

Searches for invisible Higgs boson decays at the ATLAS experiment

Ben Rosser

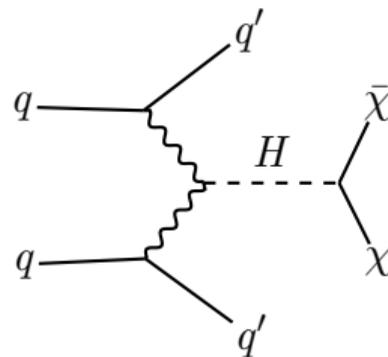
University of Pennsylvania
On behalf of the ATLAS collaboration

July 28, 2020

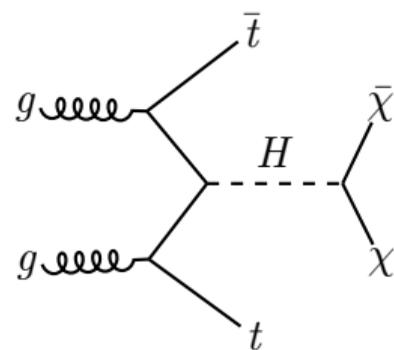


Introduction: Higgs to Invisible

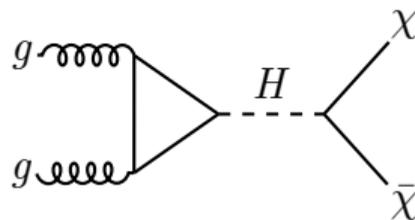
- Search for signature of Higgs production plus large missing transverse momentum.
- Very unlikely process in Standard Model; branching ratio $\mathcal{B}_{H \rightarrow \text{inv.}} \approx 1.05 \times 10^{-3}$ (from $H \rightarrow ZZ^* \rightarrow 4\nu$).
- Can be significantly enhanced in various BSM scenarios, including Higgs coupling to dark matter ("Higgs portal").
- Most sensitive channel is vector boson fusion (**VBF**); stronger background rejection than gluon-gluon fusion (**ggF**) due to its distinct event topology.



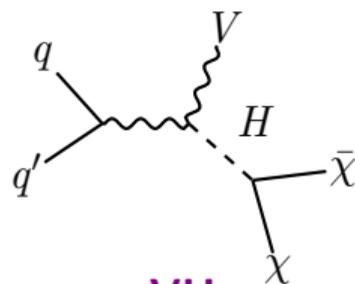
VBF



ttH

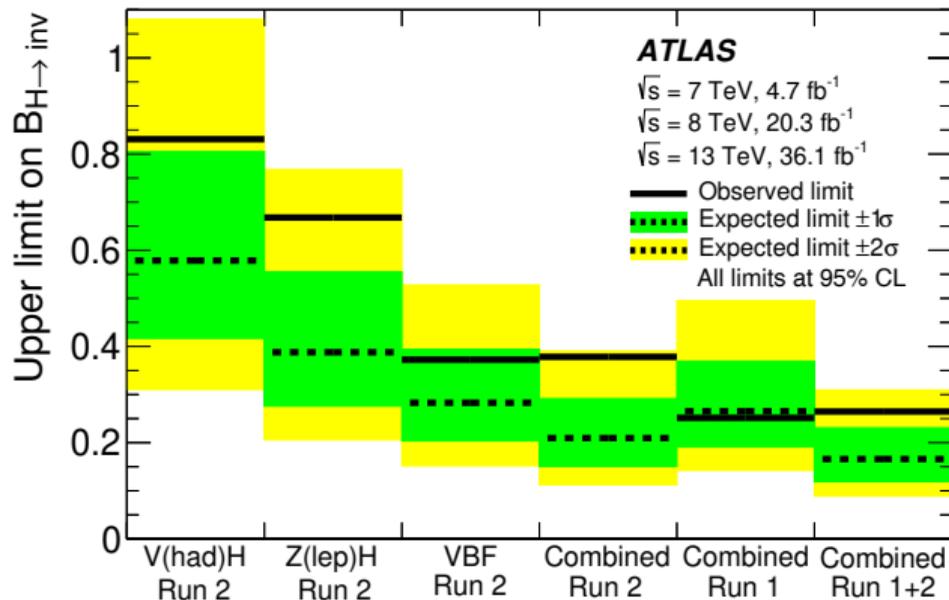


ggF



VH

Invisible Analyses in ATLAS

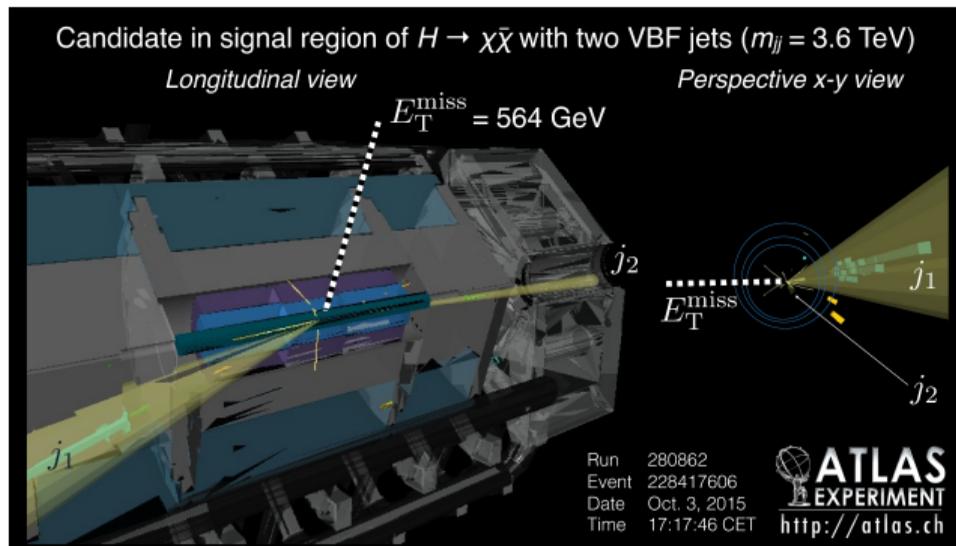


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- Previous observed (expected) ATLAS limits on $\mathcal{B}_{H \rightarrow \text{inv}}$ with partial run 2 data:
 - **V(had)H:** 0.83 ($0.58^{+0.23}_{-0.16}$)
 - **Z(lep)H:** 0.67 ($0.39^{+0.17}_{-0.11}$)
 - **VBF:** 0.37 ($0.28^{+0.11}_{-0.08}$)
 - **Combination:** 0.26 ($0.17^{+0.07}_{-0.05}$)
- New results with full run 2 (139 fb^{-1}) data! Will discuss today:
 - Updated **VBF** result released in April: [ATLAS-CONF-2020-008](#)
 - New interpretation of **mono-jet** analysis (**ggF**), released for ICHEP: [ATLAS-CONF-2020-048](#)

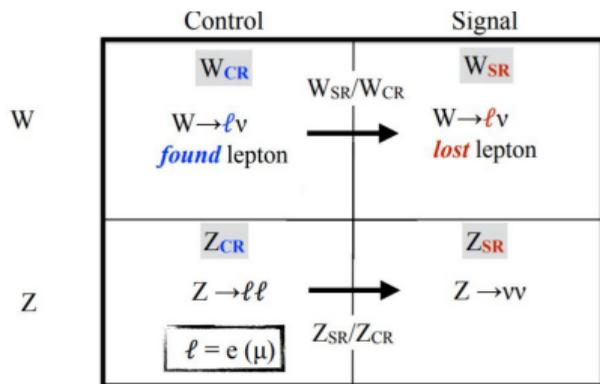
VBF Higgs to Invisible

- VBF analysis strategy: search for jet pair with large rapidity gap plus large E_T^{miss} .
- Main backgrounds: $Z(\nu\nu)$ +jets, $W(l\nu)$ +jets with lost lepton.
- Changes from previous 36.1 fb^{-1} result:
 - Reoptimized analysis; increased Higgs signal acceptance by 50%.
 - 1D m_{jj} binning replaced with 3D m_{jj} , $\Delta\phi_{jj}$, N_{jets} binning.
 - Work to improve V+jets modelling and reduce MC stat uncertainty in background estimation.
- See [Amanda Steinhebel's poster](#) for more information!

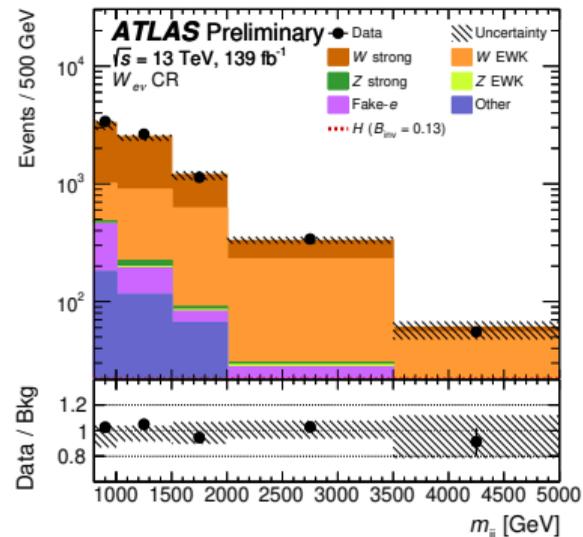
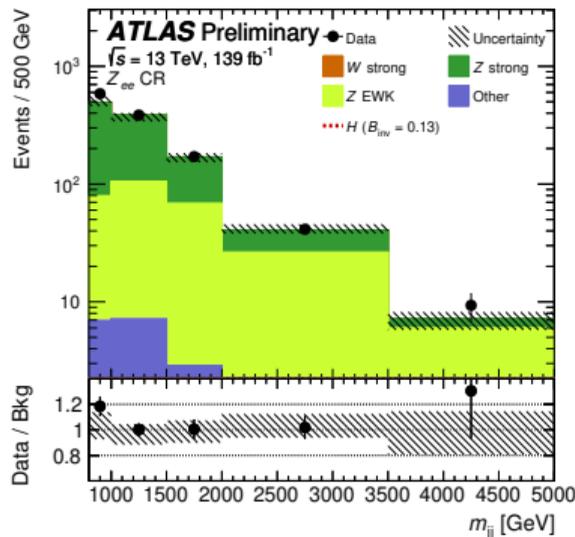


- Two jets in opposite hemispheres, not back to back.
- No additional central jets.
- Large dijet invariant mass, $m_{jj} > 0.8 \text{ TeV}$.
- Large $E_T^{\text{miss}} > 200 \text{ GeV}$.

V+jets Background Modelling

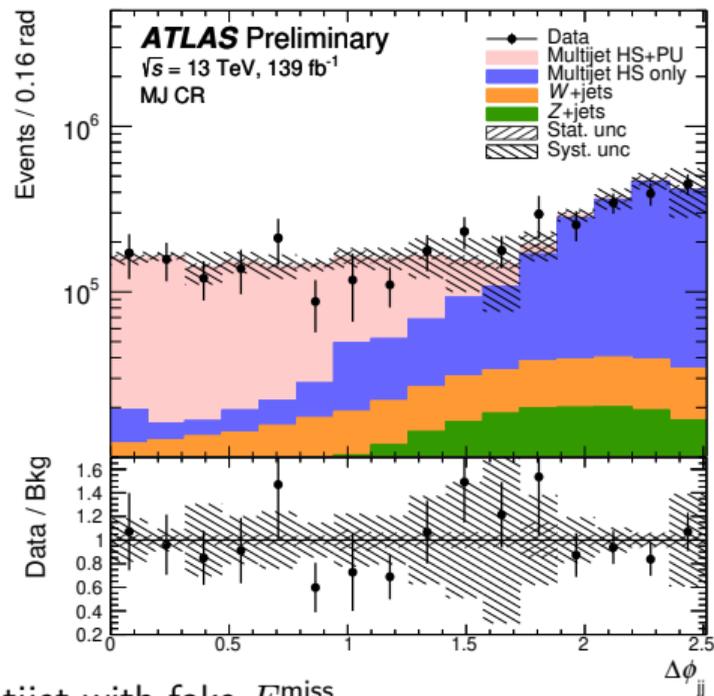
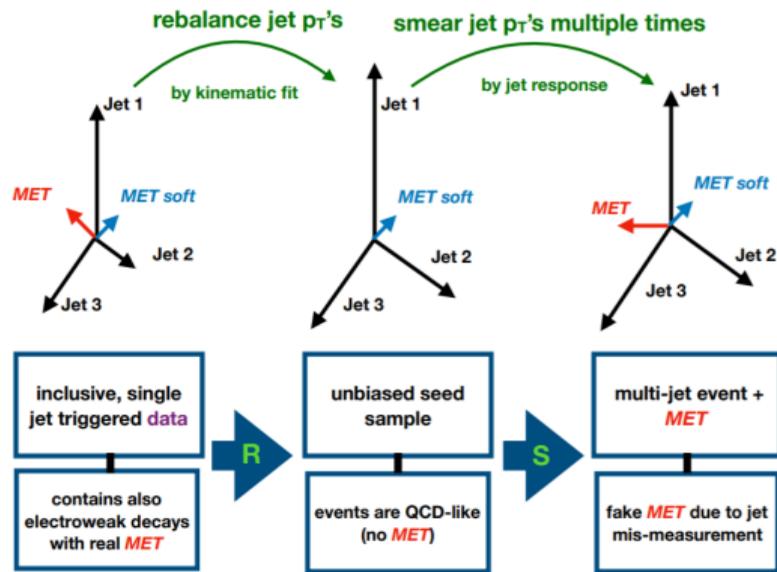


$$B_{estimate}^{SR} = N_{data}^{CR} \frac{B_{MC}^{SR}}{B_{MC}^{CR}}$$



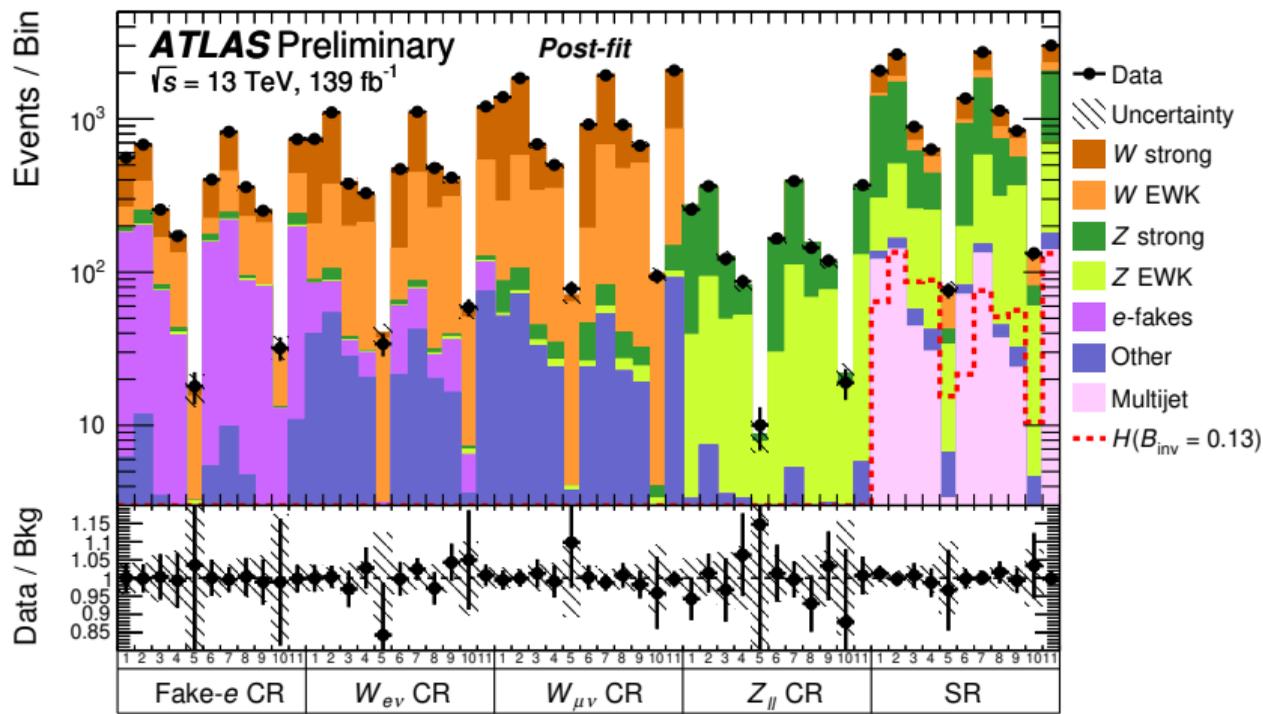
- Partially data-driven technique: transfer factors from one (W), two (Z) lepton control regions.
- Collaborated with Sherpa authors to enhance high m_{ij} phase space in NLO V+jets MC.
- Signal region MC (B_{MC}^{SR}) rescaled by control region data/MC ratio ($N_{data}^{CR}/B_{MC}^{CR}$).
- Procedure done for each bin; separate transfer factors for W and Z processes.

Multijet Background Estimation



- Data-driven rebalance and smear technique for multijet with fake E_T^{miss} .
- Hard-scatter, hard-scatter + pileup components normalized by fit to $\Delta\phi_{jj}$ in loose multijet control region ($E_T^{\text{miss}} > 100 \text{ GeV}$, $m_{jj} > 200 \text{ GeV}$). Closure checked in low- E_T^{miss} and low- m_{jj} signal region.

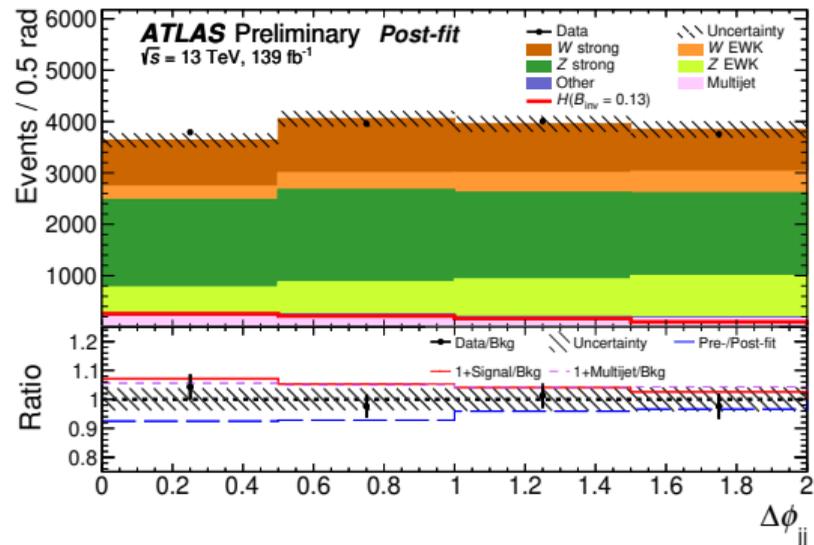
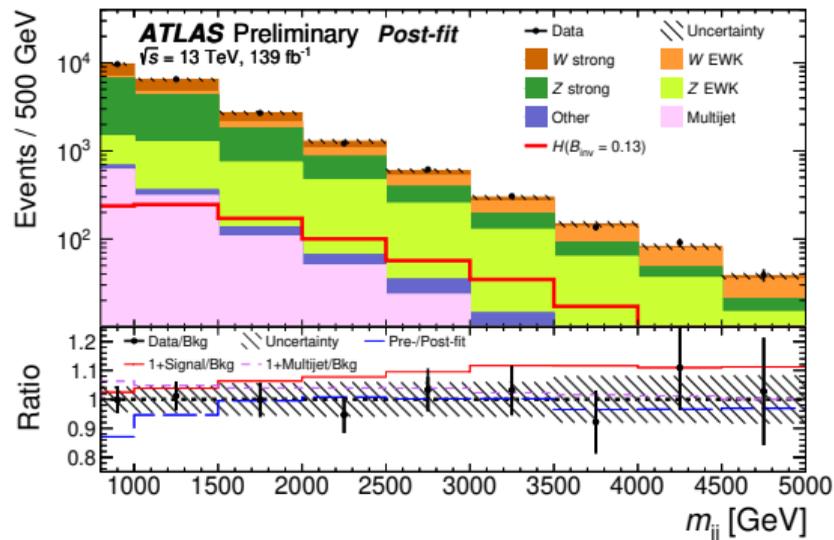
VBF Fit Results



- Transfer factors from W, Z regions applied in simultaneous 5×11 -bin fit across all regions.
- Extra fake electron transfer factor to estimate misidentified multijet background in $W_{e\nu}$ control region.
- No significant disagreement with background seen after fit.

VBF Post-Fit Distributions

- Post-fit distributions show consistency with background-only hypothesis.
- Higgs signal normalized to expected limit on $\mathcal{B}_{H \rightarrow \text{inv}}$.
- Signal yield **87% VBF**, 12% ggF, remainder VH.

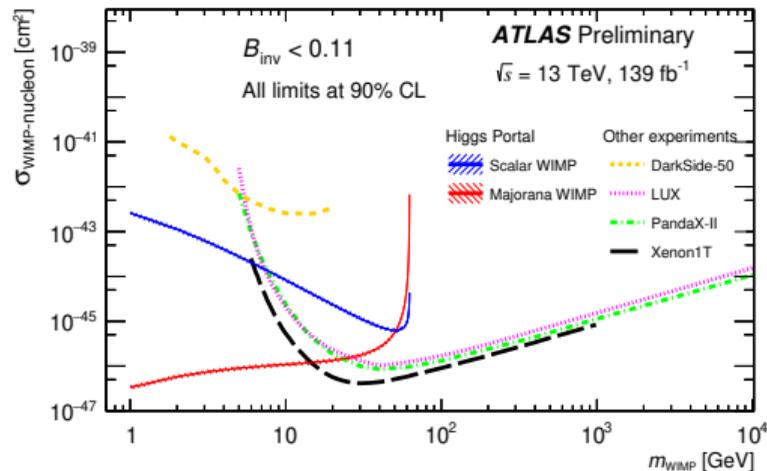


Full Run 2 VBF Limit

| Observed | Expected | +1 σ | -1 σ | +2 σ | -2 σ |
|----------|----------|-------------|-------------|-------------|-------------|
| 0.132 | 0.132 | 0.183 | 0.095 | 0.248 | 0.071 |

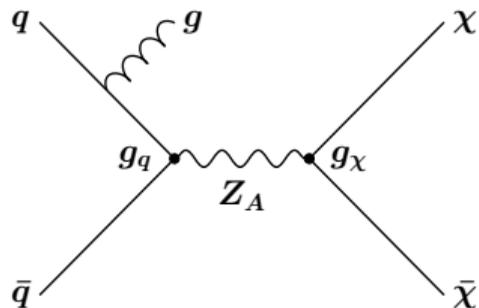
- 95% confidence upper limit $\mathcal{B}_{H \rightarrow \text{inv.}}$ set at **0.13**.
- Significant improvement from 36.1 fb⁻¹ result: 0.37 (0.28^{+0.11}_{-0.08}).
- Largest impact Δ on limit from data statistics, followed by background estimation (V+jets and multijet).

| Source | Δ [%] |
|-----------------------|--------------|
| Jet energy scale | 1.8 |
| Jet energy resolution | 5.5 |
| Lepton | 4.6 |
| Other | 1.9 |
| Multijet | 7.0 |
| V+jets theory | 1.6 |
| Signal theory | 1.0 |
| MC stats. | 7.9 |
| Data stats. | 17.3 |

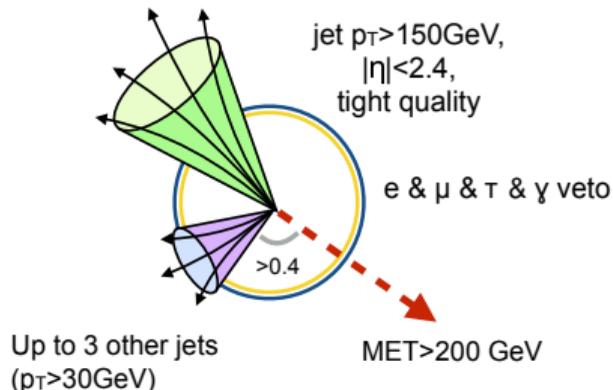


- $\mathcal{B}_{H \rightarrow \text{inv.}}$ limit interpreted as limit on spin-independent WIMP-nucleon elastic scattering cross-section in Higgs portal model.
- Complementary with direct detection experiments.

Monojet: Introduction



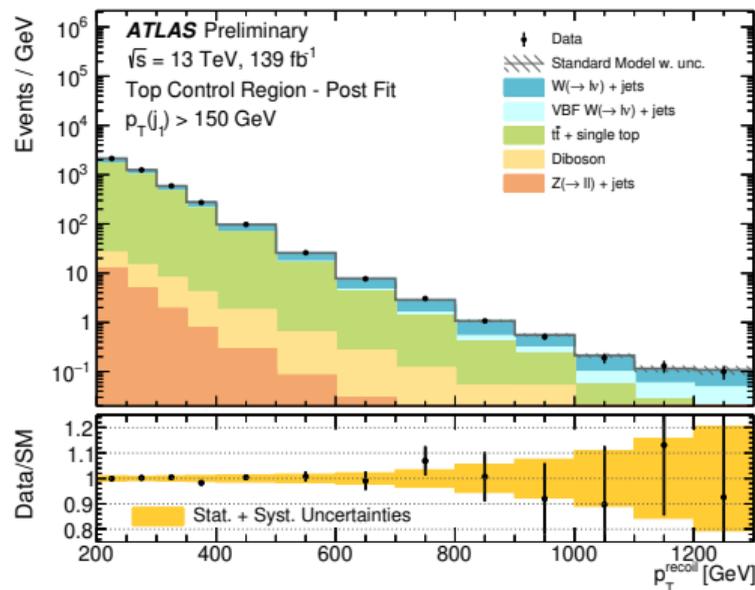
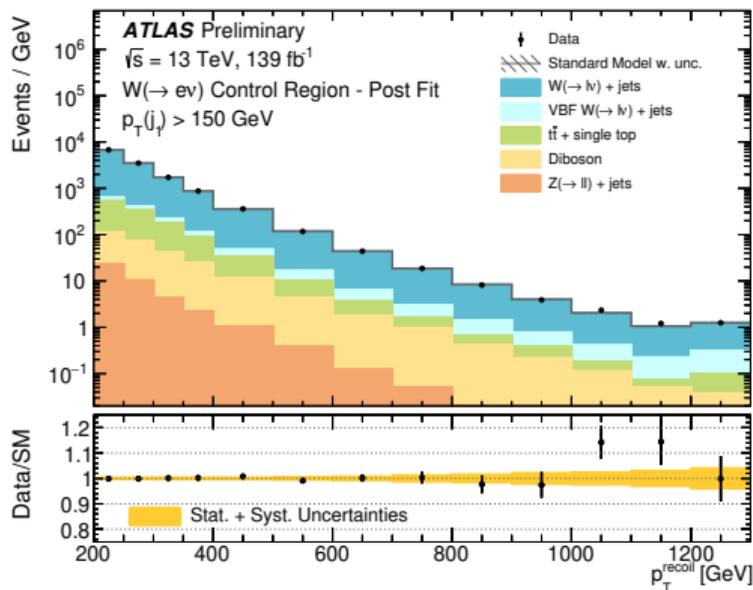
MET trigger



- Monojet analysis strategy: search for at least one jet (initial state radiation) plus large E_T^{miss} .
- Main backgrounds same as VBF: strong $Z(\nu\nu)$ +jets, $W(l\nu)$ +jets with lost lepton.
- Many possible dark matter interpretations, including ggF Higgs to invisible. (See [Ben Carlson's talk](#) for more!)
- Improvements since previous analysis:
 - E_T^{miss} and jet p_T thresholds lowered from 250 GeV; increased sensitivity at low E_T^{miss} .
 - Lepton and photon vetoes tightened, reducing background.
 - Collaboration with theorists to improve modelling of V+jets backgrounds.

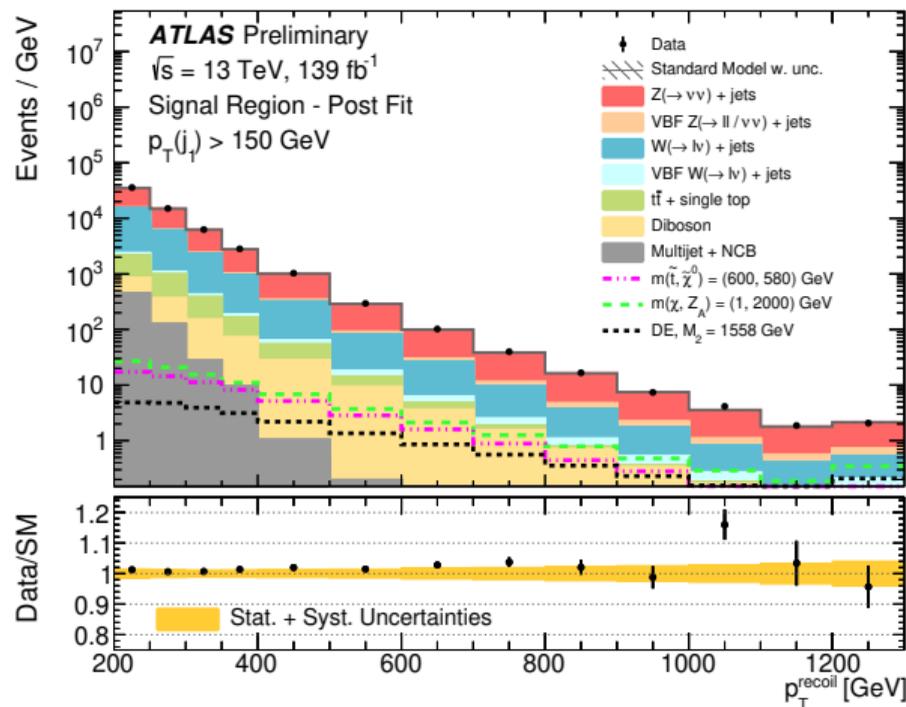
Monojet Background Estimation

- MC reweighted to NNLO QCD, nNLO EW accuracy using analytic calculations as function of boson p_T ; Z and W processes correlated ([Eur. Phys. J. C77 \(2017\) 829](#)).
- One transfer factor for both Z, W; plus two for $t\bar{t}$, single- t from top region (1 lepton, 1 b-jet).
- Control regions defined using p_T^{recoil} : vector sum of E_T^{miss} and lepton(s).



Monojet Results and H(Invisible) Interpretation

- Simultaneous shape fit to p_T^{recoil} ; no significant excess observed.
- Total uncertainty **1.2 to 4.1%** across all bins: more than 2x improvement from 36.1 fb^{-1} analysis.
- Main systematics:
 - Electron, muon ID and reco.
 - At low p_T^{recoil} : multijet.
 - At high p_T^{recoil} : V+jets estimation.
- Higgs to invisible interpretation:
 - 95% observed (expected) limit on $\mathcal{B}_{H \rightarrow \text{inv.}} = \mathbf{0.63 (0.57)}$.
 - Signal yields: **54% ggF**, followed by 34% VBF and 12% VH.

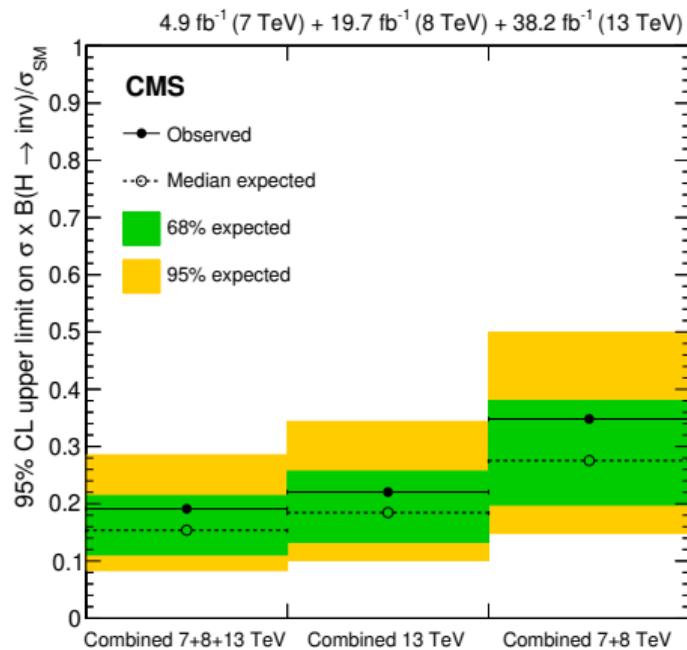
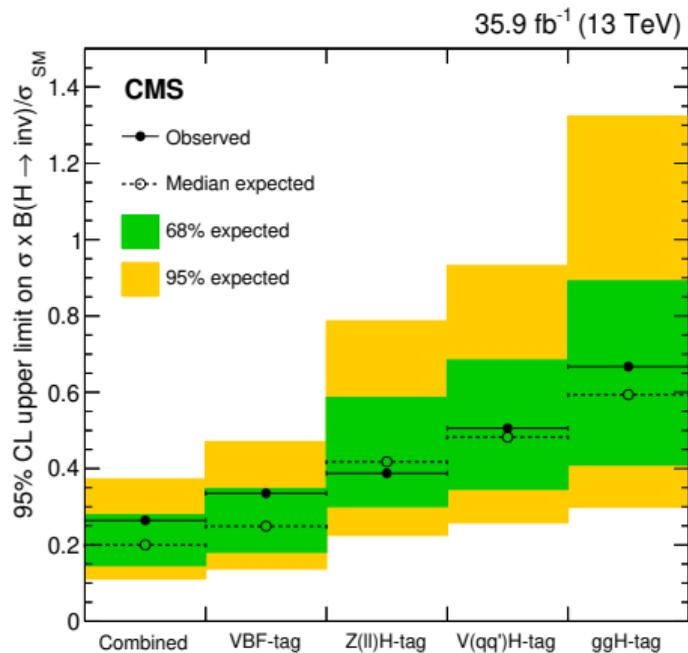


- Presented two full run 2 ATLAS searches for invisible Higgs decays:
 - VBF limit on $\mathcal{B}_{H \rightarrow \text{inv.}} = 0.132$ (0.132) significantly improved from ATLAS 36.1 fb⁻¹ results.
 - Compare with previous VBF channel (0.37 (0.28^{+0.11}_{-0.08})) and combination (0.26 (0.17^{+0.07}_{-0.05})).
 - First run 2 ATLAS limits on $\mathcal{B}_{H \rightarrow \text{inv.}}$ from monojet: 0.63 (0.57).
- Both results will be included in forthcoming Higgs to Invisible combination.
- Thank you for your attention!

Backup

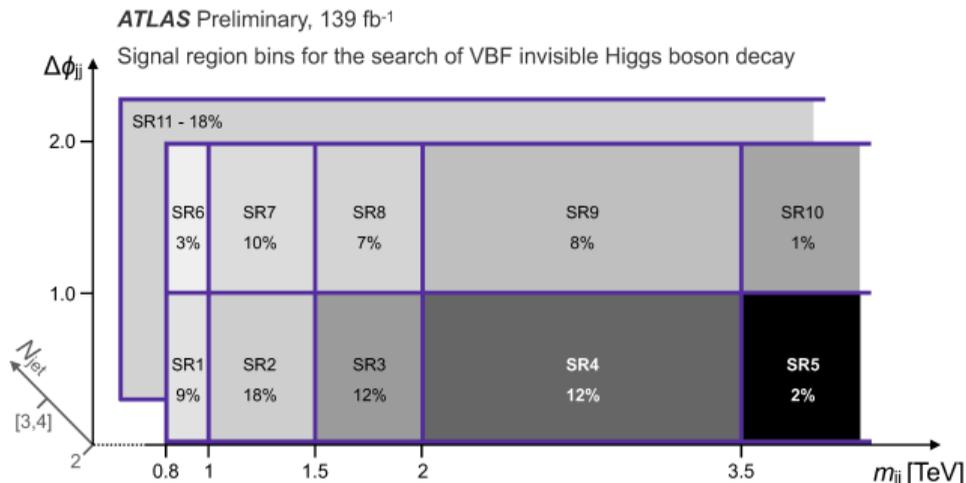
Results from CMS

- CMS limits on $\mathcal{B}_{H \rightarrow \text{inv.}}$ with 36.1 fb^{-1} of data (*Phys.Lett.B* 793 (2019) 520-551).
- VBF channel: observed (expected) limit: 0.33 (0.25).
- Run 1+2 combination: 0.19 (0.15), compared to ATLAS result: $0.26 (0.17^{+0.07}_{-0.05})$.



VBF Reoptimization and Selection

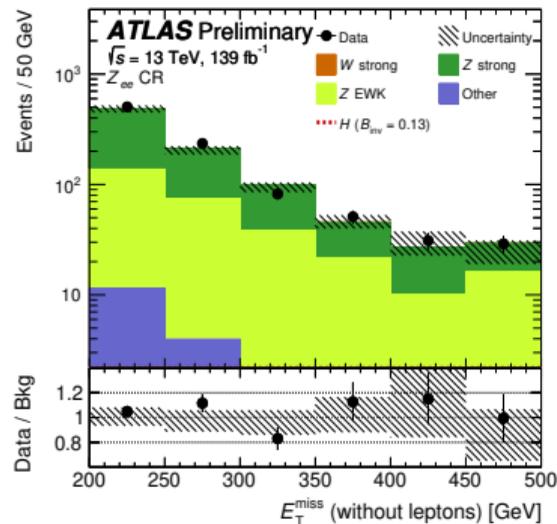
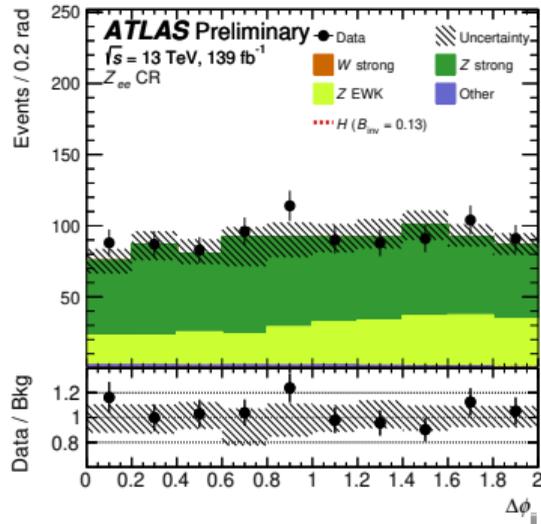
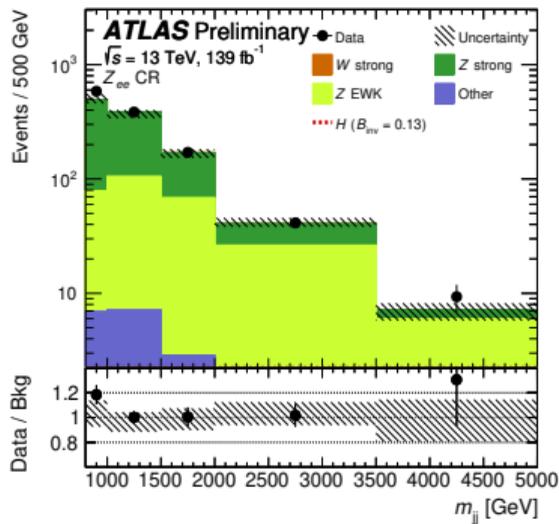
- VBF reoptimization done using 36.1 fb^{-1} dataset:
 - $m_{jj} > 0.8 \text{ TeV}$ (formerly 1 TeV).
 - $m_{jj} > 3.5 \text{ TeV}$ events separated into their own bin.
 - $\Delta\phi_{jj} < 2.0$ (formerly 1.8).
 - Third jet veto loosened, replaced with central jet veto.
- Higgs signal acceptance increased by 50%.



- 2D binning for events with $N_{\text{jets}} = 2$; five m_{jj} bins and two $\Delta\phi_{jj}$ bins.
- Eleventh bin for events with $N_{\text{jets}} = 3$ or 4 .
- Plot shows distribution of Higgs signal across bins.

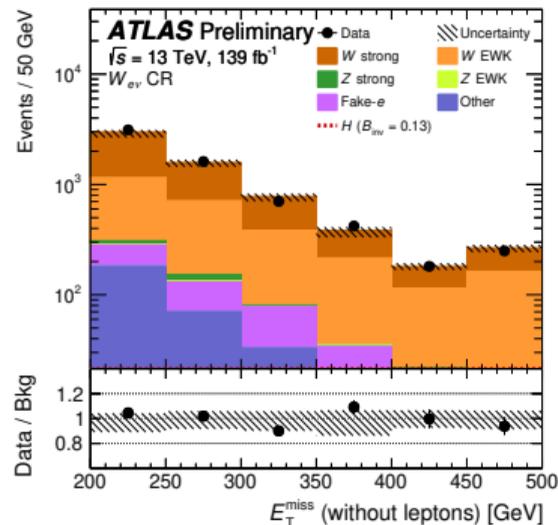
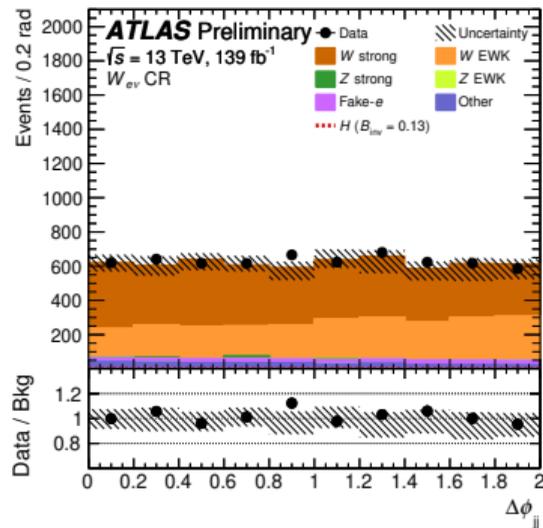
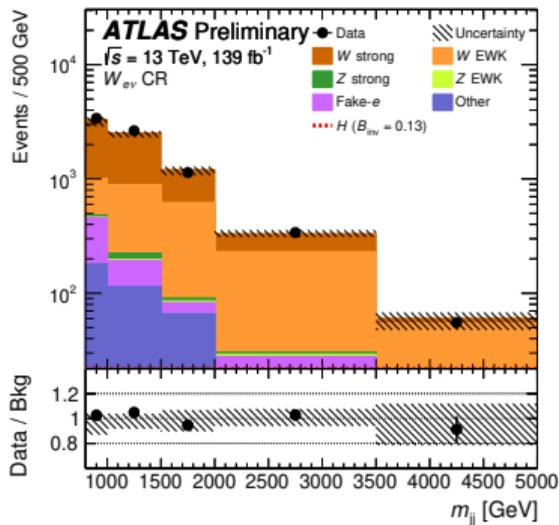
VBF: Z_{ee} Control Region

- Plots of m_{jj} , $\Delta\phi_{jj}$, and E_T^{miss} in the Z_{ee} control region, pre-fit.



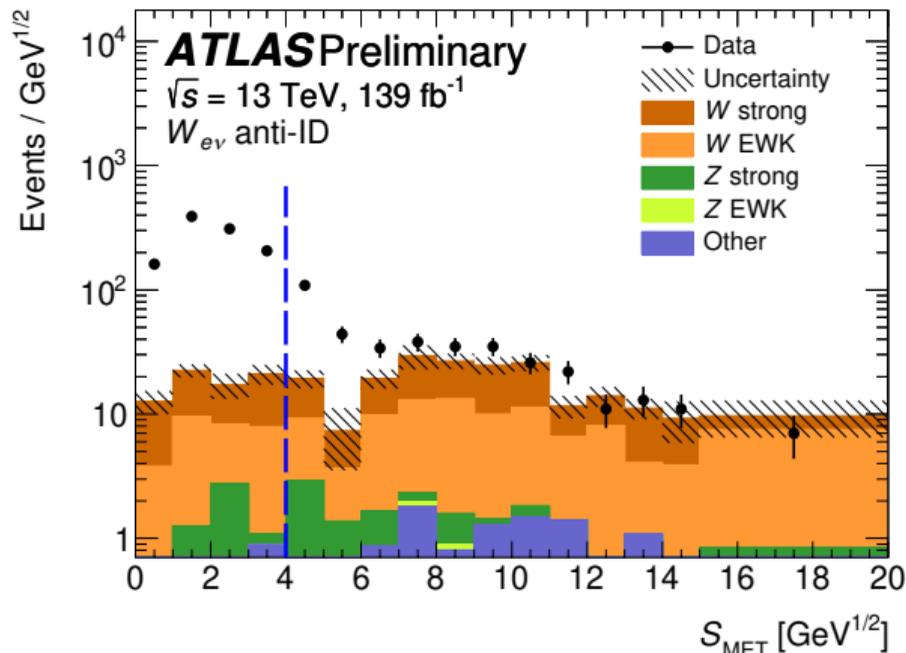
VBF: $W_{e\nu}$ Control Region

- Plots of m_{jj} , $\Delta\phi_{jj}$, and E_T^{miss} in the $W_{e\nu}$ control region, pre-fit.



VBF: Fake Lepton Estimate

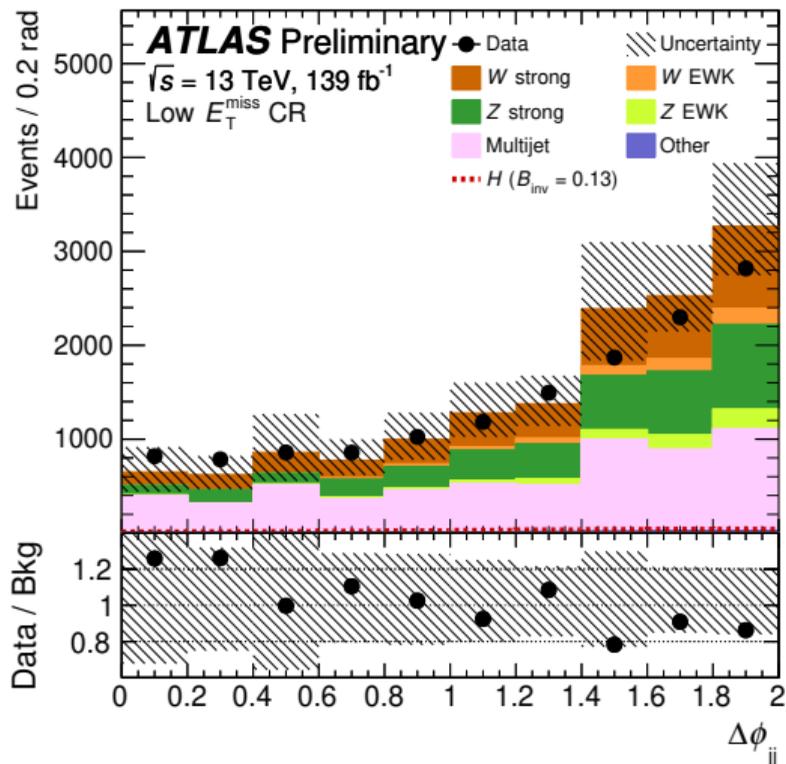
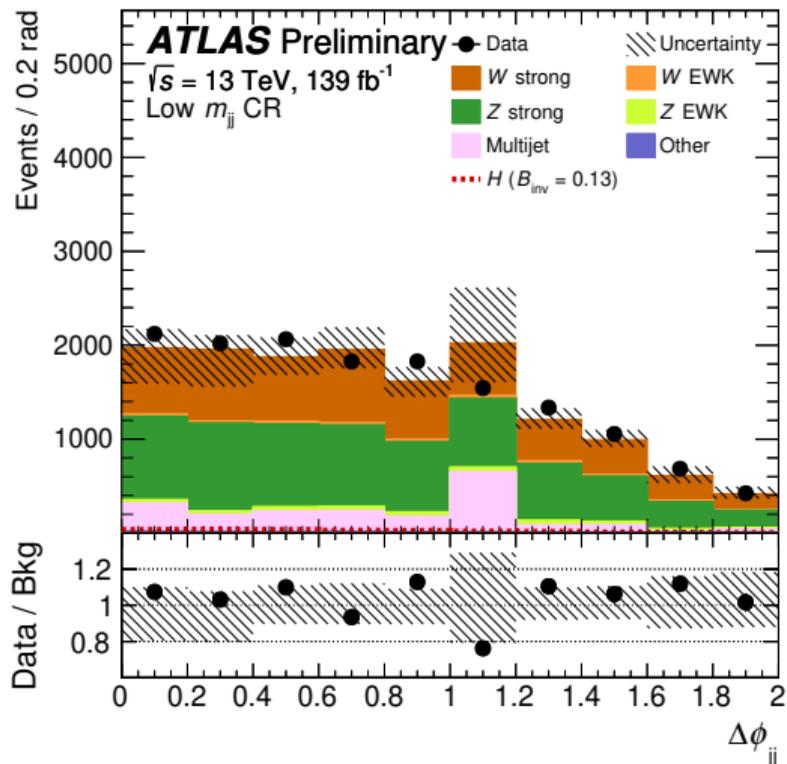
- Background in W_{ev} region: multijet events with jet reconstructed incorrectly as electron.
- Electron anti-ID region defined with loose electrons failing electron ID.
- Anti-ID S_{MET} template shape used to normalize background in fit.
- Scale factors taken as ratio of low to high S_{MET} for each m_{jj} bin.



$$S_{MET} = \frac{E_T^{\text{miss}}}{\sqrt{p_T^{j1} + p_T^{j2} + p_T^e}}$$

VBF Multijet Closure

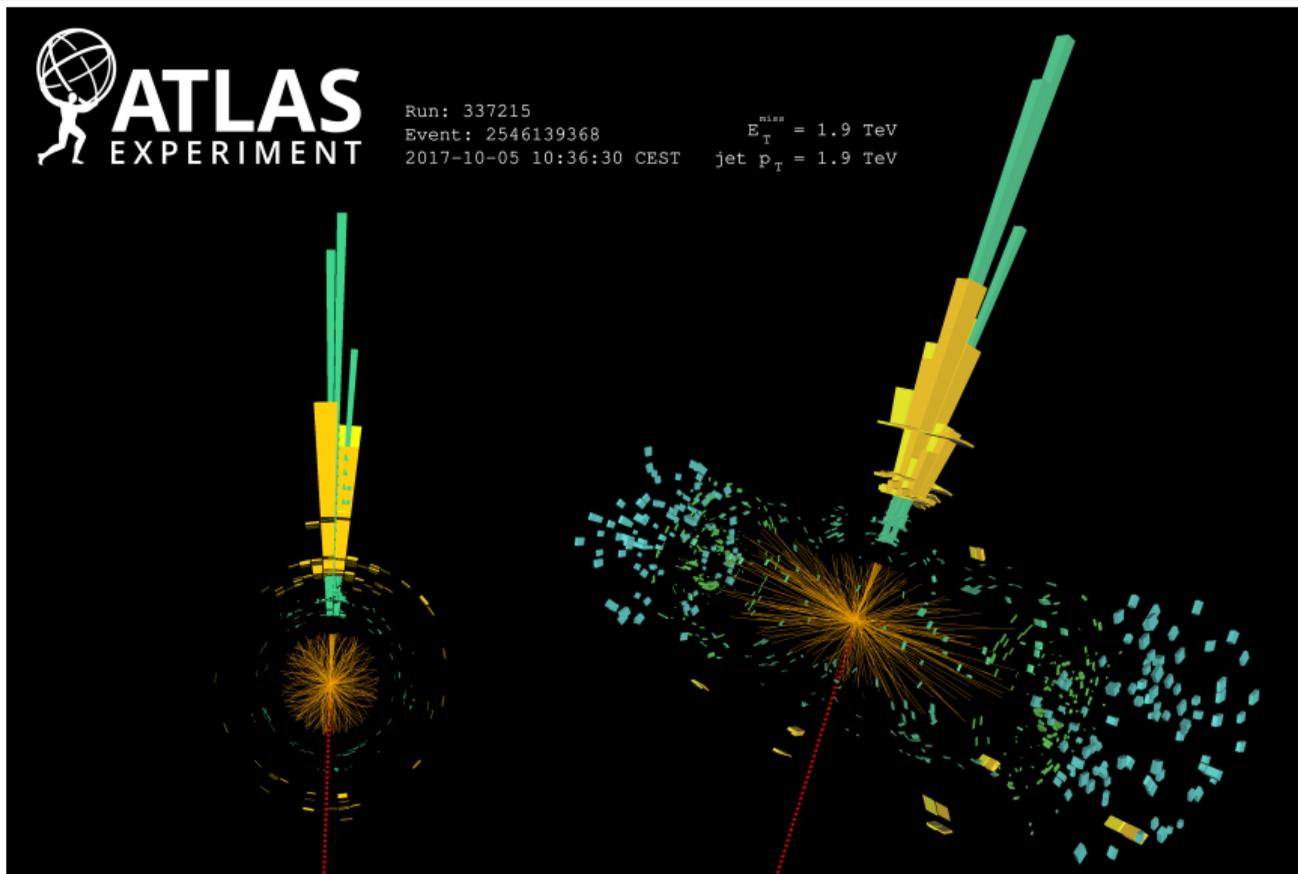
- Multijet closure checked in $100 < E_T^{\text{miss}} < 150 \text{ GeV}$ and $m_{jj} > 200 \text{ GeV}$ regions.



VBF Post-Fit Yields

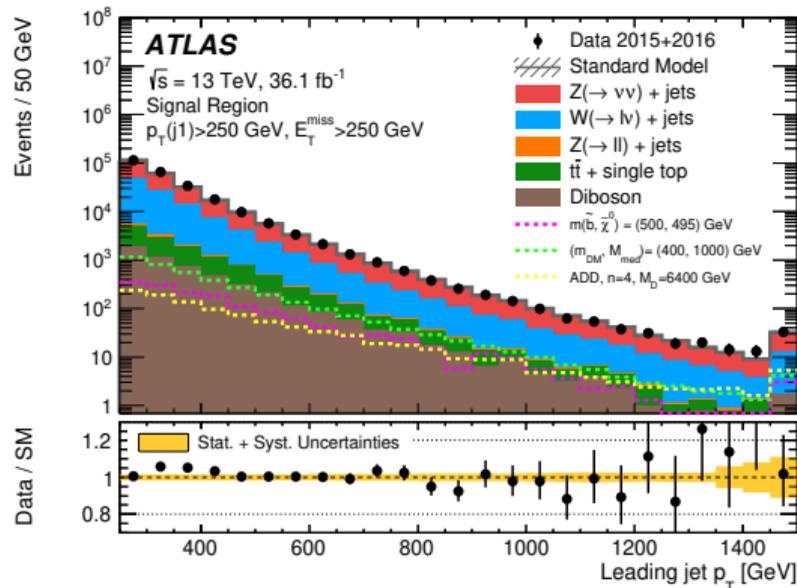
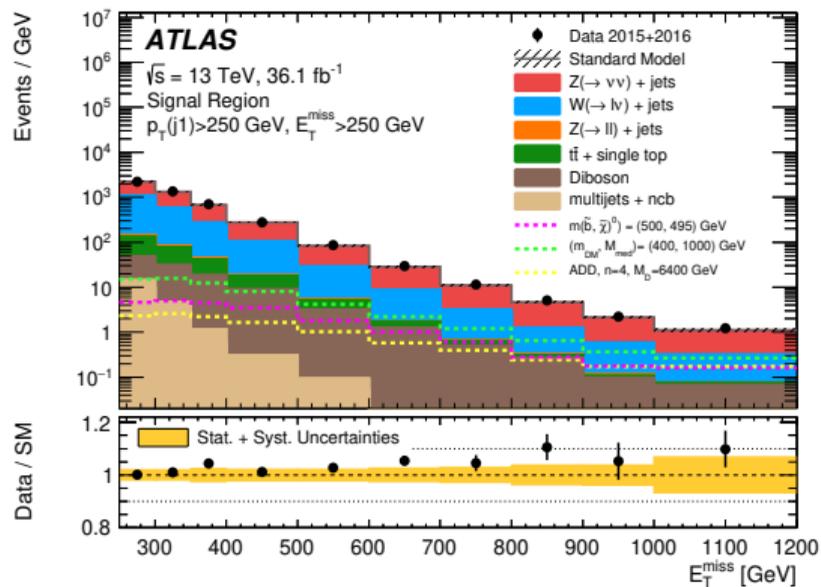
| Process | SR | $Z_{\ell\ell}$ | $W_{e\nu}$ | $W_{\mu\nu}$ | $W_{\ell\nu}$ | Fake- e CR |
|------------|-------------------|---|------------------|-------------------|-------------------|------------------|
| Z strong | $6\,810 \pm 430$ | $1\,394 \pm 81$ | 48 ± 11 | 193 ± 21 | 241 ± 23 | 153 ± 18 |
| Z EWK | $2\,660 \pm 320$ | 634 ± 75 | 12 ± 1 | 41 ± 2 | 53 ± 2 | 26 ± 2 |
| W strong | $3\,750 \pm 270$ | - | $3\,530 \pm 230$ | $6\,730 \pm 390$ | $10\,260 \pm 610$ | $1\,760 \pm 140$ |
| W EWK | $1\,380 \pm 130$ | - | $2\,140 \pm 210$ | $3\,770 \pm 370$ | $5\,910 \pm 570$ | $1\,120 \pm 120$ |
| Fake- e | - | - | 239 ± 62 | - | 239 ± 62 | $1\,190 \pm 180$ |
| Multijet | 740 ± 280 | - | - | - | - | - |
| Other | 155 ± 27 | 37 ± 27 | 322 ± 50 | 395 ± 60 | 720 ± 110 | 57 ± 7 |
| Tot. bg. | $15\,490 \pm 130$ | $2\,065 \pm 44$ | $6\,288 \pm 75$ | $11\,130 \pm 110$ | $17\,420 \pm 150$ | $4\,300 \pm 66$ |
| H (VBF) | 647 ± 52 | Predicted signal for $\mathcal{B}_{\text{inv}} = 13\%$ (observed limit) | | | | |
| H (ggF) | 90 ± 43 | | | | | |
| H (VH) | 0.81 ± 0.14 | | | | | |
| Data | 15 511 | 2 050 | 6 323 | 11 095 | 17 418 | 4 293 |

Monojet: Candidate Event



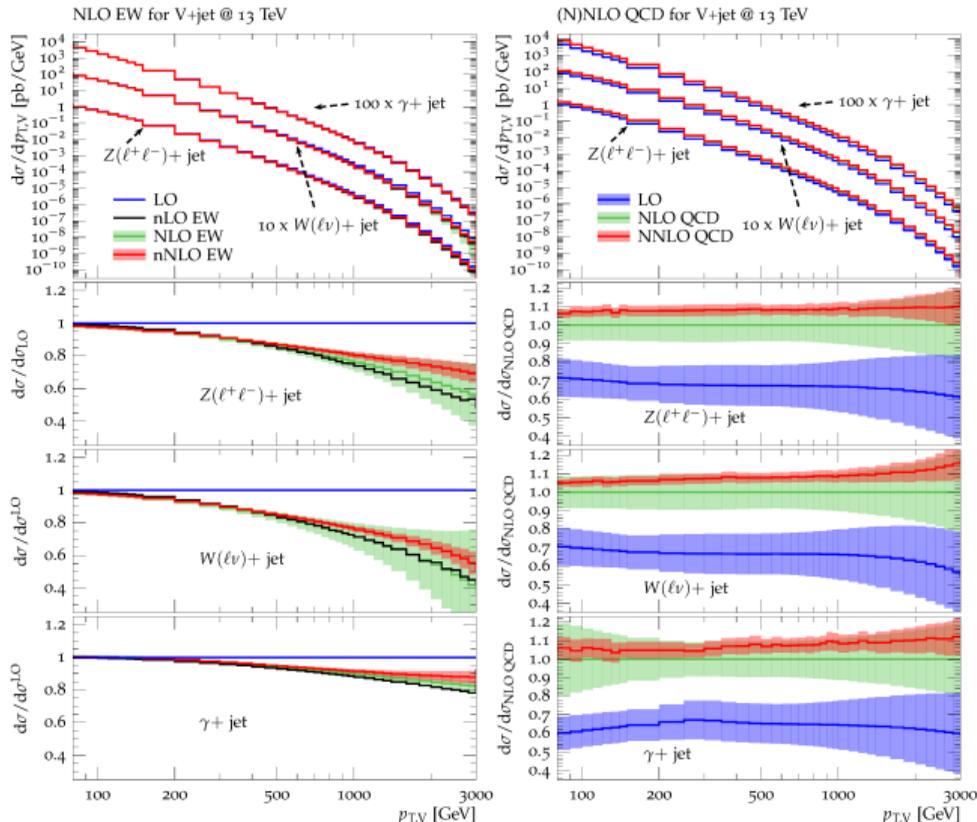
Monojet: 36.1 fb^{-1} Result

- Post-fit plots from previous ATLAS monojet analysis with data through 2016.



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Monojet: V+Jets Reweighting



- One-dimensional reweighting of MC by variable $x = p_T^V$ (for monojet).
- $\frac{d}{dx}\sigma_{MC}^V$ comes from matrix-element MC.
- $\frac{d}{dx}\sigma_{TH}^V$ provided by theorists:
 - NNLO QCD reweighting.
 - NLO + two-loop Sudakov loop (nNLO) reweighting.

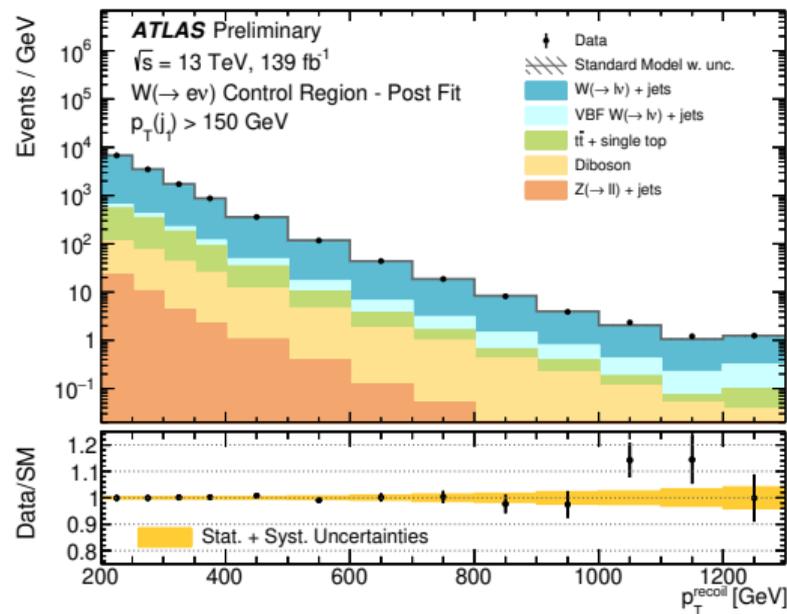
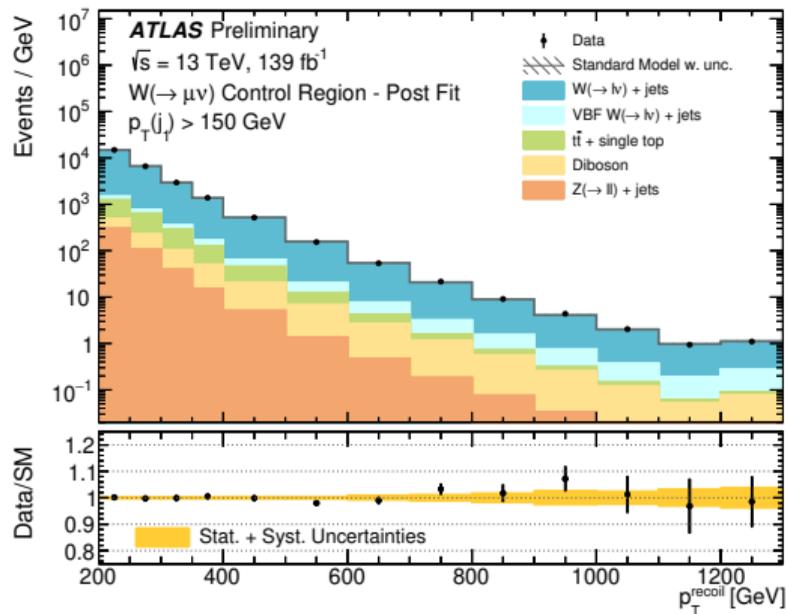
$$\frac{d}{dx} \frac{d}{d\vec{y}} \sigma^V(\vec{\epsilon}_{MC}, \vec{\epsilon}_{TH}) =$$

$$\frac{d}{dx} \frac{d}{d\vec{y}} \sigma_{MC}^V(\vec{\epsilon}_{MC}) \frac{\frac{d}{dx} \sigma_{TH}^V(\vec{\epsilon}_{TH})}{\frac{d}{dx} \sigma_{MC}^V(\vec{\epsilon}_{MC})}$$

Eur. Phys. J. C77 (2017) 829

Monojet: 1 Lepton Control Regions

- Plots of p_T^{recoil} for the 1-lepton e and μ control regions, post-fit.



Monojet: 2 Lepton Control Regions

- Plots of p_T^{recoil} for the 2-lepton ee and $\mu\mu$ control regions, post-fit.

