Standard Model studies at ATLAS

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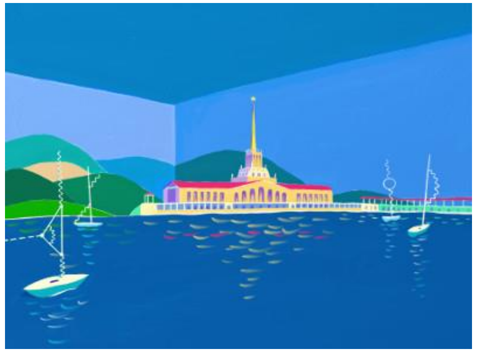
On behalf of the ATLAS Collaboration



QFTHEP Conference,
Sochi, Russia
22-29 September 2019

Standard Model measurements

- Standard Model (SM) is extremely predictive theory since its inception, which successfully resists its falsification for **about 50 years**.

- One of the principles of scientific method is: *“**Never stop verification and falsification of existing theories**”* (Galileo).
  SM measurements fully follow this principle and their two main goals are the following:
  - validate SM in new energy regime and improve precision of known SM parameters
  - test SM for **new physics** contributions (indirect search: anomalous couplings, etc), provide information about SM processes – backgrounds to direct **new physics** searches

Almost 200 SM papers were published by ATLAS since the start of LHC. Only few latest analyses are presented in these slides, more available:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

Selection of presented results, based on categories:
- Electroweak Physics: W and Z bosons, VBF/VBS, Dibosons/Tribosons…
- Direct photons
- Jet Physics
- Soft QCD, Diffraction and Forward Physics

LHC and ATLAS dataset

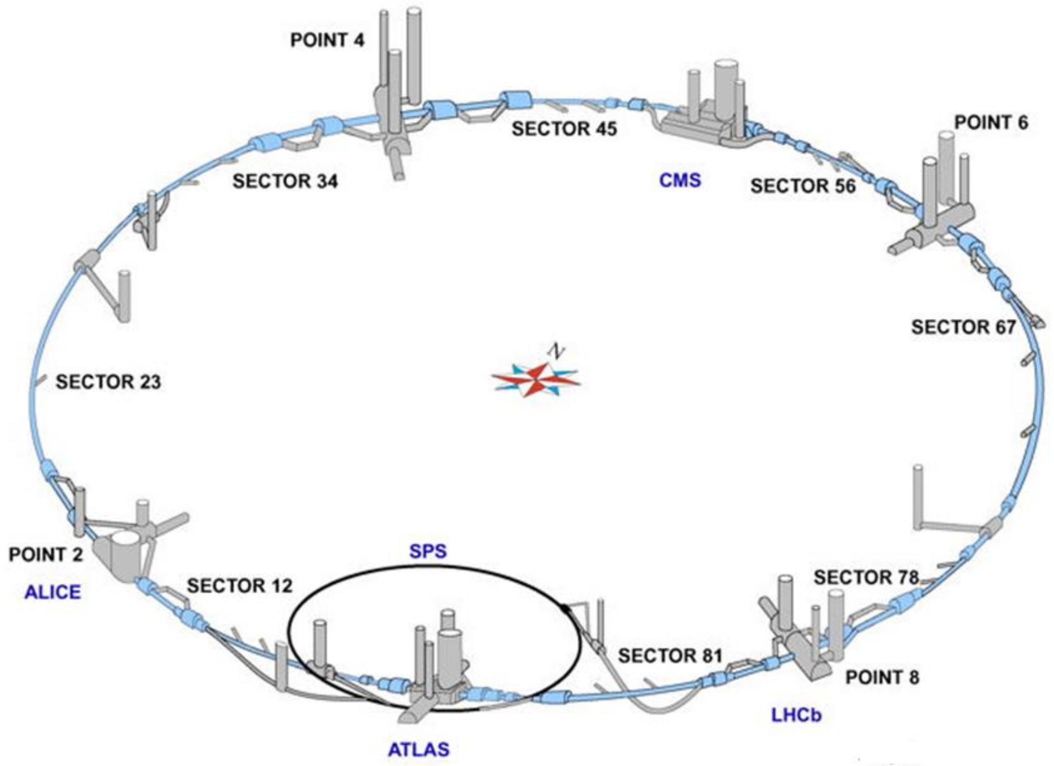
Run1:

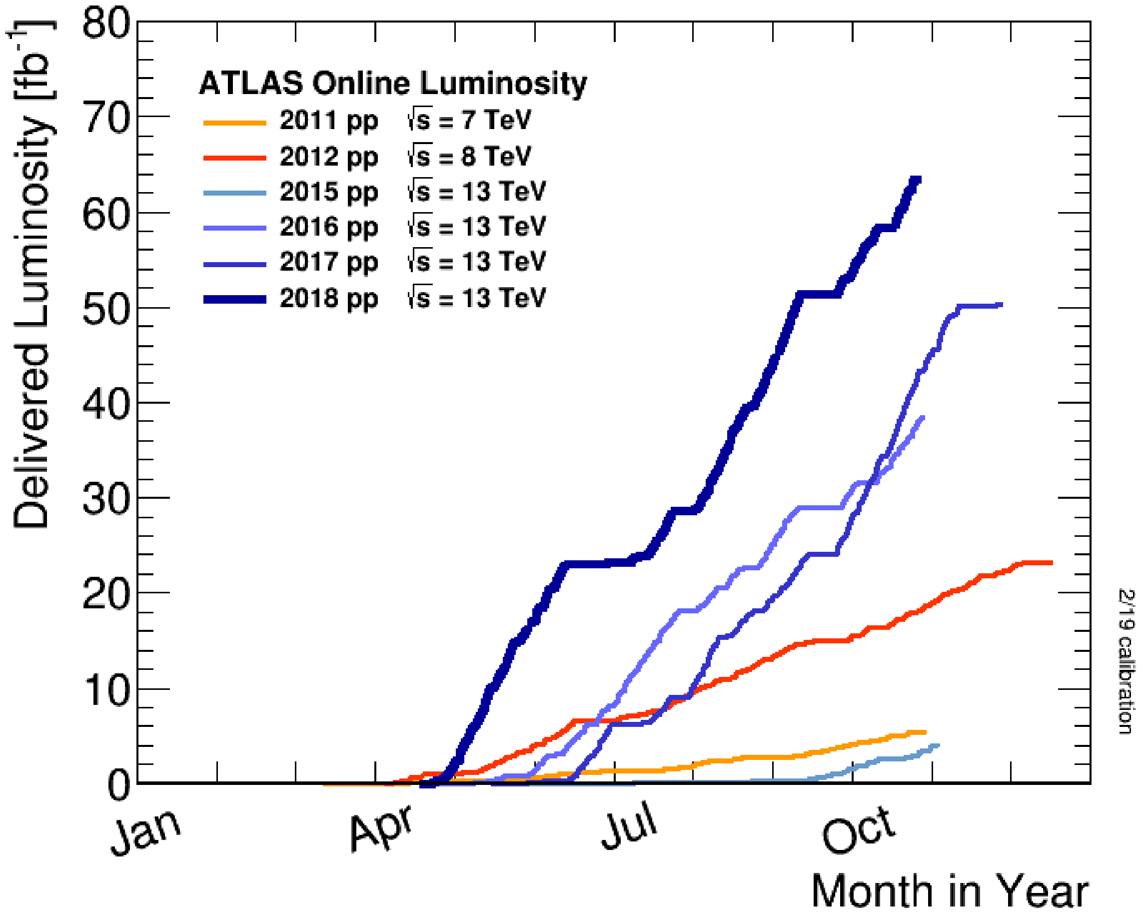
2011: √s = 7 TeV – **4.6 fb^{-1}**

2012: √s = 8 TeV – **20.3 fb^{-1}**

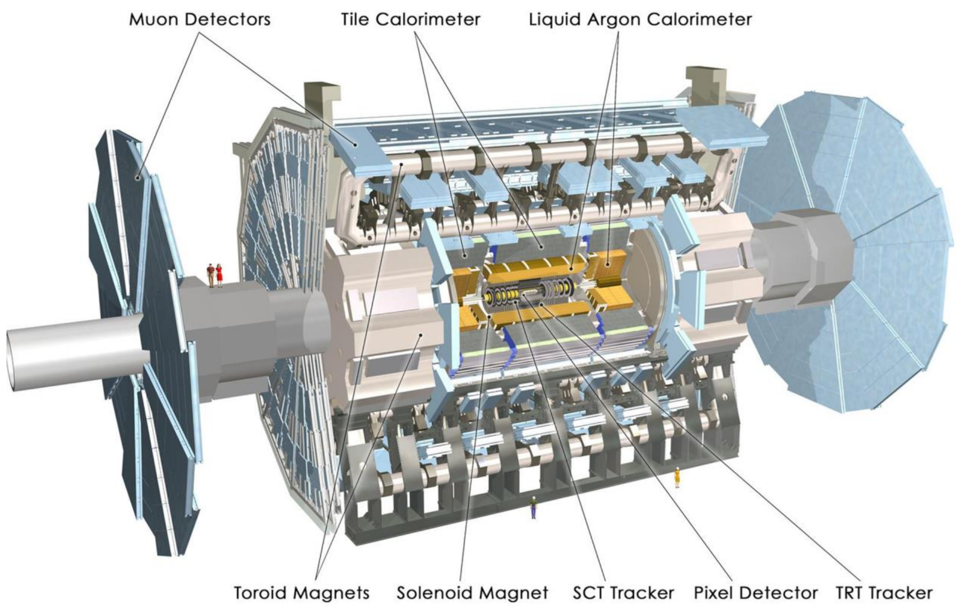
Run2:

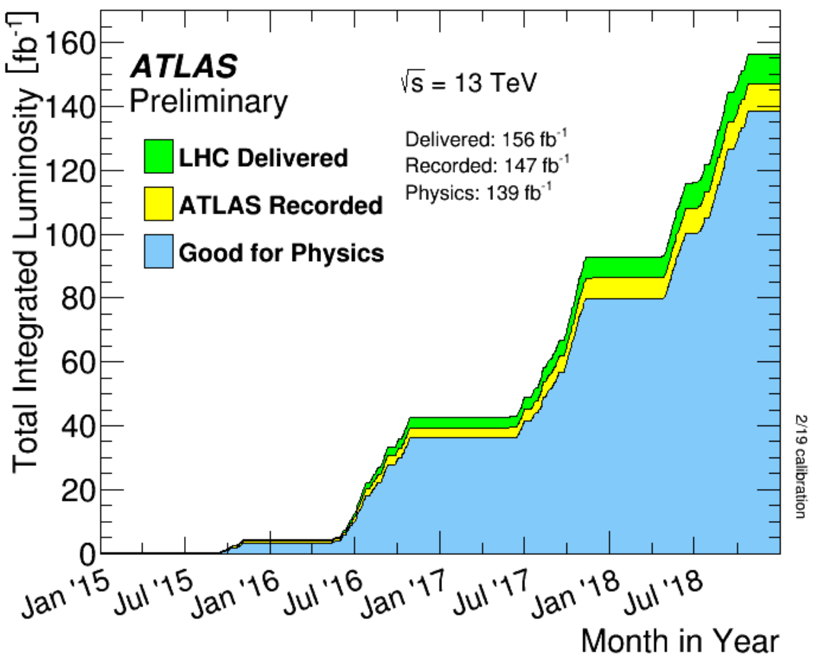
2015-2018: √s =13 TeV – **139 fb^{-1}**

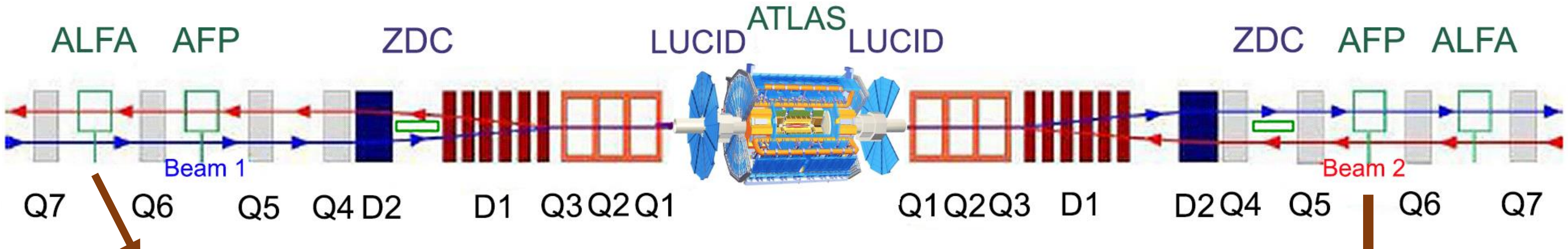




ATLAS detector and data

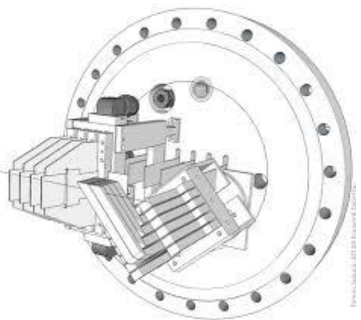


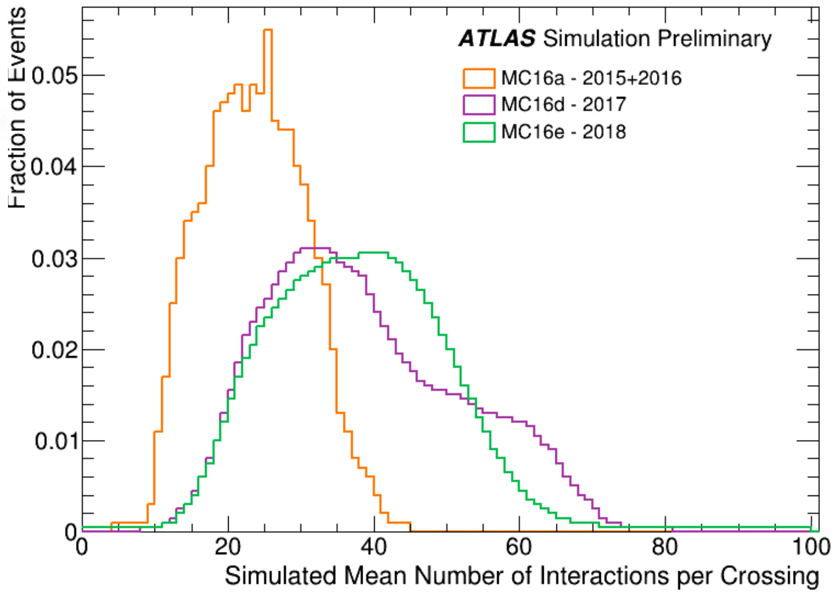




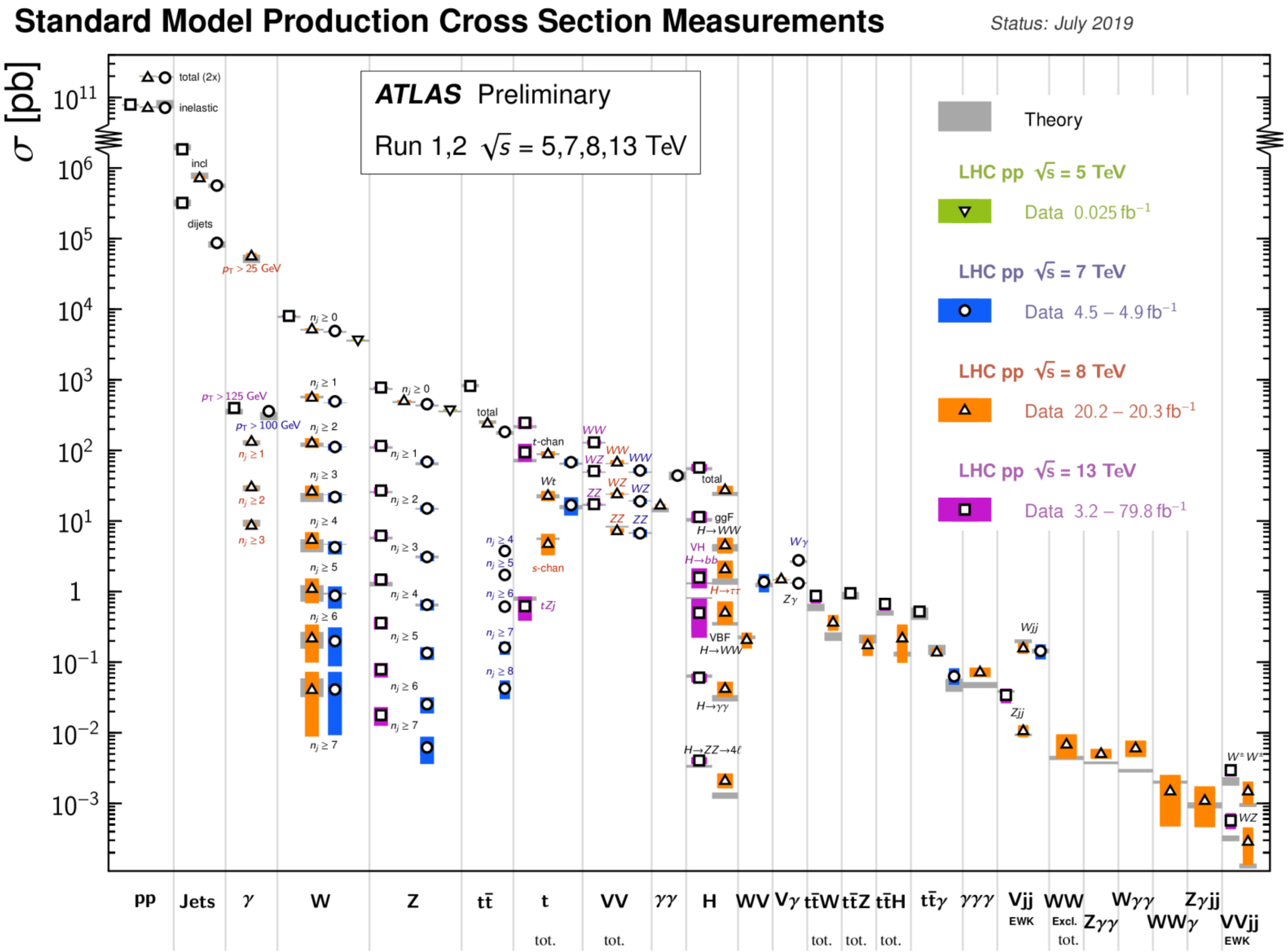
ALFA: elastic protons measurement (forward physics)

AFP: diffractive protons measurement



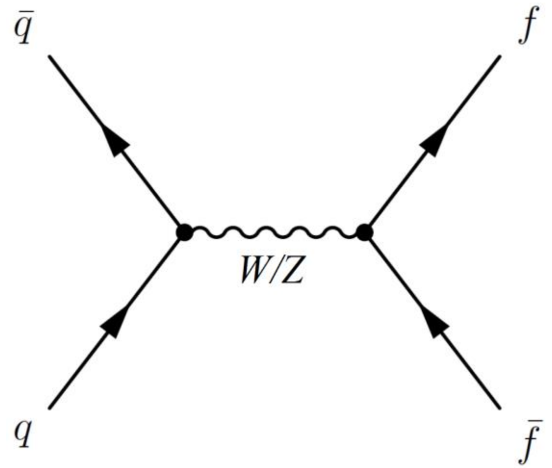


SM cross-sections summary



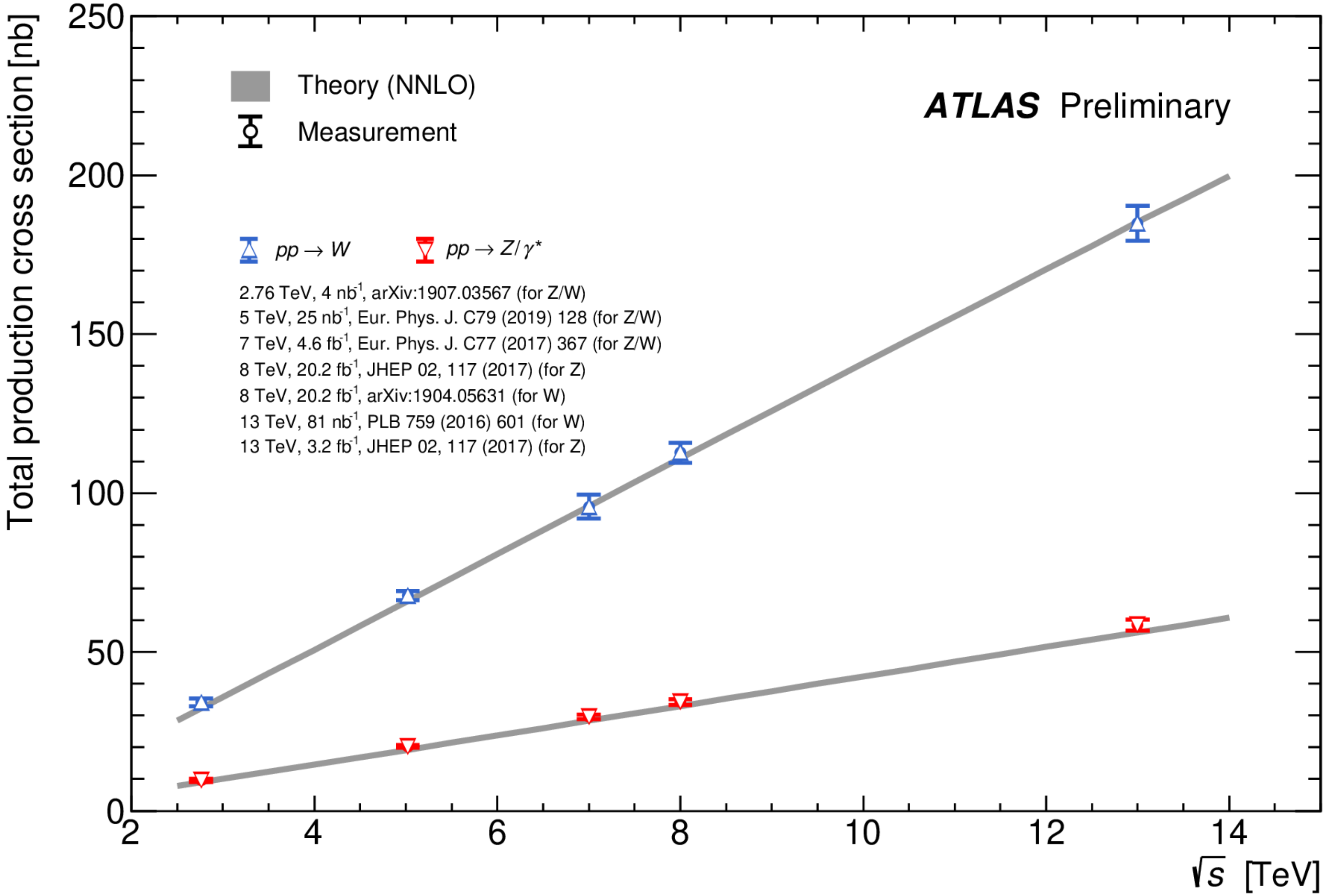
SM test measurements reached the range of about **14 orders of magnitude**:
from pp and jets down to rare triboson and VBS processes.

Electroweak physics: Single boson production



Electroweak physics: Single boson production

- Benchmark process for fixed-order calculations and predictions MC simulations of perturbative QCD (pQCD)
- Precision allows to study PDFs



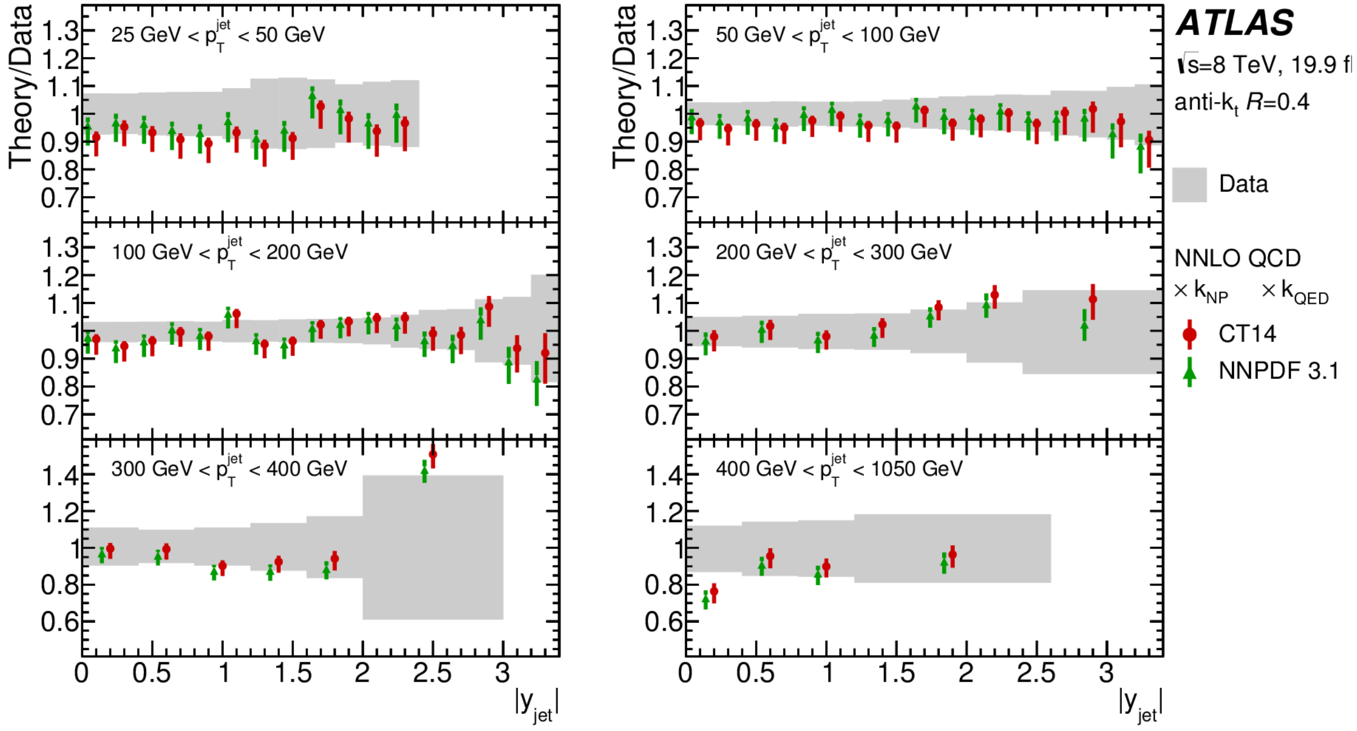
Z(ee) + jets @ 8 TeV

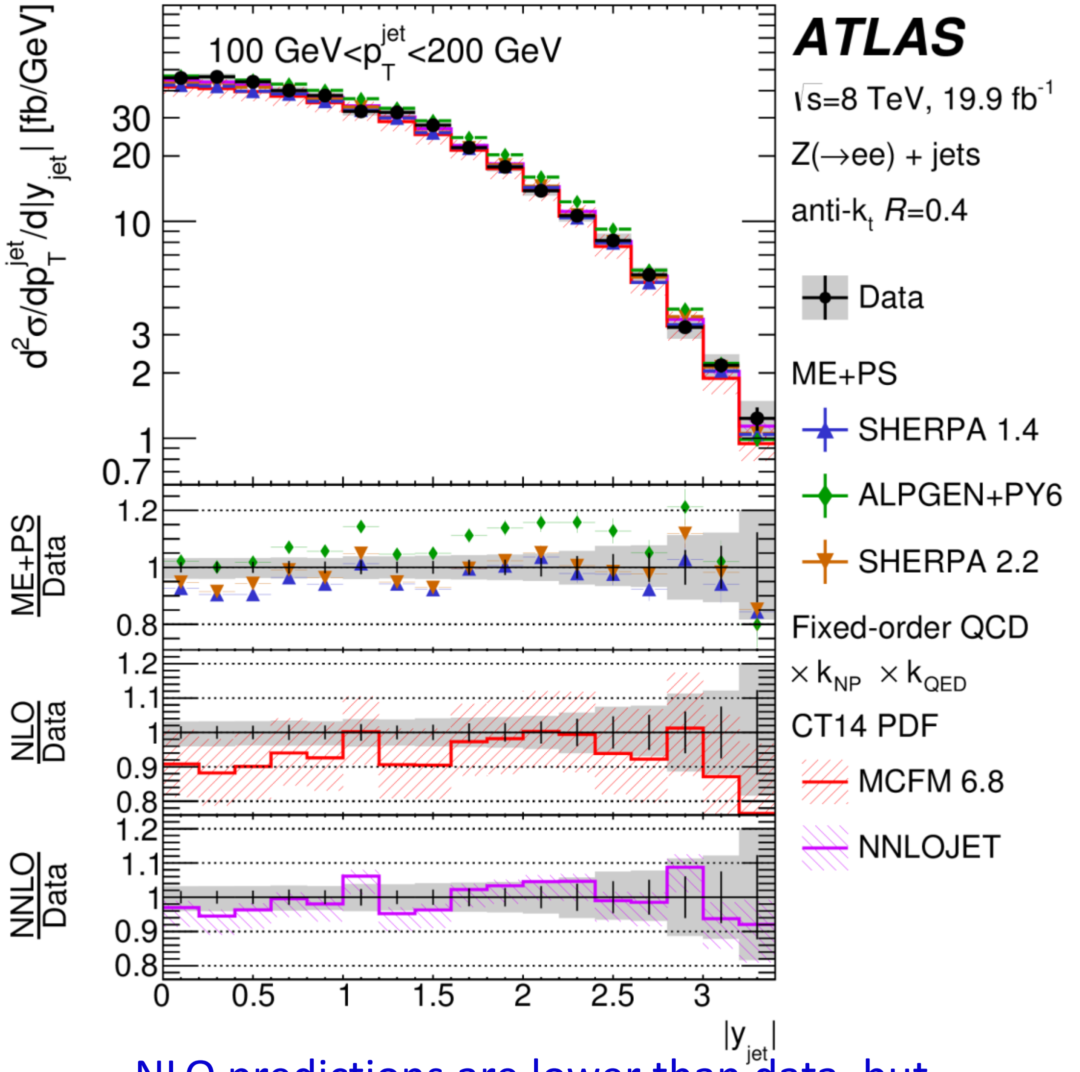
Accepted by EPJC

Data: L=19.9 fb^{-1} ± 1.9%

MC signal: Sherpa NLO; Main bkgs: multijet, W+jet, EWK+top.
Data-driven from MC sim.

➢ **Measurement** of double differential σ; constrains on PDFs.





Check of the PDF sets: all deviations (in NNLO case) covered by theoretical uncertainties.

NLO predictions are lower than data, but NNLO calculations compensate differences in most of bins

Main systematics are from signal modelling and JER+JES.

W/Z + jets @ 2.76 TeV

Submitted to EPJC

Data: L=4.0 pb^{-1} ± 3.1% (low μ) *Leptonic decay modes used, where lepton=e/μ*

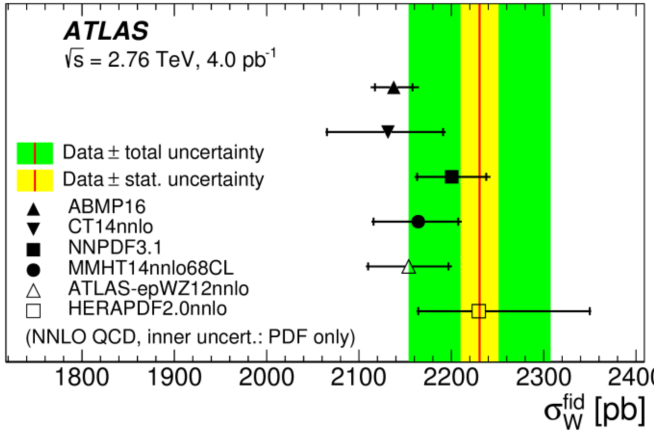
MC signal: Powheg-Box+Pythia8 NLO; Main bkgs: EWK+top, multijet (for Wjets)

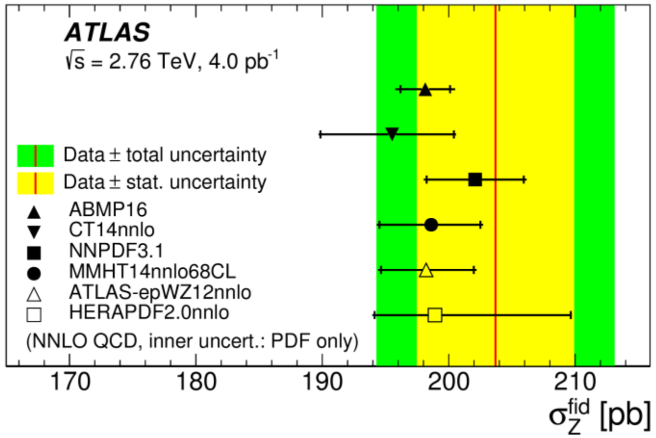
MC sim. Data-driven(template fit)

- **Measurement** of fiducial and total cross-sections at new collision energy point

$$\sigma^{tot}_{W^+\to\ell\nu} = 2312 \pm 26\,(\text{stat.}) \pm 27\,(\text{syst.}) \pm 72\,(\text{lumi.}) \pm 30\,(\text{extr.})\ \text{pb},$$
$$\sigma^{tot}_{W^-\to\ell\nu} = 1399 \pm 21\,(\text{stat.}) \pm 17\,(\text{syst.}) \pm 43\,(\text{lumi.}) \pm 21\,(\text{extr.})\ \text{pb},$$
$$\sigma^{tot}_{Z\to\ell\ell} = 323.4 \pm 9.8\,(\text{stat.}) \pm 5.0\,(\text{syst.}) \pm 10.0\,(\text{lumi.}) \pm 5.5(\text{extr.})\ \text{pb}.$$

Agreement within errors with NNLO QCD calculations.



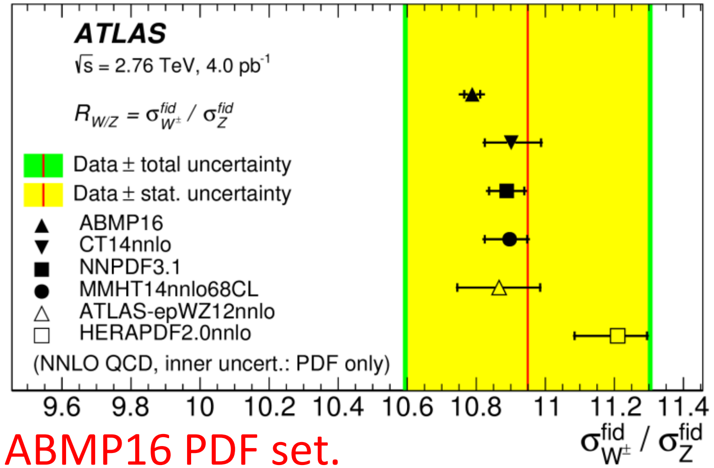


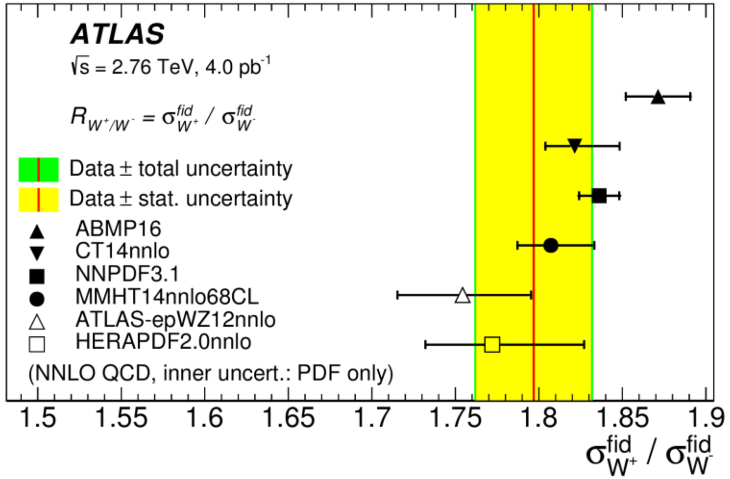
- **Measurement** of cross-sections ratios and constrains on PDFs

$$R_{W/Z} = 10.95 \pm 0.35\,(\text{stat.}) \pm 0.10\,(\text{syst.});$$
$$R_{W^+/W^-} = 1.797 \pm 0.034\,(\text{stat.}) \pm 0.009\,(\text{syst.}).$$

All PDFs are in agreement with data within errors.

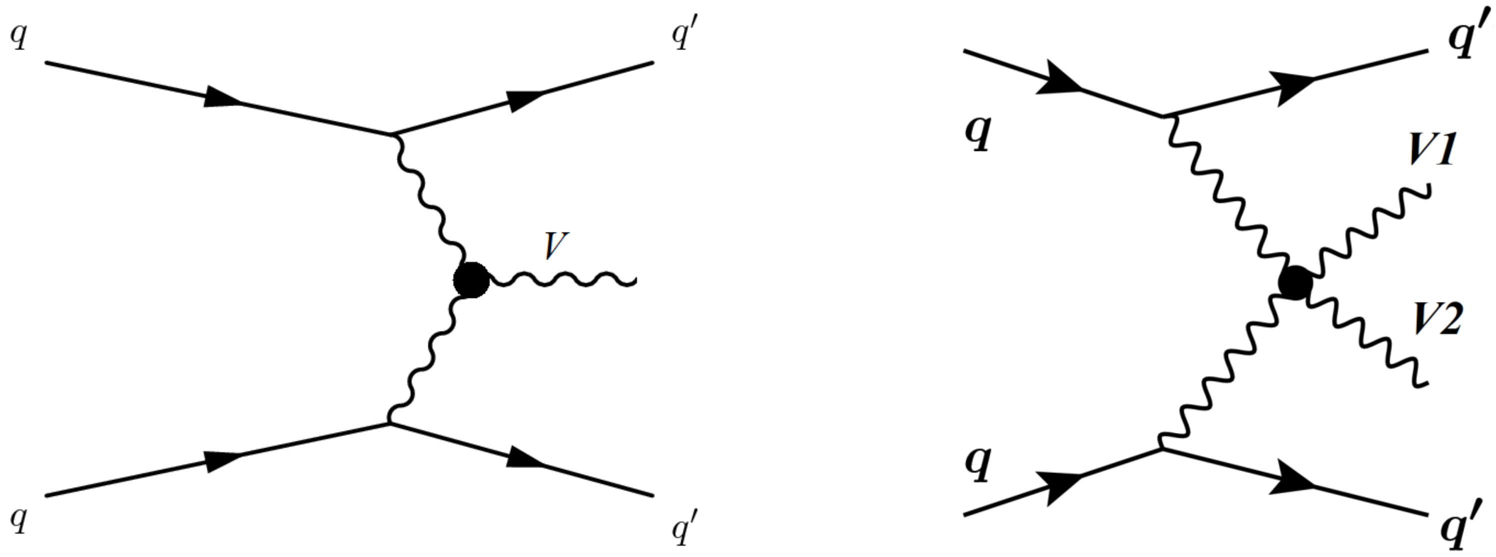
There is a slight tension between the data and the prediction using the ABMP16 PDF set.





Main uncertainties are from statistics, lepton reco+ID and multijet bkg (for Wjets).

Electroweak physics: VBF/VBS production



VBF/VBS production

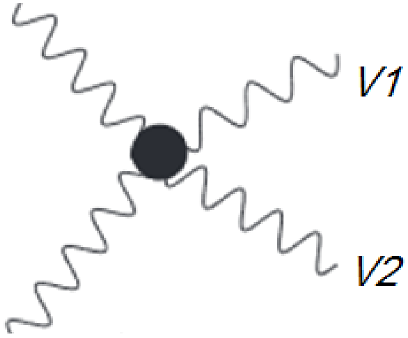
Why to measure?

- The rarest available SM processes: extremely sensitive tool to test SM predictions and search for the anomalous couplings
- VBS processes are irreducible backgrounds for the VBF Higgs boson production

Features:

- Due to backgrounds difficult to model, specific background enriched control regions (CRs) are used as a constraint
- Instead of a simple counting experiment to determine the signal cross section, a simultaneous fit is performed in bins of SR(s) and CR(s)
- Machine learning techniques are used to combine the sensitivity of many observables, sensitive to the difference between VBF/VBS signal and QCD background (+other backgrounds)
- VBF processes are sensitive to triple and VBS – to quartic anomalous gauge boson couplings (aTGCs/aQGCs), which are realized by EFT formalism:

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i + \ldots$$



where O_i and O_j are dimension-6 or dimension-8 operators, c_i – coefficients, Λ is the new physics scale.

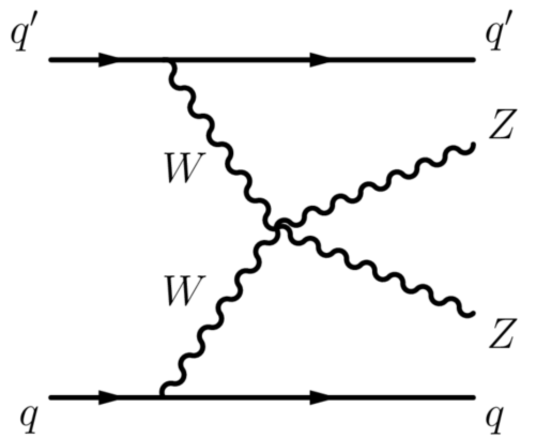
Observation of EWK ZZ @ 13 TeV

[ATLAS-CONF-2019-033]

Data: L=139 fb^{-1} ± 1.7% *4l and 2l2v modes were used, where lepton=e/μ*

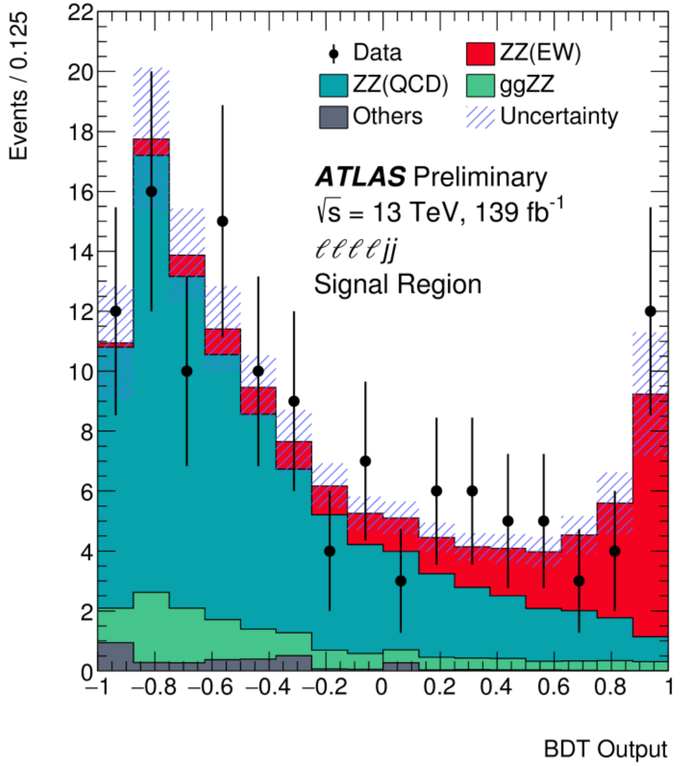
MC signal: MG5+Pythia8 LO; Main bkgs: QCD ZZjj, WZjj (for 2l2v), WZjj (for 2l2v), Zjets

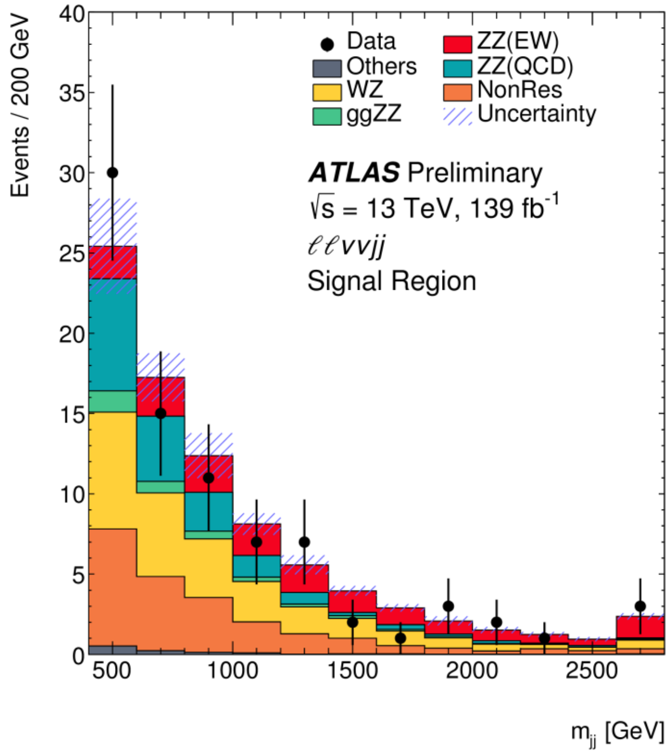
From MC, normalization from the fit to data in CR data-driven



➢ **Measurement** of integrated QCD+EWK and EWK-only cross-section

	Measured fiducial σ [fb]	Predicted fiducial σ [fb]
$\ell\ell\ell\ell jj$	$1.27 \pm 0.12(\text{stat}) \pm 0.02(\text{theo}) \pm 0.07(\text{exp}) \pm 0.01(\text{bkg}) \pm 0.03(\text{lumi})$	$1.14 \pm 0.04(\text{stat}) \pm 0.20(\text{theo})$
$\ell\ell\nu\nu jj$	$1.22 \pm 0.30(\text{stat}) \pm 0.04(\text{theo}) \pm 0.06(\text{exp}) \pm 0.16(\text{bkg}) \pm 0.03(\text{lumi})$	$1.07 \pm 0.01(\text{stat}) \pm 0.12(\text{theo})$





EWK process:

σ(obs) = **0.82±0.21 fb** (μ = 1.35±0.34)

Obs.(exp.) significance = **5.5(4.3)σ**

First observation of EWK ZZ!

Main uncertainties are from statistics, luminosity, the momentum scale and resolution of leptons and jets.

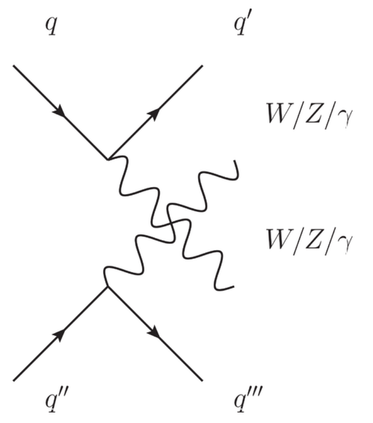
Evidence of EWK Zγ @ 13 TeV

ATLAS-CONF-2019-039

Data: $L=36.1\ fb^{-1} \pm 2.1\%$ *only lepton decay modes were used, where lepton=e/μ*

MC signal: MG5+Pythia8 LO; Main bkgs: QCD Zγjj, ttγ, Zjets

From MC, normalization from the fit (QCD Zγjj, ttγ); data-driven (Zjets)

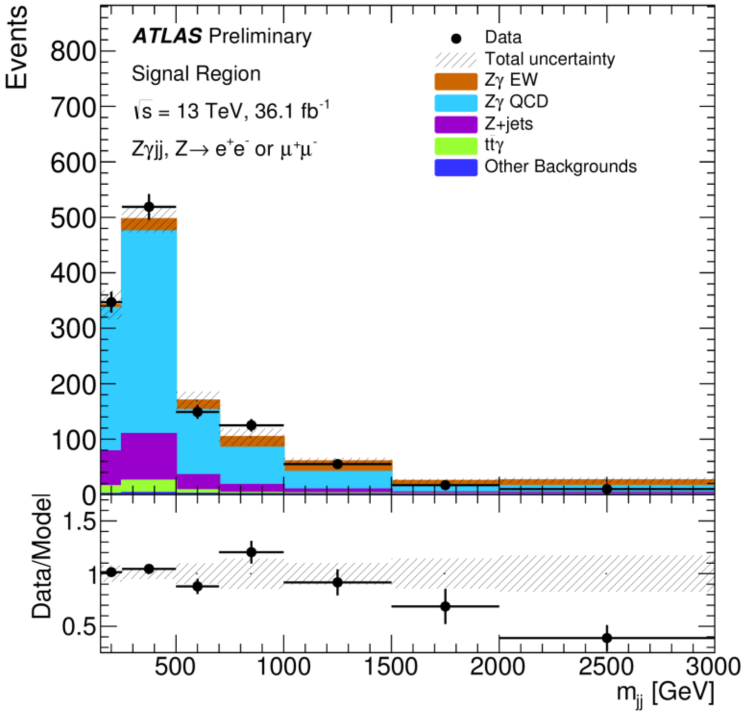


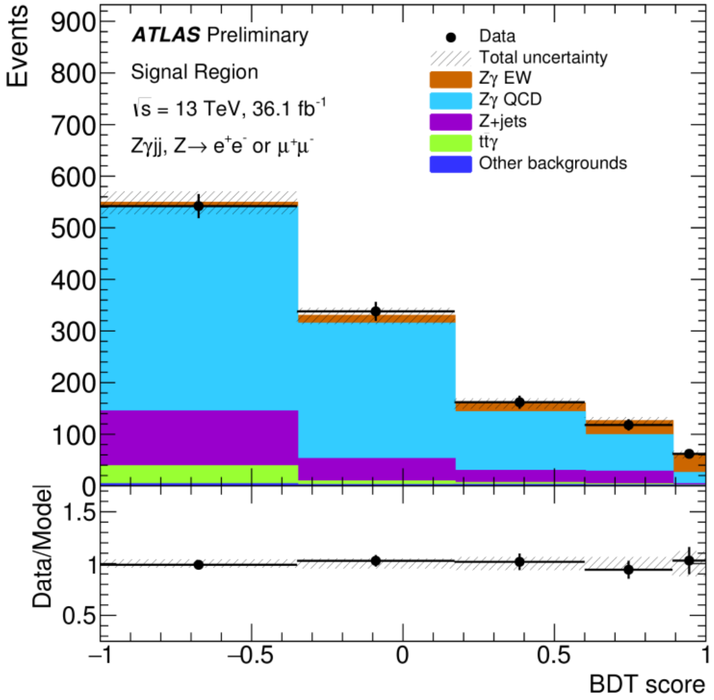
➢ **Measurement** of integrated QCD+EWK and EWK-only cross-section

QCD+EWK:

$$\sigma^{\text{fid.}}_{Z\gamma jj} = 71 \pm 2\,(\text{stat.})\ ^{+9}_{-7}\,(\text{exp. syst.})\ ^{+21}_{-17}\,(\text{mod. syst.})\ \text{fb}$$

$$\sigma^{\text{fid., MadGraph+Sherpa}}_{Z\gamma jj} = 88.4 \pm 2.4\,(\text{stat.}) \pm 2.3\,(\text{PDF} + \alpha_S)^{+29.4}_{-19.1}\,(\text{scale})\ \text{fb}$$





EWK process:

$$\sigma^{\text{fid.}}_{Z\gamma jj-\text{EW}} = 7.8\ ^{+1.5}_{-1.4}\,(\text{stat.})\ ^{+0.9}_{-1.0}\,(\text{syst.})\ ^{+1.0}_{-0.8}\,(\text{mod.})\ \text{fb}$$

$$\sigma^{\text{fid., MadGraph}}_{Z\gamma jj-\text{EW}} = 7.75 \pm 0.03\,(\text{stat.}) \pm 0.20\,(\text{PDF} + \alpha_S) \pm 0.40\,(\text{scale})\ \text{fb}$$

Obs.(exp.) significance = **4.1(3.8)σ**

ATLAS evidence of EWK Zγ!

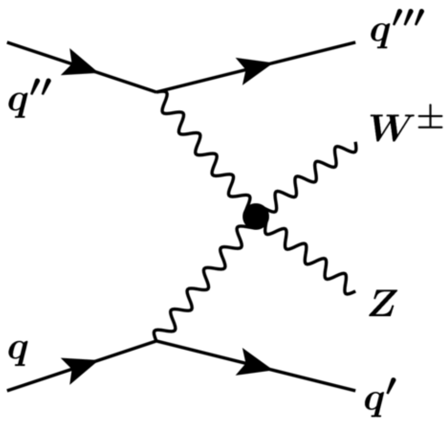
Main uncertainties are from statistics, JES, HF tagging efficiency.

Observation of EWK WZ @ 13 TeV

[Phys. Lett. B 793 (2019) 469]

Data: L=36.1 fb^{-1} ± 2.1% *only lepton decay modes were used, where lepton=e/μ*

MC signal: Sherpa LO; Main bkgs: QCD WZjj, ZZ, ttV (From MC, normalization from the fit), misID leptons (data-driven)



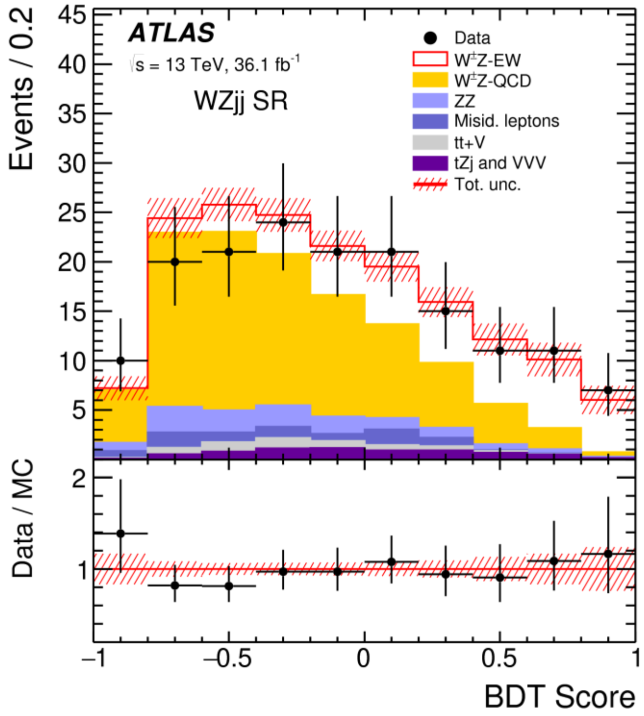
- **Measurement** of integrated QCD+EWK and EWK-only cross-section

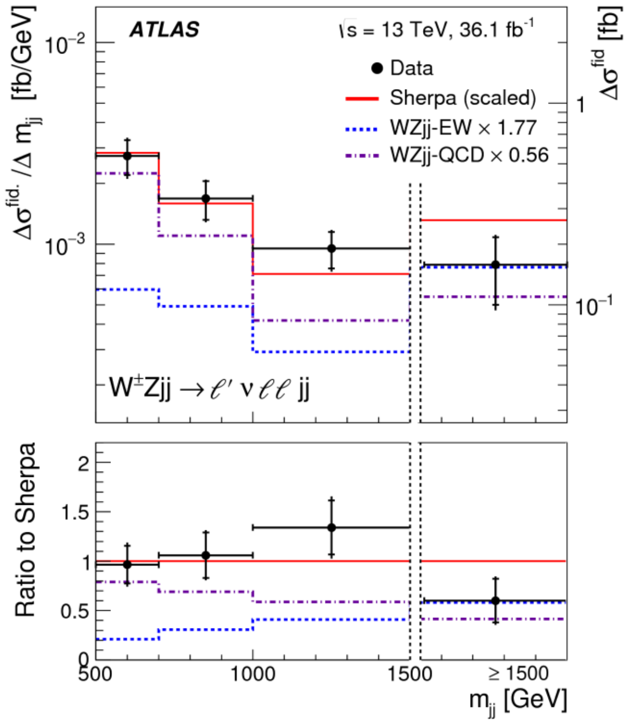
QCD+EWK:

$$\sigma^{\text{fid.}}_{W^{\pm}Zjj} = 1.68 \pm 0.16\,(\text{stat.}) \pm 0.12\,(\text{exp. syst.}) \pm 0.13\,(\text{mod. syst.}) \pm 0.044\,(\text{lumi.})\ \text{fb}$$

$$\sigma^{\text{fid., Sherpa}}_{W^{\pm}Zjj} = 2.15 \pm 0.01\,(\text{stat.}) \pm 0.05\,(\text{PDF})^{+0.65}_{-0.44}\,(\text{scale})\ \text{fb}$$

- **Measurement** of differential QCD+EWK cross-sections (vs. m_{jj}, Δy_{jj}, N_{jets}, m_T[WZ], etc)





EWK process:

$$\sigma^{\text{fid.}}_{WZjj\text{–EW}} = 0.57\ ^{+0.14}_{-0.13}\,(\text{stat.})\ ^{+0.05}_{-0.04}\,(\text{exp. syst.})\ ^{+0.05}_{-0.04}\,(\text{mod. syst.})\ ^{+0.01}_{-0.01}\,(\text{lumi.})\ \text{fb}$$

$$\sigma^{\text{fid., Sherpa}}_{WZjj\text{–EW}} = 0.321 \pm 0.002\,(\text{stat.}) \pm 0.005\,(\text{PDF})^{+0.027}_{-0.023}\,(\text{scale})\ \text{fb}$$

Obs.(exp.) significance = **5.3(3.2)σ**

First observation of EWK WZ!

Main uncertainties are from statistics, MC modelling, JES.

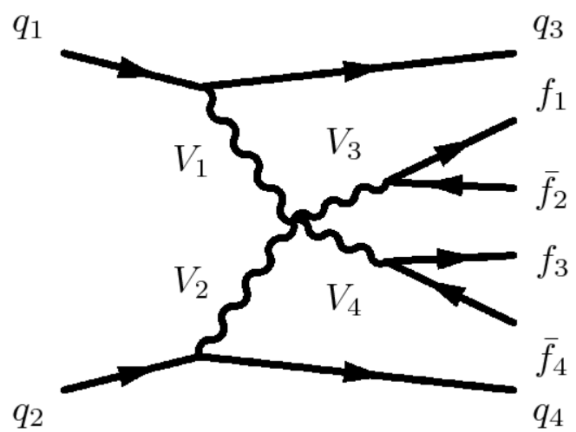
Observation of EWK ssWW @ 13 TeV

[Accepted by PRL](#)

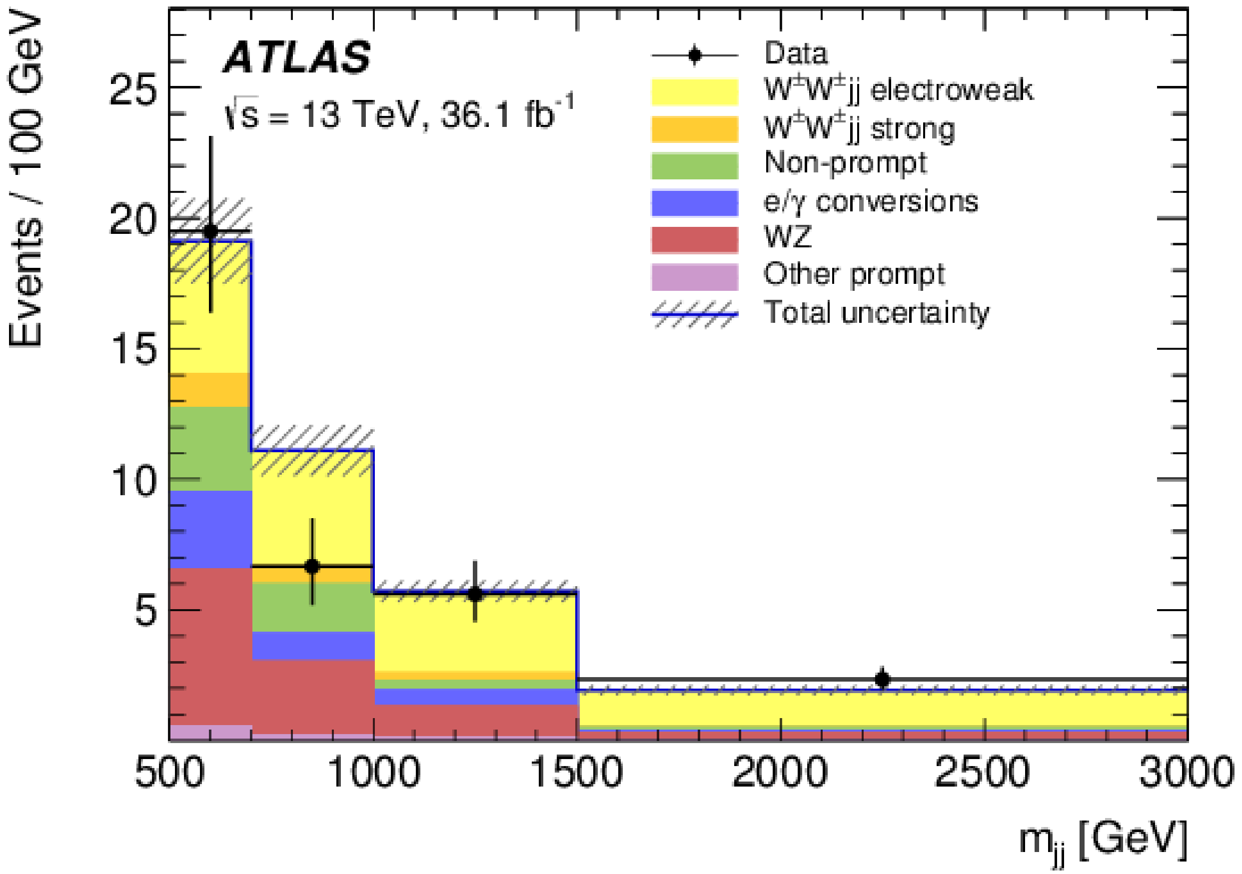
Data: L=36.1 fb^{-1} ± 2.1% *only lepton modes were used, where lepton=e/μ*

MC signal: Sherpa LO; Main bkgs: QCD ssWWjj, WZjj, Vγ, misID leptons bkg

From MC, normalization from the fit; data-driven



- **Measurement** of integrated EWK cross-section



EWK process:

$$\sigma^{\text{fid.}} = 2.89^{+0.51}_{-0.48}\,(\text{stat.})\,^{+0.24}_{-0.22}\,(\text{exp. syst.})\,^{+0.14}_{-0.16}\,(\text{mod. syst.})\,^{+0.08}_{-0.06}\,(\text{lumi.})\text{ fb}$$

$$(\mu = 1.44^{+0.26}_{-0.24}\,(\text{stat.})\,^{+0.28}_{-0.22}\,(\text{syst.}))$$

Obs.(exp.) significance = **6.5(4.4)σ**

ATLAS observation of EWK ssWW!

Main uncertainties are from statistics, MC modelling, misID lepton bkg.

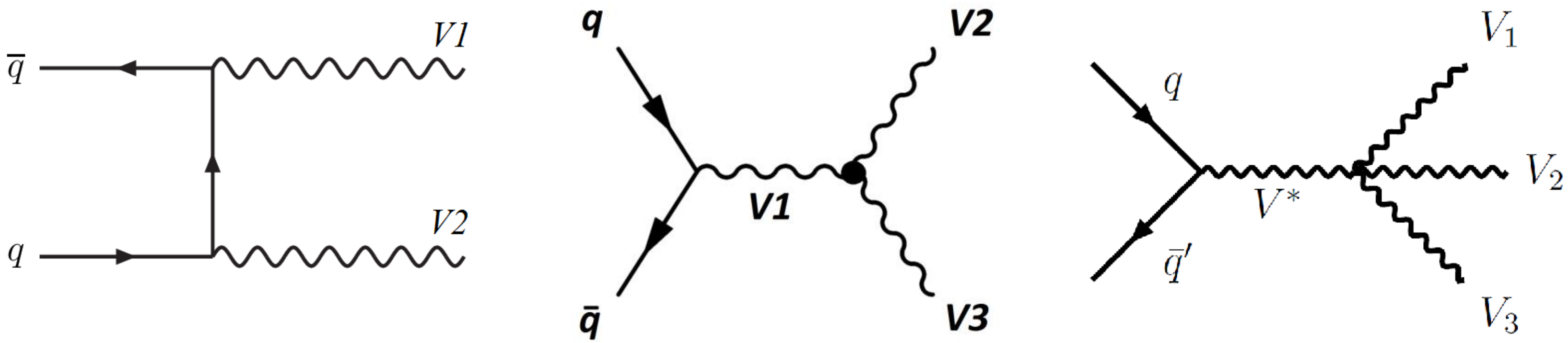
VBF/VBS summary

- These rare processes become available for measurements just on LHC experiments.

Final state of EWK production	Status
ZZ	Observed
WZ	Observed
ssWW	Observed
Zγ	Evidence (4.7σ – CMS; 4.1σ - ATLAS)
Wγ	No evidence (2.7σ - CMS)
Z	Observed
W	Observed

Amazing progress during last years!

Electroweak physics: QCD multiboson production



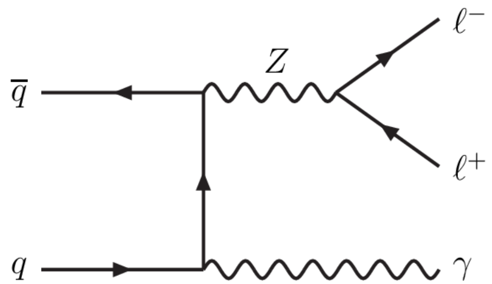
Zγ @ 13 TeV

ATLAS-CONF-2019-034

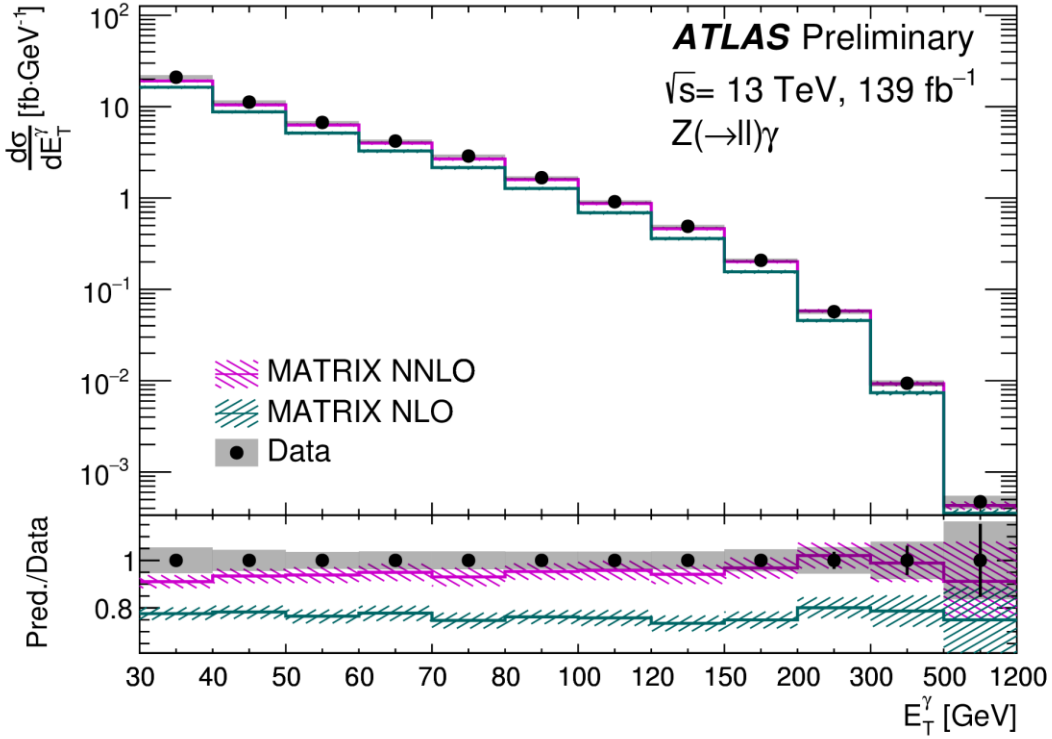
- Precision measurement, which checks NNLO theory predictions.

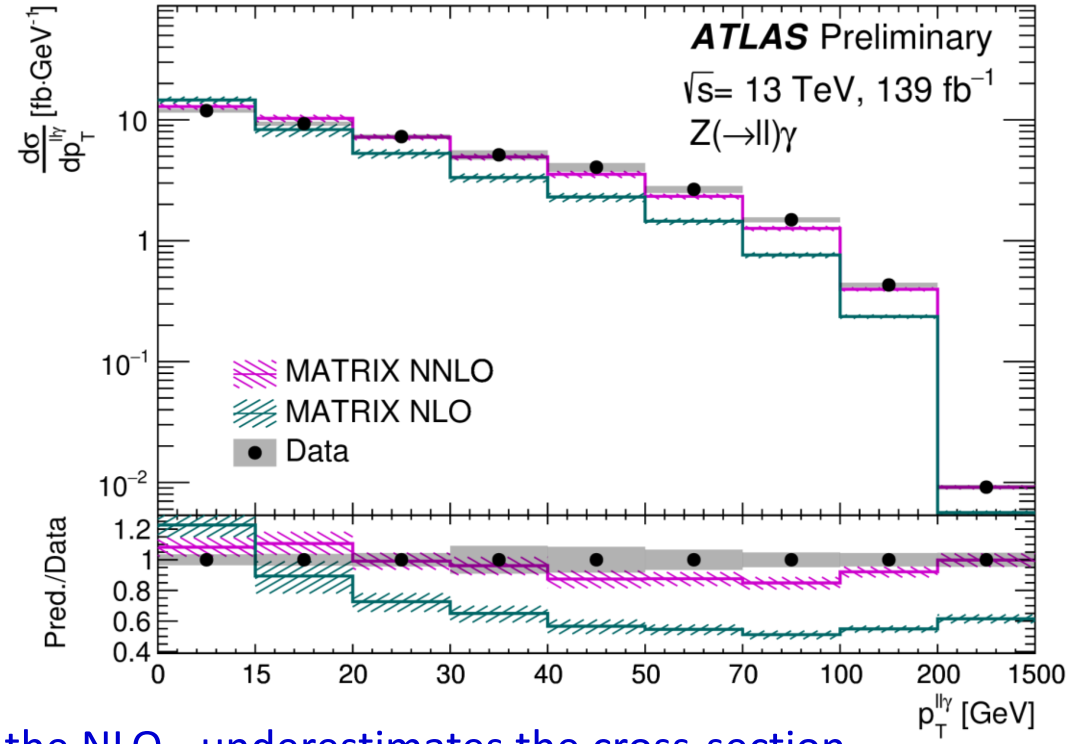
Data: L=139 fb^{-1} ± 1.7% *only lepton decay modes were used, where lepton=e/μ*

MC signal: Sherpa; Main bkgs: Zjets (data-driven), ttγ, WZ (from MC)



- **Measurement** of differential cross-sections (vs. $E_T[\gamma]$, $\eta[\gamma]$, $m_{ll\gamma}$, $p_T[ll\gamma]$)





The MATRIX prediction agrees well with the data at NNLO, while the NLO - underestimates the cross-section.

Main uncertainties are from Zjets bkg, photon efficiency, statistics.

There is a possibility to get Z and γ from different primary vertices, which leads to so-called pile-up bkg (up to 5%)

Z(νν)γ @ 13 TeV

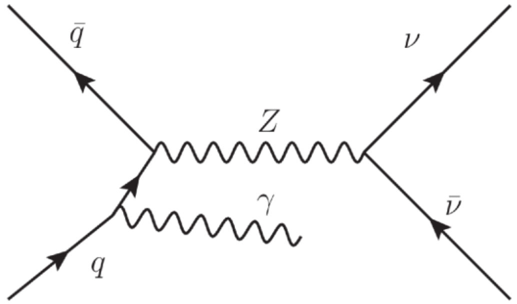
Data: L=36.1 fb^{-1} ± 2.1%

neutrino decay mode was used

[*JHEP 12 (2018) 010*]

MC signal: Sherpa NLO; Main bkgs: Wγ, γjet, e→γ misID, jet→γ misID

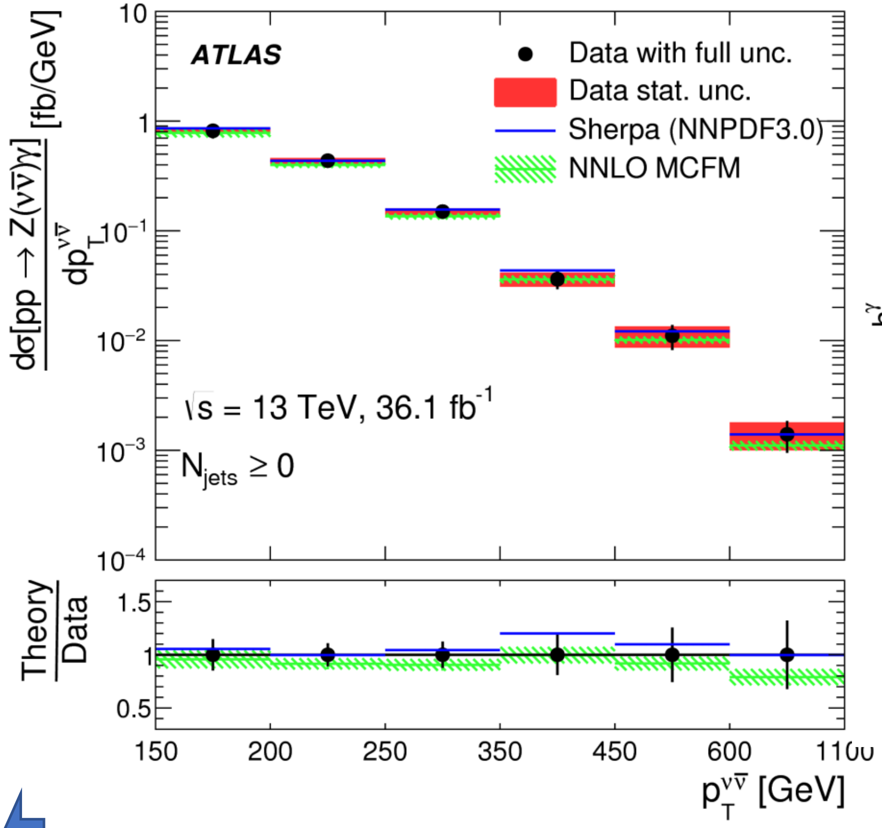
from MC with normalization from data CRs; data-driven



- **Measurement** of integrated and differential cross-sections (vs. $E_T[\gamma]$, p_T[miss], N_{jets})

$\sigma^{ext.fid.}$ [fb] Measurement	$\sigma^{ext.fid.}$ [fb] NNLO MCFM Prediction
$N_{jets} \geq 0$	
$83.7^{+3.6}_{-3.5}$ (stat.)$^{+6.9}_{-6.2}$ (syst.)$^{+1.7}_{-2.0}$ (lumi.)	78.1 ± 0.2(stat.)± 4.7(syst.)
$N_{jets} = 0$	
$52.4^{+2.4}_{-2.3}$ (stat.)$^{+4.0}_{-3.6}$ (syst.)$^{+1.2}_{-1.1}$ (lumi.)	55.9 ± 0.1(stat.)± 3.9(syst.)

Good agreement!



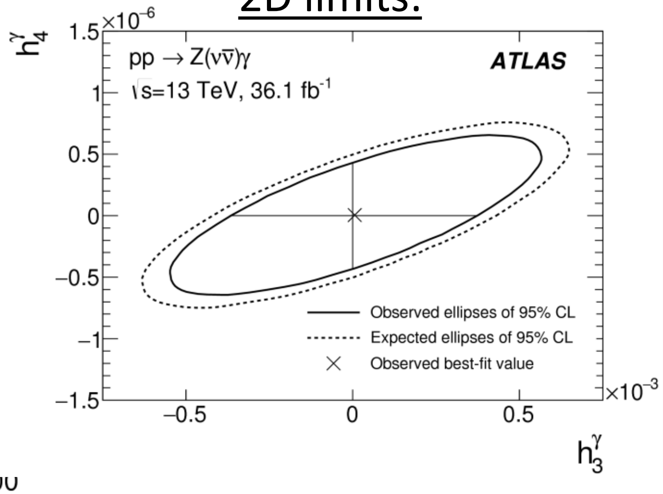
- **Setting limits** on anomalous TGC in $h_i(V)$ vertex functions and EFT formalisms

Dim-8 EFT formalism:

Parameter	Limit 95% CL Measured [TeV^{-4}]	Expected [TeV^{-4}]
$C_{\tilde{B}W}/\Lambda^4$	(−1.1, 1.1)	(−1.3, 1.3)
C_{BW}/Λ^4	(−0.65, 0.64)	(−0.74, 0.74)
C_{WW}/Λ^4	(−2.3, 2.3)	(−2.7, 2.7)
C_{BB}/Λ^4	(−0.24, 0.24)	(−0.28, 0.27)

Best limits on nTGC!

2D limits:



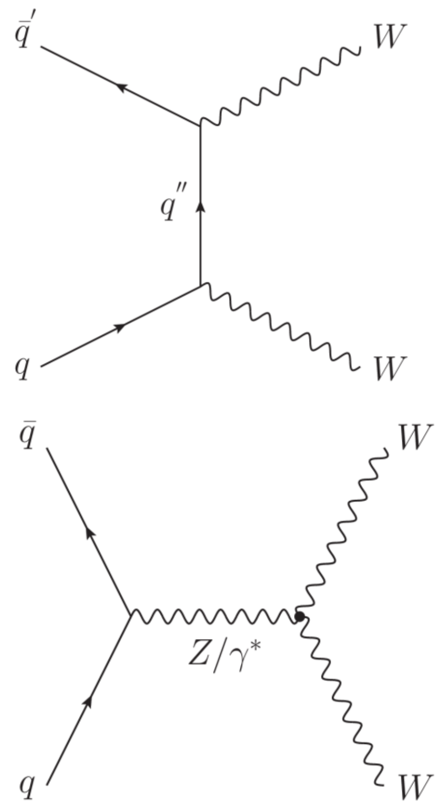
Main uncertainties are from statistics, MC modelling, data-driven bkgs.

W^+W^- @ 13 TeV

Submitted to EPJC

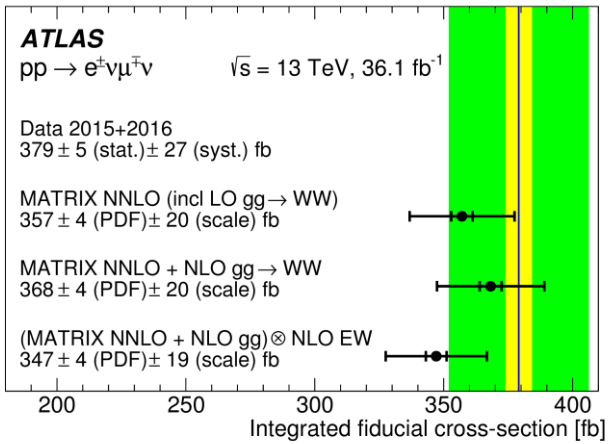
Data: L=36.1 fb^{-1} ± 2.1% *only lepton decay modes were used, where lepton=e/μ*

MC signal: Powheg-Box+Pythia8 NLO; Main bkgs: top bkg (from MC with norm from data CR), DY (from MC), Wjets (data-driven)

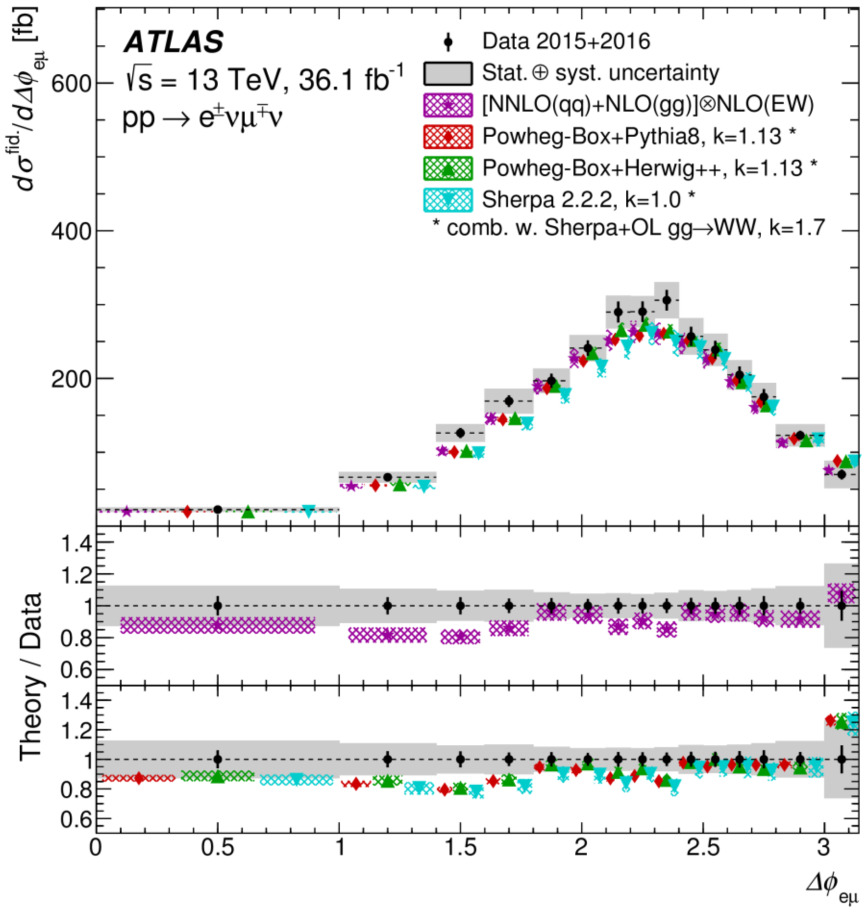


- **Measurement** of integrated and differential cross-sections (vs. p_T[lead l], $m_{e\mu}$, $\Delta\varphi_{e\mu}$, etc)

$$\sigma_{fid} = (379.1 \pm 5.0\,(stat) \pm 25.4\,(syst) \pm 8.0\,(lumi))\,fb$$



Good agreement!



- Setting limits on anomalous TGC

Dim-6 EFT formalism:

Parameter	Observed 95% CL [TeV^{-2}]	Expected 95% CL [TeV^{-2}]
c_{WWW}/Λ^2	[−3.4 , 3.3]	[−3.0 , 3.0]
c_W/Λ^2	[−7.4 , 4.1]	[−6.4 , 5.1]
c_B/Λ^2	[−21 , 18]	[−18 , 17]
$c_{\tilde{W}WW}/\Lambda^2$	[−1.6 , 1.6]	[−1.5 , 1.5]
$c_{\tilde{W}}/\Lambda^2$	[−76 , 76]	[−91 , 91]

Main uncertainties are from b-tagging, MC modelling, JES.

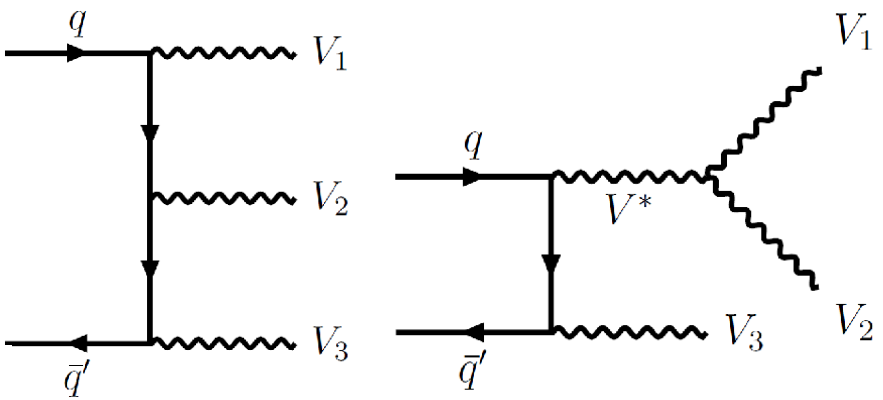
Evidence of WVV @ 13 TeV

[Accepted by PLB](#)

Data: L=79.8 fb^{-1} ± 2.0%

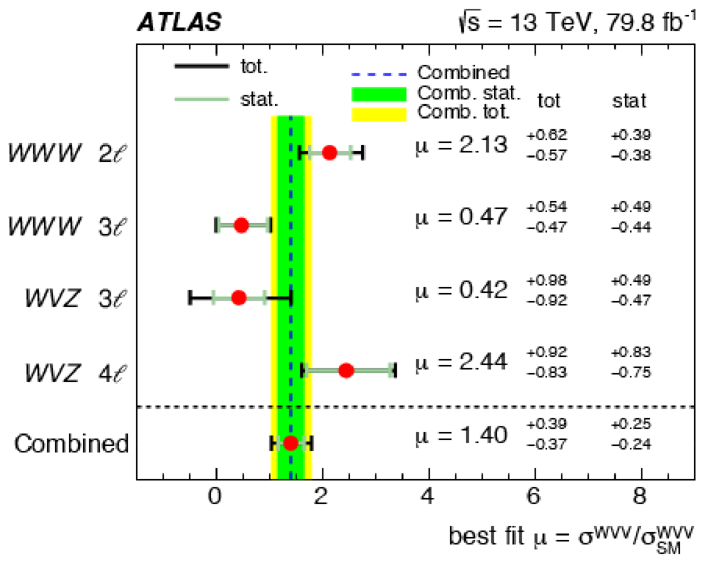
WWW→lνlνqq, WWW→lνlνlν, WWZ→lνqqll, WWZ→lνlνll, WZZ→qqllll, where l=e/μ

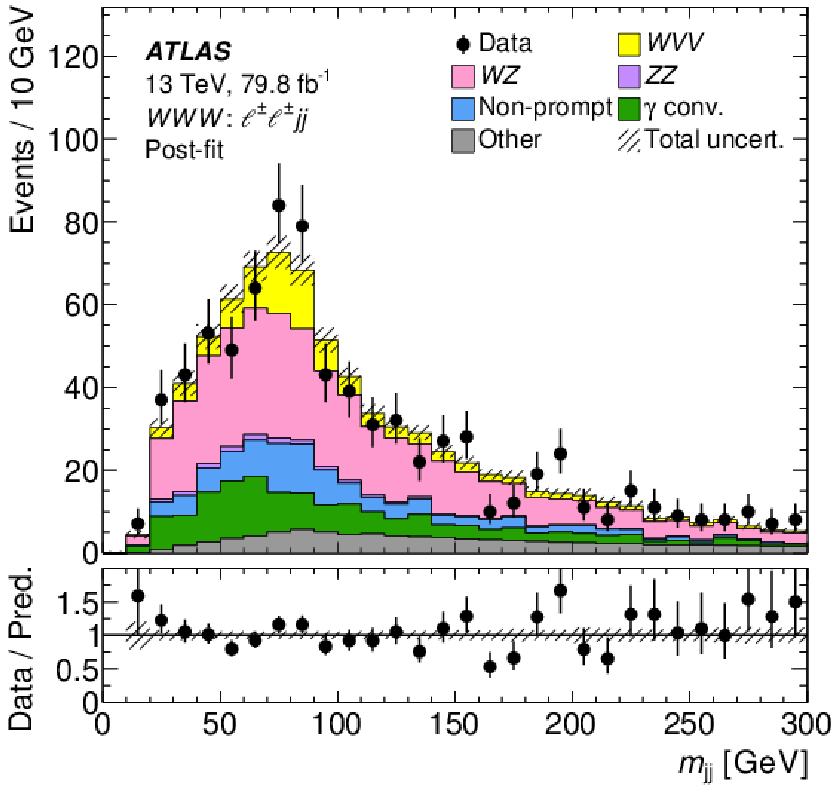
MC signal: Sherpa; Main bkgs: WZjets (from MC), non-prompt lepton bkg (data-driven)

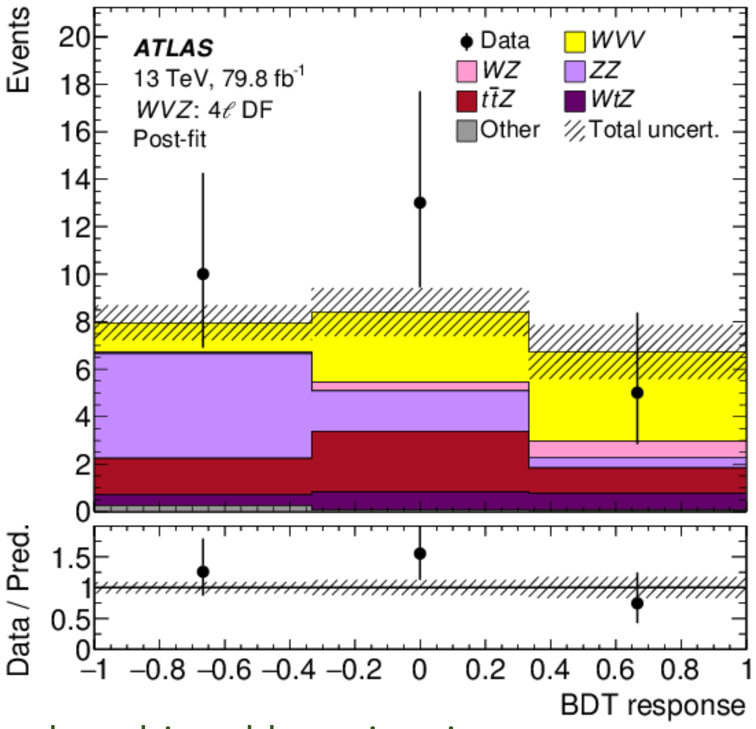


➢ **Measurement** of integrated cross-sections

$\sigma_{WWW} = 0.65^{+0.16}_{-0.15}\,(\text{stat.})\,^{+0.16}_{-0.14}\,(\text{syst.})\text{ pb}$ $\sigma_{WWZ} = 0.55 \pm 0.14\,(\text{stat.})\,^{+0.15}_{-0.13}\,(\text{syst.})\text{ pb}$







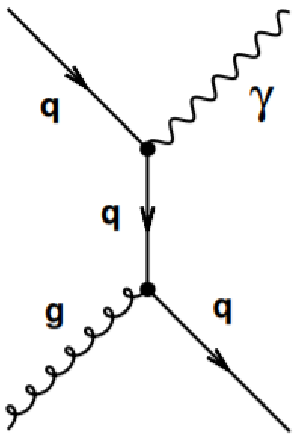
Good agreement!

Combined obs.(exp.) significance = **4.1(3.1)σ**

Evidence of triboson WVV!

Main uncertainties are from statistics, MC modelling, data-driven bkg estimations.

Direct photons



Inclusive photon ratios @ 13 TeV/8 TeV

[JHEP 04 (2019) 093]

- **Test** of pQCD with hard colourless probe
- **Testground** for MC models of prompt-photon production

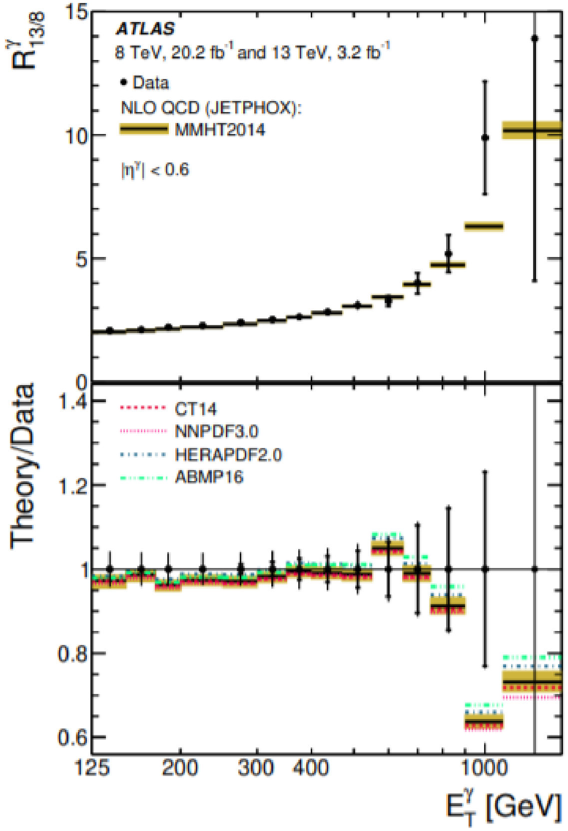
"Direct" photons:
from qg→qγ,
qq→gγ (ME)

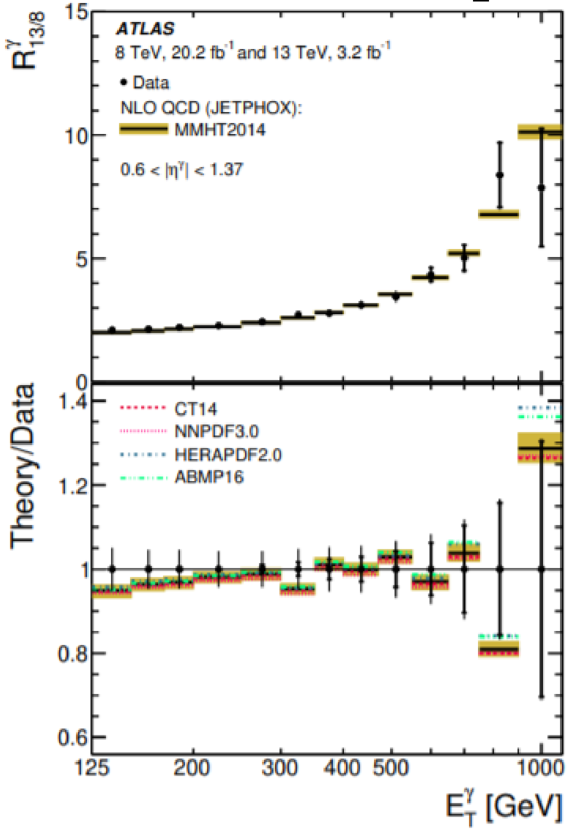
Data: L=20.2 fb^{-1} @ 8 TeV & 3.2 fb^{-1} @ 13 TeV

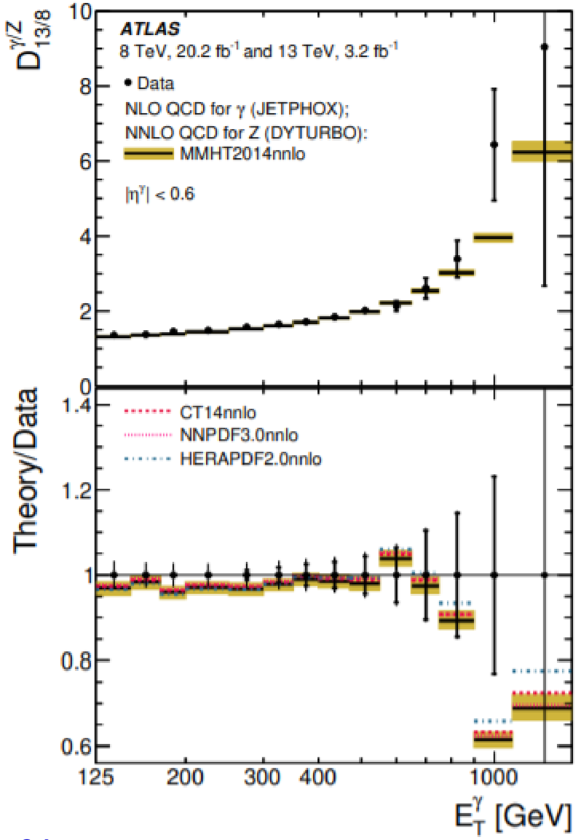
- **Measurement** of differential cross-sections ratios

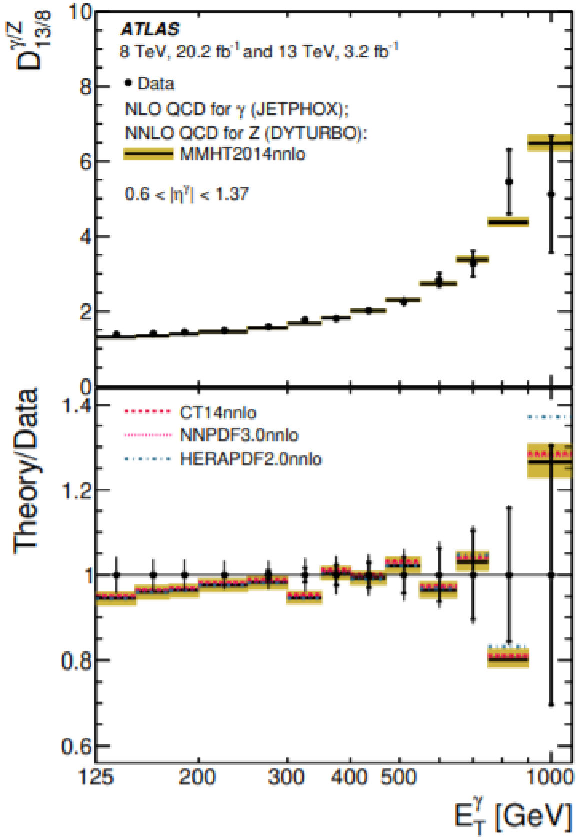
Photons are isolated, EMC shower shapes ID applied, $E_T[\gamma]$>125 GeV

$D^{\gamma/Z}_{13/8} \equiv R^{\gamma}_{13/8}/R^{Z}_{13/8}$ $R^{Z}_{13/8} \equiv \sigma^{\rm fid}_{Z}(13\ {\rm TeV})/\sigma^{\rm fid}_{Z}(8\ {\rm TeV})$









Results are in agreement with theory within errors in most of bins. Photon energy scale syst become comparable with others.

Inclusive photon @ 13 TeV

Submitted to JHEP

- **Important test** of pQCD

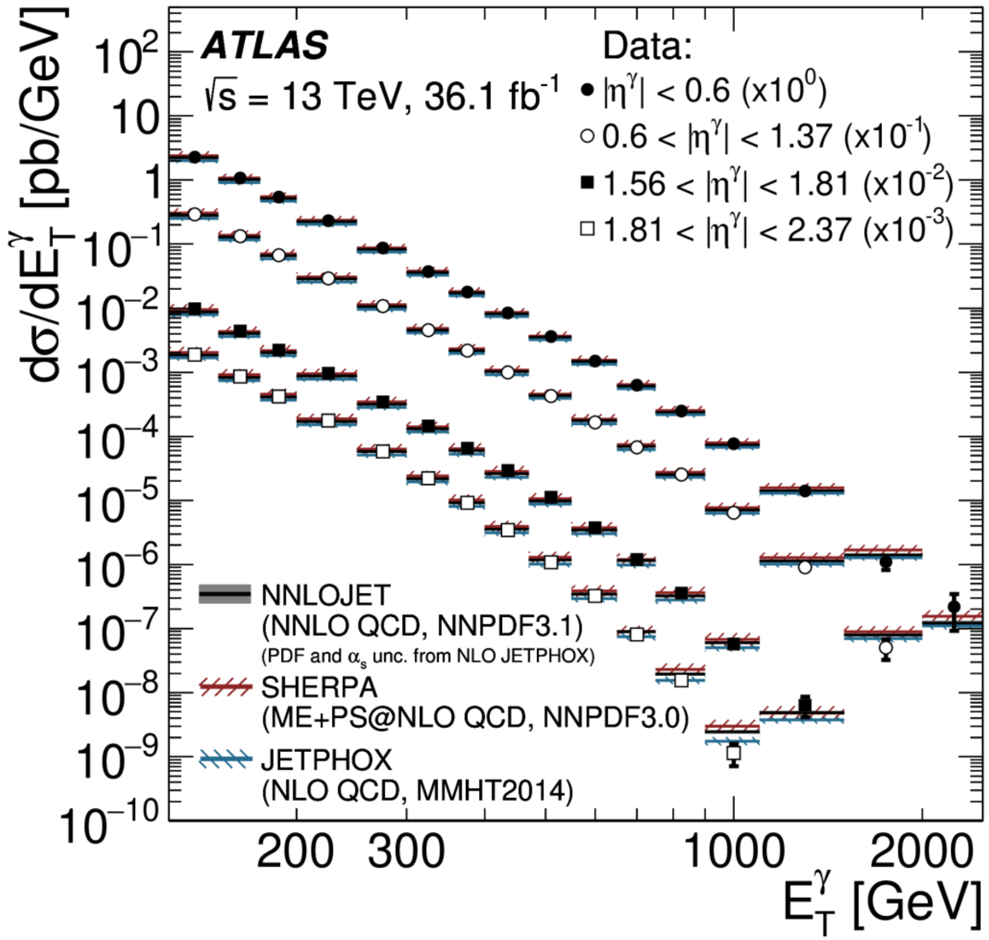
Data: L=36.1 fb^{-1} ± 2.1%

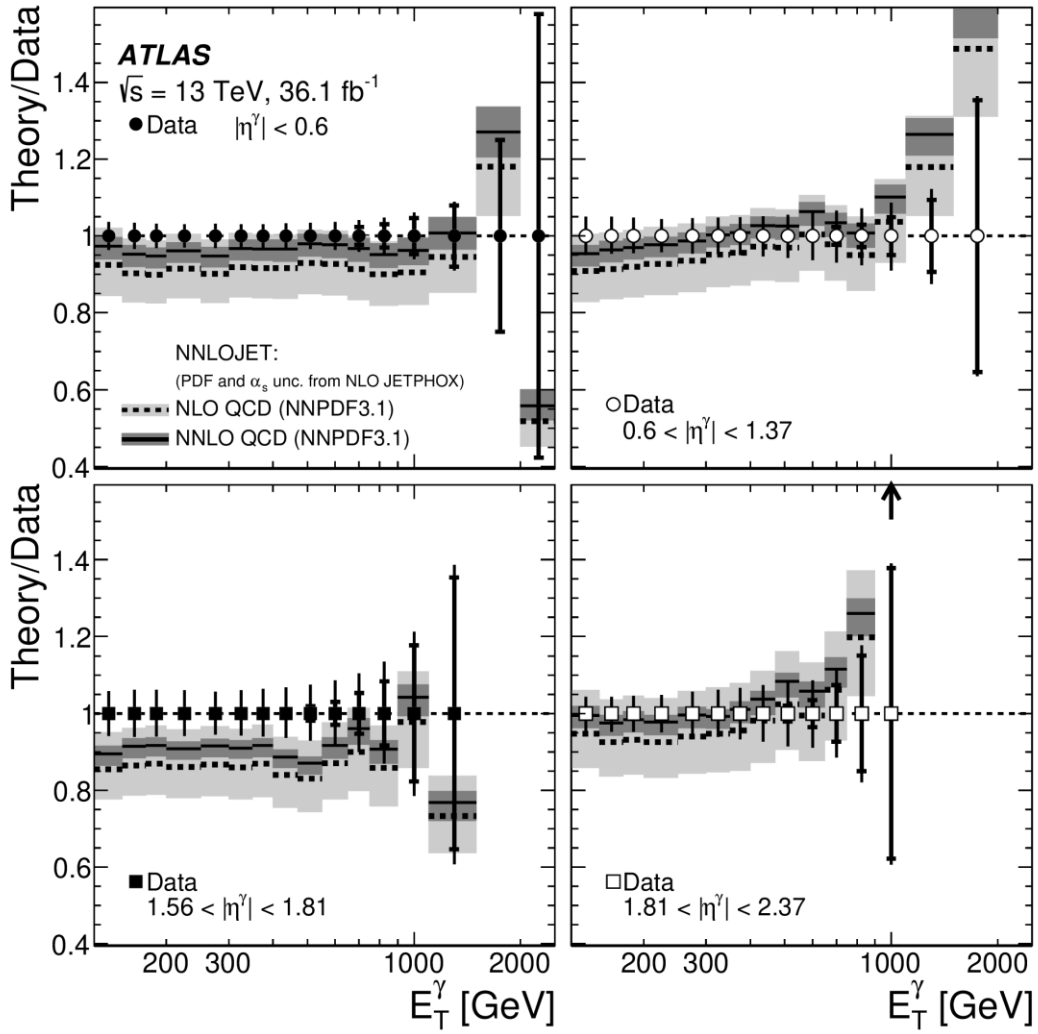
MC signal: Pythia and Sherpa; Main bkgs: jet→γ

data-driven from 2D-sideband method

Photons are isolated, EMC shower shapes ID applied, $E_T[\gamma]$>125 GeV

- **Measurement** of differential cross-sections (vs. $E_T[\gamma]$, $\eta[\gamma]$)

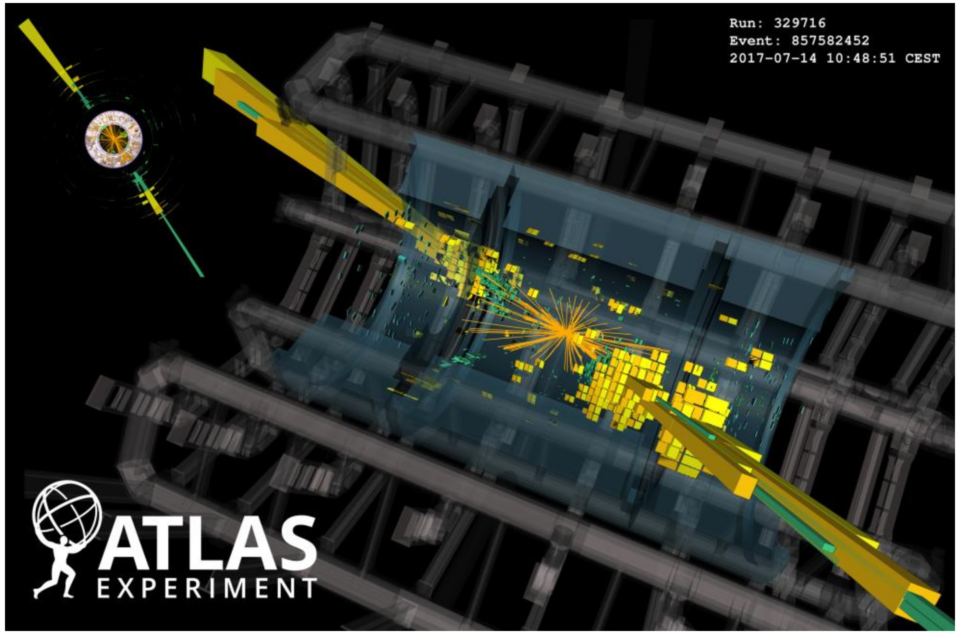




NNLO QCD prediction gives an excellent description of the data

Main uncertainties are from photon energy scale and photon ID.

Jet physics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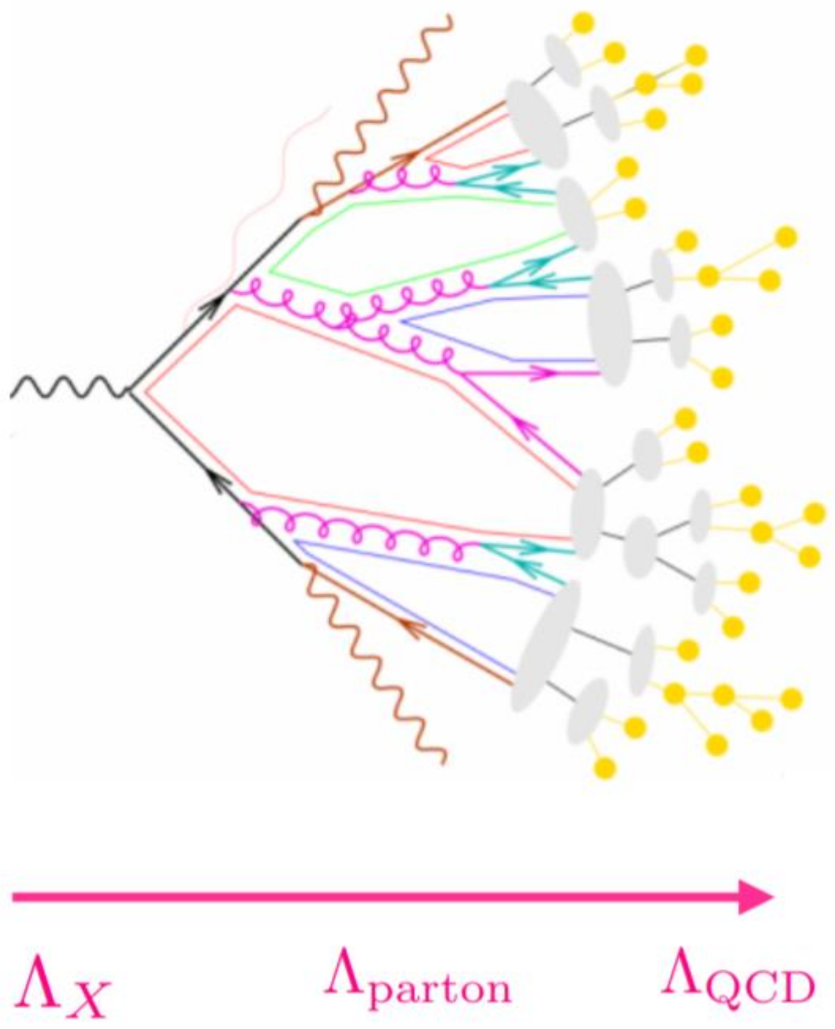
EXPERIMENT

Jet physics: Multi-scale dynamics in jet-based observables

- **Study of jets is important test of QCD** (strong coupling, PDF…) in hadron collider experiment.
- It is can be used also to **distinguish the origin of jets** between light quarks, gluons and hadronic decays of heavy particles.

Multiscale dynamics studies provide:

- Exploring the evolution of high energy quarks and gluons into hadrons
  - Multi-scale problem which straddles perturbative and non-perturbative effects
  - Good understanding necessary for precise control over observables in many physics analyses
- What's <u>Interesting</u>?
  - Testing showering and hadronization models against event shape and individual jet observables
  - Measuring how these variables evolve in a wide range of phase-space and with different jet flavors
  - Probing the structure of hadronic resonances



Jet shapes @ 13 TeV

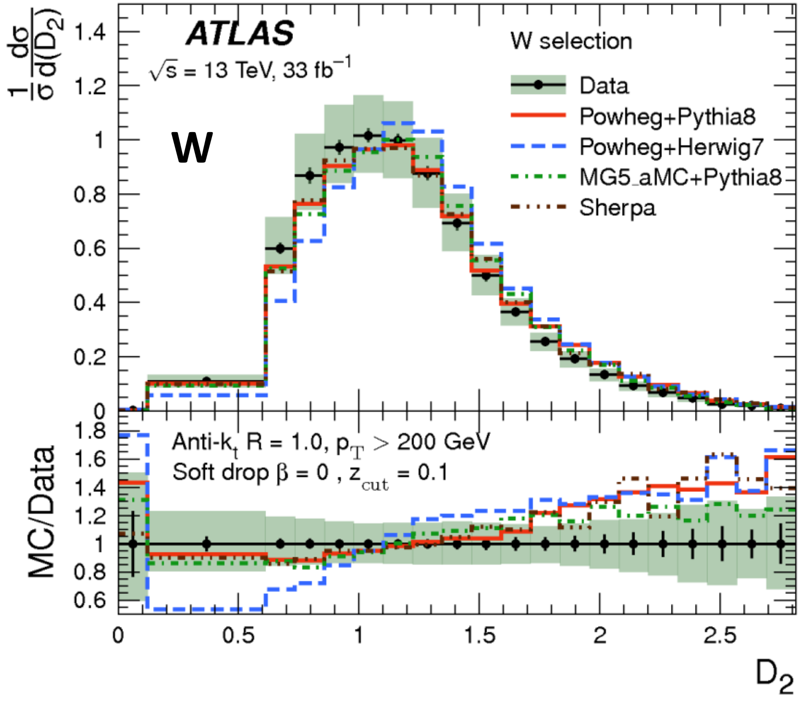
Data: L=33 fb^{-1} ± 2.2%

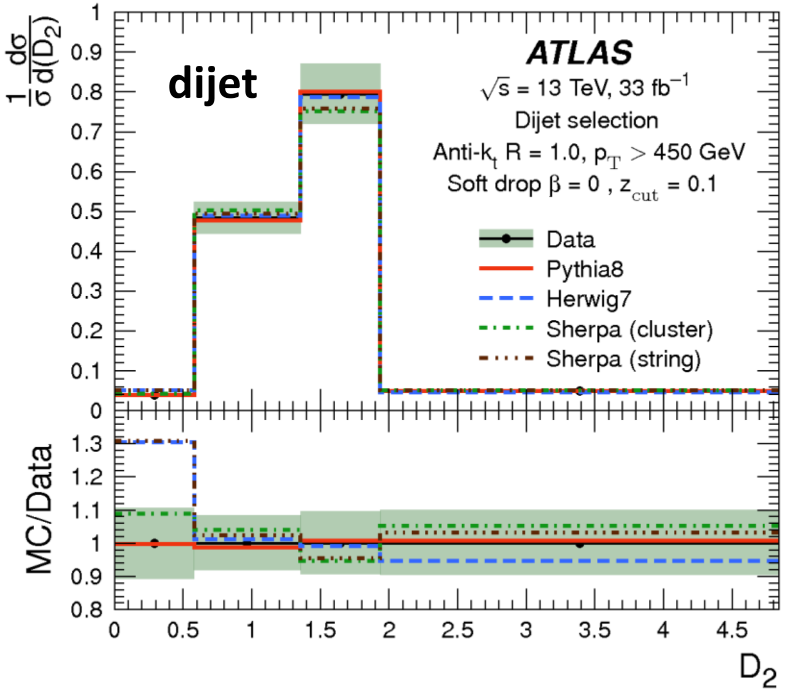
[JHEP 08 (2019) 033]

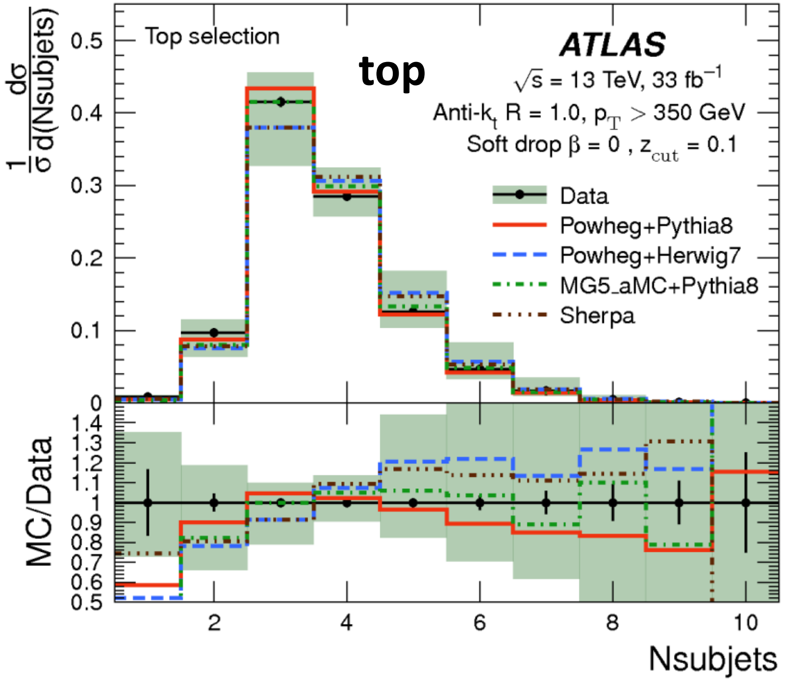
- Measurement of many jet substructure observables for trimmed and Soft Drop jets
  $N_{subjets}$, $\lambda^{\kappa}_{\beta LHA}$, e_2, e_3, C_2, D_2, τ_{21}, τ_{32}

- Modeling of these observables is important for taggers (e.g. D2 is one of the most common variables to use for tagging W bosons)

For each observable, subtract the background, then unfold to particle level







None of the MC generators completely model the data (different MC generators model well different observables)

Lund jet plane @ 13 TeV

ATLAS-CONF-2019-035

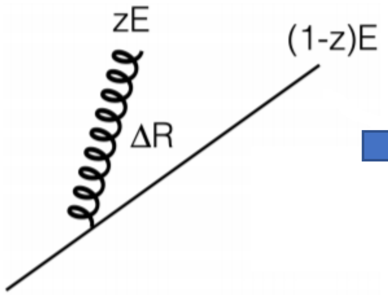
➢ New proposal to represent internal structure and formation of jets

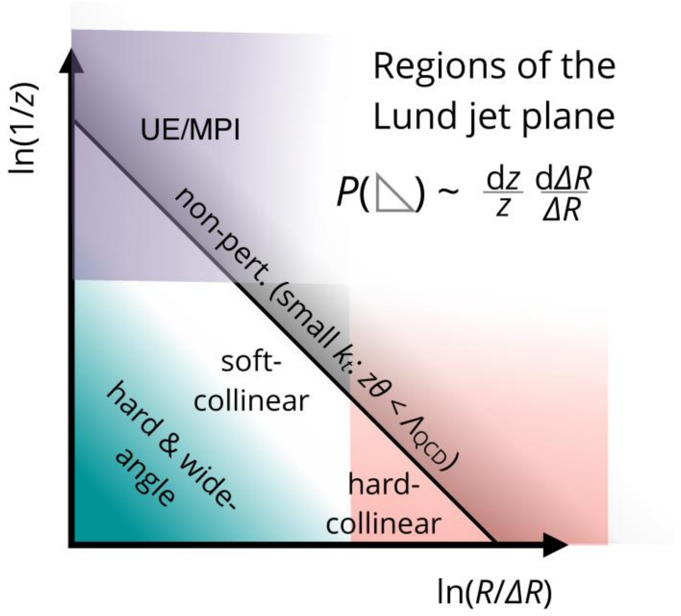
A jet may be approximated as soft emissions around a hard core which represents the originating quark or gluon

- **Lund Plane: ln(1/z) vs ln(1/θ)**

z = relative momentum of emission wrt jet core

θ = opening angle of emission relative to the jet core



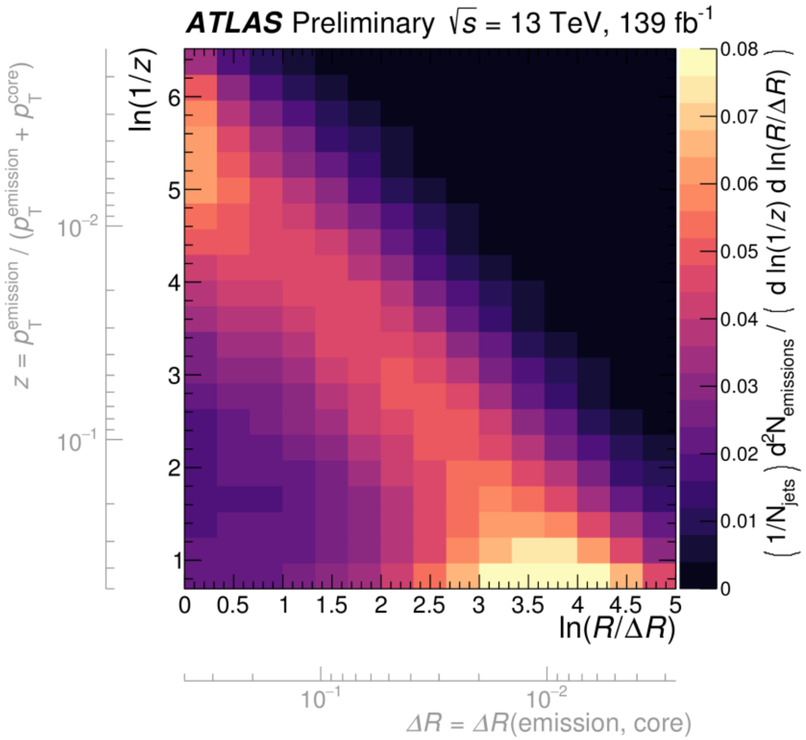


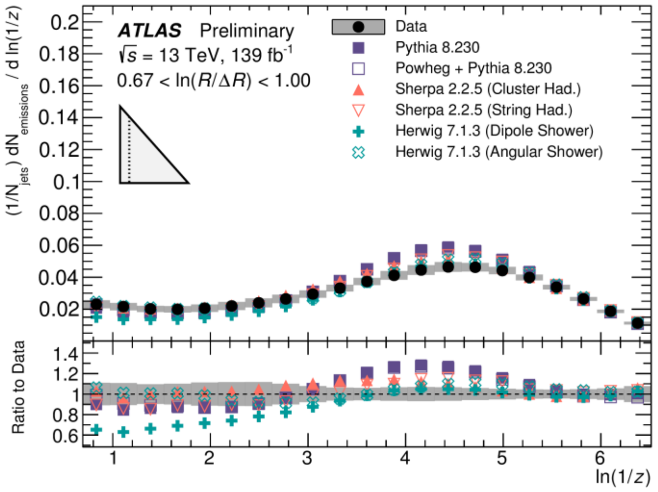
➢ **Measurement** of double differential cross-section of Lund jet plane

Data: L=139 fb^{-1} ± 1.7%

Using R = 0.4 jets

Unfolding to charged particle level

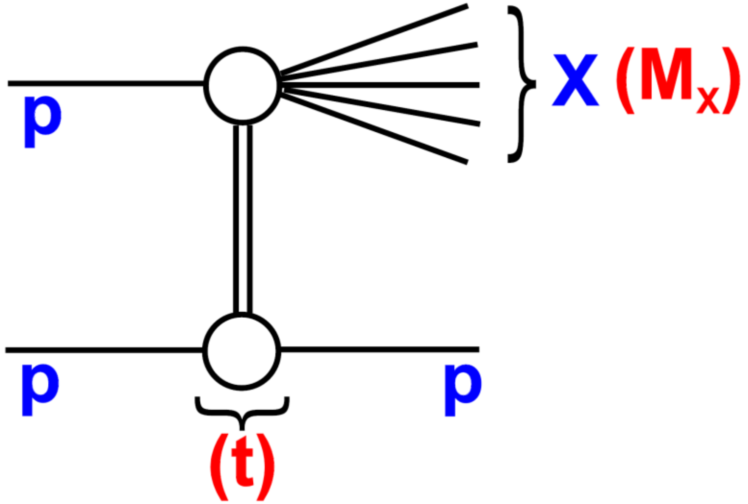


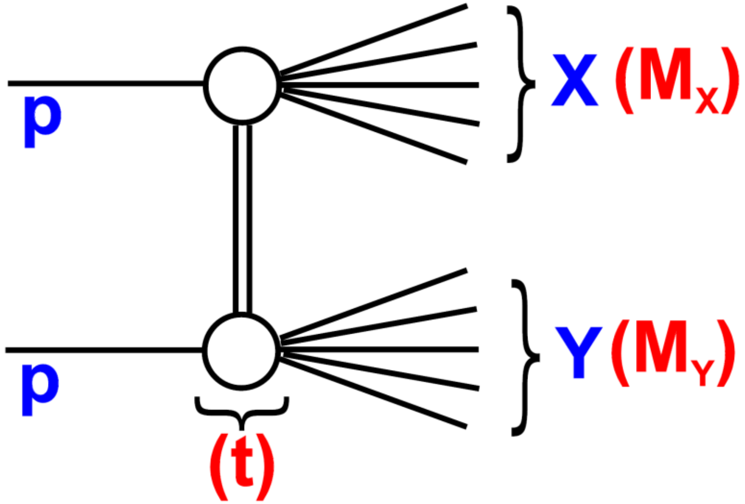


➢ The Lund Plane is the phase space of these emissions: it naturally factorizes perturbative and non-perturbative effects, UE/MPI, etc

➢ Can be used in ML-based jet discriminants

Soft QCD, Diffraction and Forward Physics

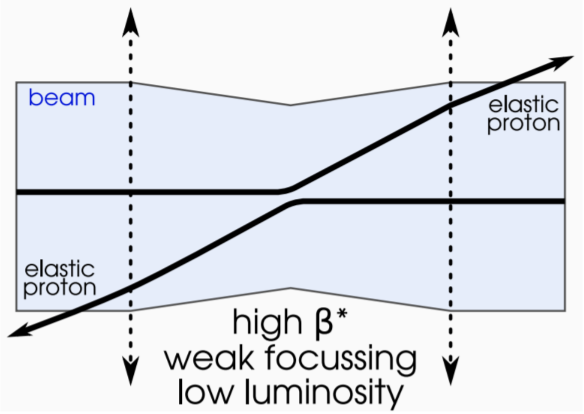




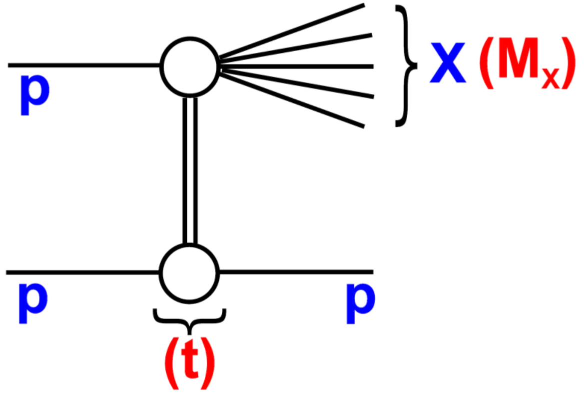
Single Diffractive Dissociation using ALFA @ 8 TeV

ATLAS-CONF-2019-012

- Most of diffraction kinematics domain is characterized by soft scales
- Can not be described by pQCD
- An important tool to probe strong interaction in its non perturbative regime
- Interactions mediated by Pomerons
- Phenomenological approach (QCD + models)



Diffraction studies are carried on special LHC runs with high β^* and consequently low luminosity. Forward ALFA detector is used.



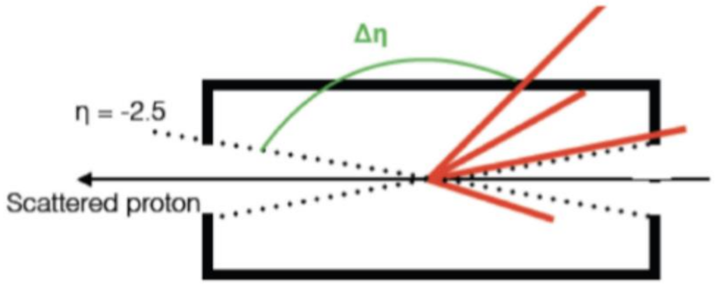
Kinematic variables:

- t – squared four-momentum transferred from the proton

$$t \approx -p_T^2$$

- ξ – momentum fraction of the proton carried by the pomeron

$$\xi = 1 - E/E_0$$
$$= M_X^2/s \approx \sum_i (E^i \pm p_z^i)/\sqrt{s}$$

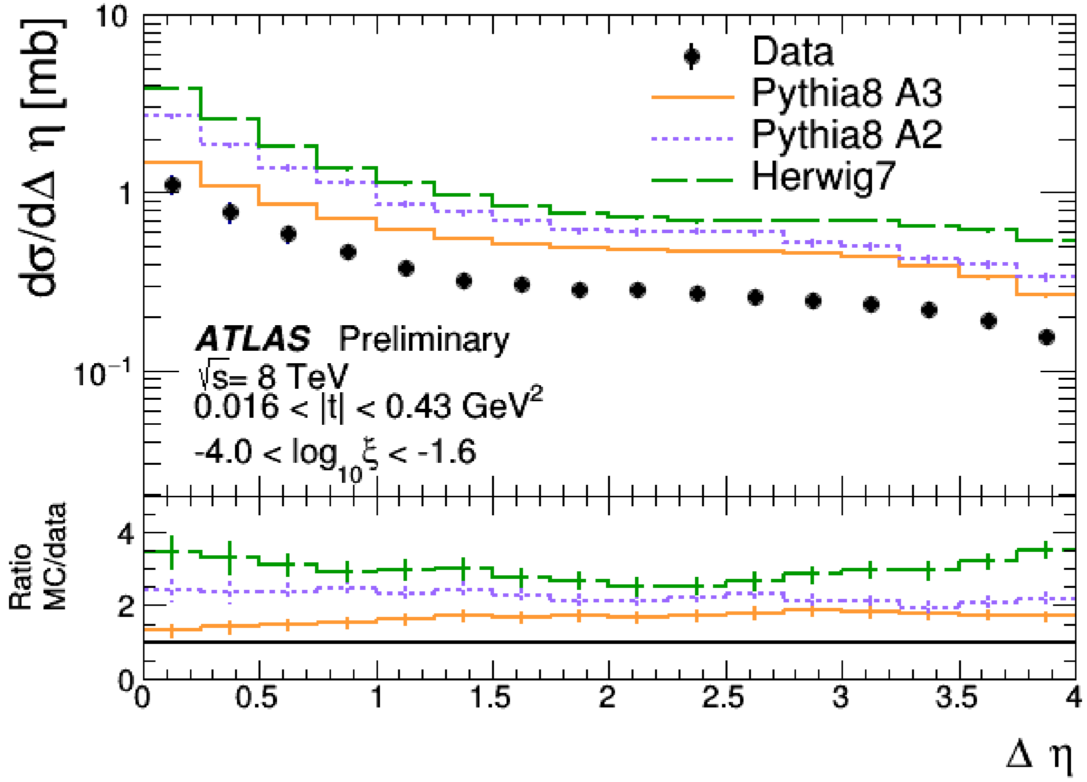


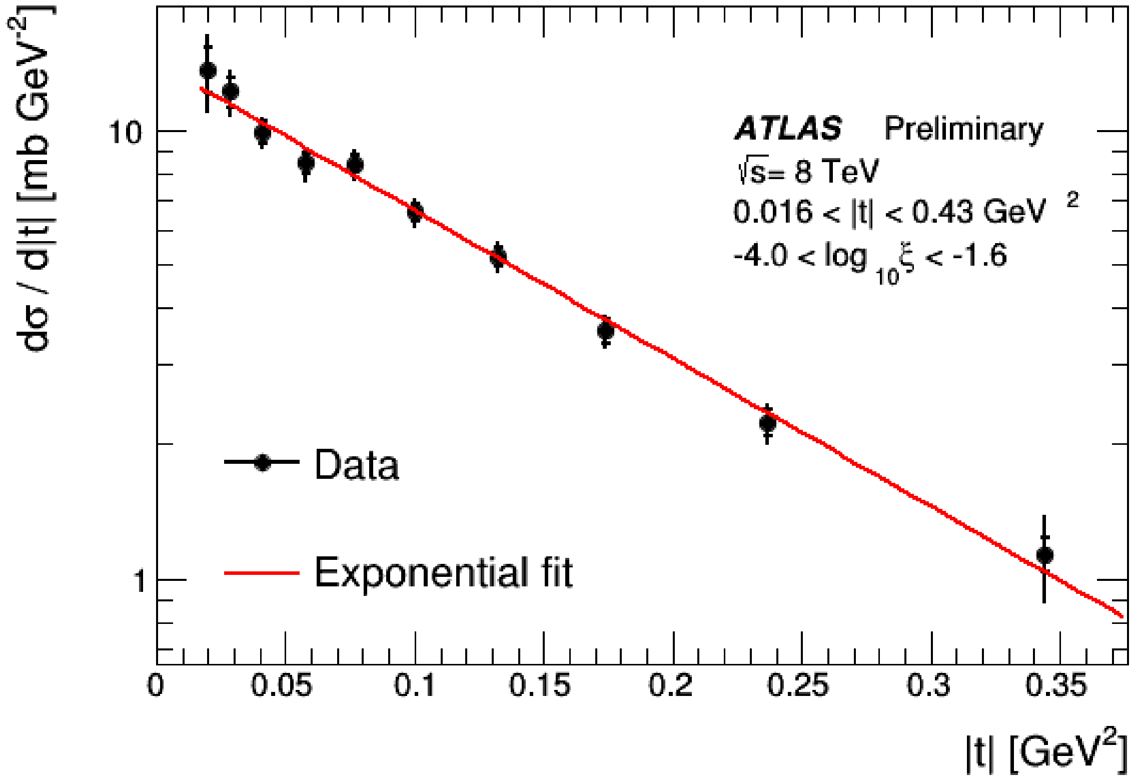
- Δη – (pseudo)rapidity gap from the tracker edge

Single Diffractive Dissociation using ALFA @ 8 TeV

ATLAS-CONF-2019-012

➢ **Measurement** of differential cross-section of Single Diffractive Dissociation





- Diffractive plateau is visible
- MCs do not describe the overall cross-section

Shape description is fine

Monte Carlo model	$\sigma_{MC}/\sigma_{data}$
PYTHIA 8, A2 tune	2.3
PYTHIA 8, A3 tune	1.5
HERWIG 7.1	3.0

Measured exponential slope:

$$B = 7.60 \pm 0.23(\text{stat.}) \pm 0.22(\text{syst.})\ \text{GeV}^{-2}$$

In agreement with Pythia 8 prediction:

PYTHIA8 A2: 7.82 GeV^{-2}, PYTHIA8 A3: 7.10 GeV^{-2}

Main systematic uncertainty from overlay background subtraction

Summary

- Early full Run2 analyses and precision Run1 analyses provide very stringent tests of SM.

- New measurements for soft QCD / Diffraction / Forward Physics, Electroweak studies, Jet Physics and Direct Photons were presented:
  - **W/Z data and photons**: consistent with SM at NNLO
  - **VBF/VBS**: most of channels were observed and the rest will be observed in near future
  - **Dibosons/Tribosons**: no surprizes so far - constraints on anomalous couplings
  - **Jets**: Lund plane is very promising method of factorizing many different effects
  - **Forward physics**: first single diffractive proton-proton cross-section measured

- LHC Run2 was very successfull: a lot of data still to be analysed!