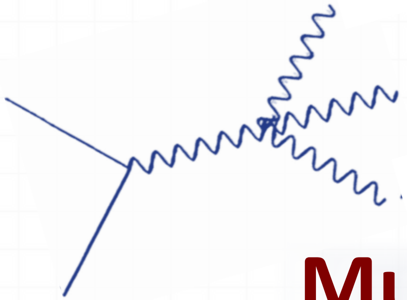
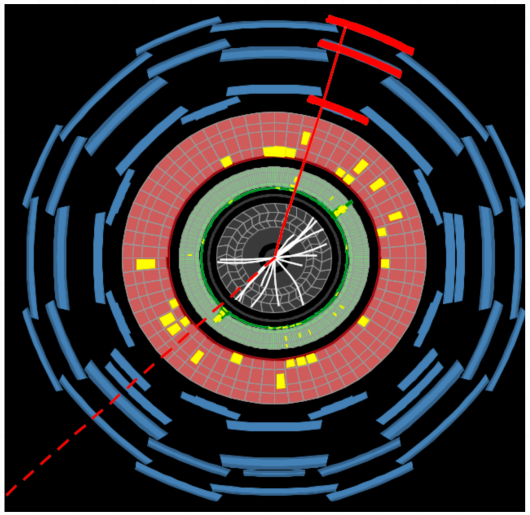
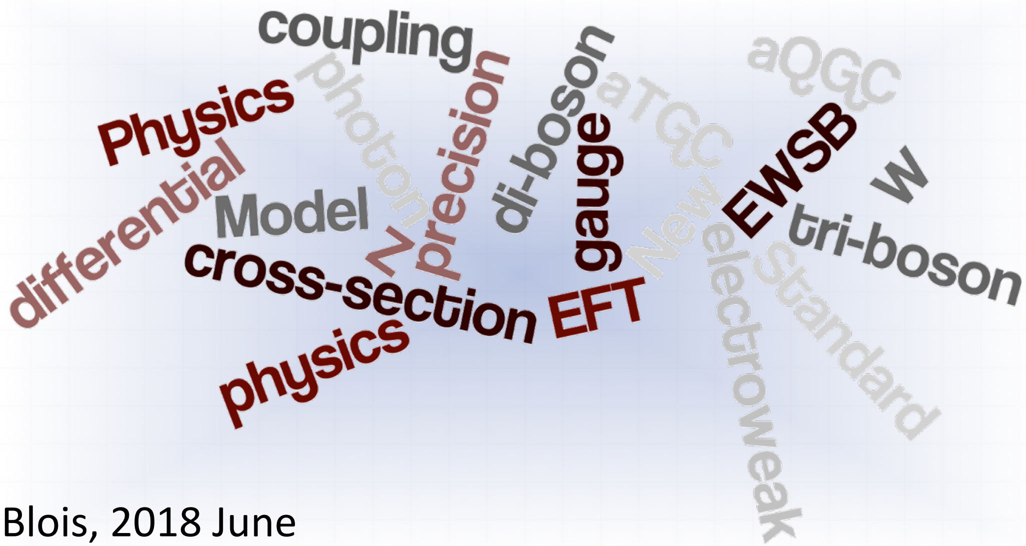


Multi-boson production at LHC

Gabriella Pásztor
(MTA-ELTE, Eötvös University, Budapest)

for the ATLAS and CMS Collaborations



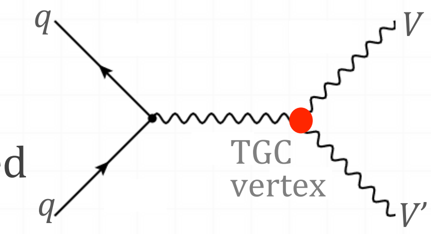


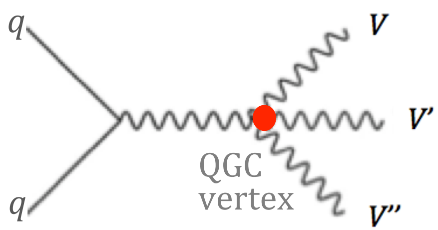
Blois, 2018 June

Multi-boson measurements

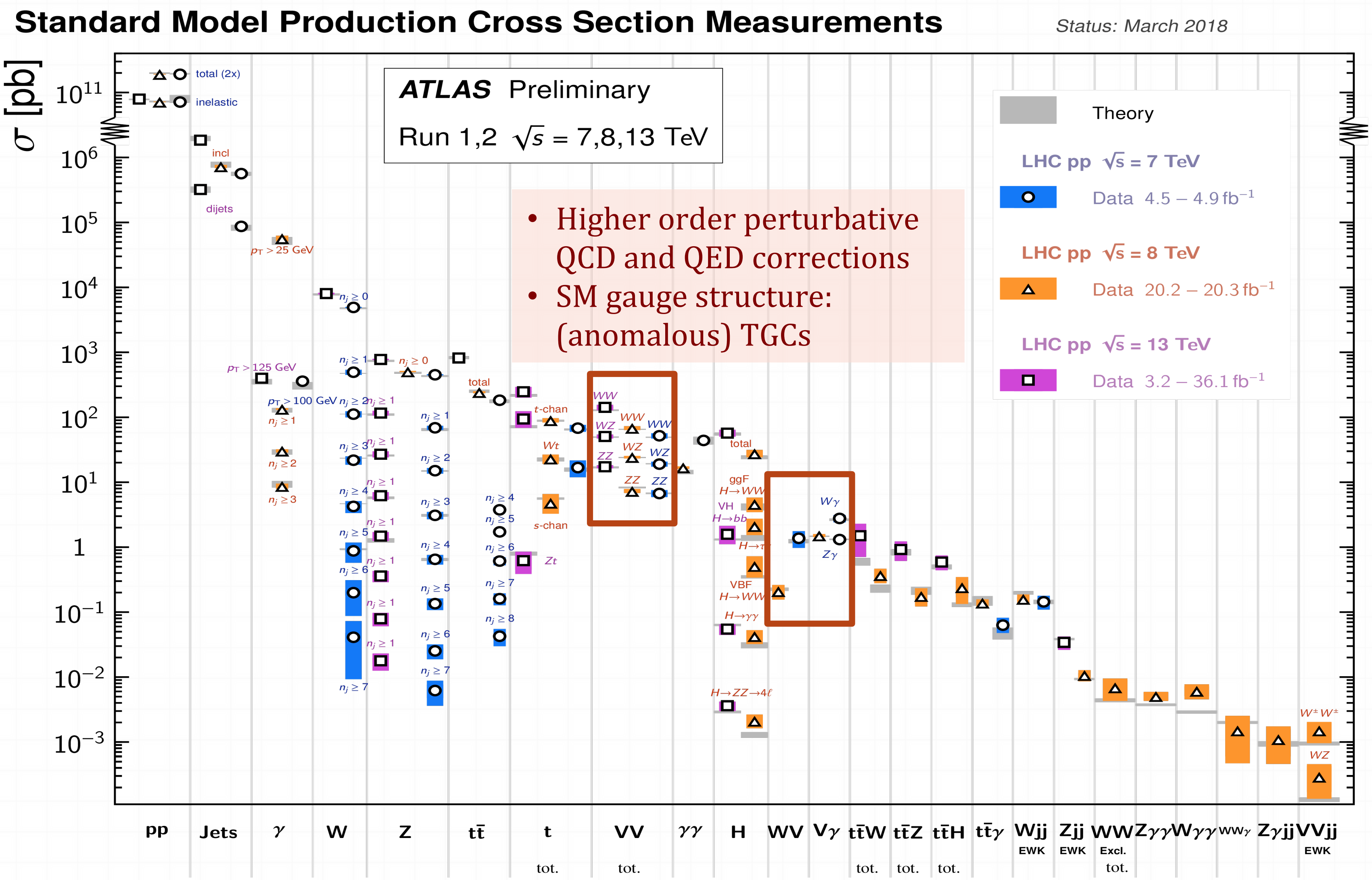
- Test of SM EW theory and perturbative QCD calculations at TeV scale
  - Differential cross-sections can highlight deficiencies in particular phase-space regions
- No direct observation of New Physics yet
  - Look for discrepancies in precision measurements
- Measurement of (anomalous) Triple / Quartic Gauge Couplings
  - Vector boson self-couplings provide fundamental test of EW theory
    - Important to understand the mechanism of EWSB
  - Pure neutral TGCs / QGCs forbidden in SM
    - WWZ, WWγ and WWZZ, WWZγ, WW$\gamma\gamma$, WWWW allowed
- Sensitive to new particles decaying to di-boson final states (SUSY, Technicolor, Little Higgs, extra dimensions…)
- Background to important physics processes (Higgs, tt, …)

- Many results from LHC, concentrate on latest ones



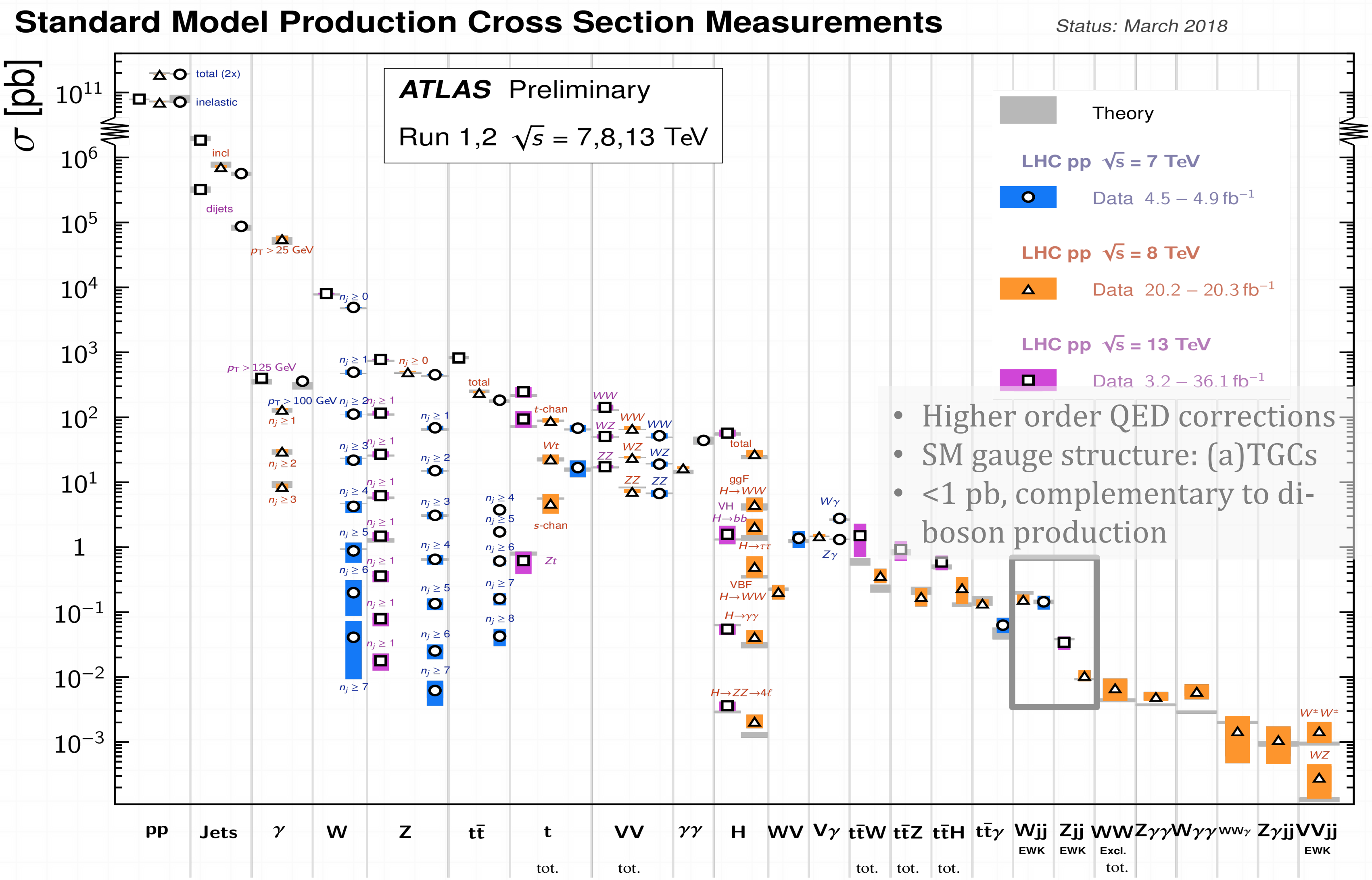


Inclusive di-boson production



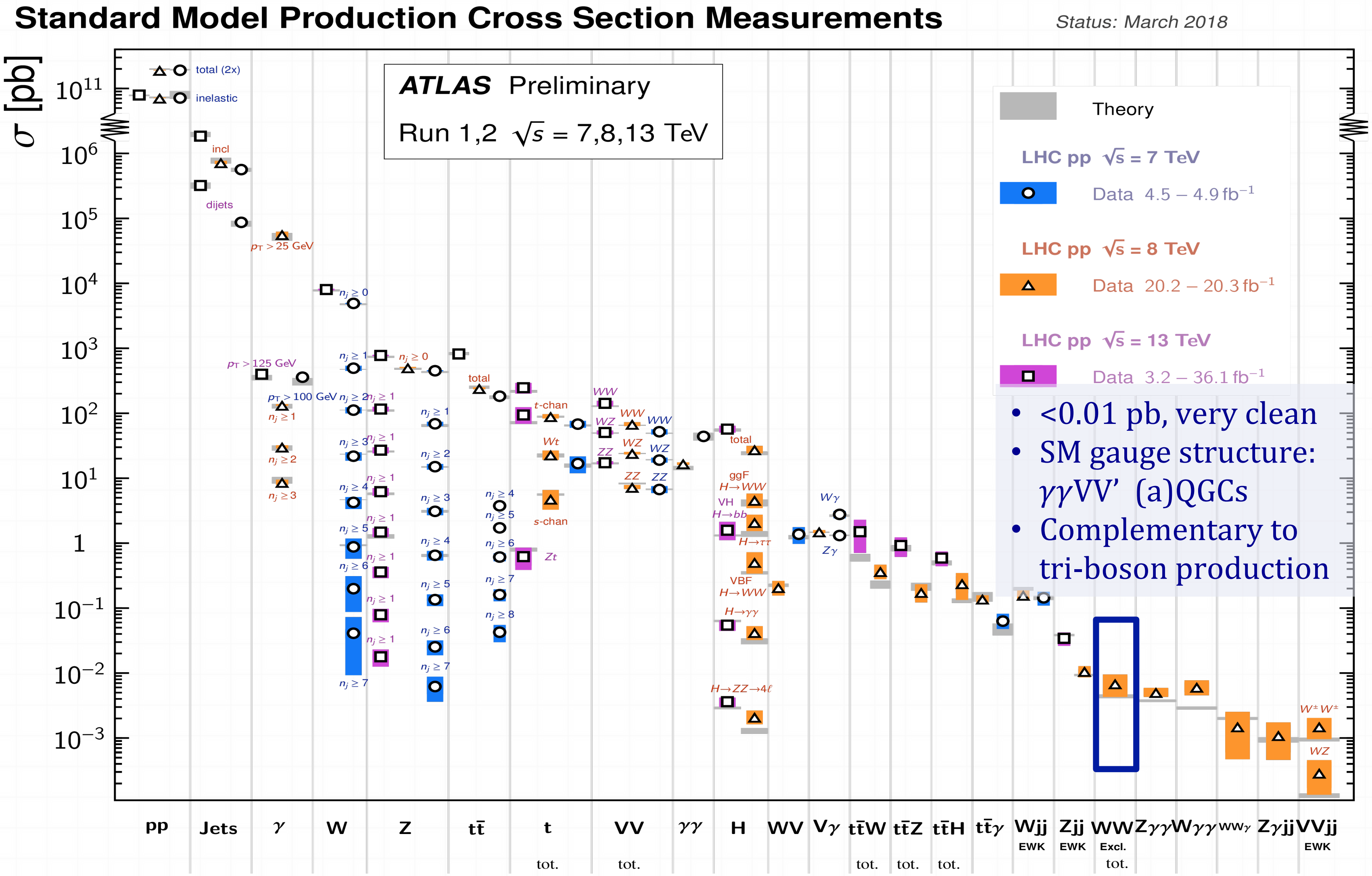
- Higher order perturbative QCD and QED corrections
- SM gauge structure: (anomalous) TGCs

EW Vjj production via Vector Boson Fusion



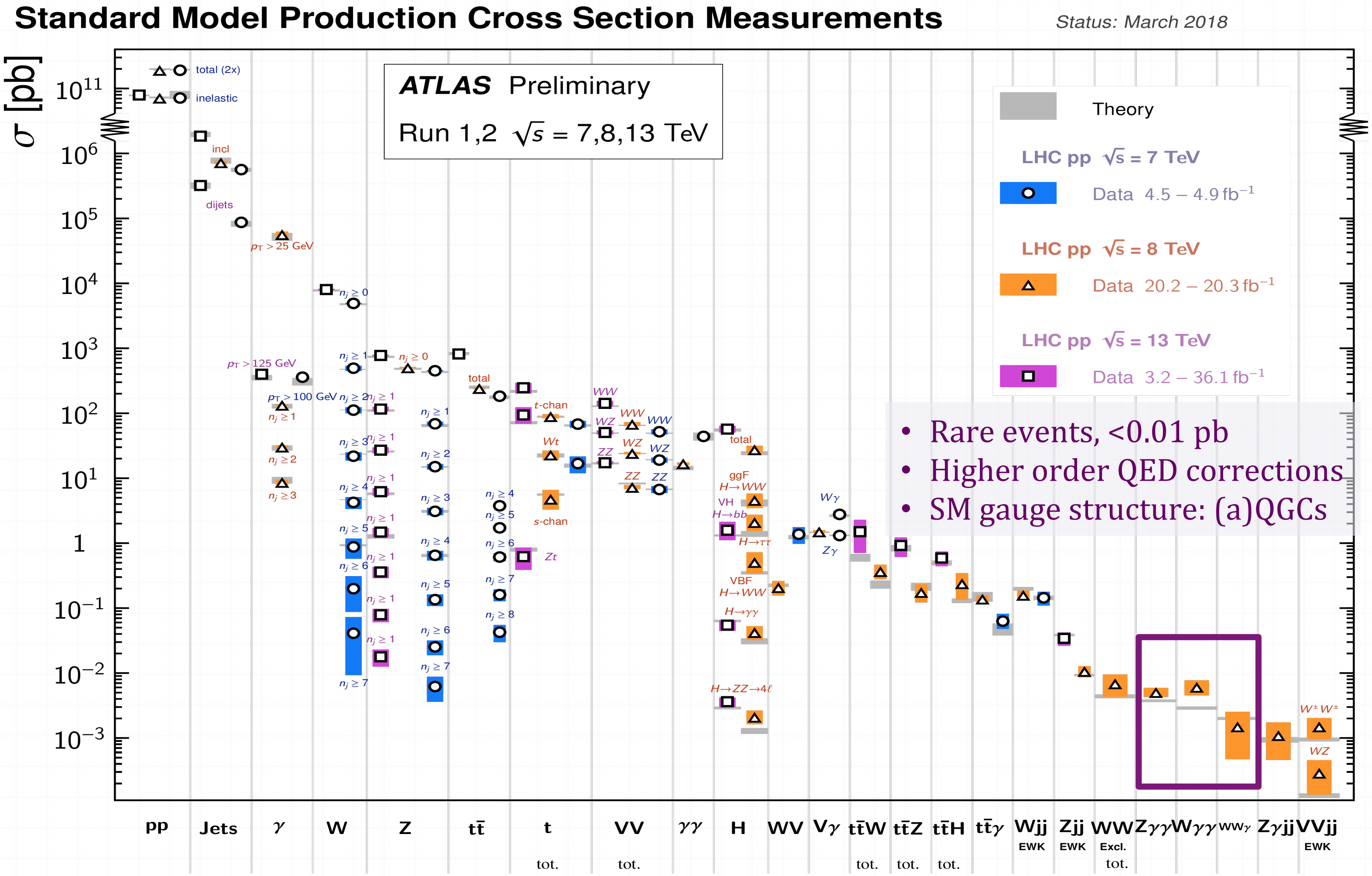
- Higher order QED corrections
- SM gauge structure: (a)TGCs
- <1 pb, complementary to di-boson production

Exclusive di-boson production



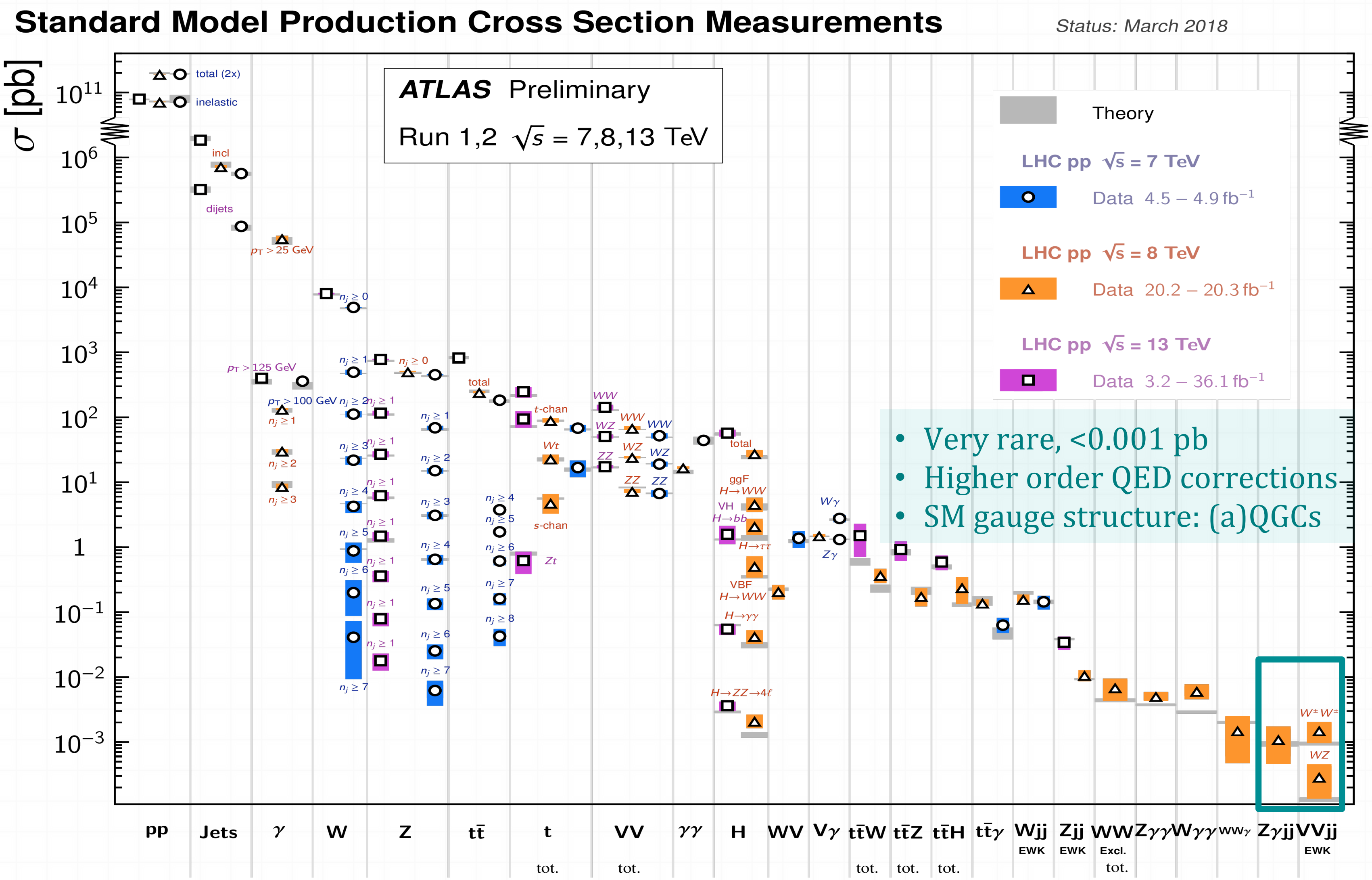
- <0.01 pb, very clean
- SM gauge structure: γγVV' (a)QGCs
- Complementary to tri-boson production

Tri-boson production



- Rare events, <0.01 pb
- Higher order QED corrections
- SM gauge structure: (a)QGCs

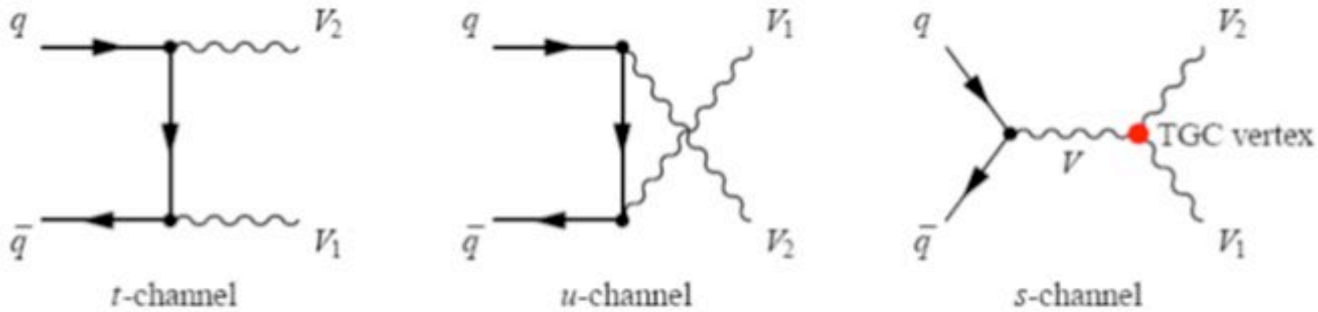
EW VVjj production via Vector Boson Scattering



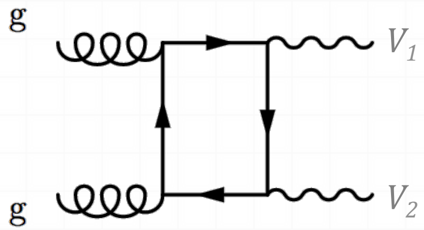
- Very rare, <0.001 pb
- Higher order QED corrections
- SM gauge structure: (a)QGCs

Di-boson measurements

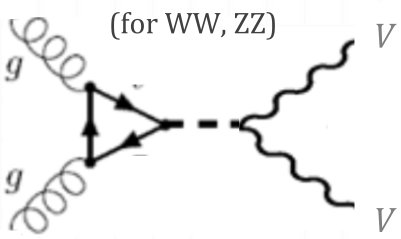
- At LO [$O(\alpha_s^0)$, $O(\alpha^2)$], qq-initiated:



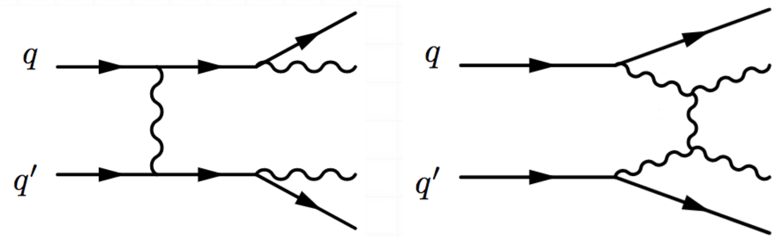
- gg-initiated production via fermion loops enters at NNLO pQCD [$O(\alpha_s^2)$]



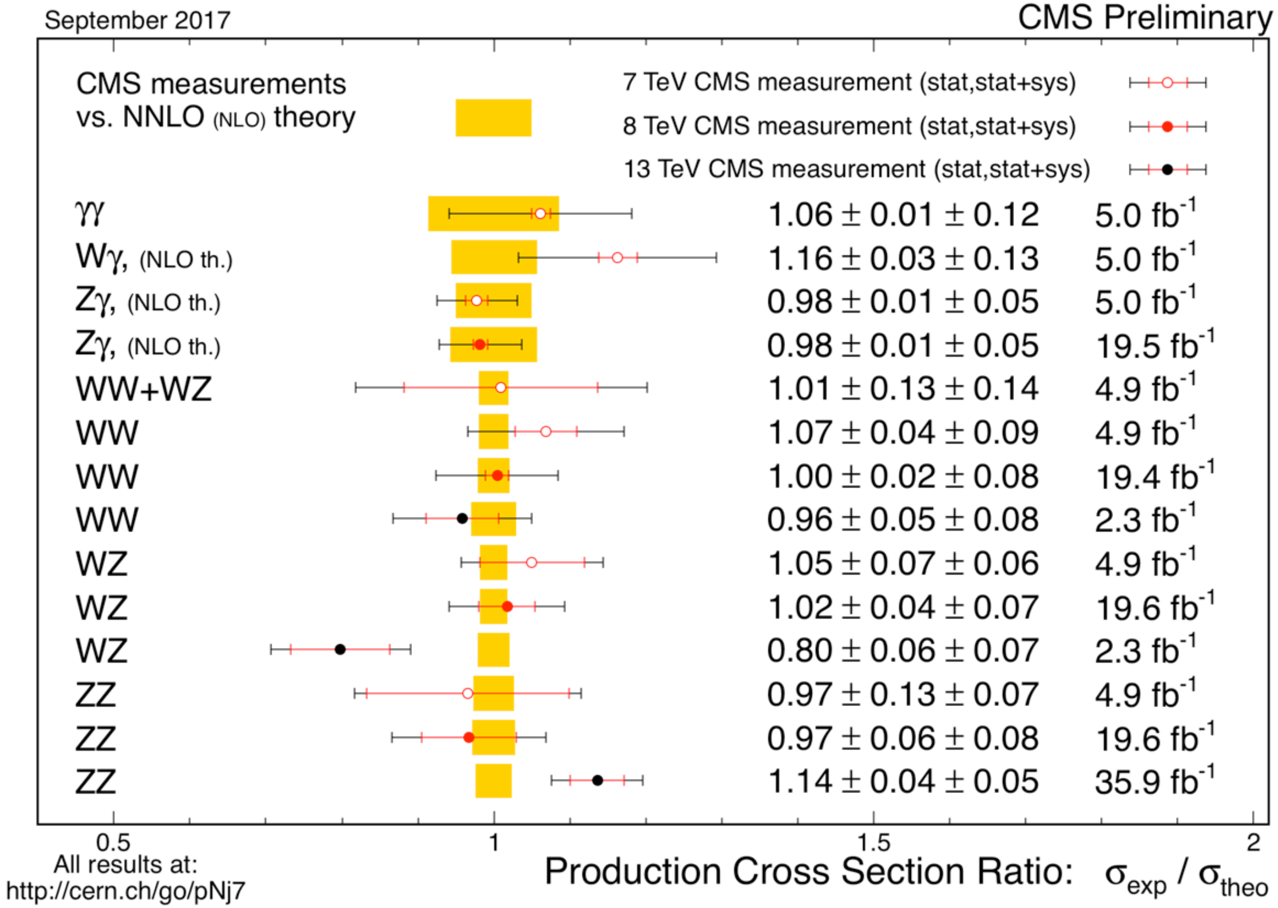
- Resonant production via Higgs boson



- Electroweak VVjj production [$O(\alpha^4)$]



Di-boson measurements

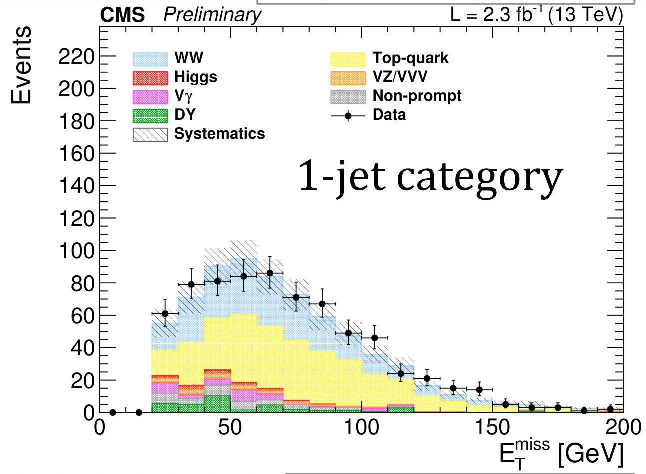


- Recent results with < 10% uncertainty
- Systematics start to dominate
- Improved agreement with NNLO pQCD calculations

W(eν)W(μν) cross-section @ 13 TeV

- Discrepancy in Run1 wrt NLO pQCD → large progress since
  - qq→WW @ NNLO+NNLL
    - p_T(WW) agrees with NLO MC (POWHEG-Box2 + Pythia8)
  - Non-resonant gg → WW @ LO (Sherpa OpenLoops with 0-1 jets), normalised to inclusive NLO xsection
  - gg→H→WW @ N^{3}LO
    - CMS does not include H→WW in signal definition
- Dominant background from top production
- ATLAS applies jet veto, CMS measures in 0 and 1 jet categories
  - Jet veto efficiency sensitive to higher order QCD corrections
  - Need pT-resummation @ NNLL (or alternative jet veto resummation)
- Largest experimental systematics: jet selection, energy scale and resolution

CMS-PAS-SMP-16-006



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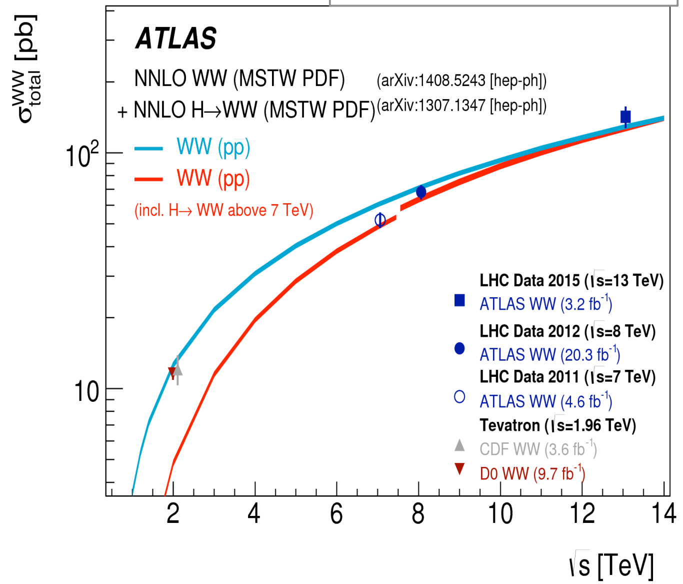
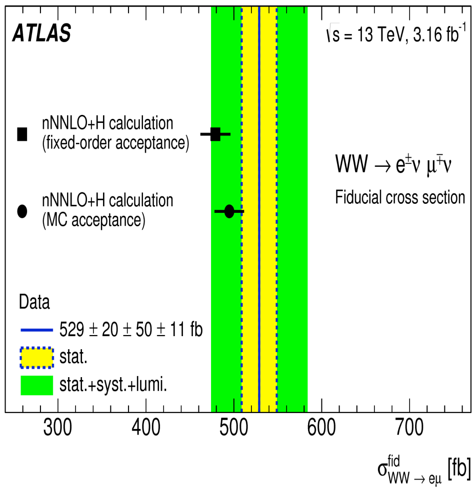
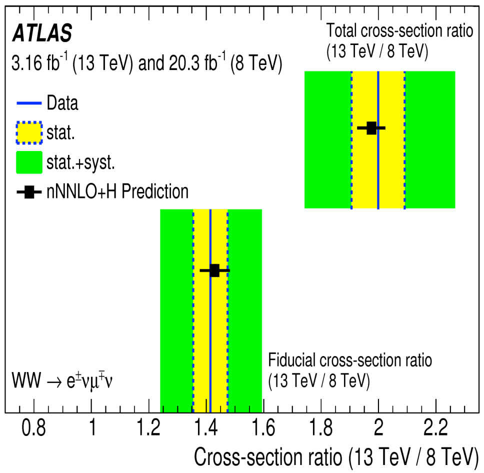


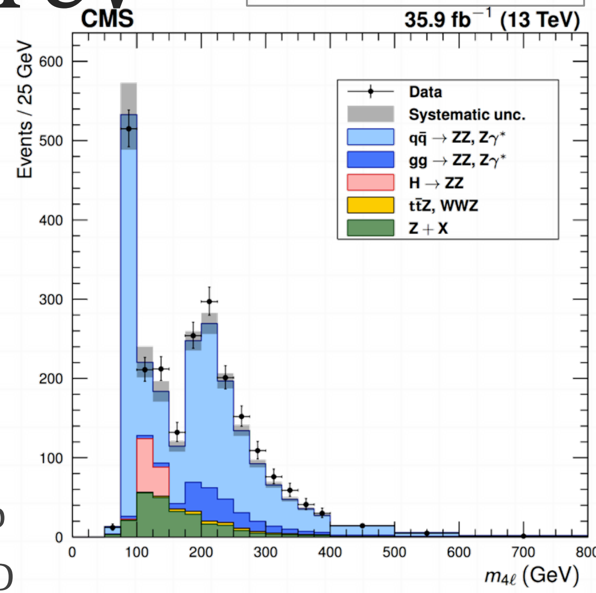




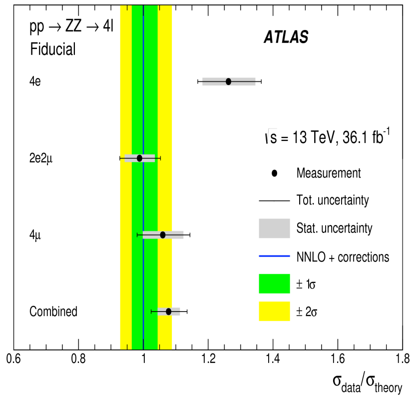
ZZ(4l) cross-section at 13 TeV

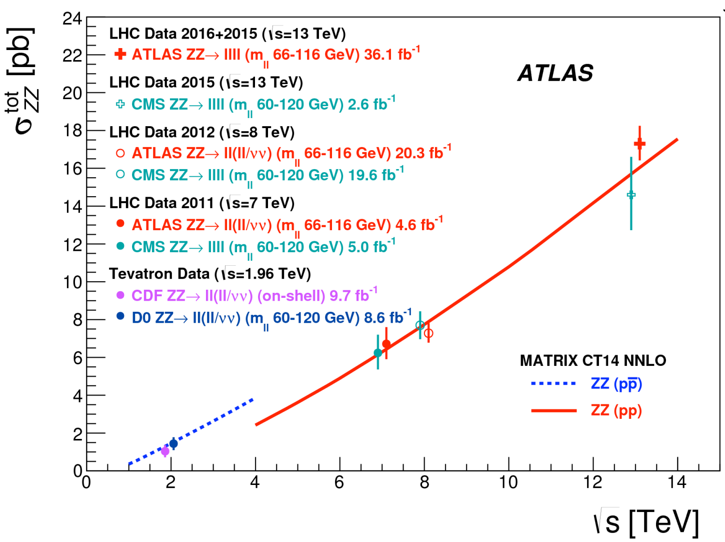
EPJC 78 (2018) 165

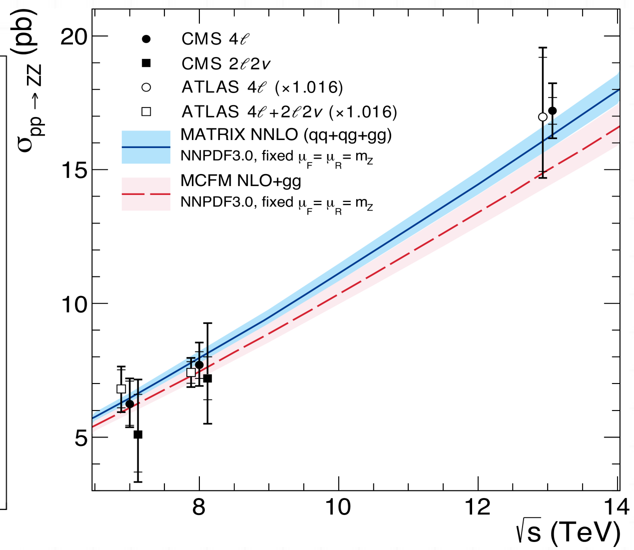
- Fully reconstructed, leptonic final state → very clean
- Only on shell (ATLAS: [66,116] GeV, CMS: [60,120] GeV)
- Main background: "fake" leptons
- Uncertainty no longer statistics dominated
- Dominant experimental uncertainty: lepton reco, ID
- Total cross-section: $\sigma_{tot} = \sigma_{fid} / (A_{ZZ} \cdot BR_{ZZ \to 4l})$
  - ATLAS: **17.3** ± 0.6 (stat) ± 0.5 (syst) ± 0.6 (lumi) pb
  - CMS: **17.2** ± 0.5 (stat) ± 0.7 (syst) ± 0.4 (theo) ± 0.4 (lumi) pb
  - Best theory (Matrix NNLO pQCD including gg@LO + NLO QCD k_{gg}=1.67 + NLO EW k_{qq}~ 0.95 + Sherpa EW ZZjj): $\mathbf{16.9}^{+0.6}_{-0.5}$ pb



PRD 97 (2018) 032005



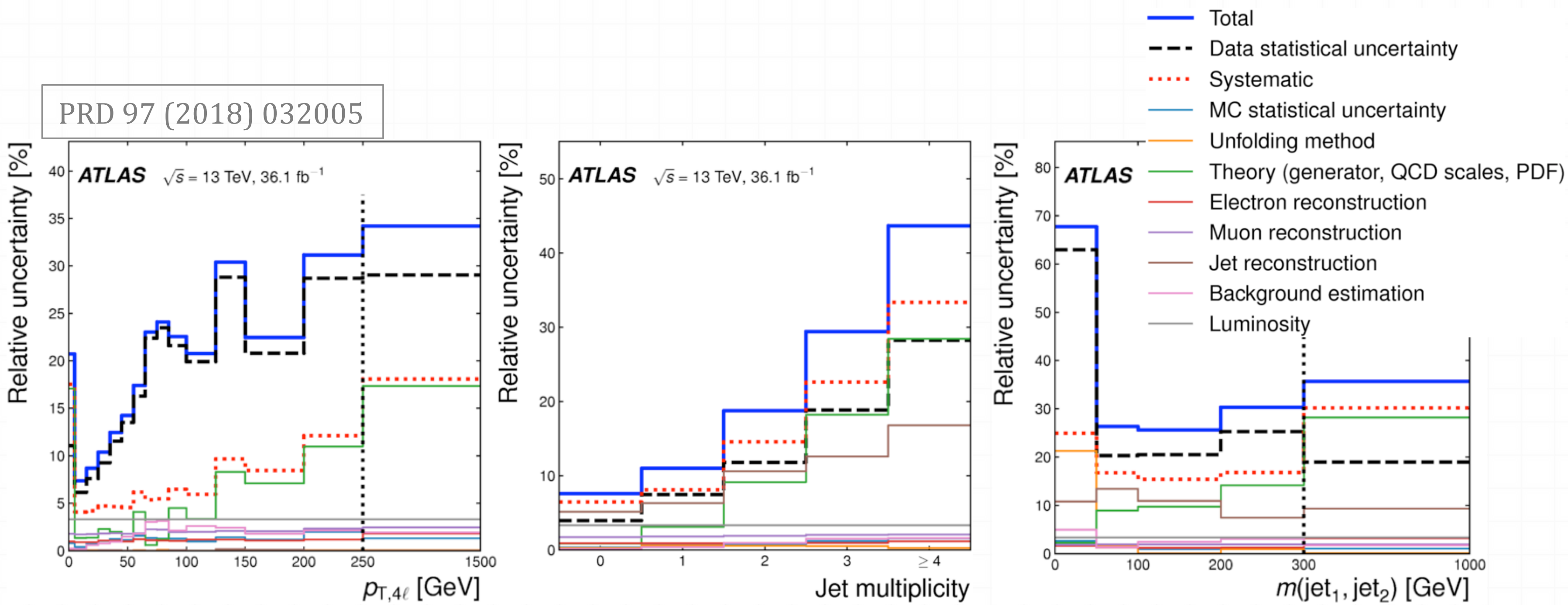




ZZ(4l) differential cross-sections

- Increasing statistics allow to access more and more differential distributions
- Test theoretical calculations , MC tools (Matrix NNLO, Sherpa, Powheg+Pythia, Madgraph_amc@NLO, MCFM…)
- Study different production mechanisms, look for new physics
- Statistic dominated
- Main experimental systematics: response matrix modeling, jet energy scale

PRD 97 (2018) 032005



ZZ(4l) differential cross-sections

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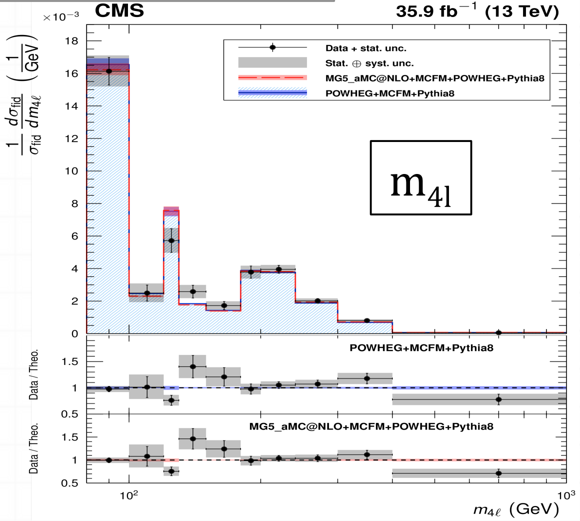
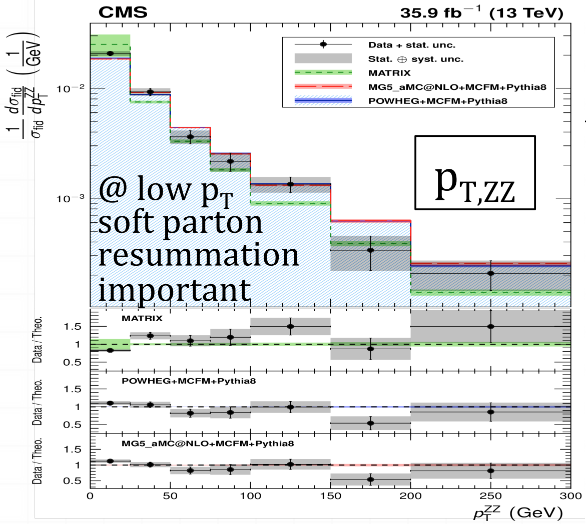
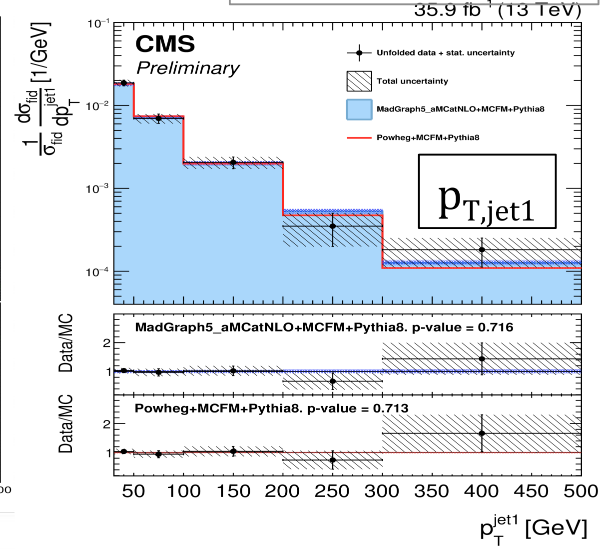
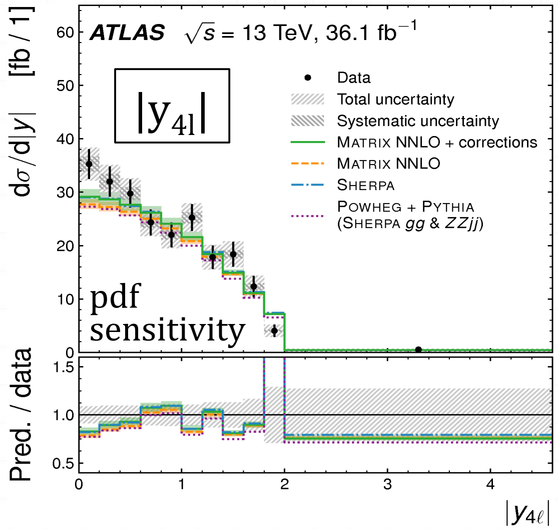
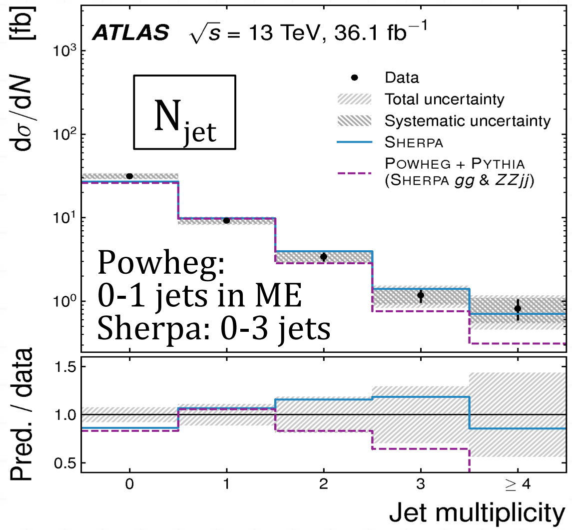
CMS PAS SMP-16-019

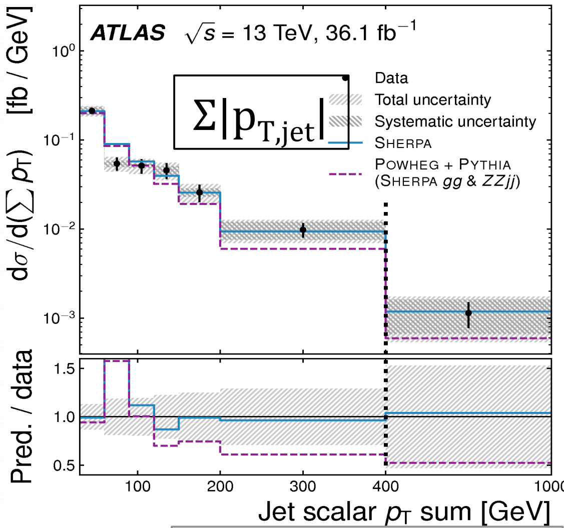










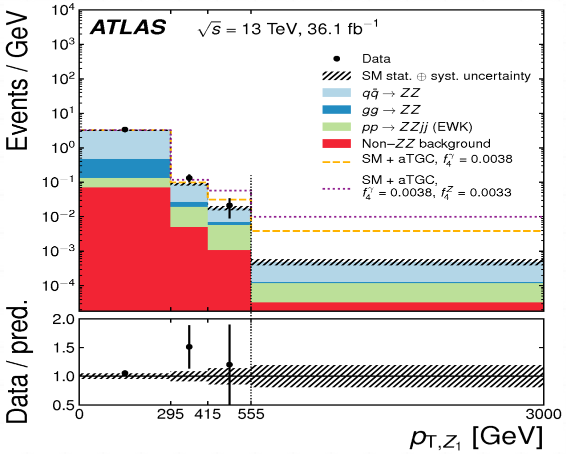


Ratios (on bottom panels) use different conventions!

PRD 97 (2018) 032005

ZZ anomalous couplings (ZZZ, ZZγ)

- Main signature: increased production at high mass, high pT
- ATLAS: leading Z p_T (NLO EW corrections available), CMS: m_{4l}



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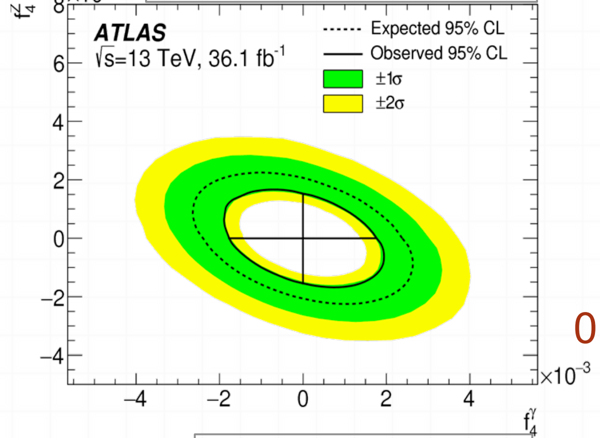

- Effective vertex function approach: CPV f_4^γ, f_4^Z and CPC f_5^γ, f_5^Z

$$\mathcal{L}_{ZZV} = -\frac{e}{M_Z^2}\Big(f_4^V(\partial_\mu V^{\mu\beta})Z_\alpha(\partial^\alpha Z_\beta) + f_5^V(\partial^\sigma V_{\sigma\mu})\tilde{Z}^{\mu\beta}Z_\beta\Big)$$

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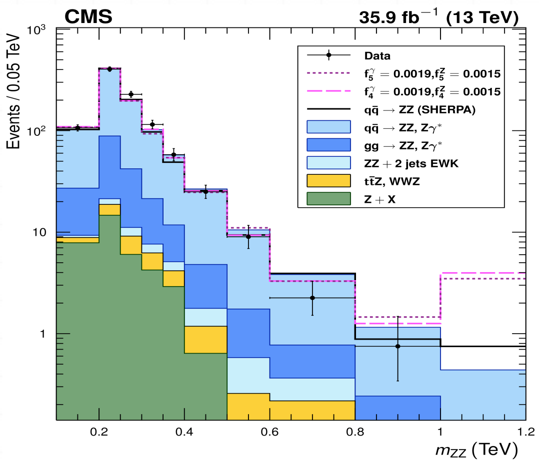
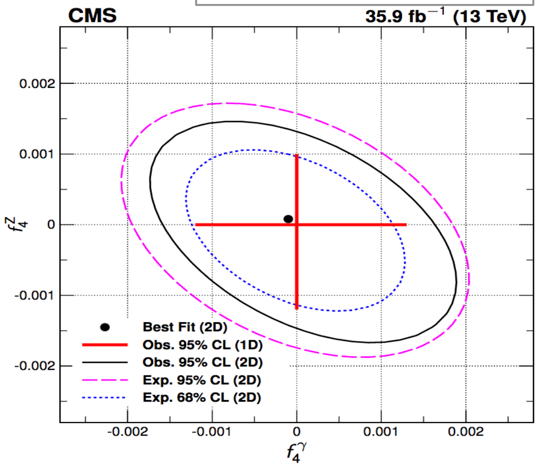
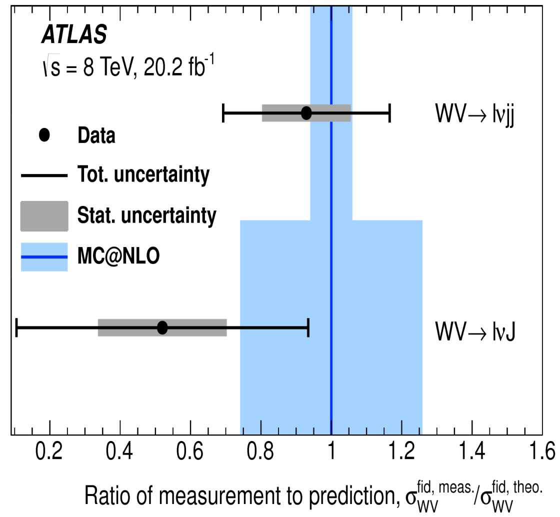




- Effective field theory with 4 dim-8 operators contributing to neutral aTGC interactions: C_{BW}/Λ^4, C_{BW}/Λ^4, C_{WW}/Λ^4, C_{BB}/Λ^4
- Linear relations between the 2 sets of parameters
- No unitarising form-factor as sensitivity within unitarity bounds

Semi-leptonic WW / WZ measurements @ 8 TeV

- Lepton (e,μ) from W + hadronic system from W/Z
  - Resolved narrow (R=0.4) jets (jj) or merged wide (R=0.8-1.0) jet (J)
    - ATLAS both lvjj and lvJ analyses, no attempt to combine
  - At high $p_T(V)$, boosted J reconstruction increases efficiency --> improved New Physics sensitivity
- Complementary to leptonic channels
  - 6x higher rate but large W+jets and top background (s/b~5-10% after selection)
    - Additional jet veto
  - W kinematics better reconstructed (only one neutrino)
  - Signal extracted fitting the mass of the hadronic system
  - Main experimental systematics: W+jets normalisation (ATLAS: 60%, CMS:20%)



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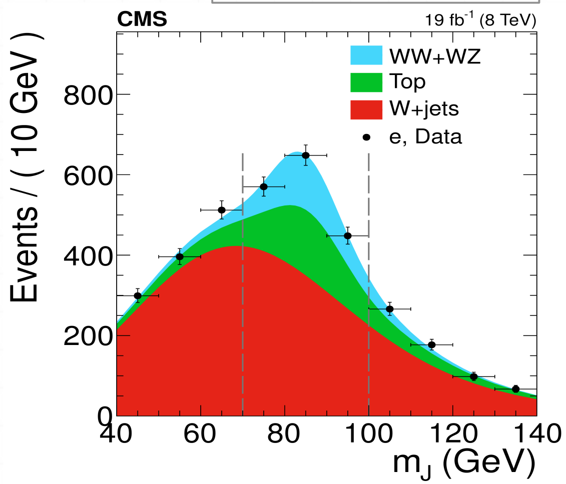

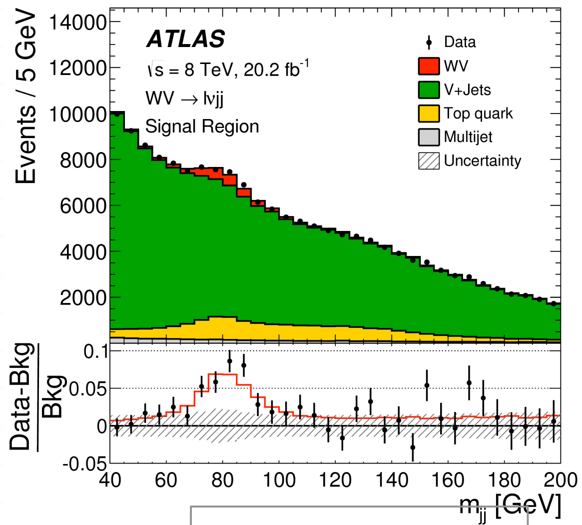

EPJC 77 (2017) 563

WV @ 8TeV: aTGC constraints

PLB 772 (2017) 21

Best aTGC sensitivity from WV → lvJ boosted topology

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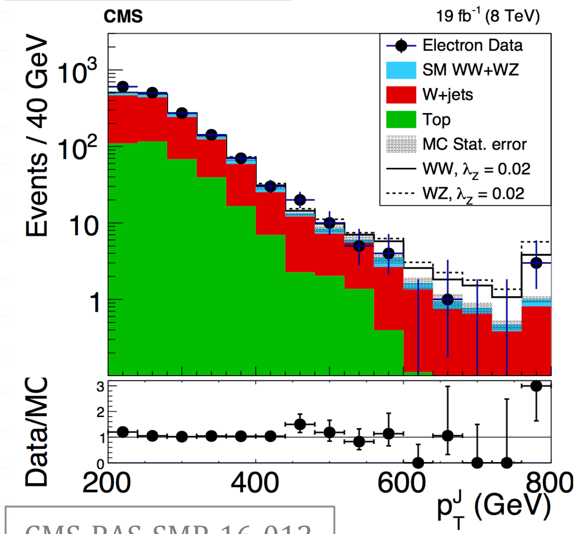
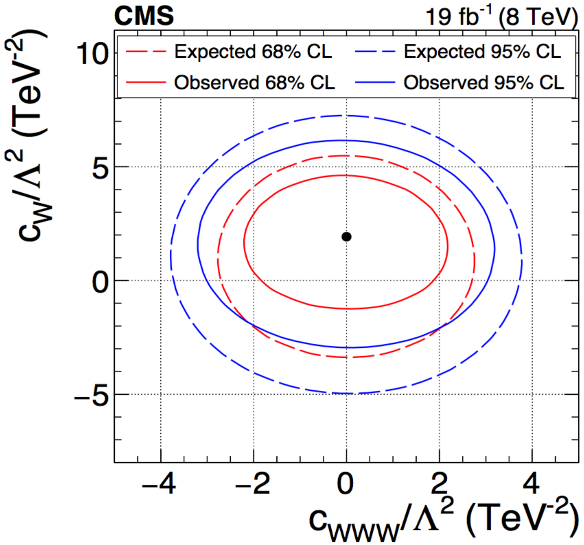
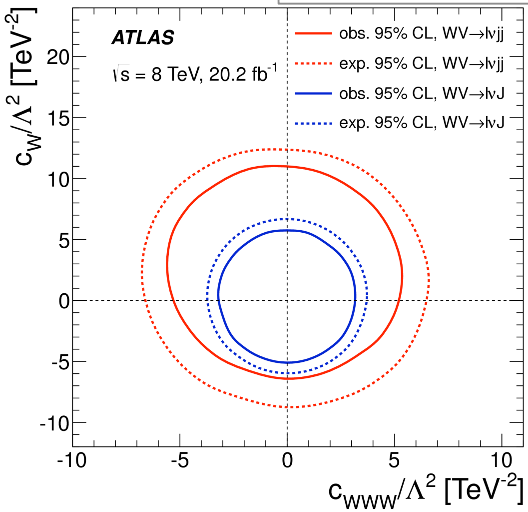
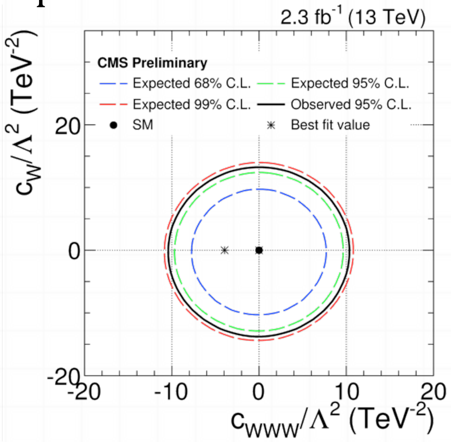






CMS-PAS-SMP-16-012

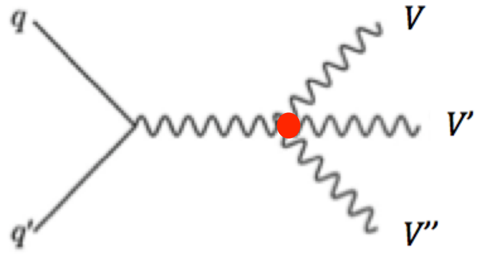
Results from 3 fb^{-1} data @ 13 TeV not yet competitive, but significant improvement expected from recorded >100 fb^{-1} data

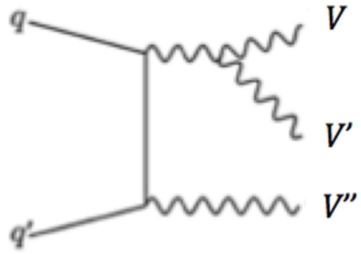


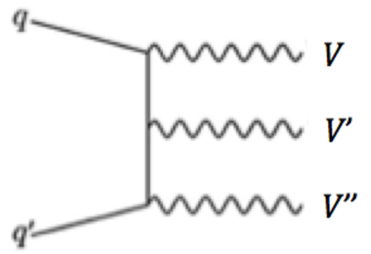
	c_{WWW}/Λ^2 (TeV^{-2})	c_B/Λ^2 (TeV^{-2})	c_W/Λ^2 (TeV^{-2})
CMS WV→lvJ	[−2.7, 2.7]	[−14, 17]	[−2.0, 5.7]
ATLAS WV→lvJ	[−3.1, 3.1]	[−19, 20]	[−5.1, 5.8]
ATLAS WV→lvjj	[−5.3, 5.3]	[−36, 43]	[−6.4, 11]
CMS WW->lvlv	[−5.7, 5.9]	[−29.2, 23.9]	[−11.4, 5.4]
ATLAS WW->lvlv	[−4.61, 4.60]	[−20.9, 26.3]	[−5.87, 10.54]
CMS WZ->lvll	[−4.6, 4.2]	[−260, 210]	[−4.2, 8.0]
ATLAS WZ->lvll	[−3.9, 4.0]	[−320, 210]	[−4.3, 6.8]

Tri-boson measurements

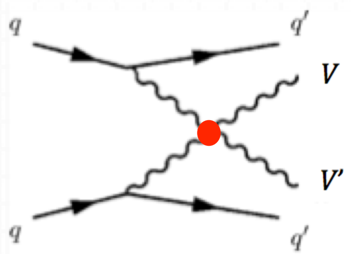
- Test non-abelian structure of EW sector predicting quartic couplings
- Tri-boson production: rare process

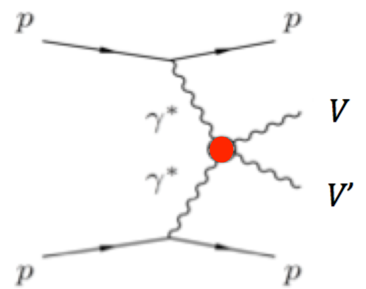






- QGCs also accessible by vector boson scattering (see dedicated talk!) and exclusive $\gamma\gamma \rightarrow$ VV'





EFT: dim-8 operators

- Deviation from SM parametrised in aQGC framework
- Extension of SM effective Lagrangian to describe aQGCs
- No effect on TGCs

WZγ WWγ W$\gamma\gamma$ Z$\gamma\gamma$

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{L}_{S,0}$, $\mathcal{L}_{S,1}$	X	X	X	O	O	O	O	O	O
$\mathcal{L}_{M,0}$, $\mathcal{L}_{M,1}$, $\mathcal{L}_{M,6}$, $\mathcal{L}_{M,7}$	X	X	X	X	X	X	X	O	O
$\mathcal{L}_{M,2}$, $\mathcal{L}_{M,3}$, $\mathcal{L}_{M,4}$, $\mathcal{L}_{M,5}$	O	X	X	X	X	X	X	O	O
$\mathcal{L}_{T,0}$, $\mathcal{L}_{T,1}$, $\mathcal{L}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,5}$, $\mathcal{L}_{T,6}$, $\mathcal{L}_{T,7}$	O	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,9}$, $\mathcal{L}_{T,9}$	O	O	X	O	O	X	X	X	X

DΦ only

$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$
$$\mathcal{L}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

$$D_\mu\Phi = (\partial_\mu - igW^j_\mu \tfrac{\sigma^j}{2} - ig' B_\mu \tfrac{1}{2})\Phi$$

DΦ and W/B

$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{L}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{L}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{L}_{M,4} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu}$$
$$\mathcal{L}_{M,5} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu}$$
$$\mathcal{L}_{M,6} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right]$$
$$\mathcal{L}_{M,7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]$$

W/B only

$$\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right]$$
$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$
$$\mathcal{L}_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right]$$
$$\mathcal{L}_{T,5} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T,6} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu}$$
$$\mathcal{L}_{T,7} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha}$$
$$\mathcal{L}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

PRD 74 (2006) 073005

WWγ, WZγ measurements @ 8 TeV

CMS results

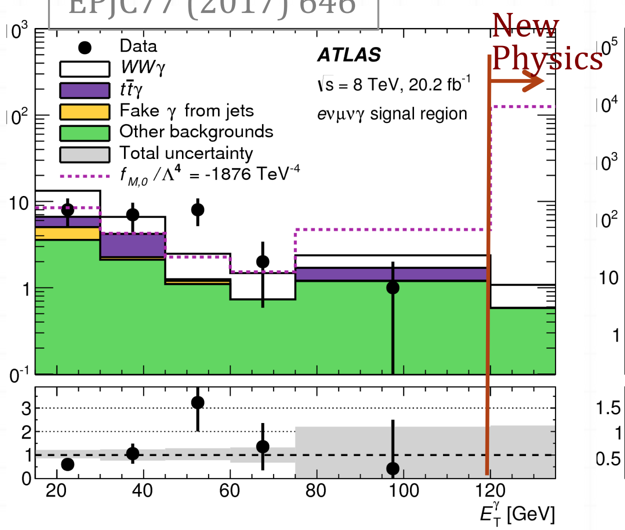
PRD90 (2014) 032008

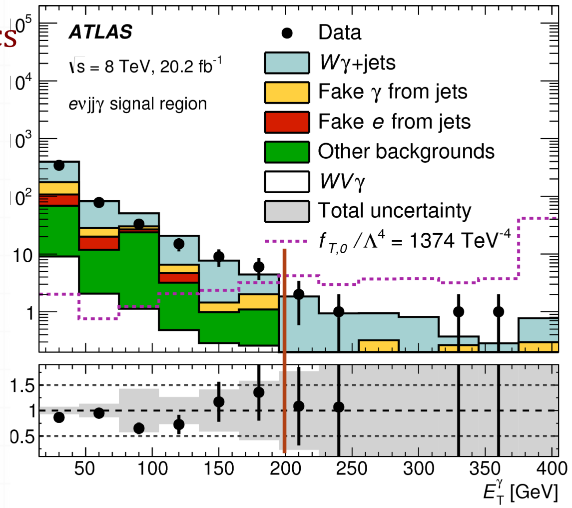
- W(eν)W(μν)γ: clean experimental signature
- W(lν)V(jj)γ: larger hadronic branching fraction
- Two fiducial regions optimized for each channel: for observation of WVγ process, for aQGC searches (high E_T^{γ})
- Not yet enough data for "evidence": 1.4σ (expected 1.6σ)
- Dominant uncertainty: data stat, signal efficiency modelling (Sherpa vs Madgraph), jet energy scale

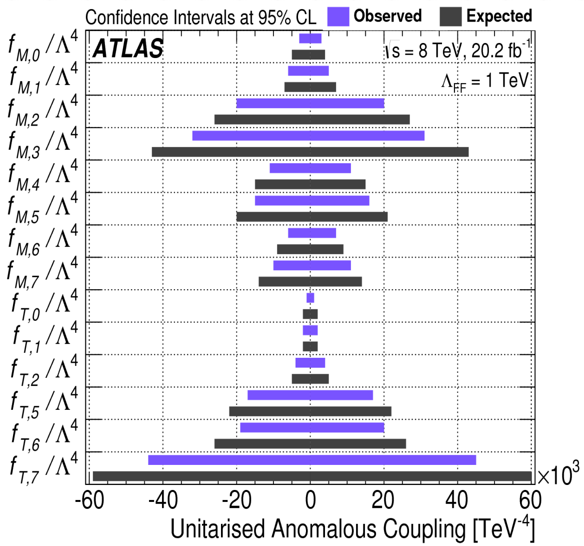
		Observed limit [fb]	Expected limit [fb]	NLO σ_{theo} [fb]
Fully leptonic	$e\nu\mu\nu\gamma$	3.7	$2.1^{+0.9}_{-0.6}$	2.0
Semileptonic	$e\nu jj\gamma$	10	16^{+6}_{-4}	2.4
	$\mu\nu jj\gamma$	8	10^{+4}_{-3}	2.2
	$\ell\nu jj\gamma$	6	$8.4^{+3.4}_{-2.4}$	2.3

$$\sigma_{\text{fid}}^{e\nu\mu\nu\gamma} = 1.5 \pm 0.9(\text{stat.}) \pm 0.5(\text{syst.})\ \text{fb}$$

EPJC77 (2017) 646

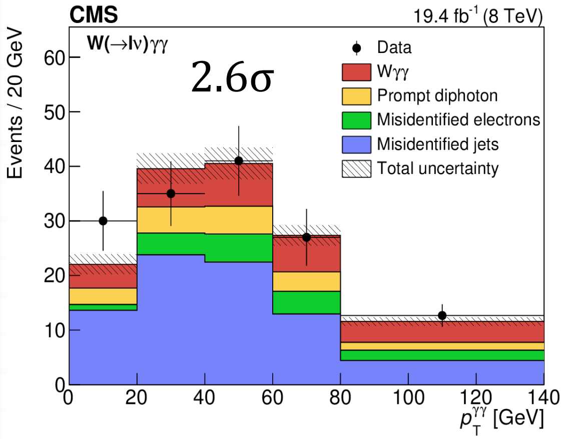


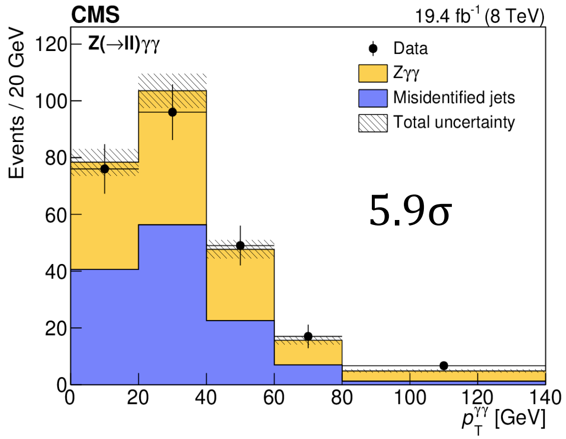




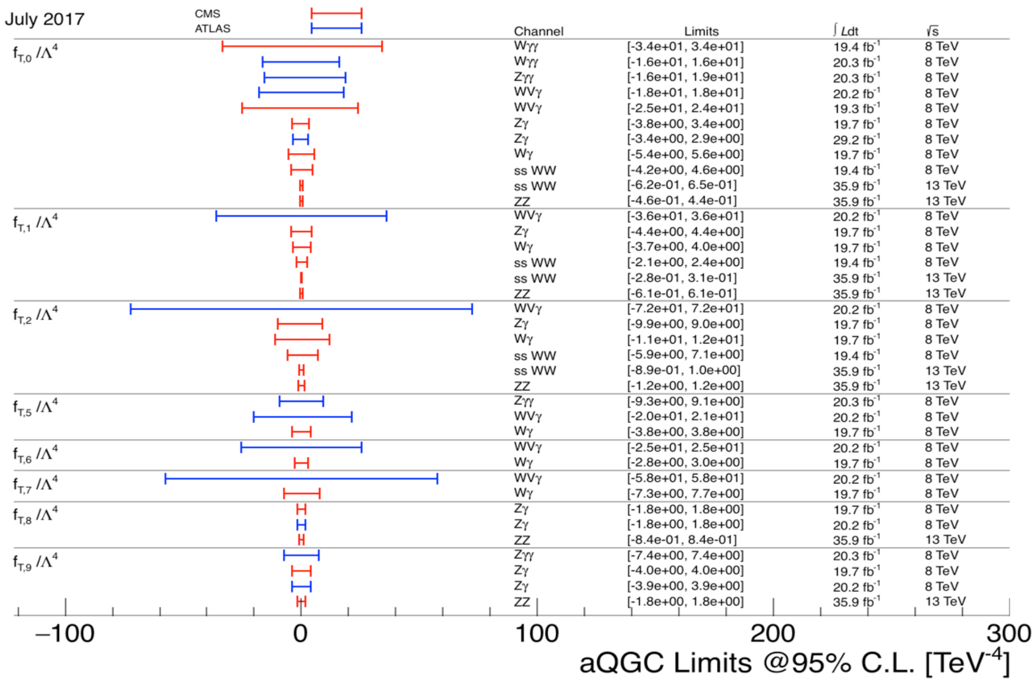
Z(ll)γγ, W(lν)γγ measurements at 8 TeV

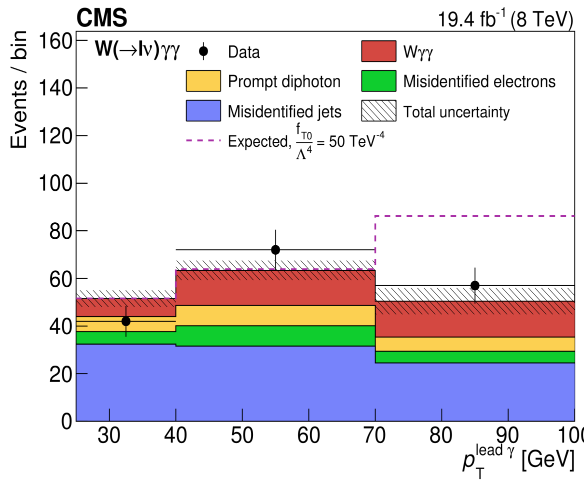
ATLAS results
Zγ(γ) PRD93 (2016) 112002
Wγγ PRL115 (2015) 031802





- ATLAS observation: Wγγ 3σ, Zγγ 6.3σ
- Dominant systematics: misidentified jet background
- Fiducial cross-section agrees well with theory
- Limits on aQGC from Wγγ





JHEP10 (2017) 072

Summary

- Di-boson measurements already systematics dominated
  - Uncertainties of less than 10% reached for fiducial and total cross-sections
  - Lots of effort to improve analyses to decrease systematic uncertainties
  - In ZZ measurement experimental uncertainty reaches luminosity uncertainty

- Differential cross-sections still statistics limited

- More precise theoretical calculations desirable (NNLO/N^3LO pQCD, NLO EW…)

- Tri-boson ($Z\gamma\gamma$) production observed ($>5\sigma$) at 8 TeV by ATLAS and CMS
- Complemented by VBF and VBS measurements

- Increased sensitivity to search for New Physics (aTGCs, aQGCs)
  - Semi-leptonic final states with larger statistics in the high energy tails boost LHC sensitivity

- 13 TeV data analyses ongoing: more than 100 fb^{-1} recorded / experiment