BROOKHAVEN NATIONAL LABORATORY

Exploring QCD at the LHC

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on behalf of the ATLAS and CMS collaborations

LFC at ECT*
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qcd: some motivation

- Understanding QCD is critical for entire physics program at LHC

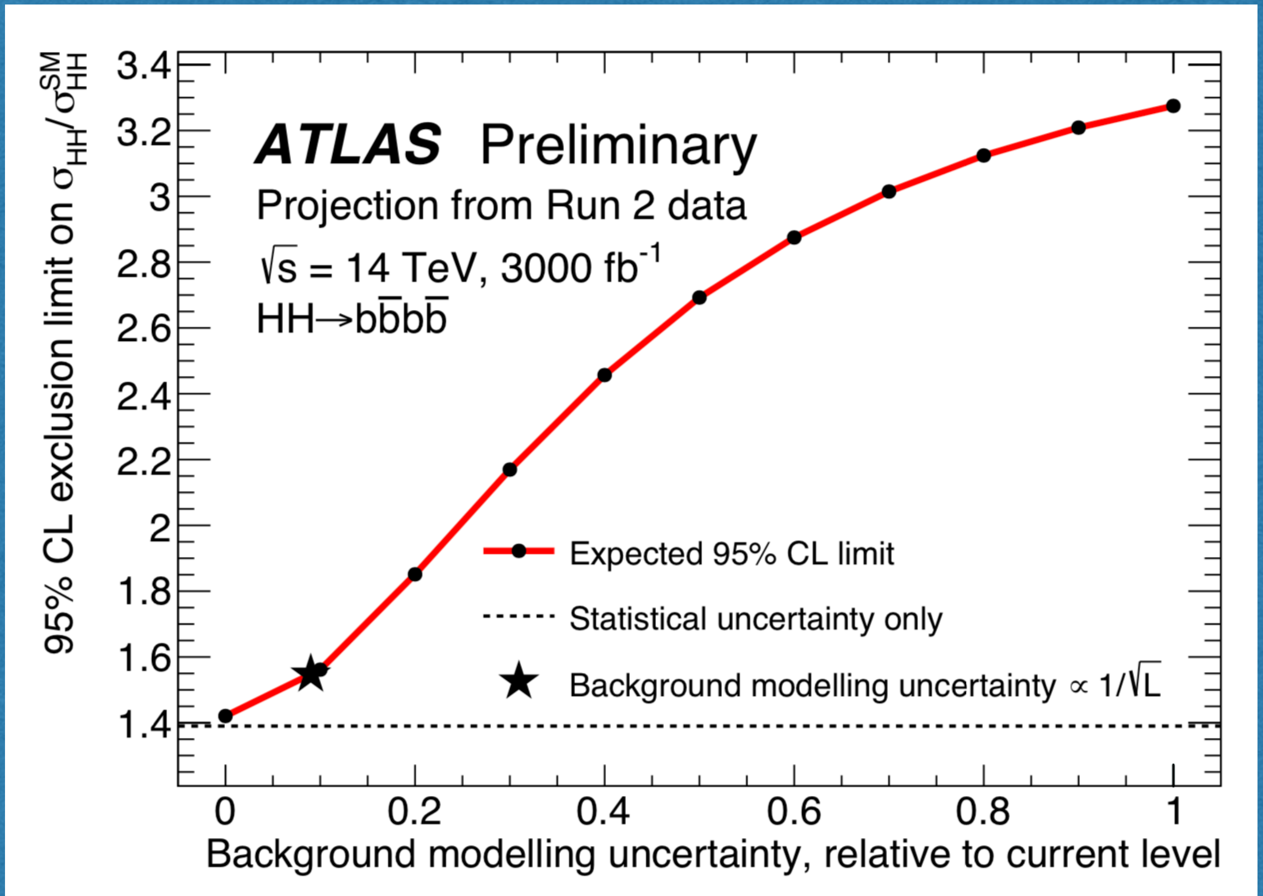
- Some of the main points of interest include

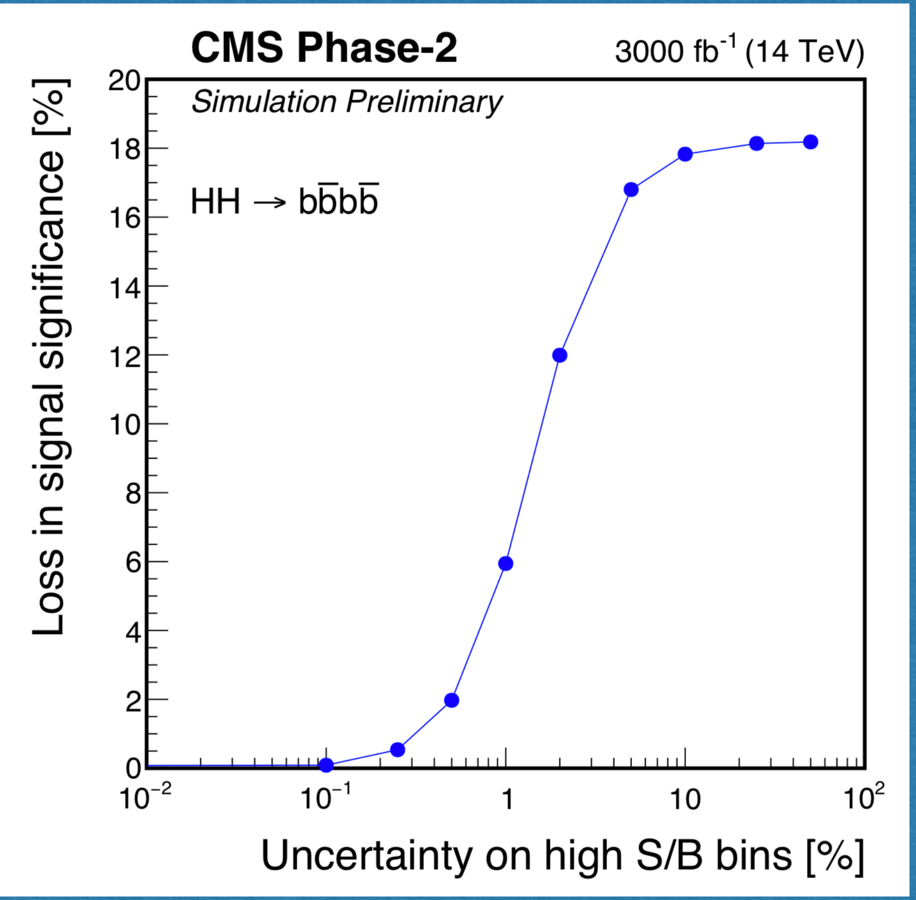
  - **Parton Distribution Functions**: necessary for any calculation at a hadron collider

  - **The strong coupling constant (α_s)**: fundamental parameter of QCD, becoming increasingly relevant for things like Higgs measurements

  - **Jet modeling**: important for creating any Monte Carlo samples, one of the dominant uncertainties for the jet energy scale corrections

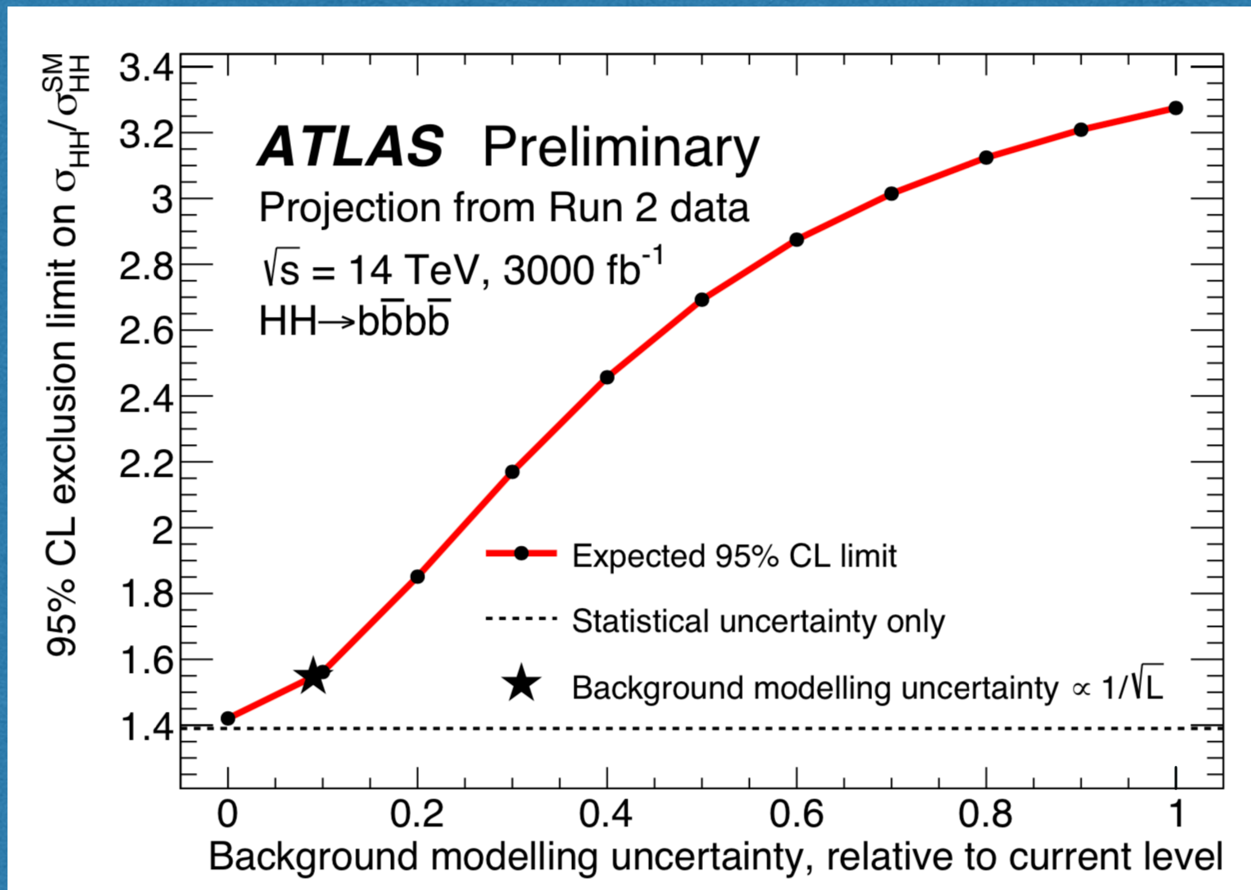
qcd: some motivation

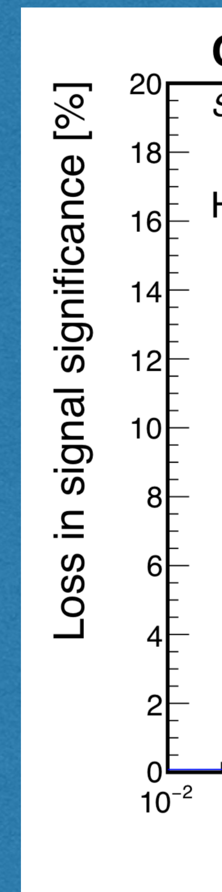




Multijet modeling for di-Higgs

qcd: some motivation





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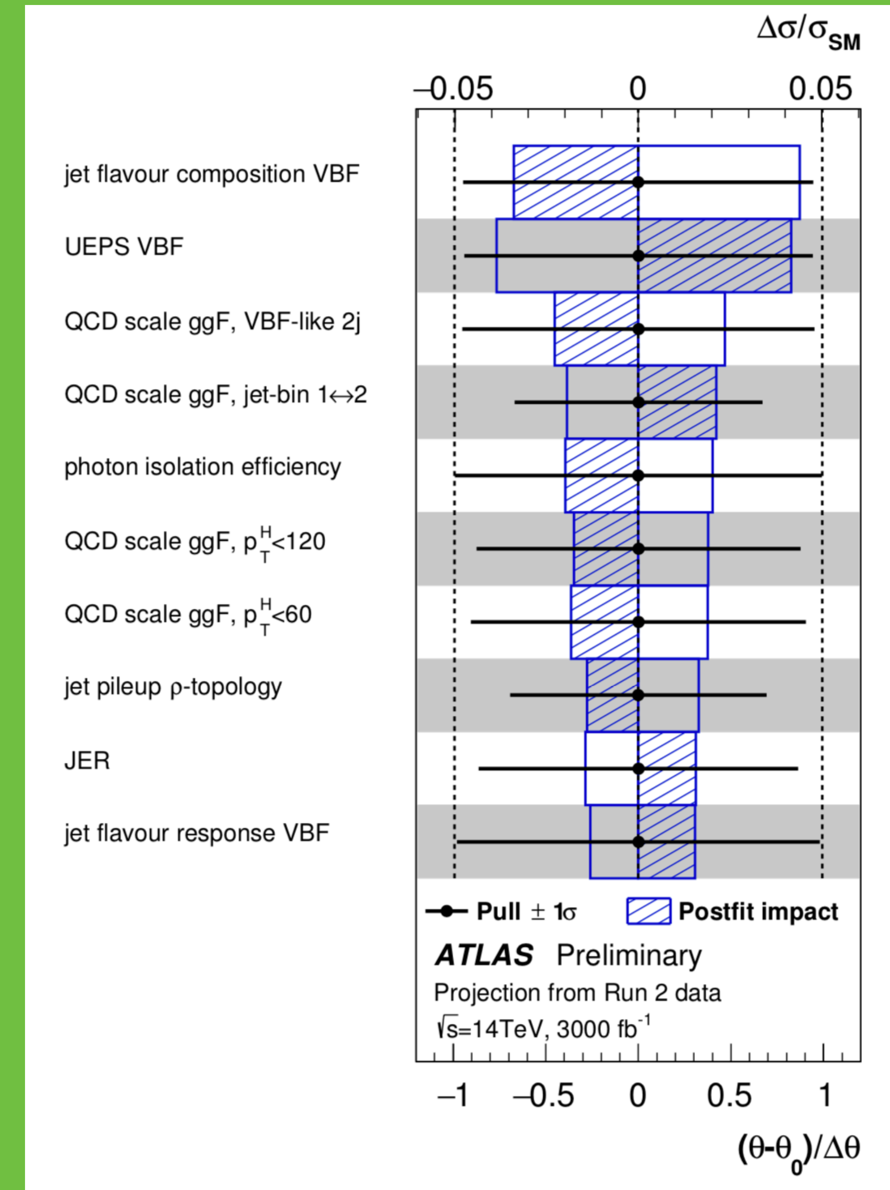
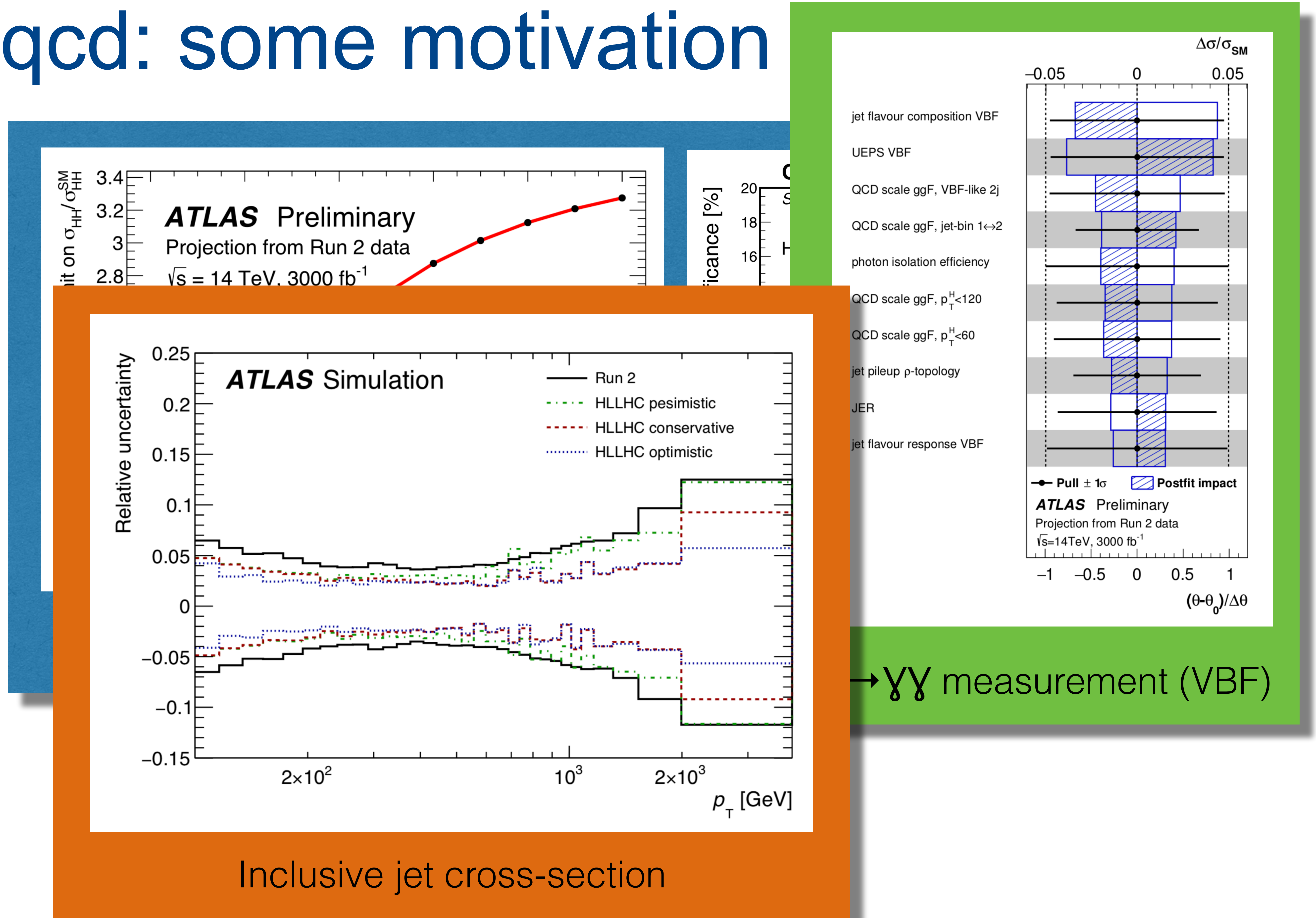


H→γγ measurement (VBF)

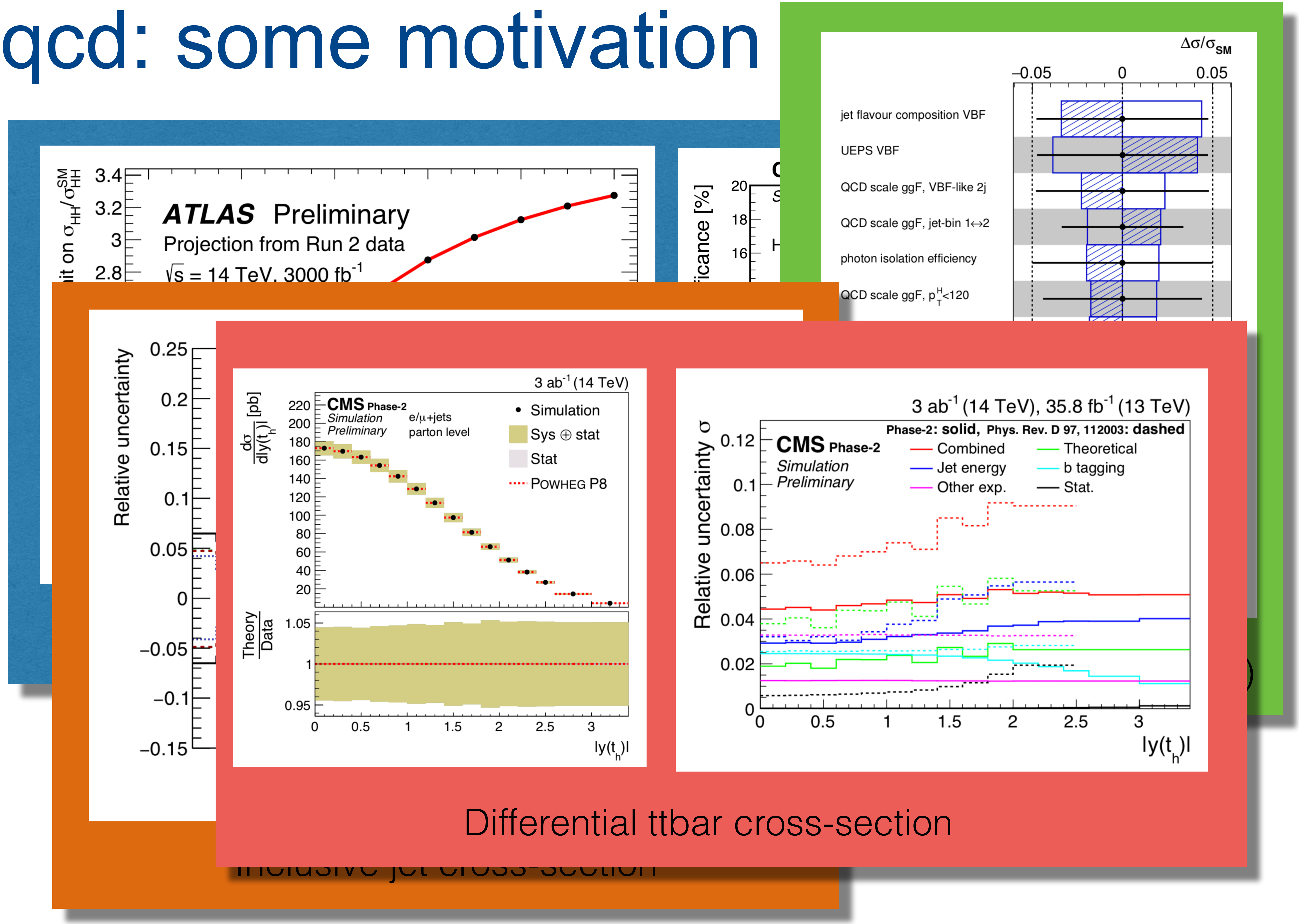
qcd: some motivation



Inclusive jet cross-section

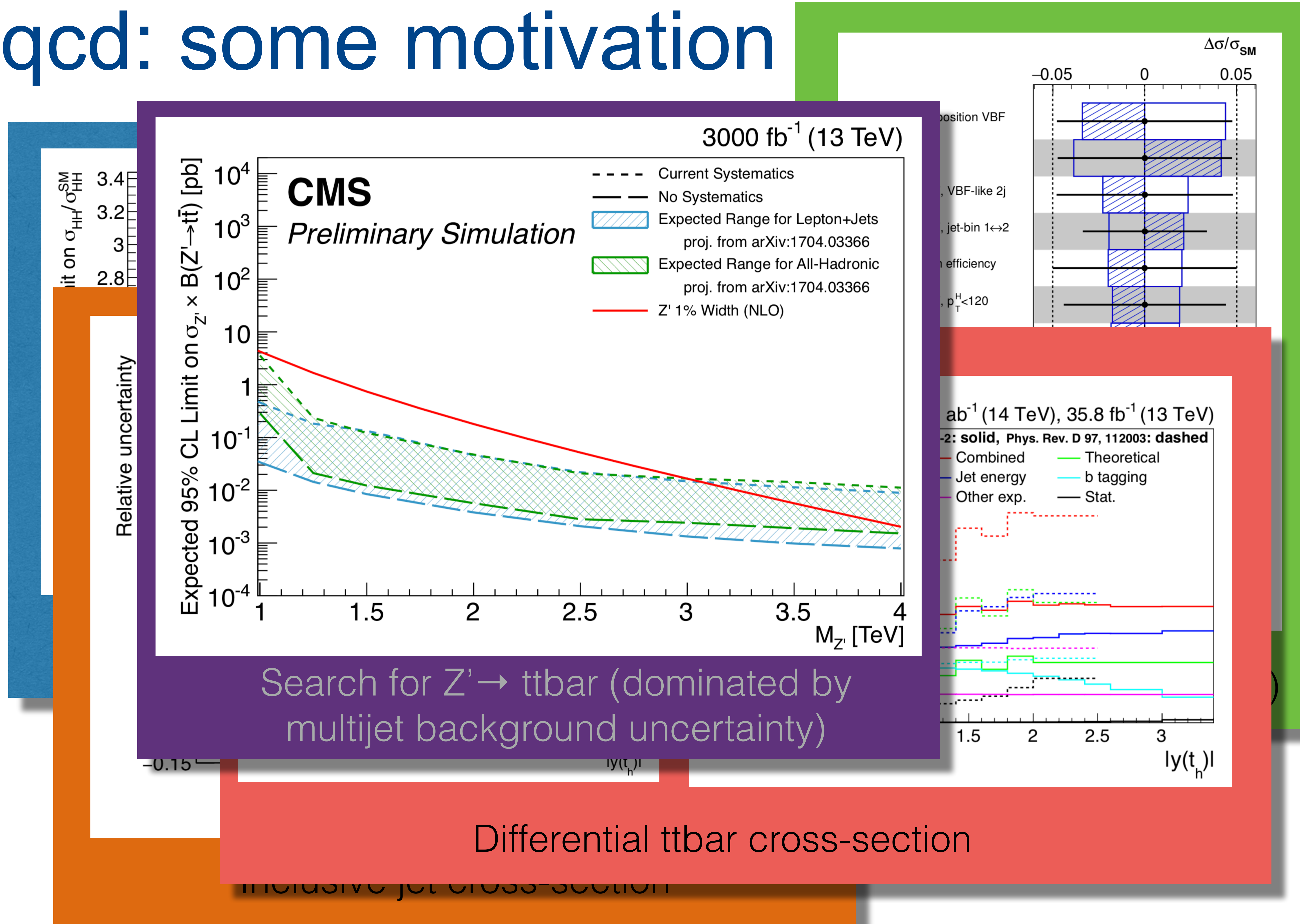
→γγ measurement (VBF)

qcd: some motivation



Differential ttbar cross-section

qcd: some motivation



qcd: some motivation

- ***Jets are ubiquitous at hadron colliders… so why is this complicated?***
  - Confinement means we cannot directly measure quarks and gluons in the final state, and need to use jets as proxies for this information
    - *Need observables which make sense in the context of jets and their substructure*
  - Jets are complicated objects
    - *Choice of jet radius can be important when looking at different effects*
  - The strong force is complicated, so need more than just measurements of the coupling constant
    - *Understanding of parton showers does not lead to understanding of hadronization*
  - Often challenging to produce calculations, so can be challenging to choose meaningful observables
    - *Only one prediction at NNLO for α_S at hadron collider so far*

qcd: some motivation

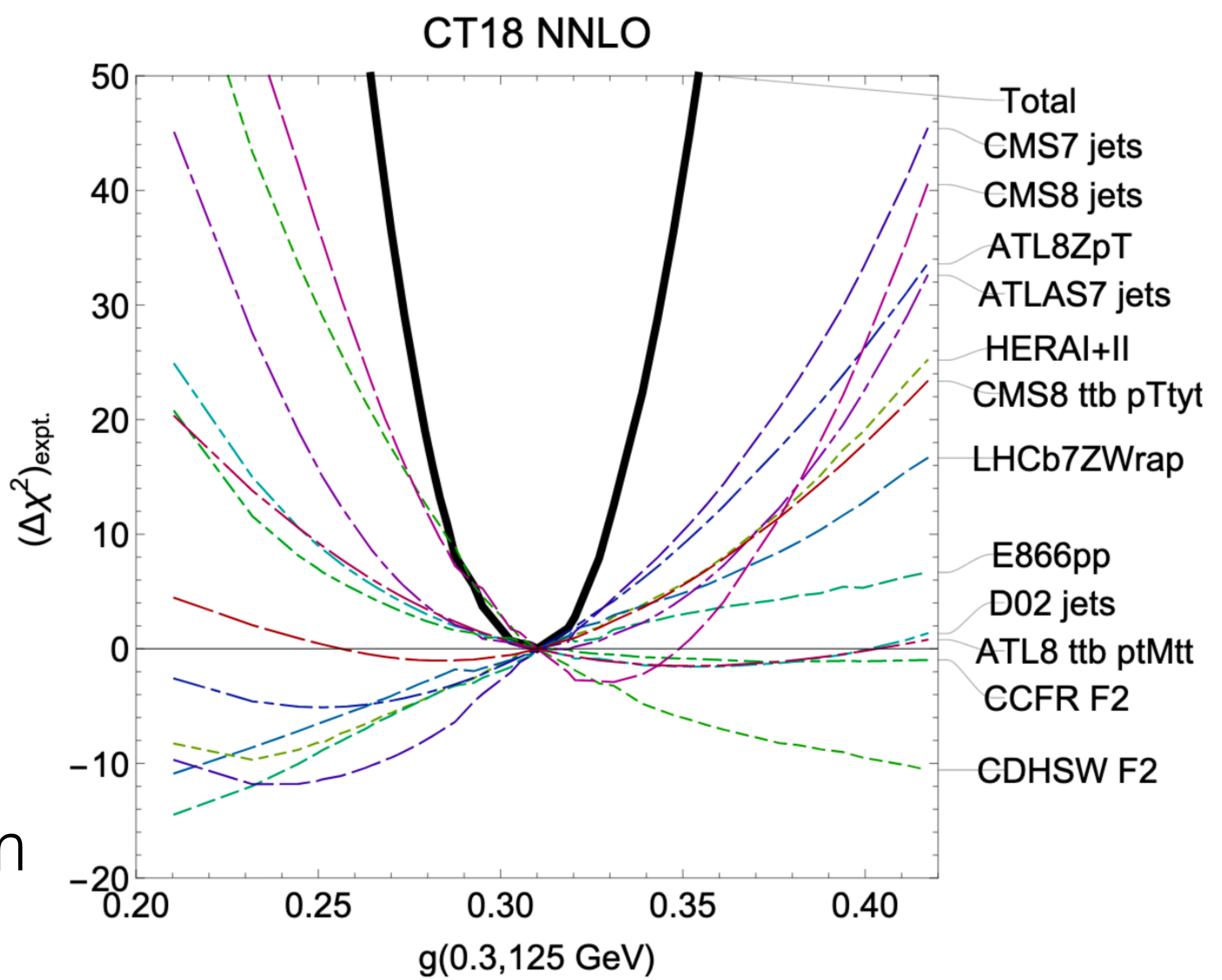
- Many exciting prospects for understanding QCD at the LHC
  - ***More statistics*** will improve high-p_T (and other stats-limited) results
  - Improvements to ***MC modeling*** could reduce uncertainties on many measurements
  - Existing measurements can be improved by rethinking ***analysis design*** and ***object reconstruction***
  - Improvements with theoretical understanding can enable ***new observables*** which are sensitive to QCD effects
- Too many analyses to cover in one talk…
  - Instead focusing on a few examples of how we can make the most of the LHC data for understanding QCD

parton distribution functions

parton distribution functions

- PDFs are a necessary component for any calculation of process at a hadron collider

- Not calculable from first principles → need measurements!
- LHC data has larger kinematic reach than previous experiments → lots of possibility for improvement
- Many measurements from the LHC already being considered for PDF fits



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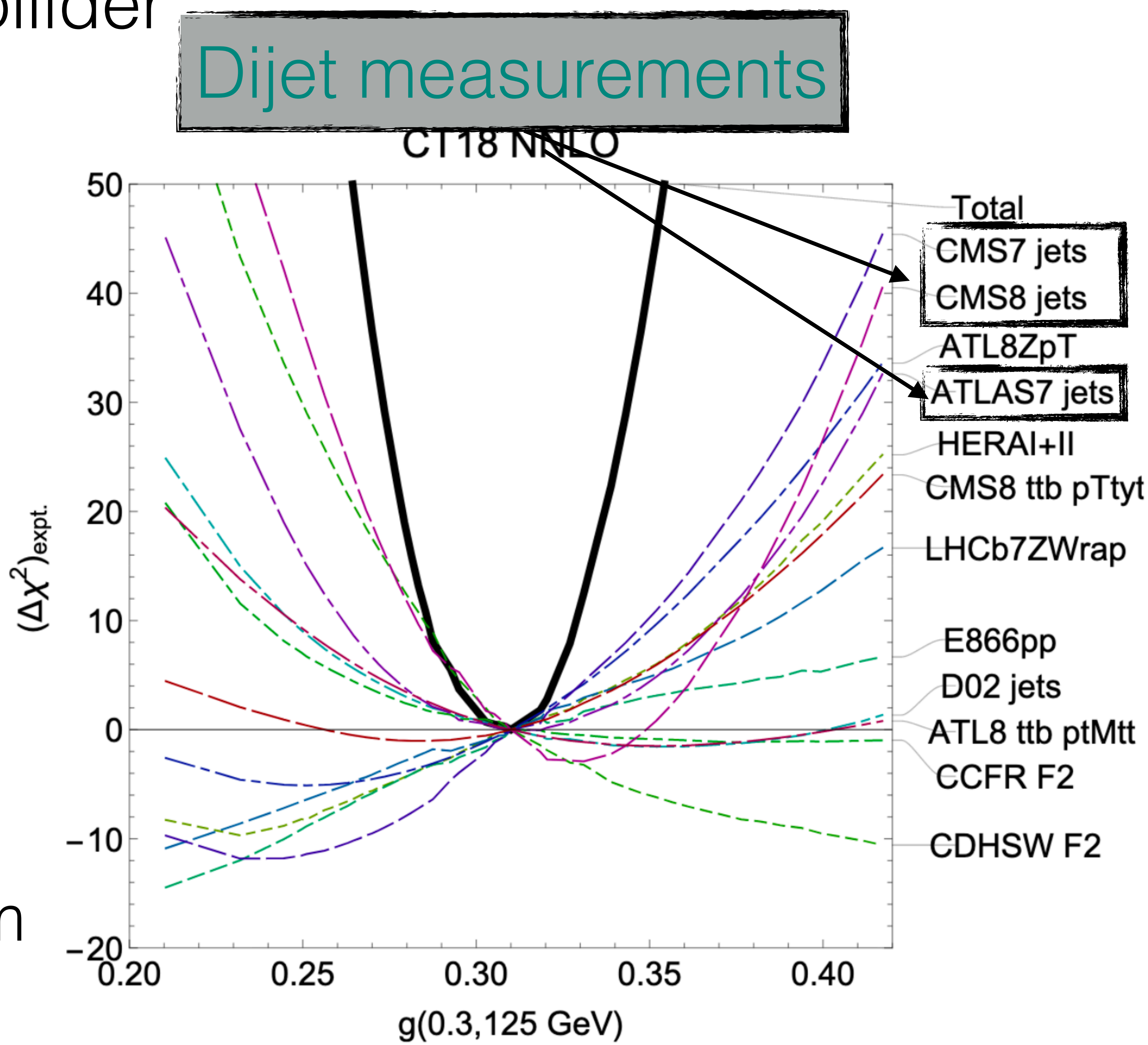

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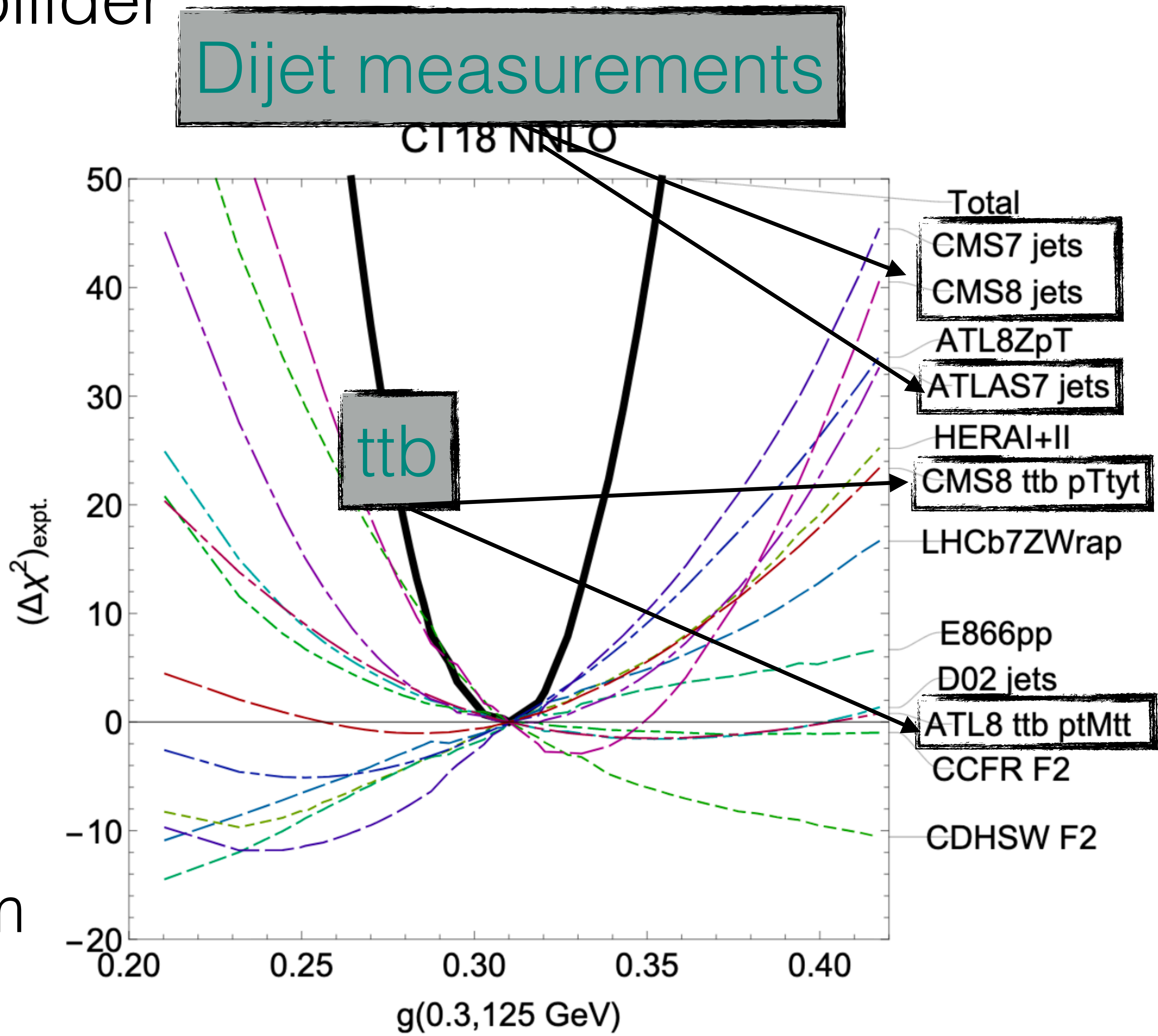

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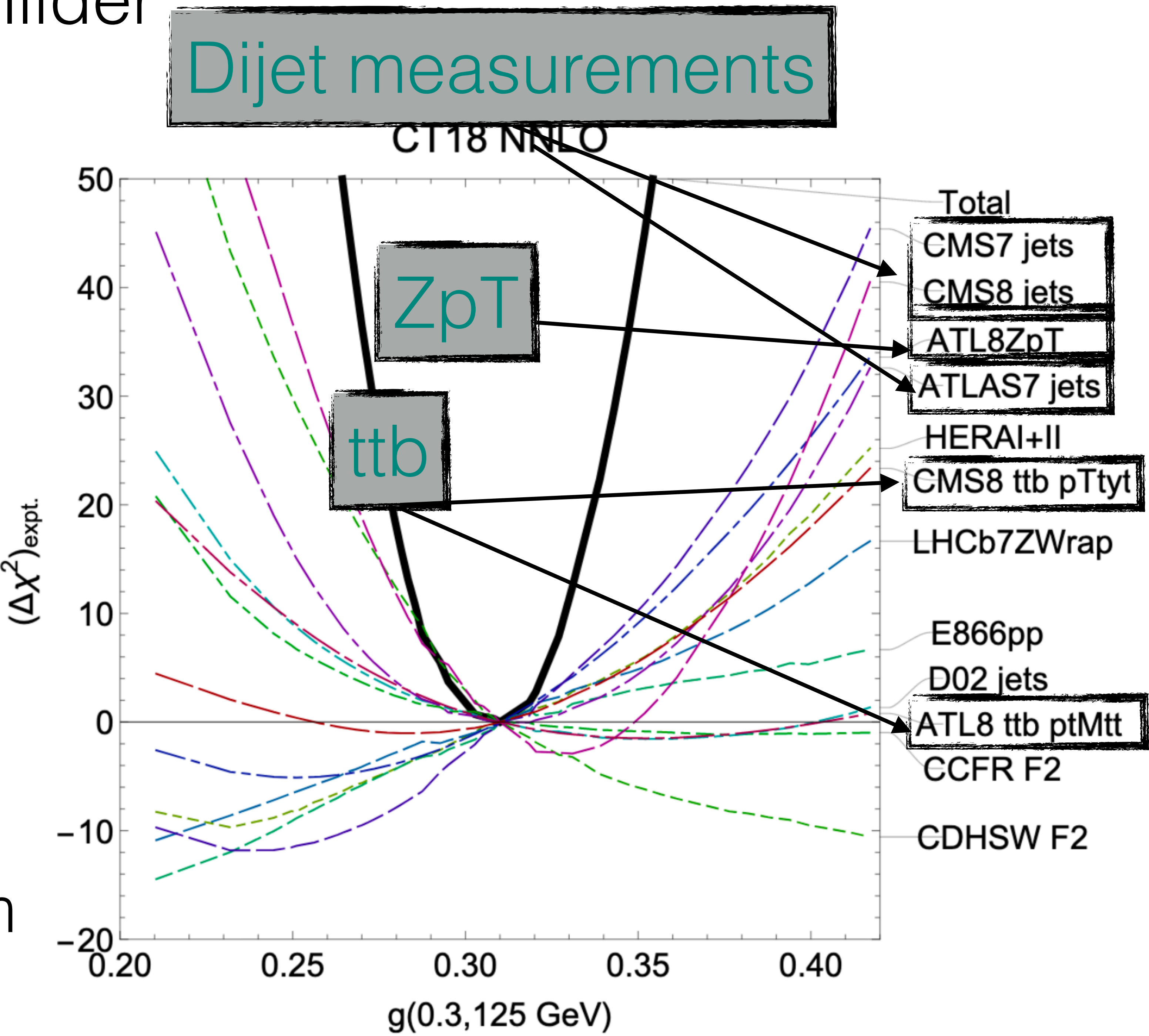

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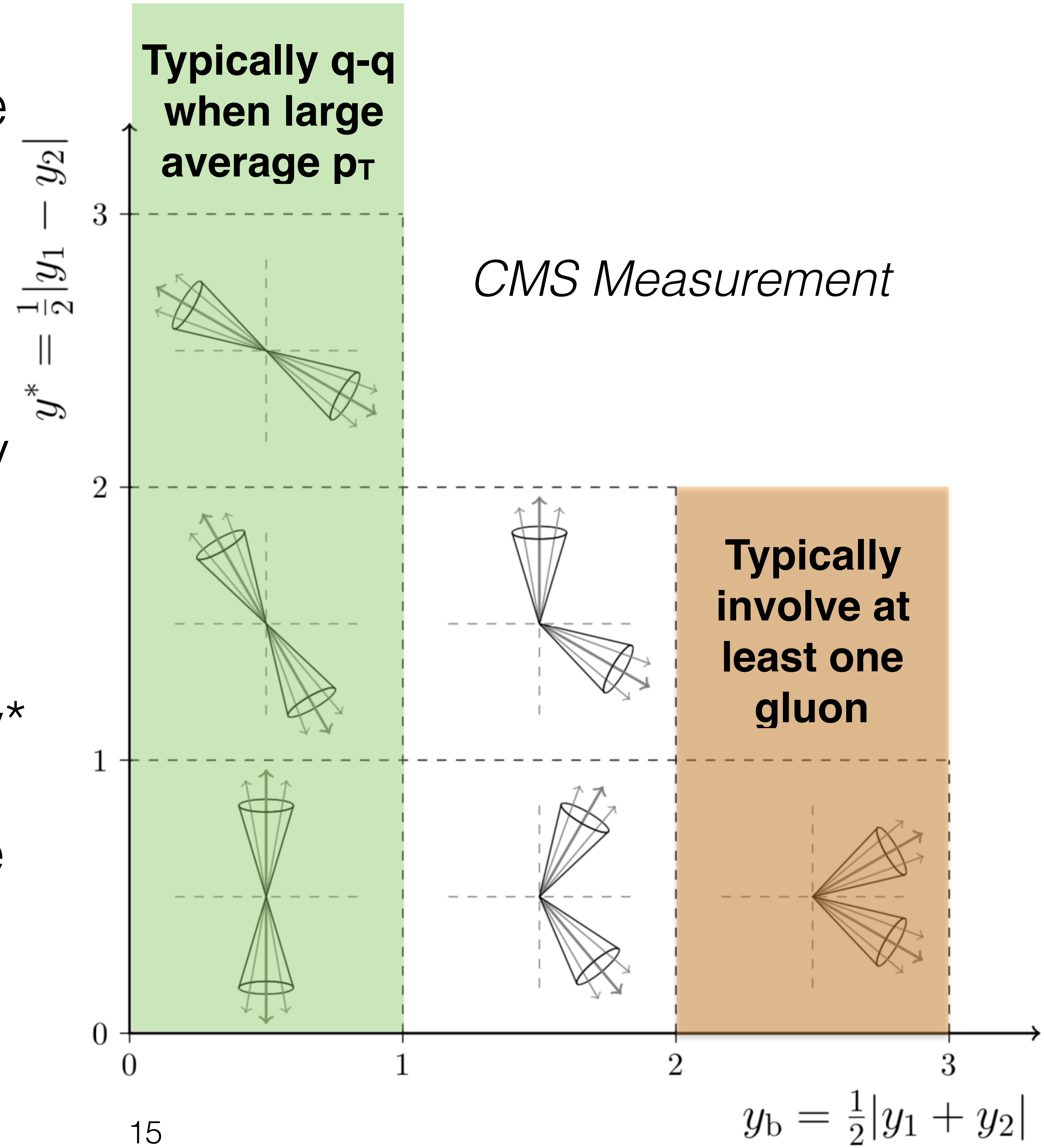
pdfs: dijet cross-section

Yellow Report (ATLAS)

ATLAS CMS

- CMS and ATLAS measure dijet x-section as a function of different observables
  - **CMS**: triple-differentially in the $p_{T,\,avg}$, y^*, y_b
  - **ATLAS**: double-differentially in m_{jj} and y^*
- Different regions of phase space dominated by different effects

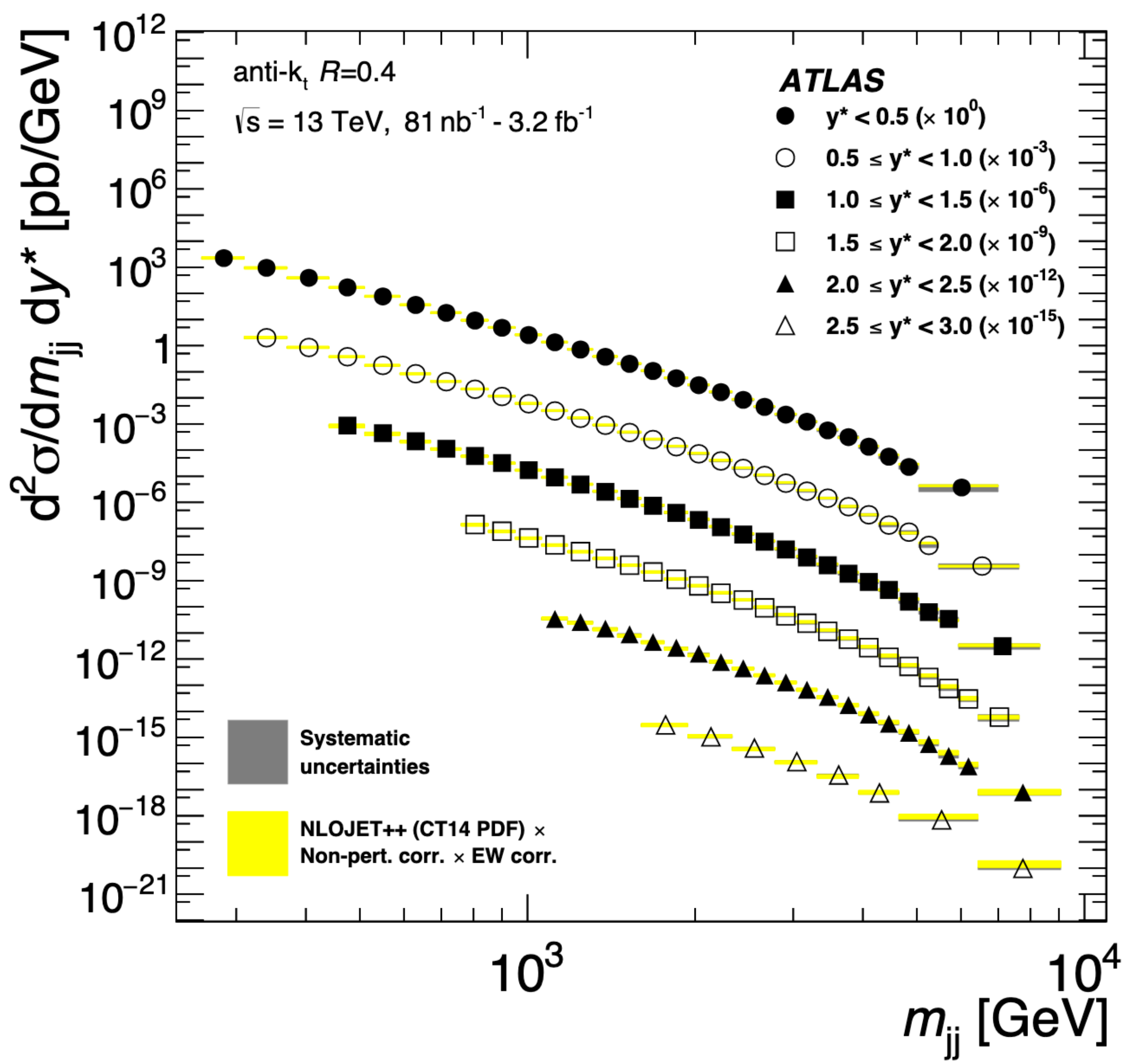


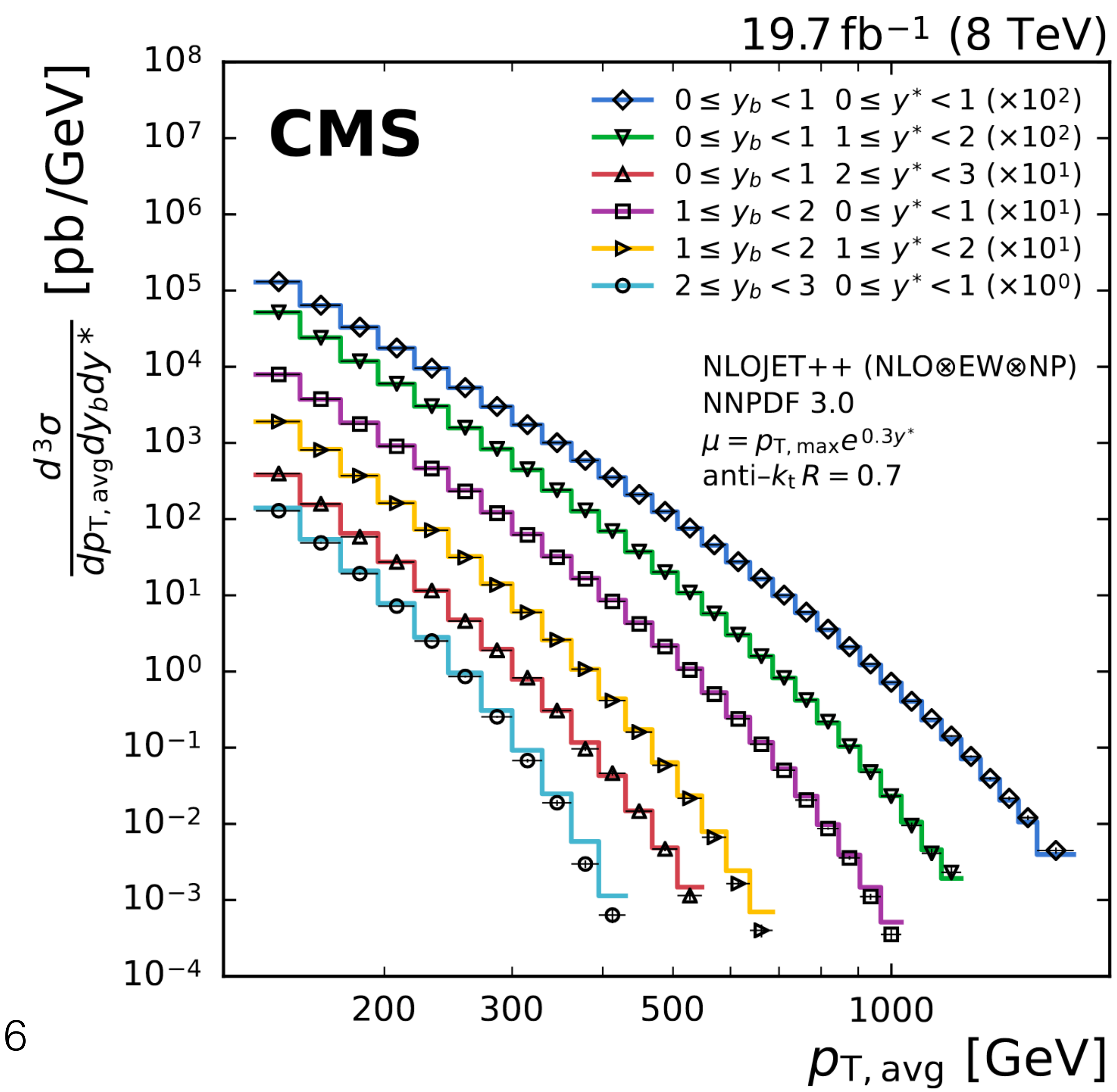
pdfs: dijet cross-section

Yellow Report (ATLAS)

ATLAS CMS

- Data is typically modeled well by NLO predictions
  - Some differences seen from CMS for larger y_b at high $p_{T,avg}$
  - Able to measure a wide phase space because of huge range of jets produced at LHC



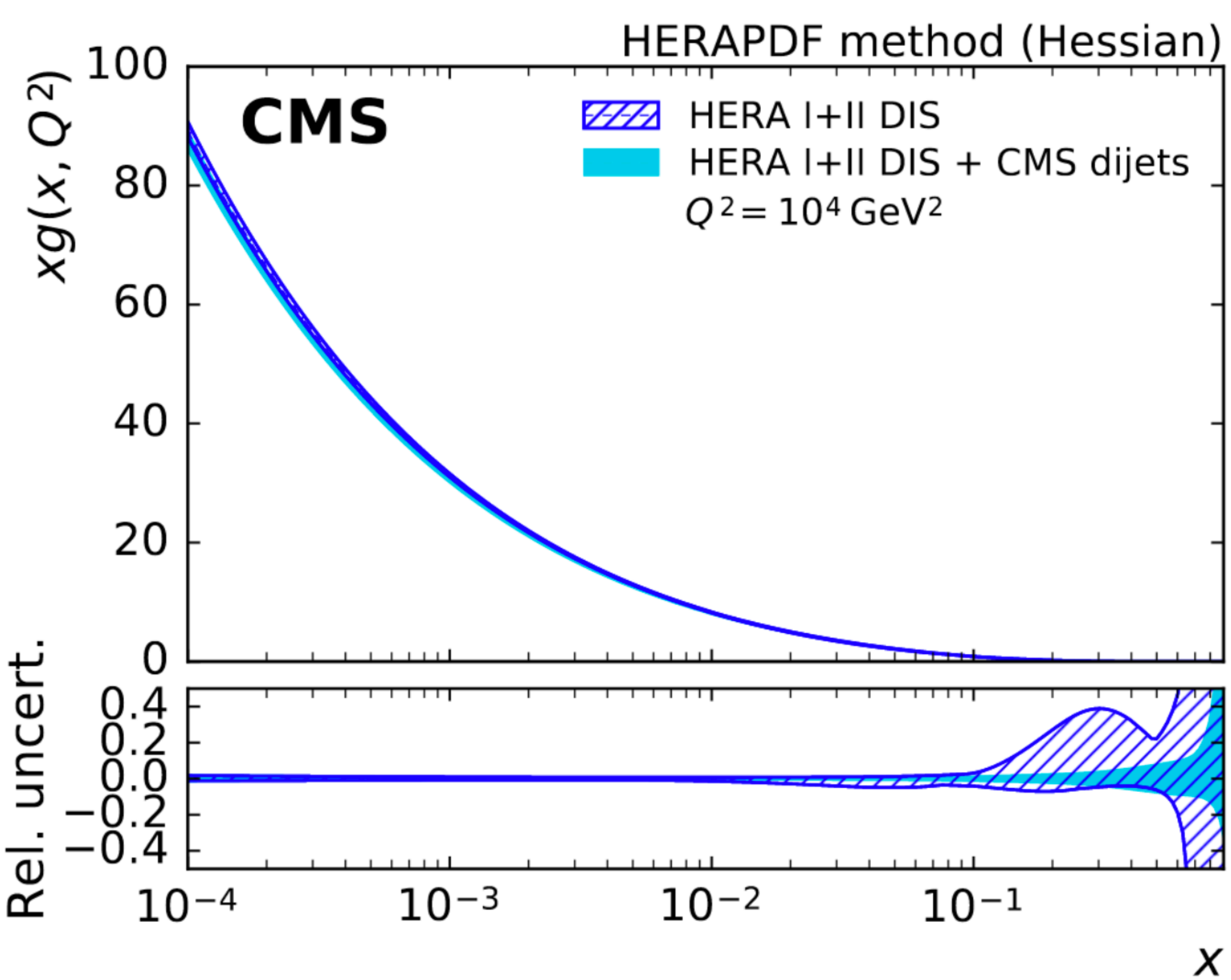


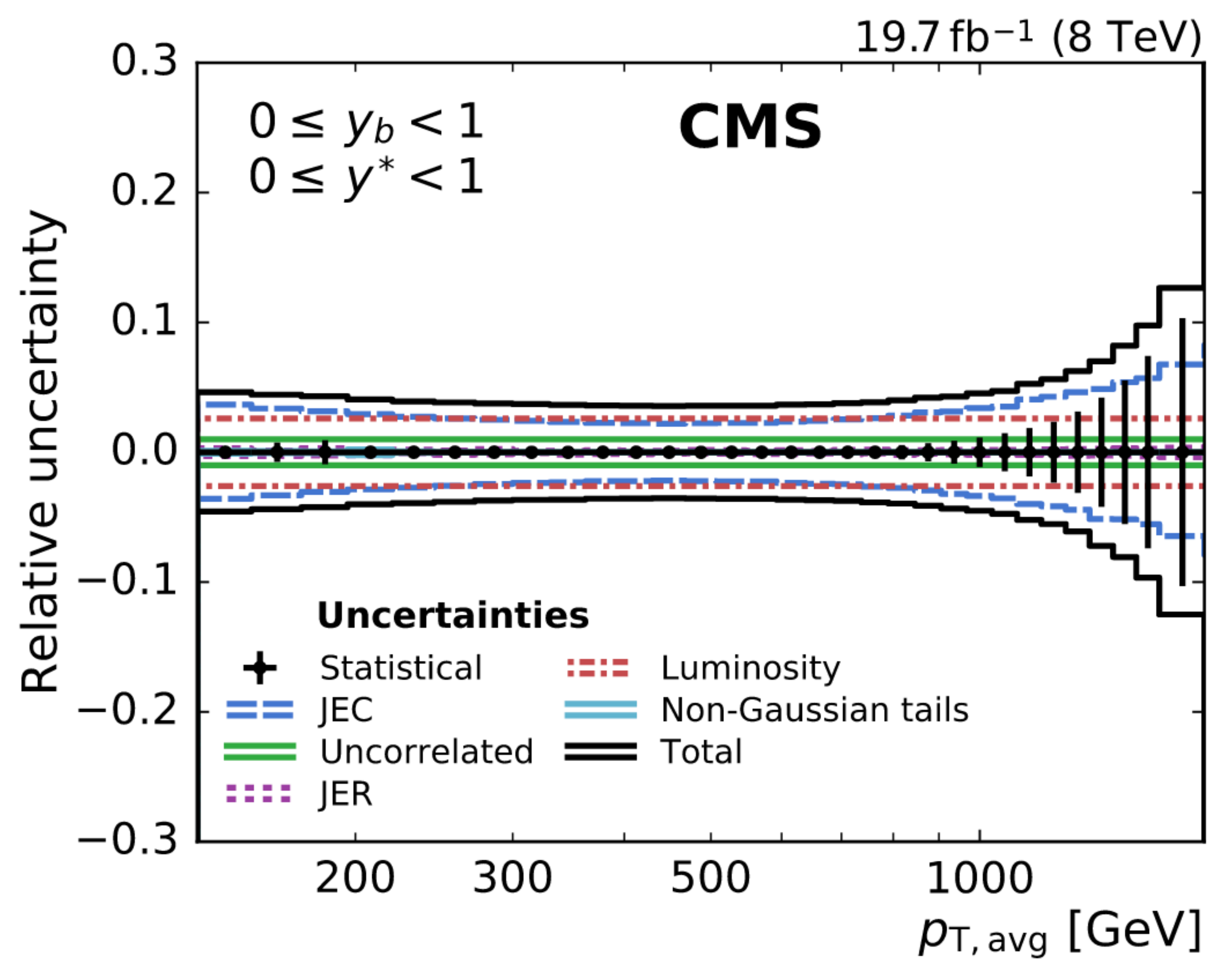
pdfs: dijet cross-section

Yellow Report (ATLAS)

ATLAS CMS

- Current measurement from CMS starts to improve constraints on gluon PDF around x=0.1
- Jet energy scale correction uncertainties are also important at high p_T
  - These will also be improved by more statistics



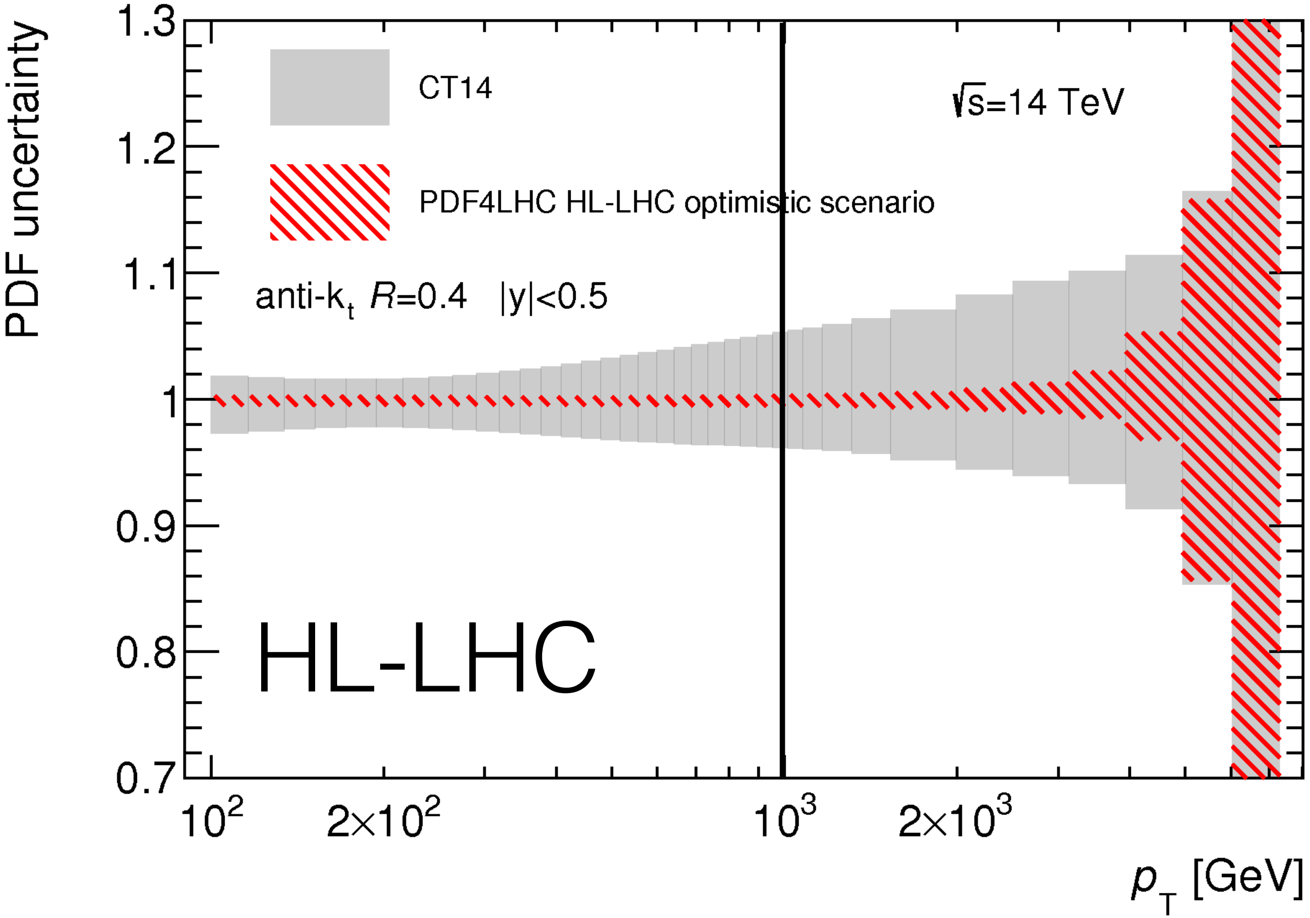


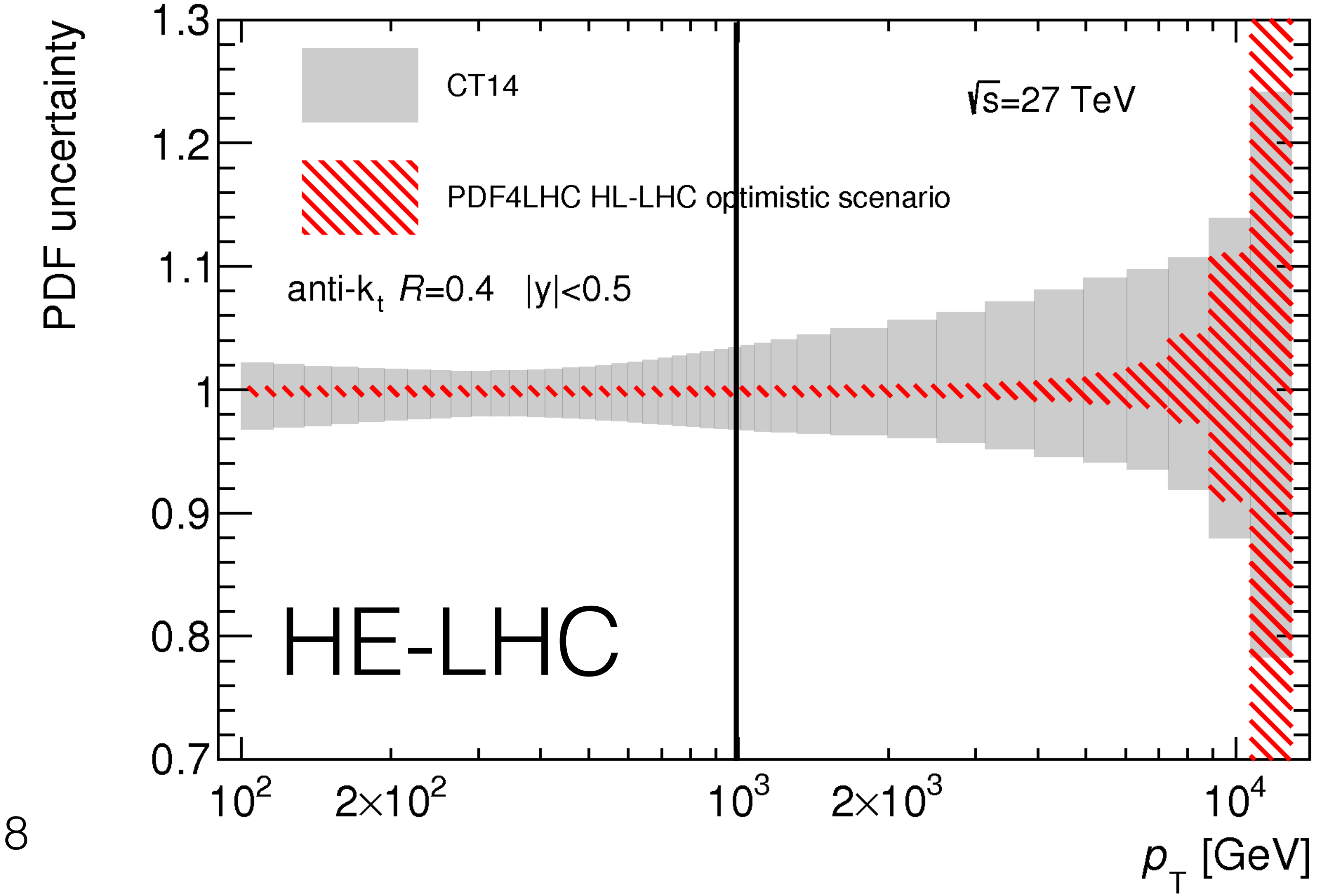
pdfs: dijet cross-section

Yellow Report (ATLAS)

ATLAS CMS

- Constraints on PDFs could be improved by both HL-LHC and HE-LHC
  - High-p_T results are ***limited by statistics*** in many places (especially in more forward regions)
- Improving these will directly impact the sensitivity of measurements like this
  - Expect LHC measurements to greatly reduce the PDF uncertainties
  - https://arxiv.org/pdf/1810.03639.pdf

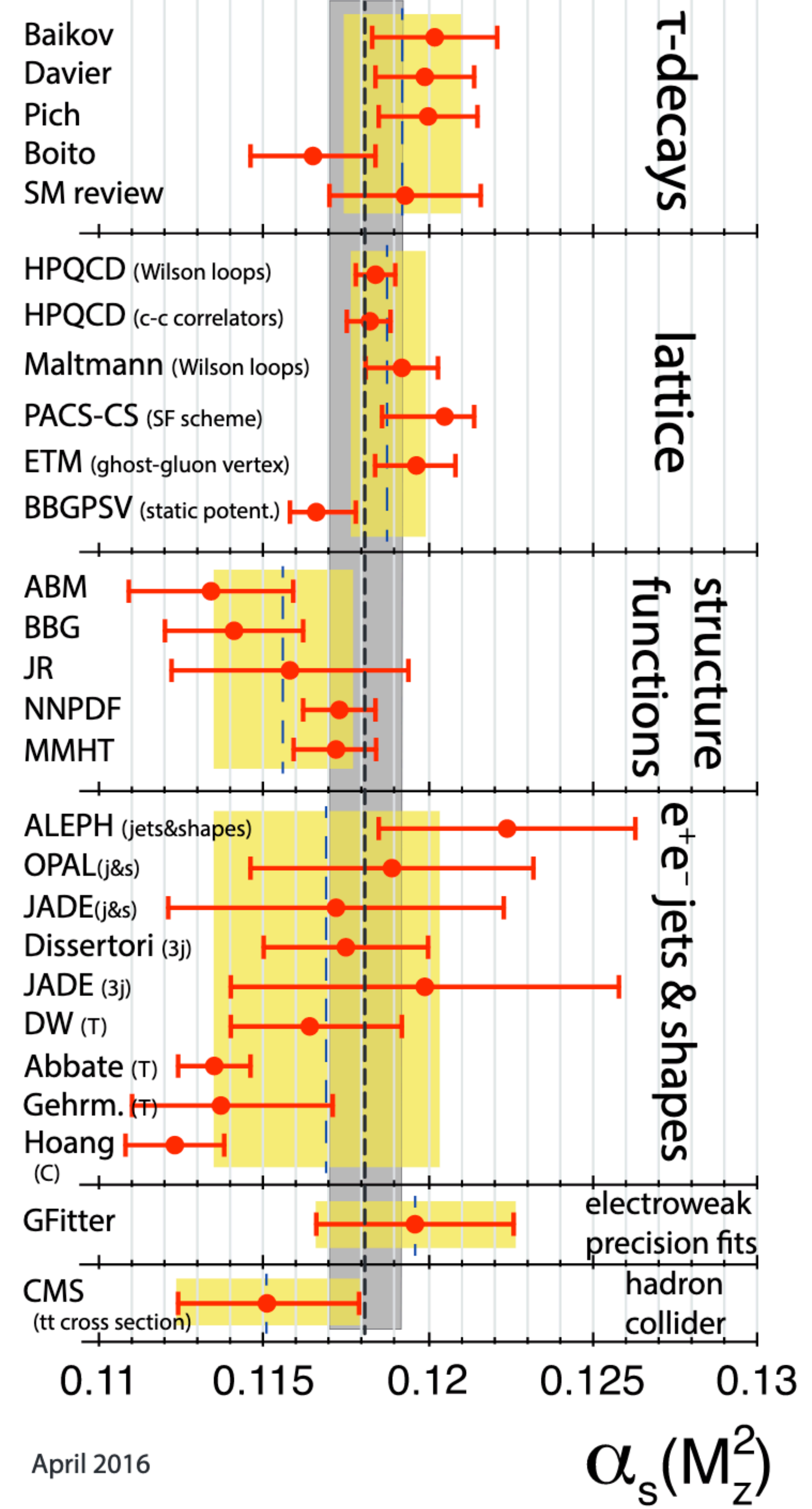




the strong coupling constant α_s

measuring α_s

- α_s is a challenging parameter to measure
  - Precise determination important for many precision measurements like for the Higgs
  - Need observables sensitive to α_s, but not too sensitive to non-perturbative effects or to PDFs
  - Need observables which are calculable to NNLO → currently only one measurement from a hadron collider!
- Significant tensions between some of the most precise measurements of α_s
  - Need independent measurements in order to understand this discrepancy



measuring α_s

- Many ideas of how to measure at the LHC
  - Proposals range from measurements which have already been done, to those which are still being understood theoretically

Already possible at NNLO

- ttbar inclusive cross section (CMS)

- Inclusive jet cross section (ATLAS, CMS)
- 3-jet mass (CMS)
- R_{32} (CMS)
- TEECs (ATLAS)

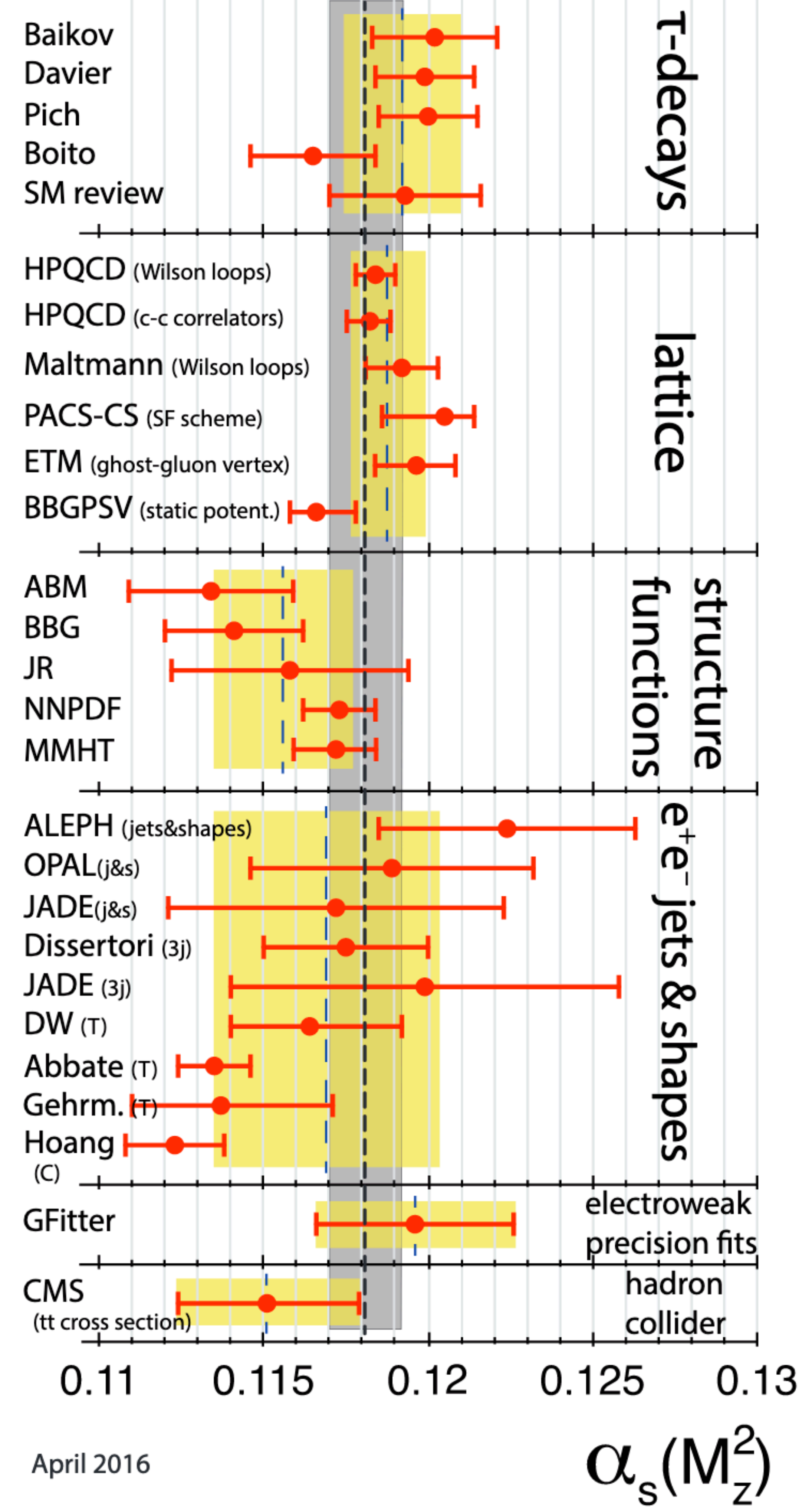
Extraction done at NLO, need better theoretical precision

- Jet mass (Les Houches)

Theoretical proposal, no measurements yet

- Soft drop thrust (BOOST)
- EECs (BOOST)
- Others?

Moving towards a theoretical proposal

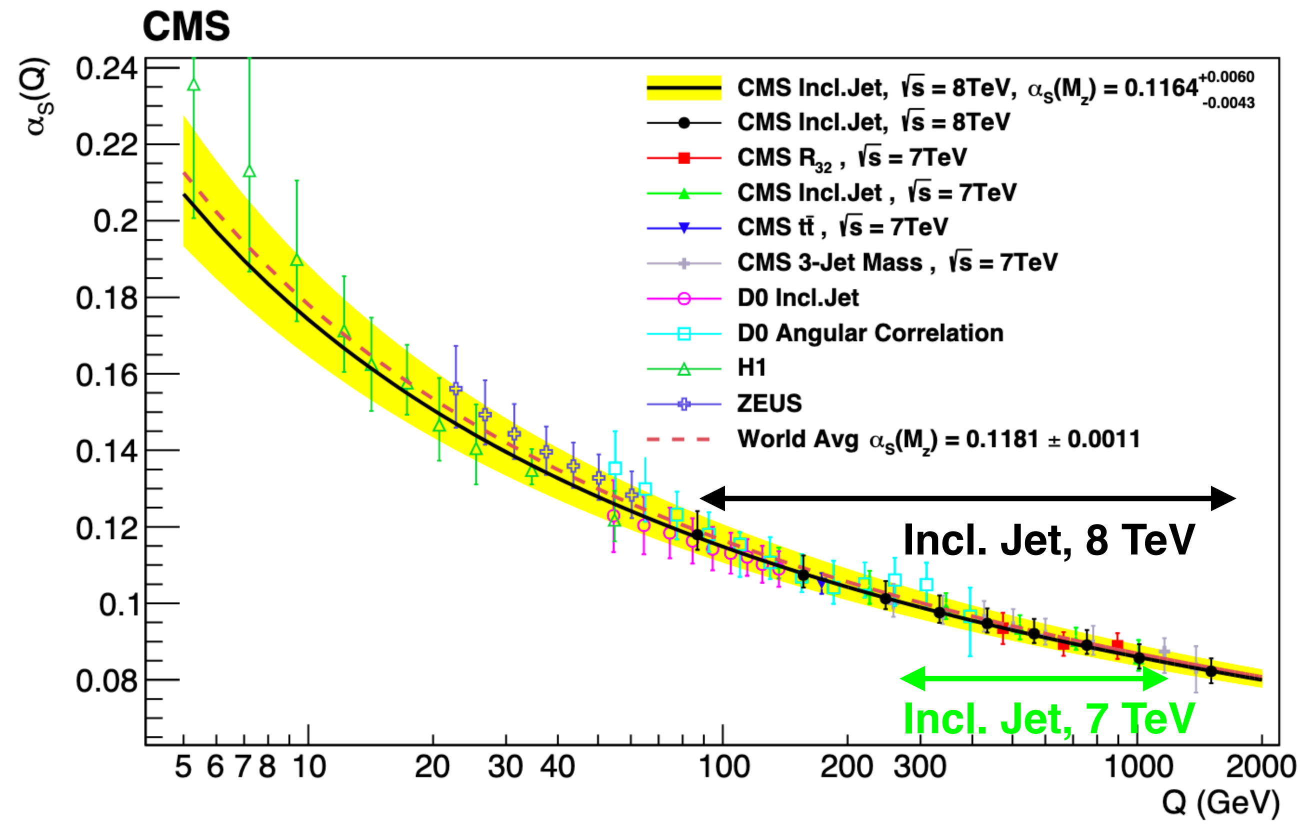


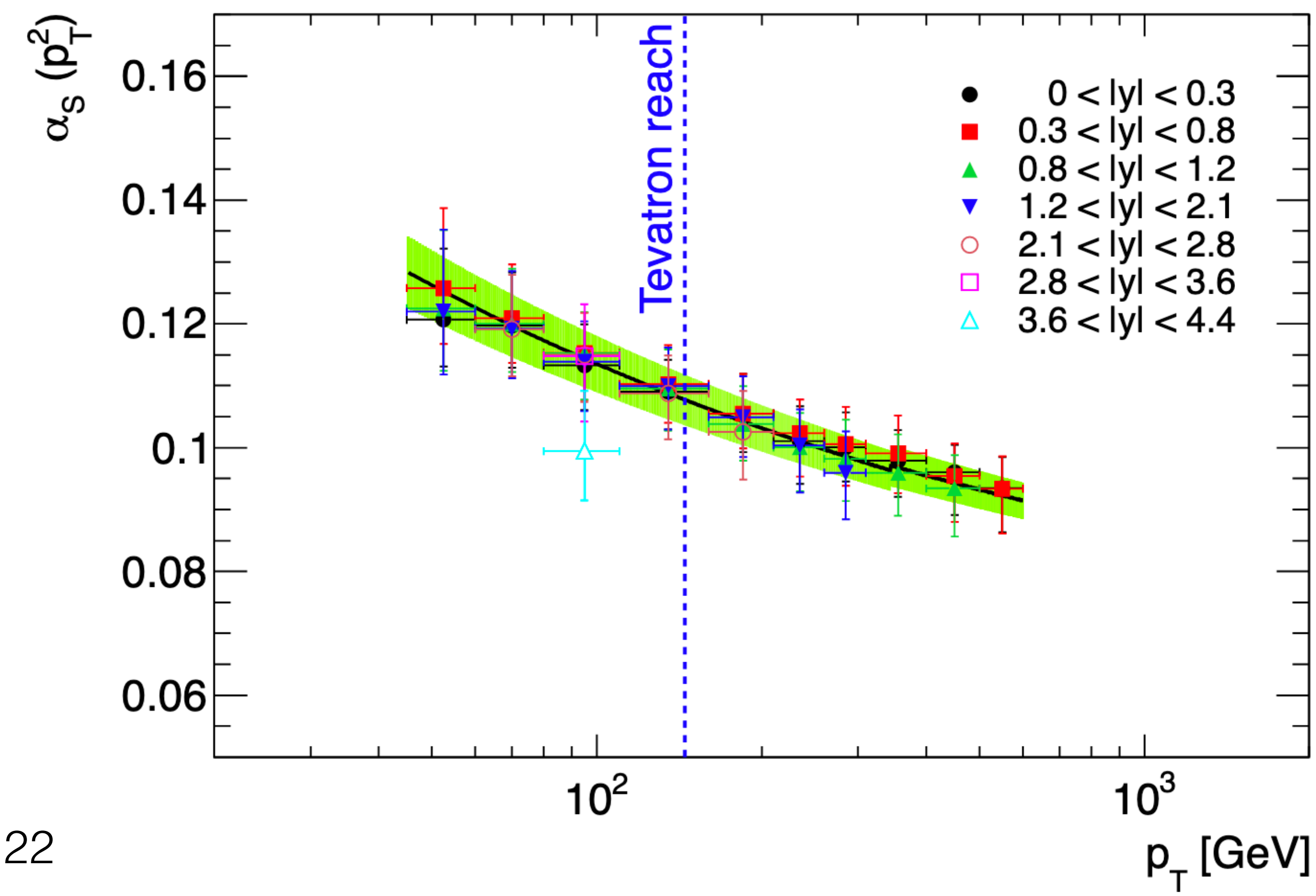
α_S: inclusive jet cross-section

Extraction using ATLAS data

CMS Measurement

- Rate of jet production closely related to α_S
- α_S has been extracted using ATLAS and CMS data (at NLO)
- Jets are produced at a wide range of scales → relevant also for understanding the running of the coupling
- Powerful observable, but many challenges associated with choice of factorization scale and non-perturbative effects



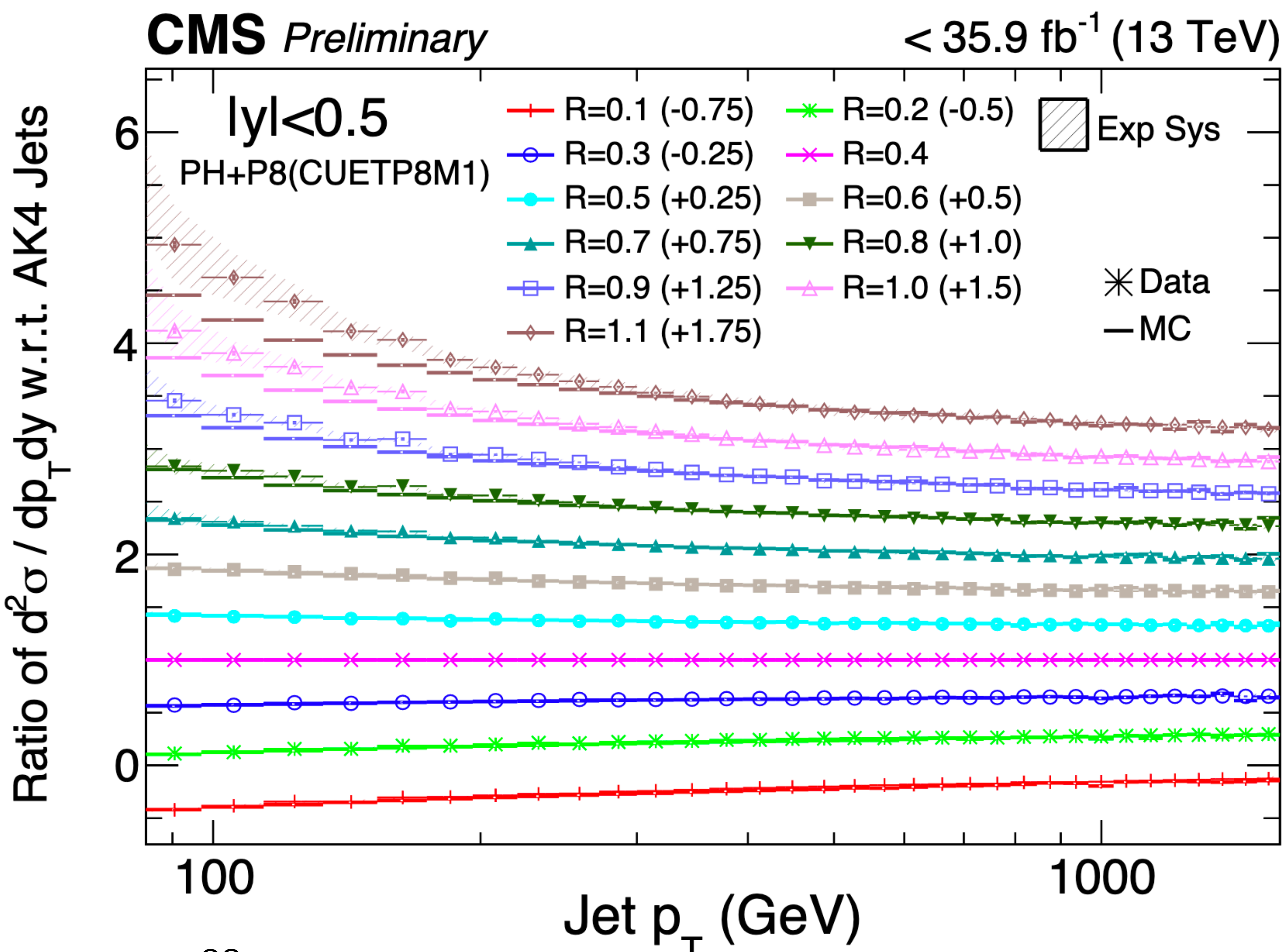


α_s: inclusive jet cross-section

CMS Measurement with R-scan

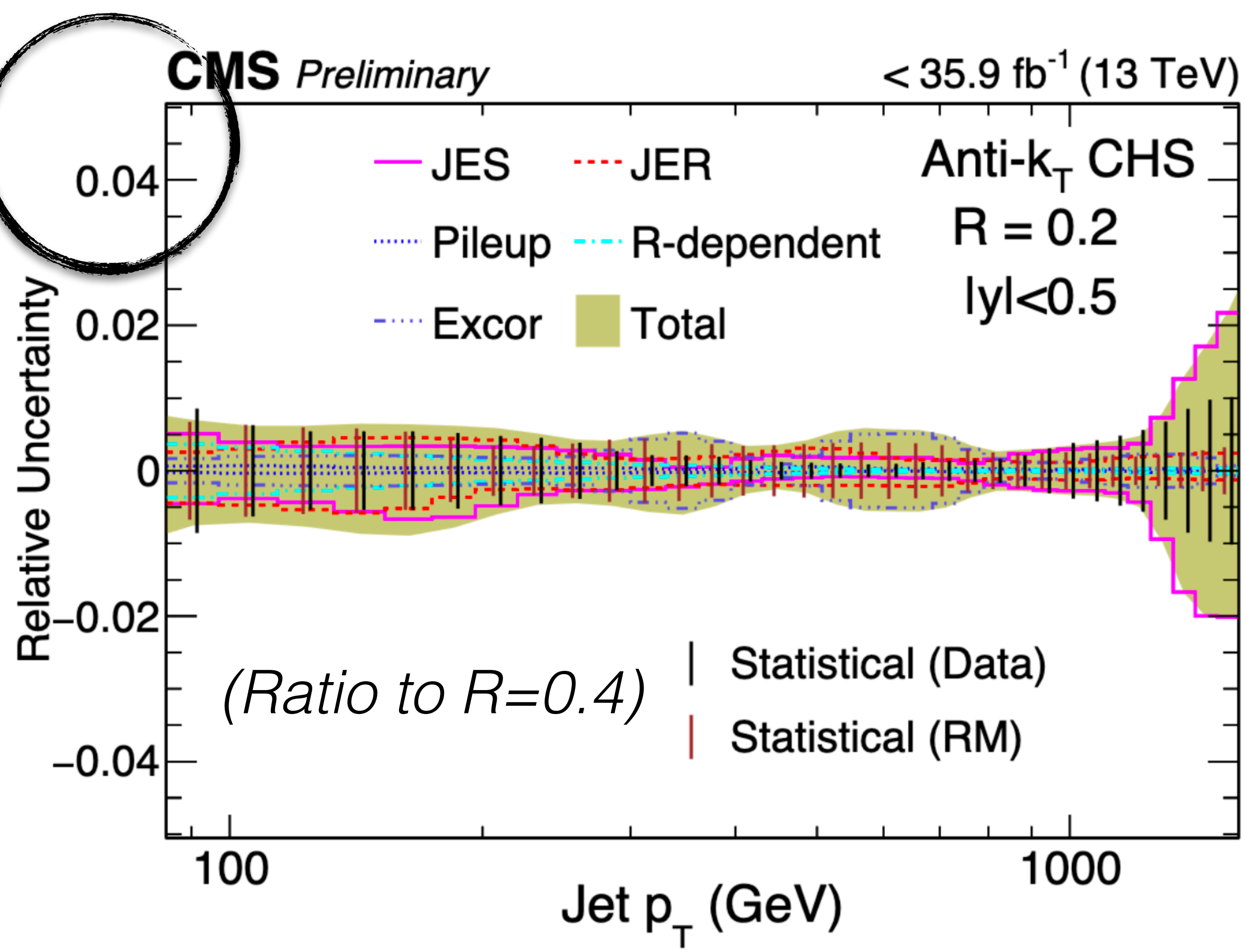
ATLAS Measurement @ 13 TeV

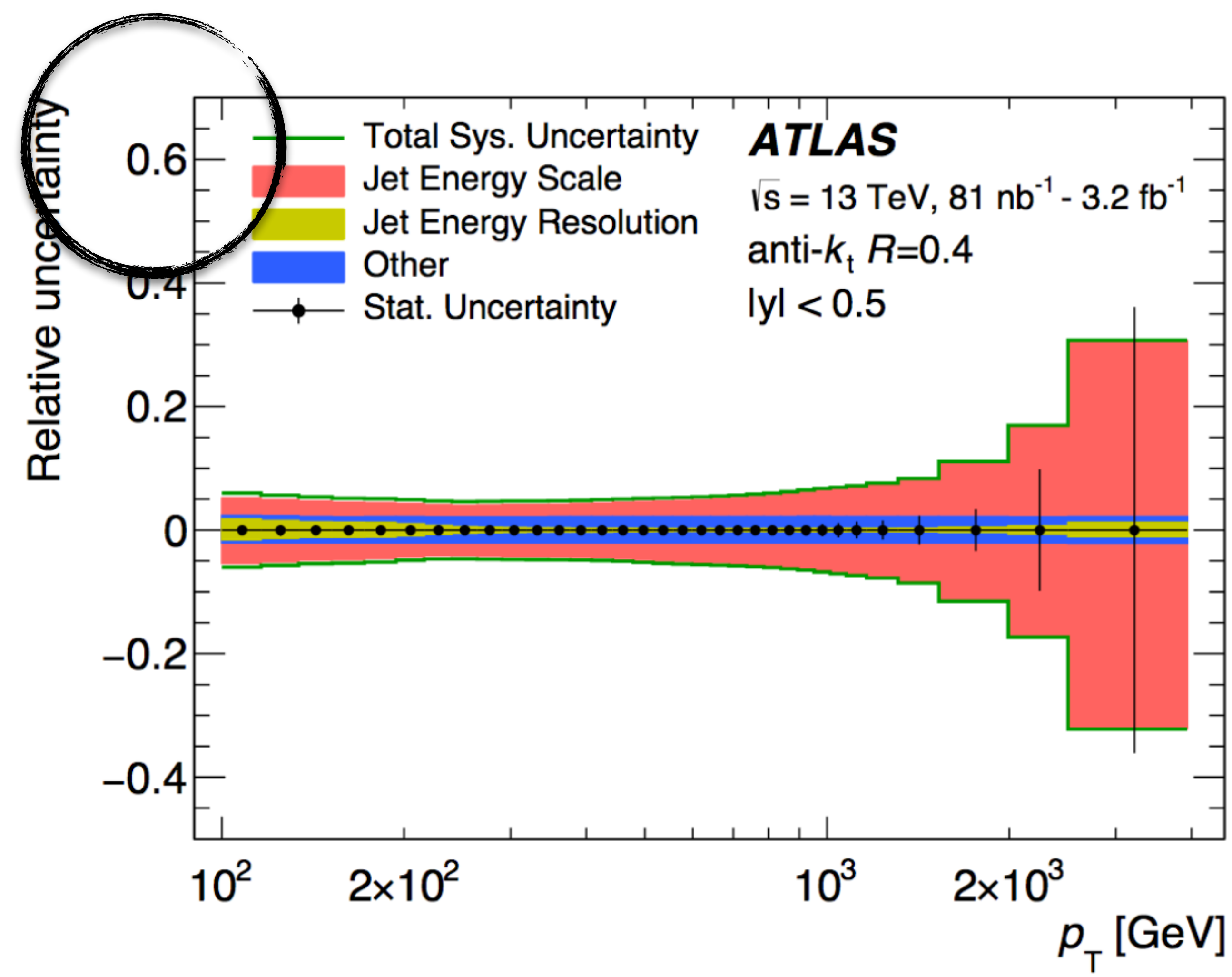
- Measured double-differentially in p_T, rapidity (y) for both ATLAS and CMS
- CMS recently measured using a range of jet radii
  - Enables better understanding of different effects within a jet
  - Some disagreement between data and MC at low p_T, particularly for large radii where modeling is important



α_S: inclusive jet cross-section

- Uncertainties dominated by jet energy scale uncertainty and statistics (at high p_T)
- Measurement of cross-section using multiple jet radii enables measurement of ratios of cross-sections
  - Significantly ***reduces size of uncertainties***
  - Example of careful analysis design improving precision of result

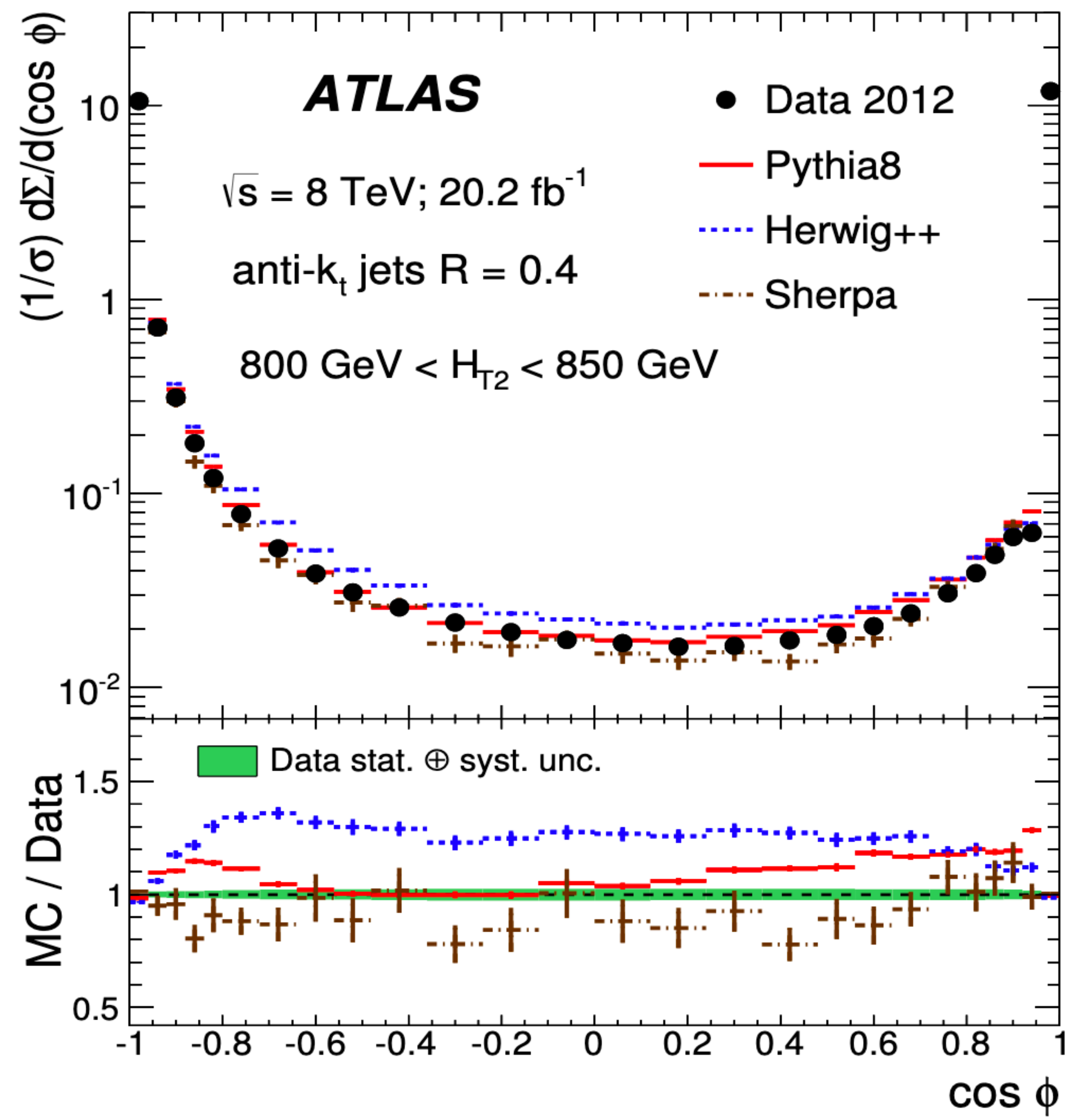




α_S: teecs

- Event shape observables can be sensitive to α_S
  - Defined continuously → more information than ratio of 3-jet / 2-jet cross sections
  - Many examples of measuring α_S at an e+e- collider using event shape observables
- The same concepts are being explored for hadron colliders (Soft drop thrust, TEECs)
  - Transverse energy-energy correlations (TEECs) are the transverse energy-weighted angular distribution of hadron pairs

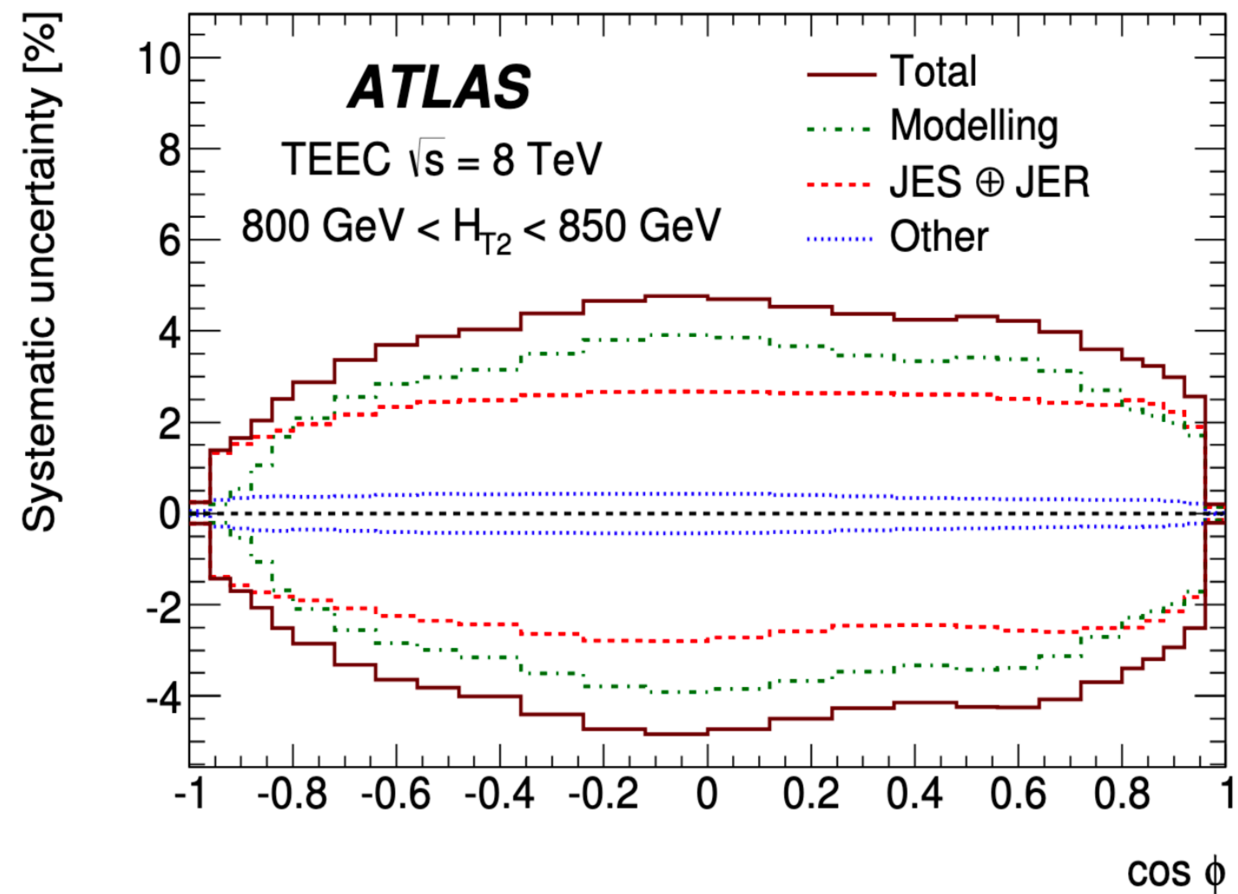
$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} \equiv \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E_{\mathrm{T}i}^{A}E_{\mathrm{T}j}^{A}}{\left(\sum_k E_{\mathrm{T}k}^{A}\right)^2}\delta(\cos\phi - \cos\phi_{ij})$$

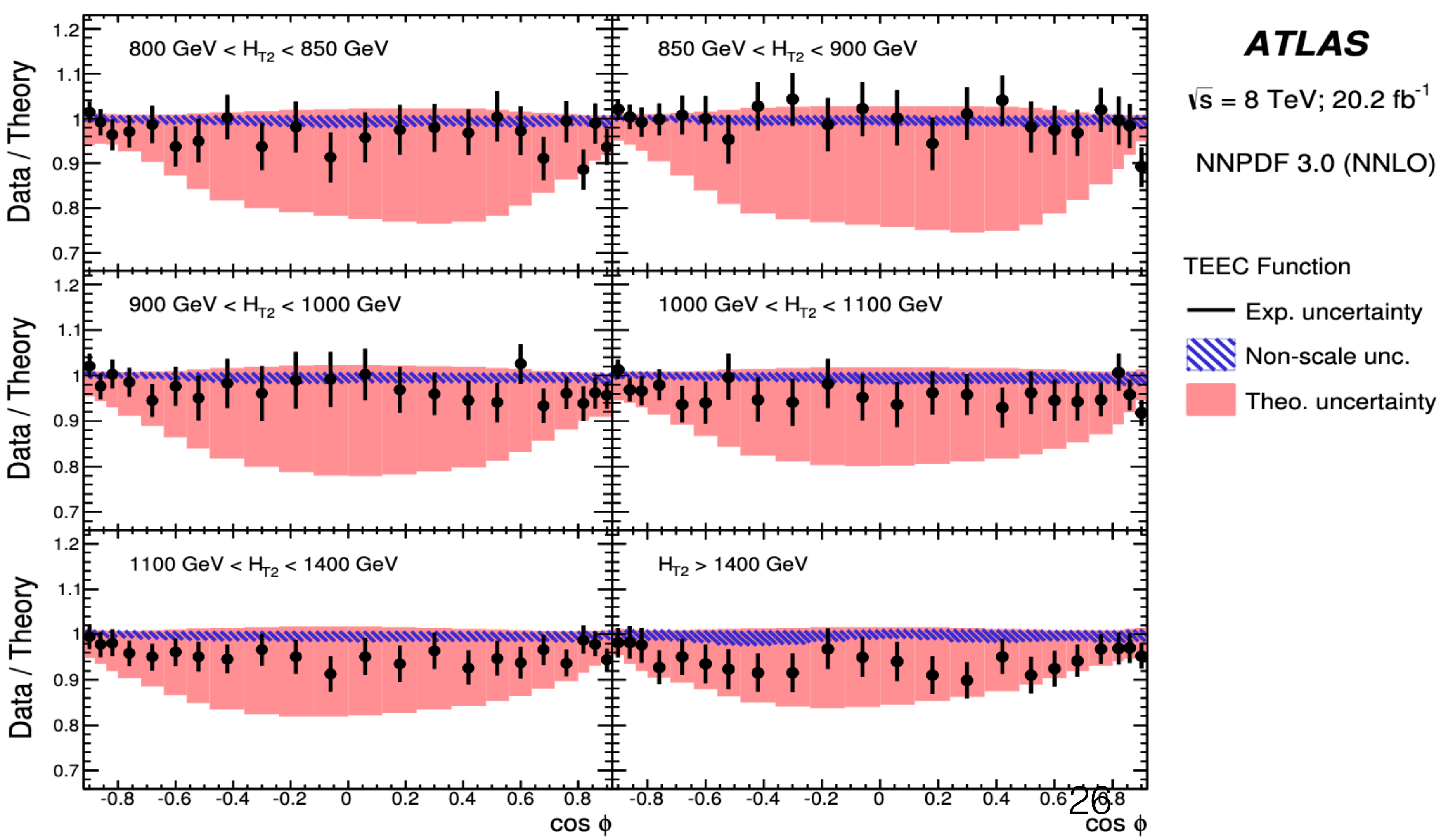


ATLAS

α_S: teecs

- α_S determined in each bin of $H_{T2} = p_{T1} + p_{T2}$
- Experimental uncertainties dominated by jet modeling and JES/JER

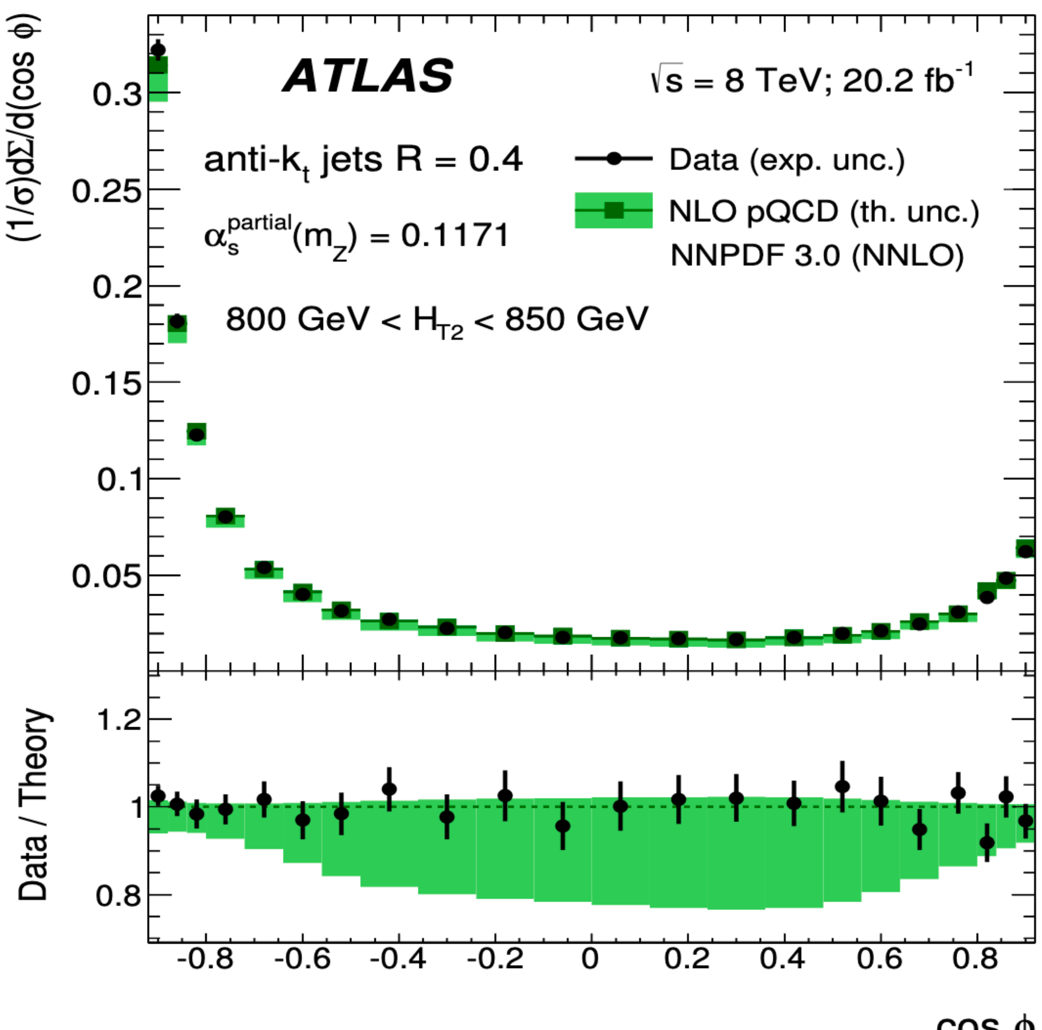


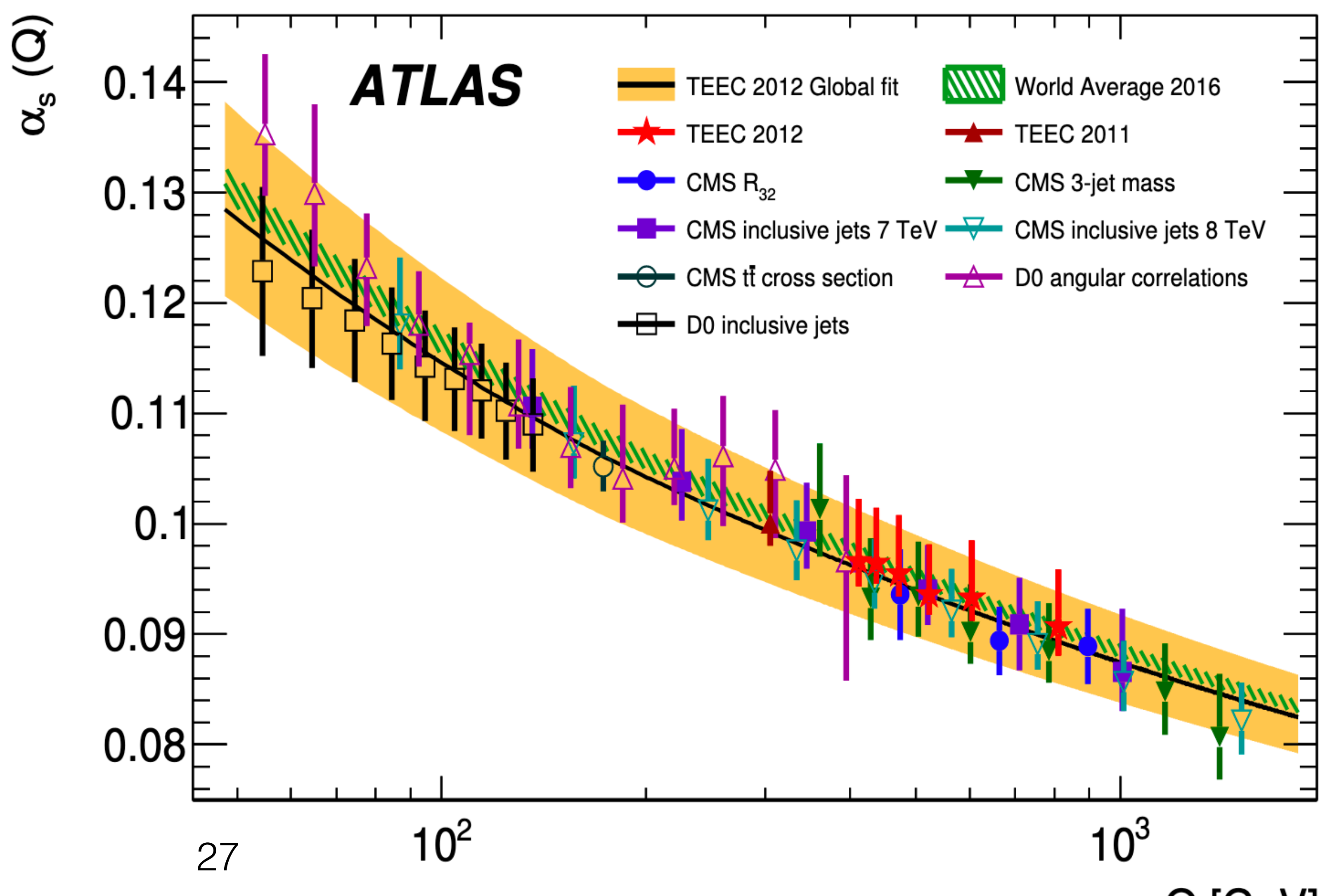


- Theoretical uncertainties typically larger than experimental uncertainties
- Theoretical uncertainties decrease for larger values of H_{T2}

α_s: teecs

- TEECs are infrared safe, and less affected by second order corrections than thrust
- Fit for α_s in different bins of H_{T2} using theoretical predictions at NLO
- Covers a smaller range than inclusive jet measurement, but still very powerful





jet modeling

jet modeling

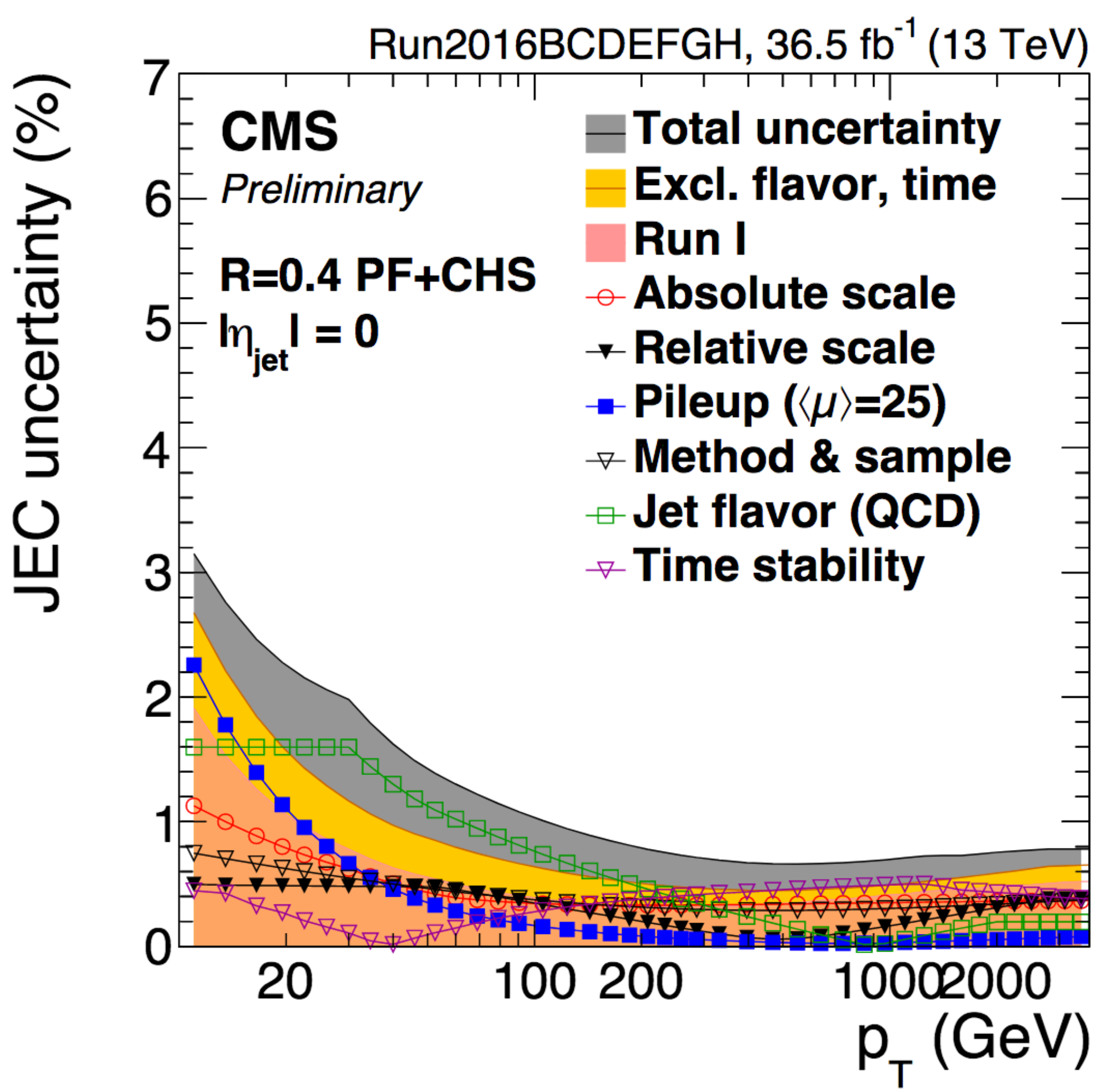
- No complete theoretical model of jet formation → rely on MC models which need to be tuned to data
  - Often tuned with things like measurements of fragmentation functions
- Often challenging to find good observables for tuning
  - Observables where different effects are factorized can be very powerful
- Theoretical understanding of jet substructure has moved forwards in recent years
  - Able to produce calculations for JSS observables beyond leading logarithmic accuracy

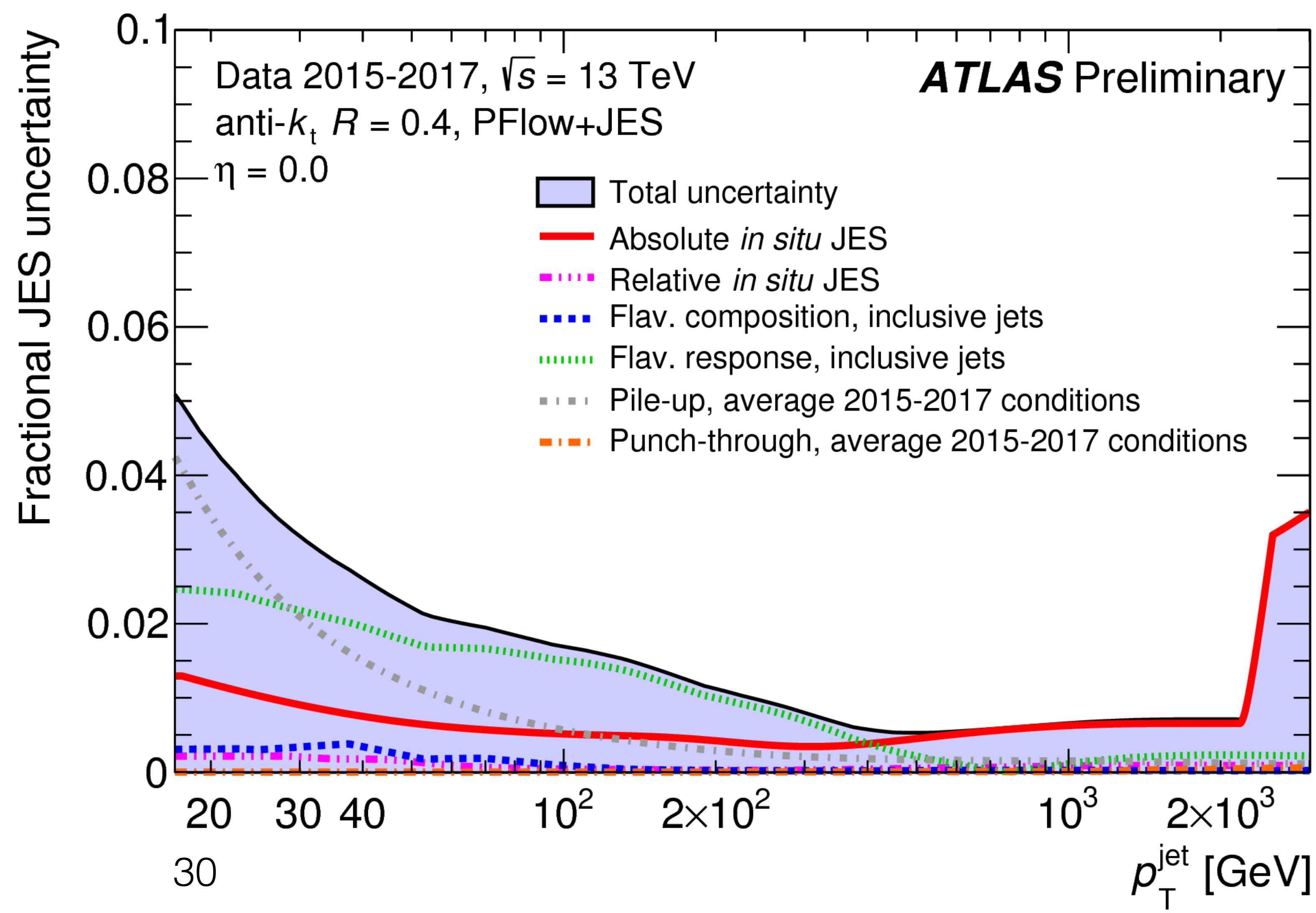
jet modeling: motivation

ATLAS

CMS

- Jet energy scale (correction) uncertainties similar for ATLAS and CMS
- ***Low-p_T region*** (p_T < ~30 GeV) dominated by pileup
- ***Middle p_T region*** (~30 GeV < p_T < ~300 GeV) dominated by flavor and modeling
- ***Highest p_T region*** (p_T > ~300 GeV) dominated by in situ (also related to modeling)



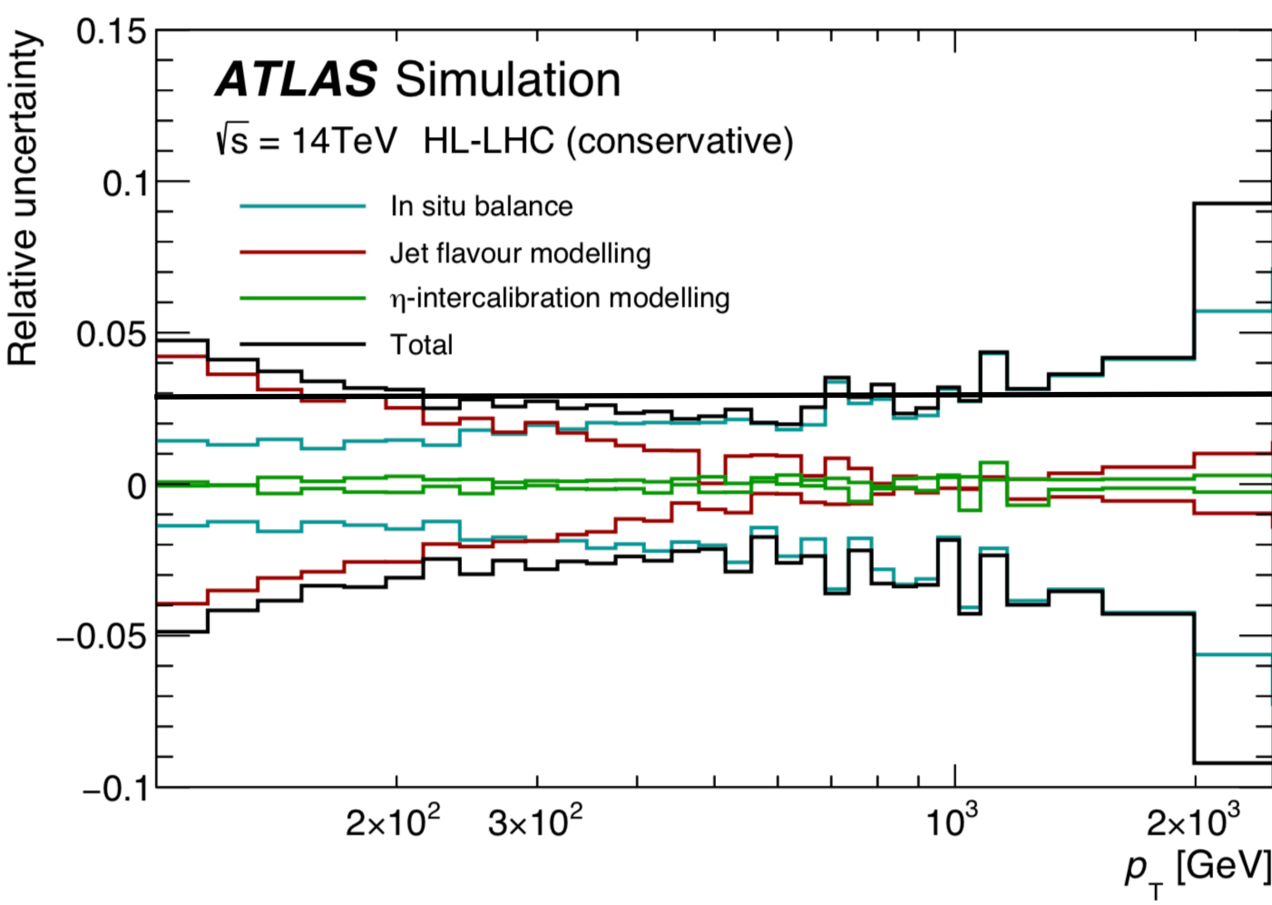


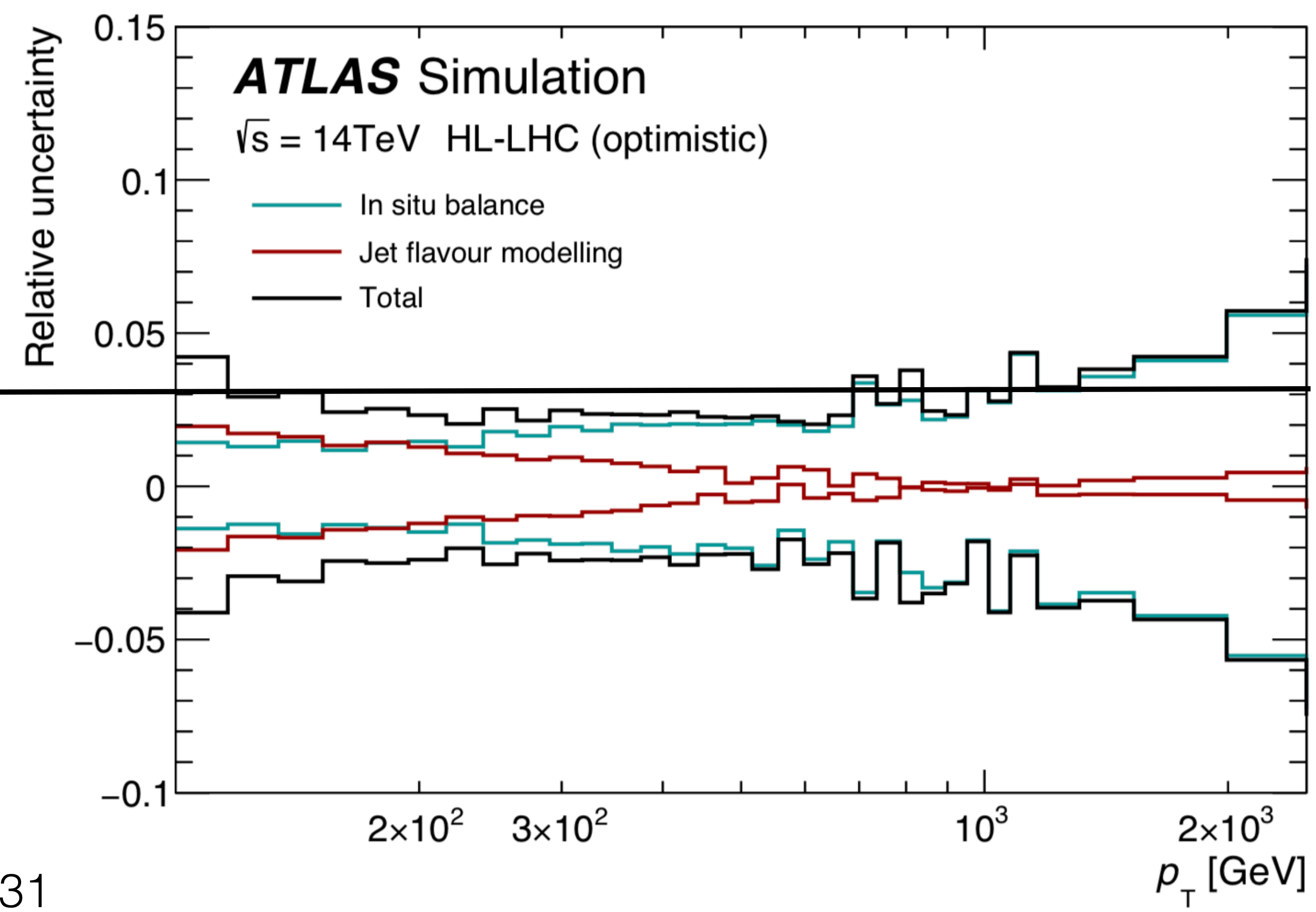
jet modeling: motivation

ATLAS

CMS

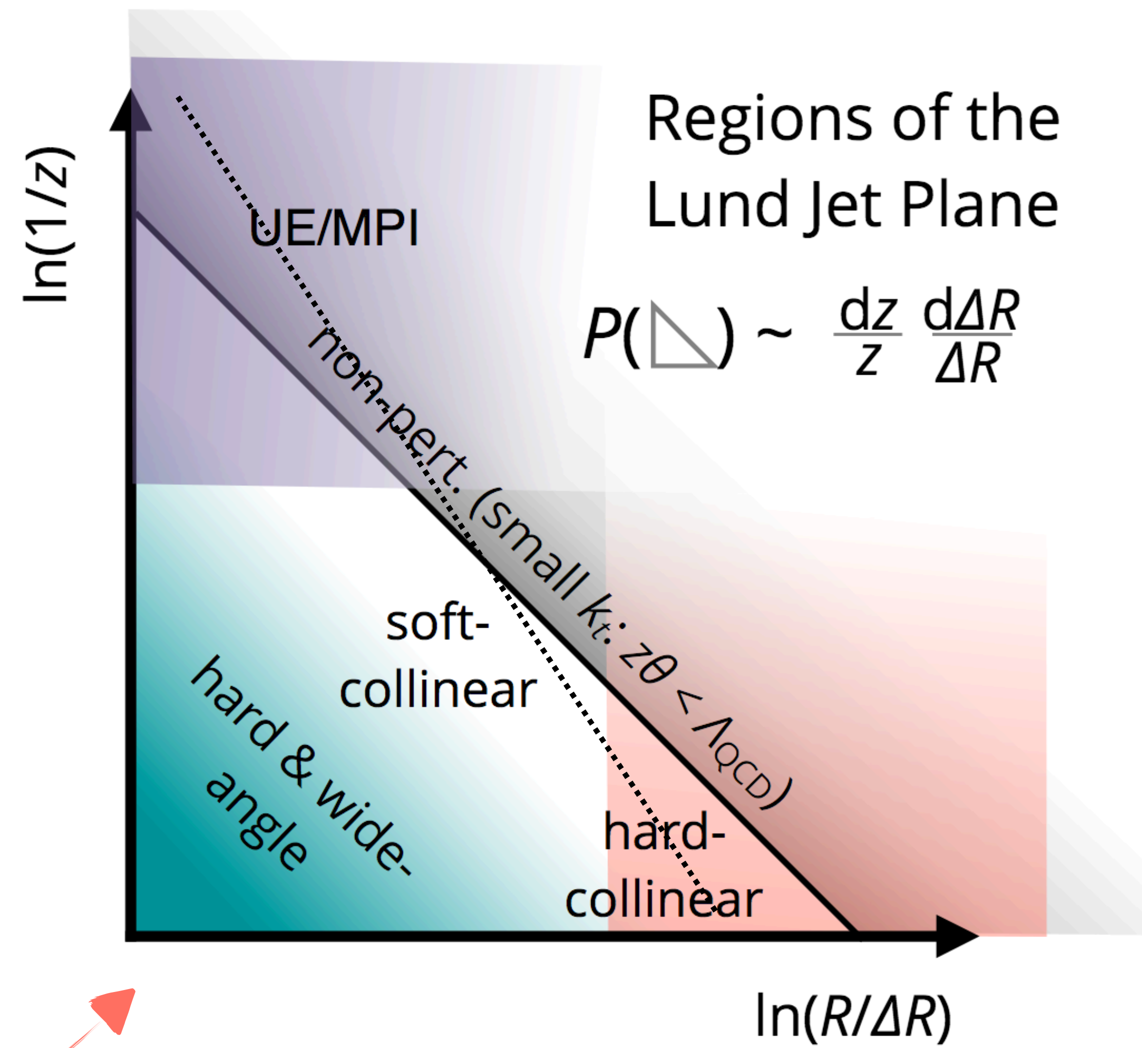
- Understanding of jet modeling directly impacts the significance of HL-LHC results
- **Conservative**
  - Eta intercalibration modeling halved, photon energy scale uncertainties halved
- **Optimistic**
  - Flavor response, photon energy scale, and rho topology uncertainty halved
  - No eta intercalibration uncertainty

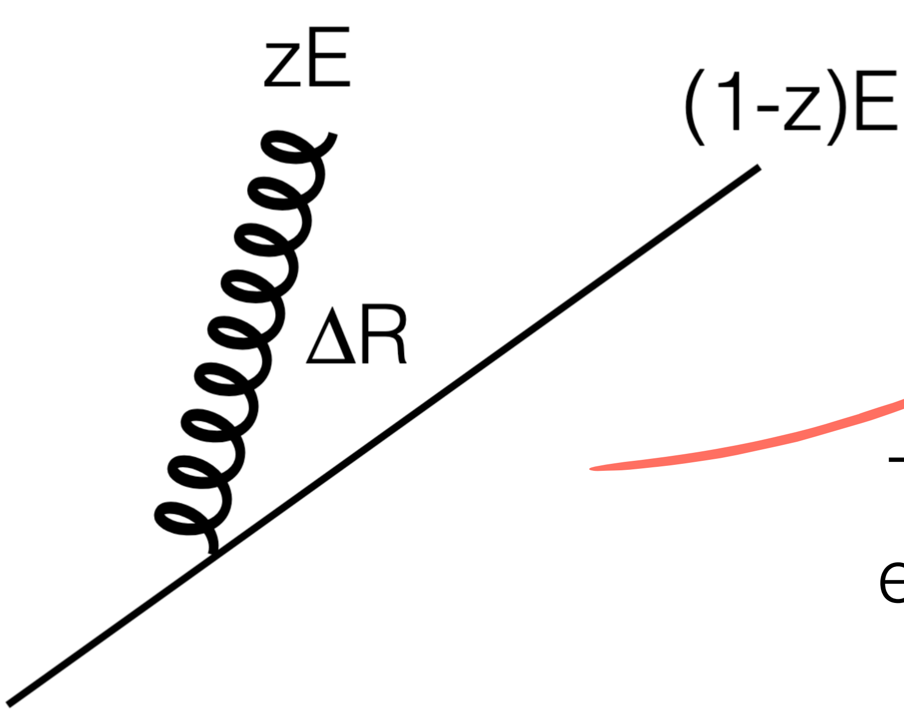




jet modeling: the lund plane

- A jet may be approximated as soft emissions around a hard core which represents the originating quark or gluon
- Emissions may be characterized by
  - z = relative momentum of emission with respect to the jet core
  - ΔR = angle of emission relative to the jet core



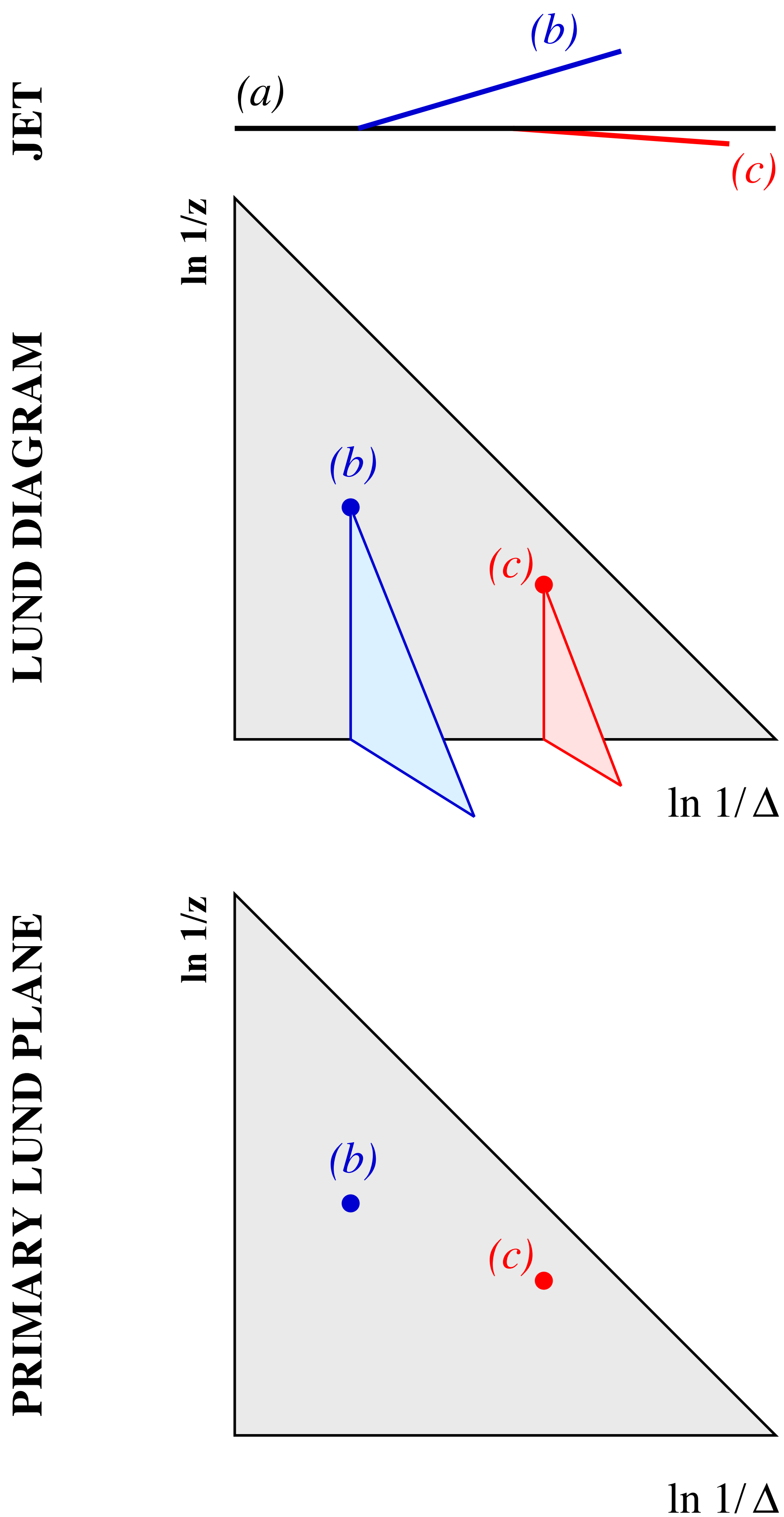


The Lund Plane is the phase space of these emissions: it naturally factorizes perturbative and non-perturbative effects, UE/MPI, etc.

jet modeling: the lund jet plane

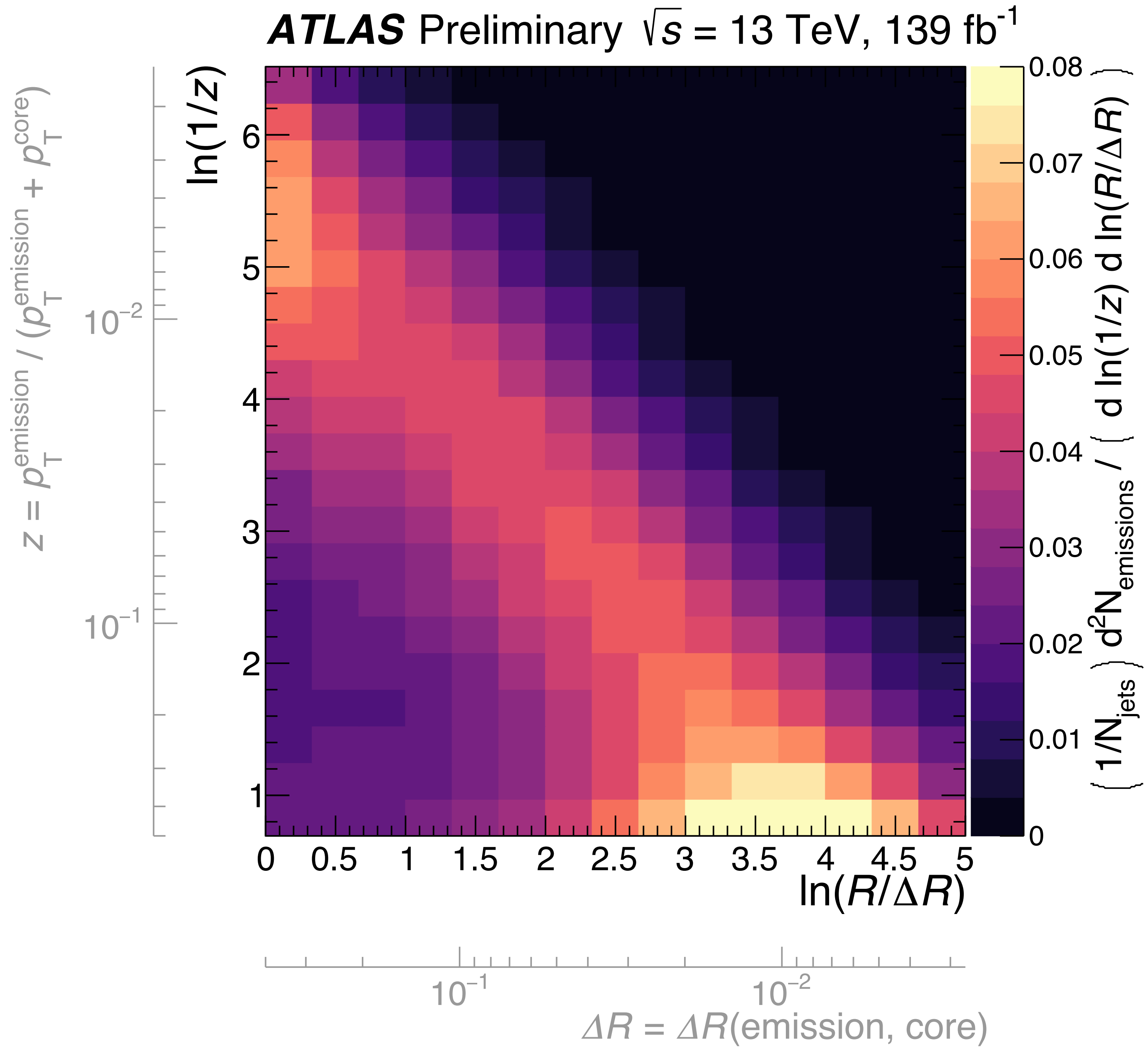
1807.04758

- Similar method may be used for understanding the issues *within a jet*
- Recluster constituents with C/A algorithm
- Decluster the jet, and plot emission on the plane
  - Emissions characterized based on their angle (ΔR), and the hardness of the splitting and $z = p_T^{emission} / p_T$
- Continue declustering the harder branch until no more emissions remain



jet modeling: the lund jet plane

- Unfolded the primary Lund plane in dijet events
- Using tracks associated to the jets in order to have precise measurements for small splittings
  - Unfolding to charged particle level
- *This observable was only proposed ~1 year ago → new ideas could lead to better understanding of QCD*



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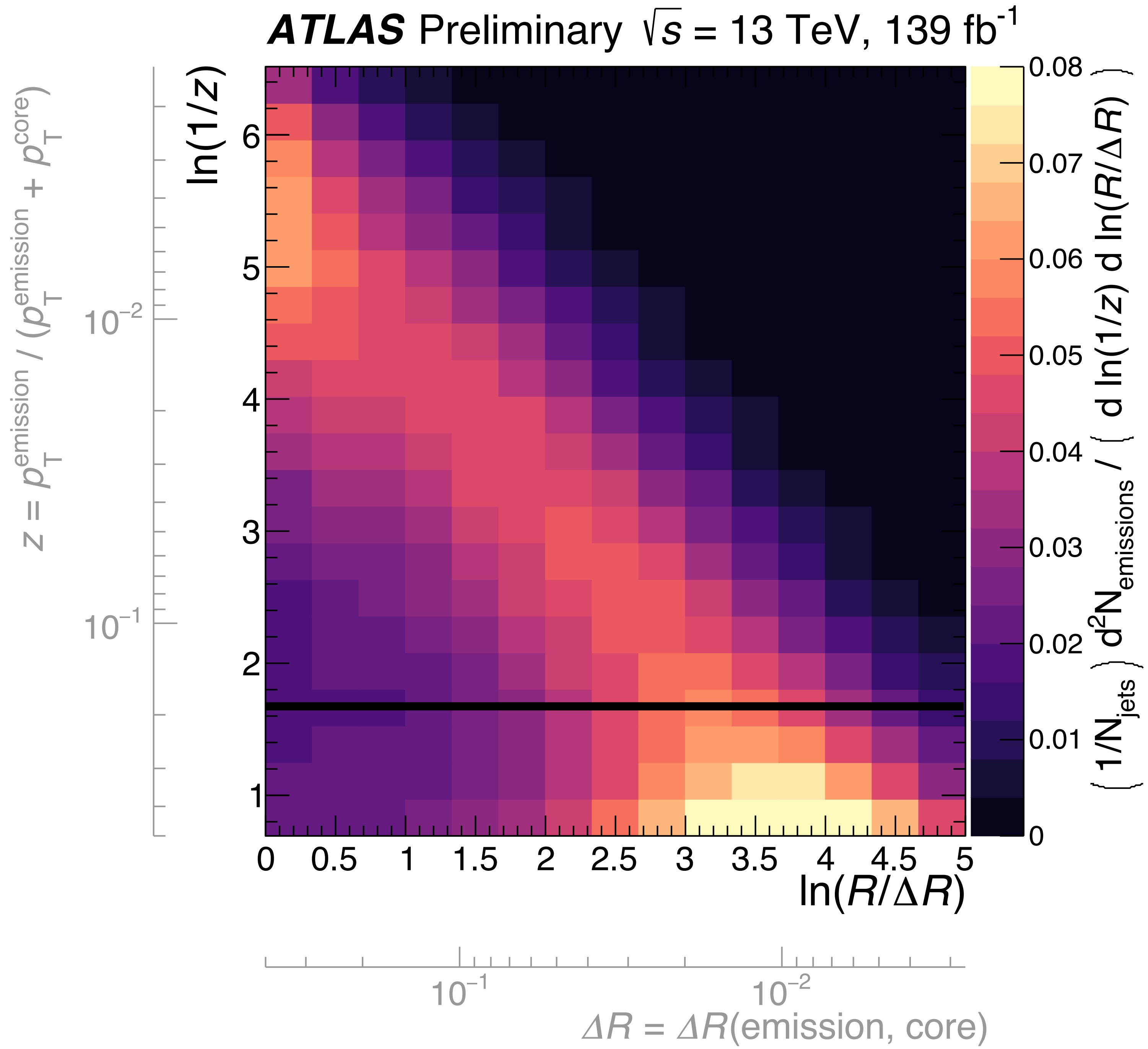

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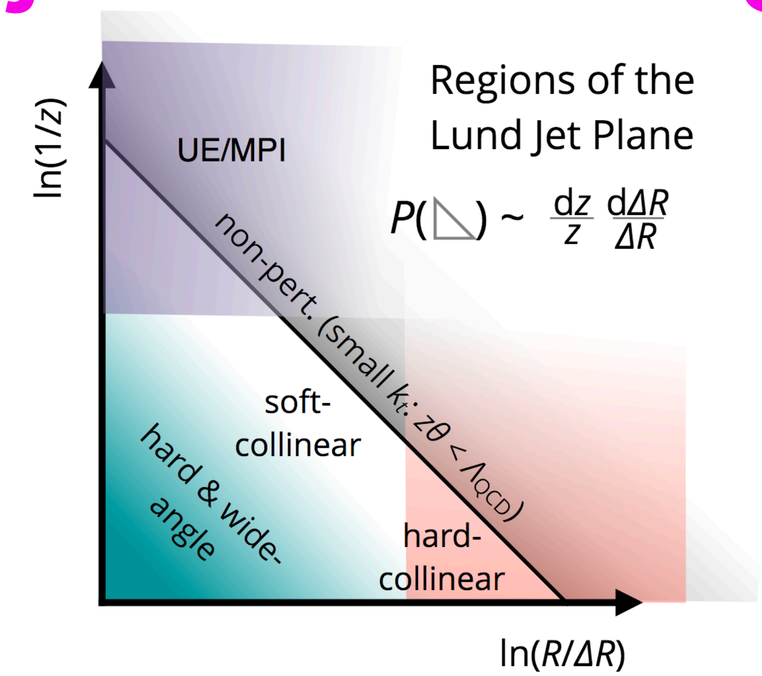
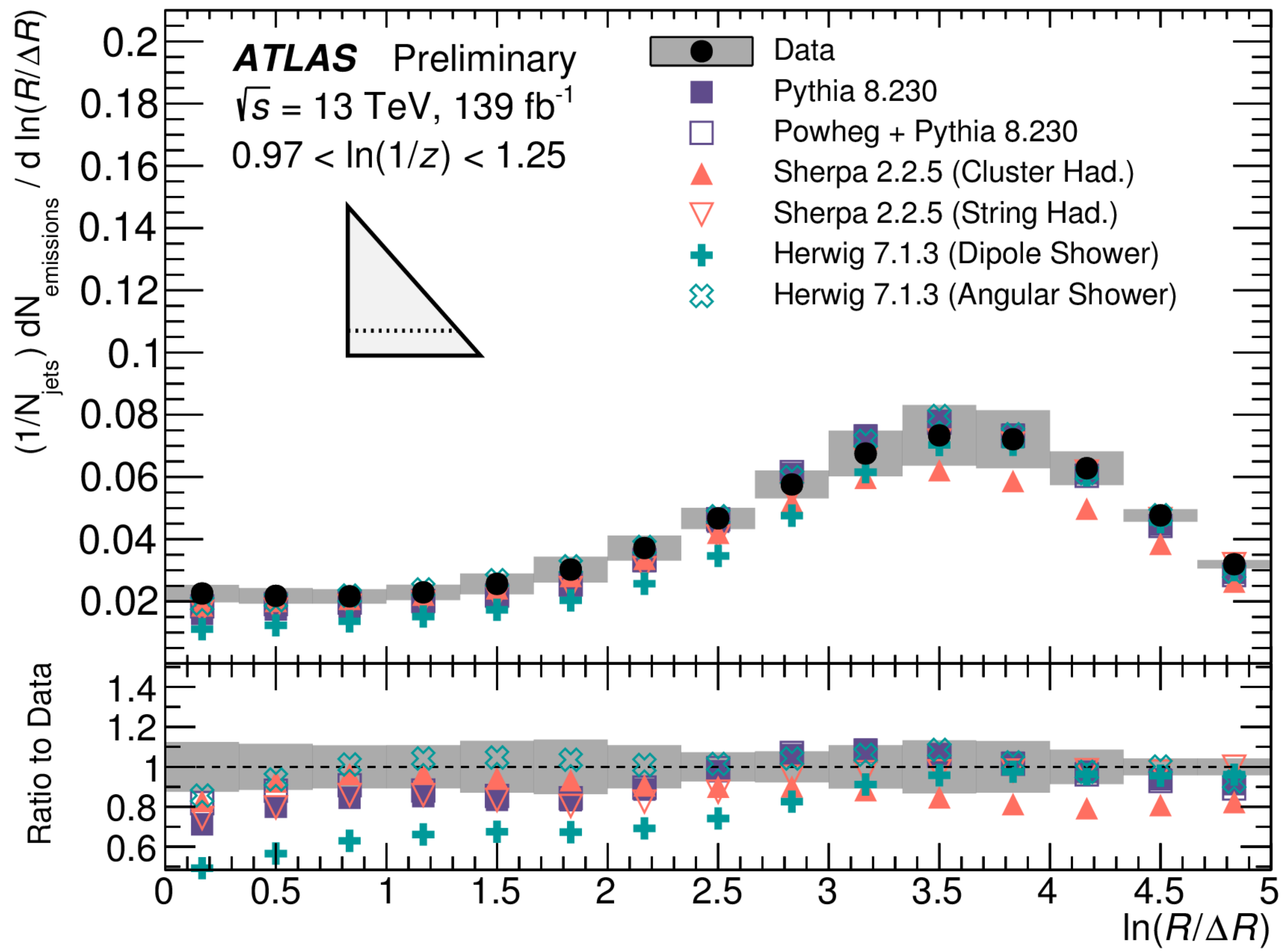
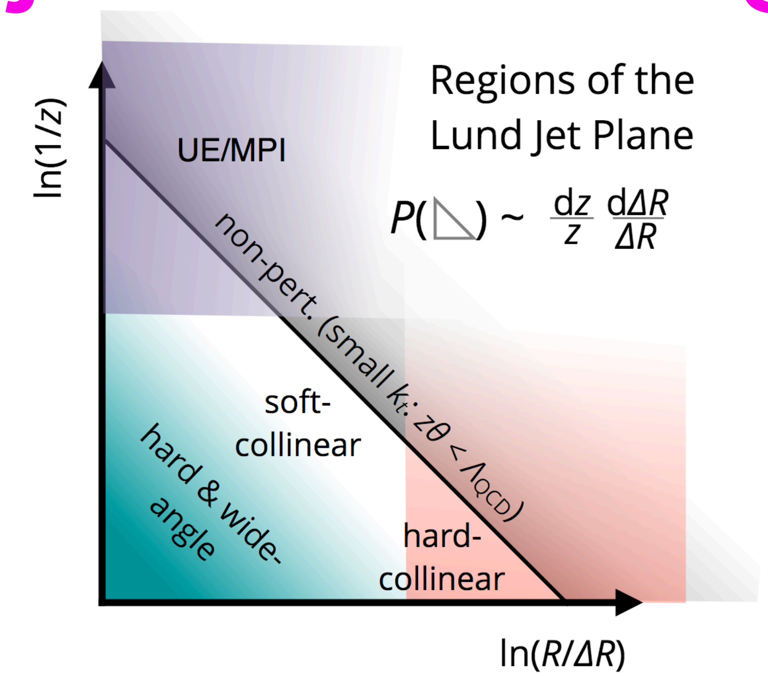
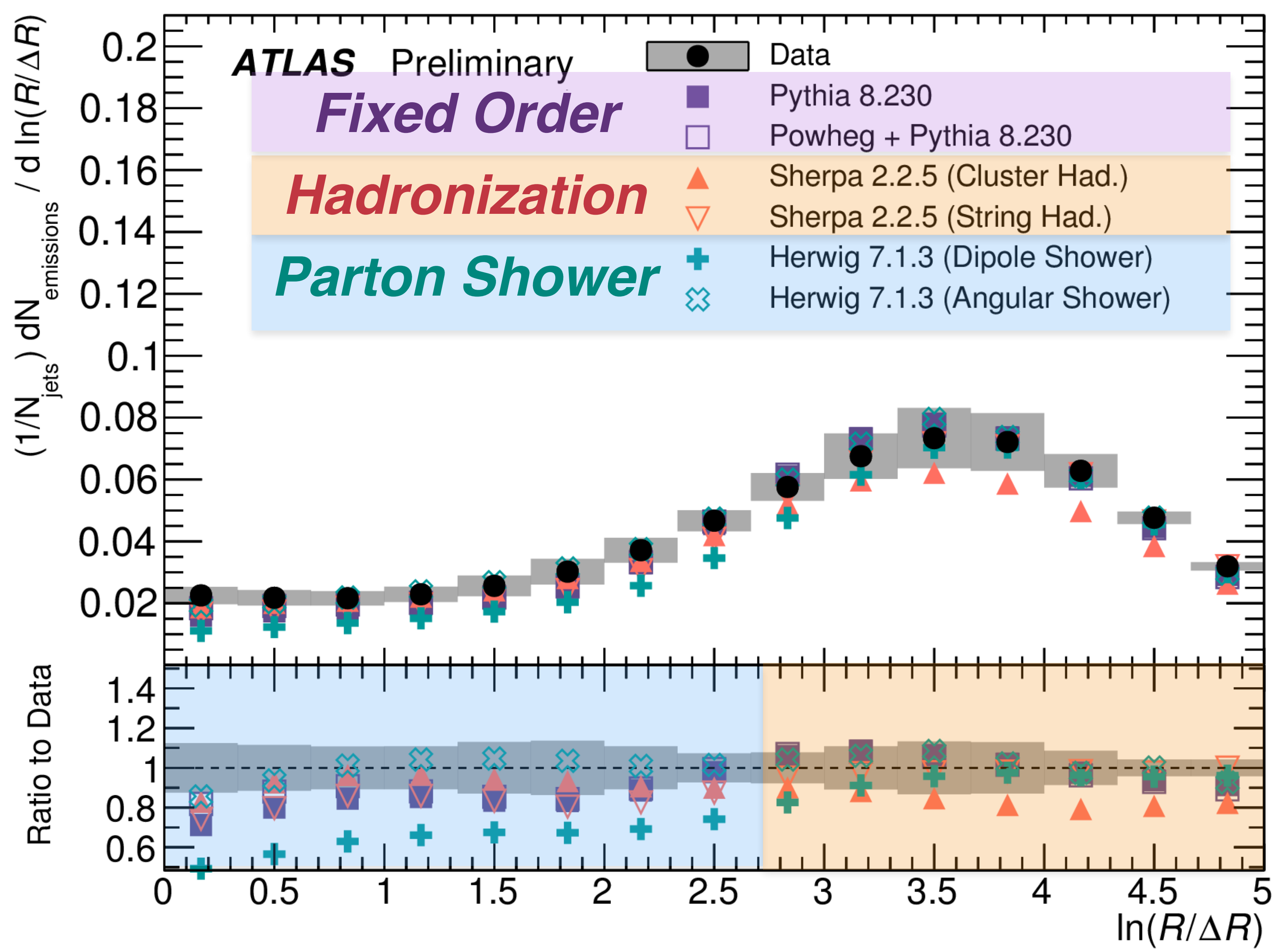




- Non-trivial differences between different generators and unfolded data
- Region dominated by hard and wide-angle splitting is affected by **parton shower**
- **Hadronization** effects in region with non-perturbative effects
- No obvious effects from **fixed order effects** (as expected)

jet modeling: the lund jet plane





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concluding thoughts

- Understanding of QCD is critical for all aspects of the LHC physics program
  - Precision for many analyses limited by PDFs, α_S, and modeling
- LHC data has already lead to advances in our understanding of QCD
- Large potential to improve understanding of QCD using the LHC data
  - More statistics will improve measurements which rely on high-p_T region
  - Improving out jet modeling will be crucial for both the JES uncertainties and in general for measurements
  - New ideas for measurements can have large impact on QCD at the LHC

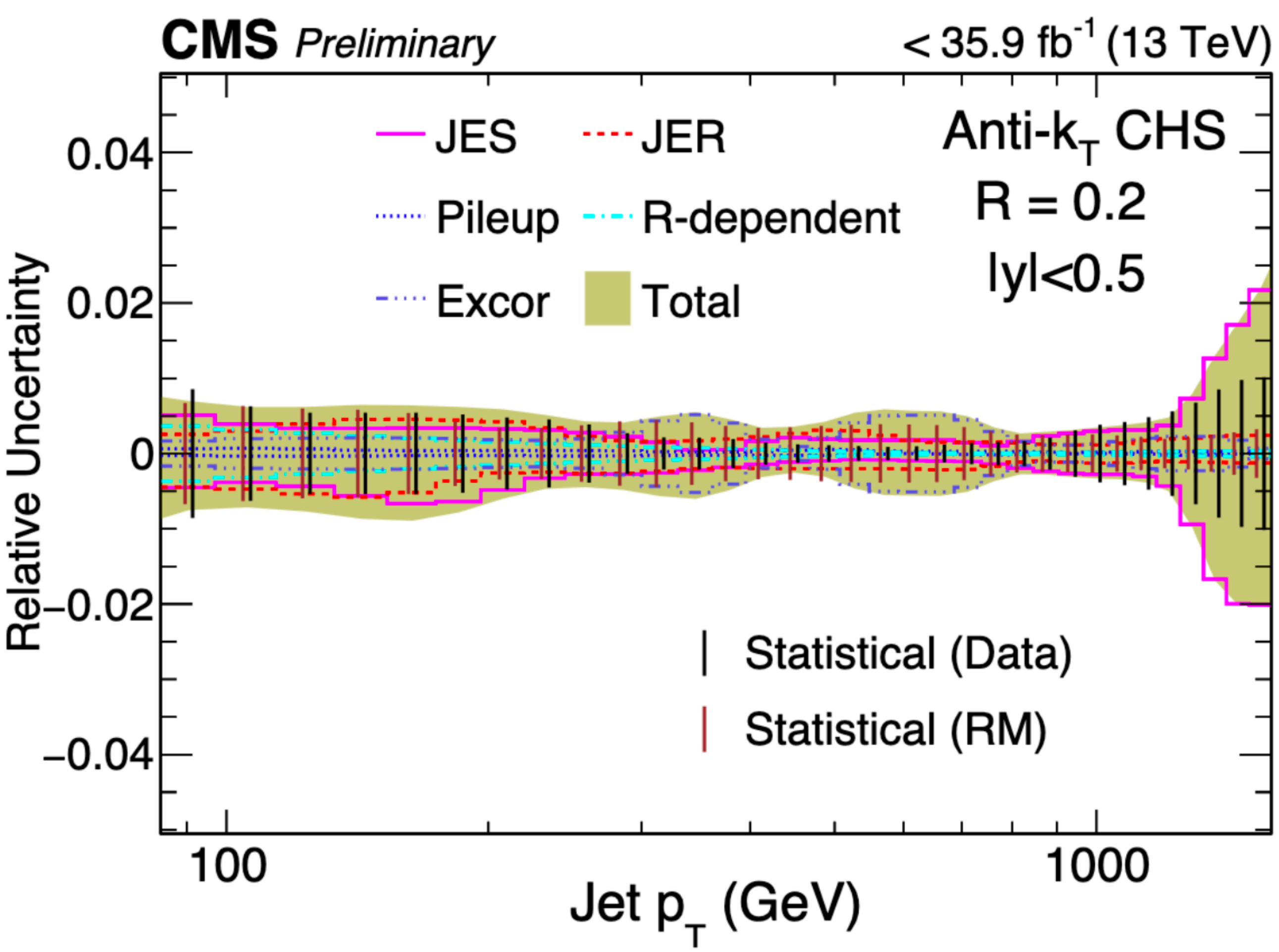
thanks!

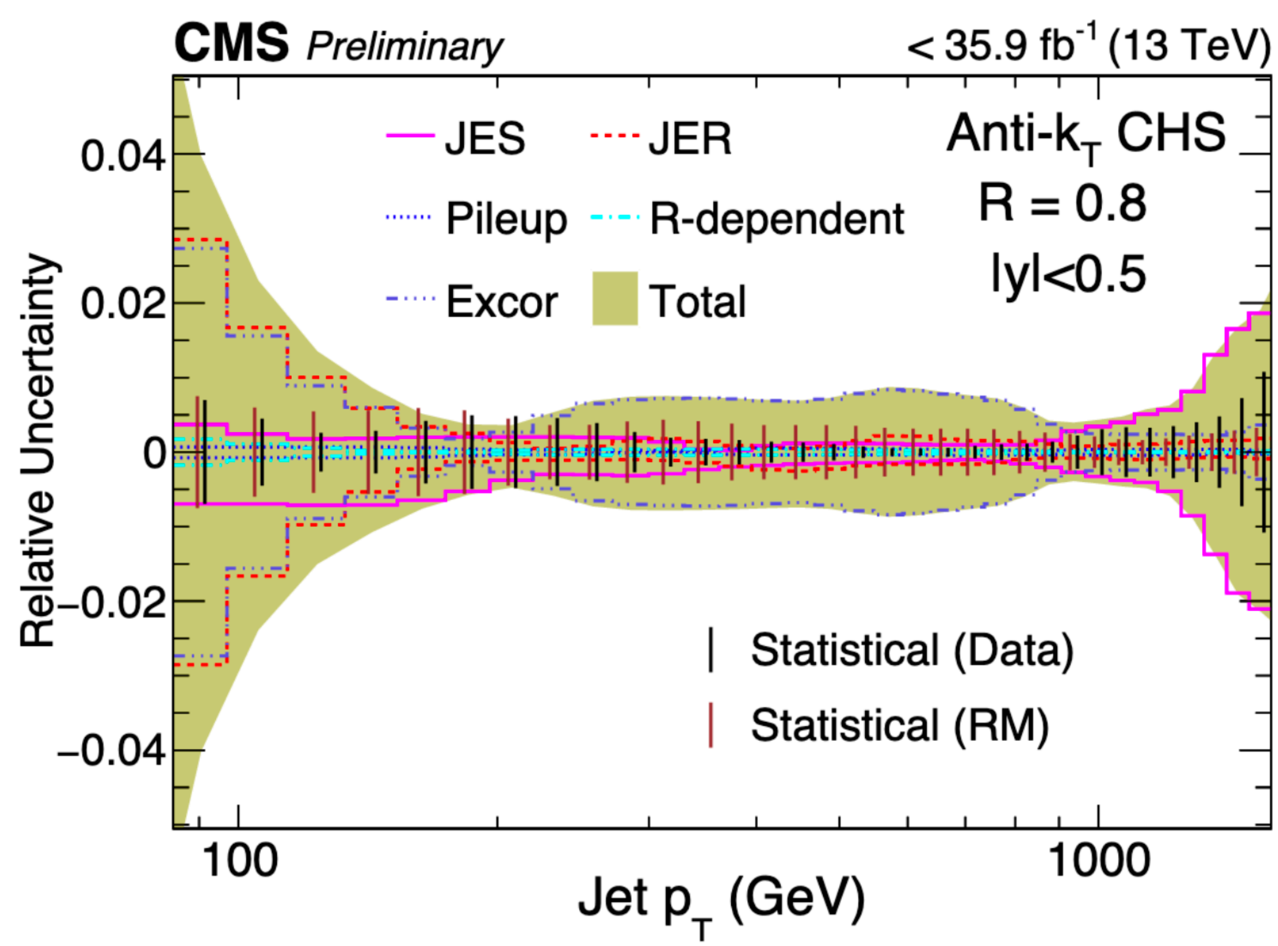
α_S: inclusive jet cross-section

CMS Measurement with R-scan

ATLAS Measurement @ 13 TeV

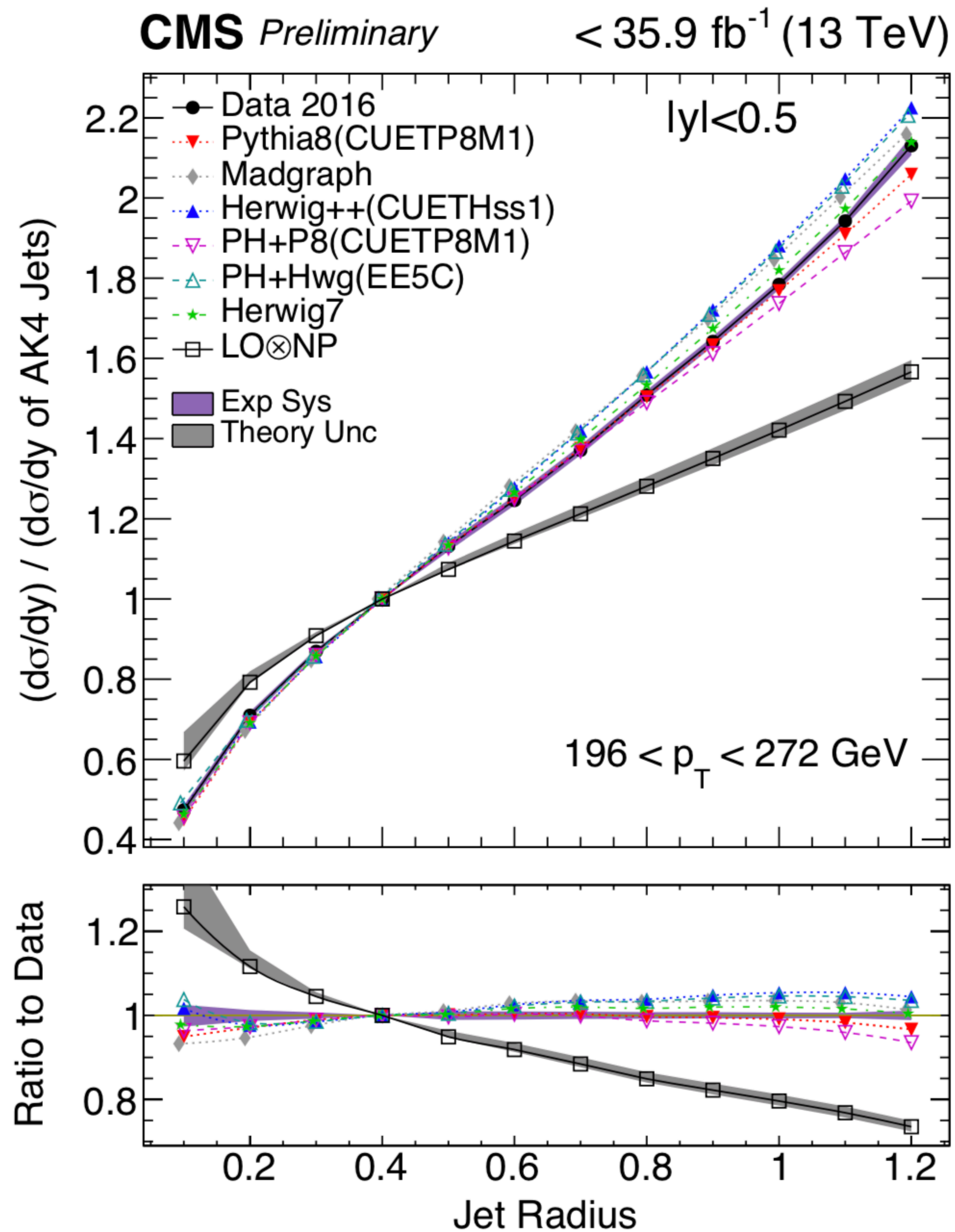
- Experimental systematic uncertainties depend on jet radius
- Not just concerned with experimental systematic uncertainties → theoretical uncertainties also mean it may be relevant to measure with large jet radius





α_s: inclusive jet cross-section

- Large jet radii correspond to larger NP corrections
  - PH+PY8 vs. PH+Hwg++ bigger than PH+Hwg++ vs. Hwg++
-

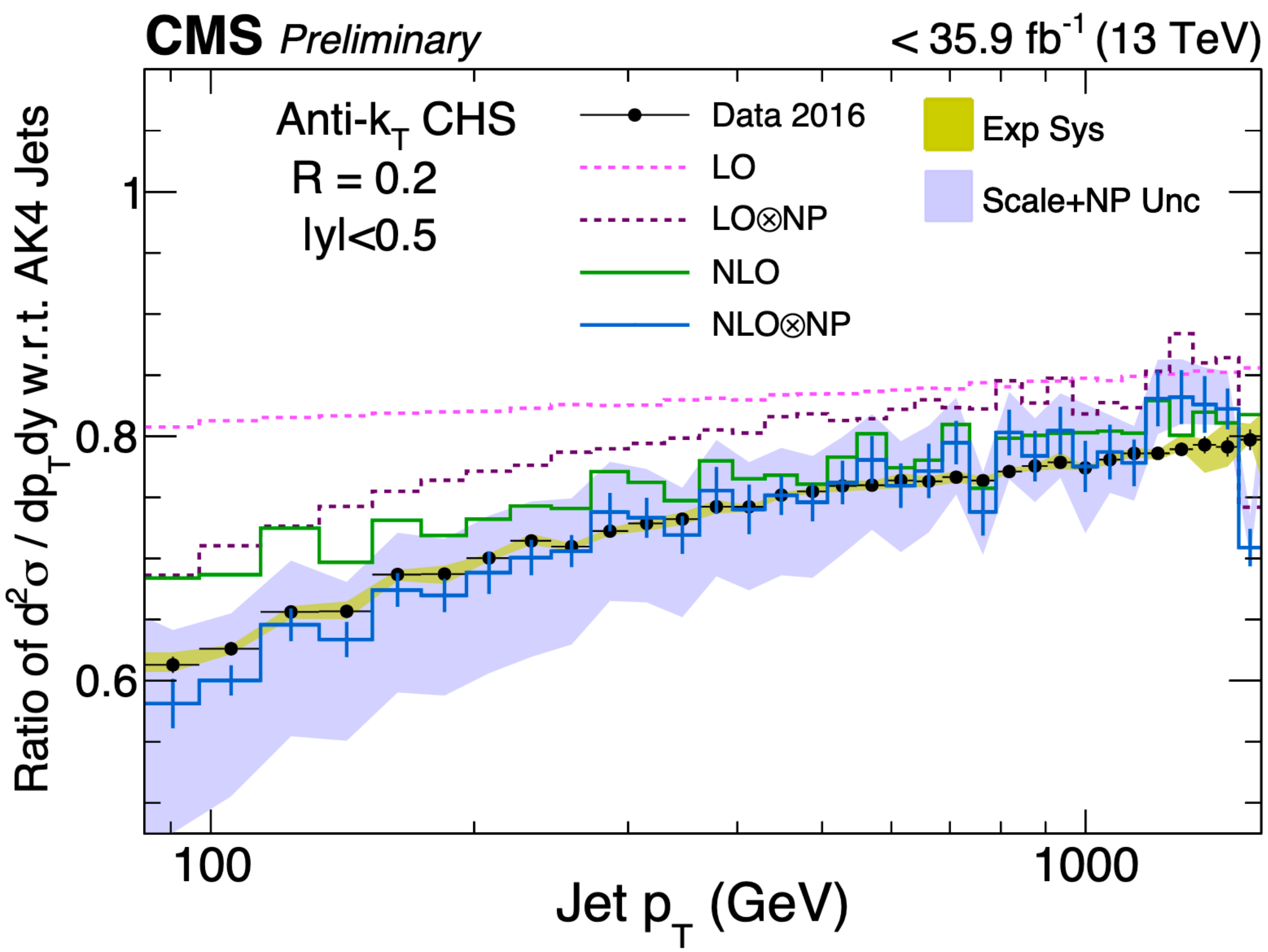


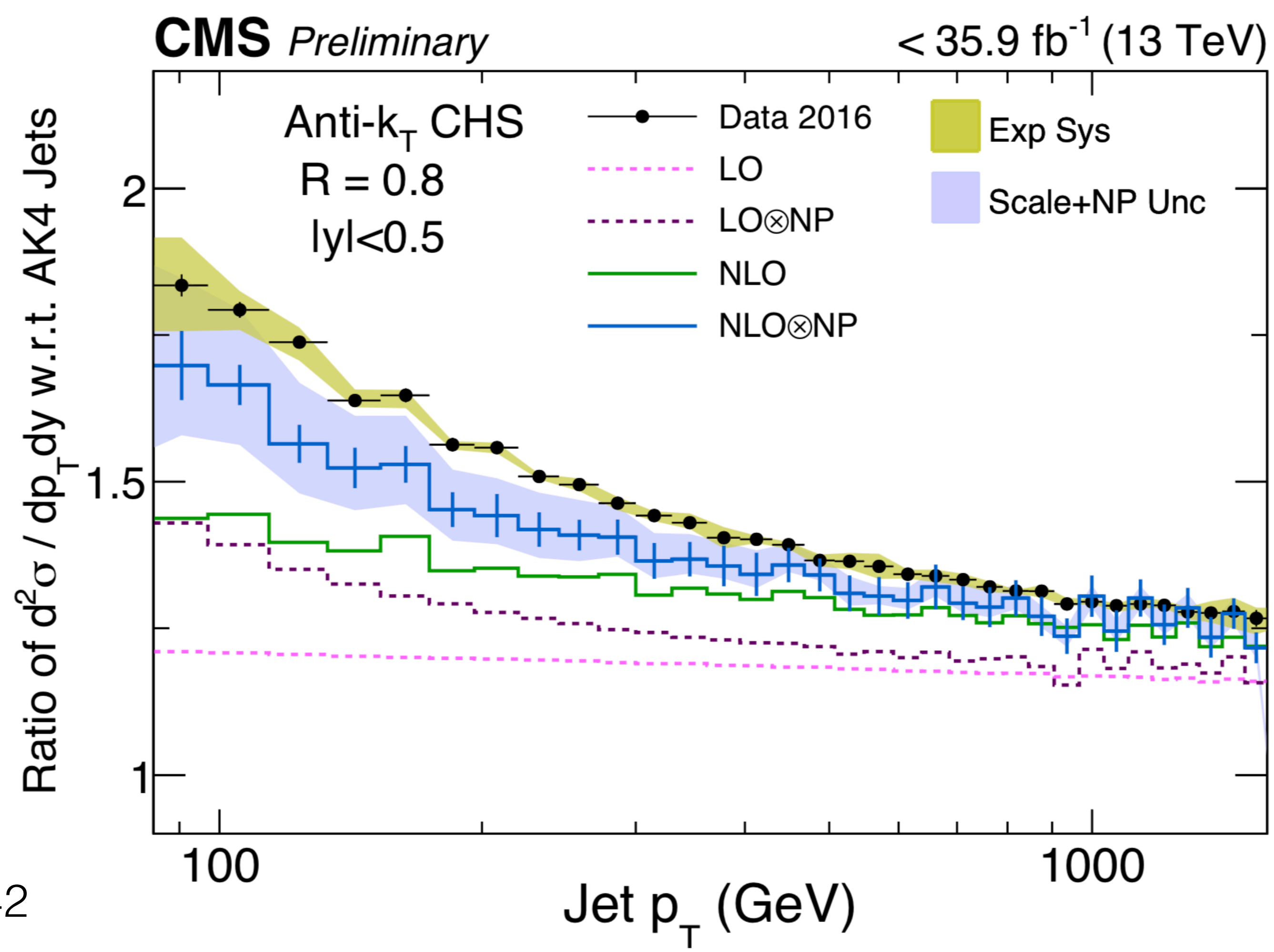
α_S: inclusive jet cross-section

CMS Measurement with R-scan

ATLAS Measurement @ 13 TeV

- Theoretical uncertainties are smaller for larger jet radii

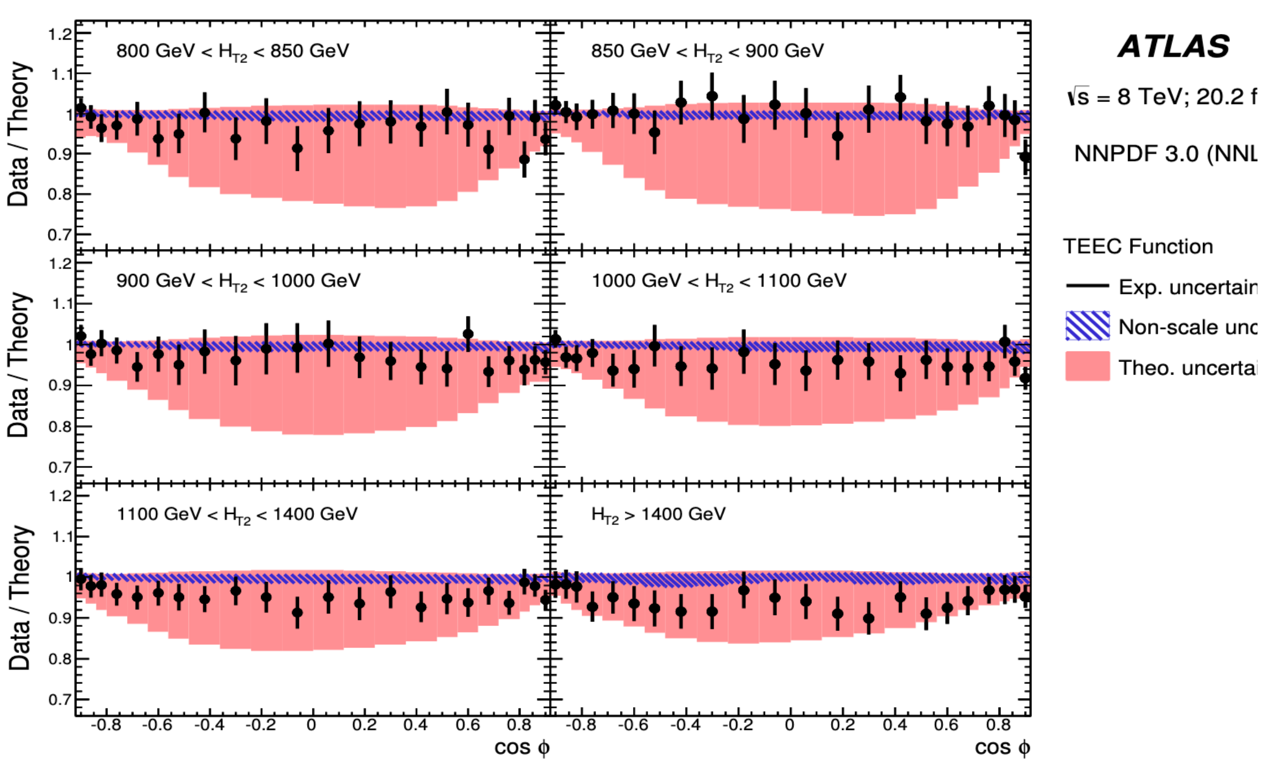


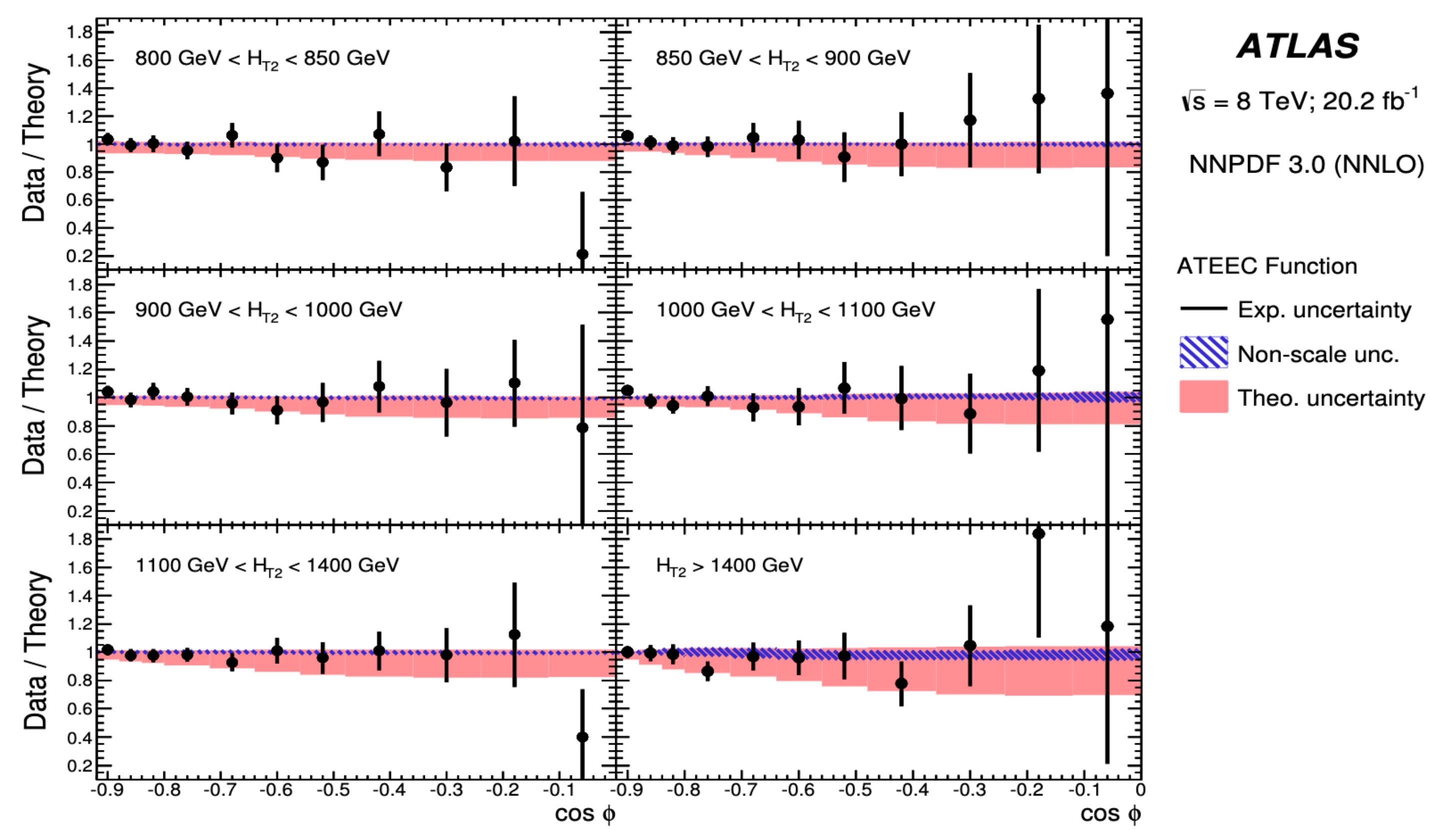


ATLAS

α_s: teecs

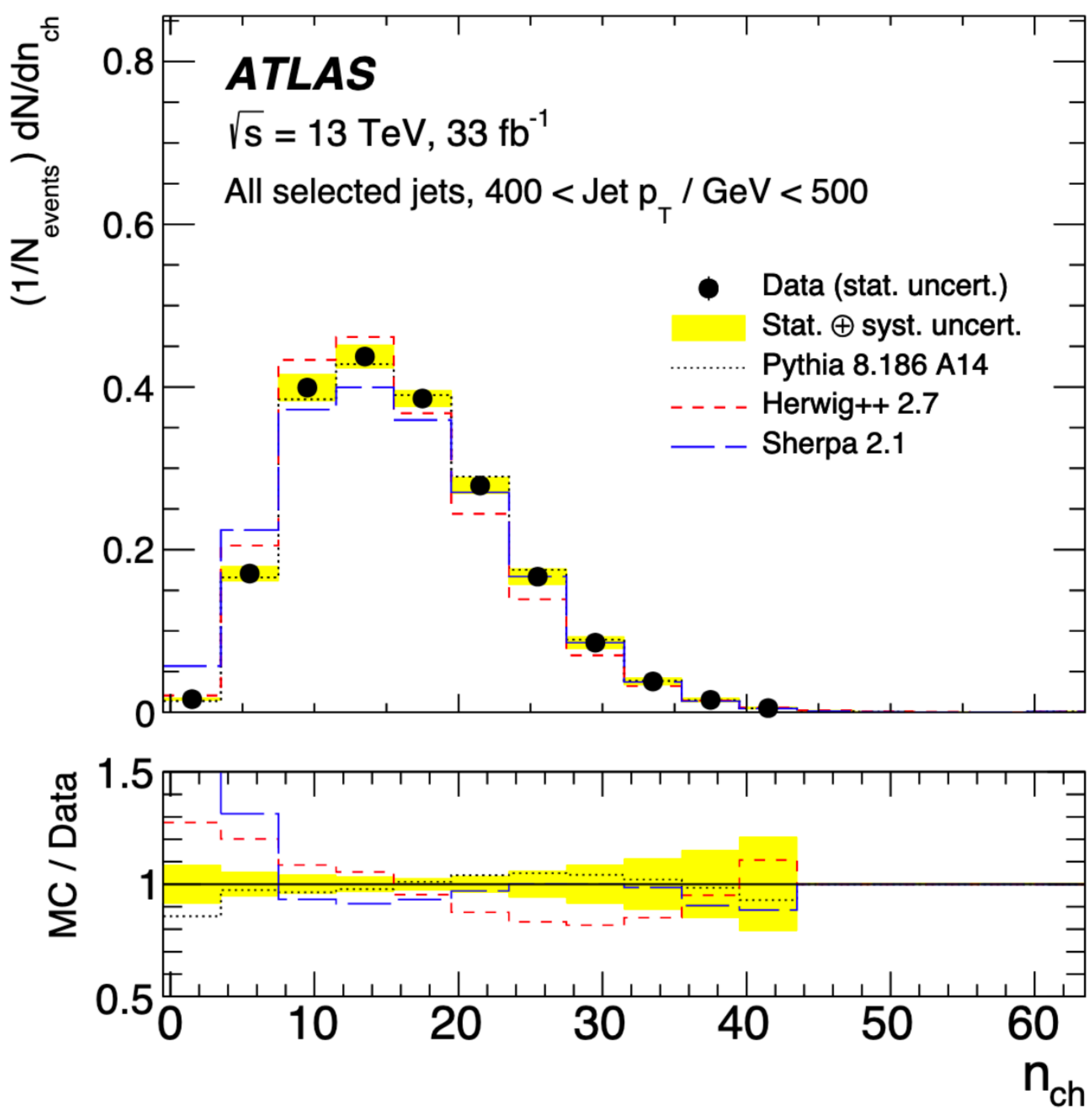
- Event shape variable which is infrared safe, and less affected by second order corrections than thrust
- Fit for α_s in different bins of H_{T2} using theoretical predictions at NLO

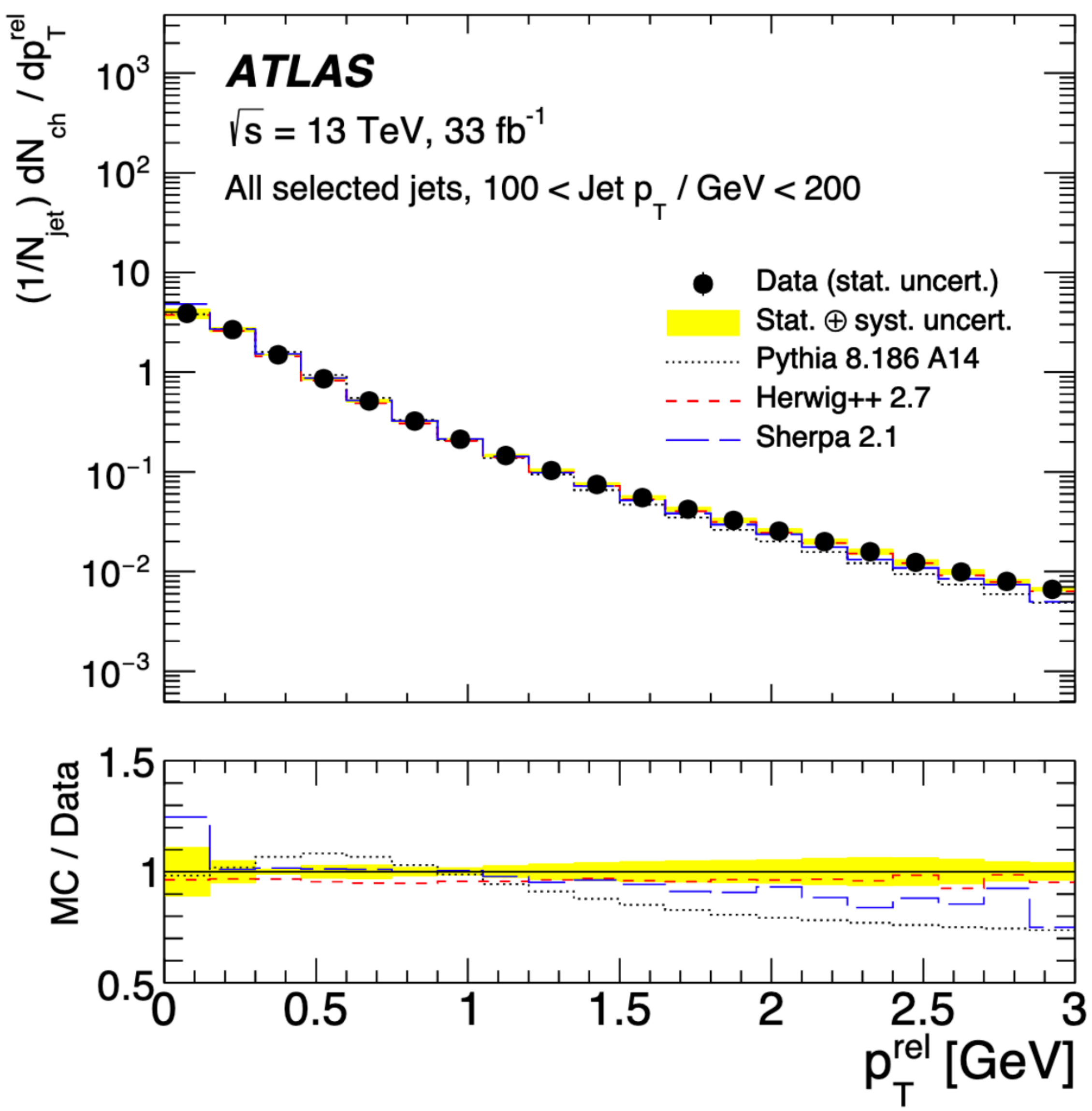




Jet fragmentation

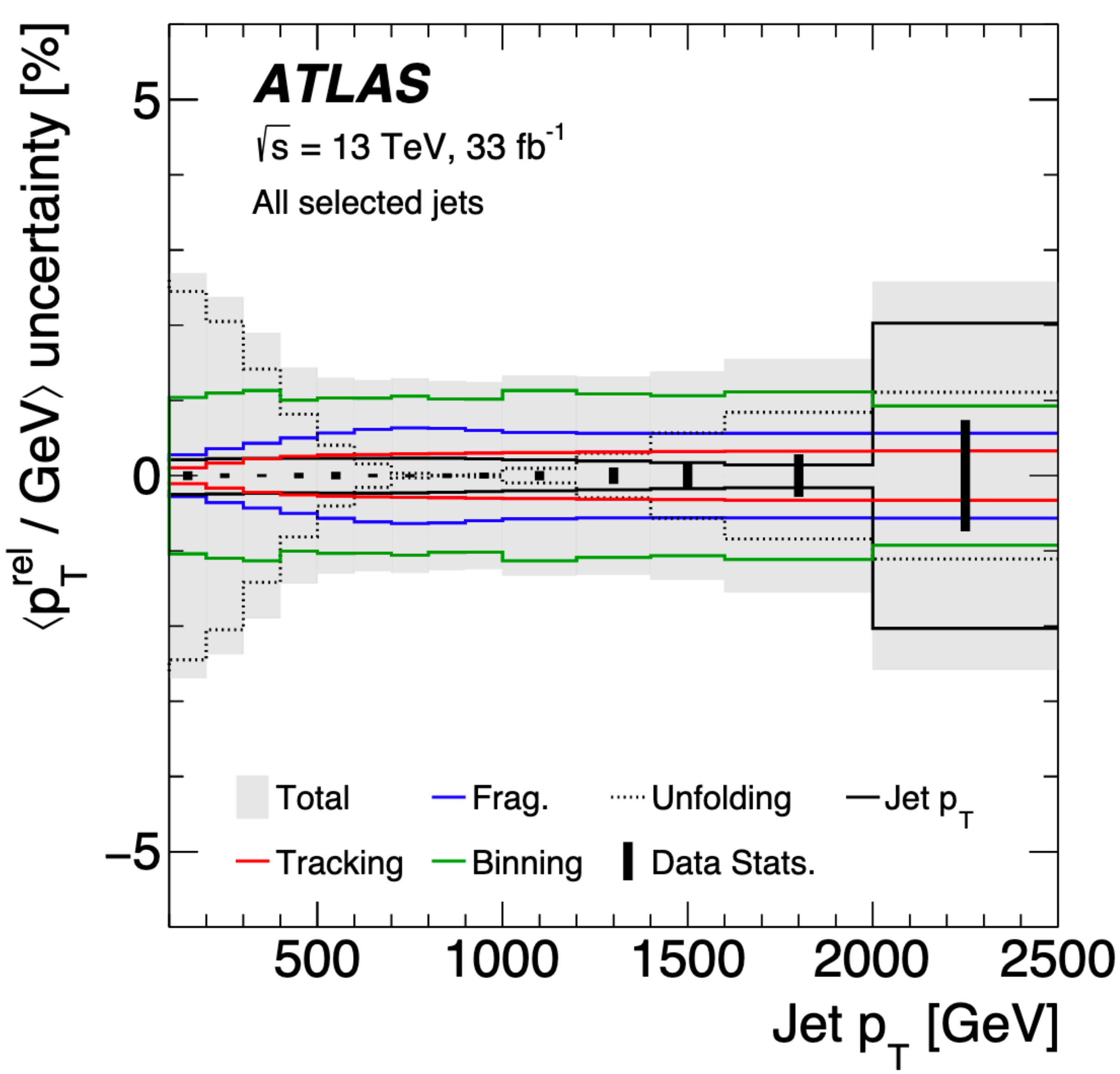
- Fragmentation functions are important for tuning MC generators
- Provide information of distribution of hadrons within a jet
- Can't be calculated from first principles, but energy dependence can be

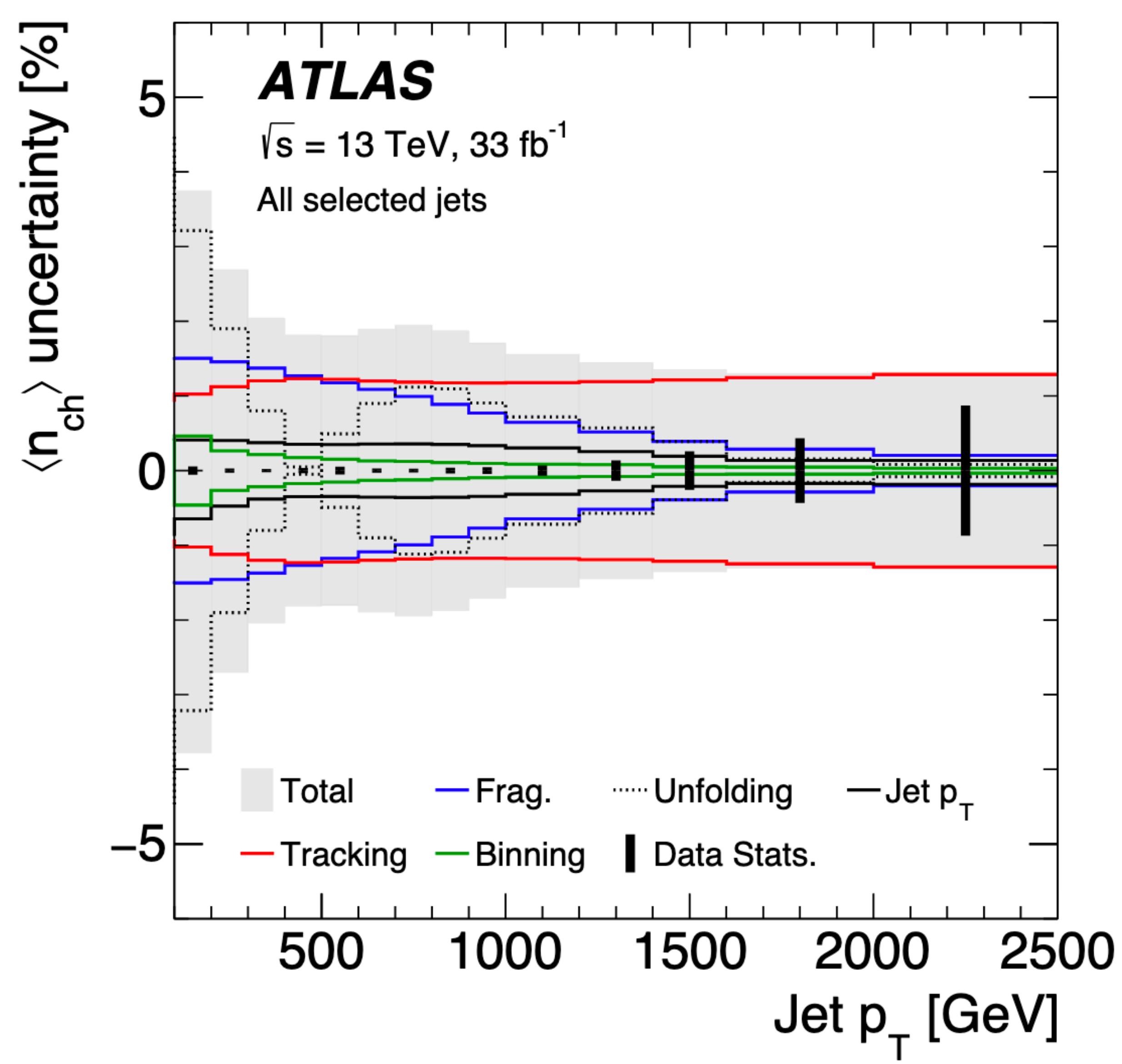




Jet fragmentation

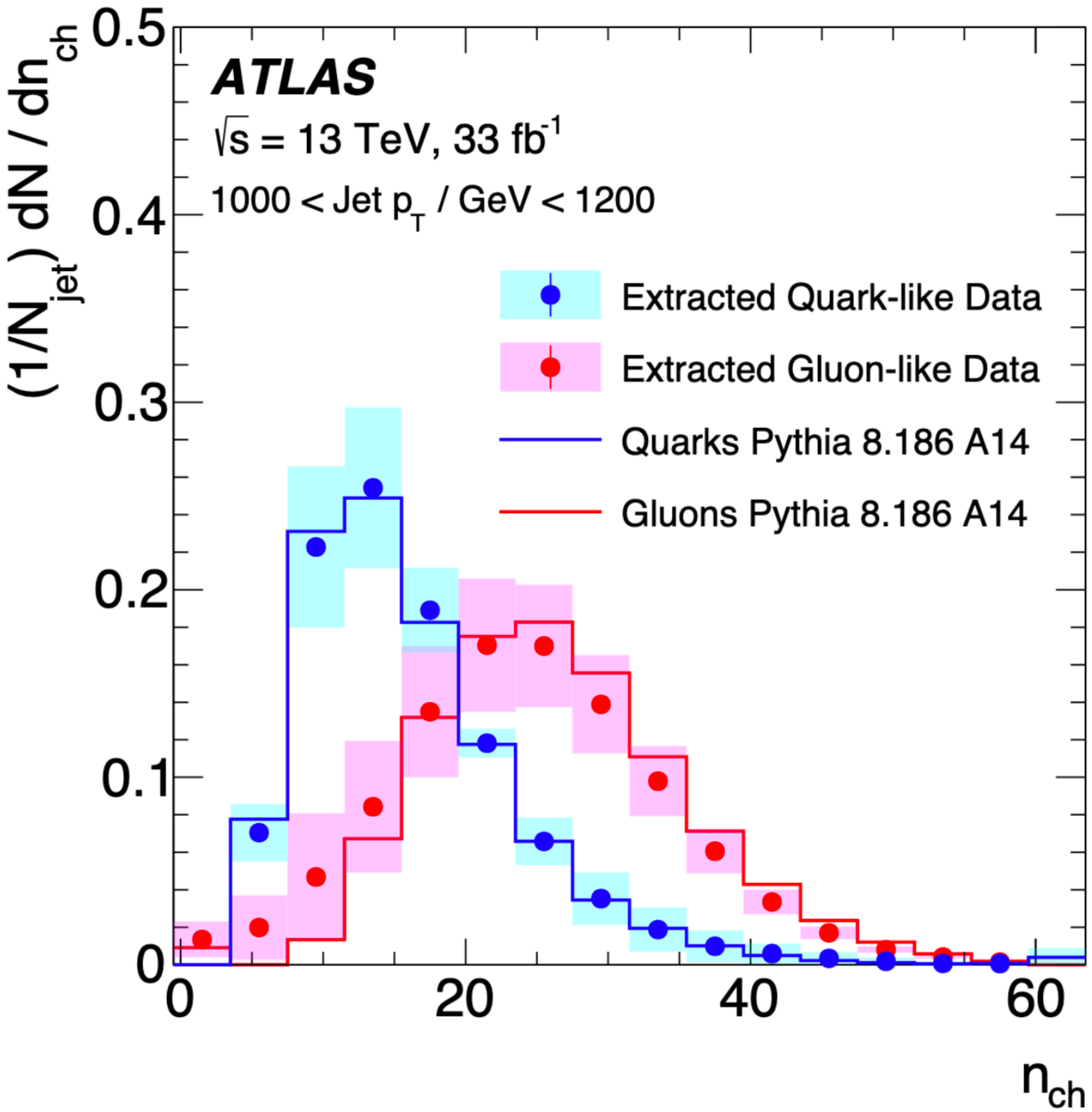
- Dominant uncertainties depend on the observable being measured and the p_T region





Jet fragmentation

- Quark-like and gluon-like distributions may be extracted by measuring in regions with different q/g composition (such as more forward and more central)



- Jet topics may be used to do this without relying on q/g fractions in simulation
  - 1802.00008
  - Results in similar behavior, but without reliance on MC labeling