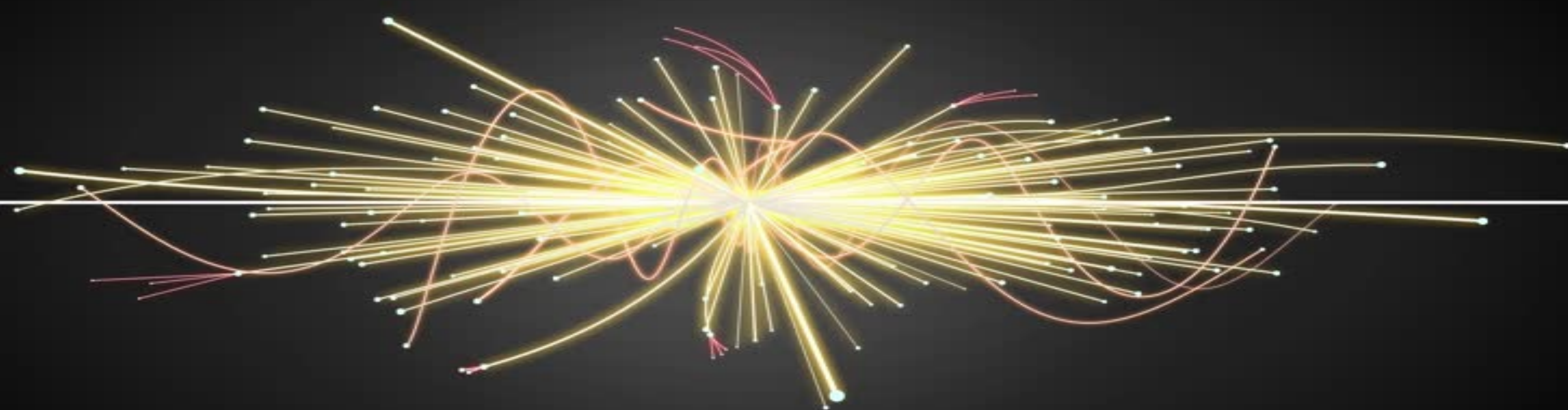
Probing QCD with the ATLAS detector



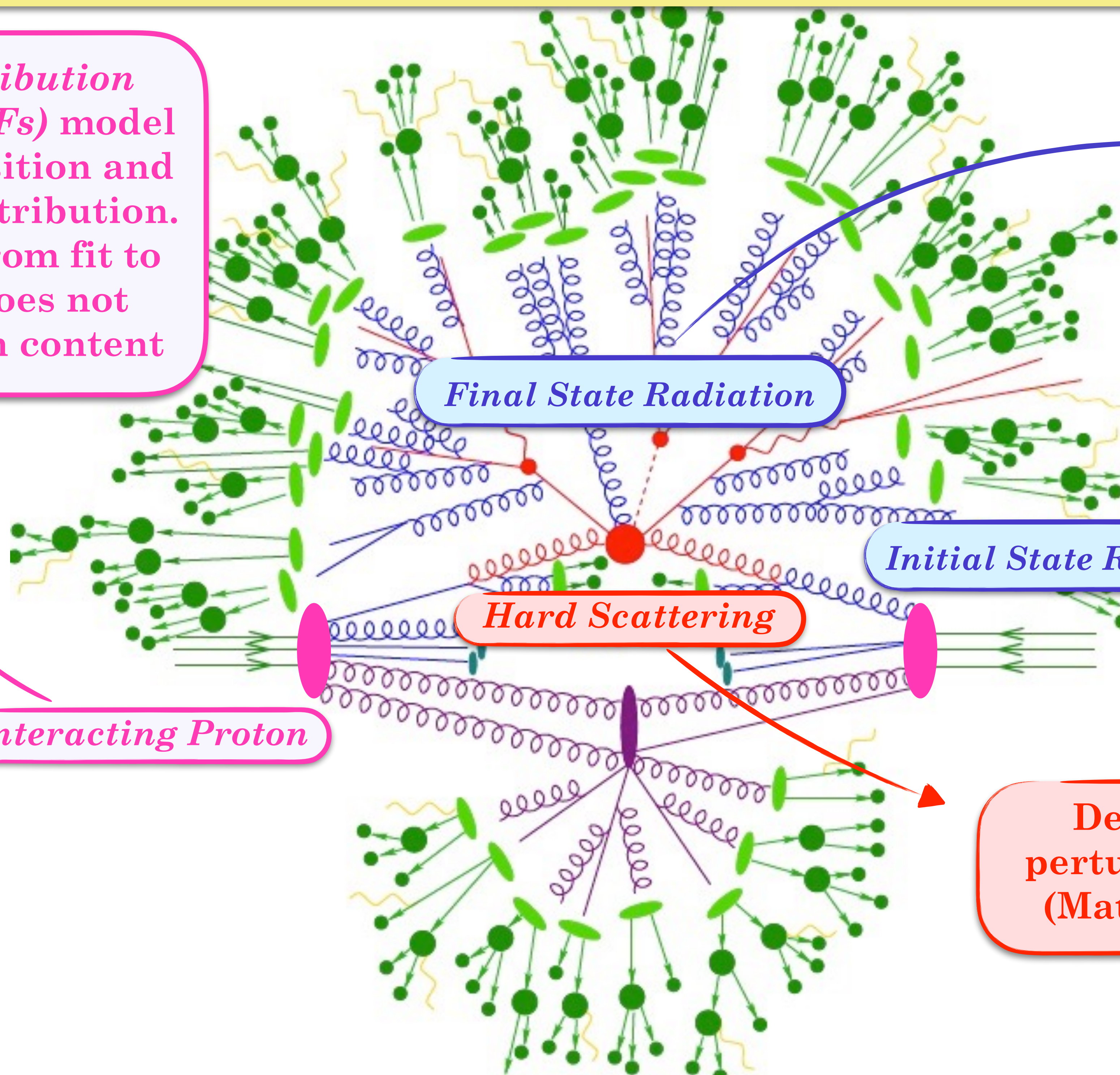
XXIV International Baldin Seminar on High Energy Physics
September 17-22 2018, Dubna

Grazia Cabras
on behalf of the ATLAS Collaboration
University of Bologna and INFN

Anatomy of a Collision

QCD describes what goes on at high-energy accelerators.
- Interacting protons act as composite objects: **partons** (quarks and gluons)

Parton Distribution Functions (PDFs) **model parton composition and momentum distribution. PDF shapes from fit to data. QCD does not predict proton content**

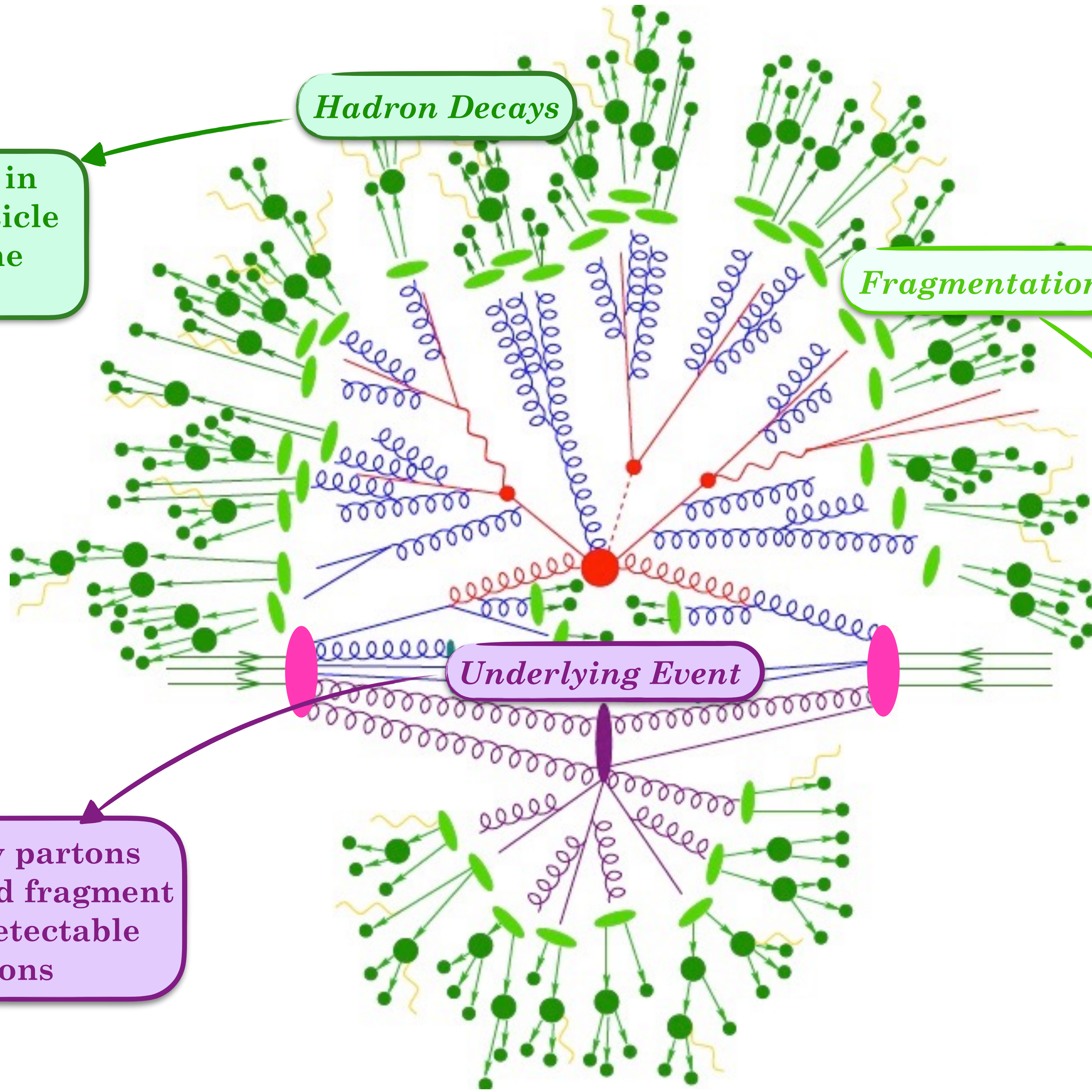


Additional QCD radiation

Described by perturbative QCD (Matrix element)

Anatomy of a Collision

Hadrons decay in other stable particle disclosed by the detector

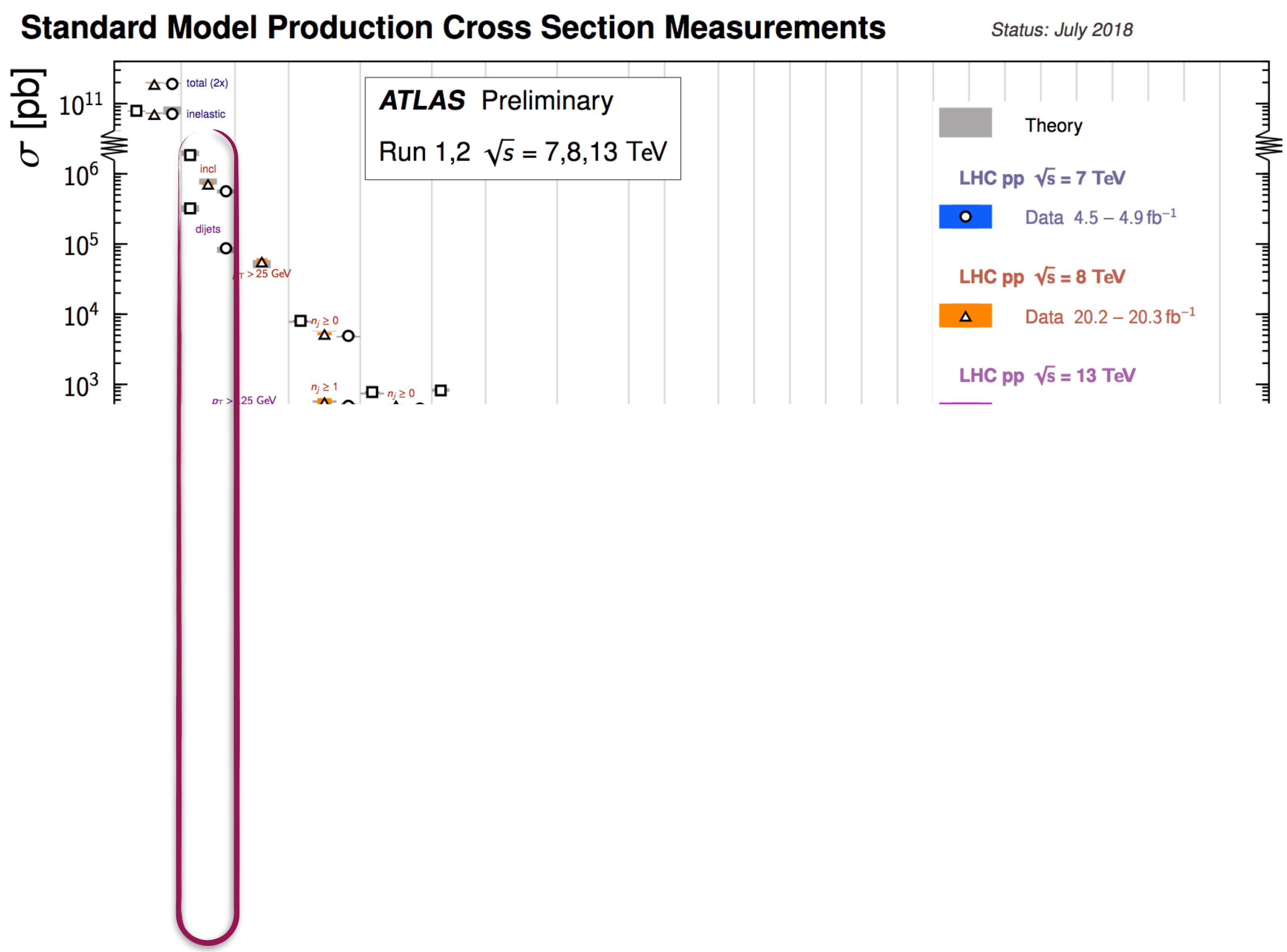


Modelling of the transition from partons to collimated particle systems: ***JETS***

Secondary partons interacts and fragment in other detectable hadrons

QCD and High Energy Accelerators

- ***Jets*** are reconstructed from the event and describe the **fragmentation** of quarks and gluons:
  - distinctive signature of short-distance interactions between partons



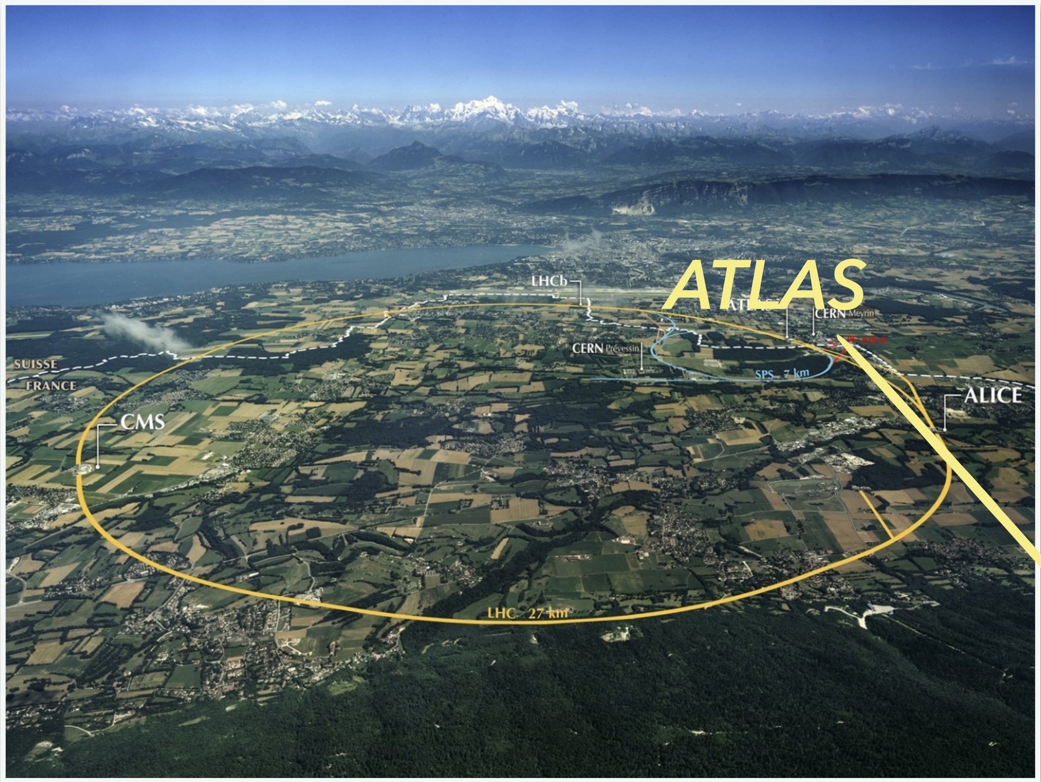
Latest Run2 results

- **QCD measurements** represent an extensive part of the ***ATLAS*** physics program:
  - soft QCD: all processes with low momentum transfer
  - hard QCD: jets physics

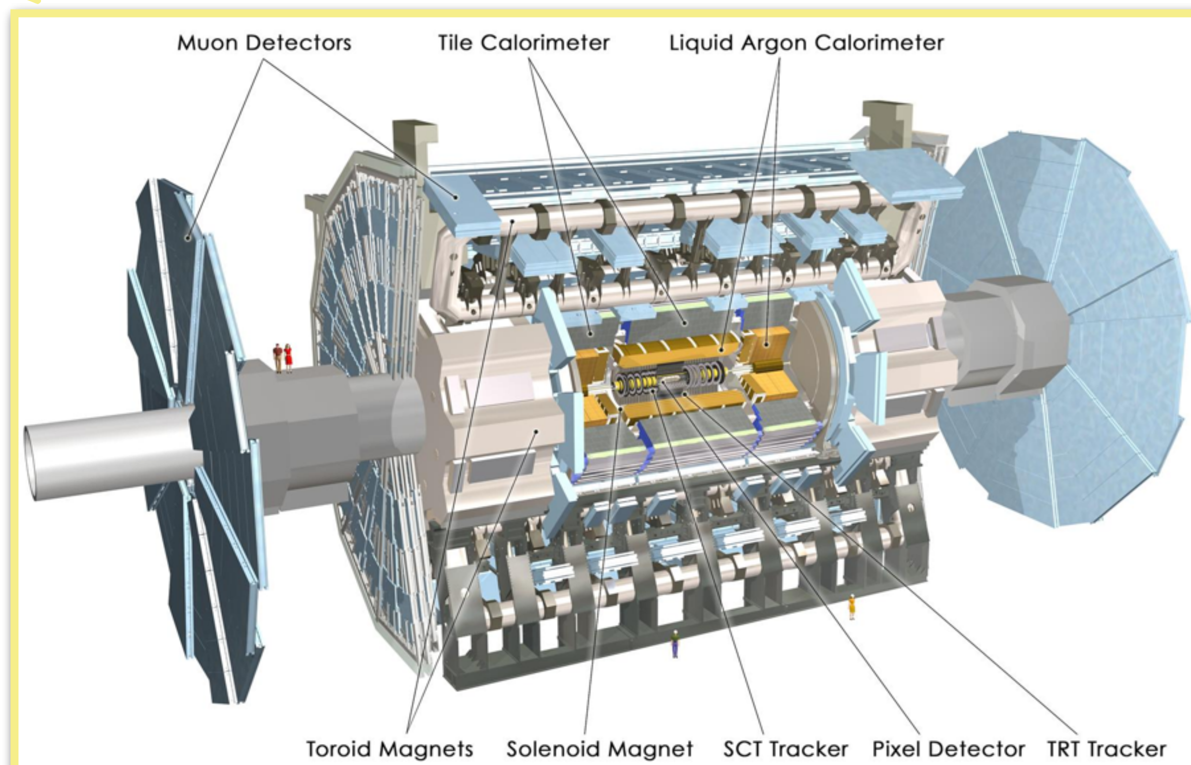
- Comparison with pQCD theoretical predictions
- Main background for Standard Model and Beyond Standard Model measurements

Probing perturbative QCD with Jets!

ATLAS @ LHC



- ***LHC*** (Large Hadron Collider) is the world's largest accelerator.
  - 27 km ring of superconducting magnets, 100 m underground
  - proton-proton collisions
  - started in 2008, during Run 2 (2015-2018) **13 TeV of center-of-mass energy**
  - 4 big experiments: ATLAS, CMS, ALICE and LHCb



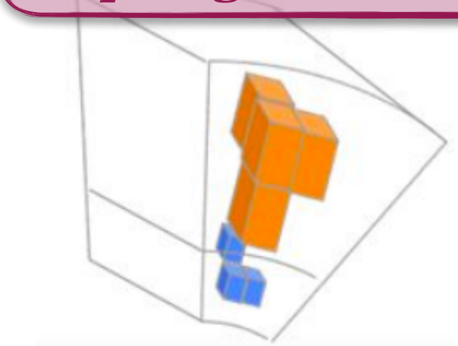
- ***ATLAS*** (A Toroidal LHC ApparatuS) is a general purpose experiment:
  - Standard Model and new physics measurements
  - 44 m long, with 25 m diameter and 7000 tons weight.

"The ATLAS Experiment at the CERN Large Hadron Collider"

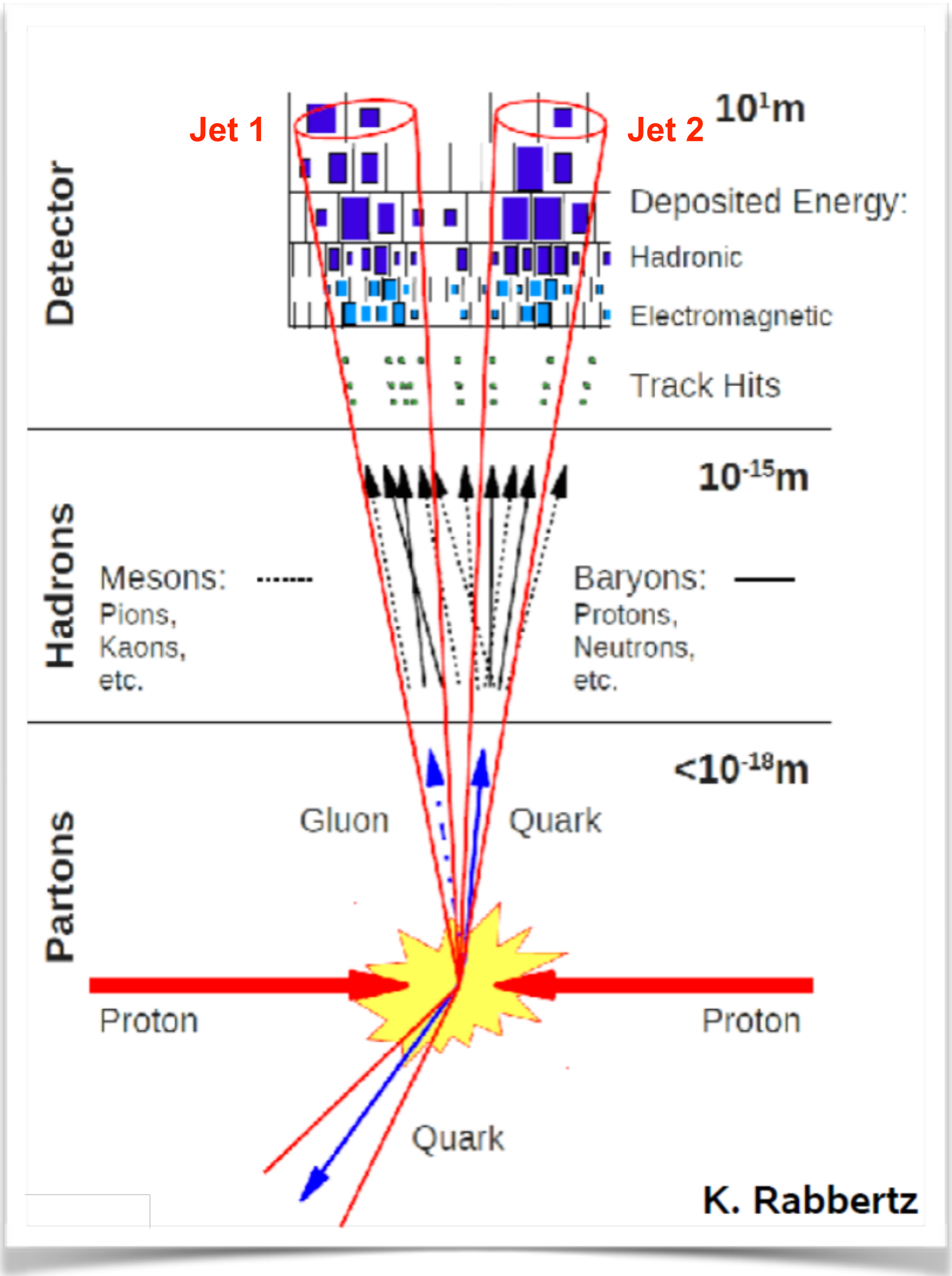
Jets in ATLAS

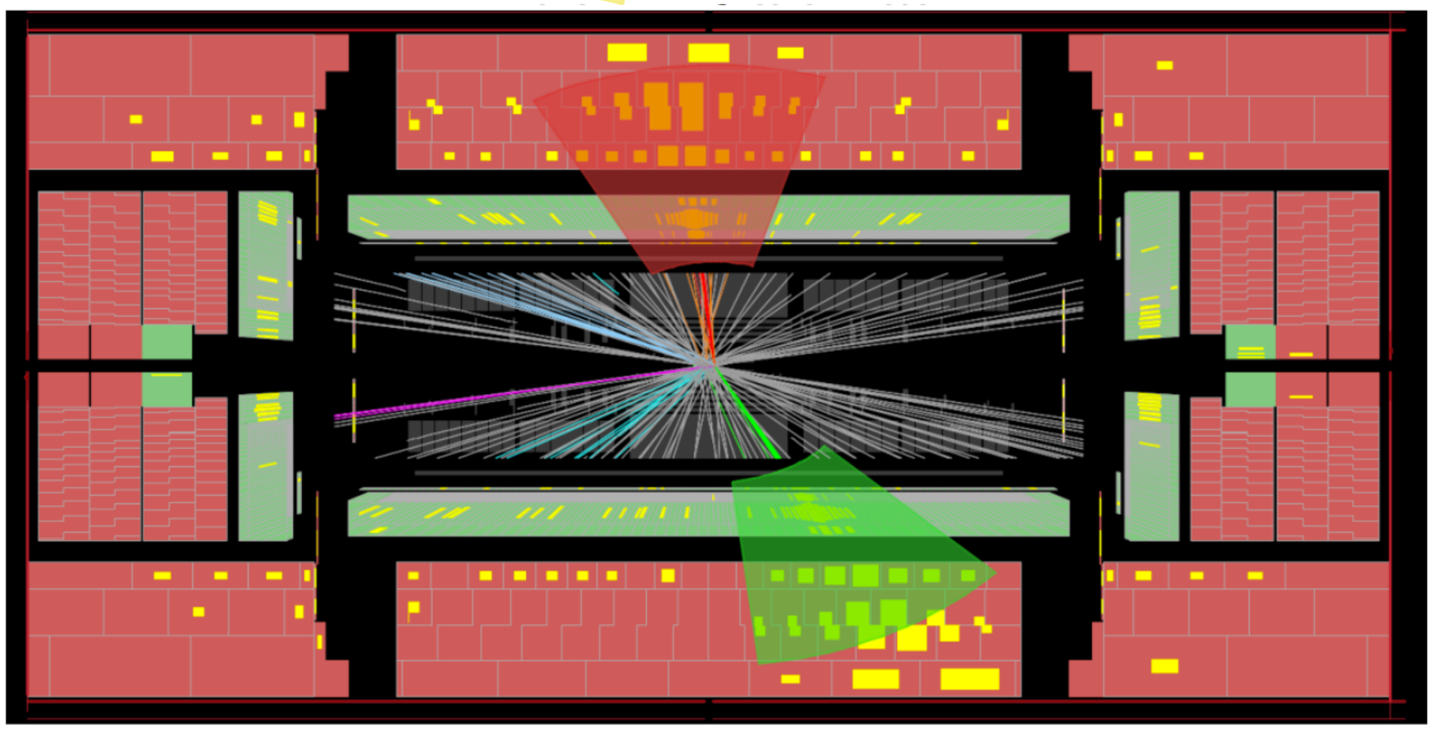
- ***Charged tracks*** in the Inner Detector (track jets)
- Clusters of topologically connected calorimeter (both electromagnetic and hadronic) deposits (***topo-clusters***)

Topological Cluster



Factorisation



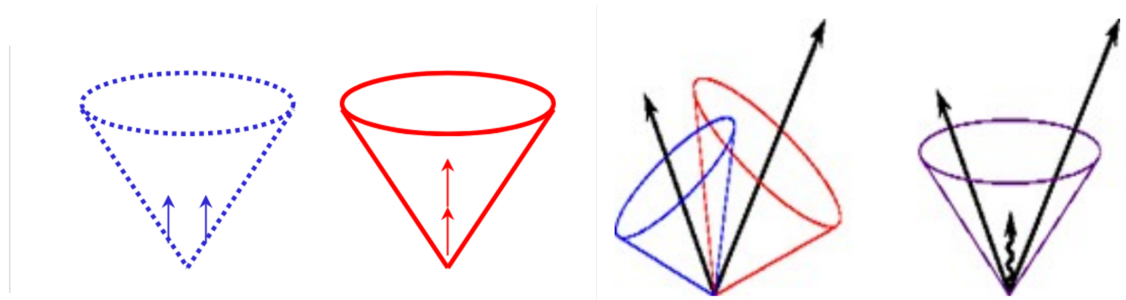


Need of a proper way to link jets to partons to understand their properties

Jet Reconstruction Algorithm

Jet Reconstruction and Calibration

- ***Jet reconstruction algorithm*** to cluster objects into a jet
- ATLAS choice is **anti-kt algorithm**: sequential recombination algorithm based on **minimum distance**
  - Depends on jet p_T and angular distance (η, φ)
- It must be:
  - ***Collinear safe***, insensitive to splitting of a hard particle
  - ***Infrared safe***, insensitive to the emission of a soft gluon



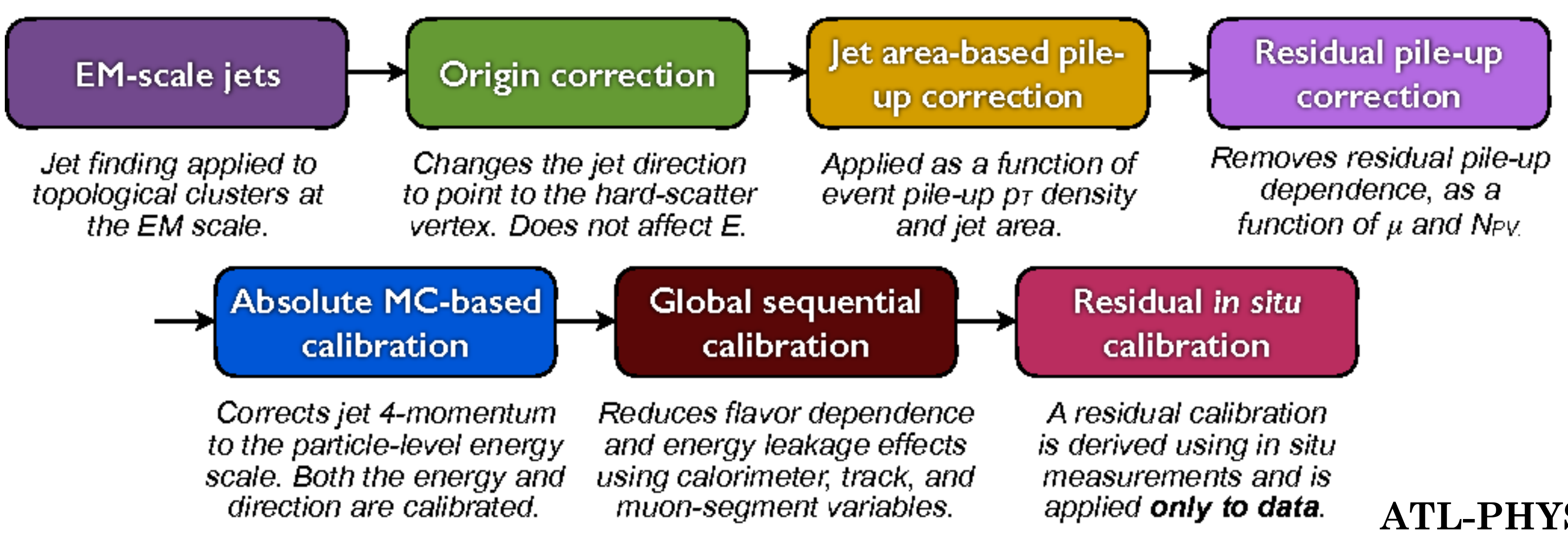
Collinear Safety ***Infrared Safety***

➡ Energy of the reconstructed jet **is not** the energy of partons due to detector effects

Jet Calibration

- ***Strategy***: combine Monte Carlo studies, information from track jets and in situ measurements

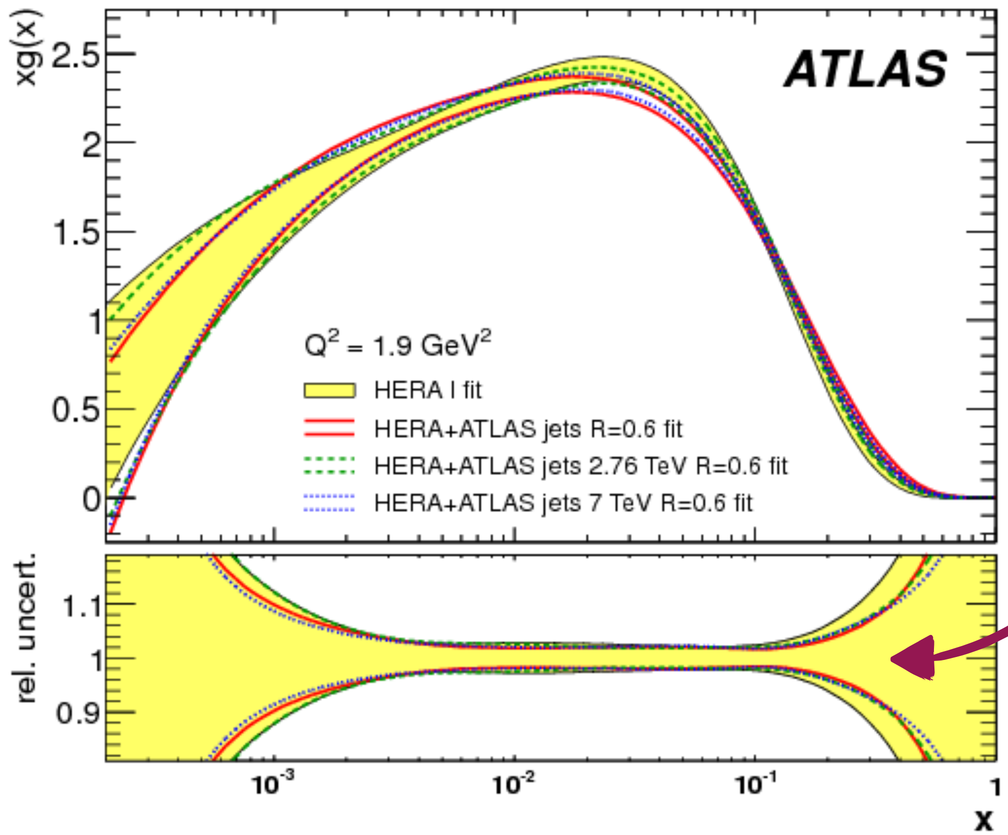
STEP-BY-STEP



ATL-PHYS-PUB-2015-036

Jet Physics @ ATLAS

HERA&ATLAS Combination: fit of the gluon PDF



https://arxiv.org/pdf/1507.00556.pdf

- ***Jet cross-section measurements***:
  - Probe proton substructure
  - Test of Monte Carlo pQCD predictions
  - Study of the strong coupling constant
  - Constrain to PDF fits

Strong constraint at high momentum fraction!

Present Talk ~ ATLAS Results:

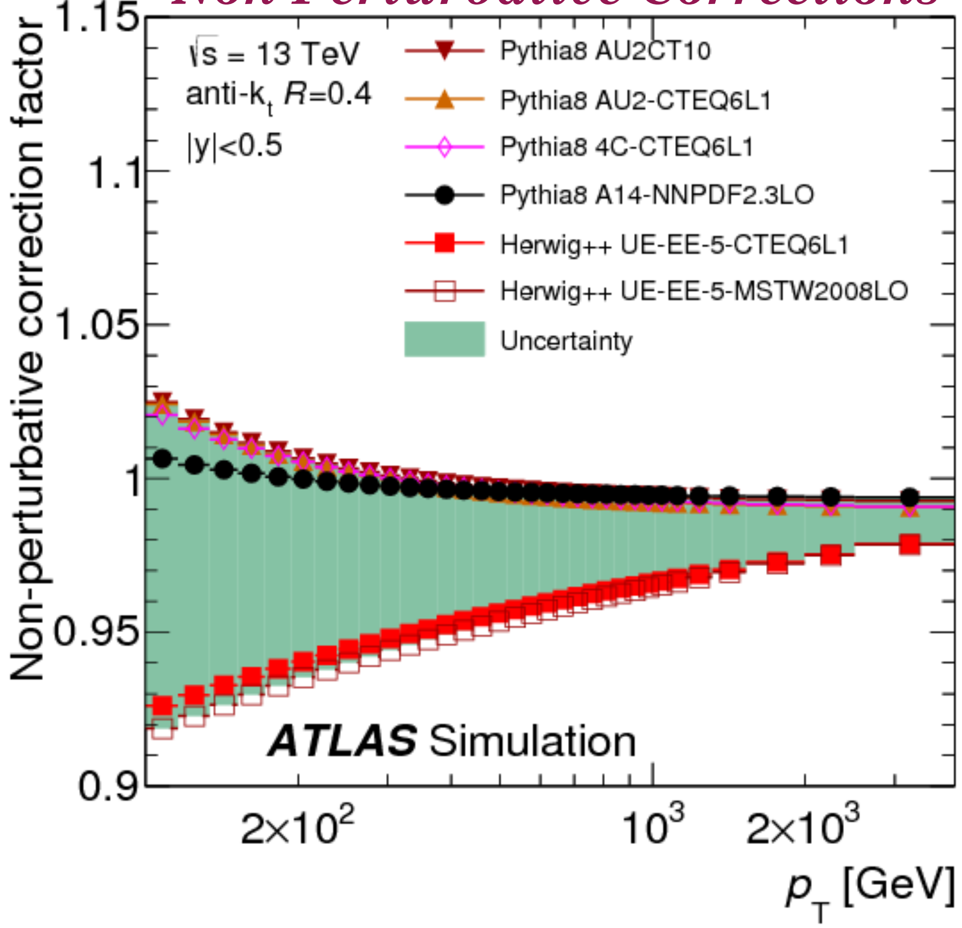
- ***Inclusive jet cross-section at 8 TeV***
- ***Inclusive jet and dijet cross-section at 13 TeV***
- ***Strong coupling from transverse energy-energy correlation at 8 TeV***
- ***Strong coupling from dijet azimuthal decorrelation at 8 TeV***

Theoretical Predictions

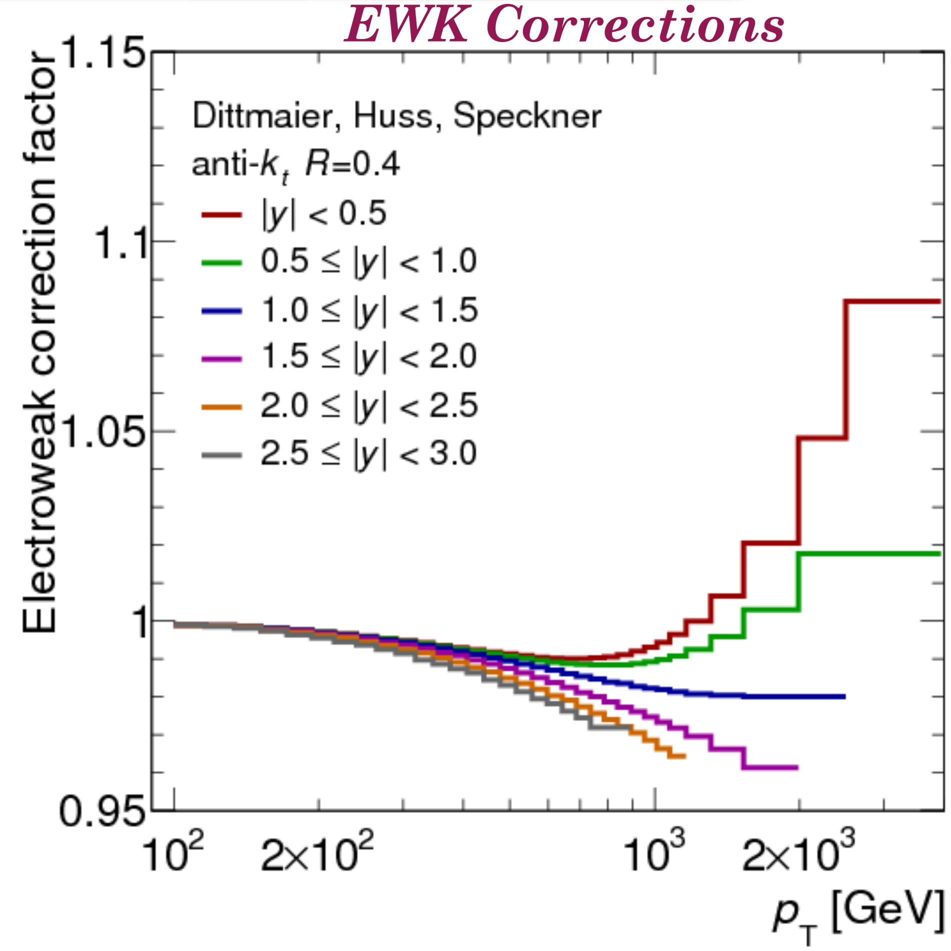
- ***Theoretical predictions***:
  - pQCD predictions from NLOJET++ with different sets of PDFs
  - *Non perturbative corrections* for hadronisation and underlying events from Pythia8 and Herwig++ (spread between them taken as ***uncertainty***)
  - *Electroweak corrections* are applied for the effects of γ and $W^{\pm}/Z$

Corrections at 13TeV for inclusive jet jet cross-section

Non Perturbative Corrections



EWK Corrections



- *NNLO pQCD* corrections became available for qualitative comparisons (not all uncertainties available yet to perform quantitative studies)

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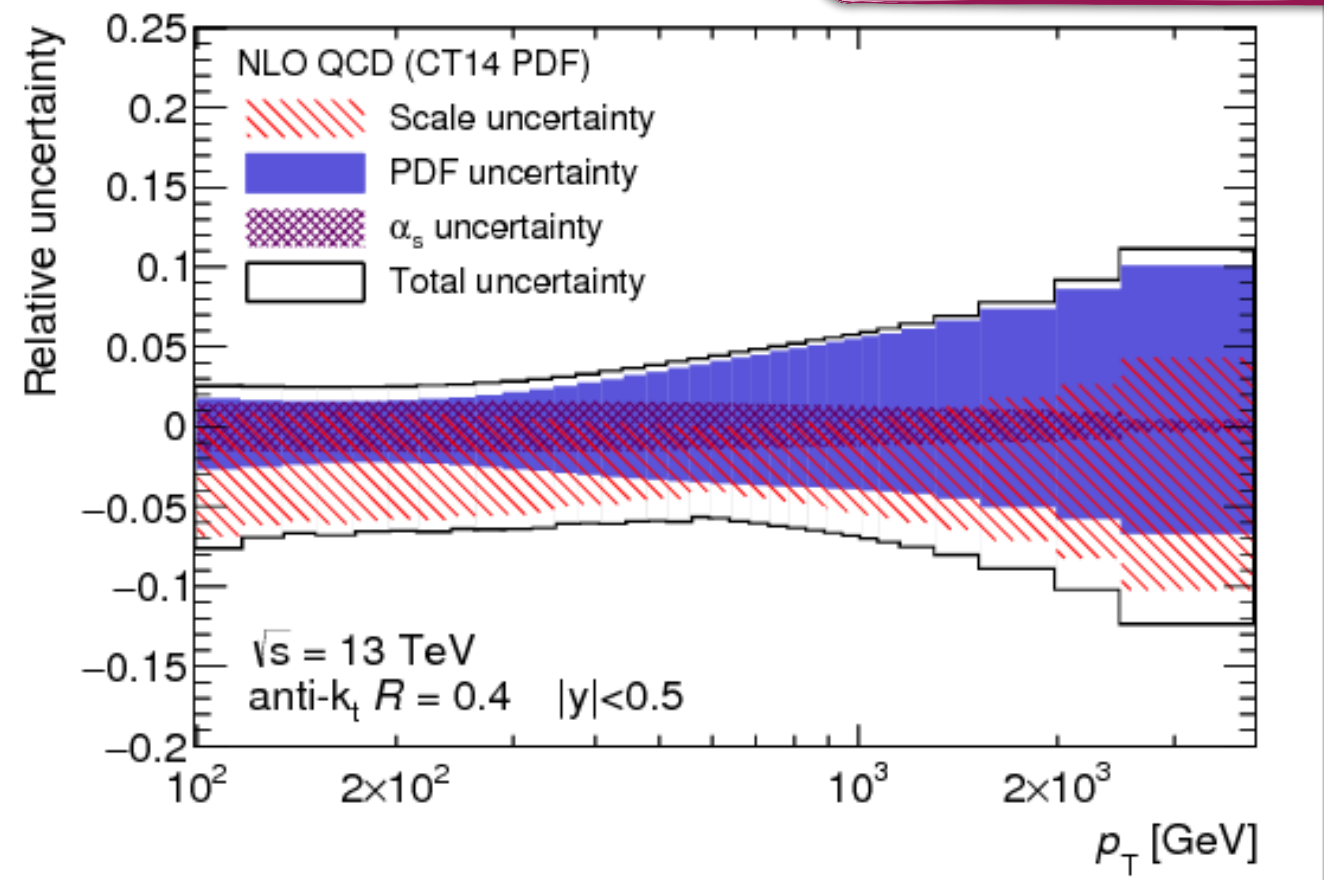
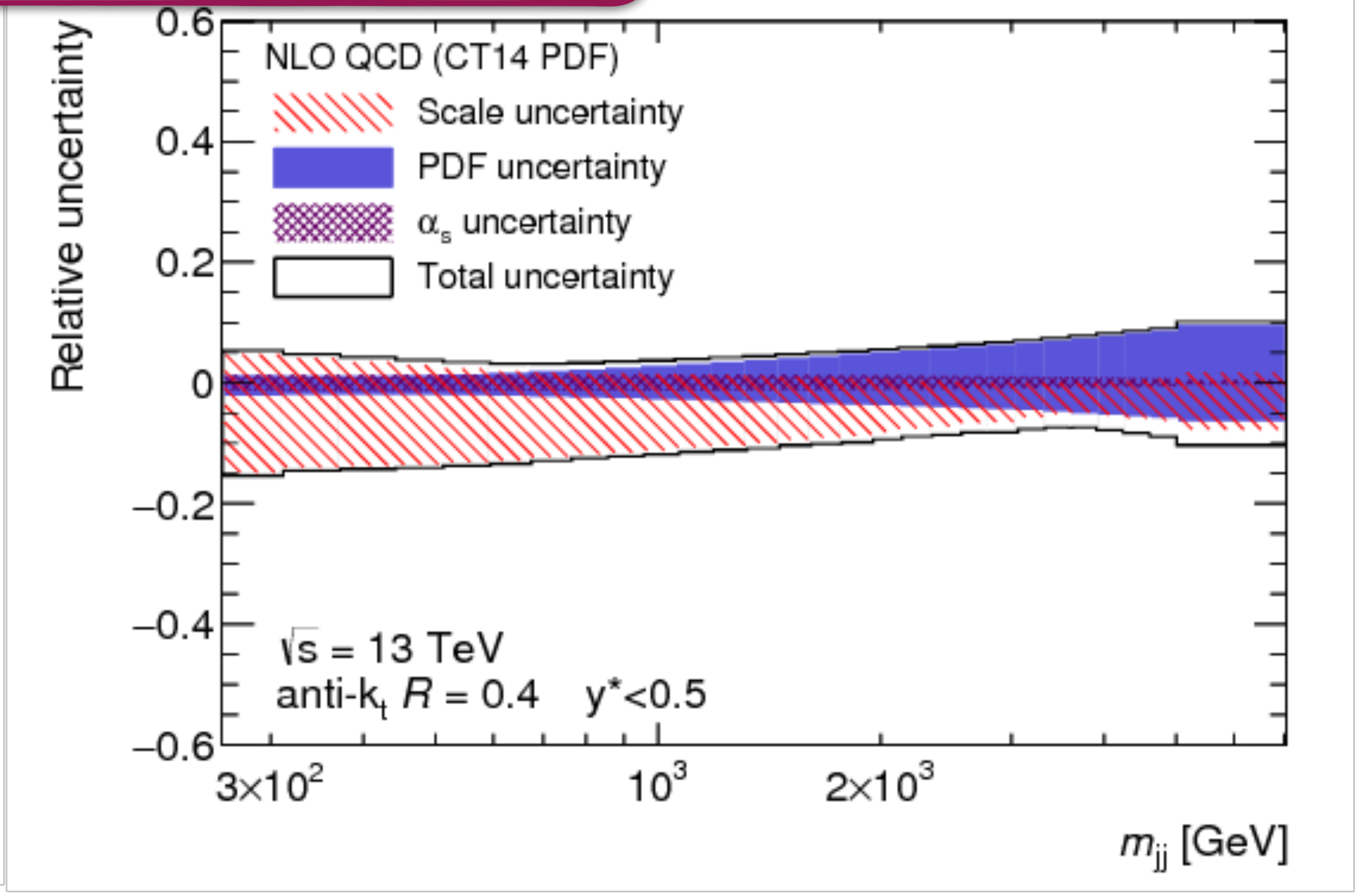
Theoretical Uncertainties

- Main uncertainties in NLO predictions (***common*** to the three analyses)
  - **PDF**: uncertainty propagated for each PDF set (prescription PDF4LHC)
  - ***Factorisation and Renormalisation scales***: varied up and down of a factor 2 ($-0.5<\mu_{R,F}<2$)
  - α_S, strong coupling constant: comparing two PDF sets that differ in the value of α_S

Theoretical Uncertainty at 13TeV





SCALE UNCERTAINTY IS DOMINANT!

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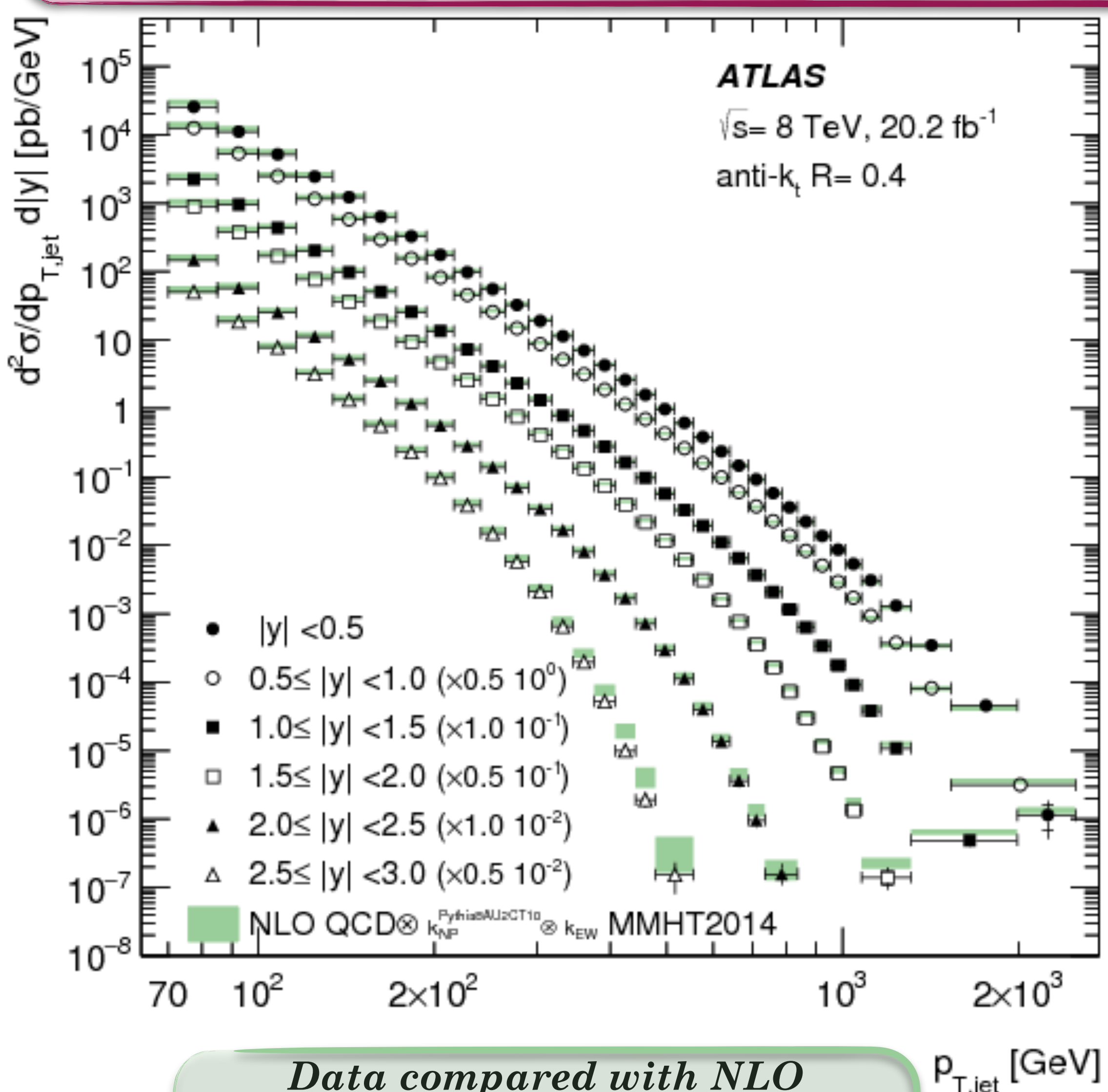
Inclusive Cross-section at 8 TeV

- Anti-kt_clustering algorithm with R = 0.4 and R = 0.6 (Backup)
- Double differential cross-section measured as a function of jet transverse momentum p_T in bins of rapidity y:
  - 70 GeV $\leq p_T \leq$ 2.5 TeV and $|y| < 3$
  - $\mu_{R,F} = p_T^{max}$

$$\frac{d^2\sigma}{dp_T dy} = \frac{N_{jets}}{\mathcal{L}\Delta p_T \Delta y}$$

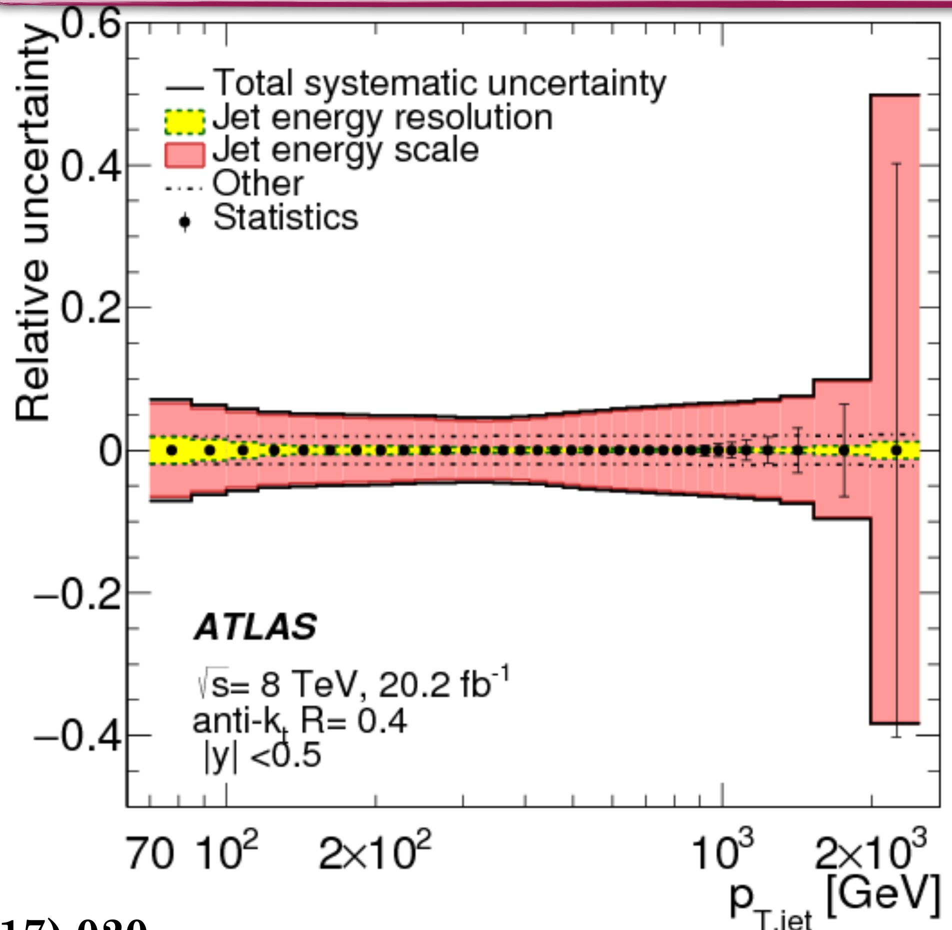
Inclusive jet cross-section (R = 0.4)



Data compared with NLO prediction with MMHT2014 PDF

- Dominant experimental uncertainty related to jet calibration (~ 5%)

Systematics on Cross-Section at 8 TeV (R=0.4)



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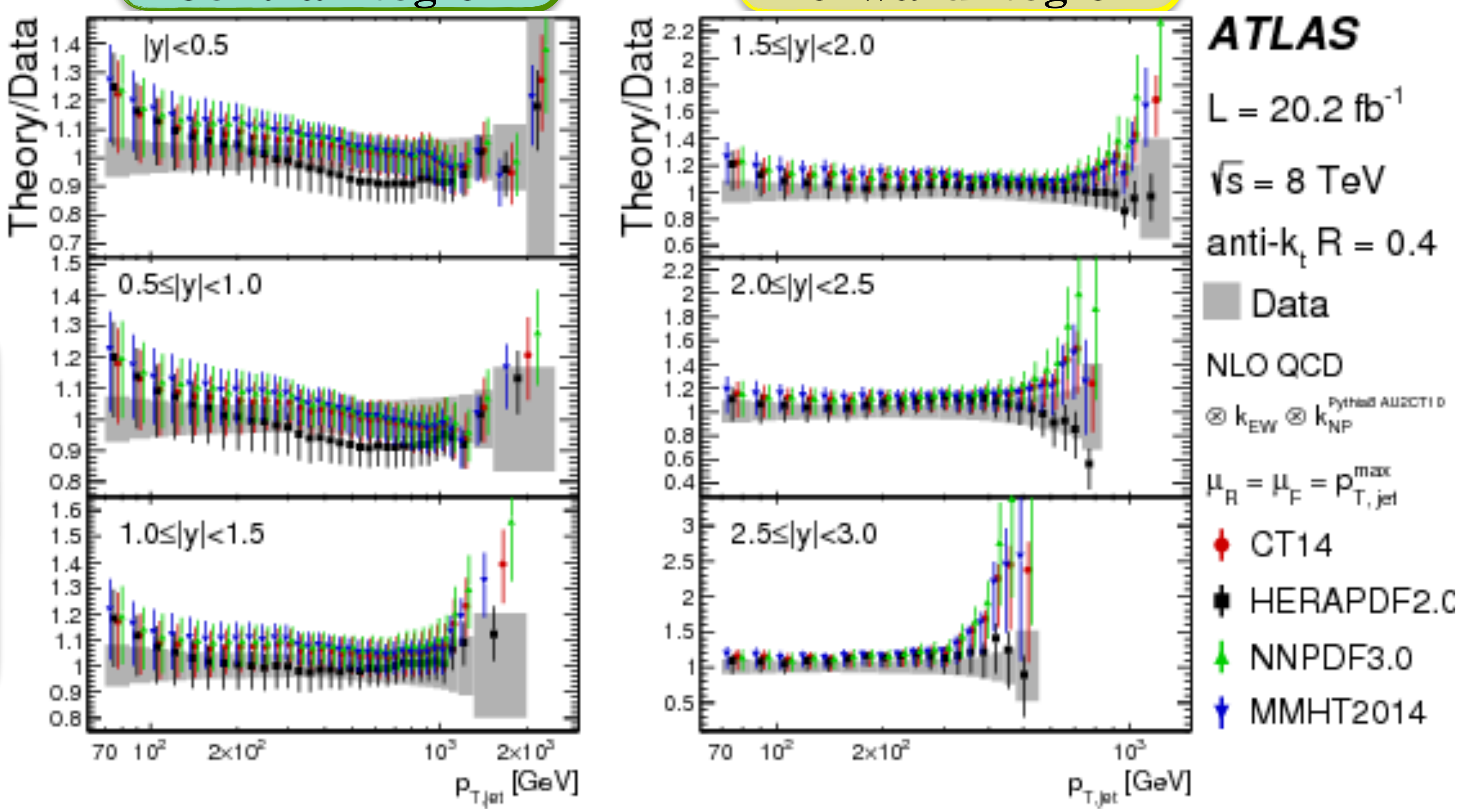
Inclusive Cross-section at 8 TeV

Qualitative comparison of data to NLO Calculation

Central Region | **Forward Region**



- All PDF sets behave similarly
- NLO QCD prediction 20% above the data both in low and high p_T

- Predictions close to data at low p_T
- At high p_T, CT14, NNPDF3.0 and MMHT2014 have predictions higher than data

➡ PDFs :CT14, **HERAPDF2.0**, NNPDF3.0, **MMHT2014**

- ***Overall***:
  - ✦ CT14 prediction gives best qualitative agreement, **HERAPDF2.0** the worst
  - ✦ Sensitivity to constrain PDFs

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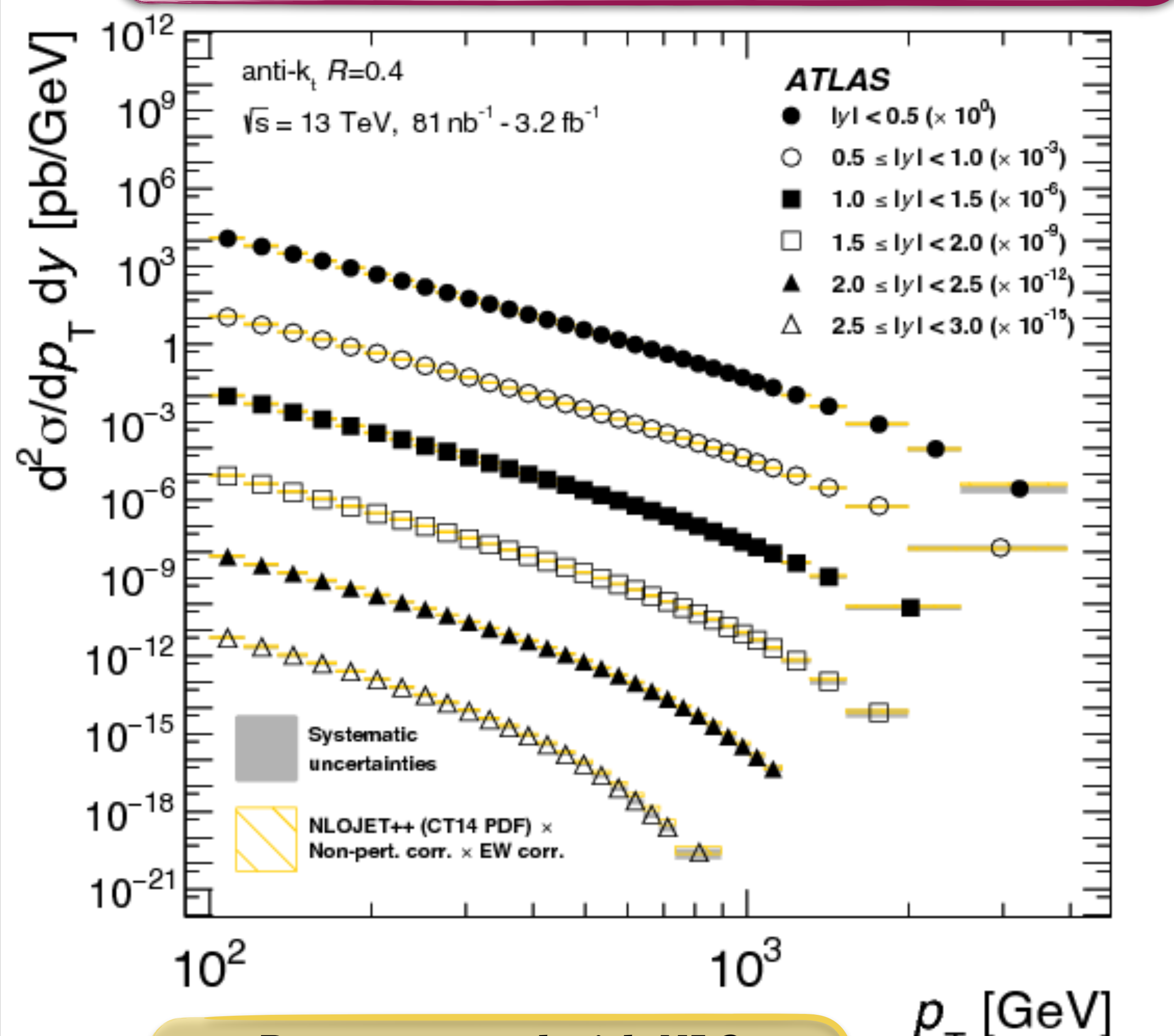
Inclusive Cross-section at 13 TeV

- Same approach of 8 TeV, except for the selection:
  - R=0.4
  - 100 GeV ≤ p_T ≤ 3.5 TeV and $|y| < 3$
  - $\mu_{R,F} = p_T^{max}$

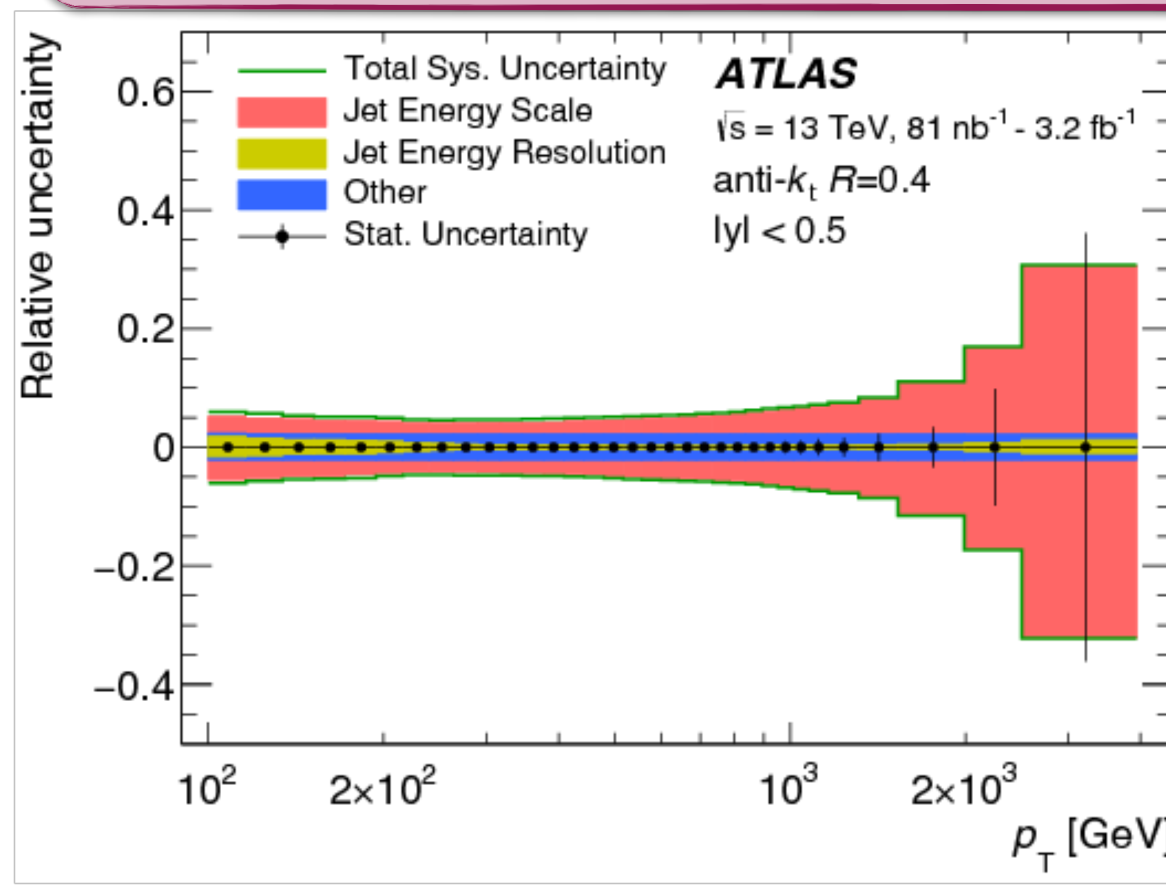
$$\frac{d^2\sigma}{dp_T dy} = \frac{N_{jets}}{\mathcal{L}\Delta p_T \Delta y}$$

Inclusive jet cross-section (R = 0.4)



Data compared with NLO prediction with CT14 PDF

Systematics on Cross-Section at 13 TeV (R=0.4)



- Jet Calibration dominant experimental uncertainty (~ 5%)

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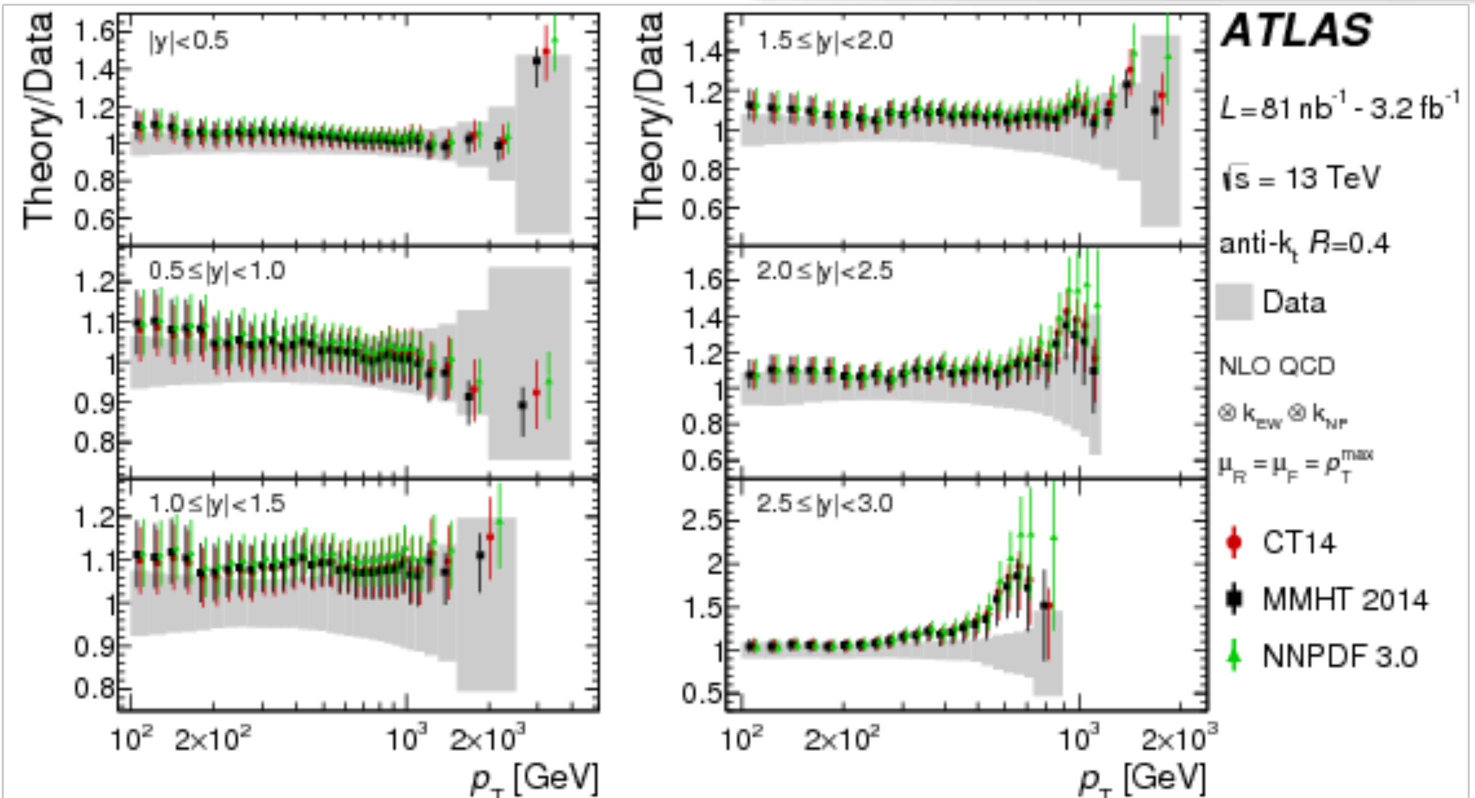
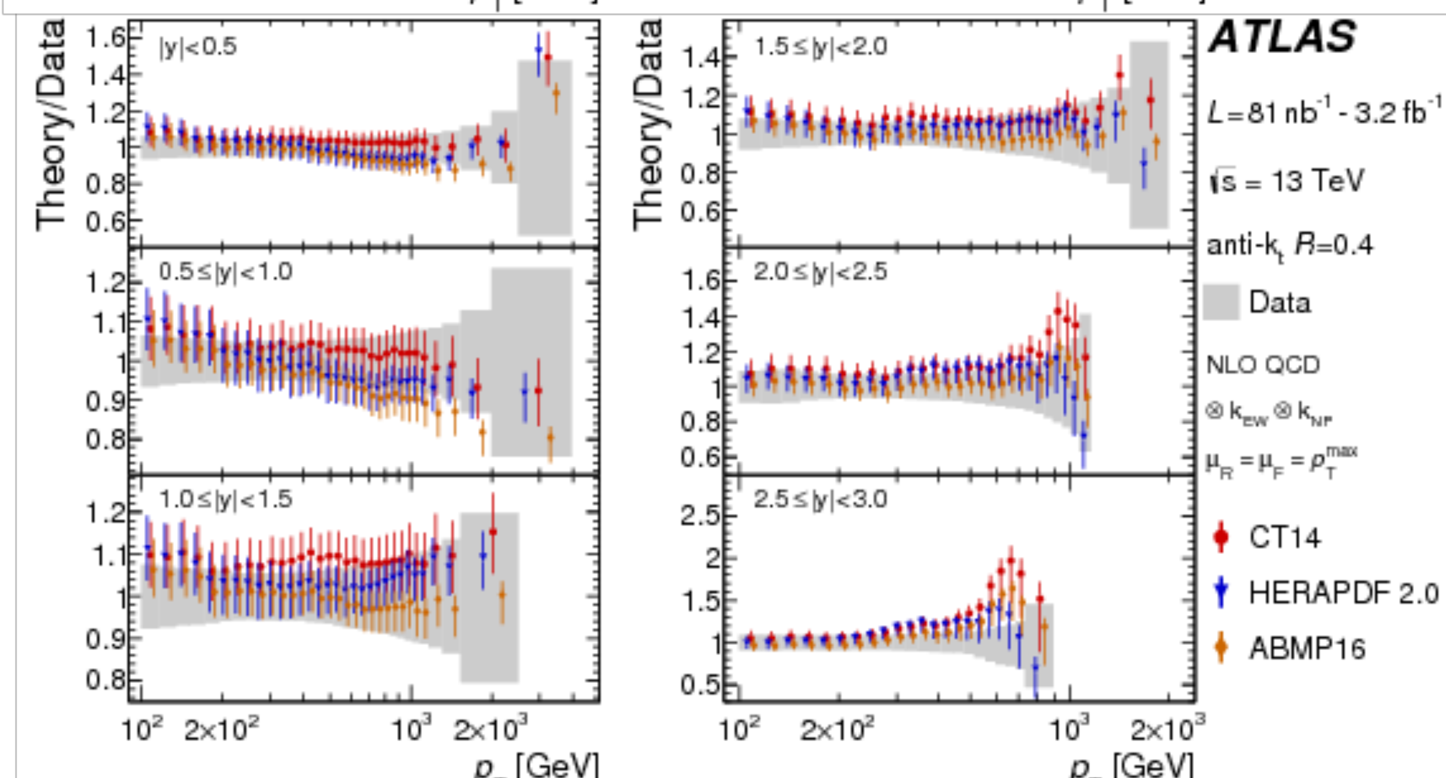
Inclusive Cross-section at 13 TeV

Qualitative comparison of data to NLO Calculation





- PDFs :**CT14**, **MMHT2014**, **NNPDF3.0**

- ***Overall***:
  - No significant deviation of the data points from the predictions
  - Behaviour compatible with 8 TeV results
  - NLO pQCD prediction overestimate data in forward region but not exceeding uncertainty

- PDFs :**CT14**, **HERAPDF2.0**, **ABMP16**

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Results at 8 TeV and 13 TeV

Quantitative comparison of data to NLO Calculation

- χ^2 goodness of the fit in each rapidity bin
- *p-values* observed

8 TeV

Rapidity ranges	CT14	MMHT2014	NNPDF3.0	HERAPDF2.0
	P_{obs}			
Anti-k$_t$ jets $R = 0.4$				
$\lvert y\rvert < 0.5$	44%	28%	25%	16%
$0.5 \leq \lvert y\rvert < 1.0$	43%	29%	18%	18%
$1.0 \leq \lvert y\rvert < 1.5$	44%	47%	46%	69%
$1.5 \leq \lvert y\rvert < 2.0$	3.7%	4.6%	7.7%	7.0%
$2.0 \leq \lvert y\rvert < 2.5$	92%	89%	89%	35%
$2.5 \leq \lvert y\rvert < 3.0$	4.5%	6.2%	16%	9.6%

13 TeV

Rapidity ranges	CT14	MMHT 2014	NNPDF 3.0	HERAPDF 2.0	ABMP16
	P_{obs}				
p_T^{max}					
$\lvert y\rvert < 0.5$	67%	65%	62%	31%	50%
$0.5 \leq \lvert y\rvert < 1.0$	5.8%	6.3%	6.0%	3.0%	2.0%
$1.0 \leq \lvert y\rvert < 1.5$	65%	61%	67%	50%	55%
$1.5 \leq \lvert y\rvert < 2.0$	0.7%	0.8%	0.8%	0.1%	0.4%
$2.0 \leq \lvert y\rvert < 2.5$	2.3%	2.3%	2.8%	0.7%	1.5%
$2.5 \leq \lvert y\rvert < 3.0$	62%	71%	69%	25%	55%

- Satisfactory description of the data by the NLO QCD prediction in all the rapidity bins
  - except for one y-bin
- Fitting in all the rapidity bins together, $P_{obs} << 10^{-3}$: **tension between data and theory**

Possible explanation: some unknown **correlation between systematics** or **incomplete theoretical description**

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Dijet Cross-section at 13 TeV

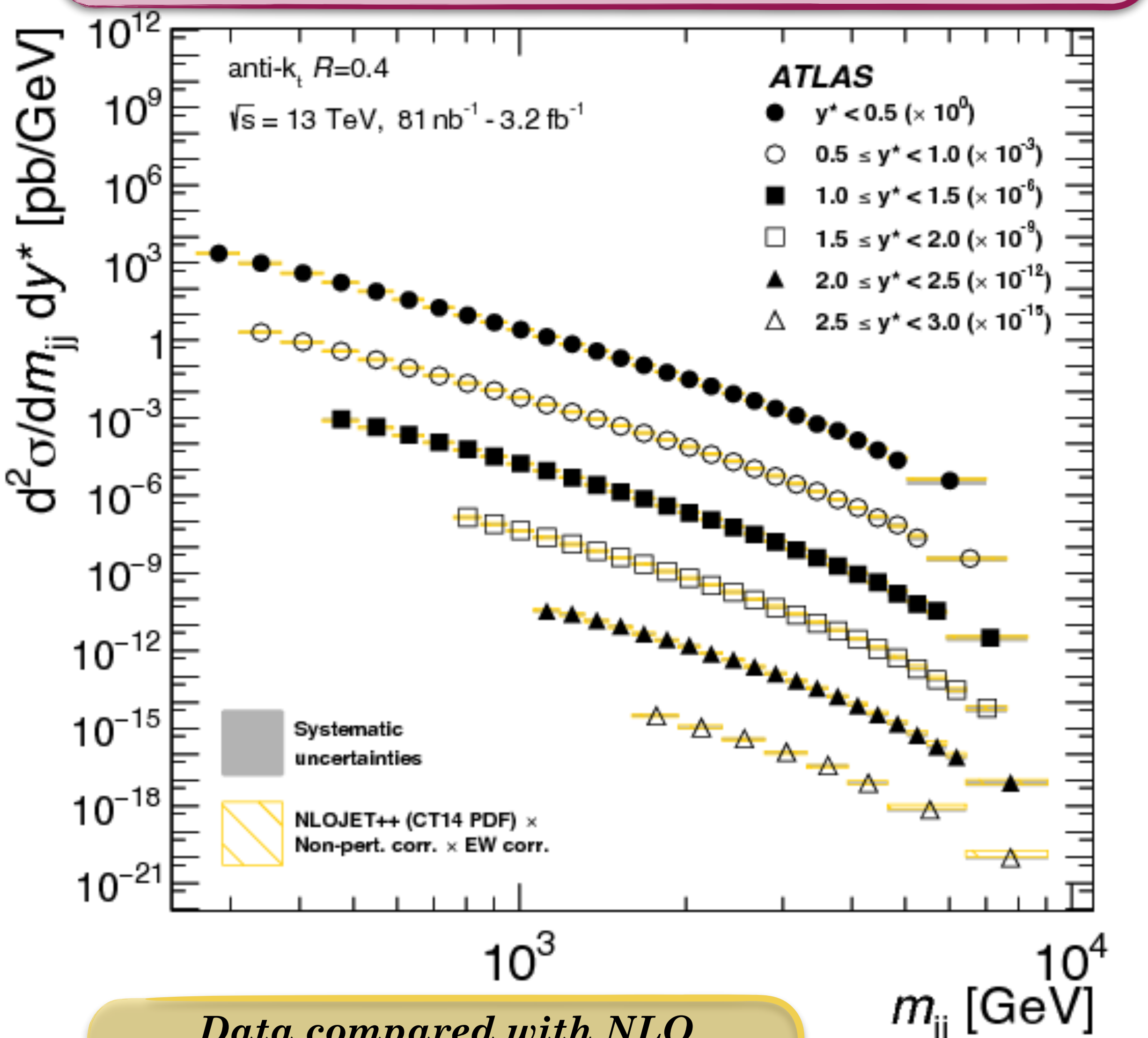
- Anti-kt_clustering algorithm with R = 0.4
- Dijet Double differential cross-section measured as a function of the invariant mass dijet system m_{jj} in 6 bins of centrality ***y****:
  - 300 GeV $\le p_T \le$ 9 TeV and $|y| < 3$
  - $\mu_{R,F} = p_T^{max}$

$$y^* = \frac{|y_1 - y_2|}{2}$$

1: highest p_T jet
2: second highest p_T jet

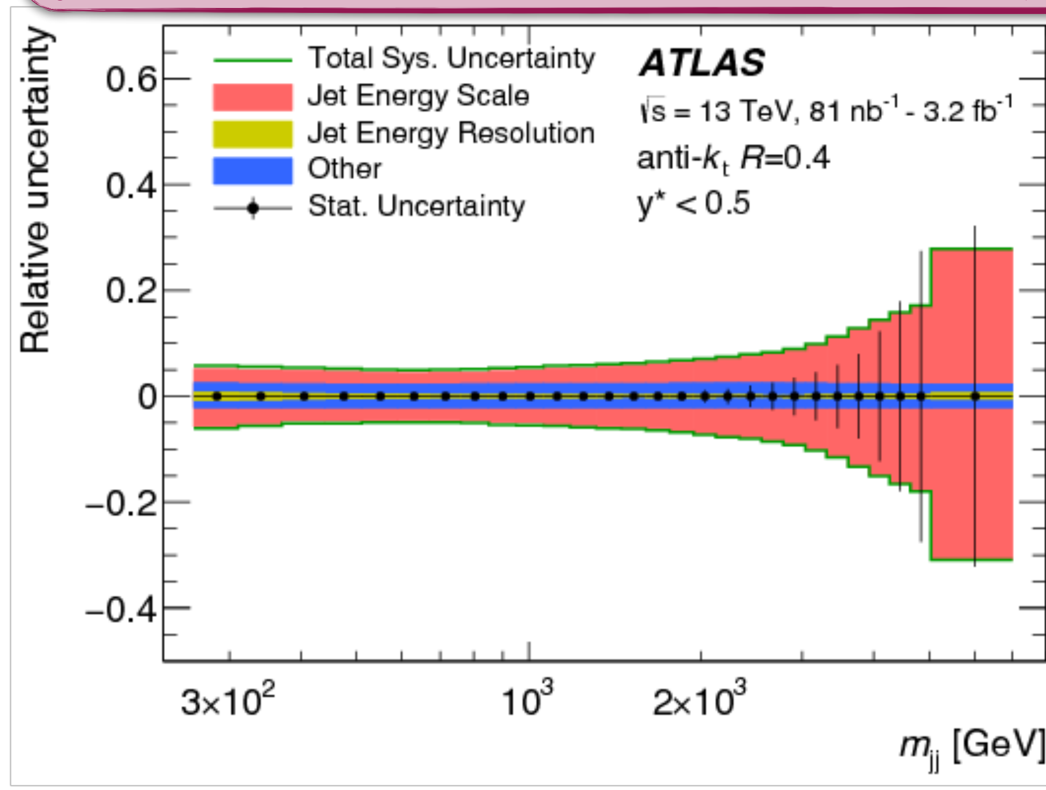
$$\frac{d^2\sigma}{dm_{jj}dy^*} = \frac{N_{jets}}{\mathcal{L}\Delta m_{jj}\Delta y^*}$$

Dijet cross-section (R = 0.4)



Data compared with NLO prediction with CT14 PDF

Systematics on Cross-Section at 13 TeV (R=0.4)



- Jet Calibration dominant experimental uncertainty (~ 5%)

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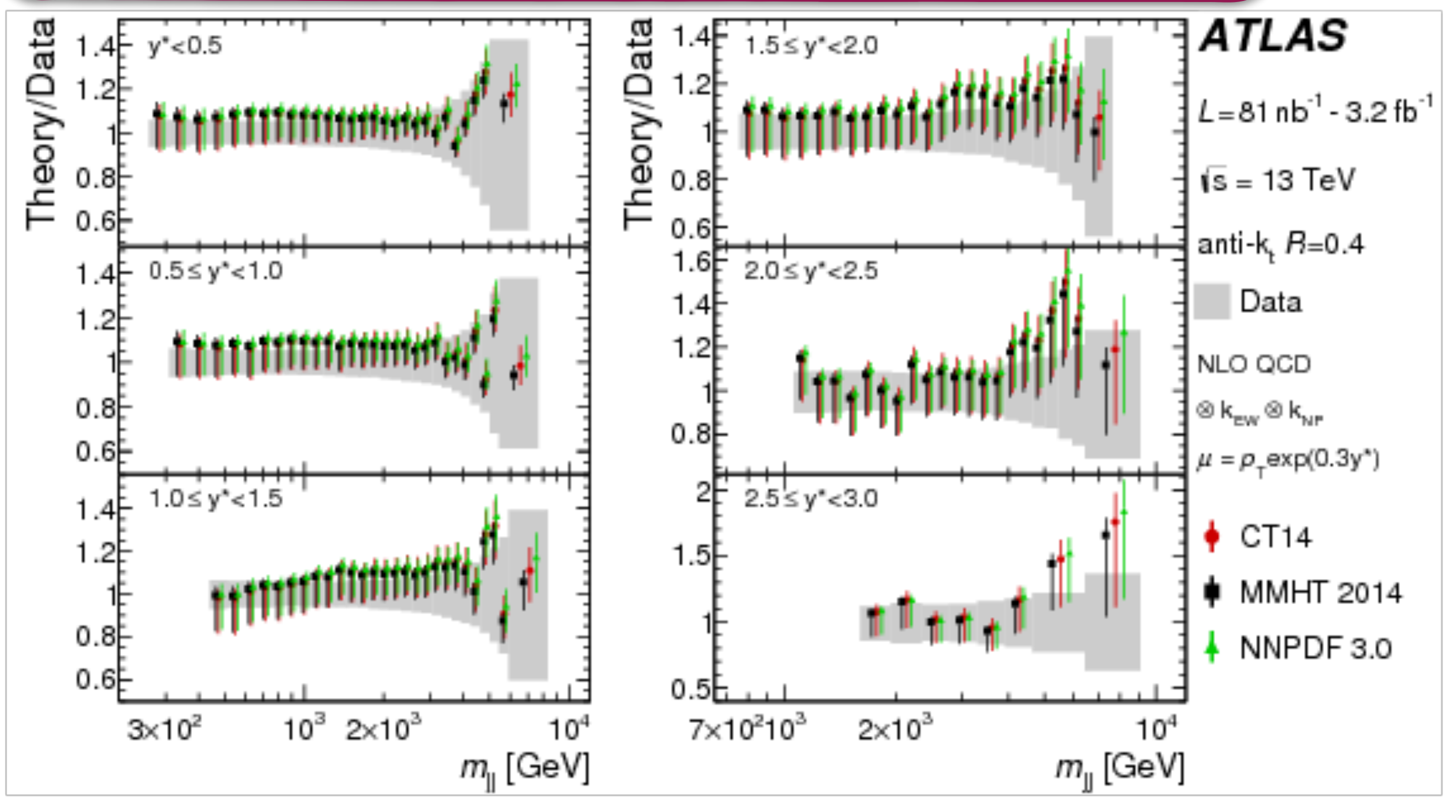
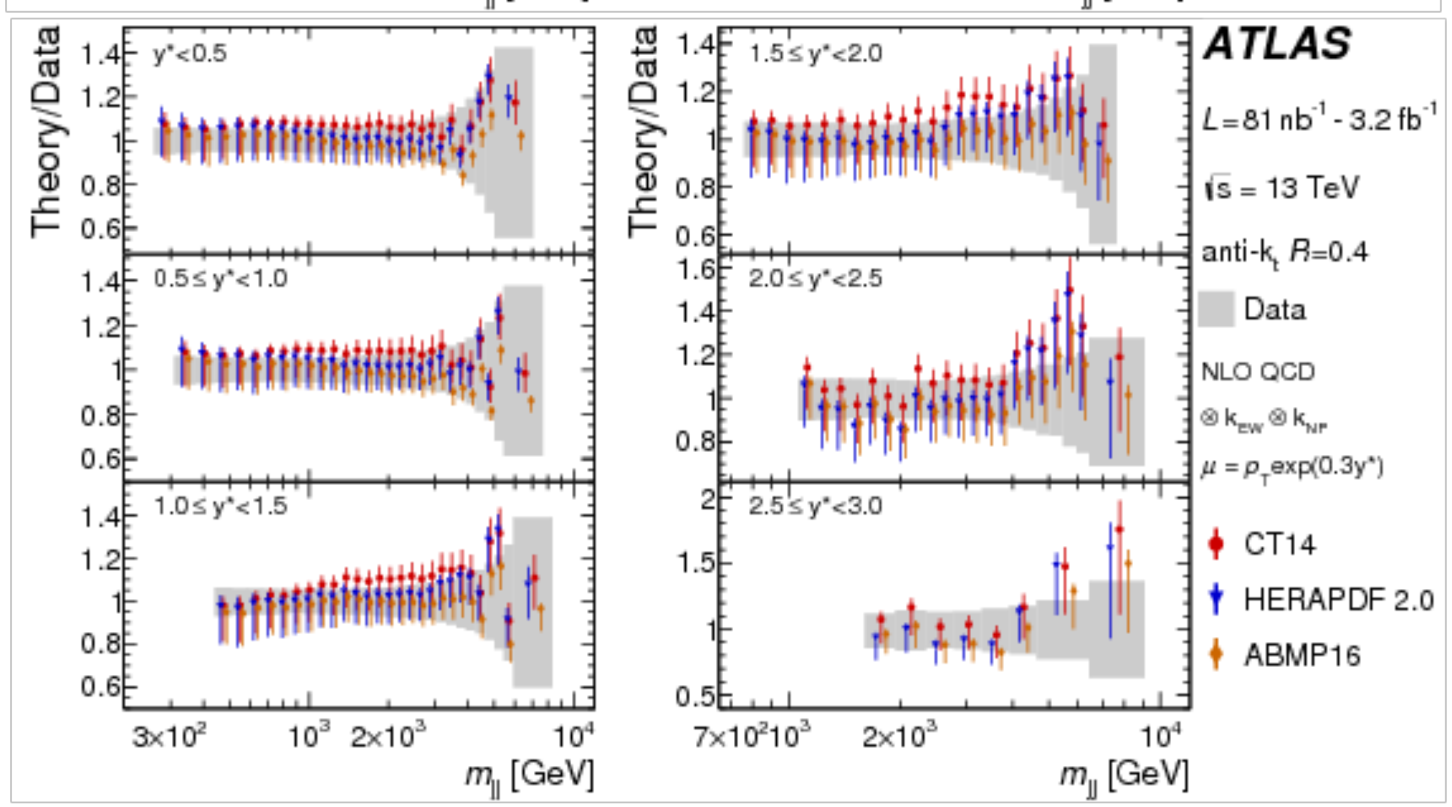
Dijet Cross-section at 13 TeV

Qualitative comparison of data to NLO Calculation



- ➡ PDFs :CT14, **MMHT2014**, NNPDF3.0

- ***Overall***: No significant deviation of the data points from the predictions



- ➡ PDFs :CT14, HERAPDF2.0, ABMP16

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Dijet Cross-section at 13 TeV

Quantitative comparison of data to NLO Calculation

y^* ranges	P_{obs} CT14	MMHT 2014	NNPDF 3.0	HERAPDF 2.0	ABMP16
$y^* < 0.5$	79%	59%	50%	71%	71%
$0.5 \leq y^* < 1.0$	27%	23%	19%	32%	31%
$1.0 \leq y^* < 1.5$	66%	55%	48%	66%	69%
$1.5 \leq y^* < 2.0$	26%	26%	28%	9.9%	25%
$2.0 \leq y^* < 2.5$	41%	34%	29%	3.6%	20%
$2.5 \leq y^* < 3.0$	45%	46%	40%	25%	38%
all y^* bins	9.4%	6.5%	11%	0.1%	5.1%

- Fair agreement between data and theory in single y* bins and when considering all events (last row)

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α_S from TEEC at 8 TeV

- Another way to probe pQCD:
  - Event shape variables → measurements of the geometry of hadronic energy flow.
- **Transverse energy-energy correlation** (TEEC) and its asymmetry (ATEEC) meaurements:
  - Event shape variable infrared safe and with small NLO corrections (both perturbative and EWK).
  - Transverse energy - weighted distribution of differences in azimuth between jets i and j.

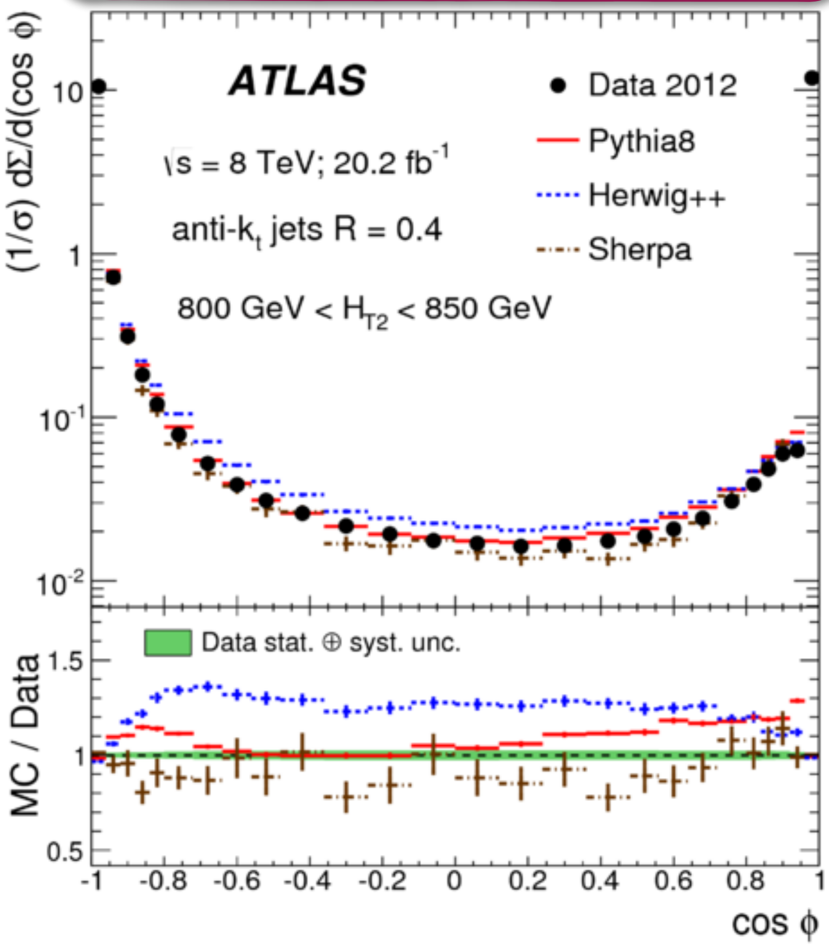
$$\frac{1}{\sigma'}\frac{d\Sigma'}{d\phi} \equiv \frac{1}{N\Delta cos\phi}\sum_{A=1}^{N}\sum_{ij}\frac{E^A_{Ti}E^A_{Tj}}{(\Sigma E^A_{Tk})^2}\delta(cos\phi - cos\phi_{ij})$$

Number of events (index A)

φ_{ij}: azimuthal angle between i and j

i and ***j*** run over all the jets in a given event

TEEC distribution example



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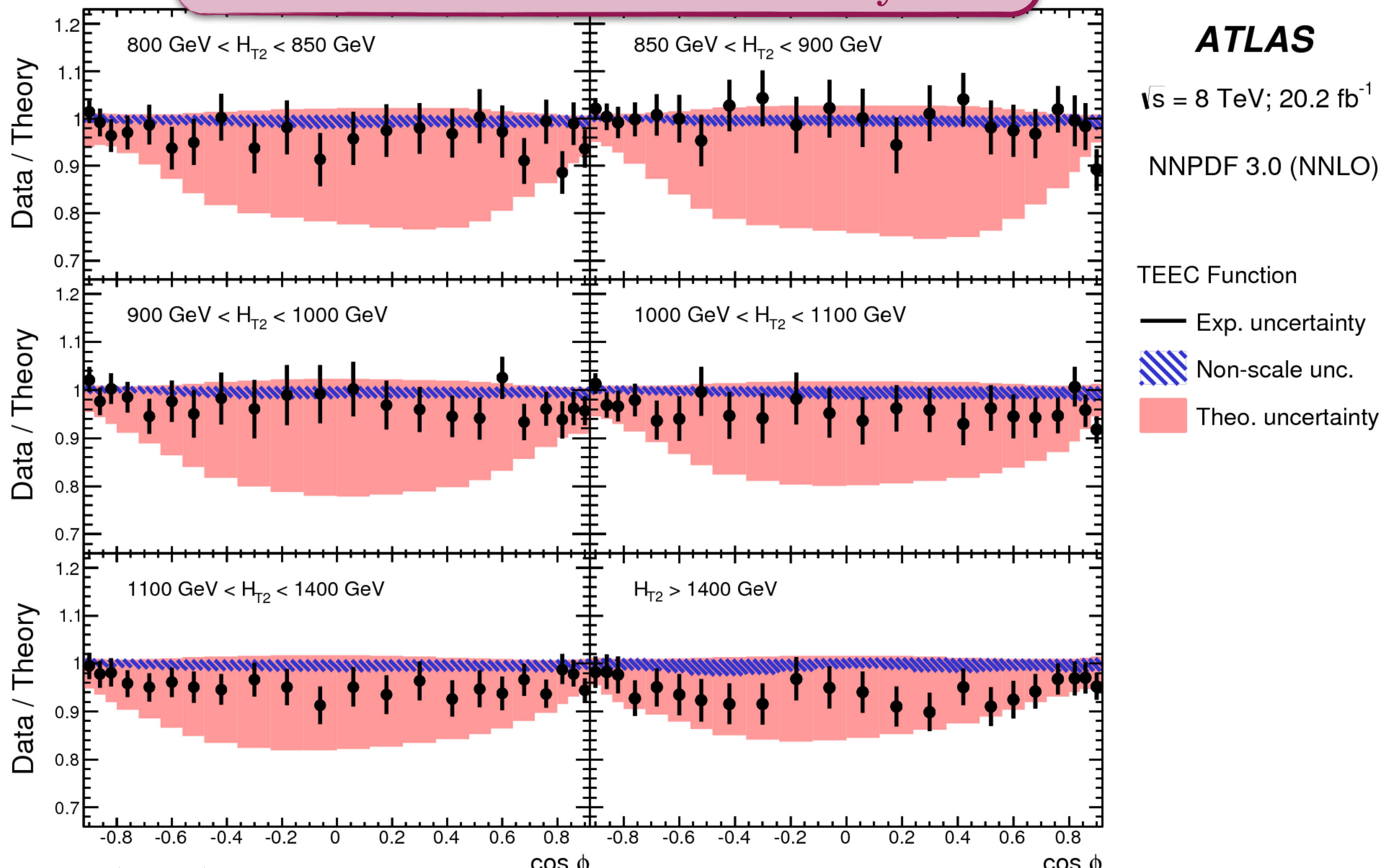
α_S from TEEC at 8 TeV

- ***Theoretical predictions***:
  - pQCD predictions from NLOJET++ with different sets of PDFs
    - MMHT2014, CT14, NNPDF3.0 and HERAPDF2.0
  - Non perturbative correction for hadronisation and underlying events from Pythia8 and Herwig++
  - Dominant related systematic uncertainty: $\mu_{R,F}$

TEEC theoretical uncertainty



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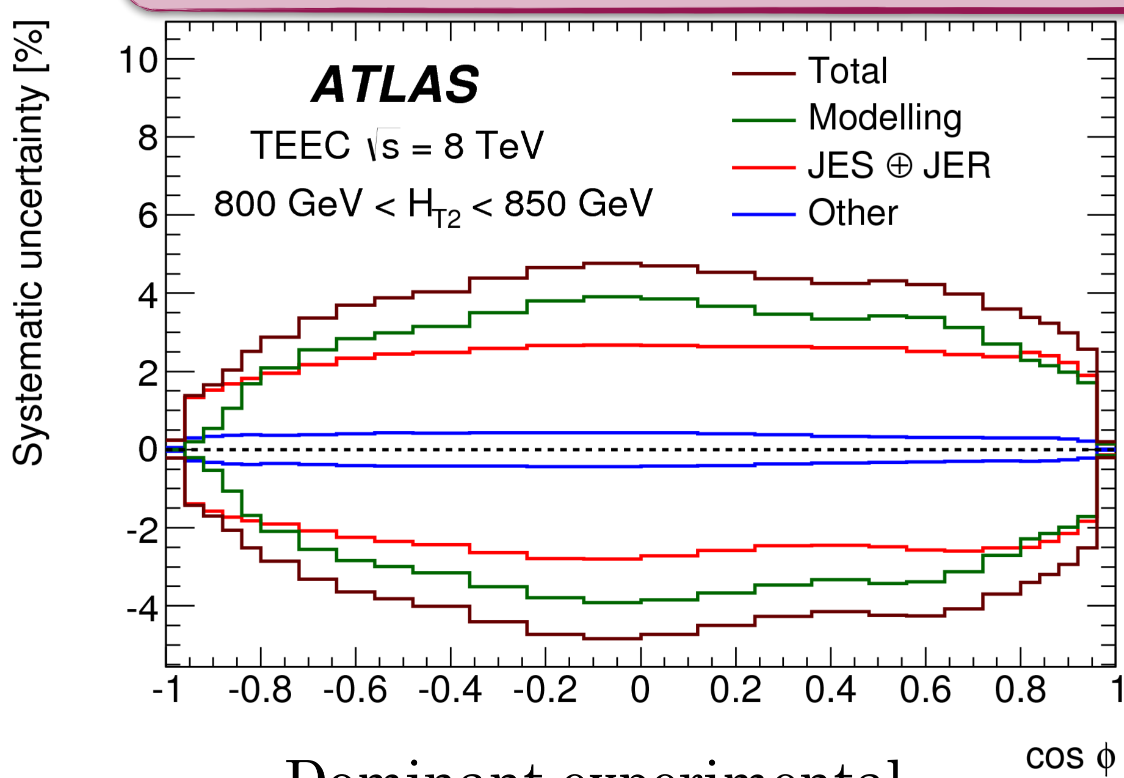
α_S from TEEC at 8 TeV

- ***Multijet systems***: jet multiplicity $<N_{jets}>=2,3$
  - $p_T > 100$ GeV and $|y| < 2.5$
- R=0.4
- $H_{T2} = P_{T1} + P_{T2}$ (sum of the transverse momentum of the two leading jets)
  - $H_{T2} > 800$ GeV for the two leading jets
- **6 H_{T2} bins**
  - Scale $Q = < H_{T2} >/2$

TEEC systematic experimental uncertainties



Dominant experimental systematic uncertainties: **MC model** and **Jet Calibration**

STRATEGY

Measurement of TEEC (ATEEC) distribution in different energy regimes (= H_{T2} bins)

↓ **Fit of individual distribution**

Determination of α_S (m_Z) in each energy regime

↓ **Renormalisation Group Equation**

Test the running of α_S

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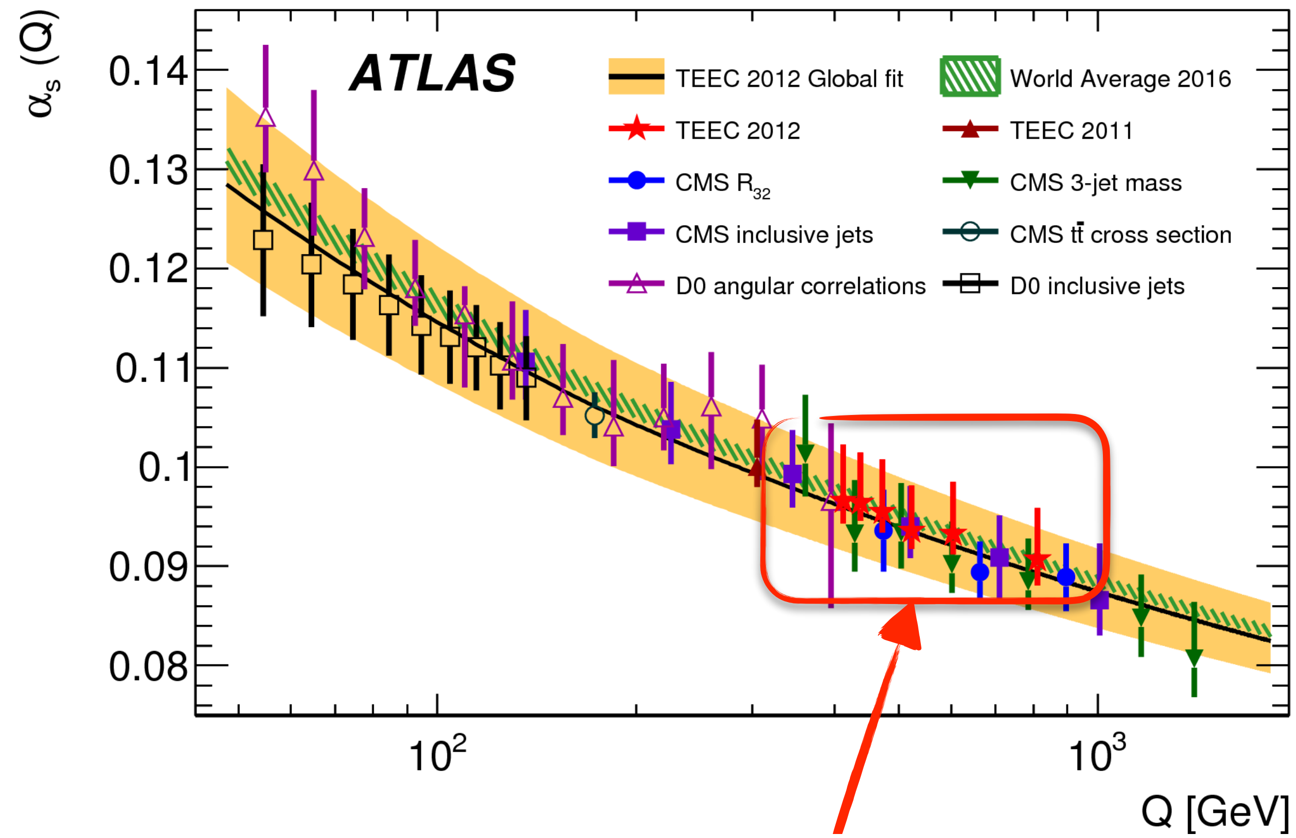
α_S from TEEC at 8 TeV

- ***How to extract α_S?***
  - TEEC (and <u>ATEEC</u>) observables are fitted to the NLOJET++ theoretical predictions, in each H_{T2} bin, singularly
  - α_S (m_Z) value for each bin
  - Each value is evolved to the corresponding energy scale using RGE
  - Final value of α_S (m_Z) obtained merging all the bins together (NNPDF3.0 has the largest PDF uncertainty: related determination quoted as result to be conservative)



$\langle Q \rangle$ (GeV)	$\alpha_s(Q^2)$ value (NNPDF 3.0)
412	0.0966 ± 0.0014 (exp.) $^{+0.0054}_{-0.0015}$ (scale) ± 0.0009 (PDF) ± 0.0001 (NP)
437	0.0964 ± 0.0012 (exp.) $^{+0.0048}_{-0.0011}$ (scale) ± 0.0009 (PDF) ± 0.0002 (NP)
472	0.0955 ± 0.0011 (exp.) $^{+0.0051}_{-0.0015}$ (scale) ± 0.0009 (PDF) ± 0.0001 (NP)
522	0.0936 ± 0.0011 (exp.) $^{+0.0043}_{-0.0010}$ (scale) ± 0.0010 (PDF) ± 0.0001 (NP)
604	0.0933 ± 0.0011 (exp.) $^{+0.0050}_{-0.0014}$ (scale) ± 0.0011 (PDF) ± 0.0003 (NP)
810	0.0907 ± 0.0013 (exp.) $^{+0.0049}_{-0.0020}$ (scale) ± 0.0011 (PDF) ± 0.0002 (NP)

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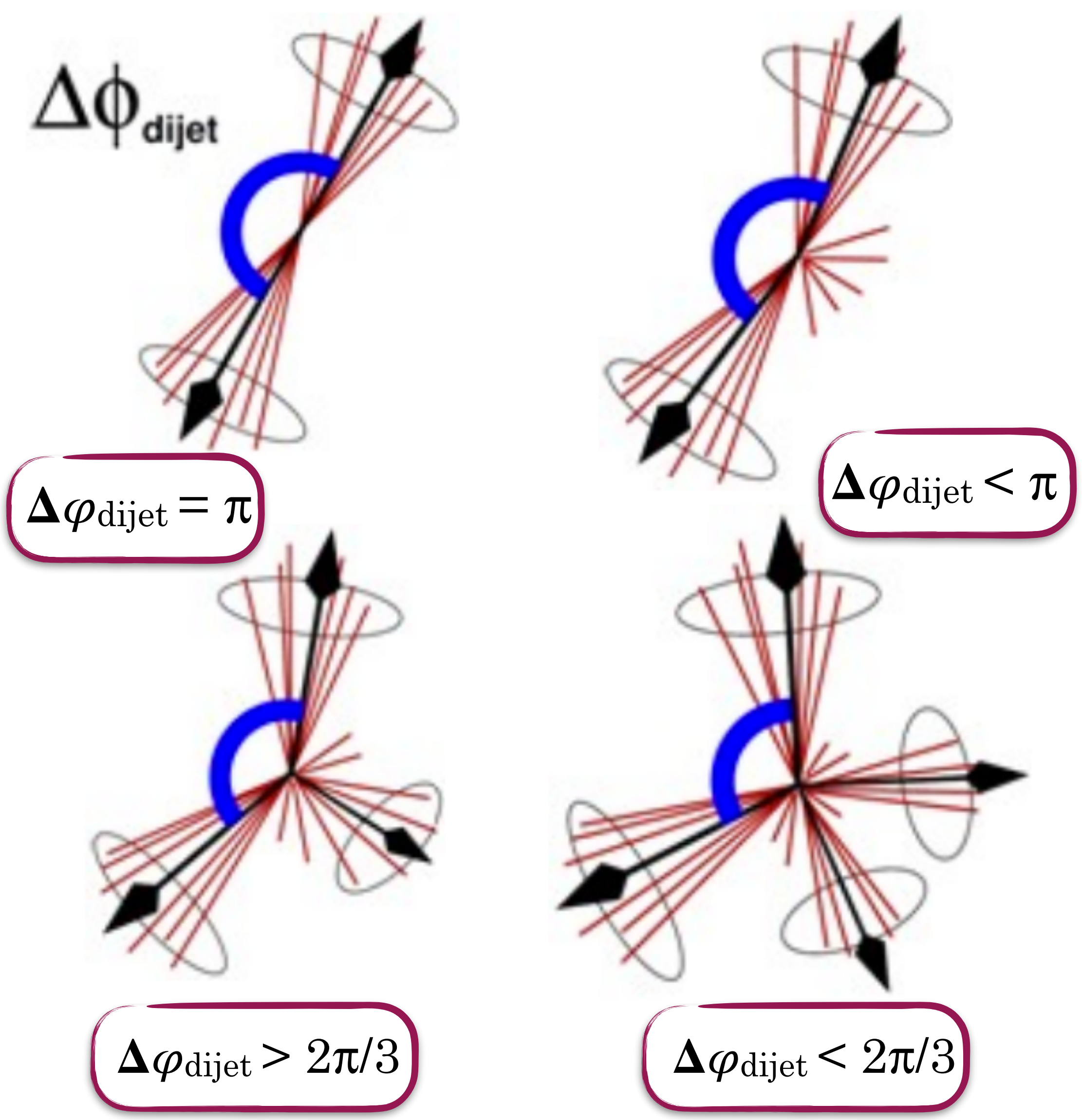
PDF	$\alpha_s(m_Z)$ value
MMHT 2014	0.1151 ± 0.0008 (exp.) $^{+0.0064}_{-0.0047}$ (scale) ± 0.0012 (PDF) ± 0.0002 (NP)
CT14	0.1165 ± 0.0010 (exp.) $^{+0.0067}_{-0.0061}$ (scale) ± 0.0016 (PDF) ± 0.0003 (NP)
NNPDF 3.0	0.1162 ± 0.0011 (exp.) $^{+0.0076}_{-0.0061}$ (scale) ± 0.0018 (PDF) ± 0.0003 (NP)
HERAPDF 2.0	0.1177 ± 0.0008 (exp.) $^{+0.0064}_{-0.0040}$ (scale) ± 0.0005 (PDF) ± 0.0002 (NP) $^{+0.0008}_{-0.0007}$ (mod)

α_S from Dijet Azimuthal Decorrelations at 8 TeV



- **$\Delta\varphi_{dijet}$**: azimuthal separation between the two leading jets
  - $= \pi$ for exclusive high-pT final states
  - $<\pi$ due to additional activity in final states
  - $<\pi$ and $> 2\pi/3$ for 3 jets in final states
  - $< 2\pi/3$ for 4 jets in final states

↓

Test of pQCD for 3 or 4 jet production:
probing higher order α_S

Fraction of inclusive jet events with $\Delta\varphi < \Delta\varphi$max:

$$R_{\Delta\phi}(H_T, y^*, \Delta\phi_{max}) = \frac{\frac{d^2\sigma_{dijet}(\Delta\phi_{dijet}<\Delta\phi_{max})}{dH_T dy^*}}{\frac{d^2\sigma_{dijet}(inclusive)}{dH_T dy^*}}$$

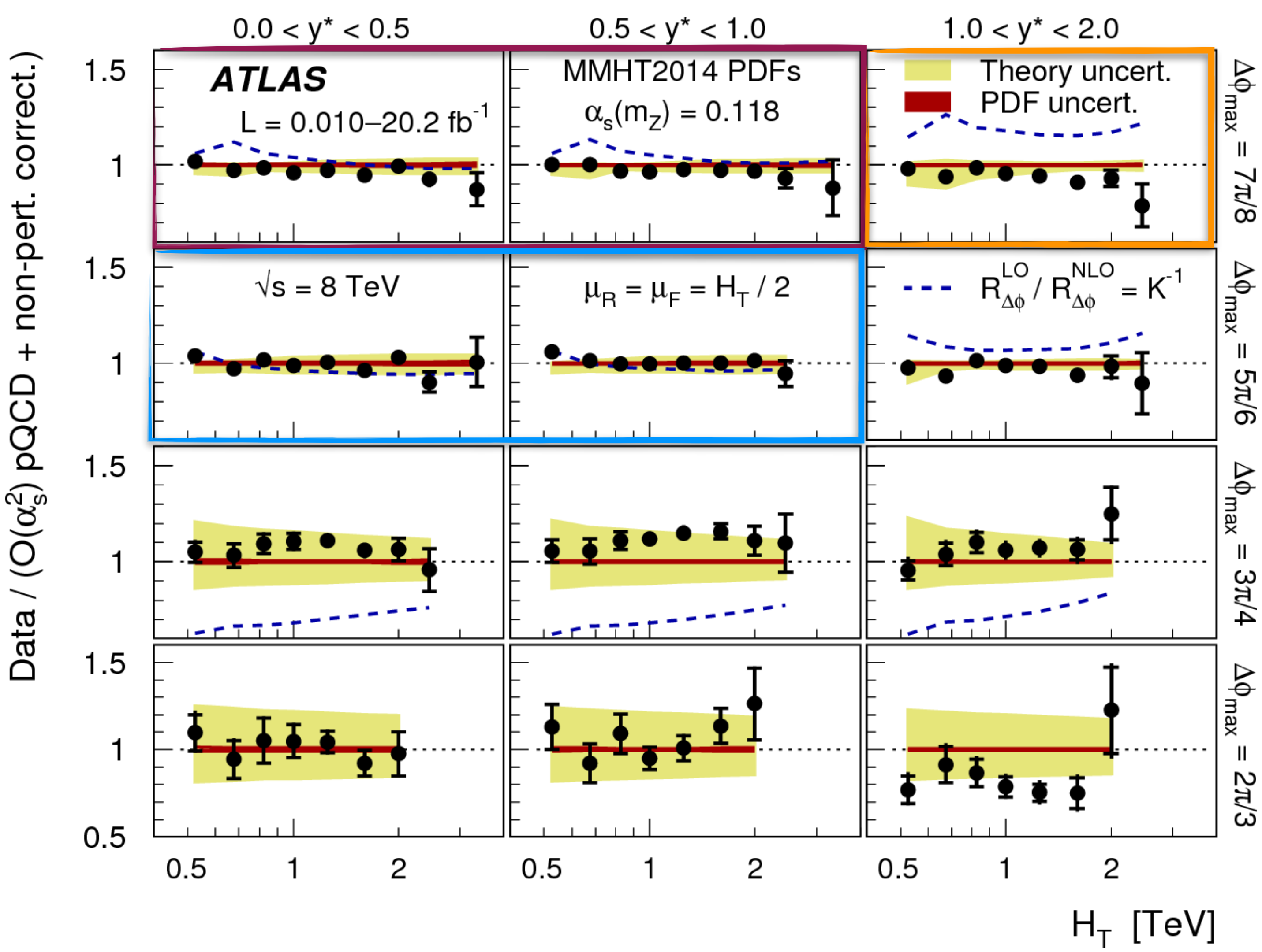
- Binned in $\Delta\varphi_{max}$: $7\pi/8$, $5\pi/6$, $3\pi/4$ (three jets, NLO predictions) and $2\pi/3$ (four jets, LO predictions)
- Binned in H_T and y^*

arXiv:1805.04691

α_S from Dijet Azimuthal Decorrelations at 8 TeV

arXiv:1805.04691

- ***Theoretical predictions***:
  - NLOJET++ for pQCD calculation
  - $\mu_{R,F} = H_T/2$
  - PDFs: MMHT2014, CT14, NNPDF2.3
- Data described by theoretical description in all kinematic regions
  - 5% for 7π/8 and 5π/6: most ***stringent tests*** of theoretical prediction
  - 10-15% for 3π/4: large scale dependence
  - 20% uncertainty dominated by scale variation for 2π/3



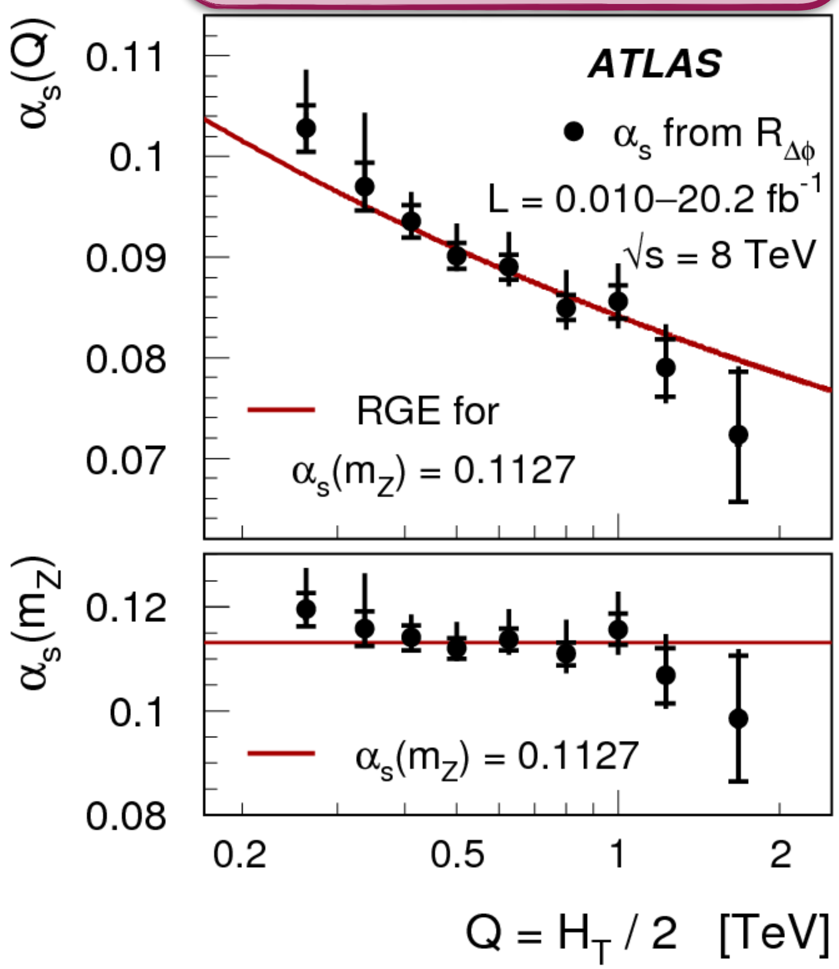
- **7π/8** chosen for α_S determination:
  - ✓ reliable pQCD prediction
  - ✓ data points from different y* regions can be combined
  - ✓ smallest statistical uncertainties
  - ◉ excluding **1<y*<2 region** due to high NLO correction
- **5π/6** also a good choice but higher statistical uncertainty!

α_S from Dijet Azimuthal Decorrelations at 8 TeV

arXiv:1805.04691

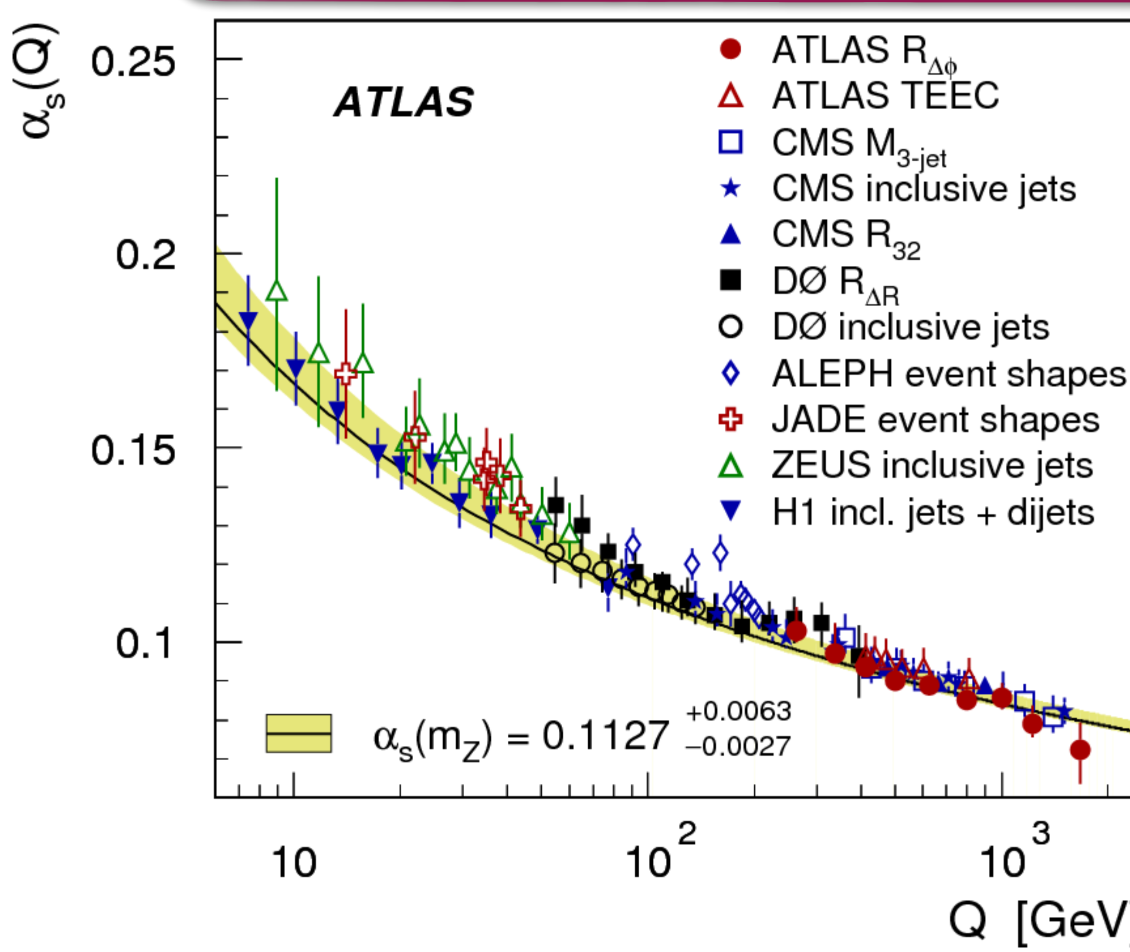
- χ^2 fit of 7π/8 points in two y* regions
- Nine values of $\alpha_S(Q)$ in Q-range 262 < Q ≤ 1675 GeV
- Combine fit to extract $\alpha_S(m_Z)$ (evolving $\alpha_S(Q)$ using RGE)

$\alpha_S(Q)$ measurement



Evolution to $\alpha_S(m_Z)$ via RGE

RΔφ measurement of $\alpha_S(m_Z)$ compared to World Average

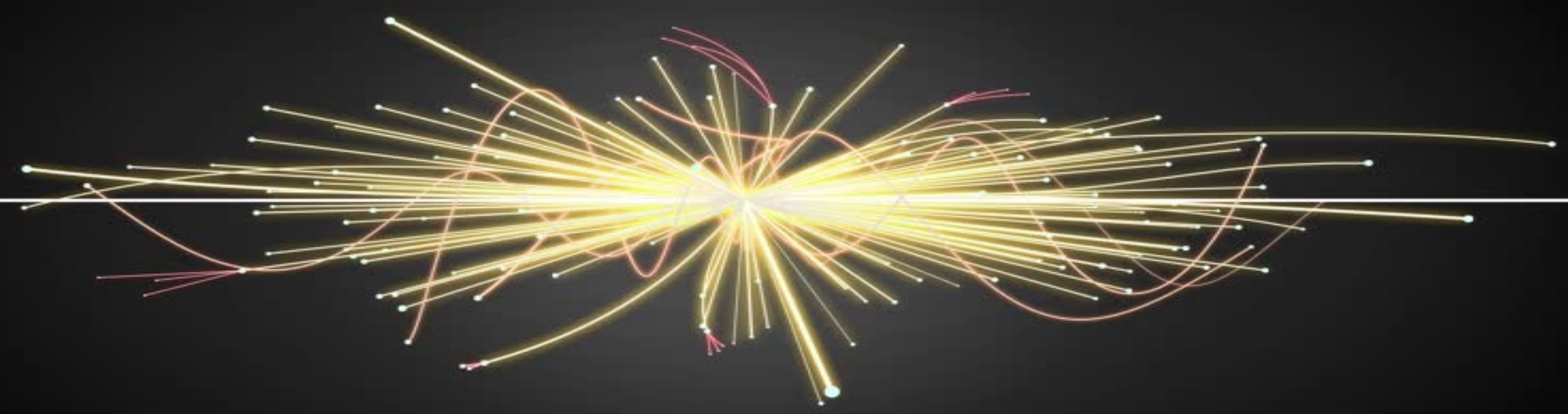


$\alpha_S(m_Z)$	Total uncert.	Statistical	Experimental correlated	Non-perturb. corrections	MMHT2014 uncertainty	PDF set	$\mu_{R,F}$ variation
0.1127	$^{+6.3}_{-2.7}$	±0.5	$^{+1.8}_{-1.7}$	$^{+0.3}_{-0.1}$	$^{+0.6}_{-0.6}$	$^{+2.9}_{-0.0}$	$^{+5.2}_{-1.9}$

Conclusions

- LHC is the ideal playground for extensive tests of QCD
- Jets are powerful tools for such goal also thanks to the excellent ATLAS performance in jet reconstruction
- ATLAS has wide physics program in the QCD field with jet cross-section, both inclusive and in association with γ and vector bosons
- ATLAS latest results on pQCD shows generally good theory-data agreement
  - investigating some tension between data and theory in inclusive jet cross-section measurements both at 8 and 13 TeV
  - determination of $\alpha_S(m_Z)$ from transverse energy-energy correlation in dijet events and from dijet azimuthal decorrelation compatible with World Average

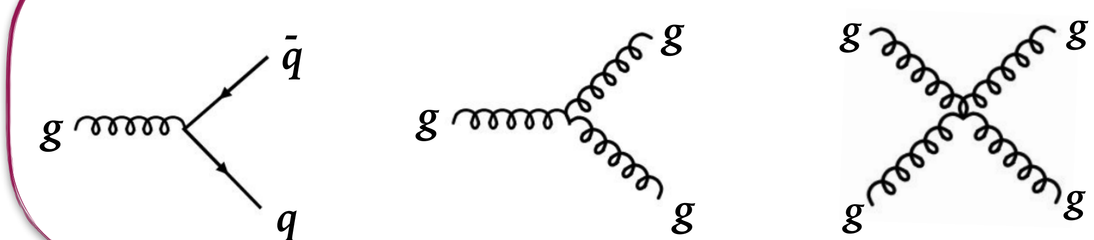
Backup

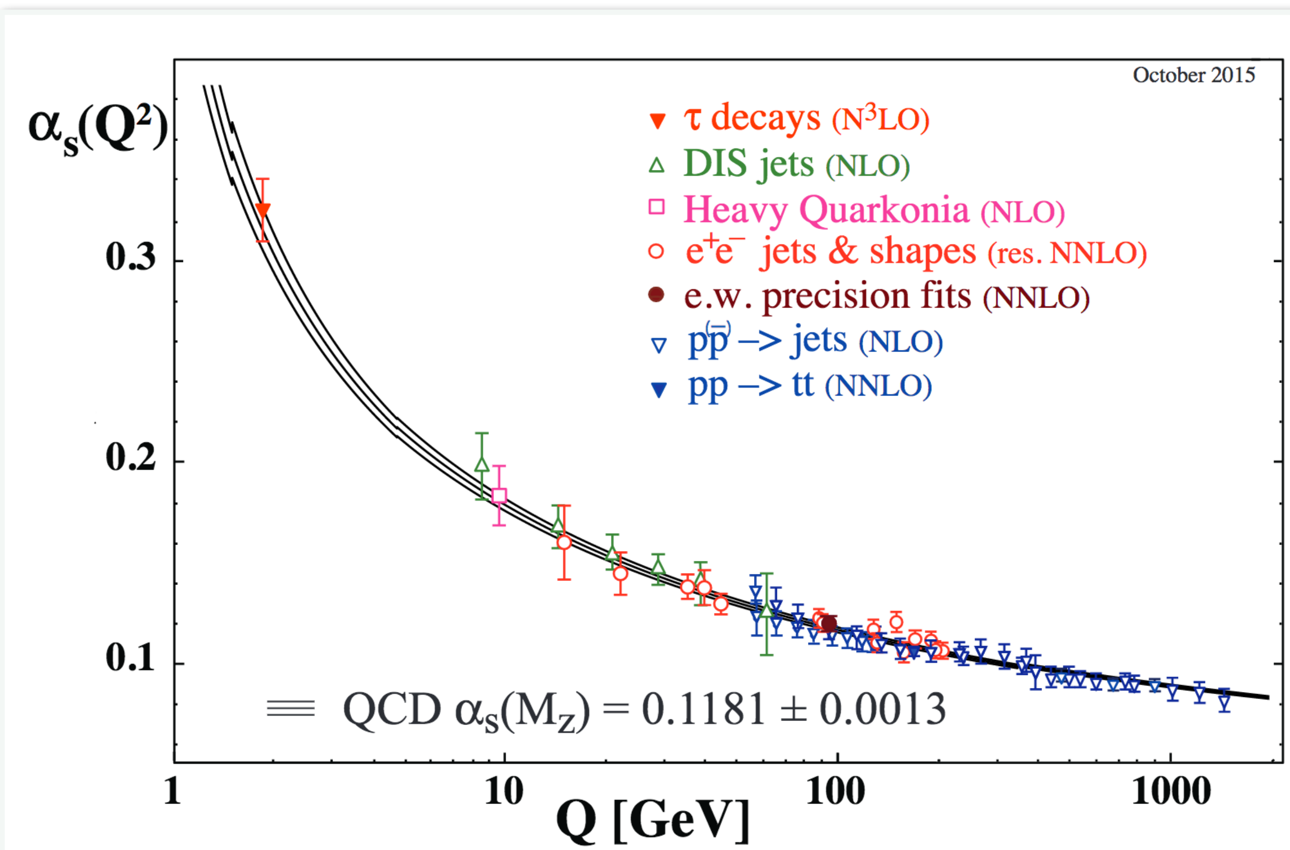


QCD

- **QCD** (Quantum ChromoDynamics) is the theory of strong interactions:
  - 3 color charges (**red**, **blue** and **green**)
  - 8 ***colored*** of gluons: gluons interact with each others!

Vertices





- No free quarks observed: **confinement**
- At high momentum transfer, quarks ***behave*** as free particles: **asymptotic freedom**

↓

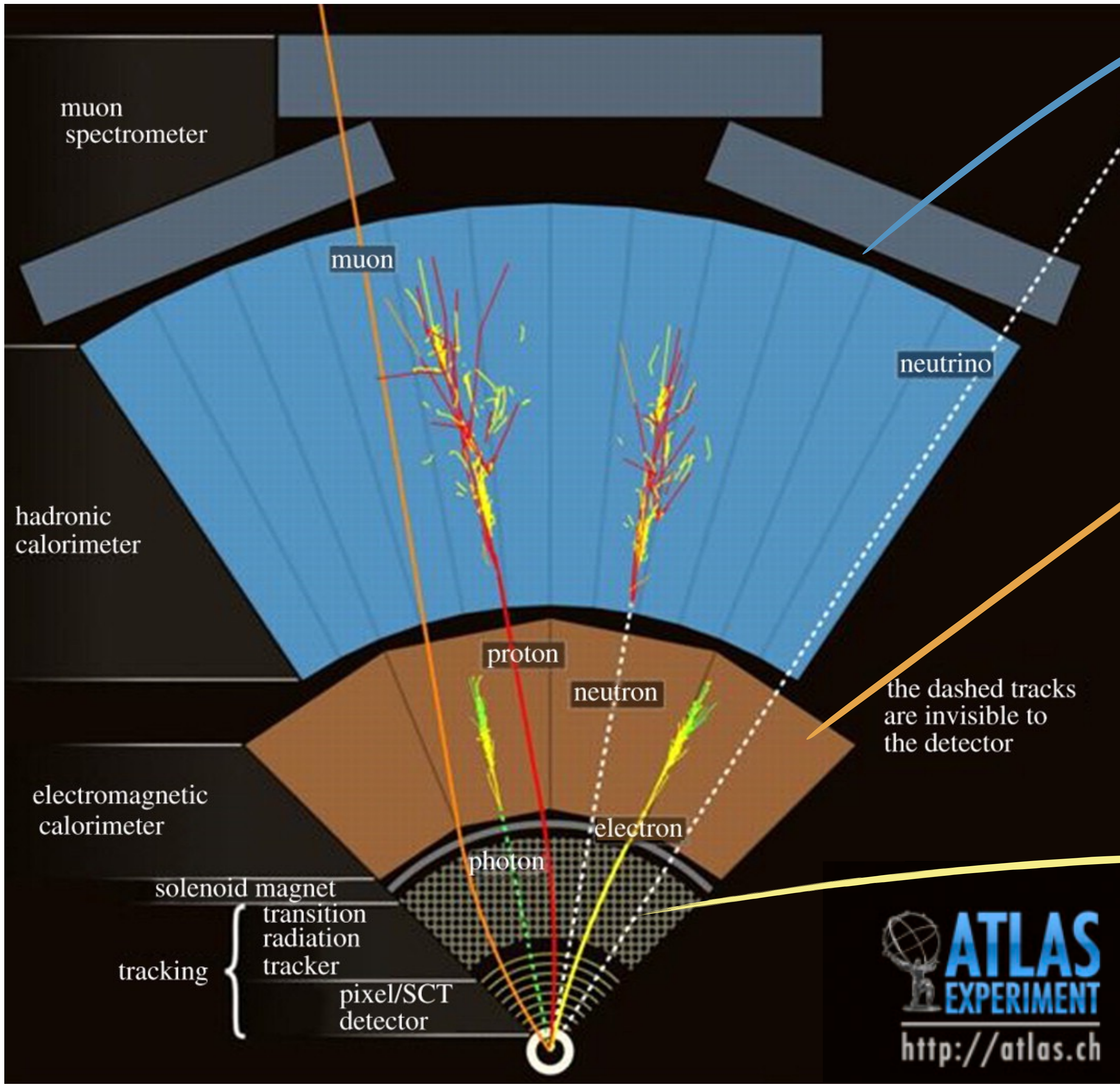
- ***Running*** coupling constant:
  - increasing with energy decrease: perturbative QCD (**pQCD**)
  - decreasing with energy increase: phenomenological approach (perturbative one no longer reliable)

Soft QCD ◀—— - - - - - - - ——▶ *Hard QCD*

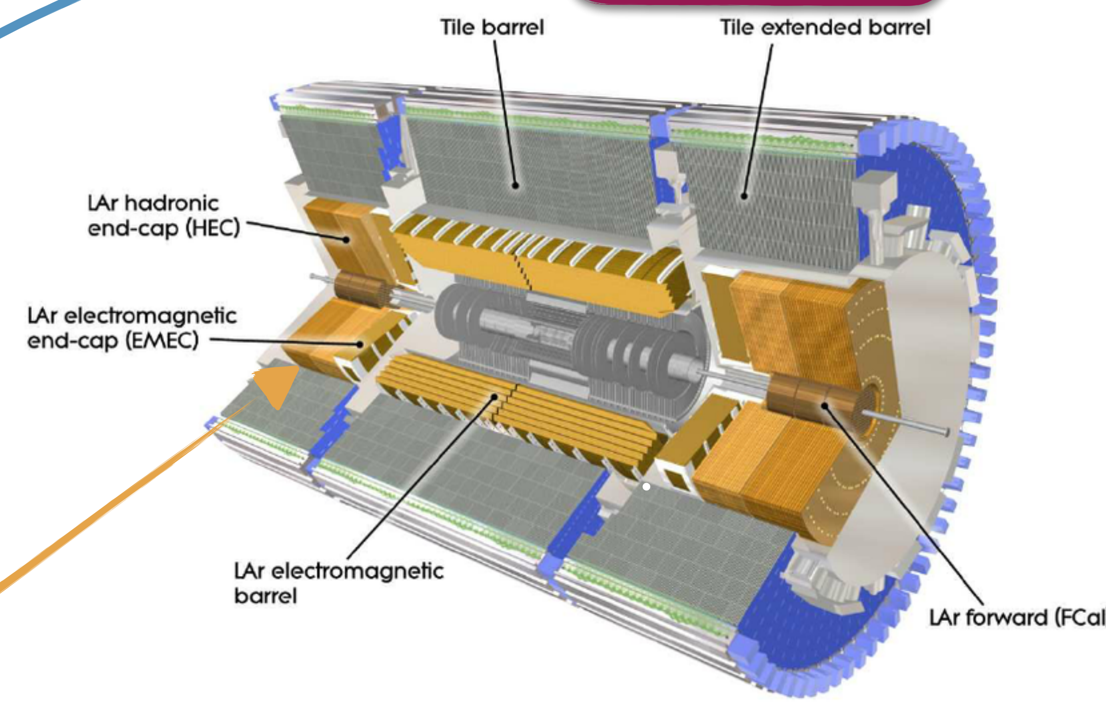
confinement ***asymptotic freedom***

Particles in ATLAS

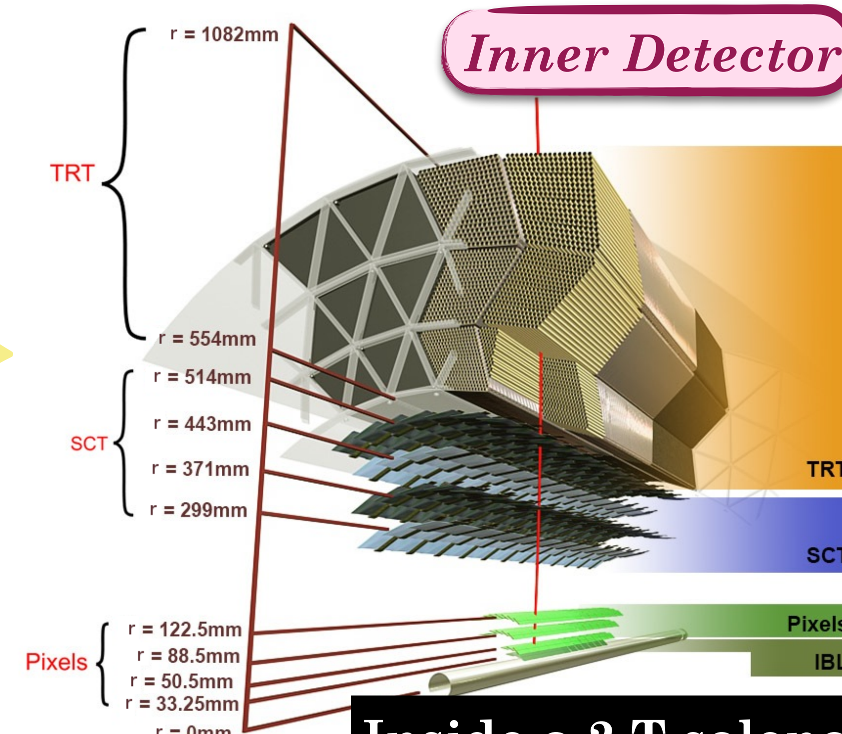
- ***ATLAS*** particle reconstruction:



Calorimeters



Inner Detector



Inside a 2 T solenoid

Jet Reconstruction

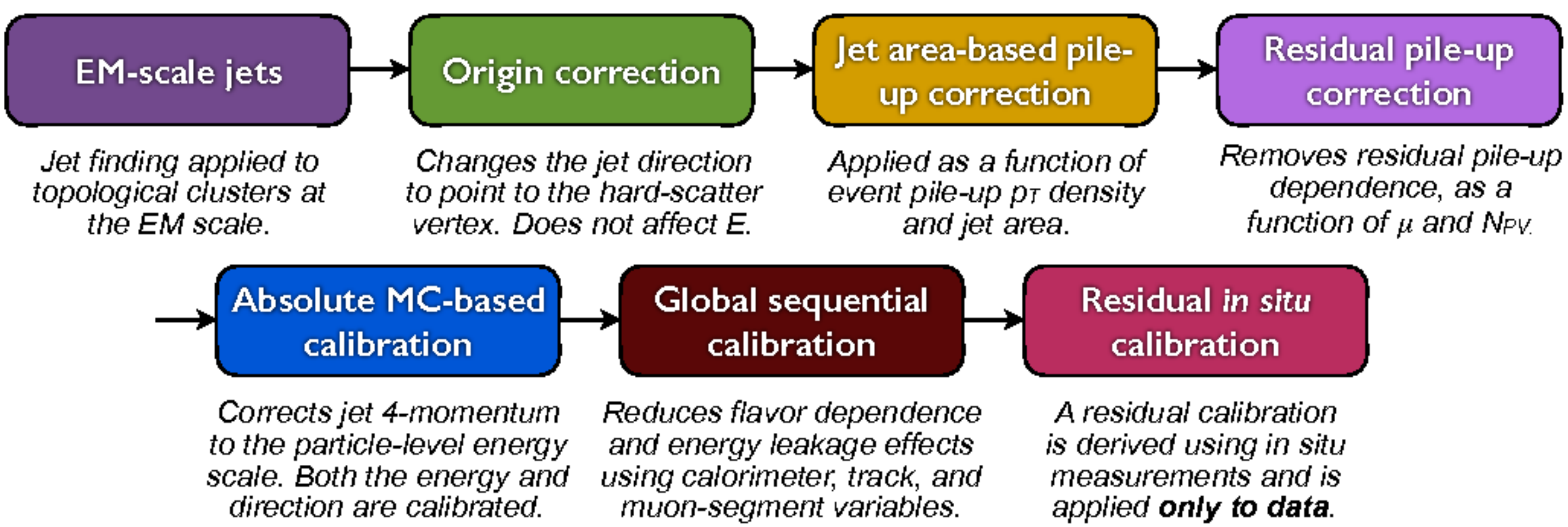
- ***Jet reconstruction algorithm*** to cluster objects into a jet
- ATLAS choice is **anti-k$_t$** algorithm: sequential recombination algorithm based on **minimum distance**
- Depends on jet p$_T$ and angular distance (η, φ)
- Procedure:
  - Find local cell i with E_{max}
  - j is the neighboring cell
  - Find $min\{d_{ij}, d_{iB}\}$
  - If $d_{ij} = min$, then recluster
  - Otherwise label i as final jet

Ingredients

- $$d_{ij} = min\left(\frac{1}{p_{ti}^2}, \frac{1}{p_{tj}^2}\right) \cdot \frac{R_{ij}^2}{R}$$
- $$d_{iB} = \frac{1}{p_{ti}^2}$$
- $R_{ij}^2 = (\phi_i - \phi_j)^2 + (\eta_i - \eta_j)^2$
- R is the radius parameter (range 0.4 - 1)

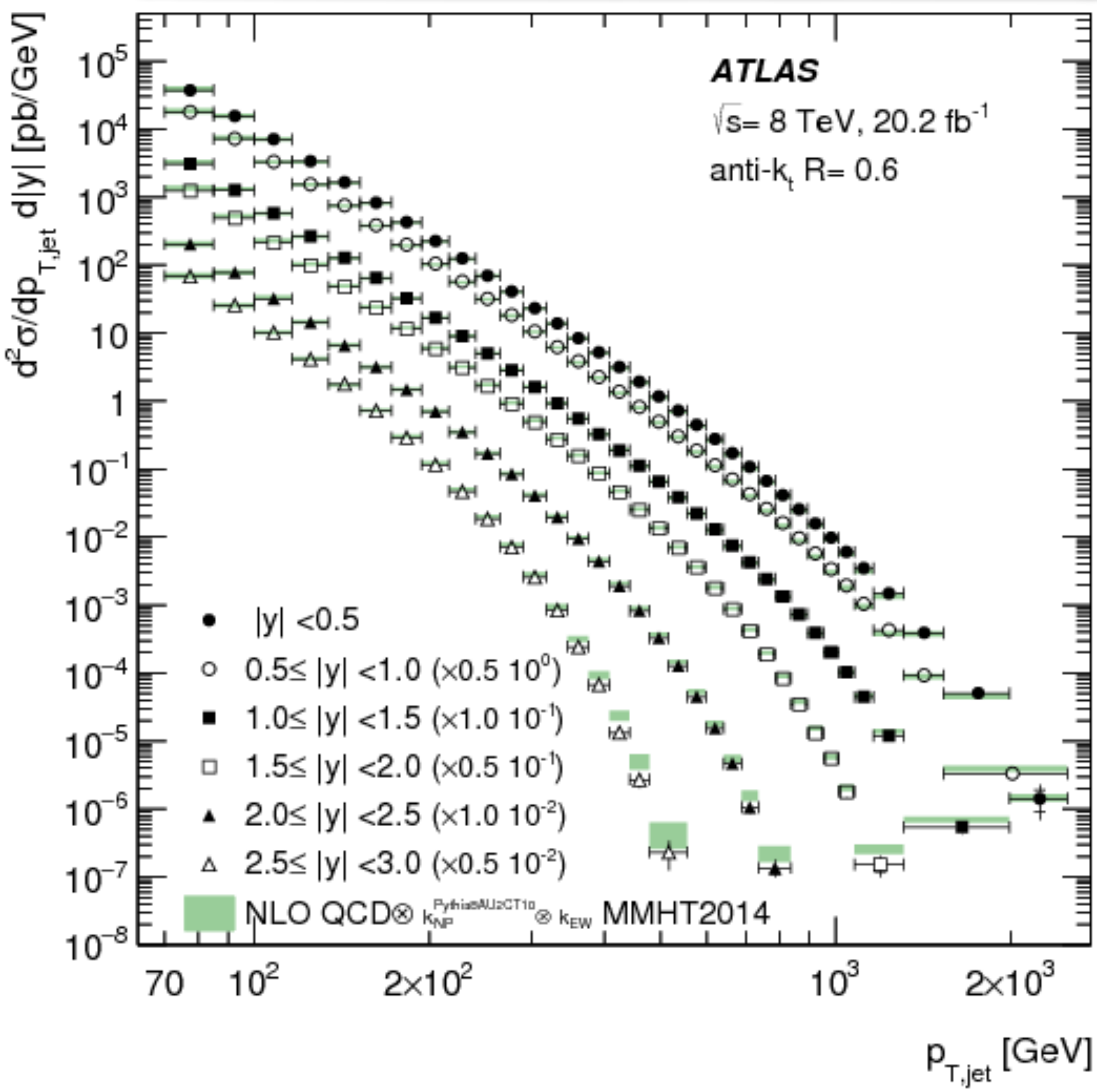
Jet Calibration

- Effects to be corrected:
  - Calorimeter non compensation: partial measurement of the energy deposited
  - Dead material: energy losses in inactive areas of the detector
  - Leakage: energy of the particles out of the calorimeters
  - Out of calorimeter radiation: energy deposit of the particles from shower not included in reconstructed jet
  - Noise threshold and particle reconstruction efficiency: electronics losses in calorimeter clustering and jet reconstruction.
  - Pile up: taking into account energy due to additional *pp* interactions
  - Jet origin correction: correct the direction of the jet to originate from primary vertex (no effects on energy)

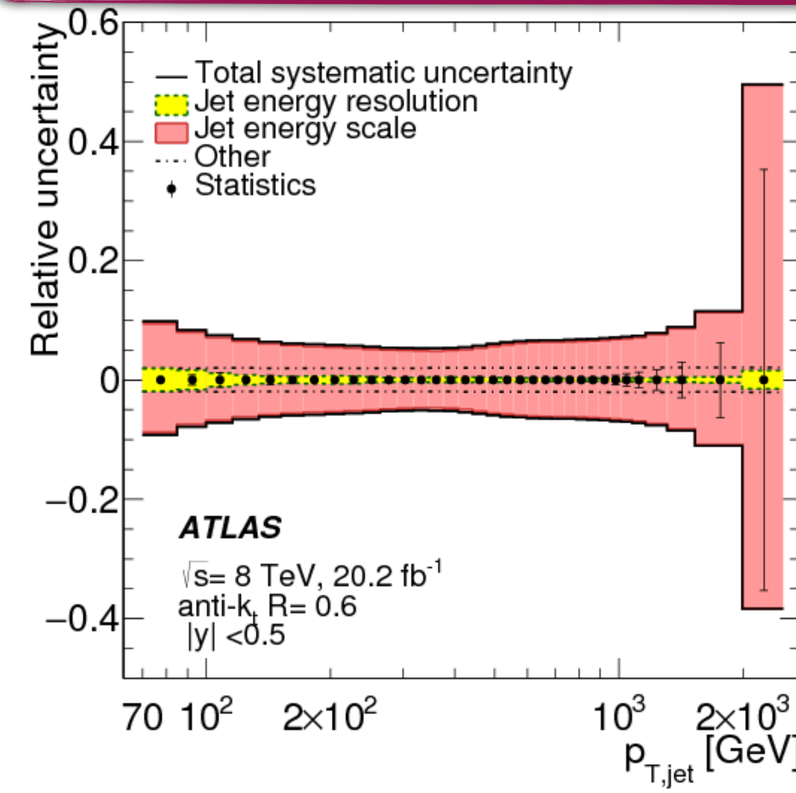


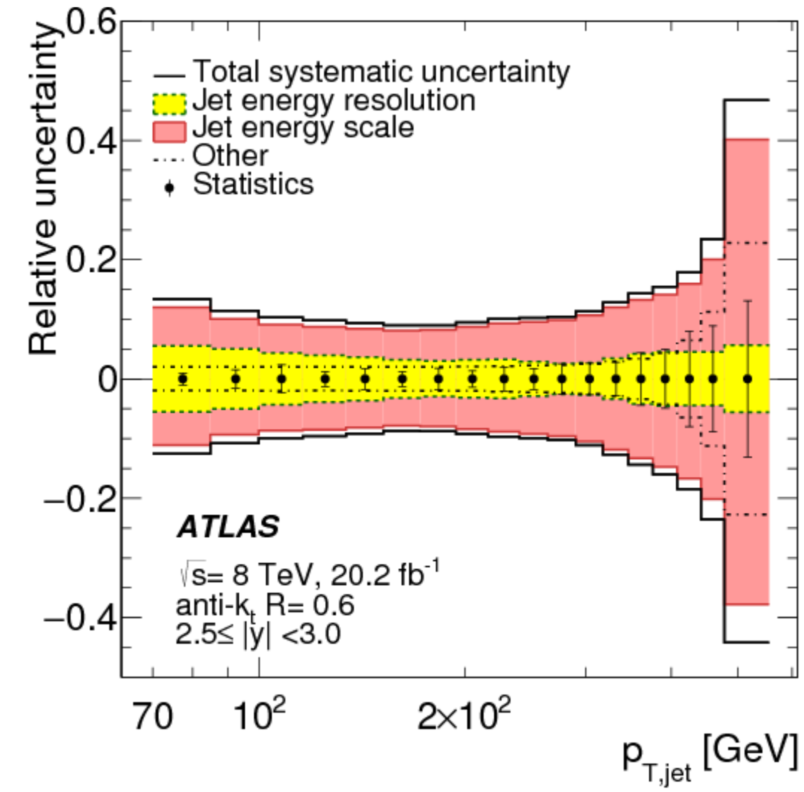
Inclusive Cross-section at 8 TeV: R=0.6

Inclusive jet cross-section (R = 0.6)



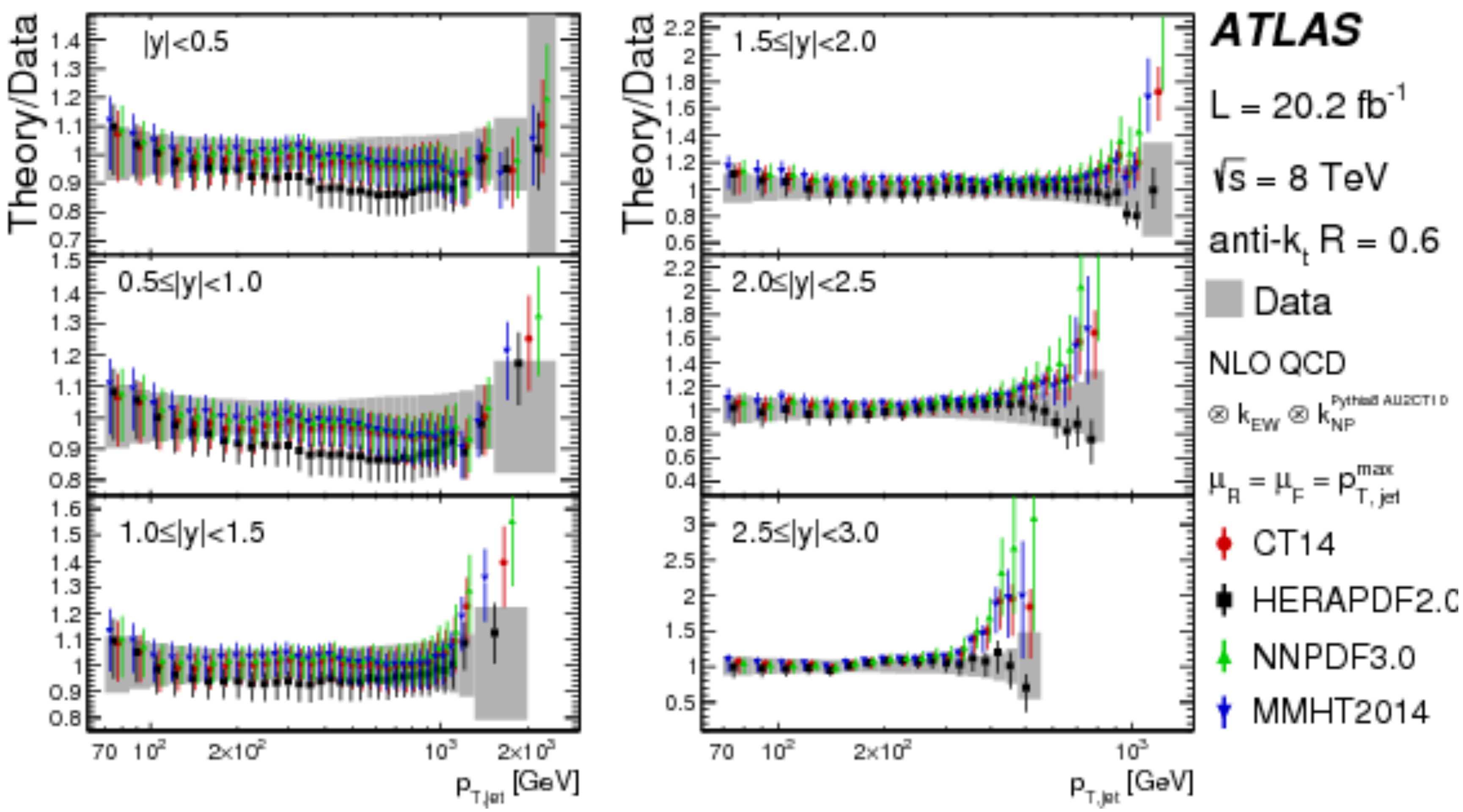
Systematics on Cross-Section at 13 TeV (R=0.6)





Inclusive Cross-section at 8 TeV: R=0.6

Qualitative comparison of data to NLO Calculation



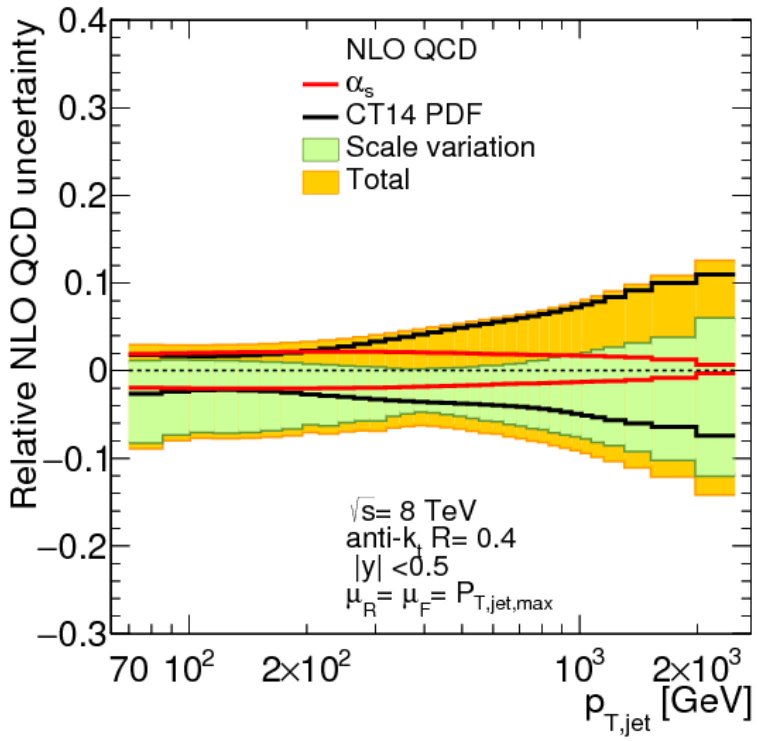
Quantitative comparison of data to NLO Calculation

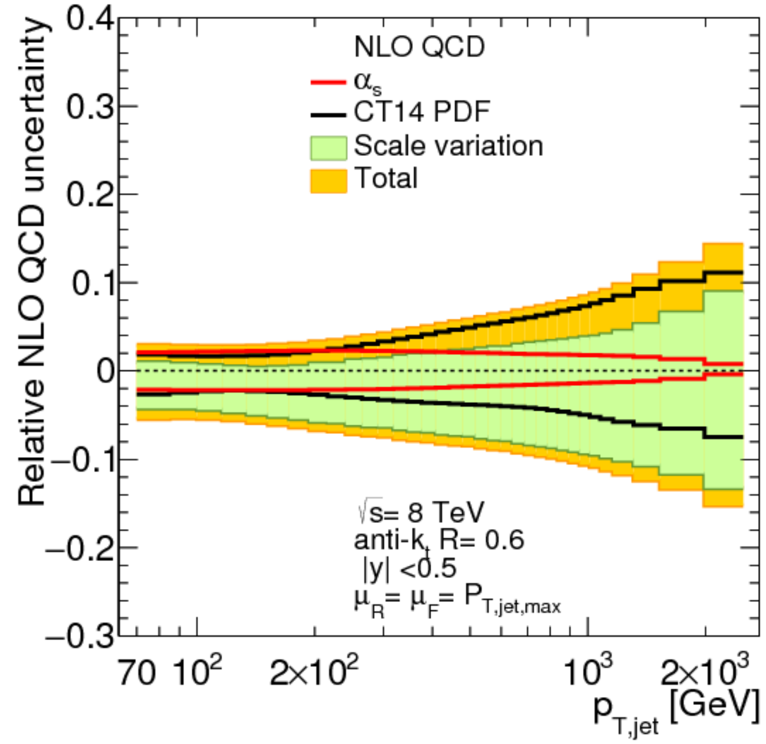
Rapidity ranges	CT14	MMHT2014	NNPDF3.0	HERAPDF2.0
	P_{obs}			
Anti-k_t jets $R = 0.6$				
$\|y\| < 0.5$	6.7%	4.9%	4.6%	1.1%
$0.5 \le \|y\| < 1.0$	1.3%	0.7%	0.4%	0.2%
$1.0 \le \|y\| < 1.5$	30%	33%	47%	67%
$1.5 \le \|y\| < 2.0$	12%	16%	15%	3.1%
$2.0 \le \|y\| < 2.5$	94%	94%	91%	38%
$2.5 \le \|y\| < 3.0$	13%	15%	20%	8.6%

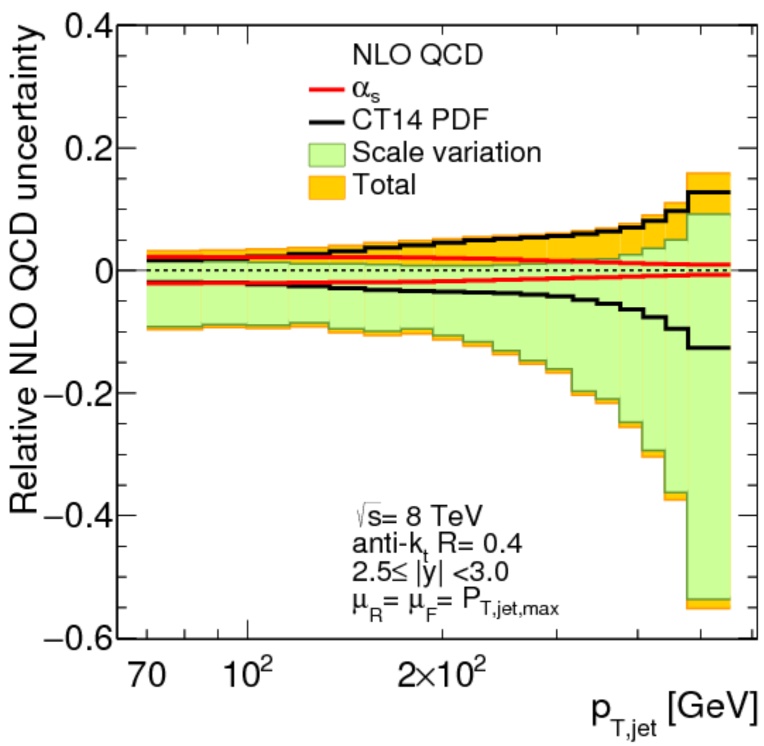
Inclusive Cross-section at 8 TeV

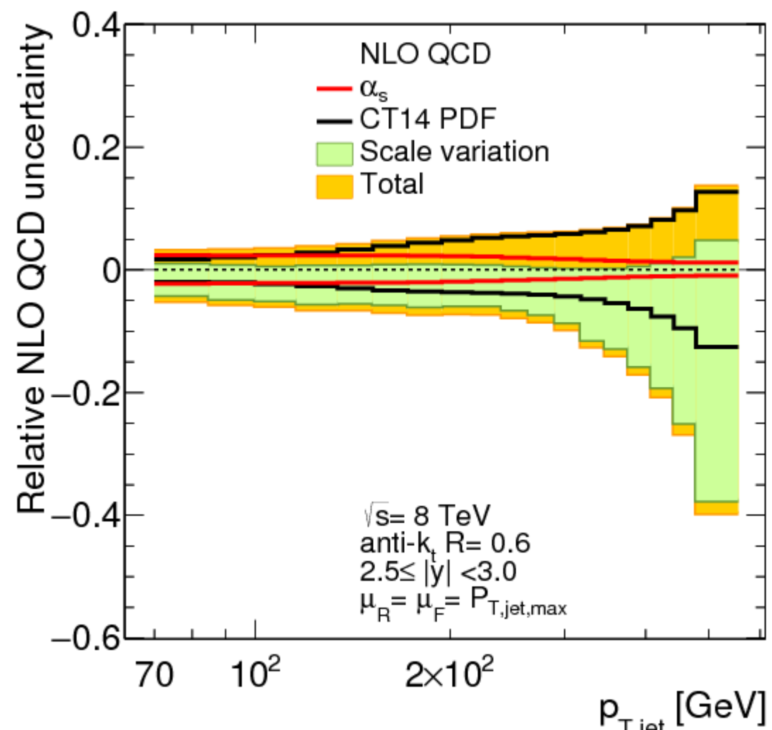
_R = 0.4_

_R = 0.6_

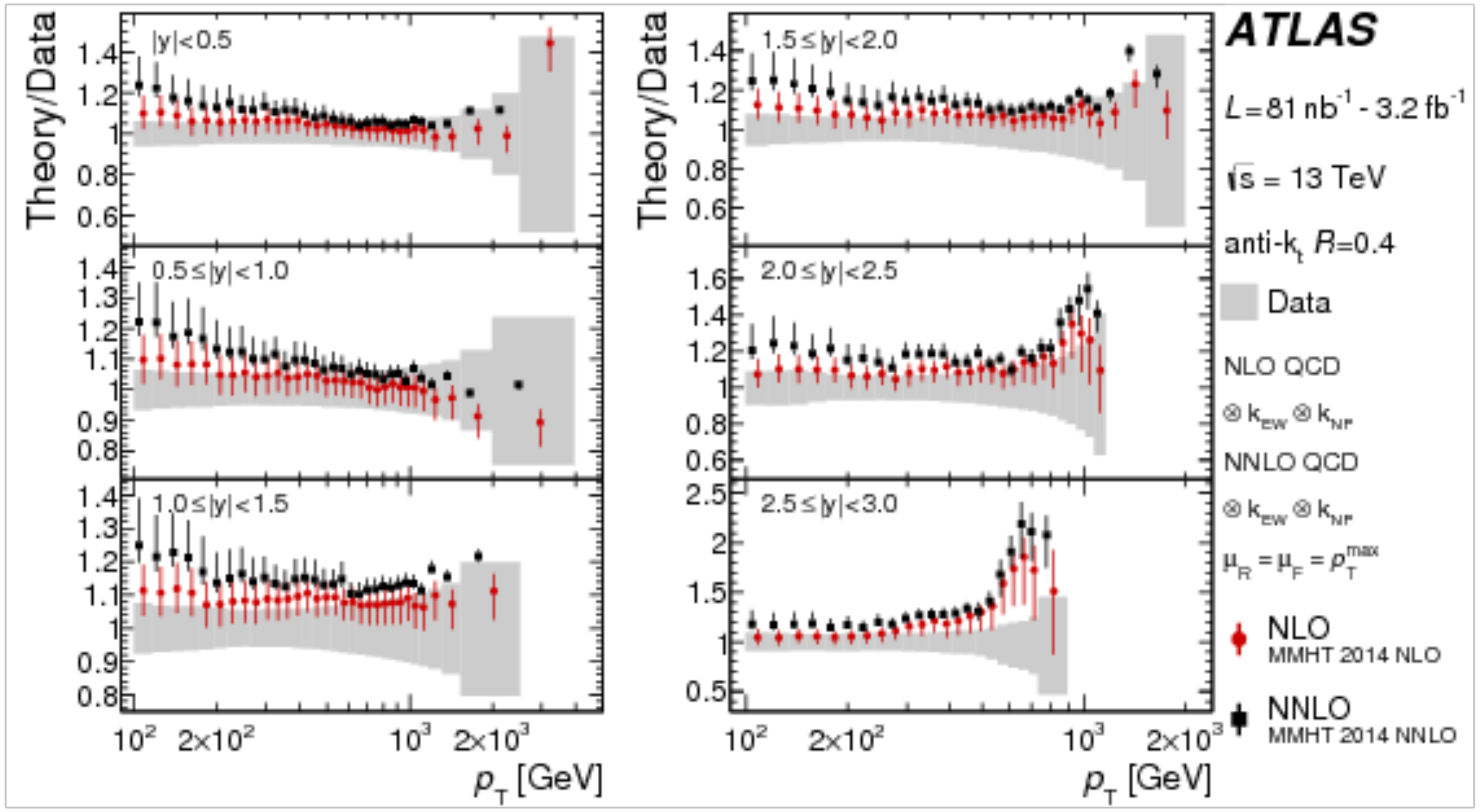


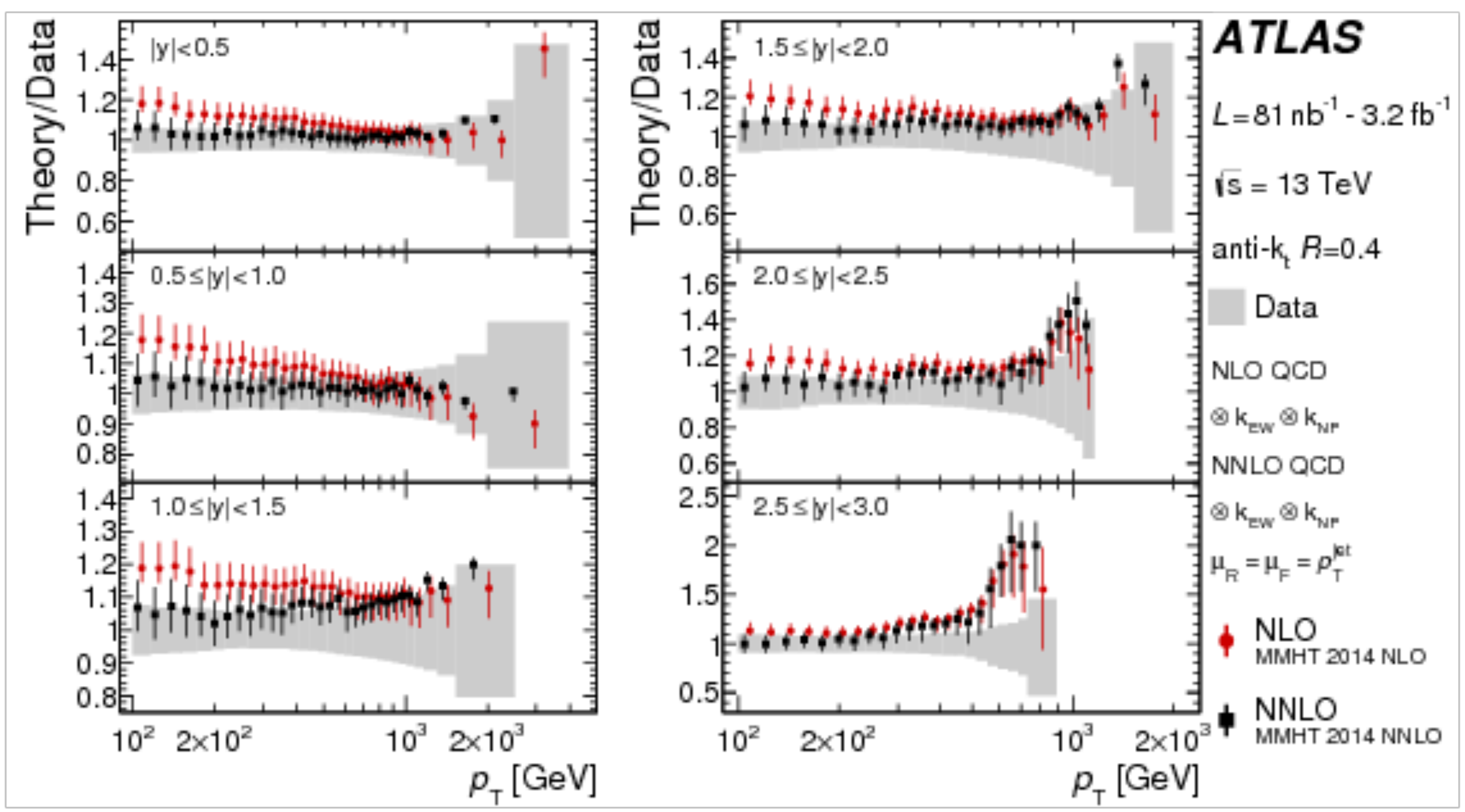






- ***Theoretical Uncertainties*** in NLO predictions:
  - CT14 PDF

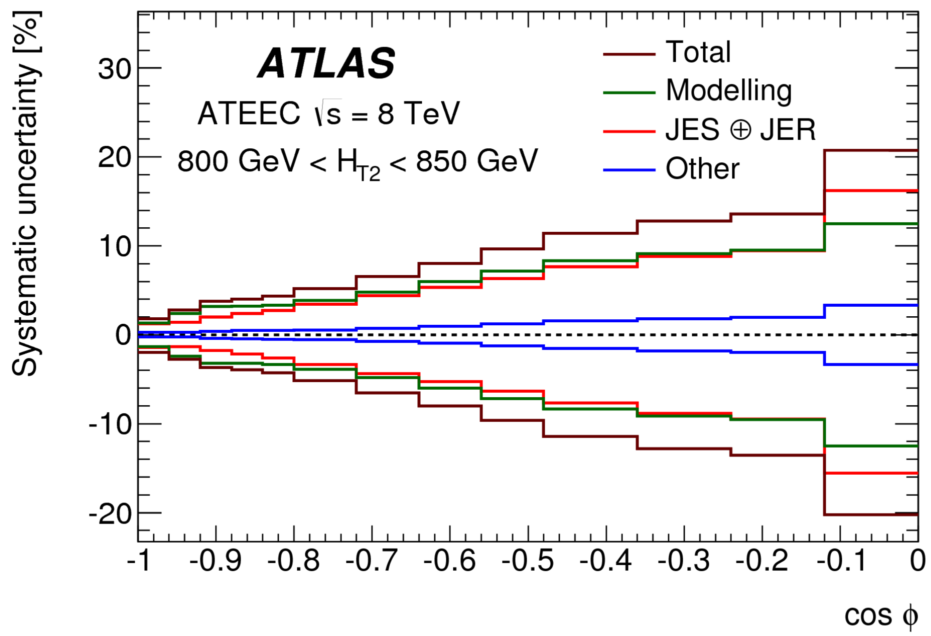




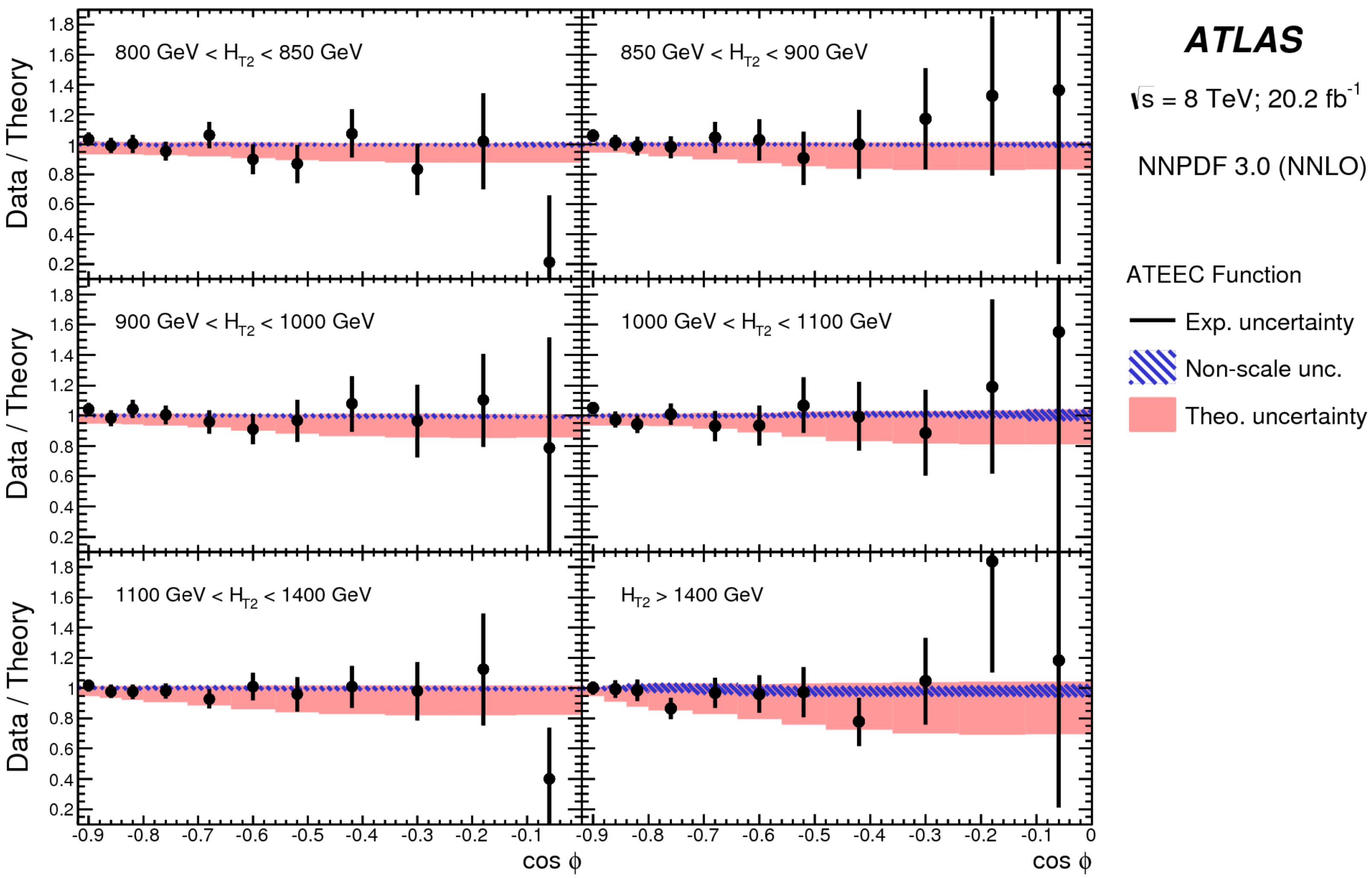
- NNLOJET with MMHT2014 NNLO PDF:
  - two $\mu_{R,F}$ scales: p_T^{max} (leading jet) and p_T

α_S from ATEEC at 8 TeV

ATEEC systematic experimental uncertainties

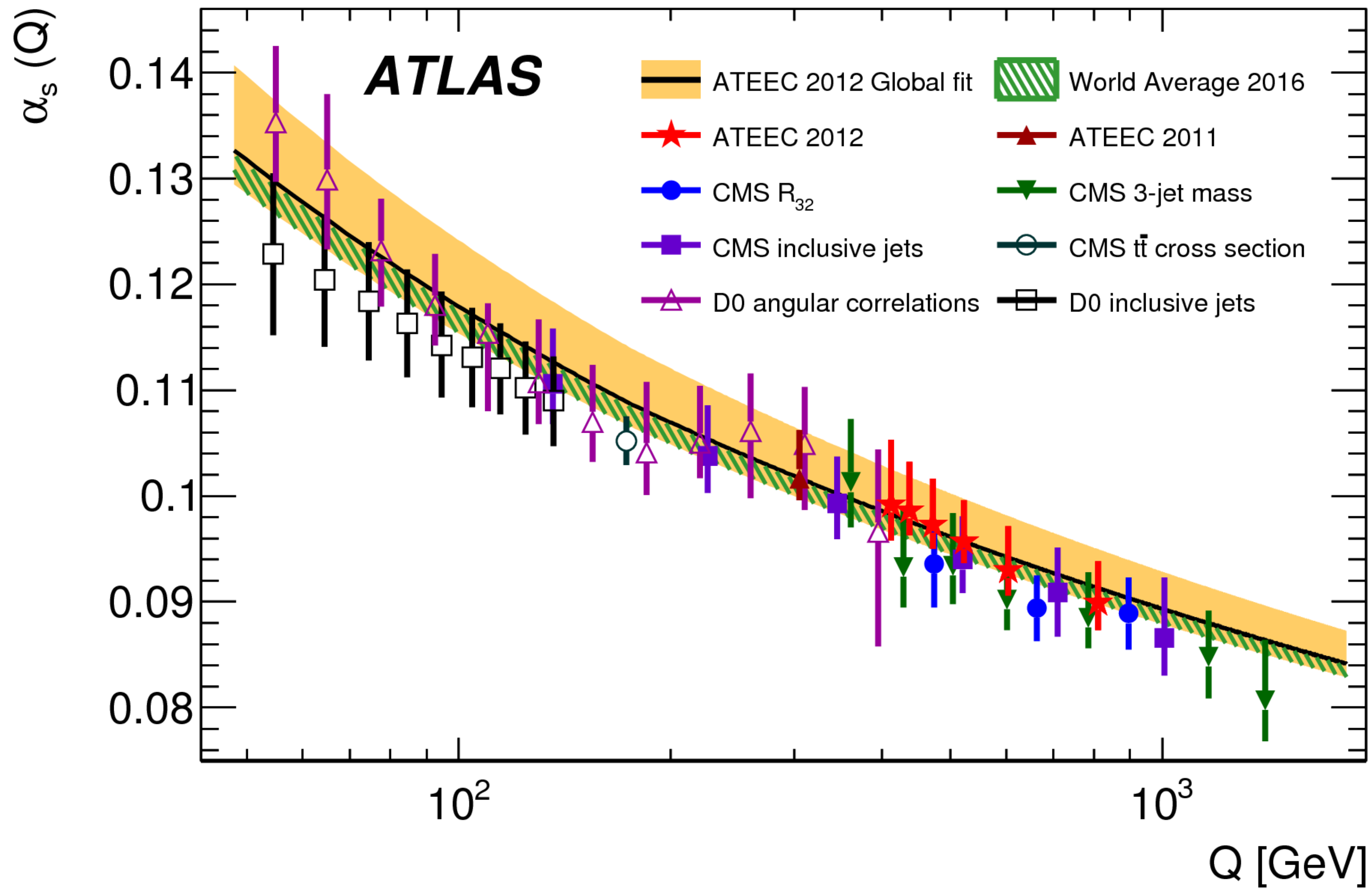


ATEEC theoretical uncertainties



α_S from ATEEC at 8 TeV

ATEEC Fit Results compared to World Average



PDF	$\alpha_s(m_Z)$ value	χ^2/N_{dof}
MMHT 2014	$0.1185 \pm 0.0012\ (\mathrm{exp.})\ ^{+0.0047}_{-0.0010}\ (\mathrm{scale}) \pm 0.0010\ (\mathrm{PDF}) \pm 0.0004\ (\mathrm{NP})$	57.0 / 65
CT14	$0.1203 \pm 0.0013\ (\mathrm{exp.})\ ^{+0.0053}_{-0.0014}\ (\mathrm{scale}) \pm 0.0015\ (\mathrm{PDF}) \pm 0.0004\ (\mathrm{NP})$	55.4 / 65
NNPDF 3.0	$0.1196 \pm 0.0013\ (\mathrm{exp.})\ ^{+0.0061}_{-0.0013}\ (\mathrm{scale}) \pm 0.0017\ (\mathrm{PDF}) \pm 0.0004\ (\mathrm{NP})$	60.3 / 65
HERAPDF 2.0	$0.1206 \pm 0.0012\ (\mathrm{exp.})\ ^{+0.0050}_{-0.0014}\ (\mathrm{scale}) \pm 0.0005\ (\mathrm{PDF}) \pm 0.0002\ (\mathrm{NP}) \pm 0.0007\ (\mathrm{mod})$	54.2 / 65