ZZ Measurements in 4ℓ final states at ATLAS

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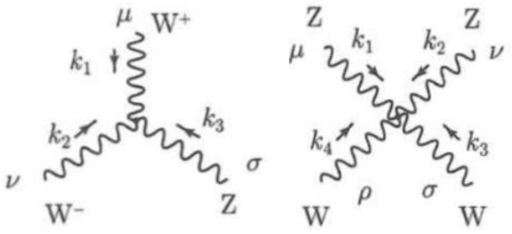
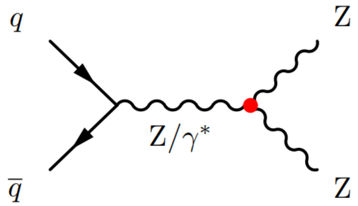
Introduction

- Multi-boson processes: a powerful probe to the electroweak gauge structure:
    - Better understand the Standard Model (SM)
        - Test directly the gauge boson self-interaction (SU(2))
        - Higgs mechanism for Electroweak Symmetry Breaking (EWSB)
            - e.g. vector boson scattering (VBS) processes for gauge unitarity
    - Search for Beyond the Standard Model (BSM) physics
        - Anomalous gauge boson coupling (aTGC, aQGC…)
        - Effective field theory (EFT), a more general way for new physics search

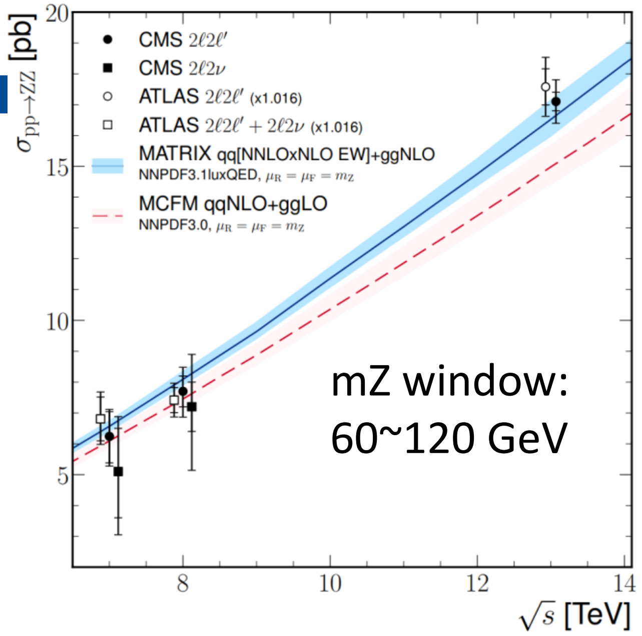


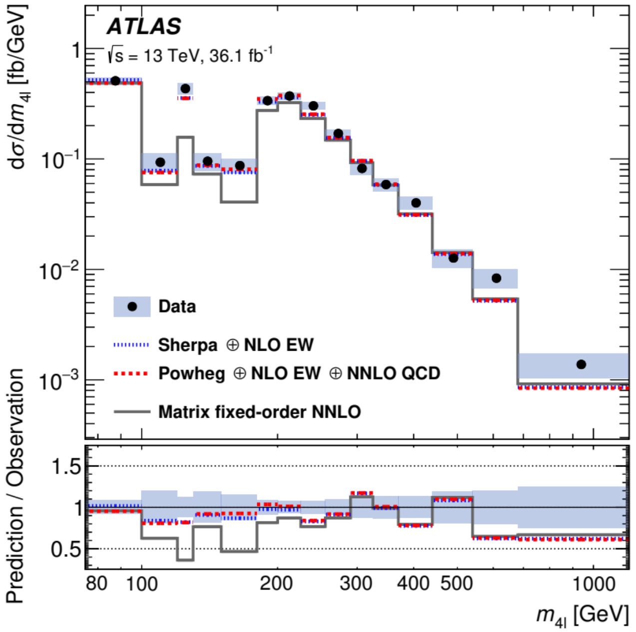


- Measurement of multi-boson processes:
    - Total cross-section
    - Differential cross-sections

Introduction

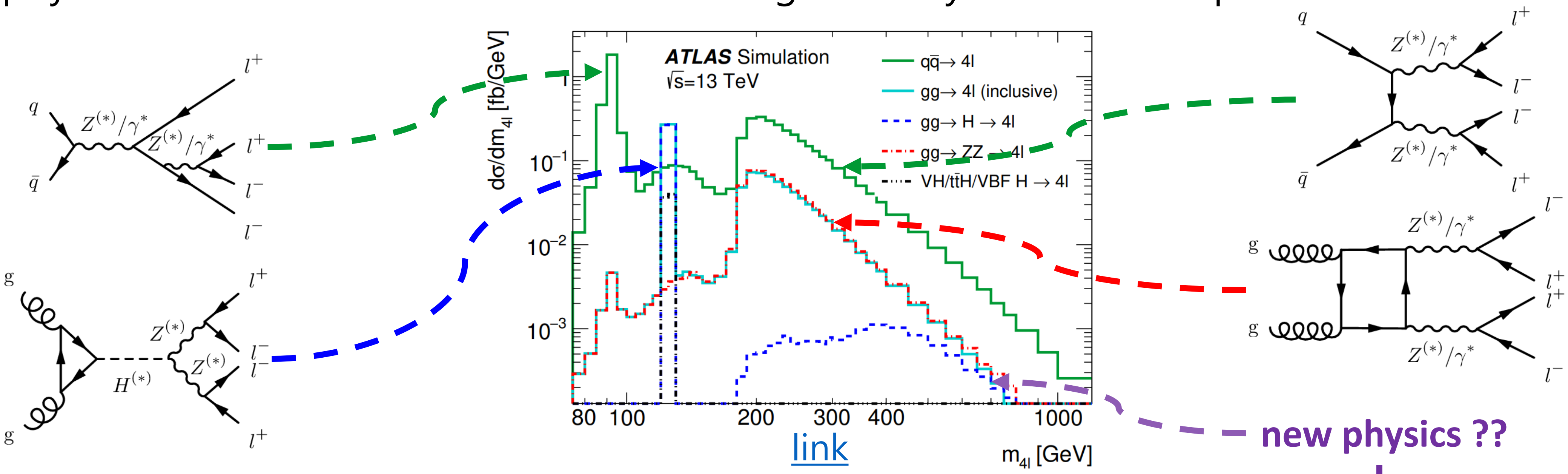
- Measurement of ZZ process
  - Clean and full-reconstructed signal for the leptonic decay ($4\ell(e,\mu)$) in experiment
  - Low cross-section comparing with other di-boson processes
- Previous study
  - 4ℓ final state was measured in the on-shell ZZ region to determine the ZZ production cross-section both at ATLAS and CMS experiment (link, link)
  - Differential cross-sections was also measured including off-shell events form Z*/γ* (link)
- We expected more precise measurement on more variables as well as more accurate test on BSM with full 13 TeV dataset

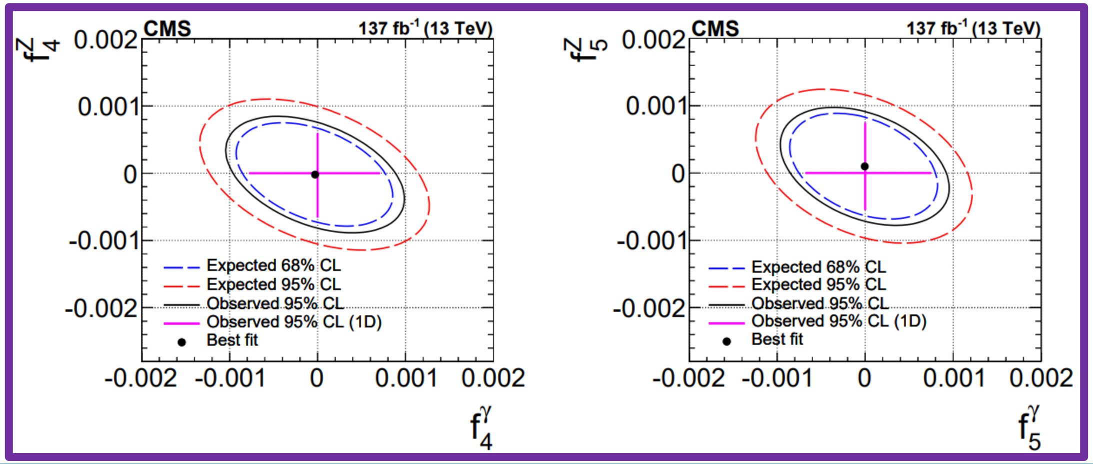


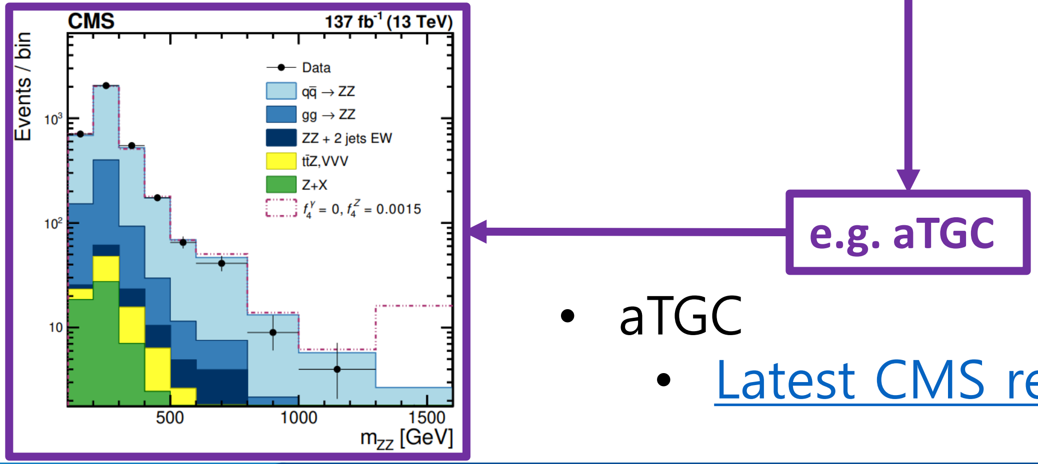


Introduction

- Rich physics contents in 4ℓ final states including not only SM but also possible BSM



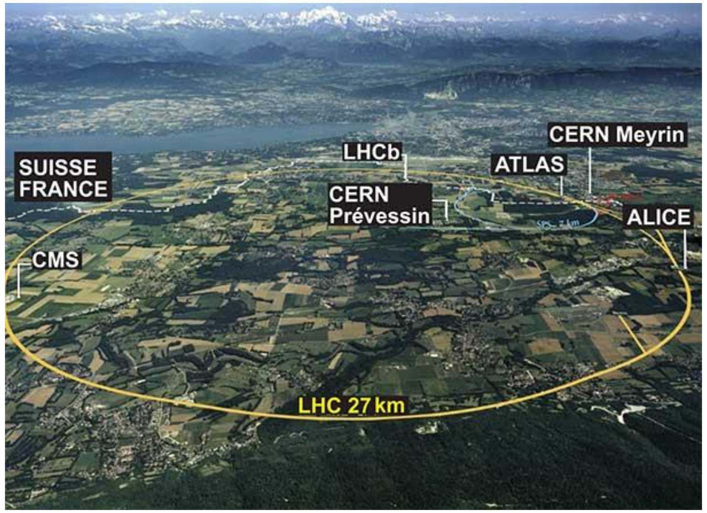


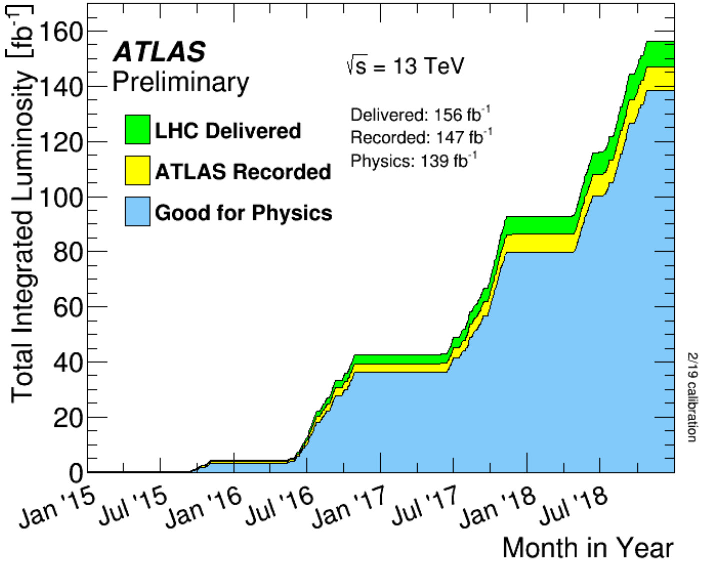


- aTGC
  - Latest CMS result

LHC

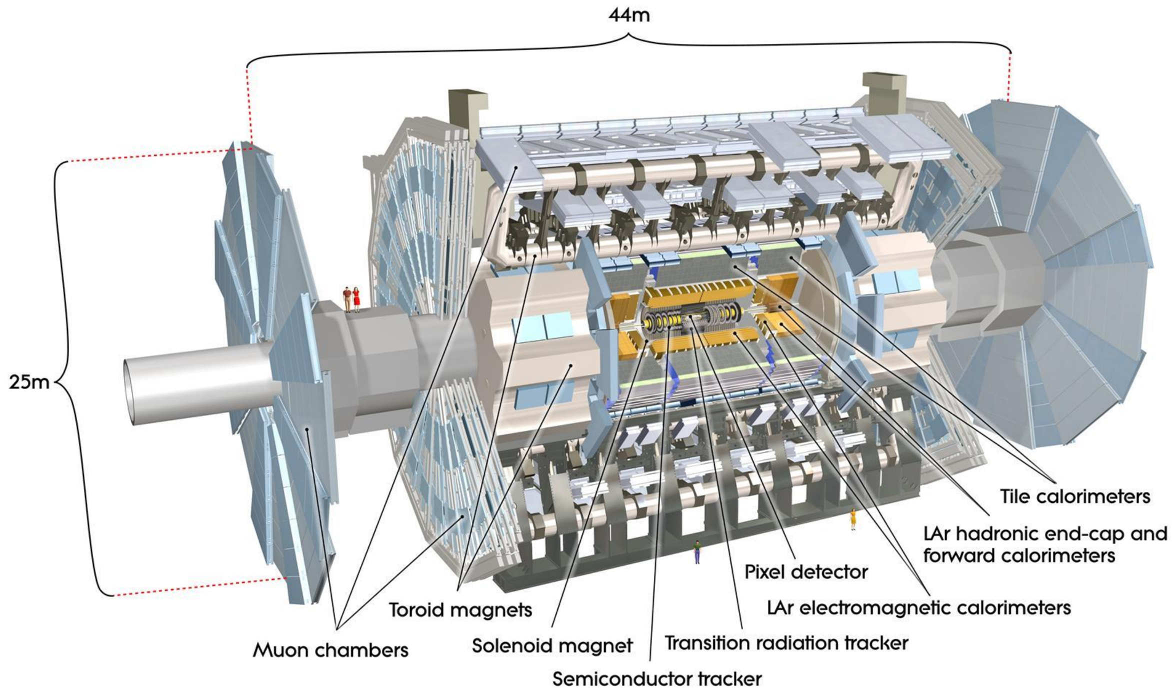
- Large Hardon Collider:
  - Most powerful accelerator in the world
    - pp collision:
    - Run-I:
      - 2010: 7 TeV 45.0 pb^{-1}(recorded)
      - 2011: 7 TeV 4.57 fb^{-1}
      - 2012: 8 TeV 20.3 fb^{-1}
    - Run-II:
      - 2015: 13 TeV 3.2 fb^{-1}
      - 2016: 13 TeV 33.0 fb^{-1}
      - 2017: 13 TeV 44.3 fb^{-1}
      - 2018: 13 TeV 58.5 fb^{-1}
    - Run-III keeps coming…

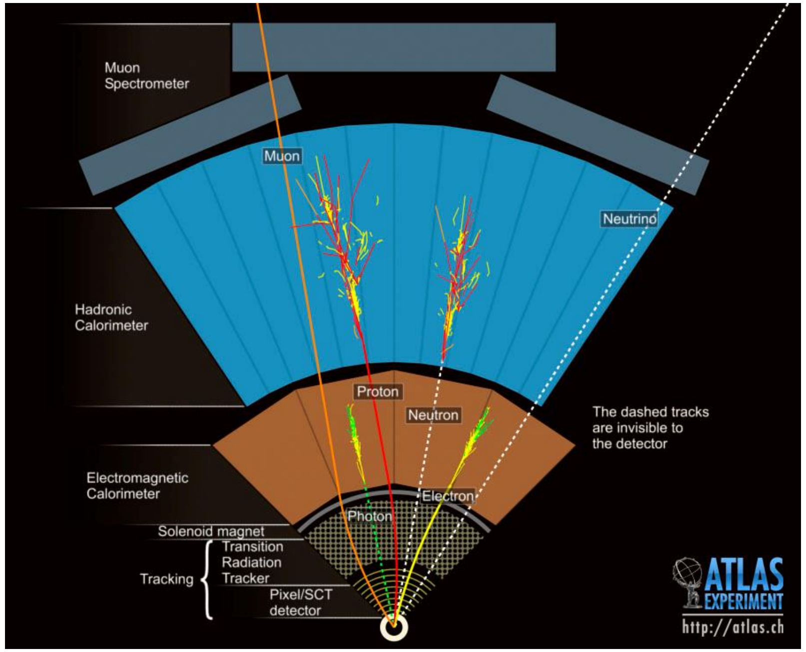




ATLAS Detector

- One of the two general purpose detectors on Large Hadron Collider (LHC)
- Sub-detectors: inner trackers, electromagnetic, hadronic calorimeters and muon spectrometer
- Object reconstruction: electron, photon; muon; jet (tagging); MET; …



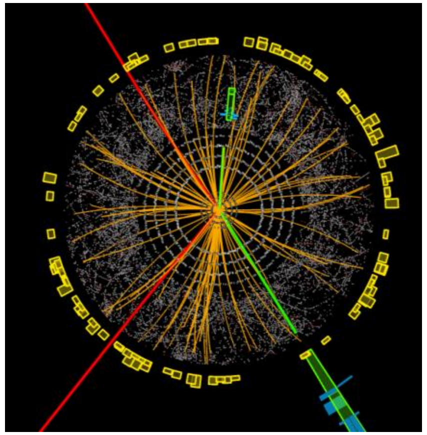


- ATLAS Run-2 (2015-2018) data corresponding to 139fb-1 of √s = 13 TeV pp collisions

Fiducial region and event selection

- **Fiducial Region**
  - Designed to be as inclusive as possible
  - Based on particle-level prompt leptons, with dressed electrons and bare muons
- **Quadruplet**: invariant mass of same-flavor opposite-sign lepton pair which is closest (second closet) to Z mass treated as primary (secondary) pair
  - One quadruplet defined in an event
  - Three flavor categories: **4μ**, **2e2μ**, **4e**

link



	Lepton selection
Muon selection	Bare, $p_T > 5$ GeV, $\|\eta\| < 2.7$
Electron selection	Dressed, $p_T > 7$ GeV, $\|\eta\| < 2.47$
	Event selection
Four-lepton signature	At least 4 leptons, with 2 Same-Flavour, Opposite-Sign pairs
Lepton kinematics	$p_T > 20/10$ GeV for leading two leptons
Lepton separation	$\Delta R_{ij} > 0.05$ for any leptons
J/ψ-Veto	$m_{ij} > 5$ GeVfor all SFOS pairs
Truth isolation	ptcone30/p_T < 0.16

- **Event Selection**
  - At first leptons are reconstructed and checked with baseline criteria
  - Event selection which mimics the fiducial definition
  - Tight criteria applied on leptons in quadruplet to mitigate misidentified or non-prompt leptons

Observables

- **Integrated cross-sections**
- **Differential cross-sections:**
  - $\mathbf{m_{4\ell}}$
  - $\mathbf{m_{4\ell}}$ in slices of $\mathbf{p^T{}_{4\ell}}$
  - $\mathbf{m_{4\ell}}$ in slices of $|\mathbf{y_{4\ell}}|$
  - $\mathbf{m_{4\ell}}$ in slices of flavor categories: **4μ, 2e2μ, 4e**

  - $\mathbf{m_{12}, m_{34}}$
  - $\mathbf{p^T{}_{12}, p^T{}_{34}}$
  - rapidity difference between two lepton pairs $|\Delta y_{pairs}|$
  - azimuthal angle between the pairs $|\Delta\varphi_{pairs}|$
  - azimuthal angle between leading/subleading leptons $|\Delta\varphi_{ll}|$
  - polarization variables $\mathbf{\cos\theta^*_{12}, \cos\theta^*_{34}}$ (θ* angle between the negative lepton in the lepton pair rest frame, and the lepton pair in the lab frame)

Single Z ($60 < m_{4\ell} < 100$ GeV)

Higgs ($120 < m_{4\ell} < 130$ GeV)

On-shell ZZ ($180 < m_{4\ell} < 2000$ GeV)

Off-shell ZZ ($20 < m_{4\ell} < 60$ GeV OR
$100 < m_{4\ell} < 120$ GeV OR
$130 < m_{4\ell} < 180$ GeV)

Physics modelling

- MC samples are generated dedicatedly for each essential process:

  - Signal
    - qqZZ
    - ggZZ
      - $m_{4\ell}$ < 130 GeV, loop-induced only
      - $m_{4\ell}$ > 130 GeV, inclusive generation taking the interference of ggF off-shell Higgs process into account
    - detailed on-shell Higgs modelling
      - ggF, VBF, ttH, VH
    - triboson production
    - ttV(V)

  - Background
    - Z+jets
    - ttbar

Physics modelling

- Accuracy and PDF set for MC samples for essential process:

qqZZ		SHERPA 2.2.2	NLO QCD@0,1 jet	NNPDF3.0NNLO
ggZZ		SHERPA 2.2.2	LO QCD@0,1 jet (k-factor reweighted to NNLO)	NNPDF3.0NNLO
Higgs	ggF	POWHEG + PYTHIA 8	NNLO QCD (normalized to N^3LO XS)	PDF4LHC15NNLO
	VBF	POWHEG + PYTHIA 8	NLO QCD (normalized to NNLO XS)	PDF4LHC15NLO
	VH	POWHEG + PYTHIA 8	NLO QCD@0,1 jet (normalized to NNLO XS)	PDF4LHC15NLO
	ttH	POWHEG + PYTHIA 8	NLO QCD	PDF4LHC15NLO
triboson		SHERPA 2.2.2	NLO	NNPDF3.0NNLO
ttV(V)		SHERPA 2.2.0	LO	NNPDF3.0NNLO

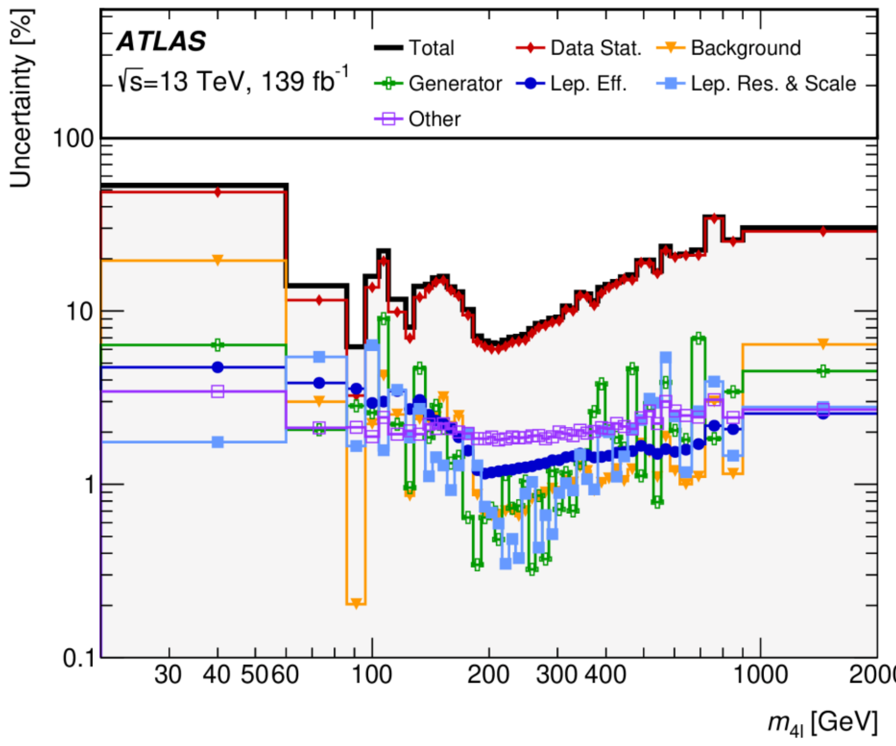
MC prediction details

Background

- Background refers to events with one or more non-prompt/fake leptons entering quadruplet, mainly from **Z+jets** and **ttbar** processes
- Background estimated with data-driven approach:
  - Fake Factor method, estimate fake factor in Control Region and transfer it into Signal Region
- Validation: Validation Region comparison; cross-check with Matrix method
- Background contributes < 10% in most bins

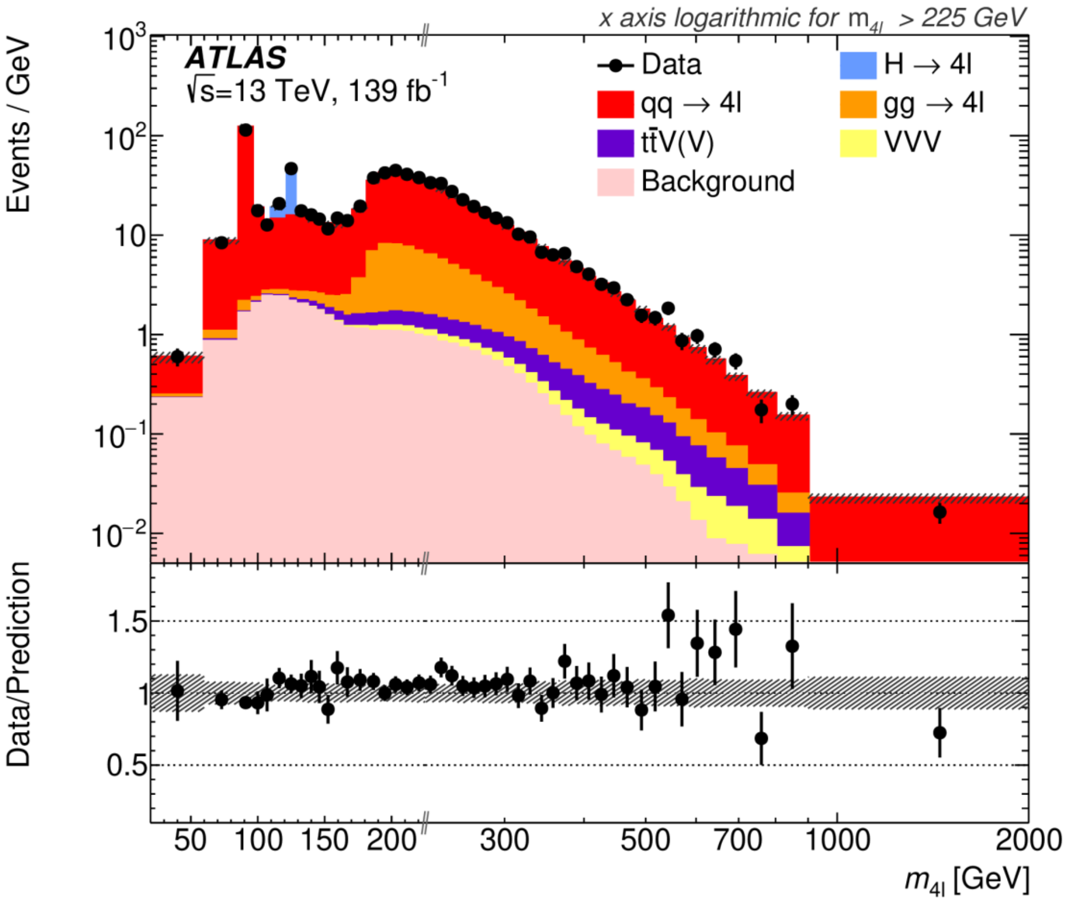
Uncertainties

- Multi-source of uncertainties are studied and estimated:
  - **Data statistics** → Predominant uncertainty
  - Experimental uncertainties → Propagated to unfolded distributions
  - Generator selection → SHERPA V.S. POWHEG + PYTHIA
  - Background → Data-driven FF, application statistics…
  - Unfolding method → Data-driven closure
  - …



Detector-level yields

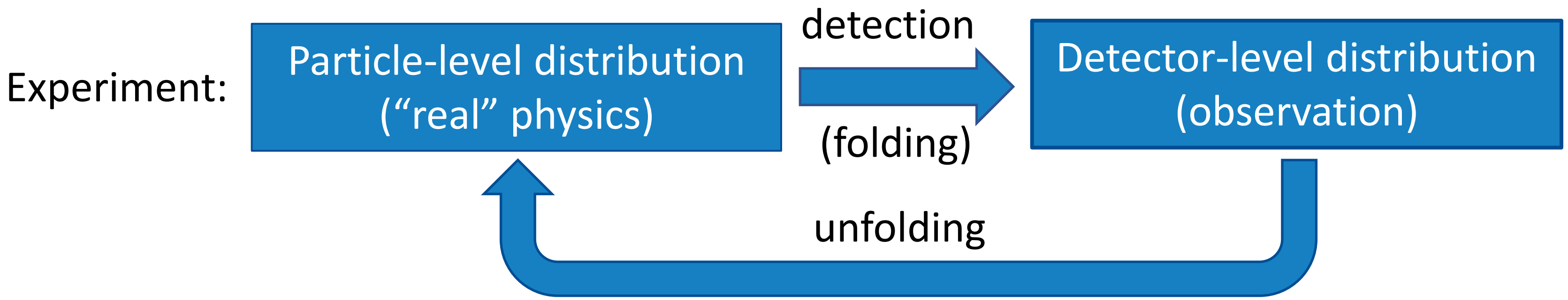
- Predicted yields V.S. data counts on detector level:



	Region				
	Full	$Z \to 4\ell$	$H \to 4\ell$	Off-shell ZZ	On-shell ZZ
$q\bar{q} \to 4\ell$	6100 ± 500	1490 ± 120	128 ± 10	800 ± 60	3640 ± 280
$gg \to 4\ell$	680 ± 90	10.8 ± 2.9	3.9 ± 0.7	49 ± 6	620 ± 80
$H \to 4\ell$	245 ± 20	2.16 ± 0.18	207 ± 17	33.5 ± 3.1	1.98 ± 0.20
VVV	35 ± 4	0.018 ± 0.005	0.127 ± 0.018	2.05 ± 0.22	32.9 ± 3.4
$t\bar{t}V(V)$	123 ± 19	1.37 ± 0.22	1.2 ± 0.2	15.5 ± 2.4	105 ± 16
Background	330 ± 50	44 ± 8	26 ± 5	129 ± 19	139 ± 30
Total Pred.	7500 ± 500	1540 ± 110	367 ± 19	1030 ± 60	4530 ± 290
Data	7755	1452	379	1095	4828

Unfolding and detector correction

- Differential measurement needs to correct the detector effects (resolution, inefficiency) and get the distributions at particle-level

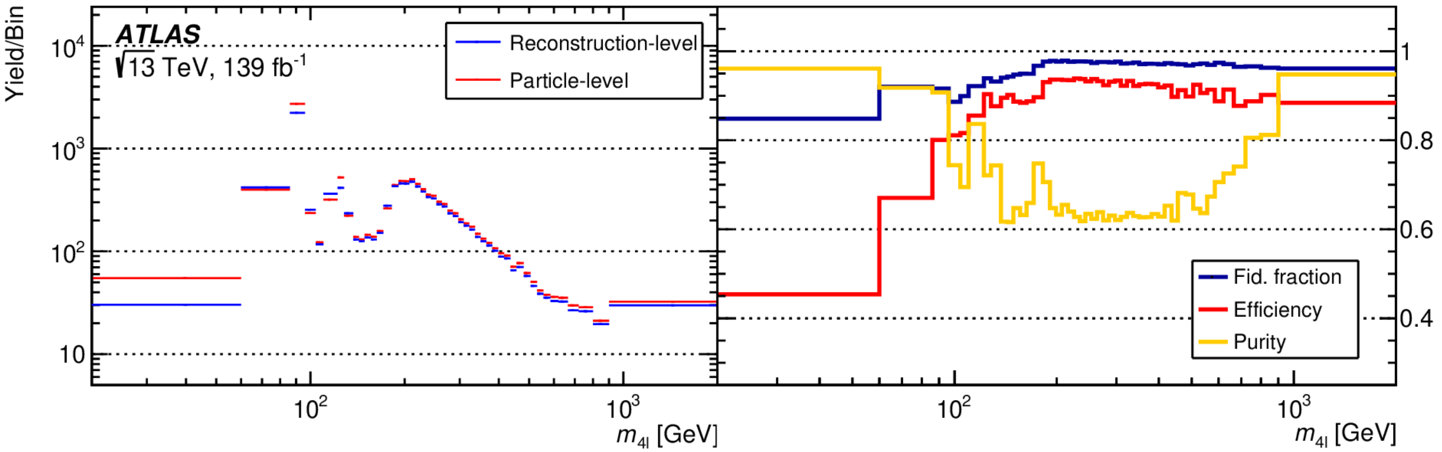


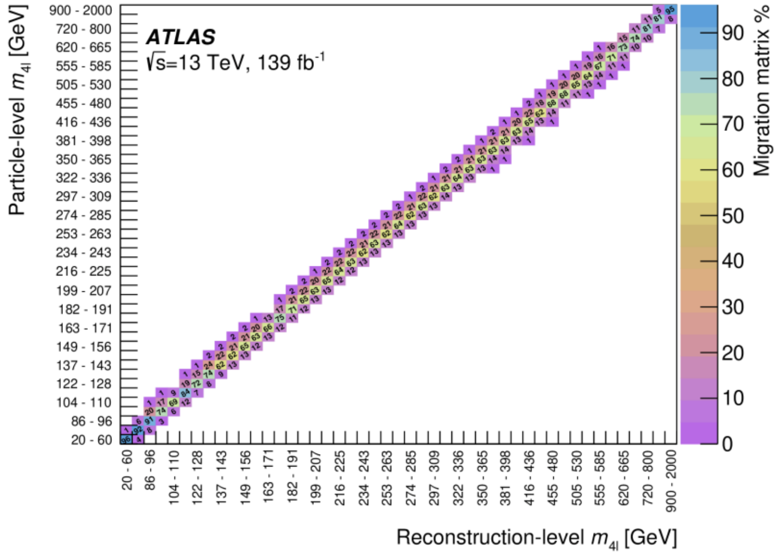
$$\begin{pmatrix} R_1 \\ \vdots \\ R_n \end{pmatrix} = \begin{pmatrix} F_{11} & \cdots & F_{1n} \\ \vdots & \ddots & \vdots \\ F_{n1} & \cdots & F_{nn} \end{pmatrix} \times \begin{pmatrix} T_1 \\ \vdots \\ T_n \end{pmatrix} \Longrightarrow \begin{pmatrix} T_1 \\ \vdots \\ T_n \end{pmatrix} = \begin{pmatrix} M_{11} & \cdots & M_{1n} \\ \vdots & \ddots & \vdots \\ M_{n1} & \cdots & M_{nn} \end{pmatrix} \times \begin{pmatrix} R_1 \\ \vdots \\ R_n \end{pmatrix}$$

Detector-level distr. | Response Matrix | Particle-level distr. | Unfolding Matrix

- The unfolded distribution could be used to retrieve differential cross-section and compare with theoretical prediction directly!

Unfolding and detector correction

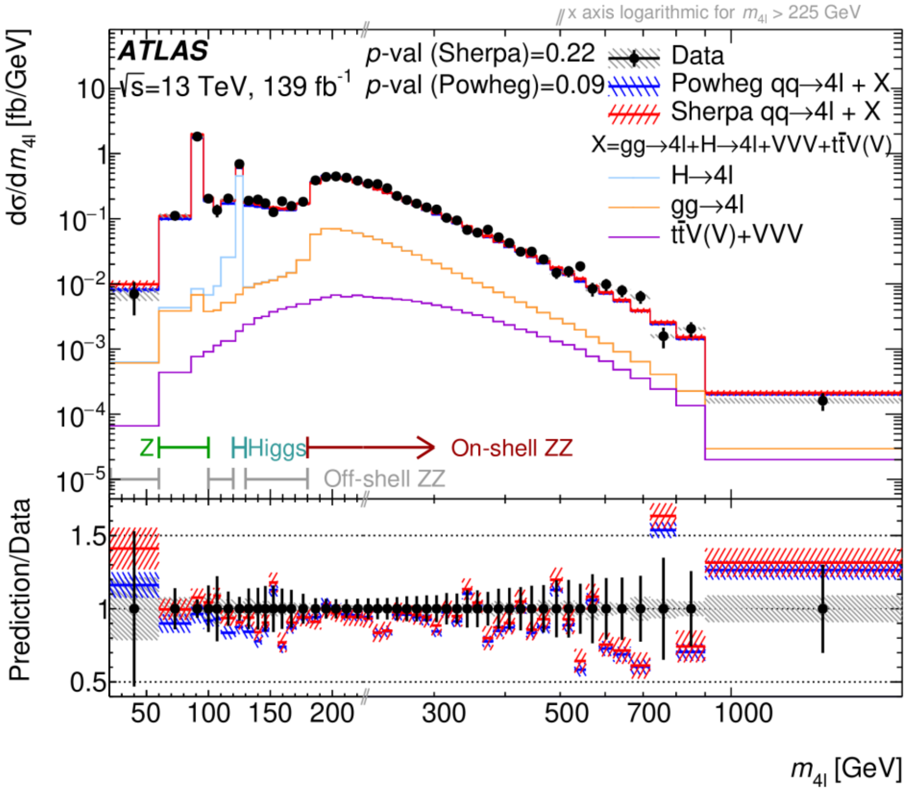




- Get unfolding ingredients (efficiency, migration matrix…) from MC simulation samples
- Validation: data-driven closure test, injection test
- Unfolding method also used to optimize the binning of distributions

Unfolded measurement

- Differential cross-section as a function of $m_{4\ell}$:

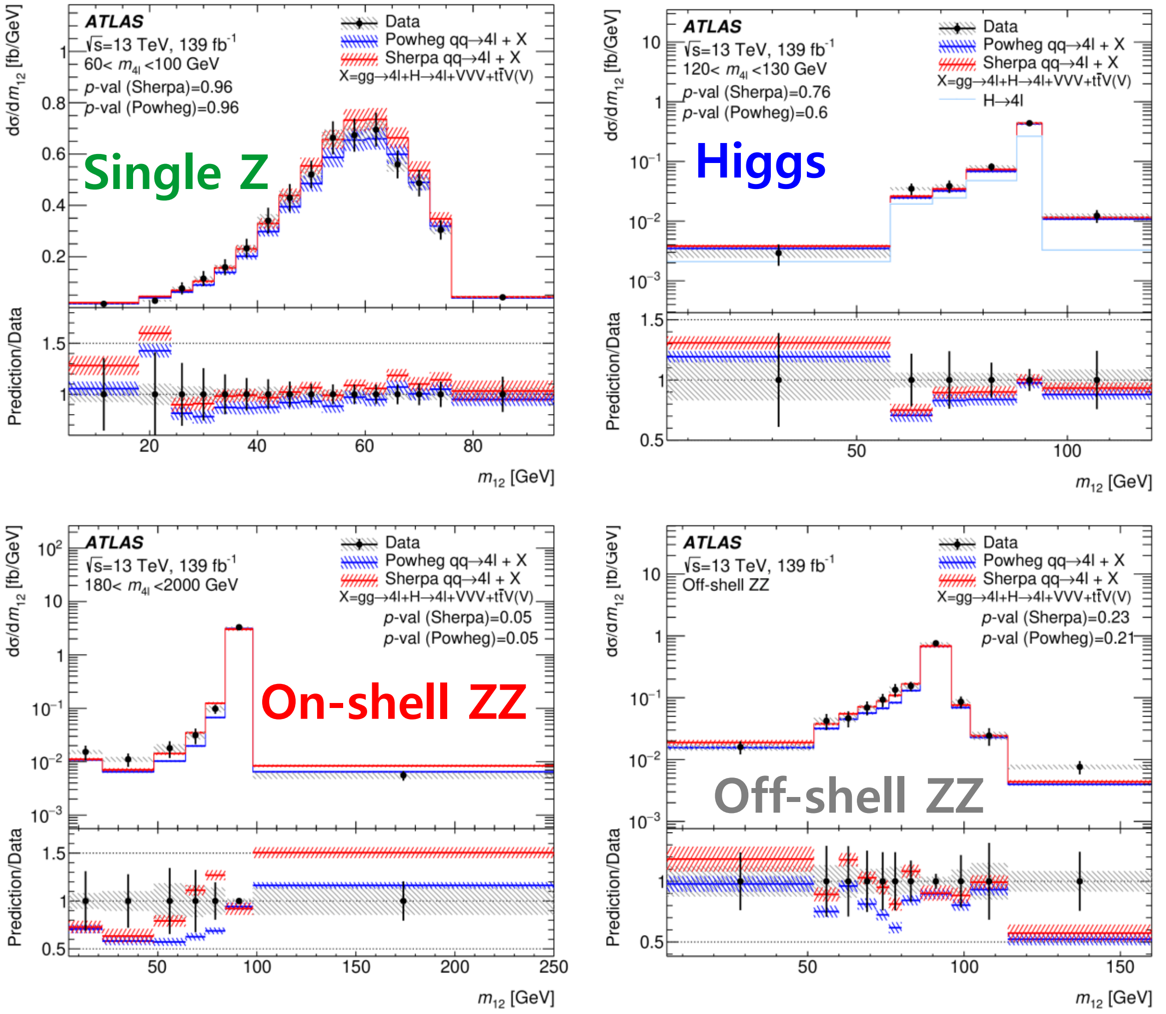


	Region				
	Full	$Z \to 4\ell$	$H \to 4\ell$	Off-shell ZZ	On-shell ZZ
Measured fiducial cross-section [fb]	88.9 ±1.1 (stat.) ±2.3 (syst.) ±1.5 (lumi.) ±3.0 (total)	22.1 ±0.7 (stat.) ±1.1 (syst.) ±0.4 (lumi.) ±1.3 (total)	4.76 ±0.29 (stat.) ±0.18 (syst.) ±0.08 (lumi.) ±0.35 (total)	12.4 ±0.5 (stat.) ±0.6 (syst.) ±0.2 (lumi.) ±0.8 (total)	49.3 ±0.8 (stat.) ±0.8 (syst.) ±0.8 (lumi.) ±1.3 (total)
SHERPA	86±5	23.6±1.5	4.57±0.21	11.5±0.7	46.0±2.9
POWHEG + PYTHIA8	83±5	21.2±1.3	4.38±0.20	10.7±0.7	46.4±3.0

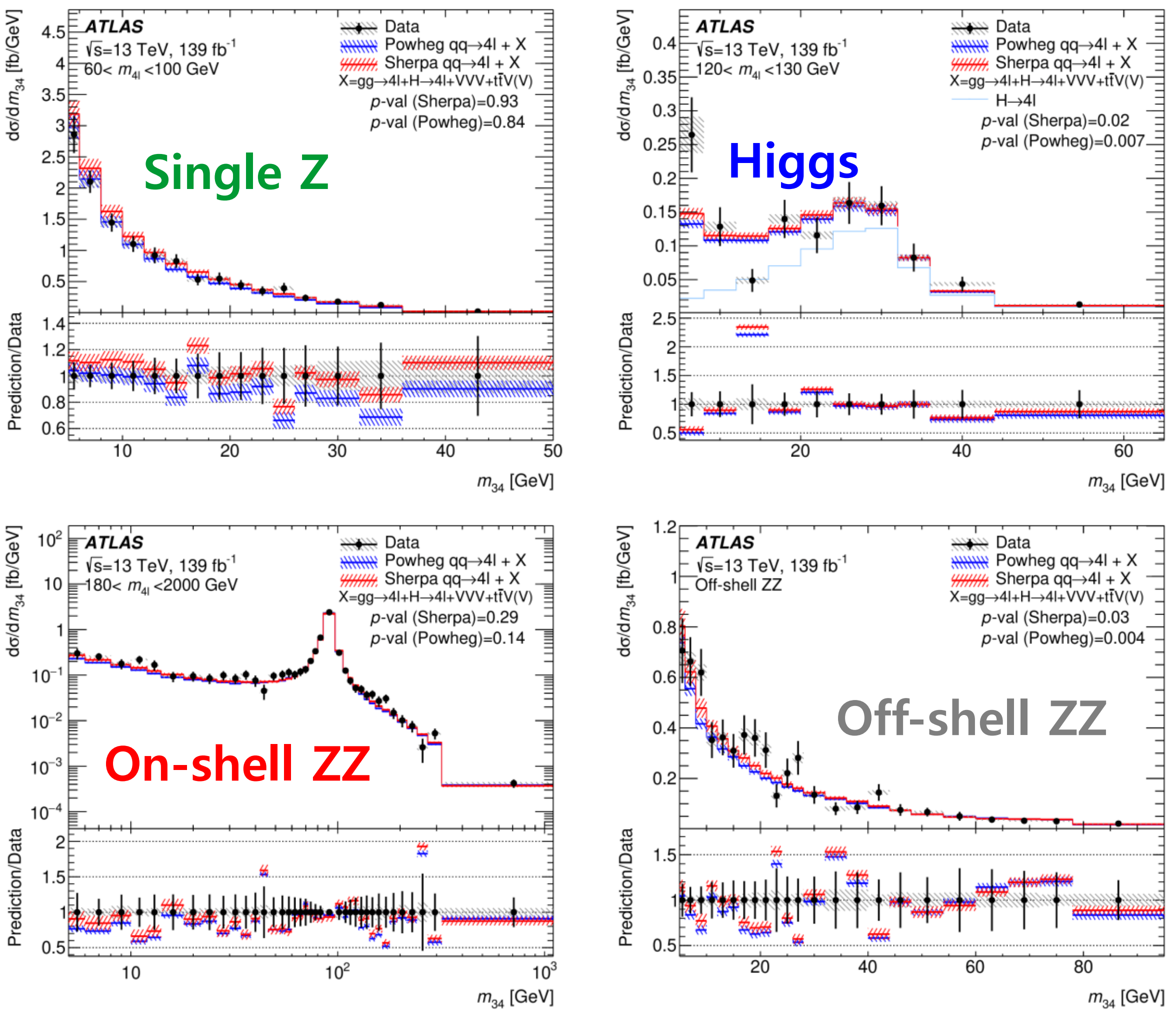
- The agreement between the data and both predictions is generally within the quoted uncertainties
- Improve the measurement precision significantly

Unfolded measurement

Differential cross-section as a function of m_{12} vs $m_{4\ell}$



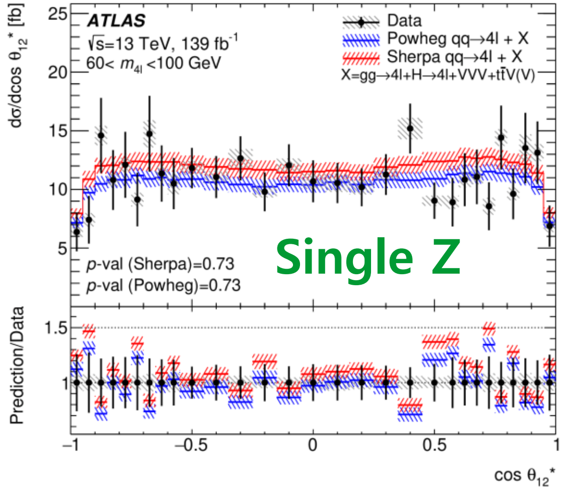
Differential cross-section as a function of m_{34} vs $m_{4\ell}$

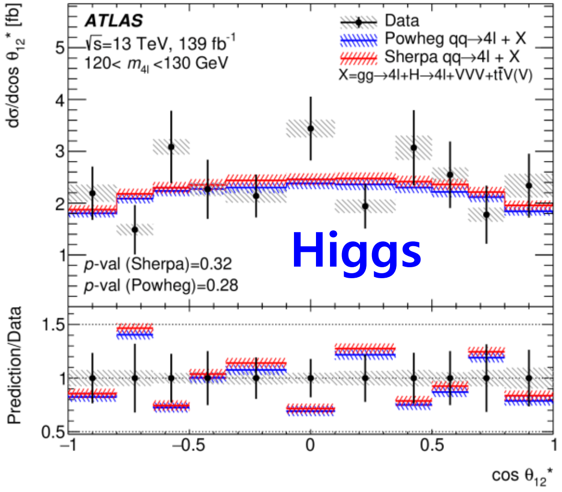


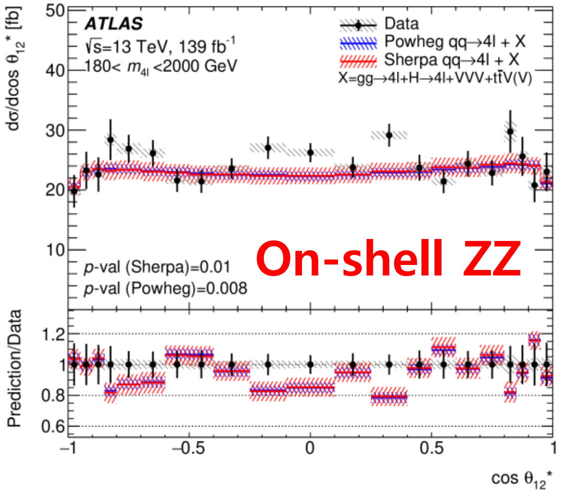
Unfolded measurement

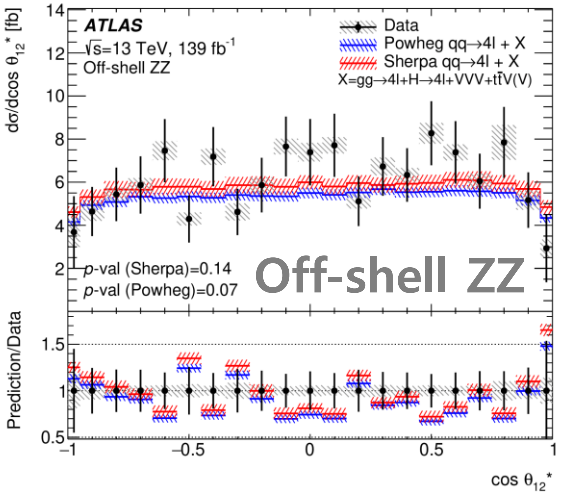
other differential cross-sections

Differential cross-section as a function of $\cos\theta^*_{12}$ vs $m_{4\ell}$

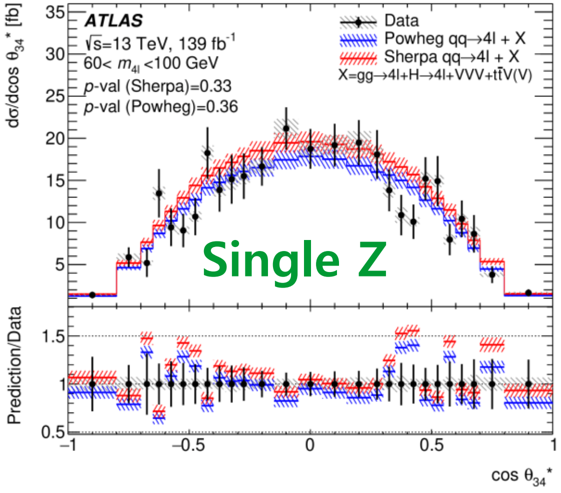


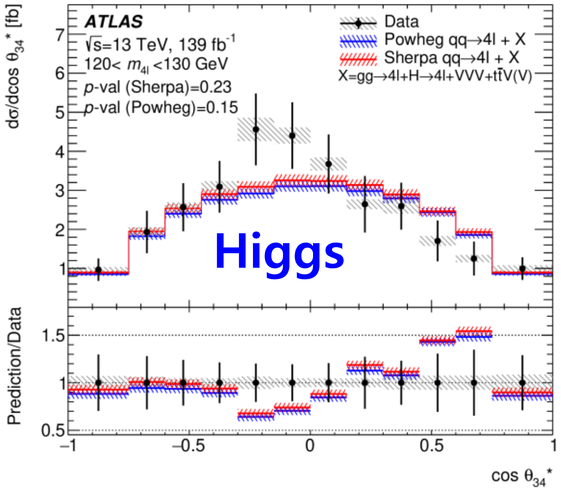


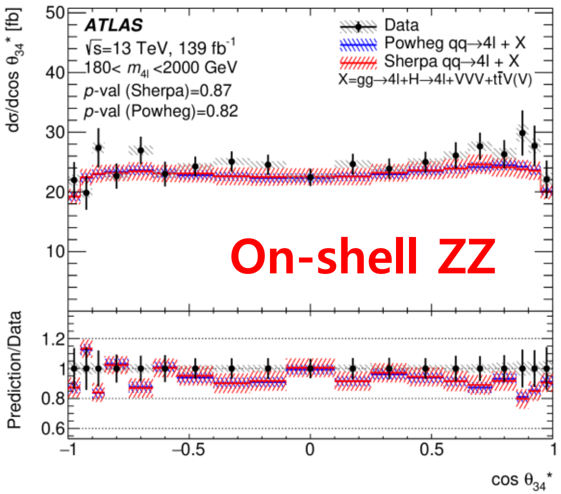


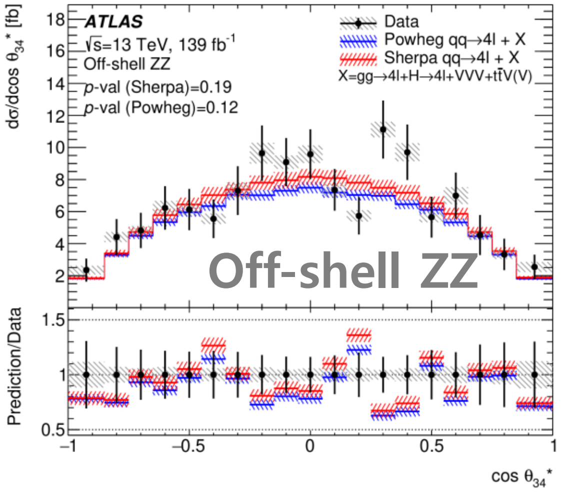


Differential cross-section as a function of $\cos\theta^*_{34}$ vs $m_{4\ell}$



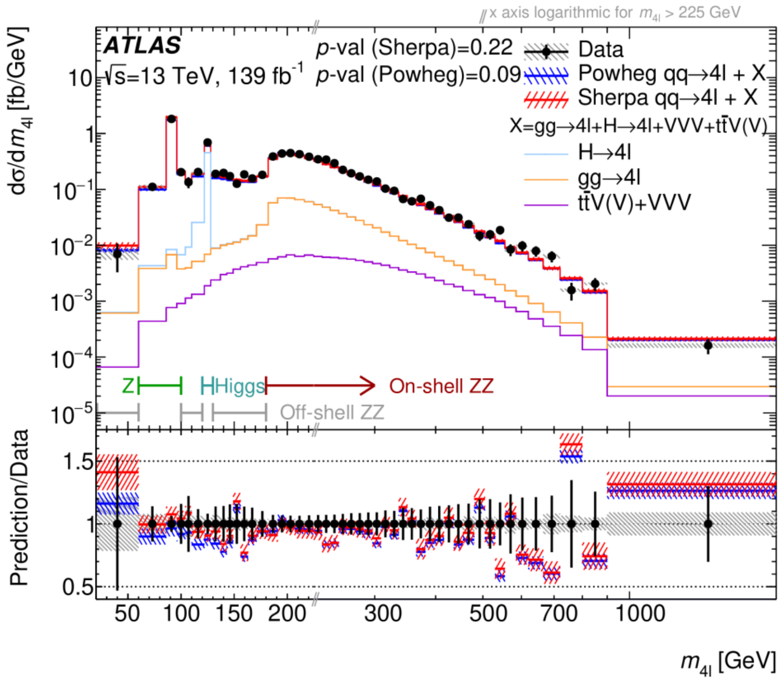






How to make use of them?

- With the precise measurements, what's next?



- $Z \to 4\ell$ Branching Ratio extraction

- BSM interpretation:
  - EFT interpretation
  - $B - L$ model interpretation

- Further re-interpretation in the future…

	Region				
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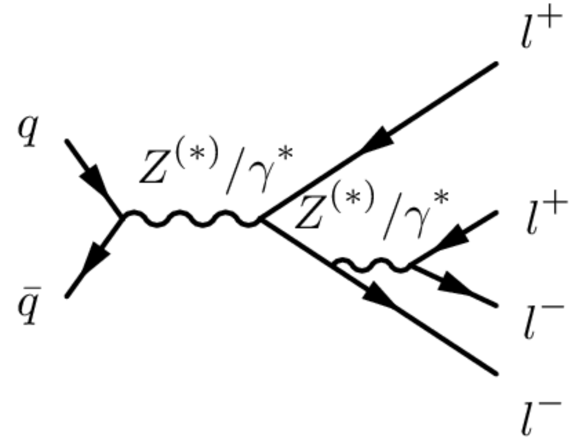
Extract $Z \to 4\ell$ Branching Ratio

- Rare process: internal conversion $Z \to 4\ell$
- Extracted the BR with measured cross-section in the $Z \to 4\ell$ region



$$\mathcal{B}_{Z\to 4l} = \frac{\left(\sigma^{\text{meas}} - \sigma^{\text{pred}}_{\text{non}-q\bar{q}\to 4l}\right) \times f_Z \times f_{non-\tau}}{\sigma_Z \times A_{\text{fid}}}$$

pred. fid. XS from non-qqZZ source

frac. of qqZZ coming from single Z prod.

Z prod. XS

ratio of qqZZ in fid. region and ext. region

frac. of events where no leptons originate from tau decays

$$\mathcal{B}_{Z\to 4l} = (4.41 \pm 0.13(\text{stat.}) \pm 0.23(\text{syst.}) \pm 0.09(\text{theory}) \pm 0.12(\text{lumi.})) \times 10^{-6} = (4.41 \pm 0.30) \times 10^{-6}$$

- Accepted as one of the experimental inputs of world average value in the latest PDG (PDG2022)

Introduction to BSM interpretation

- Utilize the numerous differential cross-sections of 4ℓ final state to test BSM/fit BSM parameters/constrain BSM
- Dig out the information far from resonances
- Statistics:
  - $\mathcal{L} = \frac{1}{\sqrt{(2\pi)^k |C|}} \exp\left(-\frac{1}{2}\left(\vec{\sigma}_{\text{data}} - \vec{\sigma}_{\text{pred}}(\mu, \vec{\theta})\right)^T C^{-1} \left(\vec{\sigma}_{\text{data}} - \vec{\sigma}_{\text{pred}}(\mu, \vec{\theta})\right)\right) \times \prod_i \mathcal{G}(\theta_i, 0, 1)$
    - $C = C_{\text{stat}}(\text{fixed to expected SM}) + \text{C}_{\text{syst}}(\text{unfolding})$ (other uncertainties)
    - nuisance parameters $\vec{\theta}$ (BSM theoretical uncertainties)
  - Multi-gaussian statistics model to characterize the correlation among bins by unfolding procedure

EFT: operators

- Constrain on Wilson coefficients of dim-6 operators in Standard-Model EFT formalism(SMEFT)
  - $\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{C_i}{\Lambda^{d_i-4}} \mathcal{O}_i$
  - $c_i \equiv \frac{c_i^{\mathrm{d}=6}}{\Lambda^2}$

- Among the full list of 59 dim-6 operators, 22 Wilson coefficients that give non-negligible contributions to the 4ℓ final state are considered

  - 3 affecting Higgs couplings: $c_{HG}, \tilde{c}_{HG}, c_{HD}$
  - 1 affecting gauge boson coupling: c_{HWB}
  - 7 affecting the $\mathrm{Z} \to \ell\ell$ vertex: $c_{Hd}, c_{Hu}, c_{He}, c_{Hl}^{(1)}, c_{Hl}^{(3)}, c_{Hq}^{(1)}, c_{Hq}^{(3)}$
  - 11 four-fermion interaction: $c_{ed}, c_{ee}, c_{eu}, c_{ld}, \; c_{le}, c_{ll}, c_{ll}^{(1)}, c_{lq}^{(1)}, c_{lq}^{(3)}, c_{lu}, c_{qe}$

- Different variables are sensitive to different coefficients

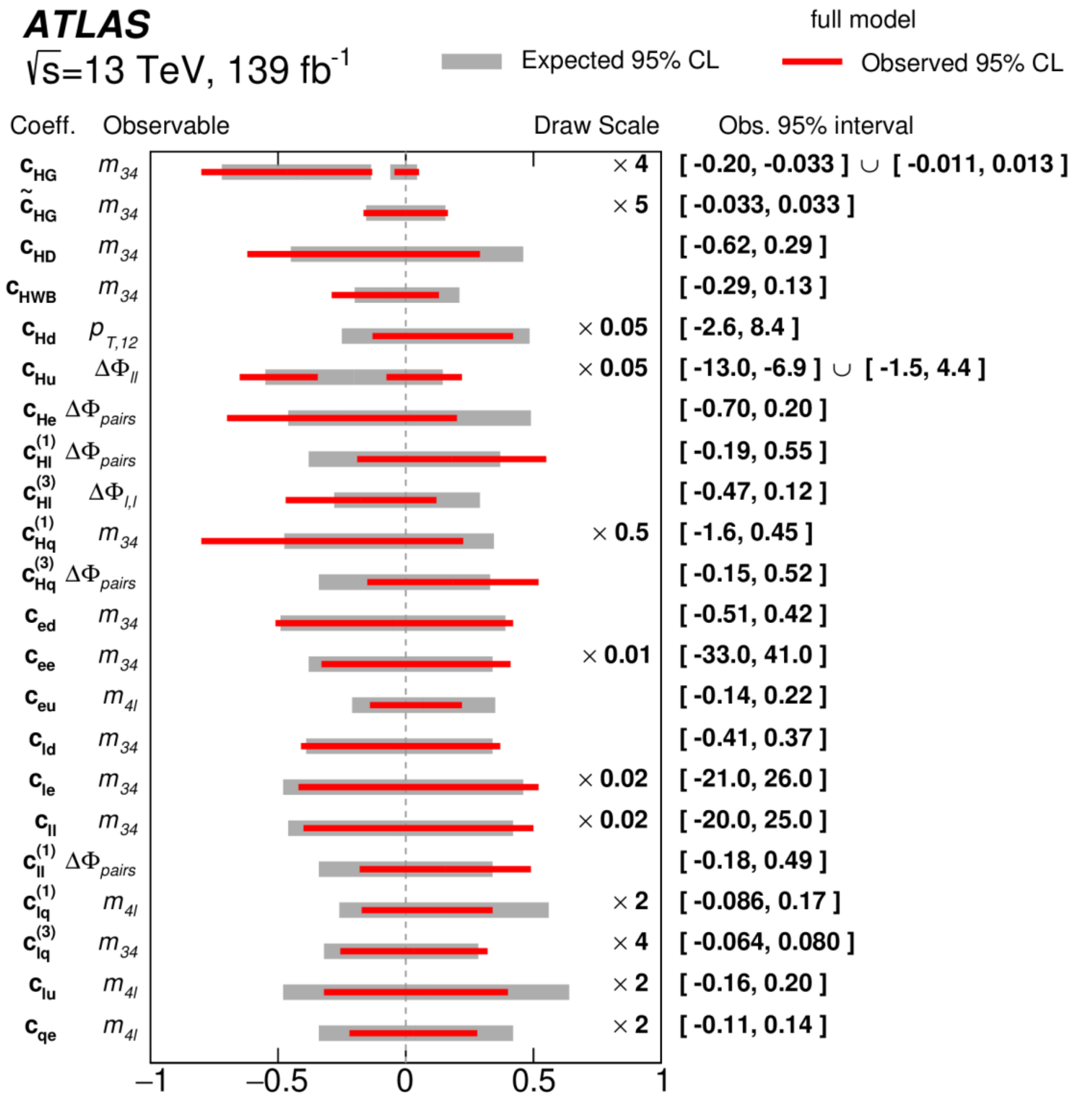
EFT: methodology

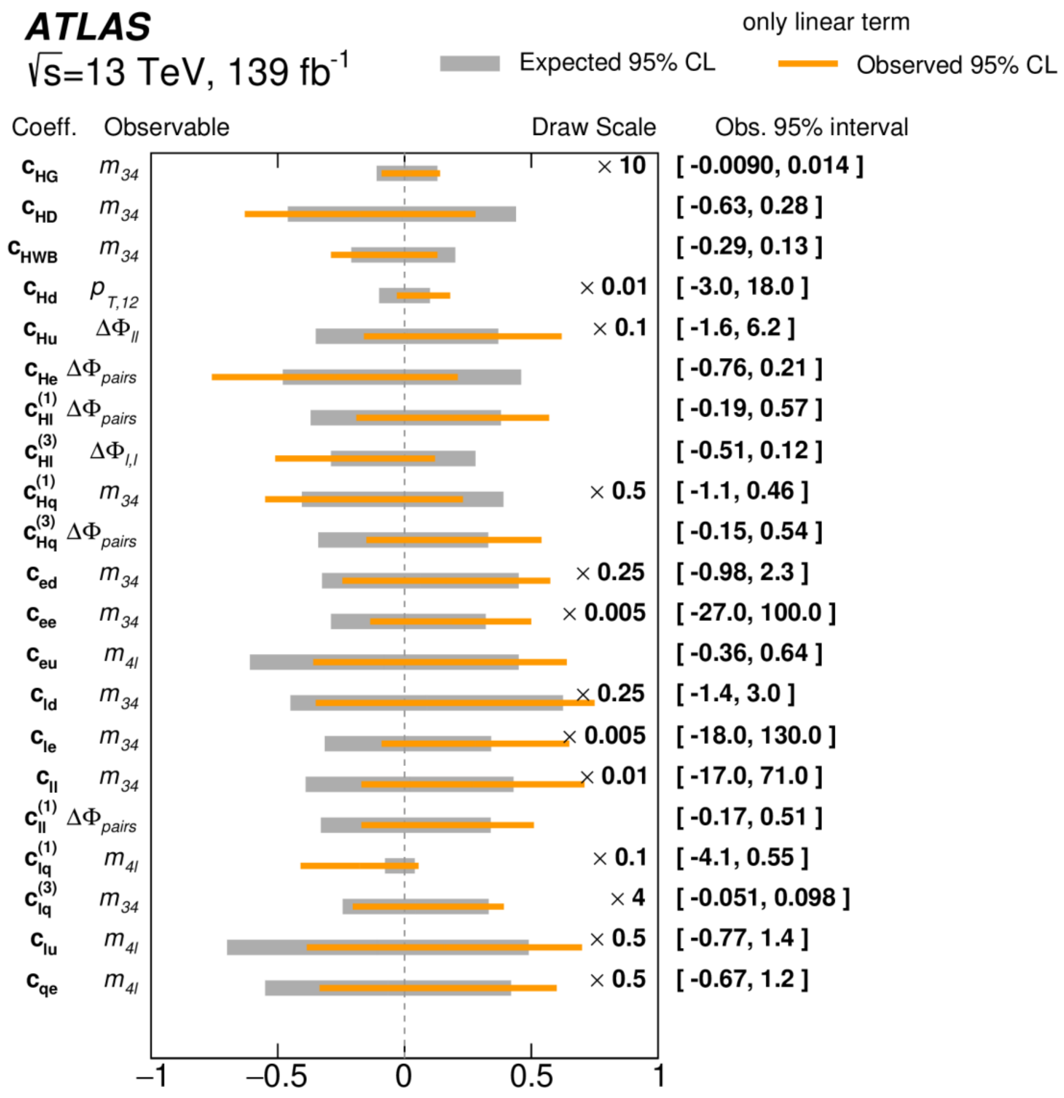
- Parametrization:
  - Matrix element: $\mathcal{M}_{\text{mix}} = \mathcal{M}_{\text{SM}} + c \cdot \mathcal{M}_{\text{BSM}}$
  - The full prediction SM+BSM can be decomposed into three components of SM term, linear term(interference), quadratic term(pure BSM):
  - $\sigma(c) = \sigma_{\text{SM}} + c \cdot \sigma_{\text{INT}} + c^2 \cdot \sigma_{\text{BSM}}$

- Generate the three components separately at LO precision in QCD
- Scale the MC with the ratio best SM to LO SM to consider the high-order effect

- The variable providing the best sensitivity is chosen to set limits for a Wilson coefficient, and a variable measured in slices counts as one variable

EFT: fitting results





B-L model: introduction

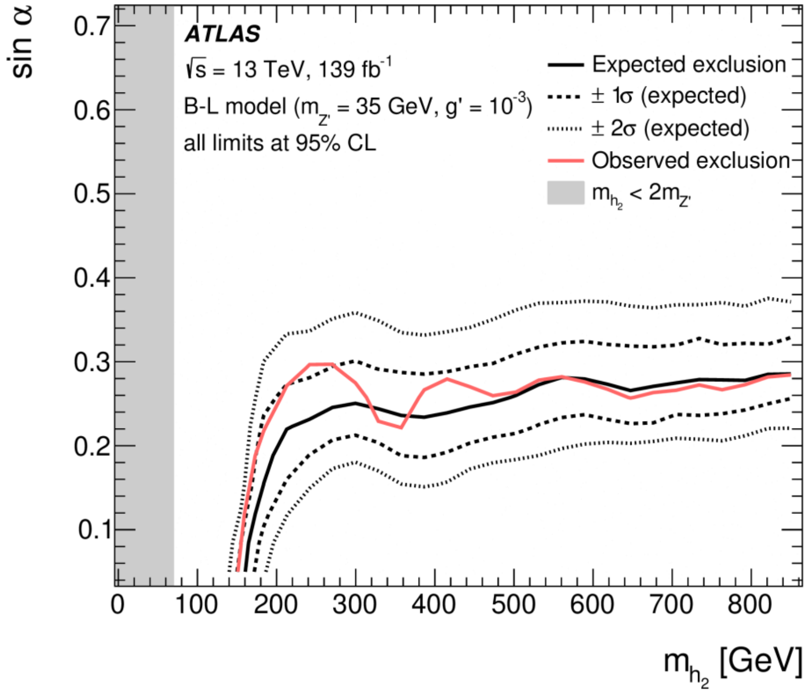
- An extension of SM with additional $U(1)_{B-L}$, with spontaneously breaks of $B-L$ symmetry, the neutrinos get mass (B-L model)
  - Model predicts new particles: gauge boson Z', exotic Higgs h_2 as well as RH neutrinos
  - Z' interacts with fermions through coupling g', and h_2 mixes with SM Higgs via mixing angle α

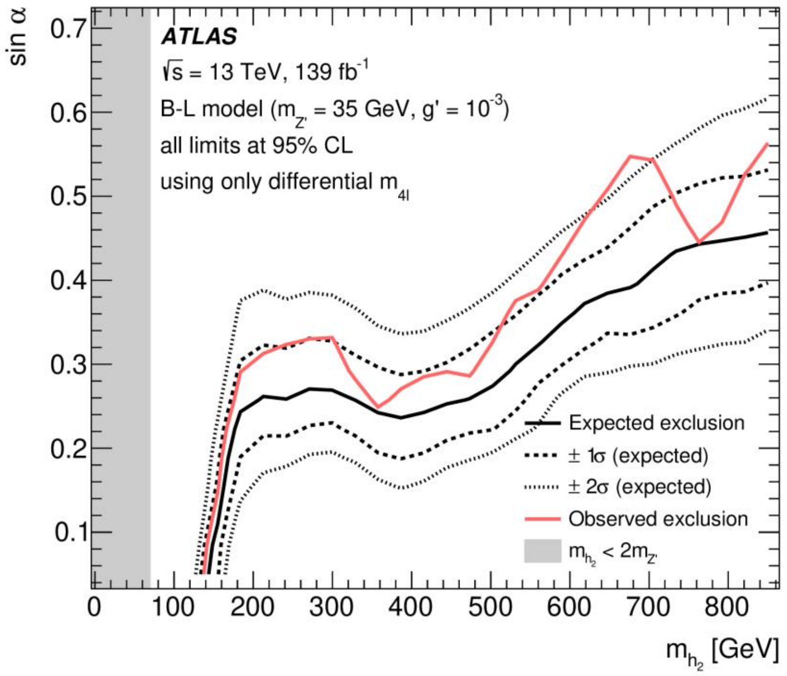
- Scenario considered: fixed parameters: low Z′ mass (35 GeV) weakly coupled to SM ($g' = 10^{-3}$)
- Set limit on 2D m_{h2} ~ sinα parameter space

- B-L samples with different parameter settings generated at particle-level with LO precision
- Same as EFT, the variable providing the best sensitivity is chosen to set limits

B-L model: limit setting

- 95% CL exclusion:
- Left: m4l only exclusion; Right: all variables included exclusion





- Sinα > 0.28 over most of the range and constraints on mh_2 above 400 GeV
- Numerous variables we measured, provide us stronger power of exclusion

Summary

- We present the measurement of various differential cross-sections in 4-lepton events with ATLAS full Run-II data at a new-precision regime

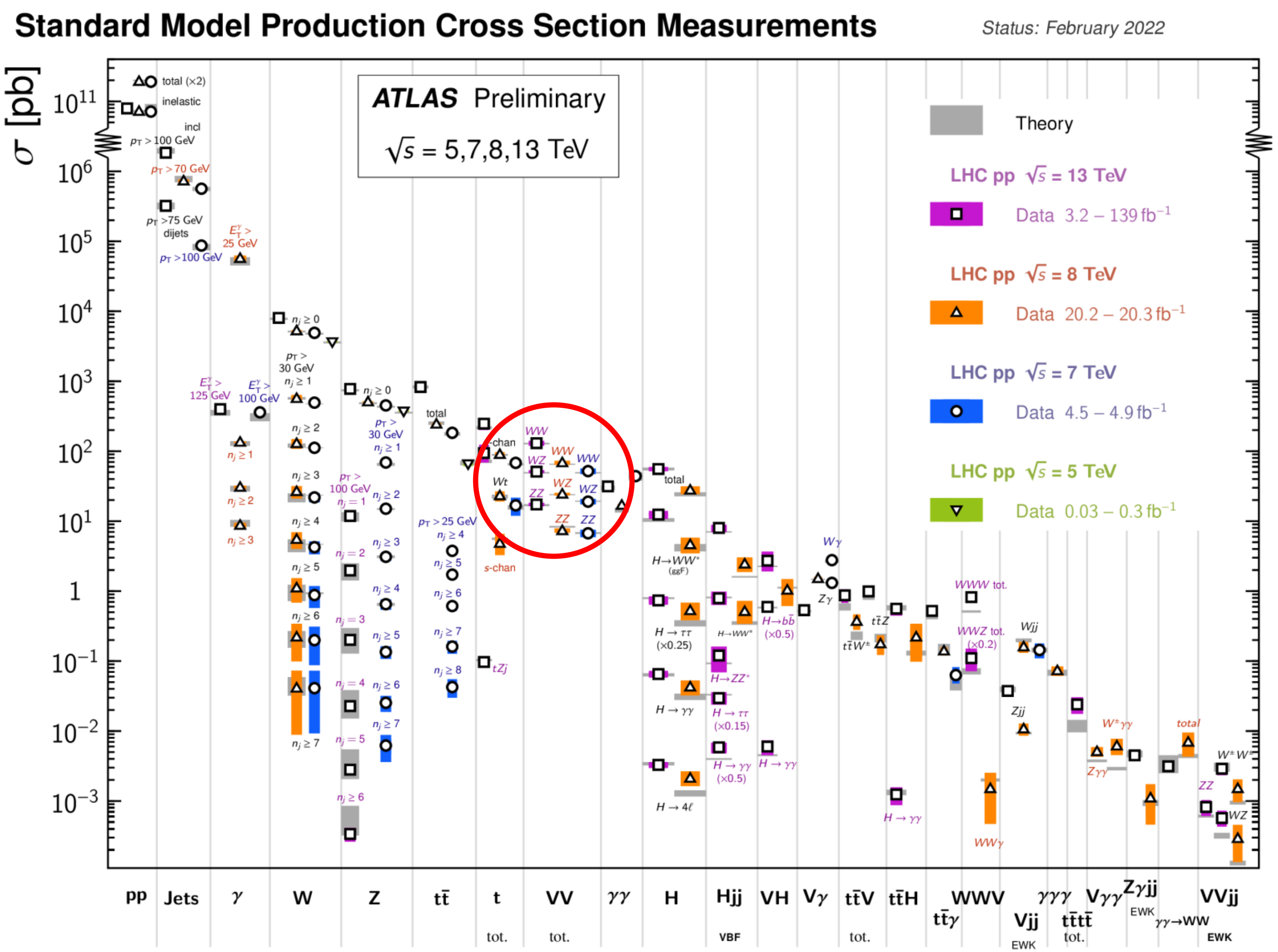
- All information are corrected to particle-level and prepared in **HEPData** with **Rivet** routine, providing convenient way for rapid future re-interpretation to both experimentalists and theorists (HEPData, Rivet routine)

- Improve the $Z \rightarrow 4l$ BR measurement

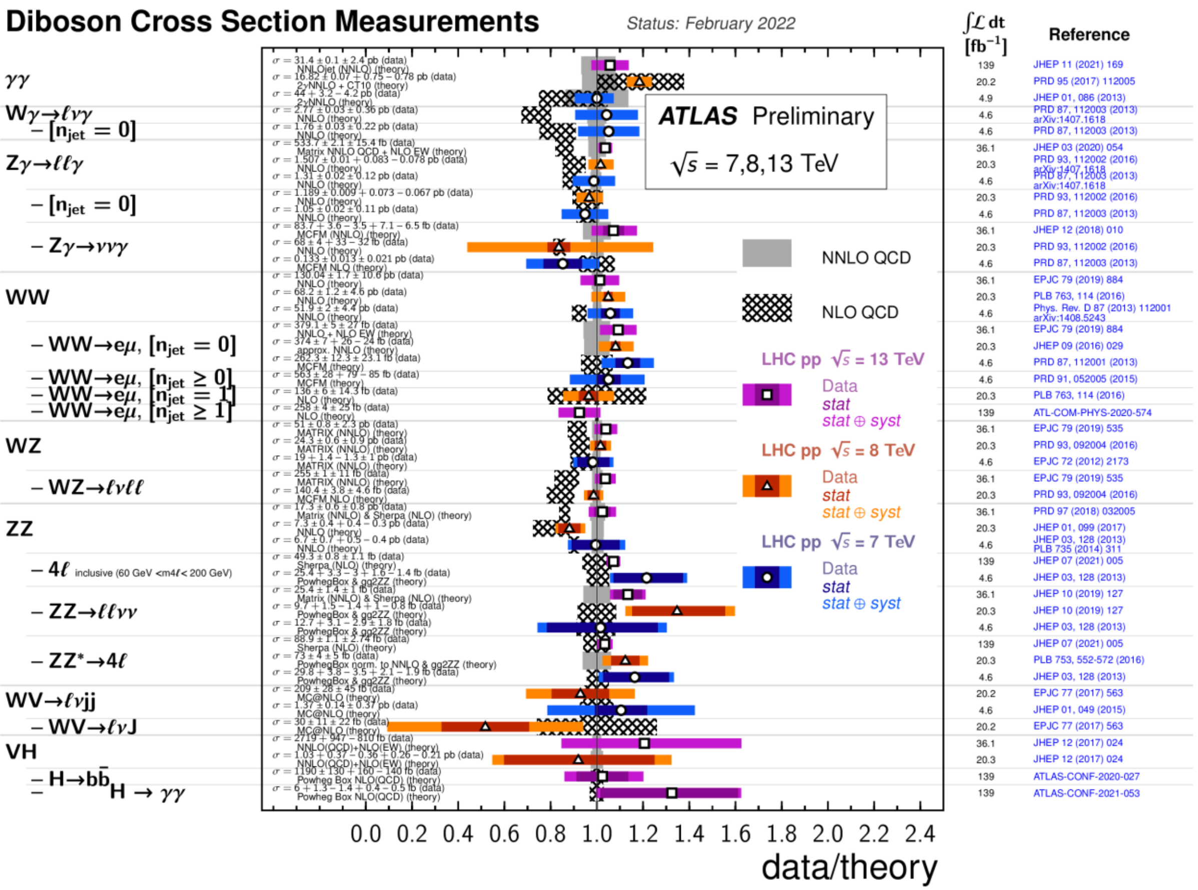
- Constraints setting on EFT dim-6 operators and gauged B-L model as an example

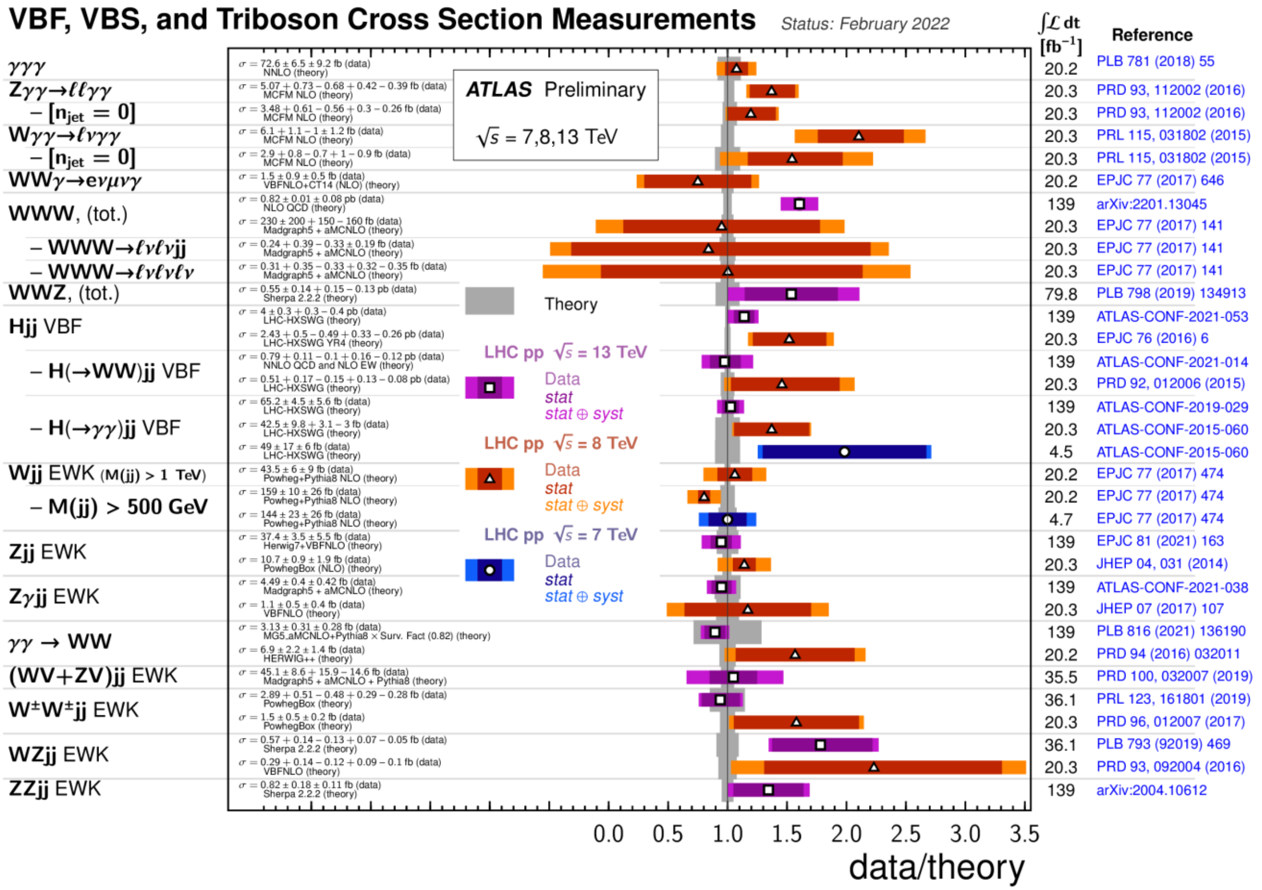
- publication of the work
    - Measurements of differential cross-sections in four-lepton events in 13 TeV proton-proton collisions with the ATLAS detector

Back-up: SM production cross-sections



Back-up: Multi-boson cross-sections

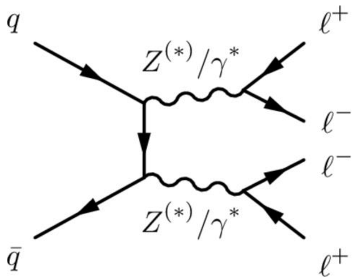


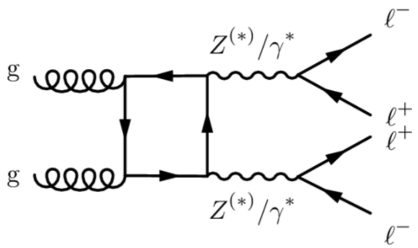


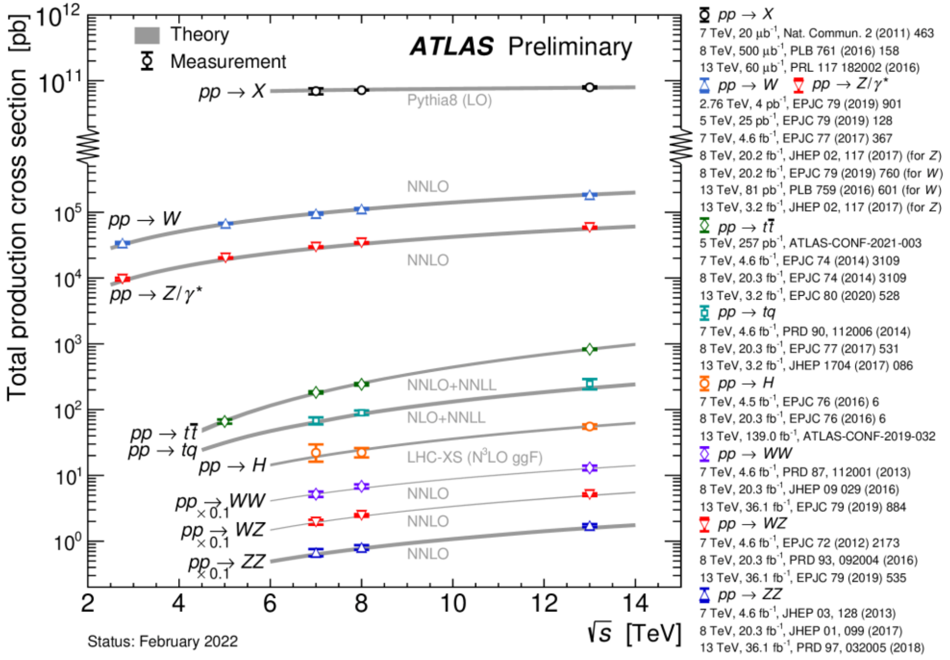
Back-up: $pp \rightarrow Z^{(*)}Z^{(*)} \rightarrow 4\ell$ at LHC

- 4ℓ final state: two same-flavor opposite-sign e or μ pairs

- Production is dominated by qq-initiated t-channel ZZ, the secondary contribution is from loop-induced ggZZ process $\mathcal{O}(10\%)$







- Resonance production contributions of HZZ as well as internal conversion of Z decay

- Even through 4ℓ channel has very low Branching Ratio (~0.4%), it is clean channel with high energy resolution

Back-up: Triggers

- data selected using a logical OR of a reduced set of lowest prescaled single, di- and tri-lepton triggers

Year	
2015	HLT_e24_lhmedium_L1EM20VH
	HLT_e60_lhmedium
	HLT_e120_lhloose
	HLT_2e12_lhvloose_L12EM10VH
2016	HLT_e26_lhtight_nod0_ivarloose
	HLT_e60_lhmedium_nod0
	HLT_e140_lhloose_nod0
	HLT_2e17_lhvloose_nod0
2017	HLT_e26_lhtight_nod0_ivarloose
	HLT_e60_lhmedium_nod0
	HLT_e140_lhloose_nod0
	HLT_2e24_lhvloose_nod0
	HLT_e24_lhvloose_nod0_2e12_lhvloose_nod0_L1EM20VH_3EM10VH
2018	HLT_e26_lhtight_nod0_ivarloose
	HLT_e60_lhmedium_nod0
	HLT_e140_lhloose_nod0
	HLT_2e17_lhvloose_nod0_L12EM15VHI
	HLT_2e24_lhvloose_nod0
	HLT_e24_lhvloose_nod0_2e12_lhvloose_nod0_L1EM20VH_3EM10VH

Year	
2015	HLT_mu20_iloose_L1MU15
	HLT_mu50
	HLT_2mu10
	HLT_mu18_mu8noL1
2016	HLT_mu26_ivarmedium
	HLT_mu50
	HLT_2mu14
	HLT_mu22_mu8noL1
2017	HLT_mu26_ivarmedium
	HLT_mu50
	HLT_2mu14
	HLT_mu22_mu8noL1
2018	HLT_mu26_ivarmedium
	HLT_mu50
	HLT_2mu14
	HLT_mu22_mu8noL1

Year	
2015	HLT_e7_lhmedium_mu24
	HLT_e17_lhloose_mu14
2016	HLT_e7_lhmedium_nod0_mu24
	HLT_e17_lhloose_nod0_mu14
	HLT_2e12_lhloose_nod0_mu10
2017	HLT_e17_lhloose_nod0_mu14
	HLT_e26_lhmedium_nod0_mu8noL1
2018	HLT_e17_lhloose_nod0_mu14
	HLT_e26_lhmedium_nod0_mu8noL1

Back-up: Fiducial region definition

- any process with at least 4 leptons in the hard scattering is considered as part of the signal

	Lepton selection
Muon selection	Bare, $p_T > 5$ GeV, $\|\eta\| < 2.7$
Electron selection	Dressed, $p_T > 7$ GeV, $\|\eta\| < 2.47$
	Event selection
Four-lepton signature	At least 4 leptons, with 2 Same-Flavour, Opposite-Sign pairs
Lepton kinematics	$p_T > 20/10$ GeV for leading two leptons
Lepton separation	$\Delta R_{ij} > 0.05$ for any leptons
J/ψ-Veto	$m_{ij} > 5$ GeVfor all SFOS pairs
Truth isolation	ptcone30/p_T < 0.16

Back-up: Event selection

- Leptons are reconstructed and checked with baseline criteria

Category	Requirement	
Kinematics	Muons :	$p_T > 5$ GeV If CaloTag: >15 GeV $\lvert\eta\rvert < 2.7$
	Electrons:	$p_T > 7$ GeV $\lvert\eta\rvert < 2.47$
Vertex association	Both :	$\lvert z_0 \sin\theta\rvert$ <0.5 mm
Identification:	Muons:	Loose ID
	Electrons:	LooseLH ID
Overlap removal: Lepton-favoured		

- Lepton pairing:

Primary pair	$\min\lvert m_{ij} - m_Z\rvert$ in all SFOS leptons pairs
Secondary pair	$\min\lvert m_{ij} - m_Z\rvert$ in the rest SFOS lepton pairs

- Event selection with fiducial definition

Category	Requirement
Event Preselection	Fire at least one lepton trigger ≥1 vertex with 2 or more tracks
Four-lepton signature	At least 4 leptons (e, μ)
Lepton kinematics	$p_T >$ 20/10 GeV for leading two leptons
Lepton separation	$\Delta R_{ij} > 0.05$ for any two leptons
J/ψ-Veto	$m_{ij} > 5$ GeVfor all SFOS pairs
Trigger matching	Baseline leptons matched to at least one lepton trigger
Quadruplet formation	At least one quadruplet with 2 Same-Flavour, Opposite-Sign (SFOS) pairs
Quadruplet categorisation	4 signal, 0 non-signal: signal region ≤ 3 signal, ≥ 1 non-signal: background control region

- Tight criteria applied on leptons in quadruplet to mitigate misidentified or non-prompt leptons

Input objects	Baseline electrons and muons that are part of the quadruplet
Isolation	FixedCutPflowLoose working point *Contribution from all other baseline leptons is subtracted*
Cosmic muon veto	Muons: $\lvert d_0\rvert$ <1 mm
Impact Parameter	Muons: d_0/σ_{d_0} <3 Electrons: d_0/σ_{d_0} <5
Stricter Electron ID	Electrons: LooseBLayerLH ID

Back-up: Event selection

jet selection

Collection:	AntiKt4EMPFlow
Kinematics:	$\|\eta\| < 4.5$
	$p_T > 30$ GeV
Signal jet (after overlap removal):	pass JVT

details of overlap removal strategy

Reject	Against	Overlap Criteria
electron	electron	shared track, $p_T^1 < p_T^2$
calo muon	electron	shared ID track
electron	muon	shared ID track
jet	electron	$\Delta R < 0.2$
jet	muon	NumTrack < 3 and ghost-associated/$\Delta R < 0.2$

Back-up: MC simulation

- qqZZ:
  - PS: MEPS@NLO Catani-Seymour dipole factorization
  - OPENLOOPS lib for virtual QCD correction
- ggZZ:
  - > 130 GeV (SM box + ggF + interference)
  - K-factor to NLO
- on-shell Higgs:
  - ggF cross-section @ N3LO
  - PS: PYTHIA8
- triboson
- ttV
  - PS: same as qqZZ

Process		Generator
$q\bar{q} \to ZZ^{(*)} \to 4\ell$	inclusive	Sherpa 2.2.2
	2 add. jets (EW)	Sherpa 2.2.2
$gg\,(\to H^{(*)}) \to ZZ^{(*)} \to 4\ell$	inclusive, $m_{4\ell} > 130$ GeV	Sherpa 2.2.2
$gg \to ZZ^{(*)} \to 4\ell$	no H, $m_{4\ell} < 130$ GeV	Sherpa 2.2.2
$pp \to H \to ZZ^{(*)} \to 4\ell$	ggF	Powheg (NNLOPS) + Pythia 8
	VBF	Powheg + Pythia 8
	ZH	Powheg + Pythia 8
	WH	Powheg + Pythia 8
	ttH	Powheg + Pythia 8
$pp \to W^{(*)}W^{(*)}Z^{(*)} \to 4\ell 2\nu$	inclusive	Sherpa 2.2.2
$pp \to W^{(*)}Z^{(*)}Z^{(*)} \to 5\ell 1\nu$	inclusive	Sherpa 2.2.2
$pp \to Z^{(*)}Z^{(*)}Z^{(*)} \to 6\ell$	inclusive	Sherpa 2.2.2
$pp \to Z^{(*)}Z^{(*)}Z^{(*)} \to 4\ell 2\nu$	inclusive	Sherpa 2.2.2
$pp \to t\bar{t} + \ell\ell$	$t\bar{t}Z$, $m_{\ell\ell} > 5$ GeV	Sherpa 2.2.0

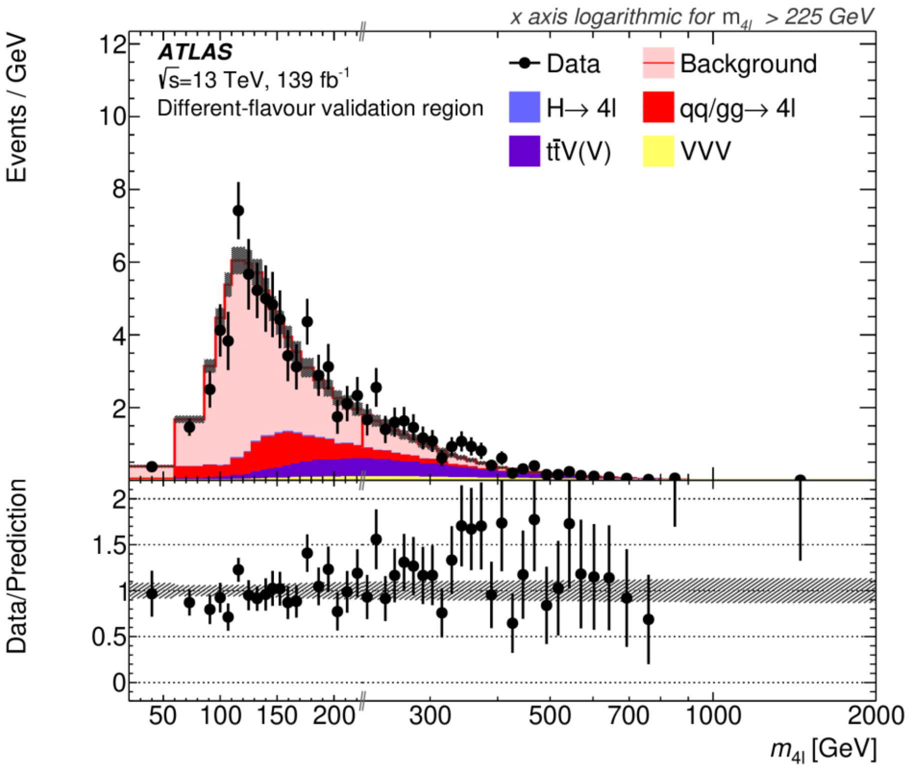
Process		Generator
$pp \to Z^{(*)} \to 2e+$ jets	≥ 4 truth leptons with $p_T > 4$GeV $m_1(\ell\ell) > 40$GeV, $m_2(\ell\ell) > 8$GeV	Sherpa 2.2.0
$pp \to Z^{(*)} \to 2\mu+$ jets	≥ 4 truth leptons with $p_T > 4$GeV, $m_1(\ell\ell) > 40$GeV, $m_2(\ell\ell) > 8$GeV	Sherpa 2.2.0
$pp \to Z^{(*)} \to 2e+$ jets	≥ 3 truth leptons with $p_T > 4$GeV veto filter of 344295	Sherpa 2.2.0
$pp \to Z^{(*)} \to 2\mu+$ jets	≥ 3 truth leptons with $p_T > 4$GeV veto filter of 344296	Sherpa 2.2.0
$pp \to Z^{(*)} \to 2e+$ jets	inclusive	Sherpa 2.2.1
$pp \to Z^{(*)} \to 2\mu+$ jets	inclusive	Sherpa 2.2.1
$pp \to Z^{(*)} \to 2\tau+$ jets	inclusive	Sherpa 2.2.1
$pp \to t\bar{t} \to 2l$	inclusive	Powheg + Pythia 8
$pp \to l\nu ll$	inclusive	Sherpa 2.2.2
$pp \to Z + \Upsilon \to 4\ell$	inclusive	Pythia 8

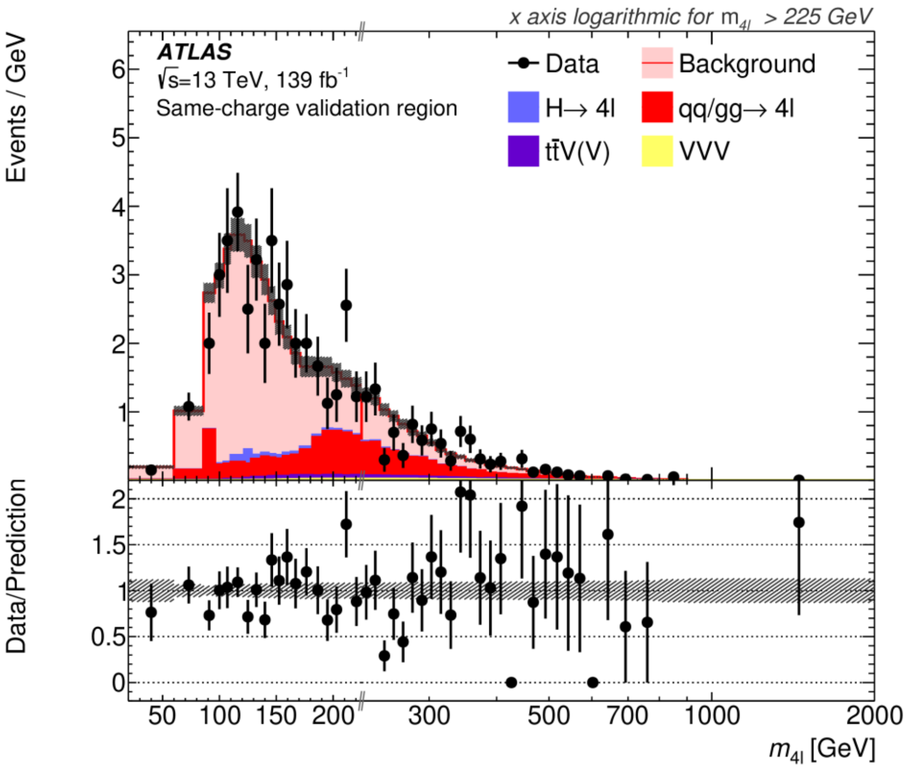
Back-up: Fake factor method

- fake factor: calculate what fraction of fake leptons is expected given the number of baseline-not-signal leptons
- calculated in Z->ll CR (events one SFOS pairs within 15 GeV of mZ and at least one other baseline lepton)
- fake factor applied to the number of baseline-not-signal leptons in each event

Back-up: Fake background validation

- validation regions: similar with SR but with one different-flavor, opposite-sign pair OR same-flavor, same-sign pair





- validate the FF method as well as cross-checking with Matrix method

Back-up: Fake background smoothing

- to suppress the statistical fluctuations
- reduce the impact of single outlier with larger FF weights
    - background estimation in fine binning for each histogram
    - smooth fine-binned distribution with Friedman’s super smoother
    - integrate smoothed distribution over coarser, target bins
    - normalized to the background yield obtained before smoothing in the first step

Back-up: Unfolding details

$$\begin{pmatrix} R_1 \\ \vdots \\ R_n \end{pmatrix} = \begin{pmatrix} \varepsilon_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \varepsilon_n \end{pmatrix} \times \begin{pmatrix} M_{11} & \cdots & M_{1n} \\ \vdots & \ddots & \vdots \\ M_{n1} & \cdots & M_{nn} \end{pmatrix} \times \begin{pmatrix} c_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & c_n \end{pmatrix} \times \begin{pmatrix} T_1 \\ \vdots \\ T_n \end{pmatrix}$$

Reco | Fiducial Correction | Migration Matrix | Efficiency Correction | Truth

Response Matrix (Fiducial Correction × Migration Matrix × Efficiency Correction)

- R and T: reco distribution & truth distribution with events passing reco or fiducial level selection respectively
- EC: reconstruction inefficiency effect of detector
- MM: smearing and resolution effect of detector
- FC: minor correction for events passing reco selection but failing truth selection

- **Iterative Bayesian unfolding technique**
  - $P_n(T_j|R_i) = \frac{P(R_j|T_i)P_{n-1}(T_i)}{\sum P(R_j|T_k)P_{n-1}(T_k)}$, $P_n(T_i) = \sum P_n(T_j|R_j)P(R_j)$
    - T_i ,R_j are the bin content at particle-, detector-level
    - 2/3 iterations, optimized based on bias and stats.

Back-up: Unfolding optimization

- statistical variation based toy study
  - toys generated randomly from the MC reco prediction
  - unfold toys with several possible iteration choices
  - estimate the bias and statistical error for each unfolded toy

- metric: **bias significance** defined as the ratio of bias and stat, indicating the size of bias comparing with stat

- we require 0.5 threshold so here the 3 Bayesian iterations is proper

- for other variables, most of them prefer 3 iterations while for mZ1, Δφll, and Δypairs 2 iterations is sufficient

Binning requirements	
# Reco events	Purity
[14,20)	80%
[20,25)	70%
≥25	60%

binning criteria

Back-up: Unfolding closure test

- MC closure:
  - direct MC reco unfolding: full closure
  - half MC reco unfolding: closure within statistical uncertainty
- data-driven closure
  - smooth data/MC ratio
  - reweight MC
  - unfold reweighted MC , compare with reweighted truth

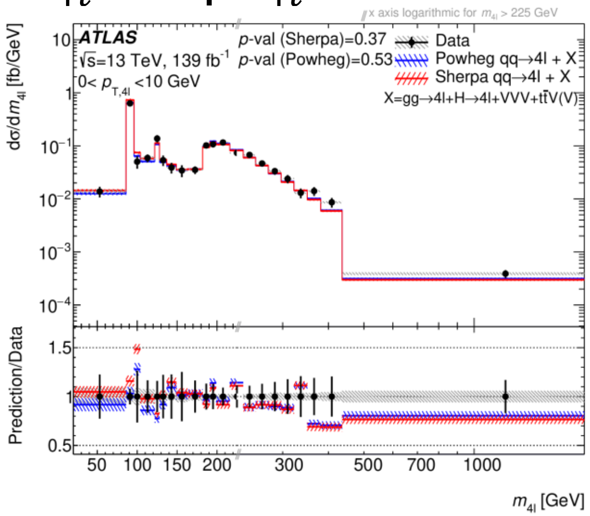
- take the difference as unfolding systematic uncertainty

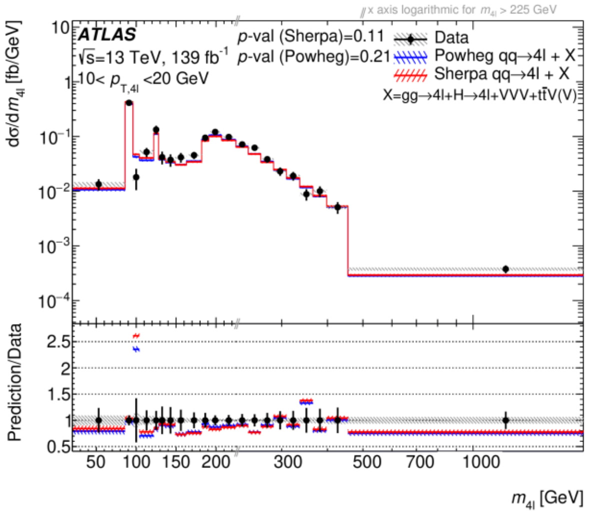
Back-up: Unfolding injection test

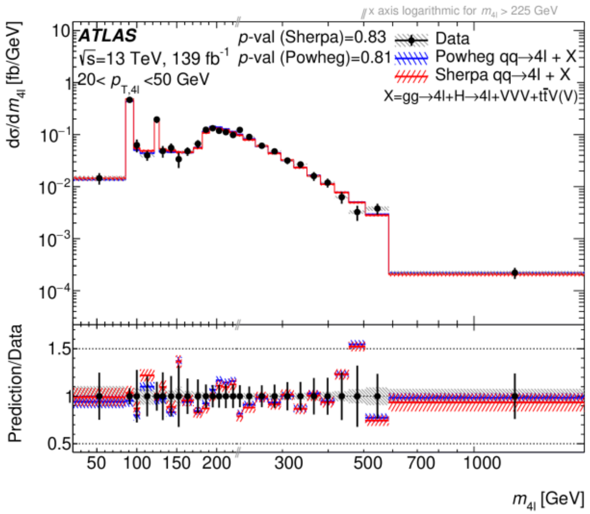
- further check on the model-independence of unfolding
  - ggF BSM Higgs mass 300GeV, width 15GeV, XS 20fb
  - ggF BSM Higgs mass 800GeV, narrow-width, XS 1fb
  - ggZZ 5-fold enhanced
- nominal unfolding is robust to broad excess over the SM prediction

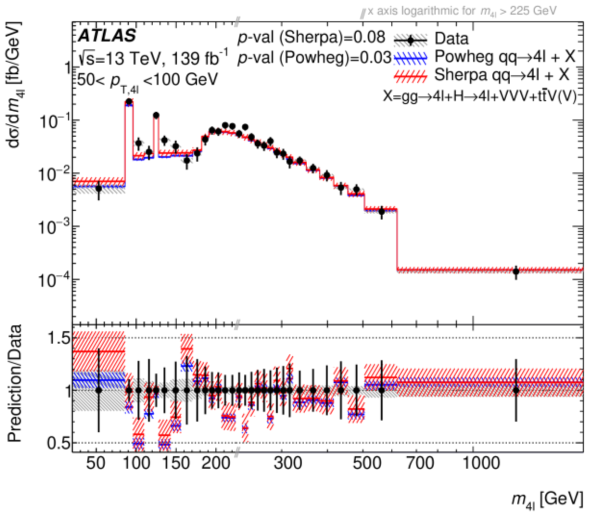
Backup: Differential X-sections

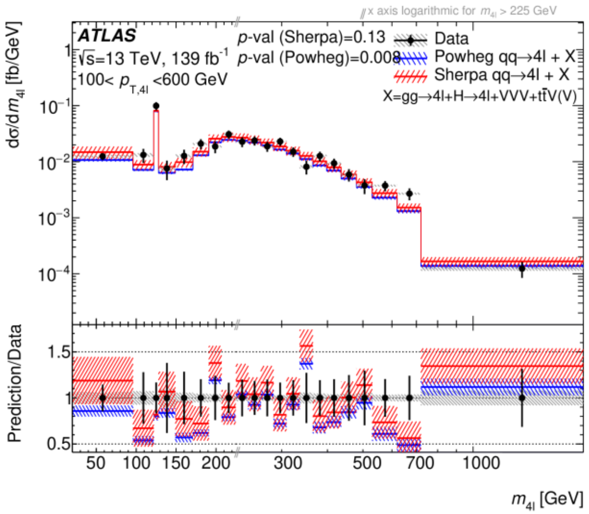
- $m_{4\ell}$ vs $p^{T}{}_{4\ell}$





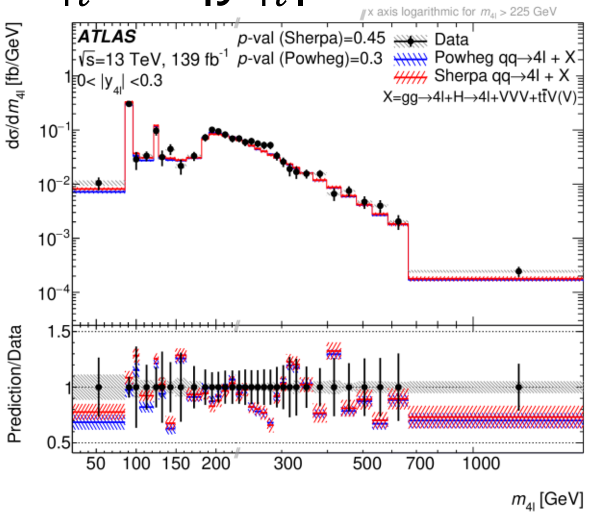


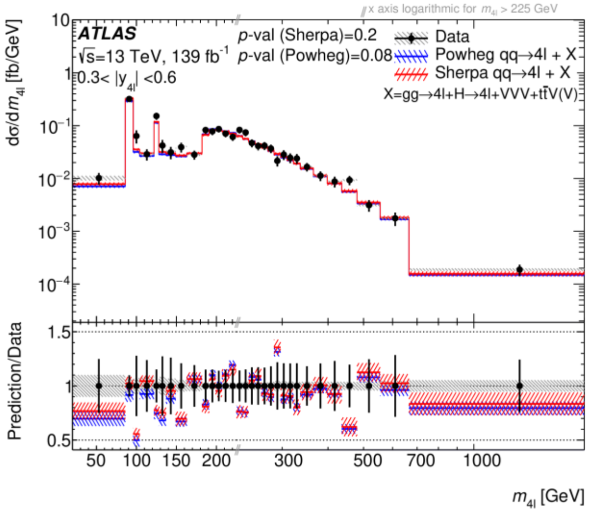


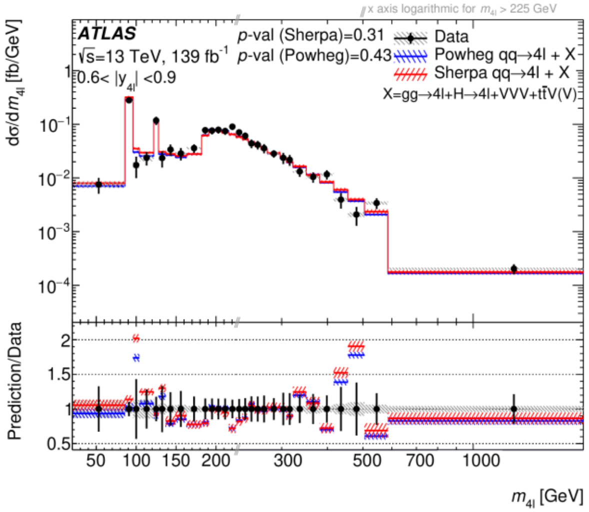


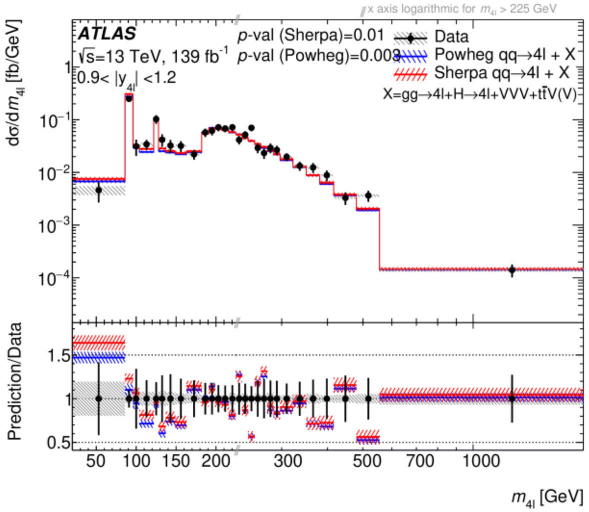
Backup: Differential X-sections

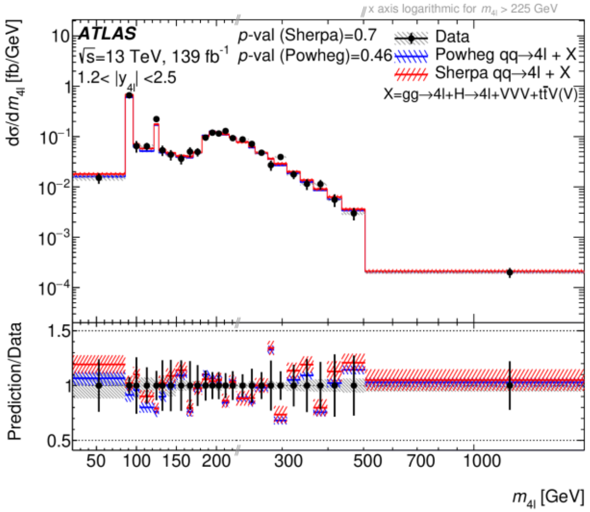
- $m_{4\ell}$ vs $|y_{4\ell}|$





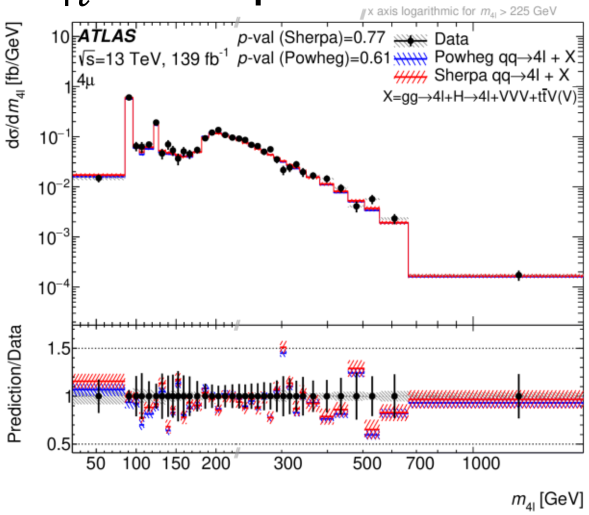


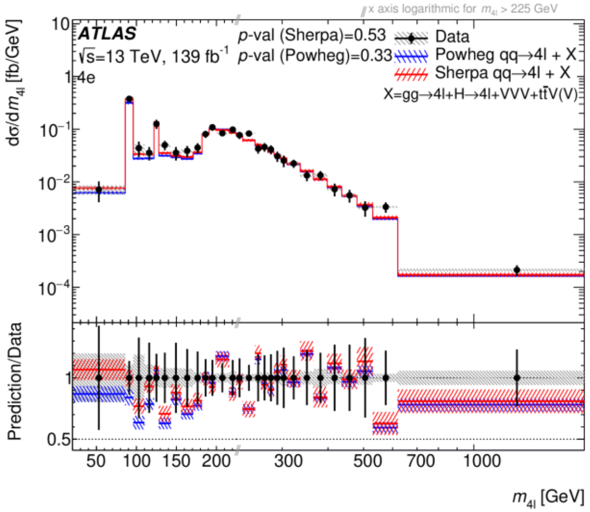


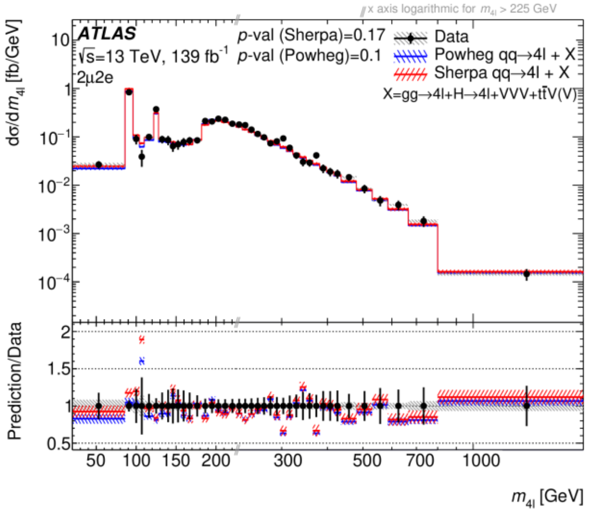


Backup: Differential X-sections

- $m_{4\ell}$ vs lepton flavor

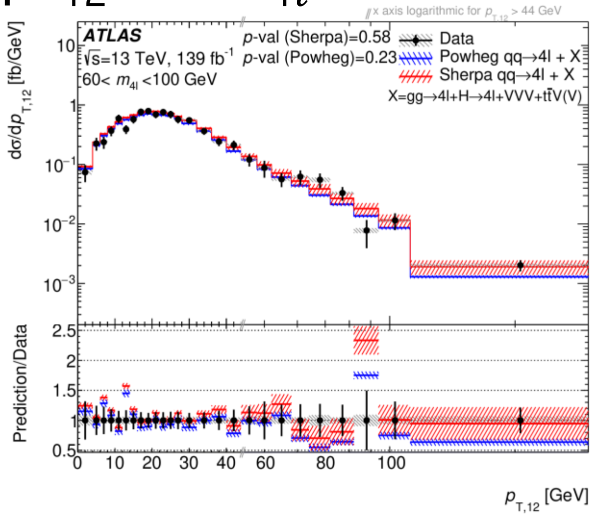


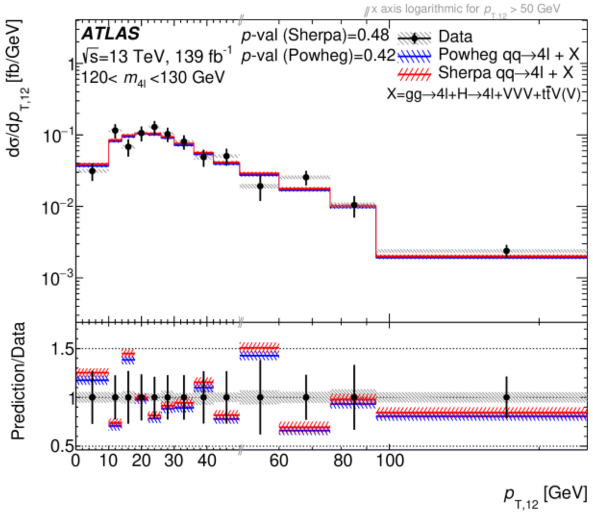


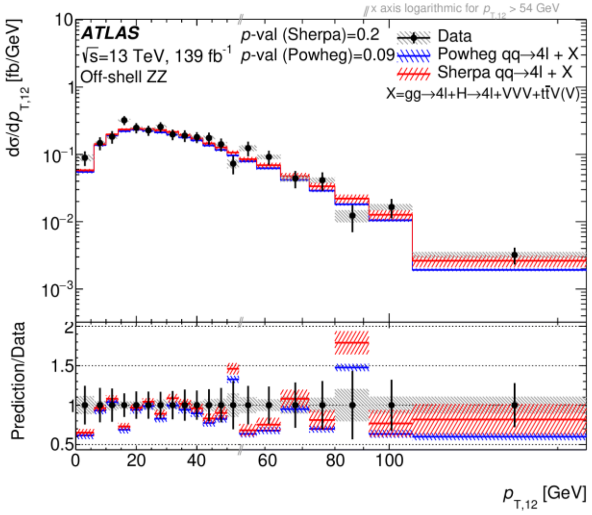


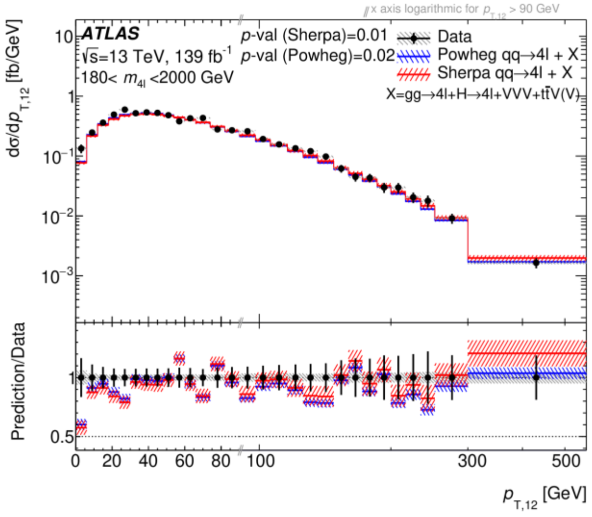
Backup: Differential X-sections

- p^T_{12} vs $m_{4\ell}$



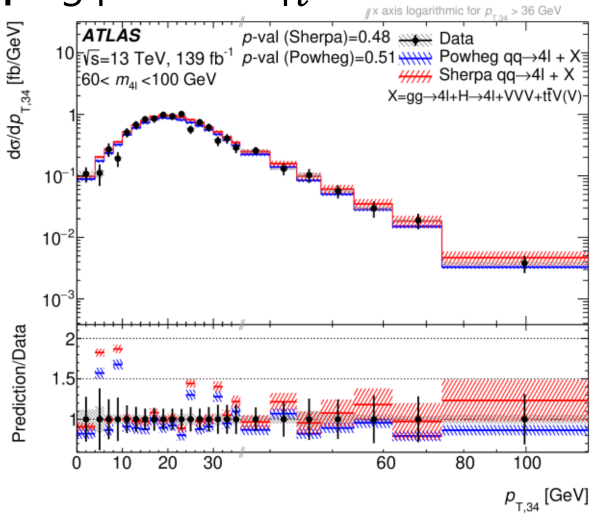


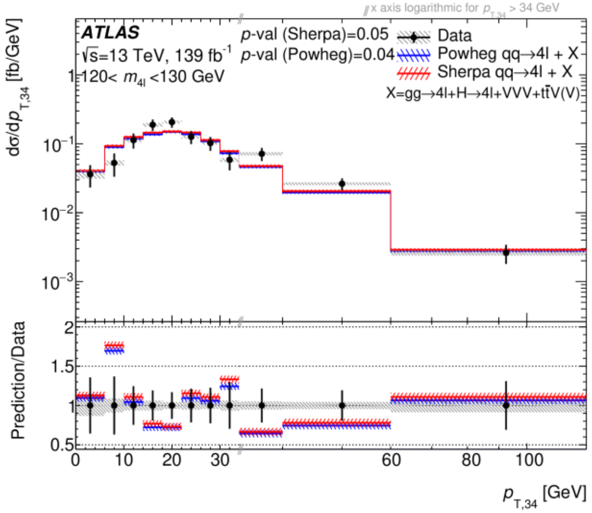


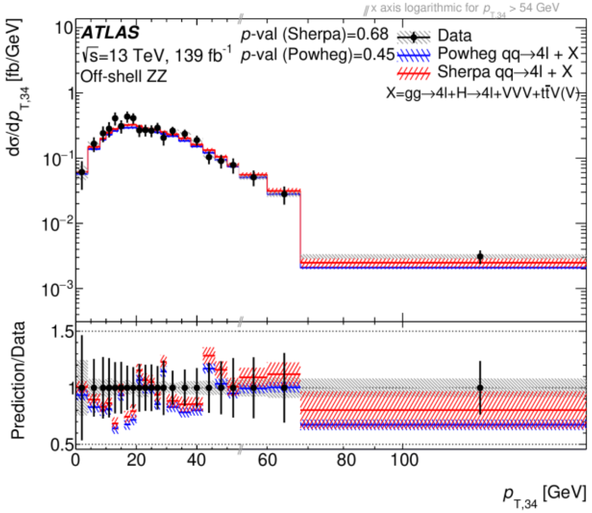


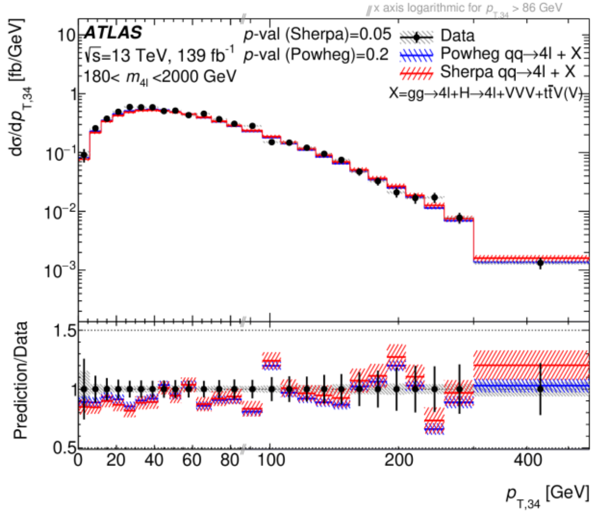
Backup: Differential X-sections

- $p^T{}_{34}$ vs $m_{4\ell}$



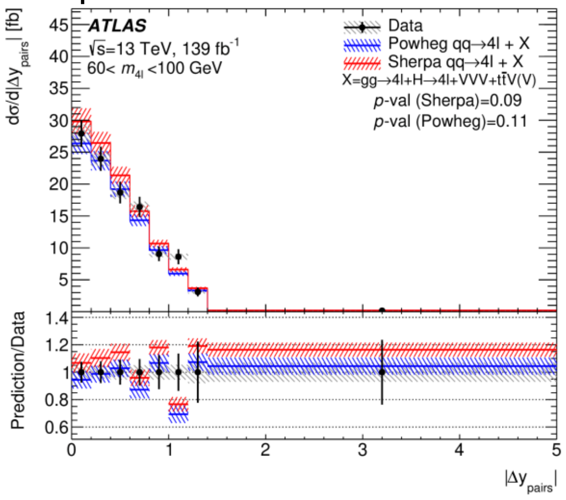


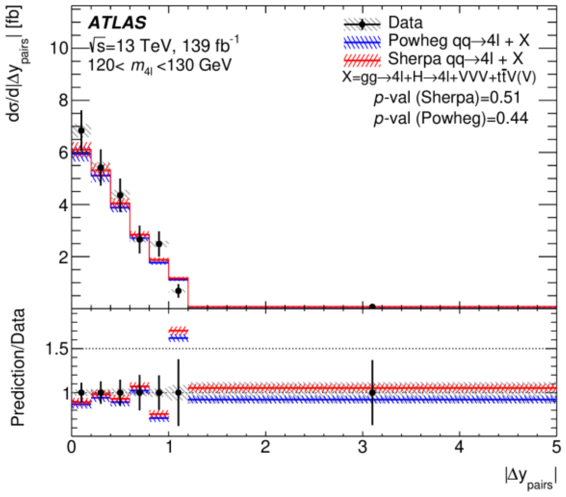


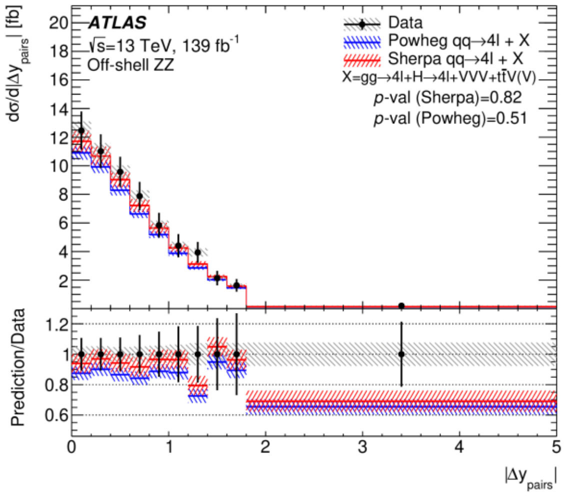


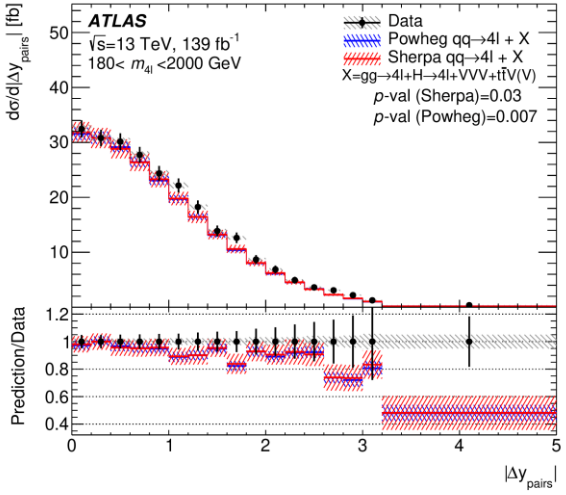
Backup: Differential X-sections

- $|\Delta y_{pairs}|$ vs $m_{4\ell}$



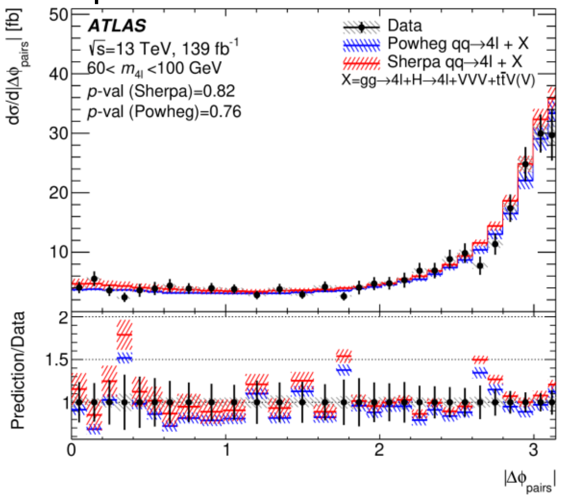


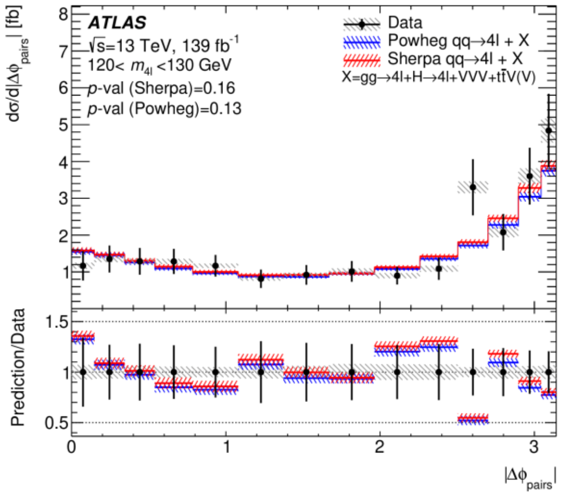


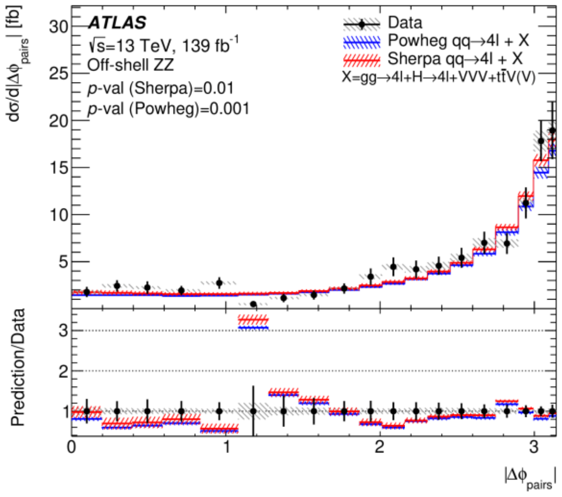


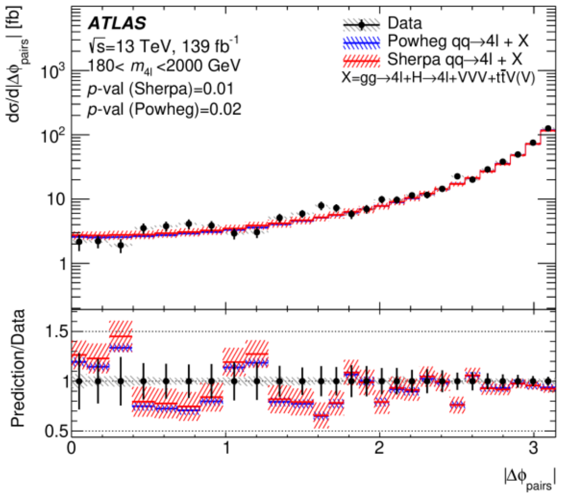
Backup: Differential X-sections

- $|\Delta\varphi_{pairs}|$ vs $m_{4\ell}$



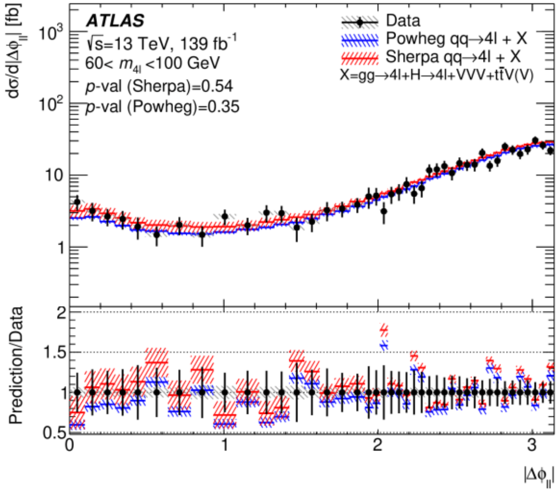


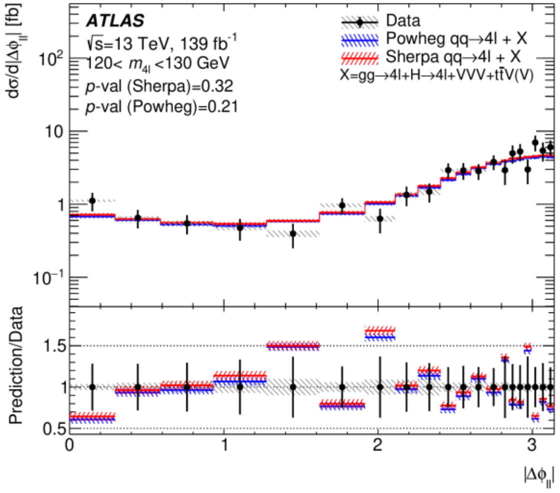


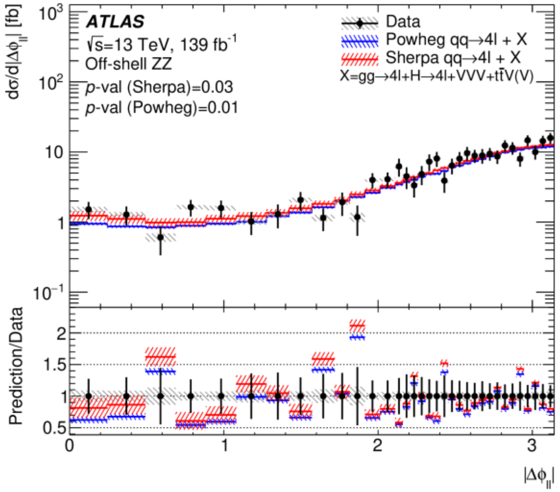


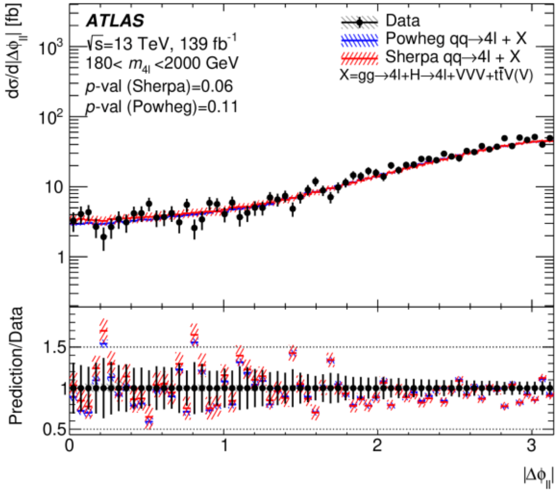
Backup: Differential X-sections

- $|\Delta\varphi_{ll}|$ vs $m_{4\ell}$









Backup: EFT methodology

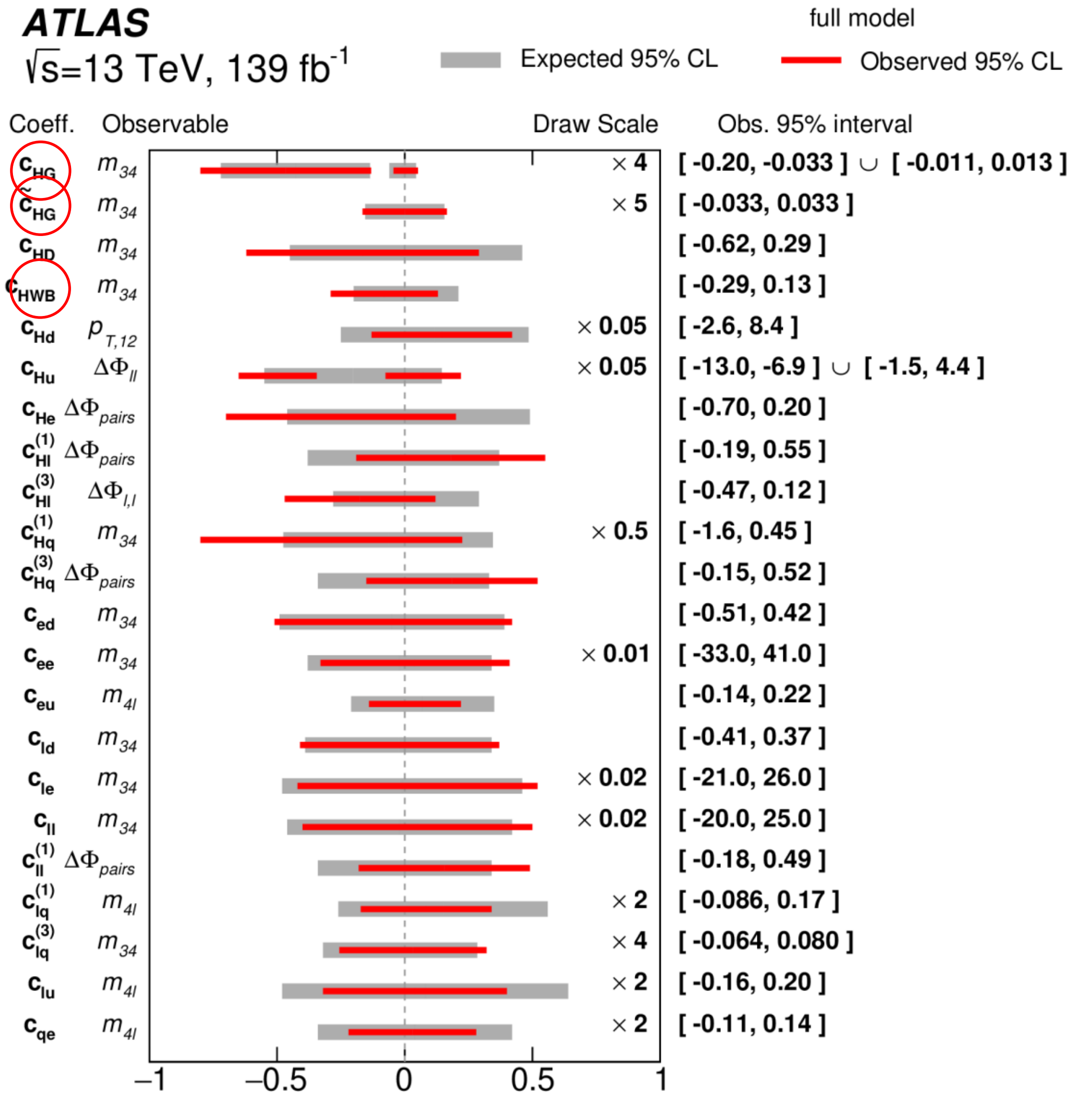
- Parametrization:
  - matrix element: $\mathcal{M}_{\text{mix}} = \mathcal{M}_{\text{SM}} + c \cdot \mathcal{M}_{\text{BSM}}$
  - the full prediction SM+BSM can be decomposed into three components of SM term, linear term(interference), quadratic term(pure BSM):
  - $\sigma(c) = \sigma_{\text{SM}} + c \cdot \sigma_{\text{INT}} + c^2 \cdot \sigma_{\text{BSM}}$

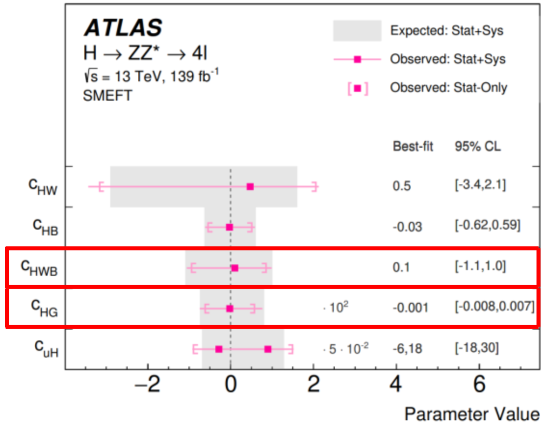
- SMEFTsim package is used for SMEFT implementations of FeynRules

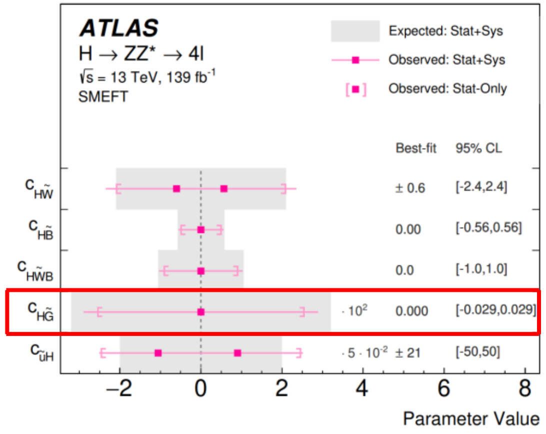
- Generate the three components separately with MadGraph5_aMC@NLO2.6.5 + Pythia8.243 at LO precision in QCD
- Scale the MC with the ratio best SM to LO SM to consider the high-order effect

- The variable providing the best sensitivity is chosen to set limits for a Wilson coefficient, and a variable measured in slices counts as one variable

Back-up: EFT: fitting results



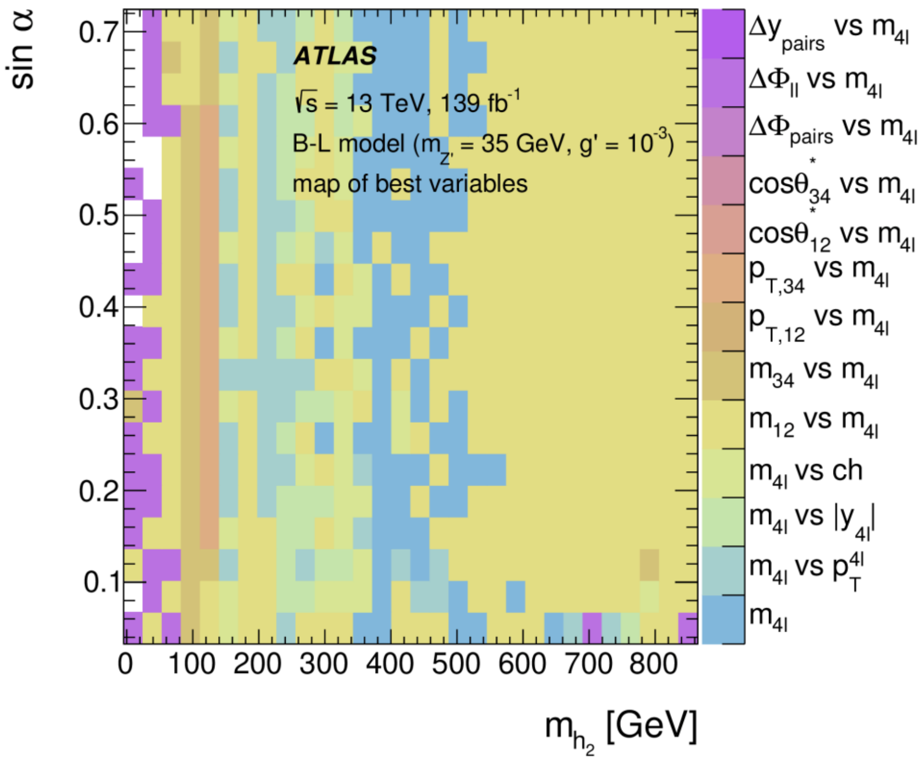




- Comparing with the same limit setting with $H \rightarrow 4\ell$ process, c_{HG} is less stringent and $\tilde{c}_{HG}$ is very similar, while for c_{HWB} the constraint is significantly more stringent

Back-up: B-L model

- BSM samples generated using Herwig7 at particle-level with LO precision
- B-L observable with greatest expected sensitivity used to set limit in a given 2D bin



Back-up: B-L model

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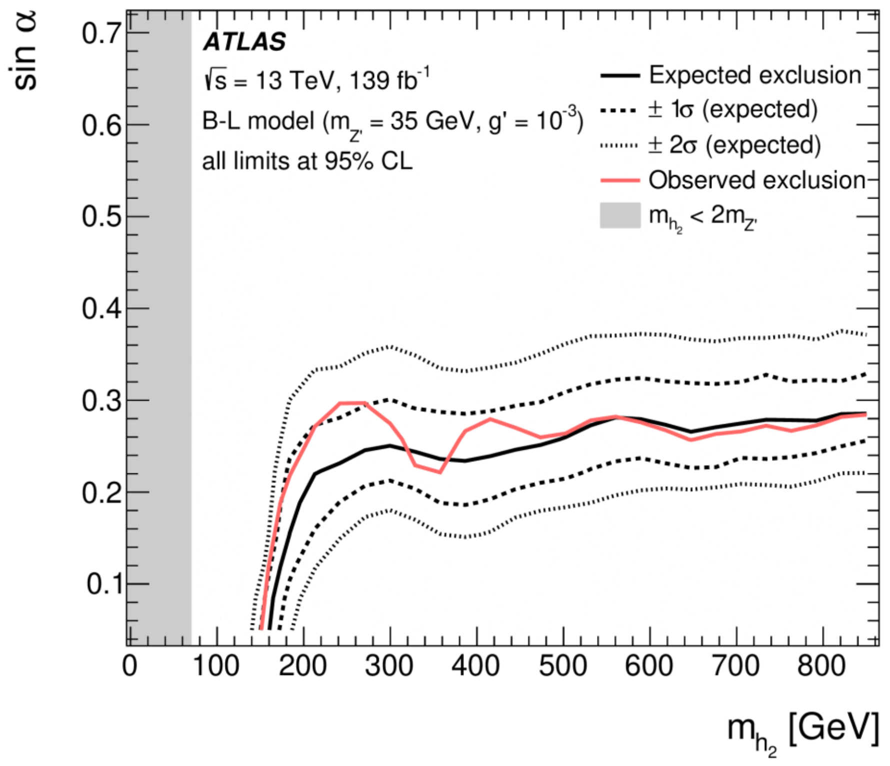

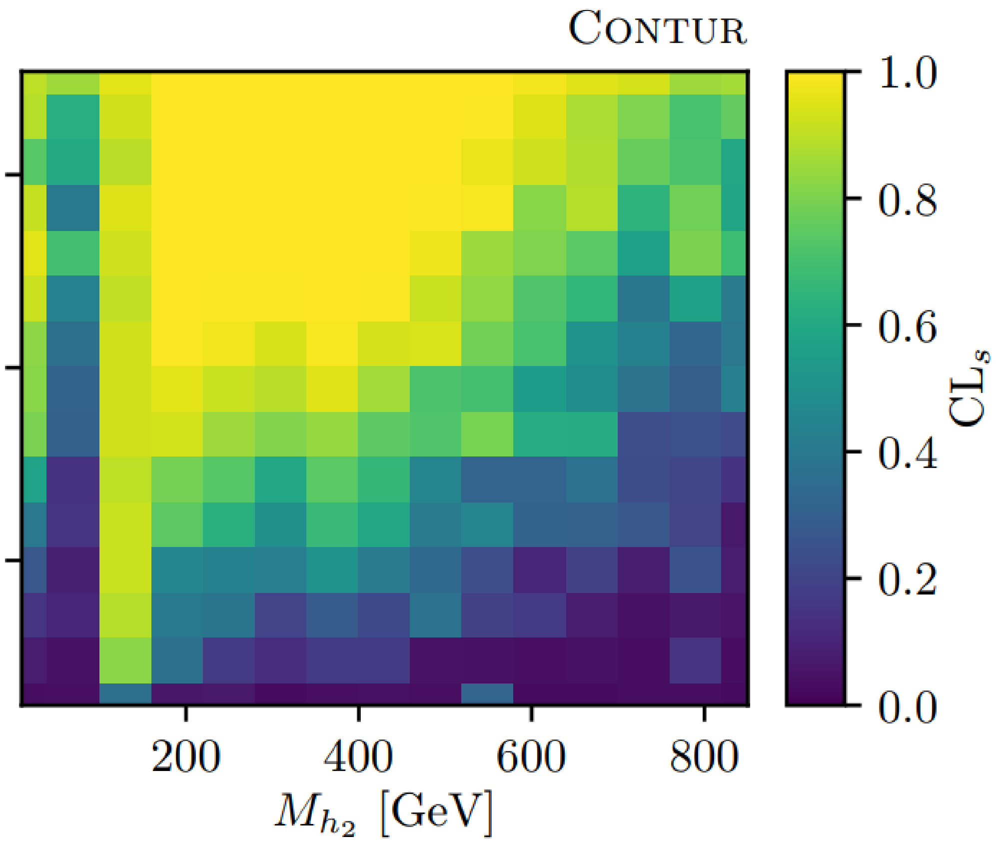

- Improvements over previous results(LHC constraints on B-L model)