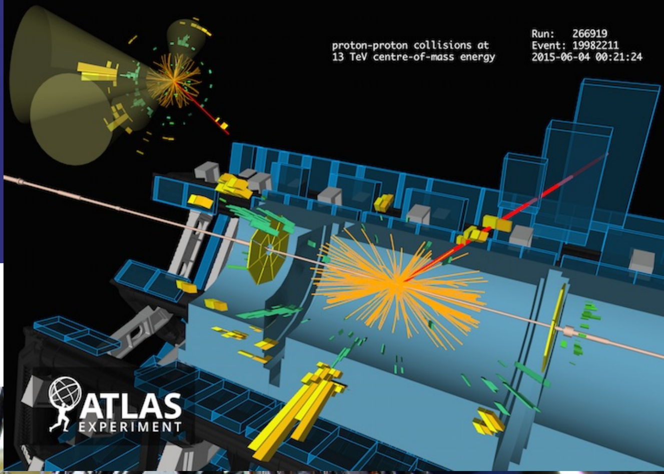
Latest measurements of multibosons of the ATLAS experiment and what to do with them

Kristin Lohwasser, University of Sheffield



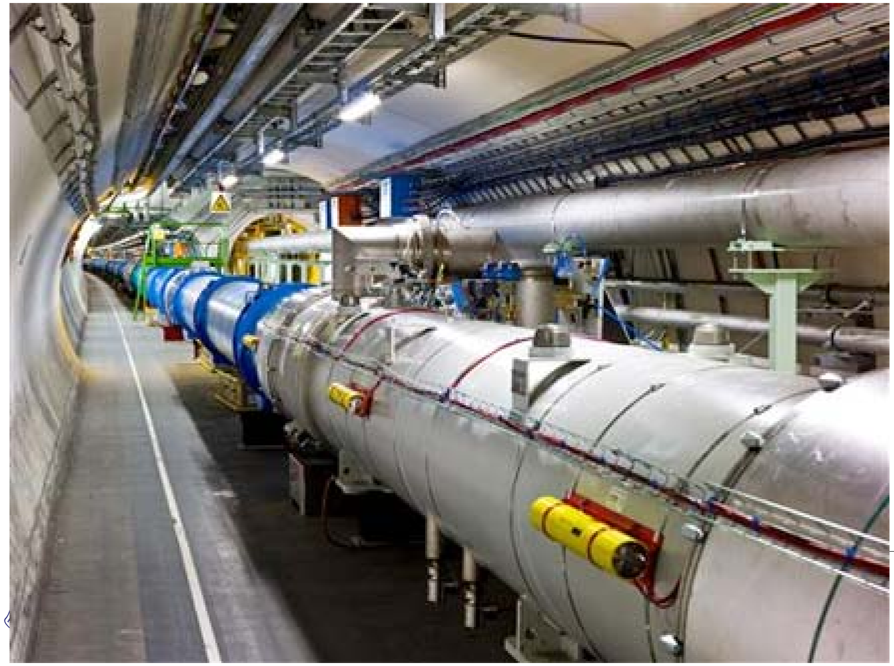
LHC Run-2: A success story (of the machine)

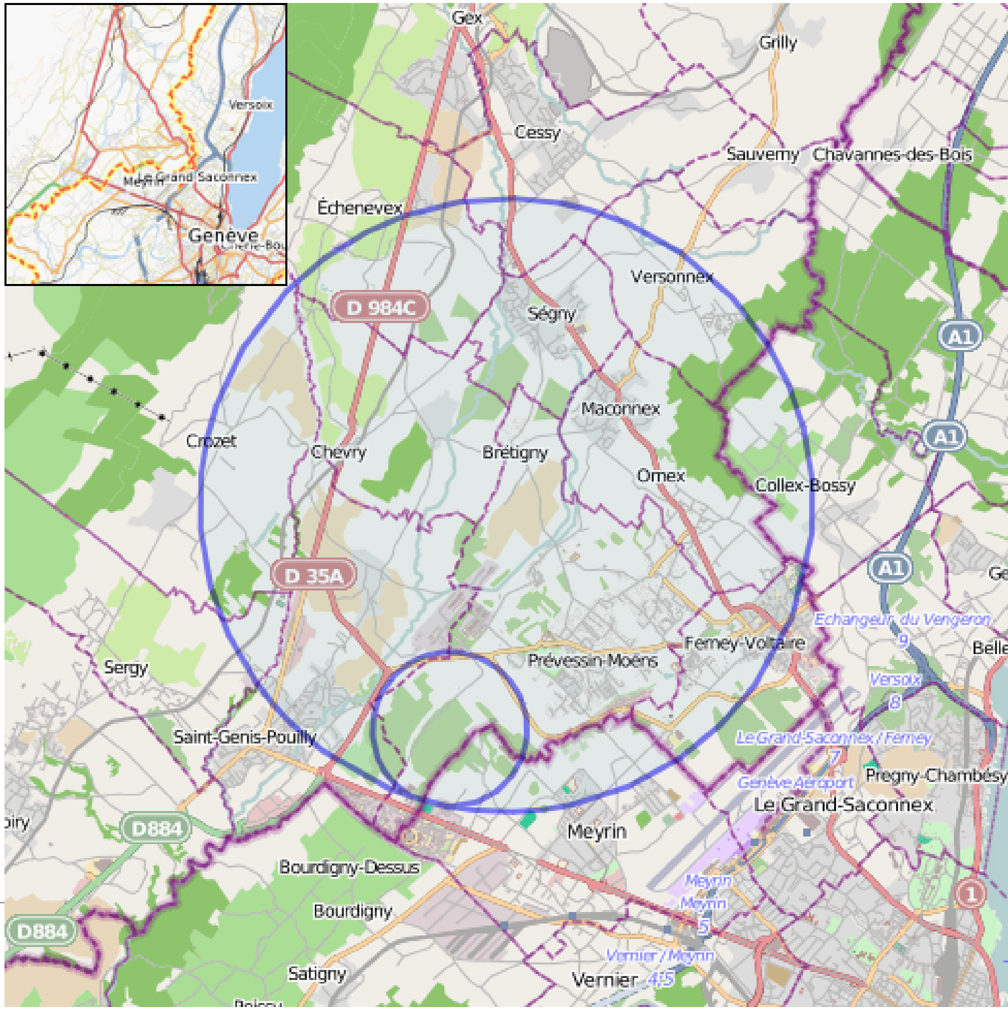
- **1982: First LHC studies**
- 2003: Start of LHC installation
- **2009: Actual start of LHC**

- 13 TeV proton-proton collisions
- "Discovery machine"
  (Higgs!! – but anything else?)

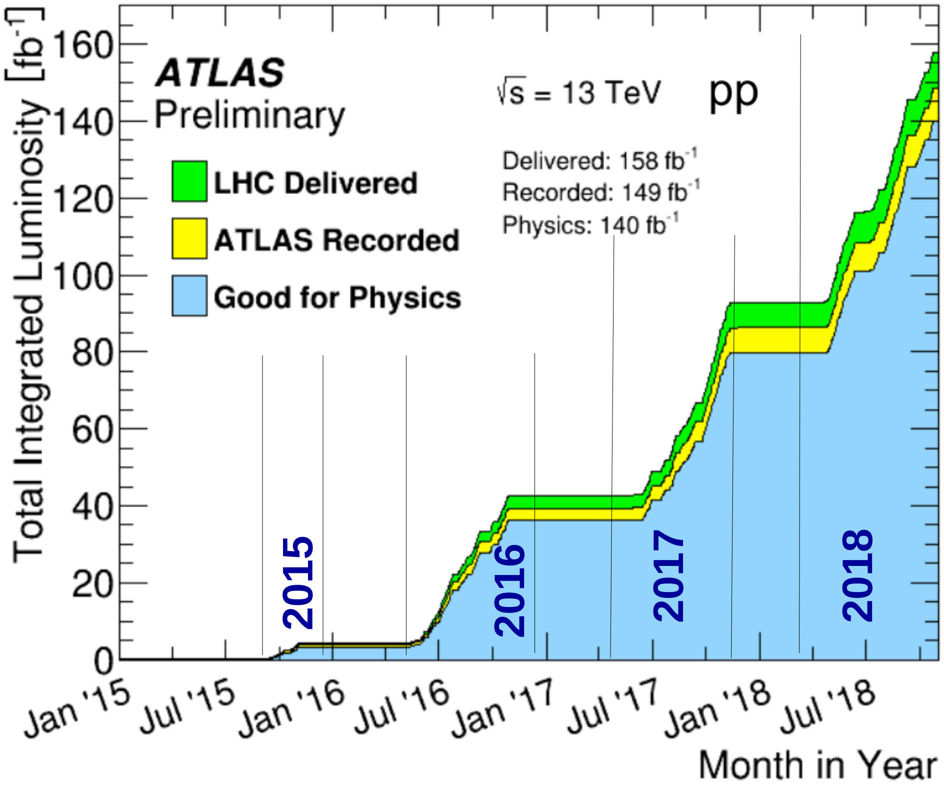
Run 2 (5.4.2015 – 3.12.2018)

- Delivered: 158 fb^{-1}
- Recorded: 149 fb^{-1} (94.3%)
- **Good f. Physics: 140 fb^{-1}** (94%)



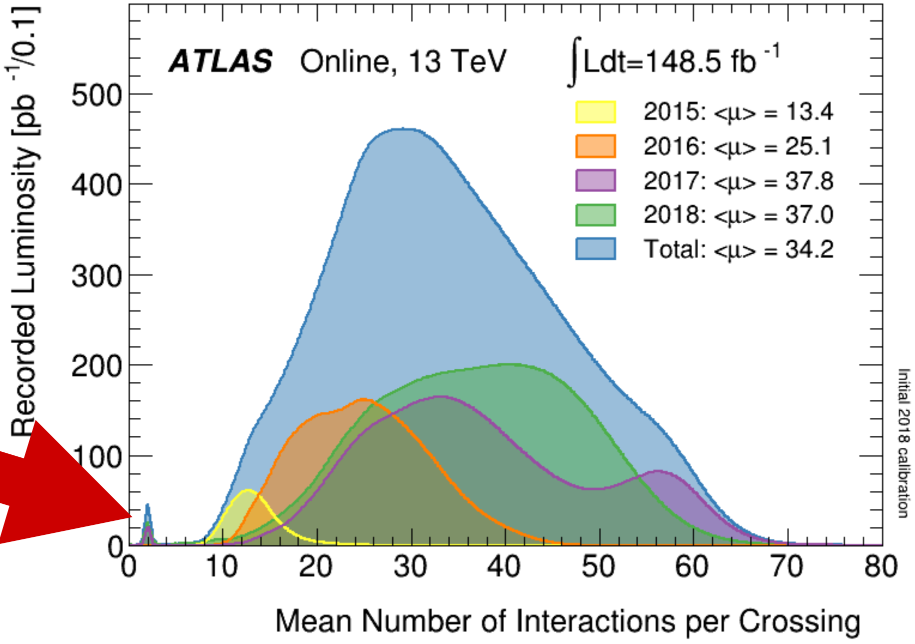


Very successful data taking period



- Steady increase of data taken at the “energy frontier”

- But this is not the whole story…..



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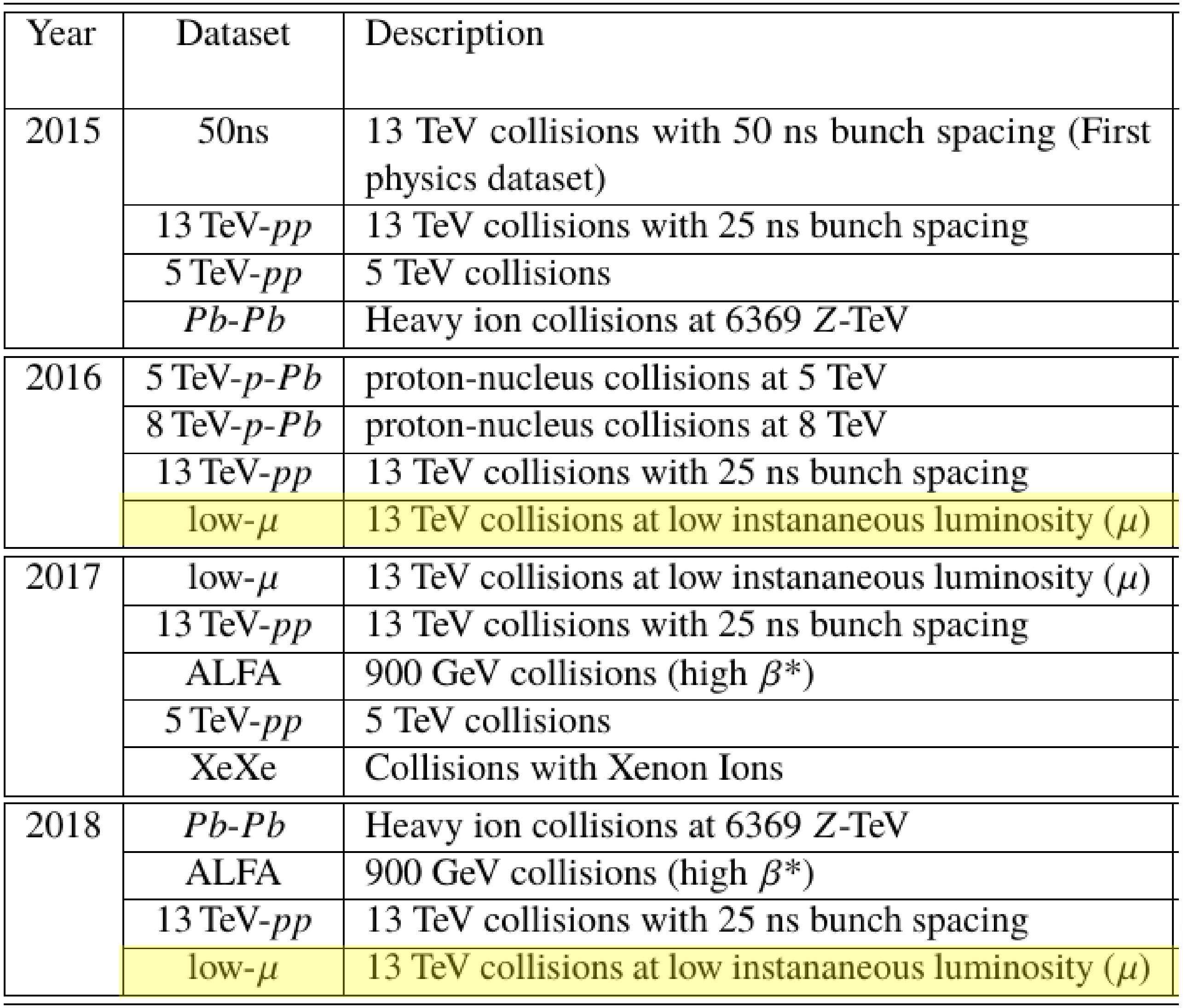
Precision physics data set: <μ> = 2



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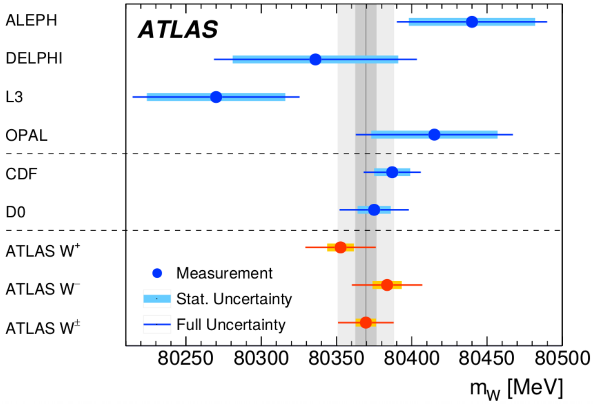
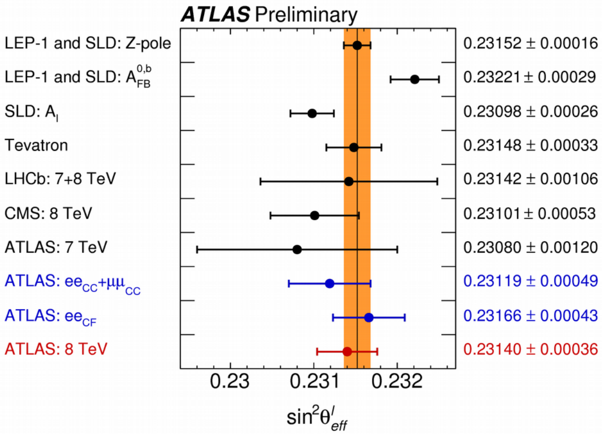
- HL-LHC m W PUB note
  https://cds.cern.ch/record/2643352
- Work in progress for m W combination with Tevatron:
  https://indico.cern.ch/event/779259/contributions/3245228/
- Weak mixing angle $\sin^2\theta$
  ATLAS-CONF-2018-037





Low energy *pp*-collisions

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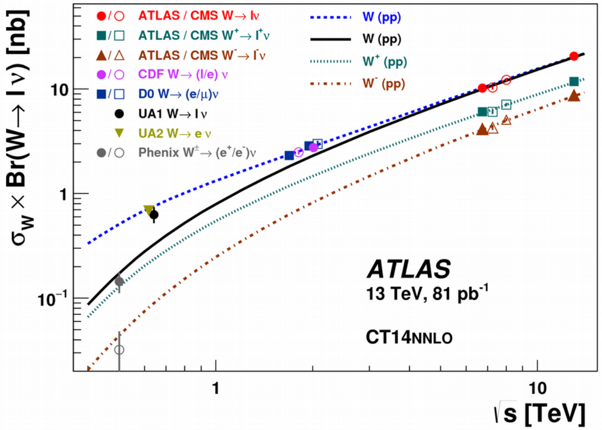
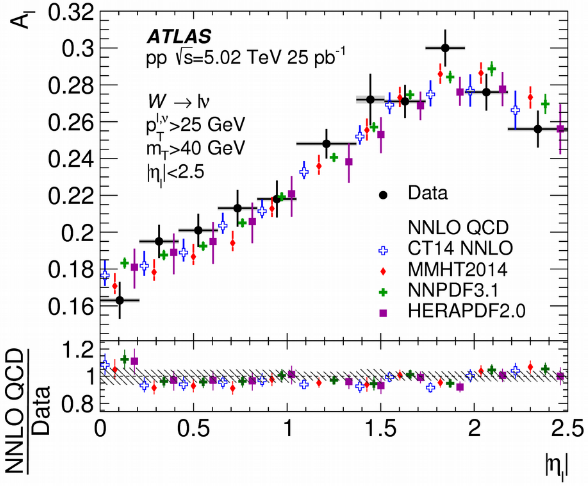
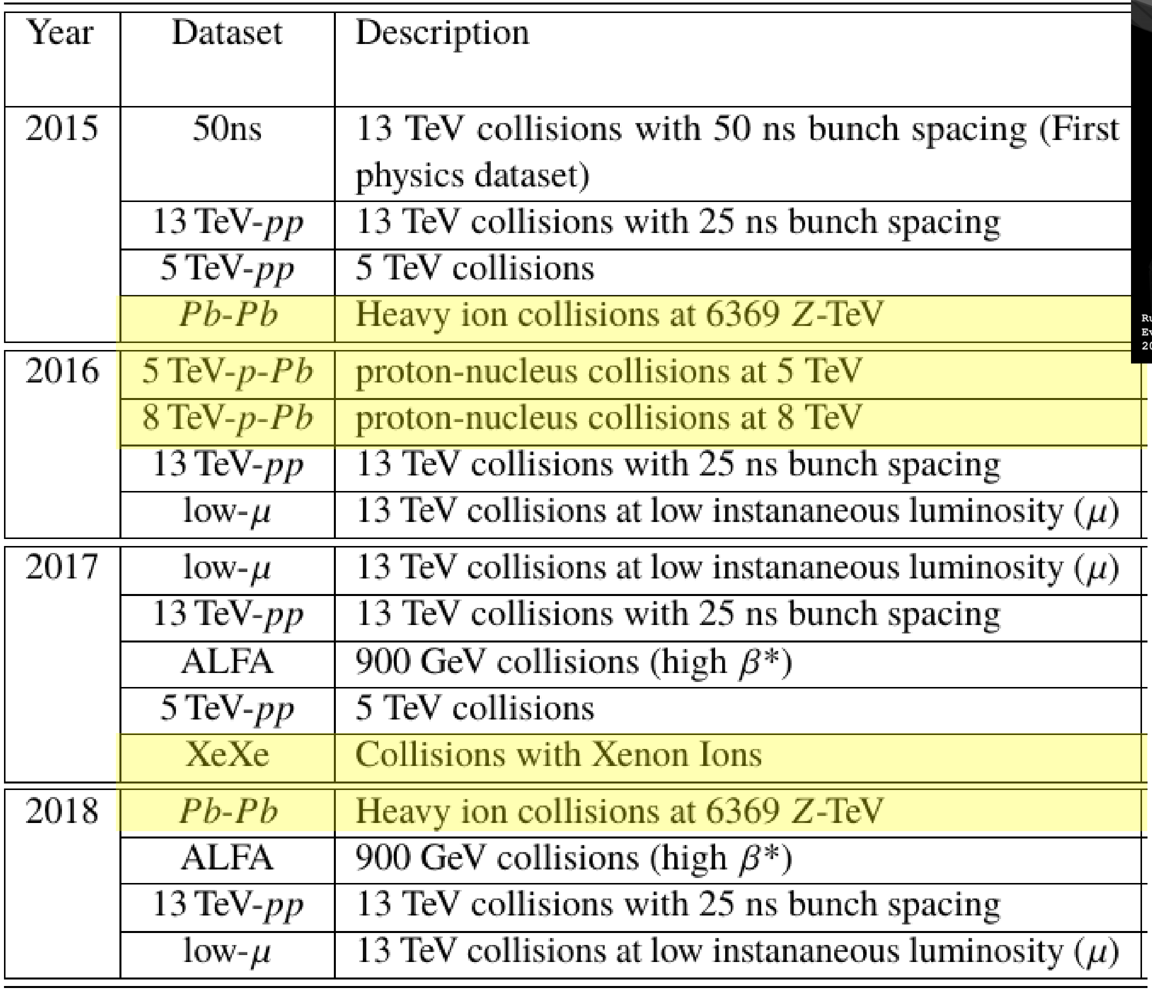
W and Z production in 5.02 TeV pp collisions

Eur. Phys. J. C 79 (2019) 128





Quark-Gluon plasma and beyond



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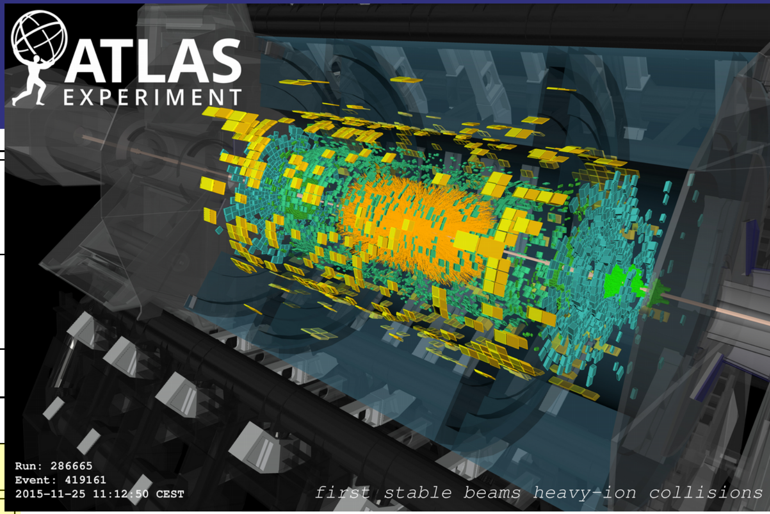
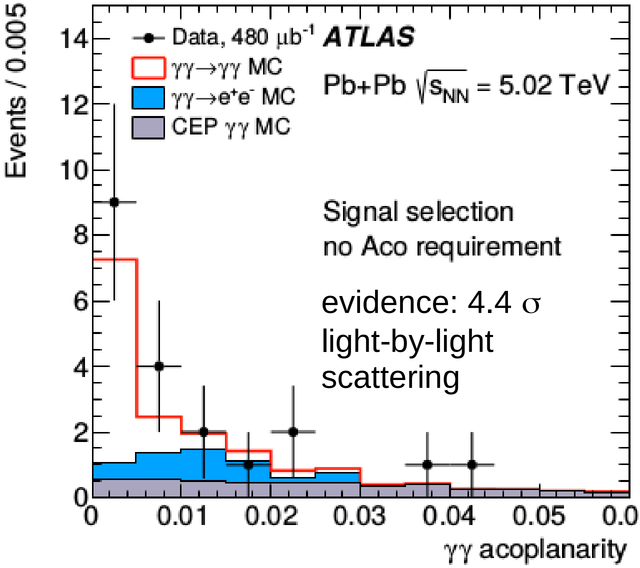
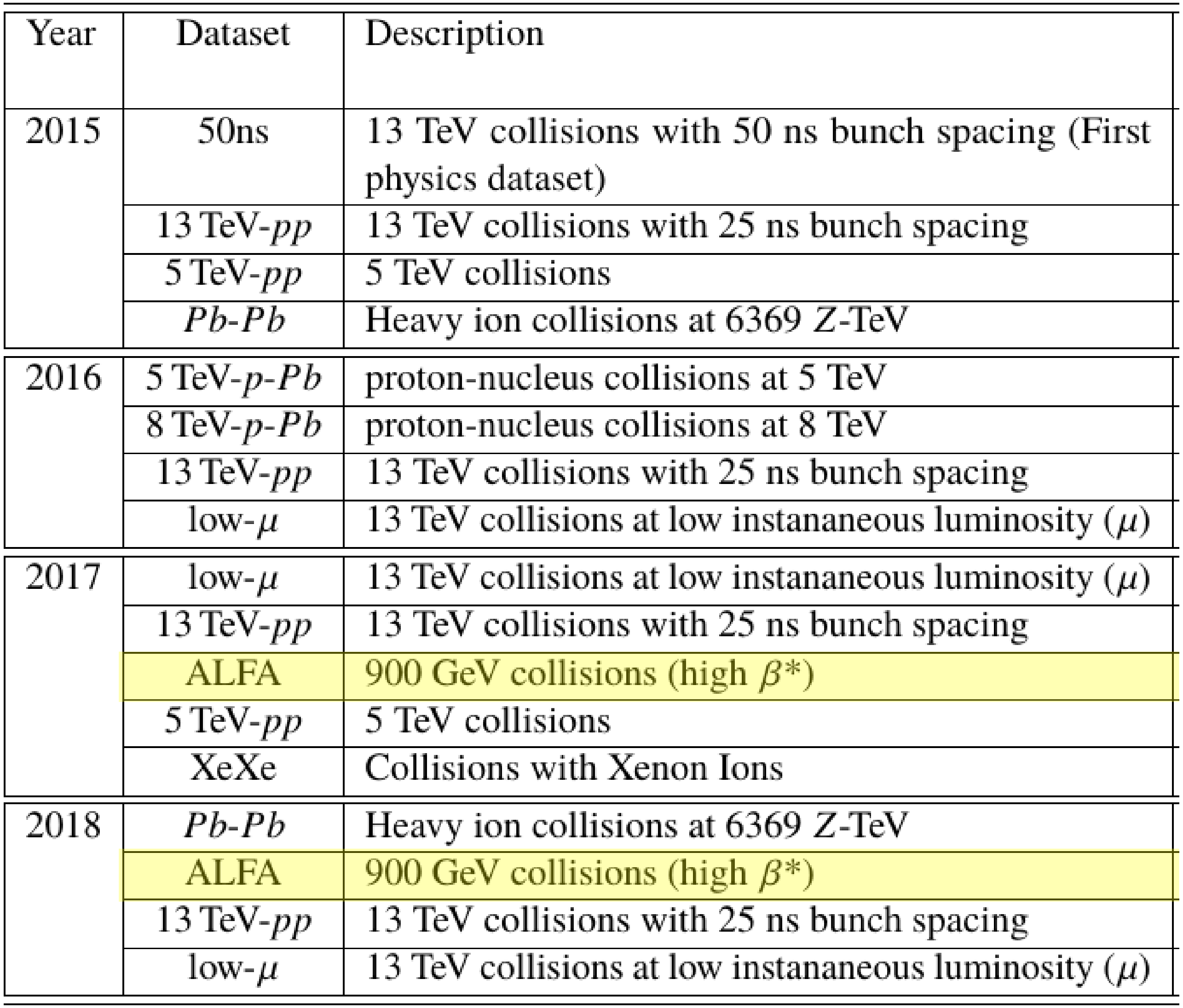




$$\varphi = \pi - (\phi_2 - \phi_1)$$

https://arxiv.org/abs/1702.01625

Minimum Bias: 900 GeV collisions



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Bose-Einstein correlations at 0.9 and 7 TeV –
Eur. Phys. J. C75 (2015) 466

Two-particle angular correlations at 0.9 and 7 TeV
JHEP 1205 (2012) 157

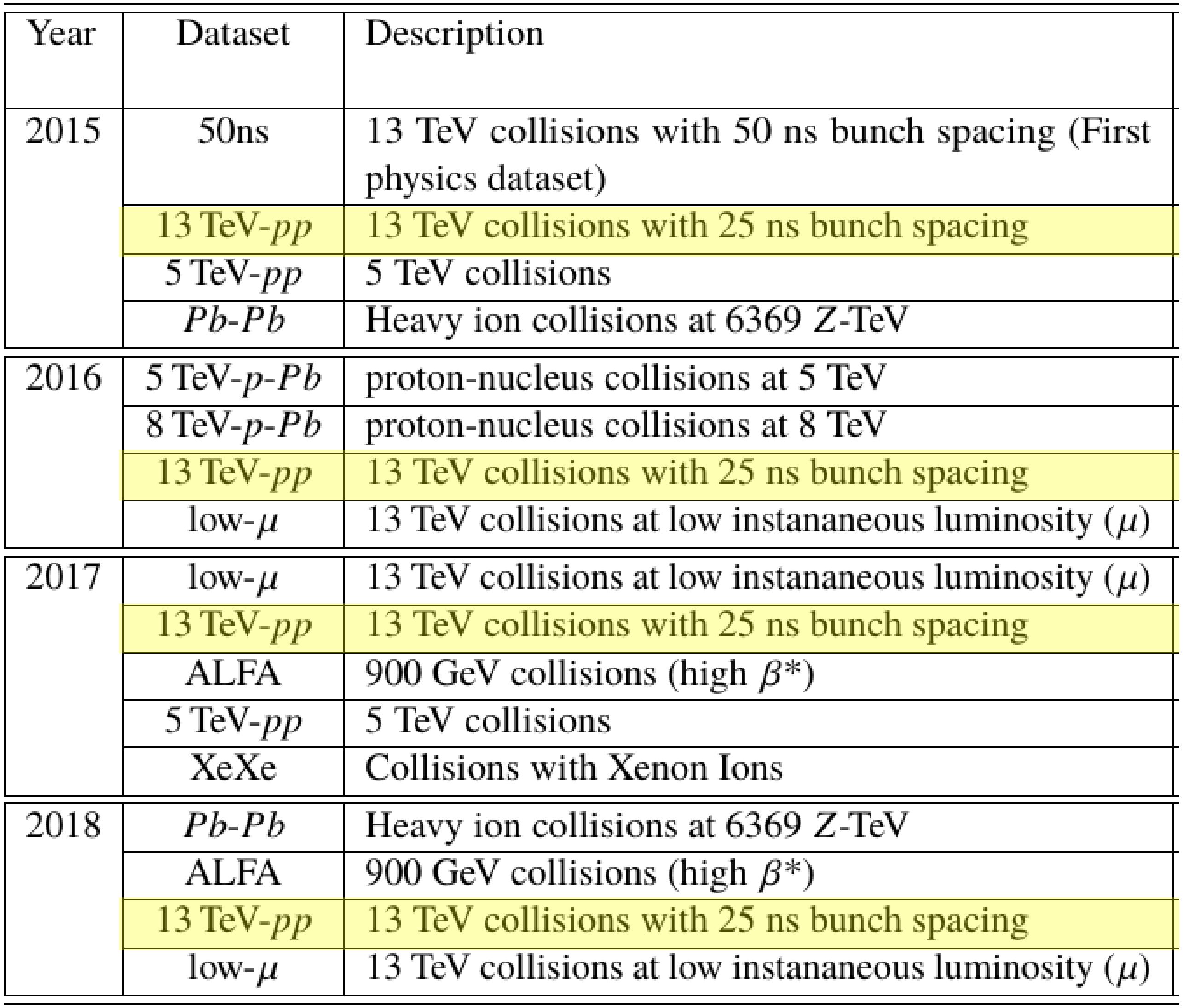
Forward-backward correlations and charged-particle azimuthal distributions at 0.9 and 7 TeV
JHEP 1207 (2012) 019

Azimuthal ordering of charged hadrons at 0.9 and 7 TeV
Phys.Rev. D86 (2012) 052005

K0 and Lambda production at 0.9 and 7 TeV
Phys.Rev. D85 (2012) 012001

The University Of Sheffield.

And finally: *pp*-collisions at high energy



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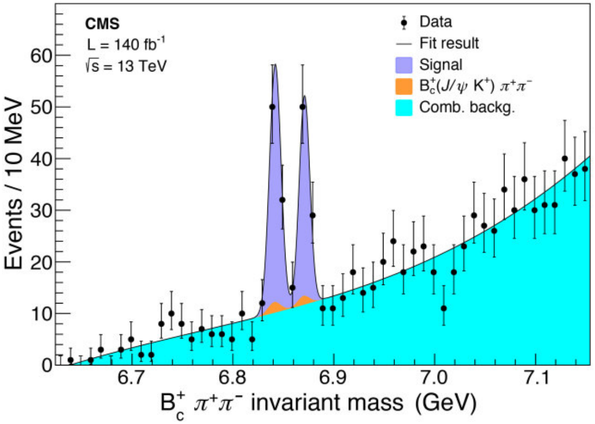
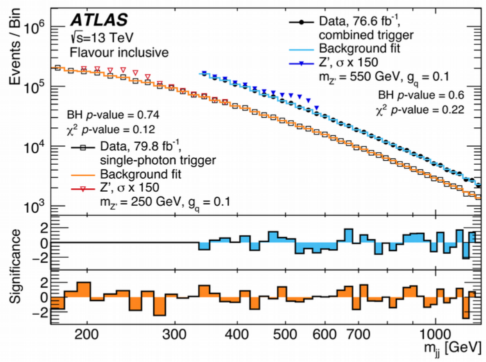
- Just above 140 fb^{-1}

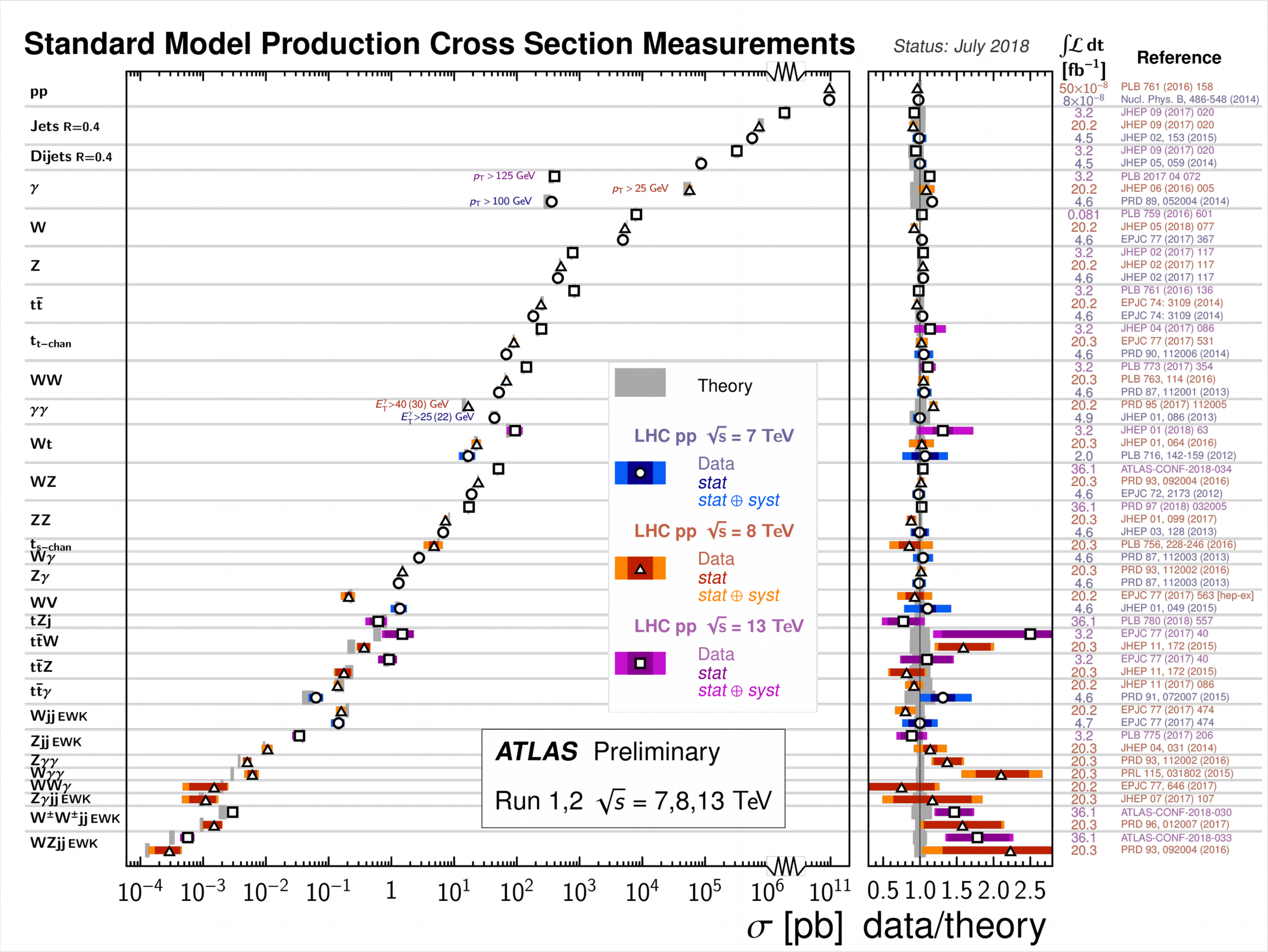
only full Run-2 result:
CMS $B_c(2s)$



ATLAS: Resolved low mass dijet resonance search with ISR with 80 fb^{-1} (2015-2017)



But so far: What we have is the Standard Model



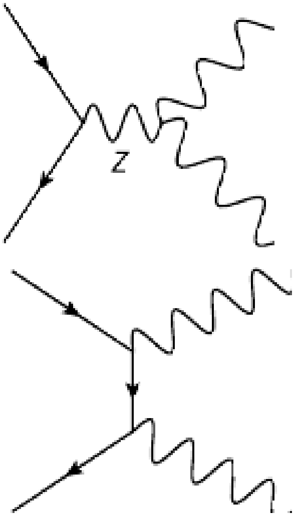
Single boson

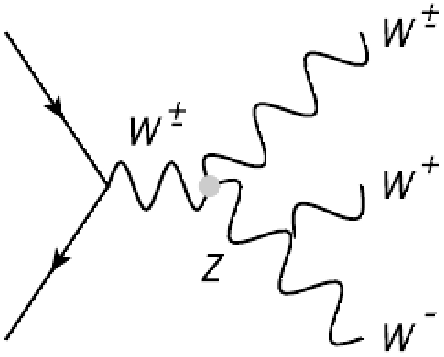
Multiboson

Triboson

Inclusive production

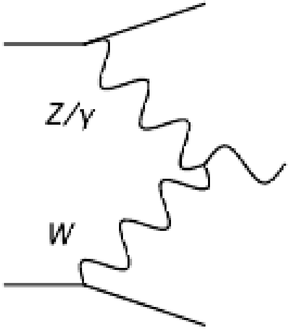
✘

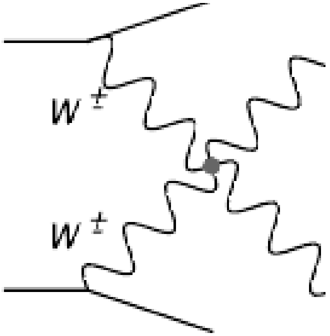




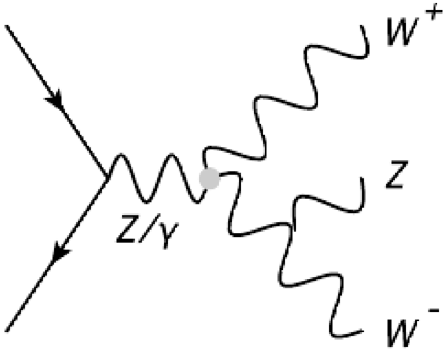
multilepton final state

Vector Boson Fusion or Scattering (VBF/VBS)





two jets with large rapidity gap



c

Inclusive production

Legend

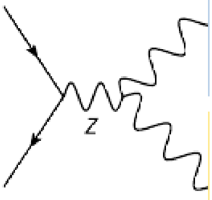
- 🟥 7 TeV
- 🟦 8 TeV
- 🟨 13 TeV (2015+16)
- ⬜ not measured

***CMS only**

O(160 pb)
↓
O(20 pb)

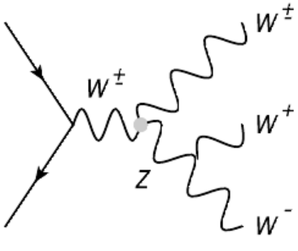
Multiboson

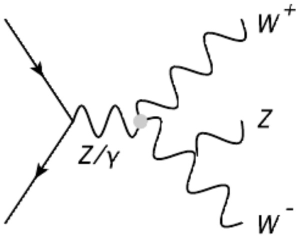
- 🟥 **Wγ**
- 🟦 **Zγ**
- 🟨 **WW**
- 🟨 **WZ**
- 🟨 **ZZ**



Triboson

- ⬜ **WWZ**
- 🟦 **WWW**
- ⬜ **WZZ**
- 🟦 **WWγ**
- 🟦 **WZγ**
- 🟦 **Wγγ**
- ⬜ **γγγ**
- ⬜ **ZZγ**
- 🟦 **Zγγ**
- ⬜ **ZZZ**





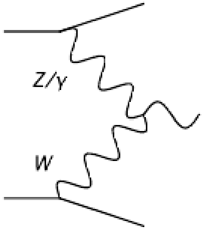
O(0.2 pb)
↓
O(0.02 pb)

Excluding BR

Vector Boson Fusion or Scattering (VBF/VBS)

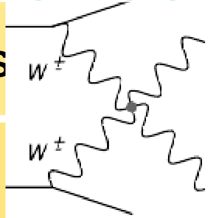
O(20 pb) - O(400 pb)

- 🟦 **W**
- 🟨 **Z**
- ⬜ **γ** not measured

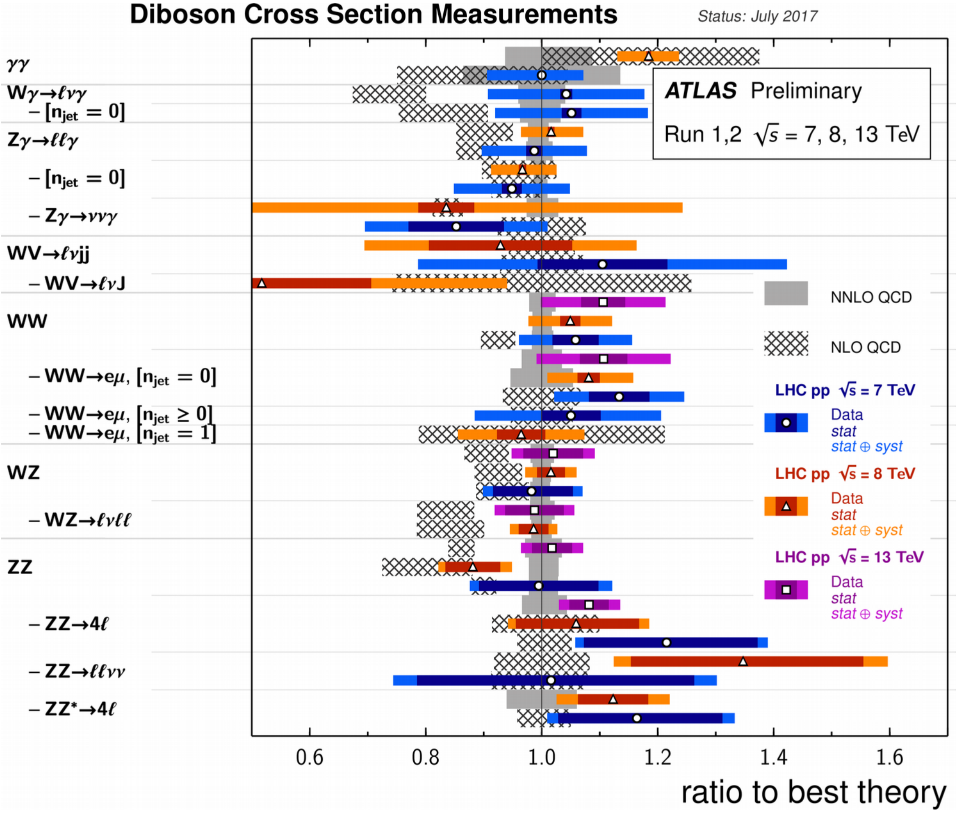


O(0.2 pb) - O(0.02 pb)

- 🟨 **WW VBS**
- 🟨 **WZ VBS**
- 🟨 ***ZZ VBS**
- 🟦 **Zγ VBS**
- ⬜ **Wγ VBS**

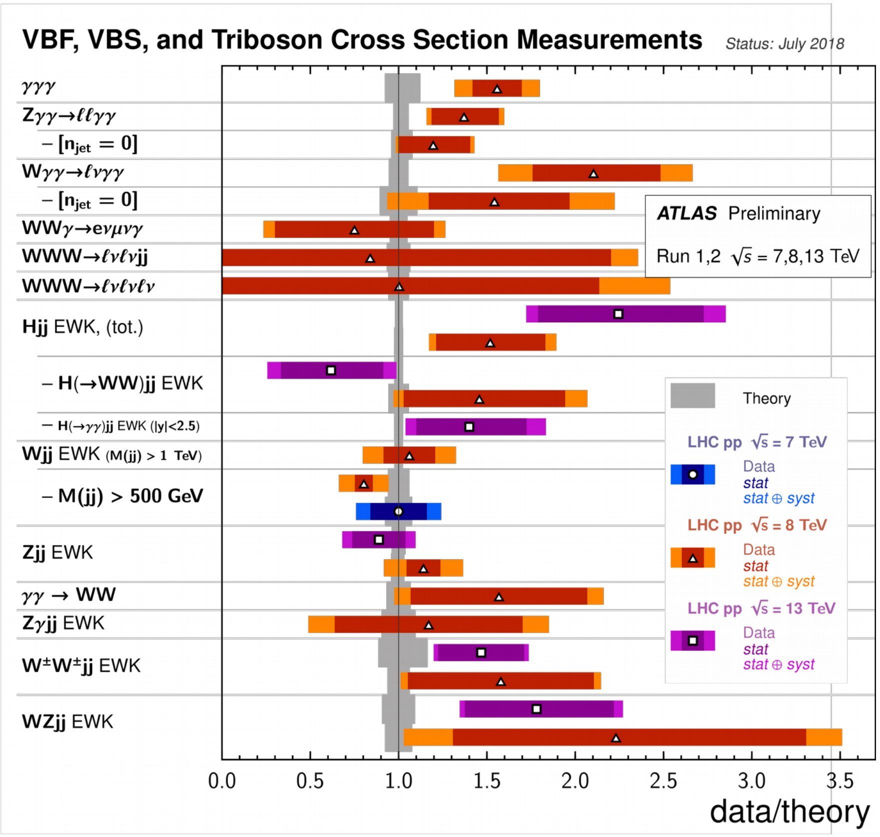


Current results



Diboson Cross Section Measurements

Status: July 2017



VBF, VBS, and Triboson Cross Section Measurements

Status: July 2018

The
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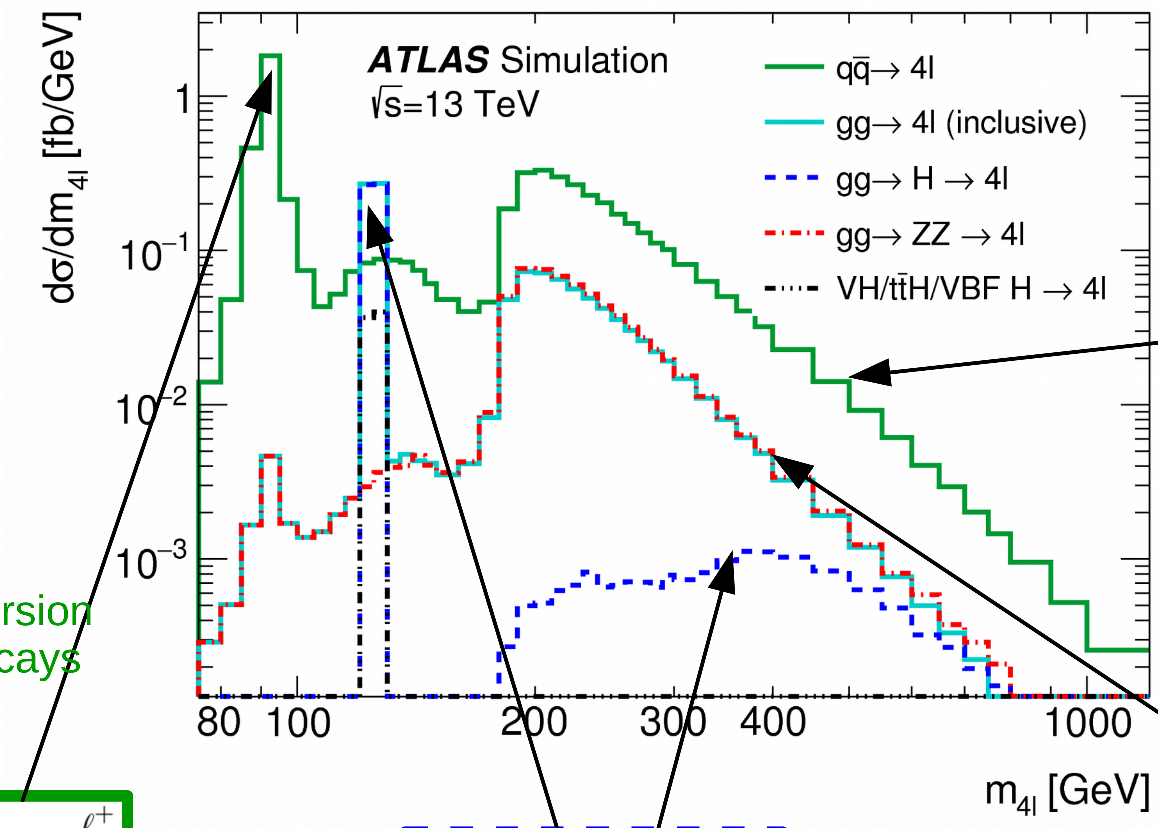
Sheffield.

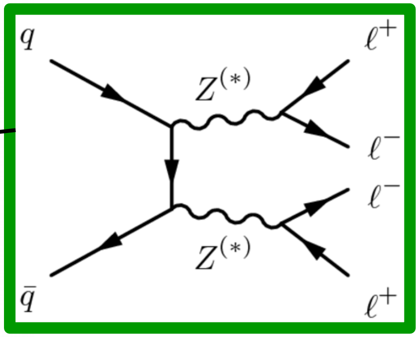
Production of Z-boson pairs

- Not just one process – no one-fits-it-all approach possible!

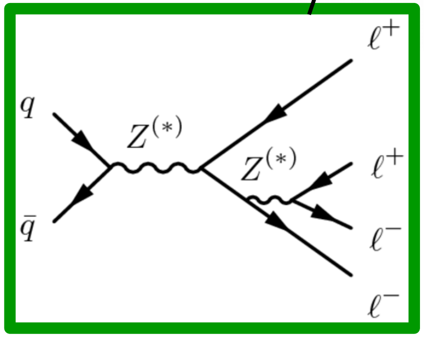
arXiv:1902.05892



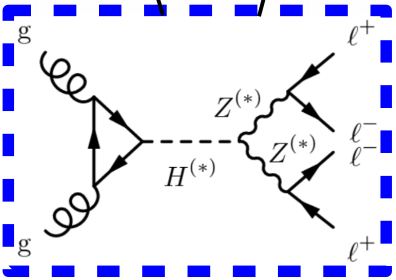
qq-induced ZZ-production (threshold above $2xM_Z$)



internal conversion in Z boson decays with peak at m_{4l}=90 GeV

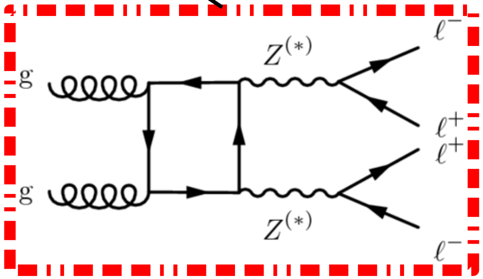


Resonant Higgs production m_{4l}=125 GeV



Offshell gg-Higgs production threshold-effect due to top-loops

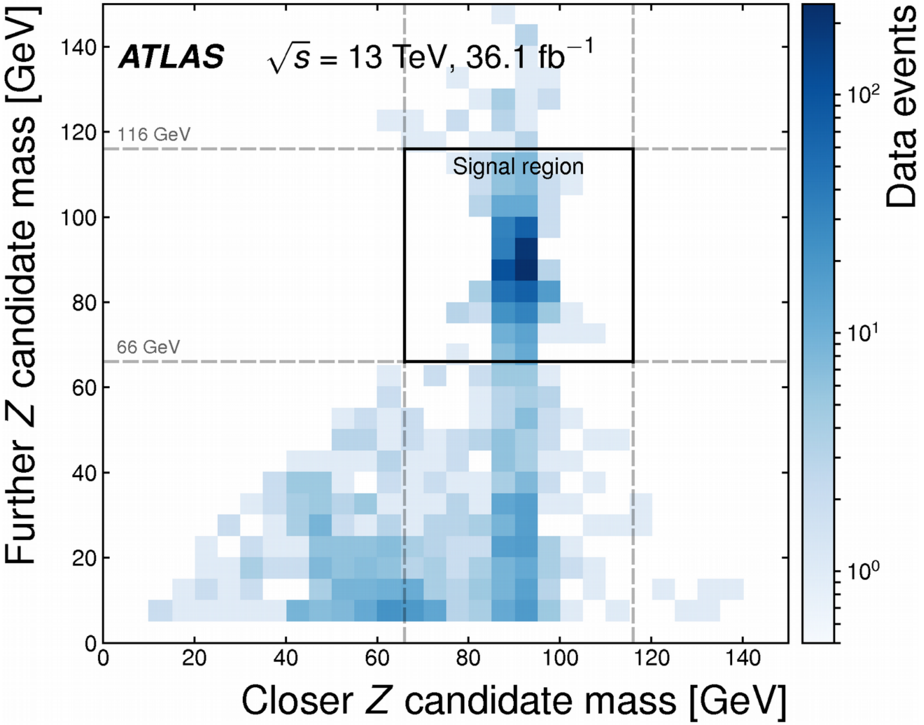
gg-induced non-resonant ZZ production (threshold above $2xM_Z$)



Selection of events

> Rough sketch of requirements

- Leptons with > 5 / 20 / 25 / 20 GeV
- Same-flavour – opposite-charge pairs
  → smallest overall $|m_Z – m_{ll}|$
- m_{ll} > 5 GeV → reject J/Ψ
- ΔR_{ll} > 0.1 (0.2) for same (opposite) flavour leptons
  → reject electrons from muon brems



- Depending on what you want to study:
  → **ZZ:** select two on-shell Z’s: 66 < m_Z < 116 GeV
  → **Lineshape:** select one on-shell Z (50<m_{12}<106 GeV) and one off-shell Z (m34<115GeV with a lower bound optimized to reject τ-lepton)
  → **Higgs:** select the Higgs mass window (not covered here)

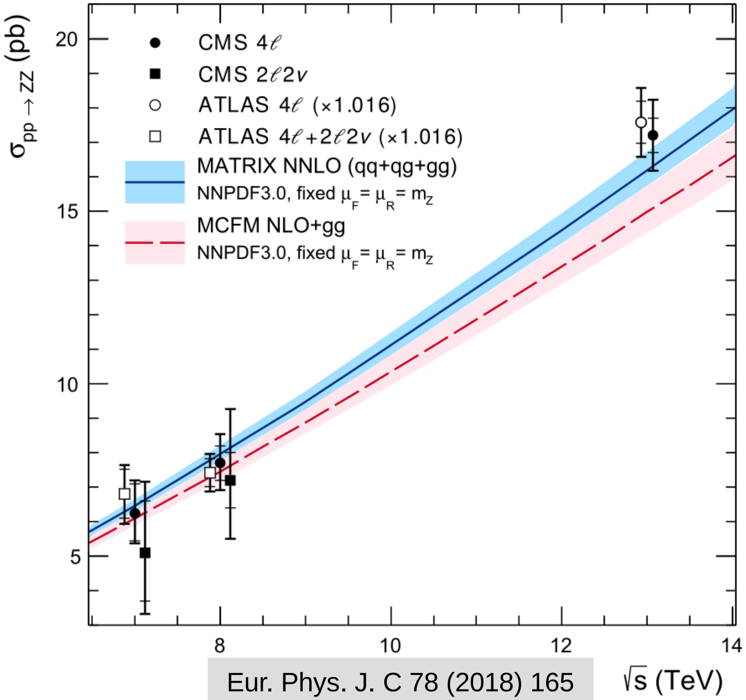
ZZ production: Total cross sections

> ATLAS and CMS agree very well – NNLO calculation needed

- ATLAS: 46.2 +/- 1.5 (stat) +/- 1.15 (syst) +/- 1.5 (lumi) → theo: 42.9 +/- 1.7 pb
- CMS: 40.9 +/- 1.3 (stat) +/- 1.4 (syst) +/- 1.0 (lumi) → theo: 36.0 +/- 0.85 pb

  → **measurement starts to be systematics dominated**

- Excess for 4e (ATLAS, 2.5 σ) not confirmed by CMS (though also more 4e than expected)



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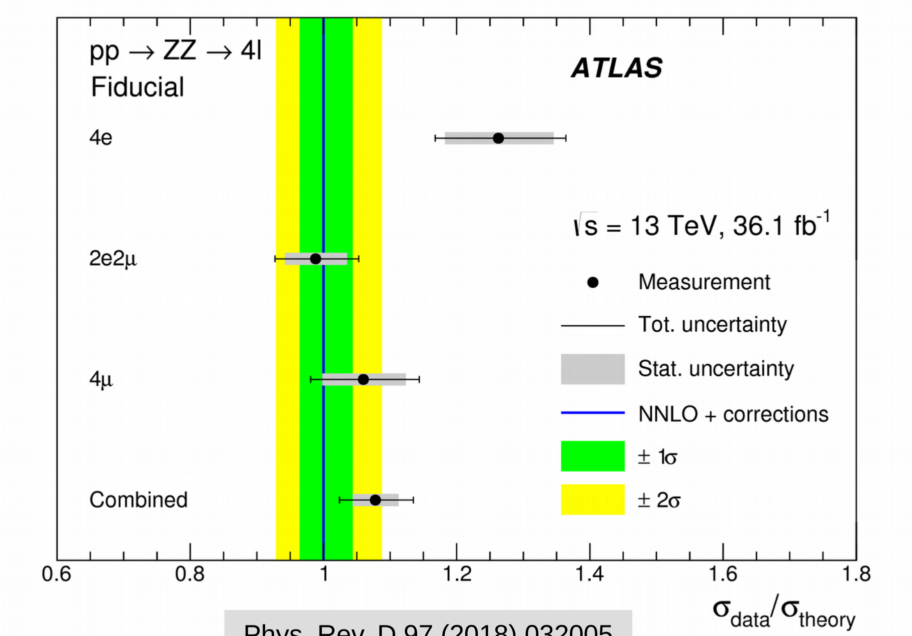
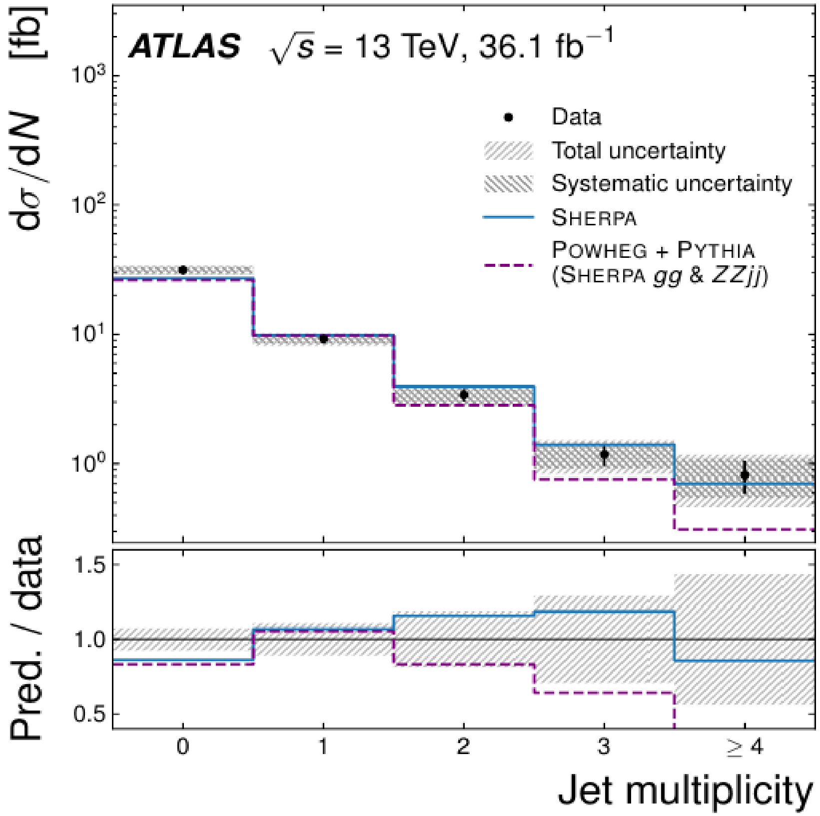


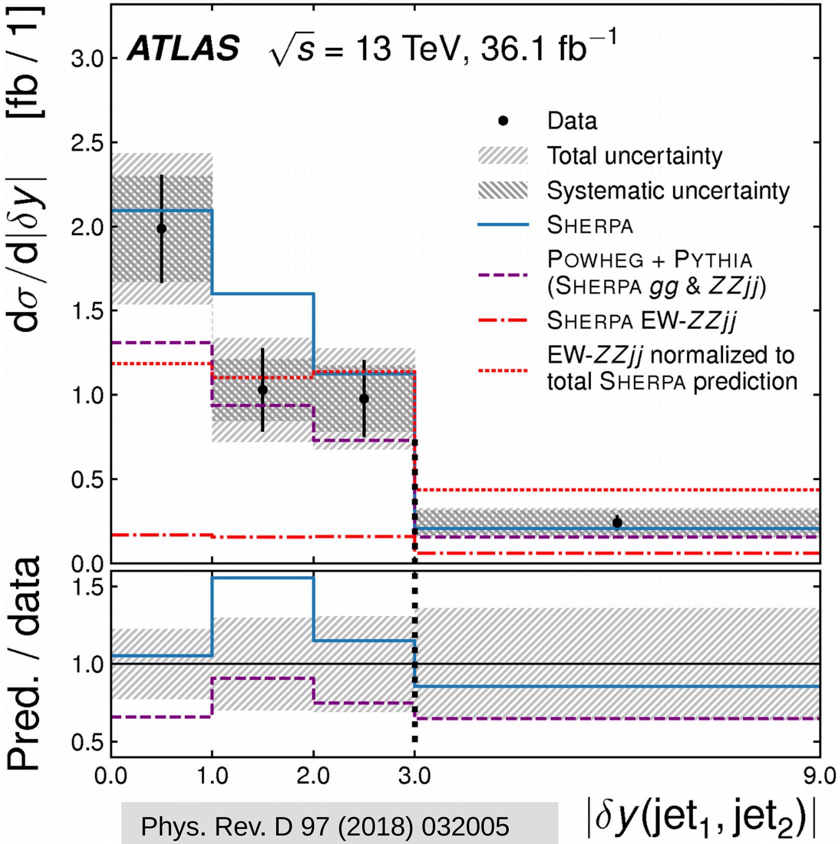
Phys. Rev. D 97 (2018) 032005

ZZ production: Differential distributions with ATLAS

> Reasonable agreement for various distributions with jets

- Important test with implications for other diboson production processes usually measured using jet vetos (→ e.g. WW)



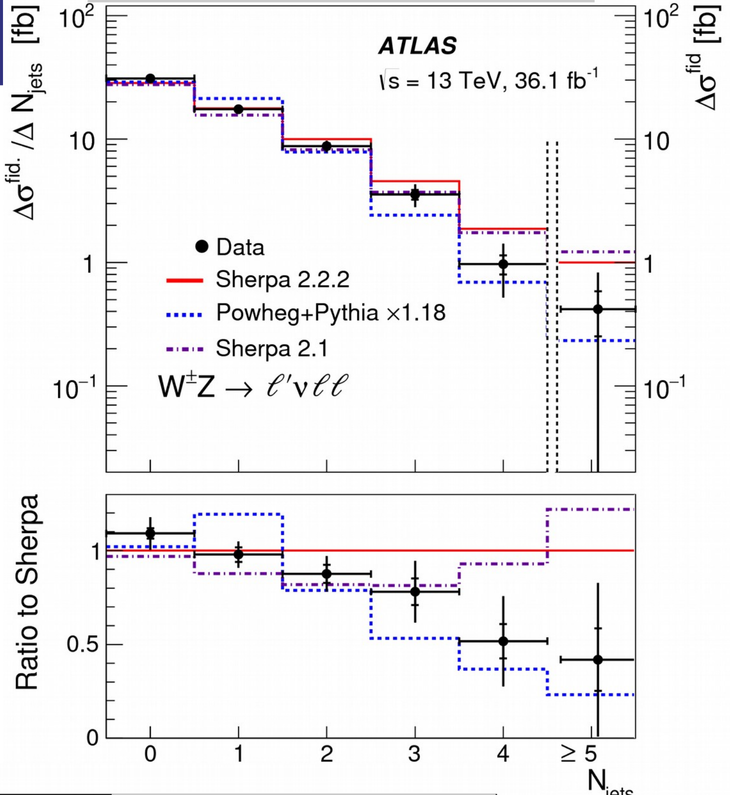


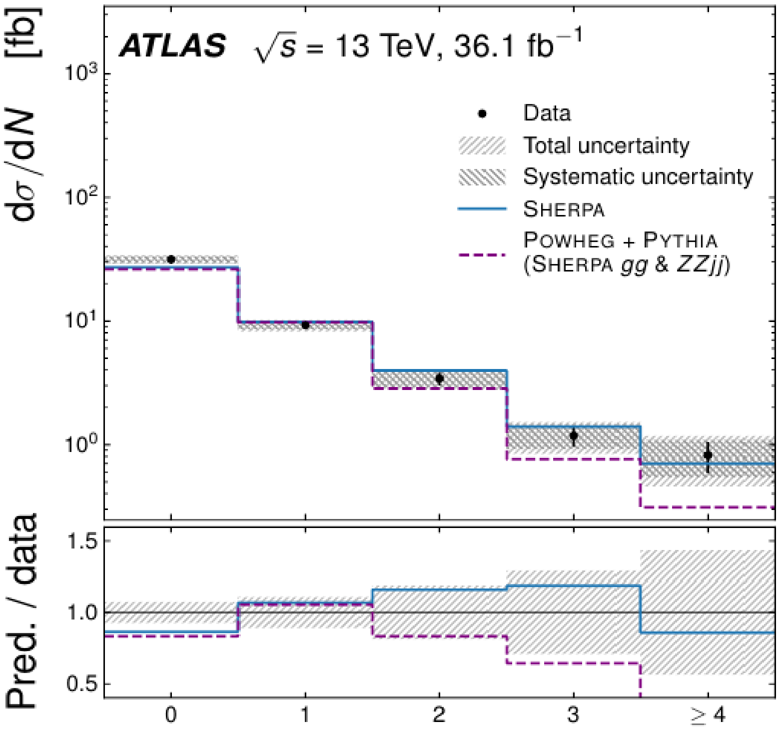
Phys. Rev. D 97 (2018) 032005

Exclusive jets in dibosons

> Similar behaviour for WW, WZ, ZZ

https://arxiv.org/abs/1902.05759





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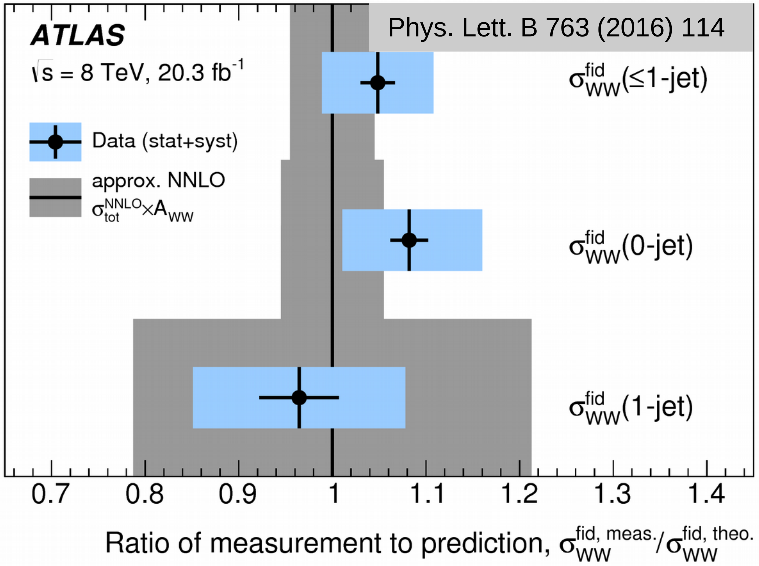
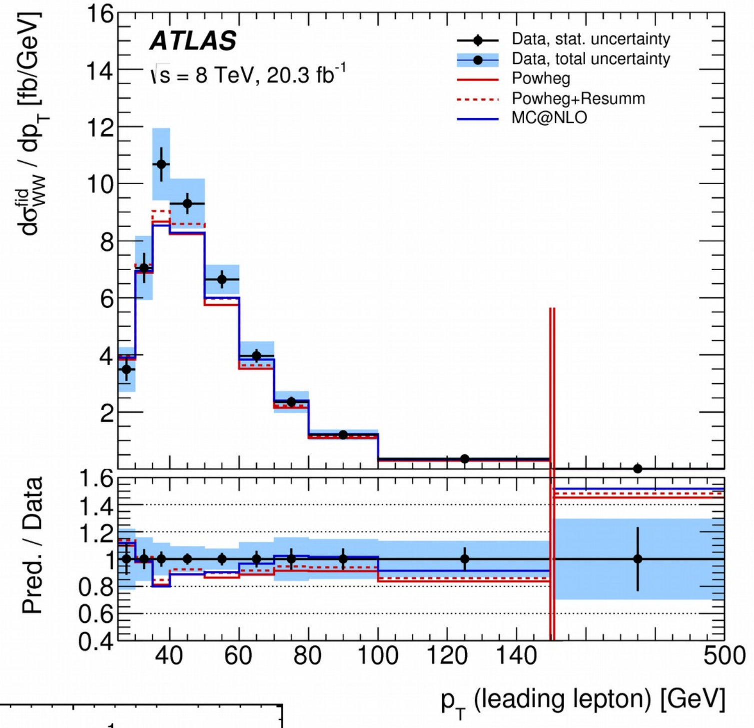


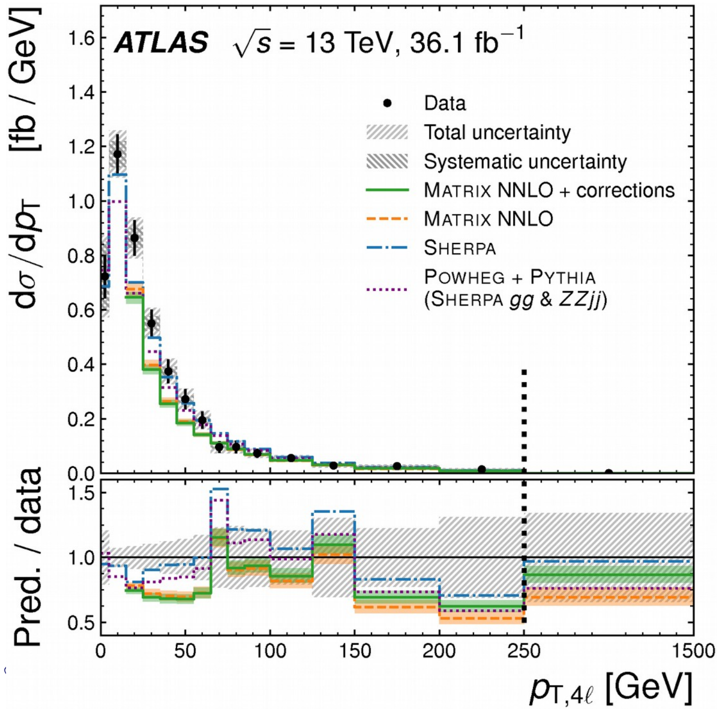
Phys. Lett. B 763 (2016) 114

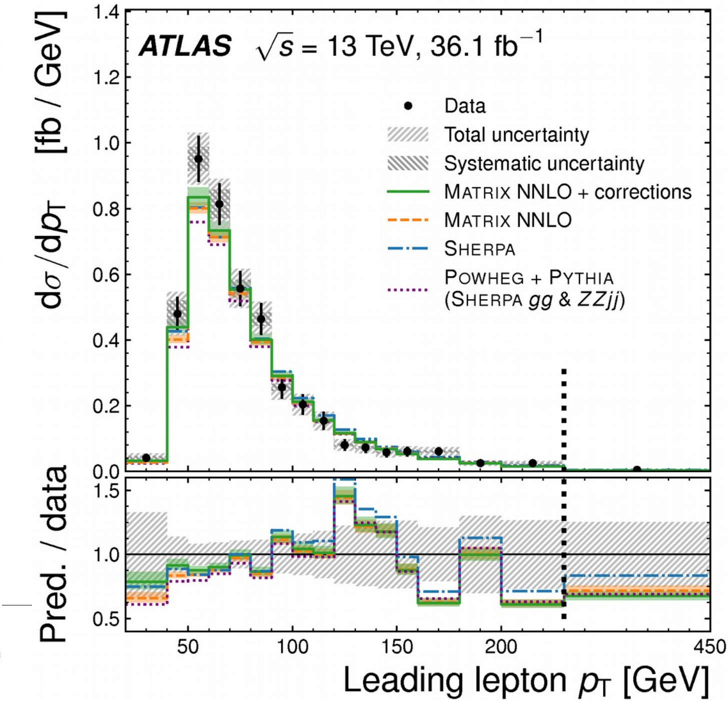
pT distributions

> **Is it in the description of the recoil of the boson system?**

- Best prediction has the gg-initiated contribution multiplied by a global NLO correction factor of 1.67.
  An NLO EW correction factor is applied in each bin. The contribution from EW-ZZ j j generated with Sherpa is added.







The M_{4l} lineshape (unfolded)

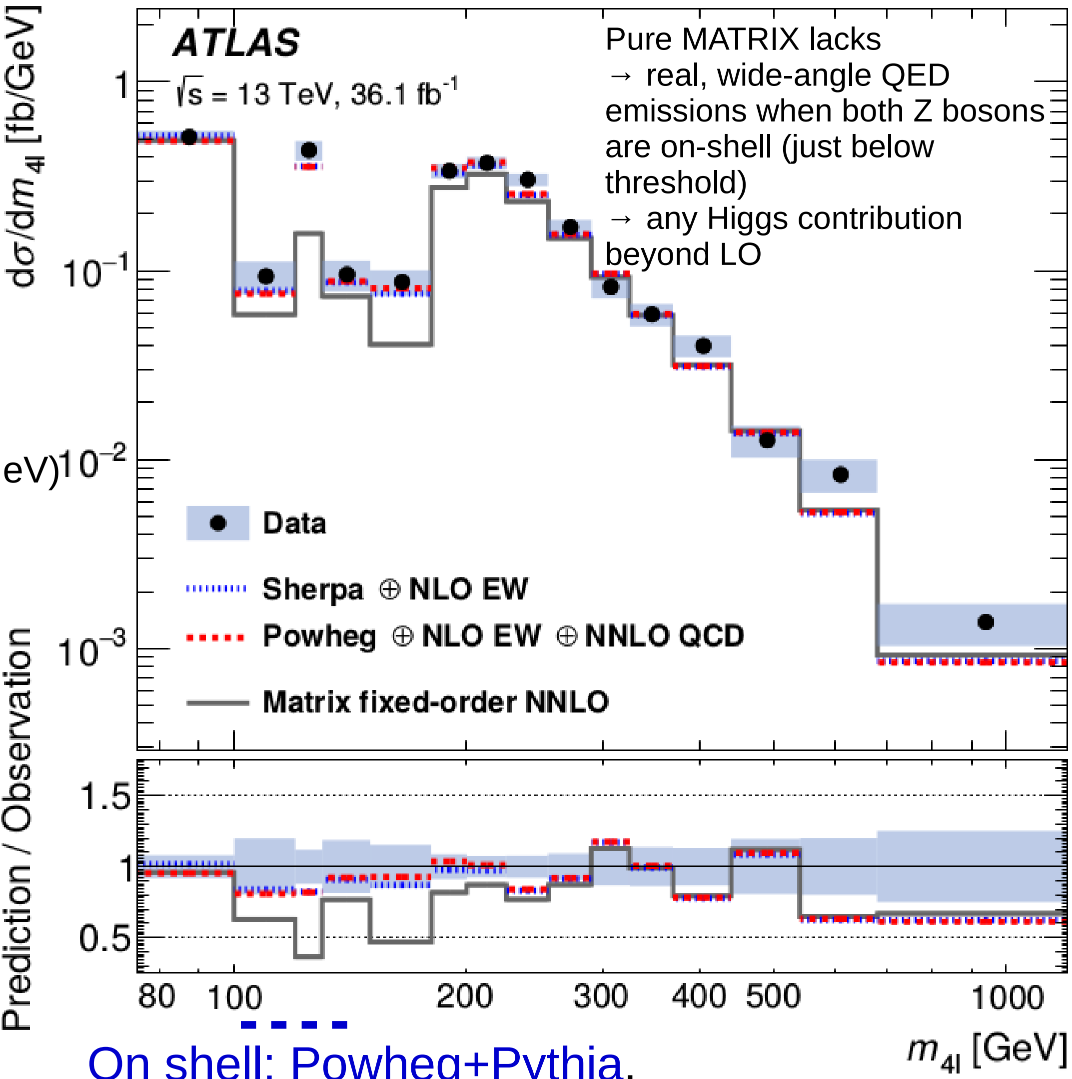
> **Generally good agreement**

> Sherpa 2.2.2
  - ME up to one parton (NLO) and up to three partons (LO), merged with the Sherpa parton shower using ME+PS@NLO prescription
  - Reweighting for virtual NLO EW effects (Biedermeier et al) applied (+3% @m_{4l}~130 GeV and −20%>800 GeV)

> Very good agreement with Powheg corrected usin MATRIX NNLO

> Sherpa 2.2.2 Real EW correction (incl. VBS scattering)

> Sherpa 2.2.2. for gg-initiated diagrams
  - 0+1 partons in LO (+NLO correction by Caola et al. by separate m_{4l}-k-factors)
  - Additional 1.2 k-factor for NNLO QCD



Pure MATRIX lacks
→ real, wide-angle QED emissions when both Z bosons are on-shell (just below threshold)
→ any Higgs contribution beyond LO

On shell: Powheg+Pythia,
NNLO QCD accuracy using the HNNLO program

Impact of theoretical progress on WW (8 TeV)

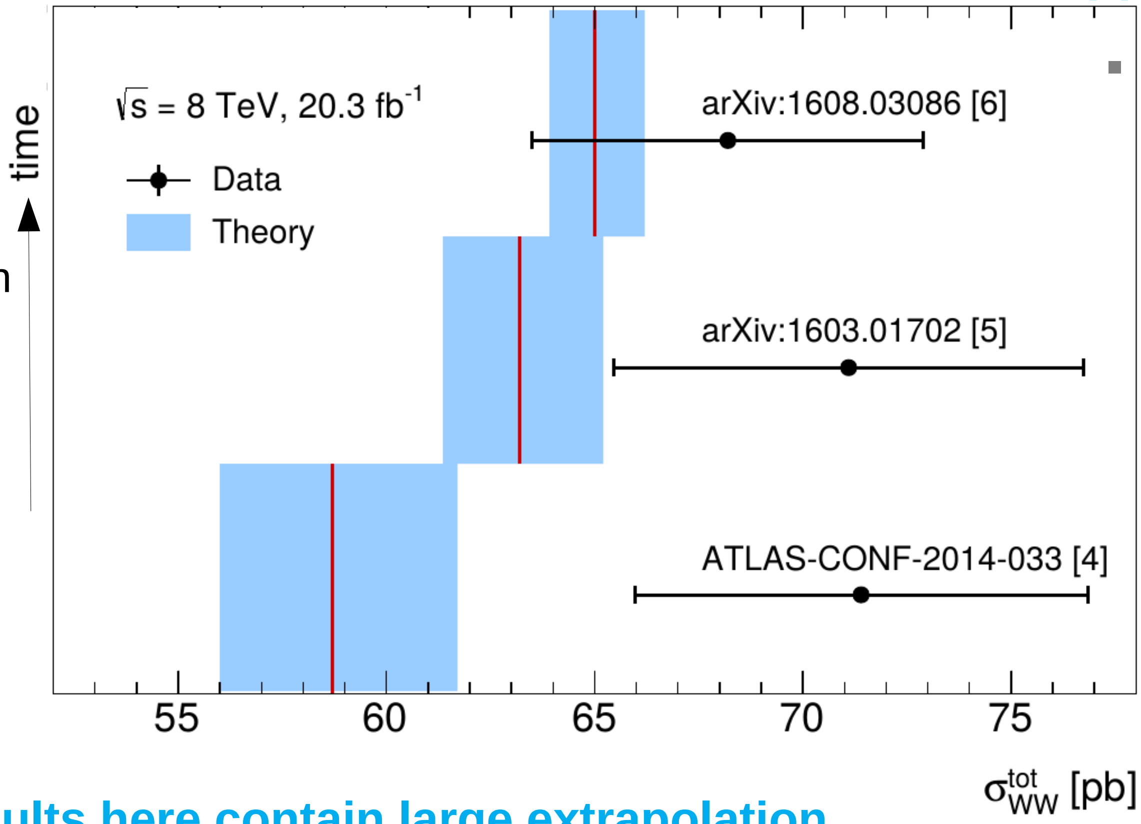
> Theory Progress

> Experimental Progress

- Extension of fiducial phase space

- Non-resonant gg NLO
- Higgs N3LO prediction

- (qq → WW) NNLO predictions
- Resummation effects due to jet veto



> Experimental results here contain large extrapolation

> Desirable: Compare theory to best fiducial measurement

The University Of Sheffield.

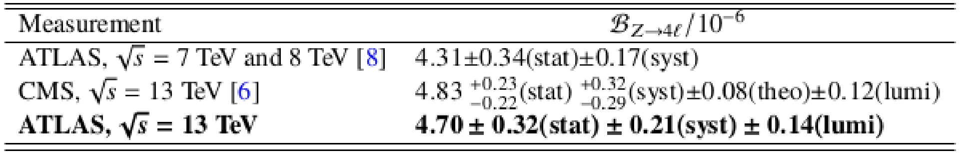
Interpretation

arXiv:1902.05892

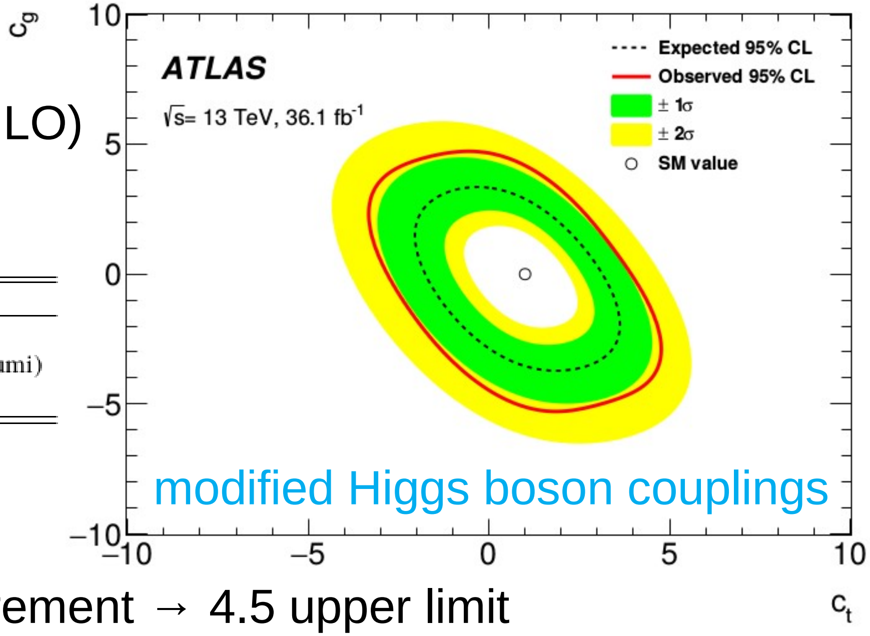
- Extracted from the unfolded distributions
- Test of the versality of the approach
  - Variation of off-shell Higgs production, or gluon-induced ZZ production, (−75% / +200% and −100% / +400% respectively)
    → true lineshape very well reproduced using the SM-based response matrix
  - Injection of additional scalar resonance (with mass= 200, 400 and 900 GeV)
    → Bias can be as large as the dominant statistical uncertainty

> Signal strength of gg → 4l production
1.3 ± 0.5 (expected value of 1.0 ± 0.4 in NLO)

> Z → 4l branching fraction



Measurement	$\mathcal{B}_{Z\to 4\ell}/10^{-6}$
ATLAS, $\sqrt{s}$ = 7 TeV and 8 TeV [8]	4.31±0.34(stat)±0.17(syst)
CMS, $\sqrt{s}$ = 13 TeV [6]	4.83 $^{+0.23}_{-0.22}$(stat) $^{+0.32}_{-0.29}$(syst)±0.08(theo)±0.12(lumi)
ATLAS, $\sqrt{s}$ = 13 TeV	**4.70 ± 0.32(stat) ± 0.21(syst) ± 0.14(lumi)**



modified Higgs boson couplings

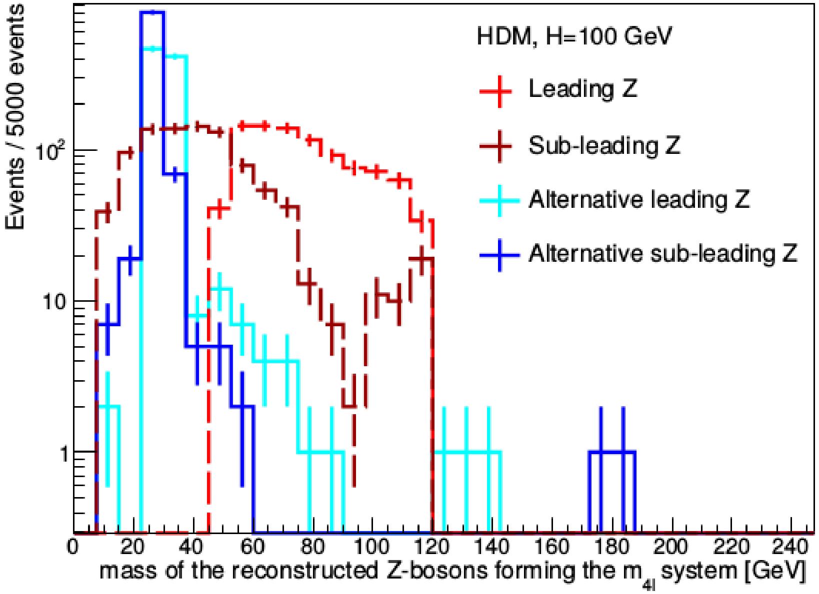
> Off-shell Higgs boson signal strength
6.5 [4.2, 7.2] 95% CL upper limit
→ to be compared with dedicated measurement → 4.5 upper limit

Reinterpretations of these unfolded data: A model

- Interpretation also outside ATLAS possible
- Fast and easy model testing

https://arxiv.org/abs/1606.05296
Contour – Butterworth et al.
https://arxiv.org/abs/1803.10379
Les Houches 2017

- Here: Two Higgs-Doublet model to explain ALEPH excess at $m_{\mu\mu}$ = 30 GeV
  - Dominant processes: h^+h^-, $h^\pm h$, $h^\pm\eta$ production decaying to $h^\pm \rightarrow \mu^\pm\nu$; $h \rightarrow \mu^+\mu^-$
  - “Primary” search channel: WW, WZ comparing the leptonic branching fractions
  - Turns out: most excluded by m4l lineshape measurement
  - Dominating decays at the mass range considered: $h^\pm \rightarrow hW$ and $h \rightarrow \mu^+\mu^-$
  - Despite actual resonance at 30 GeV, wrong pairing leads to selection in analysis
  - Neat tool to test models early on and avoid surprises!
  - Other example: V+jets as constraint for DM



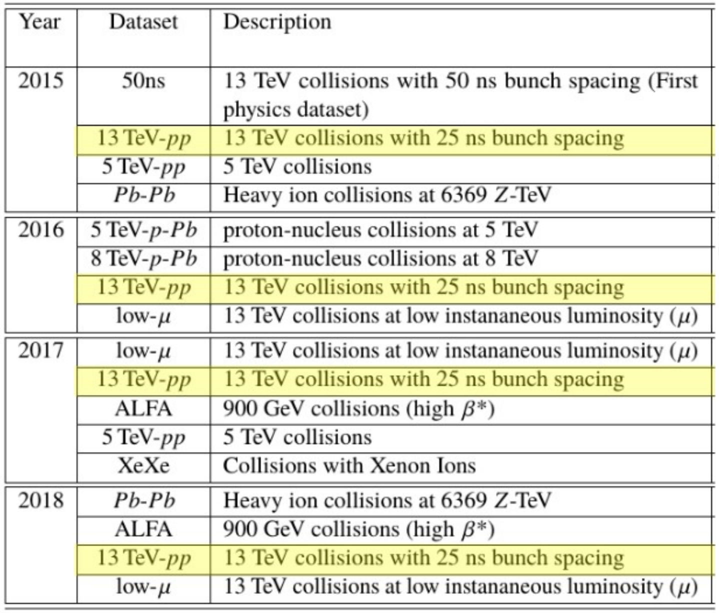
Where to go next?

> Just finished data taking – 140 fb^{-1} translates into huge data set (physically!)

  - >60 TB of di-lepton skimmed data *only*

  - Received first luminosity calculation just this week (so all numbers above are wrong)

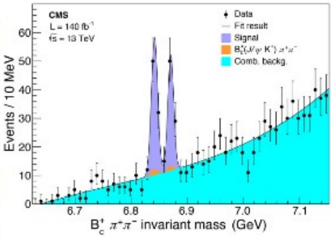
  - No final calibrations → and precision needs time (can be >130-150 NP for analysis with more than one type of object)



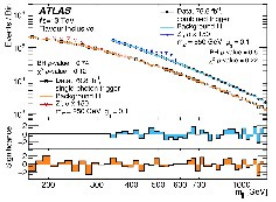
Year	Dataset	Description
2015	50ns	13 TeV collisions with 50 ns bunch spacing (First physics dataset)
	13 TeV-*pp*	13 TeV collisions with 25 ns bunch spacing
	5 TeV-*pp*	5 TeV collisions
	Pb-Pb	Heavy ion collisions at 6369 *Z*-TeV
2016	5 TeV-*p-Pb*	proton-nucleus collisions at 5 TeV
	8 TeV-*p-Pb*	proton-nucleus collisions at 8 TeV
	13 TeV-*pp*	13 TeV collisions with 25 ns bunch spacing
	low-μ	13 TeV collisions at low instananeous luminosity (μ)
2017	low-μ	13 TeV collisions at low instananeous luminosity (μ)
	13 TeV-*pp*	13 TeV collisions with 25 ns bunch spacing
	ALFA	900 GeV collisions (high β*)
	5 TeV-*pp*	5 TeV collisions
	XeXe	Collisions with Xenon Ions
2018	*Pb-Pb*	Heavy ion collisions at 6369 *Z*-TeV
	ALFA	900 GeV collisions (high β*)
	13 TeV-*pp*	13 TeV collisions with 25 ns bunch spacing
	low-μ	13 TeV collisions at low instananeous luminosity (μ)

> Just above 140 fb^{-1}

only full Run-2 result:
CMS $B_c(2s)$



ATLAS: Resolved low mass dijet resonance search with ISR with 80 fb^{-1} (2015-2017)



> So what is to be expected?

  - Observations/measurements on small, specific data sets

  - Generic searches for resonances

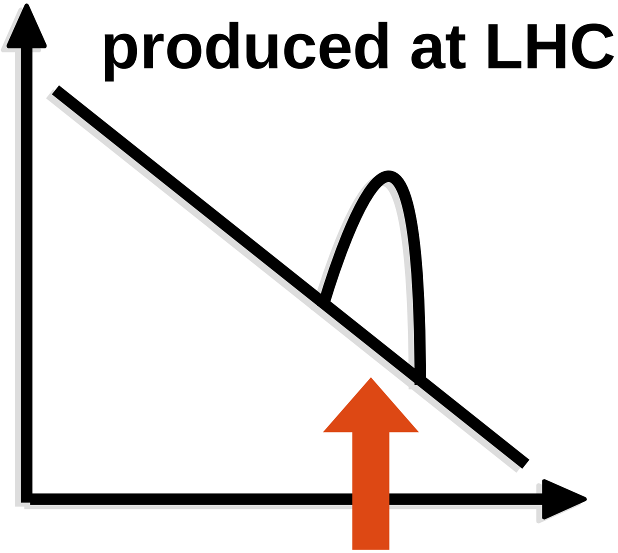
Generic searches for resonances

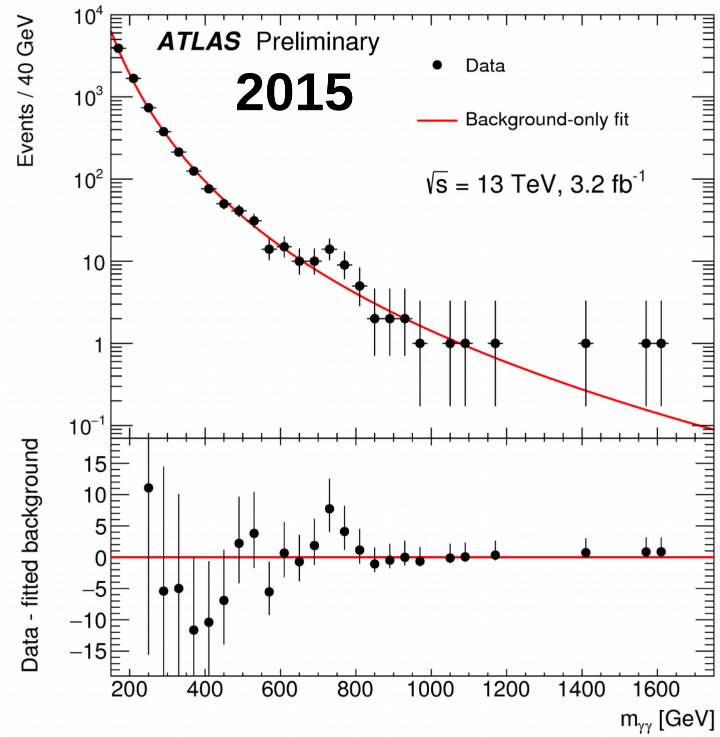
- Generic search for resonance in a (falling) distribution
- Not necessarily connected a priori with a striking theoretical motivation

Example: diphoton excess

- (Feb 2016) **~ 170 papers**
  ~165 spin-0 resonance
  ~5 spin-2 resonance
  ~1 spin-1 resonance
  ~5 parent resonance/kinematic edge

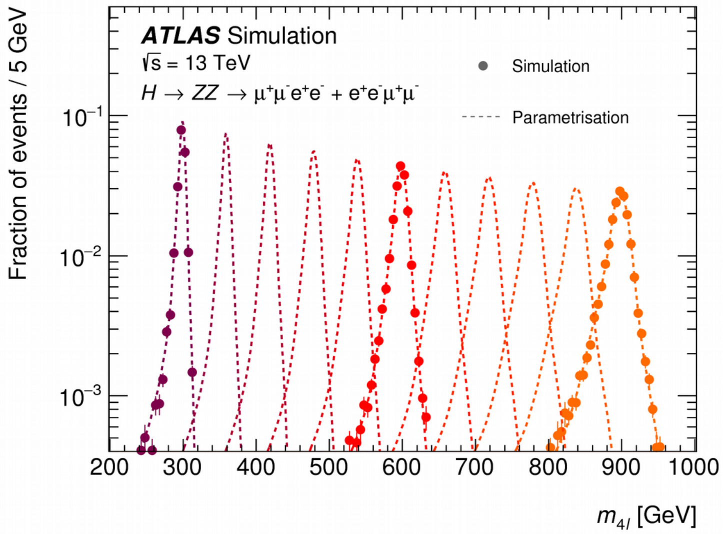
Search for resonance directly produced at LHC

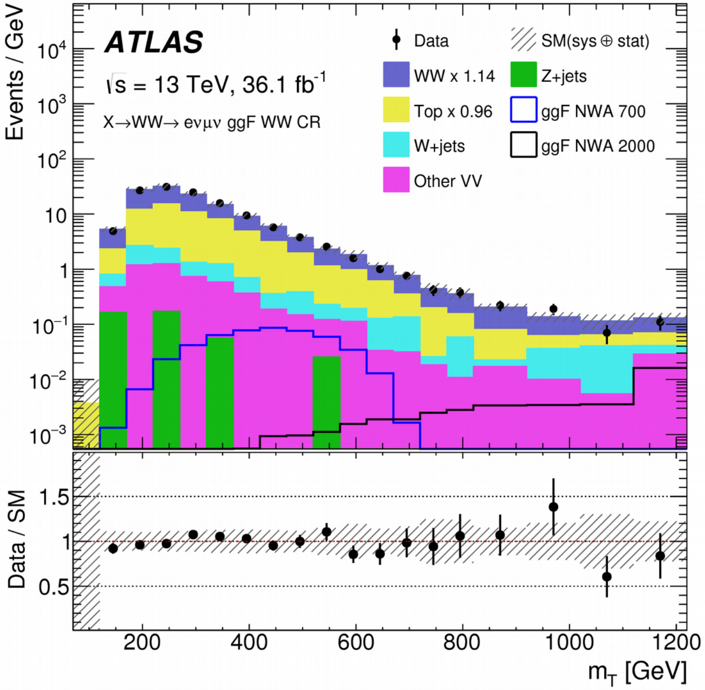




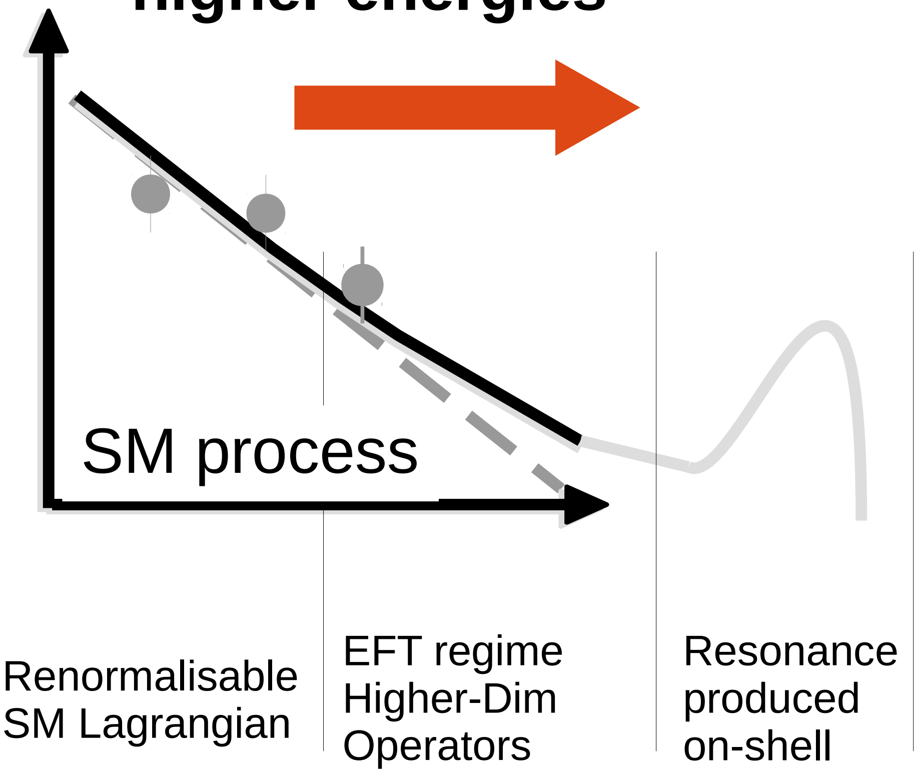
Generic searches for resonances

- Narrow width approximation (NWA)
  - width << mass (here width < 0.5% of m_H)
  - Decay products lighter, m<<M
  - M<< $\sqrt{s}$
  - Interference often neglected
- High-mass Higgs decaying to ZZ or WW (decaying to leptons)
- Often reliant on assumption of generic falling backgound shape and existence of pronounced peak
- Can be difficult to reinterpret





What if we don't reach the resonance? Effective field theory



- Generic search for **deviations in distributions** sensitive to new physics effects
- Could be sensitive to much **higher energies scales** compared to resonance searches
- Detects also new physics **without resonances or very broad resonances**

A more general look at the data: EFT

- In a more general formulation:

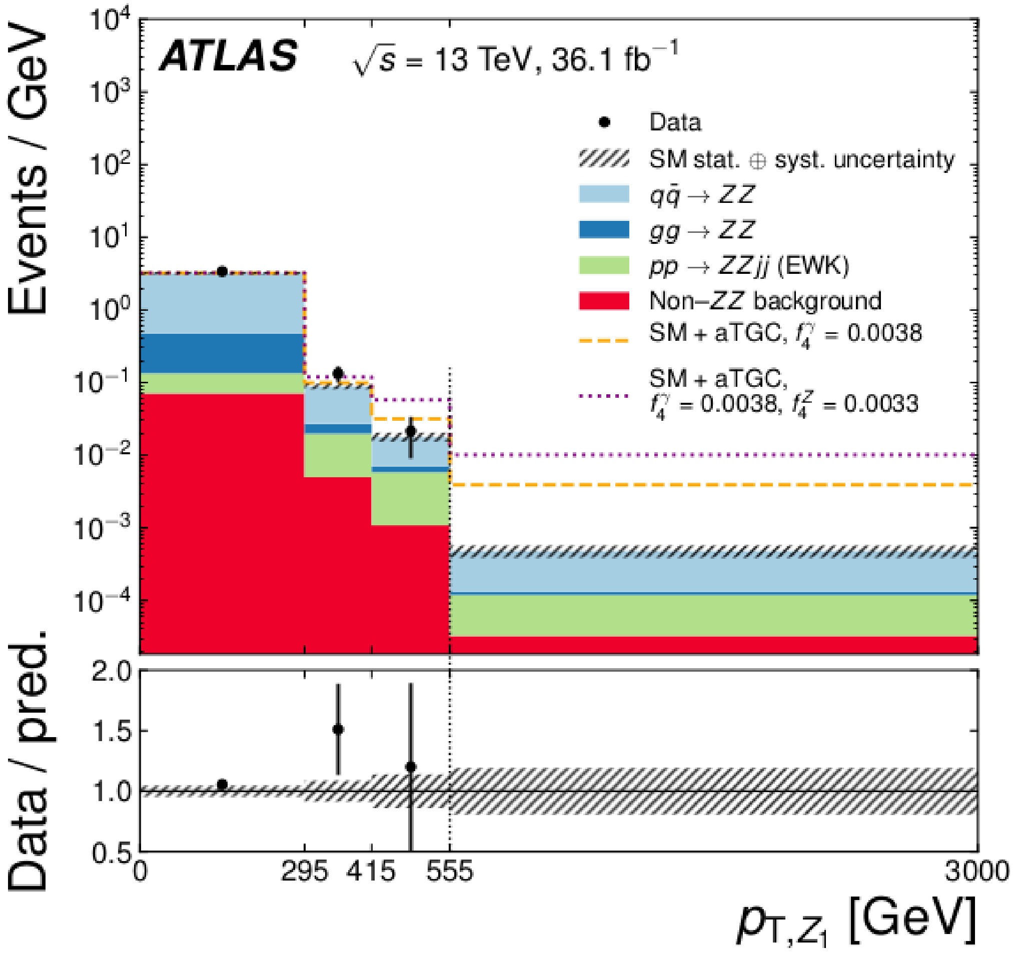
$$\sigma = \sigma^{\mathrm{SM}} + \sum_i \left(\frac{c_i^{(6)}}{\Lambda^2} \sigma_i^{(6\times\mathrm{SM})} + \mathrm{h.c.} \right) + \sum_{ij} \frac{c_i^{(6)} c_j^{(6)*}}{\Lambda^4} \sigma_{ij}^{(6\times 6)} + \sum_j \left(\frac{c_j^{(8)}}{\Lambda^4} \sigma_j^{(8\times\mathrm{SM})} + \mathrm{h.c.} \right) + \ldots$$

- Expansion of new physics in inverse of energy scale $1/\Lambda$
- Introduce new operators σ_i (respecting SM symmetries) of energy dimension $n > 4$, suppressed by increasing powers of Λ
- Captures low-energy effect of UV theory beyond Λ for $\Lambda \gg \sqrt{s}$
- Operator basis not unique, different conventions in use
- One lepton number violating dim-5 operator (but focus on dim-6 / dim-8)
- 2499 operators at dimension six, assuming flavour symmetry < 100
- Constrain EFT coefficients ⇒ constrain large classes of UV theories

Current status of EFT constraints in dibosons

- For Run-1:
  Constraints set traditionally
  in anomalous coupling framework
  and EFT in HISZ basis
  (using DimO6 model by C. Degrande)

- Targeting high-energy tails, often
  dominated by squared terms

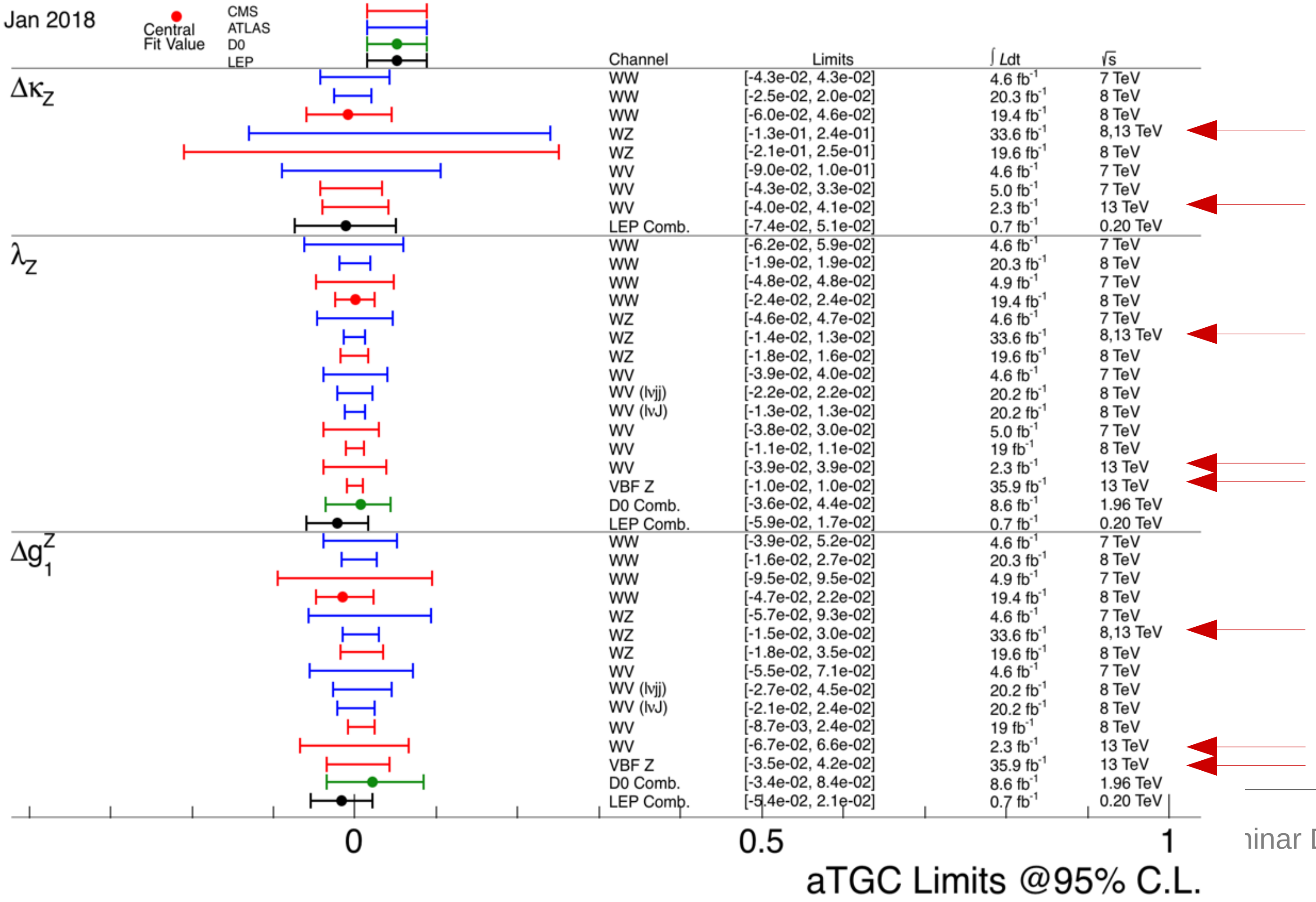


Shattering the Standard Model?

> Test for general SM extensions without results

- Independent of basis used: Zero hints for hidden new physics in **charged Multibosons** …

> LHC results superseeding all previous experiments

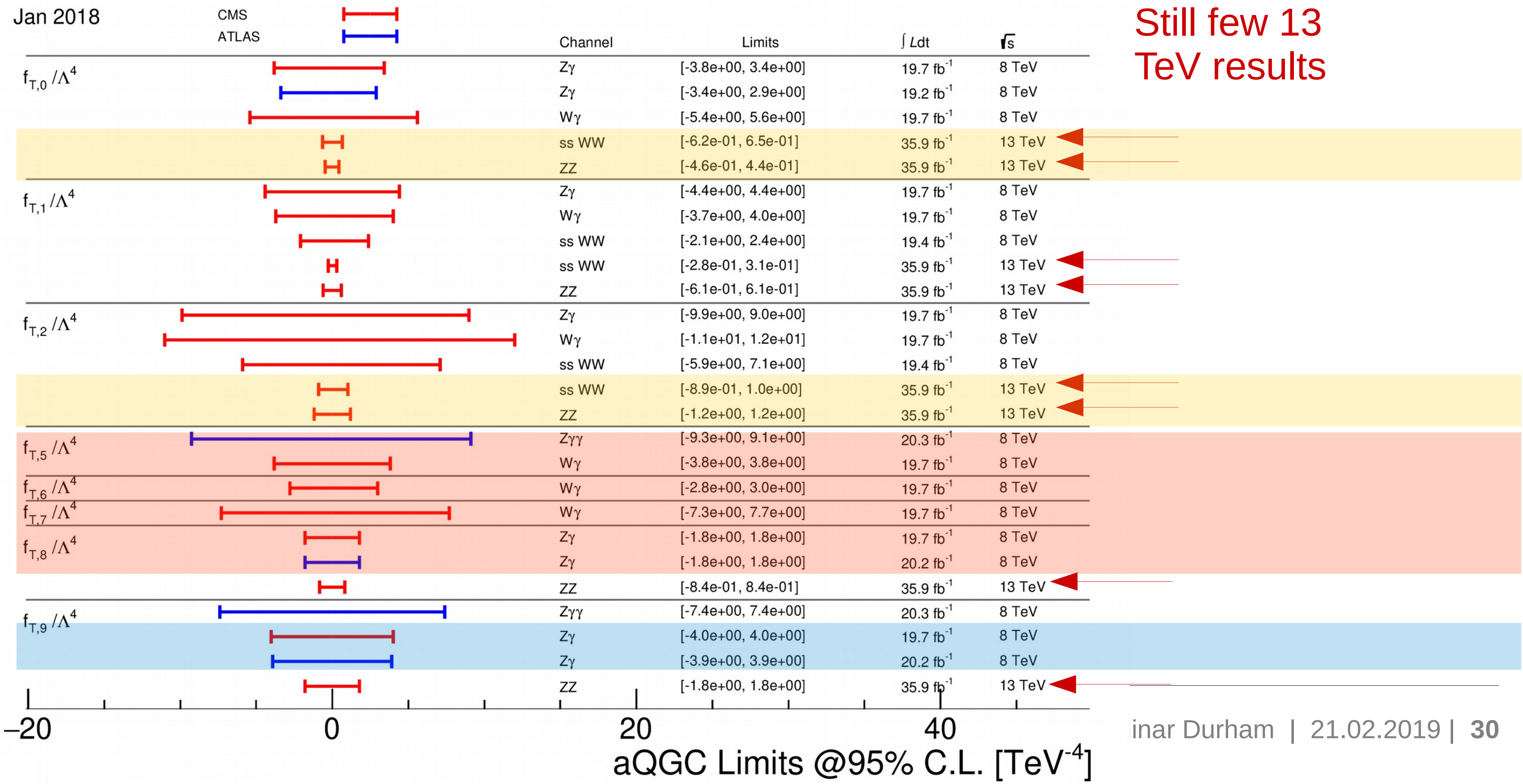


	Channel	Limits	$\int Ldt$	$\sqrt{s}$
$\Delta\kappa_Z$	WW	[-4.3e-02, 4.3e-02]	4.6 fb^{-1}	7 TeV
	WW	[-2.5e-02, 2.0e-02]	20.3 fb^{-1}	8 TeV
	WW	[-6.0e-02, 4.6e-02]	19.4 fb^{-1}	8 TeV
	WZ	[-1.3e-01, 2.4e-01]	33.6 fb^{-1}	8,13 TeV
	WZ	[-2.1e-01, 2.5e-01]	19.6 fb^{-1}	8 TeV
	WV	[-9.0e-02, 1.0e-01]	4.6 fb^{-1}	7 TeV
	WV	[-4.3e-02, 3.3e-02]	5.0 fb^{-1}	7 TeV
	WV	[-4.0e-02, 4.1e-02]	2.3 fb^{-1}	13 TeV
	LEP Comb.	[-7.4e-02, 5.1e-02]	0.7 fb^{-1}	0.20 TeV
λ_Z	WW	[-6.2e-02, 5.9e-02]	4.6 fb^{-1}	7 TeV
	WW	[-1.9e-02, 1.9e-02]	20.3 fb^{-1}	8 TeV
	WW	[-4.8e-02, 4.8e-02]	4.9 fb^{-1}	7 TeV
	WW	[-2.4e-02, 2.4e-02]	19.4 fb^{-1}	8 TeV
	WZ	[-4.6e-02, 4.7e-02]	4.6 fb^{-1}	7 TeV
	WZ	[-1.4e-02, 1.3e-02]	33.6 fb^{-1}	8,13 TeV
	WZ	[-1.8e-02, 1.6e-02]	19.6 fb^{-1}	8 TeV
	WV	[-3.9e-02, 4.0e-02]	4.6 fb^{-1}	7 TeV
	WV (lνjj)	[-2.2e-02, 2.2e-02]	20.2 fb^{-1}	8 TeV
	WV (lνJ)	[-1.3e-02, 1.3e-02]	20.2 fb^{-1}	8 TeV
	WV	[-3.8e-02, 3.0e-02]	5.0 fb^{-1}	7 TeV
	WV	[-1.1e-02, 1.1e-02]	19 fb^{-1}	8 TeV
	WV	[-3.9e-02, 3.9e-02]	2.3 fb^{-1}	13 TeV
	VBF Z	[-1.0e-02, 1.0e-02]	35.9 fb^{-1}	13 TeV
	D0 Comb.	[-3.6e-02, 4.4e-02]	8.6 fb^{-1}	1.96 TeV
	LEP Comb.	[-5.9e-02, 1.7e-02]	0.7 fb^{-1}	0.20 TeV
Δg_1^Z	WW	[-3.9e-02, 5.2e-02]	4.6 fb^{-1}	7 TeV
	WW	[-1.6e-02, 2.7e-02]	20.3 fb^{-1}	8 TeV
	WW	[-9.5e-02, 9.5e-02]	4.9 fb^{-1}	7 TeV
	WW	[-4.7e-02, 2.2e-02]	19.4 fb^{-1}	8 TeV
	WZ	[-5.7e-02, 9.3e-02]	4.6 fb^{-1}	7 TeV
	WZ	[-1.5e-02, 3.0e-02]	33.6 fb^{-1}	8,13 TeV
	WZ	[-1.8e-02, 3.5e-02]	19.6 fb^{-1}	8 TeV
	WV	[-5.5e-02, 7.1e-02]	4.6 fb^{-1}	7 TeV
	WV (lνjj)	[-2.7e-02, 4.5e-02]	20.2 fb^{-1}	8 TeV
	WV (lνJ)	[-2.1e-02, 2.4e-02]	20.2 fb^{-1}	8 TeV
	WV	[-8.7e-03, 2.4e-02]	19 fb^{-1}	8 TeV
	WV	[-6.7e-02, 6.6e-02]	2.3 fb^{-1}	13 TeV
	VBF Z	[-3.5e-02, 4.2e-02]	35.9 fb^{-1}	13 TeV
	D0 Comb.	[-3.4e-02, 8.4e-02]	8.6 fb^{-1}	1.96 TeV
	LEP Comb.	[-5.4e-02, 2.1e-02]	0.7 fb^{-1}	0.20 TeV

- Still few 13 TeV results

Shattering the Standard Model?

- **Same for pure aQGC transversal parameters**
- **Future potential for improvements obvious**
  - Combination (between channels)
  - Updates to $\sqrt{s}$ = 13 GeV
  - Combination (between experiments)



	Channel	Limits	$\int Ldt$	$\sqrt{s}$
$f_{T,0}/\Lambda^4$	Zγ	[-3.8e+00, 3.4e+00]	19.7 fb^{-1}	8 TeV
	Zγ	[-3.4e+00, 2.9e+00]	19.2 fb^{-1}	8 TeV
	Wγ	[-5.4e+00, 5.6e+00]	19.7 fb^{-1}	8 TeV
	ss WW	[-6.2e-01, 6.5e-01]	35.9 fb^{-1}	13 TeV
	ZZ	[-4.6e-01, 4.4e-01]	35.9 fb^{-1}	13 TeV
$f_{T,1}/\Lambda^4$	Zγ	[-4.4e+00, 4.4e+00]	19.7 fb^{-1}	8 TeV
	Wγ	[-3.7e+00, 4.0e+00]	19.7 fb^{-1}	8 TeV
	ss WW	[-2.1e+00, 2.4e+00]	19.4 fb^{-1}	8 TeV
	ss WW	[-2.8e-01, 3.1e-01]	35.9 fb^{-1}	13 TeV
	ZZ	[-6.1e-01, 6.1e-01]	35.9 fb^{-1}	13 TeV
$f_{T,2}/\Lambda^4$	Zγ	[-9.9e+00, 9.0e+00]	19.7 fb^{-1}	8 TeV
	Wγ	[-1.1e+01, 1.2e+01]	19.7 fb^{-1}	8 TeV
	ss WW	[-5.9e+00, 7.1e+00]	19.4 fb^{-1}	8 TeV
	ss WW	[-8.9e-01, 1.0e+00]	35.9 fb^{-1}	13 TeV
	ZZ	[-1.2e+00, 1.2e+00]	35.9 fb^{-1}	13 TeV
$f_{T,5}/\Lambda^4$	Zγγ	[-9.3e+00, 9.1e+00]	20.3 fb^{-1}	8 TeV
	Wγ	[-3.8e+00, 3.8e+00]	19.7 fb^{-1}	8 TeV
$f_{T,6}/\Lambda^4$	Wγ	[-2.8e+00, 3.0e+00]	19.7 fb^{-1}	8 TeV
$f_{T,7}/\Lambda^4$	Wγ	[-7.3e+00, 7.7e+00]	19.7 fb^{-1}	8 TeV
$f_{T,8}/\Lambda^4$	Zγ	[-1.8e+00, 1.8e+00]	19.7 fb^{-1}	8 TeV
	Zγ	[-1.8e+00, 1.8e+00]	20.2 fb^{-1}	8 TeV
	ZZ	[-8.4e-01, 8.4e-01]	35.9 fb^{-1}	13 TeV
$f_{T,9}/\Lambda^4$	Zγγ	[-7.4e+00, 7.4e+00]	20.3 fb^{-1}	8 TeV
	Zγ	[-4.0e+00, 4.0e+00]	19.7 fb^{-1}	8 TeV
	Zγ	[-3.9e+00, 3.9e+00]	20.2 fb^{-1}	8 TeV
	ZZ	[-1.8e+00, 1.8e+00]	35.9 fb^{-1}	13 TeV

Still few 13 TeV results

Problems in current EFT approaches are obvious

- Many un(cor)related operators
  - Can be compared, NOT combined

- Valid for specific scenarios → Difficult for EFT/BSM re-interpretation
  → Difficult to “interface” with theorists

- **A solution: Common Fiducial BSM/EFT cross section**

- Can be a first point of reference for any further limit setting fits (i.e. proof that the limits agree)

- easier to combine (i.e. everyone knows what to expect and how to use it)

- Experimental work is rather low (once phase space is fixed)

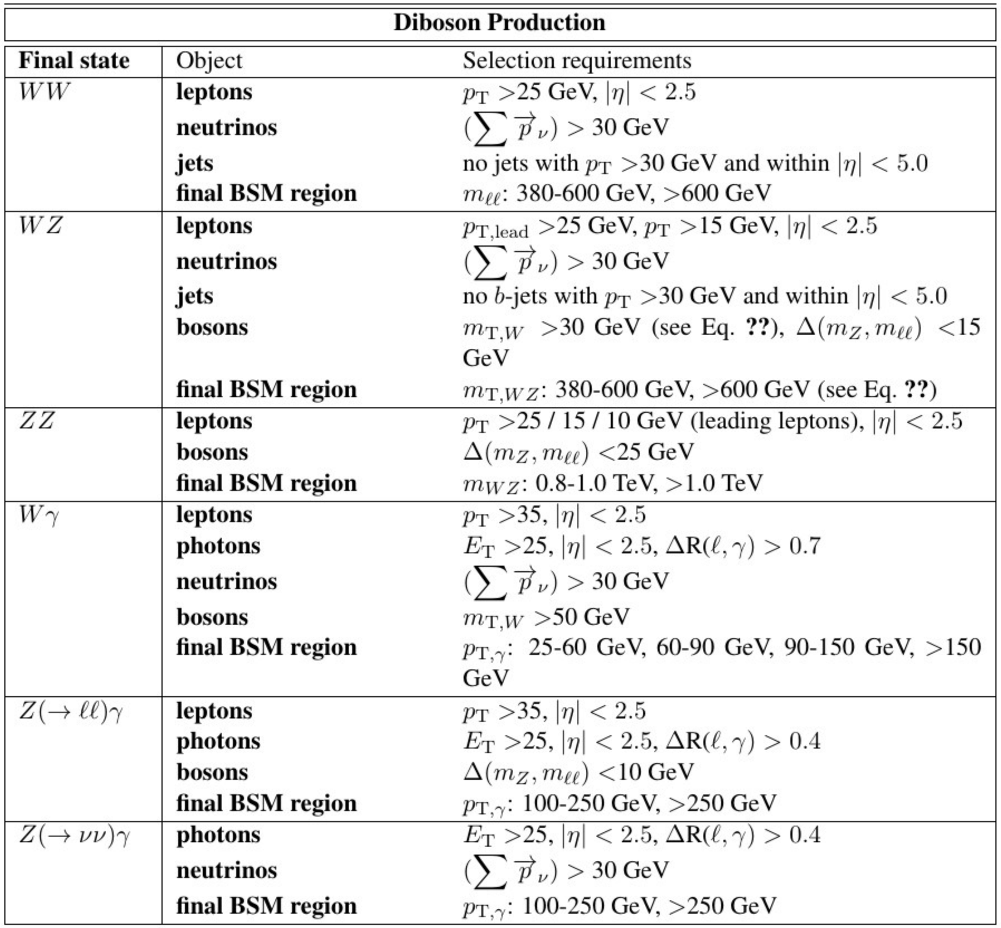
- Little model dependence for fiducial and differential cross-sections

- Need a region that both Atlas and CMS can either measure or extrapolate to with minimal theory dependence + common binning for distributions.

- Investigate uncommon operators (e.g. odd-ones: arXiv:1808.06577 [hep-ph])

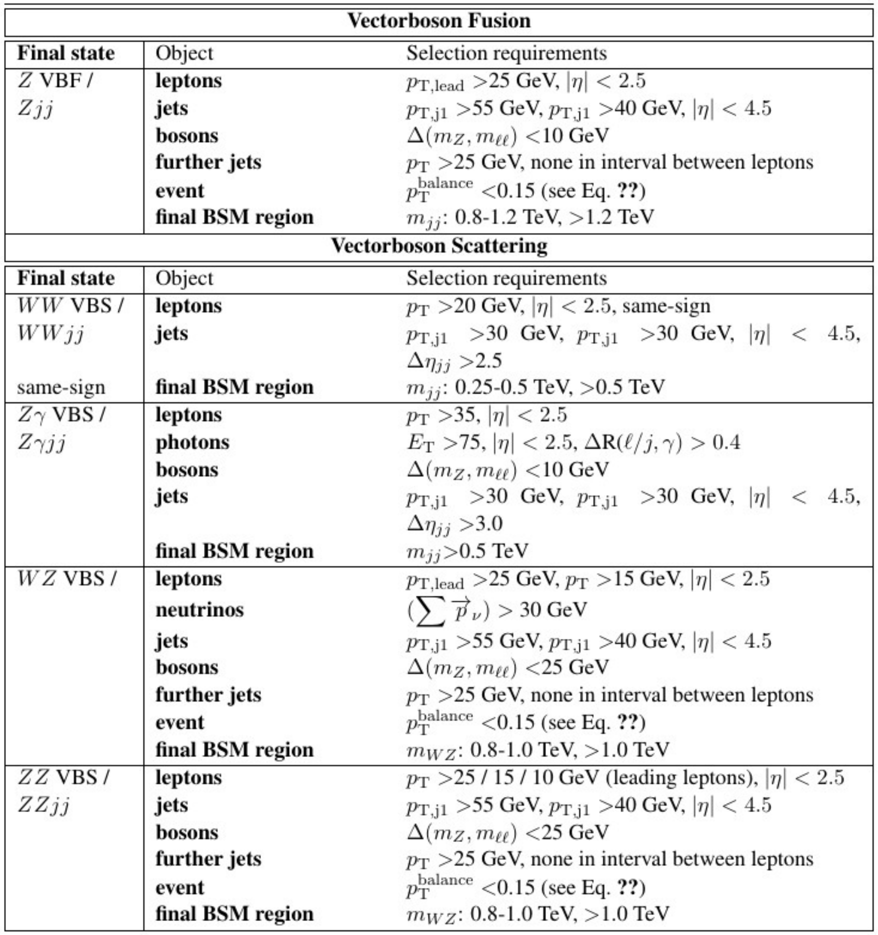
First suggestion in scope of LHC EWWG

- Trying to compile Full-Run2 recommendations for experiments



Diboson Production

Final state	Object	Selection requirements
WW	**leptons**	p_{T} >25 GeV, $\|\eta\| < 2.5$
	neutrinos	$(\sum \vec{p}_{\nu}) > 30$ GeV
	jets	no jets with p_{T} >30 GeV and within $\|\eta\| < 5.0$
	final BSM region	$m_{\ell\ell}$: 380-600 GeV, >600 GeV
WZ	**leptons**	$p_{\mathrm{T,lead}}$ >25 GeV, p_{T} >15 GeV, $\|\eta\| < 2.5$
	neutrinos	$(\sum \vec{p}_{\nu}) > 30$ GeV
	jets	no b-jets with p_{T} >30 GeV and within $\|\eta\| < 5.0$
	bosons	$m_{\mathrm{T},W}$ >30 GeV (see Eq. **??**), $\Delta(m_Z, m_{\ell\ell})$ <15 GeV
	final BSM region	$m_{\mathrm{T},WZ}$: 380-600 GeV, >600 GeV (see Eq. **??**)
ZZ	**leptons**	p_{T} >25 / 15 / 10 GeV (leading leptons), $\|\eta\| < 2.5$
	bosons	$\Delta(m_Z, m_{\ell\ell})$ <25 GeV
	final BSM region	m_{WZ}: 0.8-1.0 TeV, >1.0 TeV
$W\gamma$	**leptons**	p_{T} >35, $\|\eta\| < 2.5$
	photons	E_{T} >25, $\|\eta\| < 2.5$, $\Delta\mathrm{R}(\ell,\gamma) > 0.7$
	neutrinos	$(\sum \vec{p}_{\nu}) > 30$ GeV
	bosons	$m_{\mathrm{T},W}$ >50 GeV
	final BSM region	$p_{\mathrm{T},\gamma}$: 25-60 GeV, 60-90 GeV, 90-150 GeV, >150 GeV
$Z(\rightarrow \ell\ell)\gamma$	**leptons**	p_{T} >35, $\|\eta\| < 2.5$
	photons	E_{T} >25, $\|\eta\| < 2.5$, $\Delta\mathrm{R}(\ell,\gamma) > 0.4$
	bosons	$\Delta(m_Z, m_{\ell\ell})$ <10 GeV
	final BSM region	$p_{\mathrm{T},\gamma}$: 100-250 GeV, >250 GeV
$Z(\rightarrow \nu\nu)\gamma$	**photons**	E_{T} >25, $\|\eta\| < 2.5$, $\Delta\mathrm{R}(\ell,\gamma) > 0.4$
	neutrinos	$(\sum \vec{p}_{\nu}) > 30$ GeV
	final BSM region	$p_{\mathrm{T},\gamma}$: 100-250 GeV, >250 GeV



Vectorboson Fusion

Final state	Object	Selection requirements
Z VBF / Zjj	**leptons**	$p_{\mathrm{T,lead}}$ >25 GeV, $\|\eta\| < 2.5$
	jets	$p_{\mathrm{T,j1}}$ >55 GeV, $p_{\mathrm{T,j1}}$ >40 GeV, $\|\eta\| < 4.5$
	bosons	$\Delta(m_Z, m_{\ell\ell})$ <10 GeV
	further jets	p_{T} >25 GeV, none in interval between leptons
	event	$p_{\mathrm{T}}^{\mathrm{balance}}$ <0.15 (see Eq. **??**)
	final BSM region	m_{jj}: 0.8-1.2 TeV, >1.2 TeV

Vectorboson Scattering

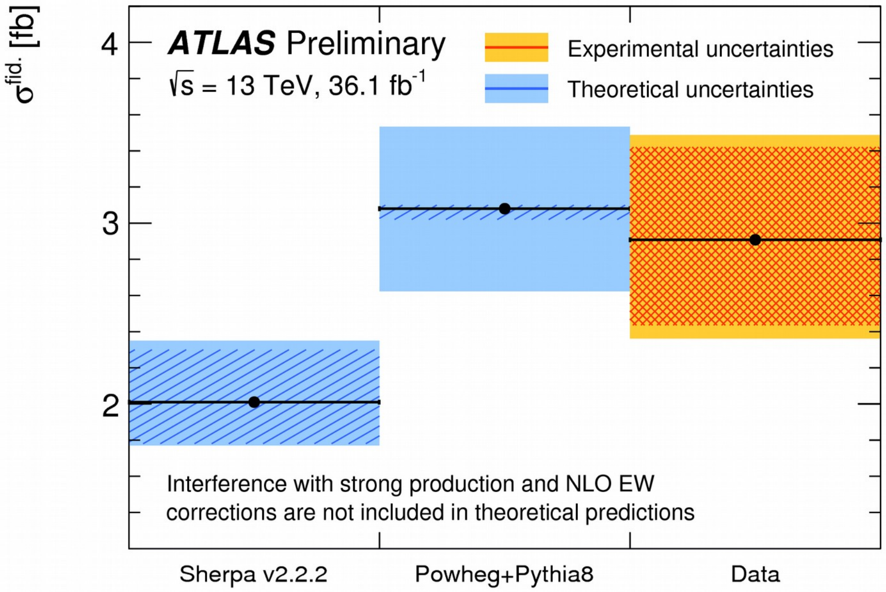
Final state	Object	Selection requirements
WW VBS / $WWjj$	**leptons**	p_{T} >20 GeV, $\|\eta\| < 2.5$, same-sign
	jets	$p_{\mathrm{T,j1}}$ >30 GeV, $p_{\mathrm{T,j1}}$ >30 GeV, $\|\eta\| < 4.5$, $\Delta\eta_{jj}$ >2.5
same-sign	**final BSM region**	m_{jj}: 0.25-0.5 TeV, >0.5 TeV
$Z\gamma$ VBS / $Z\gamma jj$	**leptons**	p_{T} >35, $\|\eta\| < 2.5$
	photons	E_{T} >75, $\|\eta\| < 2.5$, $\Delta\mathrm{R}(\ell/j,\gamma) > 0.4$
	bosons	$\Delta(m_Z, m_{\ell\ell})$ <10 GeV
	jets	$p_{\mathrm{T,j1}}$ >30 GeV, $p_{\mathrm{T,j1}}$ >30 GeV, $\|\eta\| < 4.5$, $\Delta\eta_{jj}$ >3.0
	final BSM region	m_{jj}>0.5 TeV
WZ VBS /	**leptons**	$p_{\mathrm{T,lead}}$ >25 GeV, p_{T} >15 GeV, $\|\eta\| < 2.5$
	neutrinos	$(\sum \vec{p}_{\nu}) > 30$ GeV
	jets	$p_{\mathrm{T,j1}}$ >55 GeV, $p_{\mathrm{T,j1}}$ >40 GeV, $\|\eta\| < 4.5$
	bosons	$\Delta(m_Z, m_{\ell\ell})$ <25 GeV
	further jets	p_{T} >25 GeV, none in interval between leptons
	event	$p_{\mathrm{T}}^{\mathrm{balance}}$ <0.15 (see Eq. **??**)
	final BSM region	m_{WZ}: 0.8-1.0 TeV, >1.0 TeV
ZZ VBS / $ZZjj$	**leptons**	p_{T} >25 / 15 / 10 GeV (leading leptons), $\|\eta\| < 2.5$
	jets	$p_{\mathrm{T,j1}}$ >55 GeV, $p_{\mathrm{T,j1}}$ >40 GeV, $\|\eta\| < 4.5$
	bosons	$\Delta(m_Z, m_{\ell\ell})$ <25 GeV
	further jets	p_{T} >25 GeV, none in interval between leptons
	event	$p_{\mathrm{T}}^{\mathrm{balance}}$ <0.15 (see Eq. **??**)
	final BSM region	m_{WZ}: 0.8-1.0 TeV, >1.0 TeV

- Work in progress with R. Gomez Ambrosio

Beyond dimension-8: Vector-boson scattering

- Growing number of VBS processes observed (WW, WZ)

- pT lepton > 27 GeV, MET>30 GeV
  2 jets with pT > 65 GeV and p T > 35 GeV
- Highest p T jets with m_{jj} > 500 GeV and $|\Delta y_{jj}|$ > 2
- Likelihood fit over 30 data points (including control regions for WZ production)



Sherpa VBS samples with non-optimal setting of the color flow for PS on top of VBS-like scattering processes
→ excess of central emissions from the parton shower.

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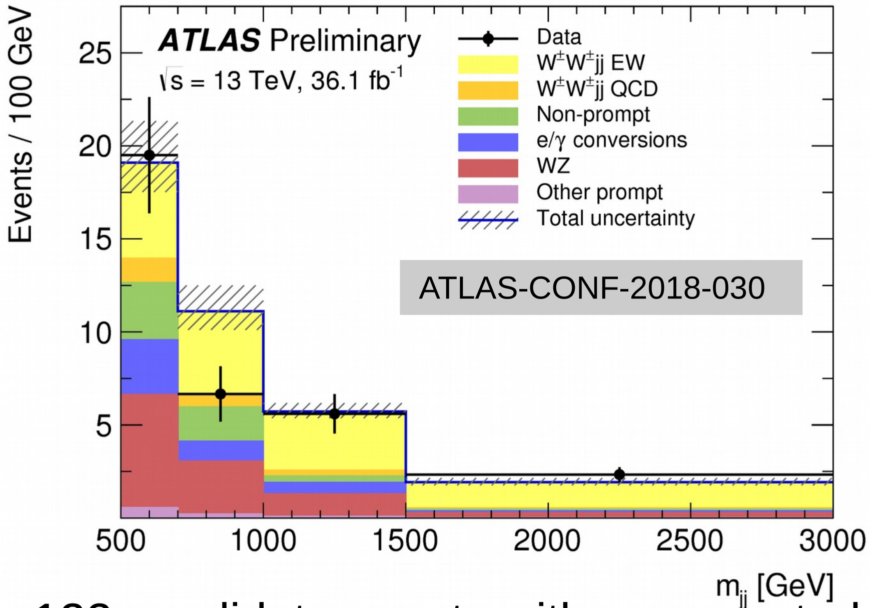

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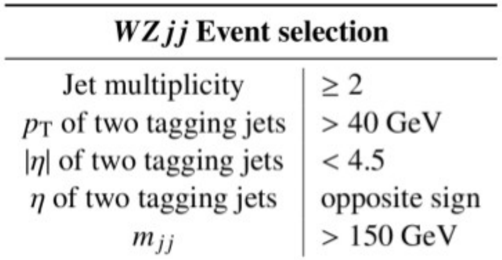
- 122 candidate events with an expected background of 69 +/- 10
- Observed significance of 6.9 (exp. 4.6)
- Signal is EW and QCD-EW interference

Beyond dimension-8: Vector-boson scattering: WZ

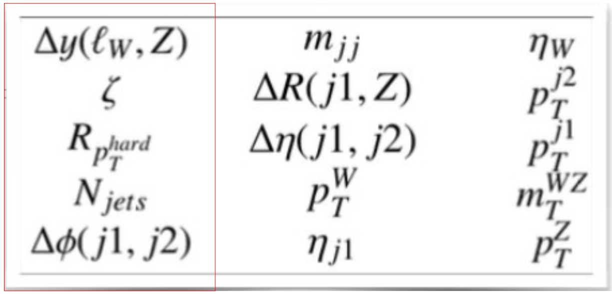
- All leptons > 15 GeV
- at least one lepton with pT>27 GeV
- 2 OS leptons within 10 GeV of m_Z , 3rd lepton > 27 GeV
- mT(W)>30 GeV



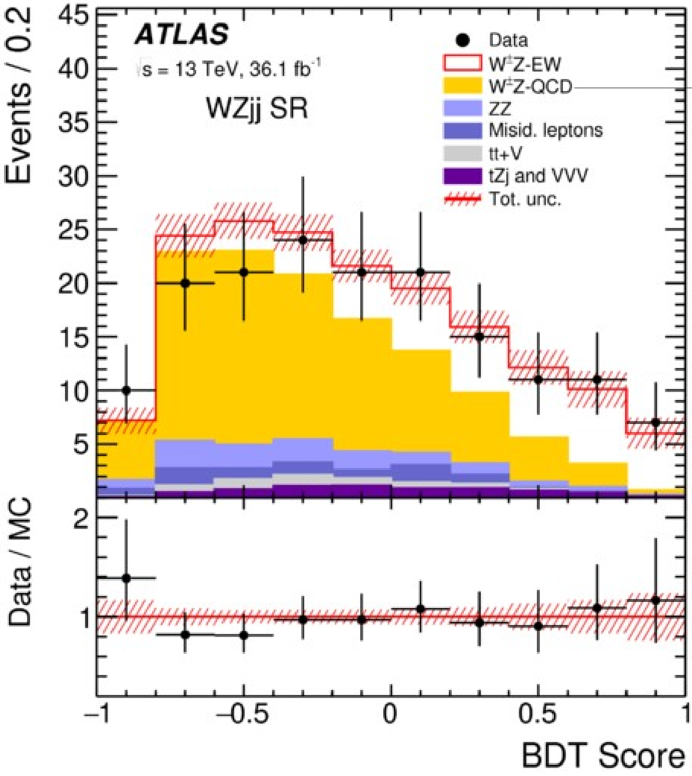
WZjj Event selection	
Jet multiplicity	≥ 2
p_T of two tagging jets	> 40 GeV
$\|\eta\|$ of two tagging jets	< 4.5
η of two tagging jets	opposite sign
m_{jj}	> 150 GeV

BDT inputs

Most relevant



$\Delta y(\ell_W, Z)$	m_{jj}	η_W
ζ	$\Delta R(j1, Z)$	p_T^{j2}
$R_{p_T^{hard}}$	$\Delta\eta(j1, j2)$	p_T^{j1}
N_{jets}	p_T^W	m_T^{WZ}
$\Delta\phi(j1, j2)$	η_{j1}	p_T^Z

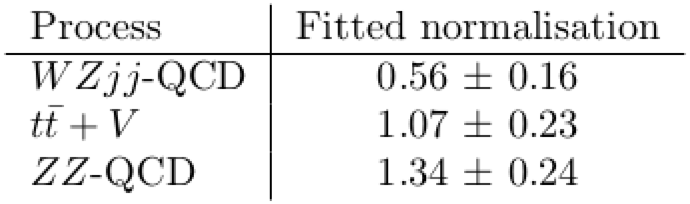


70% in SR

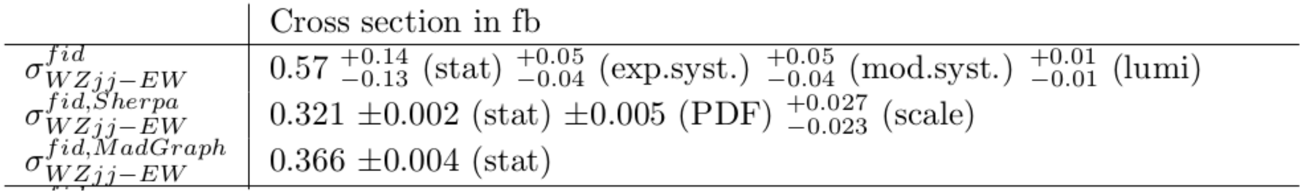
- QCD/EW interference is part of the measured signal
- Interference impact included as shape uncertainty on signal
- Size of interference: +10% of EW WZjj

Beyond dimension-8: Vector-boson scattering: WZ

- Fit in 3 control and 1 signal region
- 5.3 σ observed (3.2 σ expected)

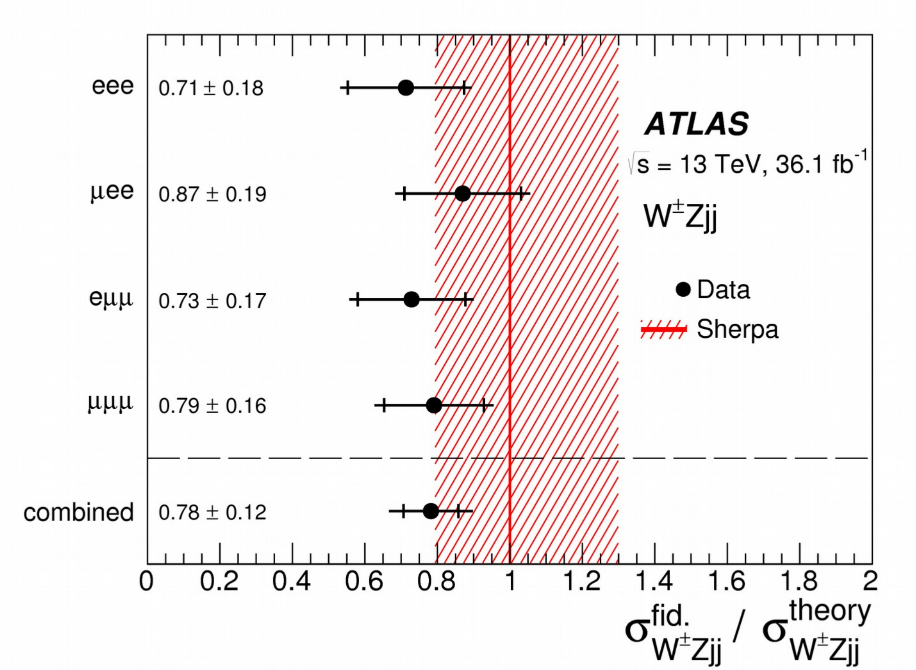


Process	Fitted normalisation
$WZjj$-QCD	0.56 ± 0.16
$t\bar{t} + V$	1.07 ± 0.23
ZZ-QCD	1.34 ± 0.24



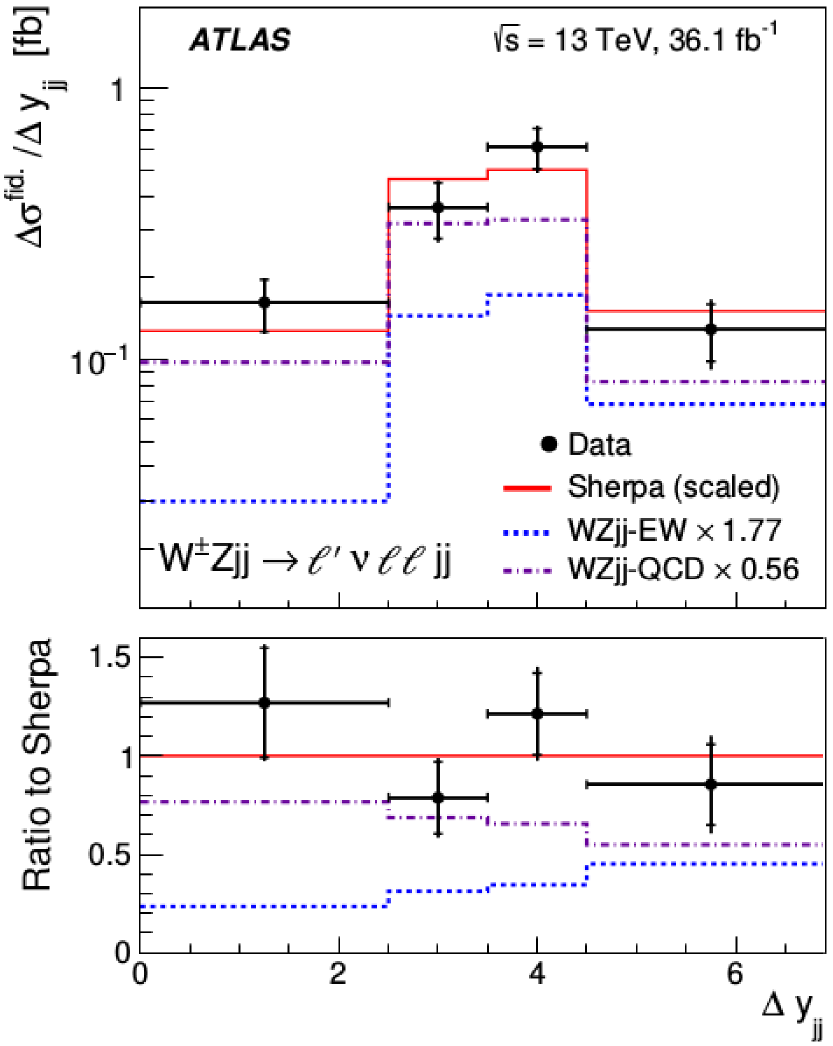
	Cross section in fb
$\sigma^{fid}_{WZjj-EW}$	$0.57\ ^{+0.14}_{-0.13}$ (stat) $^{+0.05}_{-0.04}$ (exp.syst.) $^{+0.05}_{-0.04}$ (mod.syst.) $^{+0.01}_{-0.01}$ (lumi)
$\sigma^{fid,Sherpa}_{WZjj-EW}$	0.321 ± 0.002 (stat) ± 0.005 (PDF) $^{+0.027}_{-0.023}$ (scale)
$\sigma^{fid,MadGraph}_{WZjj-EW}$	0.366 ± 0.004 (stat)

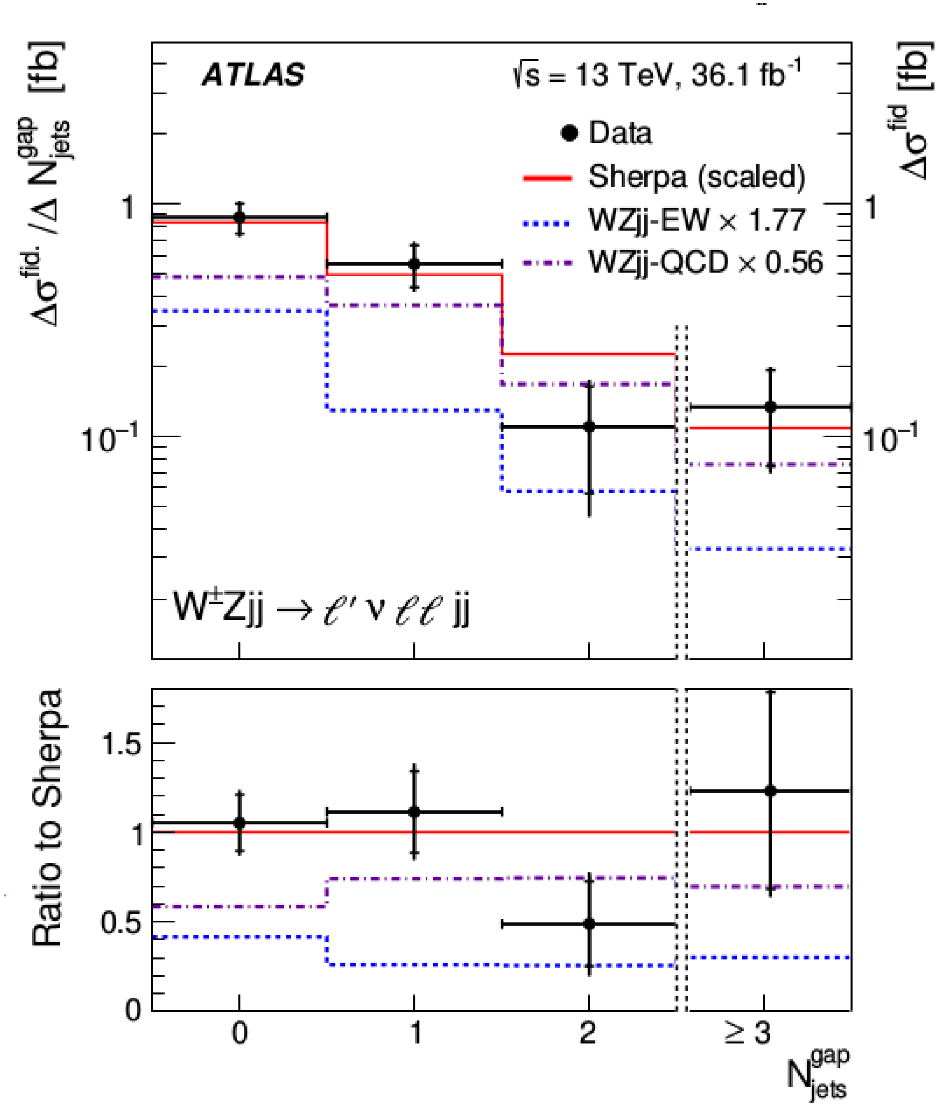
- Inclusive (Wzjj QCD+EW) cross section slightly smaller than predicted



Beyond dimension-8: Vector-boson scattering: WZ

- First look at differential distributions





Conclusions

- A wealth of data still to be expected from LHC Run-2
  - The work has just begun!

- More data → more complications:
  - What do we need to measure?
  - How do we need to measure it?

- If the first searches for generic resonance fail to deliver (real) results
  → look beyond “peaks” towards generic **effective field theories**

- Multiboson and VBS measurements in ATLAS well established
  - Unfolded results available for most processes
  - Reinterpretation possible

- For the future:
  → More measurements to come
  → investigate (common) benchmarks
  → define (common) strategies

BACKUP

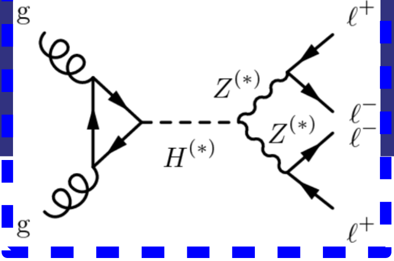
Lower bound optimization for the m4l lineshape

- Z → ττ : decays into leptons accompanied by neutrinos
  → generally lower invariant mass compared to Z→ee or Z→μμ

Higher invariant 4l mass → higher mass of second Z (but still, lower edge dominated by tau-leptons)

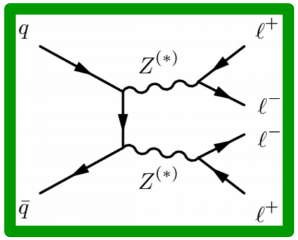
$$f(m_{4\ell}) = \left\{ \begin{array}{ll} 5\ \mathrm{GeV}, & \text{for } m_{4\ell} < 100\ \mathrm{GeV} \\ 5\ \mathrm{GeV} + 0.7 \times (m_{4\ell} - 100\ \mathrm{GeV}), & \text{for } 100\ \mathrm{GeV} < m_{4\ell} < 110\ \mathrm{GeV} \\ 12\ \mathrm{GeV}, & \text{for } 110\ \mathrm{GeV} < m_{4\ell} < 140\ \mathrm{GeV} \\ 12\ \mathrm{GeV} + 0.76 \times (m_{4\ell} - 140\ \mathrm{GeV}\ ), & \text{for } 140\ \mathrm{GeV} < m_{4\ell} < 190\ \mathrm{GeV} \\ 50\ \mathrm{GeV}, & \text{for } m_{4\ell} > 190\ \mathrm{GeV} \end{array} \right\} .$$

Matrix element calculation

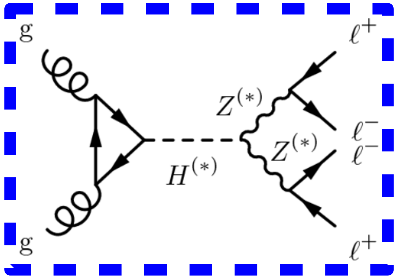


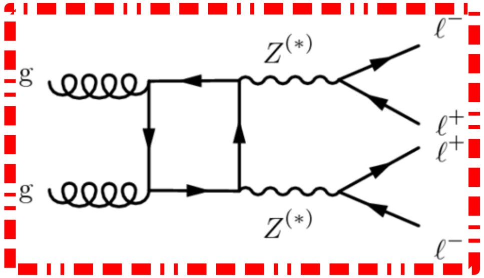
Higgs only

$$D_{\mathrm{ME}} = \log_{10}\frac{\tilde{M}^2_{gg\to H^{(*)}\to ZZ^{(*)}\to 4\ell}\left(p^{\mu}_{1,2,3,4}\right)}{\tilde{M}^2_{gg(\to H^{(*)})\to ZZ^{(*)}\to 4\ell}\left(p^{\mu}_{1,2,3,4}\right) + 0.1\cdot \tilde{M}^2_{q\bar{q}\to ZZ^{(*)}\to 4\ell}\left(p^{\mu}_{1,2,3,4}\right)},$$



Squared matrix element for process X for specific lepton 4-vectors in the given event





Plus interference

$$\tilde{M}^2_X\left(p^{\mu}_{1,2,3,4}\right) = \frac{M^2_X\left(p^{\mu}_{1,2,3,4}\right)}{\left\langle M^2_X\right\rangle\left(m_{4\ell}\right)},$$

Average squared matrix element for process X for the given m4l of that event

The squared matrix elements are computed at leading-order QCD precision using the MCFM [18] program version 8.0. The strong coupling constant is evaluated at the scale of half the four-lepton invariant mass. The Higgs boson mass is set to $m_H = 125.0$ GeV, and its width to the Standard Model prediction for this mass. Given the leading-order QCD precision, the incoming parton momenta are approximated by assuming the four-lepton centre-of-mass system is produced at rest.

The pair production of two Z bosons via the $q\bar{q} \to 4\ell$ process was simulated with the Sherpa 2.2.2 event generator [25]. Matrix elements were calculated for up to one parton at next-to-leading order (NLO) in QCD and up to three partons at leading order (LO) using Comix [26] and OpenLoops [27], and merged with the Sherpa parton shower [28] according to the ME+PS@NLO prescription [29]. The NNPDF3.0NNLO PDF set [30] was used, and the QCD renormalisation and factorisation scales were set to $m_{4\ell}/2$. The total cross-section from this calculation agrees within scale uncertainties with an NNLO QCD prediction obtained using the MATRIX program [31–34]. A reweighting for virtual NLO EW effects [35, 36] was applied as a function of the four-lepton invariant mass, $m_{4\ell}$, which modifies the differential cross-section by between +3% (for $m_{4\ell} \sim 130$ GeV) and −20% for $m_{4\ell} > 800$ GeV. The real higher-order electroweak contribution to 4ℓ production in association with two jets (which includes vector-boson scattering) is not included in the sample discussed above but it was modelled separately using Sherpa 2.2.2 with the NNPDF3.0NNLO PDF set. A second $q\bar{q} \to 4\ell$ sample was generated at NLO precision in QCD using Powheg-Box v2 [37–39] configured with the CT10 PDF set [40] and interfaced to Pythia 8.186 [41, 42] for parton showering. A correction to higher-order precision (K-factor), defined for this process as the ratio of the cross-section at NNLO QCD accuracy to the one at NLO QCD accuracy, was obtained using the MATRIX NNLO QCD prediction and applied to this sample as a function of $m_{4\ell}$, modifying the inclusive cross-section by between +10% for $m_{4\ell} < 180$ GeV and +25% for $m_{4\ell} > 800$ GeV. The reweighting for virtual NLO EW effects discussed above for the Sherpa case was also applied to this sample.

The purely gluon-initiated ZZ production process enters at next-to-next-to-leading order (NNLO) in α_S. It was modelled using Sherpa 2.2.2 [43], at LO precision for zero- and one-jet final states, and the NNPDF3.0NNLO PDF set was chosen. This sample includes the box diagram, the s-channel process proceeding via a Higgs boson, and the interference between the two. Recently, a NLO QCD calculation for the three components became available [44, 45] allowing $m_{4\ell}$ differential K-factors to be calculated with the $1/m_t$ expansion below $2m_t$, and assuming a massless quark approximation above this threshold. This NLO QCD calculation was used to correct the s-channel process $gg \to H^* \to ZZ^{(*)} \to 4\ell$, the box diagram $gg \to 4\ell$ and the interference with separate K-factors. These represent significant corrections of the order of +100% to the leading-order cross-section. There are, however, NNLO QCD precision calculations for the off-shell Higgs boson production cross-section [46, 47] which show additional enhancement of the cross-section. Since these corrections are not known differentially in $m_{4\ell}$ for all three components, the prediction for each component is scaled by an additional overall correction factor of 1.2, assumed to be the same for the signal, background and interference. This additional constant scale factor is justified by the approximately constant behaviour of the NNLO/NLO QCD prediction. In addition, a purely leading-order prediction for the $gg \to 4\ell$ process was obtained using the MCFM program [18] with the CT10 PDF set [40], interfaced to Pythia 8 [41, 42].

Uncertainties