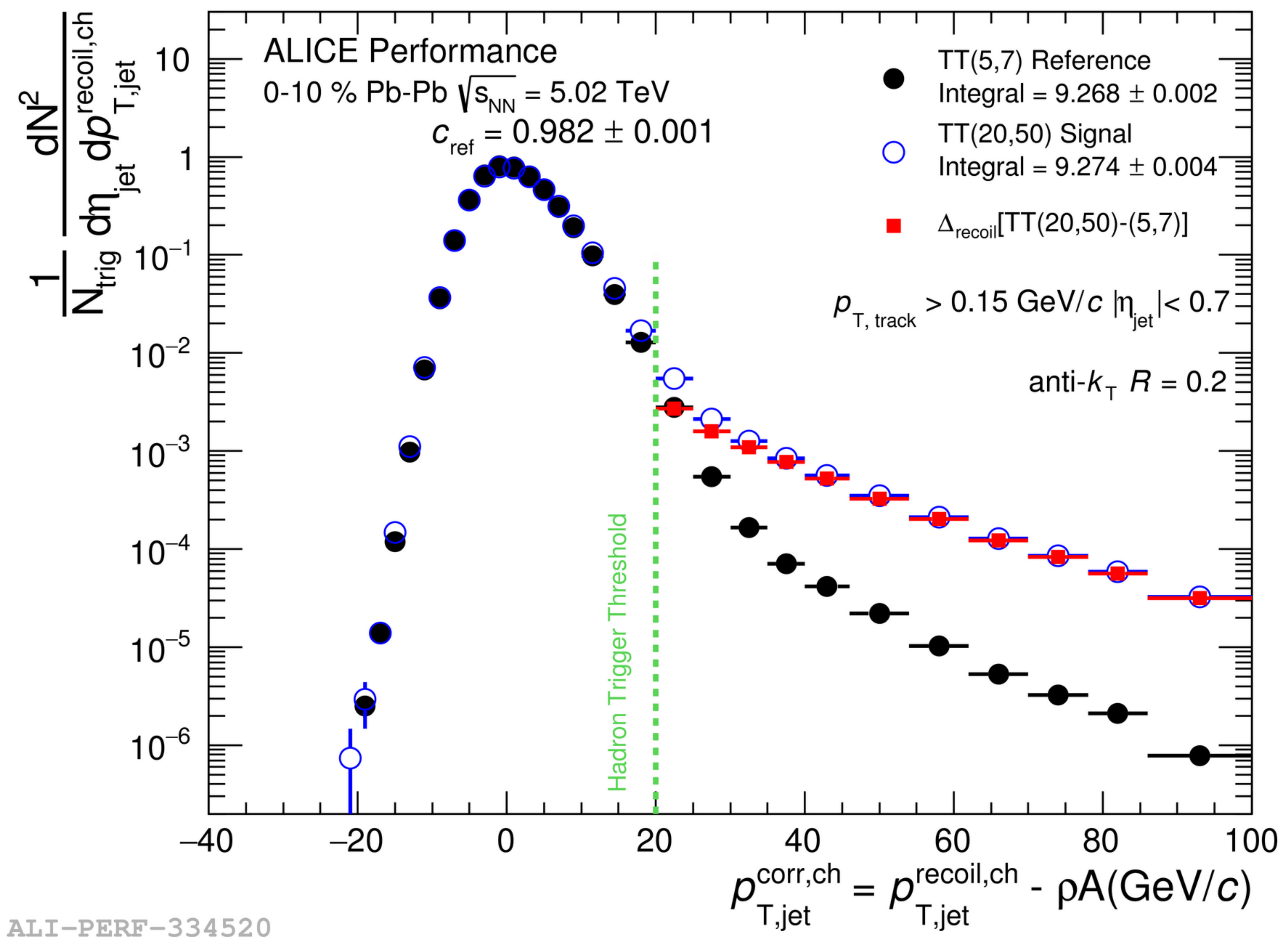
Jet acoplanarity

- 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





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

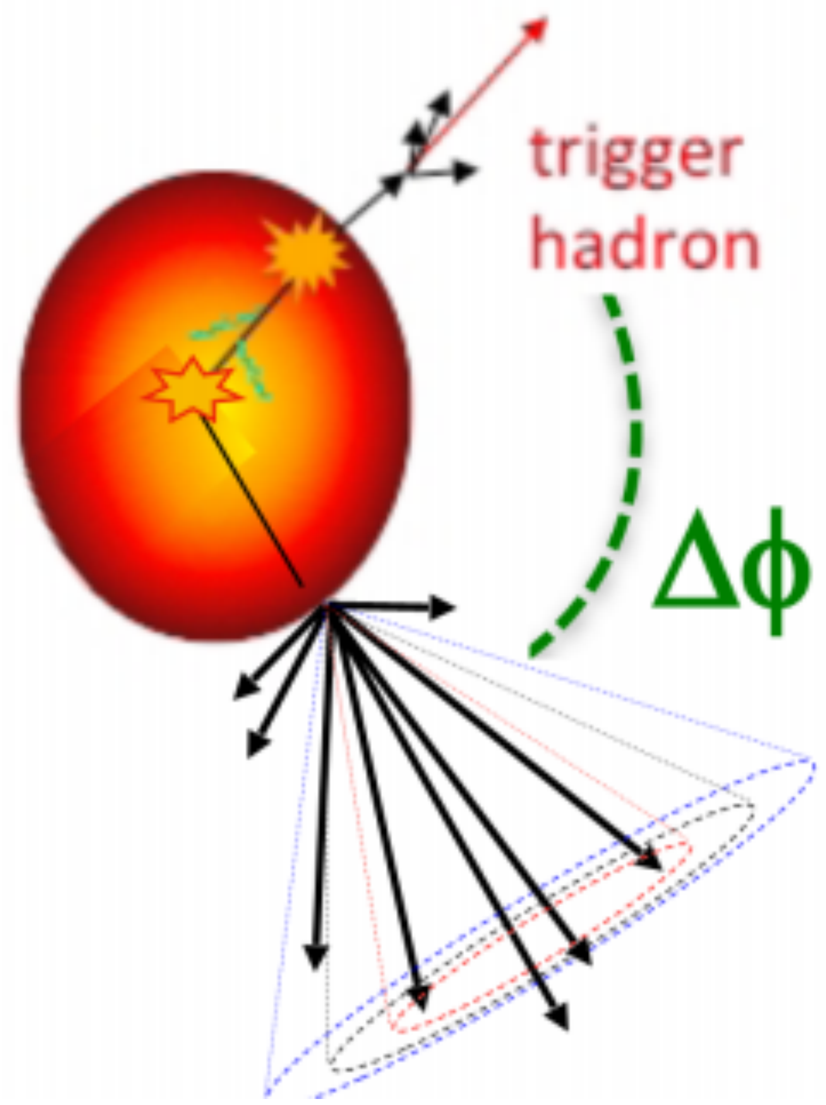
signal TT 20-50 GeV/c — reference TT 5-7 GeV/c

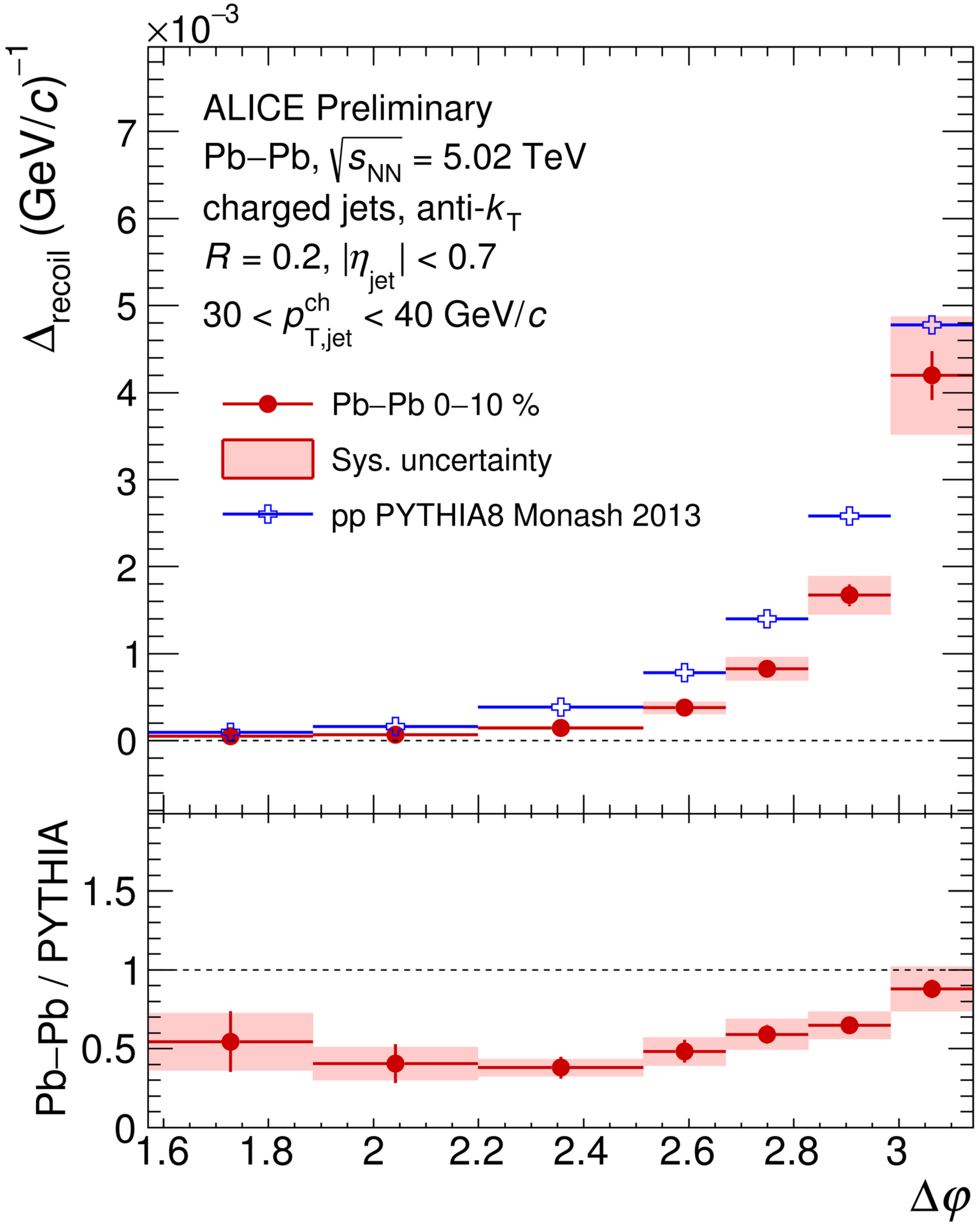
$$\Delta_{recoil} = \frac{1}{N_{trig}^{AA}} \frac{d^3N_{jet}^{AA}}{dp_{T,jet}^{ch}\, d\Delta\varphi\, d\eta_{jet}}\Bigg|_{p_{T,trig}\in TT_{Sig}} - c_{ref} \cdot \frac{1}{N_{trig}^{AA}} \frac{d^3N_{jet}^{AA}}{dp_{T,jet}^{ch}\, d\Delta\varphi\, d\eta_{jet}}\Bigg|_{p_{T,trig}\in TT_{Ref}}$$

  - Data driven subtraction of uncorrelated background

Results: jet acoplanarity

- Distributions are unfolded in 2D in $\Delta\varphi$ and p_T
  - Measure low-p_T recoil jets between 30-40 GeV/c
  - Region where vacuum Sudakov radiation is suppressed





- Central Pb-Pb compared to PYTHIA8
  - Jet yields in Pb-Pb are strongly suppressed
  - $\Delta\varphi$ narrower than vacuum expectations, may be from quantum interference effects

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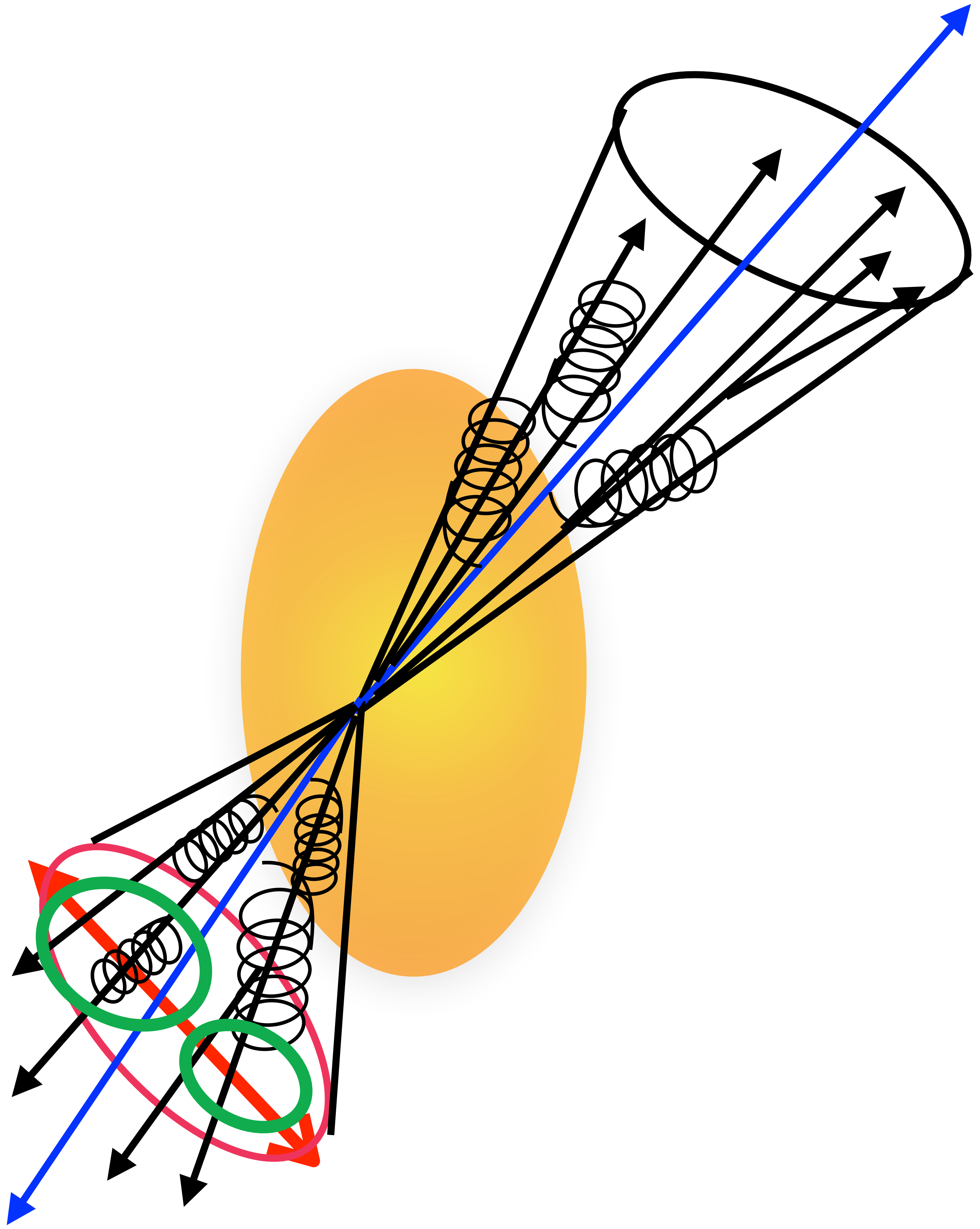

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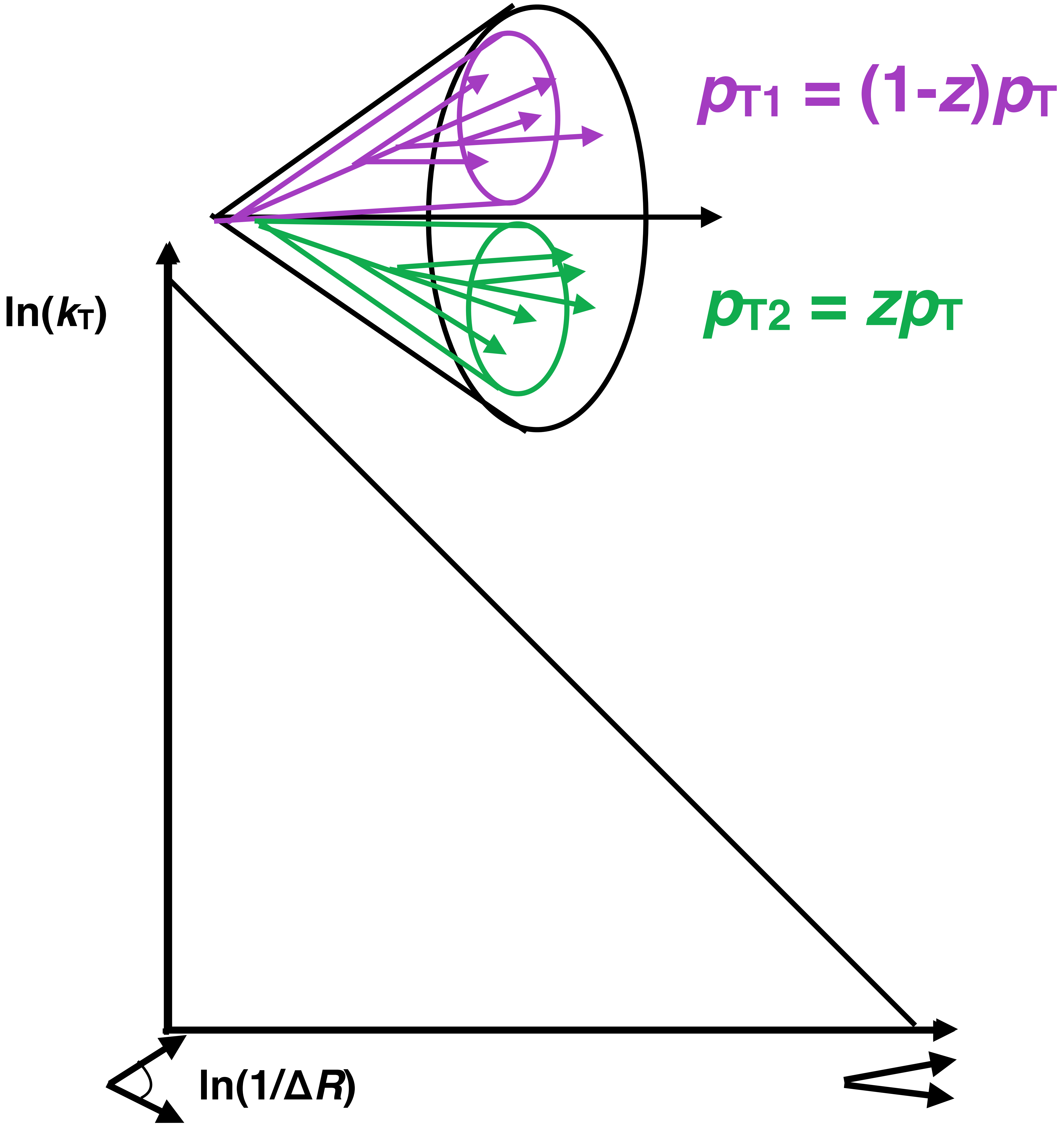
▸ *Need to understand initial and final state effects not from jet quenching*

Exploring the Lund plane: in vacuum

- Lund Diagram*: phase space of jet splitting

*Andersson et al ZPC43 (1989)
Dreyer et al JHEP 12 (2018)



arXiv:1808.03689

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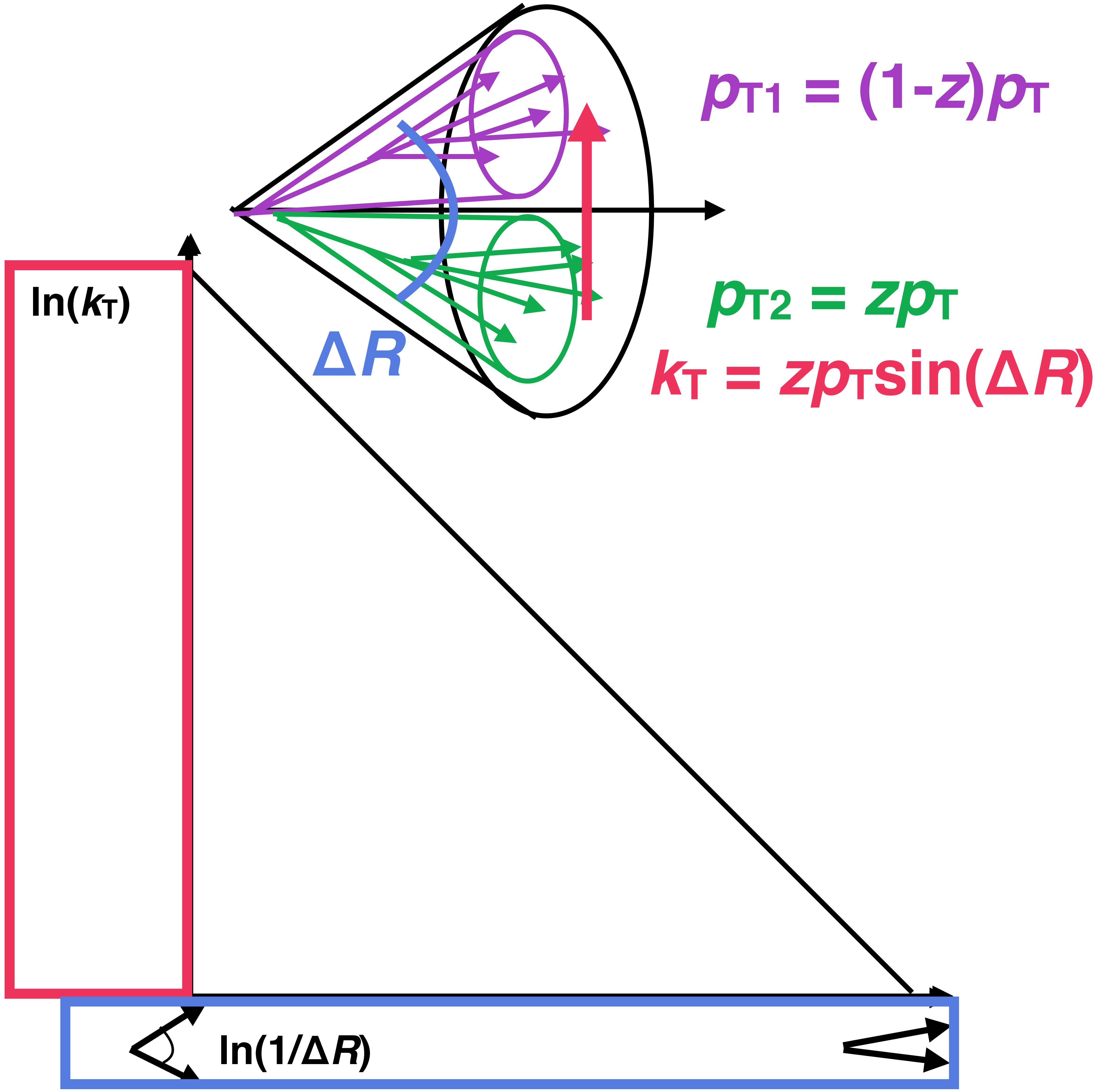
Dreyer et al JHEP 12 (2018)

- k_T: relative transverse momentum of subjets

- ΔR: opening angle between subjets



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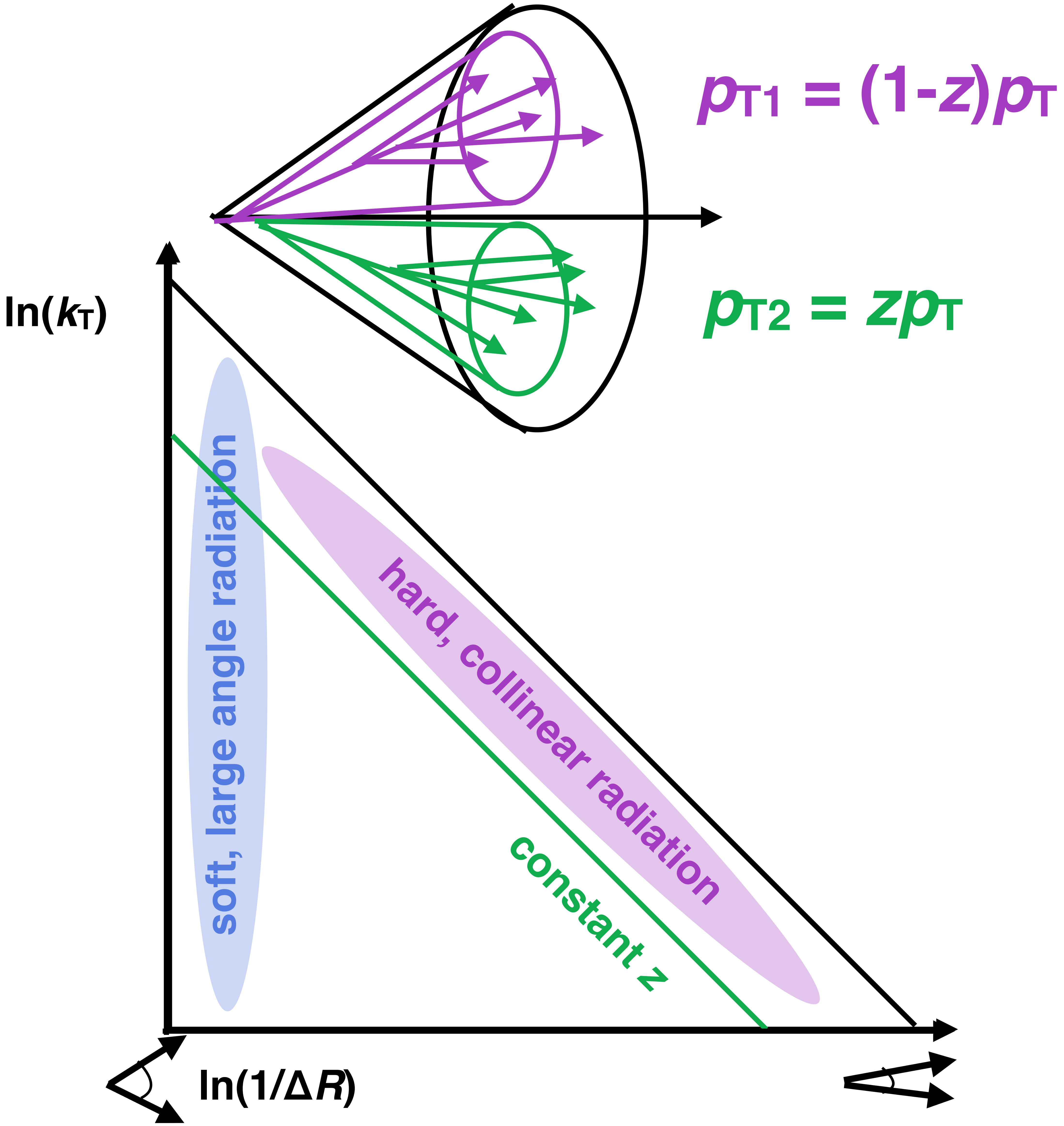

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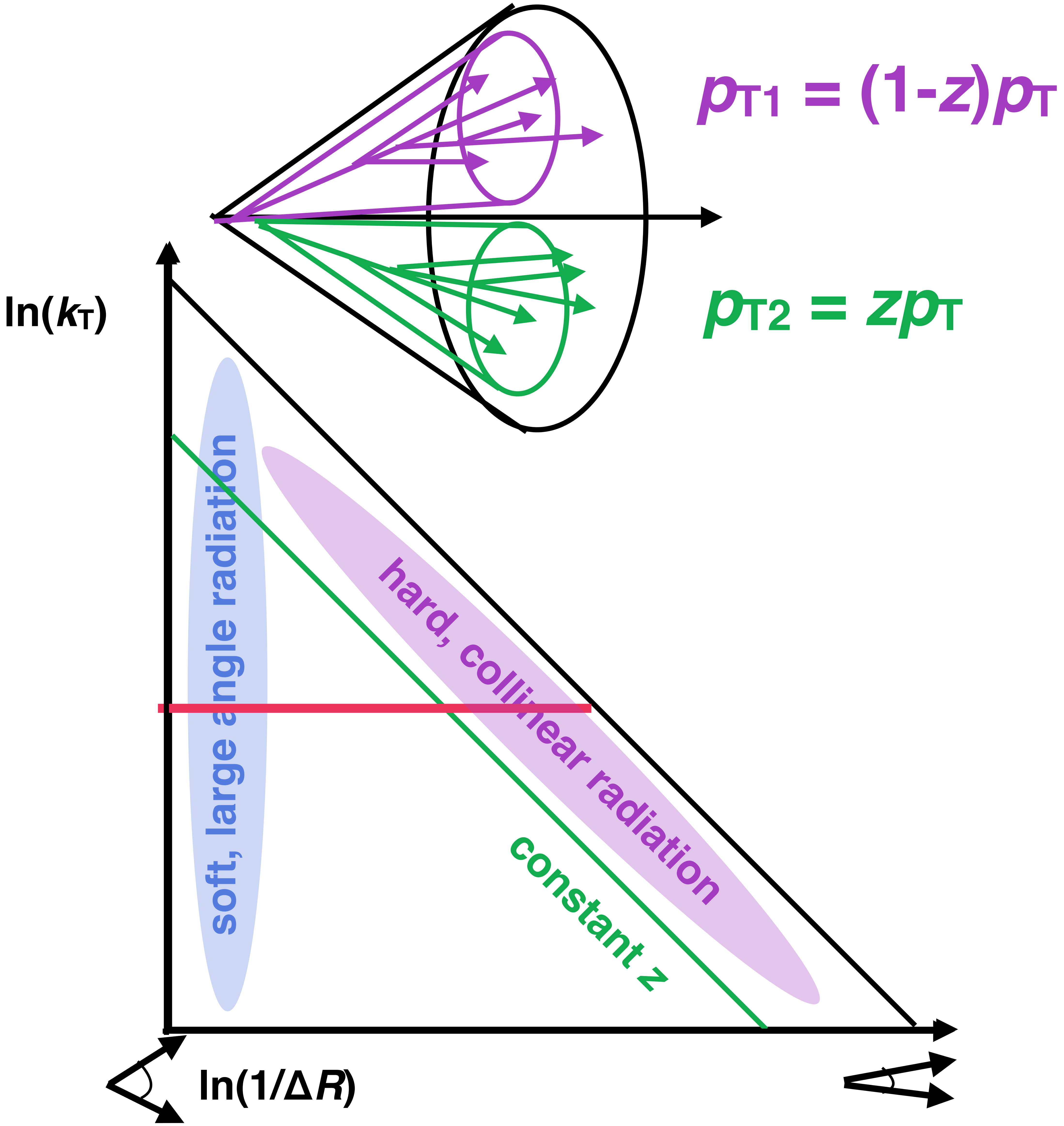

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Exploring the Lund plane: in vacuum

- Lund Diagram*: phase space of jet splitting

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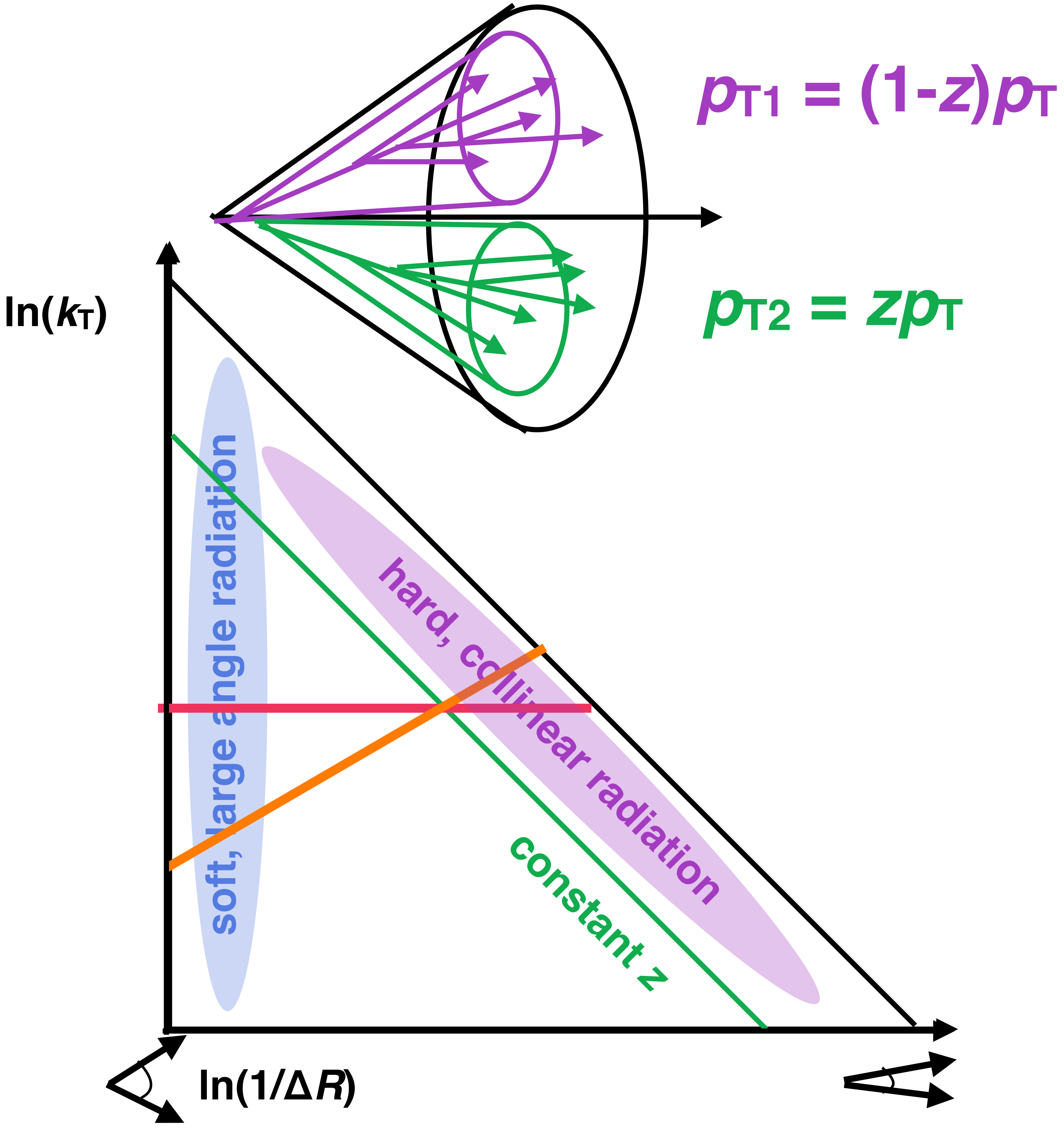
Dreyer et al JHEP 12 (2018)

- $\log(k_T) > 0$ separates perturbative from non-perturbative regime

- Formation time: how long until the splitting is formed

Dokshitzer, et.al.

$$t_f = \frac{1}{(1-z)k_T \Delta R}$$



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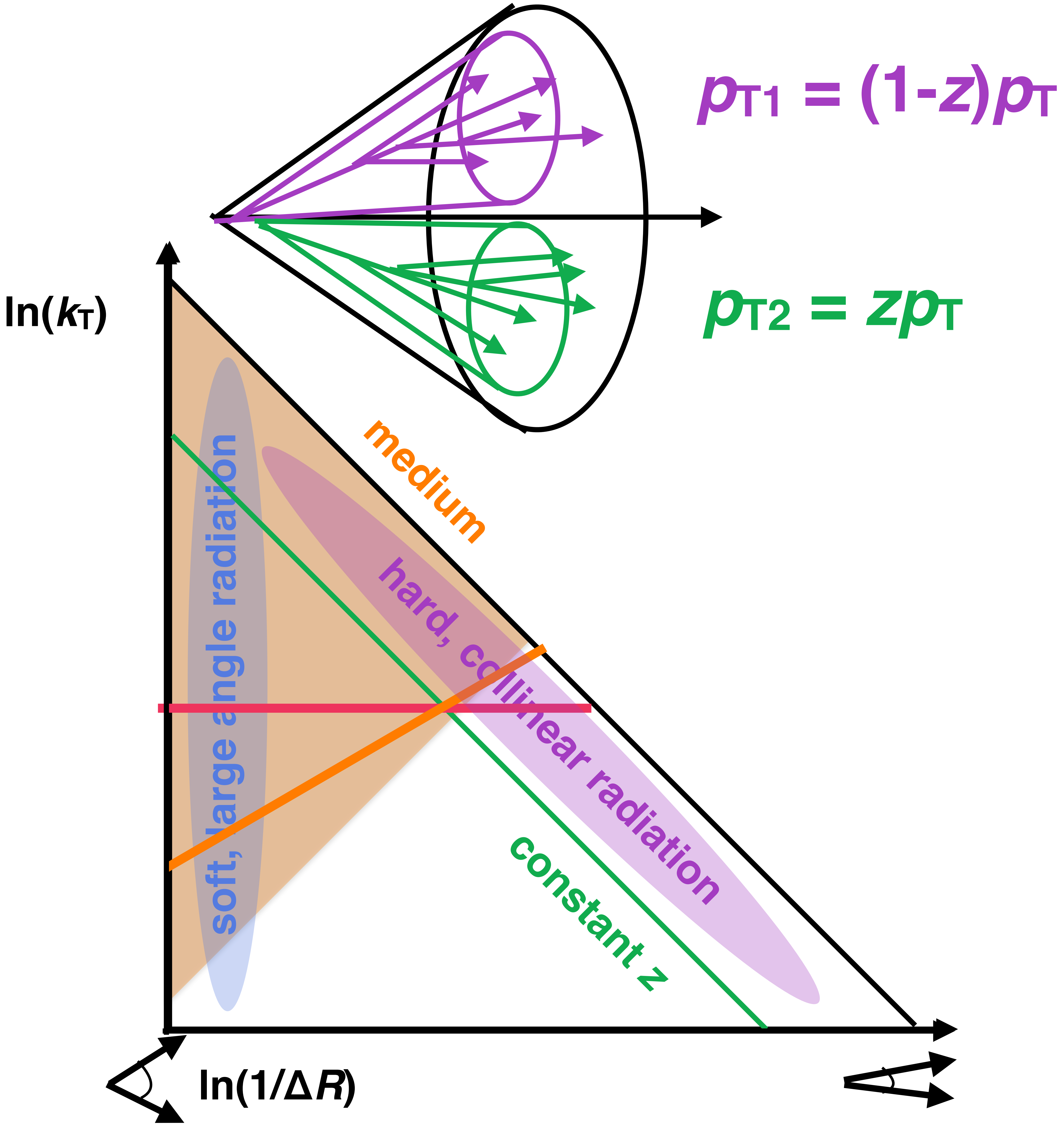
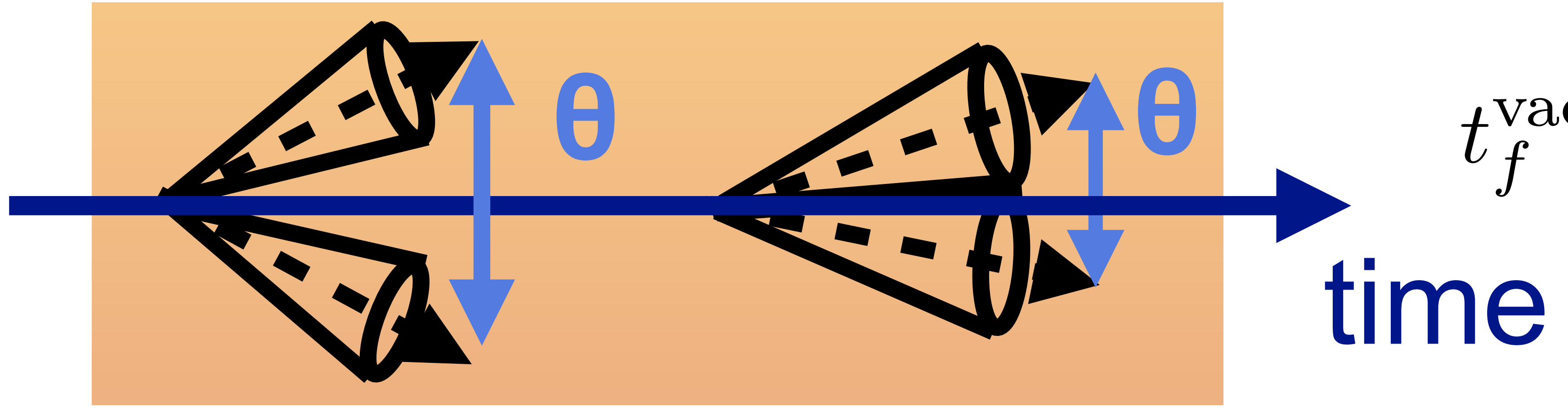
Exploring the Lund plane: in medium

- Jet splittings in HI collisions

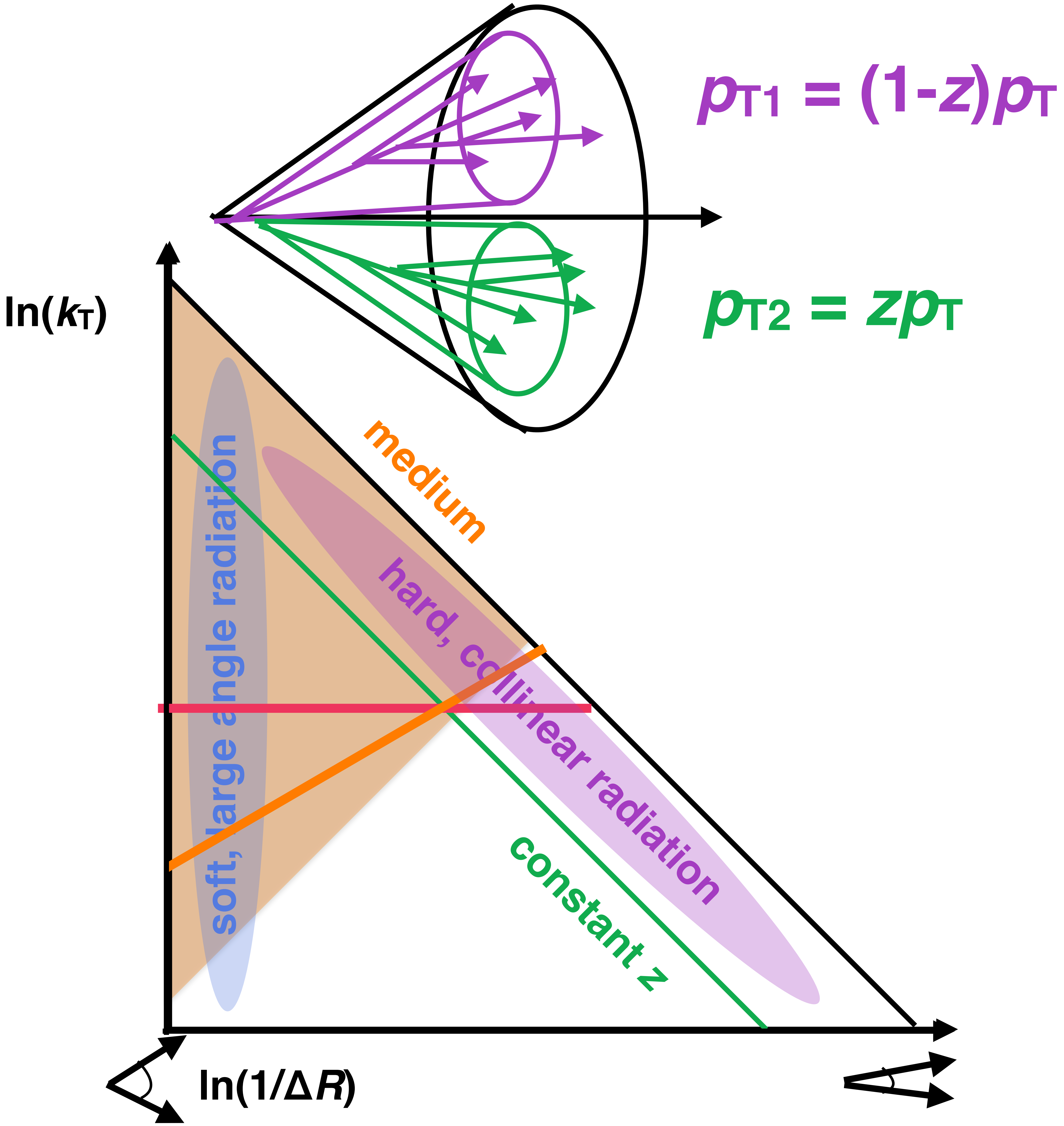


Exploring the Lund plane: in medium

- Jet splittings in HI collisions
  - Time-ordered structure: earlier/wider jets experience more medium



$$t_f^{\text{vac}} = \frac{1}{\theta^2 \omega}$$



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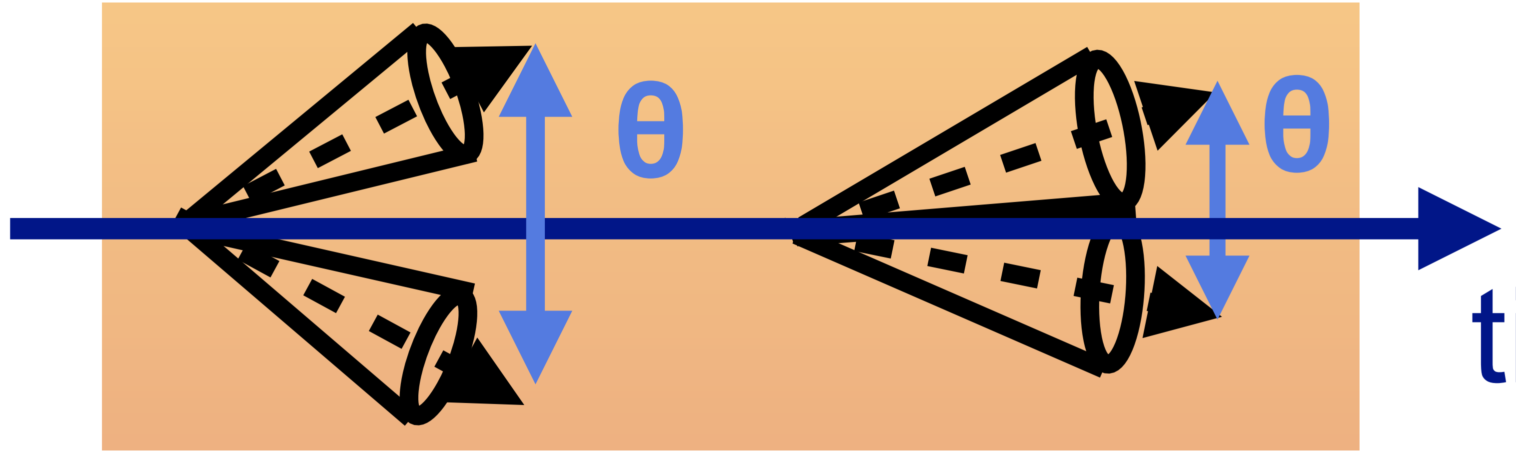

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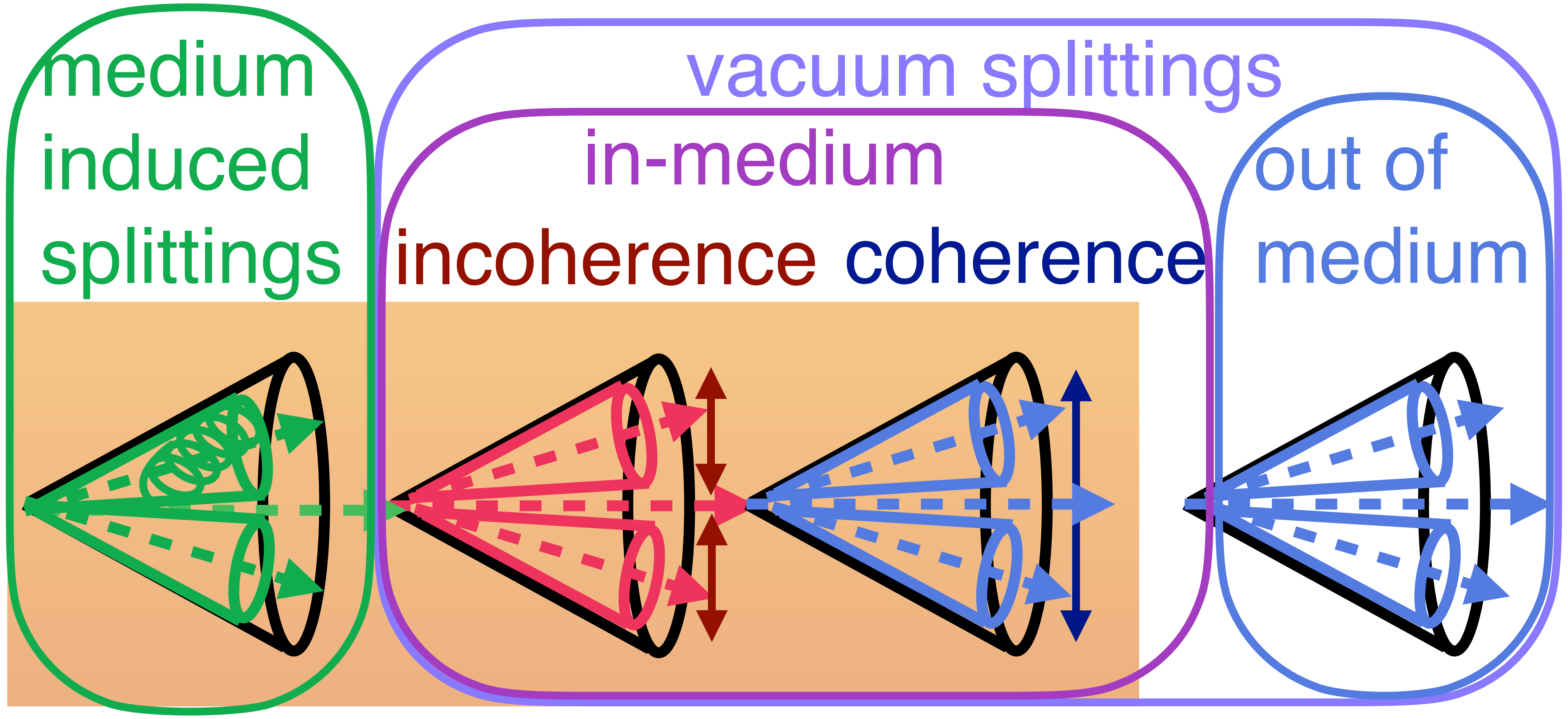
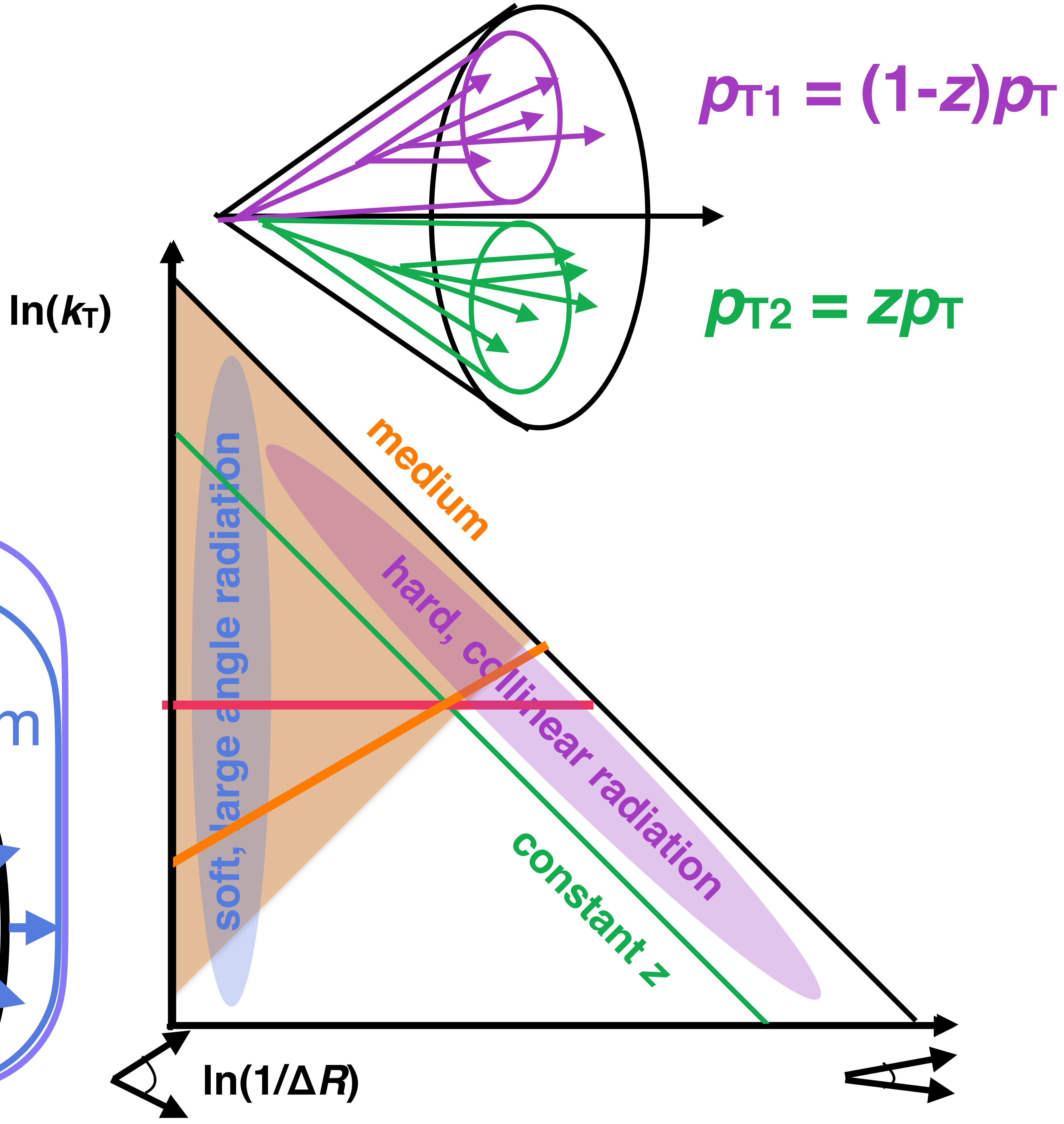
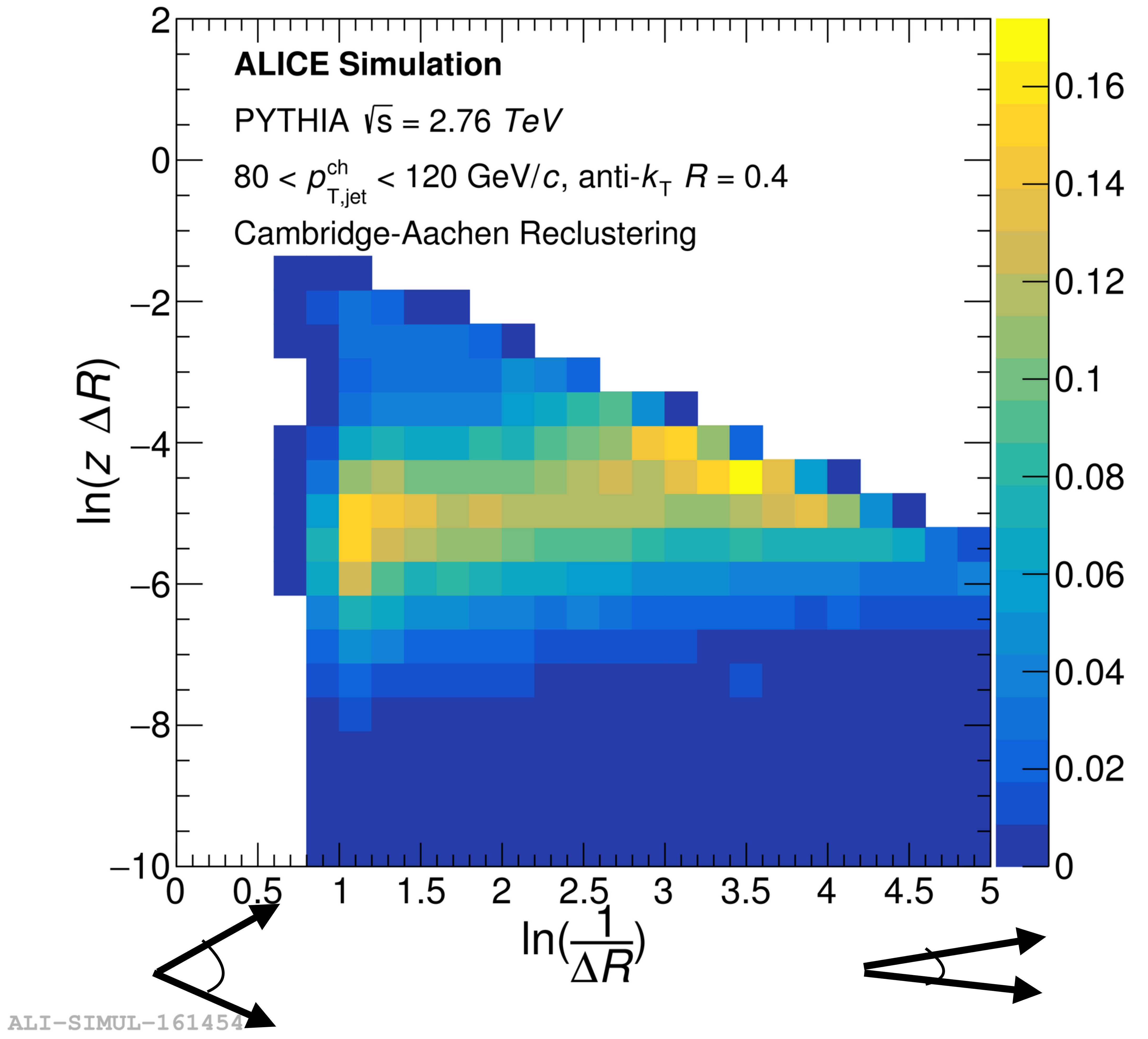




Soft drop grooming

- Method from pp selects harder splittings, removes soft background contribution
  - Pb-Pb: removes soft signal, isolate different medium effects



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- Recluster jets with Cambridge/Aachen (C/A)* to enforce angular ordering

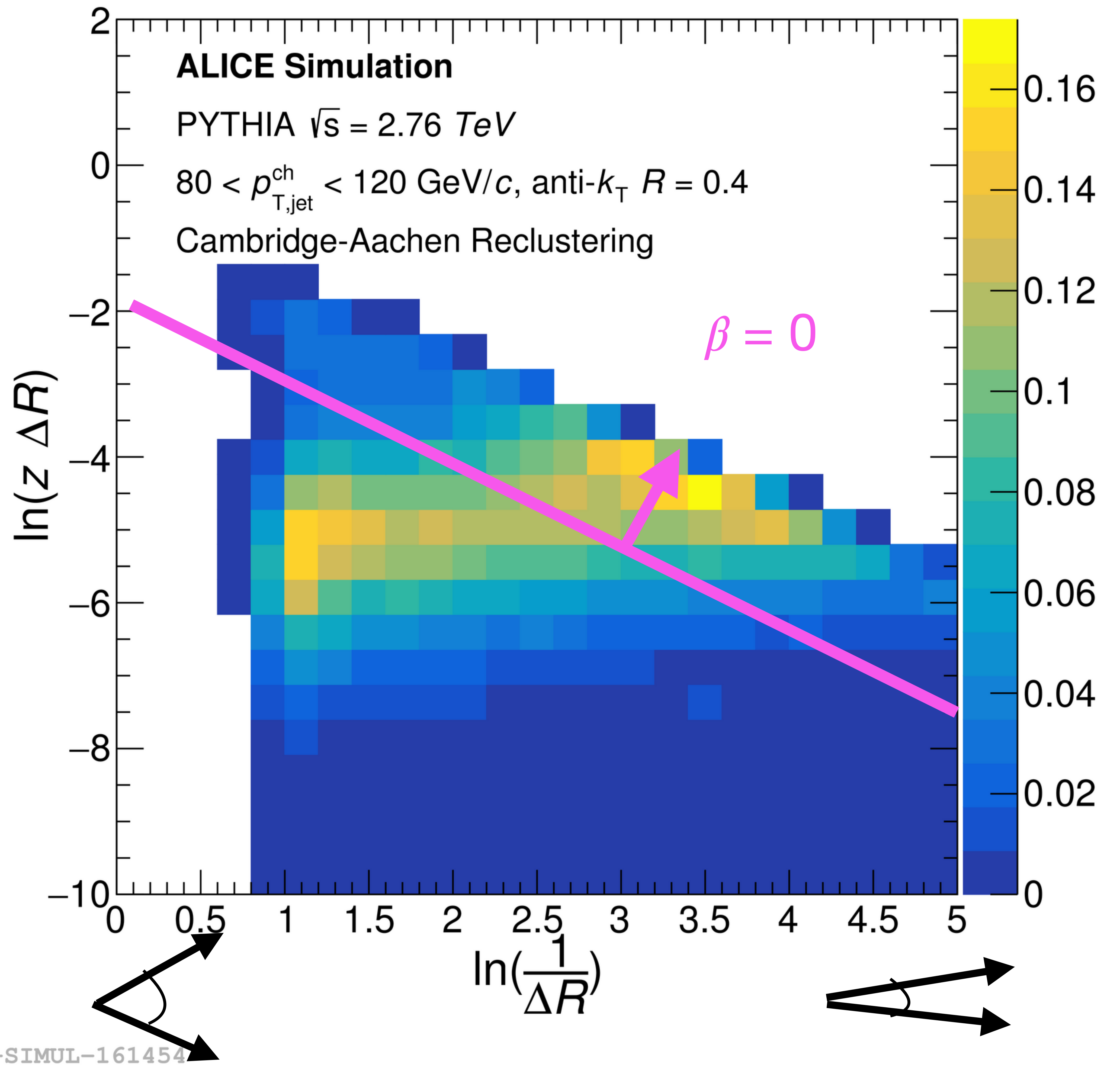
*Dokshitzer et al JHEP 9708:001,1997

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

- Soft drop grooming:

$$z_g > z_{\mathrm{cut}}\theta^{\beta}$$

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



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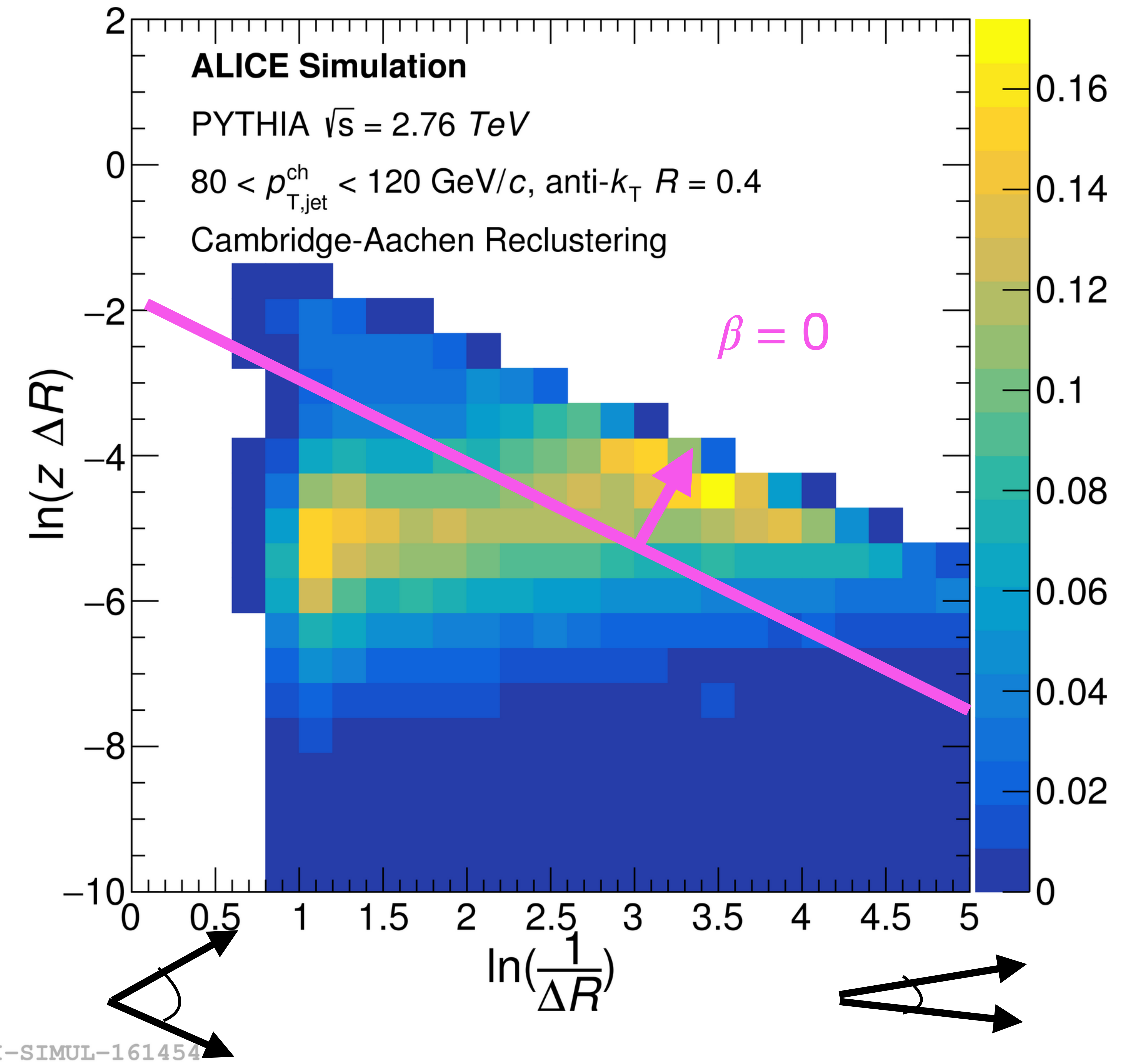
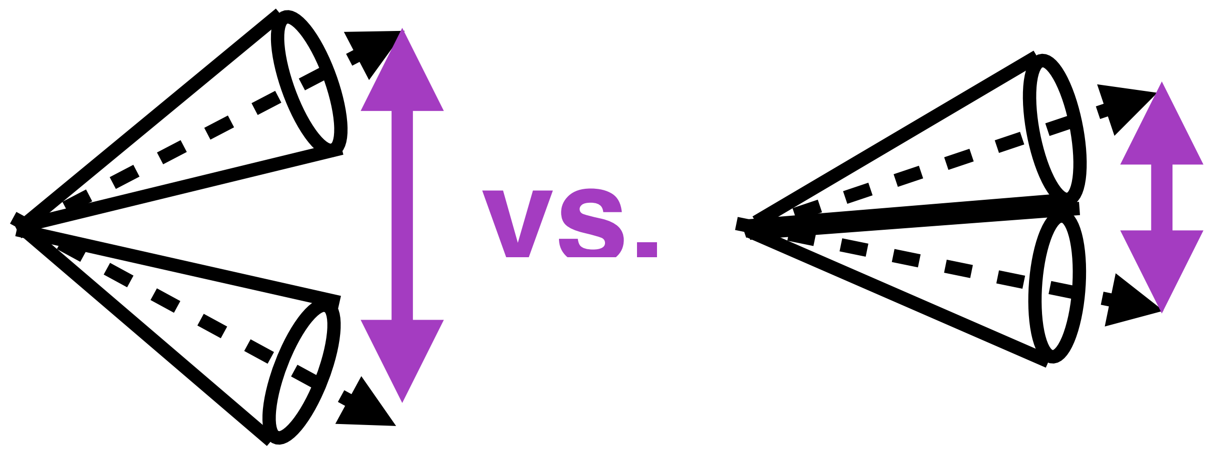
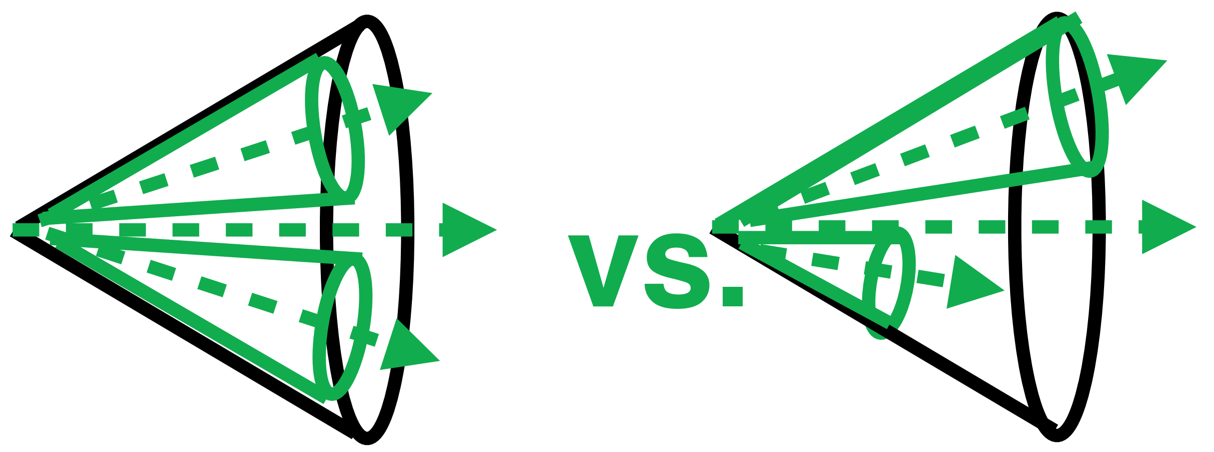


- Soft drop variables calculable in pQCD:

R_g: how far apart are the subjets?

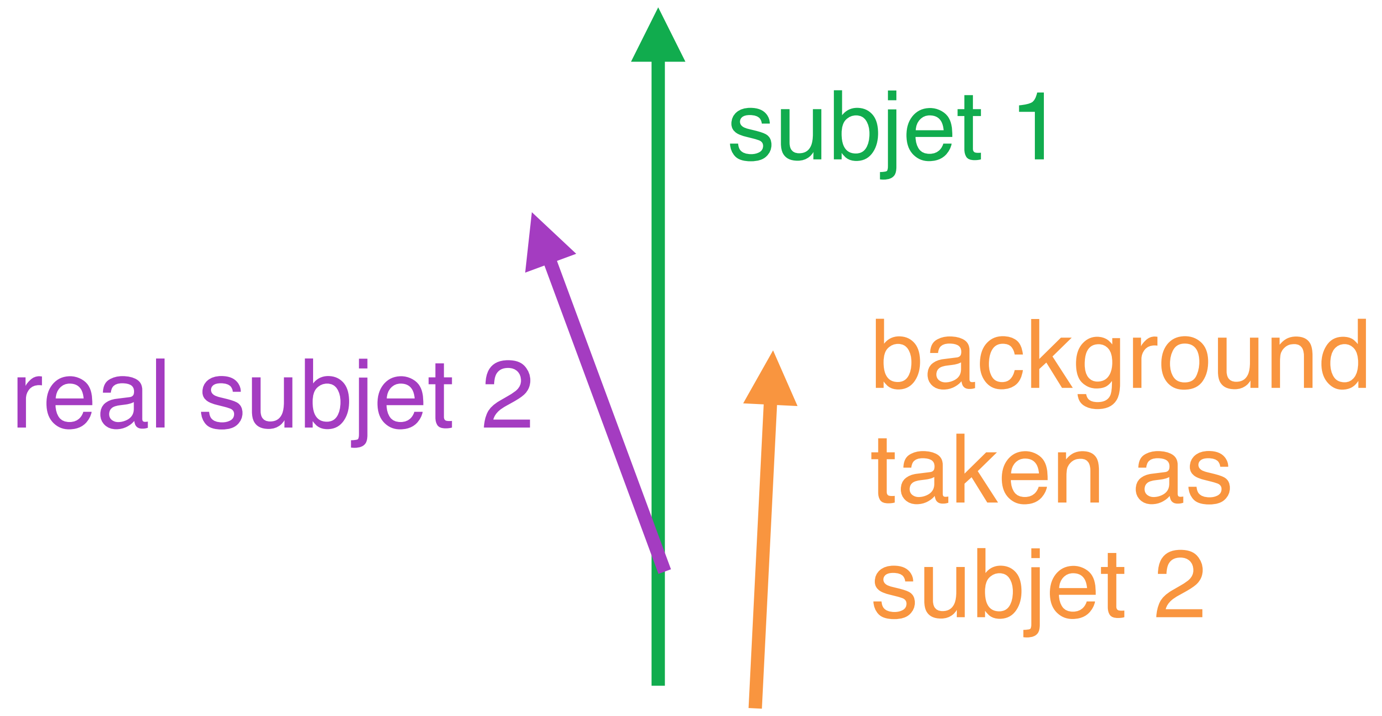


z_g: how symmetric is the jet splitting?



Background treatment

- Uncorrelated background
  leads to incorrect splittings



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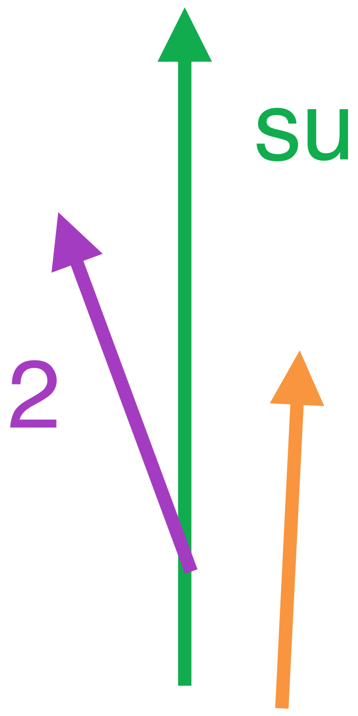
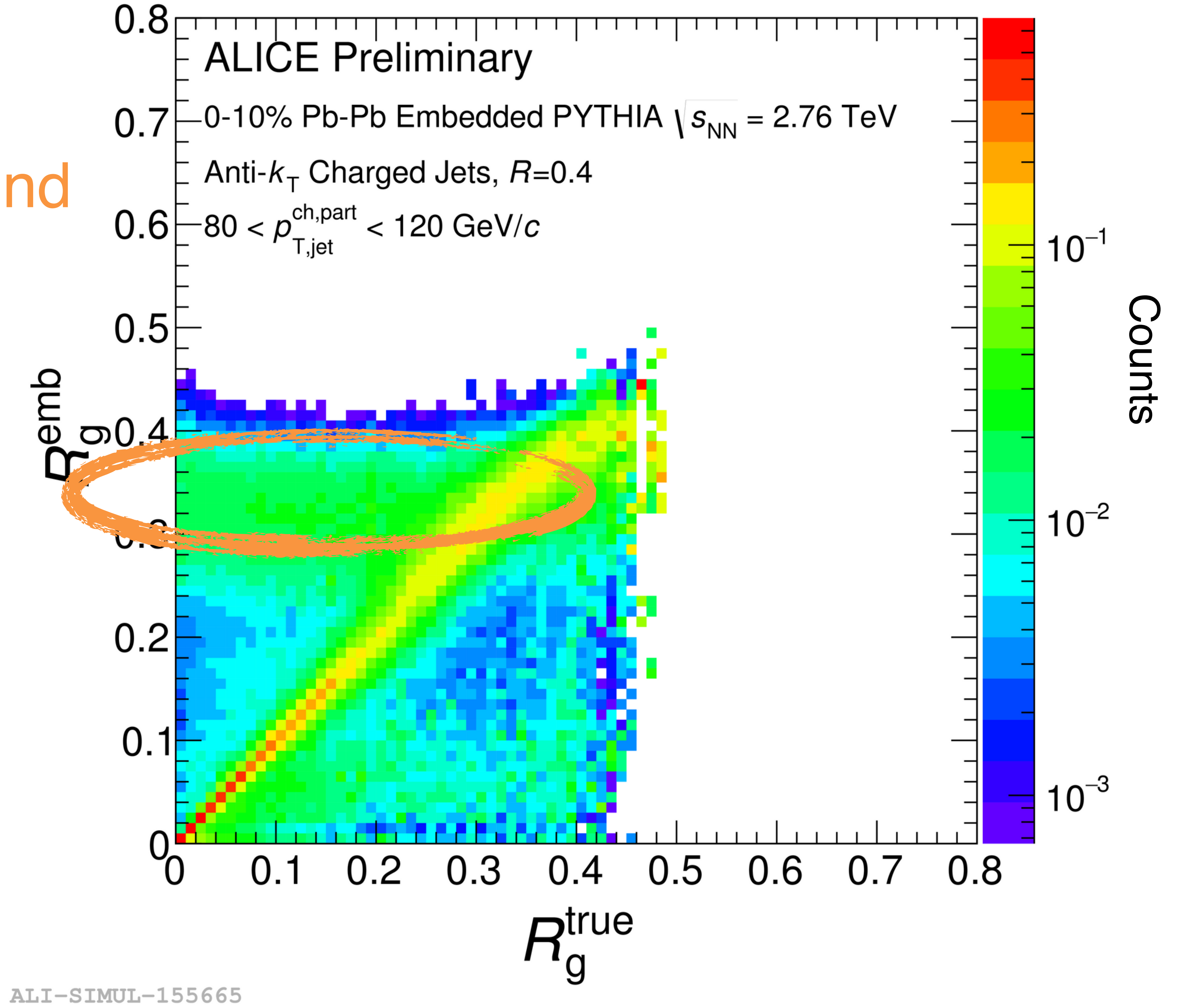


- Response built from embedding Pythia into real minimum bias Pb-Pb data to mimic background
  - *Non-diagonal response prohibits unfolding*



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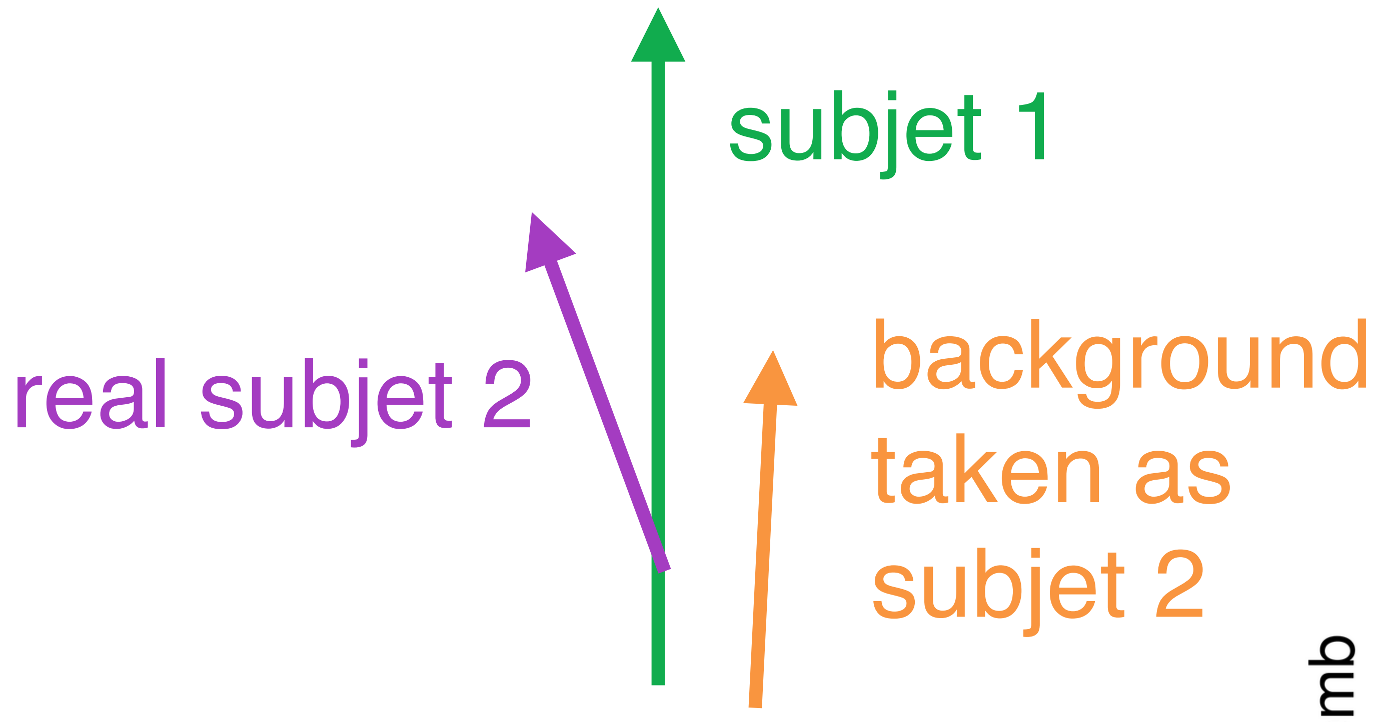

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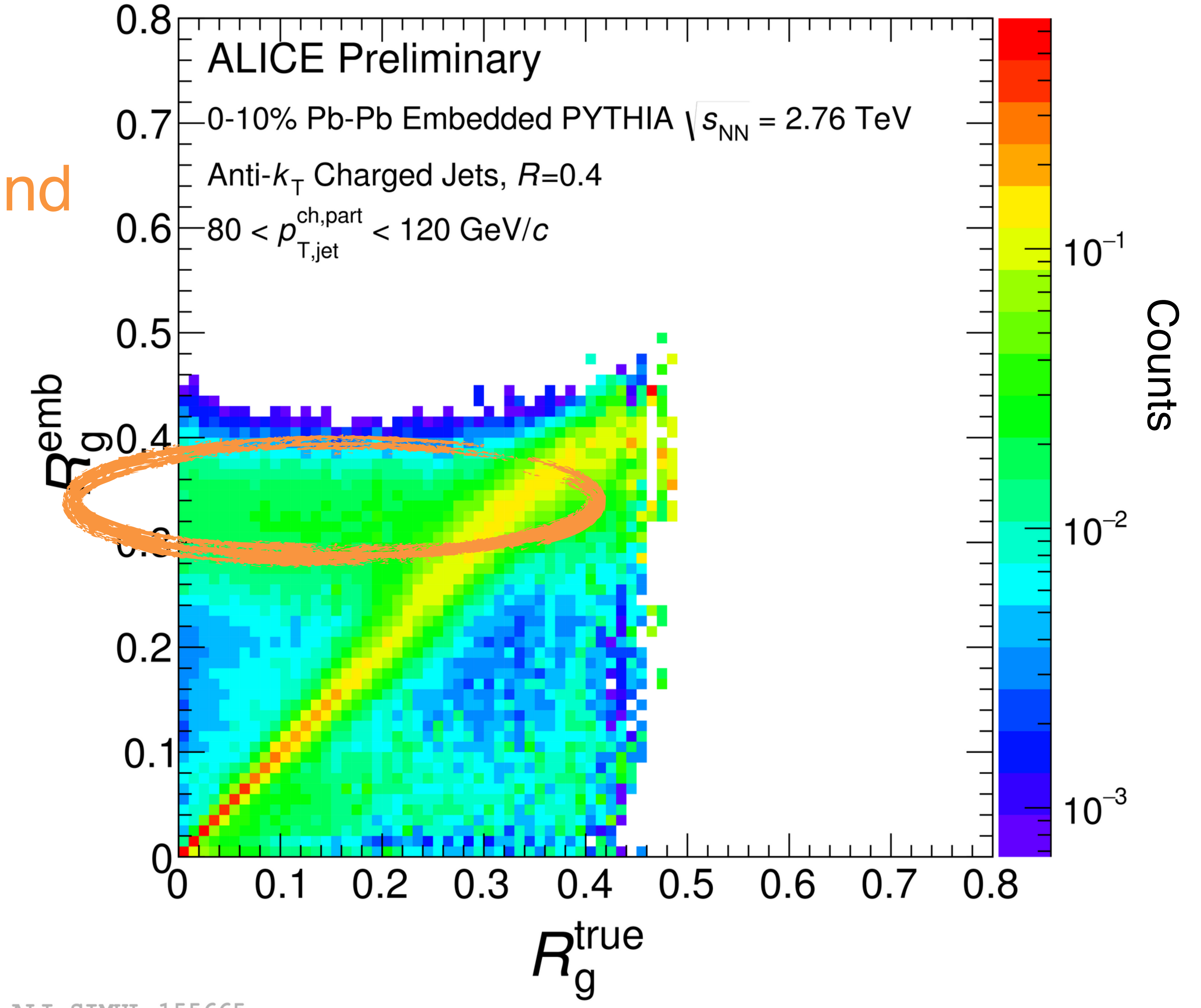
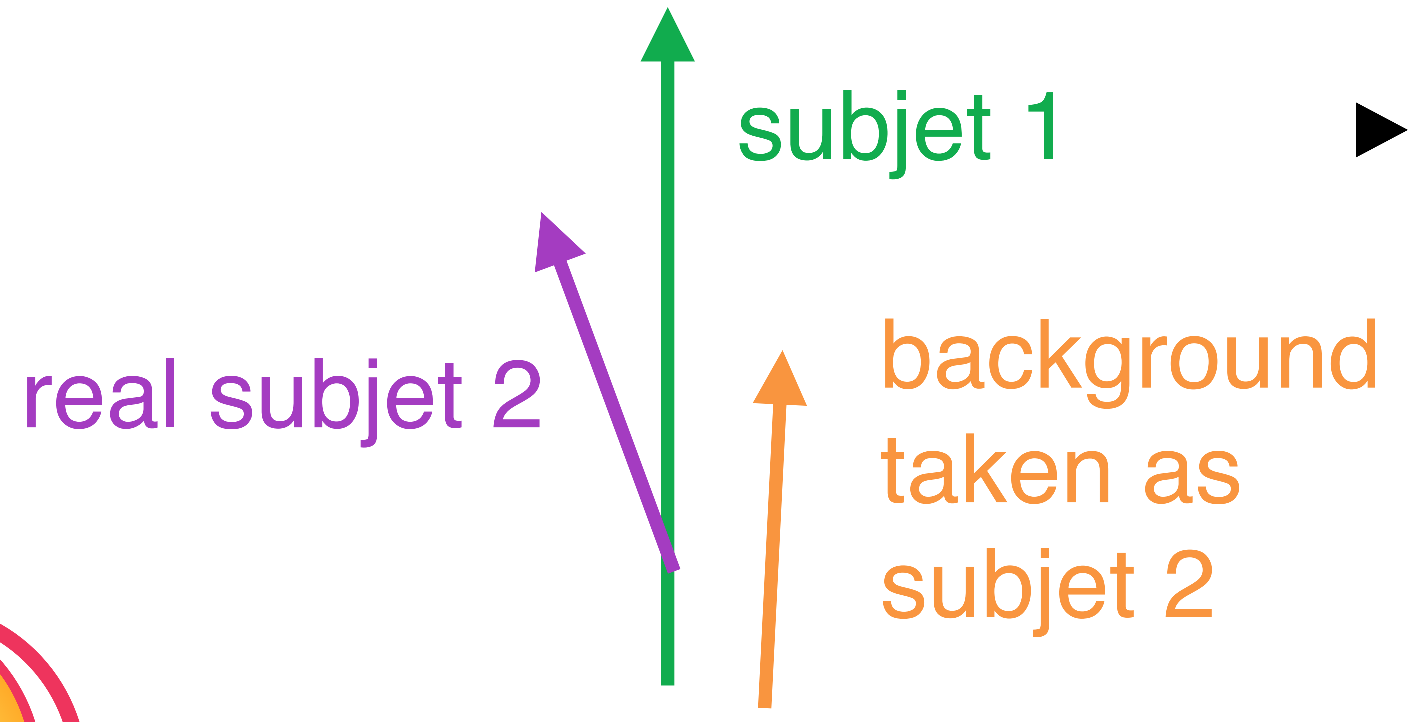


- Unfolding needed to compare to theory and to other experiments: need to suppress this background!

Background treatment

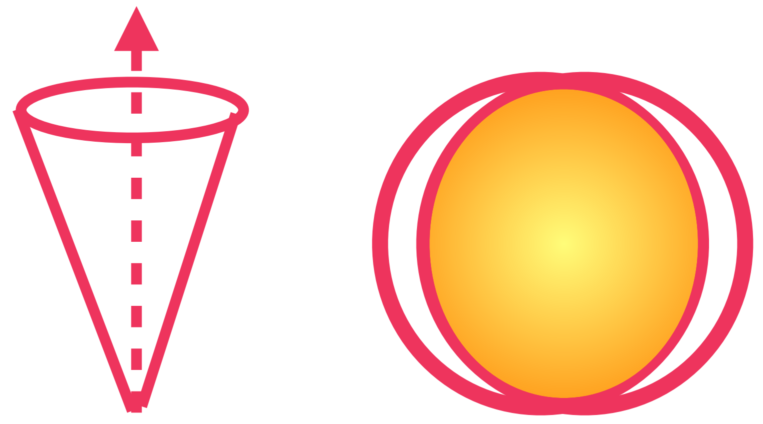
- Uncorrelated background leads to incorrect splittings



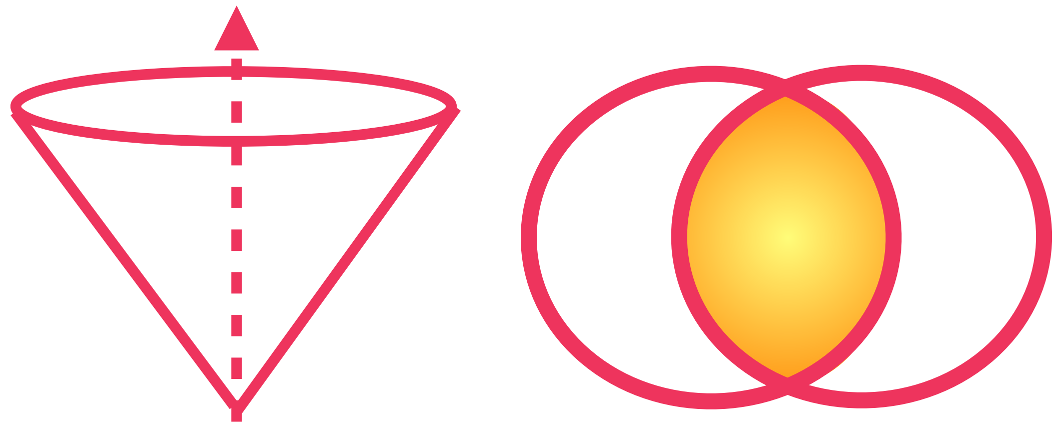
- ▸ Need to suppress the background in order to unfold

- Solutions:

1. smaller jet radii



or semi-central collisions



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

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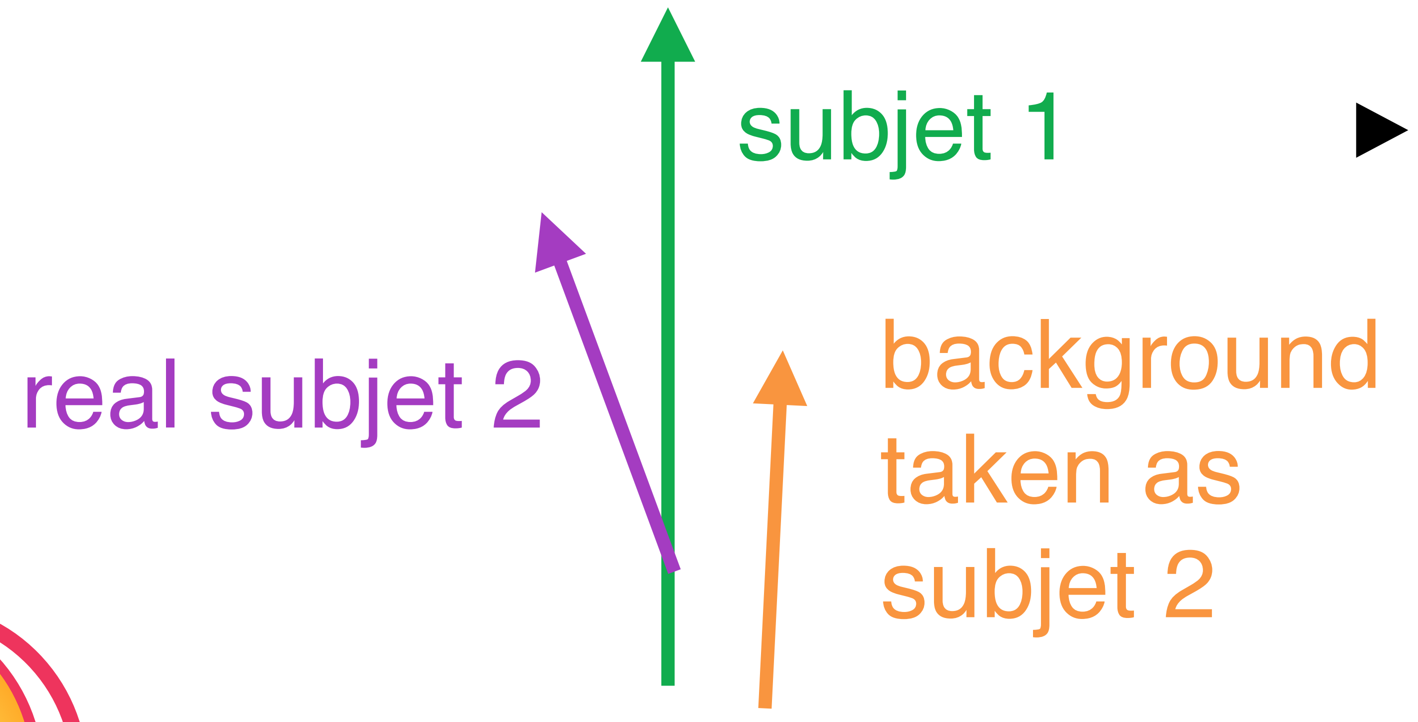

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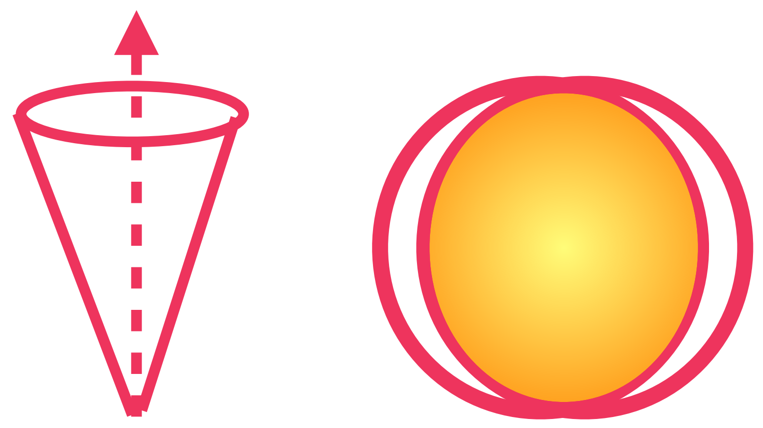

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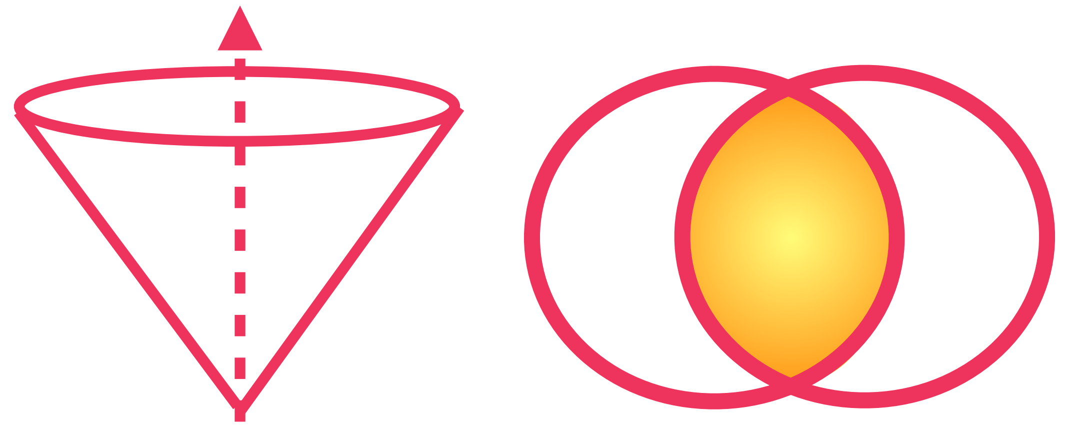

2. event-by-event constituent subtraction instead of jet-by-jet

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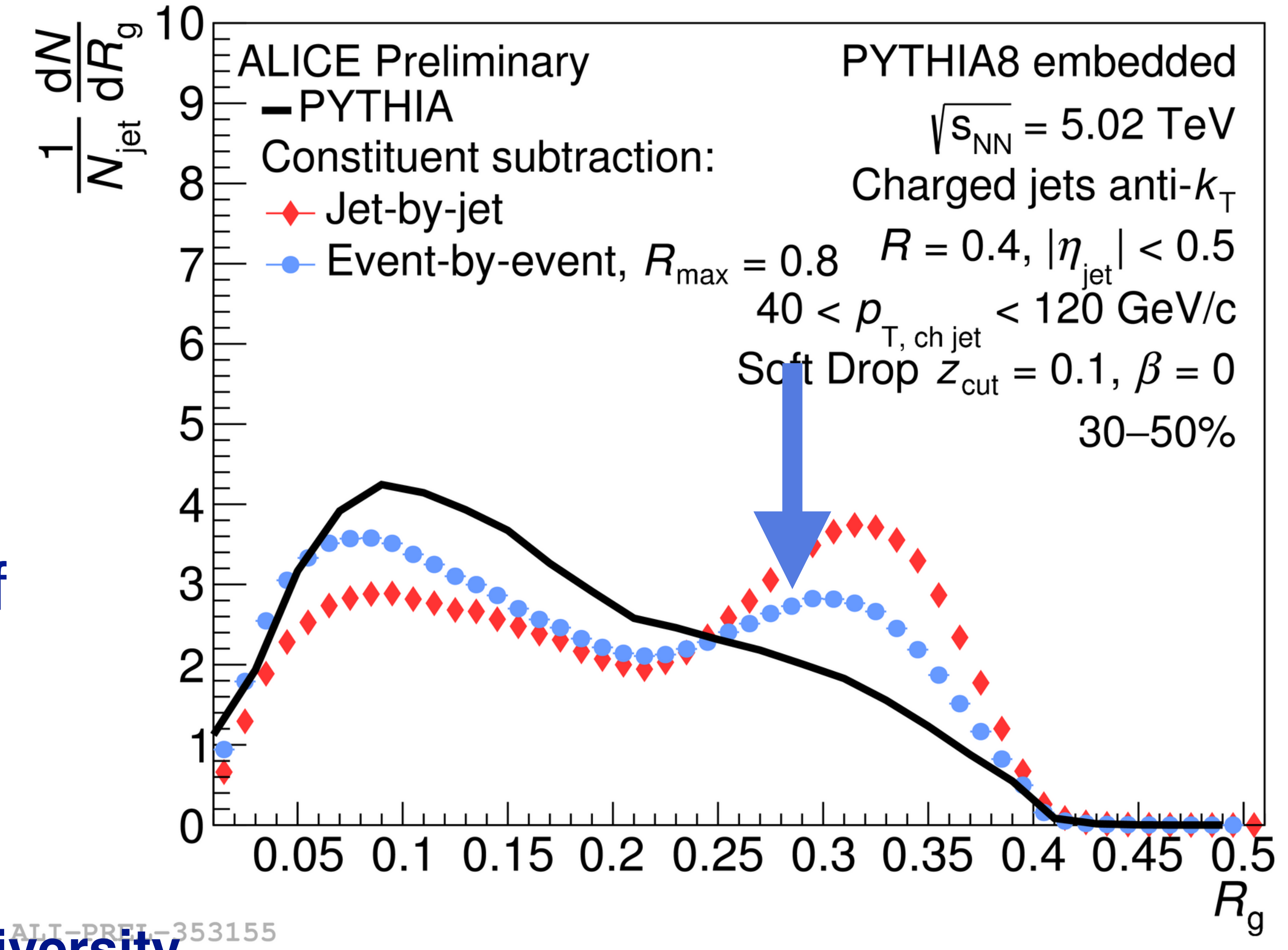

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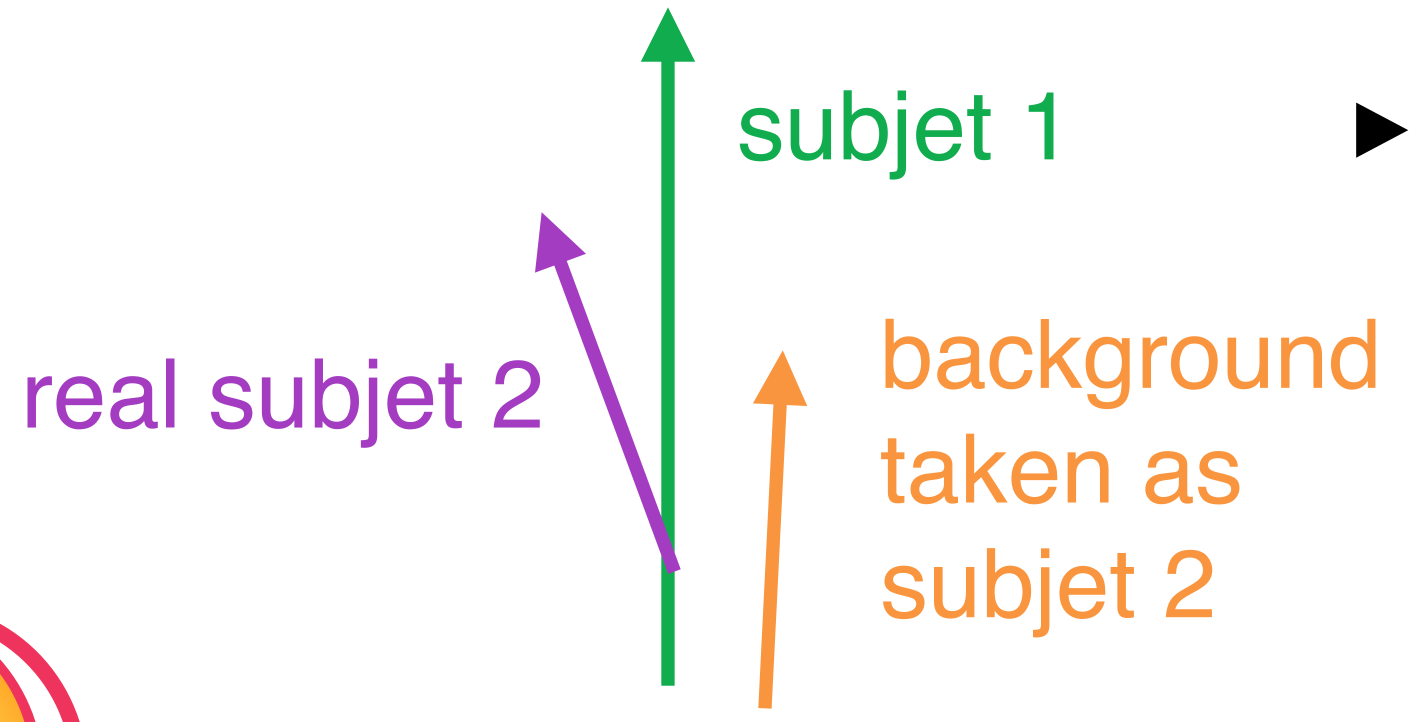

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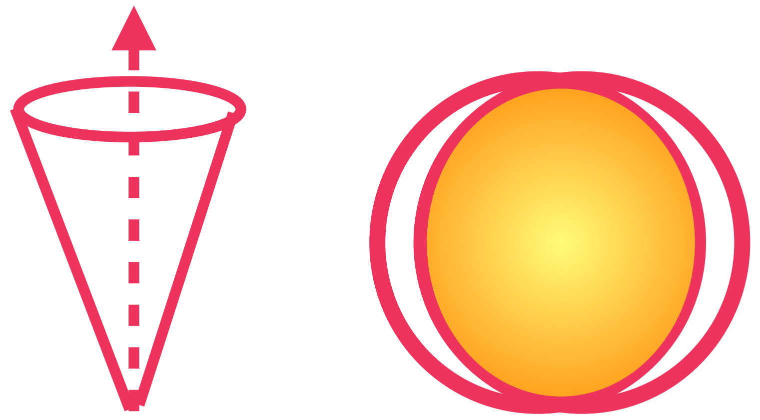
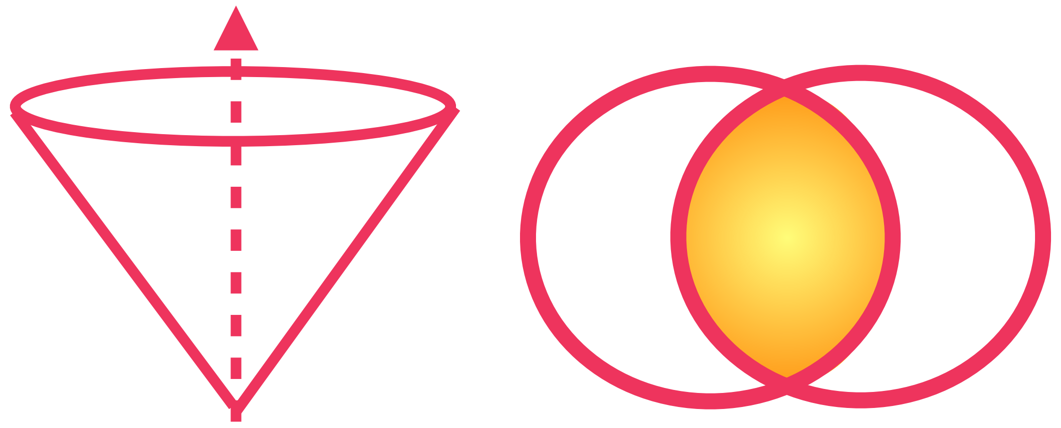
1. smaller jet radii  or semi-central collisions 

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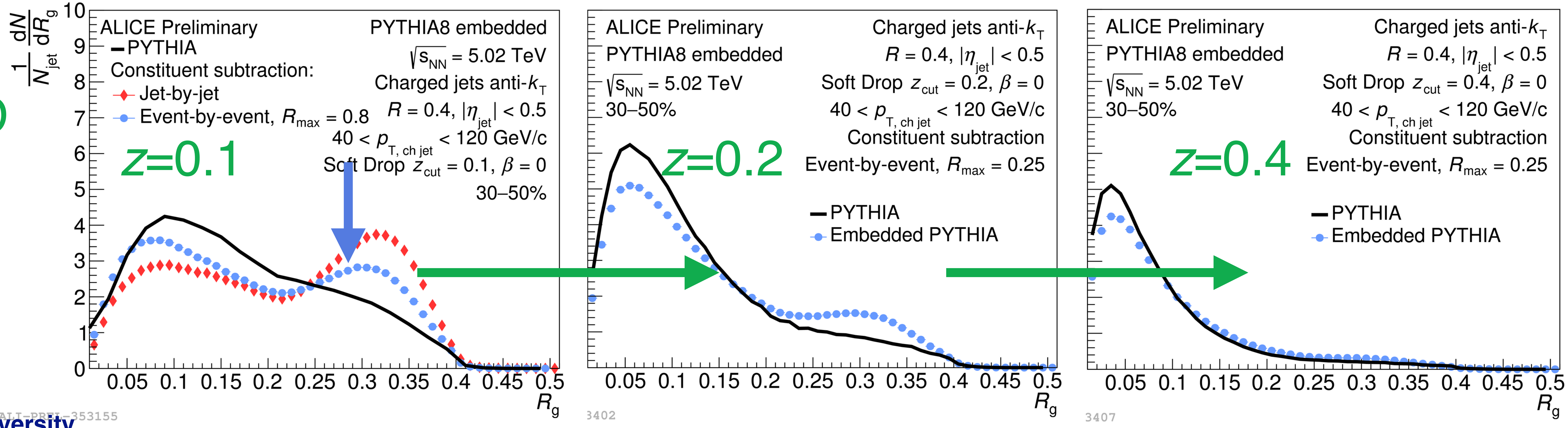
3. tighter SD condition



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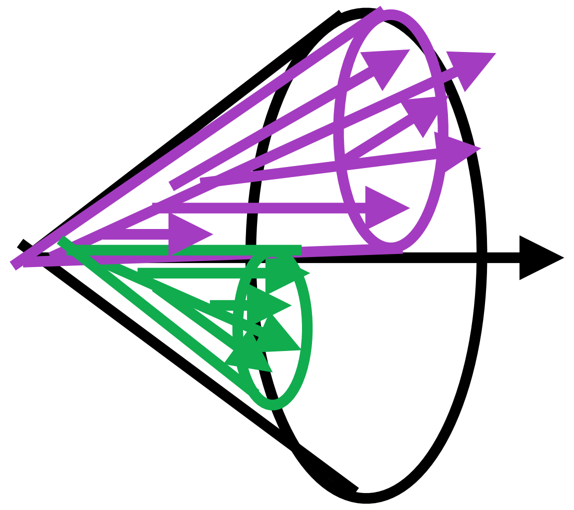
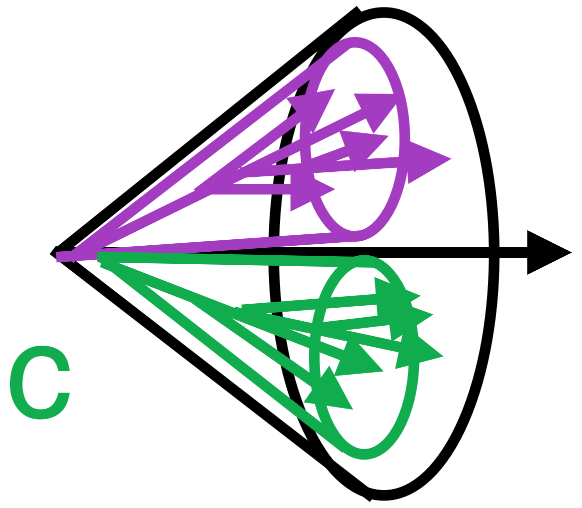
Results: z_g

low z_g: asymmetric



high z_g: symmetric



- Unfolded Pb-Pb and pp compared to models:

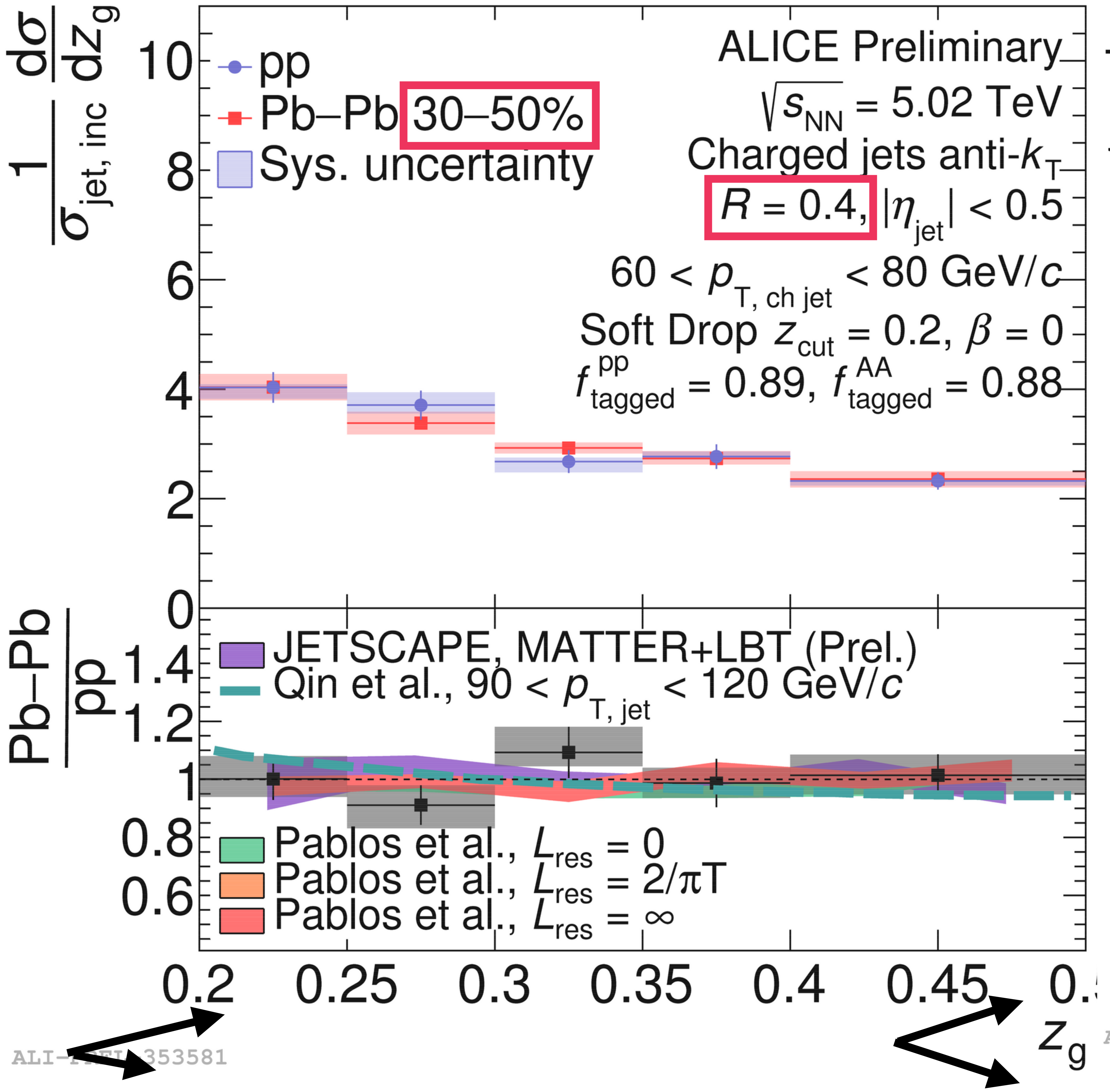
JETSCAPE: Matter+LBT
arXiv:1903.07706

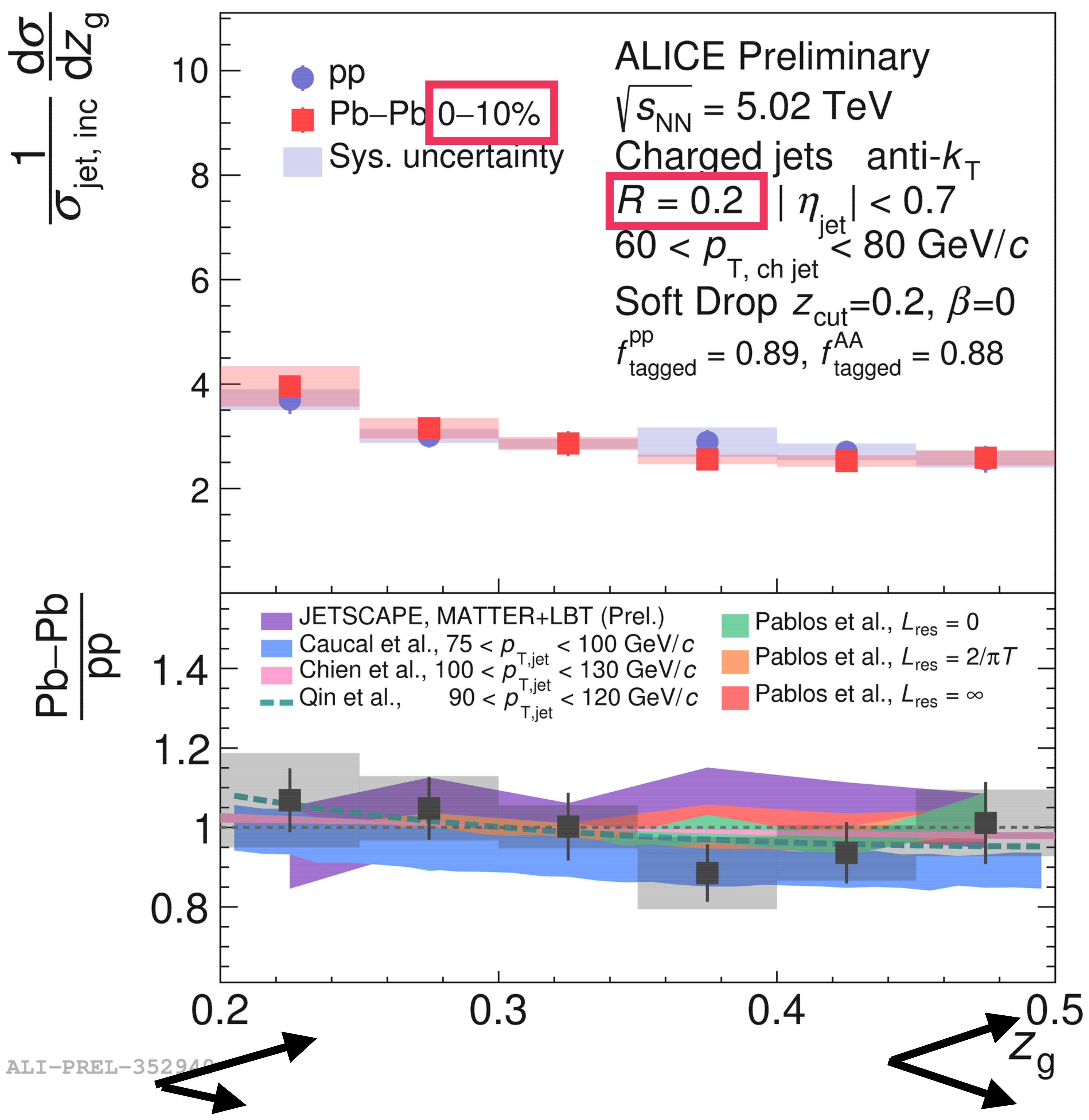
Caucal et. al: pQCD shower with vacuum and medium-induced emissions
JHEP 10 (2019) 273

Chien et. al.: Soft Collinear Effective Theory
PRL 119 (2017) 112301

Qin et. al.: higher twist with coherent energy loss
PLB 781 (2018) 423

Pablos et. al.: hybrid model using AdS/CFT with different resolution scales
-L_{res} = 0, incoherence
-L_{res} = $2/\pi T$
-L_{res} = ∞, coherence
JHEP (2020) 044





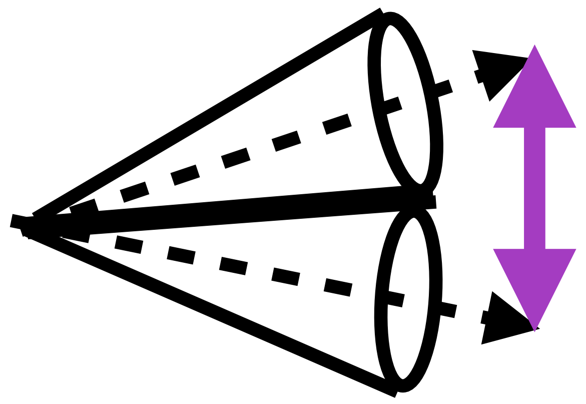
▸ *No significant modification, mostly consistent with models*

Published result hinted at a large z_g suppression but has different kinematics and isn't unfolded

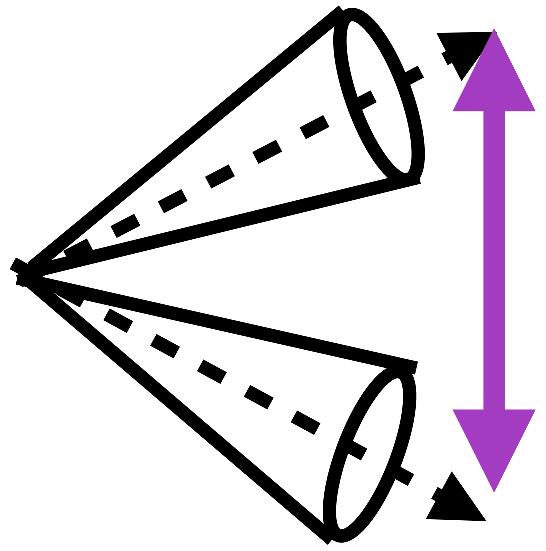
PLB 802 (2020) 135227

Results: R_g

small R_g: collimated



large R_g: wide



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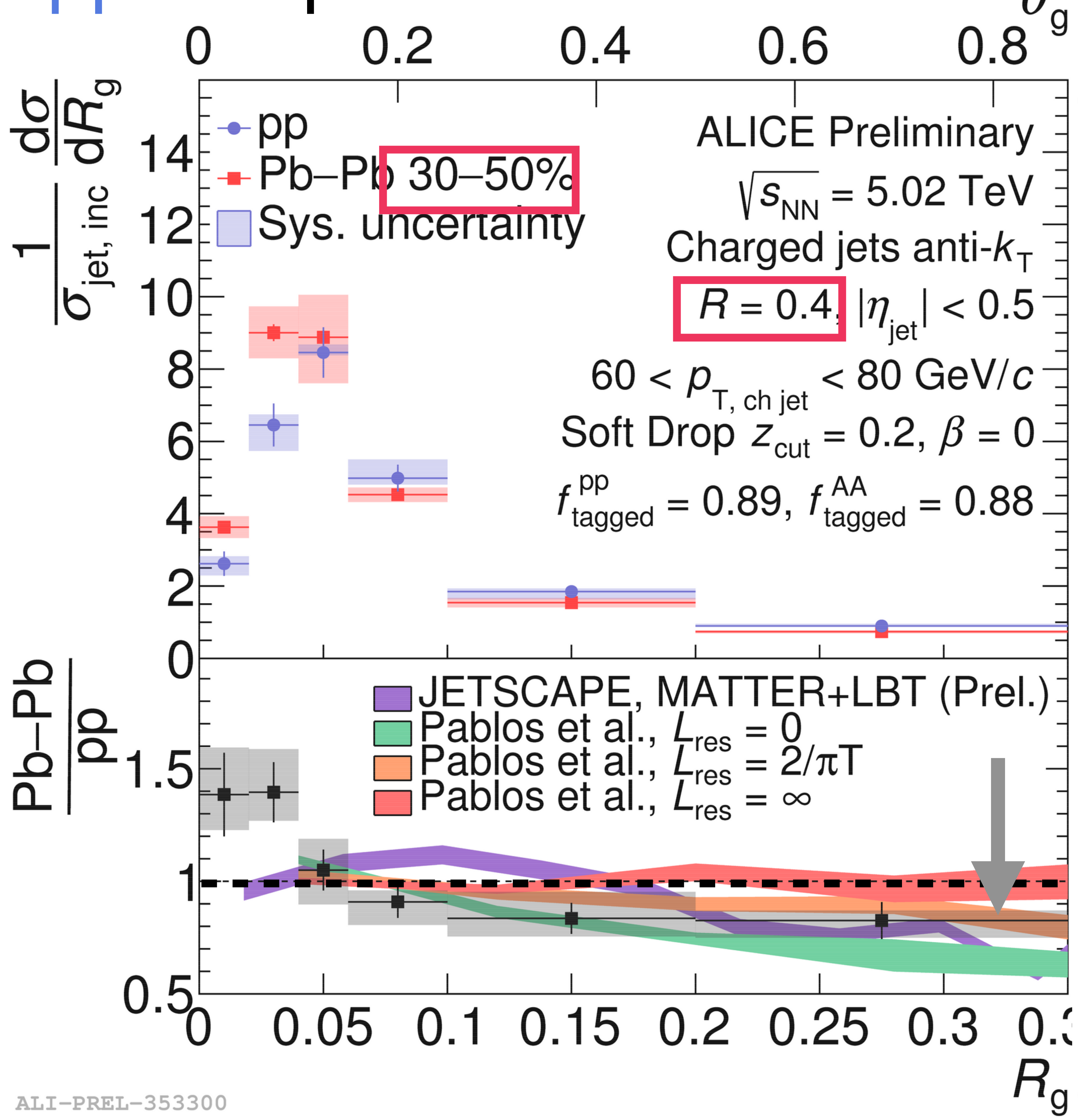
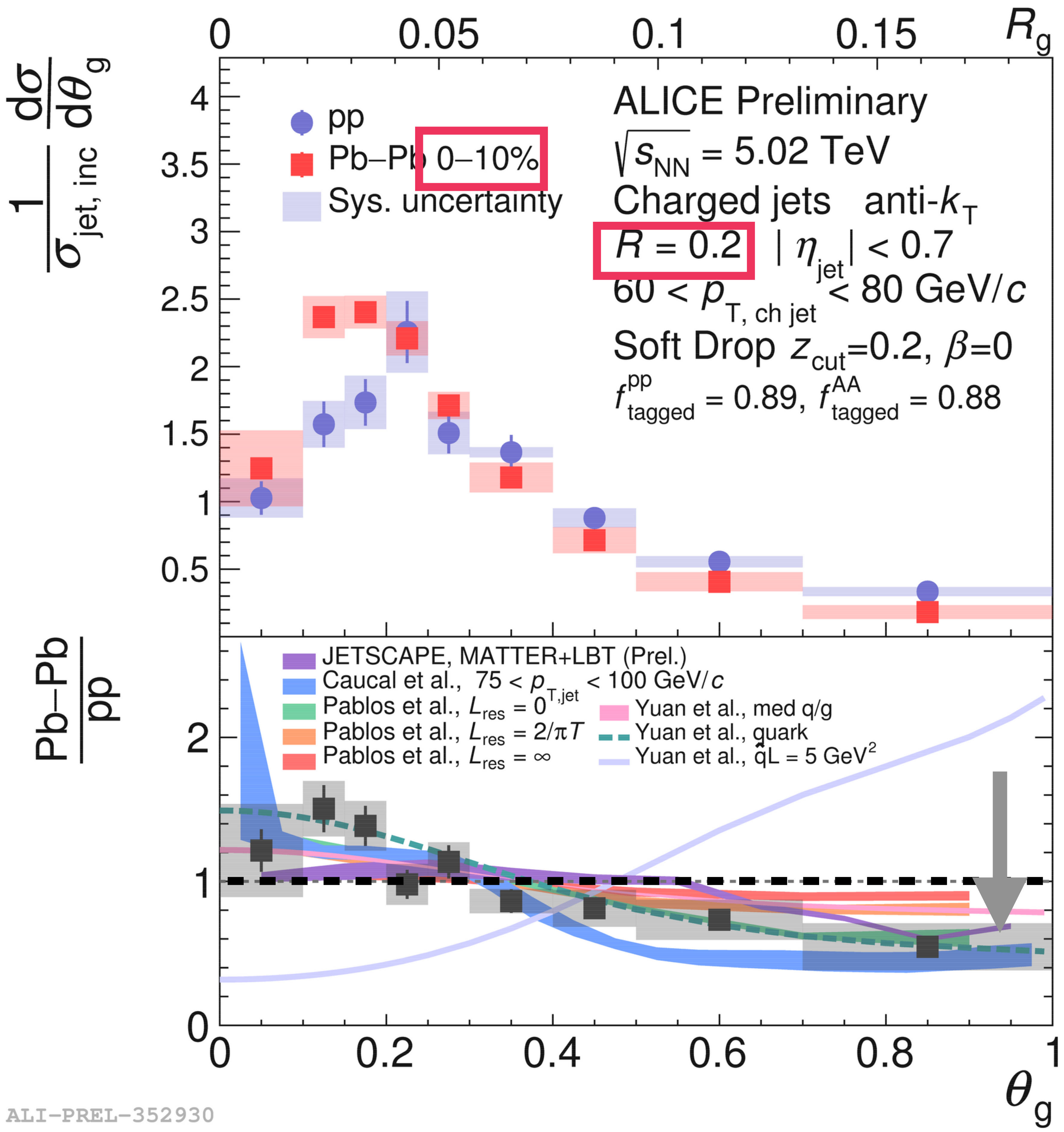
JHEP (2020) 044

Yuan et. al.:
- qhat broadening
- quark only
- medium q/g

arXiv:1907.12541





- *Modification with large angle suppression(narrowing)→ models with different in-medium interactions describe general features*

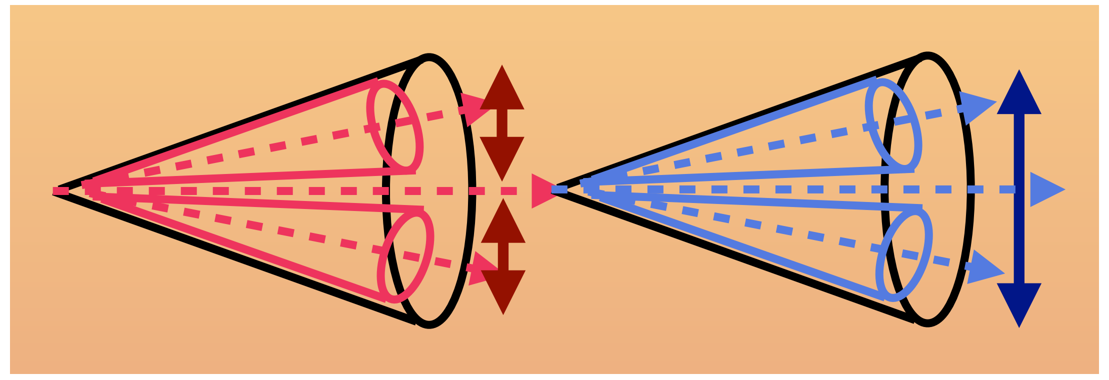
Results: R_g narrowing discussion

- Modification with large angle suppression(narrowing)

Models with different in-medium interactions describe general features:

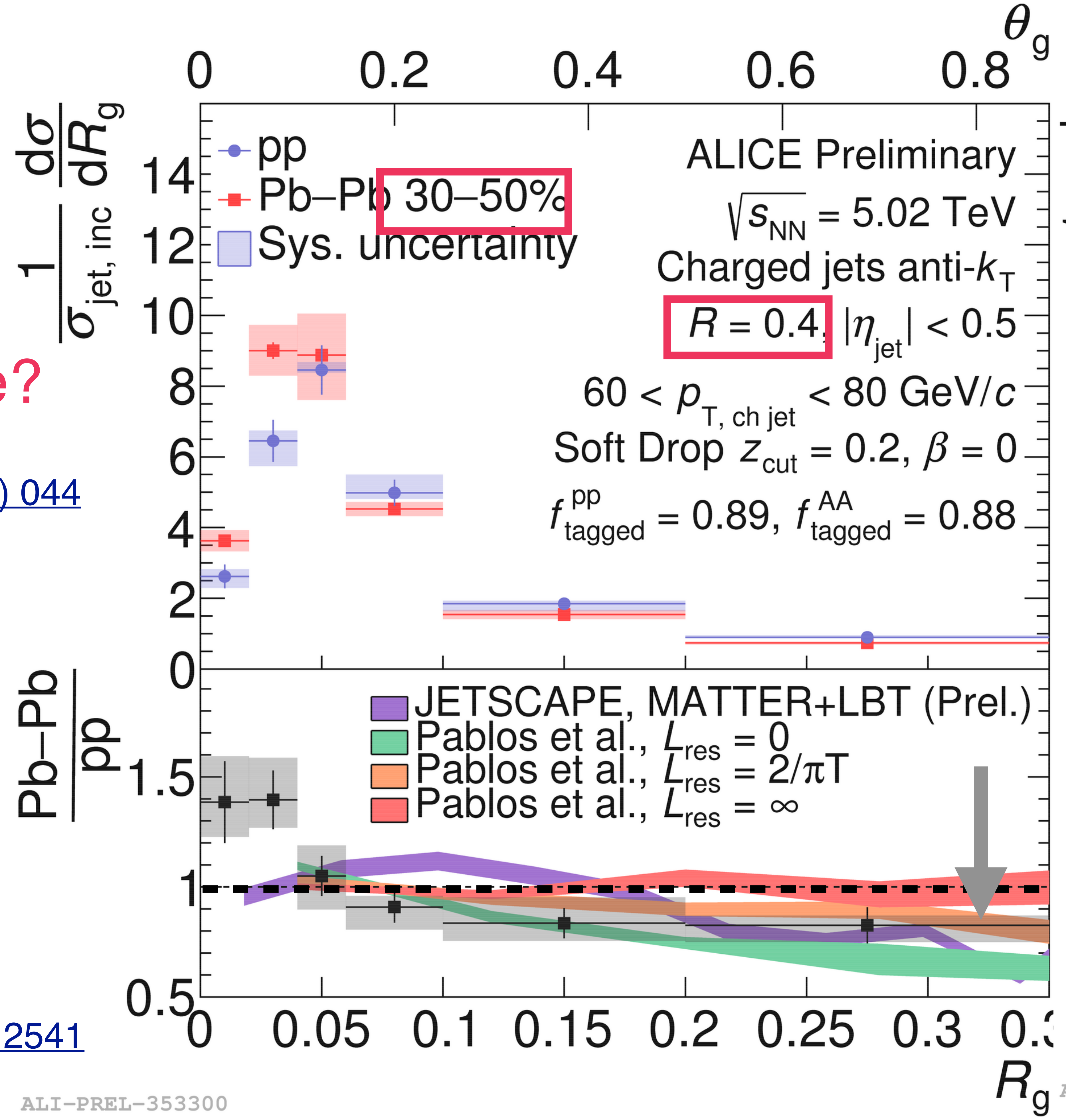
- Role of color coherence?
  - $-L_{res} = 2/\pi T$
  - $-L_{res} = \infty$, coherence
  - $-L_{res} = 0$, incoherence

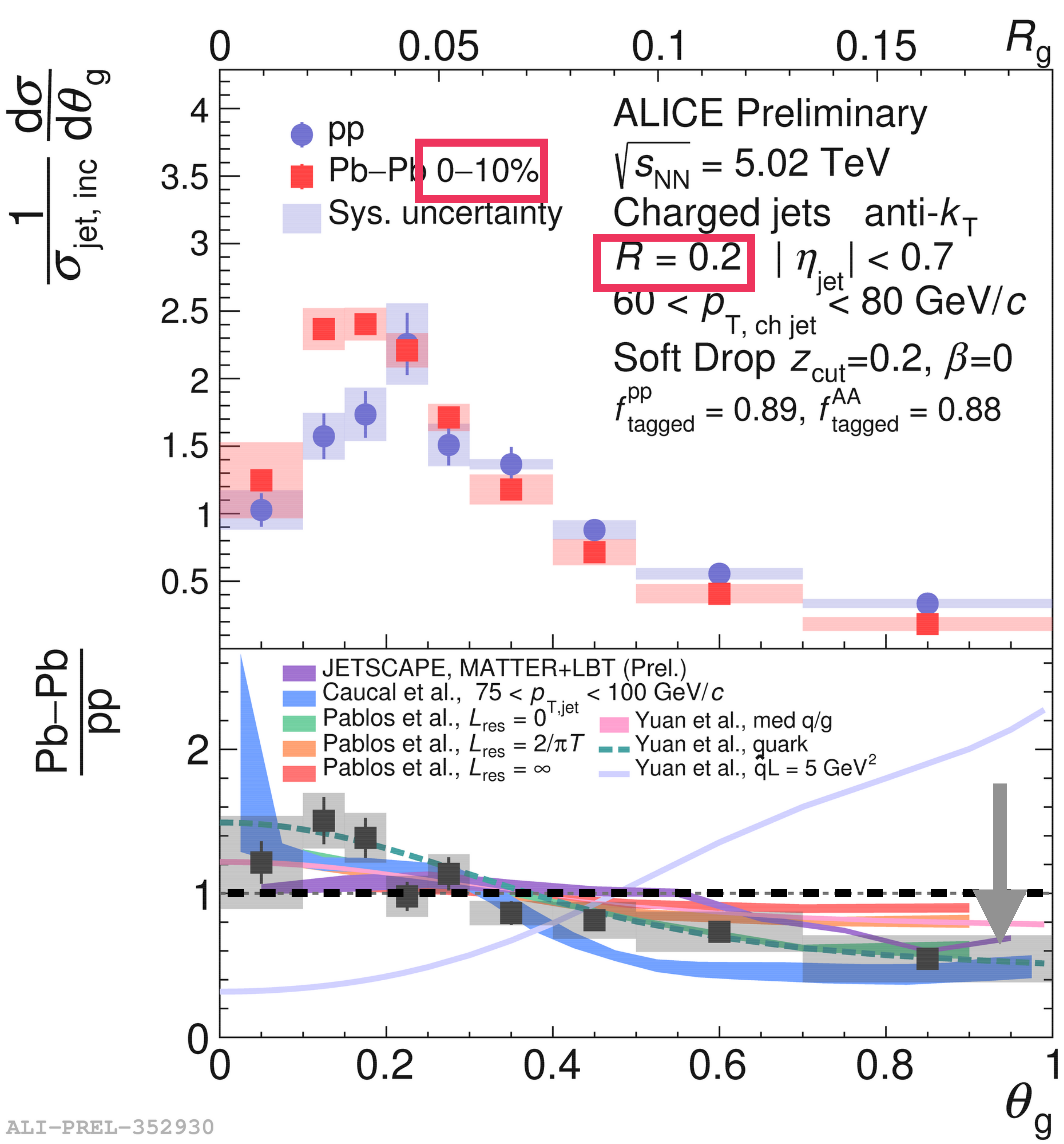
Pablos et al
[JHEP (2020) 044]



- Changing q/g fractions?
  - -quark only
  - -medium q/g

Yuan et al
[arXiv:1907.12541]





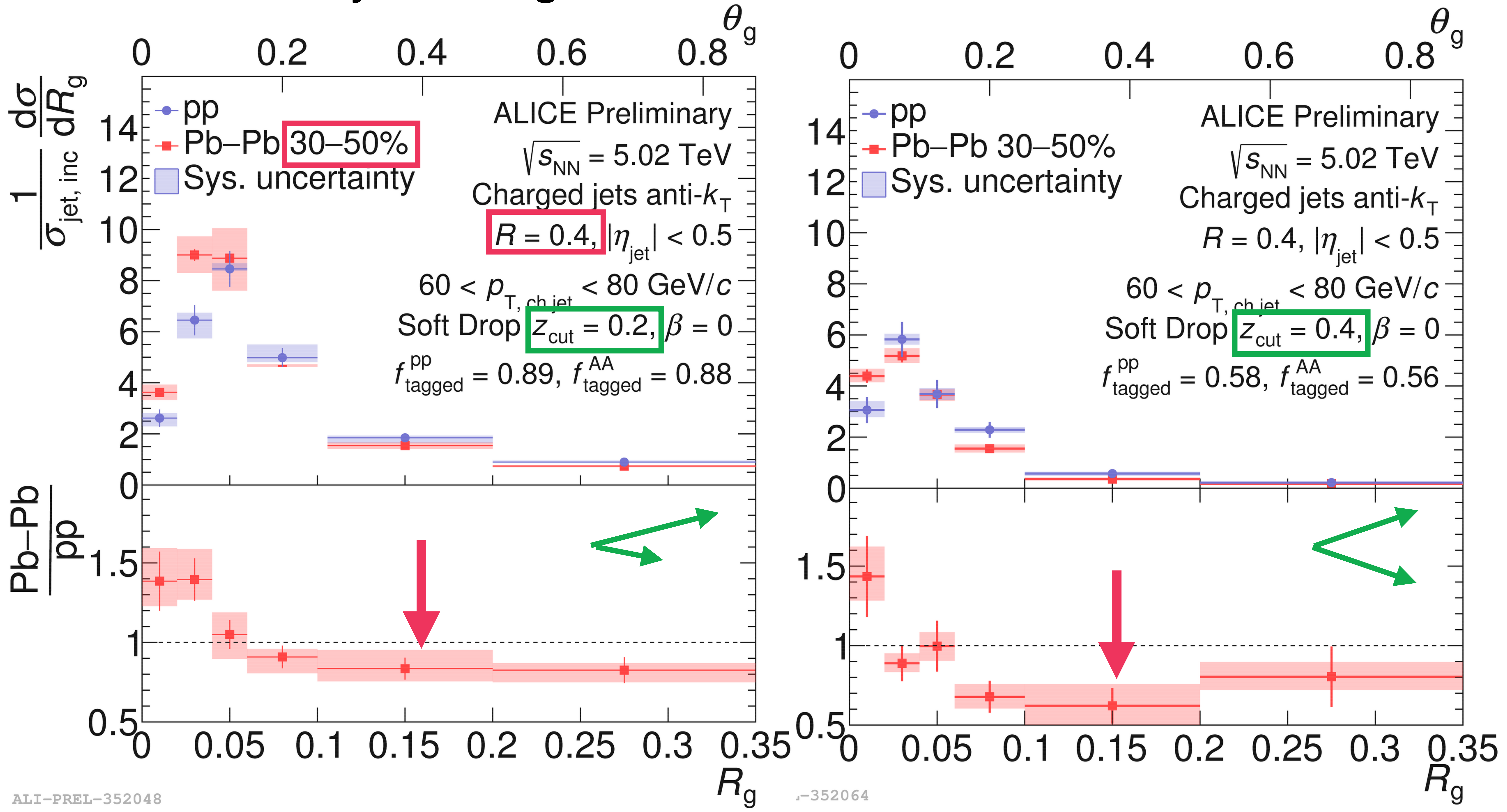
- Are wider splittings experiencing independent radiation of many prongs?
- Are wider splittings that are formed earlier more quenched?

Results: R_g dependence on z_{cut}

- Opportunity to scan Lund Plane by looking at different SD z_{cut} conditions

Possibly consistent with picture from previously published results that showed a more significant suppression of symmetry splittings for $R_g > 0.1$?

PLB 802 (2020) 135227



- Hint of a more significant suppression for more symmetric splittings

Dynamical grooming

Dynamical grooming: find hardest branch in C/A sequence

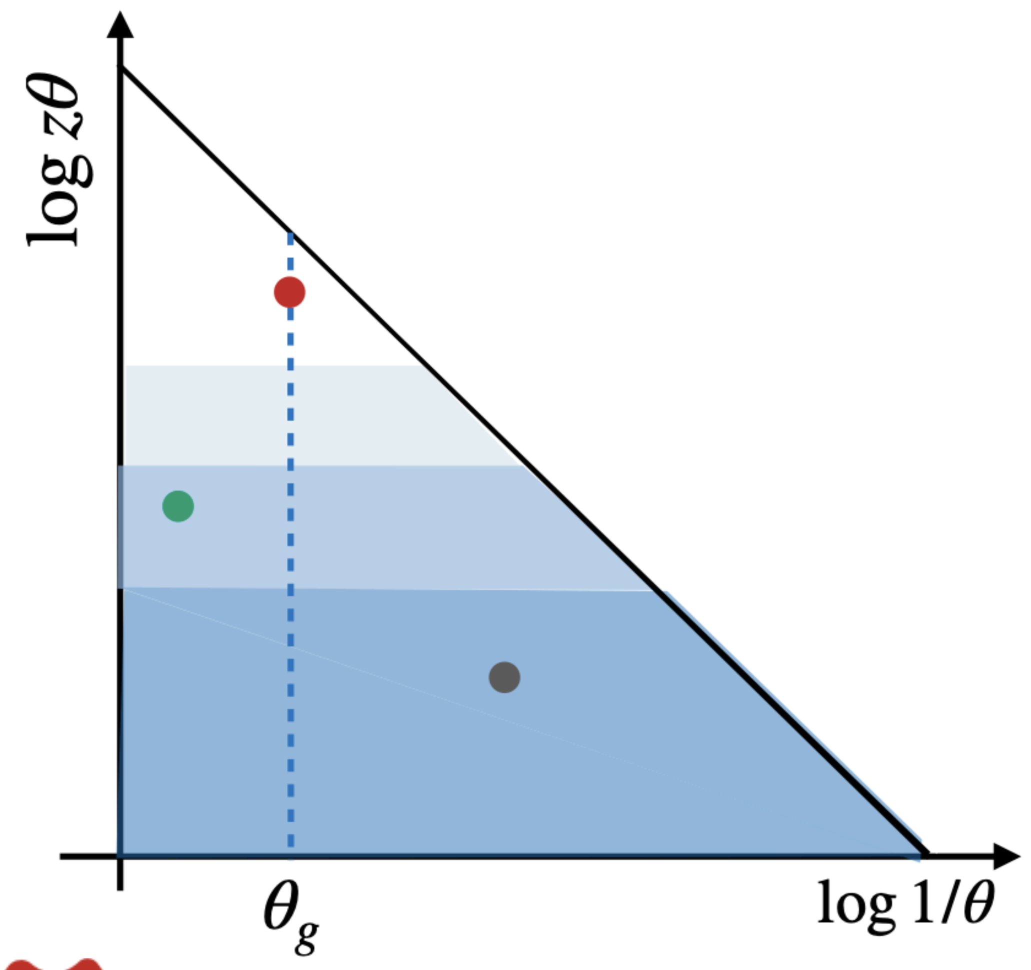
Mehtar-Tani, Soto-Ontoso, Tywoniuk PRD 101 (2020) 034004

$$\kappa^{(a)} = \frac{1}{p_{\mathrm{T}}} \max_{i \in \mathrm{C/A}} z_i(1 - z_i) p_{\mathrm{T},i} (\theta_i / R)^a$$

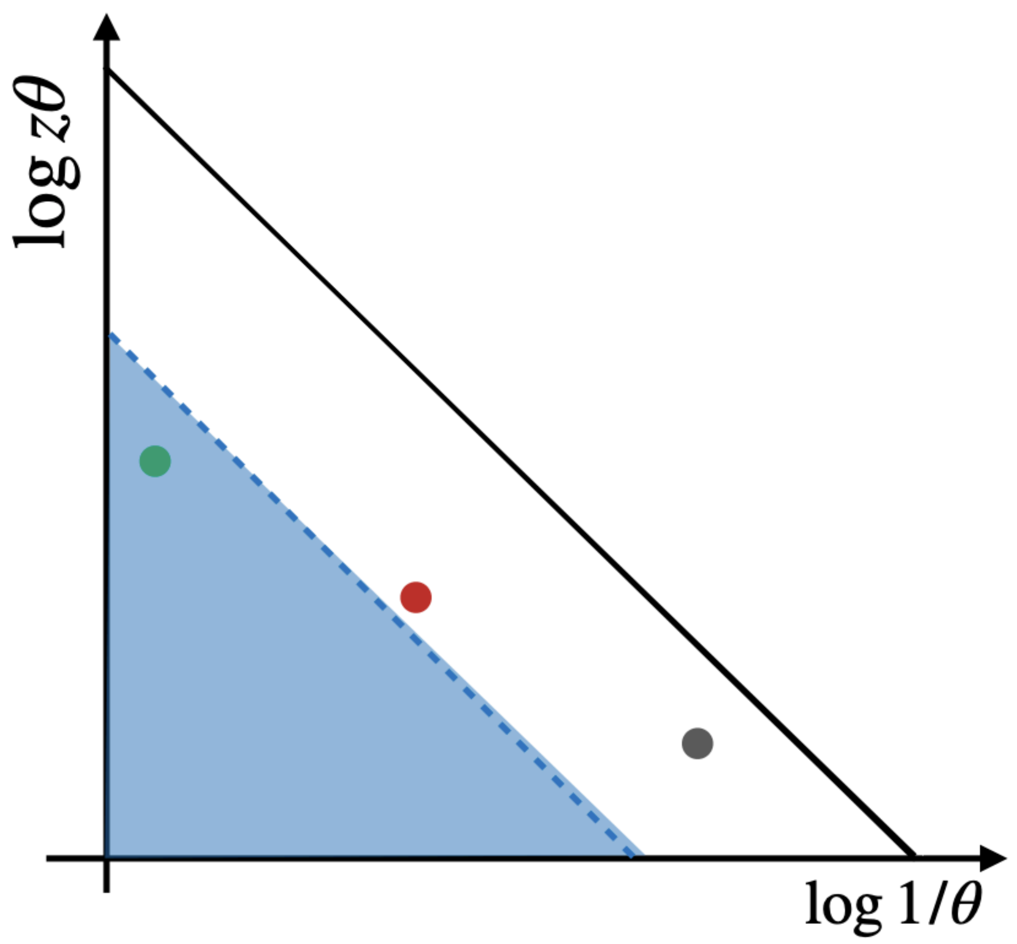
a~0: zDrop a=1: k_TDrop a=2: TimeDrop

- Varies jet-by-jet

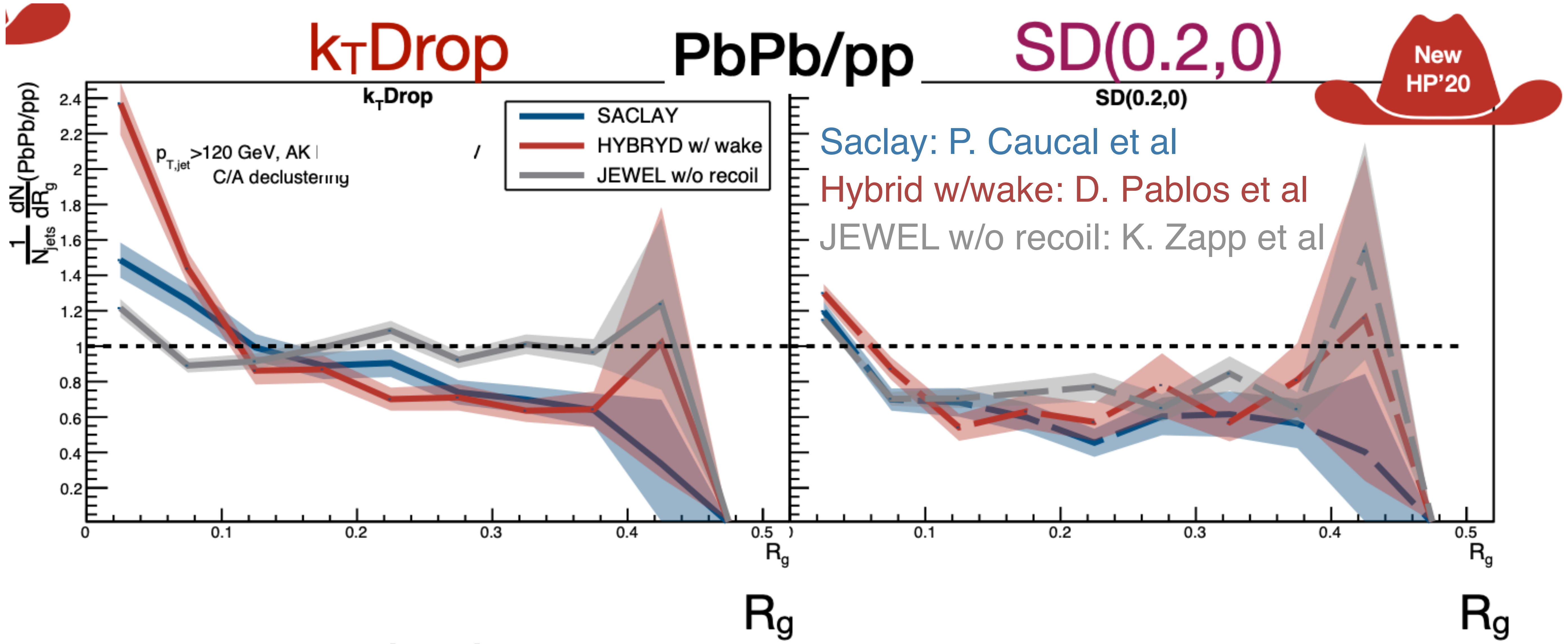
DyG:



SD:



A. Soto-Ontoso, HP2020

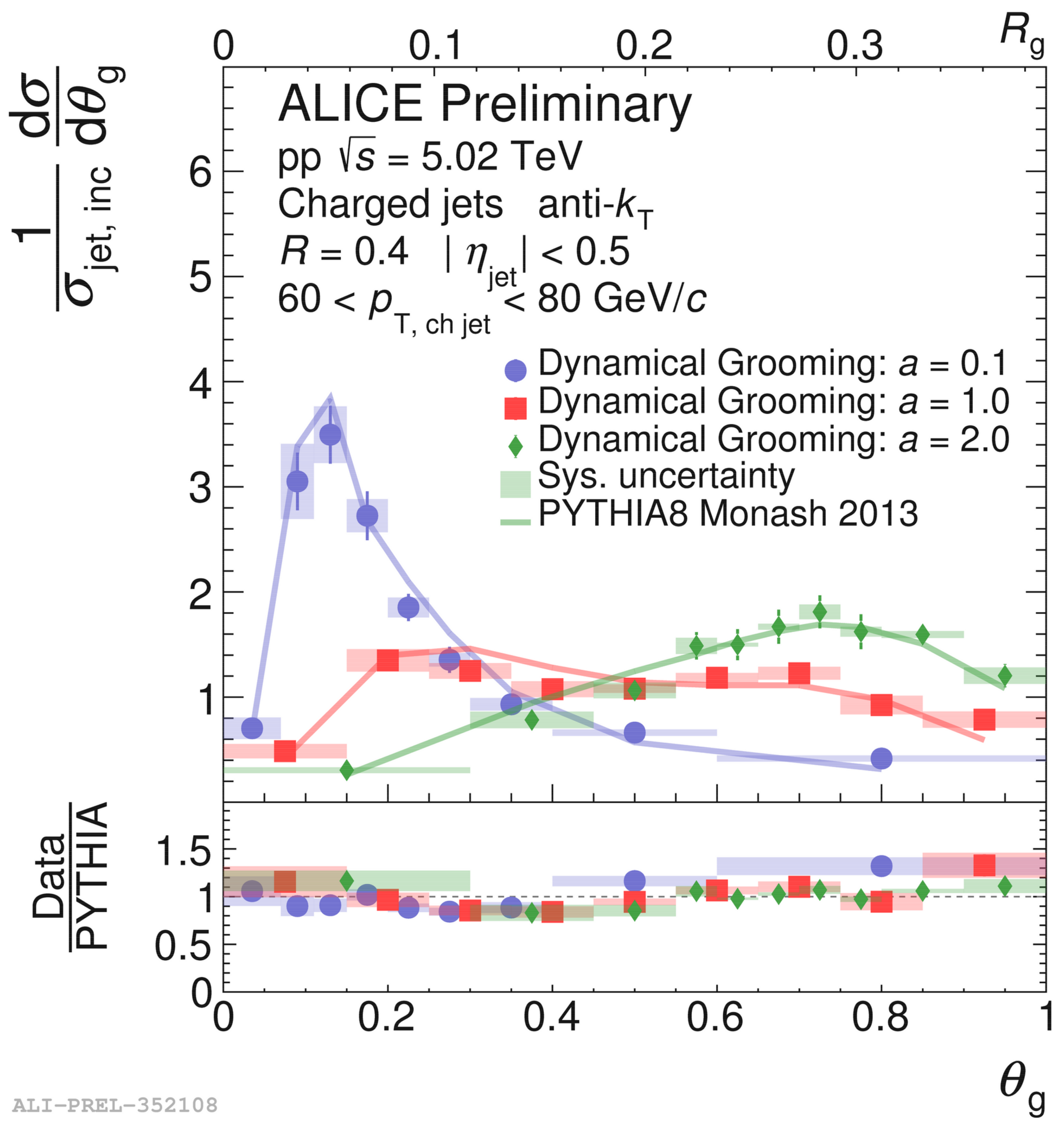


- k_TDrop distinguishes models better than SD in Pb-Pb

New results in pp collisions

- First look at dynamical grooming in pp collisions

a~0: zDrop *a*=1: k_TDrop *a*=2: TimeDrop



Looking forward to measurements in Pb-Pb

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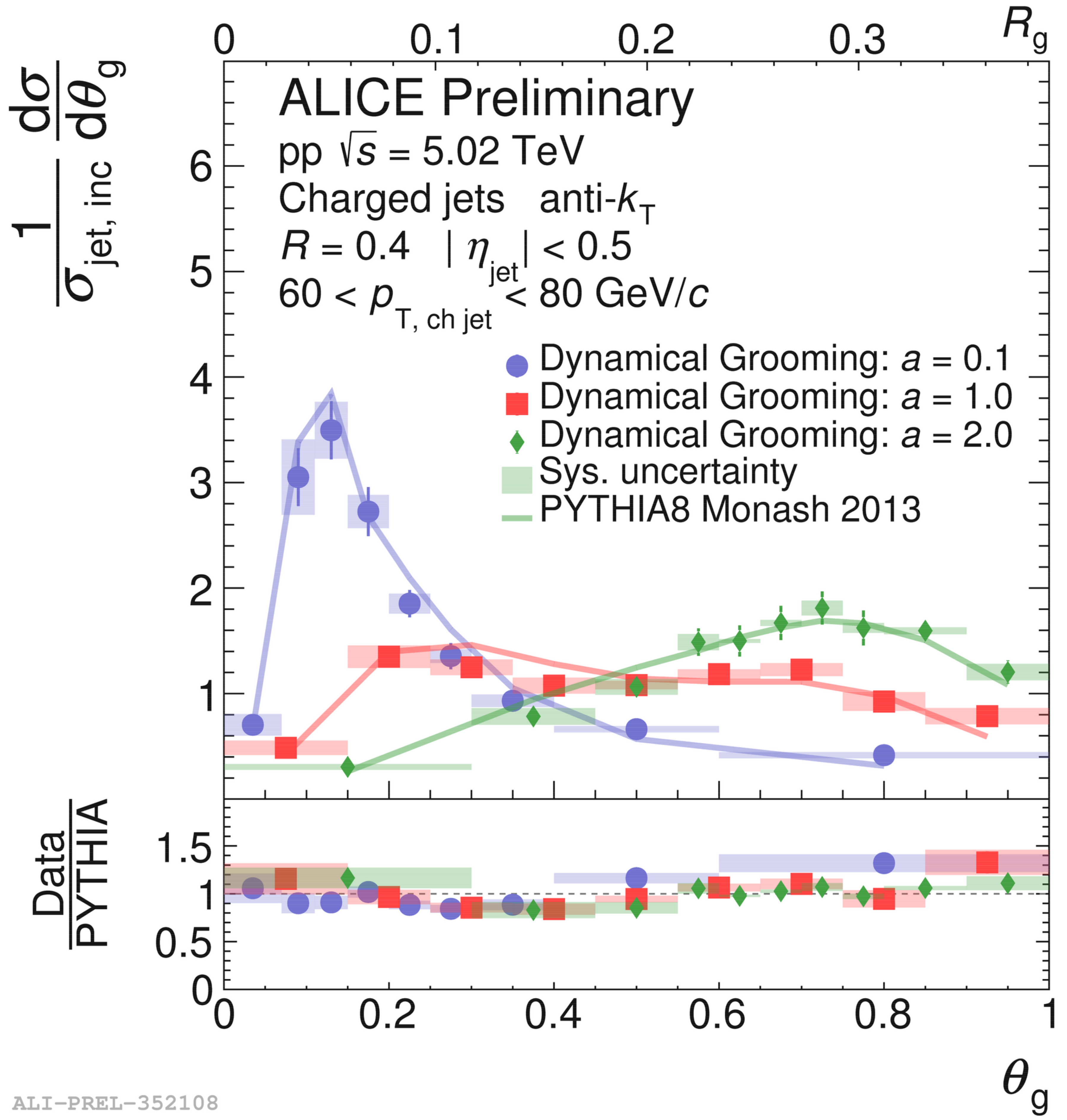
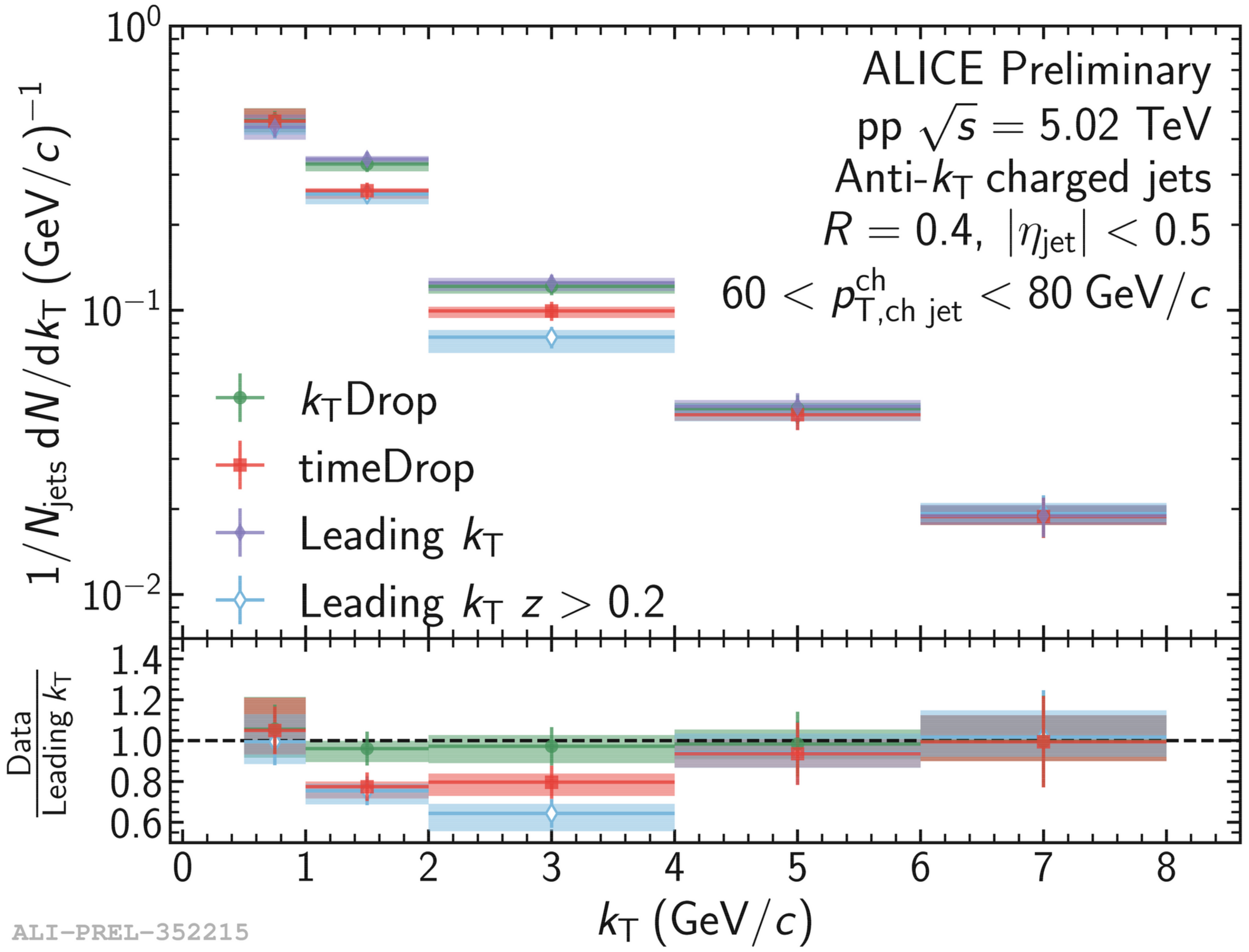
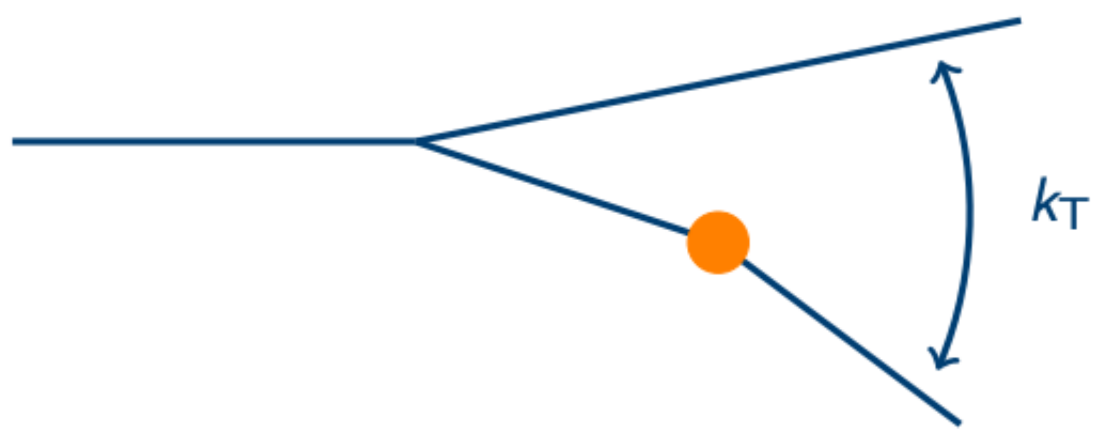




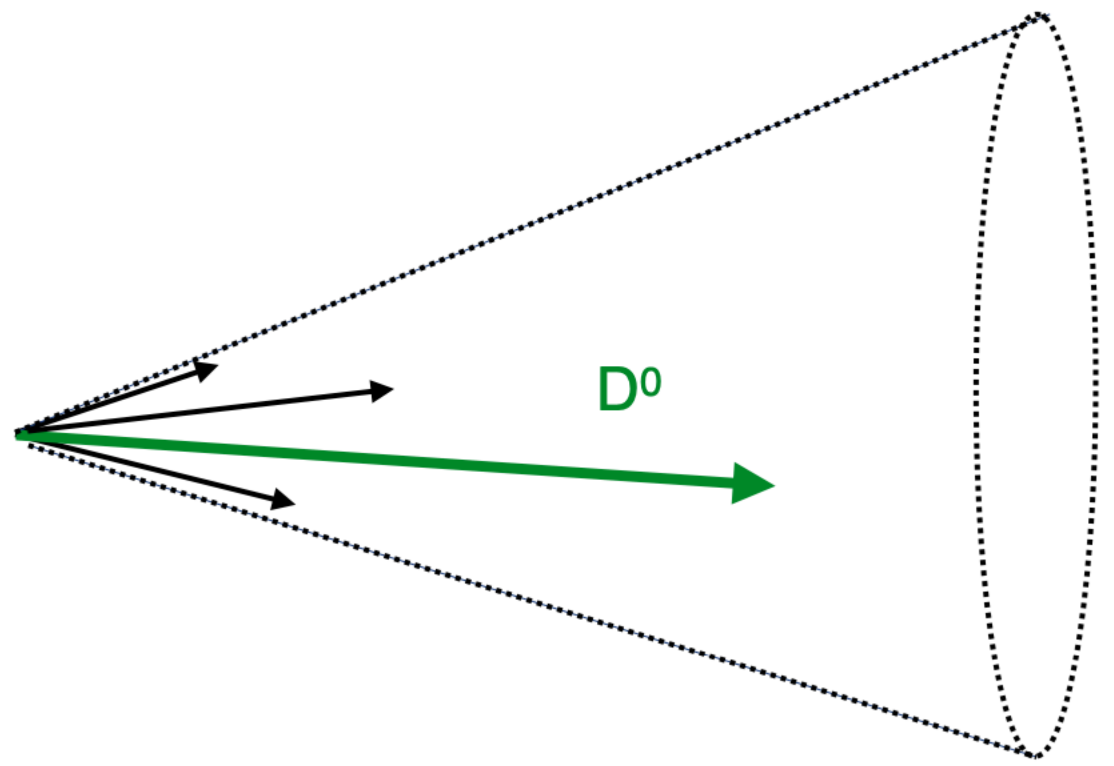
- First look at k_T distribution in pp collisions
  - Grooming methods converge at high k_T



Looking forward to measurements in Pb-Pb

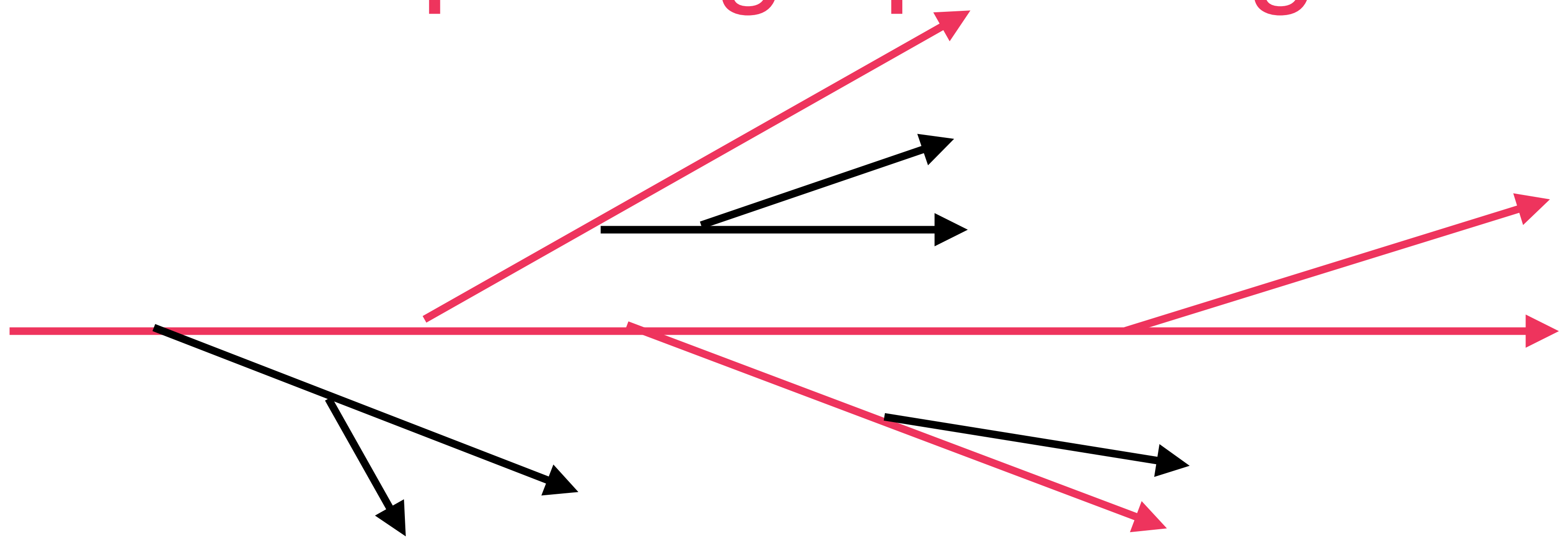
Heavy-flavor jet substructure in pp

ALICE-PUBLIC-2020-002

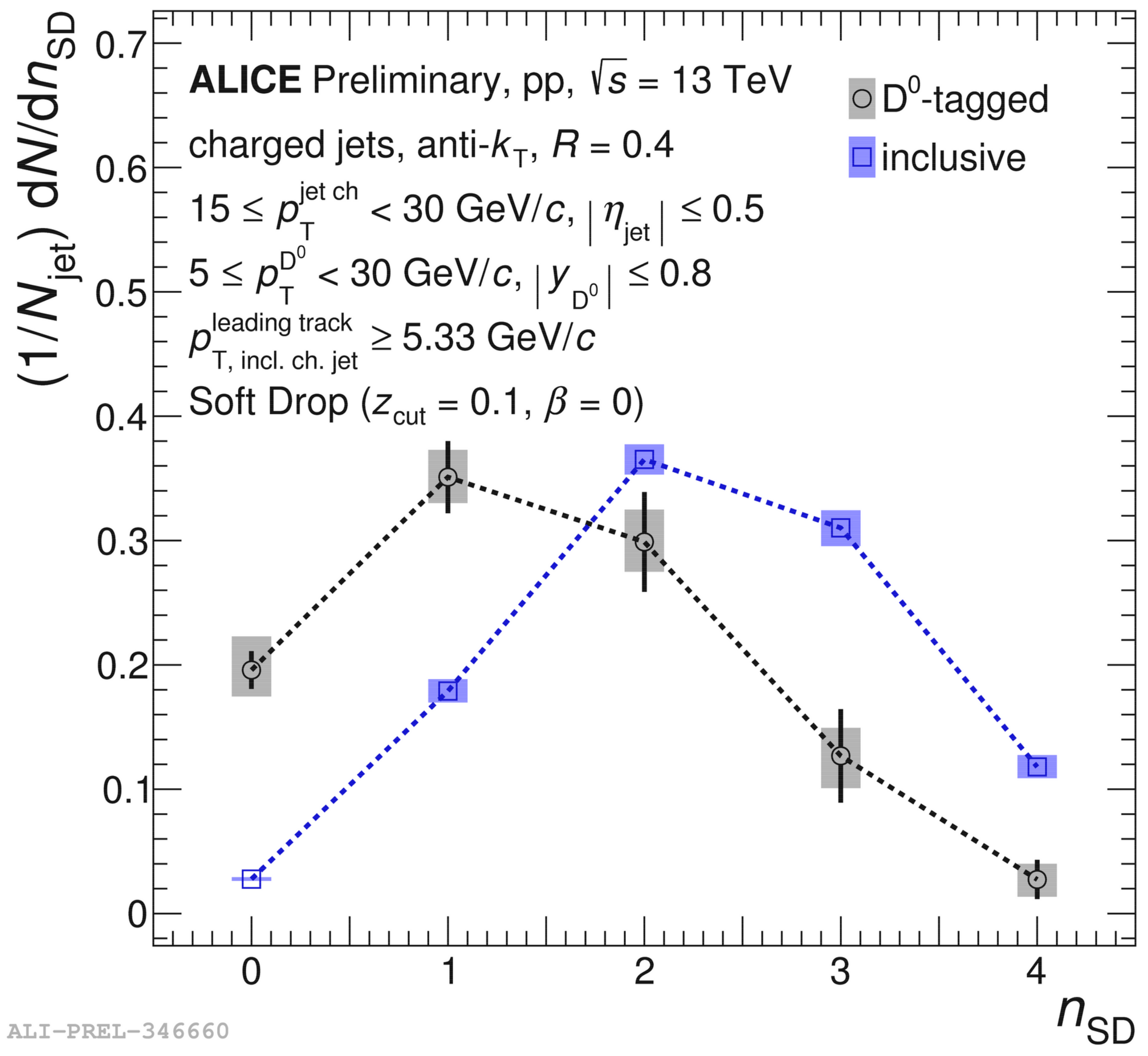


- Measure groomed jet substructure for D^0-tagged jets compared to inclusive jets to compare quark jets (i.e. charm) with inclusive jets
  - quarks should have a harder fragmentation and be more collimated

➡ 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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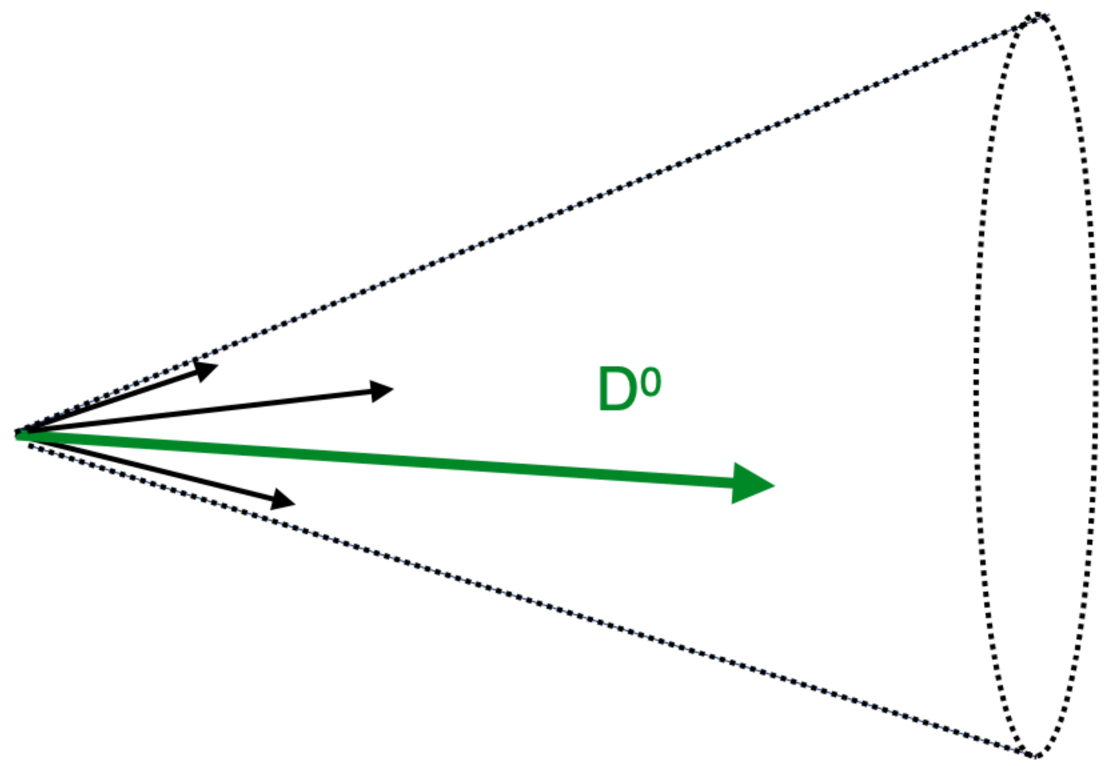
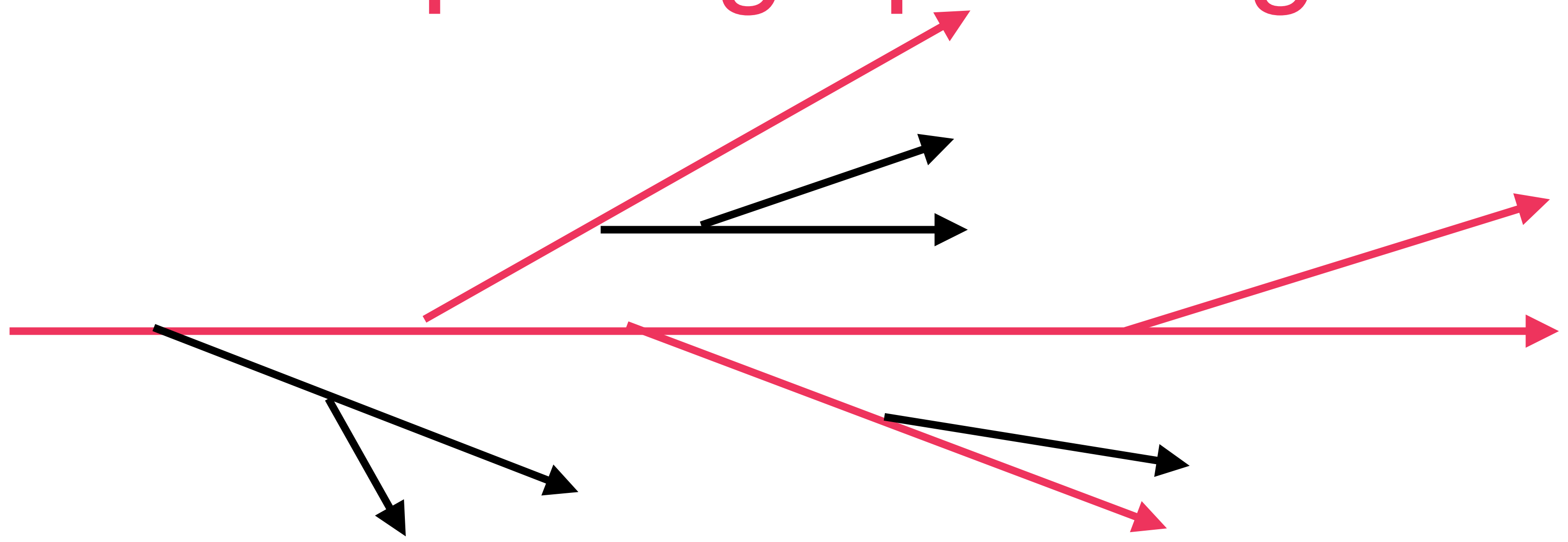
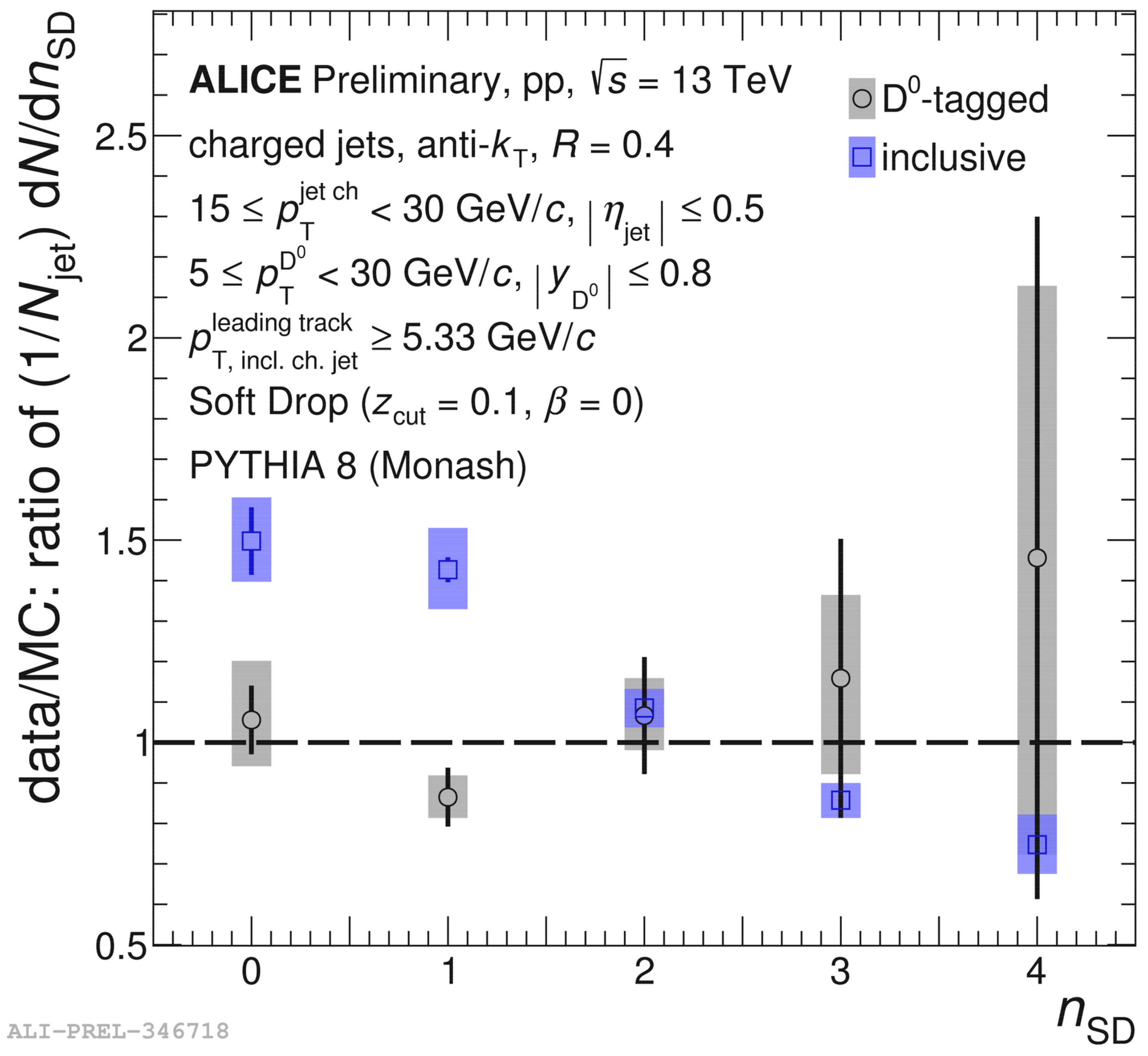
  - quarks should have a harder fragmentation and be more collimated

➡ n_{SD}: number of splittings passing SD



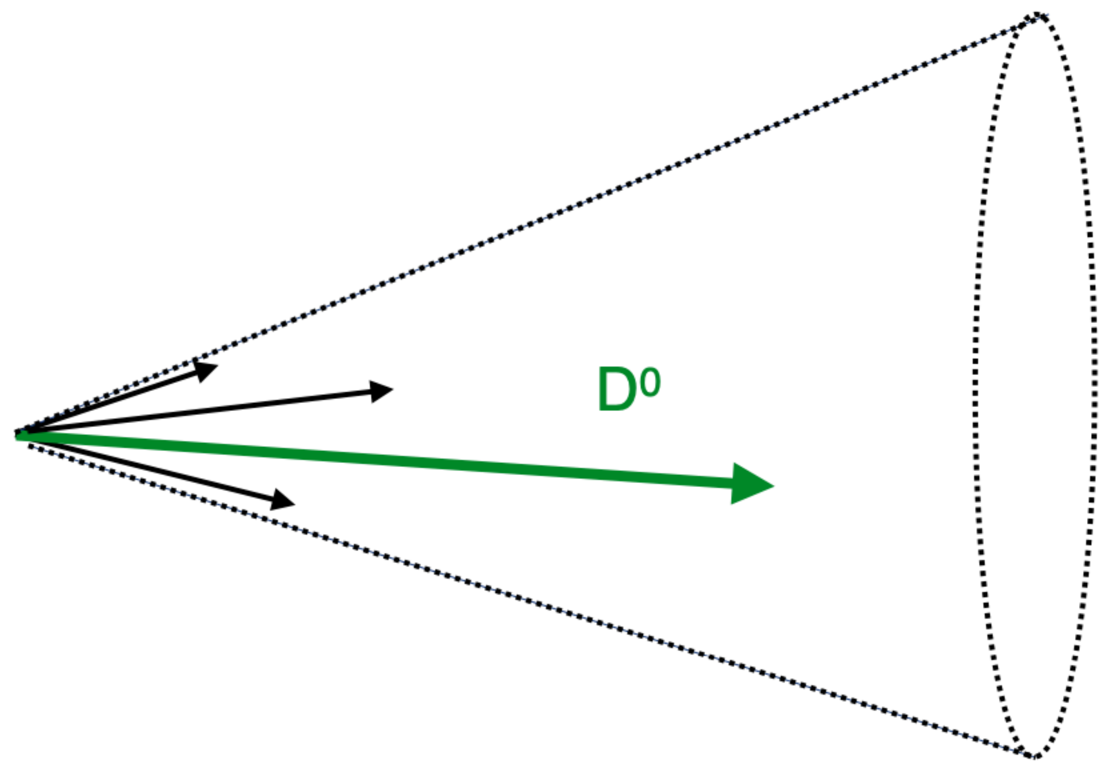




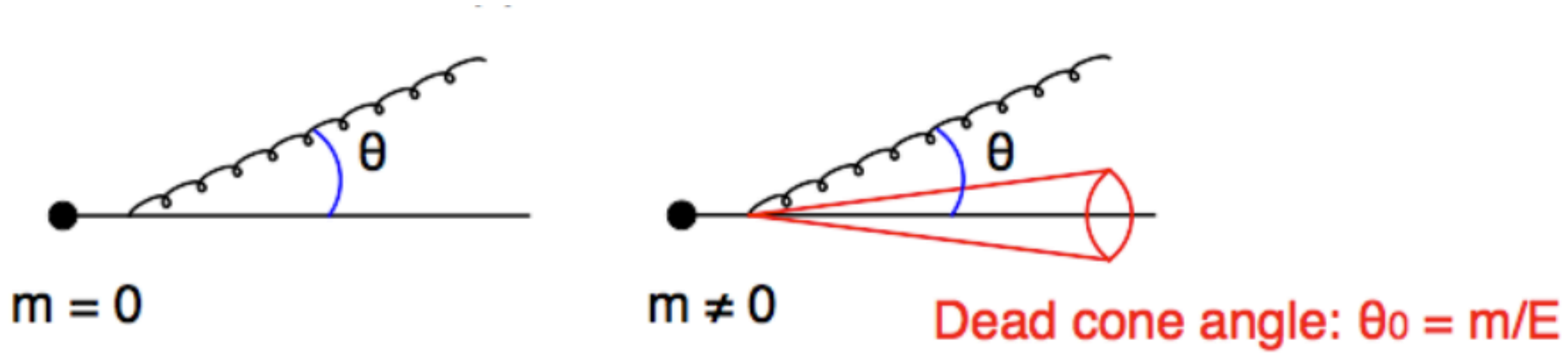
- Flavor dependence observed: harder fragment of charm quarks vs. inclusive jets
- PYTHIA mostly describes D^0-tagged but not inclusive

Heavy-flavor jet substructure in pp

- Measure groomed jet substructure for D^0-tagged jets compared to inclusive jets to compare quark jets (i.e. charm) with inclusive jets



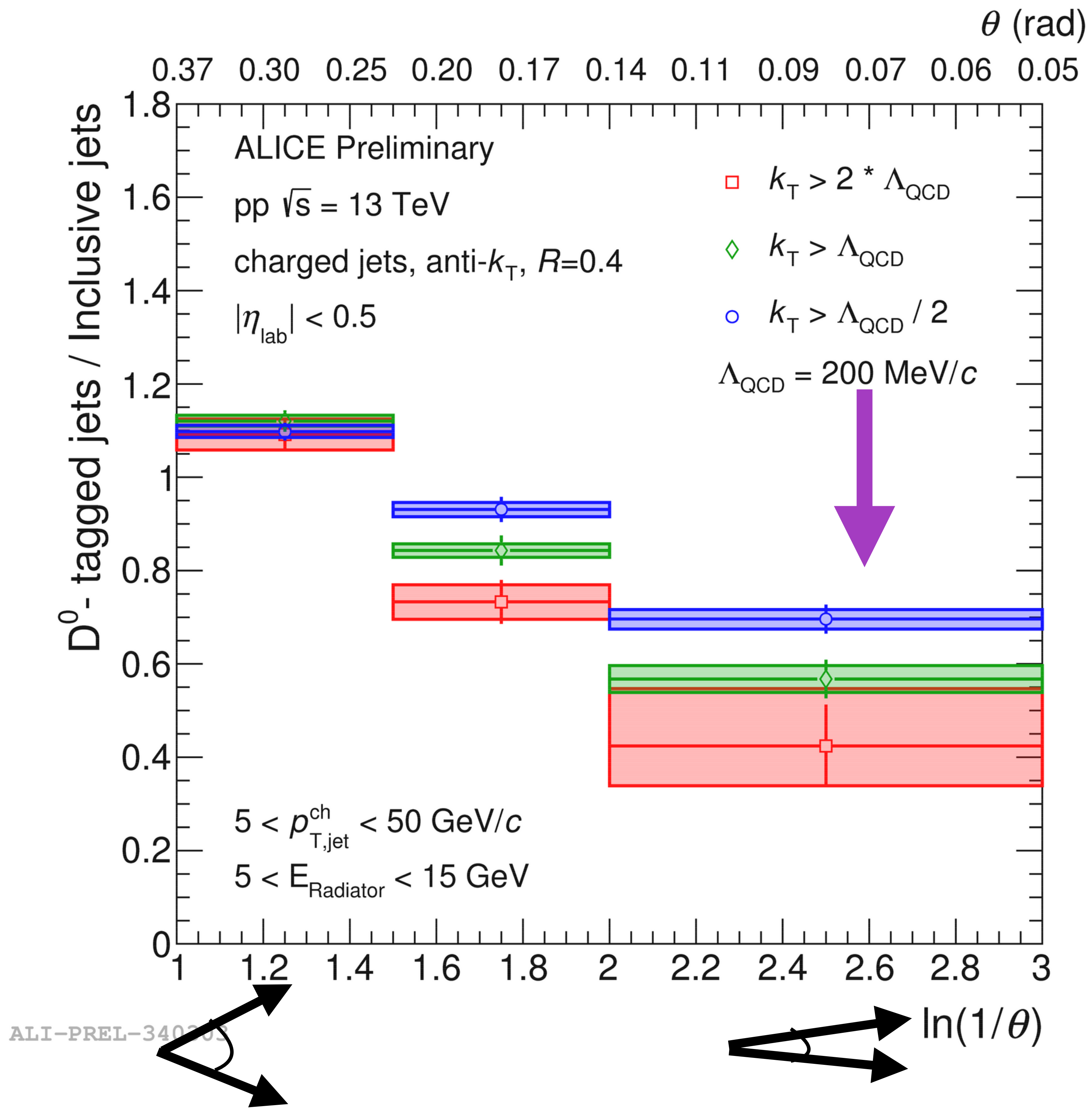
- Dead cone effect: suppression of emissions from a radiator (quark) with, $\theta < \frac{m_q}{E_q}$



- Comparing projections of the Lund plane should see a suppression at small angles for heavy quarks

Cunqueiro, Ploskon PRD 99, 074027

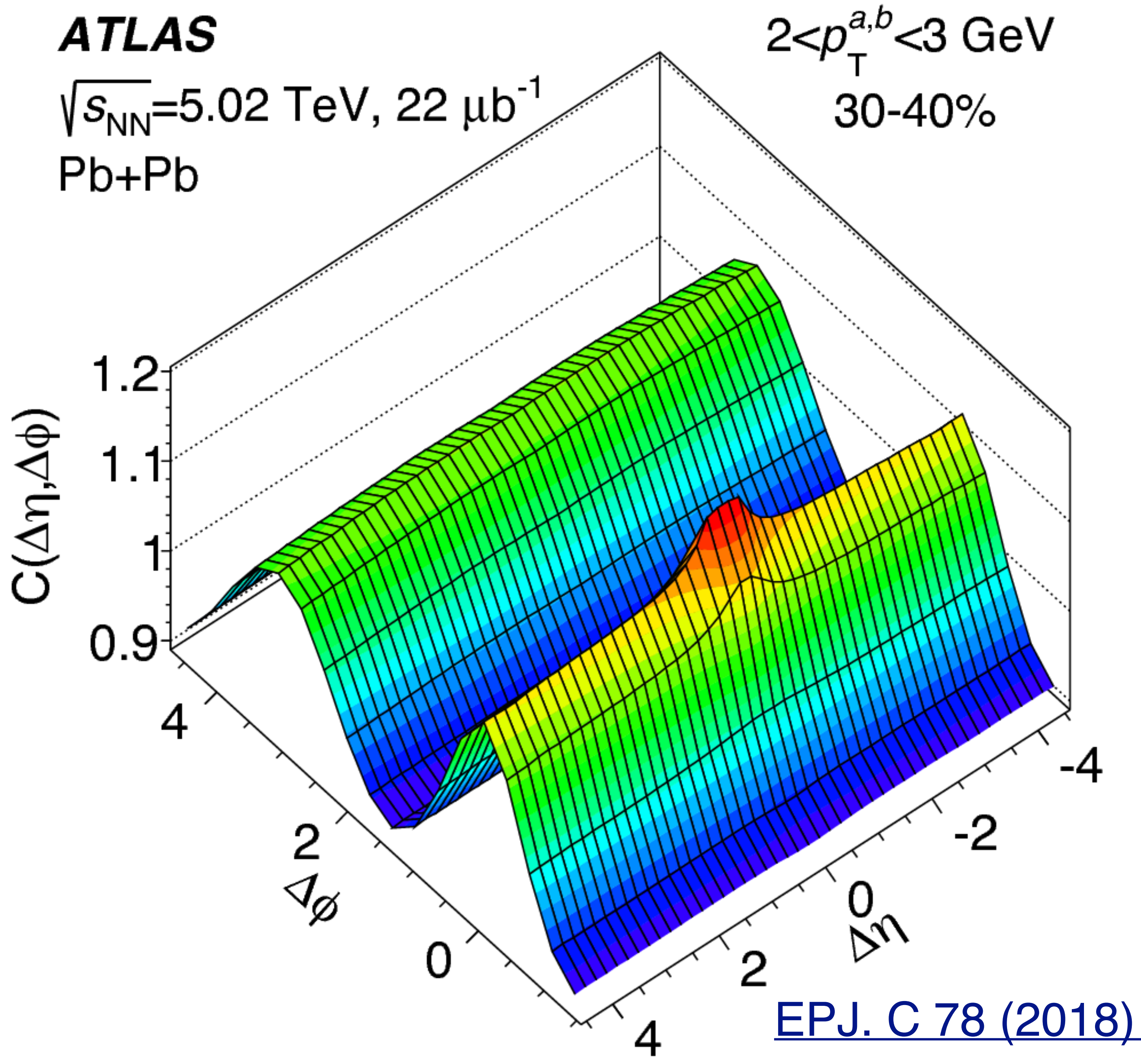
  - Significant suppression at small angles!



Jets and hadrons in small systems

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

Semi-central Pb-Pb



EPJ. C 78 (2018) 997

Jets and hadrons in small systems

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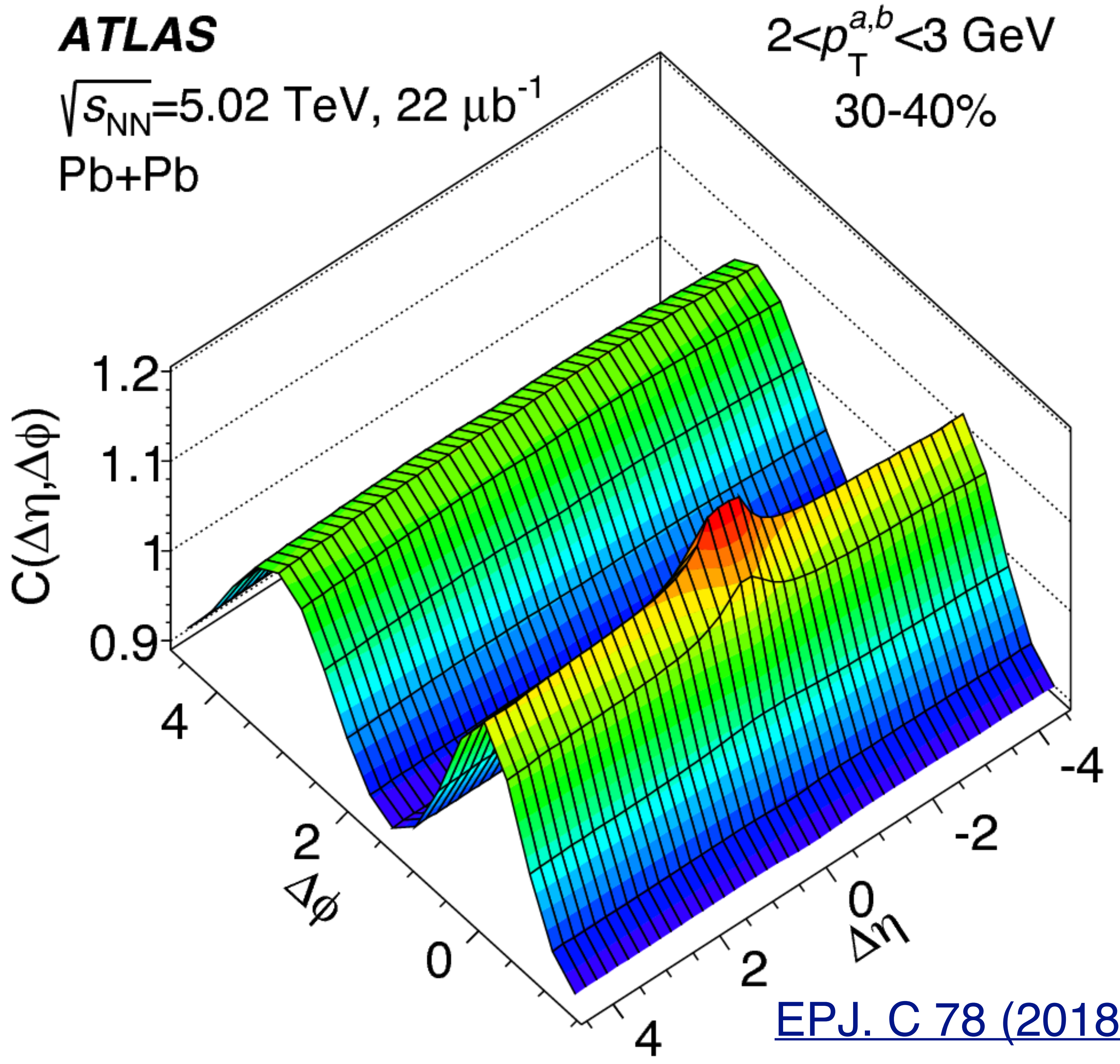
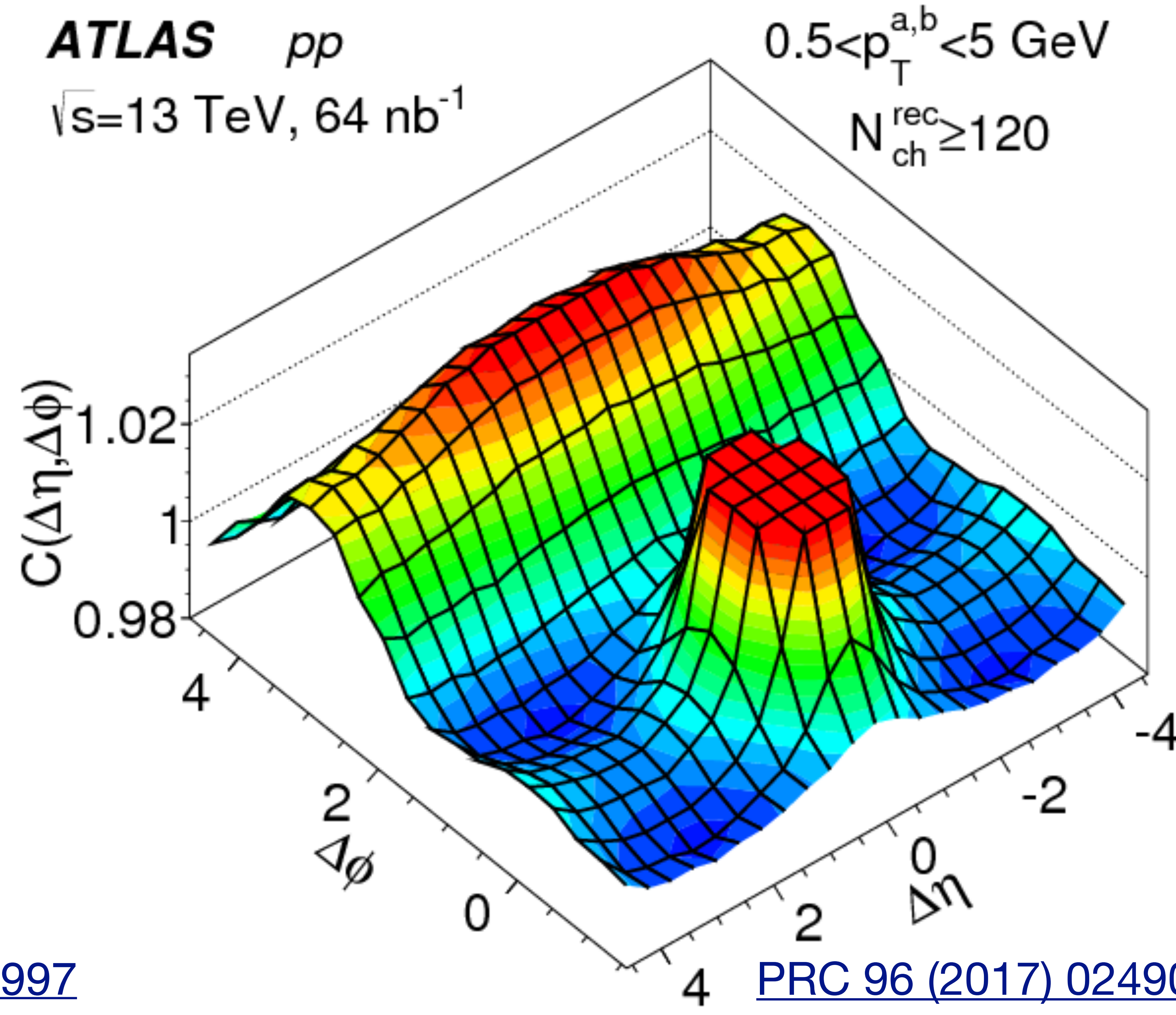


[EPJ. C 78 (2018) 997](#)

High multiplicity pp

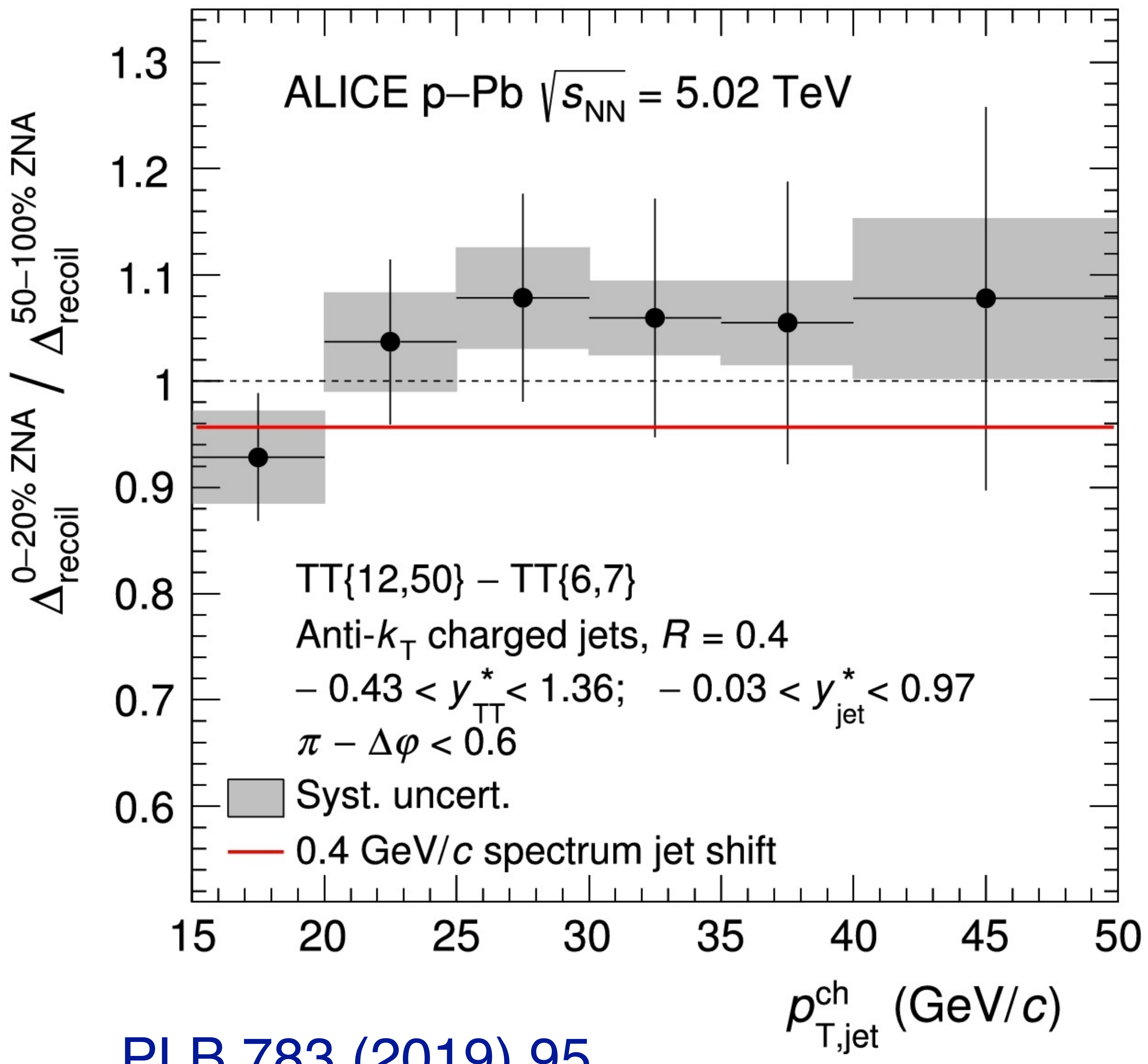


[PRC 96 (2017) 024908](#)

- Also seen in small collisions systems: p-Pb and high multiplicity (HM) pp collisions

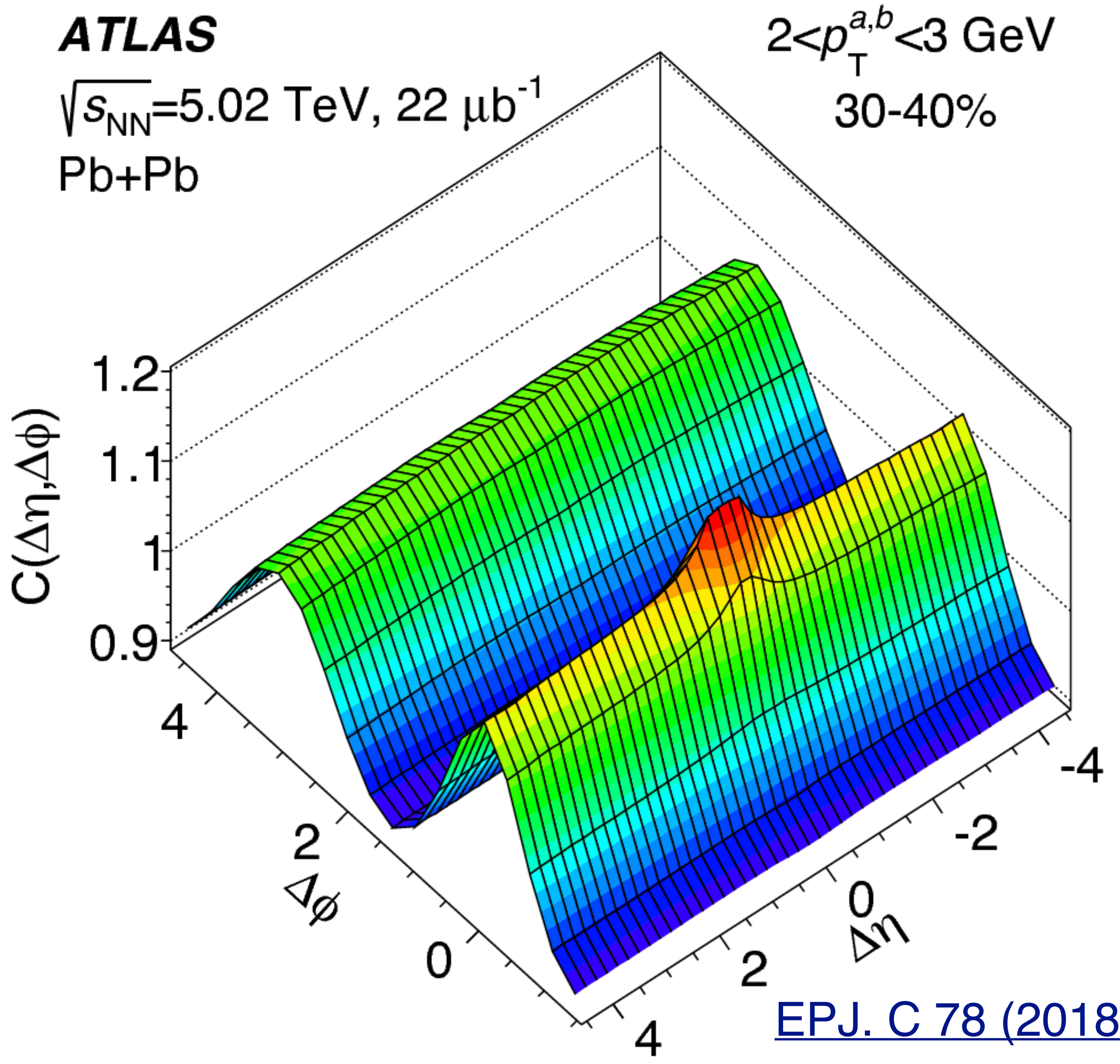
Jets and hadrons in small systems

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



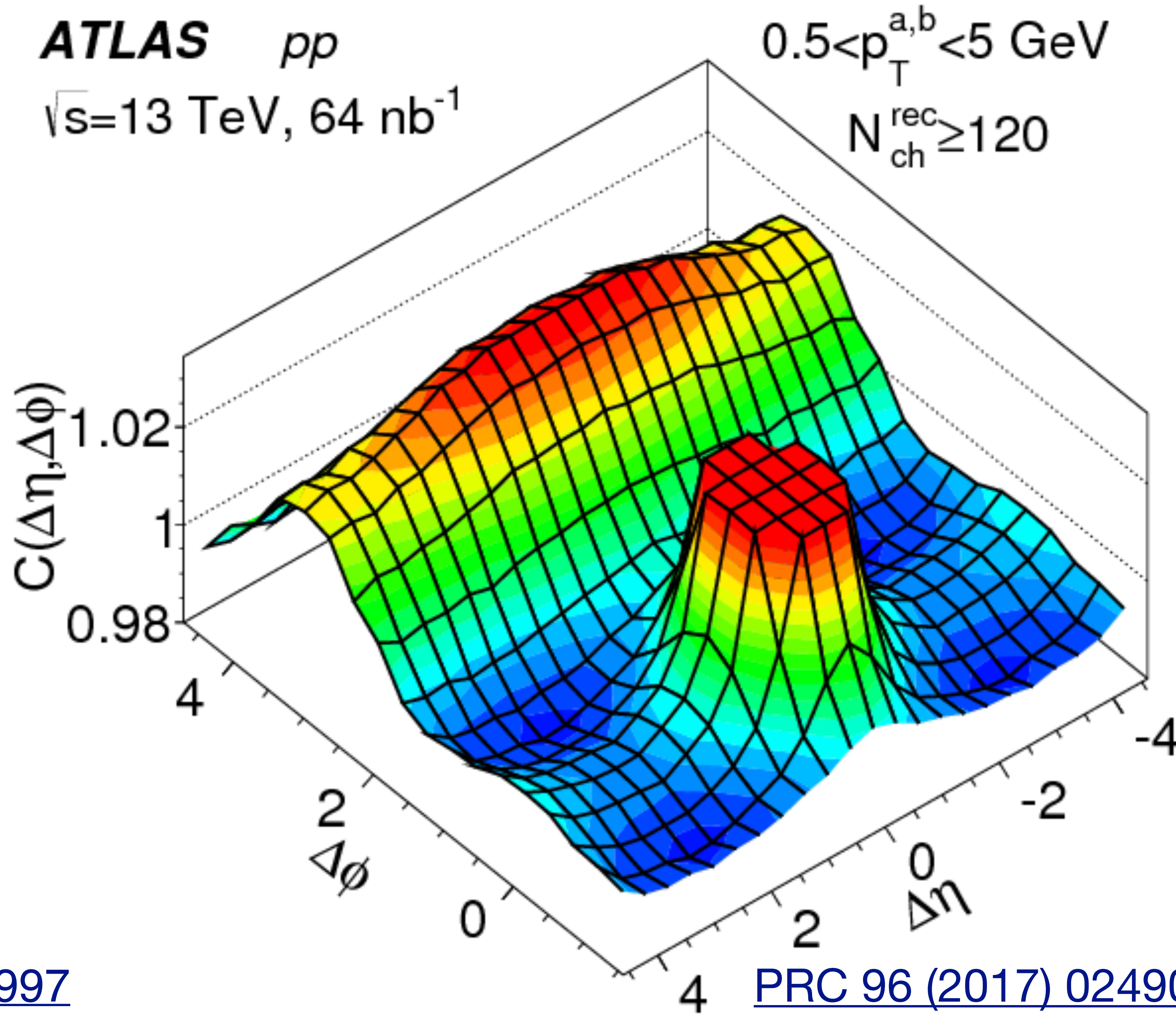
PLB 783 (2019) 95

Semi-central Pb-Pb



EPJ. C 78 (2018) 997

High multiplicity pp

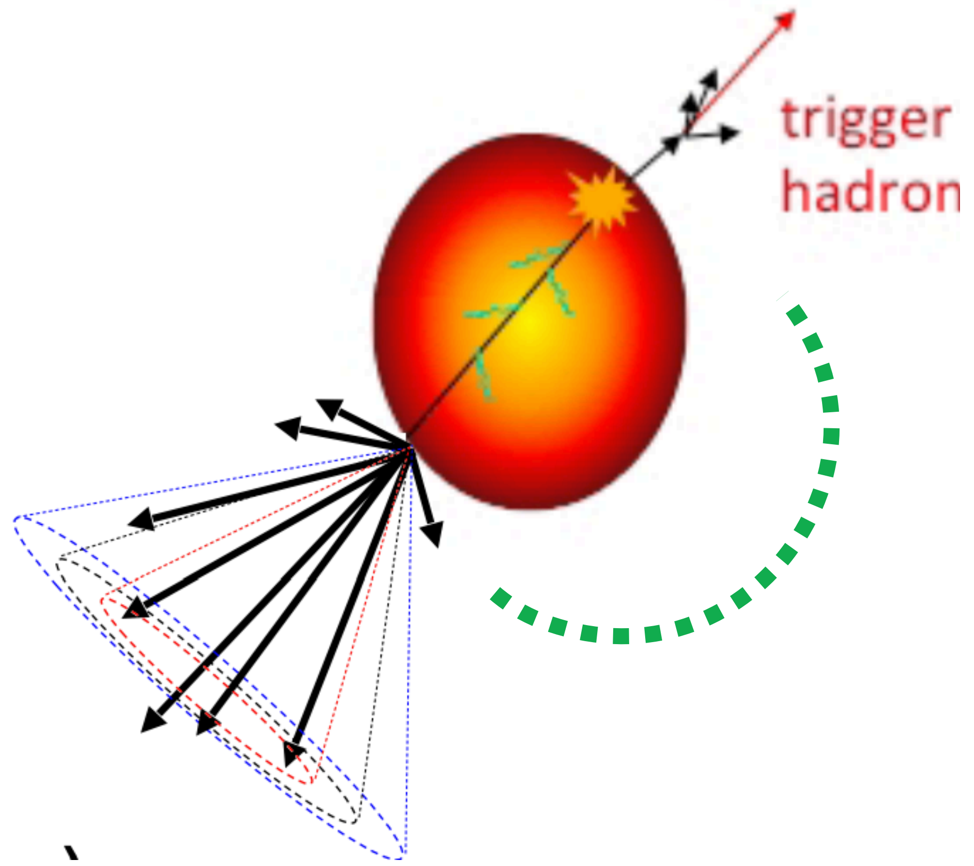


PRC 96 (2017) 024908

- ▸ 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?

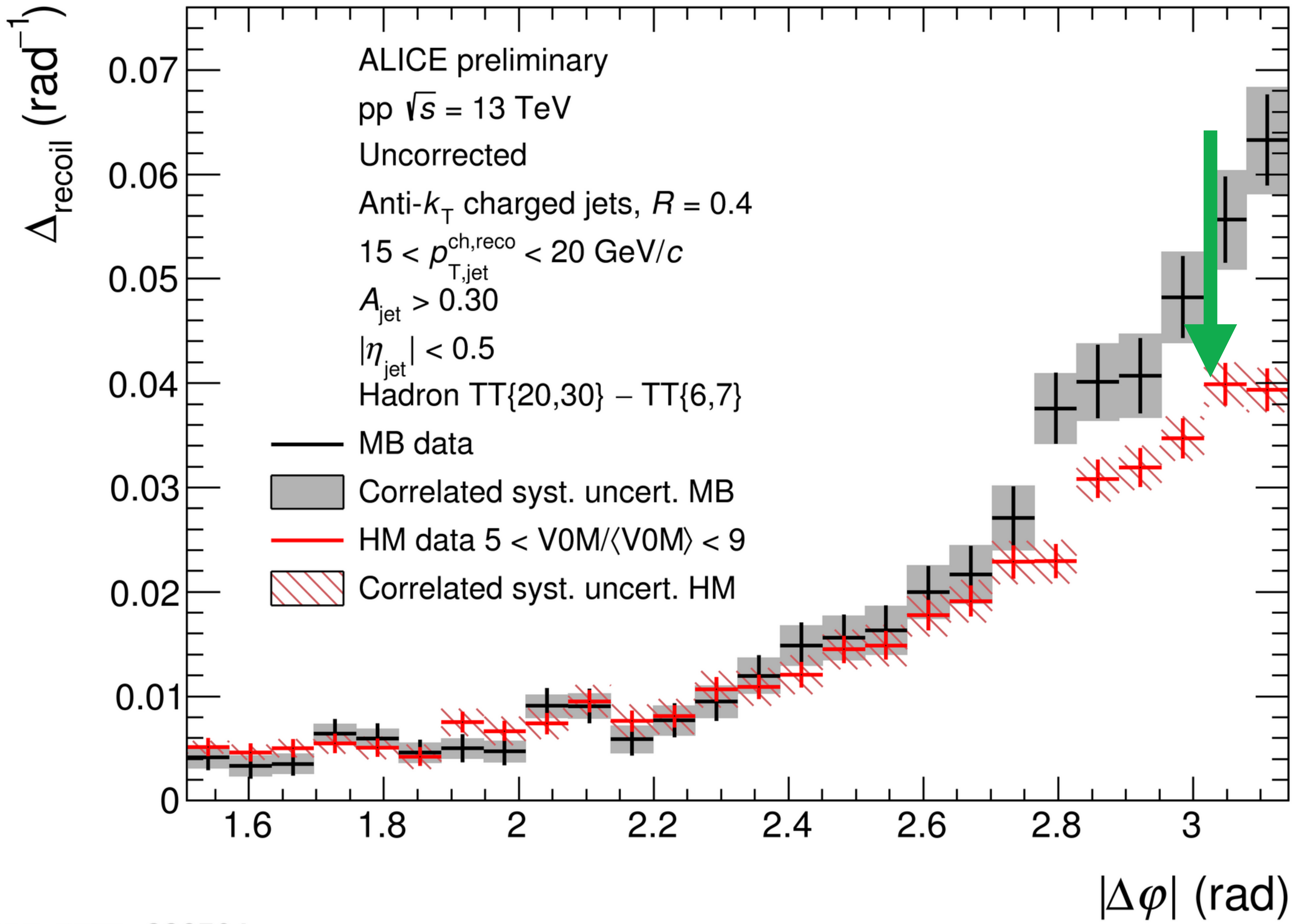


- Look at jet acoplanarity in **HM** compared to **MB** pp collisions

HM: $5 < (V0M/\langle V0M \rangle) < 9$

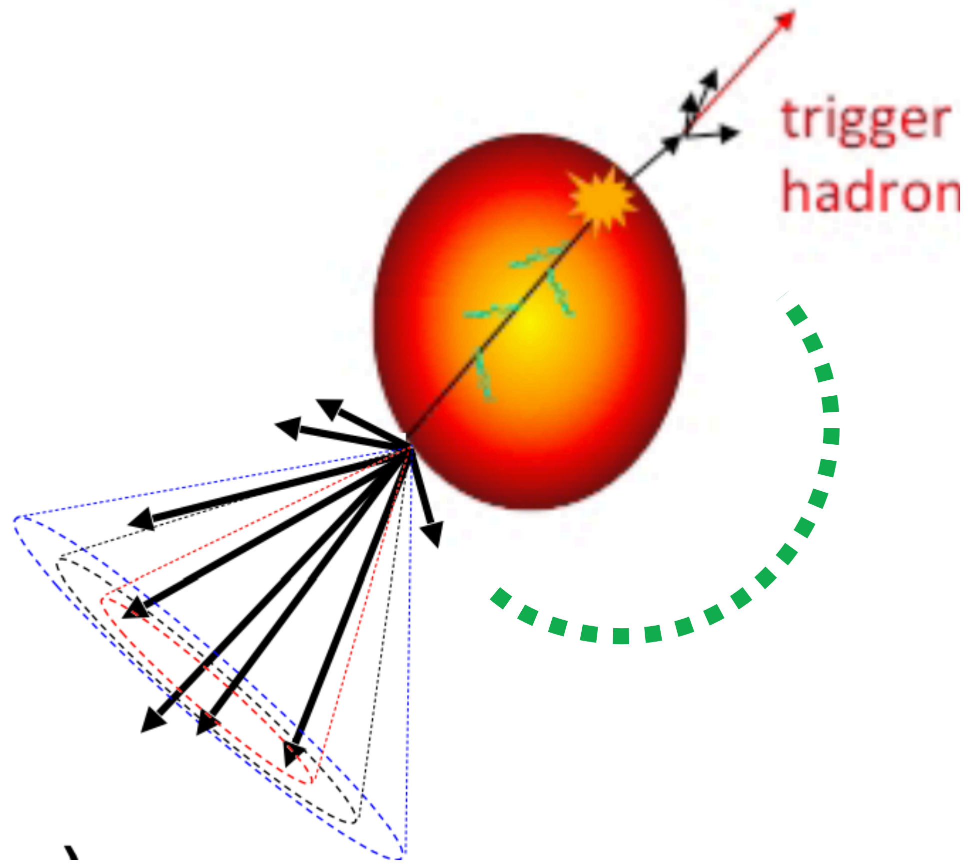
V0M is the number of charged, final state particles in the V0A and V0C forward detectors

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



ALI−PREL−339704

Jet quenching in pp collisions?



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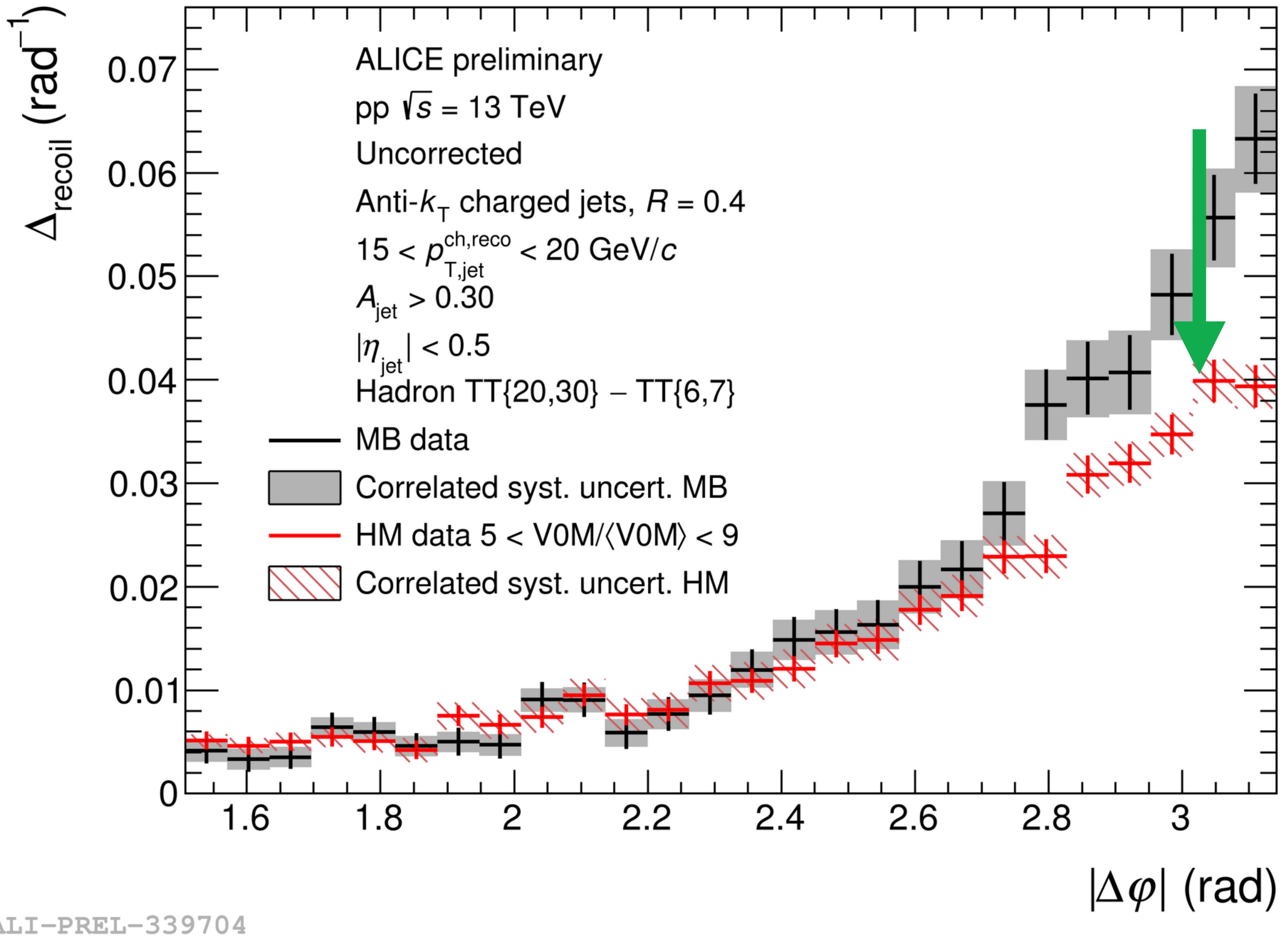
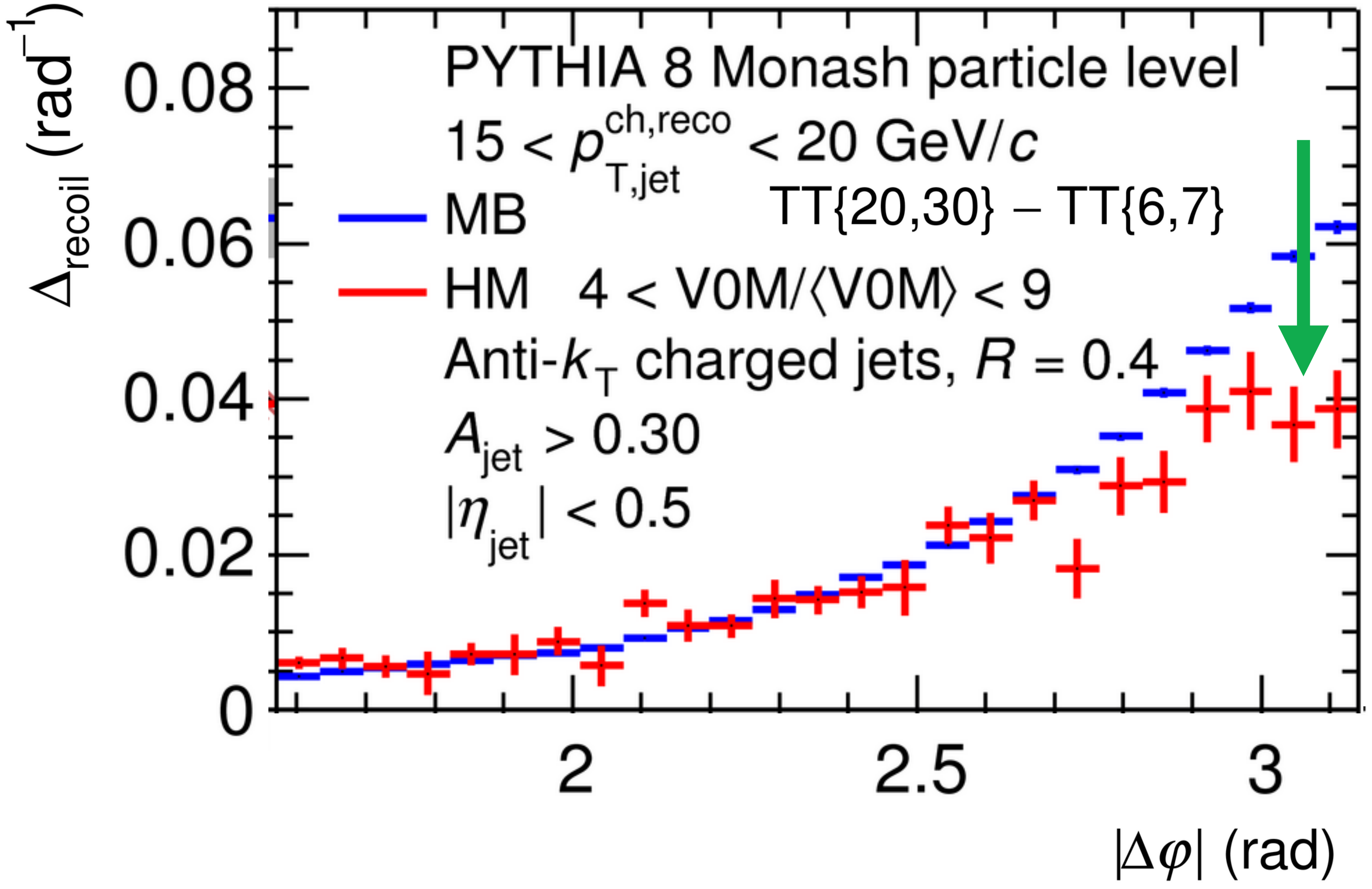




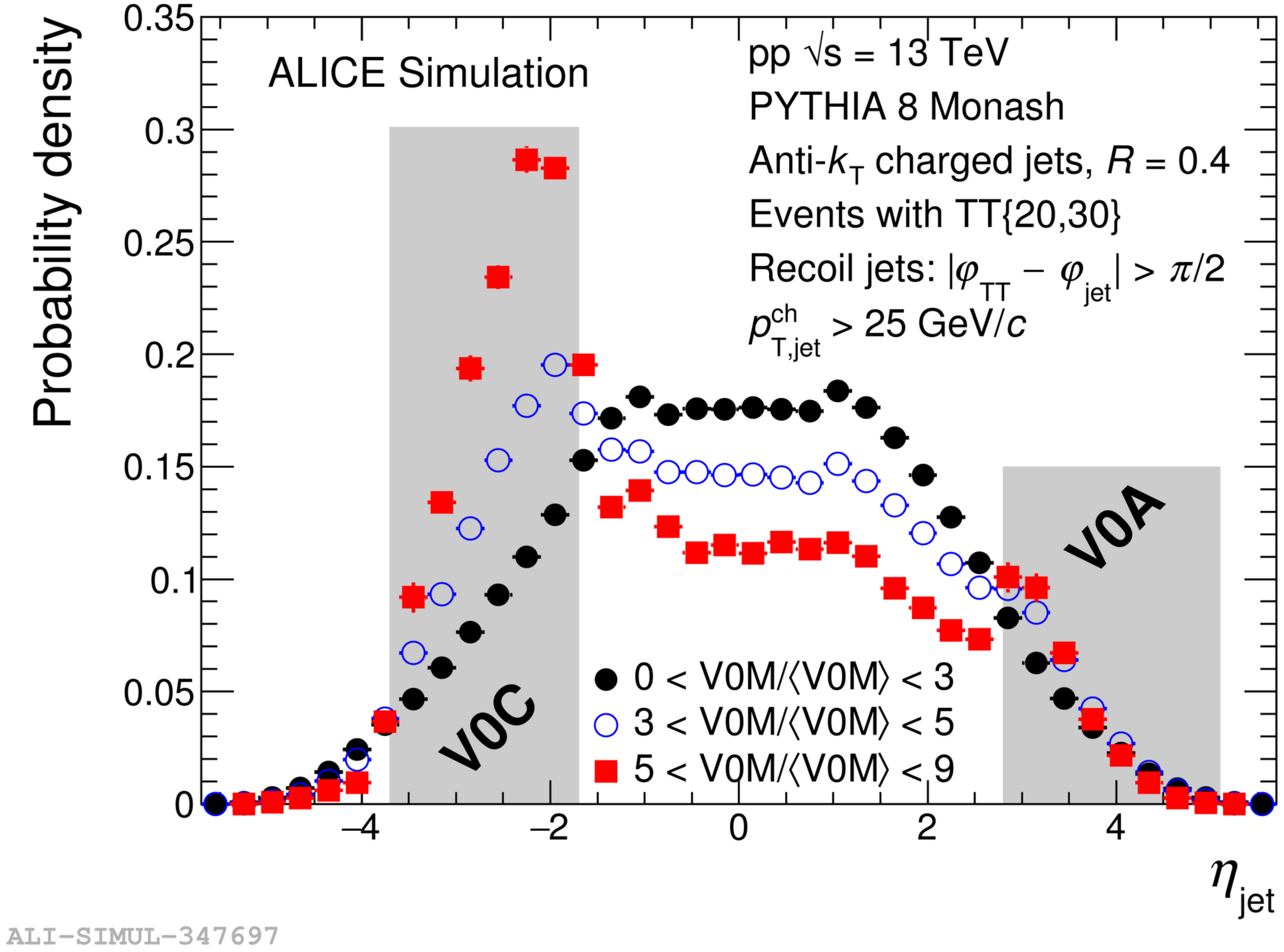
- Look at jet acoplanariy in **HM** compared to **MB** in PYTHIA8 simulations

▸ Similar effect seen! What's happening?

PYTHIA studies: multi-jet bias?

- Could the HM selection be biased towards multi-jet events?
  - Look at rapidity distributions for recoil jets in PYTHIA

Bias seen in forward region with HM selection!



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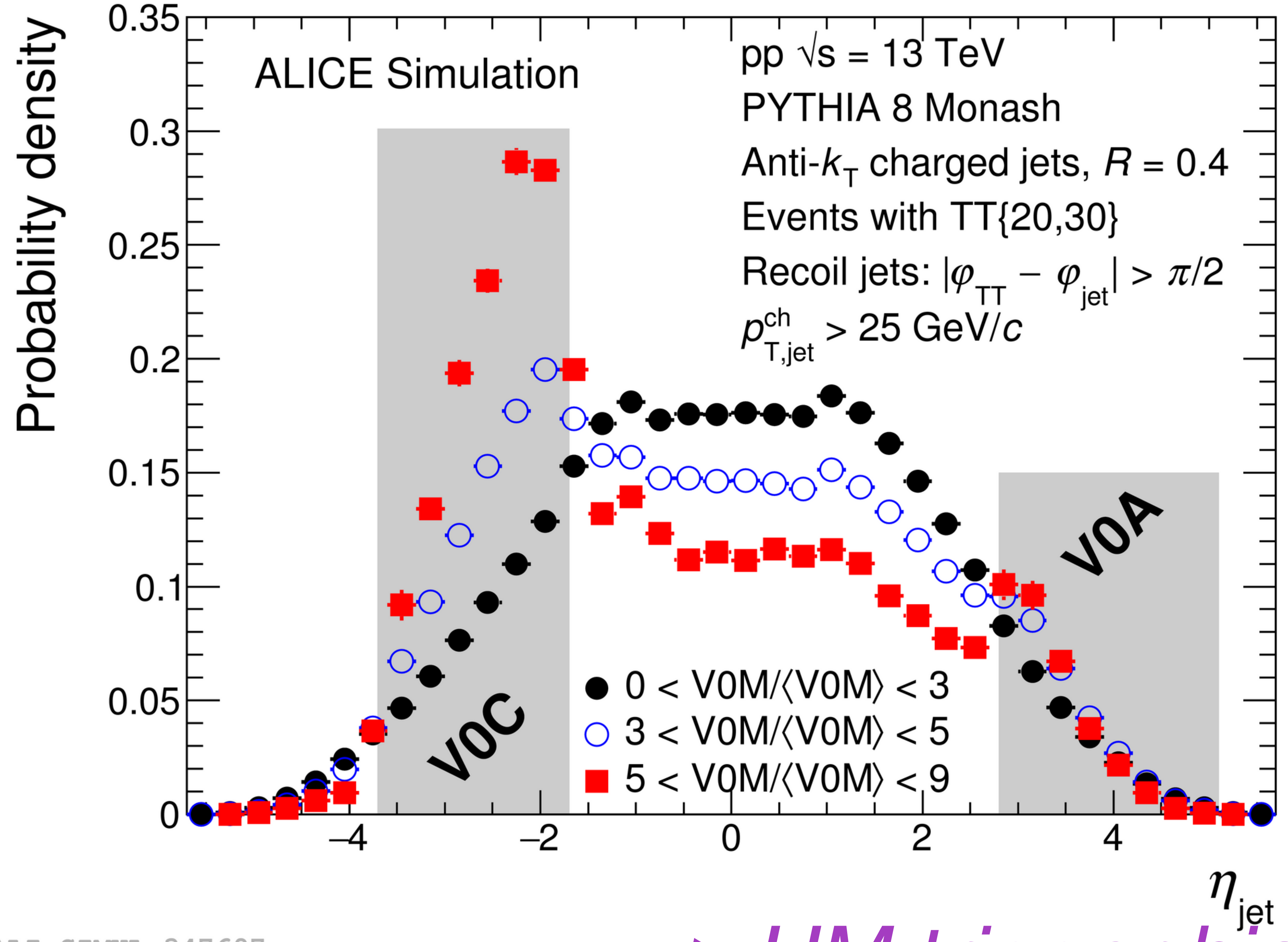
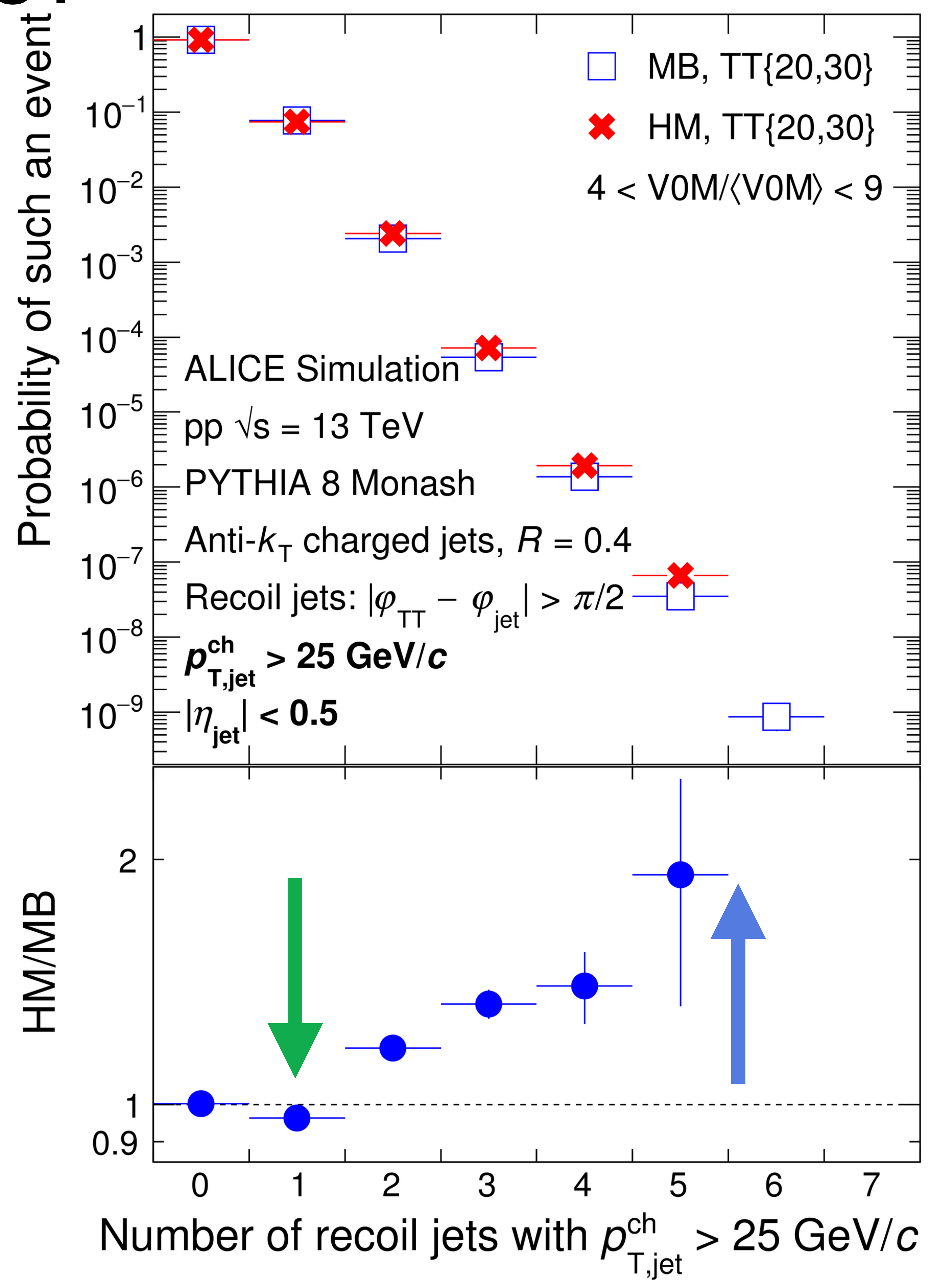


ALI-SIMUL-347697

▸ Compare distributions of number of recoil jets above a certain p_T

HM suppresses events with 1 recoil and enhances events with multi-jets

Could account for the suppression in $\Delta\varphi$



ALI-SIMUL-347715

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

Conclusion

- ALICE has an array of new results that further our understanding of the QGP
  - New constrains on nPDFs with light meson R_{pPb} at very high p_T
  - New measurements of jet quenching:
    - ➡ Jet suppression measured at lower p_T using ML techniques
    - ➡ Suppression and narrowing of jet acoplanarity in HIs at low recoil jet p_T
    - ➡ First unfolded groomed jet substructure measurements indicates a narrowing of jets in HIs
  - Measurements in pp collisions:
    - ➡ First measurement of dynamical grooming → promising to measure in Pb-Pb
    - ➡ HF-tagged jet substructure shows a flavor dependence
    - ➡ Jet quenching studies in pp reveal a bias to multi-jets with HM triggers
- Together these measurements further our understanding of the microscopic structure of the QGP in new regions of phase space!

Outlook

- Short term on existing Run 2 data:
  - Dynamical grooming in Pb-Pb collisions
  - Extension of ML techniques to other variables like jet substructure
  - Extend the study of the multi-jet HM bias to real data
- Longer term for Run 3:
  - Increased luminosity and continuous read-out system for the TPC

    ➡ Allows for precision measurements of jet quenching
  - Upgraded ITS will allow for improvements to the HF-tagging

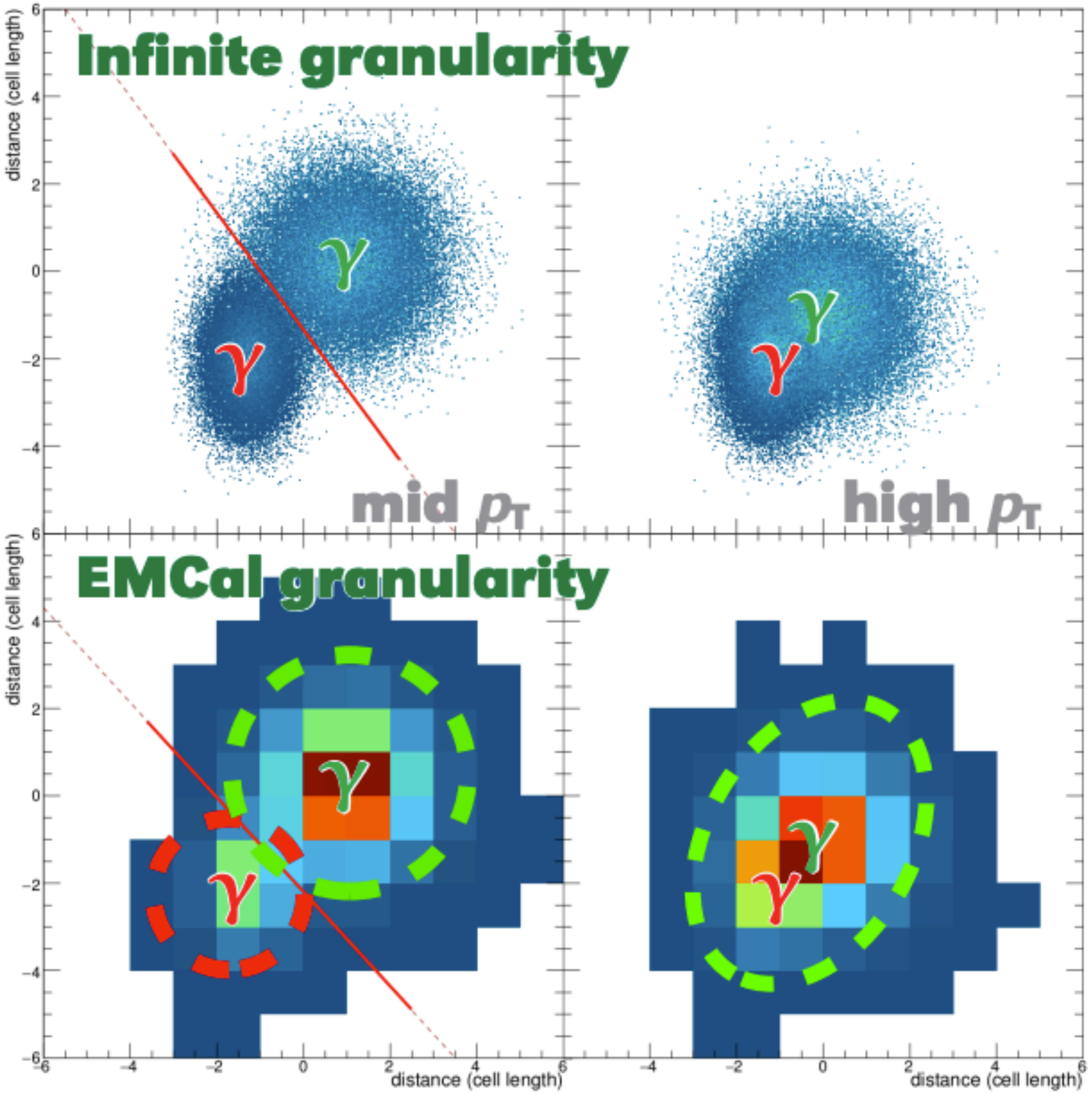
    ➡ Continue HF-tagged jet substructure measurements (also in Pb-Pb!)

    ➡ Scan of the mass for the dead cone effect

    ➡ Other inclusive jet measurements can be extended to HF-tagged jets

Backup

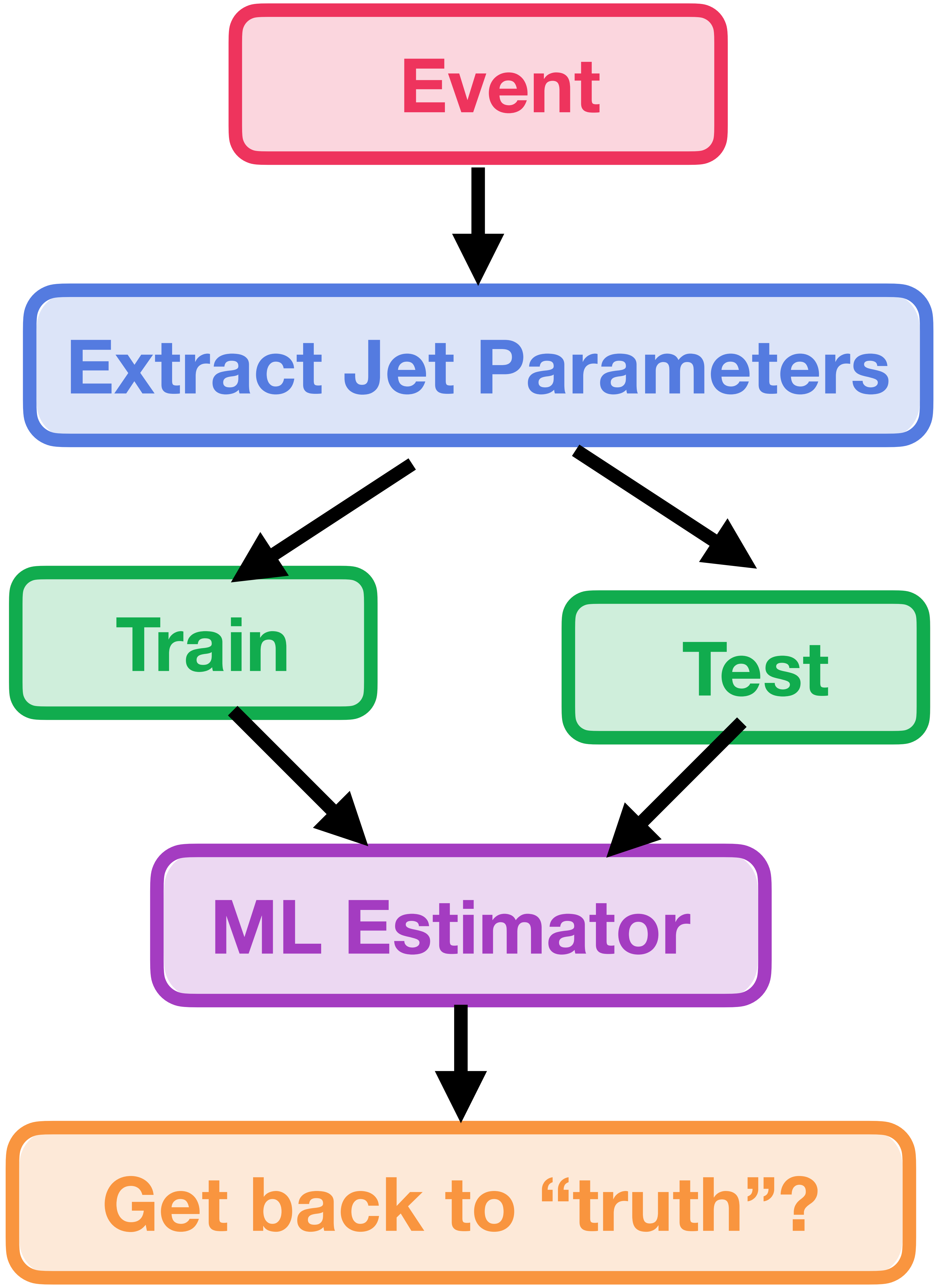
Measuring light mesons to high p_T



π^0s opening angles smaller than resolution at high p_T

Fix: use long axis of cluster as discriminator

ML approach: method



- Embedding pp PYTHIA events into real Pb-Pb data
- Optimized for method performance and how important/correlated they are
  - Area-based corrected
  - 12 leading constituents
  - jet angularity
  - 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

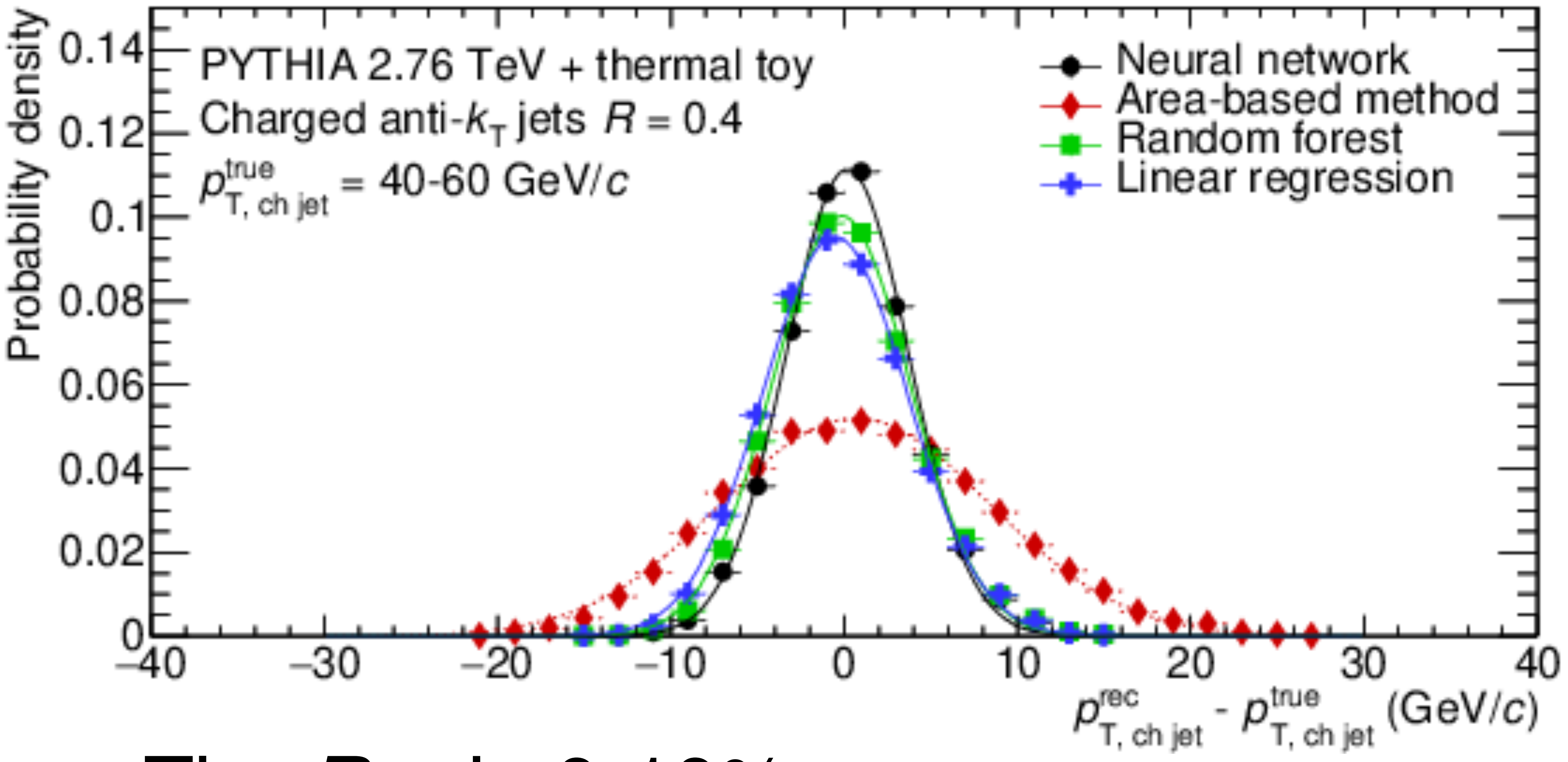
Feature	Score	Feature	Score
Jet p_{T} (no corr.)	**0.1355**	$p^{1}_{\mathrm{T,const}}$	0.0012
Jet mass	0.0007	$p^{2}_{\mathrm{T,const}}$	**0.0039**
Jet Area	0.0005	$p^{3}_{\mathrm{T,const}}$	0.0015
Jet p_{T} (area based corr.)	**0.7876**	$p^{4}_{\mathrm{T,const}}$	0.0011
LeSub	0.0004	$p^{5}_{\mathrm{T,const}}$	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

Phys. Rev. C 99, 064904 (2019)

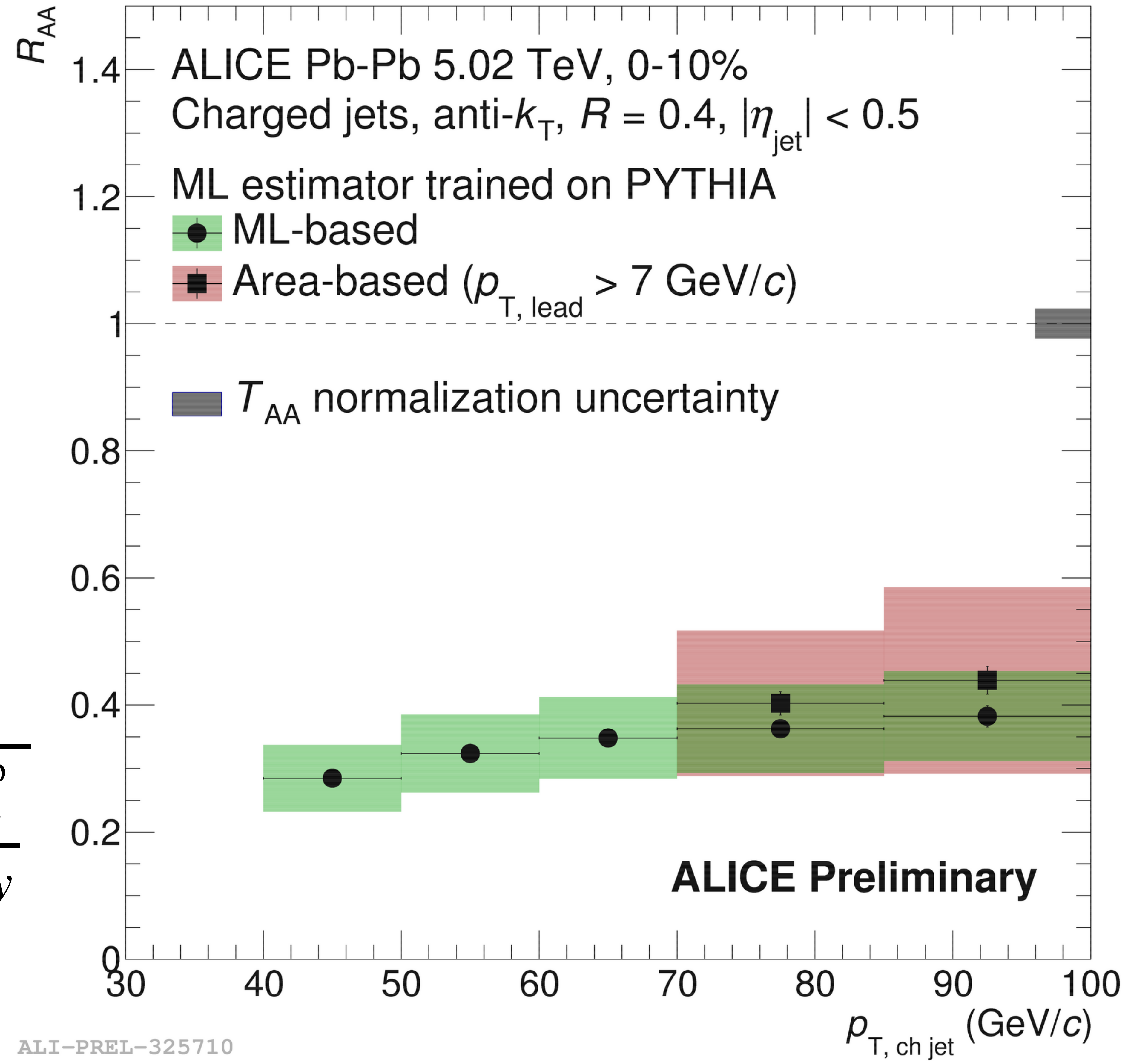
▸ Iteratively remove unimportant and/or highly correlated feature!

ML approach: charged jets

Phys. Rev. C 99, 064904 (2019)



- ML method improves resolution over area-based -> unfold to lower p_T

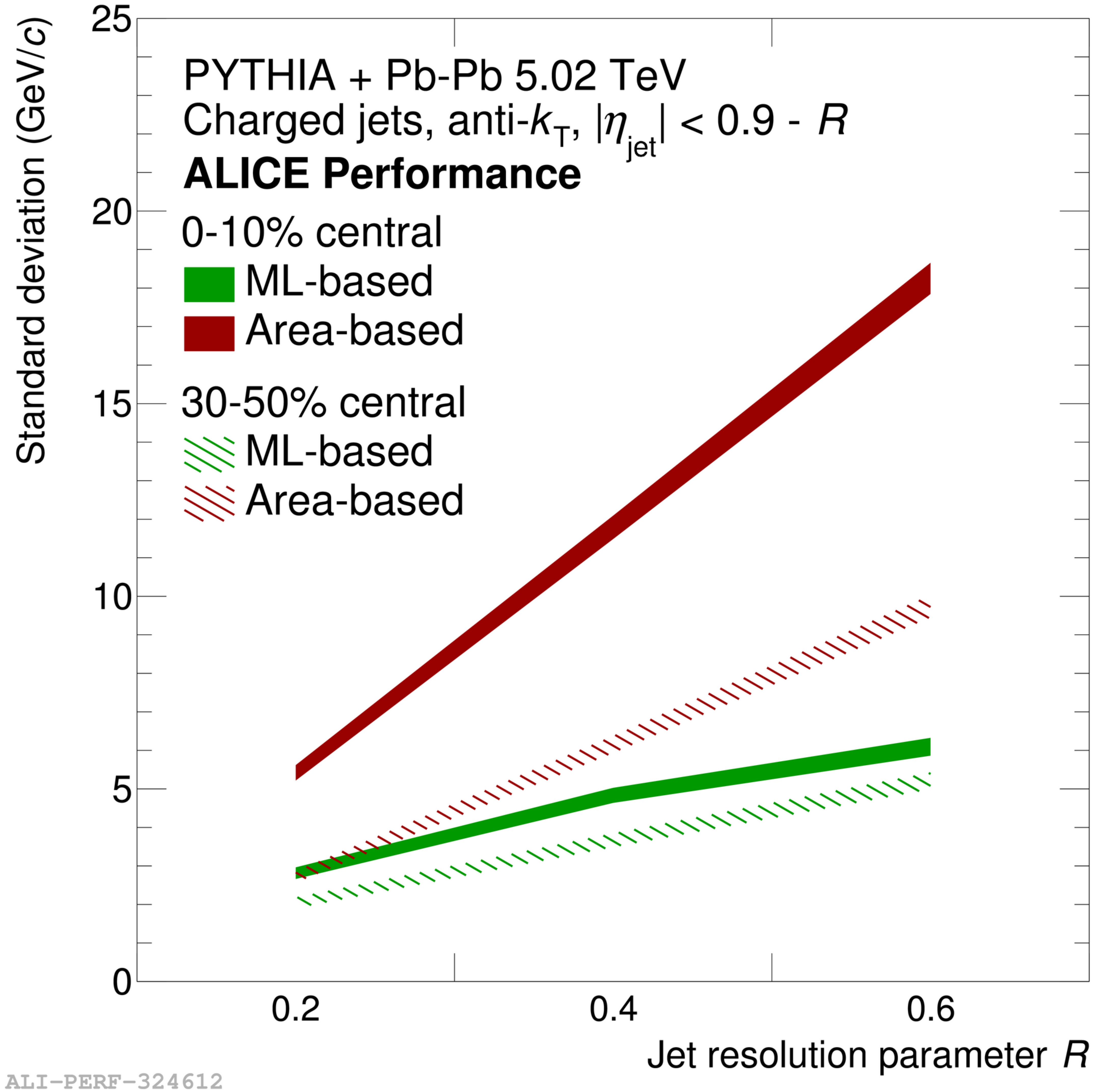


- The R_{AA} in 0-10% ALICE data with the ML-based and area-based method with a leading track bias are consistent!

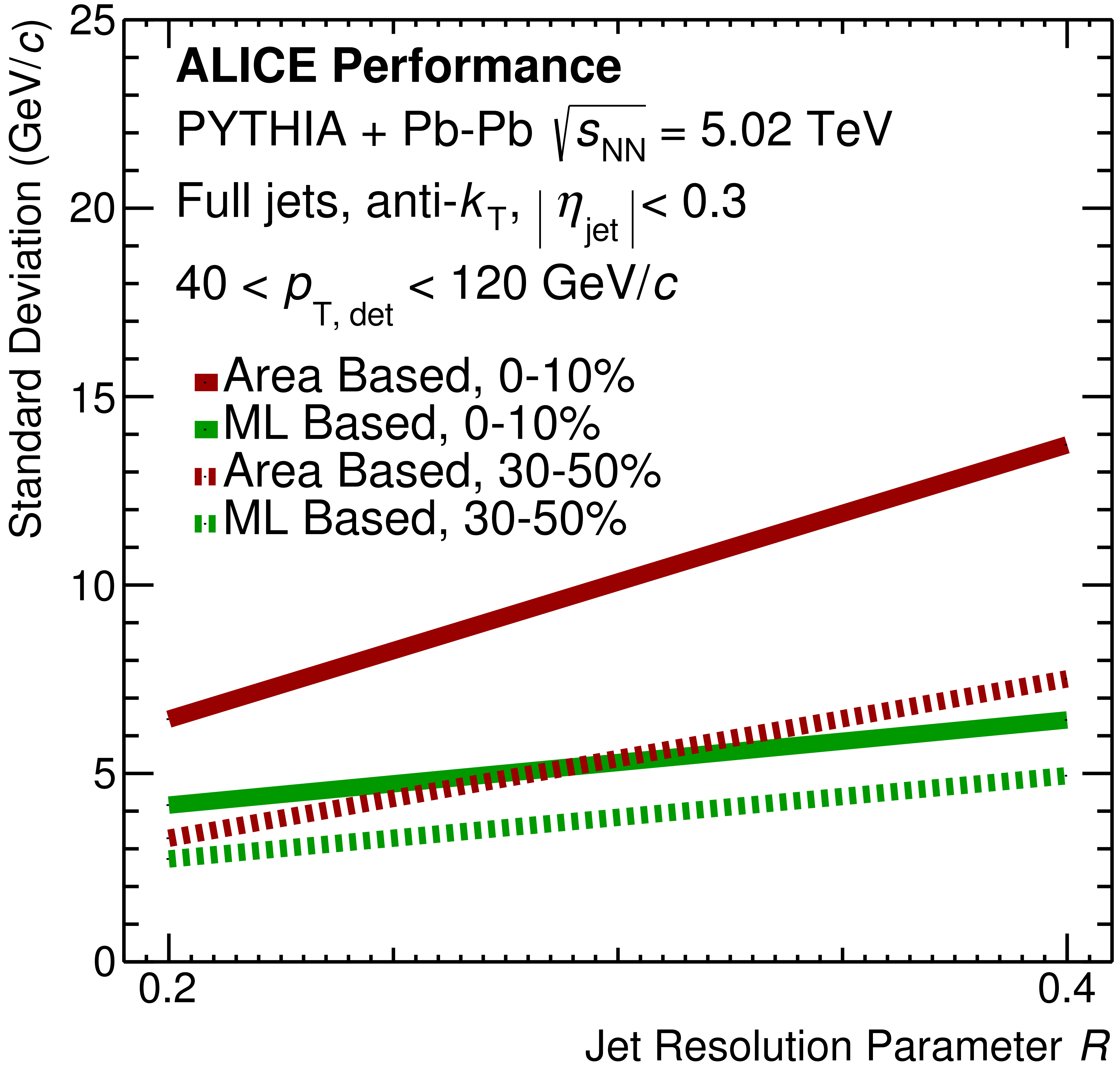
$$R_{AA} = \frac{\frac{1}{N_{event}} \frac{d^2 N_{jet}^{PbPb}}{dp_T dy}\Big|_{cent}}{\frac{< N_{coll} >_{cent}}{\sigma_{inel}} \times \frac{d^2\sigma_{jet}^{pp}}{dp_T dy}}$$

p_T reach now down to 40 GeV/c, reduced uncertainties

ML approach: performance



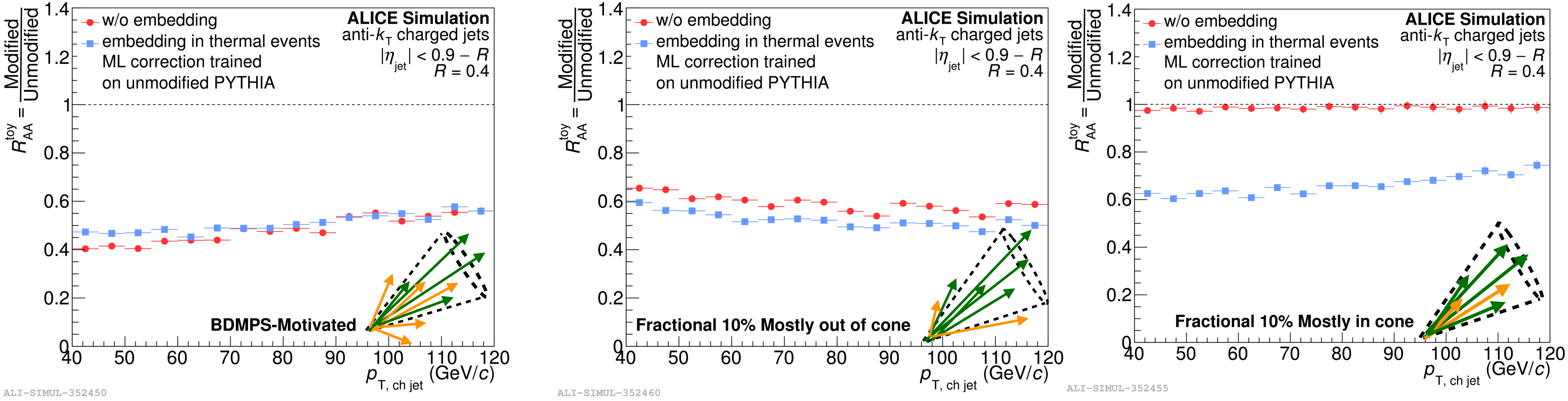
ALI-PERF-324612



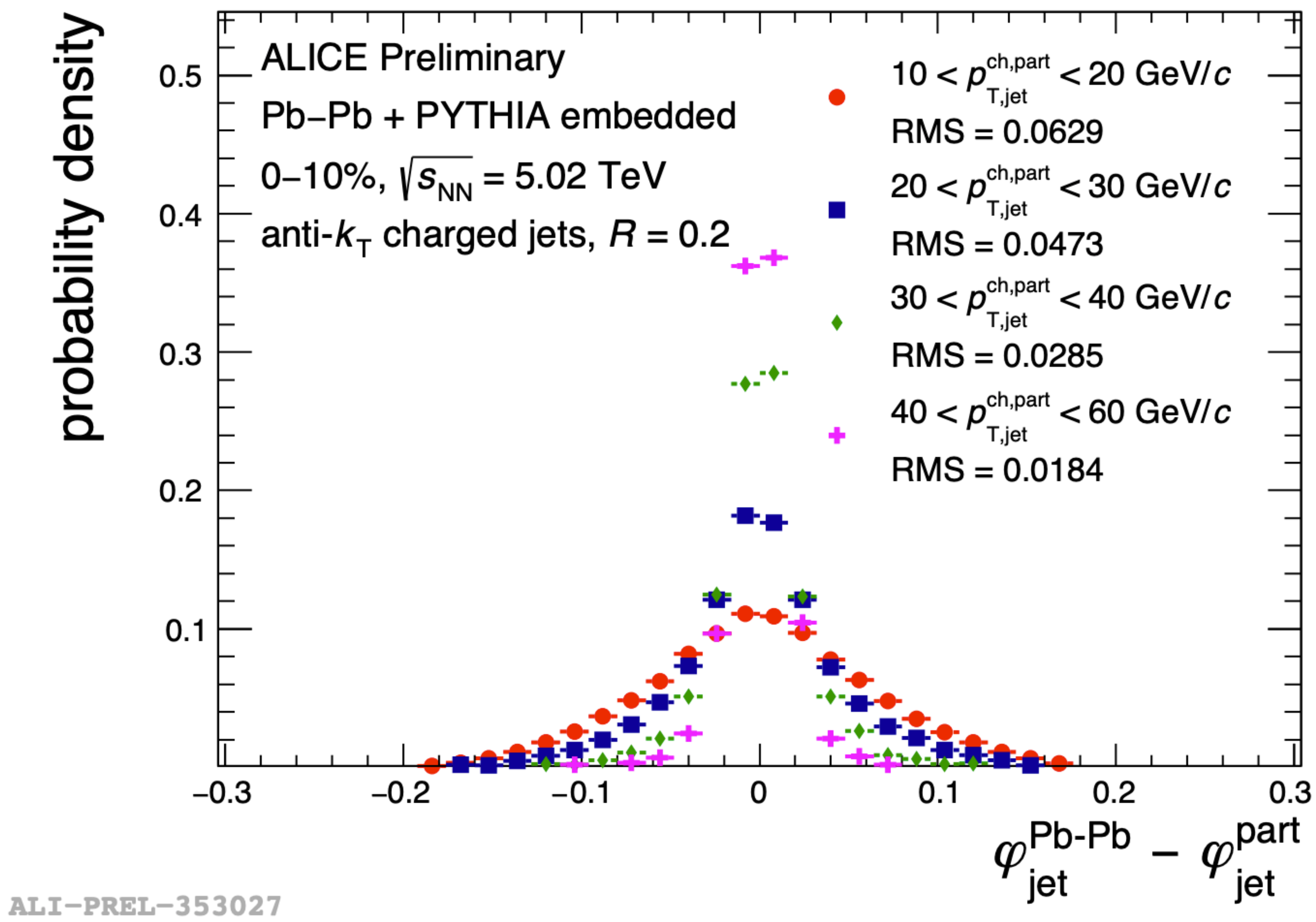
ALI-PERF-339976

Laura Havener, Yale University

ML approach: fragmentation



Back-up: jet acoplanarity



Good resolution, 50 mrad for 25 GeV jets

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

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

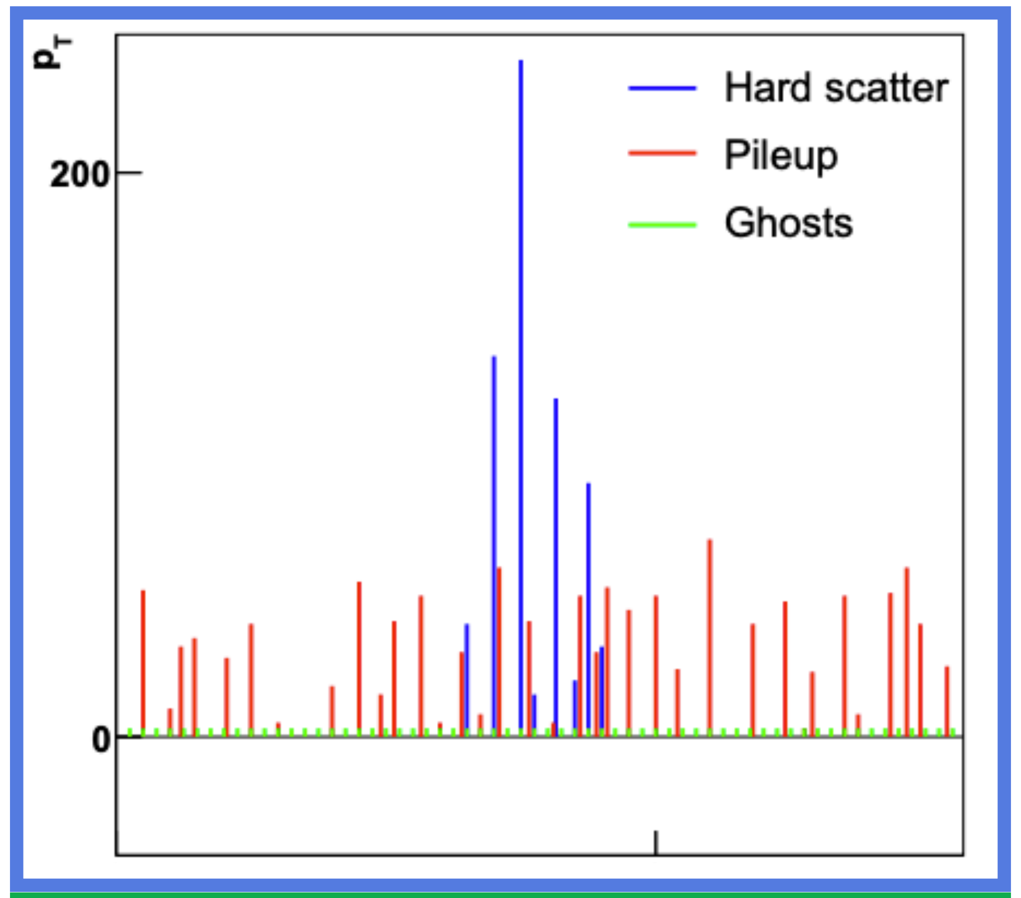
$$m_{\mathrm{g}} = A_{\mathrm{g}}\rho_m$$

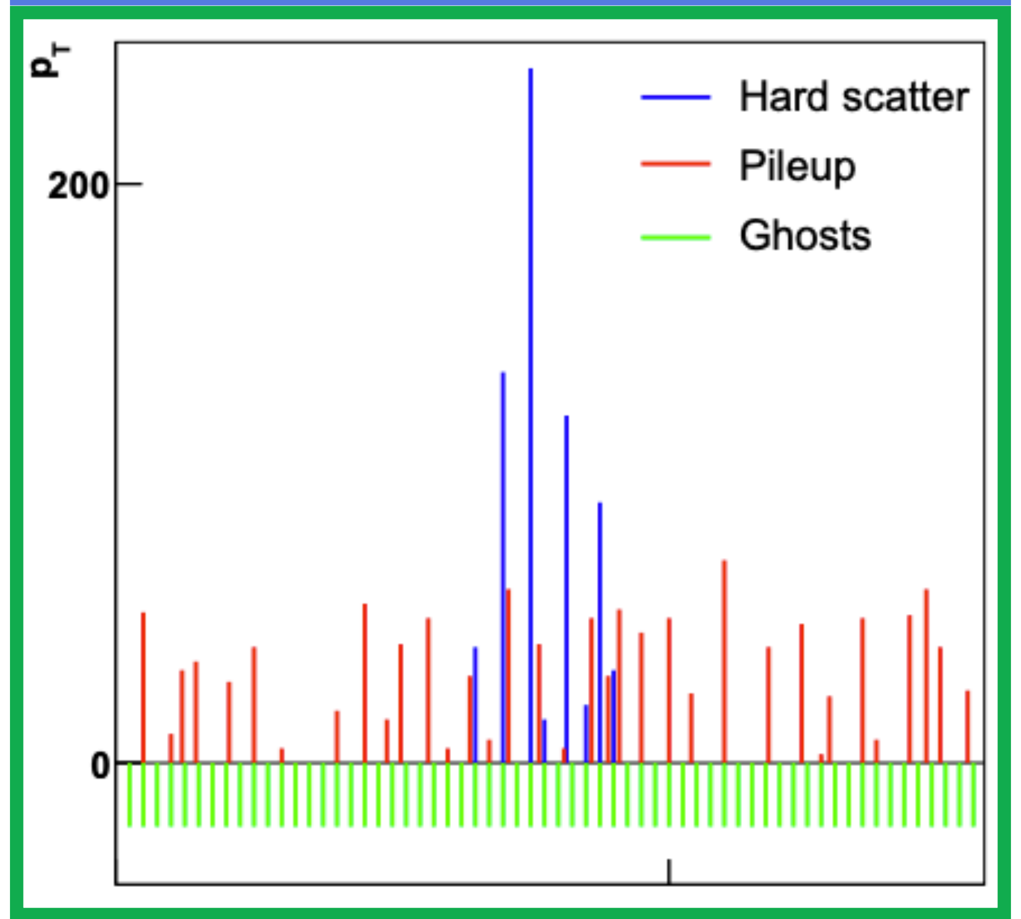
- Calculate distance between each particle and ghost for each pair and sort in ascending order
- Iteratively change the momentum and mass of each ghost/particle until no more pairs remain

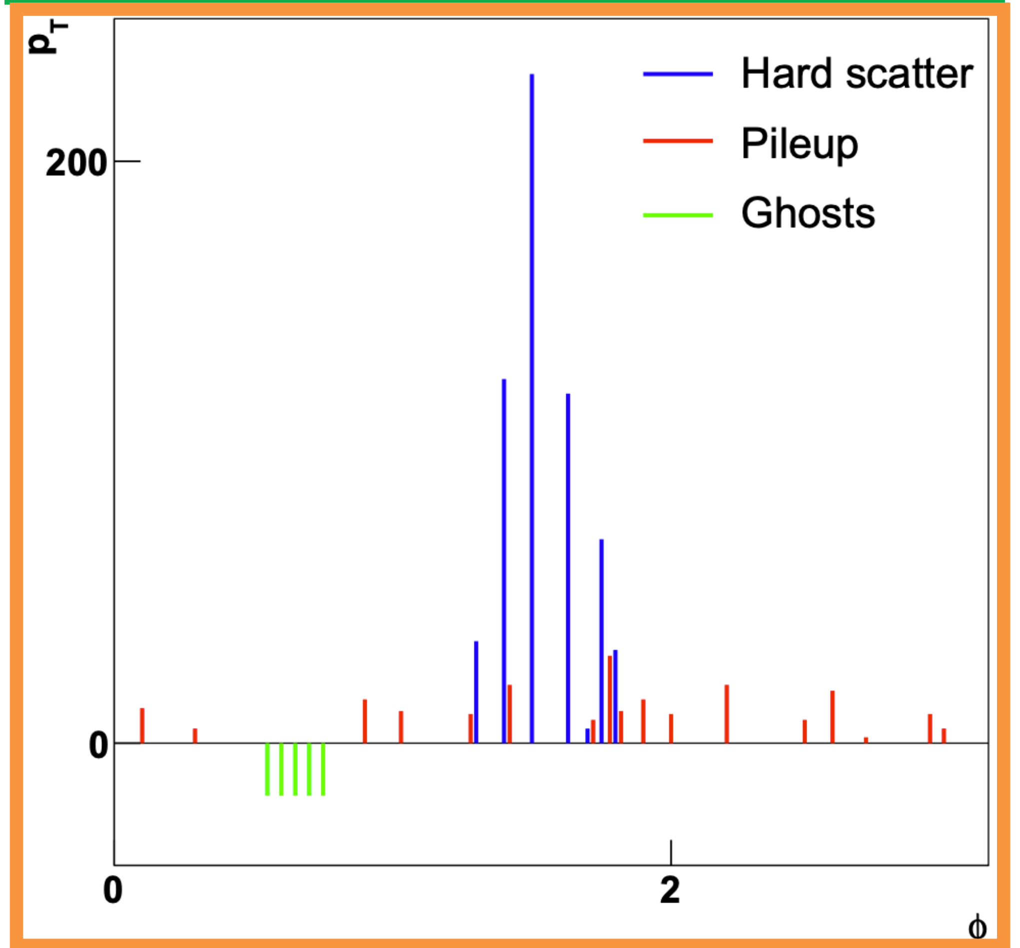
if ($p_T > p_T^g$) $\quad p_T = p_T - p_T^g \quad p_T^g = 0$ $\qquad\qquad p_T^g = p_T^g - p_T \quad p_T = 0$

- Discard particles with 0 momentum

JHEP 1908 (2019) 175





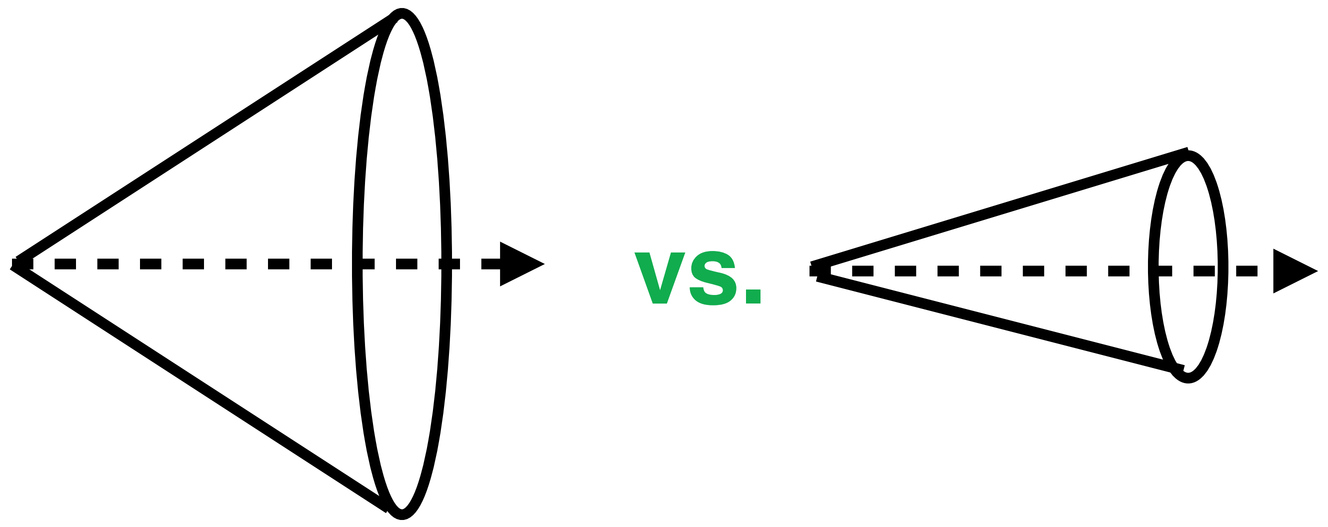


Laura Havener, Yale University

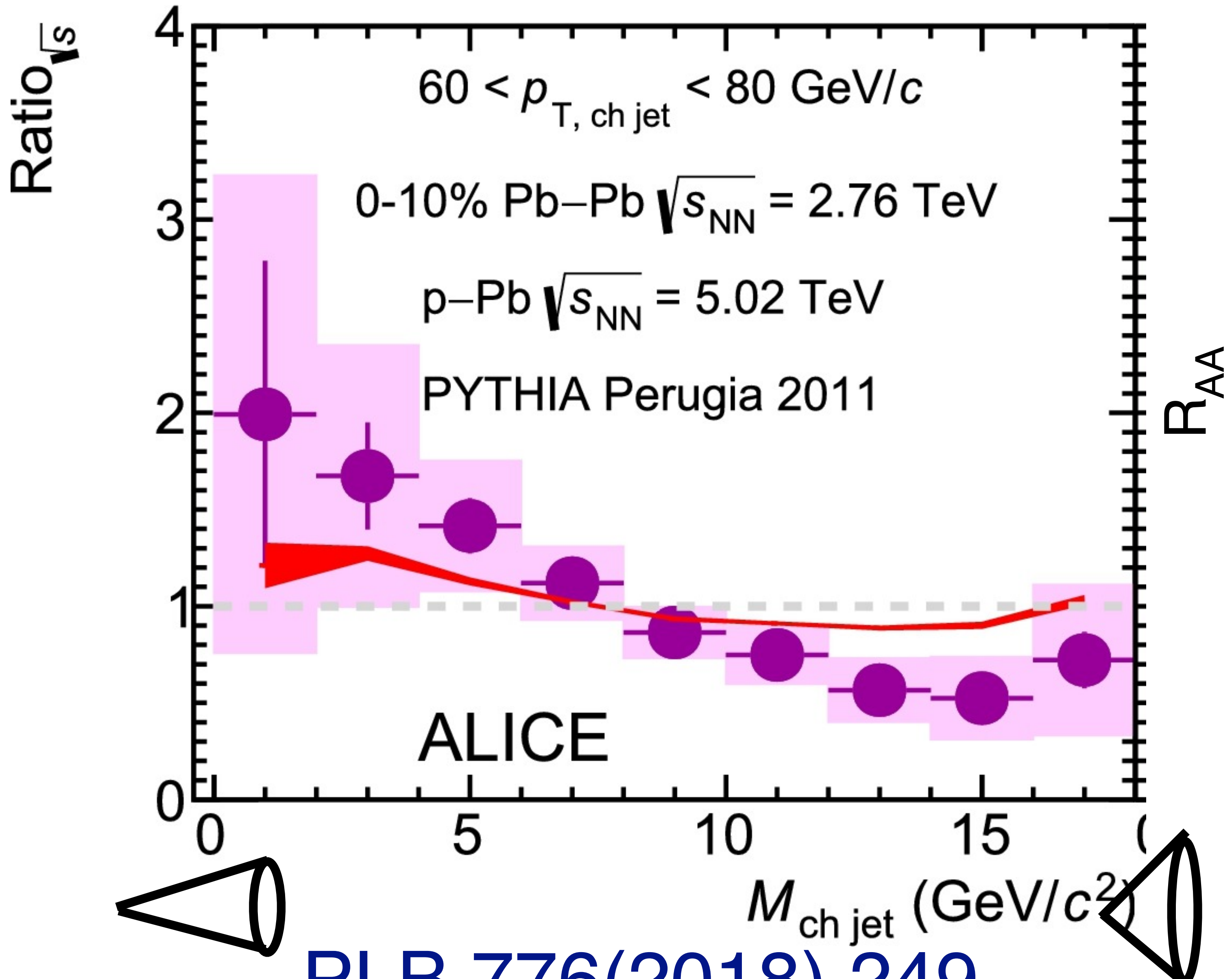
Jet substructure

- Many jet substructure measurements in HIs
- Ex: jet mass

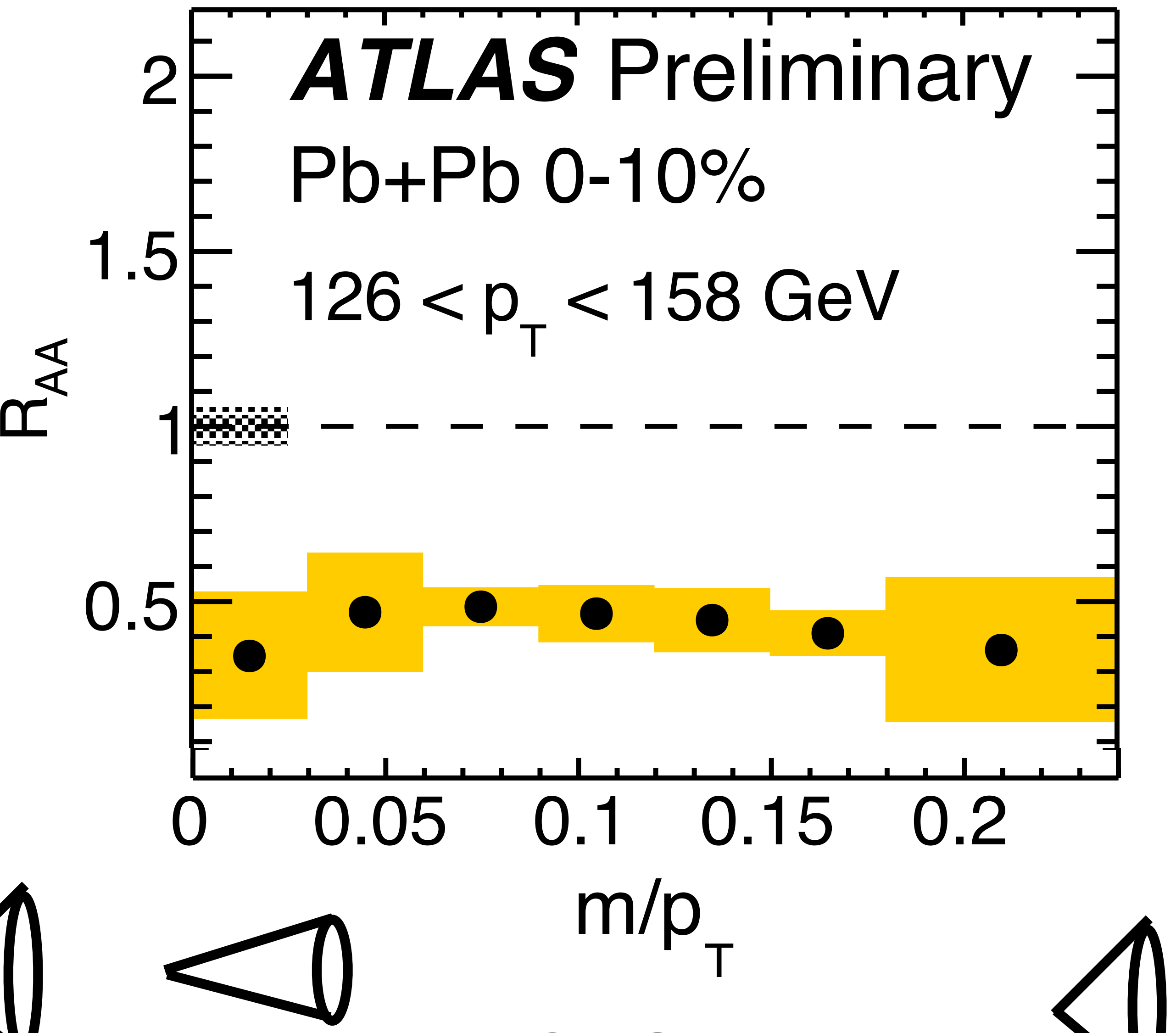
How wide are the jets?



- Insensitive to medium effects?
  - Possible cancellation of effects:
    - Softening and broadening of constituents
      - Inside cone->larger mass
      - Outside cone->smaller mass
    - Medium recoil->larger mass



PLB 776(2018) 249



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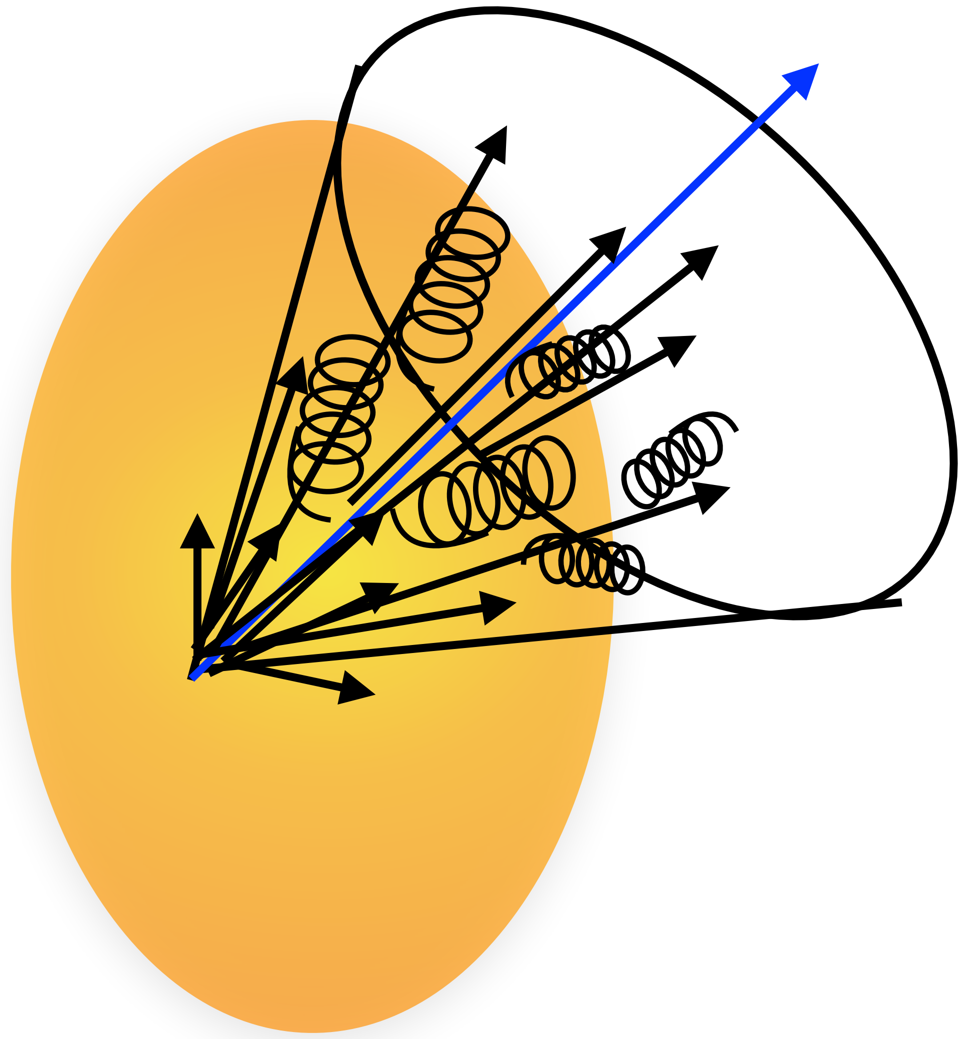
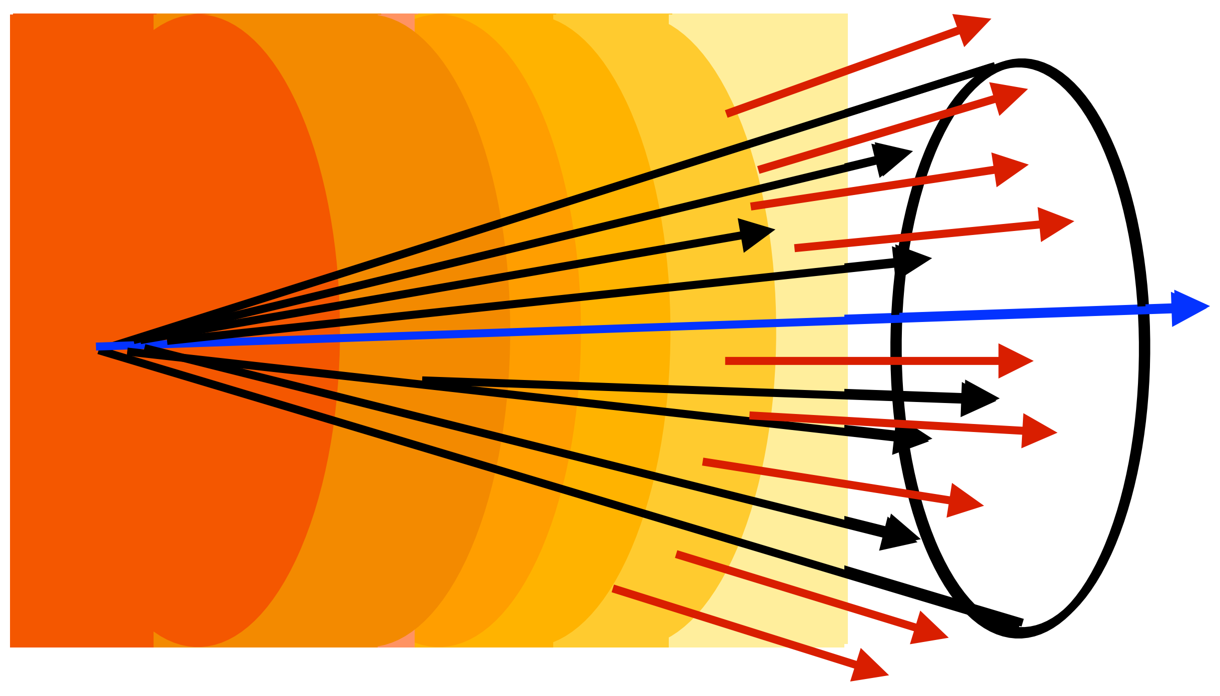
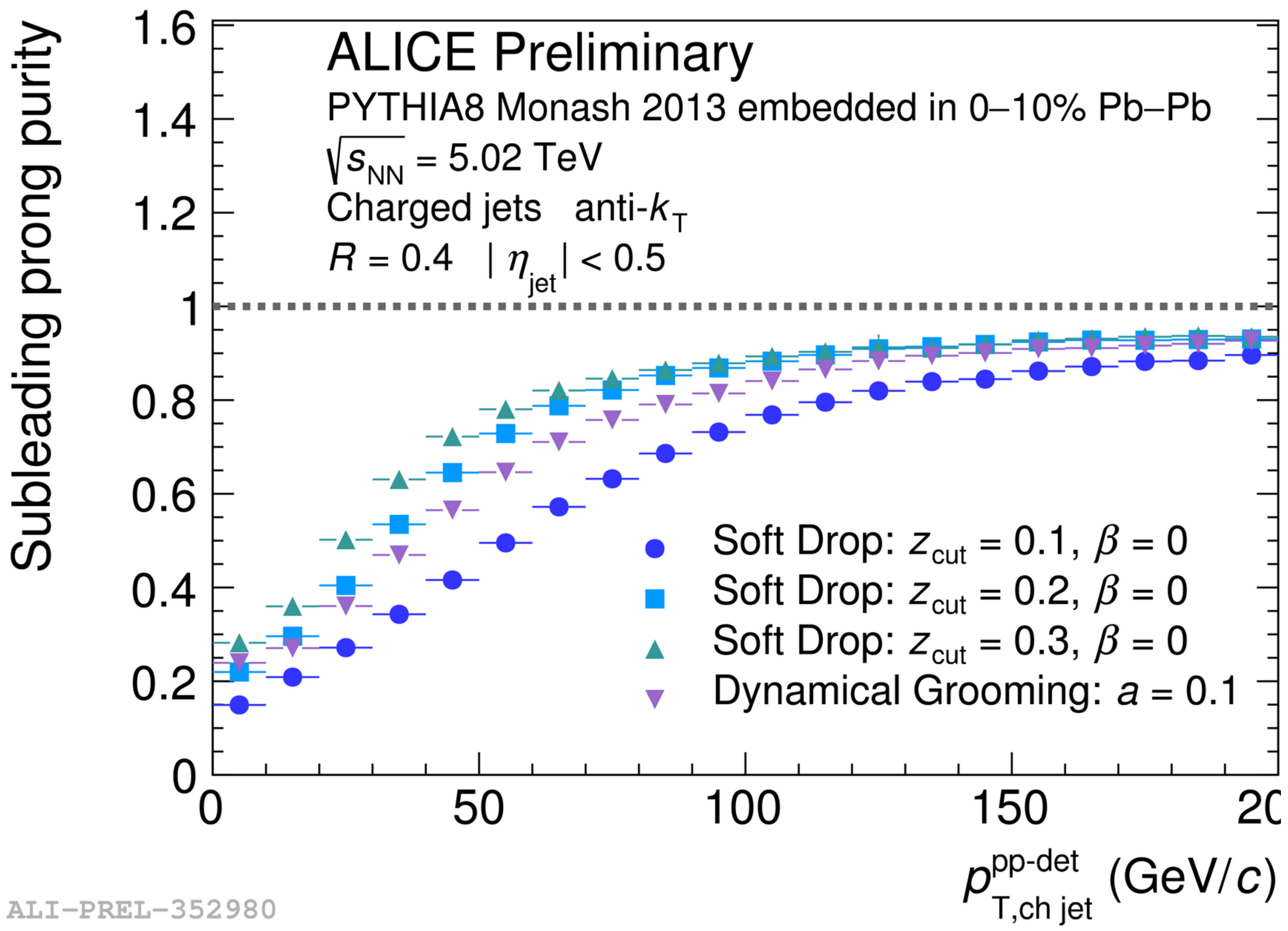
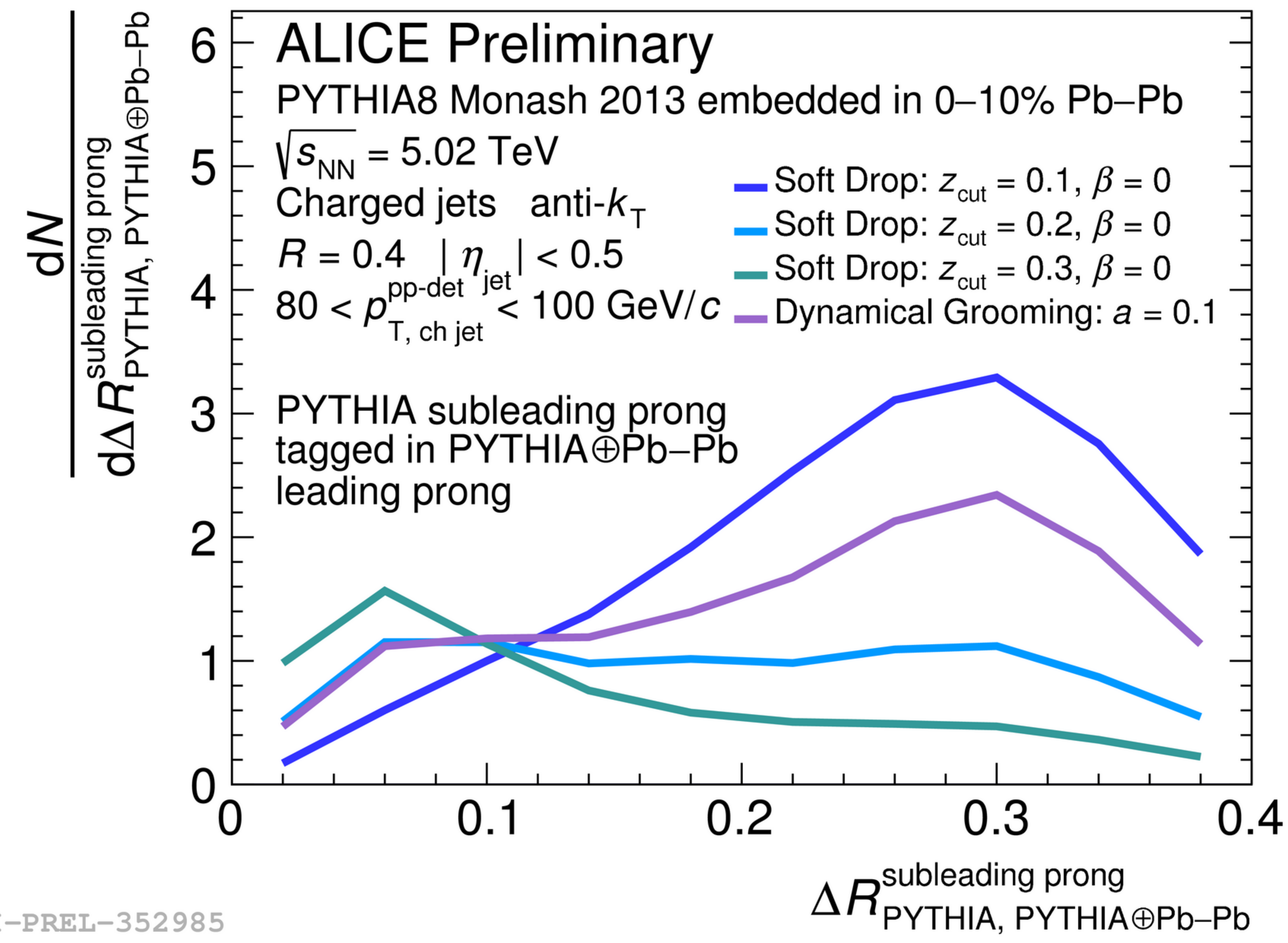




Background treatment

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

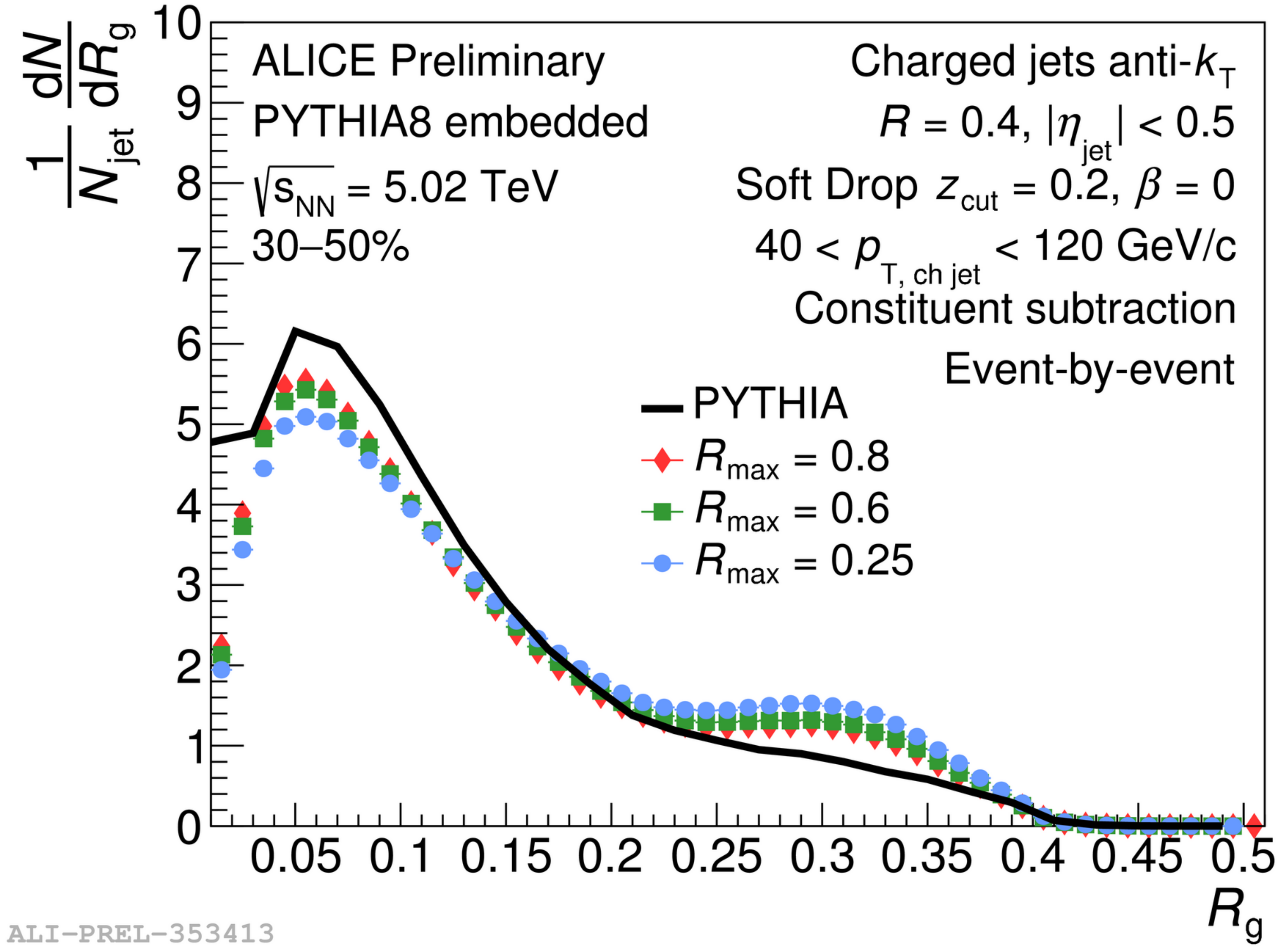


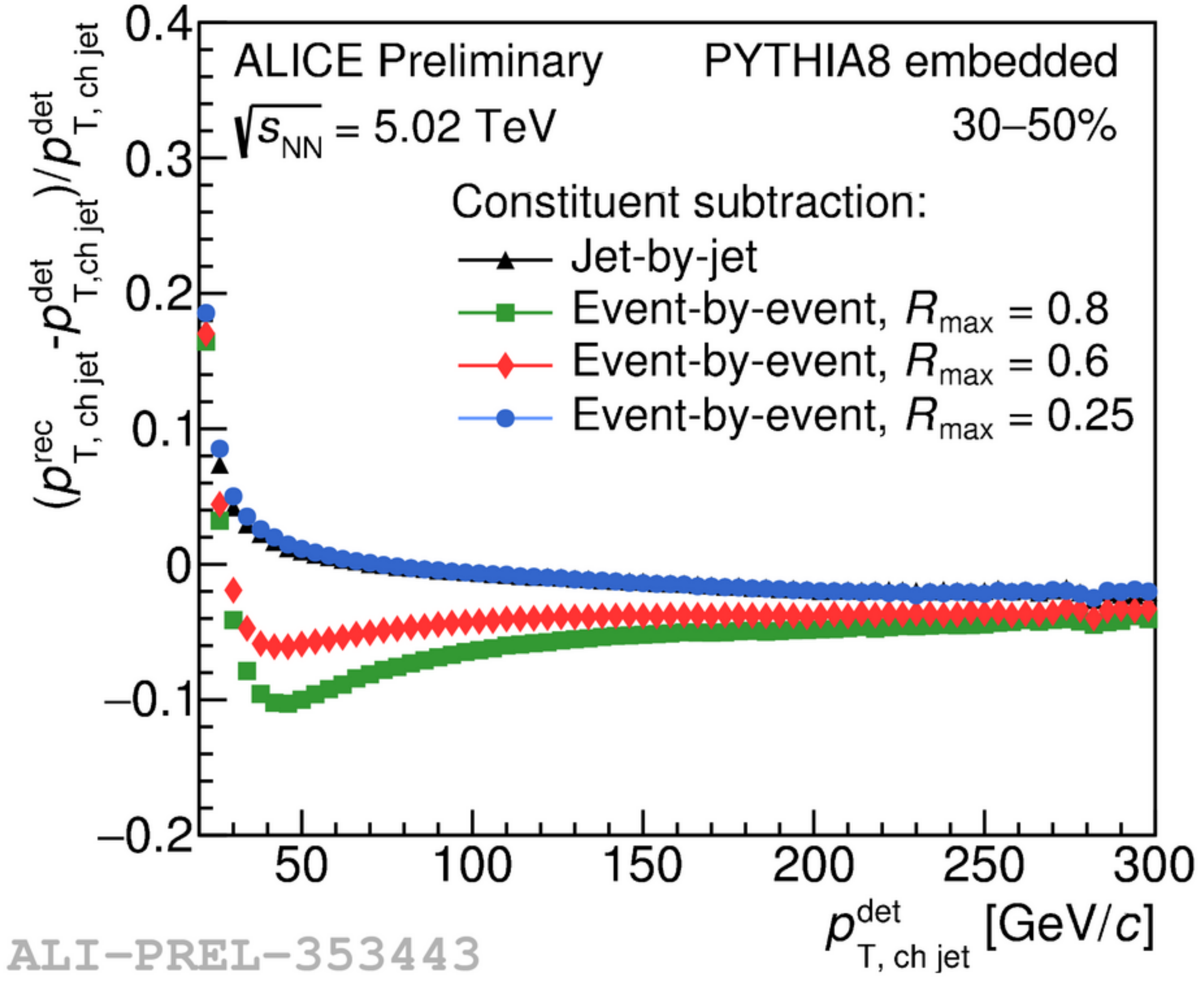


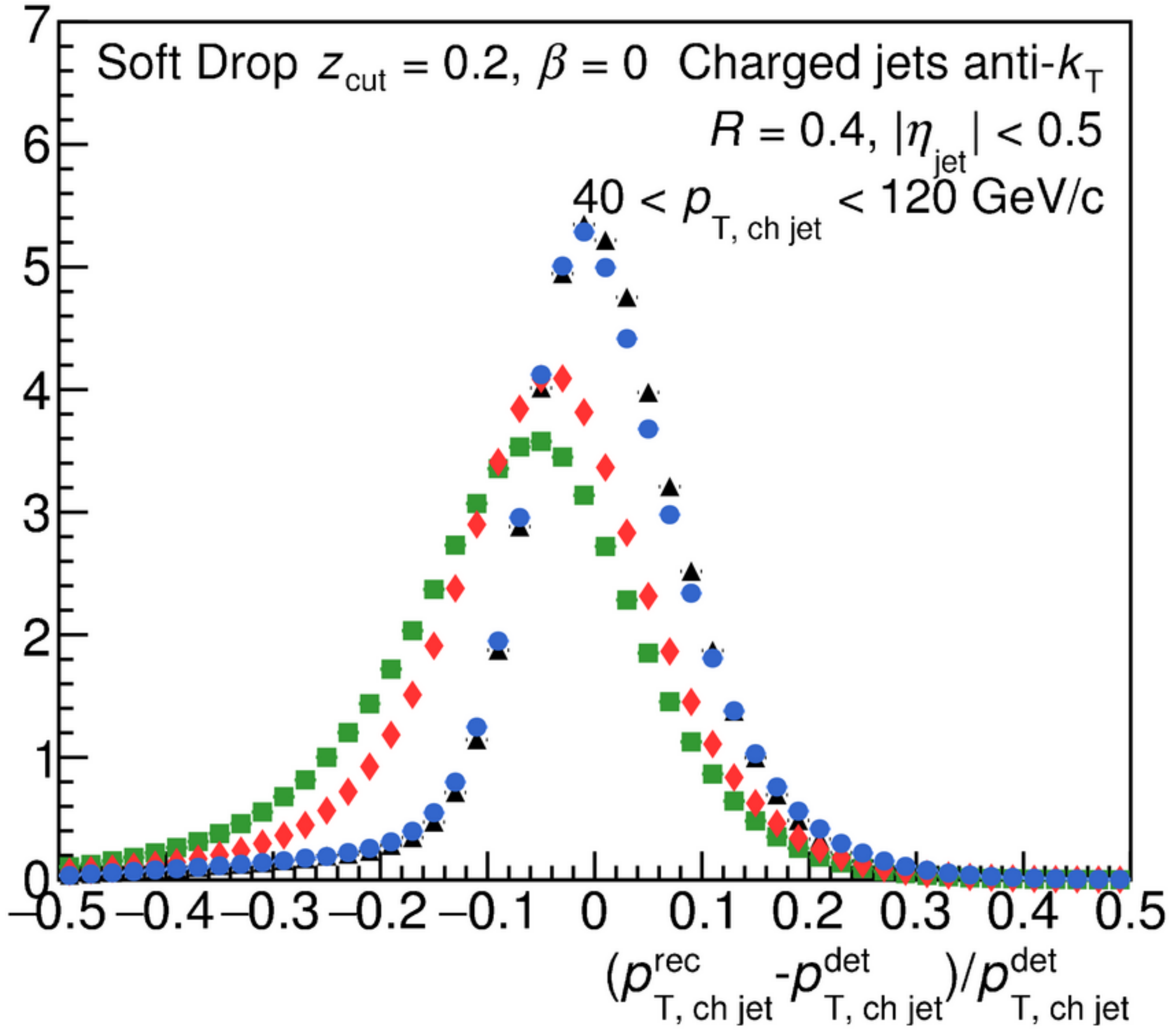
Event-by-event CS

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

JHEP 1908 (2019) 175

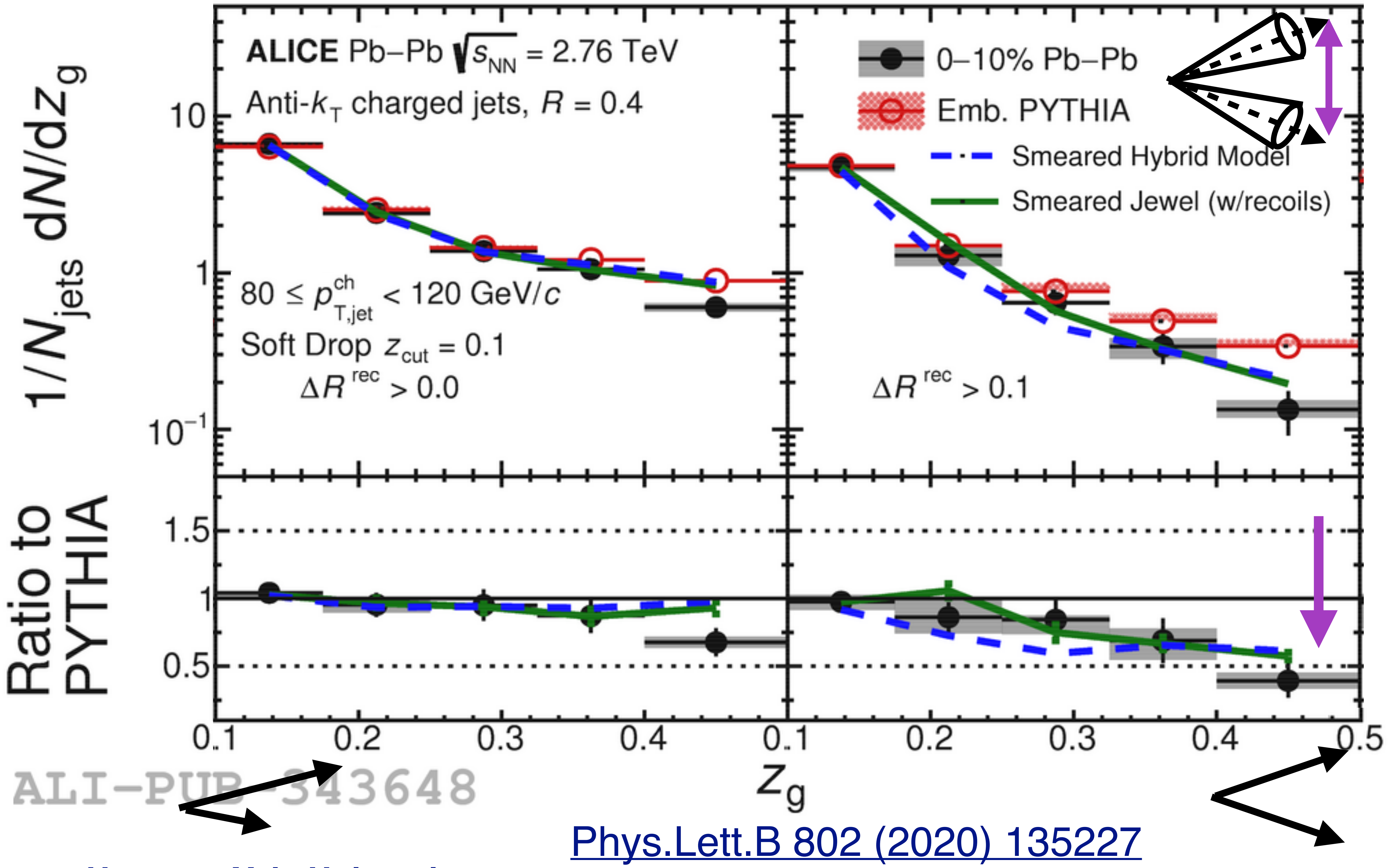




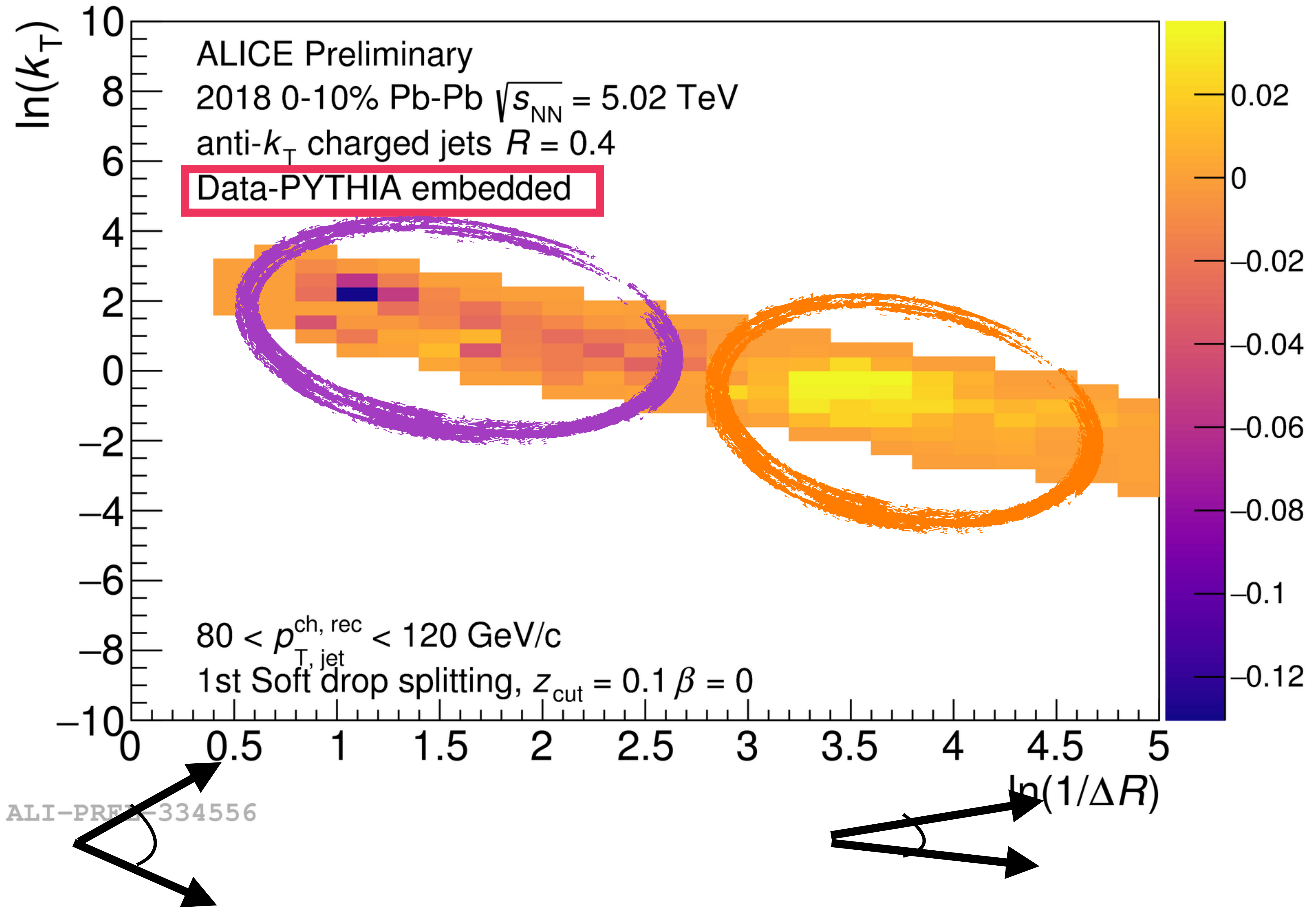


Groomed substructure: previous results

- Hint of suppression at large angles and enhancement at small angles
- Strong modification of symmetric splittings at larger angles

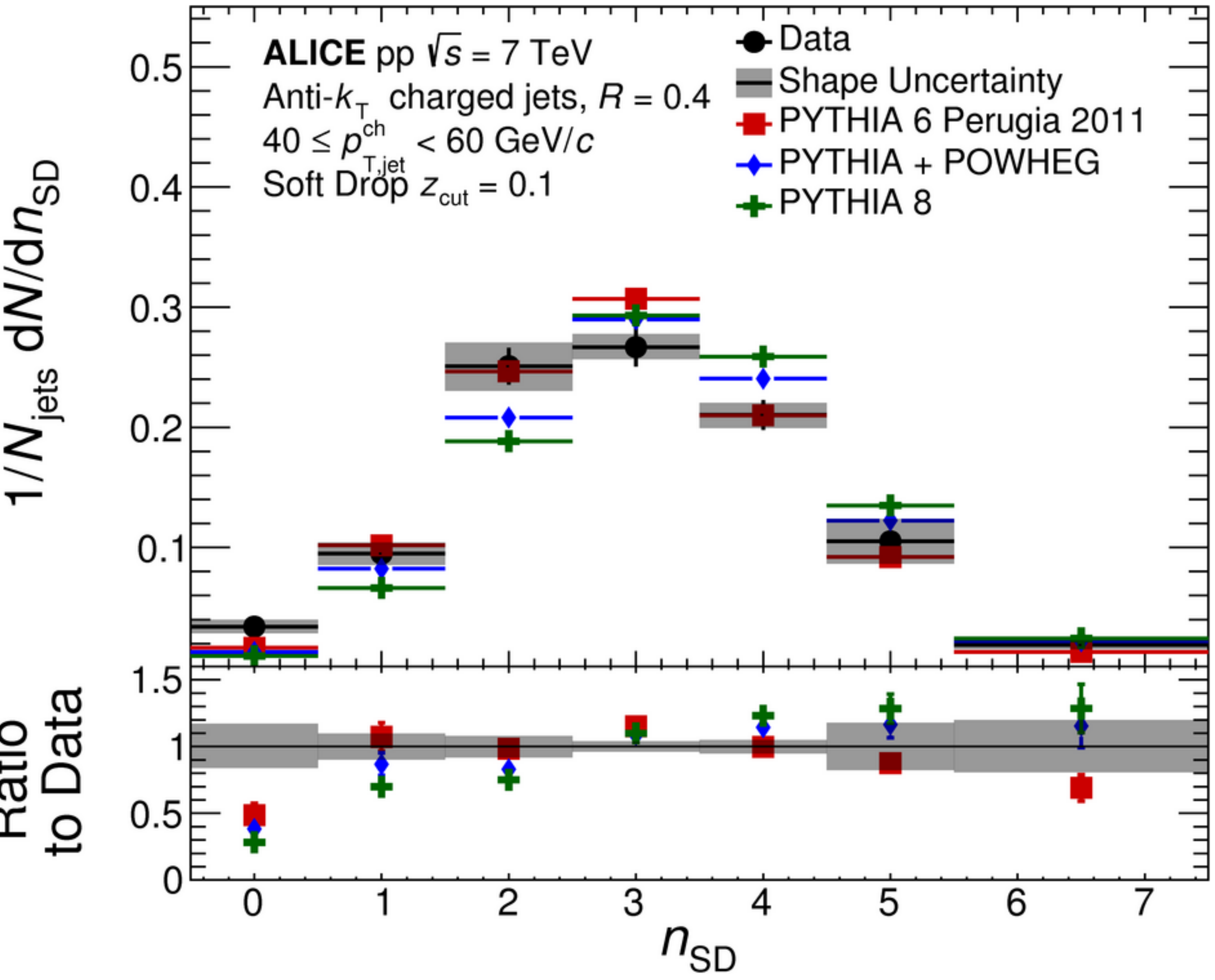


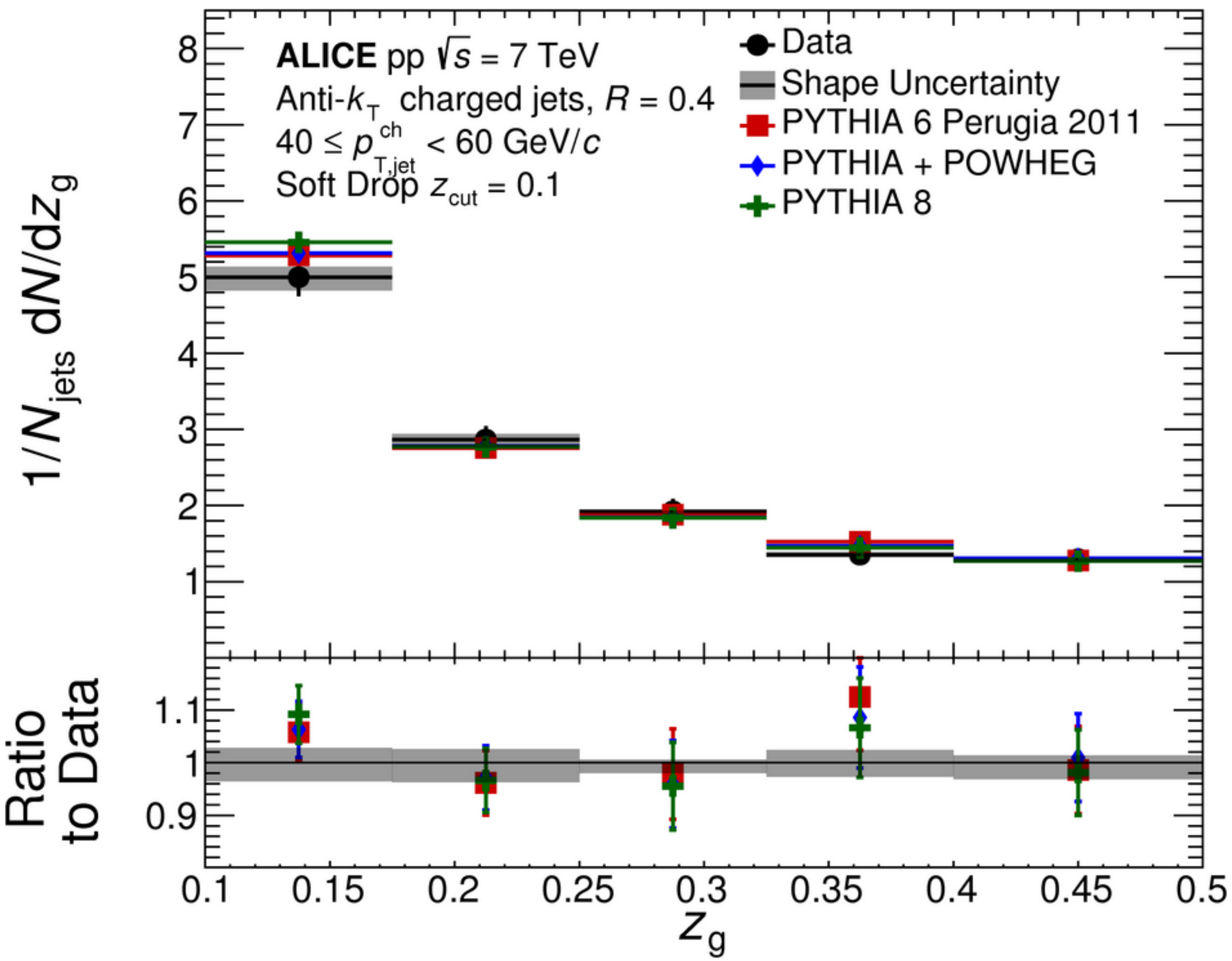
[Phys.Lett.B 802 (2020) 135227](#)



- Caveat: large fraction of background splittings so physics interpretation relies on the background being reproduced in embedding

z_g and n_{SD} in pp collisions at 7 TeV

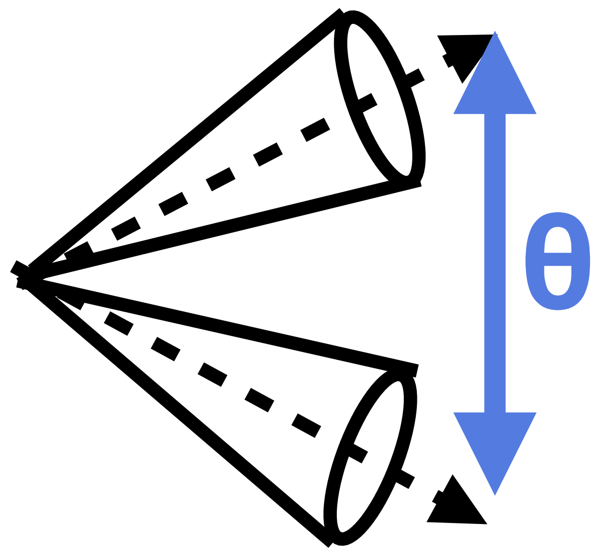




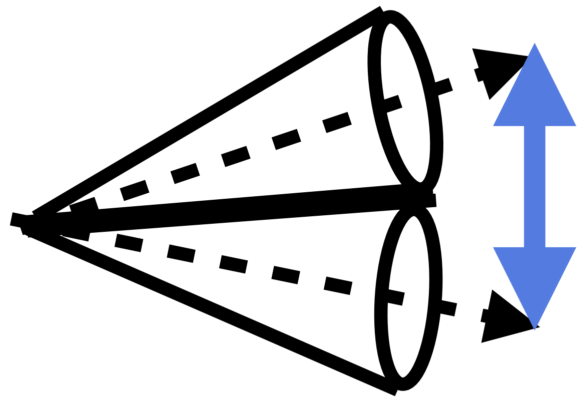
arXiv:1905.02512v1

θ_g: subjet separation

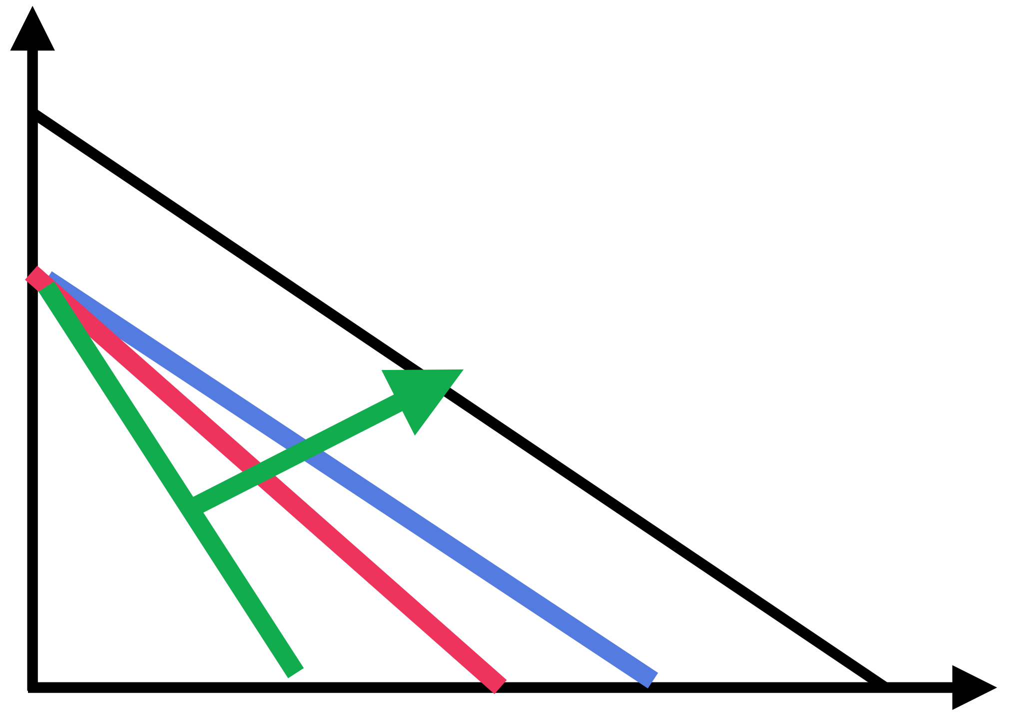
- pp collision data at 5.02 TeV L_{int} = 18.0 nb^{-1} unfolded for detector effects



vs.



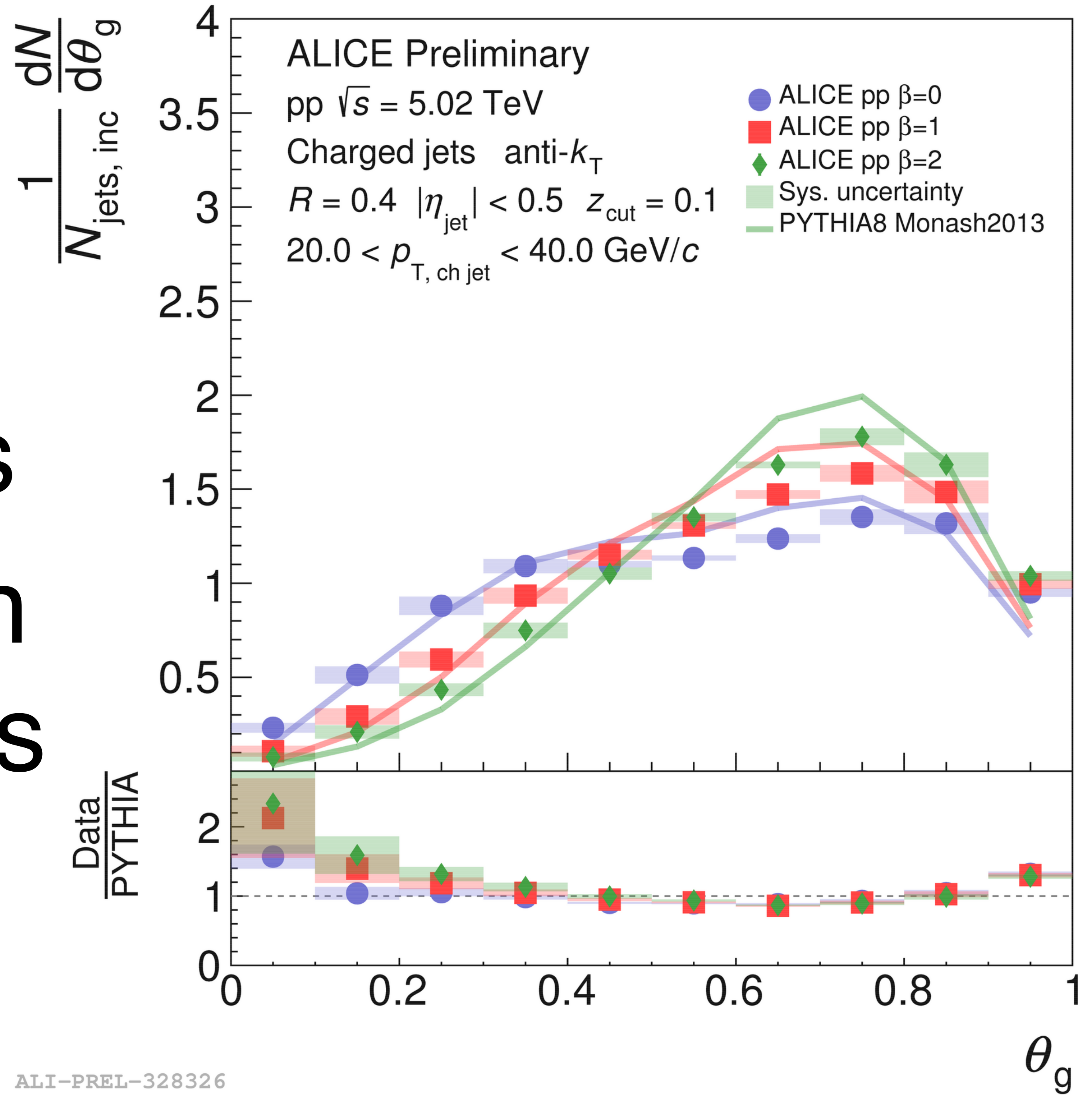
$z_g > z_{cut}\,\theta^{\beta}$

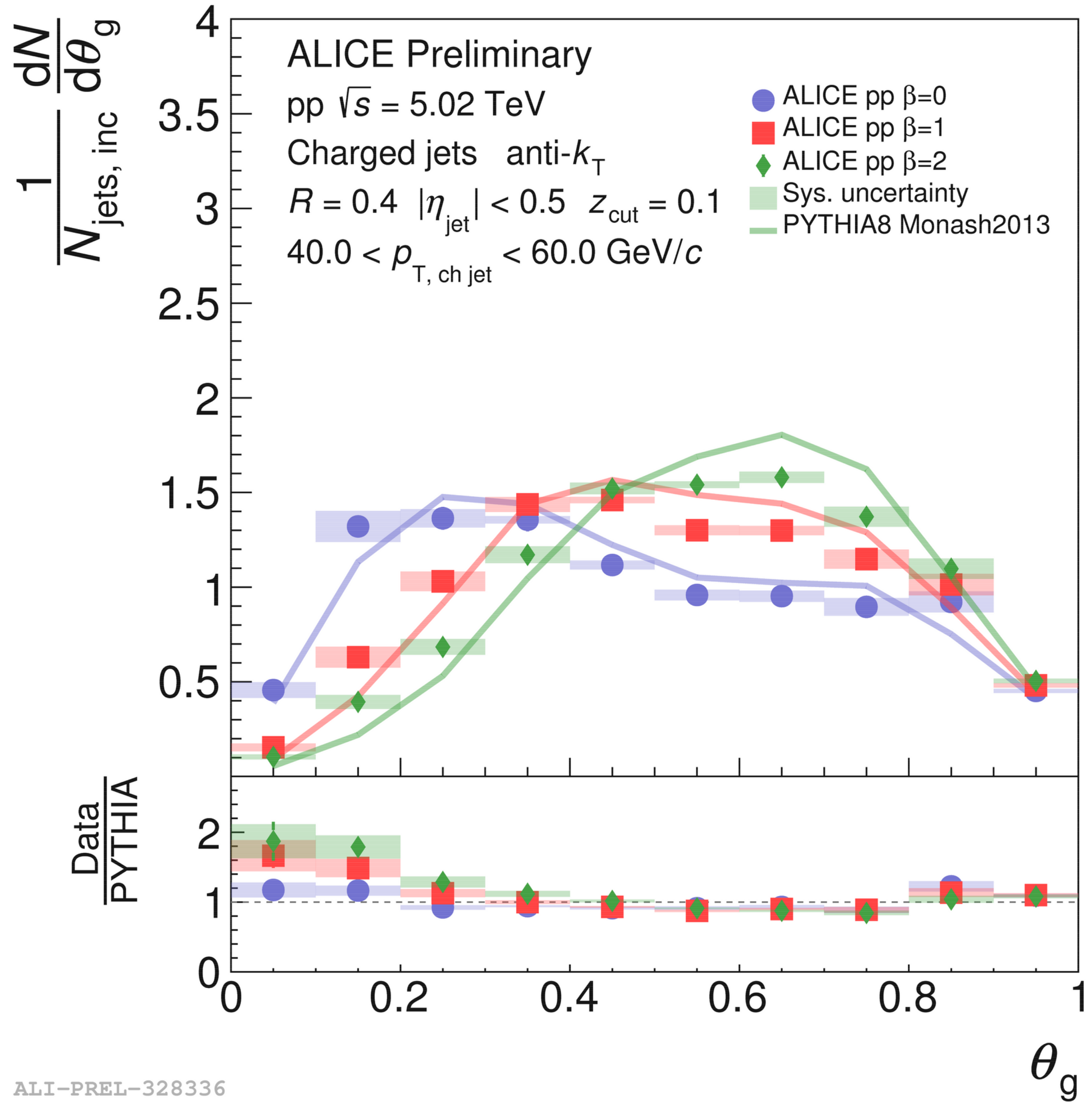


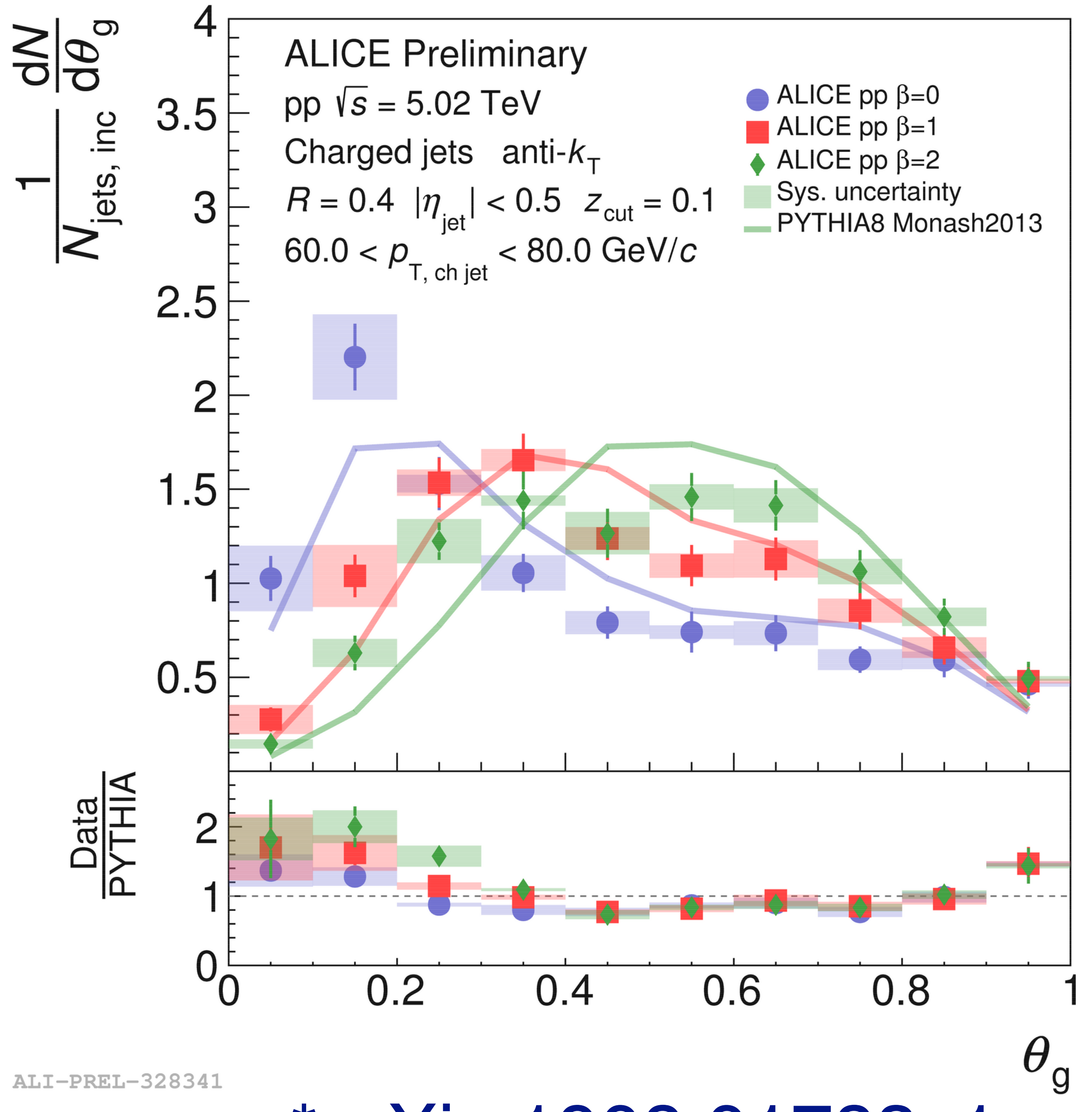
$$\theta_g = \frac{R_g}{R} = \frac{\sqrt{\Delta\eta^2 + \Delta\phi^2}}{R}$$

- Dependence on grooming (β) measured:
  - *Useful to constrain pQCD calculations and non-perturbative effects**

- Increasing β increases contribution of wider jets







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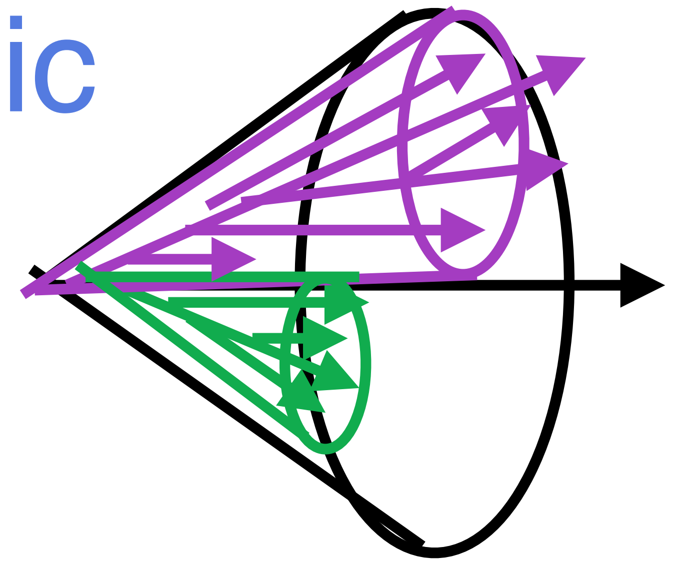
*arXiv:1908.01783v1

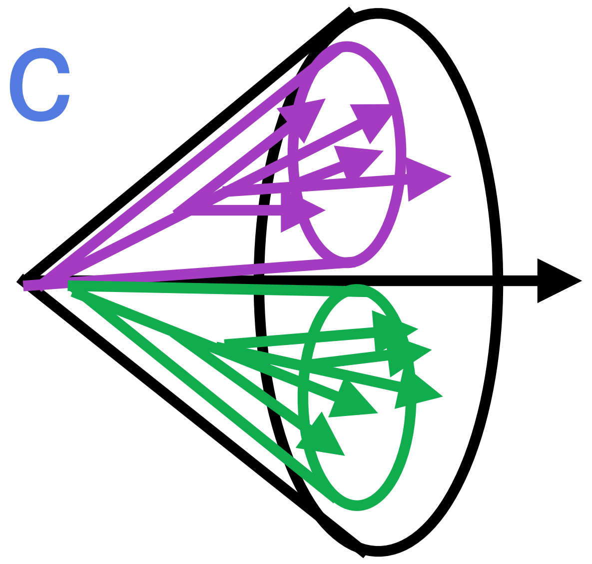
z_g: jet splitting

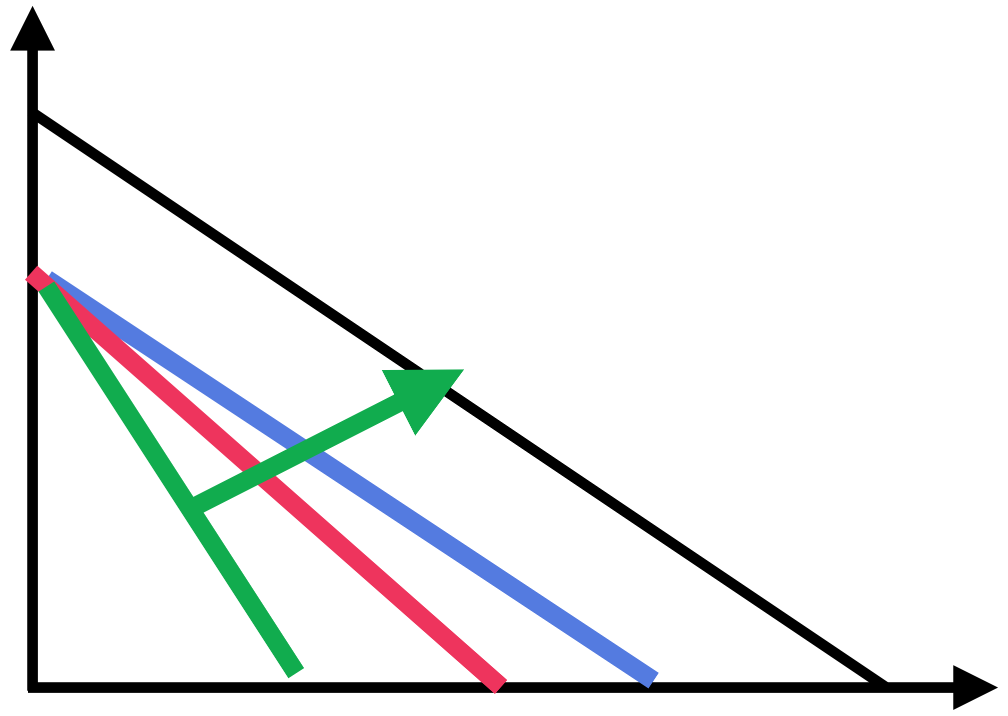
$$z_g = \frac{\min(p_{Ti}, p_{Tj})}{p_{Ti} + p_{Tj}}$$

asymmetric splitting: low z_g

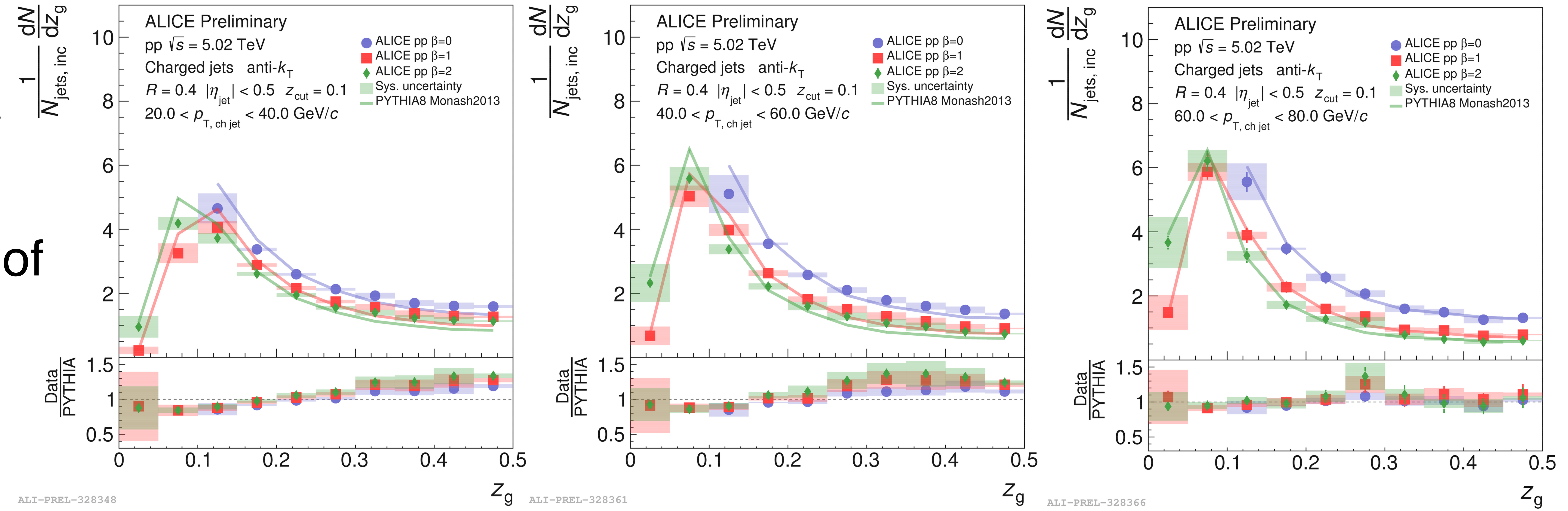


symmetric splitting: high z_g





- Increasing β increases contribution of asymmetric jets



- Both θ_g and z_g mostly consistent with PYTHIA8
- Serve as baseline for future unfolded Pb-Pb measurements

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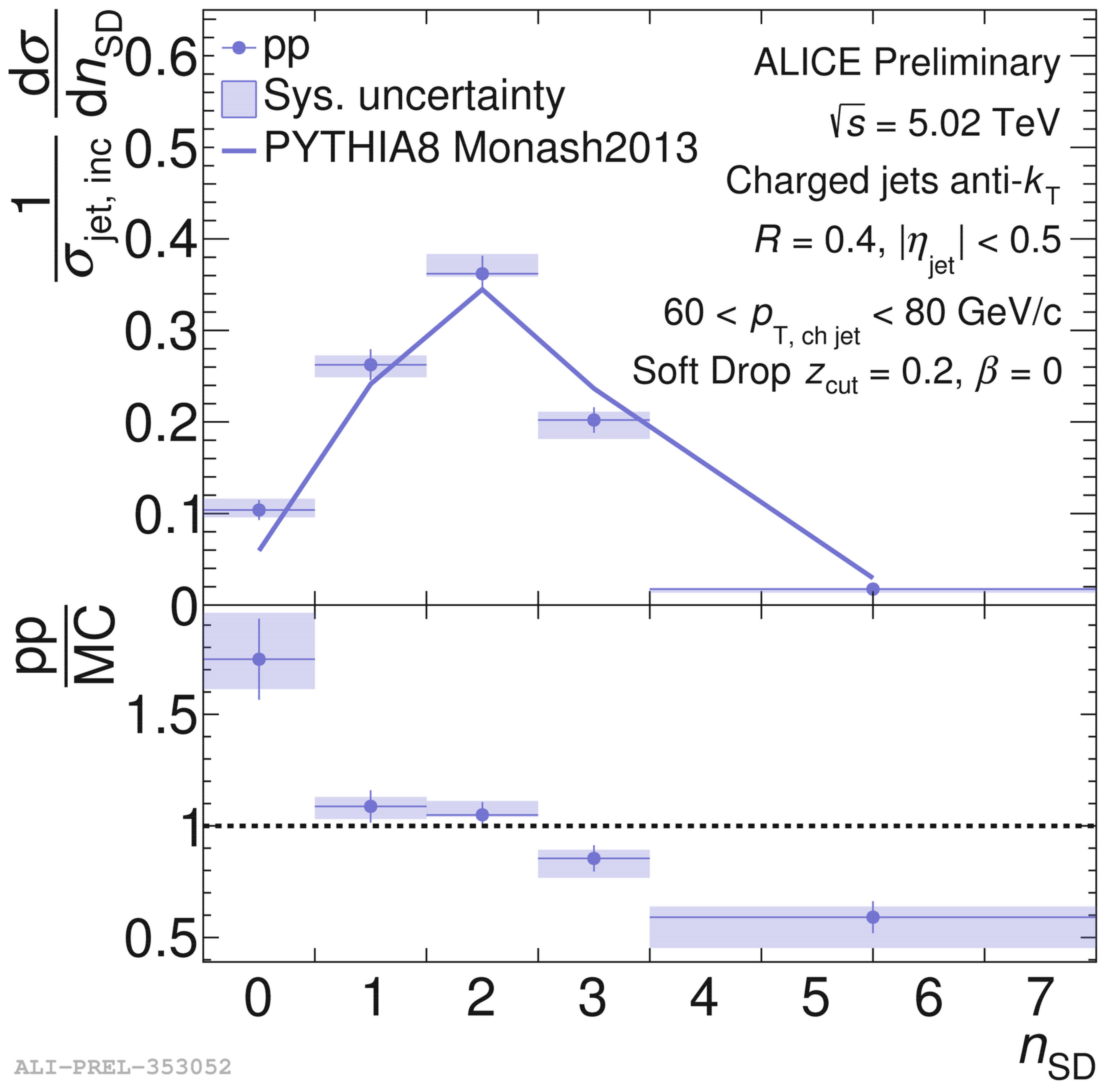
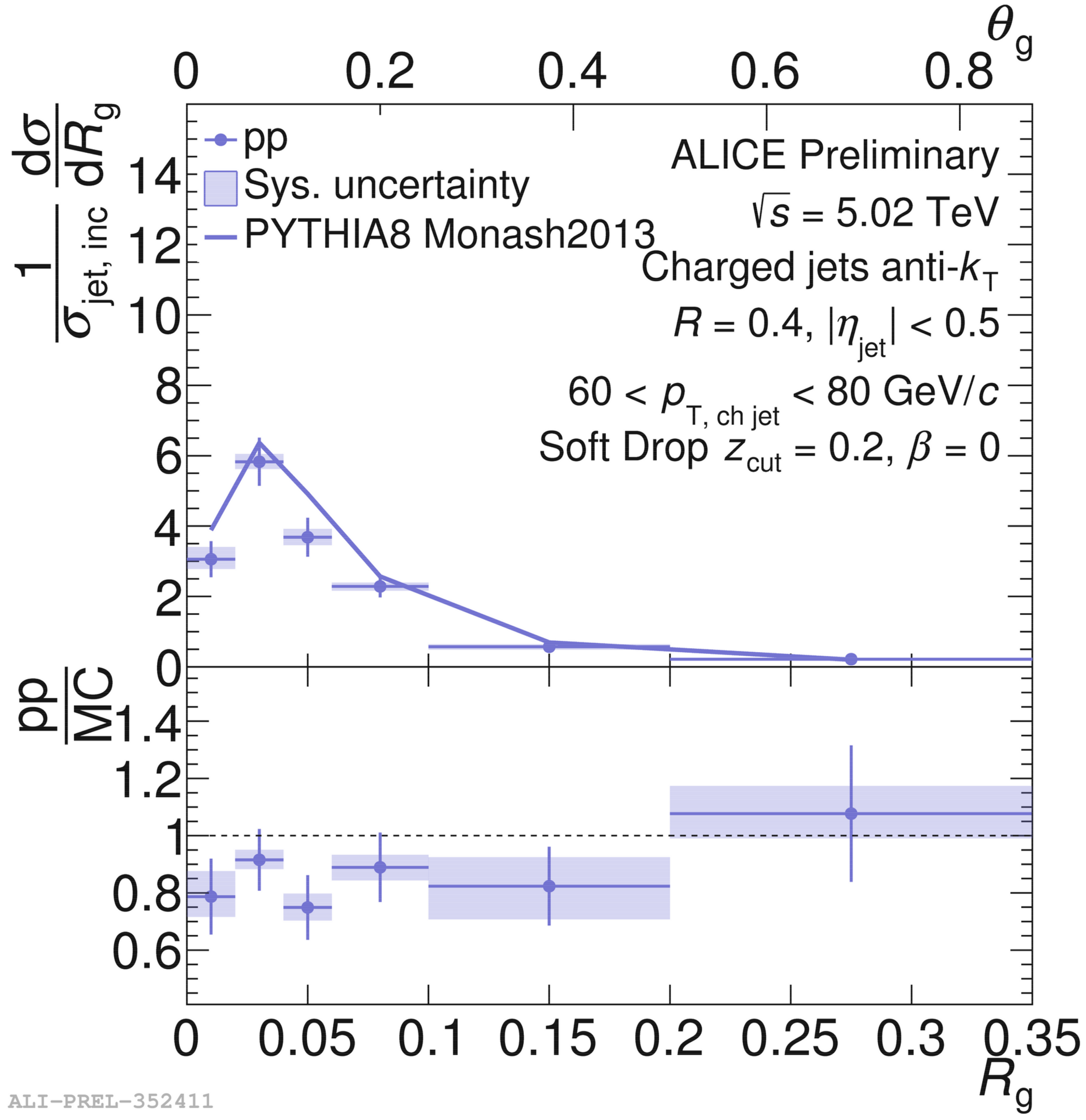
Pythia to pp comparisons at 5.02 TeV





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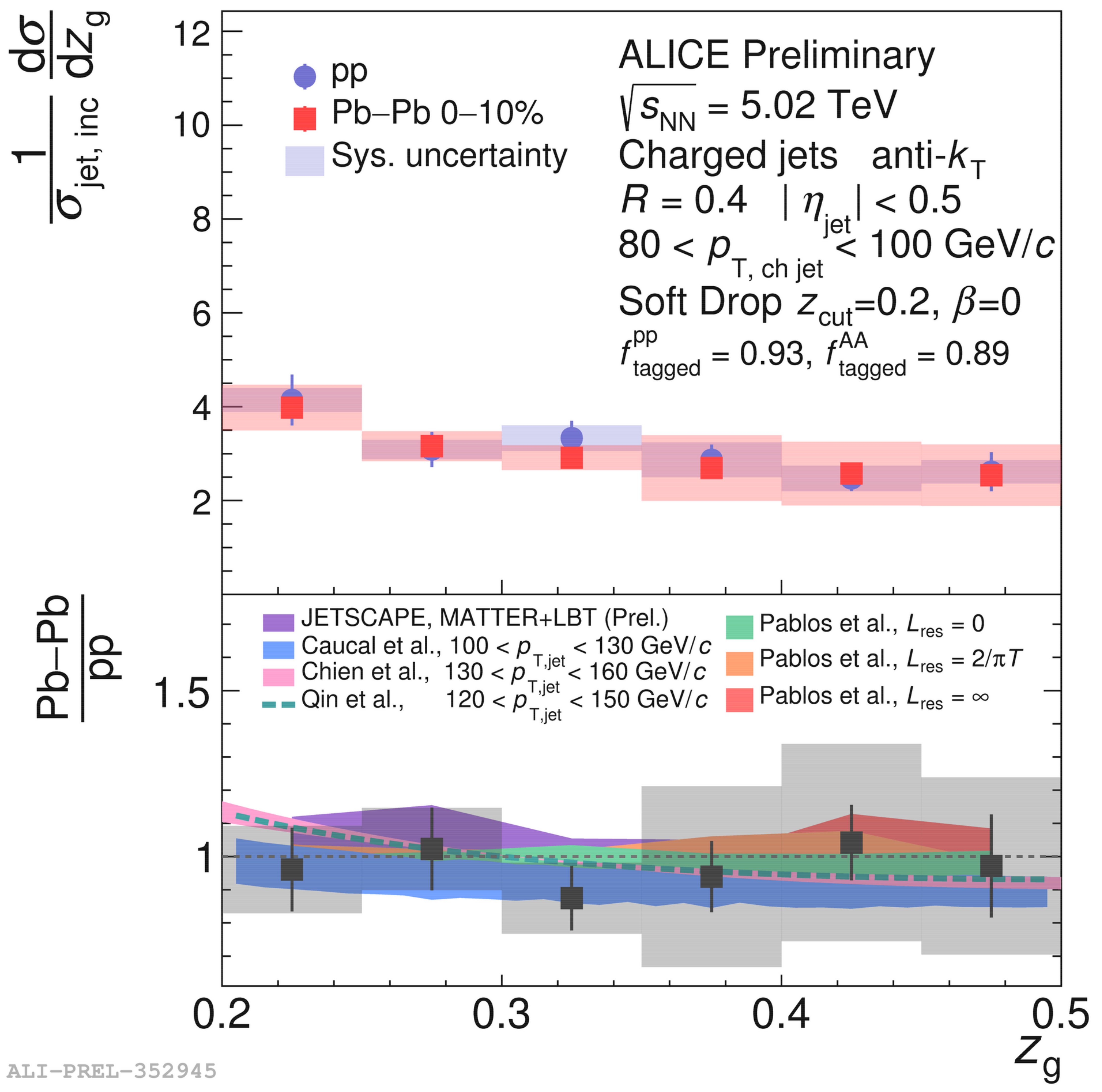
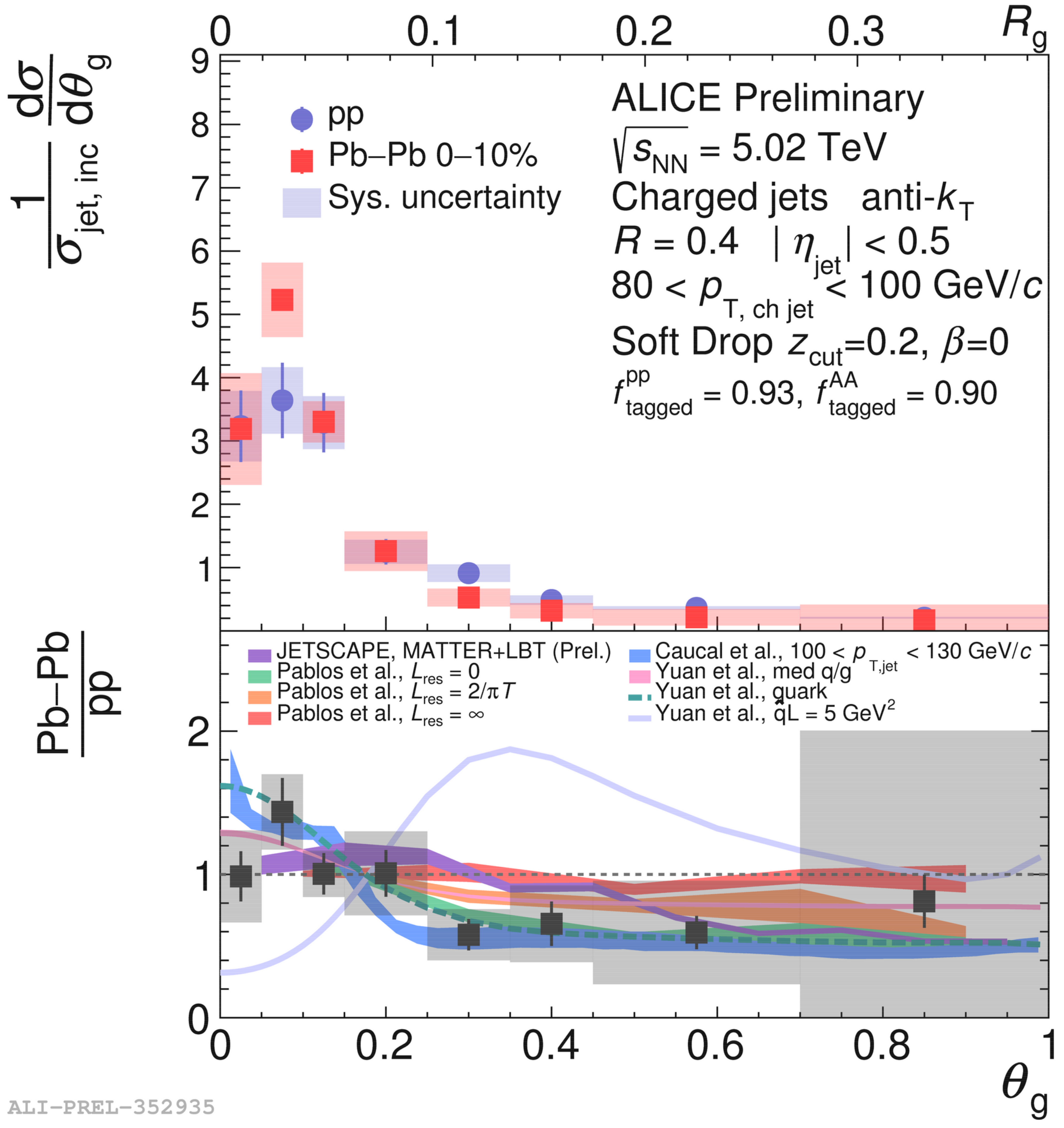
z_g and R_g in Pb-Pb collisions R=0.4





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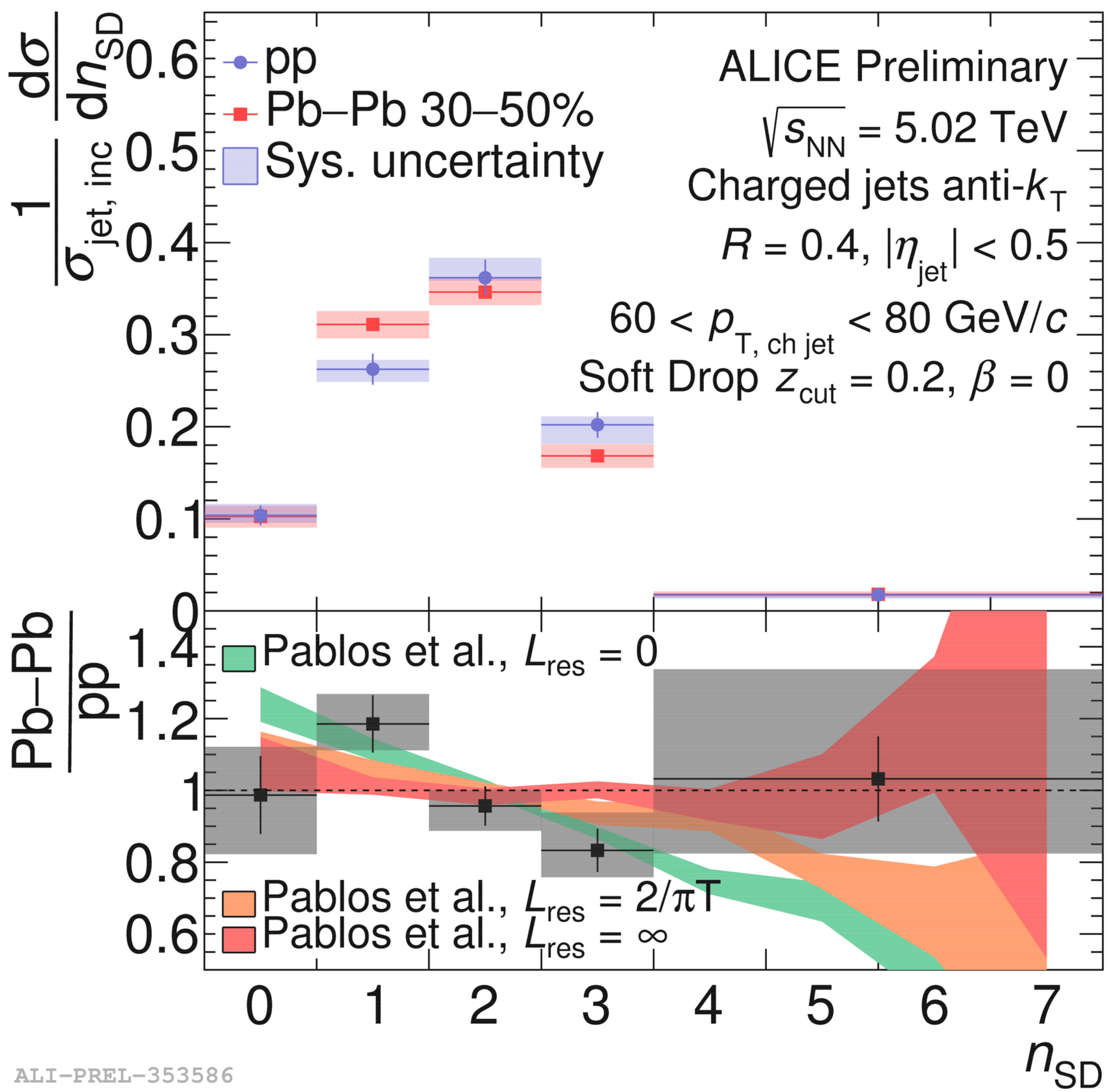
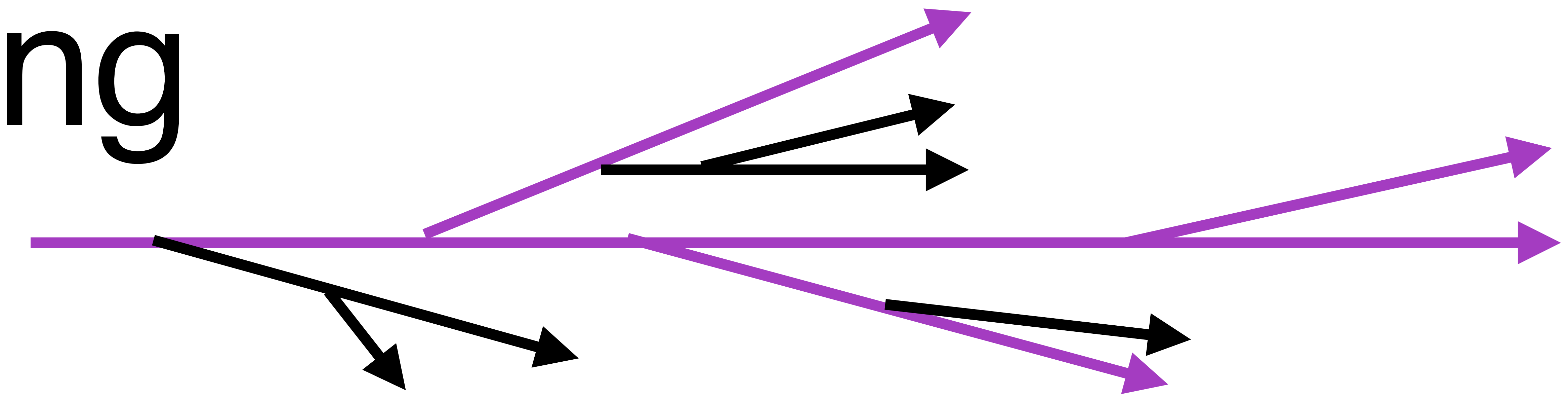
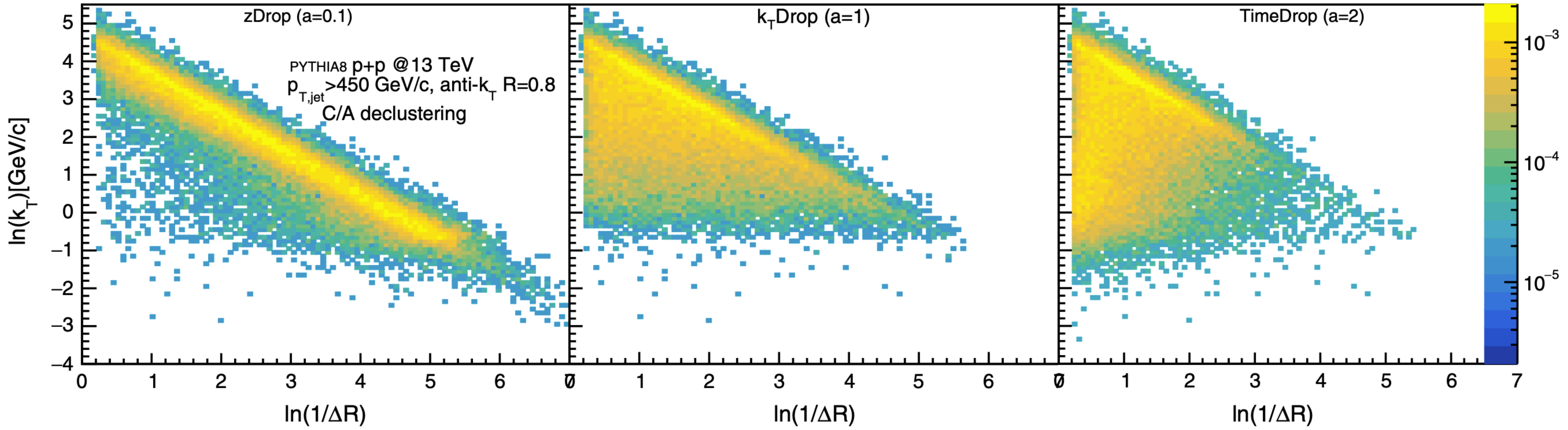
n_{SD}: iterative declustering

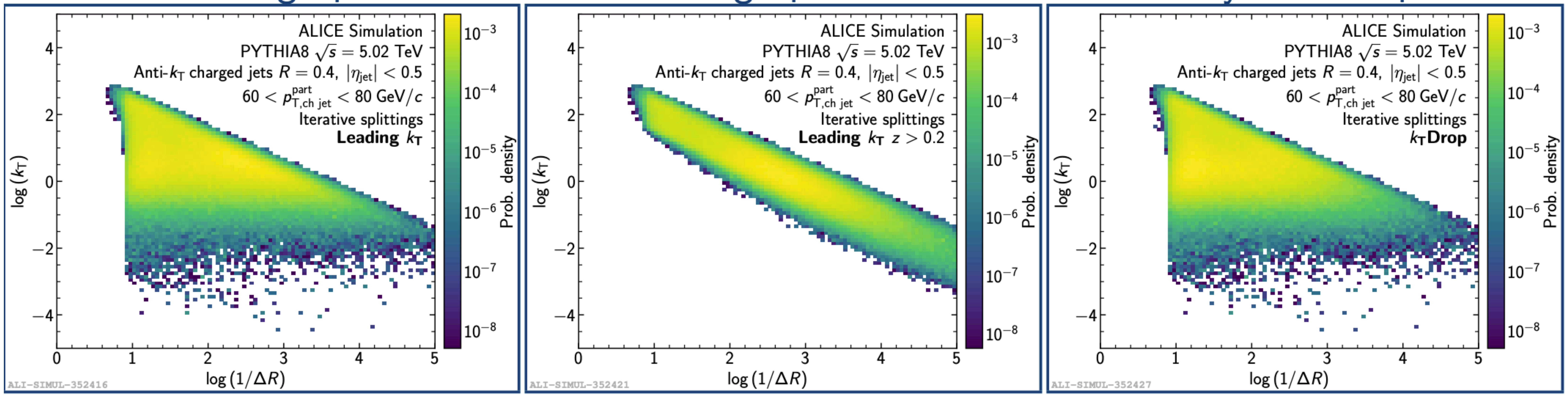




Back-up: grooming methods



Leading k_T | Leading k_T $z > 0.2$ | Dynamical k_T



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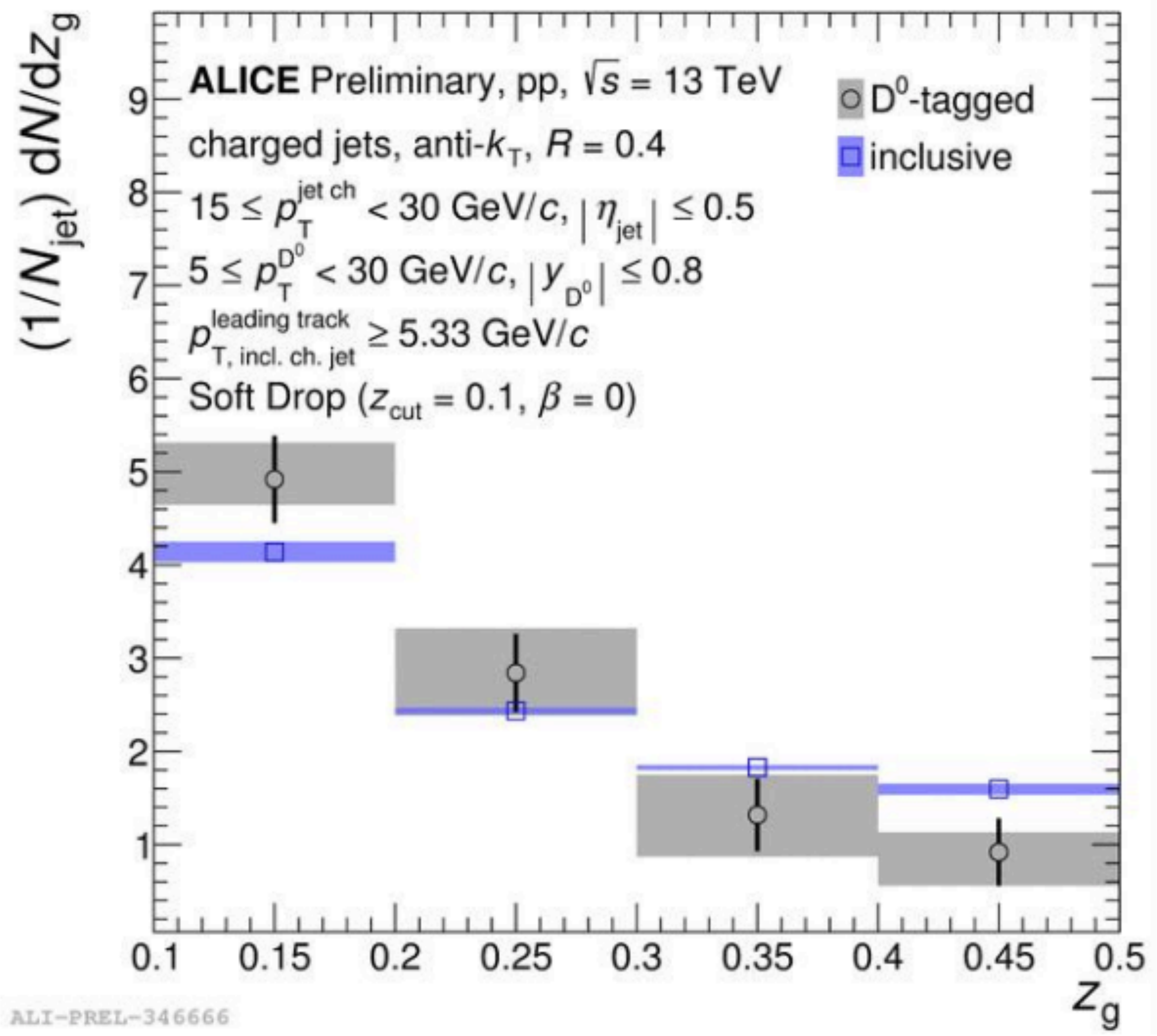
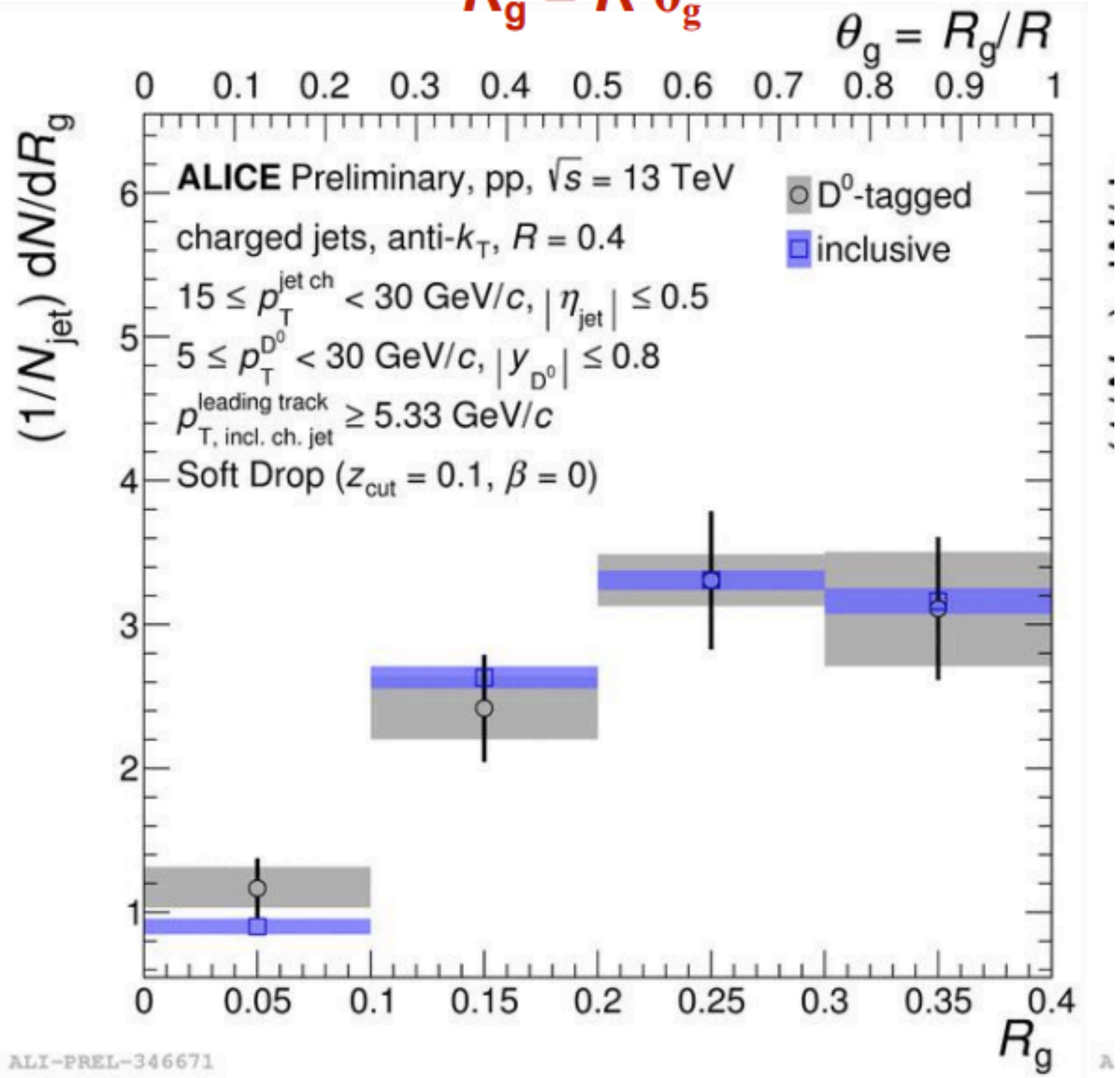
Back-up: HP substructure

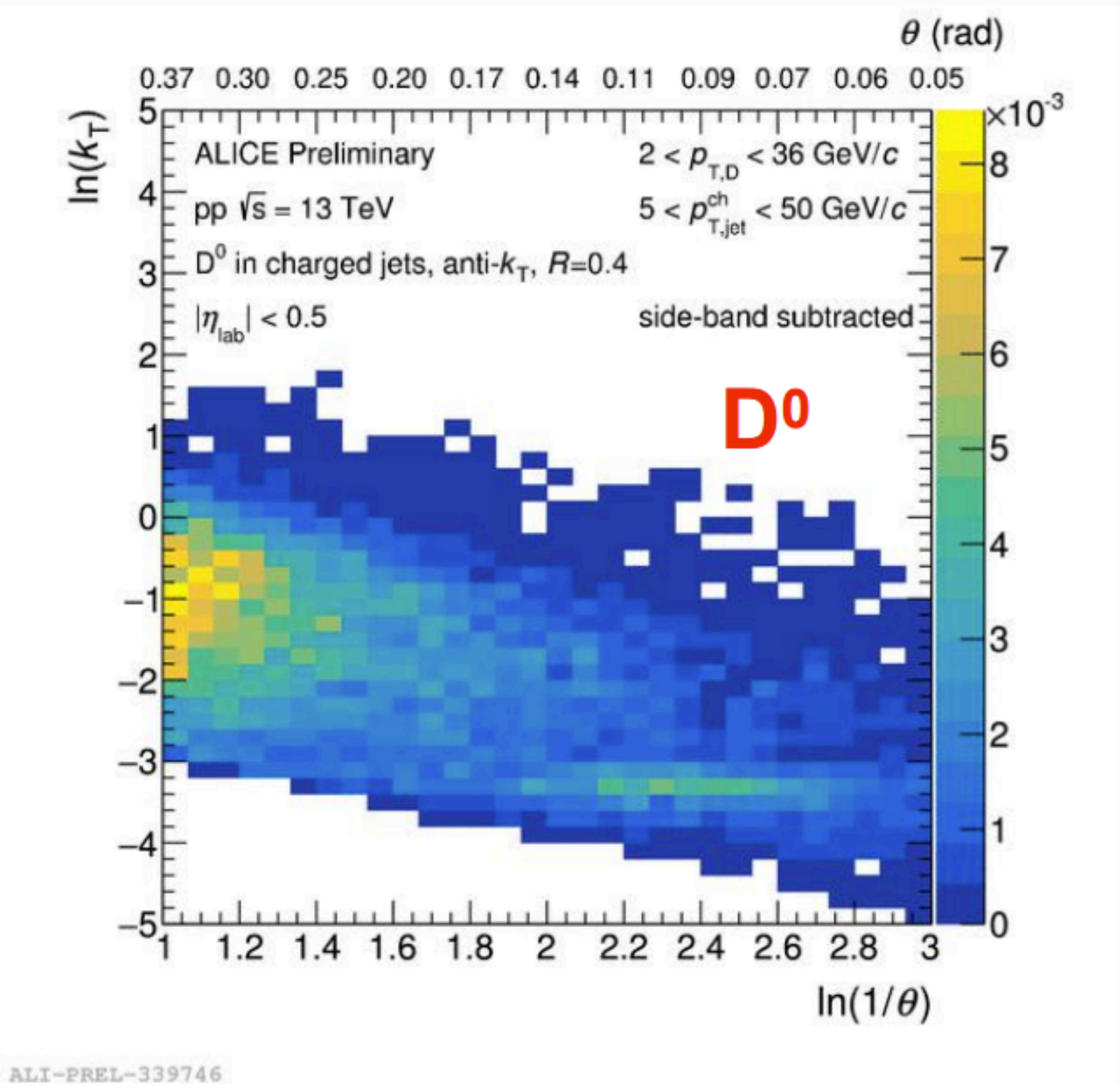
z_g

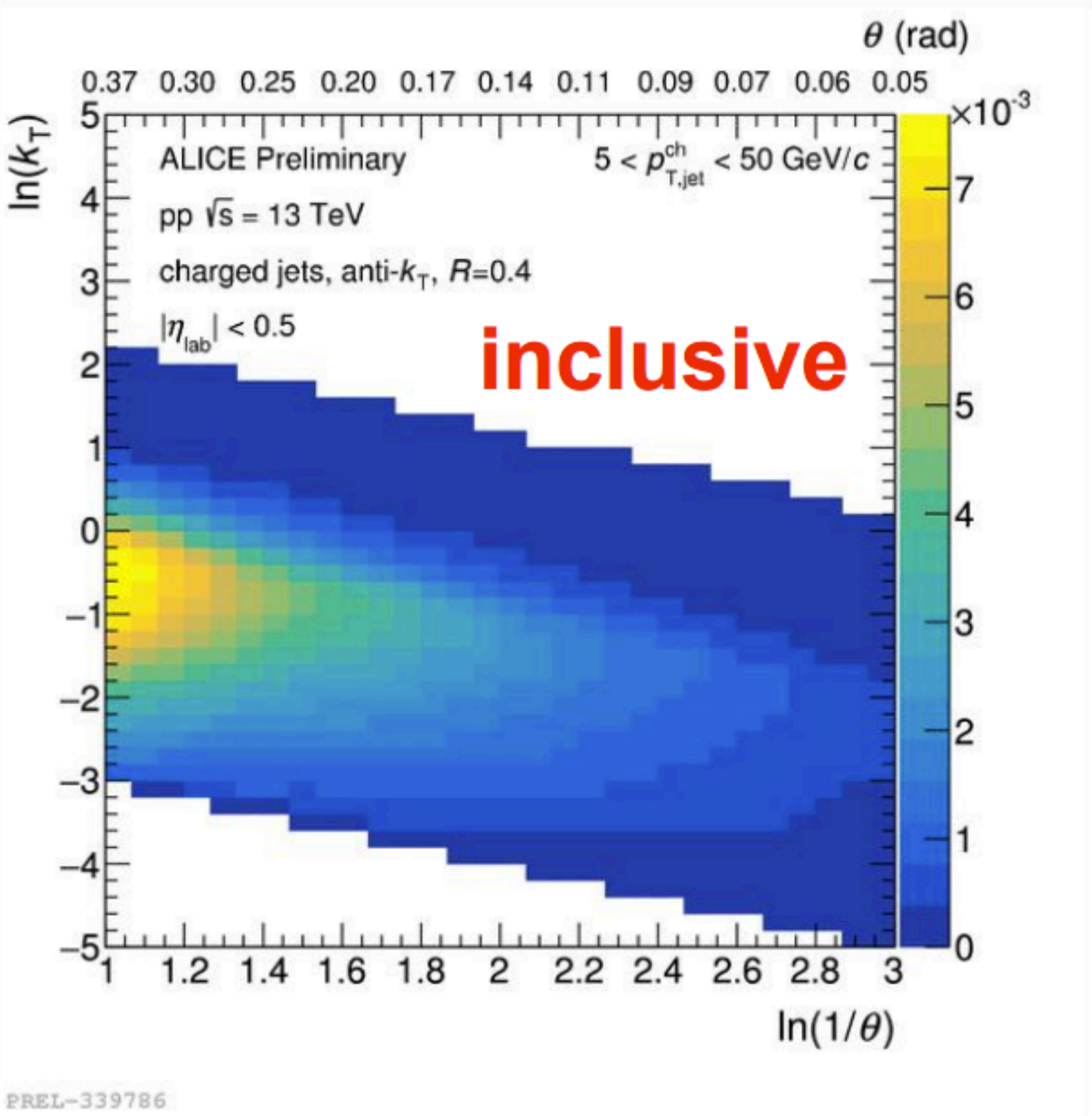


$R_g = R\ \theta_g$

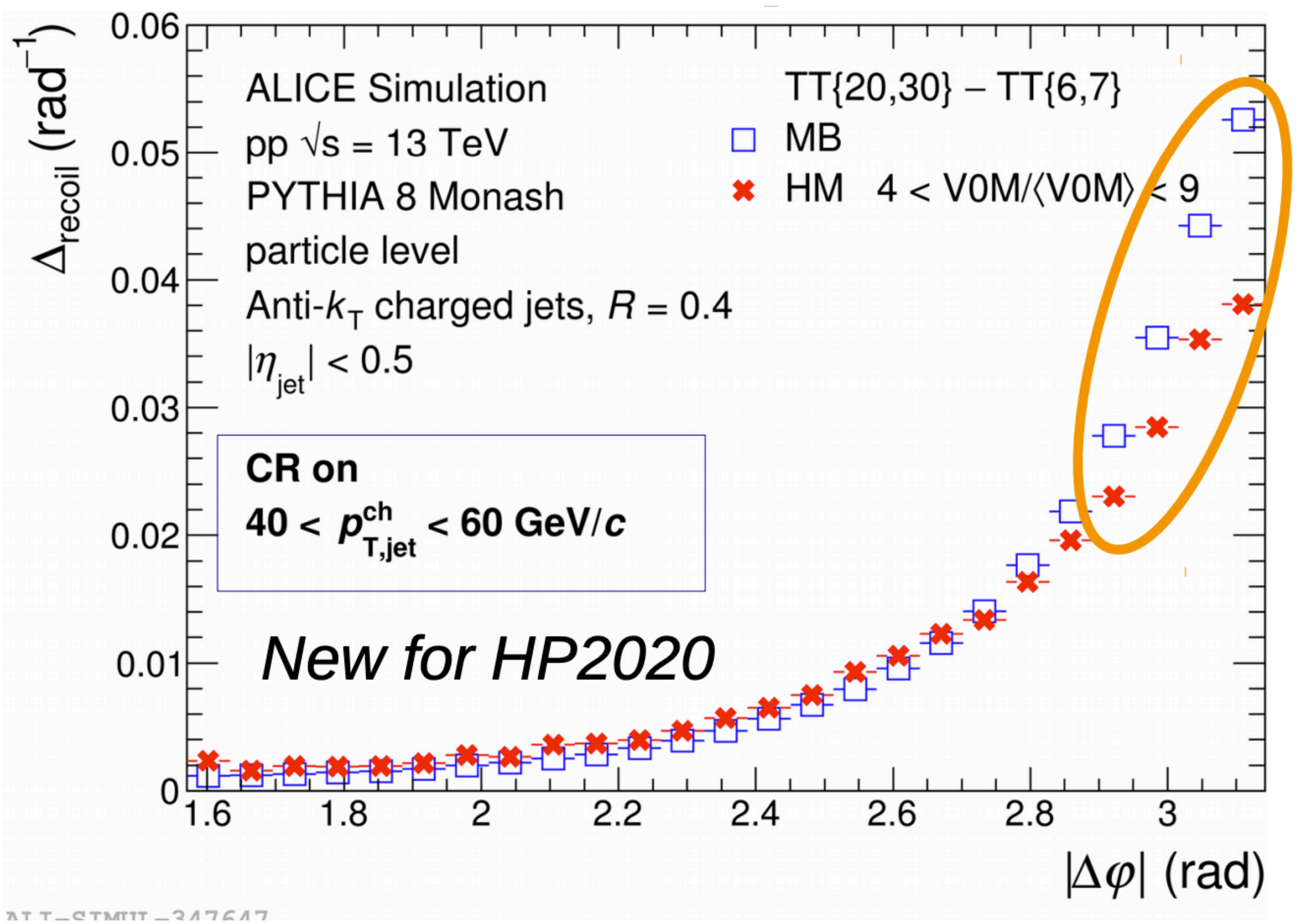


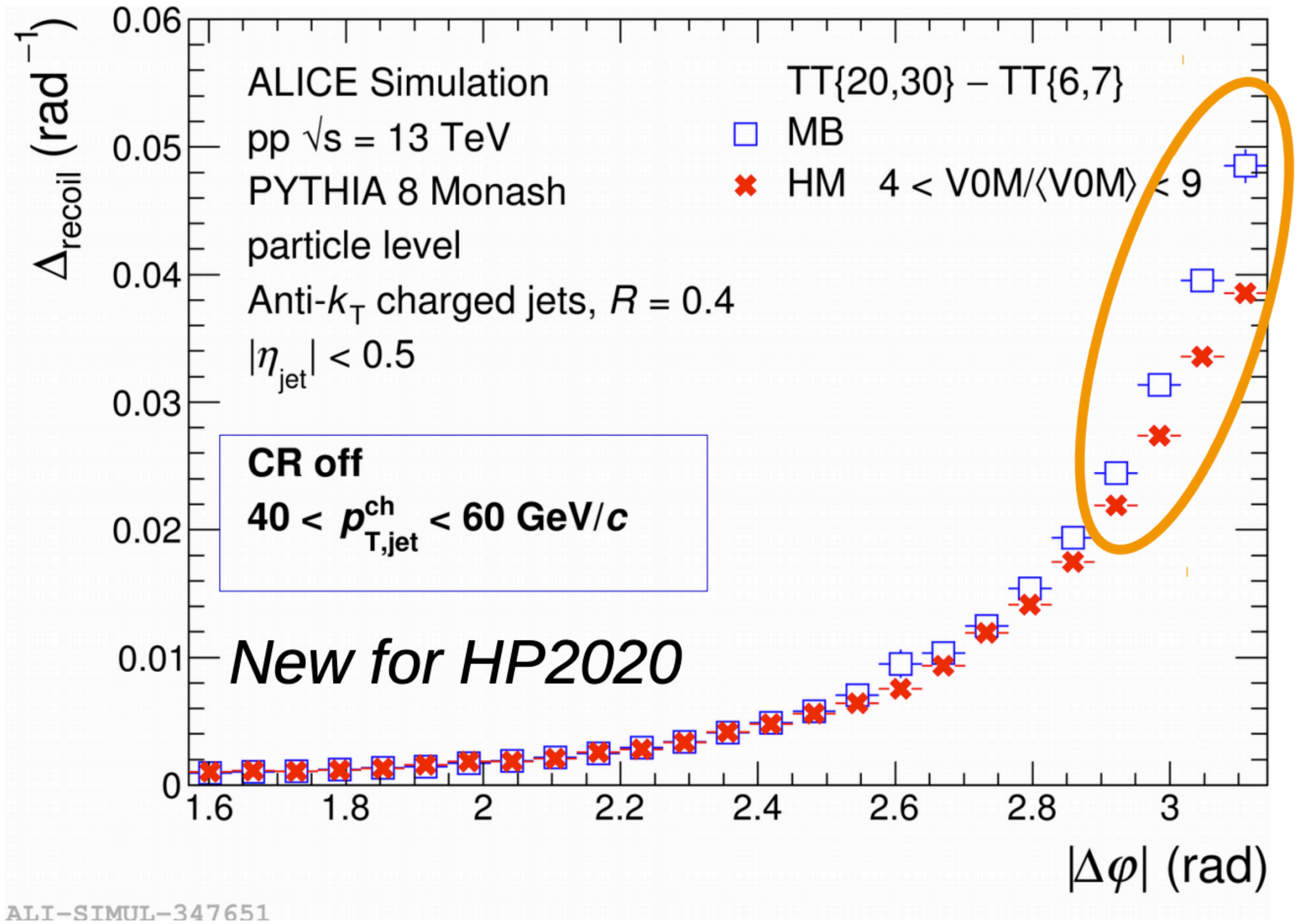
Back-up: dead cone





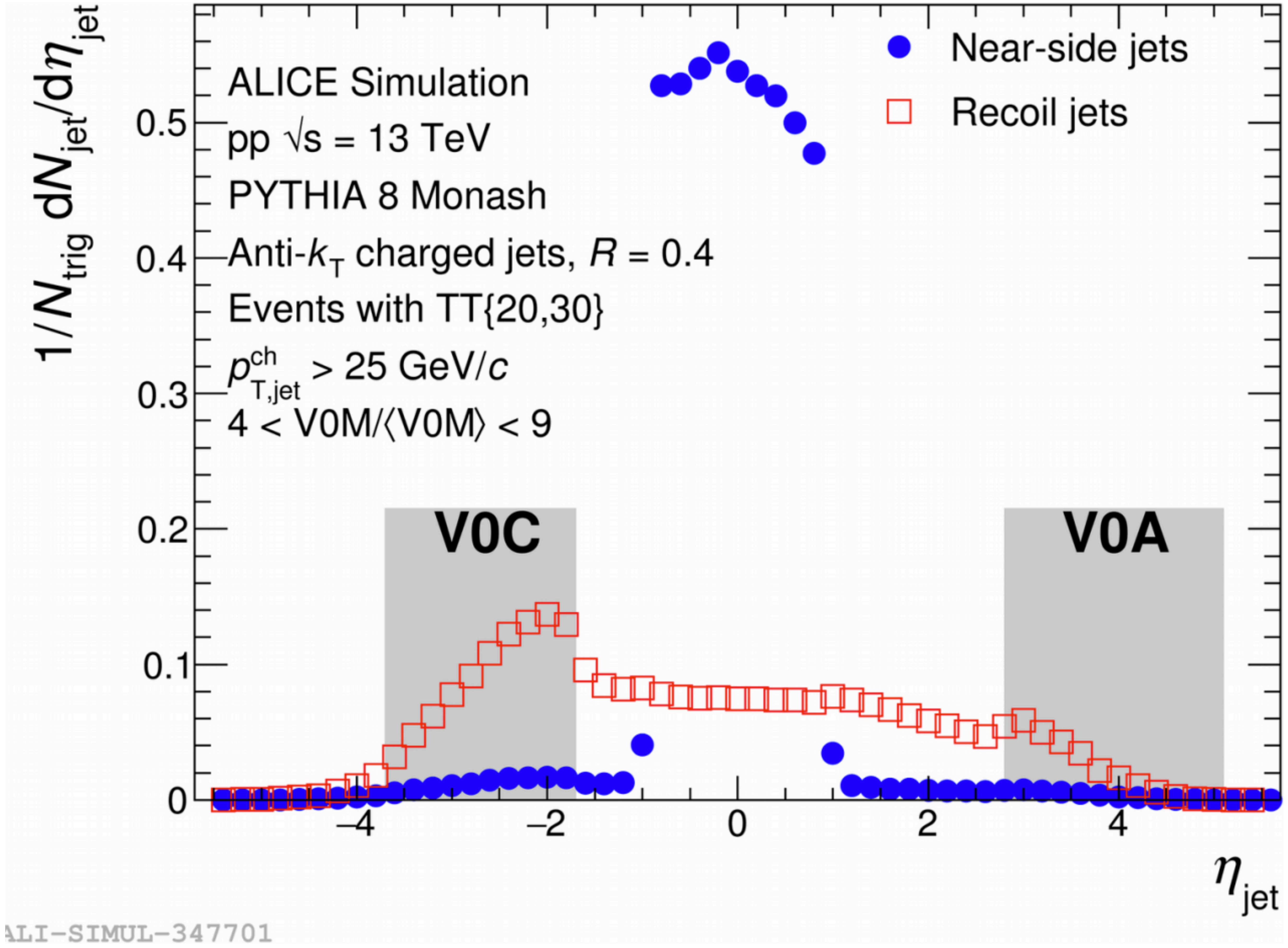
Back-up: pp jet quenching





Color reconnection on/off in Pythia does not cause bias

Back-up: pp jet quenching



Recoil jets have the strongest bias