

ATLAS Run 2 Physics Results

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US LHC Users Association Annual Meeting

On behalf of the ATLAS Collaboration



THE UNIVERSITY OF
CHICAGO



- Recent results confront the Standard Model with high-precision and state-of-the-art techniques
- Advances in experimental methods for hadronic final states yield new insights and opportunities
- Impacts felt across the ATLAS Physics Program

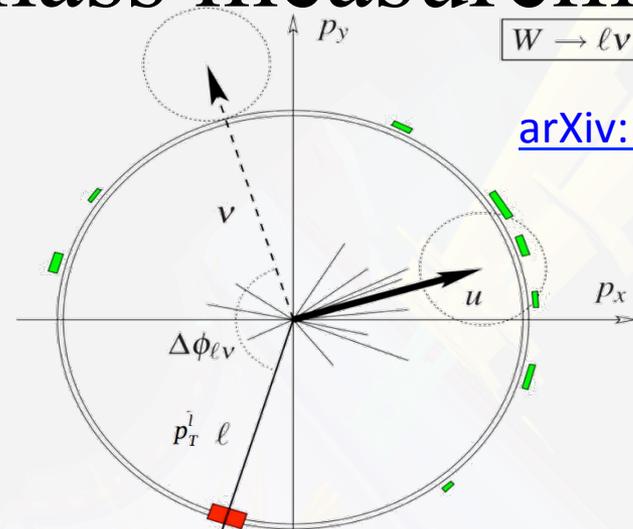
Will highlight this today with several high precision measurements and new physics searches in ATLAS

Recent precision W mass measurements

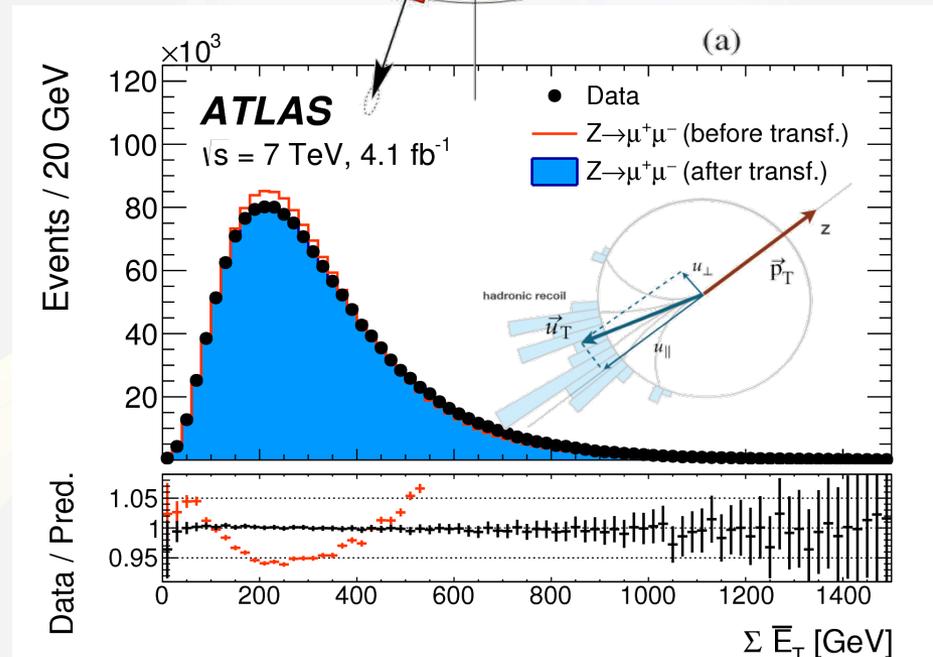
Sophisticated **hadronic recoil measurements (u)** and corrections allow for high-precision estimates of (missing) transverse momentum and mass of the W boson

Extensively tested and calibrated using **leptonic Z decays**

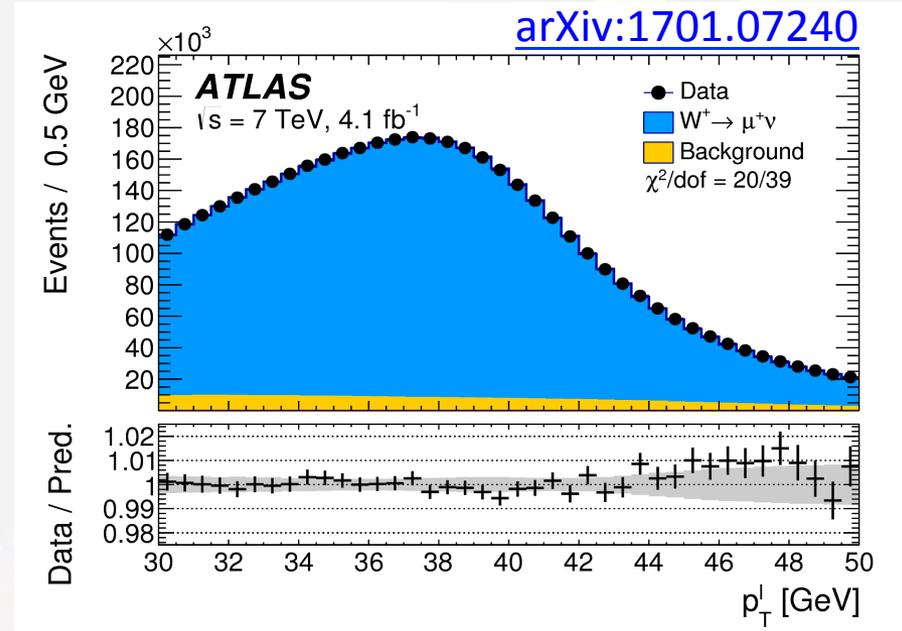
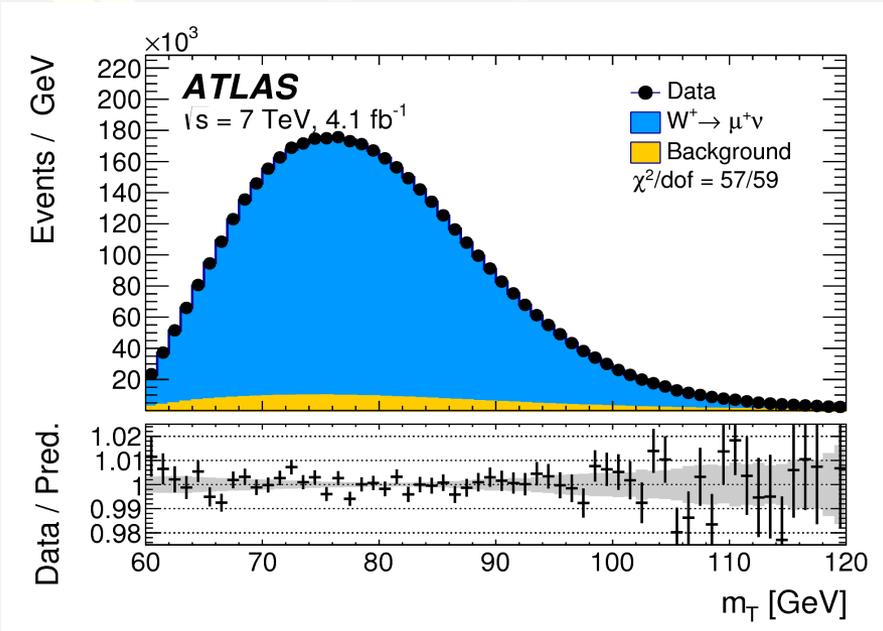
Systematic uncertainties for the transverse mass measurement of the W mass reduced to the level of **13 MeV** due to these calibrations



[arXiv:1701.07240](https://arxiv.org/abs/1701.07240)



Recent precision W mass measurements



[arXiv:1701.07240](https://arxiv.org/abs/1701.07240)

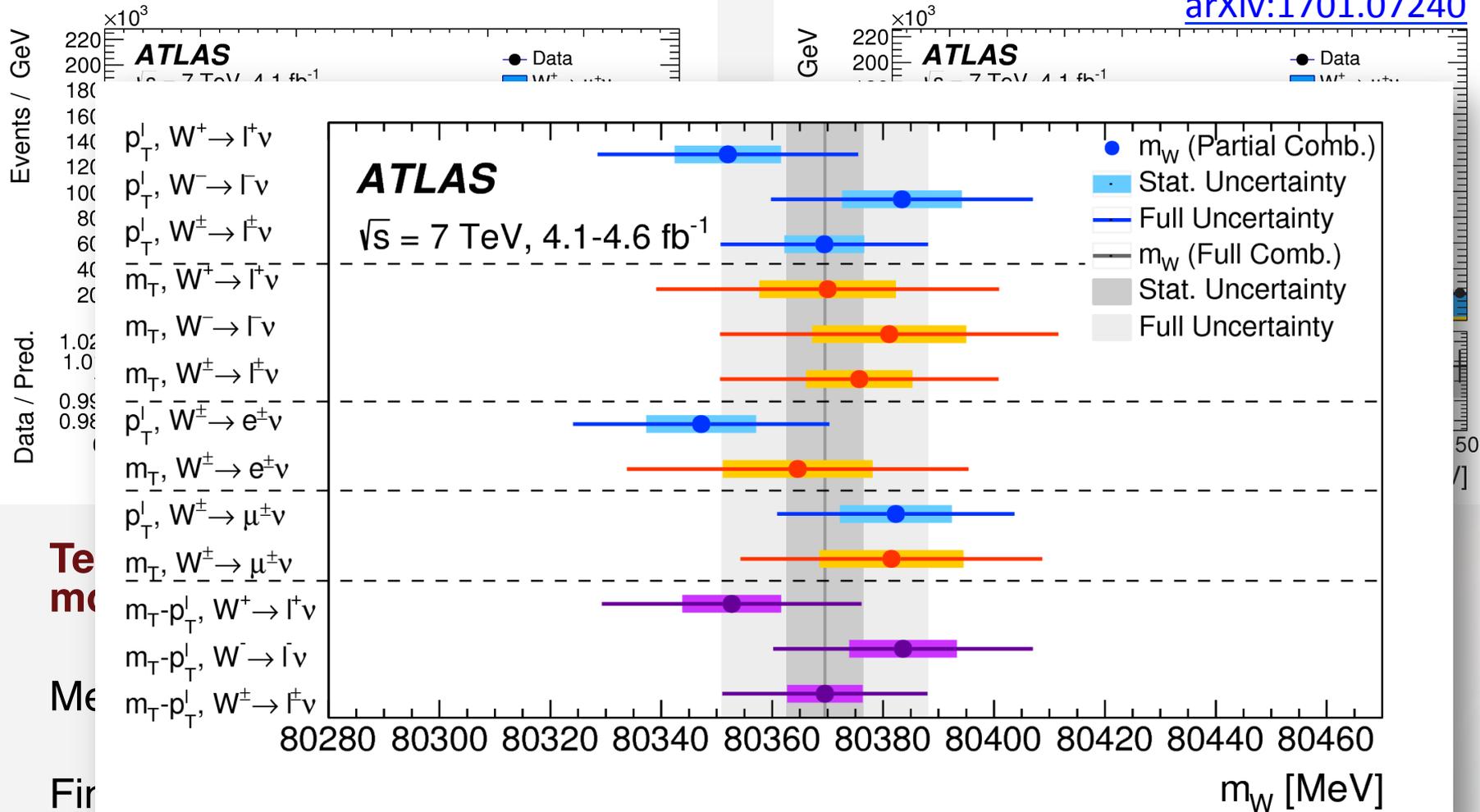
Template fits to the **transverse mass** and the **lepton transverse momentum** are used to extract the W boson mass from the data.

Measurements are split among lepton **flavor** and **charge**.

Final W boson mass is determined from a **combination** of the lepton and transverse mass measurements.

Recent precision W mass measurements

[arXiv:1701.07240](https://arxiv.org/abs/1701.07240)



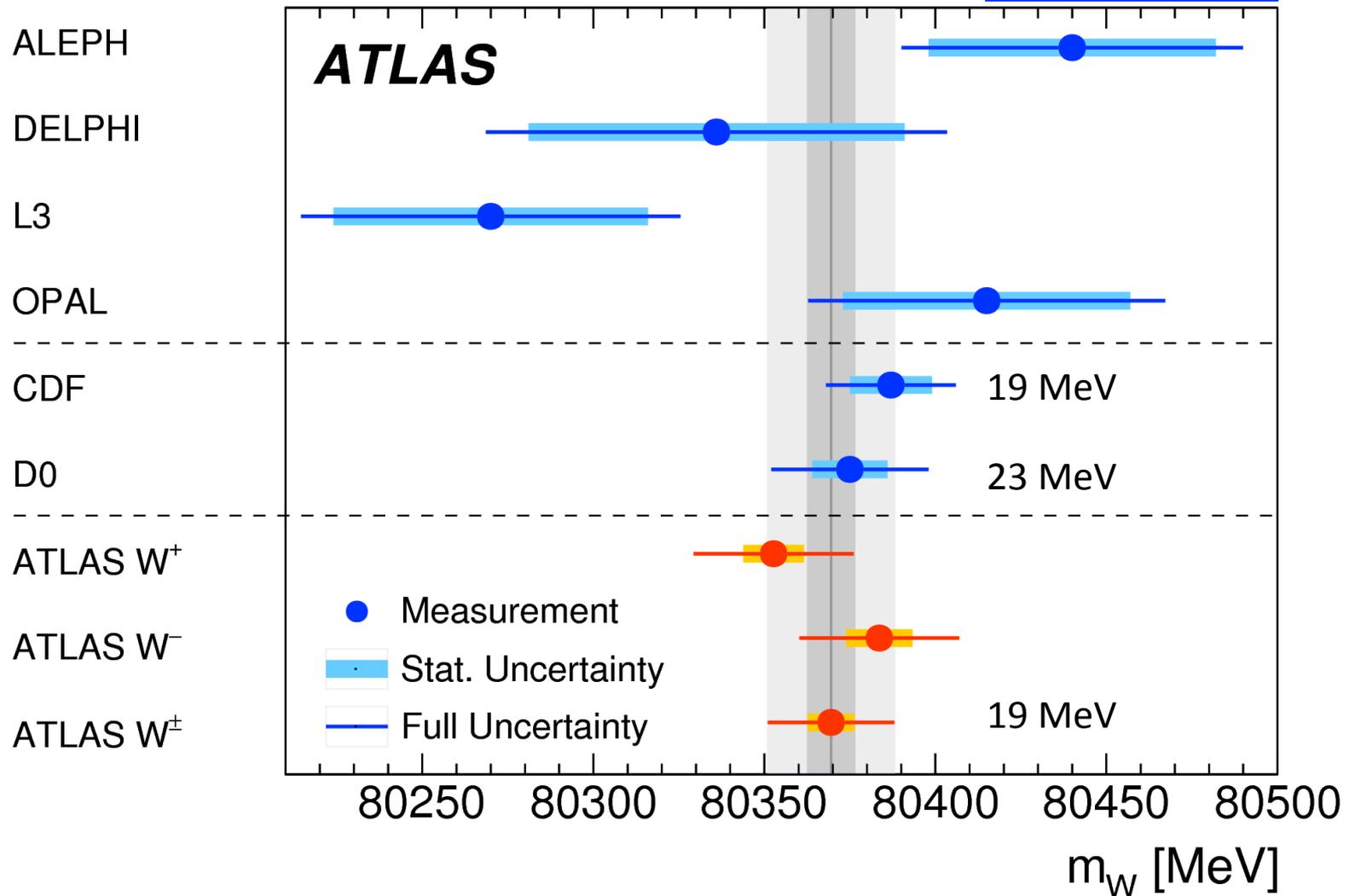
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transverse mass measurements.

Recent precision W mass measurements

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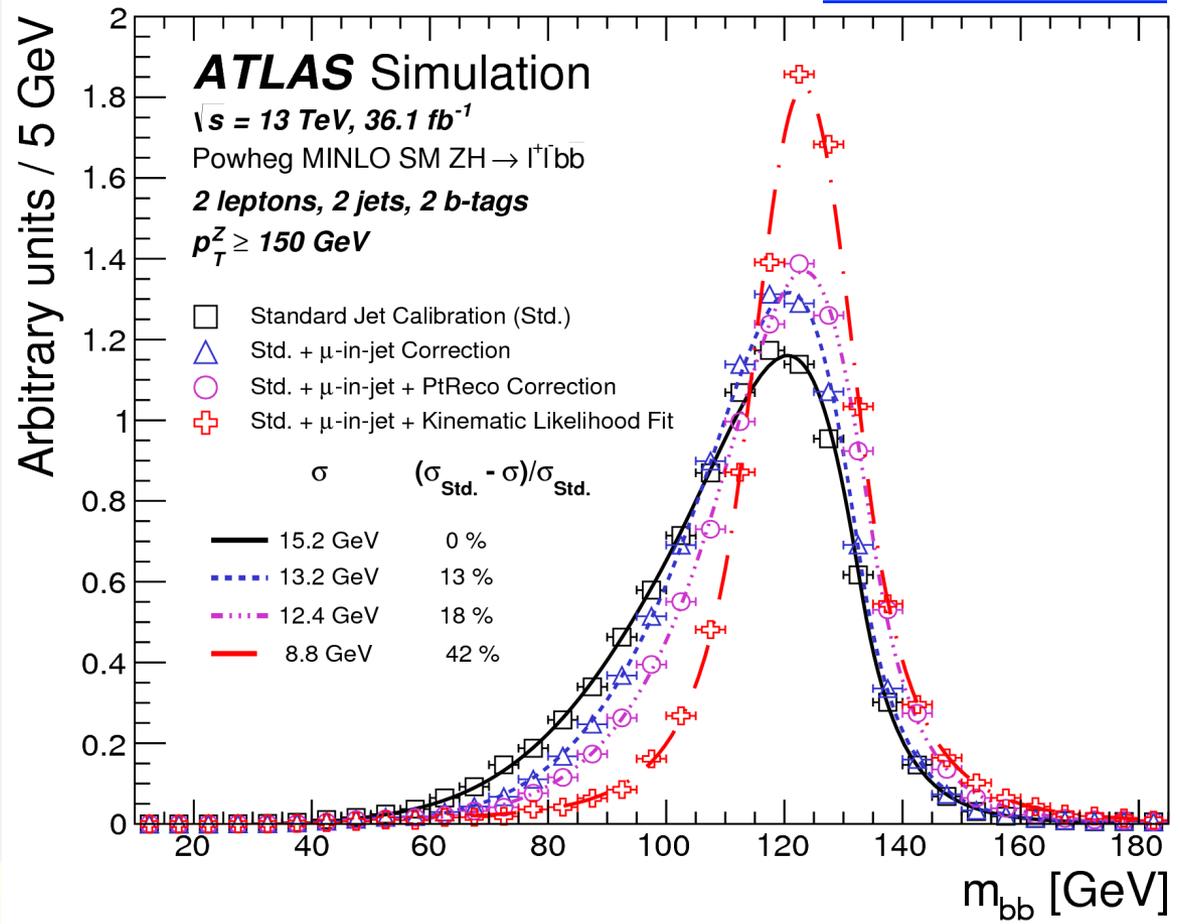


Higgs decays to heavy fermions

A crucial aspect of the endeavor to prove direct evidence of Higgs decays to pairs of b-quarks is the **invariant mass resolution for this massive resonance.**

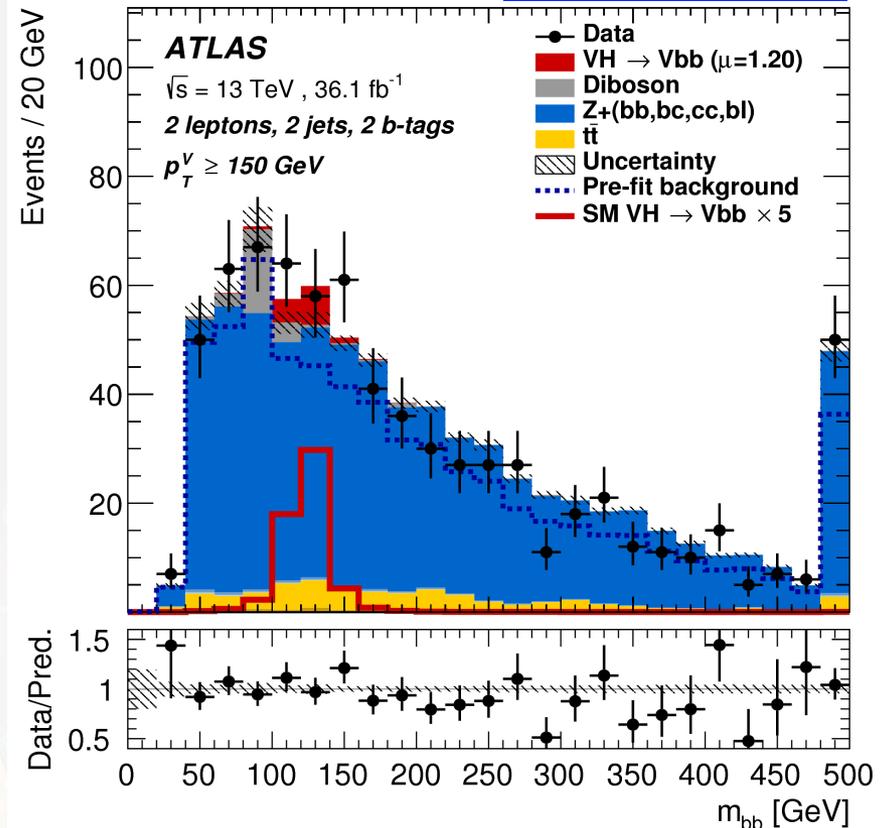
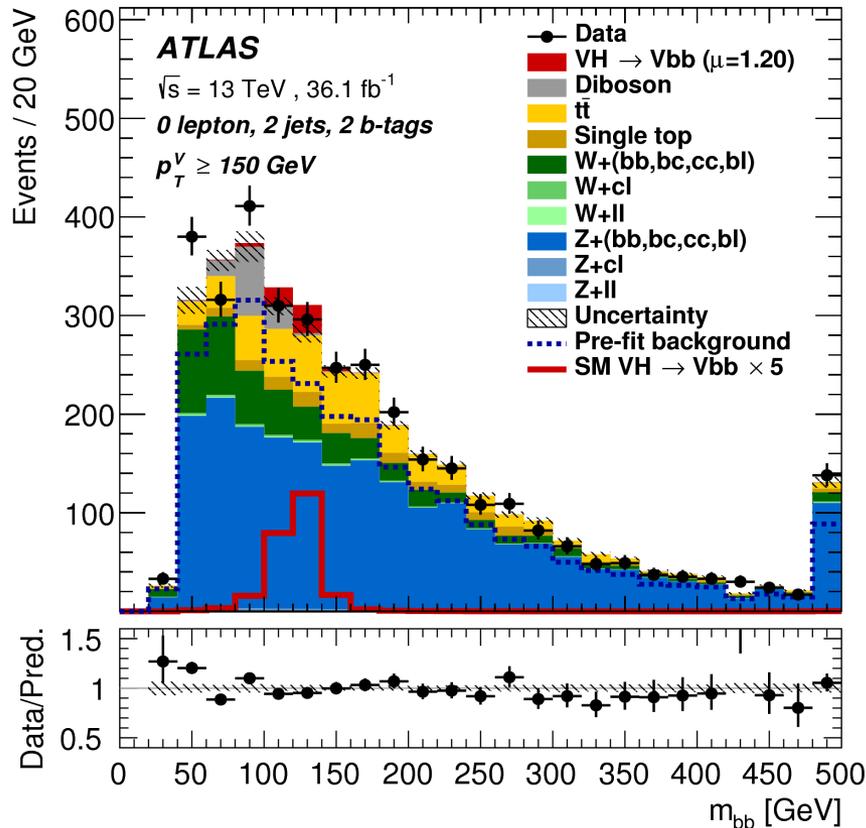
A series of **sophisticated jet kinematic calibrations** is required to provide optimal performance in this challenging channel.

A **43% relative improvement results in a 7% fractional mass resolution** in this complex final state



Higgs decays to heavy fermions

[arXiv:1708.03299](https://arxiv.org/abs/1708.03299)

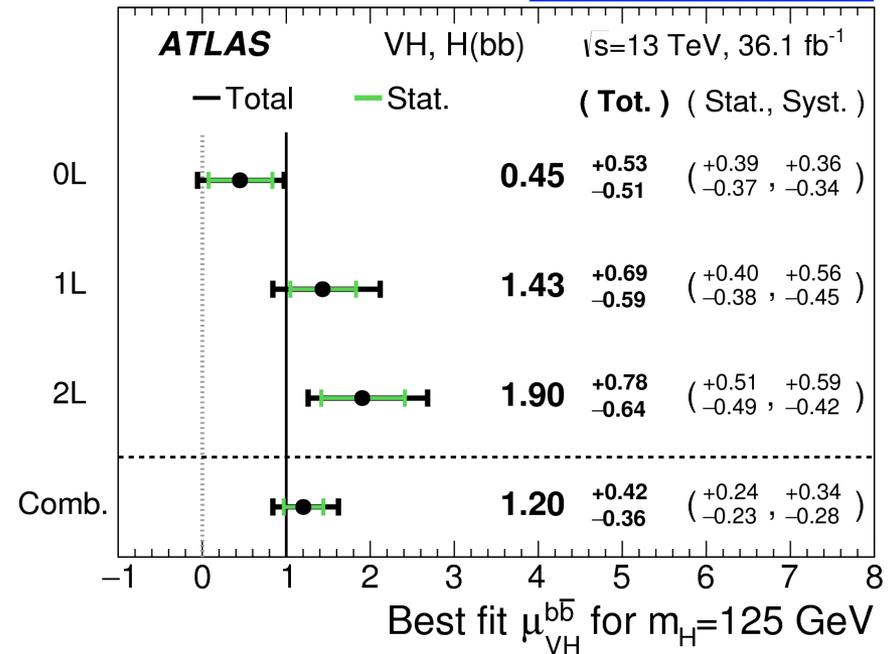
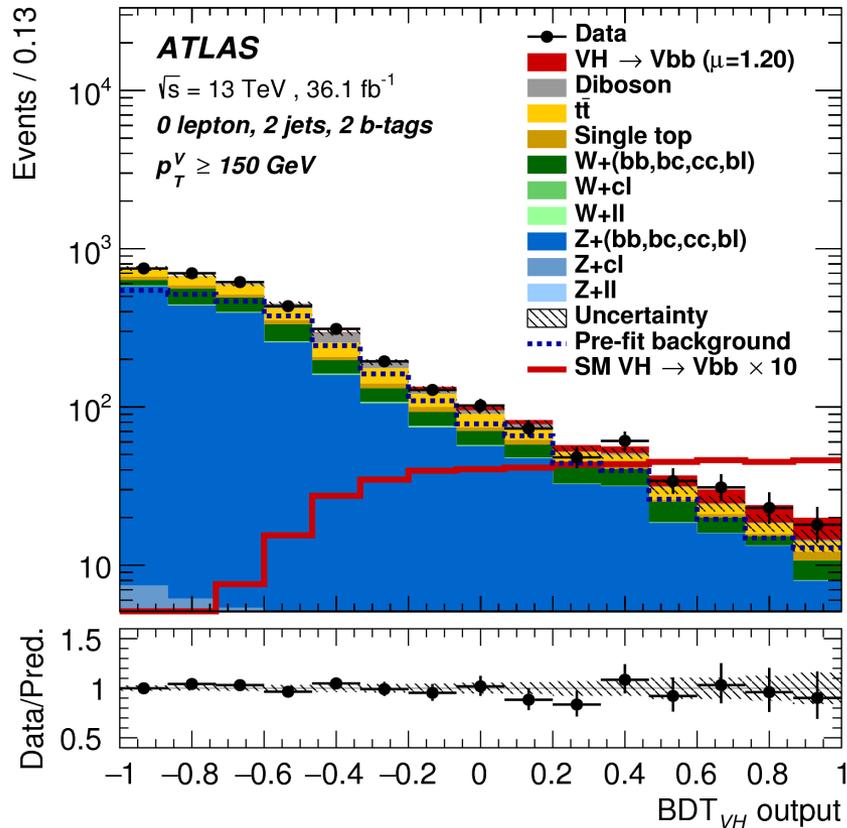


Analysis is split into **lepton multiplicities (0-2)**, **jet multiplicities (2-3)**, and **vector boson transverse momentum (75-150 GeV, 150+ GeV)**.

Primary analysis strategy is based on a **multivariate (BDT) discriminant** using up to **13 input variables**. Validation performed using **two alternative approaches**, including an explicit **dijet mass analysis**.

Higgs decays to heavy fermions

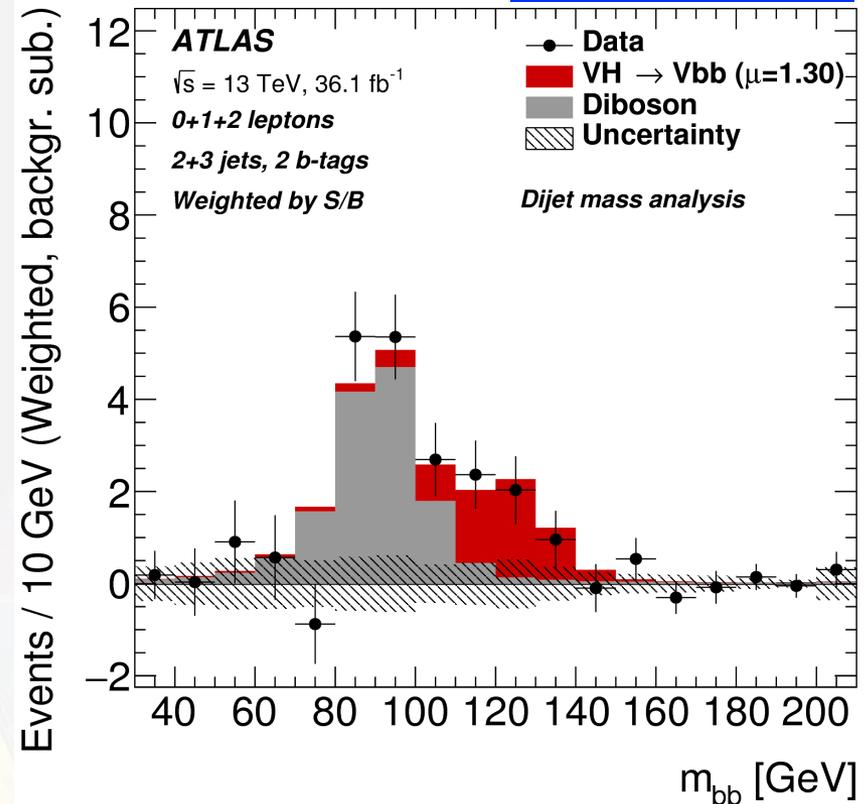
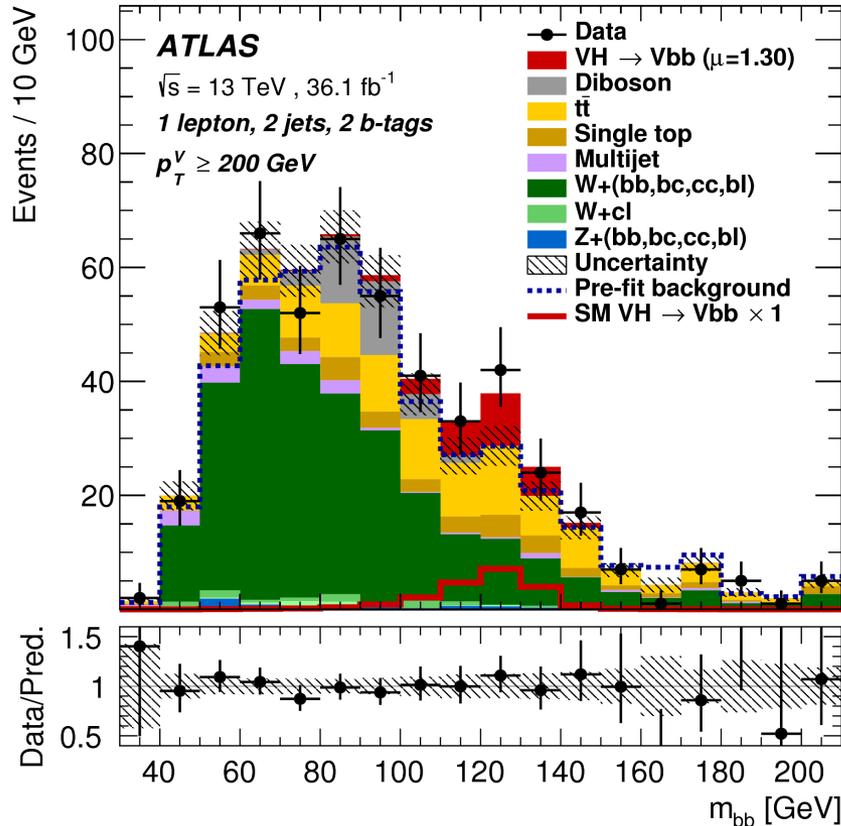
[arXiv:1708.03299](https://arxiv.org/abs/1708.03299)



Sensitivity **dominated by 0-lepton selection** ($E_T^{\text{Miss}} > 150 \text{ GeV}$ + angular selection criteria).

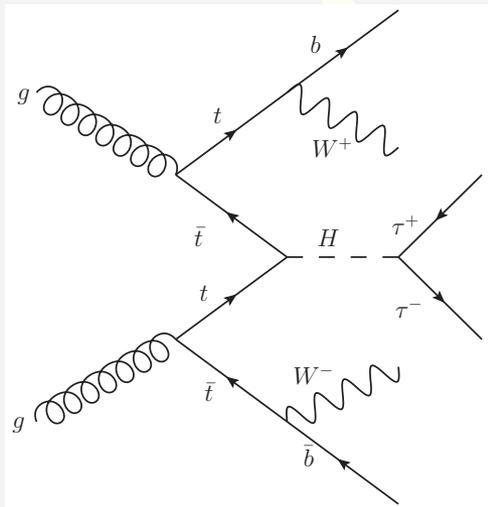
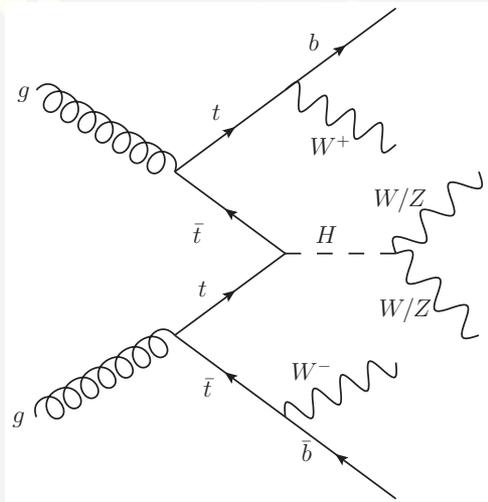
Higgs decays to heavy fermions

[arXiv:1708.03299](https://arxiv.org/abs/1708.03299)



Evidence for Higgs decays to heavy fermions observed with a significance of 3.5σ .

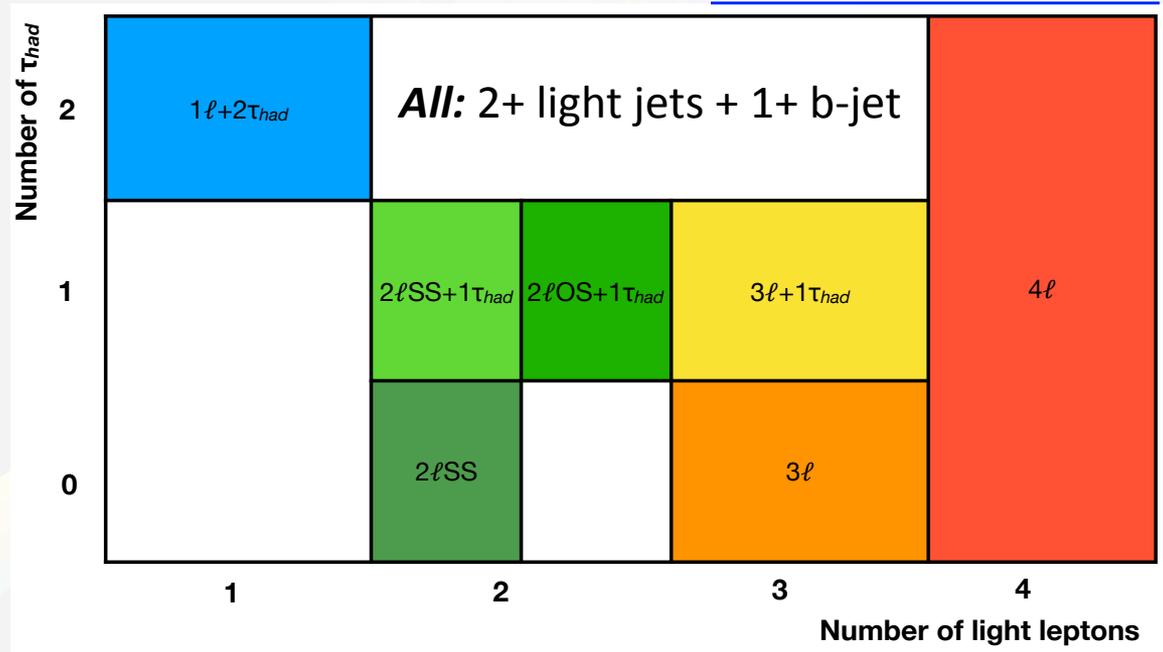
Higgs coupling to top quarks



Significant open question in Higgs physics is the top Yukawa coupling and observation of Higgs production in association with top quark pairs.

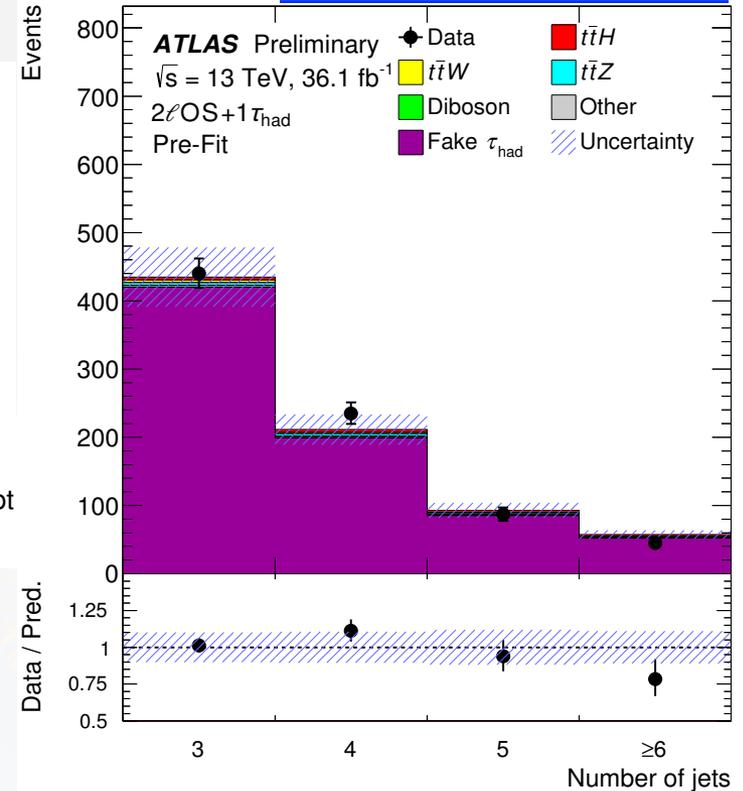
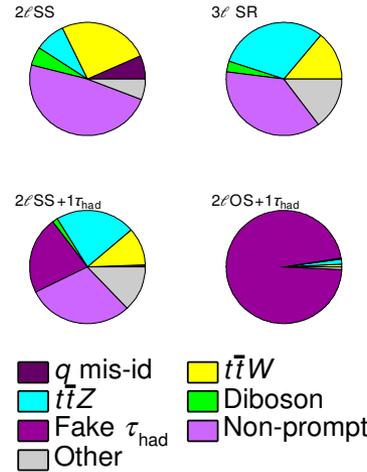
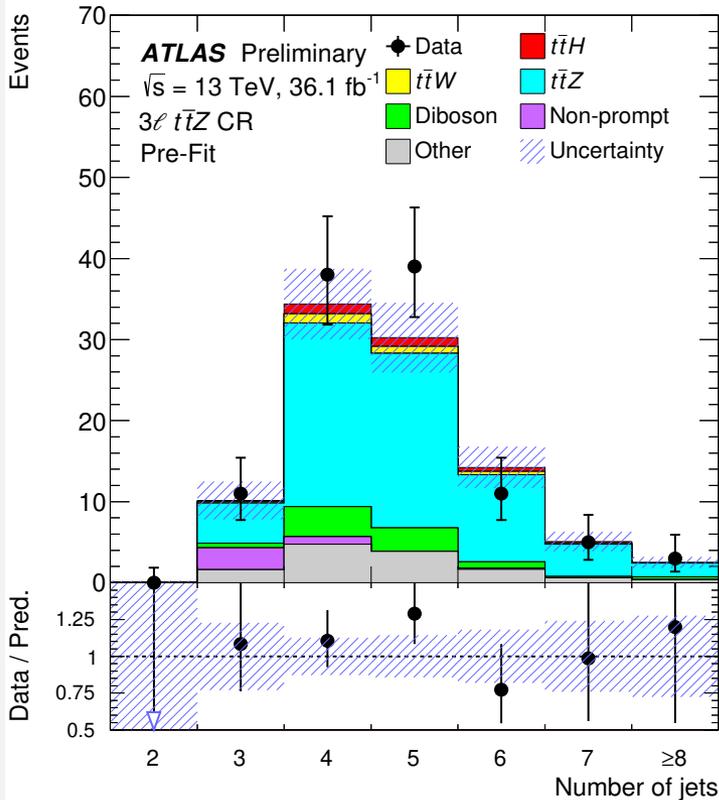
New analysis released last week focuses on the multi-lepton final states for this process.

[ATLAS-CONF-2017-077](#)



Higgs coupling to top quarks

ATLAS-CONF-2017-077



Most sensitive final states are the:

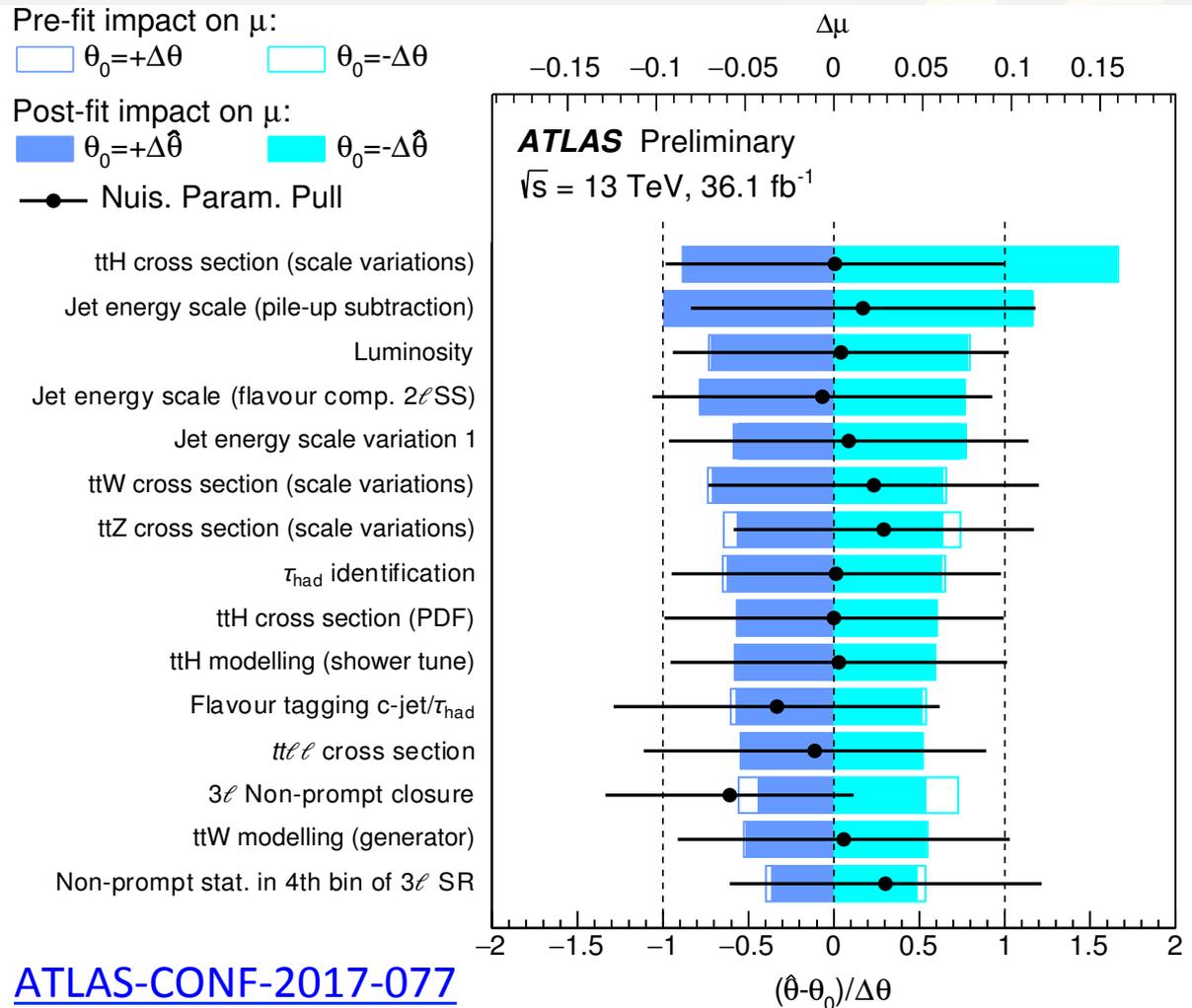
- Same-sign 2-lepton signatures (with or without hadronic taus)
- 3-lepton signatures

Critical issues are **associated production backgrounds** ($t\bar{t}+Z$, $t\bar{t}+W$), **fake hadronic taus**, and **non-prompt leptons**

Higgs coupling to top quarks

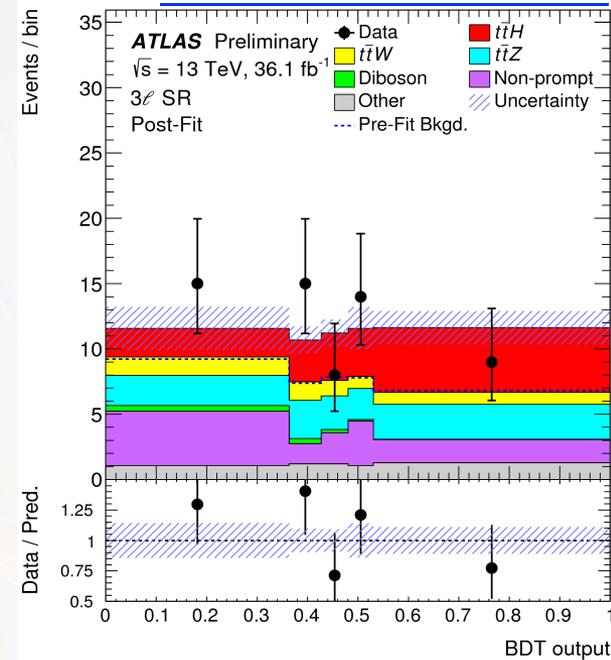
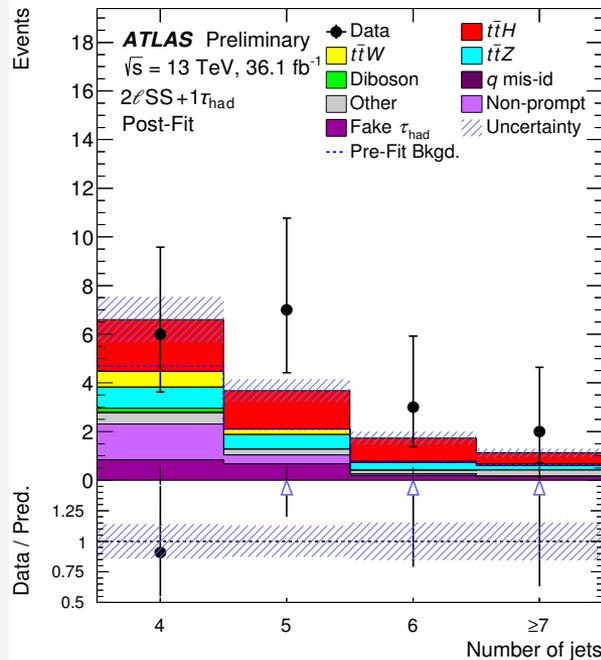
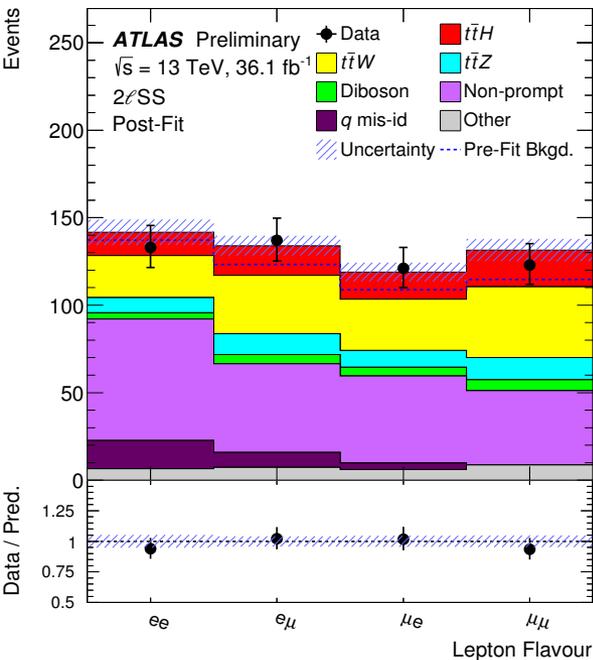
Systematic uncertainties are dominated by modeling and **hadronic final state measurement uncertainties**

- Jet energy scale
- Flavor tagging



Higgs coupling to top quarks

ATLAS-CONF-2017-077



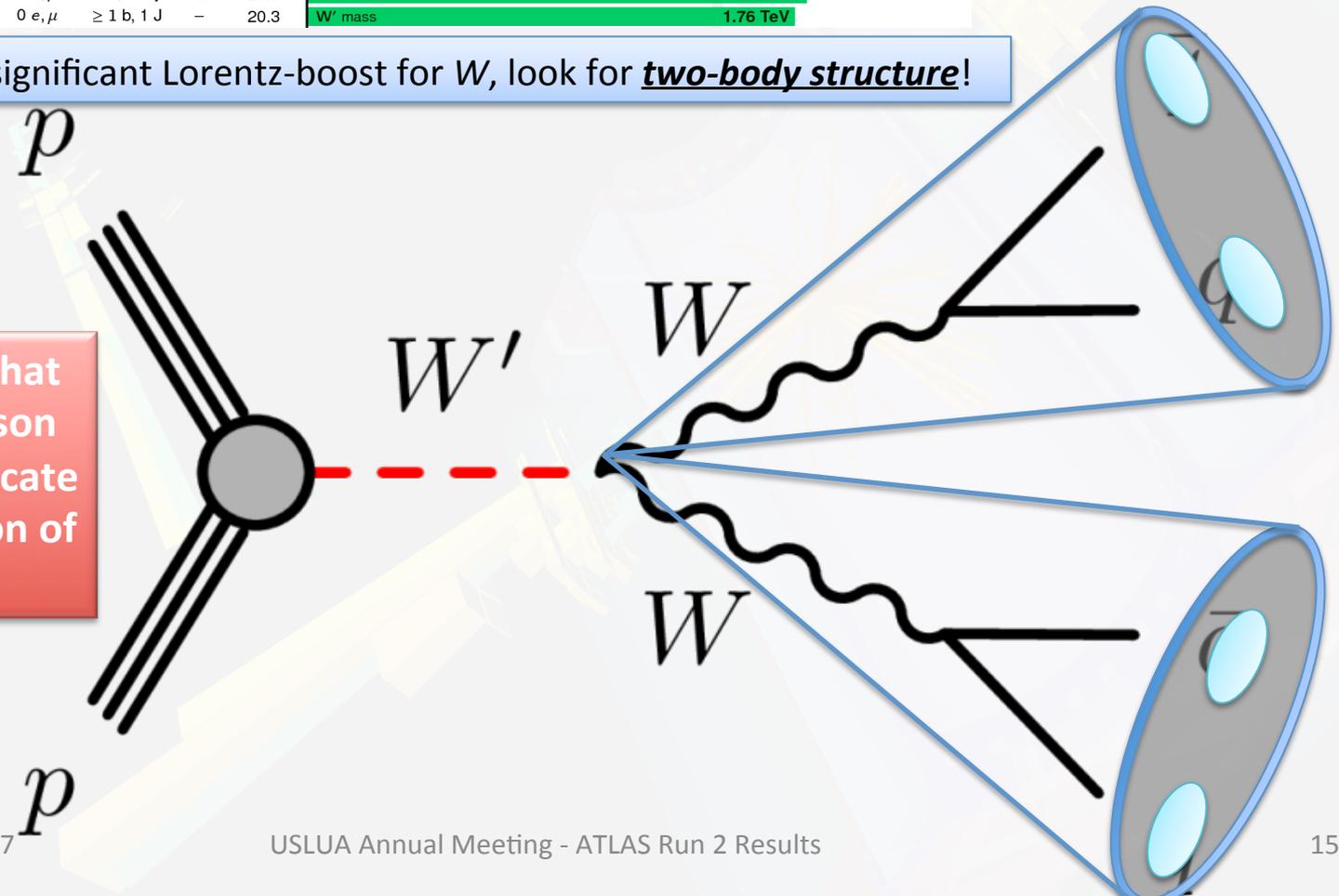
Channel	Best fit μ				Significance			
	Observed		Expected		Observed	Expected		
$2\ell\text{OS}+1\tau_{\text{had}}$	1.7	$^{+1.6}_{-1.5}$ (stat.)	$^{+1.4}_{-1.1}$ (syst.)	1.0	$^{+1.5}_{-1.4}$ (stat.)	$^{+1.2}_{-1.1}$ (syst.)	0.9 σ	0.5 σ
$1\ell+2\tau_{\text{had}}$	-0.6	$^{+1.1}_{-0.8}$ (stat.)	$^{+1.1}_{-1.3}$ (syst.)	1.0	$^{+1.1}_{-0.9}$ (stat.)	$^{+1.2}_{-1.1}$ (syst.)	-	0.6 σ
4ℓ	-0.5	$^{+1.3}_{-0.8}$ (stat.)	$^{+0.2}_{-0.3}$ (syst.)	1.0	$^{+1.7}_{-1.2}$ (stat.)	$^{+0.4}_{-0.2}$ (syst.)	-	0.8 σ
$3\ell+1\tau_{\text{had}}$	1.6	$^{+1.7}_{-1.3}$ (stat.)	$^{+0.6}_{-0.2}$ (syst.)	1.0	$^{+1.5}_{-1.1}$ (stat.)	$^{+0.4}_{-0.2}$ (syst.)	1.3 σ	0.9 σ
$2\ell\text{SS}+1\tau_{\text{had}}$	3.5	$^{+1.5}_{-1.2}$ (stat.)	$^{+0.9}_{-0.5}$ (syst.)	1.0	$^{+1.1}_{-0.8}$ (stat.)	$^{+0.5}_{-0.3}$ (syst.)	3.4 σ	1.1 σ
3ℓ	1.8	$^{+0.6}_{-0.6}$ (stat.)	$^{+0.6}_{-0.5}$ (syst.)	1.0	$^{+0.6}_{-0.5}$ (stat.)	$^{+0.5}_{-0.4}$ (syst.)	2.4 σ	1.5 σ
$2\ell\text{SS}$	1.5	$^{+0.4}_{-0.4}$ (stat.)	$^{+0.5}_{-0.4}$ (syst.)	1.0	$^{+0.4}_{-0.4}$ (stat.)	$^{+0.4}_{-0.4}$ (syst.)	2.7 σ	1.9 σ
Combined	1.6	$^{+0.3}_{-0.3}$ (stat.)	$^{+0.4}_{-0.3}$ (syst.)	1.0	$^{+0.3}_{-0.3}$ (stat.)	$^{+0.3}_{-0.3}$ (syst.)	4.1 σ	2.8 σ

Searching for New Physics with Lorentz-boosted W/Z bosons

Gauge bosons	Decay Channels				Mass Limits		
	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	-	36.1	Z' mass	4.5 TeV
	SSM $Z' \rightarrow \tau\tau$	2τ	-	-	36.1	Z' mass	2.4 TeV
	Leptophobic $Z' \rightarrow bb$	-	$2 b$	-	3.2	Z' mass	1.5 TeV
	Leptophobic $Z' \rightarrow tt$	$1 e, \mu$	$\geq 1 b, \geq 1 J/2j$	Yes	3.2	Z' mass	2.0 TeV
	SSM $W' \rightarrow \ell\nu$	$1 e, \mu$	-	Yes	36.1	W' mass	5.1 TeV
	HVT $V' \rightarrow WV \rightarrow qq\bar{q}\bar{q}$ model B	$0 e, \mu$	$2 J$	-	36.7	V' mass	3.5 TeV
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel	-	-	36.1	V' mass	2.93 TeV
	LRSM $W'_R \rightarrow tb$	$1 e, \mu$	$2 b, 0-1 j$	Yes	20.3	W' mass	1.92 TeV
	LRSM $W'_R \rightarrow tb$	$0 e, \mu$	$\geq 1 b, 1 J$	-	20.3	W' mass	1.76 TeV

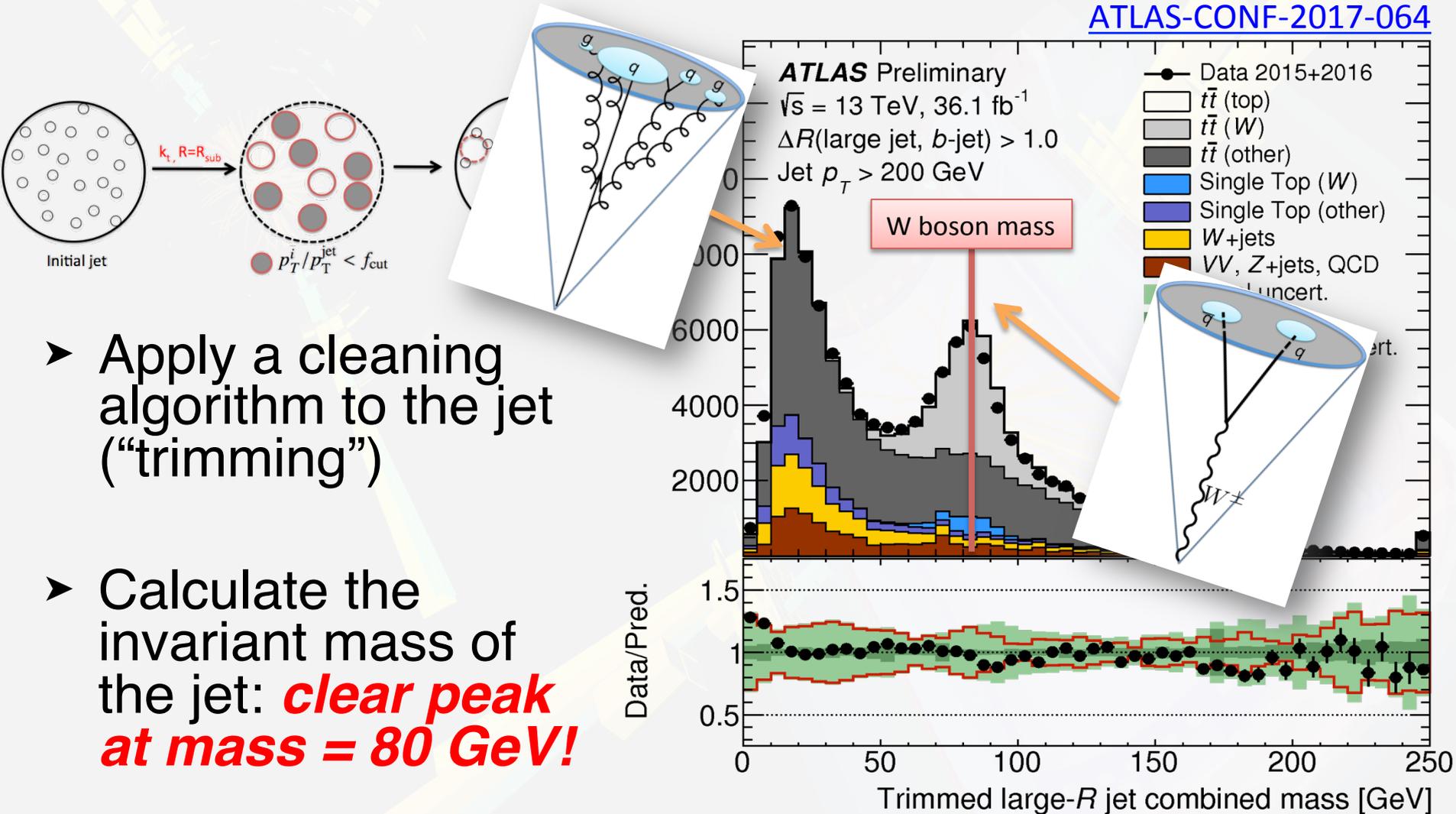
If $M_{W'} \gg M_W$ then significant Lorentz-boost for W , look for **two-body structure!**

New particles that decay to W boson pairs would indicate a new generation of matter !



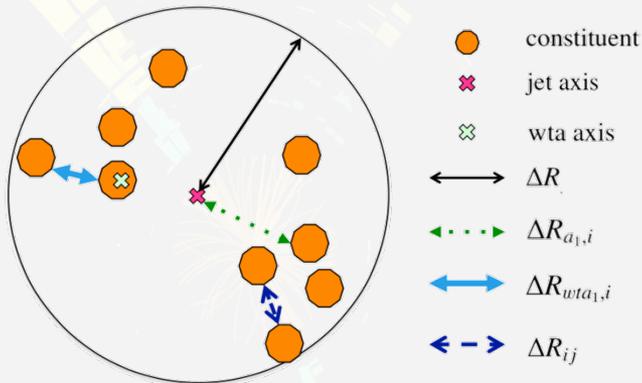
Imaging W jets in the data

[ATLAS-CONF-2017-064](#)



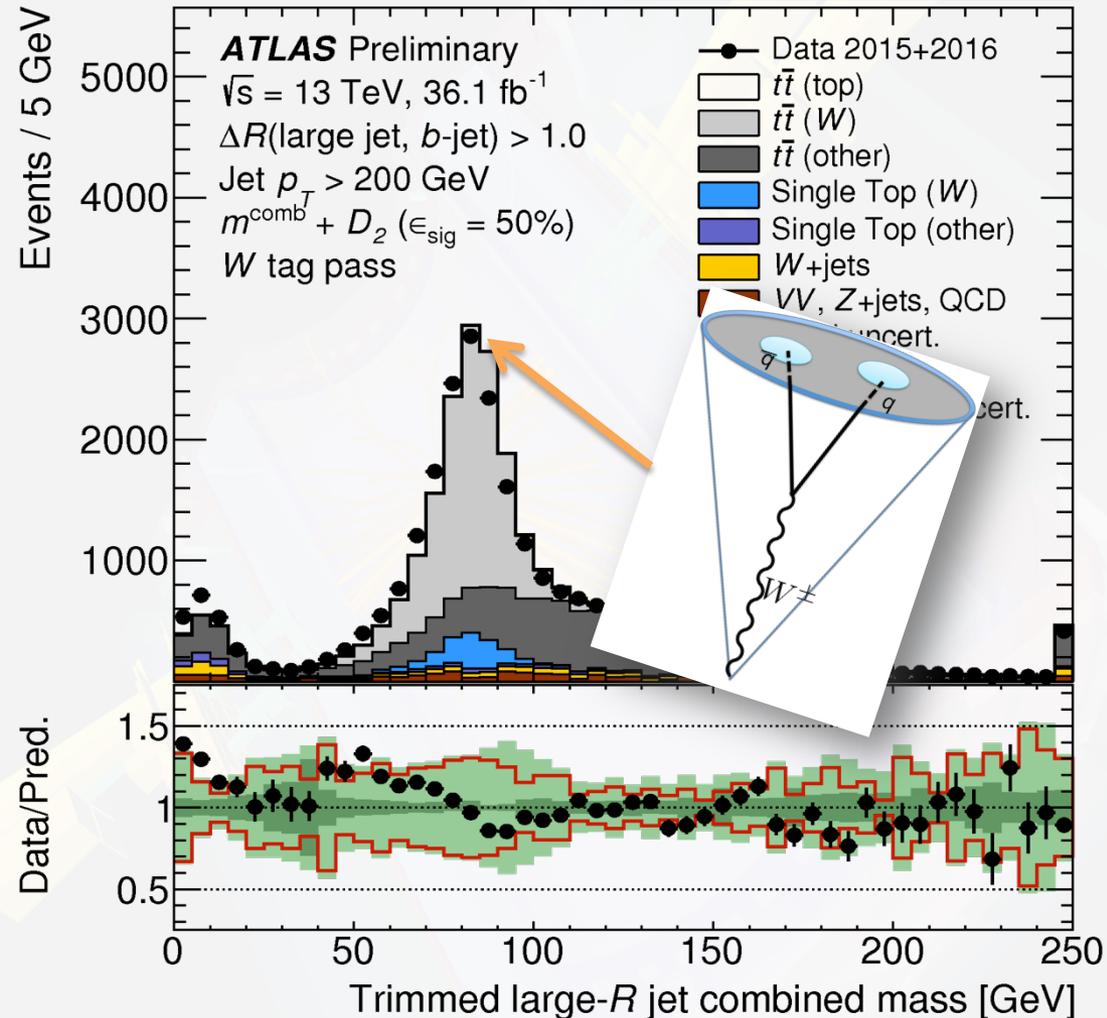
- Apply a cleaning algorithm to the jet (“trimming”)
- Calculate the invariant mass of the jet: **clear peak at mass = 80 GeV!**

Imaging W jets in the data

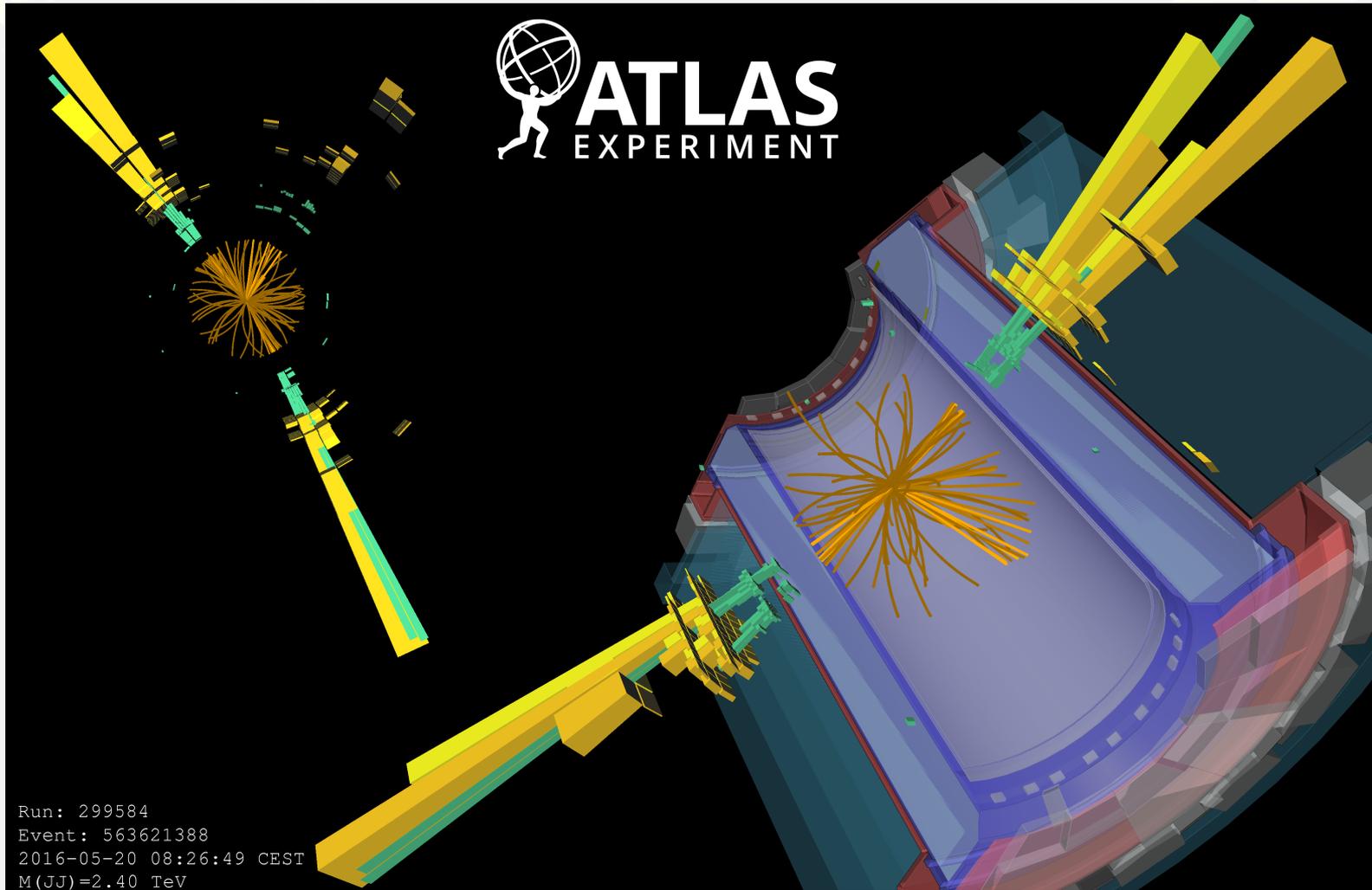


- Refine the measurement with detailed **structural information**
 - Energy-energy correlation functions (multi-point)
 - Substructure multiplicity
- Calculate the invariant mass of the the new jets: **significant improvement of mass reconstruction!**

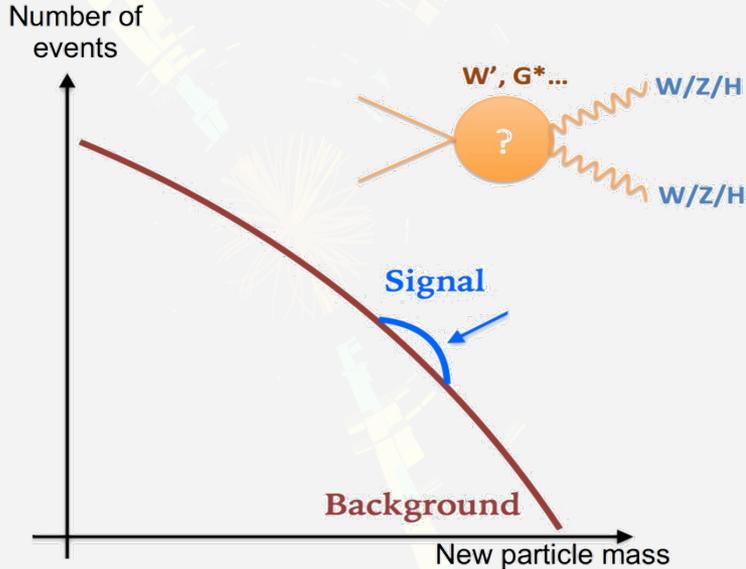
[ATLAS-CONF-2017-064](#)



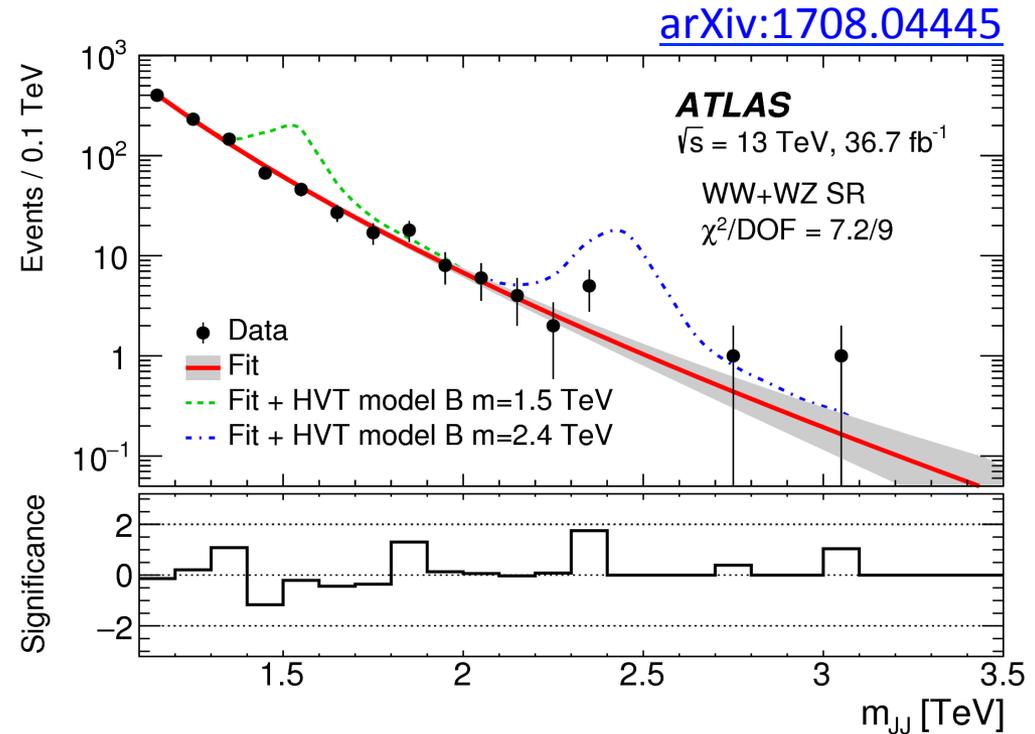
Searching for new massive particles using Lorentz-boosted W/Z bosons



Searching for new massive particles using Lorentz-boosted W/Z bosons

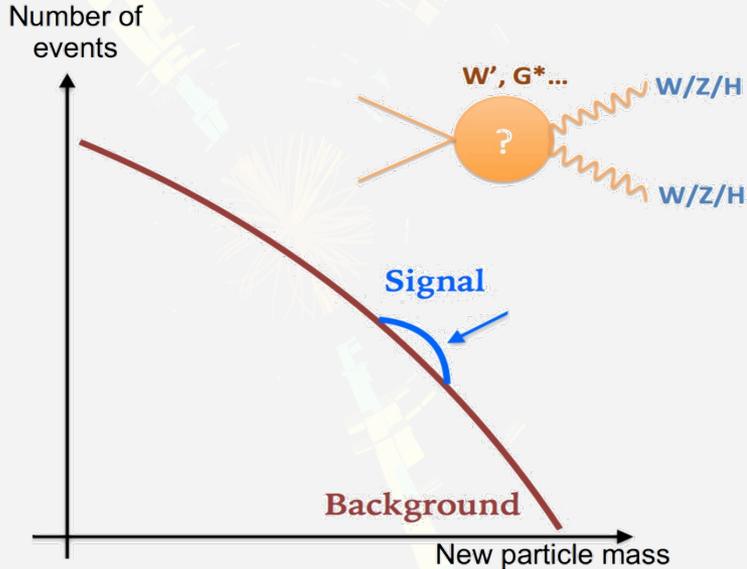


- Search for a mass peak corresponding to the new particle

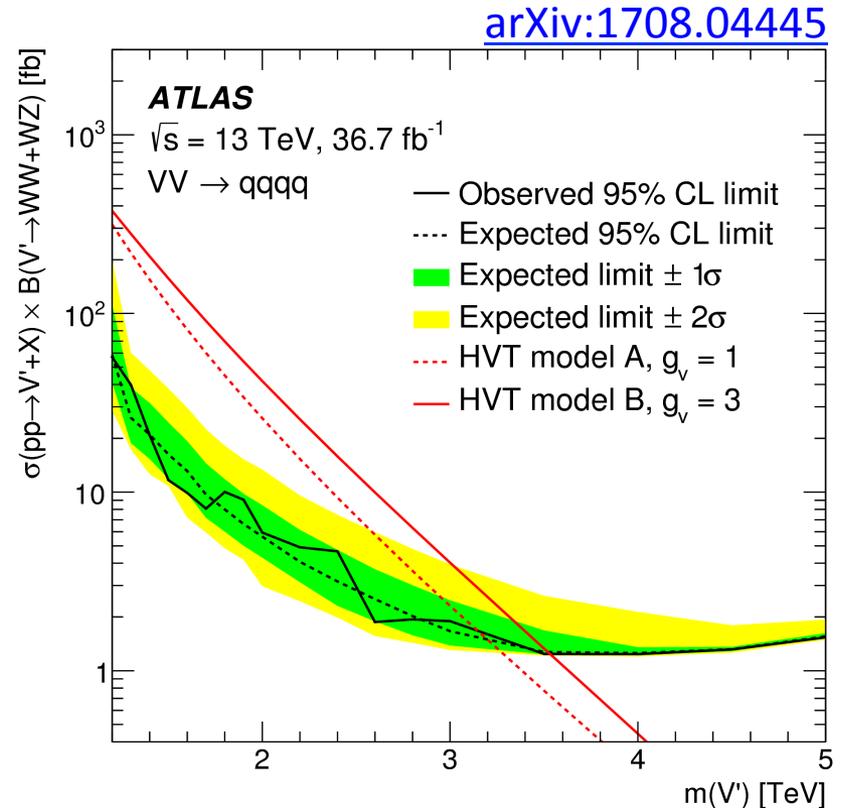


- Observe W candidate pairs with up to 2.5 TeV invariant mass
- $>1 \text{ TeV}$ transverse momentum for each candidate W boson!

Searching for new massive particles using Lorentz-boosted W/Z bosons

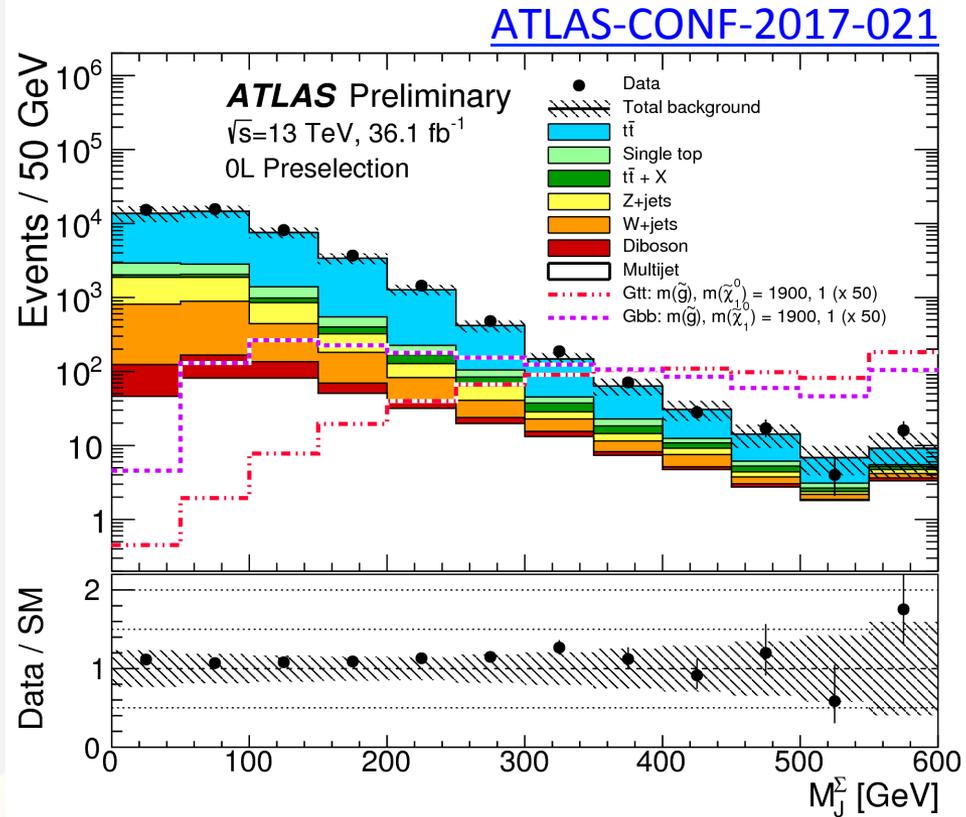
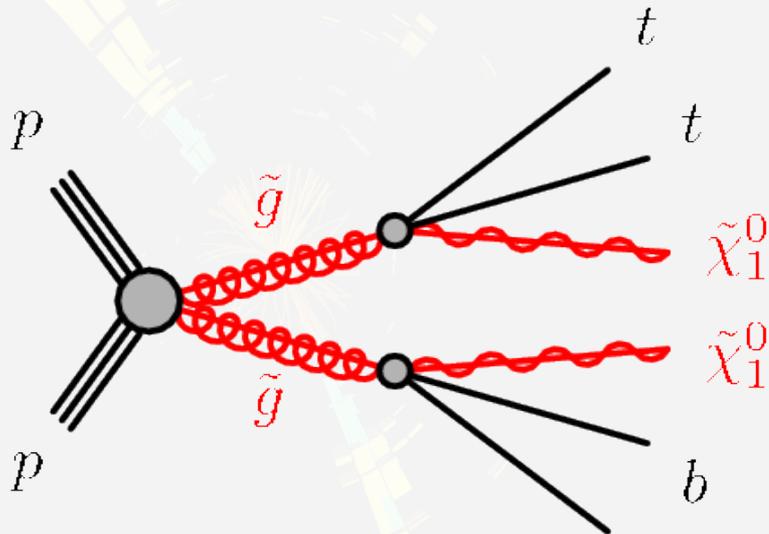


- Search for a mass peak corresponding to the new particle



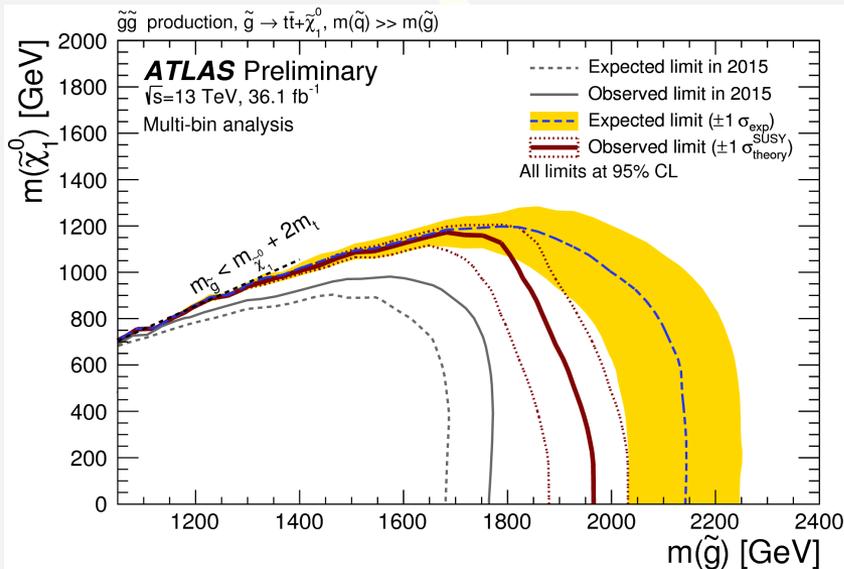
- Observe W candidate pairs with up to 2.5 TeV invariant mass
- >1 TeV transverse momentum for each candidate W boson!

SUSY searches using these techniques



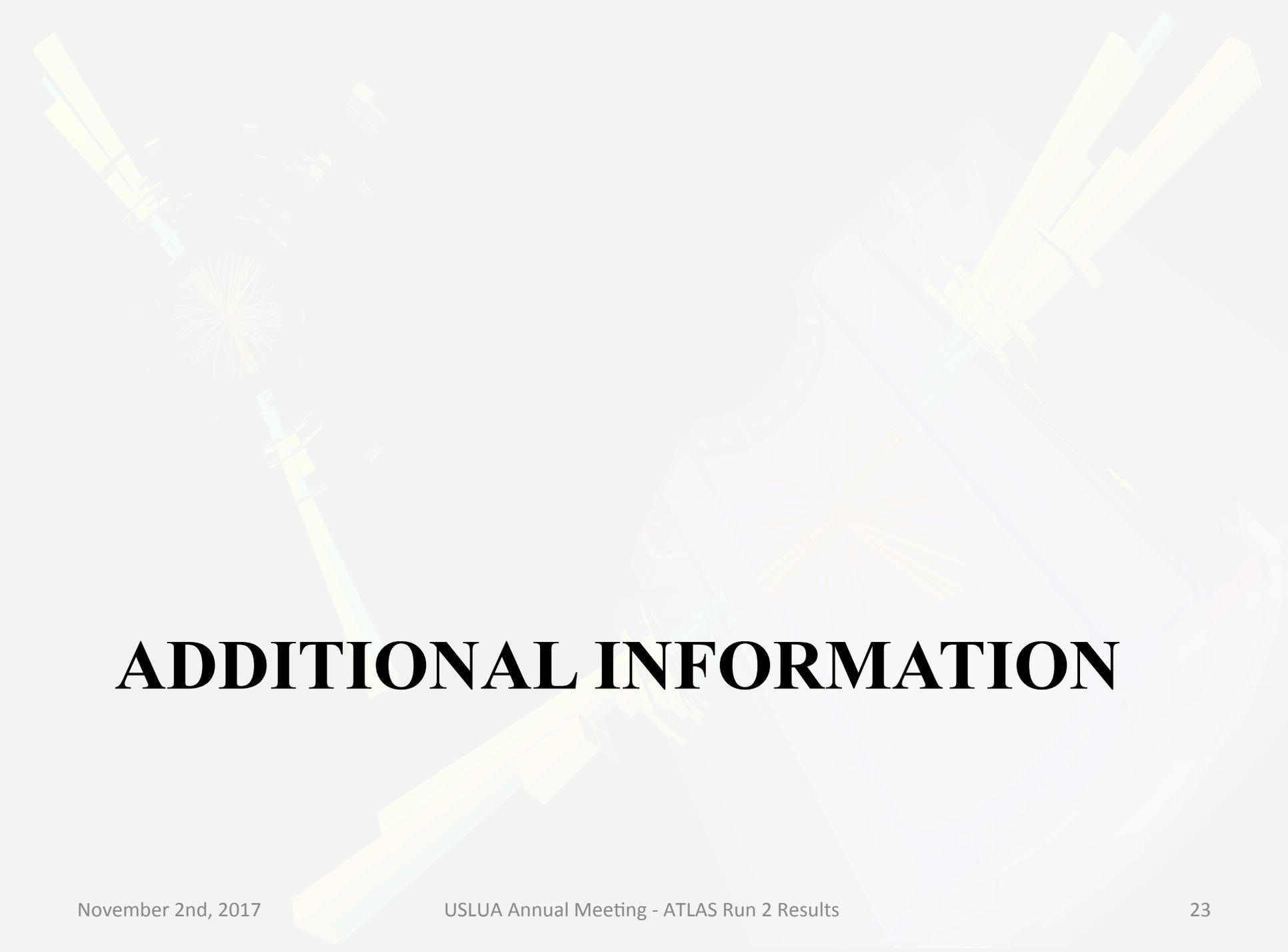
Critical applications of these techniques in all aspects of our physics program.

Some of the most sensitive searches for strongly produced SUSY to date!



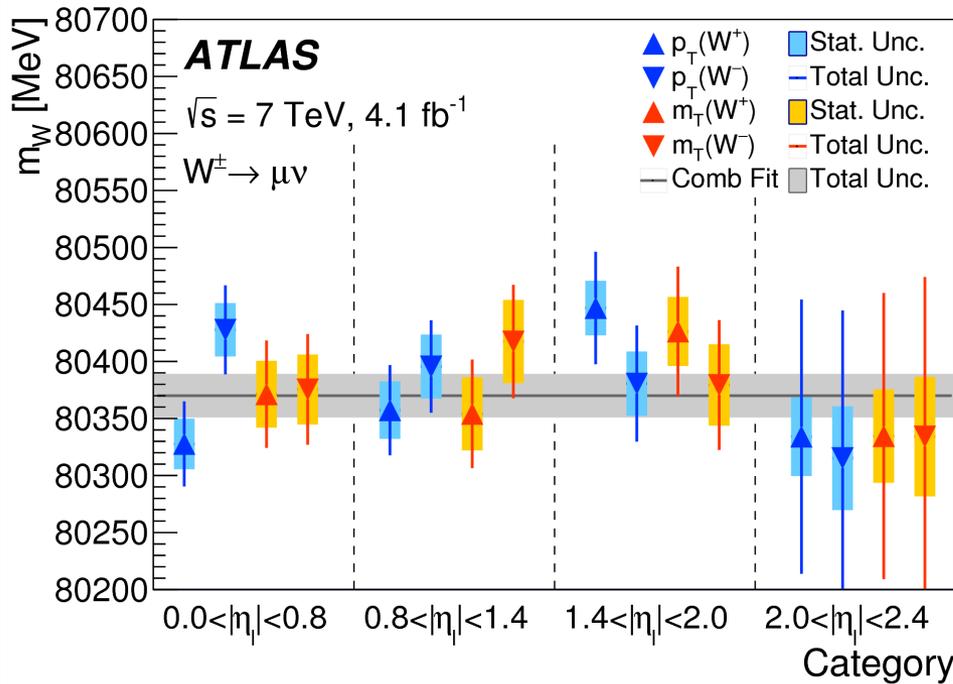
- Recent results confront the Standard Model with high-precision and state-of-the-art techniques
- Advances in experimental methods for hadronic final states yield new insights and opportunities
- Impacts felt across the ATLAS Physics Program

Thank you!



ADDITIONAL INFORMATION

Systematic uncertainties for the W mass



Consistency checks across numerous channels and detector regions.

Detailed assessments of individual systematic uncertainties including dedicated corrections is what permits this excellent performance.

W-boson charge Kinematic distribution	W^+		W^-		Combined	
	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
$\langle \mu \rangle$ scale factor	0.2	1.0	0.2	1.0	0.2	1.0
$\Sigma \bar{E}_T$ correction	0.9	12.2	1.1	10.2	1.0	11.2
Residual corrections (statistics)	2.0	2.7	2.0	2.7	2.0	2.7
Residual corrections (interpolation)	1.4	3.1	1.4	3.1	1.4	3.1
Residual corrections ($Z \rightarrow W$ extrapolation)	0.2	5.8	0.2	4.3	0.2	5.1
Total	2.6	14.2	2.7	11.8	2.6	13.0

Selection criteria for Higgs+ttbar

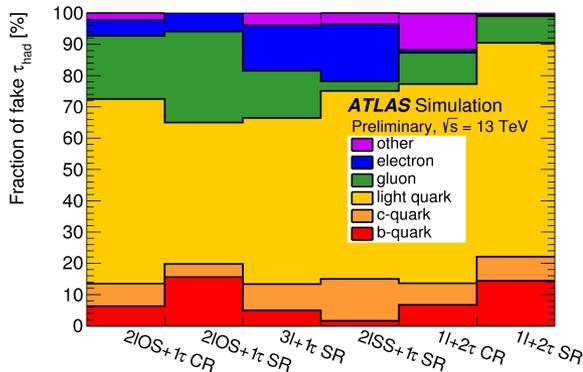
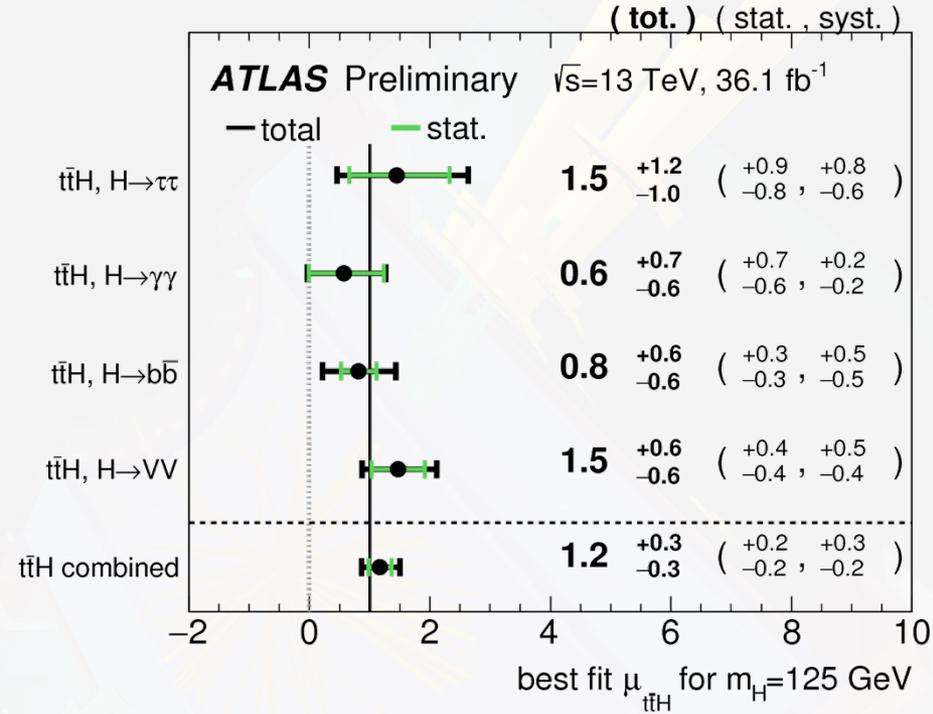
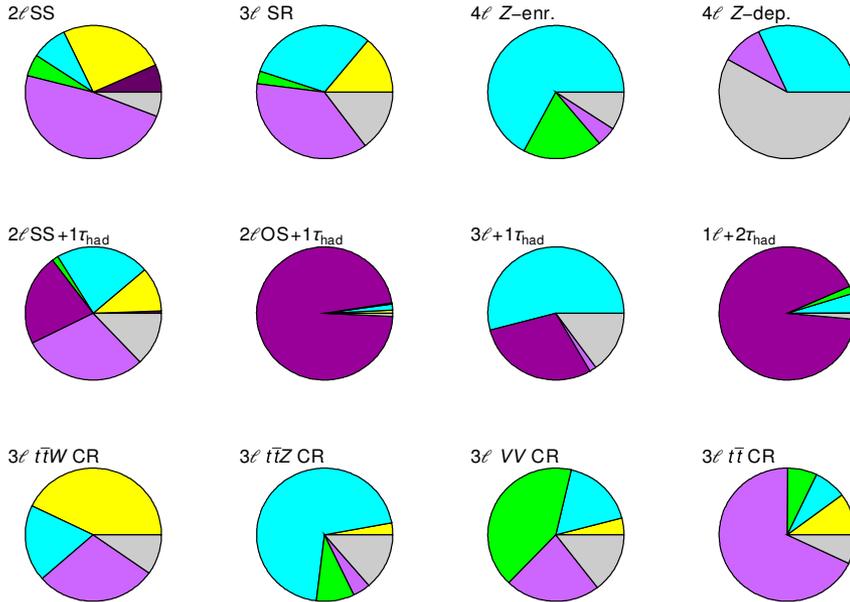
- Jet requirements: $N_{\text{jets}} \geq 2$, $N_{b\text{-jets}} \geq 1$
 - 2ISS, 2ISS+1tau: $N_{\text{jets}} \geq 4$
 - 2IOS+1tau, 1l+2 τ_{had} : $N_{\text{jets}} \geq 3$
- Signal to background ratio ranging from few % to >40% in some channels (4l, 3l+1tau)
- Very different background contributions:
 - Fake/non-prompt light and τ_{had} leptons
 - Irreducible backgrounds: ttW + ttZ and other rare Standard Model processes

Channel	Selection criteria
Common	$N_{\text{jets}} \geq 2$ and $N_{b\text{-jets}} \geq 1$
2 ℓ SS	Two very tight light leptons with $p_{\text{T}} > 20$ GeV Same charge light leptons Zero medium τ_{had} candidates $N_{\text{jets}} \geq 4$; $N_{b\text{-jets}} < 3$
3 ℓ	Three light leptons with $p_{\text{T}} > 10$ GeV; sum of light lepton charges ± 1 Two same-charge leptons must be very tight and have $p_{\text{T}} > 15$ GeV The opposite-charge lepton must be loose, isolated and pass the non-prompt BDT Zero medium τ_{had} candidates $m(\ell^+\ell^-) > 12$ GeV and $ m(\ell^+\ell^-) - 91.2$ GeV > 10 GeV for all SFOC pairs $ m(3\ell) - 91.2$ GeV > 10 GeV
4 ℓ	Four light leptons; sum of light lepton charges 0 Third and fourth leading leptons must be tight $m(\ell^+\ell^-) > 12$ GeV and $ m(\ell^+\ell^-) - 91.2$ GeV > 10 GeV for all SFOC pairs $ m(4\ell) - 125$ GeV > 5 GeV Split 2 categories: Z-depleted (0 SFOC pairs) and Z-enriched (2 or 4 SFOC pairs)
1 ℓ +2 τ_{had}	One tight light lepton, with $p_{\text{T}} > 27$ GeV Two medium τ_{had} candidates of opposite charge, at least one being tight $N_{\text{jets}} \geq 3$
2 ℓ SS+1 τ_{had}	Two very tight light leptons with $p_{\text{T}} > 15$ GeV Same charge light leptons One medium τ_{had} candidate, of opposite charge to that of the light leptons $N_{\text{jets}} \geq 4$ $ m(ee) - 91.2$ GeV > 10 GeV for ee events
2 ℓ OS+1 τ_{had}	Two loose and isolated light leptons, with $p_{\text{T}} > 25, 15$ GeV One medium τ_{had} candidate Opposite charge light leptons One medium τ_{had} candidate $m(\ell^+\ell^-) > 12$ GeV and $ m(\ell^+\ell^-) - 91.2$ GeV > 10 GeV for all SFOC pairs $N_{\text{jets}} \geq 3$
3 ℓ +1 τ_{had}	3 ℓ selection, except: One medium τ_{had} candidate, of opposite charge to the total charge of the light leptons The two same-charge leptons must be tight and have $p_{\text{T}} > 10$ GeV The opposite-charge lepton must be loose and isolated

Details for Higgs+ttbar

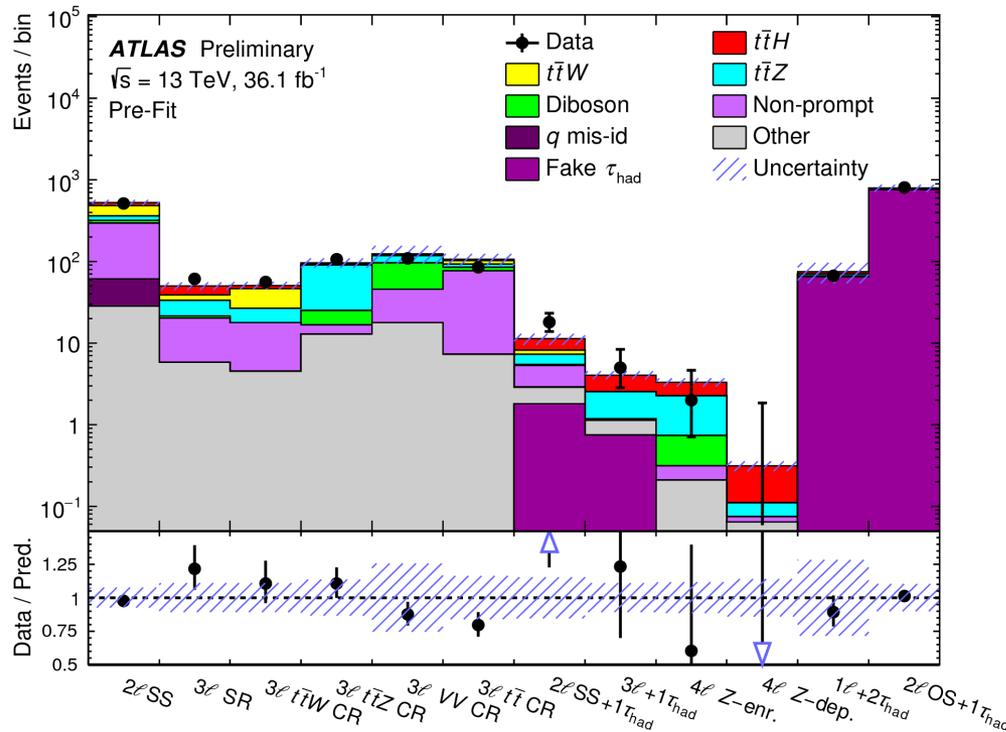
ATLAS Preliminary
 $\sqrt{s} = 13$ TeV

q mis-id $t\bar{t}W$
 $t\bar{t}Z$ Diboson
 Fake τ_{had} Non-prompt
 Other



Channel	Observed		Best fit μ		Expected		Significance	
	Observed	Best fit μ	Expected	Observed	Expected	Observed	Expected	
$2lOS+1\tau_{had}$	$1.7^{+1.6}_{-1.5}$ (stat.)	$+1.4$ (syst.)	$1.0^{+1.5}_{-1.4}$ (stat.)	$+1.2$ (syst.)	$+1.2$ (syst.)	-1.1 (syst.)	0.9σ	0.5σ
$1l+2\tau_{had}$	$-0.6^{+1.1}_{-0.8}$ (stat.)	$+1.1$ (syst.)	$1.0^{+1.1}_{-0.9}$ (stat.)	$+1.2$ (syst.)	$+1.2$ (syst.)	-1.1 (syst.)	-	0.6σ
$4l$	$-0.5^{+1.3}_{-0.8}$ (stat.)	$+0.2$ (syst.)	$1.0^{+1.7}_{-1.2}$ (stat.)	$+0.4$ (syst.)	$+0.4$ (syst.)	-0.2 (syst.)	-	0.8σ
$3l+1\tau_{had}$	$1.6^{+1.7}_{-1.3}$ (stat.)	$+0.6$ (syst.)	$1.0^{+1.5}_{-1.1}$ (stat.)	$+0.4$ (syst.)	$+0.4$ (syst.)	-0.2 (syst.)	1.3σ	0.9σ
$2lSS+1\tau_{had}$	$3.5^{+1.5}_{-1.2}$ (stat.)	$+0.9$ (syst.)	$1.0^{+1.1}_{-0.8}$ (stat.)	$+0.5$ (syst.)	$+0.5$ (syst.)	-0.3 (syst.)	3.4σ	1.1σ
$3l$	$1.8^{+0.6}_{-0.6}$ (stat.)	$+0.6$ (syst.)	$1.0^{+0.6}_{-0.5}$ (stat.)	$+0.5$ (syst.)	$+0.5$ (syst.)	-0.4 (syst.)	2.4σ	1.5σ
$2lSS$	$1.5^{+0.4}_{-0.4}$ (stat.)	$+0.5$ (syst.)	$1.0^{+0.4}_{-0.4}$ (stat.)	$+0.4$ (syst.)	$+0.4$ (syst.)	-0.4 (syst.)	2.7σ	1.9σ
Combined	$1.6^{+0.3}_{-0.3}$ (stat.)	$+0.4$ (syst.)	$1.0^{+0.3}_{-0.3}$ (stat.)	$+0.3$ (syst.)	$+0.3$ (syst.)	-0.3 (syst.)	4.1σ	2.8σ

Details and uncertainties for ttH

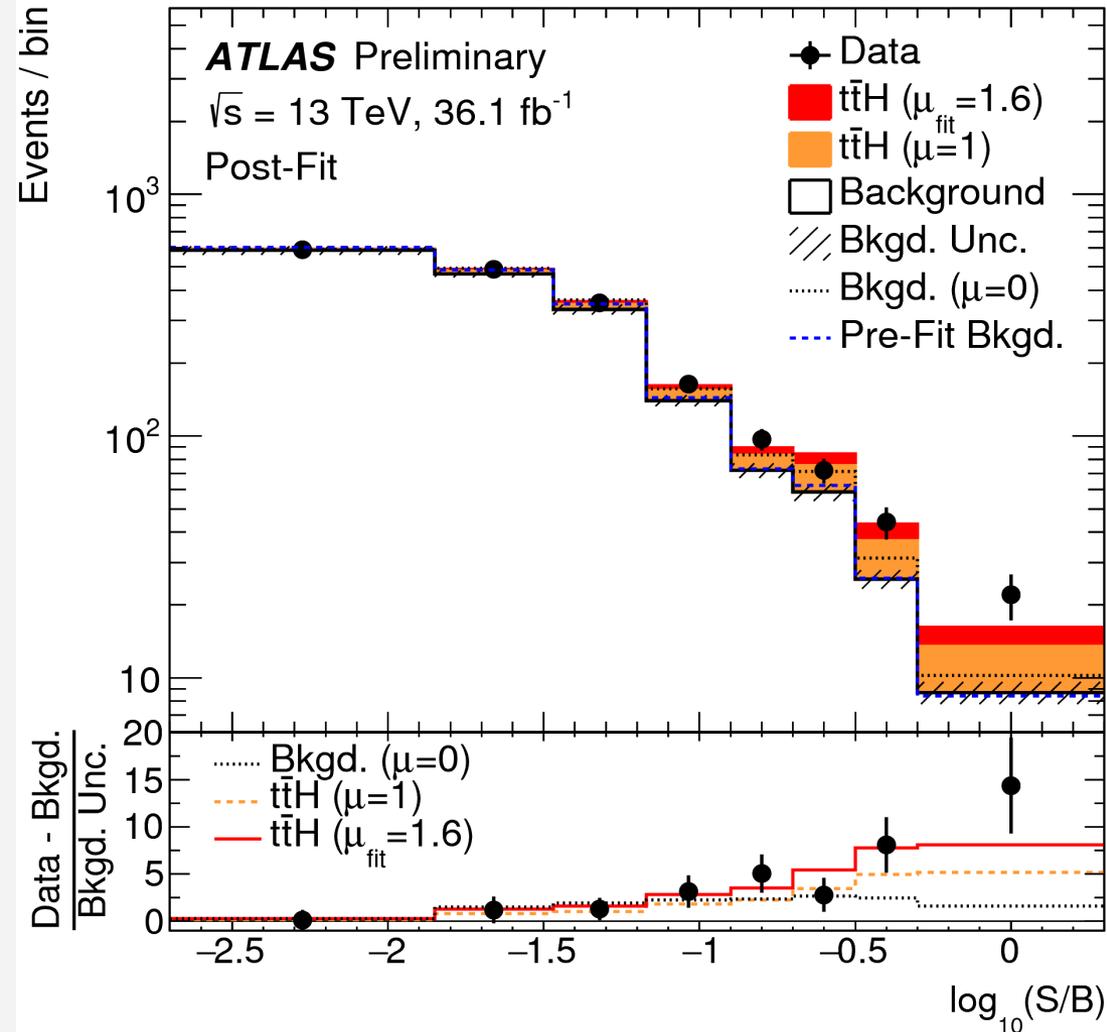


Comparison of prediction to data before the fit in the eight signal and four control regions. The systematic uncertainties in the predicted yields are indicated by the hashed blue band.

Uncertainty Source	$\Delta\mu$	
$t\bar{t}H$ modelling (cross section)	+0.20	-0.09
Jet energy scale and resolution	+0.18	-0.15
Non-prompt light-lepton estimates	+0.15	-0.13
Jet flavour tagging and τ_{had} identification	+0.11	-0.09
$t\bar{t}W$ modelling	+0.10	-0.09
$t\bar{t}Z$ modelling	+0.08	-0.07
Other background modelling	+0.08	-0.07
Luminosity	+0.08	-0.06
$t\bar{t}H$ modelling (acceptance)	+0.08	-0.04
Fake τ_{had} estimates	+0.07	-0.07
Other experimental uncertainties	+0.05	-0.04
Simulation statistics	+0.04	-0.04
Charge misassignment	+0.01	-0.01
Total systematic uncertainty	+0.39	-0.30

Summary of the uncertainties affecting the combined value of μ .

Details for Higgs+ttbar

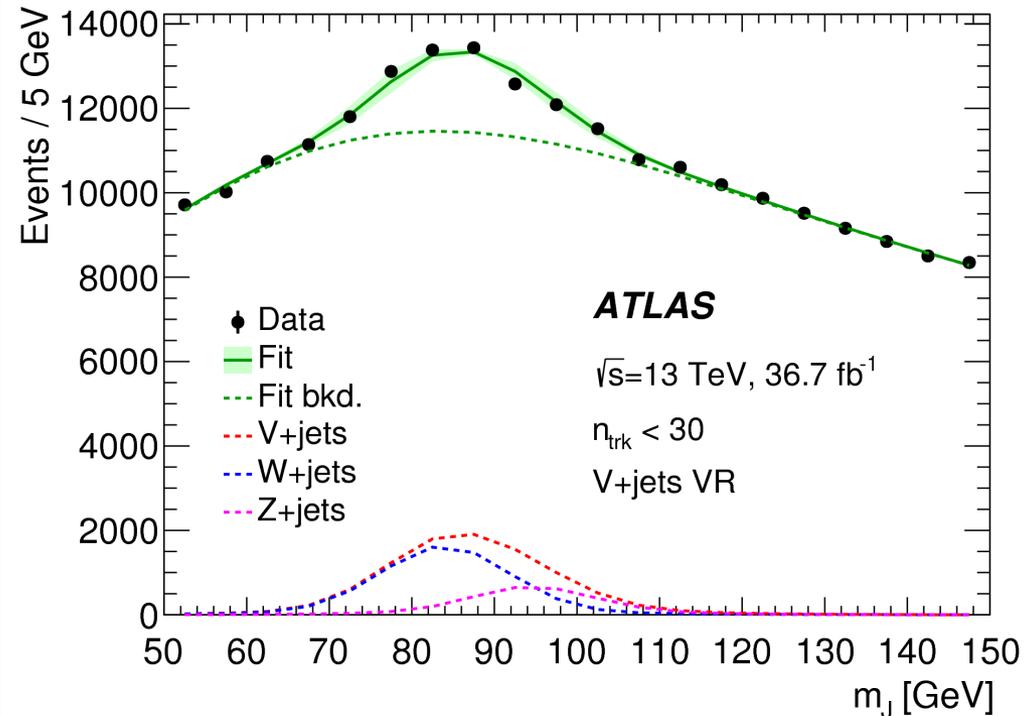
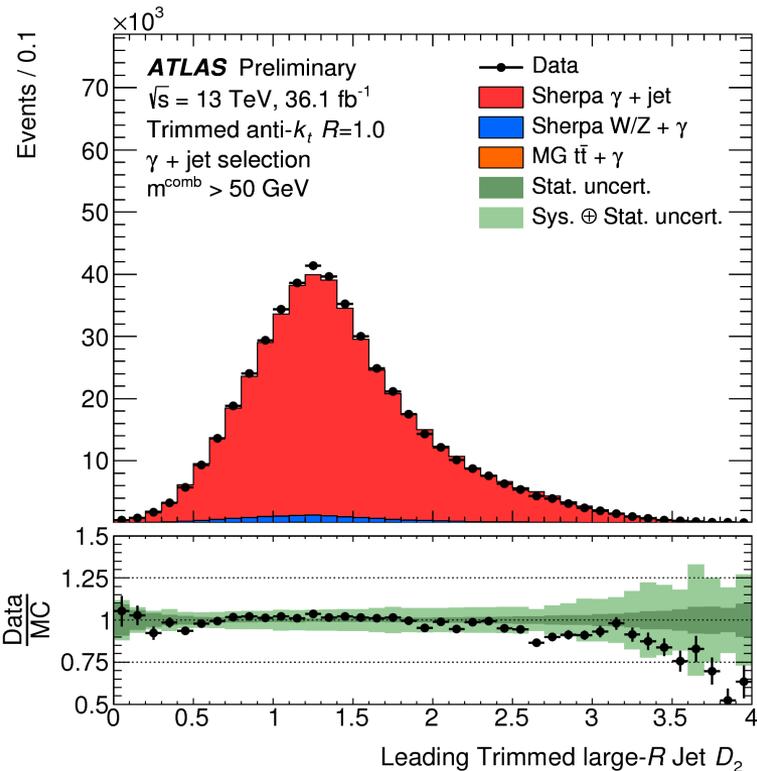


Event yields as a function of $\log_{10}(S/B)$ for data, background and a Higgs boson signal with $m_H = 125 \text{ GeV}$.

The discriminant bins in all signal regions are combined into bins of $\log_{10}(S/B)$, where S is the expected signal yield and B the background yield from the unconditional fit.

Validation of boosted boson tagging

In-situ tests of boson tagging
with analysis selections →



← Detailed data/MC comparisons
for all observables, including
precision measurements

Boosted object calibrations and systematics

