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

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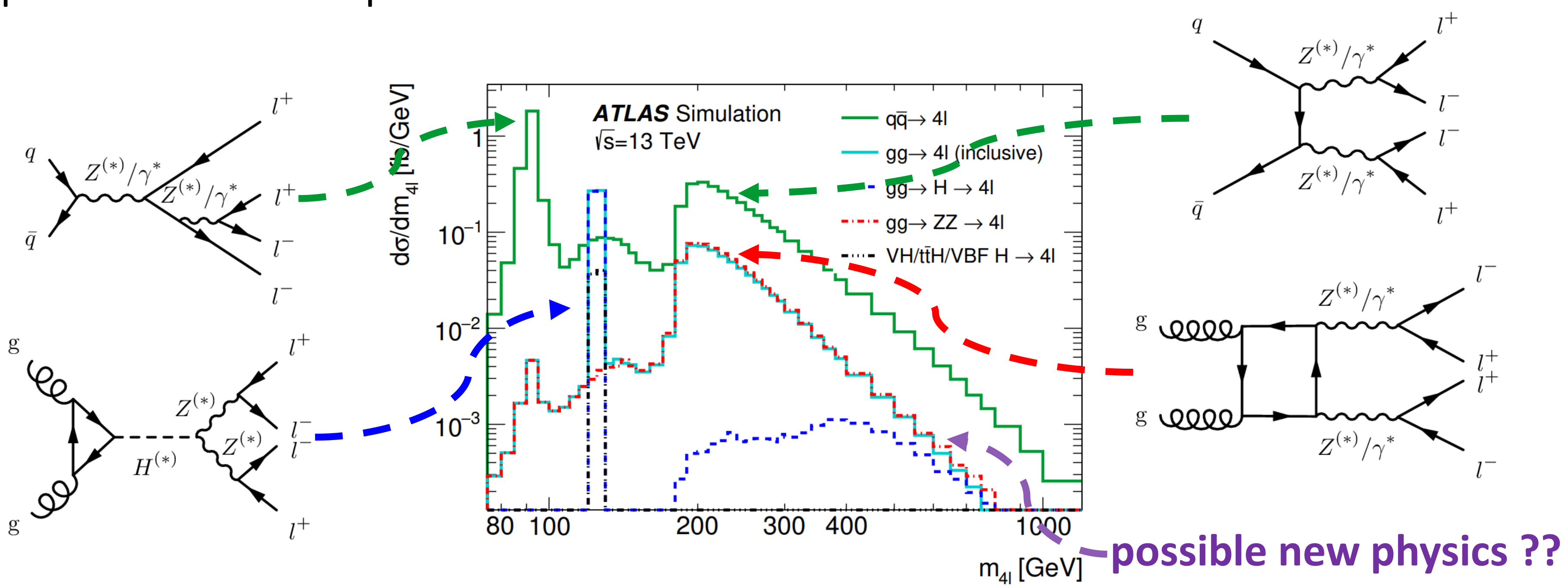
Motivation

- four-lepton final state (two same-flavor opposite-sign e or μ pairs)
  - contains rich physics theoretically
  - relatively clean experimentally

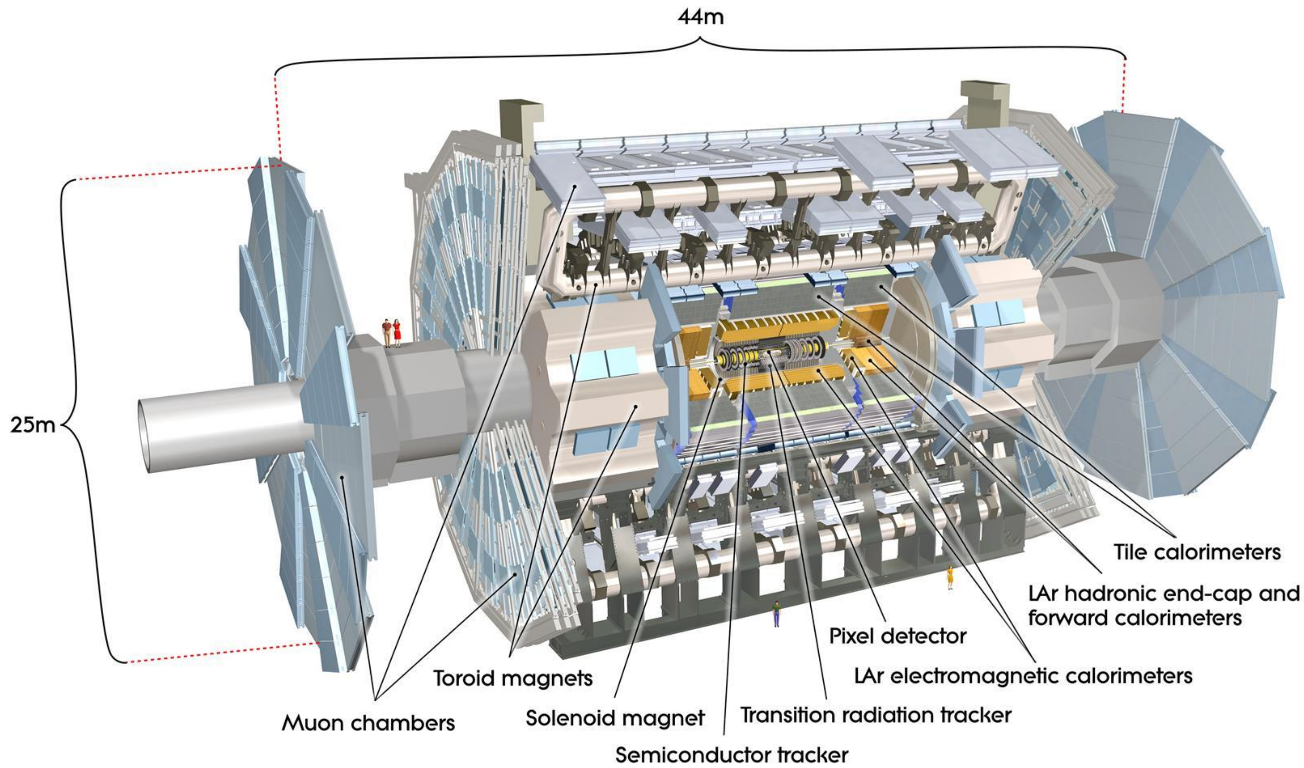
- precise measurements and tests on SM

- potential BSM interpretation



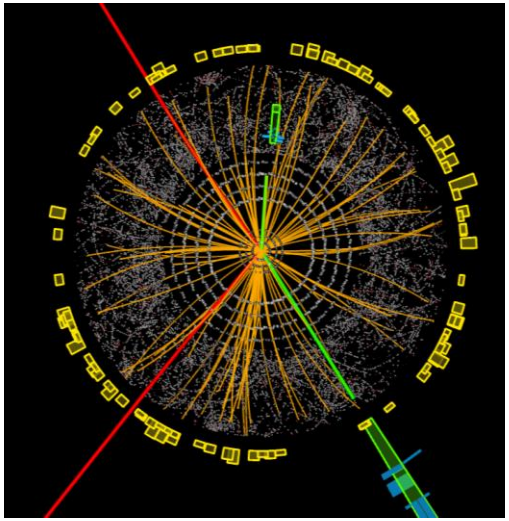
ATLAS detector

- one of the two general purpose detectors on Large Hadron Collider
- sub-detectors: inner trackers, electromagnetic and hadronic calorimeters and muon spectrometer



- ATLAS Run-2 (2015-2018) data corresponding to 139fb^{-1} of $\sqrt{s}$ = 13 TeV pp collisions

Introduction



- **Fiducial Region**
  - designed to be as **inclusive** as possible
  - based on particle-level prompt leptons, with dressed electrons and bare muons
  - any process with at least 4 leptons in the hard scattering is considered as part of the signal

- **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**

- **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

Introduction

- **Observables**
  - integrated cross-sections
  - differential cross-sections:
    - $\mathbf{m_{4l}}$
    - $\mathbf{m_{4l}}$ in slices of $\mathbf{p^T_{4l}}$
    - $\mathbf{m_{4l}}$ in slices of $\mathbf{|y_{4l}|}$
    - $\mathbf{m_{4l}}$ 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 $\mathbf{|\Delta y_{pairs}|}$
    - azimuthal angle between the pairs $\mathbf{|\Delta\phi_{pairs}|}$
    - azimuthal angle between leading/subleading leptons $\mathbf{|\Delta\phi_{ll}|}$
    - 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 ($60 < m_{4l} < 100$ GeV)

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

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

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

MC simulation

- MC samples are generated dedicatedly for each essential process

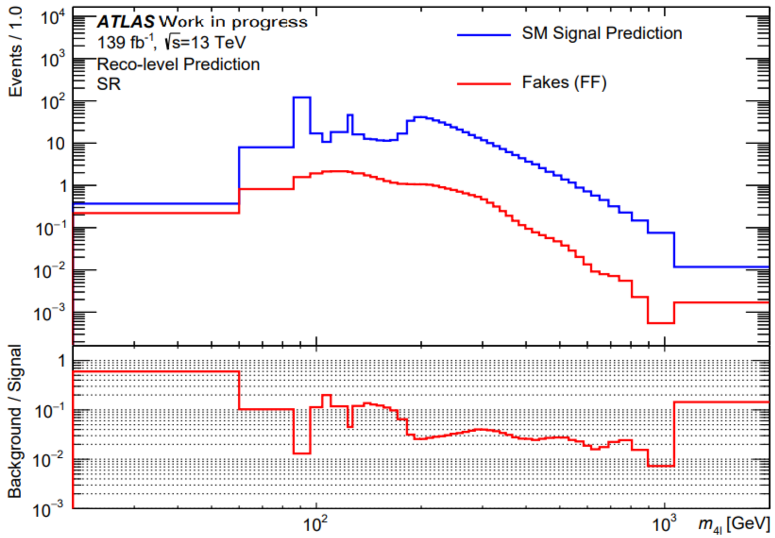
qqZZ		NLO QCD@0,1 jet|NNPDF3.0NNLO
ggZZ		LO QCD@0,1 jet|NNPDF3.0NNLO
Higgs	ggF	NNLO QCD|PDF4LHCNNLO
	VBF	NLO QCD|PDF4LHC15
	VH, ttH	NLO QCD|PDF4LHC15
triboson		NLO@inclusive|NNPDF3.0NNLO
ttV		LO|NNPDF3.0NNLO

MC prediction details

Background & Detector effect

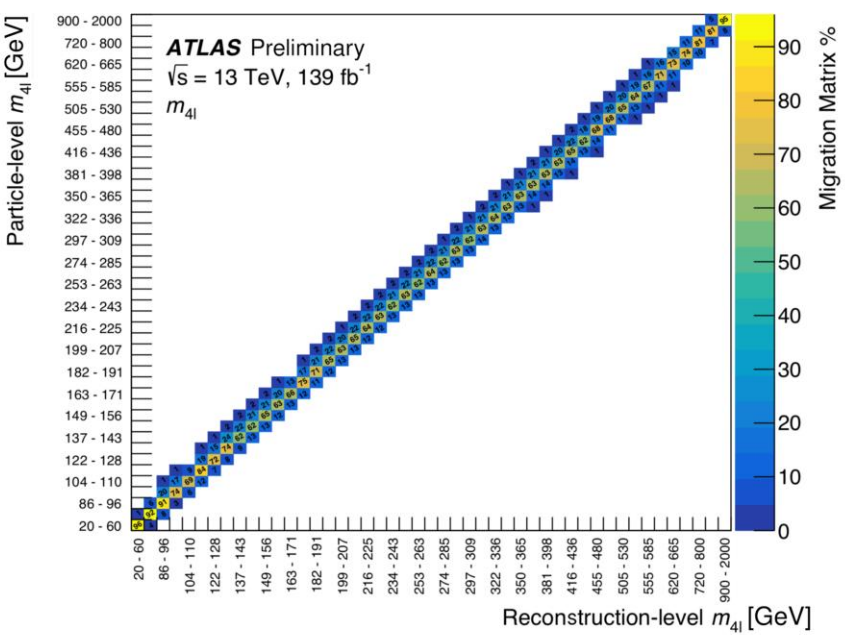
➢ Background estimation

- background refers to events with one or more non-prompt/fake leptons entering quadruplet, mainly from **Z+jets** and **ttbar** processes
- data-driven approach: Fake Factor method to estimate background
- background contributes < 10% in most bins

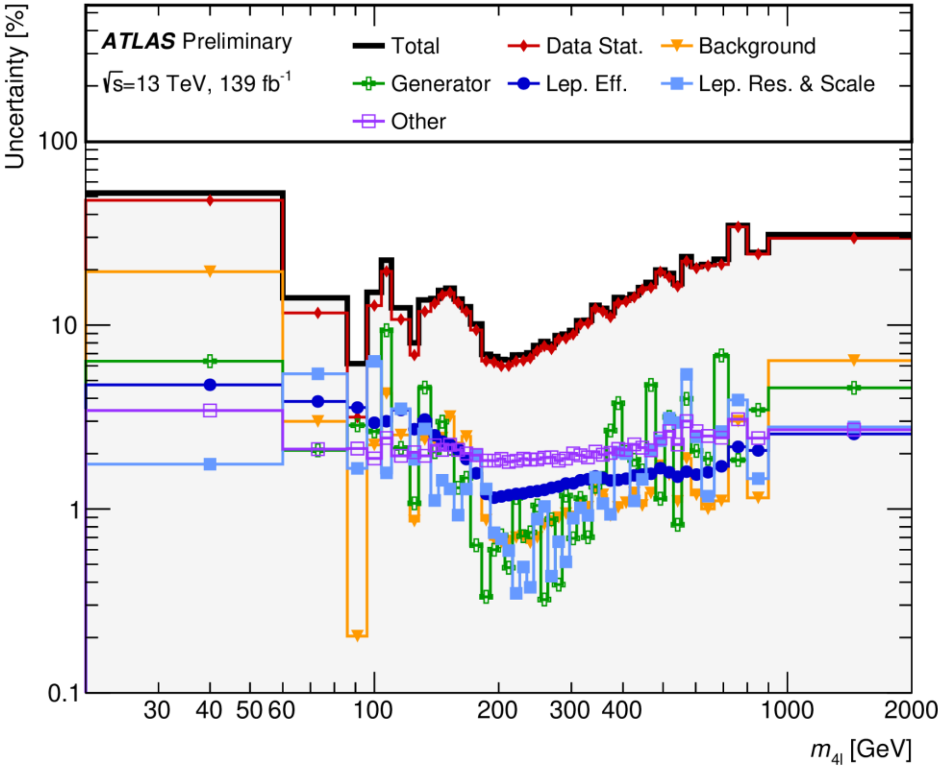


➢ Detector corrections

- aim to measure particle-level distributions **corrected for detector effects** (resolution, inefficiency)
  - pre-unfolding efficiency correction per leptons in quadruplet
  - iterative Bayesian unfolding process
- binning of distributions optimization based on unfolding method



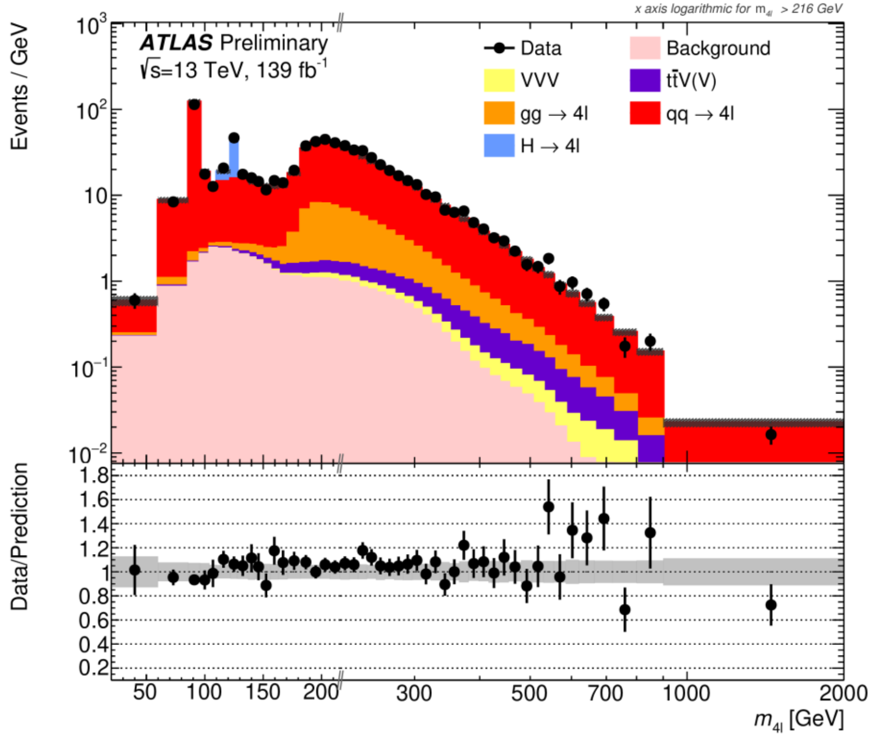
Uncertainties



- **data statistical uncertainty** dominates most of bins in almost all distributions
- other sources of uncertainties are the background estimation, lepton reconstruction, identification, isolation and track-to-vertex association, lepton resolution and scale, generator selection, unfolding, etc.

Detector-level yields

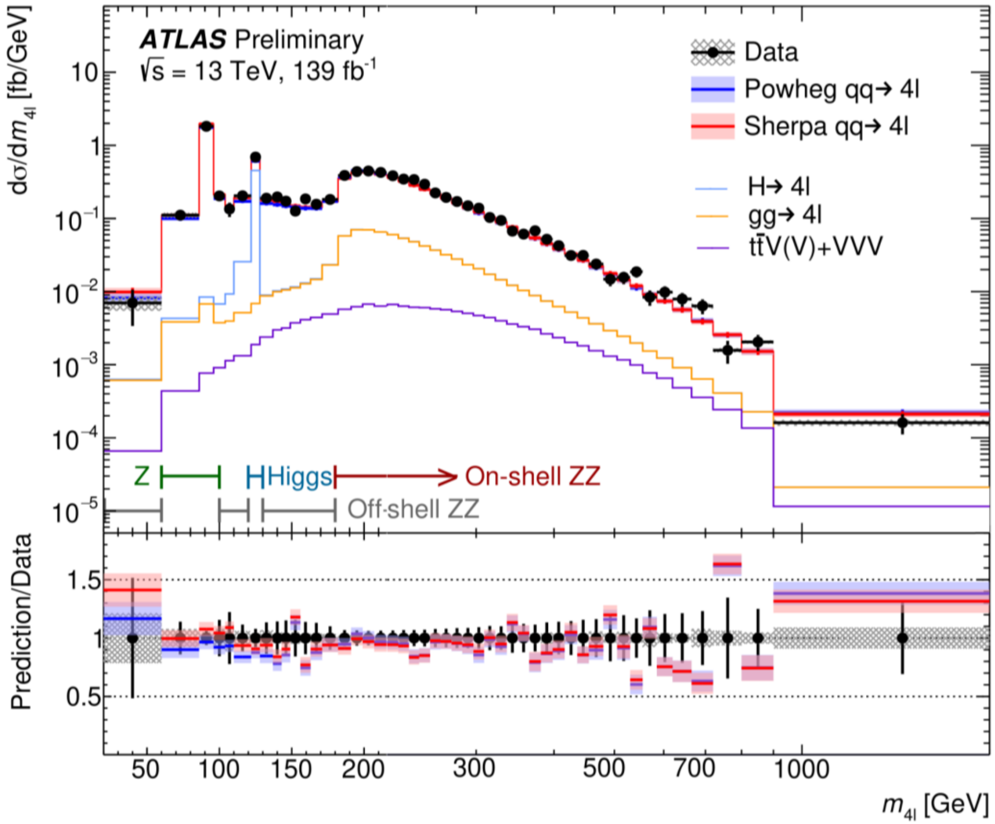
- predicted yields V.S. data counts on detector level



	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 ± 0.2
VVV	35 ± 14	0.018 ± 0.008	0.13 ± 0.05	2.1 ± 0.8	33 ± 13
$t\bar{t}V(V)$	123 ± 19	1.37 ± 0.22	1.2 ± 0.2	15.5 ± 2.4	105 ± 16
Background	330 ± 50	44 ± 8	26 ± 5	129 ± 20	139 ± 31
Total Pred.	7500 ± 500	1540 ± 110	367 ± 19	1030 ± 60	4530 ± 290
Data	7755	1452	379	1095	4828

Measurement results

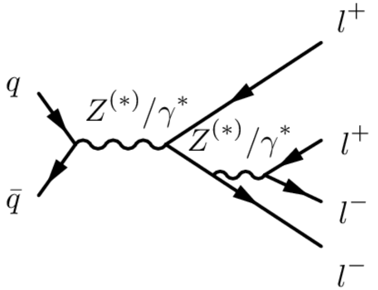
- differential cross-section as a function of m_{4l}:



- the agreement between the data and both predictions is generally within the quoted uncertainties
- two predictions show almost the same distribution

[integrated and other differential cross-sections]

Interpretation: $Z \to 4l$ Branching ratio



- rare process: internal conversion $Z \to 4l$
- extracted the BR with measured cross-section in the $Z \to 4l$ region

pred. fid. XS from non-qqZZ source

frac. of qqZZ coming from single Z prod.

$$\mathcal{B}_{Z\to4l} = \frac{\left(\sigma^{\mathrm{meas}} - \sigma^{\mathrm{pred}}_{\mathrm{non}-q\bar{q}\to4l}\right) \times f_Z \times f_{non-\tau}}{\sigma_Z \times A_{\mathrm{fid}}}$$

Z prod. XS

ratio of qqZZ in fid. region and ext. region

frac. of events where no leptons originate from tau decays

$$\mathcal{B}_{Z\to4l} = (4.41 \pm 0.13(\mathrm{stat.}) \pm 0.23(\mathrm{syst.}) \pm 0.09(\mathrm{theory}) \pm 0.12(\mathrm{lumi.})) \times 10^{-6} = (4.41 \pm 0.30) \times 10^{-6}$$

Interpretation: B-L model

- BSM with spontaneously $U(1)_{B-L}$ gauge symmetry breaking, interesting model giving birth to neutrino mass: B-L model
- new particles introduced: Z', exotic Higgs h_2 and RH neutrinos
  - Z' interacts with SM through coupling g' and h_2 mixes with SM Higgs with mixing angle α

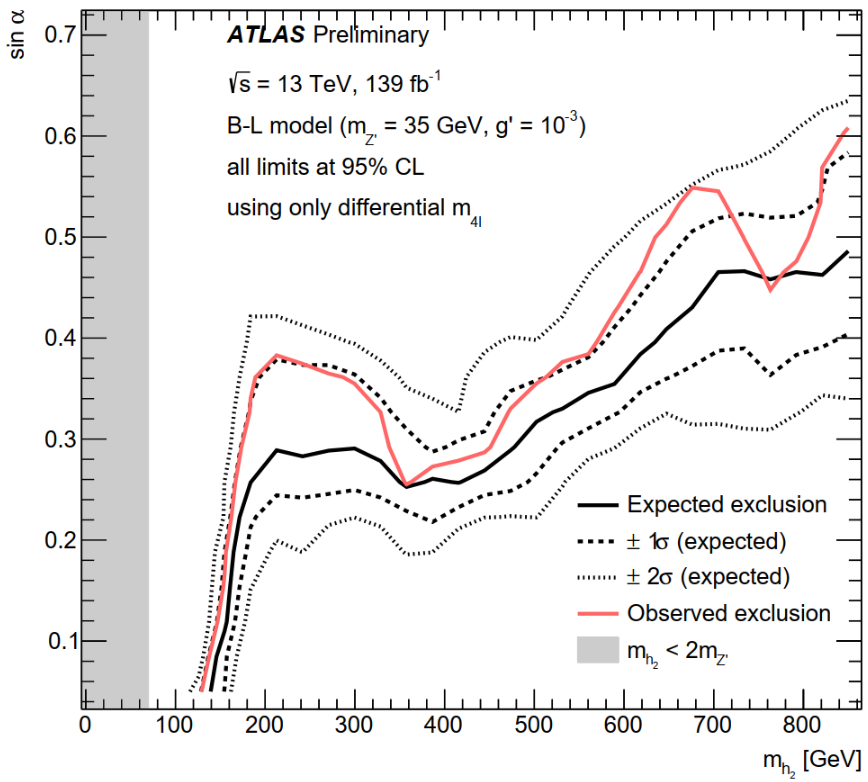
- scenario considered: fixed parameters: low Z' mass (35 GeV) weakly coupled to SM ($g' = 10^{-3}$)
- differential cross-sections as a function of rich variables providing best expected sensitivity to set limit on 2D m_{h2} ~ sinα parameter space

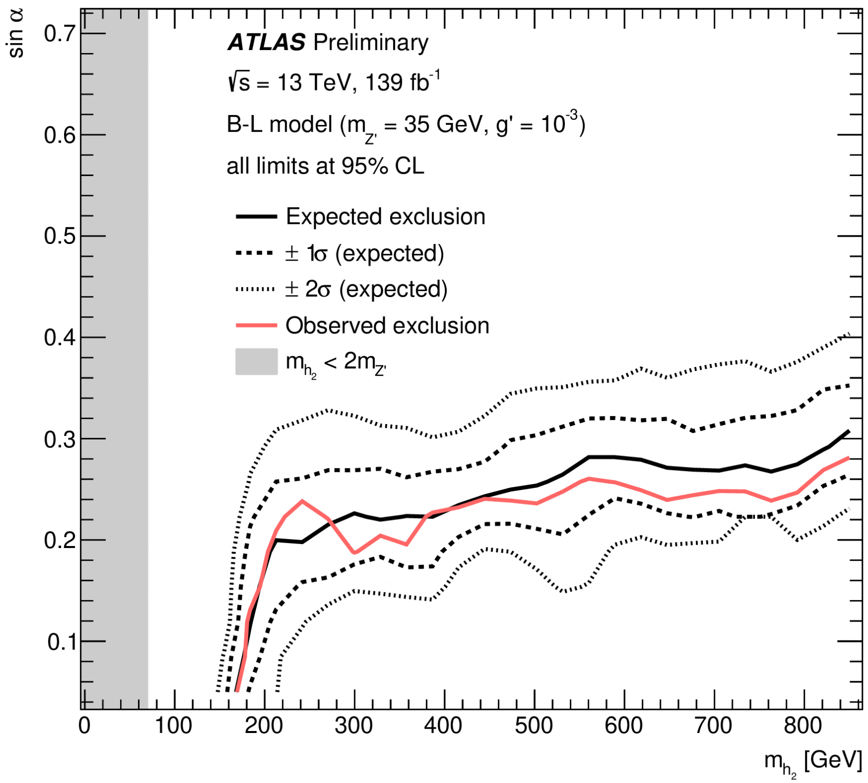
- statistics: multi-gaussian likelihood function to include the covariance among bins from unfolding

- BSM samples generated using Herwig7 at particle-level with LO precision

B-L model interpretation

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





- numerous variables we measured, provide us stronger power of exclusion

Summary

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

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

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

- constraints setting on example gauged B-L model, improving the parameter exclusion limit

- reference public CONF note

Thank you for your attention!

Back-up

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, $p_{\mathrm{T}} > 5$ GeV, $\|\eta\| < 2.7$
Electron selection	Dressed, $p_{\mathrm{T}} > 7$ GeV, $\|\eta\| < 2.47$
	Event selection
Four-lepton signature	At least 4 leptons, with 2 Same-Flavour, Opposite-Sign pairs
Lepton kinematics	$p_{\mathrm{T}} > 20/10$ 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/$p_{\mathrm{T}} < 0.16$

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	DSID
$q\bar{q} \to ZZ^{(*)} \to 4\ell$	inclusive	Sherpa 2.2.2	364250
	2 add. jets (EW)	Sherpa 2.2.2	364364
$gg\ (\to H^{(*)}) \to ZZ^{(*)} \to 4\ell$	inclusive, $m_{4\ell} > 130$ GeV	Sherpa 2.2.2	345706
$gg \to ZZ^{(*)} \to 4\ell$	no H, $m_{4\ell} < 130$ GeV	Sherpa 2.2.2	345708
$pp \to H \to ZZ^{(*)} \to 4\ell$	ggF	Powheg (NNLOPS) + Pythia 8	345060
	VBF	Powheg + Pythia 8	346228
	ZH	Powheg + Pythia 8	345038
	WH	Powheg + Pythia 8	345039 345040
	ttH	Powheg + Pythia 8	346342 346341 346340
$pp \to W^{(*)}W^{(*)}Z^{(*)} \to 4\ell 2\nu$	inclusive	Sherpa 2.2.2	364243
$pp \to W^{(*)}Z^{(*)}Z^{(*)} \to 5\ell 1\nu$	inclusive	Sherpa 2.2.2	364245
$pp \to Z^{(*)}Z^{(*)}Z^{(*)} \to 6\ell$	inclusive	Sherpa 2.2.2	364247
$pp \to Z^{(*)}Z^{(*)}Z^{(*)} \to 4\ell 2\nu$	inclusive	Sherpa 2.2.2	364248
$pp \to t\bar{t} + \ell\ell$	$t\bar{t}Z$, $m_{\ell\ell} > 5$ GeV	Sherpa 2.2.0	410142

Process		Generator	DSID
$pp \to Z^{(*)} \to 2e$+ jets	≥ 4 truth leptons with $p_{\mathrm{T}} > 4$GeV $m_1(\ell\ell) > 40$GeV, $m_2(\ell\ell) > 8$GeV	Sherpa 2.2.0	344295
$pp \to Z^{(*)} \to 2\mu$+ jets	≥ 4 truth leptons with $p_{\mathrm{T}} > 4$GeV, $m_1(\ell\ell) > 40$GeV, $m_2(\ell\ell) > 8$GeV	Sherpa 2.2.0	344296
$pp \to Z^{(*)} \to 2e$+ jets	≥ 3 truth leptons with $p_{\mathrm{T}} > 4$GeV veto filter of 344295	Sherpa 2.2.0	344297
$pp \to Z^{(*)} \to 2\mu$+ jets	≥ 3 truth leptons with $p_{\mathrm{T}} > 4$GeV veto filter of 344296	Sherpa 2.2.0	344298
$pp \to Z^{(*)} \to 2e$+ jets	inclusive	Sherpa 2.2.1	364114-364127
$pp \to Z^{(*)} \to 2\mu$+ jets	inclusive	Sherpa 2.2.1	364100-364113
$pp \to Z^{(*)} \to 2\tau$+ jets	inclusive	Sherpa 2.2.1	364128-364141
$pp \to t\bar{t} \to 2l$	inclusive	Powheg + Pythia 8	410472
$pp \to l\nu ll$	inclusive	Sherpa 2.2.2	364253
$pp \to Z + \Upsilon \to 4\ell$	inclusive	Pythia 8	800041-800044

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: event selection

1. baseline lepton selection

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		

3. signal lepton selection

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: $d_0/\sigma_{d_0} < 3$
	Electrons: $d_0/\sigma_{d_0} < 5$
Stricter Electron ID	Electrons: LooseBLayerLH ID

2. detector-level event selection

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

Back-up: event selection

jet selection

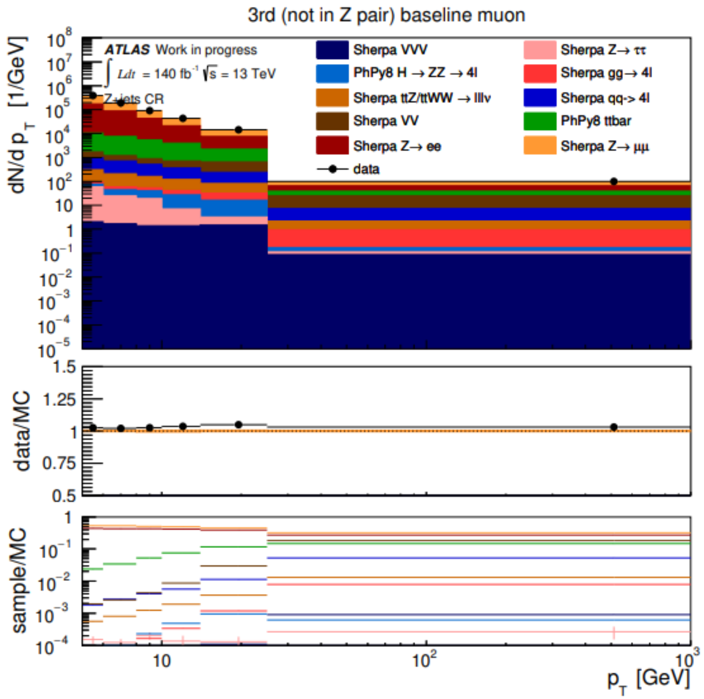
Collection:	AntiKt4EMPFlow
Kinematics:	$\|\eta\| < 4.5$
	$p_{\mathrm{T}} > 30$ GeV
Signal jet (after overlap removal):	pass JVT

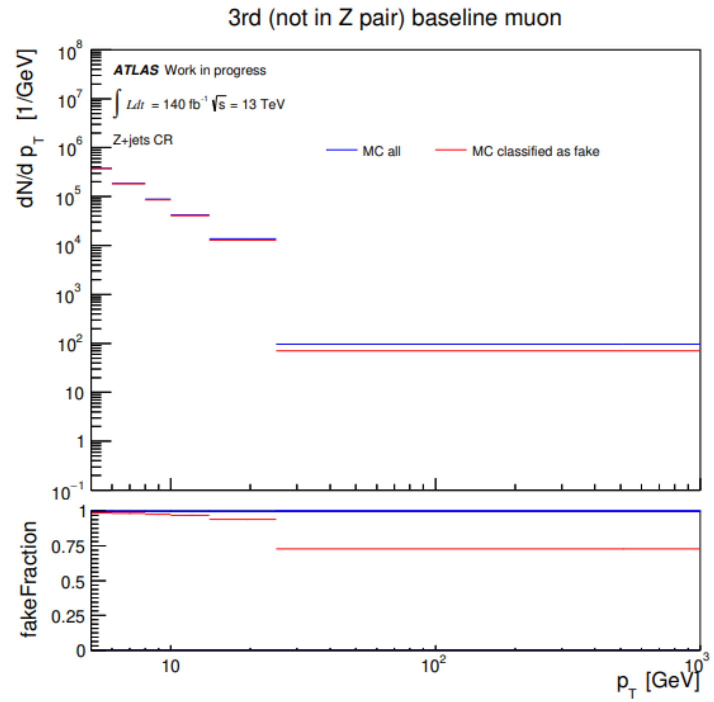
details of overlap removal

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	ΔR <0.2
jet	muon	NumTrack < 3 and ghost-associated/ΔR <0.2

Back-up: fake factor method

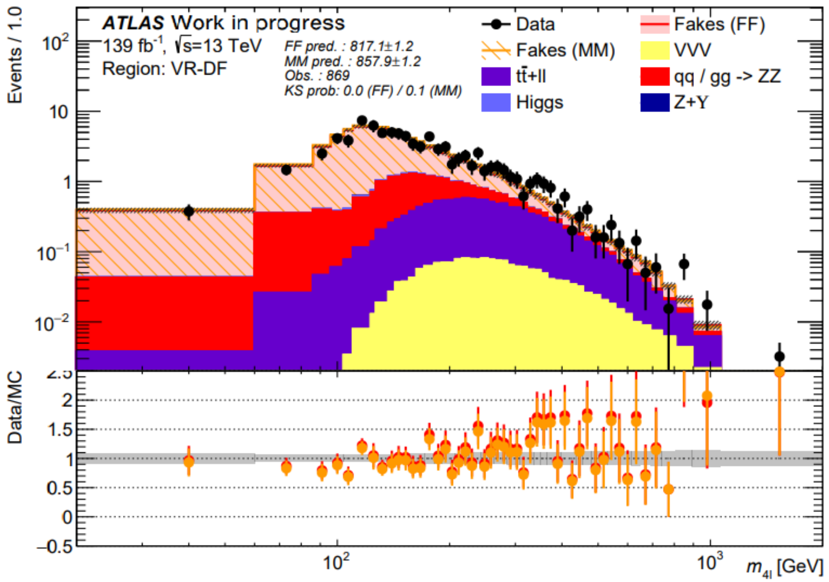
- fake factor: calculate what fraction of fake leptons is expected given the number of baseline-not-signal leptons
- calculated in Z->ll CR (events one SFOS pairs within 15 GeV of mZ and at least one other baseline lepton)
- fake factor applied to the number of baseline-not-signal leptons in each event

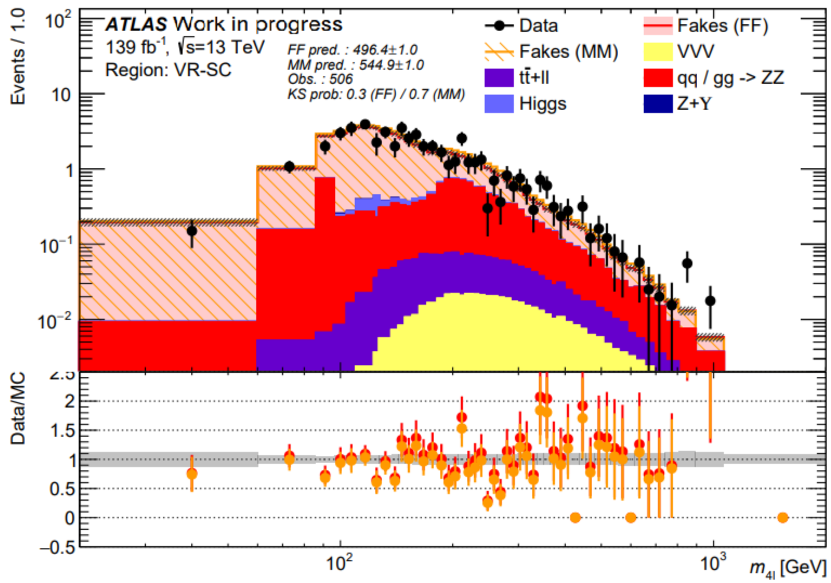




Back-up: background validation

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

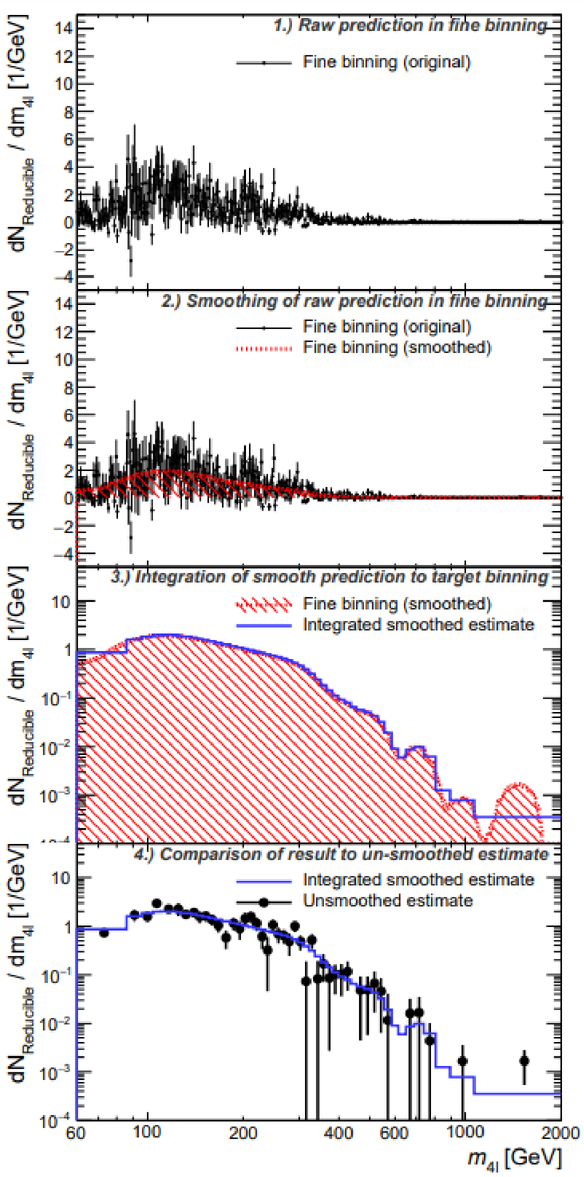




- validate the FF method as well as cross-checking with Matrix method

Back-up: 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: detector corrections

- pre-unfolding efficiency correction per leptons in quadruplet
    - per-event weight: $\prod_{i=1}^{4} \frac{1}{\varepsilon_i(p_{Ti},\eta_i)}$

- iterative Bayesian unfolding process
    - $P_n(T_j|R_i) = \frac{P(R_j|T_i)P_{n-1}(T_i)}{\sum P(R_j|T_k)P_{n-1}(T_k)}$, $P_n(T_i) = \sum P_n(T_j|R_j)P(R_j)$
    - T_i, R_i is the bin content at the *i*th bin

- iterative Bayesian unfolding with either 2/3 iterations, optimized based on the bias and statistical uncertainty

- validation: data-driven closure test

- injection test demonstrate the robustness to BSM

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 mZ_1, $\Delta\phi_{ll}$, and Δy_{pairs} 2 iterations is sufficient

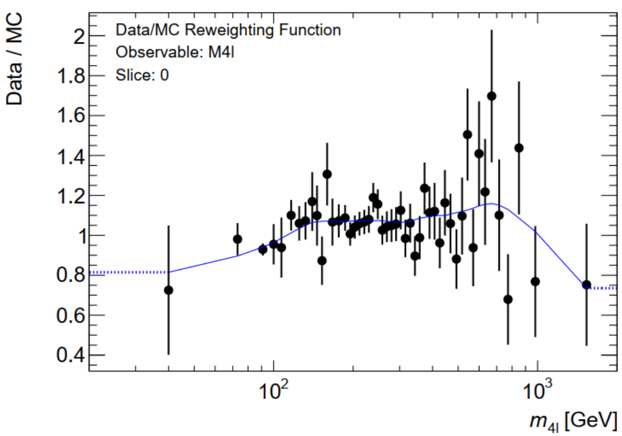
Binning requirements	
# Reco events	**Purity**
[14,20)	80%
[20,25)	70%
≥25	60%

binning criteria

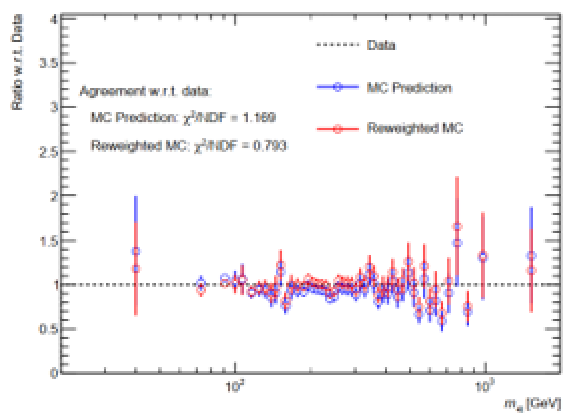
Back-up: unfolding data-driven test

- 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

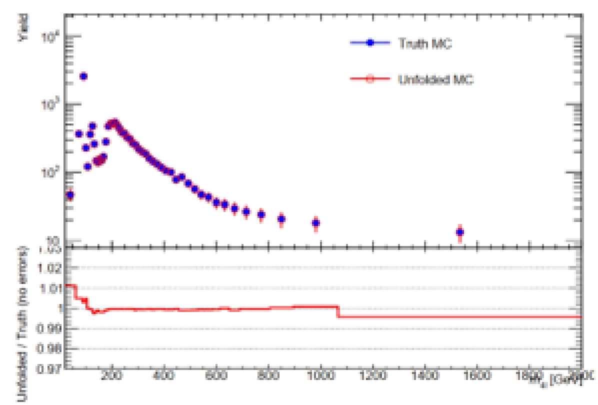
reweighting function fit



before/after reweighting



unfolding and comparison

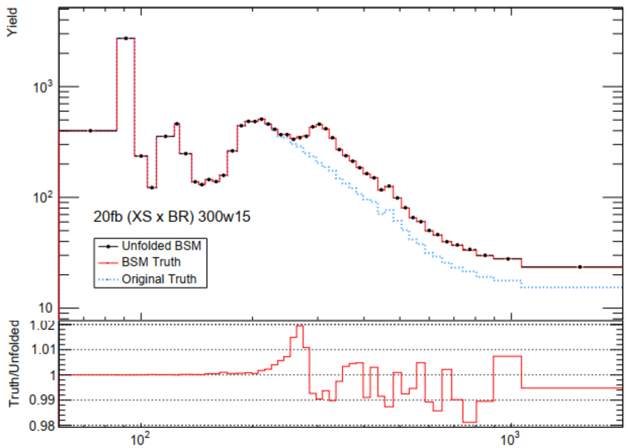


- take the difference as unfolding systematic uncertainty

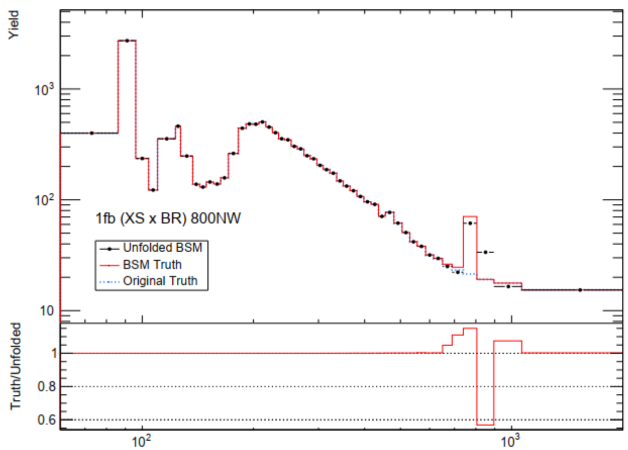
Back-up: unfolding injection test

- further check on the model-independence of unfolding

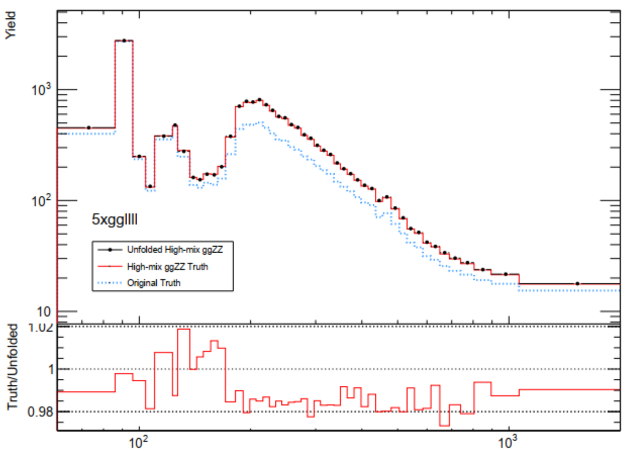
ggF BSM Higgs mass 300GeV, width 15GeV, XS 20fb



ggF BSM Higgs mass 800GeV, narrow-width, XS 1fb



ggZZ 5-fold enhanced



- nominal unfolding is robust to broad excess over the SM prediction

- pre-unfolding correction improves the comparison of unfolded vs particle yields in most cases

Back-up: measurement results

- inclusive fiducial cross-sections (in full phase-space and defined regions):

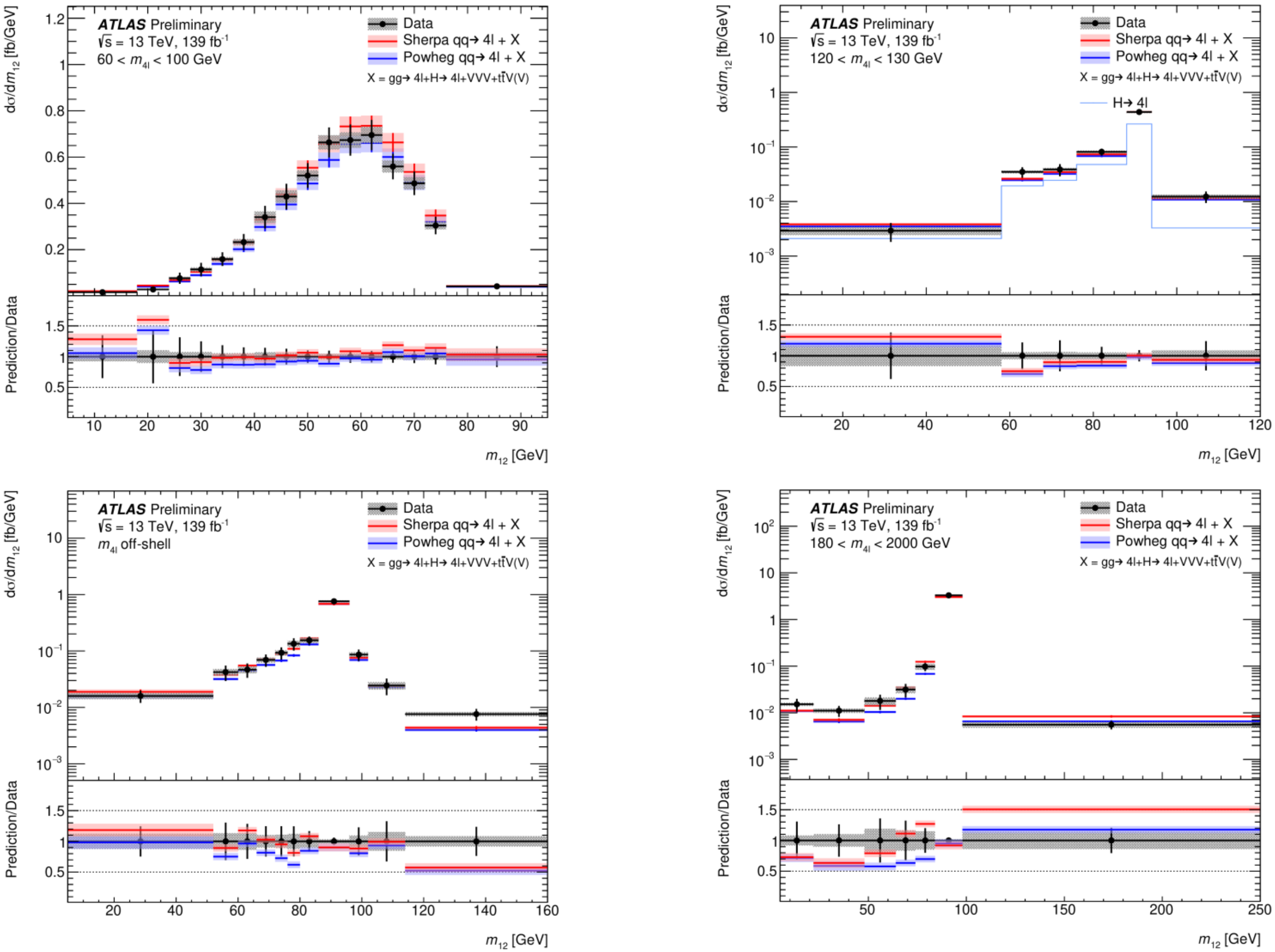
	Region				
	Full	$Z \to 4\ell$	$H \to 4\ell$	Off-shell ZZ	On-shell ZZ
Measured fiducial cross-section [fb]	88.9 ±1.1 (stat.) ±2.3 (syst.) ±1.5 (lumi.) ±3.0 (total)	22.1 ±0.7 (stat.) ±1.1 (syst.) ±0.4 (lumi.) ±1.3 (total)	4.76 ±0.29 (stat.) ±0.18 (syst.) ±0.08 (lumi.) ±0.35 (total)	12.4 ±0.5 (stat.) ±0.6 (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

- measured cross-sections are compared to Sherpa and Powheg providing different modelling of qqZZ

- in all regions data and MC are consistent within the uncertainties

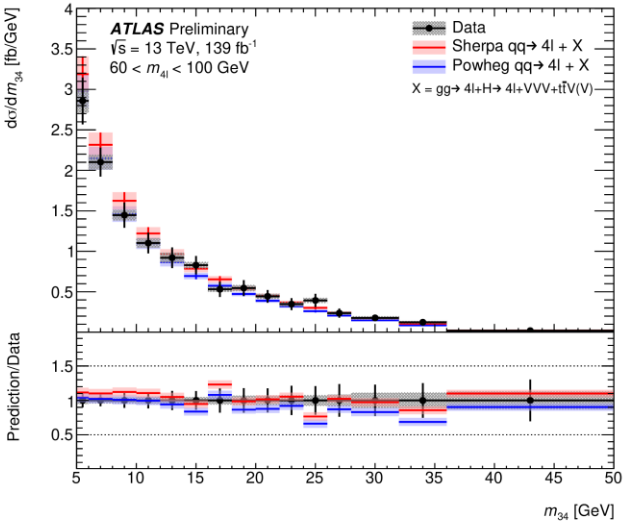
Back-up: measurement results

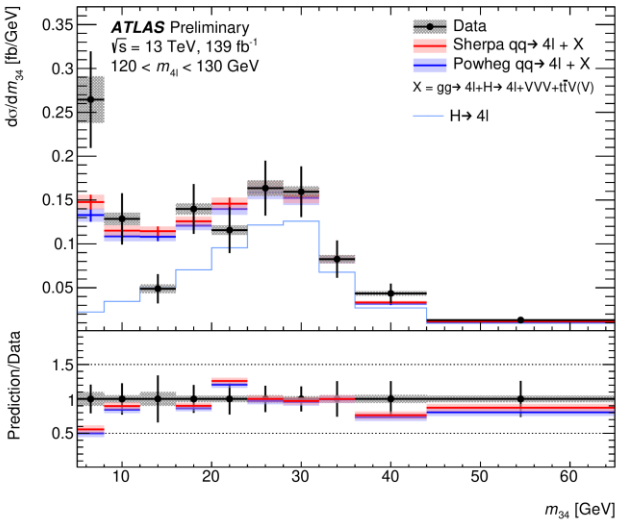
- m12 differential cross-sections in all regions

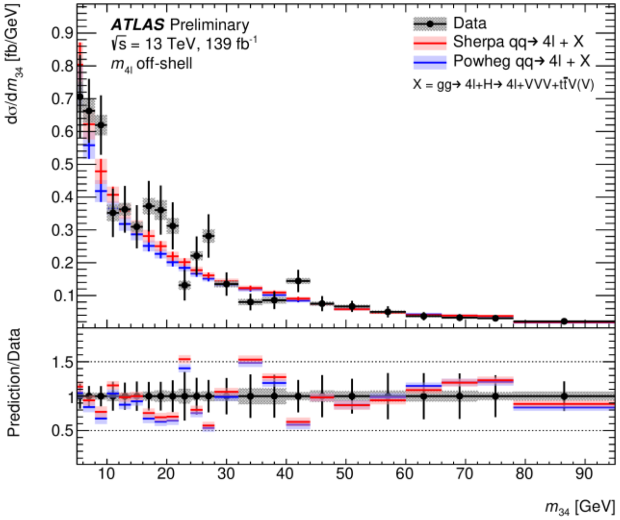


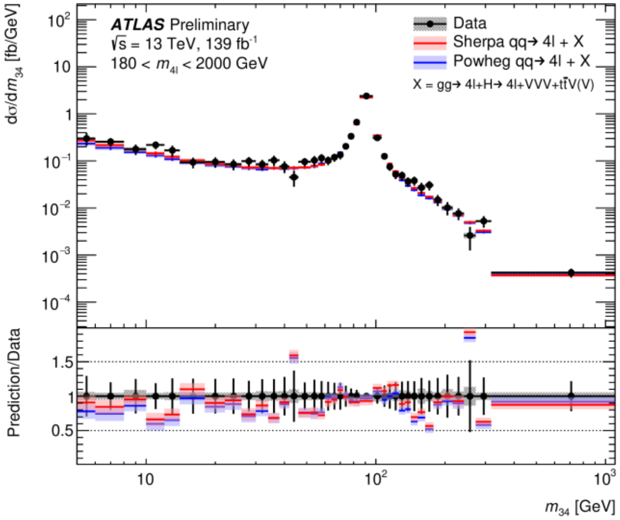
Back-up: measurement results

- m34 differential cross-sections in all regions



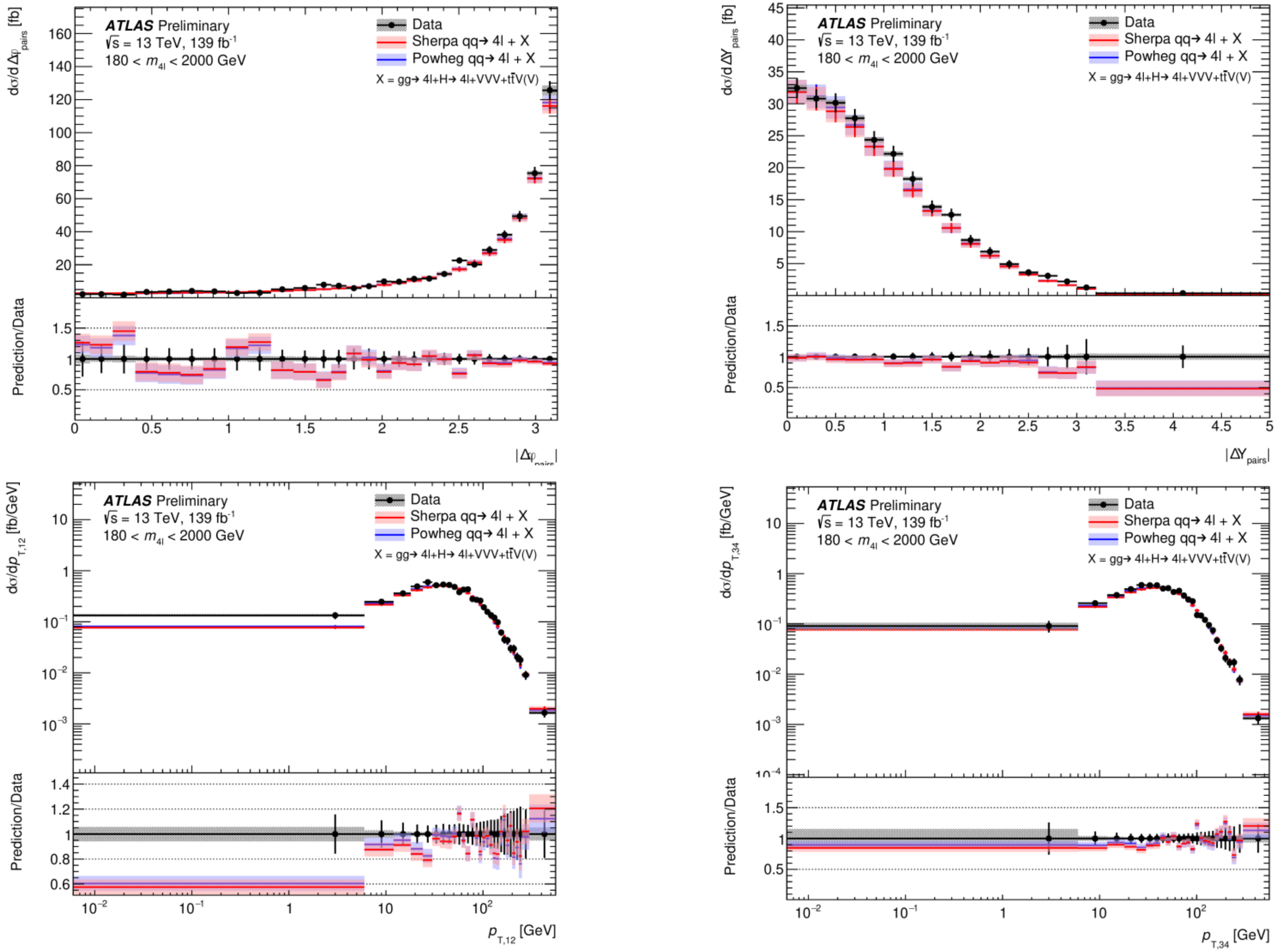






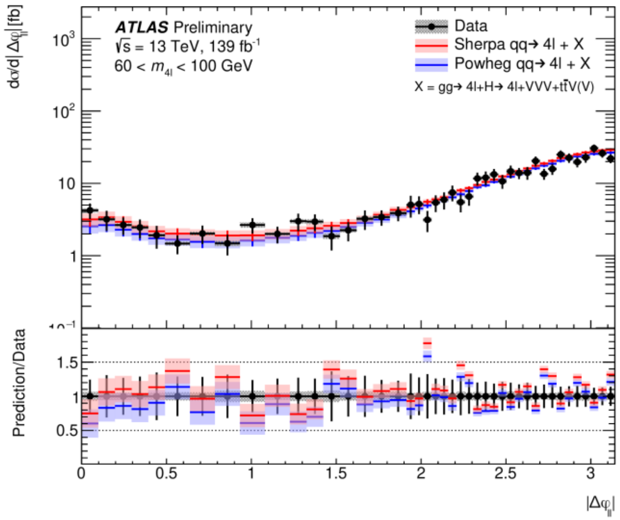
Back-up: measurement results

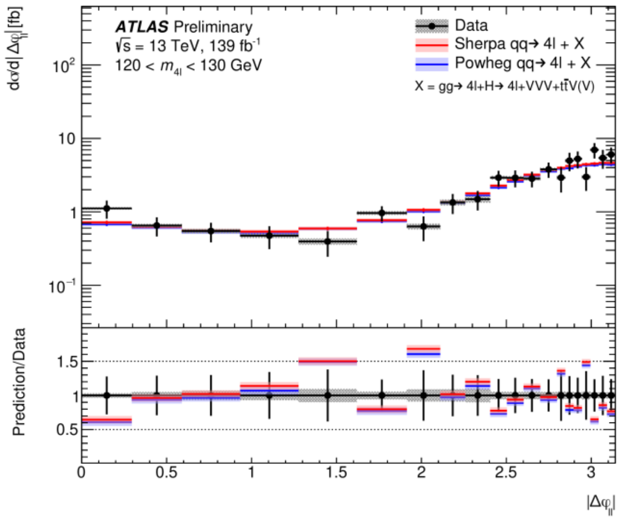
- $|\Delta\phi_{pairs}|$,$|\Delta y_{pairs}|$, $p^T{}_{12}$, $p^T{}_{34}$ differential cross-sections in on-shell region:

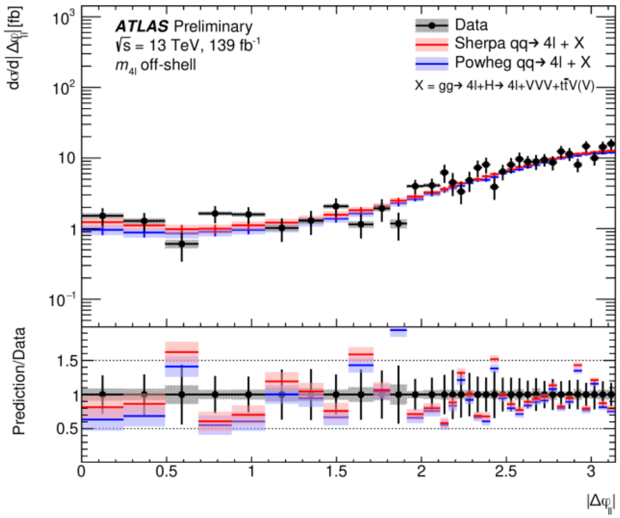


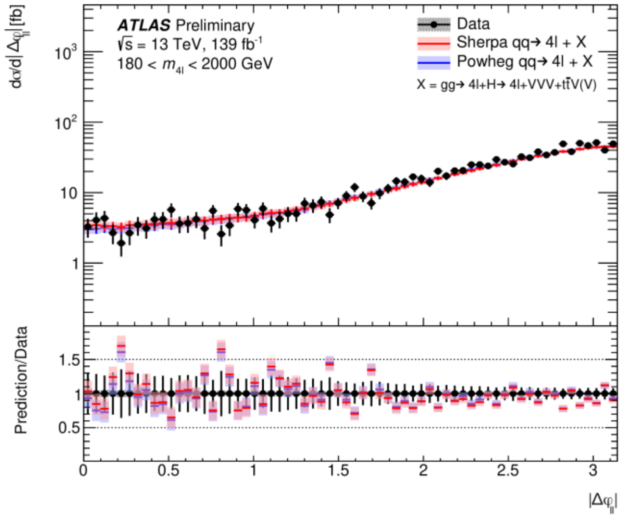
Back-up: measurement results

- $|\Delta\phi_{ll}|$ differential cross-sections in all regions



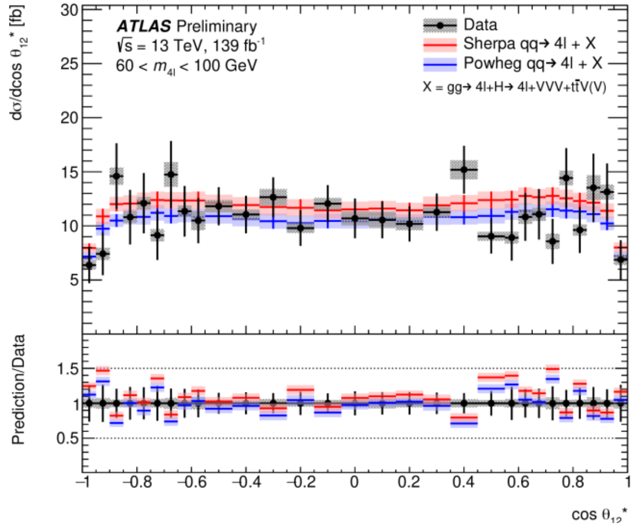


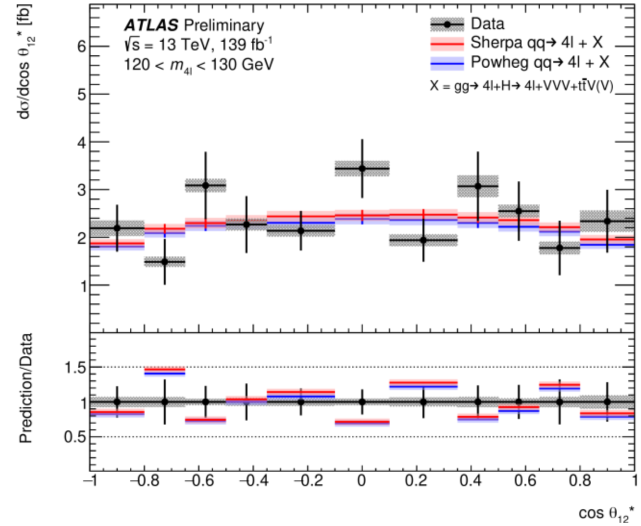


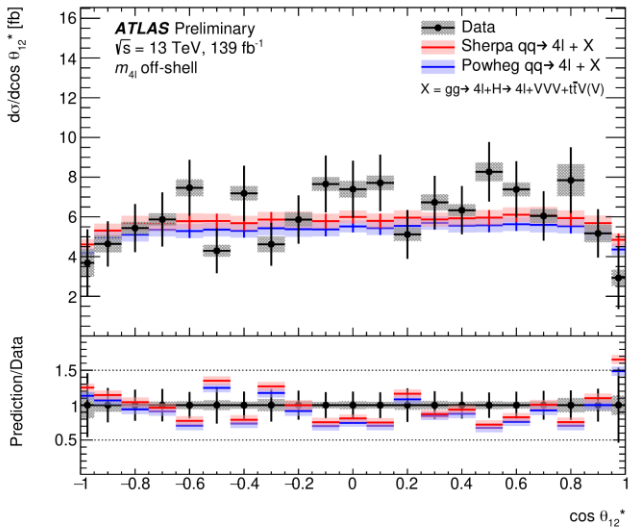


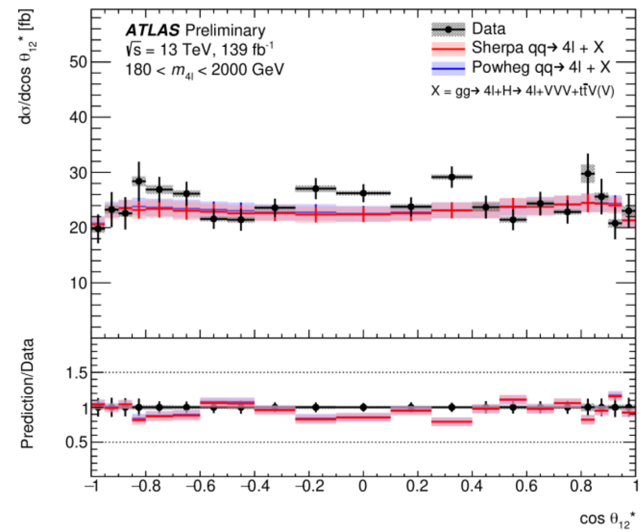
Back-up: measurement results

- $\cos\theta^*_{12}$ differential cross-sections in all regions



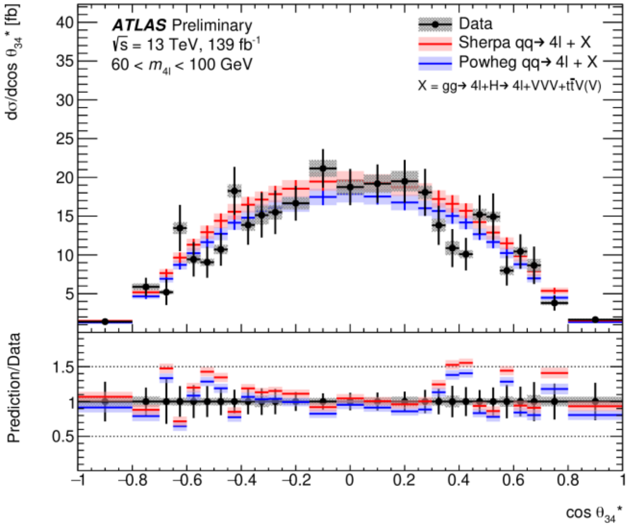


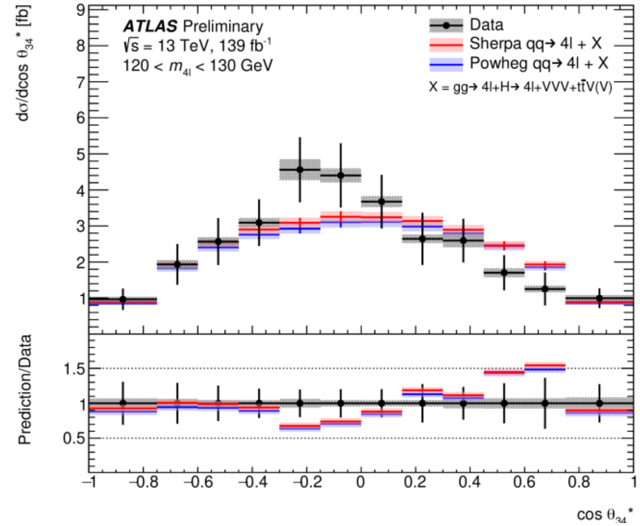


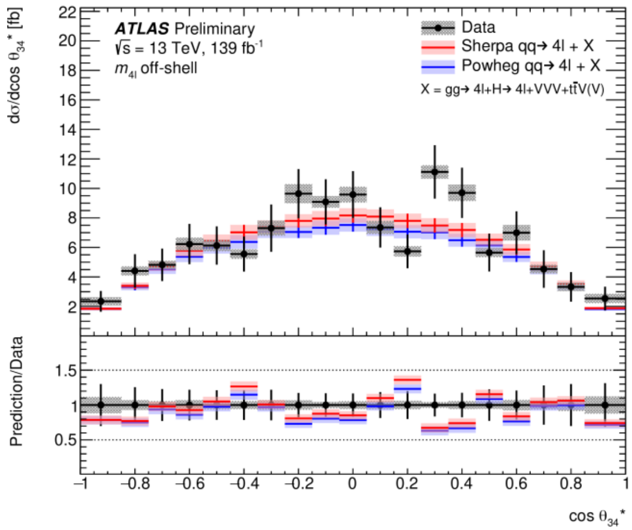


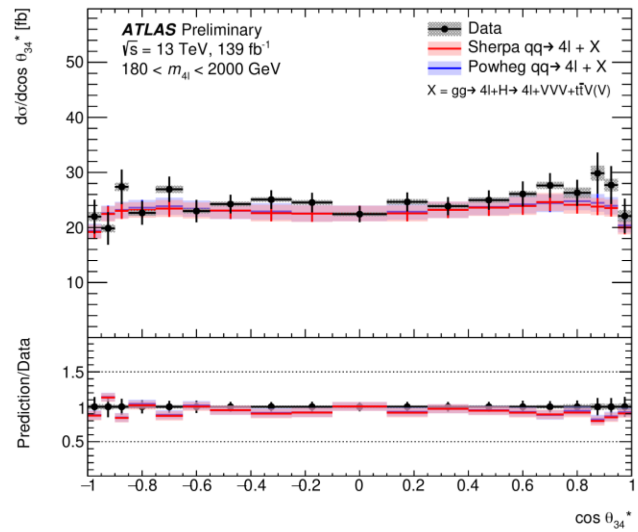
Back-up: measurement results

- $\cos\theta^*_{34}$ differential cross-sections in all regions







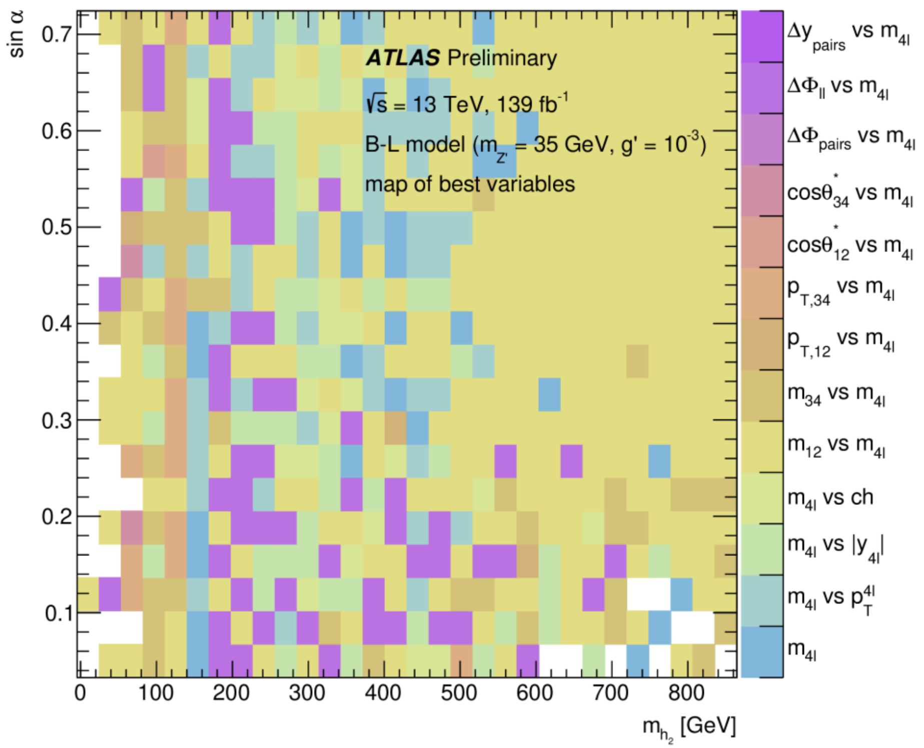


Back-up: B-L model interpretation

- multi-gaussian likelihood:

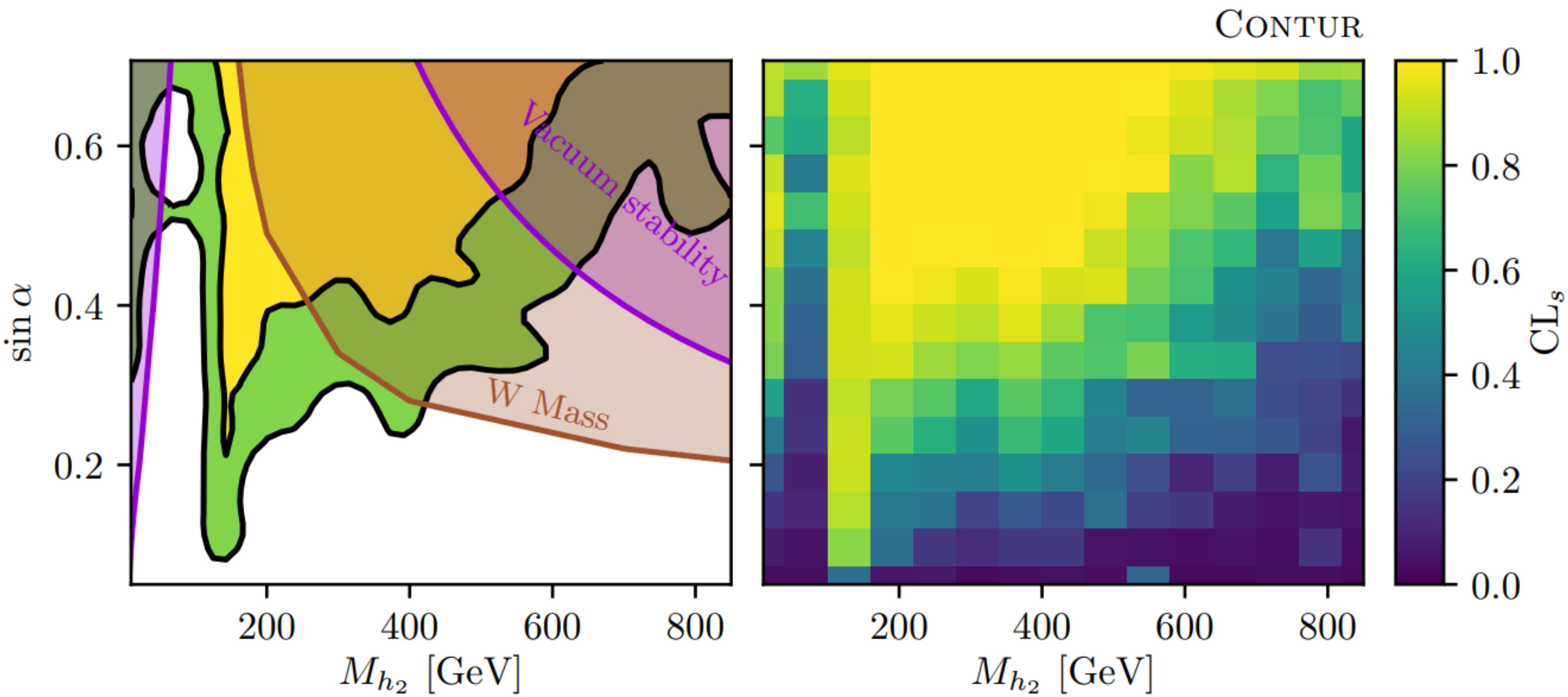
$$\mathcal{L}(\mu) = \frac{1}{\sqrt{(2\pi)^k|C|}} \exp(-\frac{1}{2}(\vec{\sigma}_{data} - \vec{\sigma}_{pred}(\mu))^T C^{-1}(\vec{\sigma}_{data} - \vec{\sigma}_{pred}(\mu)))$$

- “most sensitive variable” map:



Back-up: B-L model interpretation

- LHC constraints on B-L model:



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