Jet Measurements in *pp* collisions

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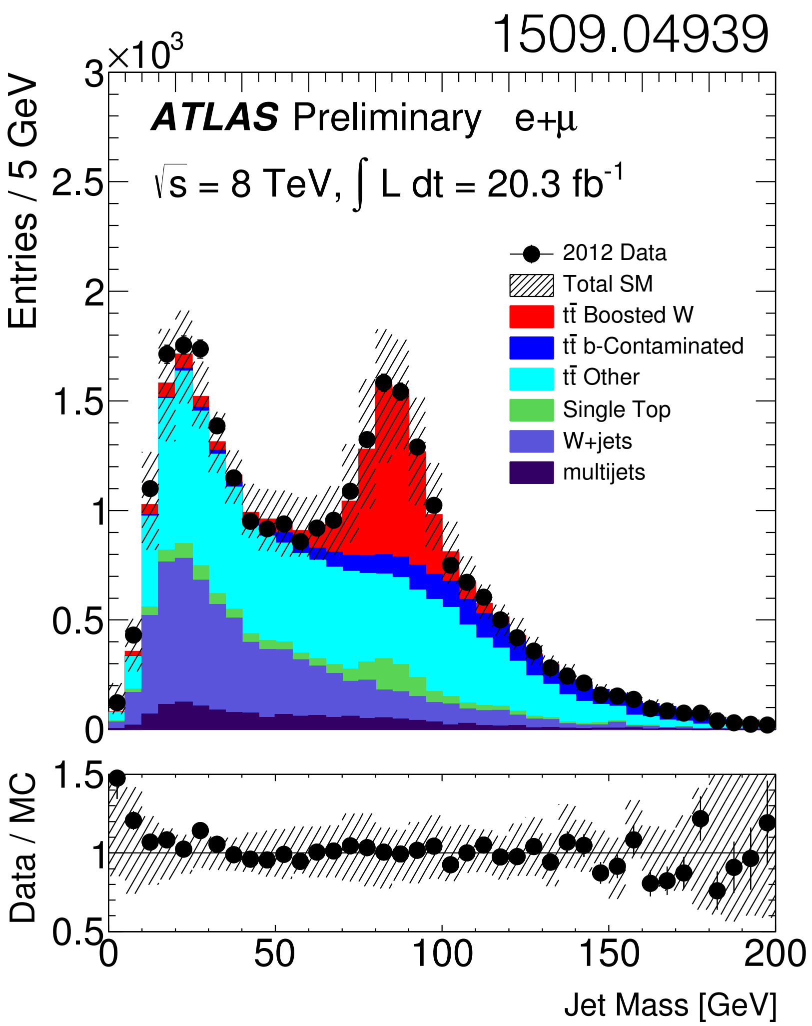
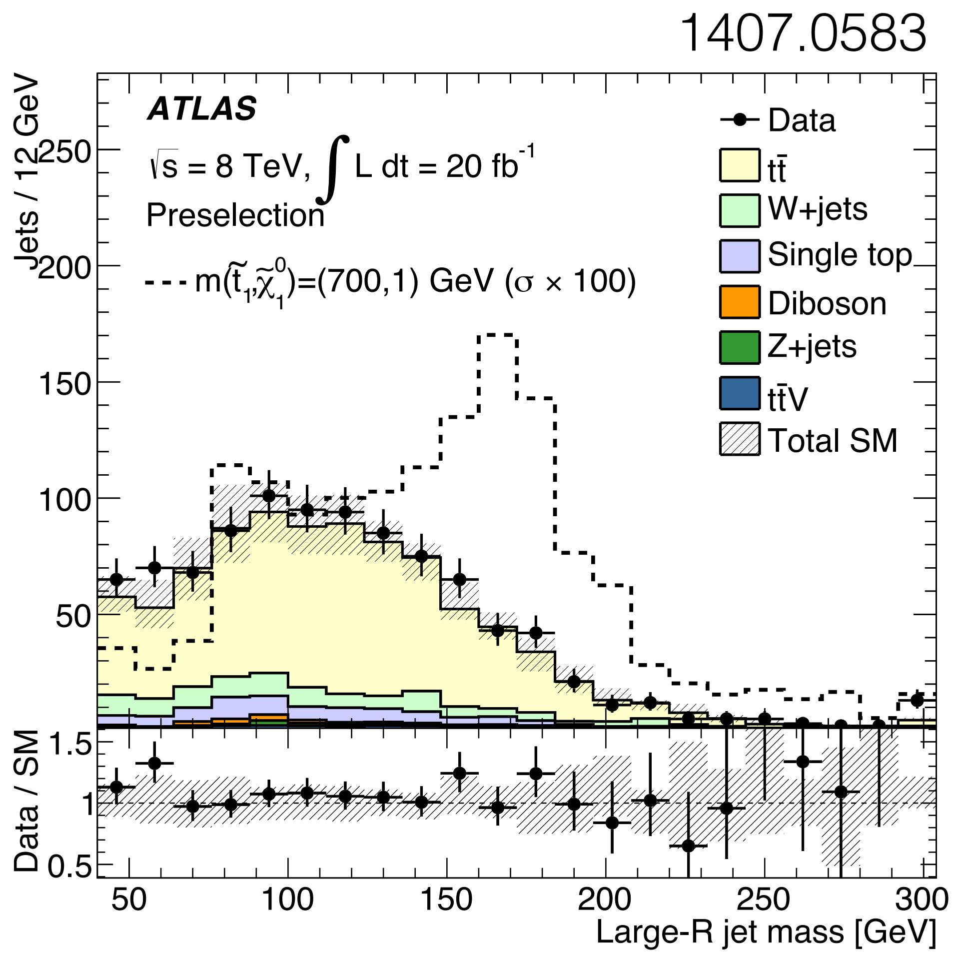
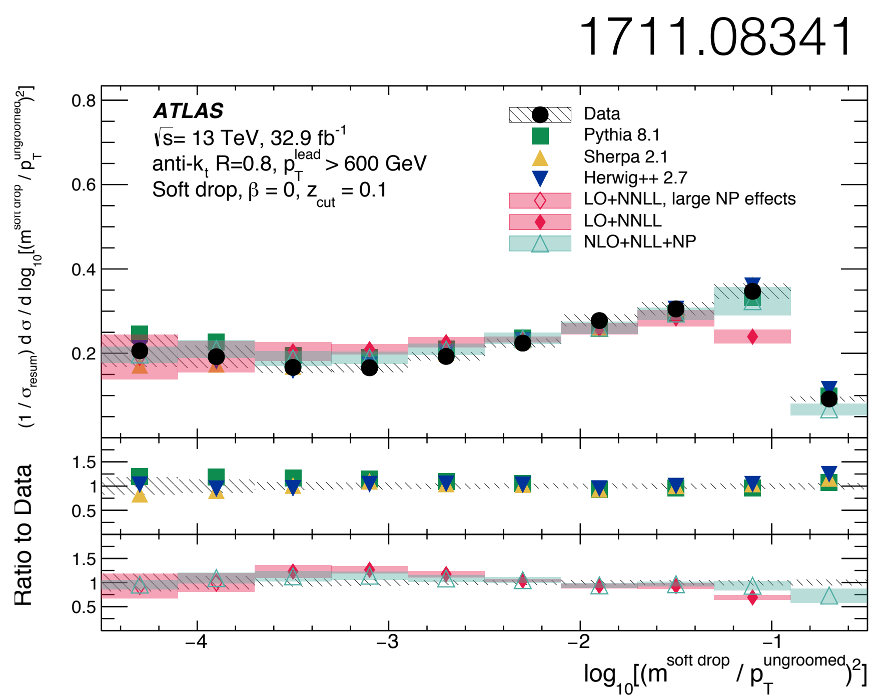
Jetscape 2018

Disclaimer: I have not attempted to have an equal balance across experiments. In many cases, there are analogous results from other collaborations. I can provide references upon request.

First: What is a measurement?







Performance Study

New Physics Search

Precision QCD

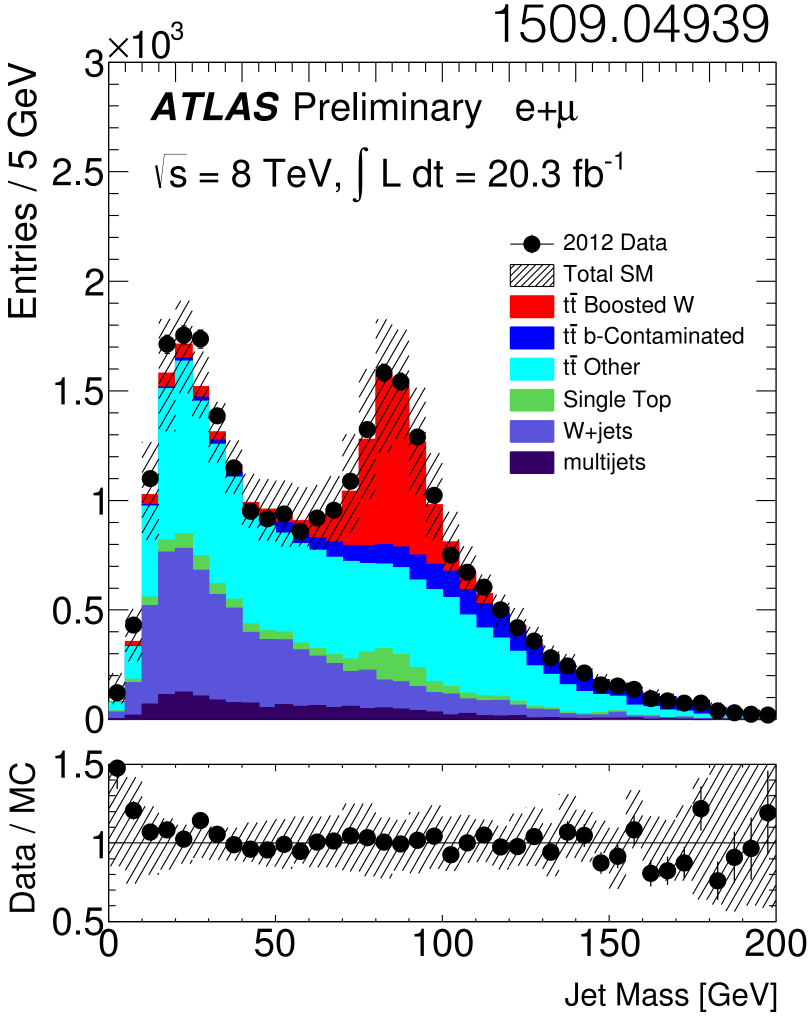
Hint: Only one of these is a measurement …

First: What is a measurement?

These are not measurements

Goal: Optimize/**develop** an algorithm, test it in data, develop a calibration, and/or derive uncertainties.

1509.04939



Performance Study

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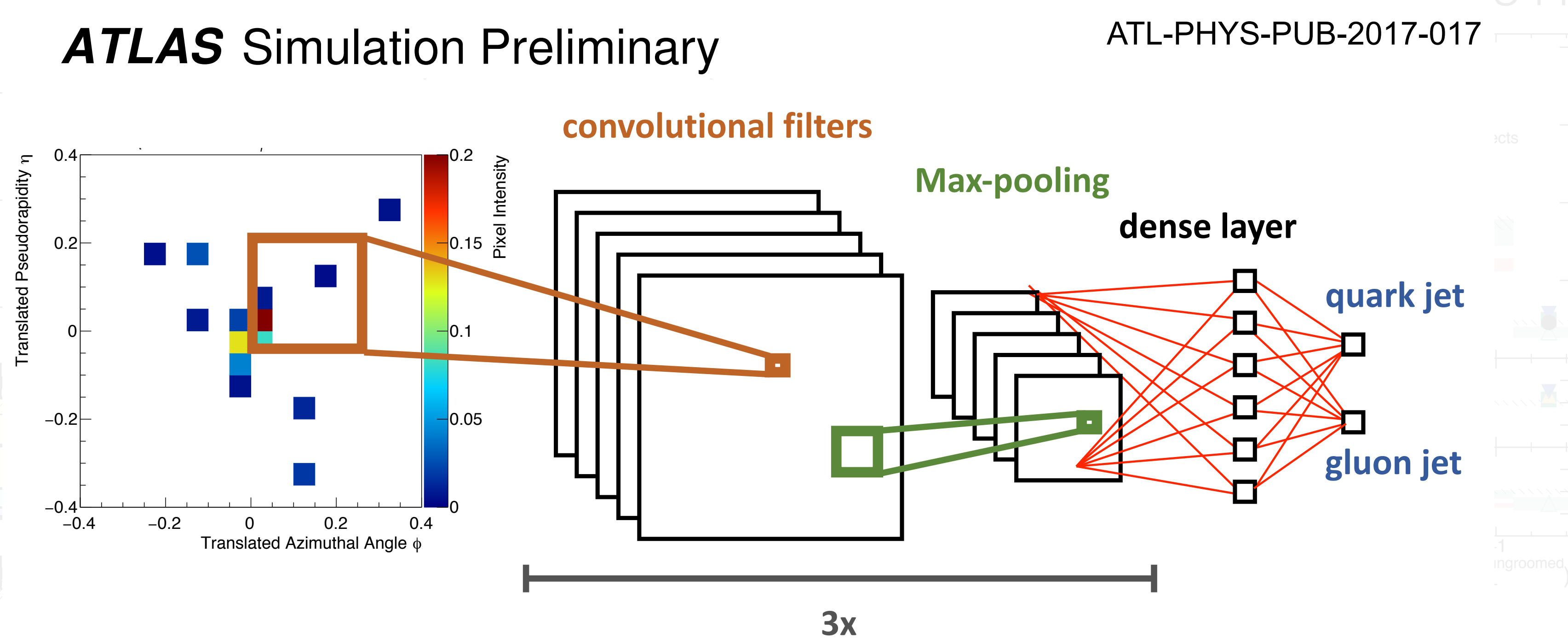

e.g. quark/gluon tagging with machine learning

N.B. I won't say more about ML in this talk … always happy to discuss though! We also hosted a recent ML4Jets workshop at LBNL.

First: What is a measurement?

These are not measurements

Goal: Optimize/develop an algorithm, test it in data, develop a calibration, and/or **derive uncertainties.**

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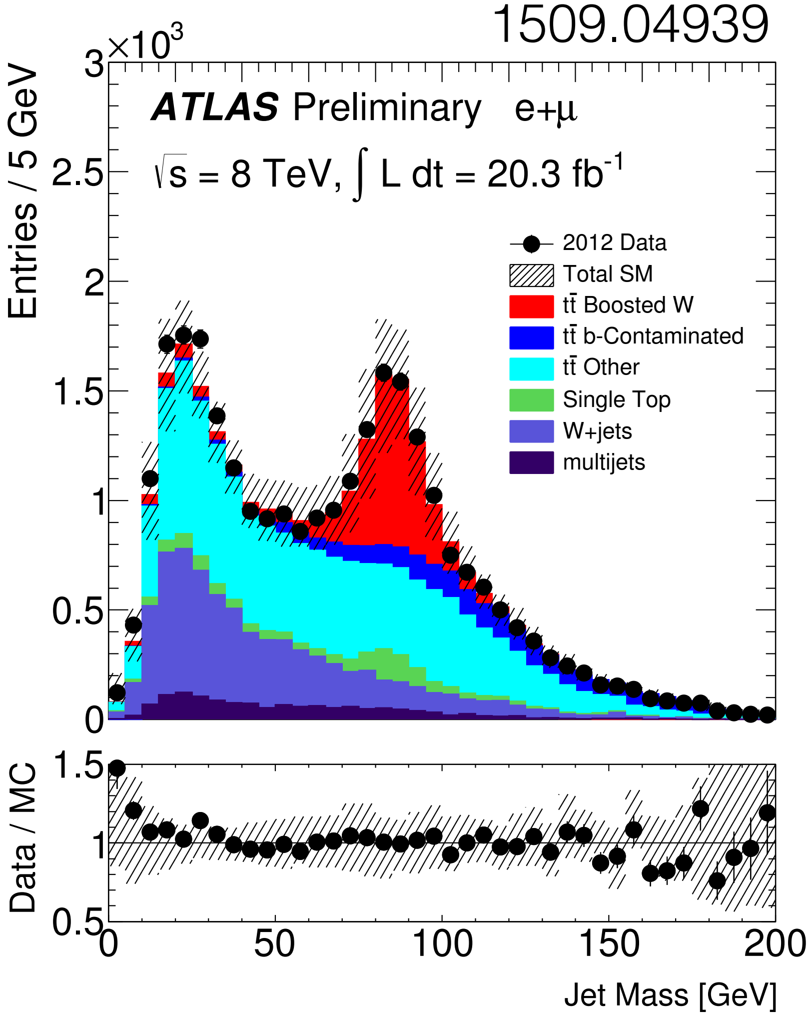

Performance Study

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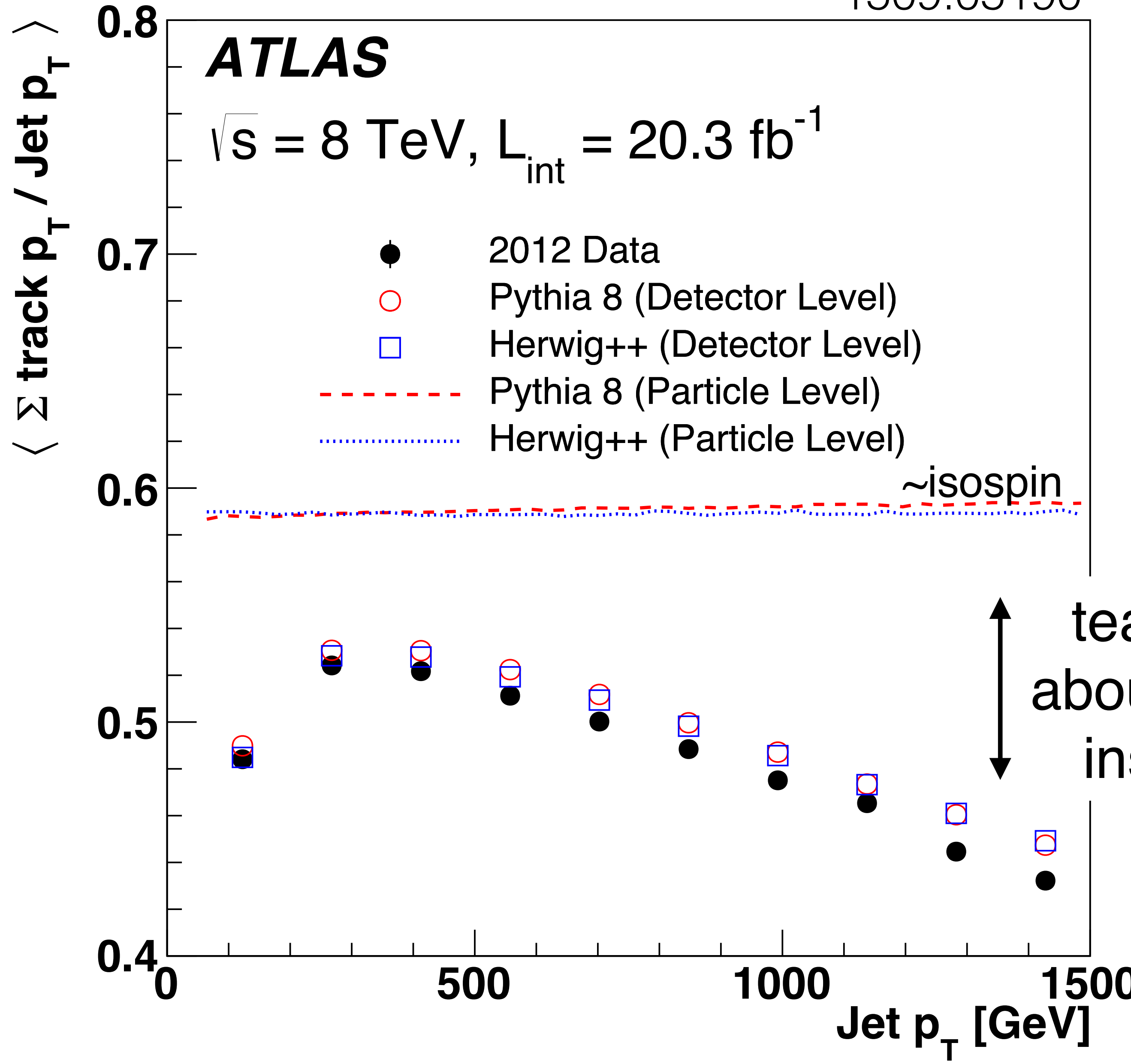

teaches us about tracking inside jets

First: What is a measurement?

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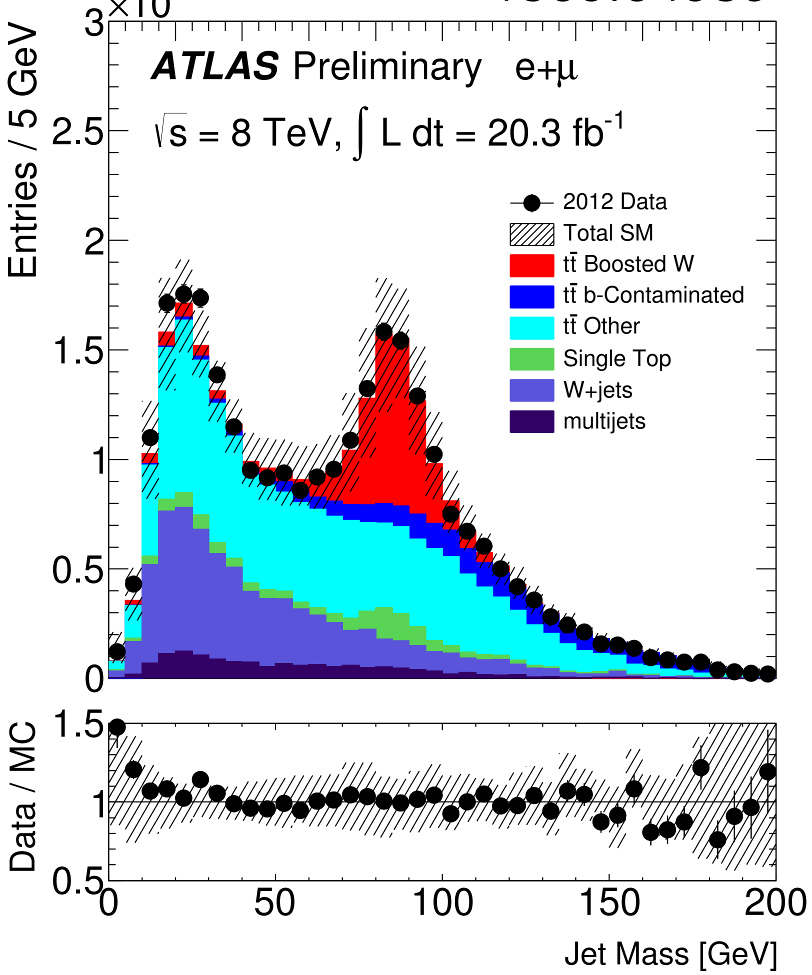
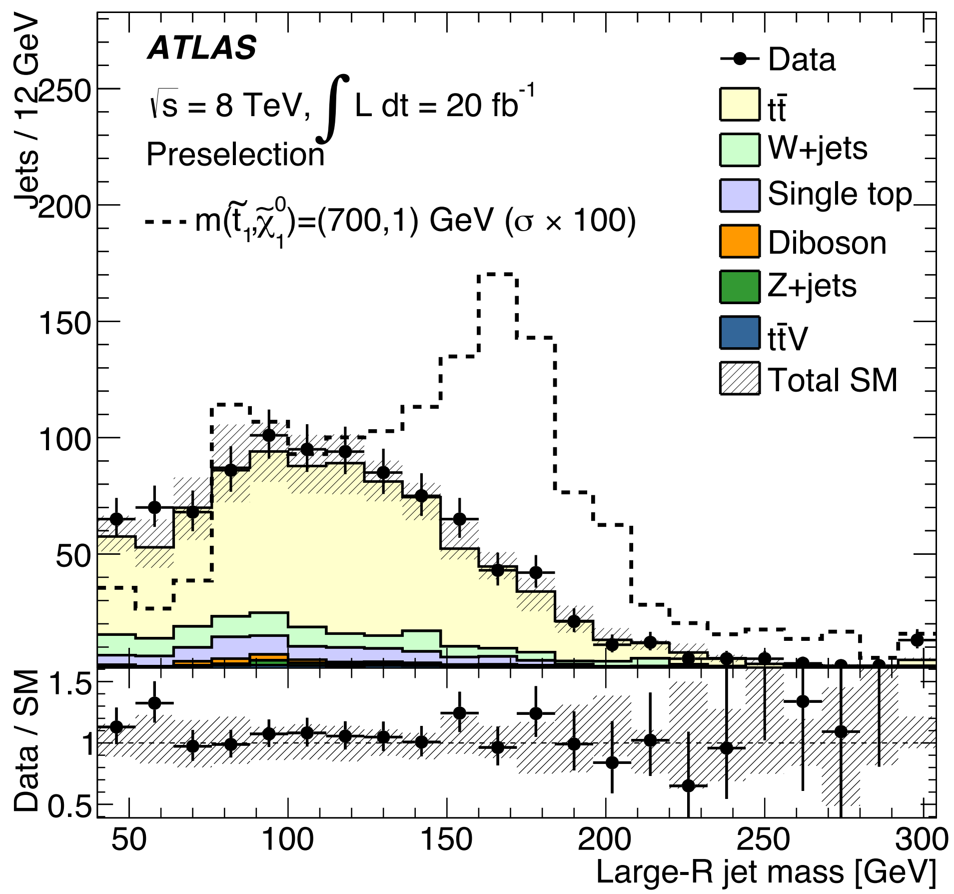


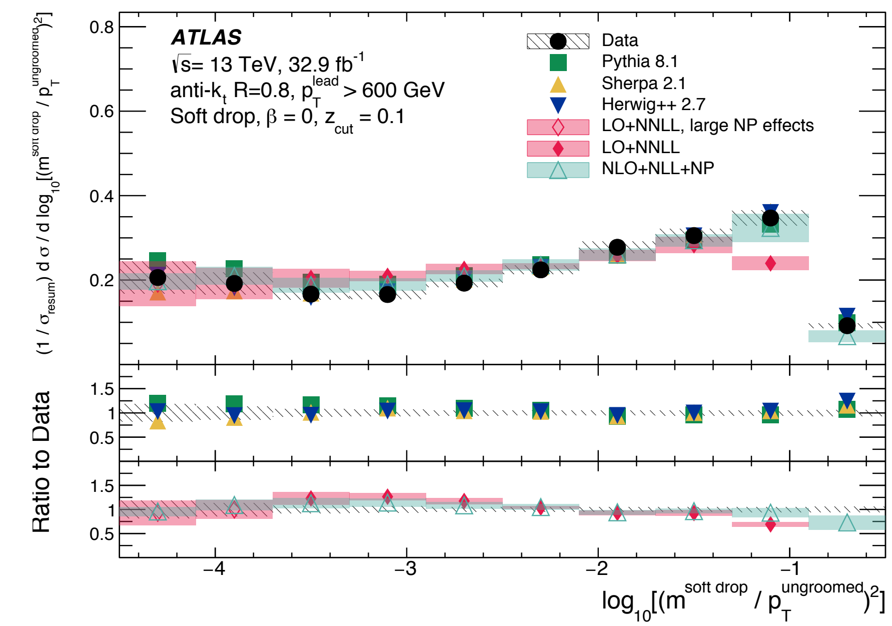
Performance Study

1407.0583



New Physics Search

1711.08341



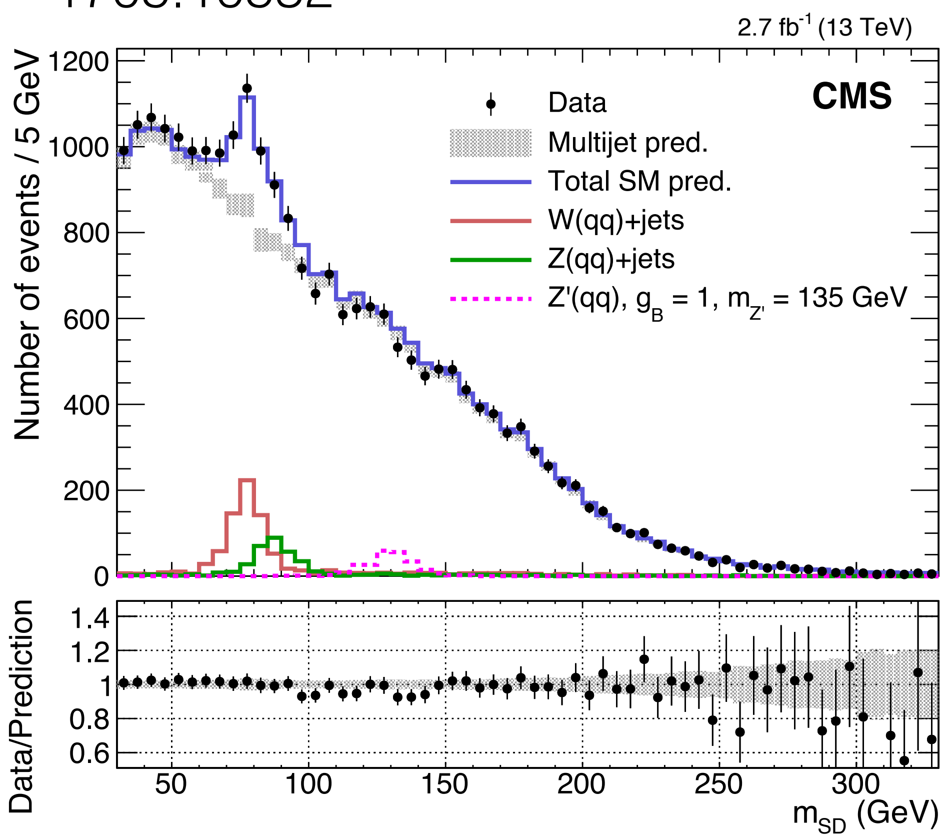
Precision QCD

First: What is a measurement?

These are not measurements

Extending UA1/2 limits with single jet mass

1705.10532



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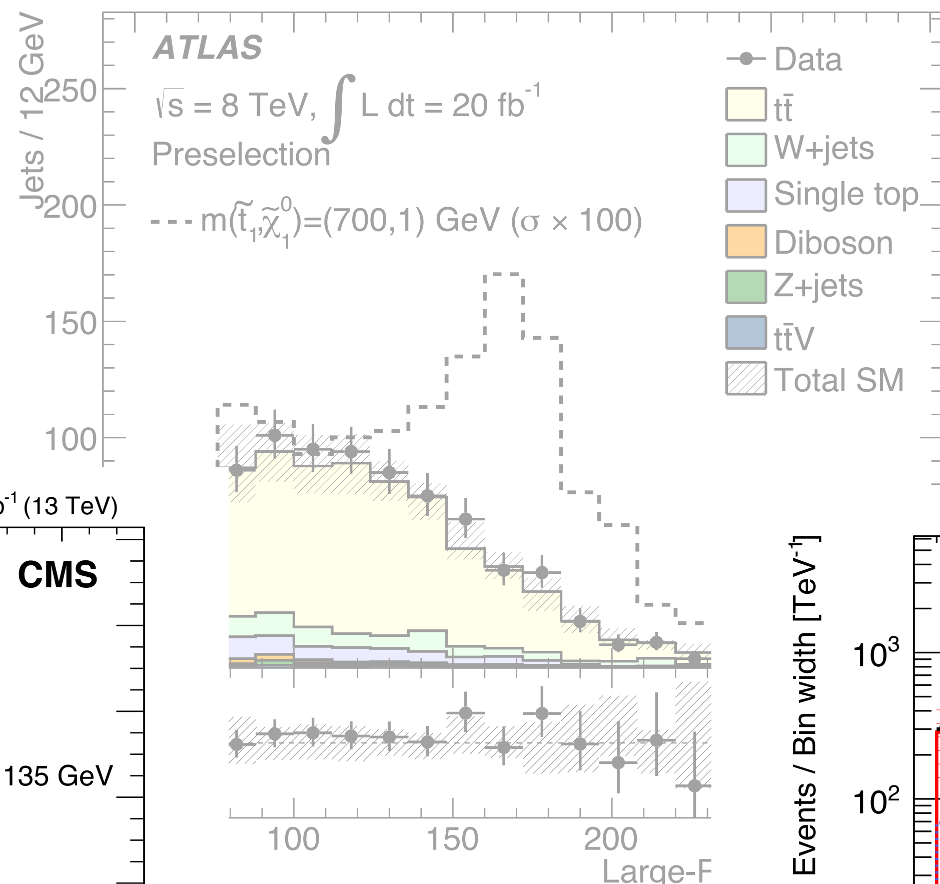
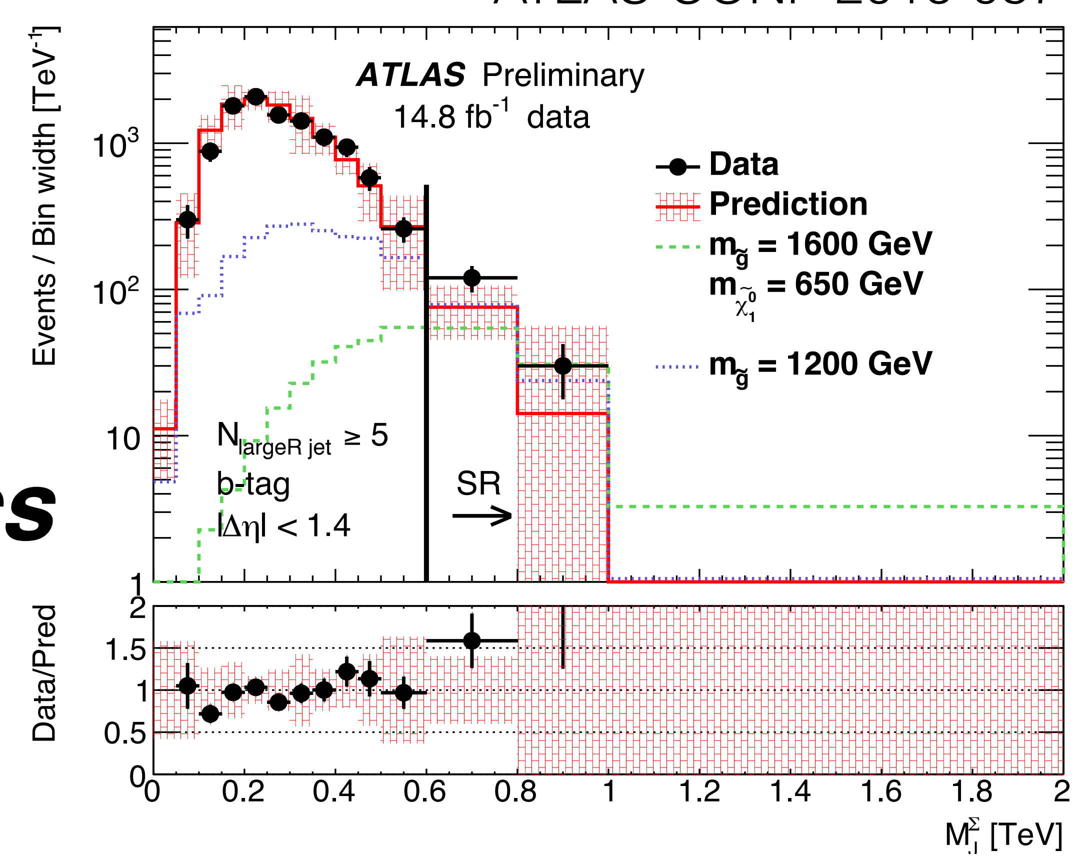


New Physics Search

Exploiting factorization for all-hadronic & high-multiplicity

ATLAS-CONF-2016-057



First: What is a measurement?

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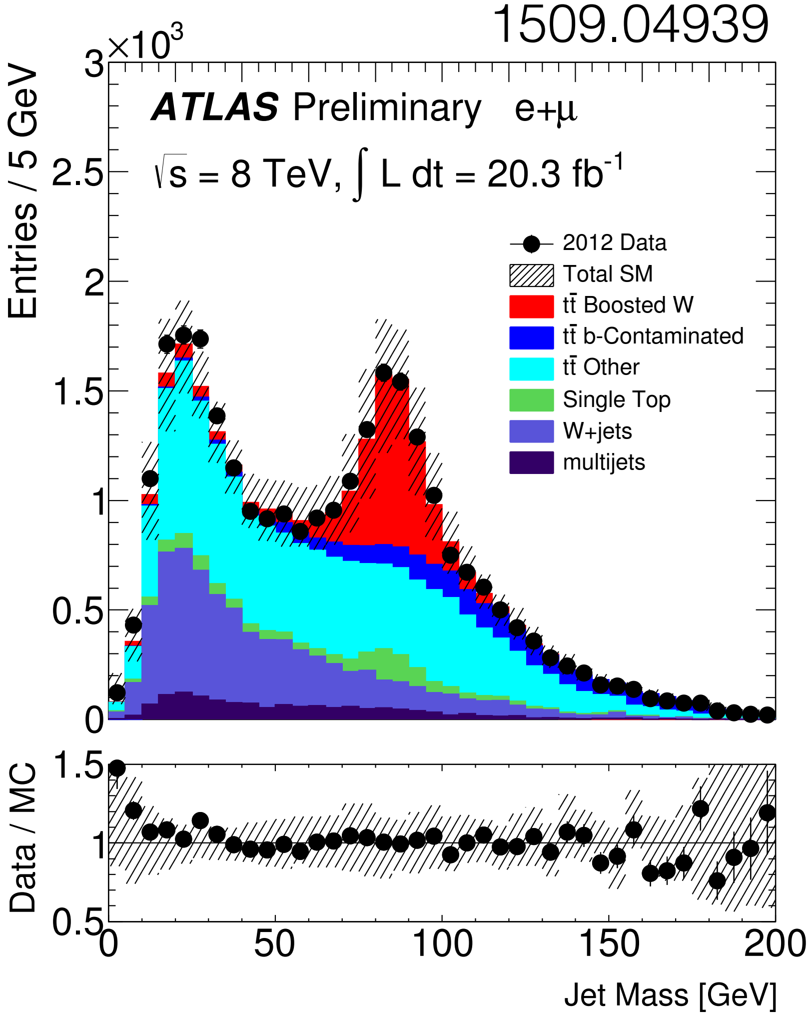

Performance Study

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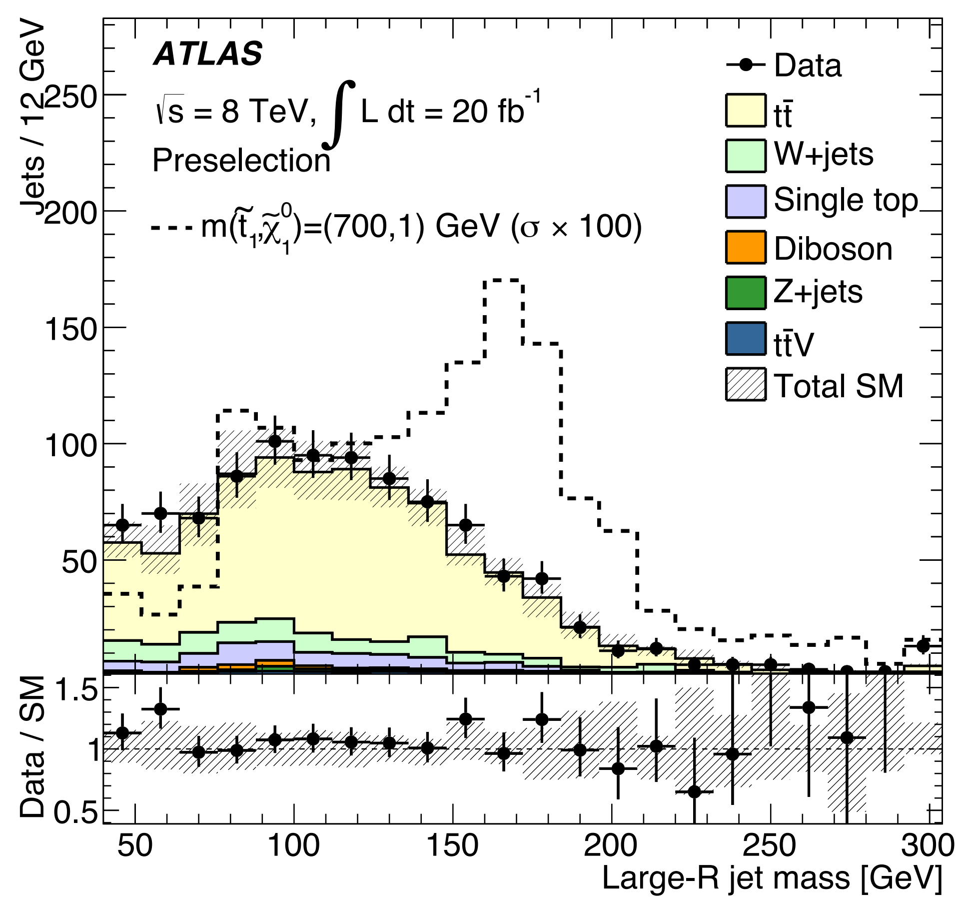

New Physics Search

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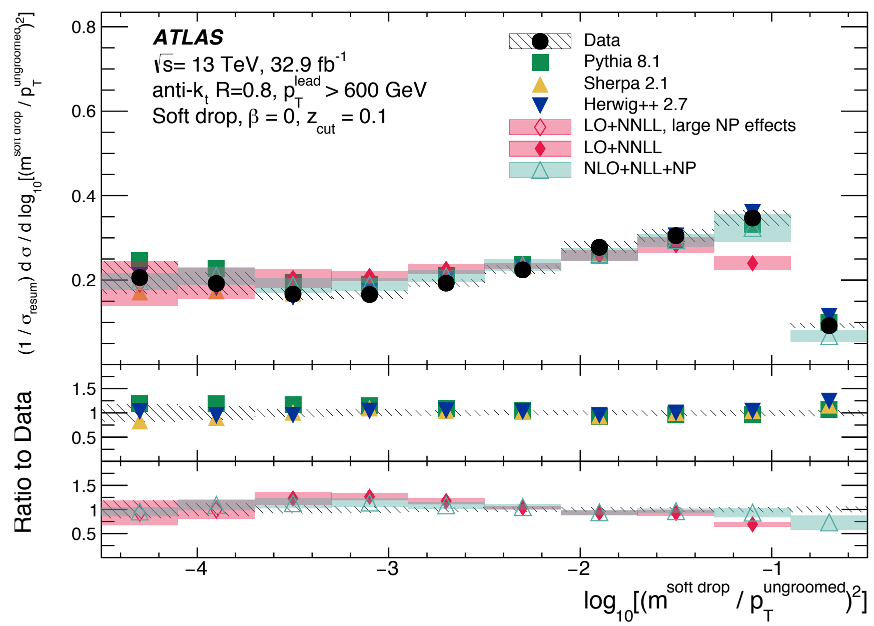

Precision QCD

First: What is a measurement?

- correct for detector effects.

- aiming for O(%) uncertainties.

- goal: constrain the SM, probe it in a new regime, and/or provide input for MC/PDF tuning/fitting.

These are measurements!

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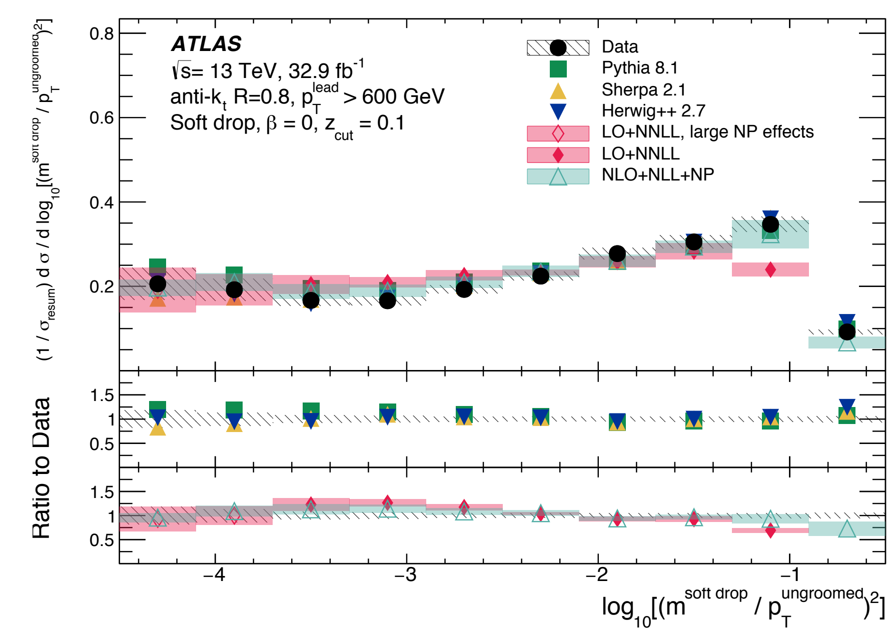
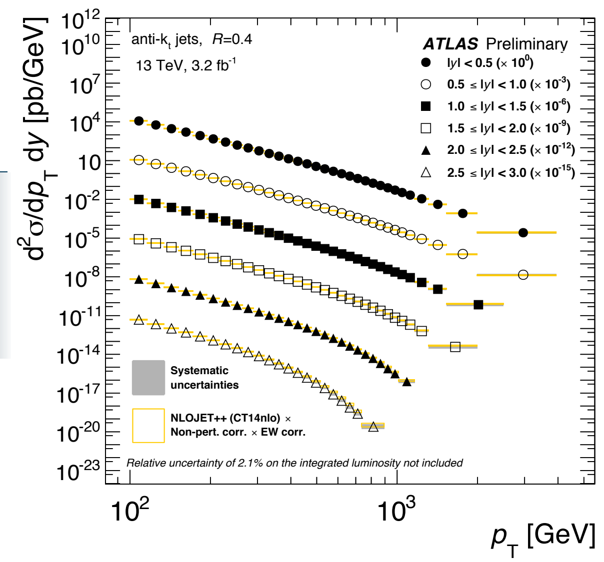


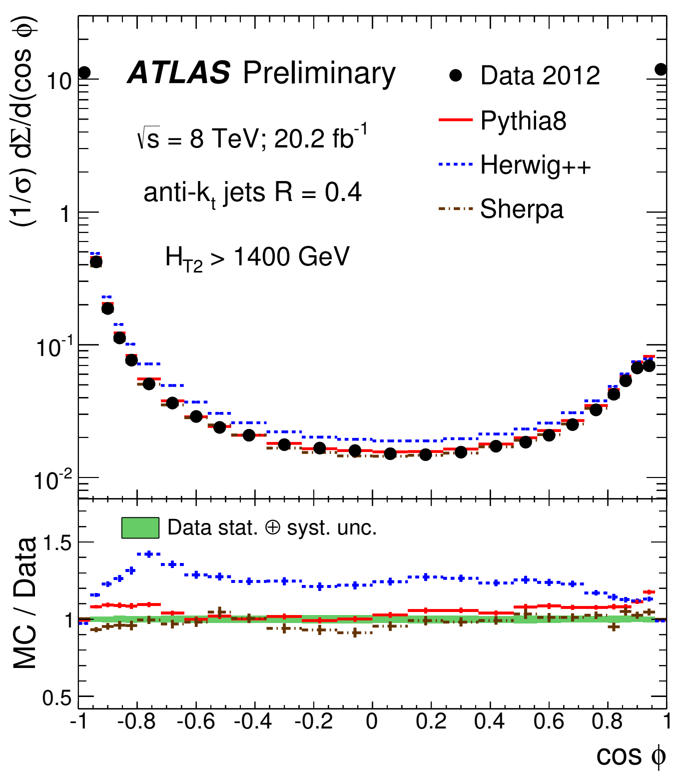
There are many measurements **with** jets, but I'll focus on measurements **of** jets and their internal structure

→ ***Precision QCD*** ←

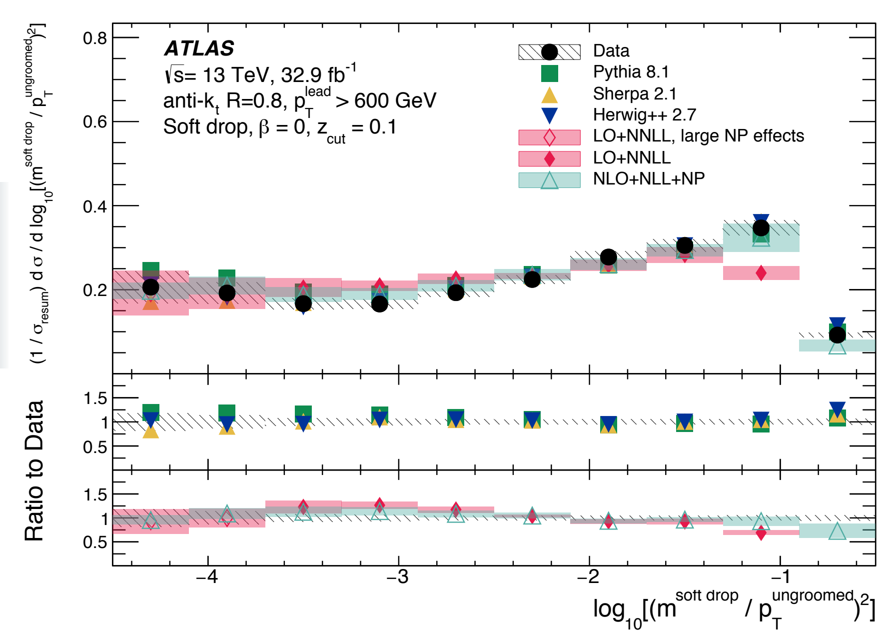
Jet Measurements

Part I: Jet Multiplicity and Energies



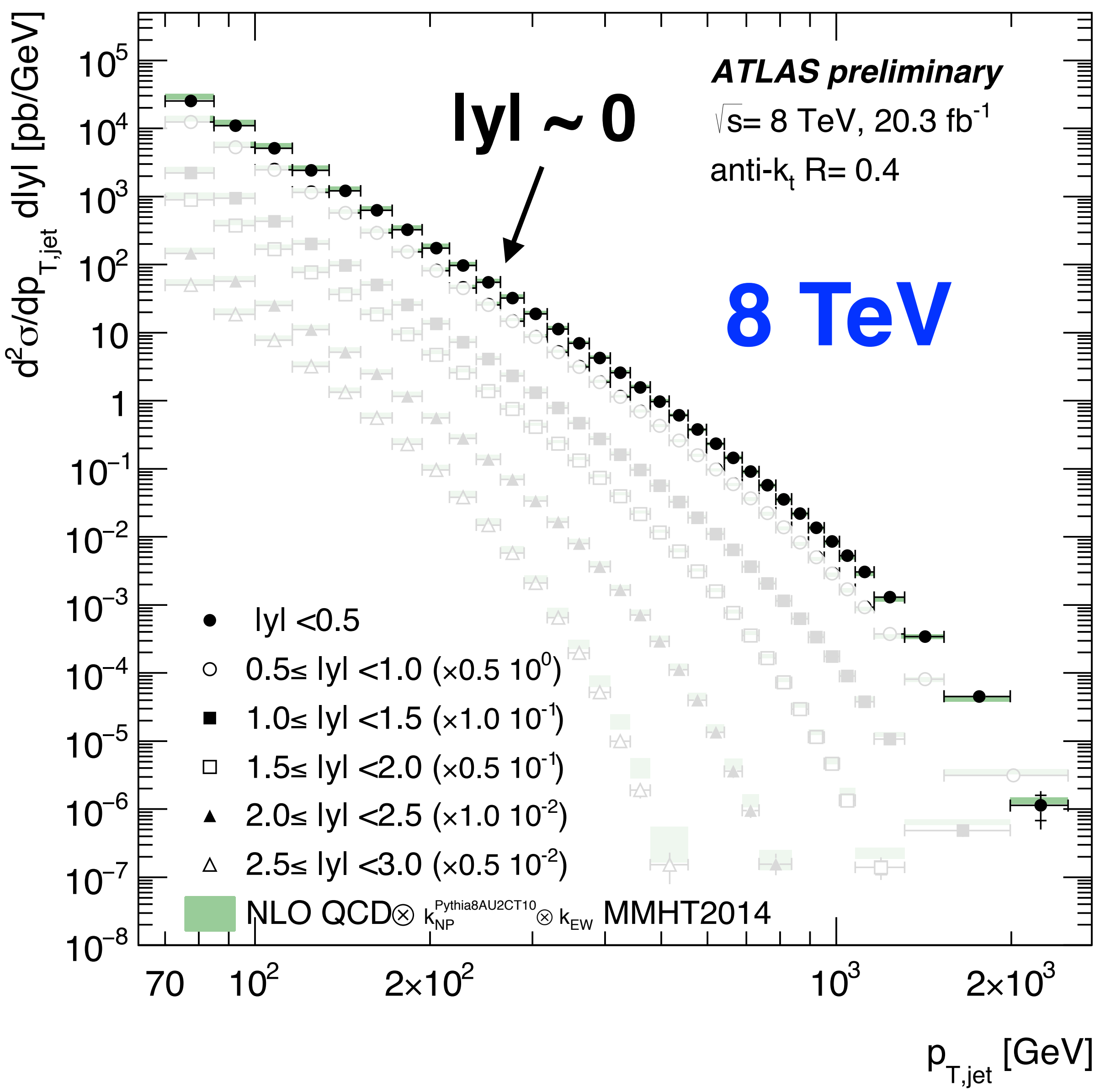


Part II: Event Shapes



Part III: Inside Jets

1706.03192



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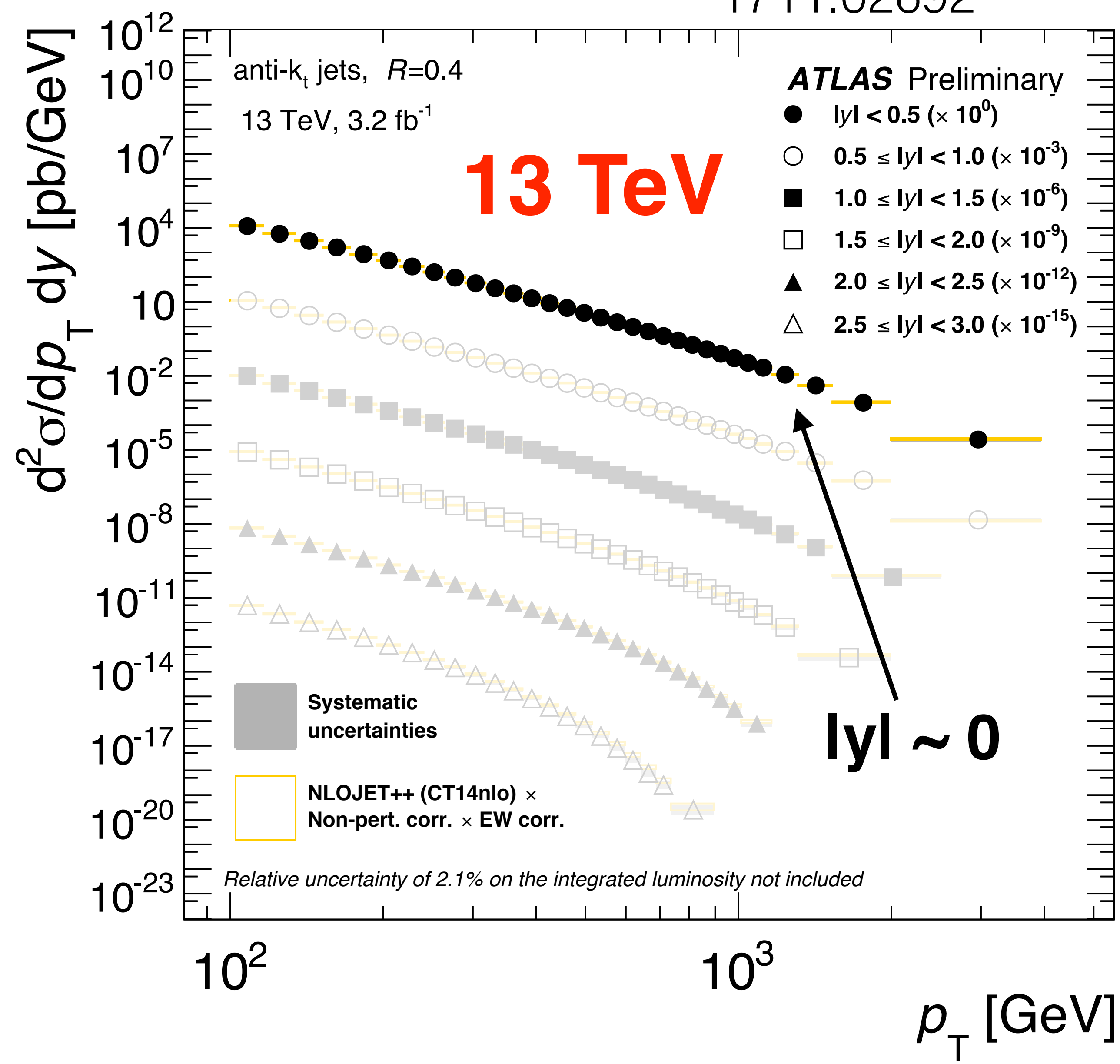


Reach: **~2 TeV @ 20.3 fb^{-1}** **~3 TeV @ 3.2 fb^{-1}**

Inclusive anti-k_t Jet Cross-Sections

(binned in rapidity, *y*)

NLO is accurate over many orders of magnitude

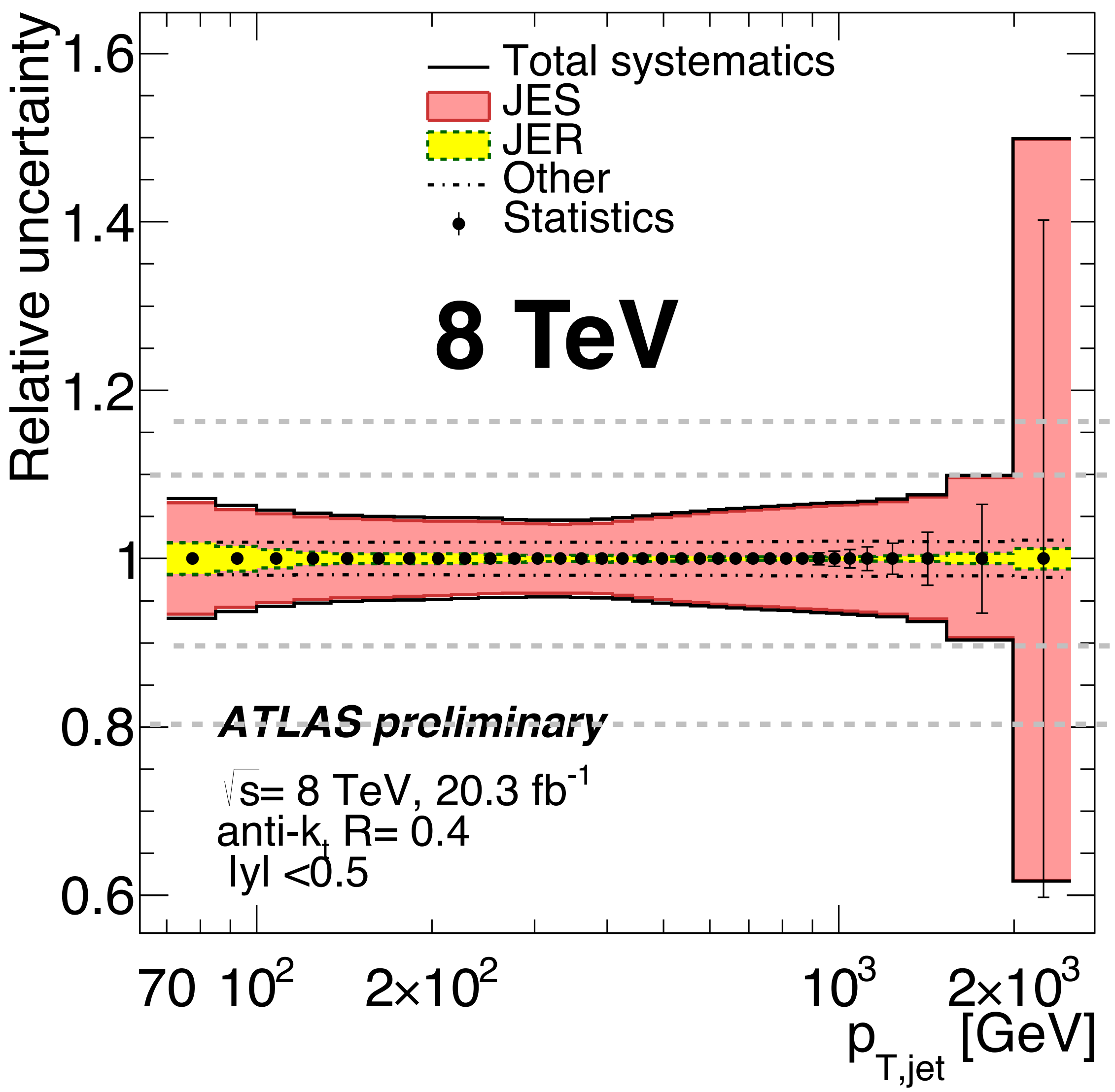
1706.03192 1711.02692

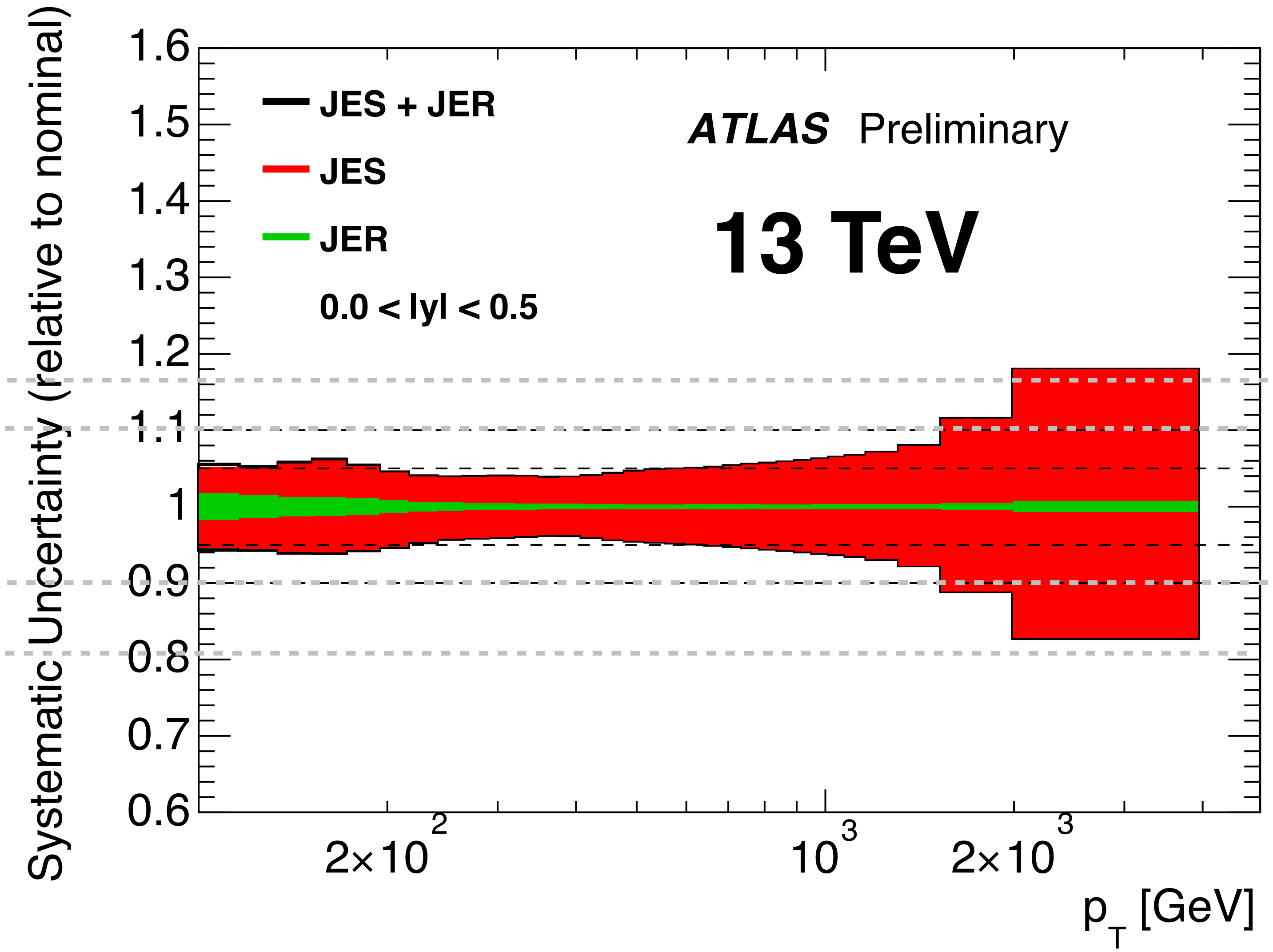
Run 2 already reaching/surpassing 8 TeV precision!

very important for probing proton structure, in particular the gluon PDF

JES = jet energy scale (bias)

JER = jet energy resolution (standard deviation)





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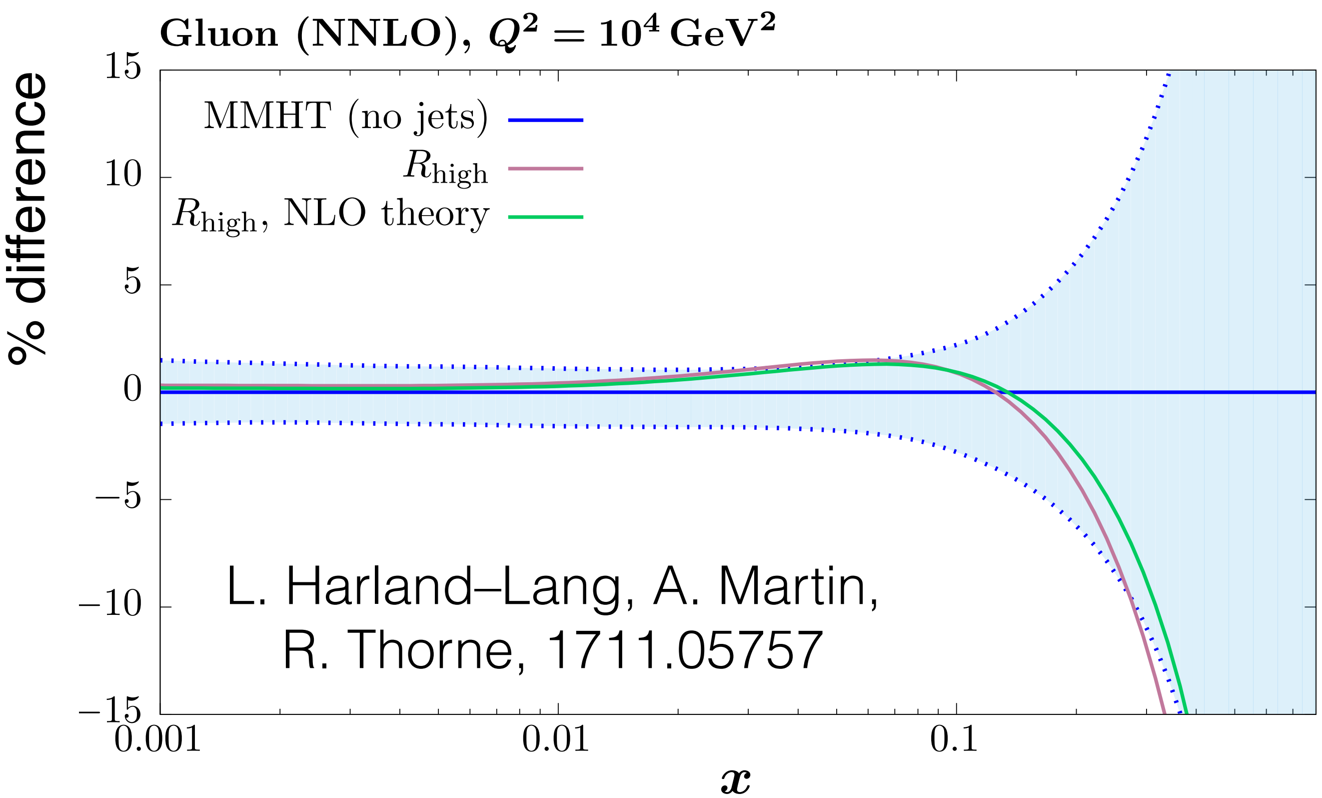
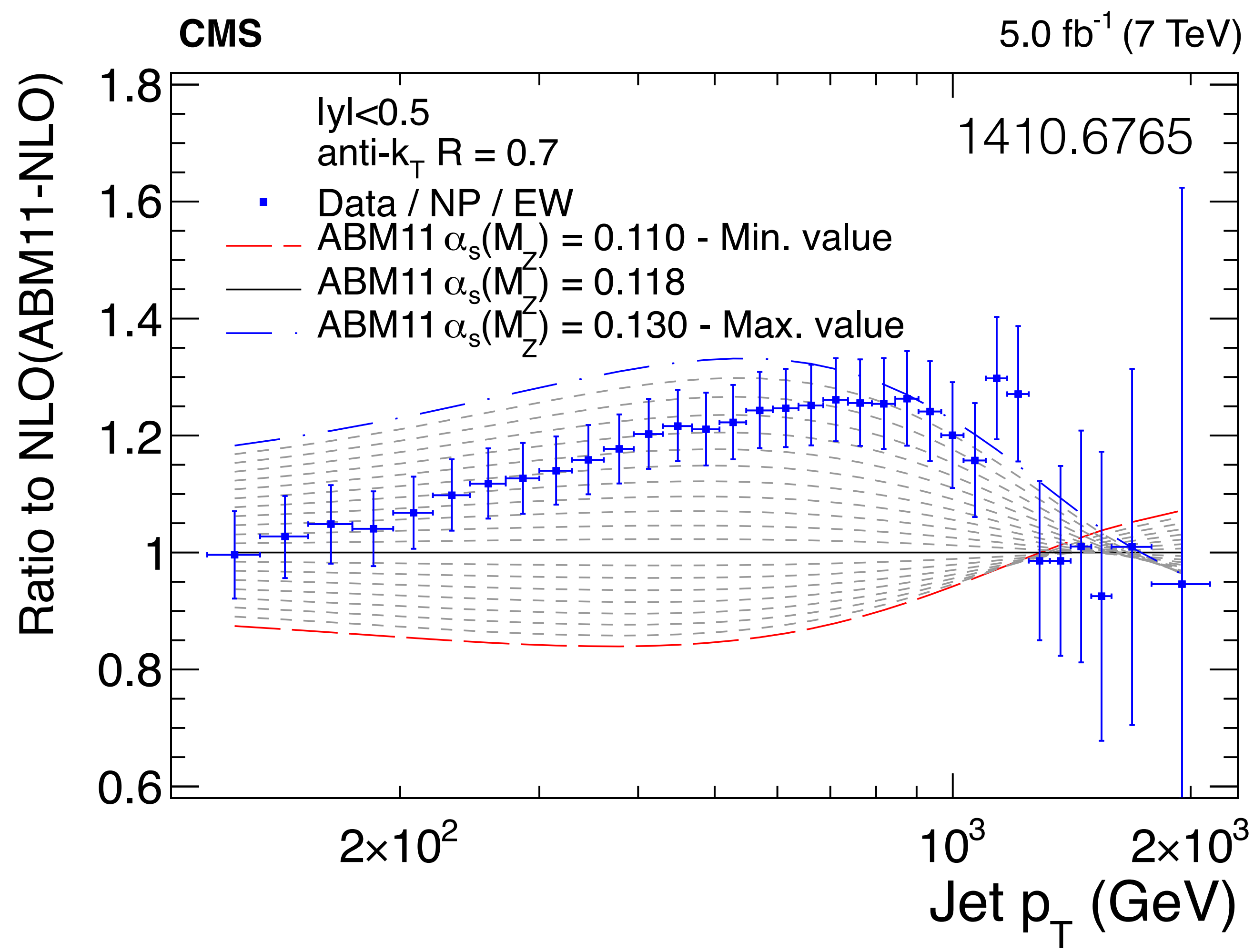


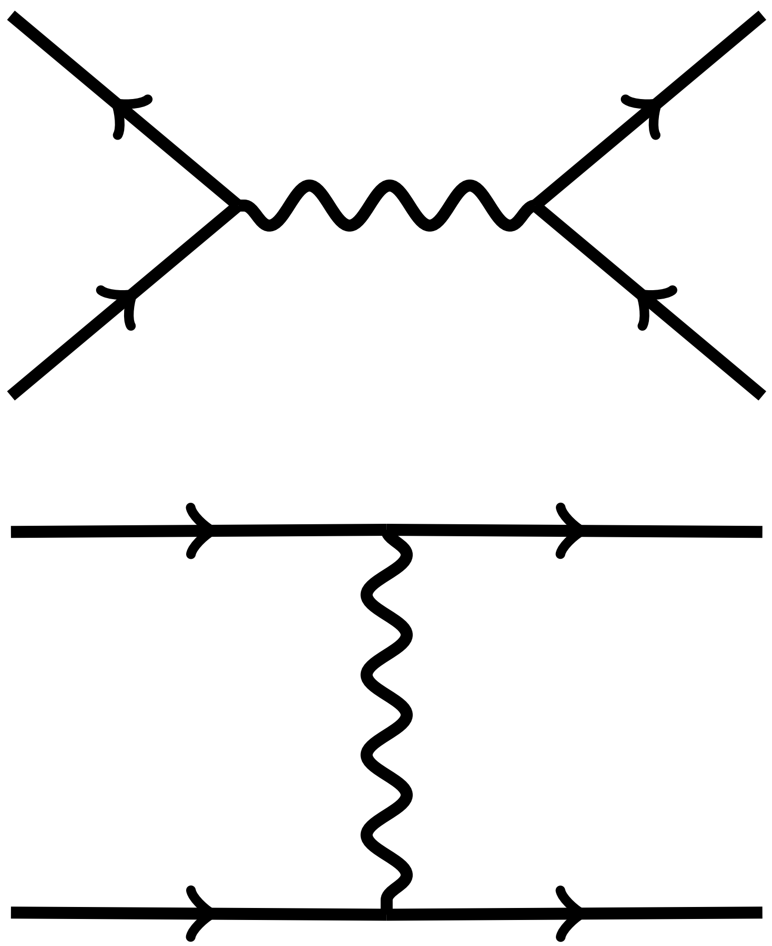


- important input to high-x gluon PDF

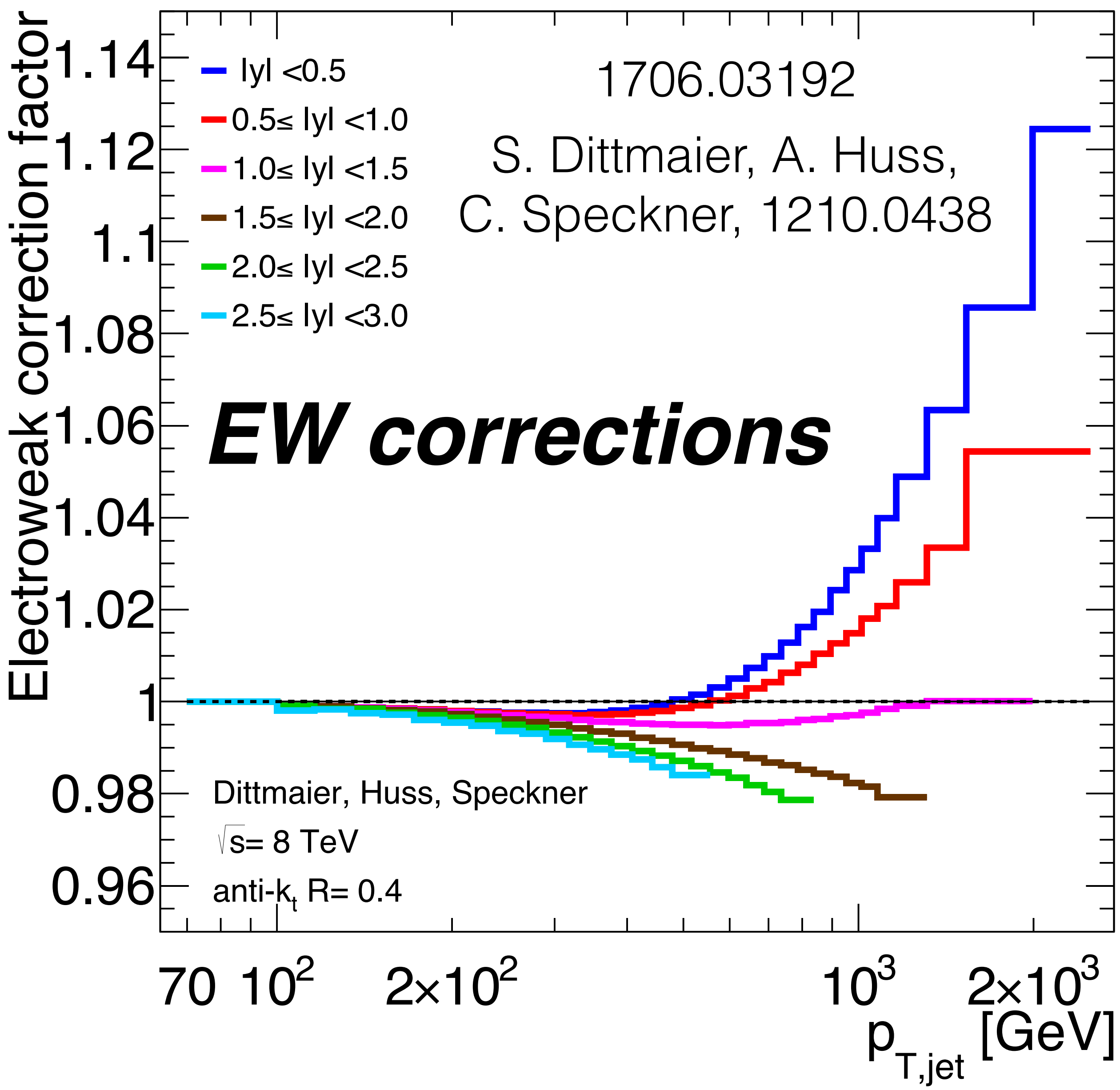
- can be used to extract as
(calculations now at NNLO so can even make the PDG!)

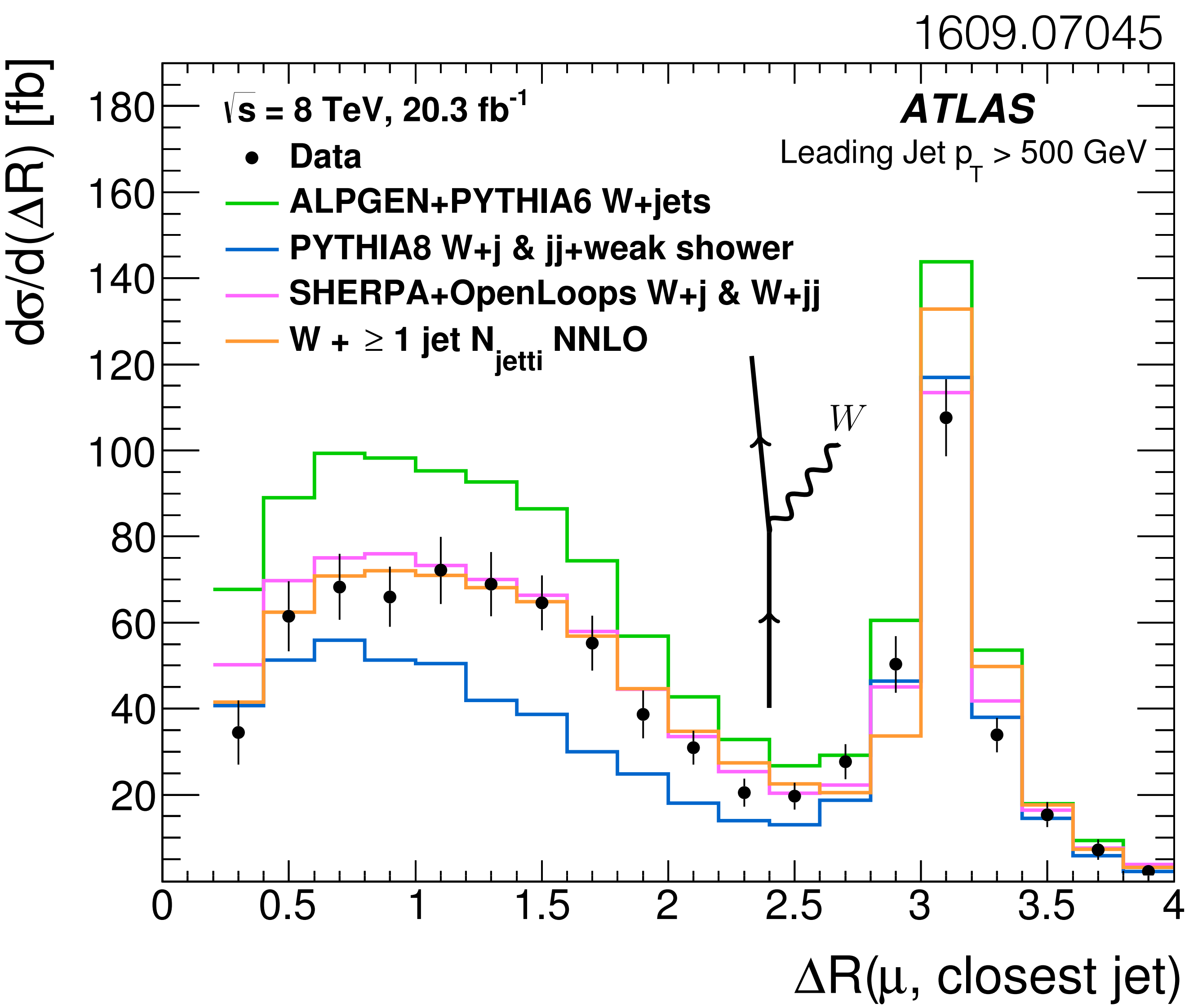
We are probing a regime where NP effects are negligible.

…but electroweak corrections are not small!

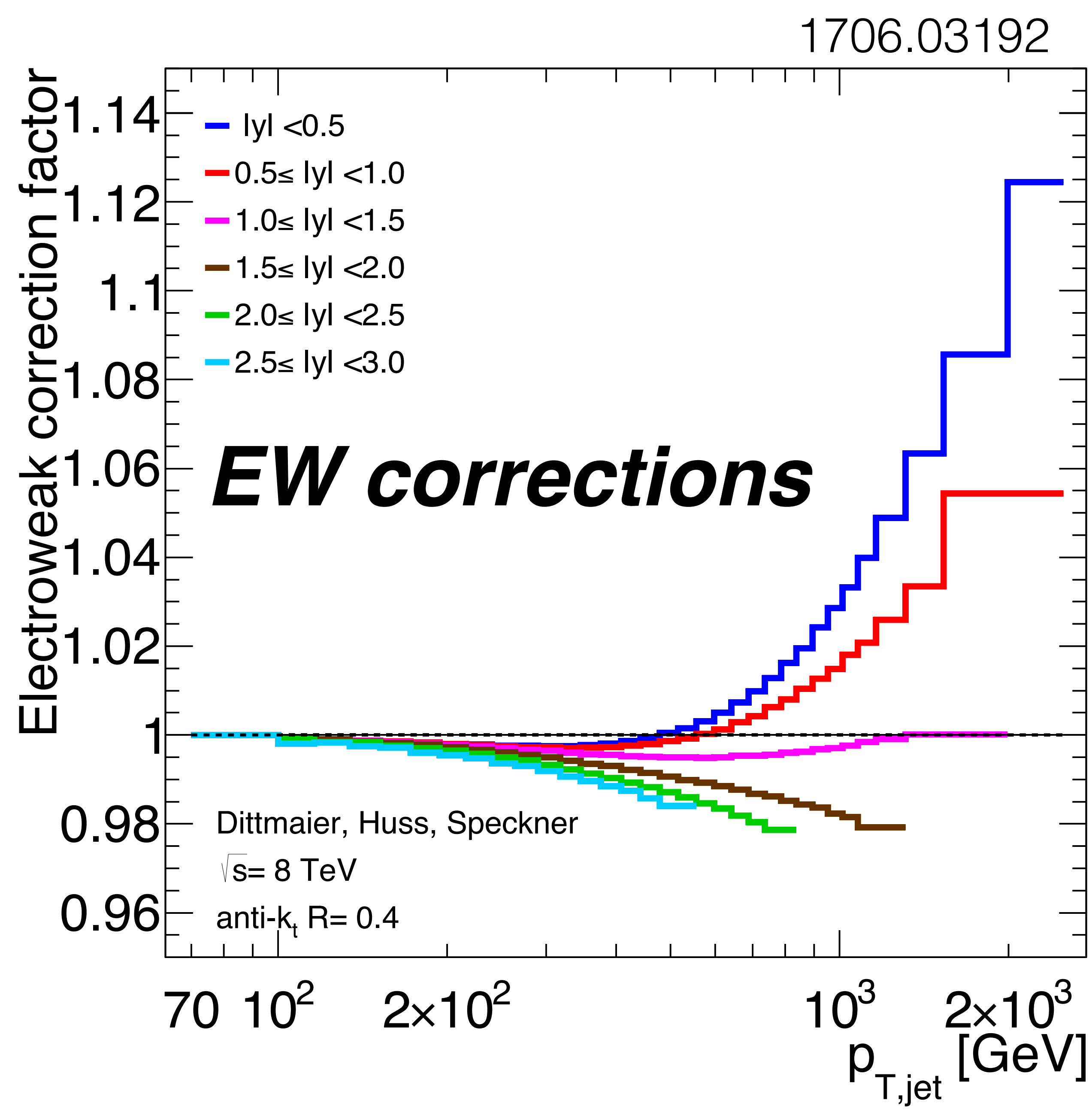


(LO diagrams)





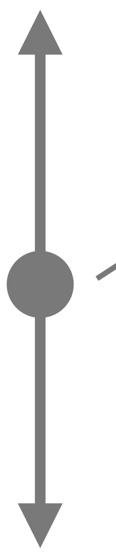
"W from jet" "W+jet"

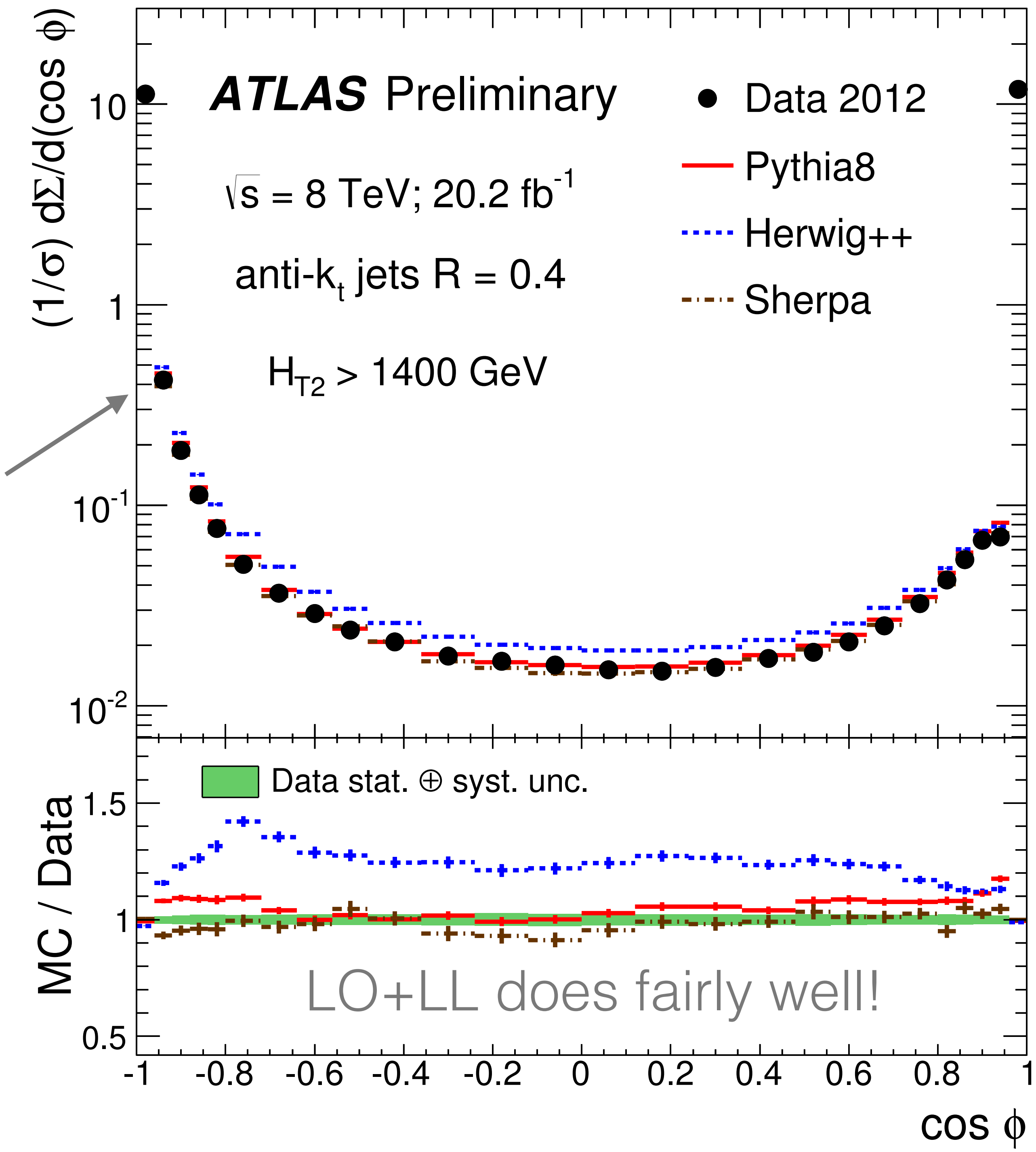


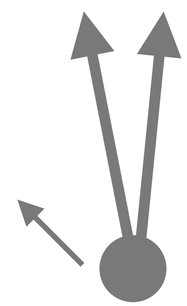
In fact, real EW emissions are measurable!

Not well-modeled by all setups, including dedicated weak shower

1707.02562







Event shapes played a key role in precision QCD at e^+e^-

One observable is the **Transverse Energy-Energy Correlation Function** (TEEC)

$H_{T2} = p_{T1} + p_{T2}$

(sets the hard scale)

$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}(\cos\phi) = \sum_{\text{events}}\sum_{i,j=1}^{n_{\text{jets}}} \frac{E_{T,i}E_{T,j}}{\left(\sum_{k=1}^{n_{\text{jet}}} E_{T,k}\right)^2}\delta(\cos\phi - \cos\phi_{ij})$$

(defined as dimensionless cross-section)

Part II: Event Shapes

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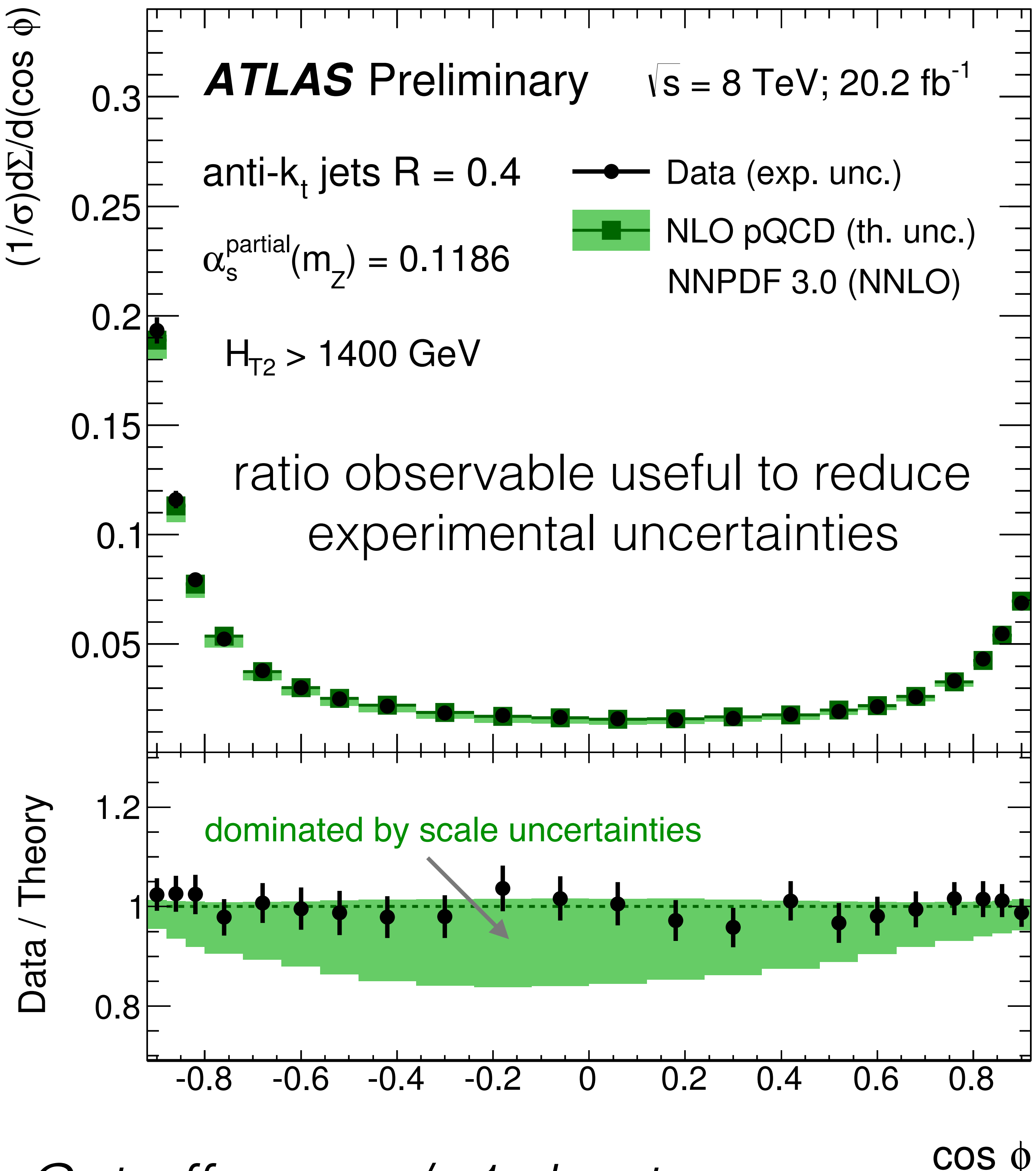
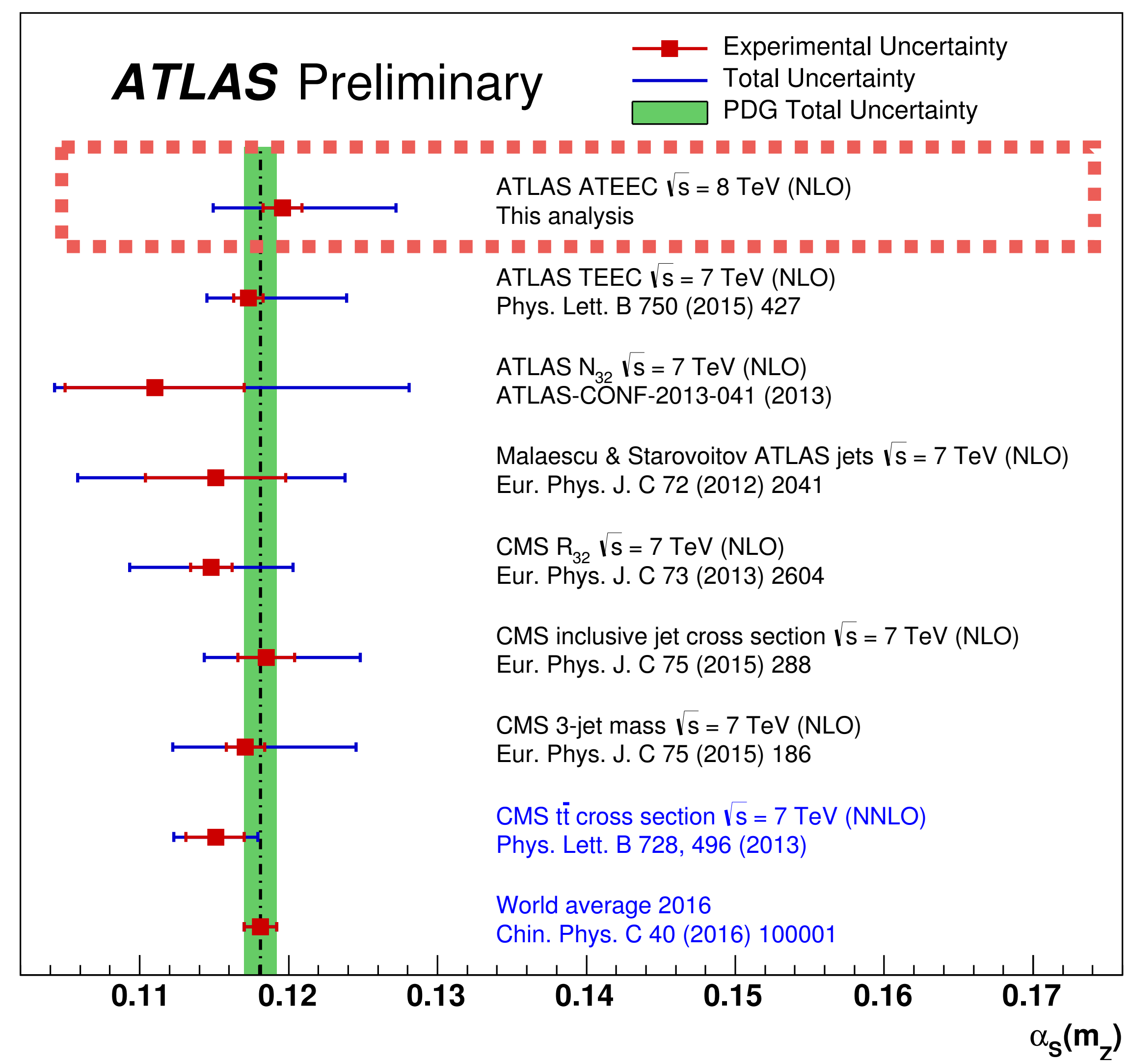


Cut off near +/- 1 due to resummation sensitivity

χ^2 fit for α_s

using unfolded data

(N.B. LO $= \mathcal{O}(\alpha_s^3)$)



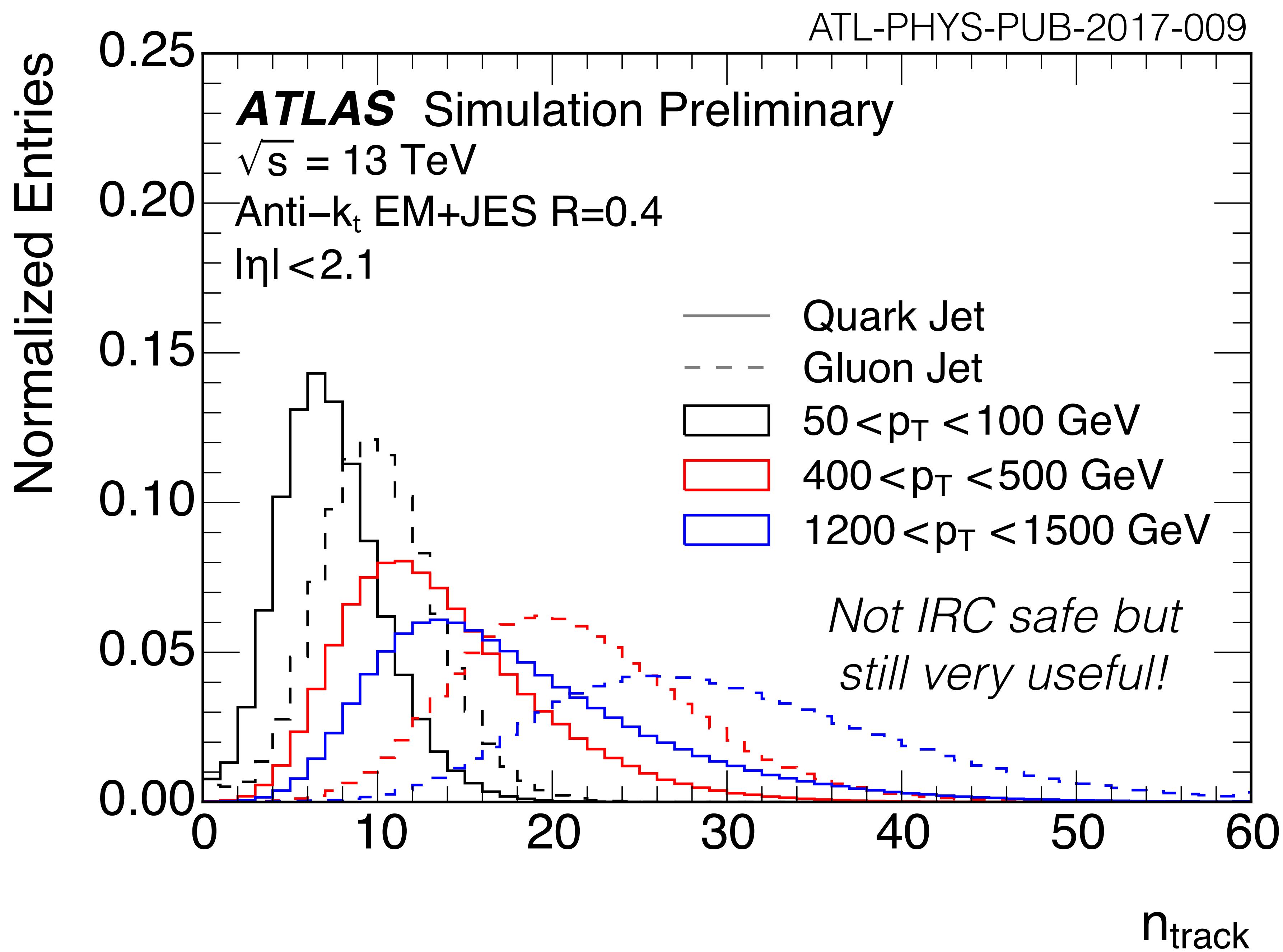
consistent with other *pp* jet extractions

The radiation pattern inside jets probes a different regime of QCD

The most basic of all observables is particle multiplicity

Charged particle tracks are our proxy for particles

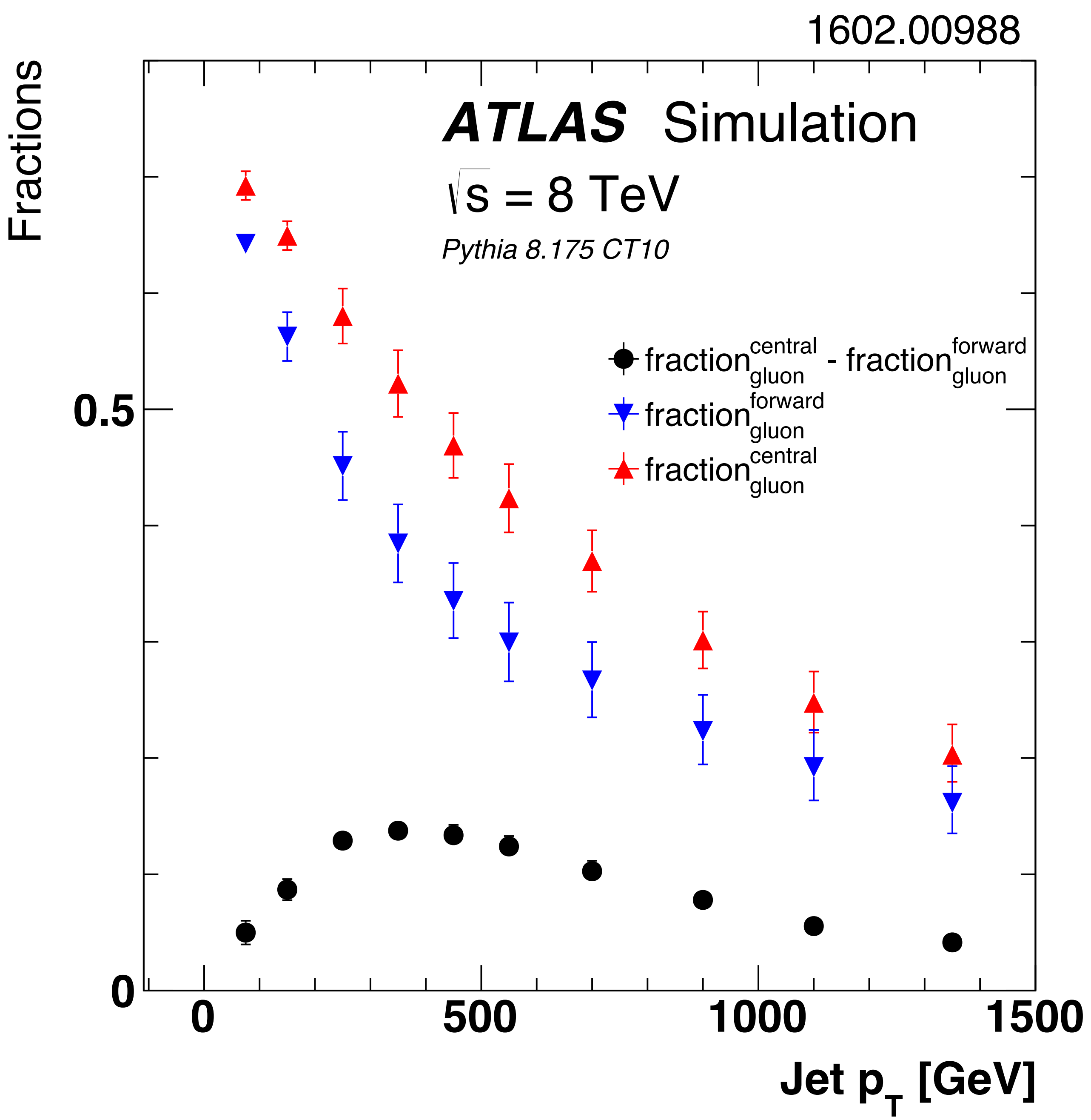
ATL-PHYS-PUB-2017-009



Multiplicity scales with the color charge (C_F/C_A): useful for distinguishing q/g*!

At LL, this is actually* ***all* *that distinguishes q/g*

Charged-particle Multiplicity



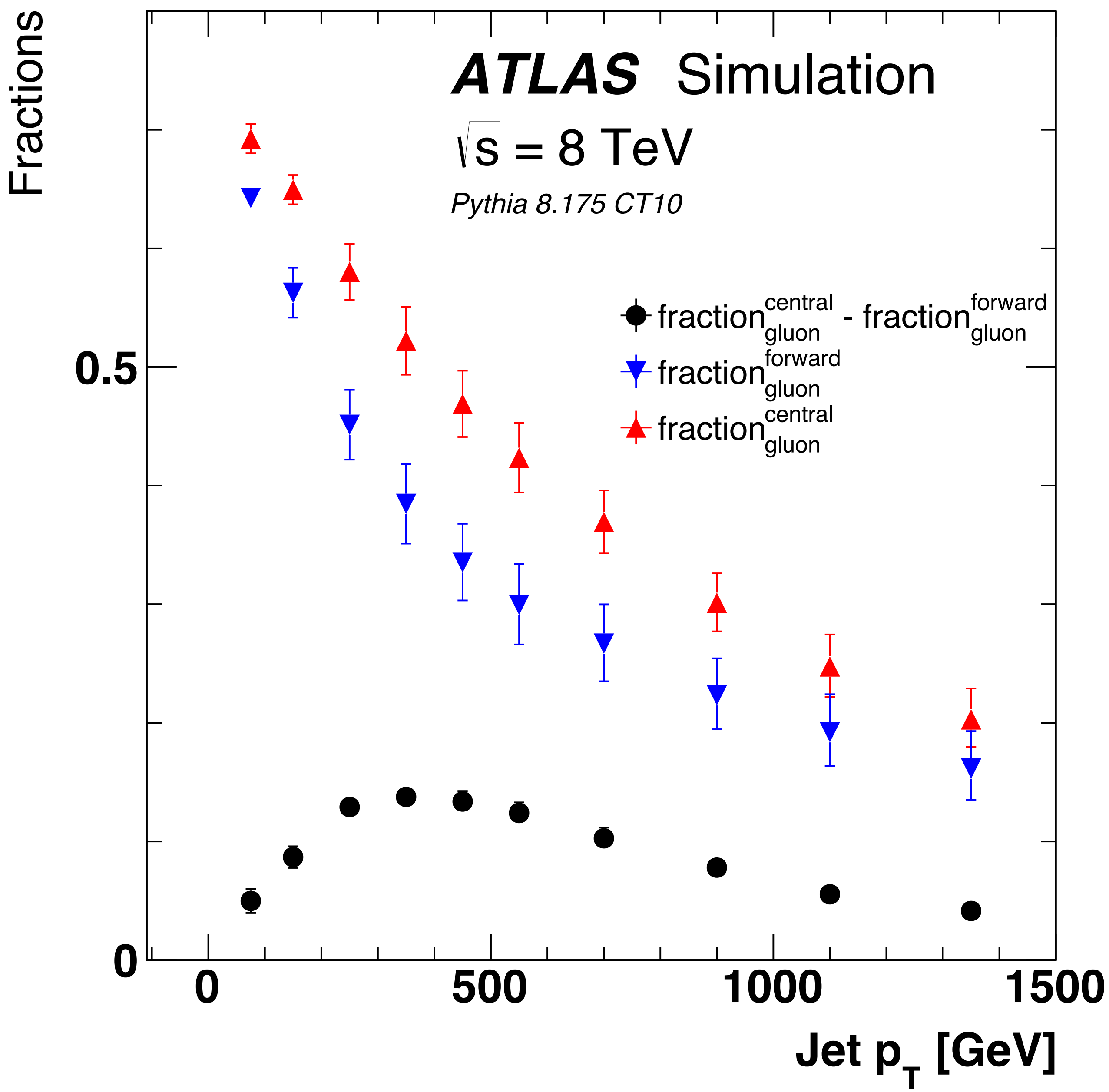
We can use (jet) kinematic information to extract separate q/g jet substructure

$$\langle n^{\mathrm{f}}_{\mathrm{charged}}\rangle = f^{\mathrm{f}}_{\mathrm{q}}\langle n^{q}_{\mathrm{charged}}\rangle + f^{\mathrm{f}}_{\mathrm{g}}\langle n^{g}_{\mathrm{charged}}\rangle$$
$$\langle n^{\mathrm{c}}_{\mathrm{charged}}\rangle = f^{\mathrm{c}}_{\mathrm{q}}\langle n^{q}_{\mathrm{charged}}\rangle + f^{\mathrm{c}}_{\mathrm{g}}\langle n^{g}_{\mathrm{charged}}\rangle$$

from PDF ⊕ ME

q/g multiplicity separately measured by exploiting rapidity (for a fixed p_T, quark jets tend to be more forward)

Even though it is not IRC-safe, it is still possible to estimate the p_T-dependence in pQCD.



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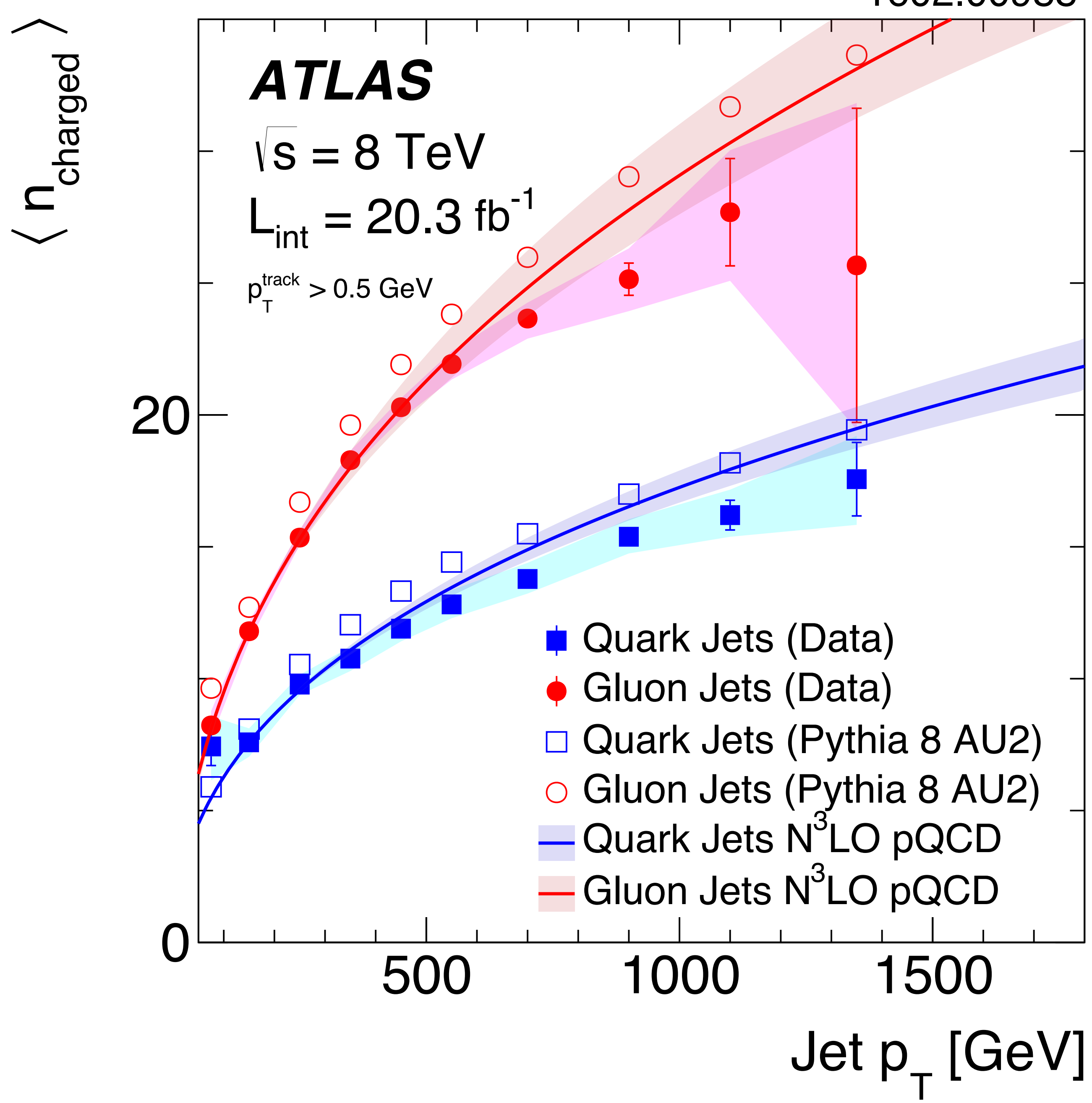
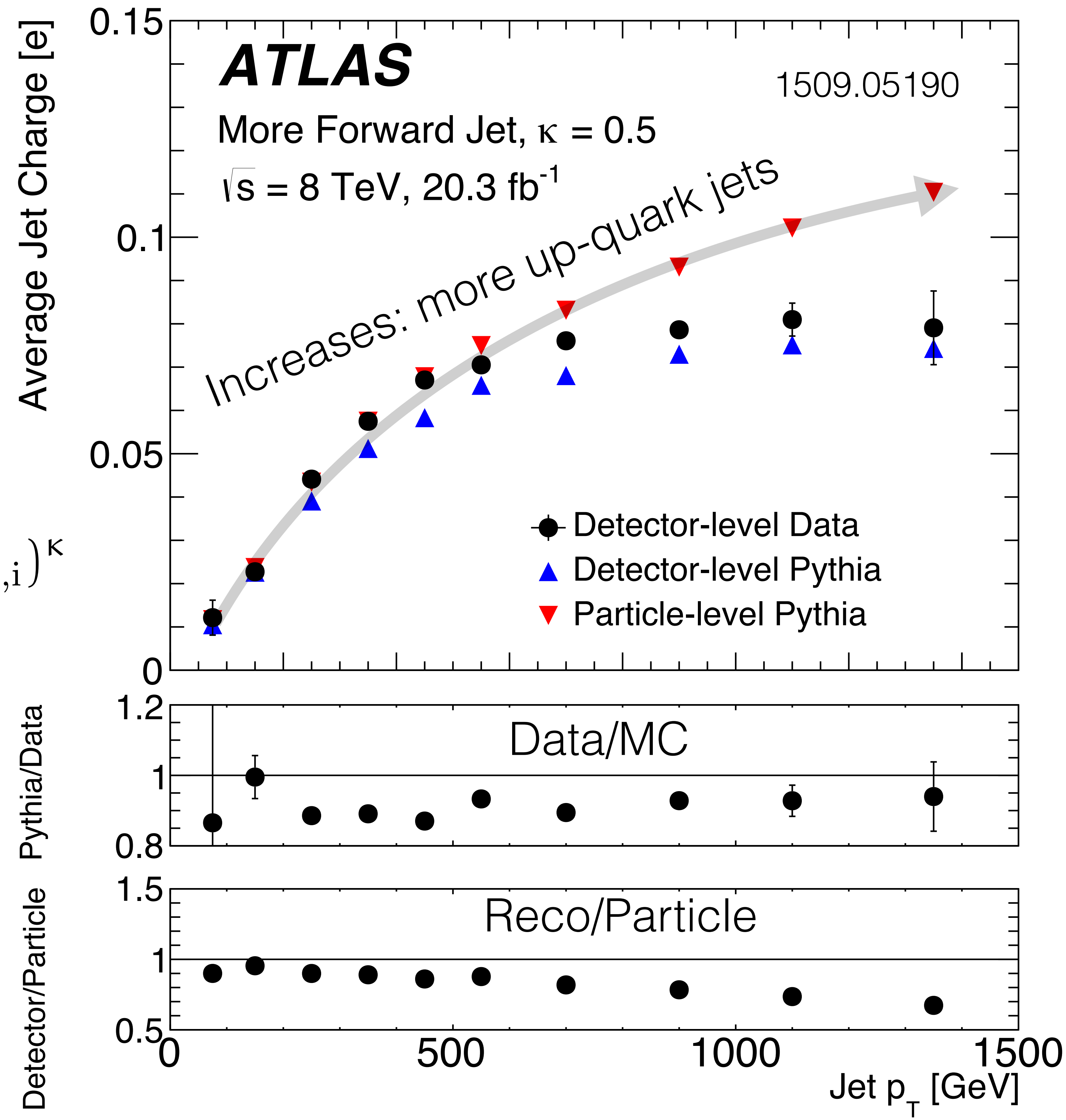


Interestingly, we find a better description of the data by increasing the FSR α_s (but this creates tension with LEP tuning)

Next: weight the tracks .. start with their charge!

$$Q_J = \frac{1}{(p_{TJ})^\kappa} \sum_{i \in \mathbf{Tracks}} q_i \times (p_{T,i})^\kappa$$

Allows us to look inside the proton "by eye" - more up quarks at high x!



Jet Charge Beyond PDFs

What happens when we 'remove' the PDF?
Does the jet charge for jets of a particular type depend on p_T?

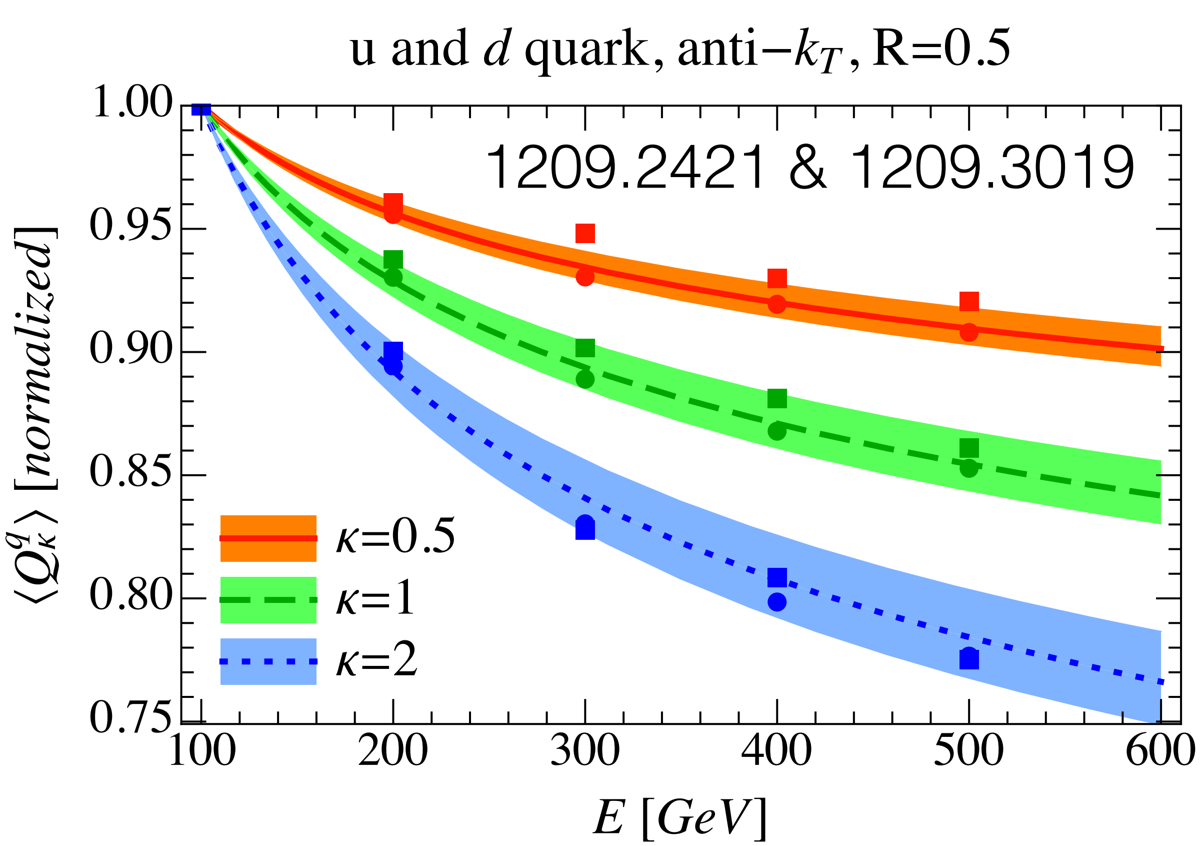
$$\langle Q_J \rangle = [1 + \mathcal{O}(\alpha_s)] \sum_h Q_h \widetilde{D}_q^h(\kappa, E \times R)$$

(scale violation)

h = hadron

Moment of a **fragmentation function**

Prediction:
$c < 0$ and $dc/d\kappa < 0$



non-perturbative…but we know how it evolves with scale!

$$\frac{p_T}{\langle Q_\kappa \rangle} \frac{d}{dp_T} \langle Q_\kappa \rangle = \frac{\alpha_s}{\pi} \widetilde{P}_{qq}(\kappa) \equiv c(\kappa)$$

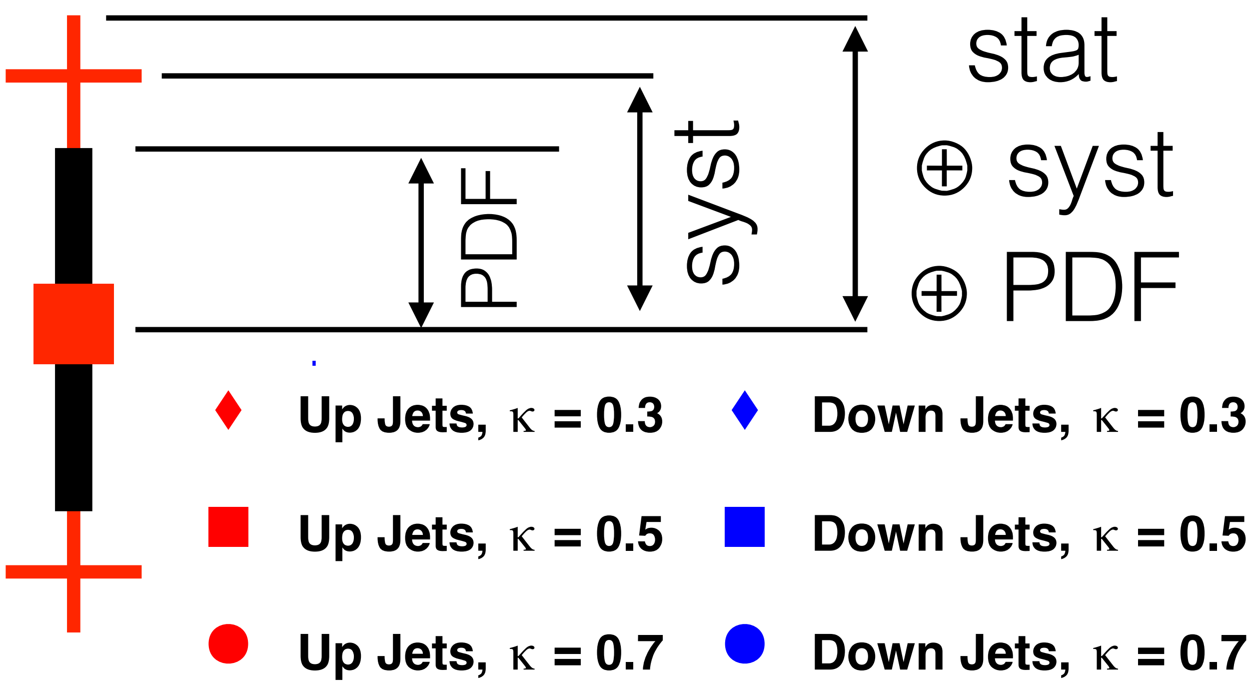
Moment of a **splitting function**

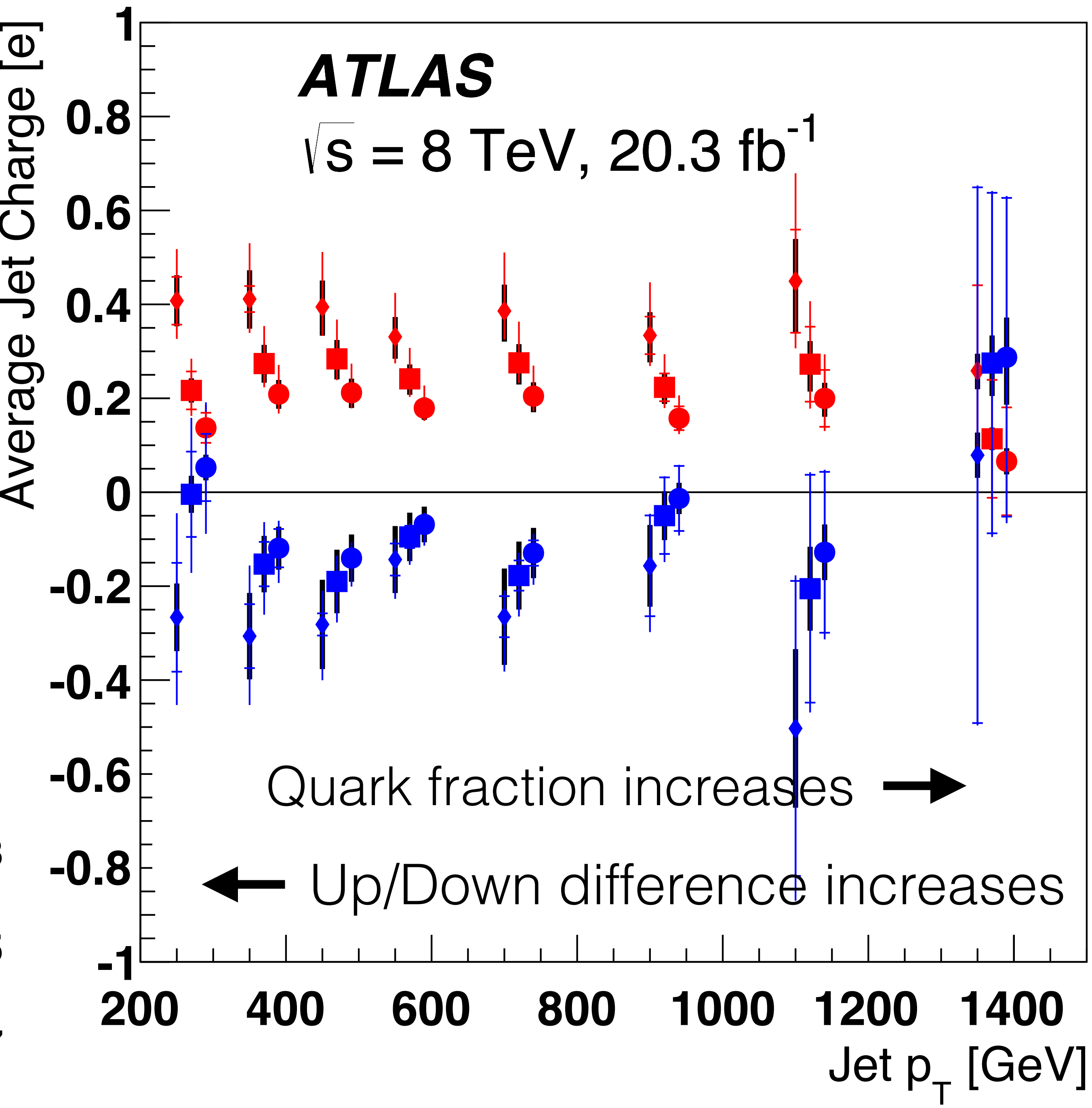
Jet charge per flavor: extraction

$$\langle Q_i^{\text{forward}} \rangle = \left(f_{\text{up,i}}^{\text{forward}} - f_{\text{anti-up,i}}^{\text{forward}} \right) Q_i^{\text{up}} + \left(f_{\text{down,i}}^{\text{forward}} - f_{\text{anti-down,i}}^{\text{forward}} \right) Q_i^{\text{down}}$$

$$\langle Q_i^{\text{central}} \rangle = \left(f_{\text{up,i}}^{\text{central}} - f_{\text{anti-up,i}}^{\text{central}} \right) Q_i^{\text{up}} + \left(f_{\text{down,i}}^{\text{central}} - f_{\text{anti-down,i}}^{\text{central}} \right) Q_i^{\text{down}}$$

Can exploit the η-dependence of the flavor fractions *f* to extract the **up**- and **down**-quark jet charge in each p_T bin.

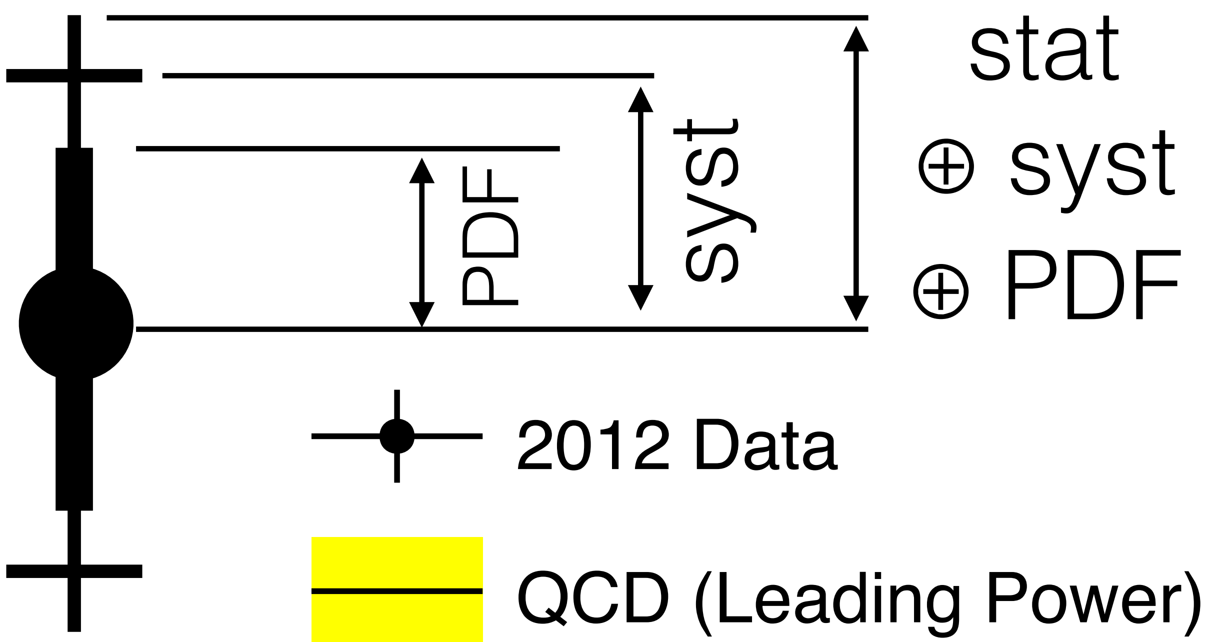


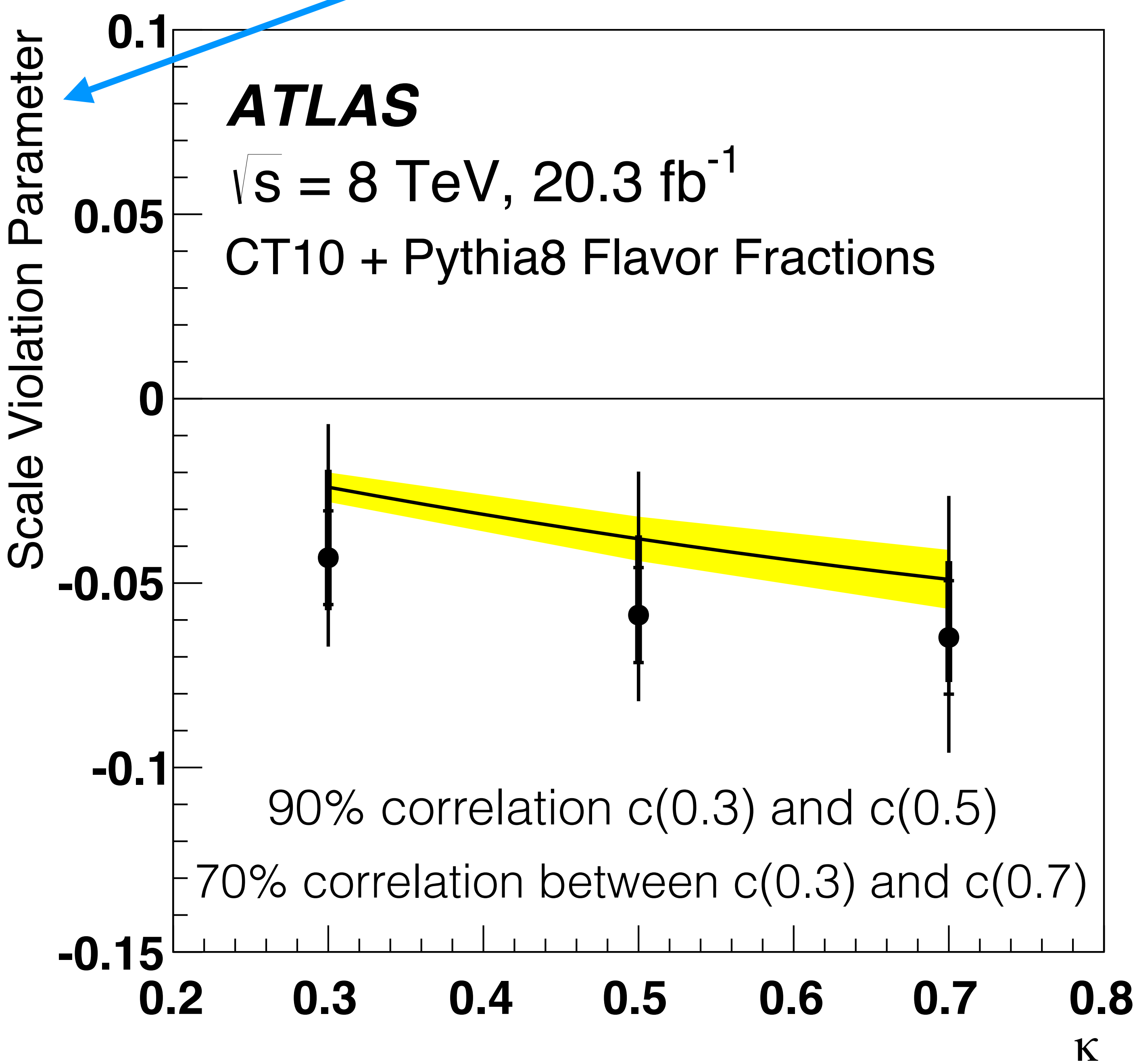


$$\langle Q_i \rangle \approx \sum \alpha_{f,i} \bar{Q}_f (1 + c_f \log(p_{T,i}/\bar{p}_T))$$

Question: accounting for PDFs, does jet charge depend on p_T?

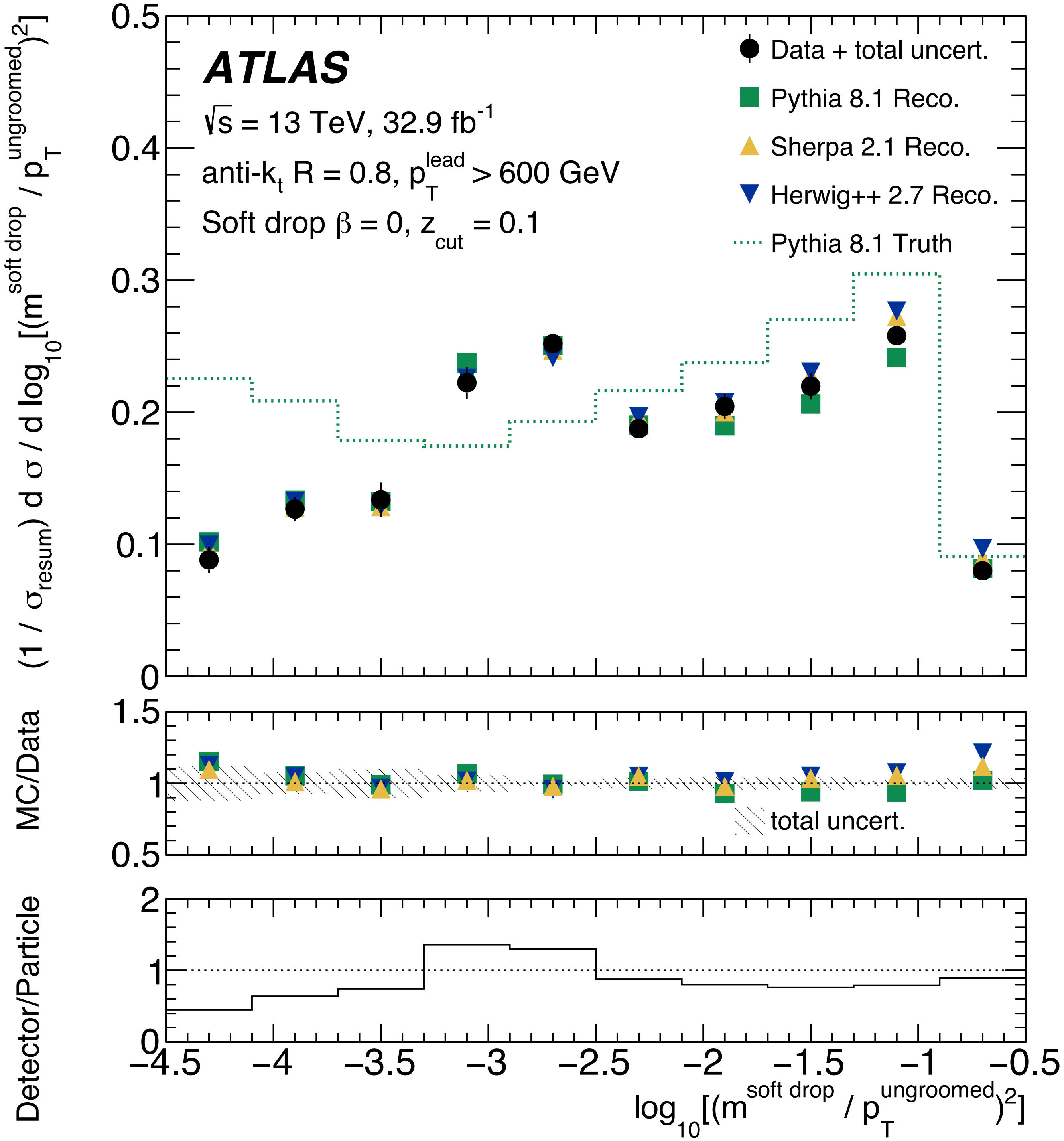
Data and theory agree: Yes!





[1209.2421 & 1209.3019]

Fully Perturbative: Jet Mass



NP regime

resummation regime

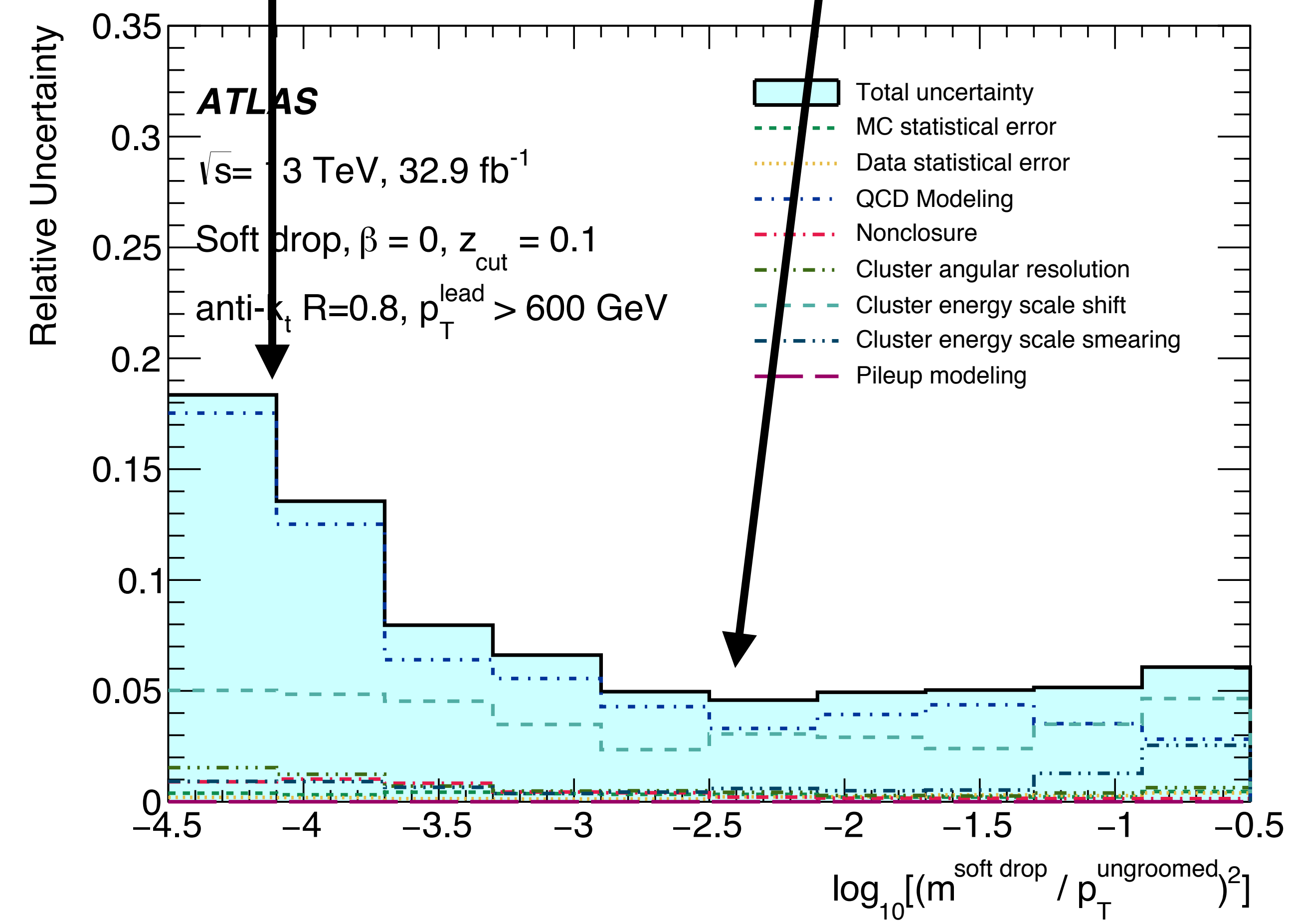
fixed-order regime

Recent theory advances: jet mass now calculated at (N)NLL!

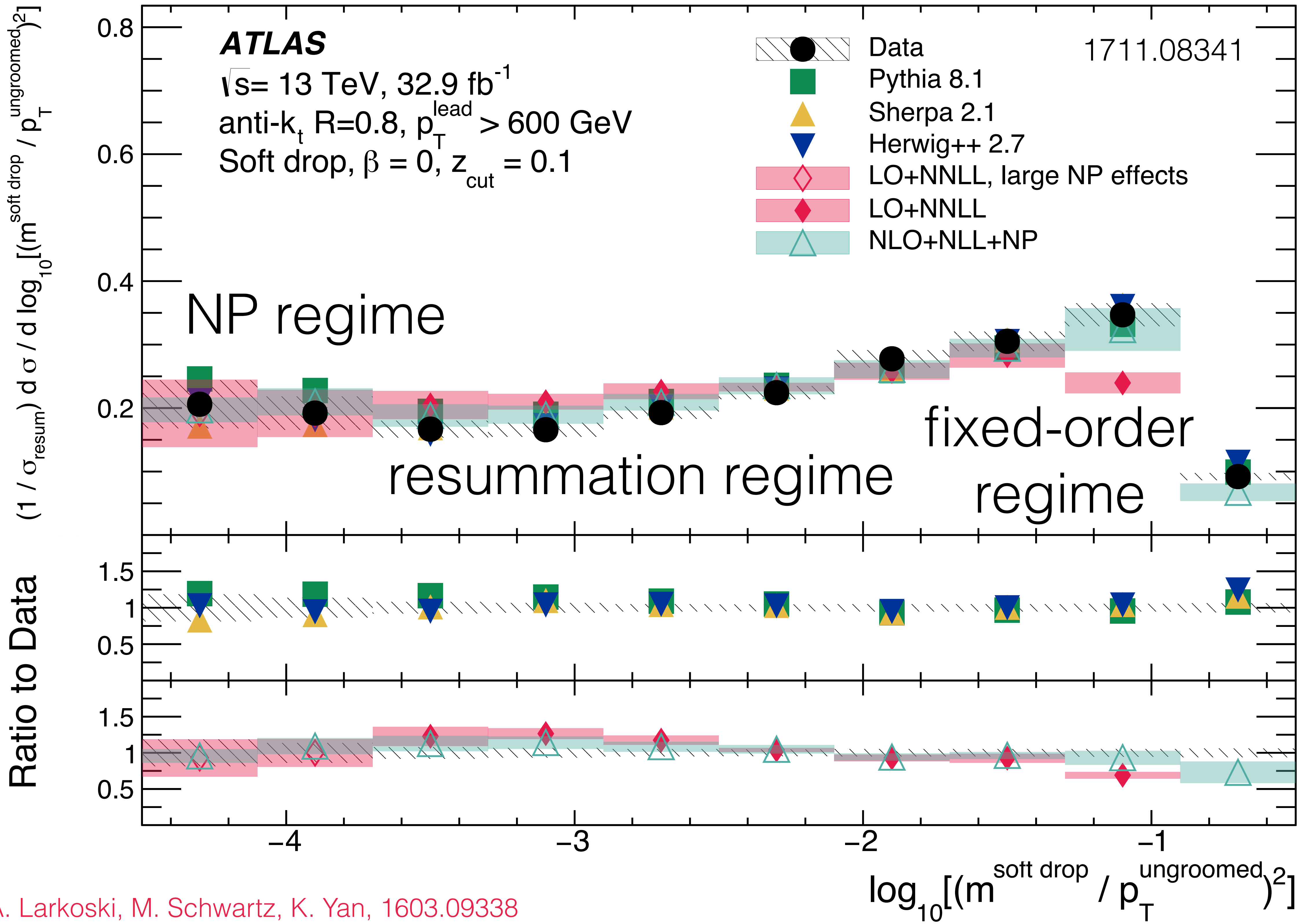
Can we match the precision experimentally?

NP modeling

cluster energy



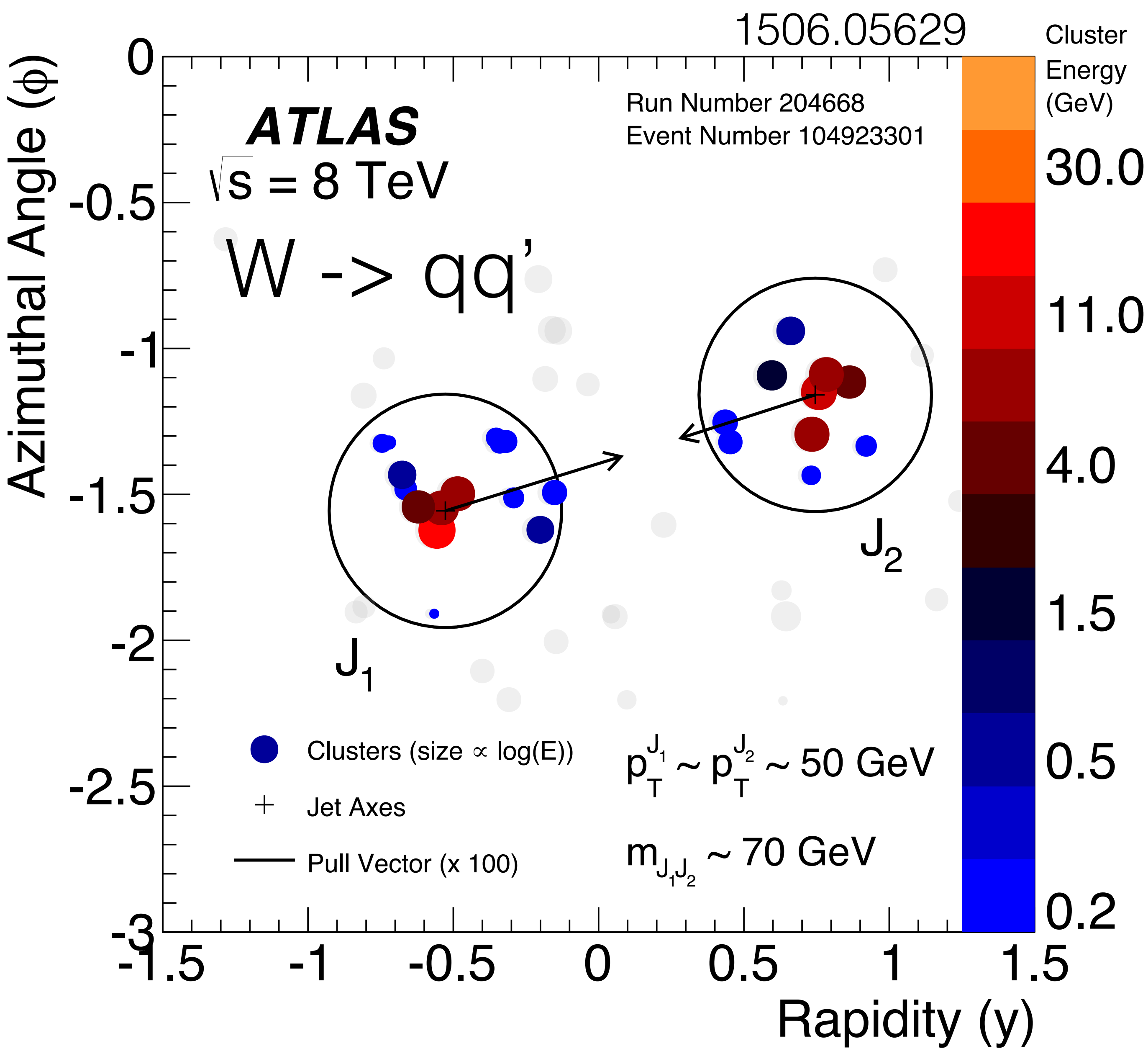
Soft-drop Jet Mass

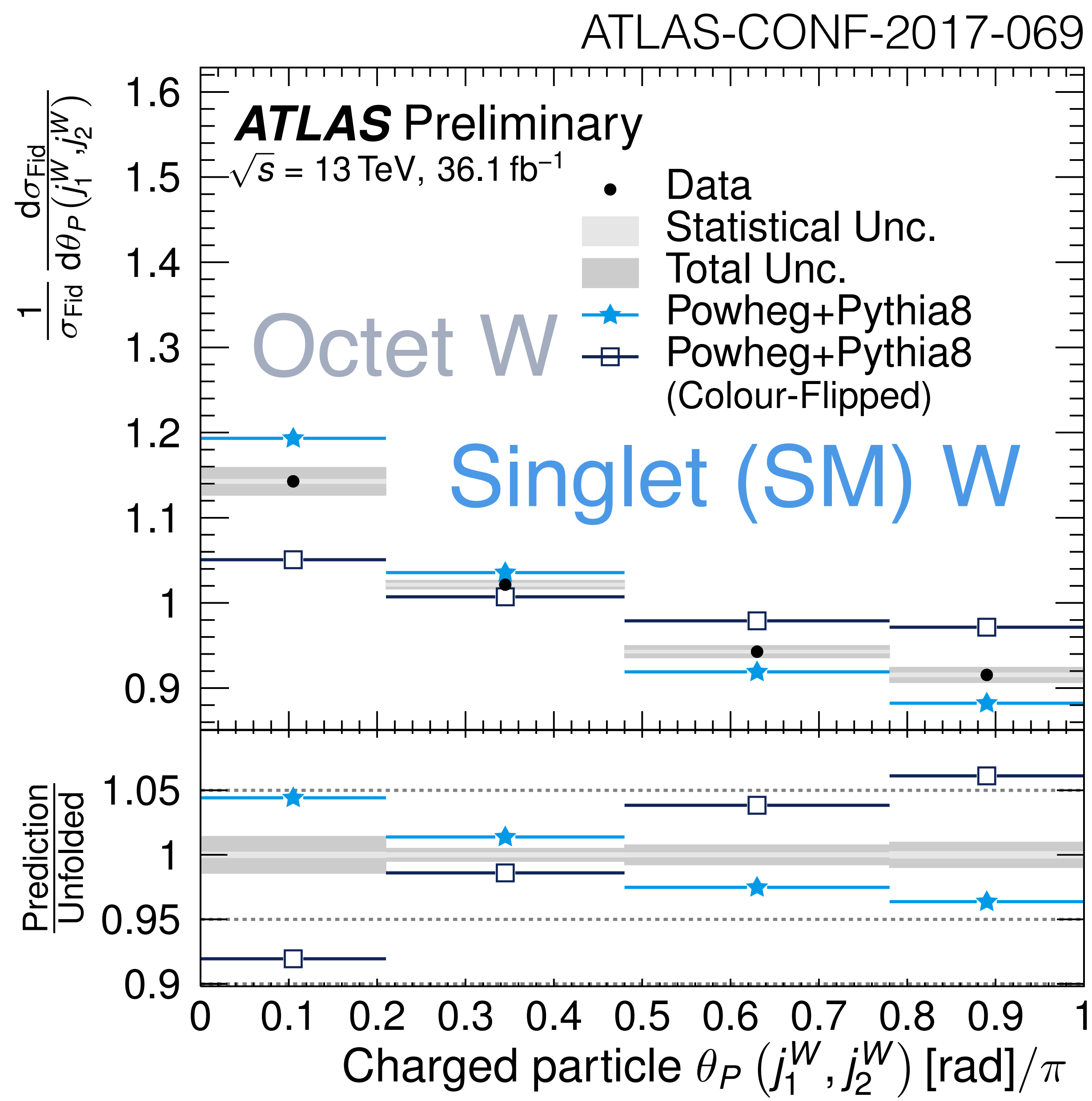


C. Frye, A. Larkoski, M. Schwartz, K. Yan, 1603.09338

S. Marzani, L. Schunk, G. Soyez, 1704.02210

Last measurement: colorflow



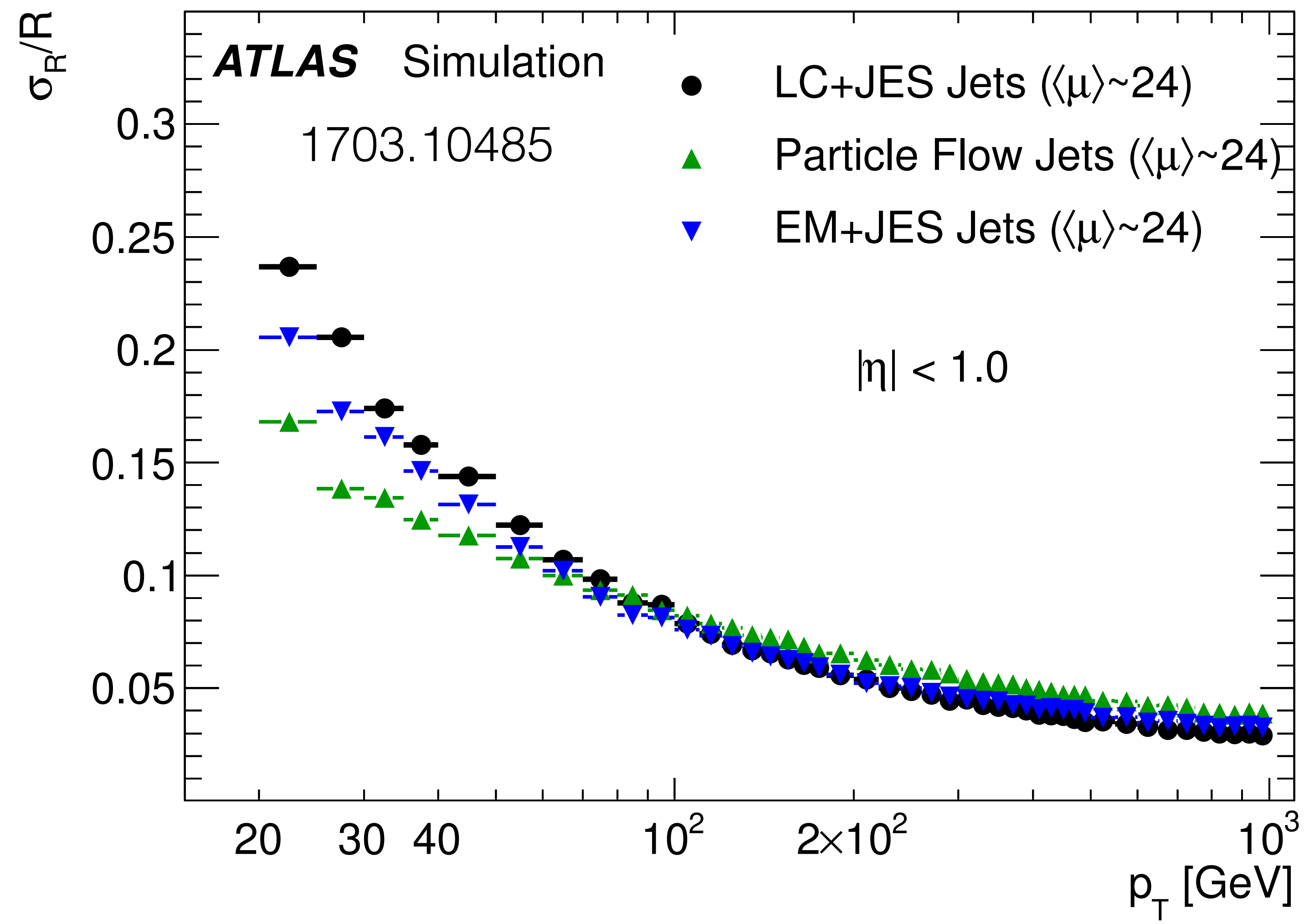


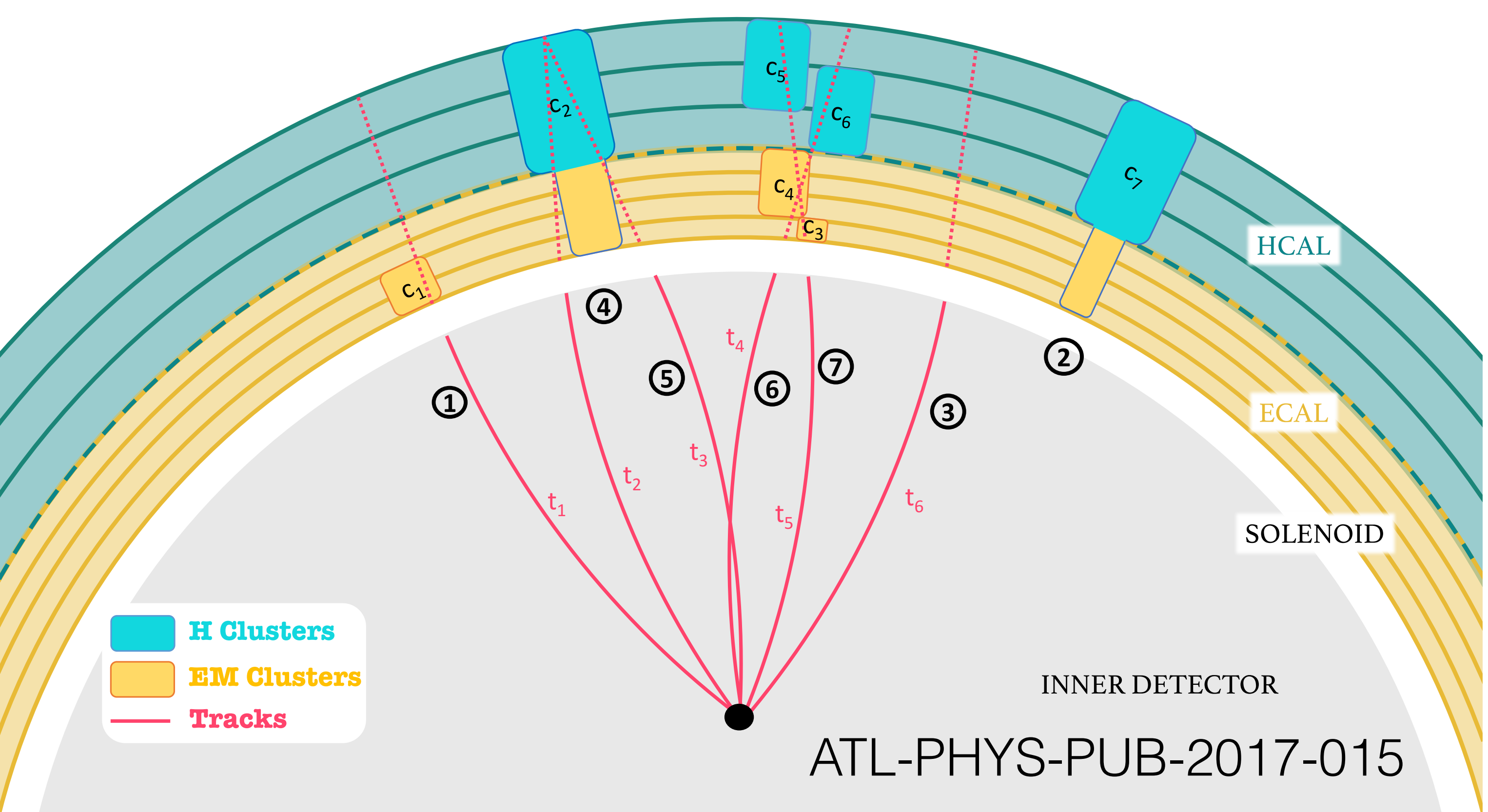
The jet pull angle measures how much the radiation pattern from one jet leans toward another.

Just to show that there is still work to do!

The "vacuum" jet program is probing all aspects of the rich structure of QCD

There are exciting new opportunities in the near future; in particular with **tracking inside jets**!





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More: track-assisted jet substructure, Track-Calo Clusters

Even more: constituent-based pileup subtraction.

New Tools: Constituent pileup subtraction

Precision jet (substructure) at the LHC and HL-LHC will require better pileup mitigation.

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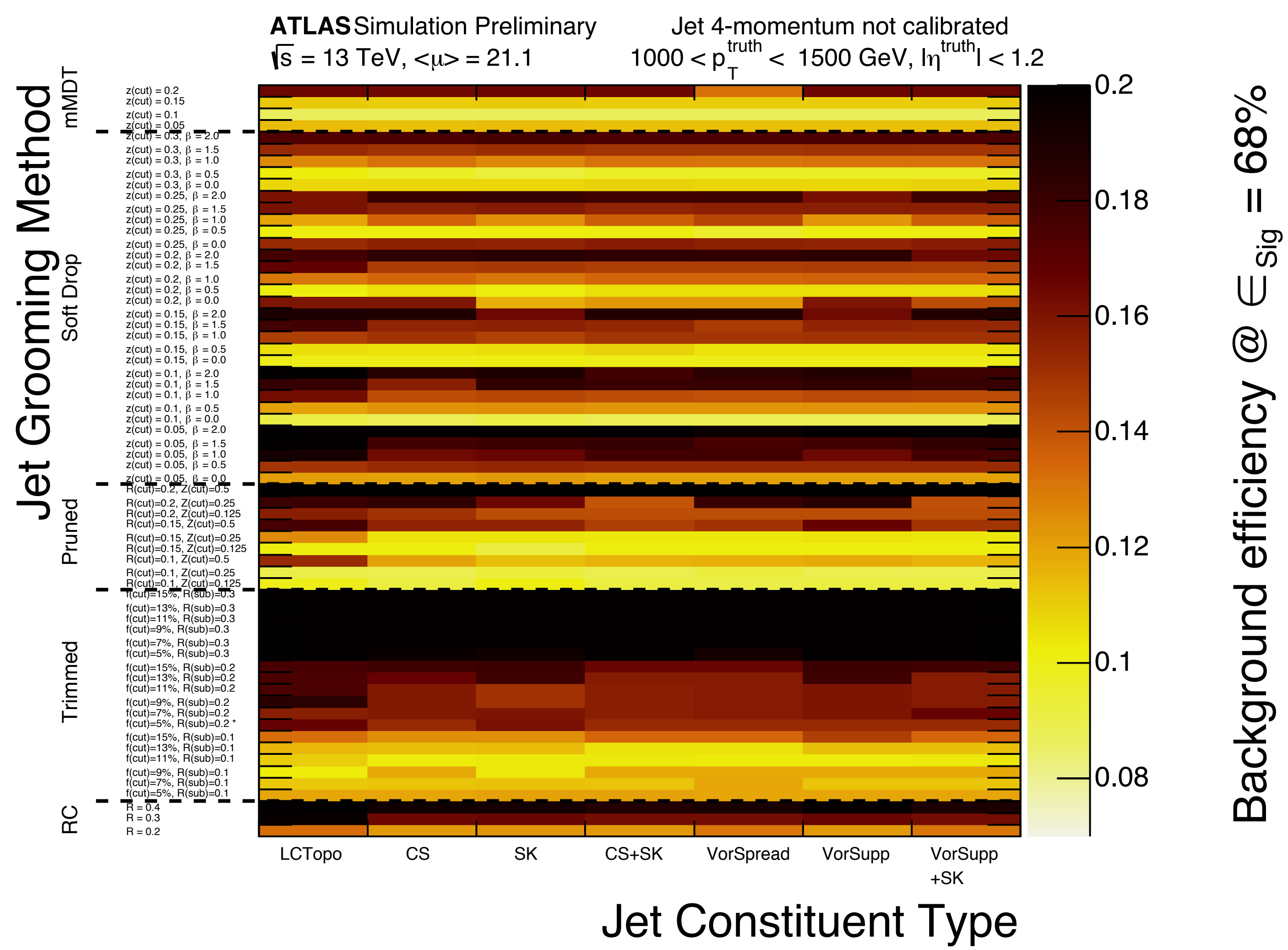
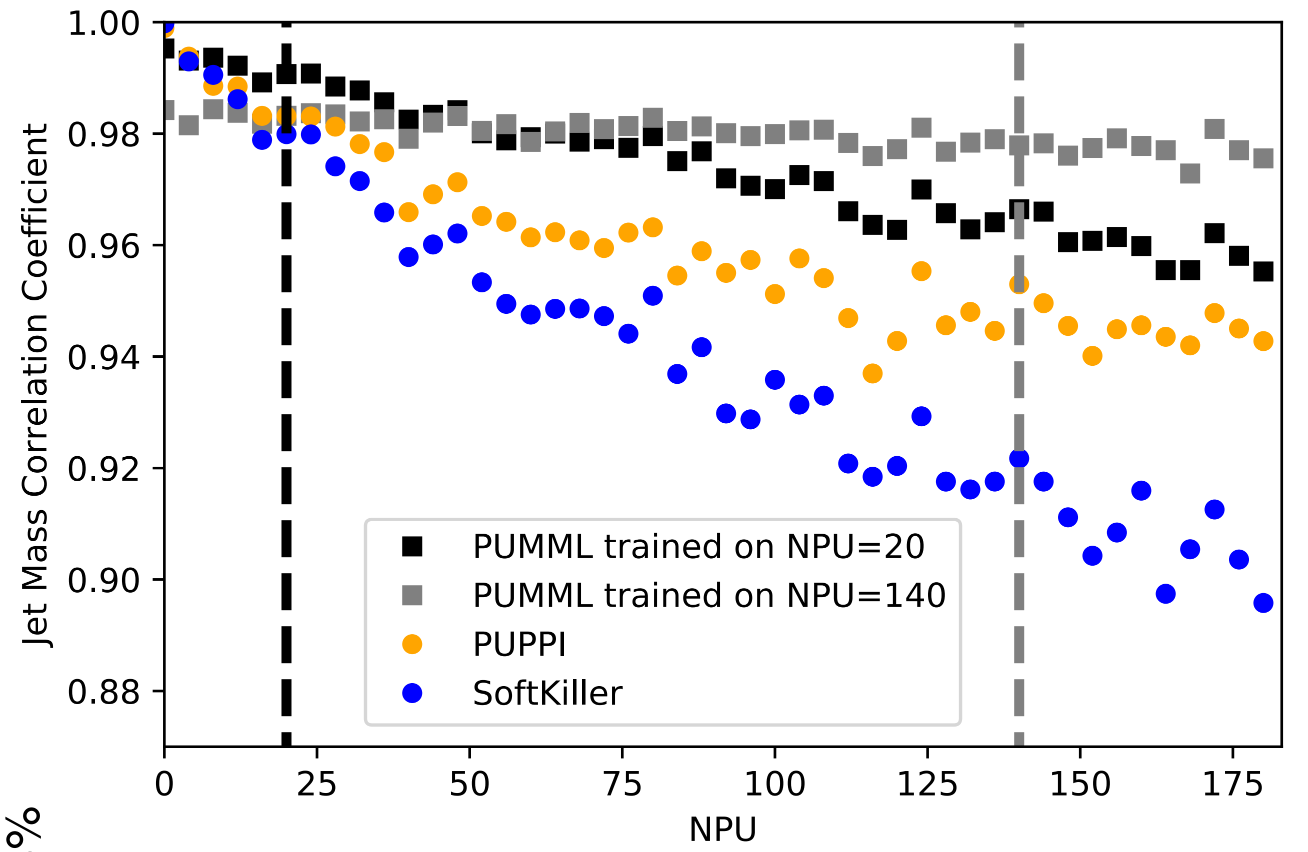




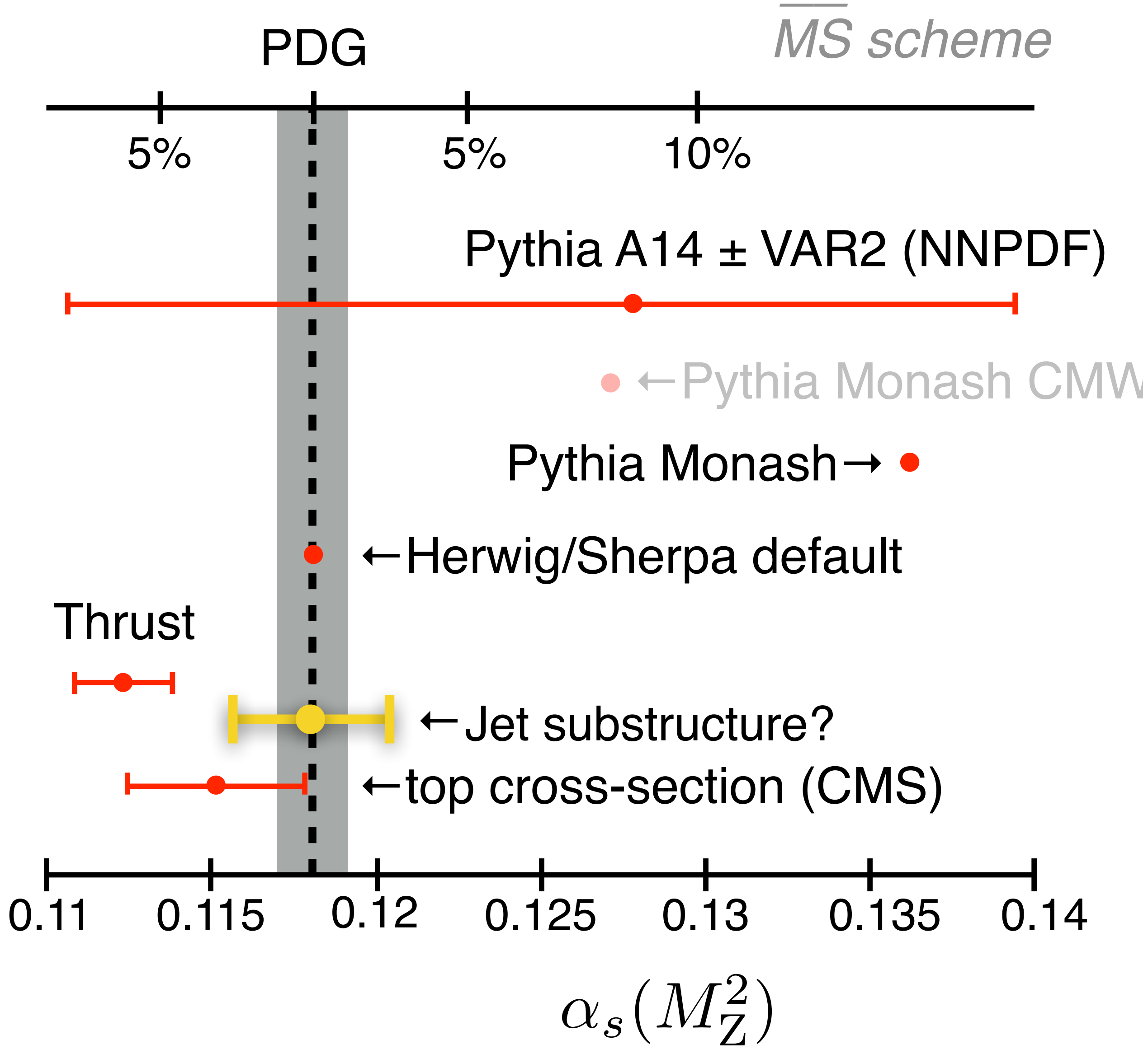
P. Komiske, E. Metodiev, **BPN**, M. Schwartz, 1707.08600

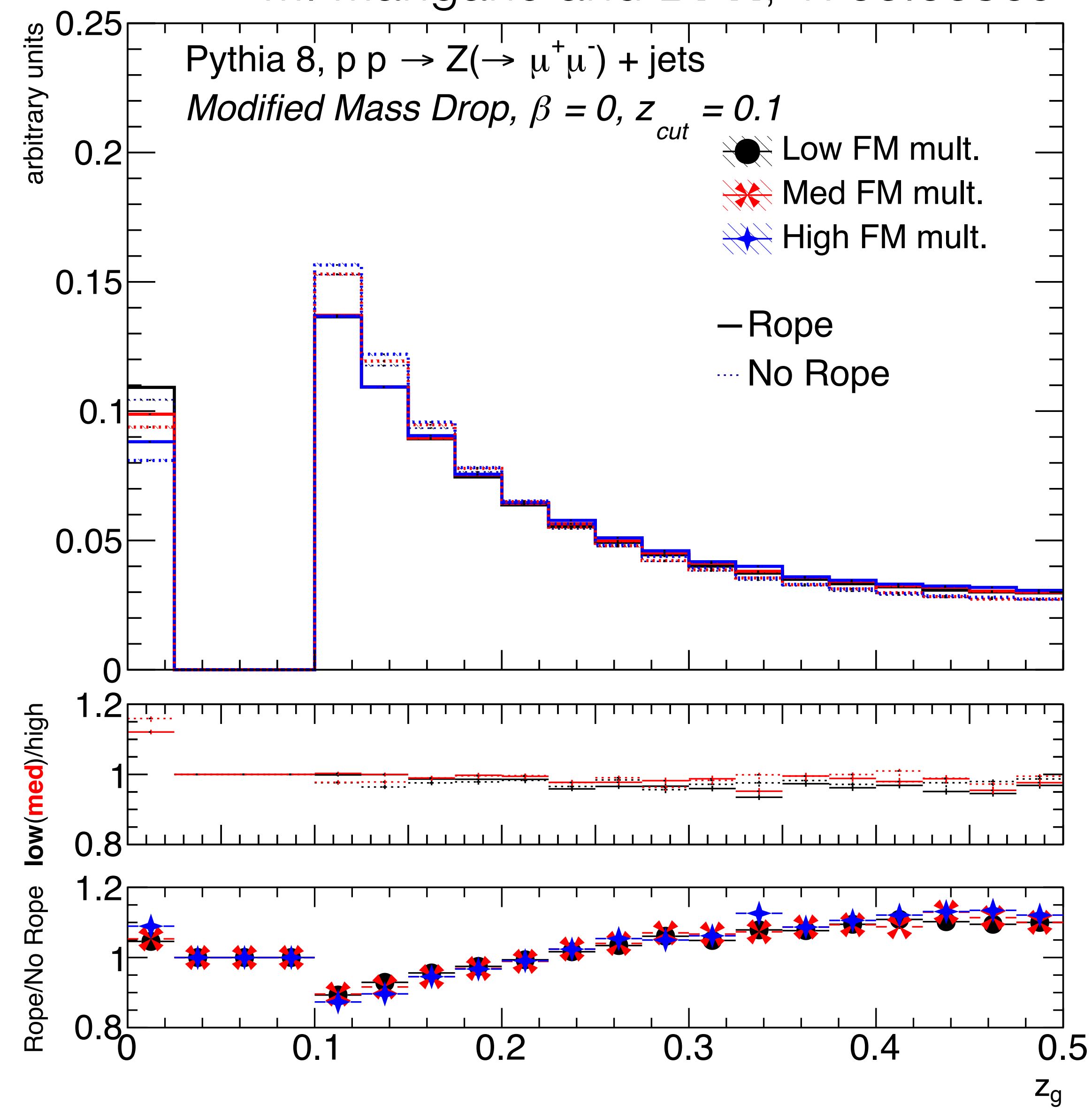
Many studies on-going to optimize/improve our algorithms. This is a very active area in pp!

many of these also (will also) work for HI…

The future

We have big ambitions … the fun times have just begun!





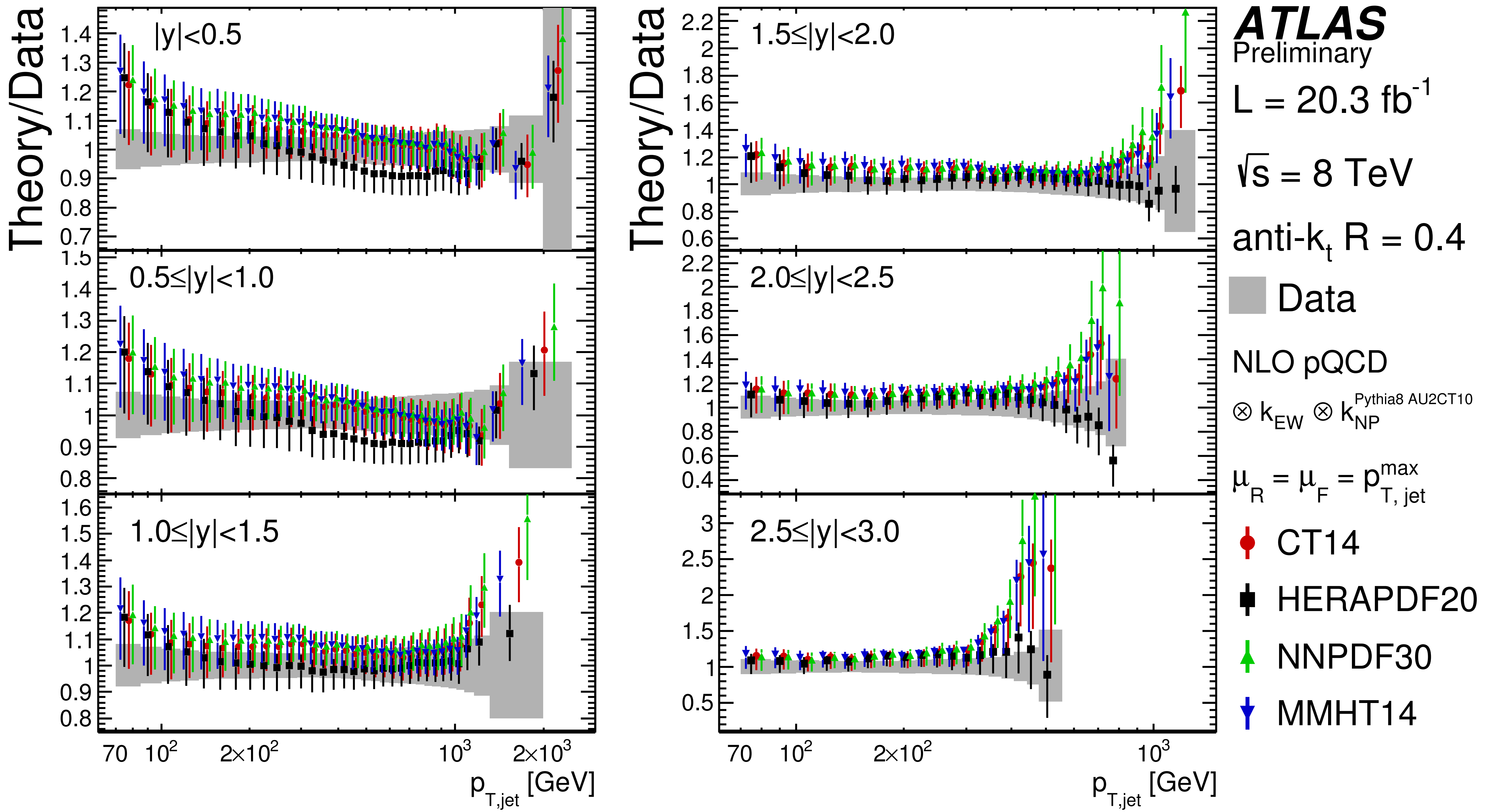
I. Moult, **BPN**, G. Soyez, J. Thaler, et al. (Les Houches Jet WG 2017)

Questions?


ATLAS
EXPERIMENT
Run: 302347
Event: 753275626
2016-06-18 18:41:48 CEST

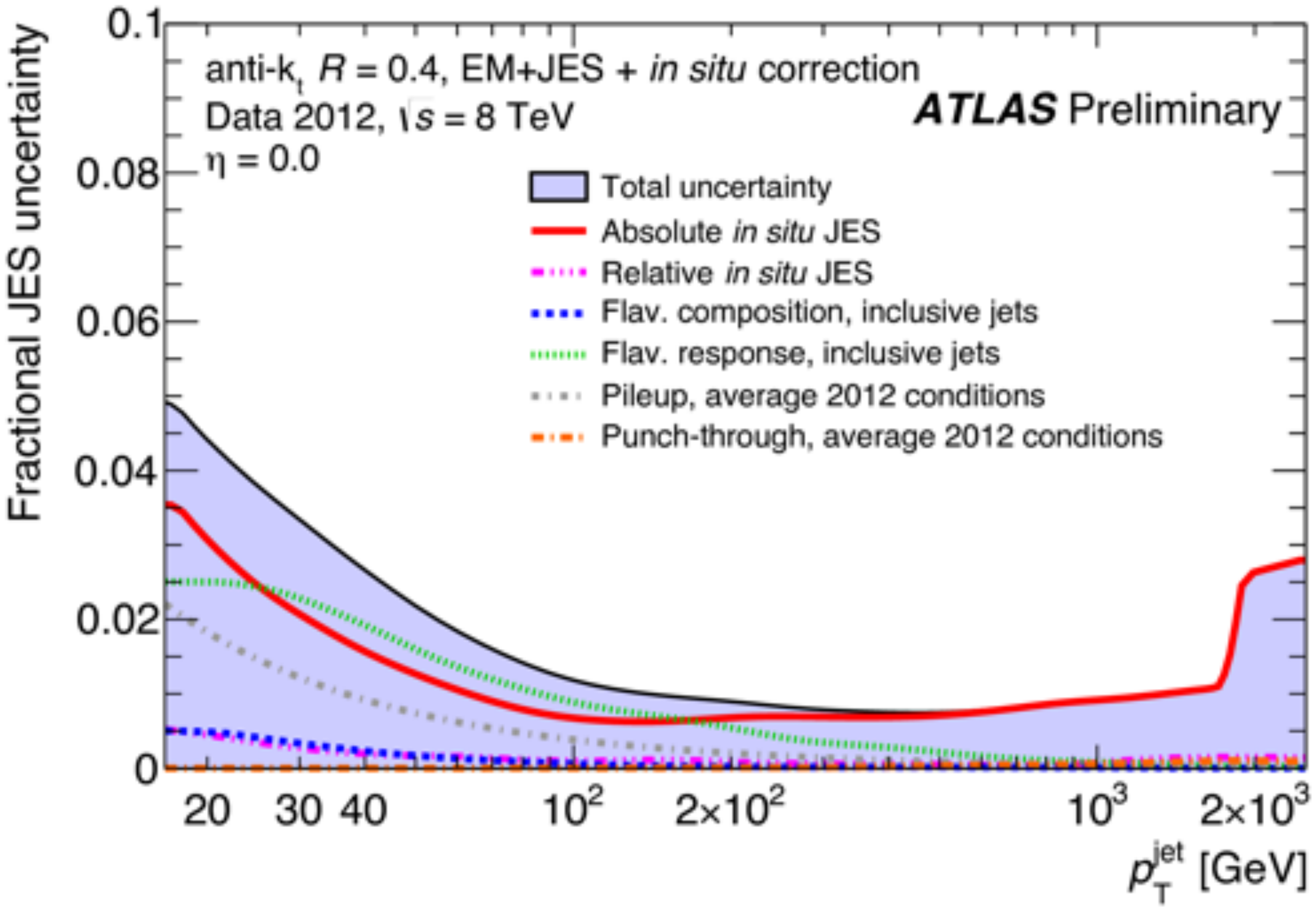
Backup

Jet Cross-sections

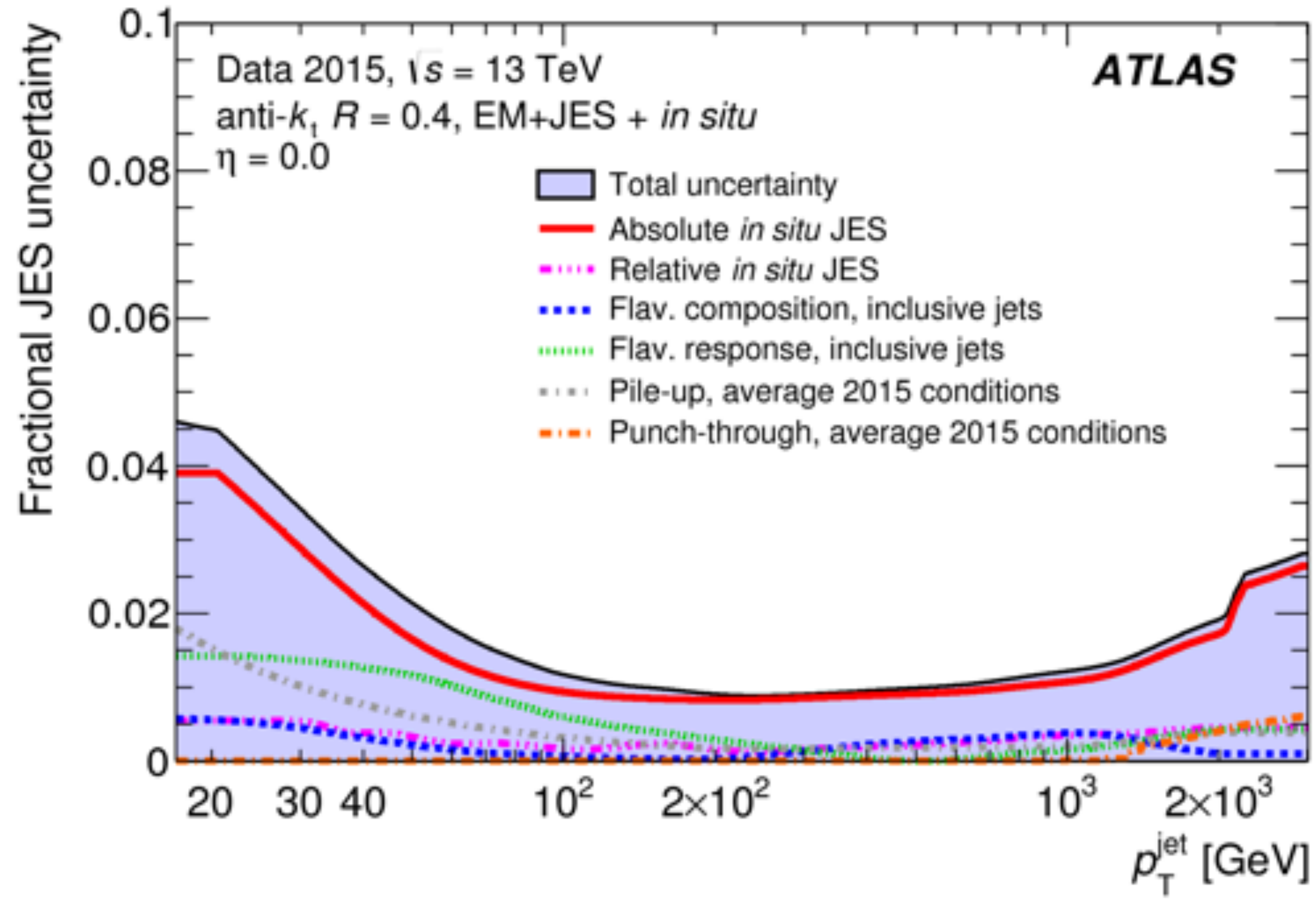


Jet Energy Scale Uncertainty

ATLAS-CONF-2015-037

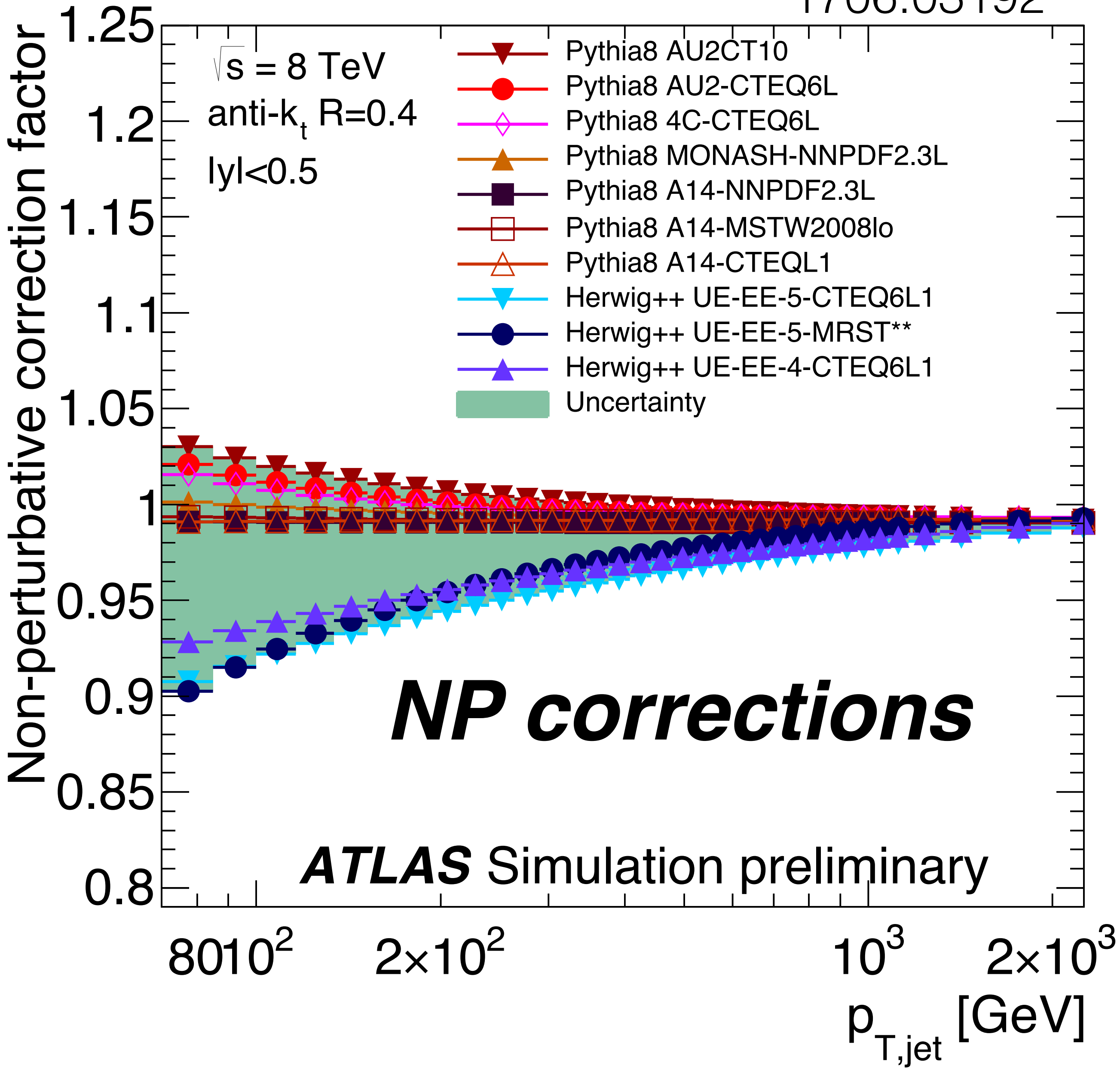


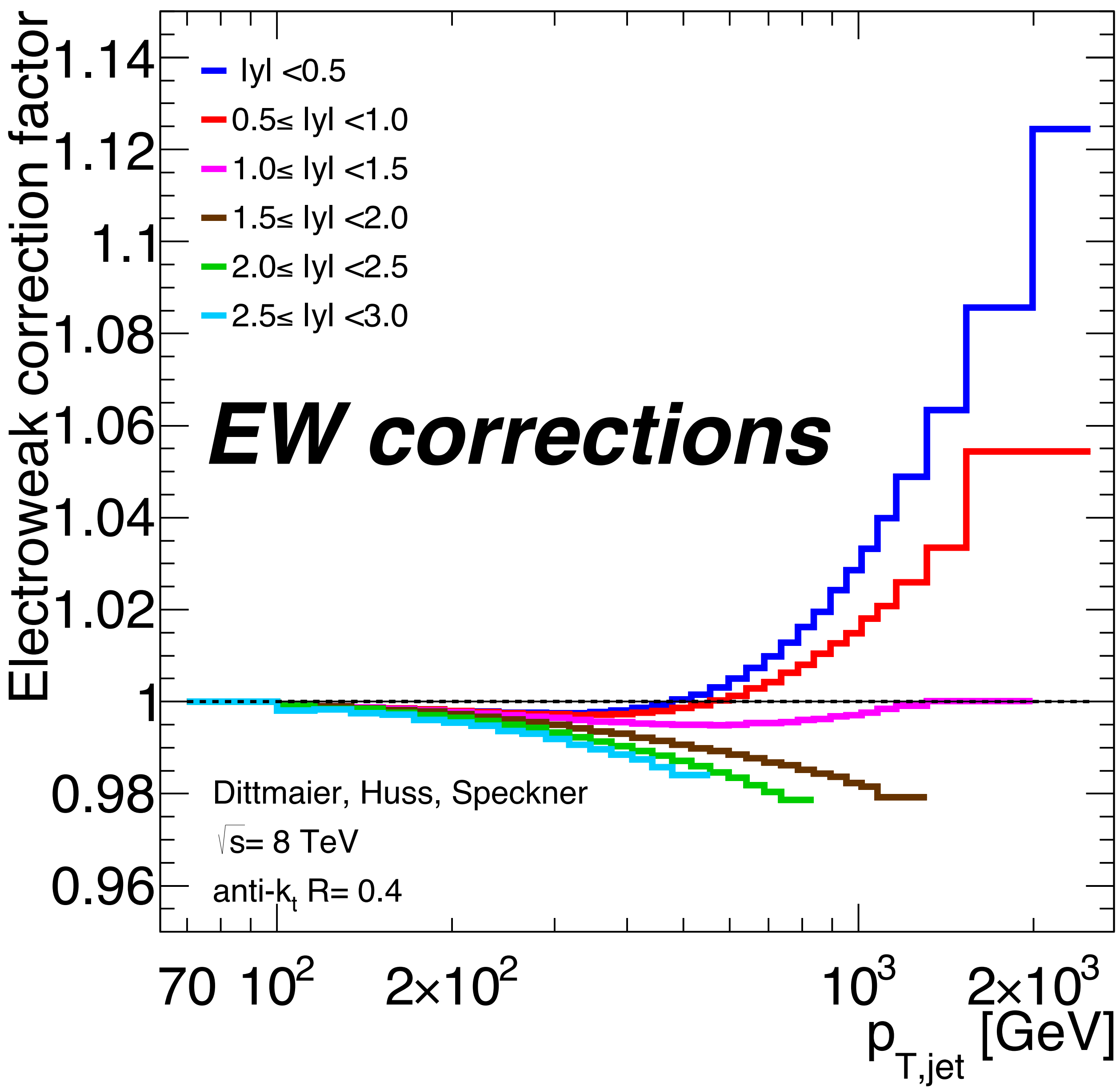
PERF-2016-04



We are probing a regime where NP effects are negligible.

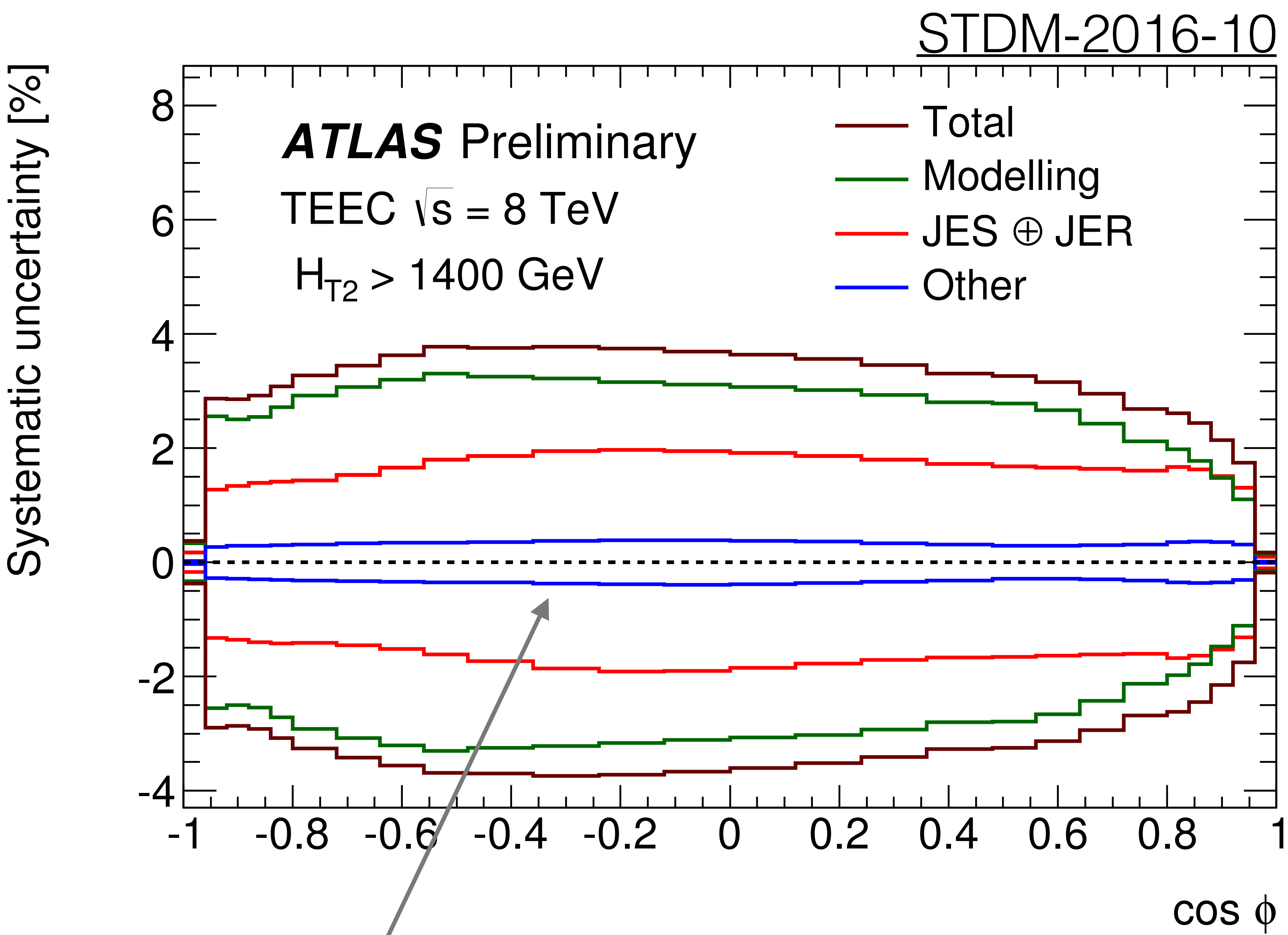
1706.03192





But electroweak corrections are not small!

Part II: Energy-energy correlation uncertainties

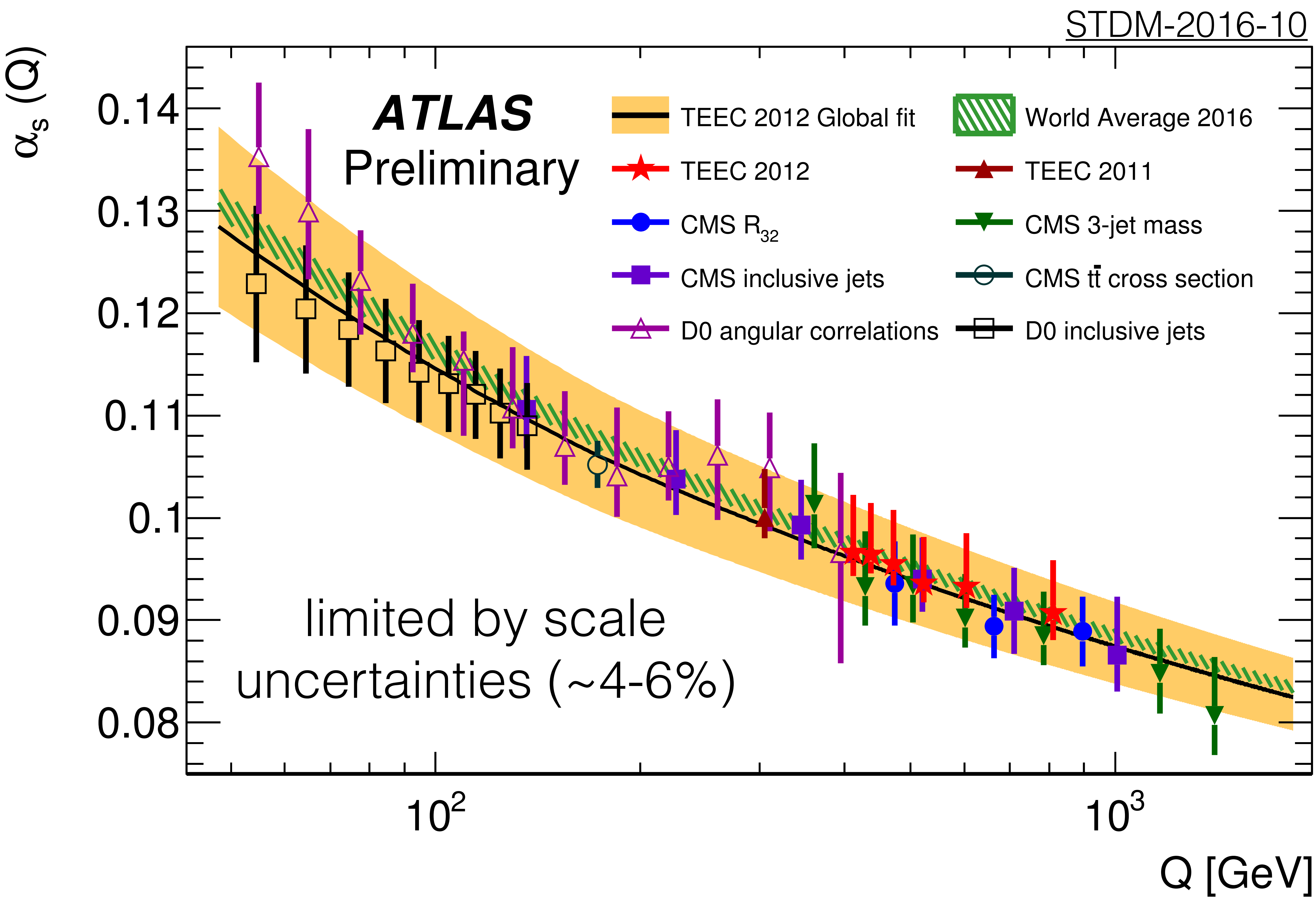


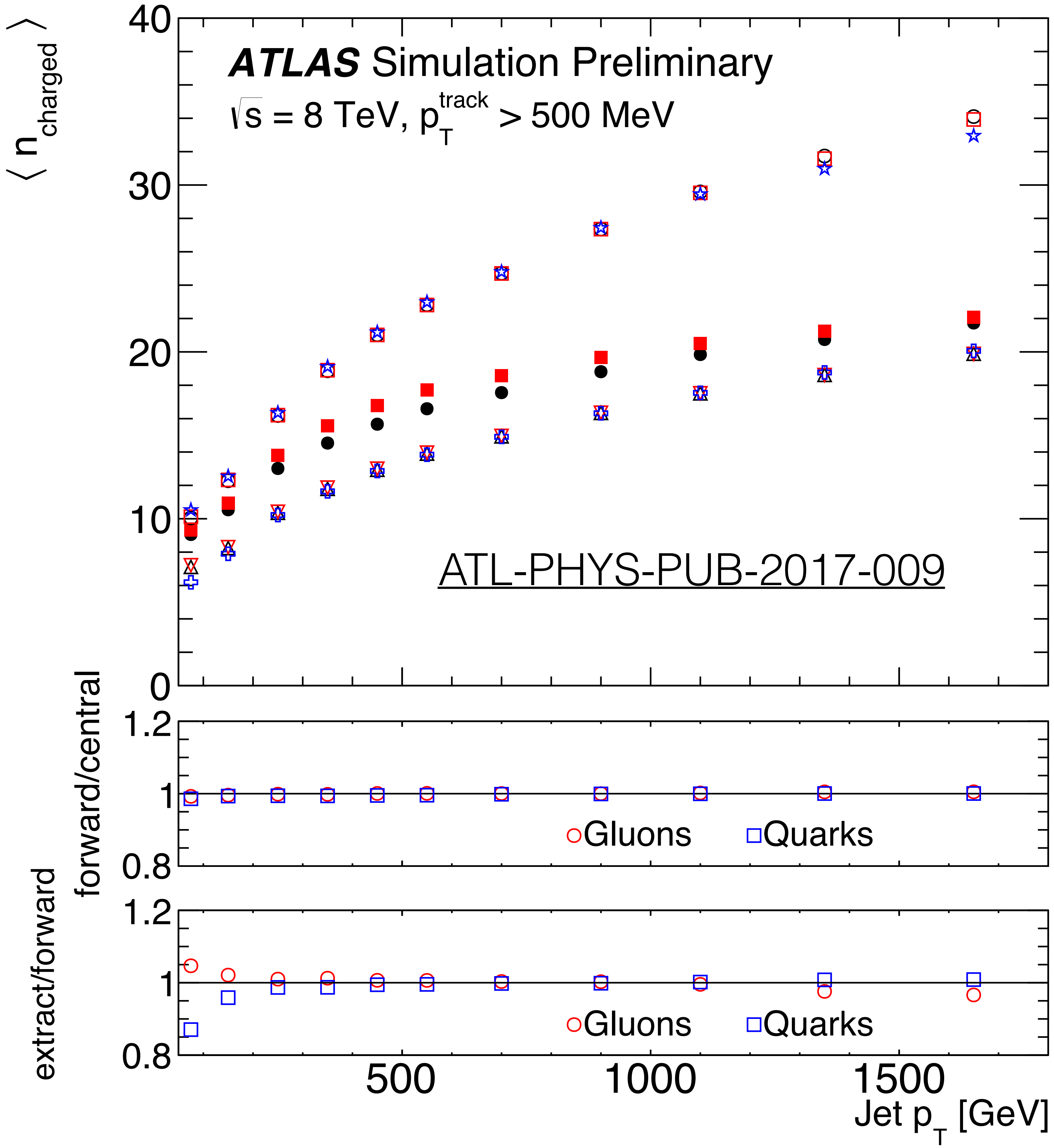
jet angular resolution

By construction, designed to be less sensitive to JES

(~5% for the xs measurement for comparable energy)

More sensitive in the middle to do softer gluon radiation


STDM-2016-10
ATLAS
Preliminary
TEEC 2012 Global fit
World Average 2016
TEEC 2012
TEEC 2011
CMS R32
CMS 3-jet mass
CMS inclusive jets
CMS tt̄ cross section
D0 angular correlations
D0 inclusive jets
limited by scale
uncertainties (~4-6%)
αs (Q)
0.14
0.13
0.12
0.11
0.1
0.09
0.08
10^2
10^3
Q [GeV]

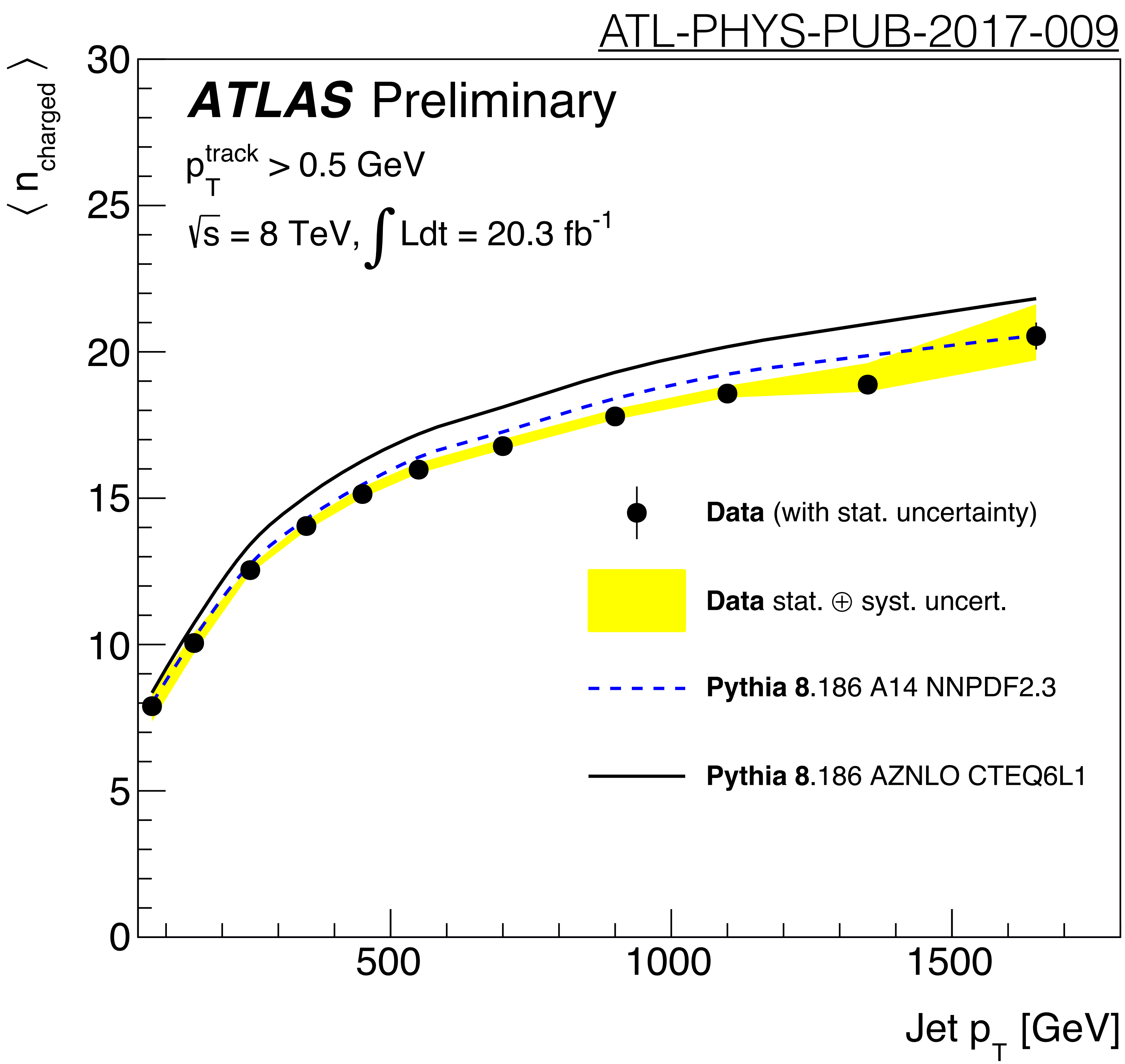


Closure Test

- ■ More central jet (inclusive)
- □ More central jet (gluons)
- ▽ More central jet (quarks)
- ✚ Quarks (extracted)

- ● More forward jet (inclusive)
- ○ More forward jet (gluons)
- △ More forward jet (quarks)
- ☆ Gluons (extracted)

Part III: Multiplicity with various UE tunes



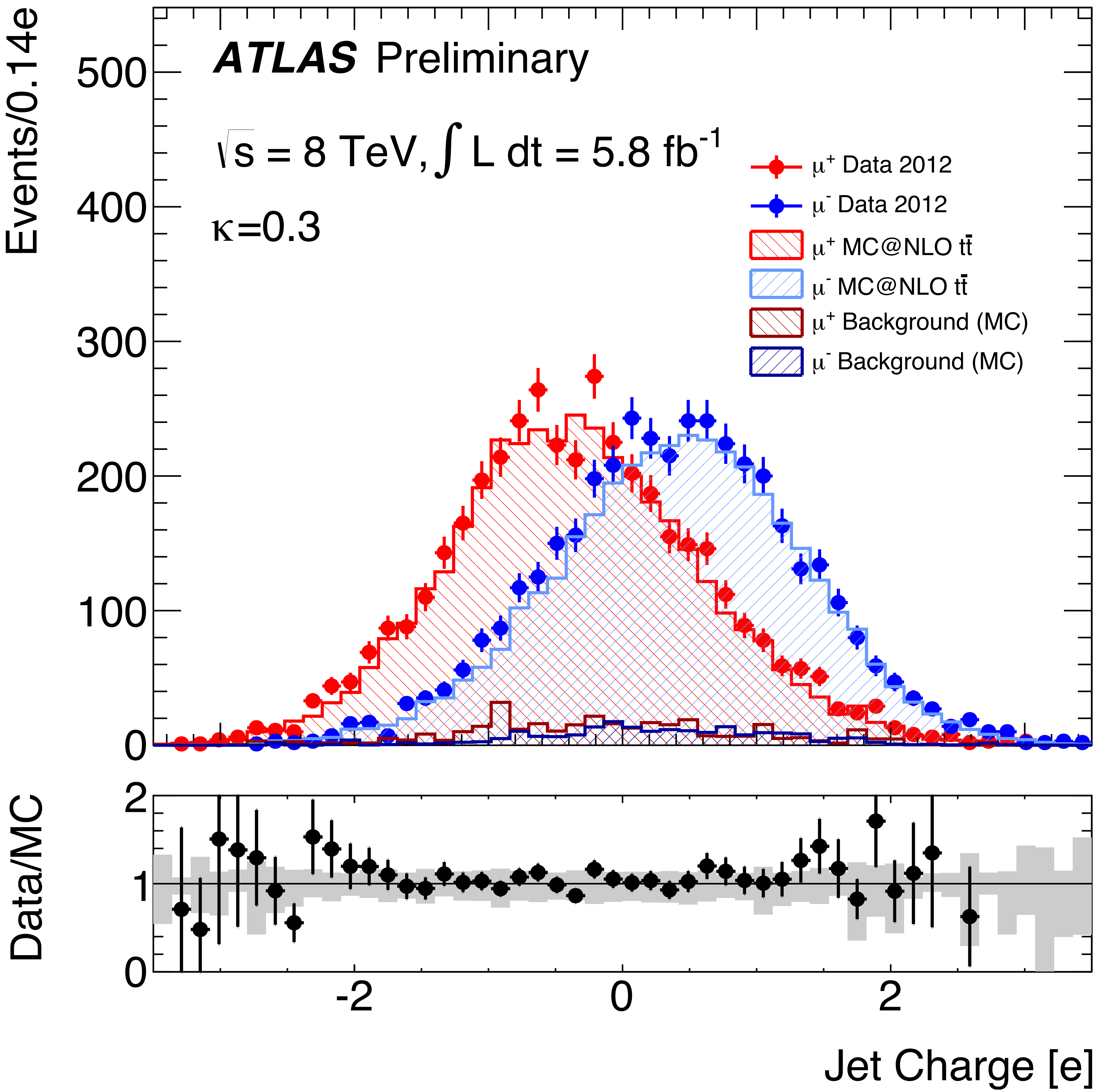
difference: alpha FSR 10% smaller

As part of this effort, we have also studied UE tuning

The ATLAS **A14 tune** is a better model than the Pythia 8 default (Monash) and the ATLAS **AZNLO tune** used for many Higgs analyses

This is a key challenge for the Hep-ex and Hep-ph communities!

Jet Charge



$$Q_J = \frac{1}{(p_{TJ})^\kappa} \sum_{i \in \mathbf{Tracks}} q_i \times (p_{T,i})^\kappa$$