LHCP2021

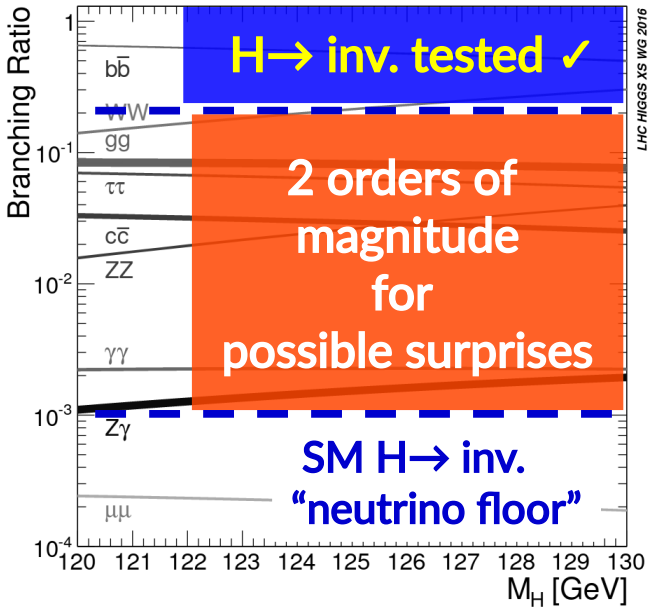
Higgs → Invisible at the LHC

June 7th, 2021

Andreas Albert,
on behalf of the ATLAS and CMS collaborations

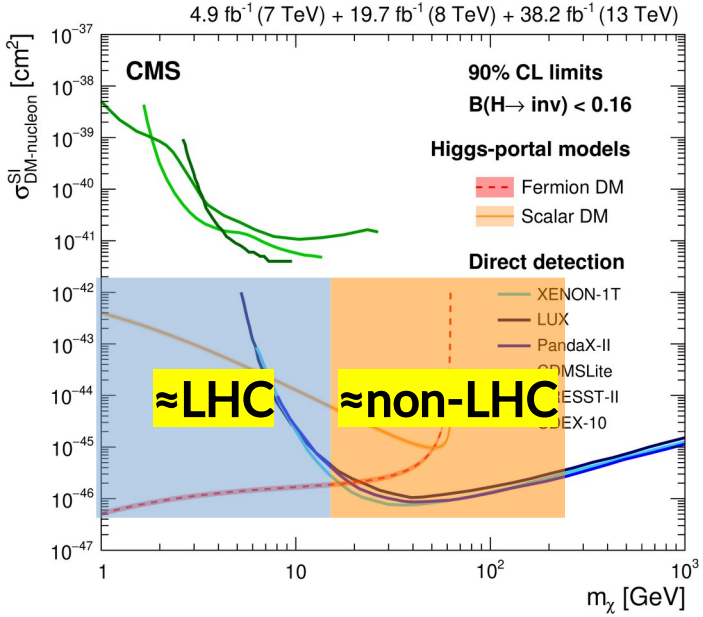
Why H(inv) at the LHC?

1. The SM has a precise prediction here, and we should test it



(visible modes already being tested to better precision)

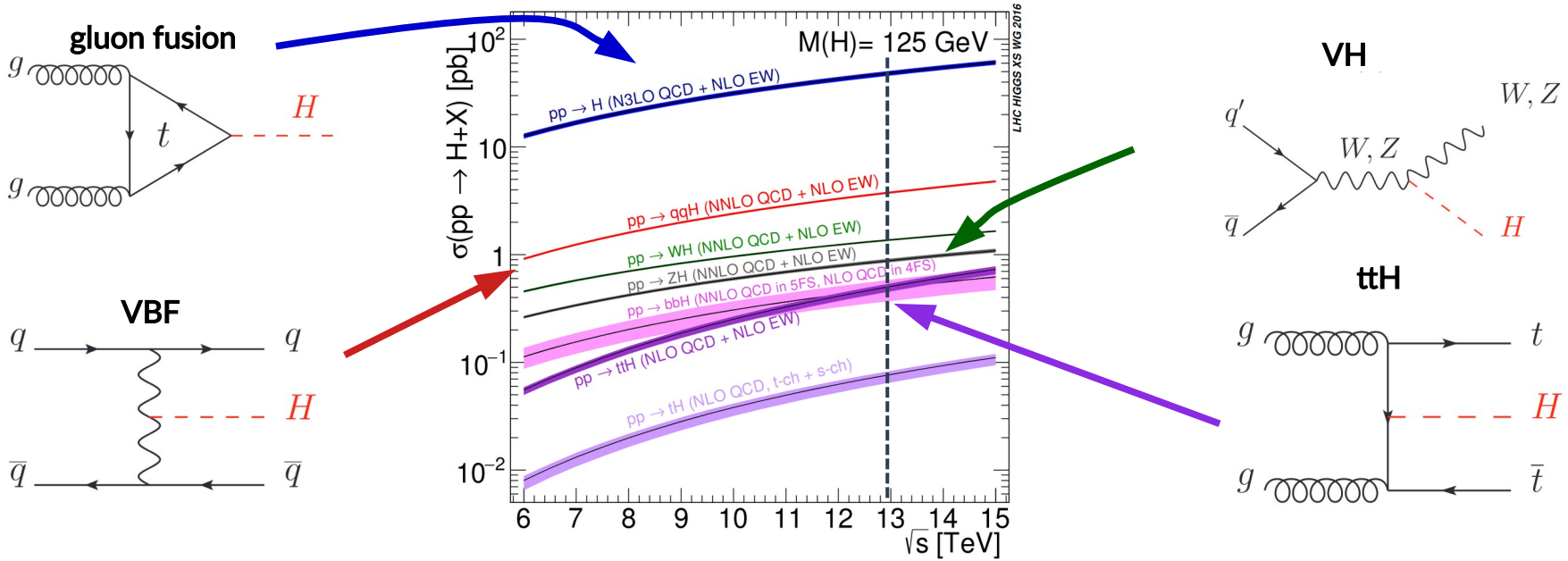
2. Higgs portal DM could be hard to discover elsewhere



(details are model dependent)

H(125) → invisible searches are driven by production modes

Search strategies are optimized by production mode



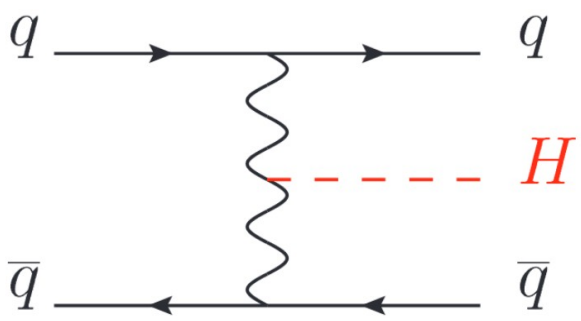
Main considerations: Trigger and background

→ Trade-off between production cross section and selection handles

Note: direct searches assume SM H prod

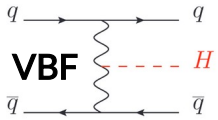
Results for all channels exist, will focus on full Run-2 (~140fb^{-1})

PDG Higgs review



VBF

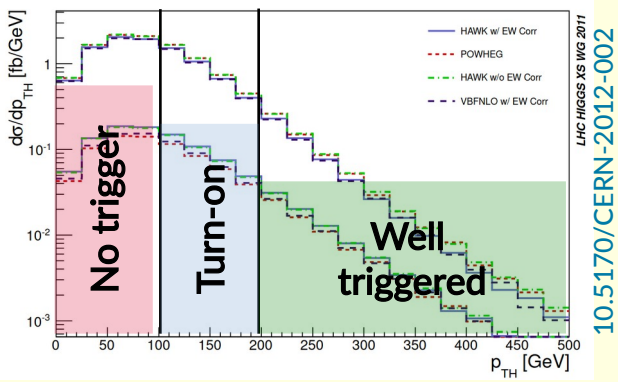
VBF H(inv) basics



Experimental signature for VBF H(inv) is jets + p_T^{miss}

→ **Rely on p_T^{miss}-based trigger**

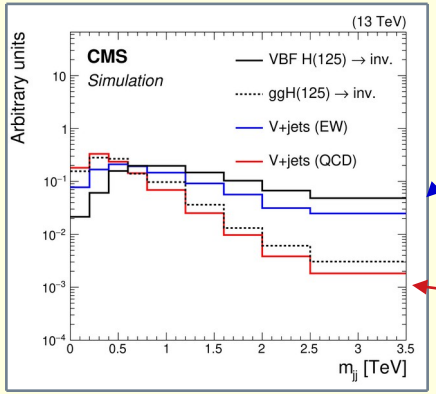
$p_T^{miss} \approx p_T(H)$

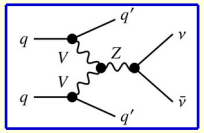


Bulk of pt spectrum not triggered
→ Trigger is limitation for hadronic searches

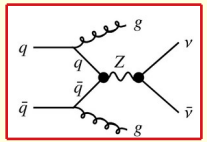
(exact values depend on data set and experiment)

Main background from Z(vv), W(lv)jets





VBF-like BG production
"EWK"



DY-like BG production
"QCD"

Jet properties allow to separate signal vs QCD BG, but irreducible BG remains

VBF ATLAS: selection and categorization

Basic selection

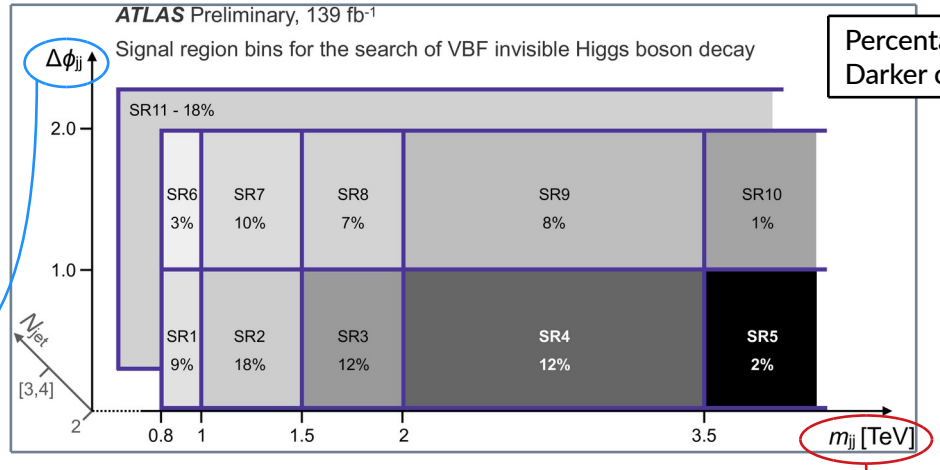
- p_T^{miss} trigger
- p_T^{miss} > 200 GeV

Leading jets:

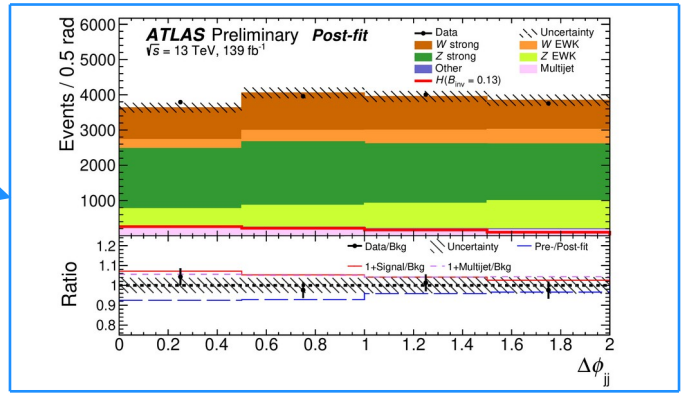
- $p_{T,1/2}$ > 80 / 50 GeV
- $\Delta\varphi(j,j) < 2.0$
- $\eta_1 \times \eta_2 < 0$
- $\Delta\eta(jj) > 3.8$
- m(jj) > 800 GeV

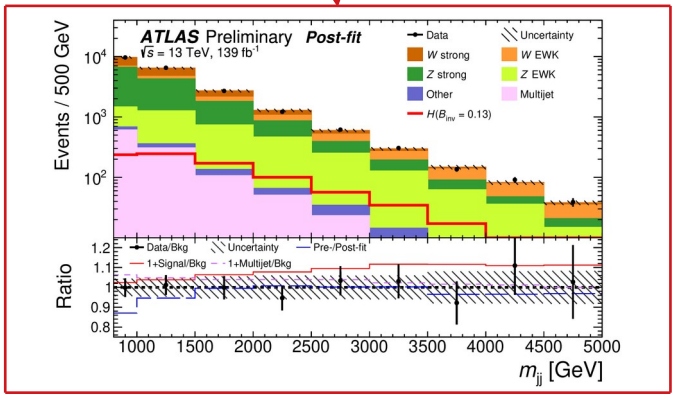
Veto on extra photons, leptons etc

Final binning in m_{jj}, $\Delta\Phi_{jj}$, N_{jet}

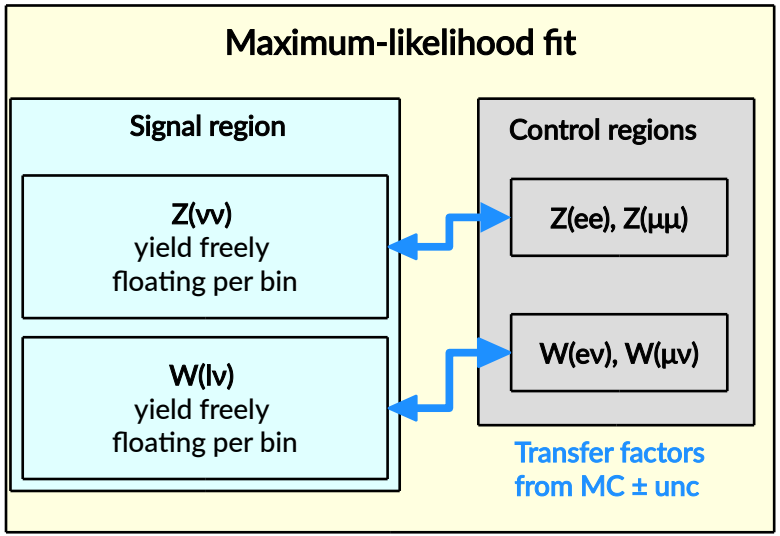


Percentage = fraction of total signal
Darker color shade = higher S/B





ATLAS VBF fit and result

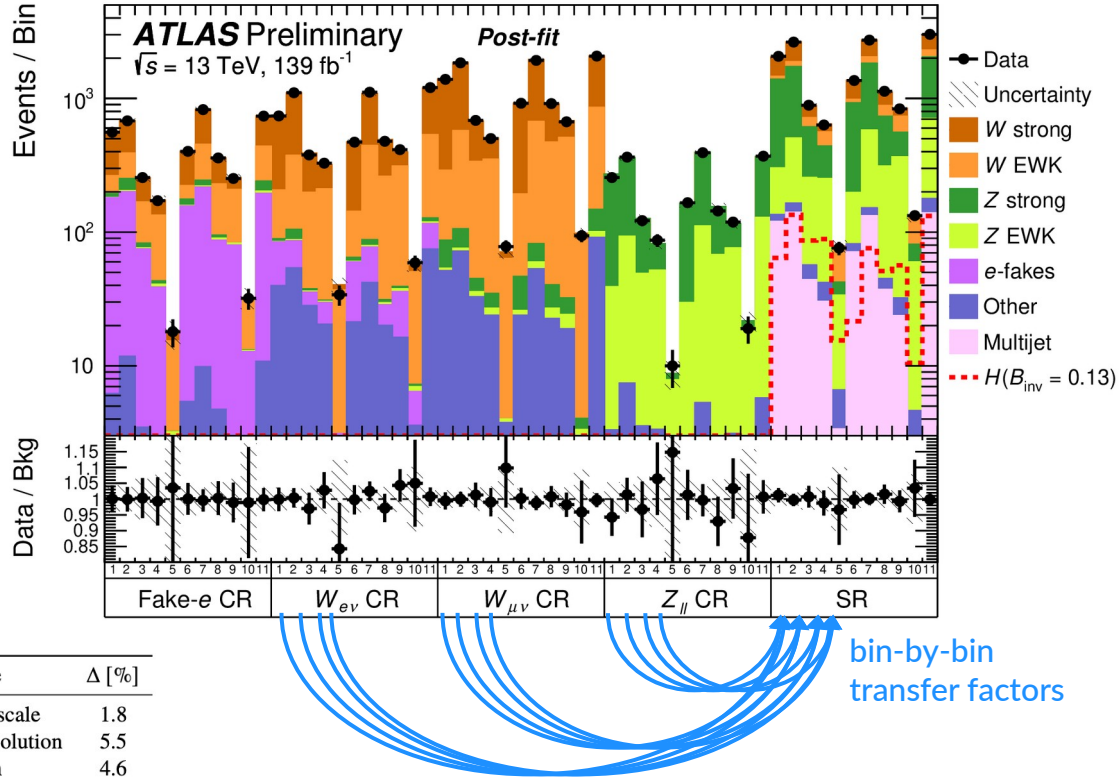


Commonly used fit strategy

BG shape and norm. from data,
2 × N_{bins} unconstrained parameters,
shared between DY and VBF production

→ **many uncertainties cancel in ratio,** especially theory

+ additional control samples for multijets



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

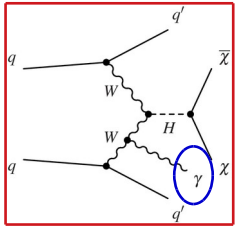
Data agree well with background-only hypothesis

BR(H→ inv) < 13 % (13% exp)

Strategy not limited by systematics, yet

VBF + photon (ATLAS)

Sibling to hadronic VBF analysis



Photon radiation off W defines signature, cuts down background significantly

Basic selection looser than hadronic VBF

p_T^{miss} trigger

p_T^{miss} > 150 GeV

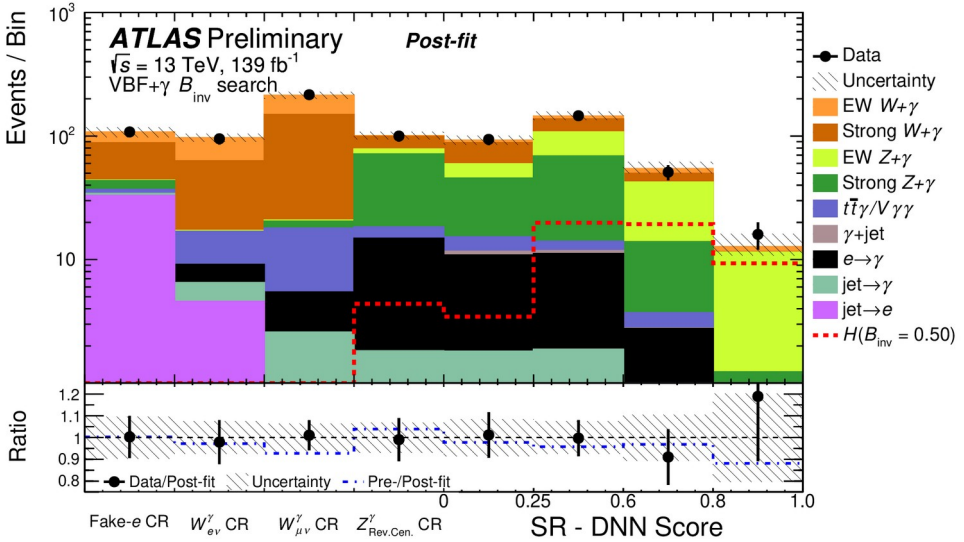
15 GeV < $p_T(\gamma)$ < 110 GeV

photon not aligned with jet

Leading jets:

- $p_{T,1/2}$ > 60 / 50 GeV
- $\Delta\varphi(j,j) < 2.5$
- $\eta_1 \times \eta_2 < 0$
- $\Delta\eta(j,j) > 3.0$
- $m(j,j)$ > 250 GeV

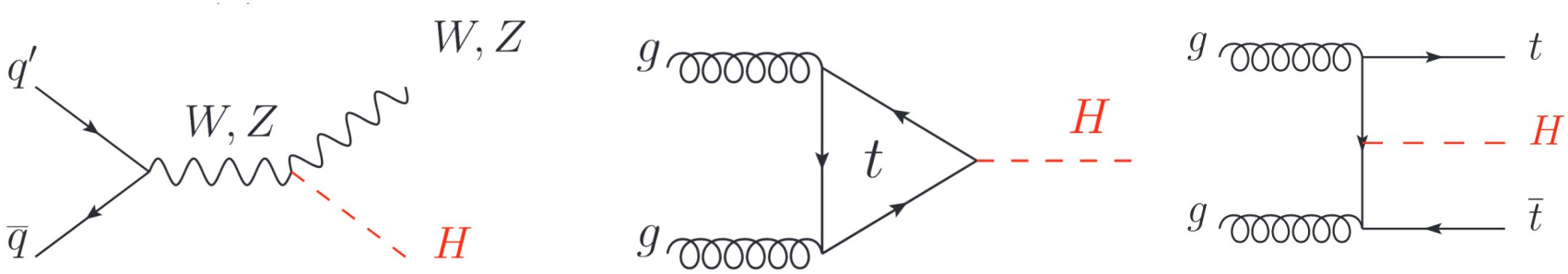
Signal discrimination via deep neutral network
training method optimizes for H→inv limit,
taking into account approximate uncertainty from fit approach



Single-bin CRs help constrain normalizations

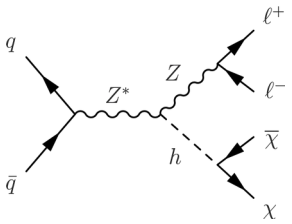
Signal region binned in DNN score

BR(H→ inv) < 37 % (34% exp)



VH, ggH, ttH

CMS Z(ll)H(inv)

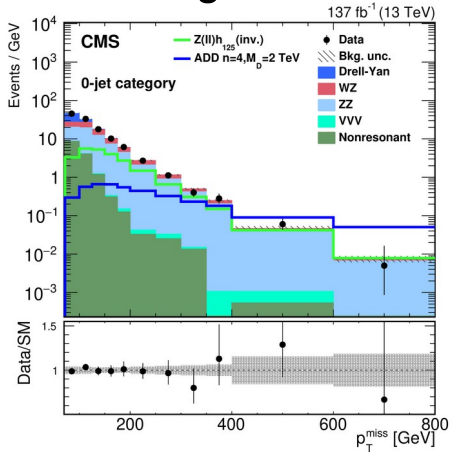


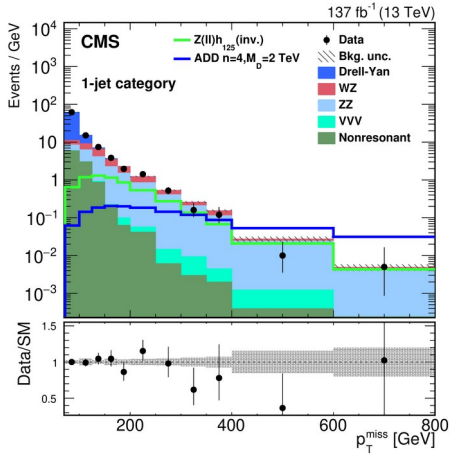
Good Z(ll) candidate
lepton triggers,
$p_T(l) > 25 / 20$ GeV
$|m(ll) - m_Z| < 15$ GeV

Moderate ptmiss
$p_T^{miss} > 100$ GeV

Z and p_T^{miss} balanced, back to back
$|p_T^{miss} - p_T^{ll}| / p_T^{ll} < 0.4$
$\Delta\varphi(p_T^{miss}, p_T^{ll})$

Signal





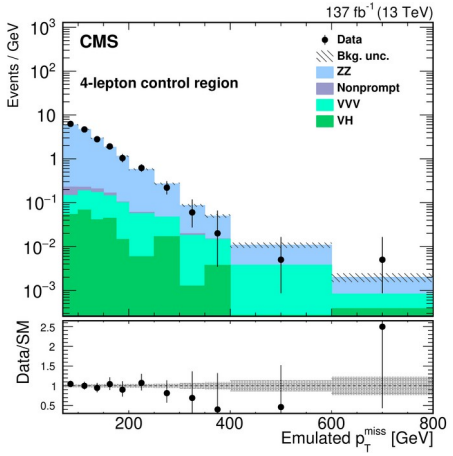
SR binned in Njets
→ control DY + fake p_T^{miss}

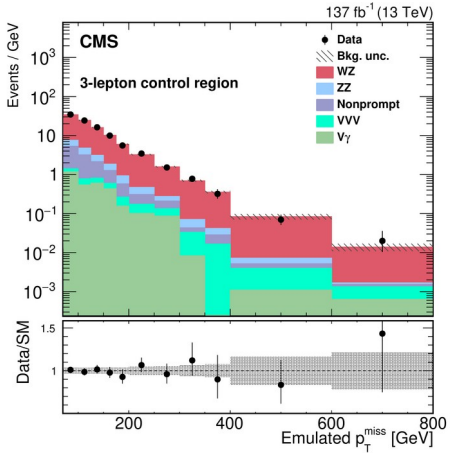
Signal extraction from p_T^{miss}

Z(ll)Z(vv) via 4-lep CR

Z(ll)W(lv) via 3-lep CR

Control





BR(H→ inv) < 25 % (29% exp)

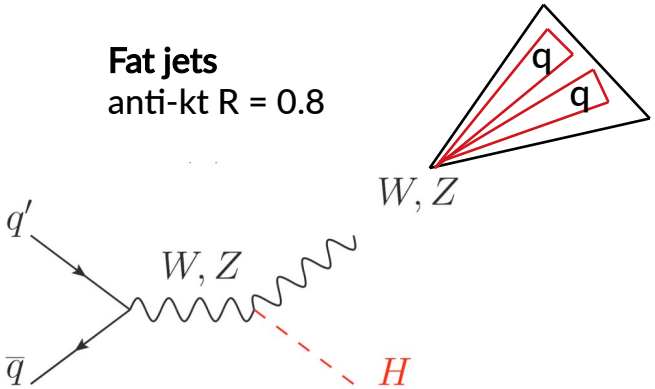
10.1140/epjc/s10052-020-08739-5

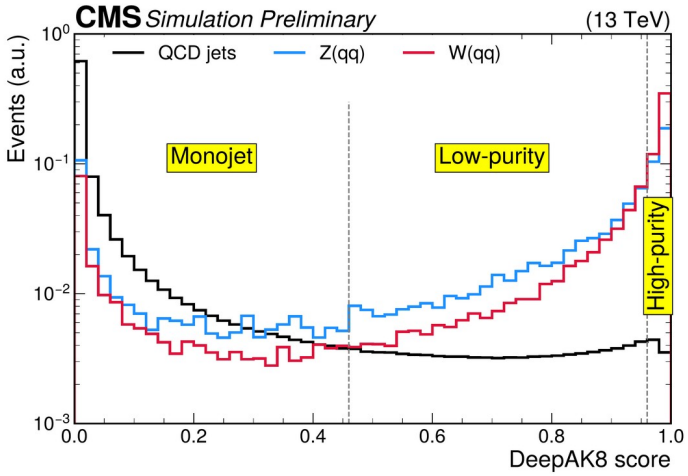
Combined V(qq)H + ggH search (CMS)

CMS-PAS-EXO-20-004

Use neural network tagger to distinguish V(qq) from QCD fat jets
Generic "DeepAK8" tagger 10.1088/1748-0221/15/06/P06005

Fat jets
anti-kt R = 0.8





Inclusive common selection
p_T^{miss} trigger
p_T^{miss} > 250 GeV
no leptons, photons

one of three categories

Mono-V: Target V(qq)H
fat jet pt > 250 GeV, |η|<2.4
jet mass window 65-120 GeV

high-purity
90% VH

low-purity
40% VH

Monojet: captures ggH + ISR jet
narrow jet pt > 100, |η| < 2.4
→ 75% ggH, 20% VBF

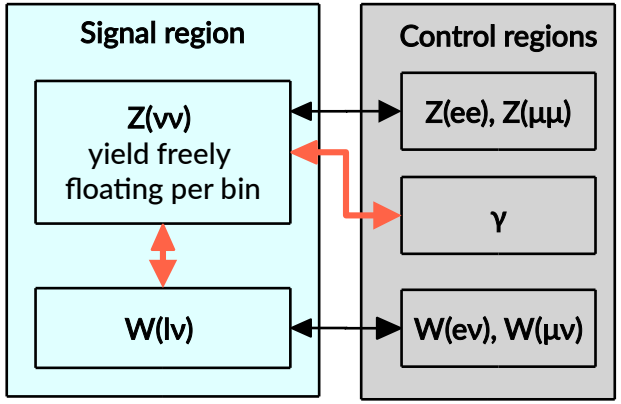
(percentages of total signal)

New analysis of 101 fb^{-1} includes statistical comb. with 2016 result 10.1103/PhysRevD.97.092005

CMS-PAS-EXO-20-004

Combined V(qq)H + ggH search (CMS)

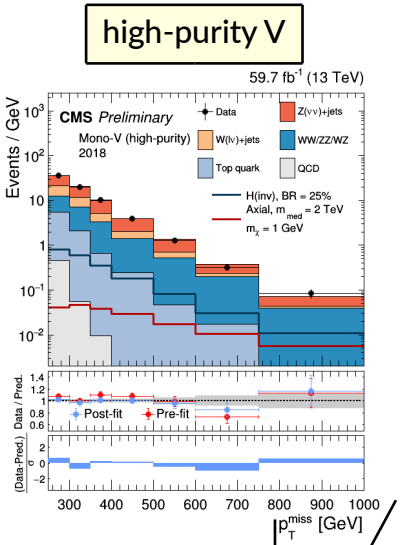
Fit strategy with additional Z/W and Z/γ transfer

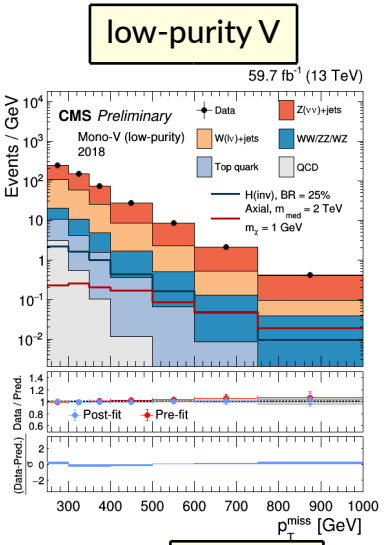


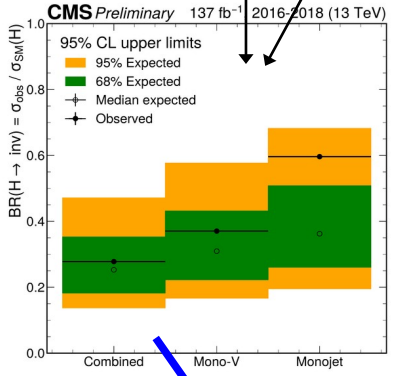
→ **Fewer free parameters (= 1× N_{bins})**

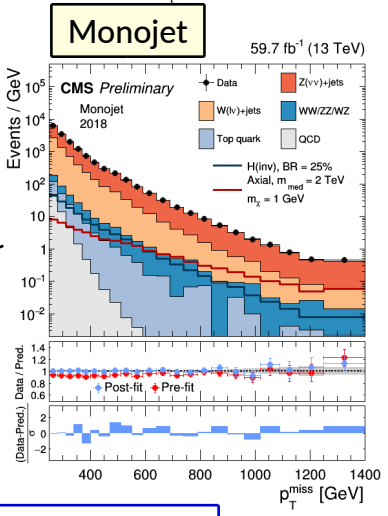
Cross-process theory uncertainty under control thanks to dedicated theory predictions
→ 10.1140/epjc/s10052-017-5389-1

Main uncs from lepton, photon reco, SR multijet





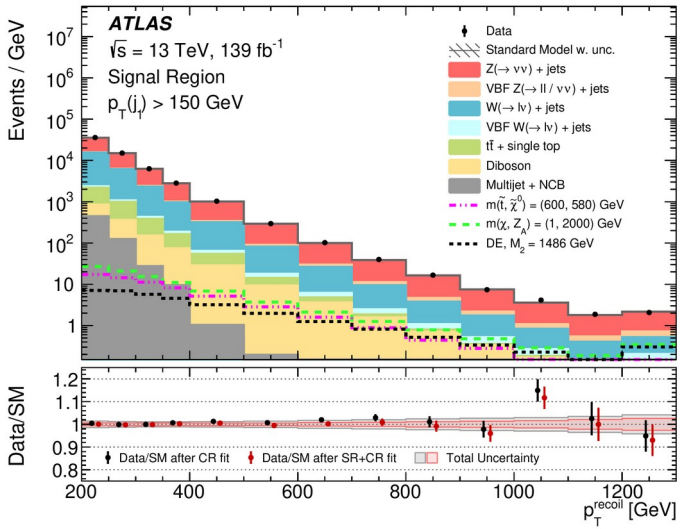




BR(H→ inv) < 28 % (25% exp)

ATLAS ggH, ttH

ggH from inclusive search in jets + p_T^{miss}



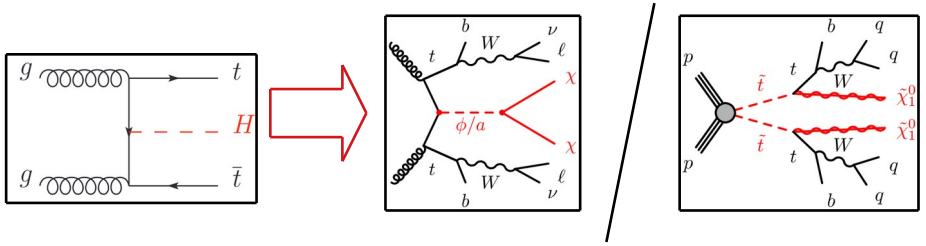
Similar approach to CMS monojet

total BG uncertainty ≈ 1.5 – 4.2 % (!)

BR(H→ inv) < 34 % (39% exp)

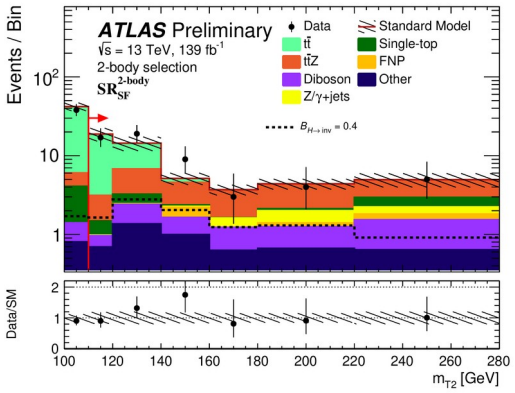
arXiv:2102.10874

ttH(inv) from reinterp. of tt+DM / stop searches



Main sensitivity from top → leptons

use MT2 to separate ttbar vs ttbar + extra ptmiss



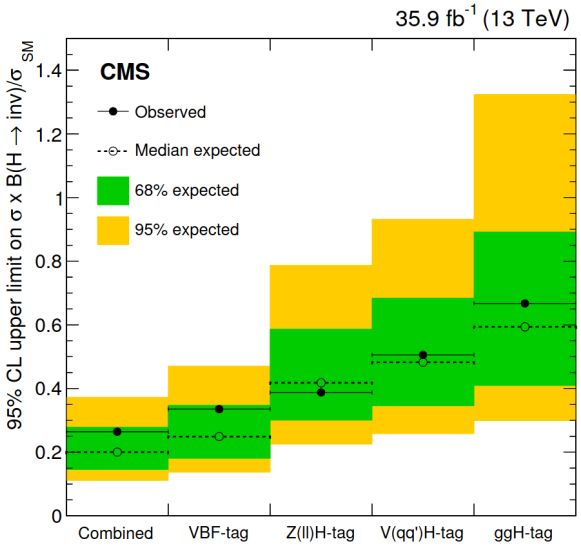
BR(H→ inv) < 40 % (36% exp)

10.1007/JHEP04(2021)165
10.1140/epjc/s10052-020-8102-8
ATLAS-CONF-2020-052

Combinations

Combinations are final endgame of H(inv) searches

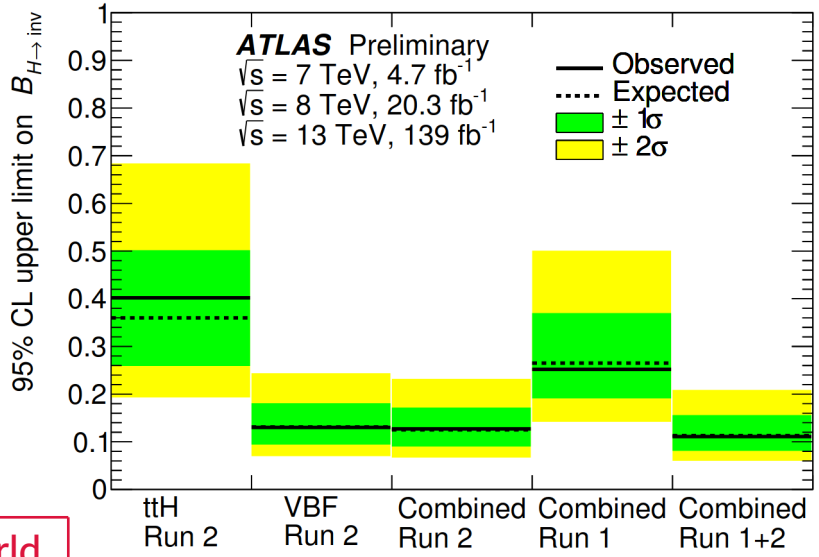
CMS early Run-2 (2016) + 2015 + Run-1



BR(H→ inv) < 19 % (15% exp)

No full Run-2 VBF, ttH, combination, yet

ATLAS full Run-2 VBF + ttH + Run-1



Current world best!

BR(H→ inv) < 11 % (11% exp)

No full Run-2 VH, yet. Combination partial.

Significant additions still to come in both experiments

Expect to crack 10% threshold with Run-2 direct searches!

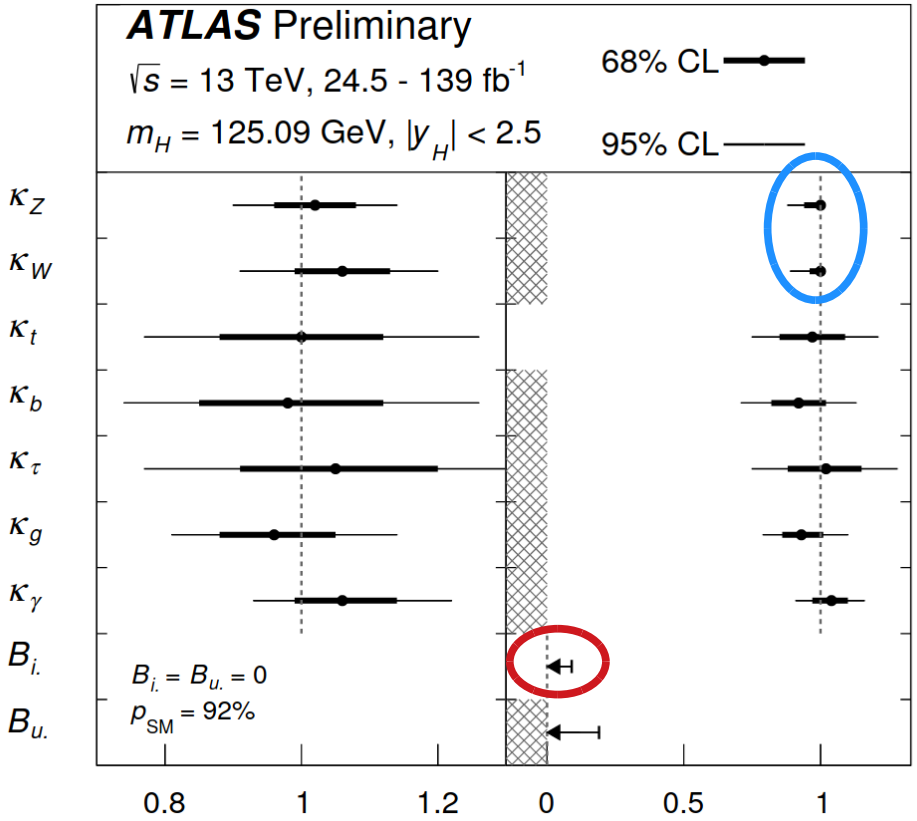
Indirect constraints from coupling fits

Pictured: ATLAS full Run-2 ATLAS-CONF-2020-027

Combination with visible channels can further tighten constraints indirectly

Need assumptions to limit total Higgs width, here $\kappa_W, \kappa_Z \leq 1$

Constraint from VBF already tightened to **9%** here

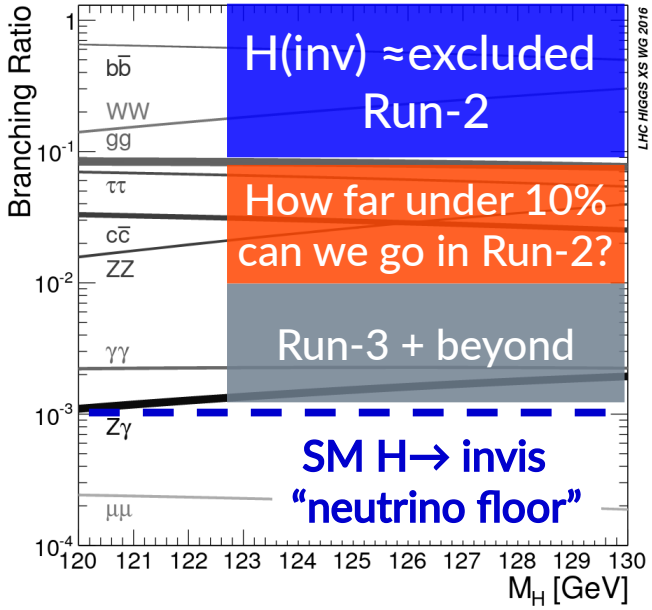


Not pictured: CMS 2016 combination Eur. Phys. J. C 79 (2019) 421

(all exclusions @ 95% CL)

Summary

- **H→ inv searches are well-motivated tests of SM + DM observation option**
- **Pursued in all production modes. Most sensitive: VBF**
  - Best single-channel result to date from ATLAS VBF: BR < 13%
- **Combinations including full Run-2 will probe ≈ 10% threshold**
  - Best partial combination so far from ATLAS: BR < 11%
- **Future sensitivity to be driven by VBF channel**
  - Statistical uncertainty still big → More data will help
  - Improvement fronts:
    - Cross-process transfer factors? → Battle theory uncertainties
    - Better triggers?
    - Ultimate limitations will be experimental:
      - Lepton, photon, QCD multijet estimation precision
- **Indirect constraints can further strengthen exclusion**
  - current best BR < 9%



Post-session zoom:
ID 662 4723 6089
PW "hinv"
Link

Backup

Summary of results

Experiment	Channel	Expected	Observed	Full Run-2 included?	Reference
ATLAS	VBF	0.13	0.13	✓	ATLAS-CONF-2020-008
	VBF + γ	0.34	0.37	✓	ATLAS-CONF-2021-004
	ggH	0.39	0.34	✓	arxiv:2102.10874
	V(qq)H	0.58	0.83	2016 only	10.1007/JHEP10(2018)180
	Z(ll)H	0.39	0.67	2016 only	10.1016/j.physletb.2017.11.049
	ttH	0.36	0.40	✓	ATLAS-CONF-2020-052
	Combination (VBF, ttH, Run-1)	0.11	0.11	✓	ATLAS-CONF-2020-052
CMS	VBF	0.25	0.33	2016 only	10.1016/j.physletb.2019.04.025
	ggH + V(qq)H	0.25	0.28	✓	CMS-PAS-EXO-20-004
	Z(ll)H	0.25	0.29	✓	10.1140/epjc/s10052-020-08739-5
	ttH	0.48	0.46	2016 only	CMS-PAS-HIG-18-008
	Combination	0.15	0.19	up to 2016	10.1016/j.physletb.2019.04.025

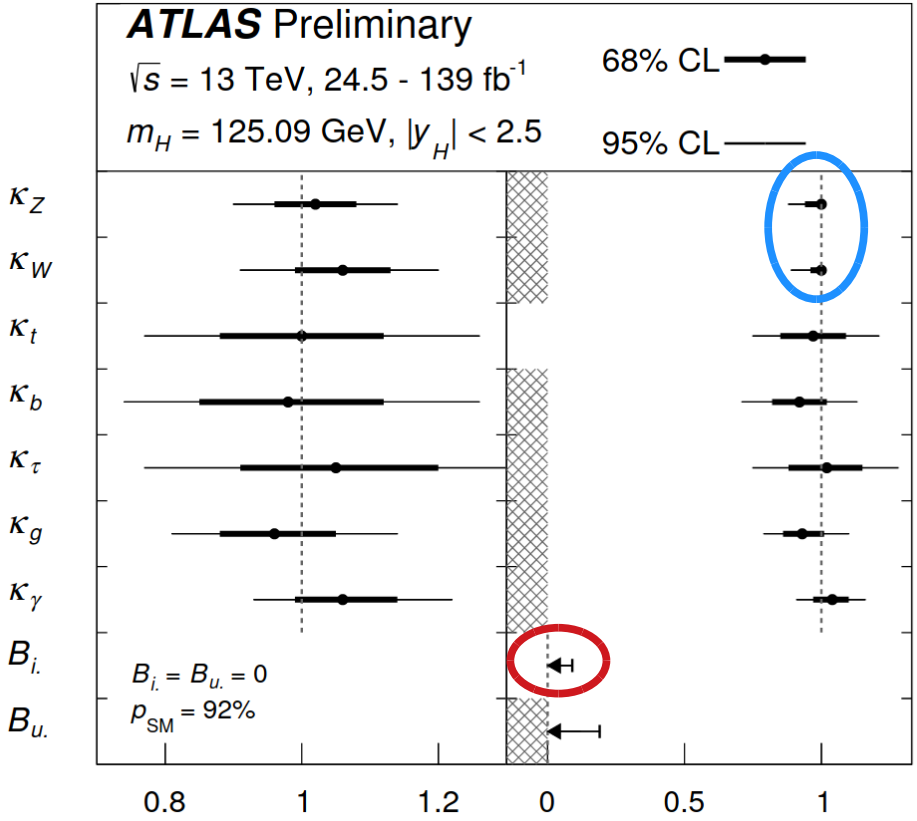
Constraints from Higgs property grand combinations

Grand combinations of measurements in different Higgs modes are used to set constraints on generic coupling modifiers (See e.g. arxiv:1307.1347 for details on framework)

Most recent result from ATLAS includes VBF H(inv) full Run-2 result to constrain BR(H→ inv)

Without assumption on total H width, cannot further constrain H→ inv here

If one assumes $\kappa_W, \kappa_Z \leq 1$, total H width is limited, and H(inv) constraint tightens to **9%** already



Modifiers for coupling of Higgs to given particle

Backup: ATLAS VBF analysis

Jet binning

Main analysis focus on 2-jet events. Events with 3-4 jets are in separate bin.
Extra selection requirements aimed to identify whether extra jets are consistent with radiation

$$C_i = \exp\left(-\frac{4}{(\eta^{j1} - \eta^{j2})^2}\left(\eta^i - \frac{\eta^{j1} + \eta^{j2}}{2}\right)^2\right)$$

$$m_i^{rel} = \frac{\min\{m_{j1,i}, m_{j2,i}\}}{m_{jj}}$$

C small → extra jet is far in η from average of leading jets

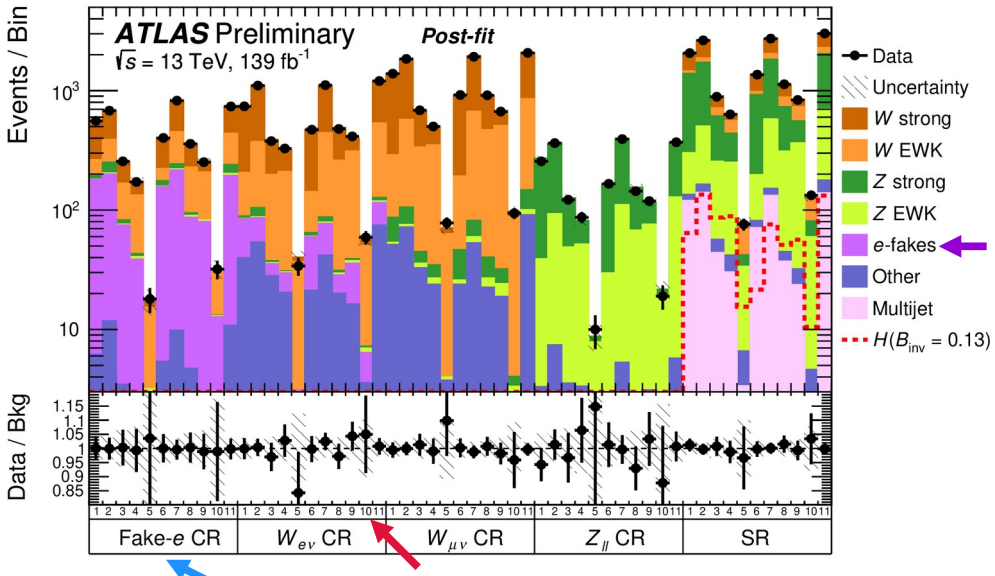
m small → jet is FSR-like

Require $C_i < 0.6$, $m_i^{rel} < 0.05$ for 3rd, 4th jet if present
(a jet is counted if p_T>25 GeV)

VBF: Electron fakes

$$S_{\mathrm{MET}} = \frac{E_{\mathrm{T}}^{\mathrm{miss}}}{\sqrt{p_{\mathrm{T}}^{\mathrm{j1}} + p_{\mathrm{T}}^{\mathrm{j2}} + p_{\mathrm{T}}^{e}}}$$

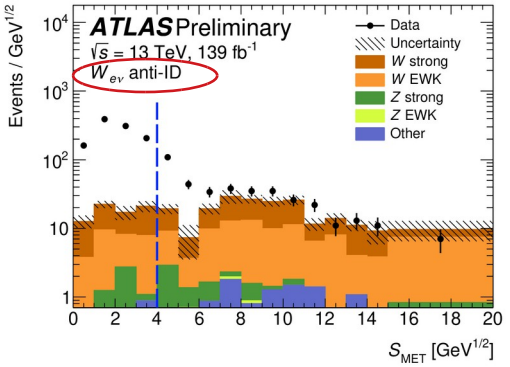
Goal: estimate events with fake electrons in W CR

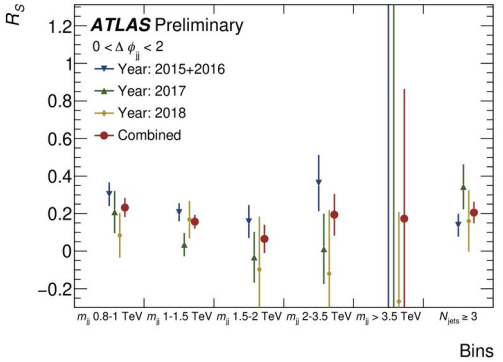


Method: Add additional Fake-e CR to the fit

same as regular Wev, but with inverted p_T^{miss} significance S_{MET} → enriched in fakes

Transfer factor from low S_{MET} → high S_{MET} from sample with inverted ele ID





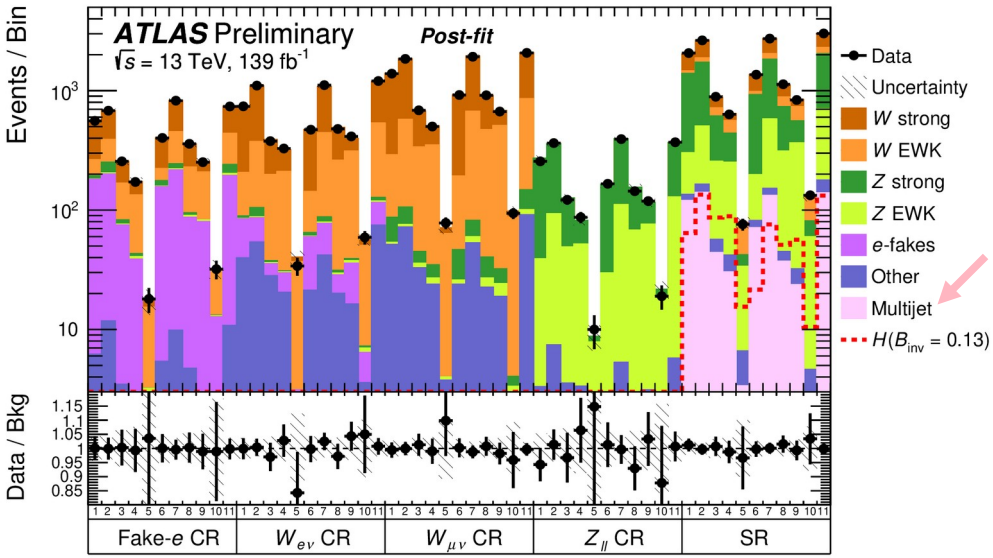
SR Multijet estimate

Estimation via "rebalance and smear":

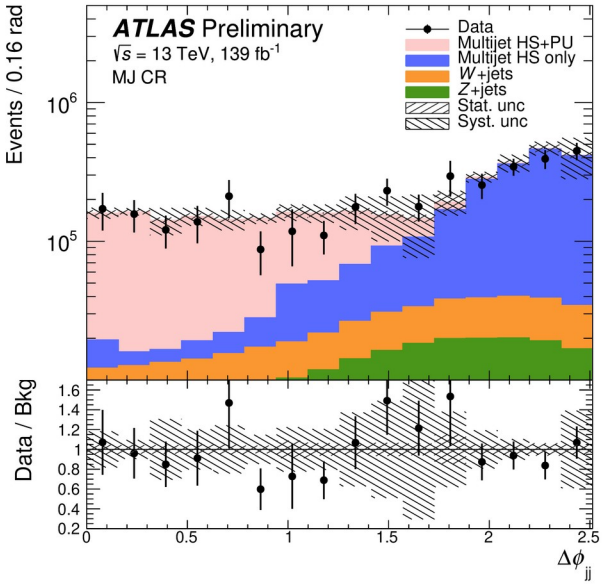
- Obtain inclusive multijet sample from single jet triggers
- Rebalance = Vary jet momenta within uncertainties to minimize p_T^{miss}
- Smear = generate toy events by smearing rebalanced jets many times
  → Apply SR selection on toy events

- Estimate done separately for events with ("Hard scatter + pile-up") and without jets failing vertex assignment ("Hard scatter only")

Goal: estimate multijet events in SR

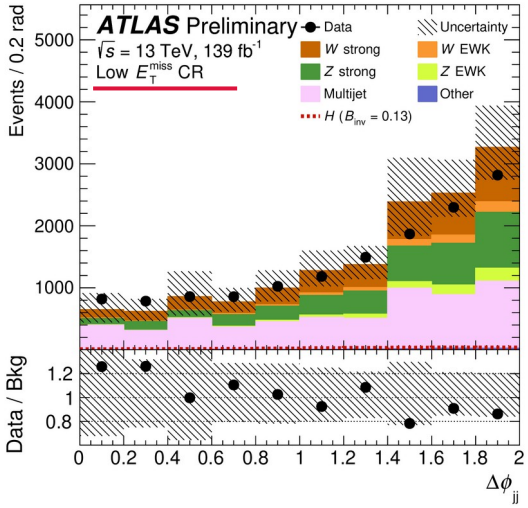


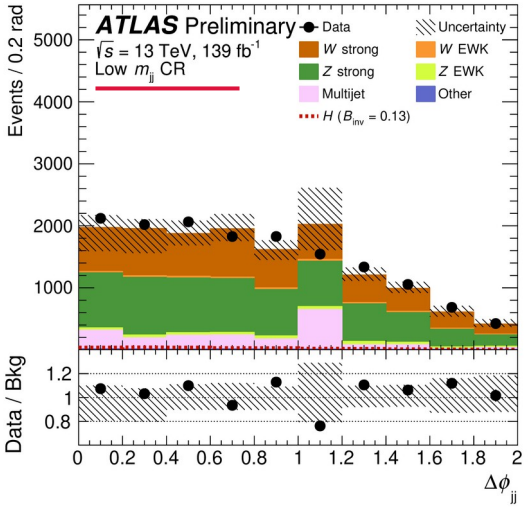
Template normalization in Δφ(j,j) fit
(CR @ p_T^{miss} > 100 GeV)



SR Multijet estimate: Validation + uncertainty

Validate estimate in SR-adjacent validation regions





Average template normalization factor from both regions propagated to SR

Half difference of normalization factors used as non-closure uncertainty, which is dominant effect

Period	Event yield	Uncertainties				
		stat.	non-closure $\Delta\phi_{jj} < 1$	non-closure $1 < \Delta\phi_{jj} < 2$	JER core	JER tail
2015+16	85	10%	100%	100%	35%	18%
2017	231	8%	72%	47%	19%	3%
2018	289	9%	32%	62%	22%	5%

Likelihood function

Freely floating scaling factors β are common for given process in all regions
→ Ratio of Z(SR)/Z(CR) is as predicted from MC, modulo constrained uncertainties
same for W

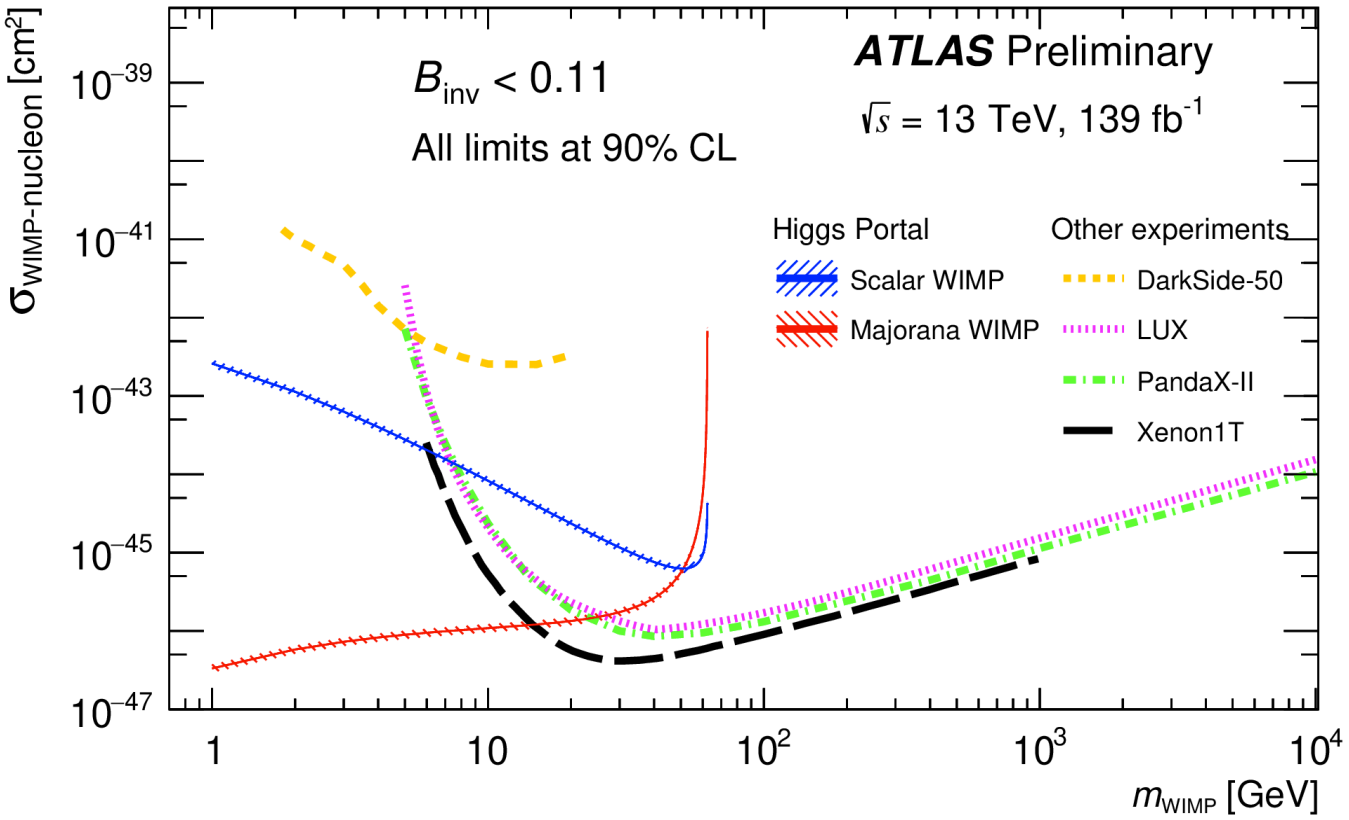
$$
\begin{aligned}
\mathcal{L}(\mu, \vec{\beta}_Z, \vec{\beta}_W, \vec{n}_{\text{fake}}, \vec{\theta}) = \; & \prod_i \mathcal{P}\left(N_i^{\text{SR}} \mid \beta_{Z,i} \cdot B_{Z,i}^{\text{SR,MC}} + \beta_{W,i} \cdot B_{W,i}^{\text{SR,MC}} + B_{\text{MJ},i}^{\text{SR}} + B_{\text{other},i}^{\text{SR,MC}} + \mu \cdot S_i^{\text{SR,MC}}\right) \\
& \prod_i \mathcal{P}\left(N_i^{\text{ZCR}} \mid \beta_{Z,i} \cdot B_{Z,i}^{\text{ZCR,MC}} + B_{\text{non-}Z,i}^{\text{ZCR}}\right) \\
& \prod_i \mathcal{P}\left(N_i^{W\mu\nu\text{CR}} \mid \beta_{W,i} \cdot B_{W,i}^{W\mu\nu\text{CR,MC}} + B_{\text{non-}W,i}^{W\mu\nu\text{CR,MC}}\right) \\
& \prod_i \mathcal{P}\left(N_i^{We\nu\text{CR}} \mid \beta_{W,i} \cdot B_{W,i}^{We\nu\text{CR,MC}} + B_{\text{non-}W,i}^{We\nu\text{CR,MC}} + R_{S,i} \cdot n_{\text{fake},i}\right) \\
& \prod_i \mathcal{P}\left(N_i^{\text{fake-}e\text{ CR}} \mid \beta_{W,i} \cdot B_{W,i}^{\text{fake-}e\text{ CR,MC}} + B_{\text{non-}W,i}^{\text{fake-}e\text{ CR,MC}} + n_{\text{fake},i}\right) \\
& \prod_j \mathcal{G}\left(0 \mid \theta_j\right),
\end{aligned}
$$

Ratio of Z/W freely determined from data

Simulation samples

Process	Generator	ME Order	PDF	Parton Shower	Tune
Strong V+jets	Sherpa v2.2.1, Sherpa v2.2.7 (m_{jj}-filtered)	NLO (up to 2-jets), LO (up to 4-jets)	NNPDF3.0nnlo	Sherpa MEPS@NLO	Sherpa
Electroweak V+jets	Sherpa v2.2.1 reweighted by Herwig 7 in m_{jj}	LO (up to 4-jets), NLO (reweighting)	NNPDF3.0nnlo	Sherpa MEPS@LO	Sherpa
VV+jets (including $gg \rightarrow VV$+jets)	Sherpa v2.2.1 or Sherpa v2.2.2	NLO (up to 1-jet), LO (up to 3-jets)	NNPDF3.0nnlo	Sherpa MEPS@NLO	Sherpa
Electroweak VV+jets	Sherpa v2.2.1 or Sherpa v2.2.2	LO	NNPDF3.0nnlo	Sherpa MEPS@LO	Sherpa
V+jets α_{EW}^3 interference	MadGraph5_aMC@NLO	LO	PDF4LHC15	Pythia8	
$t\bar{t}$	PowhegBox v2	NLO	NNPDF3.0nlo	Pythia8	A14
QCD multijet	Pythia 8.230	LO	NNPDF2.3lo	Pythia8	A14
ggF Higgs	Powheg NNLOPS	NNLO	PDF4LHC15 NNLO	Pythia8	AZNLO
VBF Higgs	Powheg	NLO	PDF4LHC15	Pythia8	AZNLO
VH Higgs	PowhegBox v2	NLO	PDF4LHC15	Pythia8	AZNLO

Direct detection comparison

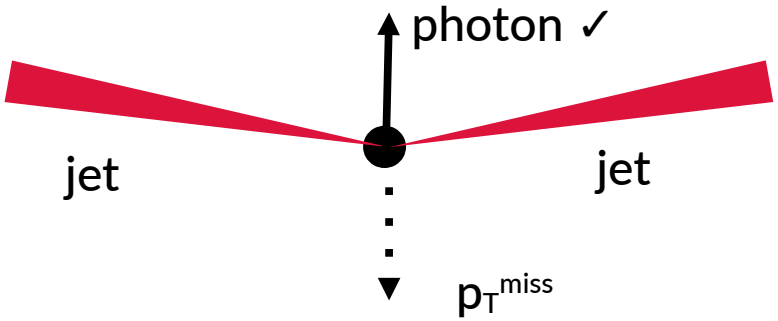


Backup: ATLAS VBF + photon analysis

Selection

$$C_\gamma = \exp\left(-\frac{4}{(\eta_1-\eta_2)^2}(\eta_\gamma - \frac{\eta_1+\eta_2}{2})^2\right),$$

Photon centrality requirement favors photons close to average η of jets



Variable	SR	$W^\gamma_{\mu\nu}$ CR	$W^\gamma_{e\nu}$ CR	$Z^\gamma_{\text{Rev.Cen.}}$ CR	Fake−e CR
p_T (j_1) [GeV]			> 60		
p_T (j_2) [GeV]			> 50		
N_{jet}			2,3		
$N_{b\text{-jet}}$			< 2		
$\Delta\phi_{jj}$			< 2.5 [2.0]		
$\lvert\Delta\eta_{jj}\rvert$			> 3.0		
$\eta(j_1)\times\eta(j_2)$			< 0		
C_3			< 0.7		
m_{jj} [TeV]			> 0.25		
E_T^{miss} [GeV]	> 150	–	> 80	> 150	< 80
$E_T^{miss,lep\text{-}rm}$ [GeV]	–	> 150	> 150	–	> 150
$E_T^{jets,no\text{-}jvt}$ [GeV]			> 130		
$\Delta\phi(j_i, E_T^{miss,lep\text{-}rm})$			> 1.0		
N_γ			1		
p_T (γ) [GeV]		> 15, < 110 [> 15, <max(110,0.733 × m_T)]			
C_γ	> 0.4	> 0.4	> 0.4	< 0.4	> 0.4
$\Delta\phi(\gamma, E_T^{miss,lep\text{-}rm})$			> 1.8 [–]		
N_ℓ	0	1 μ	1 e	0	1 e
p_T (ℓ) [GeV]			> 30		

Neural network

Three hidden layers + input feature pass through
ReLU → ReLU → ReLU → Sigmoid
training with dropout + batch norm.

Train in epochs with standard binary cross-entropy loss on loosened phase space

After every epoch, evaluate approximate signal significance measure
keep epoch weight effect only if significance increases

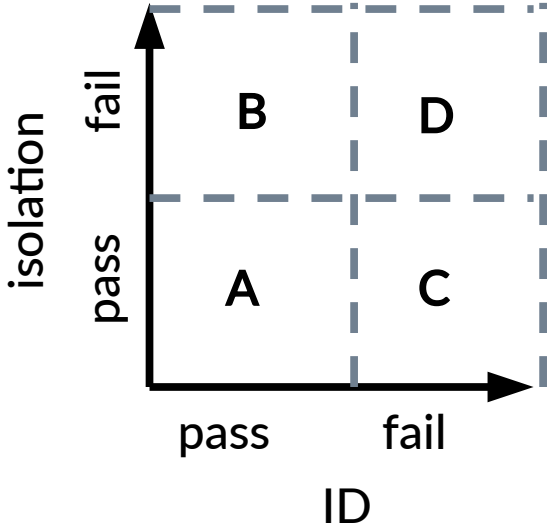
$$\mathcal{E}^{-1} = \sqrt{\sum_{i \in bins} \mathcal{E}_i^{-2}}, \qquad \mathcal{E}_i = 2\frac{\sqrt{b_i + \left(b_i^{V\gamma} \cdot \frac{\sqrt{d_i(\mathrm{CR}) + \sum_{j \in \mathrm{ev}} w_{i,j}(\mathrm{CR})}}{b_i^{V\gamma}(\mathrm{CR})}\right)^2 + \sum_{j \in \mathrm{ev}} w_{i,j}^2}}{s_i}$$

b = background
d = data
s = signal
w = MC weights

Fake estimate

jet → γ fake

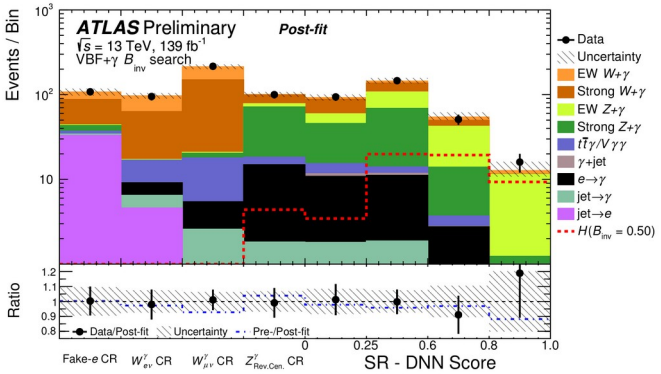
ABCD in photon ID/iso plane:



A = B × C / D

+ correlation corr from MC

e → γ fake



fake rate determined in Z→ ee events (tag & probe)

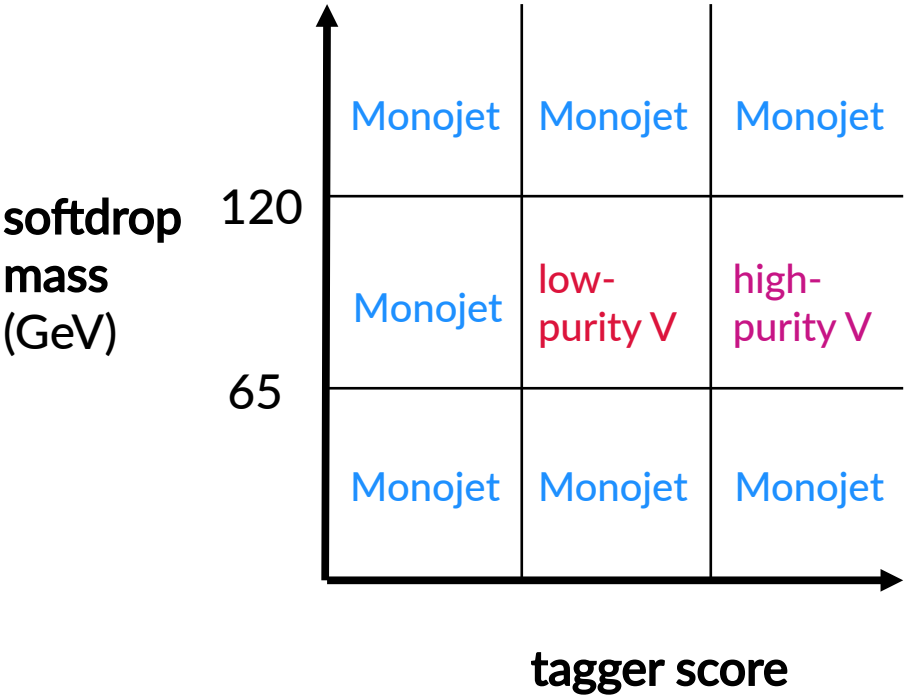
fake rate from 1.5 – 9% (depends on |η|, p_T)

applied to events from CR in which photon replaced by electron

total uncertainty is 30% at low p_T, 15% at high p_T

Backup: CMS V(qq)H + ggH

Categorization



Categorization is two-dimensional

Events failing mono-V selection go to monojet category (also if no fat jet found in event)

Backup: ATLAS ttH

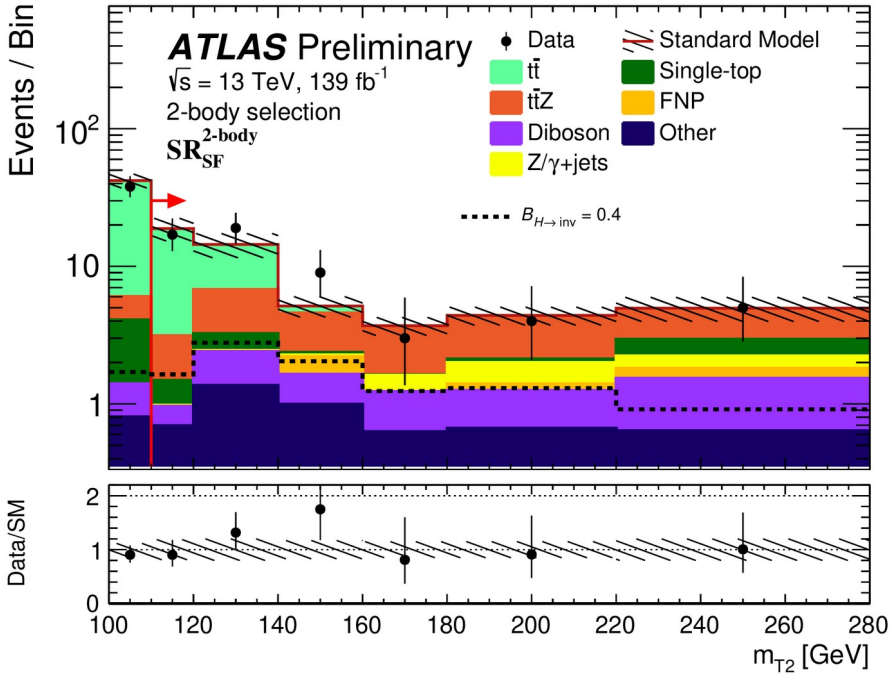
ATLAS ttH dileptonic

$p_{T,i}$ are known charged lepton momenta

$$m_{T2}(\mathbf{p}_{T,1}, \mathbf{p}_{T,2}, \mathbf{p}_T^{miss}) = \min_{\mathbf{q}_{T,1}+\mathbf{q}_{T,2}=\mathbf{p}_T^{miss}} \{\max[\, m_T(\mathbf{p}_{T,1}, \mathbf{q}_{T,1}), m_T(\mathbf{p}_{T,2}, \mathbf{q}_{T,2})\,]\}$$

$q_{T,i}$ are unknown neutrino momenta

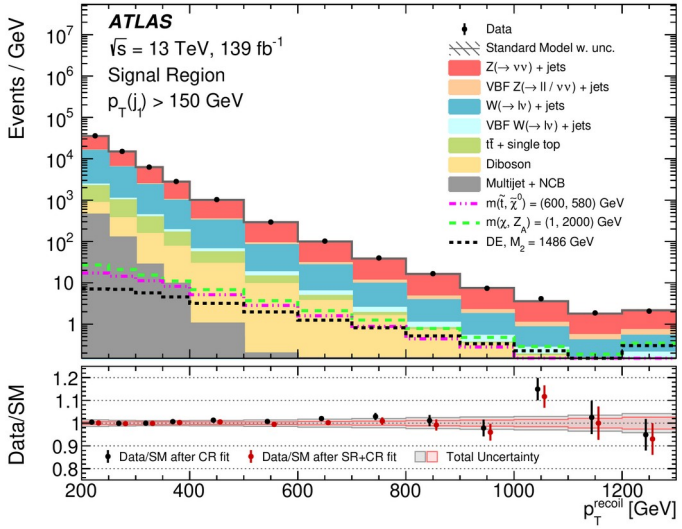
SM background
with W decays
has kinematic endpoint
at m_W (washed out here)



High-MT2 populated
by processes with
additional p_T^{miss},
such as ttZ or ttH(inv)

BG shape from MC,
norm from tt and ttZ CRs

ATLAS monojet



Requirement	SR	$W \to \mu\nu$	$Z \to \mu\mu$	$W \to e\nu$	$Z \to ee$	Top
Primary vertex	at least one with ≥ 2 associated tracks with $p_T > 500$ MeV					
Trigger	E_T^{miss}			single-electron		E_T^{miss}, single-electron
p_T^{recoil} cut	$E_T^{miss} > 200$ GeV	$\lvert \mathbf{p}_T^{miss} + \mathbf{p}_T(\mu) \rvert > 200$ GeV	$\lvert \mathbf{p}_T^{miss} + \mathbf{p}_T(\mu\mu) \rvert > 200$ GeV	$\lvert \mathbf{p}_T^{miss} + \mathbf{p}_T(e) \rvert > 200$ GeV	$\lvert \mathbf{p}_T^{miss} + \mathbf{p}_T(ee) \rvert > 200$ GeV	$\lvert \mathbf{p}_T^{miss} + \mathbf{p}_T(\mu) \rvert > 200$ GeV or $\lvert \mathbf{p}_T^{miss} + \mathbf{p}_T(e) \rvert > 200$ GeV
Jets	up to 4 with $p_T > 30$ GeV, $\lvert\eta\rvert < 2.8$					
$\lvert\Delta\phi(\text{jets}, \mathbf{p}_T^{recoil})\rvert$	> 0.4 (> 0.6 if 200 GeV < E_T^{miss} ≤ 250 GeV)					
Leading jet	$p_T > 150$ GeV, $\lvert\eta\rvert < 2.4$, $f_{ch}/f_{max} > 0.1$					
b-jets	any	none	any	none	any	at least one
Electrons or muons	none	exactly one muon, with $p_T > 10$ GeV, $30 < m_T < 100$ GeV; no electron	exactly two muons, with $p_T > 10$ GeV, $66 < m_{\mu\mu} < 116$ GeV; no electron	exactly one electron, tight, with $p_T > 30$ GeV, $\lvert\eta\rvert \notin (1.37, 1.52)$, tight isolation, $30 < m_T < 100$ GeV; no muon	exactly two electrons, with $p_T > 30$ GeV, $66 < m_{ee} < 116$ GeV; no muon	same as for $W \to \mu\nu$ or same as for $W \to e\nu$
τ-leptons	none					
Photons	none					

Source of uncertainty and effect on the total SR background estimate [%]			
Flavor tagging	0.1 – 0.9	τ-lepton identification efficiency	0.1 – 0.07
Jet energy scale	0.17 – 1.0	Luminosity	0.01 – 0.05
Jet energy resolution	0.15 – 1.3	Noncollision background	0.2 – 0.0
Jet JVT efficiency	0.01 – 0.03	Multijet background	1.0 – 0.0
Pileup reweighting	0.4 – 0.24	Diboson theory	0.01 – 0.22
E_T^{miss} resolution	0.34 – 0.04	Single-top theory	0.13 – 0.28
E_T^{miss} scale	0.5 – 0.25	$t\bar{t}$ theory	0.06 – 0.7
Electron and photon energy resolution	0.01 – 0.08	V+jets τ-lepton definition	0.04 – 0.16
Electron and photon energy scale	0.3 – 0.7	V+jets pure QCD corrections	0.24 – 1.1
Electron identification efficiency	0.5 – 1.0	V+jets pure EW corrections	0.17 – 2.2
Electron reconstruction efficiency	0.15 – 0.2	V+jets mixed QCD–EW corrections	0.02 – 0.7
Electron isolation efficiency	0.04 – 0.19	V+jets PDF	0.01 – 0.7
Muon identification efficiency	0.03 – 0.9	VBF EW V+jets backgrounds	0.02 – 1.1
Muon reconstruction efficiency	0.4 – 1.5	Limited MC statistics	0.05 – 1.9
Muon momentum scale	0.1 – 0.7		
Total background uncertainty in the Signal Region: 1.5%–4.2%