# A detector-corrected ATLAS measurement of four leptons designed for re-interpretation

https://arxiv.org/abs/1902.05892 Accepted by JHEP 04 (2019) 048 (as of yesterday!)

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Seminar at University College London 12/04/19

# ATLAS Searches and Measurements

# Analysis Differences

**Precision Measurements**

- Detector-corrected (takes time and can be complex)

**Searches**

- Detector-dependent, fast, simple-as-possible analyses

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- Selection usually based on Standard Model (SM) process (but *shouldn’t* assume it)

## Searches

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# Analysis Differences

## Precision Measurements

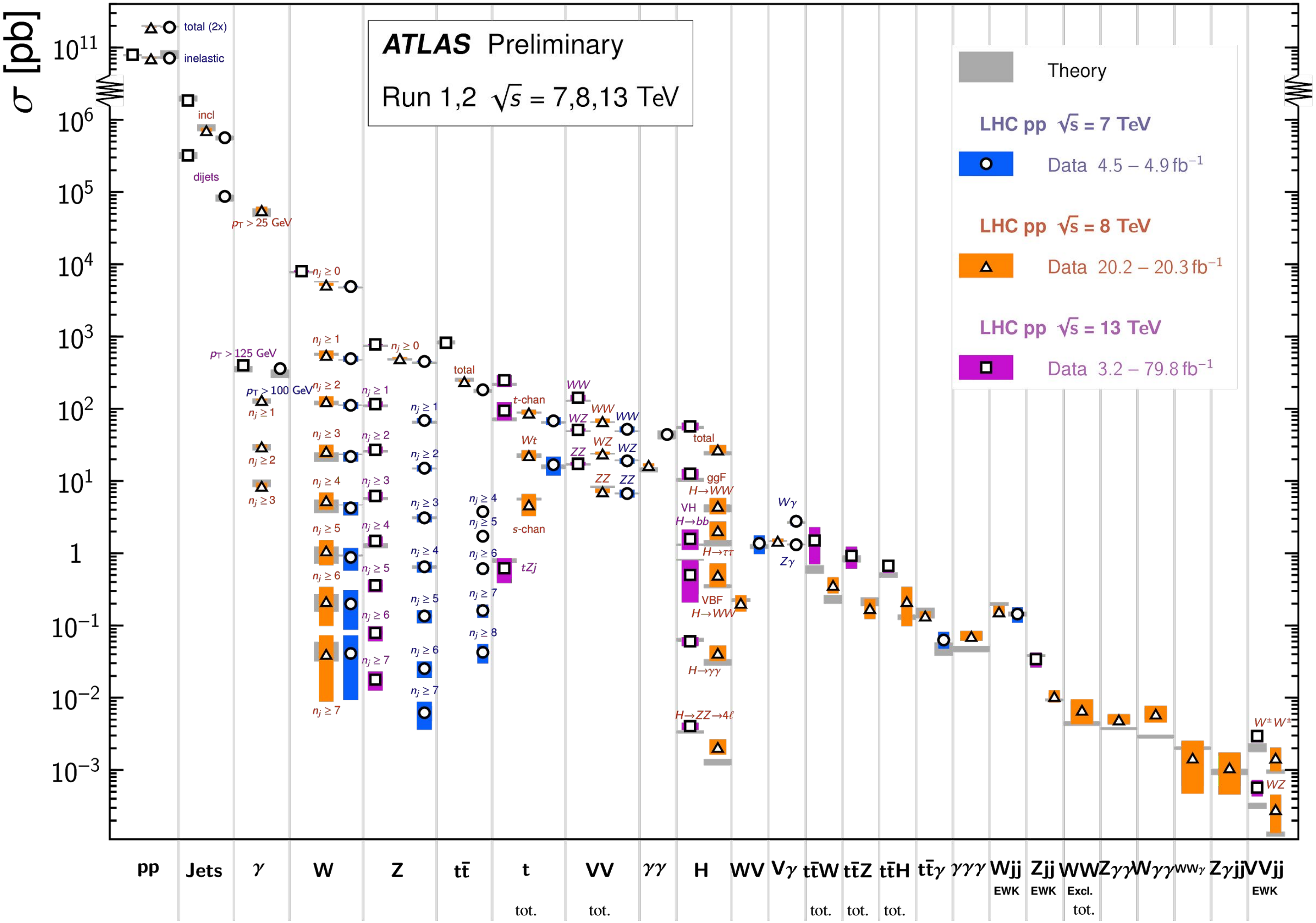
- Detector-corrected (takes time and can be complex)
- Selection usually based on Standard Model (SM) process (but *shouldn't* assume it)
- Usually measure total and/or differential cross-sections as a function of key observables

## Searches

- Detector-dependent, fast, simple-as-possible analyses
- Selection usually based on one or more benchmark Beyond Standard Model (BSM) models
- Usually measure number of events in signal region(s) and use this to place exclusion limits on models of choice (or hopefully discover one day!)

# Standard Model Production Cross Section Measurements

*Status: July 2018*



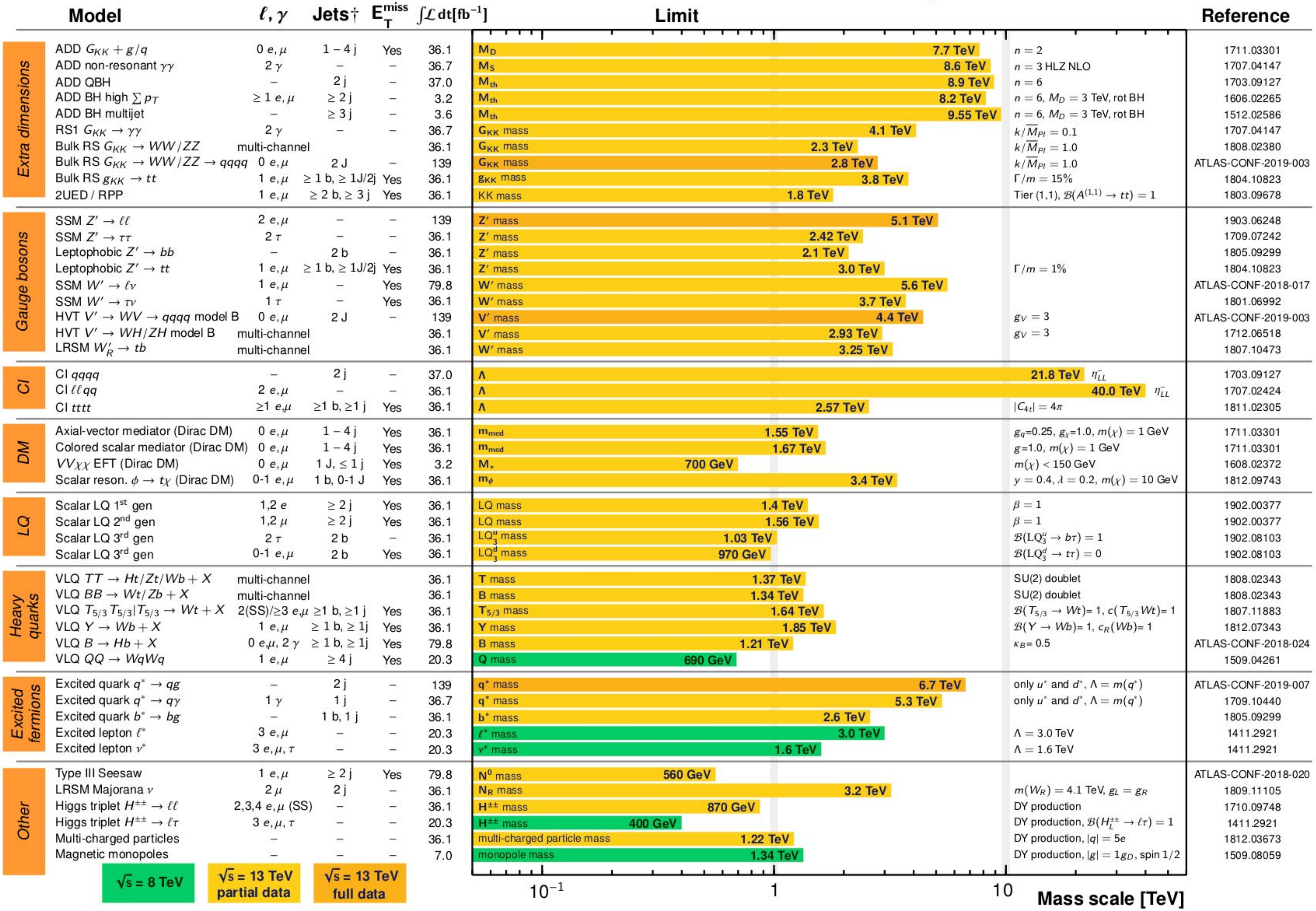
# ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: March 2019

**ATLAS** Preliminary

$\int \mathcal{L}\,dt = (3.2 - 139)\ \mathrm{fb}^{-1}$

$\sqrt{s} = 8, 13$ TeV



| | Model | $\ell, \gamma$ | Jets† | $E_T^{miss}$ | $\int \mathcal{L}\,dt[\mathrm{fb}^{-1}]$ | Limit | | Reference |
|---|---|---|---|---|---|---|---|---|
| Extra dimensions | ADD $G_{KK} + g/q$ | 0 $e, \mu$ | 1 – 4 j | Yes | 36.1 | $M_D$ 7.7 TeV | $n = 2$ | 1711.03301 |
| | ADD non-resonant $\gamma\gamma$ | 2 $\gamma$ | – | – | 36.7 | $M_S$ 8.6 TeV | $n = 3$ HLZ NLO | 1707.04147 |
| | ADD QBH | – | 2 j | – | 37.0 | $M_{th}$ 8.9 TeV | $n = 6$ | 1703.09127 |
| | ADD BH high $\sum p_T$ | $\geq 1$ $e, \mu$ | $\geq 2$ j | – | 3.2 | $M_{th}$ 8.2 TeV | $n = 6$, $M_D = 3$ TeV, rot BH | 1606.02265 |
| | ADD BH multijet | – | $\geq 3$ j | – | 3.6 | $M_{th}$ 9.55 TeV | $n = 6$, $M_D = 3$ TeV, rot BH | 1512.02586 |
| | RS1 $G_{KK} \to \gamma\gamma$ | 2 $\gamma$ | – | – | 36.7 | $G_{KK}$ mass 4.1 TeV | $k/\overline{M}_{Pl} = 0.1$ | 1707.04147 |
| | Bulk RS $G_{KK} \to WW/ZZ$ | multi-channel | | | 36.1 | $G_{KK}$ mass 2.3 TeV | $k/\overline{M}_{Pl} = 1.0$ | 1808.02380 |
| | Bulk RS $G_{KK} \to WW/ZZ \to qqqq$ | 0 $e, \mu$ | 2 J | – | 139 | $G_{KK}$ mass 2.8 TeV | $k/\overline{M}_{Pl} = 1.0$ | ATLAS-CONF-2019-003 |
| | Bulk RS $g_{KK} \to tt$ | 1 $e, \mu$ | $\geq 1$ b, $\geq 1$J/2j | Yes | 36.1 | $g_{KK}$ mass 3.8 TeV | $\Gamma/m = 15\%$ | 1804.10823 |
| | 2UED / RPP | 1 $e, \mu$ | $\geq 2$ b, $\geq 3$ j | Yes | 36.1 | KK mass 1.8 TeV | Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$ | 1803.09678 |
| Gauge bosons | SSM $Z' \to \ell\ell$ | 2 $e, \mu$ | – | – | 139 | $Z'$ mass 5.1 TeV | | 1903.06248 |
| | SSM $Z' \to \tau\tau$ | 2 $\tau$ | – | – | 36.1 | $Z'$ mass 2.42 TeV | | 1709.07242 |
| | Leptophobic $Z' \to bb$ | – | 2 b | – | 36.1 | $Z'$ mass 2.1 TeV | | 1805.09299 |
| | Leptophobic $Z' \to tt$ | 1 $e, \mu$ | $\geq 1$ b, $\geq 1$J/2j | Yes | 36.1 | $Z'$ mass 3.0 TeV | $\Gamma/m = 1\%$ | 1804.10823 |
| | SSM $W' \to \ell\nu$ | 1 $e, \mu$ | – | Yes | 79.8 | $W'$ mass 5.6 TeV | | ATLAS-CONF-2018-017 |
| | SSM $W' \to \tau\nu$ | 1 $\tau$ | – | Yes | 36.1 | $W'$ mass 3.7 TeV | | 1801.06992 |
| | HVT $V' \to WV \to qqqq$ model B | 0 $e, \mu$ | 2 J | – | 139 | $V'$ mass 4.4 TeV | $g_V = 3$ | ATLAS-CONF-2019-003 |
| | HVT $V' \to WH/ZH$ model B | multi-channel | | | 36.1 | $V'$ mass 2.93 TeV | $g_V = 3$ | 1712.06518 |
| | LRSM $W'_R \to tb$ | multi-channel | | | 36.1 | $W'$ mass 3.25 TeV | | 1807.10473 |
| CI | CI $qqqq$ | – | 2 j | – | 37.0 | $\Lambda$ 21.8 TeV $\eta^-_{LL}$ | | 1703.09127 |
| | CI $\ell\ell qq$ | 2 $e, \mu$ | – | – | 36.1 | $\Lambda$ 40.0 TeV $\eta^-_{LL}$ | | 1707.02424 |
| | CI $tttt$ | ≥1 $e,\mu$ | ≥1 b, ≥1 j | Yes | 36.1 | $\Lambda$ 2.57 TeV | $\lvert C_{4t}\rvert = 4\pi$ | 1811.02305 |
| DM | Axial-vector mediator (Dirac DM) | 0 $e, \mu$ | 1 – 4 j | Yes | 36.1 | $m_{med}$ 1.55 TeV | $g_q$=0.25, $g_\chi$=1.0, $m(\chi) = 1$ GeV | 1711.03301 |
| | Colored scalar mediator (Dirac DM) | 0 $e, \mu$ | 1 – 4 j | Yes | 36.1 | $m_{med}$ 1.67 TeV | $g$=1.0, $m(\chi) = 1$ GeV | 1711.03301 |
| | $VV\chi\chi$ EFT (Dirac DM) | 0 $e, \mu$ | 1 J, $\leq 1$ j | Yes | 3.2 | $M_*$ 700 GeV | $m(\chi) < 150$ GeV | 1608.02372 |
| | Scalar reson. $\phi \to t\chi$ (Dirac DM) | 0-1 $e, \mu$ | 1 b, 0-1 J | Yes | 36.1 | $m_\phi$ 3.4 TeV | $y = 0.4$, $\lambda = 0.2$, $m(\chi) = 10$ GeV | 1812.09743 |
| LQ | Scalar LQ 1st gen | 1,2 $e$ | $\geq 2$ j | Yes | 36.1 | LQ mass 1.4 TeV | $\beta = 1$ | 1902.00377 |
| | Scalar LQ 2nd gen | 1,2 $\mu$ | $\geq 2$ j | Yes | 36.1 | LQ mass 1.56 TeV | $\beta = 1$ | 1902.00377 |
| | Scalar LQ 3rd gen | 2 $\tau$ | 2 b | – | 36.1 | $LQ_3^u$ mass 1.03 TeV | $\mathcal{B}(\mathrm{LQ}_3^u \to b\tau) = 1$ | 1902.08103 |
| | Scalar LQ 3rd gen | 0-1 $e, \mu$ | 2 b | Yes | 36.1 | $LQ_3^d$ mass 970 GeV | $\mathcal{B}(\mathrm{LQ}_3^d \to t\tau) = 0$ | 1902.08103 |
| Heavy quarks | VLQ $TT \to Ht/Zt/Wb + X$ | multi-channel | | | 36.1 | T mass 1.37 TeV | SU(2) doublet | 1808.02343 |
| | VLQ $BB \to Wt/Zb + X$ | multi-channel | | | 36.1 | B mass 1.34 TeV | SU(2) doublet | 1808.02343 |
| | VLQ $T_{5/3}T_{5/3} \mid T_{5/3} \to Wt + X$ | 2(SS)/≥3 $e,\mu$ | ≥1 b, ≥1 j | Yes | 36.1 | $T_{5/3}$ mass 1.64 TeV | $\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1 | 1807.11883 |
| | VLQ $Y \to Wb + X$ | 1 $e, \mu$ | $\geq 1$ b, $\geq 1$j | Yes | 36.1 | Y mass 1.85 TeV | $\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1 | 1812.07343 |
| | VLQ $B \to Hb + X$ | 0 $e,\mu$, 2 $\gamma$ | $\geq 1$ b, $\geq 1$j | Yes | 79.8 | B mass 1.21 TeV | $\kappa_B$= 0.5 | ATLAS-CONF-2018-024 |
| | VLQ $QQ \to WqWq$ | 1 $e, \mu$ | $\geq 4$ j | Yes | 20.3 | Q mass 690 GeV | | 1509.04261 |
| Excited fermions | Excited quark $q^* \to qg$ | – | 2 j | – | 139 | $q^*$ mass 6.7 TeV | only $u^*$ and $d^*$, $\Lambda = m(q^*)$ | ATLAS-CONF-2019-007 |
| | Excited quark $q^* \to q\gamma$ | 1 $\gamma$ | 1 j | – | 36.7 | $q^*$ mass 5.3 TeV | only $u^*$ and $d^*$, $\Lambda = m(q^*)$ | 1709.10440 |
| | Excited quark $b^* \to bg$ | – | 1 b, 1 j | – | 36.1 | $b^*$ mass 2.6 TeV | | 1805.09299 |
| | Excited lepton $\ell^*$ | 3 $e, \mu$ | – | – | 20.3 | $\ell^*$ mass 3.0 TeV | $\Lambda = 3.0$ TeV | 1411.2921 |
| | Excited lepton $\nu^*$ | 3 $e, \mu, \tau$ | – | – | 20.3 | $\nu^*$ mass 1.6 TeV | $\Lambda = 1.6$ TeV | 1411.2921 |
| Other | Type III Seesaw | 1 $e, \mu$ | $\geq 2$ j | Yes | 79.8 | $N^0$ mass 560 GeV | | ATLAS-CONF-2018-020 |
| | LRSM Majorana $\nu$ | 2 $\mu$ | 2 j | – | 36.1 | $N_R$ mass 3.2 TeV | $m(W_R) = 4.1$ TeV, $g_L = g_R$ | 1809.11105 |
| | Higgs triplet $H^{\pm\pm} \to \ell\ell$ | 2,3,4 $e, \mu$ (SS) | – | – | 36.1 | $H^{\pm\pm}$ mass 870 GeV | DY production | 1710.09748 |
| | Higgs triplet $H^{\pm\pm} \to \ell\tau$ | 3 $e, \mu, \tau$ | – | – | 20.3 | $H^{\pm\pm}$ mass 400 GeV | DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$ | 1411.2921 |
| | Multi-charged particles | – | – | – | 36.1 | multi-charged particle mass 1.22 TeV | DY production, $\lvert q\rvert = 5e$ | 1812.03673 |
| | Magnetic monopoles | – | – | – | 7.0 | monopole mass 1.34 TeV | DY production, $\lvert g\rvert = 1g_D$, spin 1/2 | 1509.08059 |

🟩 $\sqrt{s}$ = 8 TeV

🟨 $\sqrt{s}$ = 13 TeV partial data

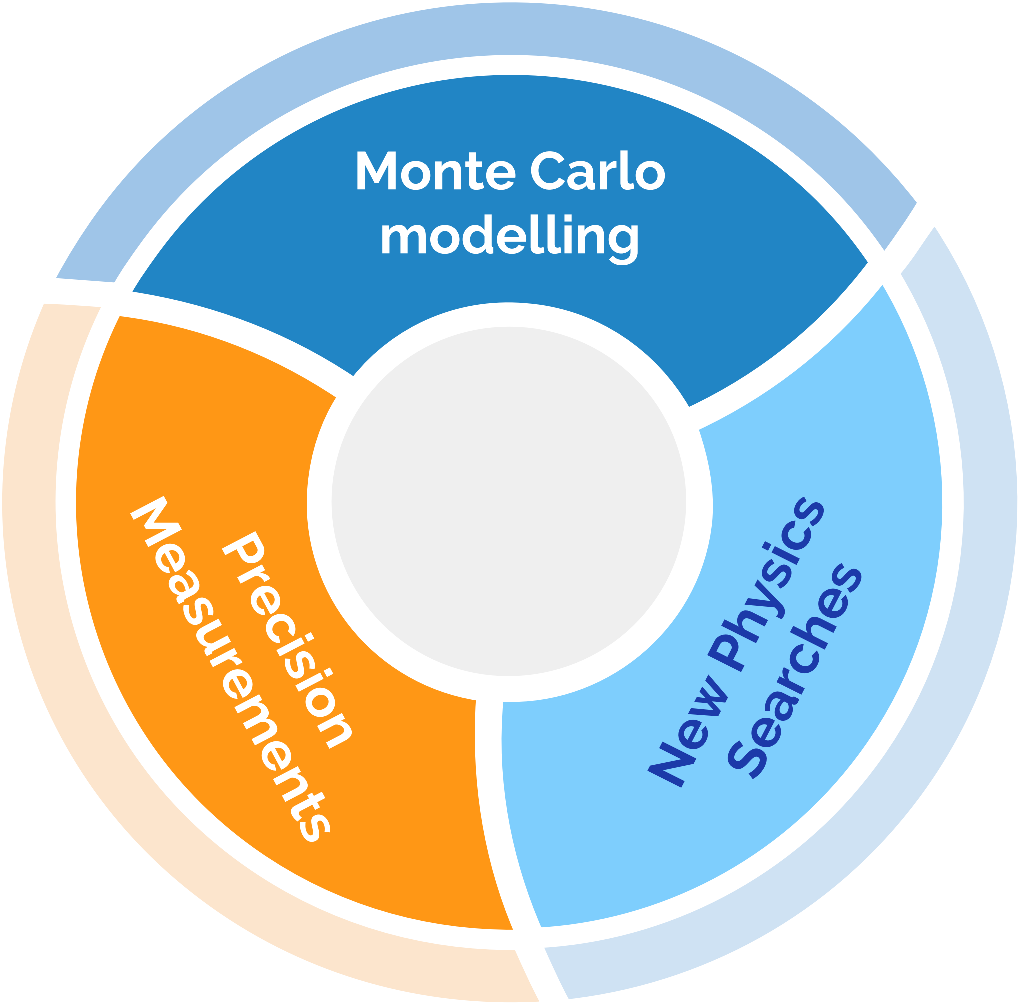
🟧 $\sqrt{s}$ = 13 TeV full data

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

# Blurring the Edges

# Feedback Loop



# Different Approaches

**Cross-section level search**

Measure cross-sections in region sensitive to BSM physics e.g. jet(s)+missing transverse energy: Eur Phys J C 77 (2017) 765

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Produces precise information useful for modelling in future + potential sensitivity to BSM: arxiv:1902.00377

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### Reinterpreting Measurements

Testing sensitivity of existing cross-section results to new physics theories e.g. CONTUR: https://contur.hepforge.org

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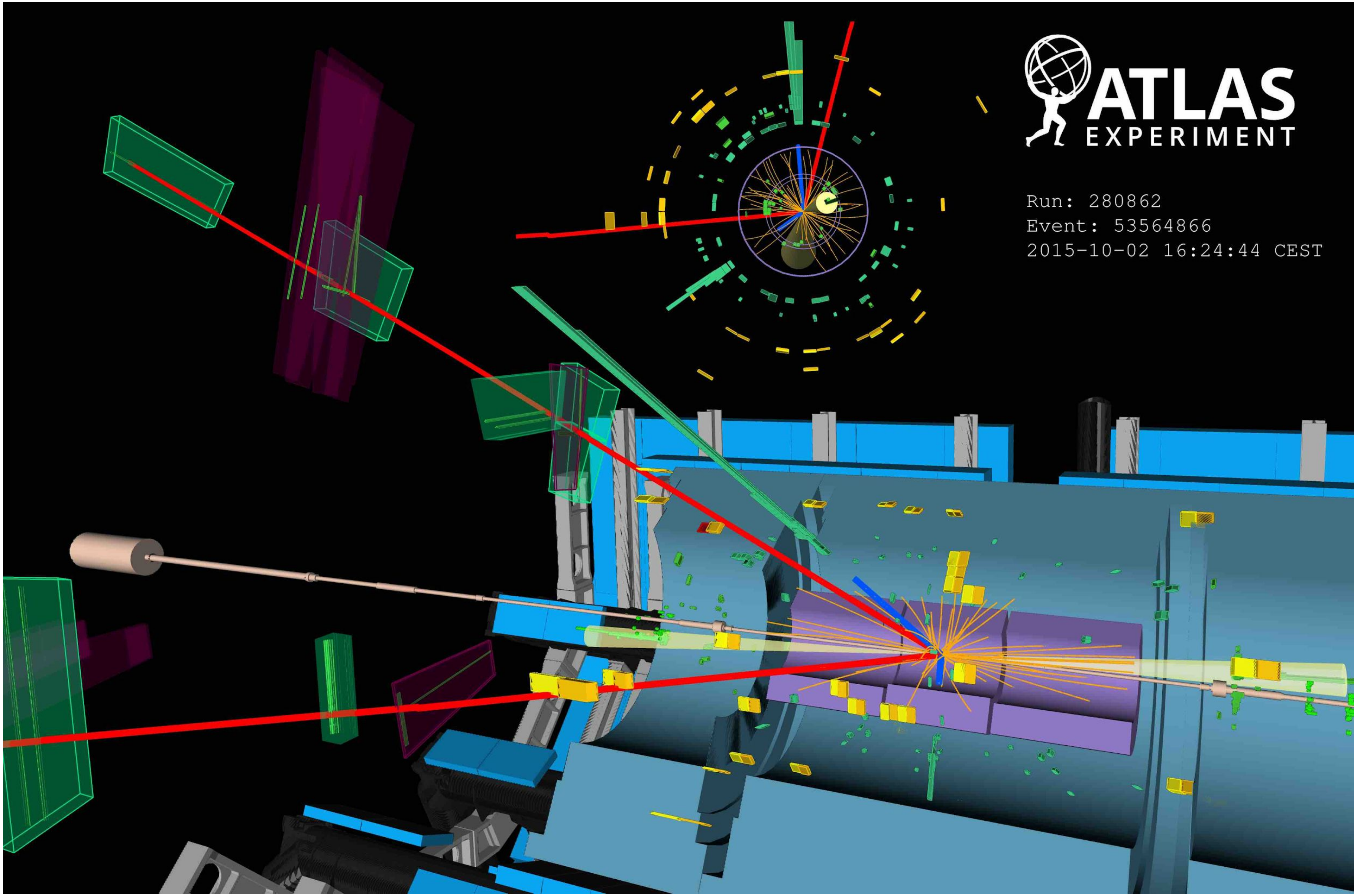
## BSM sensitive measurements

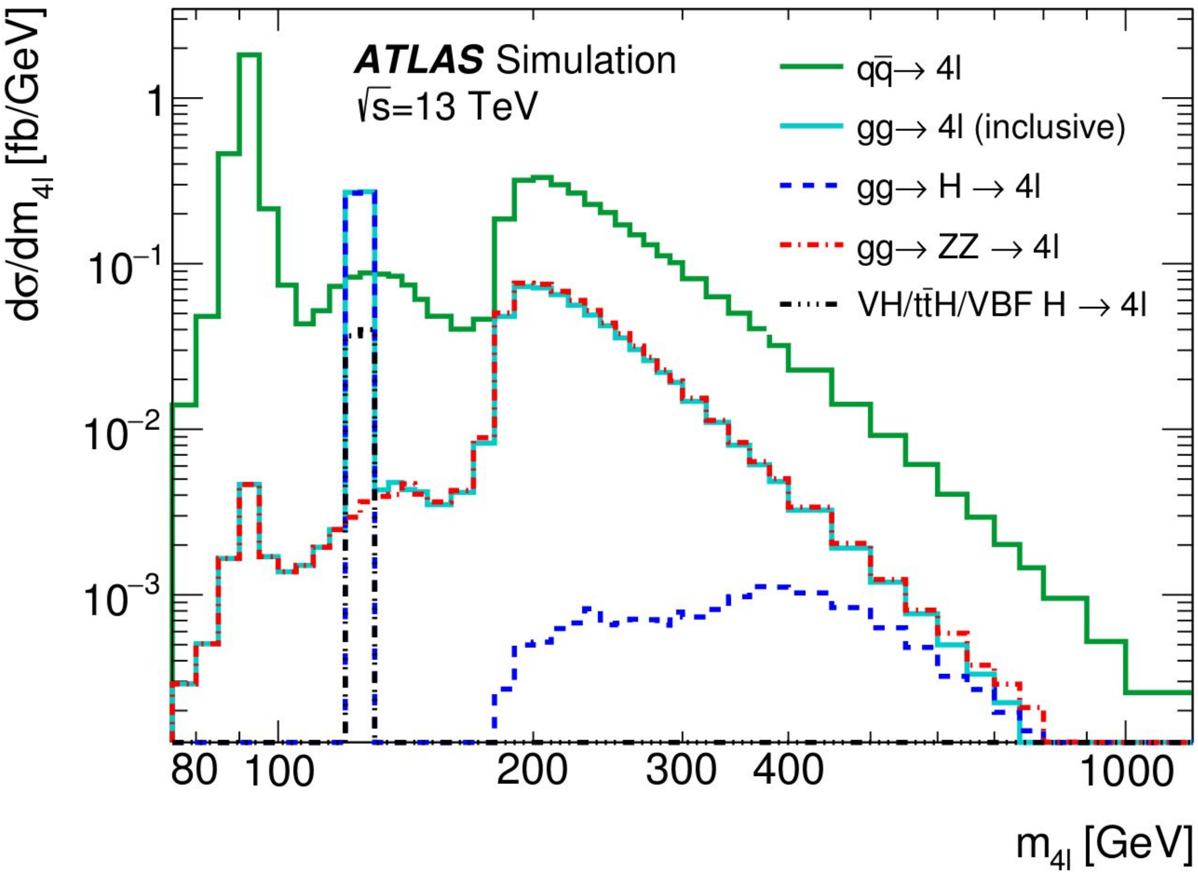
Make SM measurement as re-interpretable and model-independent as possible, e.g: four leptons: https://arxiv.org/abs/1902.05892

# Four Lepton Mass Spectrum

# Four Lepton Events



# Four Lepton Events



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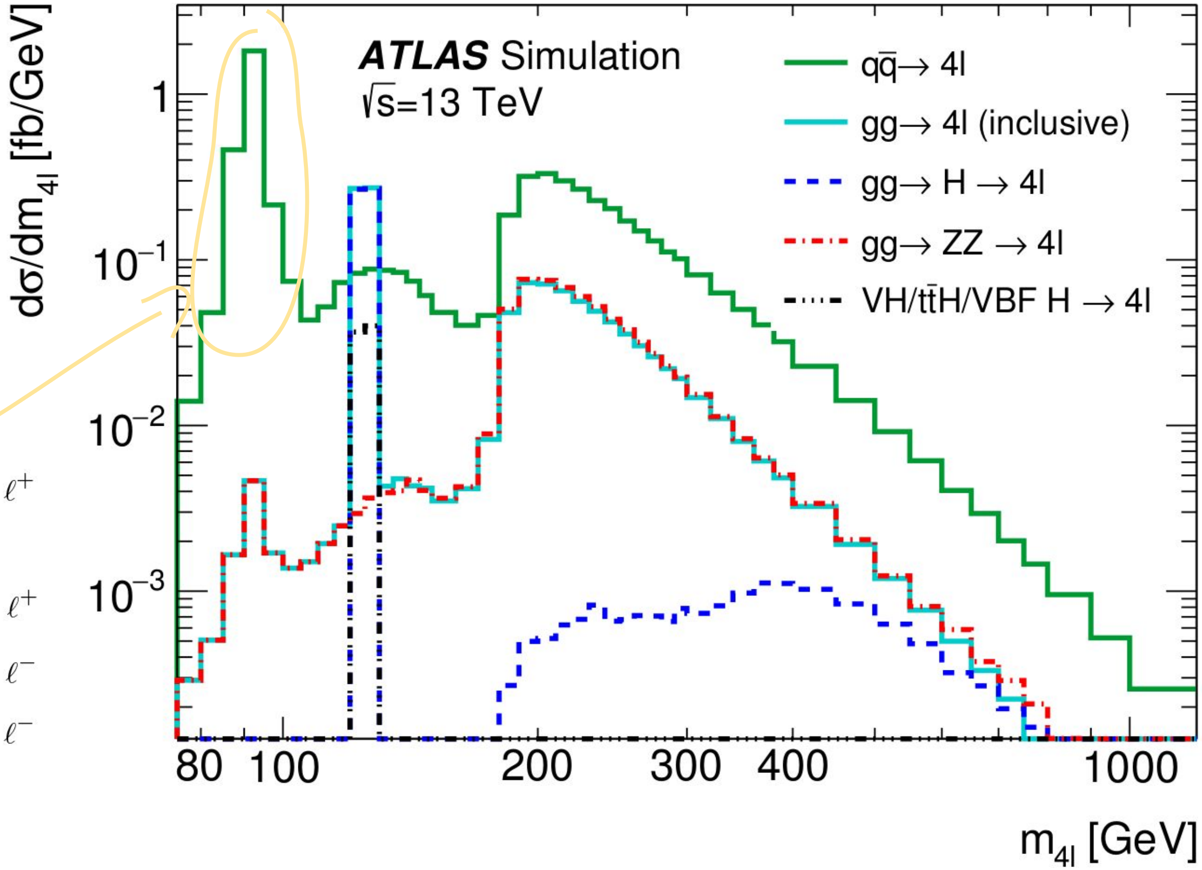

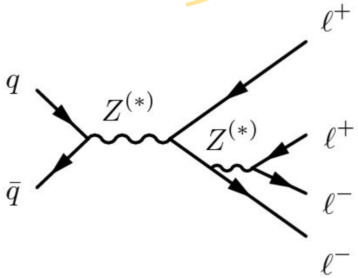

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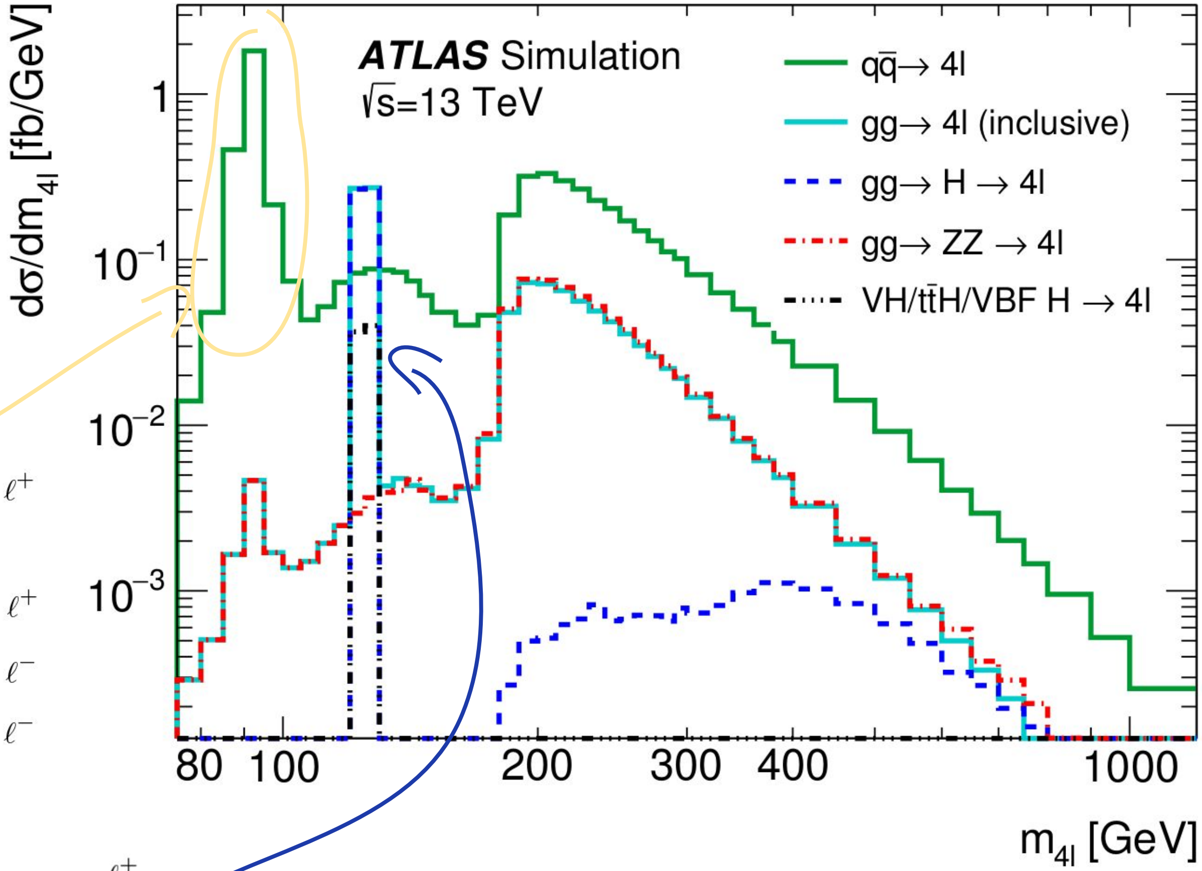

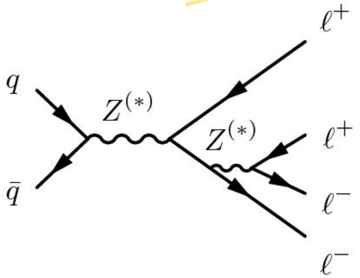

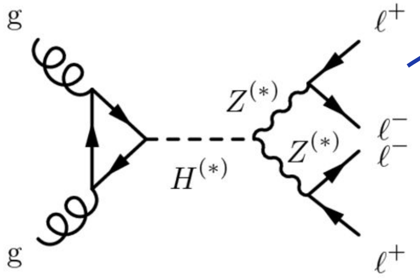

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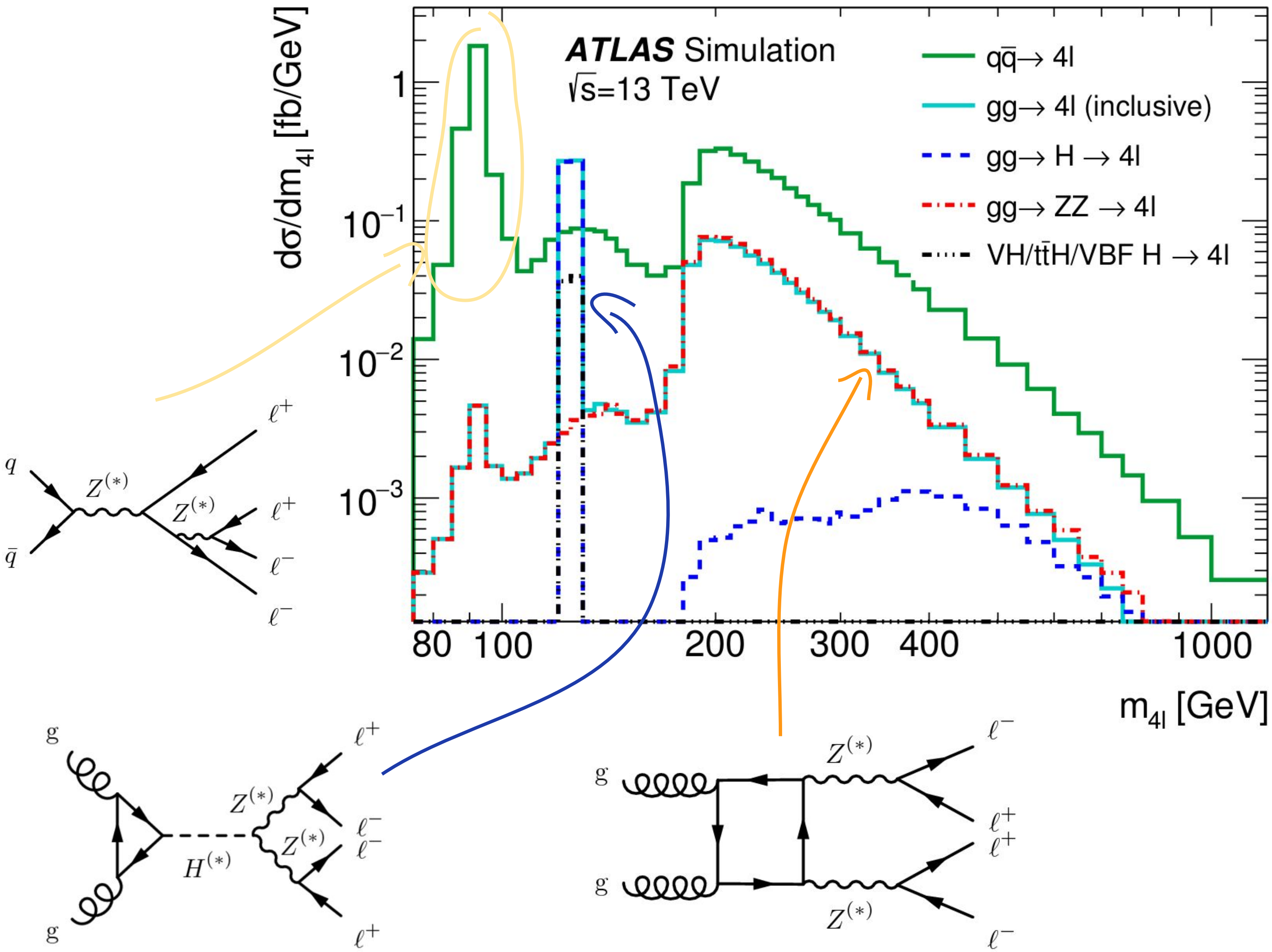

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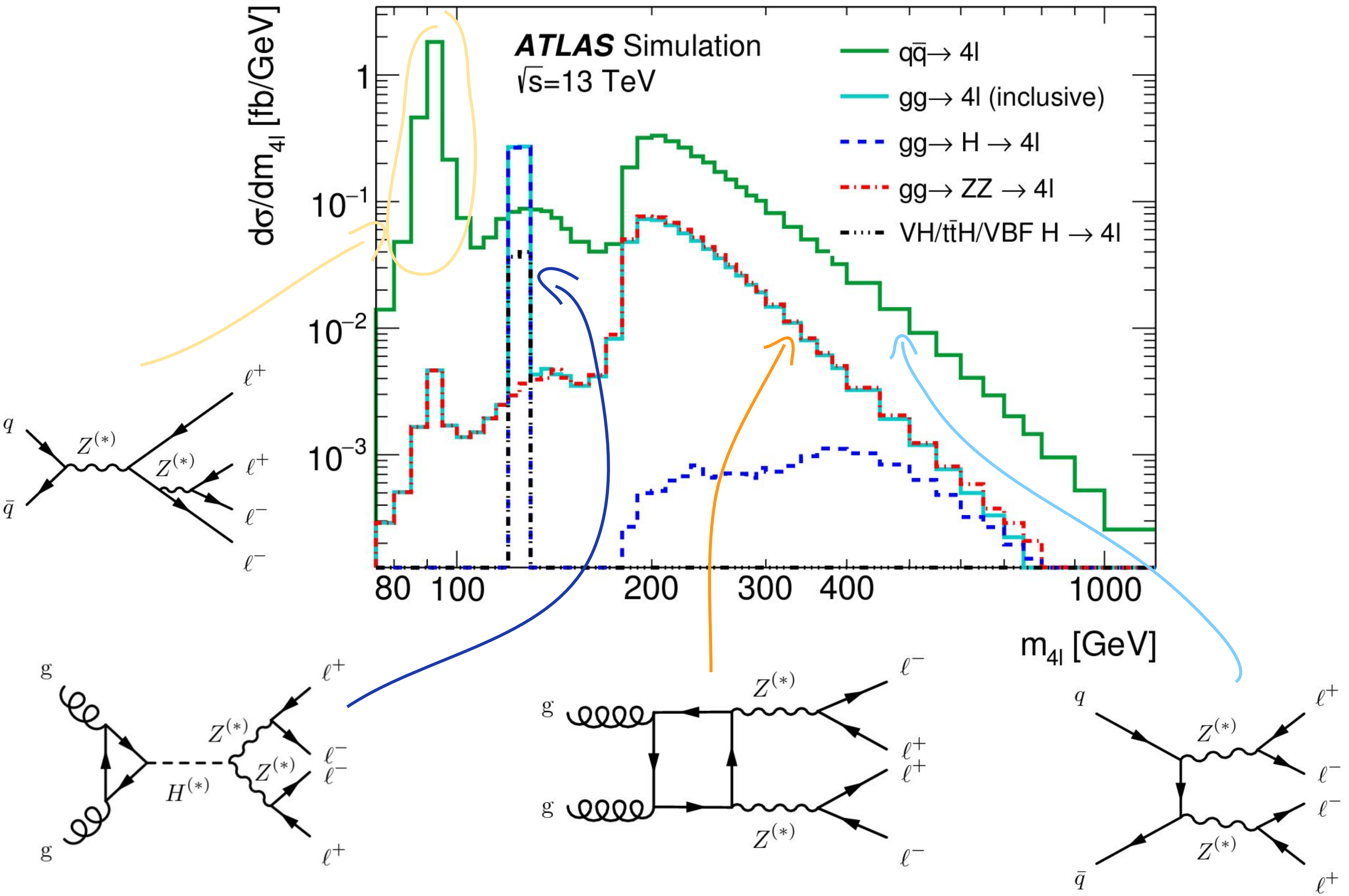

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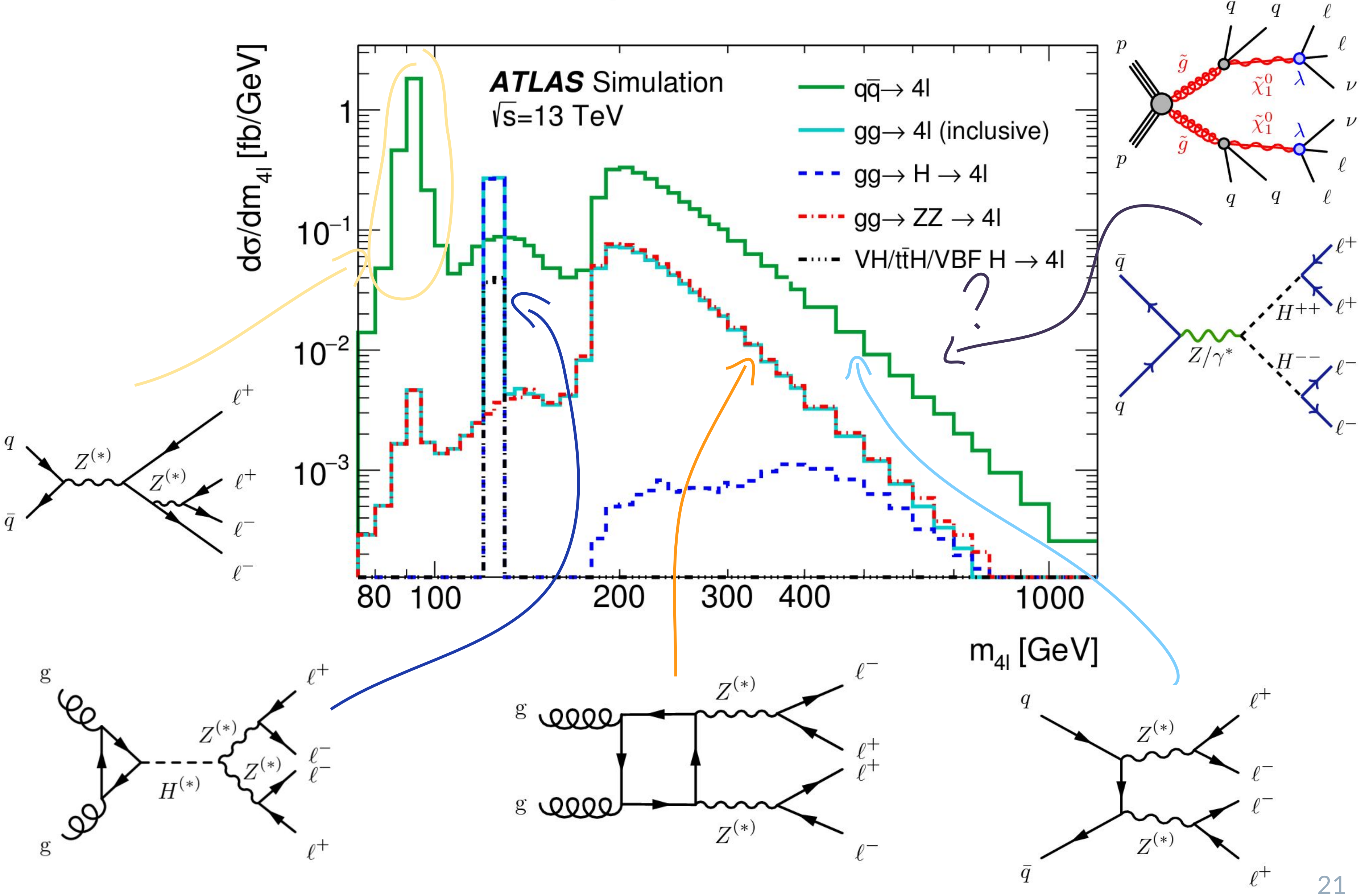
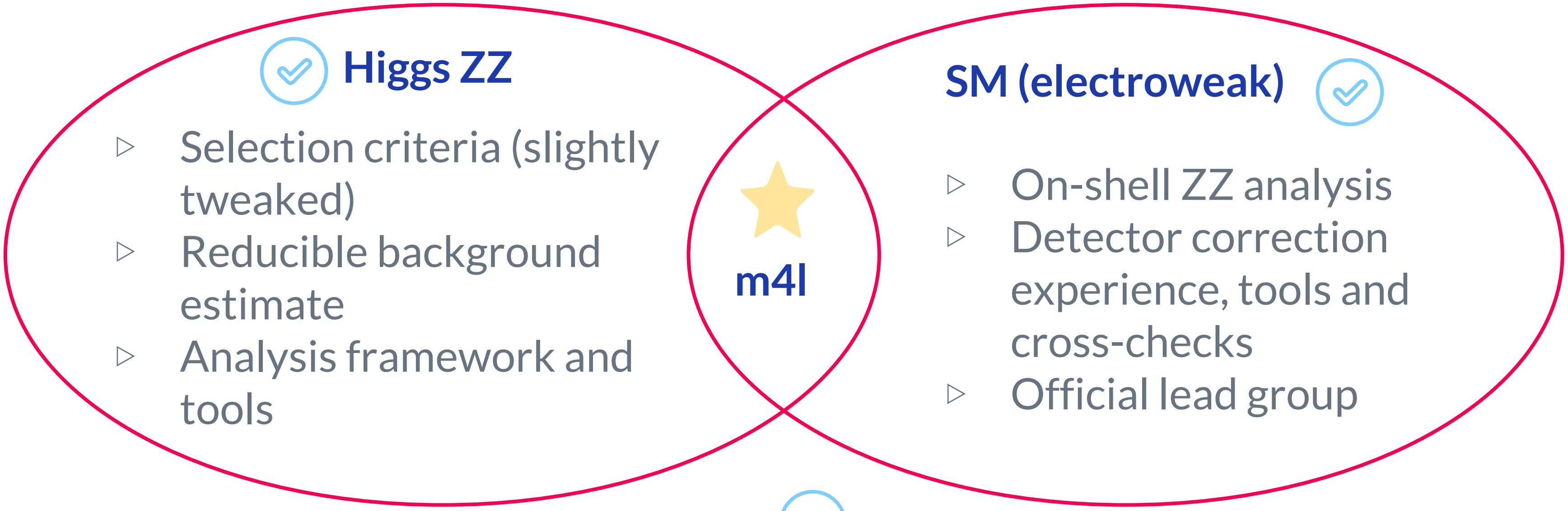


# 2015+2016 Data Analysis

# Advancing my quest for involvement in all ATLAS physics groups…



✓ **Higgs ZZ**

- Selection criteria (slightly tweaked)
- Reducible background estimate
- Analysis framework and tools

**m4l**

**SM (electroweak)** ✓

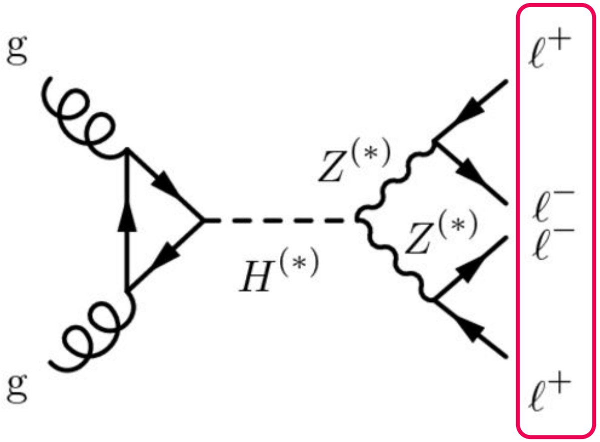
- On-shell ZZ analysis
- Detector correction experience, tools and cross-checks
- Official lead group

✓ Previously Supersymmetry and Exotics! ✓

- *Proof-of concept* first analysis of this kind
- Small team so sharing resources was very helpful!
- Moving away from this for next round → more inclusive and straightforward selection

# Fiducial Region Definition

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

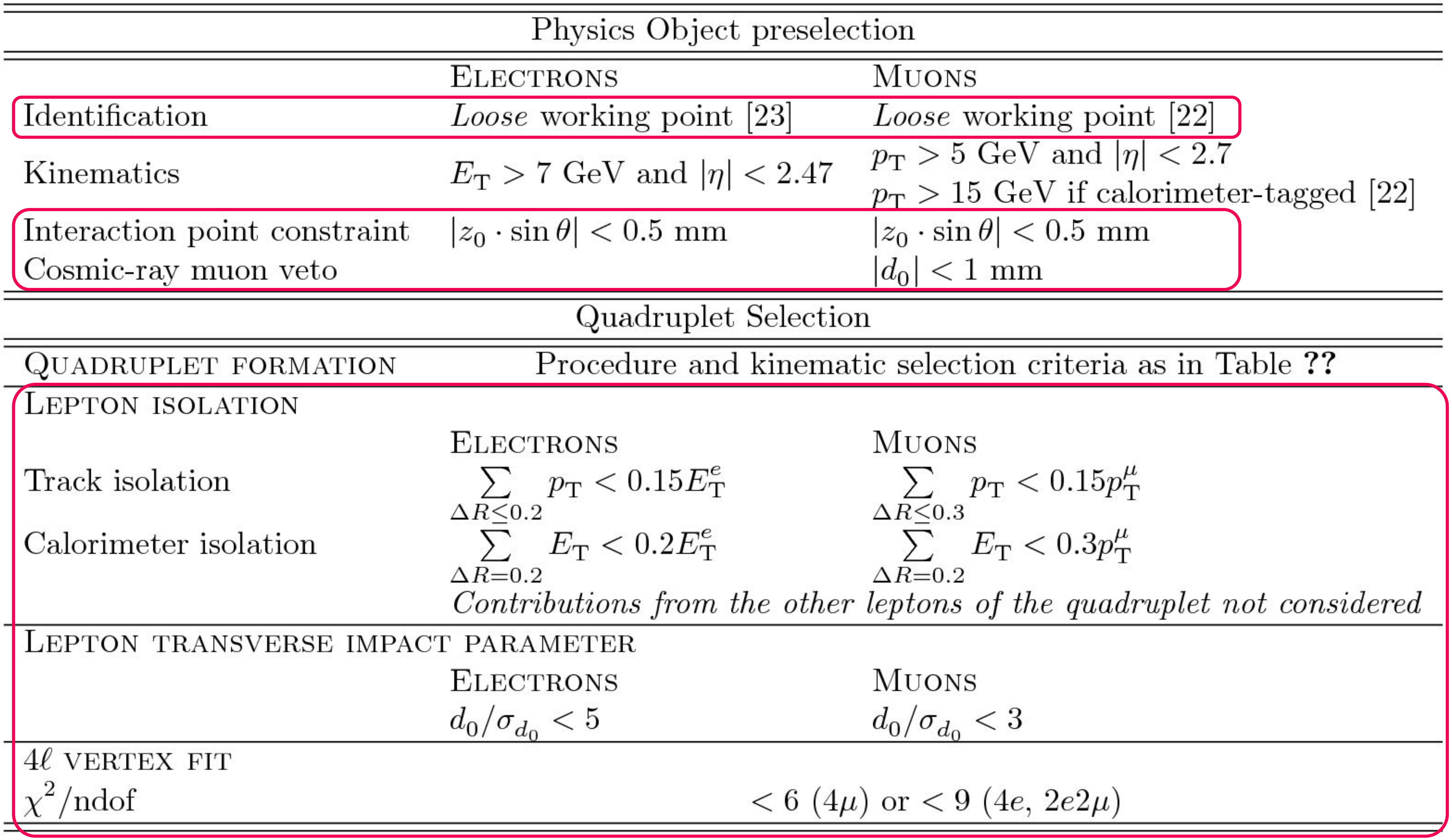


- At least ***4 leptons*** - muon (electron) pT > 5 (7) GeV, |η| < 2.7 (2.47) - (>20/15/10 GeV in pair)
- Form two pairs of ***same flavour, opposite sign*** (SFOS)leptons, e.g. $e^+e^-e^+e^-$, $e^+e^-\mu^+\mu^-$, $\mu^+\mu^-\mu^+\mu^-$
- Pair with dilepton mass closest to Z boson mass ***primary pair*** - 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)

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

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

# Reconstruction-level selection



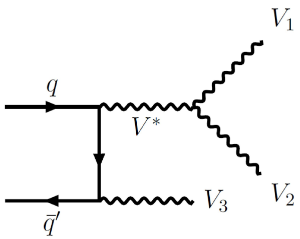
| | | |
|---|---|---|
| Physics Object preselection | | |
| | Electrons | Muons |
| Identification | *Loose* working point [23] | *Loose* working point [22] |
| Kinematics | $E_\mathrm{T} > 7$ GeV and $\vert\eta\vert < 2.47$ | $p_\mathrm{T} > 5$ GeV and $\vert\eta\vert < 2.7$<br>$p_\mathrm{T} > 15$ GeV if calorimeter-tagged [22] |
| Interaction point constraint | $\vert z_0 \cdot \sin\theta\vert < 0.5$ mm | $\vert z_0 \cdot \sin\theta\vert < 0.5$ mm |
| Cosmic-ray muon veto | | $\vert d_0\vert < 1$ 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 |
| | $d_0/\sigma_{d_0} < 5$ | $d_0/\sigma_{d_0} < 3$ |
| $4\ell$ vertex fit | | |
| $\chi^2$/ndof | $< 6$ ($4\mu$) or $< 9$ ($4e$, $2e2\mu$) | |

# Composition

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

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

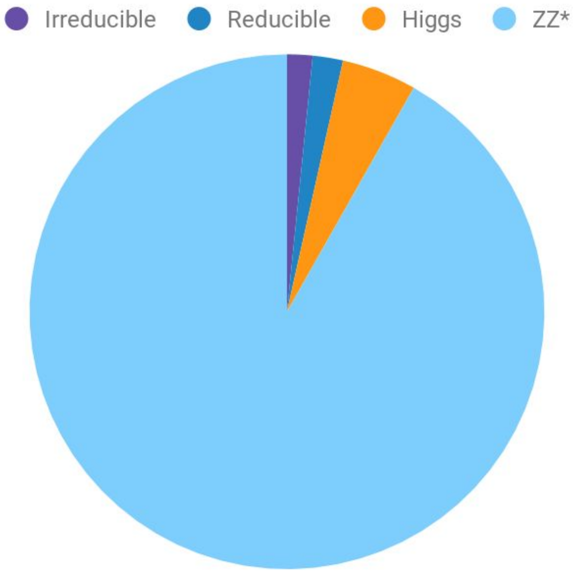
## Irreducible



- ▷ 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



# Signal Simulation

**Higgs Signal:**

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

**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

**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:**

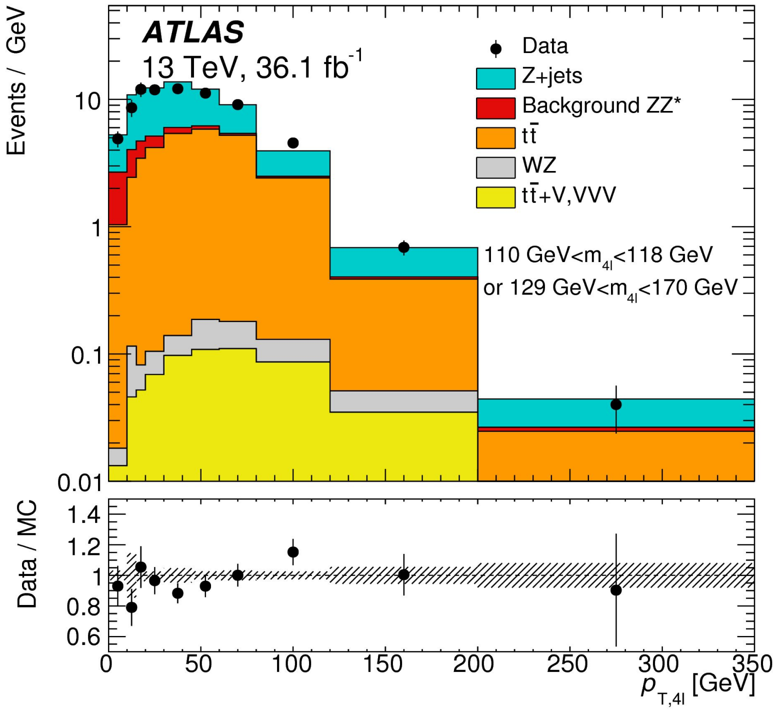
- Z+jets, Sherpa NLO 0,1,2j, LO 3,4 j
- tt, WZ Powheg

**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:

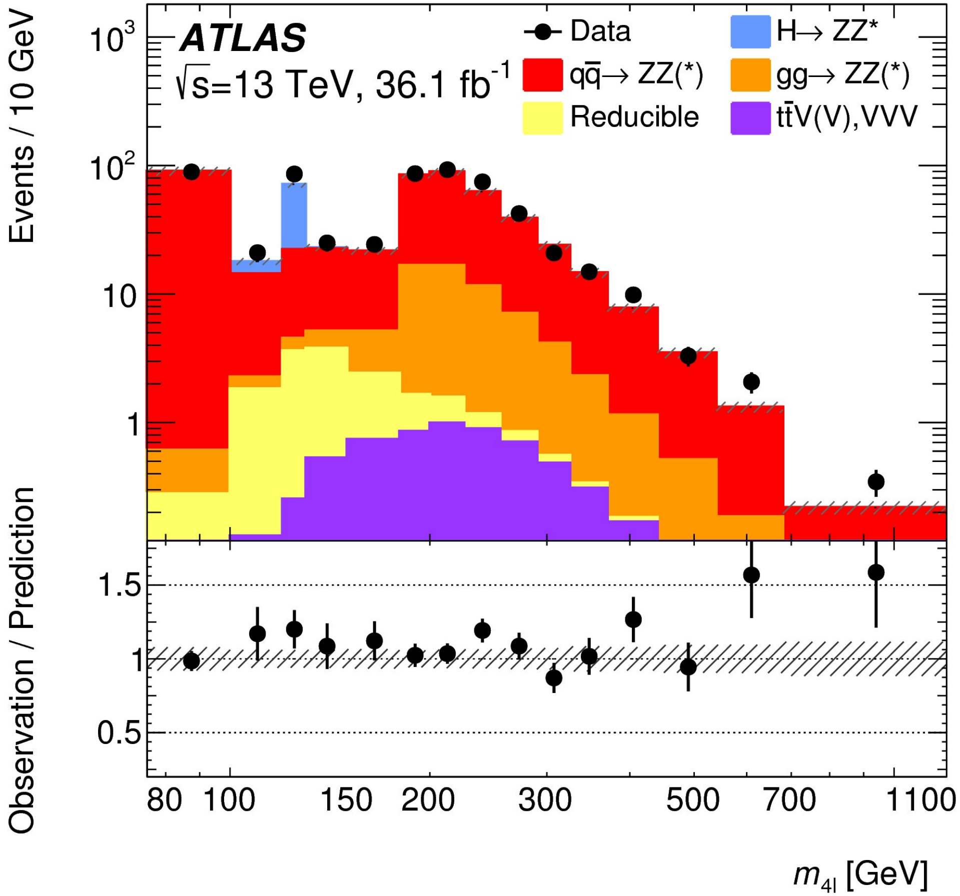
- ▷ Loosened region to check estimation
- ▷ Compare multiple alternative methods

# Distributions

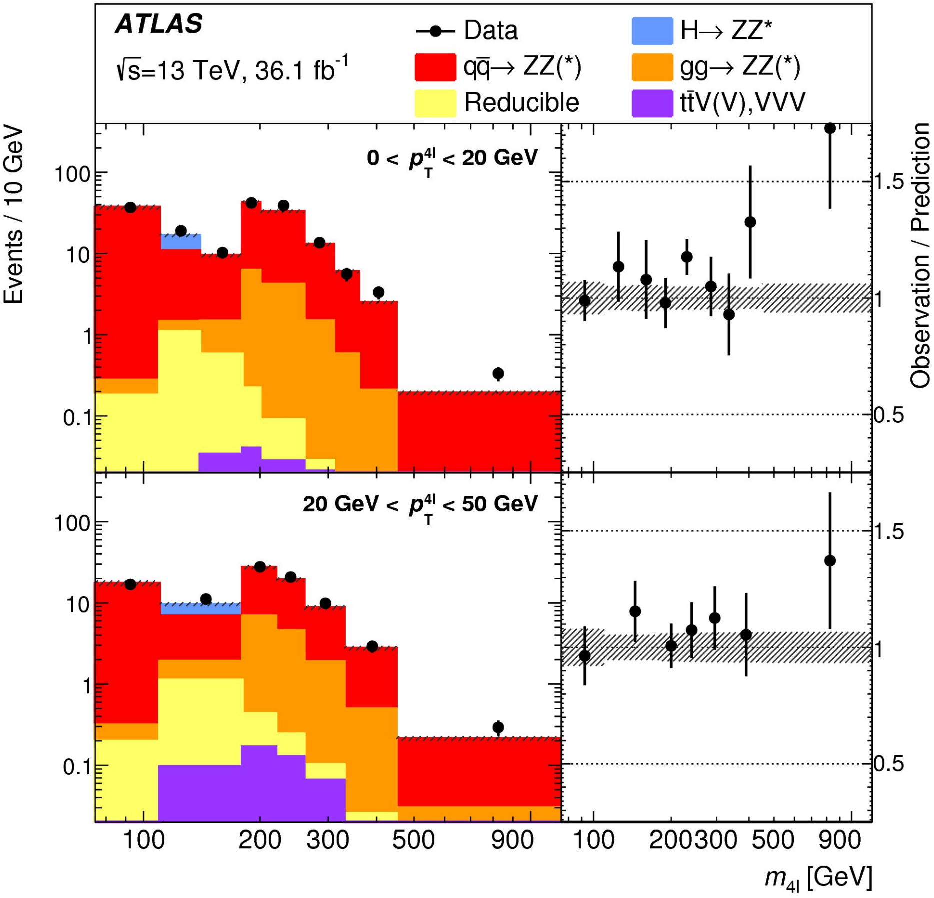
**Double Differential Distributions:**

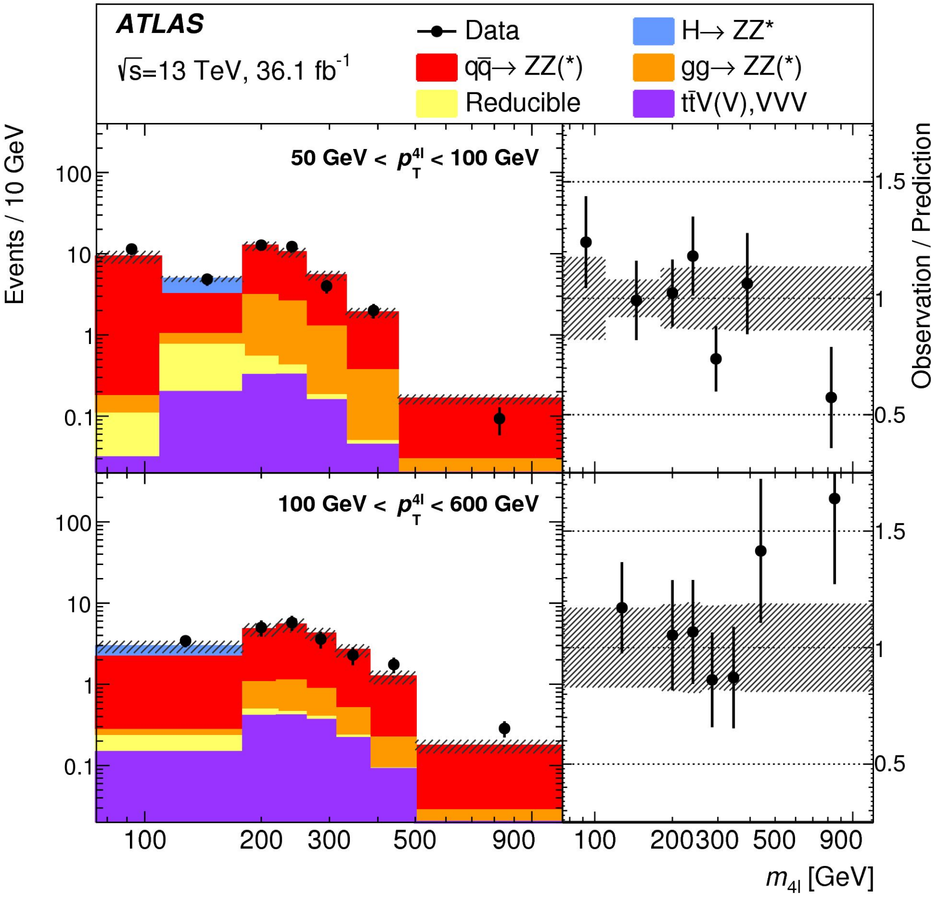
- Measure m4l in fairly coarse bins of other interesting variables;
    - ***Transverse momentum $p_T^{4l}$***
    - ***Rapidity $y_{4l}$***
    - ***Lepton Flavours - eeee/eeμμ/μμμμ***
    - ***Matrix element discriminant***
- Potential increased sensitivity
- Improved modelling in future can be fed in

**Star of the show - four lepton mass**



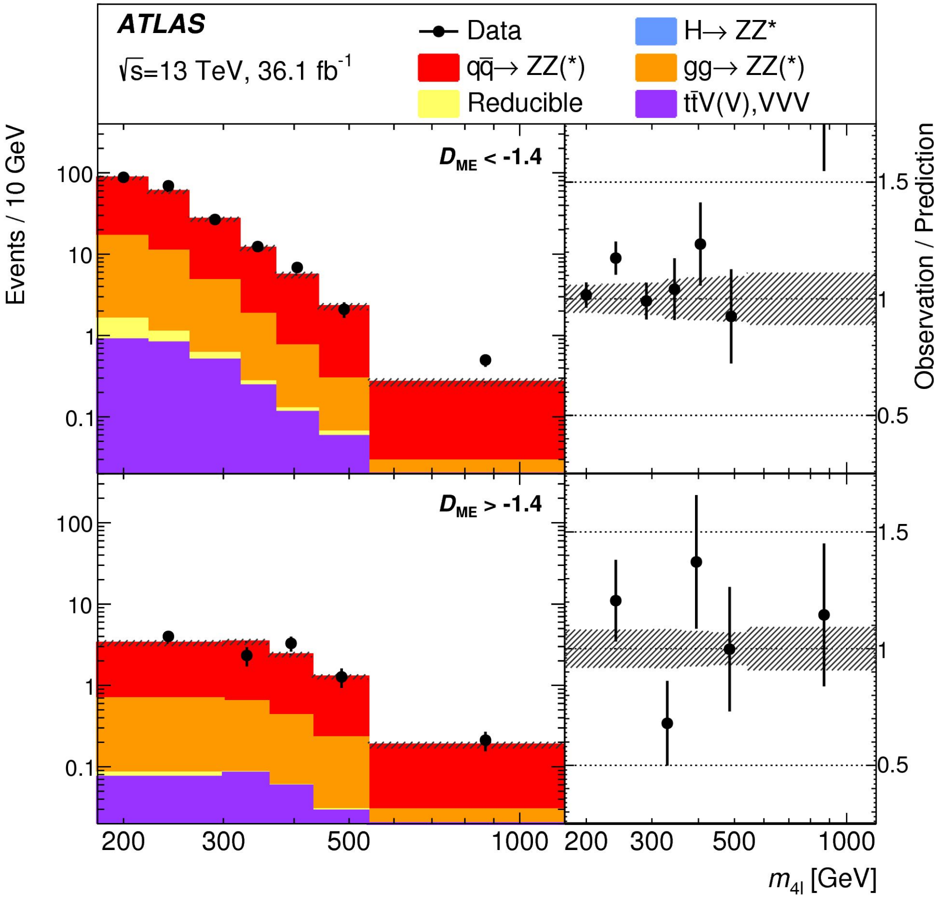
# Double differential example - $P_T^{4l}$





# 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?:

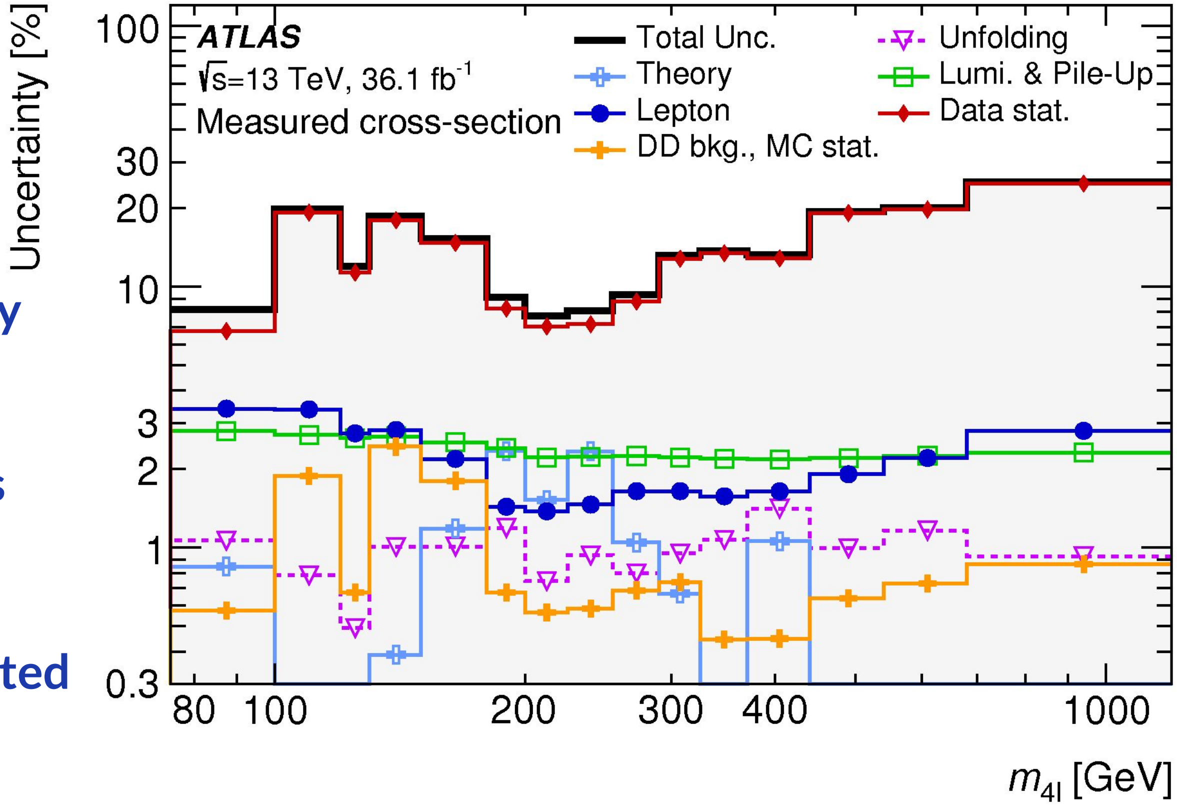
- Calculated using *Z boson production angles* and *decay angles*
- Matrix element for qqZZ, ggZZ and gg→ H→ ZZ calculated in MCFM
- Can help **separate off-shell Higgs production** from other processes by splitting into two bins

# Uncertainty Sources

**Dominated by statistical uncertainty**

**Lepton dominated by reconstruction, identification and isolation efficiencies**

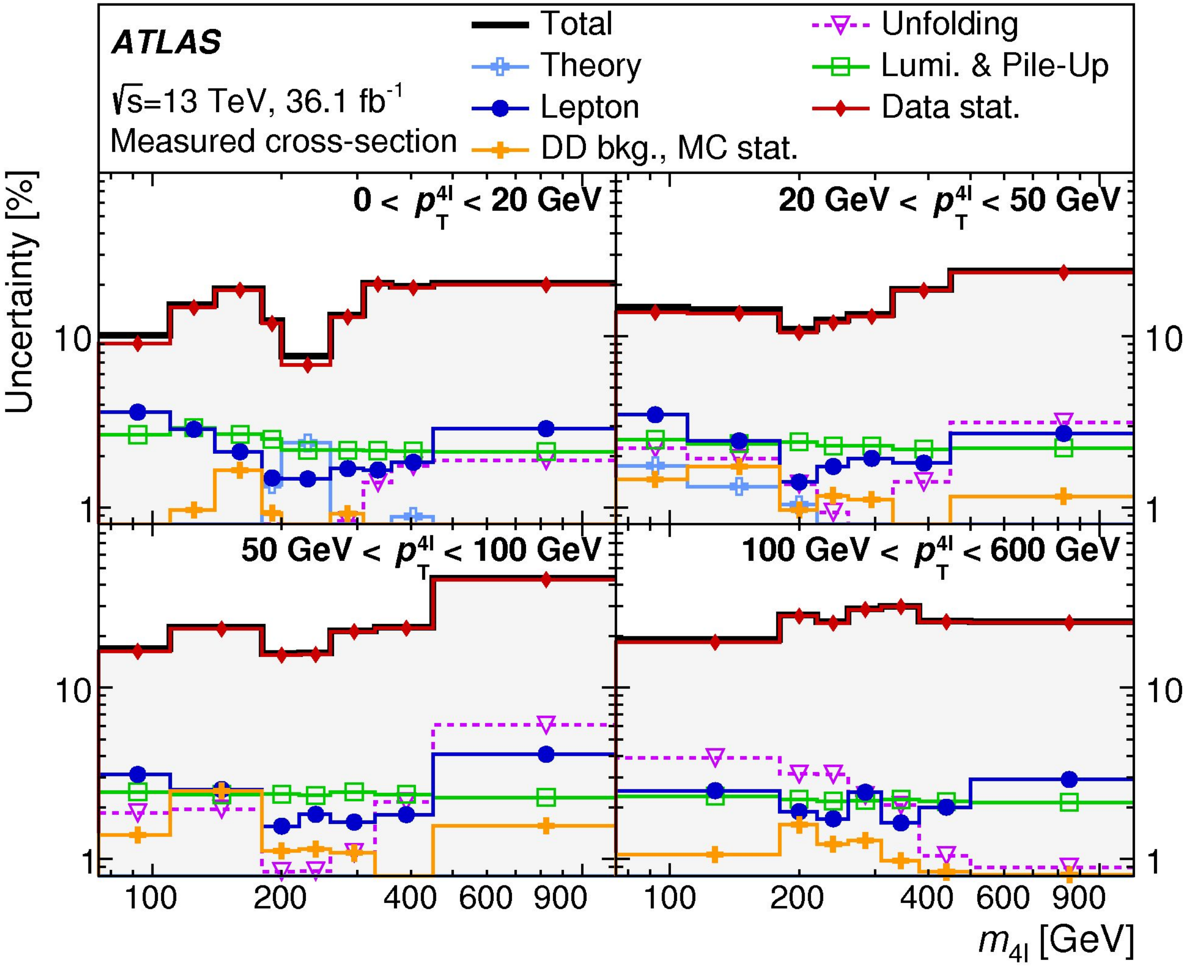
**Data has a flat ~2% uncertainty associated with luminosity measurement**



**Smaller contributions from:**

- Unfolding procedure - estimated by unfolding reweighted truth MC, also includes generator uncertainty for qq→ MC simulation
- Data-driven background estimation, combined for ee and $\mu\mu$
- Theoretical uncertainty includes scale, PDF set and parton showering choices

# Uncertainty Sources

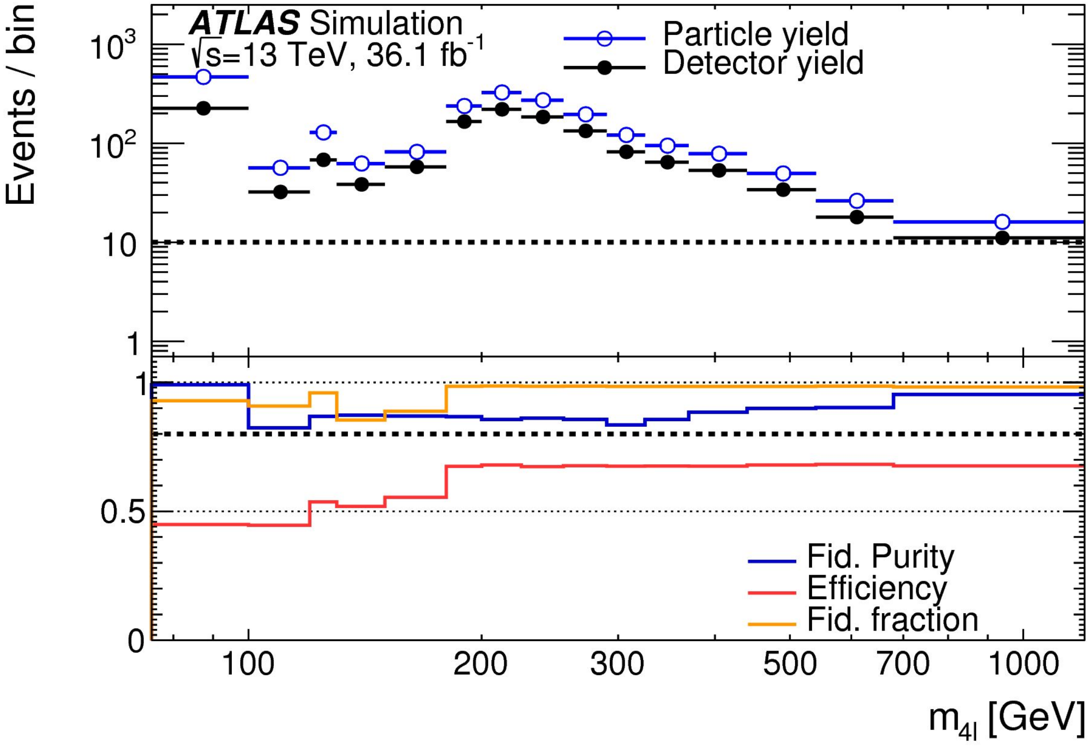


**Relative sizes do vary across distributions, with exception of luminosity and pileup, but always dominated by statistical uncertainty**

# Unfolding

**Correct for effects the detector has on measured data:**

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



**Efficiency:**

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

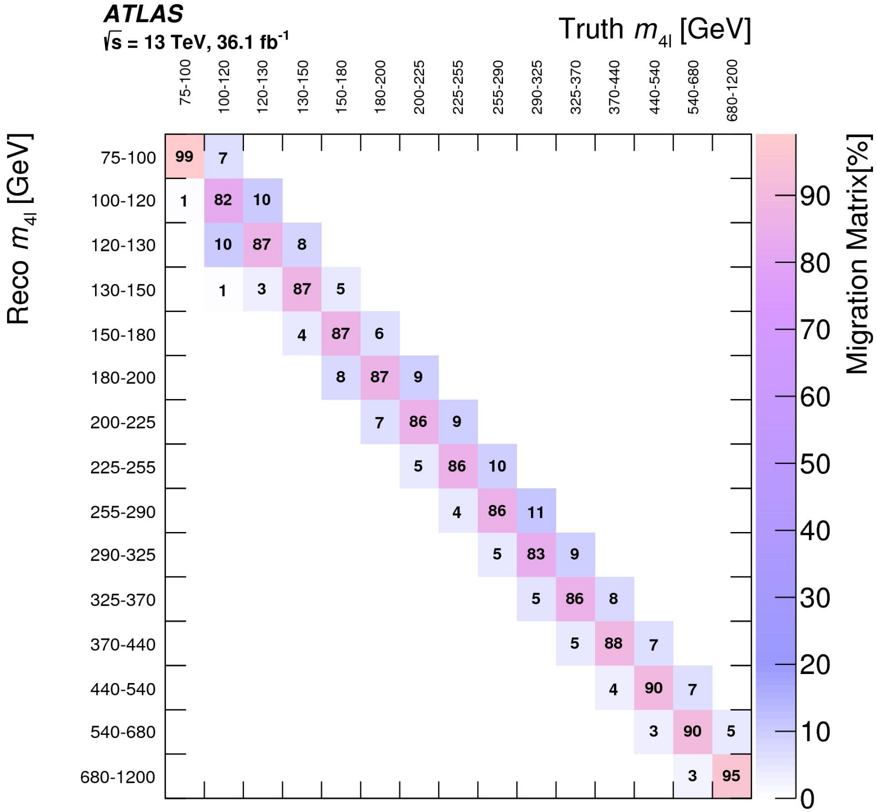
**Fiducial Fraction:**

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



| | 75-100 | 100-120 | 120-130 | 130-150 | 150-180 | 180-200 | 200-225 | 225-255 | 255-290 | 290-325 | 325-370 | 370-440 | 440-540 | 540-680 | 680-1200 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 75-100 | 99 | 7 | | | | | | | | | | | | | |
| 100-120 | 1 | 82 | 10 | | | | | | | | | | | | |
| 120-130 | | 10 | 87 | 8 | | | | | | | | | | | |
| 130-150 | | 1 | 3 | 87 | 5 | | | | | | | | | | |
| 150-180 | | | | 4 | 87 | 6 | | | | | | | | | |
| 180-200 | | | | | 8 | 87 | 9 | | | | | | | | |
| 200-225 | | | | | | 7 | 86 | 9 | | | | | | | |
| 225-255 | | | | | | | 5 | 86 | 10 | | | | | | |
| 255-290 | | | | | | | | 4 | 86 | 11 | | | | | |
| 290-325 | | | | | | | | | 5 | 83 | 9 | | | | |
| 325-370 | | | | | | | | | | 5 | 86 | 8 | | | |
| 370-440 | | | | | | | | | | | 5 | 88 | 7 | | |
| 440-540 | | | | | | | | | | | | 4 | 90 | 7 | |
| 540-680 | | | | | | | | | | | | | 3 | 90 | 5 |
| 680-1200 | | | | | | | | | | | | | | 3 | 95 |

**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

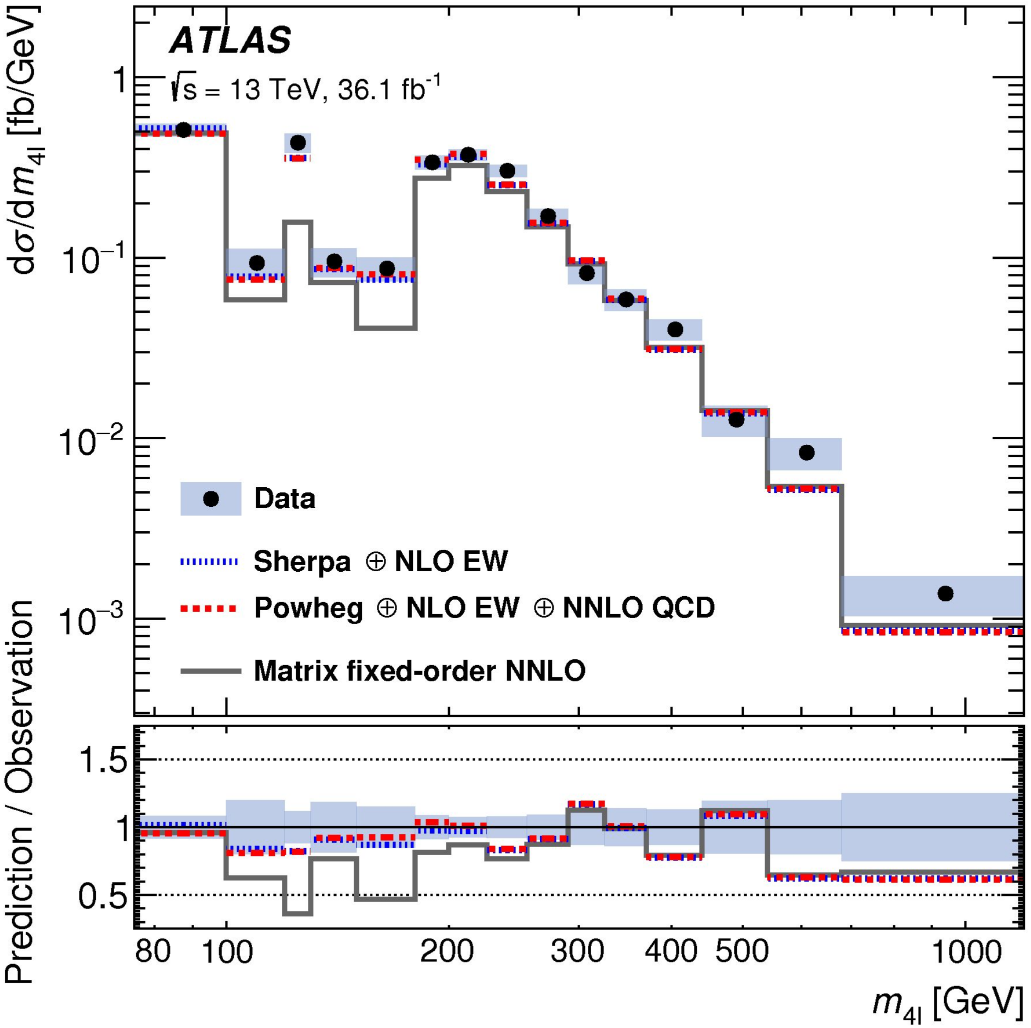
**Subtract background from data**

**Multiply observation in each bin by fiducial fraction**

**Iterative Bayesian method to correct for bin migration**

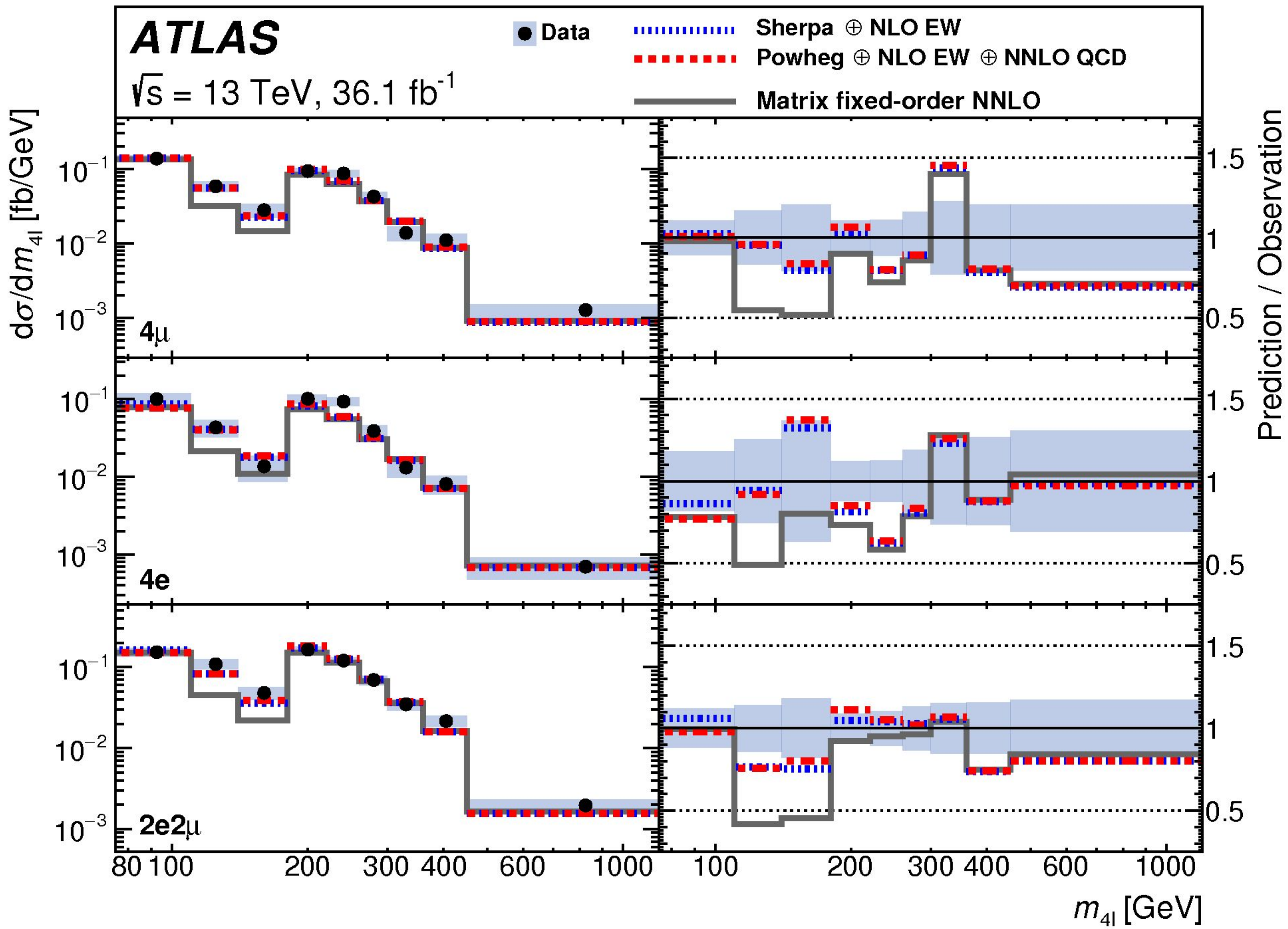
**Divide each bin by reconstruction efficiency**

# 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



# (Re-)Interpretations

# Statistical Procedure

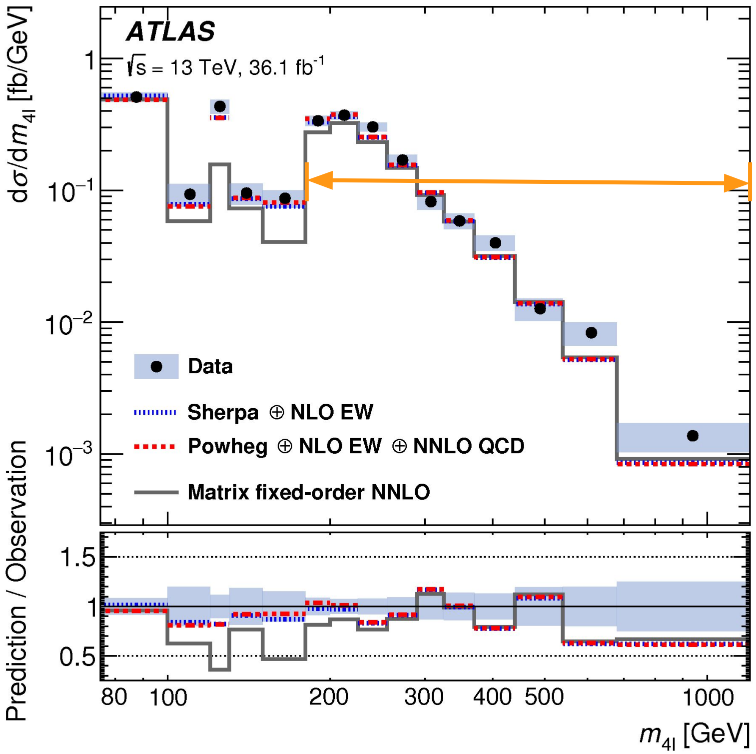
$$\chi^2 = (y_{\text{data}} - y_{\text{pred}})^{\text{T}} C^{-1} (y_{\text{data}} - y_{\text{pred}})$$

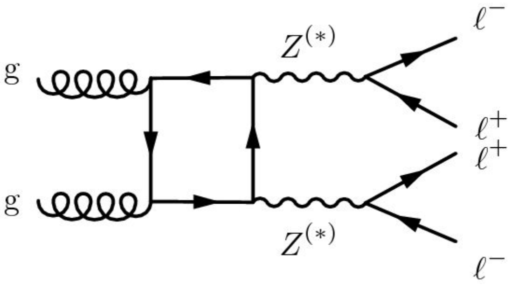
- Use **chi-squared function** as exponential component of Gaussian likelihood quantifying agreement between data and prediction.
- Predicted values are a function of the **parameter of interest (POI)** and **nuisance parameter (NP)** used for uncertainty sources.
- The covariance matrix is scaled dependent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

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

- **$R_K = N_K^{\text{pred}}(\text{POI,NP})/N_K^{\text{pred}}(\text{POI=SM, NP=0})$** 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 **$\text{CL}_\text{S}$** method with a confidence level of 95%.

# Gluon-induced production signal strength





**Measured:** 1.3±0.5

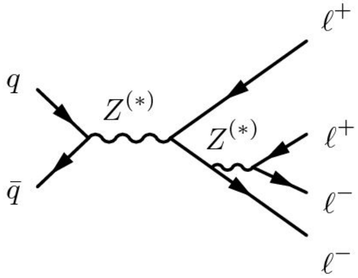
**Expected:** 1.0±0.4

**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

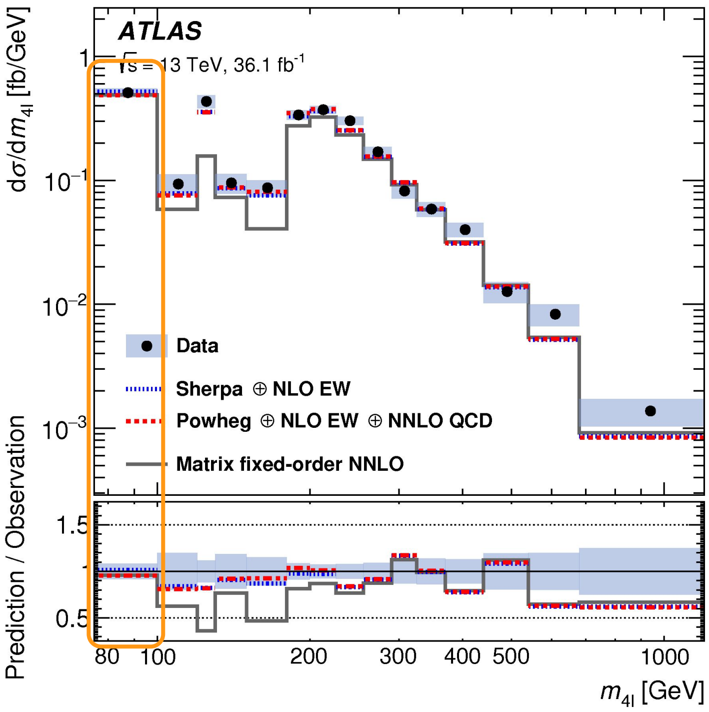
# Z→ llll branching fraction

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



**Interpretation:**

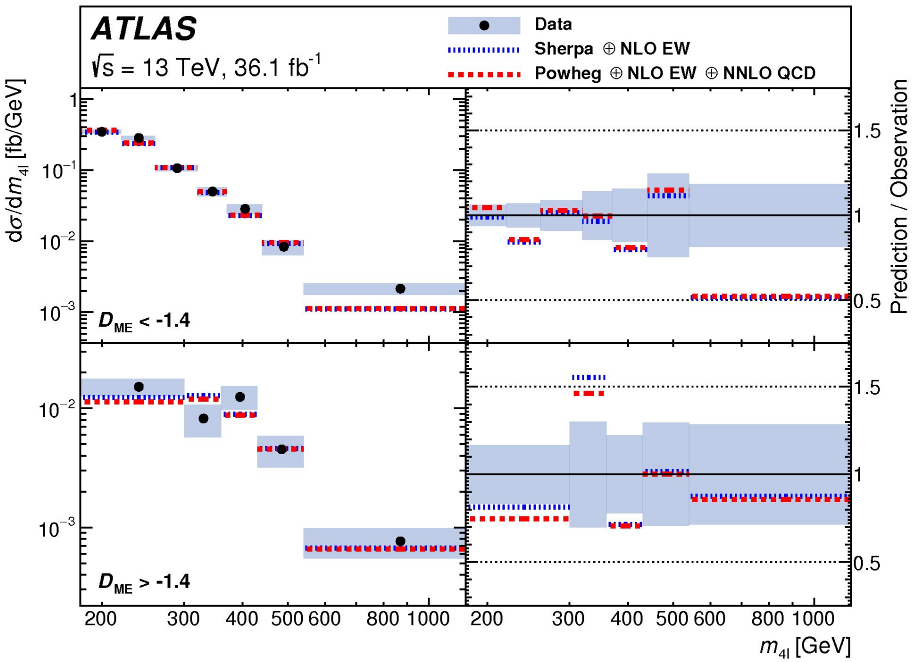
- $N_{\text{fid}}$ is number of detector corrected events in first bin
- $f_{\text{non-res}}$ is the fraction of non-resonant events in this bin
- $\sigma_Z$ is total Z production cross-section
- $\mathcal{L}$ is the luminosity
- $A_{\text{fid}}$ is the acceptance



| Measurement | $\mathcal{B}_{Z\to 4\ell}/10^{-6}$ |
|---|---|
| ATLAS, $\sqrt{s} = 7$ TeV and 8 TeV [8] | $4.31\pm0.34(\text{stat})\pm0.17(\text{syst})$ |
| CMS, $\sqrt{s} = 13$ TeV [6] | $4.83\ ^{+0.23}_{-0.22}(\text{stat})\ ^{+0.32}_{-0.29}(\text{syst})\pm0.08(\text{theo})\pm0.12(\text{lumi})$ |
| **ATLAS, $\sqrt{s} = 13$ TeV** | $\mathbf{4.70 \pm 0.32(stat) \pm 0.21(syst) \pm 0.14(lumi)}$ |

**Measured $\sigma_z$ 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
- ▷ $\mu_H^{OS}$ is measured/observed cross-section for this process

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

**Measured 95% upper limit on signal strength:** 6.5

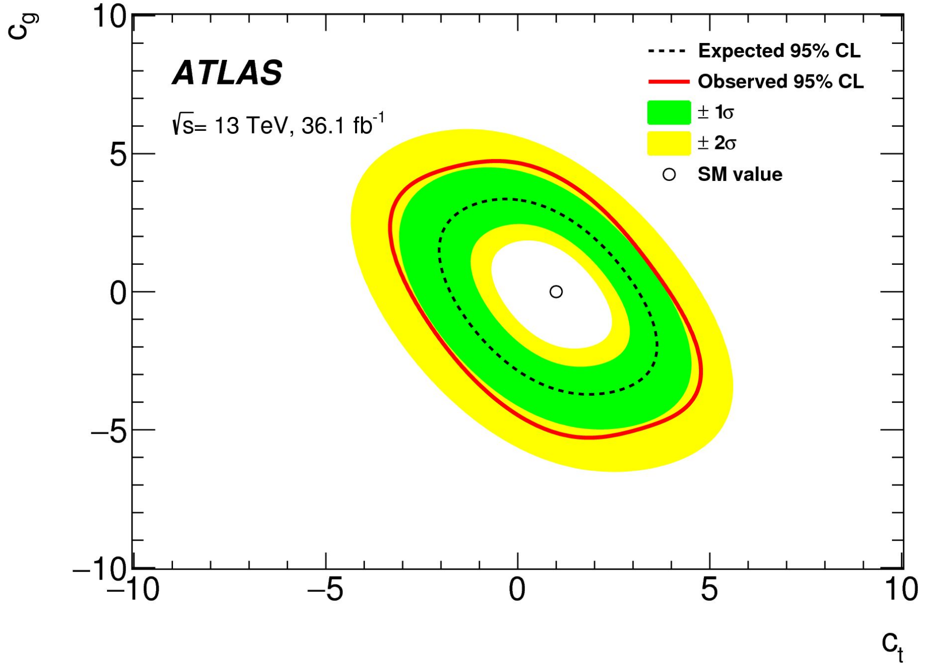
**Expected 95% upper limit on signal strength:** 5.4 [4.2, 7.2]

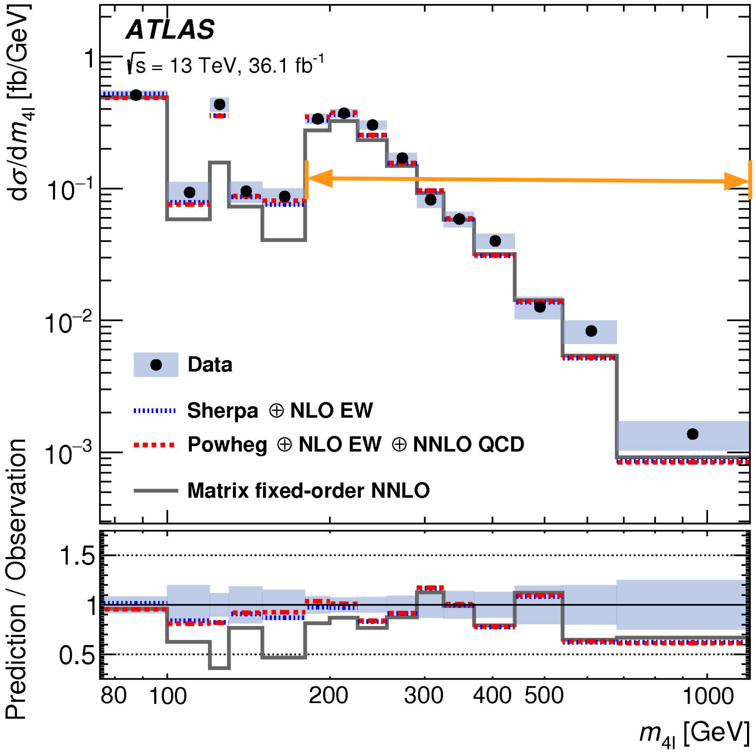
**Reconstruction-level dedicated Higgs result:** 4.5

# Modified Higgs boson 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→ 4l to prediction
- gg→ 4l yield is parameterised as function of couplings
- Vary everything within theoretical uncertainties

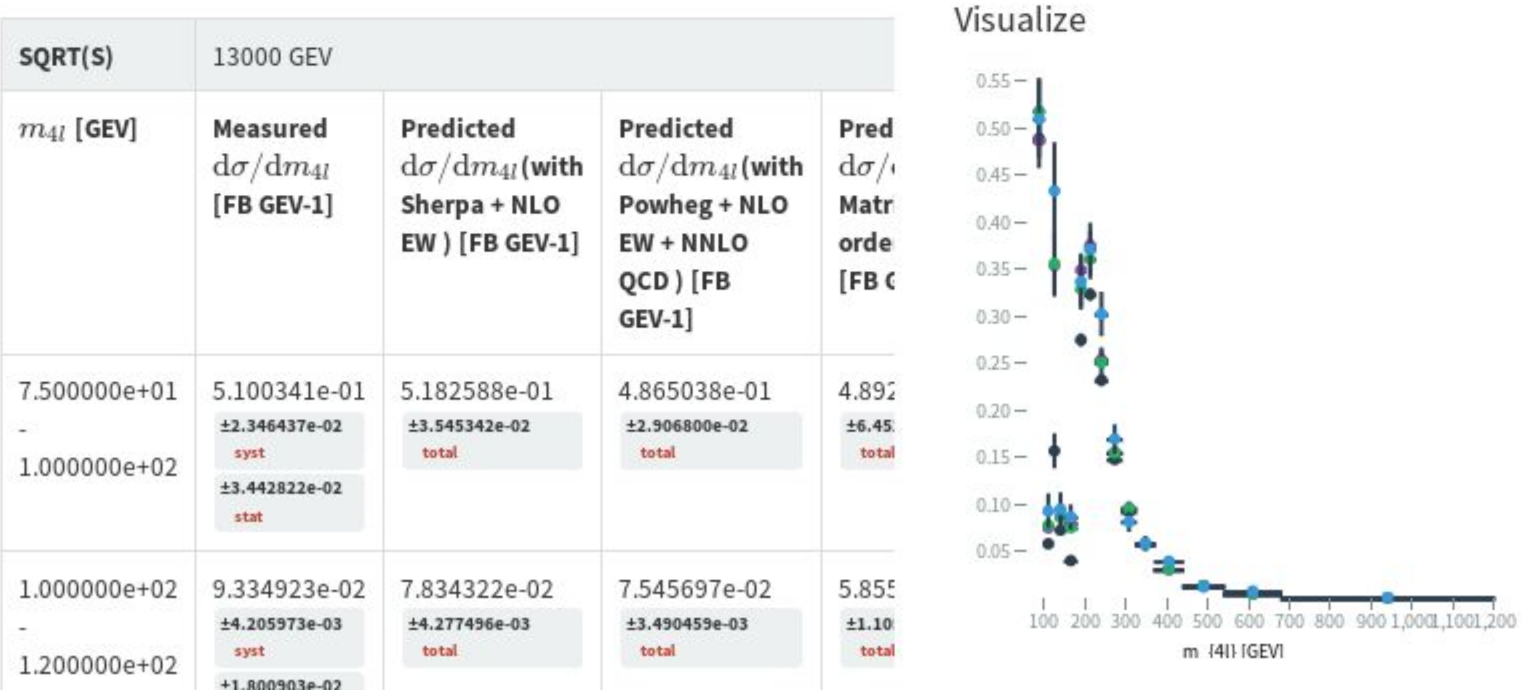
# Re-interpreting

**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, predictions used and sources of uncertainty, as well as covariance matrices split into statistical, systematic and background sources https://www.hepdata.net/record/ins1720442

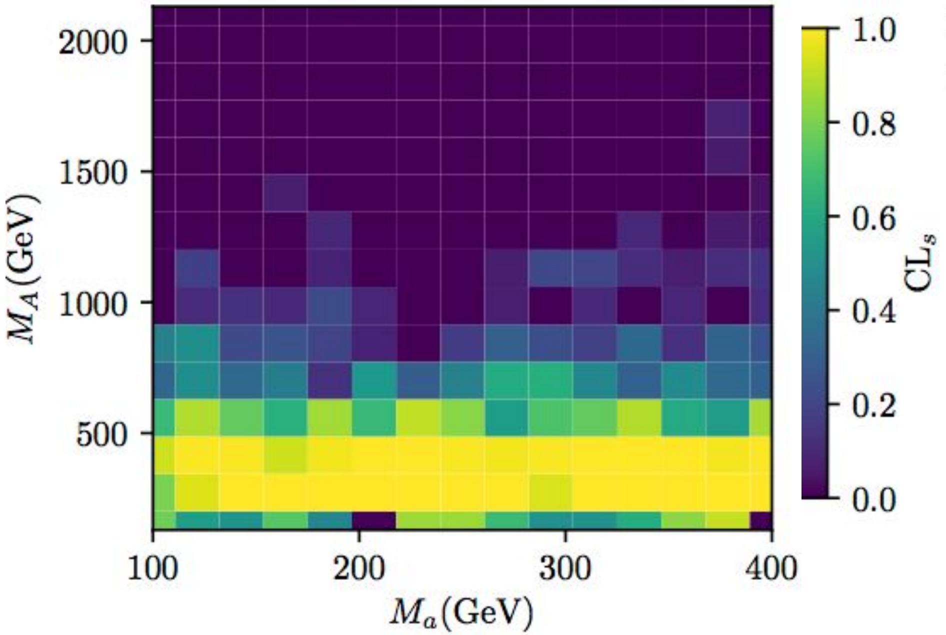


| SQRT(S) | 13000 GEV | | | |
|---|---|---|---|---|
| $m_{4l}$ [GEV] | Measured $d\sigma/dm_{4l}$ [FB GEV-1] | Predicted $d\sigma/dm_{4l}$ (with Sherpa + NLO EW ) [FB GEV-1] | Predicted $d\sigma/dm_{4l}$ (with Powheg + NLO EW + NNLO QCD ) [FB GEV-1] | Pred $d\sigma/$ Matr orde [FB |
| 7.500000e+01 -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

Visualize

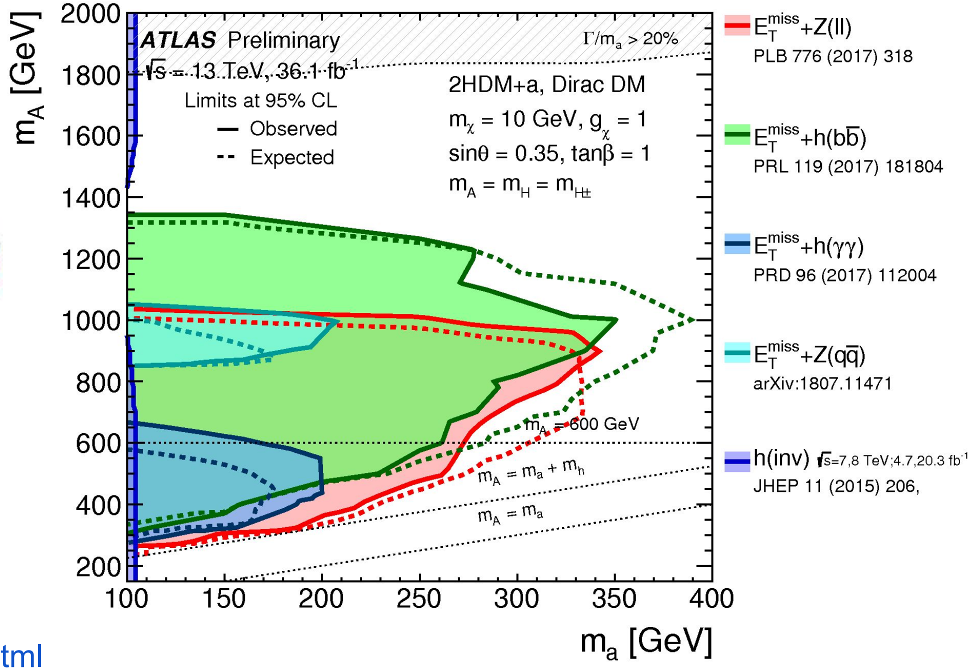
# 2HDM example

## Four Lepton Sensitivity



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

## Existing Search Limits



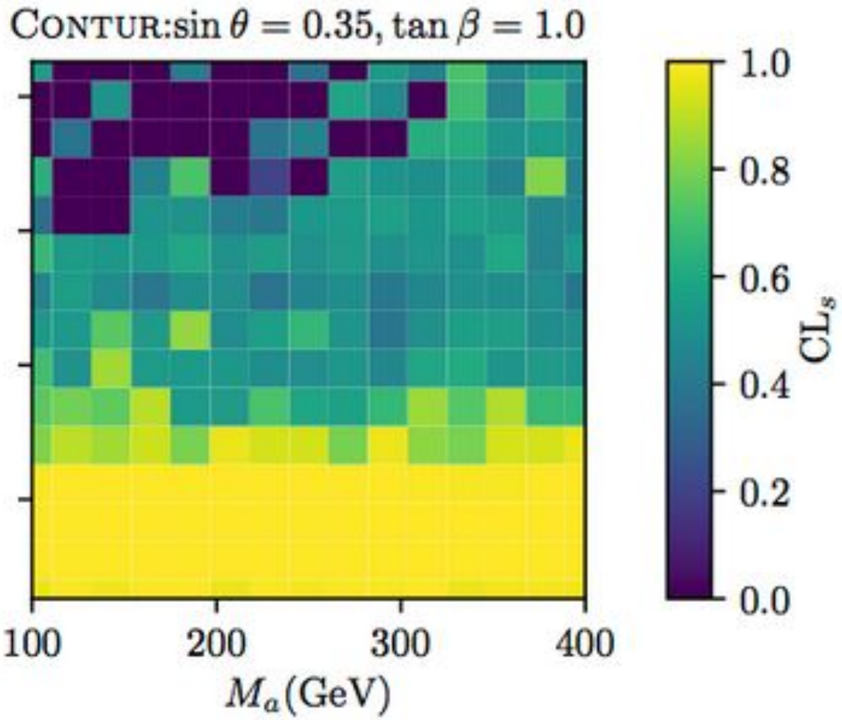
### Two Higgs-Doublet Dark Matter Model with Pseudoscalar Mediator:

- 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

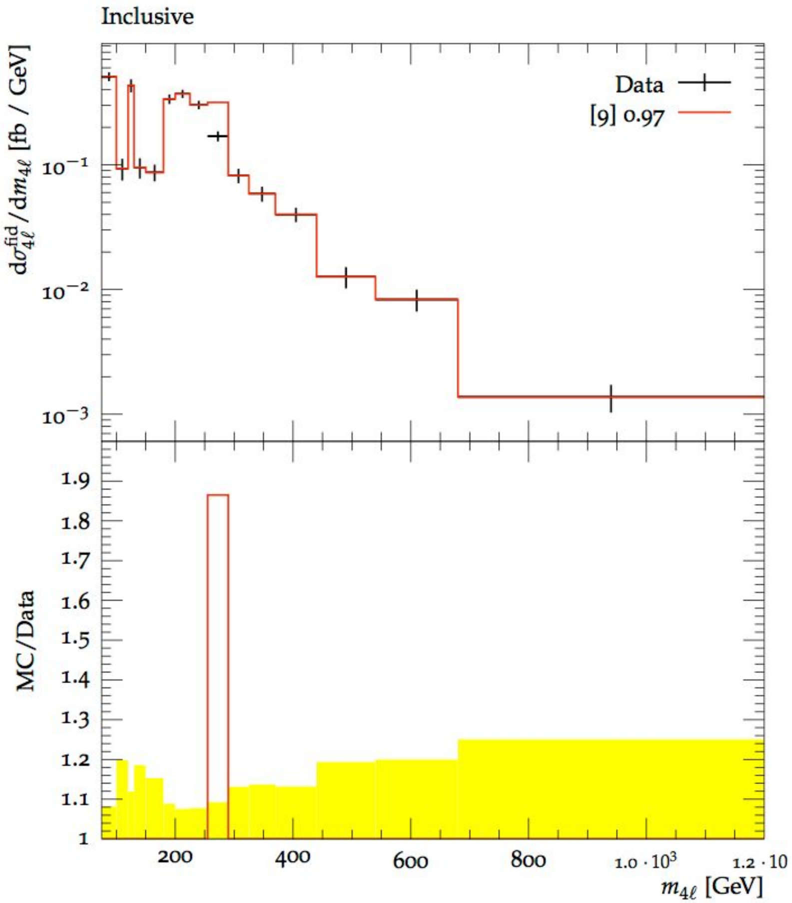
- Lots of models can produce four leptons
- In this case, cover region of phase space not excluded by ATLAS yet
- Quick and easy to check many final states, new models and mess with parameter settings

# 2HDM example

**Combined CONTUR sensitivity**



**Four Lepton Sensitivity - MA=270 GeV, Ma = 230 GeV**

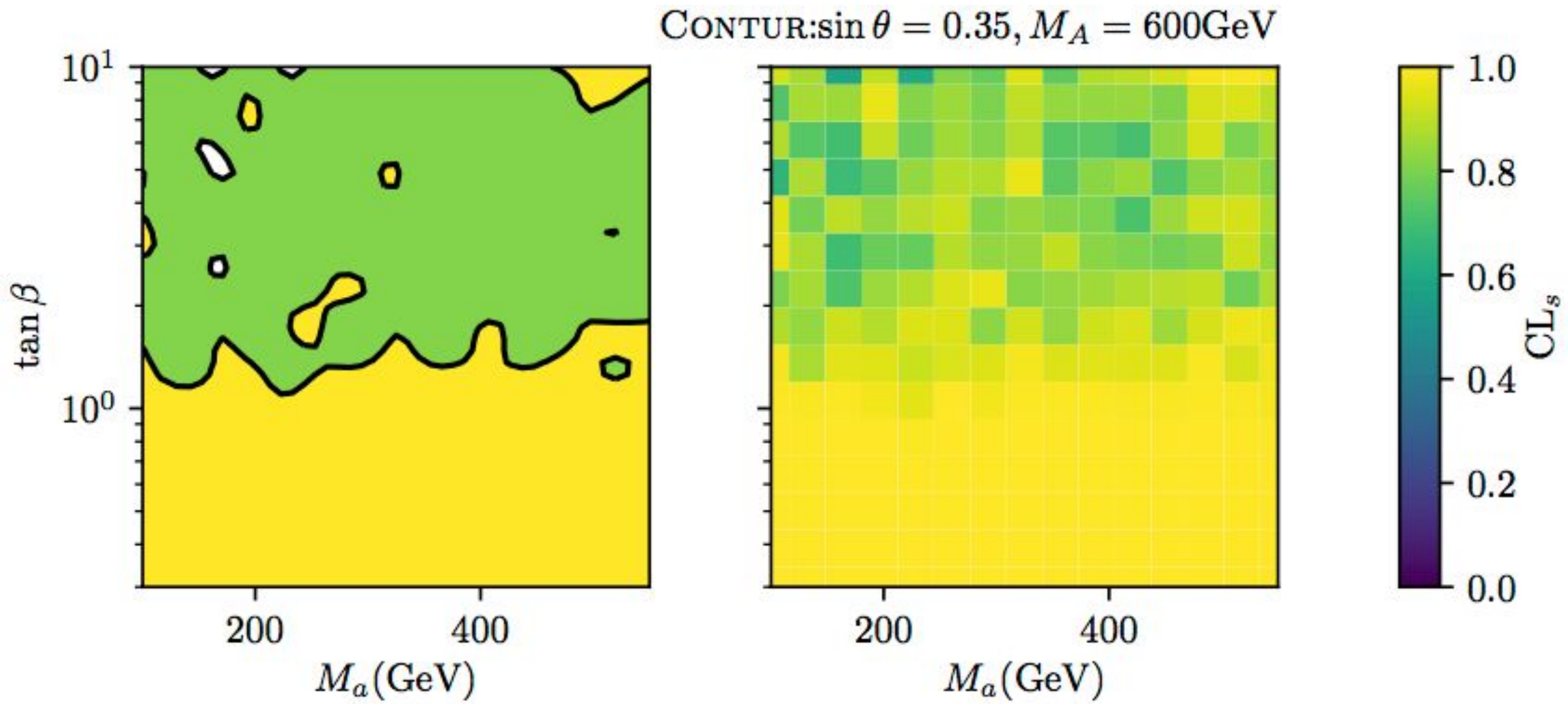


- Can see which bin is sensitive - CONTUR uses *one per analysis* currently to avoid correlations
- Can combine sensitivity from all available analyses

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

# 2HDM example

**Varying other parameters**



- Sensitivity for all combined analyses.
- Easy to make changes to model and re-run
- Can also split to see main contributions to sensitivity

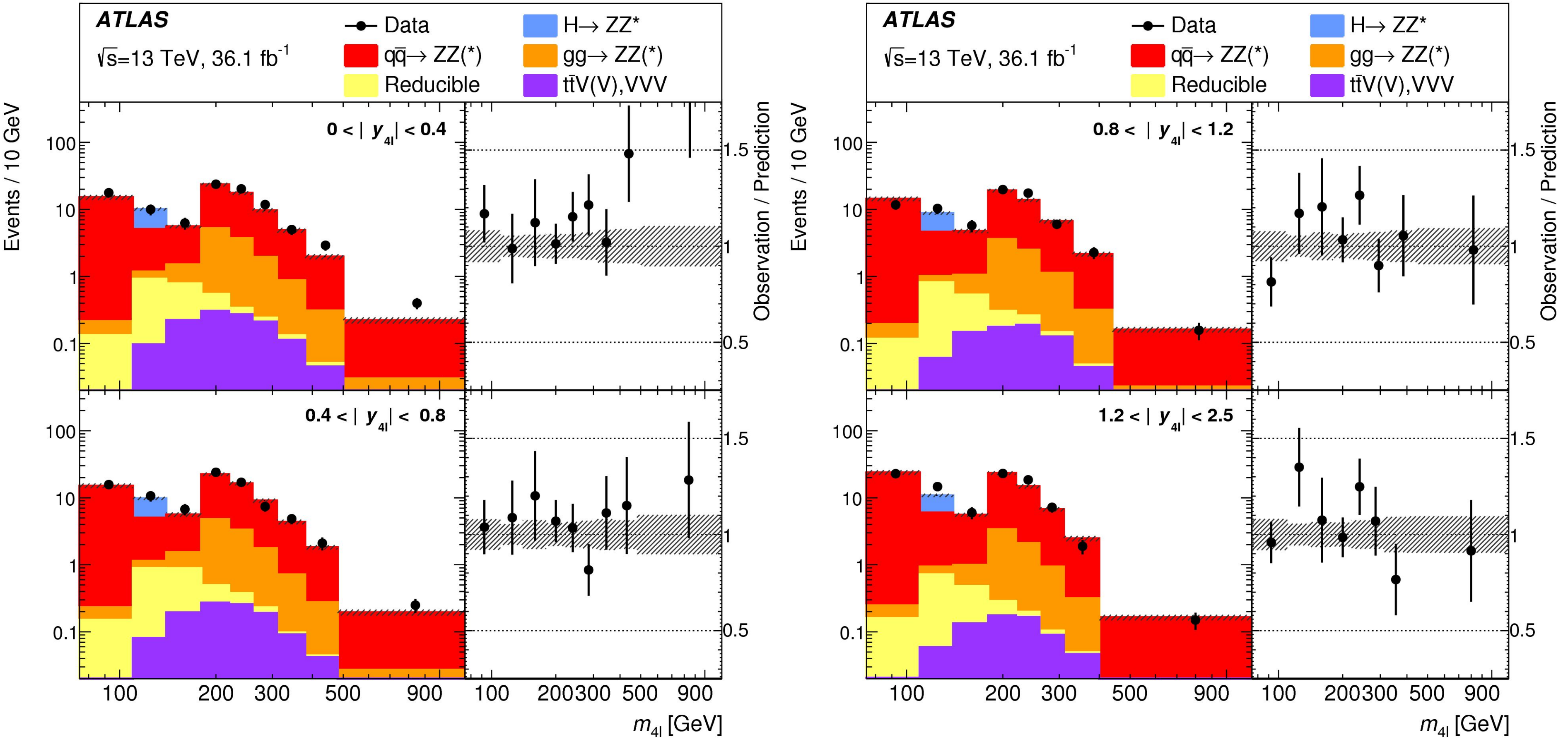
https://contur.hepforge.org/results/Pseudoscalar_2HDM/index.html

# Summary

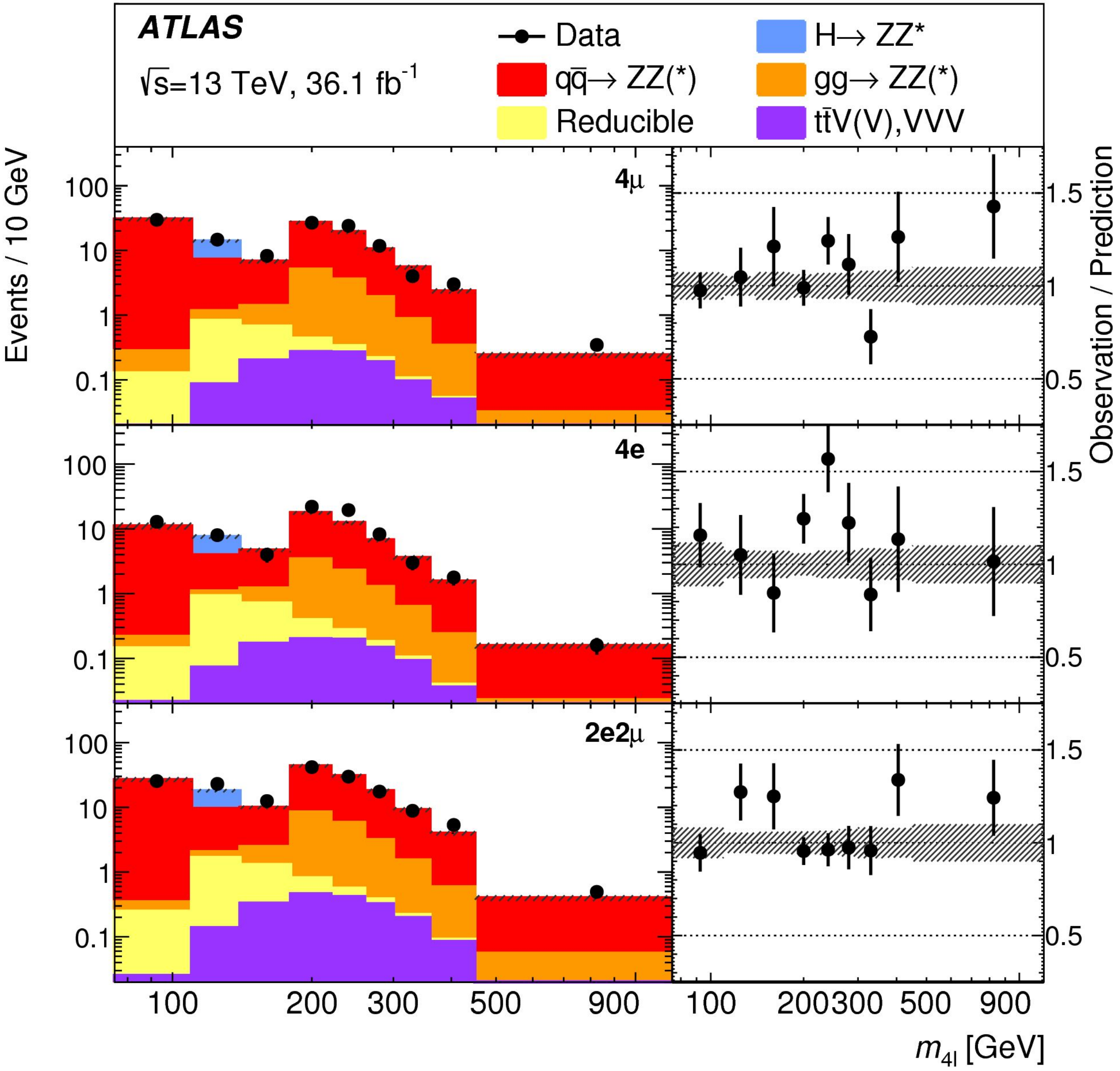
- **Four Lepton** events measured by ATLAS sensitive to wide range of physics processes
- Select **same flavour opposite charge** lepton pairs with mass close to Z boson mass
  - Low contribution from backgrounds
  - Look at **mass** of four leptons in both selected pairs
- **Correct for effects of detector** on observed physics objects and kinematic properties
- Resulting 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**
- Complements traditional searches

# Backup

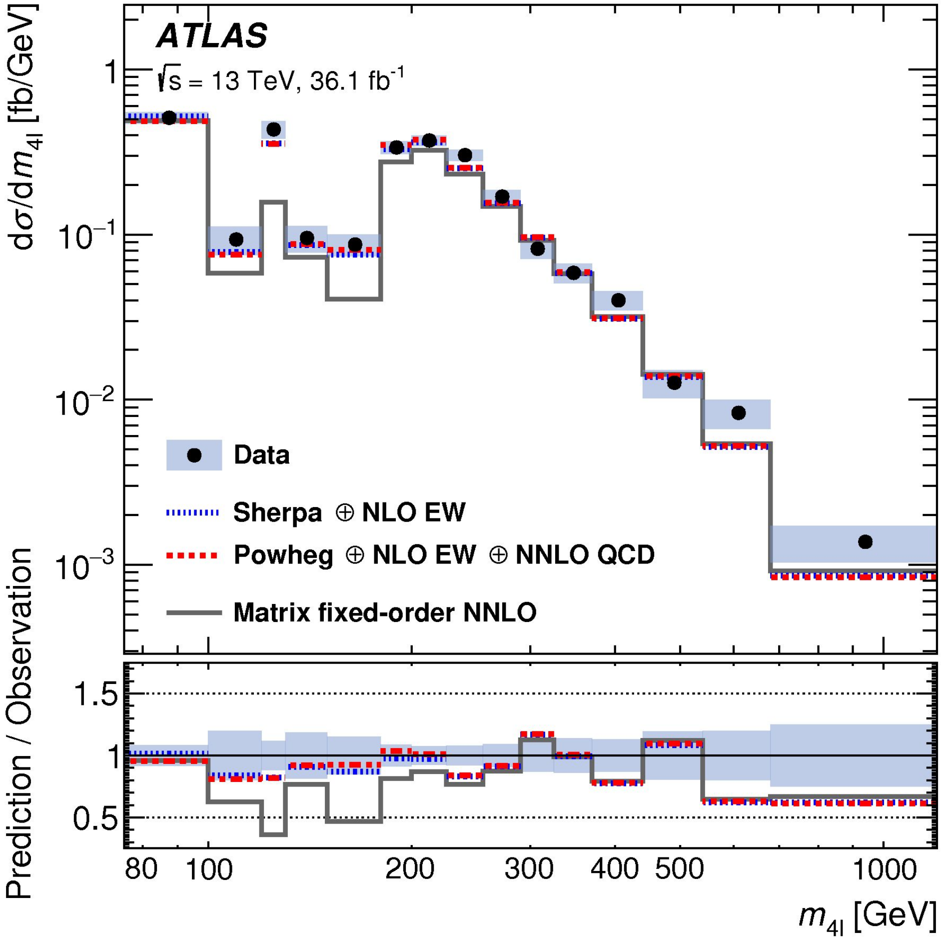
# Double differential example - $y_{4l}$



# Double differential example - flavour



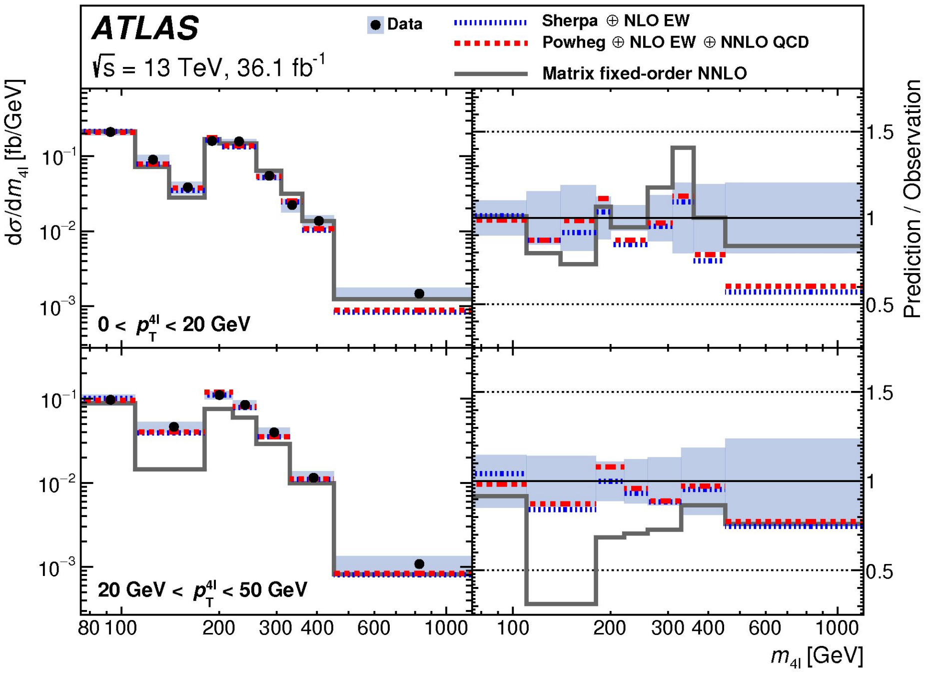
# Differential Cross-sections

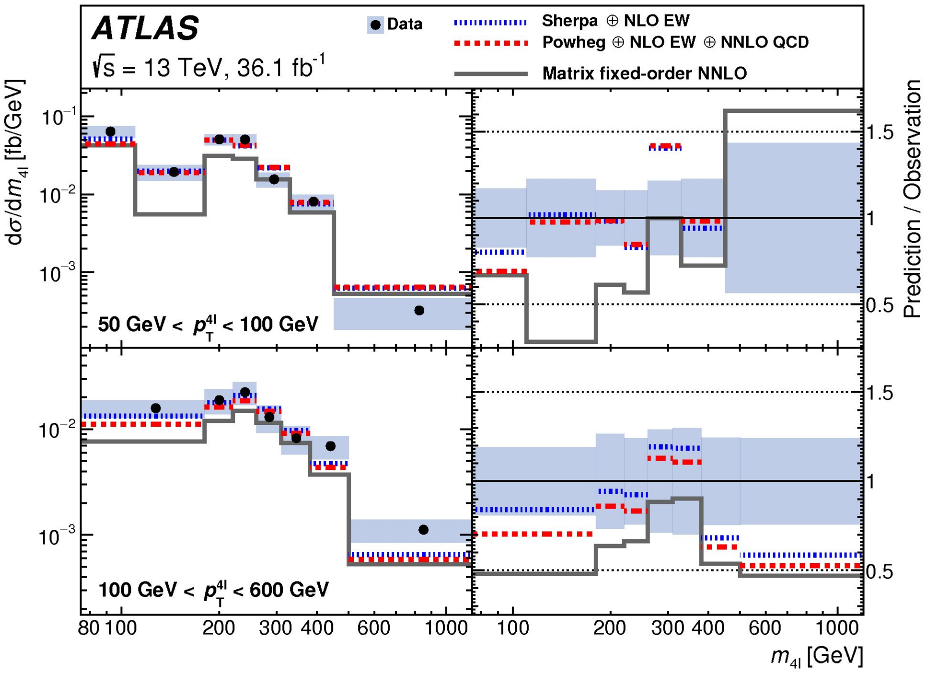


**Comparison to various predictions:**

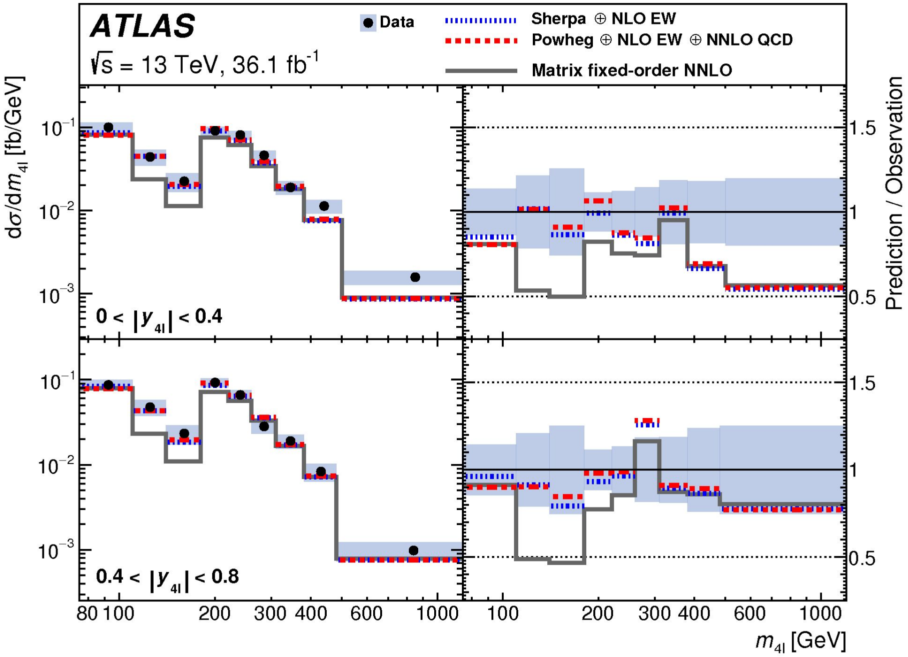
- Sherpa and Powheg agree very well → validates reweighting of Powheg with MATRIX NNLO QCD k-factors
- Sherpa doesn't need this, intrinsic higher accuracy sufficient
- Missing real wide-angle QED emission in events for on-shell ZZ causes underestimation from MATRIX wrt full generators
- gg→ 4l and higgs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

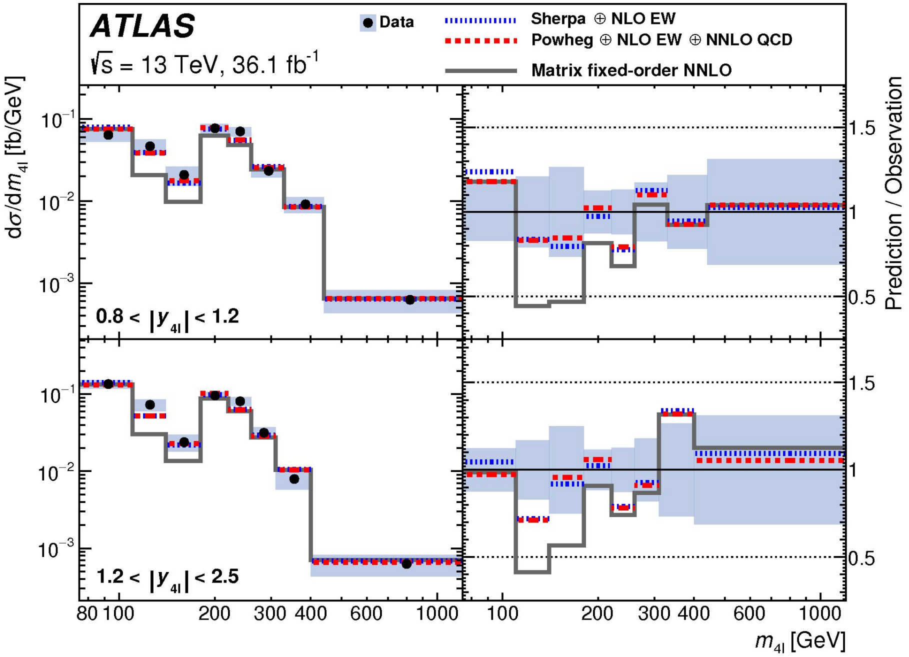
# Differential Cross-sections - $P_T^{4l}$



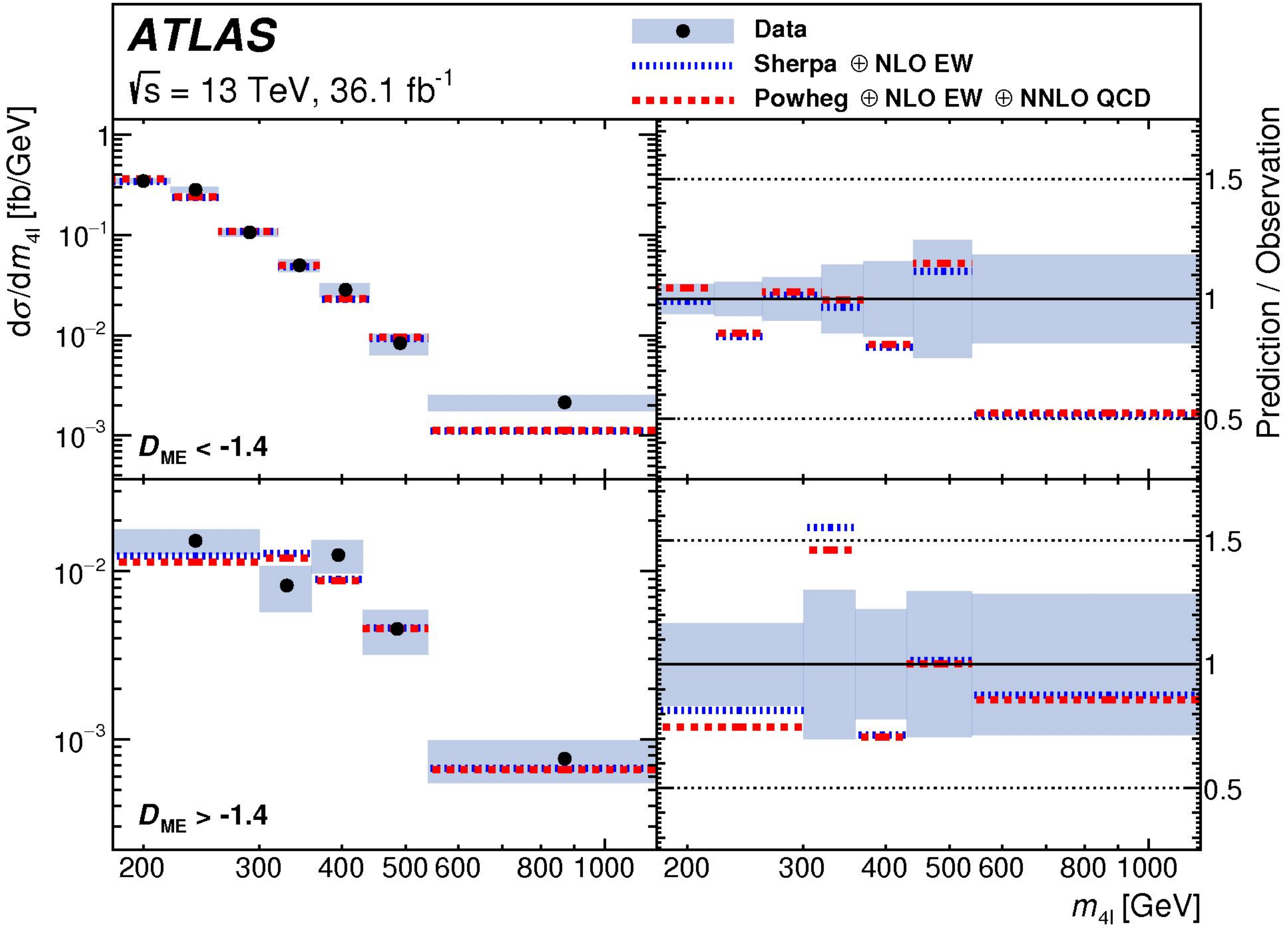


# Differential Cross-sections - $Y_{4l}$





# Differential Cross-sections - $D_{ME}$



# Met + jets cross-section

- Measure ratio of cross-section for Z→ νν to Z→ ll processes
- Cancel a lot of sources of uncertainty
- Sensitive to BSM scenarios producing missing transverse energy and jet(s)
- Limits comparable to detector-level search
- Results re-interpretable for any model with these criteria