Overview of the latest jet physics results from ALICE

James Mulligan for the ALICE Collaboration
Lawrence Berkeley National Lab

Fundamental QCD with Jets

proton-proton collisions

Test pQCD techniques: Parton showers, resummations, power corrections, …

Constrain non-perturbative effects: Hadronization, underlying event

Constrain PDFs, α_s

Reference for heavy-ion collisions: Which observables are under theoretical control?

Fundamental QCD with Jets

ALICE

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Reference for heavy-ion collisions: Which observables are under theoretical control?

Pb-Pb collisions

Test models of jet quenching in the quark-gluon plasma: Strongly-coupled vs. weakly-coupled jet-medium interaction, …

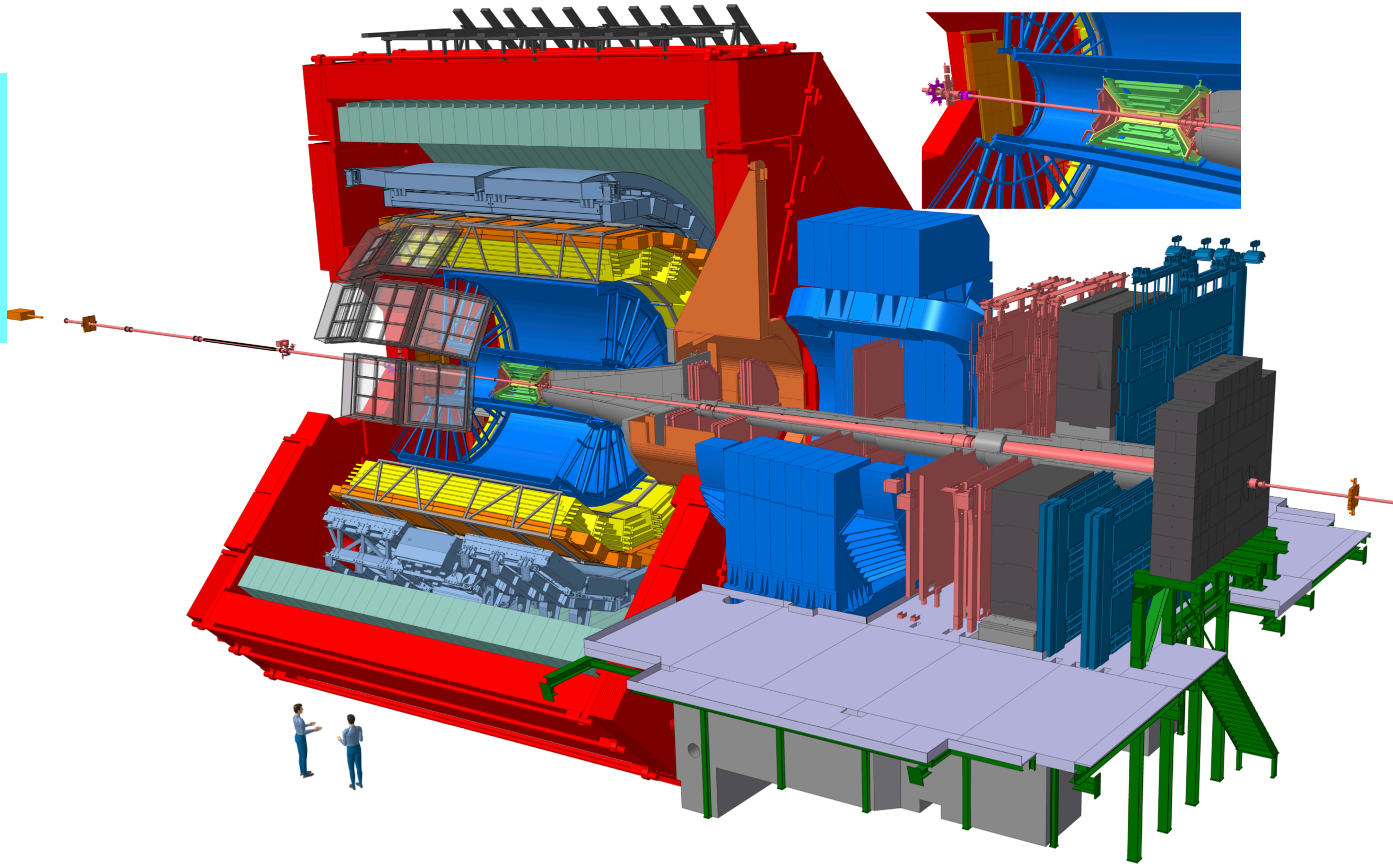
Constrain medium bulk properties: Transverse momentum diffusion coefficient, $\hat{q}$

Constrain structure of the quark-gluon plasma: What are the relevant degrees of freedom? Quasiparticle structure?

Test factorization/universality in high-*T* QCD

Jets in ALICE

ALICE reconstructs jets at mid-rapidity $(|\eta| < 0.9)$ with a high-precision tracking system (ITS+TPC) and EMCal

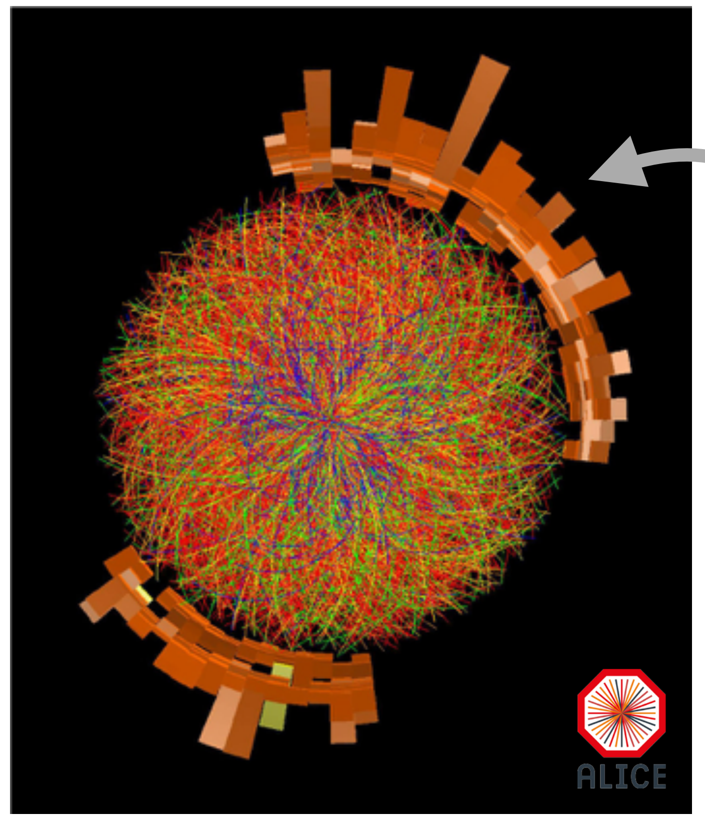


Charged particle jets

- Pro: High-precision spatial resolution to resolve particles; Experimentally simpler
  - → **Ideal for precise jet substructure measurements**
- Con: Additional modeling to compare to theory

Full jets (charged tracks + EMCal π^0, γ)

- Pro: Direct comparison to theory
- Con: Significant experimental complication; Limited EMCal coverage



EMCal φ acceptance: 107°

ALICE is very good for:

- Jet substructure
- Low-p_T tracks: 150 MeV/c
- Particle Identification

ALICE is not so good for:

- High statistics
- High p_T > ~100 GeV/c
- Jets at forward/backward rapidity

Jet substructure

A powerful class of observables

Sensitive to a wide span of scales

Provide complementary information to disentangle multiple QCD effects

Many are analytically calculable from pQCD

Groomed jet substructure

Recluster and groom jet to expose hard splitting

Soft Drop: $z < z_{\mathrm{cut}}\theta^{\beta}$

Dasgupta, Fregoso, Marzani, Salam 1307.0007
Larkoski, Marzani, Soyez, Thaler 1402.2657
Larkoski, Marzani, Thaler 1502.01719

Theoretical control: Isolate a pQCD-dominated, calculable observable in the complicated heavy-ion environment

Identifies quantities related to the **ordering of hard splittings in parton showers**, which may give us a handle on pathlength/coherence effects in AA

Jet substructure

ALICE

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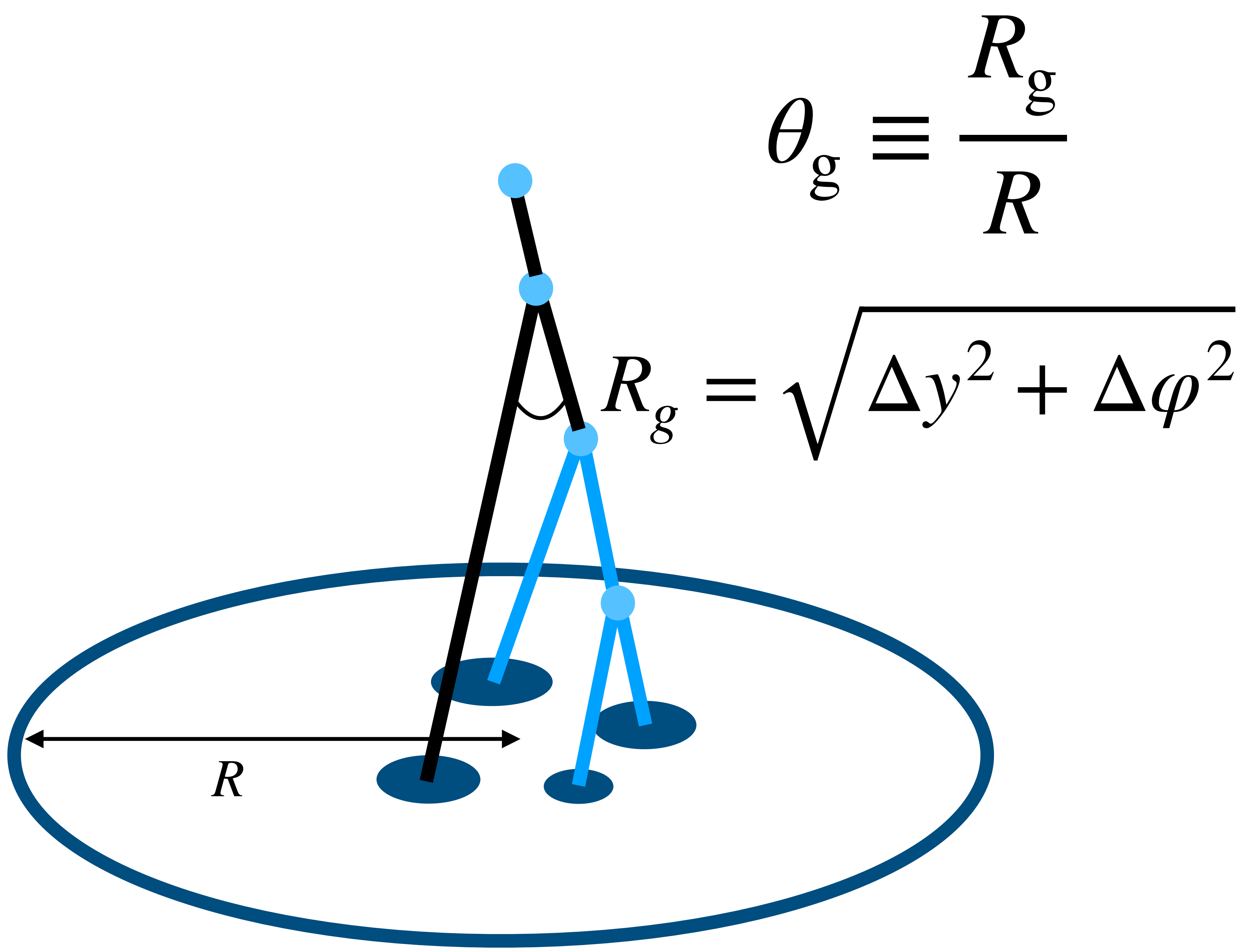
- Sensitive to a wide span of scales
  - Provide complementary information to disentangle multiple QCD effects
- Many are analytically calculable from pQCD



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Jet substructure

Many New Preliminary in Summer 2020

ALICE

pp collisions

Dynamical grooming: $z_g, \theta_g, k_\mathrm{T}$

Jet angularities: λ_β

D^0**-tagged jets:** z_g, θ_g

Dead cone

Leticia Cunqueiro Mendez
Thurs July 30, 09:30

Datasets:

$\sqrt{s} = 5.02$ TeV
$\mathscr{L}_\mathrm{int} = 18.0\ \mathrm{nb}^{-1}$

$\sqrt{s} = 13$ TeV
$\mathscr{L}_\mathrm{int} = 22.5\ \mathrm{nb}^{-1}$

Unfolded distributions

Dynamical Grooming
proton-proton collisions

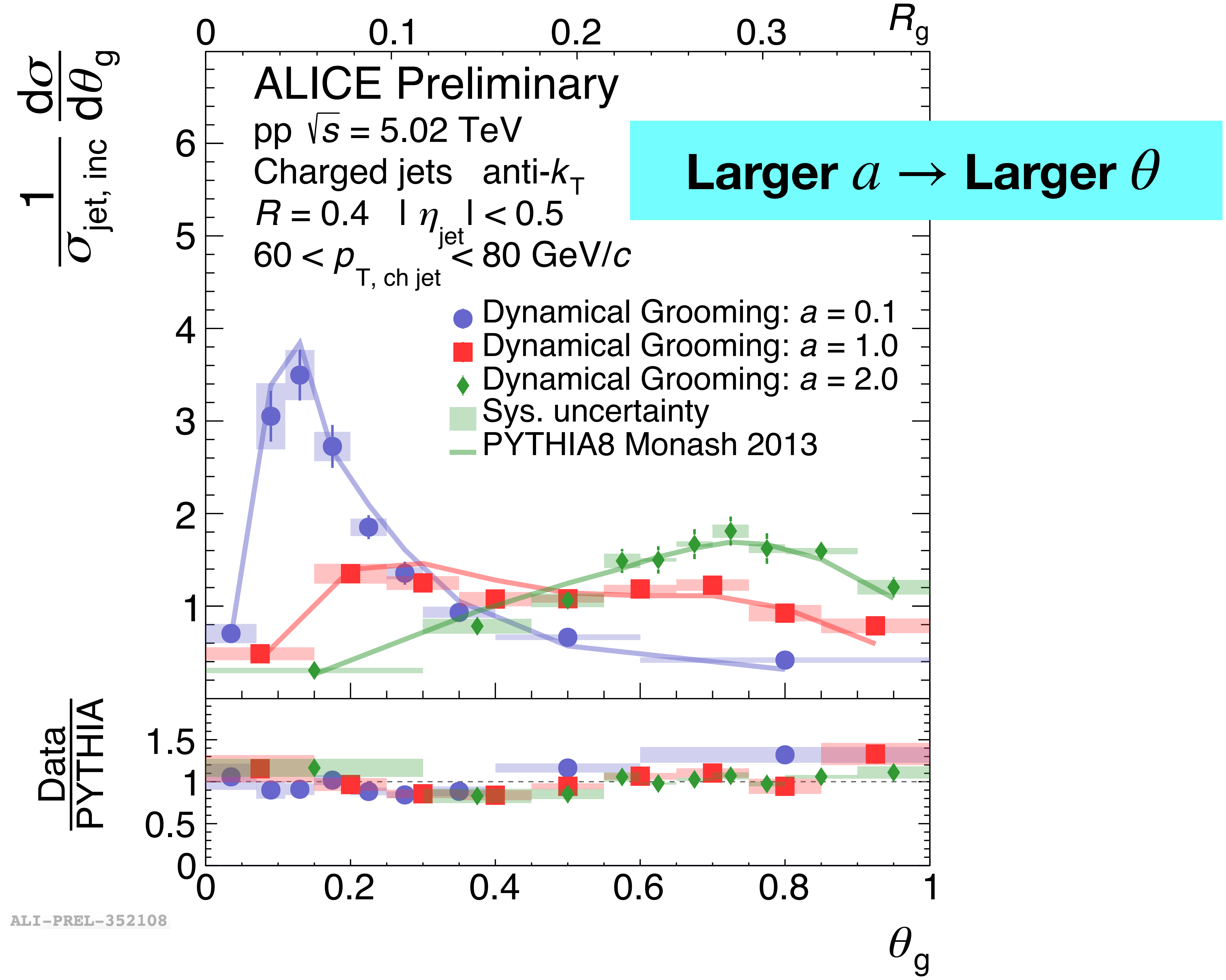
New Preliminary

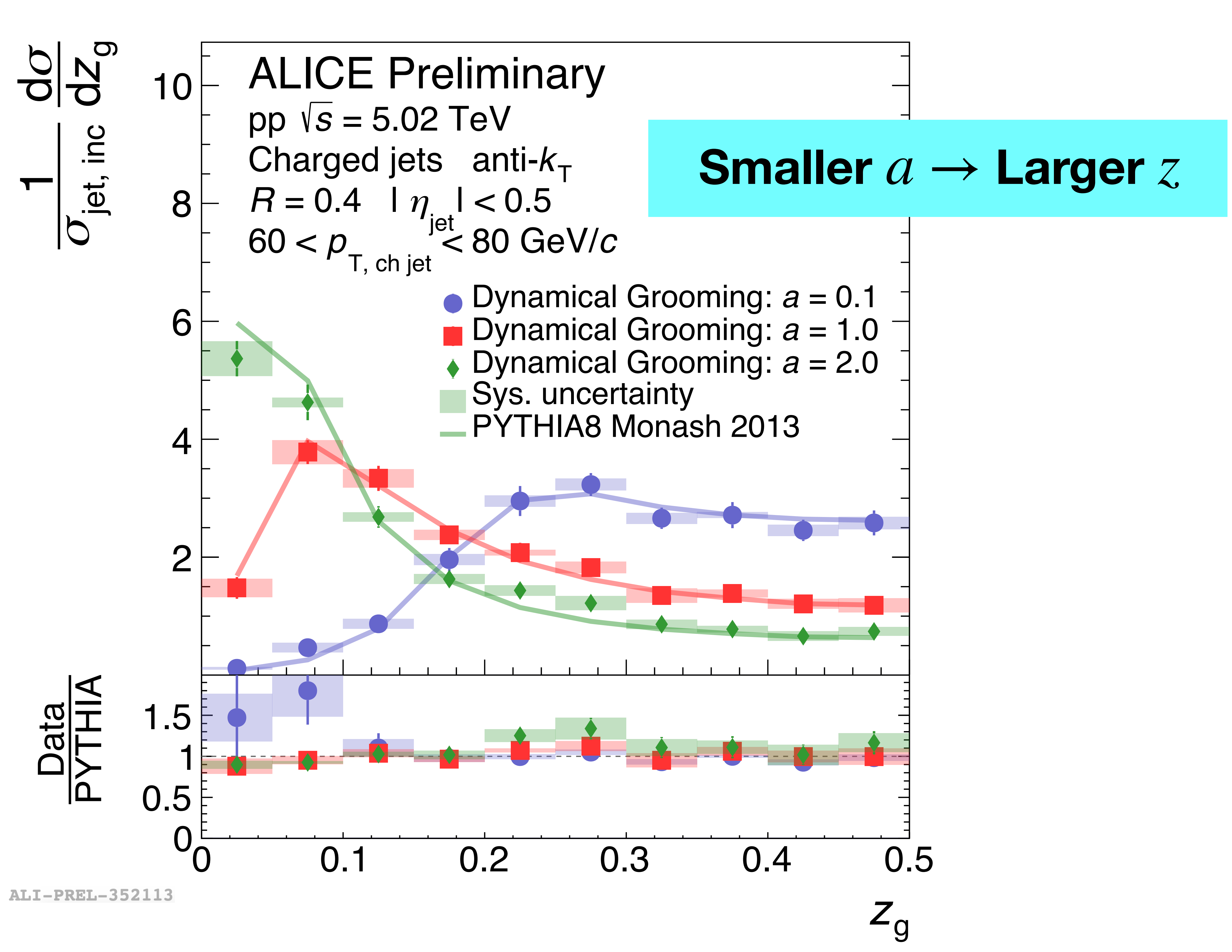
Y. Mehtar-Tani, A. Soto-Ontoso, K. Tywoniuk
PRD 101 (2020) 034004

Identify splitting in C/A tree as the **maximum** of a particular grooming condition:

$$z_i(1 - z_i)p_{T,i}\theta_i^a$$

$a \to 0$ hardest z
$a = 1$ hardest k_T
$a = 2$ smallest t_f





First measurement of Dynamical Grooming → Well described by PYTHIA

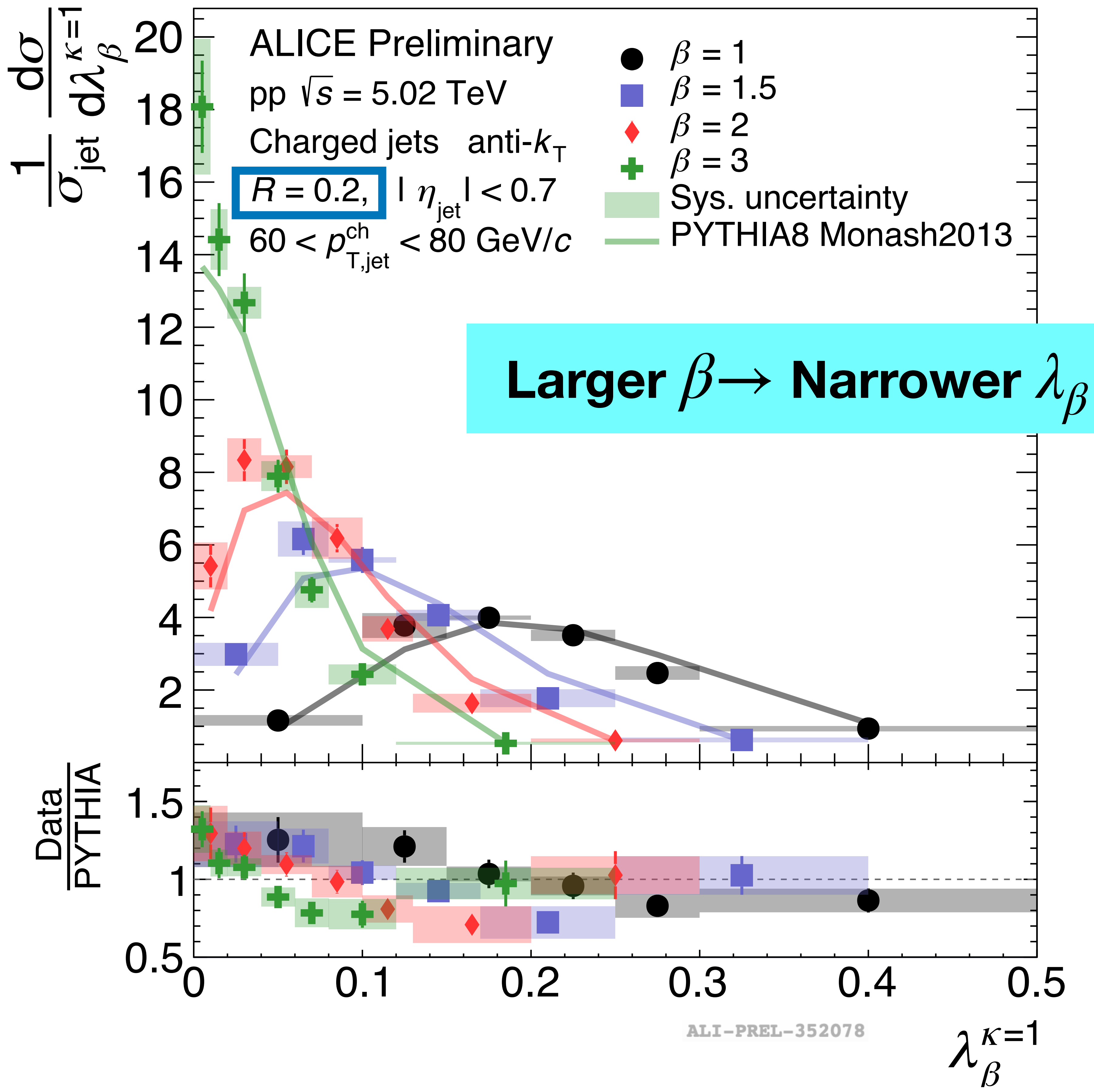
Jet angularities

proton-proton collisions

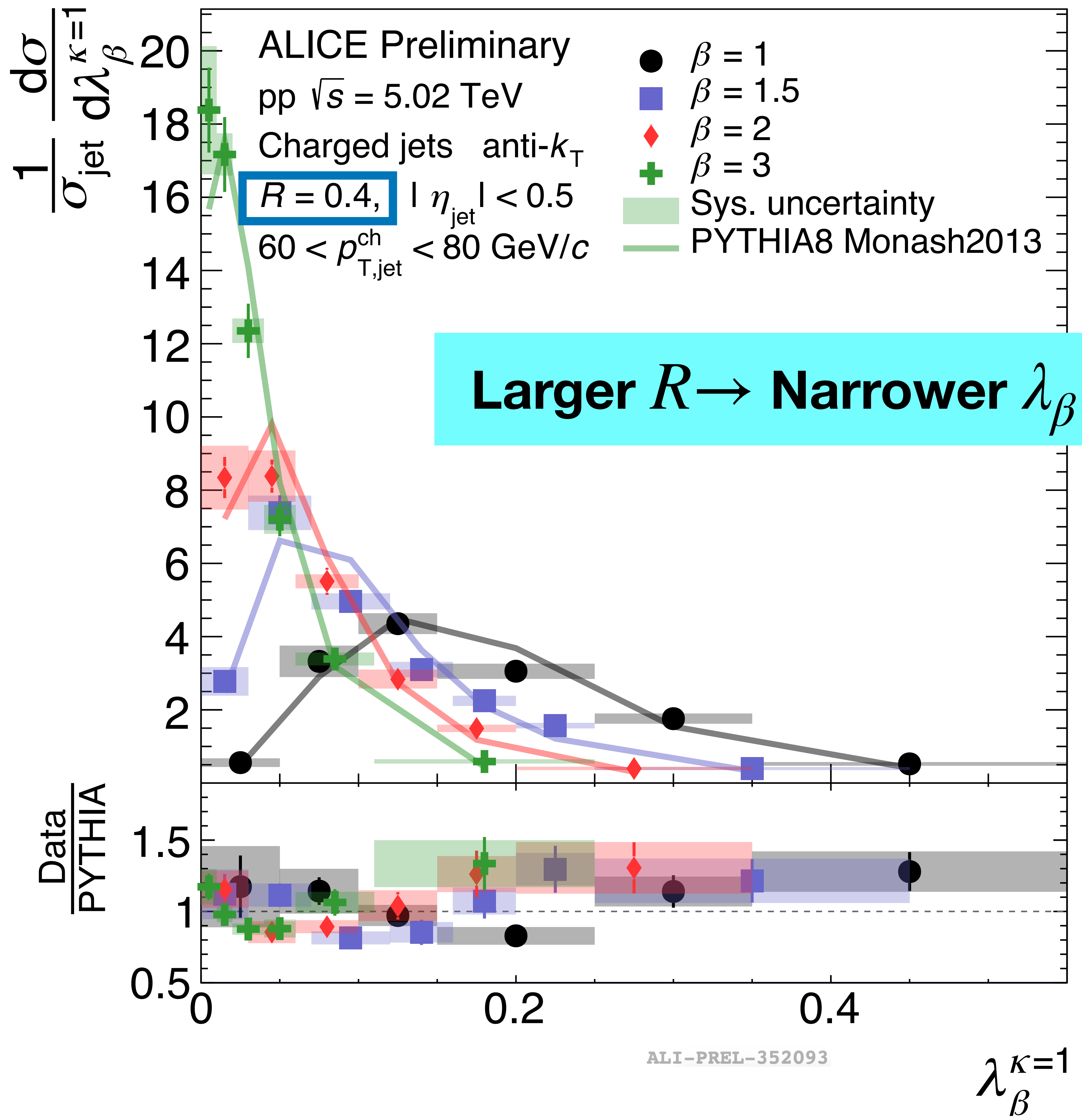
New Preliminary

$$\lambda_\beta^\kappa \equiv \sum_{i \in \text{jet}} \left(\frac{p_{T,i}}{p_{T,\text{jet}}}\right)^\kappa \left(\frac{\Delta R_{jet,i}}{R}\right)^\beta$$

Measurements for multiple R, β systematically ⟶ test pQCD predictions



Larger β → Narrower λ_β



Larger R → Narrower λ_β

Reasonably well-described by PYTHIA

Jet substructure

ALICE

Pb-Pb collisions

Soft Drop: z_g, θ_g

Dataset:

$\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

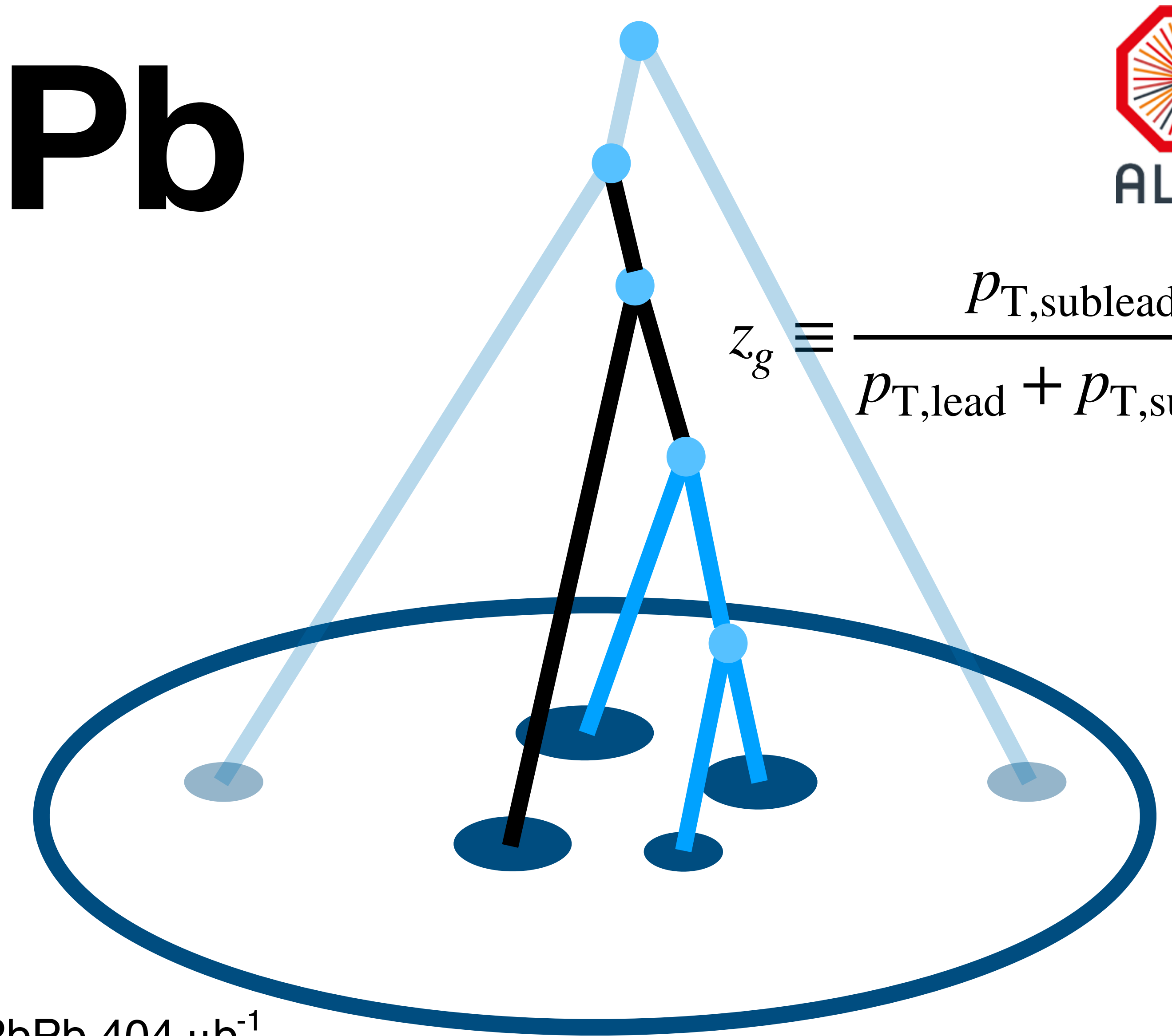
$\mathscr{L}_{\mathrm{int}} = 0.12\ \mathrm{nb}^{-1}$

Unfolded distributions

Groomed jet substructure in Pb-Pb

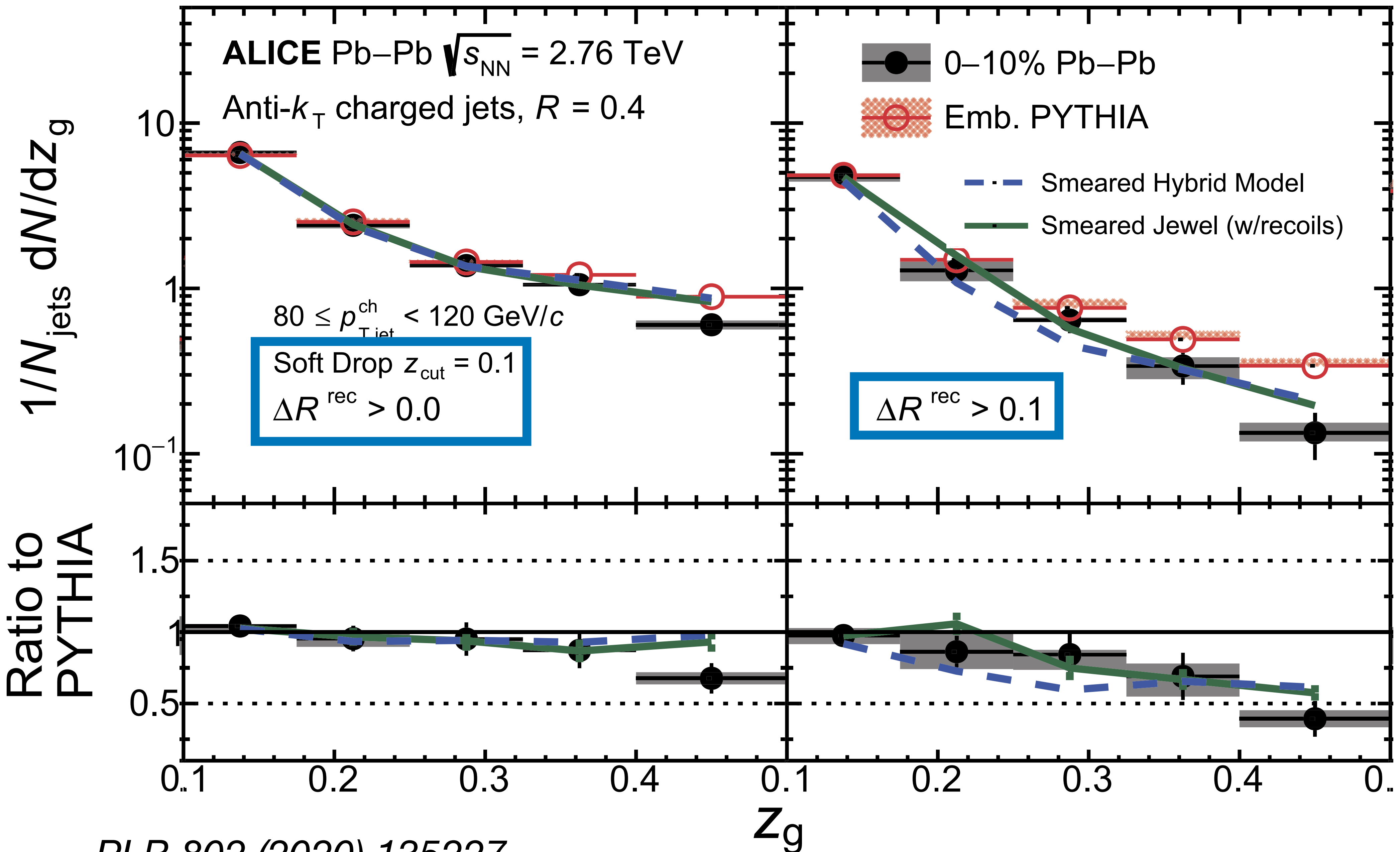
Groomed jet momentum fraction, z_g

Modification of splitting function?
Coherent vs. incoherent energy loss?

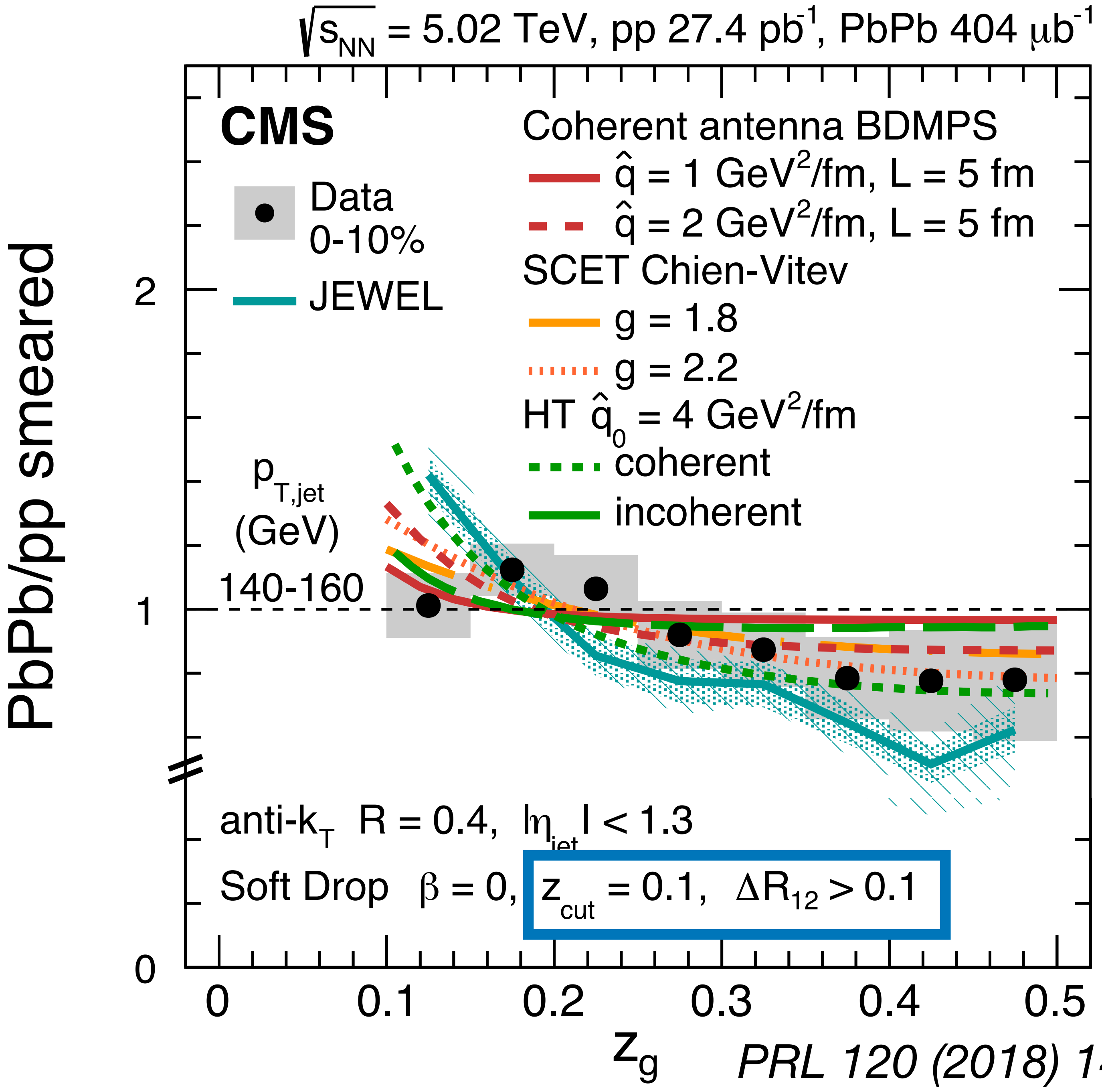


$$z_g \equiv \frac{p_{\mathrm{T,sublead}}}{p_{\mathrm{T,lead}} + p_{\mathrm{T,sublead}}}$$

Previous measurements: Slight suppression?



PLB 802 (2020) 135227



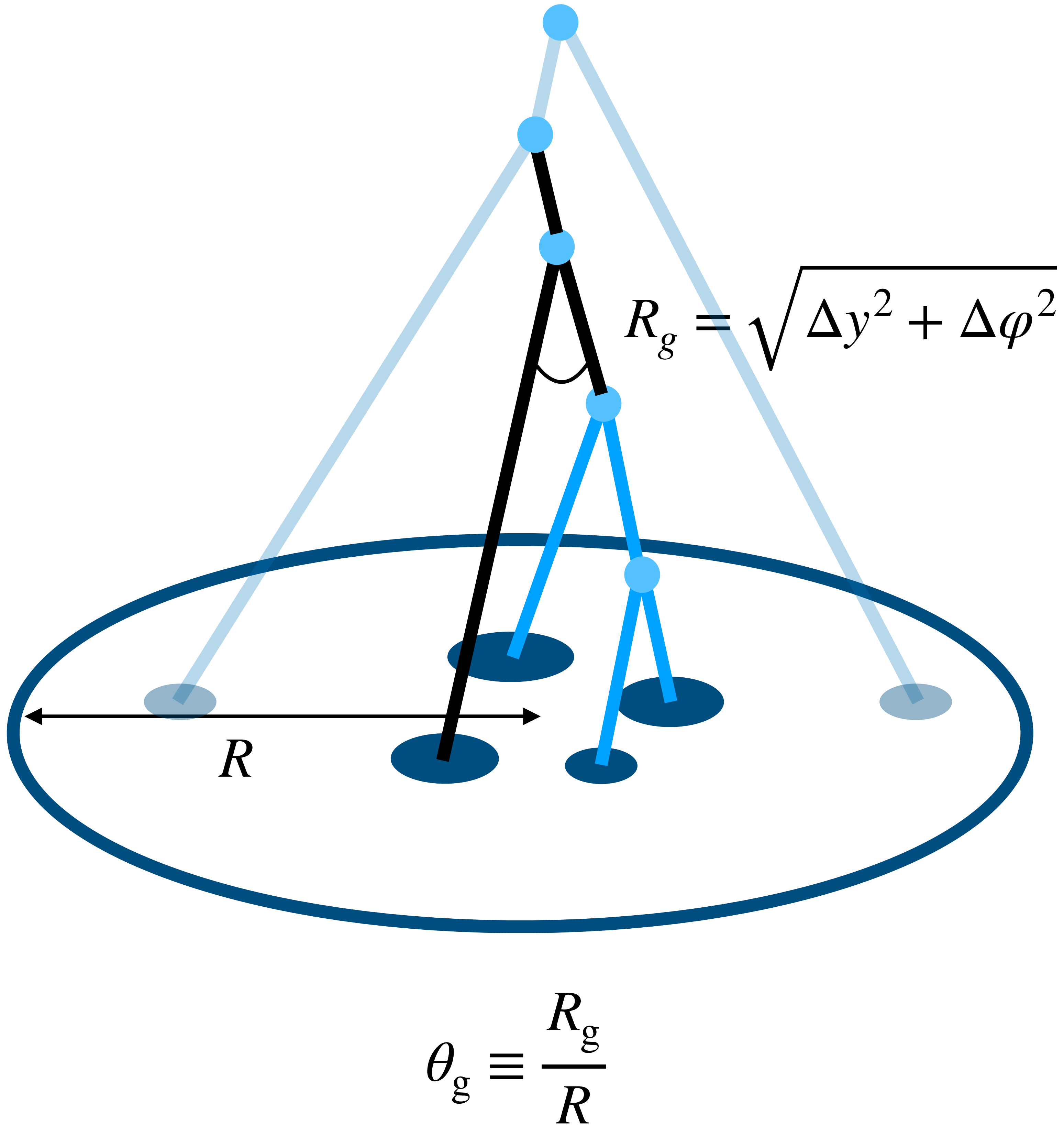
PRL 120 (2018) 142302

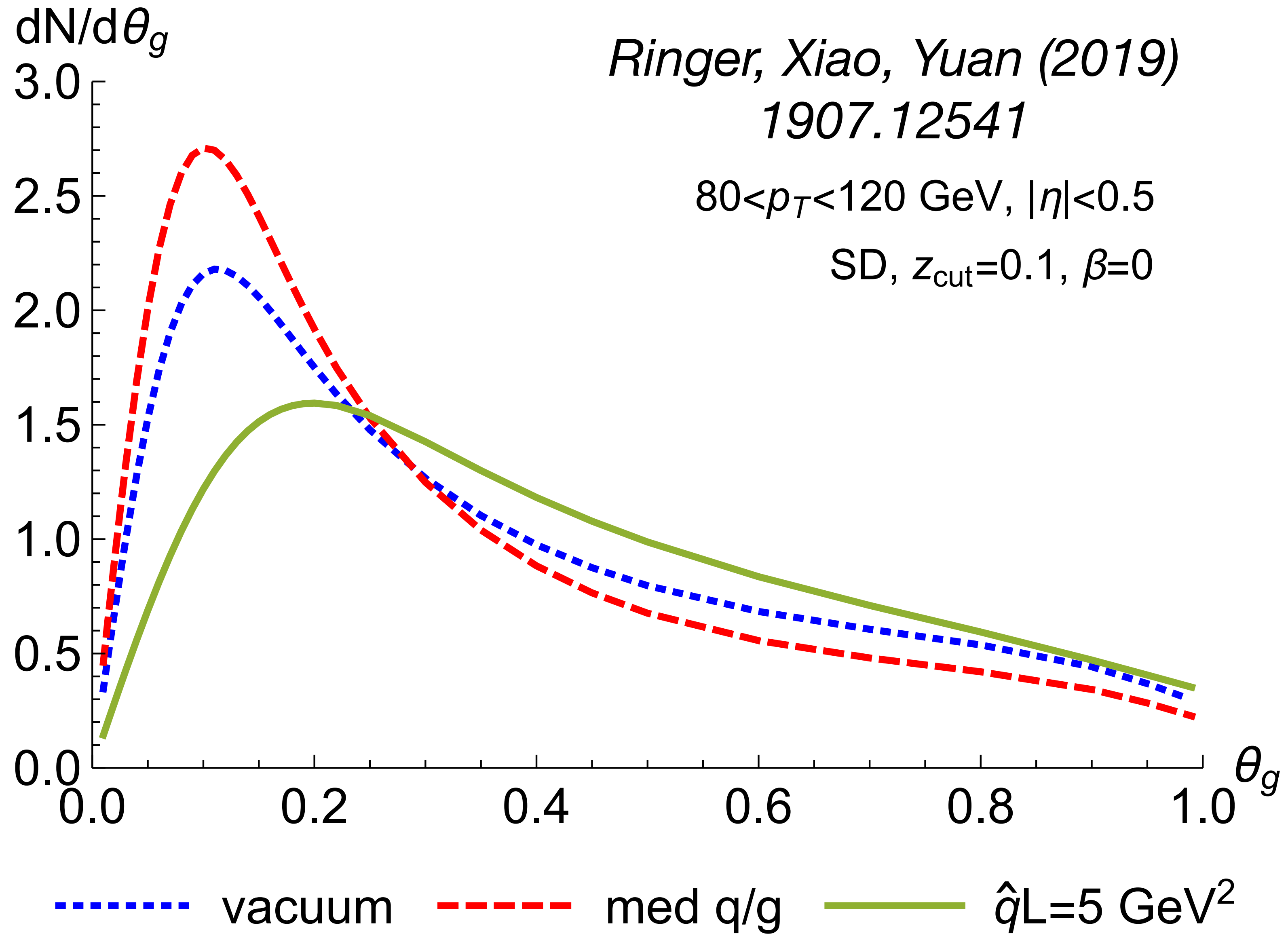
Also: STAR NPA 967 (2017)

Never unfolded for detector effects and background fluctuations in heavy-ion collisions

Groomed jet substructure in Pb-Pb

Groomed jet radius, θ_g





Medium-induced gluon radiation ($\hat{q}$) broadens jets

Energy loss selects narrow jets

q-g fractions, coherent vs. incoherent energy loss

And more, e.g. $t_f \sim 1/\theta_g^2$ affects path-length

→ **Disentangle and constrain these effects**

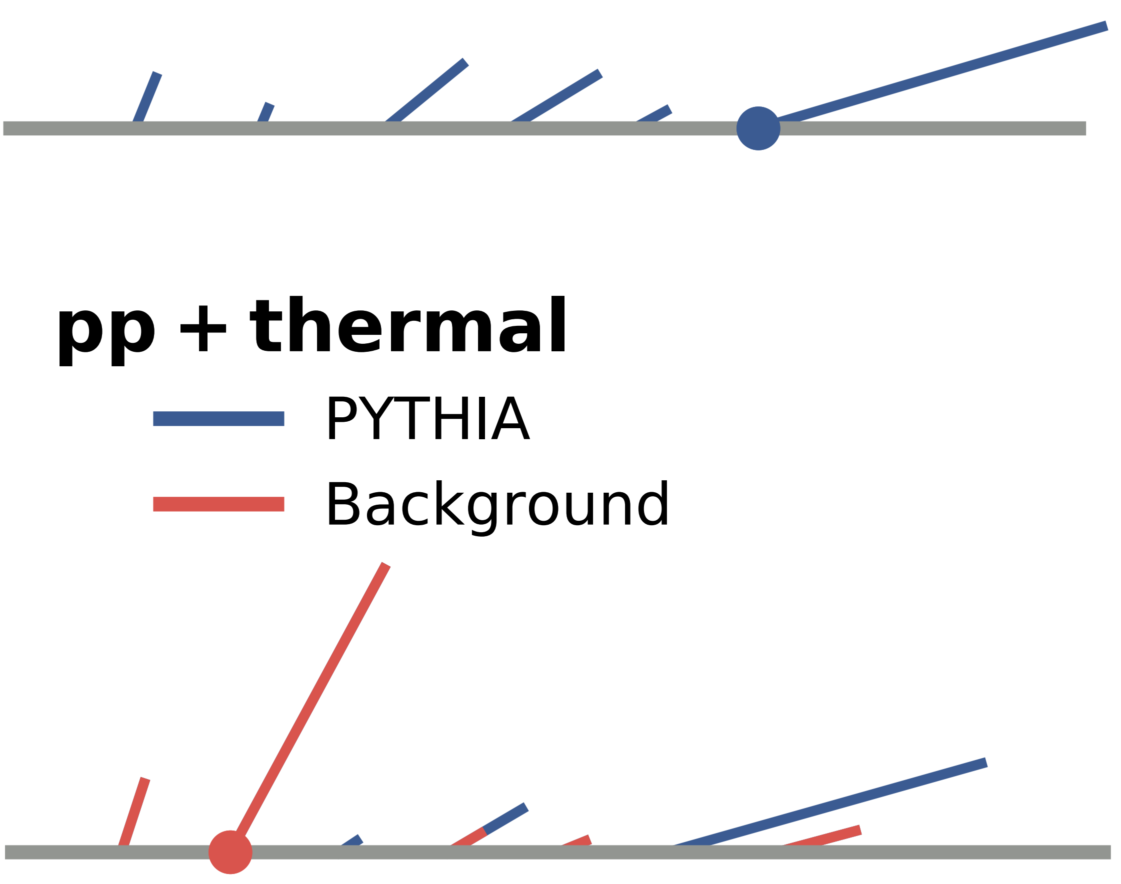
Never measured in heavy-ion collisions

Identifying groomed jet splittings in Pb-Pb

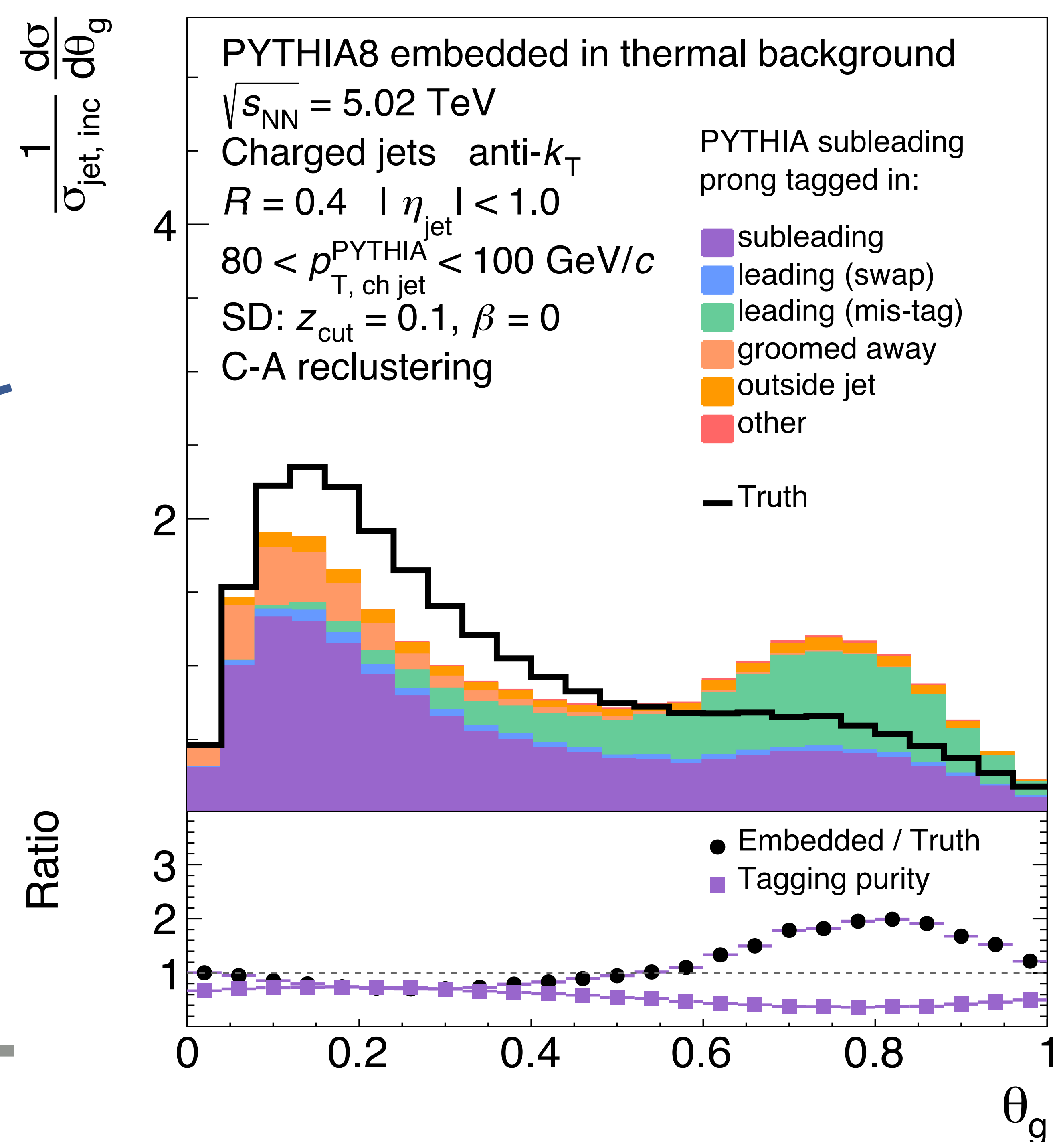
Embed PYTHIA into Pb-Pb background to estimate the fraction of subleading prongs in PYTHIA that are reconstructed in the subleading prong of the combined event

pp
Soft Drop $z_{cut} = 0.1$
CA reclustering
$p_{T,\,jet} = 49$ GeV/c

pp + thermal
PYTHIA
Background



JM, M. Ploskon
2006.01812



Large number of misidentified Soft Drop splittings predominantly at large angle

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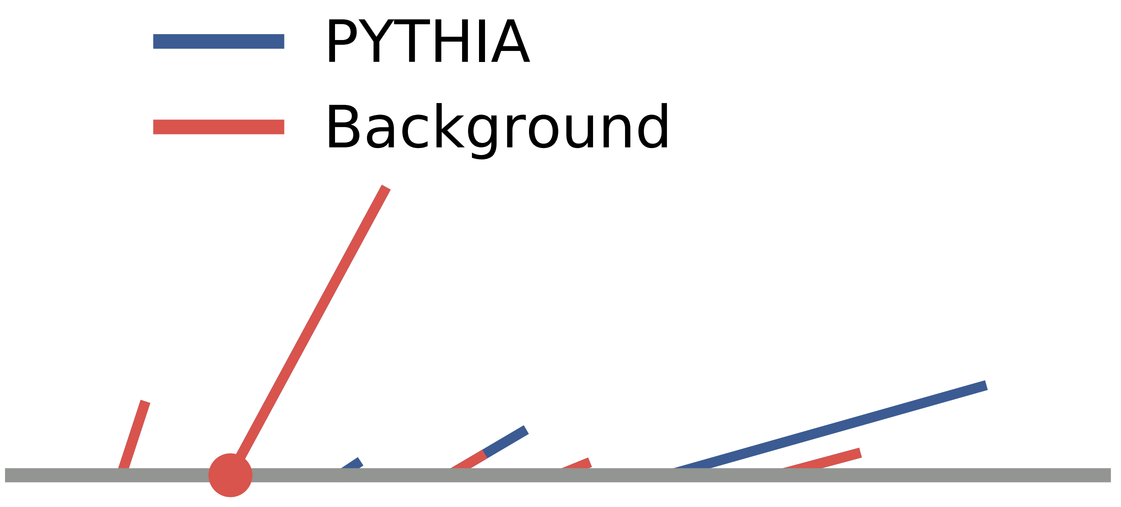

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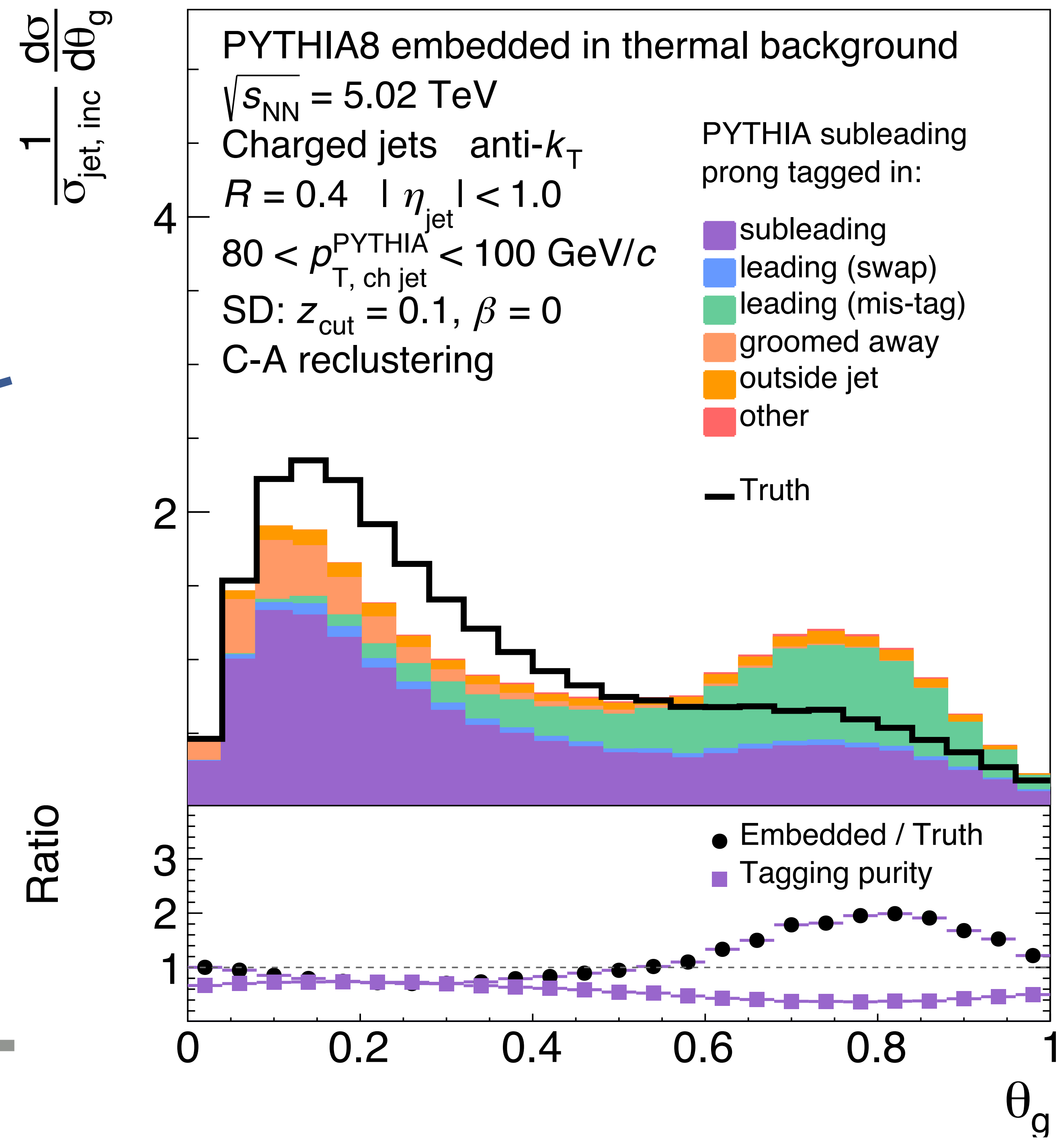

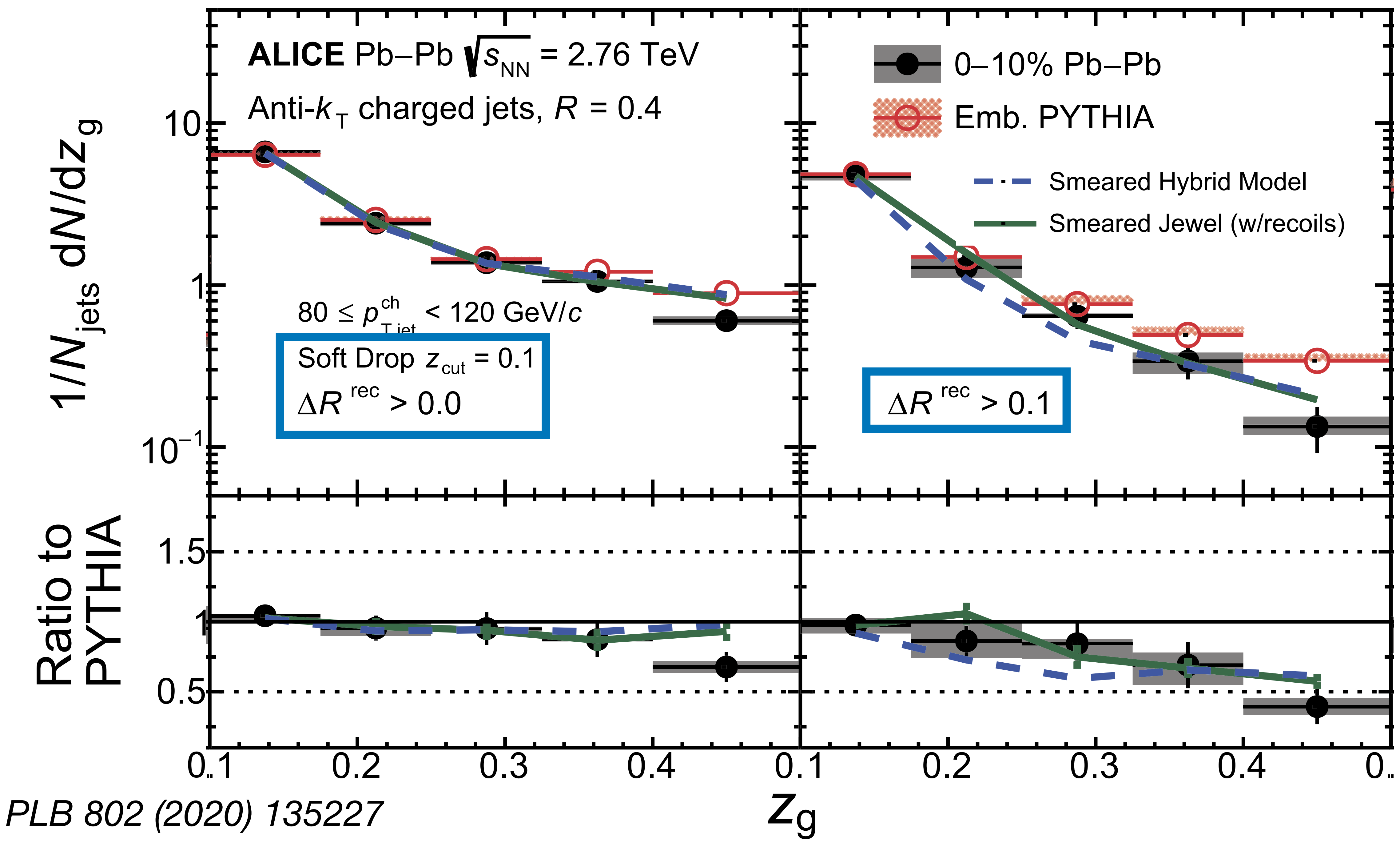

PLB 802 (2020) 135227

→ **Large number of misidentified Soft Drop splittings predominantly at large angle**

Previous measurements with $z_{\mathrm{cut}} = 0.1$ are significantly contaminated with background

Identifying groomed jet splittings in Pb-Pb

Embed PYTHIA into Pb-Pb background to estimate the fraction of subleading prongs in PYTHIA that are reconstructed in the subleading prong of the combined event

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Soft Drop $z_{\mathrm{cut}} = 0.1$
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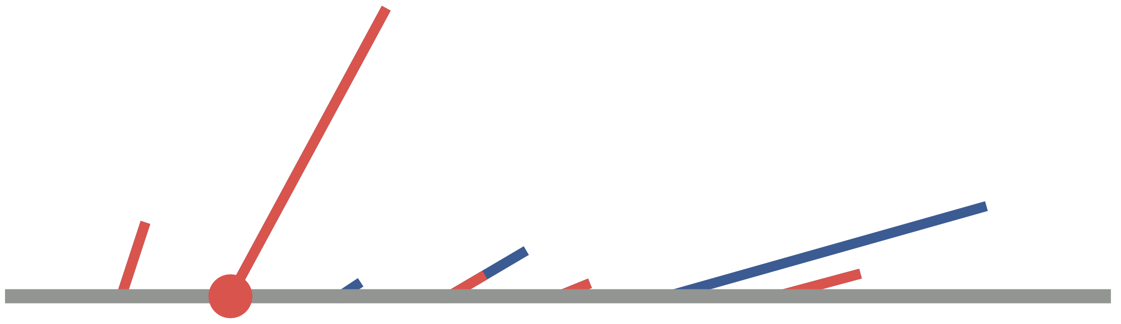
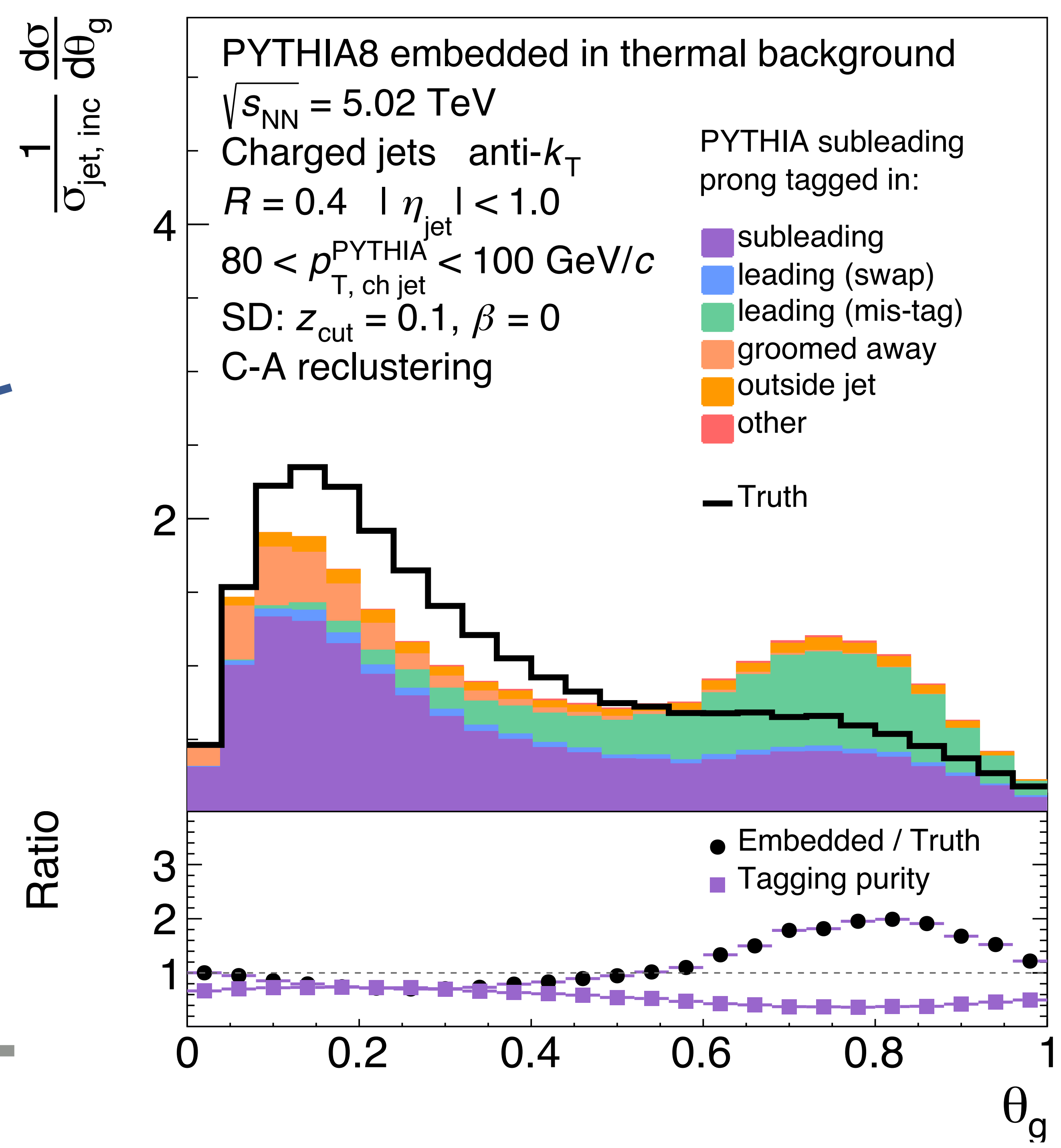
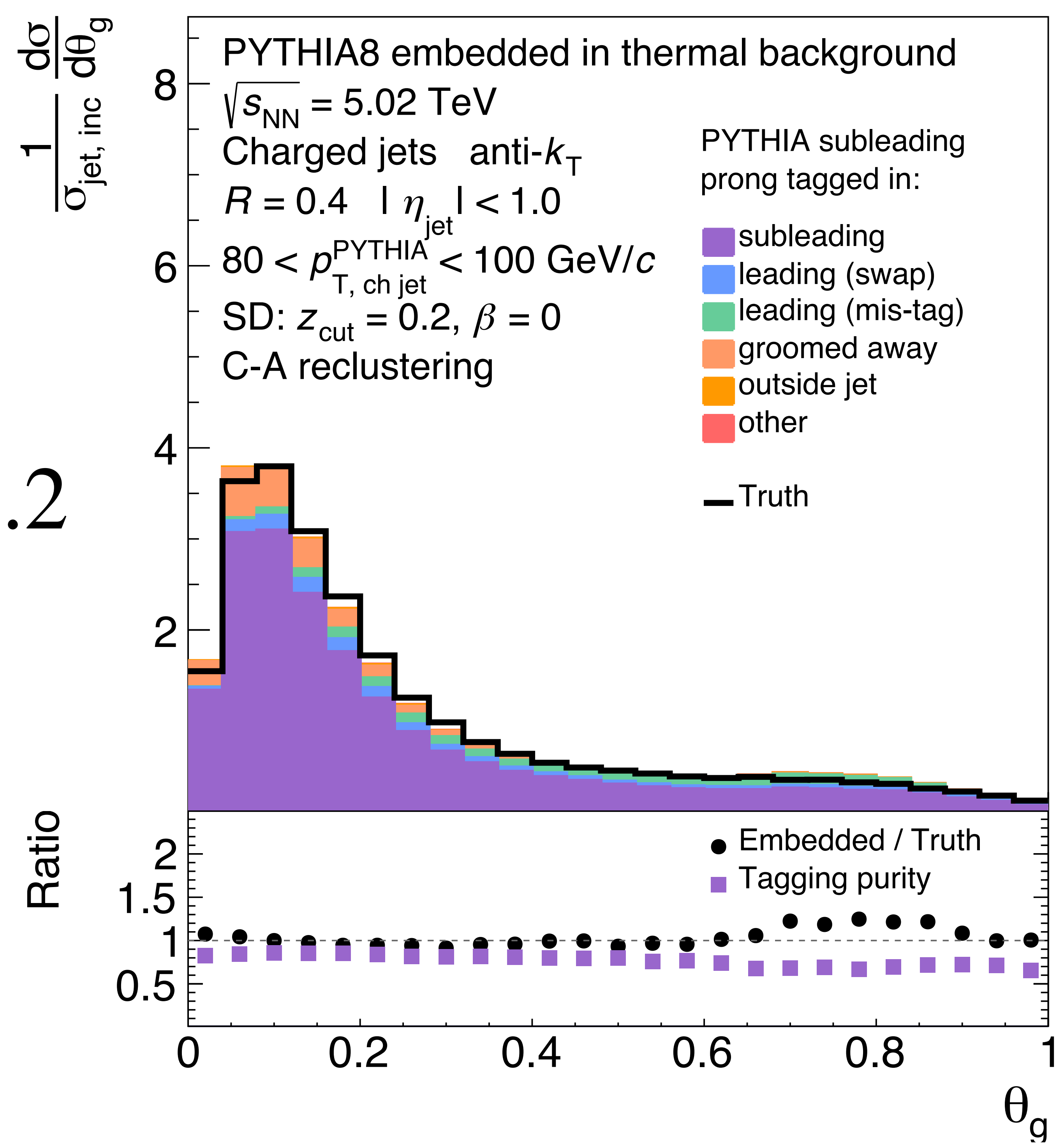


JM, M. Ploskon 2006.01812



$z_{\mathrm{cut}} = 0.1 \longrightarrow z_{\mathrm{cut}} = 0.2$



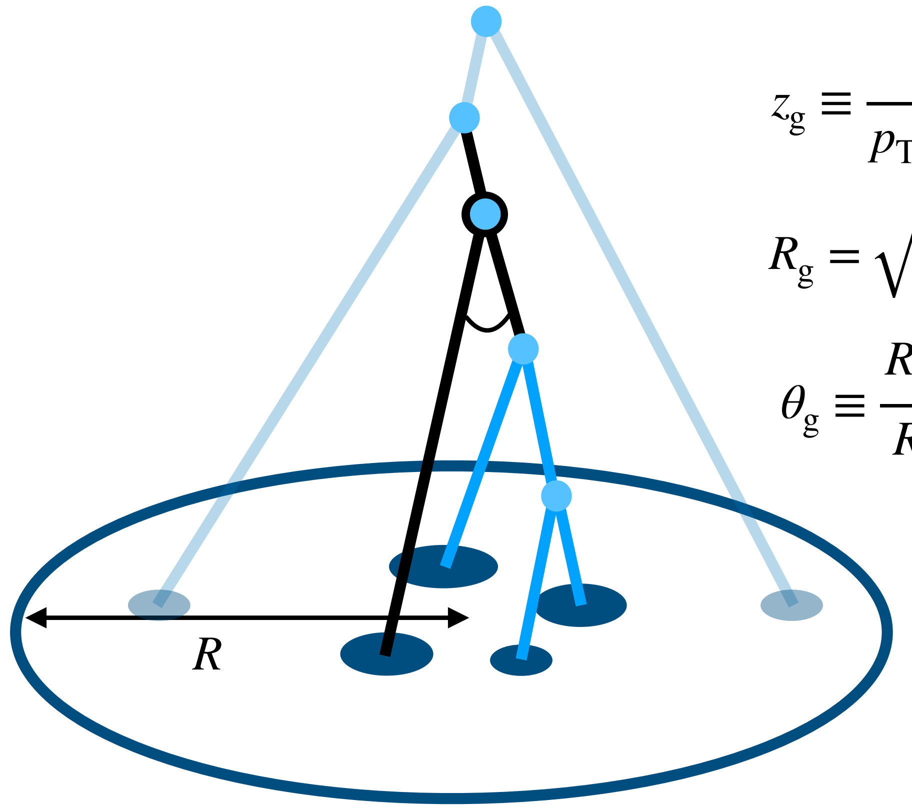
Our solution: Measure in the (approximately) background-free part of phase space

Raising z_{cut} removes mis-identified splittings and reduces their impact

This leaves ~5-10% mis-tagged splittings ⟶ Unfolded measurement feasible

Results — Soft Drop z_g, θ_g

Pb-Pb 0-10%



$$z_g \equiv \frac{p_{T,\text{subleading}}}{p_{T,\text{leading}} + p_{T,\text{subleading}}}$$

$$R_g = \sqrt{\Delta y^2 + \Delta\varphi^2}$$

$$\theta_g \equiv \frac{R_g}{R}$$

JETSCAPE *1903.07706*

Multi-stage energy loss
MATTER+LBT

Caucal et al. *JHEP 10 (2019) 273*

pQCD parton shower, vacuum-like + medium-induced emissions

Chien, Vitev *PRL 119 (2017) 112301*

Soft Collinear Effective Theory

Qin et al. *PLB 781 (2018) 423*

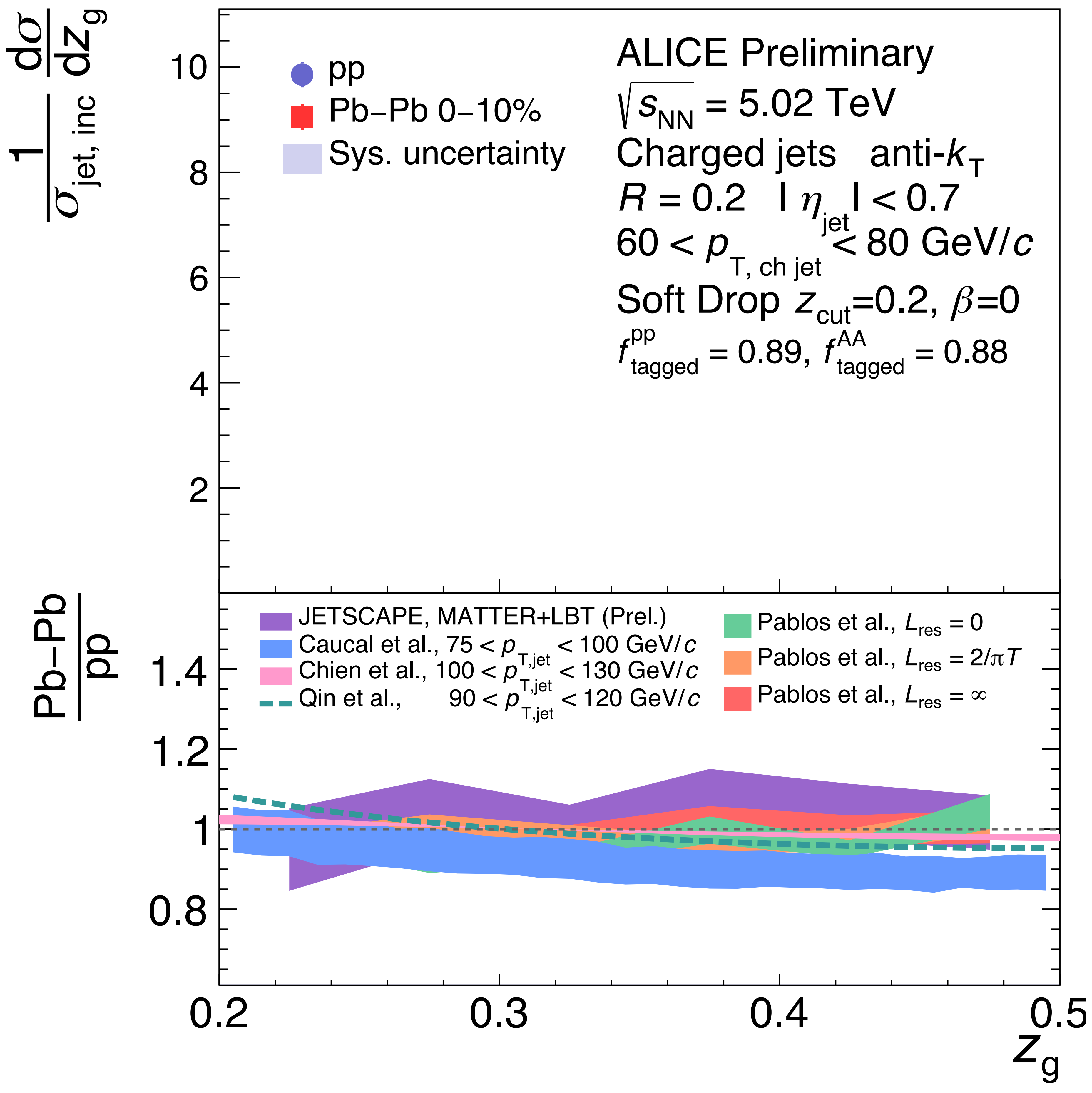
Higher-Twist, coherent energy loss

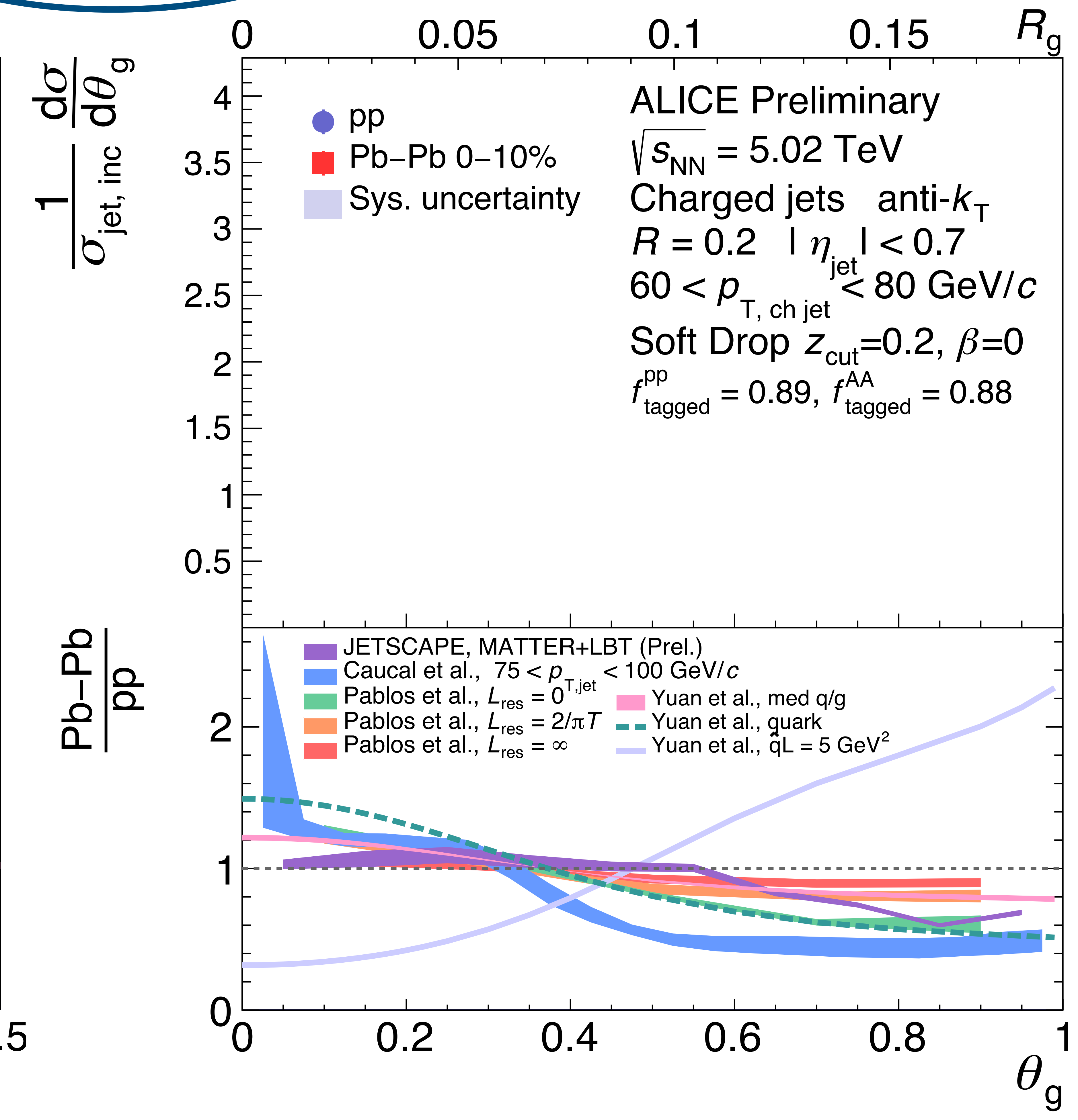
Pablos et al. *JHEP (2020) 044*

Hybrid model based on AdS/CFT

Yuan et al. *1907.12541*

Two approaches:
(1) Modification of q/g fractions
med q/g fractions from:
Ringer et al. PRL 122 (2019)
(2) $\hat{q}$ broadening





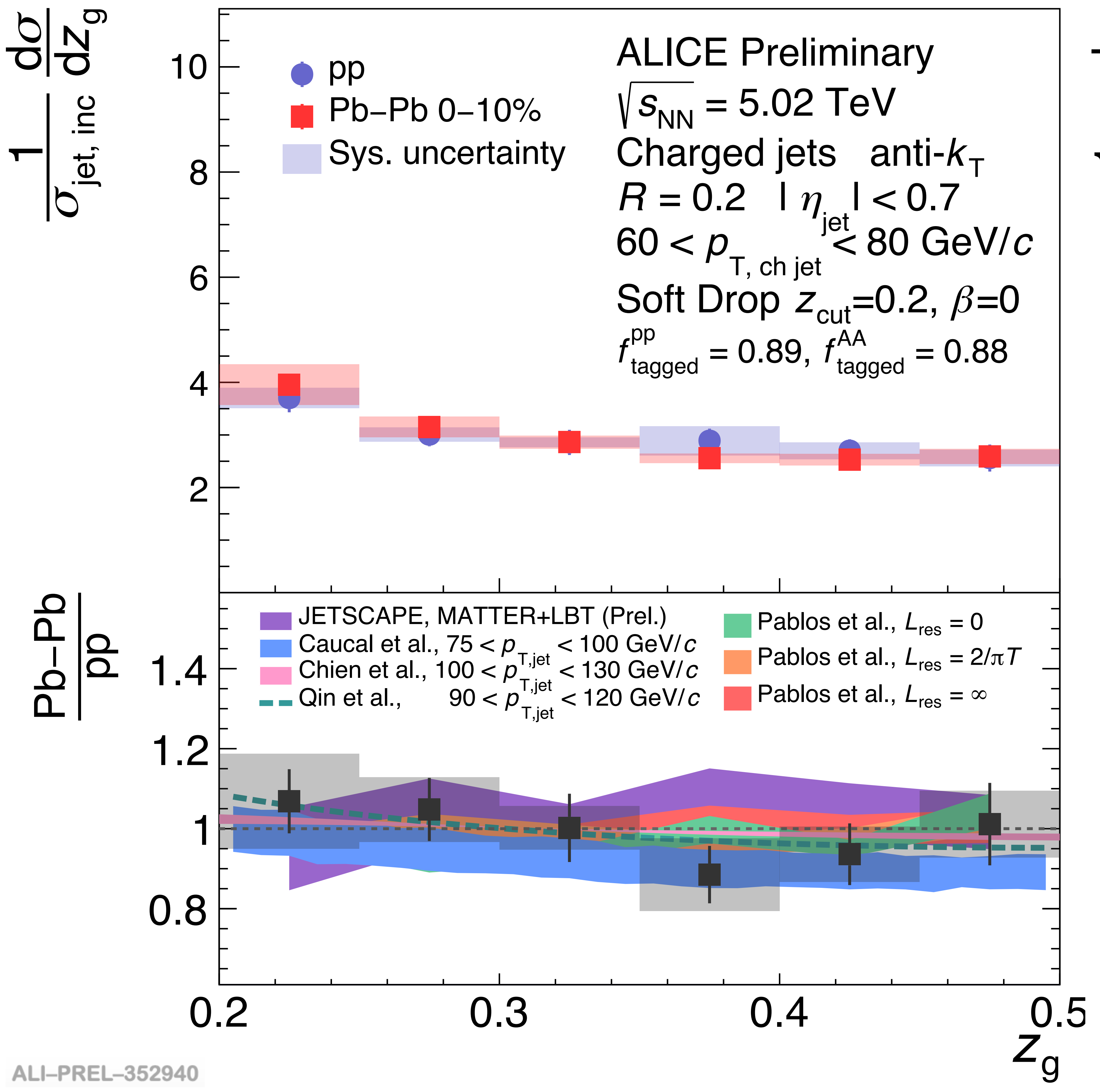
Results — Soft Drop z_g, θ_g

New Preliminary

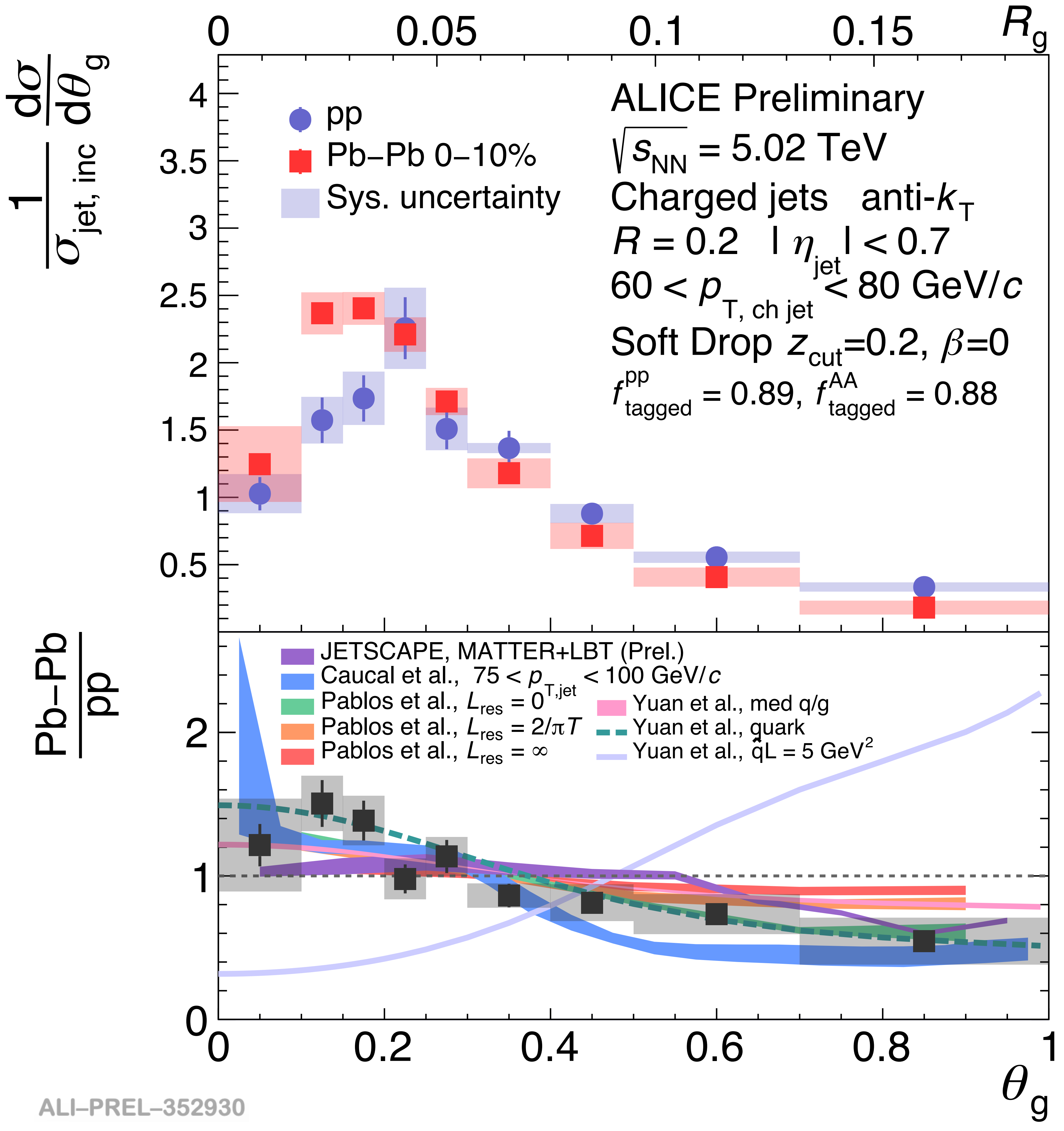
Pb-Pb 0-10%

Fully corrected for background and detector effects

No significant modification of z_g distribution



Modification of θ_g: Collimation / Narrowing



Results — Soft Drop z_g, θ_g

New Preliminary

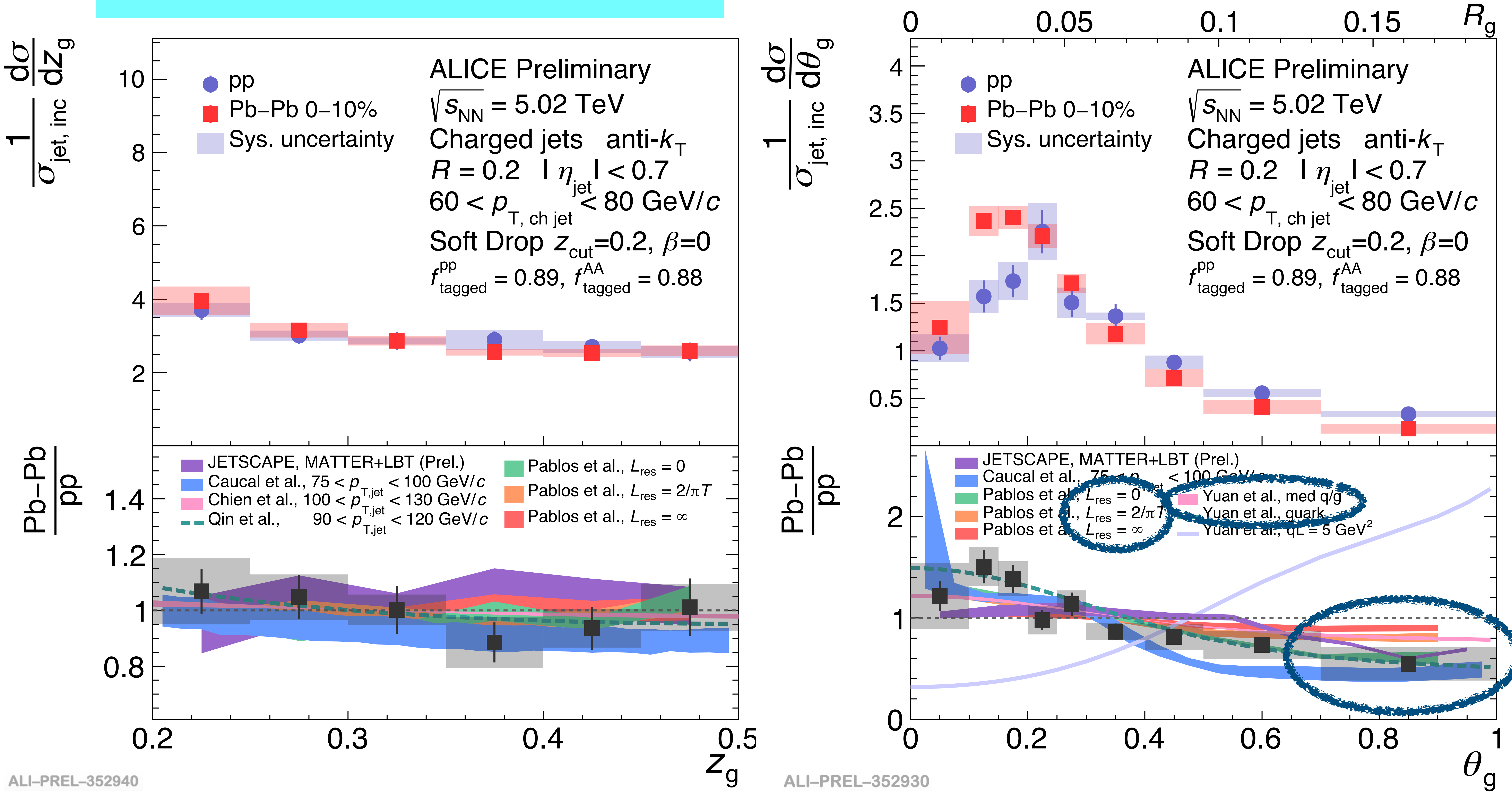
Pb-Pb 0-10%

Fully corrected for background and detector effects

Data seem to favor incoherent energy loss and/or large q/g suppression

No significant modification of z_g distribution

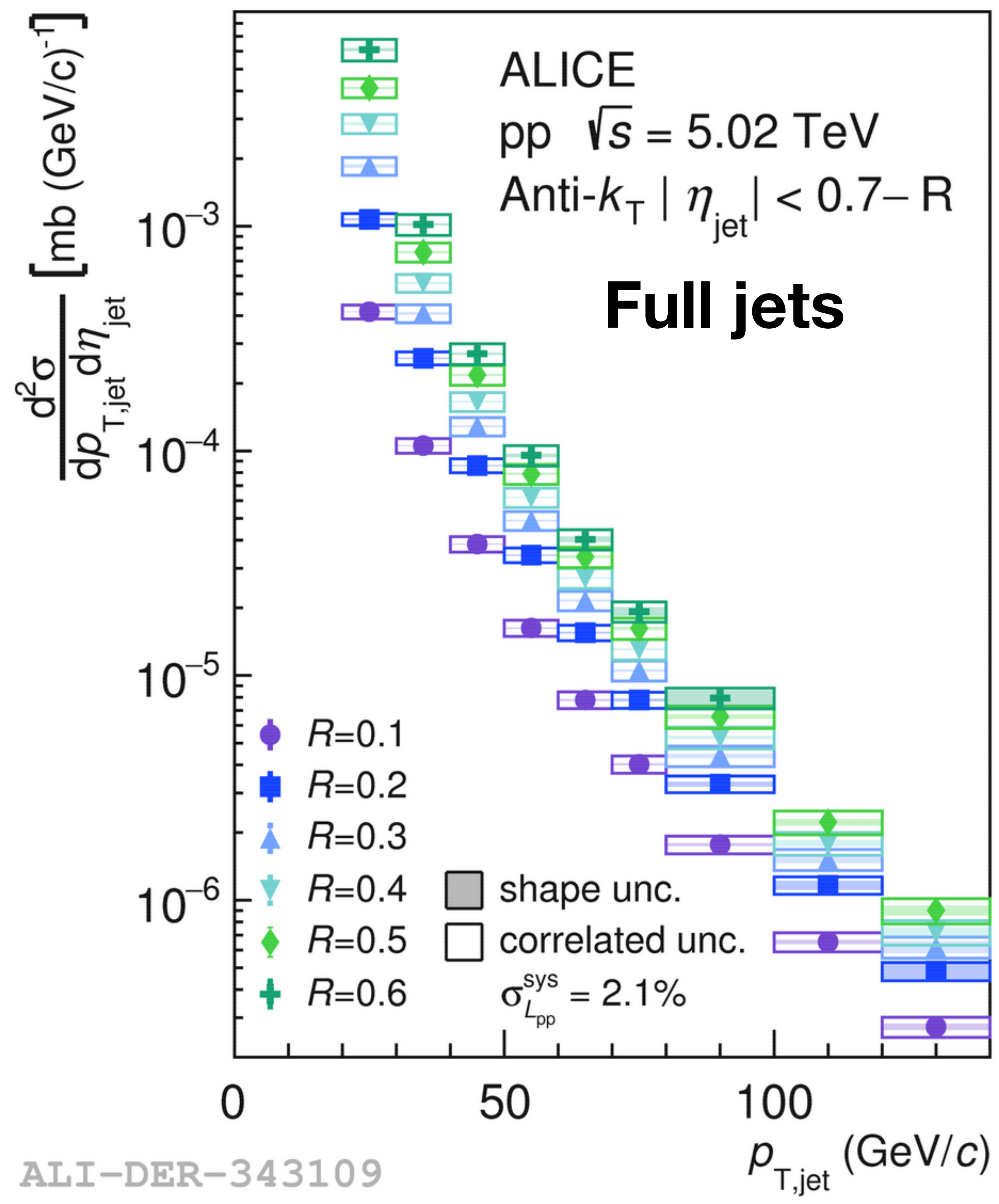
Modification of θ_g: Collimation / Narrowing

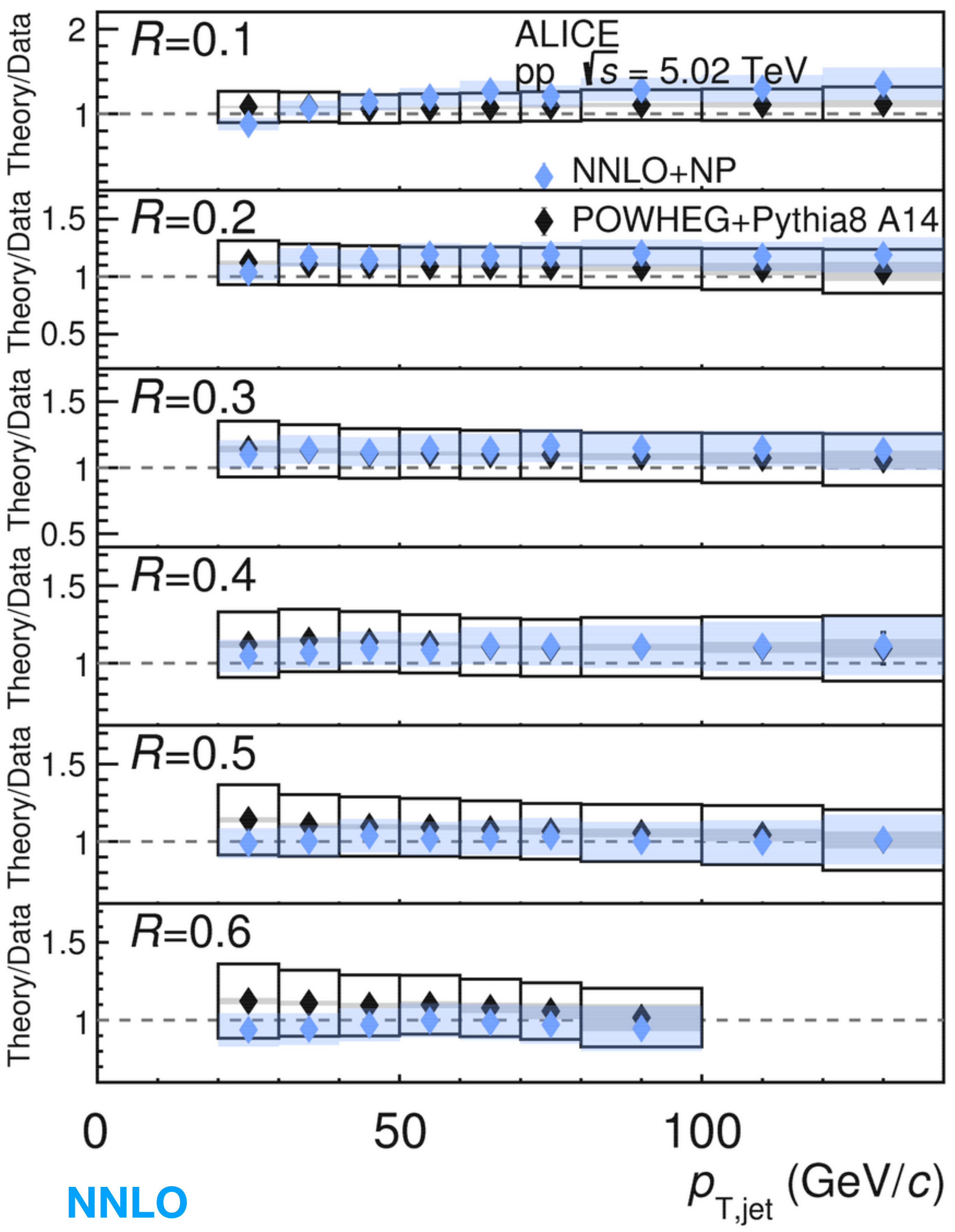


Inclusive jet cross-sections

proton-proton collisions

PRC 101 034911 (2020)





NNLO

Currie, Glover, Pires PRL 118 072002 (2017)

POWHEG+Pythia

Aliolo et al. JHEP 43 (2010), JHEP 4 (2011)

Sjöstrand et al. JHEP05 (2006) 026, CPC 178 (2008) 852

Theoretical approaches

Fixed-order calculations: NLO, NNLO

Resummed calculations: e.g. $(\alpha_s \ln 1/R^2)^n$

Parton showers

NNLO contributions are significant

Currie, Glover, Pires PRL 118 072002 (2017)
Czakon et al. JHEP 262 (2019)

NLL resummations are significant

Liu, Moch, Ringer PRL 119 (2017) 212001

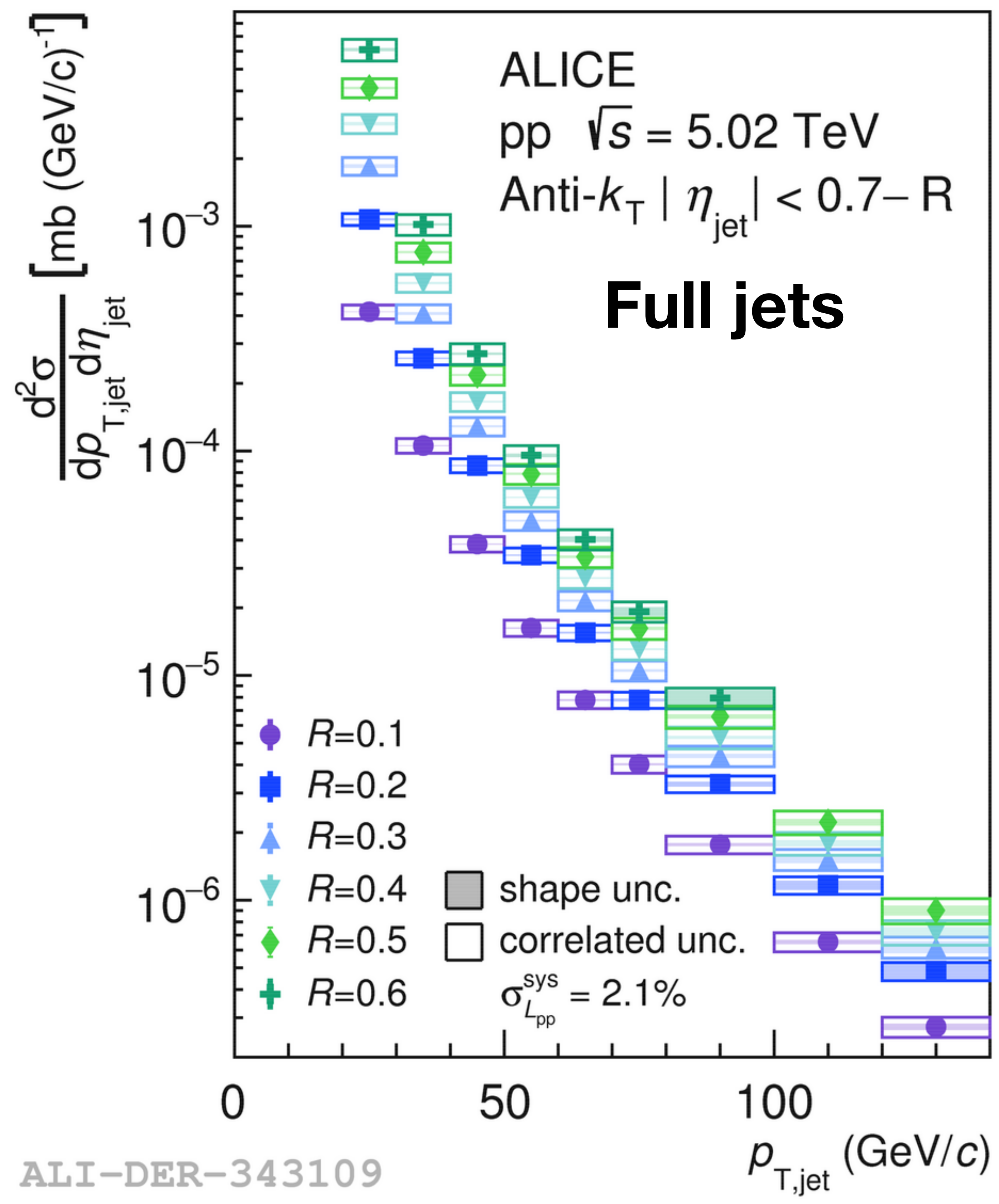
See also CMS 2005.05159 (2020)

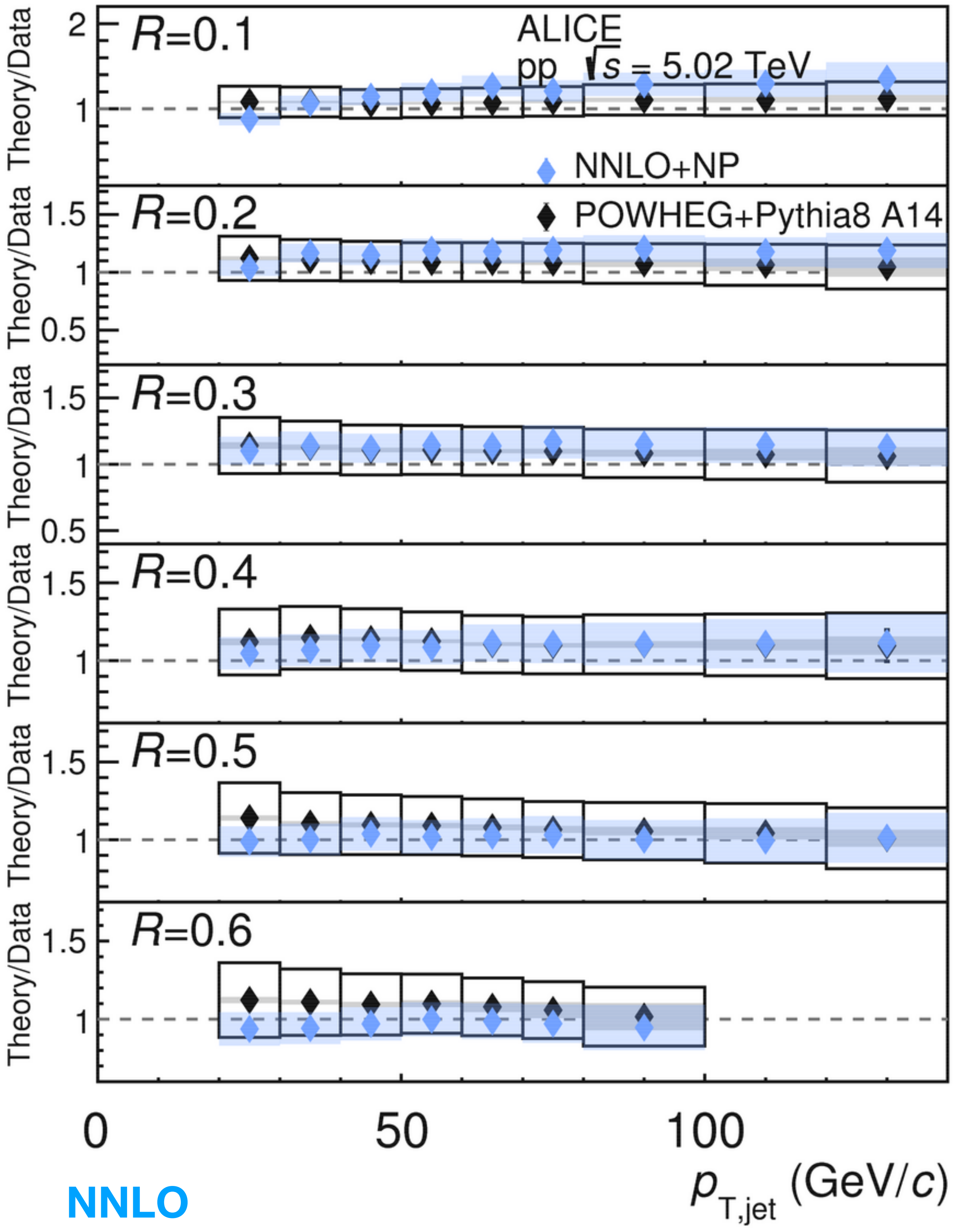
Inclusive jet cross-sections

Modification in Pb-Pb

Suppression of jet yields in heavy-ion collisions relative to scaled pp collisions

PRC 101 034911 (2020)





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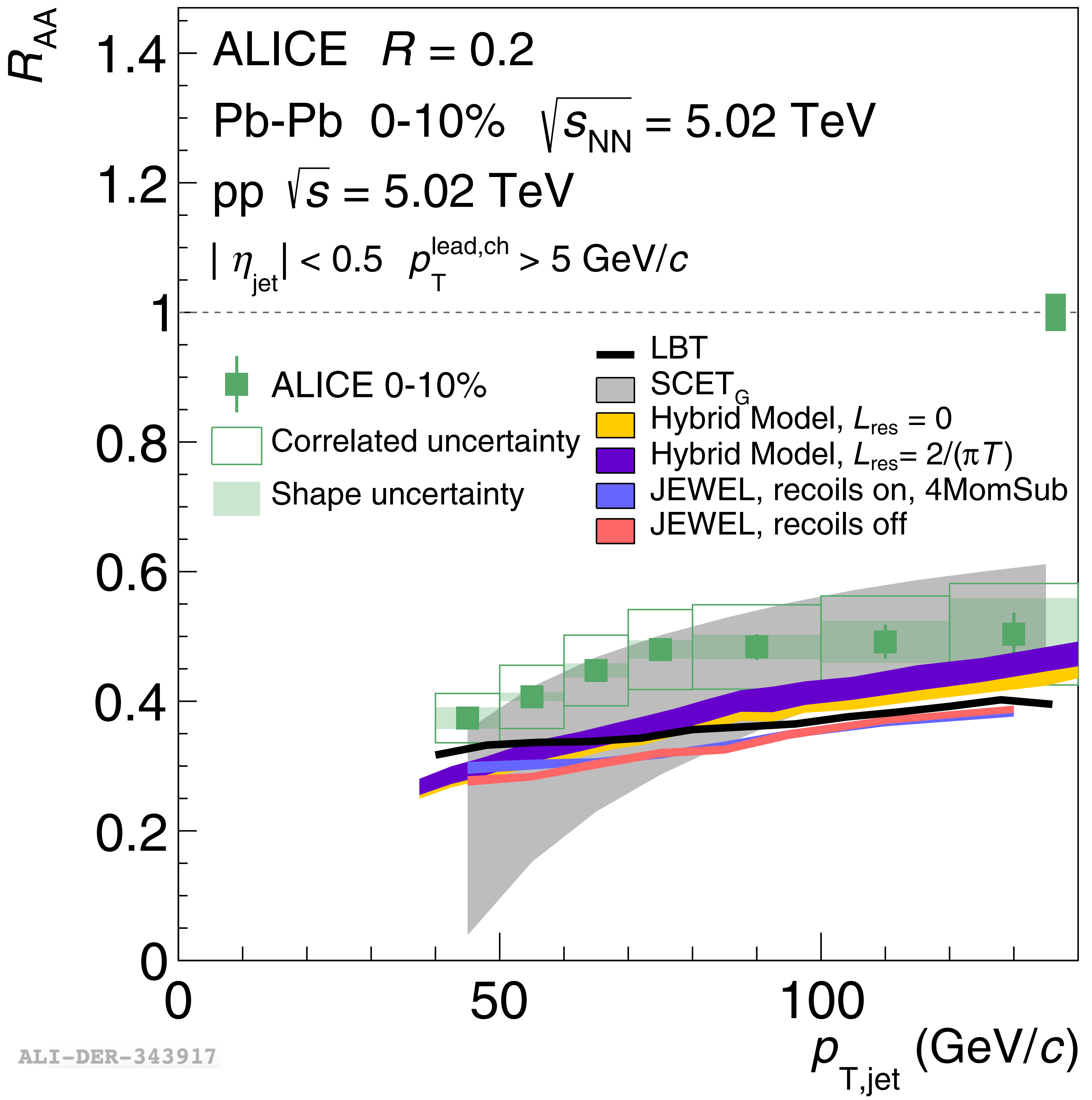
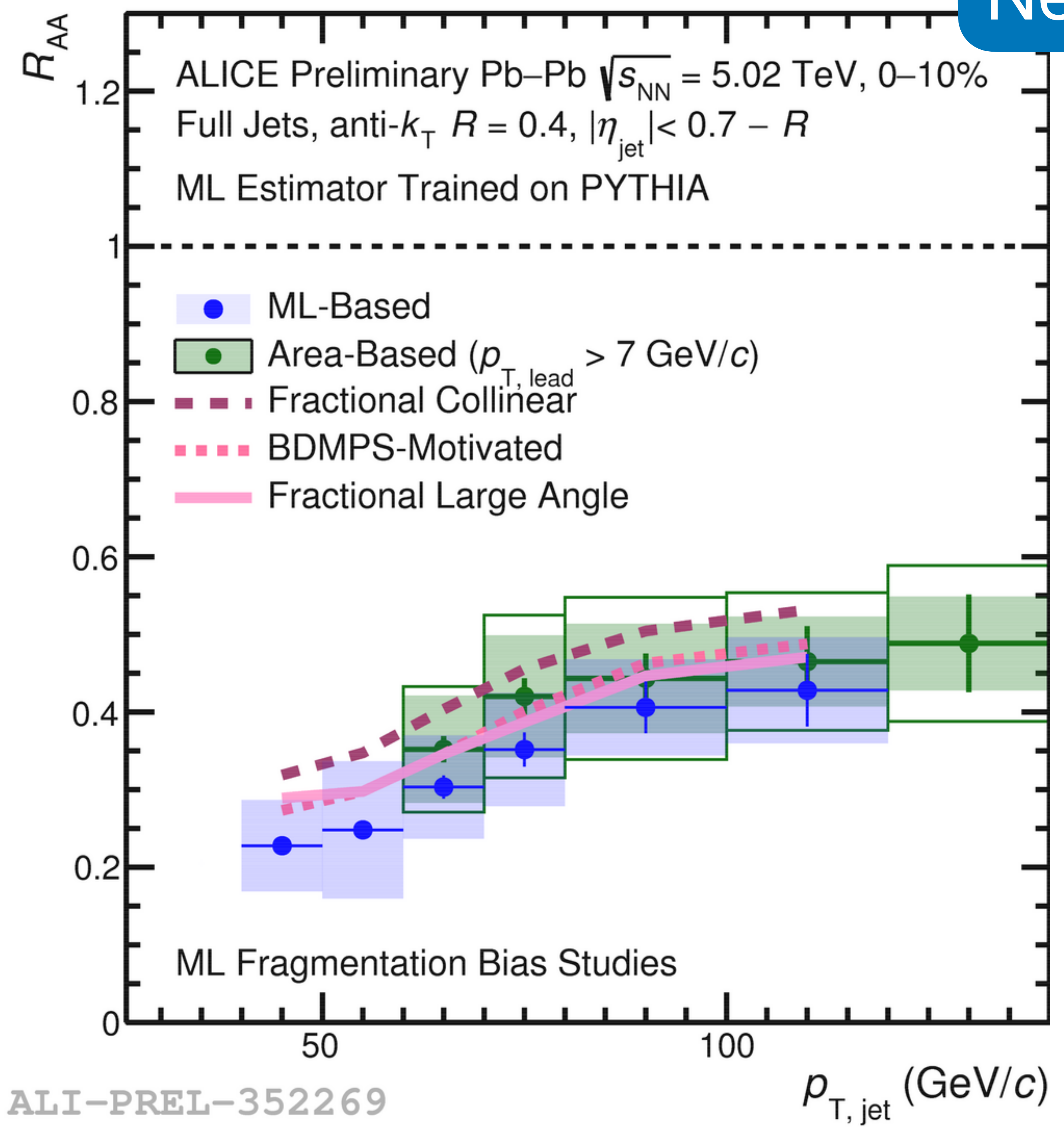


Inclusive jet cross-sections

Modification in Pb-Pb

Exploring new methods: Machine Learning based background subtraction

New Preliminary

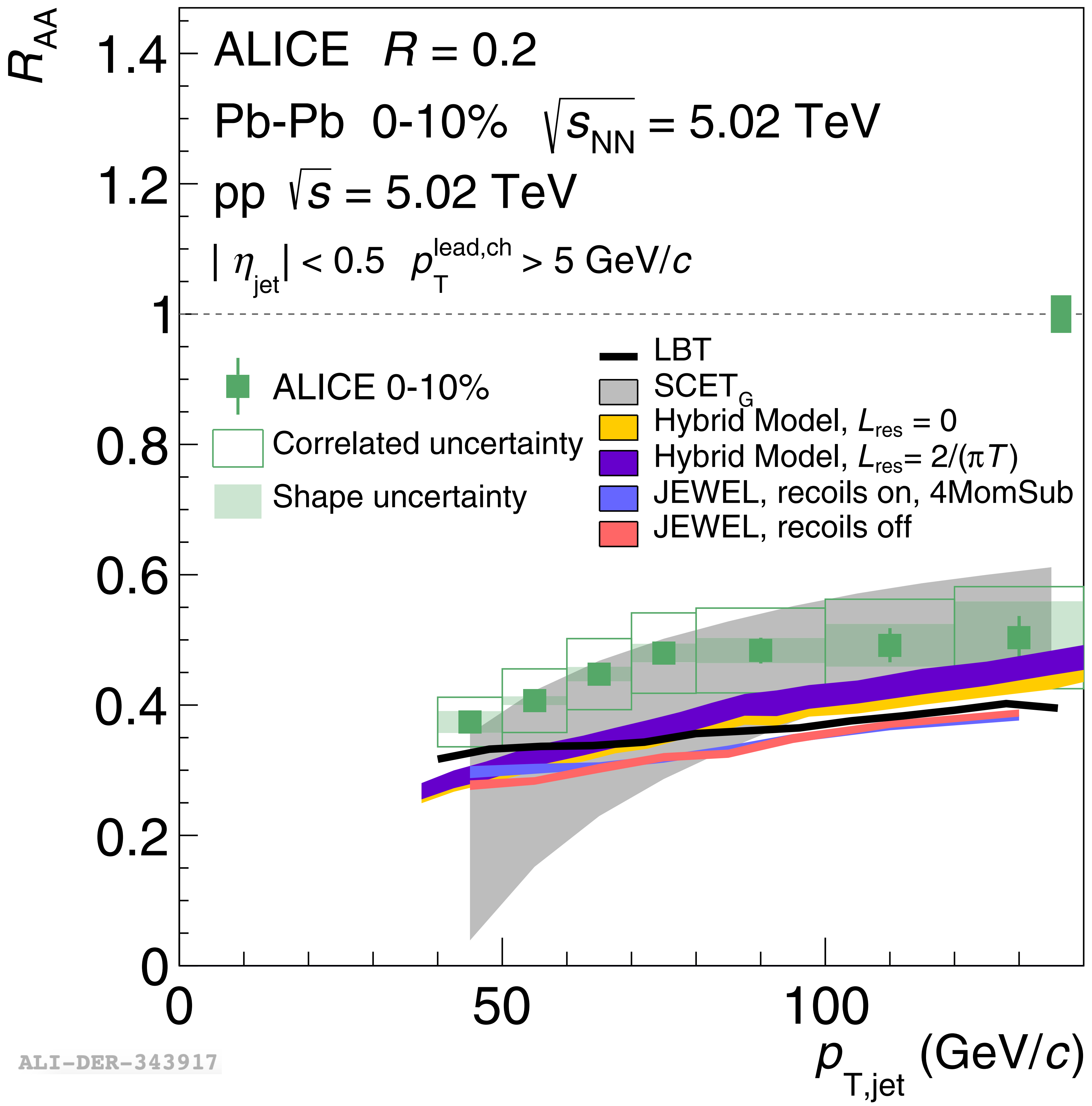


Caution: Introduces large model-dependence

Open question: How to properly quantify bias?

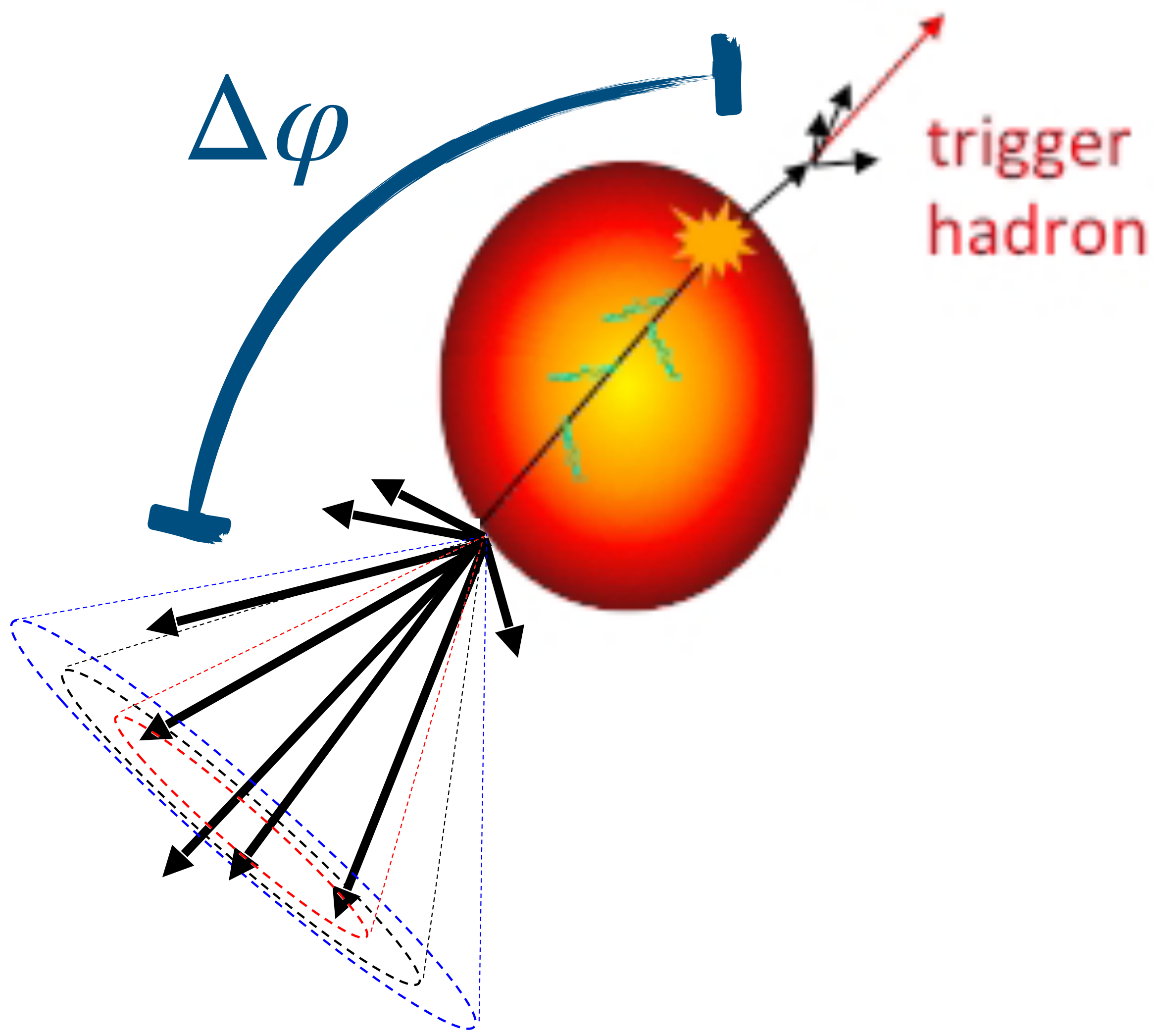
Suppression of jet yields in heavy-ion collisions relative to scaled pp collisions

PRC 101 034911 (2020)



Semi-inclusive hadron-jet correlations

ALICE JHEP 2015 9 (2015) 170
STAR PRC 96 (2017) 024905



Measure semi-inclusive yield of jets recoiling from a trigger hadron:

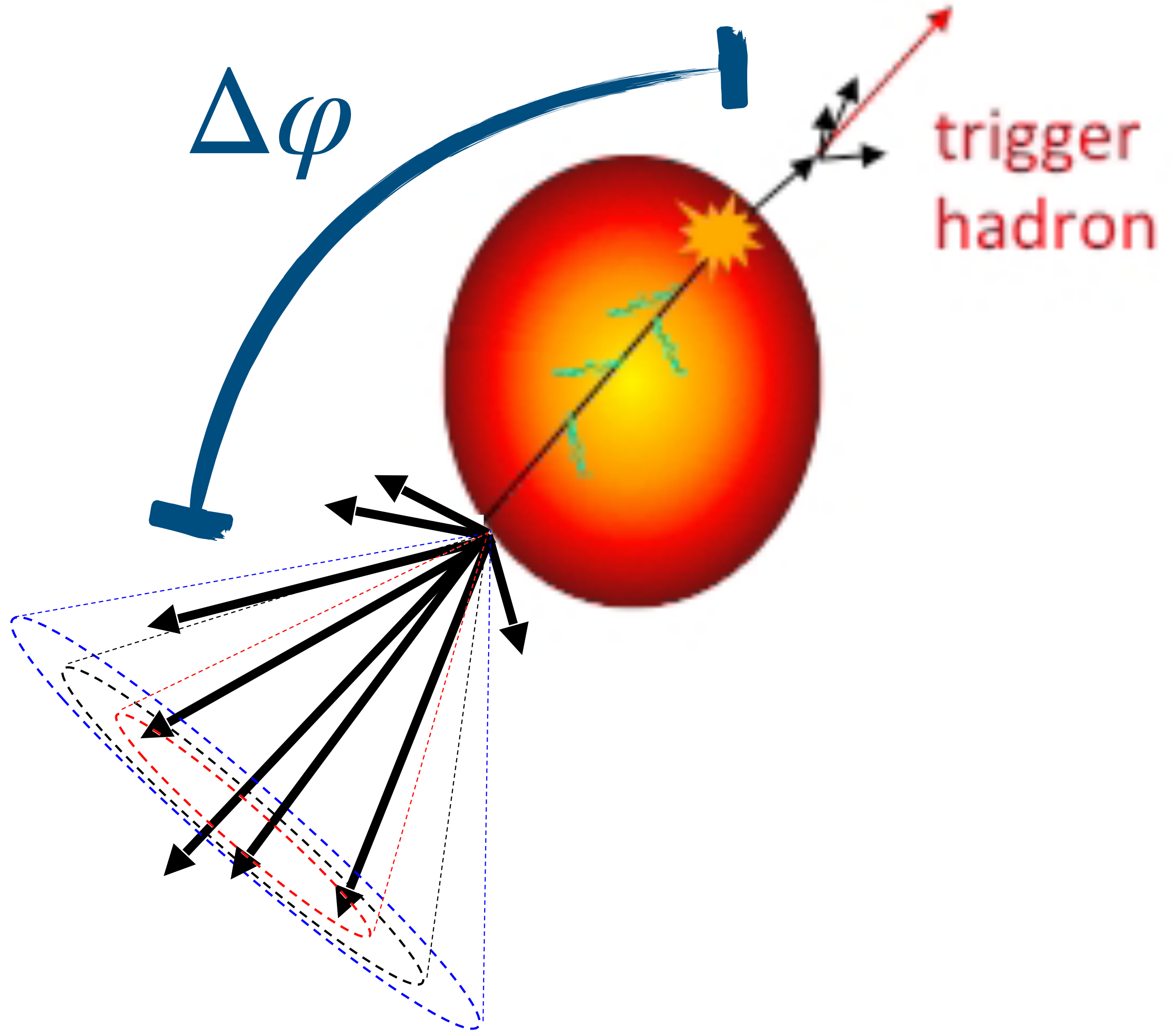
$$\frac{1}{\mathrm{N}^{\mathrm{AA}}_{\mathrm{trig}}} \frac{\mathrm{d}^2\mathrm{N}^{\mathrm{AA}}_{\mathrm{jet}}}{\mathrm{d}p^{\mathrm{ch}}_{\mathrm{T,jet}}\mathrm{d}\eta_{\mathrm{jet}}}\Bigg|_{p_{\mathrm{T,trig}}\in\mathrm{TT}} = \left(\frac{1}{\sigma^{\mathrm{AA}\rightarrow\mathrm{h+X}}} \cdot \frac{\mathrm{d}^2\sigma^{\mathrm{AA}\rightarrow\mathrm{h+jet+X}}}{\mathrm{d}p^{\mathrm{ch}}_{\mathrm{T,jet}}\mathrm{d}\eta_{\mathrm{jet}}}\right)\Bigg|_{p_{\mathrm{T,h}}\in\mathrm{TT}}$$

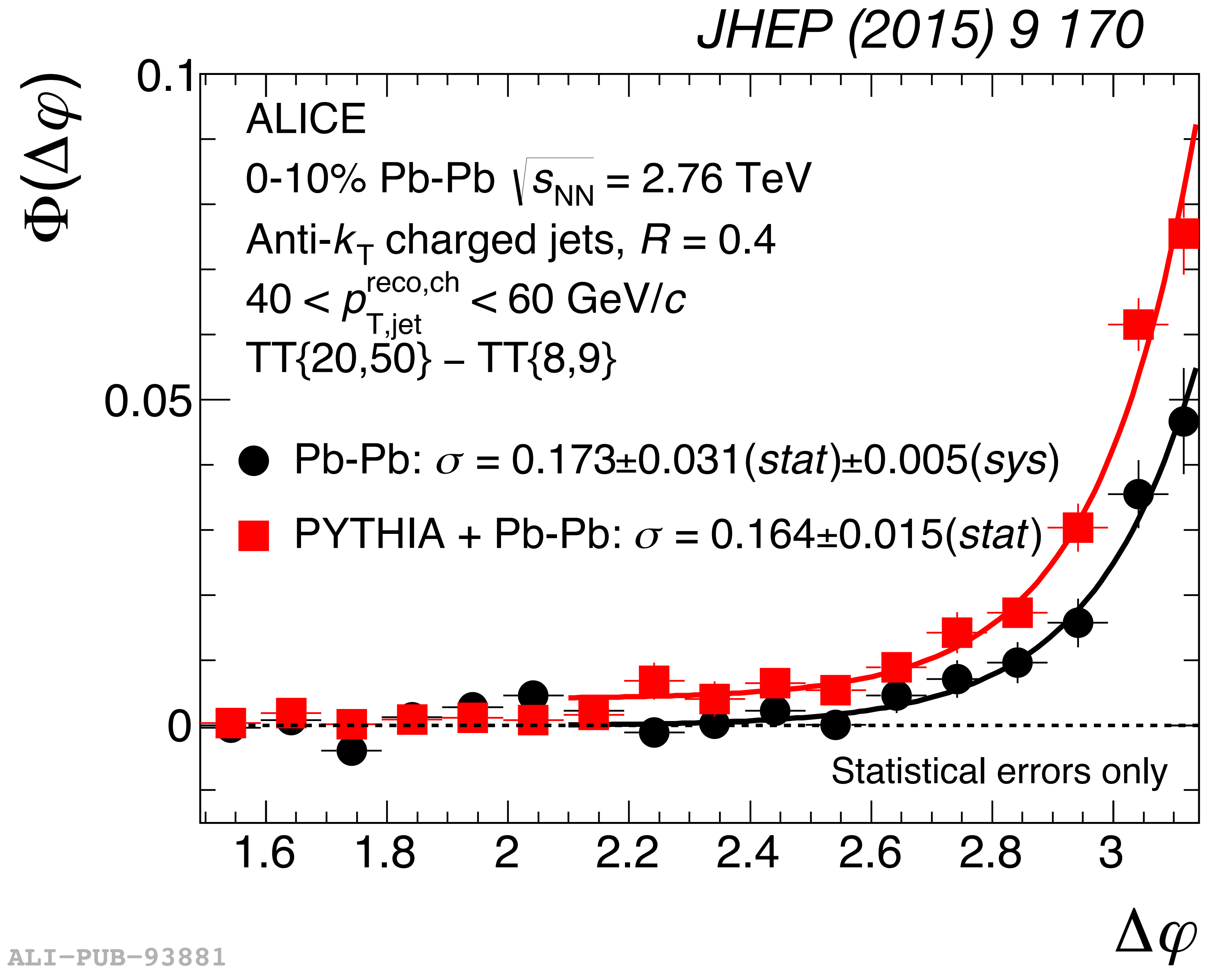
Well-suited to statistical background subtraction procedure in heavy-ion collisions

Allows low-p_{T}, large-*R* measurements

Semi-inclusive hadron-jet correlations

ALICE JHEP 2015 9 (2015) 170
STAR PRC 96 (2017) 024905





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Well-suited to statistical background subtraction procedure in heavy-ion collisions

Allows low-p_T, large-*R* measurements

Angular distribution may be sensitive to:

Large-angle deflection

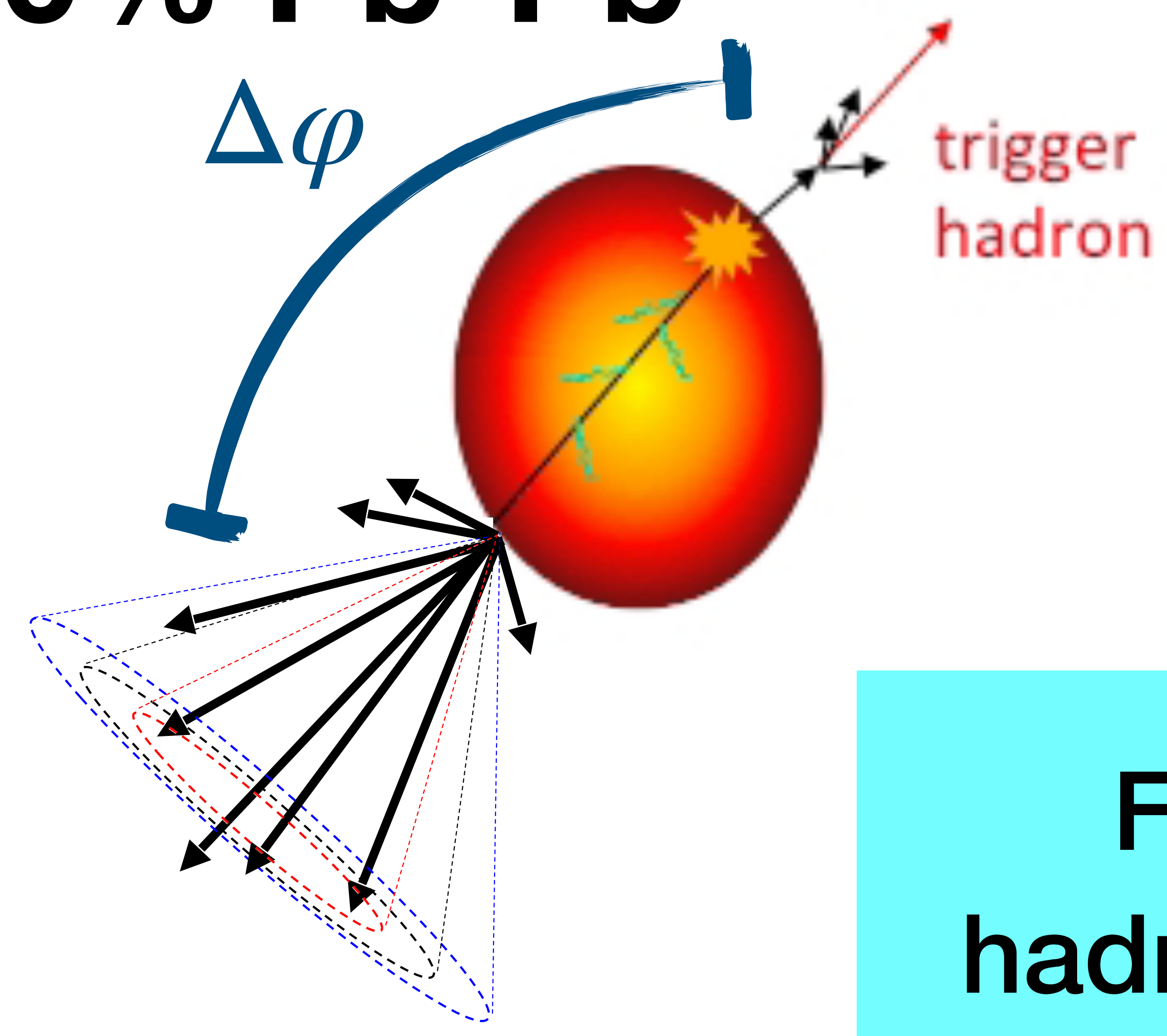
D'Eramo, Rajagopal, Yin JHEP 01 (2019) 172

Jet broadening: $\hat{q}$

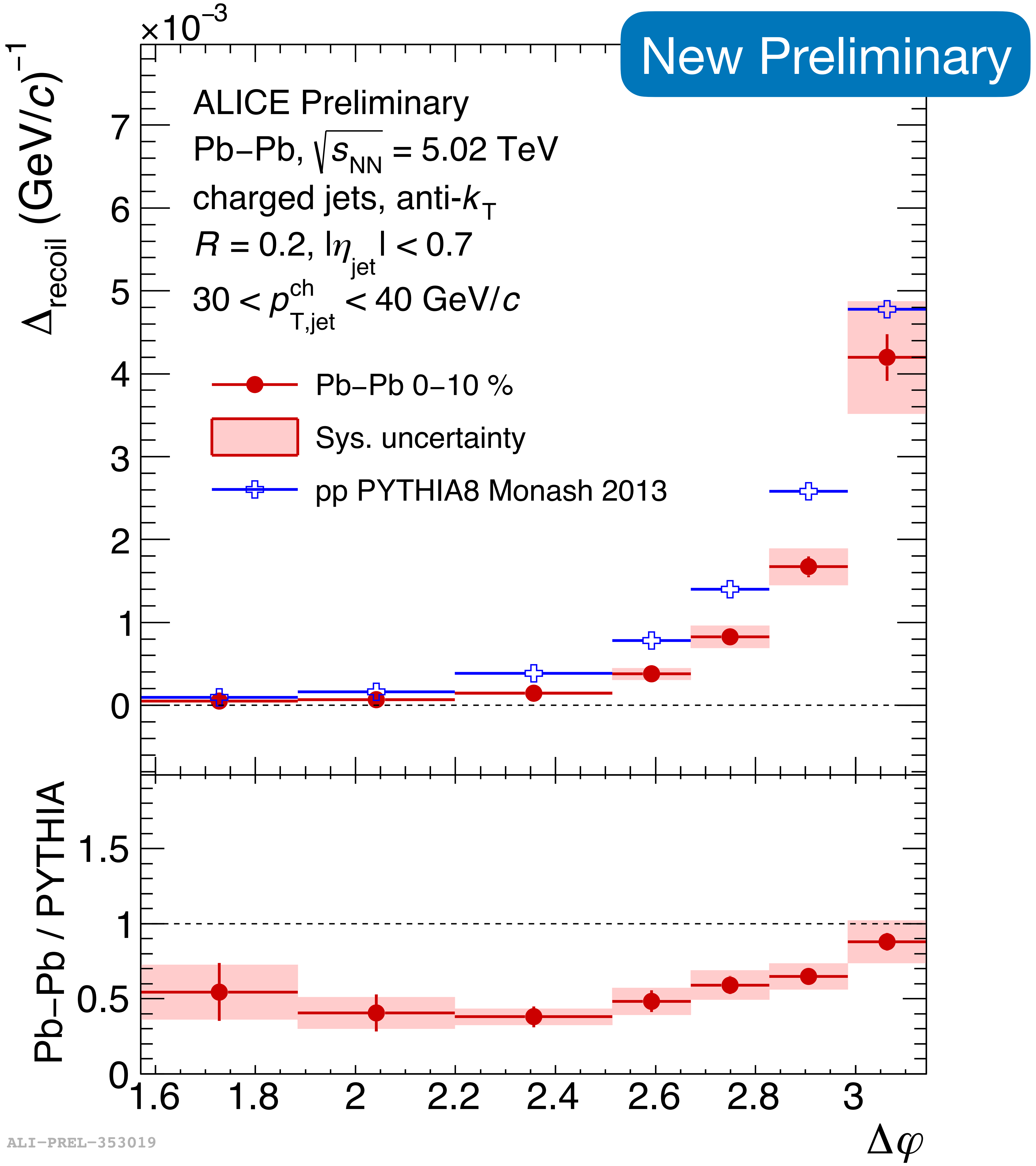
Chen et al., PLB 772 (2017) 672
Gyulassy et al., 1808.03238
Zakharov, 2003.10182

Semi-inclusive hadron-jet correlations

0-10% Pb-Pb



First fully-corrected hadron-jet $\Delta\varphi$ distibution



Two observations:

Suppression of Pb-Pb yields relative to PYTHIA

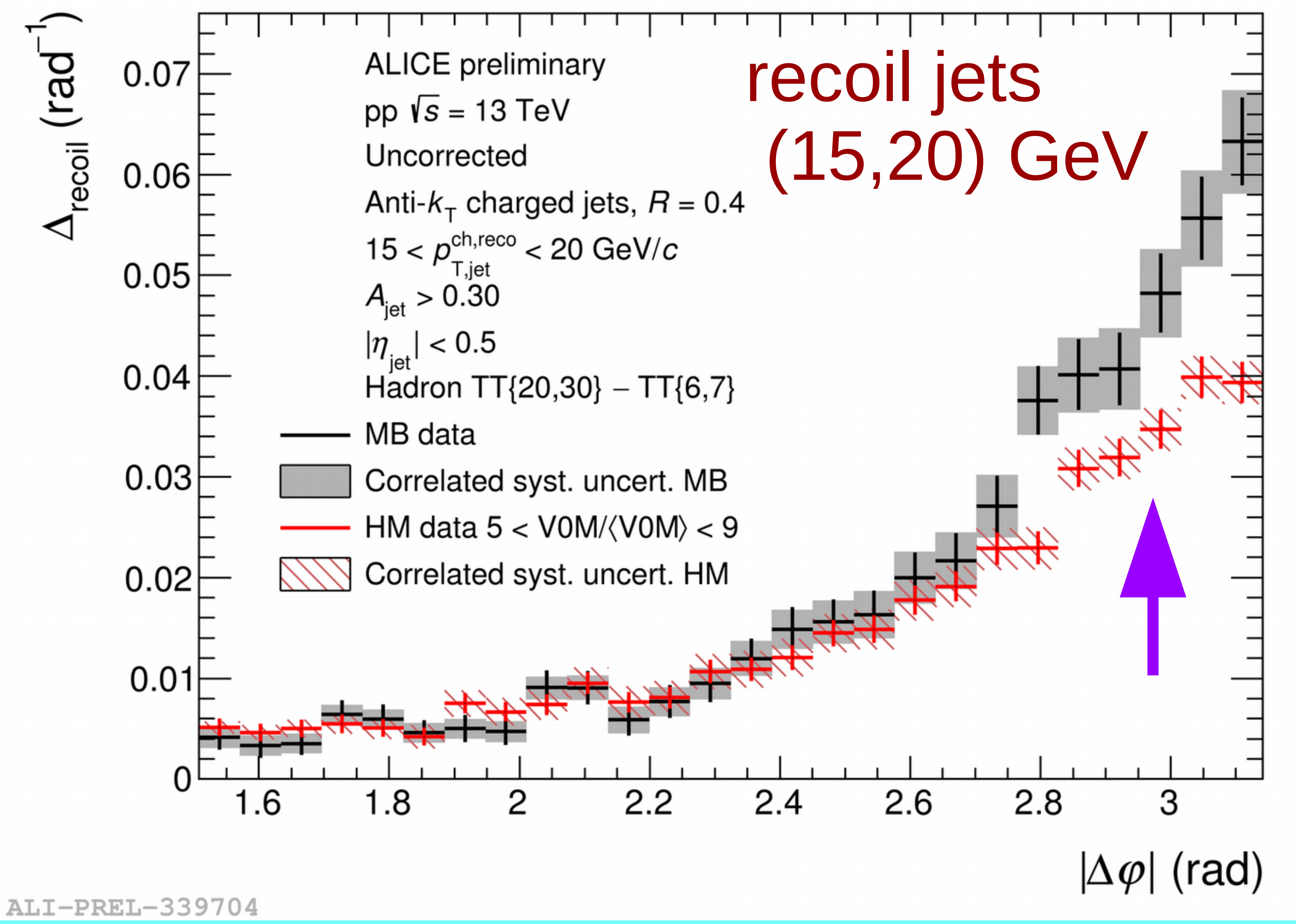
Narrowing of $\Delta\varphi$ distribution towards $\Delta\varphi = \pi$

Role of radiative corrections? *Zakharov, 2003.10182*

Semi-inclusive hadron-jet correlations

High-multiplicity proton-proton collisions

Significant modification of $\Delta\varphi$ distributions in High-Multiplicity (HM) compared to Minimum Bias (MB)



Similar effect seen in PYTHIA — what is its origin?

Semi-inclusive hadron-jet correlations

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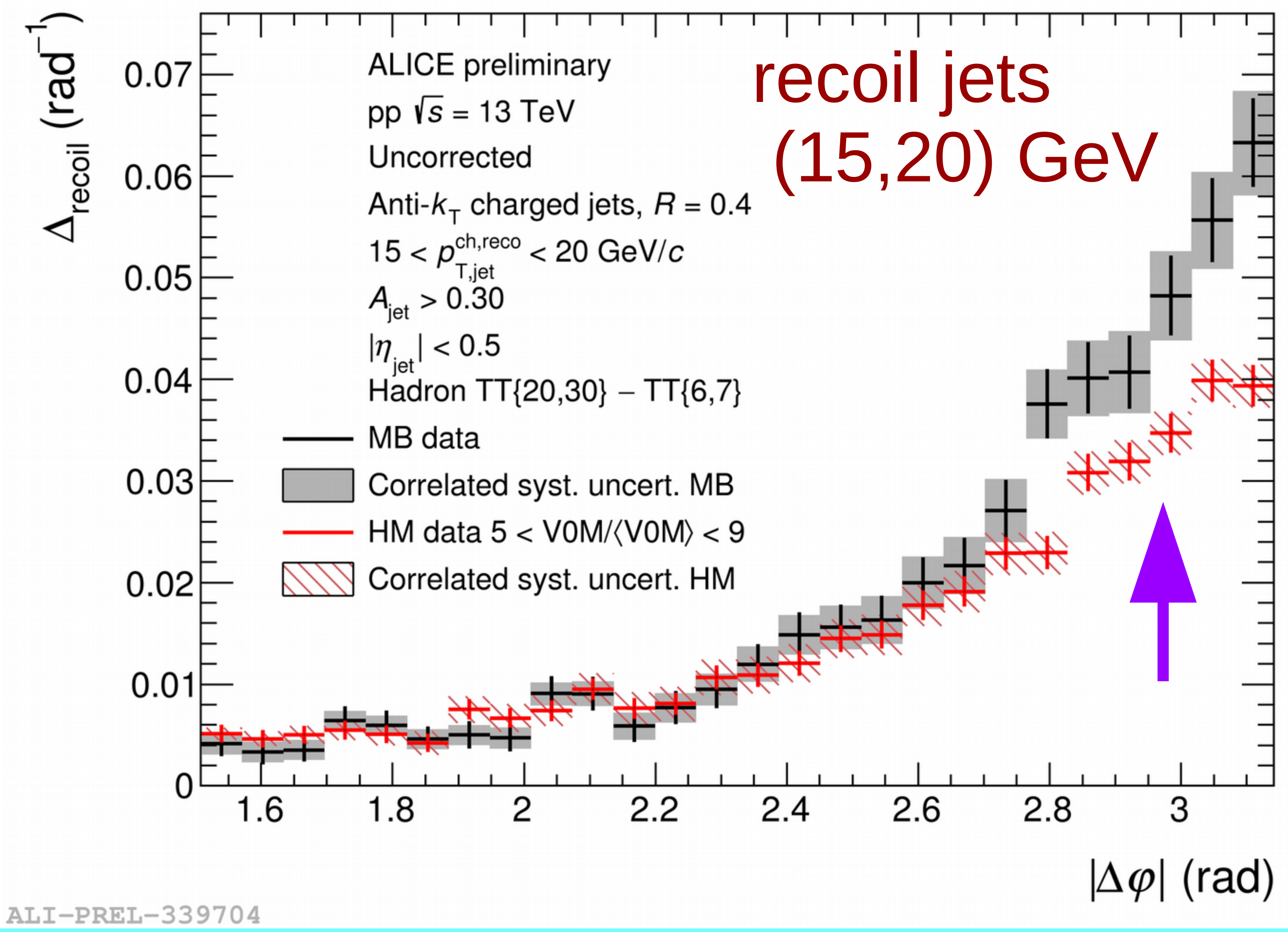
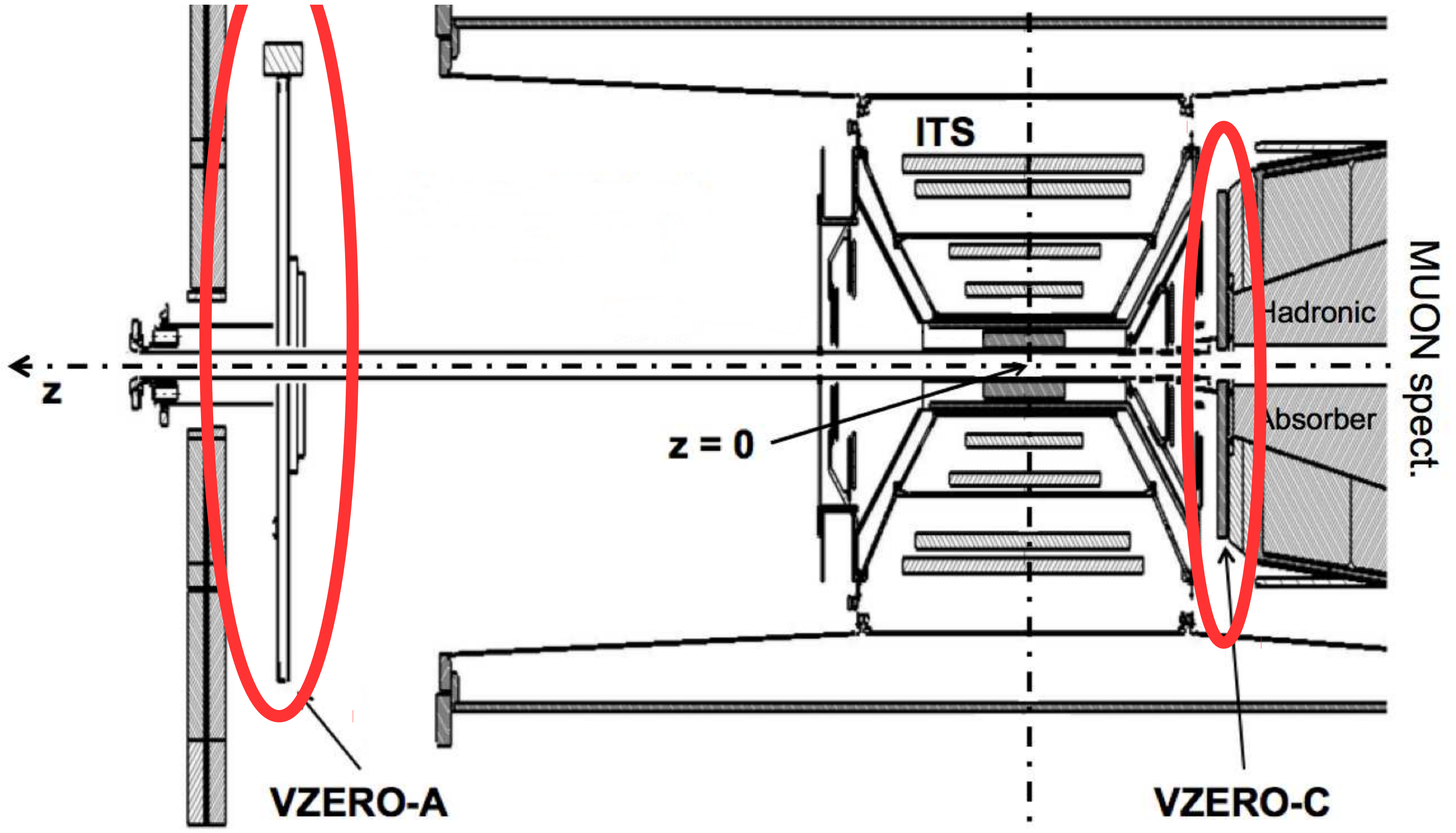


Similar effect seen in PYTHIA — what is its origin?

HM trigger constructed from forward scintillators:

$$5 < \frac{V0A + V0A}{\langle V0A + V0C \rangle} < 9$$

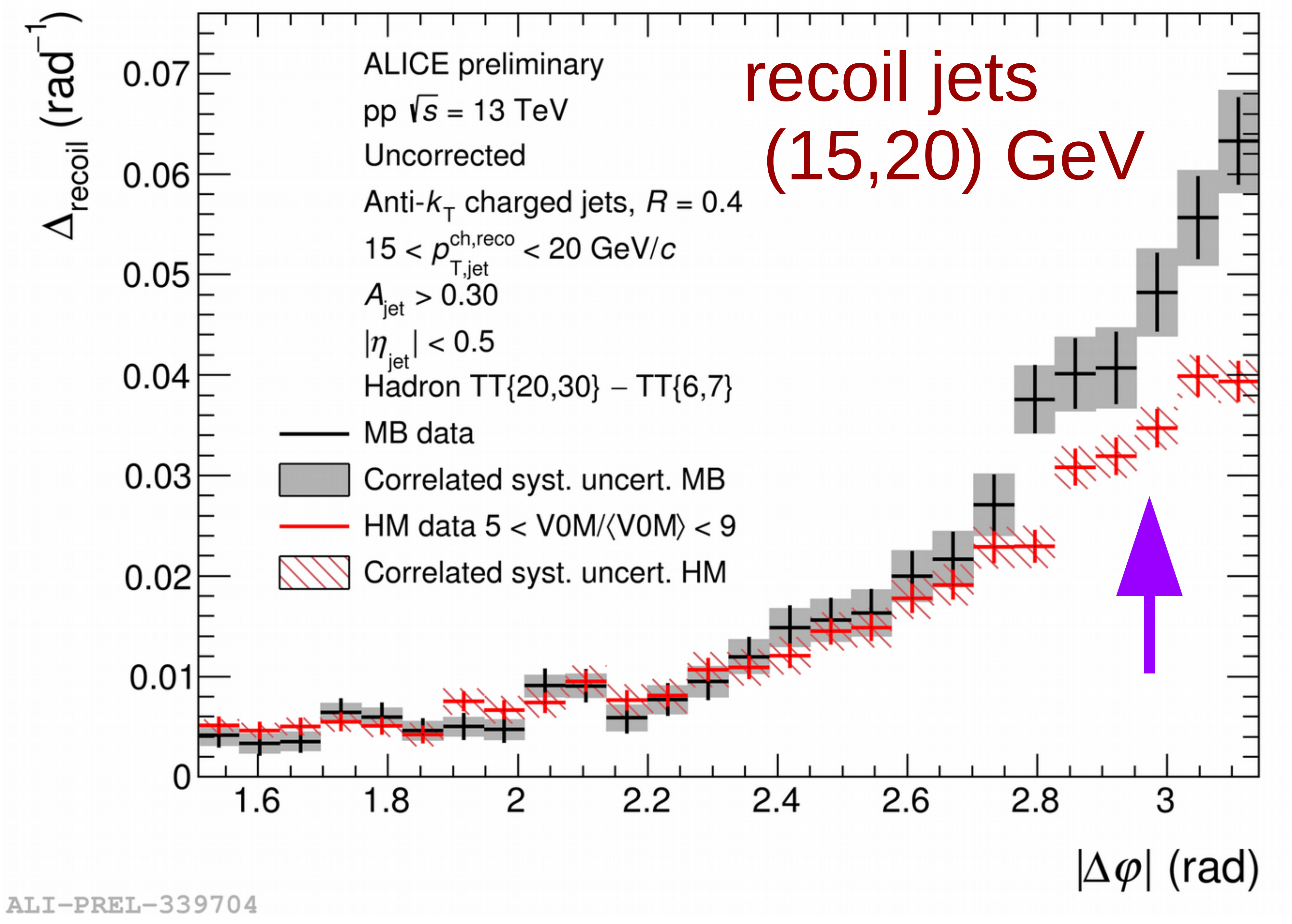


V0A : 2.8 < η < 5.1   V0C : -3.7 < η < -1.7

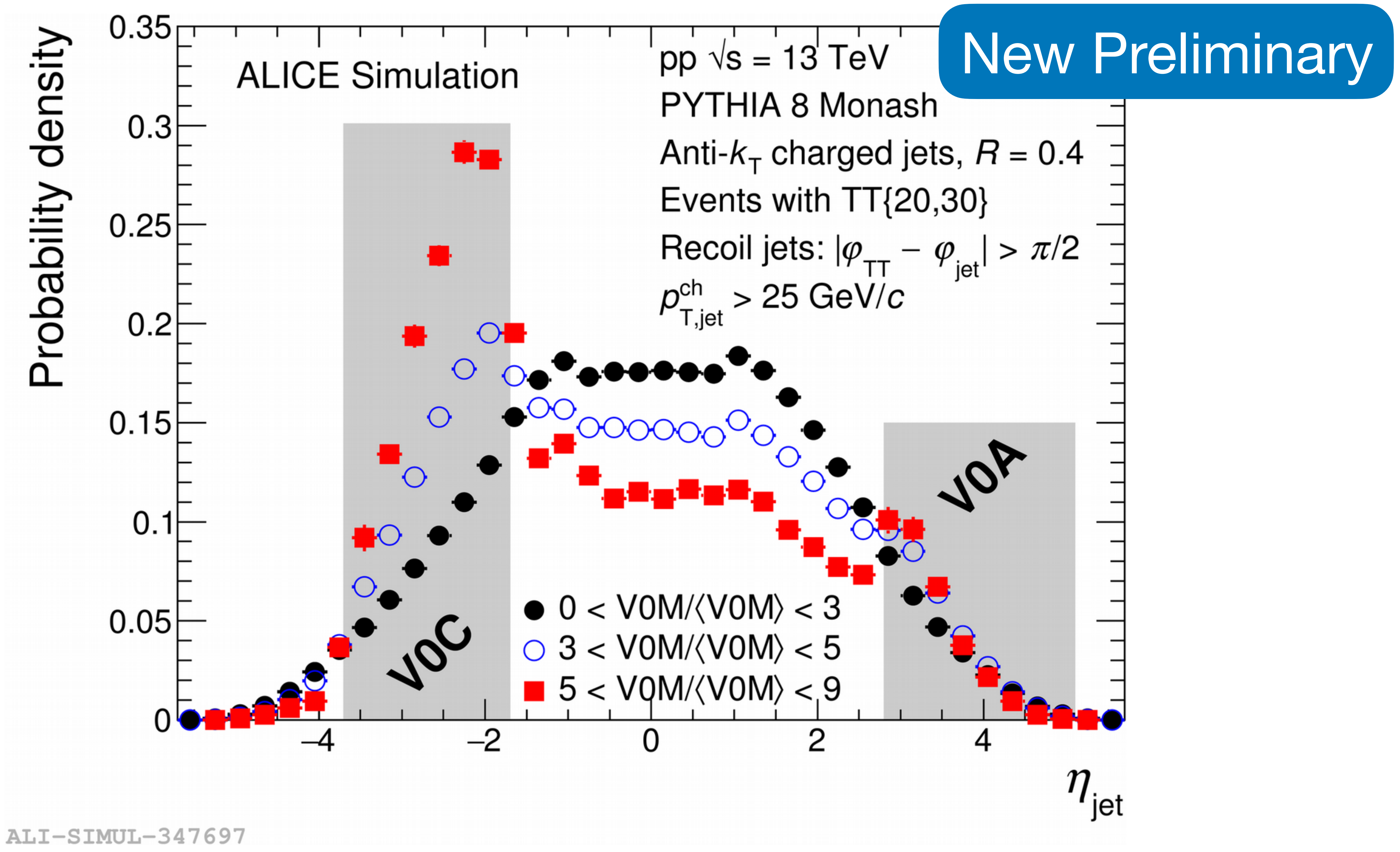
Semi-inclusive hadron-jet correlations

High-multiplicity proton-proton collisions

Significant modification of $\Delta\varphi$ distirbutions in High-Multiplicity (HM) compared to Minimum Bias (MB)



HM trigger induces forward-backward rapidity bias for recoil jets



High-multiplicity requirement biases towards multi-jet topologies

Summary

ALICE has a rich QCD jet program in both pp and Pb-Pb collisions

Jet substructure measurements

A variety of groomed and ungroomed observables in pp collisions
First fully corrected measurements of Soft Drop z_g, θ_g in heavy-ion collisions

Inclusive and semi-inclusive measurements

Inclusive cross-sections test pQCD calculations and constrain jet quenching models
Semi-inclusive techniques allow low-p_{T} measurements to probe jet acoplanarity

And more not covered!

LHC Run 3 will open new jet possibilities:
Heavy-flavor, differential measurements, correlations, …

Backup

Soft Drop — D^0-tagged jets
proton-proton collisions

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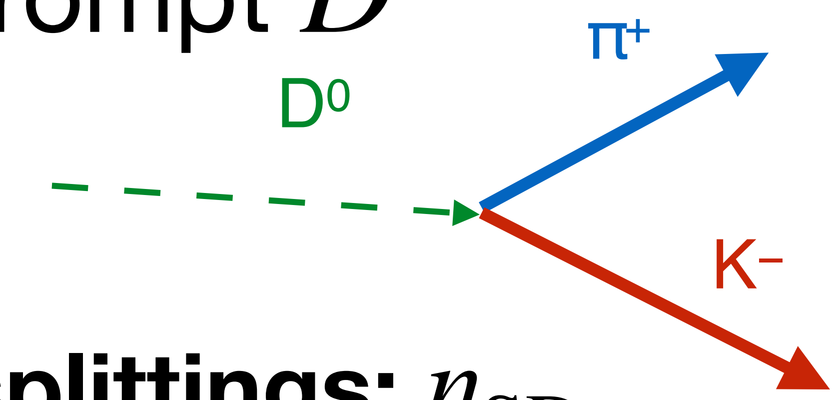
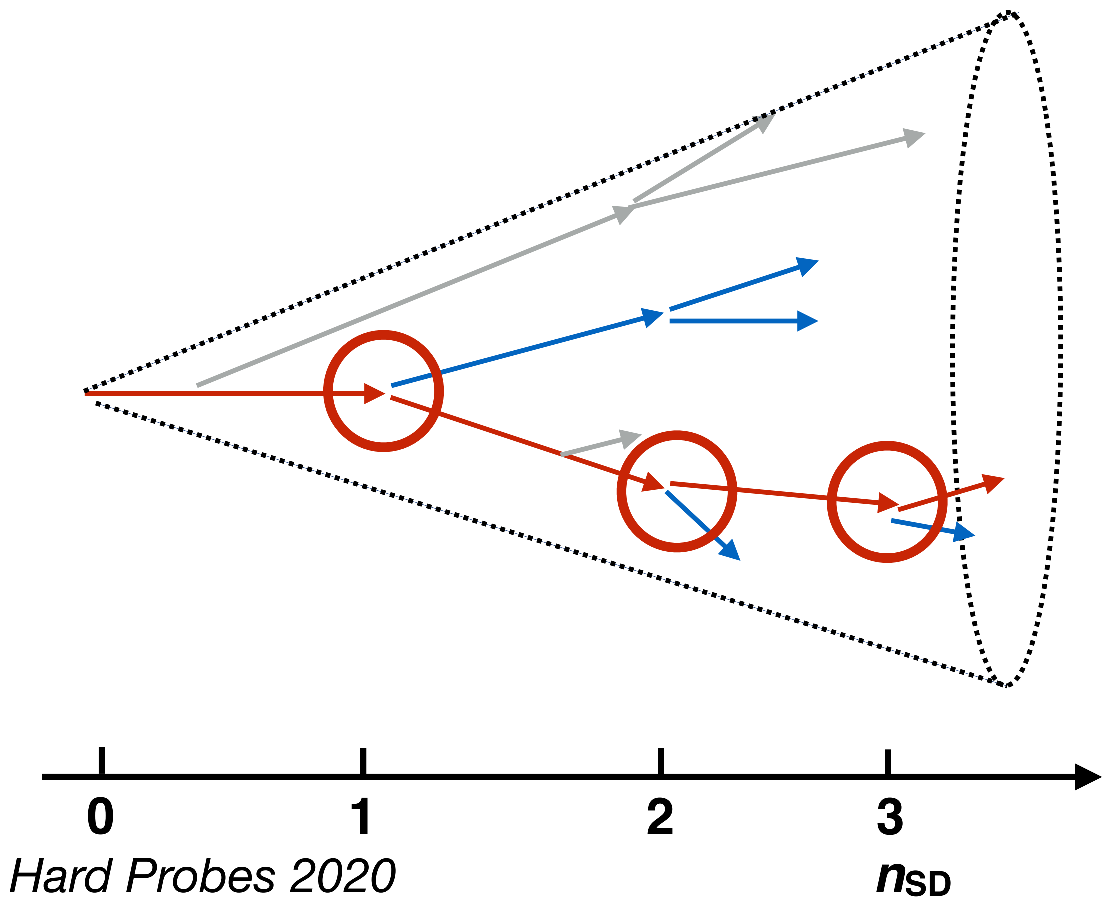
D^0-tagged jet: A jet containing a prompt D^0



Total number of iterative Soft Drop splittings: n_{SD}



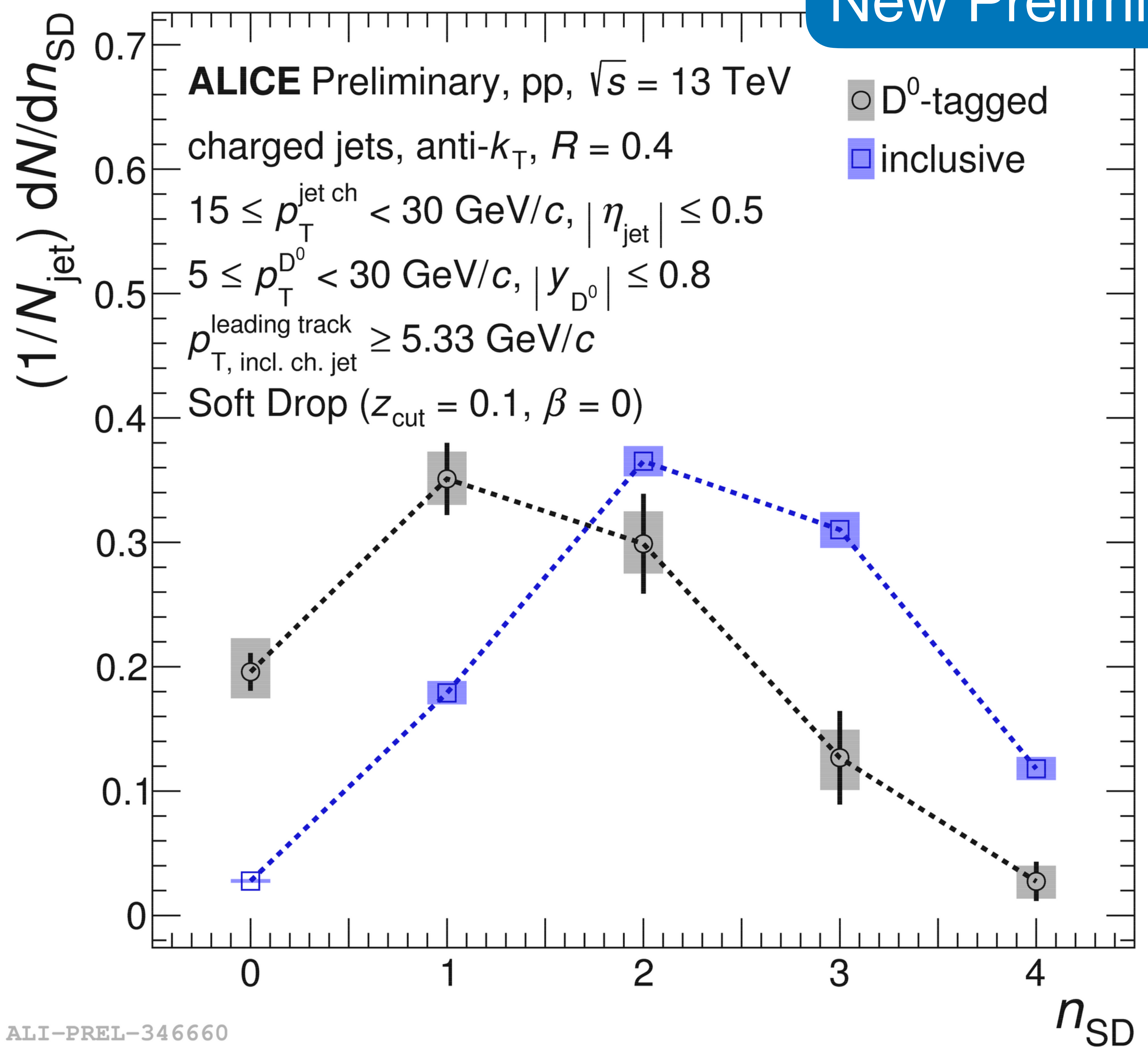
V. Kucera, Hard Probes 2020

Goal: Constrain charm fragmentation

Dead-cone effect

Quark vs. gluon differences

New Preliminary



Harder fragmentation of charm quark compared to inclusive jets

Soft Drop — D^0-tagged jets

New Preliminary

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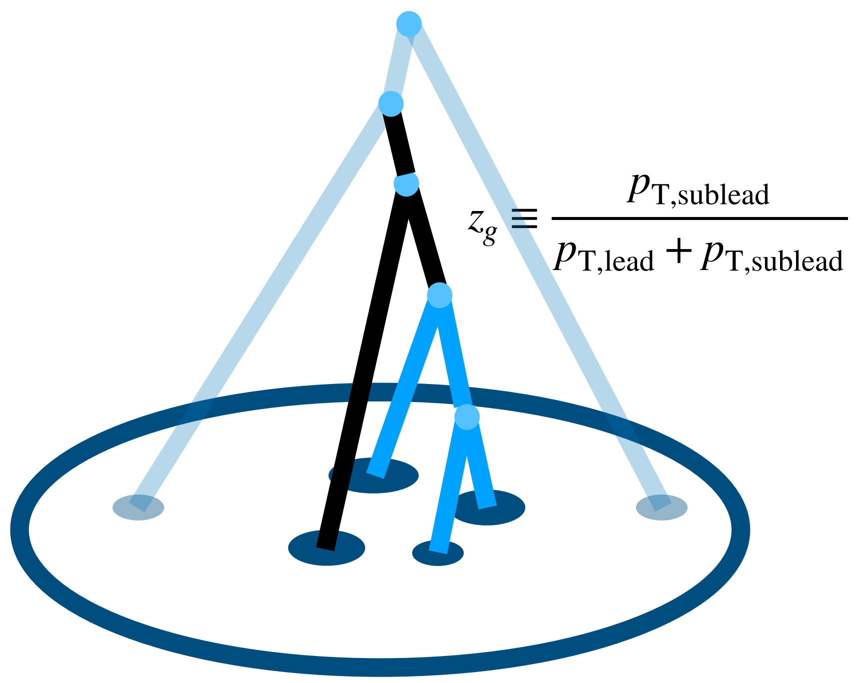
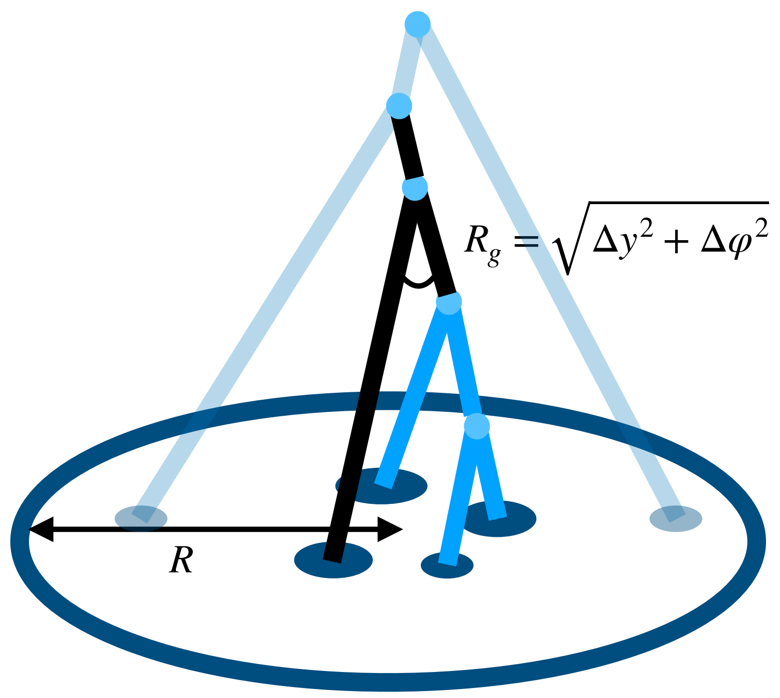
ALICE

Recluster and groom jet to expose hard splitting

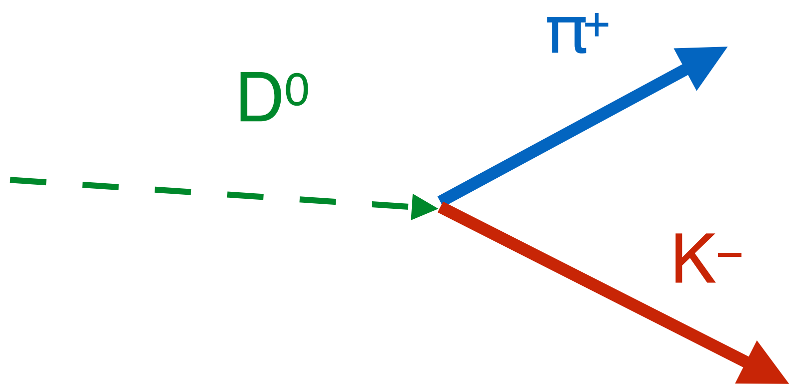
Soft Drop: $z < z_{cut}\theta^{\beta}$

Dasgupta, Fregoso, Marzani, Salam 1307.0007
Larkoski, Marzani, Soyez, Thaler 1402.2657
Larkoski, Marzani, Thaler 1502.01719





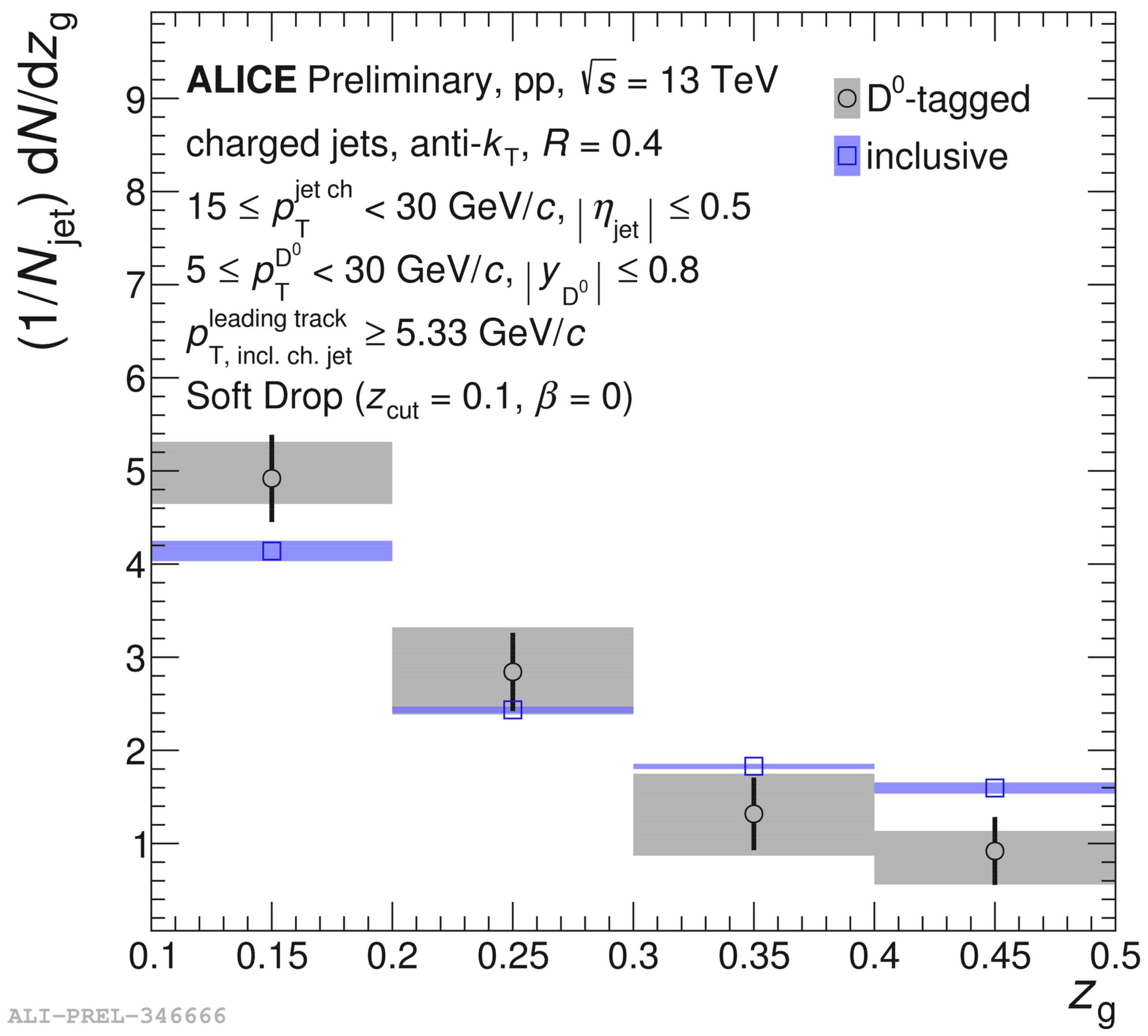
D^0-tagged jet: A jet containing a prompt D^0

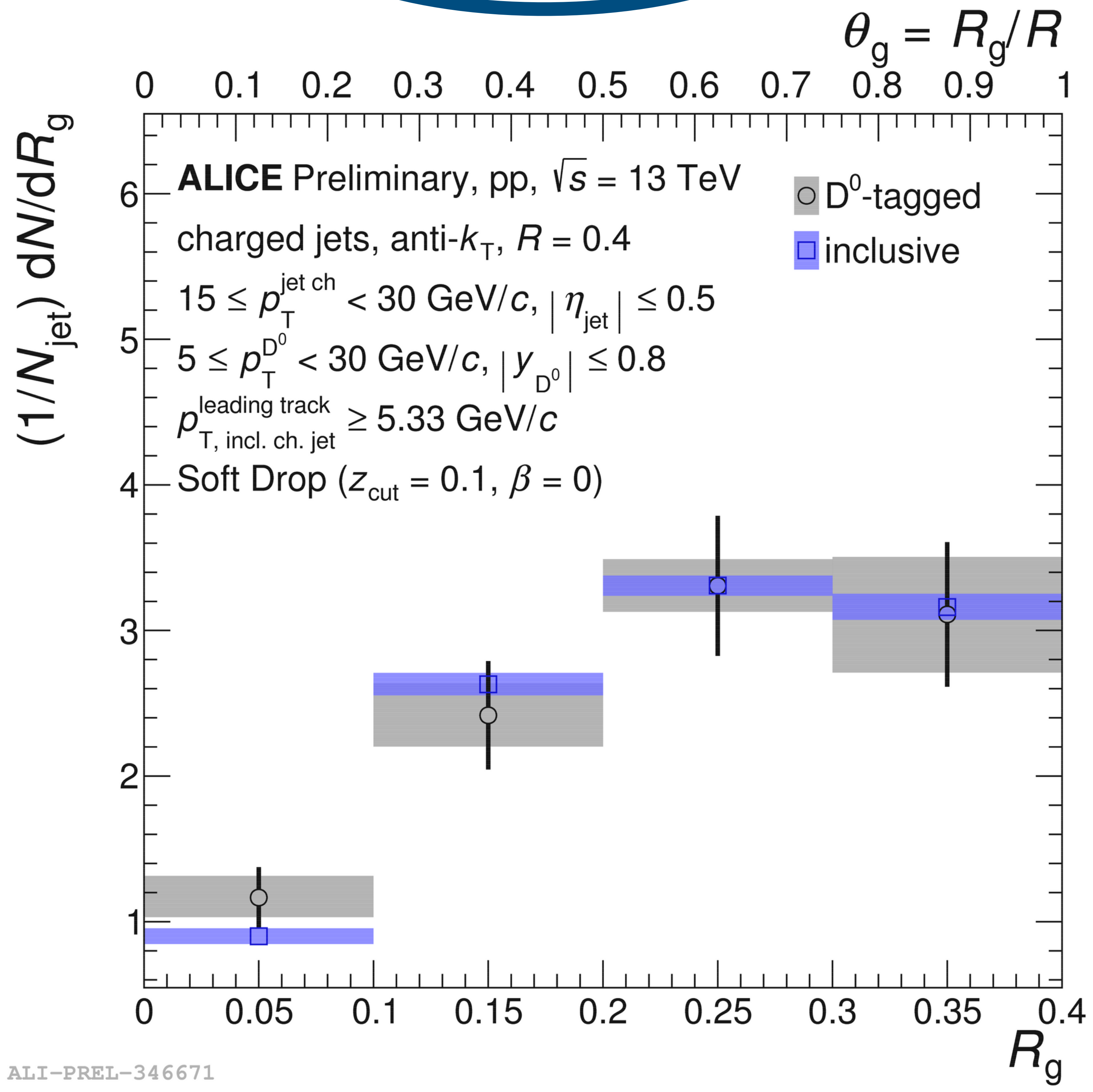


Physics effects

Dead-cone

Quark vs. gluon





No significant modification of D^0-tagged compared to inclusive

Dynamical Grooming

New Preliminary

Y. Mehtar-Tani, A. Soto-Ontoso, K. Tywoniuk
PRD 101 (2020) 034004

ALICE

Identify splitting in C/A tree as the **maximum** of a particular grooming condition:

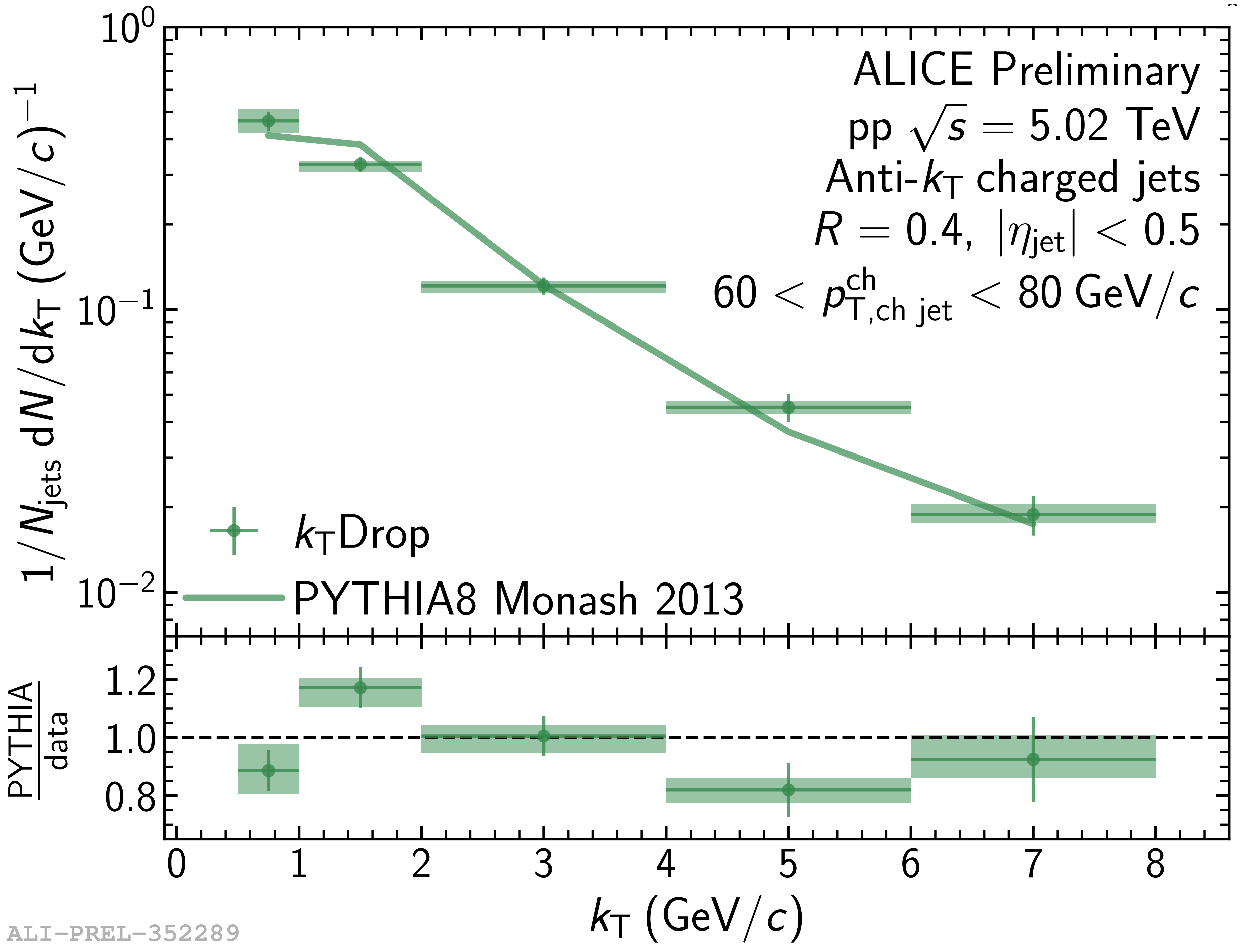
$$z_i(1 - z_i)p_{T,i}\theta_i^a$$

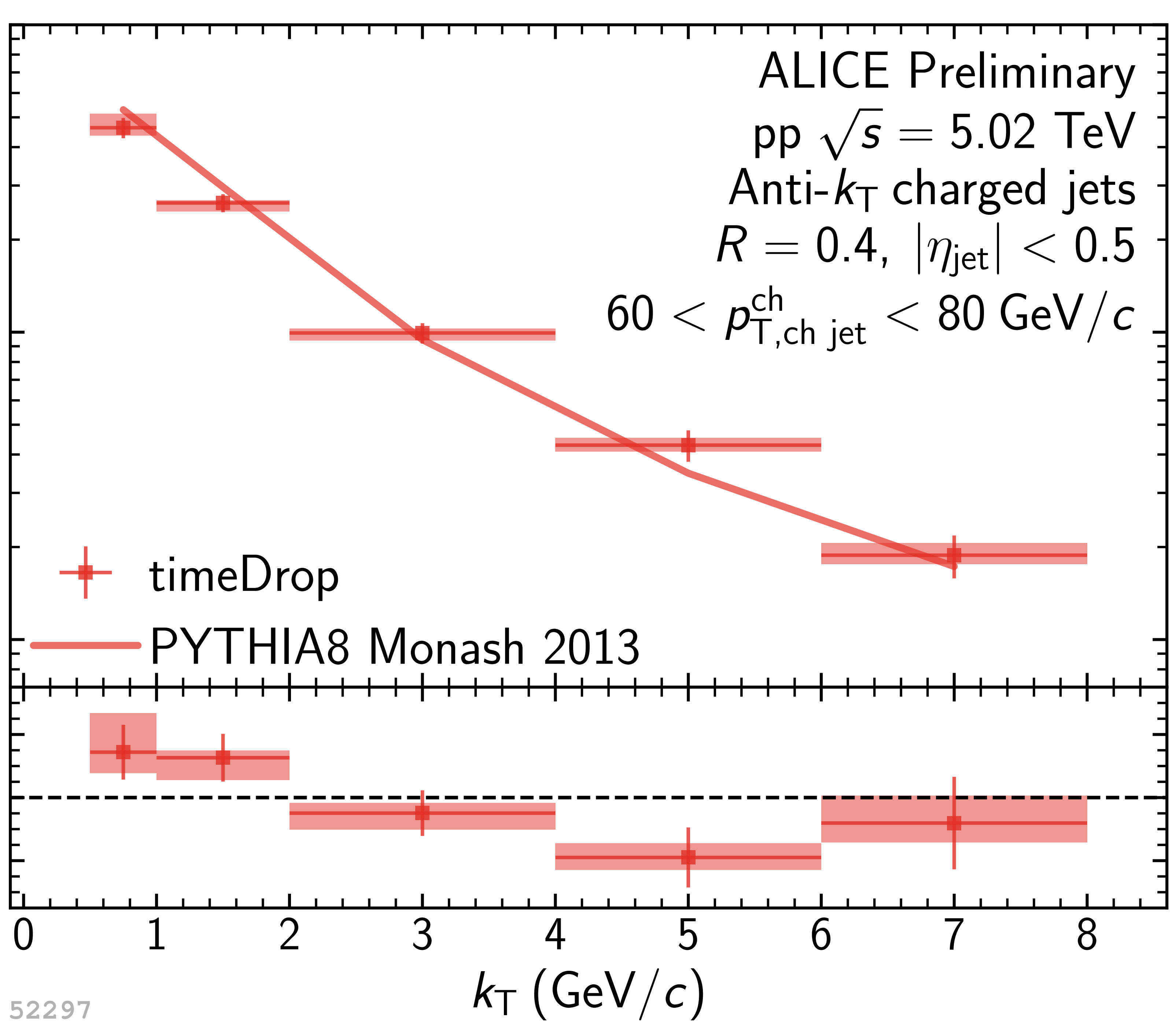
Similar to Soft Drop — except grooming condition varies jet-by-jet

$a \to 0$	hardest z
$a = 1$	hardest k_T (k_TDrop)
$a = 2$	smallest t_f (timeDrop)

First measurement of Dynamical Grooming

→ **Well described by PYTHIA**





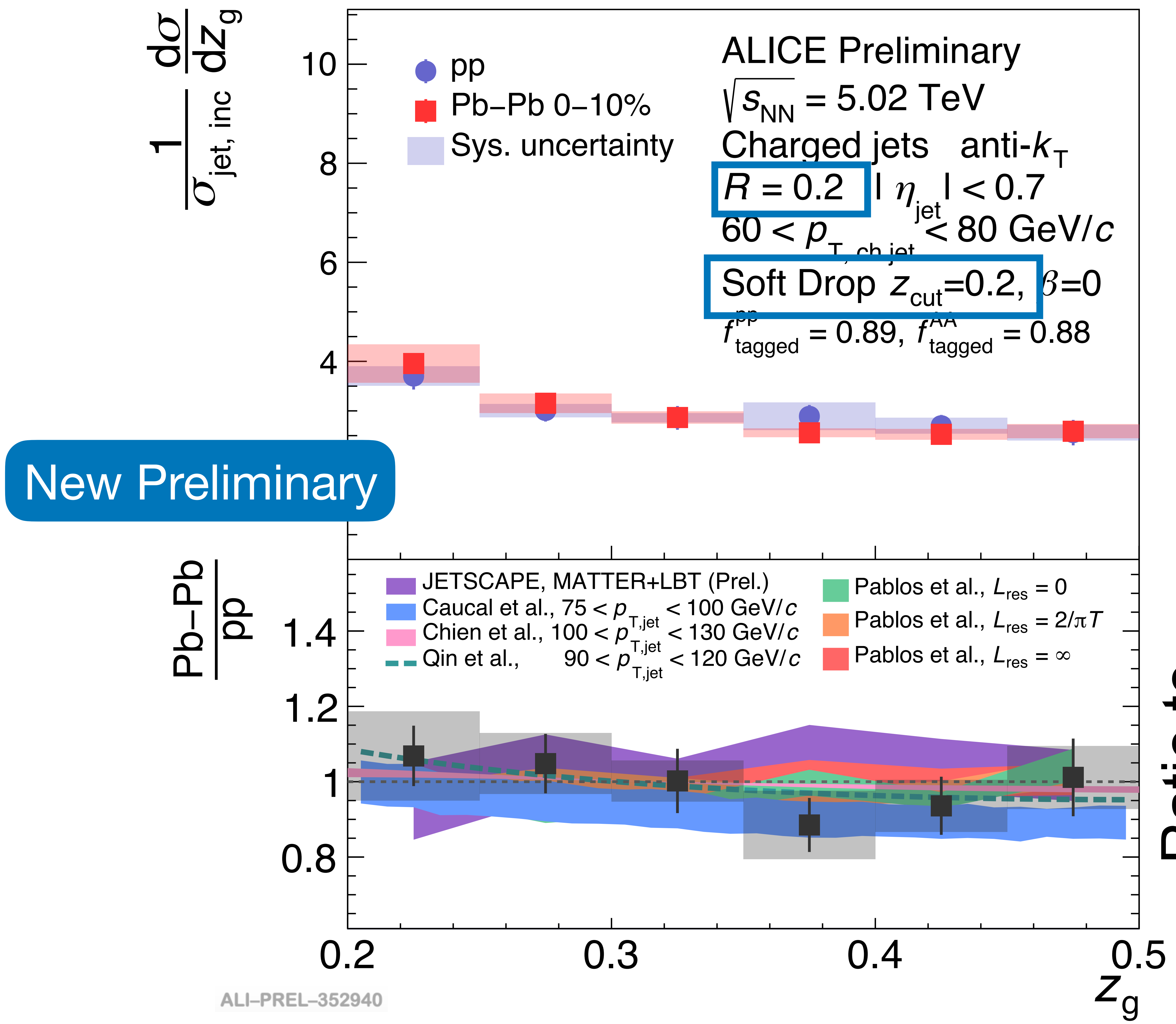
ALI-PREL-352108

k_TDrop

ALI-PREL-352113

timeDrop

Unfolded, $z_{\mathrm{cut}} = 0.2$



Not unfolded, $z_{\mathrm{cut}} = 0.1$