



Multiboson results from the LHC



Alexander A. Savin

University of Wisconsin, Madison, USA

On behalf of the ATLAS and CMS Collaborations

QCD@LHC2016, Zurich, Switzerland, 23 August 2016

Outline

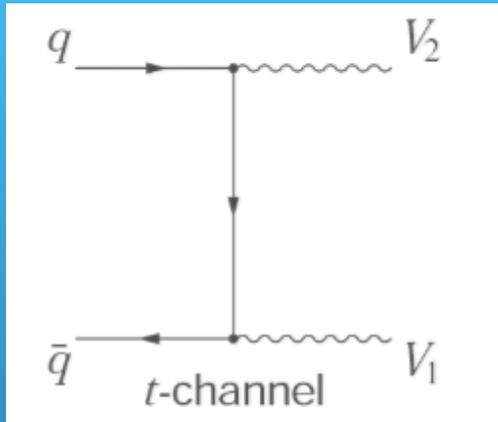
2

- Multiboson production in SM
- Recent results on multiboson cross sections: inclusive, fiducial and differential
- Electroweak production
- Triple and Quadric Couplings
- Future measurements

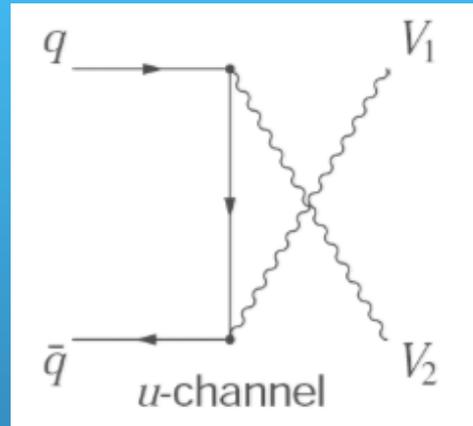


Multiboson production in SM

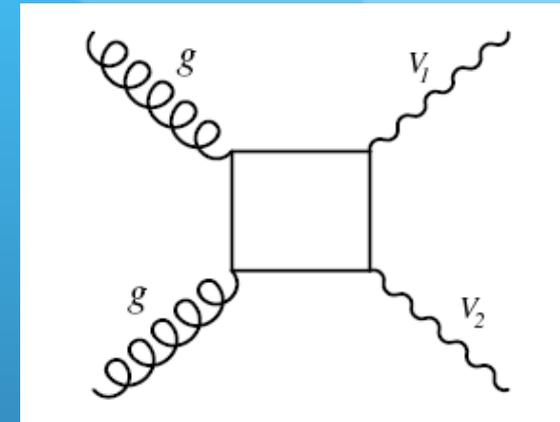
LO



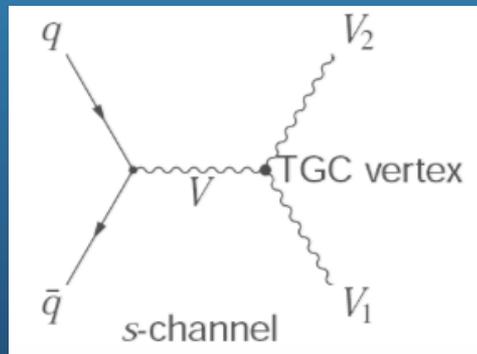
LO



NNLO



For all the channels NLO predictions are available, very recently - NNLO for most of the channels

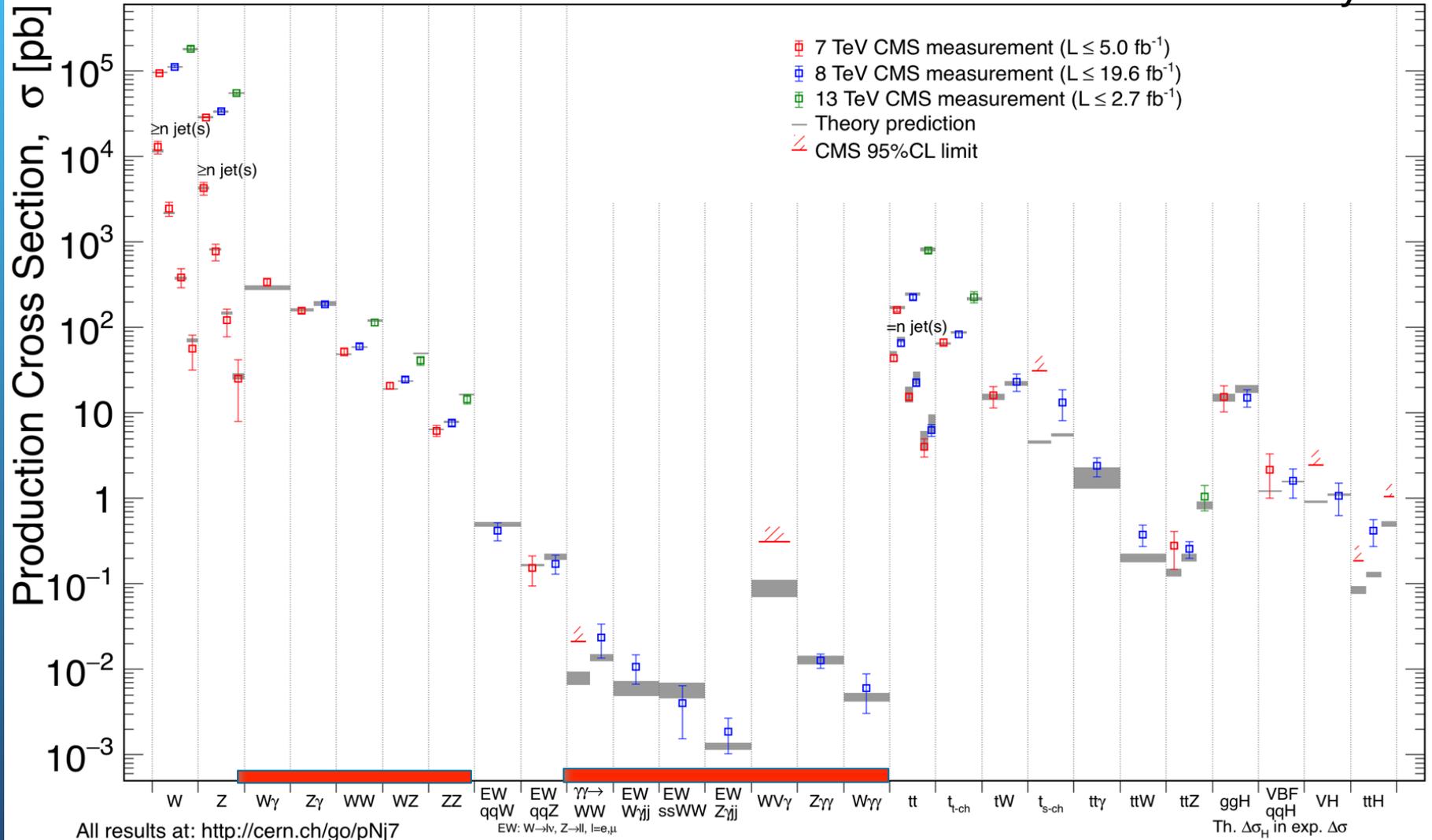


s-channel production will be discussed in the second part of the talk

CMS SM measurements

June 2016

CMS Preliminary

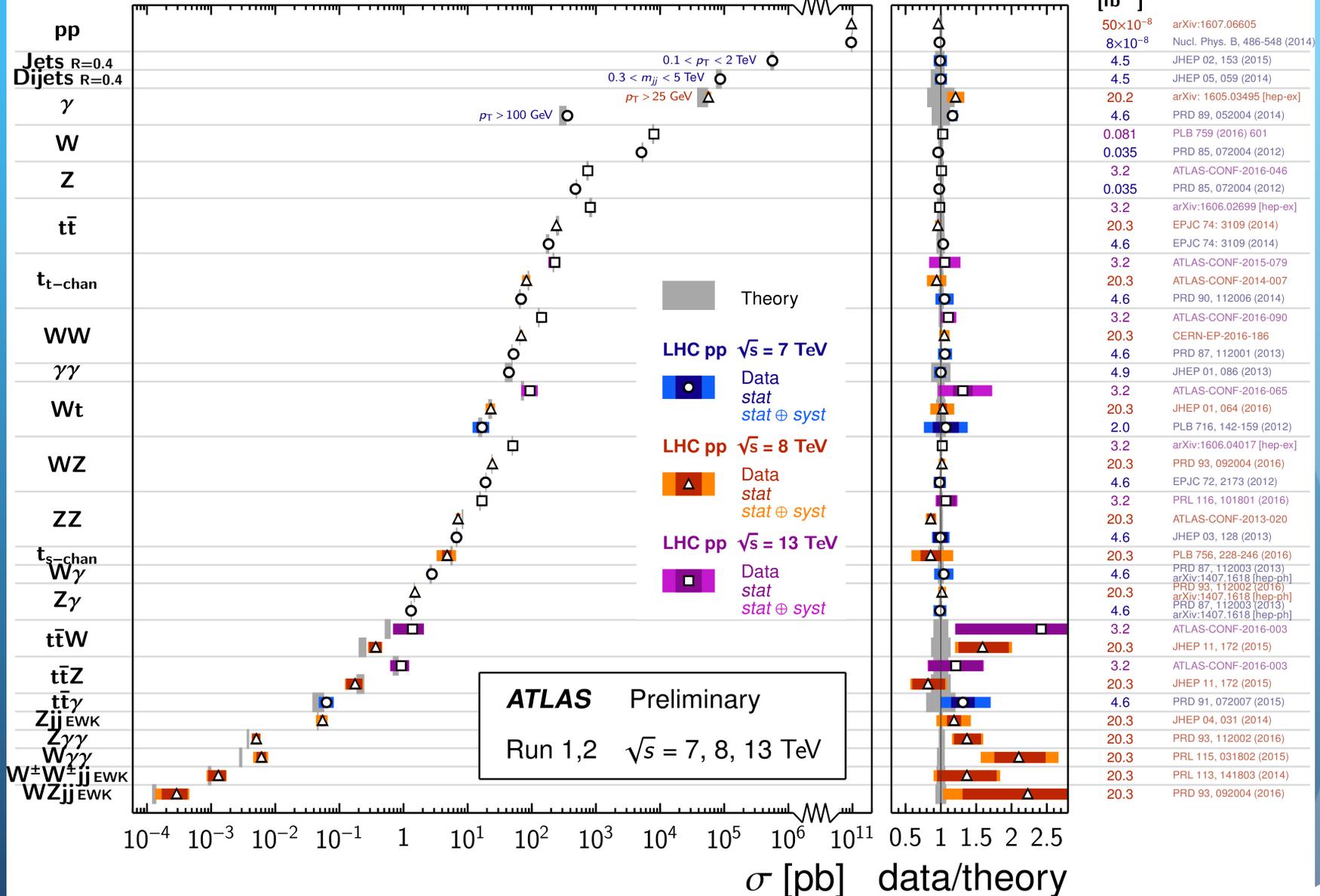


ATLAS SM measurements

Standard Model Production Cross Section Measurements

Status: August 2016 $\int \mathcal{L} dt$
[fb⁻¹]

Reference



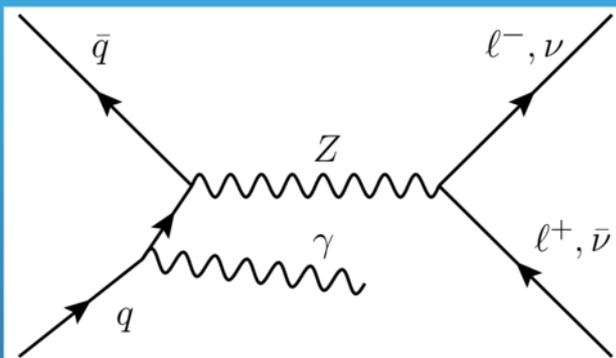
$Z\gamma(\gamma)$ production

ATLAS 8 TeV: Phys.Rev.D 93 (2016) 112002

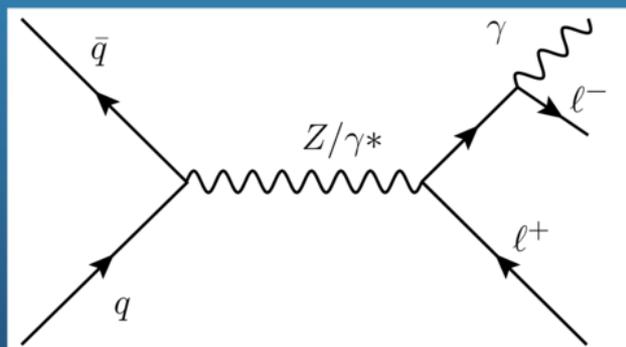
CMS 8 TeV: Phys.Lett.B 760 (2016) 448 ; SMP-15-008 (W/Z $\gamma\gamma$)

CMS 13 TeV: CMS-PAS-16-004

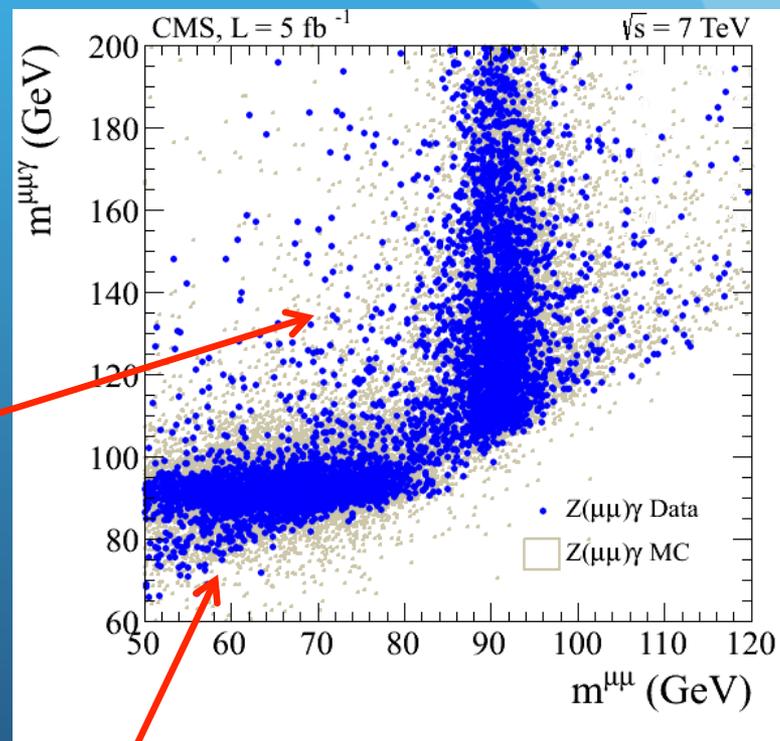
Initial State Radiation



Final State Radiation

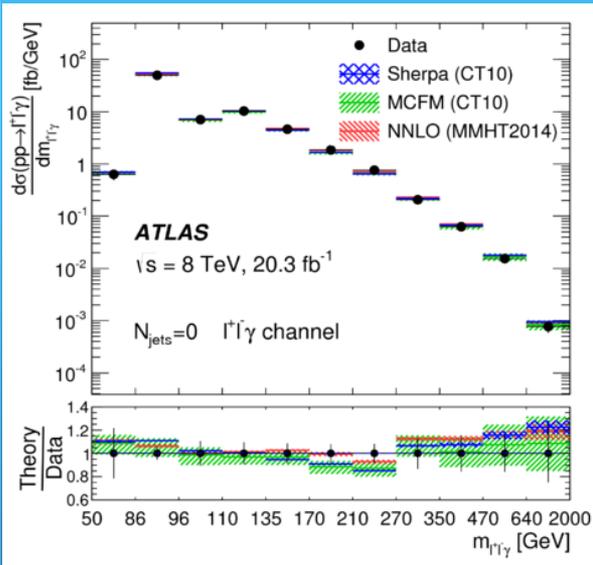


ISR



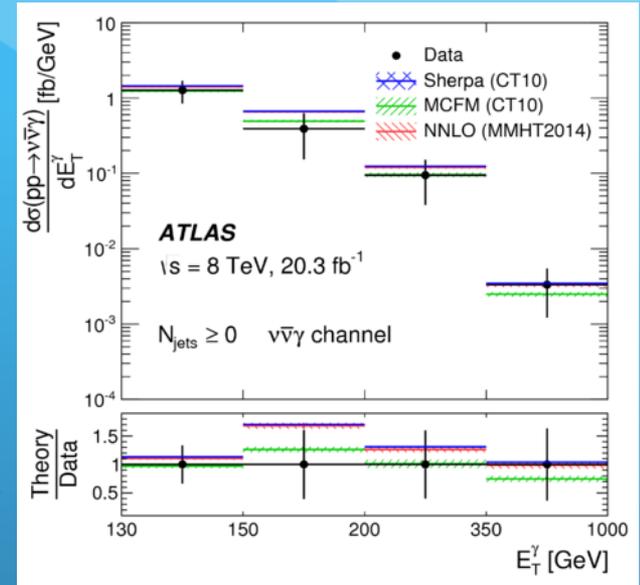
FSR

Z γ production



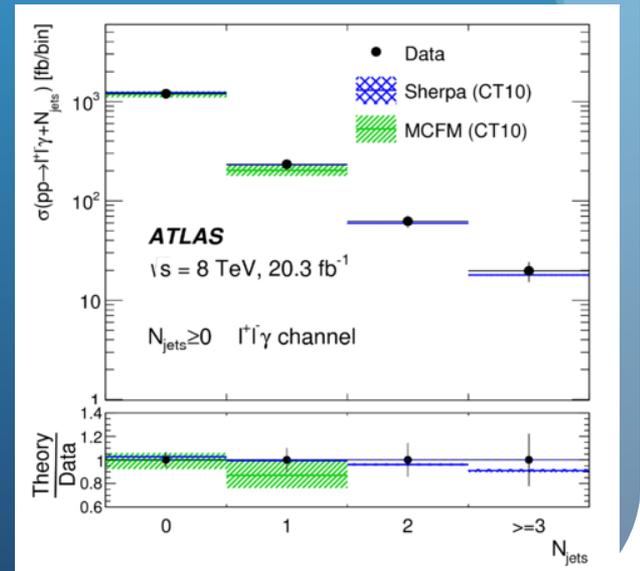
Two isolated electrons or muons and a photon ($ll\gamma$)

High- p_T photon and missing energy ($\nu\nu\gamma$)

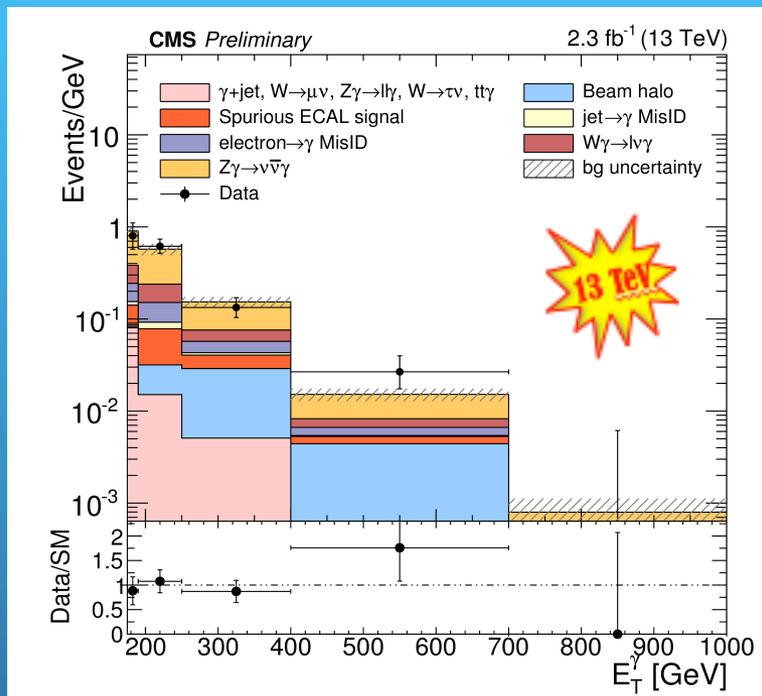


Jets : $p_T > 30 \text{ GeV}$; $|\eta| < 4.5$

The SM predictions describe well the differential distributions



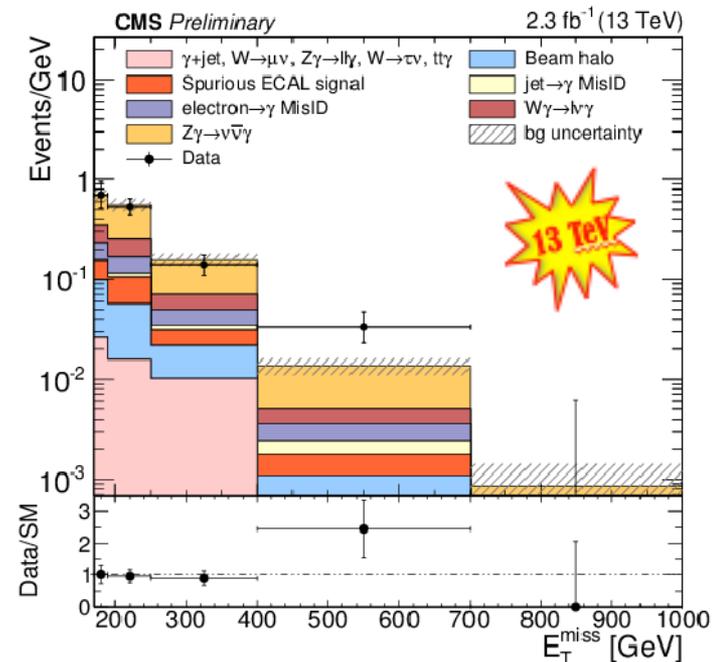
$Z(\nu\nu)\gamma$ production



First 13 TeV measurement.
Two neutrinos
(missing energy)
and a high- p_T photon

The measured cross section
 $66.5 \pm 13.6(\text{stat}) \pm 14.3(\text{syst}) \pm 2.2(\text{lumi}) \text{fb}$
 agrees with NNLO
 $65.5 \pm 3.3 \text{fb}$

23/08/2016

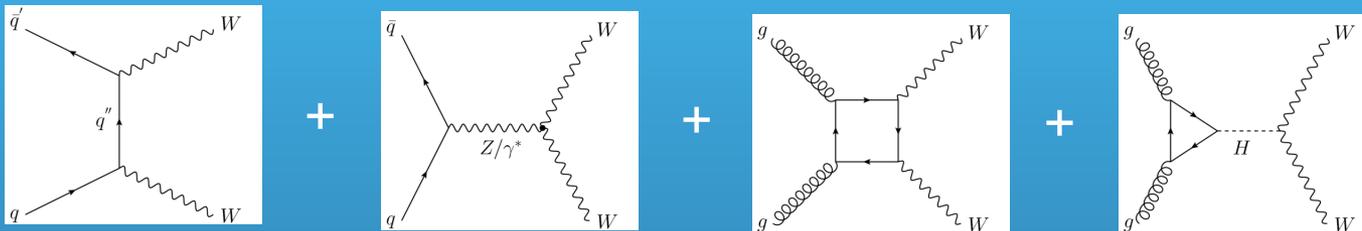


WW production

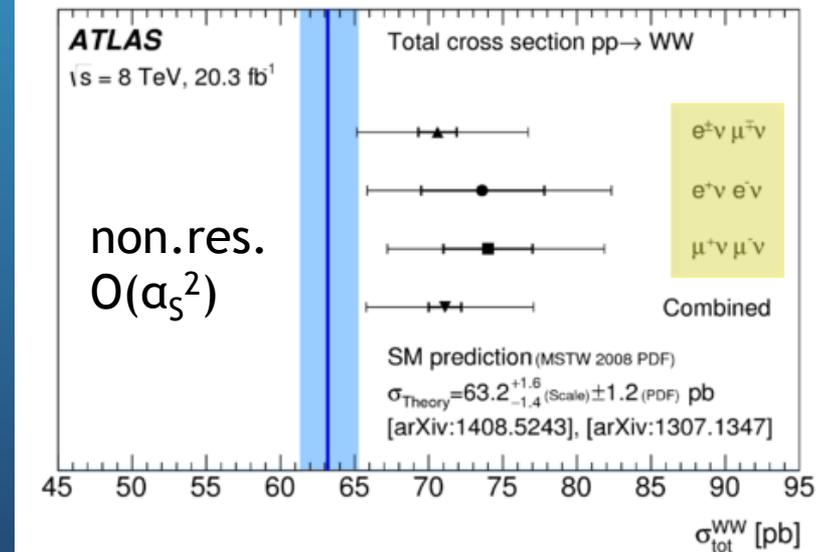
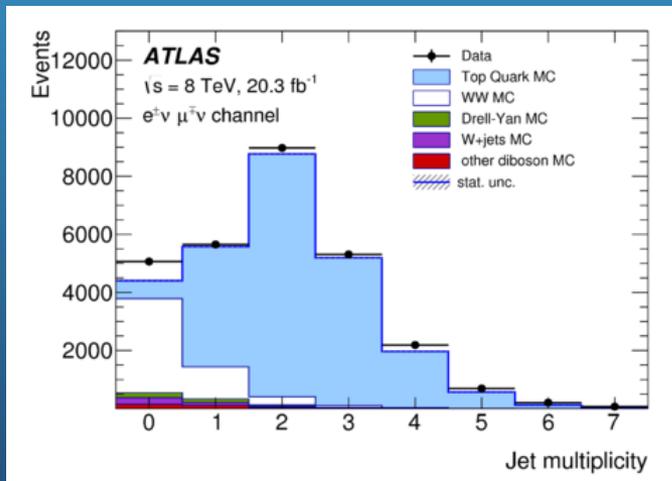
ATLAS 8 TeV: arXiv:1603.01702 ; arXiv:1608.03086

ATLAS 13 TeV: ATLAS-CONF-2016-090

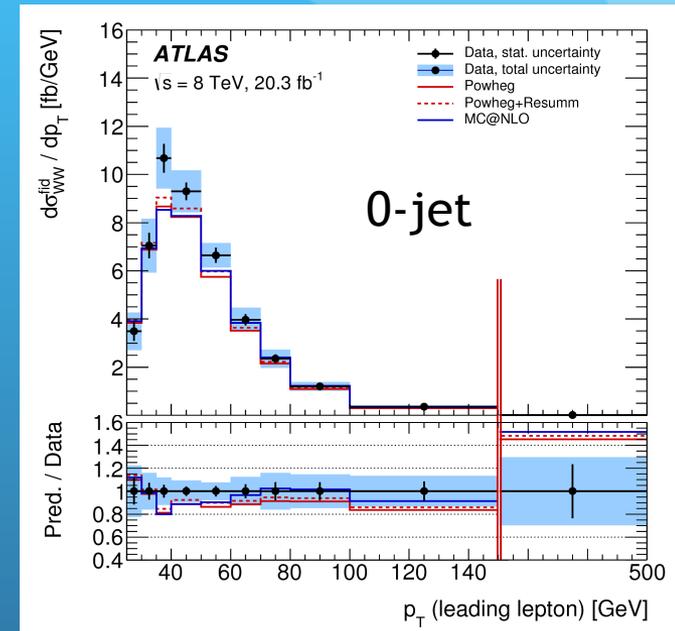
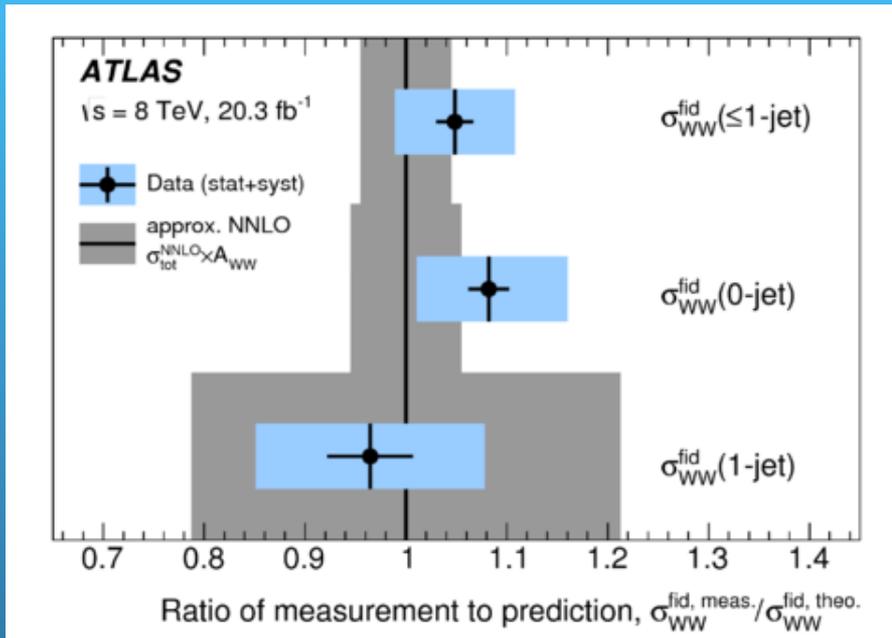
CMS 8 TeV: EPJ C76 (2016) 401 ; **13 TeV:** CMS-SMP-PAS-16-006



Same and different flavor opposite charged lepton pair ;
missing energy, 0 jets $P_T > 25$ GeV

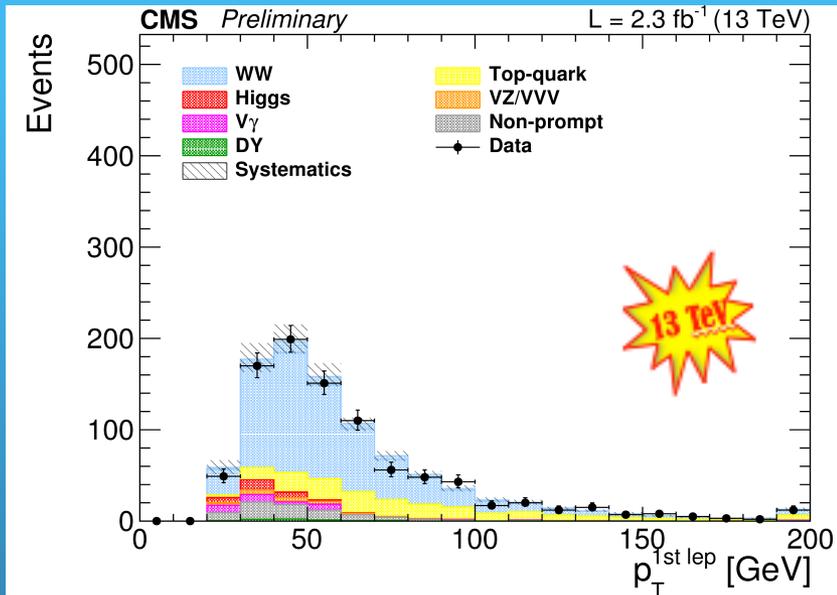


WW production



- * cross section for 0- and 1-jet events ;
- * 1/0 - ratio of cross sections 0.36 ± 0.05 ;
- * differential shapes are well described by the predictions

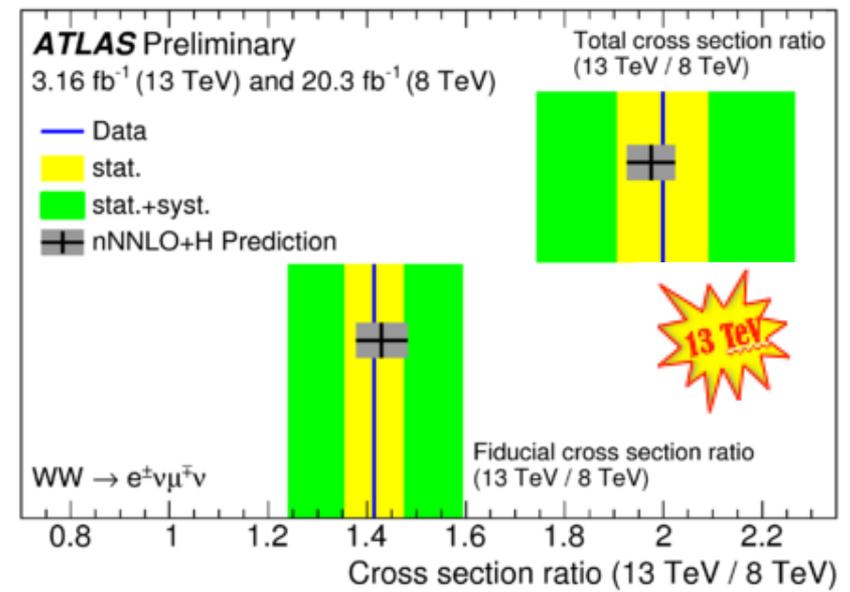
WW production



Electron and muon of opposite charge and missing energy ($>20 \text{ GeV}$), events with 0 or 1 jet of $p_T > 30 \text{ GeV}$, 3rd lepton and b-jet veto



The measured cross section $115.3 \pm 5.8(\text{stat}) \pm 5.7(\text{syst}) \pm 6.4(\text{theo}) \pm 3.6(\text{lumi}) \text{ pb}$ agrees with NNLO $120.3 \pm 3.6 \text{ pb}$

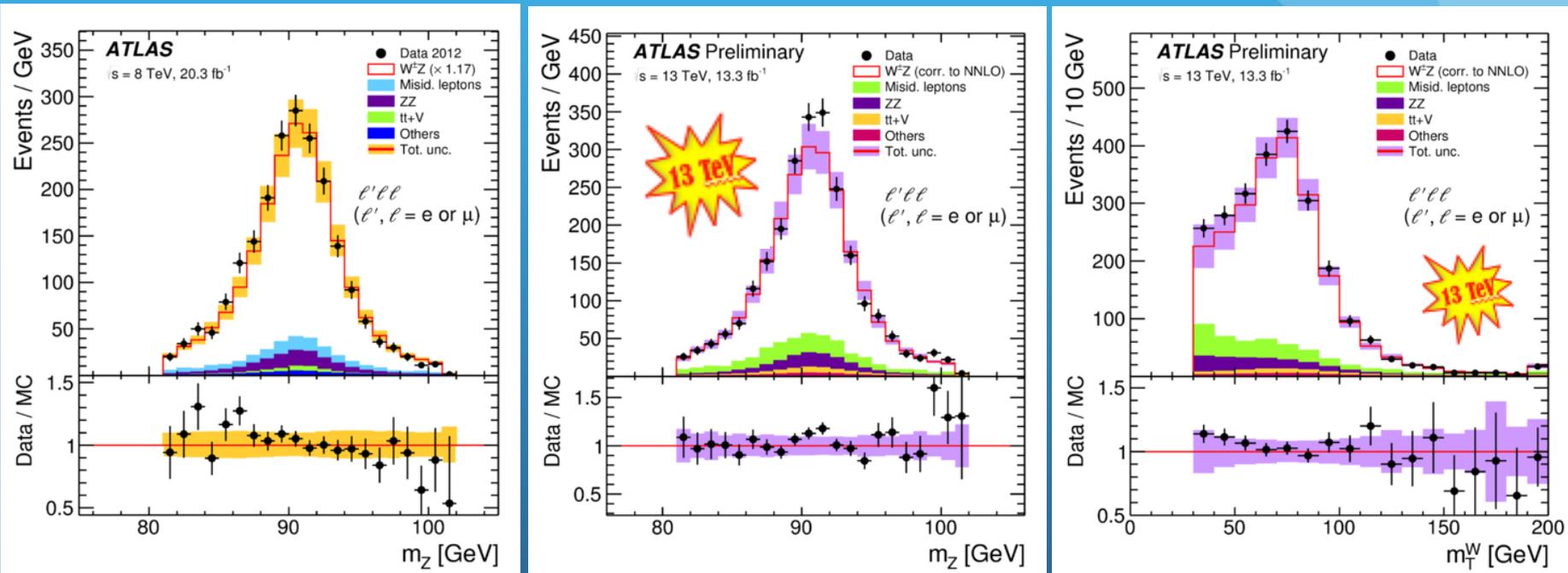


WZ Production

ATLAS 8 TeV: Phys.Rev.D 93 (2016) 092004

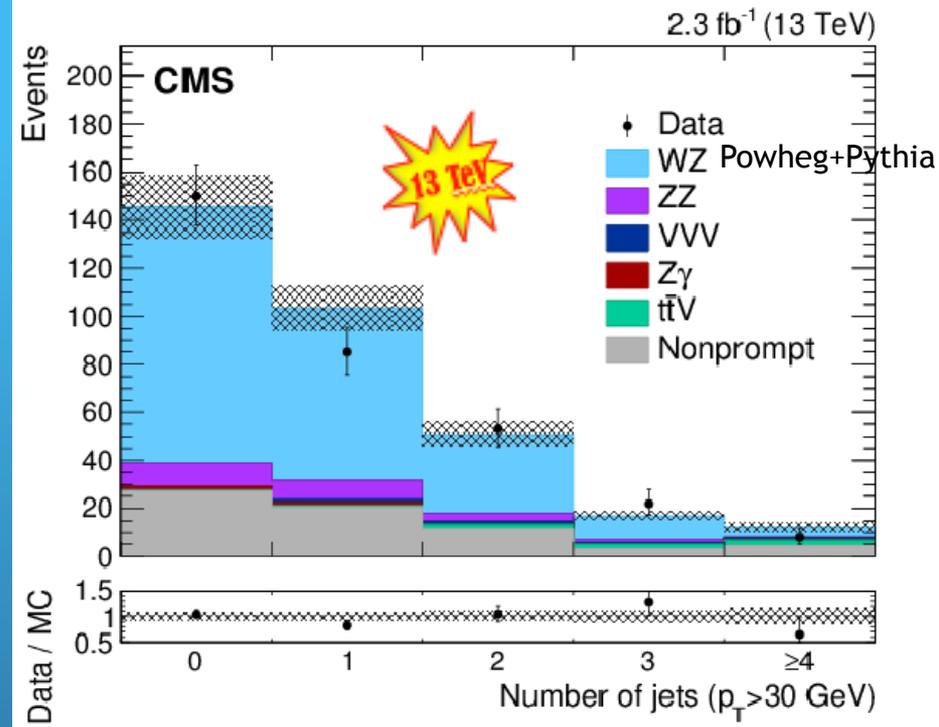
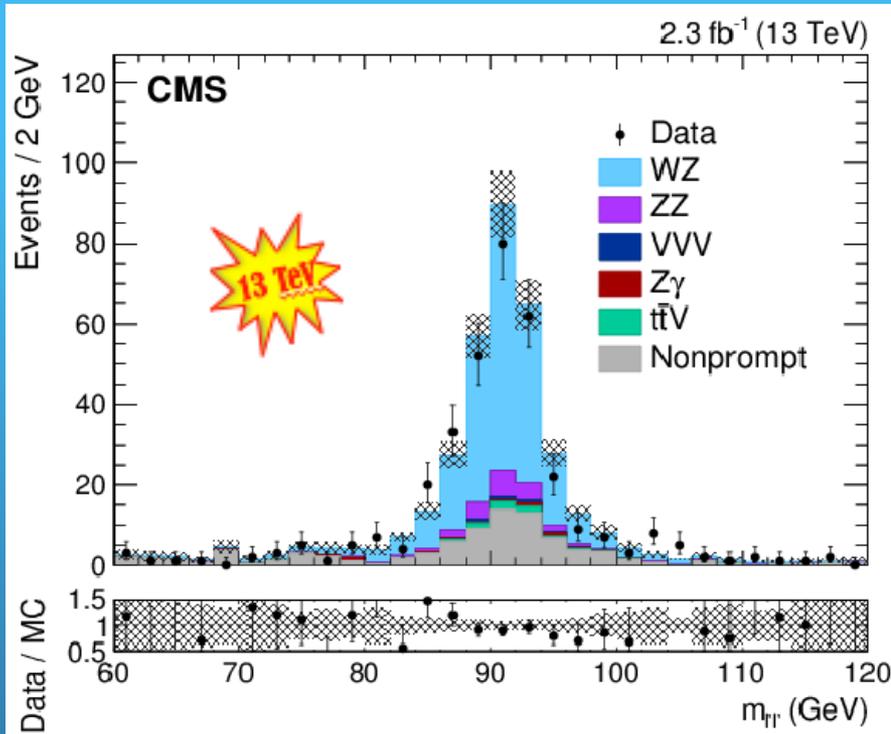
ATLAS 13 TeV: ATLAS-CONF-2016-043, arXiv:1606.04017

CMS 13 TeV: arXiv:1607.06943



Exactly 3 isolated leptons, one pair should form Z, tighter requirements on the lepton from W, CMS: b-jet veto

WZ Production



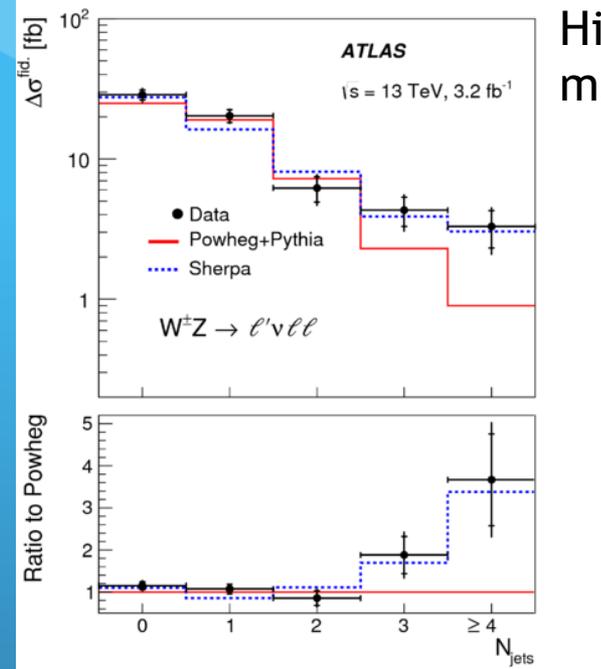
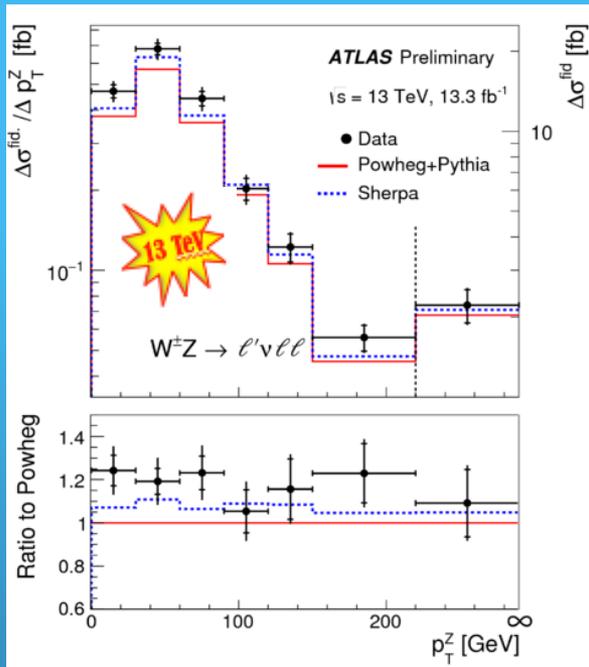
Simulation describes data well ; top background additionally suppressed by b-jet veto

CMS: $39.9 \pm 3.2(\text{stat}) + 2.9 / - 3.1(\text{syst}) \pm 0.4(\text{theo}) \pm 1.3(\text{lumi})$ pb

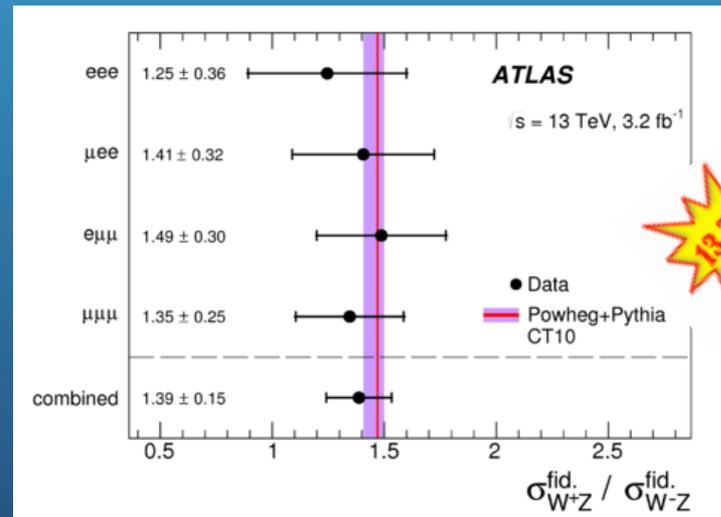
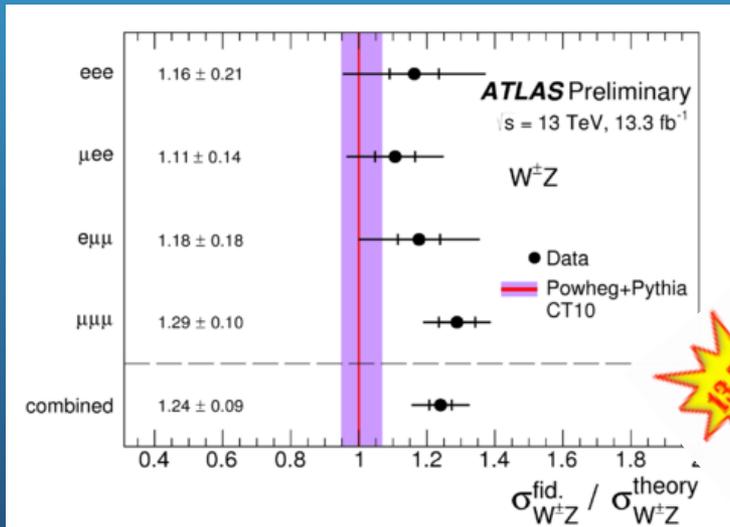
ATLAS: $50.6 \pm 2.6(\text{stat}) \pm 2.0(\text{syst}) \pm 0.9(\text{theo}) \pm 1.2(\text{lumi})$ pb

NNLO (MATRIX) : 50.0 ± 1.1 fb NLO MCFM $44.9 + 2.2 / - 1.8$ fb

WZ Production

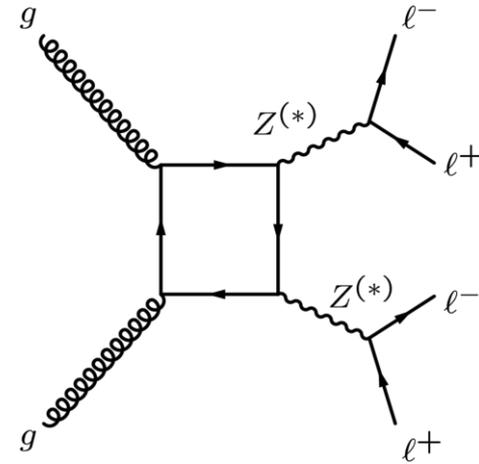
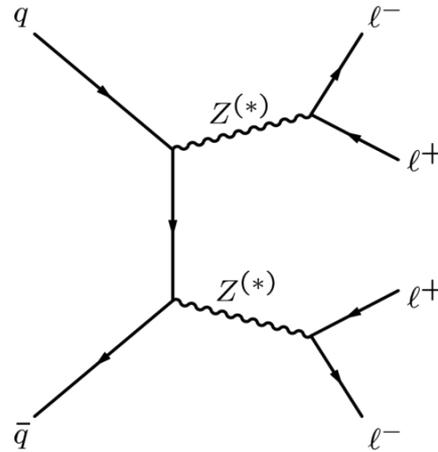


High-jet¹⁴
multiplicity

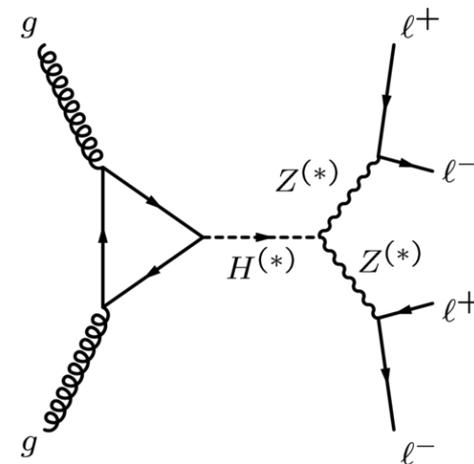
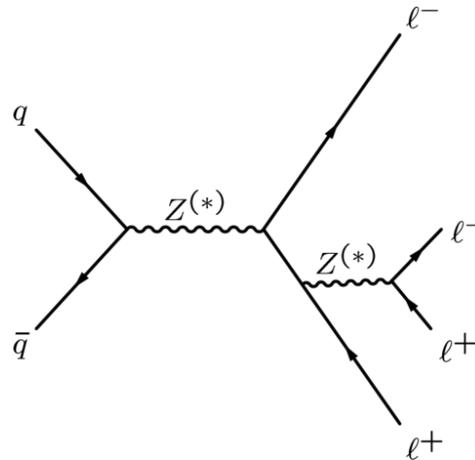


ZZ Production ($m_{ZZ} > 70$ GeV)

Non-resonant



Resonant



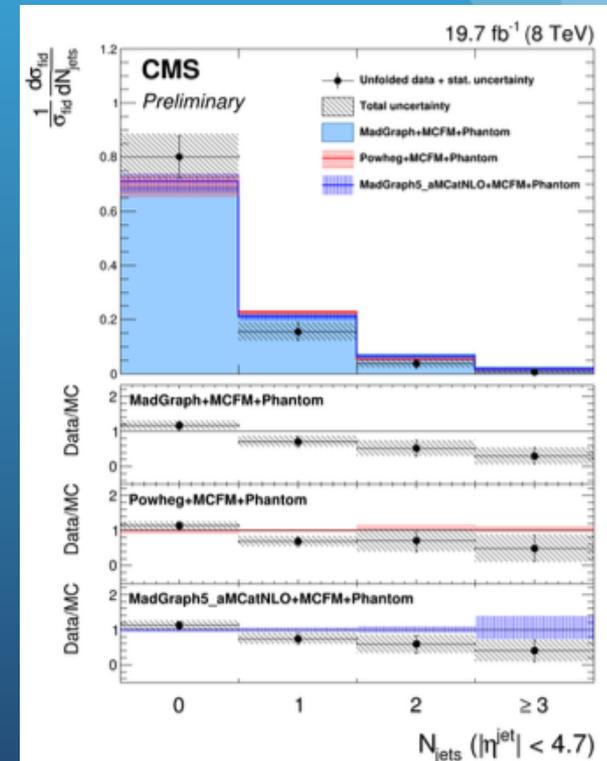
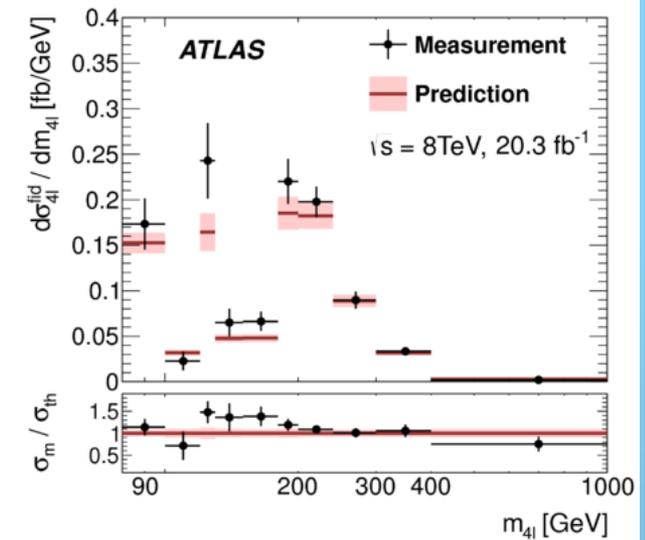
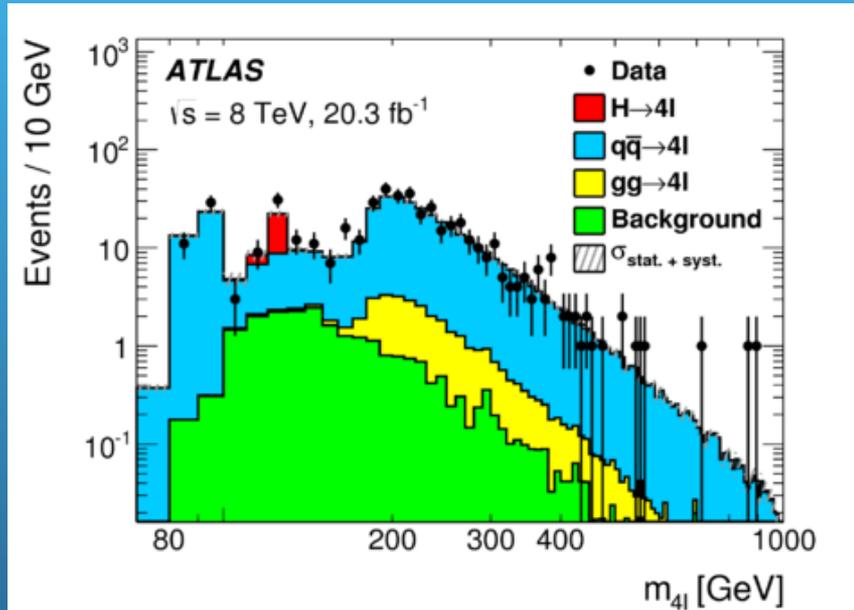
ZZ Production

ATLAS 8 TeV: Phys.Lett. B 753 (2015) 552

ATLAS 13 TeV: Phys.Rev.Lett. 116 (2016) 101801

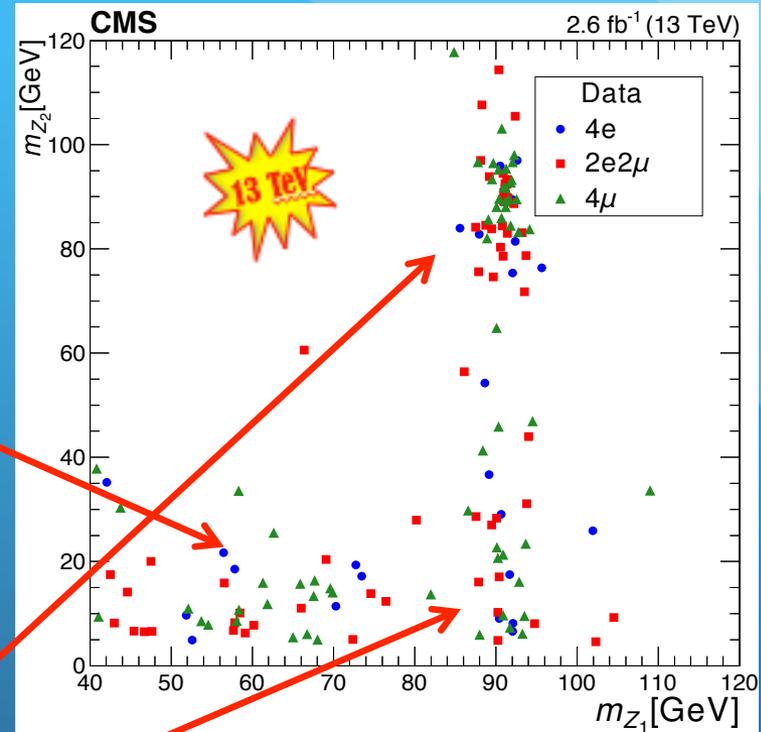
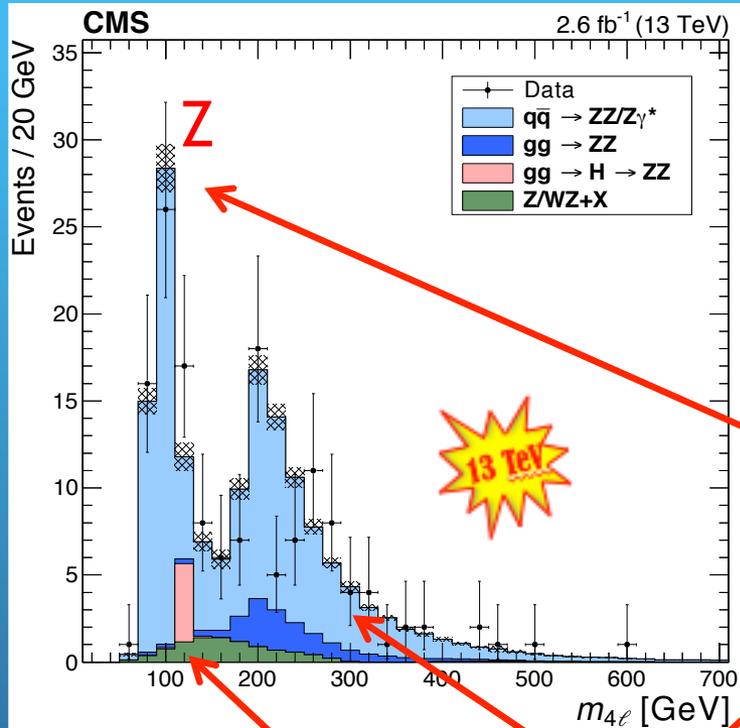
CMS 8 TeV: CMS-PAS-SMP-15-012

CMS 13 TeV: arXiv:1607.08834



- Four leptons, muons or electrons ;
- Almost background free “golden Higgs channel”

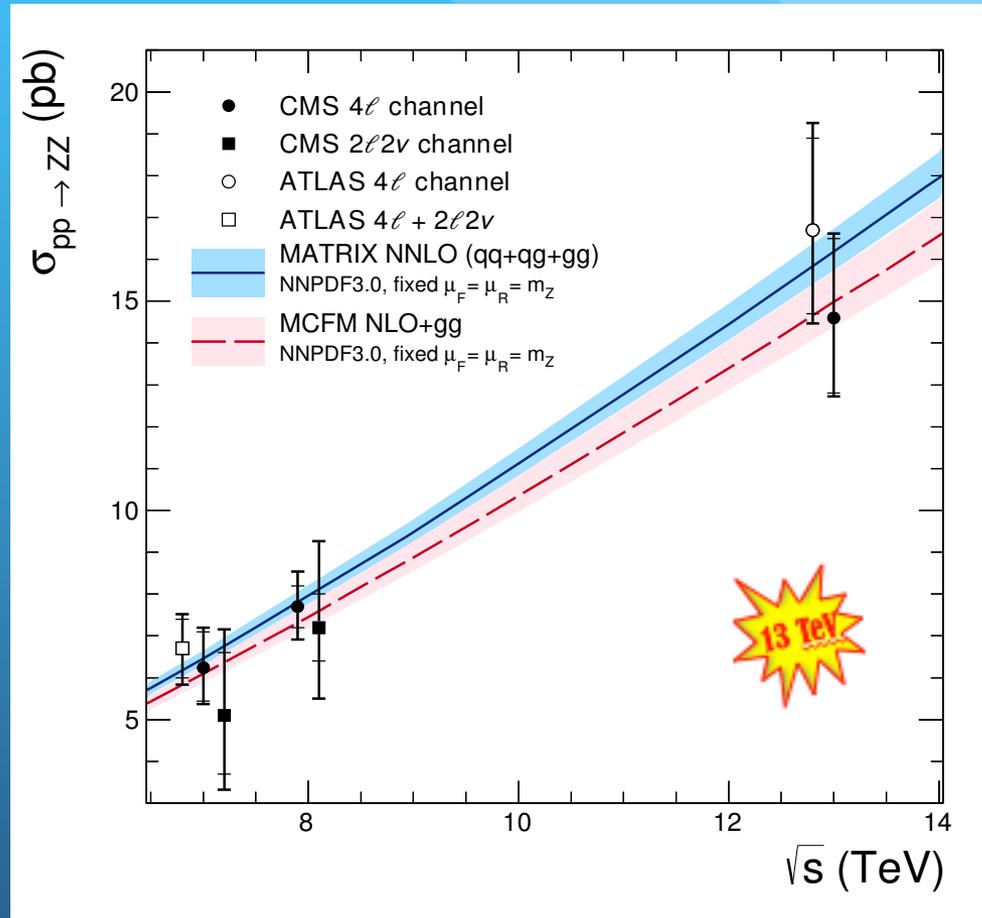
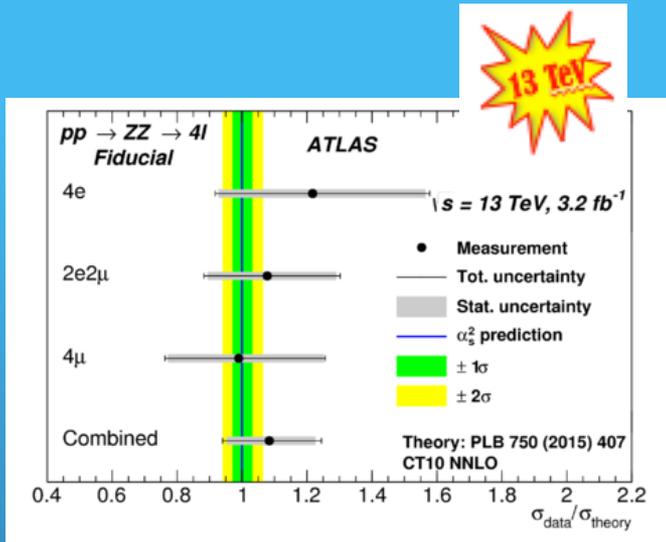
ZZ Production



Higgs 125

Well separated contributions in the mass correlation plot

ZZ Production



Within uncertainties the data are described by both NLO and NNLO predictions.

Should have more precise measurements by Moriond 2017

ATLAS diboson measurements

Diboson Cross Section Measurements

Status: August 2016

$\int \mathcal{L} dt$
[fb⁻¹]

Reference

$\gamma\gamma$

$W\gamma \rightarrow \ell\nu\gamma$

- [$n_{jet} = 0$]

$Z\gamma \rightarrow \ell\ell\gamma$

- [$n_{jet} = 0$]

- $Z\gamma \rightarrow \nu\nu\gamma$

$WV \rightarrow \ell\nu qq$

WW

- $WW \rightarrow e\mu$, [$n_{jet} = 0$]

- $WW \rightarrow e\mu$, [$n_{jet} \geq 0$]

- $WW \rightarrow e\mu$, [$n_{jet} = 1$]

WZ

- $WZ \rightarrow \ell\nu\ell\ell$

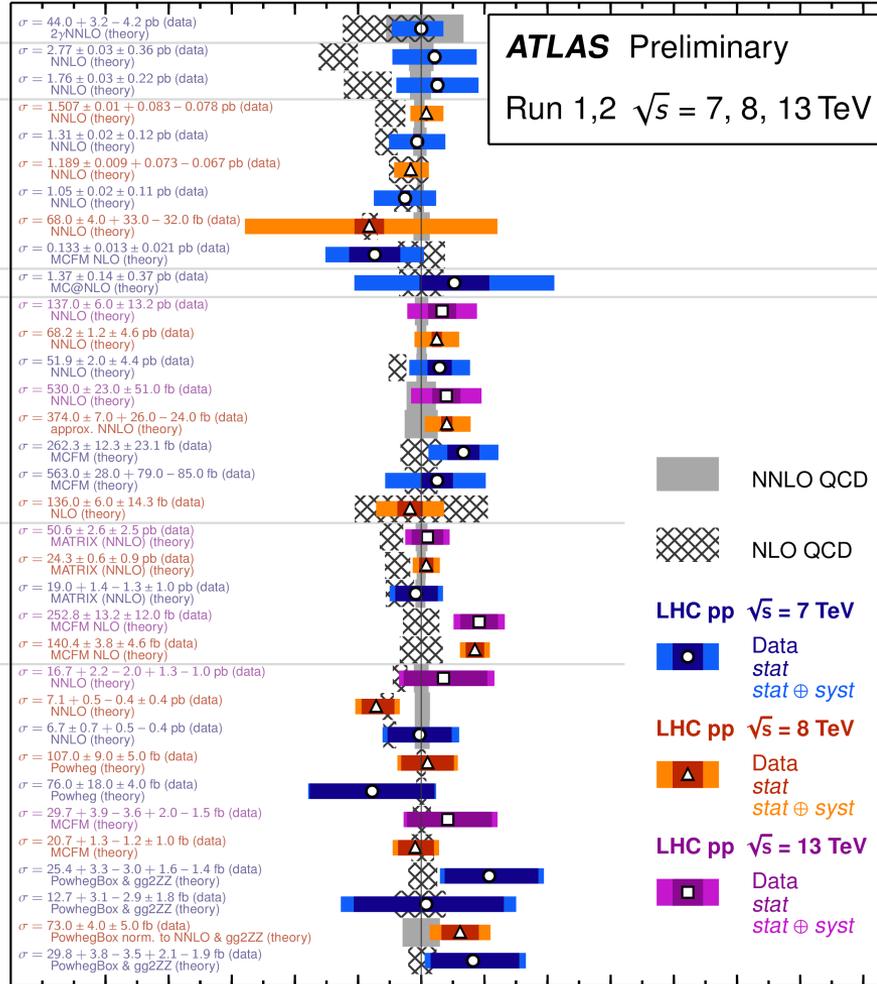
ZZ

- $ZZ \rightarrow 4\ell$, (tot.)

- $ZZ \rightarrow 4\ell$

- $ZZ \rightarrow \ell\ell\nu\nu$

- $ZZ^* \rightarrow 4\ell$



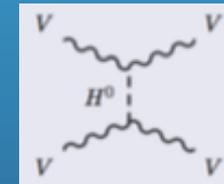
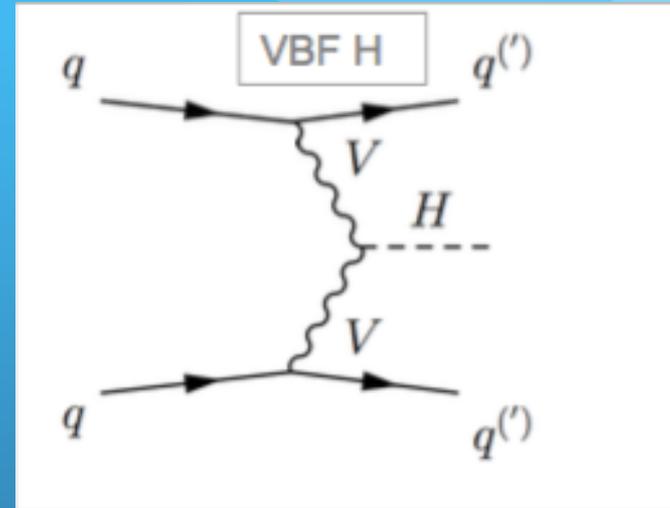
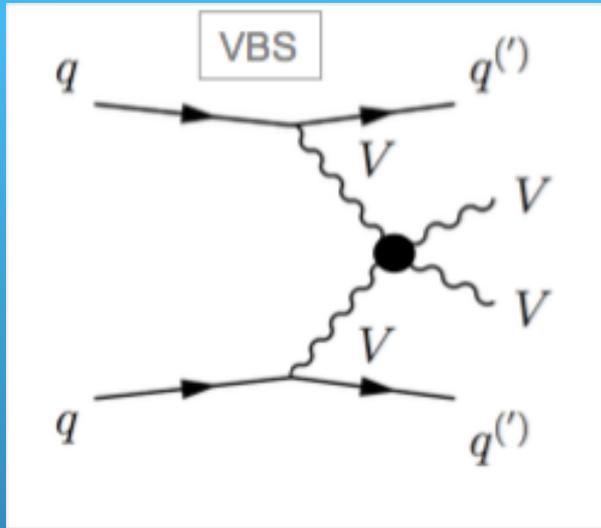
Legend:

- NNLO QCD
- ▨ NLO QCD
- LHC pp $\sqrt{s} = 7$ TeV
- Data stat
- Data stat ⊕ syst
- LHC pp $\sqrt{s} = 8$ TeV
- ▲ Data stat
- △ Data stat ⊕ syst
- LHC pp $\sqrt{s} = 13$ TeV
- Data stat
- Data stat ⊕ syst

0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4
ratio to best theory

Diboson EWK production

- Vector Boson Scattering

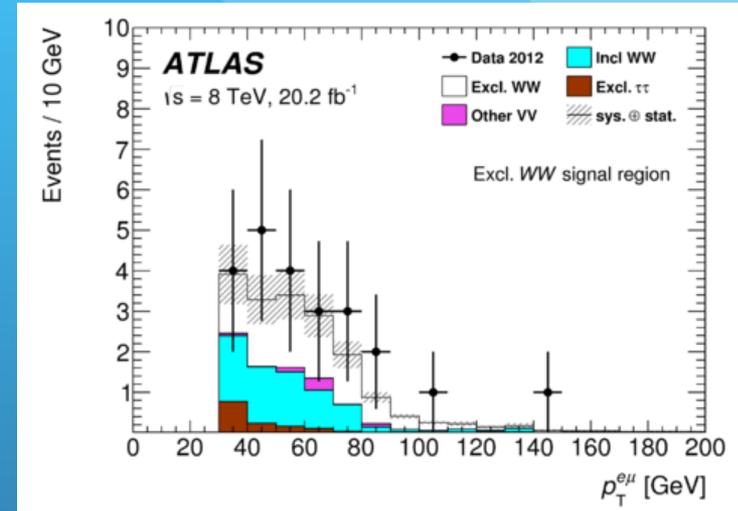
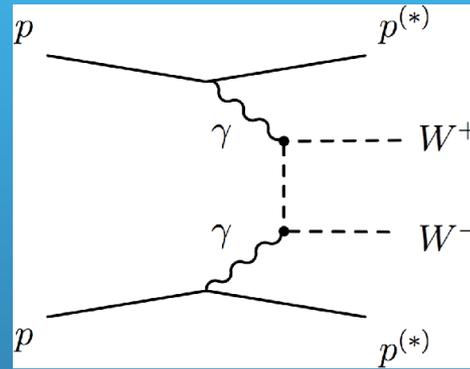
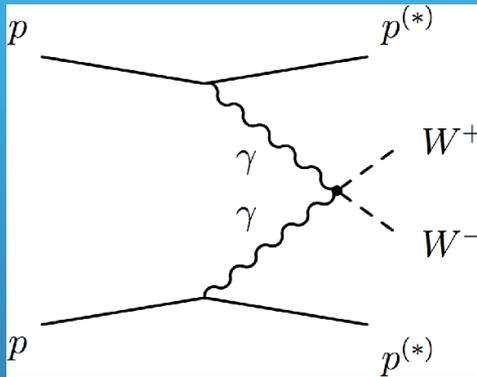


- In absence of H , $V_L V_L$ violates unitarity
- Experimentally - two forward, high p_T -jets, high-mass dijet system, jets separated in rapidity
- Some evidence of EWK $W^\pm W^\pm jj$: PRL 113 (2014) 141803, PRL 114 (2015) 051801

Exclusive WW production

ATLAS 8 TeV: arXiv:1607.03745

CMS 8 TeV: arXiv:1604.04464



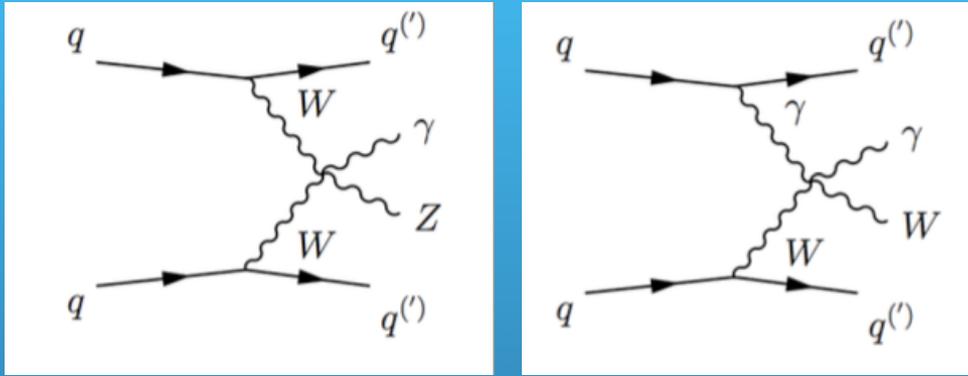
- electron-muon pairs with opposite charge, no other tracks in the detector, dilepton mass > 20 GeV

$$\sigma_{\gamma\gamma \rightarrow W^+W^- \rightarrow e^\pm\mu^\mp X}^{\text{Measured}} = (N_{\text{data}} - N_{\text{background}}) / (\mathcal{L} \epsilon A) = 6.9 \pm 2.2 \text{ (stat.)} \pm 1.4 \text{ (sys.) fb}$$

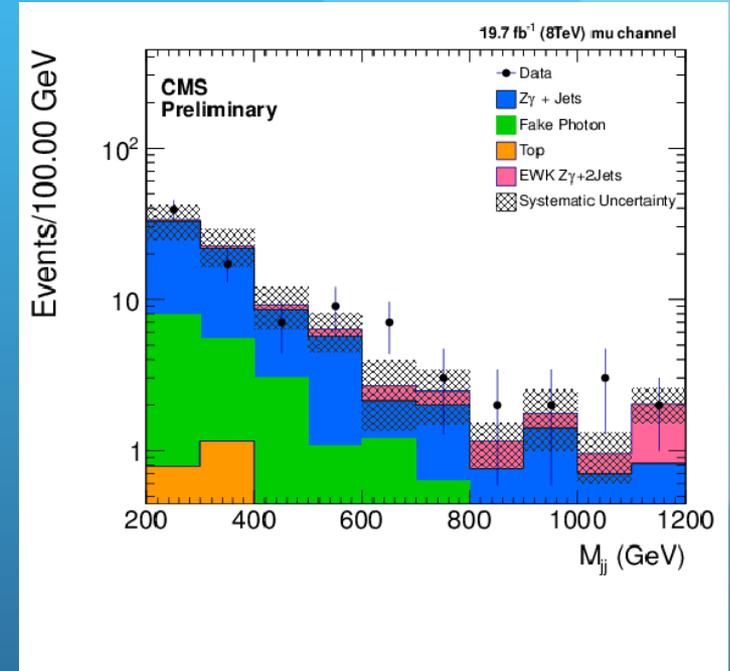
- CMS observed 13(2) events for expected 3.9 ± 0.6 events for 8(7) TeV - 3.6σ excess

EWK $W\gamma jj$ and $Z\gamma jj$ production

CMS 8 TeV: CMS-SMP-14-011, CMS-SMP-14-018



- Electrons and muons, jets $p_T > 30$ GeV, central photon, $m_{jj} > 700$ (400) GeV and $|\Delta\eta_{jj}| > 2.4$ (2.5) for $W(Z)\gamma jj$



EWK $W\gamma jj$: 10.8 ± 4.1 (stat.) ± 3.4 (syst.) ± 0.3 (lumi.) fb

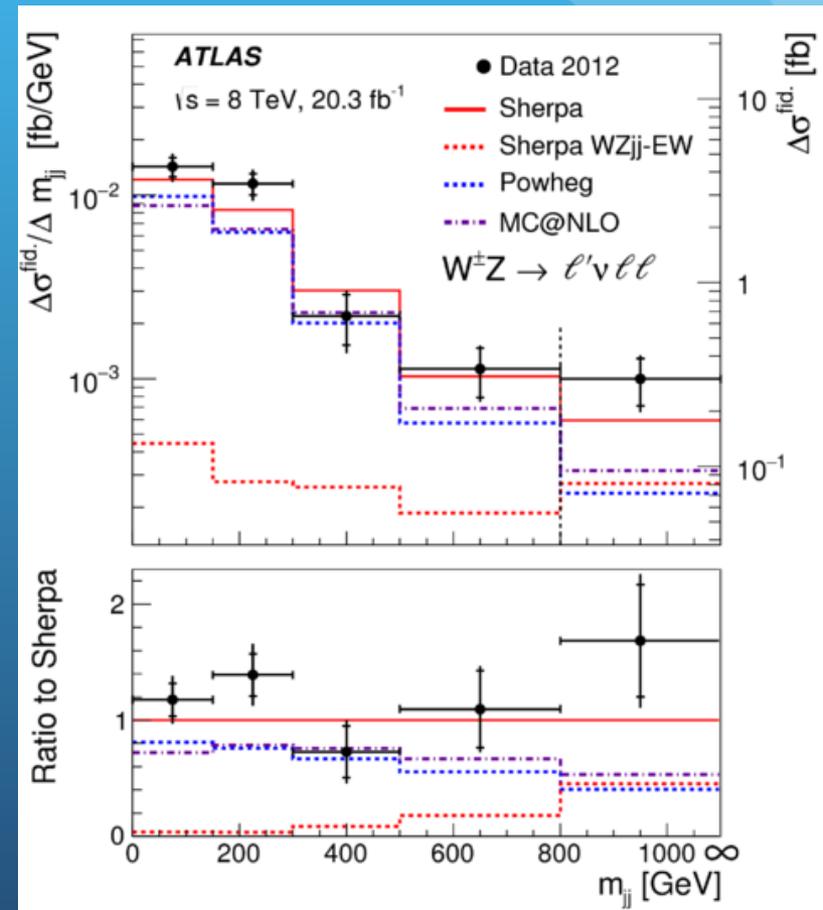
EWK $Z\gamma jj$: $1.86^{+0.89}_{-0.75}$ (stat.) $^{+0.41}_{-0.27}$ (syst.) ± 0.05 (lumi.) fb

EWK WZjj production

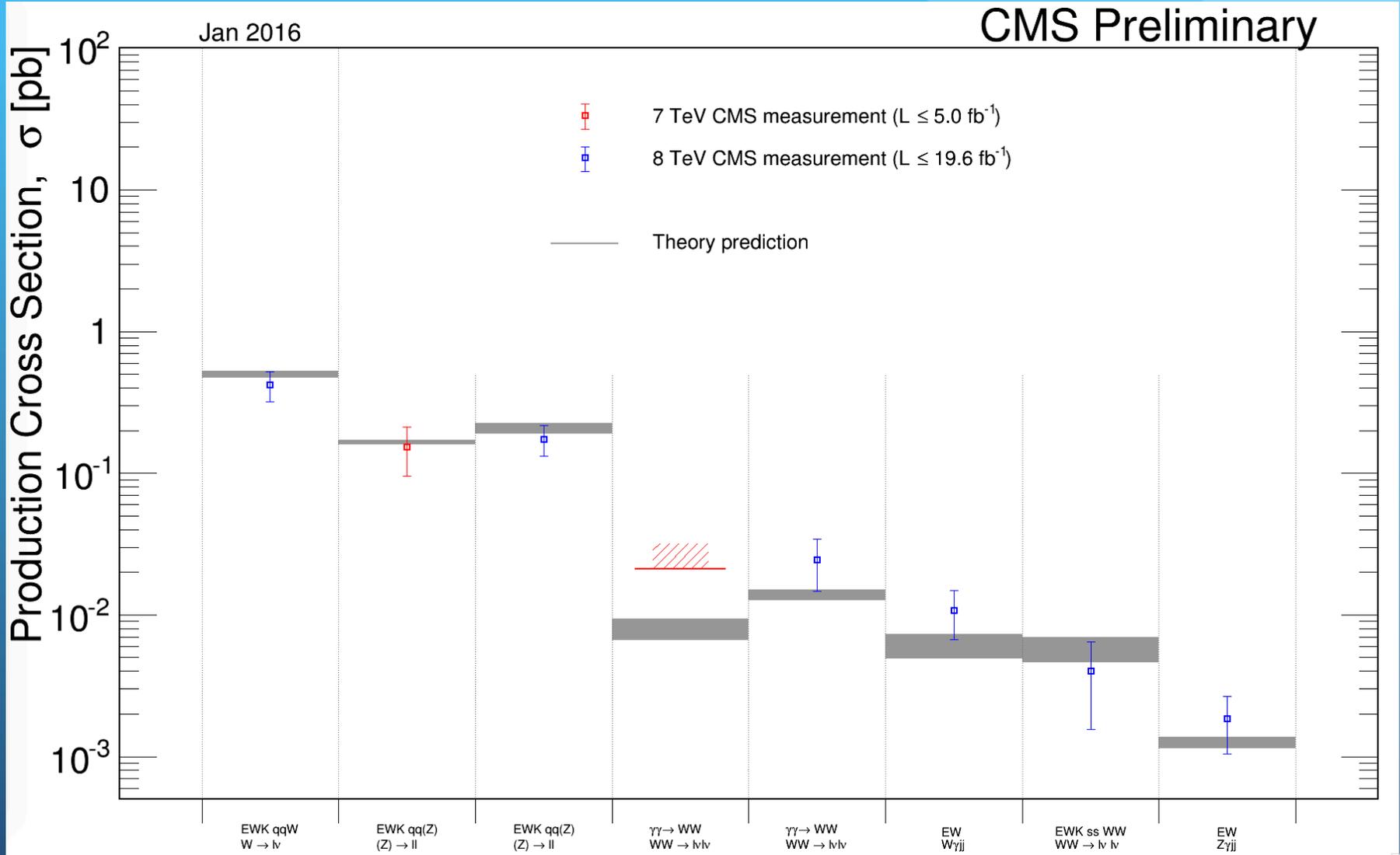
ATLAS 8 TeV: PRD 93 (2016) 092004

CMS 8 TeV: PRL 114 (2015) 051801

- CMS measures inclusive WZjj at dijet masses above 300 GeV in WW EWK analysis
- ATLAS at masses above 500 GeV set 95% upper limit on fiducial VBS cross sections at 0.63 fb



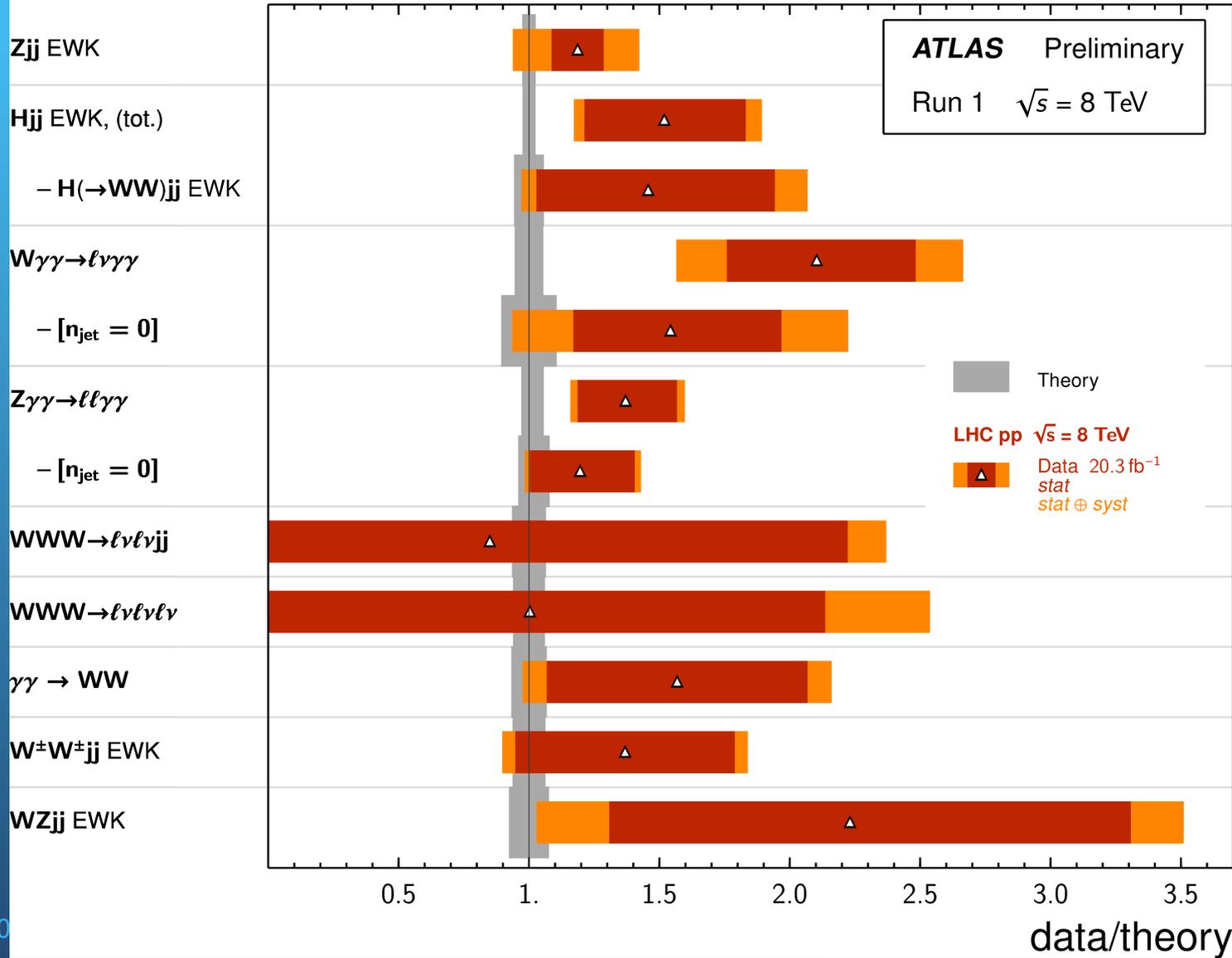
CMS EWK summary



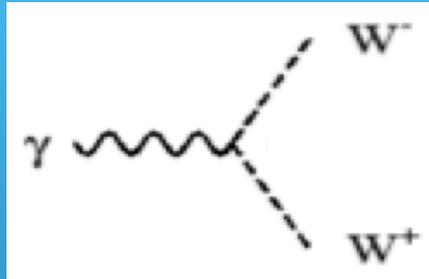
ATLAS EWK summary

VBF, VBS, and Triboson Cross Section Measurements

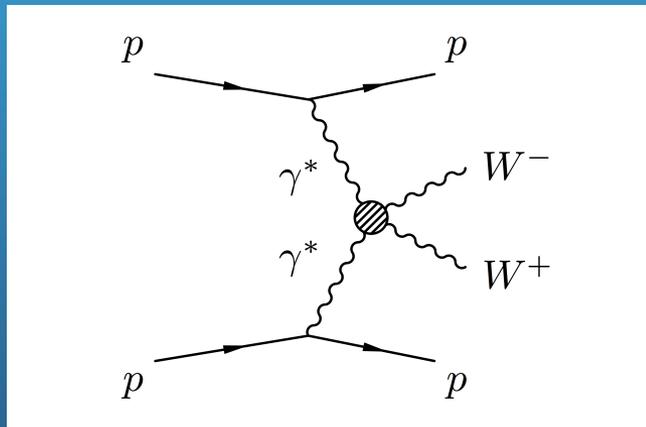
Status: August 2016



Triple and Quartic Gauge Couplings



Allowed in SM: $WW\gamma$, WWZ
 Not allowed: $Z\gamma\gamma$, $ZZ\gamma$, ZZZ



Allowed in SM: $WW\gamma\gamma$, ... , $WWWW$
 Not allowed: $ZZ\gamma\gamma$, $ZZZZ$

Are there variations from SM couplings at high energy scales?

Anomalous couplings - extending the SM

* Effective vertex approach

Nucl. Phys. B282 (1987) 253

$$\Gamma_{Z_1 Z_2 V}^{\alpha\beta\mu} = i e \frac{q_V^2 - m_V^2}{m_Z^2} \left\{ f_4^V (q_V^\alpha g^{\beta\mu} + q_V^\beta g^{\mu\alpha}) + f_5^V \epsilon^{\alpha\beta\mu\rho} (q_{Z_1\rho} - q_{Z_2\rho}) \right\}$$

$$\Gamma_{Z\gamma V}^{\alpha\beta\mu} = i e \frac{q_V^2 - m_V^2}{m_Z^2} \left\{ h_1^V (q_\gamma^\mu g^{\alpha\beta} - q_\gamma^\alpha g^{\beta\mu}) + h_2^V \frac{q_V^\alpha}{m_Z^2} (q_\gamma q_V g^{\beta\mu} - q_\gamma^\mu q_V^\beta) + h_3^V \epsilon^{\alpha\beta\mu\rho} q_{\gamma\rho} + h_4^V \frac{q_V^\alpha}{m_Z^2} \epsilon^{\mu\beta\rho\sigma} q_{V\rho} q_{\gamma\sigma} \right\}$$

* Effective Lagrangian approach

$$\mathcal{L}_{WWV} = -ig_{WWV} \left\{ g_1^V (W_{\mu\nu}^+ W^{-\mu} V^\nu - W_\mu^+ V_\nu W^{-\mu\nu}) + \kappa_V W_\mu^+ W_\nu^- V^{\mu\nu} + \frac{\lambda_V}{m_W^2} W_{\mu\nu}^+ W^{-\nu\rho} V_\rho^\mu - ig_5^V \epsilon^{\mu\nu\rho\sigma} [W_\mu^+ (\partial_\rho W_\nu^-) - (\partial_\rho W_\mu^+) W_\nu^-] V_\sigma \right\},$$

Phys. Rev. D41 (1990) 2113

* Effective Field Theory approach

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{n=1}^{\infty} \sum_i \frac{c_i^{(n)}}{\Lambda^n} \mathcal{O}_i^{(n+4)}$$

Phys. Rev. D48 (1993) 2182

Form-factor and unitarity violation

- Non-zero anomalous coupling - tree-level unitarity violation at high energy
- Effective Lagrangian and effective vertex - unitarity is preserved by introducing a form-factor

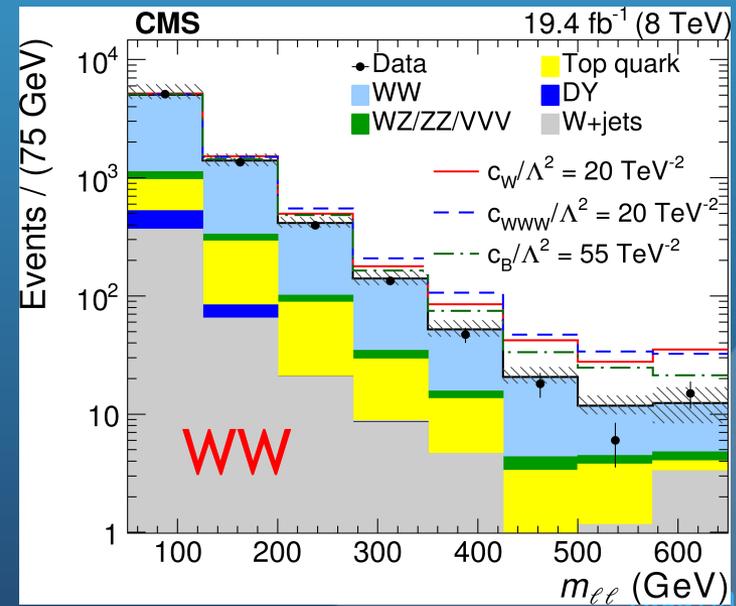
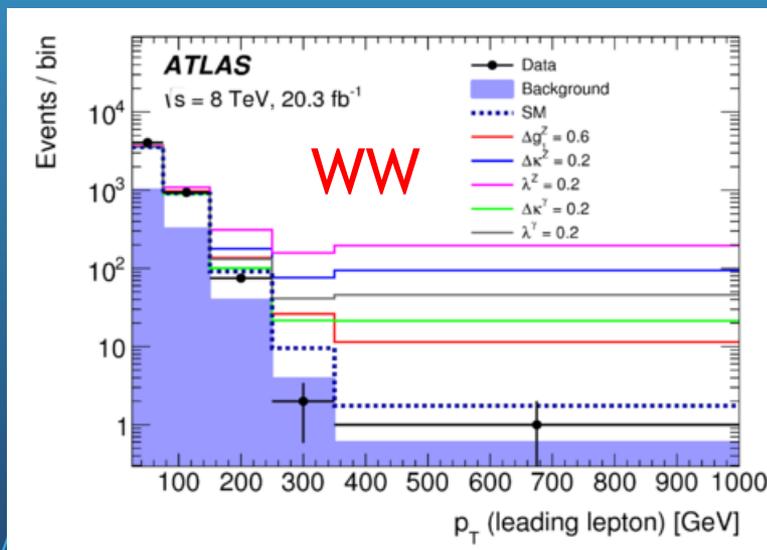
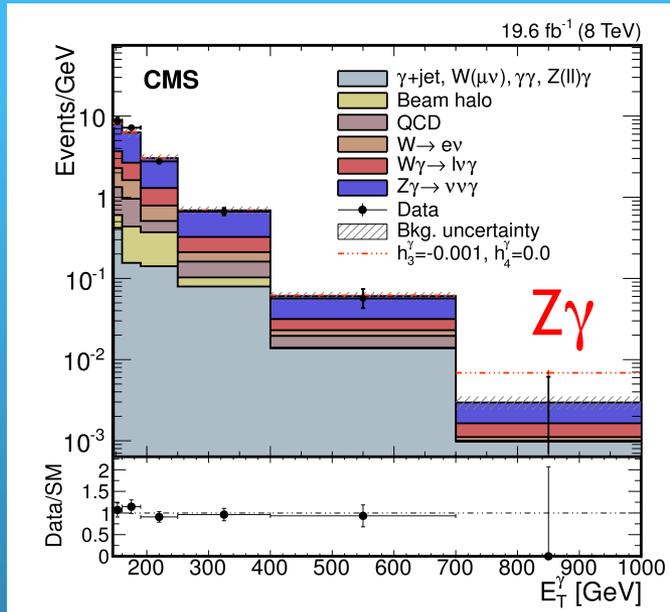
$$\alpha(\hat{s}) = \frac{\alpha_0}{(1 + \hat{s} / \Lambda_{FF})^n}$$

- In CMS we set limits without form-factor/ ATLAS does with and without
- Results with $\Lambda \sim 3-4$ TeV are similar to those without Λ
- Transition between formulation is only possible in no-form-factor approach

How the couplings are measured

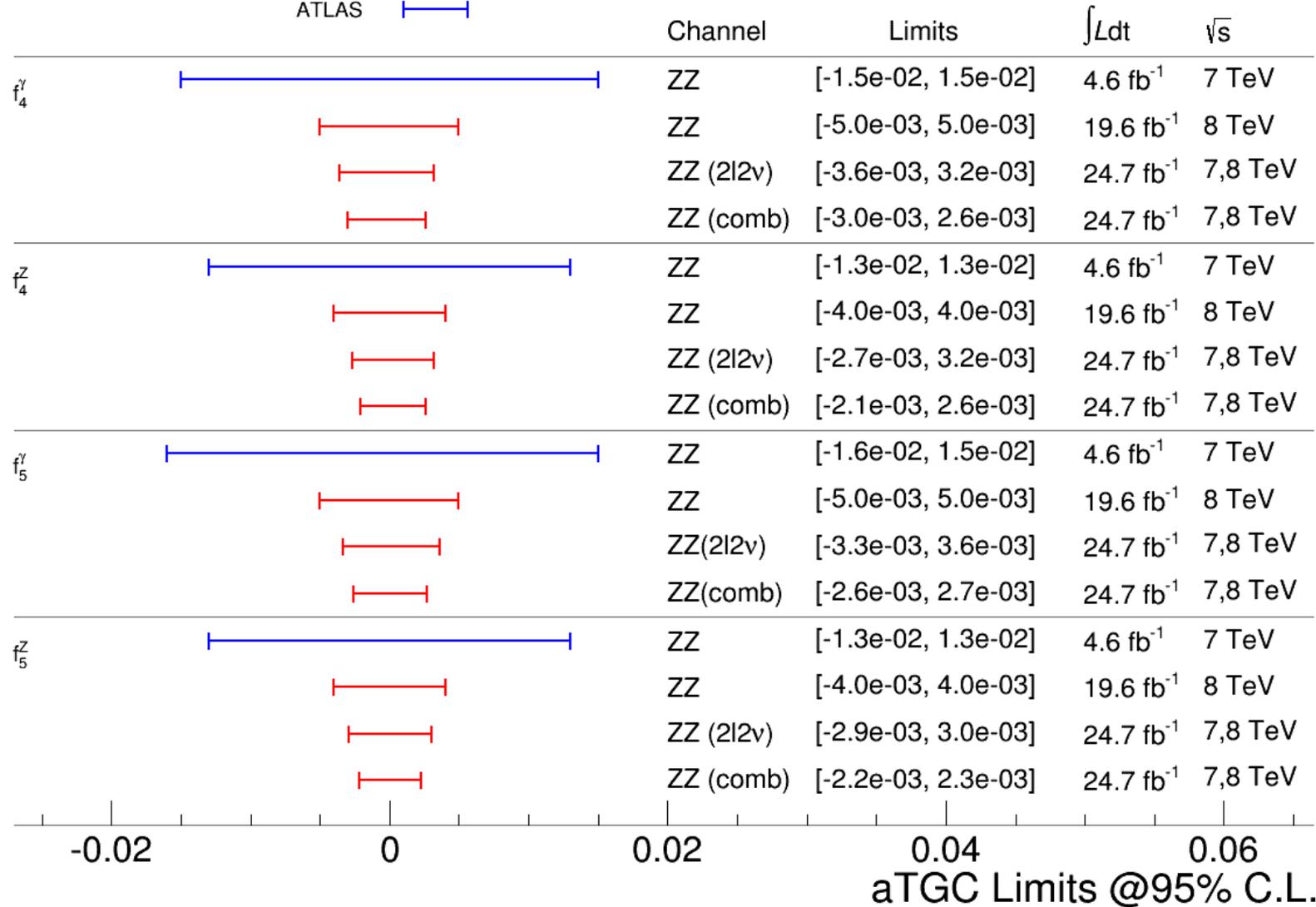
Sensitive distributions:

- p_T of the leading leptons/ photon
- invariant mass of diboson system
- Expecting increased cross section at high energies

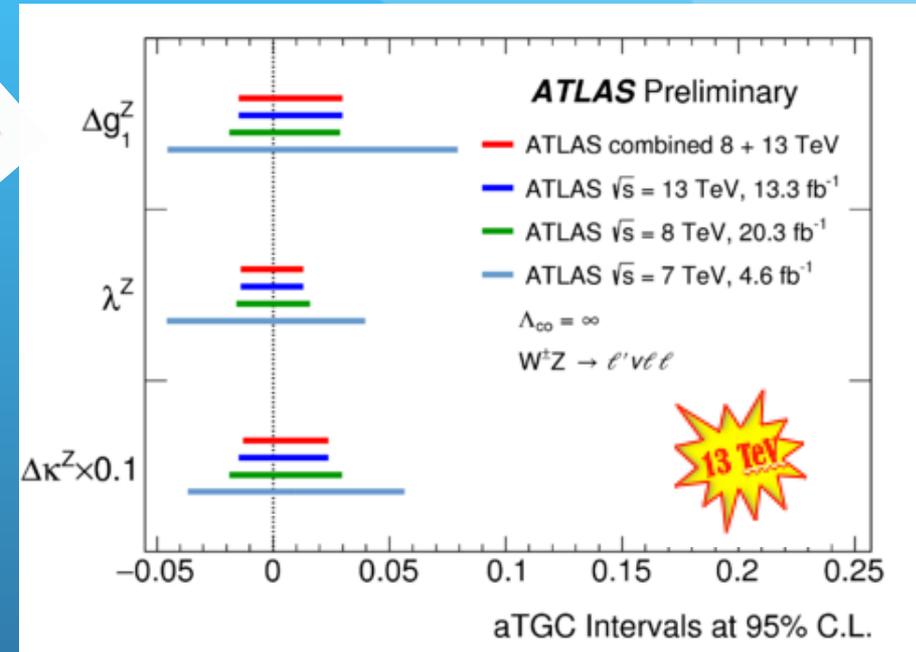
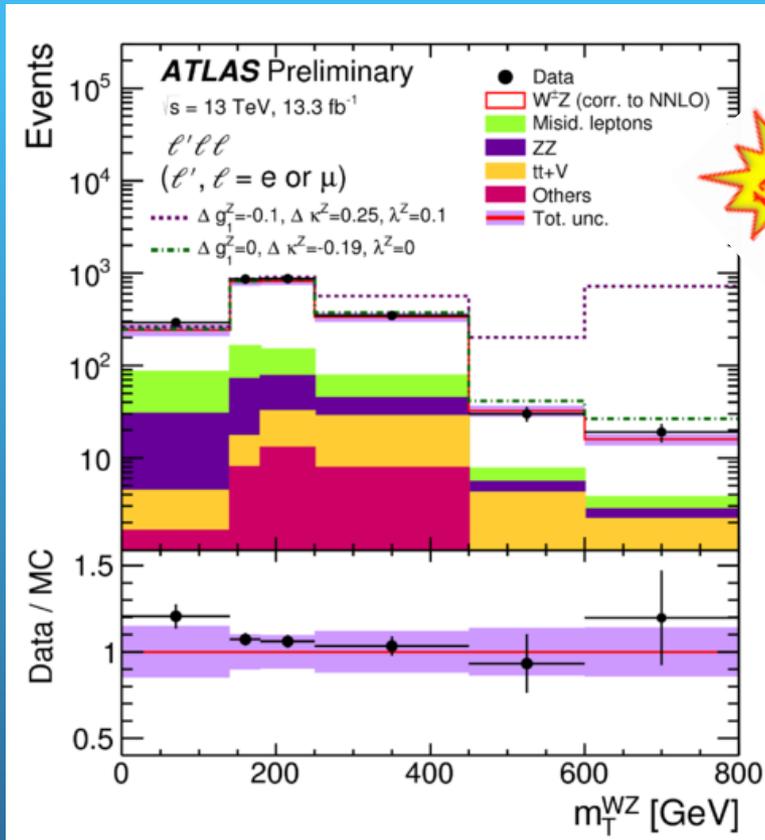


Limits on neutral aTGC

Mar 2016

 CMS
 ATLAS
 


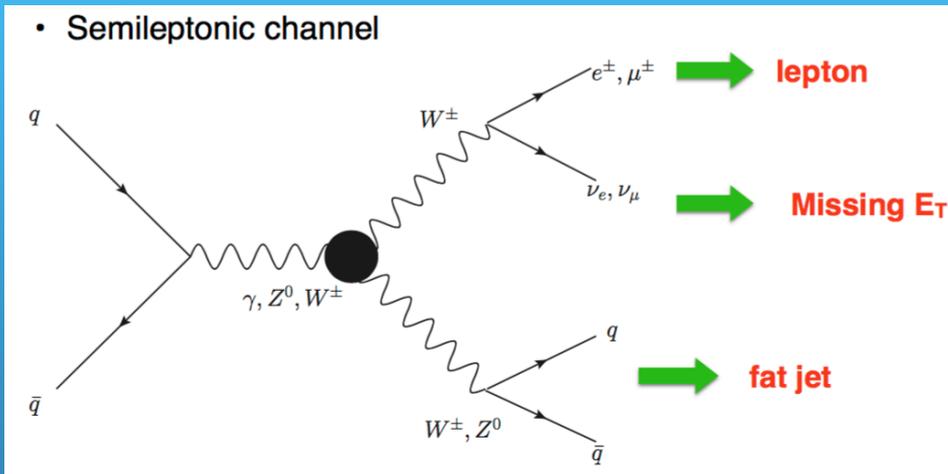
First limits using 13 TeV data !



Looking forward to see results with higher statistics soon !

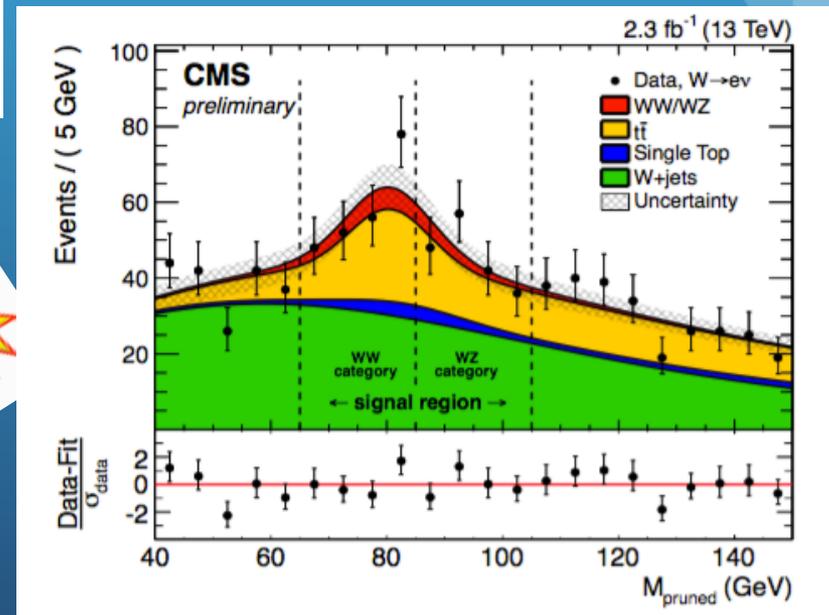
Study of WV production

CMS 13 TeV: CMS-PAS-SMP-16-012



High p_T electron or muon +
Missing E_T +
Jet (AK8) +
veto on additional lepton or b-jet
AK4

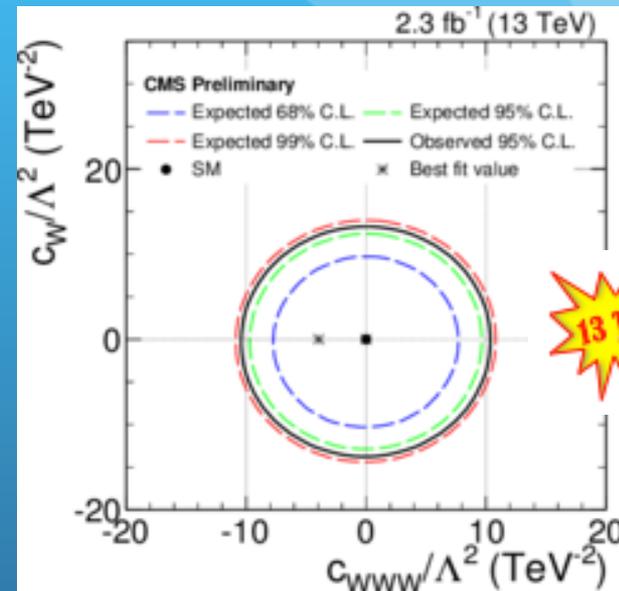
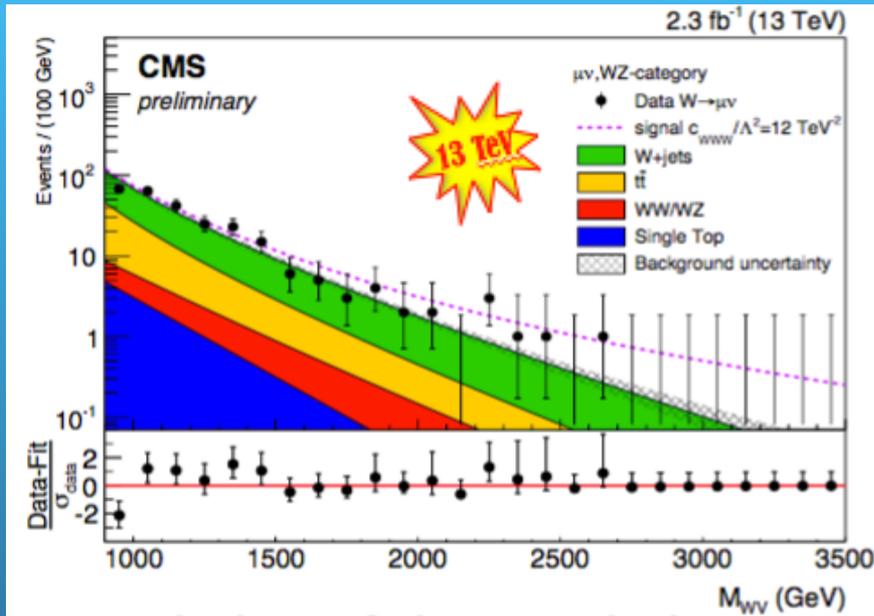
Using pruned mass
(merged jet) for
background evaluation



WW and WZ enhanced regions

Study of WV production

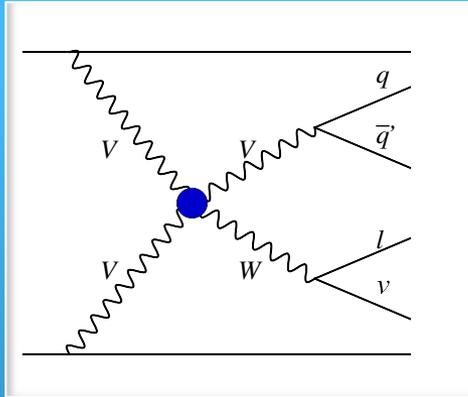
Using mass of WV system for aTGC



	aTGC	expected limit	observed limit
EFT param.	$\frac{c_{WWW}}{\Lambda^2}$ (TeV ⁻²)	[-8.73 , 8.70]	[-9.46 , 9.42]
	$\frac{c_W}{\Lambda^2}$ (TeV ⁻²)	[-11.7 , 11.1]	[-12.6 , 12.0]
	$\frac{c_B}{\Lambda^2}$ (TeV ⁻²)	[-54.9 , 53.3]	[-56.1 , 55.4]
Vertex param.	λ	[-0.036 , 0.036]	[-0.039 , 0.039]
	Δg ₁ ^Z	[-0.066 , 0.064]	[-0.067 , 0.066]
	Δκ _Z	[-0.038 , 0.040]	[-0.040 , 0.041]

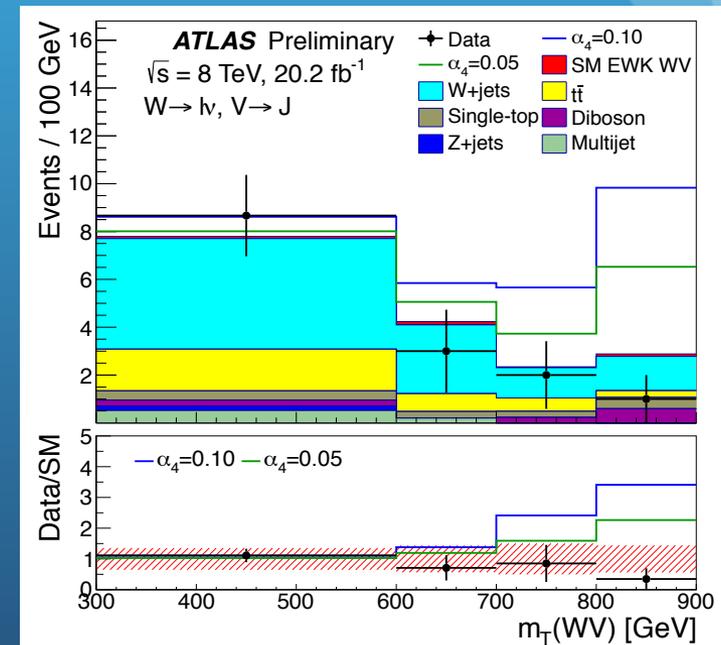
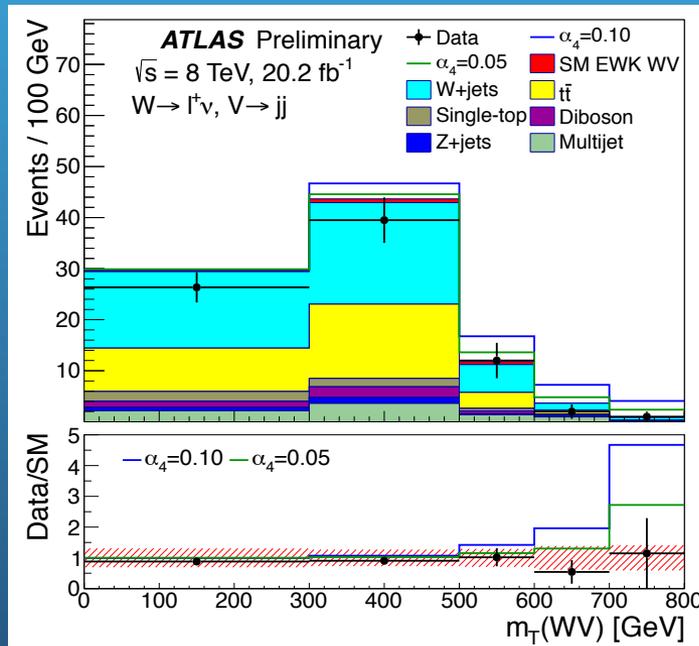
Will be significantly improved with the whole 2015-2016 stats

Study of WV production (VBS)



ATLAS 8 TeV: in preparation

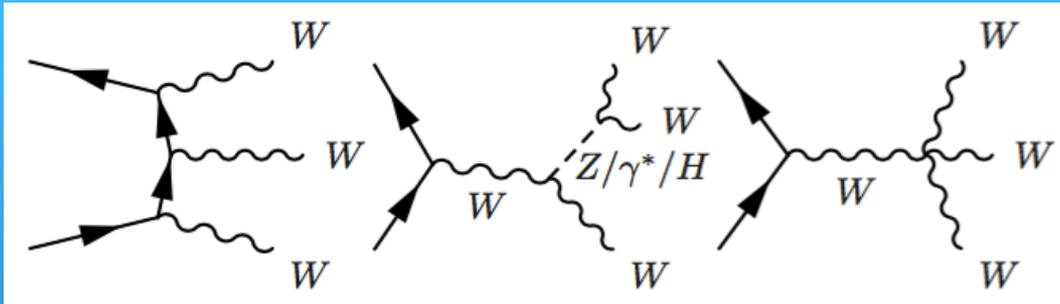
Can be resolved (jj) or merged (J)



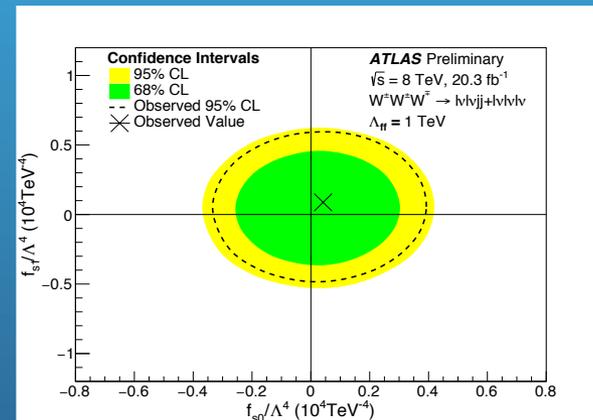
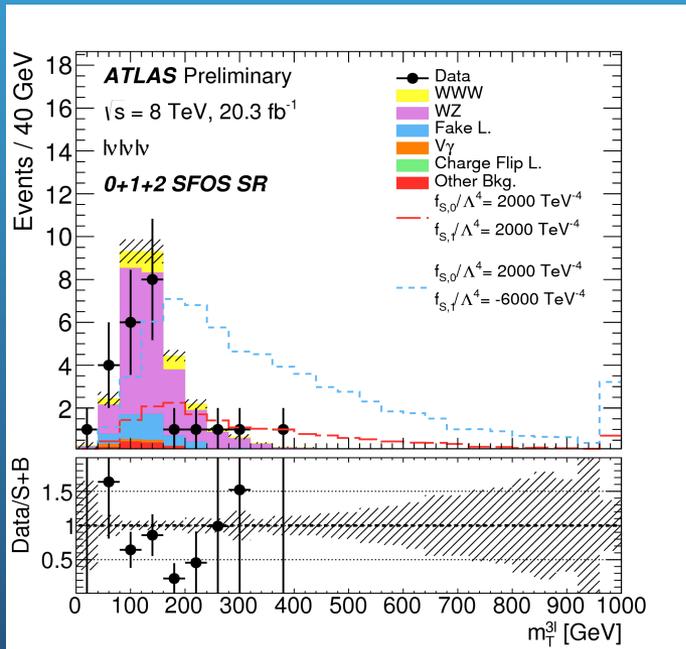
$$-0.024 < \alpha_4 < 0.030 \text{ and } -0.028 < \alpha_5 < 0.033$$

Study of WWW production

ATLAS 8 TeV: in preparation



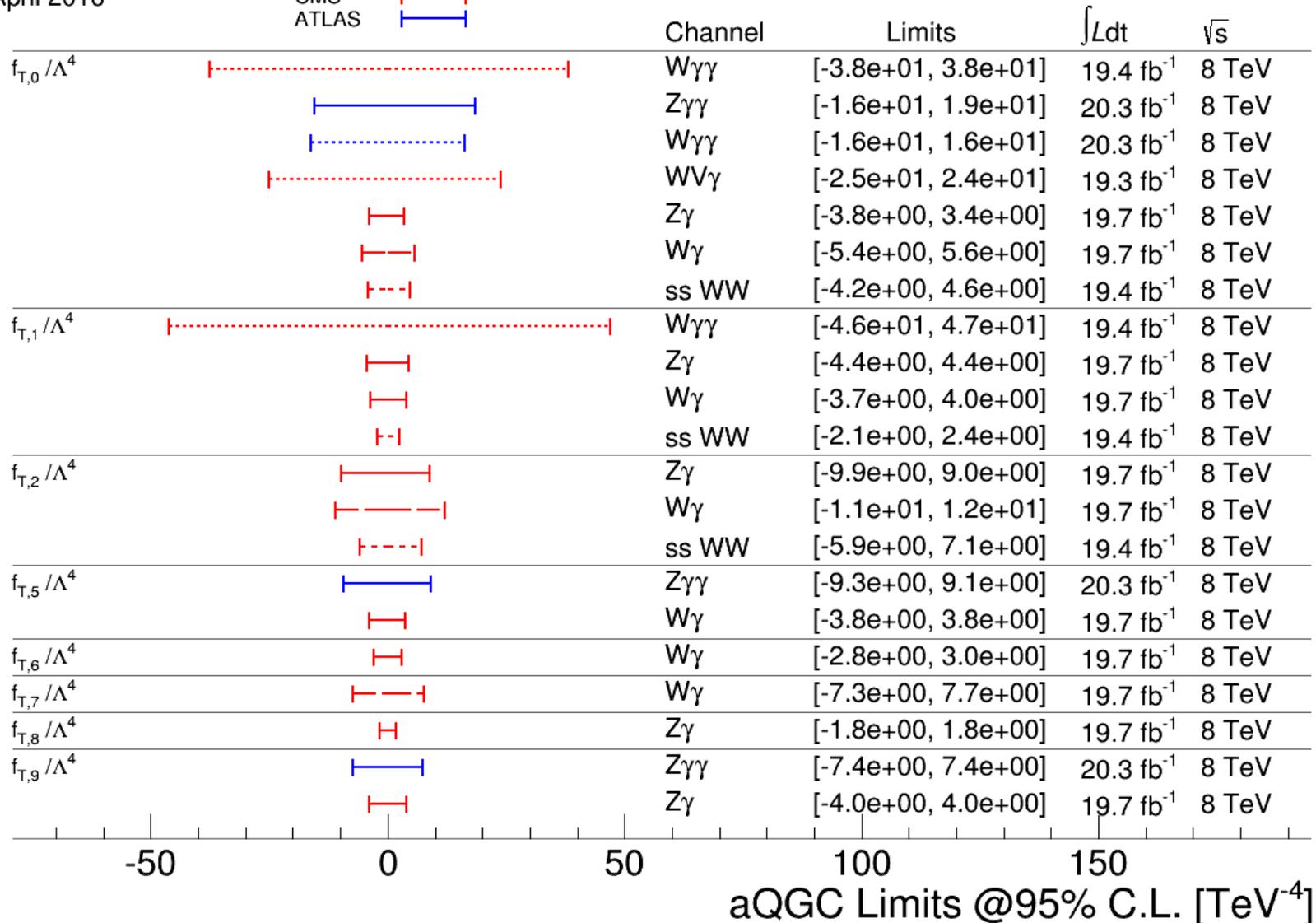
Upper 95% CL observed limit on SM WWW cross section 730 fb with expected 560 fb on the absence of the WWW production



Λ_{FF} [TeV]	Expected CI [$\times 10^4 \text{ TeV}^{-4}$]		Observed CI [$\times 10^4 \text{ TeV}^{-4}$]	
	$f_{S,0}/\Lambda^4$	$f_{S,1}/\Lambda^4$	$f_{S,0}/\Lambda^4$	$f_{S,1}/\Lambda^4$
0.5	[-0.40, 0.42]	[-0.58, 0.65]	[-0.41, 0.44]	[-0.62, 0.70]
1	[-0.39, 0.42]	[-0.56, 0.63]	[-0.37, 0.41]	[-0.56, 0.63]
2	[-0.24, 0.26]	[-0.36, 0.42]	[-0.23, 0.24]	[-0.35, 0.39]
3	[-0.20, 0.22]	[-0.33, 0.36]	[-0.20, 0.21]	[-0.30, 0.34]
∞	[-0.17, 0.17]	[-0.29, 0.32]	[-0.17, 0.17]	[-0.27, 0.30]

Limits on aQGC

April 2016

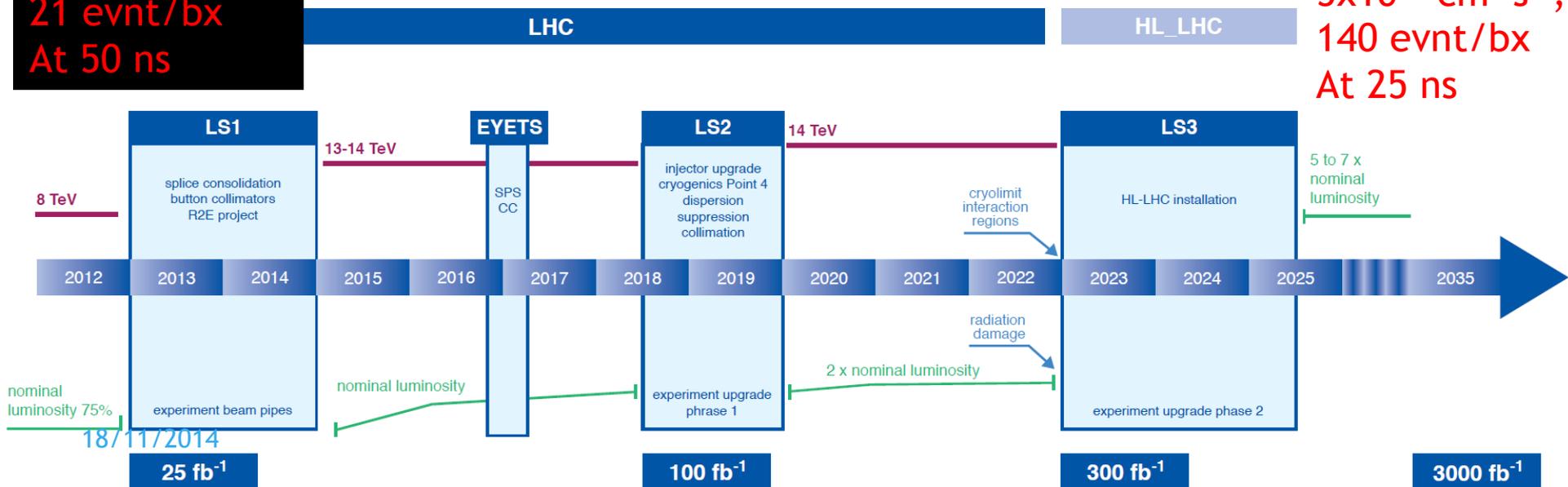
 CMS
 ATLAS
 




New LHC / HL-LHC Plan

$7 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$;
 21 evnt/bx
 At 50 ns

$5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$;
 140 evnt/bx
 At 25 ns



Summary

Expect updates and new results
with full 2015-2016 statistics

30 fb⁻¹

for Moriond 2017 !