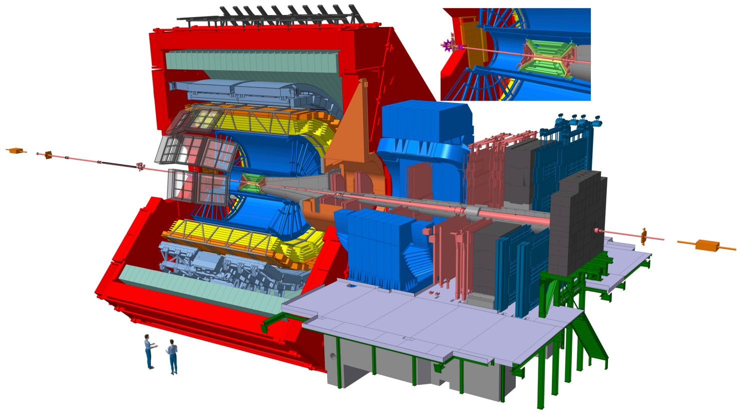
Jet and heavy-flavor measurements in pp collisions with ALICE

James Mulligan
for the ALICE Collaboration



Santa Fe Jets and Heavy Flavor Workshop
Feb 3 2020

Berkeley
UNIVERSITY OF CALIFORNIA

BERKELEY LAB

Jets and heavy flavor in pp collisions

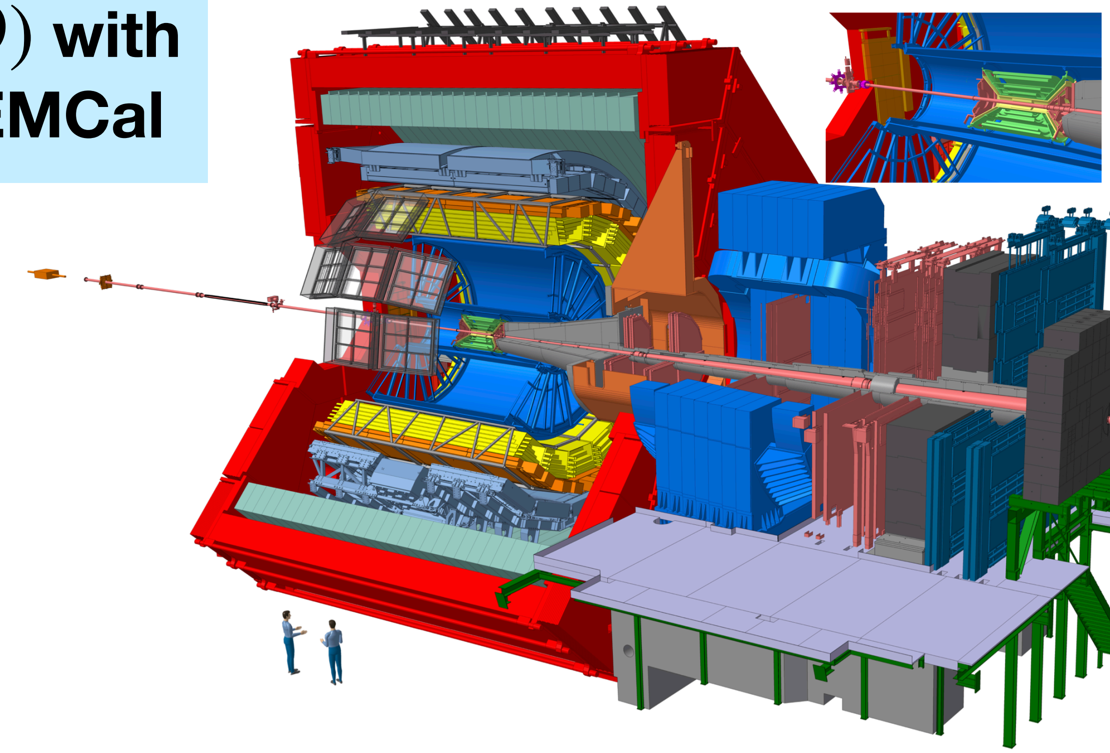
A landscape to test our fundamental understanding of QCD

Jets	Heavy flavor
Test pQCD approaches (parton showers, resummations, power corrections, …)	**Understand production mechanisms** (HF-jet production, gluon splitting, resummations, J/ψ formation, …)
Constrain non-perturbative effects: Hadronization, UE	**Constrain FFs and small-*x* PDFs**
Constrain PDFs, α_s	**Constrain non-perturbative effects:** Hadronization

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

Jets in ALICE

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

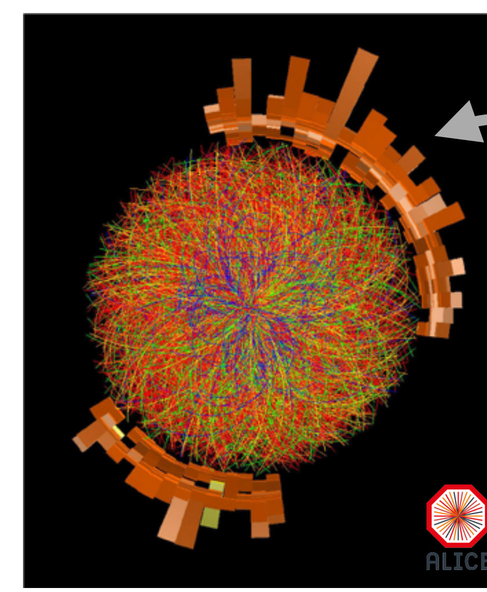


Charged particle jets

- Pro: High-precision spatial resolution to resolve particles; Experimentally simpler
- 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

Inclusive jet cross-section

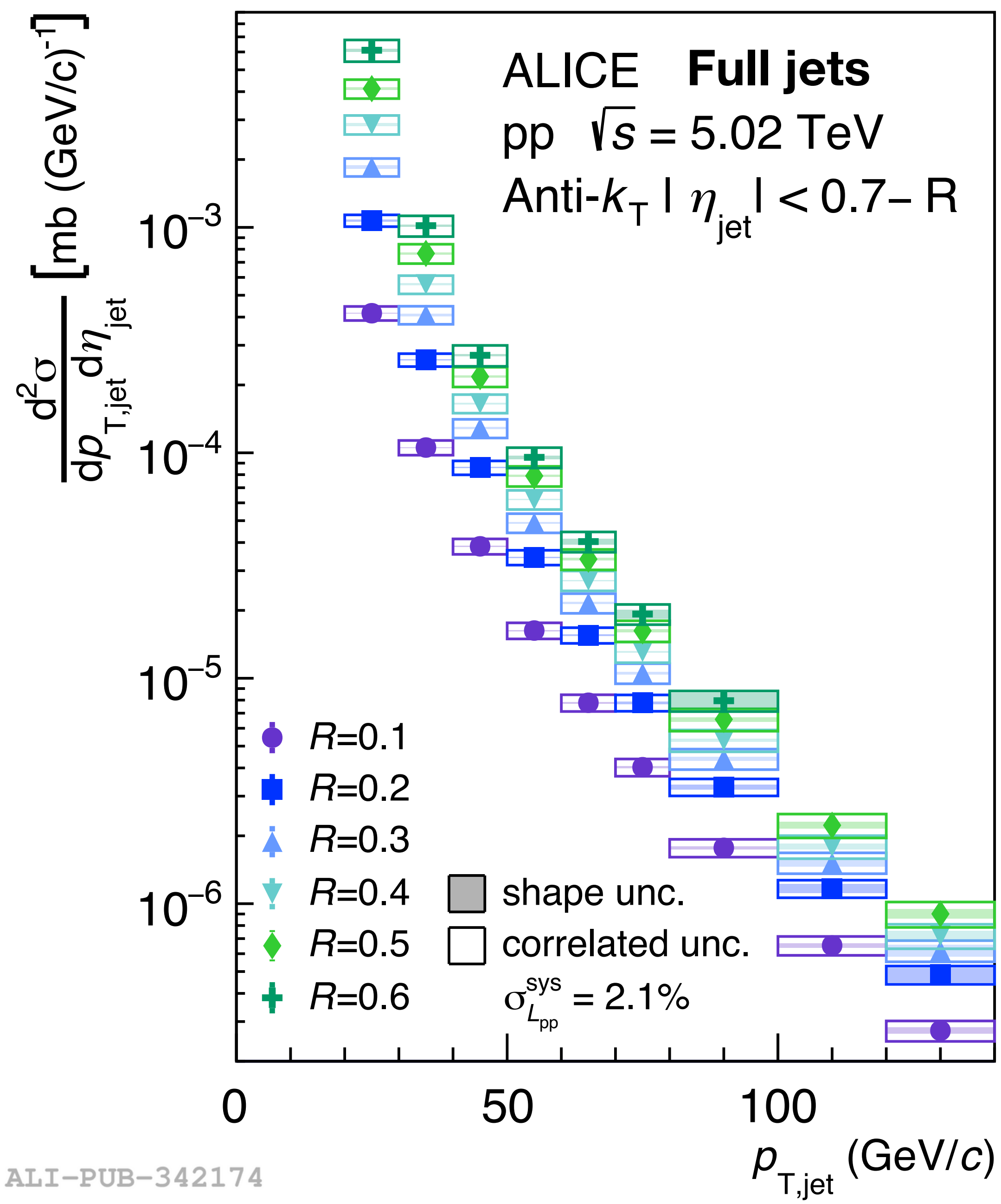
arXiv:1909.09718

The jet cross-section at different R can constrain the contributions from:

pQCD

Underlying Event

Hadronization



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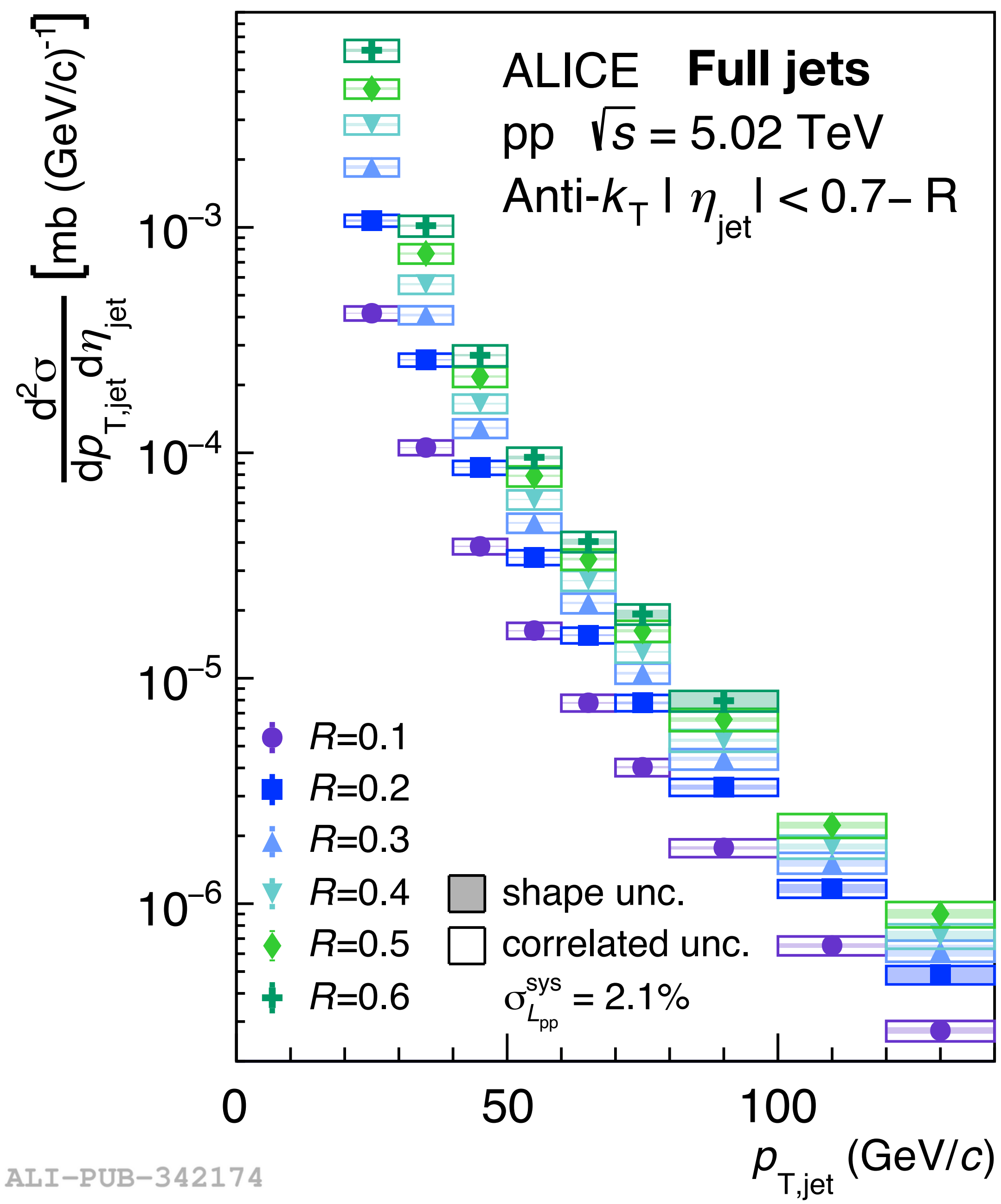

Theoretical approaches

Fixed-order calculations:
NLO, NNLO

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

Parton showers

Inclusive jet cross-section

arXiv:1909.09718

The jet cross-section at different *R* can constrain the contributions from:

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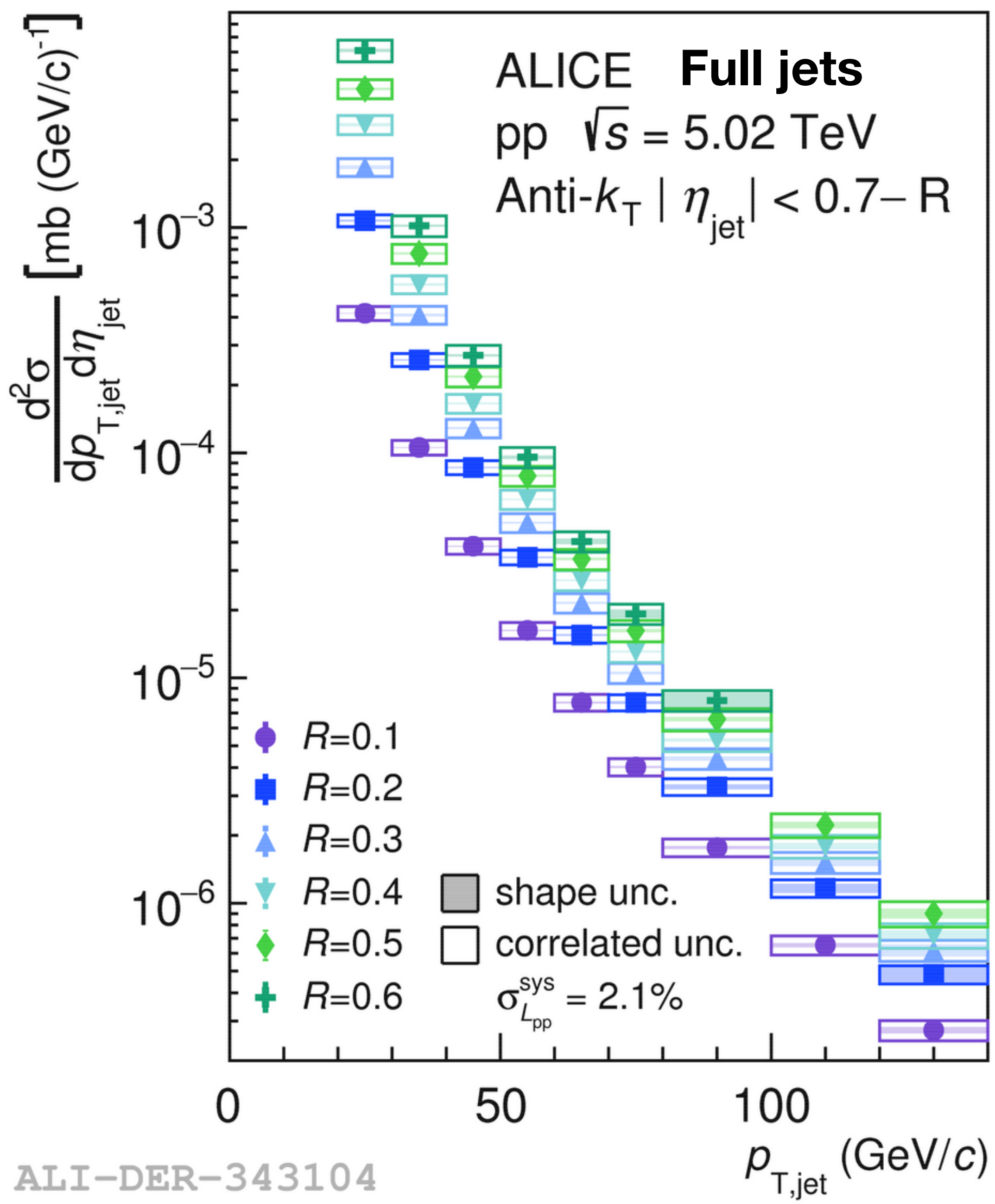

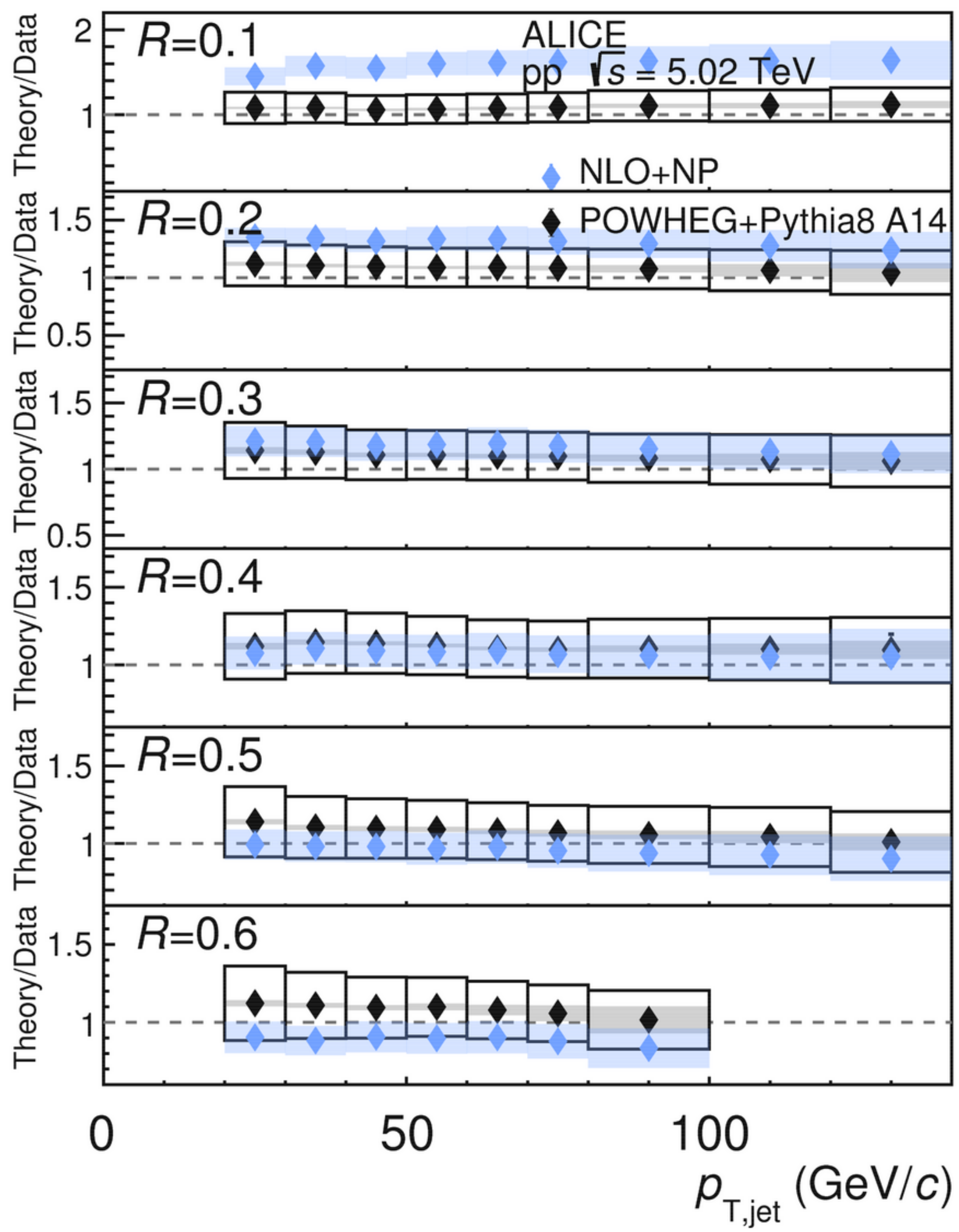

NLO

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

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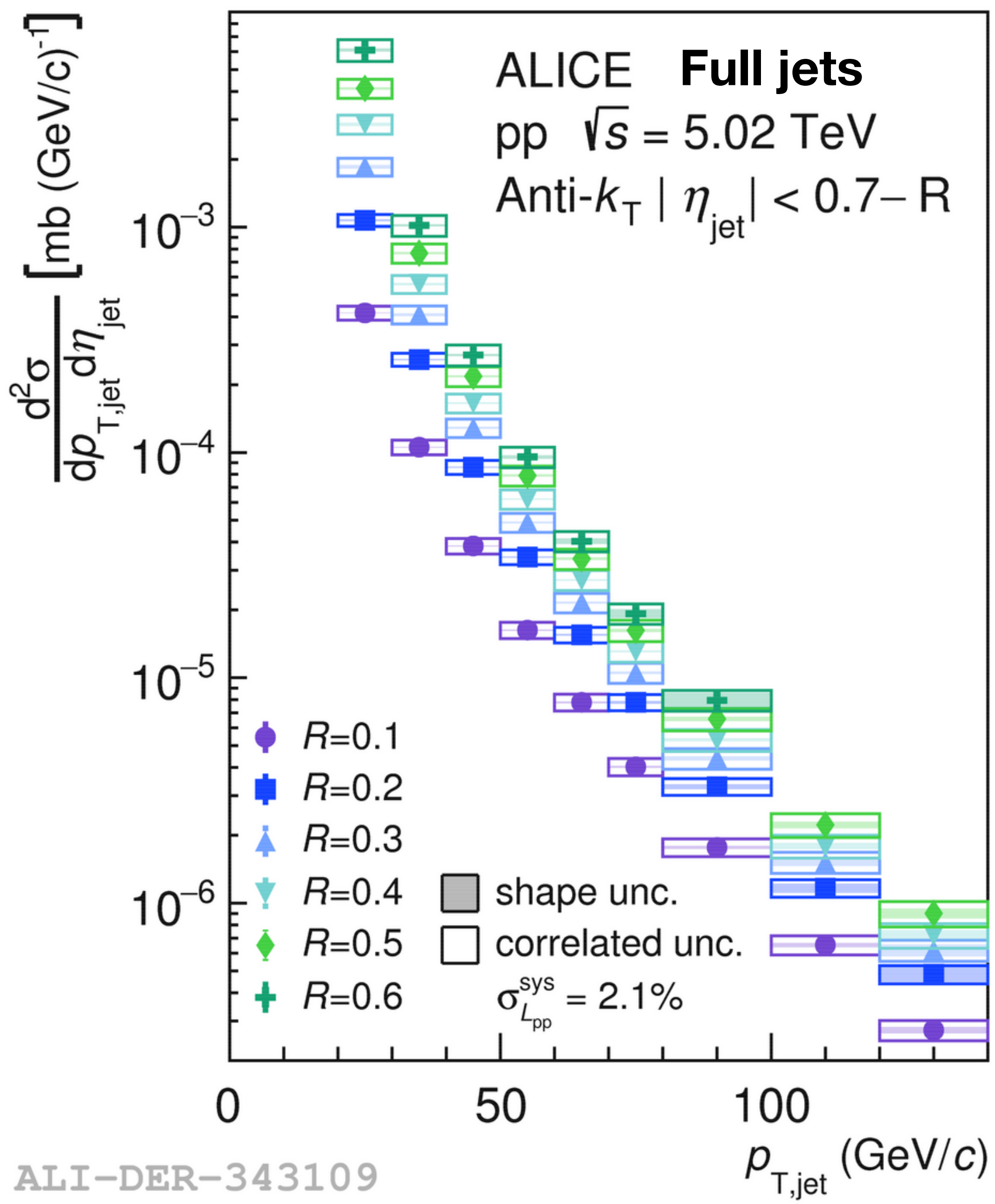

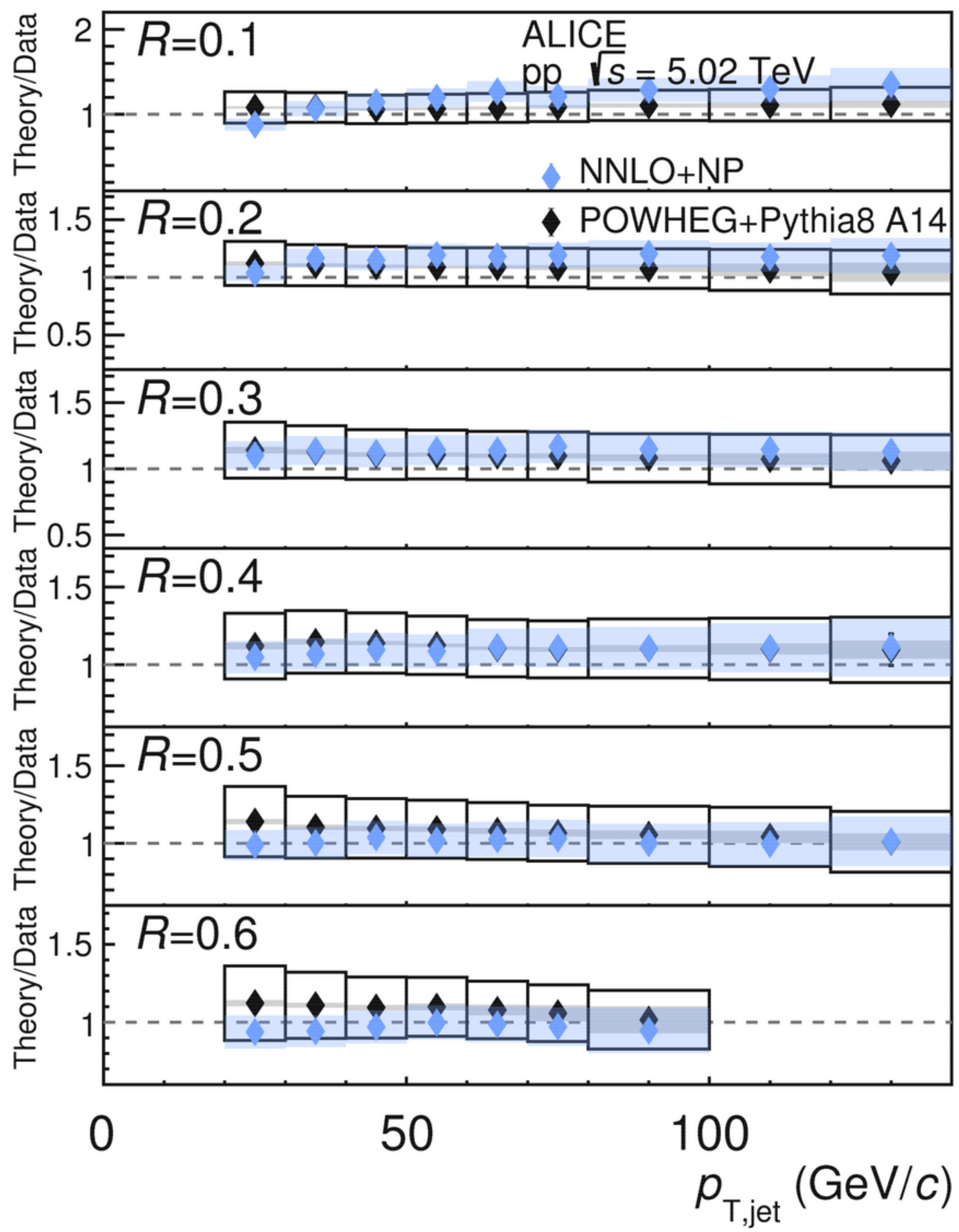

NNLO

Currie, Glover, Pires
PRL 118 072002 (2017)

See also:
Czakon et al.
JHEP 262 (2019)

POWHEG+Pythia

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

Sjöstrand et al.
JHEP05 (2006) 026
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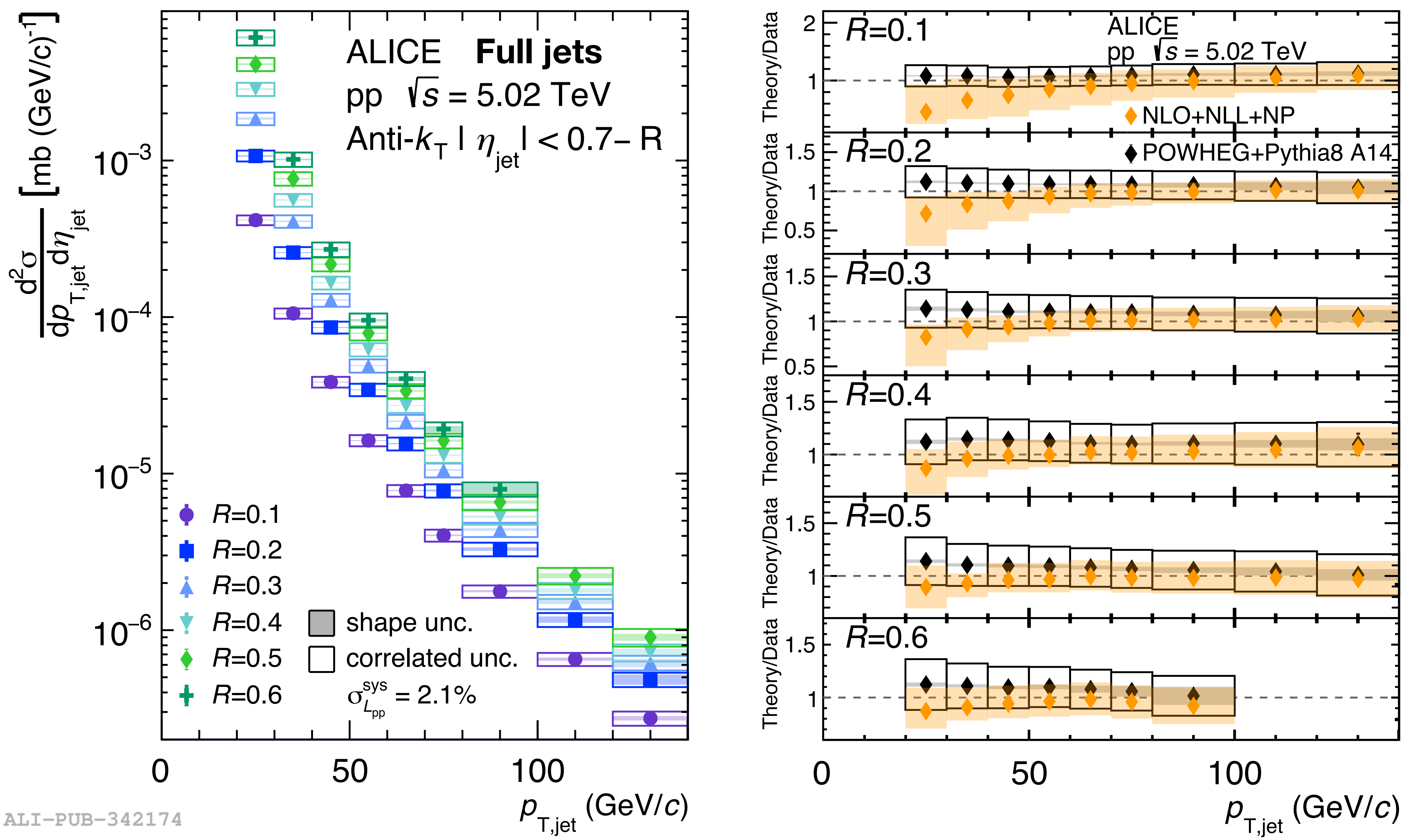

NLO+NLL

Liu, Moch, Ringer
PRL 119 (2017) 212001
PRD 97 (2018) 056026

Kang, Ringer, Vitev
JHEP 1610, 125 (2016)

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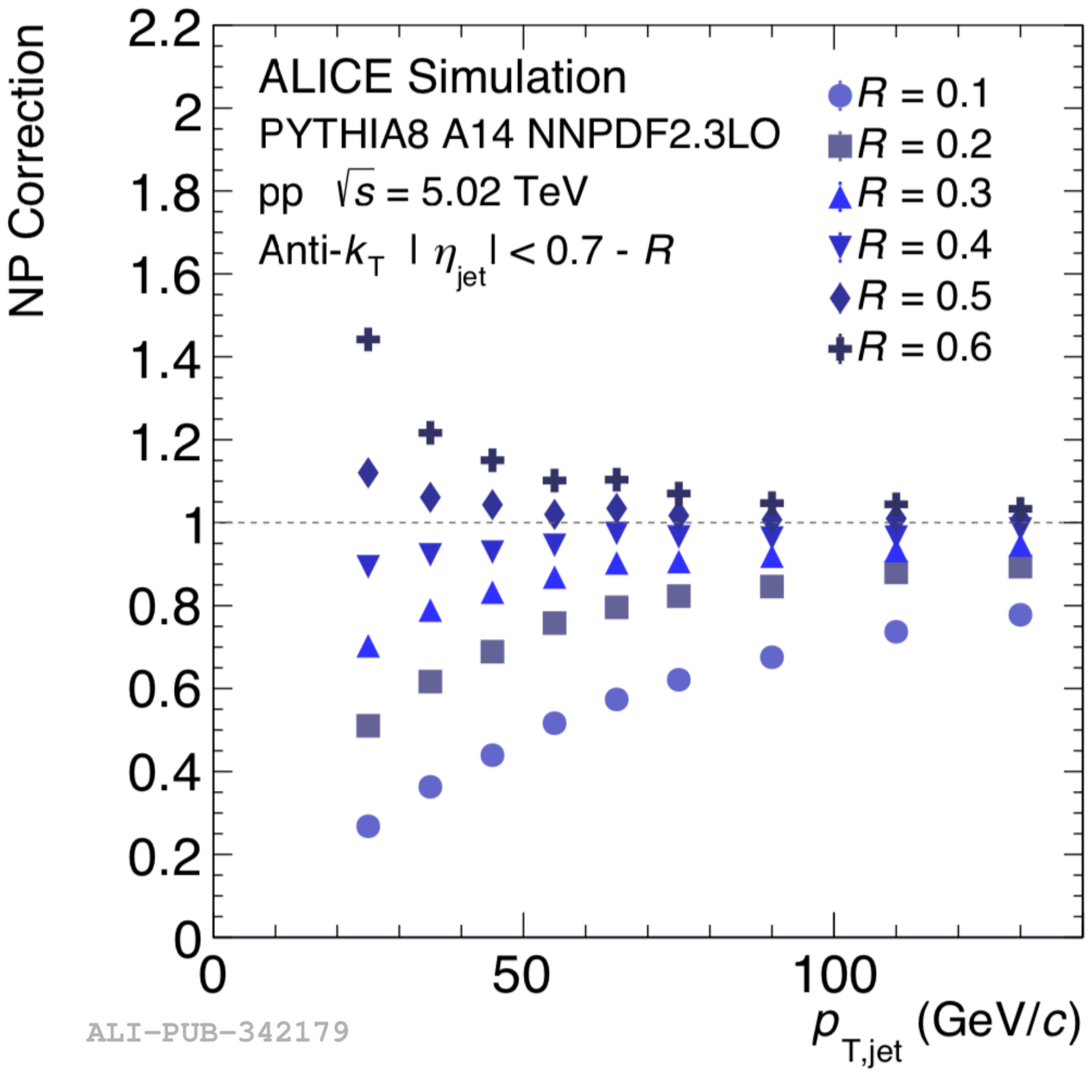
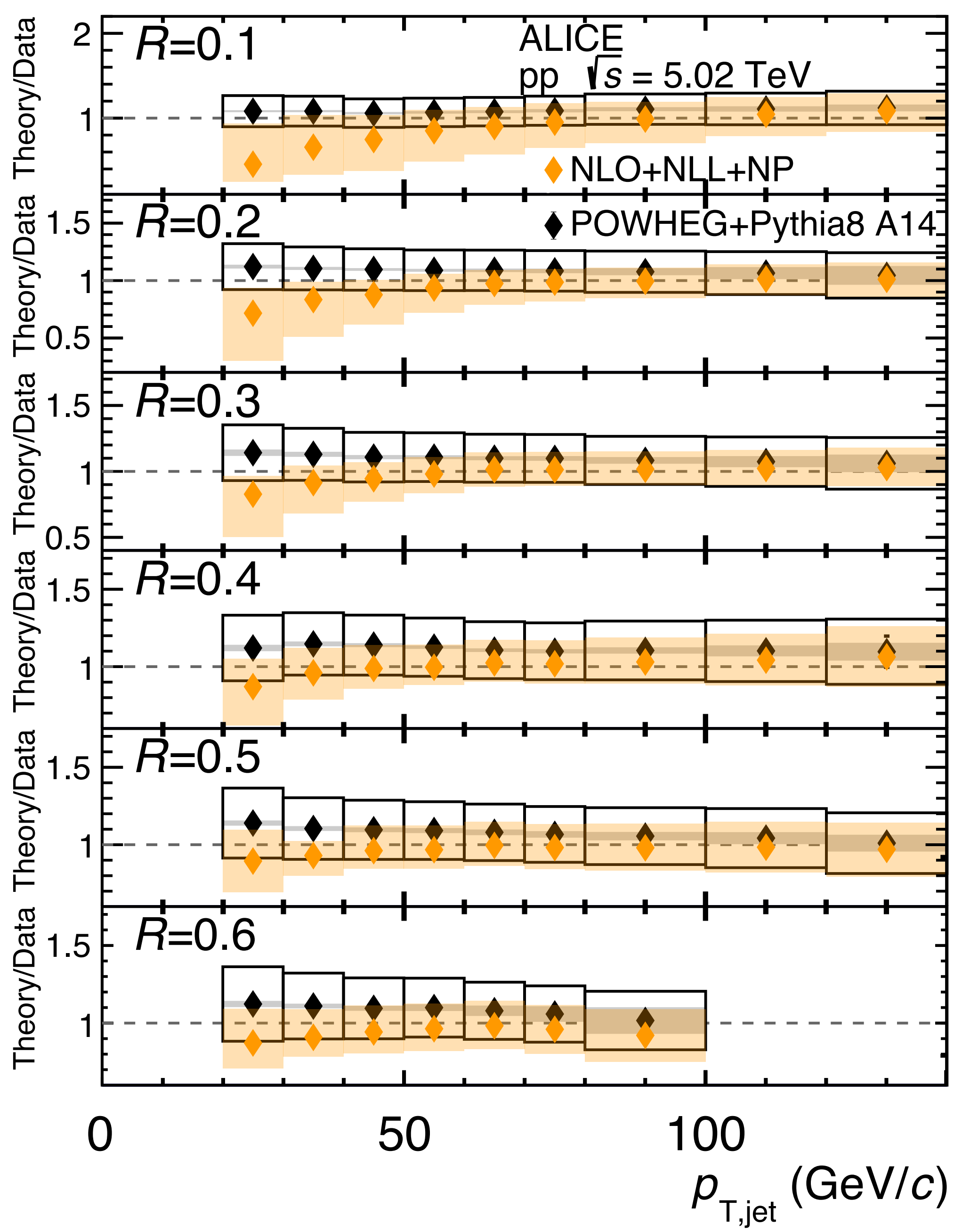
pQCD | **Underlying Event** | **Hadronization**





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POWHEG+Pythia

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

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

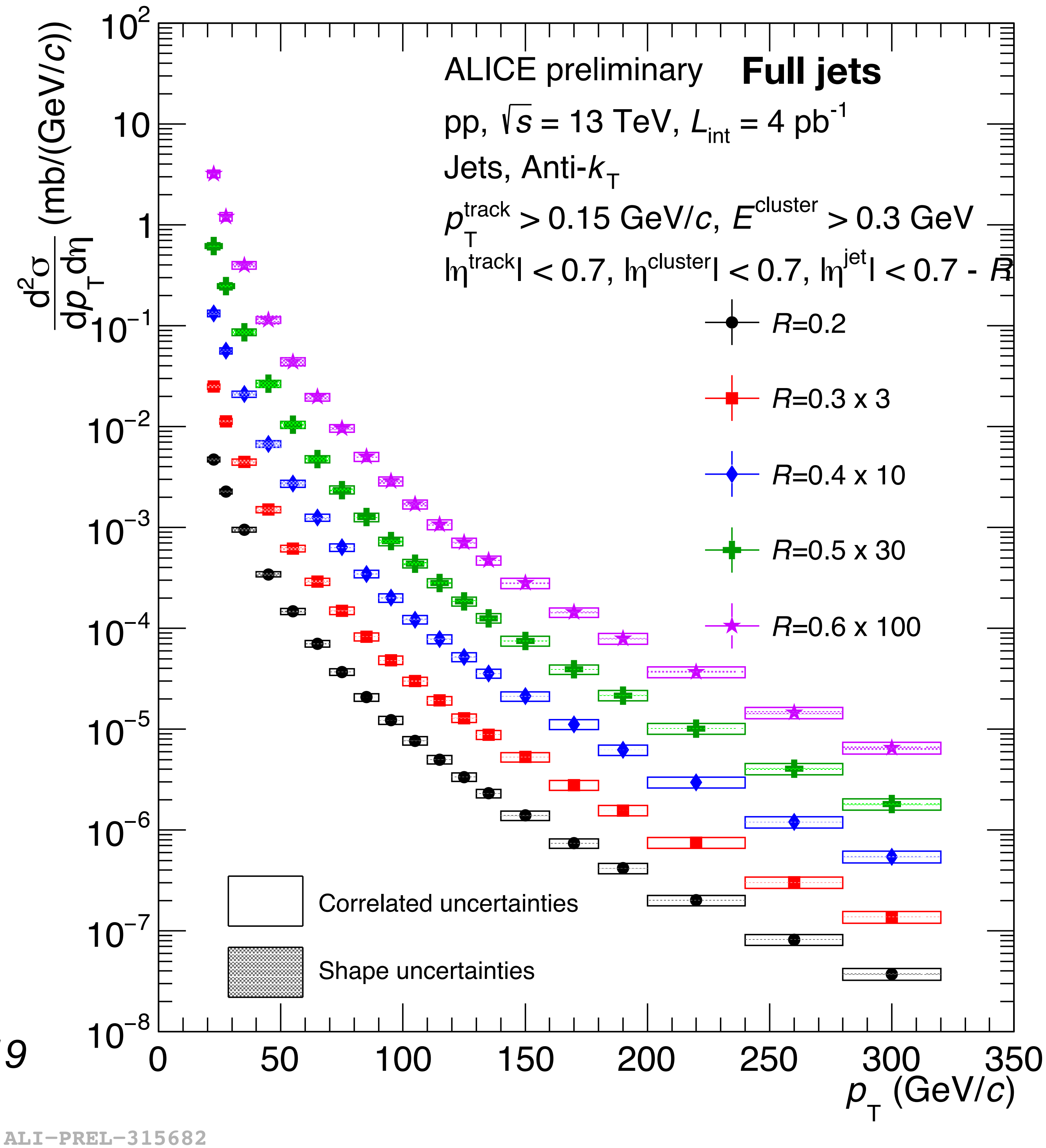
Non-perturbative effects are very large at low-p_T

Inclusive jet cross-section

New high-p_T reach for ALICE!

Enabled by EMCal jet trigger and validation of high-p_T tracking performance

M. Fasel
Hard Probes 2019

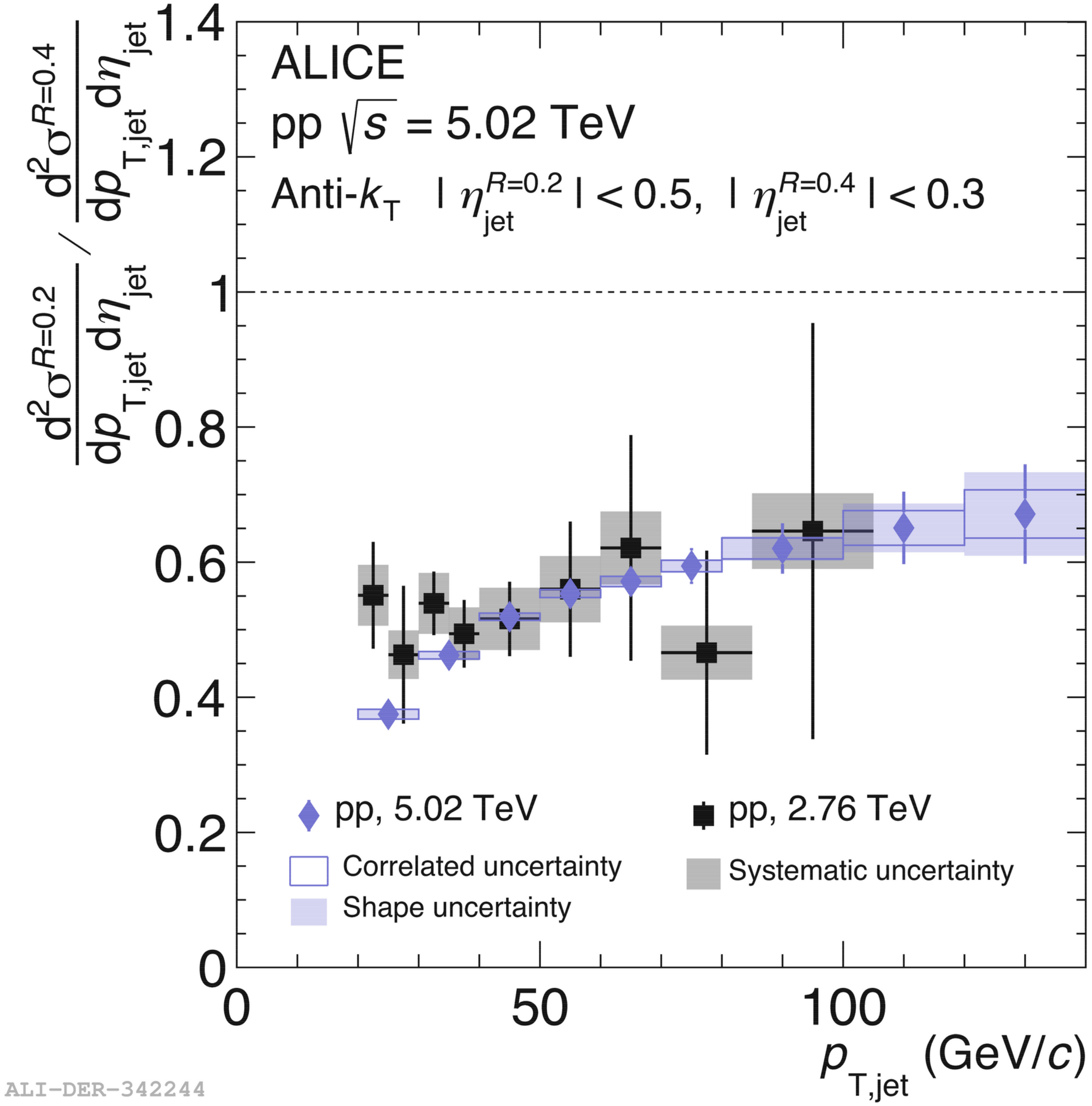


Inclusive jet cross-section ratio

arXiv:1909.09718

The jet cross-section at different R can constrain the contributions from:

pQCD **Underlying Event** **Hadronization**



The ratio of cross-sections at different R allows significant cancellation of experimental systematic uncertainties

High-precision constraints on the *R*-dependence of the inclusive jet cross-section

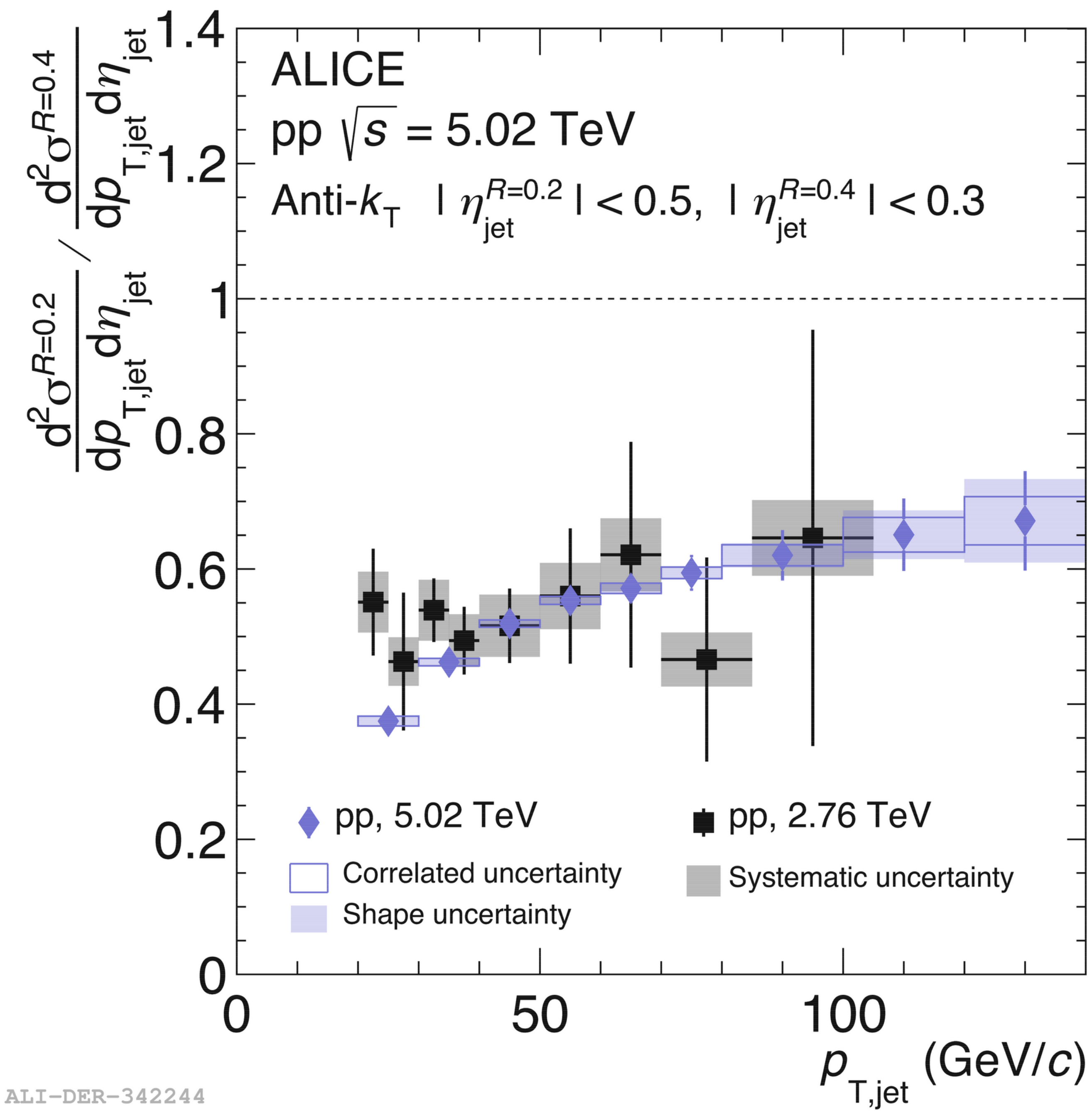
Note: An even better way may be to report correlations in uncertainties between different R

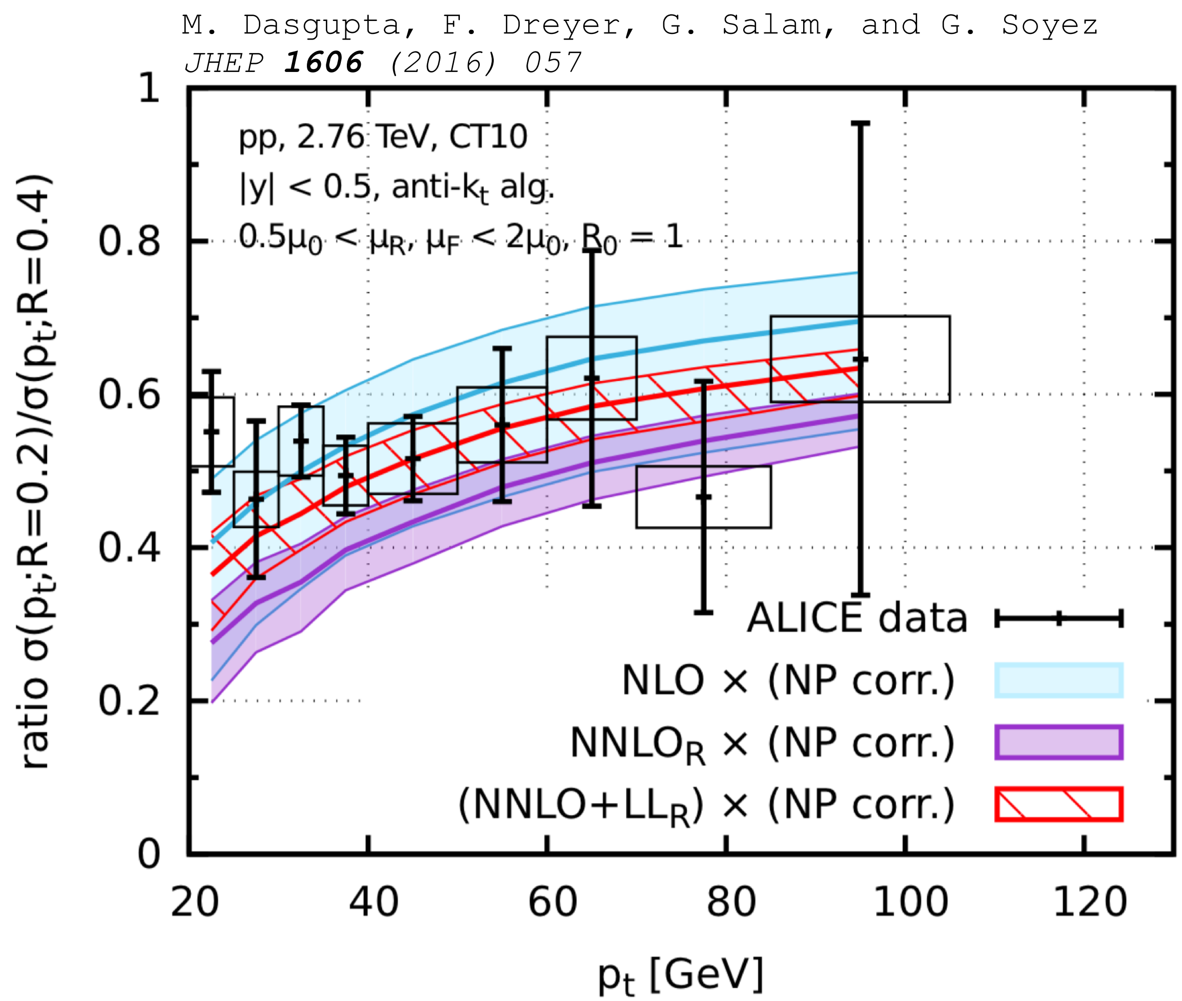
Inclusive jet cross-section ratio

arXiv:1909.09718

The jet cross-section at different R can constrain the contributions from:

pQCD | **Underlying Event** | **Hadronization**





Inclusive jet cross-section ratio

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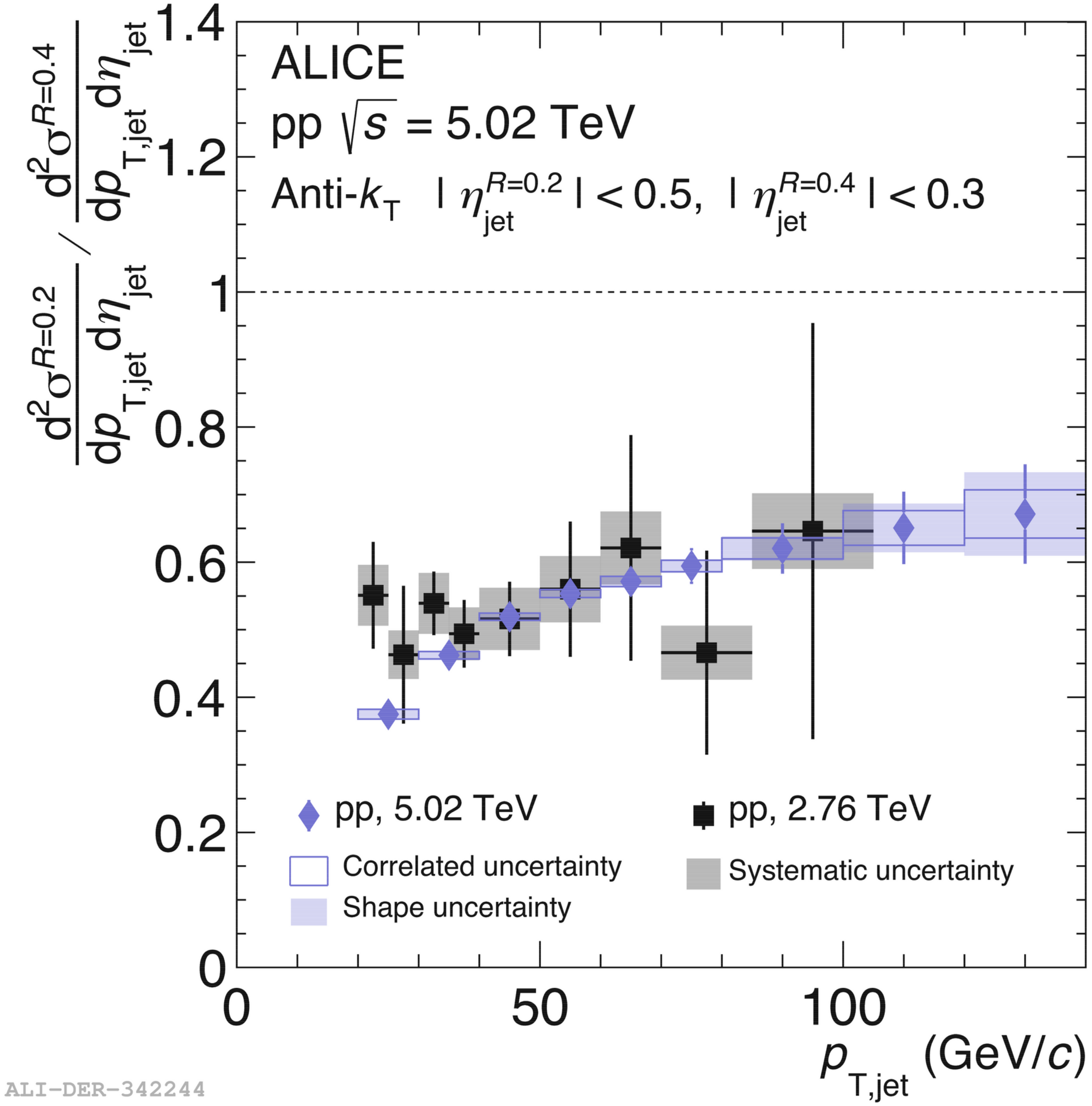
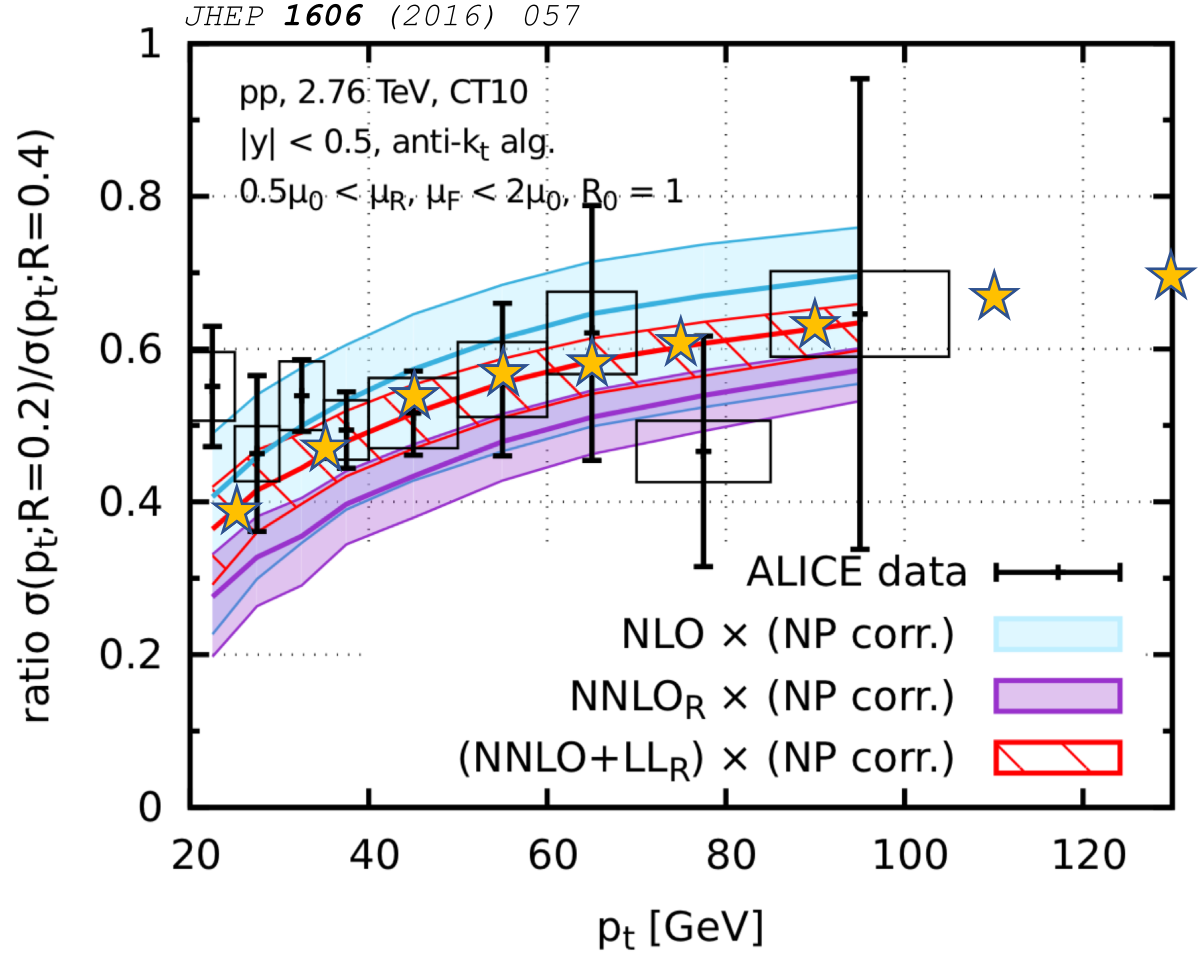
The jet cross-section at different *R* can constrain the contributions from:

pQCD **Underlying Event** **Hadronization**



M. Dasgupta, F. Dreyer, G. Salam, and G. Soyez
JHEP **1606** (2016) 057



New data **clearly** prefer the NNLO LL$_R$-based calculation. But needs calculations at the right energy to be certain. Currently underway…

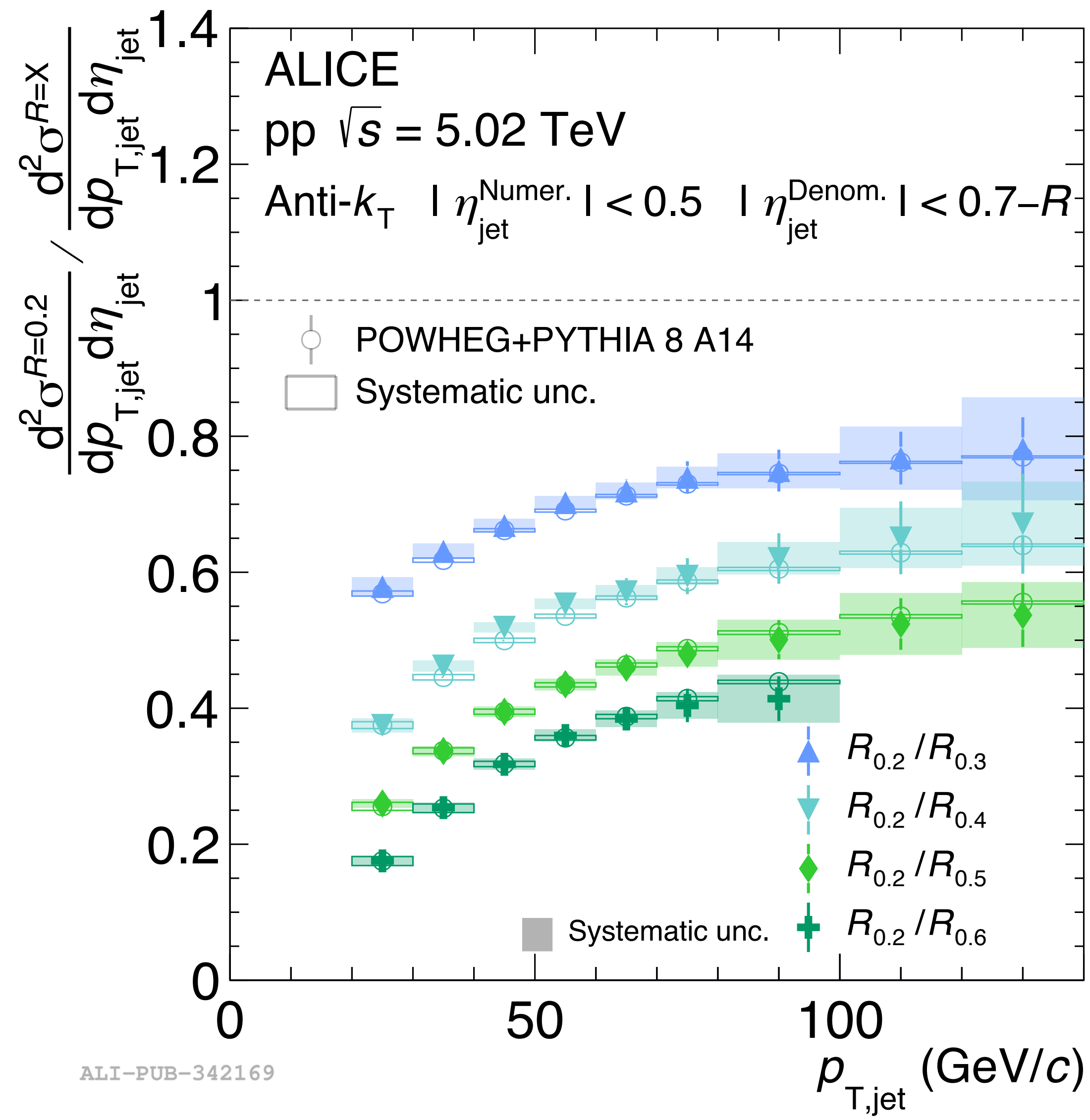
Eliane Epple
LHCEW-Jets Group

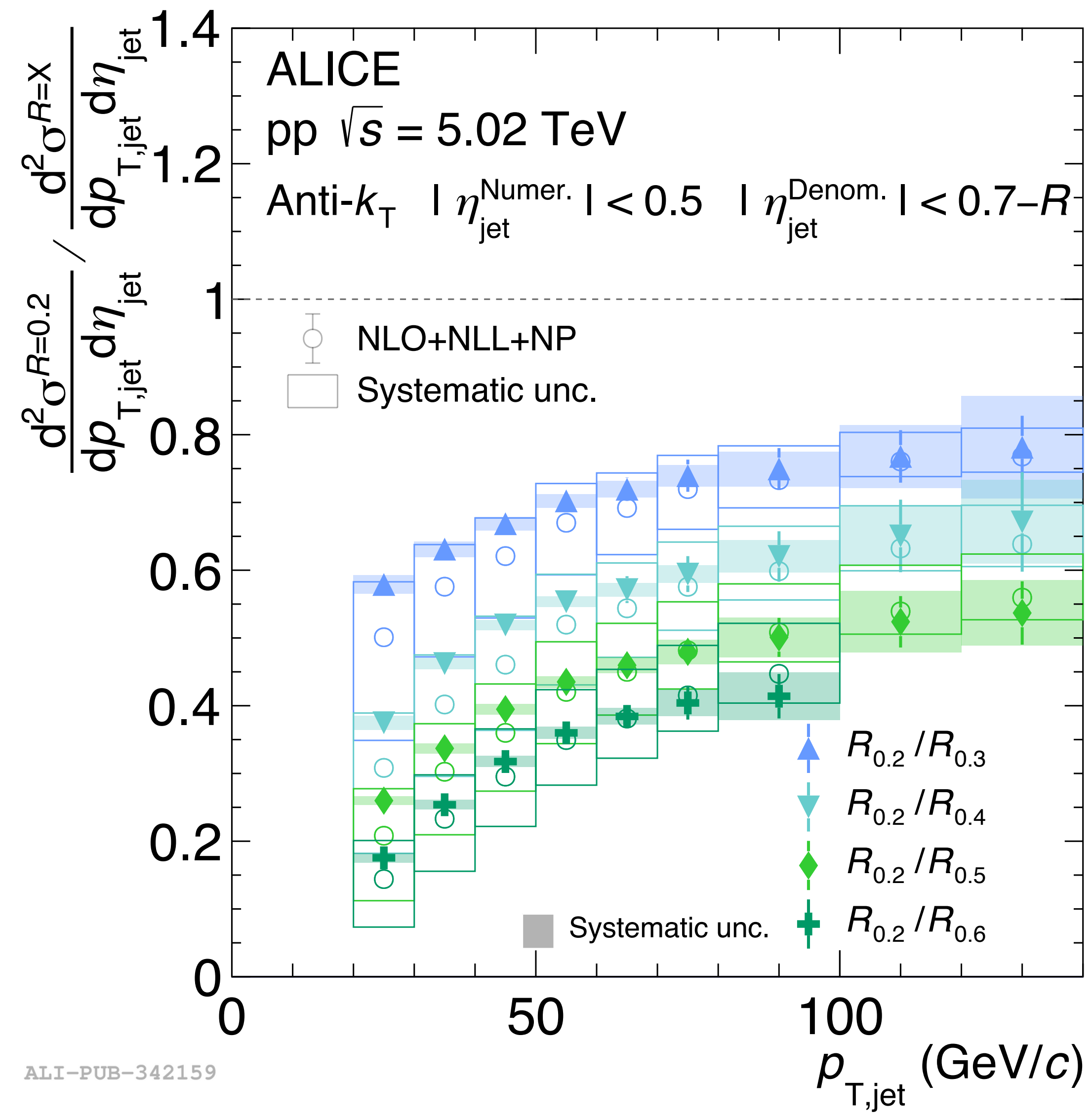
Inclusive jet cross-section ratio

arXiv:1909.09718

The jet cross-section at different *R* can constrain the contributions from:

pQCD | **Underlying Event** | **Hadronization**





Systematic uncertainties in analytical calculation do not cancel… driven by sensitivity to non-perturbative scale. Can it be improved?

Groomed jet substructure

1 **Jet reclustering**

Recluster jet constituents to identify jet features (Lund plane, subjets, etc.)

2 **Jet grooming**

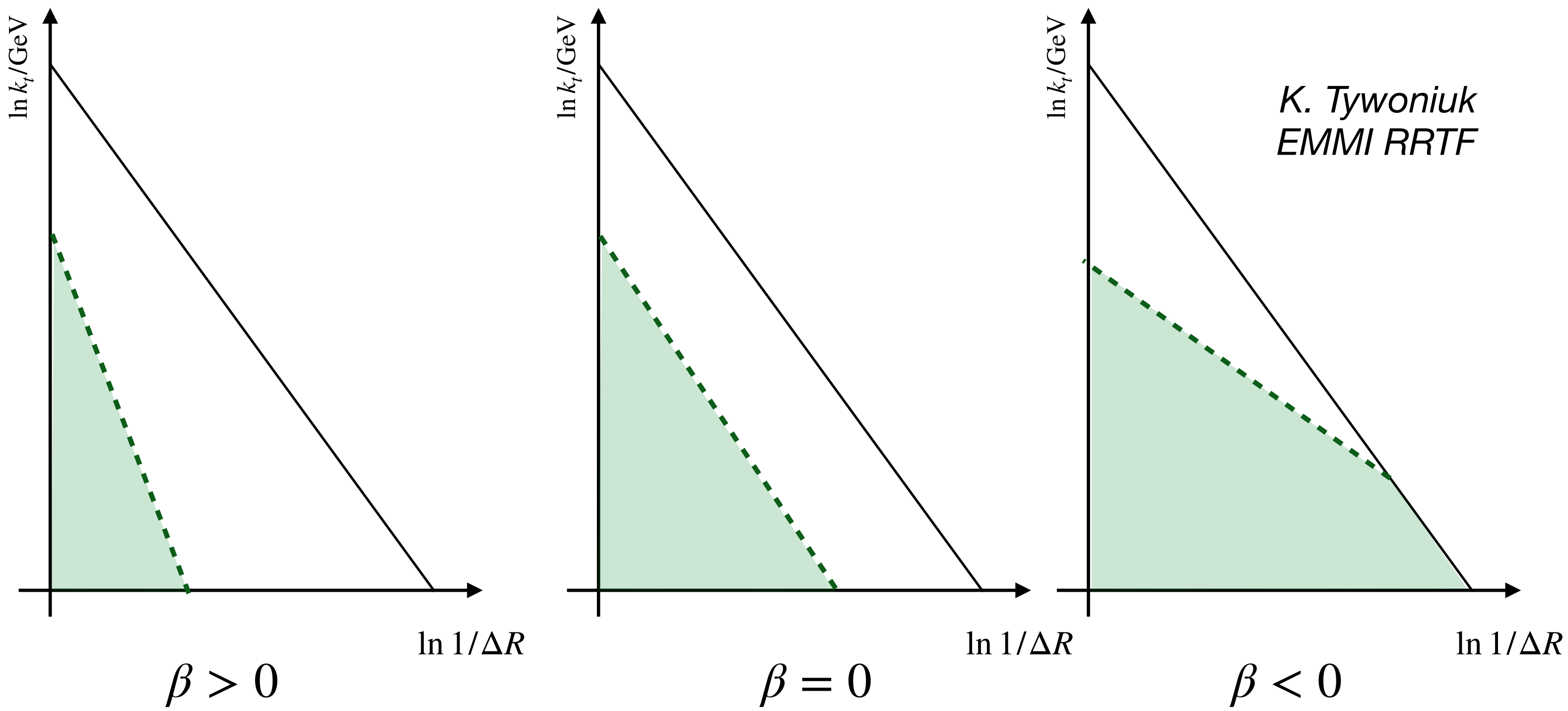
Preferentially remove non-perturbative contributions, NGLs
Tag hard splitting
→ Well-controlled comparisons to pQCD calculations

The Soft Drop algorithm introduced the grooming parameter β to improve IRC-safety of groomed observables

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

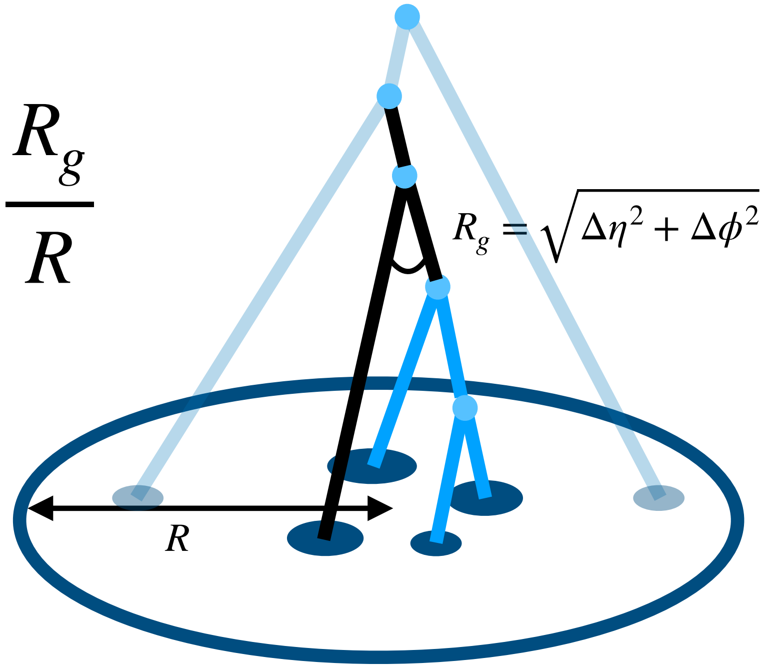
$$z > z_{\mathrm{cut}}\theta^{\beta}$$

As β increases, less collinear radiation is groomed away



Groomed jet radius

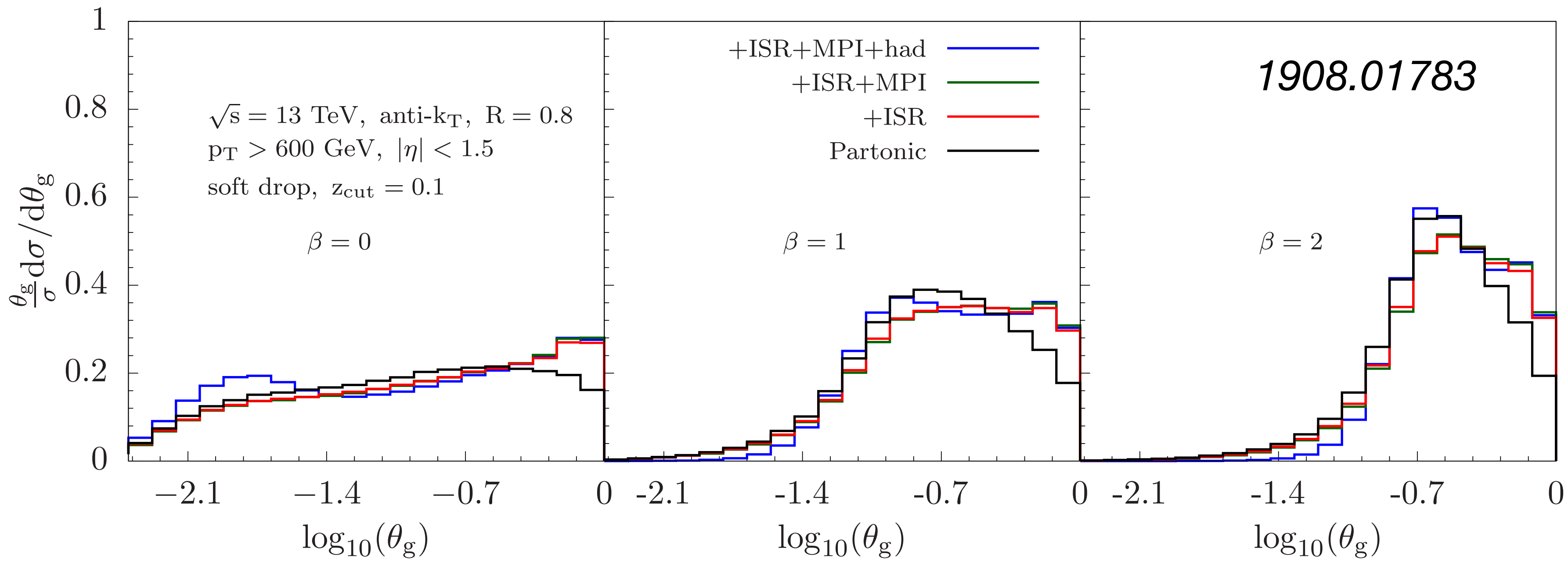
$$\theta_g \equiv \frac{R_g}{R}$$



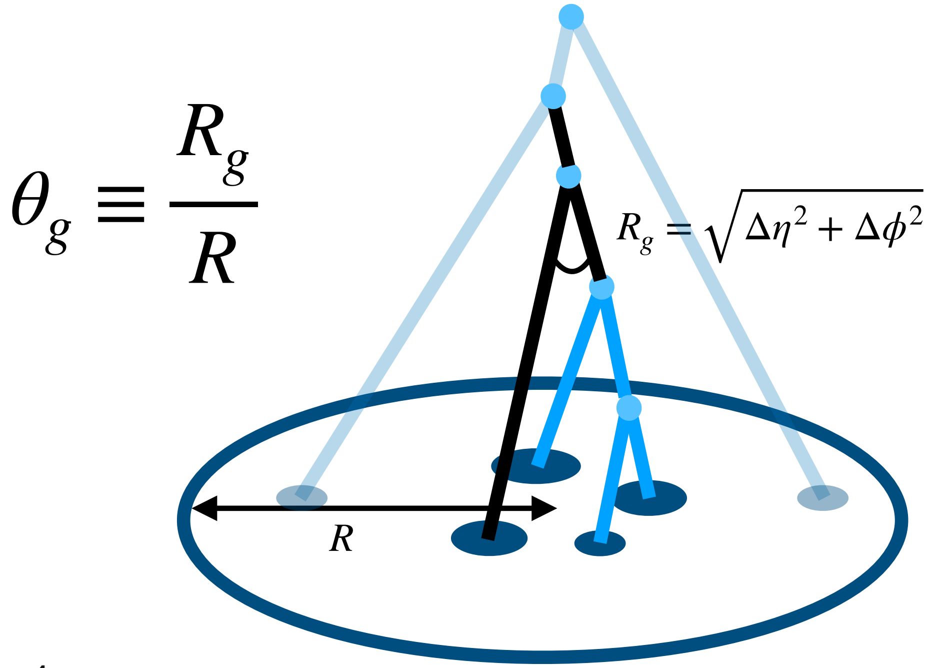
Goals of pp measurement

1. Test NLL pQCD calculations and role of non-perturbative effects
   Kang, Lee, Liu, Ringer 1908.01783 *ATLAS 1912.09837*
2. Serve as baseline for Pb—Pb measurements *Ringer, Xiao, Yuan 1907.12541*

Tool: Vary grooming settings Measure the β-dependence of the groomed jet radius



Groomed jet radius

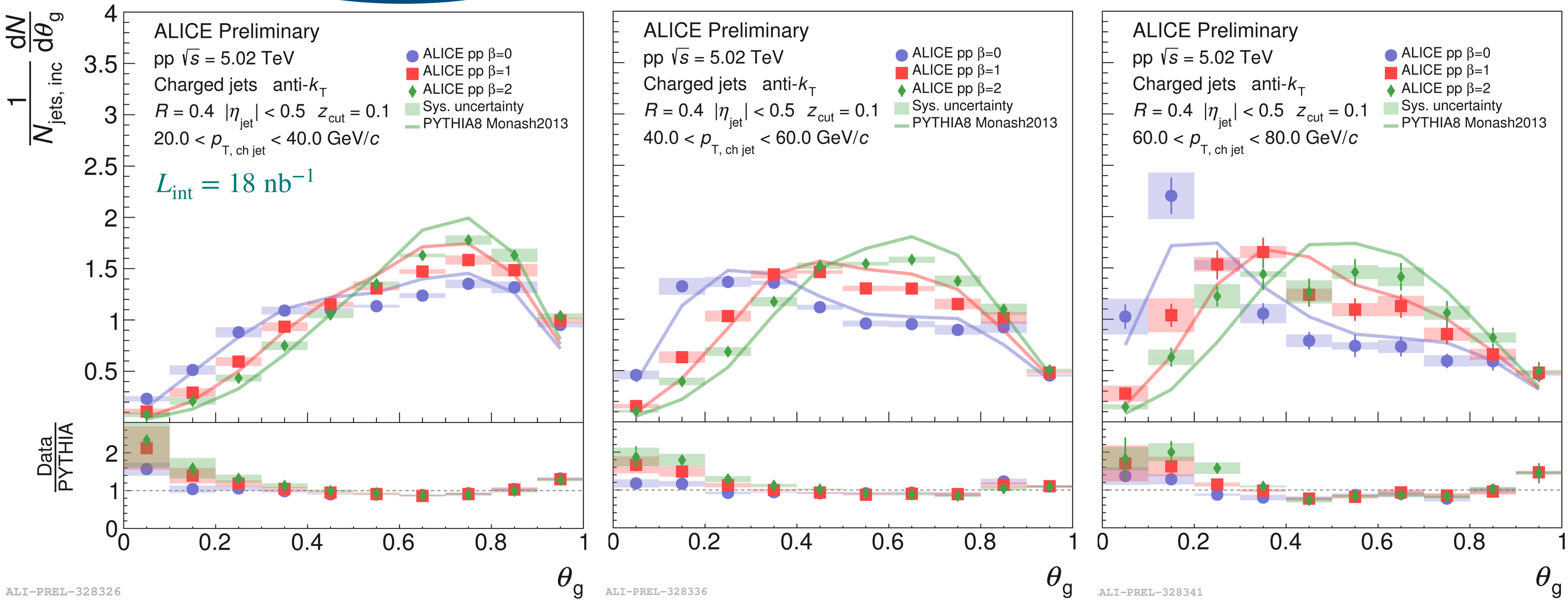


Larger p_{T} → More collimated jets

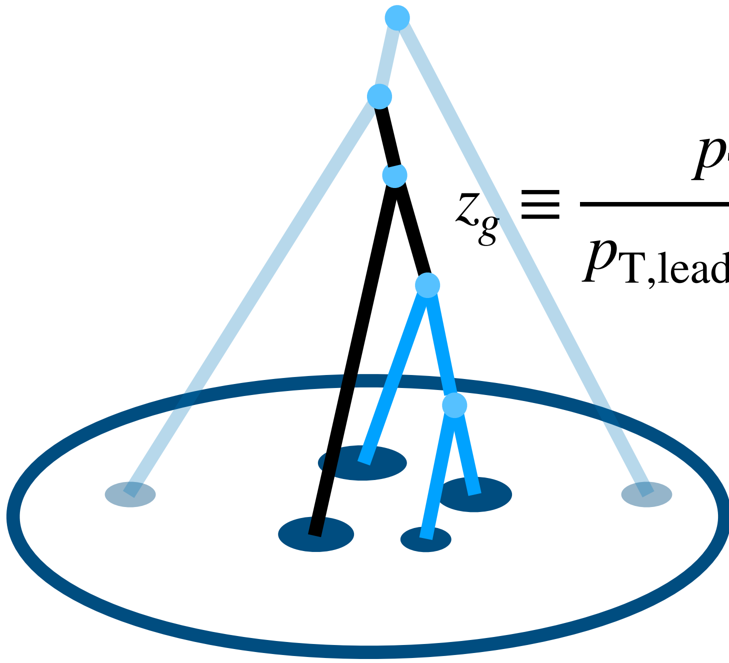
Smaller β → More collimated jets

Reasonably well-described by PYTHIA

Analytical NLL comparisons coming…



Groomed jet momentum fraction



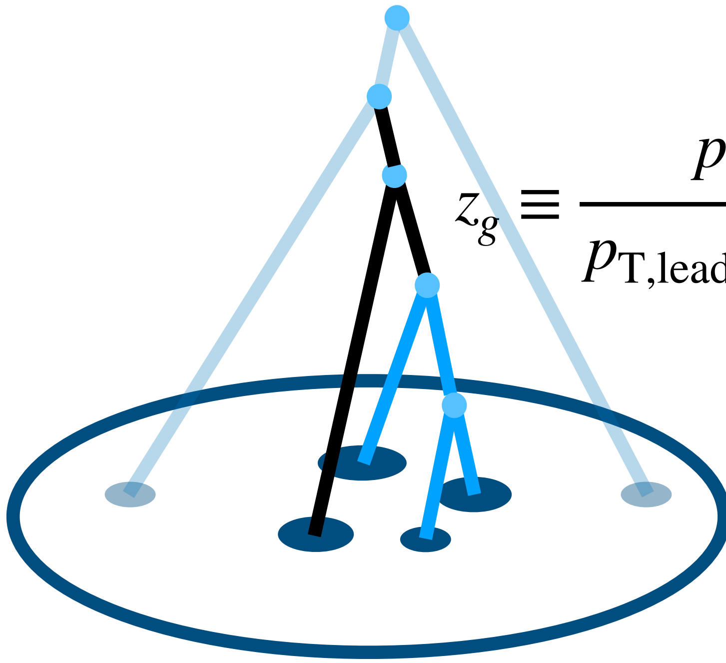
$$z_g \equiv \frac{p_{\mathrm{T,sublead}}}{p_{\mathrm{T,lead}} + p_{\mathrm{T,sublead}}}$$

Goals of pp measurement

1. Test perturbative accuracy: z_g has only been calculated to LL

2. Serve as baseline for Pb—Pb measurements *ALICE 1905.02512* *CMS PRL 120, 142302 (2018)*

Groomed jet momentum fraction

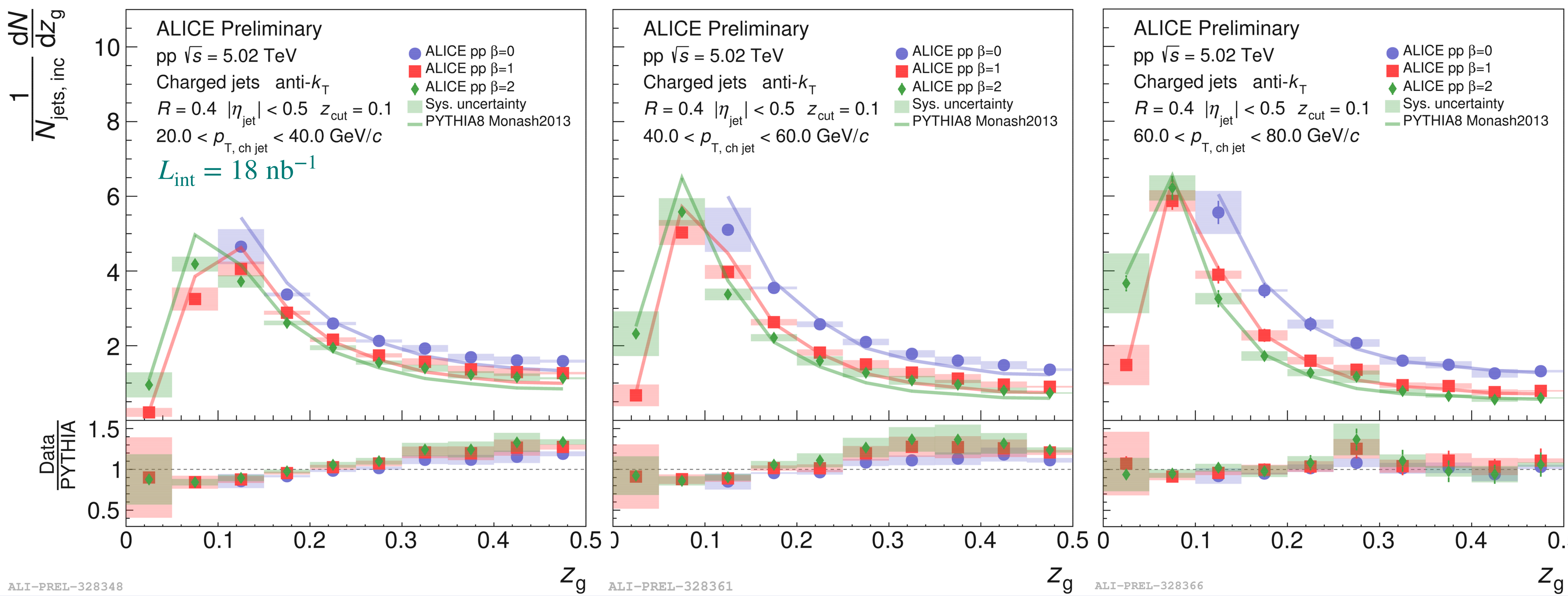


$$z_g \equiv \frac{p_{\mathrm{T,sublead}}}{p_{\mathrm{T,lead}} + p_{\mathrm{T,sublead}}}$$

Weak p_{T} dependence

Reasonably well-described by PYTHIA

Analytical comparisons coming…



Heavy flavor in ALICE

ALICE reconstructs heavy-flavor several ways:

- **Hadronic charm decays at mid-rapidity:** Tracking system (ITS+TPC), TOF

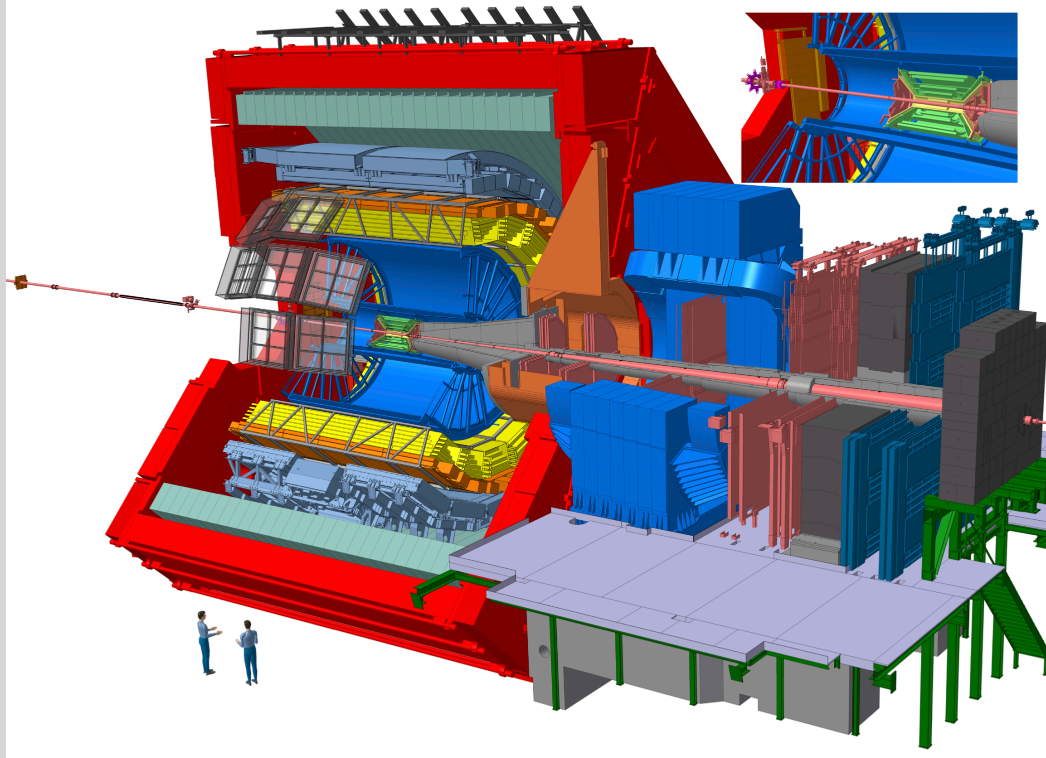
  Direct reconstruction of prompt and non-prompt open charm using Topology, PID, Invariant mass

- **Semi-leptonic charm/beauty decays at mid-rapidity (electron) and forward rapidity (muon):** Tracking system (ITS+TPC), TOF, EMCal, muon spectrometer

  Inclusive or exclusive production

- **Quarkonia at mid-rapidity (electrons) or forward rapidity (muons)**

  Prompt and non-prompt at mid-rapidity
  Inclusive at forward rapidity



ALICE is very good for:

- Low-p_{T} open heavy flavor and quarkonium
- Vertexing, PID; Muon arm

ALICE is not so good for:

- High statistics (high-p_{T})

Heavy-flavor jets

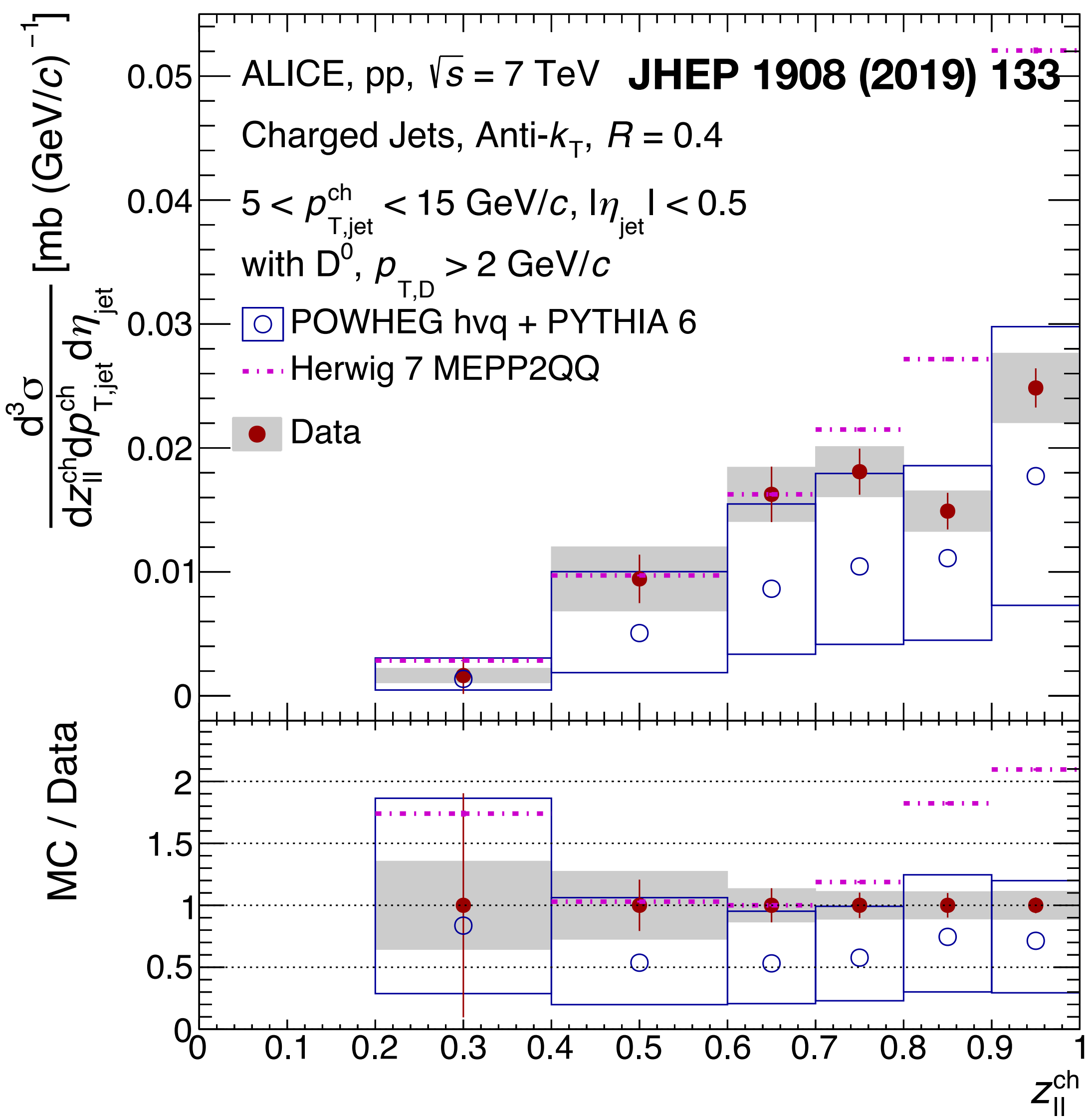
D^0-tagged jets

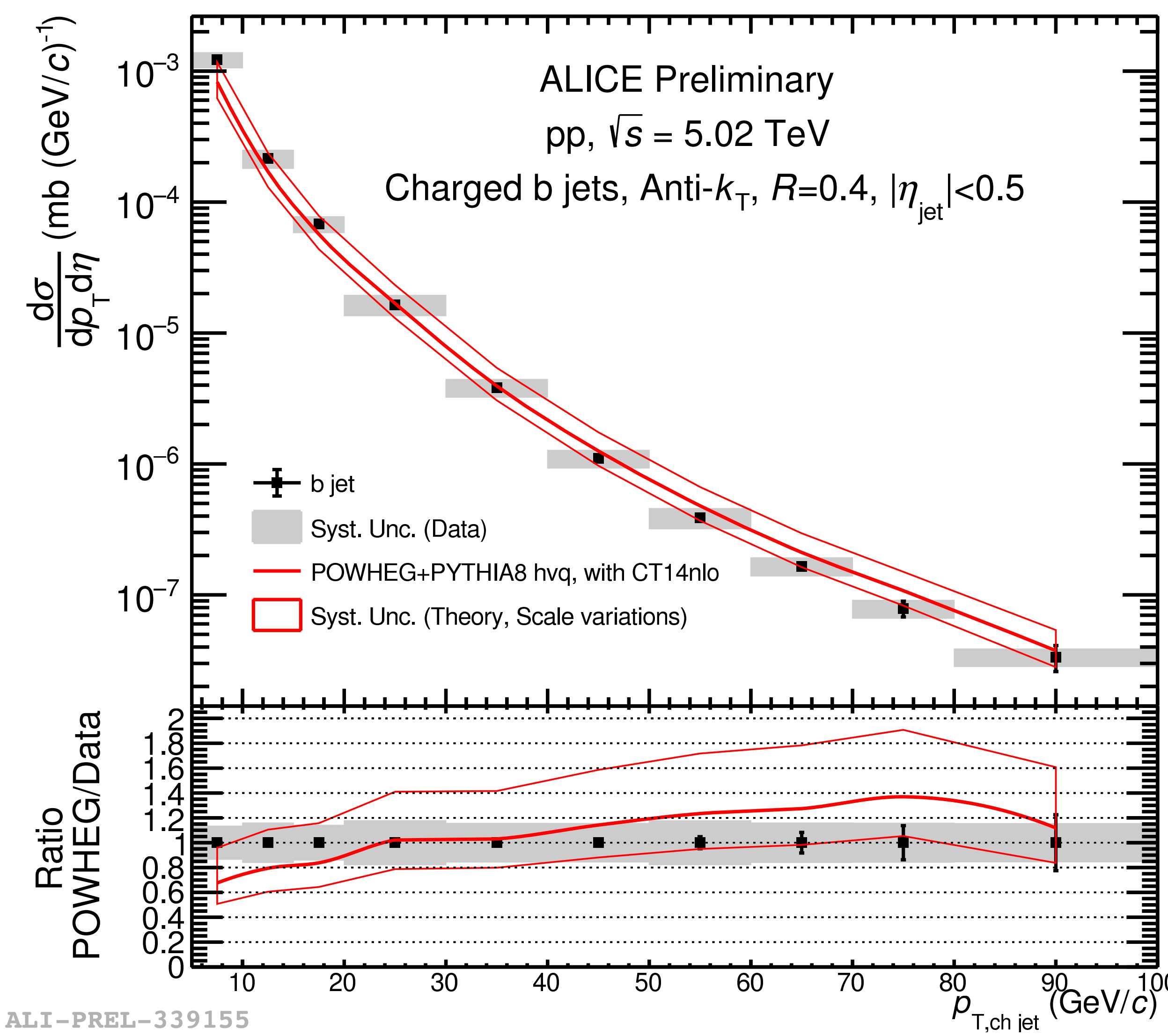
D^0 reconstructed from hadronic decay and clustered in charged jet

Need more precise predictions!

b-tagged jets

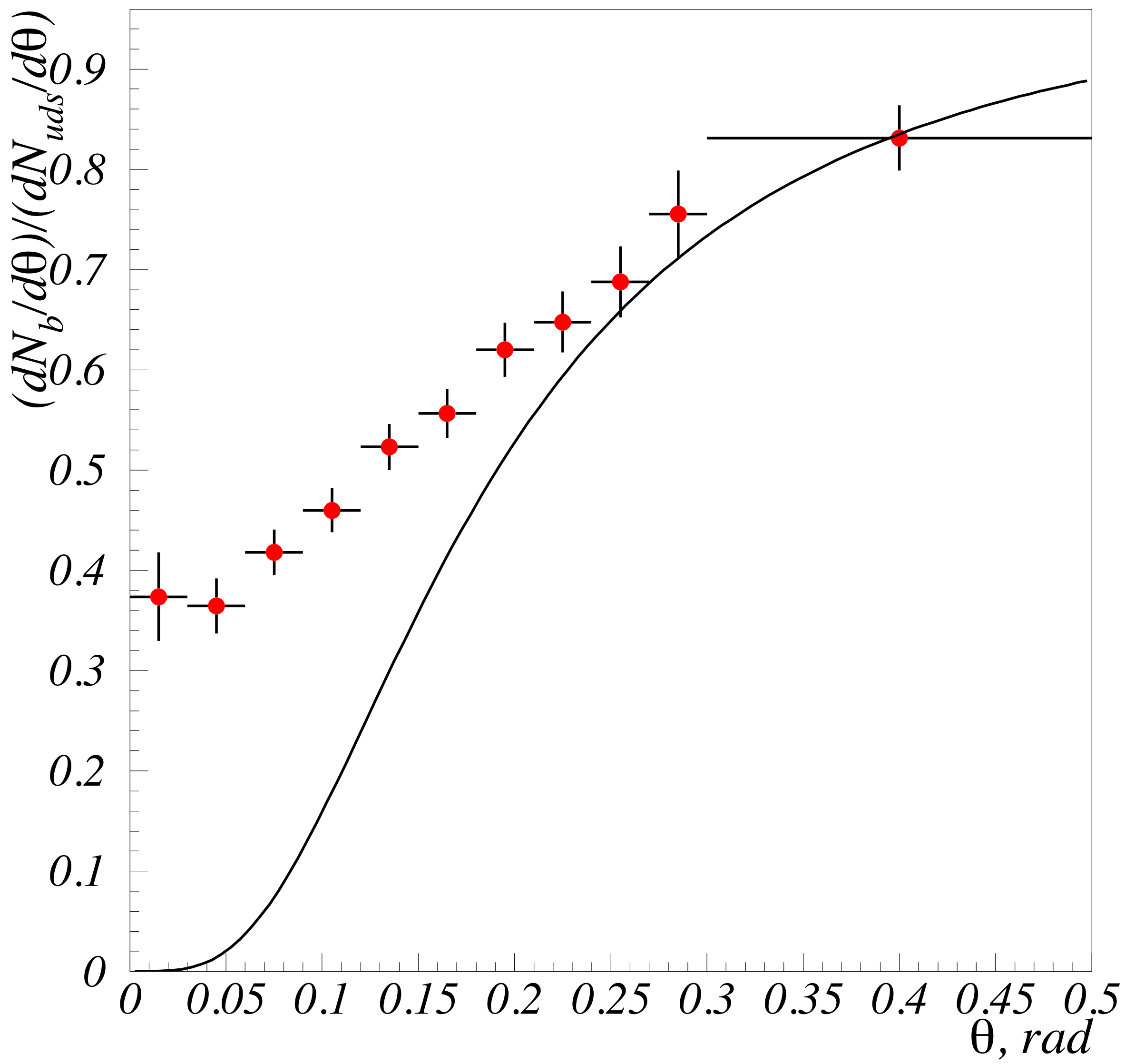
Two b-tagging algorithms:
- Secondary vertex
- Displaced tracks





Dead cone

Suppression of radiation emitted by a quark for $\theta < \frac{m_q}{E_q}$



Measurement in e^+e^- by comparing angular distribution of jet fragments in *b, c, uds* jets

Note: clean environment

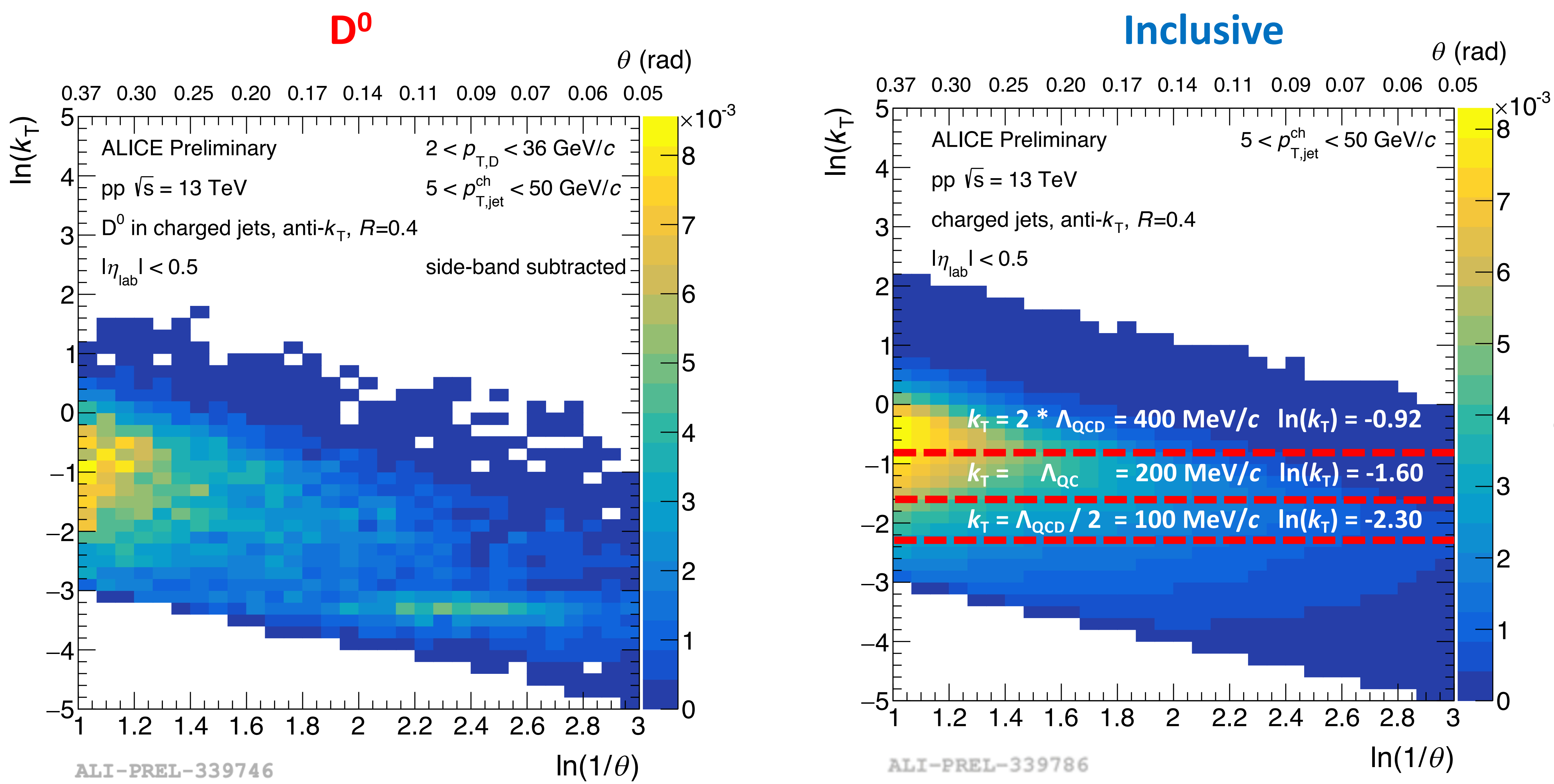
DELPHI-2004-037 CONF 712

Dead cone in ALICE

Analysis strategy: Re-cluster jets and apply k_{T} cut to remove hadronization/UE/decay contamination in pp collisions

L. Cunqueiro, M. Ploskon PRD 99, 074027

Jet substructure of D^0-tagged jets

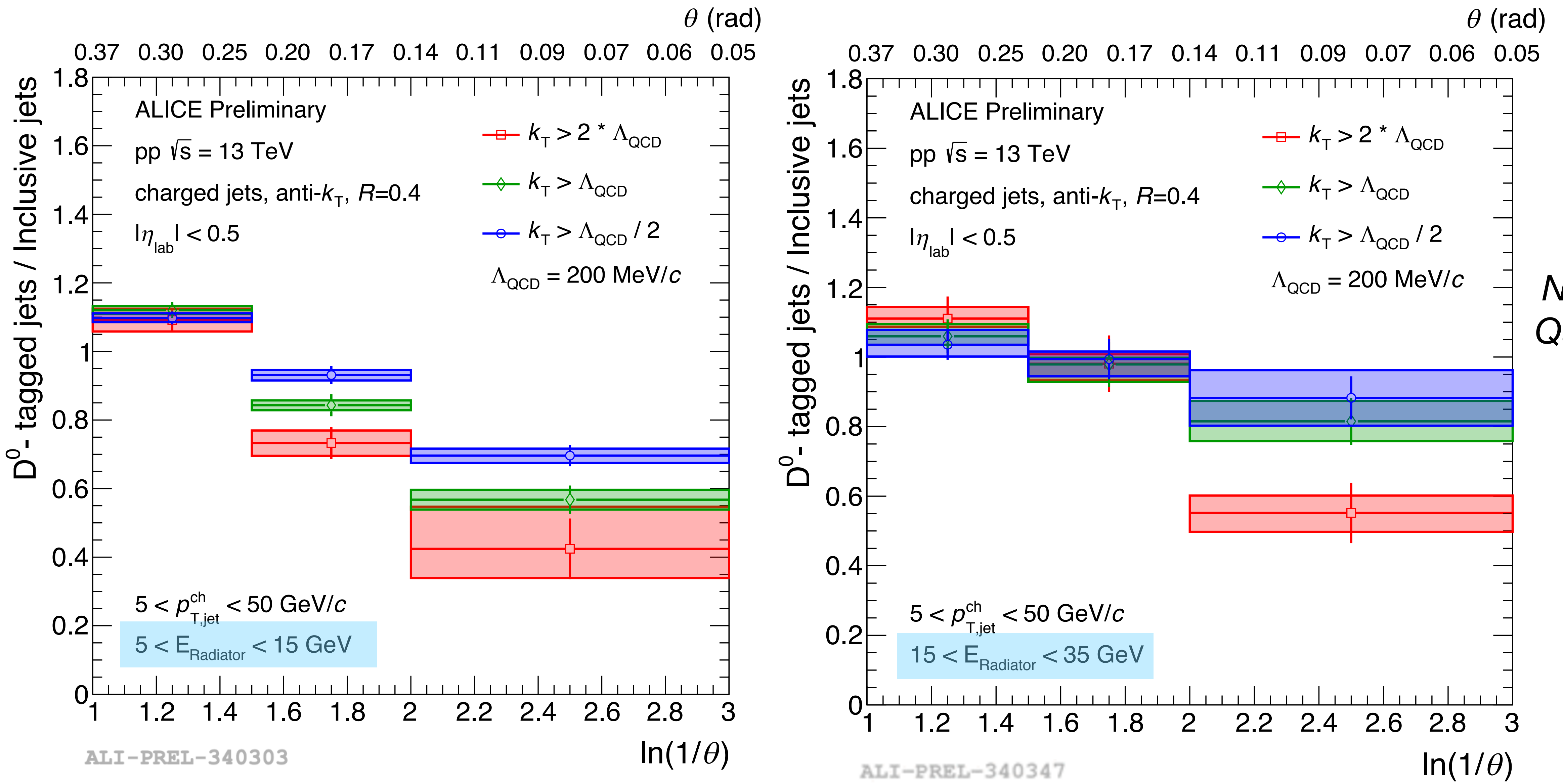


N. Zardoshti Quark Matter 2019

Dead cone in ALICE

Suppression of small-angle splittings in D^0-tagged jets relative to inclusive jets

First direct measurement of the dead cone effect in pp collisions



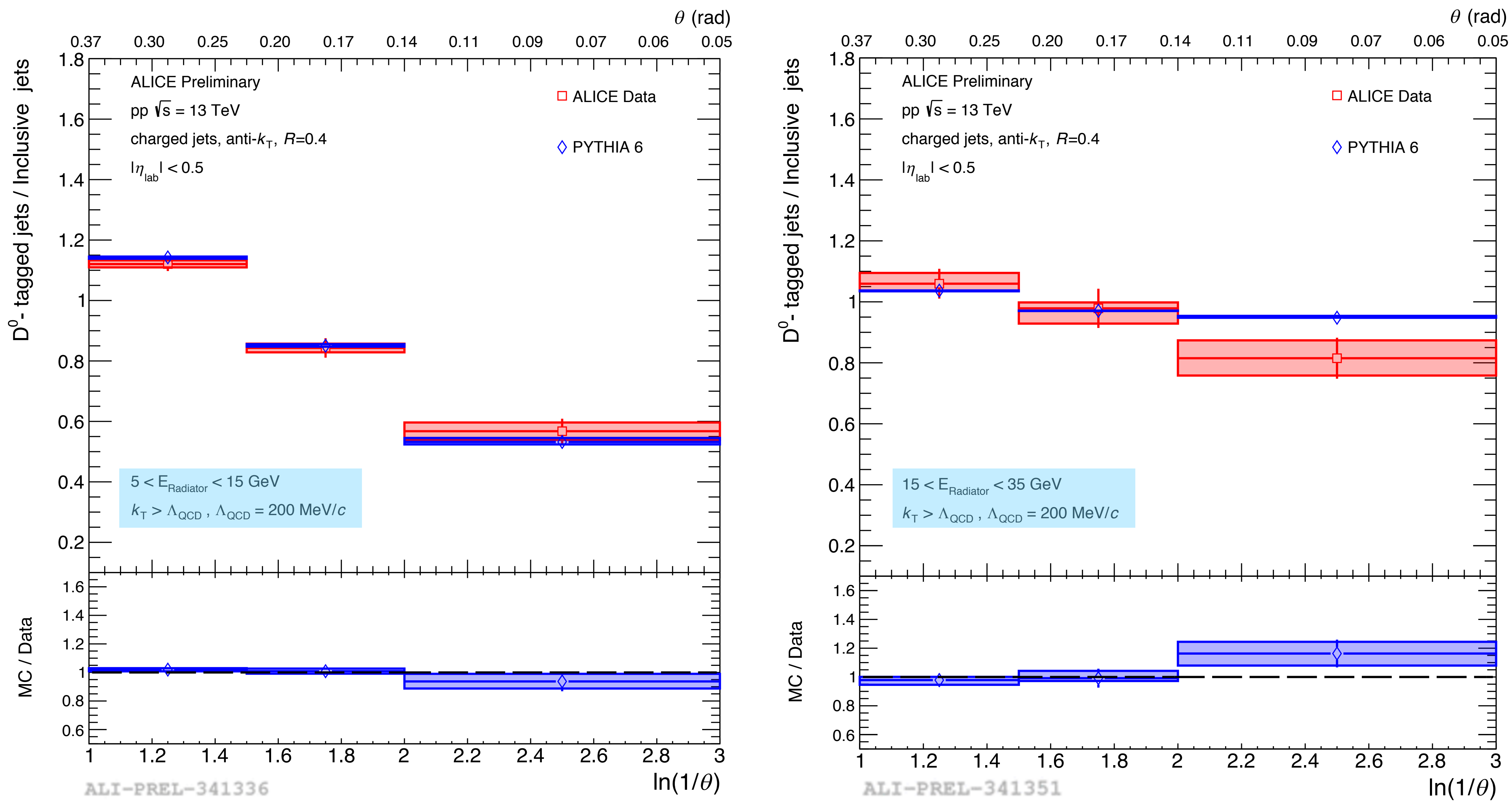
N. Zardoshti Quark Matter 2019

Suppression decreases as E_{radiator} increases: $\theta < m_q/E_q$

Suppression increases as k_{T} cut increases: Removal of contamination

Dead cone in ALICE

Jet substructure of D^0-tagged jets



N. Zardoshti Quark Matter 2019

Results are described reasonably well by PYTHIA6 at detector-level

Quarkonium: J/ψ

Production of $c\bar{c}$: perturbative

Evolution of $c\bar{c} \rightarrow \mathrm{J}/\psi$: non-perturbative

NRQCD approach: Combine perturbative expansion with Long-Distance Matrix Elements (LDME) extracted from data

Challenge: Describe both production cross-section and polarization

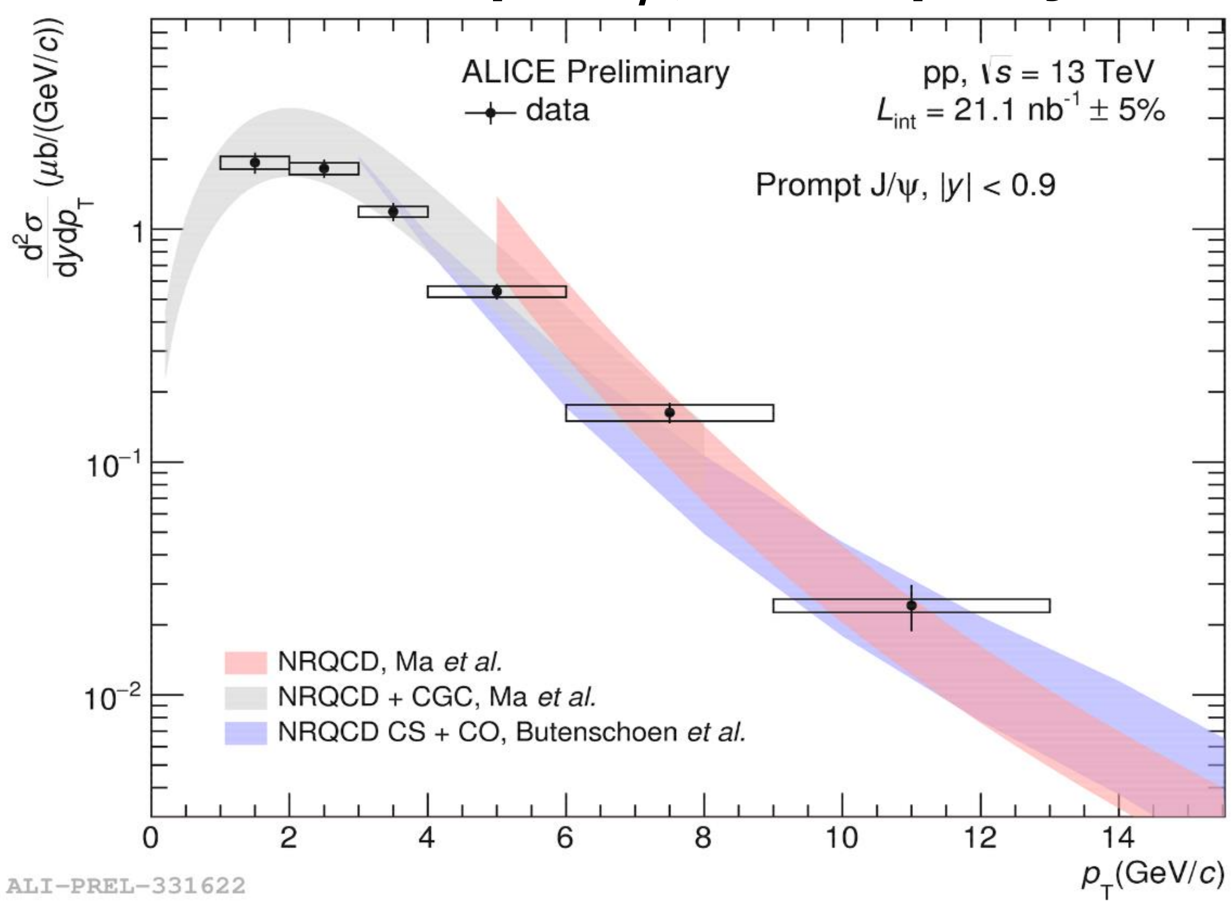
Remains an open question…

ALICE EPJ C78 (2018) 7, 562
CMS PLB 727 (2013)
LHCb EPJ C73 (2013) 11, 2631
…

Quarkonium: J/ψ

Prompt J/ψ production: Can be directly compared to theoretical models

Prompt J/ψ, mid-rapidity

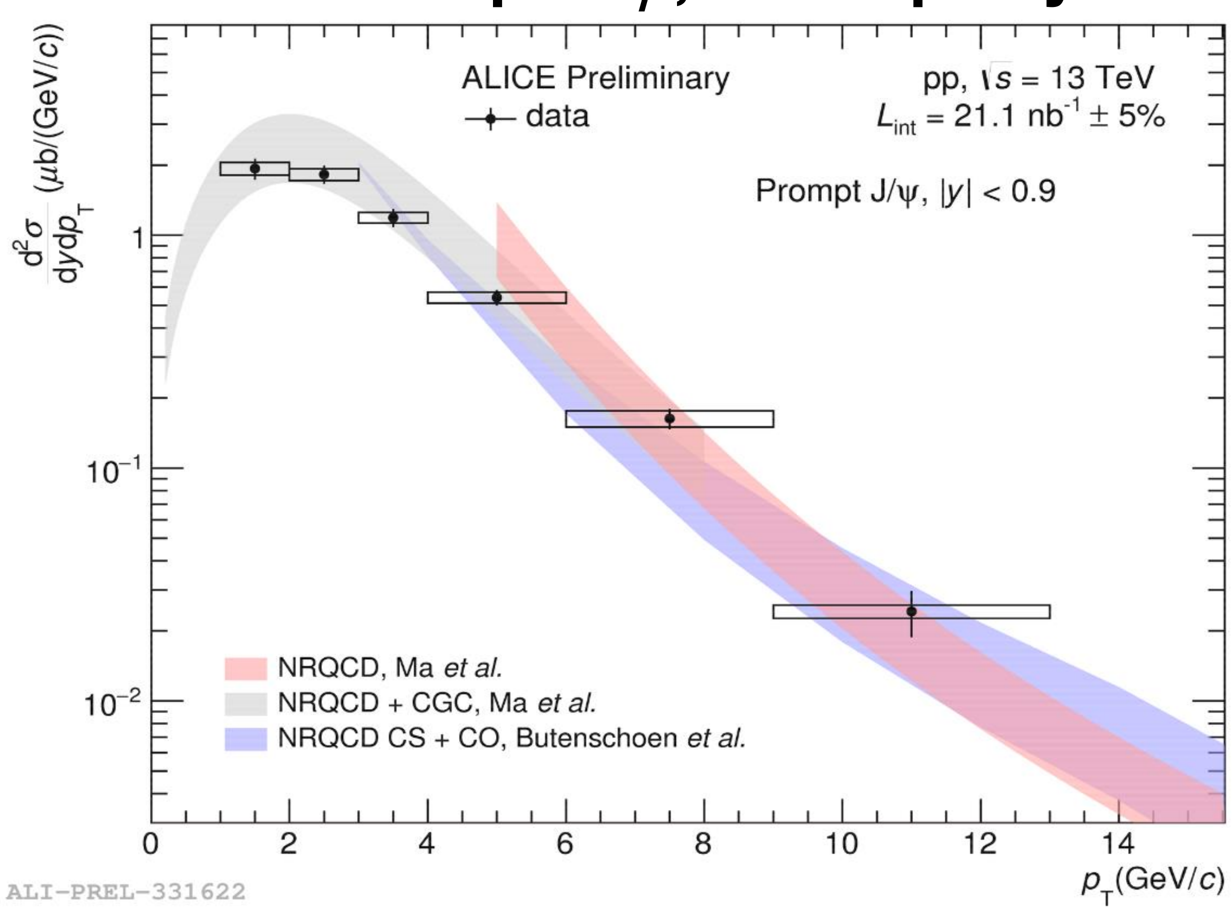


NRQCD-based models describe the data at mid-rapidity — but uncertainties are large!

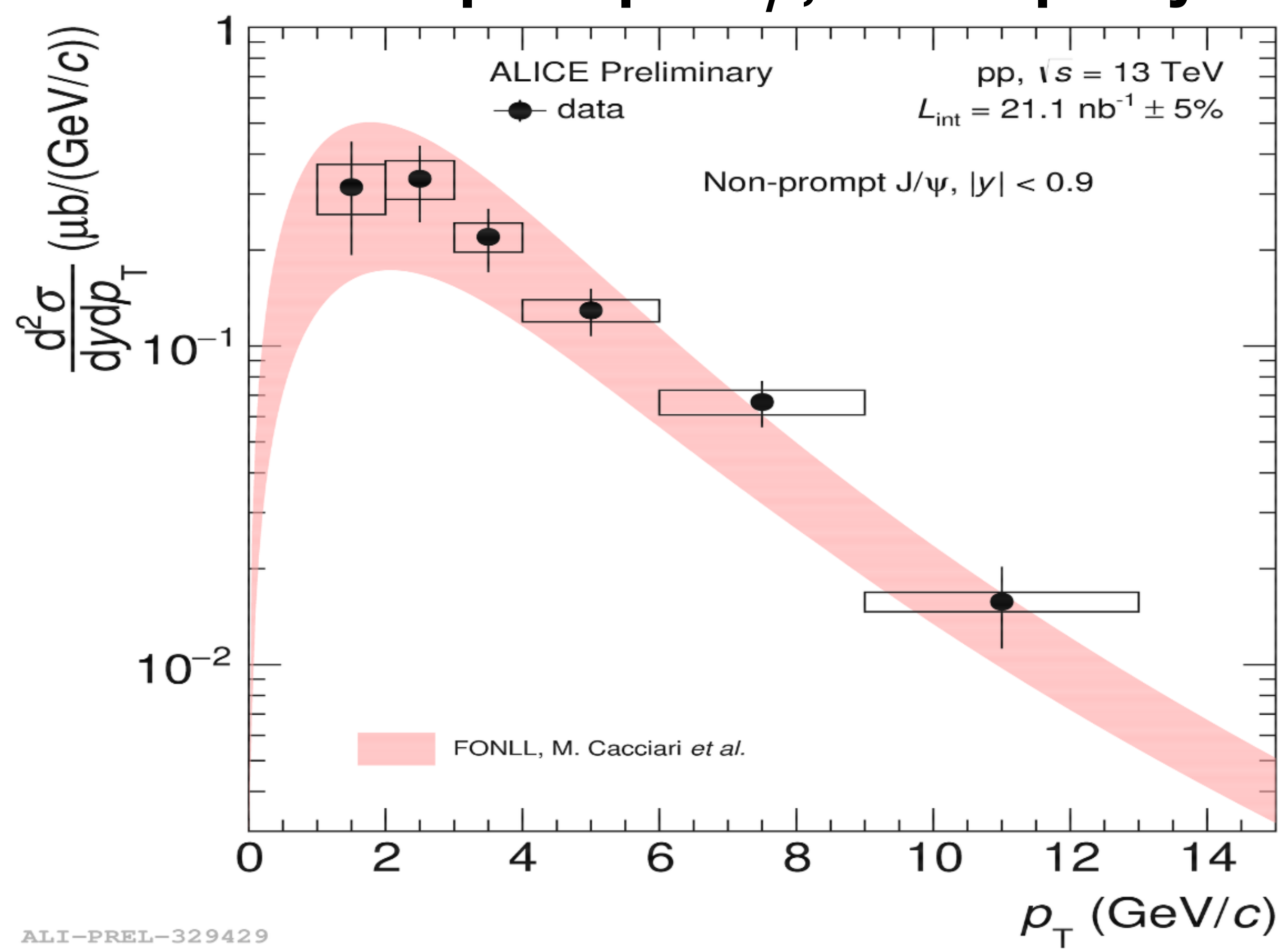
Quarkonium: J/ψ

Prompt J/ψ production: Can be directly compared to theoretical models

Prompt J/ψ, mid-rapidity



Non-prompt J/ψ, mid-rapidity



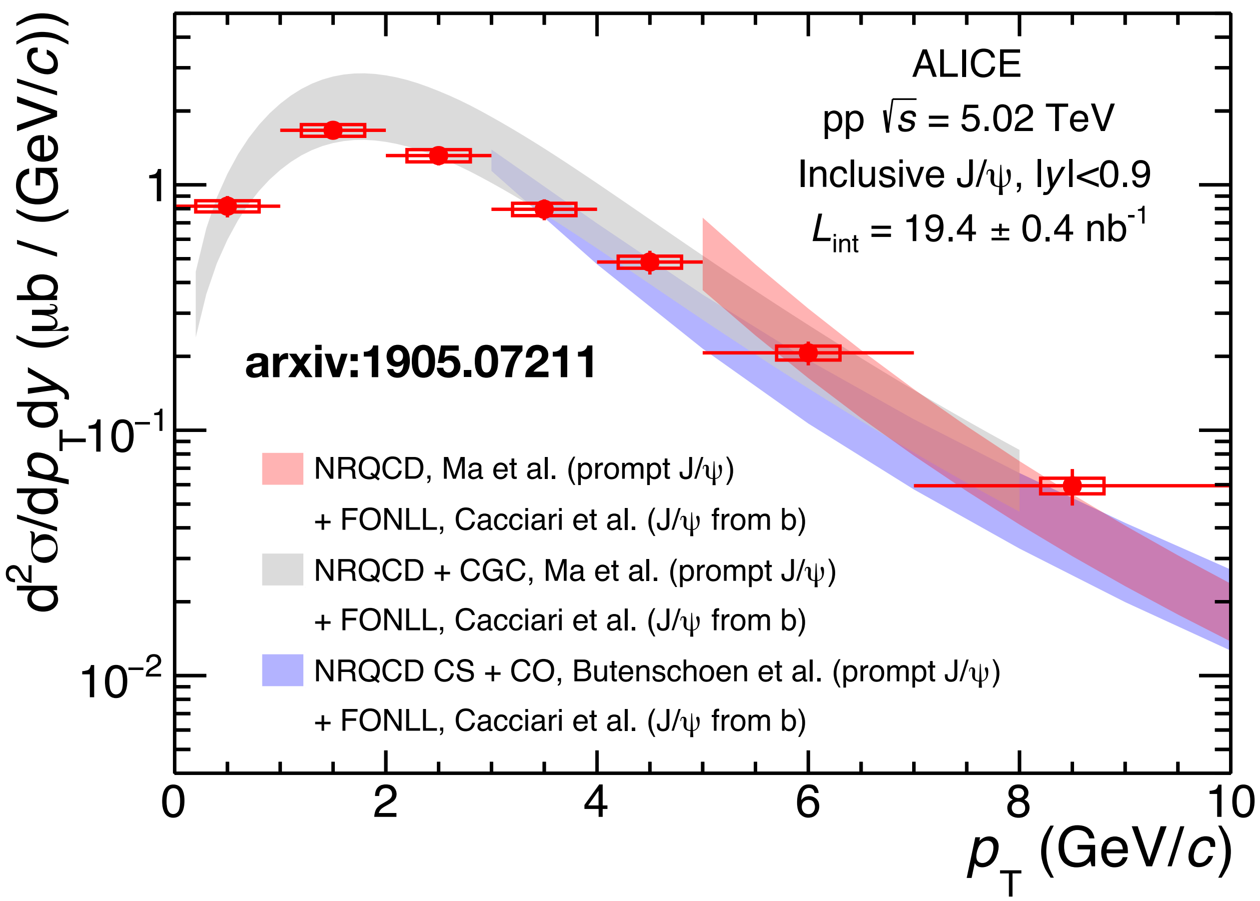
NRQCD-based models describe the data at mid-rapidity — but uncertainties are large!

FONLL successfully describes the non-prompt component

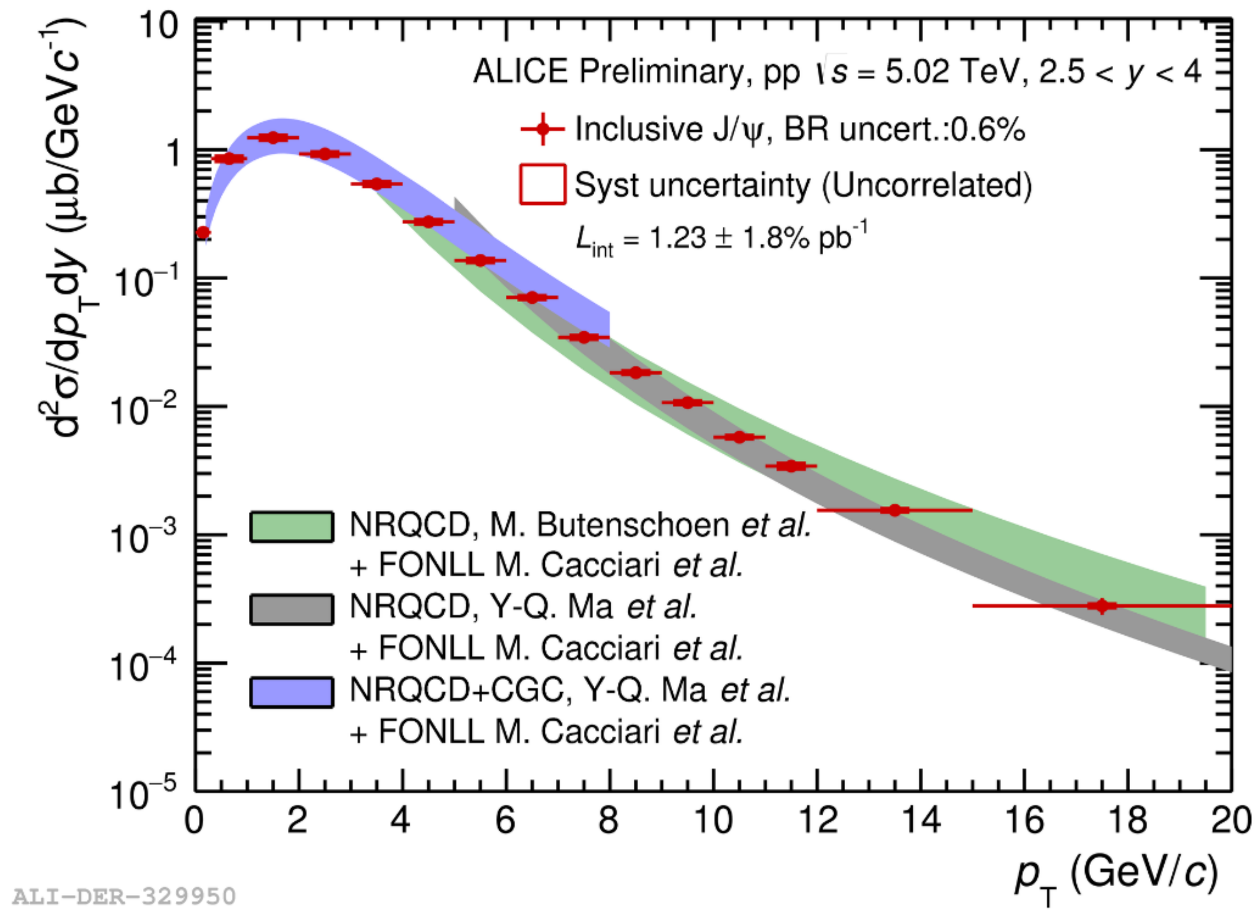
Quarkonium: J/ψ

Inclusive J/ψ production: Use FONLL to model B feed-down contribution

Inclusive J/ψ, mid-rapidity



Inclusive J/ψ, forward-rapidity

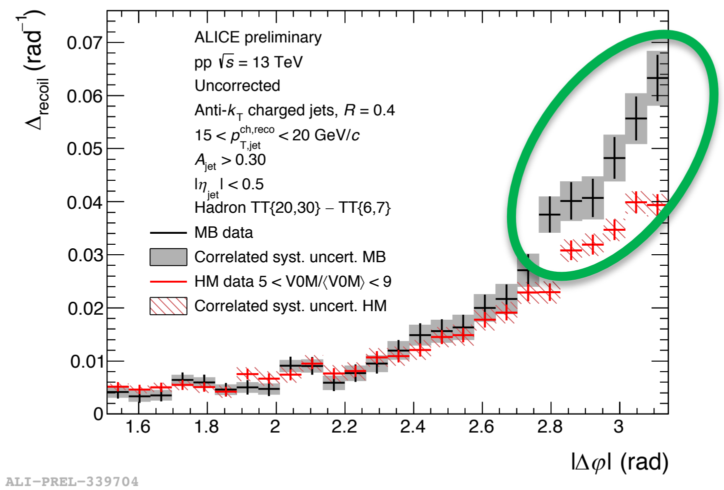


NRQCD-based models describe the data at both mid-rapidity and forward rapidity — but uncertainties are large!

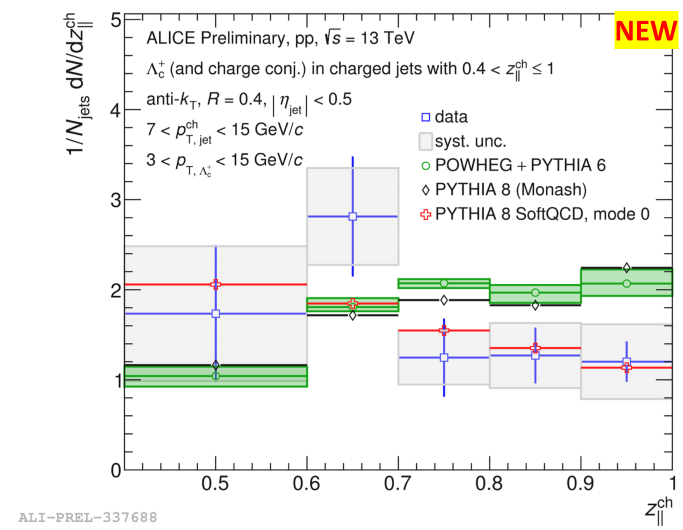
Many more Jet and Heavy Flavor Results

ALICE

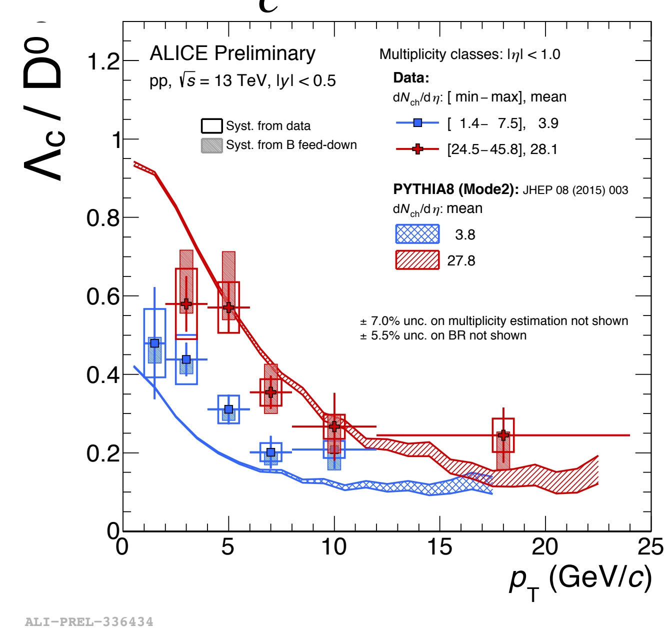
Hadron-jet correlation in high-multiplicity pp



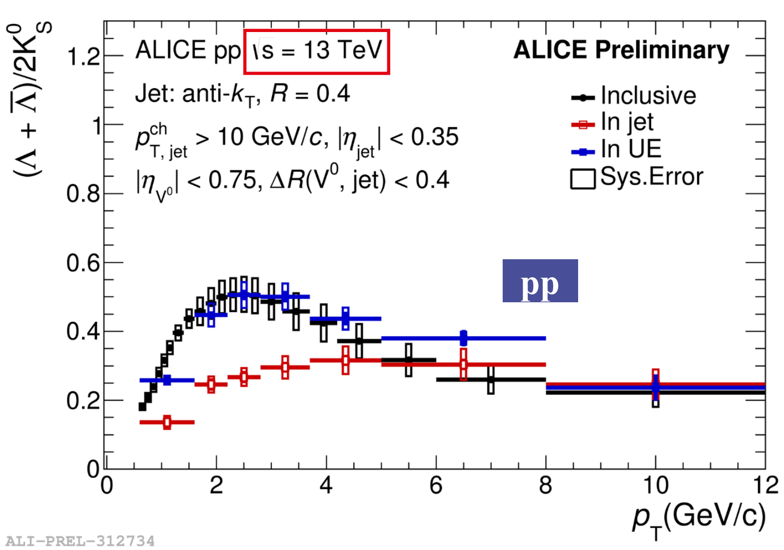
Λ_c^+ in jets



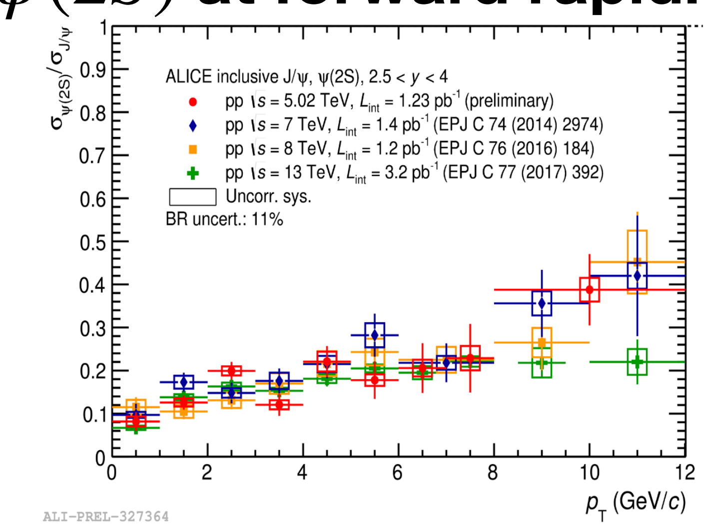
Λ_c/D^0 ratio



Strangeness in jets



$\psi(2S)$ at forward rapidity



And more…

Summary

ALICE has a rich jet and heavy-flavor program in pp collisions

Inclusive jets

R-dependence measured at low-p_{T}

Extension of p_{T} reach to 300 GeV/*c*

Groomed jet substructure

Soft Drop θ_g, z_g measured as a function of grooming parameter β

Heavy-flavor jets

D-jets and b-jets

First direct measurement of dead cone effect in pp collisions

J/ψ **production:** mid- and forward-rapidity, prompt and non-prompt

And many more not covered!