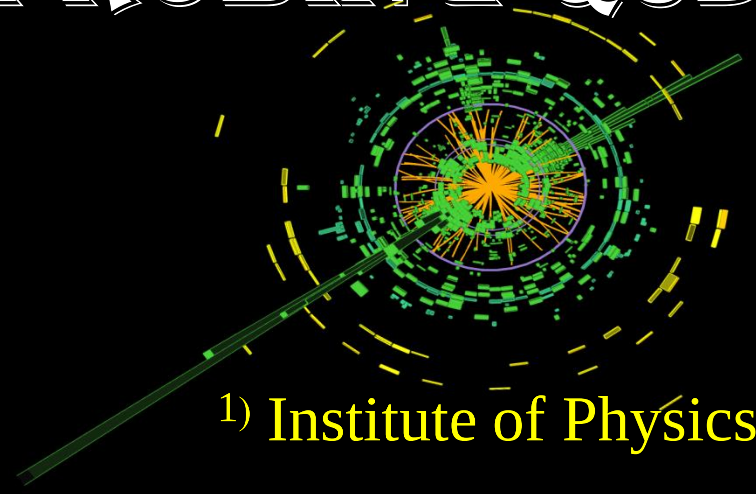
PROBING QCD WITH THE ATLAS DETECTOR



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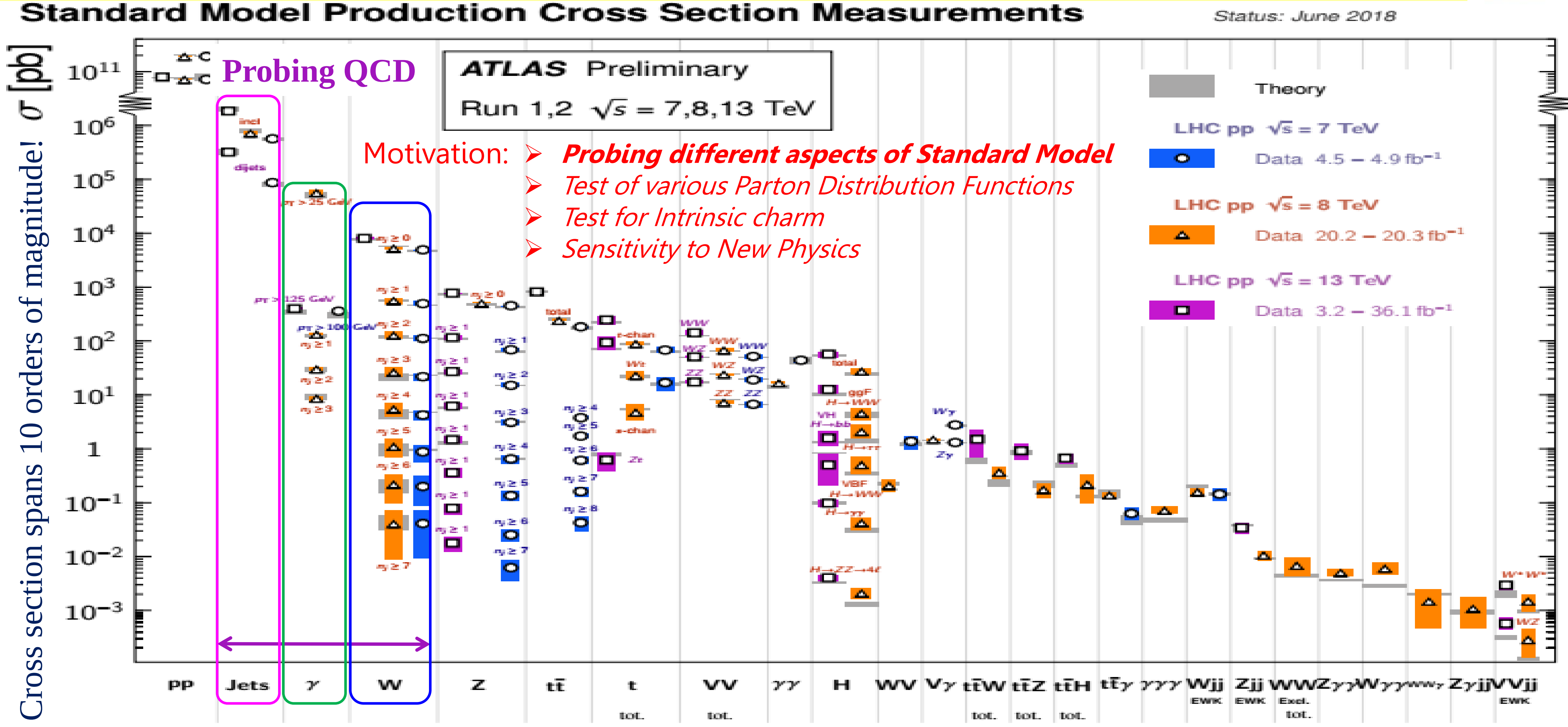
27 June 2018, International Workshop on QCD, Matera, Italy

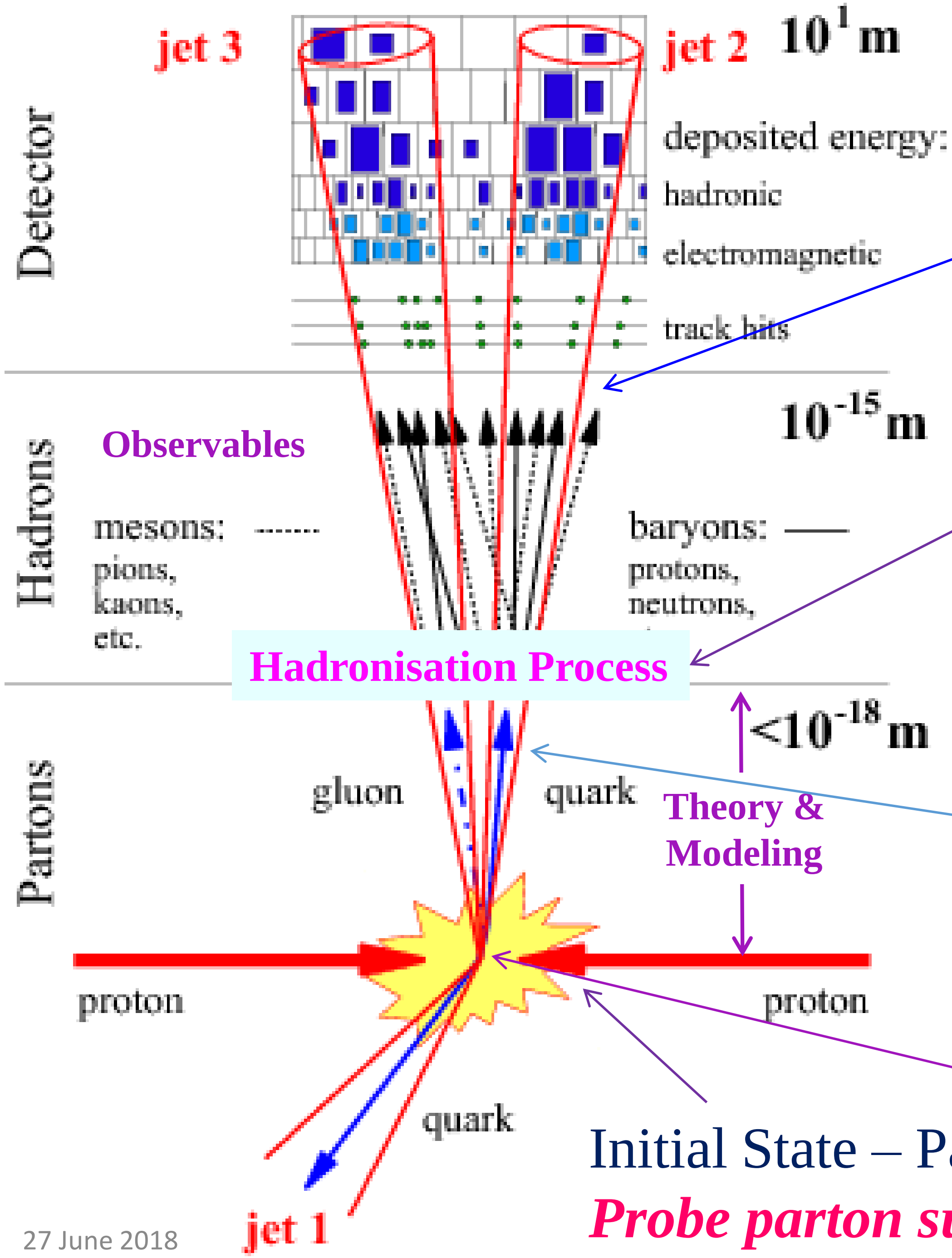
STANDARD MODEL MEASUREMENTS



Motivation:
- ***Probing different aspects of Standard Model***
- *Test of various Parton Distribution Functions*
- *Test for Intrinsic charm*
- *Sensitivity to New Physics*

New cross-sections measurements in pp at 8 & 13 TeV: Jet; Dijet; γ+Heavy Flavour Jet; W+Jets

JETS



Jets: *narrow collimated clusters of stable particles produced by the fragmentation of a hard parton*

Probe highest p_T → best handles on searches for new physics

Parton fragmentation

- Phenomenological models (PYTHIA, HERWIG, ...)
- Matching to fixed order

Parton shower (PS)

- Soft- and collinear approximations
- Mismatch between kinematics of virtual and real corrections: *soft-gluon resummation*

Hard scattering – perturbative Quantum ChromoDynamics (pQCD) predictions at fixed-orders QCD calculations: Leading Order (LO), Next–to–LO (NLO), Next–to–Next–to–LO (NNLO)

Initial State – Parton Distribution Functions (PDFs)

***Probe parton substructure** → test QCD through wide energy range*

JET PHYSICS IN PP-COLLISIONS: MOTIVATION

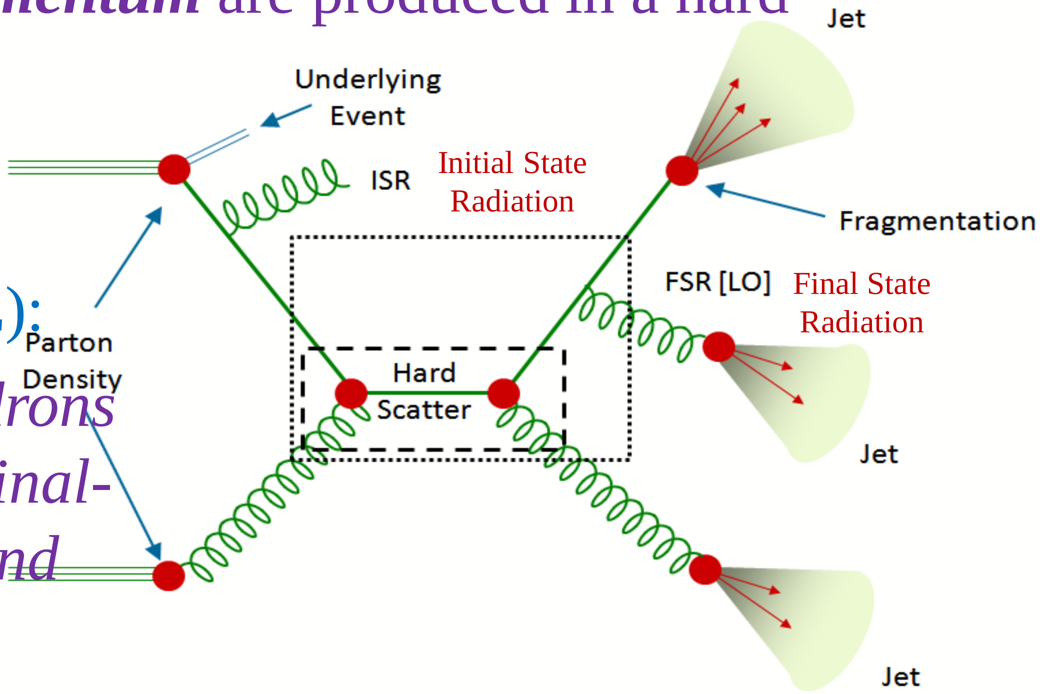
ATLAS EXPERIMENT

*Jets are **crucial** for our understanding of the Standard Model*

Probing of the Quantum ChromoDynamics (QCD) → *Jets are the result of fragmentation of partons produced in a scattering process*

In High-Energy Particle collisions – *two main phases:*

- **Perturbative phase**: partons with ***high-transverse momentum*** are produced in a hard-scattering process at a scale Q
- **Non-perturbative phase**: partons convert in hadrons *emitting gluons and $q\bar{q}$-pairs* an interplay between Hadronization Process (HP) and Underlying Event (UE):



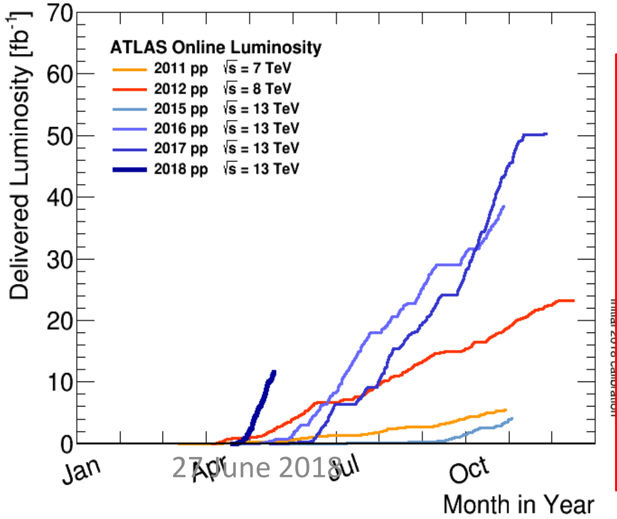
- **Hadronisation Process**: *transition from partons to hadrons*
- **Underlying Event**: *a) initial-state radiation (ISR), b) final-state radiation (FSR), c) multiple-parton interactions and d) colour-reconnection effects*

*Effects of **HP** and **UE** depend on Jet radius parameter and are most pronounced at low p_T*

All these aspects of high energy collisions can be Probed in the Jet Physics

A TOROIDAL LHC APPARATUS (ATLAS)

Subdetector	Operational Fraction
AFP	93.8%
ALFA	99.9%
CSC Cathode Strip Chambers	95.3%
Forward LAr Calorimeter	99.7%
Hadronic End-Cap Lar Cal	99.5%
LAr EM Calorimeter	100 %
LVL1 Calo Trigger	99.9%
LVL1 Muon RPC Trigger	99.8%
LVL1 Muon TGC Trigger	99.9%
MDT Muon Drift Tubes	99.7%
Pixels	97.8%
RPC Barrel Muon Chambers	94.4%
SCT Silicon Strips	98.7%
TGC End-Cap Muon Cha	99.5%
Tile Calorimeter	99.2%
TRT Transit Rad Tracker	97.2%



Air-core Muon spectrometer

(μ *Trigger/tracking and Toroid Magnets*)

Precision Tracking:

- **MDT** (Monitored Drift Tubes)
- **CSC** (Cathode Strip Chambers) $|\eta| > 2.4$

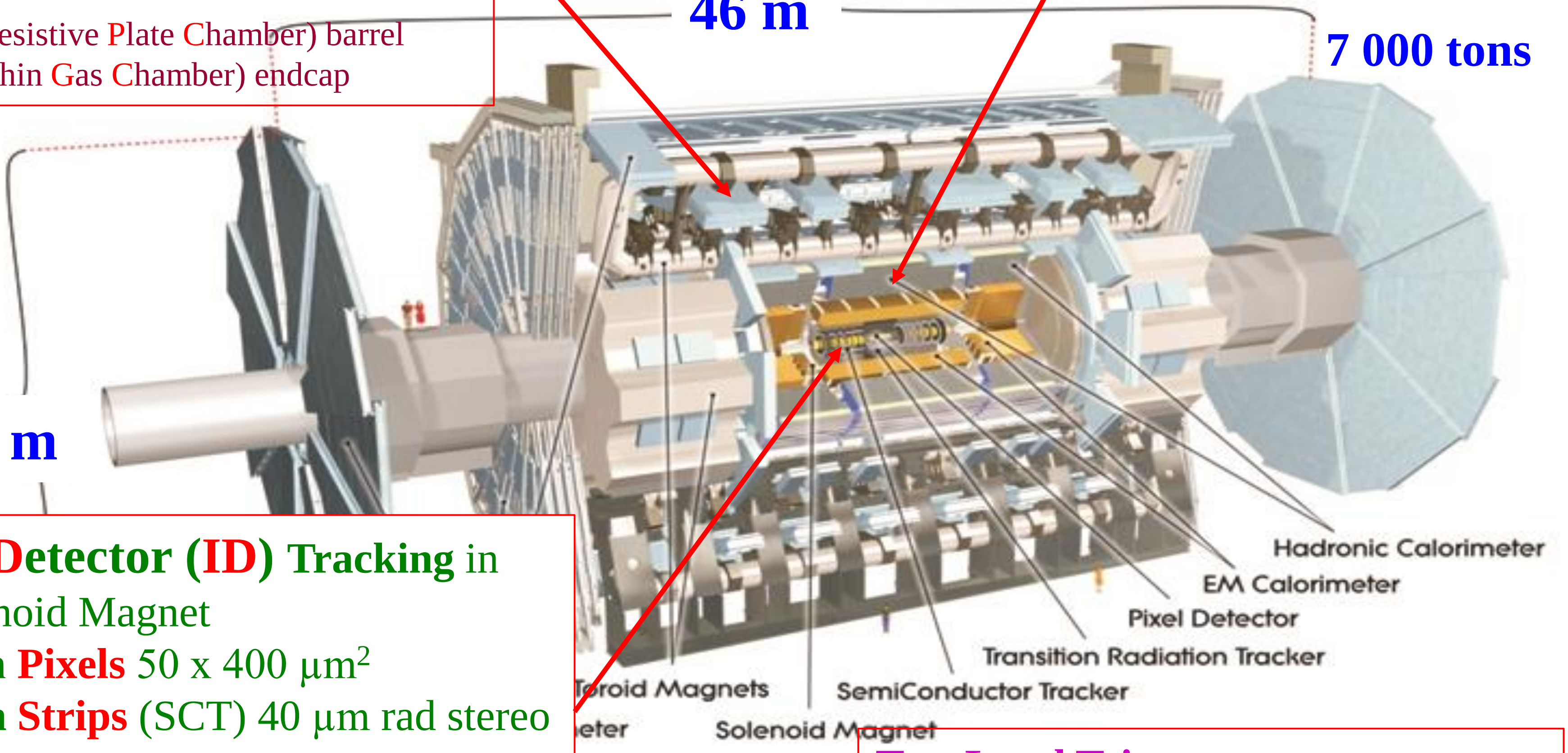
Trigger:

- **RPC** (Resistive Plate Chamber) barrel
- **TGC** (Thin Gas Chamber) endcap

Longitudinally segmented Calorimeter:

EM and Hadronic energy

- **LiquidAr** EM barrel and End-cap & Hadronic End-cap
- **Tile** calorimeter (Fe-scintillator) Hadronic barrel



Inner Detector (ID) Tracking in 2T Solenoid Magnet

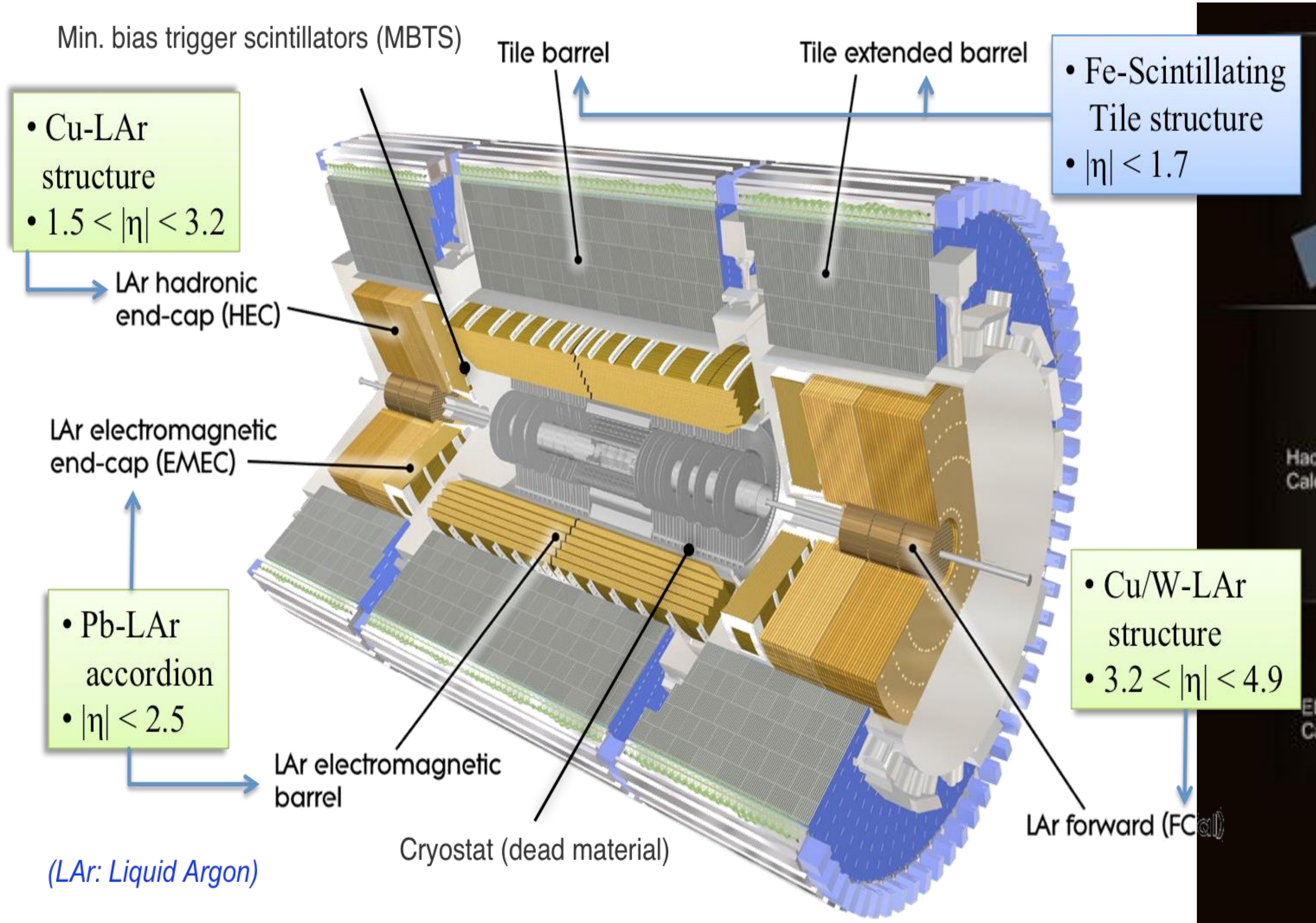
- **Silicon Pixels** 50 x 400 μm^2
- **Silicon Strips** (SCT) 40 μm rad stereo strips
- **Transition Radiation Tracker** (**TRT**) up to 36 points/track

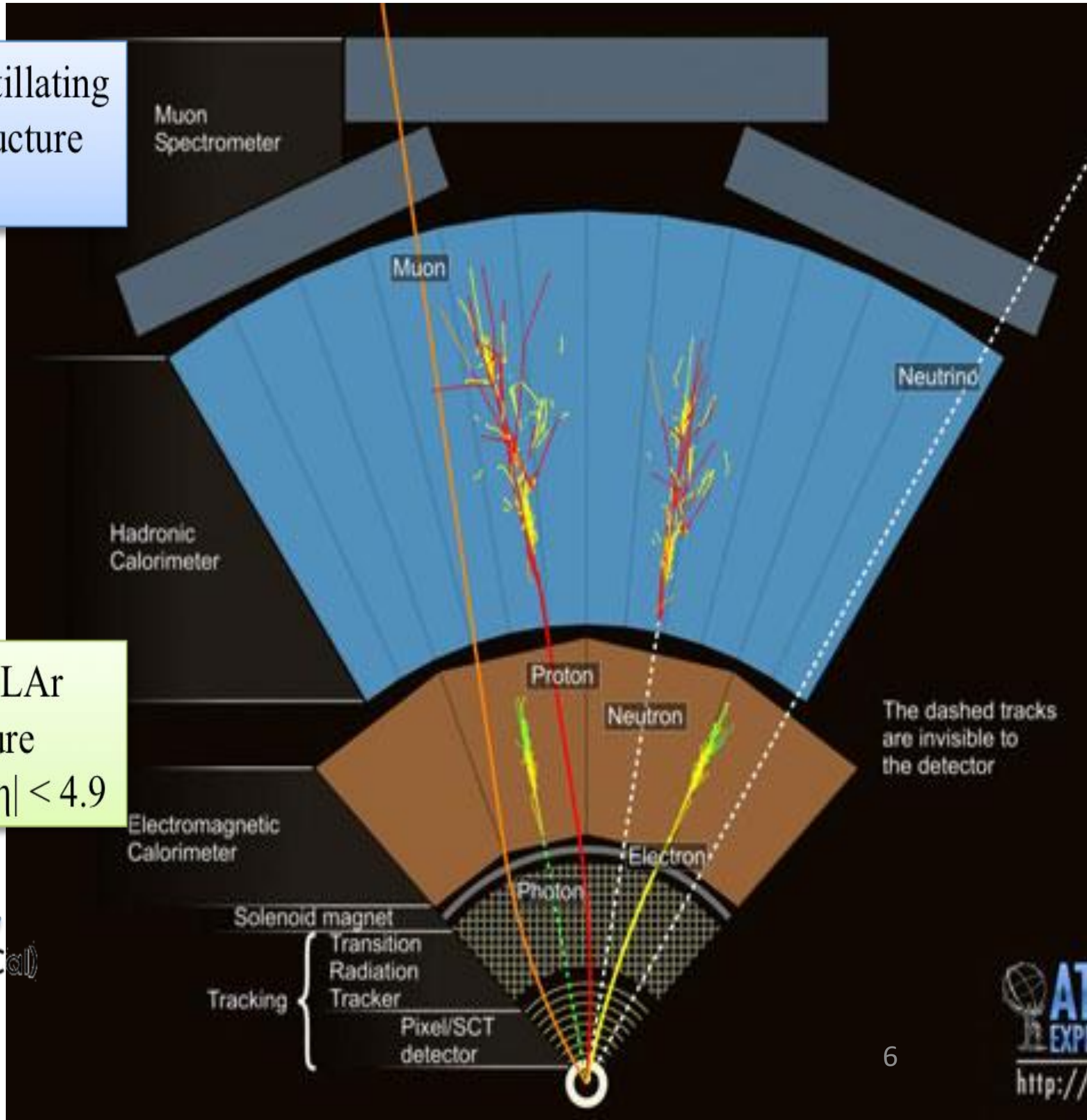
Two Level Trigger system

- **L1 – hardware**: **100 kHz**, **2.5 μs** latency
- **HLT – farm**: merge the former **L2** and **Event Filter 1.5 kHz**, **0.2 s** latency

ATLAS CALORIMETERS

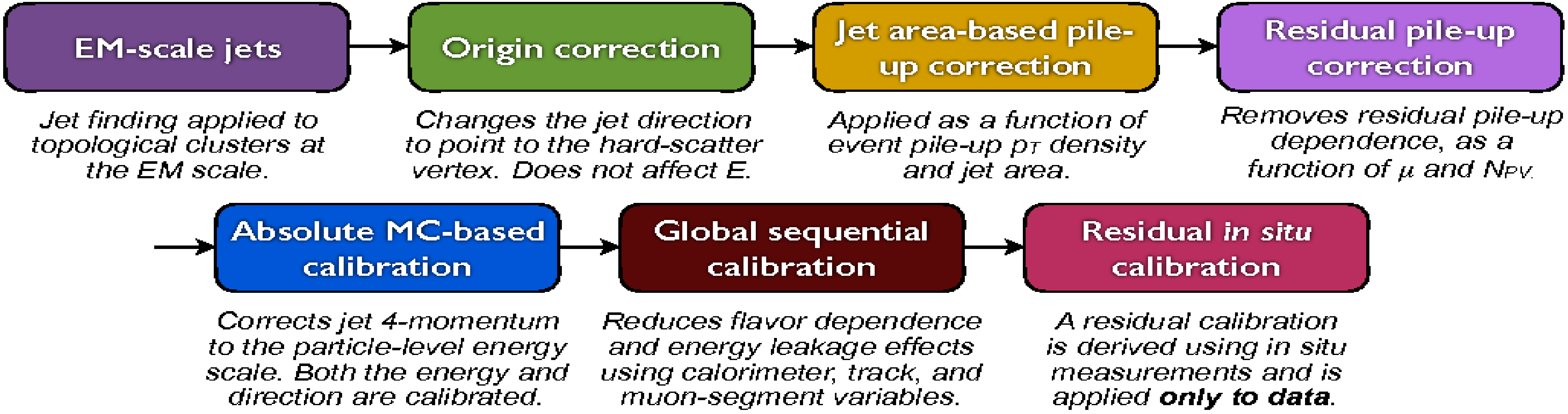
- **Very stable** performance
- **Improved stability** of new Tile power supplies
- Good operation efficiency: ~**100% for Lar & Tile**
- LAr using 4 sample readout to achieve 100 kHz





JET RECONSTRUCTION

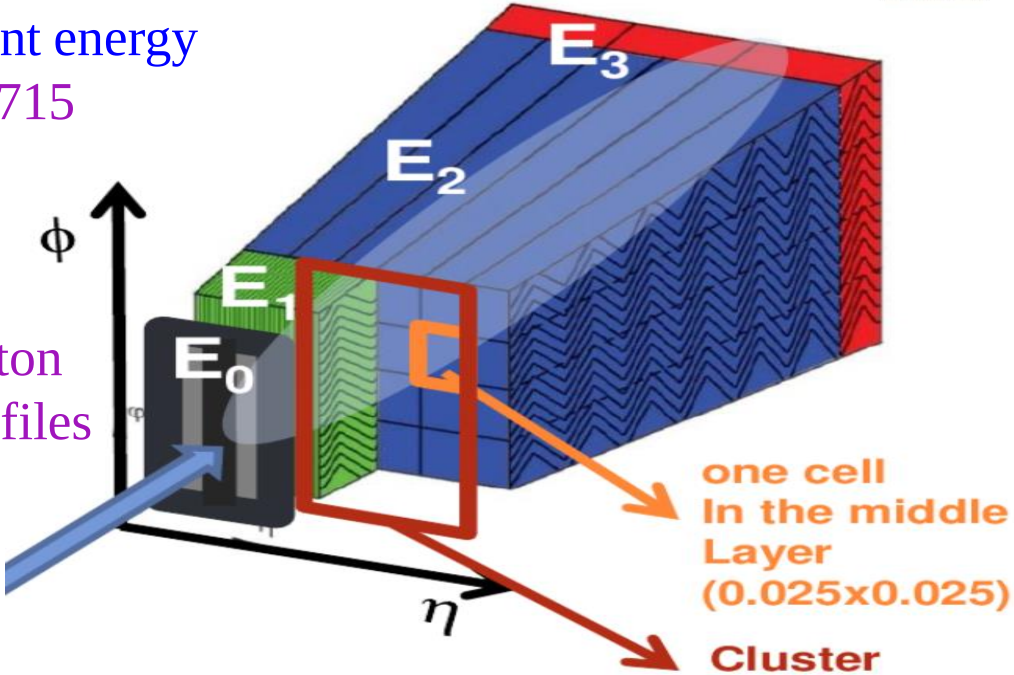
- A set of Single-Jet Triggers with different thresholds used to collect data
- Only events with at least one Primary Vertex, reconstructed ≥2 tracks with p_T>400 MeV
- Primary Vertex with the highest $\sum p_T{}^2$ of associated tracks is selected as the hard-scatter vertex
- Jets reconstructed by the anti-k_t algorithm: jets are clustered using two values of R=0.4 & 0.6
- Multi-step process to an Jet Energy Calibration:

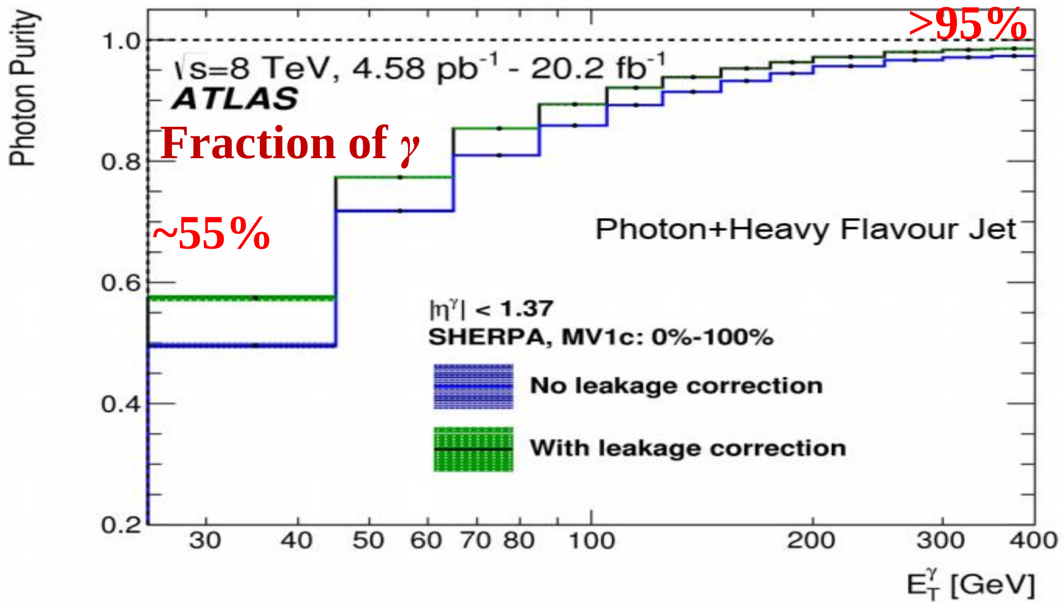


- Jets corrected for experimental effects: resolutions, efficiency, …
- Jets unfolding for cross-sections are defined at the particle-level final state

DIRECT PHOTON & ELECTRON (FOR $W \to e\nu$) RECONSTRUCTION

- ❑ Search for seed energy clusters in the EM calorimeter with significant energy
- ➢ Form a cluster from cells in a rectangular region $\Delta\eta\times\Delta\varphi=0.125\times0.1715$ around seed
- ❖ Selected in barrel $|\eta^{\gamma}|<1.37$ & end-cap $1.56<|\eta^{\gamma}|<2.37$; excluding transition region between barrel & endcap ECAL $1.37<|\eta^{\gamma}|<1.56$
- ✓ Photon identification: classify as electron, photon, or converted photon matching cluster with tracks; use lateral and longitudinal energy profiles of the photon/ electron electromagnetic shower
- ❑ **Calorimeter isolation** in region $\Delta R=0.4$ around photon with requirement $E_T^{iso}<0.0042 \times E_T^{\gamma} + 4.8$ GeV
- ➢ Converted and unconverted γ-s are calibrated separately use the tracking information to correct the Calorimeter response for upstream energy losses and leakage
- ❖ Calculate energy and direction: photon energy a weighted sum of layer energies, with corrections for detector effects
- ✓ Corrected for pileup using jet area method
- ➢ Use 2D-sidebands for remaining background
- ❖ Remove hadron and τ background
- ✓ Small electron background removed using MC





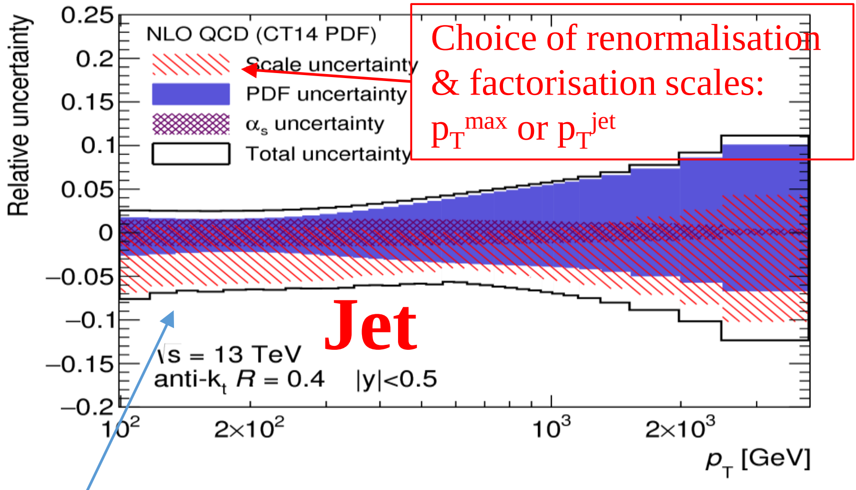
Inclusive DIJET and JET cross-sections in pp at 8 and 13 TeV

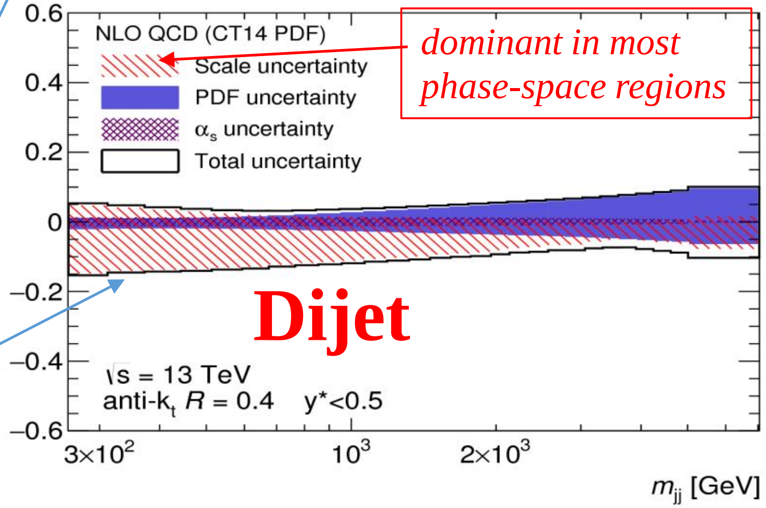
RELATIVE UNCERTAINTY: PP → JET, DIJET + X AT 13 TEV

arXiv:1711.02692

- **Dijet** *production allows to* ***Probe for higher scales***
- The double-diff. inclusive **Jet** cross-section measurement vs. p_T^{jet} & y → **0.1 TeV≤ p_T^{jet} ≤4 TeV& |y|<3**
- The double-differential inclusive **Dijet** cross-sections measurement vs. dijet mass m_{jj}**→0.3 TeV–9 TeV & $y^*=|y_1-y_2|/2 < 3$**
- **Motivation**: *a test of validity of pQCD and* ***Probing of the Parton Distribution Functions (PDF) in the proton***
- **Jets** are identified with the **anti-k_t** using ***R*=0.4**
- Jet cross section refers to Particle-Level Jets and to compare them with **NLO pQCD** predictions with Parton-Level Jets, a correction for Non-Perturbative and ElectroWeek effects is done
- **Theoretical predictions**: ***NLO pQCD*** calculated by ***NLOJET++ 4.1.3*** with several **PDF**s and different **Renormalisation** (μ_R) and **Factorisation** (μ_F) scales $\mu_R=\mu_F= p_T^{jet, max}$ for *Jet* & $\mu_R= \mu_F=p_T^{max} \times exp(0.3y^*)$ for *Dijet*
- The difference between the predictions obtained with the p_T^{max} and p_T^{jet} scale choice is treated as an additional uncertainty

p_T^{max} is the transverse momentum of the leading jet in the event
p_T^{jet} is the p_T of each individual jet in the event





Uncertainty in the **NLO pQCD** inclusive jet & dijet cross-sections

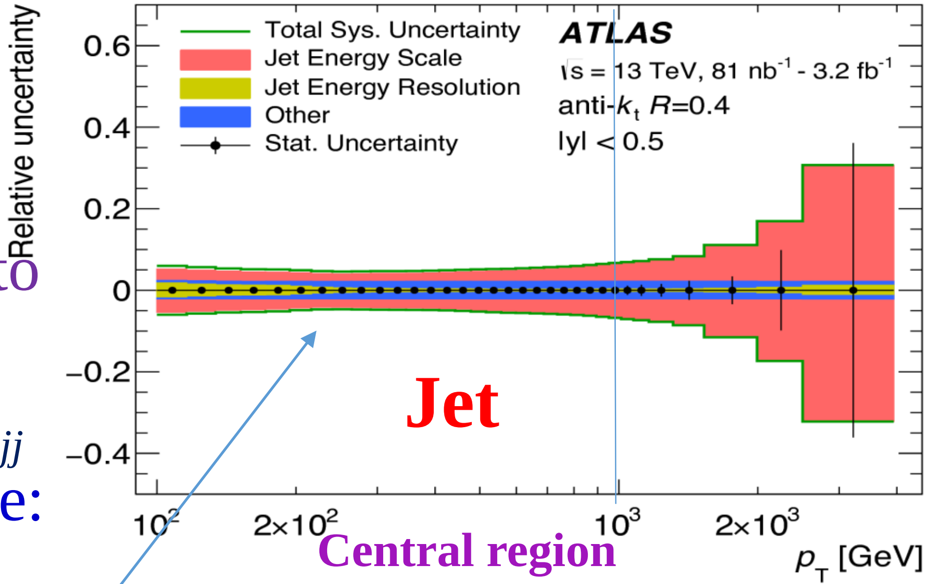
EVENT AND JET SELECTION AT 13 TEV

arXiv:1711.02692

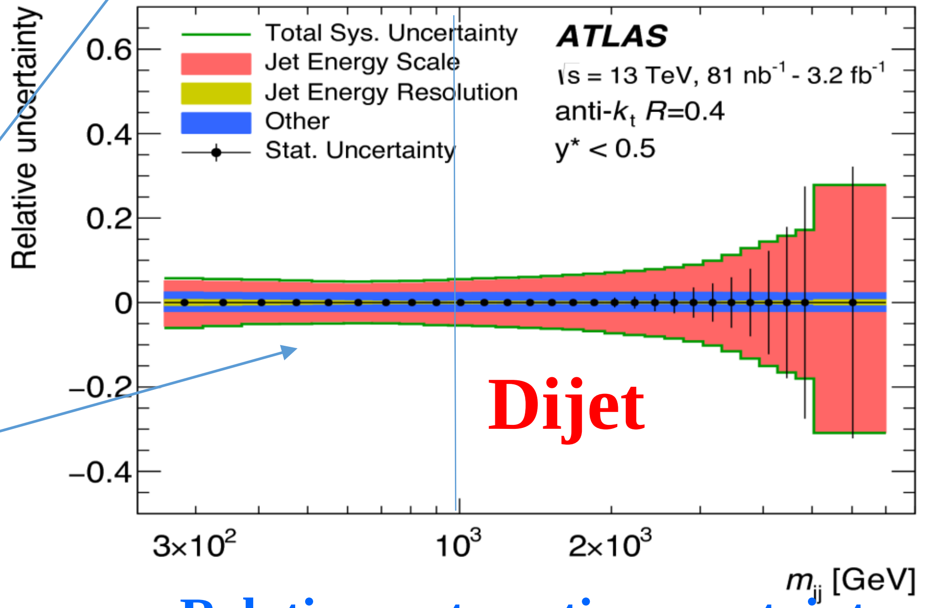
- ❑ Dataset used for measurement: pp at 13 TeV; L_{int}=3.2 fb^{-1}
- ➢ **Pile-up:** <μ> increases from **<μ>~10 to <μ>~36**
- ➢ **3-level Jet trigger**. Events with Jet: **|η|<3.2, p_T^{jet}** over a threshold. Offline data selection and Jet correction: similar to dijet case
- ❖ Cross-sec. are measured for *6 rapidity bins* as funct. p_T^{jet}, m_{jj}
- ❖ Data are **unfolded** to the **particle level** in a 3-step procedure:
  - o correction for the sample **impurities**;
  - o unfolding for the **p_T migration**;
  - o correction for the analysis **inefficiencies**

❑ **Sources of systematic uncertainty**: those associated with Jet ► reconstruction & ► calibration, ► unfolding procedure, ► luminosity measurement

❑ ***Main sources:*** ► **Jet Energy Scale** (JES) & ► **Jet Energy Resolution** (JER): for **|y|<0.5 & p_T<1 TeV** less than 10%



Central region

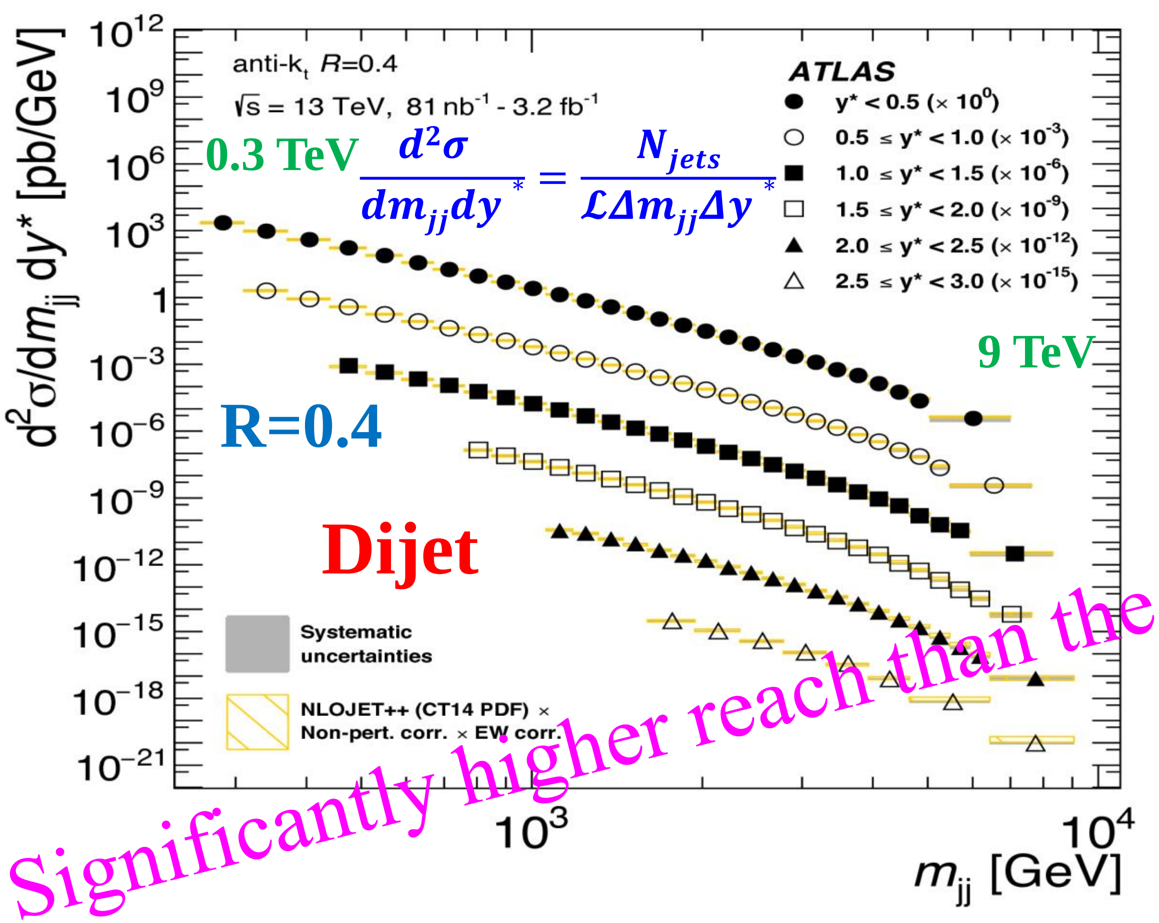


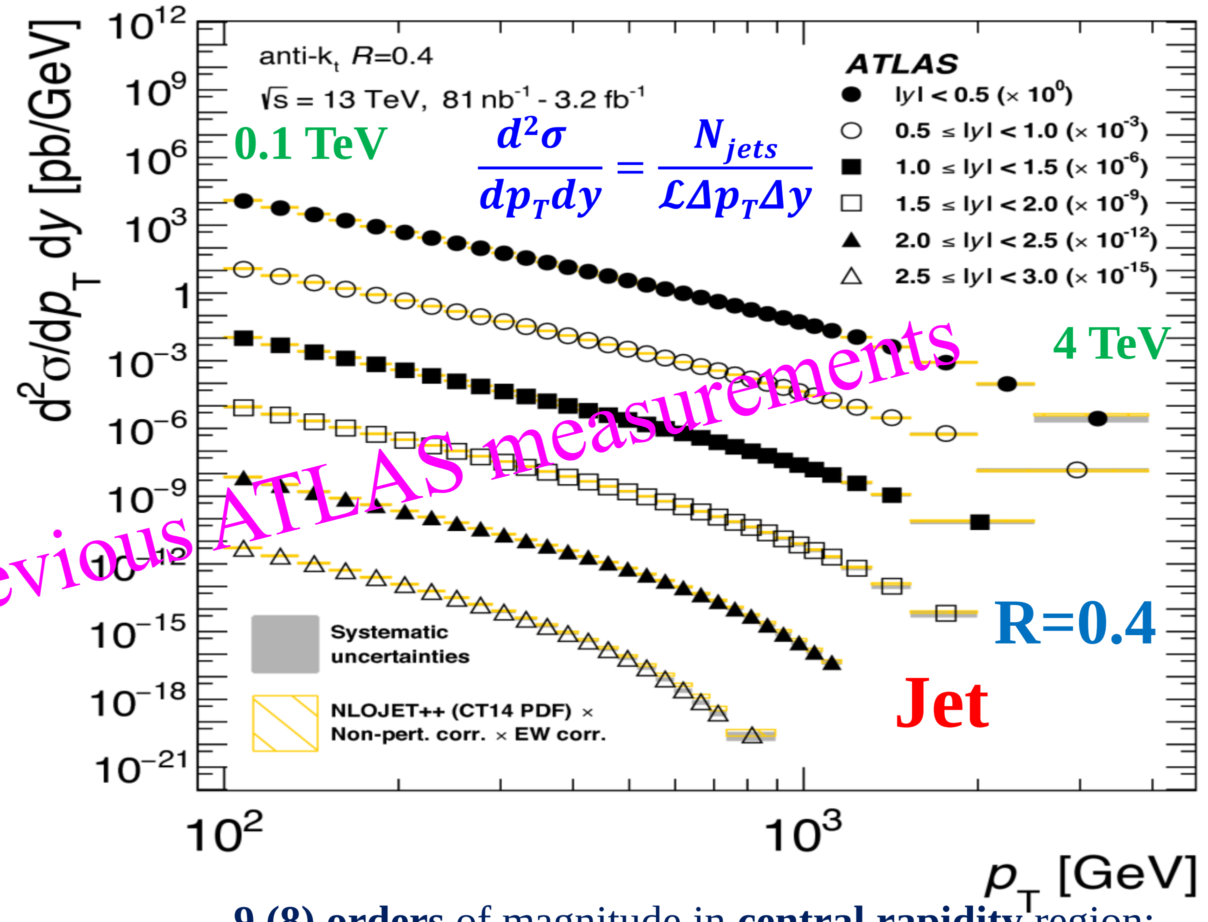
Relative systematic uncertainty

Cross-sections: pp → jet, dijet + X at 13 TeV arXiv:1711.02692

Dijet double-diff. cross-sections vs. **dijet mass (m_{jj})** and rapidity separation **($y^*=|y_1-y_2|/2$)**

Jet double-diff. cross-sections vs. **jet p_T** and rapidity separation **$|y|<3$**





Significantly higher reach than the previous ATLAS measurements

- Data are compared to **NLOJet++** *predictions* with various **PDFs (CT14),** corrected for *non-perturbative* and *EW* effects, scale: $\mu=\mu_R=\mu_F=p_T^{max}e^{0.3y^*}$

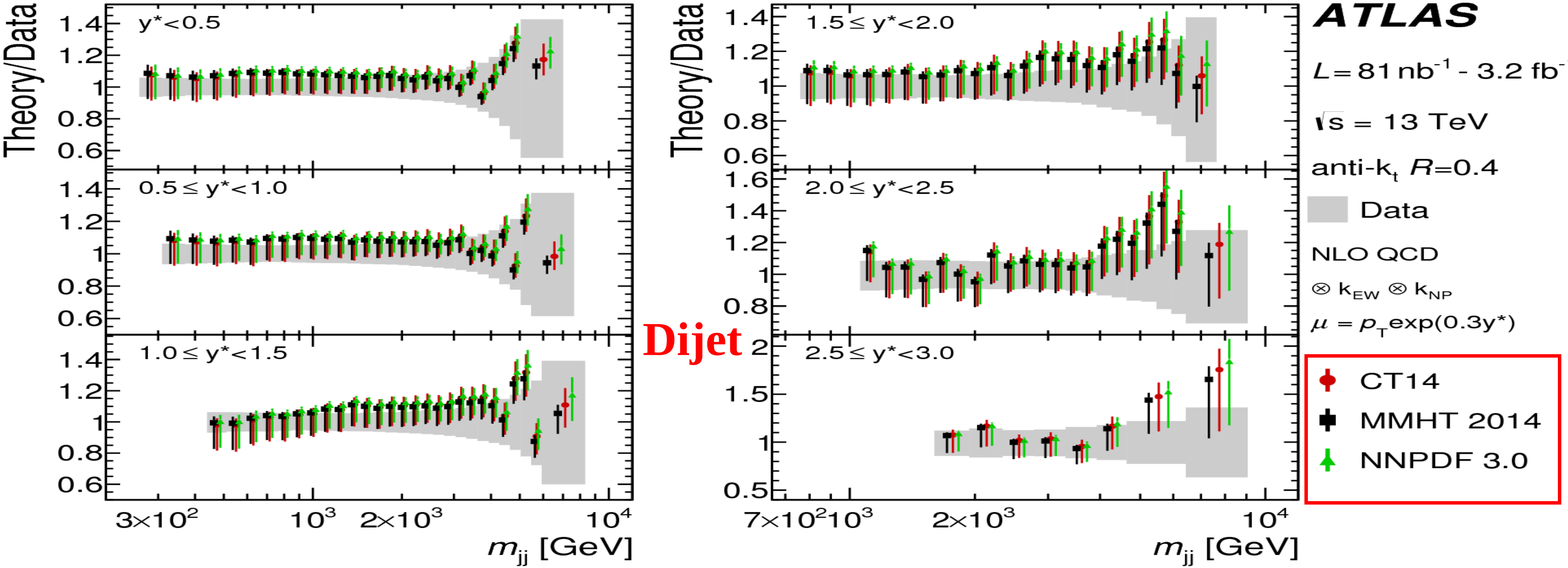
9 (8) orders of magnitude in **central rapidity** region;

- **Adequate description** of data by **NLO QCD** calculations

Theory/Data comparison pp → Dijet + X at 13 TeV

arXiv:1711.02692

Ratio of **NLOJet++** *prediction* to measurements of **Dijet** double-diff. cress-sec. vs. **Dijet** mass & y* **PDF** sets used: **CT14, MMHT 2014, NNPDF 3.0**



Dijet

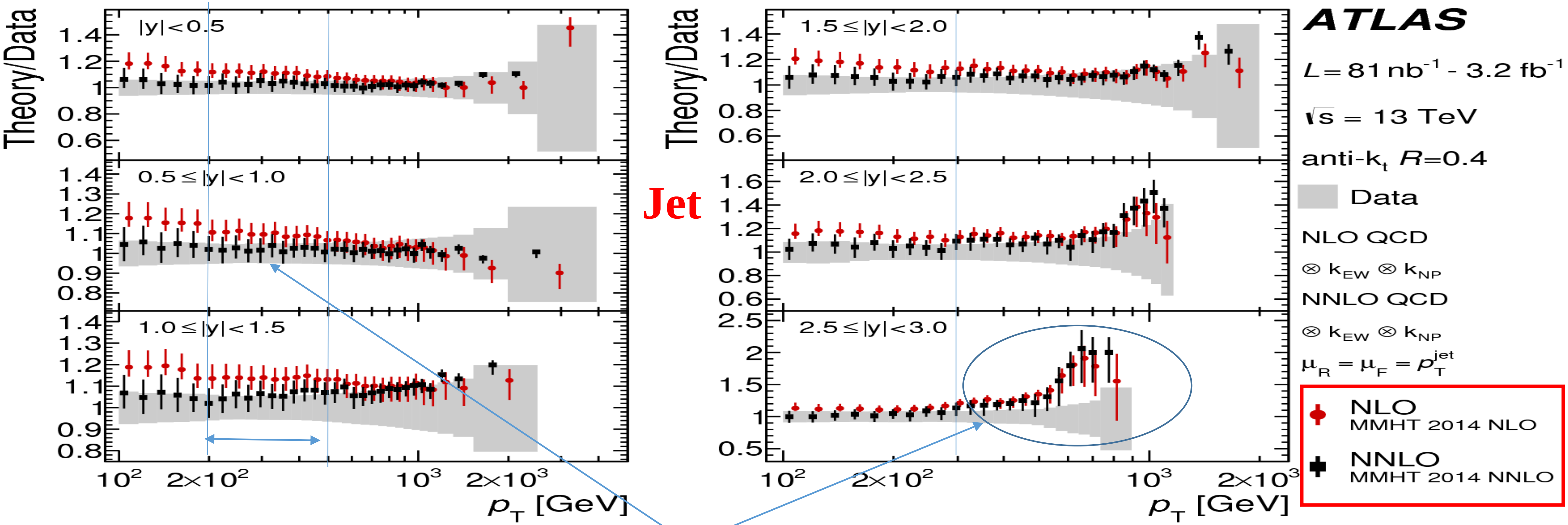
- ❑ Good description of data by **NLO pQCD** within the uncertainties
- ❑ Similar shape predicted by the studied **PDF** sets
- ➢ For **|*y**|>2**, tendency for the **NLO pQCD** prediction to overestimate the measured cross-section in the high ***m*jj**

The **CT14** case is repeated to serve as a reference for comparison

RATIOS OF THE NLO AND NNLO PQCD: PP → JET + X AT 13 TEV

arXiv:1711.02692

Ratio of **NLOJET++ (p_T^{jet} QCD scale)** *prediction* to measurements **of Jet** double-diff. cross-sec. vs. **jet p_T and y:** **PDF** sets used: **MMHT 2014 NLO, MMHT 2014 NNLO**



- ➢ **NLO pQCD** above the measurements for **$p_T \lesssim$ 200-500 GeV**
- ❑ Toward *higher* **p_T NLO pQCD** closer to data
- ➢ **p_T>300 GeV** and high ***y*** rise of NLO pQCD with respect to data (>20%)
- ❑ **Similar behaviour** *for different PDF sets*
- ❑ ***Good description by NNLO***

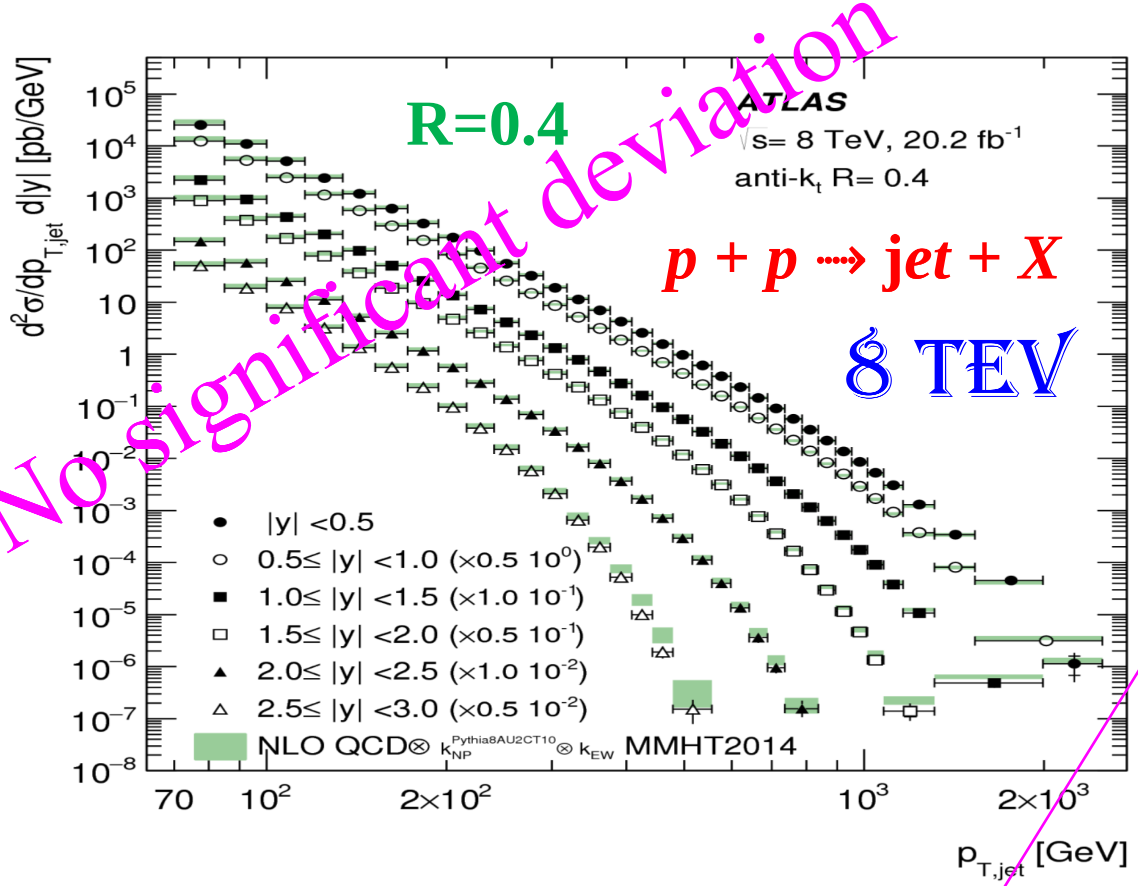
- ❑ *The differences between data and the theoretical predictions at **NNLO** are smaller than at **NLO** for the p_T^{jet} scale*
- ➢ The predictions change quite a bit when considering a different renormalisation scale: **$p_T^{jet} \rightarrow p_T^{max}$**

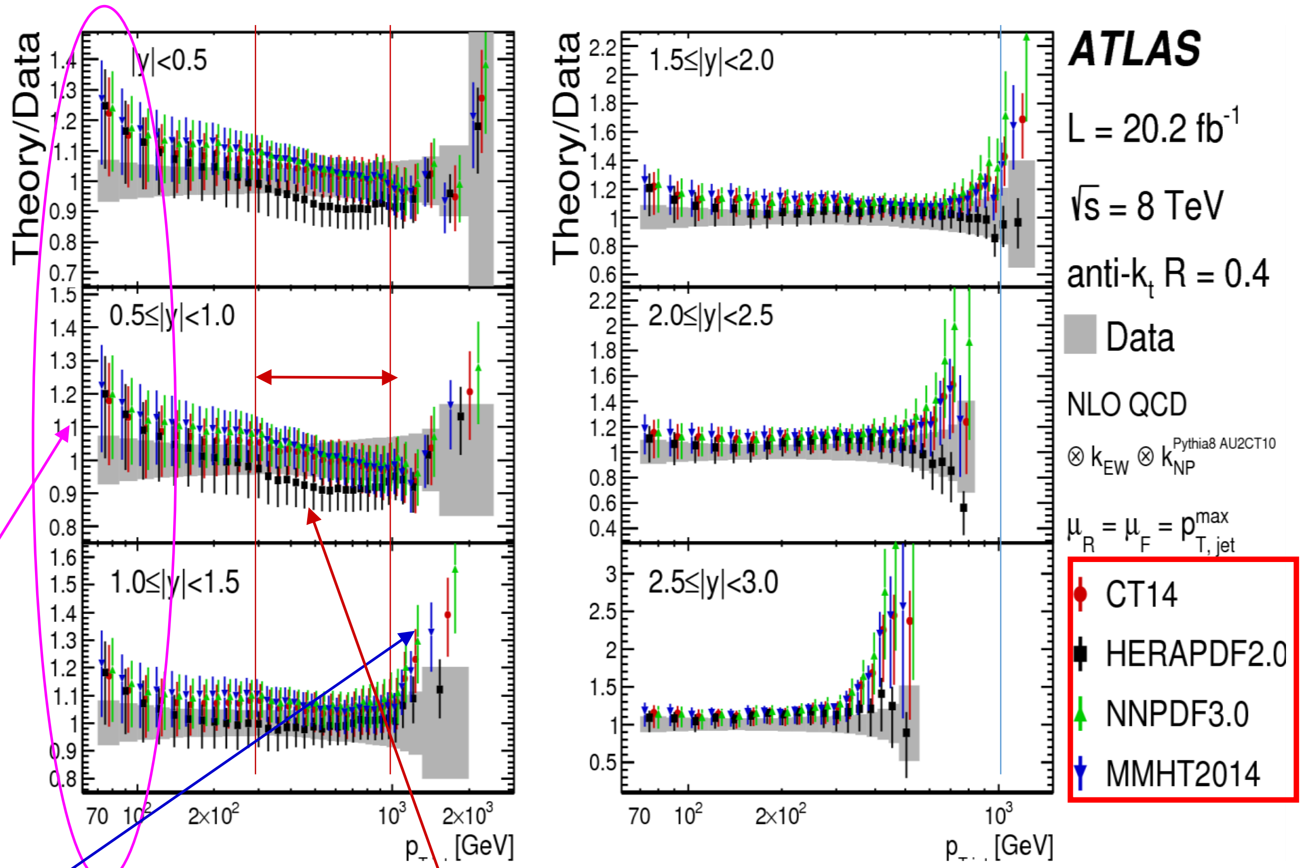
THEORY/DATA COMPARISON FOR PP → JET + X AT 8 TEV

JHEP 09 (2017) 020

Double-differential ***inclusive Jet*** cross-sections for jets with **R=0.4** vs. **jet p_T** and rapidities

data vs. **NLO pQCD** *prediction* corrected for *non-perturbative* and *EW effects*





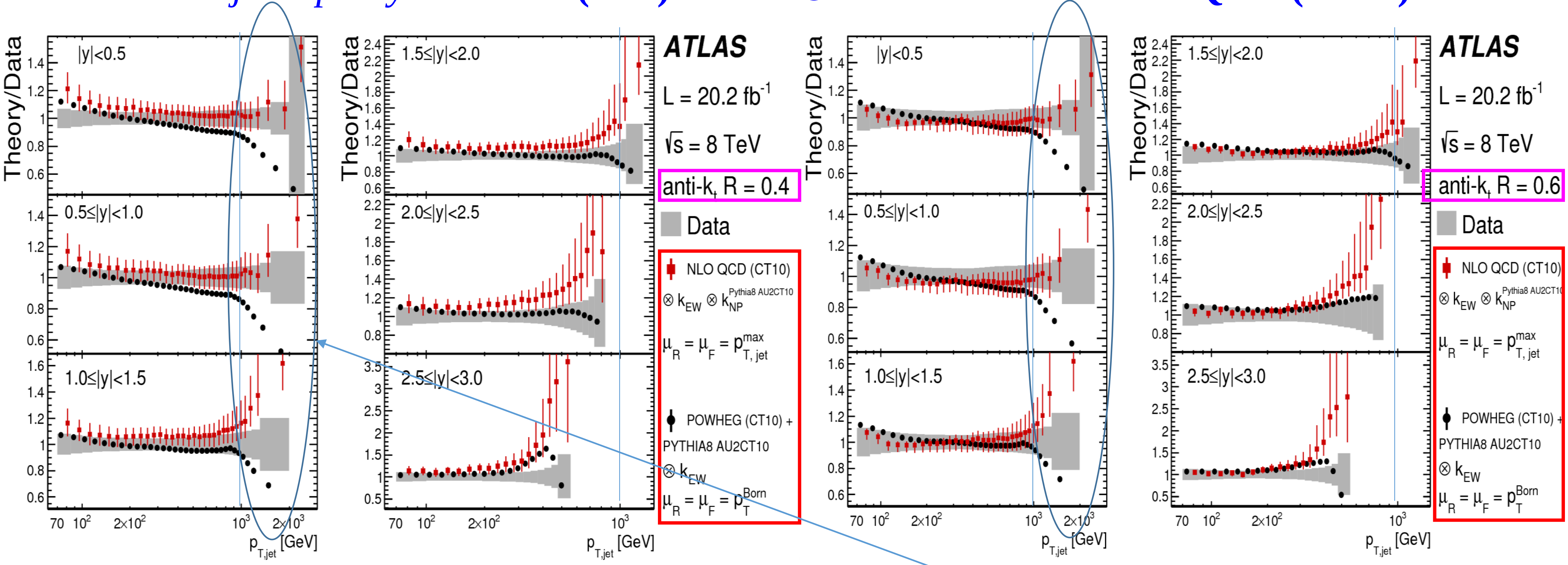
- ➢ **NLO pQCD** above the measurements for p_T^{jet} **<100 GeV**
- ❑ Toward *higher* p_T^{jet} **NLO pQCD** *closer to data*
- ➢ For p_T^{jet} **>1 TeV** rise of **NLO pQCD** respect to data on ***10-20%***

- ❑ Similar behaviour for *different PDF sets*
- ➢ **HERAPDF2.0** *significantly lower than data* in *0.3 < p_T^{jet} < 1 TeV*

COMPARISON FOR PP → JET + X AT 8 TEV: POWHEG

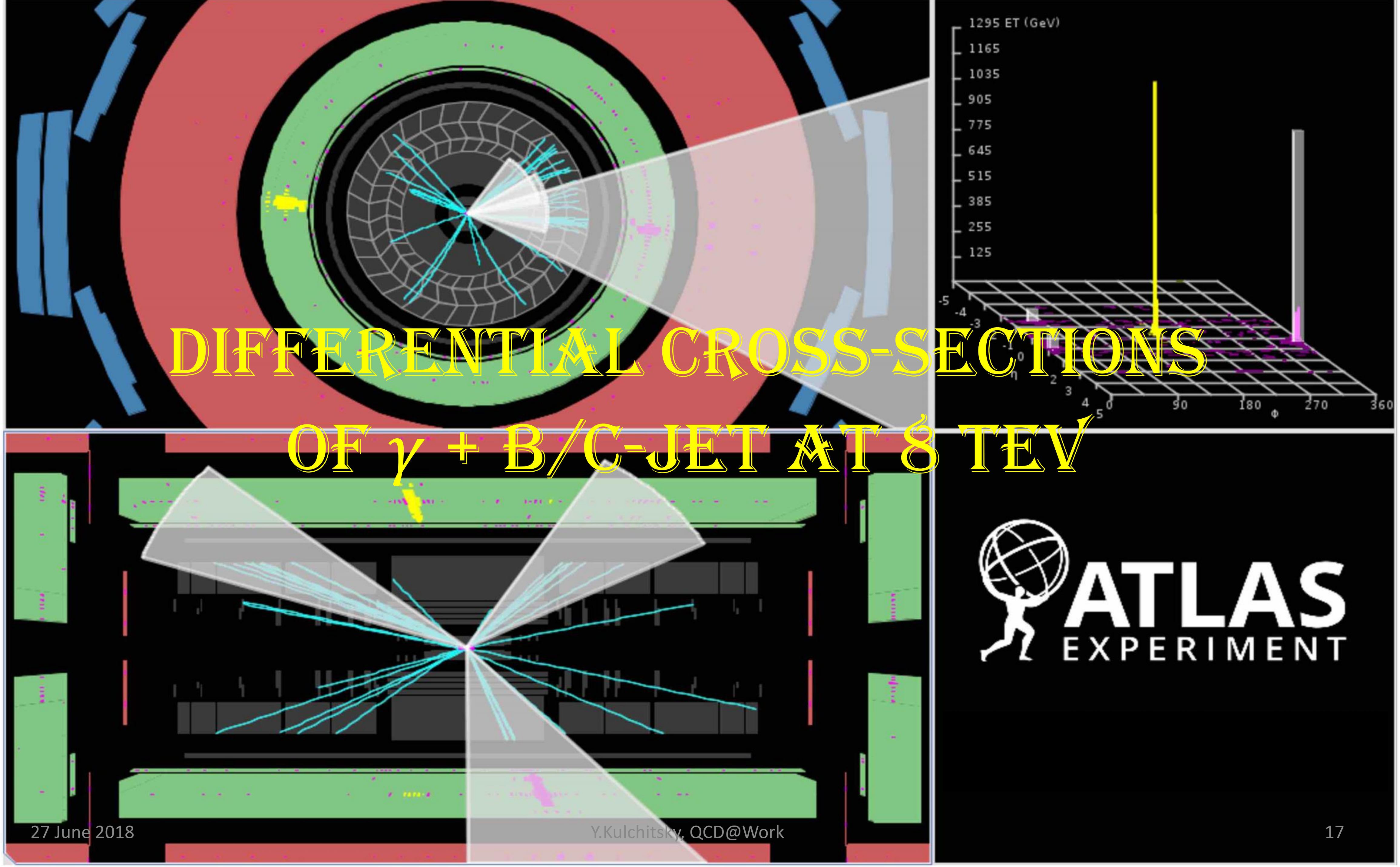
JHEP 09 (2017) 020

Ratio of *POWGEN predictions* to measured double-diff. ***inclusive Jet*** cross-section vs. *jet* p_T and *jet rapidity* – **POWGEN (C10)+PYTHIA8 AU2CT10 and NLO QCD (CT10)**



- ***POWGEN* (NLO+PS)** below **NLOJET++** at low p_T
- Toward higher p_T tendency to be *below* the data
- For p_T > **1 TeV** *different behaviour* than **NLO QCD**
- ***POWGEN*** prediction ***less dependent** on the* ***jet radius***

Differential cross-sections of γ + b/c-jet at 8 TeV



ADDITIONAL *PROBES OF QCD*: pp → γ + b/c-jet +X at 8 TeV

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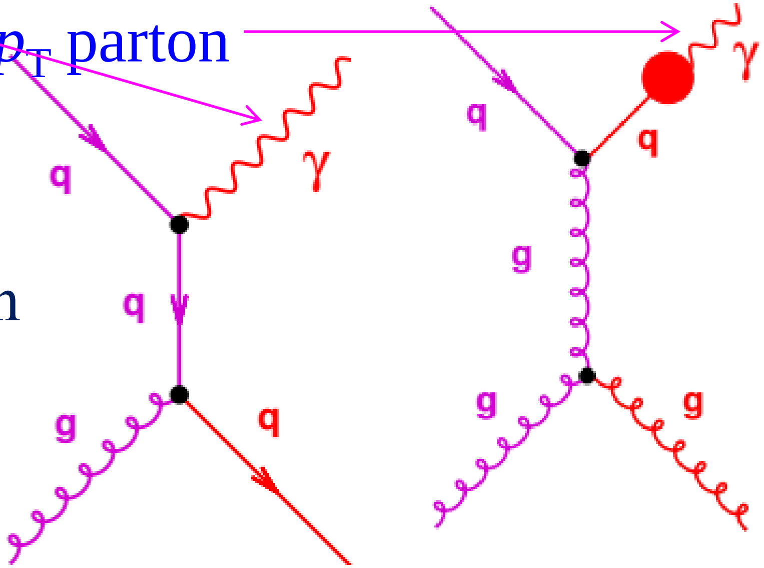
arXiv:1710.09560

- ❑ ***Deep probe*** *of proton structure, mainly* ***gluon PDF***
- ❑ ***Prompt photons*** represent a *cleaner* ***probe*** of a **hard interaction** than jet production
- ➢ **Prompt photon** production at LHC dominated by ***qg*** **→*q*γ** for ***pp*** **→γ + jet + X** events
- ➢ **Inclusive photons** can be produced by **two** main mechanism:
  - ✓ ***Direct-photon*** – γ produced in the hard interaction
  - ✓ **Fragmentation** – γ coming from the fragmentation of a high-p_T parton



- ➢ *Essential to require the* ***photon to be isolated***:
  - ○ Calorimeter isolation $E_T^{iso} < E_T^{max}$ in a cone of radius ***R=0.4*** with $E_T^{\gamma} > 25$ ***GeV*** (suppress π^0 (η^0 …) →$\gamma\gamma$ and fragmentation contribution)
- ➢ *The measurement is performed in bins of* E_T^{γ} *for 2 regions of* $|\eta^{\gamma}|$:
  - ○ ***central region*** with **$|\eta^{\gamma}|<1.37$** for $25 \le E_T^{\gamma} \le 400$ ***GeV***
  - ○ ***forward region*** with $1.56<|\eta^{\gamma}|<2.37$ for $25 \le E_T^{\gamma} \le 350$ ***GeV***
- ➢ *Jet* p_T *reduced to* $p_T^{jet} > 20$ ***GeV***

- ○ Strictly distinguishable only at **Leading Order (LO)**
- ○ Precise measurements are testing ground for **pQCD**

RECONSTRUCTION OF PP → γ + B/C-JET +X

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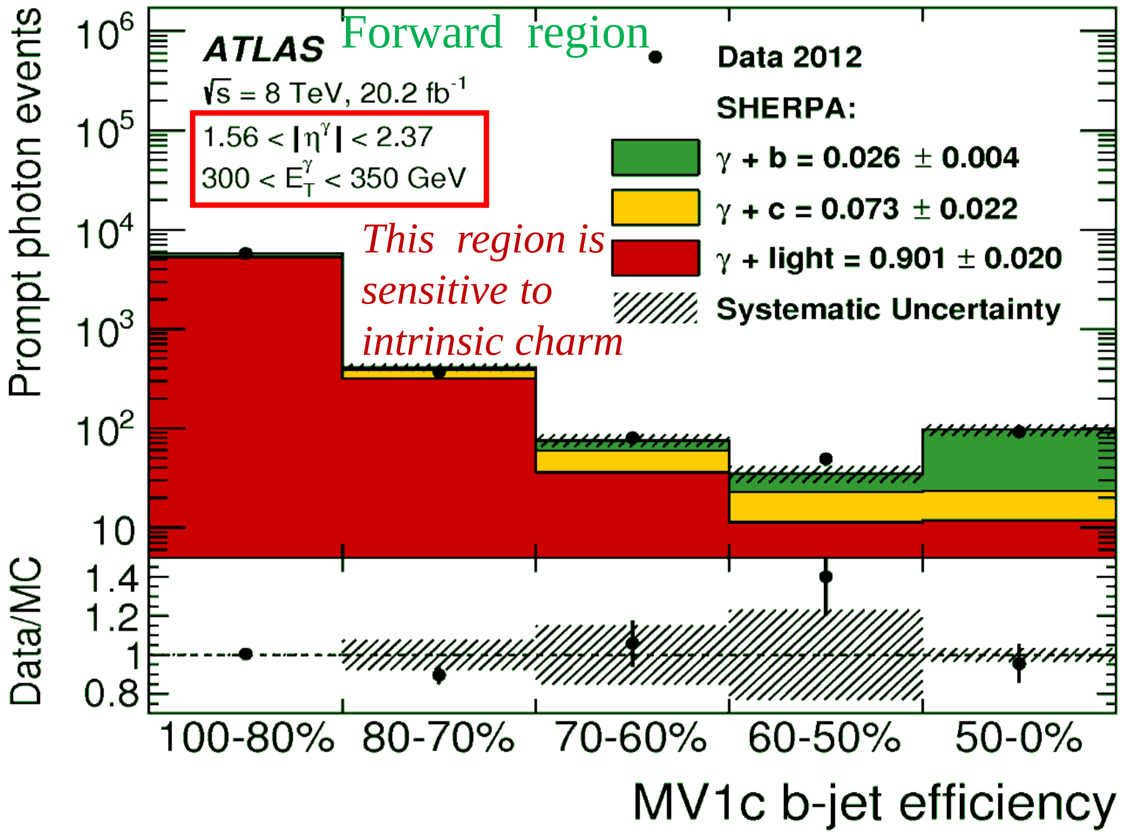
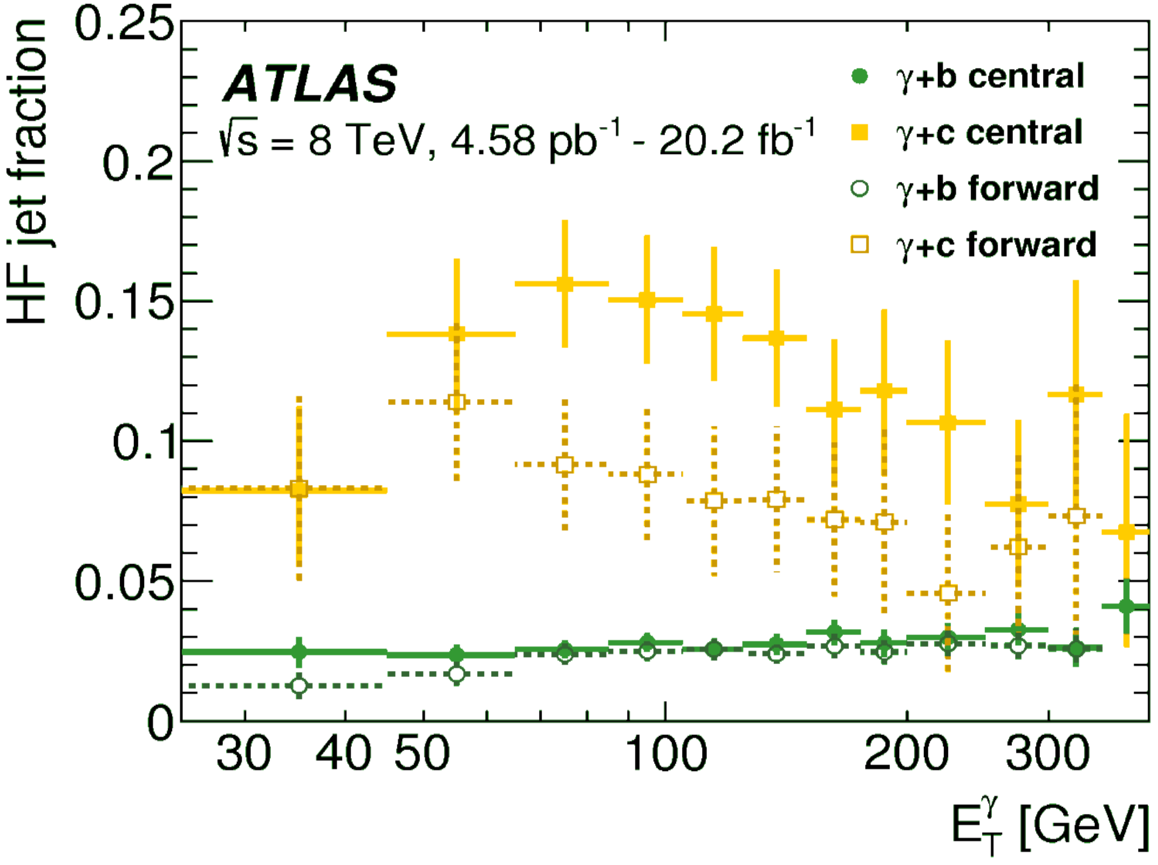
- *The addition of Heavy Flavour (HF) Jet using **MV1c** (neural network) algorithm:*
  - ***Is trained*** to specifically identify ***b-jets*** with enhanced rejection of ***c-jets***
  - *Uses discriminants* from ***3 other algorithms*** based on different aspects of **jet tracking** information from *Secondary Vertices*
  - Perform maximum likelihood template fit





CROSS-SECTIONS $pp \rightarrow \gamma$ + b-JET +X AT 8 TEV

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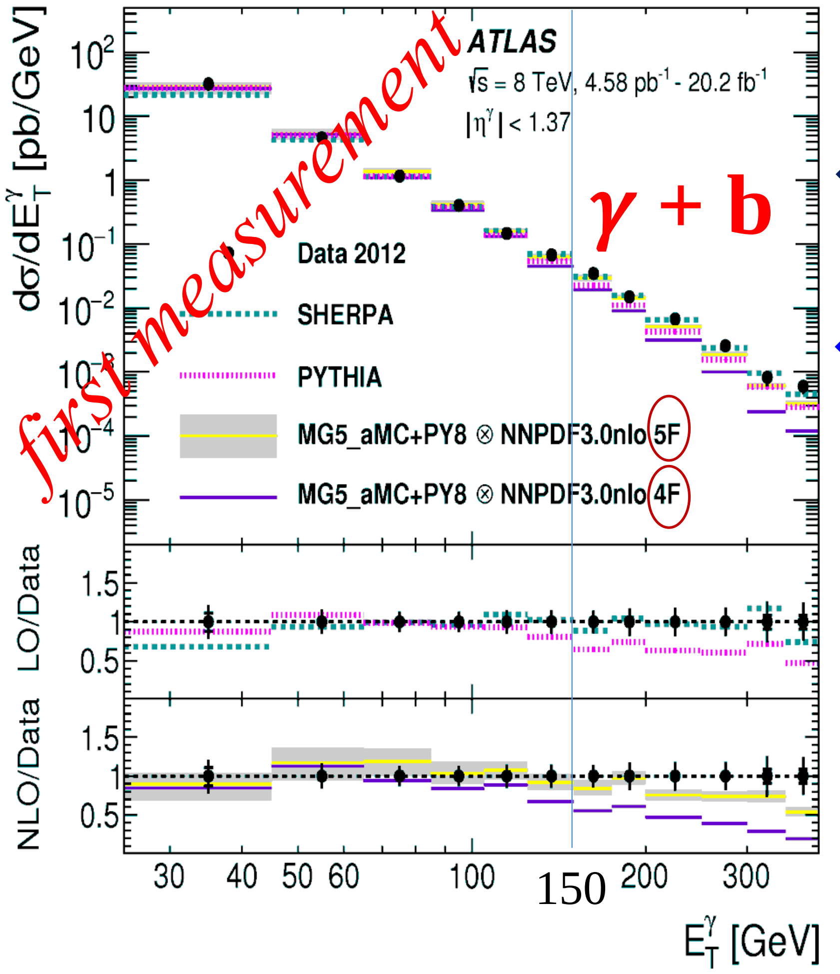
- Leading γ: $E_t^\gamma \geq 25$ GeV, $|\eta^\gamma|<1.37$, $1.56<|\eta^\gamma|<2.37$; $E_T^{iso} < 0.0042\times E_T^\gamma+4.8$ GeV
- Leading Jet: $\Delta R^{\gamma\text{-jet}} = \sqrt{(\Delta y)^2+(\Delta\varphi)^2} > 1$, $p_T^{jet} > 20$ GeV, $|y^{jet}| < 2.5$

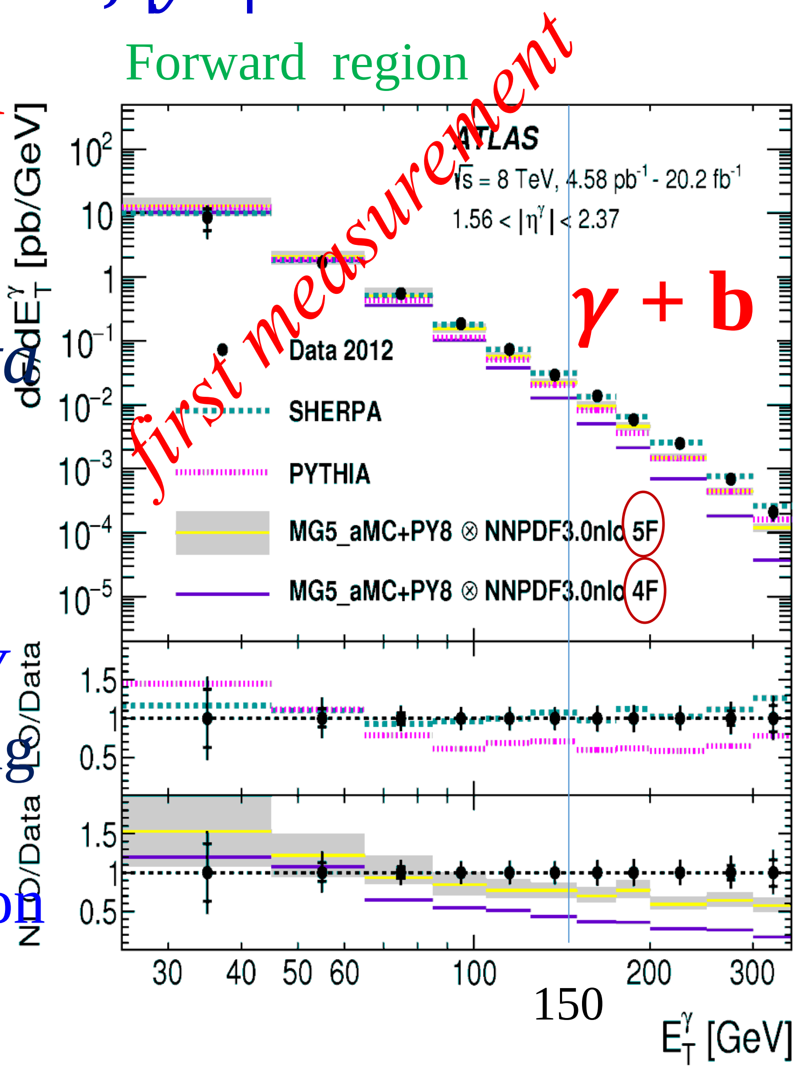
Central region



Best description is provided by *SHERPA* for γ + b

- *Above* **150 GeV** *in* **γ + b** ***PYTHIA*** *underestimates data*
- Both **NLO** *agree at low* E_T in *γ+b;* ***5F*** *(five-flavour) scheme performs better* than ***4F*** (four-flavour) *for* $125<E_T<200$ *GeV*
  - At higher $\mathbf{E_T}$ gluon splitting is important
  - High order (HO) calculation needed at higher $\mathbf{E_T}$

Forward region



CROSS-SECTIONS PP → γ + C-JET +X AT 8 TEV

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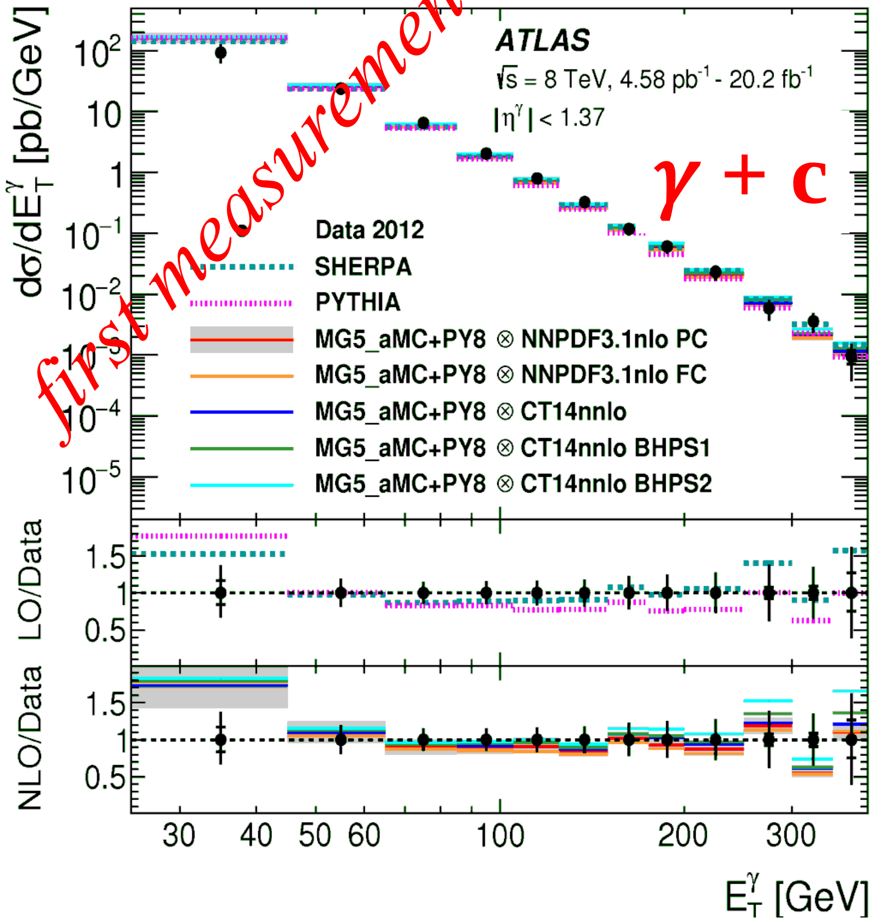
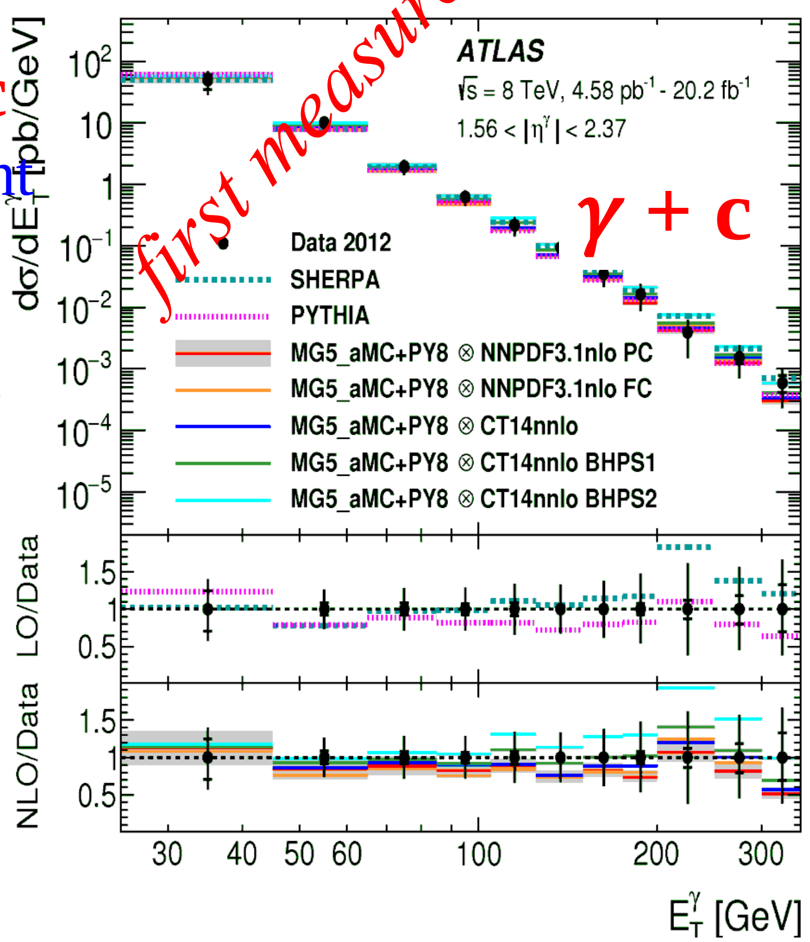
- ❑ ***Madgraph5_aMC@NLO*** with *several **PDF** sets* → *with different intrinsic charm (IC)* **content/ model** and ***5F/4F*** (five-flavour)/(four-flavour) **flavor-schemes** comparison
- ➢ ***4F*** worse description at high E_T^γ (large $\log(m_b/E_T^\gamma)$ terms)

Central region



- ❑ **All the predictions are in agreement** with data for ***γ+c***
  - ❖ Gluon splitting less important at this E_T^γ region
  - ➢ *All **intrinsic charm (IC)** predict higher forward cross section as expected*
  - ❖ **BHPS2** deviates the most
  - ➢ ***PDFs with/without IC** give deviations similar **to the measurement uncertainties***

Forward region



Δ_{sys}~15%: main contribution due to jet flavour determination. Stat. dominated in the E_T^γ tails 10-40%.

RATIO CENTRAL/FORWARD PP → γ + B/C-JET +X AT 8 TEV

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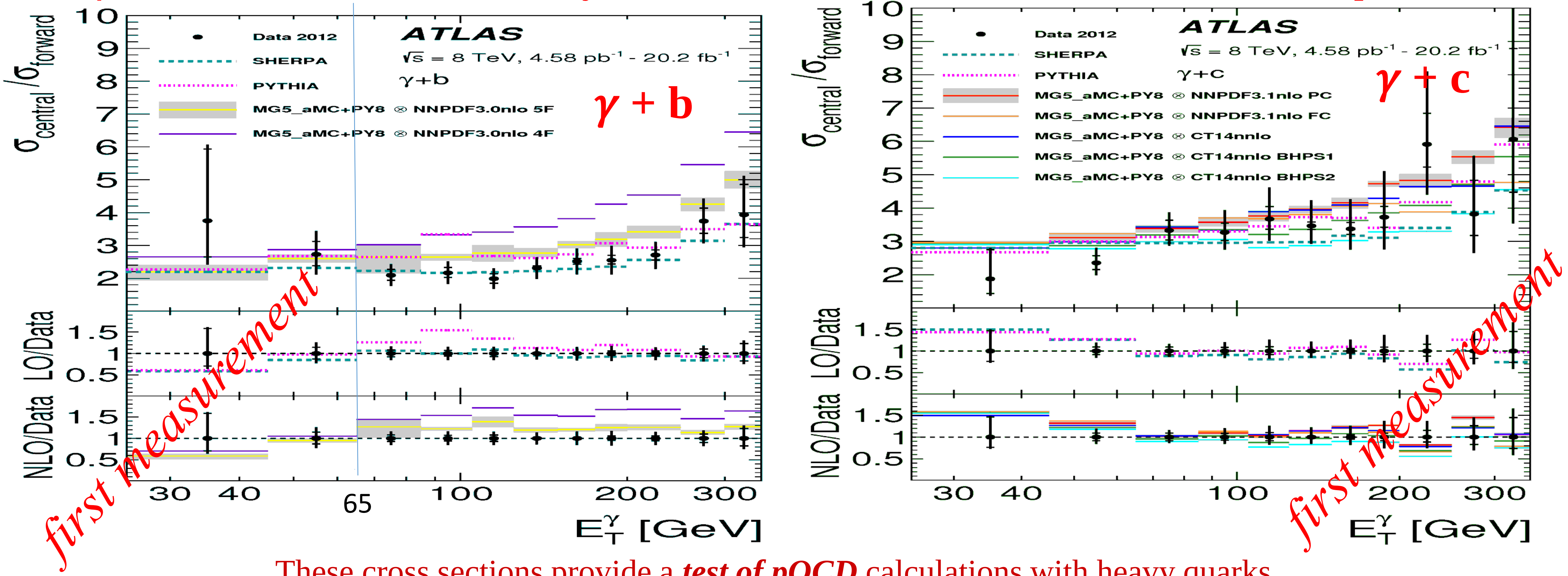
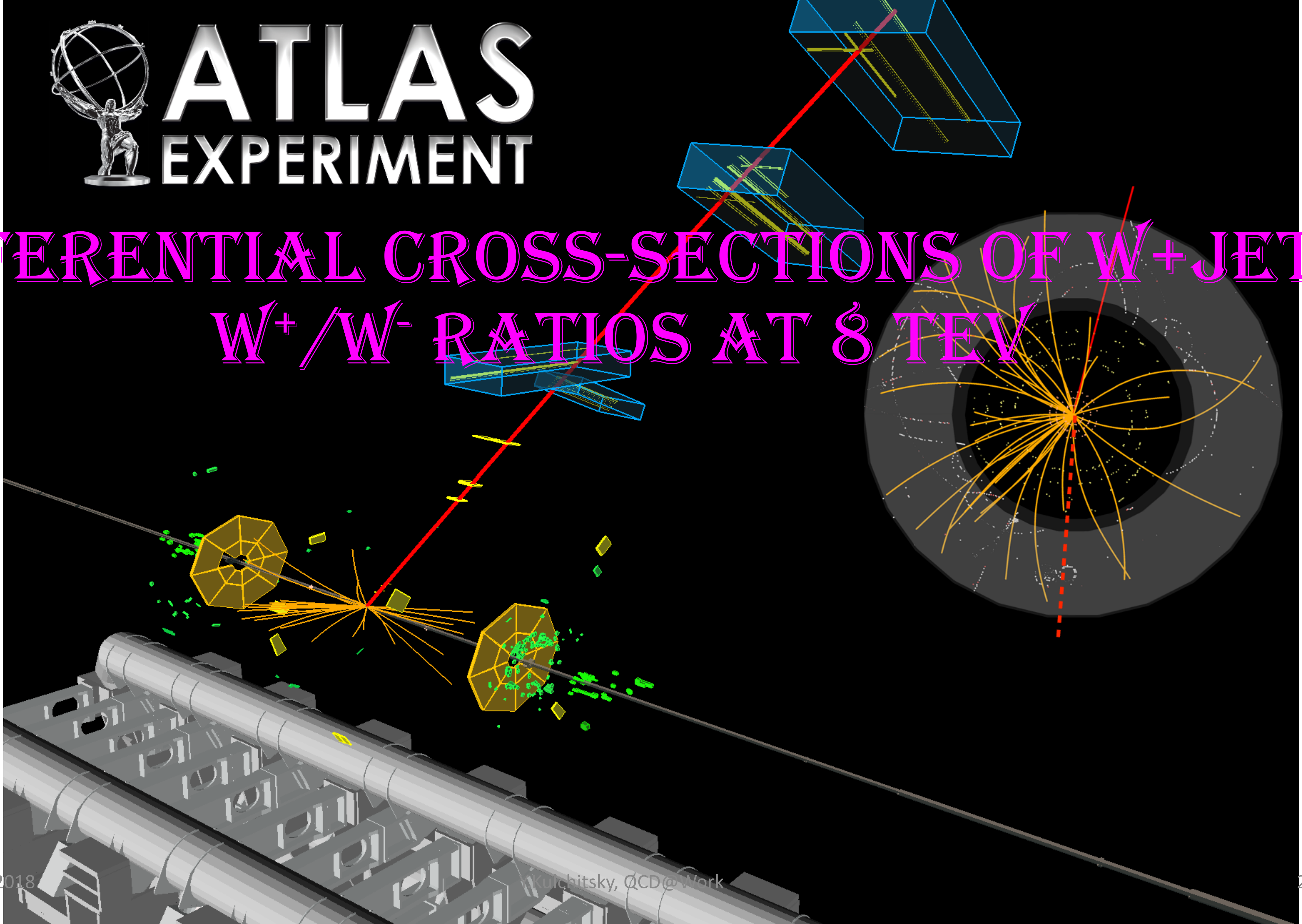
- ***SHERPA***, which generates additional partons in the matrix element and uses a massive ***5F scheme***, provides a **better description** of the measured cross sections and cross-section ratios than ***MADGRAPH5_AMC@NLO***
- The ***4F and 5F NLO*** predictions for the cross-section ratios consistently **overestimate** the data for ***E_T^γ > 65 GeV***
- In **γ + c** the measurement accuracy matches the deviations between the theoretical predictions



These cross sections provide a ***test of pQCD*** calculations with heavy quarks and are ***sensitive to the b- and c-quark PDFs***

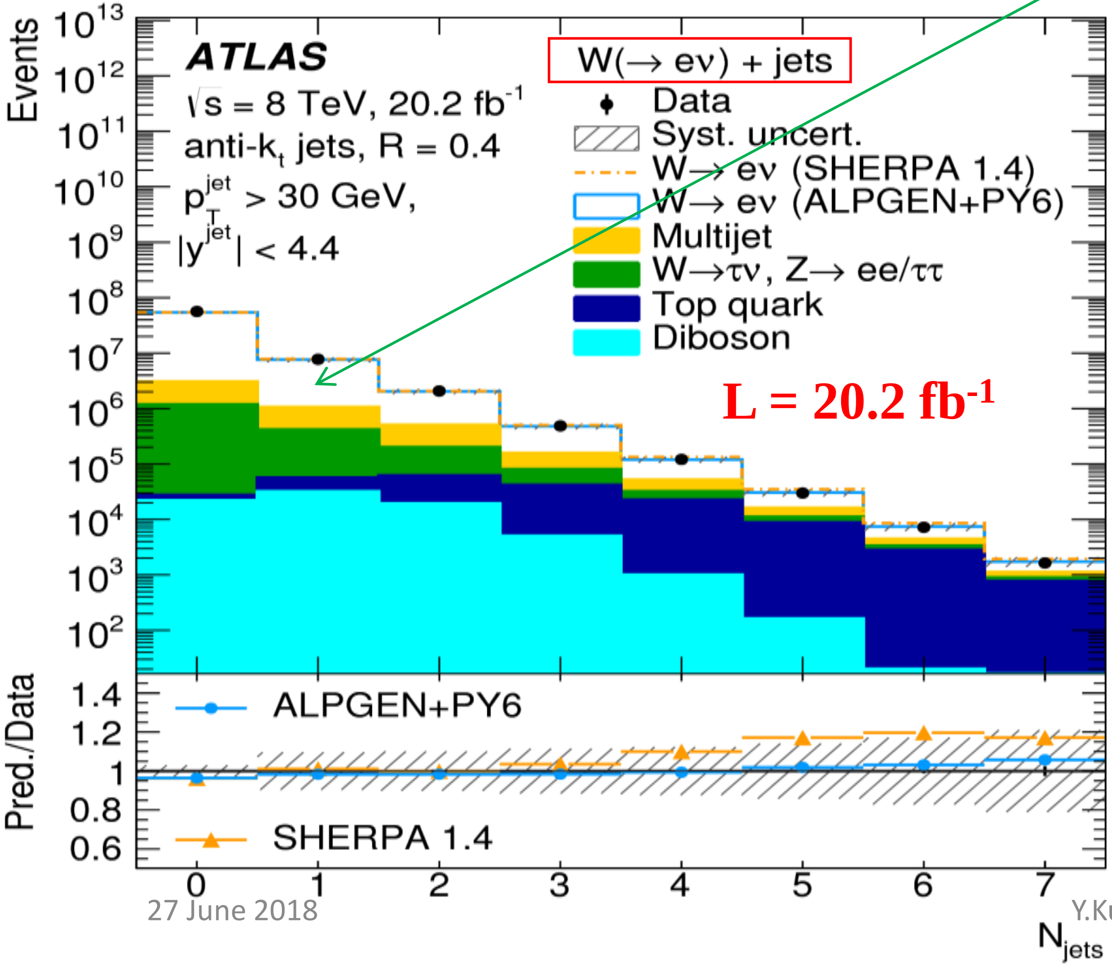
Differential cross-sections of W+jets, W^+/W^- ratios at 8 TeV

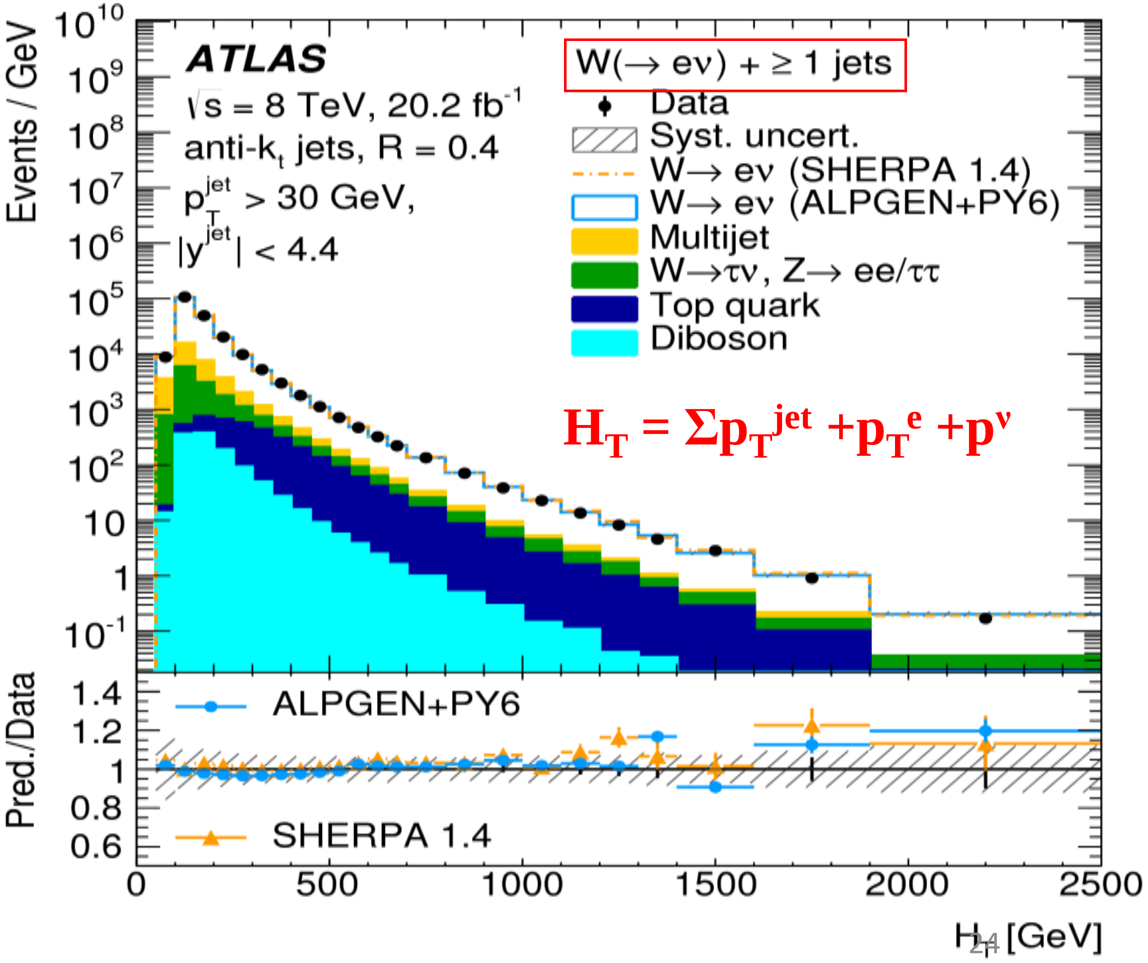


ADDITIONAL PROBES OF THE SM: pp → W + JETS, W^+/W^- RATIOS AT 8 TEV

arXiv:1711.03296

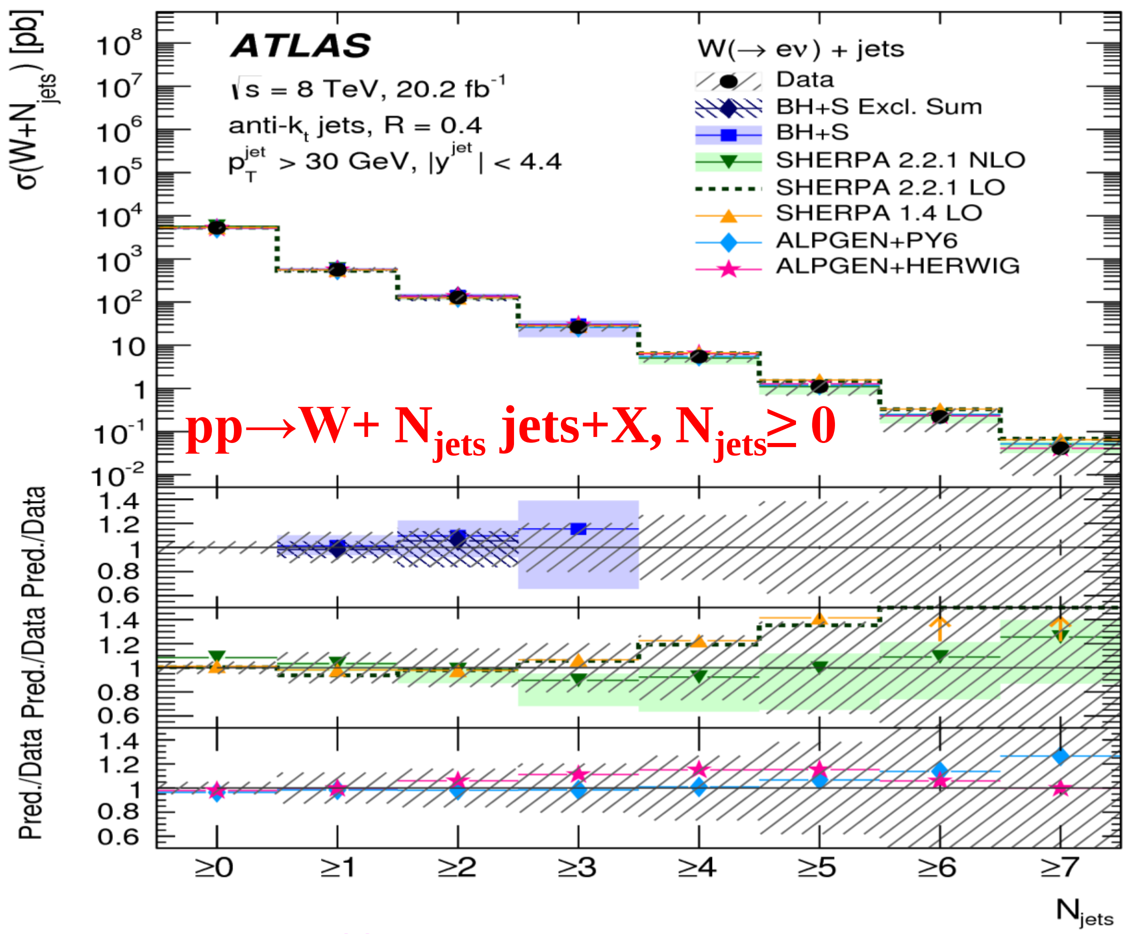
- **W→eν** production with *Jets association*
  - One Electron: $|\eta^e|<2.47$ (excl. $1.37<|\eta^e|<1.52$), $p_T^e>25$GeV
  - Jet: anti-k_T, **R^{jet} =0.4, p_T^{jet}>30 GeV, $|y|$<4.4** , b-veto
  - Track (Calorim.) e isolation: **$\Sigma p_T(\Delta R<0.3)/p_T^e$ <0.07 (0.14)**
  - Electron-Jet distance: ΔR(e, jet) > 0.4
  - **E_T^{miss}>25 GeV; $m_T=\sqrt{\{2p_T^e p_T^\nu[1-\cos(\varphi^e-\varphi^\nu)]\}}$> 40 GeV**
  - Suppress by electron isolation & low momentum contributions to E_T^{miss} from tracks, not calorimeter deposits
- Challenge–Backgrounds → ***Multijet is dominant at low N_{jets}***





DIFFERENTIAL CROSS-SECTIONS: PP → W + JETS AT 8 TEV
arXiv:1711.03296

- ❑ Cross section at ***High Jet multiplicity*** is sensitive to ***differences in MC generators***
- ❖ Cross section measured differentially as a function of characteristic variables:
  - ➢ **jet p_T , jet y, N_{jets}, H_T** (*scalar sum of the p_T of all visible objects*) and **W boson p_T**



N_{jets} differential cross section

Differential cross section as a function of Jet multiplicity:

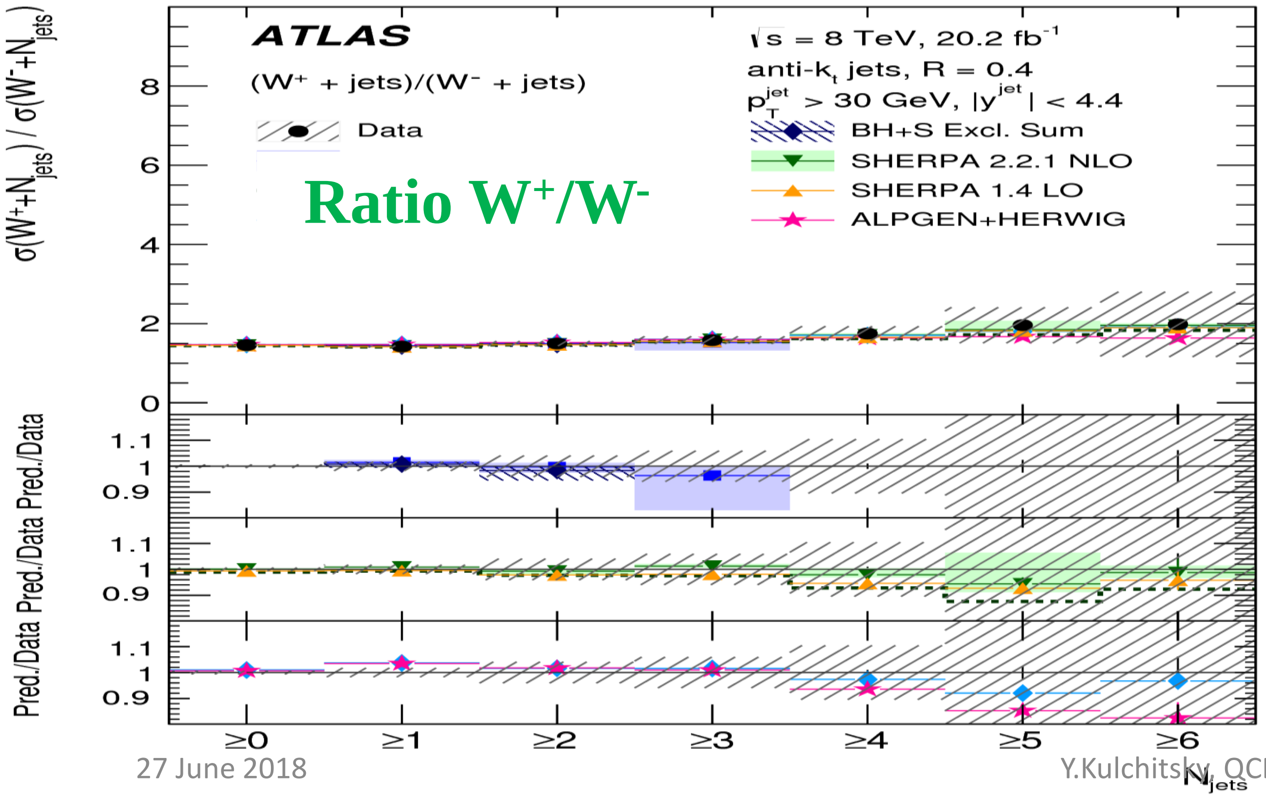
1. **BLACKHAT+SHERPA NLO** with ≤3 partons with Non-perturbative corrections applied
2. **SHERPA 2.2.1 NLO** is NLO for ≤2 partons + LO for ≤3 partons + Parton Shower (PS)
3. **SHERPA 2.2.1 LO** is LO for ≤3 partons + PS
4. **SHERPA 1.4 LO** is LO for ≤4 partons + PS
5. **ALPGEN+PY6** is LO for ≤5 partons + PS
6. **ALPGEN+HERWIG** is LO for ≤5 partons + PS

Predictions vary substantially once the **Number of Jets** exceeds the **Number of Partons** included in the matrix element calculation

W^+/W^- RATIOS FOR PP → W + JETS AT 8 TEV

arXiv:1711.03296

- ❑ The *W+/W-* cross-section ratio can be measured to high precision as many of the experimental and theoretical uncertainties cancel out
- ➢ **NLO SHERPA** provides a good description
- ❖ **LO SHERPA** diverges from the data at high multiplicities



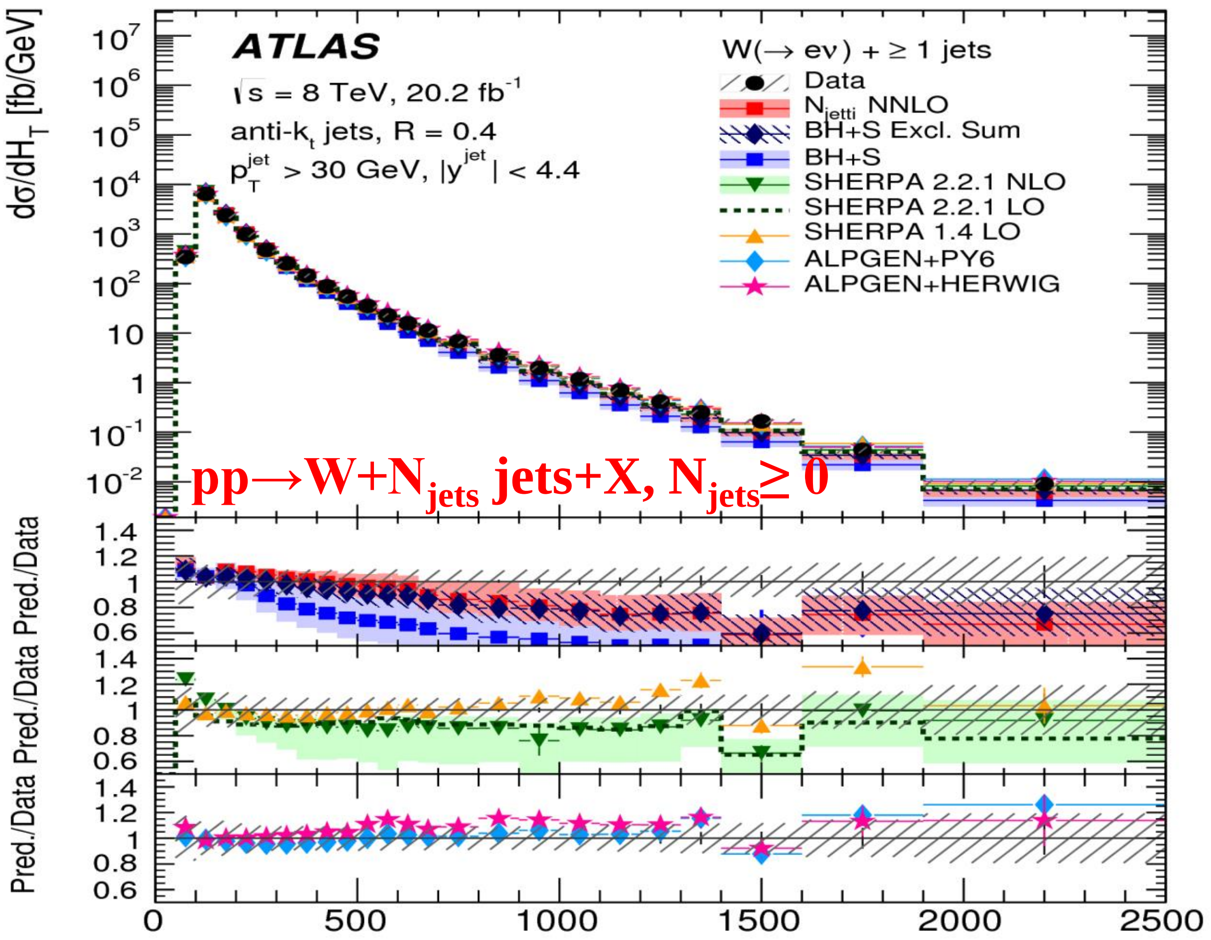
- ❖ Offset in **ALPGEN+PS** for $\mathbf{W^+/W^-}$ **+ ≥1jet**: due to matrix element (ME) calculation and/or **u/d**-ratio in the **LO PDF**
- ❑ Data/predictions agreement much improved in $\mathbf{W^+/W^-}$: *theory mismodelling related to jet emission cancels out in the ratio*

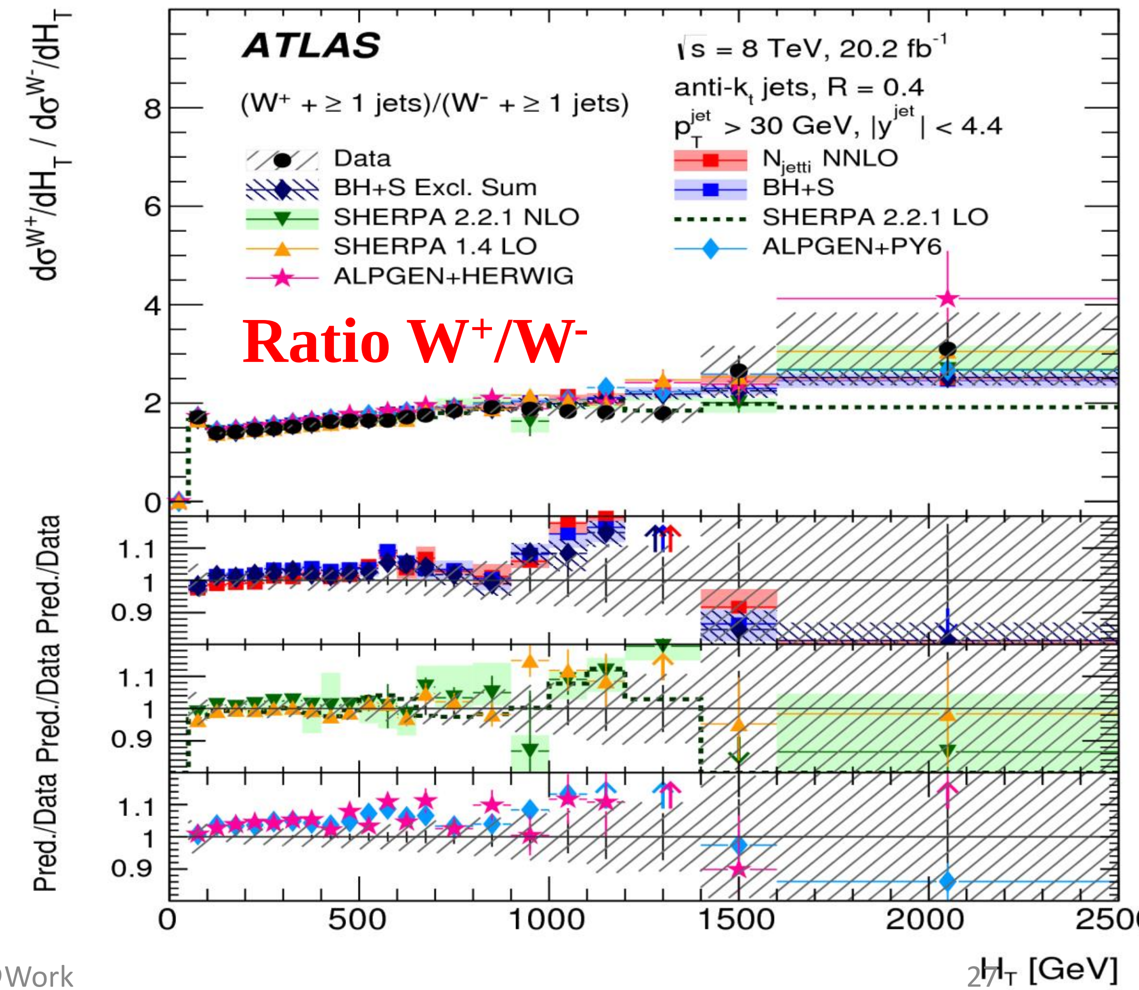
1. Overall the jet mismodelling cancels out in the ratio
2. Previously dominant Jet Energy Scale (JES) uncertainty cancels out
3. **ALPGEN-LO** predictions have an offset in the ***≥1 jet*** bin in the ***W^+/W^- ratio*** outside the experimental uncertainties
4. Suggests that there is a problem in the matrix element calculation or with the ***u/d*** -ratio in the **LO PDF**

Cross-sections of pp → W + jets, W^+/W^- ratios at 8 TeV

arXiv:1711.03296

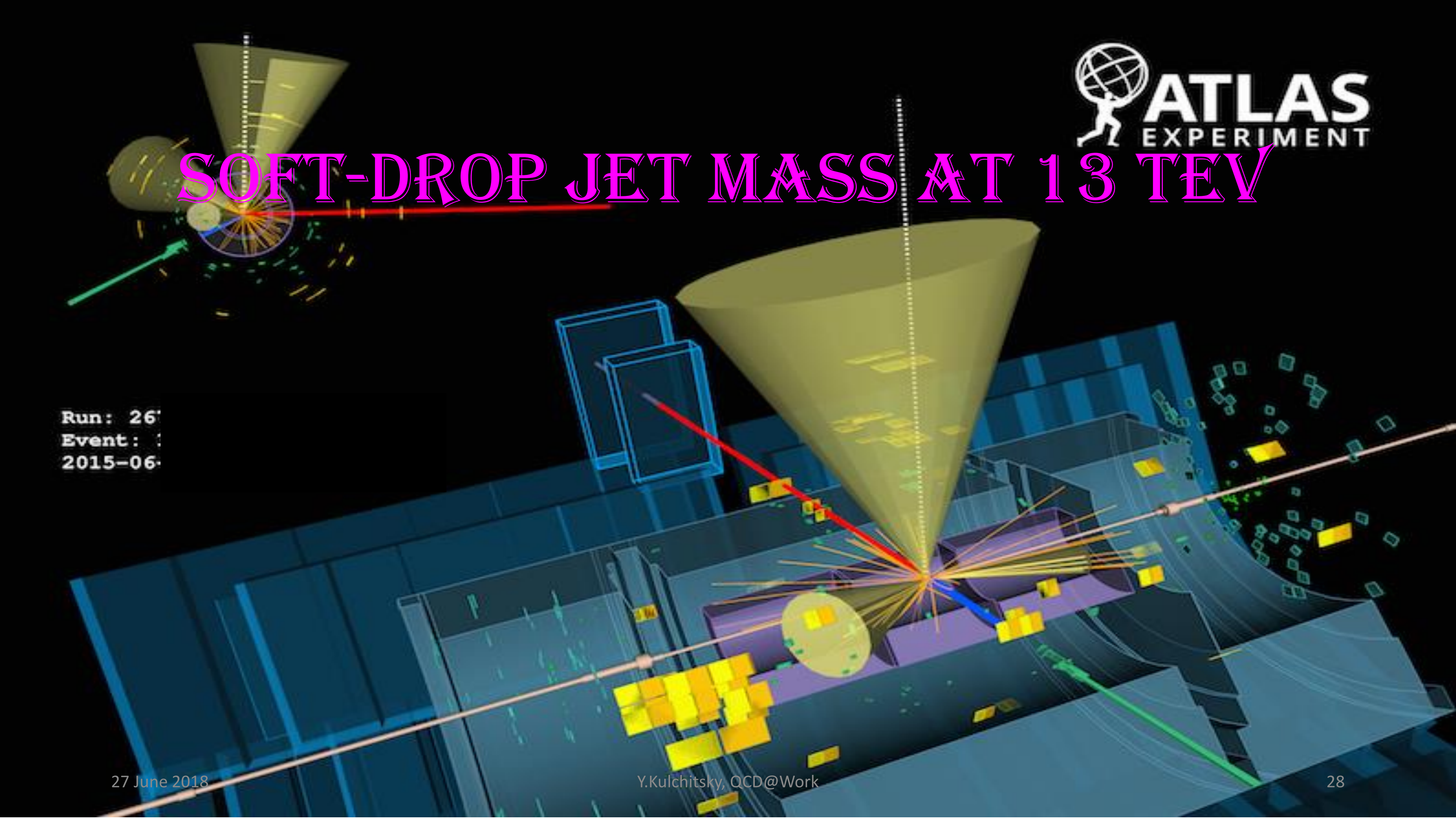
- Large, well understood dataset ***Probing*** up to a *few TeV scale*
- **W+/W-** cross-section-ratio observables: ***Jet** energy scale on other uncertainties mostly cancel*
- ***Alpgen+PY6*** *and* ***Sherpa 2.2 NLO*** *(Run 2 ATLAS default) describe data well*





$$H_T = \Sigma p_T^{jet} + p_T^{e} + p^{\nu}$$

SOFT-DROP JET MASS AT 13 TEV



SOFT-DROP JET MASS IN PP → JET + X AT 13 TEV

arXiv:1711.08341

ATLAS EXPERIMENT

Motivation

- ❑ Precision calculations of ***jet substructure moments*** like the jet mass are difficult since they are ***sensitive to soft and wide-angle radiation***
- ➢ Systematically ***removing soft and wide angle radiation*** from a jet with the ***soft drop grooming algorithm*** can allow for *precision calculations* as well as *improved experimental resolution*
- ❑ ***Probing QCD*** beyond the *parton shower accuracy*, ***starting new era of precision Jet SubStructur (JSS);*** *improving the understanding of JSS properties*

Jet Reconstruction with *Soft Drop*

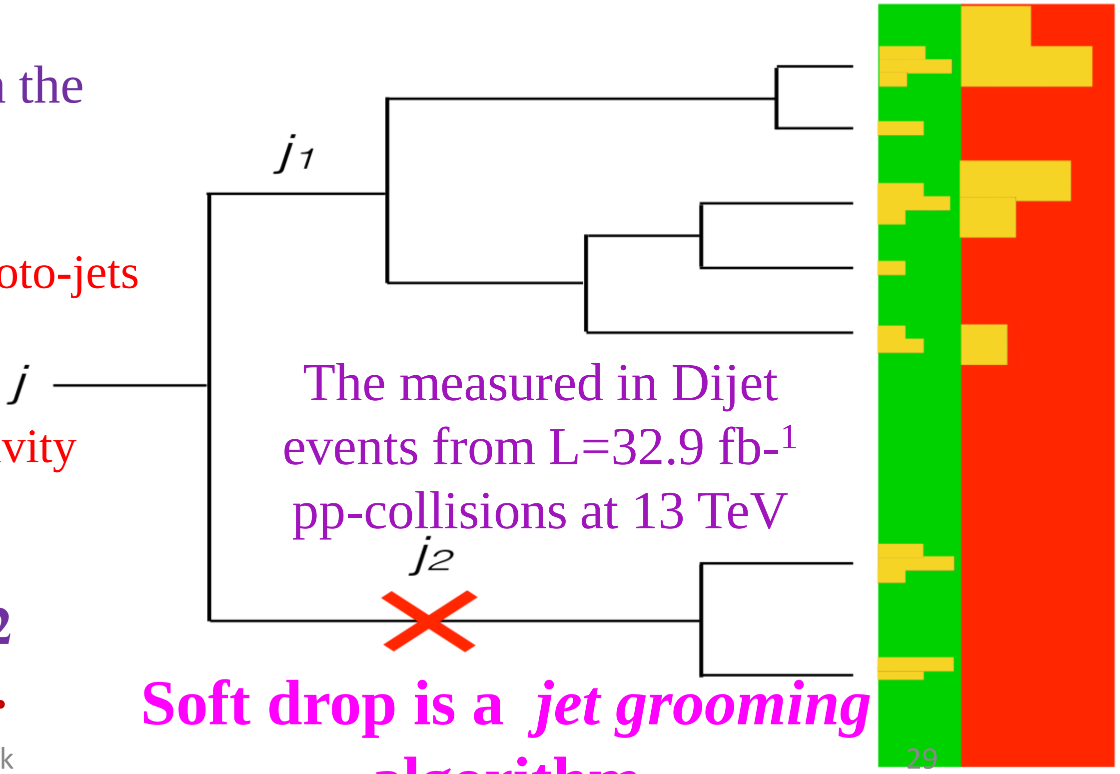
- ➢ Create **R=0.8 anti-k_T jets**, and recluster their constituents with the *Cambridge/Aachen algorithm*
- ❑ Starting from the last branch of the clustering history, check if

$$\frac{\min(p_{T,j1}, p_{T,j2})}{(p_{T,j1}+p_{T,j2})} > z_{cut} \left(\frac{\Delta R_{j1,j2}}{R}\right)^{\beta}$$

Distance proto-jets

Scale of energy removed

Sensitivity tuning



The measured in Dijet events from L=32.9 fb-[1] pp-collisions at 13 TeV

- ➢ z_{cut} sets the *scale of energy removal*: use z_{cut} **= 0.1**
- ➢ β determines the sensitivity to *wide-angle radiation*: **β = 0, 1, 2**
- ❑ ***If this condition is not satisfied, the softer branch is removed. Once this condition is satisfied, the algorithm terminates***

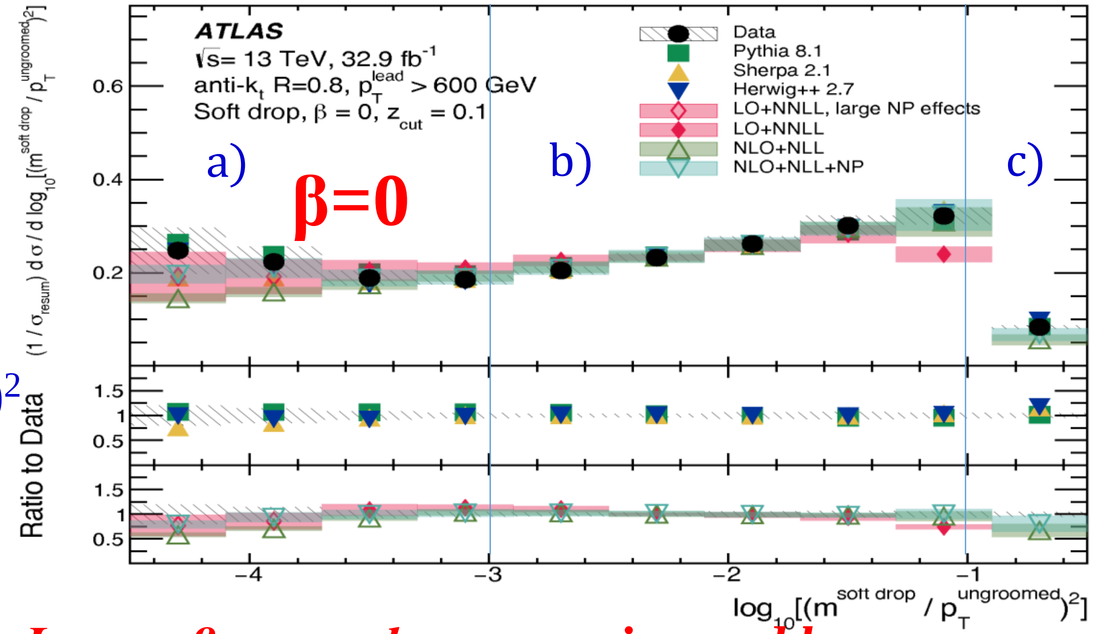
Soft drop is a *jet grooming* algorithm

Results: SOFT-DROP JET MASS IN PP → JET + X AT 13 TEV

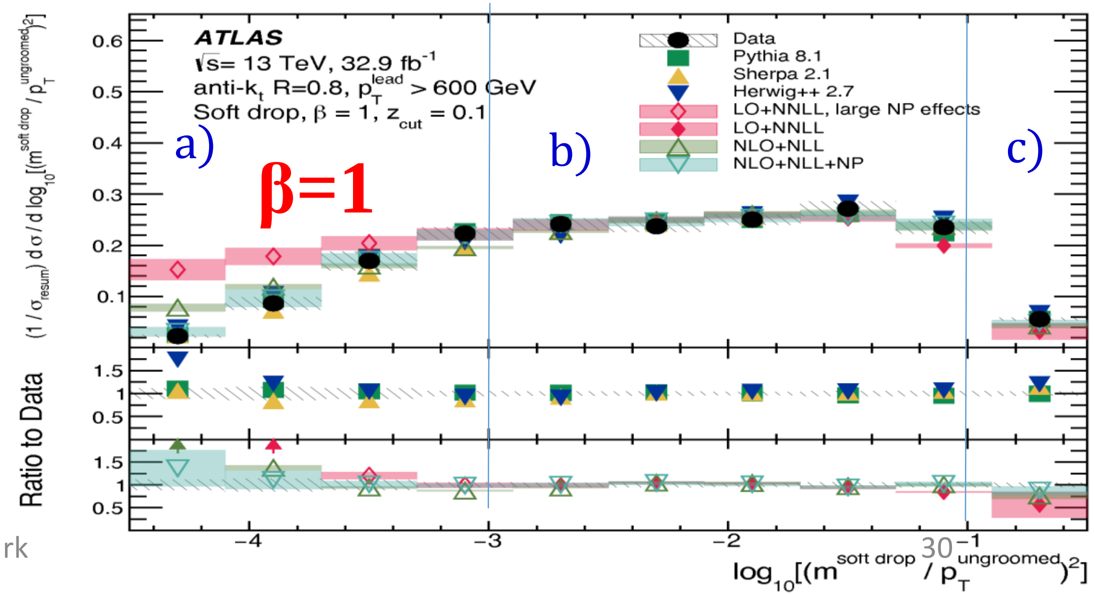
arXiv:1711.08341

- ❑ Measured ***the soft drop jet mass*** and compared to ***two QCD predictions*** with accuracy beyond Leading-Logarithm (LL)
- ➤ Three main regimes for $\rho = \log_{10}\left[\left(\frac{m^{Softdrop}}{p_T^{ungroomed}}\right)^2\right]$

  a) **ρ<-3:** *non-perturbative regime*; b) **-3 ρ<-1:** *resummation regime*; c) **ρ>-1:** *fixed order regime*; $(m^{softdrop})^2 = (\Sigma E)^2 - (\Sigma p)^2$
- ❑ ***Resummation regime*** *should be most accurate for MC and Leading Order (LO) + Next-to-Next-to-Leading-Logarithm (NNLL),* while *fixed order regime should be most accurate for Next-to-Leading Order (NLO)+NLL*
- ❖ Predictions agree with measurement in regions where non-perturbative effects are small
- ❖ Less good agreement with predictions and measurement at small ***ρ*** particularly for higher ***β***
- ❑ *PYTHIA, SHERPA, HERWIG all do an excellent job of describing the data over the entire mass range*



❑ *Larger β means less grooming and lees agreement*



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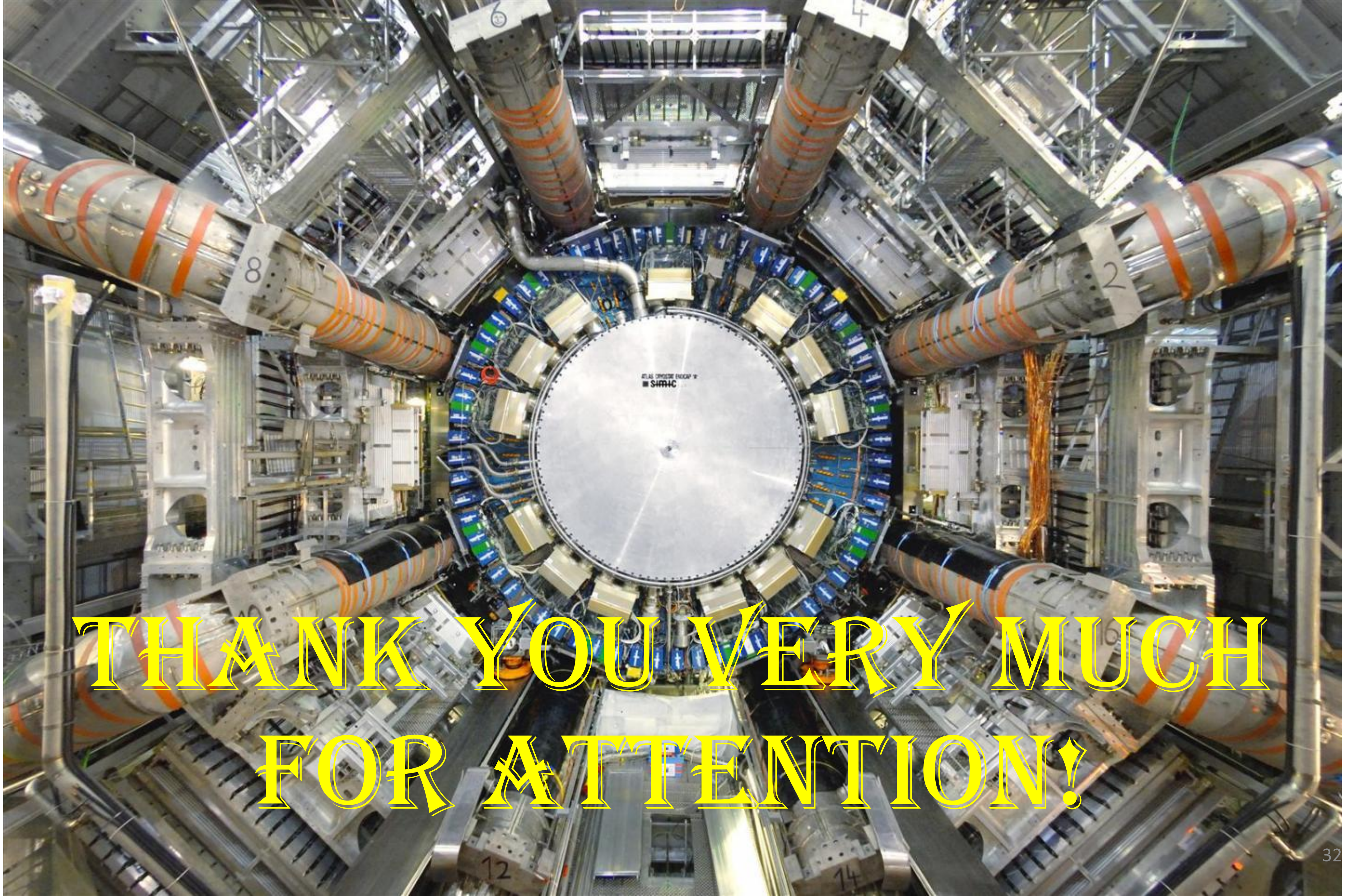
CONCLUSIONS

- ***Probing different aspects of our understanding of the Standard Model***
- ***Great variety of precision QCD results***
- The latest results from the ATLAS collaboration involving ***jets, dijets, photons in association with heavy flavors jets and vector bosons in association with jets***, measured at center of mass energies of *8 and 13 TeV* obtained
- *All measured cross-sections are compared to state-of-the art theory predictions*
- The *first measurement* of ***γ+Heavy Flavour jet*** at the LHC. For ***γ + b*** the *best description is provided by* ***Sherpa***; the *NLO underestimates* the data. The ***γ + c*** measurement has ***larger experimental uncertainties***: *PDFs with/without* ***intrinsic charm*** *give deviations similar to the measurement uncertainties*
- Measured the ***soft drop jet mass*** and compared to two QCD predictions with accuracy beyond *Leading-Logarithm*



Thank you very much for attention!

BACKUP SLIDES

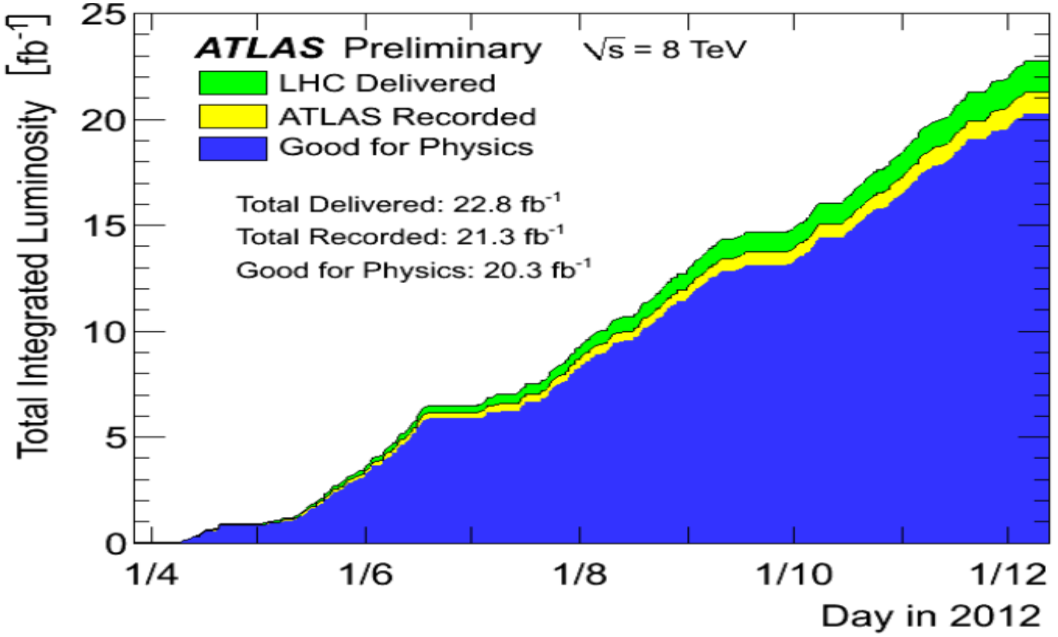
OUTLINE OF THE TALK

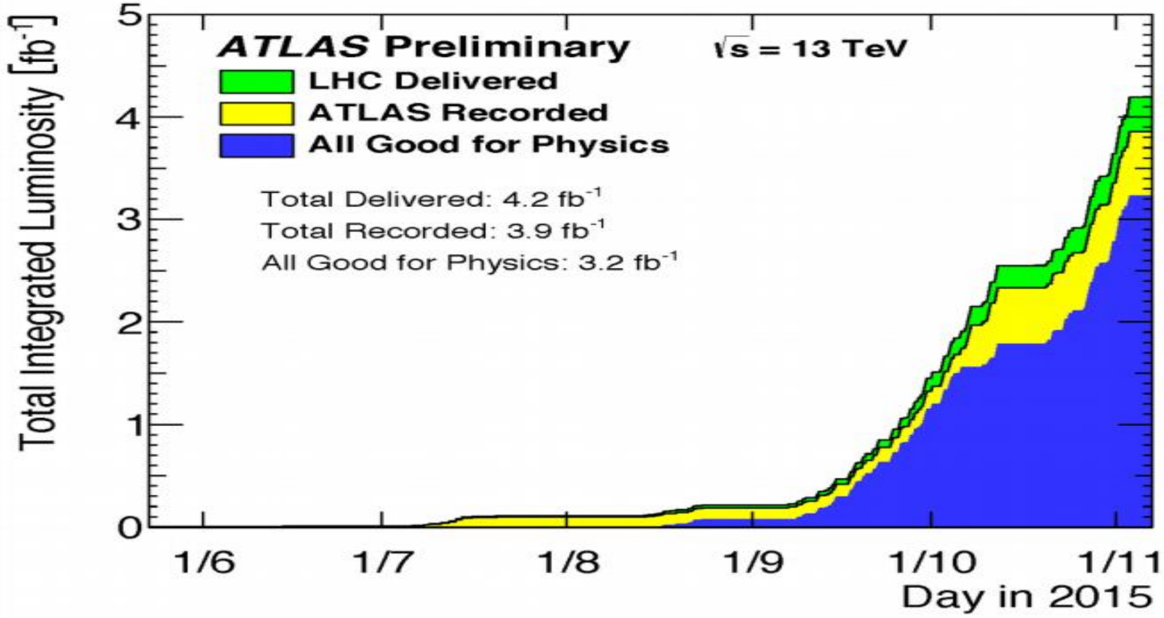
- New Standard Model results
- Motivation: Jet physics
- ATLAS detector
    - Reconstruction of physical objects: Jets, photons/electrons
- Jet physics in pp-collisions at 8 &13 TeV
    - Inclusive Jet and Dijet cross-sections at *13 TeV* *(arXiv:1711.02692)*
        - *Comparison inc. Dijet & inc. Jet at 13 TeV*
    - Inclusive Jet cross-section at *8 TeV* *(JHEP 09 (2017) 020)*
    - Differential cross-sections of γ+heavy-flavour Jet at *8 TeV* *(Phys.Lett.B776(2018) 295)*
        - *Comparison $\gamma + b$ and $\gamma + c$ at 8 TeV*
        - *Intrinsic charm*
    - Differential cross-sections of W + Jets & W^+/W^- ratios at *8 TeV* *(arXiv:1711.03296)*
    - Soft-drop Jet mass at *13 TeV* *(arXiv:1711.08341)*
- Conclusions

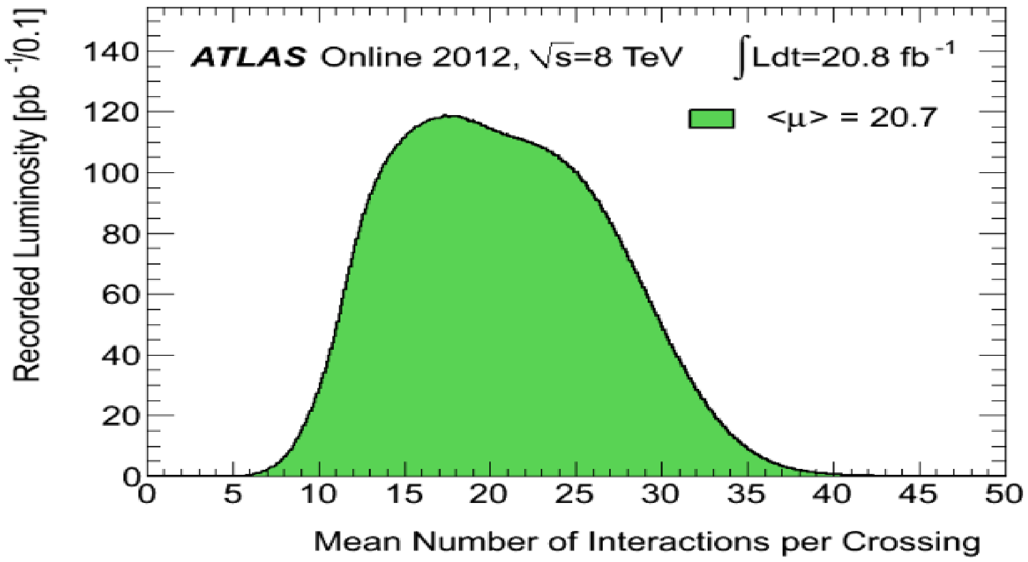
PUBLICATIONS

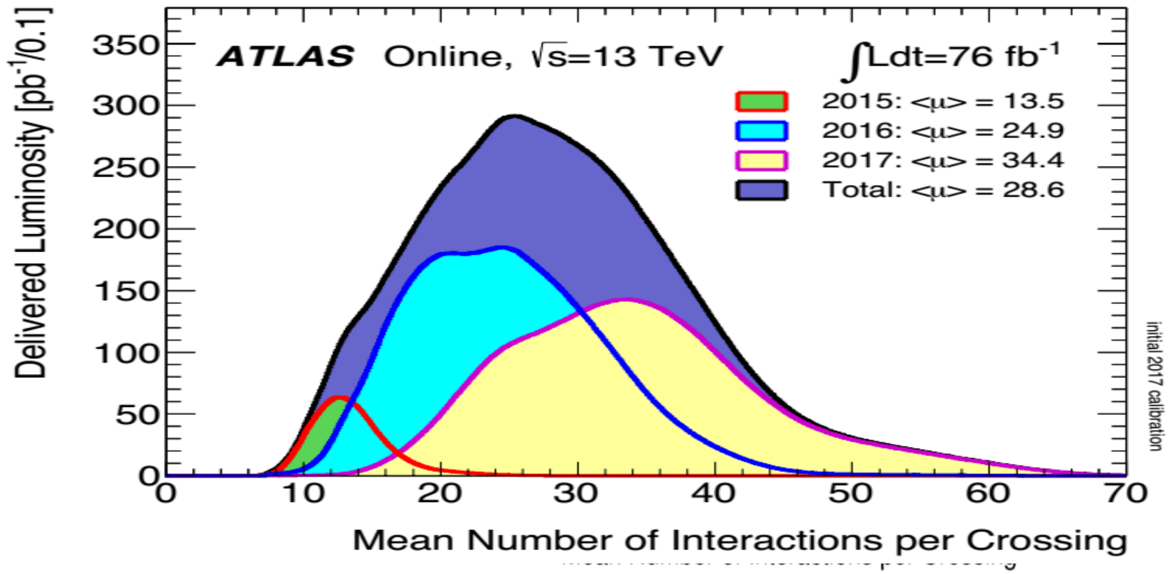
- Measurement of *inclusive* ***jet and dijet*** cross-sections in proto-proton collisions at $\sqrt{s}=13$ *TeV* with the ATLAS detector, ***arXiv:1711.02692***
- Measurement of the ***inclusive jet*** cross-sections in proton–proton collisions at $\sqrt{s}=8$ *TeV* with the ATLAS detector, *arXiv:1706.03192*, ***JHEP 09 (2017) 020***
- Measurement of differential cross sections of ***isolated-photon*** *plus* ***heavy-flavour jet*** production in pp collisions at $\sqrt{s}=8$ *TeV* using the ATLAS detector; *arXiv:1710.09560*, ***Phys. Lett. B 776 (2018) 295***
- Measurement of differential cross sections and $W+/W-$ cross-section ratios for ***W boson production in association with jets*** at $\sqrt{s}=8$ *TeV* with the ATLAS detector, ***arXiv:1711.03296***
- A measurement of the ***soft-drop jet mass*** in pp collisions at $\sqrt{s}=13$ *TeV* with the ATLAS detector, ***arXiv:1711.08341***

ATLAS Data at 8 and 13 TeV







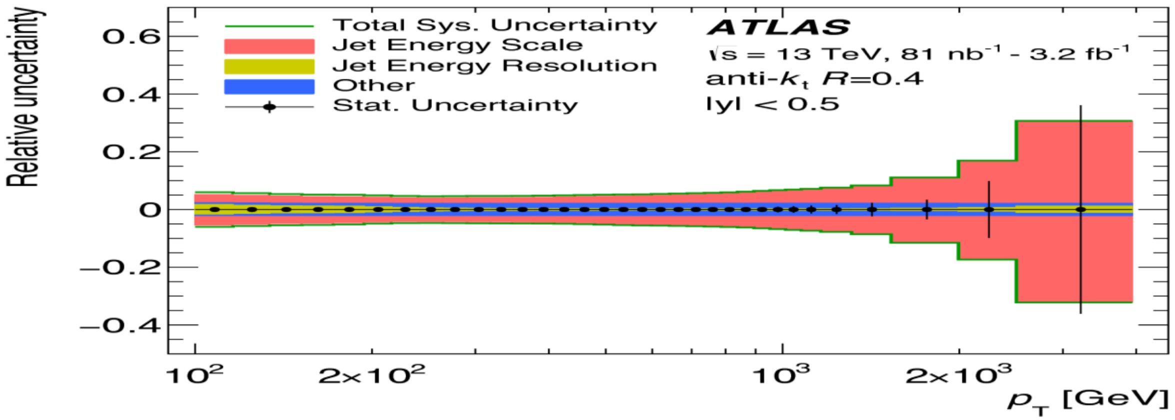


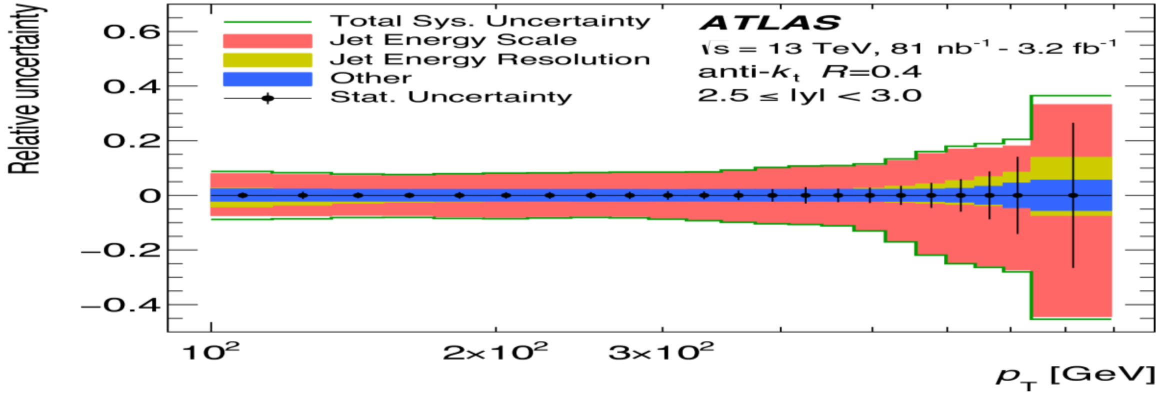
Relative systematic uncertainties: pp → jet, dijet + X at 13 TeV

arXiv:1711.02692

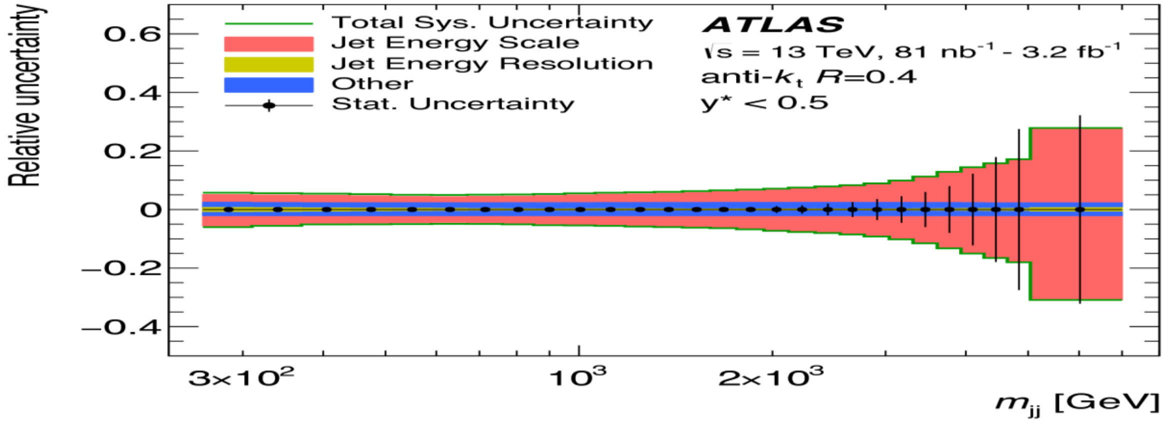
Relative systematic uncertainty for the inclusive jet cross-section as a function of the jet (dijet) p_T (m_{jj}) for the first (left) and last (right) |y| (y*) bins. The individual uncertainties are shown in different colours: the JES, JER, jet cleaning, luminosity & unfolding.

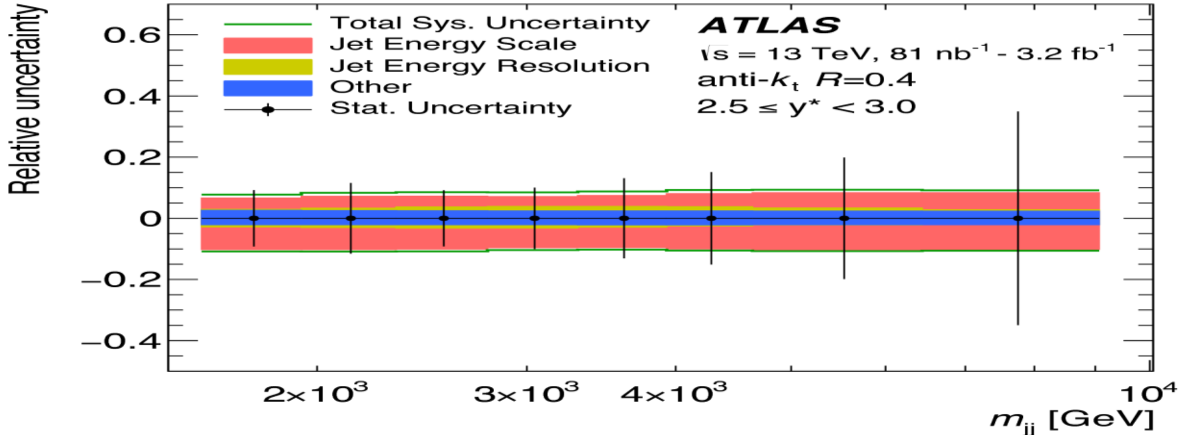
Jet





Dijet



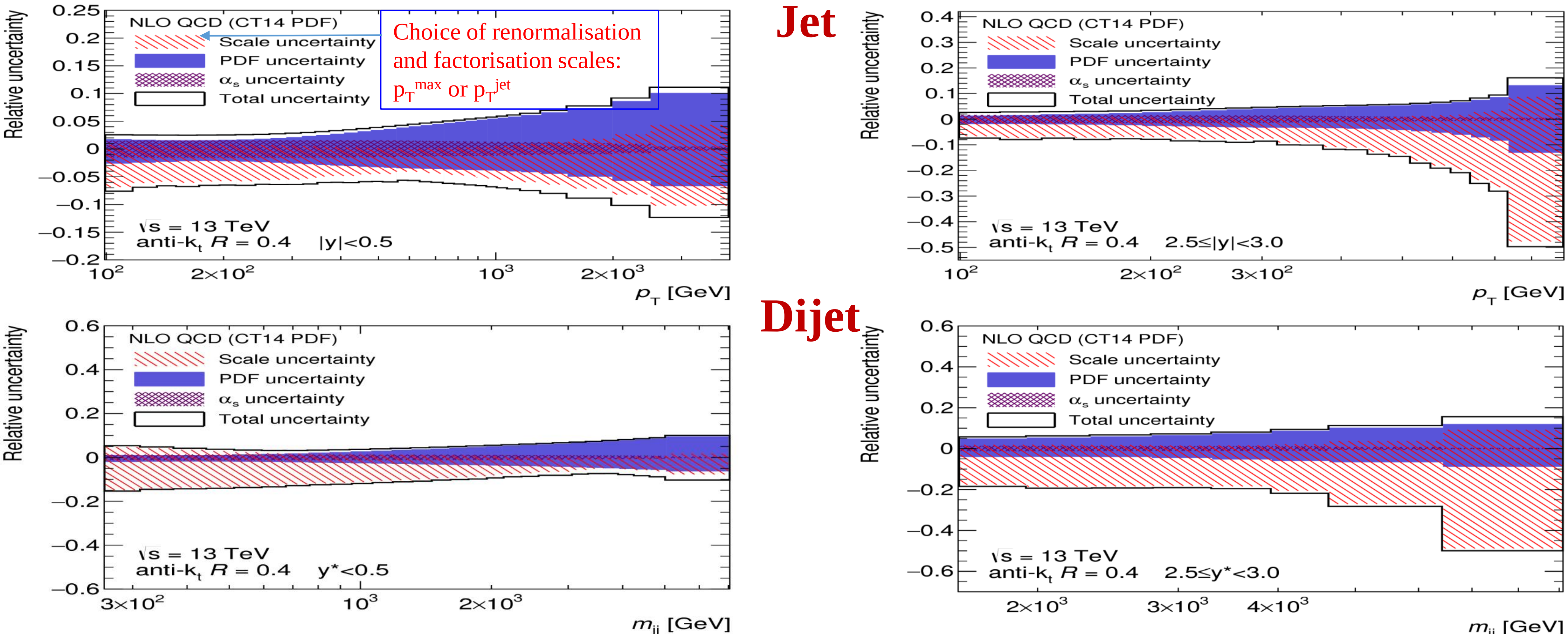


In the central (forward) region the total uncertainty in the inclusive jet measurement is about 5%(8%) at medium p_T of 300-600 GeV. The uncertainty increases towards both lower and higher p_T reaching 6%(10%) at low p_T and 30% ([-45%,+40%]) at high p_T. The total uncertainty in the dijet measurement is about 5%(10%) at medium m_{jj} of 500-1000 GeV (2000-3000 GeV) in the first (last) y* bin. The uncertainty increases towards both lower and higher m_{jj} reaching 6% at low m_{jj} and 30% at high m_{jj} in the first y* bin. In the last y∗ bin no significant dependence on m_{jj} is observed.

Relative NLO QCD uncertainties: pp → jet, dijet + X at 13 TeV

arXiv:1711.02692

Relative NLO QCD uncertainties in the jet cross-sections calculated using **CT14 PDF**. Top (bottom) panels correspond to the first and last |y| (y*) bins for the jet (dijet). The uncertainties: renormalisation and factorisation scale, the α_s, PDF & total are shown.



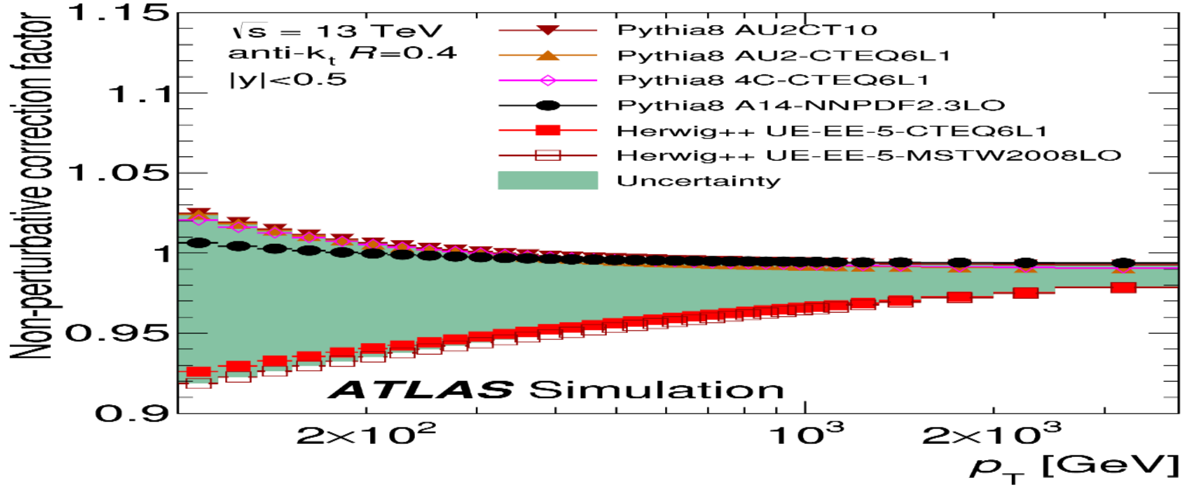
The uncertainty due to the [1] **choice of renormalisation and factorisation scale** is ***dominant in most phase-space regions***, rising from 10% (20%) at about p_T=100 GeV (m_{jj}=300 GeV) in the central |y| (y*) bin to about 50% in the highest p_T (m_{jj}) bins in the most forward |y| (y*) region. The [2] **PDF** uncertainties vary 2-12% depending on the jet p_T & |y| (m_{jj}, y*). The contribution

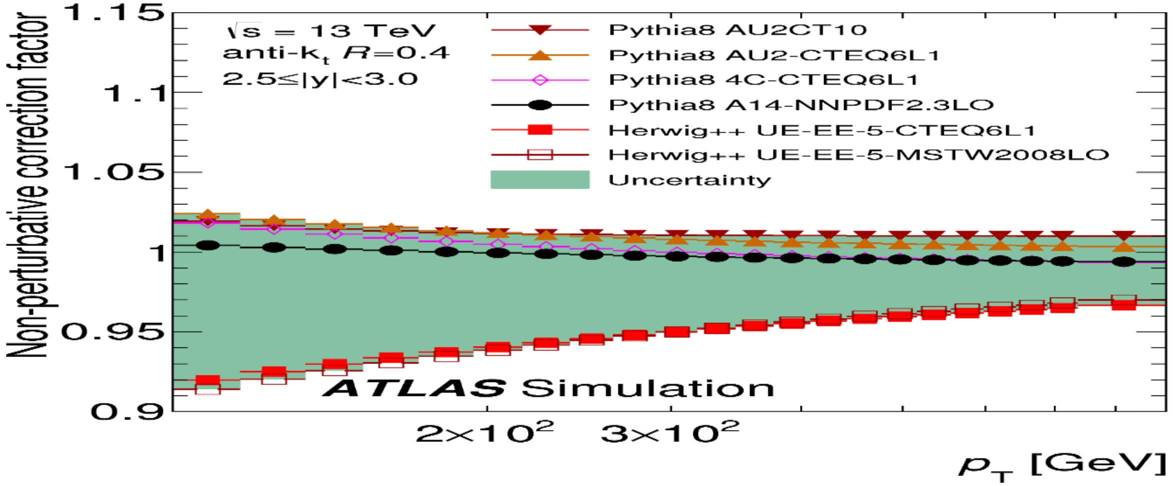
NON-PERTURBATIVE CORRECTION FACTORS: PP → JET, DIJET + X AT 13 TEV

arXiv:1711.02692

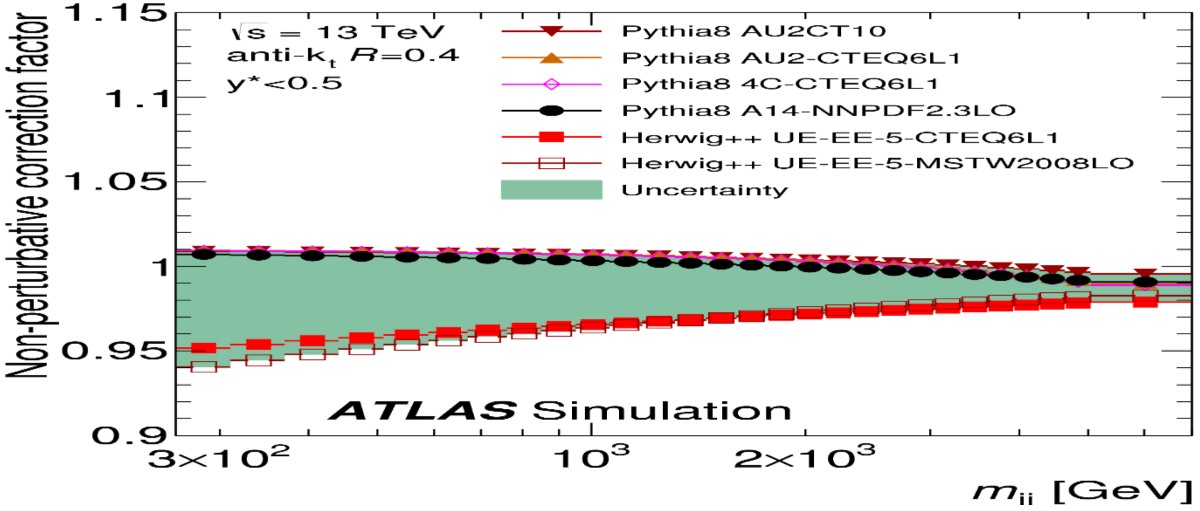
Non-perturbative correction factors for the (jet, dijet) **NLO pQCD** prediction as a function of (p_T^{jet}, m_{jj}) for (left) the first (|y|, y*) bin and for (right) the last (|y|, y*) bin. The corrections are derived using **Pythia 8 A14** with the **NNPDF2.3 LO PDF set**

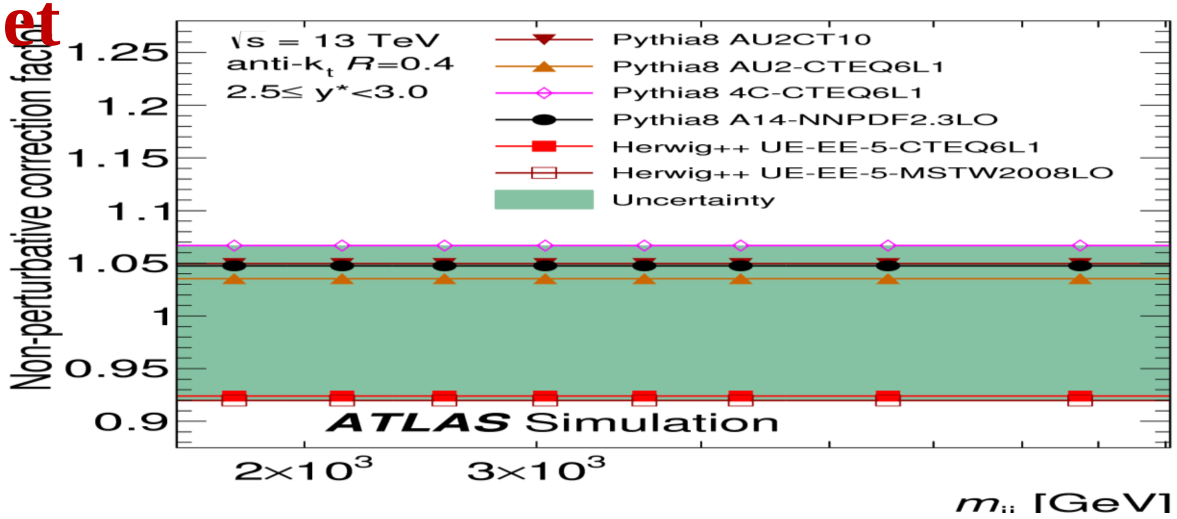
Jet





Dijet



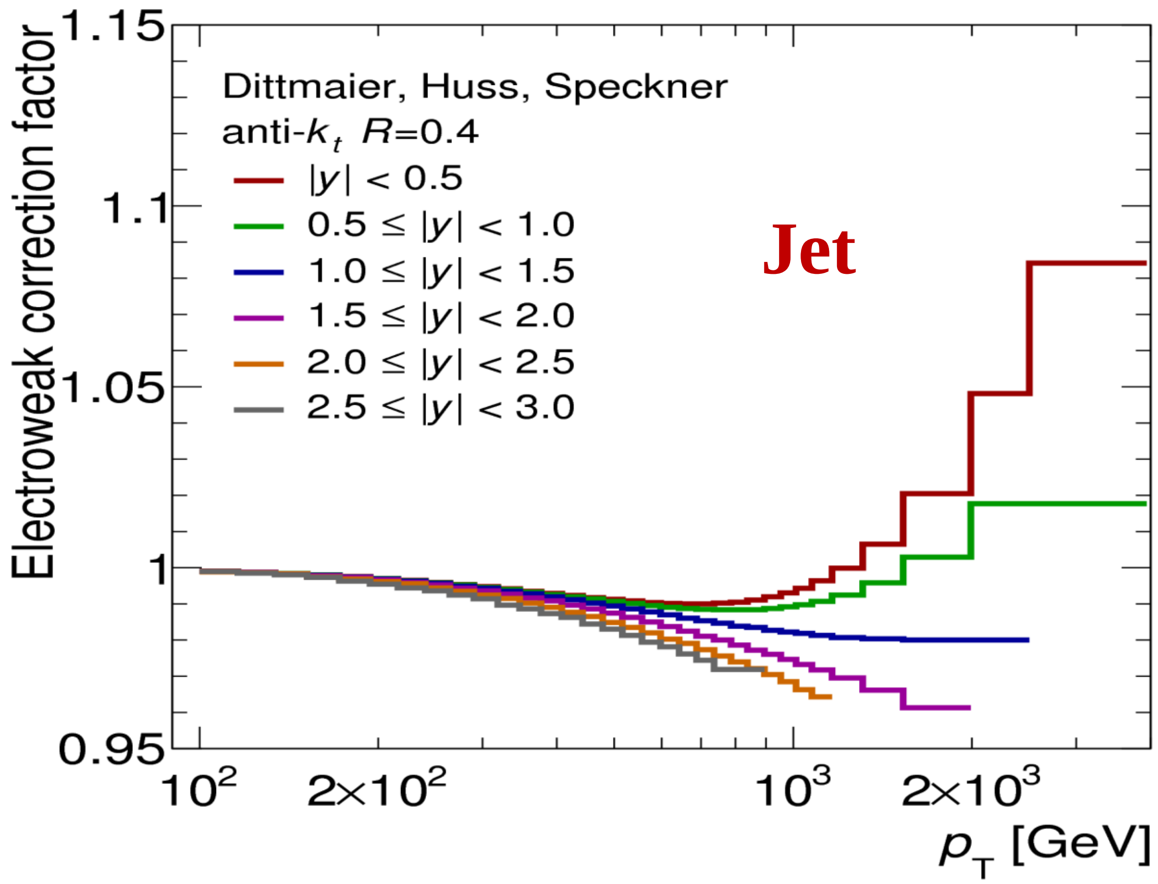


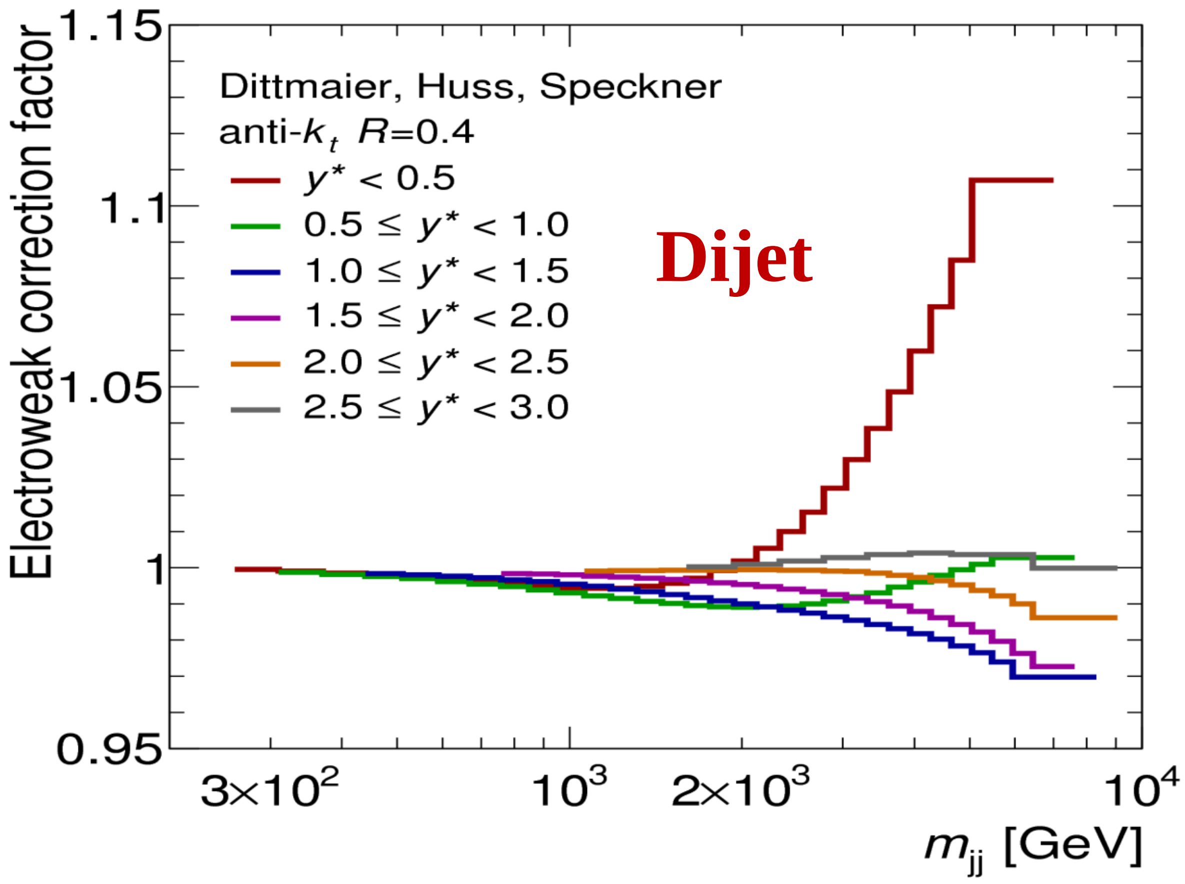
The values of the correction are: for jet → 0.92-1.03 at low p_T and 0.98-0.99 (0.97-1.01) at high p_T for the first (last) |y| bin & for dijet → 0.94-1.01 (0.98-0.99) at low (high) m_{jj} for the first y* bin and for the last y* bin is a fixed range 0.92-1.07

Electroweak correction factors: pp → jet, dijet + X at 13 TeV

arXiv:1711.02692

- The NLO pQCD predictions are corrected for the **effects of γ and $W^{\pm}/Z$ interactions** at tree and one-loop level
- Electroweak correction factors for the inclusive jet (dijet) cross-section as function of **jet p_T (m_{jj})** for |y| (y*) bins





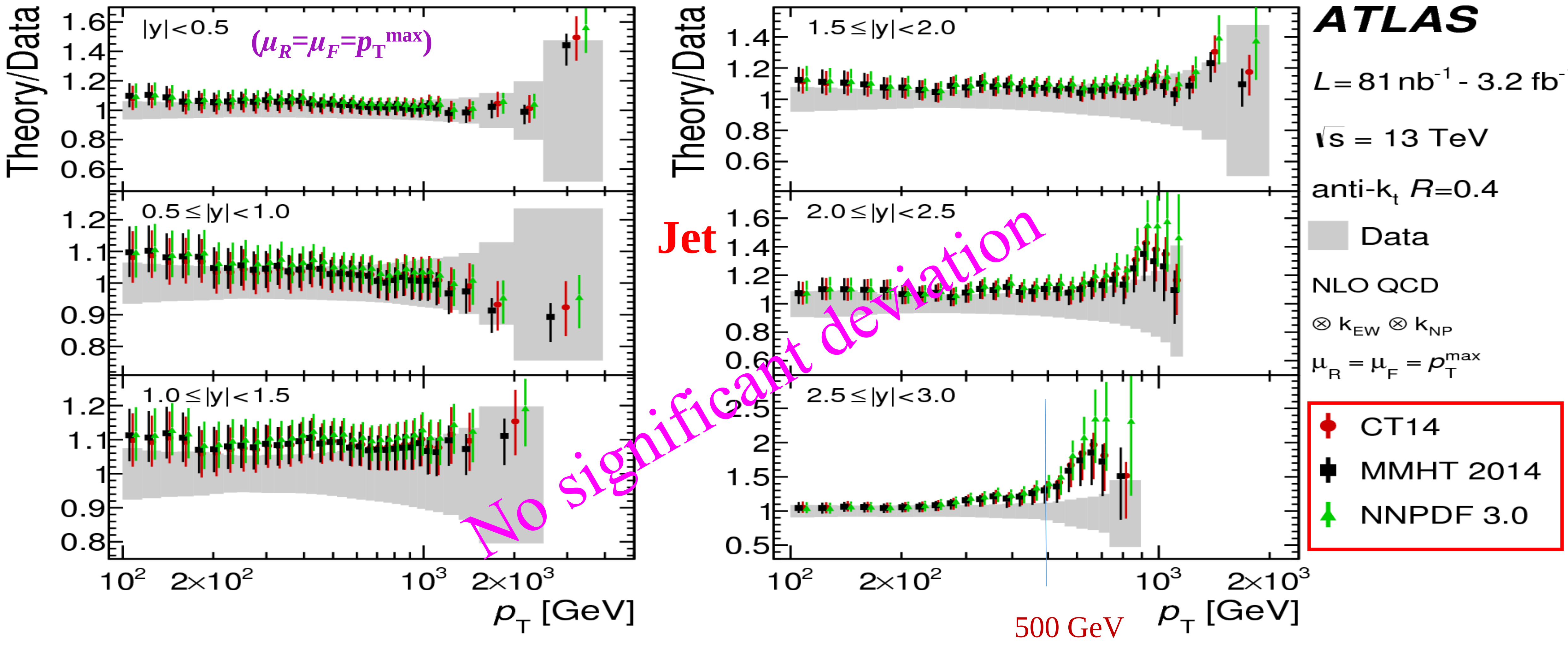
- The electroweak correction is small for low jet p_T and for low m_{jj}
- For jets the correction reaches 8% at the highest p_T (3 TeV) for the central |y| bin and is less than 4% for the rest of the |y| bins
- For dijets the EW correction reaches 11% at m_{jj} = 7 TeV for the central y* bin and less than 3% for the rest of the y* bins

THEORY/DATA COMPARISON FOR PP → JET + X AT 13 TEV

arXiv:1711.02692

Ratio of **NLOJet++ prediction** to measurements **of Jet** double-diff. cross-sec. vs. **Jet** p_T and y

PDF sets used: **CT14, MMHT 2014, NNPDF 3.0**



- Good description of data by **NLO pQCD** within the uncertainties
- Similar shape predicted by the studied **PDF** sets

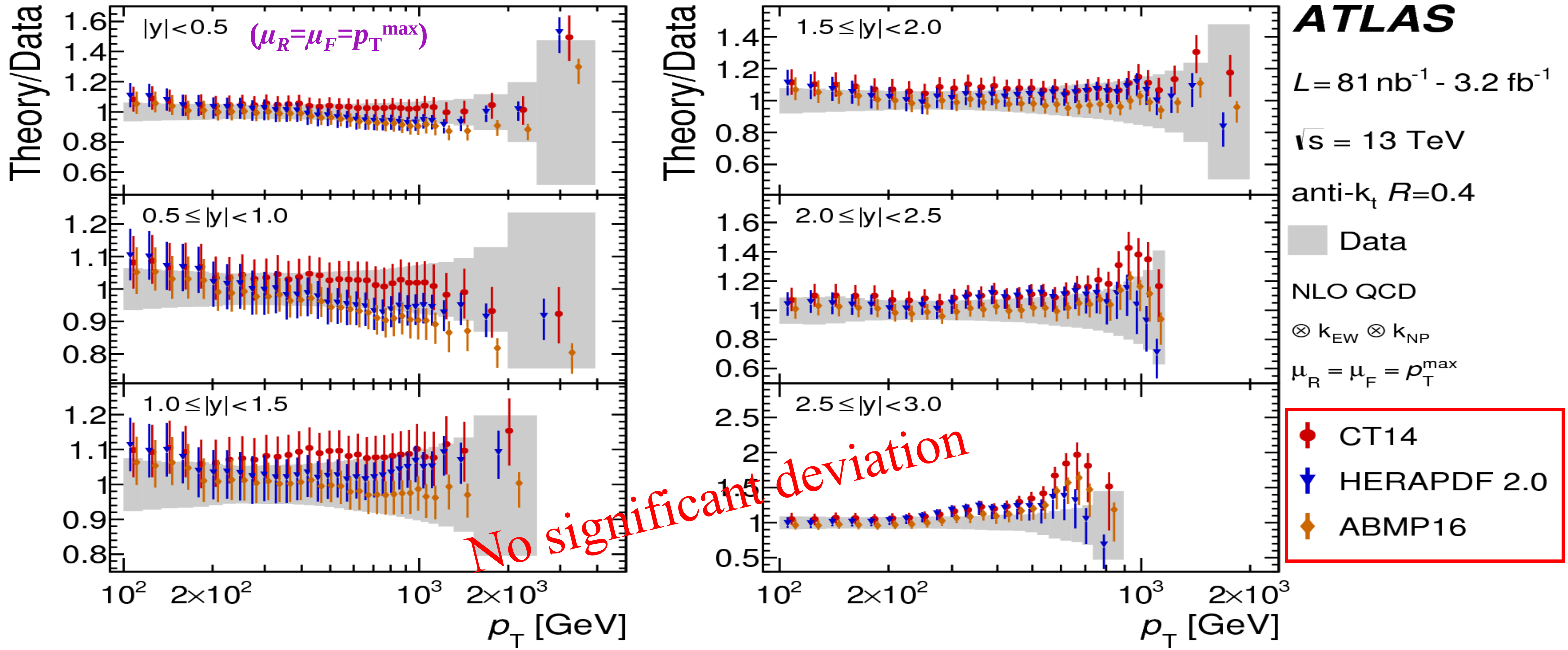
The **CT14** case is repeated to serve as a reference for comparison

THEORY/DATA COMPARISON FOR JET CROSS SECTION AT 13 TEV

arXiv:1711.02692

Ratio of **NLOJet++ prediction** to measurements **of Jet** double-diff. cross-sec vs **jet** p_T and y

PDF sets used**: CT14, HERAPDF 2.0, ABMP16**

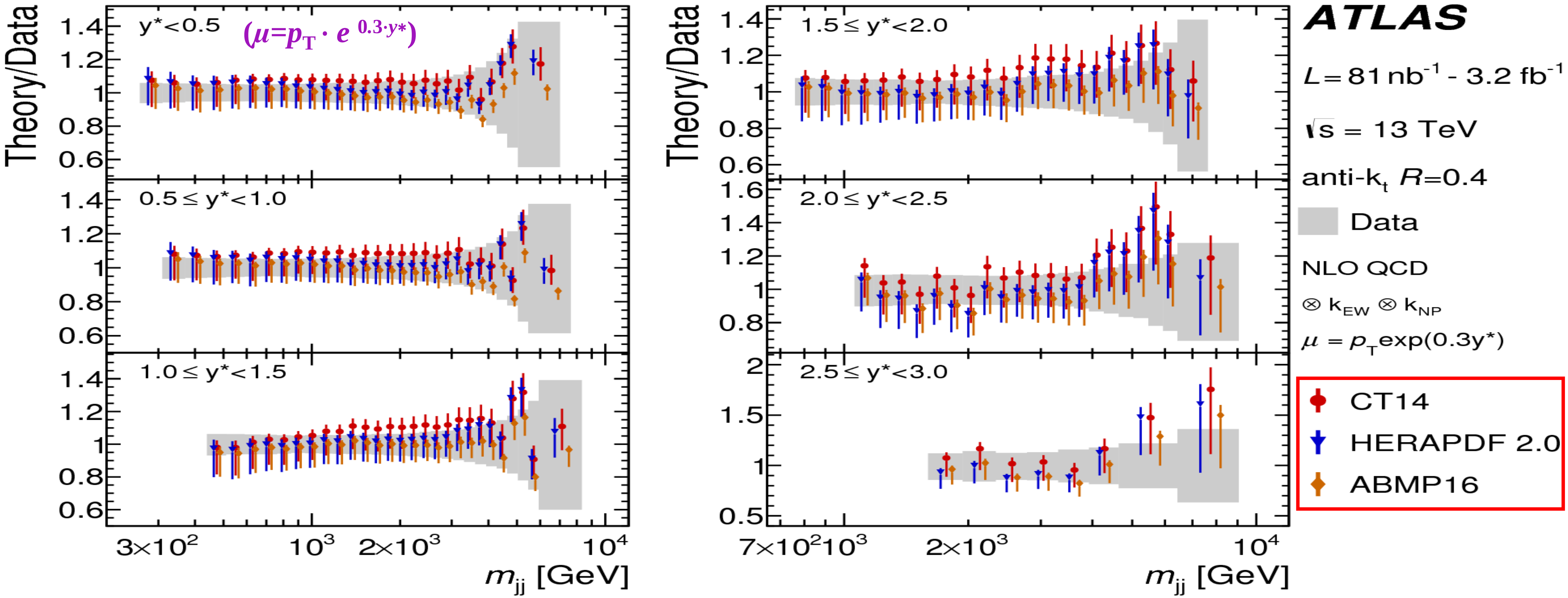


The **CT14** case is repeated to serve as a reference for comparison

THEORY/DATA COMPARISON FOR DIJET CROSS SECTION AT 13 TEV

arXiv:1711.02692

Ratio of **NLOJet++ prediction** to measurements **of Dijet** double-diff. cross-sec vs **dijet** mass and y* PDF sets used**: CT14, HERAPDF2.0, ABMP16**

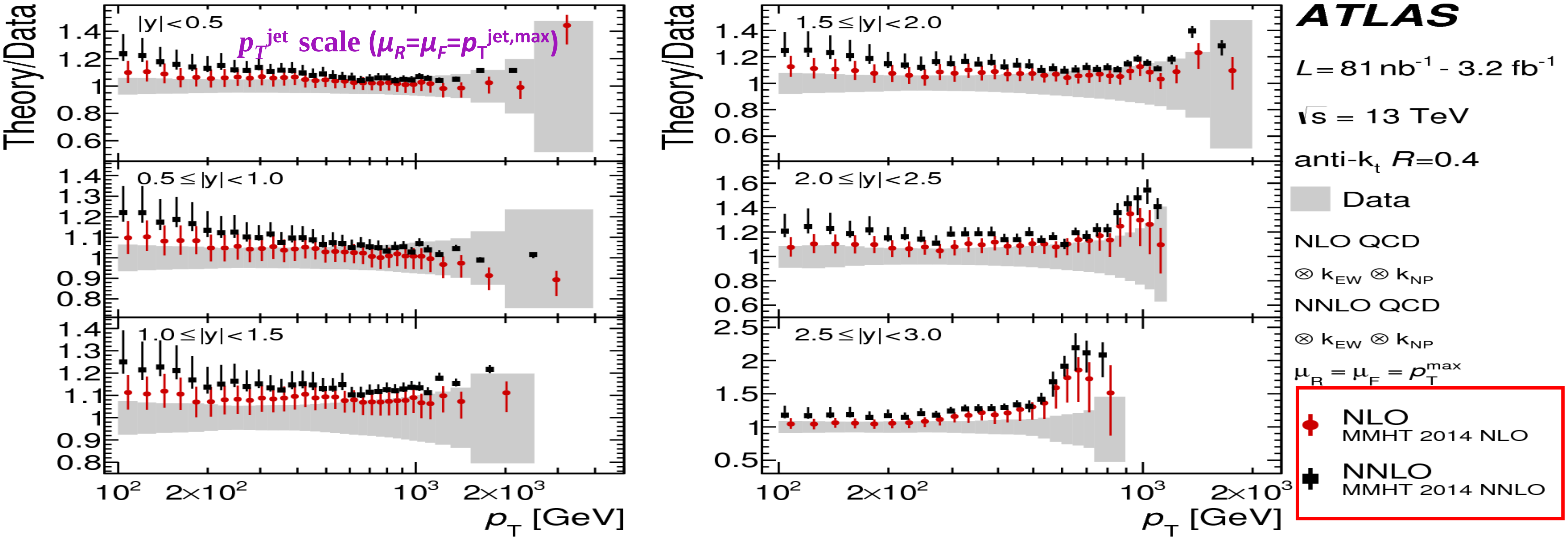


The **CT14** case is repeated to serve as a reference for comparison

RATIOS NLO OR NNLO PQCD/DATA FOR PP → JET + X AT 13 TEV

arXiv:1711.02692

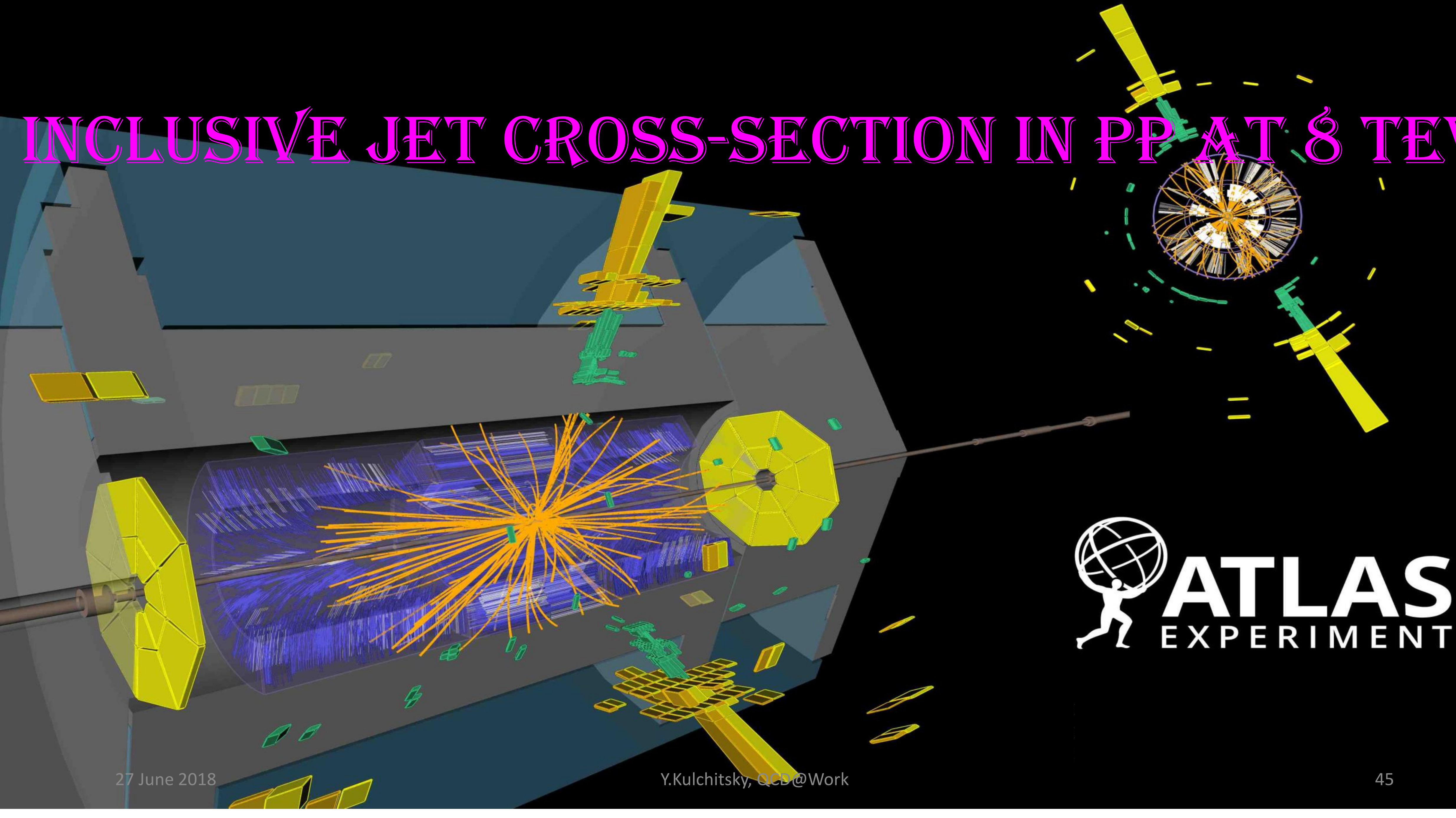
Ratio of **NLOJet++ (p_T^{max} QCD scale) prediction** to measurements **of Jet** double-diff. cross-sec vs **p_T ^{jet} and y:** PDF sets used**: MMHT 2014 NLO, MMHT 2014 NNLO**



- **NLO pQCD** describes the measurements within uncertainties
- Toward higher p_T **NLO pQCD** closer to data
- p_T>**300** GeV and high *y* rise of **NLO pQCD** with respect to data **(>20%)**
- **NNLO** above measurements for p_T**<500 GeV**

The differences between data and the theoretical predictions at NNLO are larger than at NLO for the p_T^{max} scale choice

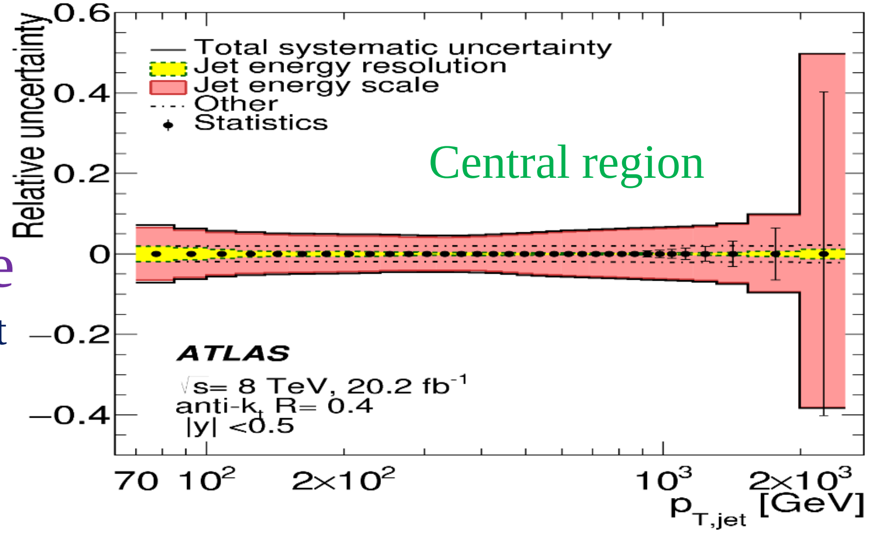
Inclusive jet cross-section in pp at 8 TeV

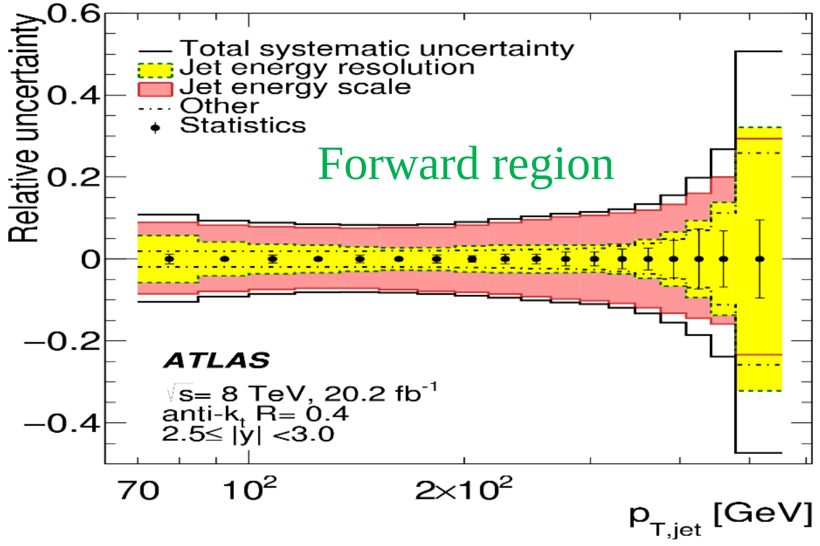


Event & Jet selection for pp → jet + X at 8 TeV

JHEP 09 (2017) 020

- L_{int}=20.2 fb^{-1}
- Pile-up: <μ> increases from **<μ>~10 to <μ>~36**
- 3-level jet trigger: events with p_T^{jet} over a threshold, $|\eta|<3.2$
- Offline data selection and Jet correction: similar to Dijet case
- Cross-sections are measured for **6 rapidities** as function p_T^{jet}
- Data are unfolded to the particle level in a 3-step procedure:
  - correction for the sample impurities;
  - unfolding for the p_T migration;
  - correction for the analysis inefficiencies





- Sources of systematic uncertainty: those associated with jet reconstruction and calibration, unfolding procedure, and luminosity measurement
- Main sources: Jet Energy Scale (JES) & Jet Energy Resolution (JER) For $|y|<0.5$ & $p_T^{jet}<1$ TeV less than 10%

Relative systematic uncertainty

UNCERTAINTY FOR $pp \rightarrow$ JET + X AT 8 TEV

JHEP 09 (2017) 020

ATLAS EXPERIMENT

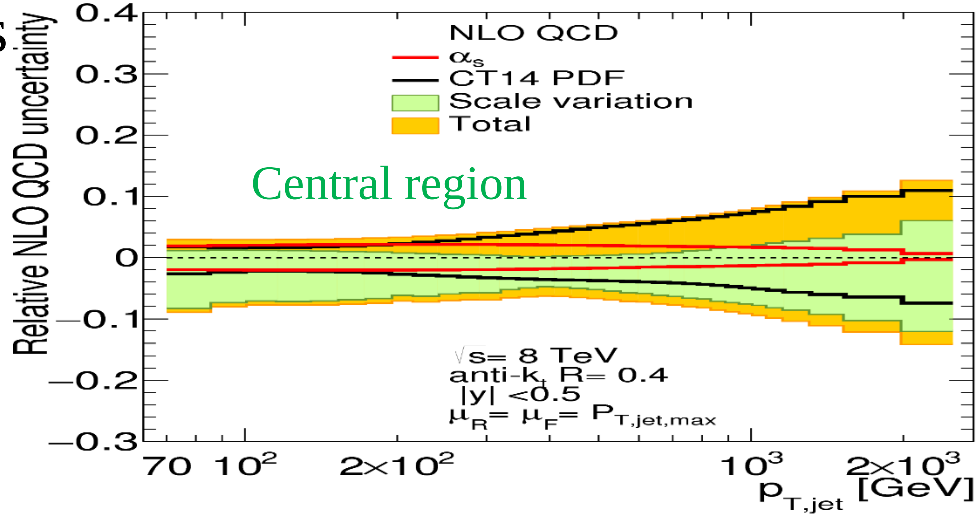
The double-diff. inclusive jet cross-section measurement vs p_T-jet &y: kinematic region: **70 GeV≤p_T^{jet}≤2.5 TeV& |y|<3**

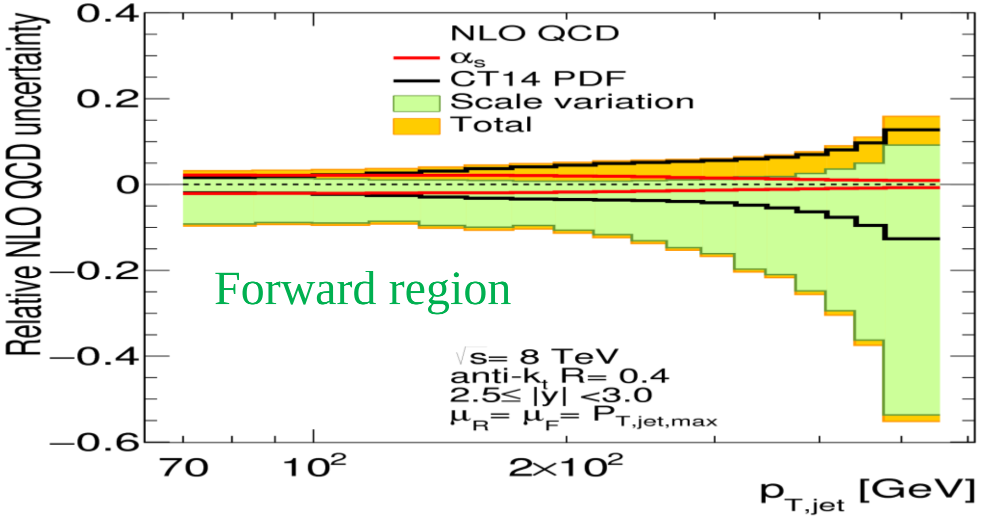
- **Motivation**: a test of validity of pQCD and probing of the parton distribution functions (PDFs) in the proton

- Jets are identified with the **anti-k_t** using the jet radius, ***R*=0.4 & *R* = 0.6**

- Jet cross section refers to particle-level jets and to compare them with NLO pQCD predictions with parton-level jets, a correction for non-perturbative and electroweek effects is done.

- **Theoretical predictions**: NLO pQCD calculated by **NLOJET++ 4.1.3** with several PDFs and different renormalisation and factorisation scales $\mu_R=\mu_F=p_T^{jet;max}$ to cover missing higher order corrections.





Uncertainty in the NLO pQCD prediction of inclusive jet X-sec vs jet p_T – potential of jet physics for improving PDFs

INCLUSIVE JET CROSS-SECTION FOR: PP → JET + X AT 8 TEV

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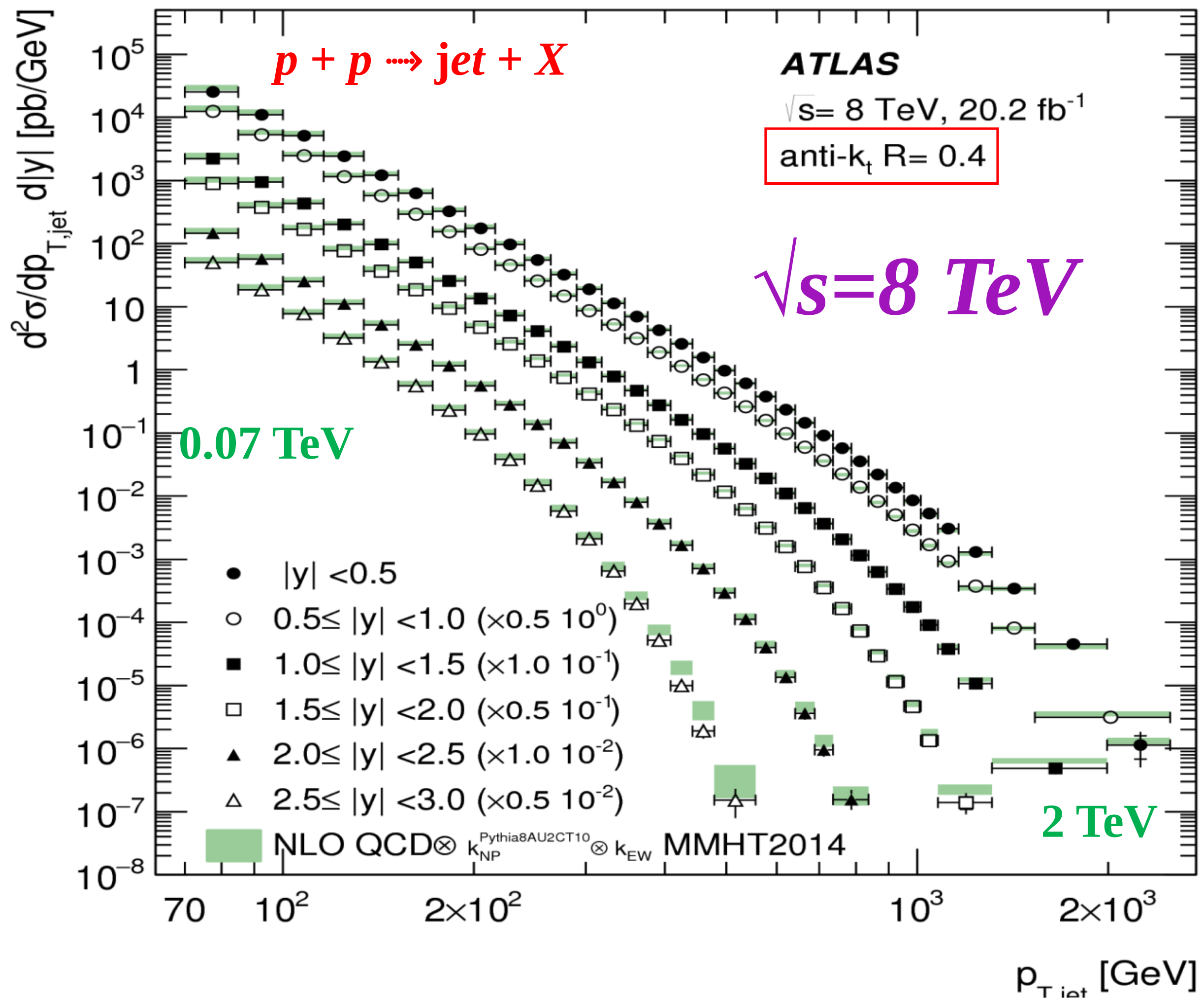
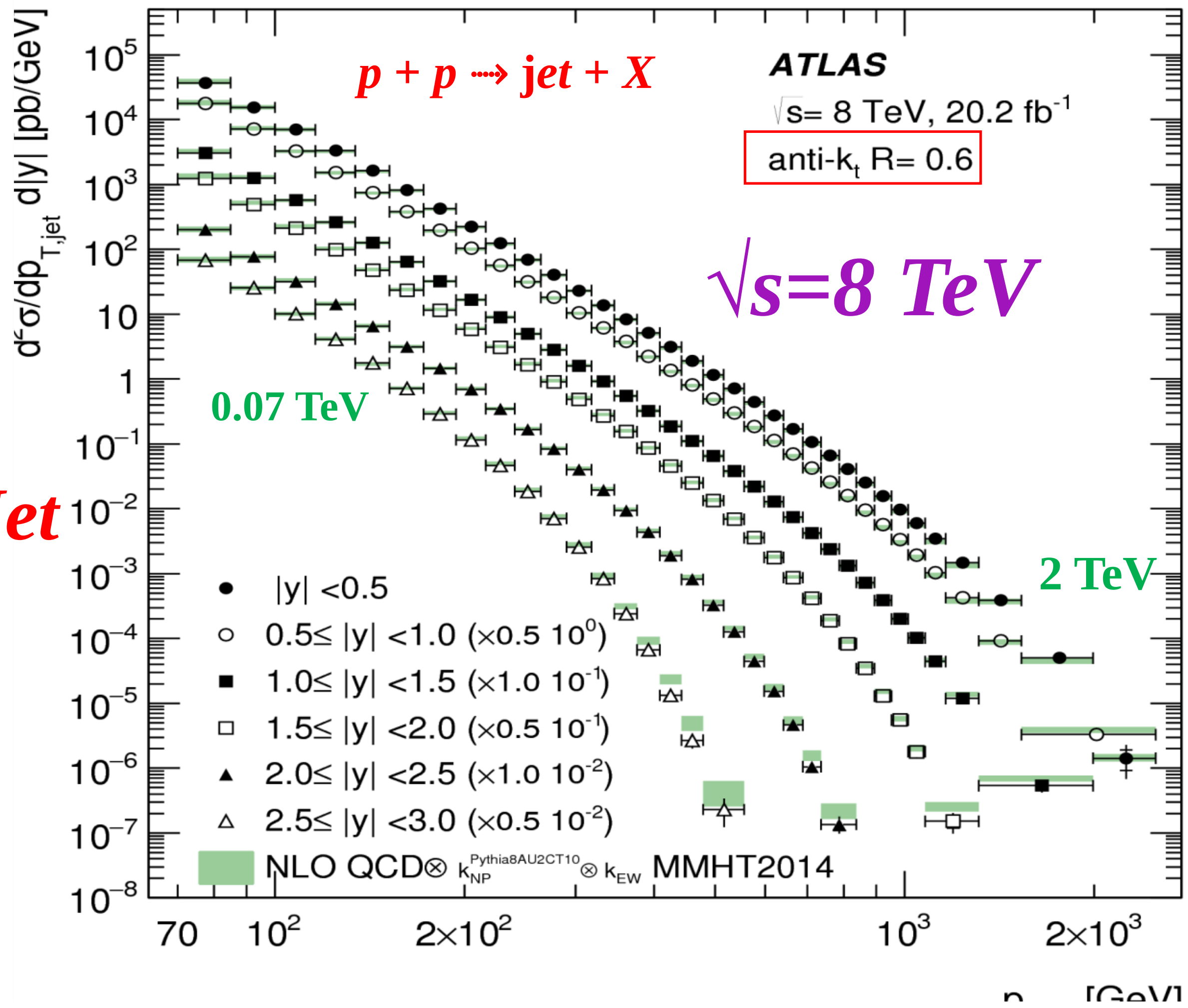
Double-differential ***inclusive Jet*** cross-sections for ***Jets*** with ***R=0.4*** & ***0.6*** vs. ***p_T^{jet} & |y|***

data vs NLO pQCD prediction corrected for non-perturbative and EW effects



Jet



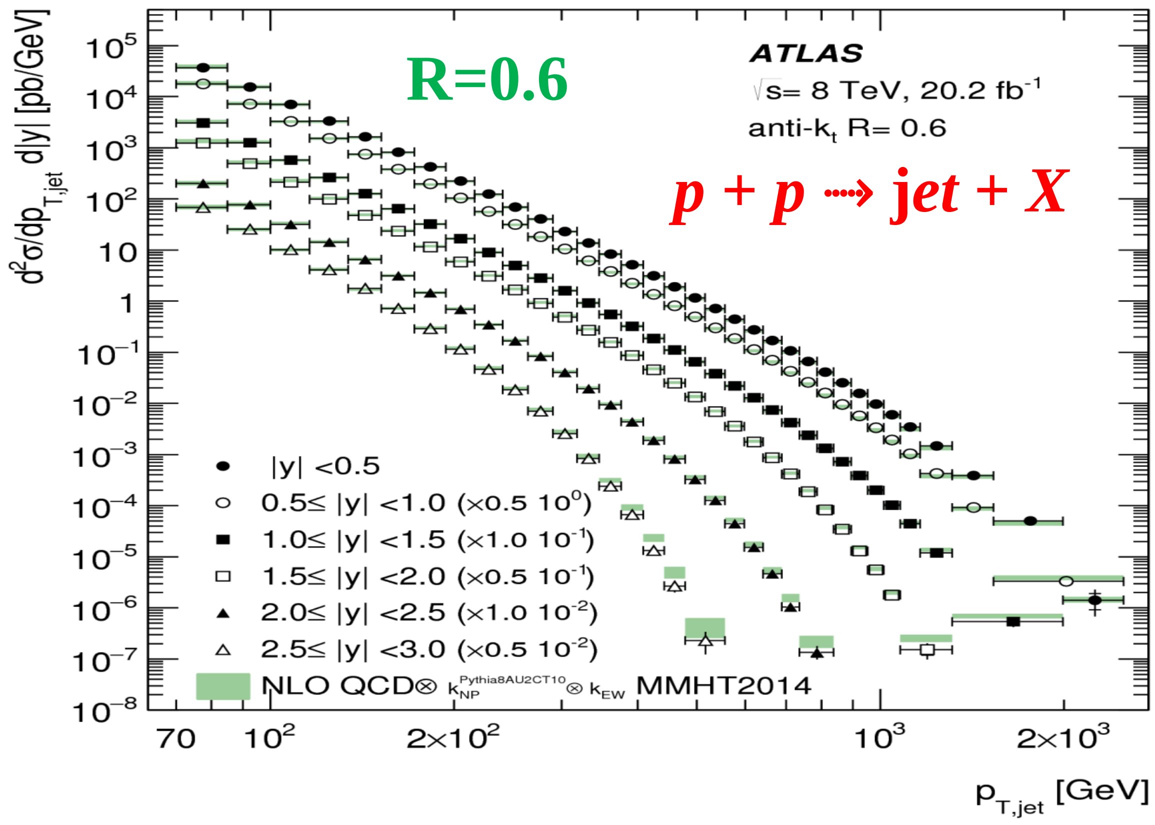
p_T^{jet} > 70 GeV; |y|<3; anti-k_T jets with R=0.4 and R=0.6

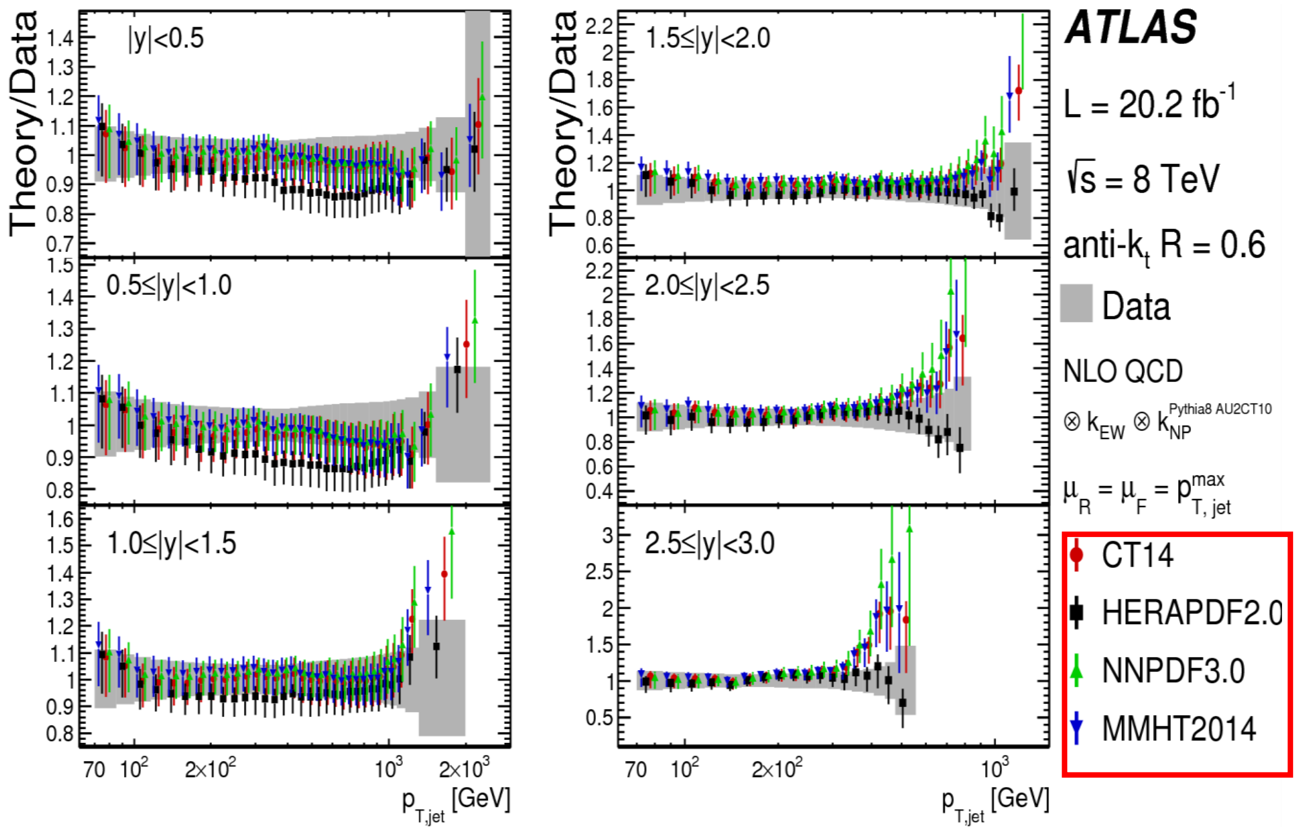
THEORY/DATA COMPARISON FOR PP → JET + X AT 8 TEV

JHEP 09 (2017) 020

Double-differential ***inclusive Jet*** cross-sections for jets with **R=0.6** vs. ***jet p_T*** and ***rapidities***

data vs. **NLO pQCD** prediction corrected for non-perturbative and EW effects





Ratio of **NLO pQCD** predictions to measured double-diff. inclusive **Jet** cross-section vs jet p_T and jet rapidity: different **NLO PDF** sets used **CT14, HEPARDf2.0, NNPDF3.0, MMHT2014**

RATIO NLO QCD FOR $pp \to$ JET + X AT 8 TEV

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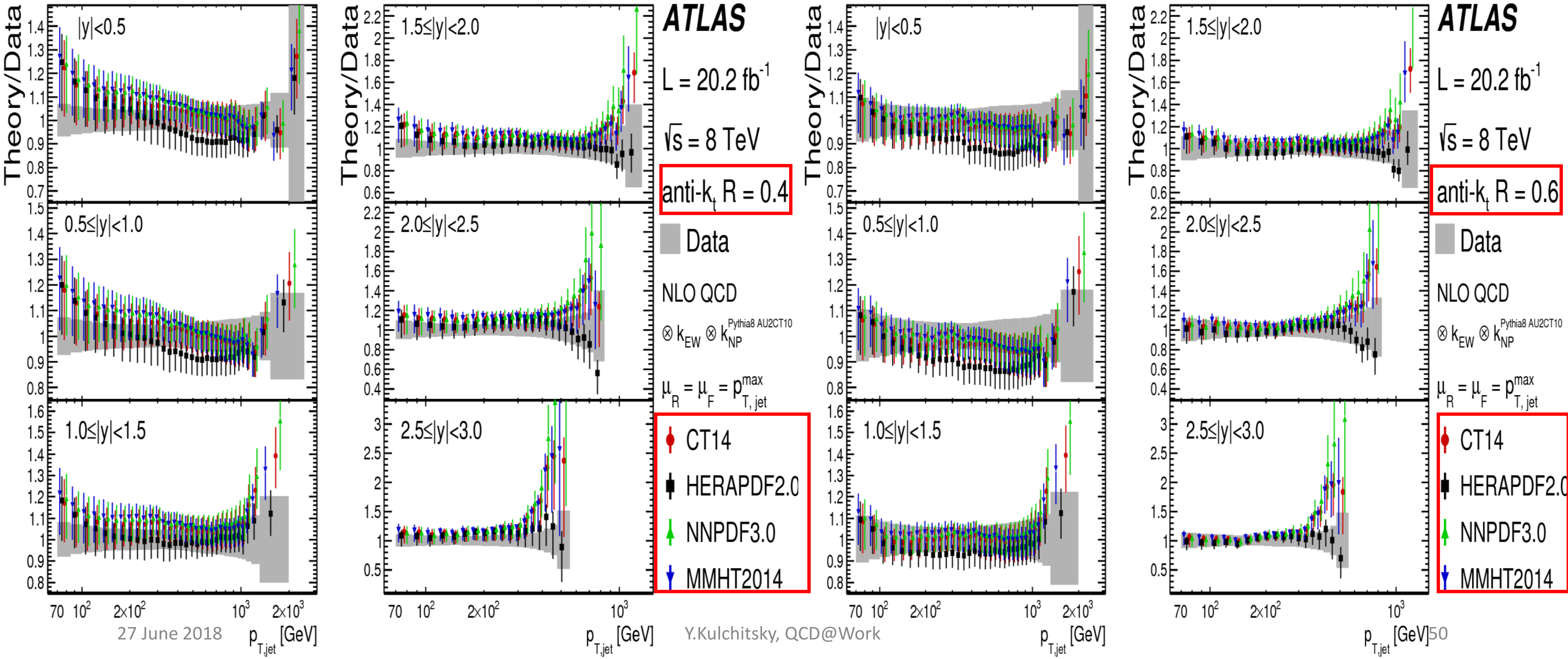
Ratio of **NLO pQCD** predictions to measured double-diff. inclusive jet X-section vs jet p_T and jet rapidity – different **NLO PDF** sets used: **CT14, HERAPDF2.0, NNPDF3.0, MMHT2014**

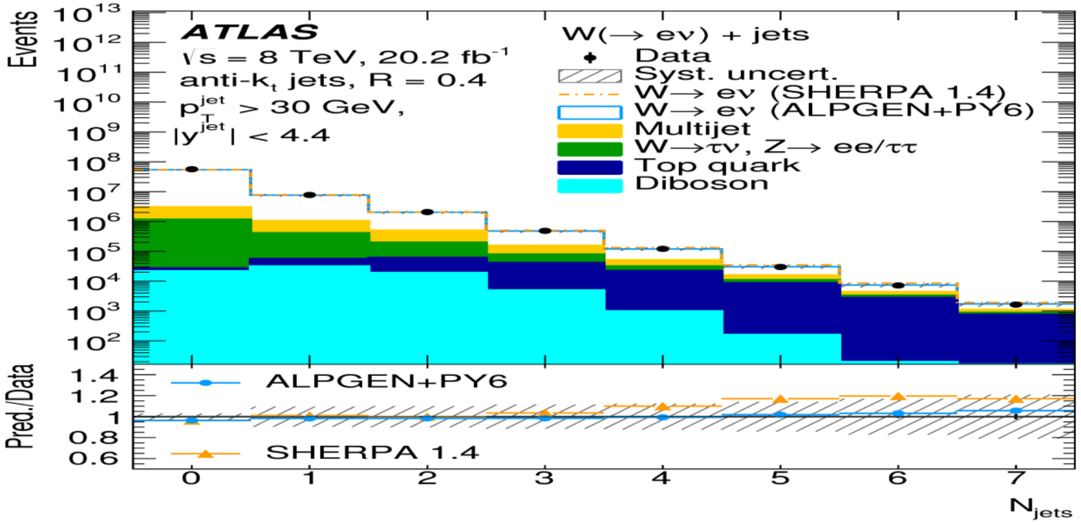


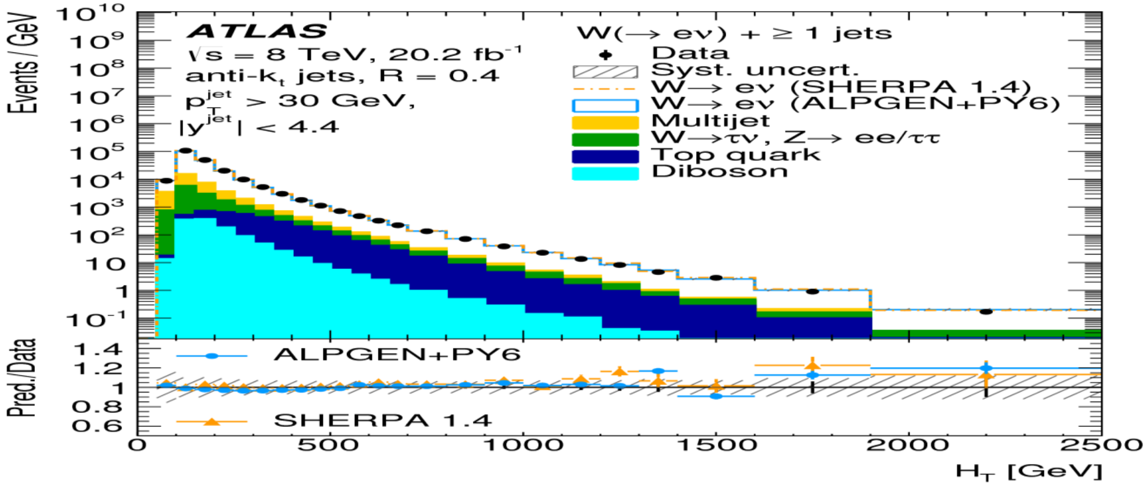
Cross-sections of pp → W + jets, W⁺/W⁻ ratios at 8 TeV

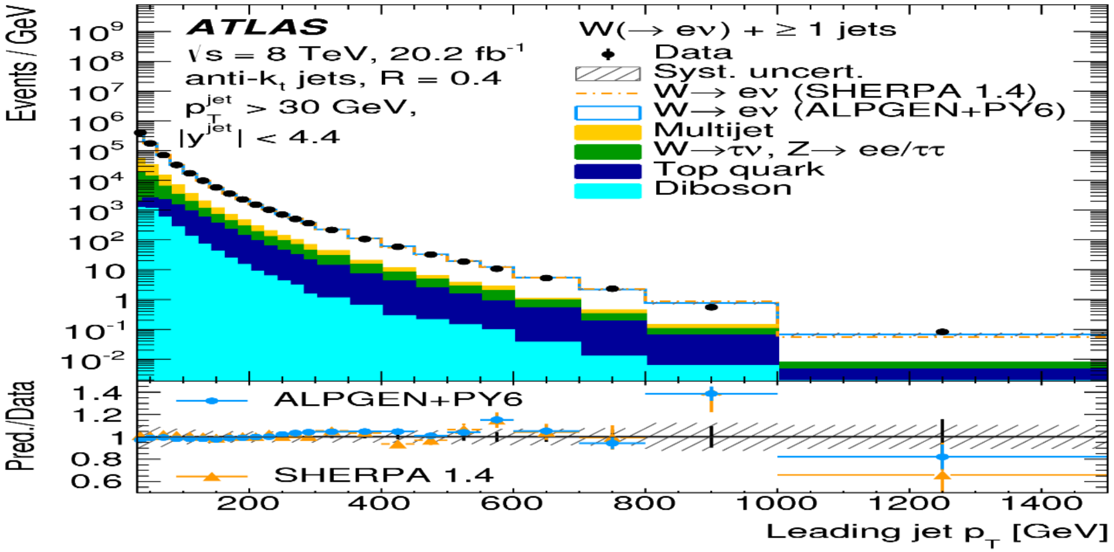
arXiv:1711.03296

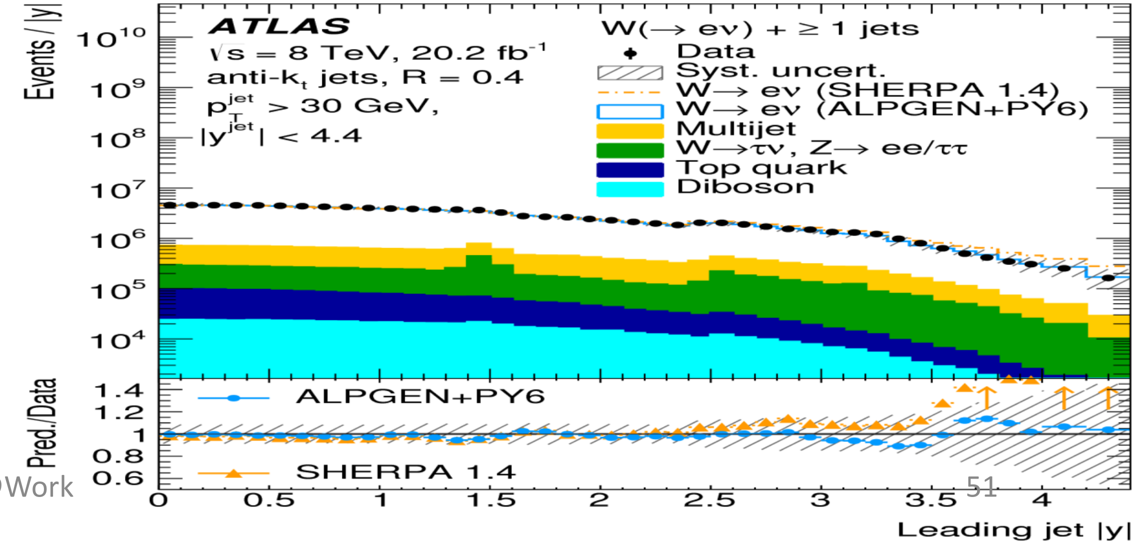
ATLAS EXPERIMENT

- W(→eν) production in association with jets
  - Include forward jets: |y| < 4.4
- **Challenge – Backgrounds** → Multijet: Dominant at low N_{jets}
  - Suppress by electron isolation & low momentum contributions to E_T^{miss} from tracks, not calorimeter deposits





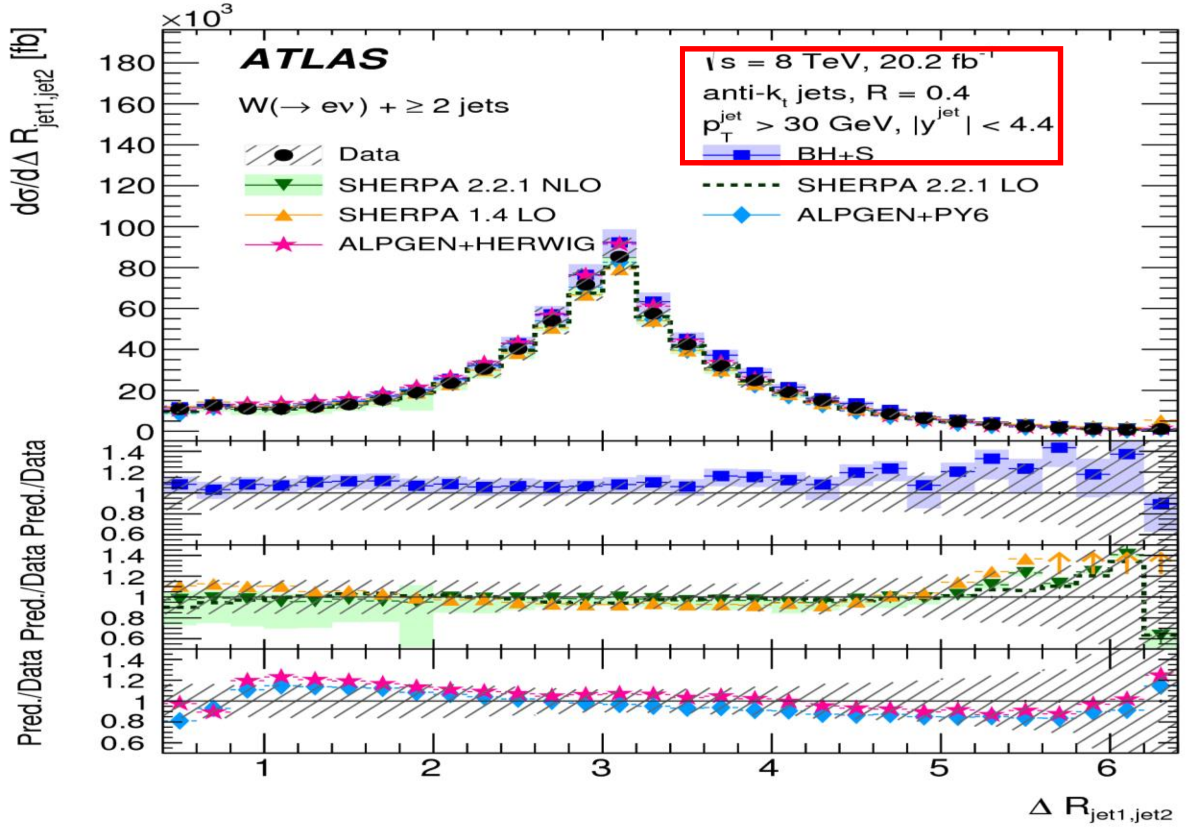


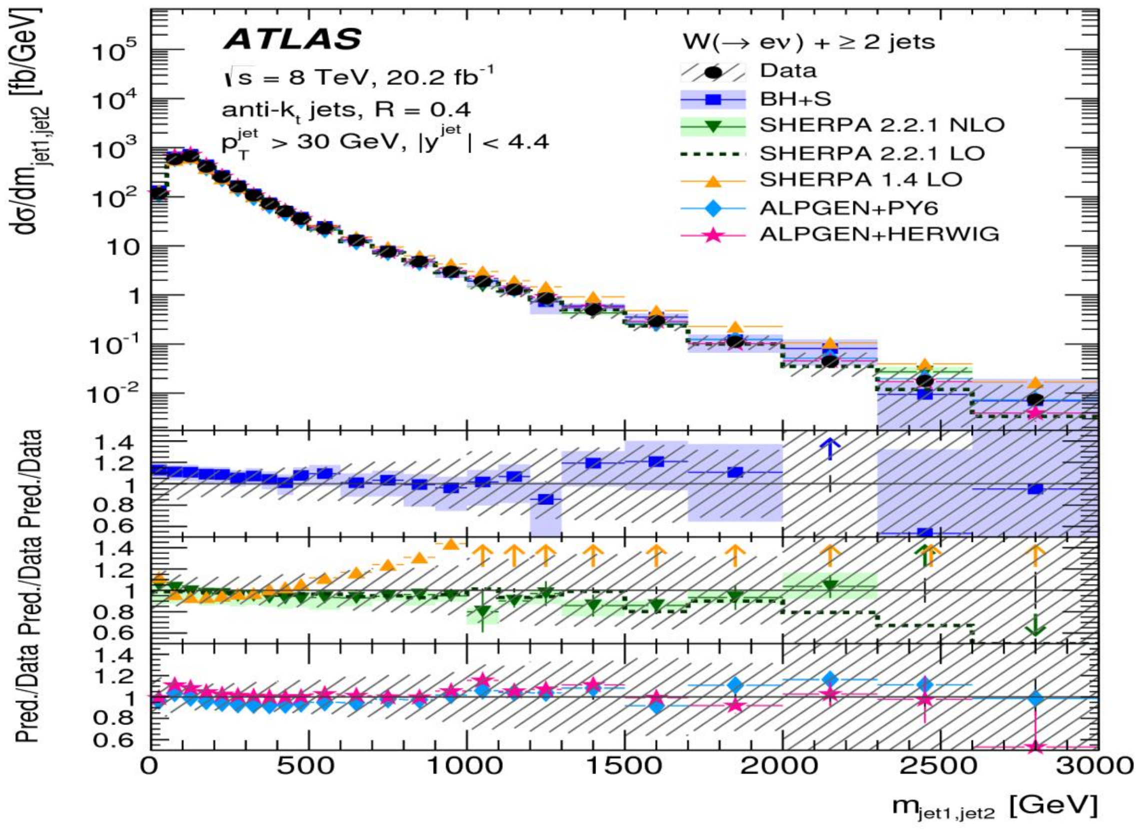


CROSS-SECTIONS OF pp → W + JETS, W^+/W^- RATIOS AT 8 TEV

arXiv:1711.03296

- $\Delta R_{jet1,jet2}$ and $M_{jet1,jet2}$ (*Dijet invariant mass*) sensitive to **hard parton radiation** at large angles and different ME/PS matching schemes
- **Sherpa 1.4** predicts too many events at large $\Delta R_{jet1,jet2}$ and $M_{jet1,jet2}$
- Both **Alpgen+Herwig** and **Alpgen+Py6** do not describe $\Delta R_{jet1,jet2}$ well



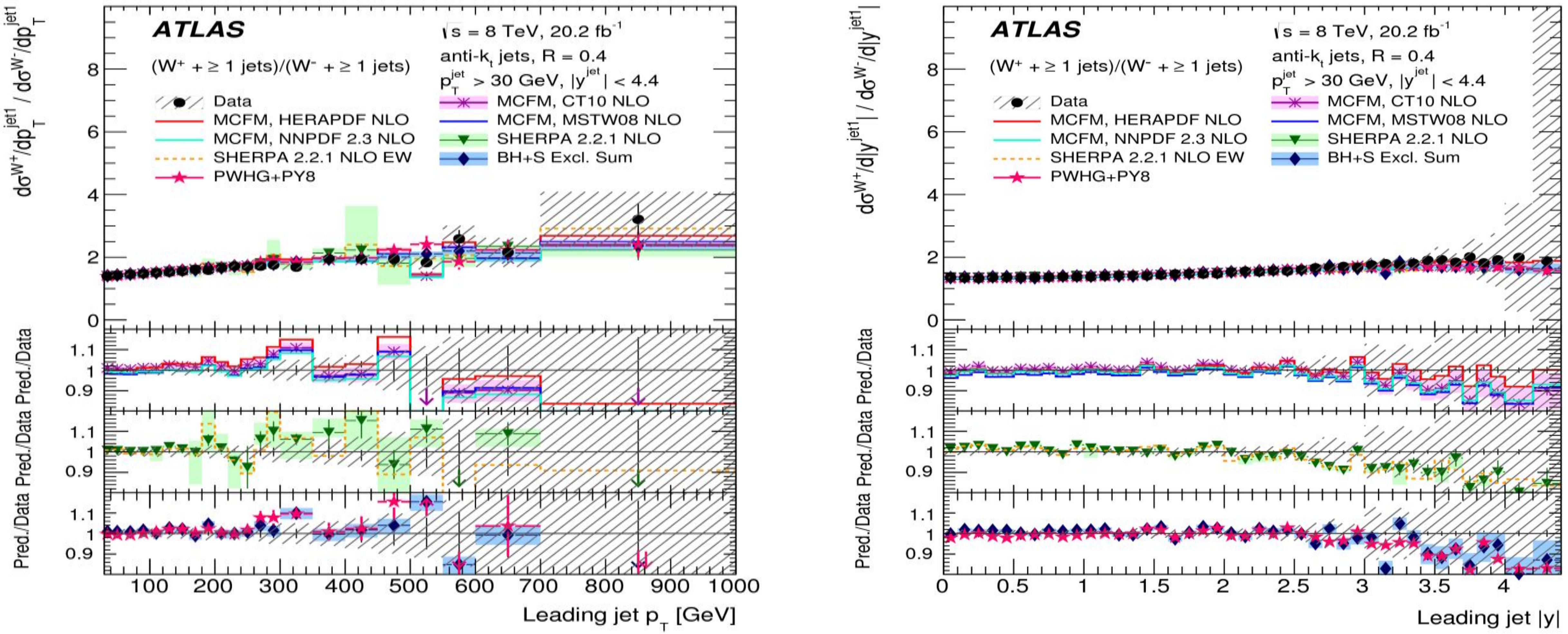


However, there is no single prediction that is able to describe all distributions well

Cross-sections of pp → W + jets, W⁺/W⁻ ratios at 8 TeV

arXiv:1711.03296

- **MCFM** predictions differ by **~2−5 %** depending on the PDF set used
- Differences between data and **MCFM** predictions above experimental uncertainties for W boson **p_T~200−400 GeV** → results useful for PDF fits



CROSS-SECTIONS OF $pp \rightarrow W$ + JETS, W^+/W^- RATIOS AT 8 TEV

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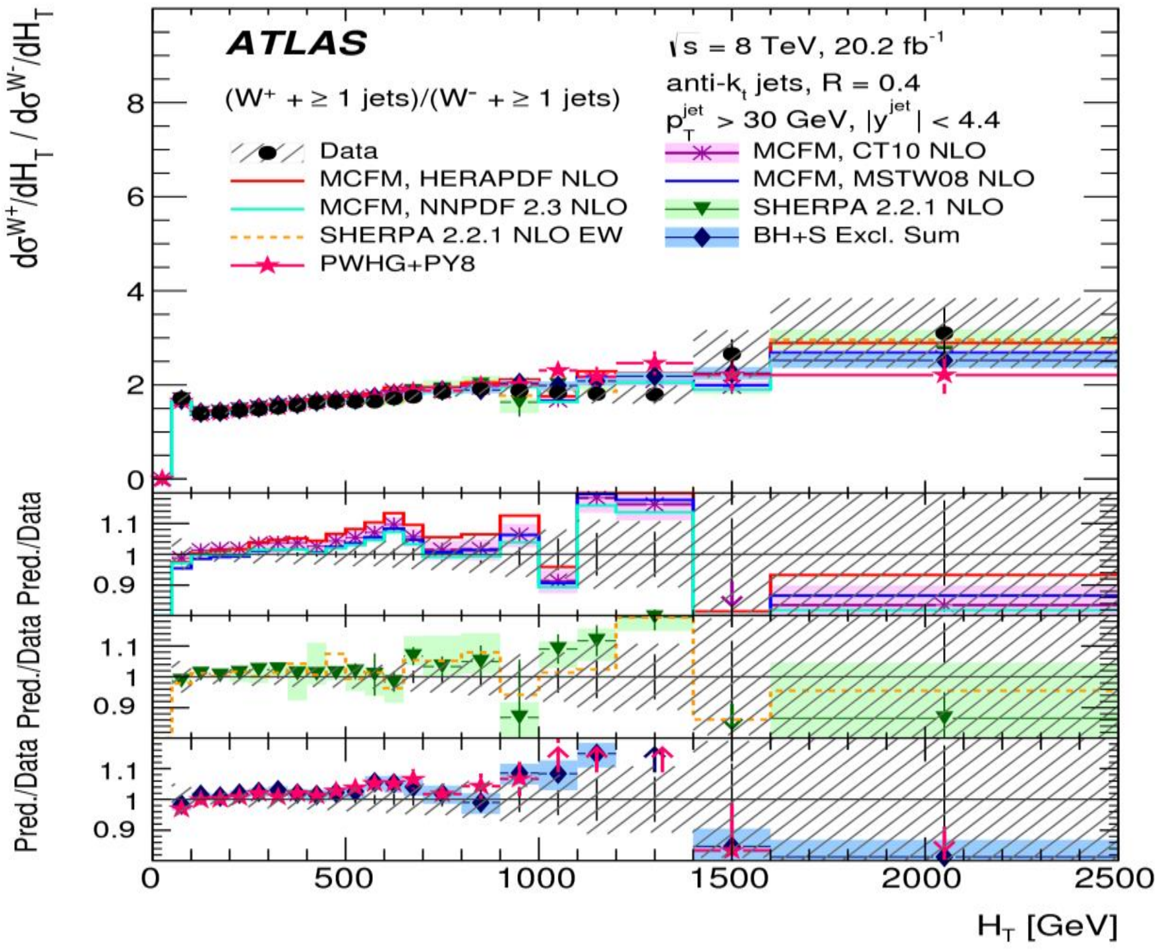

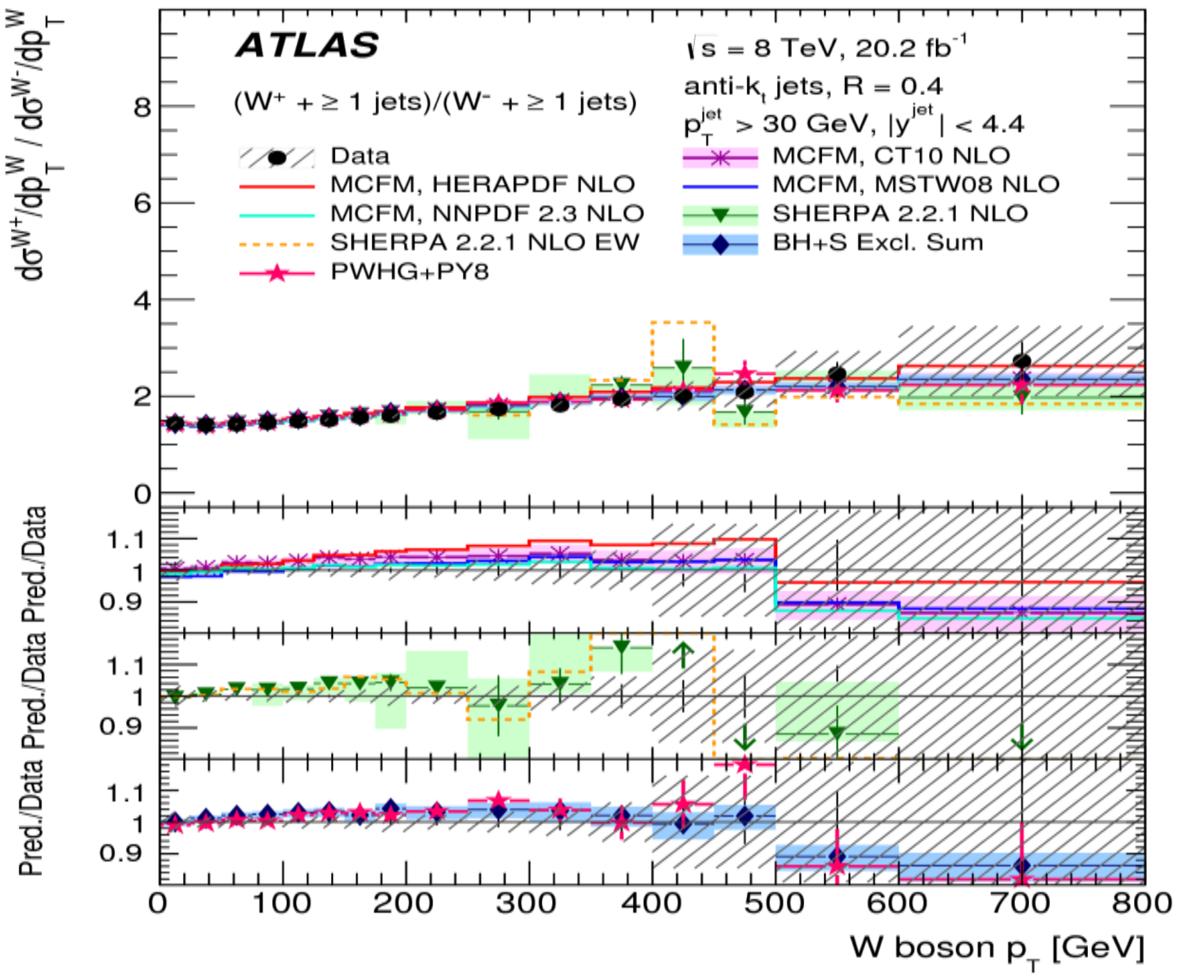

SOFT-DROP JET MASS IN $pp \to$ JET + X AT 13 TEV

arXiv:1711.08341

ATLAS EXPERIMENT

Event Selection

- $p_T^{lead} > 0.6$ *TeV*, to be fully efficient for the lowest unprescaled trigger
- Apply ***Dijet*** selection: $p_T^{lead} < 1.5 * p_T^{sublead}$
- Measure as a function of $\rho = \log_{10}\left[\left(\frac{m^{softdrop}}{p_T^{ungroomed}}\right)^2\right]$; ρ depends logarithmically on p_T, so final result are binned inclusively in p_T; Soft drop jet mass: $(m^{softdrop})^2 = (\Sigma E)^2 - (\Sigma p)^2$
- Simultaneously unfold in p_T and ρ and normalize each p_T bin between -3 & -1 in ρ

Uncertainties

Cluster Energy Scale Shift: Data/MC difference in the E/p ratio used to determine a shift for clusters

Cluster Energy Scale Smearing: Data/MC difference in E/p ratio used to determine a smearing in the energy scale of clusters

Cluster Angular Resolution:

- Use the distribution of **ΔR** (track, cluster) to determine an angular smearing of cluster of **5 mrad**;
- Dominated by modeling uncertainties at low mass, with cluster energy scale uncertainties also very important at moderate and high mass