Novel probes of QCD: Precision Jet Substructure at the LHC

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o.b.o. the ATLAS, CMS, LHCb & ALICE Collaborations

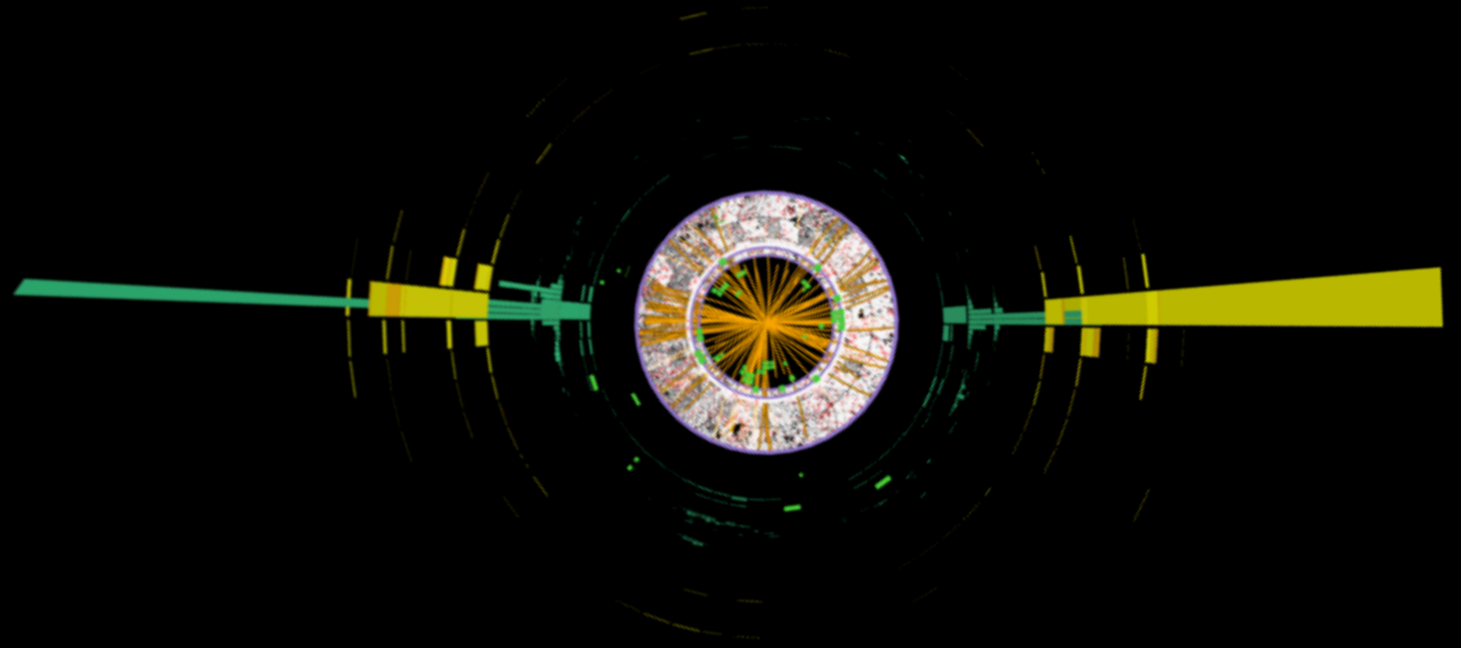
2019 American Physical Society Department of Particles & Fields Meeting
Northeastern University, Boston, USA

THE UNIVERSITY OF ARIZONA

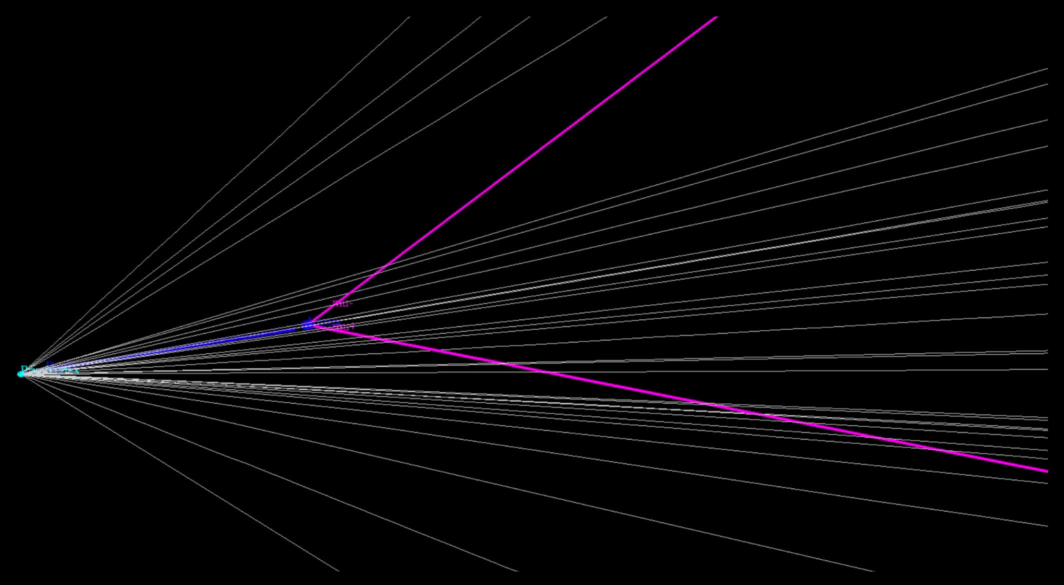
ATLAS EXPERIMENT

"More is Different"

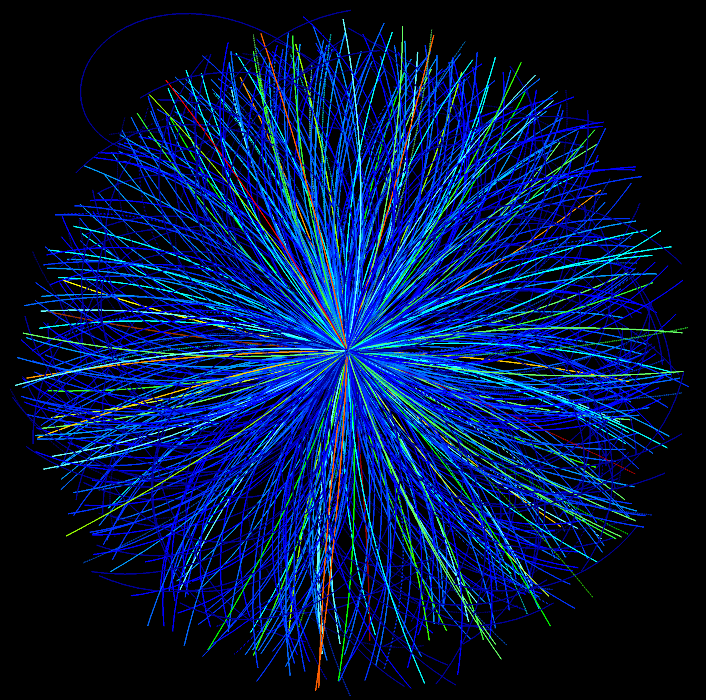
Jets



Hadrons



Quark-Gluon Plasma



One reason that QCD is fascinating because it demonstrates *emergent behaviour* —

just because you know the QCD Lagrangian doesn't mean you understand all of its physics!

$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4} F^{a}_{\mu\nu} F^{\mu\nu\, a} + \bar{\psi} i \not{D} \psi$$

During Run 2 of the LHC, **all four large collaborations** are testing QCD using a novel techniques in a challenging setting:

within jets!

… and by **working closely with our hep-ph colleagues**, they're doing it with higher precision than ever before!

P. W. Anderson, 10.1126/science.177.4047.393

Slide adapted from A. Larkowski, BOOST 2017 Theory Introduction

Precision JSS @ LHC Run 2

ATLAS	CMS	LHCb	ALICE
Soft Drop Mass https://arxiv.org/abs/1711.08341 *Jet Pull* https://arxiv.org/abs/1805.02935 *g(bb) at small ΔR* *https://arxiv.org/abs/1812.09283* *JSS Observables in multijets and ttbar* https://arxiv.org/abs/1903.02942 *Fragmentation properties* *https://arxiv.org/abs/1906.09254* *Z(bb)+γ* *https://arxiv.org/abs/1907.07093* *Lund jet plane* ***(new!)*** *ATLAS-CONF-2019-035*	*Soft Drop Mass in Pb+Pb* https://arxiv.org/abs/1805.05145 *Soft Drop Mass* https://arxiv.org/abs/1807.05974 *Jet shapes in ttbar* https://arxiv.org/abs/1808.07340 *Top mass (XCone)* ***(new!)*** CMS-PAS-TOP-19-005	*J/ψ in jets* https://arxiv.org/abs/1701.05116 *Charged hadron multiplicity* https://arxiv.org/abs/1904.08878	*Track jet XS & fragmentation* *https://arxiv.org/abs/1809.03232* z_g *and* N_{SD} https://arxiv.org/abs/1905.02512

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCJetSubstructureMeasurements

Precision JSS @ ~~LHC Run 2~~ Today!

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Lund jet plane ***(new!)*** *ATLAS-CONF-2019-035*			

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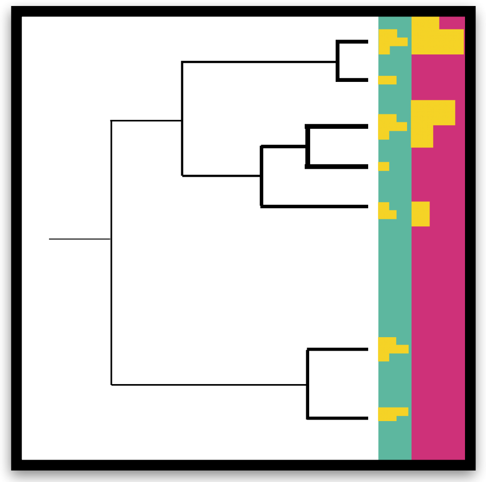

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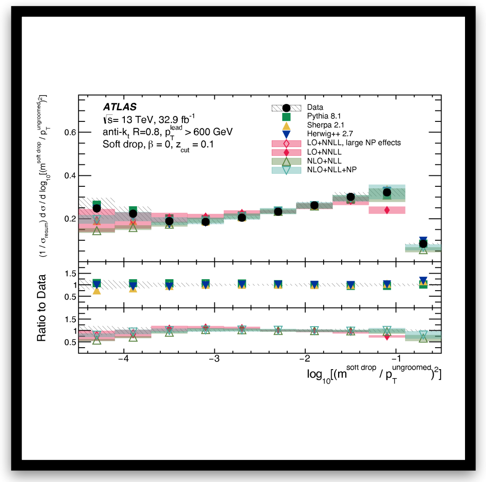

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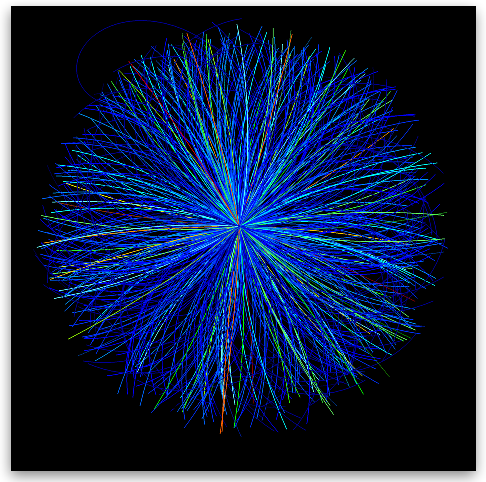
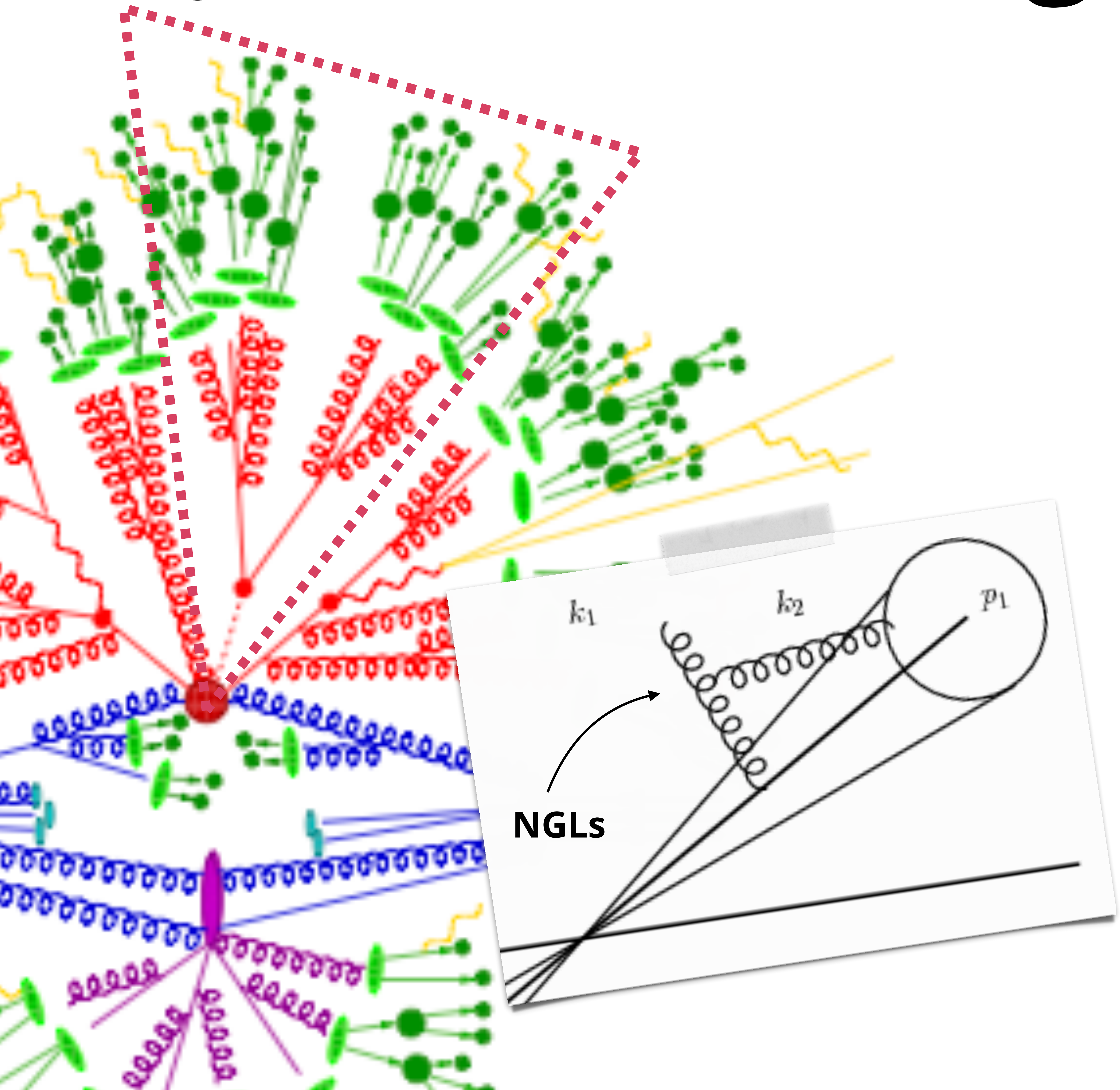
— Jet mass measurements from ATLAS and CMS.



3. What is the future of precision JSS?

— New directions from ALICE and LHCb in ions and quarkonium production.

Jets and non-global logarithms

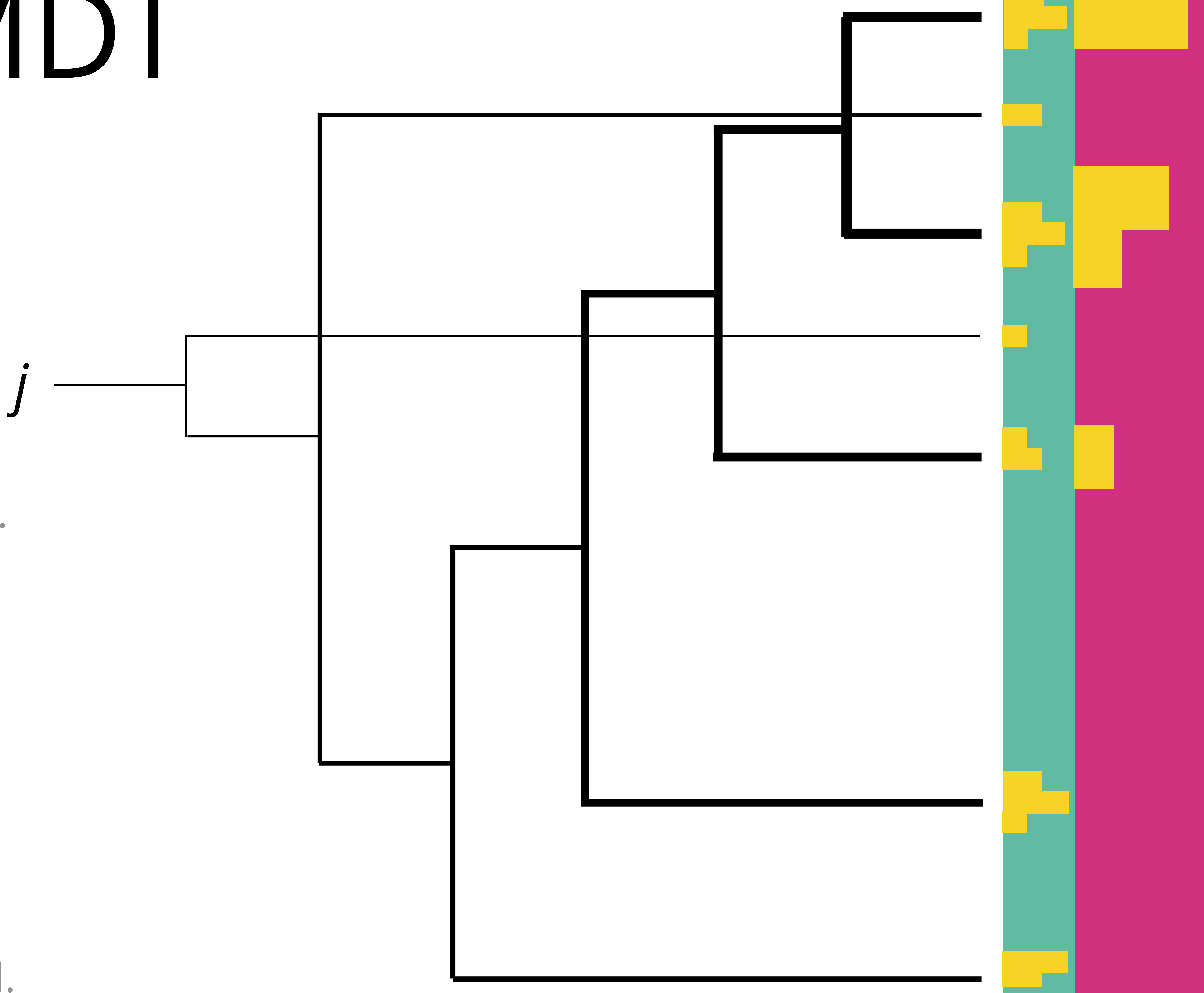


- Jets have long been used as probes of QCD, however high-precision calculations of their **substructure** were unavailable.
    - Jets have a hard boundary — divergent **non-global logarithms** blocked theoretical progress!
- The **Soft Drop / mMDT** algorithm provided a way to remove **soft and wide-angle radiation** from jets: it is **formally insensitive to NGLs**.
- For more details on state-of-the-art JSS calculations, see F. Ringer and Y.-T. Chien here @ DPF19-QCD.

Soft Drop / mMDT

This grooming algorithm renders jets formally insensitive to NGLs.

1. **Begin with an anti-kt jet.**
2. Recluster jet constituents using **Cambridge/ Aachen (C/A)** algorithm **(angular-ordering)**.
3. **Iterating inward from widest-angle radiation**, discard subjets when they fail the Soft Drop condition.
   - Two parameters: z_{cut} and β.
4. When the SD condition is satisfied, **stop!**
   - **Soft** and **Wide-Angle** radiation is removed.



Dasgupta, Fregoso, Marzani, Salam, JHEP09 (2013) 029,
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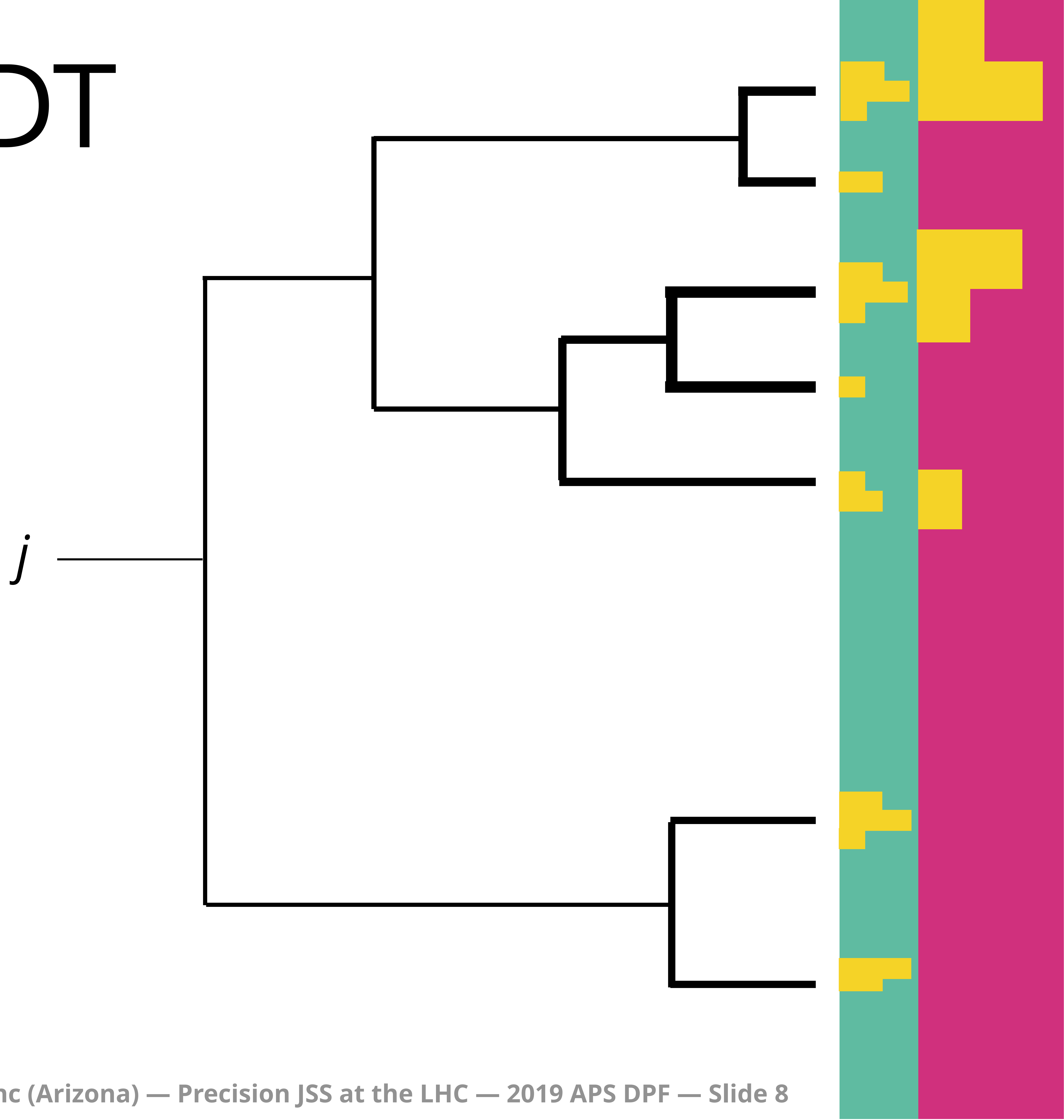

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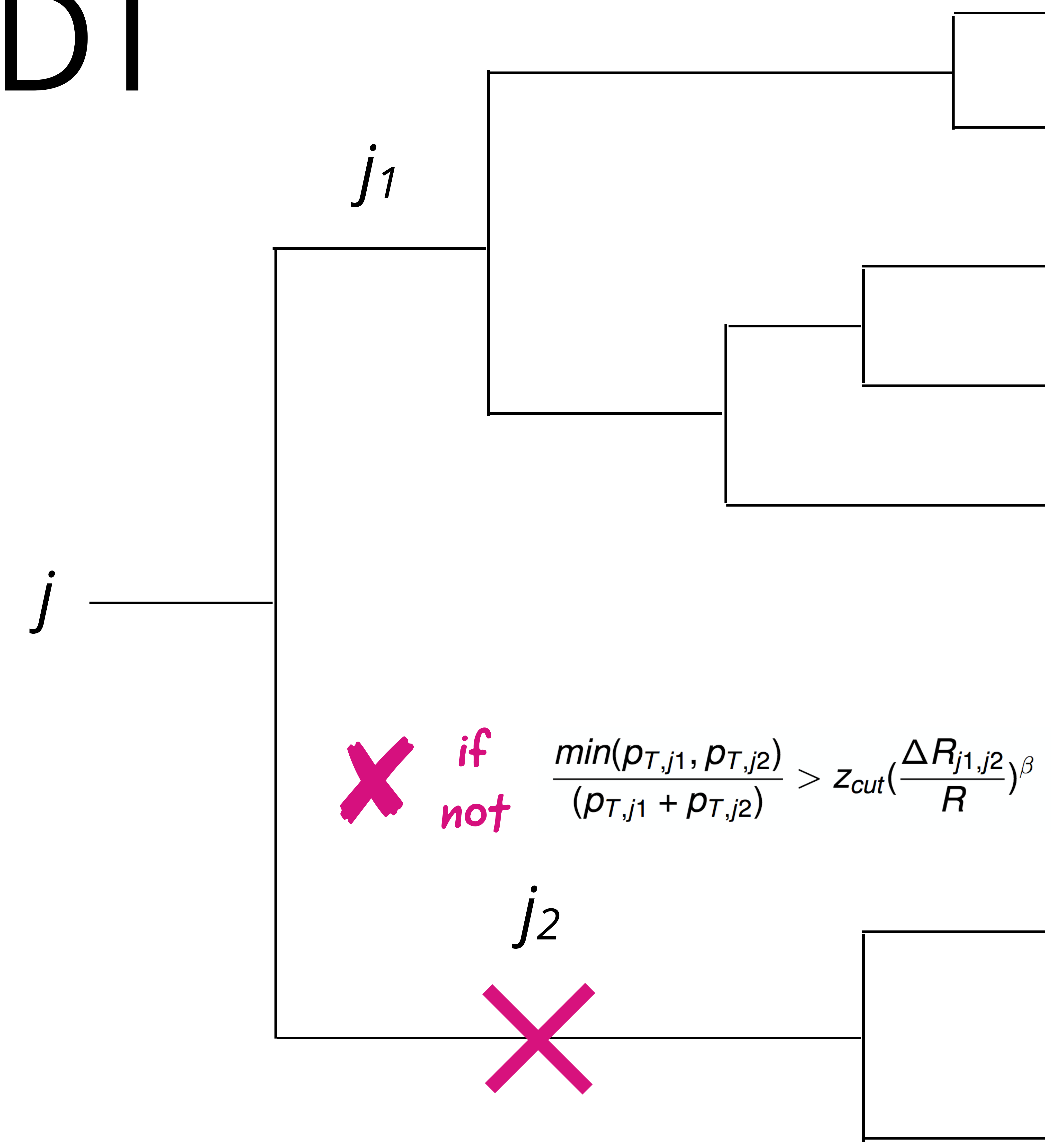

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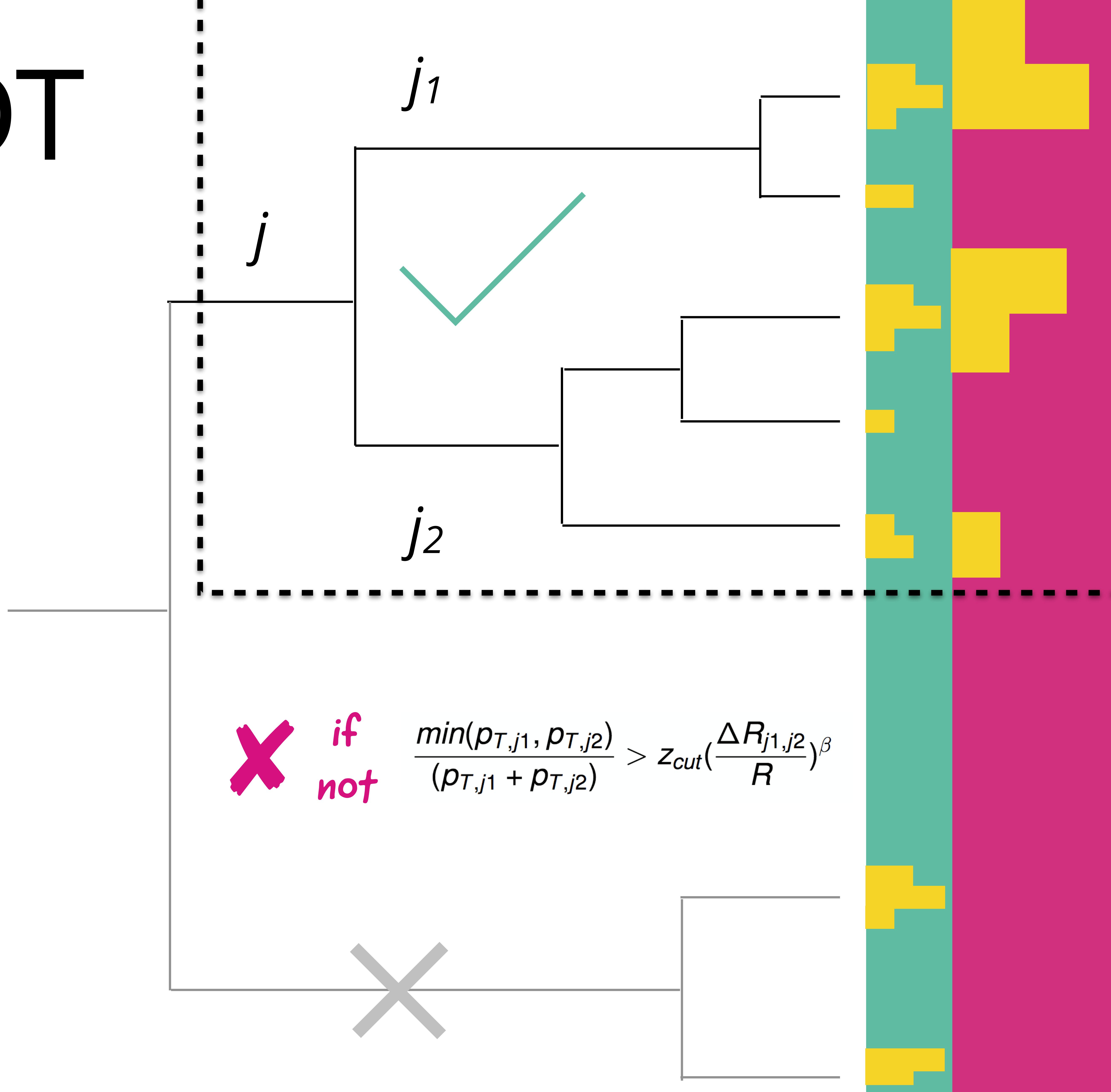

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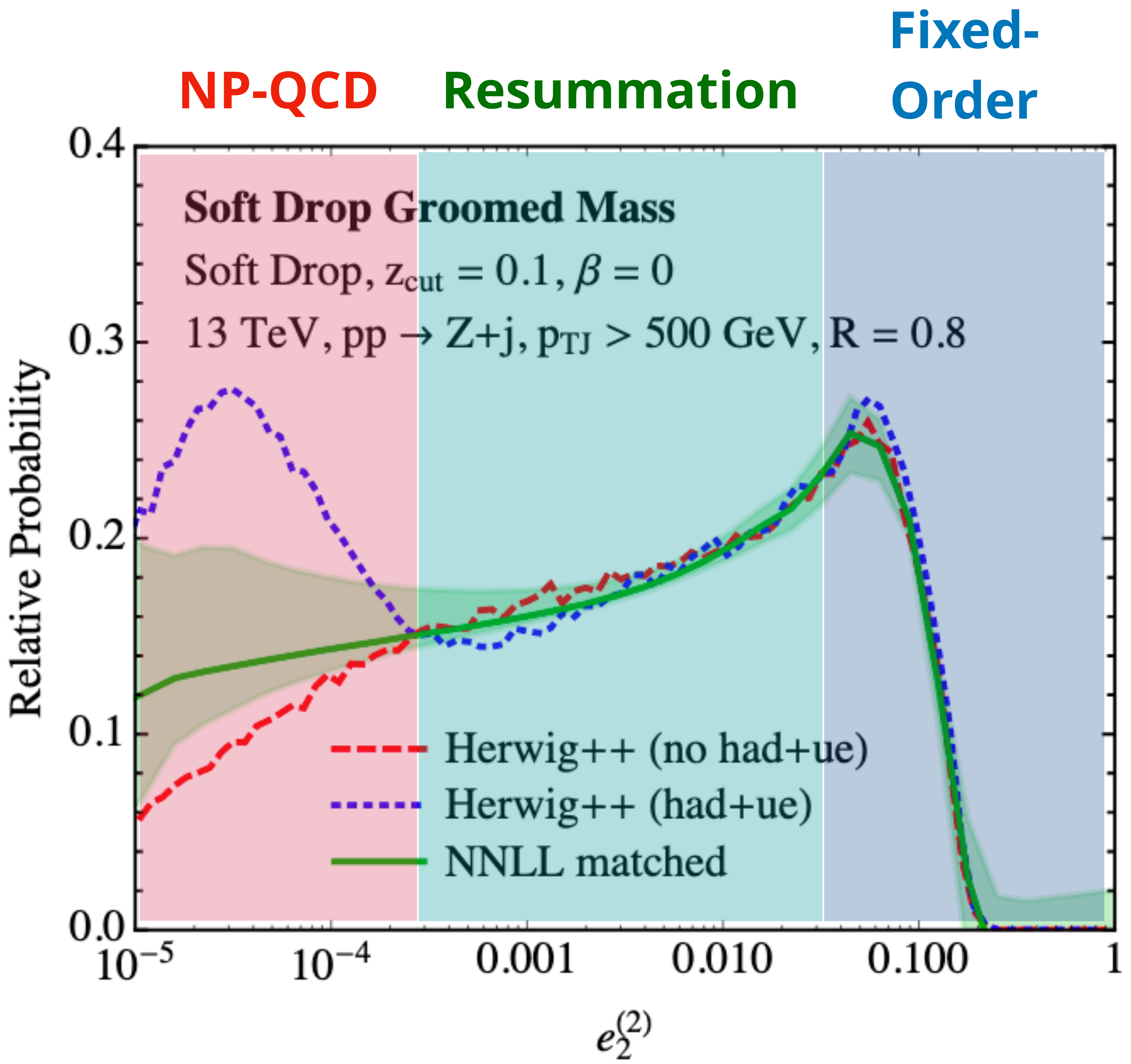
NNLL: Frye, Larkowski, Schwartz, Yan; JHEP (2016) 64, arXiv:1603.06375
NLO+NLL: Marzani, Schunk, Soyez JHEP (2017) 132, Eur. Phys. J. C (2018) 78
NLO+NLL: Kang, Lee, Liu, Ringer; JHEP (2018) 137

Soft Drop Jet Mass

- The first JSS observable to understand is the **Soft Drop jet mass for light-quark & gluon jets**.
  - ~0 @ LO, sensitive to higher-order physics.
- **First calculations @ >LL were available for the mass**, and **it still leads the pack** in terms of precision.
- Different effects in QCD **factorise naturally** as a function of the mass.
  - Calculations are valid in the **resummation (intermediate mass) region.**



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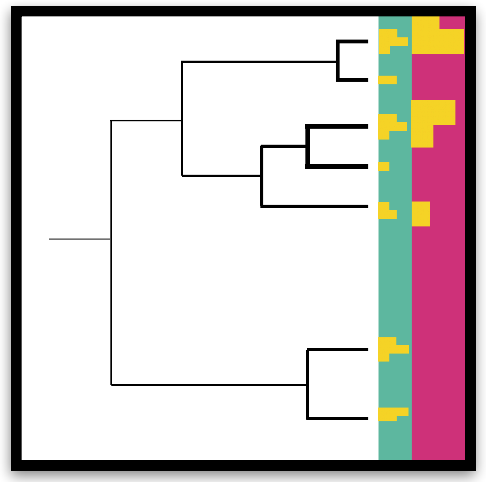

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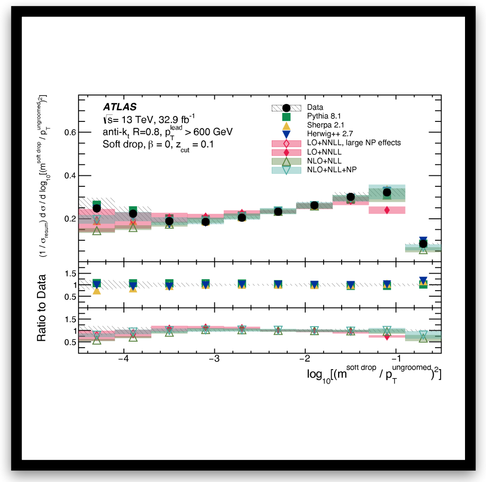

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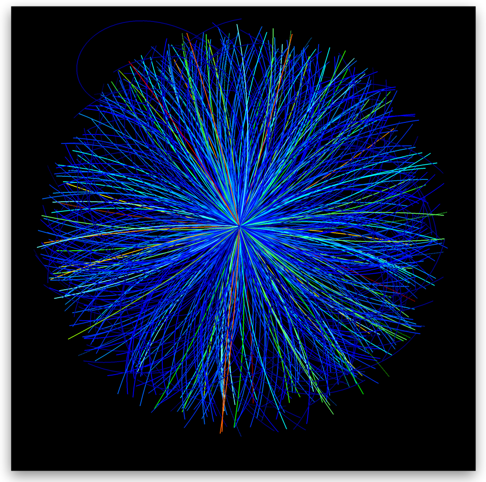

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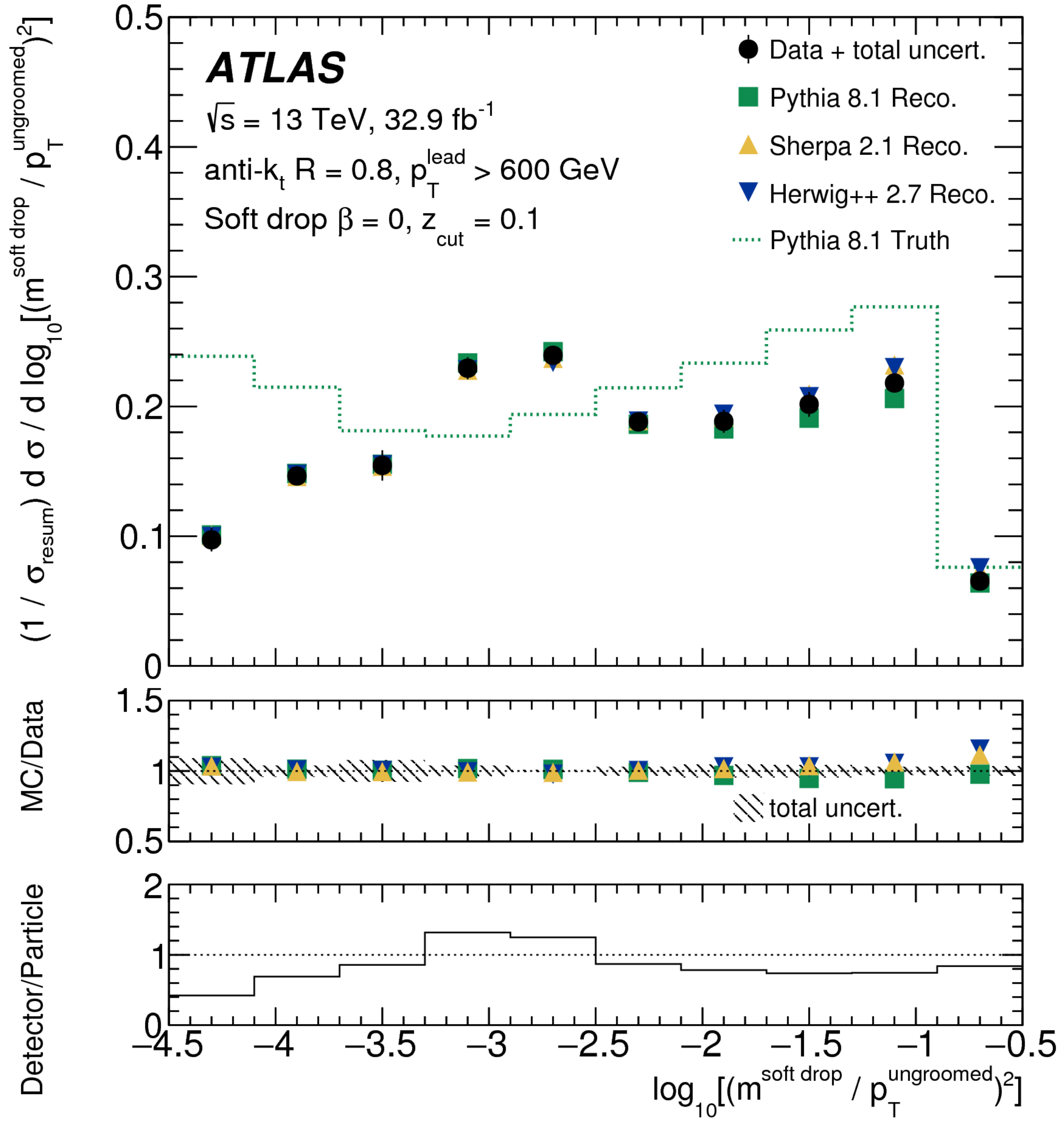
Soft Drop Jet Mass

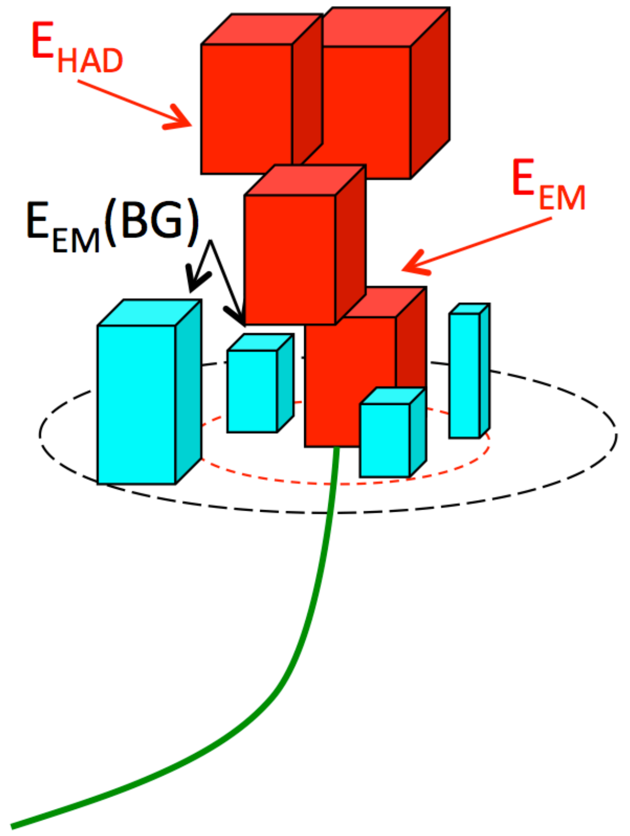


- **Goal:** unfolded jet mass spectrum in data, which can be compared to new precision QCD calculations.
- **Challenge:** non-trivial detector effects to account for in unfolding.
  - This distribution will be sensitive to physics modelling of constituent-level effects!
    - *i.e.* calorimeter granularity, splitting/merging, PFO algorithms, *etc*., *etc*.

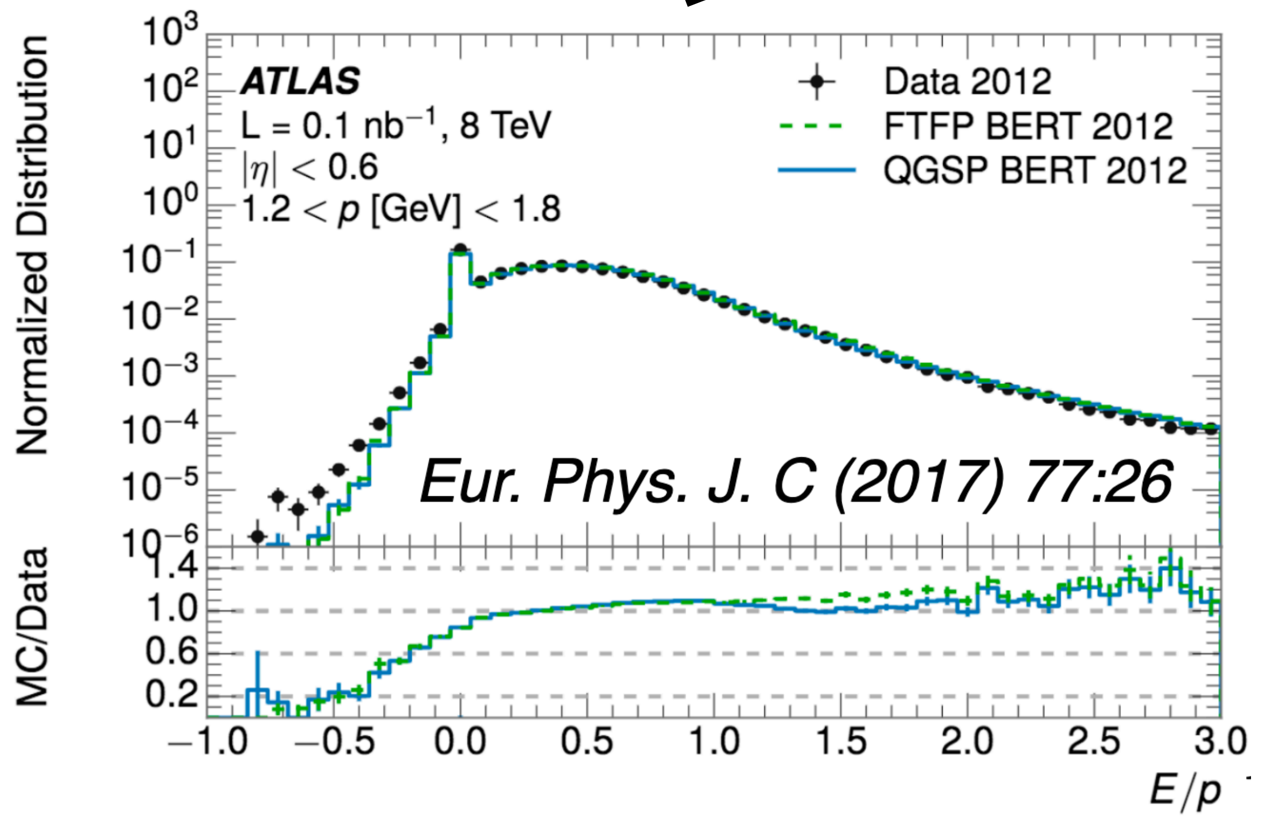
ATLAS, Phys. Rev. Lett. 121, 092001 (2018)
ATLAS, Eur. Phys. J. C (2017) 77
CMS, JHEP 11 (2018) 113
CMS-DP-2017-026

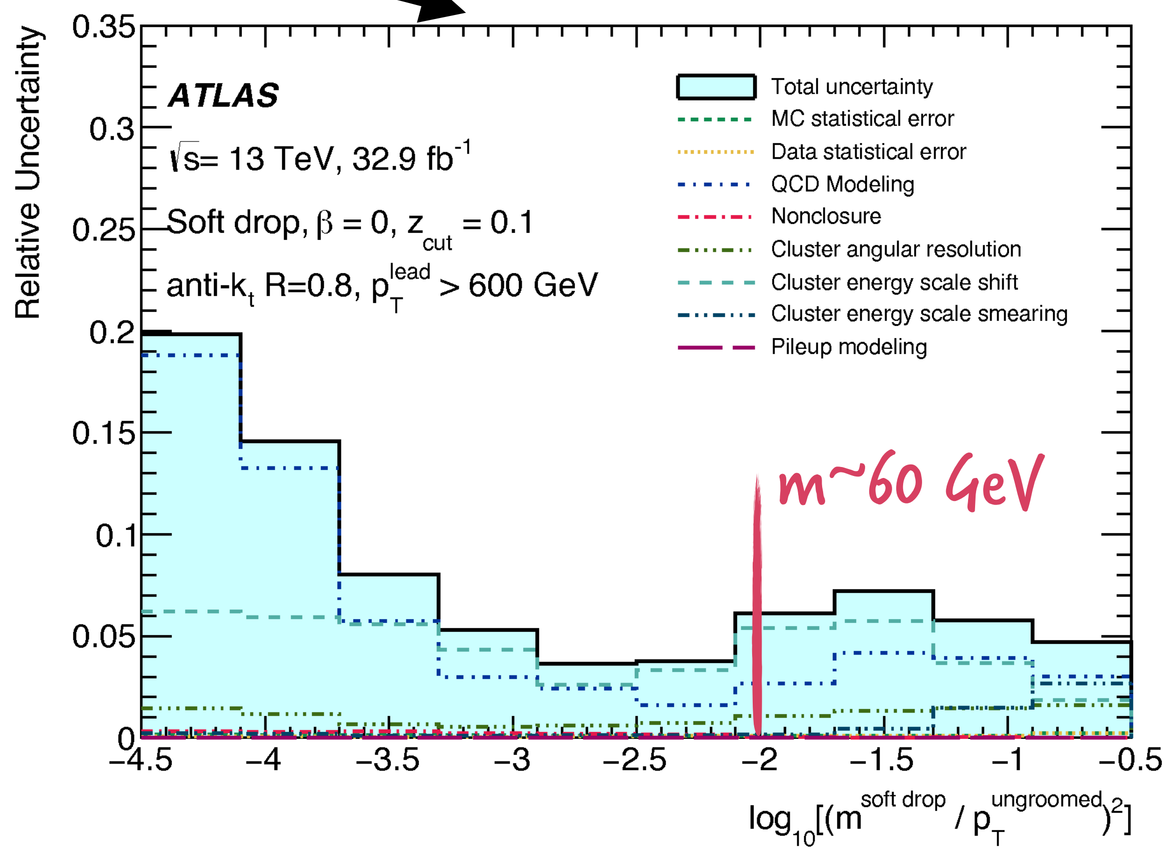
SD Mass: Systematics

ATLAS — "Bottom-Up”



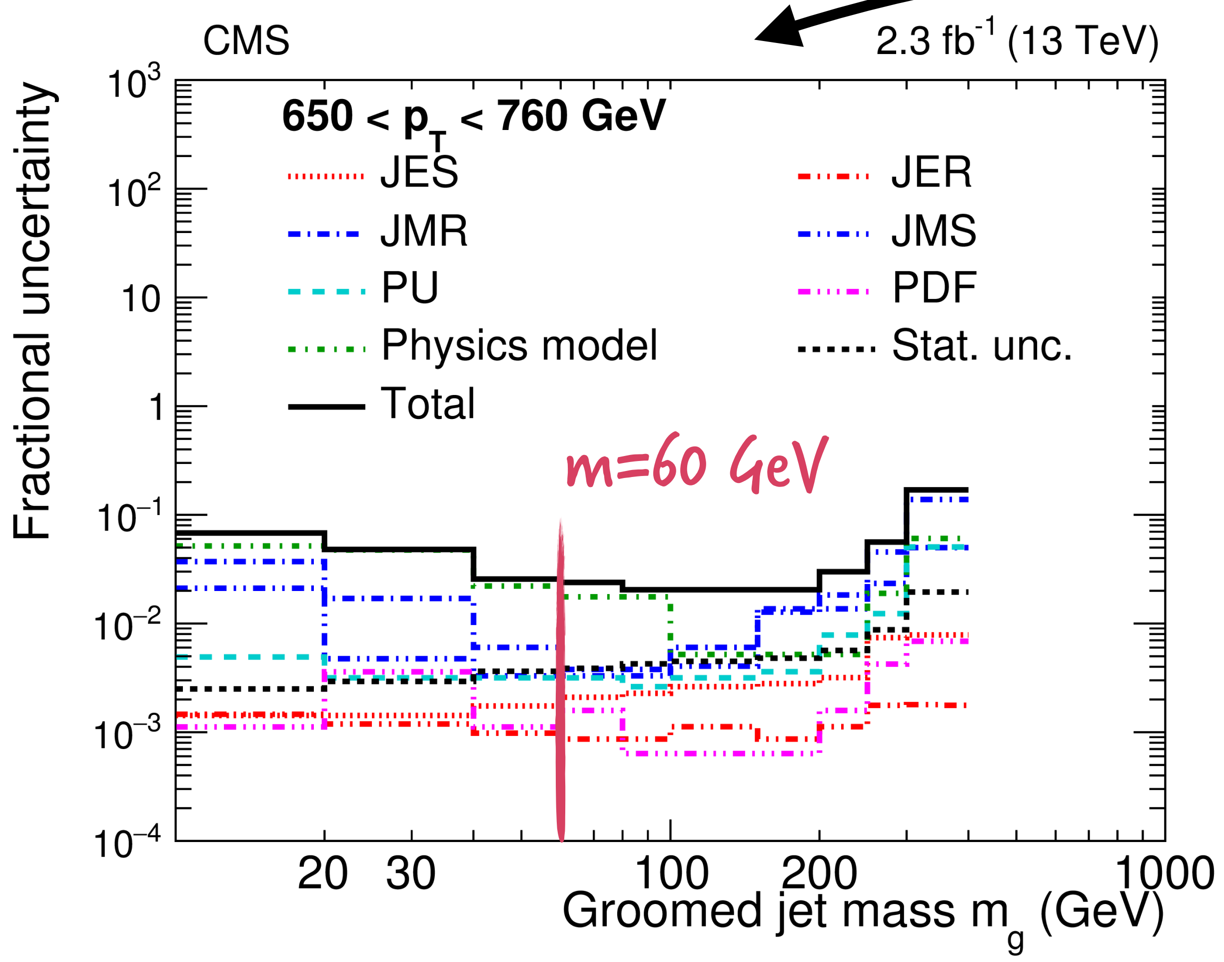
- Several systematics on the **modelling of ATLAS topo-clusters (efficiency, energy scale & resolution)** are derived from earlier measurements of the **single-hadron response** (E/p).
- Complex: requires understanding of any **collective effects** arising due to dense environment.

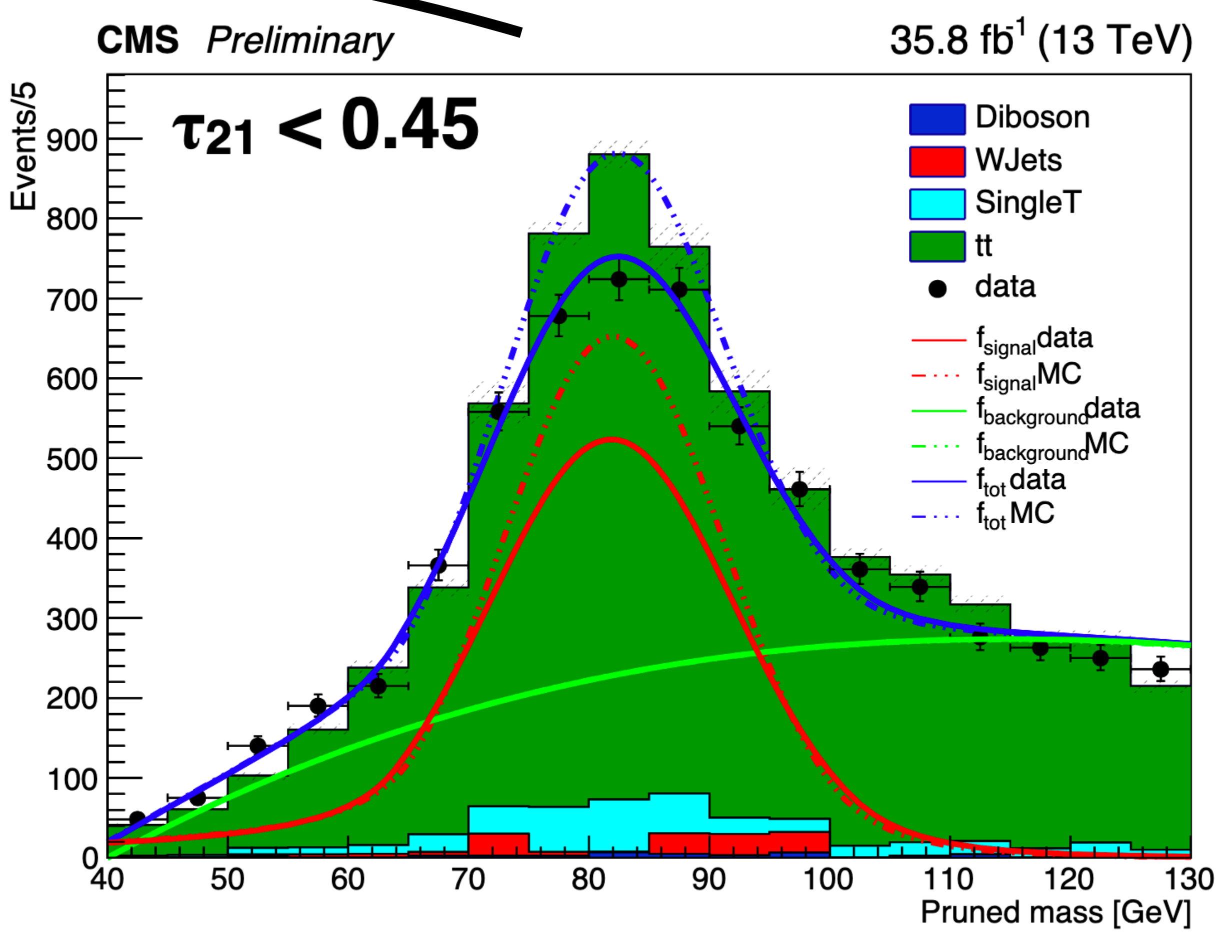




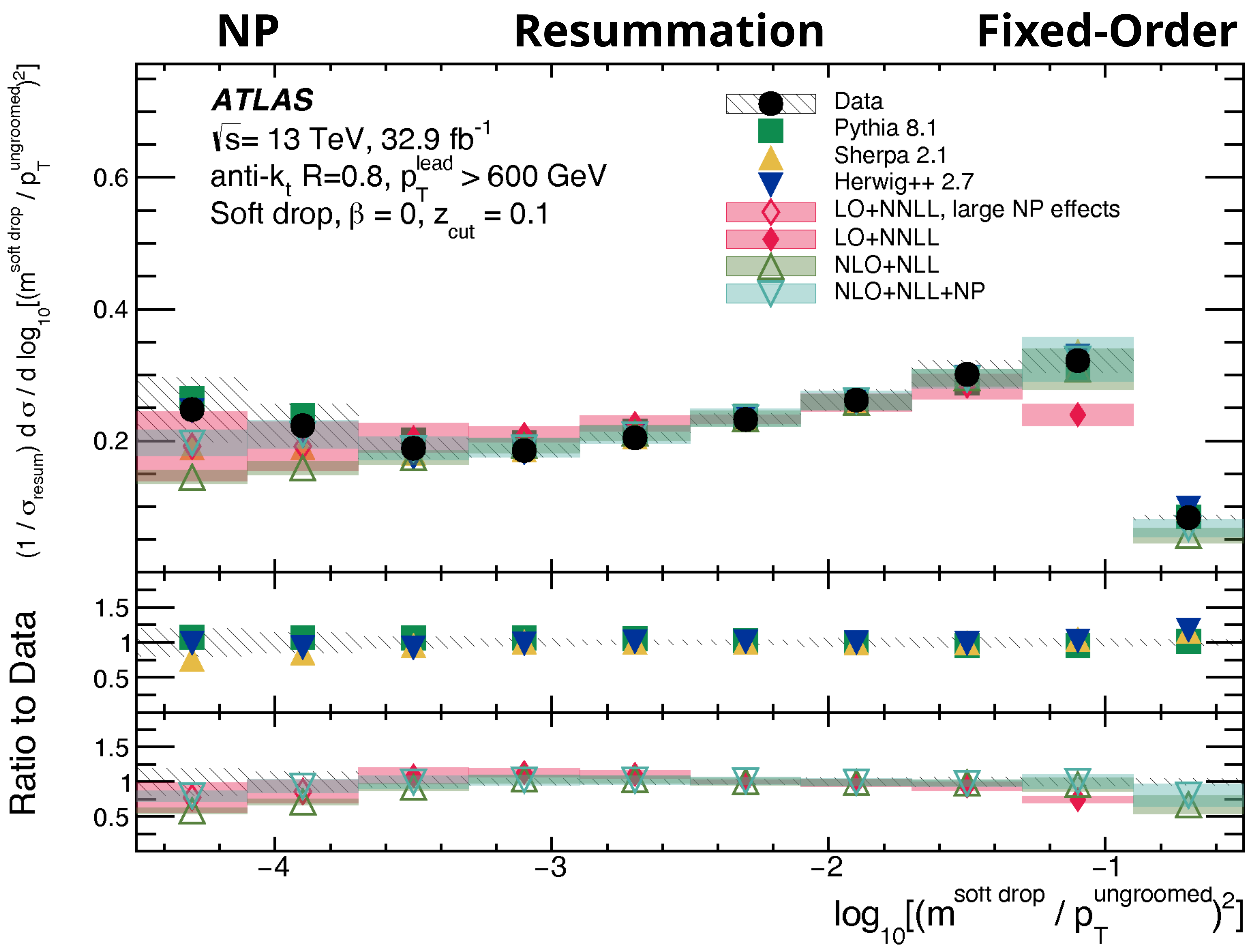
CMS — “Top-Down”

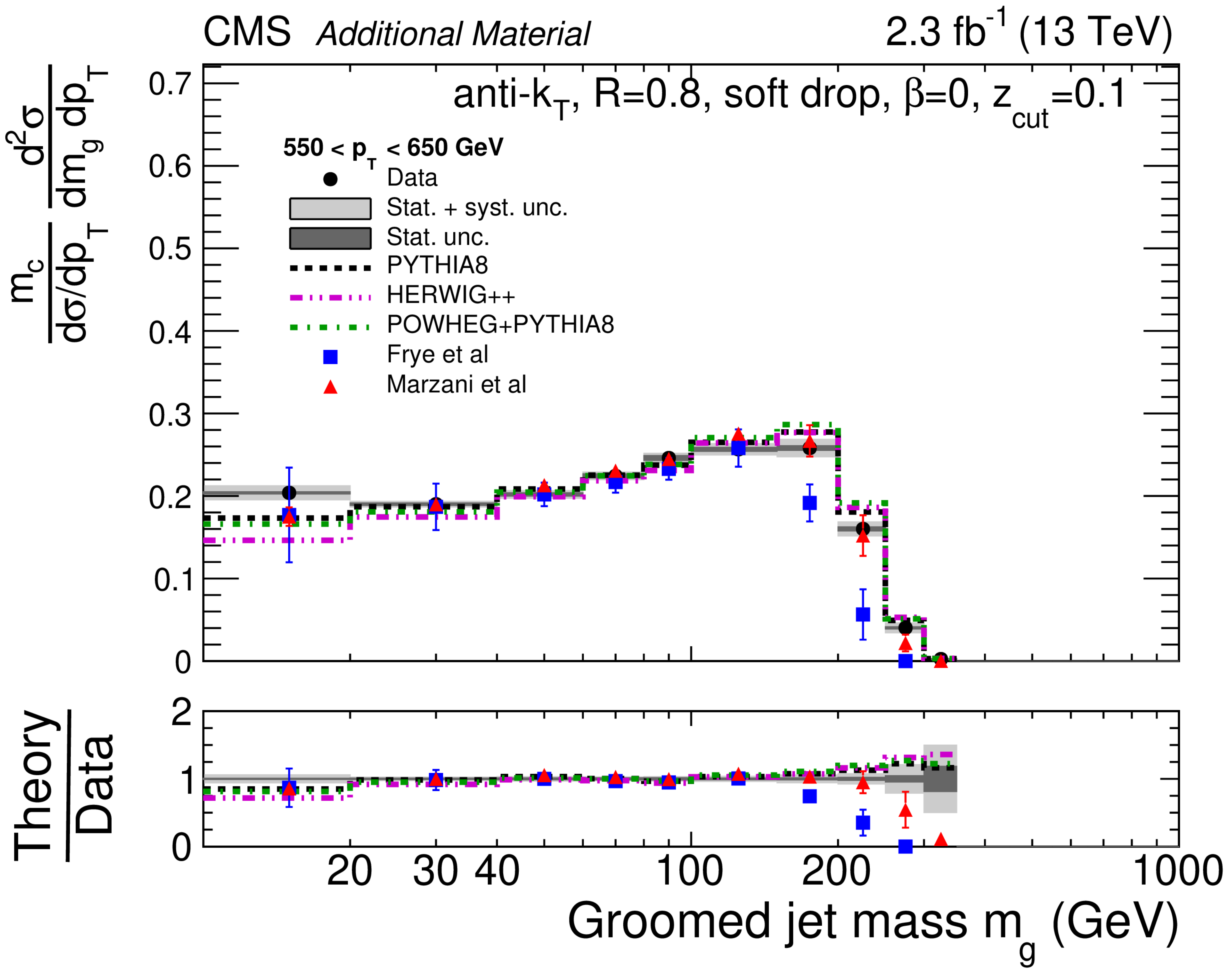
- Jet mass scale & resolution estimated from the **hadronic *W* peak in top-pair events .**
- **Simpler** scheme, but **requires extrapolation** across topologies.





Soft Drop Jet Mass





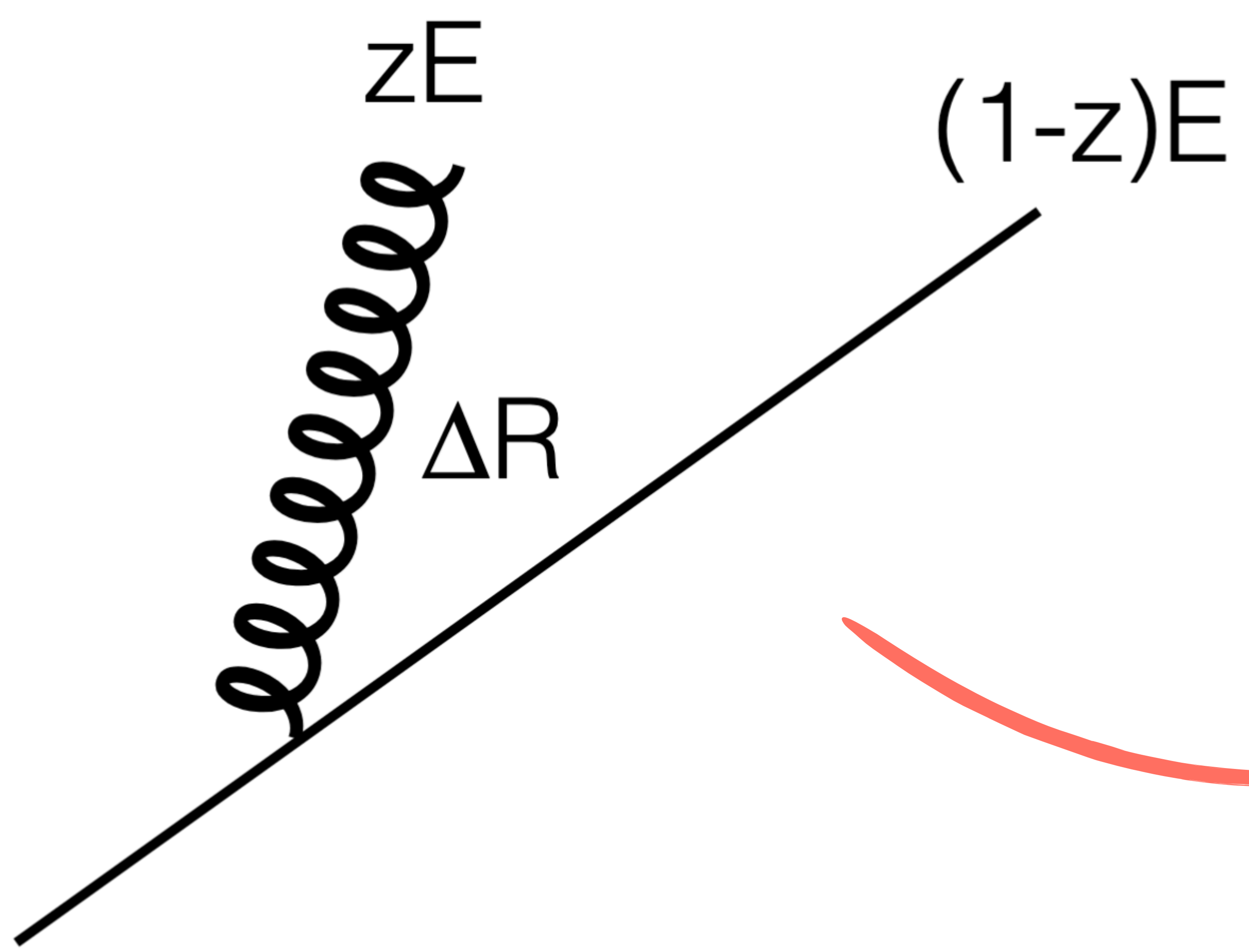
Good agreement in the ***resummation region,*** where these calculations are expected to be valid. The **NP region appears to be more difficult to describe**, both analytically and for MC programs.

The Lund Jet Plane

ATLAS-CONF-2019-035 (New for BOOST '19!)

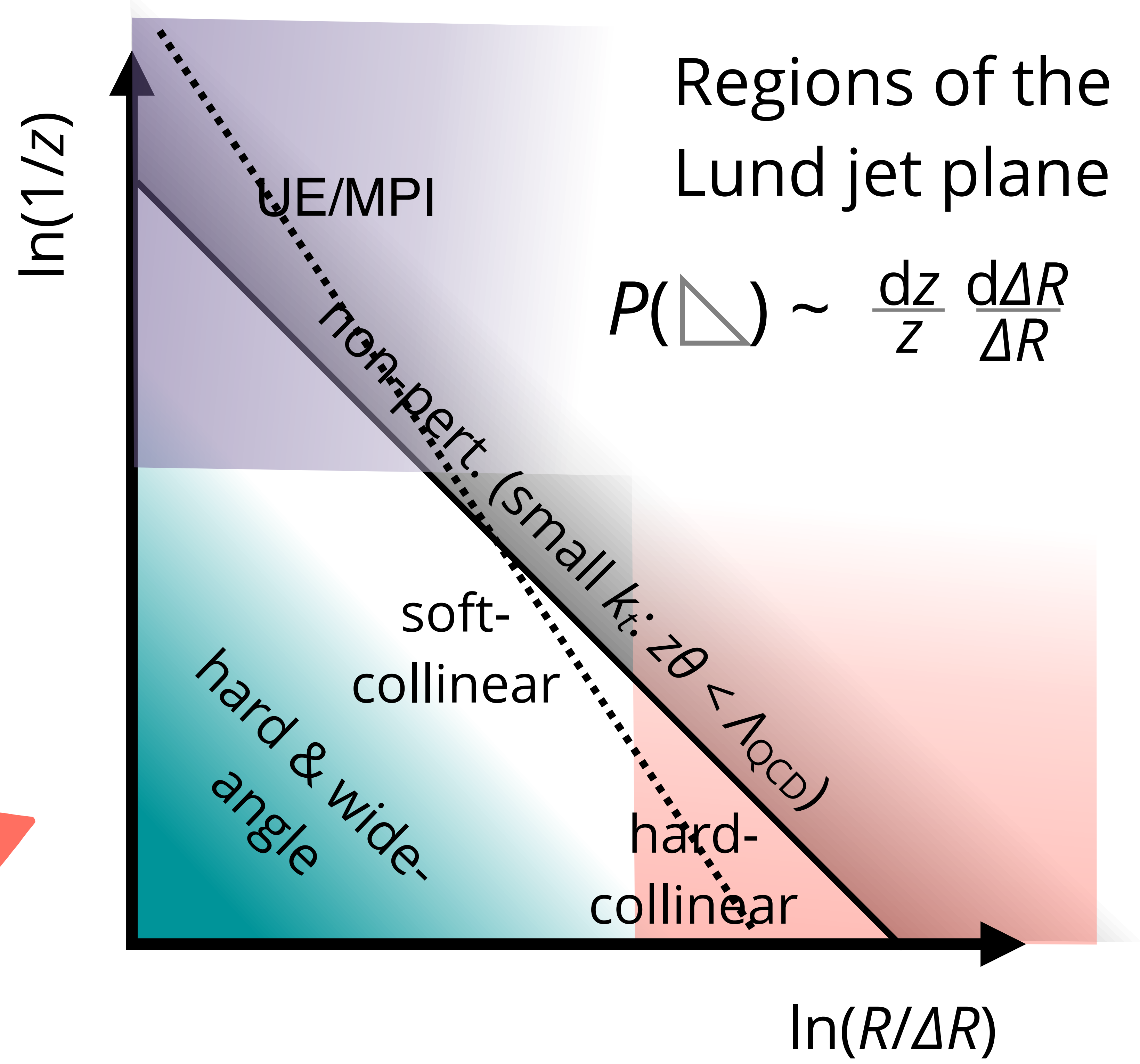
MLB Poster @ DPF

A jet may be approximated as **soft emissions** around a **hard core** which represents the originating quark or gluon.



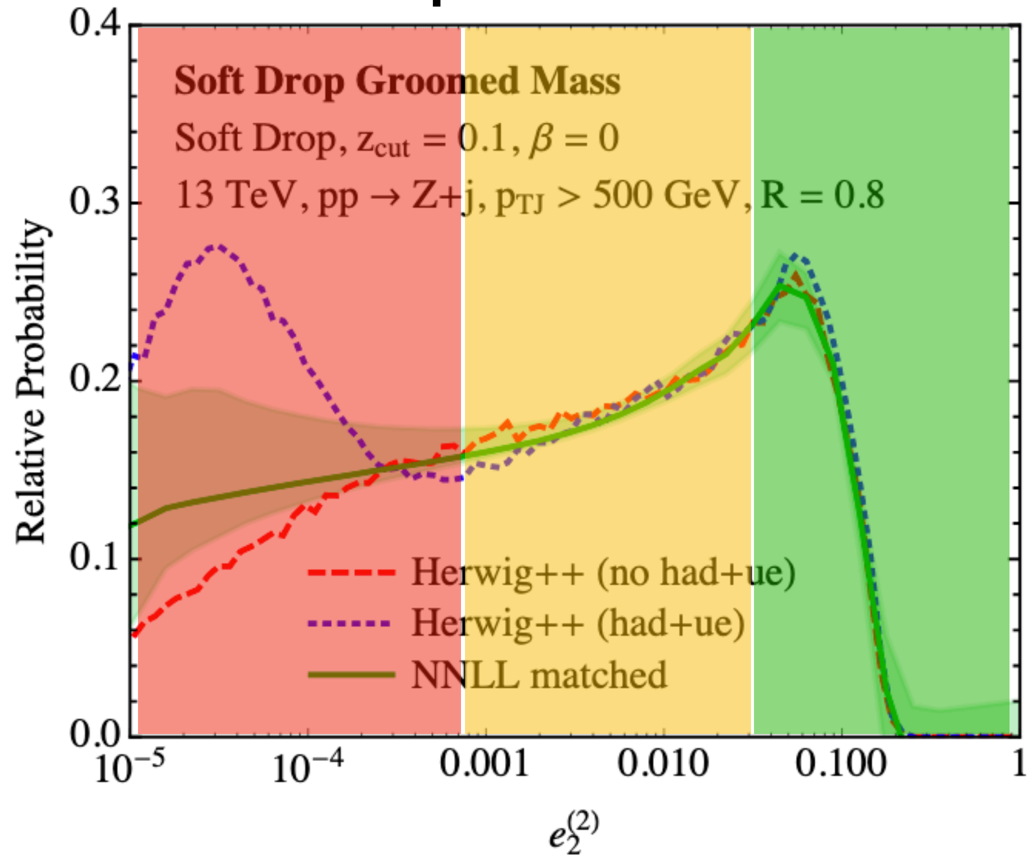
These emissions can be parameterised by their **relative momentum fraction, z**, and **angle of emission relative to the jet core, ΔR.**

$m \sim z{*}DR^2$



The Lund Plane is the phase space of these emissions: it naturally factorises perturbative and non-perturbative effects, UE/MPI, collinear splittings, *etc.*

The jet mass is just one diagonal line in this space …



So what if we could measure the whole thing?

ATLAS-CONF-2019-035 (New for BOOST '19!)

MLB Poster @ DPF

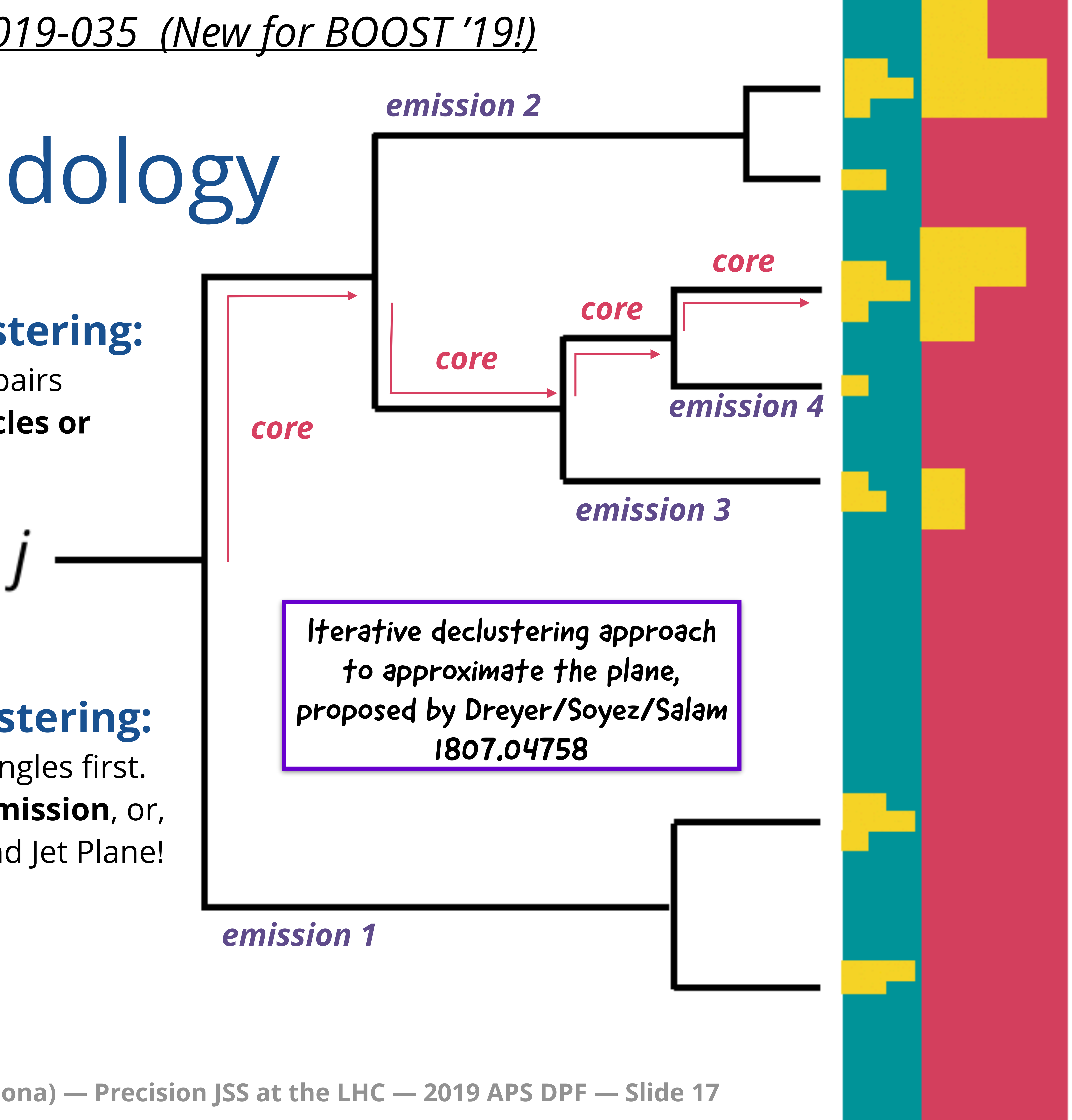
Methodology

1. C/A Reclustering:

Combine closest pairs of **charged particles or tracks!**

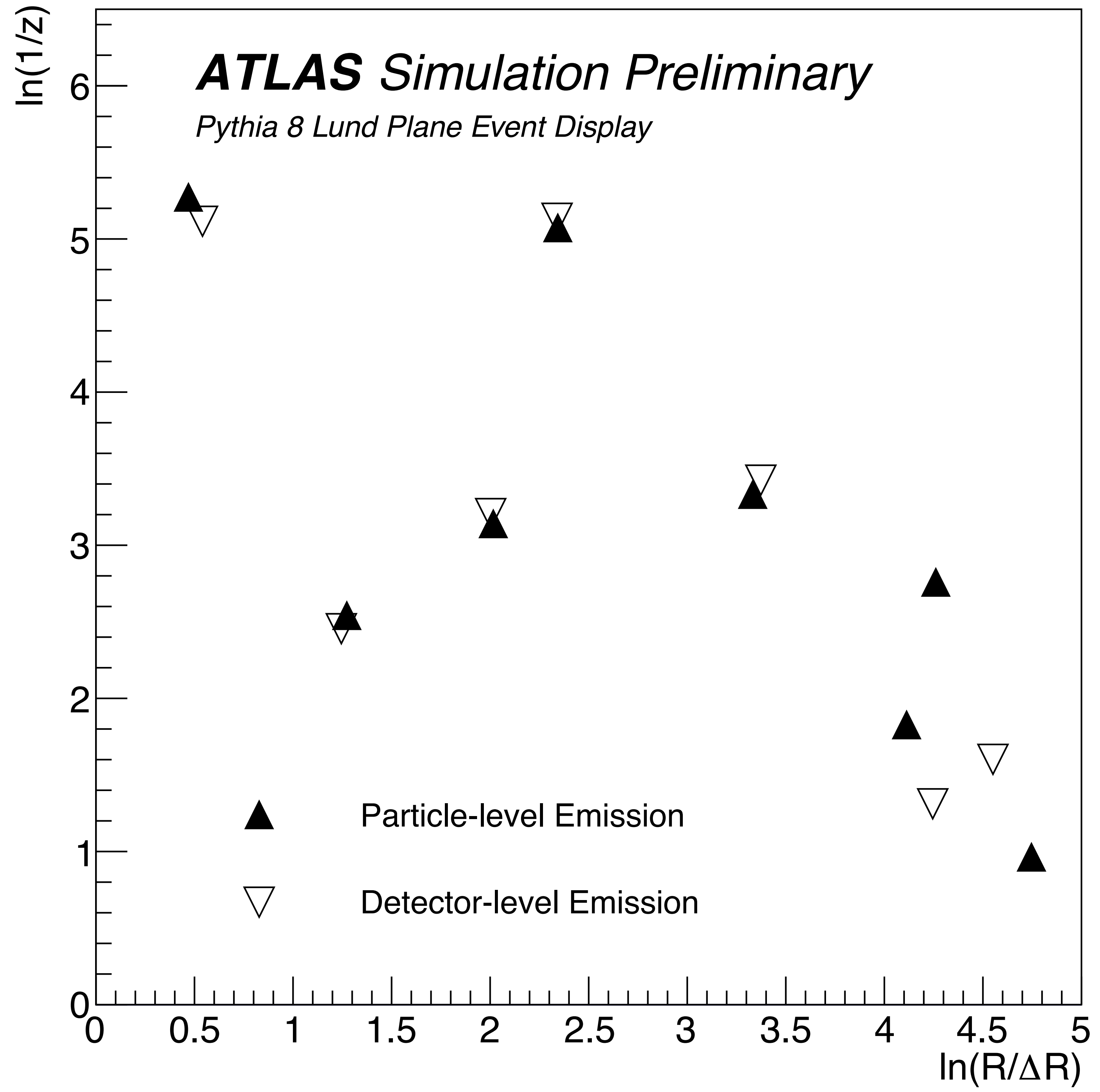
2. C/A Declustering:

Unwind, widest angles first. Each step is an **emission**, or, a point in the Lund Jet Plane!



Iterative declustering approach to approximate the plane, proposed by Dreyer/Soyez/Salam 1807.04758

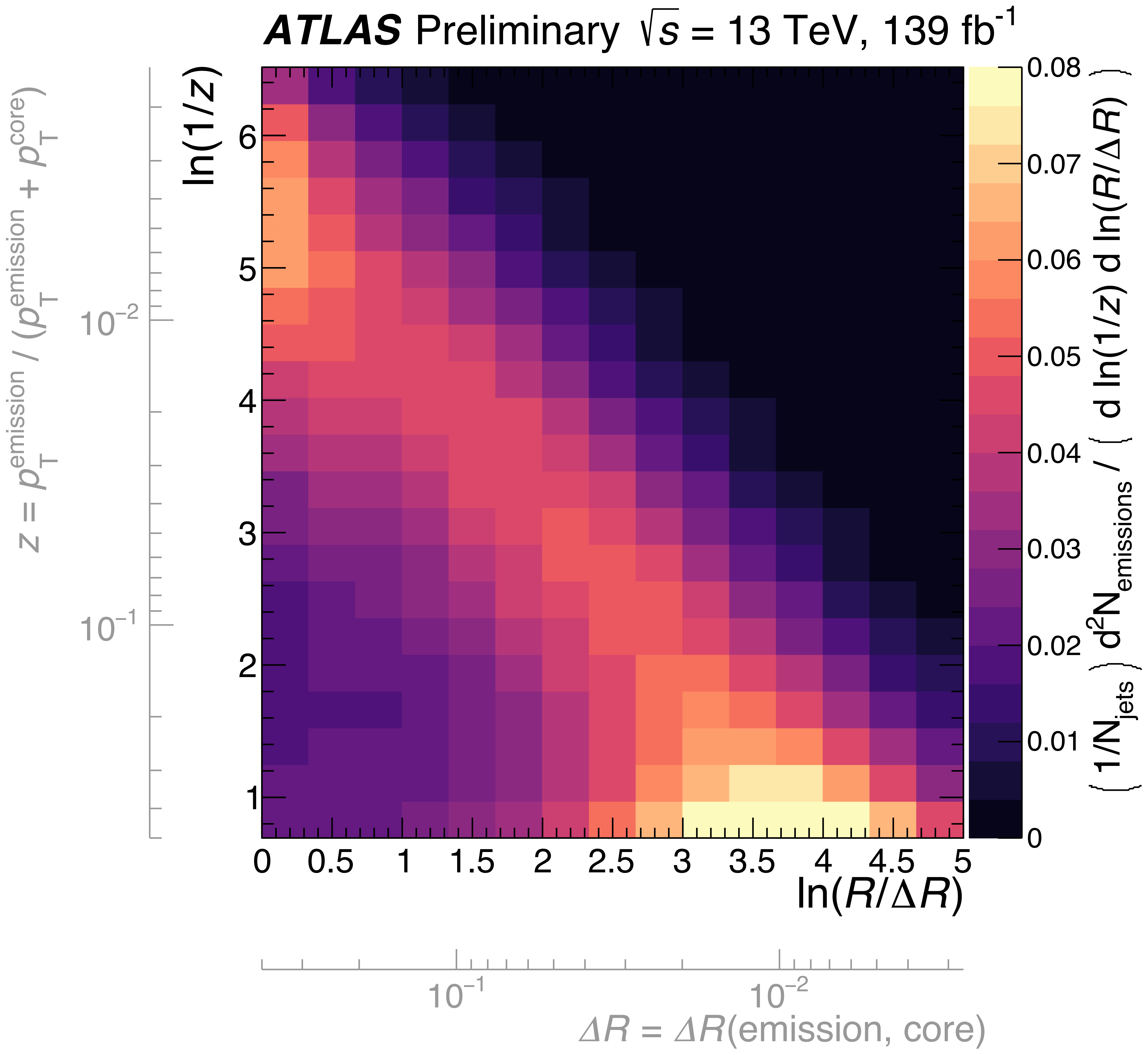
A single jet results in **a set of coordinate points** in the Lund jet plane:

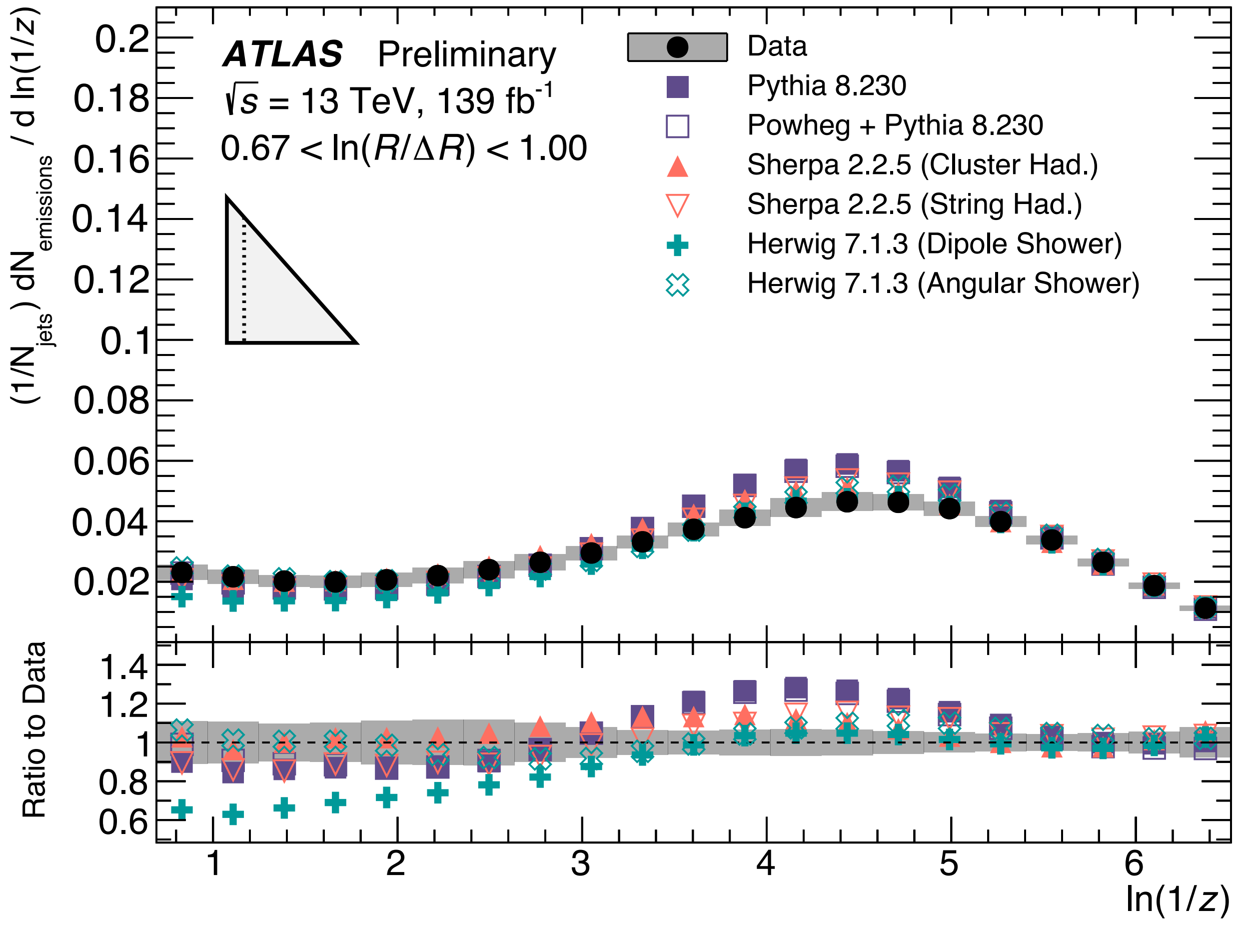


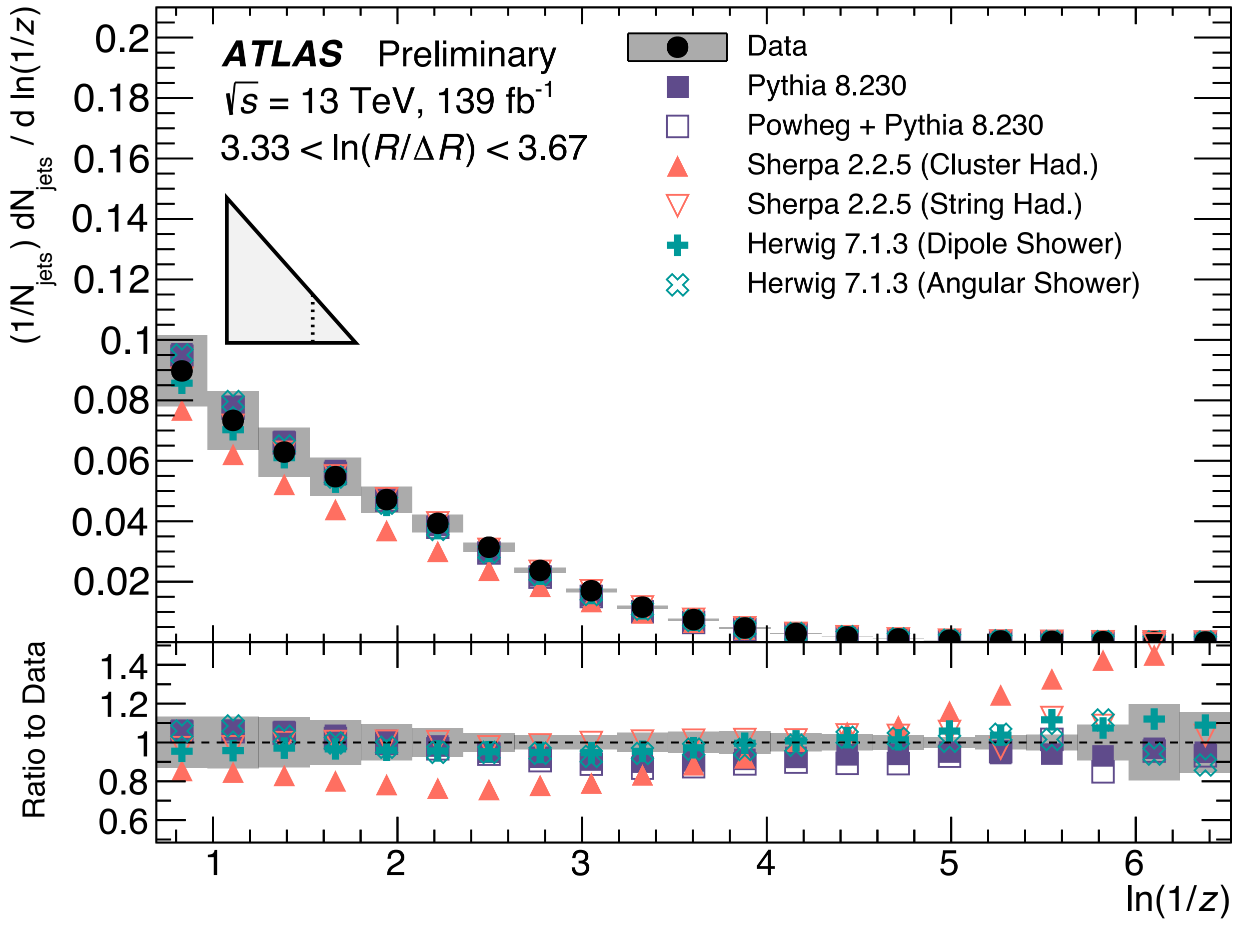
Emissions at detector- & truth-level are **geometrically matched** when constructing the response matrix.

An **iterative Bayesian unfolding procedure** is applied to correct for acceptance and detector resolution effects, with **4 iterations.**

Lund Jet Plane: Results







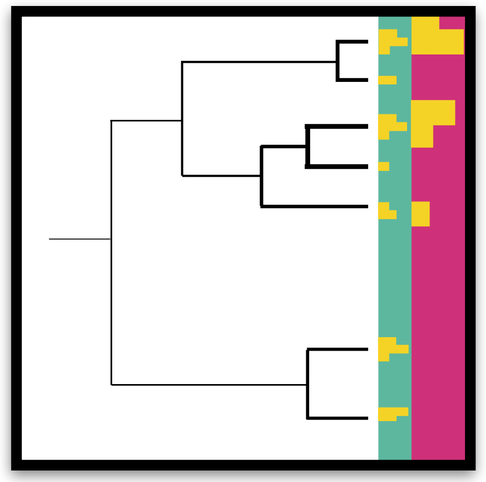
Various Monte Carlo simulations are compared to the unfolded data. **None are compatible across the entire 2D space.** In particular:

- **Hadronization effects** are large for **non-perturbative emissions**.
- **Parton shower effects** are large for **wide-angle emissions**.

Precision of ~10% or better is achieved throughout most of the Lund jet plane. The largest source of uncertainty is typically due to **Monte Carlo modelling effects** or the **jet energy scale**.

Over **115 million jets** are included in this measurement!

Outline



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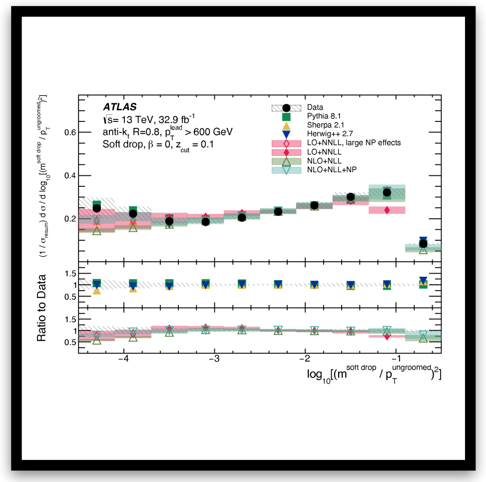

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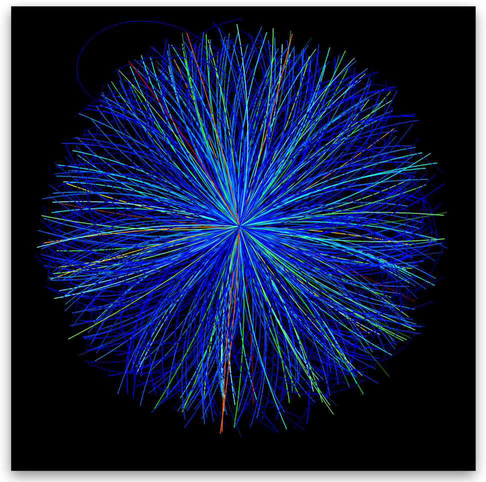

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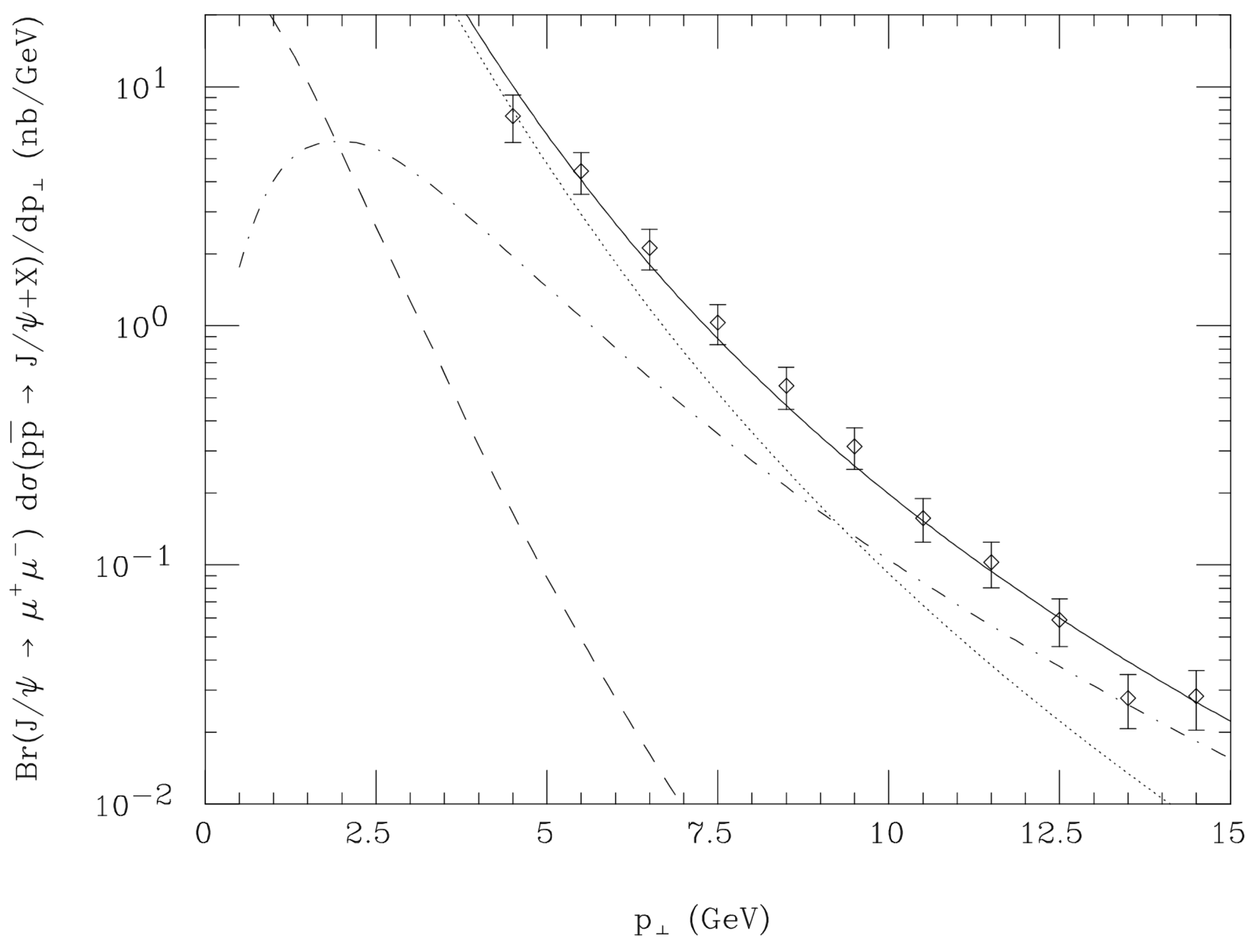
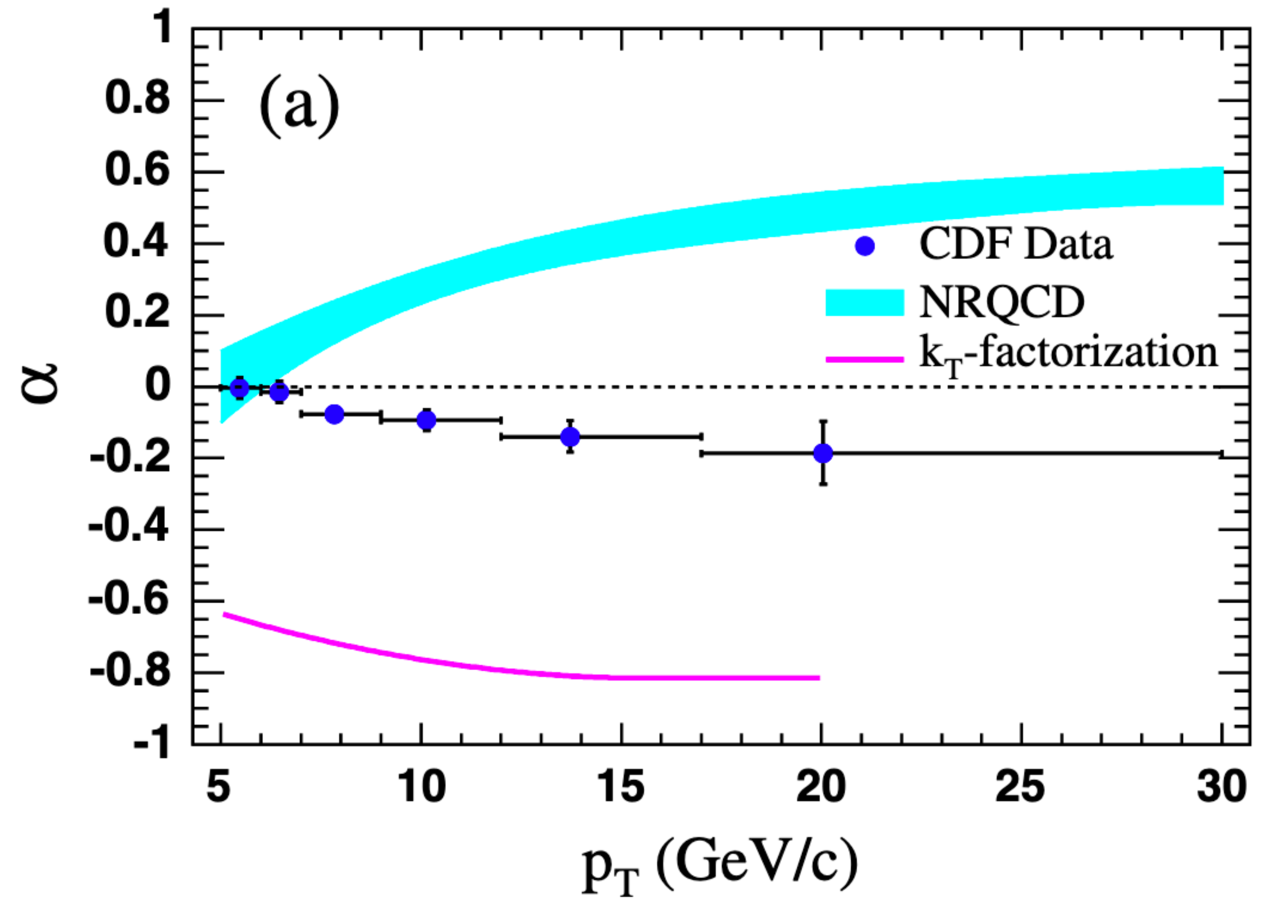
Cho & Leibovich, Phys.Rev. D53 (1996)
CDF, Phys. Rev. Lett. 99 (2007) 132001
LHCb, Eur. Phys. J. C (2011) 71
LHCb, Eur. Phys. J. C (2013) 73

Prompt J/ψ Polarisation

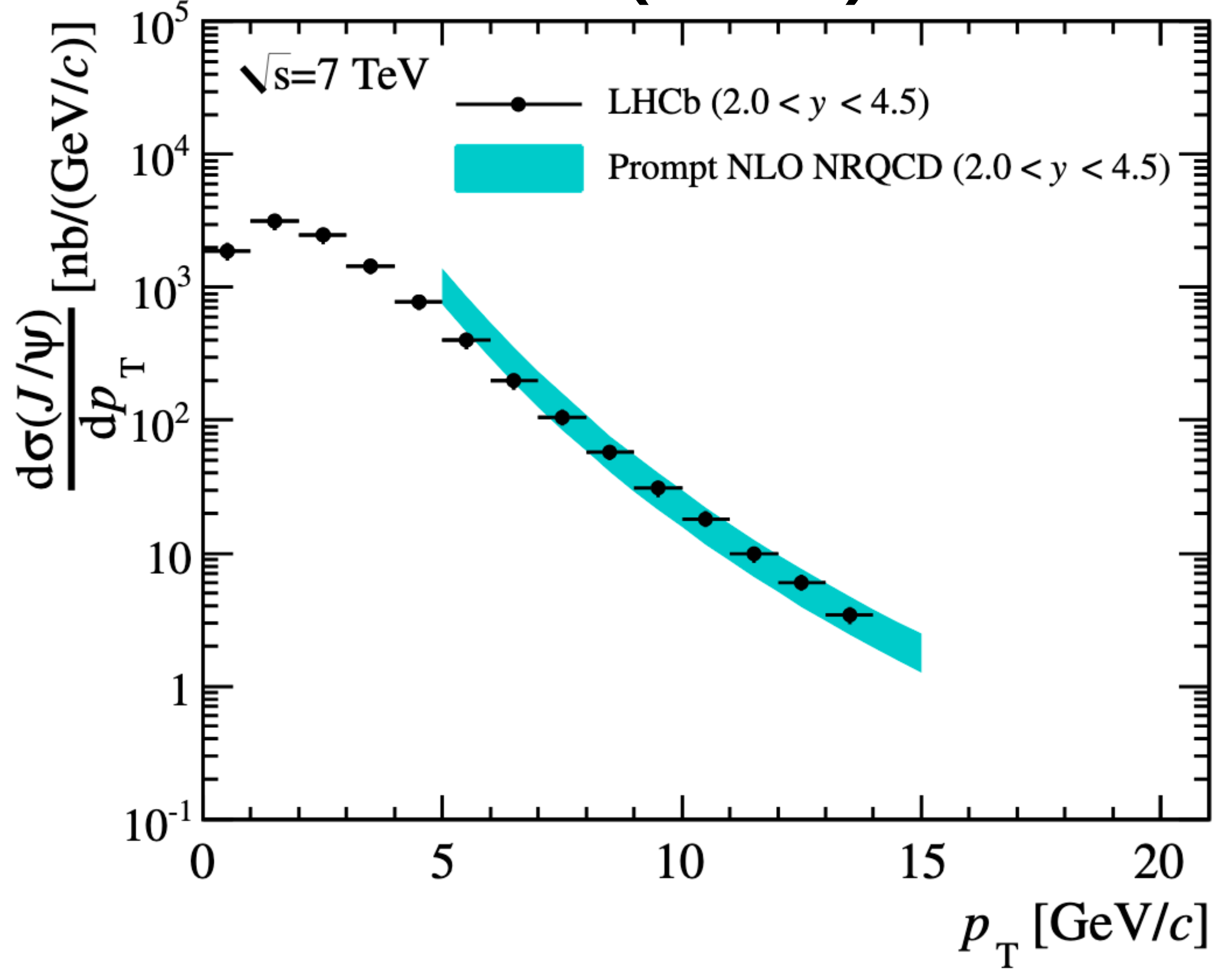
- J/ψ production occurs at the pQCD-npQCD threshold: a sensitive handle on this complex region.
    - Different J/ψ production mechanisms: ***prompt***, *feed-through* (ME) and via ***B-hadron decay*** (PS).
- Differential prompt-J/ψ production cross-sections @ Tevatron, LHC well-described by analytical NRQCD calculations …
    - … but, these predict large **transverse polarisation** which is not observed in data!

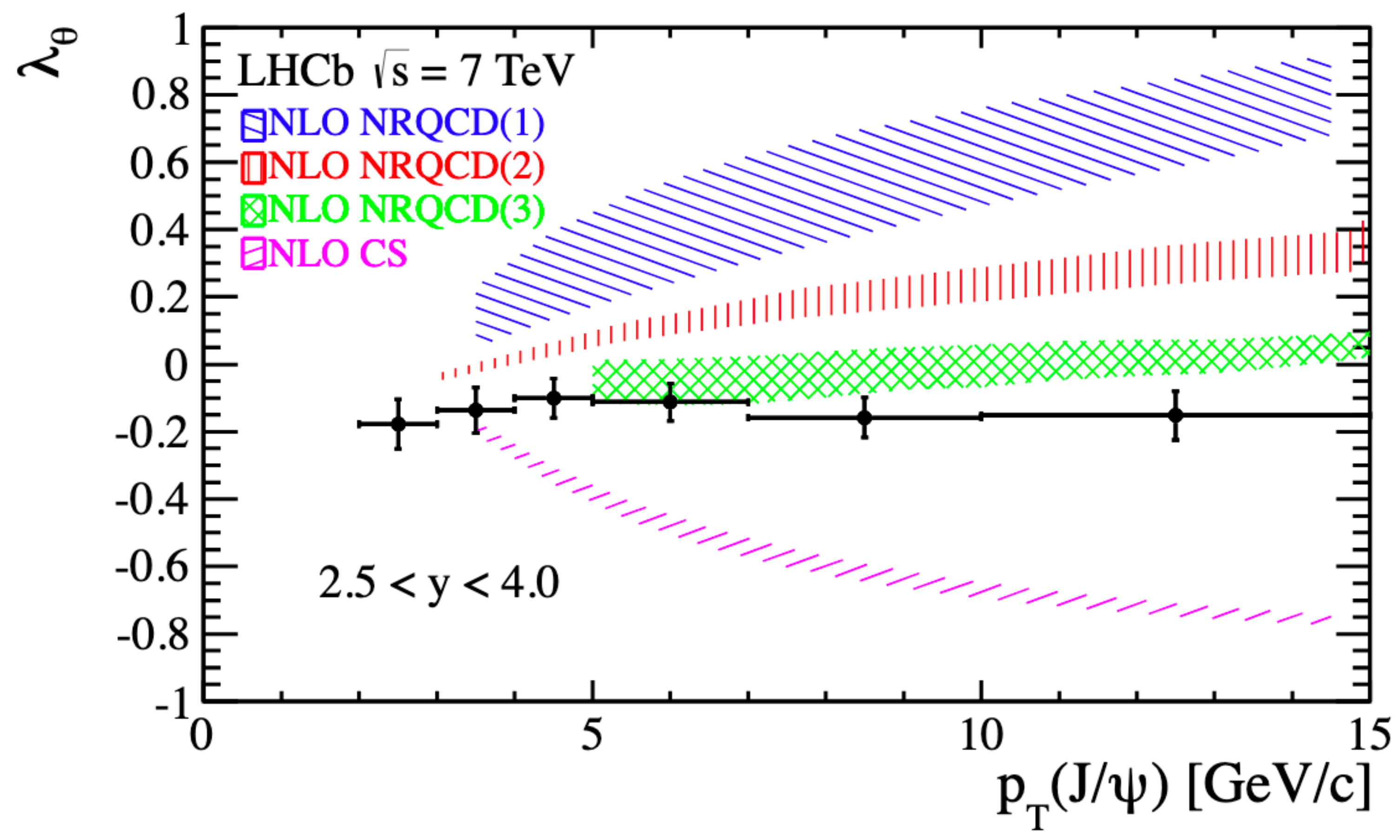
Tevatron (CDF)





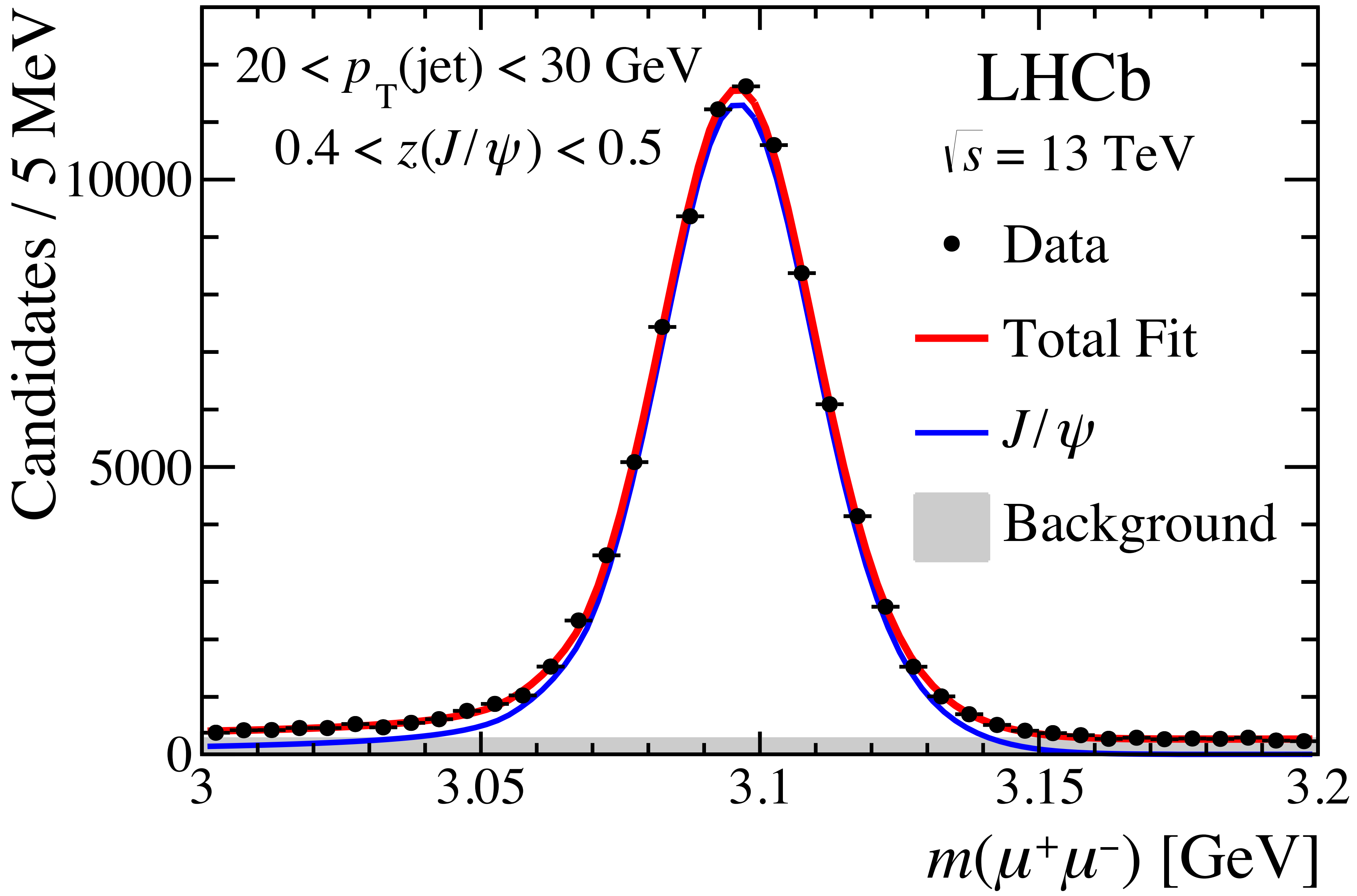
LHC (LHCb)

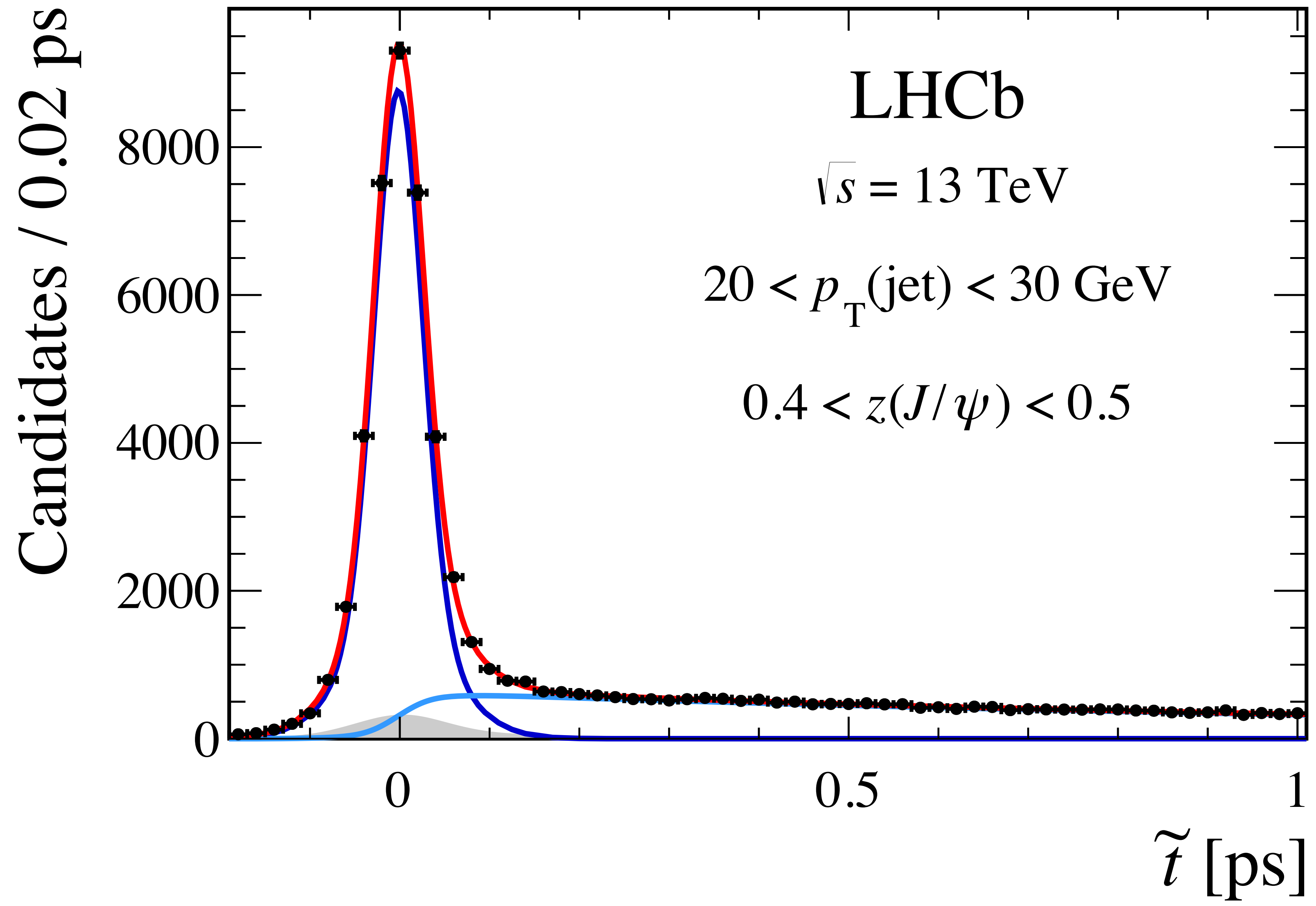




LHCb J/ψ in Jets

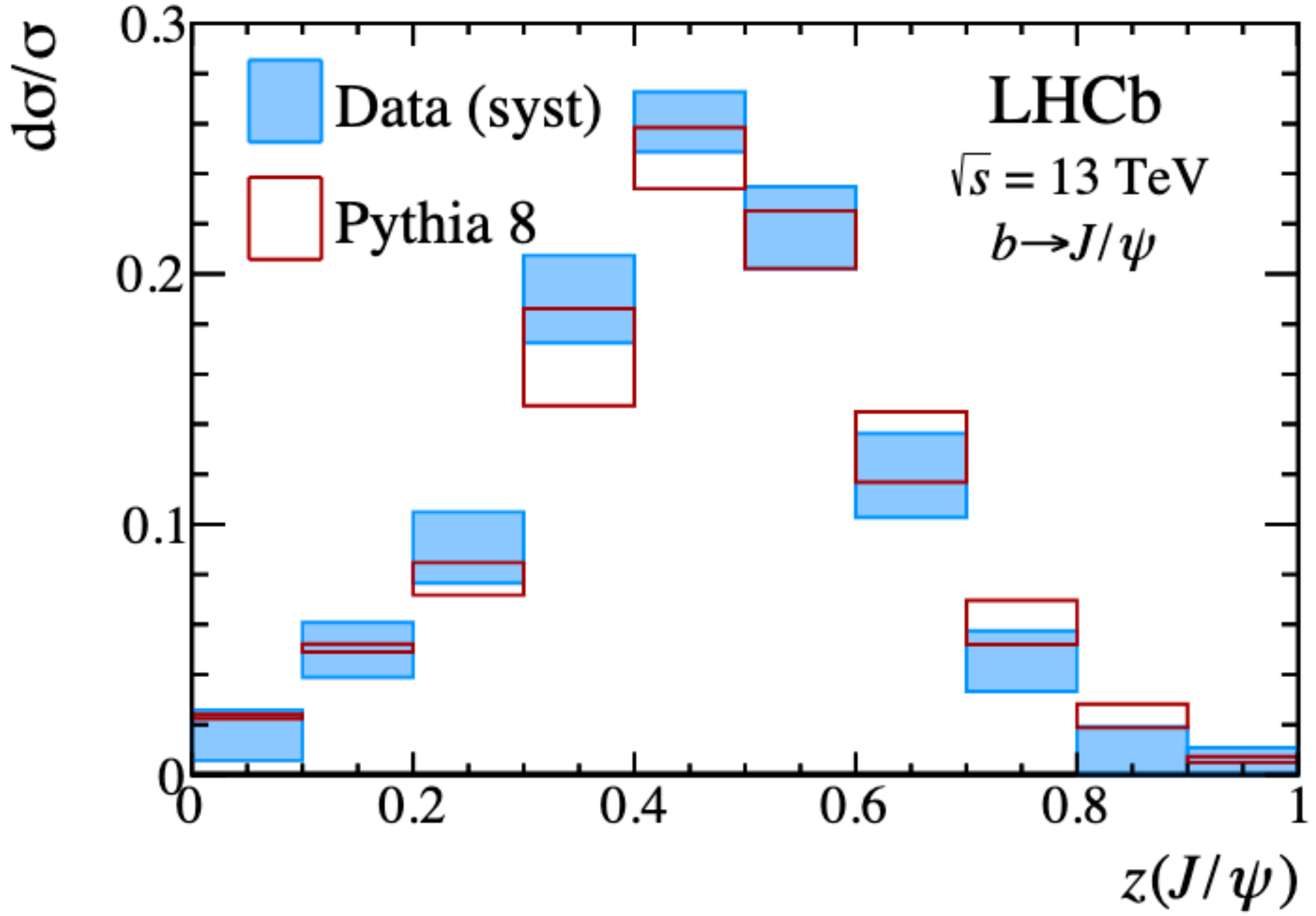
- Measurement of the momentum fraction carried by ~2 million J/ψ candidates produced within forward anti-k_t jets reconstructed by LHCb.
    - $p_T > 20$, $2.5 < |\text{eta}| < 4.0$, R=0.5.
- Prompt J/ψ decays distinguished from those originating from B hadron fragmentation using decay lifetime.

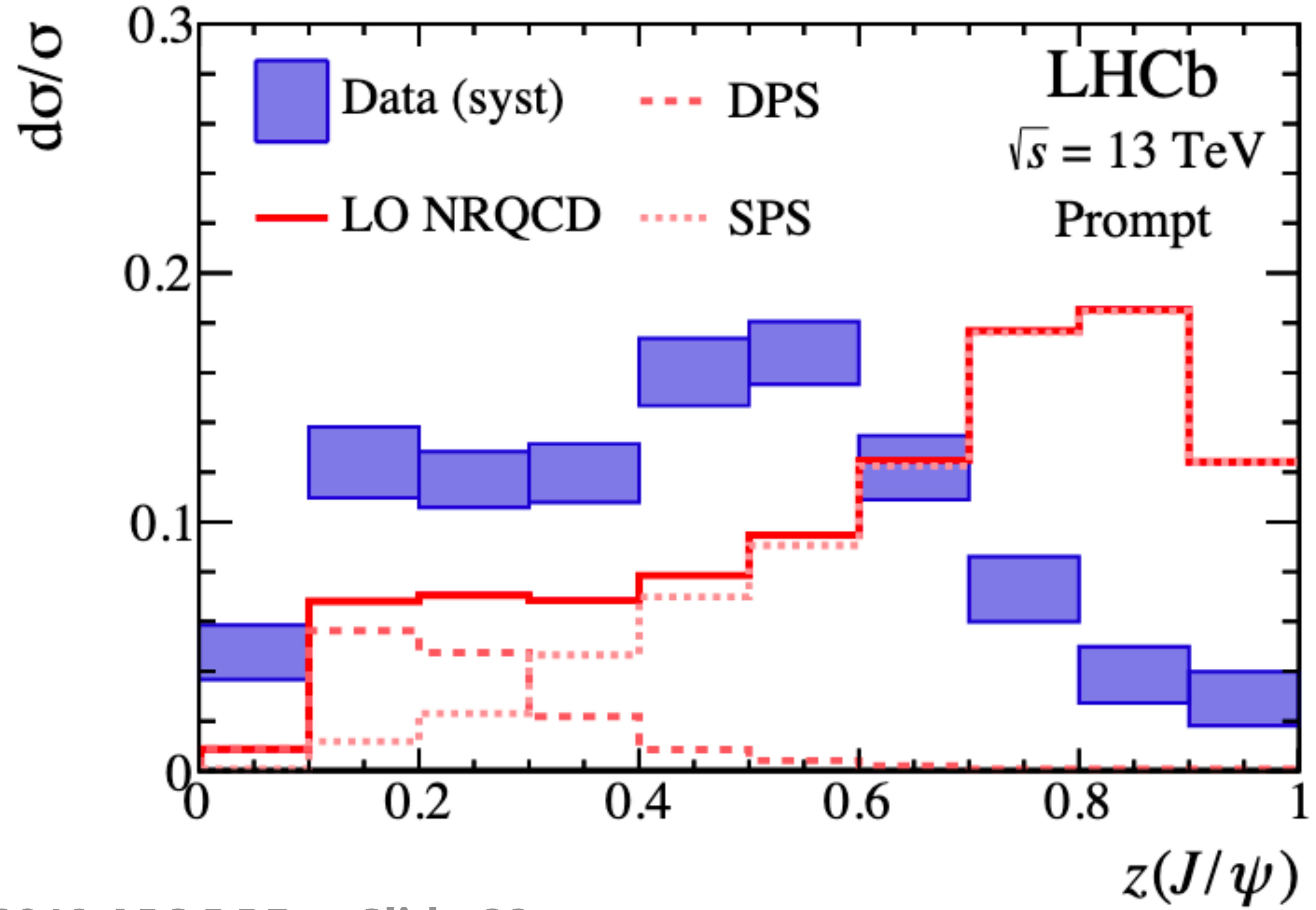




LHCb J/ψ in jets

- Unfolded $z(J/\psi)$ distributions are provided:
  - Good agreement with Pythia for J/ψ originating from B-hadron decay.
  - Prompt J/ψ results do not agree with fixed-order NRQCD.
- Prompt J/ψ are noted to be less isolated than expected.
  - If high-pT J/ψ are produced by parton-showers rather than the hard scattering, **deficiency of polarisation & isolation could be accounted for!**

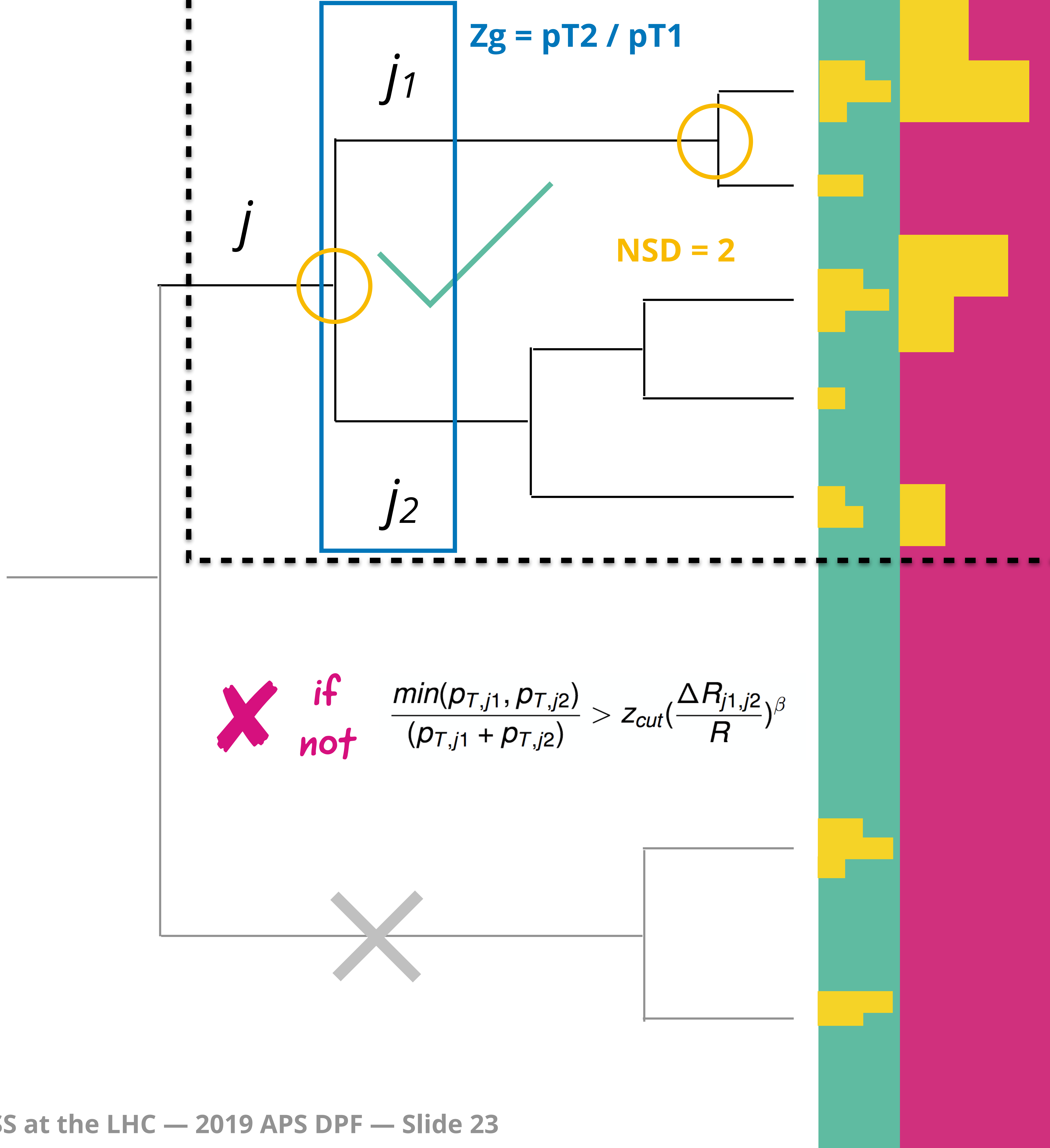




ALICE, submitted to PLB [arXiv:1905.02512]

ALICE: z_g and N_{SD}

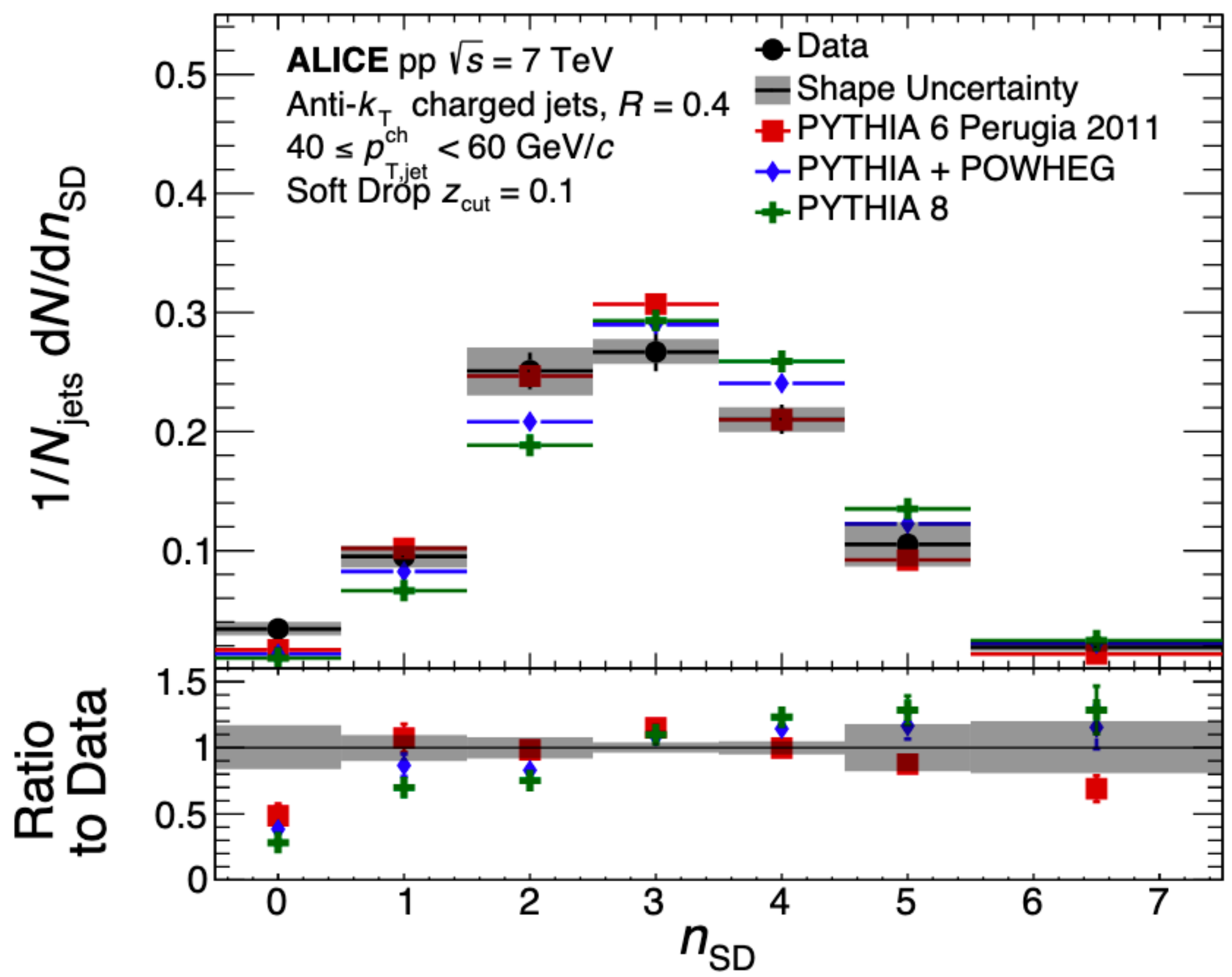
- Track-based studies in the context of **Pb+Pb and *pp* collisions.**
  - Examining the **possible quenching** effects on **JSS**, using *iterative declustering*.
    - **Observable:** N_{SD}, the "Soft Drop Multiplicity" — length of primary C/A declustering sequence after SD.
- **Key question: colour coherence.** *"When can a colour dipole be resolved by the medium as two independent colour charges?"*
  - **Observable:** z_g, the p_T balance of the hard splitting which satisfies the SD condition.

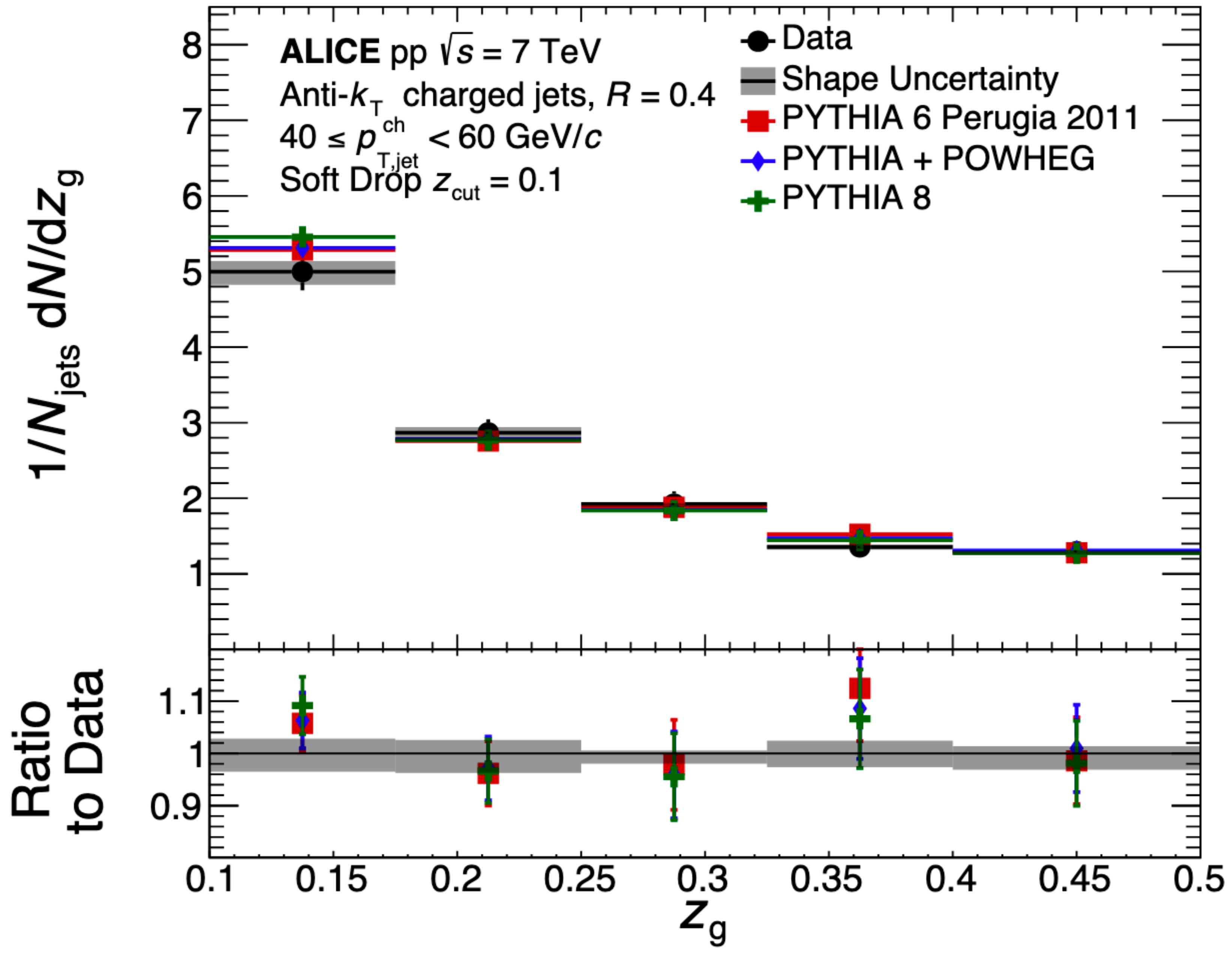


ALICE z_g and N_{SD}, *pp*

- Results for low-pT track-jets in *pp* collisions are unfolded to particle level in order to account for acceptance & detector effects.
  - Good agreement is observed in the bulk of the distributions, though some effects do not seem to be well-modelled by any MC.
  - Main systematics arise due to tracking efficiencies & unfolding.

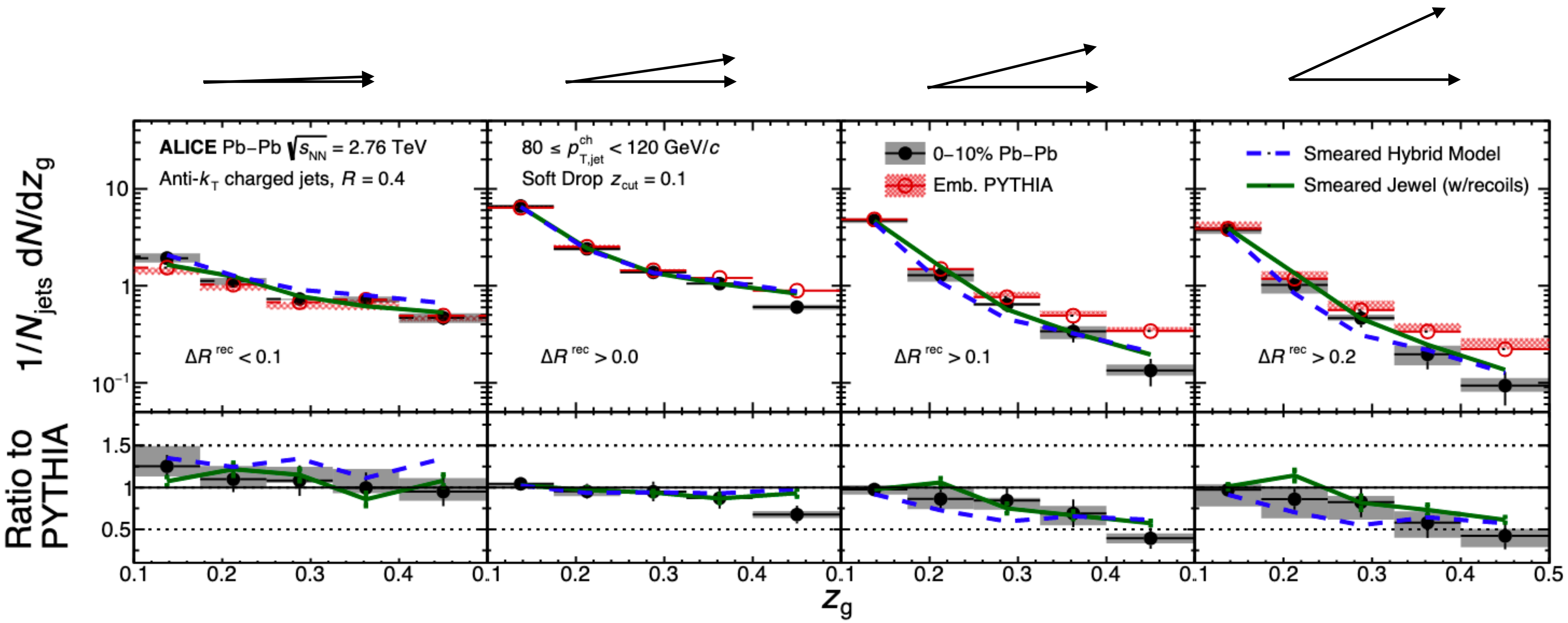
Observable	z_g			n_{SD}		
Interval	0.1–0.175	0.25–0.325	0.4–0.5	0	3	6
Tracking efficiency (%)	1.9	0.2	1.0	16.1	1.1	18.3
Prior (%)	$^{+0.0}_{-1.8}$	$^{+0.6}_{-0.0}$	$^{+1.6}_{-0.0}$	$^{+0.7}_{-0.0}$	$^{+0.0}_{-3.4}$	$^{+3.3}_{-0.0}$
Regularisation (%)	$^{+0.8}_{-0.5}$	$^{+0.2}_{-0.2}$	$^{+0.4}_{-0.5}$	$^{+0.4}_{-1.4}$	$^{+1.4}_{-1.1}$	$^{+1.7}_{-3.0}$
Truncation (%)	$^{+2.2}_{-0.0}$	$^{+1.8}_{-0.0}$	$^{+2.4}_{-0.0}$	$^{+0.0}_{-0.0}$	$^{+0.0}_{-0.1}$	$^{+4.4}_{-0.0}$
Binning (%)	0.5	4.5	1.2	N/A	N/A	N/A
Total (%)	$^{+3.0}_{-2.7}$	$^{+4.9}_{-0.3}$	$^{+3.0}_{-1.6}$	$^{+16.1}_{-16.1}$	$^{+1.8}_{-3.7}$	$^{+19.2}_{-18.5}$

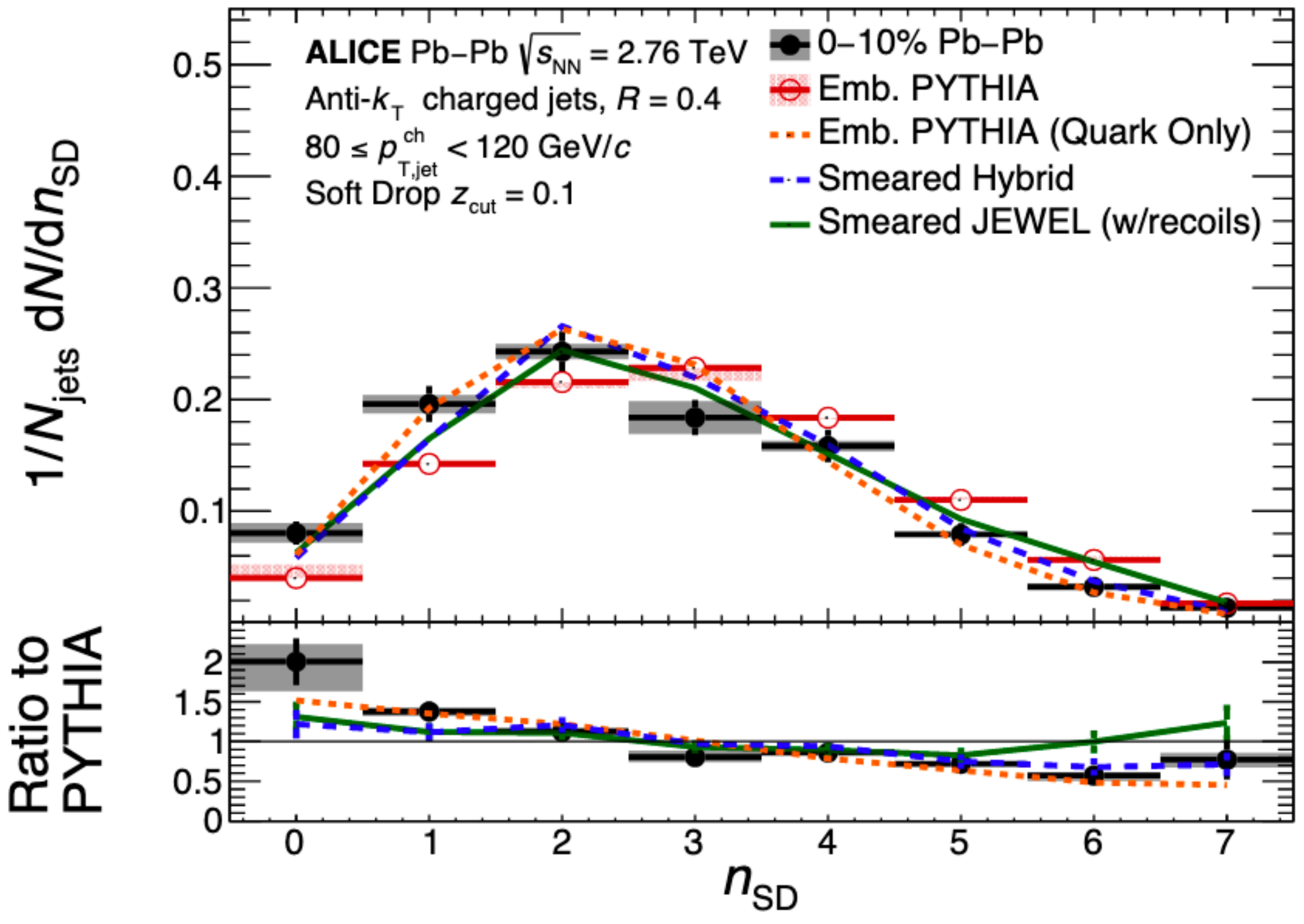




ALICE, submitted to PLB [arXiv:1905.02512]

ALICE z_g and N_{SD}, Pb+Pb





More modification than predicted is reported by reference samples for **larger angular separations** of the subjets.

Trend in data towards lower N_{SD} than in reference.

- **Interpretation:** the larger the opening-angle, the more resolved the splittings are — wide-angle splittings are more suppressed by the medium!

Concluding remarks

- **ATLAS, CMS, LHCb and ALICE have all established precision JSS measurement programmes with Run 2 data.**
    - Probing QCD inside jets with higher precision than ever before!
      Diverse analyses all provide different insights:
        - Measurements of the **jet mass by ATLAS and CMS** have been compared to the most precise calculations of jet substructure available, informing the development of our analytical understanding of JSS.
        - A new measurement of the Lund jet plane is designed to factorise physical effects, and will be made available for **Monte Carlo tuning efforts** before Run 3.
        - **LHCb is revisiting the J/Psi polarisation question** from a new point of view.
        - ALICE has presented a new measurement of z_g and N_{SD} in *pp* and Pb+Pb, **exploring questions related to colour coherence and the QGP.**
- **Please come find me to chat this week if you are interested in precision JSS and want to learn more, or get involved!**

matt.leblanc@cern.ch @TopPhysicist

Thanks for your attention!

THE UNIVERSITY OF ARIZONA

ATLAS EXPERIMENT

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCJetSubstructureMeasurements

For more JSS, see last week's agenda from BOOST 2019 @ MIT: https://indico.cern.ch/event/753914/

Auxiliary material.

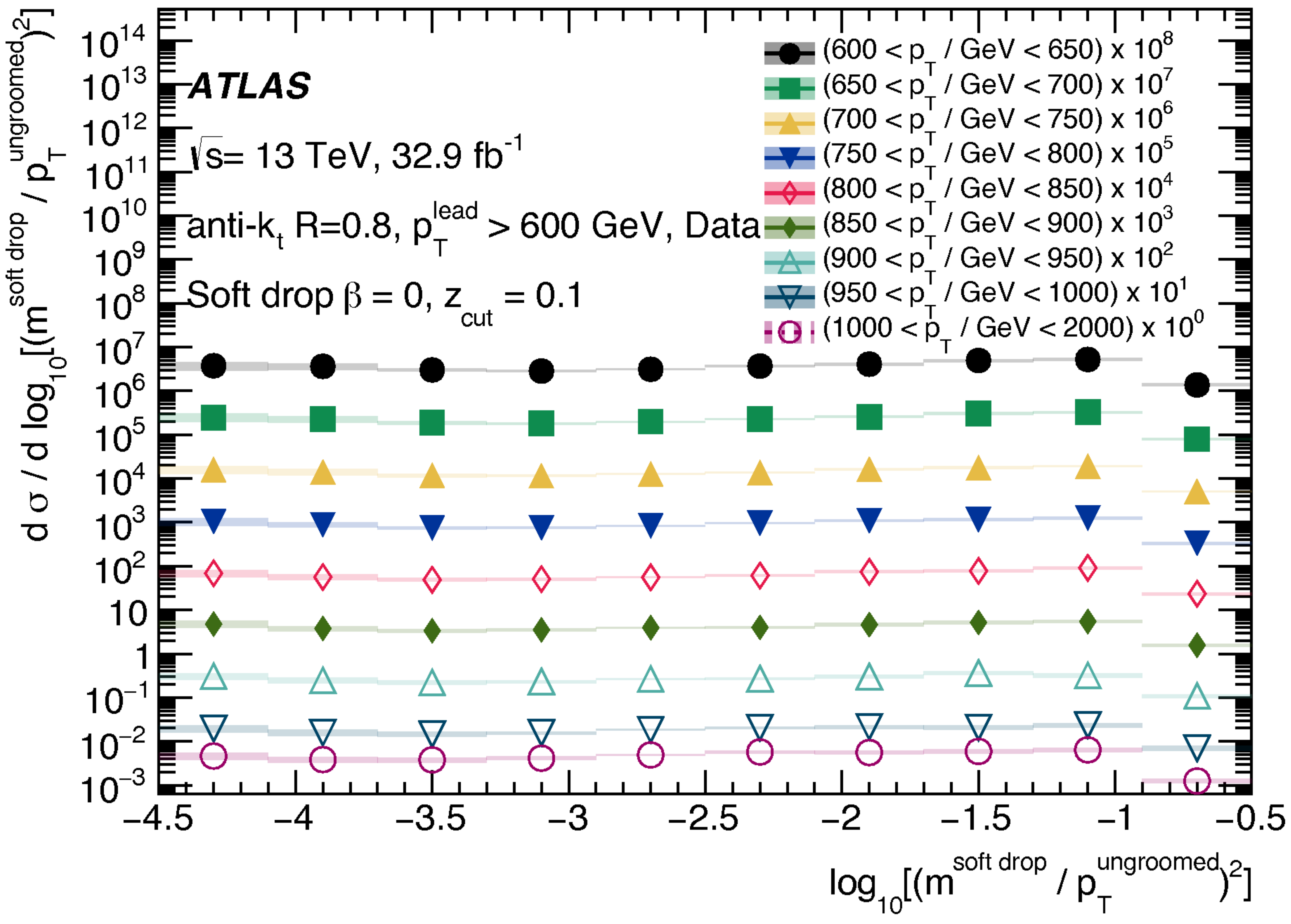
Precision JSS @ LHC Run 2

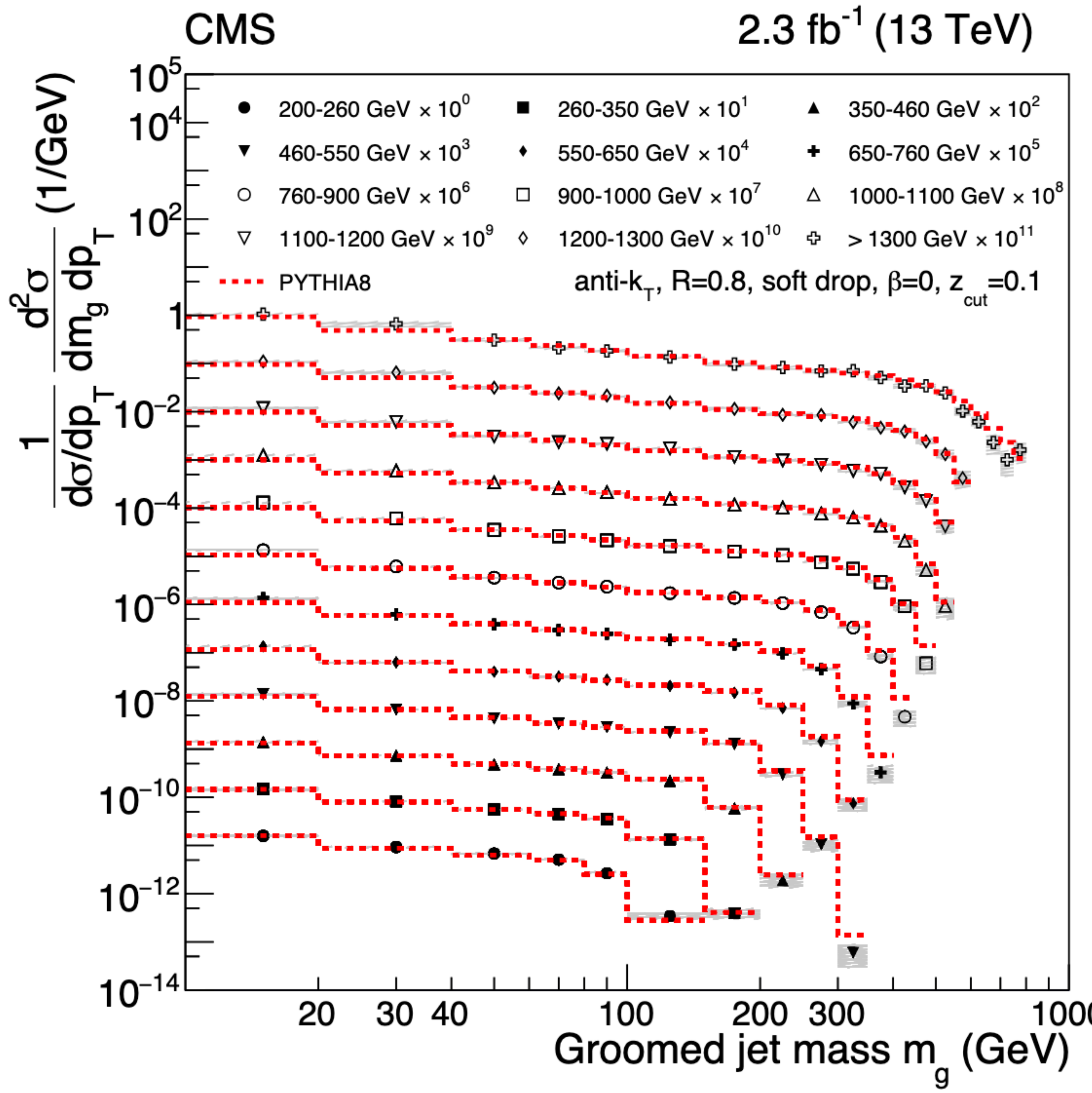
ATLAS	CMS	LHCb	ALICE
Soft Drop Mass https://arxiv.org/abs/1711.08341 *Jet Pull* https://arxiv.org/abs/1805.02935 *g(bb) at small ΔR* *https://arxiv.org/abs/1812.09283* *JSS Observables in multijets and ttbar* https://arxiv.org/abs/1903.02942 *Fragmentation properties* *https://arxiv.org/abs/1906.09254* *Z(bb)+γ* *https://arxiv.org/abs/1907.07093* *Lund jet plane* ***(new!)*** *ATLAS-CONF-2019-035*	*Soft Drop Mass in Pb+Pb* https://arxiv.org/abs/1805.05145 *Soft Drop Mass* https://arxiv.org/abs/1807.05974 *Jet shapes in ttbar* https://arxiv.org/abs/1808.07340 *Top mass (XCone)* ***(new!)*** CMS-PAS-TOP-19-005	*J/ψ in jets* https://arxiv.org/abs/1701.05116 *Charged hadron multiplicity* https://arxiv.org/abs/1904.08878	*Track jet XS & fragmentation* *https://arxiv.org/abs/1809.03232* *z_g and N_{SD}* https://arxiv.org/abs/1905.02512

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCJetSubstructureMeasurements

ATLAS, Phys. Rev. Lett. 121, 092001 (2018)
CMS, JHEP 11 (2018) 113

Soft Drop Jet Mass

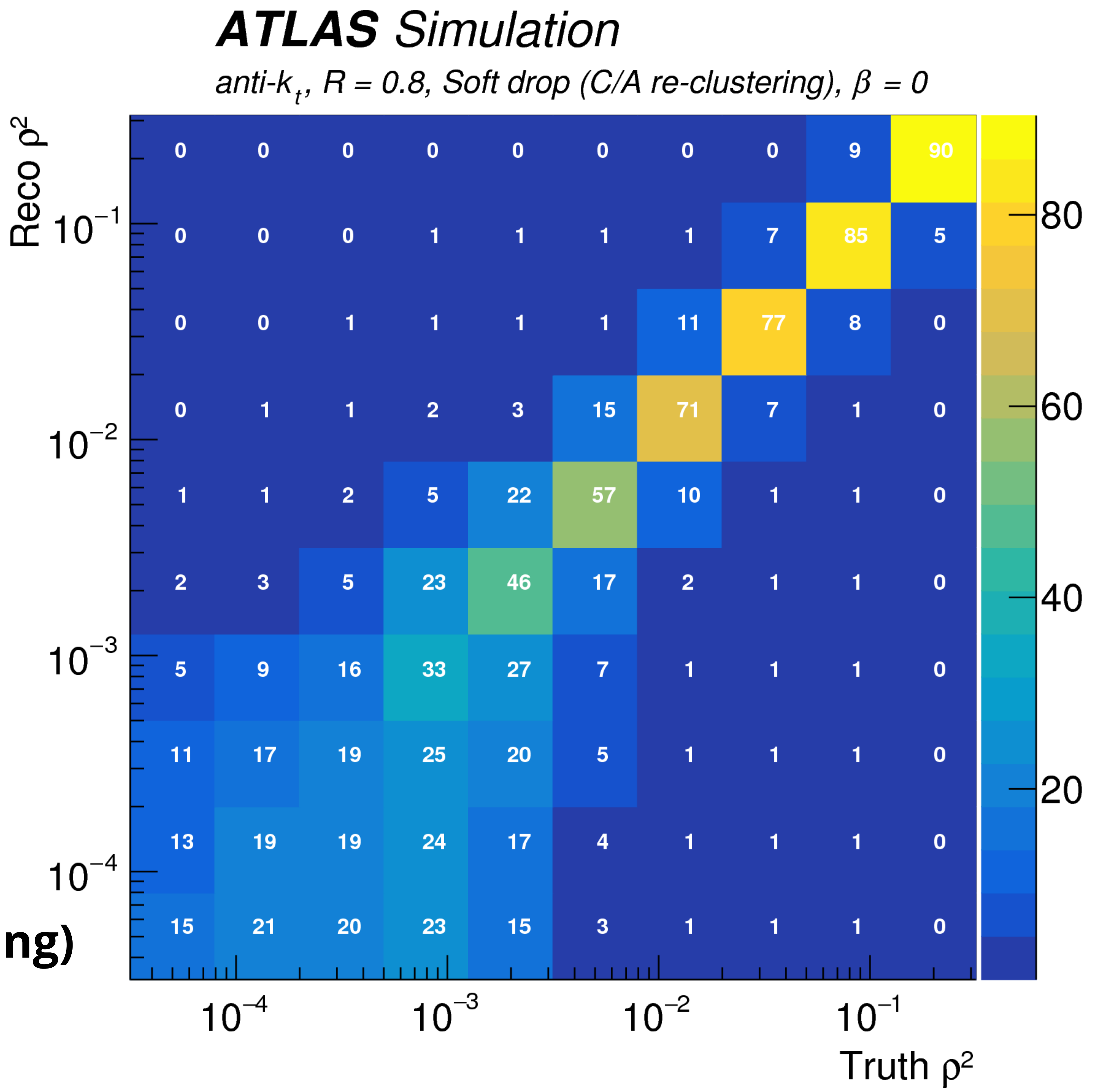


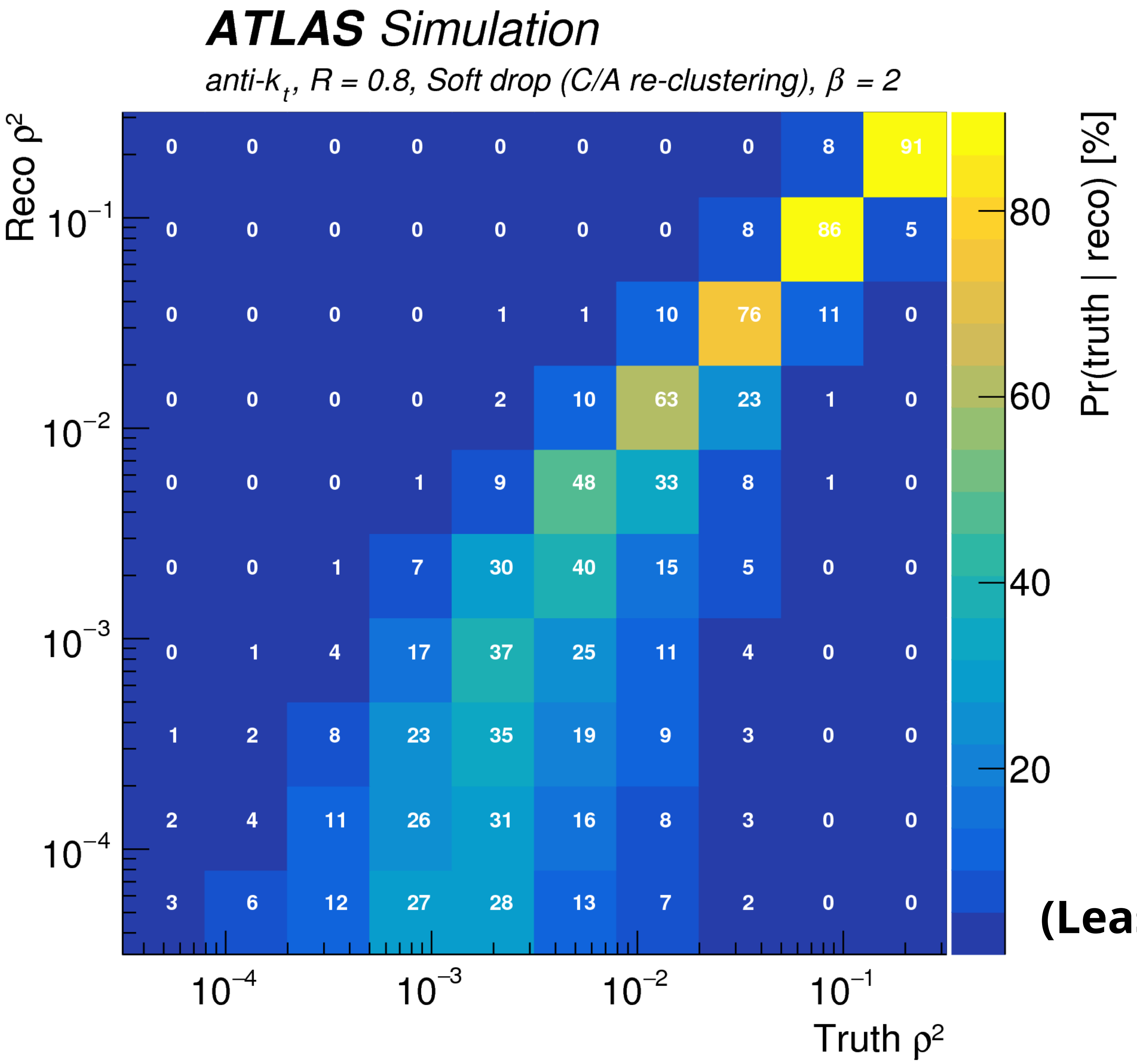


ATLAS, Phys. Rev. Lett. 121, 092001 (2018)

Soft Drop Unfolding Matrices

ß=0
(Most Grooming)



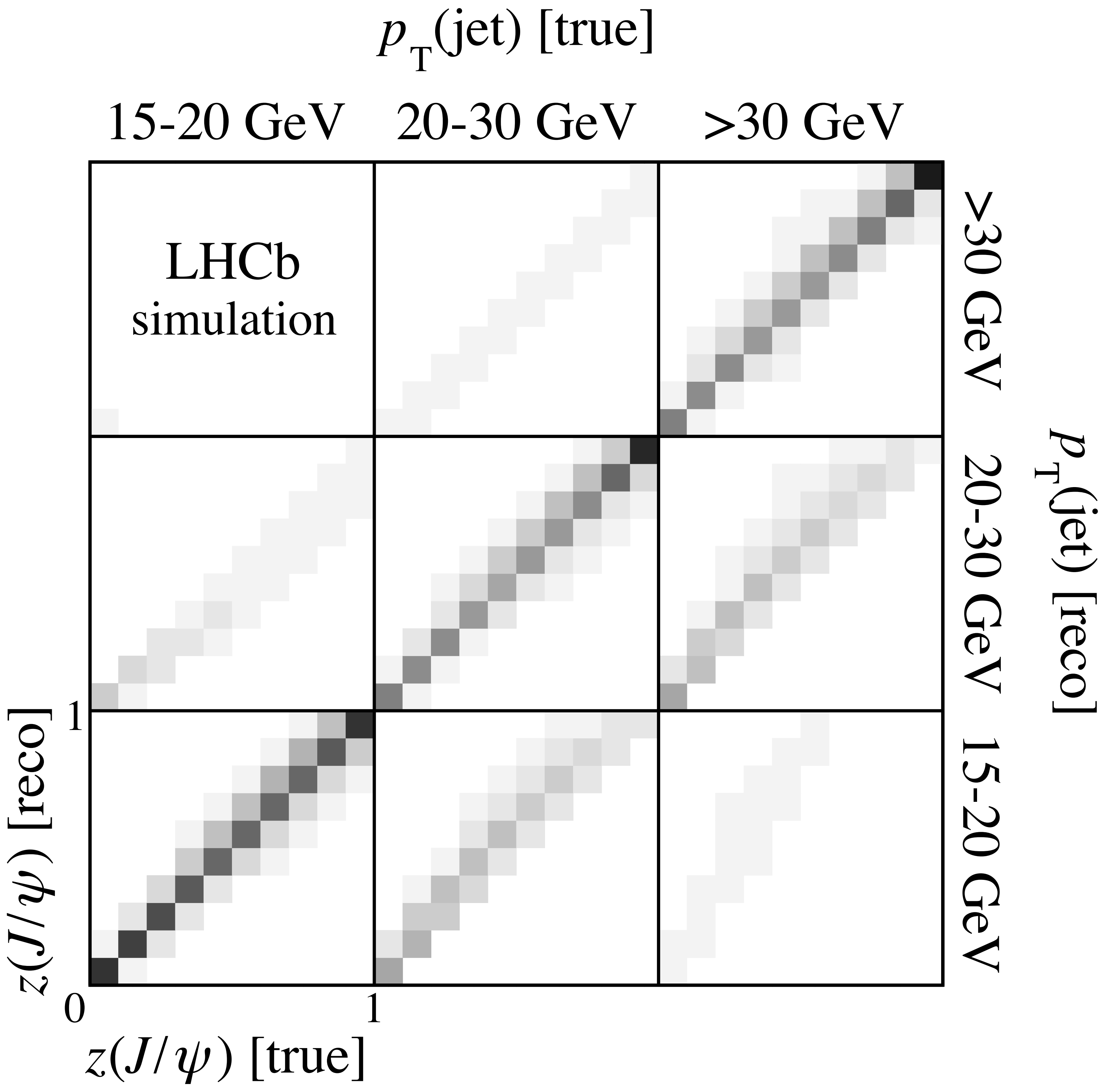


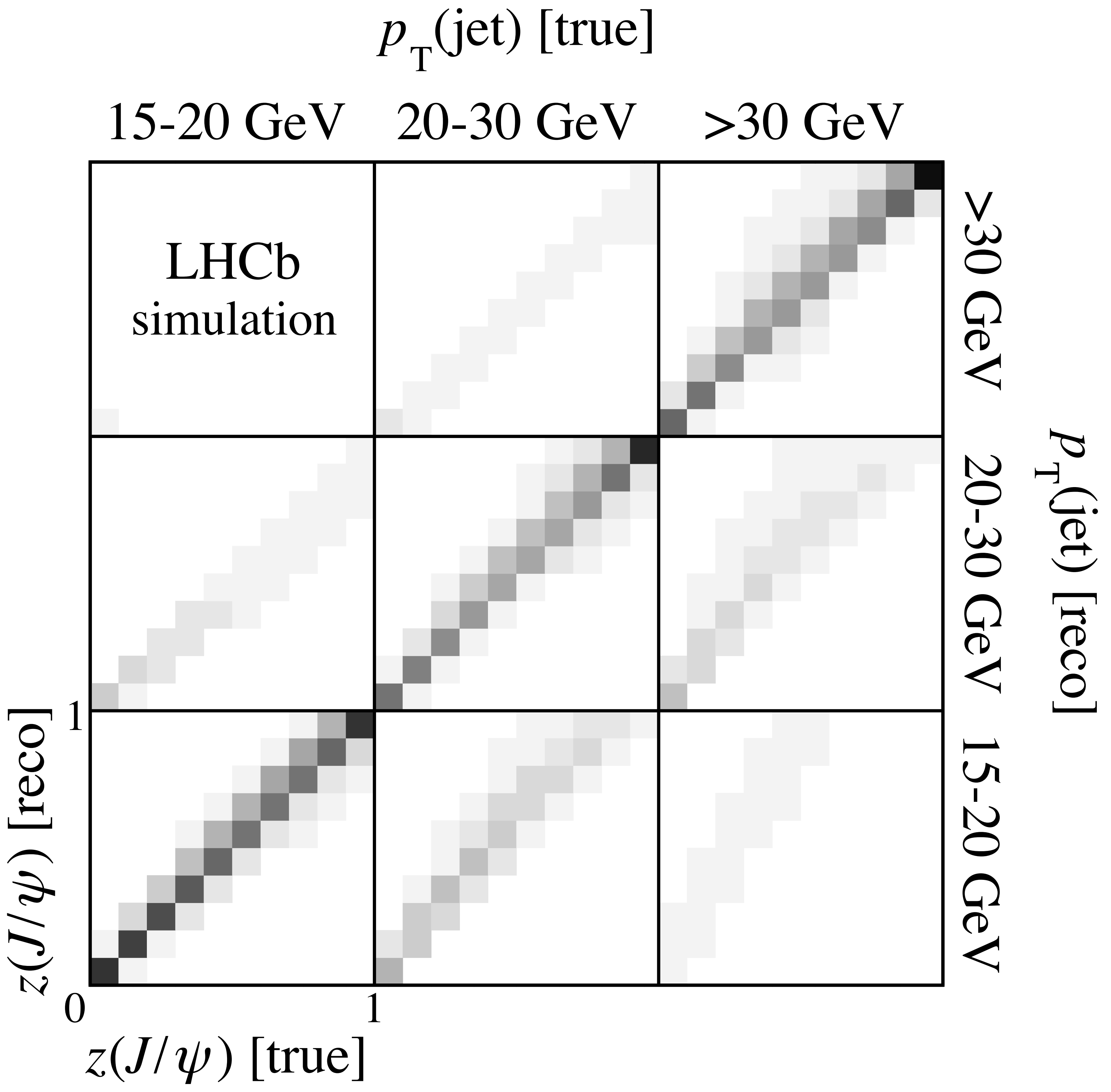
ß=2
(Least Grooming)

- Recall: Iterative Bayesian unfolding, 4 iterations.

LHCb J/ψ in jets: unfolding matrices

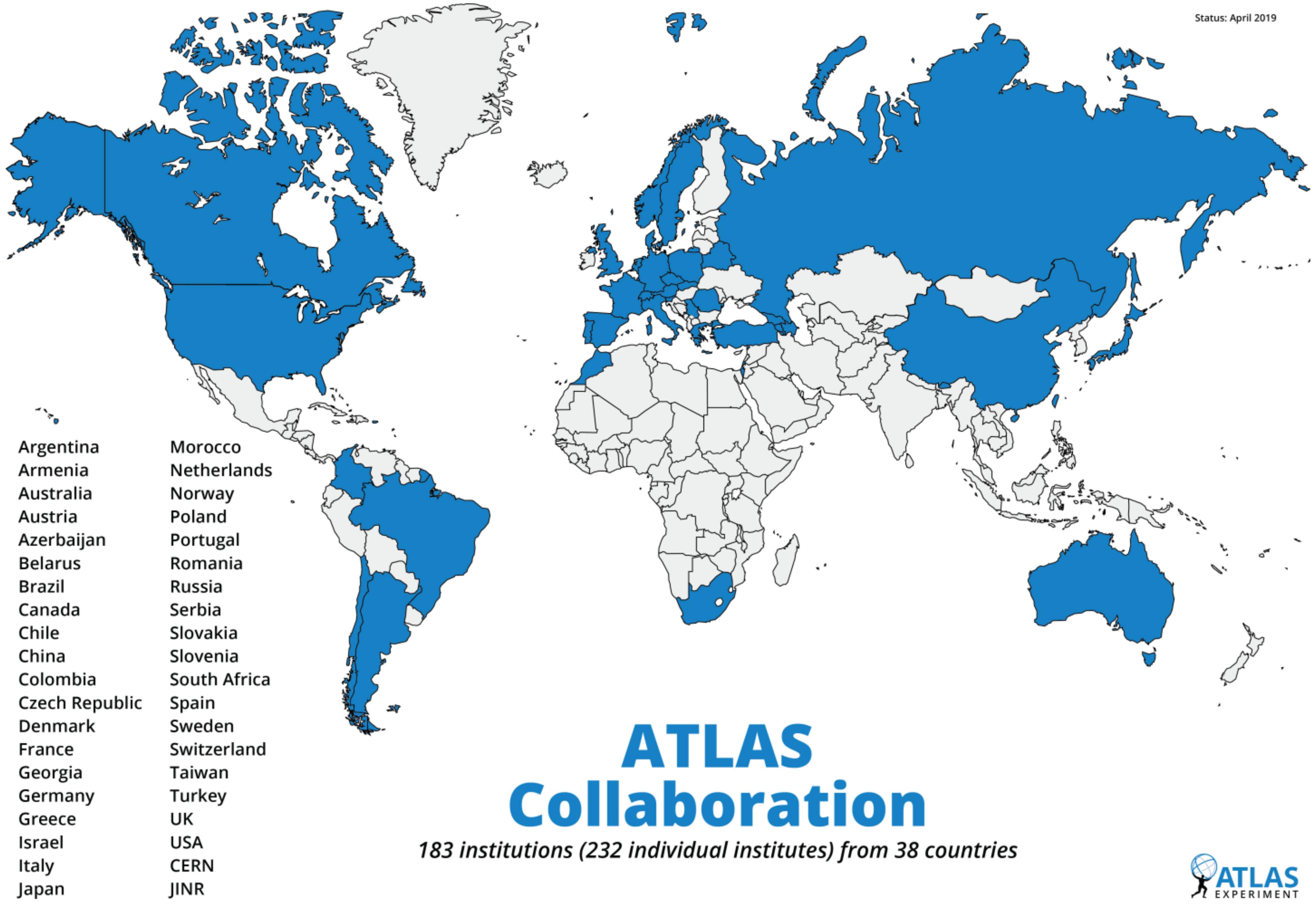
Prompt J/Psi candidates

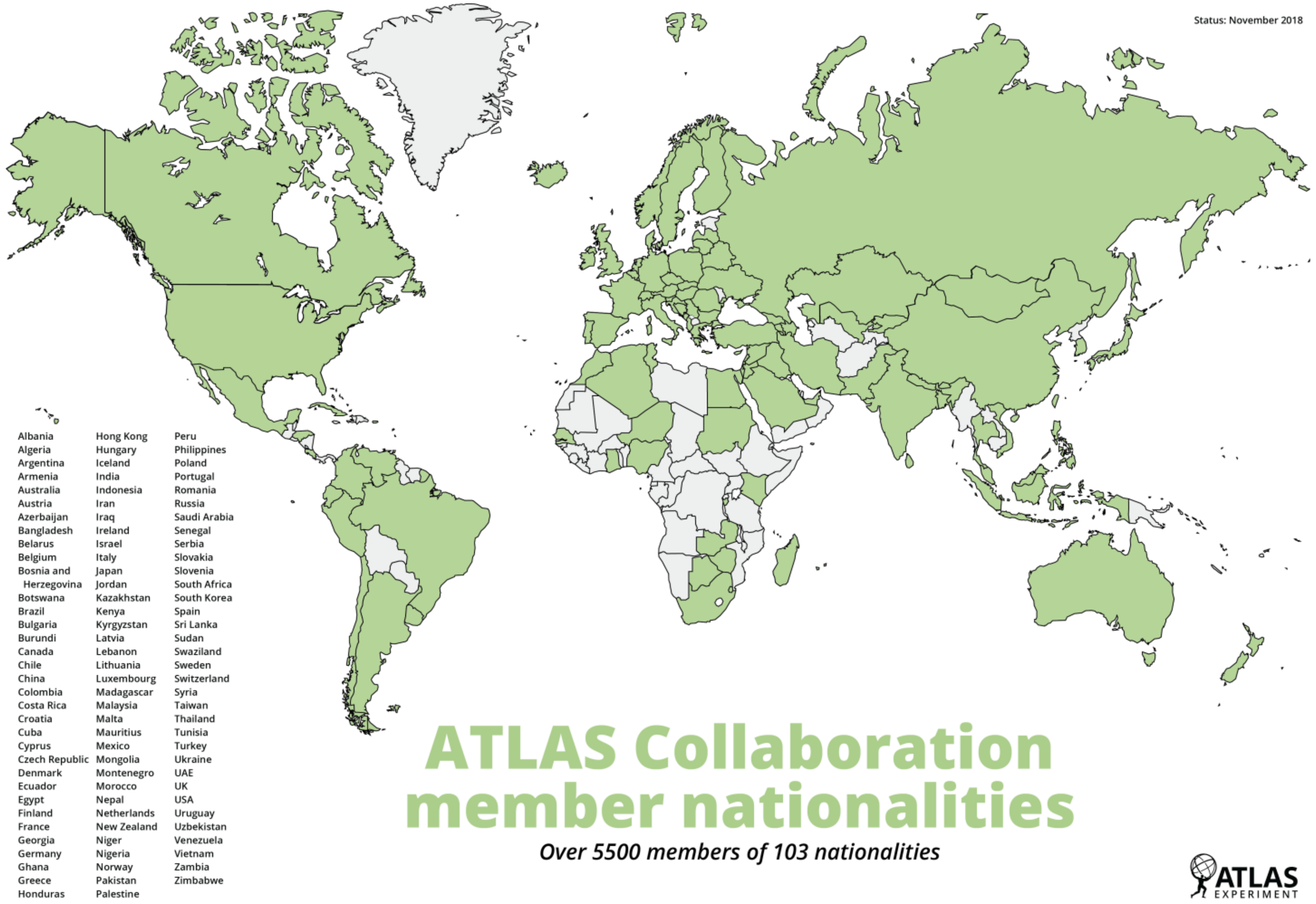




J/Psi candidates from *B* decays

The ATLAS Collaboration





A diverse collaboration with **>5500 members: ~3000 signing authors**, plus engineers, technicians, etc!

2016 ATLAS Gender & Geographic Diversity Study: **ATL-GEN-PUB-2016-001**

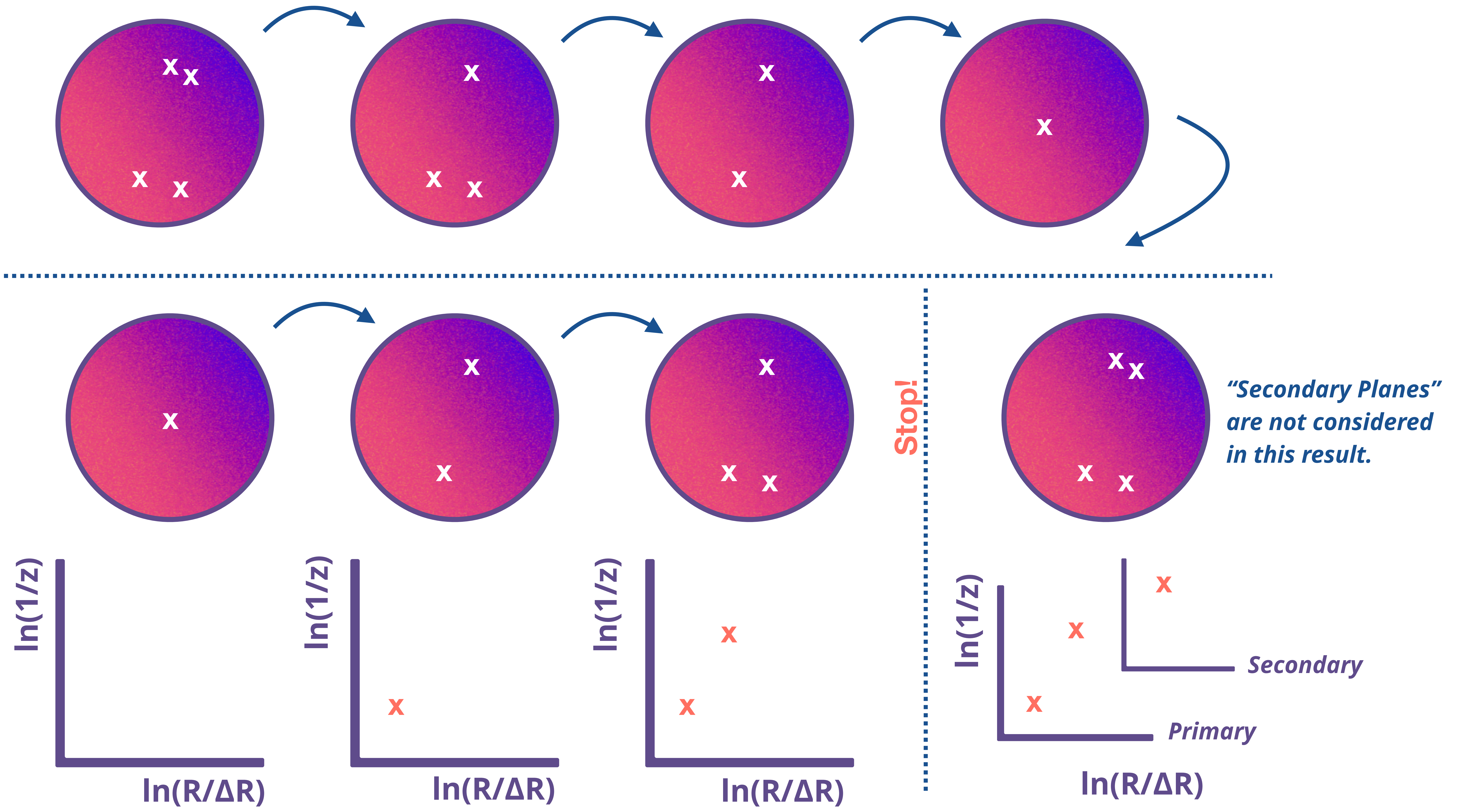
Reconstructing the Lund Jet Plane

1. C/A Reclustering:

Combine closest pairs
of charged particles or tracks!

2. C/A Declustering:

Unwind, widest angles first.
Each step is an **emission**, or,
a point in the Lund Jet Plane!



Iterative declustering approach to approximate the plane, proposed by Dreyer/Soyez/Salam 1807.04758