Probing BSM physics with SM measurements

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Standard Model and Beyond workshop 19/09/19

This Talk

All SM measurements limit BSM - but can design with this in mind

Covered

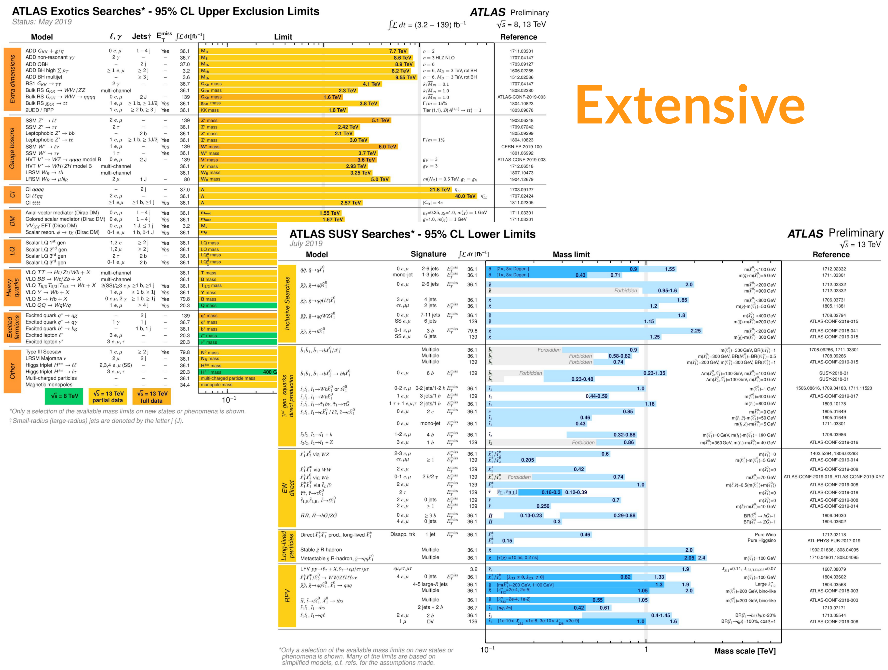
- Why bother doing this?
- What we did so far
  - Four lepton mass
  - Met + jets cross-section ratios
  - Re-interpretation
- Limitations & how can we improve?
- Outlook

Beyond Scope

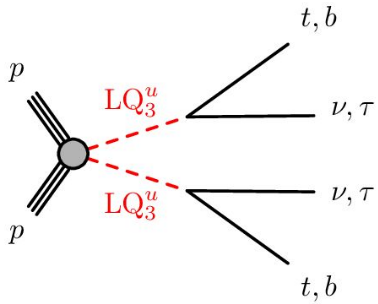
- Unfolding CRs in your search e.g : Leptoquark discussion
- CMS (nothing personal!)
- SM measurements setting limits on aTGC / EFT scenarios
- Earliest example of unfolded limit setting on ATLAS: JHEP05(2014)059

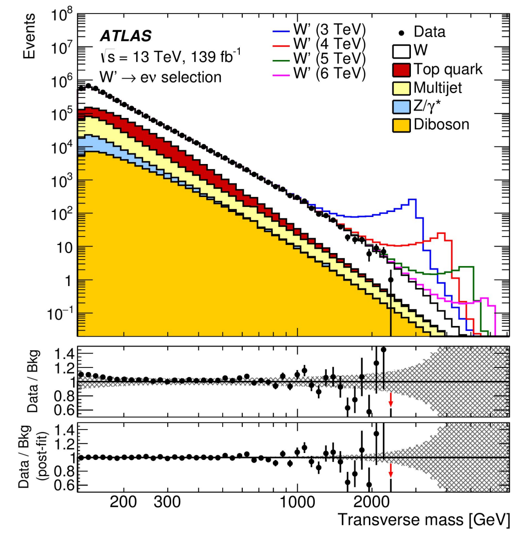
Why bother?

Dedicated Search Program



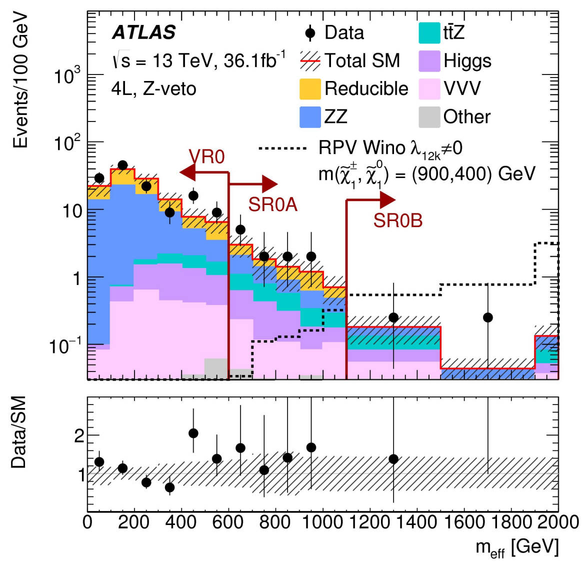
Extensive



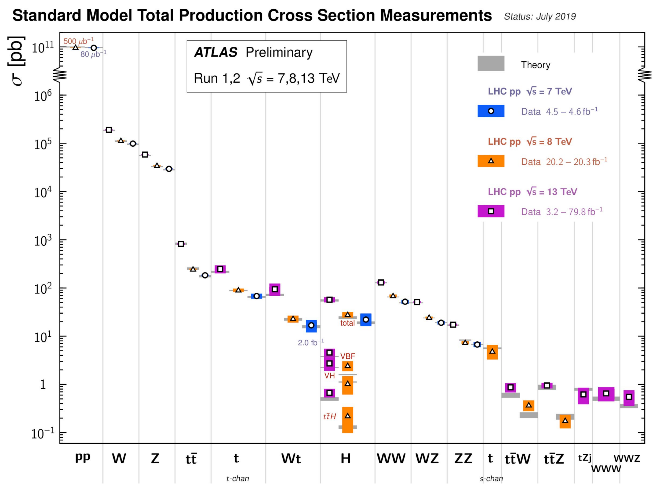


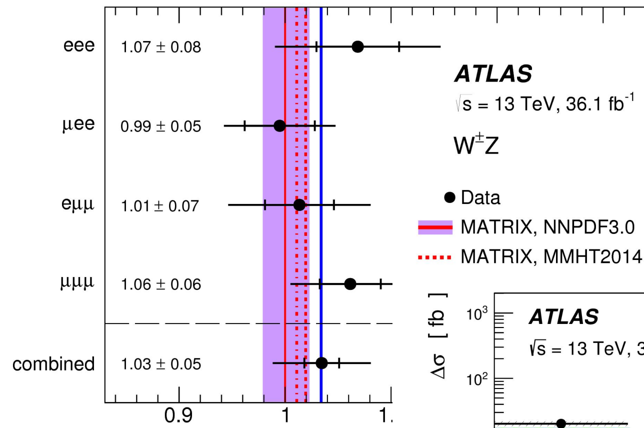
BSM signature driven

- Detector-level
- Fast
- Can bin very finely - or even un-binned

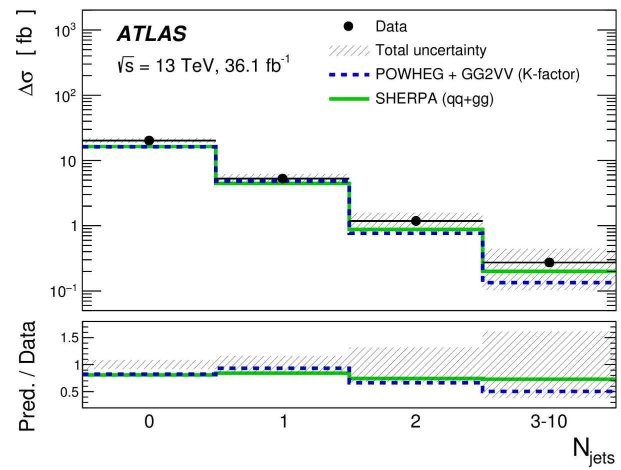


How do SM measurements differ?

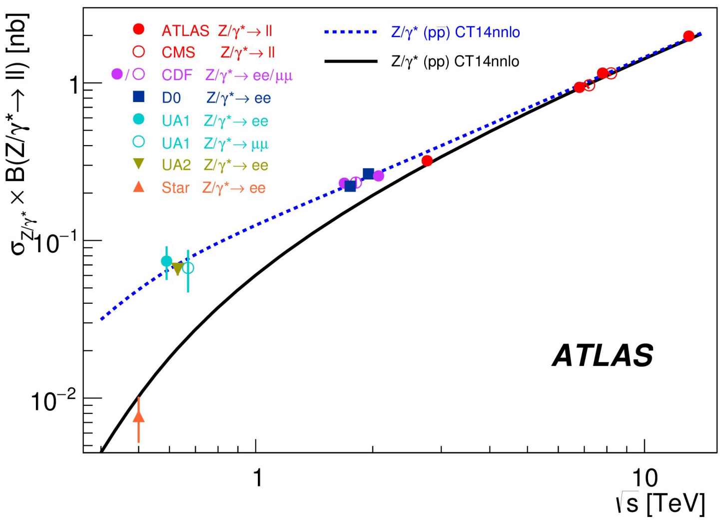




Detector Corrected



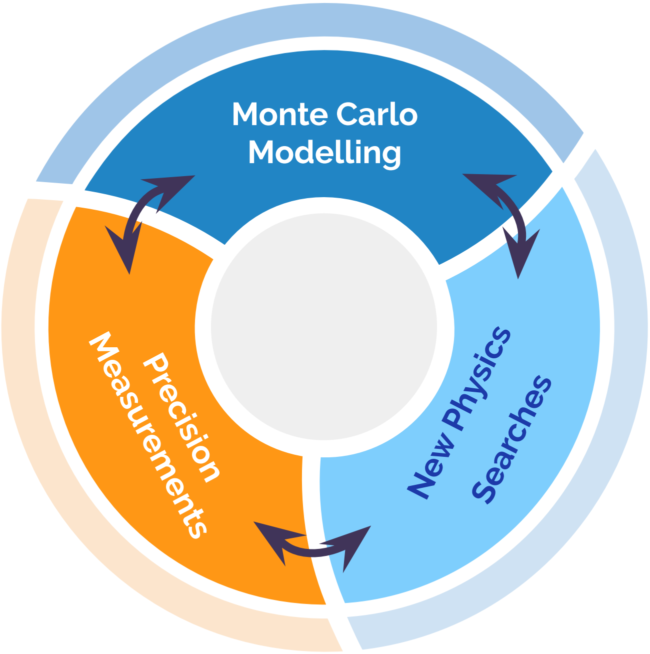
SM process-driven



Focus on precision, longevity, re-usability

Advantages

- **Can compare directly to MC without simulating the detector**
  - Quick and CPU-cheap
  - Easy to scan wide parameter space
  - Accessible to everyone
  - Can update if SM modelling improves



- **Not targeting specific process**
  - Maintain sensitivity to many scenarios

What have we done?

- **Four Lepton Mass Spectrum**

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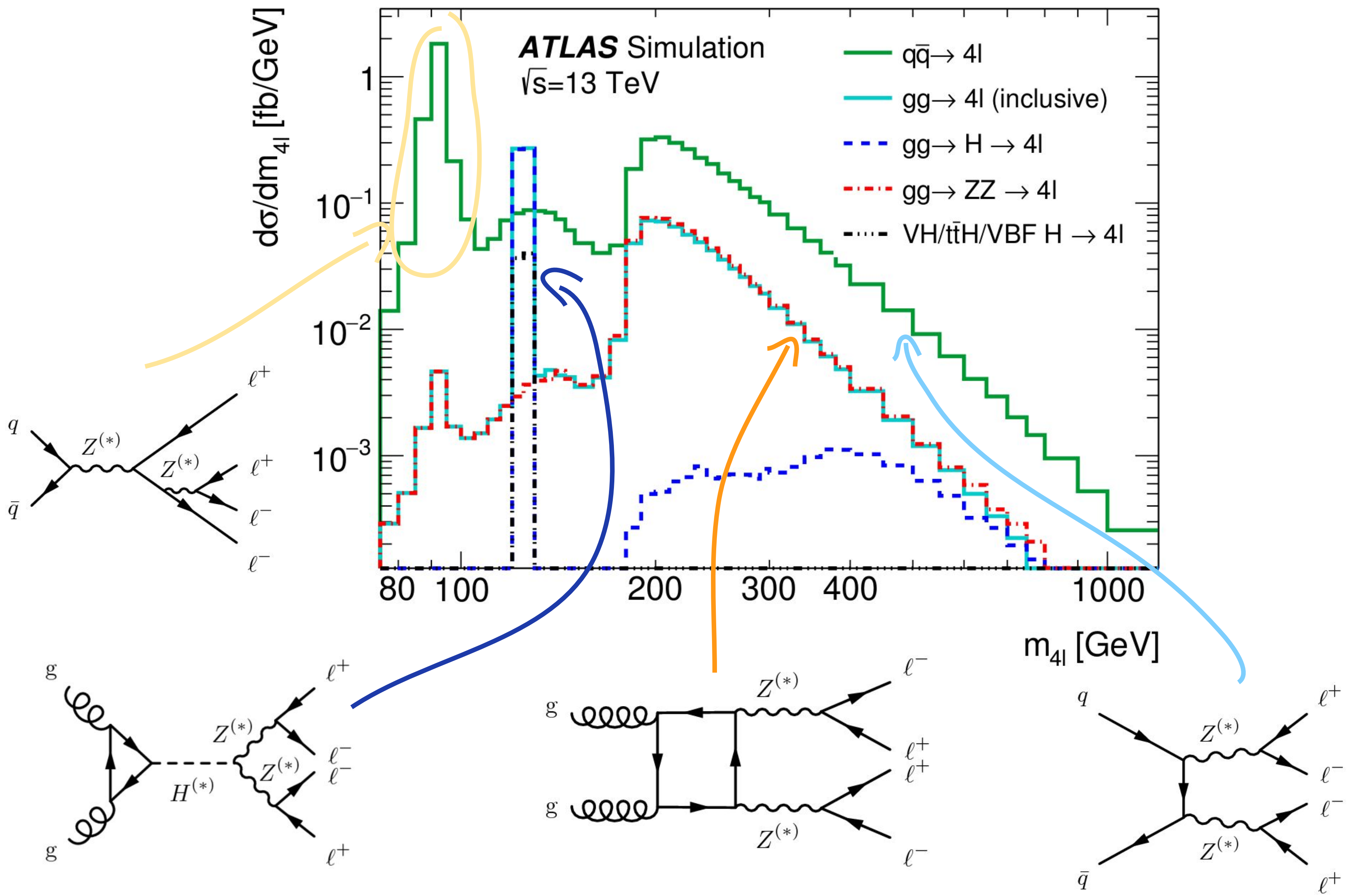
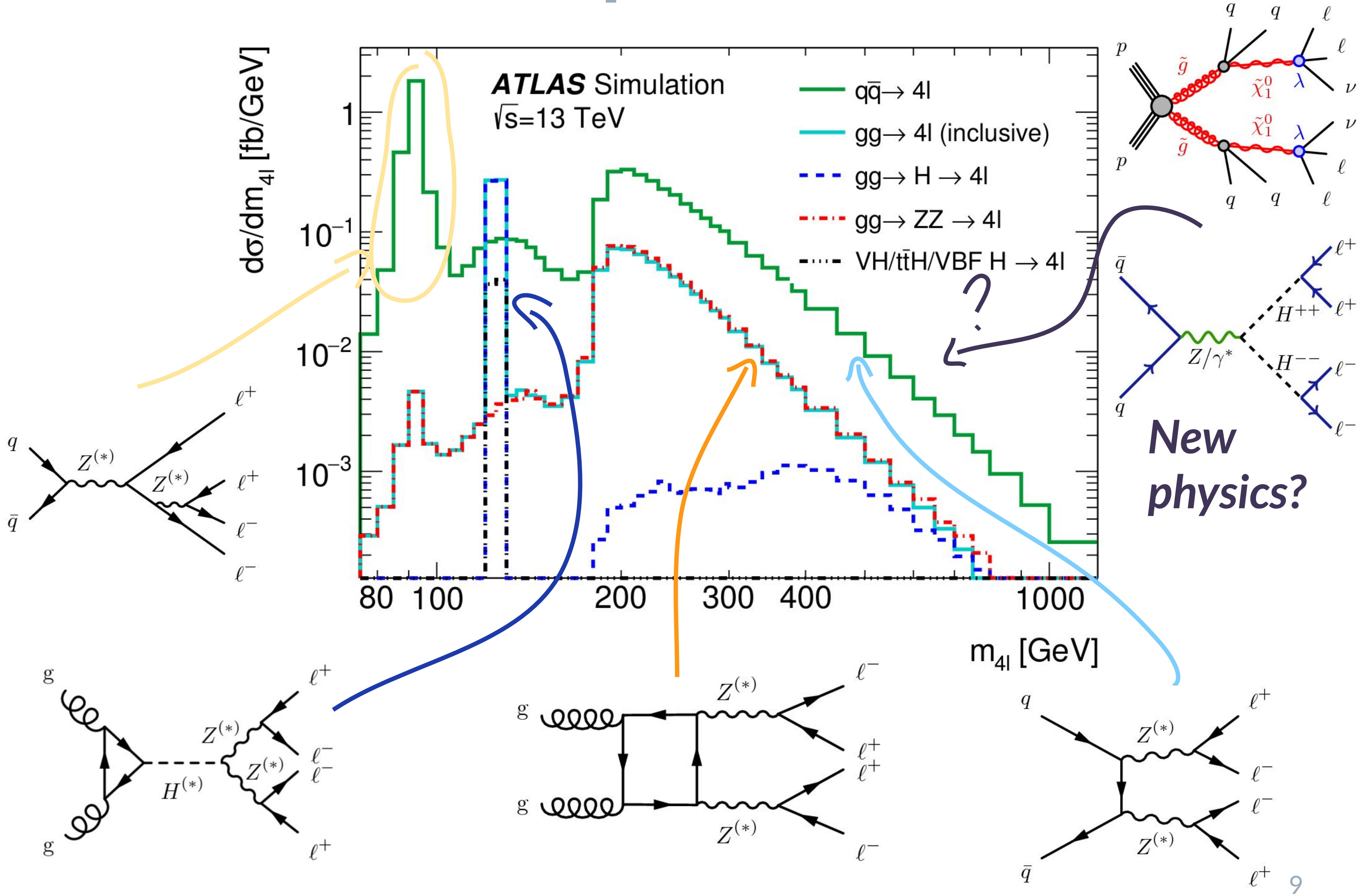
Four Lepton Events



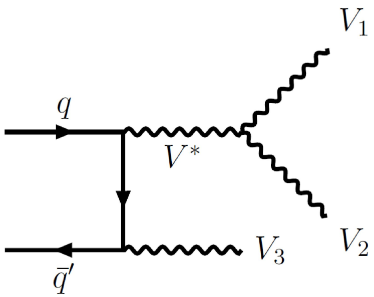
Four Lepton Events



What this gives us

Fiducial Region dominated by “signal” processes (96.5%)

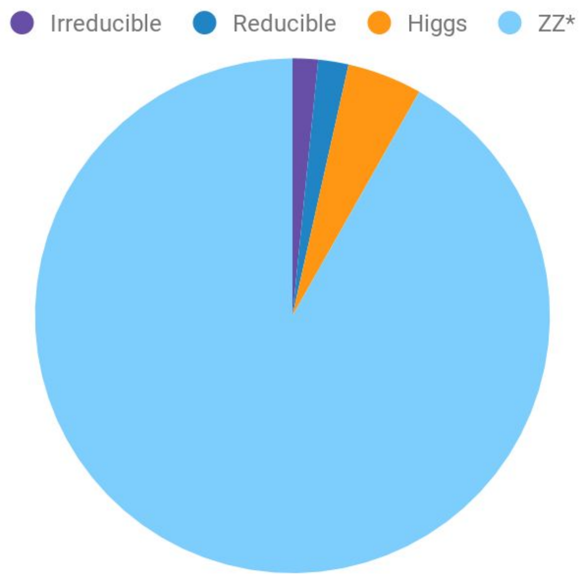
- Slightly increased WRT Higgs analysis by decreasing lower mass limit on secondary lepton pair



Revisiting for full Run 2

Irreducible

- **ZWW, ZZW, ZZZ, ttZ**
- Take from MC
- Contributes around 1.6% total events

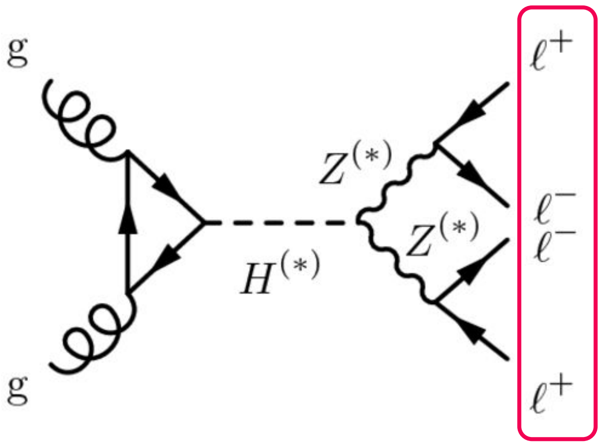


Reducible

- **Z+jets, tt, WZ**
- At least one “fake” lepton
  - Heavy flavour hadron decays
  - Muons from “light flavour” pion/kaon decays
  - Jets mis-identified as electrons
  - Electrons from photon conversions
- Contributes around 1.9% total events
- Estimated with data-driven methods

Fiducial Region Definition

Cross-section measured in region driven by kinematic acceptance of detector



- At least ***4 leptons*** - muon (electron) pT > 5 (7) GeV, |η| < 2.7 (2.47) - (>20/15/10 GeV in pair)
- Two ***same flavour, opposite sign*** (SFOS)lepton pairs, e.g. $e^+e^-e^+e^-$, $e^+e^-\mu^+\mu^-$, $\mu^+\mu^-\mu^+\mu^-$
- Pair with dilepton mass closest to Z boson mass ***primary pair*** - must be **50 - 106 GeV**, second-closest are ***secondary pair*** - uses sliding scale **f(m4l) - 115 GeV**
- Separated by ***ΔR > 0.1 (0.2)*** for same(opposite) flavours
- ***Mll > 5*** Gev for all SFOS pairs (J/Psi veto)

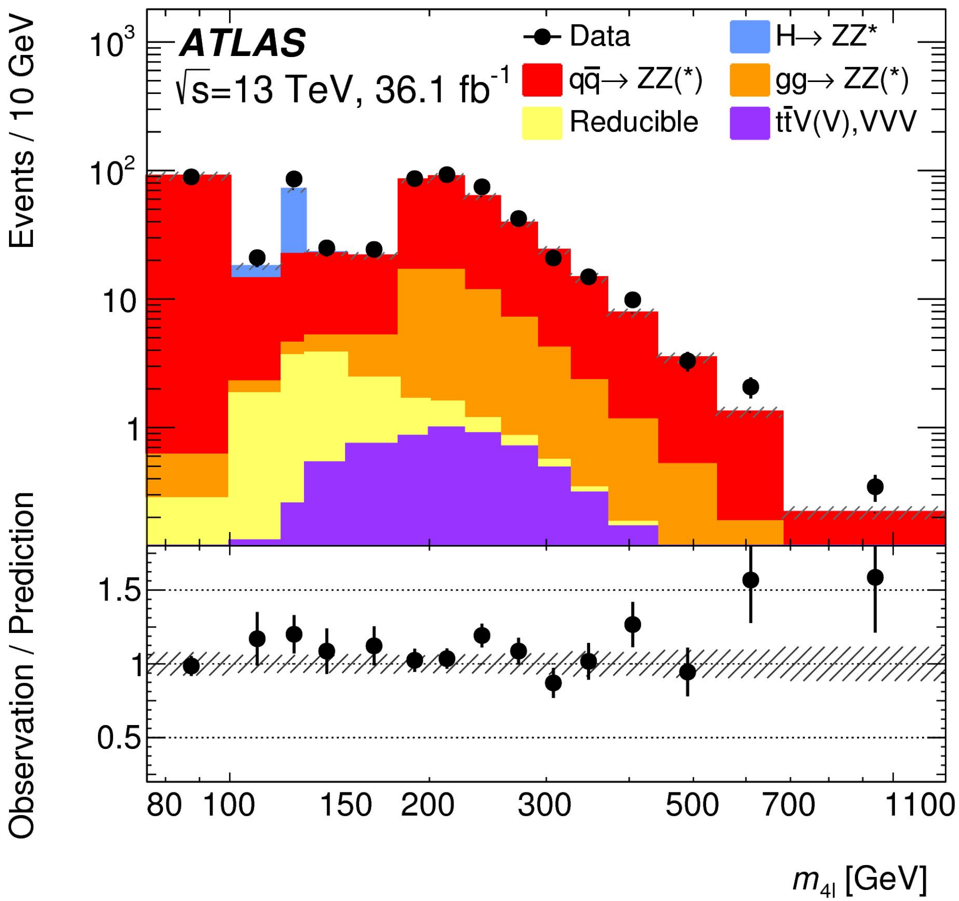
$$f(m_{4\ell}) = \begin{cases} 5\text{ GeV}, & \text{for } m_{4\ell} < 100\text{ GeV} \\ 5\text{ GeV} + 0.7 \times (m_{4\ell} - 100\text{ GeV}), & \text{for } 100\text{ GeV} < m_{4\ell} < 110\text{ GeV} \\ 12\text{ GeV}, & \text{for } 110\text{ GeV} < m_{4\ell} < 140\text{ GeV} \\ 12\text{ GeV} + 0.76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

Revisiting for full Run 2

Maintains sensitivity to Z→ 4l but suppresses leptons from tau lepton decays

Distributions

Star of the show - four lepton mass



Double Differential Distributions:

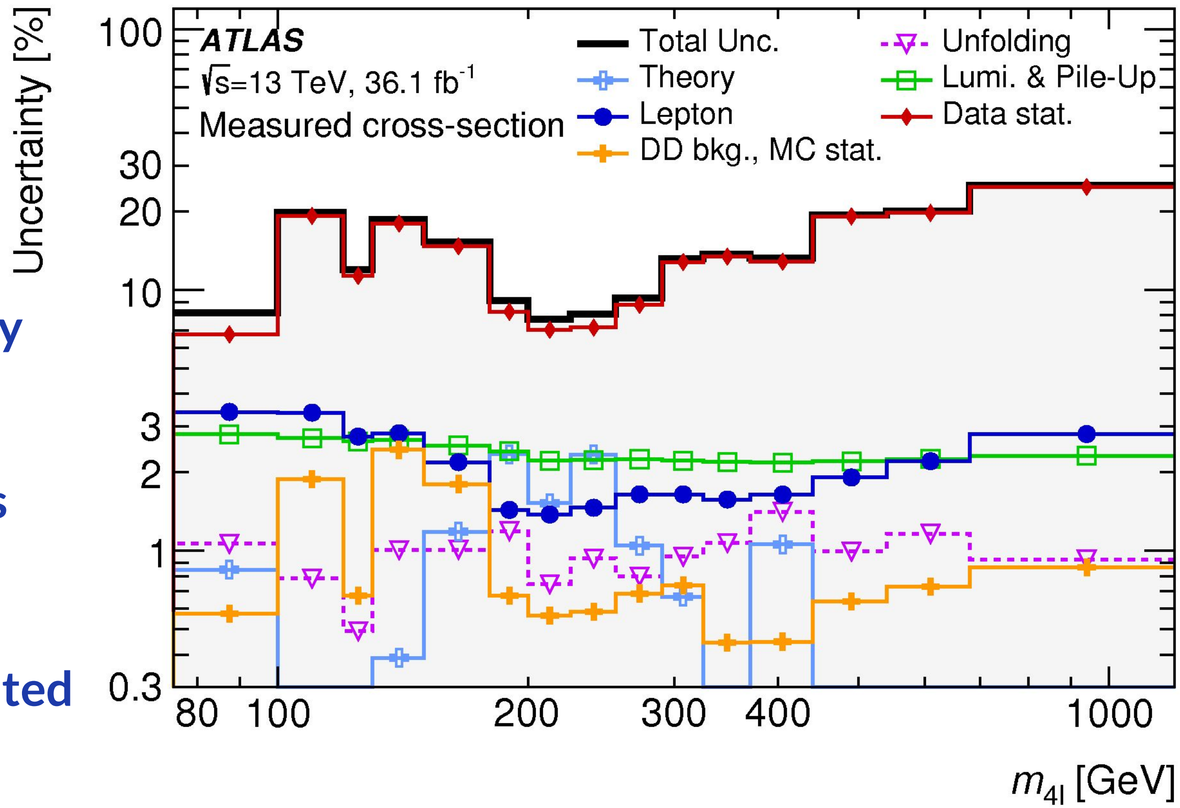
- Measure $\mathbf{m_{4l}}$ in fairly coarse bins of other interesting variables;
  - ***Transverse momentum p_T^{4l}***
  - ***Rapidity y_{4l}***
  - ***Lepton Flavours - eeee/ee$\mu\mu$/$\mu\mu\mu\mu$***
  - ***Matrix element discriminant***
- Potential increased sensitivity
- Improved modelling in future can be fed in

Uncertainty Sources

Dominated by statistical uncertainty

Lepton dominated by reconstruction, identification and isolation efficiencies

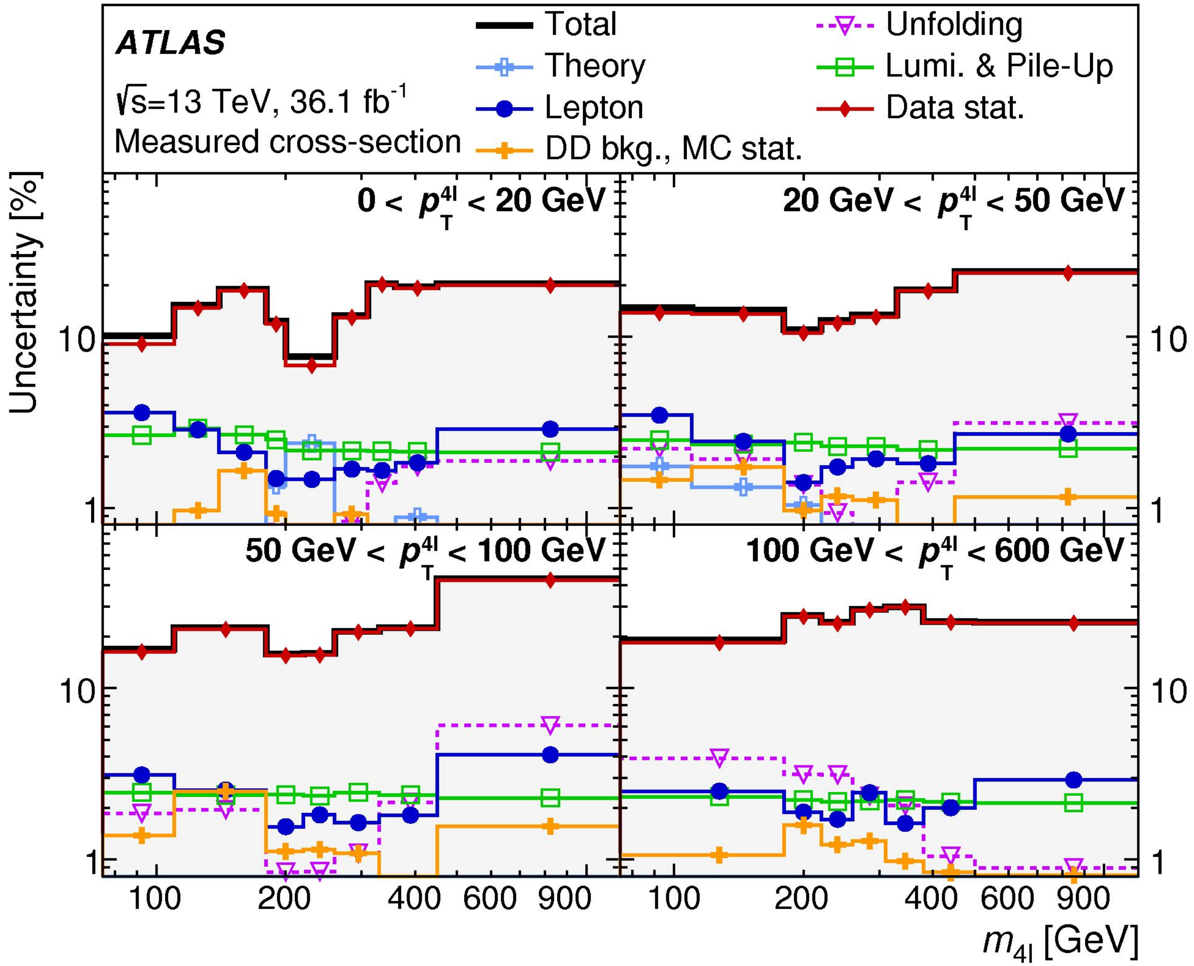
Data has a flat ~2% uncertainty associated with luminosity measurement



Smaller contributions from:

- Unfolding procedure
- Data-driven background estimation
- Theoretical uncertainty includes scale, PDF set and parton showering choices

Uncertainty Sources

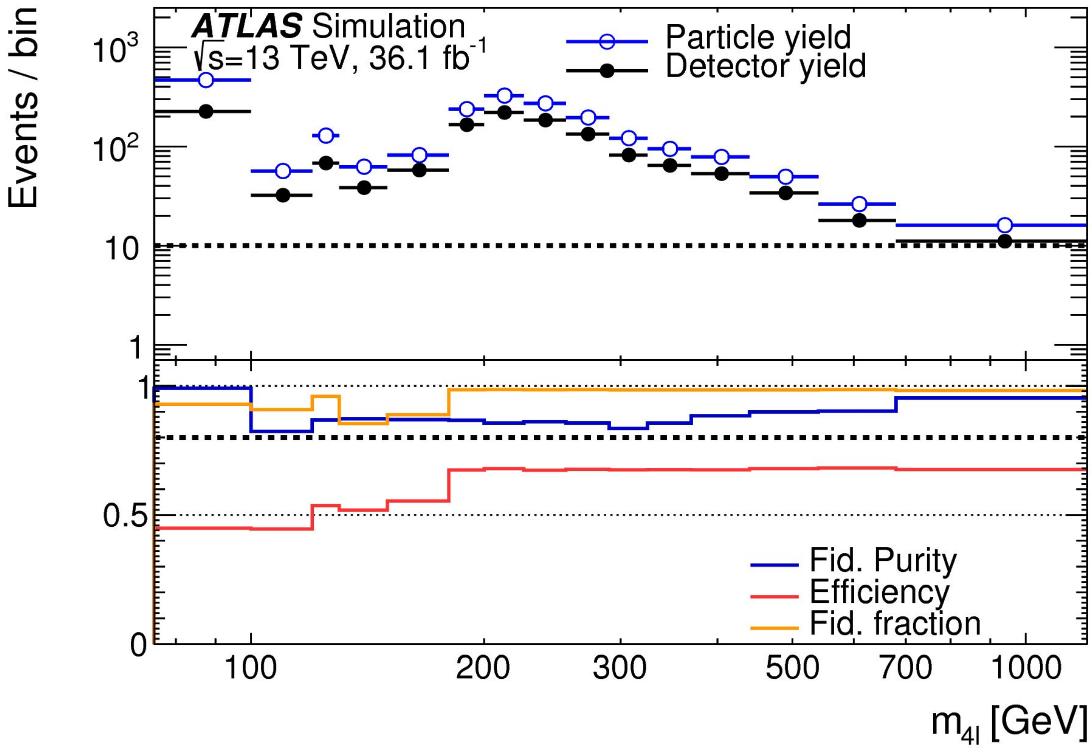


Relative sizes do vary across distributions, with exception of luminosity and pileup, but always dominated by statistical uncertainty

Unfolding

Correct for effects the detector has on measured data:

- Imperfect e.g. efficiency to reconstruct leptons, energy resolution
- Model effects by comparing "truth" and "reconstructed" objects in MC simulation



Efficiency:

Events (pass fiducial and reco-level)/pass fiducial

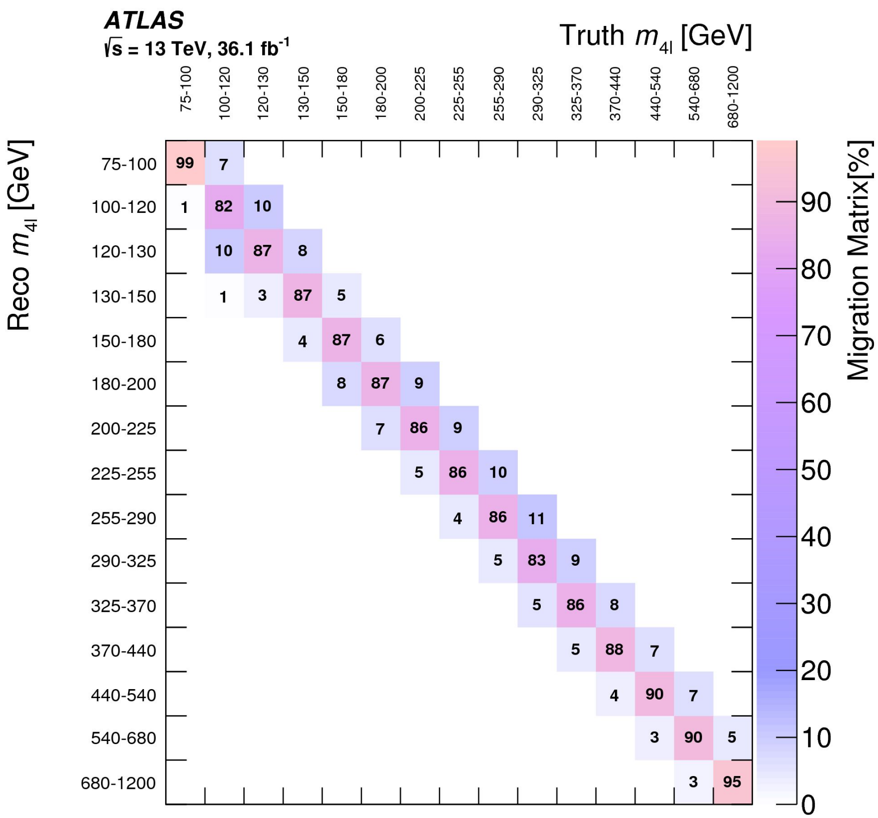
Fiducial Fraction:

Events pass reco-level but fail fiducial (detector resolution/tau leptons)

Fiducial Purity:

Probability that fiducial bin is the same as reco-level bin (in e.g. m4l)

Unfolding



Migration Matrix:

Probability that a given fiducial bin results in a given reco-level bin (in e.g. m4l) (diagonal == fiducial purity)

- Uses migration matrix
- Prior is *predicted* distribution
- Two iterations used here

Subtract background from data → **Multiply observation in each bin by fiducial fraction** → **Iterative Bayesian method to correct for bin migration** → **Divide each bin by reconstruction efficiency**

What if there's signal in our data?

- ▷ Injected possible BSM signals into MC to check the effects on the unfolding mechanism

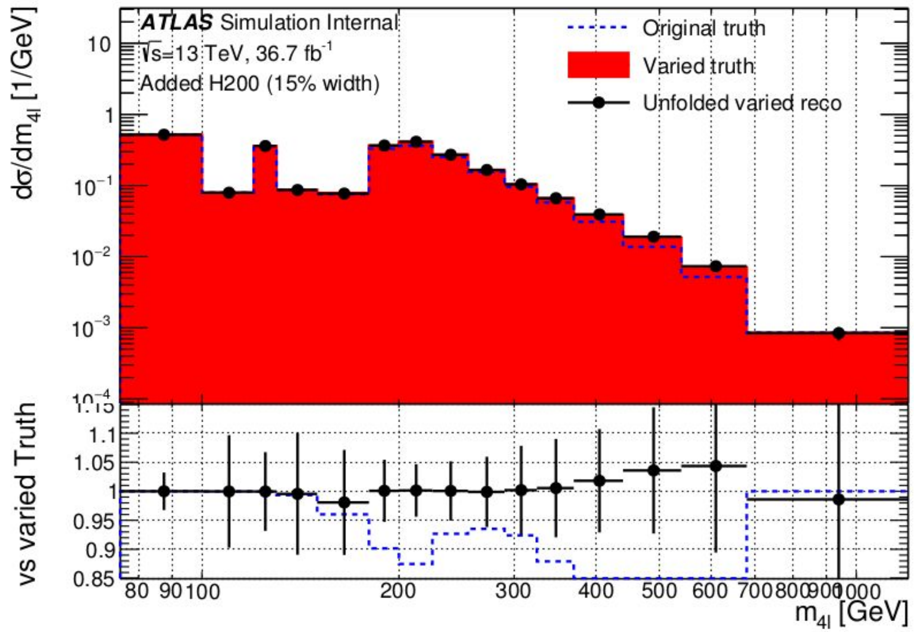
- The cross-section for the on-shell Higgs boson contribution is set to 25%/300% the SM prediction — < 5% deviation
- The non-resonant $gg \rightarrow ZZ^{(*)}$ contribution is set to 0%/500% of the SM prediction. — < 3% deviation
- An additional heavy Higgs boson with $m_{H'} = 200\text{GeV}$, $\Gamma_{H'} = 30\text{GeV}$ is injected
- An additional heavy Higgs boson with $m_{H'} = 400\text{GeV}$, $\Gamma_{H'} = 60\text{GeV}$ is injected
- An additional heavy Higgs boson with $m_{H'} = 900\text{GeV}$, $\Gamma_{H'} = 135\text{GeV}$ is injected

< 6% deviation, except for matrix element discriminant which is < 20%

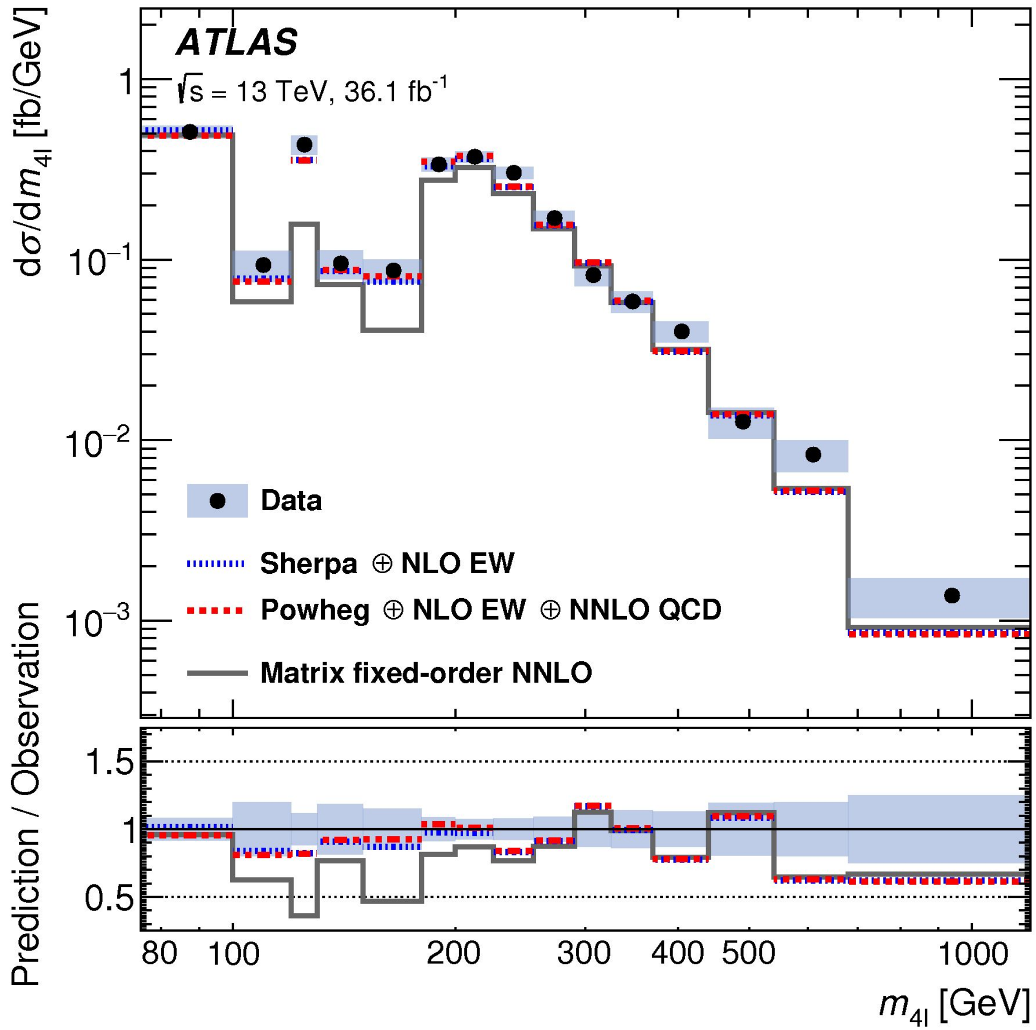
Caveat:

Need to take care interpreting unfolded limits for peaked resonances in very sensitive regions

Kinematics differences between SM and BSM will effect unfolding if BSM signal present

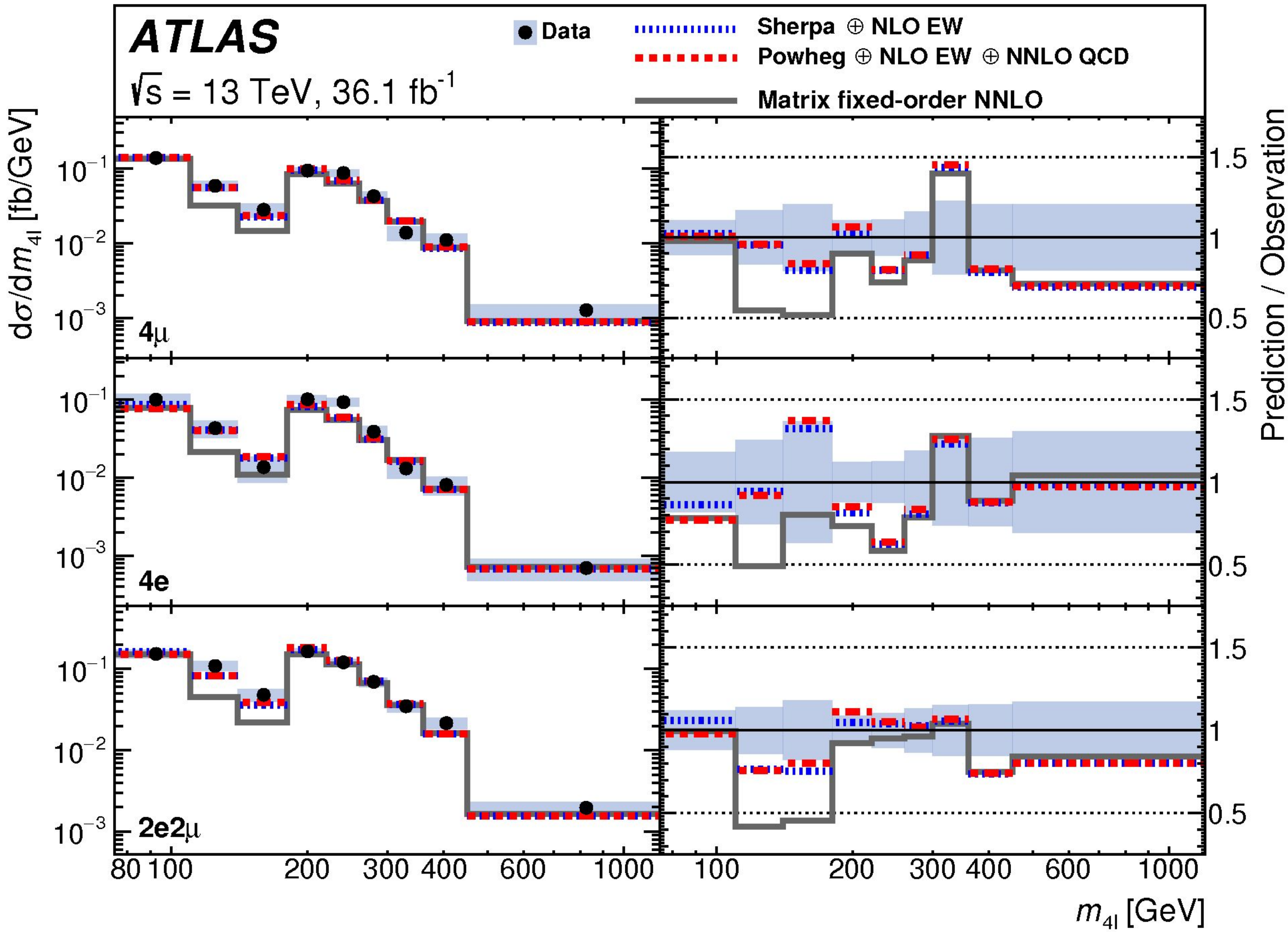


Differential Cross-sections



MATRIX is a fixed-order NNLO QCD prediction, no additional higher order corrections or QED final state radiation are included

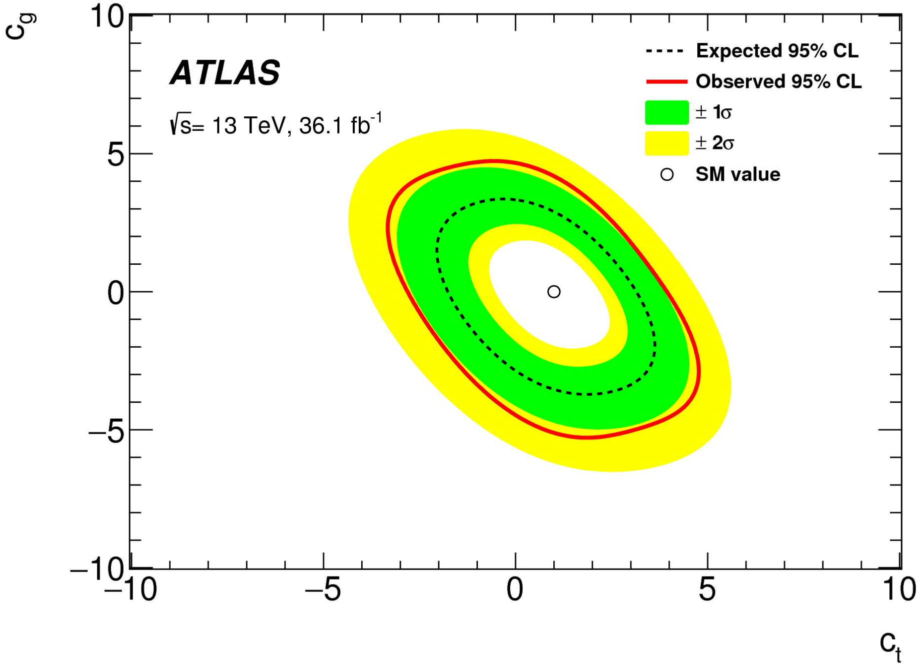
Differential Cross-sections - Flavour

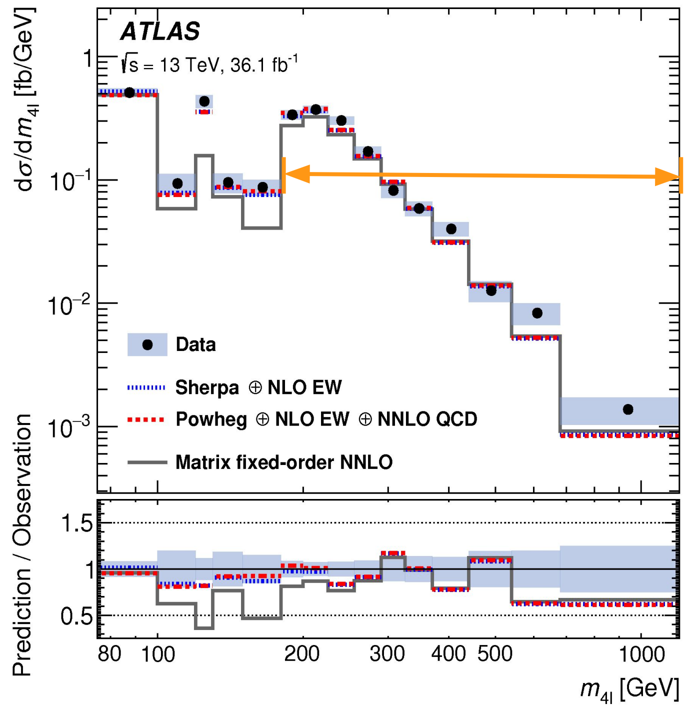


Example Interpretation: Modified Higgs couplings

Model:

- BSM modification of couplings of Higgs boson to top quark (**c_t**) and gluon (**c_g**)
- High mass region allows probing of these couplings separately, whereas on-shell can only limit $|c_t + c_g|^2$





Interpretation:

- Use m_{4l} above 180 GeV
- Fix $qq \rightarrow 4l$ to prediction
- $gg \rightarrow 4l$ yield is parameterised as function of couplings
- Vary everything within theoretical uncertainties

Other interpretations include branching fraction of single Z to four lepton decay, off-shell Higgs production strength and gluon-fusion signal strength

What have we done?

- Four Lepton Mass Spectrum
- **Met + jets cross-section ratio**

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Key concepts

Ratio:

Cancellation of systematic uncertainties and aspects of detector correction

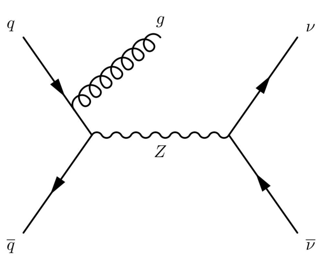
$$R_{\text{miss}} = \frac{\sigma(\not{p}_{\text{T}} + \text{jets})}{\sigma(Z \rightarrow \ell^+\ell^- + \text{jets})}$$

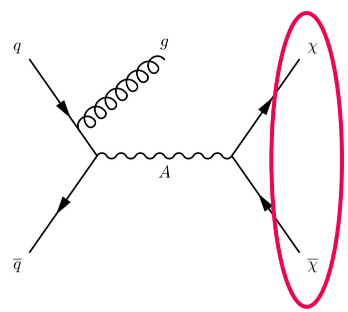
General Selection:

SM contribution to numerator comes from Z→ $\nu\nu$ decays but sensitive to BSM

≥ 1 jet

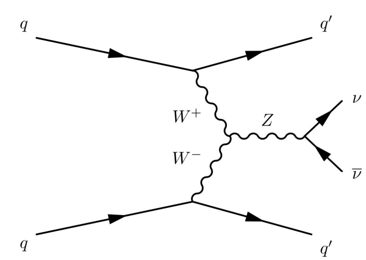
- ≥1 jet with p_T>120 GeV, |y|<2.4
- Measure R as a function of missing transverse momentum

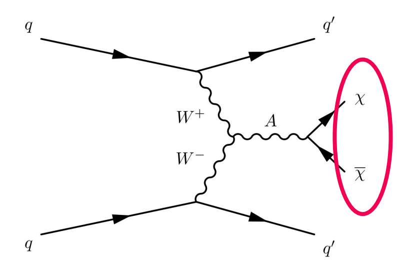




VBF

- ≥2 jet with p_T>80, 50 GeV, |y|<4.4, mjj > 200 GeV
- Veto additional jets in y-space between leading jets
- Measure R as a function of missing transverse momentum, di-jet invariant mass, and di-jet angle ϕ





Common

- pTmiss > 200 GeV, additional lepton veto, Δϕ(pTmiss, jet) > 0.4

Denominator

- SFOS lepton pair with mll 66-116 GeV, pT>80, 7 GeV, |y|<2.5
- pTmiss calculated without leptons, which are treated as invisible particles

Extending for full Run 2

What this gives us

Significant numerator contributions from backgrounds containing W bosons

- **W+jets, tt, dibosons** with un-reconstructed or out-of-acceptance lepton
- Data-driven estimation using control regions
- Estimated separately for each lepton flavour

Changing for full Run 2

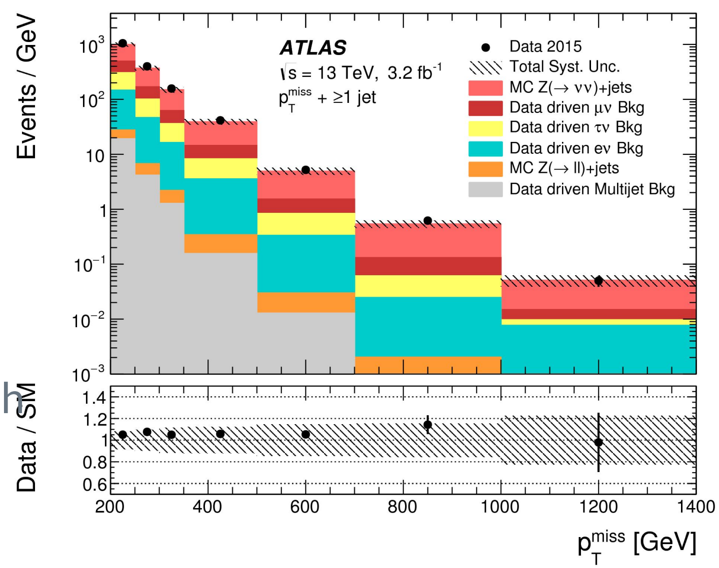
Multijets

- Small in numerator, even smaller in denominator
- Also estimated with data-driven method using QCD-enriched control regions

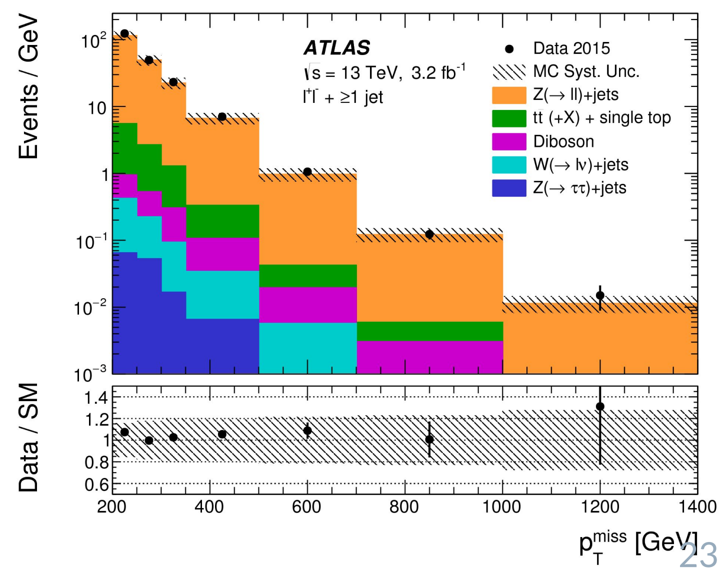
Prediction agrees well with data

- Smaller contributions estimated with MC

$Z \rightarrow \nu\nu$ (numerator) ≥ 1 jet



$Z \rightarrow ll$ (denominator) ≥ 1 jet



Uncertainties

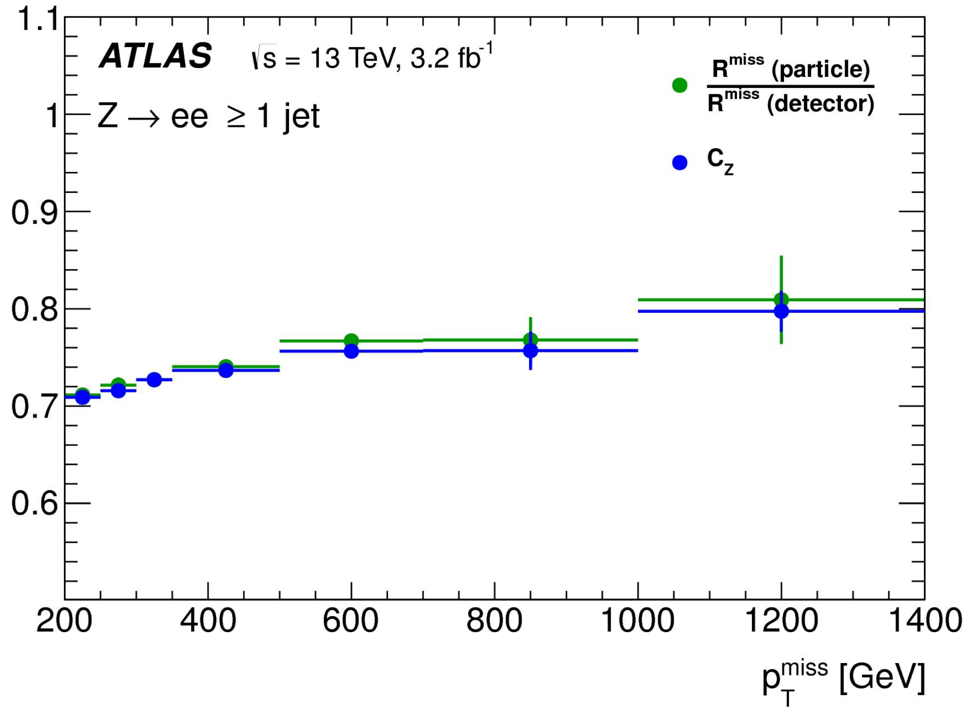
Systematic uncertainty source	Low $p_{\mathrm{T}}^{\mathrm{miss}}$ [%]	High $p_{\mathrm{T}}^{\mathrm{miss}}$ [%]	Low m_{jj} [%]	High m_{jj} [%]
Lepton efficiency	$+3.5, -3.5$	$+7.6, -7.1$	$+3.7, -3.6$	$+4.6, -4.4$
Jets	$+0.8, -0.7$	$+2.2, -2.8$	$+1.1, -1.0$	$+9.0, -0.5$
$W \to \tau\nu$ from control region	$+1.2, -1.2$	$+4.6, -4.6$	$+1.3, -1.3$	$+3.9, -3.9$
Multijet	$+1.8, -1.8$	$+0.9, -0.9$	$+1.4, -1.4$	$+2.5, -2.5$
Correction factor statistical	$+0.2, -0.2$	$+2.0, -1.9$	$+0.4, -0.4$	$+3.8, -3.6$
W statistical	$+0.5, -0.5$	$+24, -24$	$+1.1, -1.1$	$+6.8, -6.8$
W theory	$+2.4, -2.3$	$+6.0, -2.3$	$+3.1, -3.0$	$+4.9, -5.1$
Top cross-section	$+1.5, -1.8$	$+1.3, -0.1$	$+1.1, -1.2$	$+0.5, -0.4$
$Z \to \ell\ell$ backgrounds	$+0.9, -0.8$	$+1.1, -1.1$	$+1.0, -1.0$	$+0.1, -0.1$
Total systematic uncertainty	$+5.2, -5.2$	$+27, -26$	$+5.6, -5.5$	$+14, -11$
Statistical uncertainty	$+1.7, -1.7$	$+83, -44$	$+3.5, -3.4$	$+35, -25$
Total uncertainty	$+5.5, -5.4$	$+87, -51$	$+6.6, -6.5$	$+38, -27$

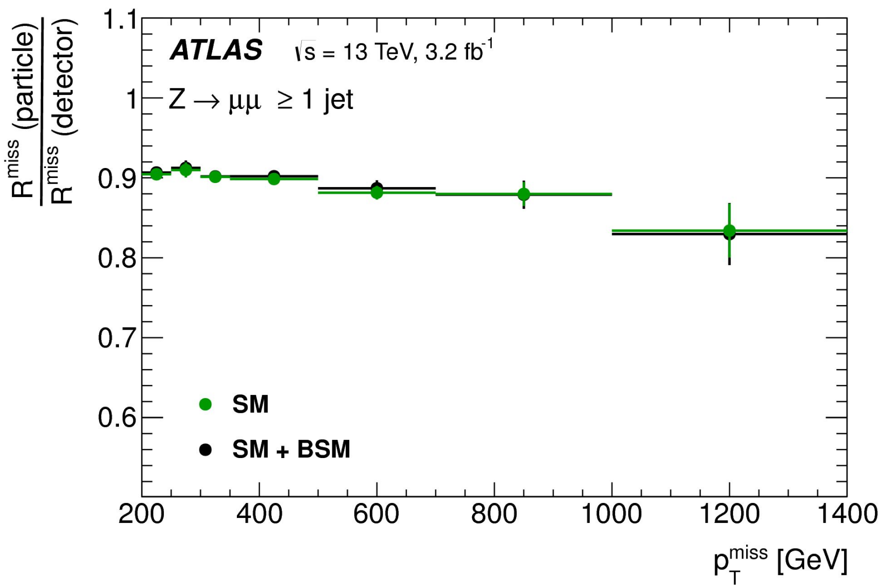
- Dominant uncertainties do depend on region of distribution
- Experimental sources dominated by **lepton reconstruction, isolation and trigger efficiencies**
- Significant contributions from **background estimation** methods, particularly the W backgrounds in lower statistics regions
- Analysis statistically limited in more sensitive tail regions due to rarer process in denominator

Unfolding

Correct for effects the detector has on measured data:

- Cancellation of effects relating to jet and p_T^{miss} variables
- Wide bins so negligible migration effects
- ***Bin-by-bin*** correction can be applied to account for remaining effects
- Agrees well with C_Z, describing just **lepton inefficiencies** in denominator $Z \rightarrow ll$ (detector)/ $Z \rightarrow ll$ (particle)



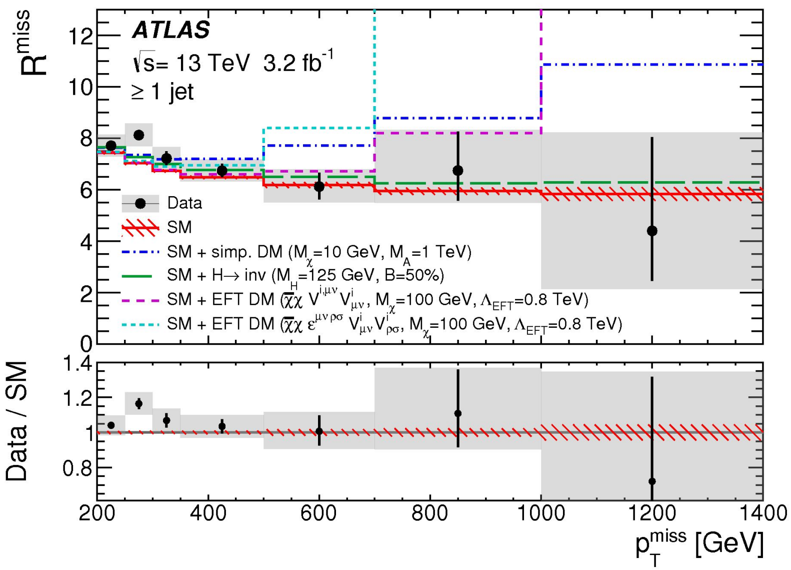


BSM effects

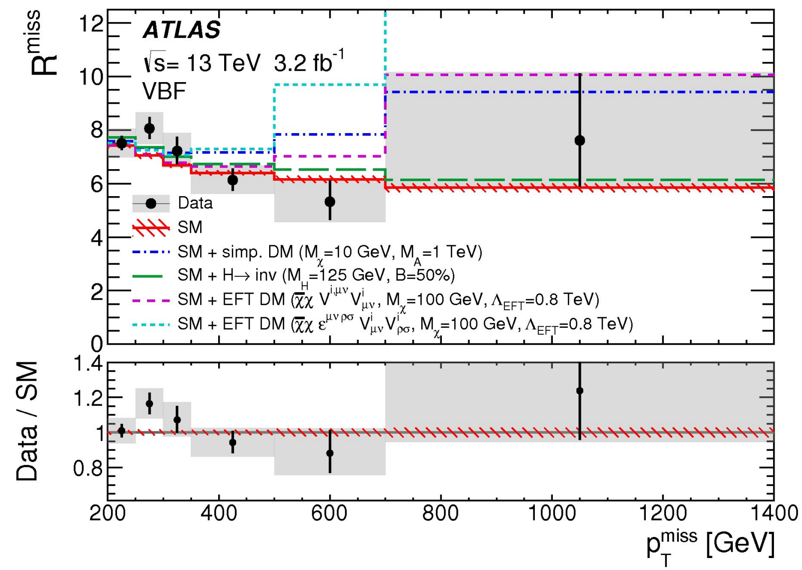
- As with m_{4l}, tested robustness to BSM signal by injecting MC
- 50% change to R vs p_T distribution - only <0.5% change to correction factor

Cross-section Results

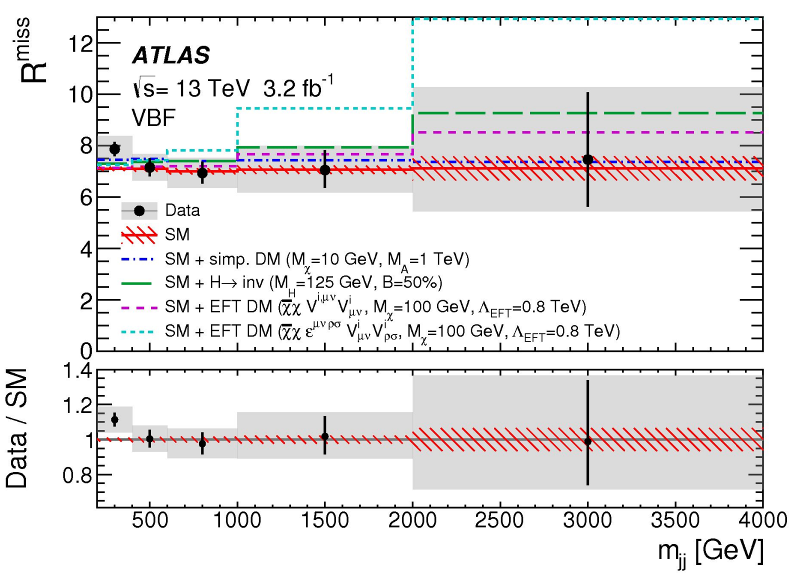
≥ 1 jet



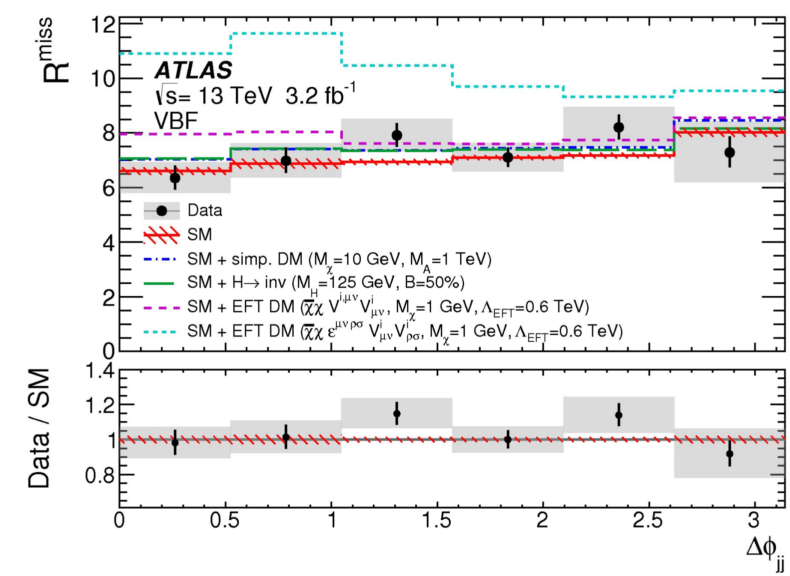
VBF



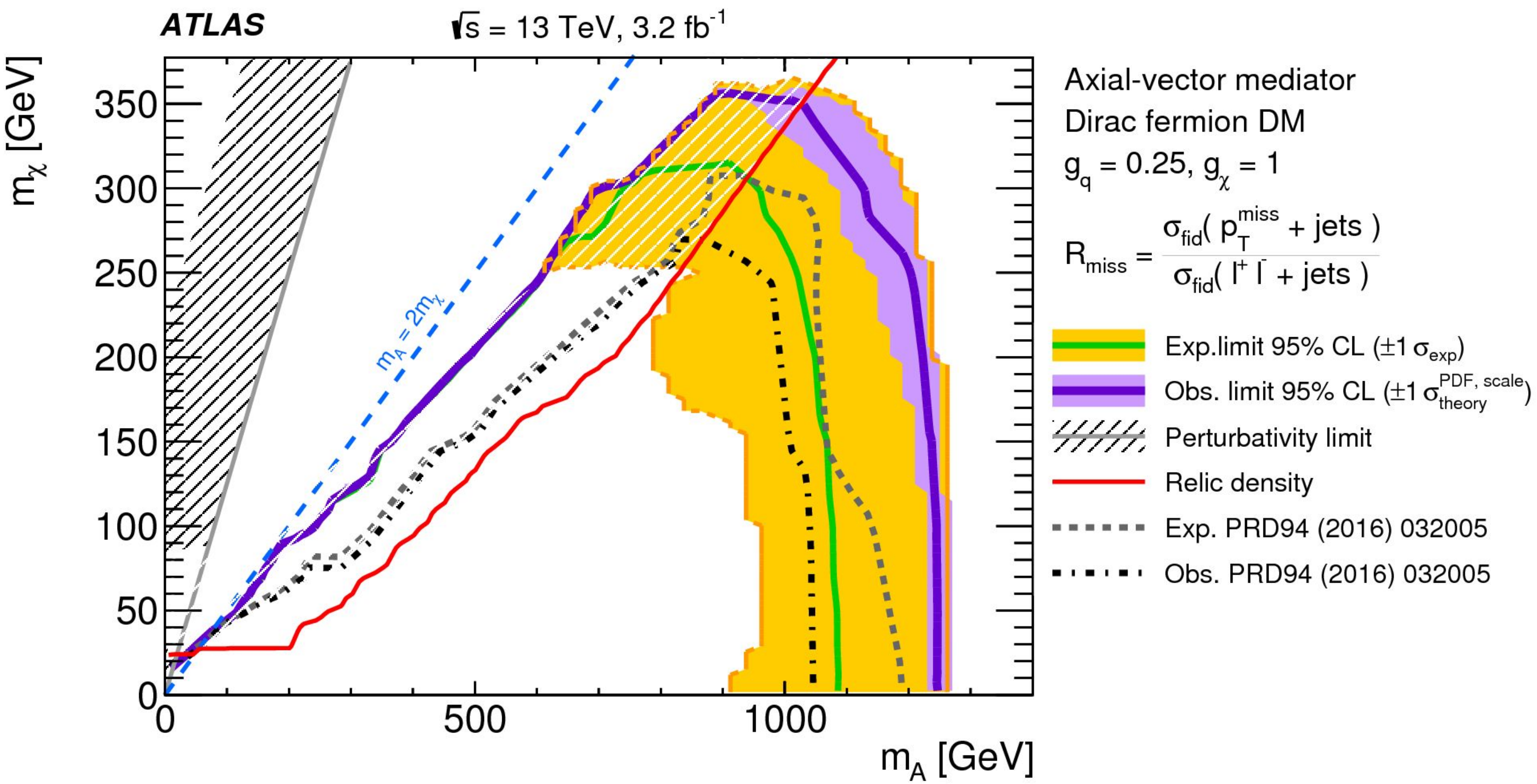
VBF



VBF



Interpretations: Dark Matter



S-channel WIMP production

- Scan over mediator mass and DM mass
- Limits competitive with existing reconstruction-level analysis in mono-jet final state
- Use 95% CLs method and include correlations between all bins of all distributions in covariance matrix

What have we done?

- Four Lepton Mass Spectrum
- Met + jets cross-section ratio
- **Re-interpretation: CONTUR**

[Arxiv:1606.05296]
[contur.hepforge.org]

[JHEP 04 (2019) 048]

[Eur. Phys. J. C 77 (2017) 765]

Re-interpreting

Rivet routine:

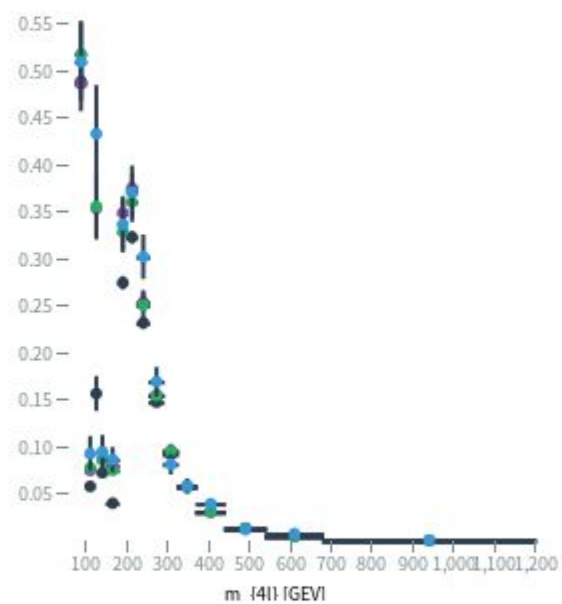
- Truth-level implementation of the analysis cross-checked against the code used for the paper available online: [ATLAS_2019_I1720442.tar.gz]
- Can take particle-level input and read measurements and predictions used directly from

Hepdata:

- Online storage of ***detector-corrected measurement***, ***particle-level predictions***, ***covariance matrices*** (split into statistical, systematic and background sources)
  https://www.hepdata.net/record/ins1720442

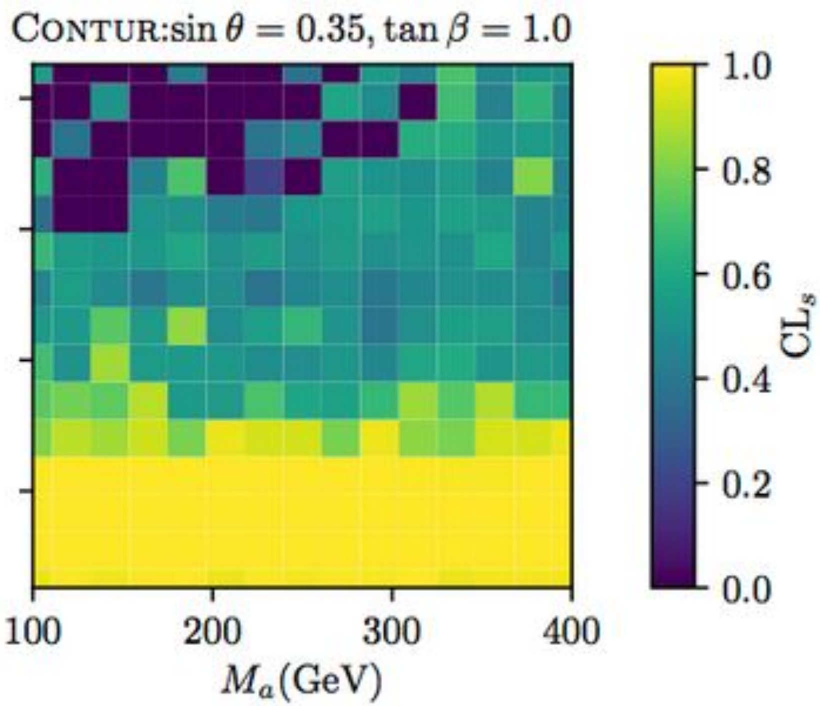
SQRT(S)	13000 GEV			
m_{4l} [GEV]	**Measured** $d\sigma/dm_{4l}$ **[FB GEV-1]**	**Predicted** $d\sigma/dm_{4l}$ **(with Sherpa + NLO EW) [FB GEV-1]**	**Predicted** $d\sigma/dm_{4l}$ **(with Powheg + NLO EW + NNLO QCD) [FB GEV-1]**	**Pred** $d\sigma/$ **Matr orde [FB G**
7.500000e+01 - 1.000000e+02	5.100341e-01 ±2.346437e-02 syst ±3.442822e-02 stat	5.182588e-01 ±3.545342e-02 total	4.865038e-01 ±2.906800e-02 total	4.892 ±6.45 total
1.000000e+02 - 1.200000e+02	9.334923e-02 ±4.205973e-03 syst ±1.800903e-02	7.834322e-02 ±4.277496e-03 total	7.545697e-02 ±3.490459e-03 total	5.855 ±1.10 total

Visualize

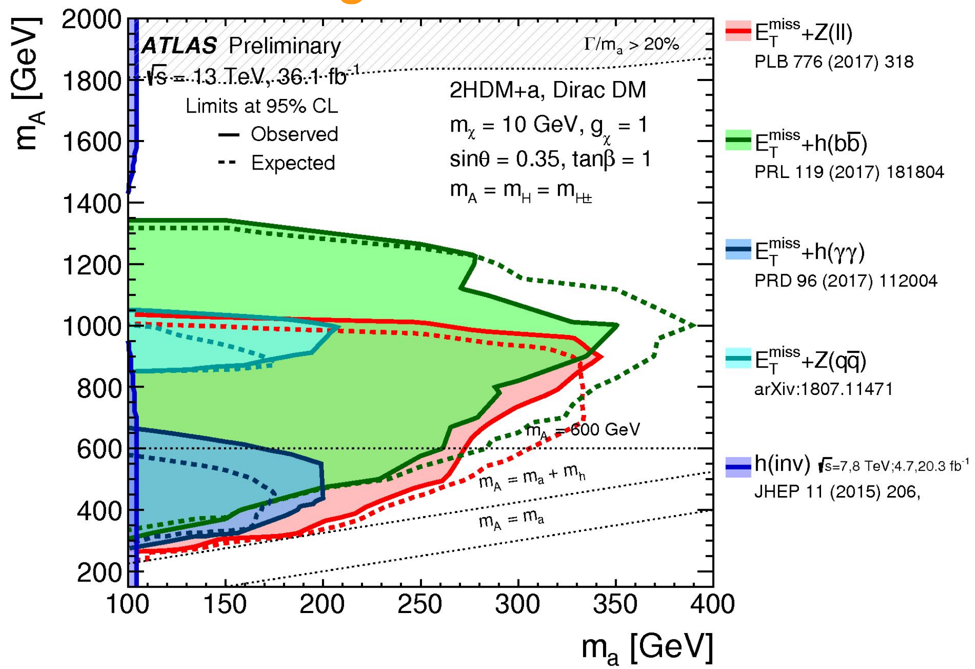


CONTUR 2HDM example

Combined Contur Sensitivity



Existing Search Limits



- Key sensitivity here comes from H→ WW measurements
- Can combine results from multiple measurements (best in each bin is used to avoid any correlation)
- Easy to make changes to the model and re-run: results for varying other parameters on web page

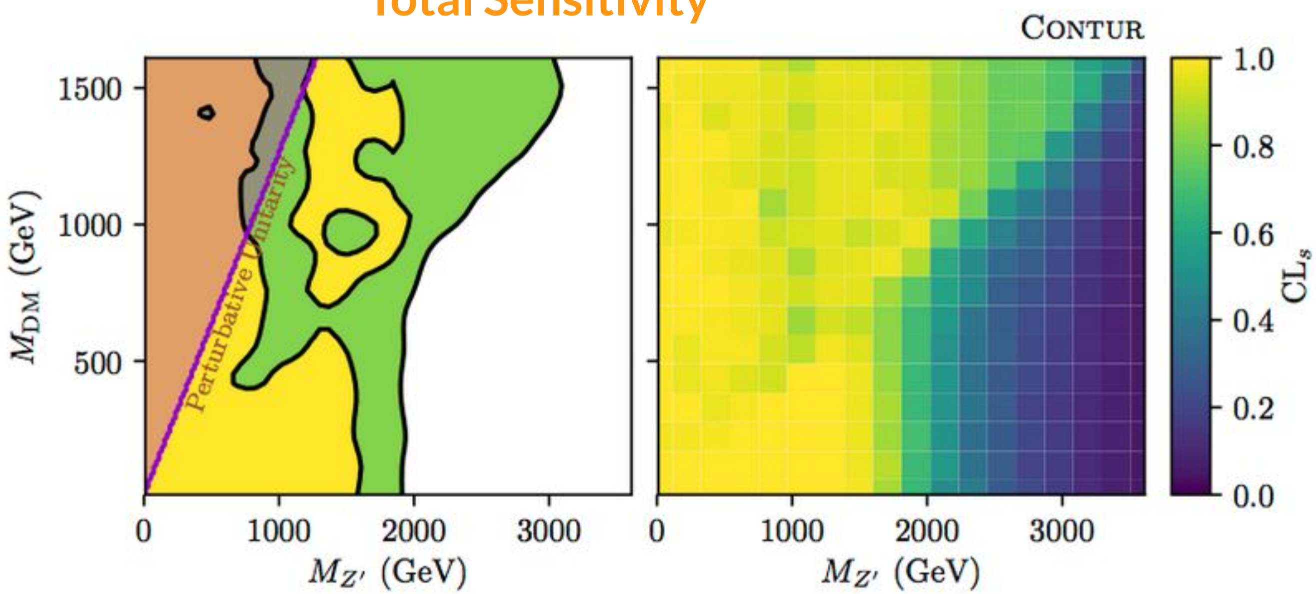
Two Higgs-Doublet Dark Matter Model with Pseudoscalar Mediator:

- A and a are 2 of 5 Higgs bosons. All other additional Higgs' have the same mass as A.
- a plays the role of mediator to dark matter
- DM candidate has mass of 10 GeV
- Taken from [Pseudoscalar_2HDMGitRepo]

https://contur.hepforge.org/results/Pseudoscalar_2HDM/index.html

Met + jets example

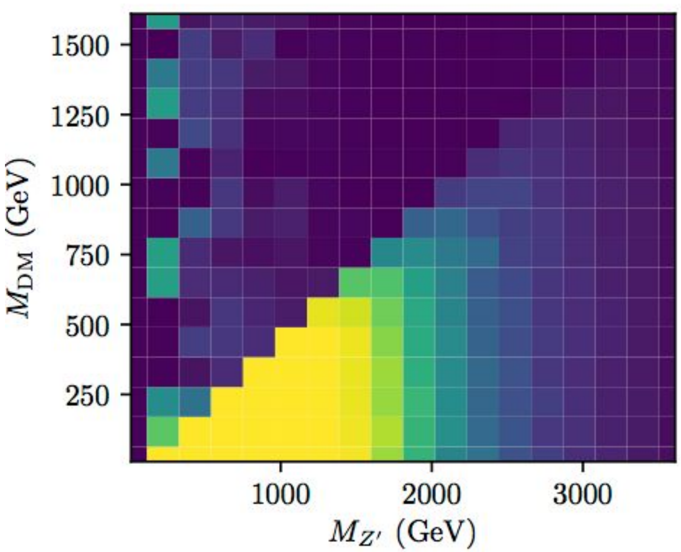
Total Sensitivity



Simplified DM model

- DM Majorana fermion Ψ interacts with SM particles via new vector particle **Z'**
- Four free parameters:
  - $M_{Z'}, M_{DM}$
  - g_q, g_{DM}

Met + jets contribution

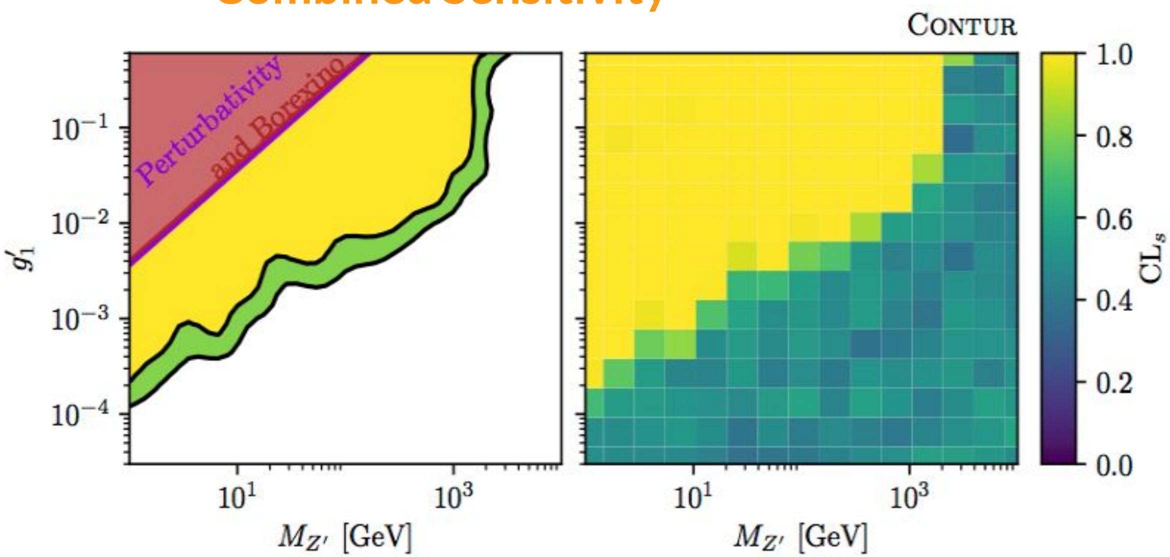


- Can split sensitivity into individual measurements
- Met + jets analysis contributes in unique phase-space
- Significant contributions in other regions come from vector boson + jets and di-jet measurements

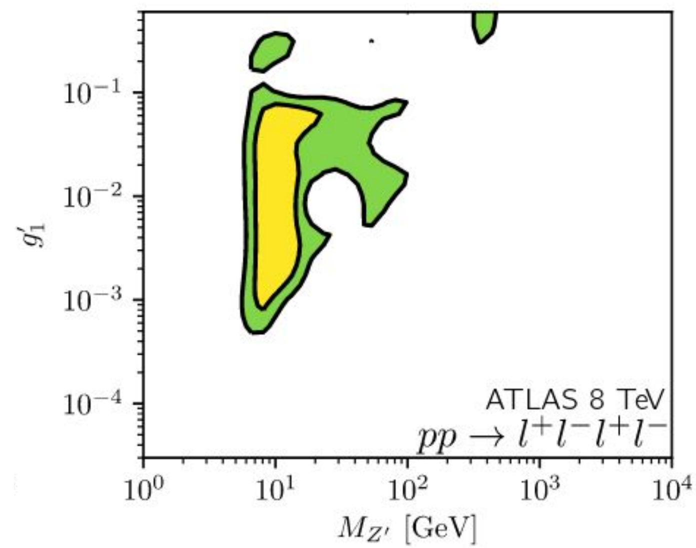
https://contur.hepforge.org/results/simplevdm1g/index.html

M_{4l} example

Combined Sensitivity



Four Lepton Sensitivity



Spontaneously broken B-L gauge symmetry:

- Broken by additional SM singlet Higgs
- Also has additional heavy neutrinos and new gauge boson **Z'**
- Additional free parameters:
  - $M_{Z'}$, $g_{1'}$
  - M_{h2}, $\sin\alpha$
  - M_{Ni}, V_{lN}

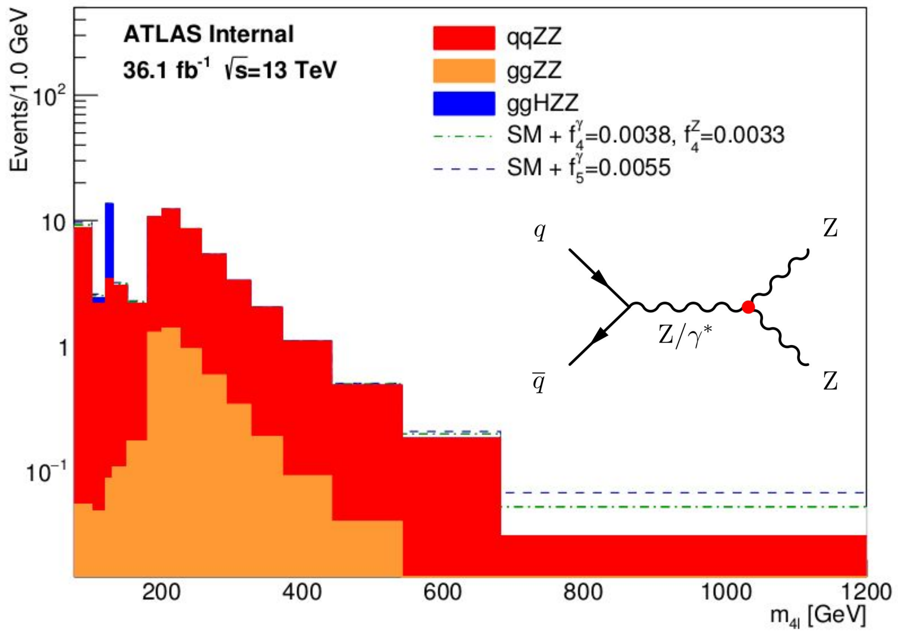
- Provides good example where four lepton analysis can provide sensitivity
- Many scenarios can produce multiple leptons in final state
- Easy to test new scenarios with this framework

LHC Constraints on a B-L Gauge Model using Contur: S. Amrith, J. M. Butterworth, F. F. Deppisch, W. Liu, A. Varma, and D. Yallup

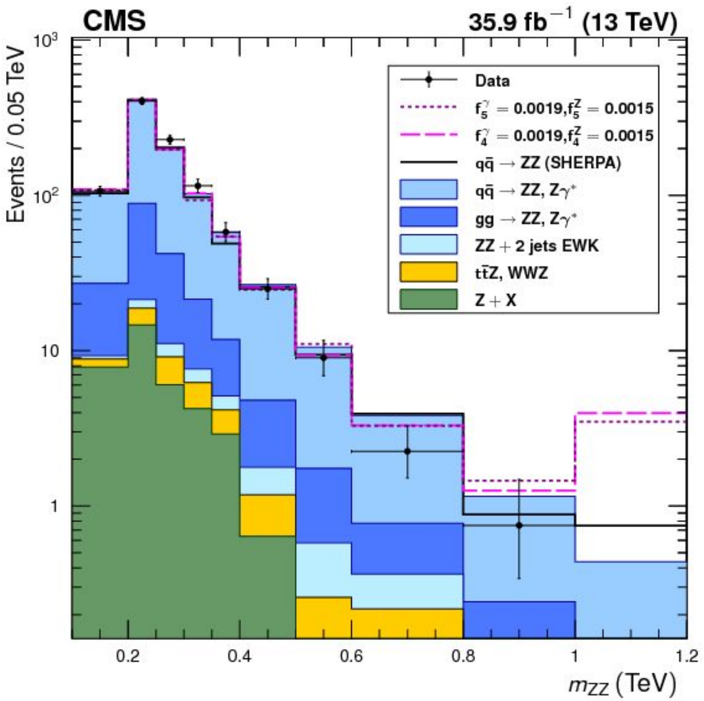
Limitations & how we can we improve

Binning, statistics and sensitivity

M_{4l} Binning

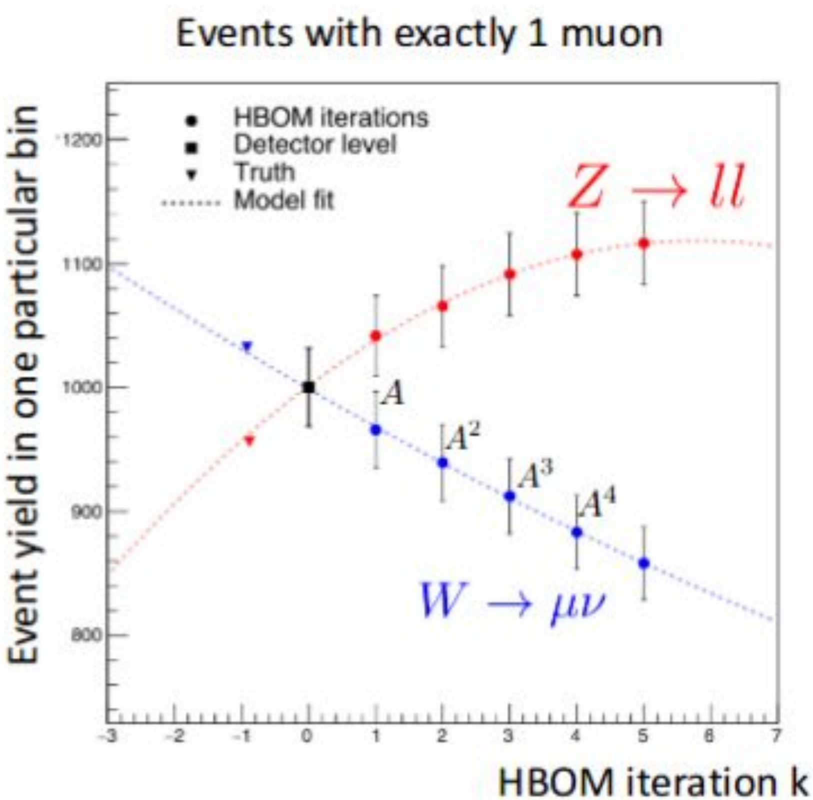


Reco-level CMS result



- To maintain validity of unfolding and limit setting bins require:
    - Small migrations
    - At least ten expected events per bin (inter-related with purity)
- Will bin more finely in future → increase statistics with increased luminosity and more common final states
- Some regions limited by detector resolution

SM-BSM Kinematic Differences



HBOM: Hit Backspace Once More

- Iteratively (k times) apply operator encapsulating effect of ATLAS detector → try and remove effect of ***lepton inefficiencies***

$$N^{reco}(k) = A^k(N^{reco})$$

- **Doesn't matter if BSM signals have different lepton kinematics to SM**
- Still need to use some standard unfolding to correct for other effects

Difficulties

- Some complications for complex final states if fiducial and reconstructed selection differs
- Investigating whether these can be comatted using "hybrid" selection using truth leptons and reconstructed selection for all other objects e.g. jets

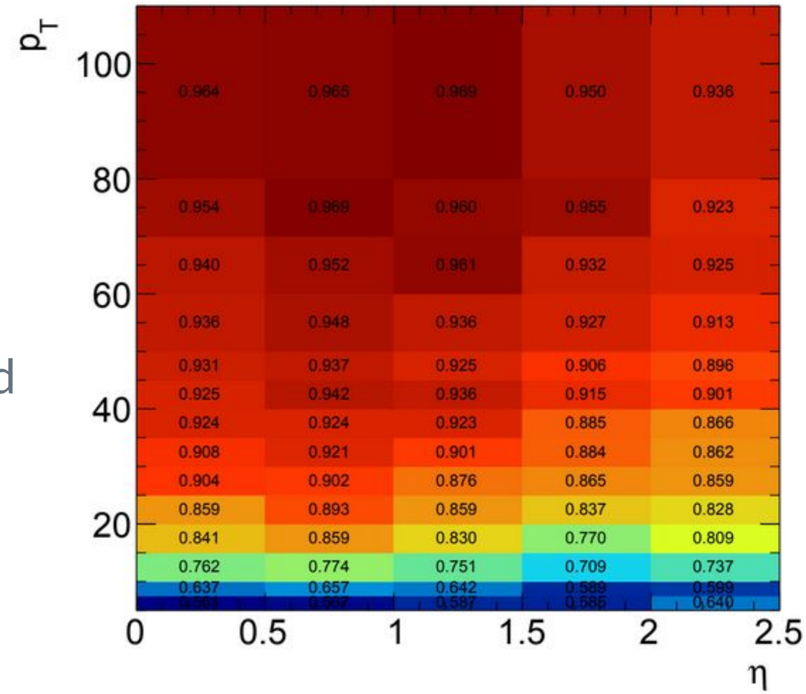
[HBOM method for unfolding detector effects: J Monk and C Oropeza-Barrera]()

A simpler method?

Pre-unfolding:

- Use data-driven methodology to ***remove per-lepton inefficiencies*** as a function of relevant kinematics before unfolding
- Investigating in **m_{4l}** analysis - measure efficiencies separately for electrons and muons and apply inverse
- Aim to remove related SM dependence from unfolded results

Example Electron Efficiencies



- Would improve robustness to resonant signals
- Decrease uncertainty in unfolding method itself?
- Studies ongoing - need to understand how best to separate effects relating to leptons and other effects like migration

What if there's signal in our "backgrounds"?

Met + jets analysis

- **Signals producing 1 lepton:** could enter into W background estimation and would therefore be subtracted - ***cannot interpret with this measurement***
- **Signals producing 2 leptons:** can only reliably be constrained if kinematics similar to SM - ***aim to address this with previous methods***

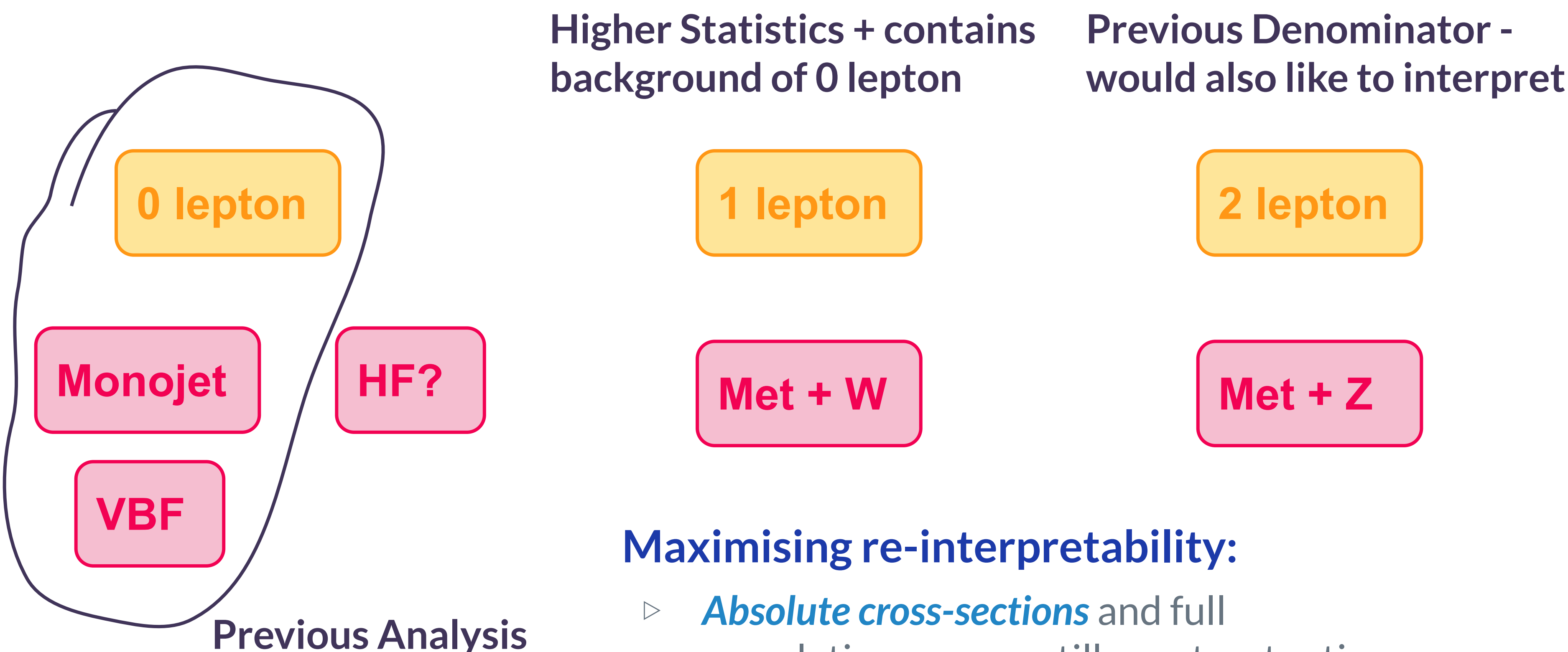
New categorised strategy

M4l analysis

- **Signals producing four leptons but not through Z boson decay** - ***no sensitivity with this measurement***

- Remove as much process-dependence as possible from new selection
- Consider irreducible backgrounds as part of signal → pre-unfolding should address lepton kinematic differences

Categorised Met + jets (+other!)

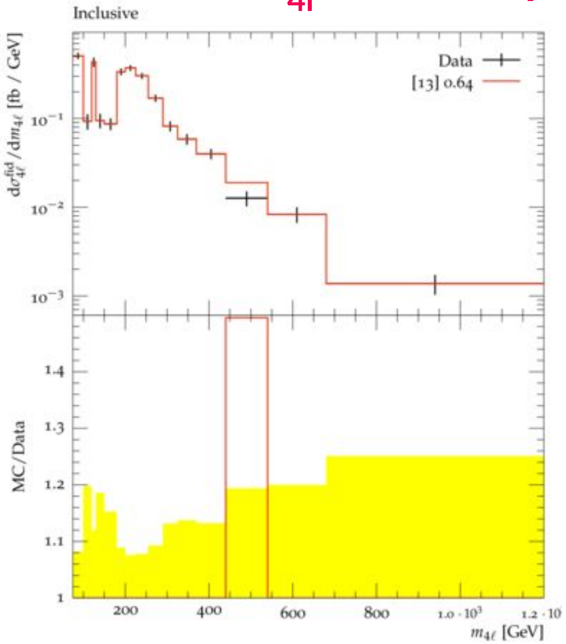


Maximising re-interpretability:

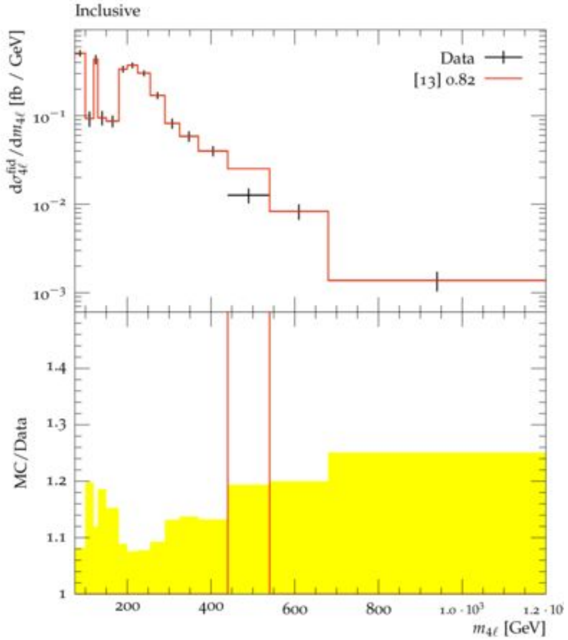
- ***Absolute cross-sections*** and full correlations → can still construct ratios
- Include ***additional unfolded regions*** → higher statistics for ratio construction, more options for interpretation
- Background-subtracted **and *inclusive*** processes

Loosening M_{4l} Cuts

Published m_{4l} Sensitivity



Sensitivity with no upper mass bound



- Current analysis makes measurement ***more inclusive*** by loosening selection as much as possible
- Includes allowing lepton pair masses to vary from Z value

Random example: B-L model from arXiv:1811.11452, $M_{Z'}$=200 GeV, M_{H2} = 450 GeV

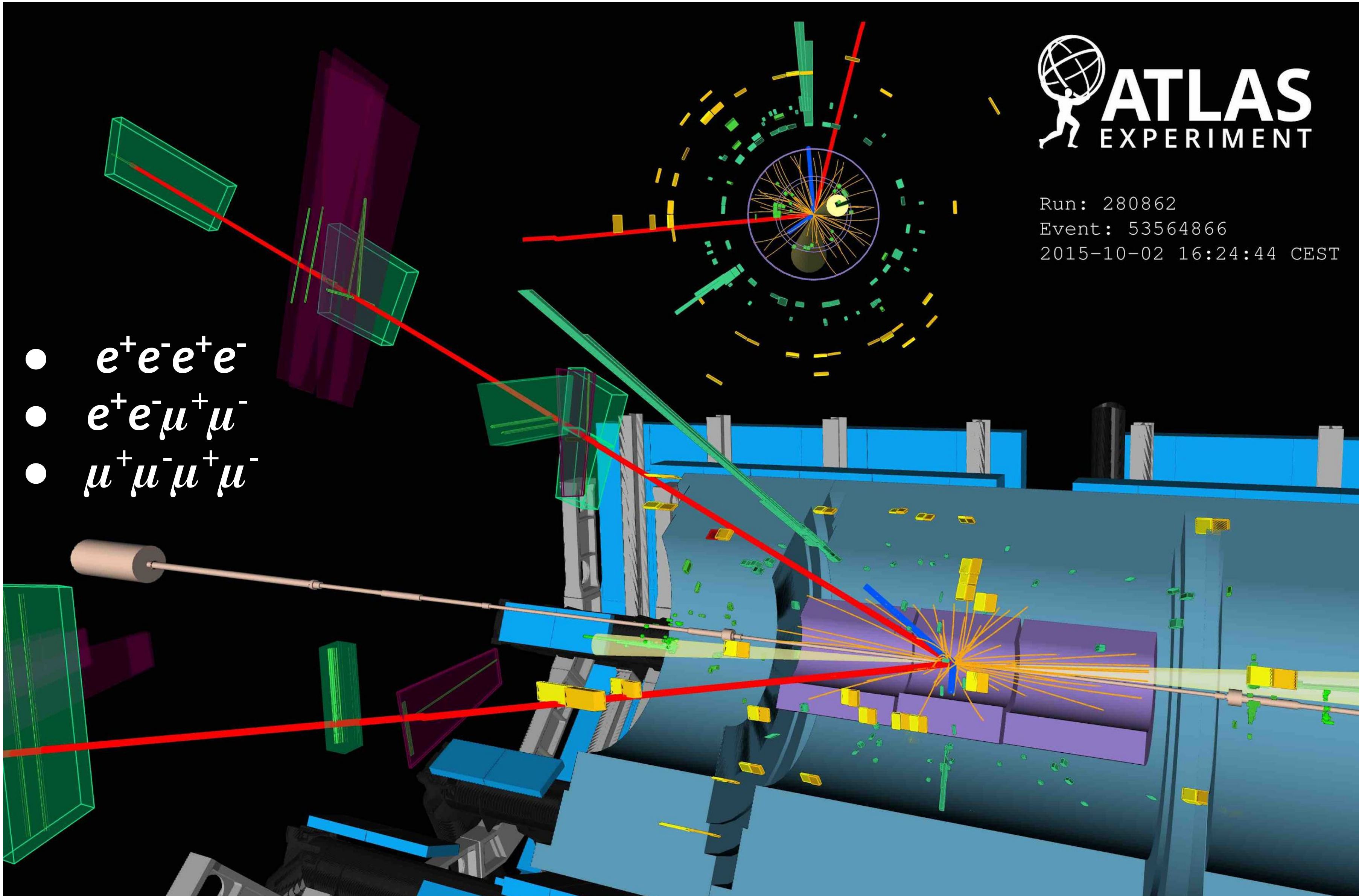
- CONTUR can also be used when ***designing*** searches/measurements
- Easy to gauge effect of simple modifications on many models without generating any detector-level MC (or run over it!)

Summary & Outlook

- Detector-corrected cross-sections easy to compare to theoretical predictions made by *anyone*
  - **Including new physics predictions!**
  - **No need to simulate detector**
  - **Fast, easy, broad parameter space scans**
- Can design SM measurements to emphasise these properties and complement existing searches
- Two examples already on to full Run 2 analyses:
  - **Four lepton mass lineshape**
  - **Met + jets cross-section analysis**
- Lots of areas for improvement, crucially;
  - **Try to correct for model dependent kinematics**
  - **Move to more inclusive measurements**
  - **Expand existing analyses to measure more!**

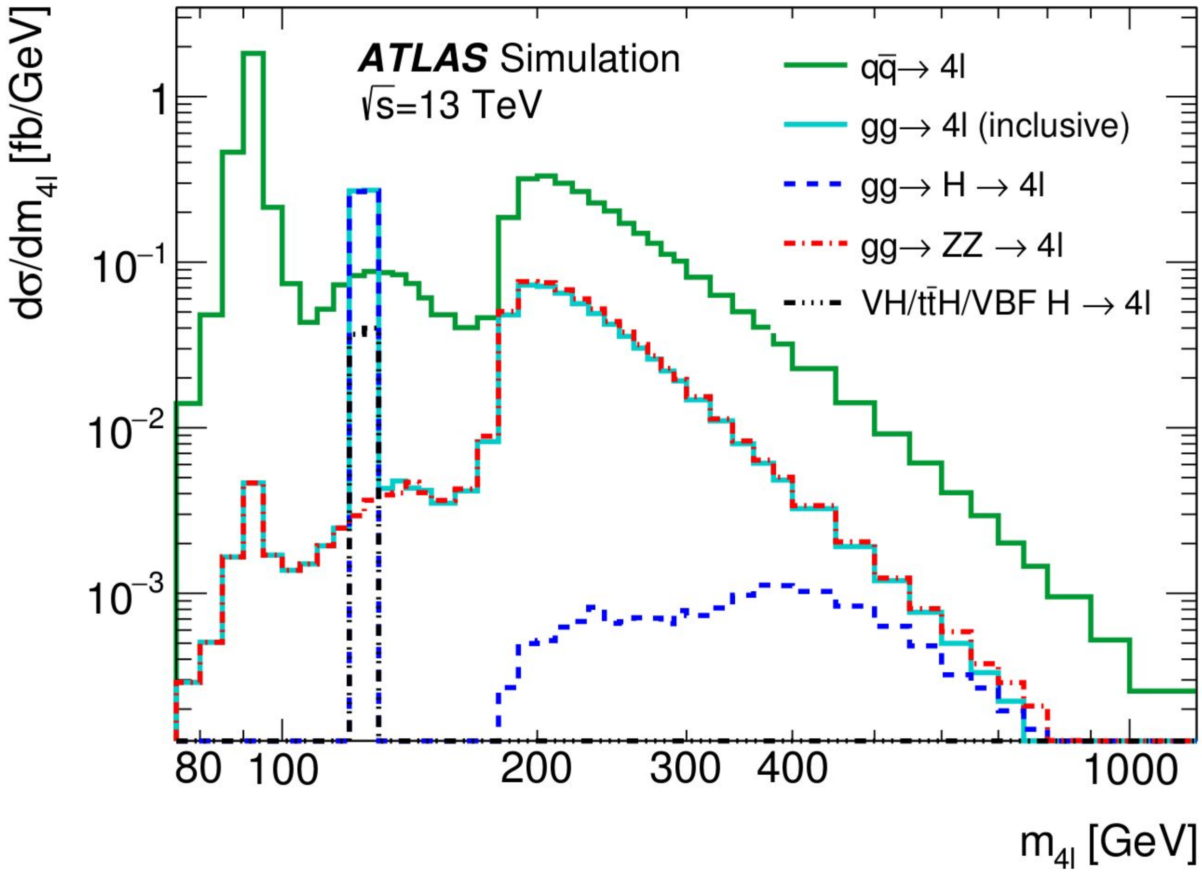
Backup

Four Lepton Events

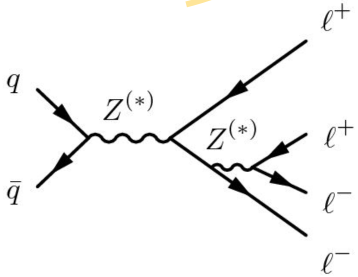


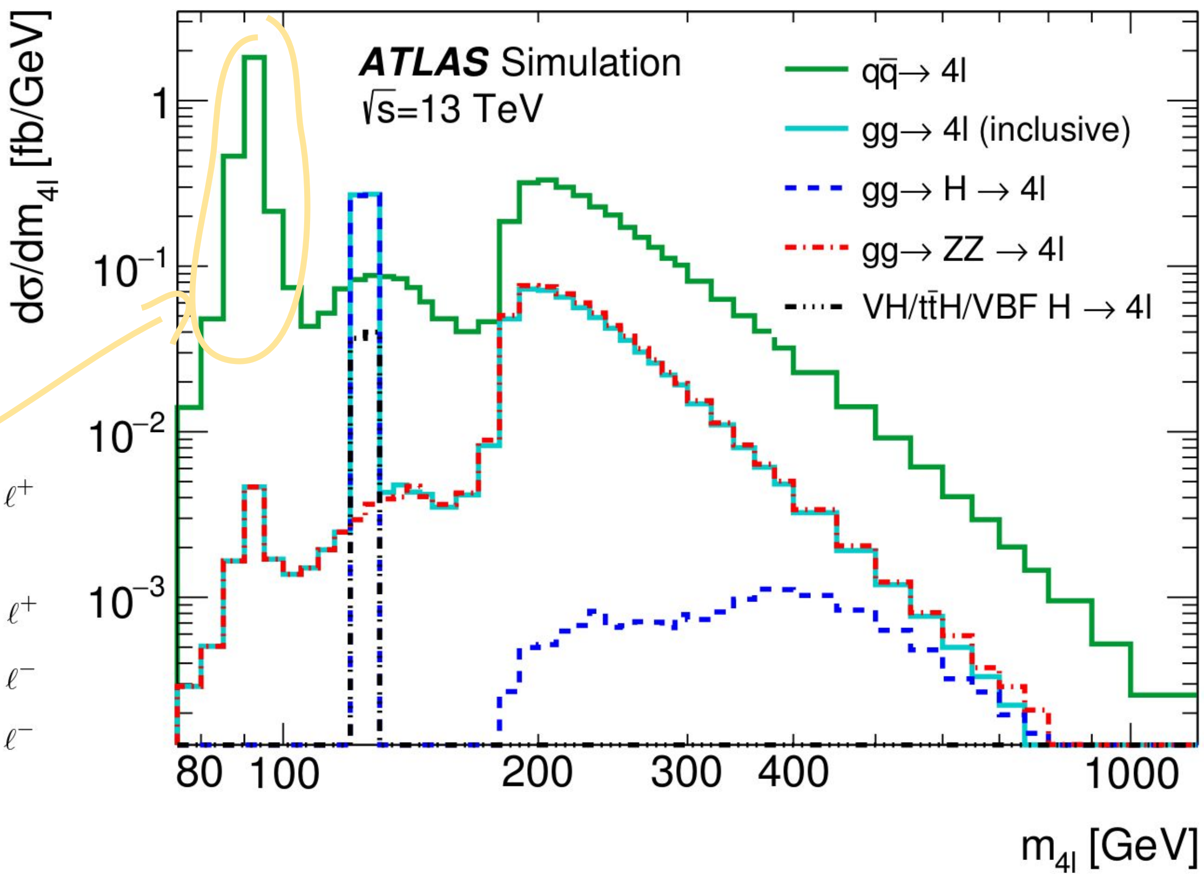
- $e^+e^-e^+e^-$
- $e^+e^-\mu^+\mu^-$
- $\mu^+\mu^-\mu^+\mu^-$

Four Lepton Events

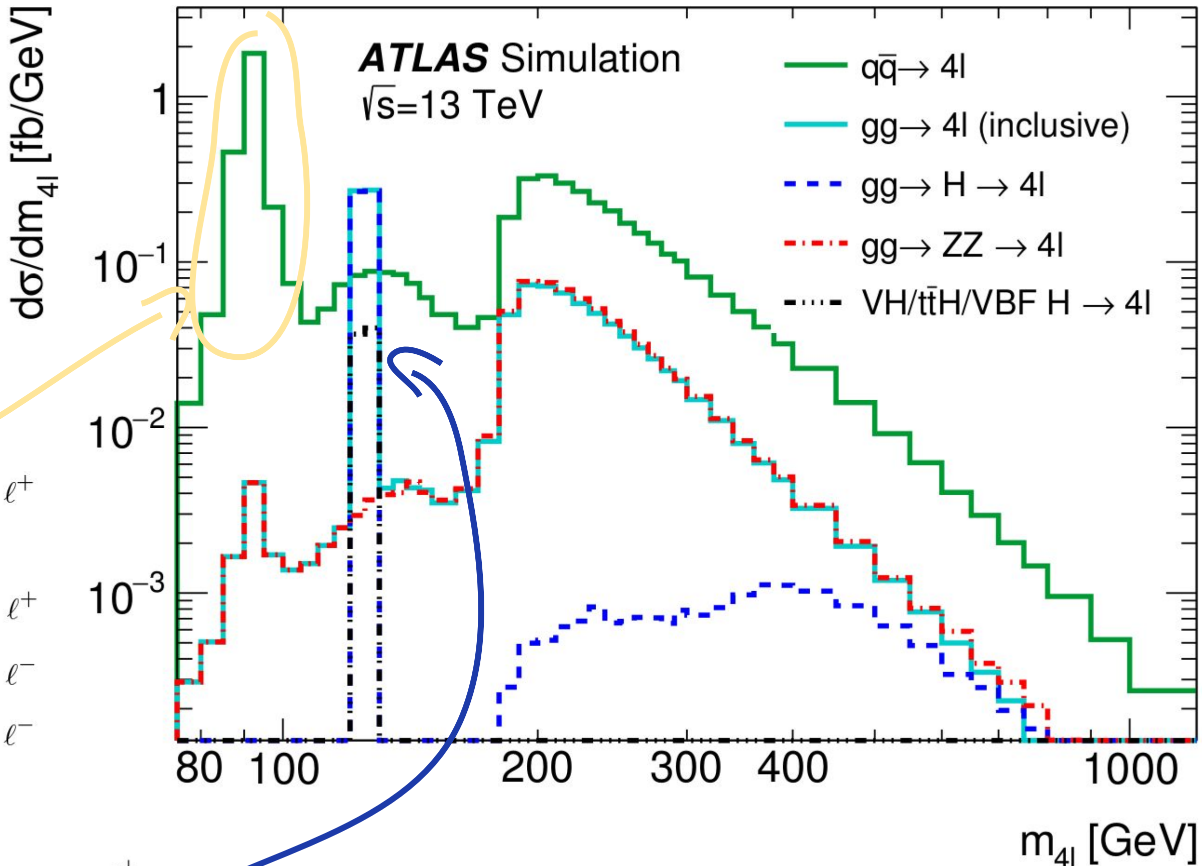


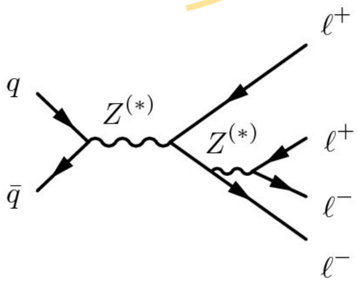
Four Lepton Events

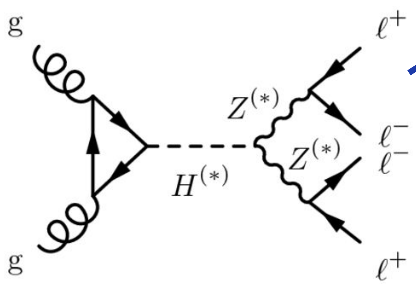




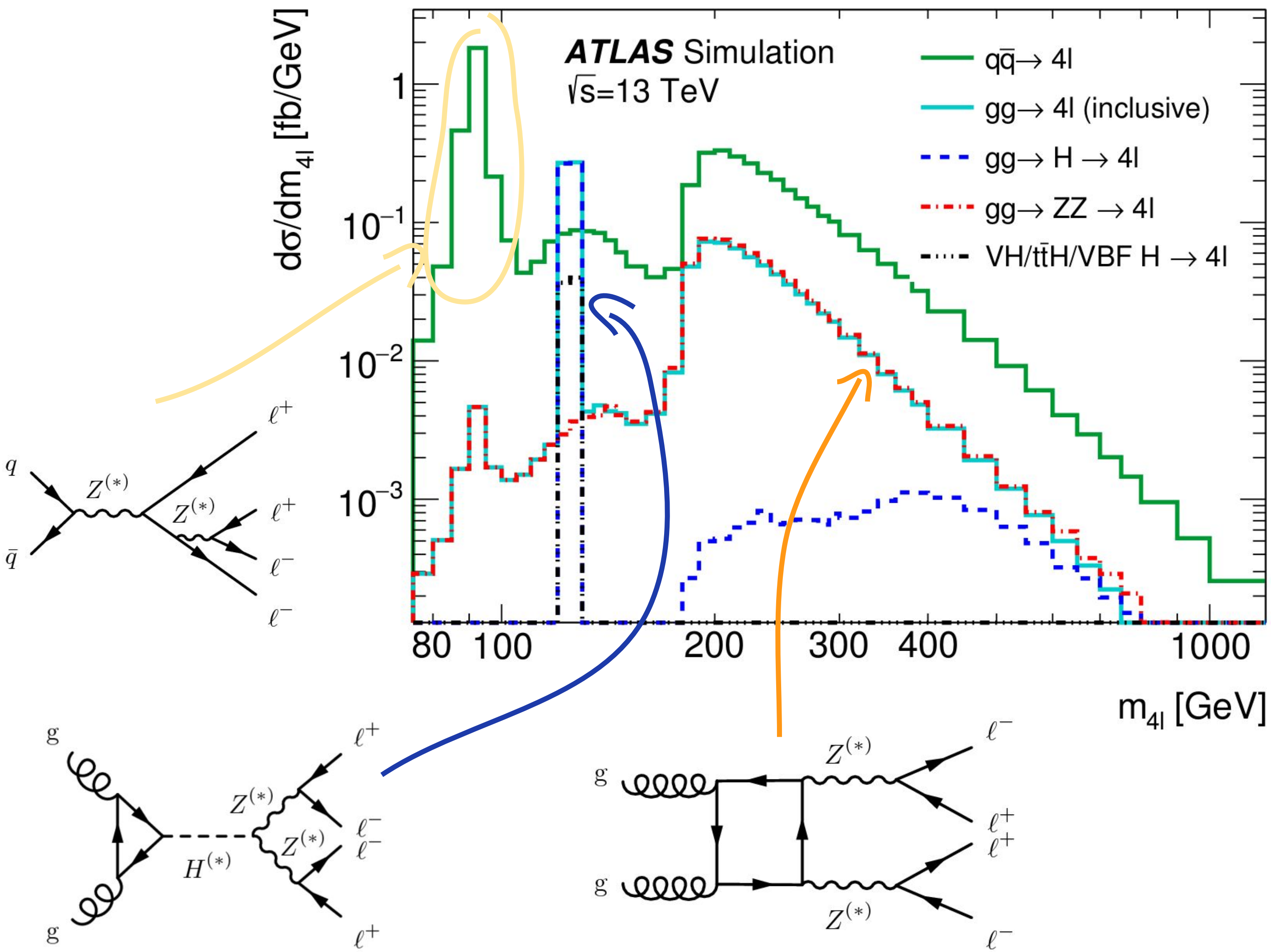
Four Lepton Events







Four Lepton Events



Reconstruction-level selection

Physics Object preselection		
	ELECTRONS	MUONS
Identification	*Loose* working point [23]	*Loose* working point [22]
Kinematics	$E_{\mathrm{T}} > 7$ GeV and $\lvert\eta\rvert < 2.47$	$p_{\mathrm{T}} > 5$ GeV and $\lvert\eta\rvert < 2.7$ $p_{\mathrm{T}} > 15$ GeV if calorimeter-tagged [22]
Interaction point constraint	$\lvert z_0 \cdot \sin\theta\rvert < 0.5$ mm	$\lvert z_0 \cdot \sin\theta\rvert < 0.5$ mm
Cosmic-ray muon veto		$\lvert d_0\rvert < 1$ mm

Quadruplet Selection		
QUADRUPLET FORMATION	Procedure and kinematic selection criteria as in Table ??	
LEPTON ISOLATION		
	ELECTRONS	MUONS
Track isolation	$\sum_{\Delta R \leq 0.2} p_{\mathrm{T}} < 0.15 E_{\mathrm{T}}^{e}$	$\sum_{\Delta R \leq 0.3} p_{\mathrm{T}} < 0.15 p_{\mathrm{T}}^{\mu}$
Calorimeter isolation	$\sum_{\Delta R = 0.2} E_{\mathrm{T}} < 0.2 E_{\mathrm{T}}^{e}$	$\sum_{\Delta R = 0.2} E_{\mathrm{T}} < 0.3 p_{\mathrm{T}}^{\mu}$
	Contributions from the other leptons of the quadruplet not considered	
LEPTON TRANSVERSE IMPACT PARAMETER		
	ELECTRONS	MUONS
	$d_0/\sigma_{d_0} < 5$	$d_0/\sigma_{d_0} < 3$
4ℓ VERTEX FIT		
χ^2/ndof	< 6 (4μ) or < 9 ($4e$, $2e2\mu$)	

Signal Simulation

Higgs Signal:

- Gluon fusion - Powheg NNLOPS
- Vector Boson fusion - Powheg VBFH
- Associated Boson - Powheg
- qqH - MG5_aMC@NLO

Irreducible Background:

- ttV(V) - Sherpa 2.2.1 LO scaled to NLO QCD + EWK
- VVV - Sherpa 2.1 NLO for 0 jets, LO for 1, 2 jets

Reducible Background:

- Z+jets, Sherpa NLO 0,1,2j, LO 3,4 j
- tt, WZ Powheg

qq→ ZZ:

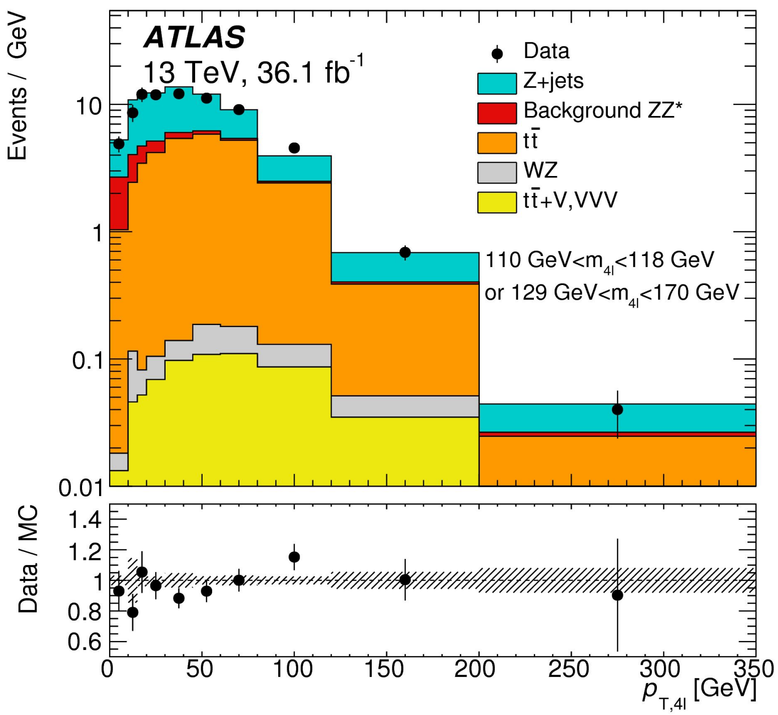
- Sherpa 2.2.2 NLO for 0,1 jets, LO for 2,3 jets, + NLO EWK corrections
- Electroweak 4l+jj Sherpa 2.2 NLO at 2 jets
- Generator cross-check samples - PowhegBox+Pythia8 + NNLO QCD + NLO EWK

gg→ ZZ:

- Sherpa 2.2 LO for 0, 1 jets, + NLO QCD + flat NNLO/NLO k-factor of 1.2
- Separate samples for process via/not via Higgs, and interference

Reducible Background Estimation

Control Region



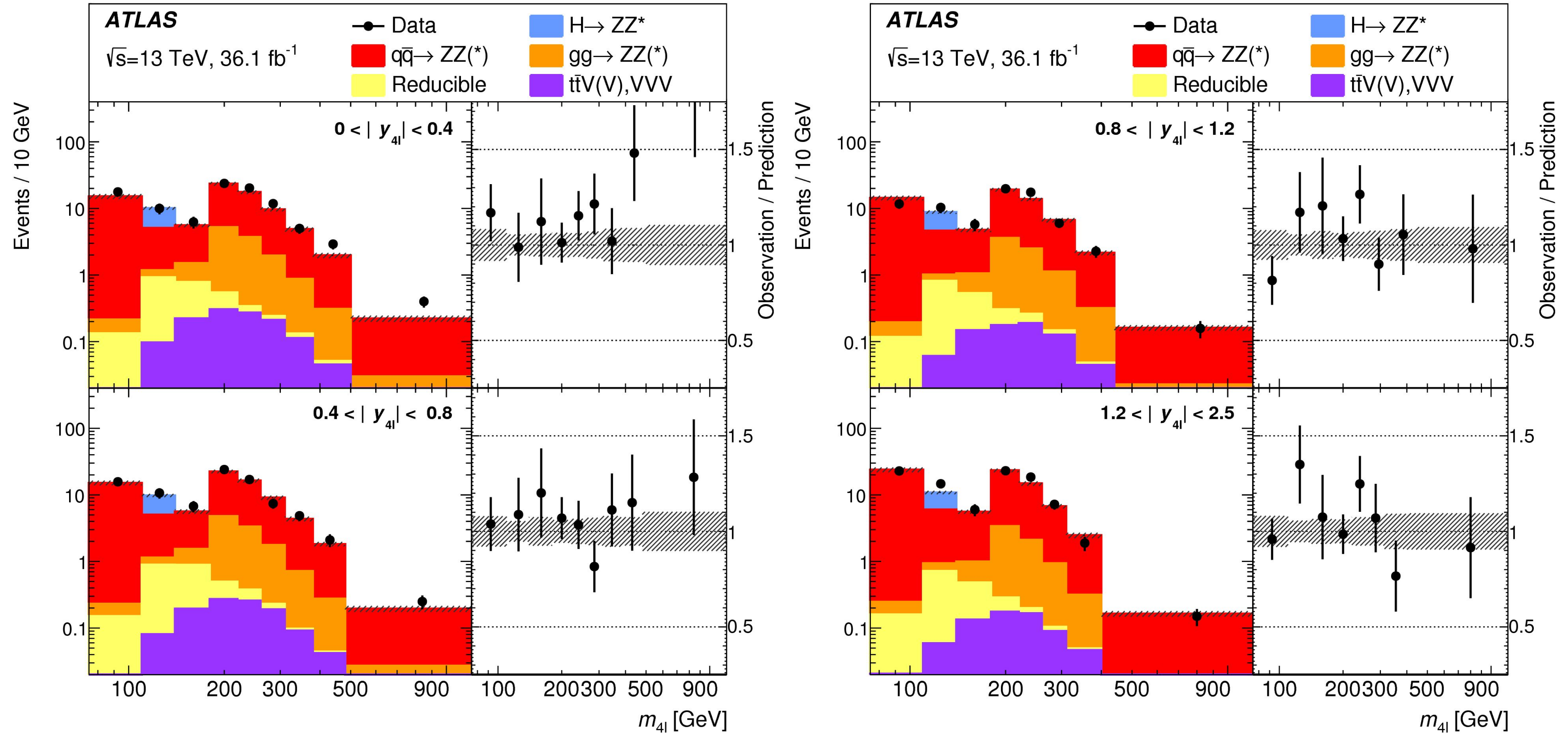
Methodology:

- Split into **ll+ee** and **ll+$\mu\mu$**
- Target processes with different efficiencies, e.g. heavy flavour and light flavour in control regions
- Reversed/relaxed/altered selections WRT signal selection
- Define **transfer factors** for yields in CRs → yields in signal region
- Shape taken from MC except for light flavour ll+ee case

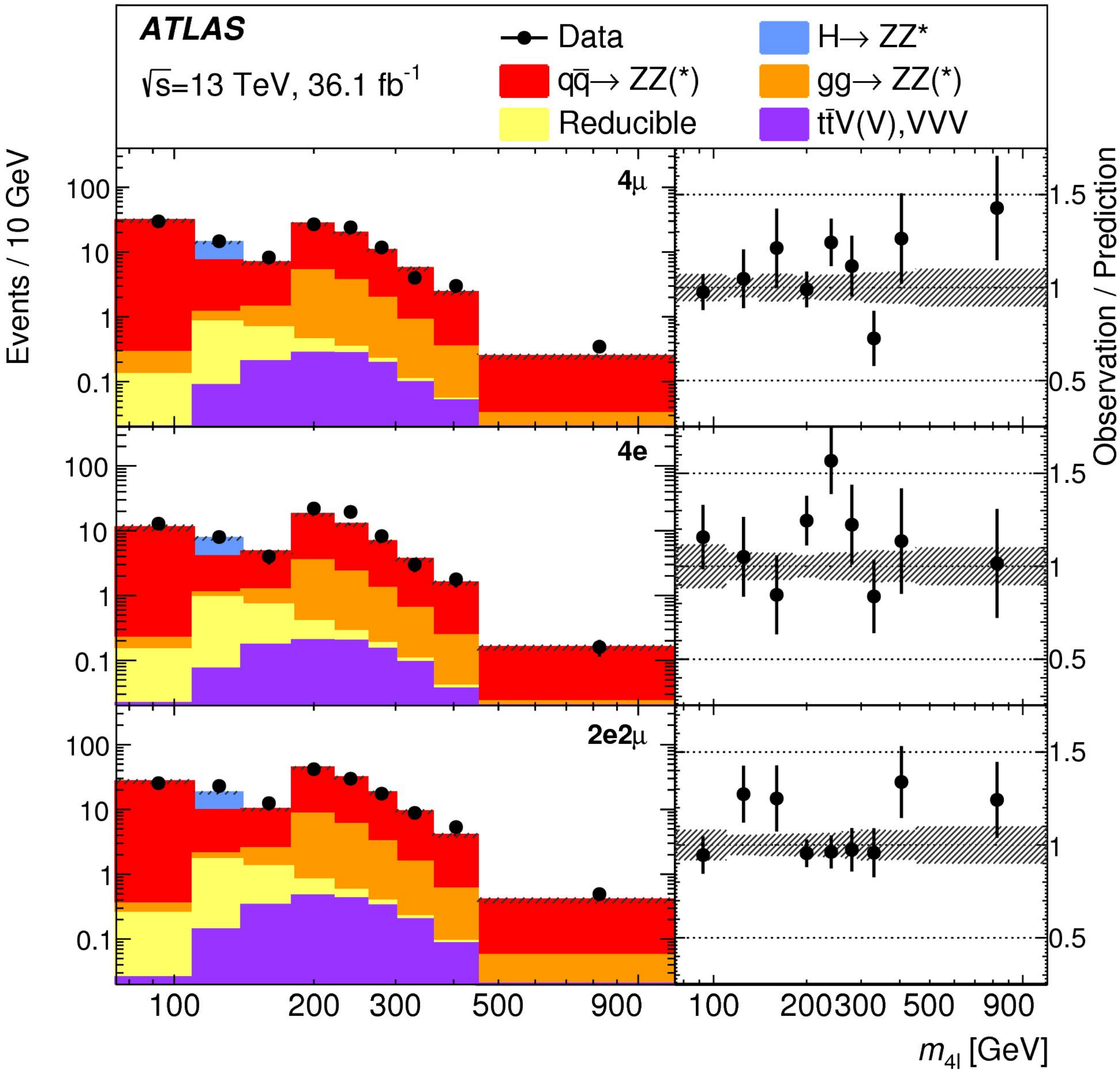
Validation:

- Loosened region to check estimation
- Compare multiple alternative methods

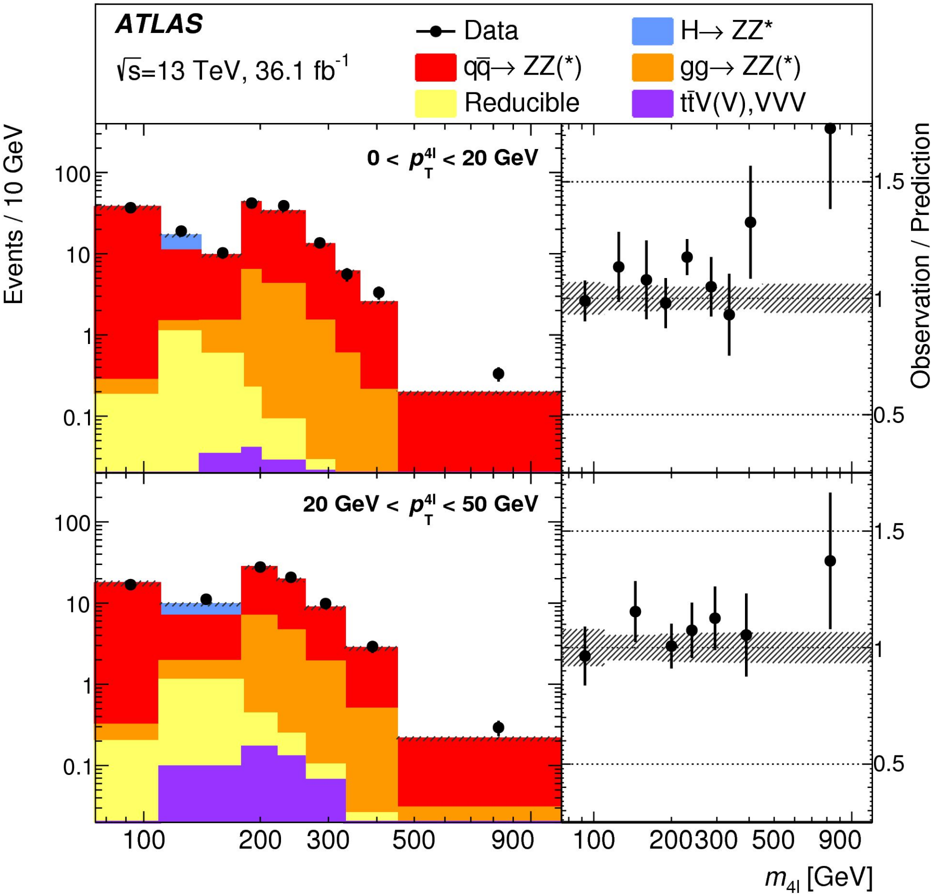
Double differential example - y_{4l}

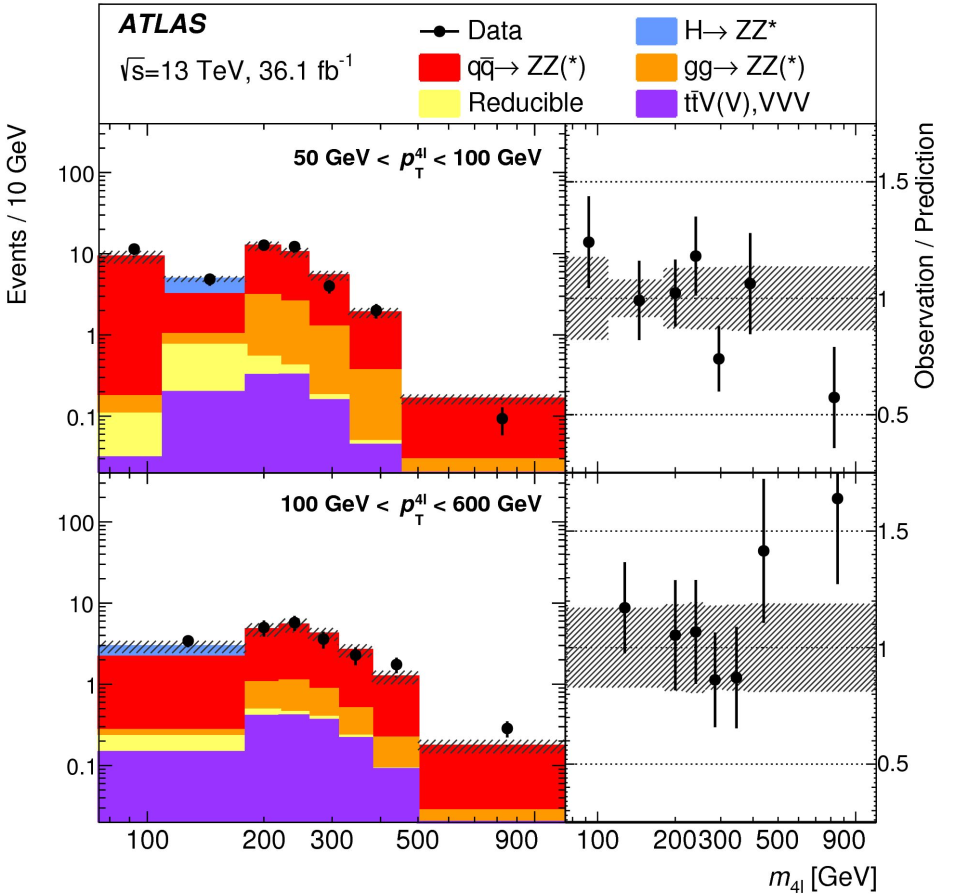


Double differential example - flavour



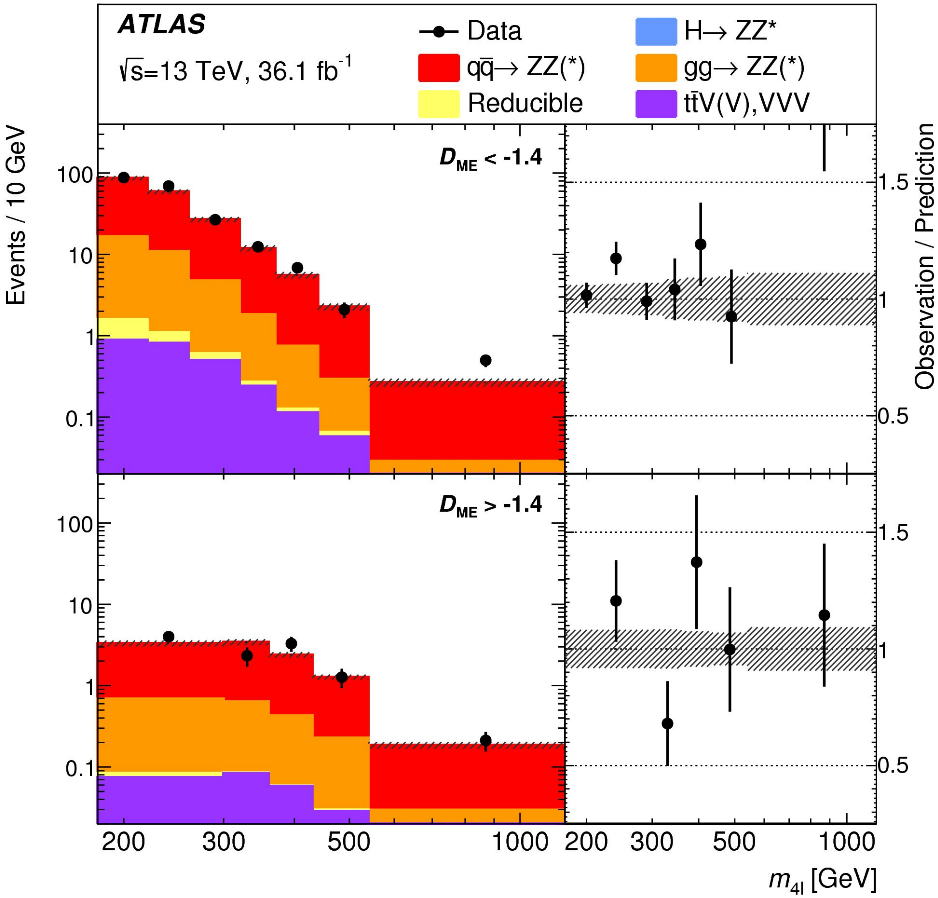
Double differential example - P_T^{4l}





Matrix element discriminant - D_{ME}

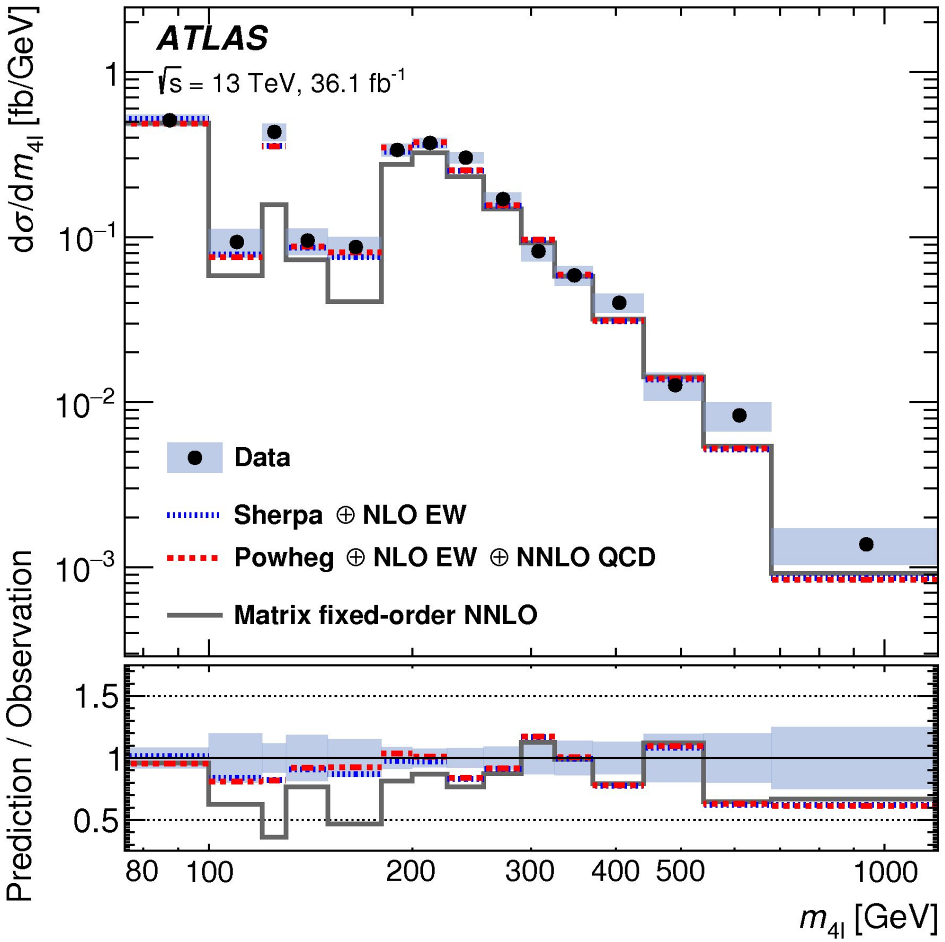
$$D_{\mathrm{ME}} = \log_{10} \frac{\tilde{M}^2_{gg\to H^{(*)}\to ZZ^{(*)}\to 4\ell}\left(p^{\mu}_{1,2,3,4}\right)}{\tilde{M}^2_{gg(\to H^{(*)})\to ZZ^{(*)}\to 4\ell}\left(p^{\mu}_{1,2,3,4}\right) + 0.1\cdot \tilde{M}^2_{q\bar{q}\to ZZ^{(*)}\to 4\ell}\left(p^{\mu}_{1,2,3,4}\right)},$$



What is it?:

- Calculated using *Z boson production angles* and *decay angles*
- Matrix element for qqZZ, ggZZ and gg→ H→ ZZ calculated in MCFM
- Can help **separate off-shell Higgs production** from other processes by splitting into two bins

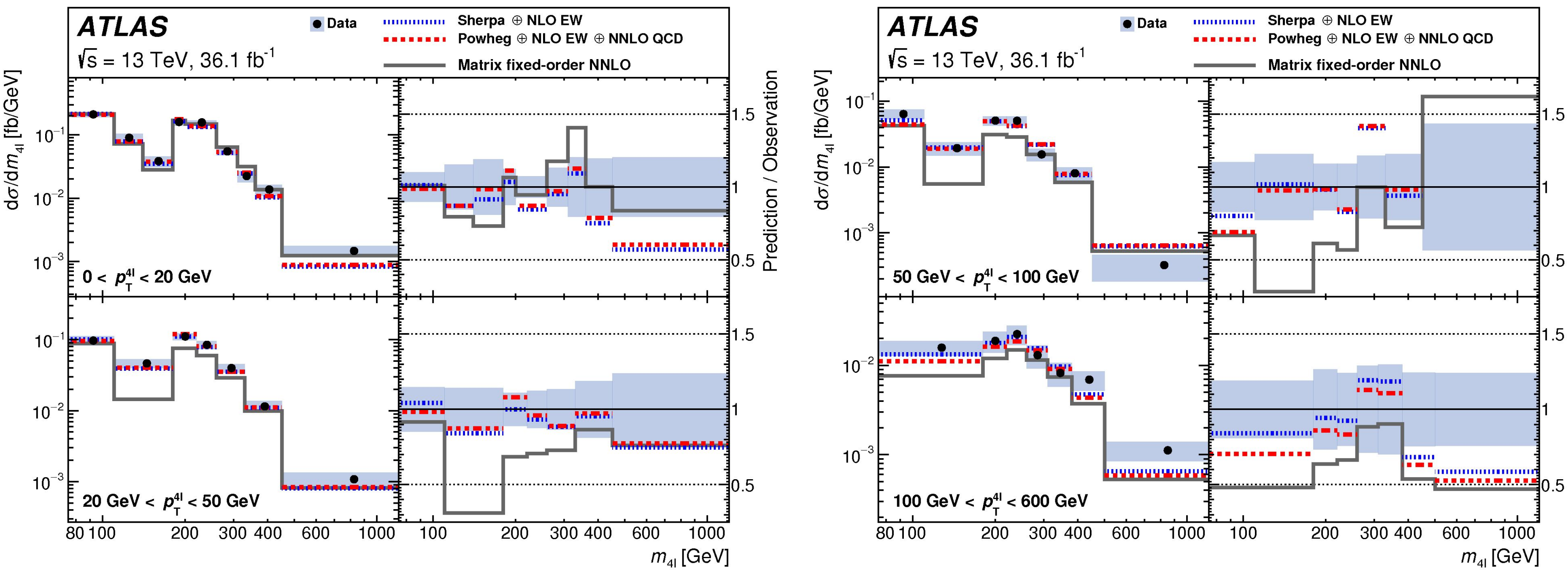
Differential Cross-sections



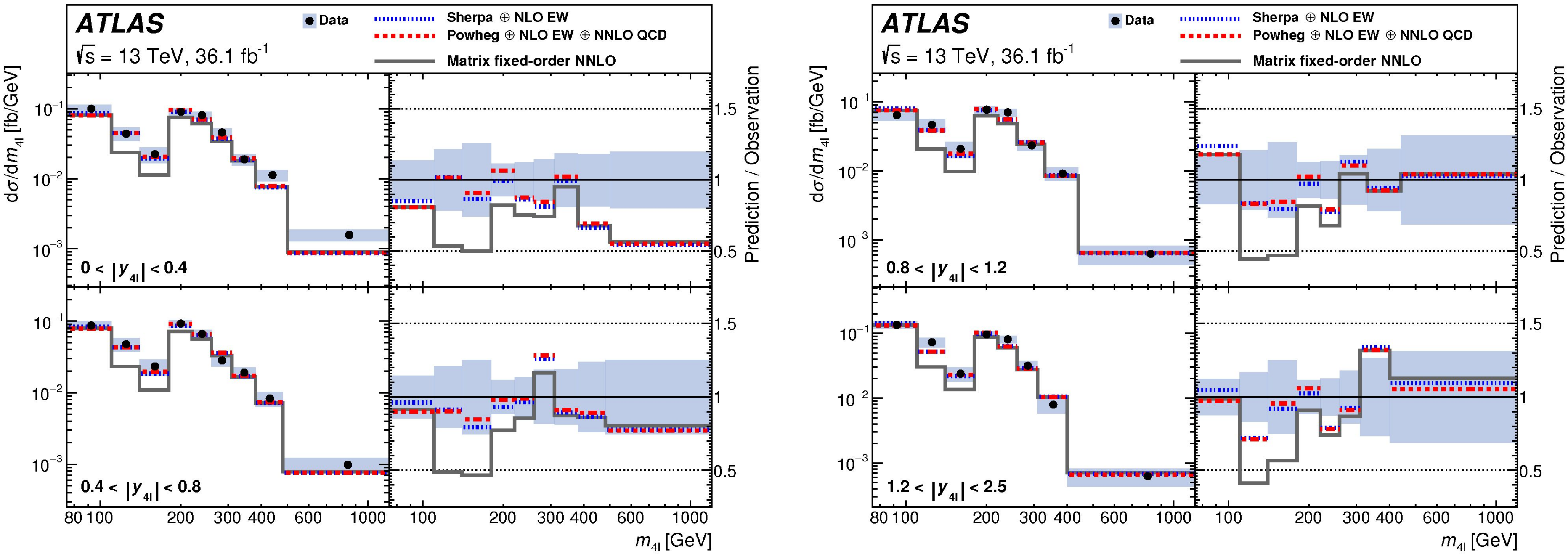
Comparison to various predictions:

- ▷ Sherpa and Powheg agree very well → validates reweighting of Powheg with MATRIX NNLO QCD k-factors
- ▷ Sherpa doesn't need this, intrinsic higher accuracy sufficient
- ▷ Missing real wide-angle QED emission in events for on-shell ZZ causes underestimation from MATRIX wrt full generators
- ▷ gg→ 4l and higgs processes are == LO for fixed-order MATRIX, whereas generators have higher order contributions → more underestimations for MATRIX

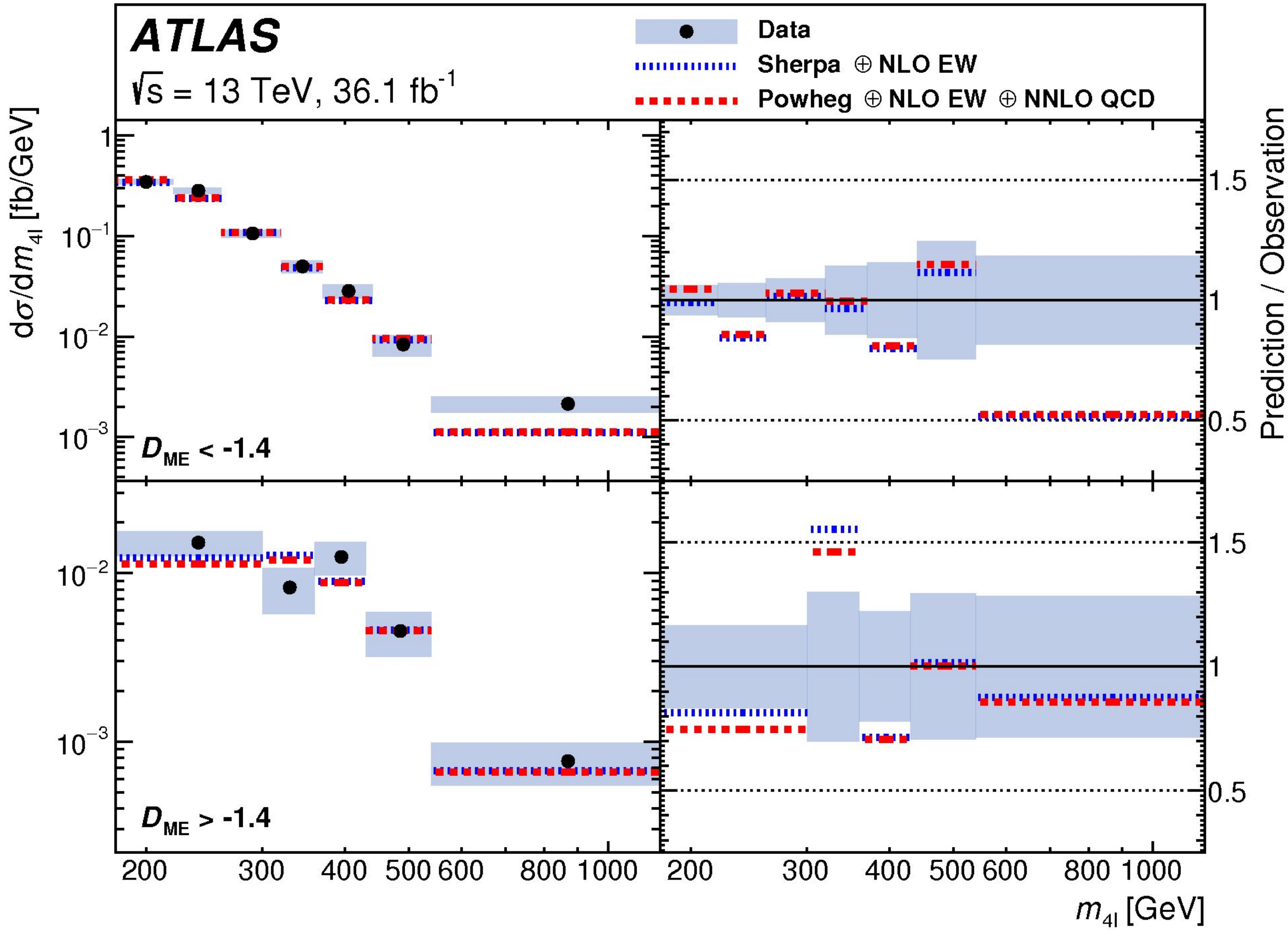
Differential Cross-sections - P_T^{4l}



Differential Cross-sections - Y_{4l}



Differential Cross-sections - D_{ME}



Statistical Procedure

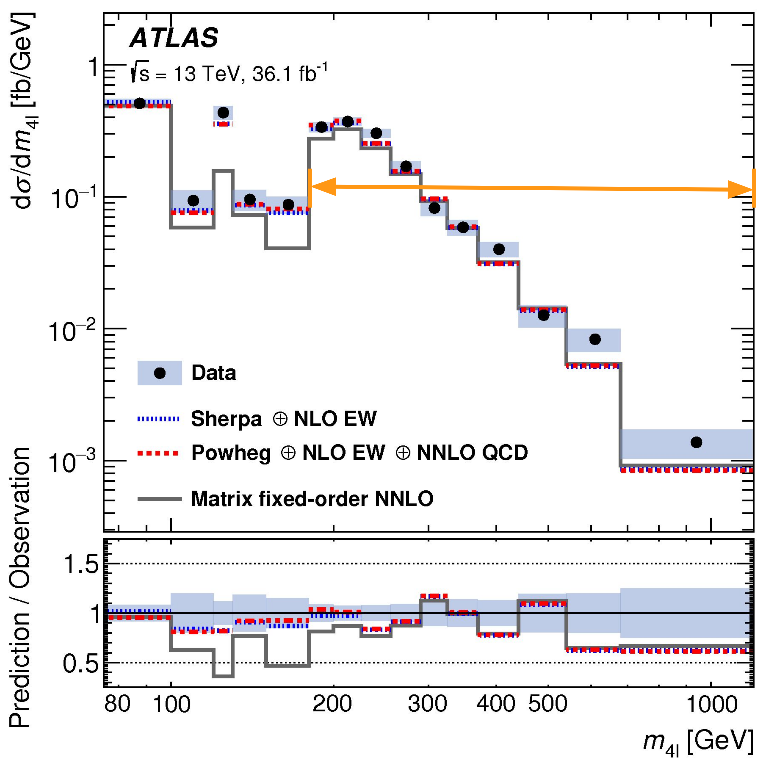
$$\chi^2 = (y_{\mathrm{data}} - y_{\mathrm{pred}})^{\mathrm{T}} C^{-1} (y_{\mathrm{data}} - y_{\mathrm{pred}}).$$

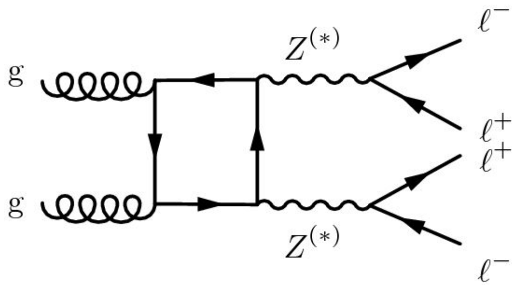
- Use **chi-squared function** as exponential component of Gaussian likelihood quantifying agreement between data and prediction.
- Predicted values are a function of the **parameter of interest (POI)** and **nuisance parameter (NP)** used for uncertainty sources.
- The covariance matrix is *scaled* dependent on the POI and NP to account for this.

$$C(i,j) = R_i \times R_j \times C^{\mathrm{SM}}_{\mathrm{syst}}(i,j) + \sqrt{(R_i \times R_j)} \times C^{\mathrm{SM}}_{\mathrm{stat}}(i,j) + C^{\mathrm{SM}}_{\mathrm{bkg}}(i,j)$$

- **$R_K = N_K^{pred}(POI,NP)/N_K^{pred}(POI=SM, NP=0)$** quantifies the scaling.
- Contributions from the systematic, statistical and background uncertainties.
- Theory uncertainties don’t enter the covariance matrix but have an NP each for shape, and for normalisation.
- Limits are set with **CL_S** method with a confidence level of 95%.

Gluon-induced production signal strength





Measured: 1.3±0.5

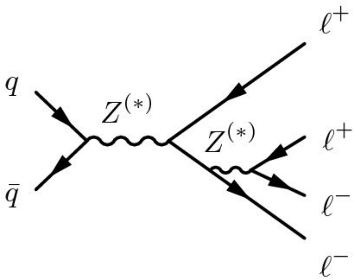
Expected: 1.0±0.4

Interpretation:

- Larger contribution once both Z's can be on-shell → *use bins above 180 GeV*
- M_{4l} distribution has NLO QCD available (other distributions give consistent results)
- qqZZ→ 4l fixed to prediction
- gg→ 4l prediction scaled by signal strength (*measured xsec/SM predicted xsec*) in a scan
- Predictions can vary within theoretical uncertainties using NPs

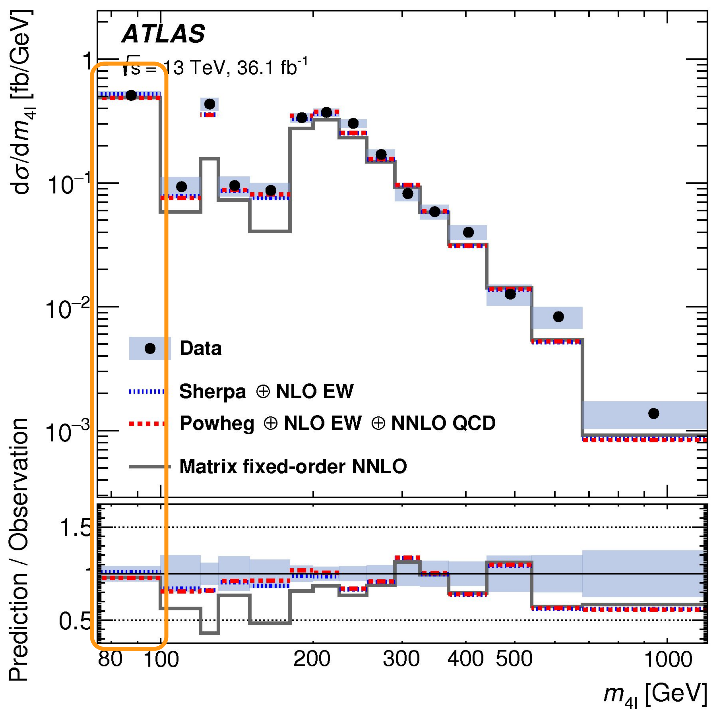
Z→ llll branching fraction

$$\mathcal{B}_{Z\to 4\ell} = \frac{N_{\text{fid}} \times (1 - f_{\text{non-res}})}{\sigma_Z \times A_{\text{fid}} \times \mathcal{L}}$$



Interpretation:

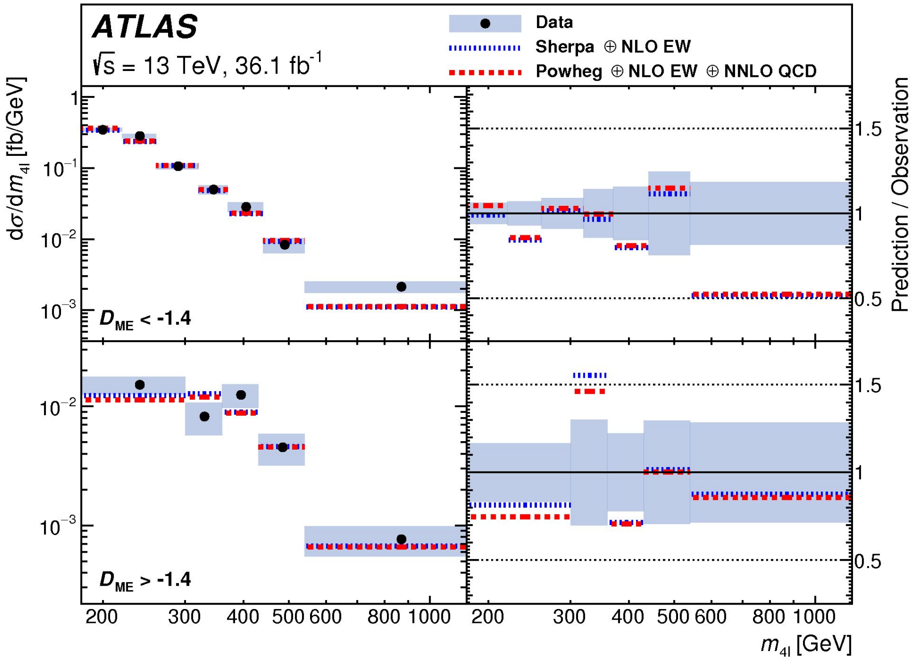
- N_{fid} is number of detector corrected events in first bin
- $f_{\text{non-res}}$ is the fraction of non-resonant events in this bin
- σ_Z is total Z production cross-section
- $\mathcal{L}$ is the luminosity
- A_{fid} is the acceptance



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

Measured σ_z taken from https://arxiv.org/abs/1603.09222

Off-shell Higgs signal strength



Interpretation:

- D_{ME} distribution used for this interpretation
- Fix qq→ 4l to prediction and scan signal strength as for gg→ 4l
- μ_H^{OS} is measured/observed cross-section for this process

$$N^{gg\to 4\ell}\left(\mu_H^{\mathrm{OS}}\right) = \left(\mu_H^{\mathrm{OS}} - \sqrt{\mu_H^{\mathrm{OS}}}\right) \times \boxed{N_{\mathrm{SM}}^{gg\to H^*\to ZZ^{(*)}\to 4\ell}} + \left(1 - \sqrt{\mu_H^{\mathrm{OS}}}\right) \times \boxed{N_{\mathrm{SM}}^{gg\to 4\ell(\mathrm{box})}} + \sqrt{\mu_H^{\mathrm{OS}}} \times \boxed{N_{\mathrm{SM}}^{gg\to 4\ell}}$$

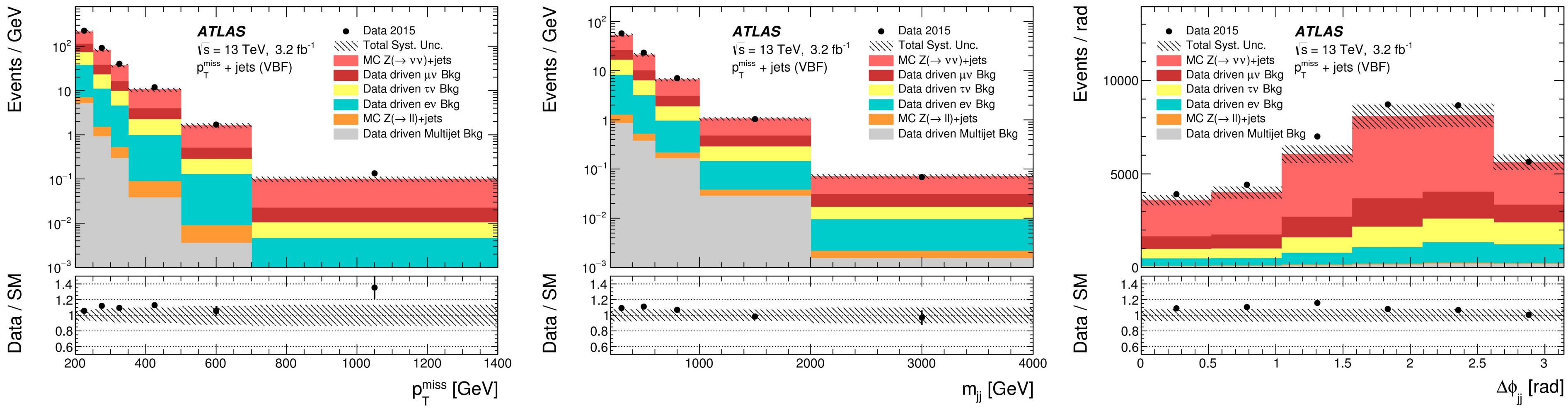
Measured 95% upper limit on signal strength: 6.5

Expected 95% upper limit on signal strength: 5.4 [4.2, 7.2]

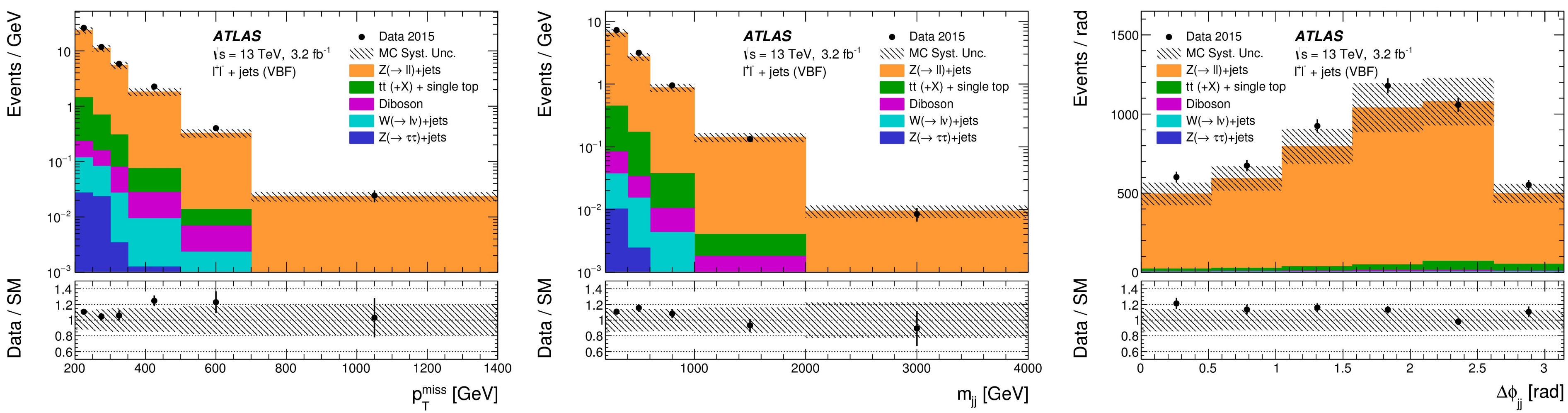
Reconstruction-level dedicated Higgs result: 4.5

VBF region

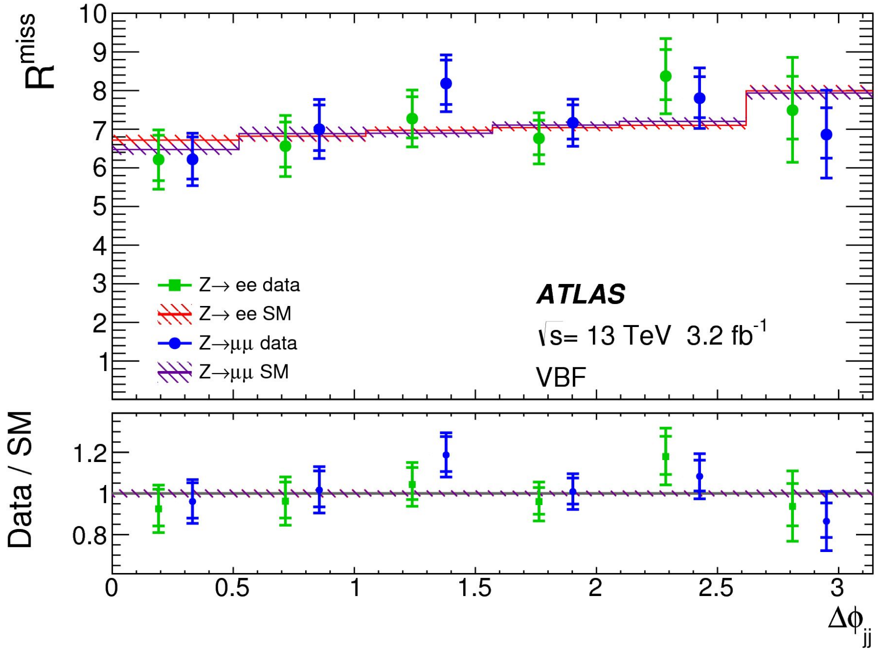
Z→ νν (numerator)



Z→ ll (denominator)



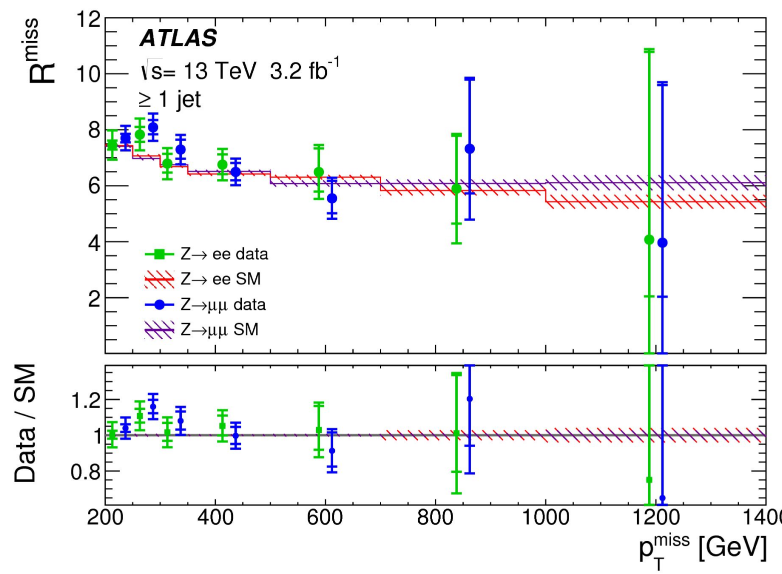
Flavour Combination



Ratio measured separately for electrons and muons

- Results were then combined using a "Best Linear Unbiased Estimator" framework
- Produces weighted combination accounting for correlations between all uncertainty sources in all bins

- Statistical uncertainty correlation between bins was calculated with a bootstrap method
- P-value for compatibility between the two channels in all four distributions is **74%**



Statistical Procedure

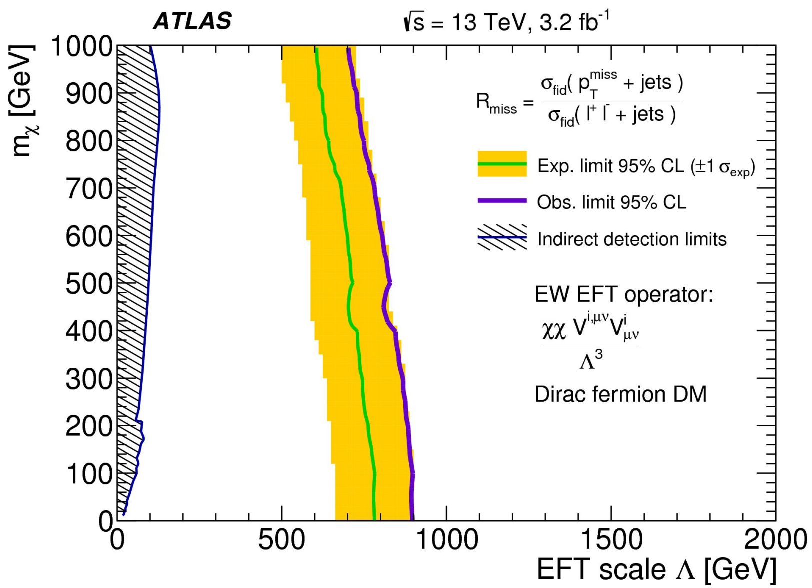
$$\chi^2 = (y_{\rm data} - y_{\rm pred})^{\rm T} C^{-1} (y_{\rm data} - y_{\rm pred})$$

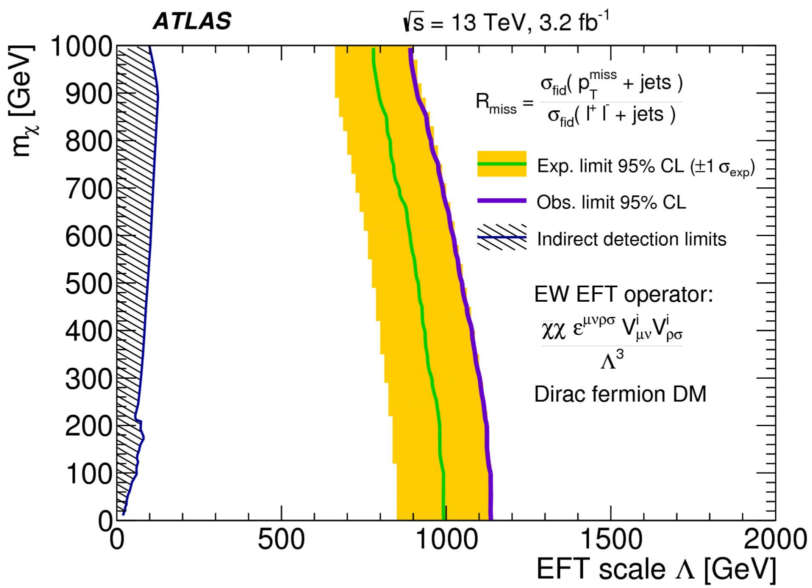
- Use **chi-squared function** (as with m_{4l})
- Covariance matrix is constructed using a bootstrap method
  - contains correlations for statistical and systematic uncertainty sources between all bins of all distributions
- Set limits for BSM scenarios:

$$1 - CL = \int_{\chi^2_{DM+SM} - \chi^2_{SM}}^{\infty} \chi^2(x; 2\,\text{d.o.f.})\,\mathrm{d}x$$

- All components provided so any DM prediction can be combined with SM predictions, uncertainties and correlations to calculate a limit

Interpretations





- Unfolded cross-sections also used to limit production of **dark matter in Effective Field Theory** which only interacts with electroweak gauge bosons, with different operator sets

- Lastly, an upper limit is set on ***Higgs bosons decaying to invisible particles*** (production rate x branching fraction) of **0.46** - expected is **0.59 [0.47, 1.13]** compared to dedicated search which observed **0.28** (expected 0.31)