Probing QCD at High Energy,

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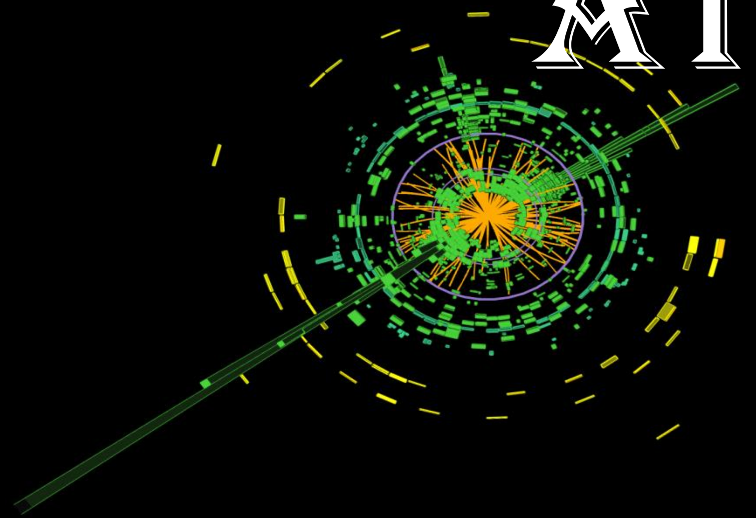
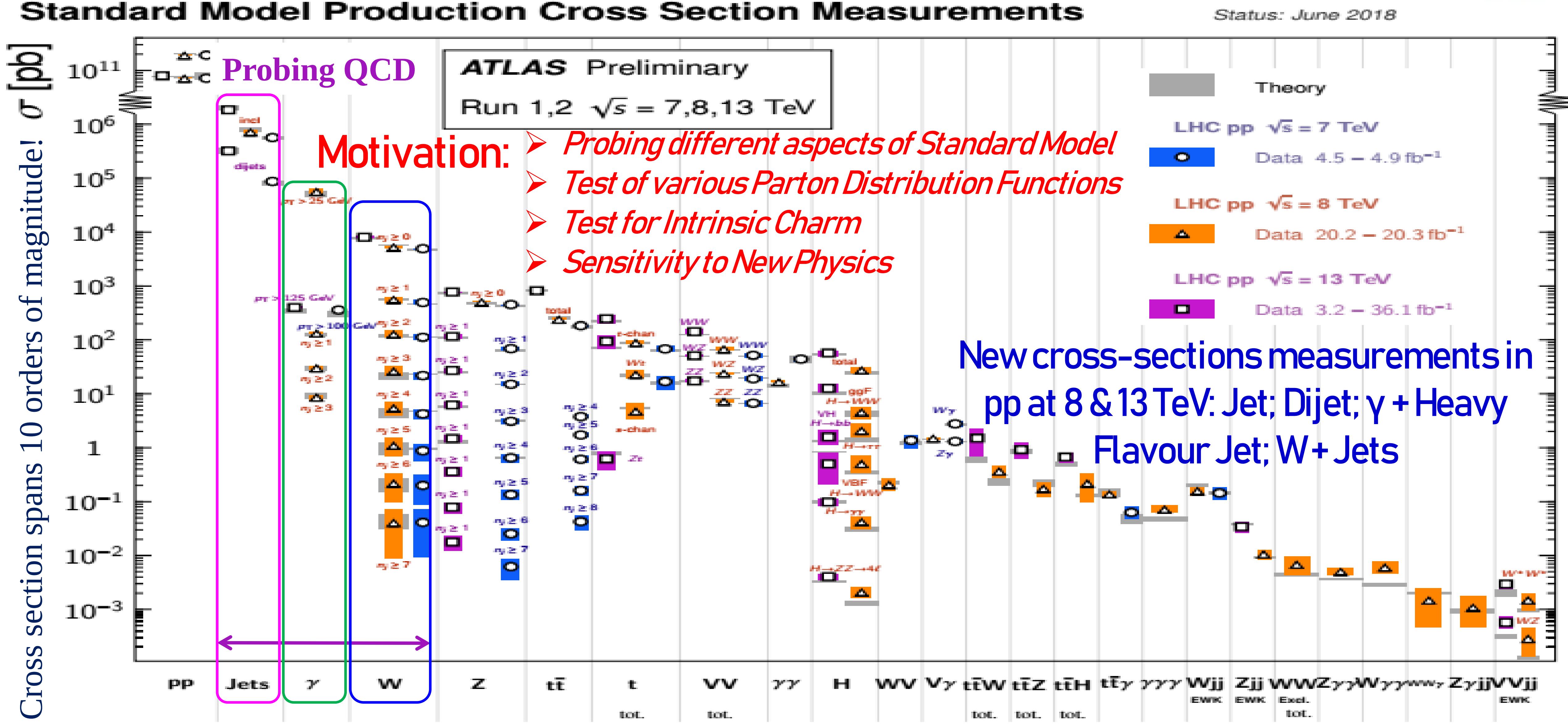
New Trends in High-Energy Physics,
Budva, Becici, Montenegro



STANDARD MODEL MEASUREMENTS

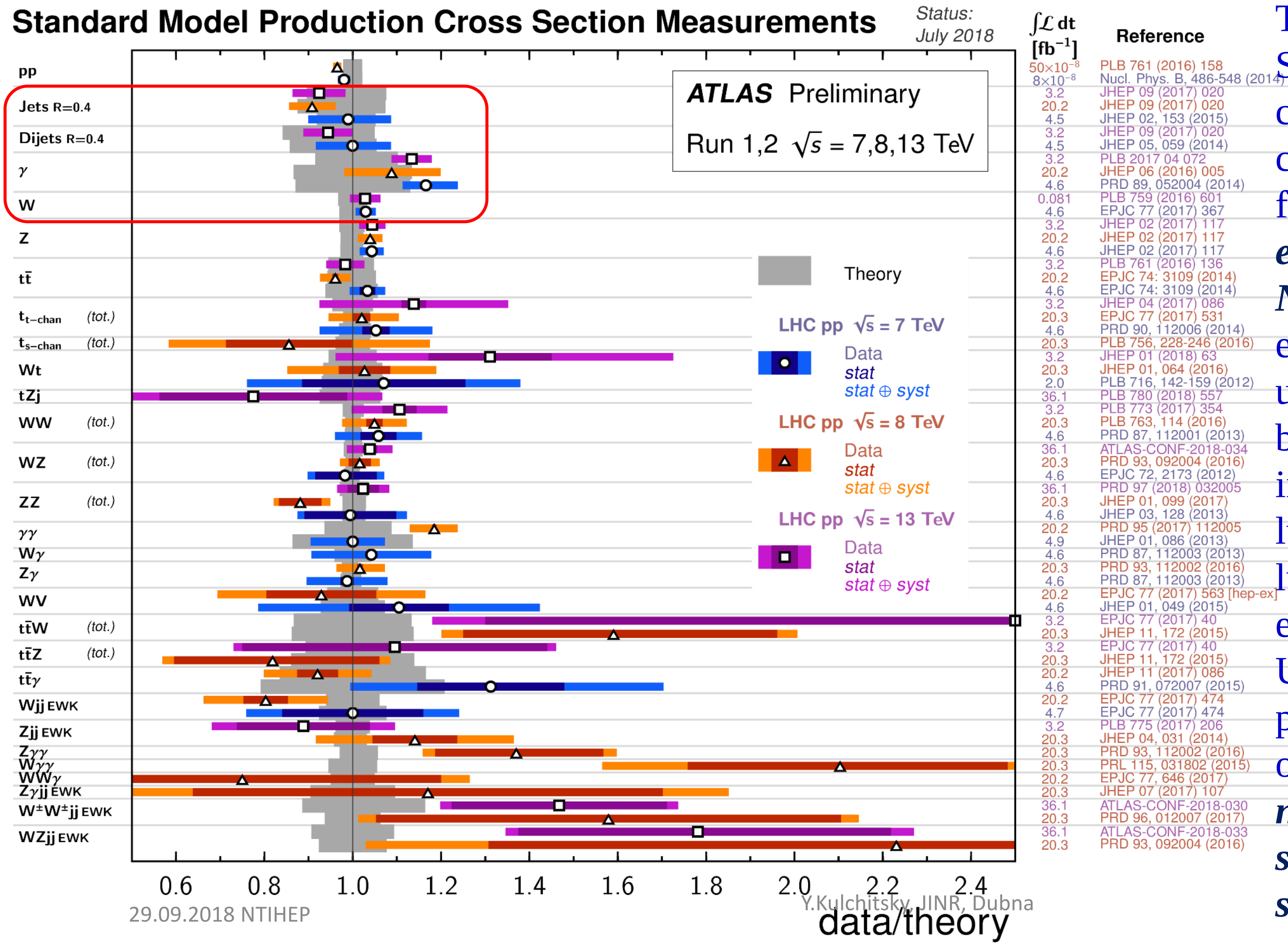


Motivation:

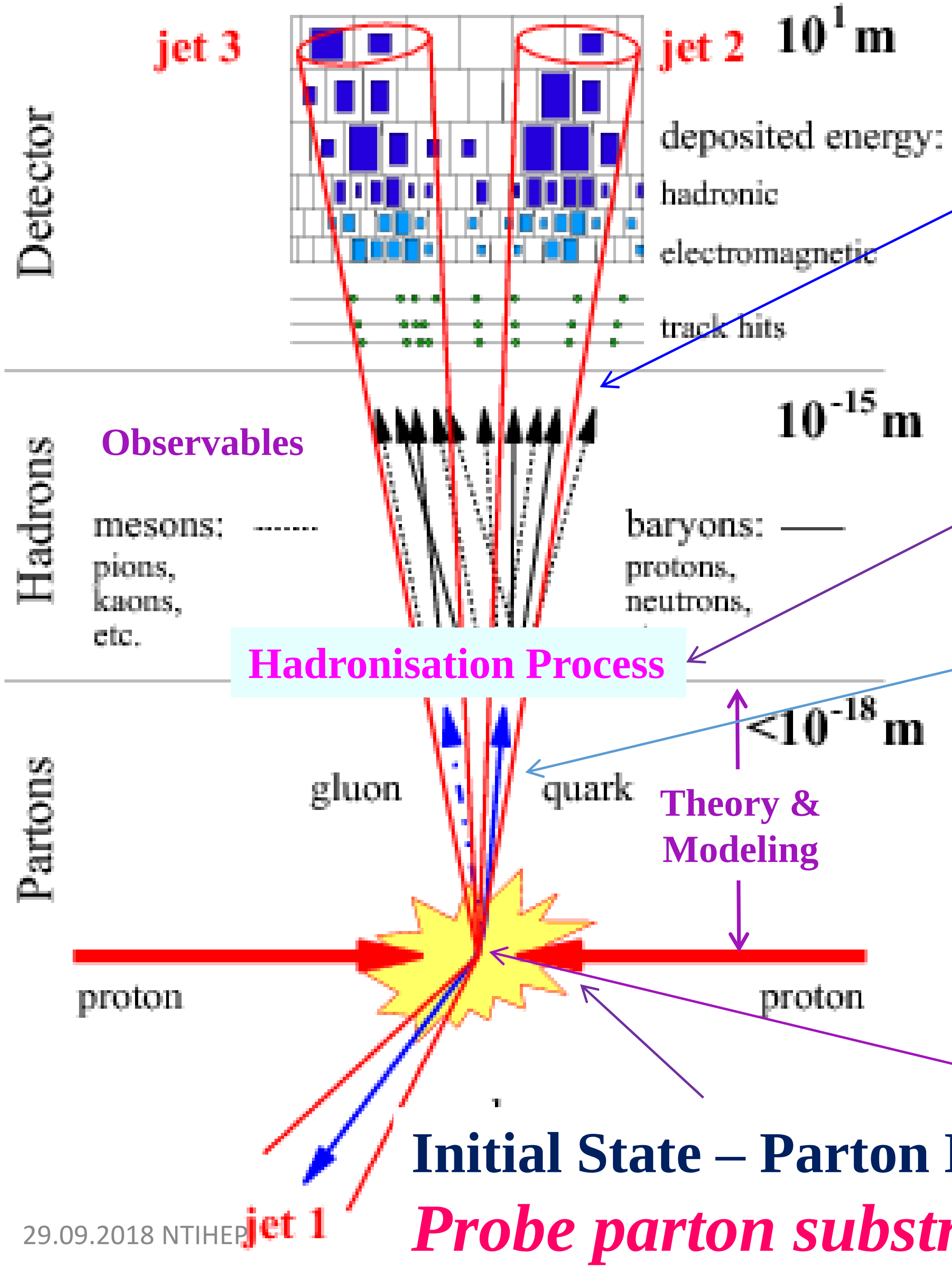
- *Probing different aspects of Standard Model*
- *Test of various Parton Distribution Functions*
- *Test for Intrinsic Charm*
- *Sensitivity to New Physics*

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

STANDARD MODEL X-SECTION MEASUREMENTS



The data/theory ratio for several SM total and fiducial production cross section measurements, corrected for leptonic branching fractions. ***All theoretical expectations were calculated at NLO or higher.*** The dark-color error bar represents the statistical uncertainly. The lighter-color error bar represents the full uncertainty, including systematics and luminosity uncertainties. The luminosity used and reference for each measurement are also shown. Uncertainties for the theoretical predictions are quoted from the original ATLAS papers. ***They were not always evaluated using the same prescriptions for PDFs and scales.***



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

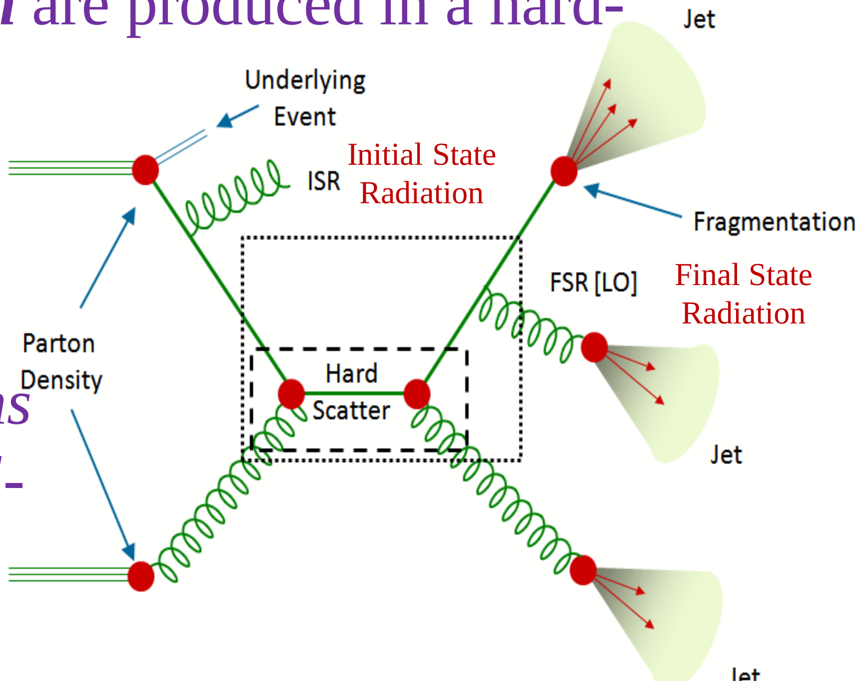
ATLAS EXPERIMENT

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):*
  - **Hadronization 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*

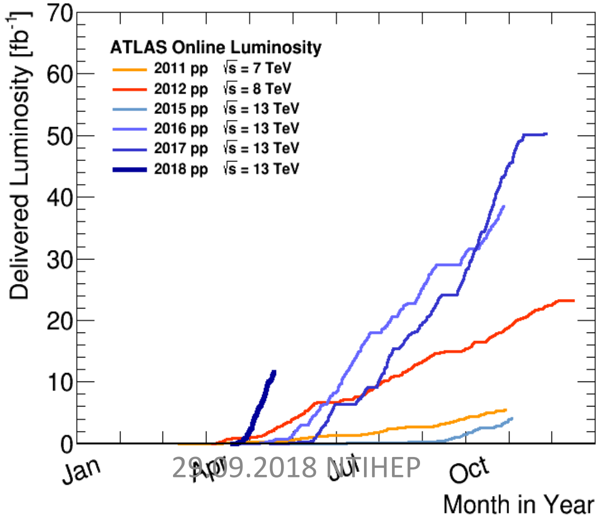


- *Effects of **HP** and **UE** depend on **Jet radius parameter** and are **most pronounced at low p_T***

❖ ***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) |η| >2.4

Trigger:

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

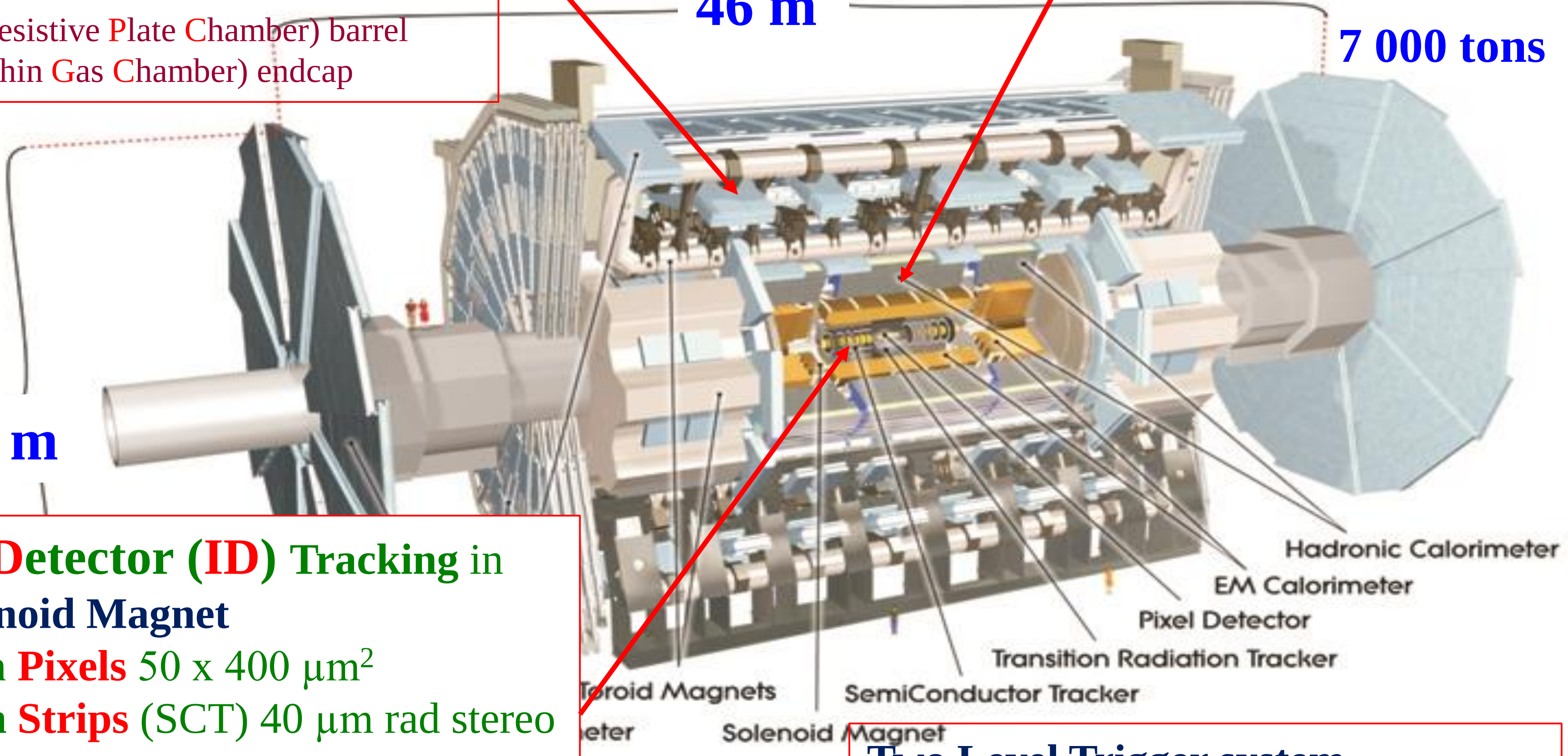
Longitudinally segmented Calorimeter: *EM and Hadronic energy*

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

46 m

7 000 tons

25 m



Inner Detector (ID) Tracking in 2T Solenoid Magnet

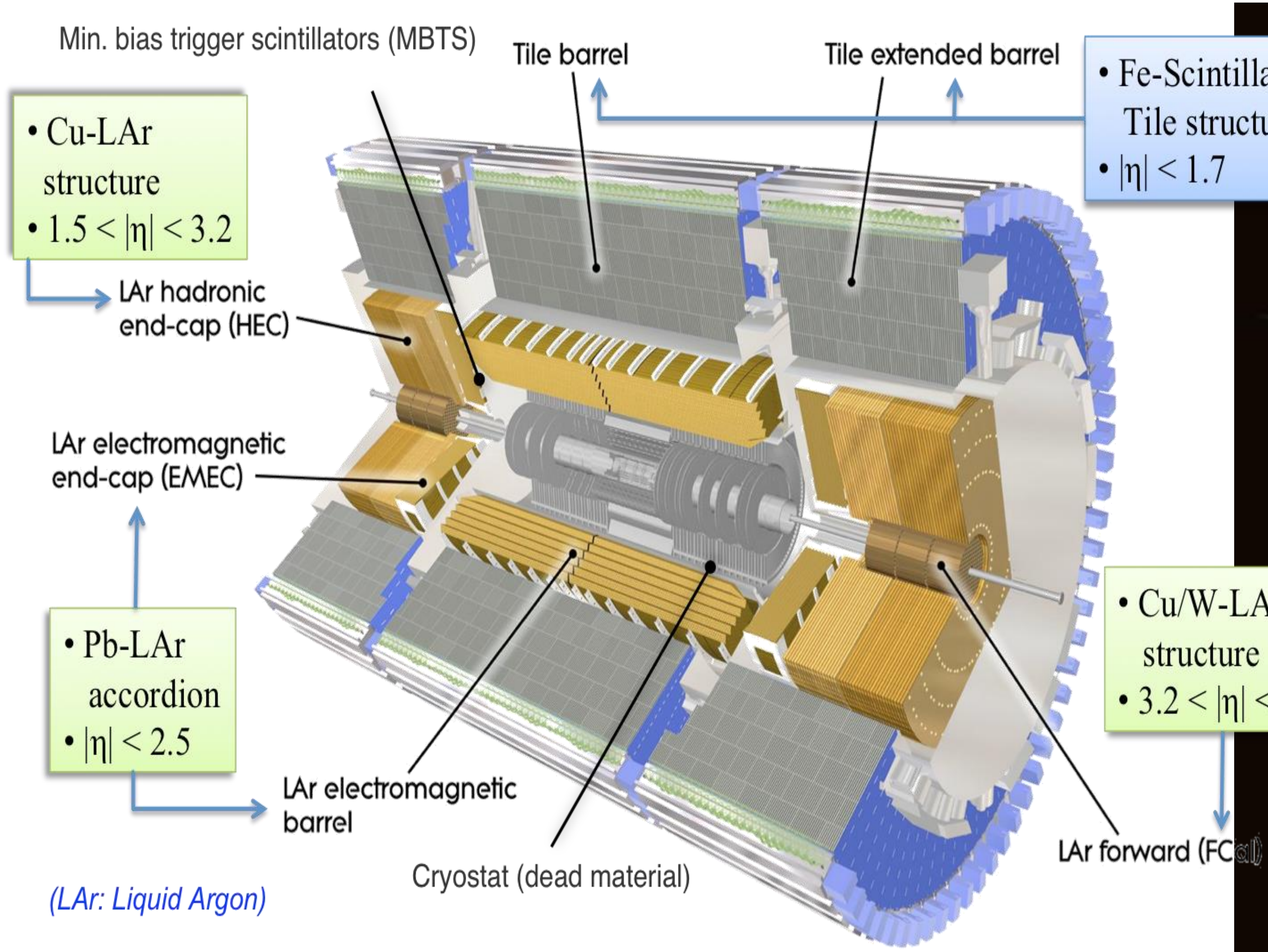
- **Silicon Pixels** 50 x 400 μm^2
- **Silicon Strips** (SCT) 40 μm rad stereo strips
- **Transition Radiation Tracker** (**TRT**) up to 36 points/track

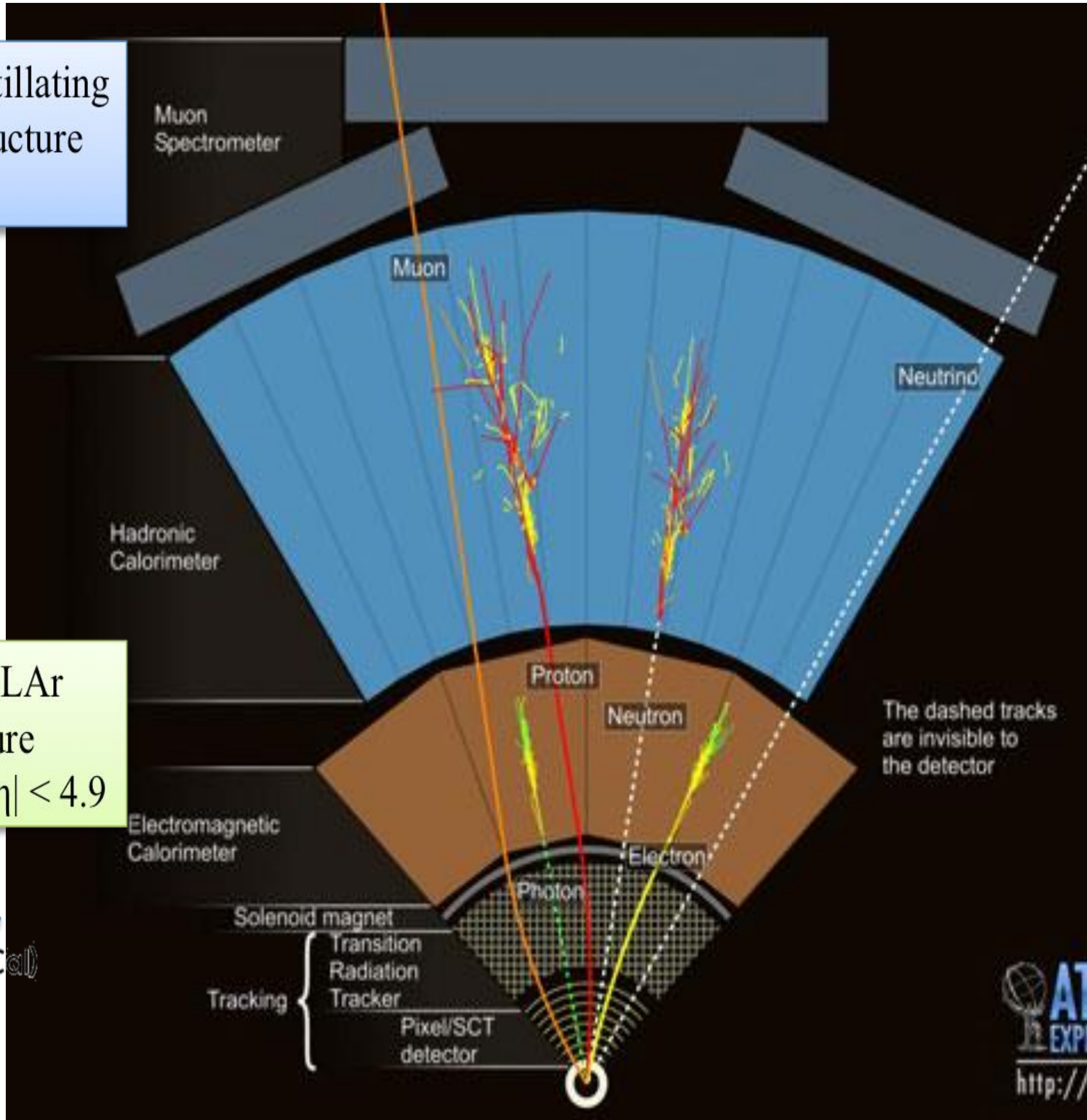
Two Level Trigger system

- **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

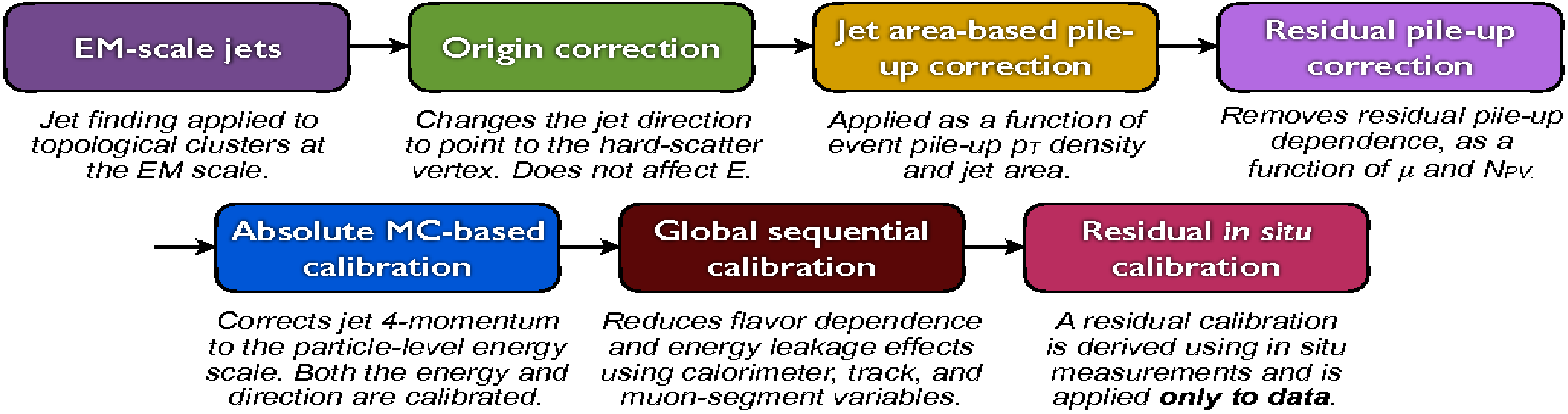
- **Lar & TileCal >> Very stable** performance
- **Improved stability** of new Tile power supplies
- **Good operation efficiency: ~100% for LAr & Tile**
- LAr using 4 sample readout to achieve 100 kHz





JET RECONSTRUCTION

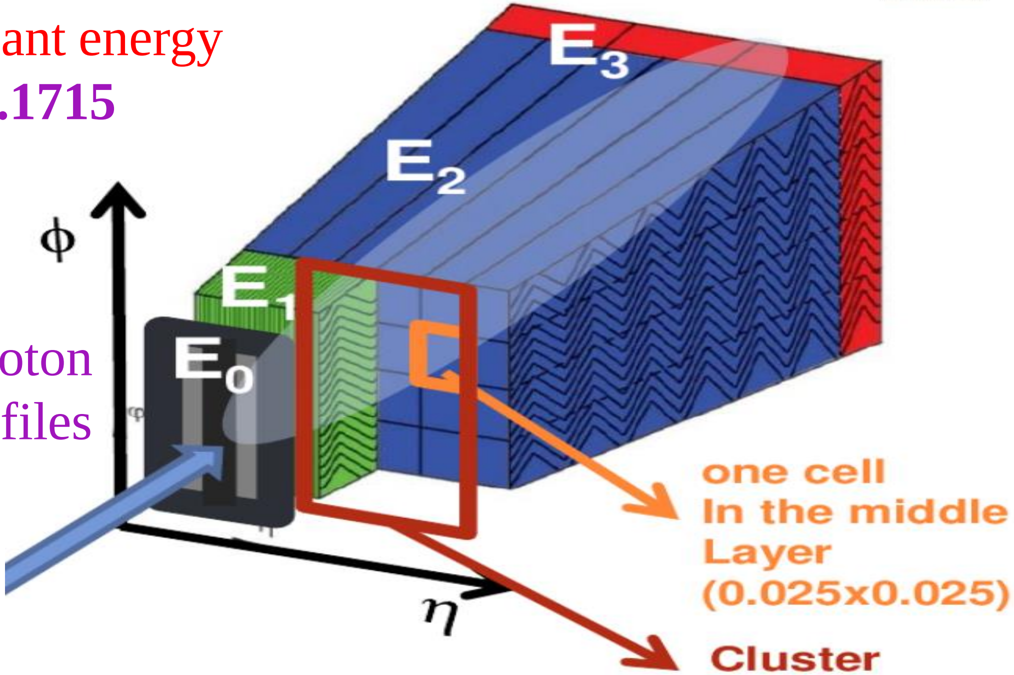
- A set of **Single-Jet Triggers** with different thresholds used to collect data
- Only events with **at least one Primary Vertex**, reconstructed ≥2 tracks with p_T>400 MeV
- Primary Vertex with the highest $\sum p_T{}^2$ of associated tracks is selected as the hard-scatter vertex
- Jets reconstructed 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***:

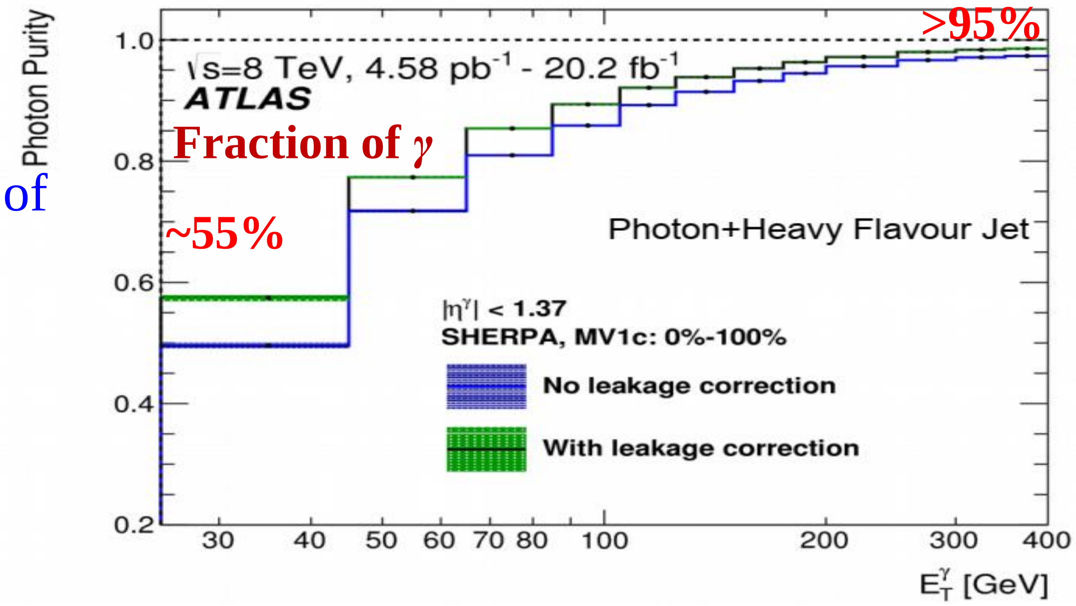


- **Jets corrected for experimental effects**: *resolutions, efficiency, …*
- **Jets unfolding** for cross-sections are defined at the ***particle-level final state***

DIRECT PHOTON & ELECTRON RECONSTRUCTION

- ❑ Search for **seed energy clusters** in the EM calorimeter with significant energy
- ➢ **Form a cluster from cells** in a rectangular region **Δη×Δφ=0.125×0.1715** 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 **ΔR=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

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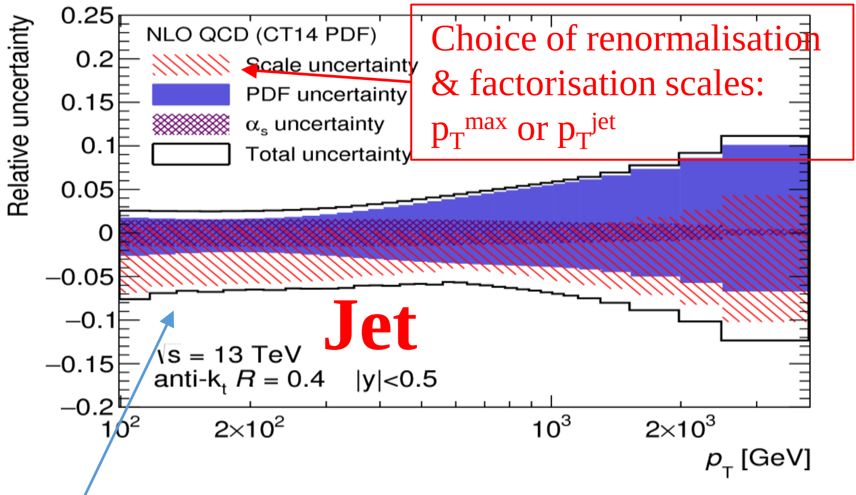
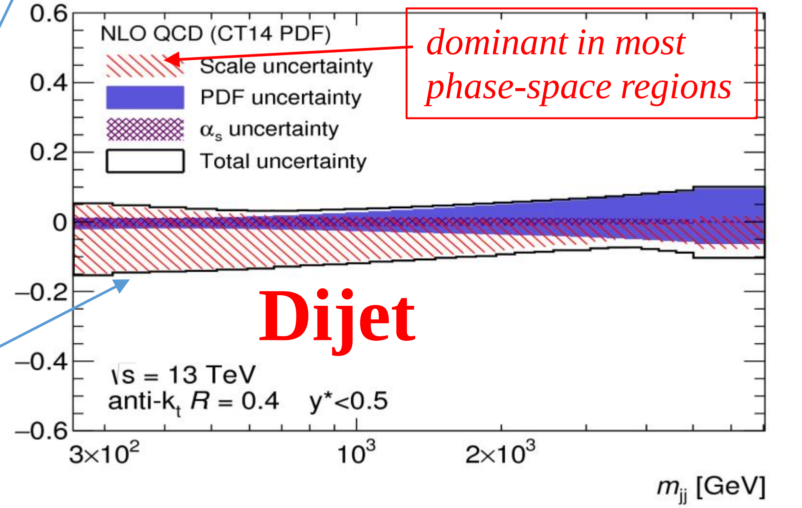
- ***Dijet** production allows to **Probe for higher scales***
  - The double-diff. inclusive **Jet** cross-section measurement vs. p_T^{jet} & y → **0.1 TeV≤ p_T^{jet} ≤4 TeV & |y|<3**
  - The double-differential inclusive **Dijet** cross-sections measurement vs. **dijet** mass **m_{jj}→0.3 TeV–9 TeV & $y^*=|y_1-y_2|/2 < 3$**
- **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 (NP) and ElectroWeek (EW) 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

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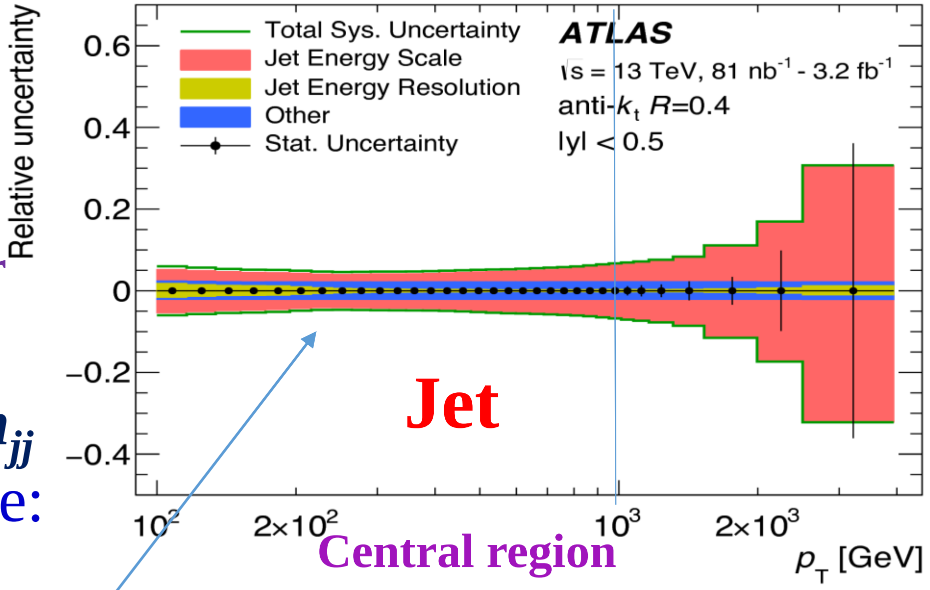
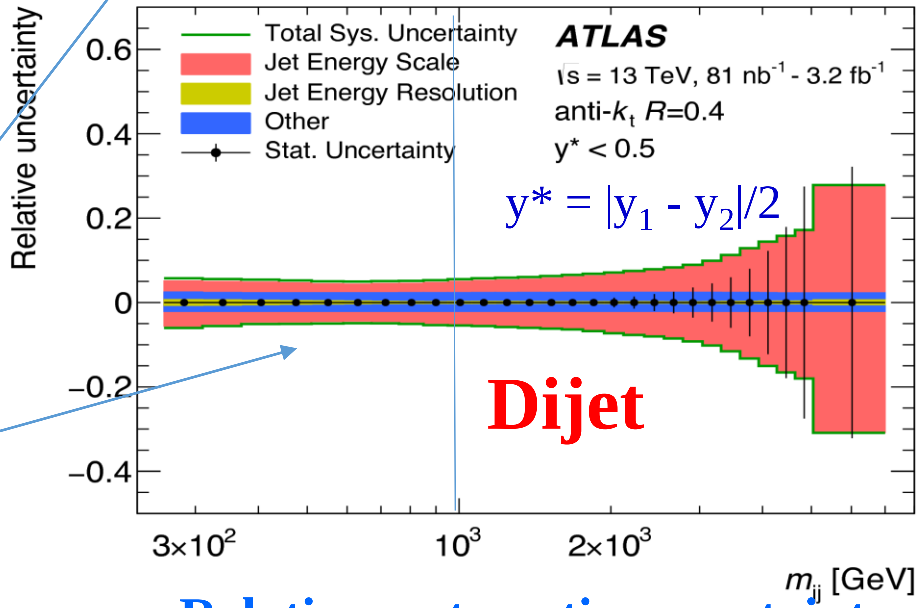
- ❑ Dataset used for measurement: pp at 13 TeV; $\mathbf{L_{int}=3.2\ fb^{-1}}$
- ➢ **Pile-up:** <μ> increases from **<μ>~10 to <μ>~36**
- ➢ **Two-level Jet trigger**. Events with Jet: **|η|<3.2, $\mathbf{p_T^{jet}}$** over a threshold. Offline data selection and **Jet correction**: similar to **Dijet** 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:
  - correction for the sample **impurities**;
  - unfolding for the $\mathbf{p_T}$ **migration**;
  - 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 & $\mathbf{p_T}$<1 TeV** less than 10%





Relative systematic uncertainty

CROSS-SECTIONS: $pp \to$ JET, DIJET + X AT 13 TEV

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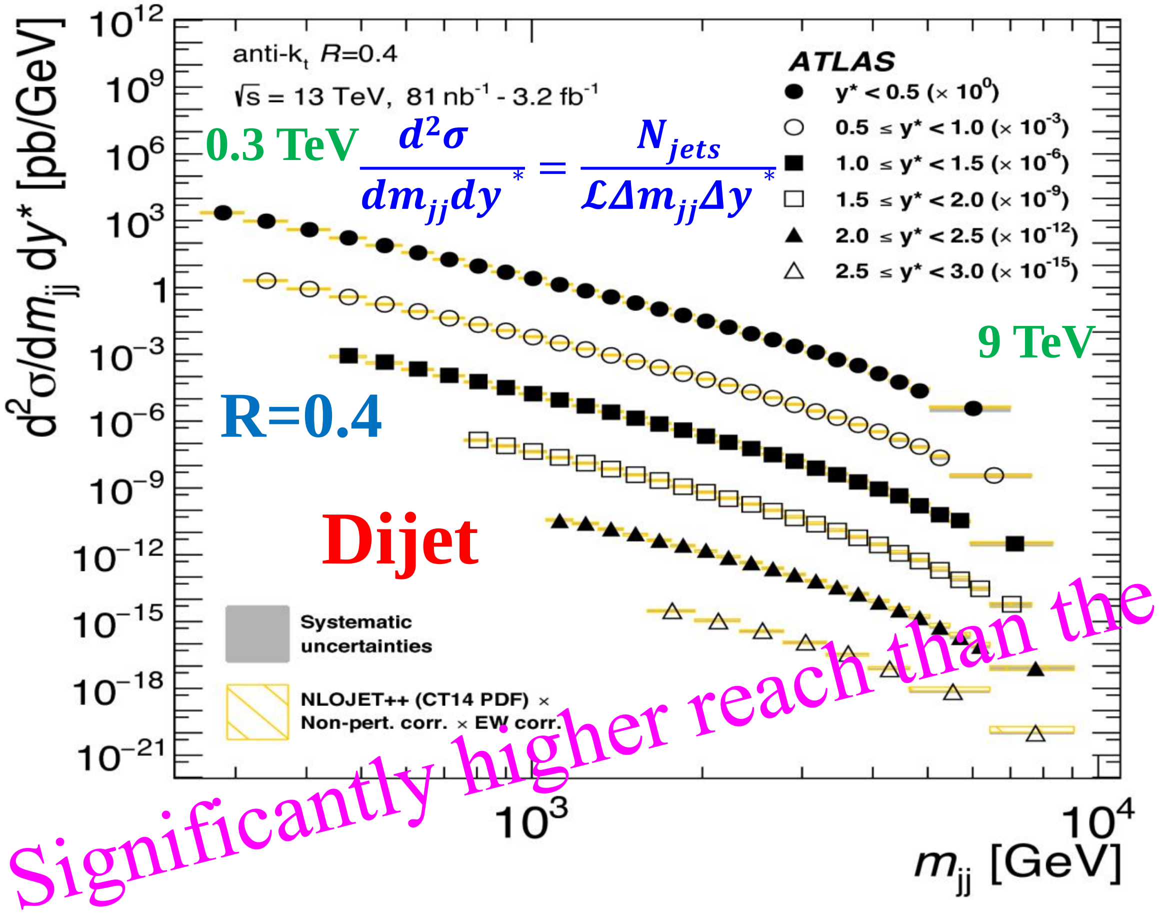
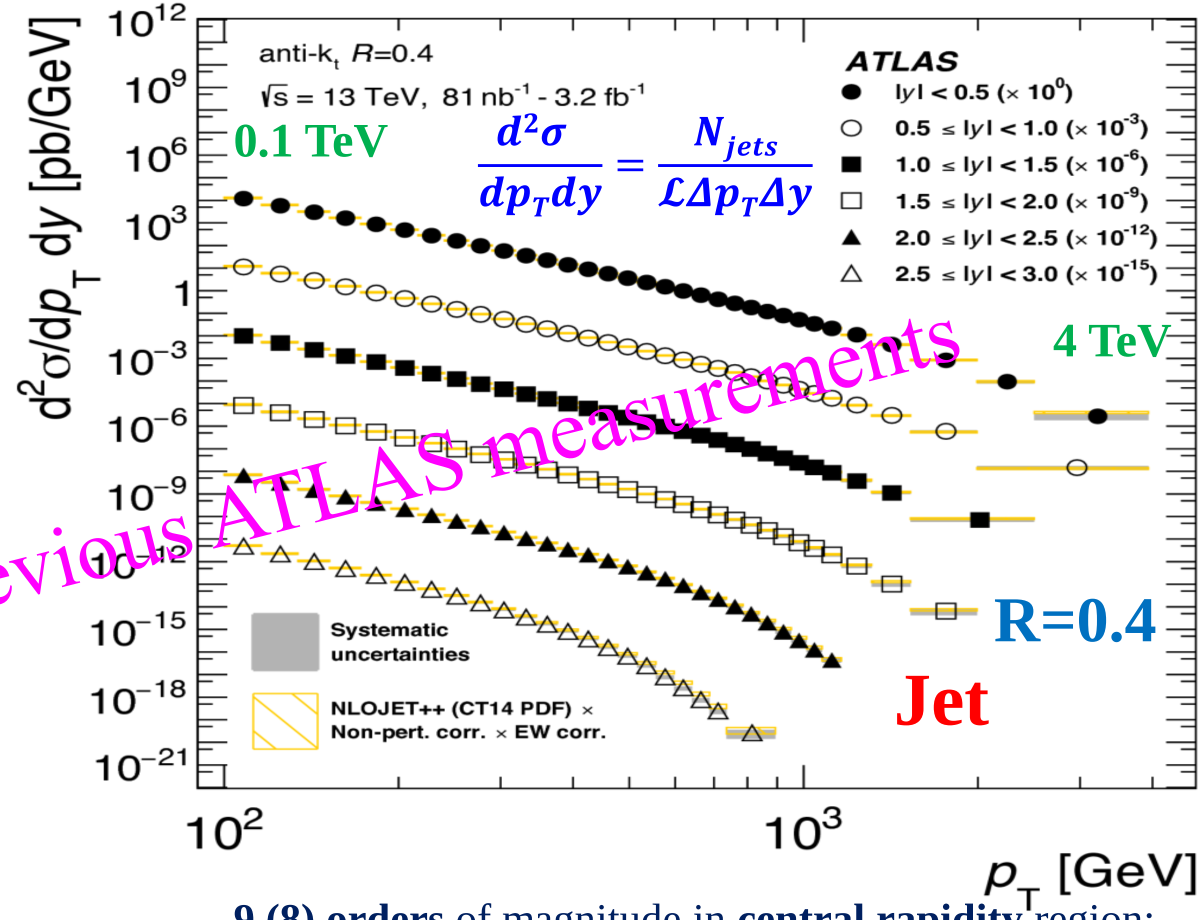
ATLAS EXPERIMENT

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** $|y|<3$





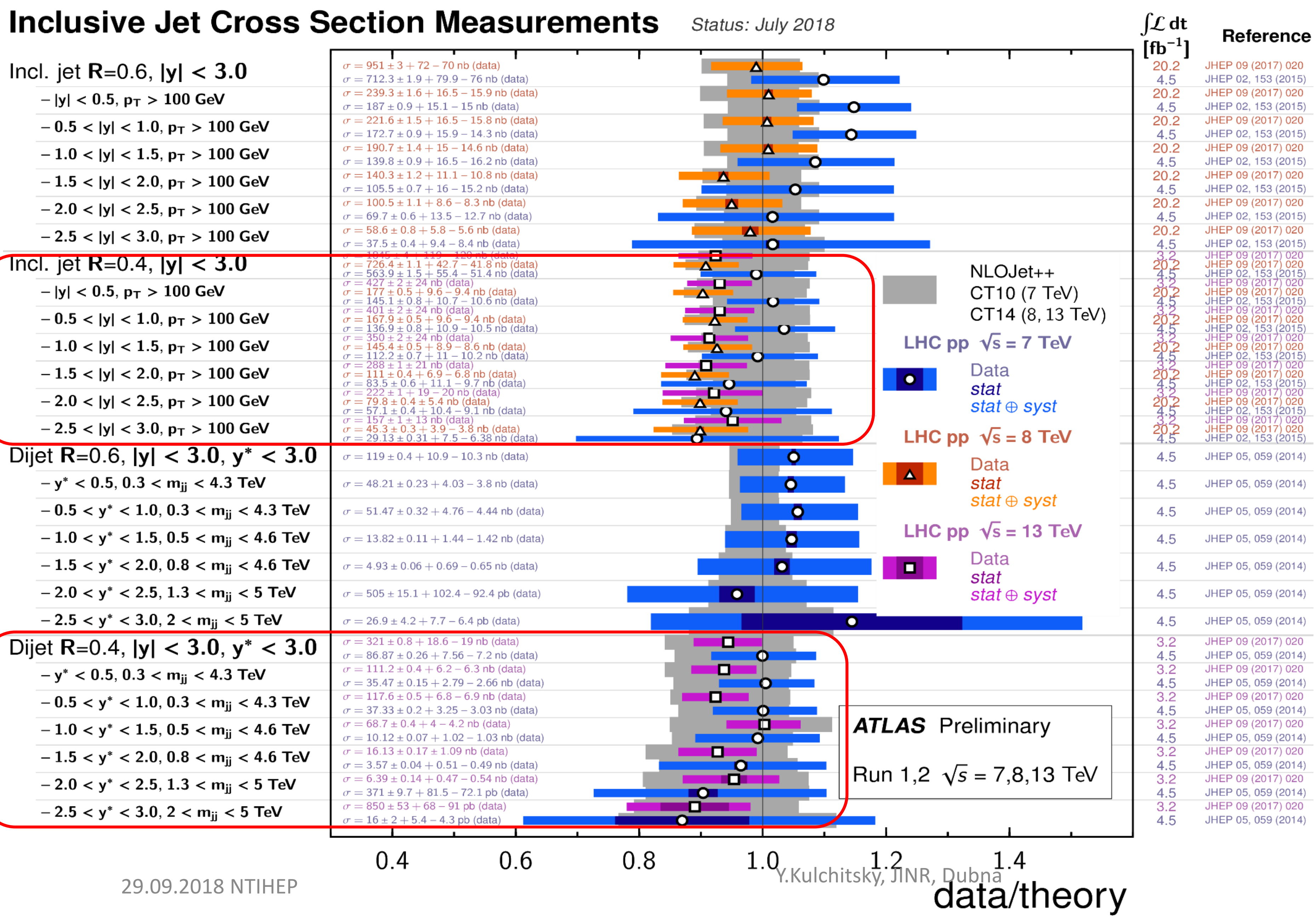
Significantly higher reach than the previous ATLAS measurements

- ❑ 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

INCLUSIVE JETS & DIJETS X-SECTION MEASUREMENTS



The data/theory ratio for several inclusive jet fiducial production cross section measurements. All theoretical expectations were calculated at NLO or higher. The dark-color error bar represents the statistical uncertainly. The lighter-color error bar represents the full uncertainty, including systematics and luminosity uncertainties. The luminosity used and reference for each measurement are also shown. Uncertainties for the theoretical predictions are quoted from the original ATLAS papers. At 7 TeV the **CT10 PDF** set and at 8 TeV and **13 TeV CT14 PDF** was used in the calculation of the theory prediction. For the dijets measurement, $y^* = |y_1 - y_2|/2$.

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

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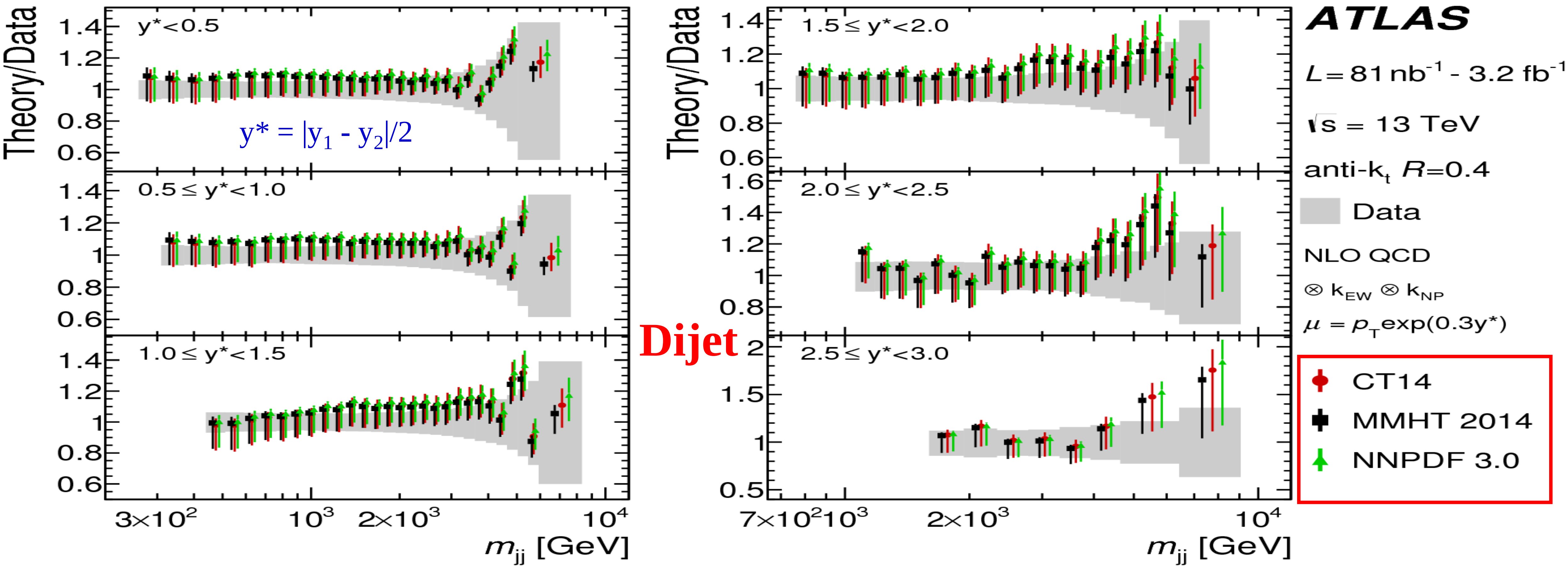
Ratio of **NLOJet++** *prediction* to measurements of **Dijet** double-diff. cress-sec. vs. **Dijet** mass & y* **PDF** sets used: **CT14, MMHT 2014, NNPDF 3.0**



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

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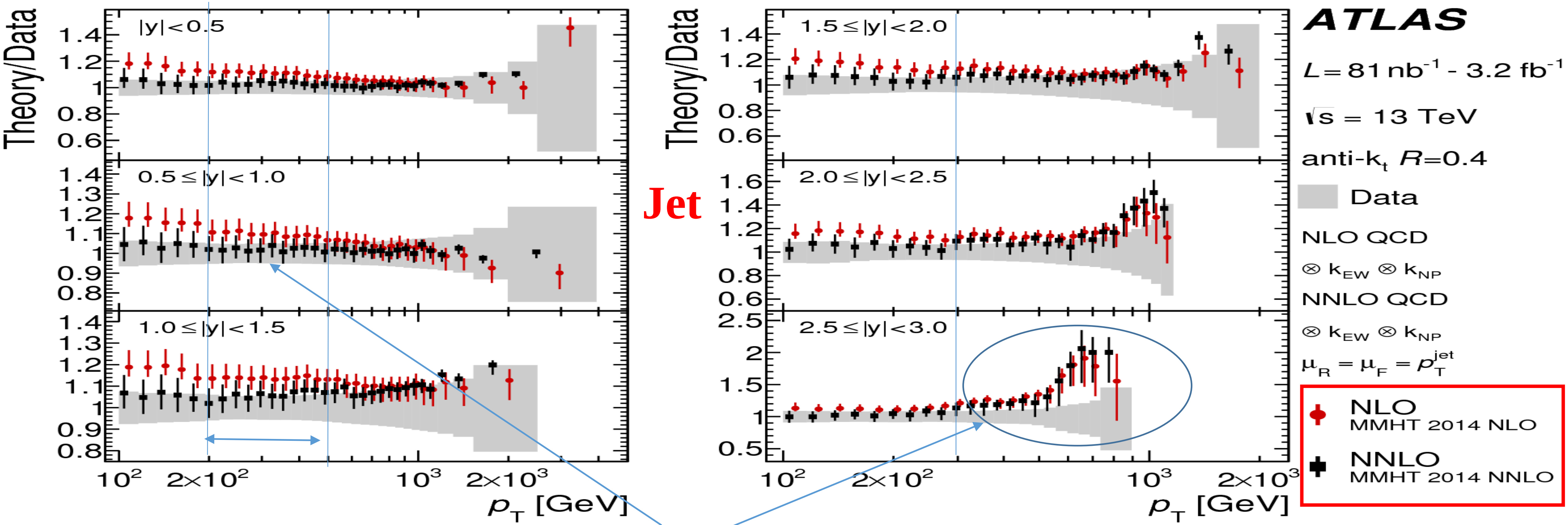
Ratio of **NLOJET++ (p_T^{jet} QCD scale)** *prediction* to measurements **of Jet** double-diff. cross-sec. vs. **jet p_T and y: PDF** sets used: **MMHT 2014 NLO, MMHT 2014 NNLO**



- **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

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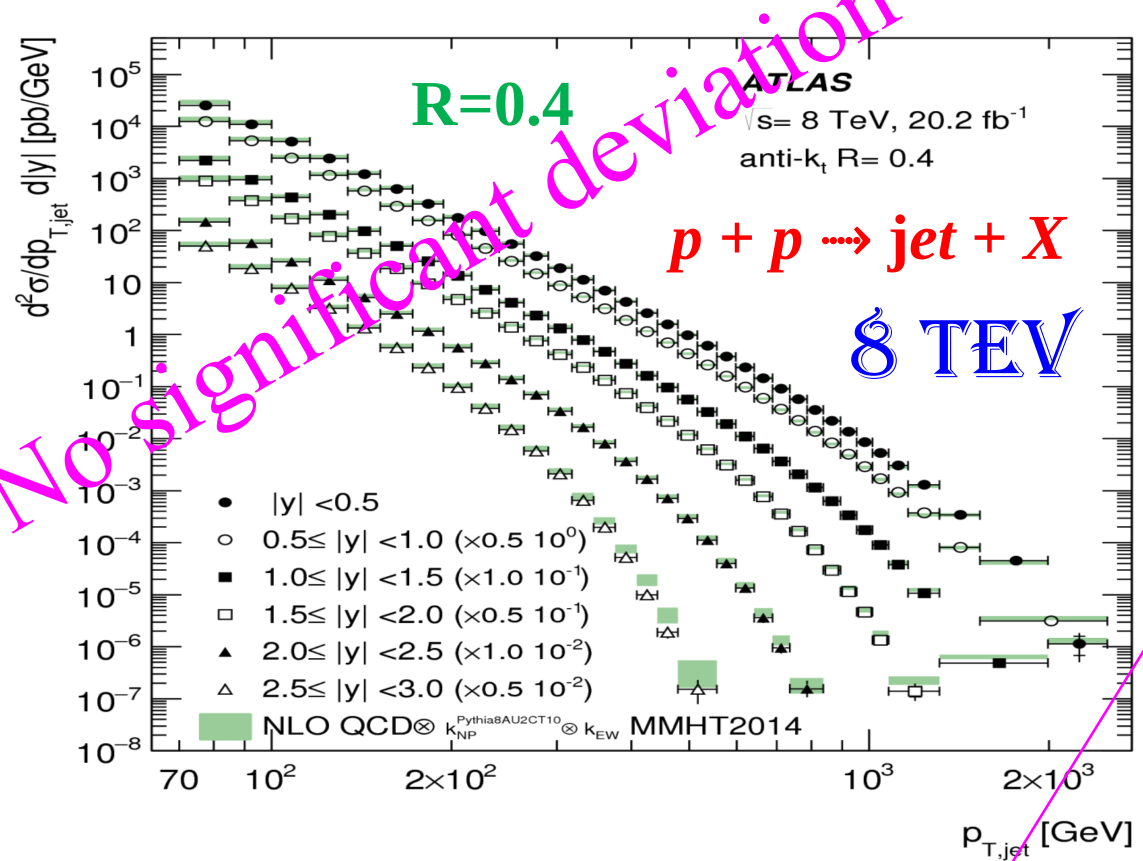
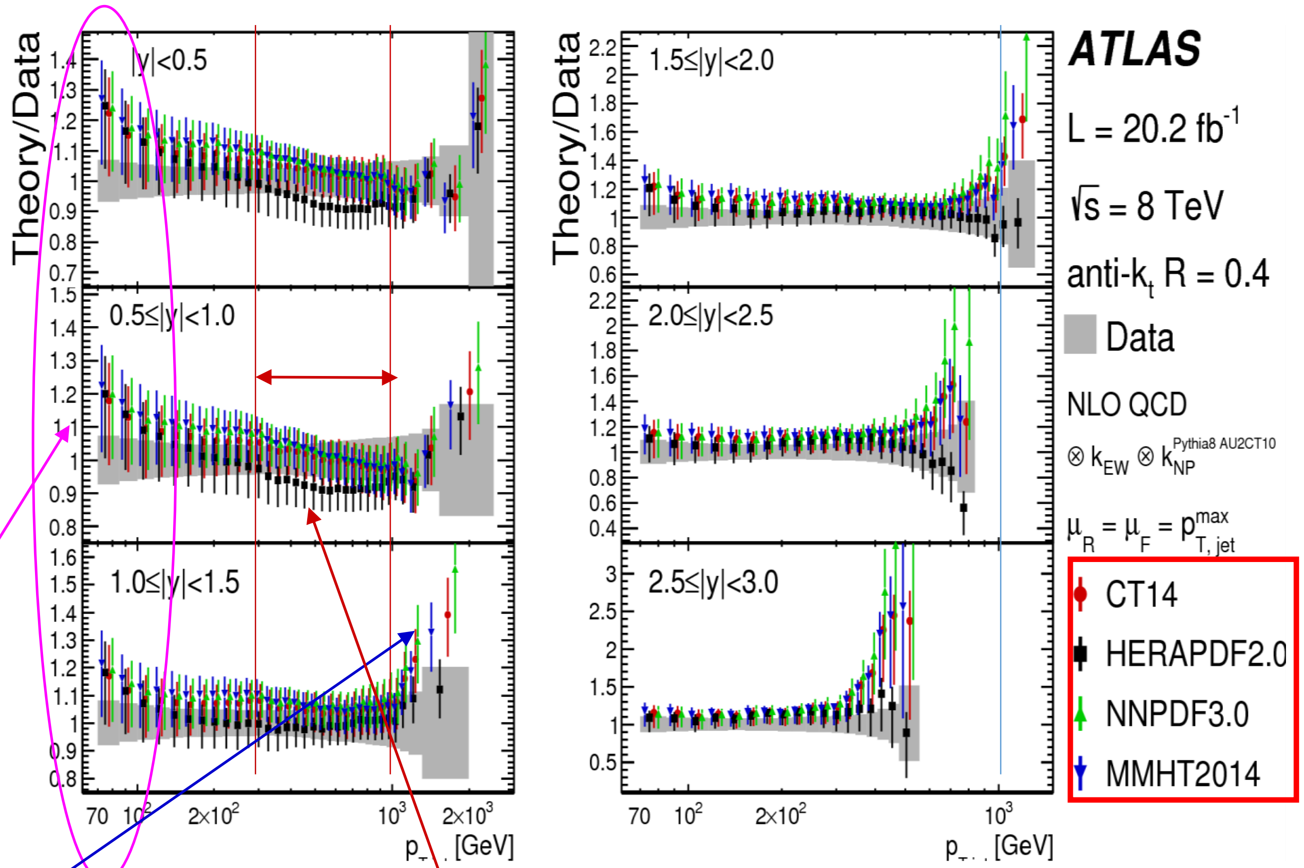
Double-differential ***inclusive Jet*** cross-sections for jets with **R=0.4** vs. **jet p_T** and rapidities

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





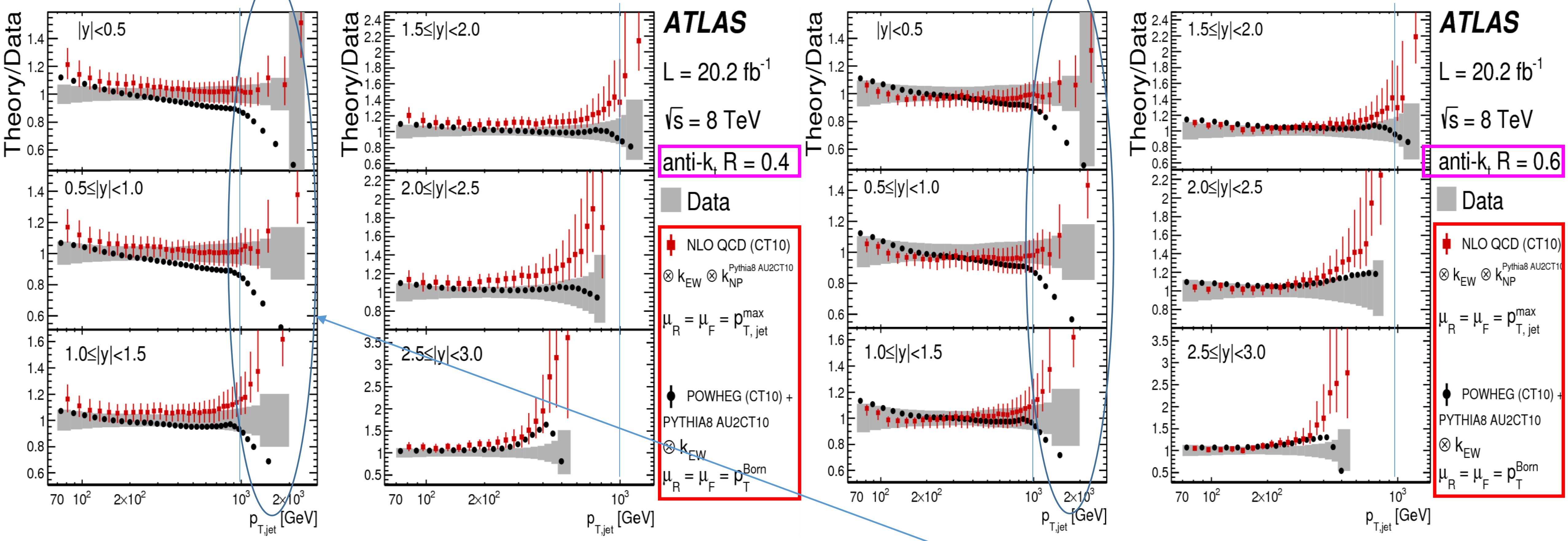
- **NLO pQCD** above the measurements for ***p_T^{jet}* <100 GeV**
- **Toward *higher p_T^{jet}* NLO pQCD *closer to data***
- For ***p_T^{jet}*** **>1 TeV** rise of **NLO pQCD** respect to data on ***10-20%***

- **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

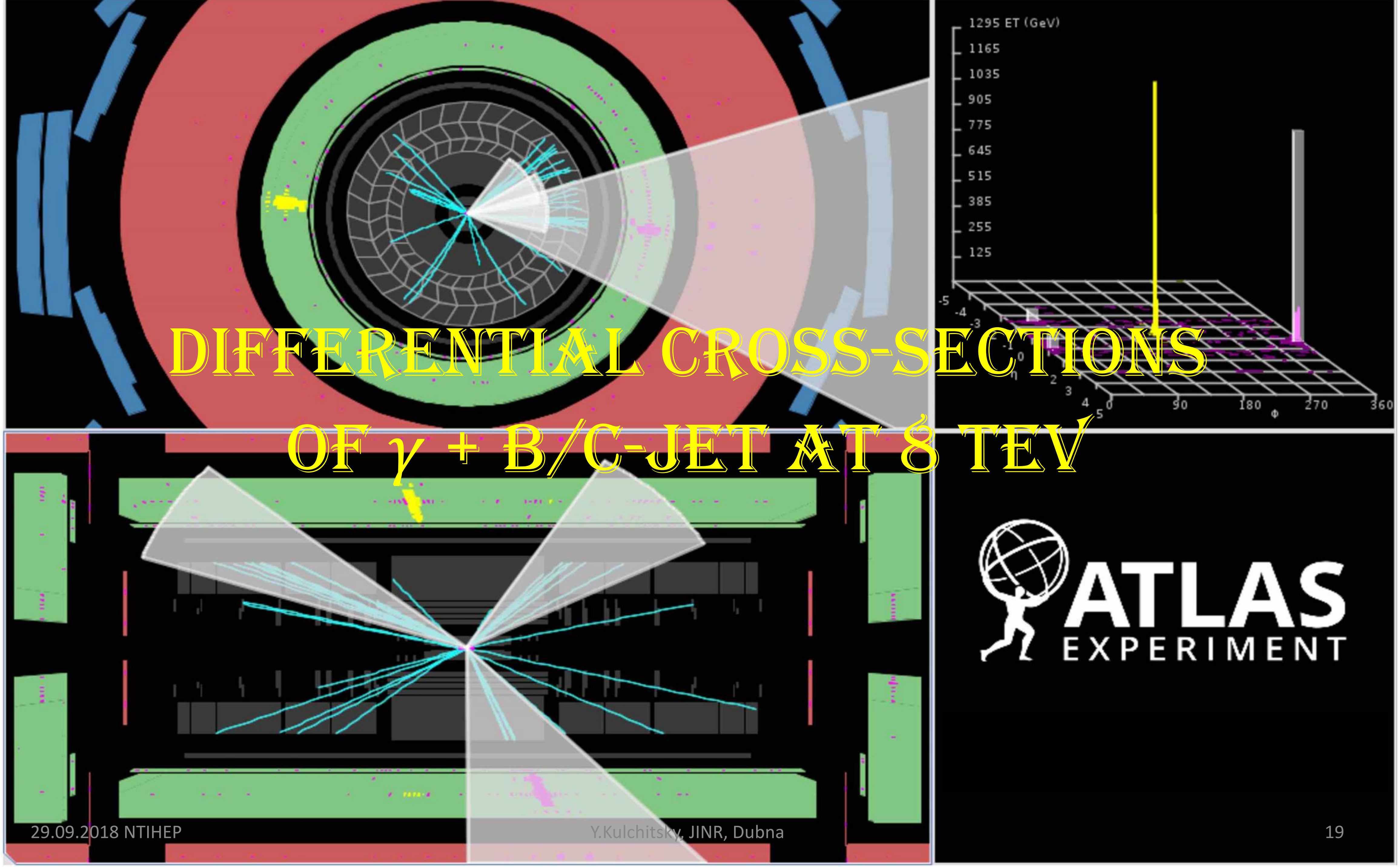
JHEP 09 (2017) 020

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*: $pp \to \gamma$ + b/c-jet +X at 8 TeV

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ATLAS EXPERIMENT

❑ ***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*** $\to q\gamma$ for ***pp*** $\to \gamma$ **+ 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

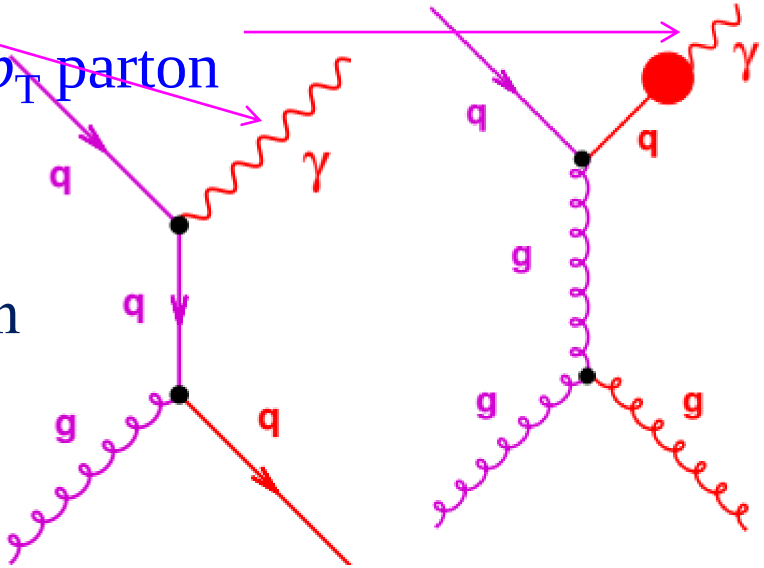
➢ *Essential to require the* ***photon to be isolated***:

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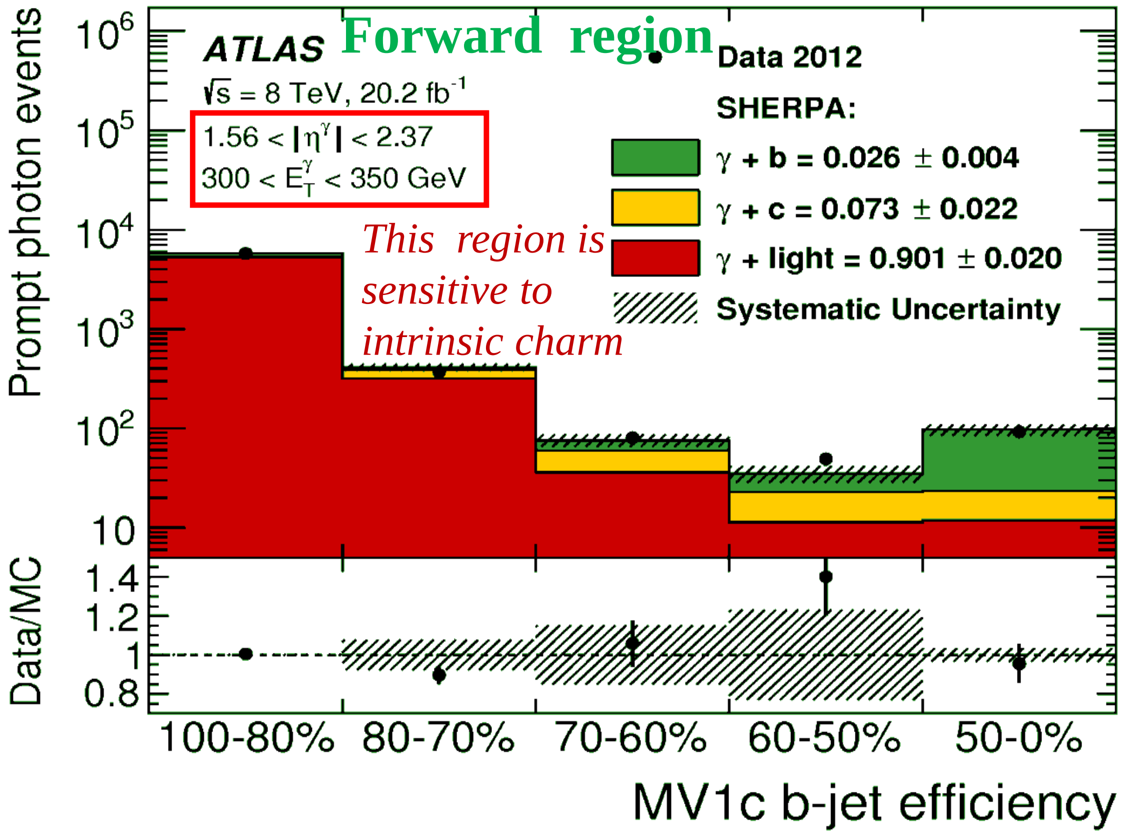
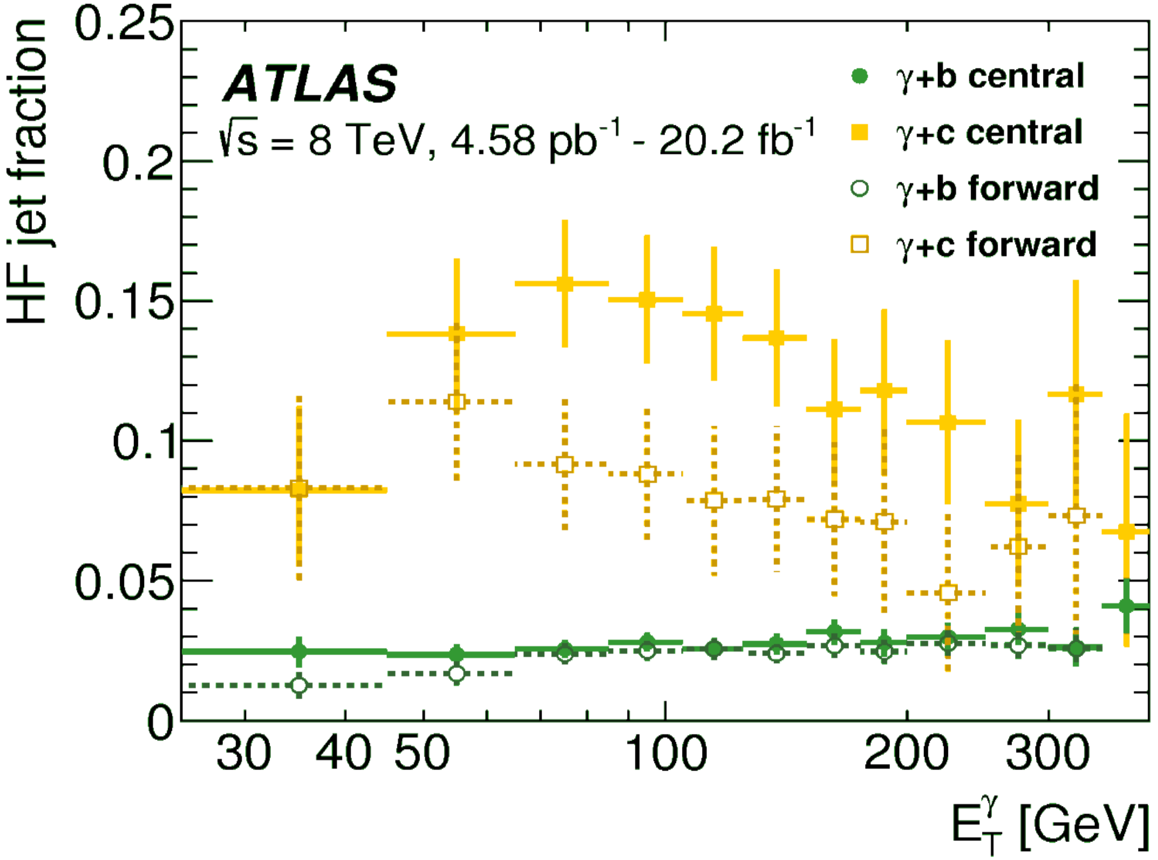
- *The addition of Heavy Flavour (HF) Jet using **MV1c** (neural network) algorithm:*
  - ***Is trained*** to specifically identify ***b-jets*** with enhanced rejection of ***c-jets***
  - *Uses discriminants* from ***3 other algorithms*** based on different aspects of **jet tracking** information from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





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

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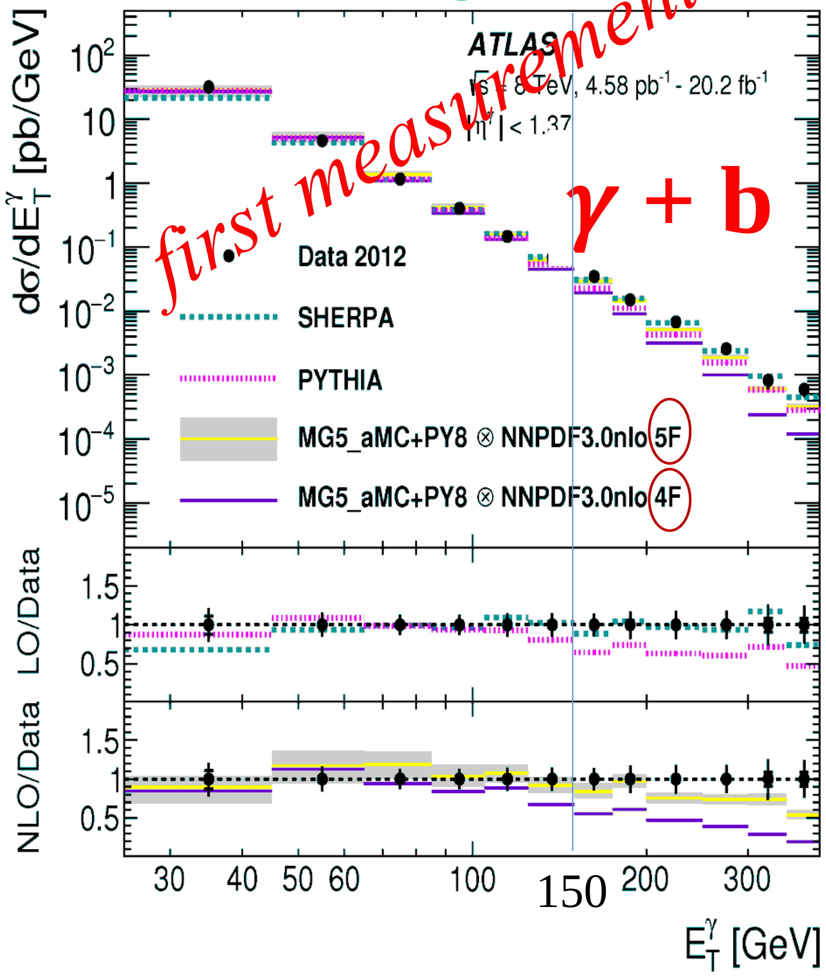
ATLAS EXPERIMENT

- **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, $|y^{jet}| < 2.5$

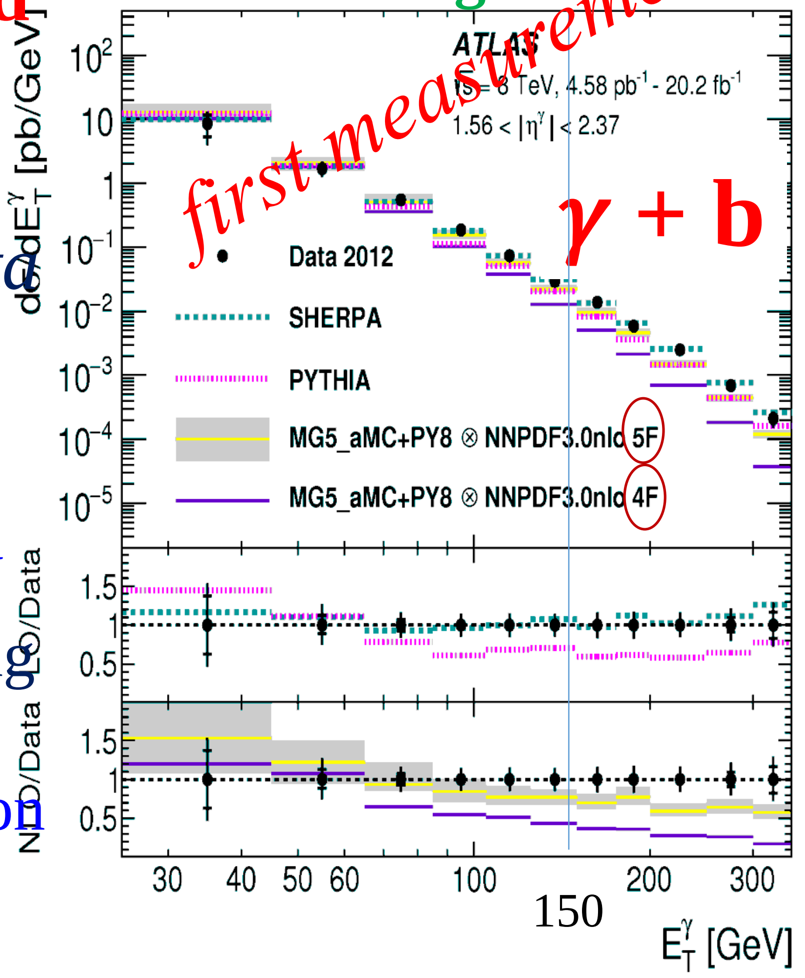
Central region



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 E_T gluon splitting is important
  - High order (HO) calculation needed at higher E_T

Forward region



CROSS-SECTIONS pp → γ + c-jet +X at 8 TeV

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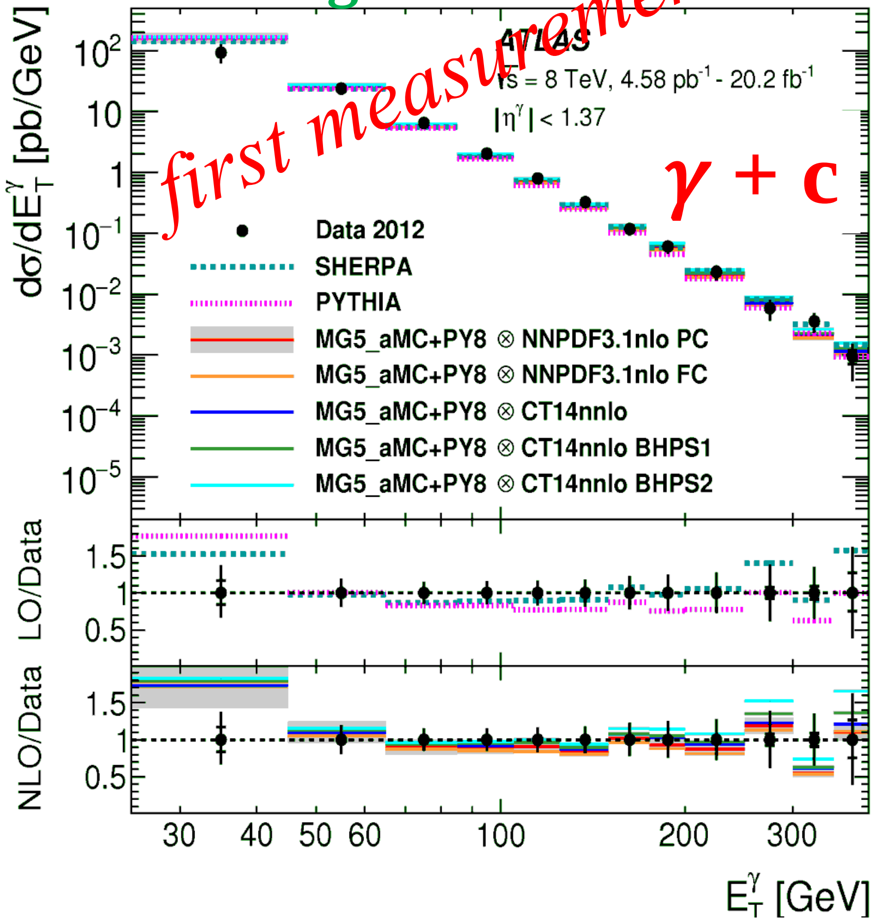
- ❑ ***MadGraph5_aMC@NLO*** with *several* ***PDF*** *sets* → *with different* ***intrinsic charm (IC)*** **content/ model** and ***5F/4F*** (five-flavour)/(four-flavour) **flavor-schemes** comparison

➢ ***4F* worse description at high E_T^γ** (large $\log(m_b/E_T^\gamma)$ terms)

Central region

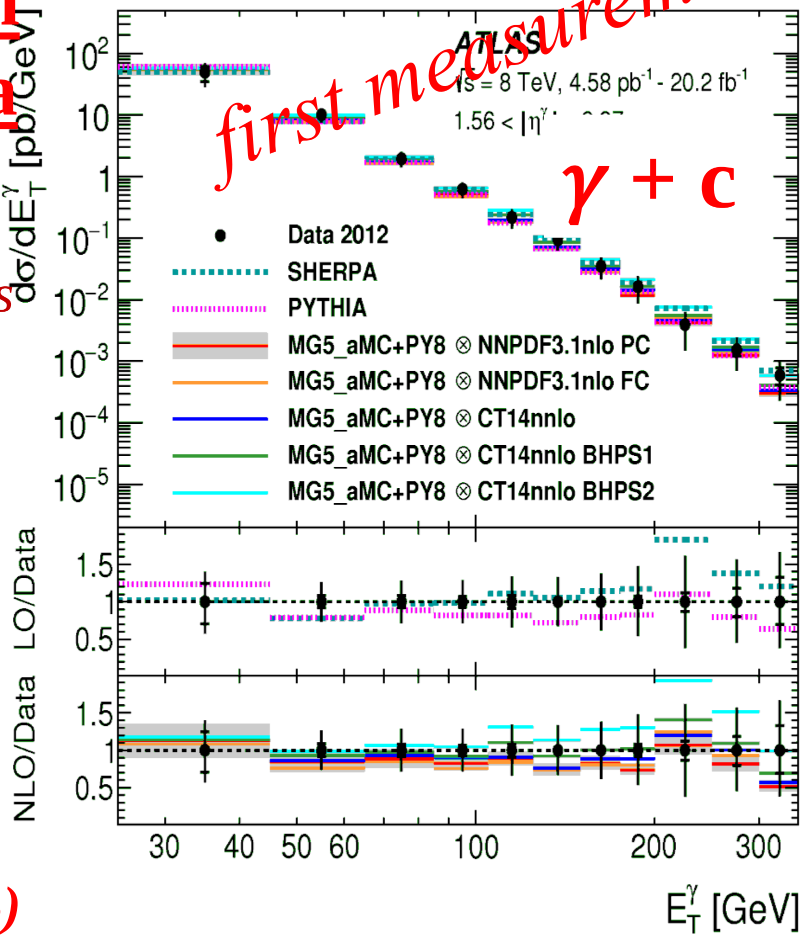


❑ **All the predictions are in agreement with γ+c data**

- ❖ Gluon splitting less important at this E_T^γ region
- ➢ *All* ***IC*** *predict* ***higher*** *forward cross section as expected*
- ❖ **BHPS2** deviates the most from nominal PDF by factor 1.5
- ❖ **BHPS1** give intermediate values
- ➢ ***PDFs with/without IC*** *give deviations similar* ***to the measurement uncertainties***

PDFs: NNPDF3.1nlo (IC 0.26%); BHPS1 (IC 0.6%); BHPS2 (IC 2.1%)

Forward region

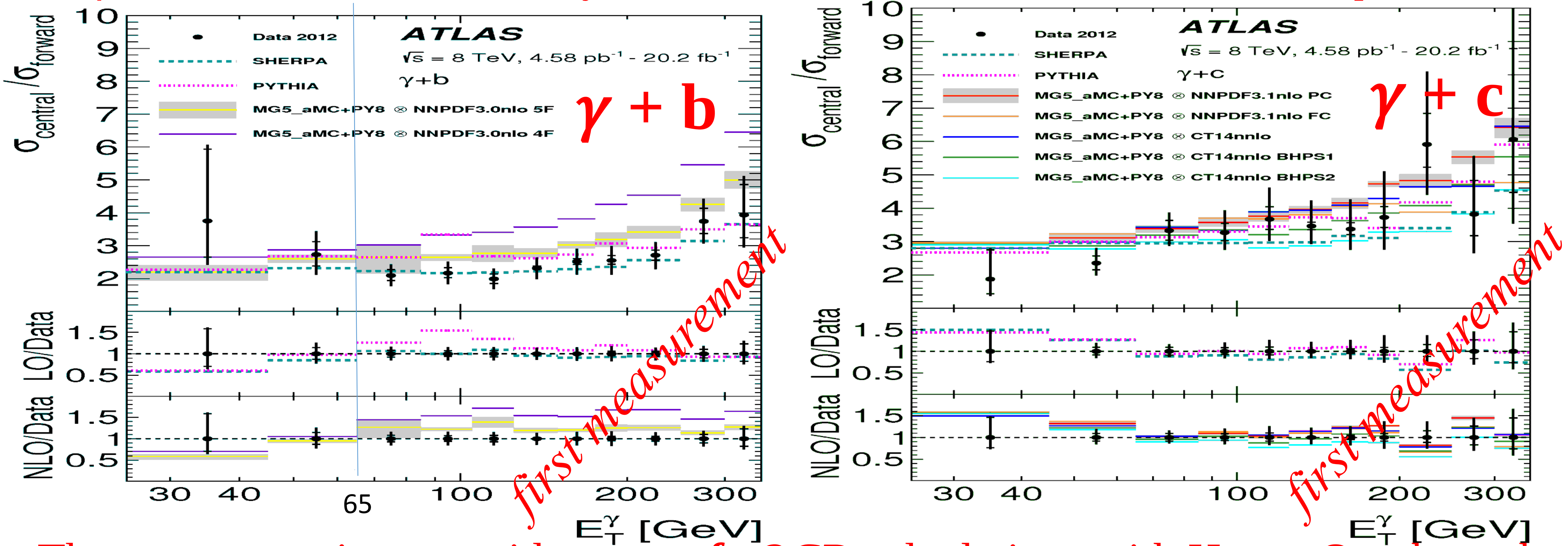


Δ_{sys}~15%: main contribution due to jet flavour determination. Stat. dominated in the E_T^γ tails 10-40%.

RATIO CENTRAL/FORWARD pp → γ + b/c-jet +X at 8 TeV

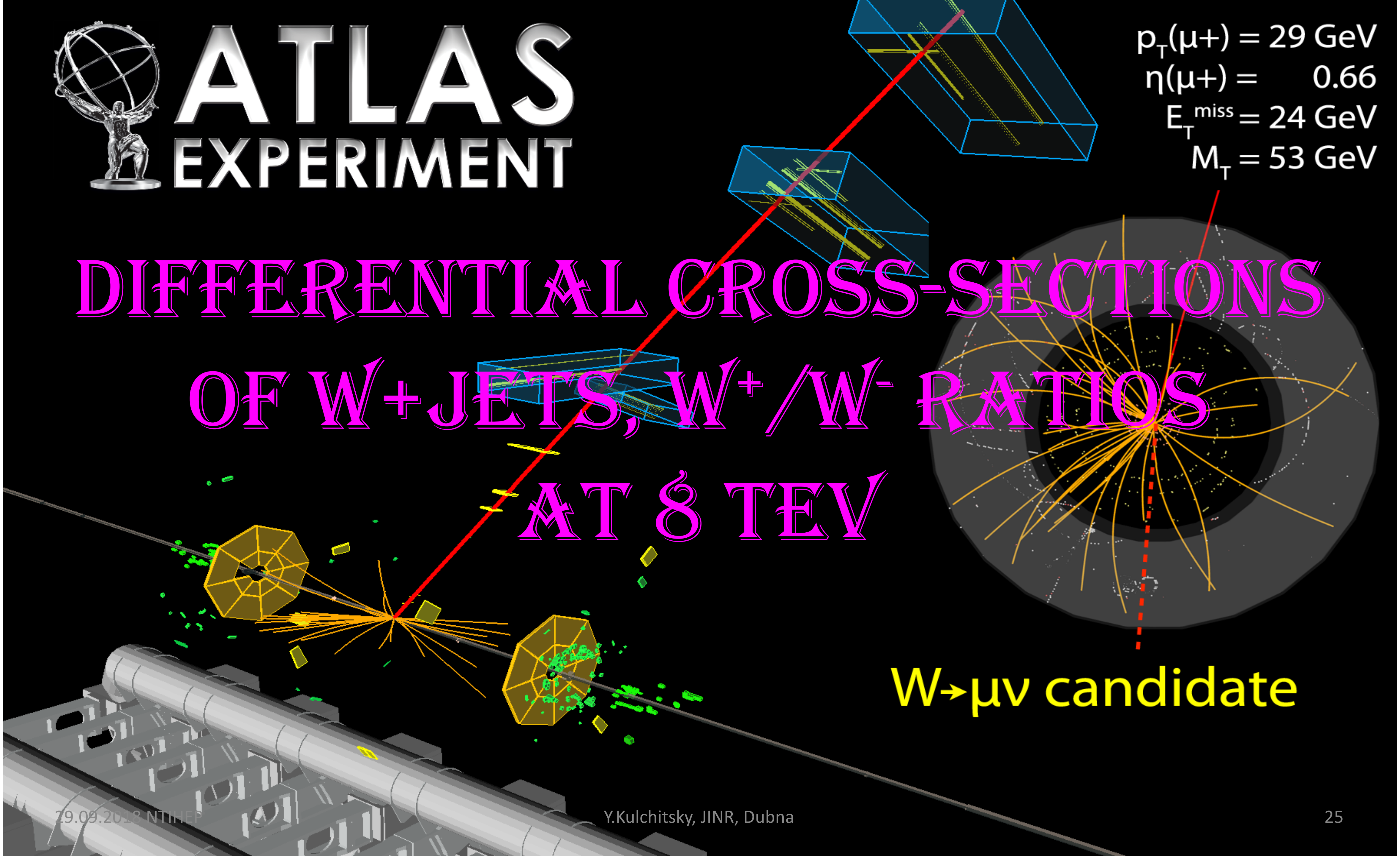
Phys. Lett. B 776 (2018) 295

- ***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 $E_T^{\gamma} > 65$ 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



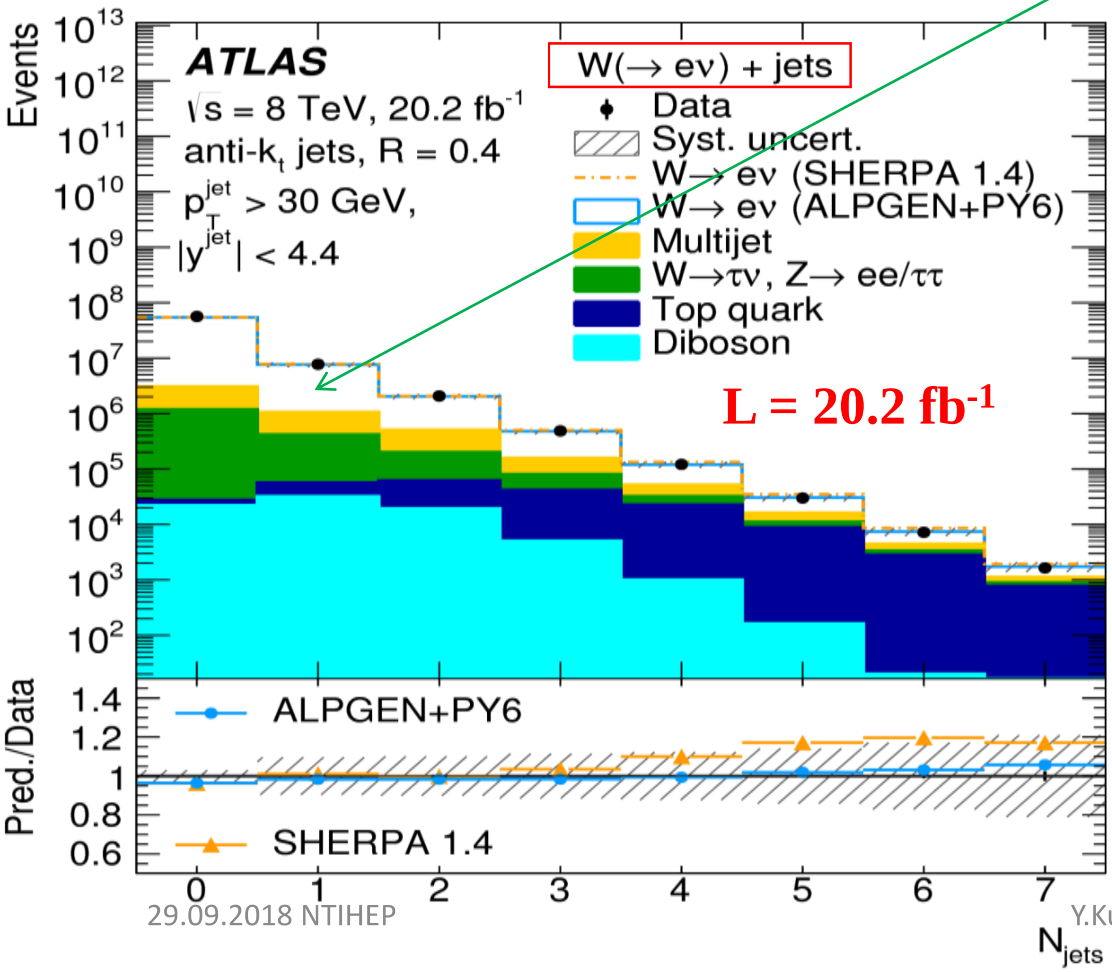
ADDITIONAL PROBES OF THE SM: pp → W + JETS, W^+/W^- RATIOS AT 8 TEV

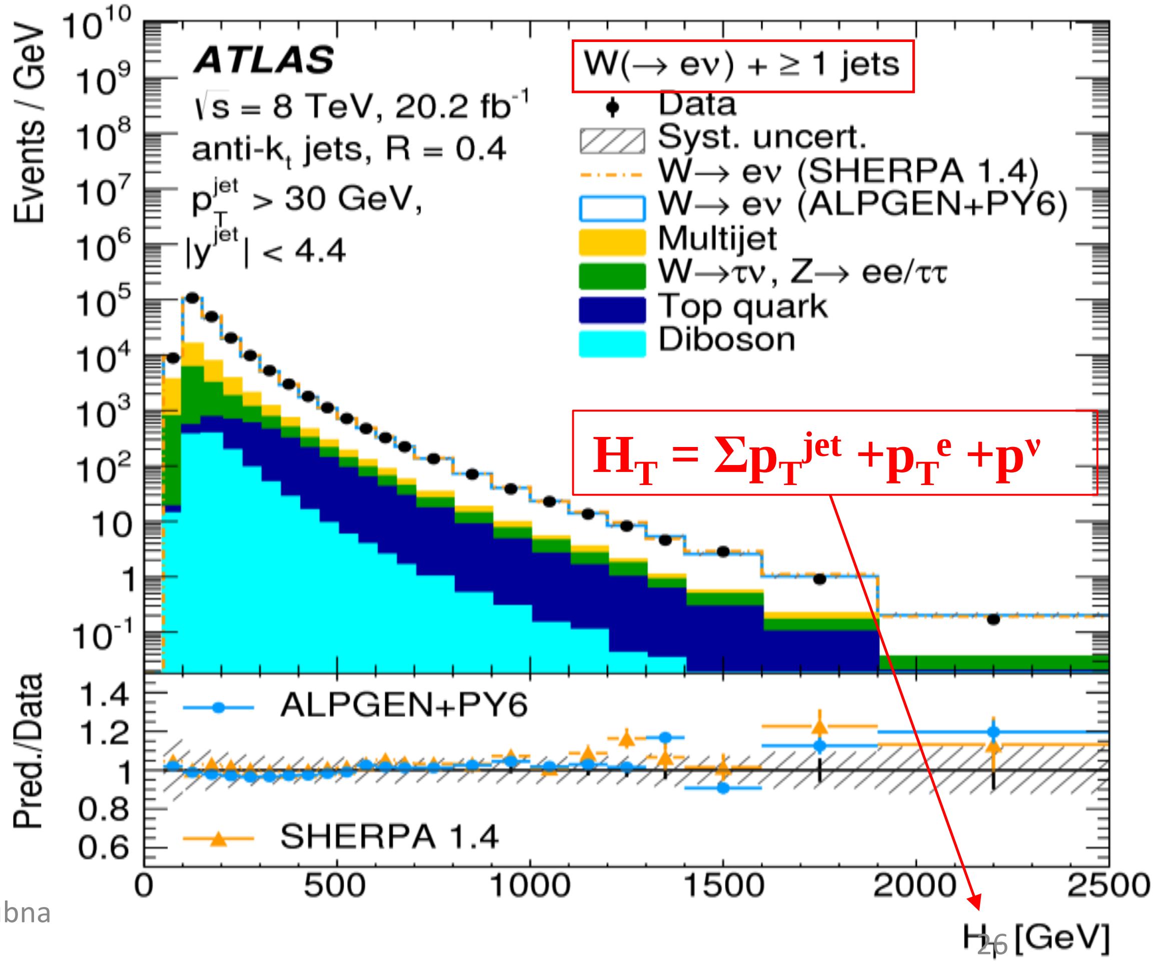
JHEP 05 (2018) 077

❑ 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**: $\Delta R(e, jet) > 0.4$
- $E_T^{miss}>25$ **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}



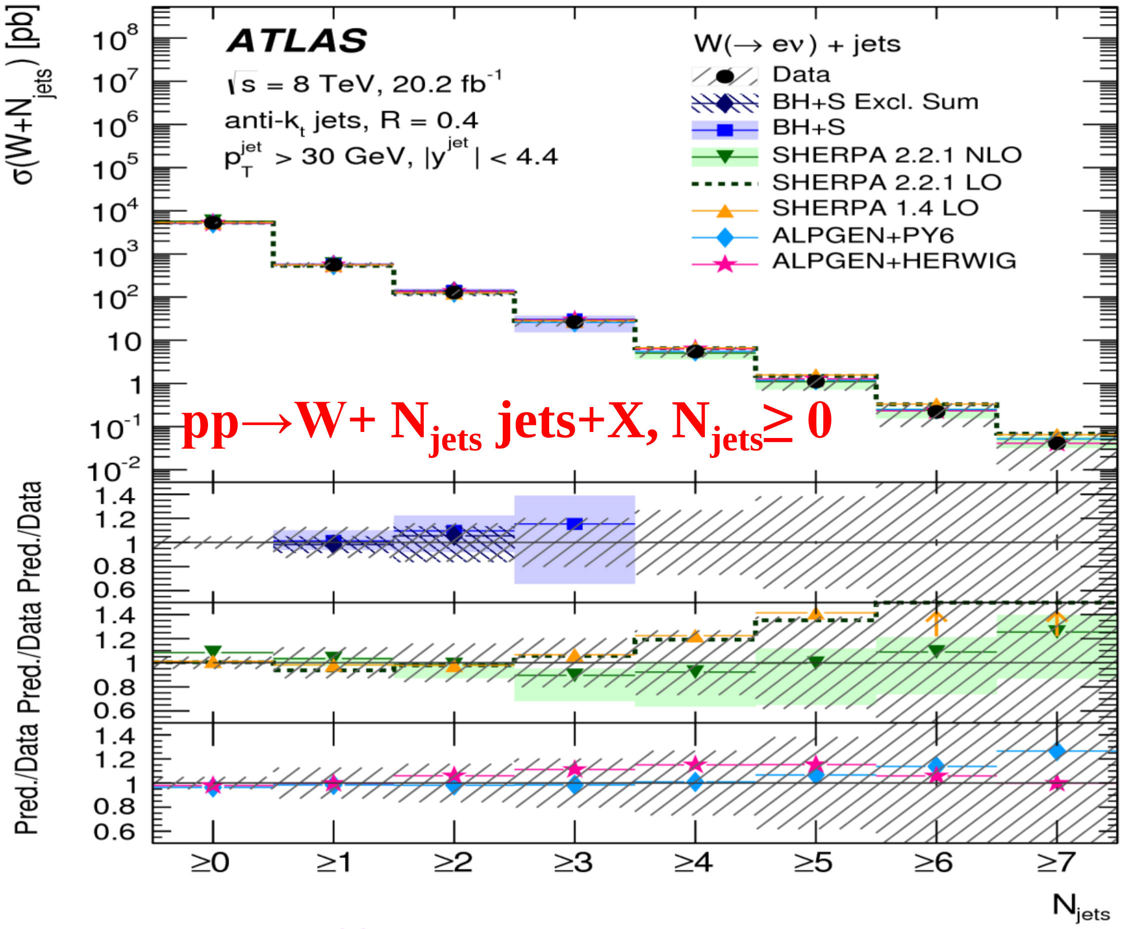


DIFFERENTIAL CROSS-SECTIONS: pp → W + JETS AT 8 TEV

JHEP 05 (2018) 077

ATLAS EXPERIMENT

- ❑ 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 in comparison with MCs:

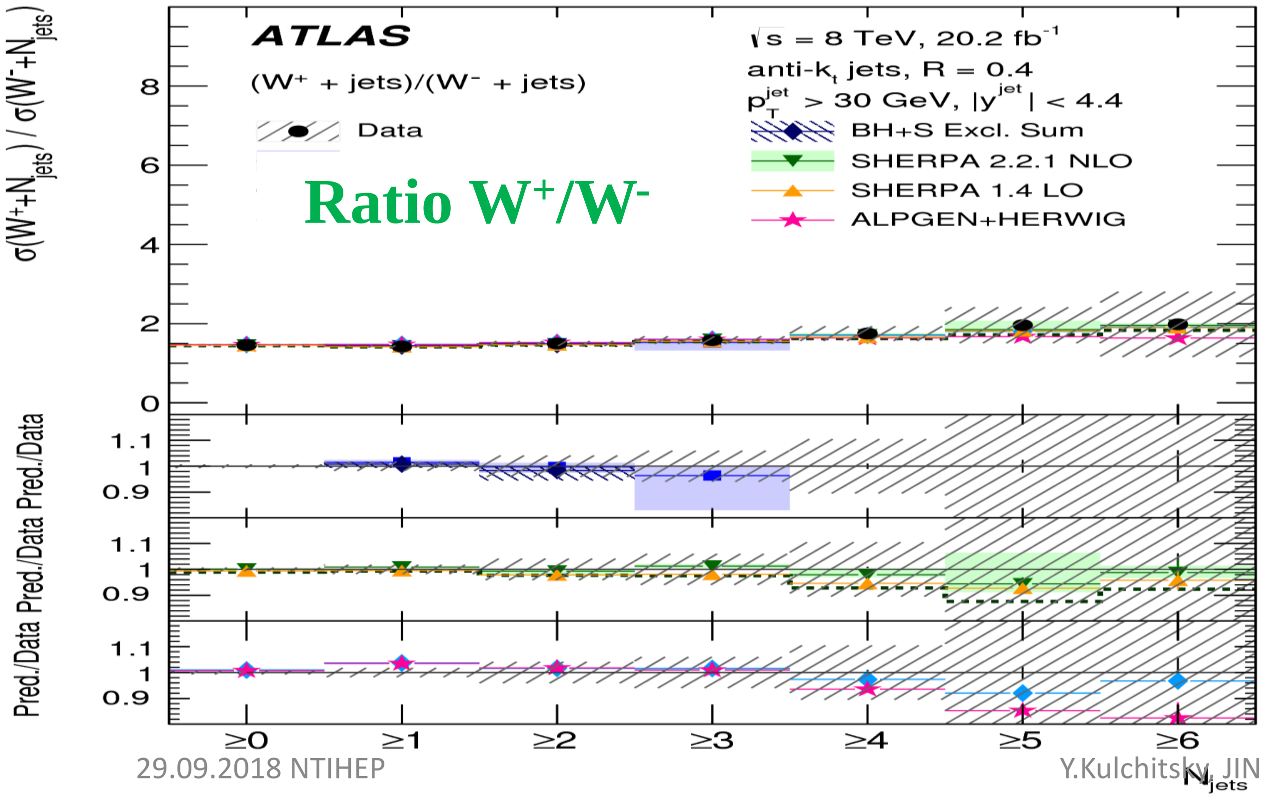
1. **BLACKHAT+SHERPA NLO** with ≤3 partons with Non-perturbative corrections applied
2. **SHERPA 2.2.1 NLO** is NLO for ≤2 partons + LO for ≤3 partons + Parton Shower (PS)
3. **SHERPA 2.2.1 LO** is LO for ≤3 partons + PS
4. **SHERPA 1.4 LO** is LO for ≤4 partons + PS
5. **ALPGEN+PY6** is LO for ≤5 partons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

JHEP 05 (2018) 077

- 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



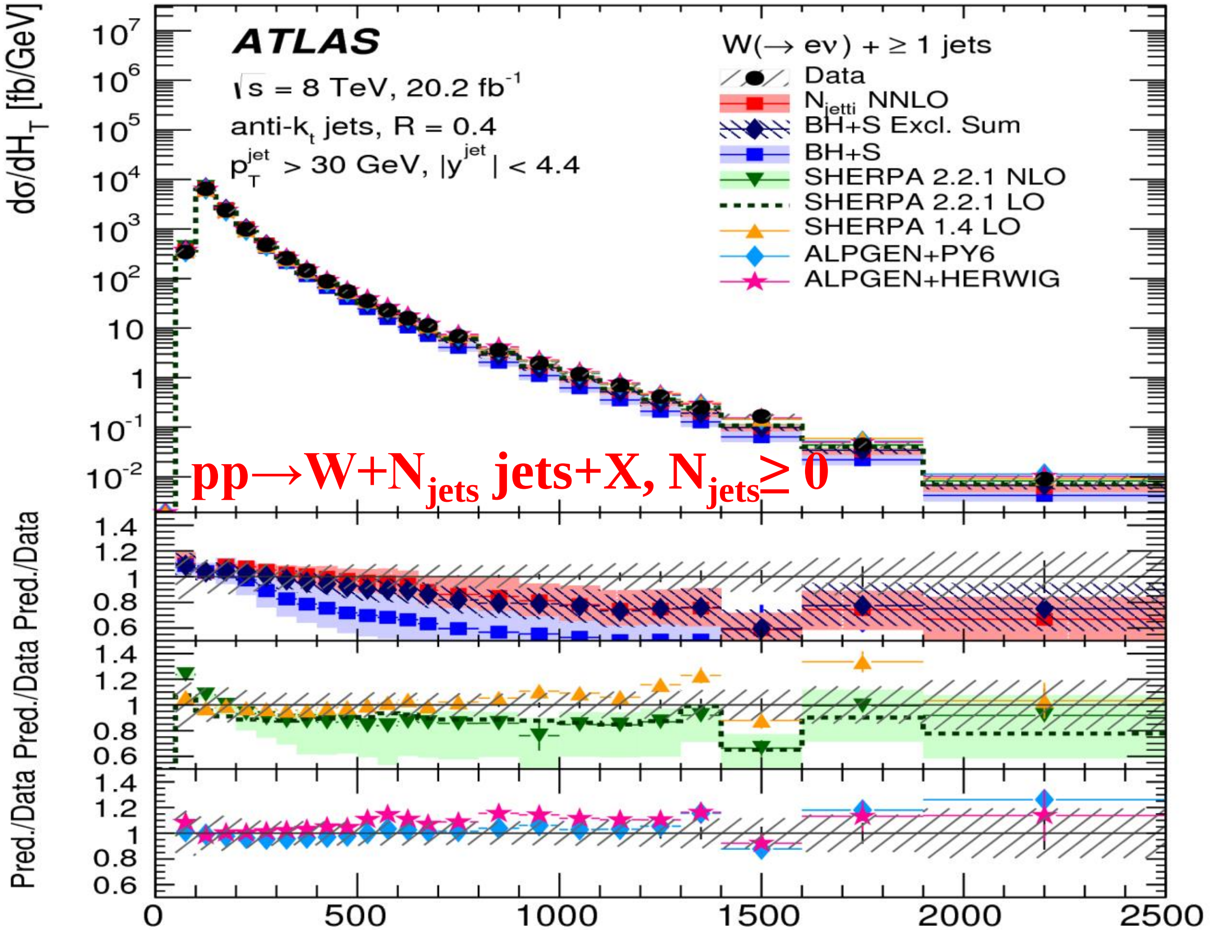
- Offset in **ALPGEN+PS** for **W^+/W^- + ≥1jet**: due to matrix element (ME) calculation and/or **u/d**-ratio in the **LO PDF**
- **Data/predictions** agreement much improved in **W^+/W^-**: *theory mismodelling related to jet emission cancels out in the ratio*

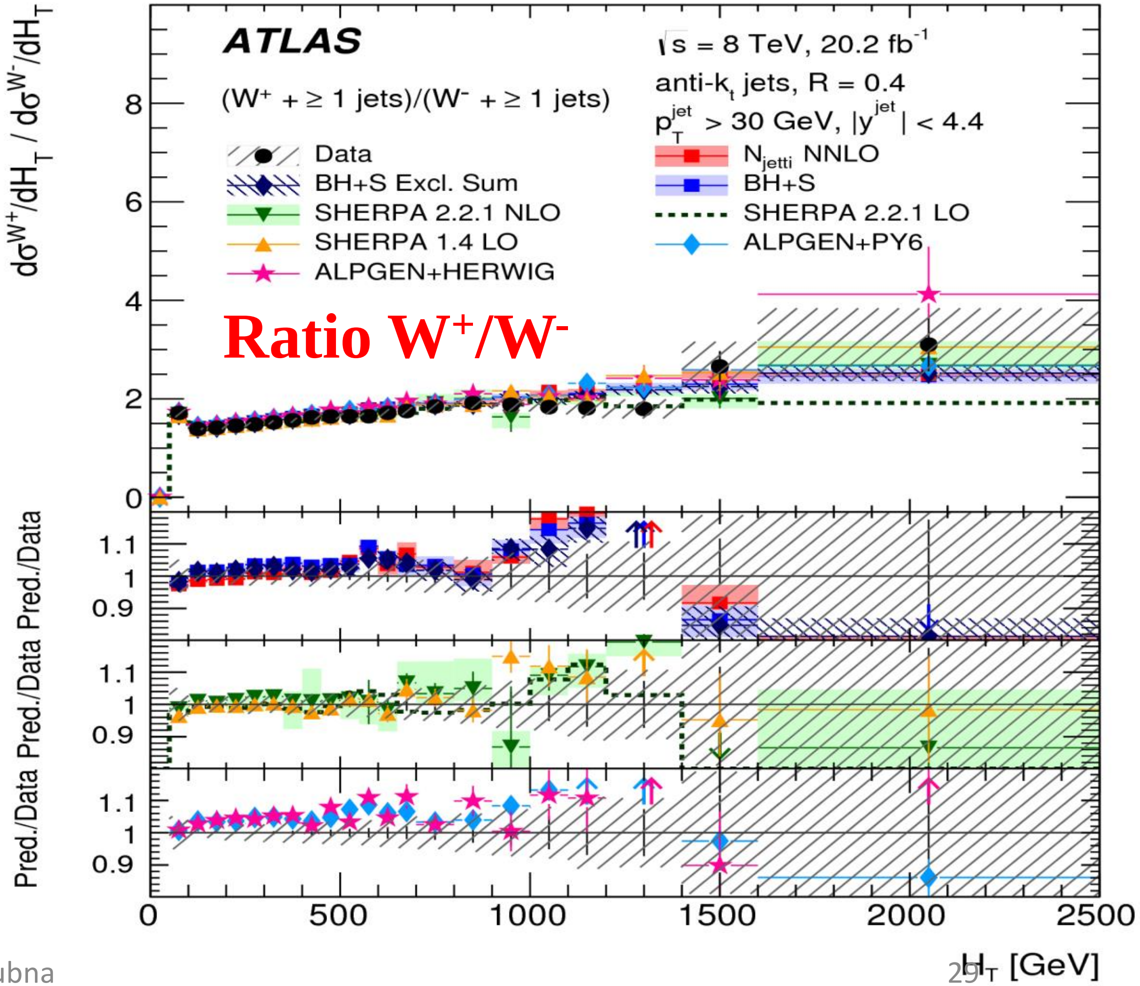
1. Overall the jet mismodelling cancels out in the ratio
2. Previously dominant Jet Energy Scale **(JES) uncertainty cancels out**
3. **ALPGEN-LO** predictions have an offset in the ***≥1 jet*** bin in the ***W^+/W^- ratio*** outside the experimental uncertainties
4. Suggests that there is a problem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

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

JHEP 05 (2018) 077

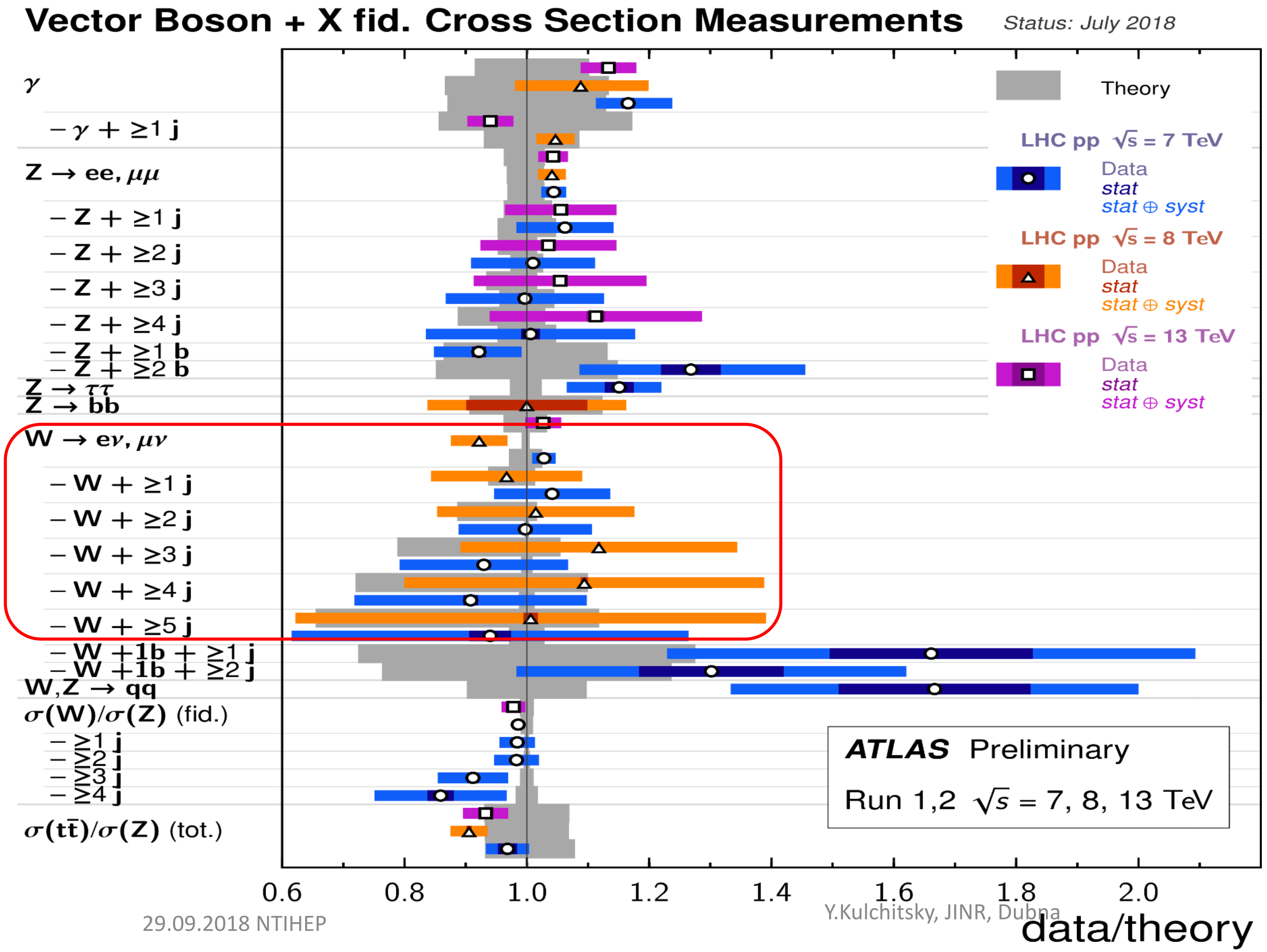
- ❑ Large, well understood dataset ***Probing*** up to a ***few TeV scale***
  - ➢ **W+/W-** cross-section-ratio observables: ***Jet** energy scale on other uncertainties mostly cancel*
- ❑ **ALPGEN+PY6** and **SHERPA 2.2 NLO** *(Run 2 ATLAS default)* ***describe data well***





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

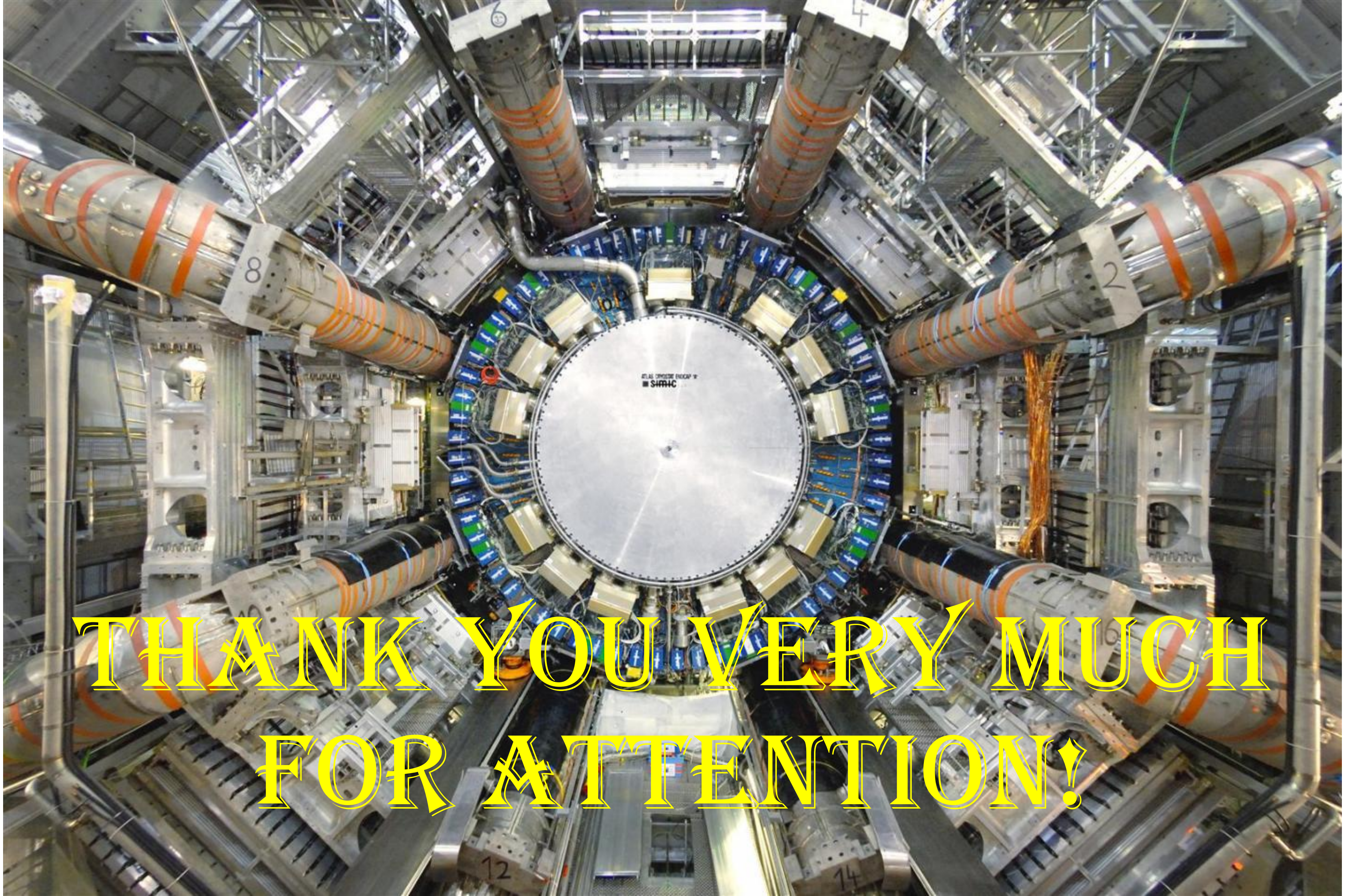
Vector Bosons + X cross section measurements



The data/theory ratio for several single-boson fiducial production cross section measurements, corrected for leptonic branching fractions. All theoretical expectations were calculated at NLO or higher. The dark-color error bar represents the statistical uncertainly. The lighter-color error bar represents the full uncertainty, including systematics and luminosity uncertainties. The luminosity used and reference for each measurement are also shown. Uncertainties for the theoretical predictions are quoted from the original ATLAS papers. They were not always evaluated using the same prescriptions for PDFs and scales.

CONCLUSIONS

- ***Probing different aspects of our understanding of the Stand Model***
- ***Great variety of precision QCD results***
  - The latest results from the ATLAS 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, 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*



Thank you very much for attention!

ATLAS EXPERIMENT

BACKUP SLIDES

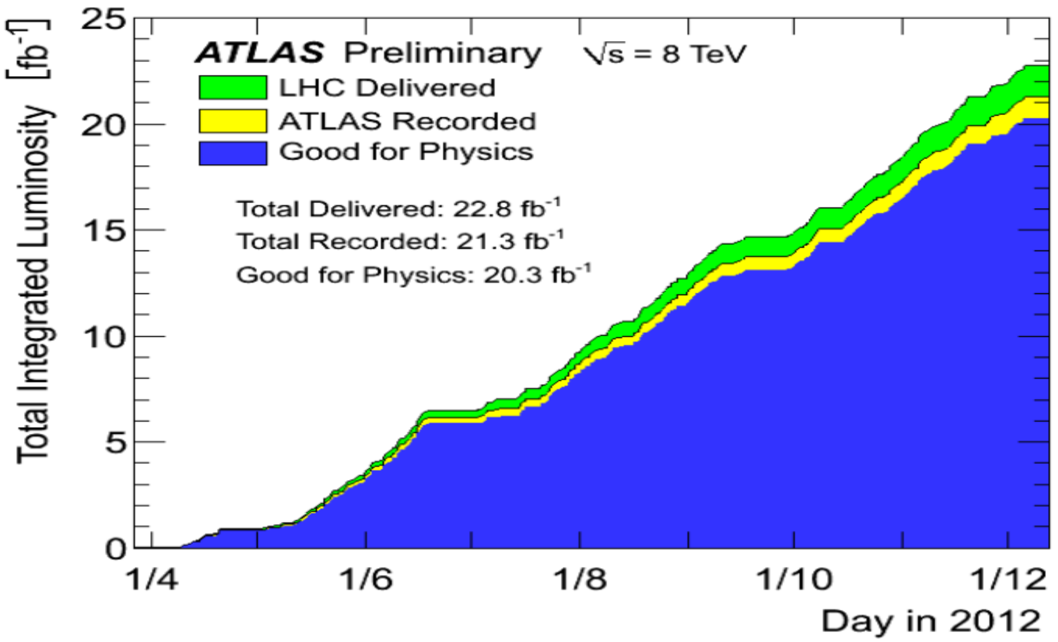
OUTLINE OF THE TALK

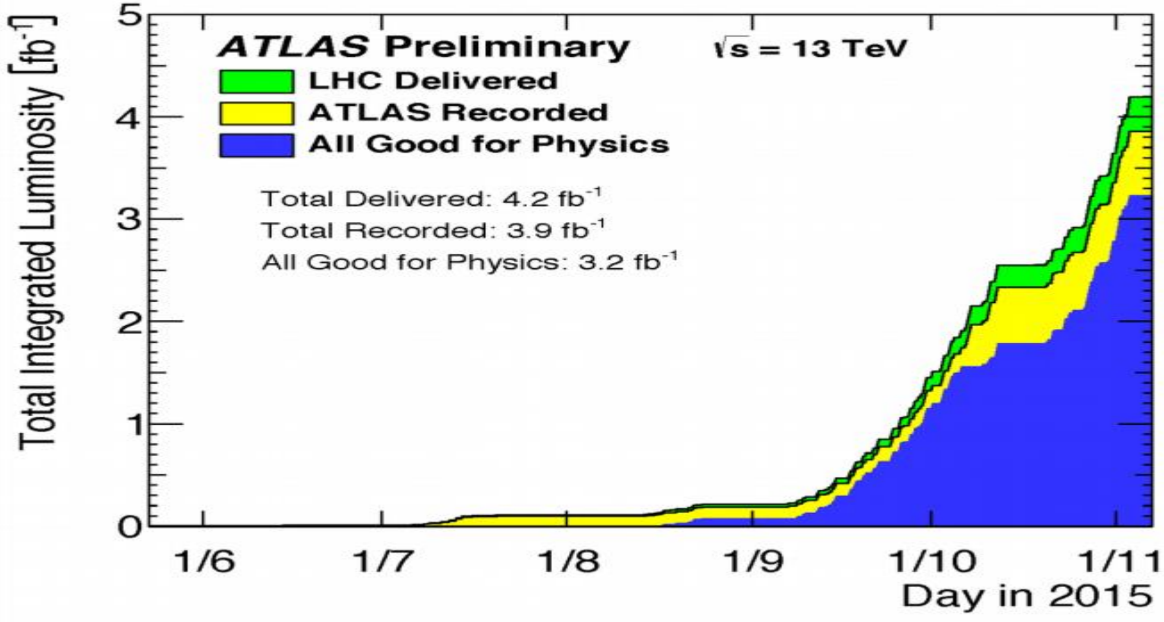
- New Standard Model results
- Motivation: Jet physics
- ATLAS detector
  - Reconstruction of physical objects: Jets, photons/electrons
- Jet physics in pp-collisions at 8 &13 TeV
  - Inclusive Jet and Dijet cross-sections at *13 TeV* *(JHEP 05 (2018) 195)*
    - *Comparison inc. Dijet & inc. Jet at 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* *(JHEP 05 (2018) 077)*
  - Soft-drop Jet mass at *13 TeV* *(Phys. Rev. Lett. 121 (2018) 092001)*
- Conclusions

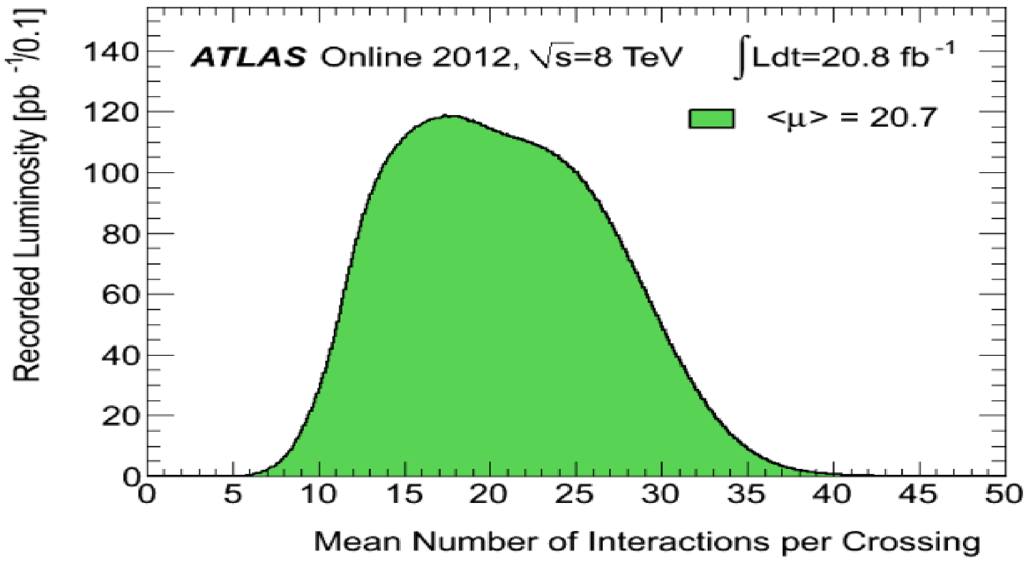
PUBLICATIONS

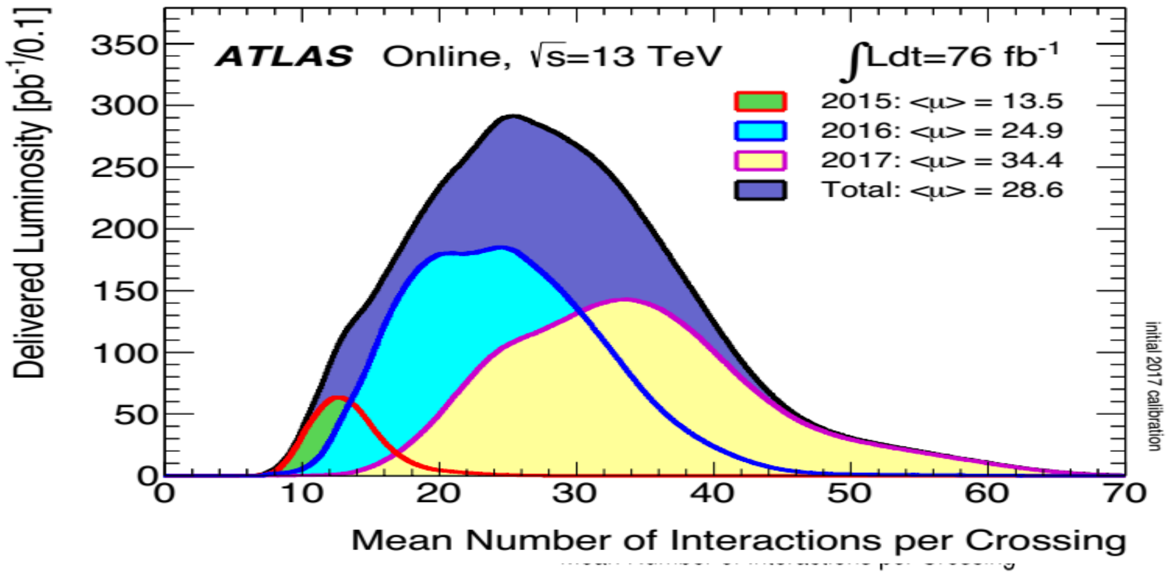
- Measurement of *inclusive* ***jet and dijet*** cross-sections in proto-proton collisions at $\sqrt{s}=13$ *TeV* with the ATLAS detector, *arXiv:1711.02692*, ***JHEP 05 (2018) 195***
- Measurement of the ***inclusive jet*** cross-sections in proton–proton collisions at $\sqrt{s}=8$ *TeV* with the ATLAS 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*, ***JHEP 05 (2018) 077***
- A measurement of the ***soft-drop jet mass*** in pp collisions at $\sqrt{s}=13$ *TeV* with the ATLAS detector, *arXiv:1711.08341*, ***PRL 121, 092001 (2018)***

ATLAS DATA AT 8 AND 13 TEV







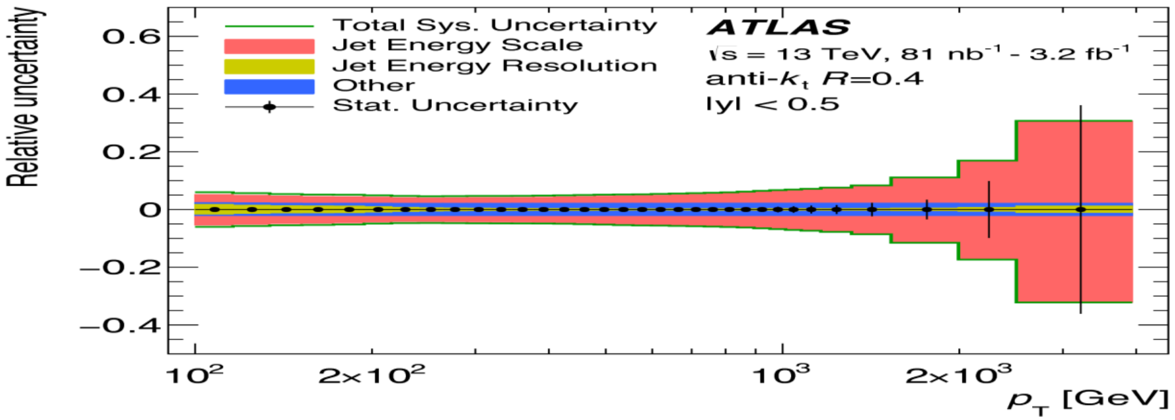


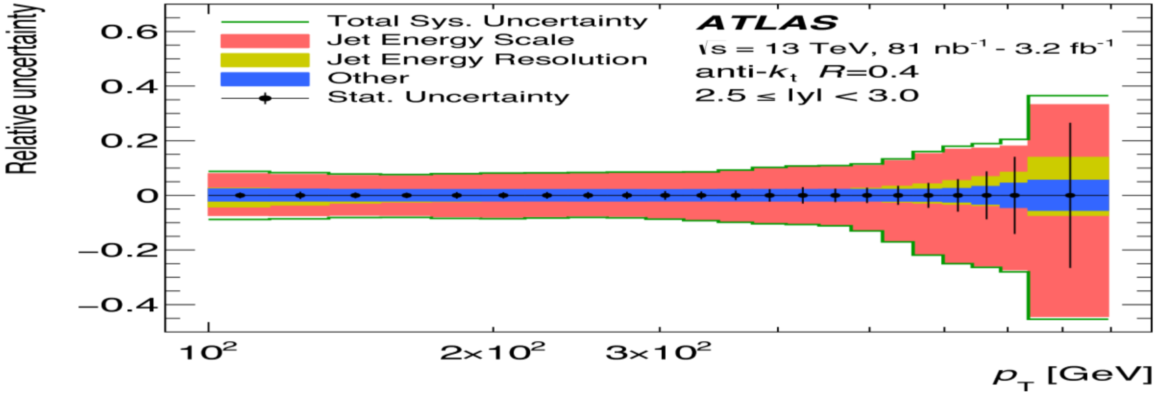
Relative Systematic Uncertainties: pp → jet, dijet + X at 13 TeV

arXiv:1711.02692

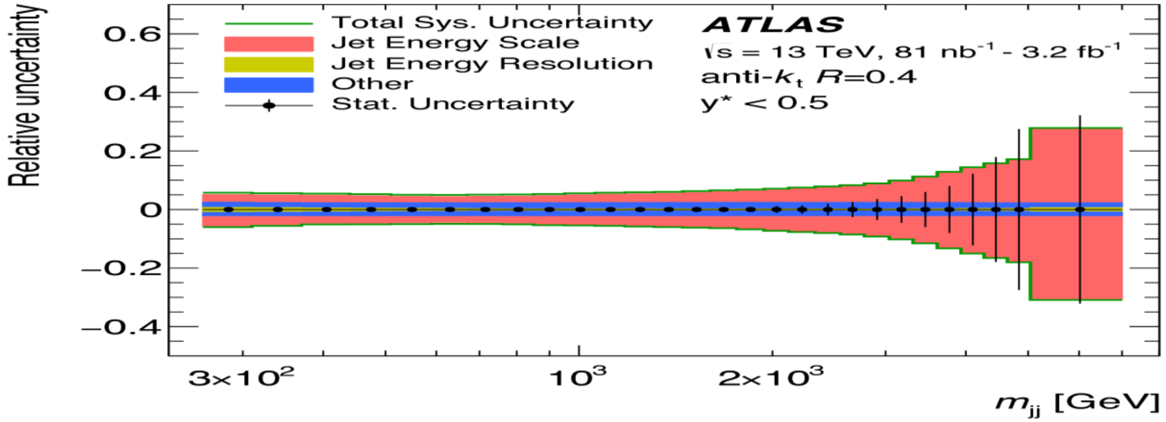
Relative systematic uncertainty for the inclusive jet cross-section as a function of the jet (dijet) p_T (m_{jj}) for the first (left) and last (right) |y| (y*) bins. The individual uncertainties are shown in different colours: the JES, JER, jet cleaning, luminosity & unfolding.

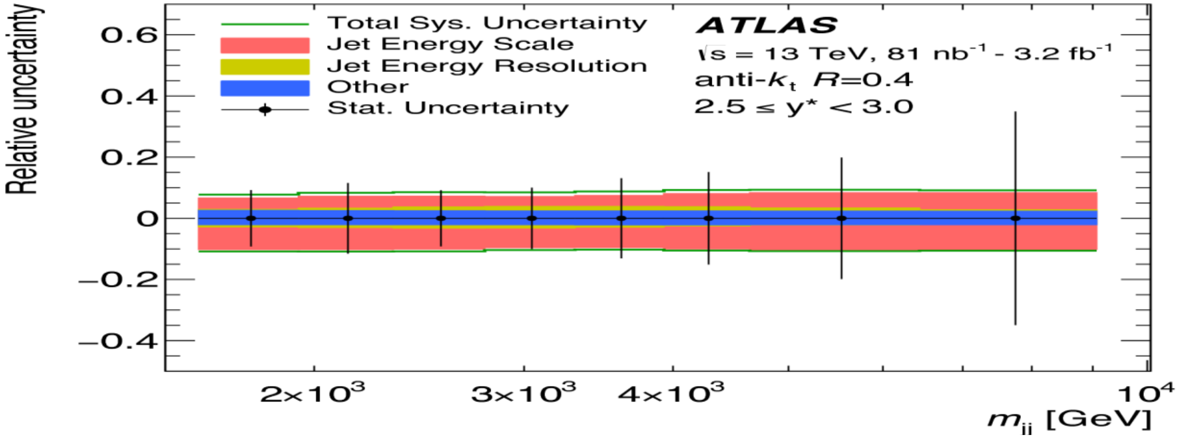
Jet





Dijet



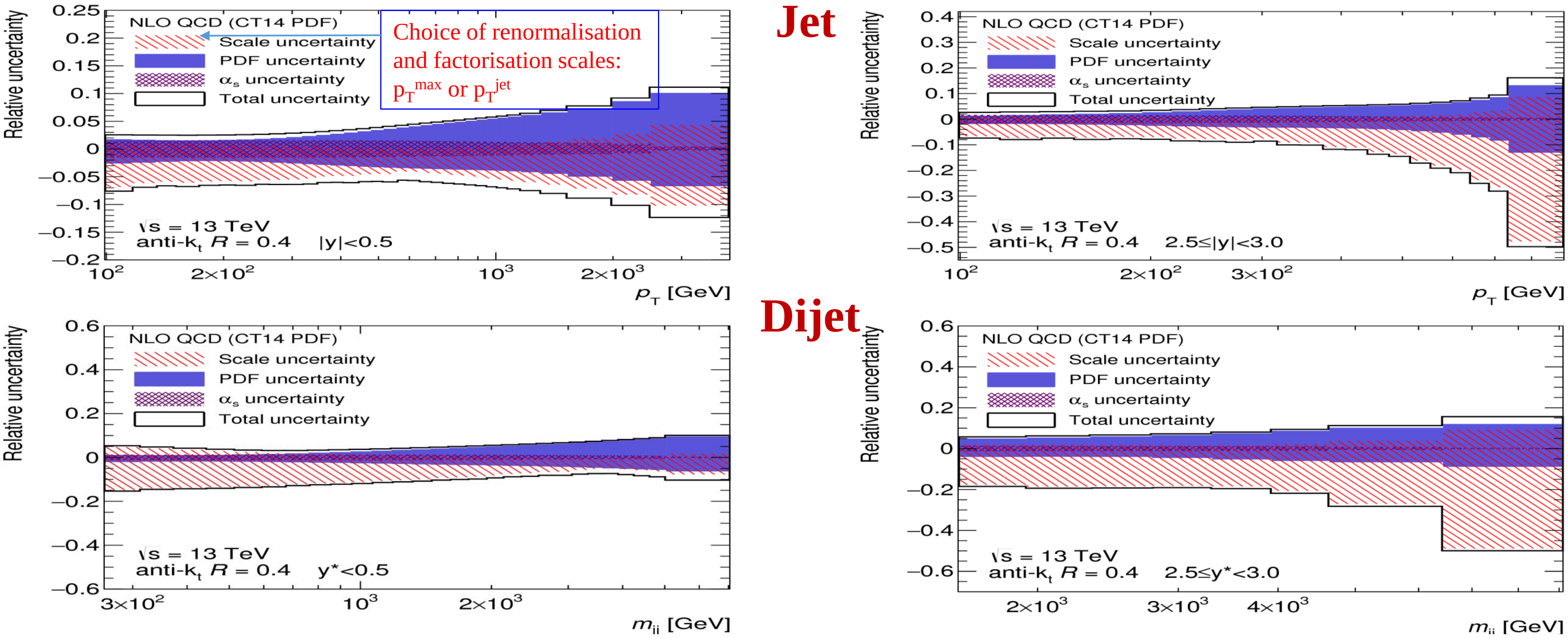


In the central (forward) region the total uncertainty in the inclusive jet measurement is about 5%(8%) at medium p_T of 300-600 GeV. The uncertainty increases towards both lower and higher p_T reaching 6%(10%) at low p_T and 30% ([-45%,+40%]) at high p_T. The total uncertainty in the dijet measurement 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.



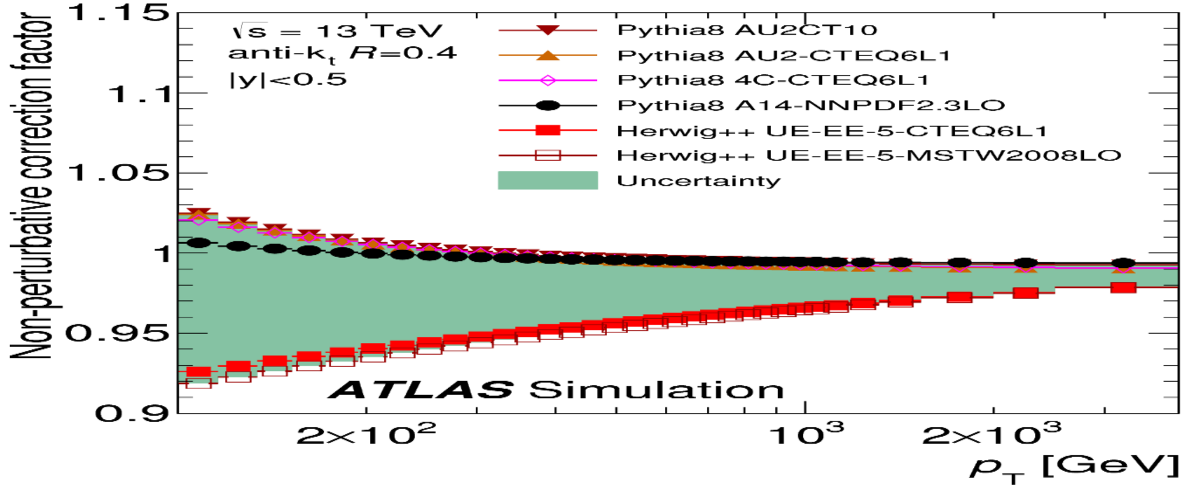
The uncertainty due to the [1] **choice of renormalisation and factorisation scale** is ***dominant in most phase-space regions***, rising from 10% (20%) at about p_T=100 GeV (m_{jj}=300 GeV) in the central |y| (y*) bin to about 50% in the highest p_T (m_{jj}) bins in the most forward |y| (y*) region.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

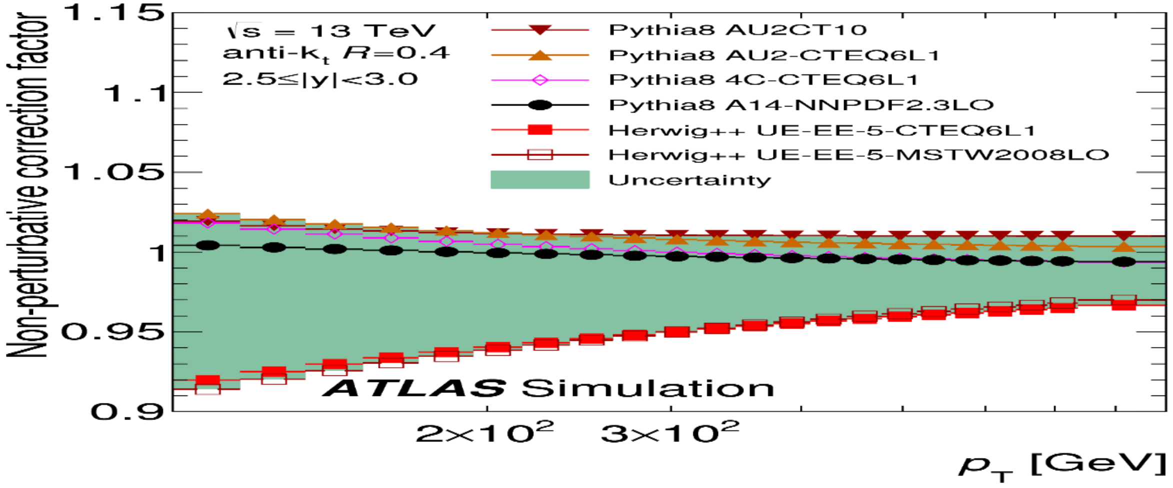
NON-PERTURBATIVE CORRECTION FACTORS: PP → JET, DIJET + X AT 13 TEV

arXiv:1711.02692

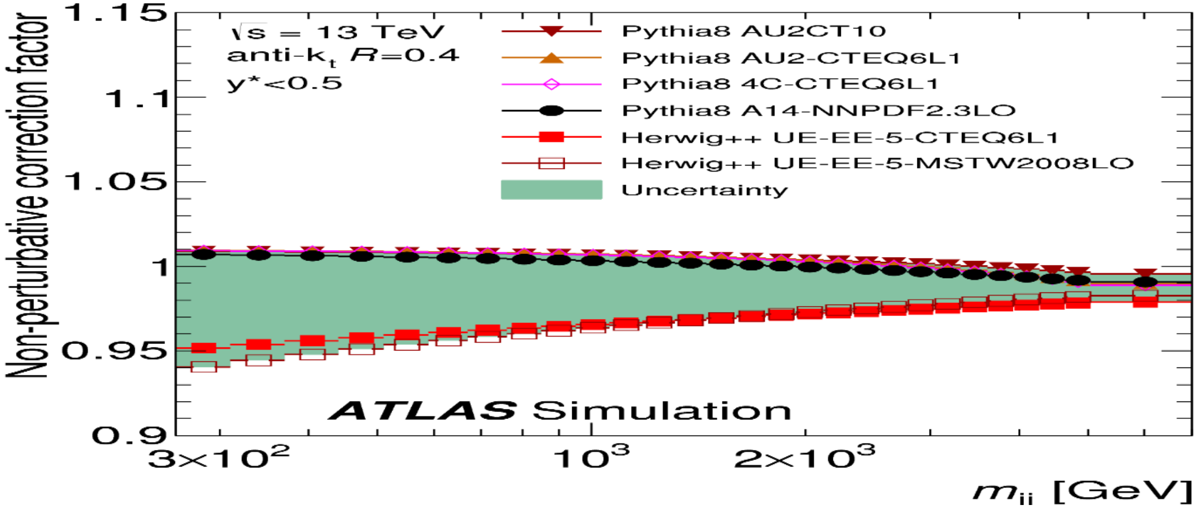
Non-perturbative correction factors for the (jet, dijet) **NLO pQCD** prediction as a function of (p_T^{jet}, m_{jj}) for (left) the first (|y|, y*) bin and for (right) the last (|y|, y*) bin. The corrections are derived using **Pythia 8 A14** with the **NNPDF2.3 LO PDF set**

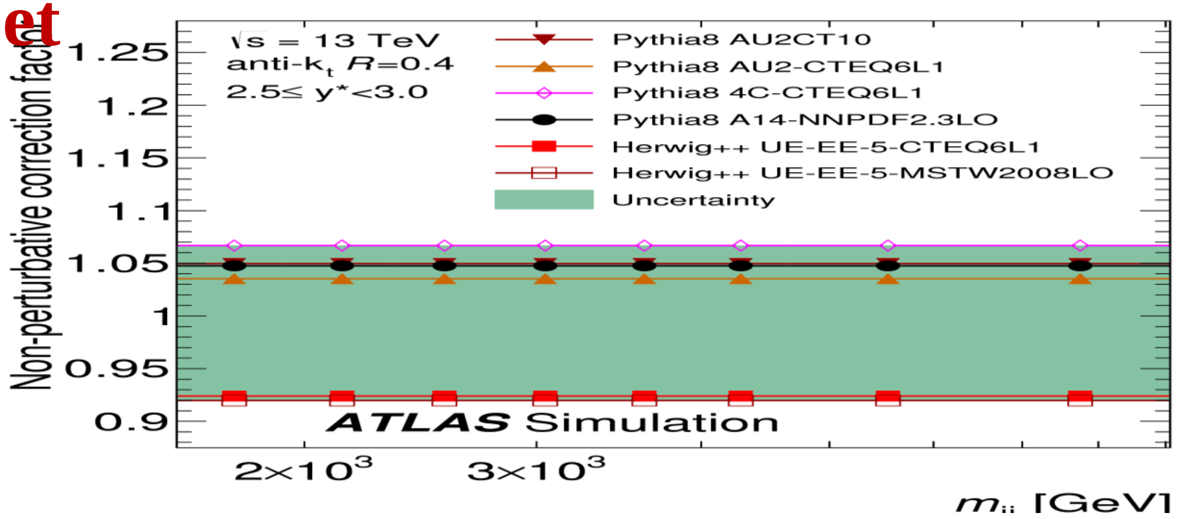
Jet





Dijet



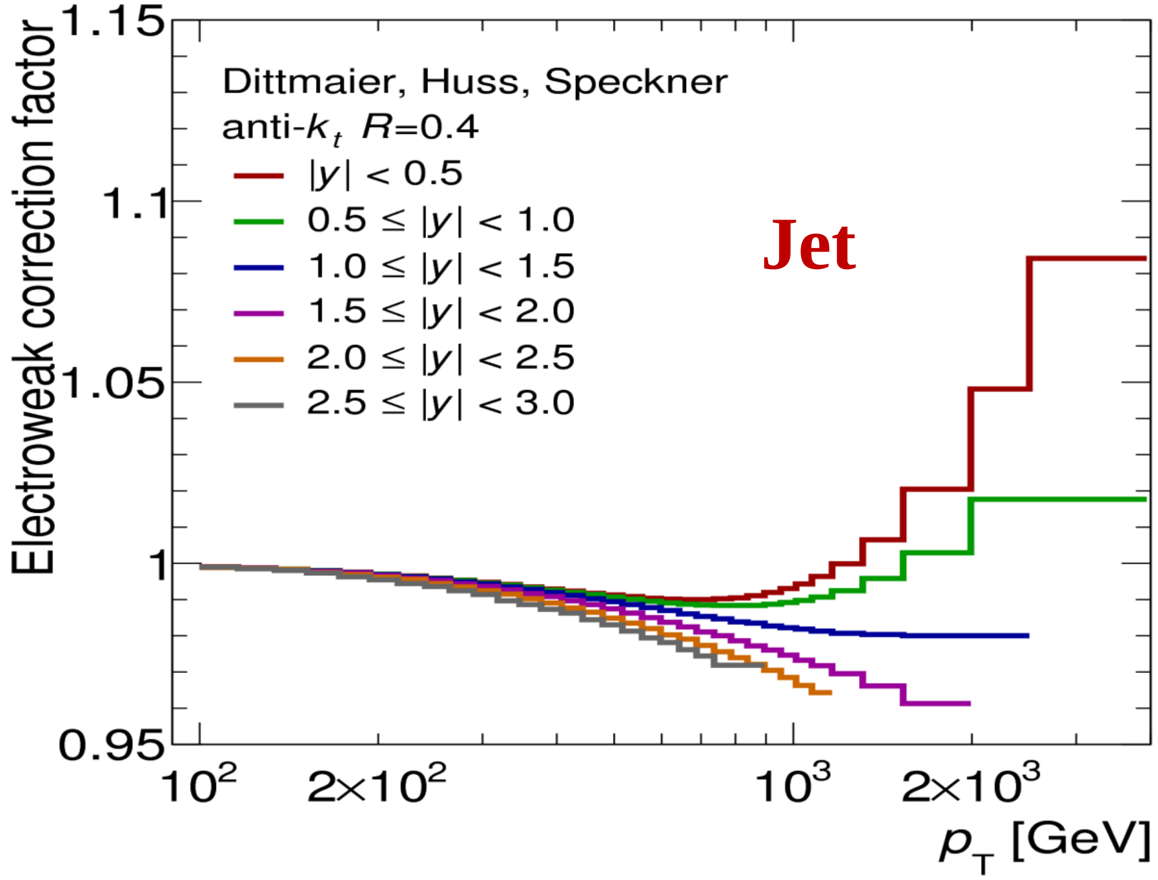


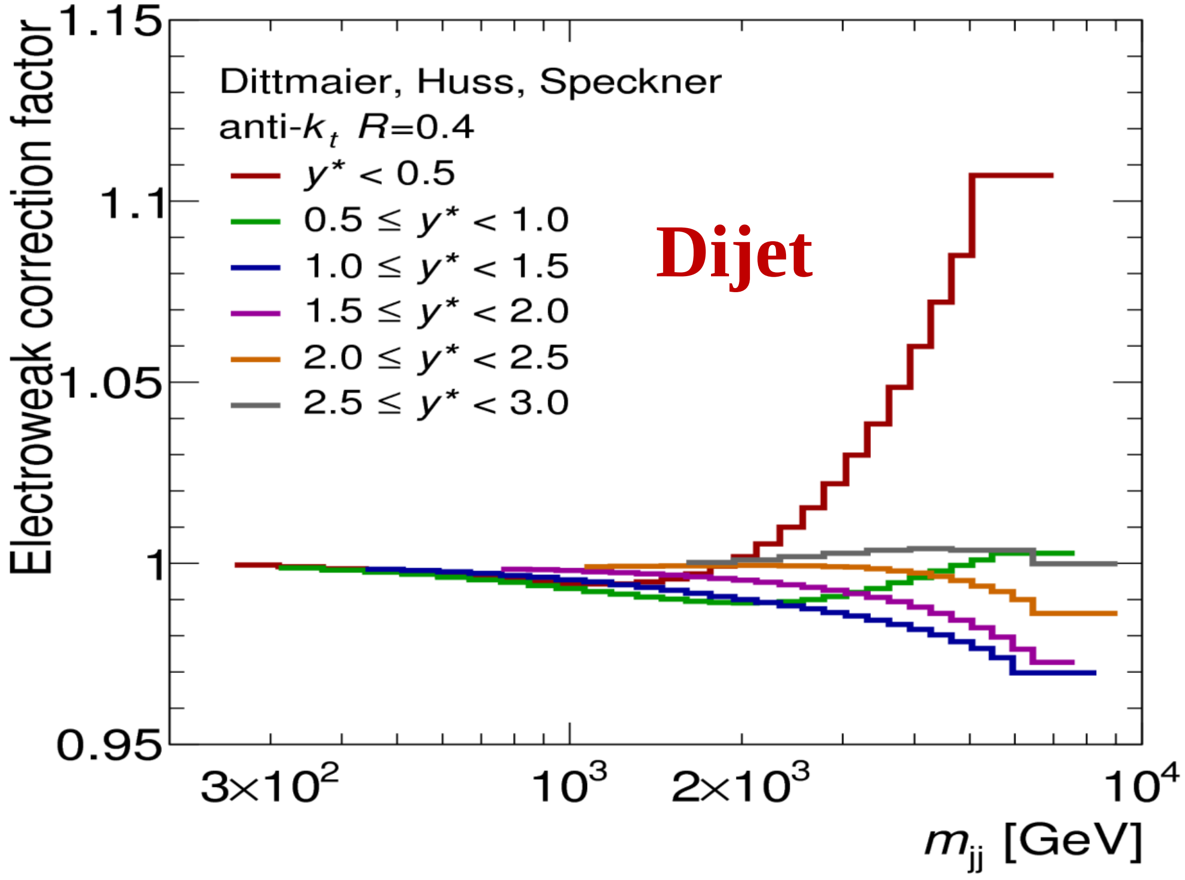
The values of the correction are: for jet → 0.92-1.03 at low p_T and 0.98-0.99 (0.97-1.01) at high p_T for the first (last) |y| bin & for dijet → 0.94-1.01 (0.98-0.99) at low (high) m_{jj} for the first y* bin and for the last y* bin is a fixed range 0.92-1.07

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





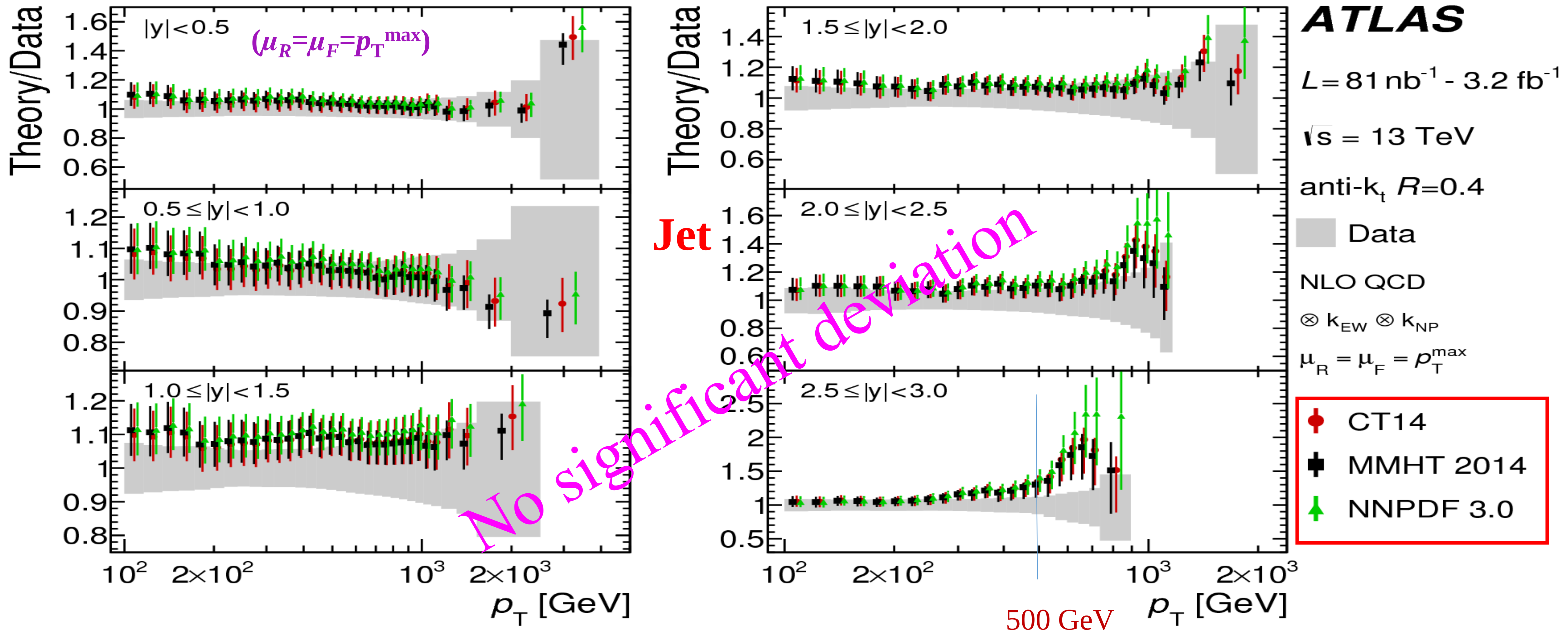
- The electroweak correction is small for low jet p_T and for low m_{jj}
- For jets the correction reaches 8% at the highest p_T (3 TeV) for the central |y| bin and is less than 4% for the rest of the |y| bins
- For dijets the EW correction reaches 11% at m_{jj} = 7 TeV for the central y* bin and less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

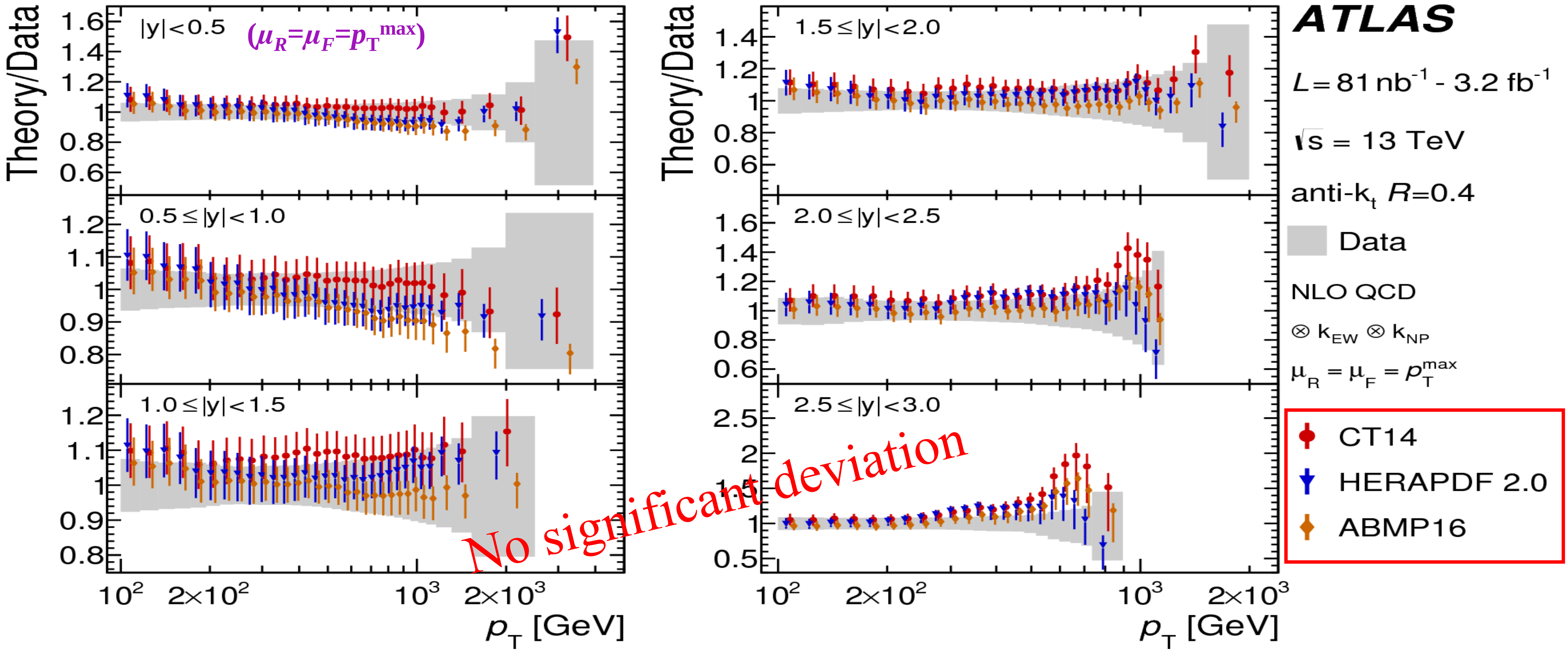
The **CT14** case is repeated to serve as a reference for comparison

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**

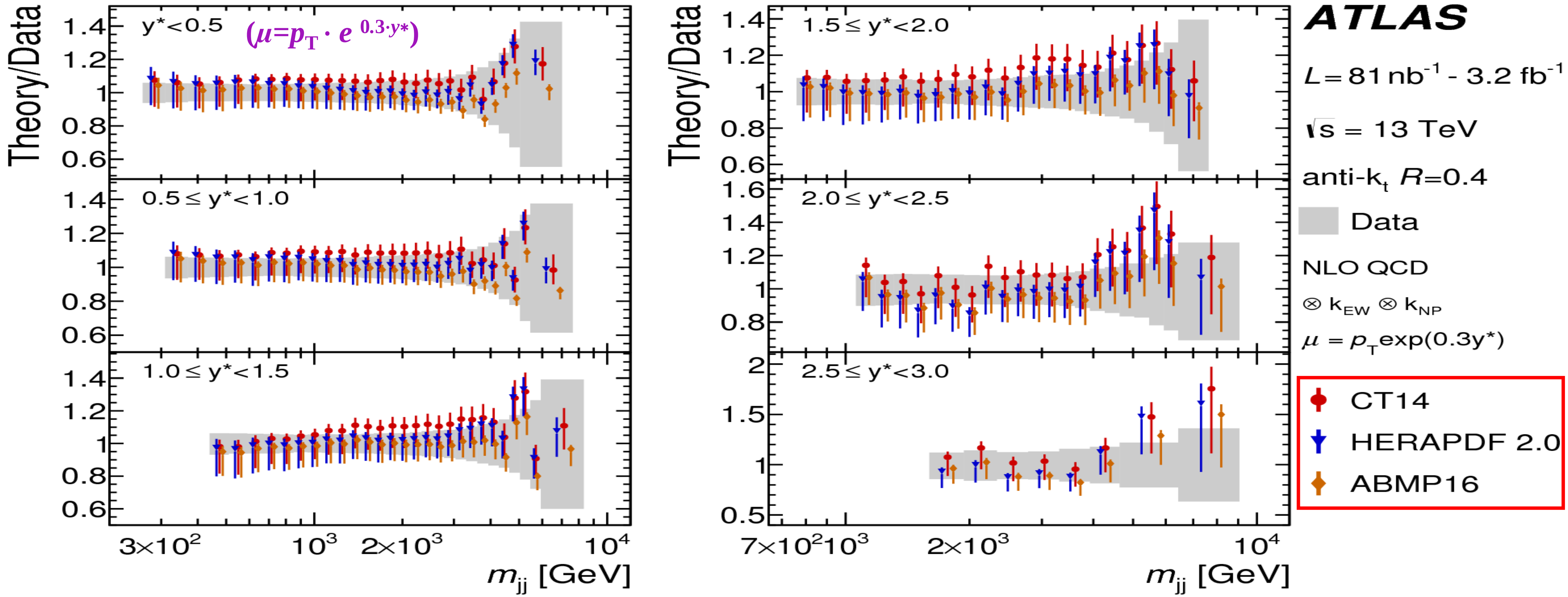


The **CT14** case is repeated to serve as a reference for comparison

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**

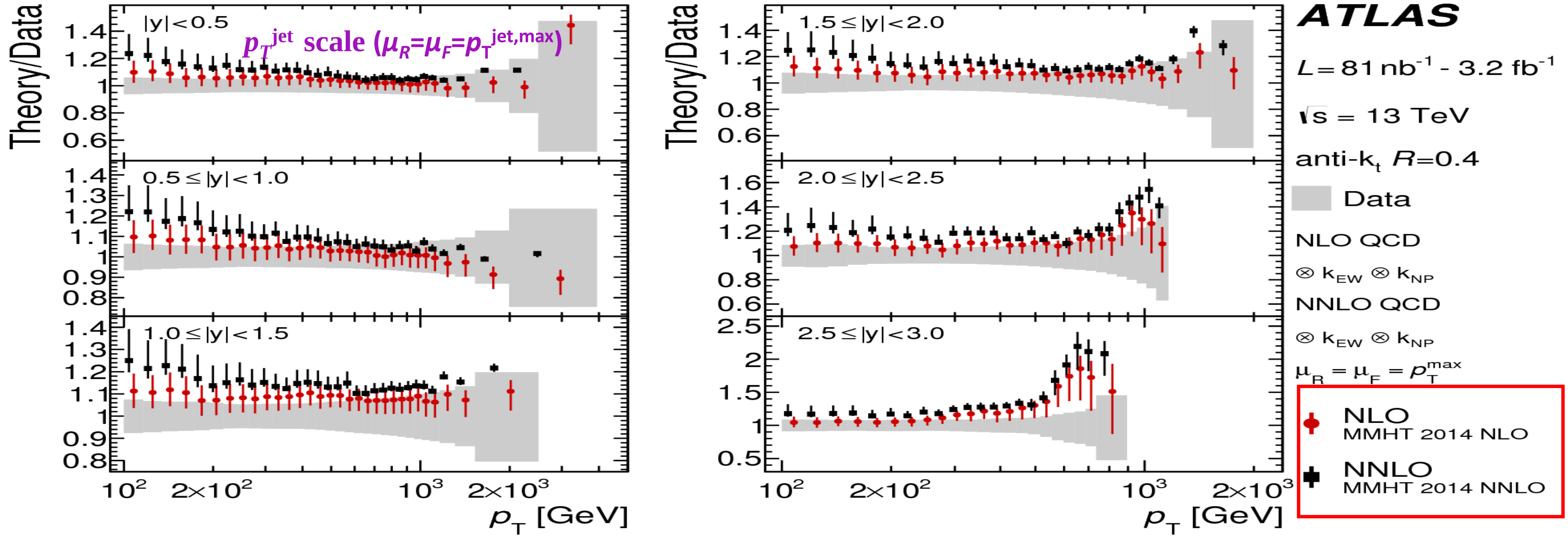


The **CT14** case is repeated to serve as a reference for comparison

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

arXiv:1711.02692

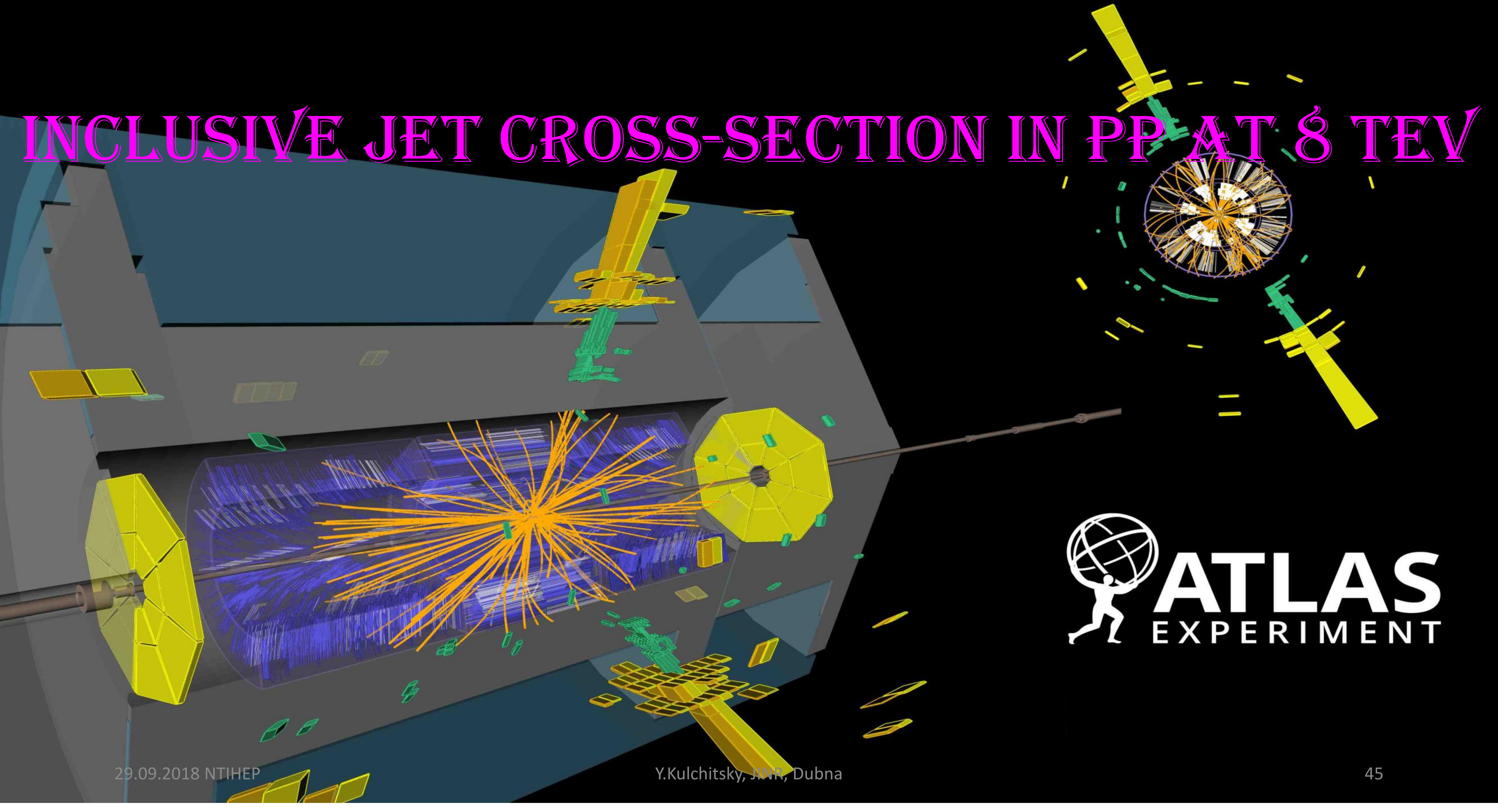
Ratio of **NLOJet++ (p_T^{max} QCD scale) prediction** to measurements **of Jet** double-diff. cross-sec vs **p_T ^{jet} and y:** PDF sets used**: MMHT 2014 NLO, MMHT 2014 NNLO**



- **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

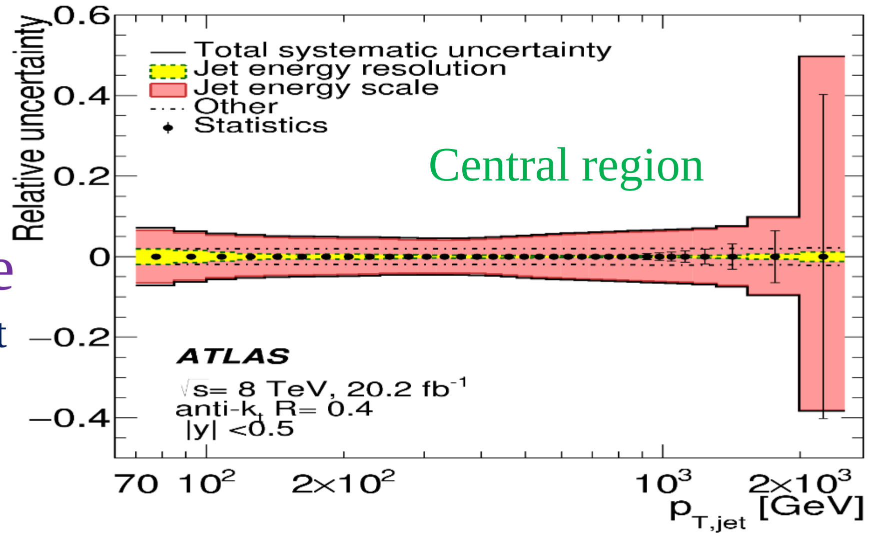
Inclusive jet cross-section in pp at 8 TeV

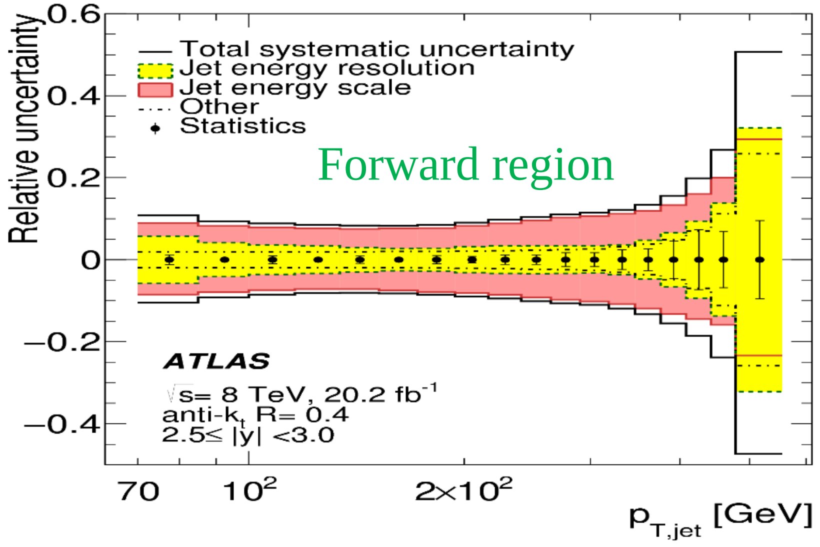


Event & Jet Selection for pp → jet + X at 8 TeV

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, |η|<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





Relative systematic uncertainty

- 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%

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

JHEP 09 (2017) 020

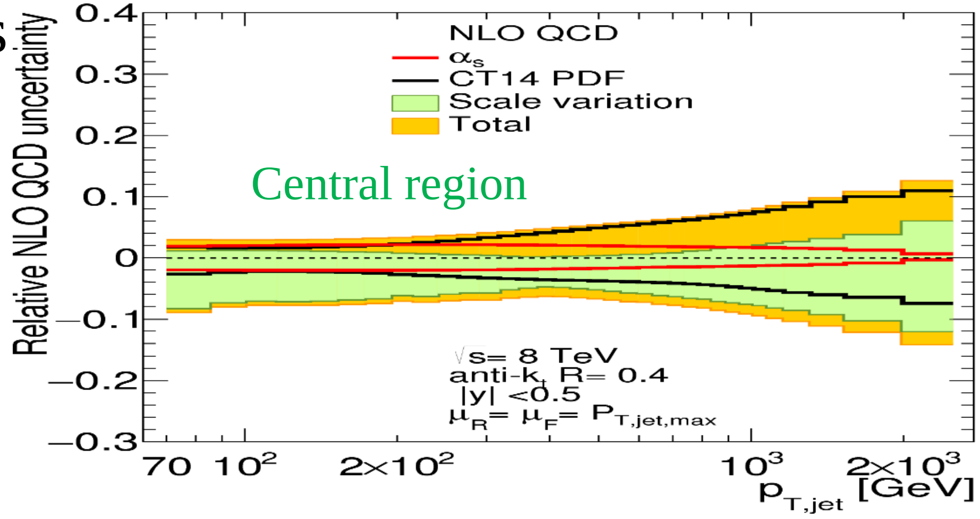
The double-diff. inclusive jet cross-section measurement vs p_T-jet &y: kinematic region: **70 GeV≤p_T^{jet}≤2.5 TeV& |y|<3**

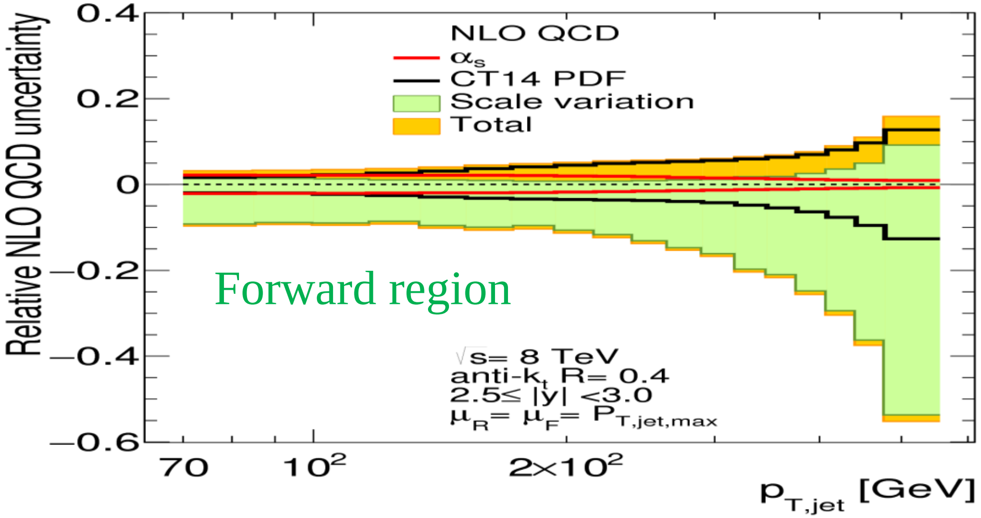
- **Motivation**: a test of validity of pQCD and probing of the parton distribution functions (PDFs) in the proton

- 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.





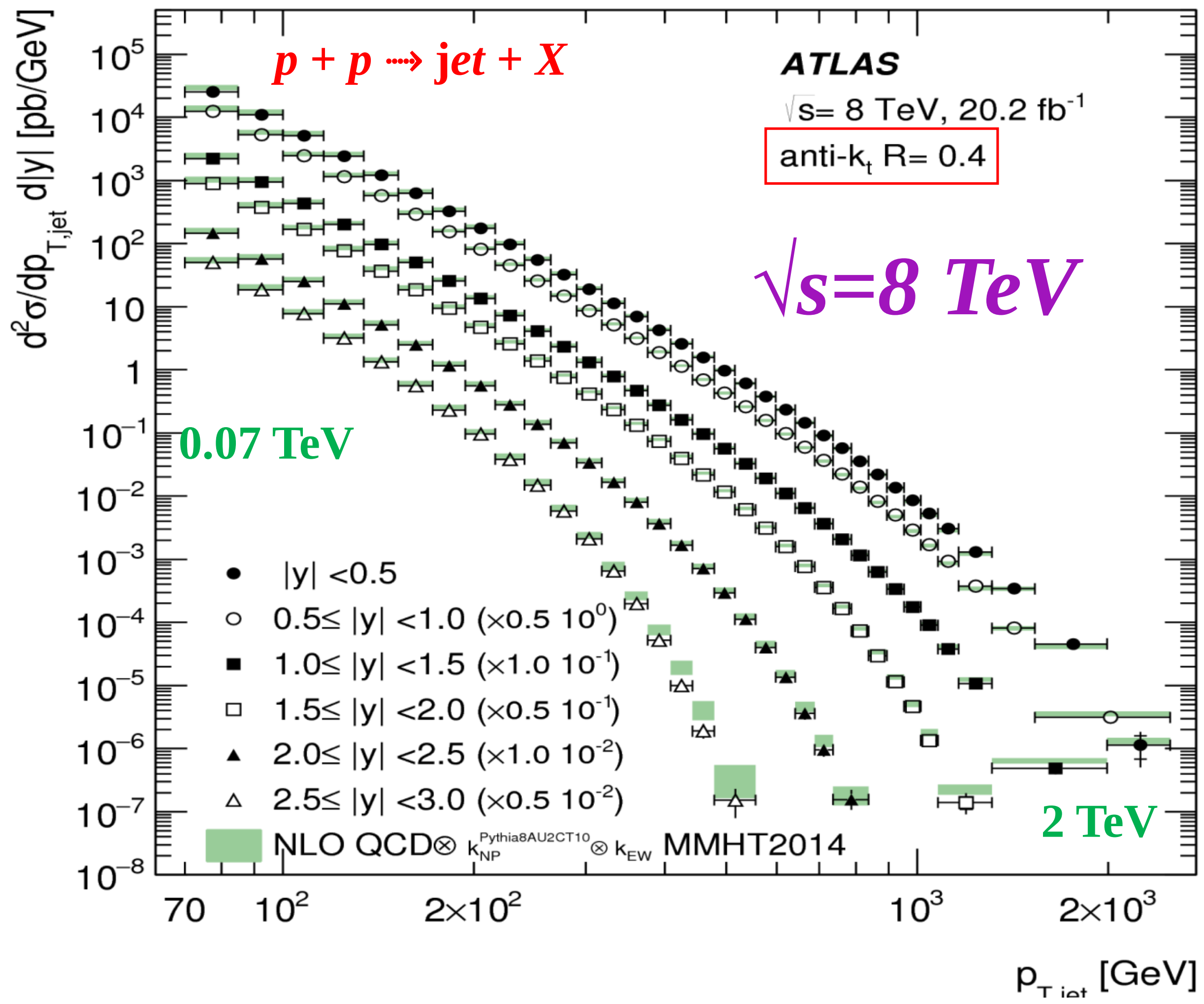
Uncertainty in the NLO pQCD prediction of inclusive jet X-sec vs jet p_T – potential of jet physics for improving PDFs

Inclusive Jet Cross-Section for: pp → jet + X at 8 TeV

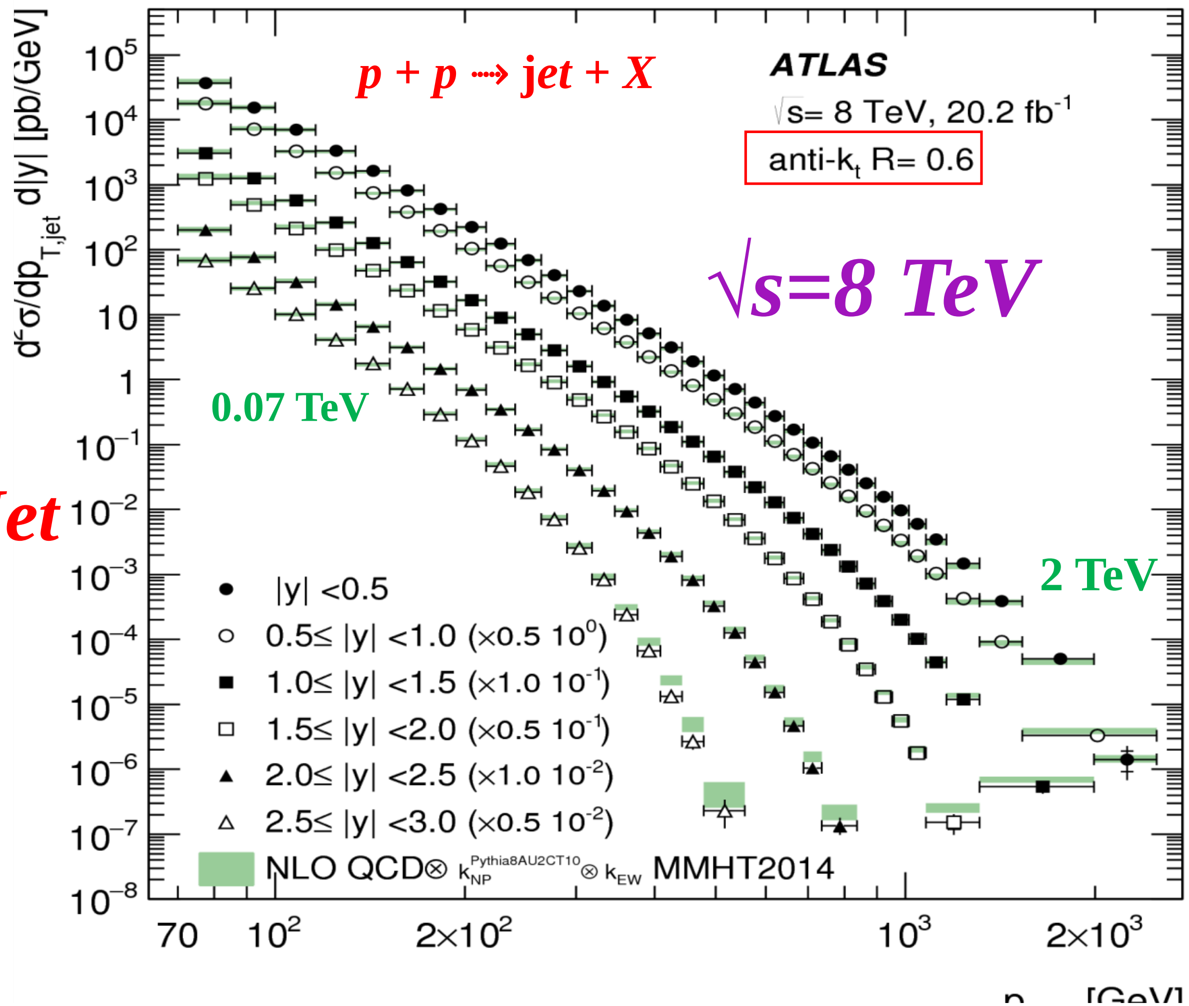
JHEP 09 (2017) 020

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



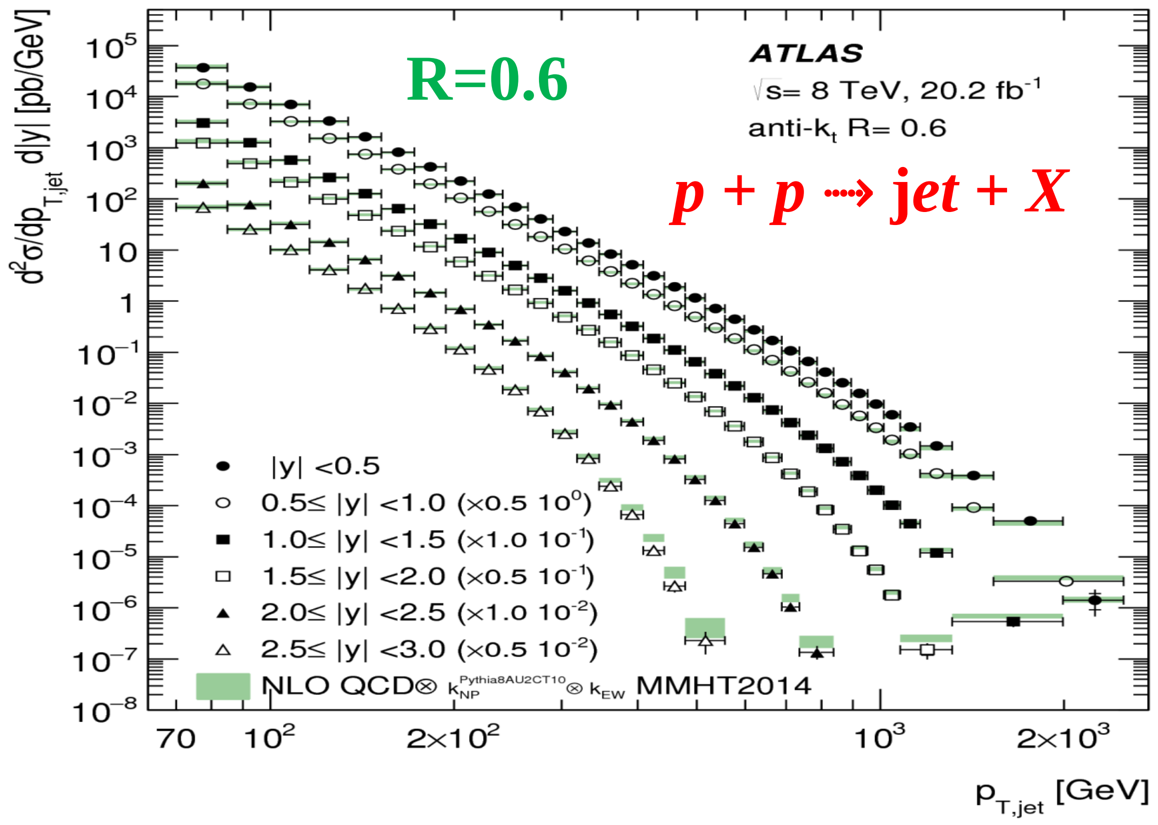
p_T^{jet} > 70 GeV; |y|<3; anti-k_T jets with R=0.4 and R=0.6

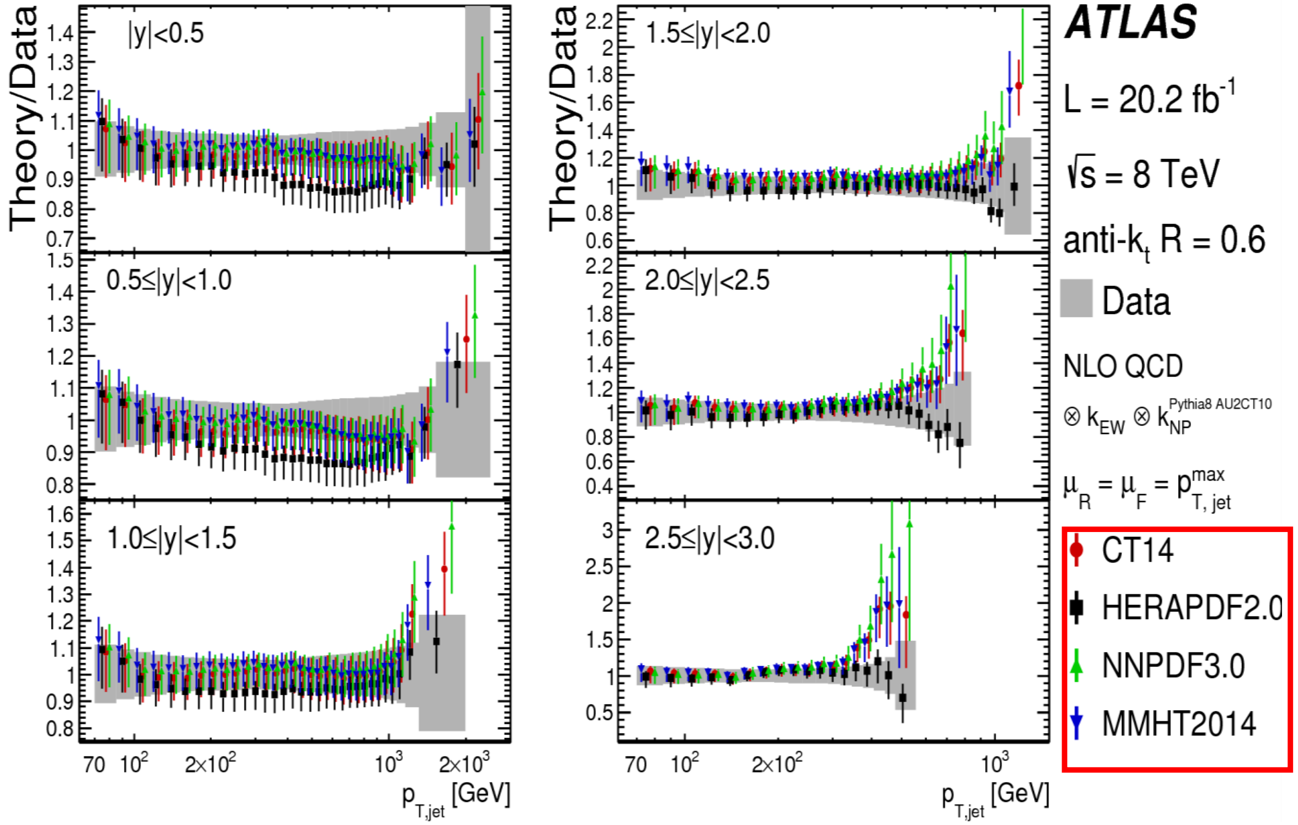
THEORY/DATA COMPARISON FOR PP → JET + X AT 8 TEV

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



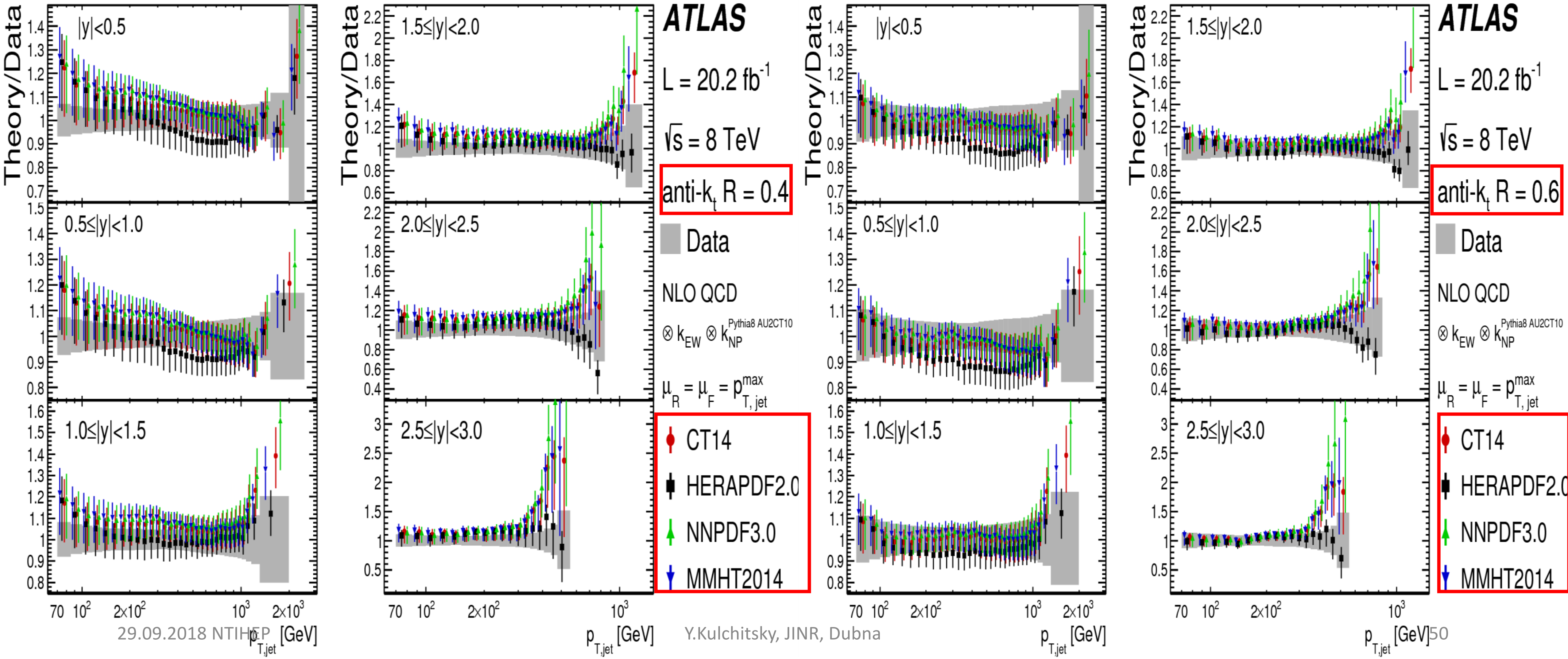


Ratio of **NLO pQCD** predictions to measured double-diff. inclusive **Jet** cross-section vs jet p_T and jet rapidity: different **NLO PDF** sets used **CT14, HEPARDf2.0, NNPDF3.0, MMHT2014**

Ratio NLO QCD for pp → jet + X at 8 TeV

JHEP 09 (2017) 020

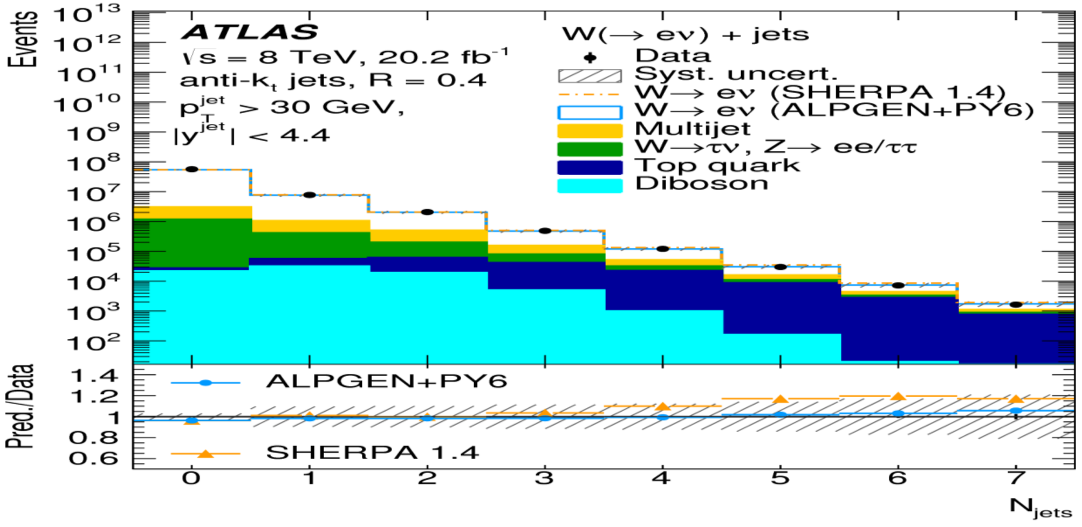
Ratio of **NLO pQCD** predictions to measured double-diff. inclusive jet X-section vs jet p_T and jet rapidity – different **NLO PDF** sets used: **CT14, HERAPDF2.0, NNPDF3.0, MMHT2014**

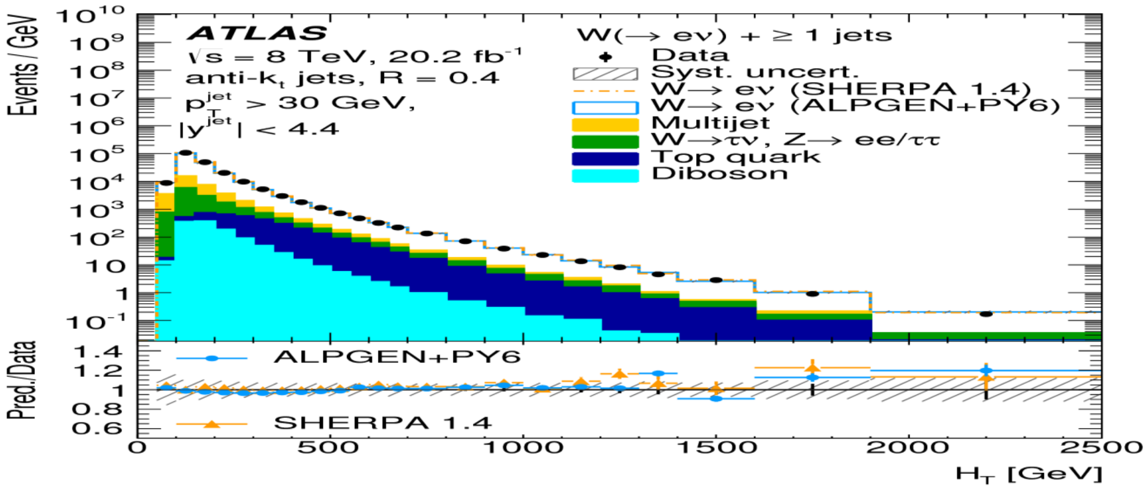


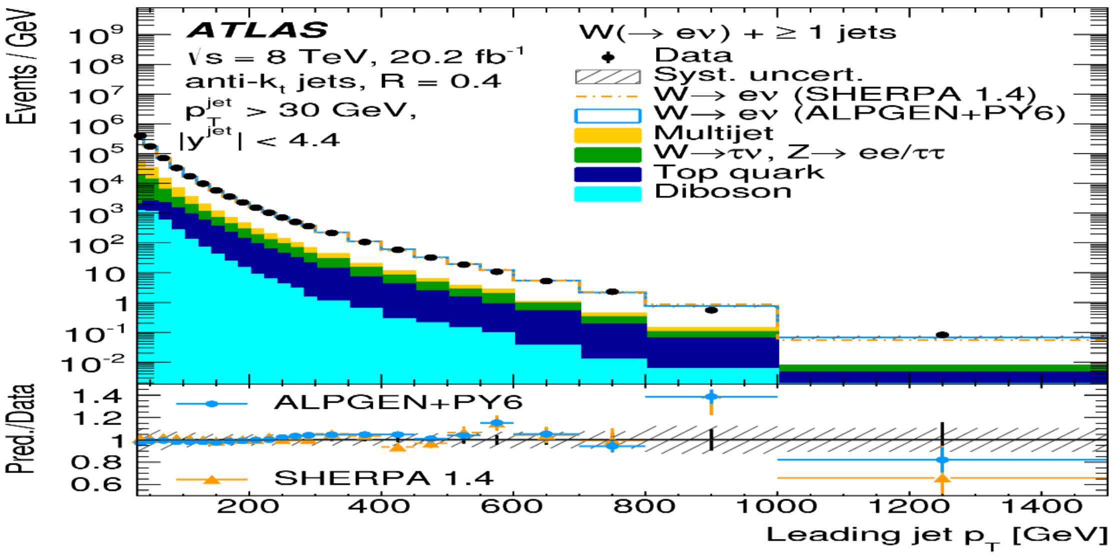
CROSS-SECTIONS OF PP → W + JETS, W^+/W^- RATIOS AT 8 TEV

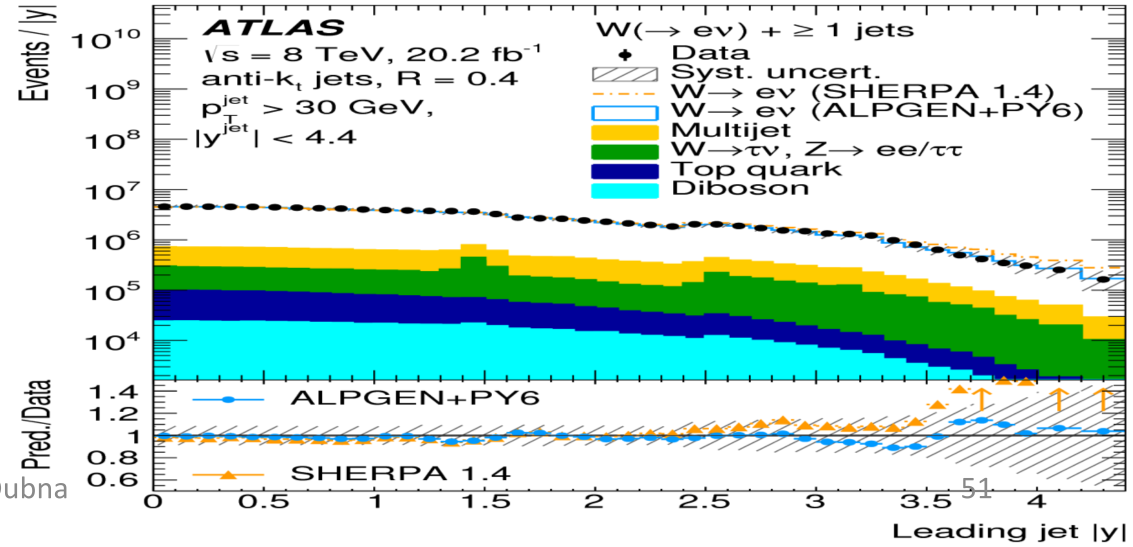
arXiv:1711.03296

- 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





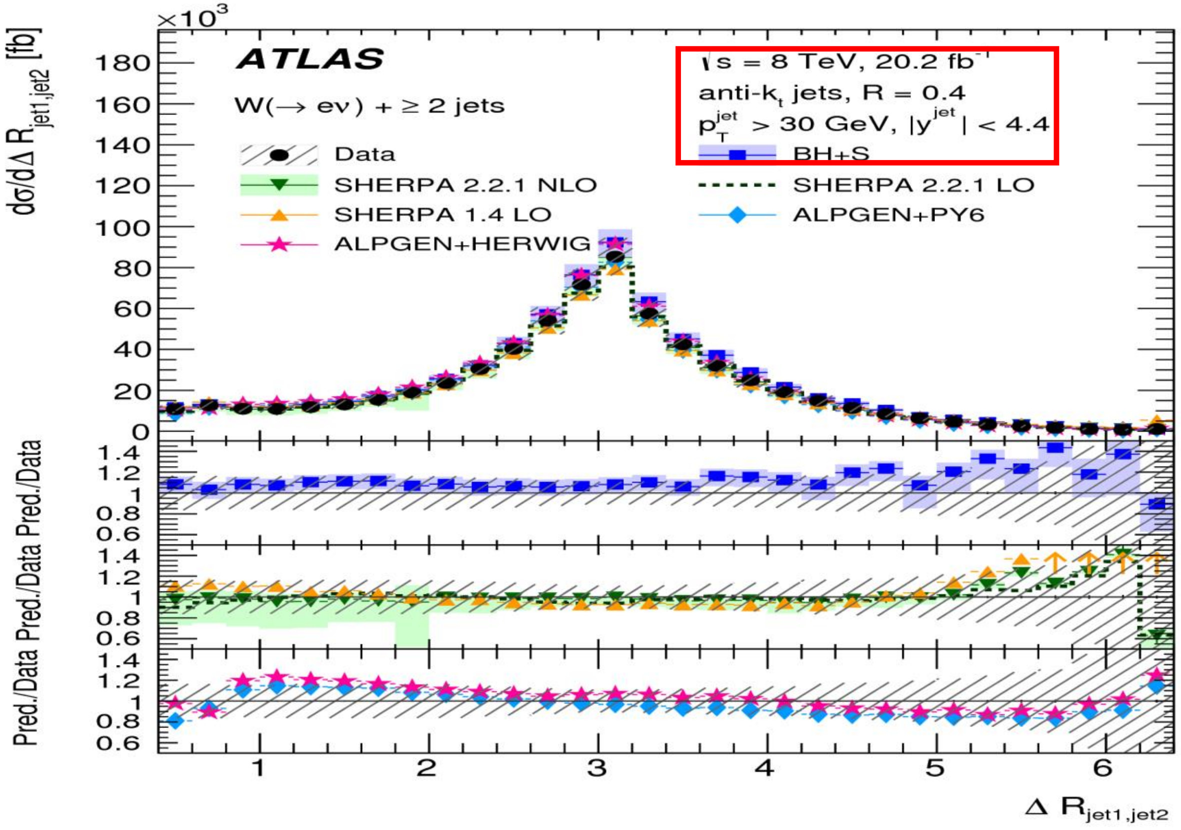


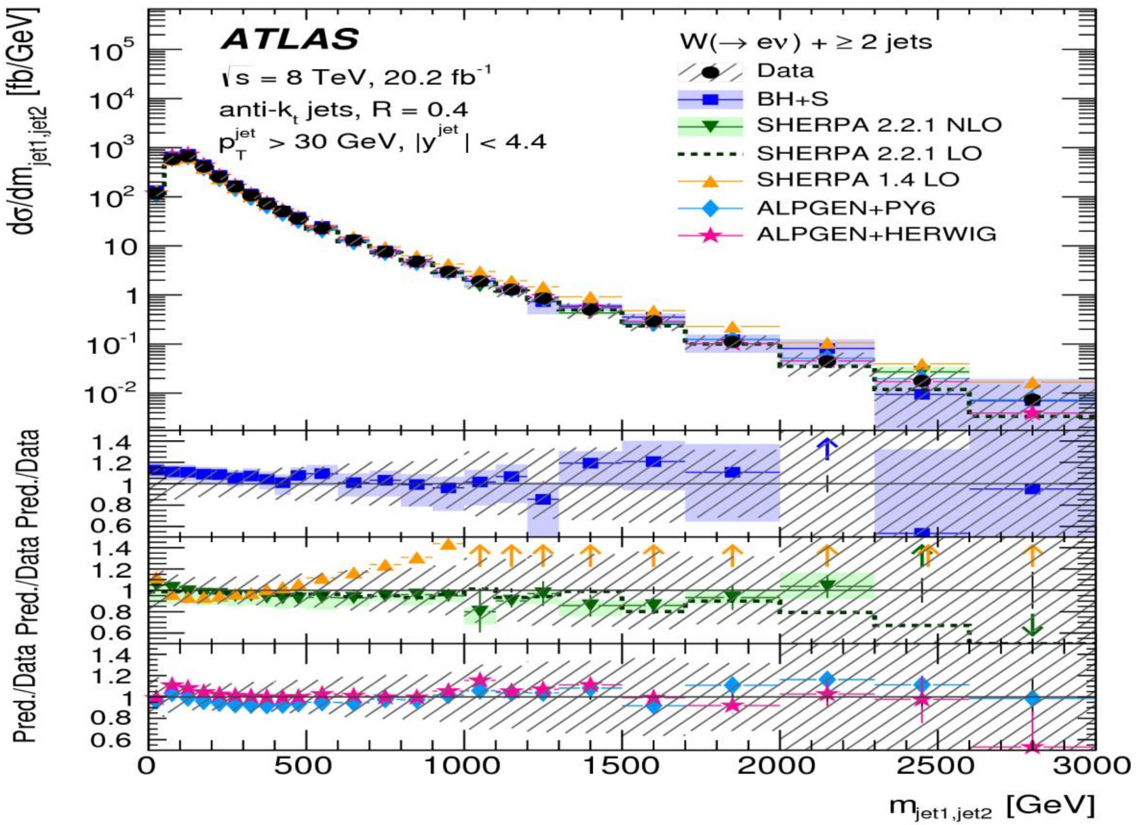


Cross-sections of pp → W + jets, W+/W- ratios at 8 TeV

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



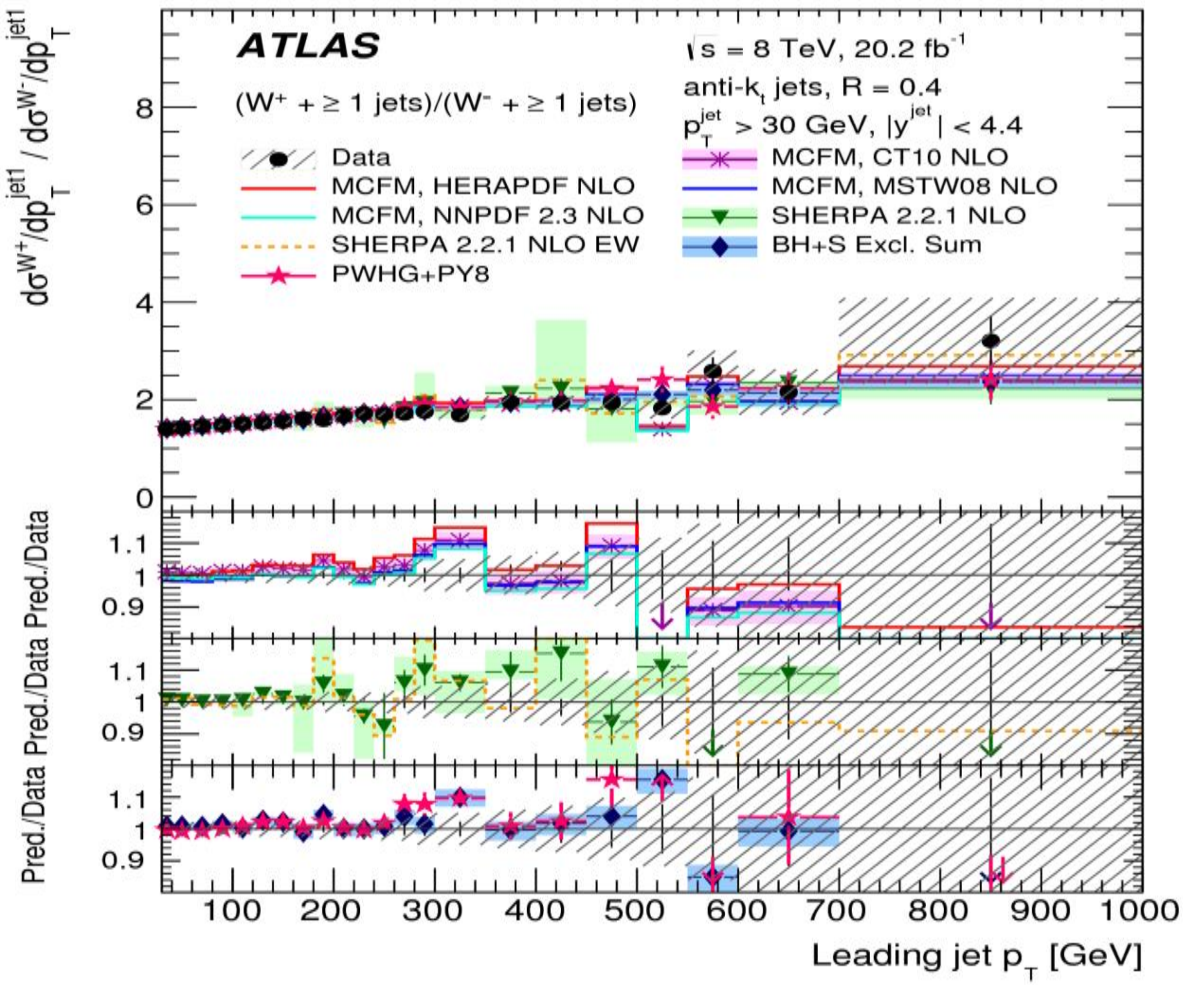


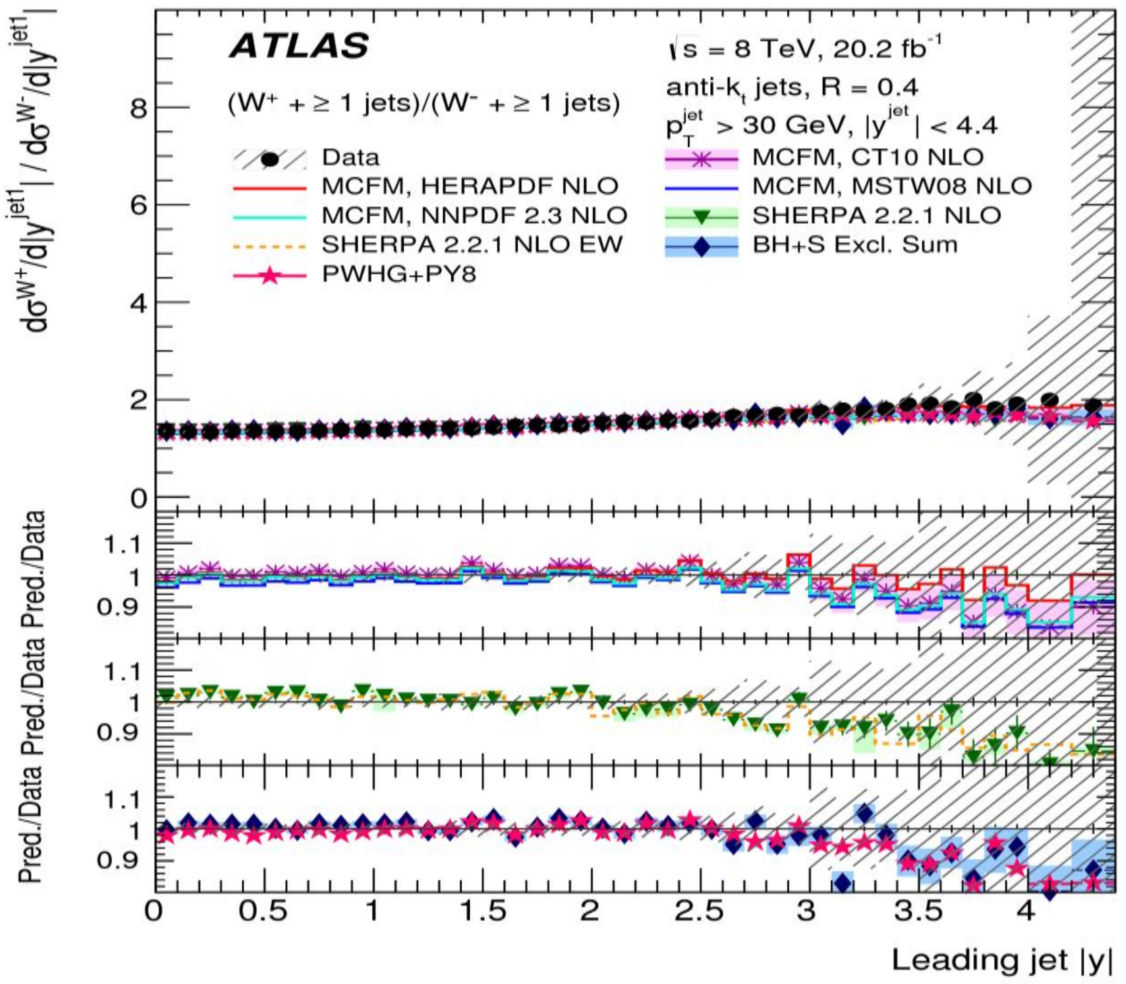
However, there is no single prediction that is able to describe all distributions well

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

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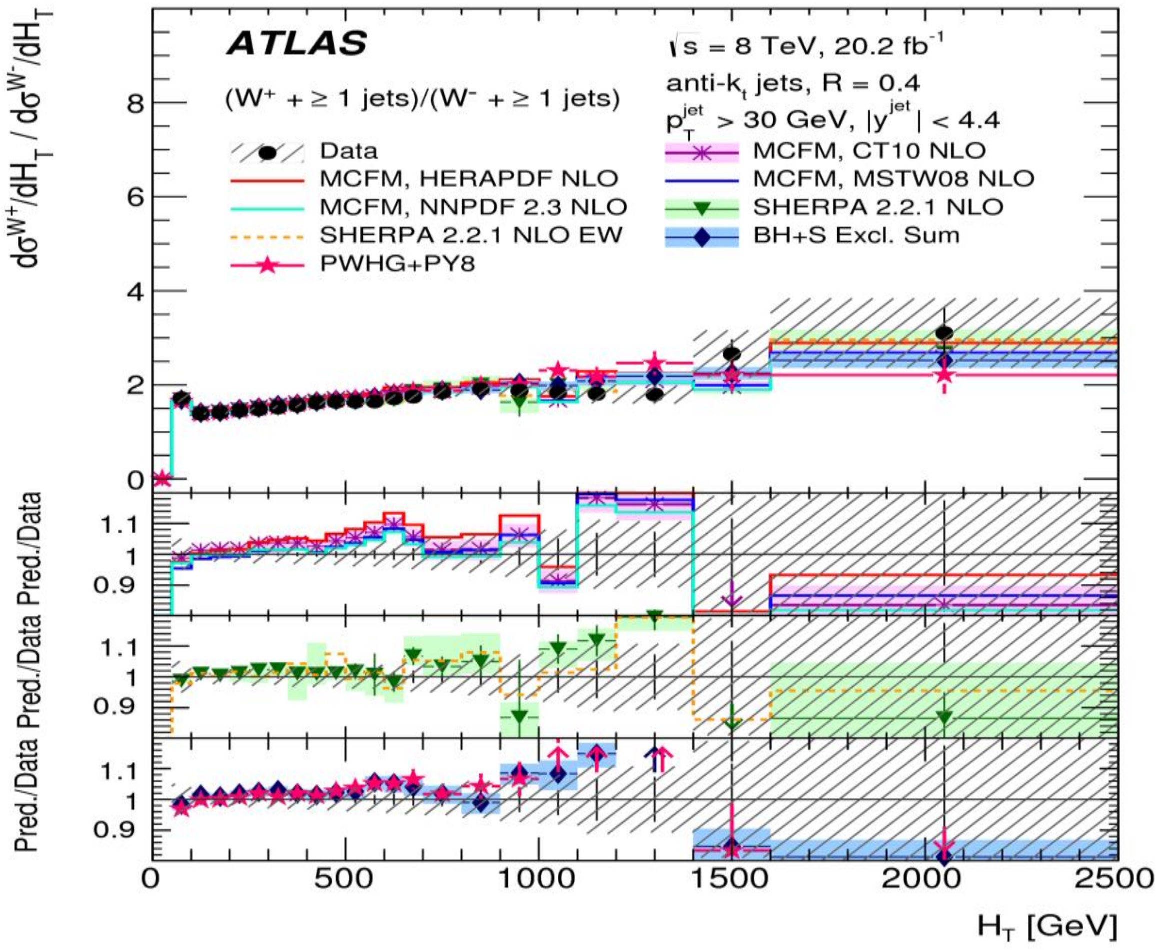
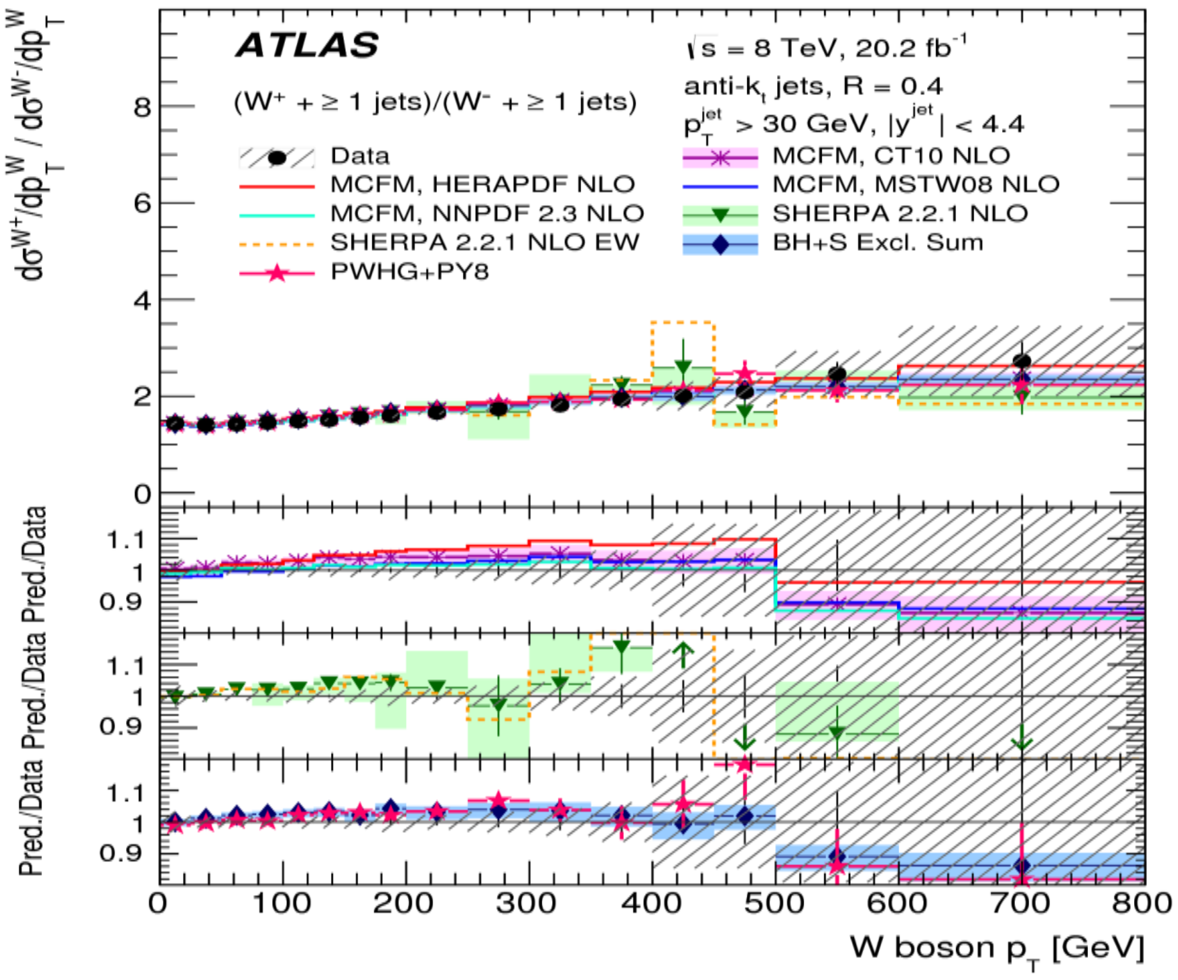
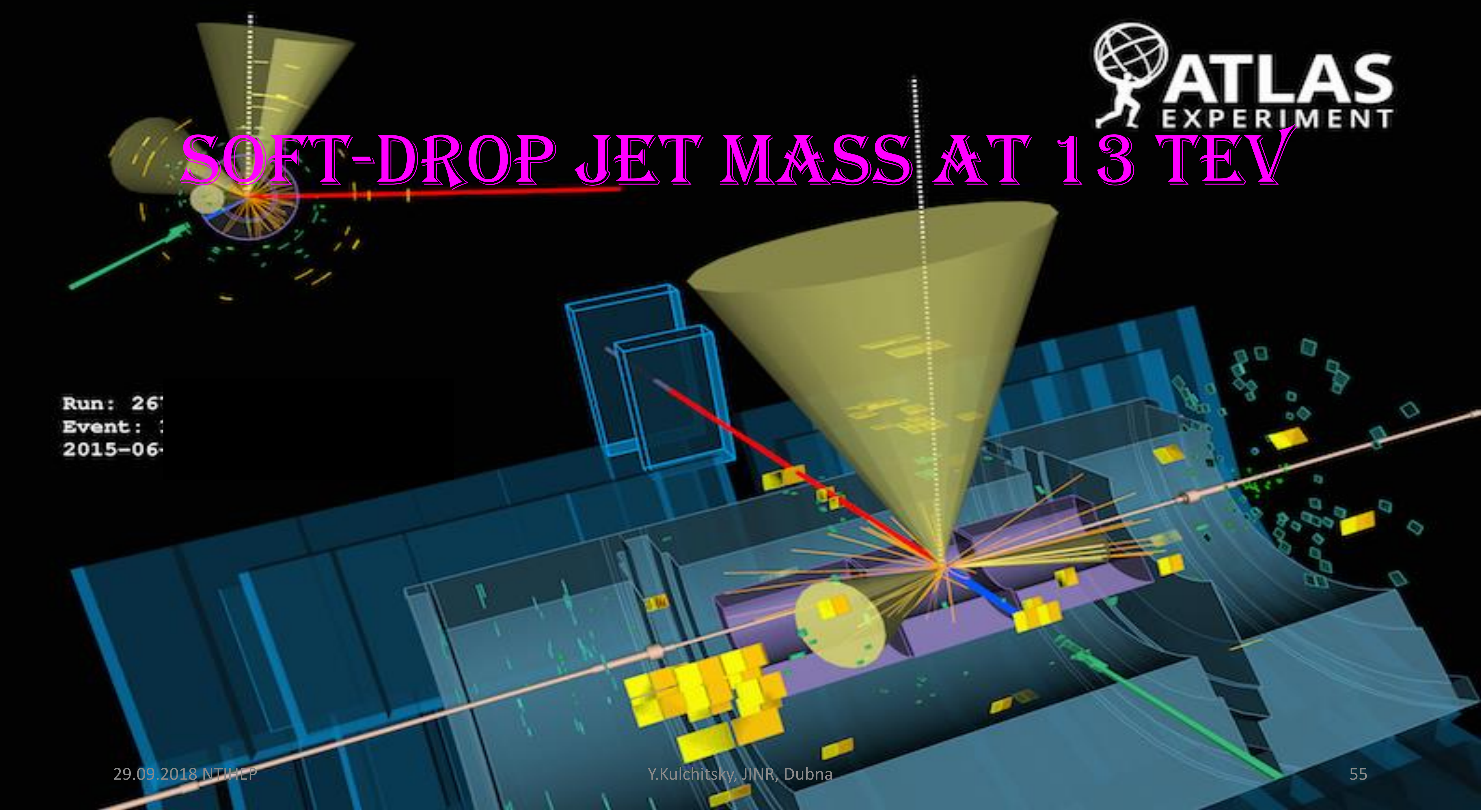




SOFT-DROP JET MASS AT 13 TEV



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

Phys. Rev. Lett. 121 (2018) 092001

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*

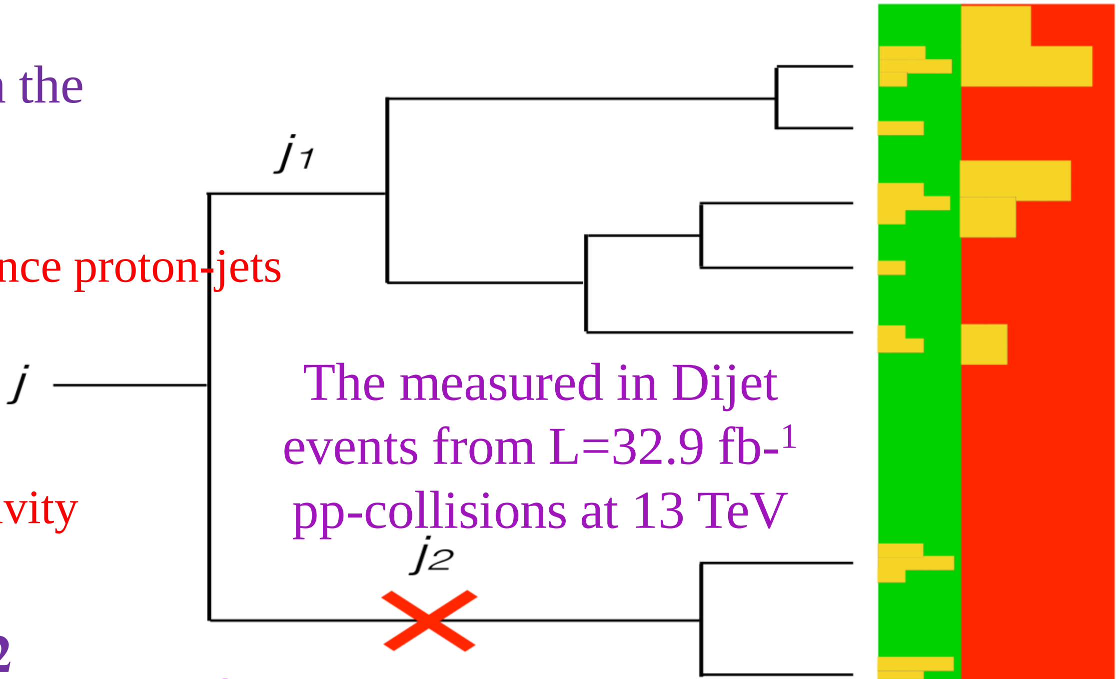
- ➢ Create **R=0.8 anti-k_T jets**, and recluster their constituents with the *Cambridge/Aachen algorithm*
- ❑ Starting from the last branch of the clustering history, check if

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

← Distance proton-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

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

Phys. Rev. Lett. 121 (2018) 092001

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

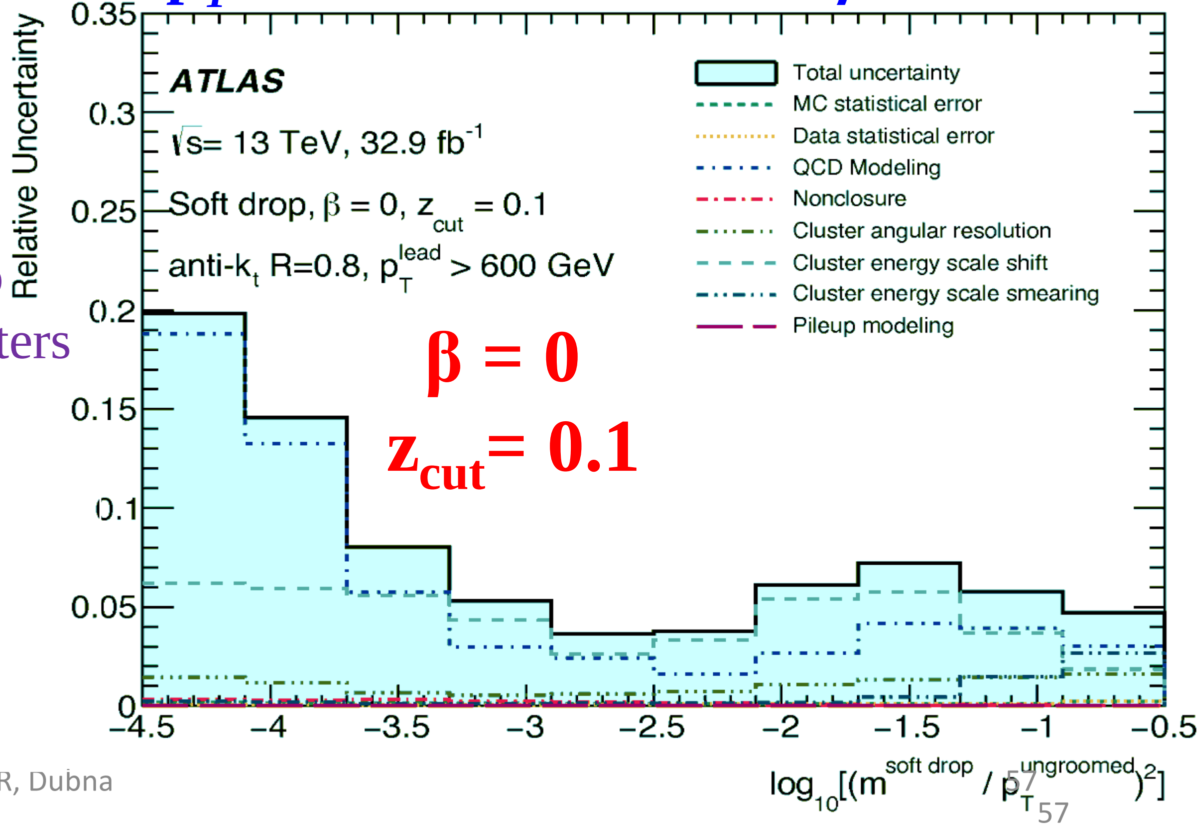
Cluster Energy Scale Shift: Data/MC difference in the E/p ratio used to determine a shift for clusters

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



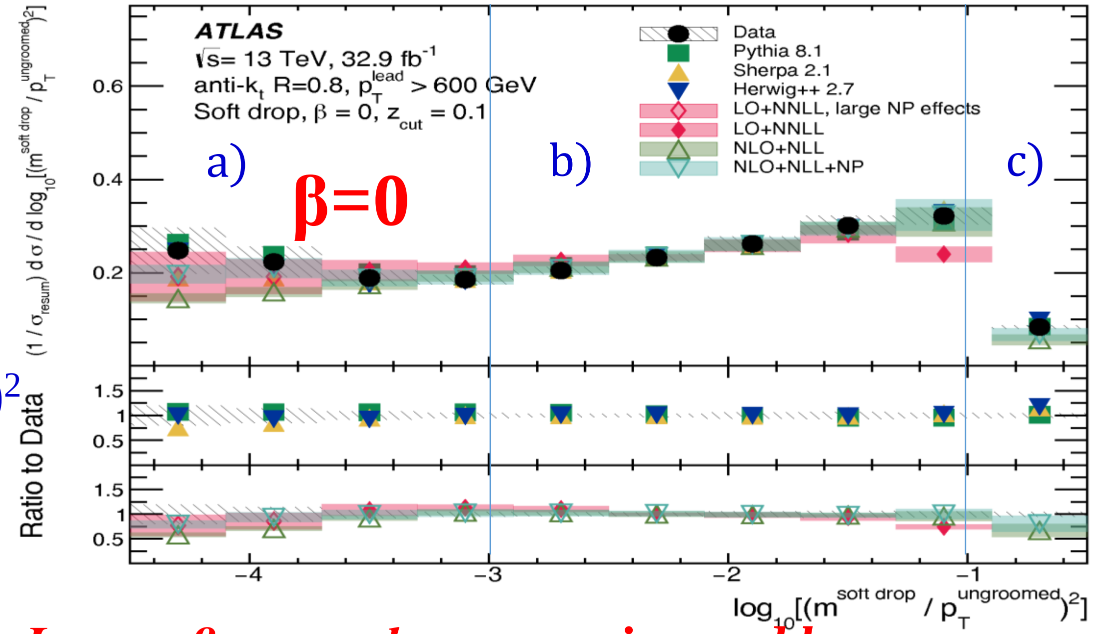
Results: SOFT-DROP JET MASS IN PP → JET + X AT 13 TEV

Phys. Rev. Lett. 121 (2018) 092001

- 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*