

QCD measurements at high energies

QCD@LHC 2026

University of Oxford

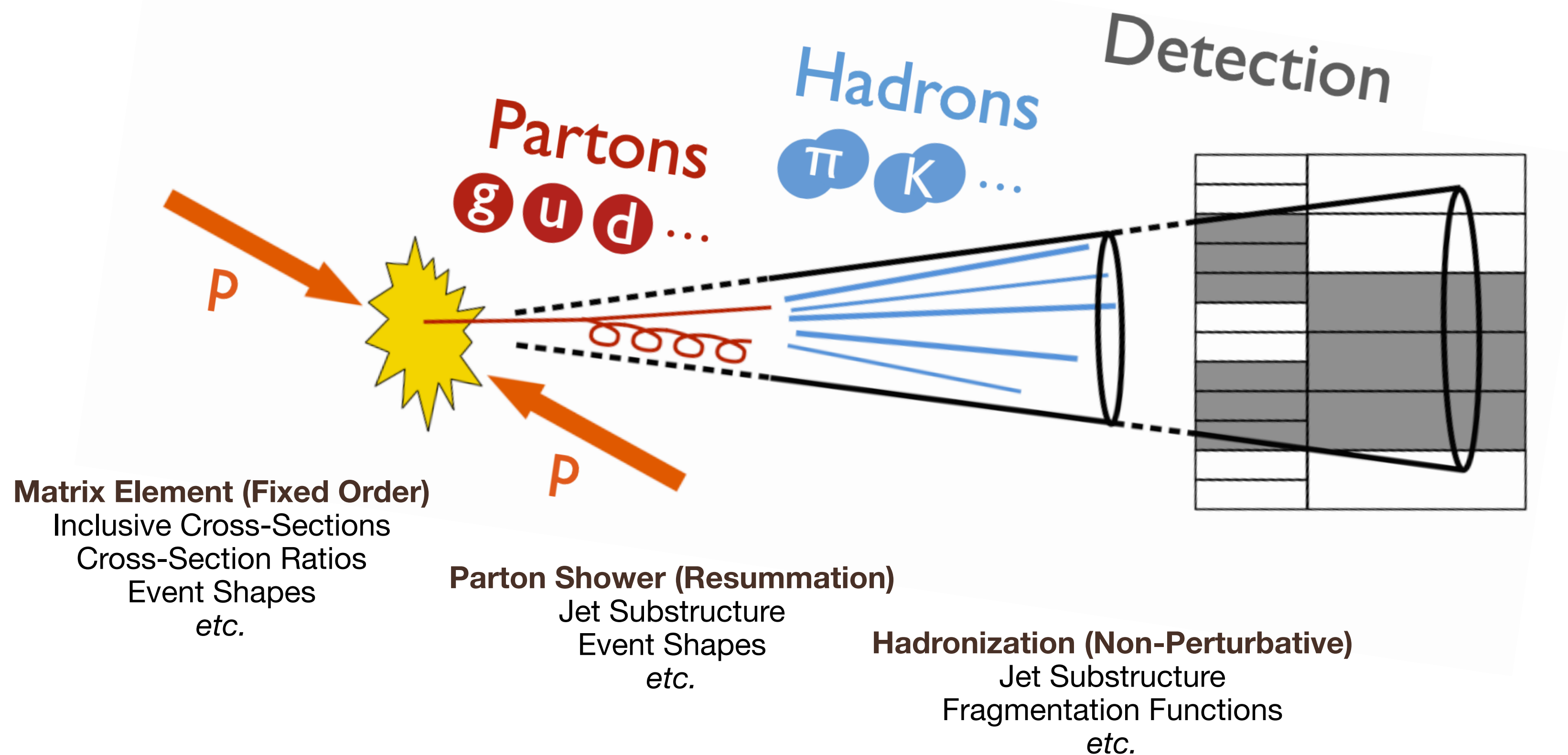
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BROWN
Department of Physics

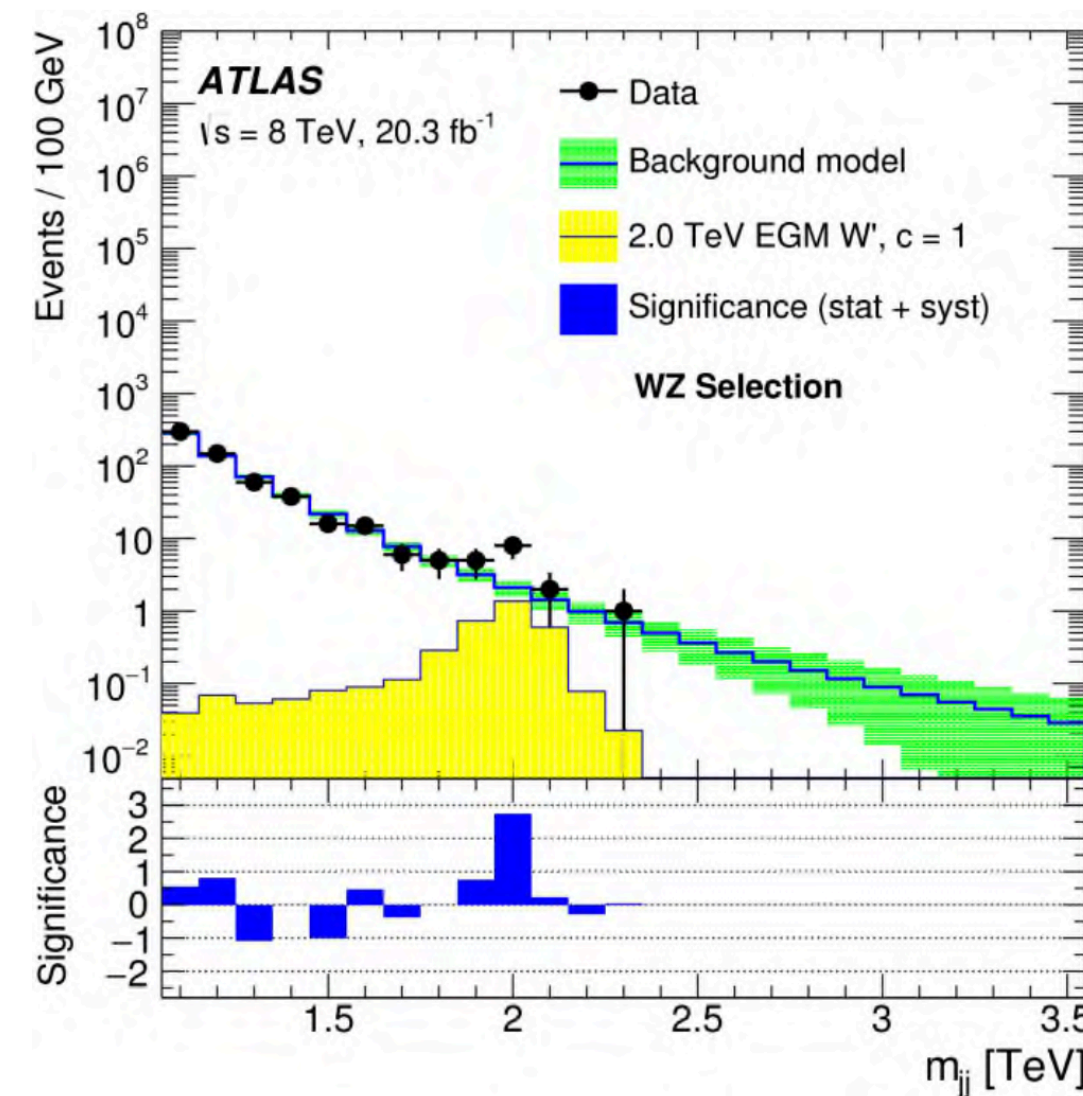
QCD at high energies is jetty

Studies of QCD at high energies involve **jets**, which are multifaceted, multi-scale probes of the strong interaction's dynamics.



A single measurement typically probes multiple scales & effects simultaneously!

What was happening w/ high energy jets the first time I visited Oxford ...

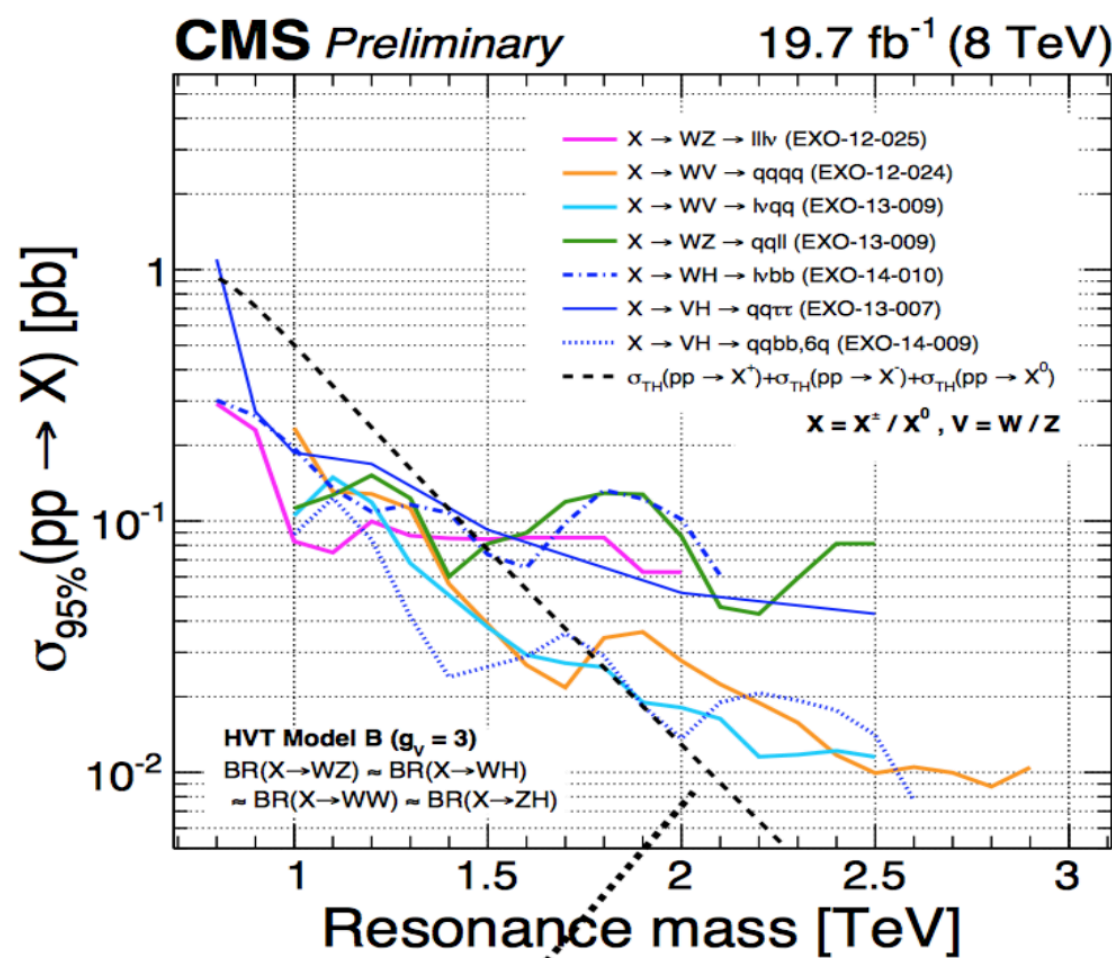


Priors and Prejudice

T. LeCompte (2013)
via N. Trahn @ BOOST (2015)



- I asked about two dozen people if they would believe a result only on a boosted signature
 - Nobody gave an unqualified “yes”
 - Everyone said “it would depend what it was”
 - There was a desire for a confirming result
 - A second channel
 - Interestingly, the same thing from the other experiment was viewed as weak confirmation. The concern is that there is some common systematic.



- Better integration of the “boosted community” in the experiments can only help
 - People need to get comfortable with these new ideas, and this is one way to do this
 - A parade of SM results using boostology would be helpful
 - Top Group sociology enters into this in non-trivial ways

A. Larkoski @
BOOST 2015,
theory summary

How does the boosted community fit into the broader QCD community?

What precision measurements and calculations can we do?

How can what we have learned inform more general QCD issues?

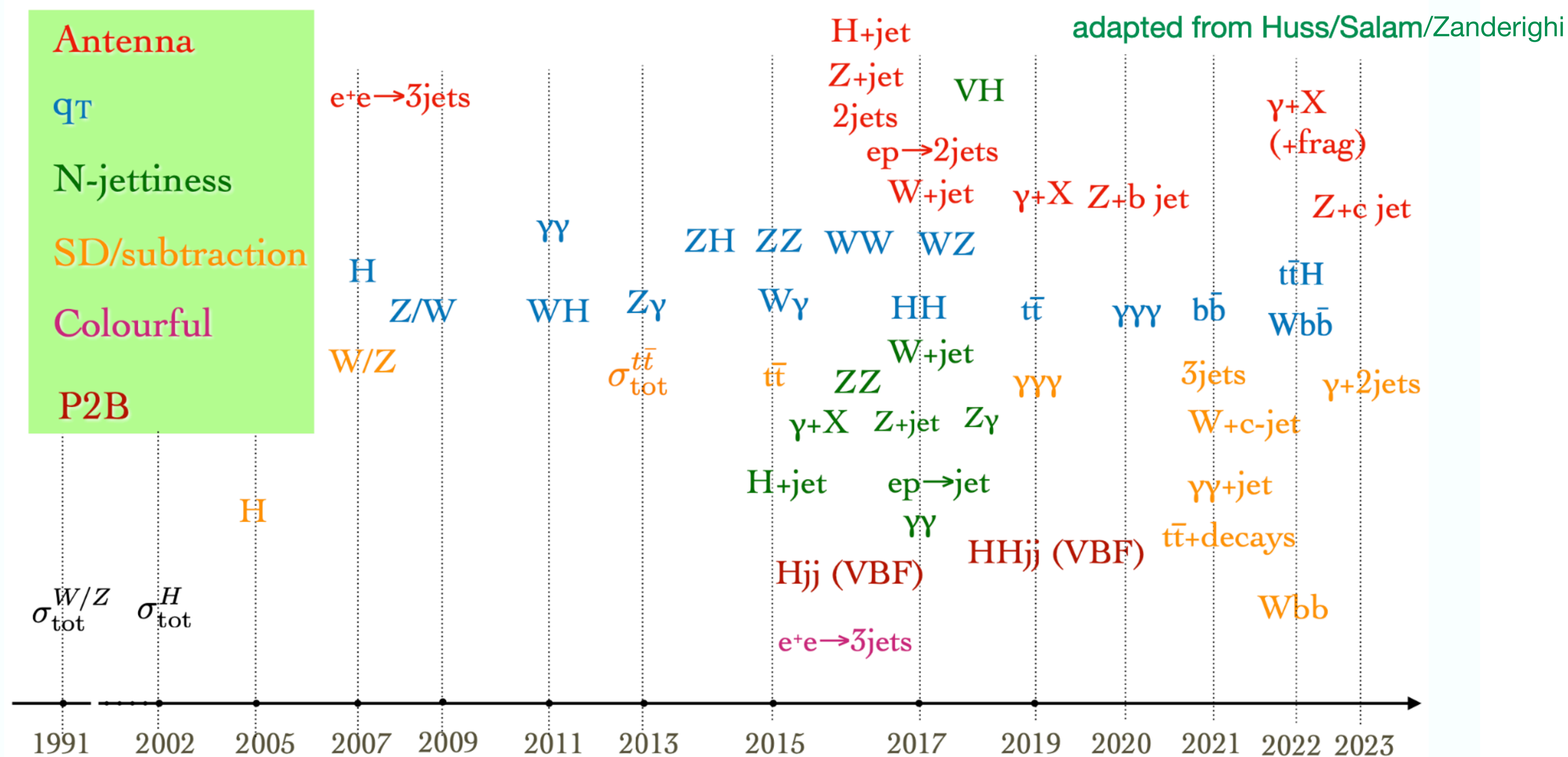
Today, work at the theory-experiment interface is progressing our understanding of QCD faster than ever before.

1. Experiment rises to meet NNLO theory

2. Massive implications

3. High-Luminosity QCD

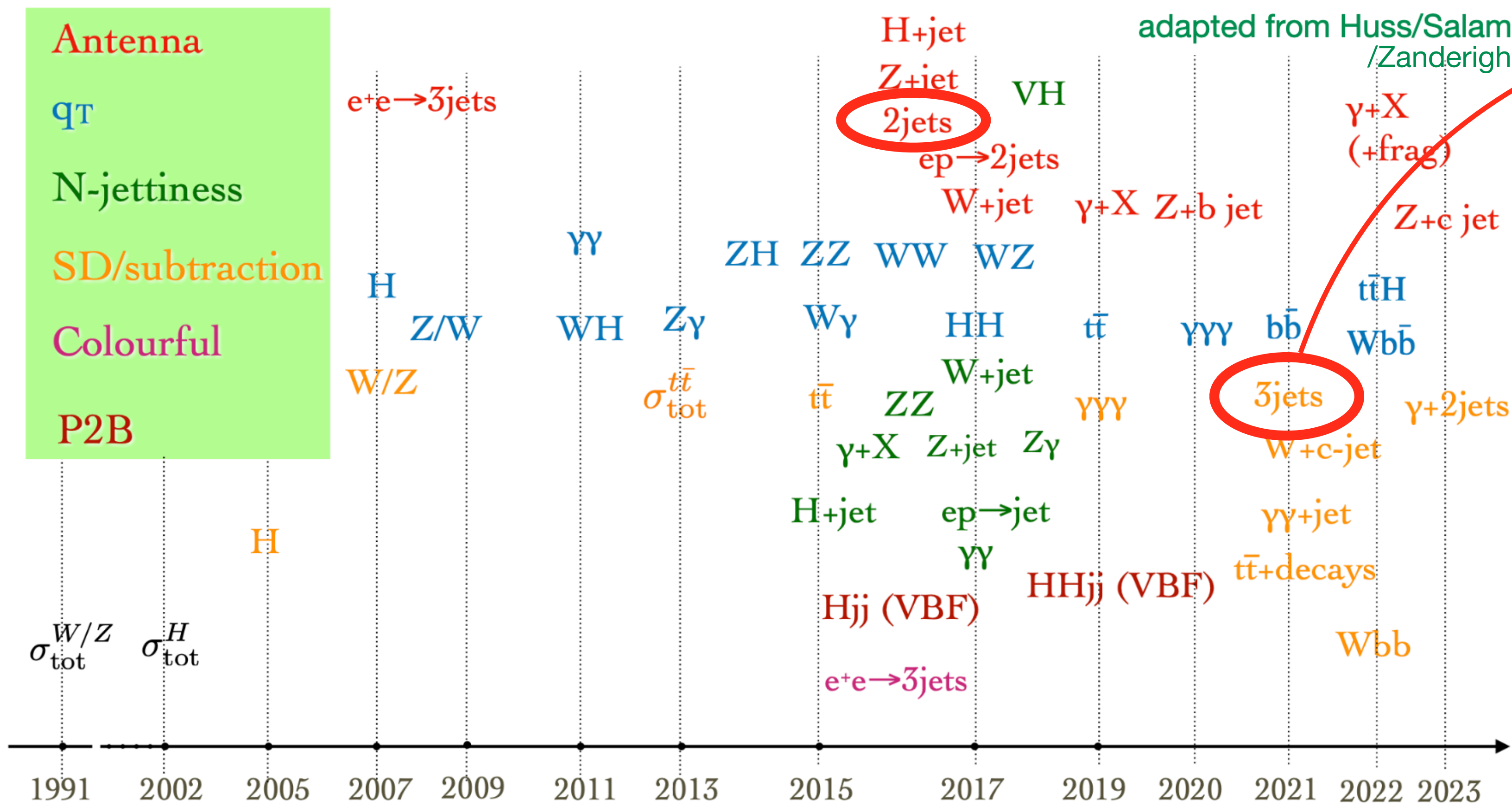
NNLO timeline



Different colour: different way to handle intermediate divergences

The dream is to have NNLO fully automated for generic processes [Sotnikov]

NNLO timeline



Different colour: different way to handle intermediate divergences

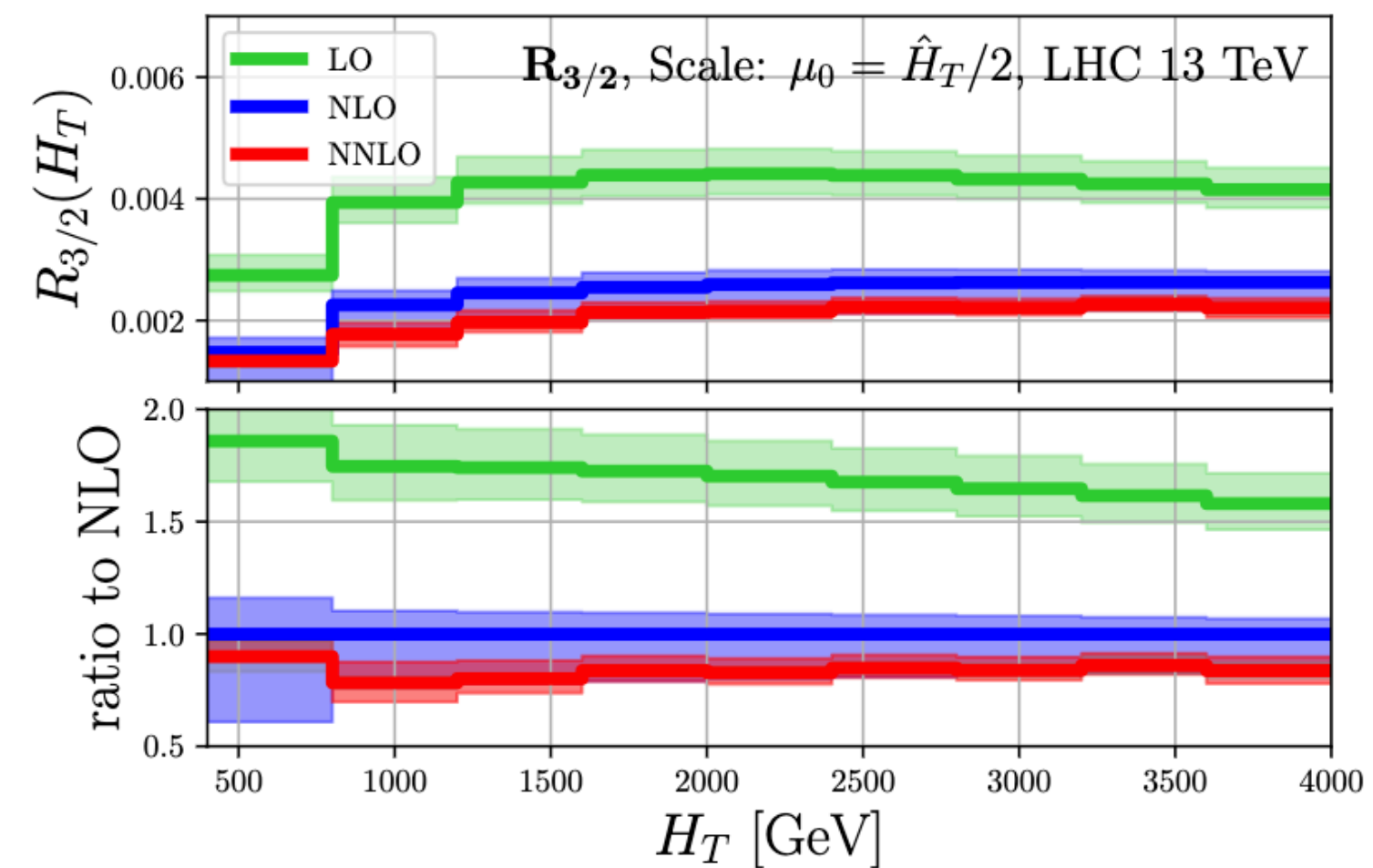
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[Submitted on 9 Jun 2021 (this version), **latest version 26 Aug 2022 (v2)**]

Tour de force in Quantum Chromodynamics: A first next-to-next-to-leading order study of three-jet production at the LHC

Michał Czakoń, Alexander Mitov, René Poncelet

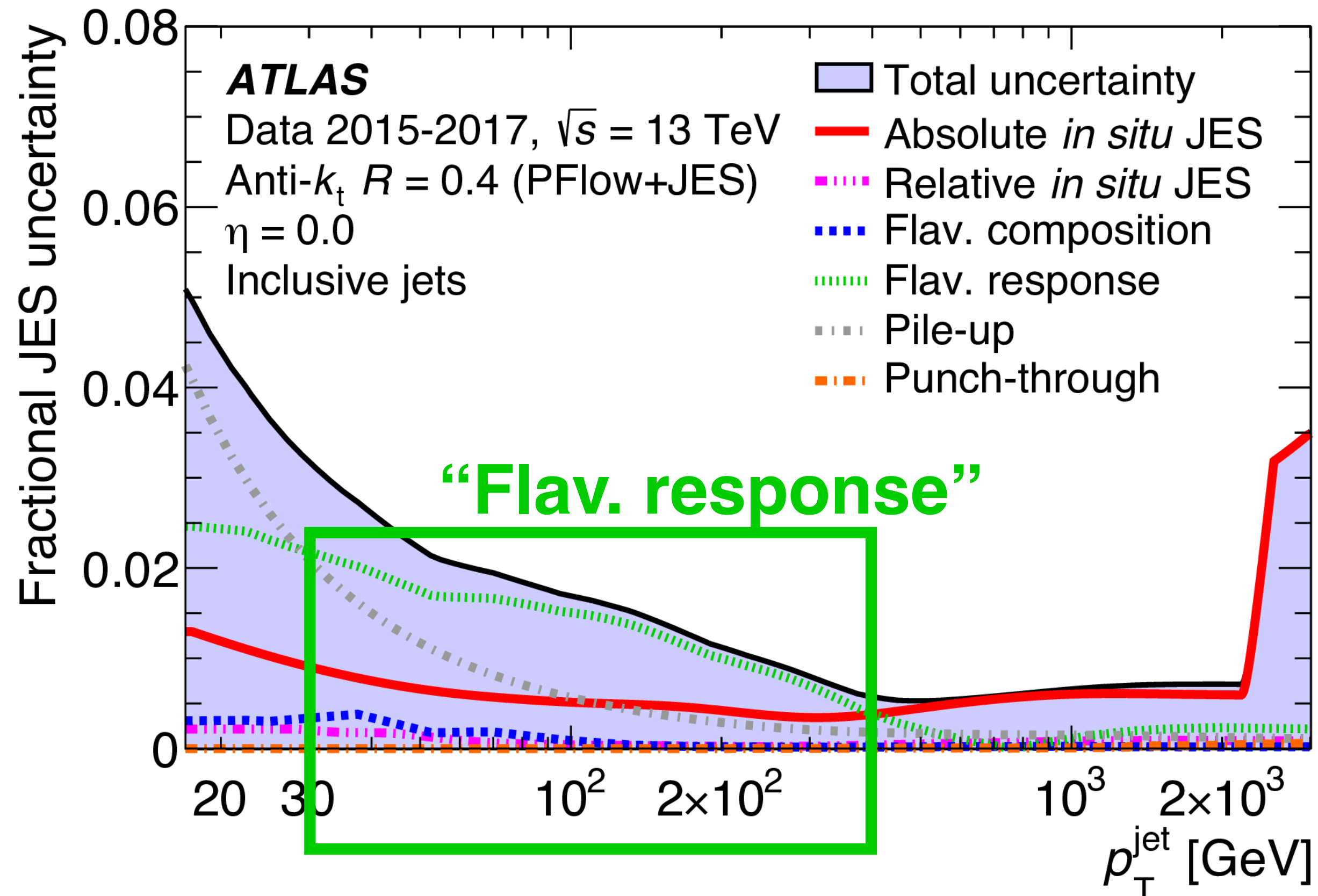
2106.05331v2



- Major reduction in scale uncertainties that had limited prior comparisons w/ measurement
- Took $\sim 10^6$ hours to run! (~ 100 CPU-years)
- At the time, most recent measurements of R_{32} at the LHC were from 2011-2013!

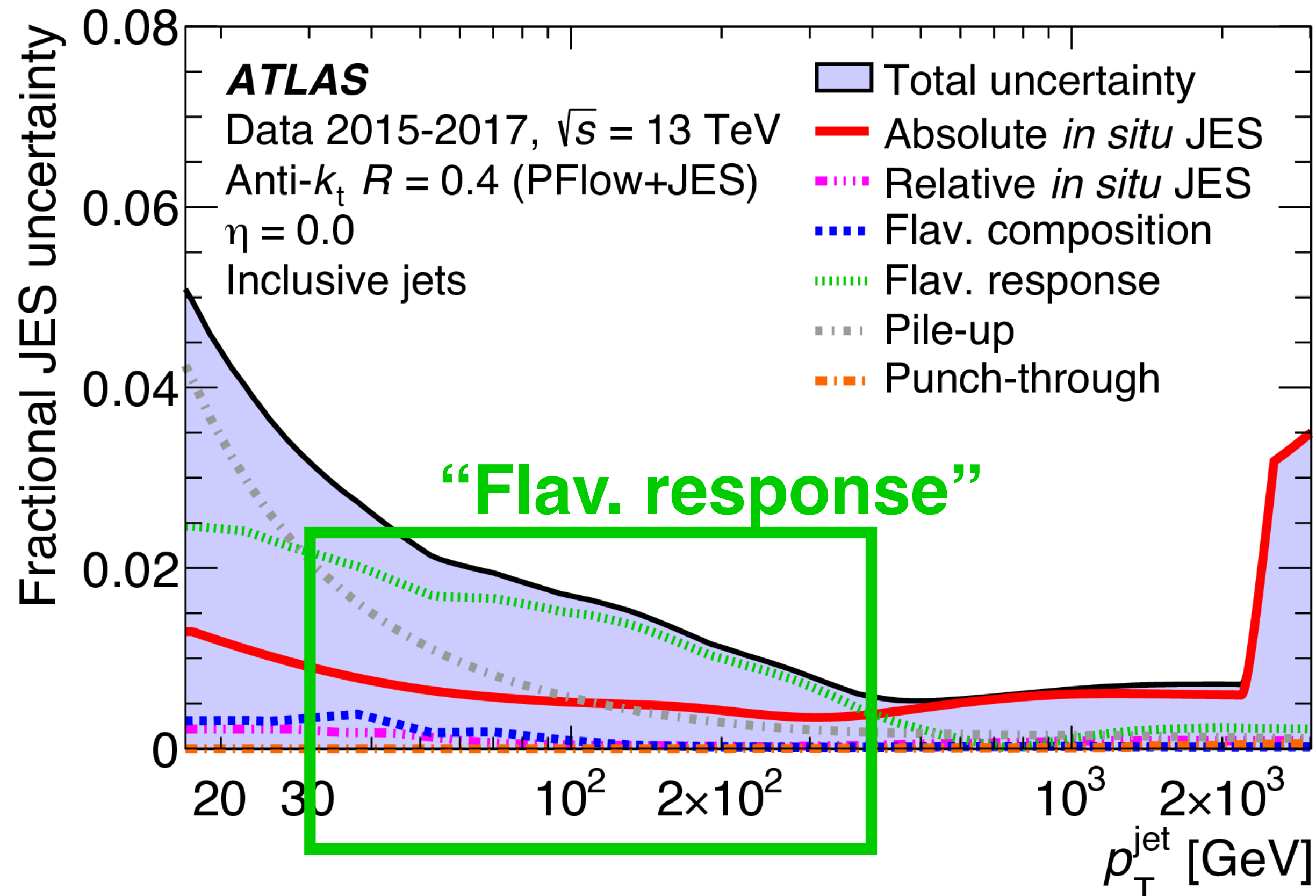
ATLAS 1107.2092, CMS 1106.0647, 1304.7498

Understanding the details: flavour response

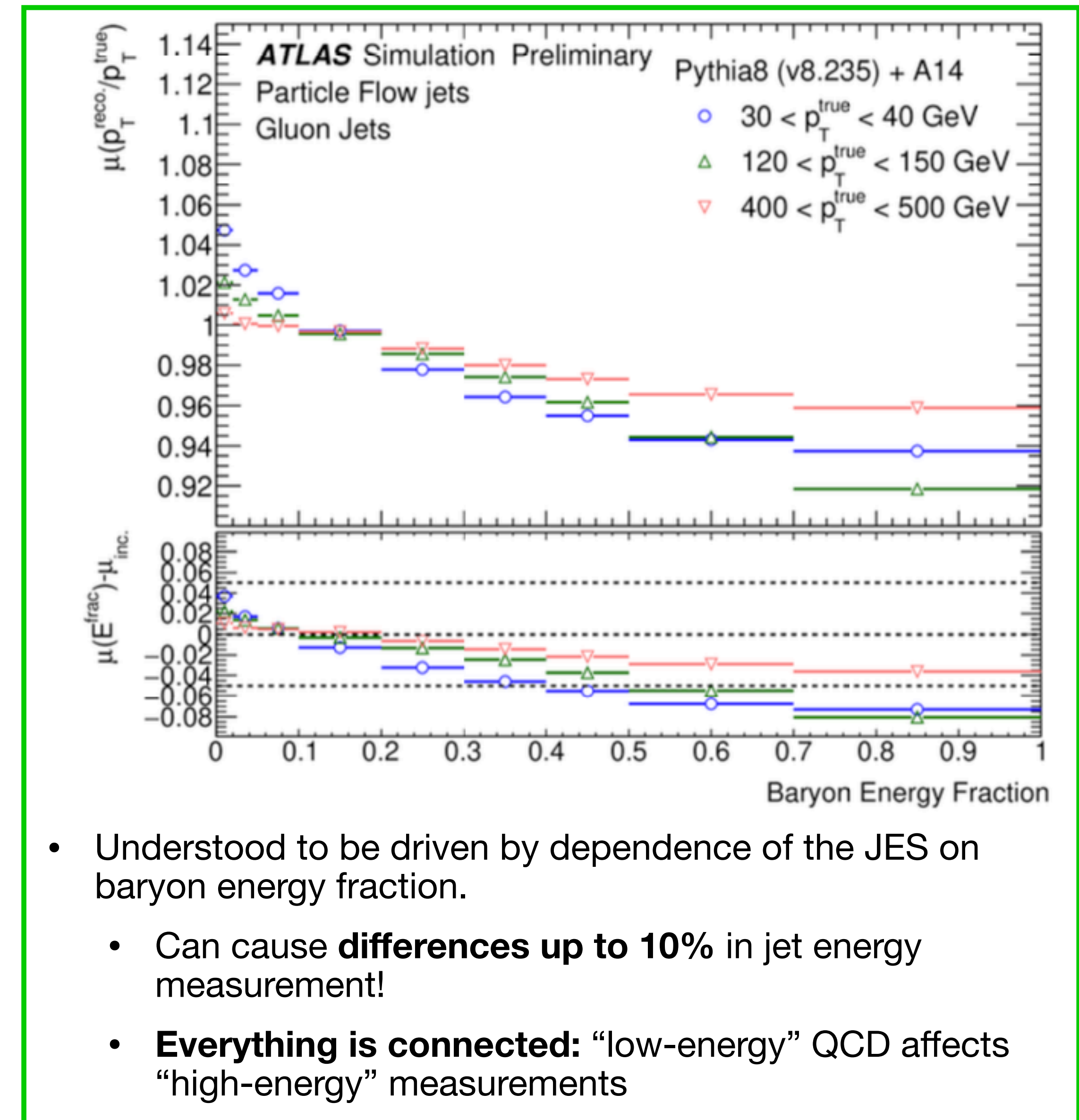


- Most of the “third jets” would have a p_T in a kinematic region with large **jet energy scale (JES)** uncertainties.
- Driven by differences in the **modelling of the detector response to quark- and gluon-initiated jets.**

Understanding the details: flavour response

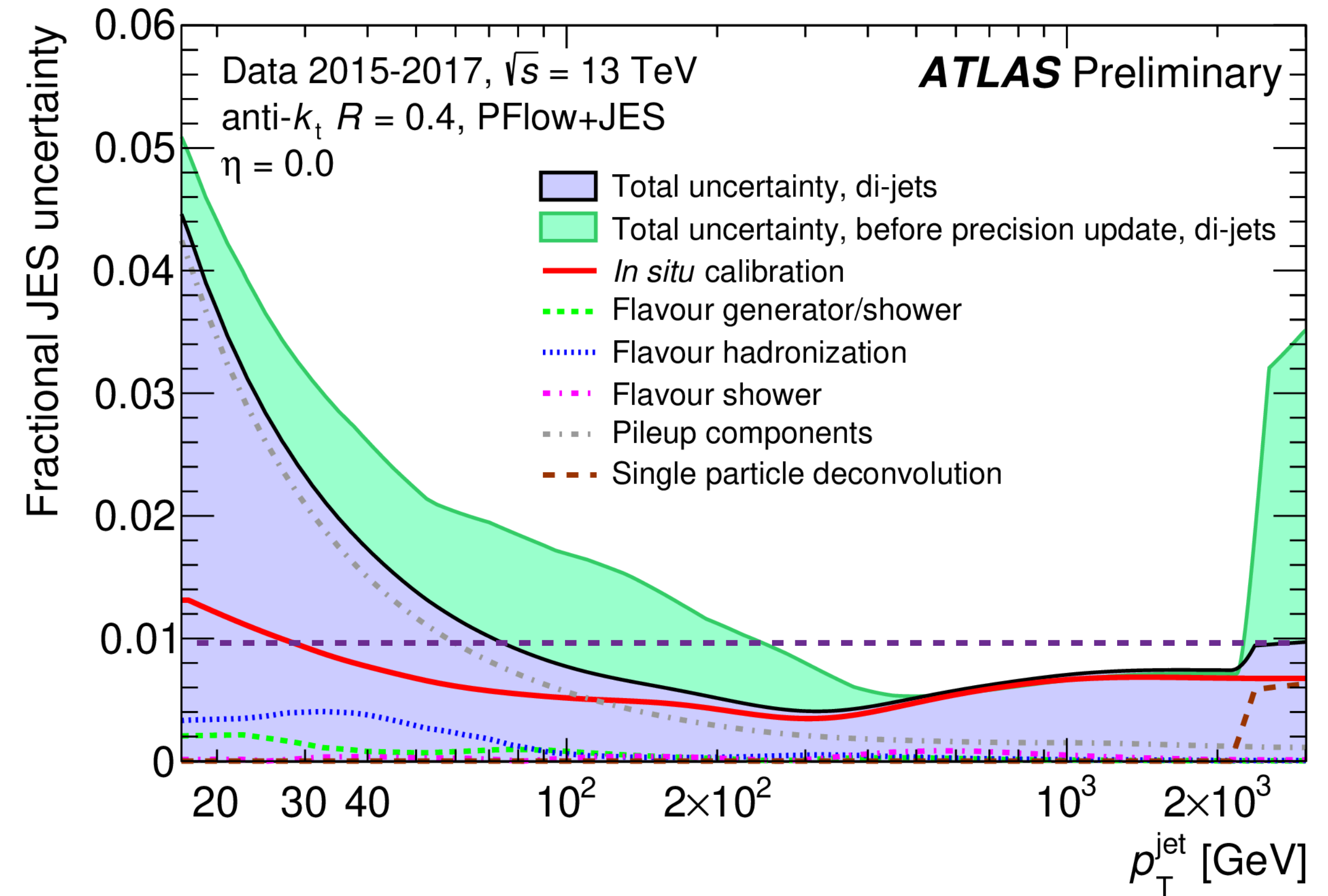
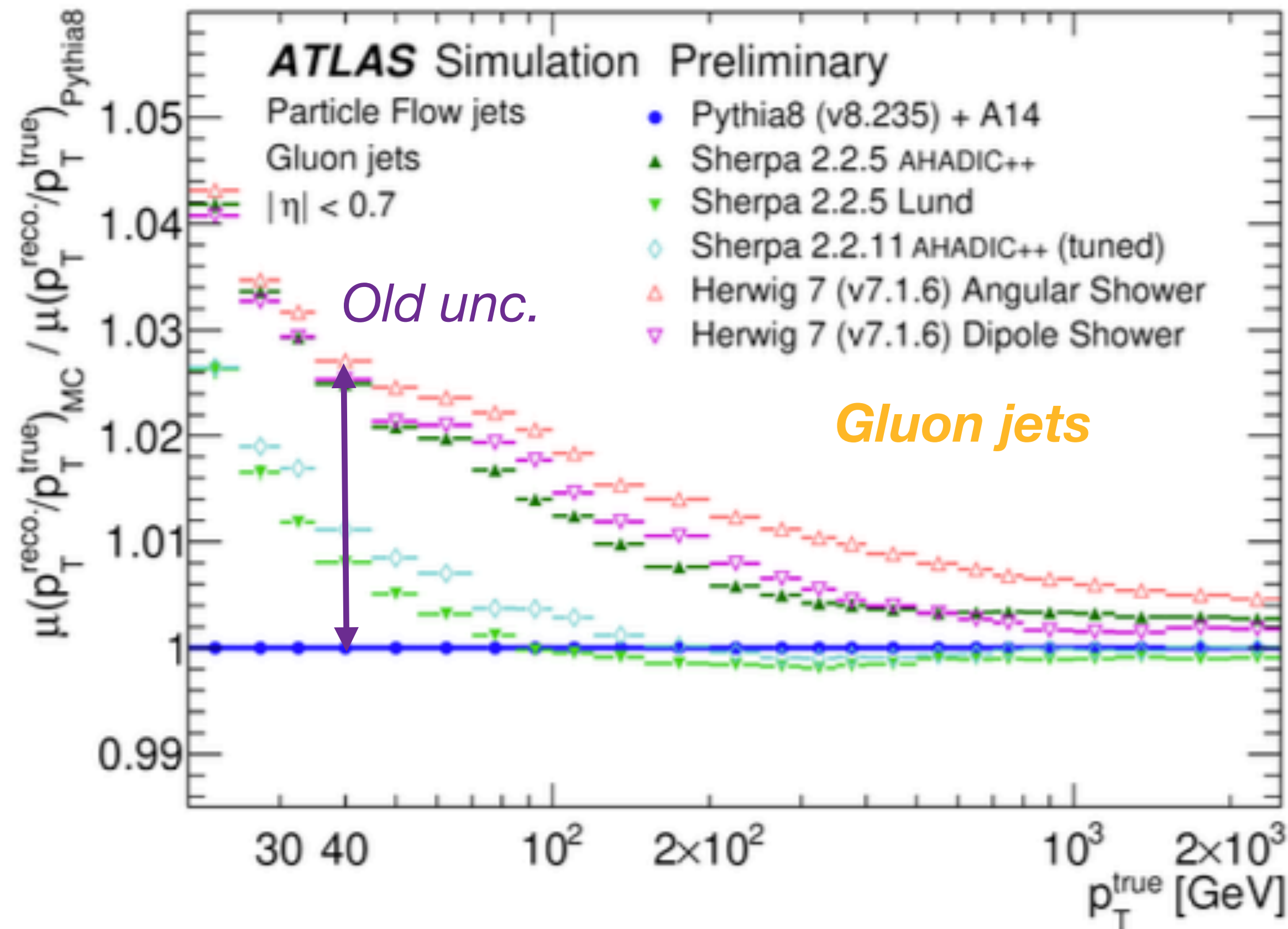


- Most of the “third jets” would have a p_T in a kinematic region with large **jet energy scale (JES)** uncertainties.
- Driven by differences in the **modelling of the detector response to quark- and gluon-initiated jets.**



- Understood to be driven by dependence of the JES on baryon energy fraction.
 - Can cause **differences up to 10%** in jet energy measurement!
 - **Everything is connected:** “low-energy” QCD affects “high-energy” measurements

Understanding the details: flavour response



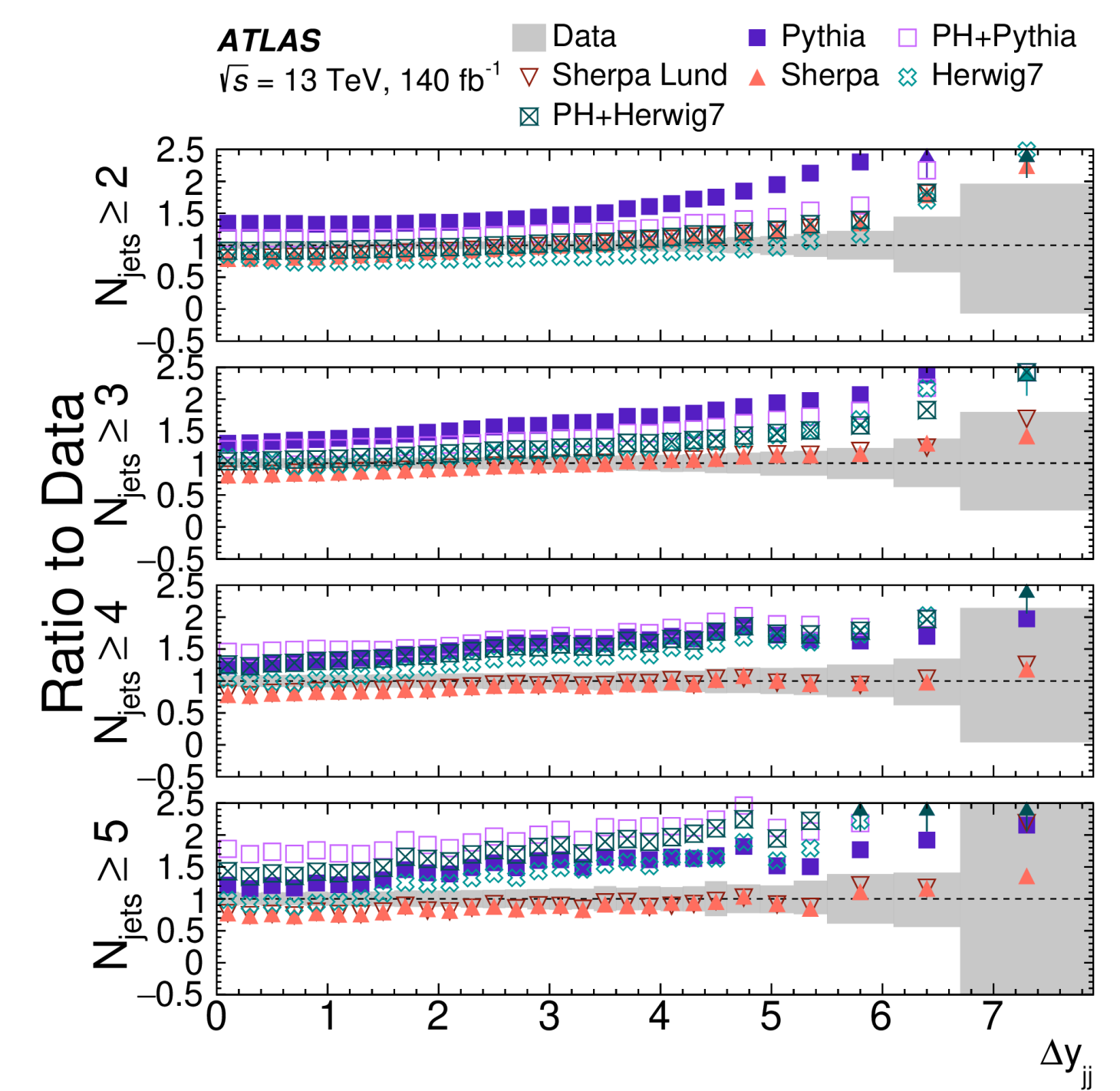
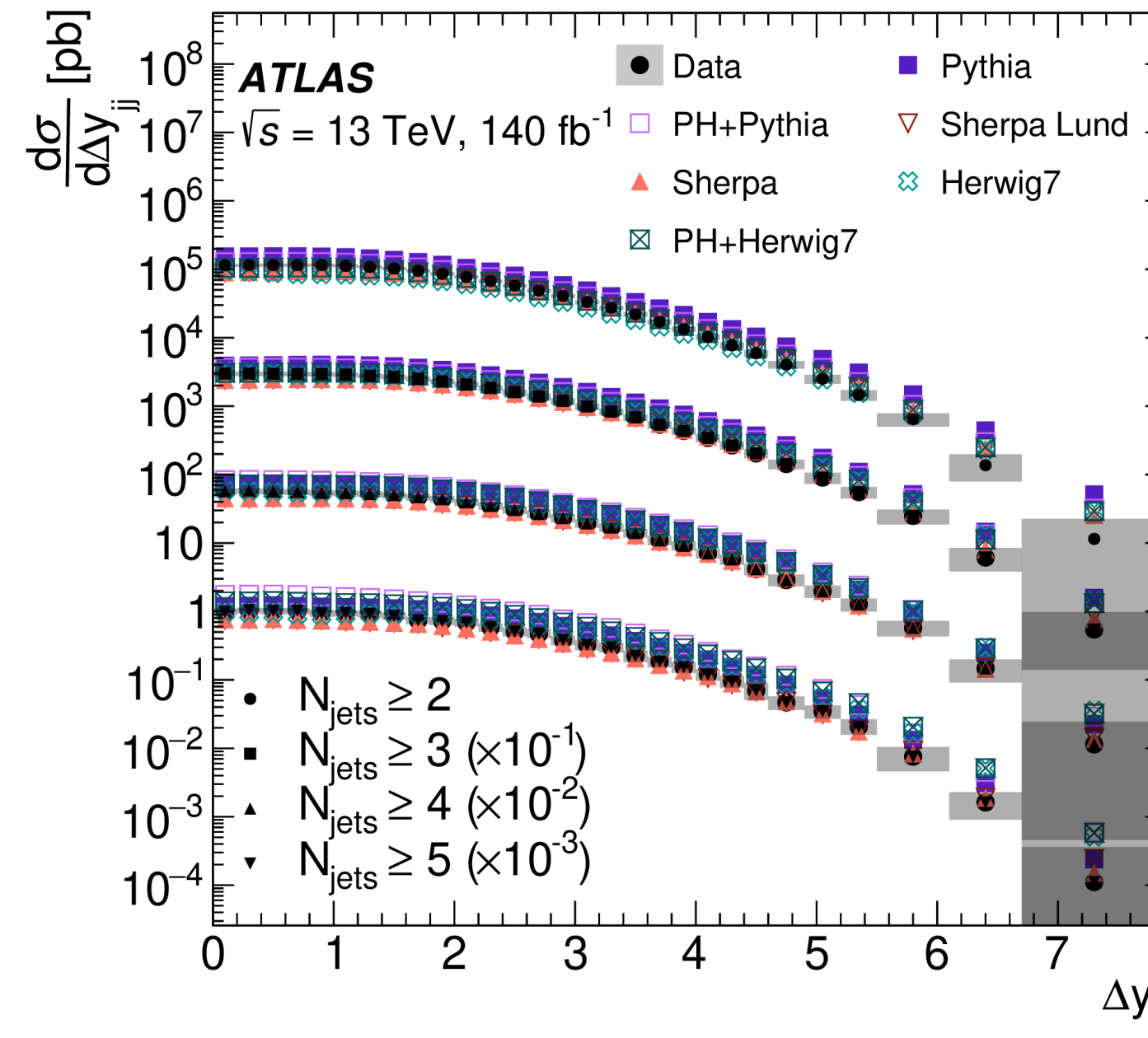
- Around this time, Sherpa was re-tuning their model and paid particular attention to this quantity, which enabled a more intelligent modelling uncertainty to be defined with ATLAS multi jet samples.

See also LH 2023 [2406.00708](#)

- Updated uncertainties factorize different physical effects → percent-level JES for ATLAS above ~60 GeV!
- Approaching ‘optimistic’ HL-LHC projections in Run 2 conditions *ATLAS & CMS, [1902.10229](#)*

ATLAS R_{32}

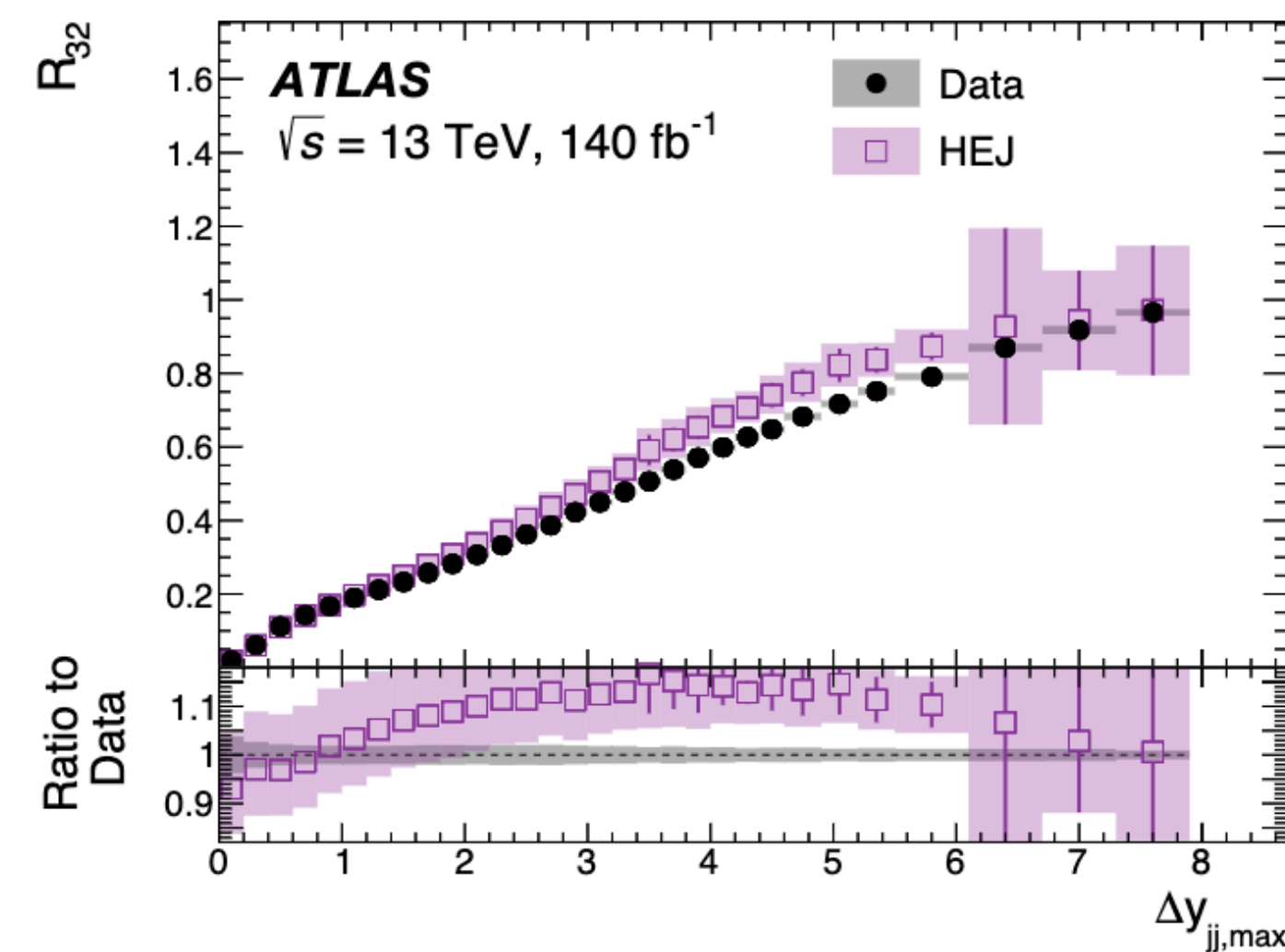
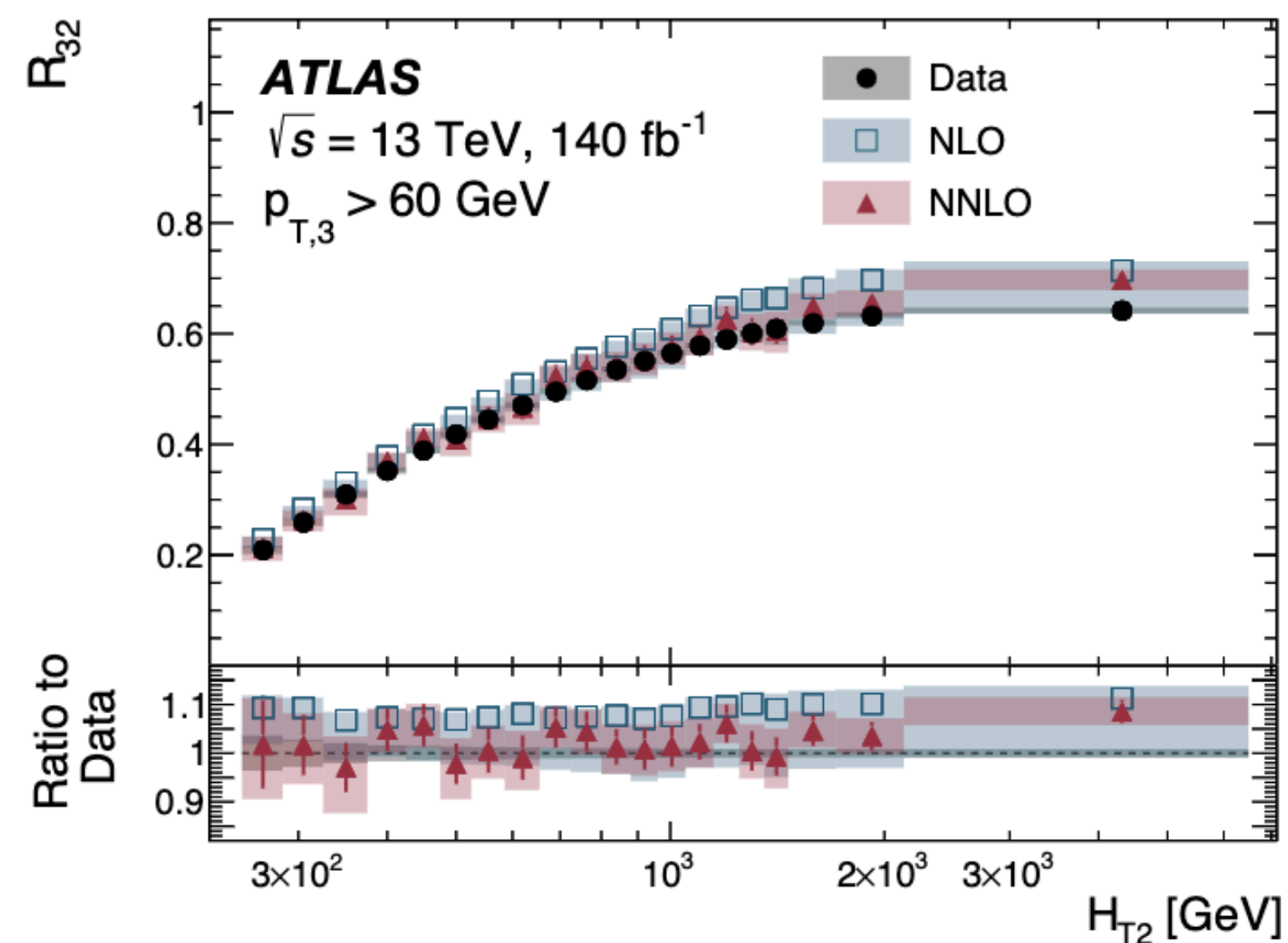
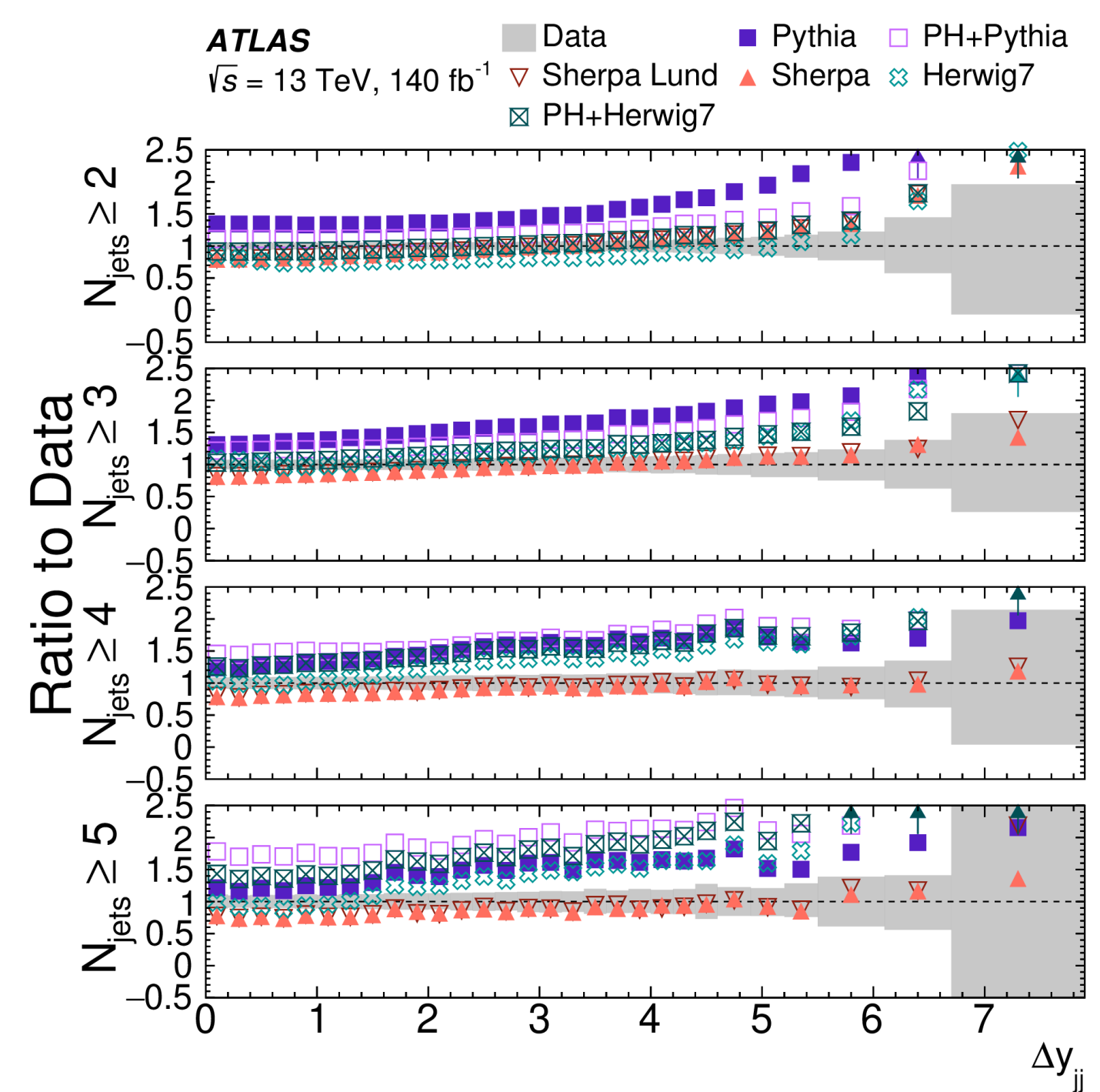
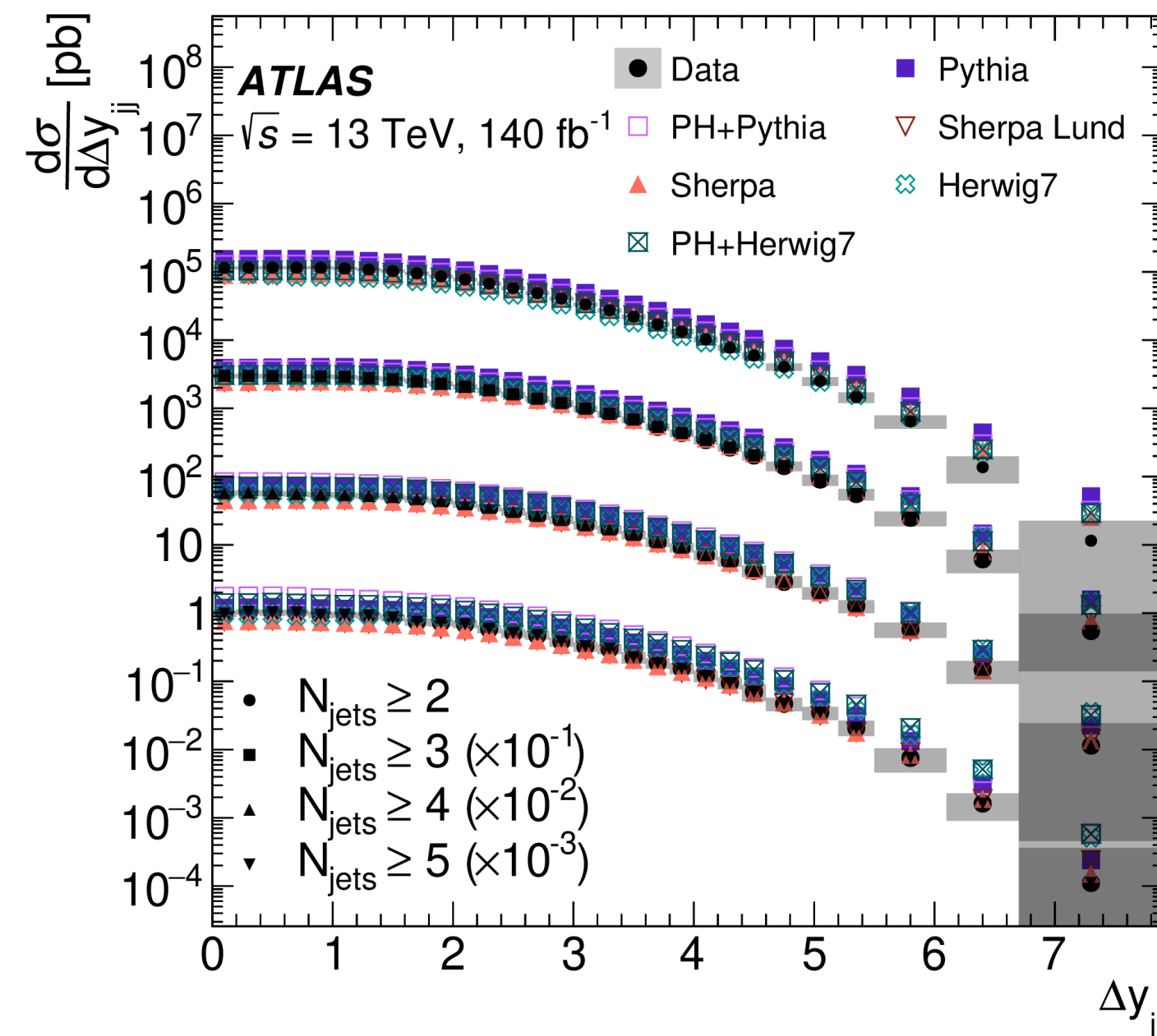
- Precise double- and triple-differential measurement of jet production rates.
- 3D:** HT2 vs. jet multiplicity, 3rd jet p_T
- 2D:** Δy_{jj} , m_{jj} vs. jet multiplicity (+variants)
- Many measurement bins limited by luminosity and PDF uncertainties!
- Multijet cross-section ratios constructed from differential measurements (R_{32} , R_{42} , R_{43} , R_{54})



*A wide variety of MC setups were tested—
in this example, NLO MCs perform
describe Δy_{jj} well for 2-jet final states, while
Sherpa does better for higher multiplicities.*

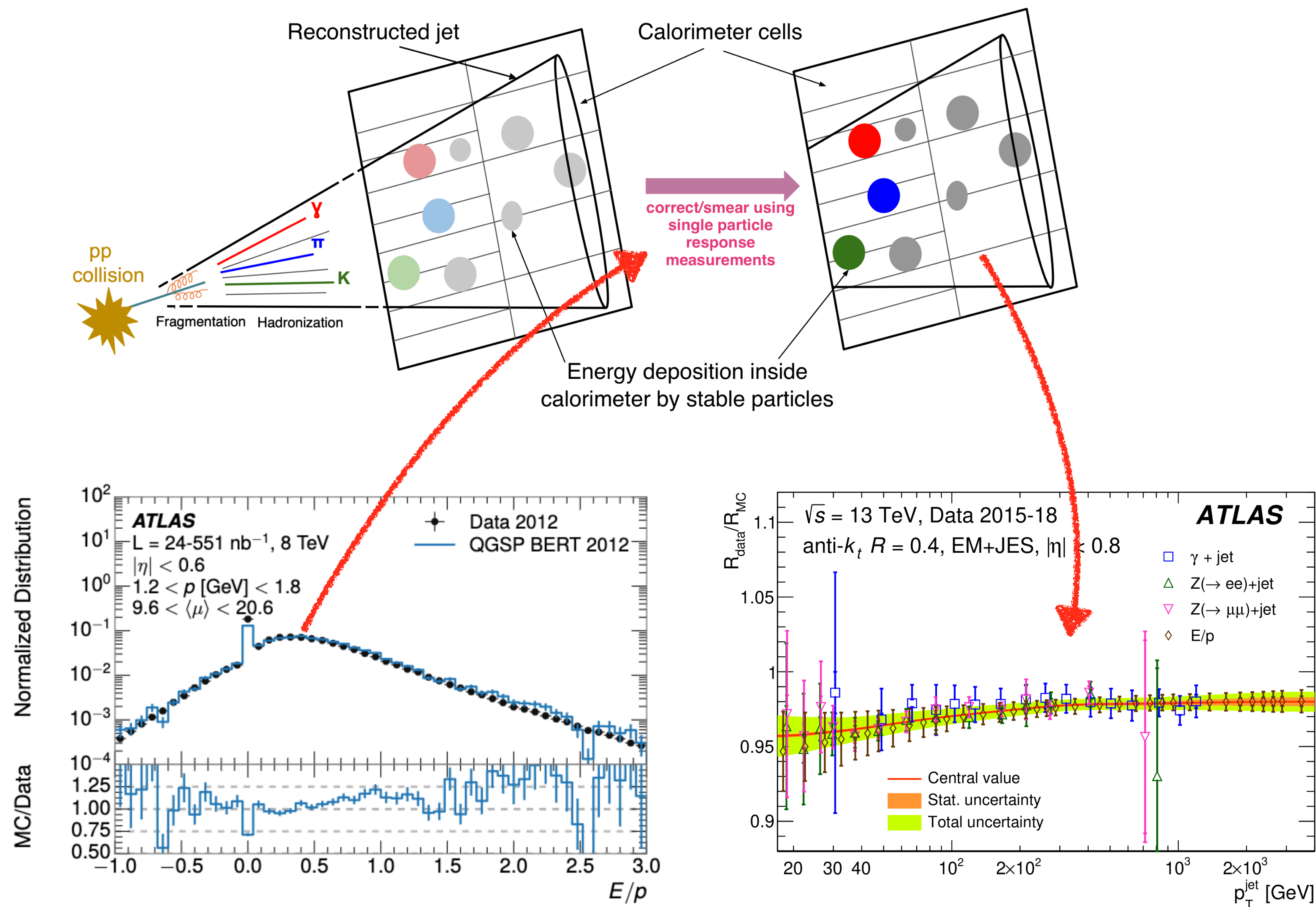
ATLAS R_{32}

- Precise double- and triple-differential measurement of jet production rates.
 - 3D:** H_{T2} vs. jet multiplicity, 3rd jet p_T
 - 2D:** Δy_{jj} , m_{jj} vs. jet multiplicity (+variants)
- Precision limited by JES at high H_{T2} , sometimes comparable to modelling & statistical uncertainties.
- Multijet cross-section ratios constructed from differential measurements (R_{32} , R_{42} , R_{43} , R_{54})
 - NNLO prediction agrees well with data, limited by statistical uncertainty on theory prediction → **compute-limited!**
 - Angular measurements compared to HEJ prediction.
[See Jeppe Andersen's slides from Monday for more on HEJ!](#)

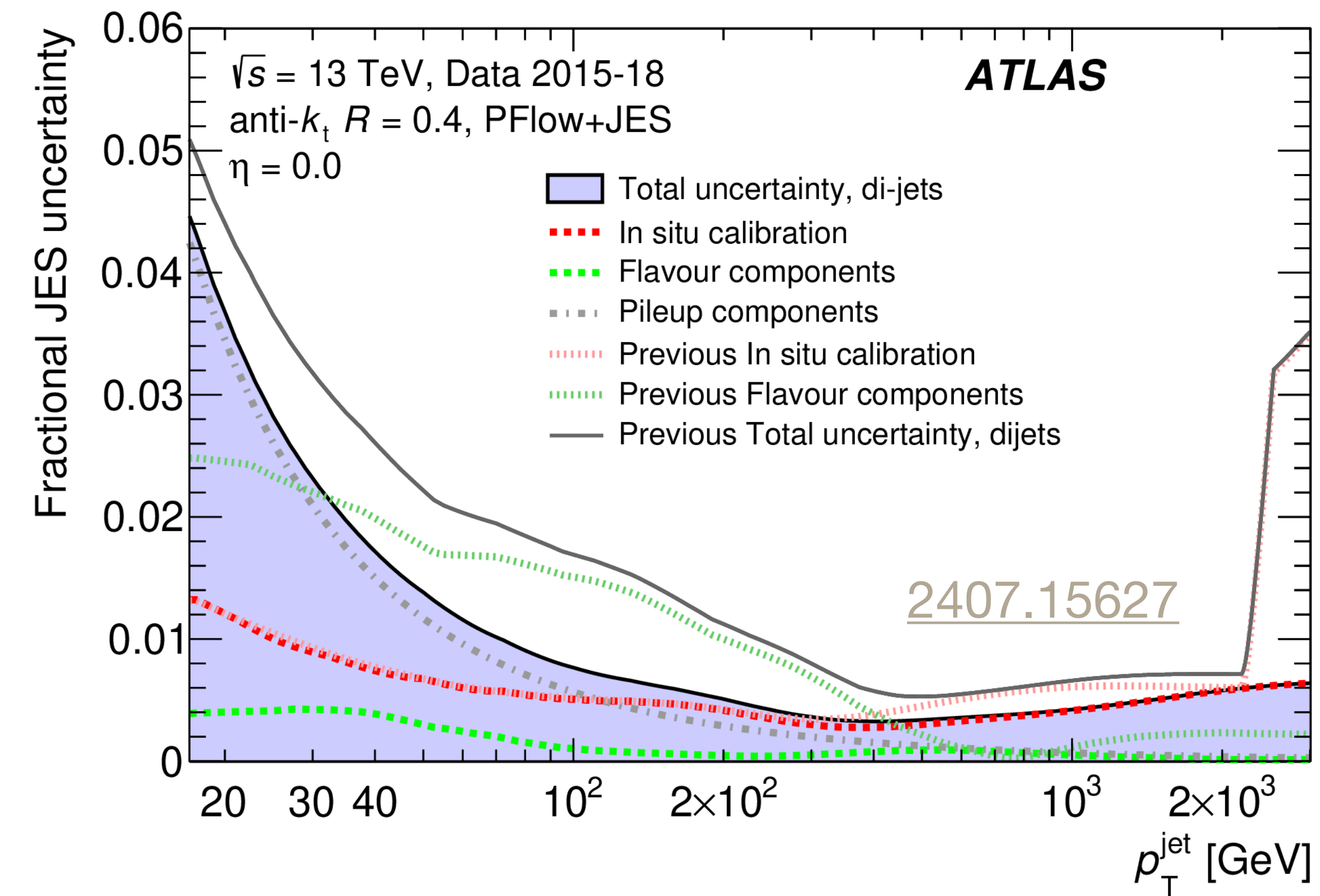


ATLAS Single-Hadron Jet Calibration

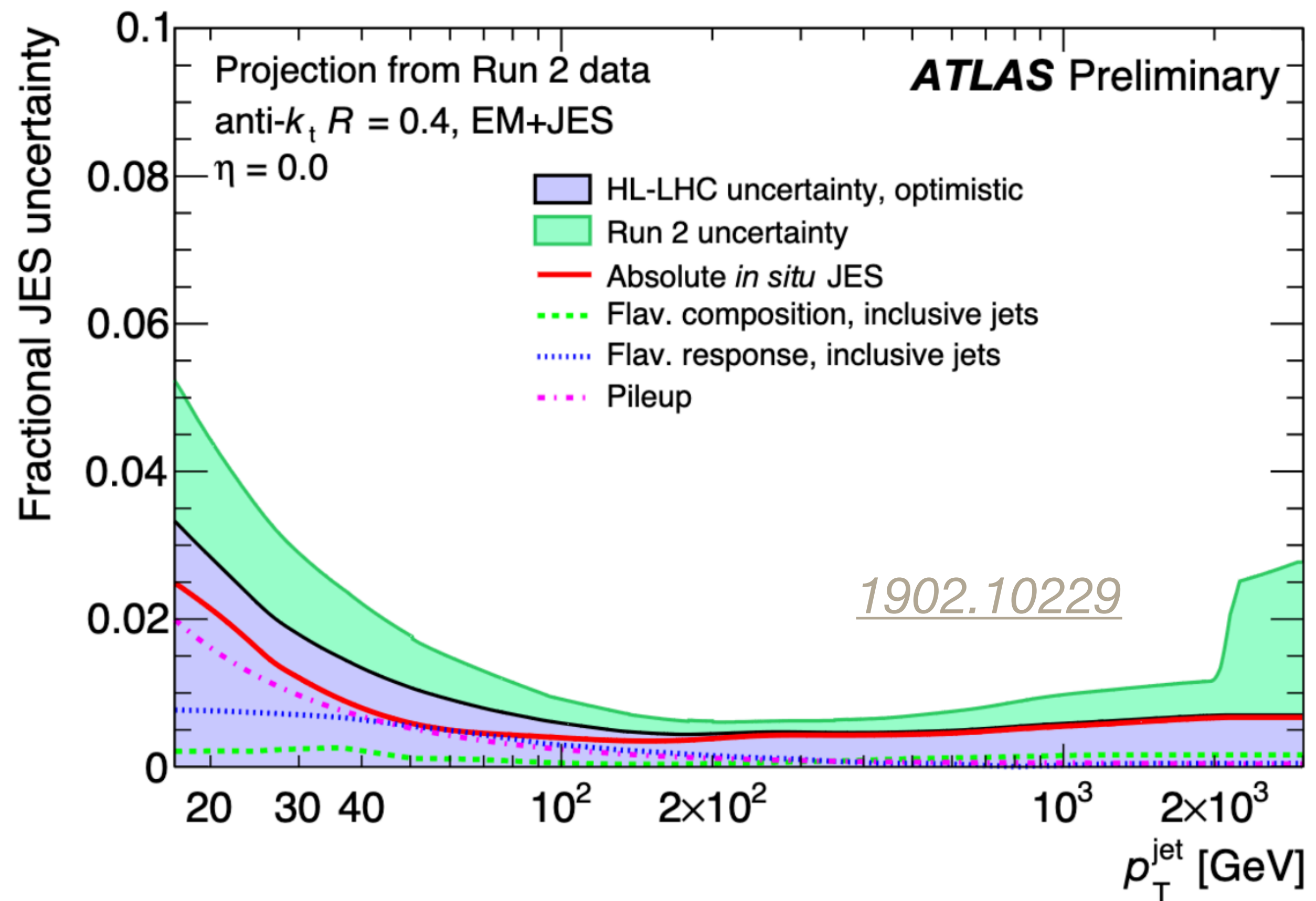
- Further work to reduce ATLAS jet energy scale uncertainties included the development of a calibration based on **single-hadron response measurements**.
- Smearing of individual particle measurements in simulation reproduces the *in situ* balance correction.
- Improves on balance-based calibration by incorporating **high- p_T $W \rightarrow \tau\nu$ measurement**.
- Can be extended to **different jet radii while tracking correlations** between uncertainty sources.



ATLAS 2108.09043



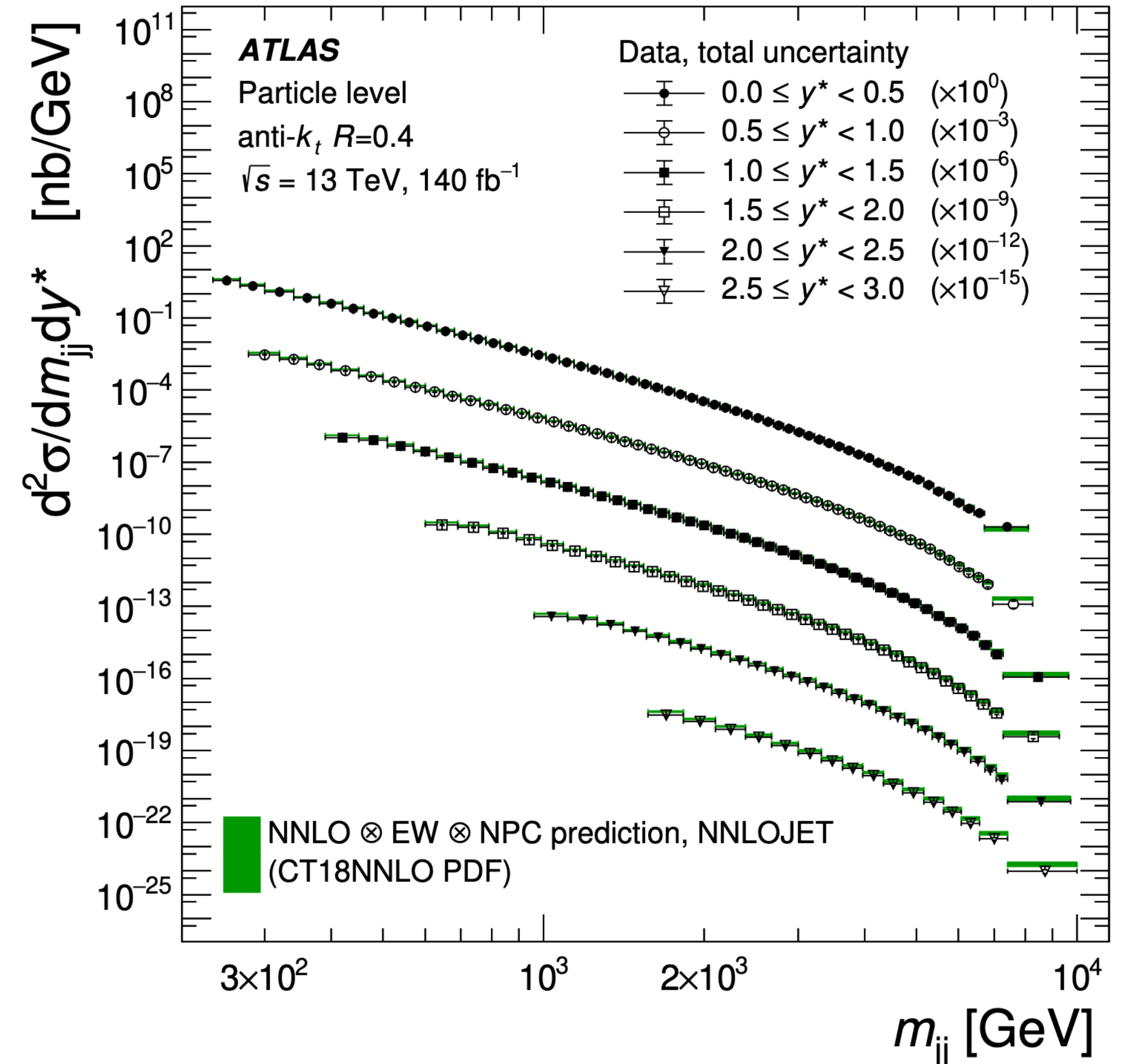
Final ATLAS Run 2 JES uncertainty:
 ~0.3% at 300 GeV, ~0.6% at 4 TeV



“Optimistic” HL-LHC Projection

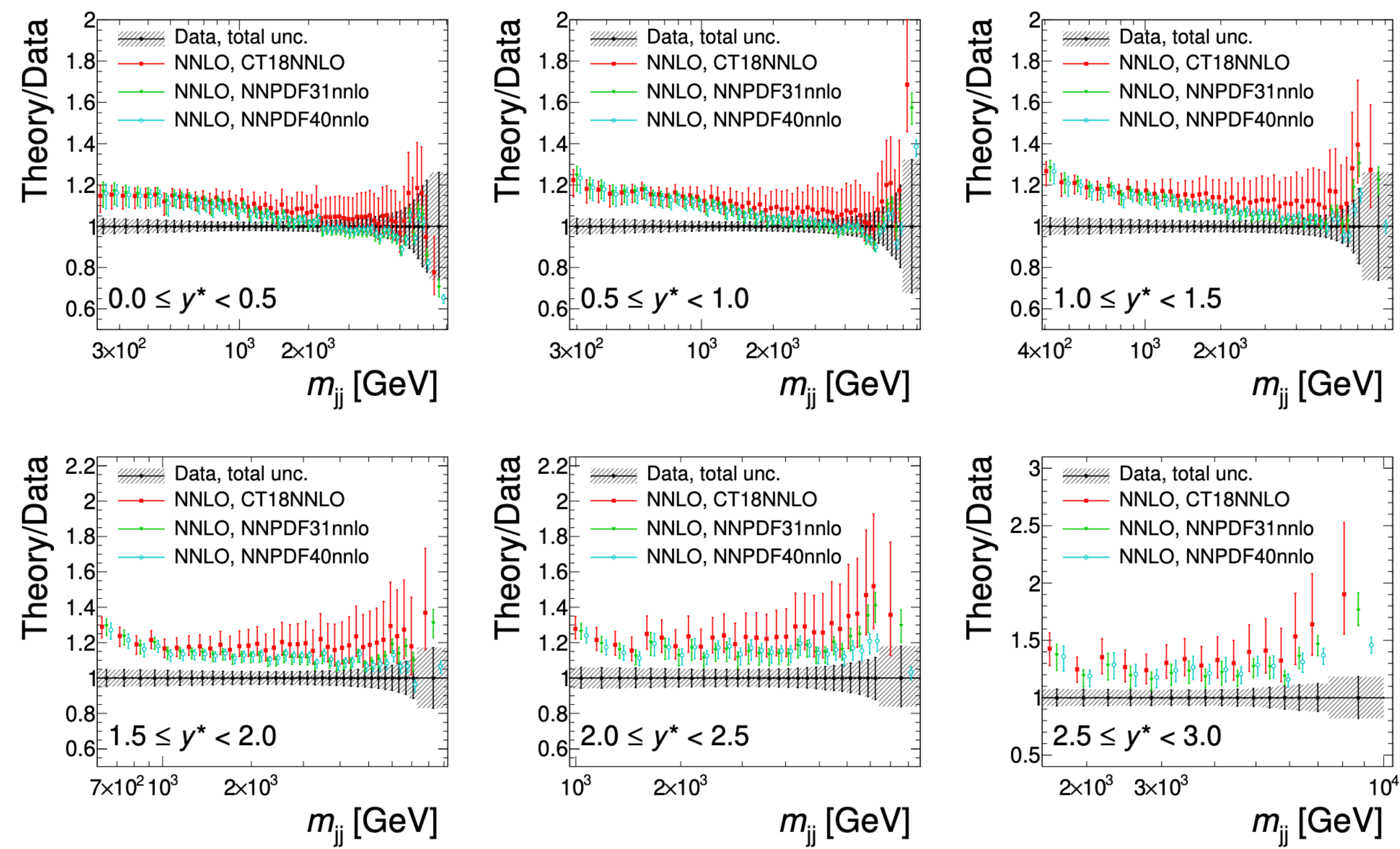
ATLAS Dijet Cross-Section

- Unfolded cross-sections compared to full-colour NNLO pQCD prediction from NNLOJET.
- Non-perturbative and electroweak corrections applied.
- Binned in either (m_{jj}, y^*) or $(m_{jj}, y_{\text{boost}})$



ATLAS Dijet XS

- Unfolded cross-sections compared to full-color NNLO pQCD prediction from NNLOJET.
- Non-perturbative and electroweak corrections applied.
- Binned in either (m_{jj} , y^*) or (m_{jj} , y_{boost})
- Predictions over-estimate the measured cross-sections by 15~20%, with best qualitative agreement observed for the NNPDF4.0NNLO PDF set.
- Best per-bin $\chi^2/\text{d.o.f.}$ values for CT18, best overall for ATLASpdf21T3.
- Correlations of JES nuisance parameters in fit play an important role!*
Amanda Sarkar Monday 11h10



ATLAS
Particle level

$\sqrt{s} = 13 \text{ TeV}, 140 \text{ fb}^{-1}$
anti- k_t $R=0.4$

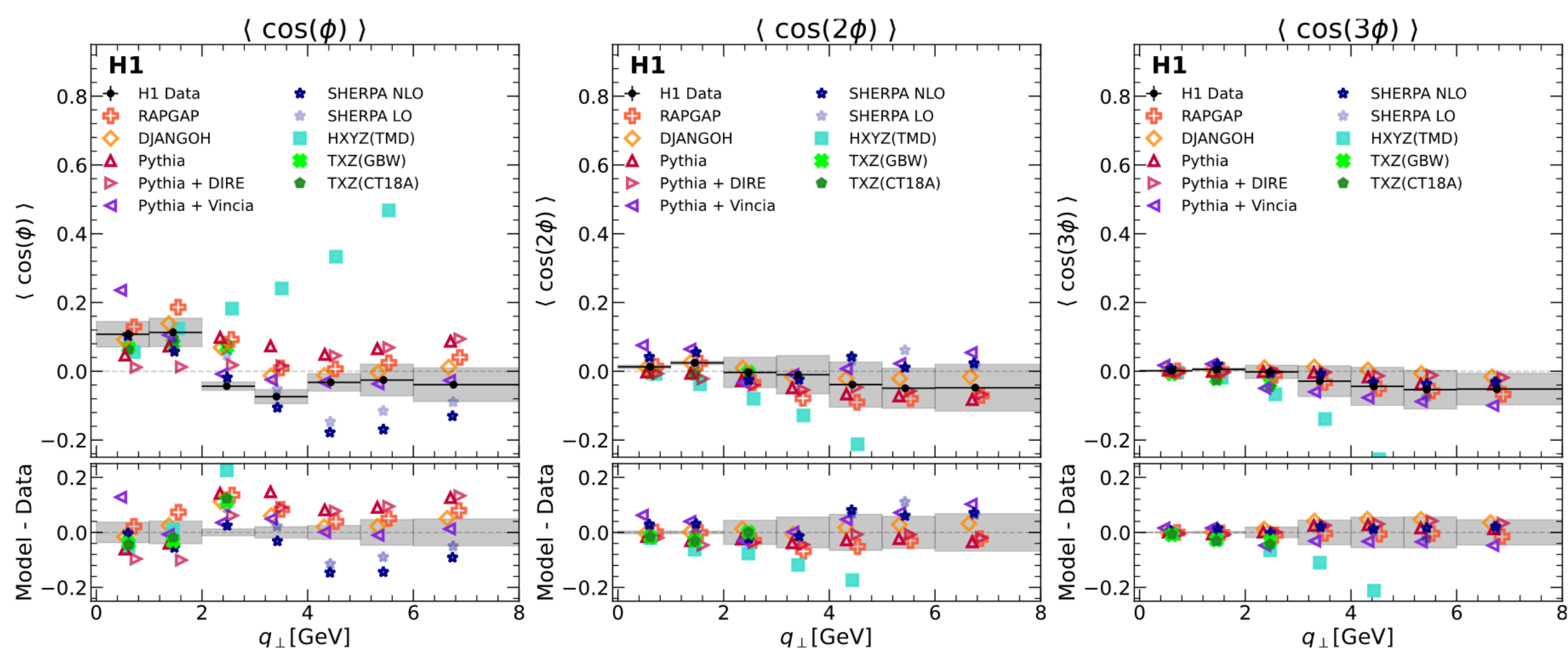
$\mu_R = \mu_F = m_{jj}$
 $\alpha_s(m_Z) = 0.118$

pQCD
 $\otimes \text{EW} \otimes \text{NPC}$

	χ^2/ndf				
	CT18NNLO	NNPDF3.1NNLO	NNPDF4.0NNLO	MSHT2020NNLO	ATLASpdf21T3
$y^* < 0.5$	58/58	68/58	59/58	61/58	58/58
$0.5 \leq y^* < 1.0$	62/54	70/54	63/54	67/54	59/54
$1.0 \leq y^* < 1.5$	56/45	67/45	63/45	65/45	58/45
$1.5 \leq y^* < 2.0$	51/36	59/36	57/36	54/36	63/36
$2.0 \leq y^* < 2.5$	30/28	41/28	36/28	34/28	39/28
$2.5 \leq y^* < 3.0$	17/16	21/16	17/16	21/16	19/16
$0.0 \leq y^* < 3.0$	329/237	343/237	342/237	347/237	288/237

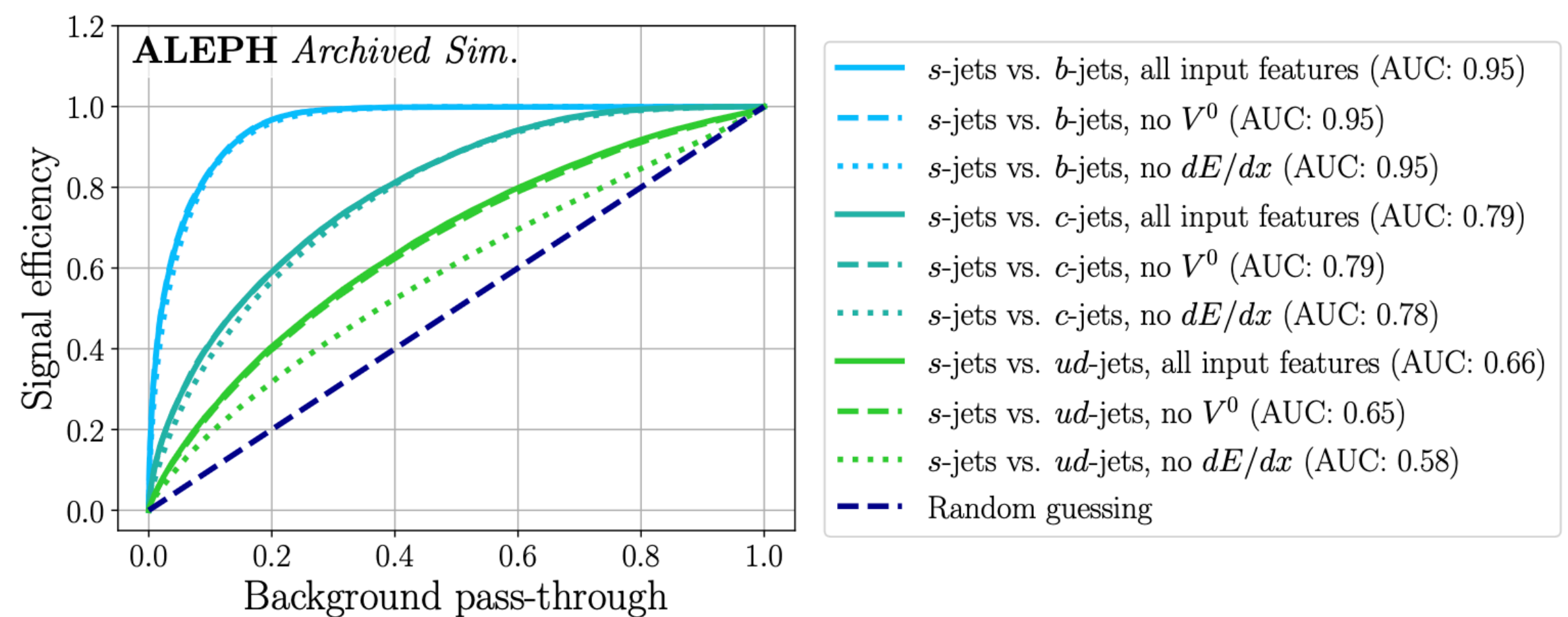
Using everything we've got

- Growing interest in using archival datasets for analysis.
- Enabling new comparisons between theory and measurement
See [Yi Chen's talk](#) on recent highlights with LEP data, today at 16h40!
- Proof-of-Concept studies to prepare for future colliders
[2412.14092](#) *H1 studies in prep for EIC*
[2603.06524](#) *Modern flavor tagging @ALEPH*



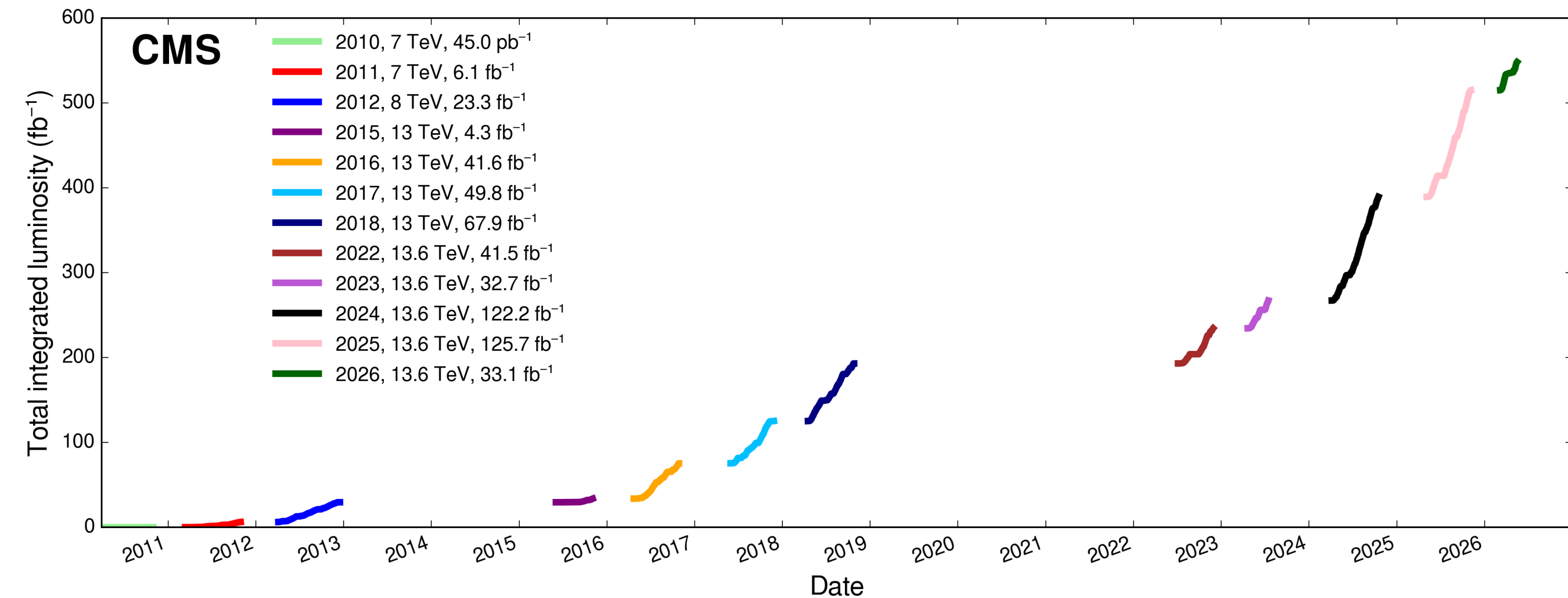
Measurements of azimuthal angular lepton-jet asymmetries at H1, improving understanding backgrounds for proton structure measurements at HERA & future EIC!

Study of modern flavor-tagging algorithms in archival ALEPH data to understand strange tagging prospects at FCC-ee!



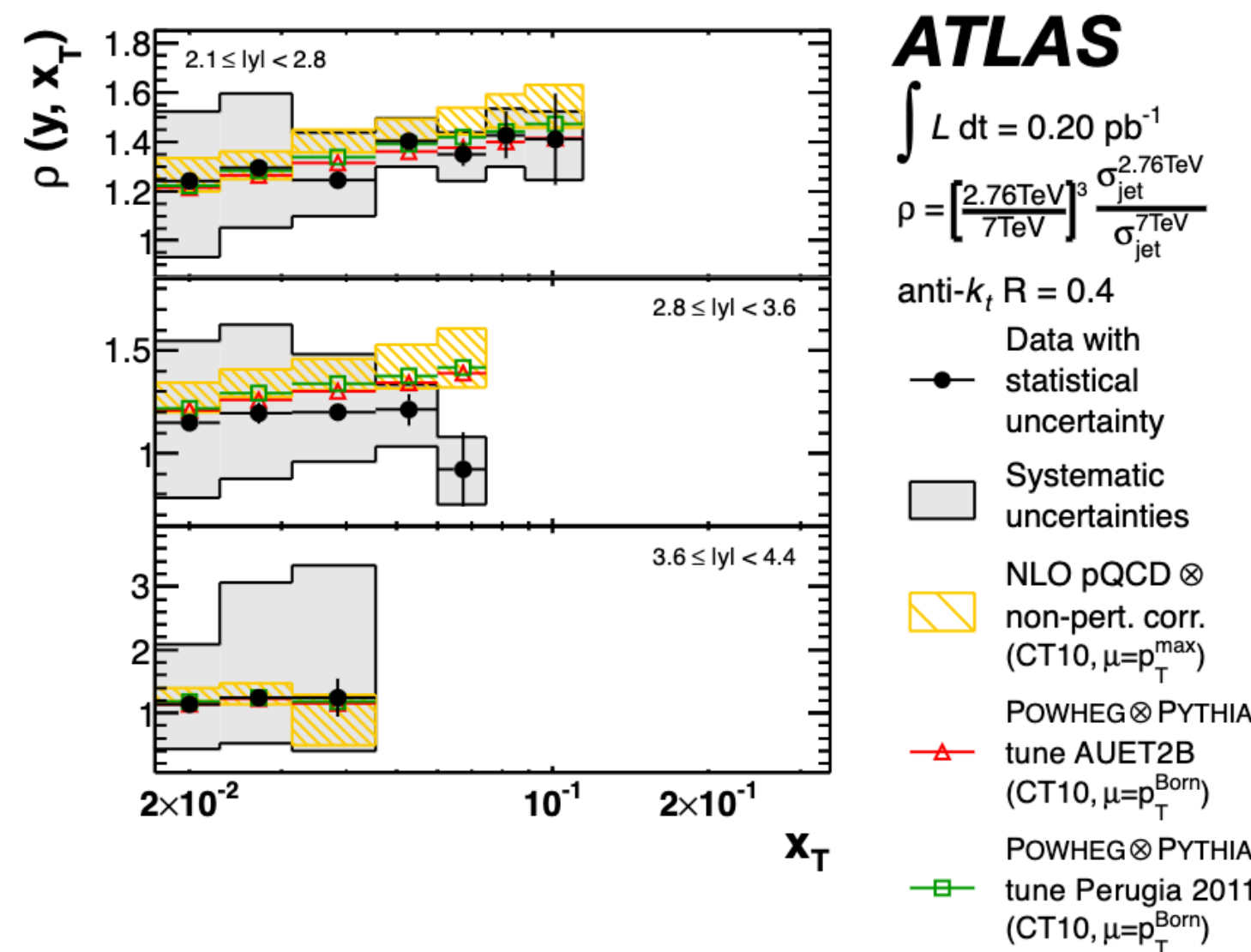
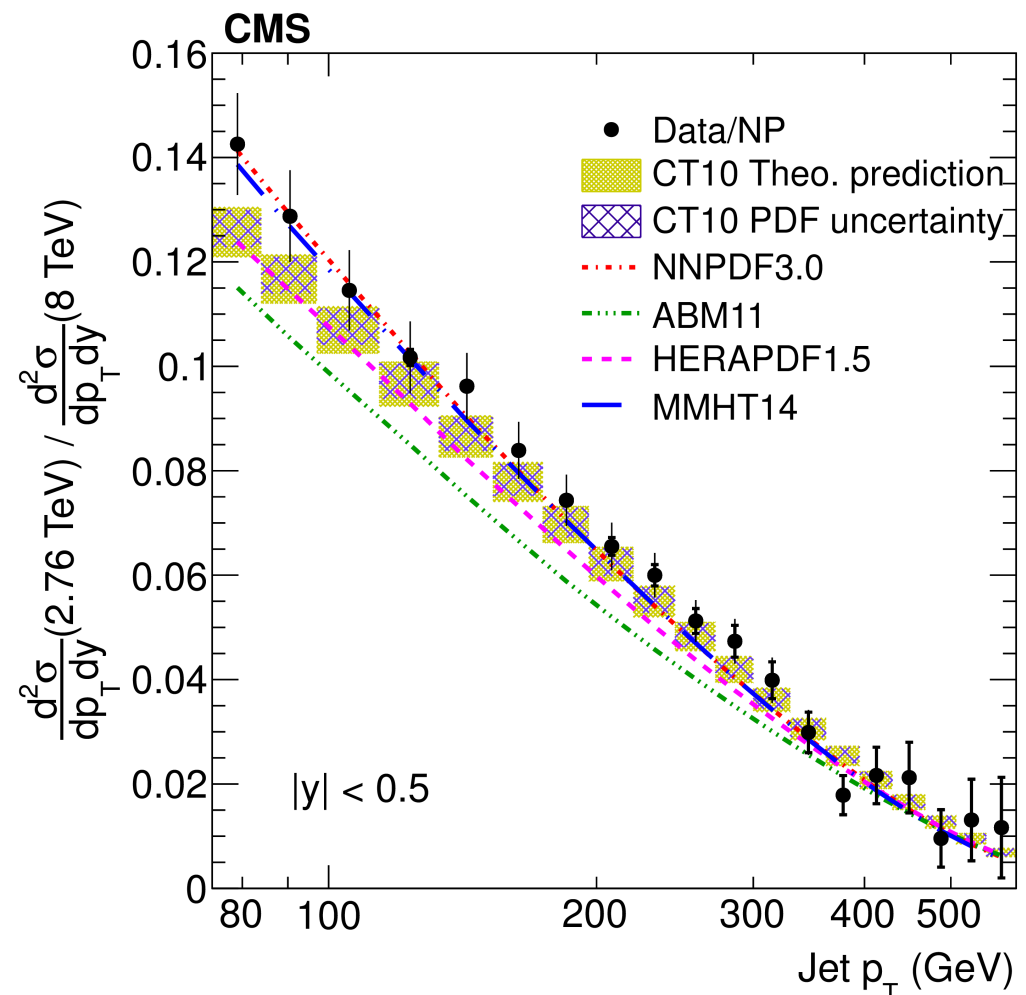
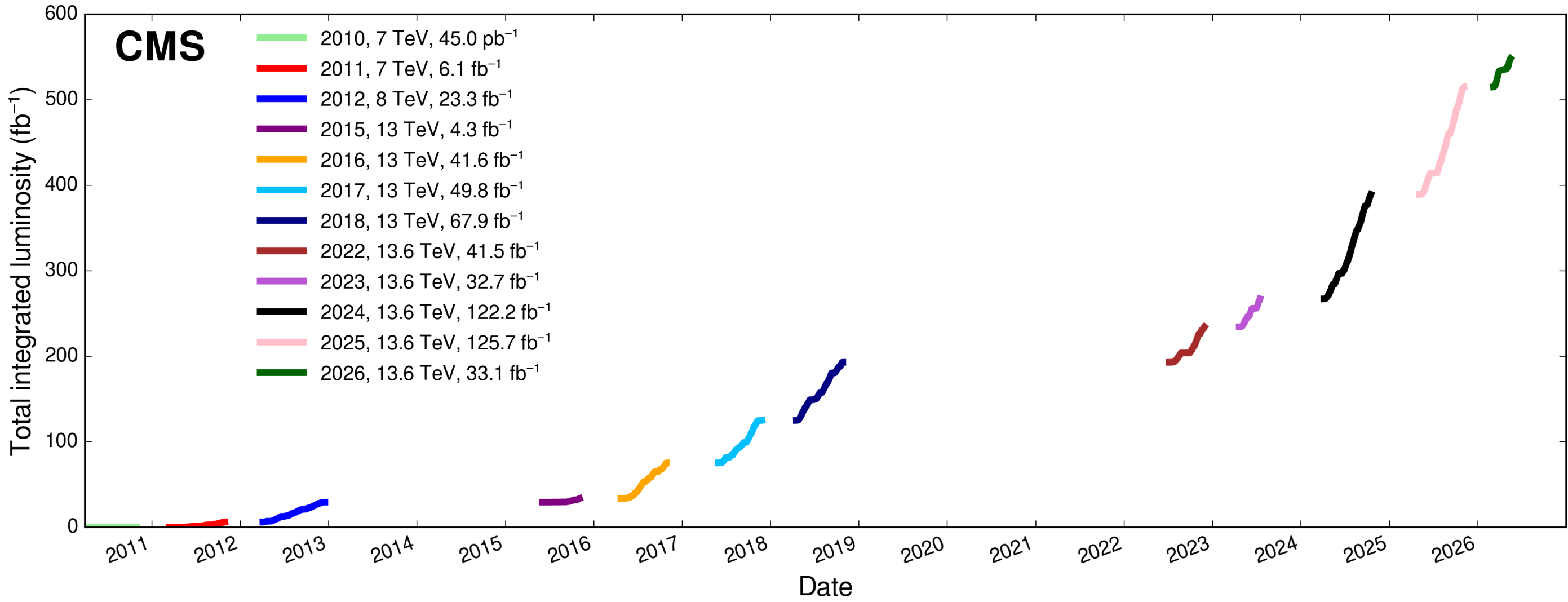
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- The LHC has also collected many distinct datasets so-far: are they forgotten as time passes, or is 'more different' when it comes to data?



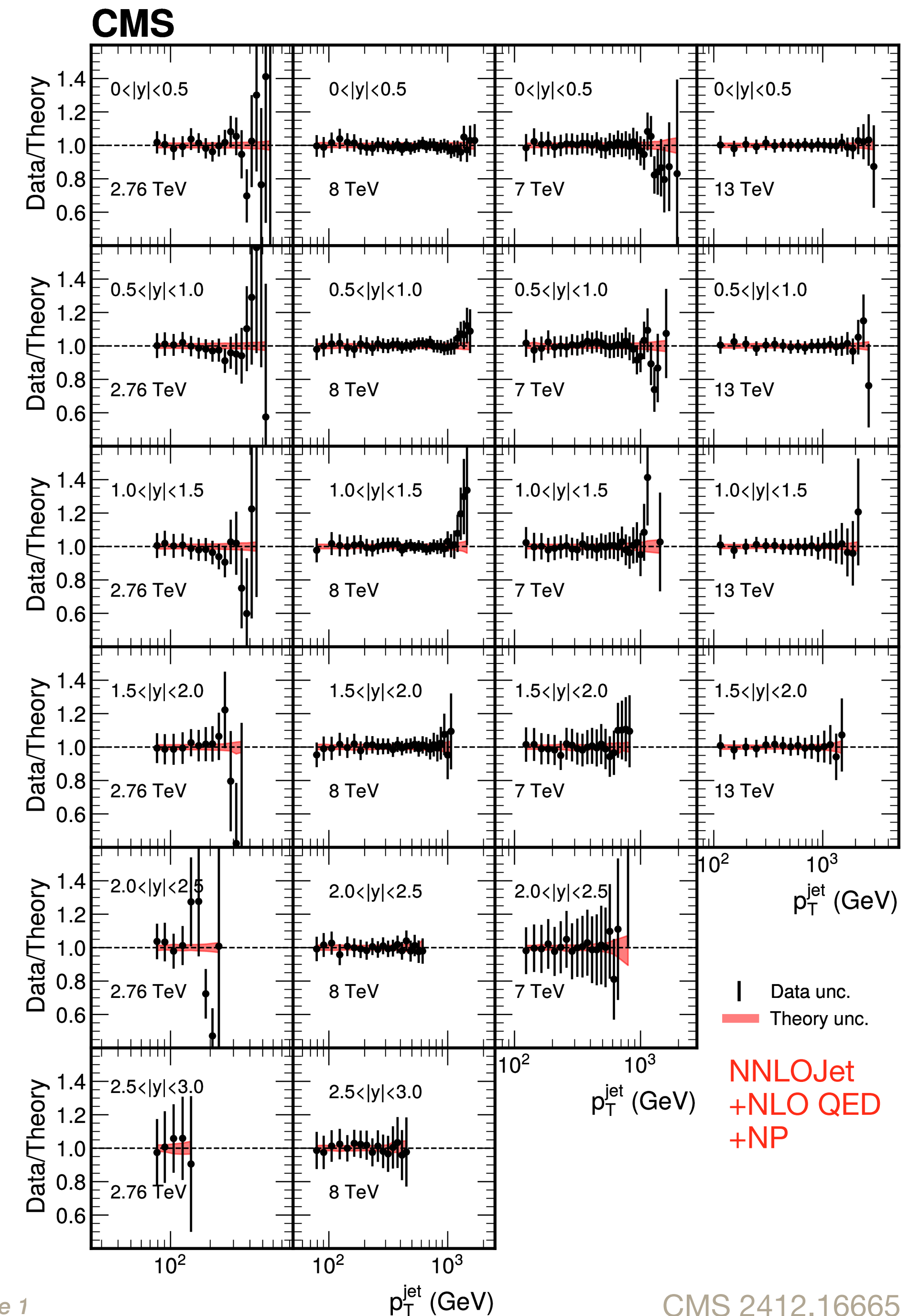
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- Ratios of jet cross sections have previously been used in PDF fits (2.76 TeV / 7 TeV).



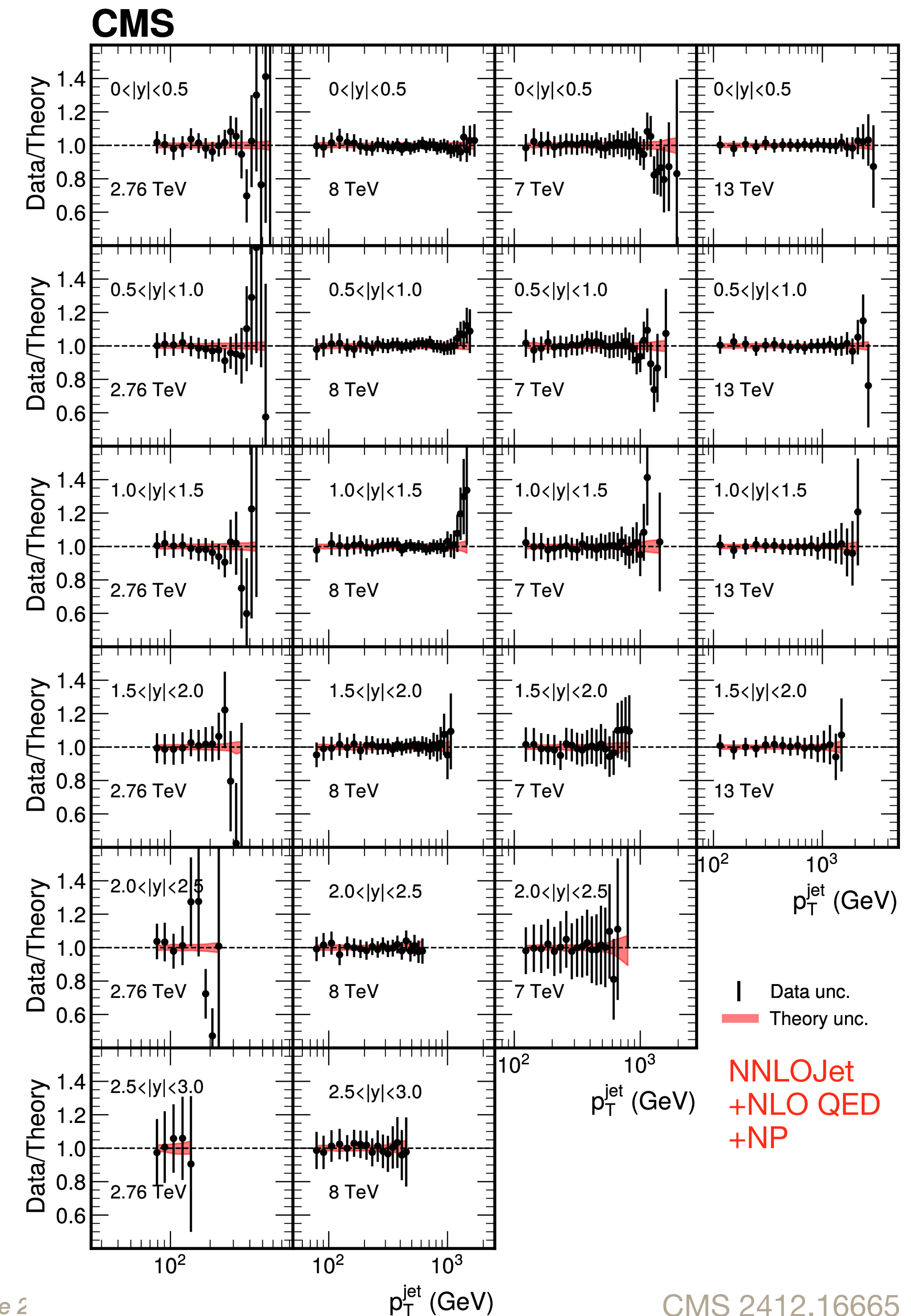
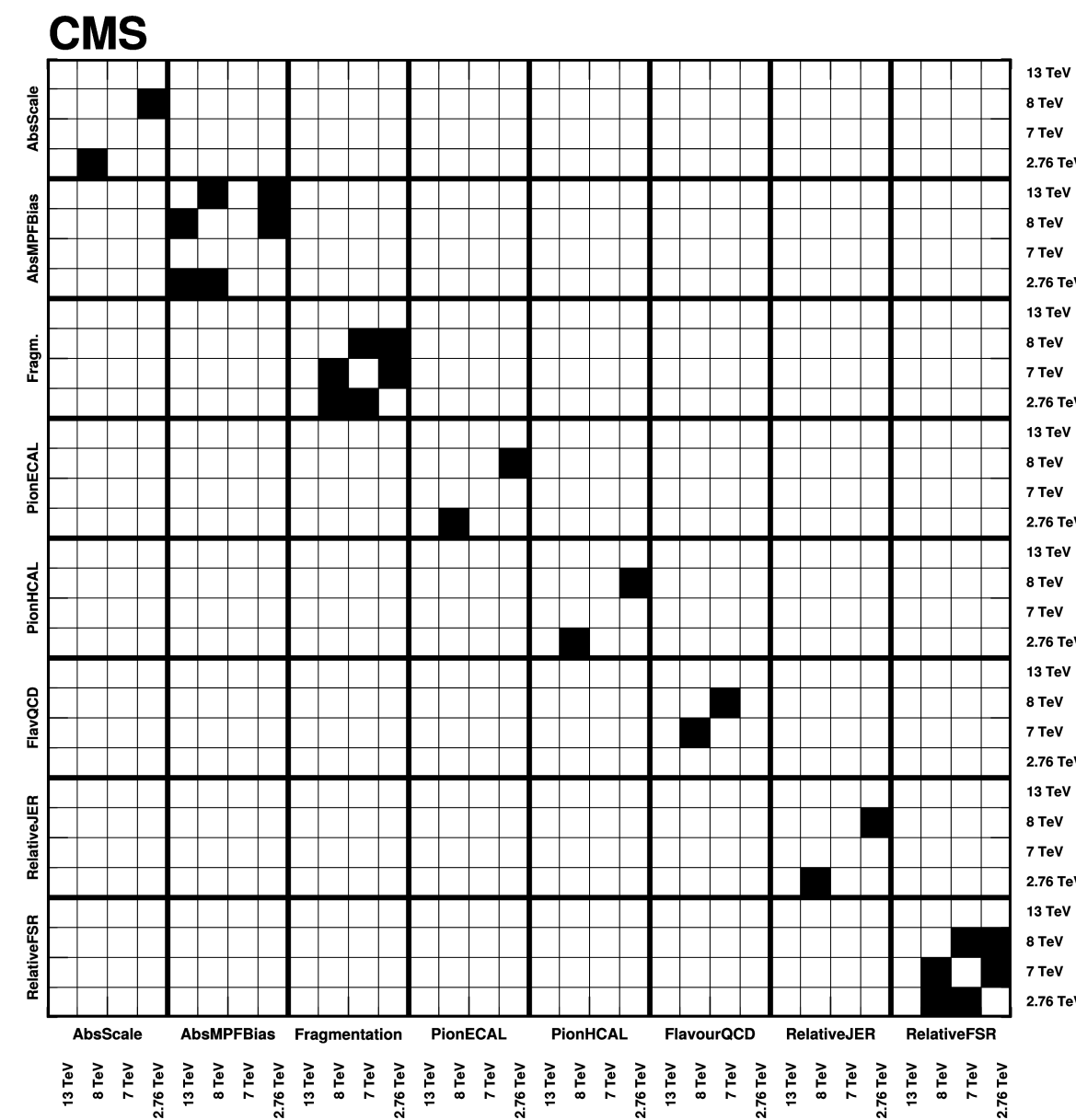
CMS incl. jets combination

- Four double-differential inclusive jet cross-section measurements performed for direct comparison and simultaneous study.
 - $\sqrt{s} = 2.76 \text{ TeV}, 7 \text{ TeV}, 8 \text{ TeV}, 13 \text{ TeV}$
- Unfolded cross-sections in different data sets compared to **NNLOJet** fixed-order theory predictions
 - Small subleading colour contributions
 - Electroweak corrections @ NLO, up to 11% in forward region
 - Non-perturbative QCD corrections 5~20%, ~4% unc.

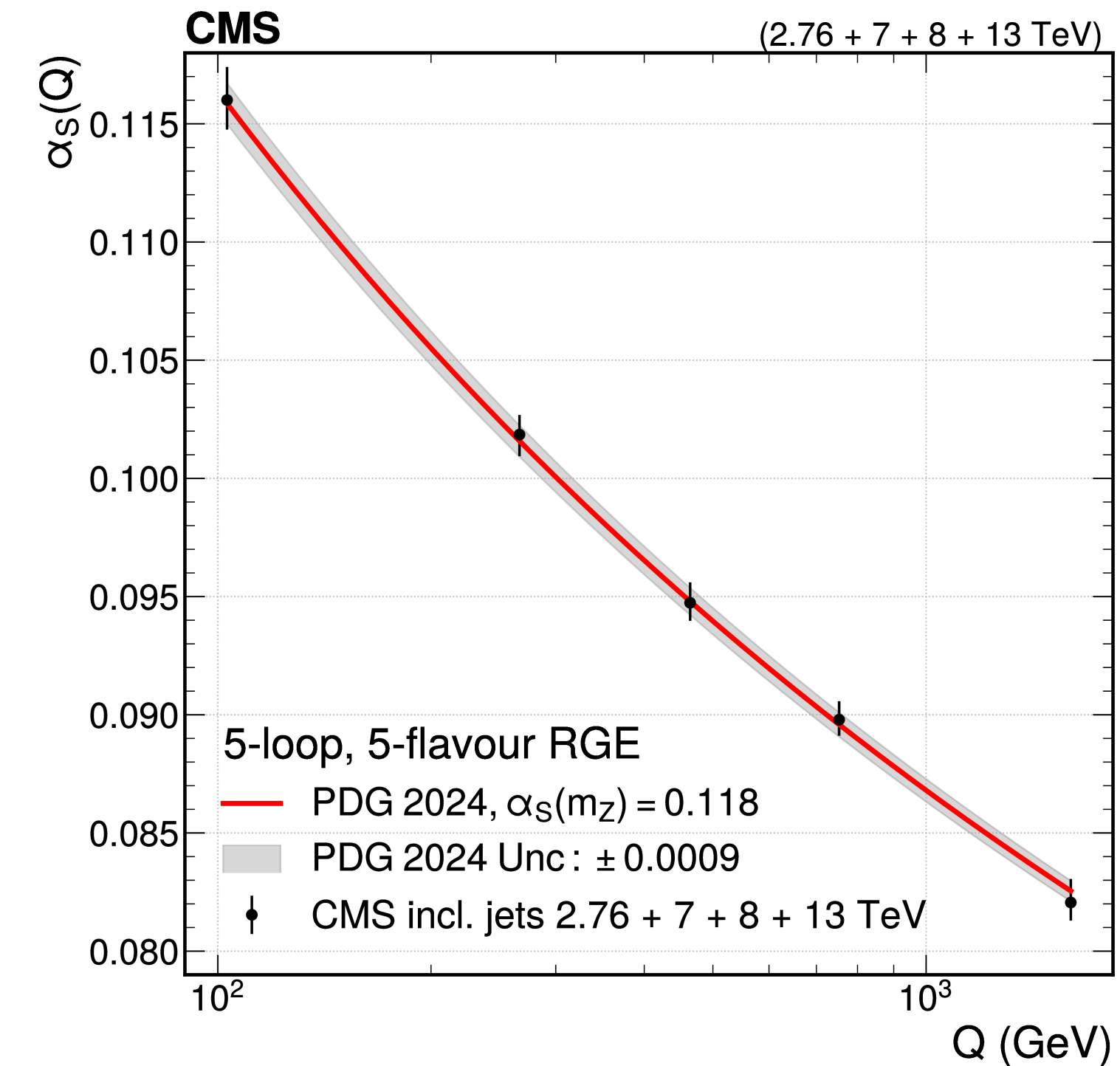
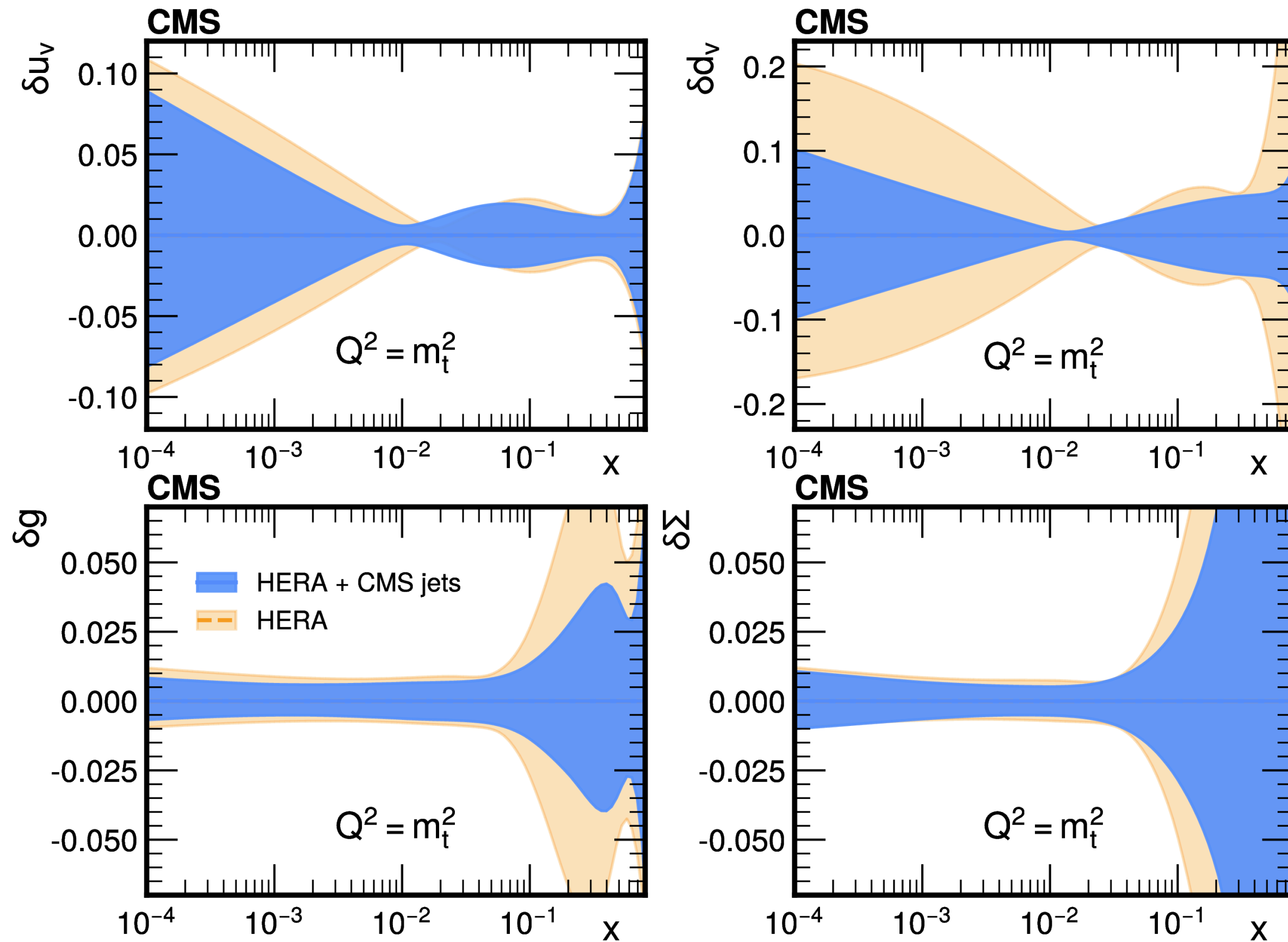


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 - All measurements use $R=0.7$ jets and track jet energy correction nuisance parameters.
 - PDF fits are sensitive to the treatment of such correlations! [ATLAS 2112.11266](#)
- Amanda Sarkar Monday 11h10



CMS incl. jets QCD analysis



$$\alpha_s(m_Z) = 0.1176^{+0.0009}_{-0.0009} (\text{fit})^{+0.0006}_{-0.0004} (\text{model})^{+0.0009}_{-0.0012} (\text{scale})^{+0.}_{-0.0001} (\text{param.})$$

- **Simultaneous extraction of PDFs and strong coupling at NNLO**, from HERA+CMS data.
 - Constraints on high- x gluon and d_v PDFs improved by CMS jet data.
- **Most precise determination of the strong coupling from jet data to-date**; good agreement with the PDG world average.
- **Running of strong coupling tested across $Q = 100 \text{ GeV} - 1.6 \text{ TeV}$ from a single analysis!** Agrees w/ QCD RGE.

1. Experiment rises to meet NNLO theory

2. Massive implications

3. High-Luminosity QCD

Flavour fragmentation

- Heavy-flavour fragmentation is central to much of the LHC physics program.
- QCD
- Higgs measurements
- Top measurements
- BSM
- Related uncertainties limit our precision!
- Modern flavor taggers exploit jet substructure / fragmentation more than displaced vertices, etc.
- The best pizza is made with the best ingredients. 🍕

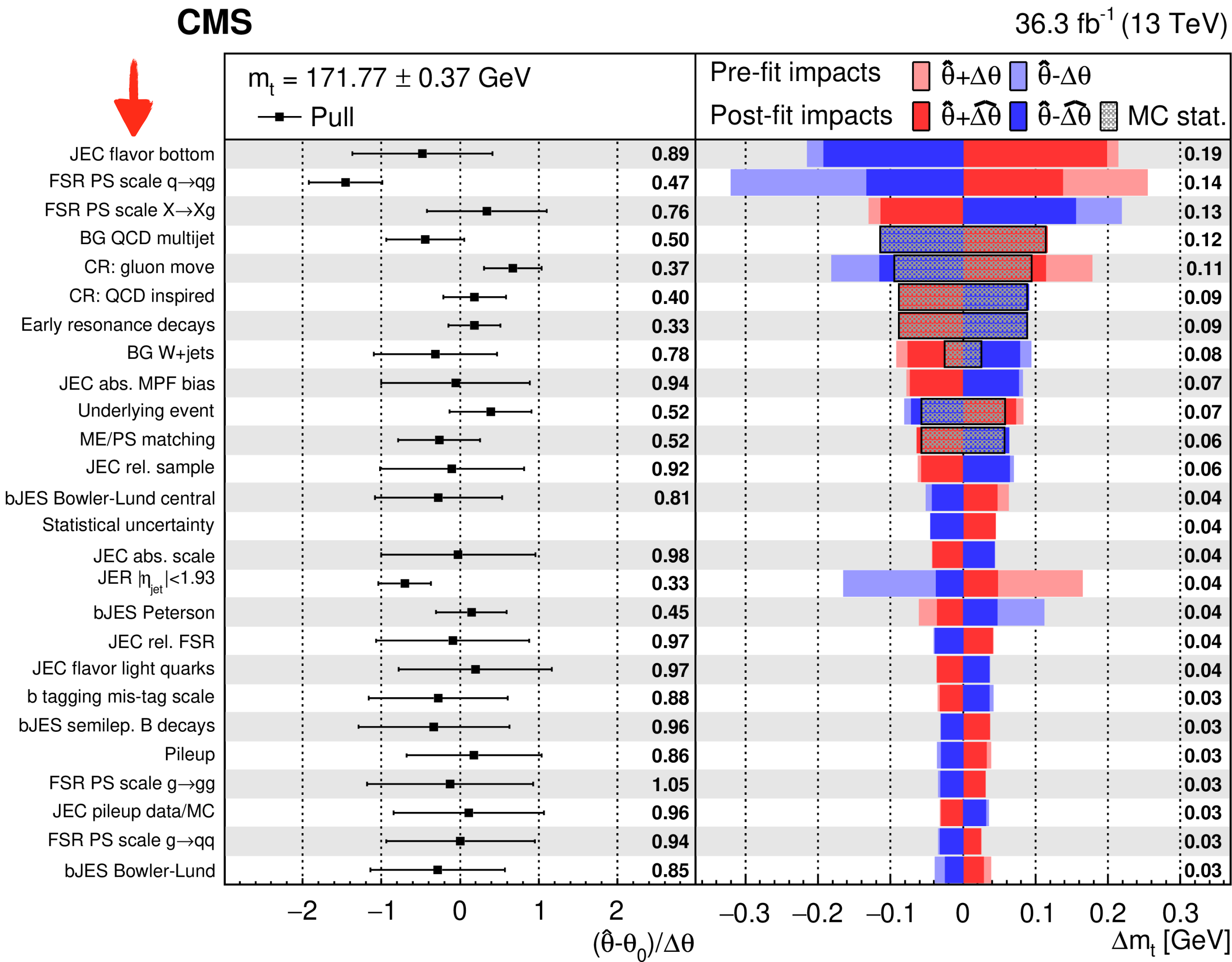
and are dominated by the uncertainties of the $t\bar{t}$ + jets background modelling. Experimental uncertainties amount to ± 0.10 , dominated by the jet energy scale and resolution as well as b tagging related uncertainties. Systematic uncertainties due to the size of the various simulated

CMS $HH \rightarrow b\bar{b}\tau\tau$ [*]

the main sources of uncertainty in the signal yield are evaluated for various hypothesised signals. The dominant systematic uncertainty stems from the double b -tagging algorithm (20–30%). It is derived in

ATLAS $HH \rightarrow b\bar{b}b\bar{b}$ [*]

m_t with profile likelihood (CMS)



Perturbative mass effects: the Dead Cone

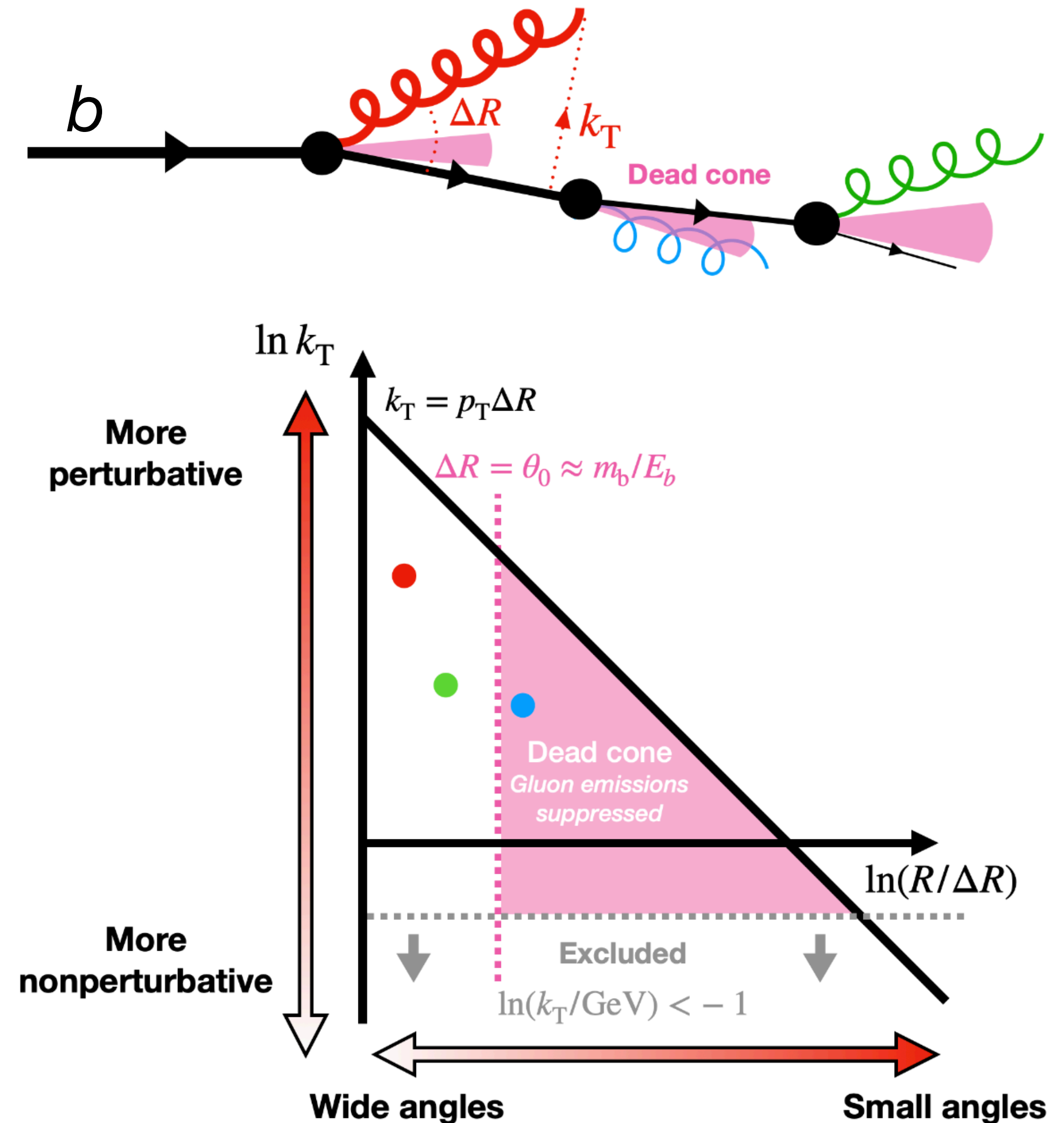
- Precise modelling of heavy quark mass effects is essential to obtain an accurate description of QCD, and for processes involving b-quarks (Higgs, top, BSM).
- LO probability for collinear gluon emission from a massive quark radiator:

$$P = \theta^2 d\theta^2 / [\theta^2 + (m_q / E_q)^2]^2$$

Dead-Cone Effect:

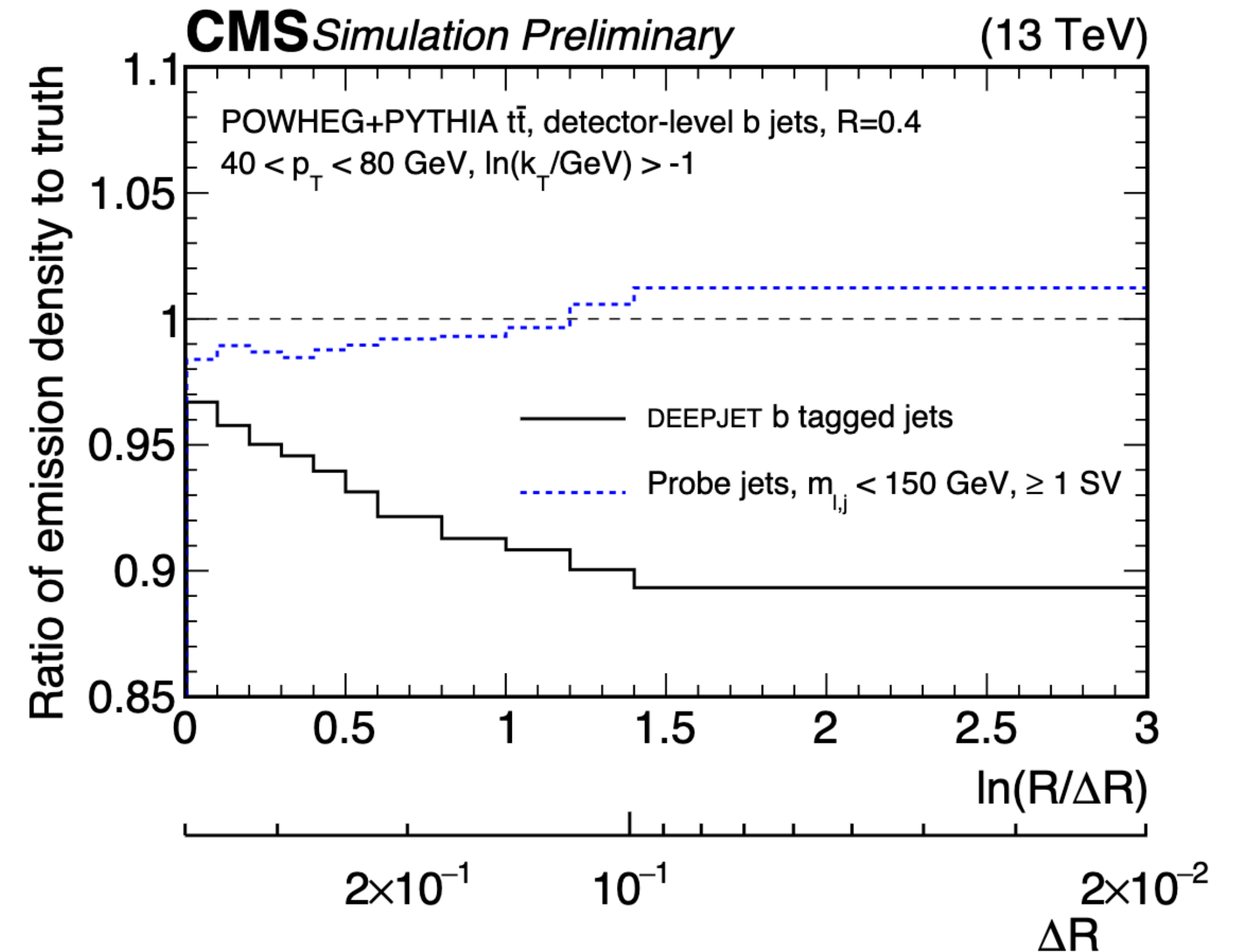
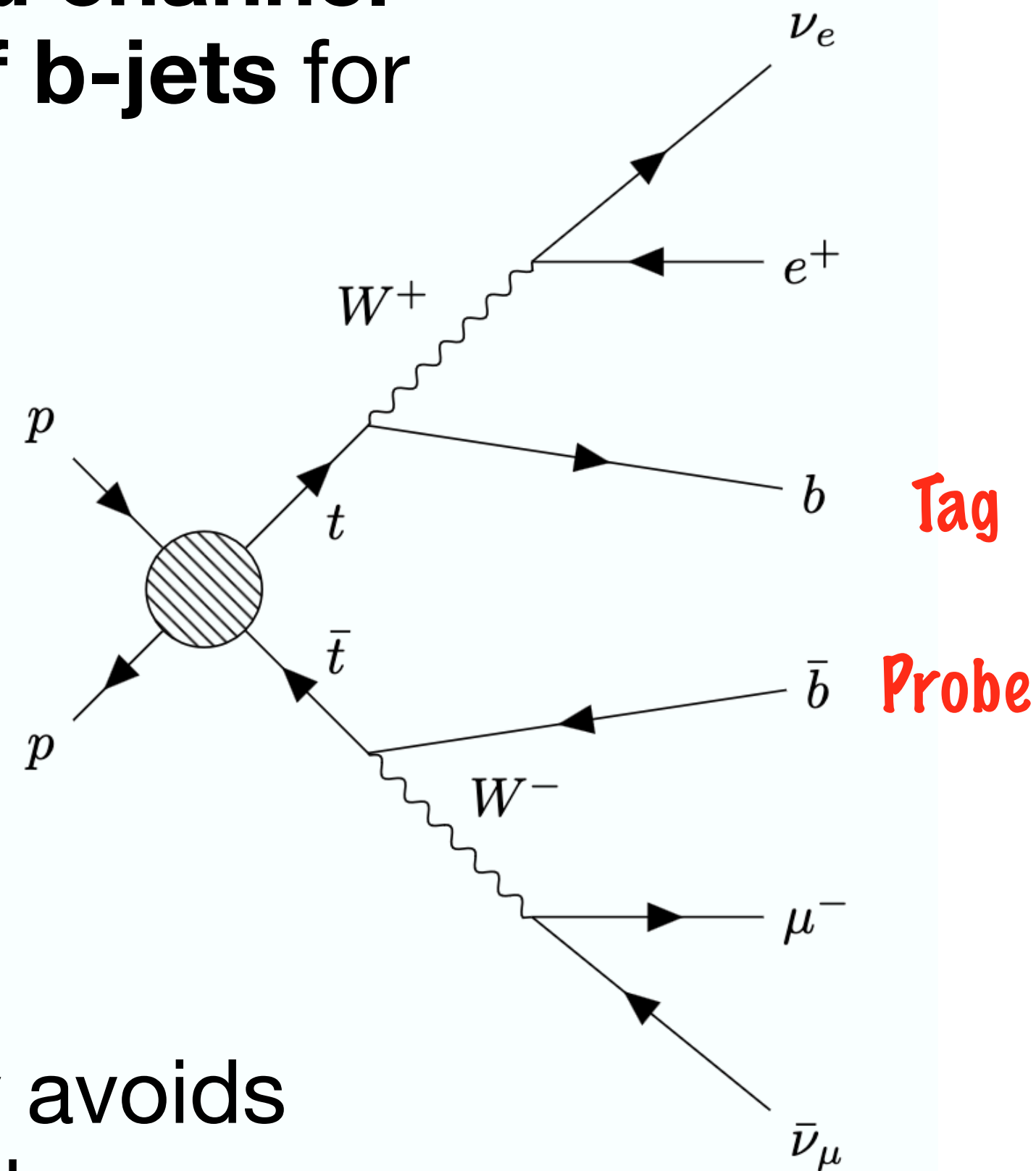
Radiation suppressed for $\theta_0 = m_q / E_q$

- Lund jet plane picture of JSS: iteratively decluster jet constituents with C/A and study splittings.
 - QCD radiation obeys angular ordering.
 - ... but the B-hadron decay products don't!



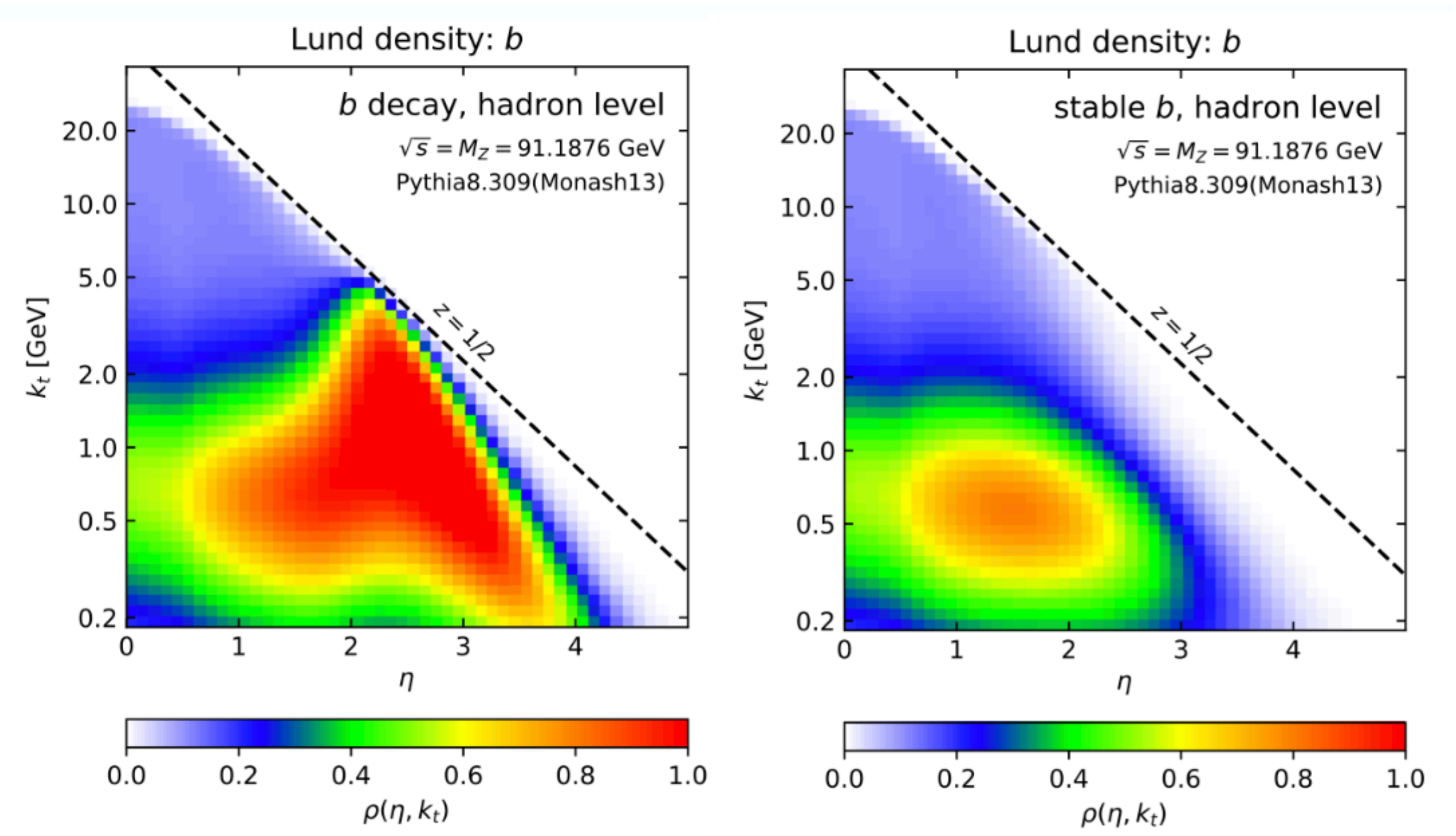
$t\bar{t}$ tag & probe

- Dileptonic $t\bar{t}$ events selected with **lepton triggers in e- μ channel** gives **pure sample of b-jets** for measurement.
- Dead cone is most pronounced at low energies**, so this sample is well-suited.
- Tag & Probe** strategy avoids b-tagging requirement on measured jets, **avoiding bias & associated systematics**.



B-hadron reconstruction

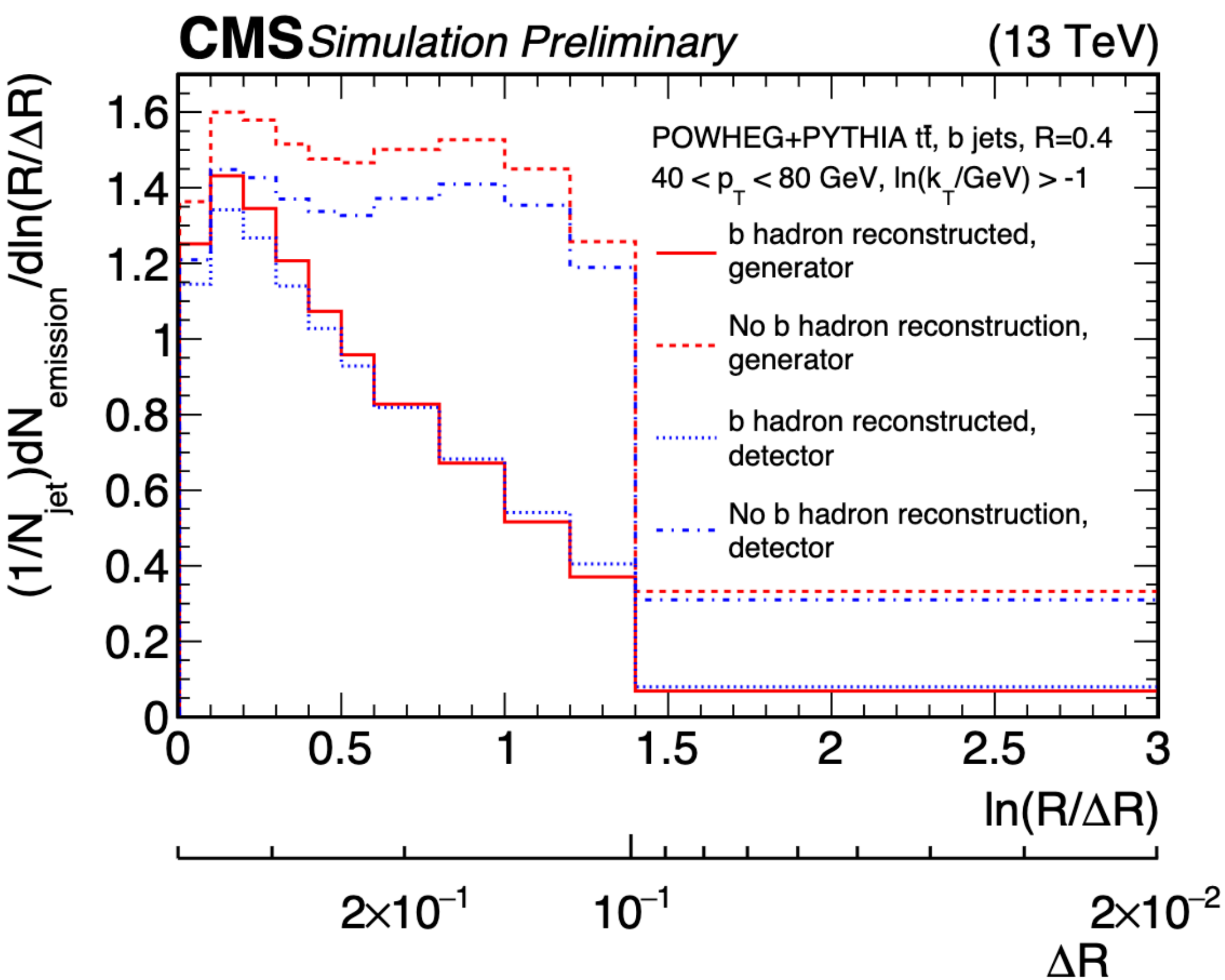
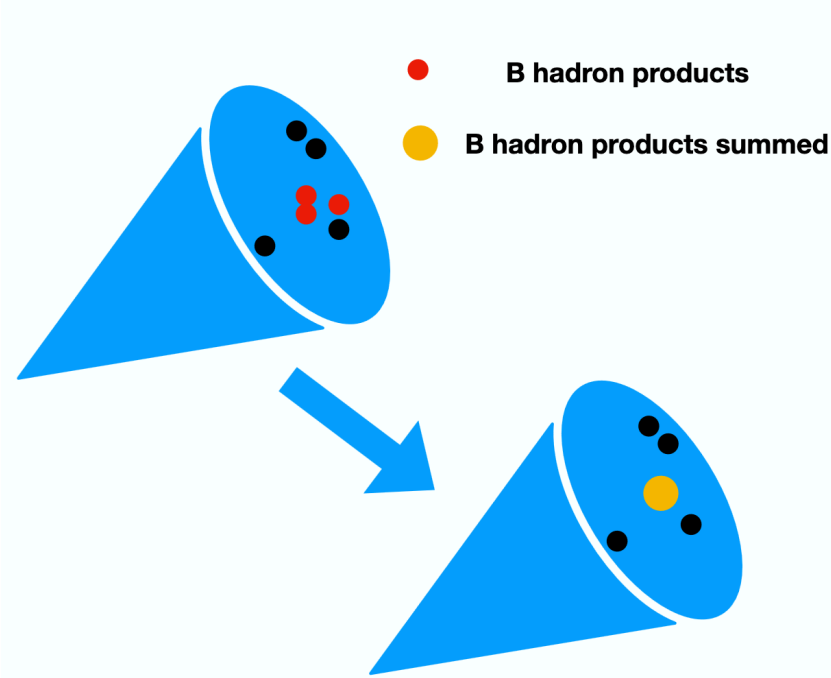
- **B-hadron decays do not follow QCD angle-ordering**, spoiling LJP reconstruction.



LJP with (left) or without (right) B decays [*]

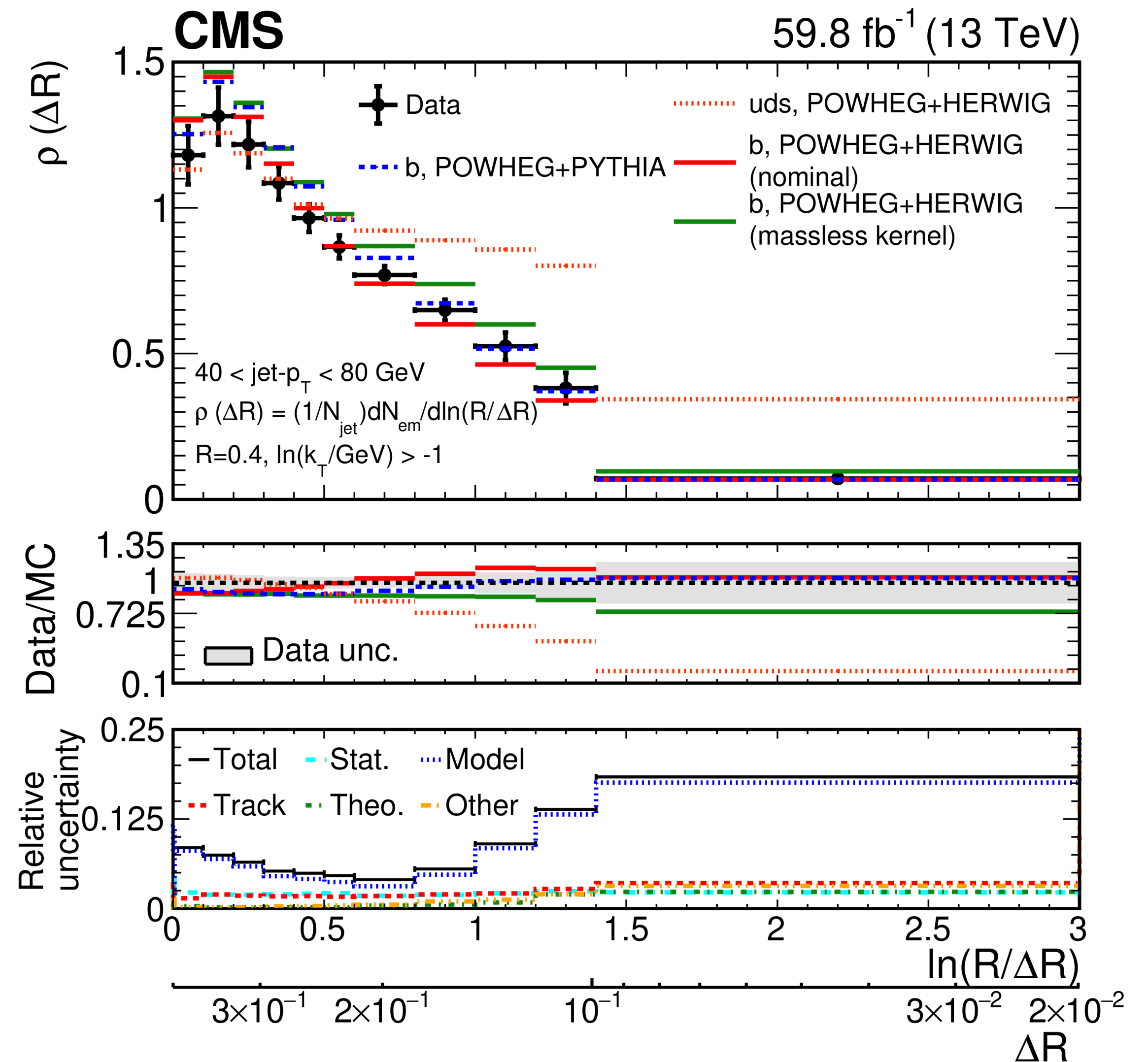
Figures from [Lida Kalipoliti @ BOOST 2024](#)

- **Transformer Encoder (TFE)** identifies B-hadron decays based on **jet, tracking & SV** info.
- Significantly improves measurement resolution!



Evidence for the Dead Cone in b-jets

- Nominal Pythia prediction **overestimates** the measured cross-section in the **wide-angled** region.
- Nominal Herwig **underestimates** emissions in the **intermediate region**.
- Two massless references, **light jet** and **b-jet massless kernel**, overestimate the measured cross-section.
- b-jet fragmentation modified by more than just dead cone effect: **npQCD** and **kinematic** effects can complicate interpretation vs. light jets.
- Massless kernel** obtained by setting the b-quark mass to 0 during Herwig parton shower, then bringing them back on-shell by momentum shuffling between color-connected partons.
- Data strongly prefer predictions with dead cone** (4.3σ)



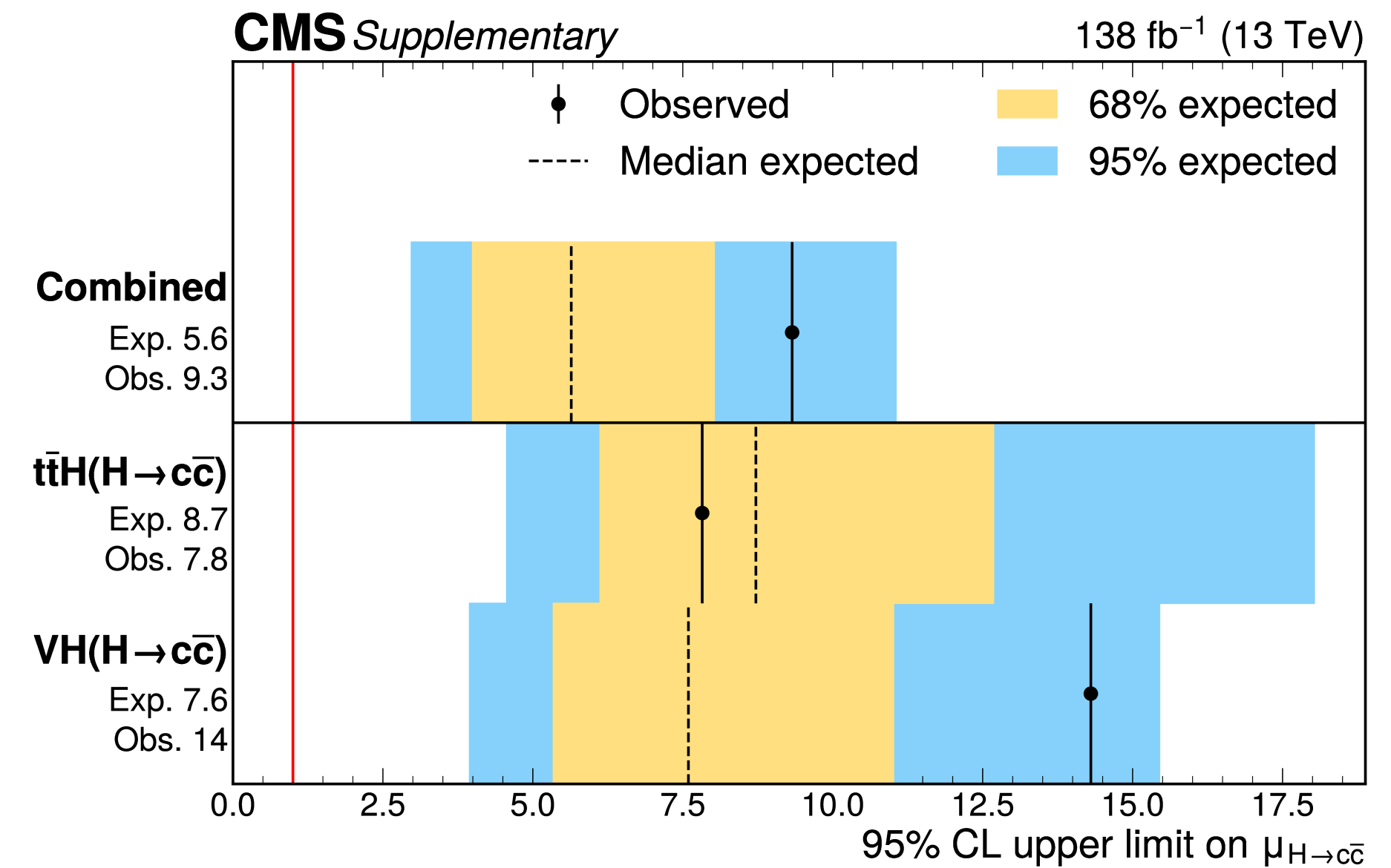
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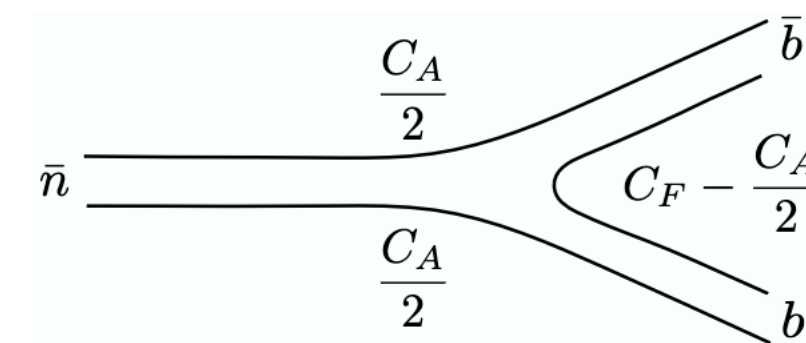
3. High-Luminosity QCD

What can we expect at the HL-LHC?

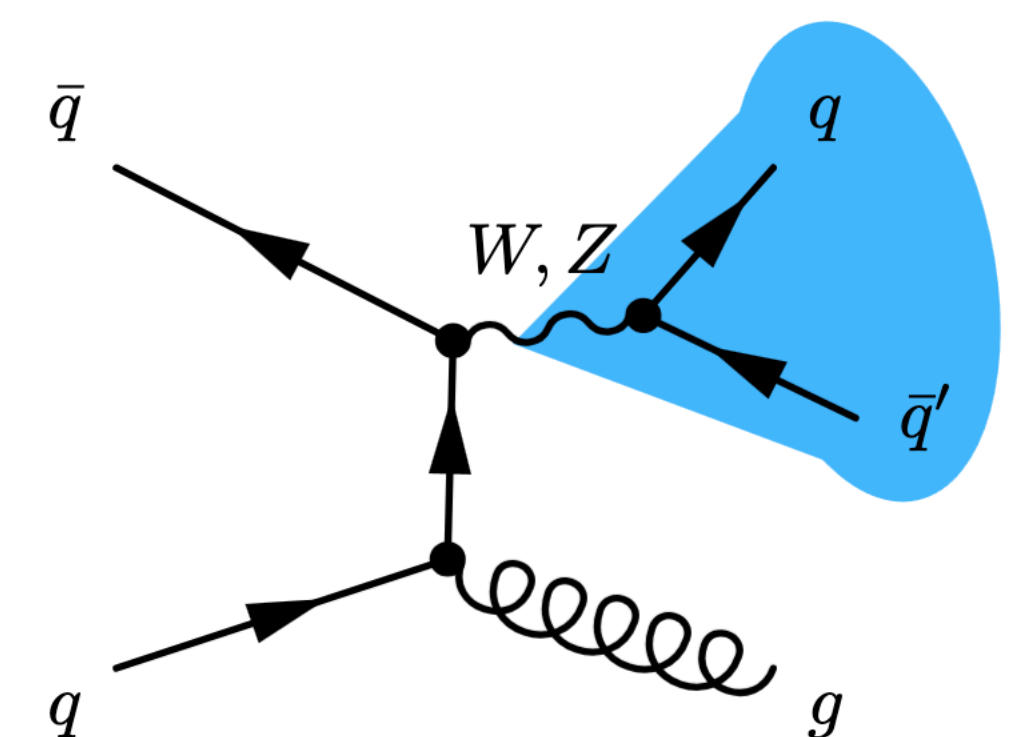
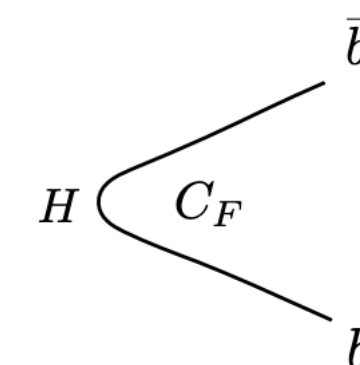
- $H \rightarrow b\bar{b}$ has been called the ‘holy grail’ of jet substructure, $H \rightarrow c\bar{c}$ once thought impossible.
- Heavily reliant on powerful, fully-supervised AI/ML tagging algorithms.
 - Calibrations for these taggers currently use $g \rightarrow b\bar{b}$, $g \rightarrow c\bar{c}$ proxies.
- Differences between color singlet radiation patterns are expected.
- Sophisticated AI/ML classifiers can potentially tell the difference.
- Can we instead study color singlets?
 - One approach will be to study bosons recoiling against another object (gluon or photon)



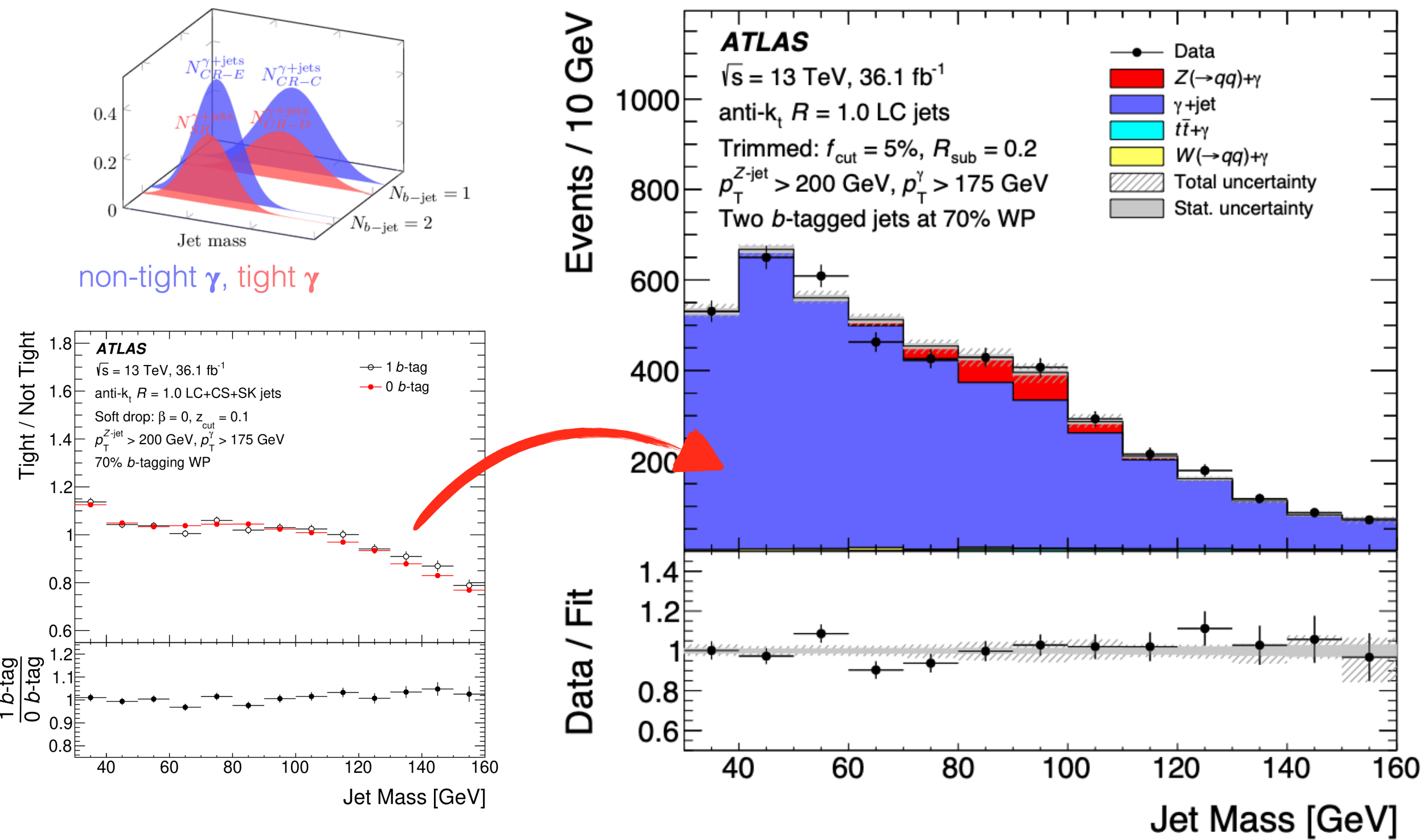
Octet



Singlet

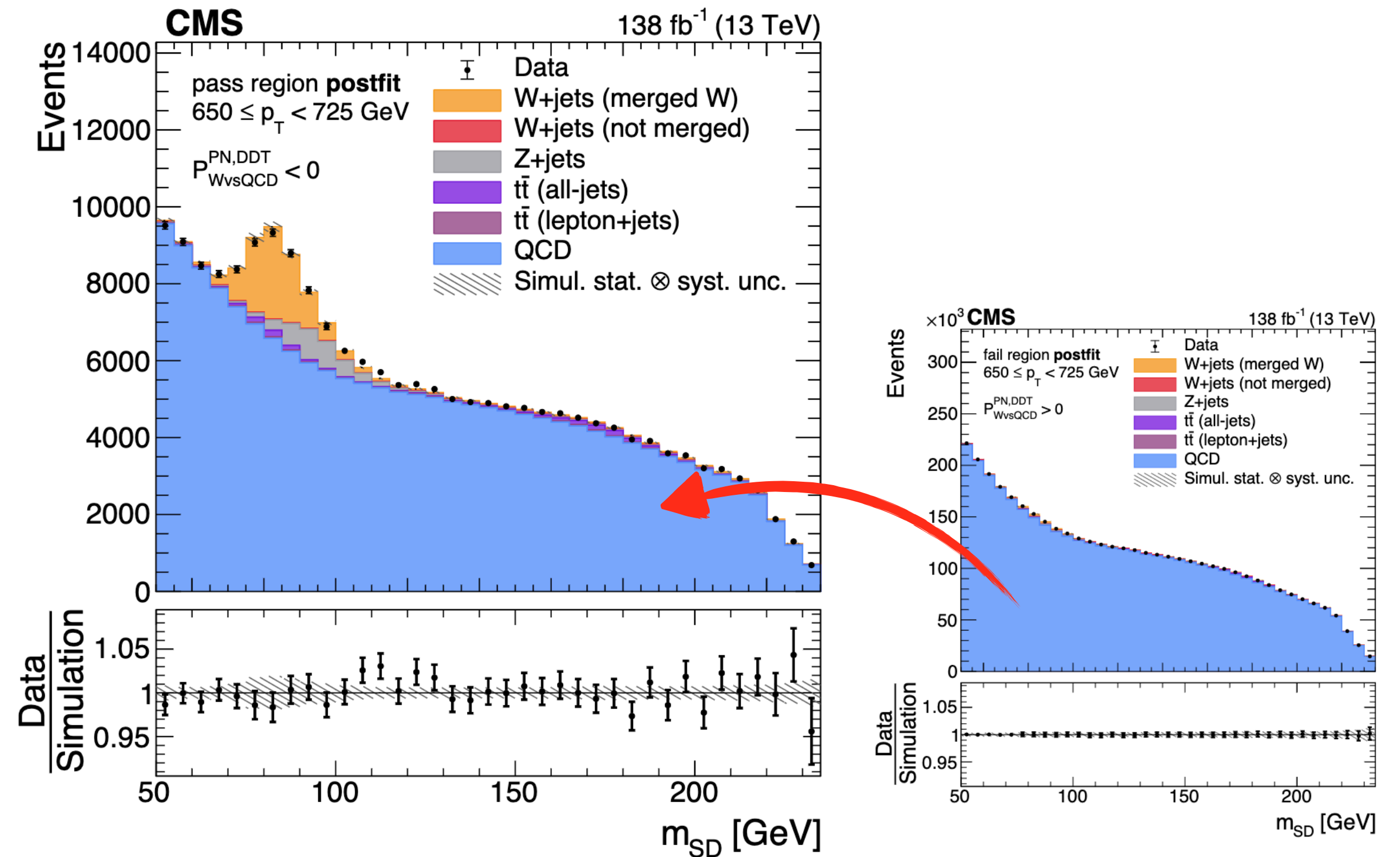


Recoiling bosons



Control

Signal

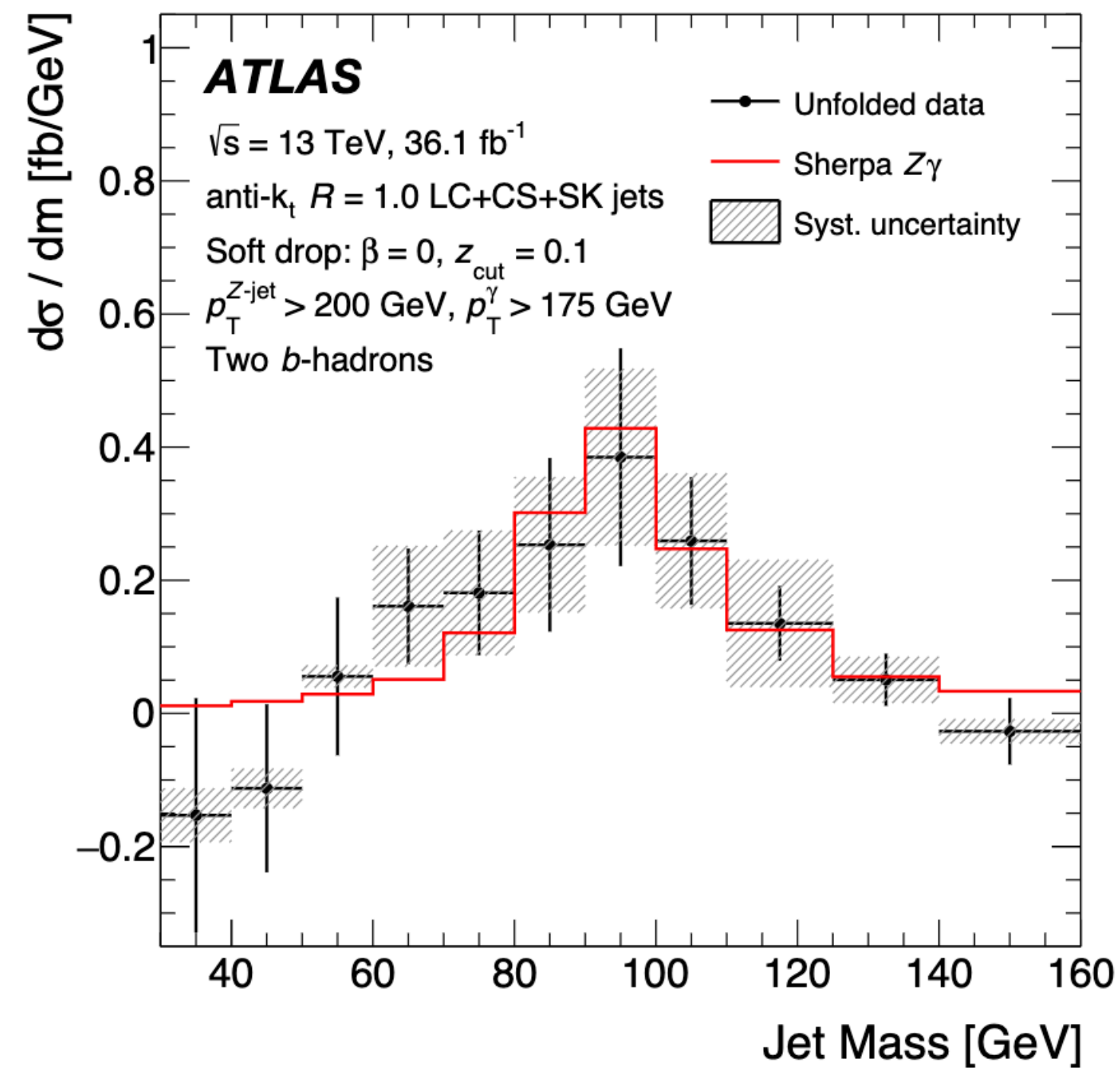


Signal

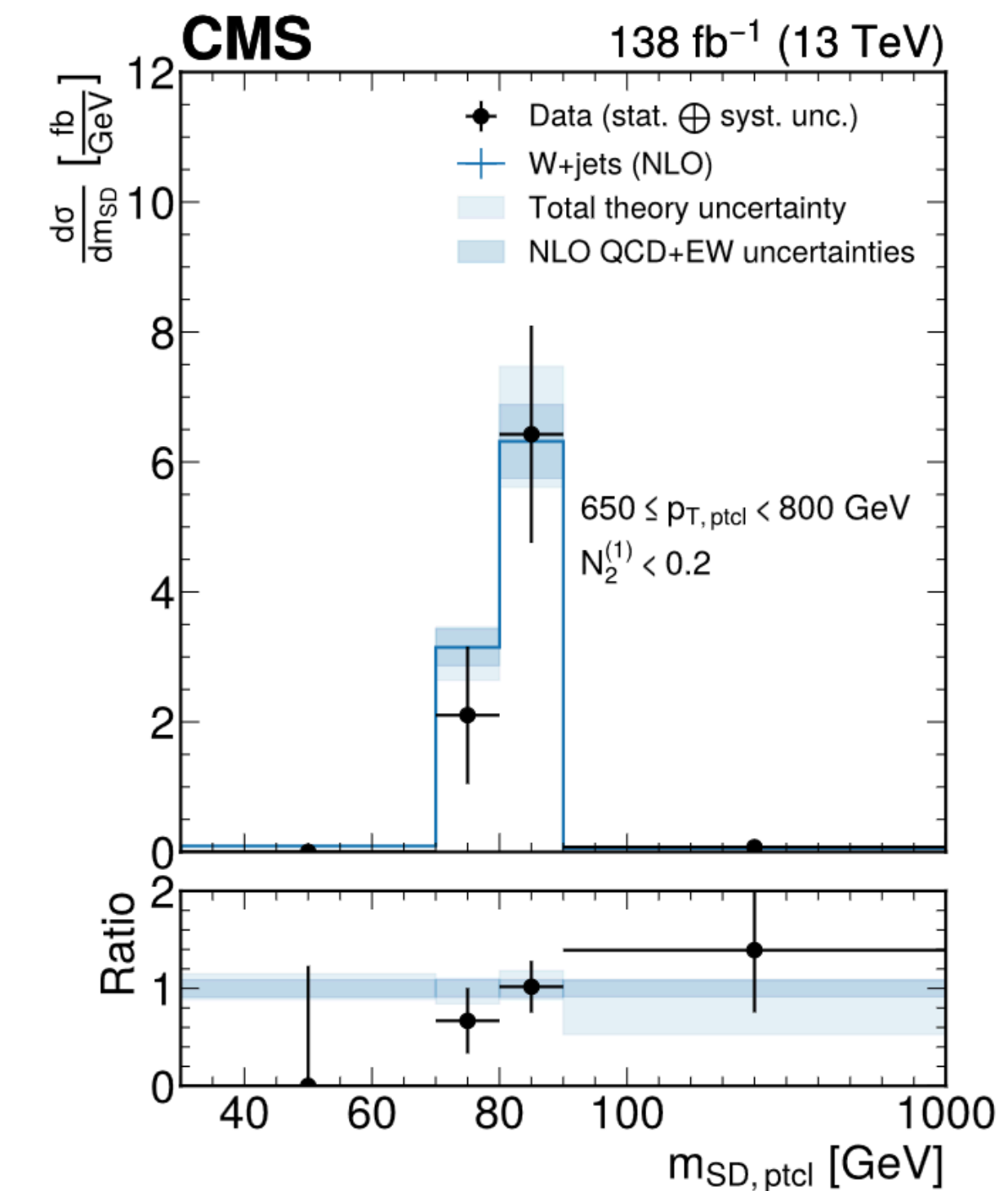
Control

- Measurements with large backgrounds, but recoil-based approach facilitates data-driven estimates.
- S+B template fits extrapolating across photon isolation & b -jet multiplicity, or in sidebands constructed using AI/ML decorrelation techniques.

Z(bb) & W(qq) jet mass lineshapes



$$\sigma_{Z(\rightarrow b\bar{b})\gamma}^{\text{soft drop}} = 12.5 \pm 4.9 \text{ (stat.)} \pm 3.1 \text{ (syst.) fb}$$



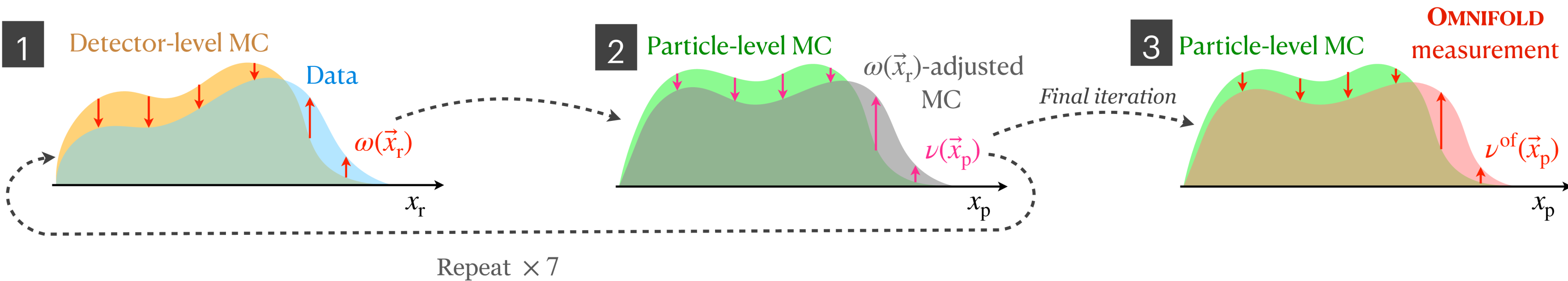
$$m_W = 80.85 \pm 0.55 \text{ GeV} \\ (0.36 \text{ stat.}, 0.44 \text{ syst.})$$

- Proof-of-concepts for probing heavy-flavour, colour-singlet physics.
- Such measurements have large uncertainties due to statistical & modelling effects, but will improve with time — watch this space in Run 4!

Going high-dimensional

- An increasing number of high-dimensional, unbinned measurements
- **Omnifold** technique utilizes AI/ML classifiers to learn the detector response & regularize unfolding
 - Classifier reweights particle-level MC to obtain measured distribution.
- Unbinned techniques could lead to significant improvements over current methods.
- *c.f.* Neural Simulation Based Inference (NSBI) improvements to Higgs width extraction.

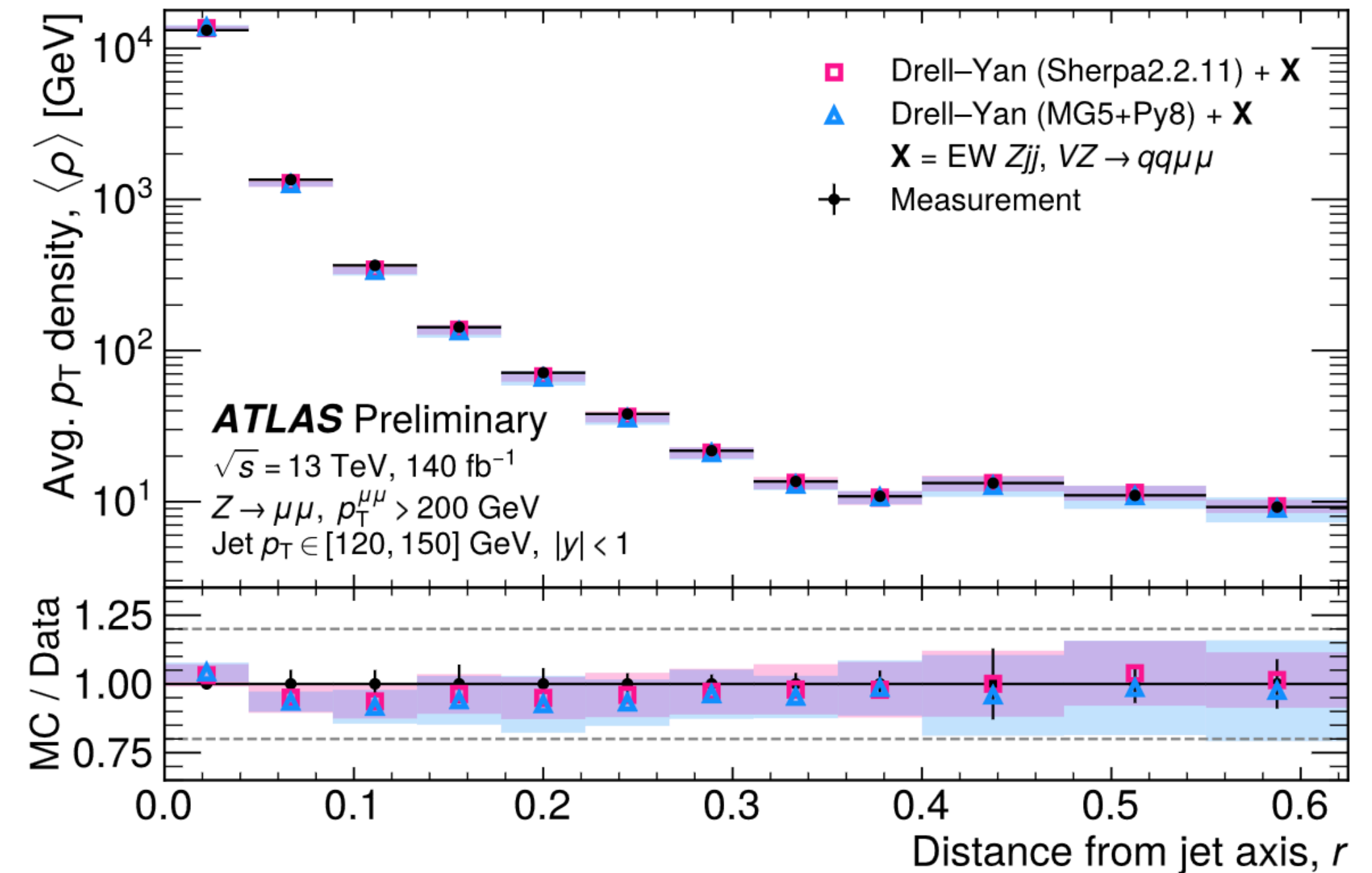
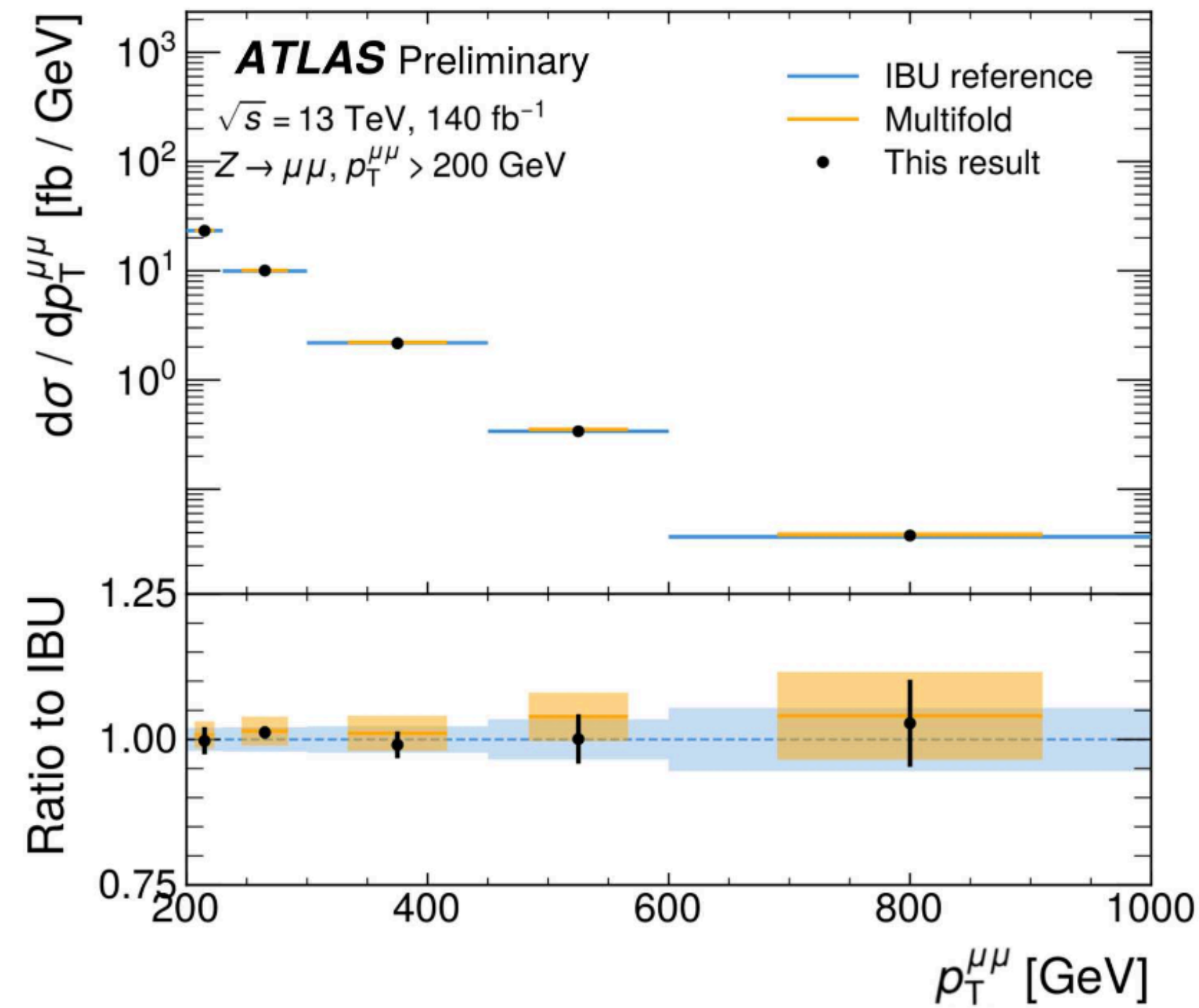
ATLAS [2412.01548](#)



Canelli et al. 2507.09582

Experiment	Paper Link	Dimensions	Final State	Momentum Selection
ATLAS [23]	2405.20041	24	Z+jets	$p_T^{\ell\ell} > 200 \text{ GeV}$
ATLAS [24]	2502.02062	6	Dijets	$p_T^{j1} > 240 \text{ GeV} \ \& \ p_T^{j1} < 1.5 \ p_T^{j2}$
CMS [25]	2505.17850	8	Minimum bias	$> 2 \text{ charged particles with } p_T > 0.5 \text{ GeV}$
H1 [26]	2108.12376	8*	High Q^2 DIS	$Q^2 > 150 \text{ GeV}^2$
H1 [27]	2303.13620	10	High Q^2 DIS	$Q^2 > 150 \text{ GeV}^2$
H1 [28]	2412.14092	8*	High Q^2 DIS	$Q^2 > 150 \text{ GeV}^2$
H1 [29]	H1prelim-25-031	Variable	High Q^2 DIS	$Q^2 > 150 \text{ GeV}^2$
LHCb [30]	2208.11691	4	Z+hadrons in jets	$20 < p_T^j < 100 \text{ GeV}$ and $p_T^h > 0.25 \text{ GeV}$
STAR [31]	2307.07718	6	Jets	$20 < p_T^j < 50 \text{ GeV}$
STAR [32]	2403.13921	7	Jets in heavy ions	$20 < p_T^j < 45 \text{ GeV}$
T2K [33]	2504.06857	6	Muon + Proton	$p^p > 450 \text{ MeV}$ for single transverse variables

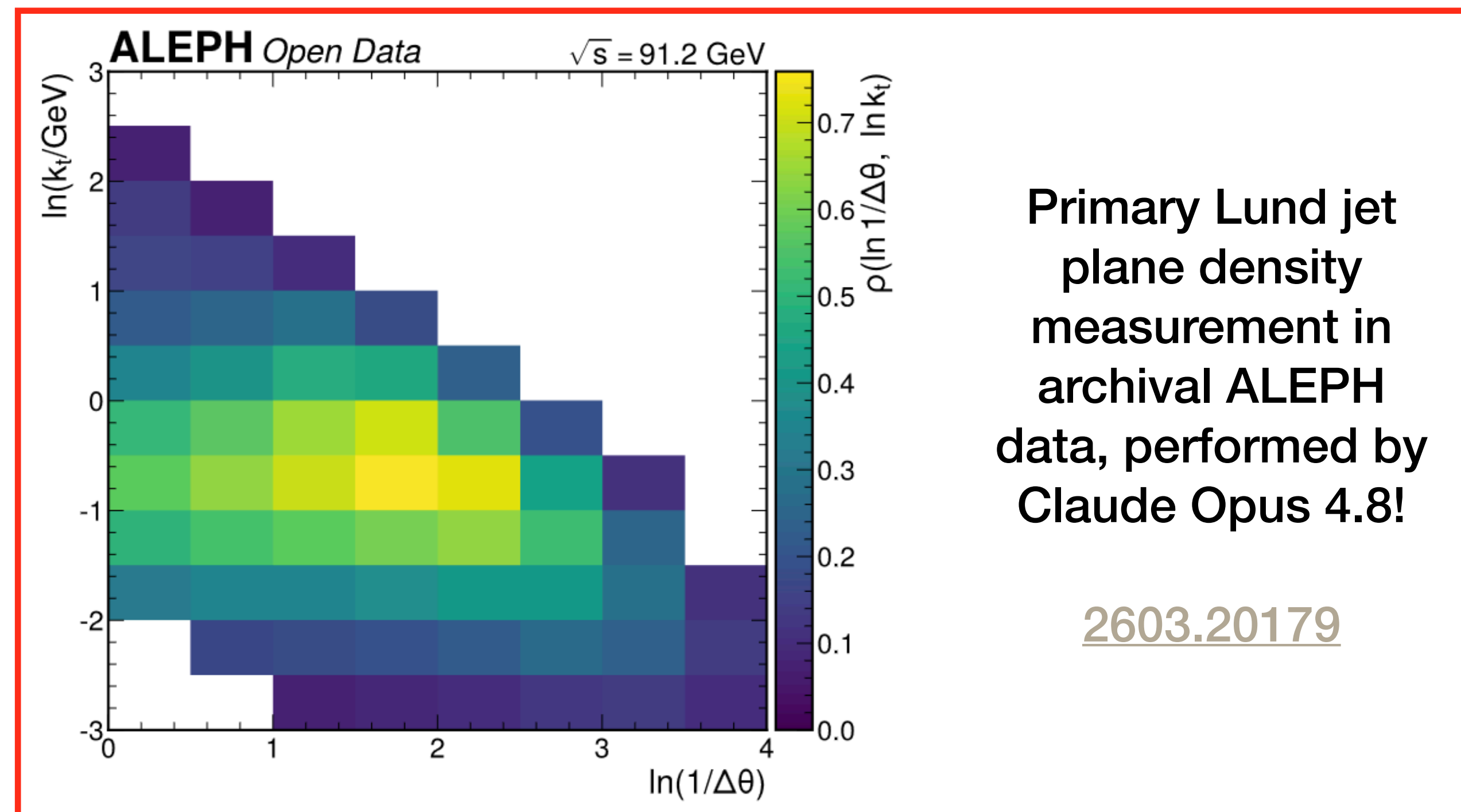
ATLAS Fully-Differential Z+Jets



- Method **validated against IBU** and lower-dimensional unbinned approach ('multifold').
- Allows for the construction of arbitrary observables from published weights *ex post facto*: comparison of various jet algorithms, complex observables (EEC, intrinsic dimension) showcase utility of this approach.
- **Significant investment of computing resources** to produce such results:
 how to ensure better standardization & adoption of such measurement products? **Incompatible w/ HEPData**

Who will do the work?

- The measurements I presented were, to my knowledge, *mainly* the result of human effort.
- Several recent demonstrations of agentic physics analysis, e.g. [Moreno et al. 2603.20179](#)
- **AI has the potential to be transformative for the way we do physics analysis.**
 - Could spend less time debugging pipelines, more time connecting results, synthesizing ideas, teaching one another ...
- Scientific AI and automation should expand what we can discover while **preserving our scientific agency and responsibility for the results.**
- *Tilman will call this slide dramatic @10h00 on Friday morning — don't miss it!*



Conclusions

Conclusions

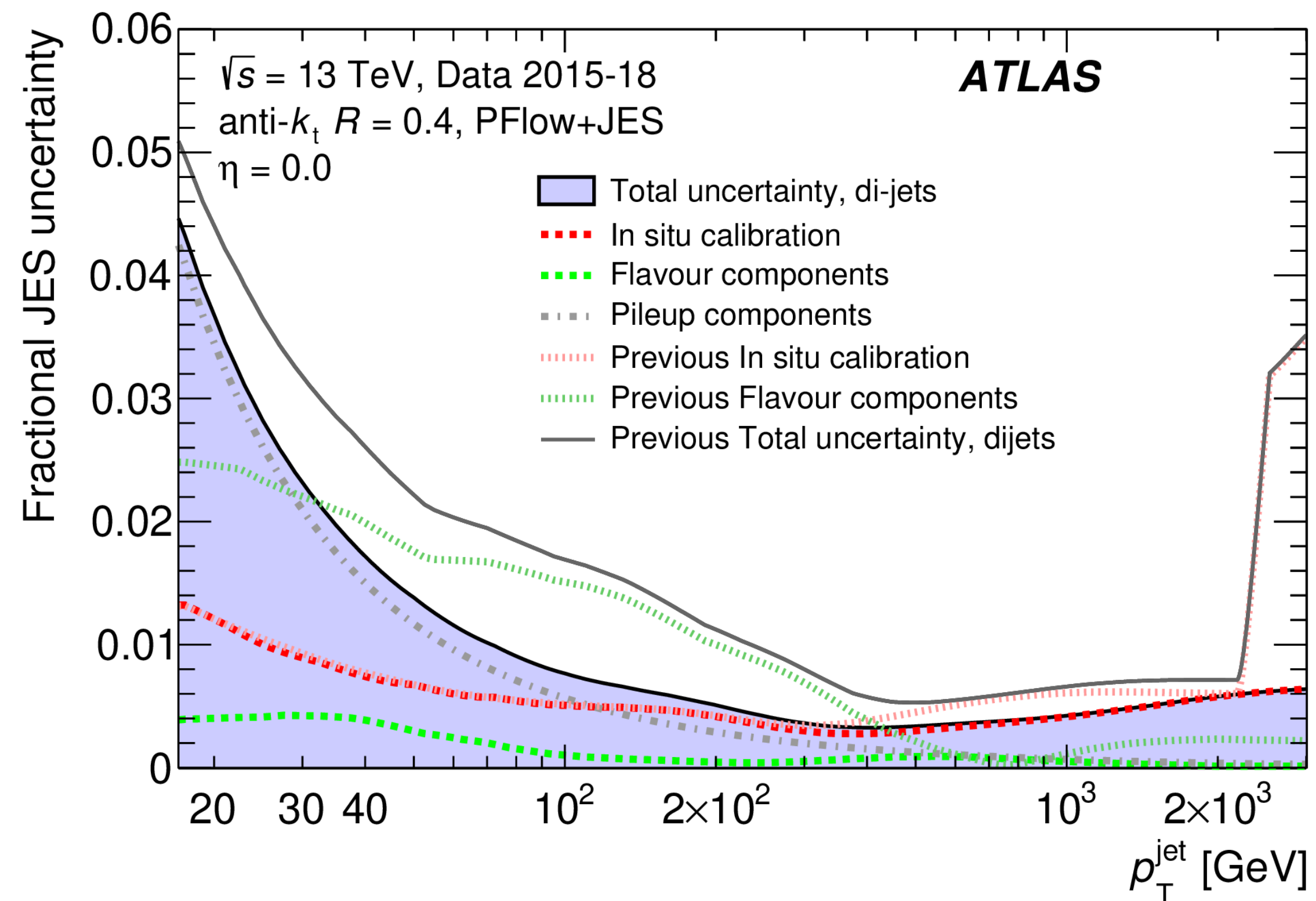
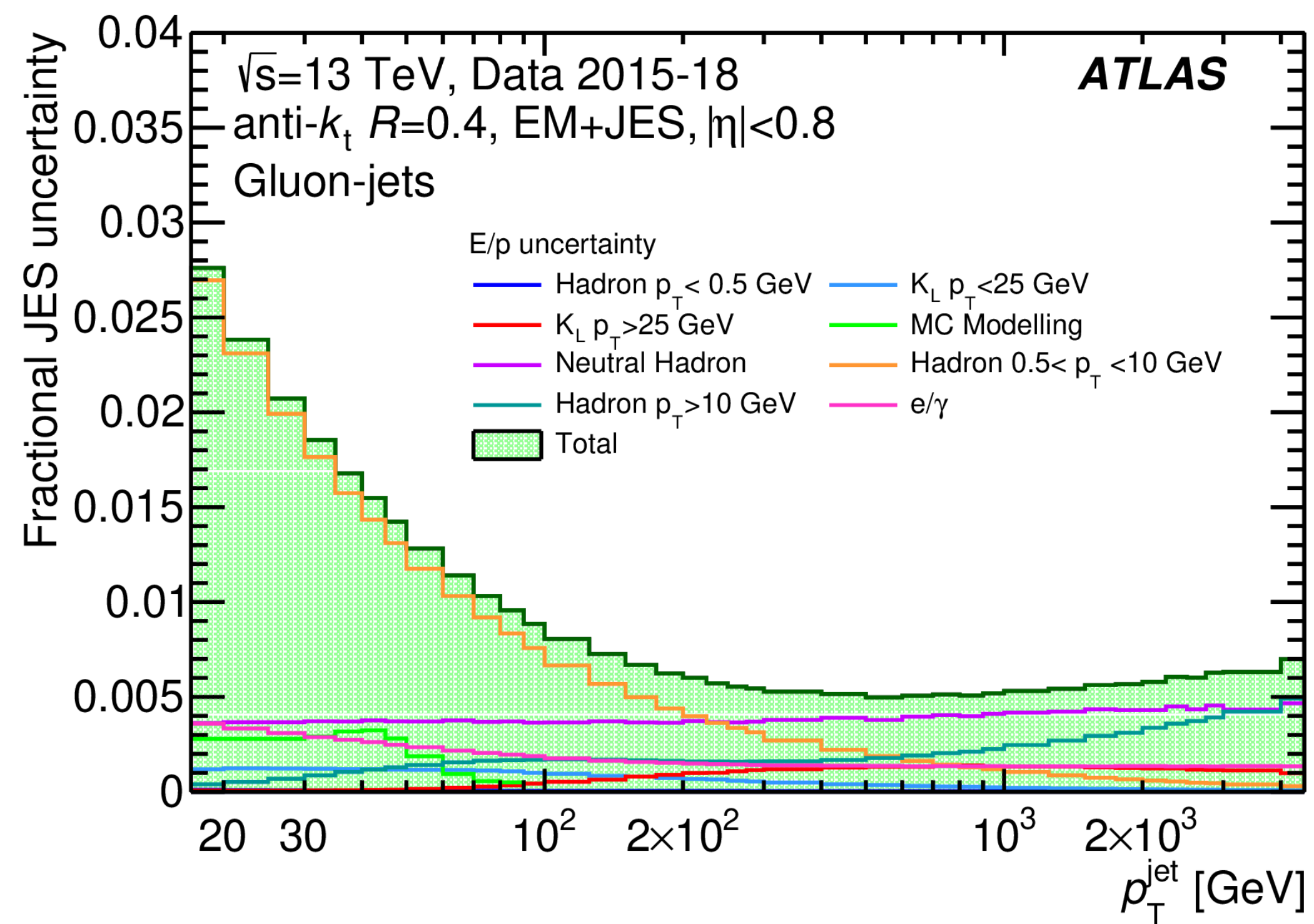
- A parade of legacy SM results using ‘boostology’ has been taking place with Run 2 data.
- We are not afraid to **apply knowledge of QCD dynamics within jets** to get the most out of LHC data!
- Measurements with high-energy & boosted jets are helping to drive a **virtuous cycle of experiment-theory interactions**.
- Let’s continue this into the High-Luminosity Era!
- High-energy QCD measurements are also the site of many studies incorporating **interdisciplinary** data science techniques.
- AI/ML and unbinned methods, but also Optimal Transport, Topic Modeling, agentic workflows and more.



Aim High!

Extra

ATLAS Single-Hadron Jet Calibration



R32 uncertainties

