Search for Dark Matter in Events with a Single Boson and Missing Transverse Momentum with ATLAS

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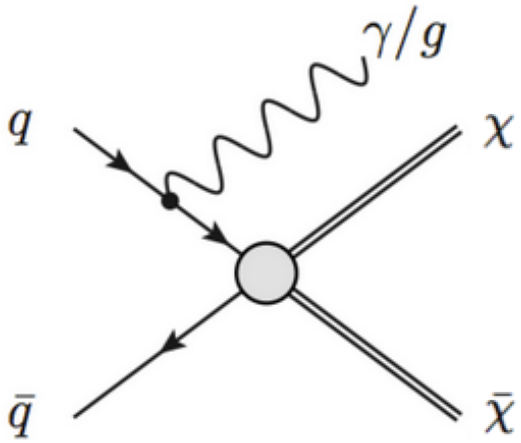
BOSON + E_T^{MISS}: SIGNATURE

- **Dark Matter (DM) production at colliders:**
  - Missing Transverse Momentum (E_T^{miss}) from DM particles χ
    - DM does not interact with the detector
  - Recoiling against standard model (SM) particles
    - Typically radiated from initial state

X+E_T^{miss} signature

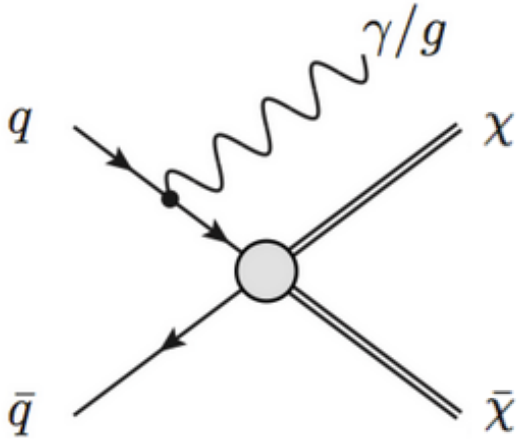


j+E_T^{miss}, **γ+E_T^{miss}**, V+E_T^{miss}:
Initial state radiation

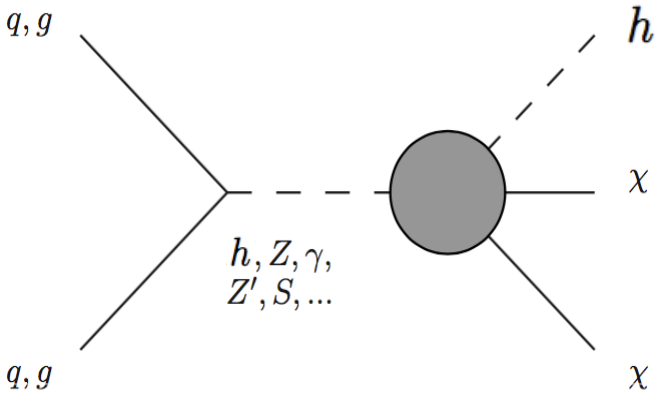
BOSON + E_T^{MISS}: SIGNATURE

- **Dark Matter (DM) production at colliders:**
  - Missing Transverse Momentum (E_T^{miss}) from DM particles χ
    - DM does not interact with the detector
  - Recoiling against standard model (SM) particles
    - Typically radiated from initial state
  - Higgs discovery → new opportunity to search for DM!
    - Mono-Higgs directly probes DM production mechanism!

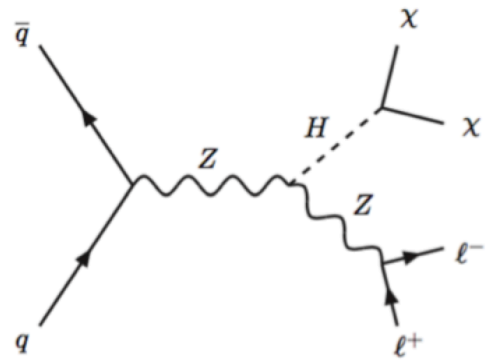
X+E_T^{miss} signature



j+E_T^{miss}, **γ+E_T^{miss}**, V+E_T^{miss}:
Initial state radiation



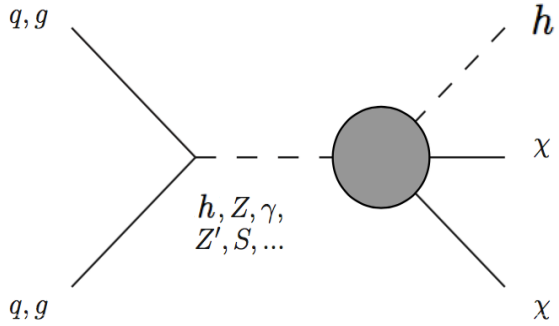
Higgs+E_T^{miss}:
Direct probe of BSM



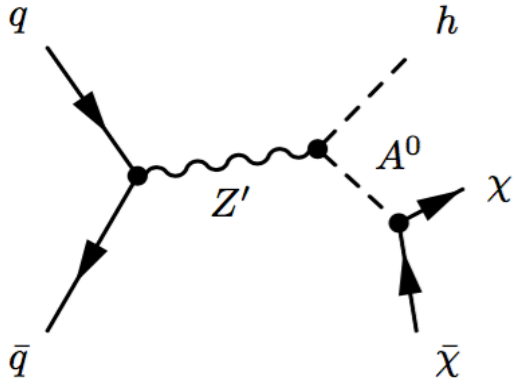
Higgs → invisible:
optional if $m_\chi < m_h/2$

BOSON + E_T^{MISS}: INTERPRETATION

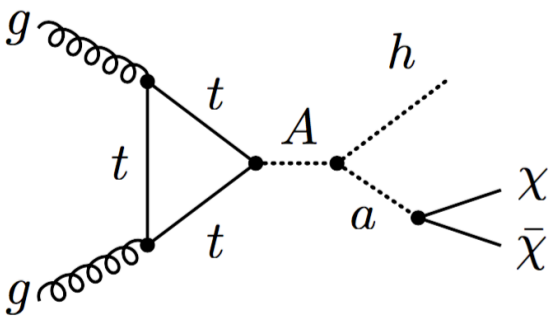
- **Mono-Higgs as example:**
  - **1) Effective field theory**



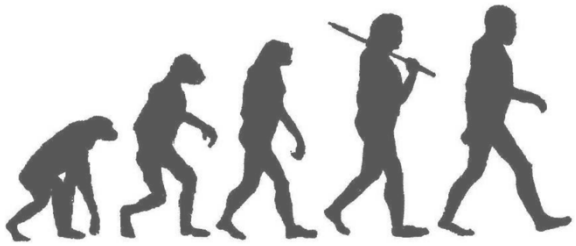
  - **2) Simplified models**
    - Richer kinematics + phenomenology



Z'-2HDM model
JHEP 06 (2014) 078
+ arXiv:1507.00966



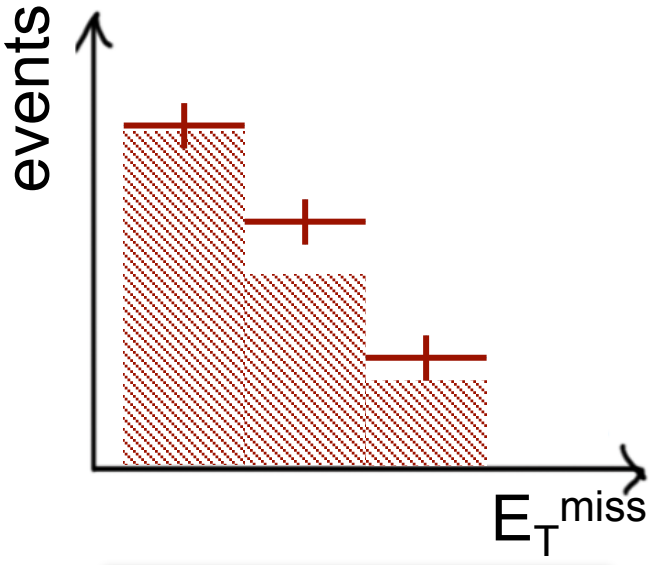
2HDM+a model
arXiv:1701.07427



  - **3) Limits on h + DM production with minimal model dependence**
    - Allows easy re-interpretation

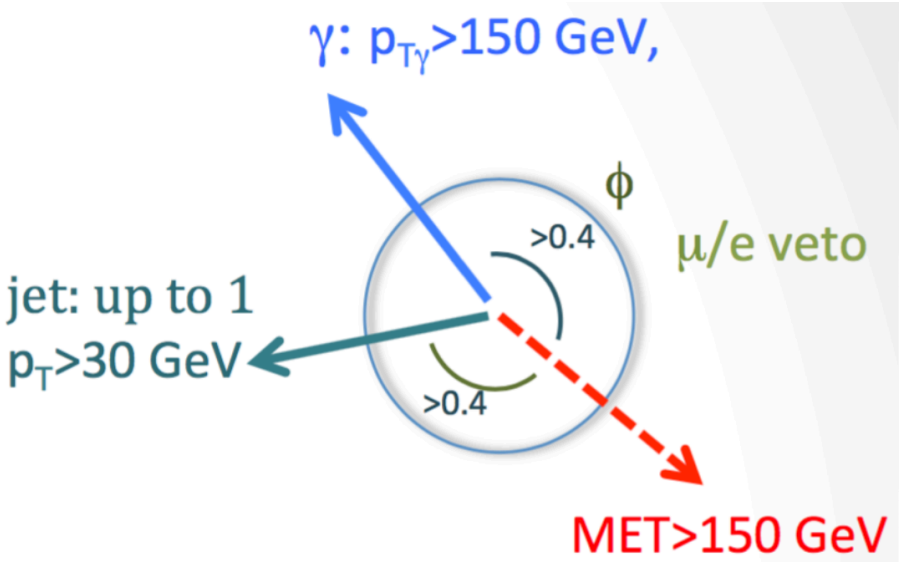
PHOTON + E_T^{MISS} [1]

- **Analysis strategy:**
  - Require γ + E_T^{miss} > 150 GeV
  - Look for excess



5 E_T^{miss} bins
3 inclusive,
2 exclusive

Selection overview



[1] *CERN-EP-2017-044*

- **Backgrounds (from MC):**
  - Irreducible:
    - SM Z(vv)+γ (55-75%)
  - Reducible:
    - W(lv)+γ (10-15%), γ+jet (2-10%), e,jet→ γ fakes (10-15%)
  - **Overview of signal regions (SR) and control regions (CR):**

0 lepton SR	1 lepton CR	2 lepton CR	γ-jet CR
Signal	Constrain W+γ	Constrain Z(vv)+γ using Z($\ell\ell$)+γ	Constrain γ+jet

PHOTON + E_T^{MISS}

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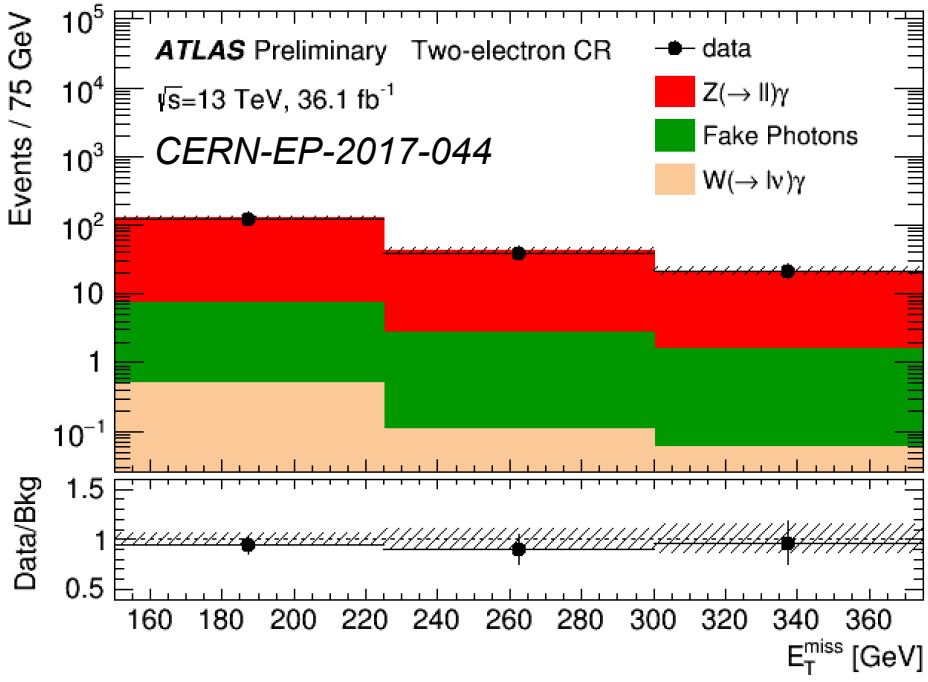
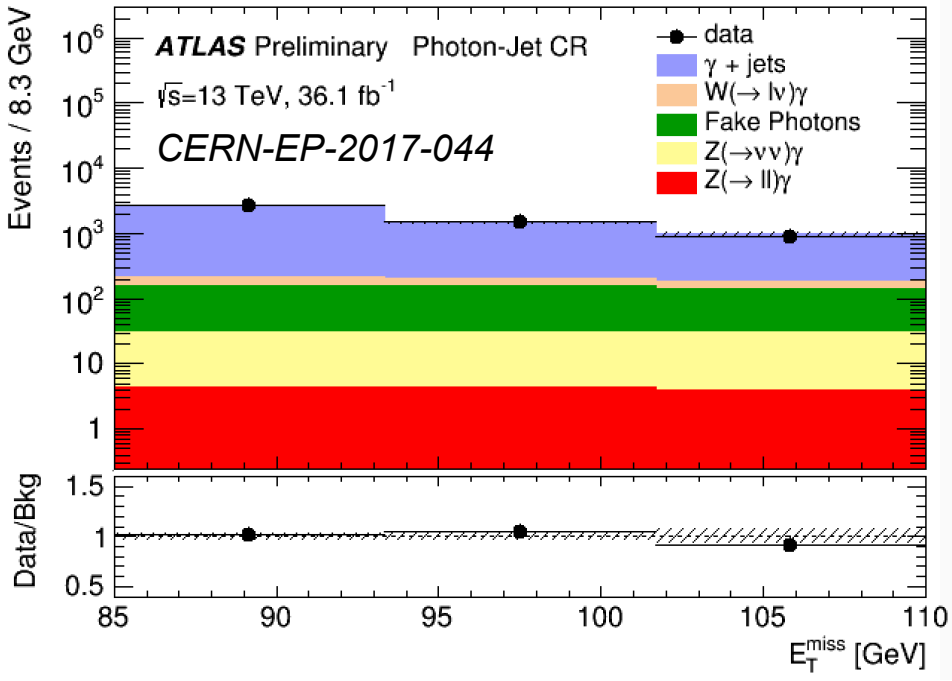
- **Kinematic similarity** between SR and CRs:
  - SR (0 leptons): $p_T^V = E_T^{miss}$ V = Z→vv
  - 1μCR: $p_T^V = p_T(\mu, E_t^{miss})$ V = W→μv
  - 2ℓCR (ee or $\mu\mu$): $p_T^V = p_T(\ell\ell)$ V = Z→$\ell\ell$
  - Most selections identical in SR, 1μCR, 2ℓ-CR
  - γ+jet: 85 GeV < E_T^{miss} < 110 GeV, remove E_T^{miss} significance cut

PHOTON + E_T^{MISS}

- **Trigger:**
  - $p_T^{\gamma} > 140$ GeV
- **E_T^{miss} "Significance"** (reject γ+jet with pile up):
  - $E_T^{miss}/\sqrt{\Sigma E_T} > 8.5\ \mathrm{GeV}^{1/2}$

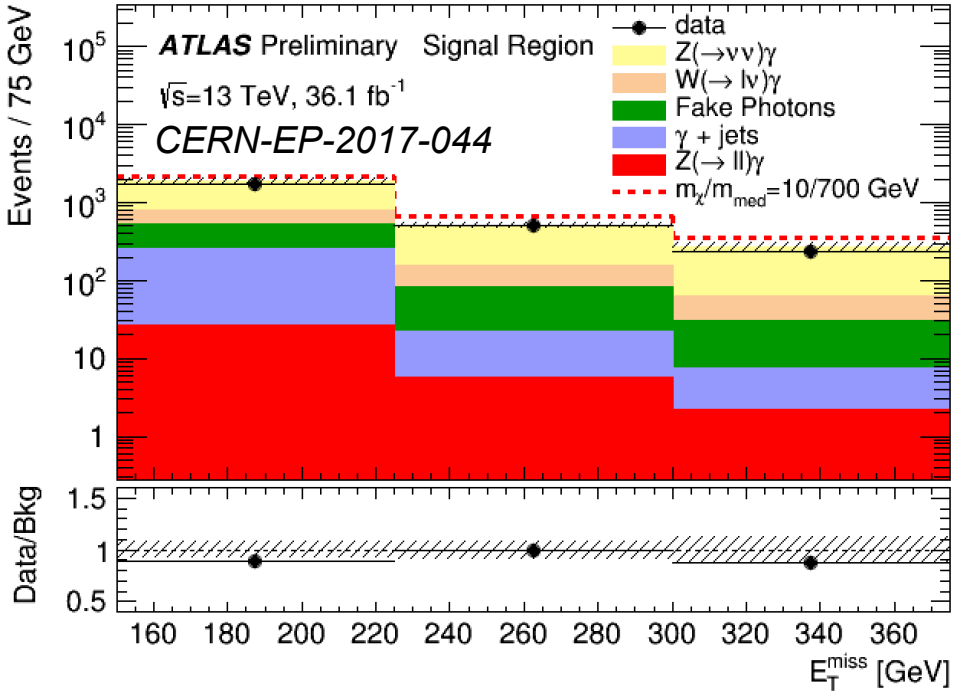
- Good data/MC agreement in control region:

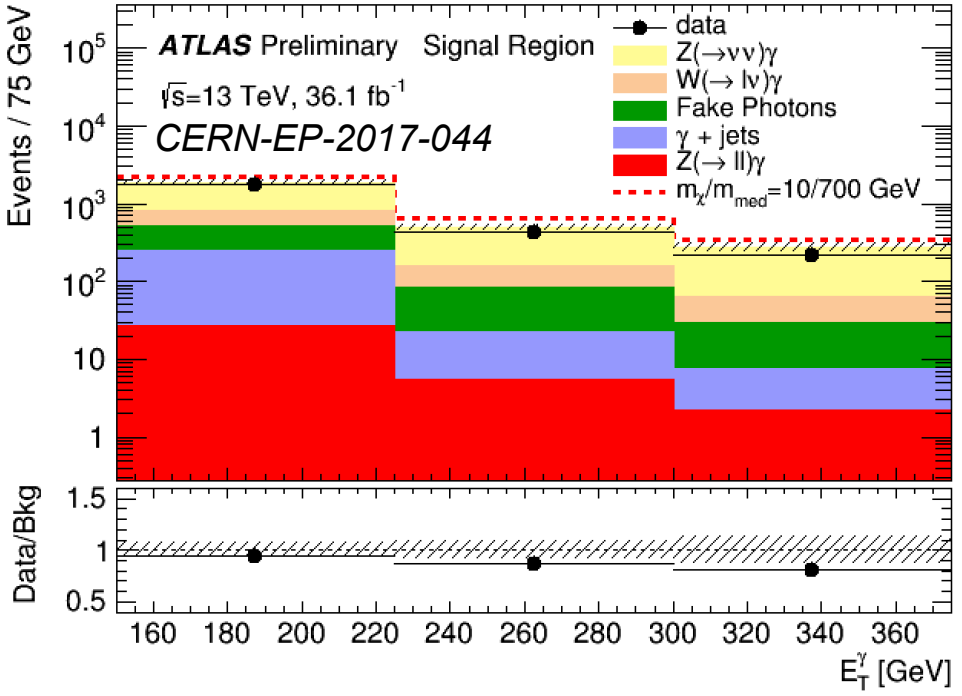




PHOTON + E_T^{MISS}: RESULTS

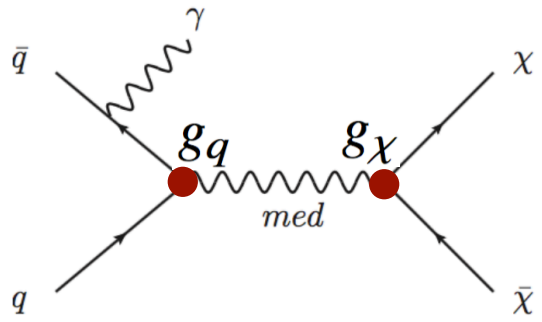
- **Signal Region:**
  - Not much space for new physics



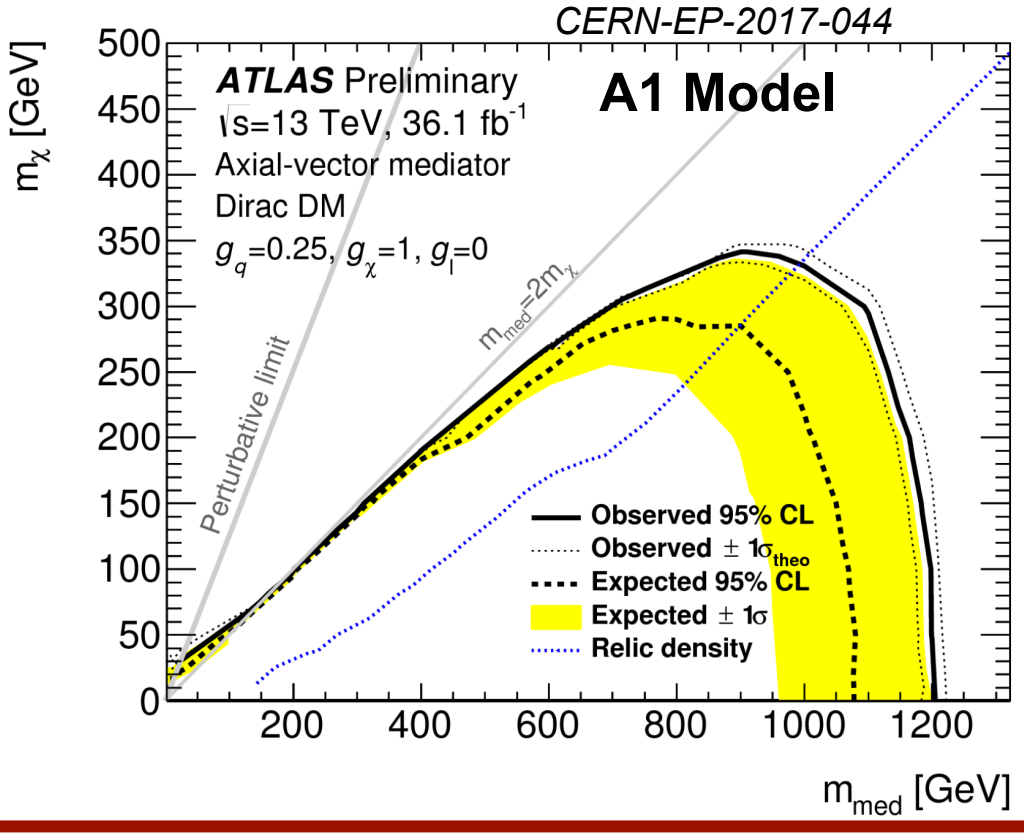


- **Strong exclusions on representative models:**

Model	Mediator	g_q	g_χ	g_ℓ
A1	axial-vector	0.25	1	0
A2	axial-vector	0.1	1	0.1
V1	vector	0.25	1	0
V2	vector	0.1	1	0.01



- *(other models not shown)*



PHOTON + E_T^{MISS}: "MODEL-INDEPENDENT" LIMITS

- **Limits on γ+DM events with minimal model dependence**
  - Assume back-to-back topology of γ and E_T^{miss}
  - Set limits on **visible cross section**:

$$\sigma_{\text{vis}} = \sigma \times A \times \varepsilon$$

reconstruction and selection efficiency

*Acceptance to fall into given E_T^{miss} bin and pass **particle-level** selections*

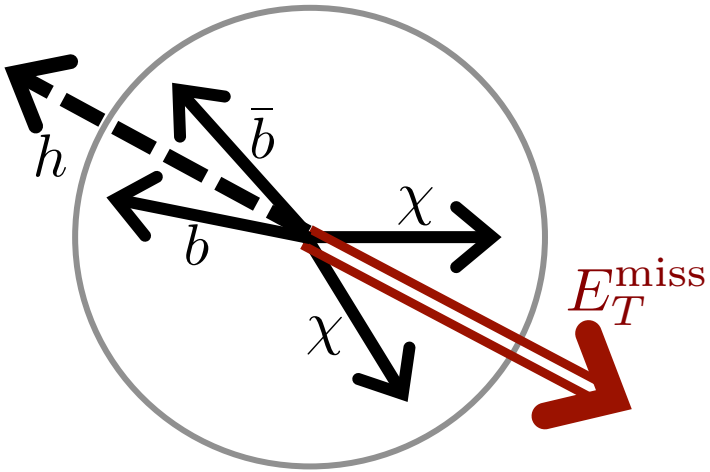
  - Translate into **limits on fiducial cross section** $\sigma \times A$
  - Residual dependence of A and ε on the event topology in given E_T^{miss} bin
    - Estimate by studying a range of models, take weakest limit

CERN-EP-2017-044	$\sigma \times A$ limit [fb]		
Region	SRI1	SRI2	SRI3
95% CL observed	7.0	3.7	2.3
95% CL expected	10.6	4.5	3.0
95% CL expected ($\pm 1\sigma$)	14.5, 7.7	6.2, 3.3	4.2, 2.2
A [%]	14–48	5–31	2–19
ϵ [%]	84–95	73–86	64–85

$h \to b\bar{b}$

New!

Highest BR = 58%
High SM backgrounds

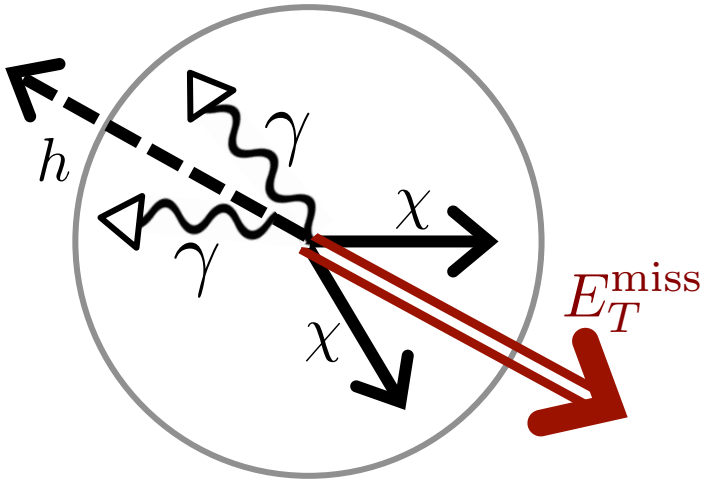


ATLAS-CONF-2017-028

$h \to \gamma\gamma$

New!

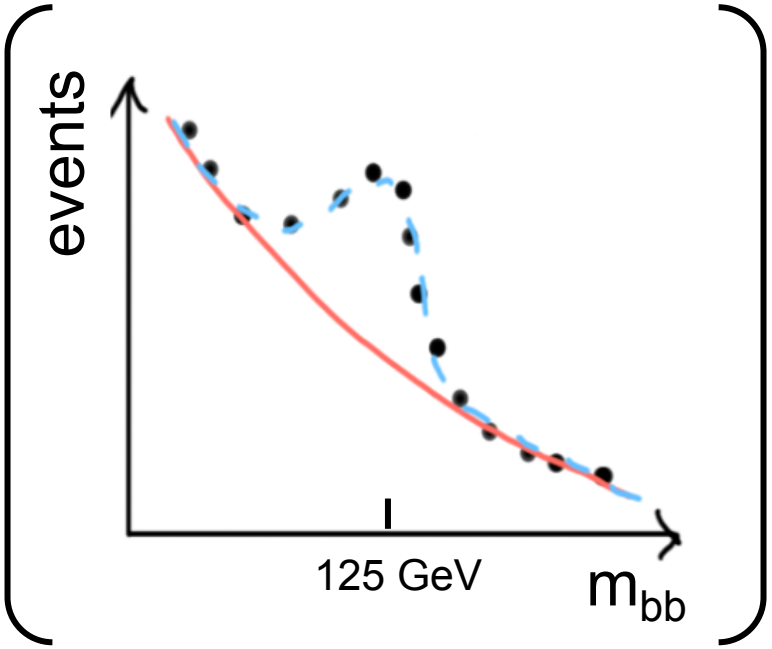
Low BR = 0.2%
High purity in m_h window



ATLAS-CONF-2017-024
(not shown today)

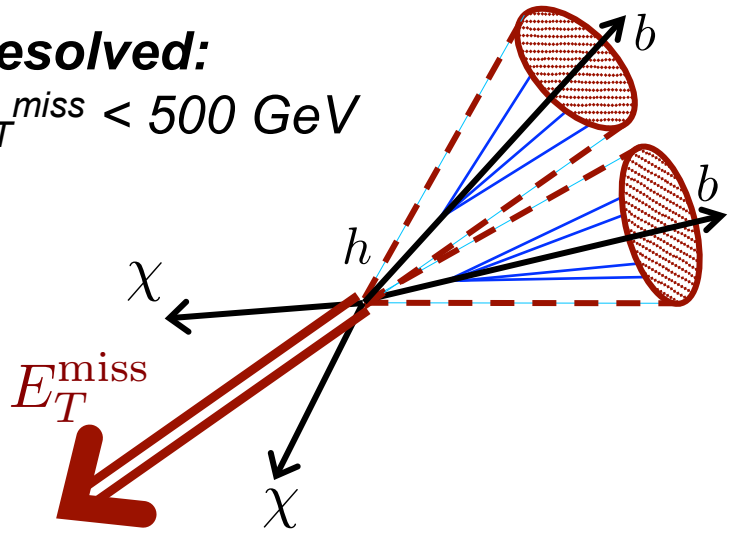
KIRCHHOFF-INSTITUT FÜR PHYSIK

- **Analysis strategy:**
  - Require E_T^{miss}
  - Look for excess in m_{bb} distribution:

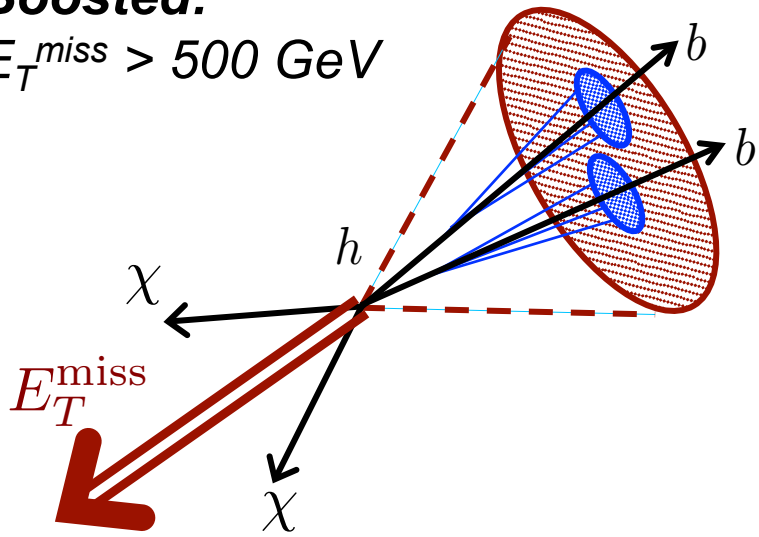


× (1, 2 b-tags)
× 4 E_T^{miss} bins

Resolved:
$E_T^{miss} < 500$ GeV



Boosted:
$E_T^{miss} > 500$ GeV



[1] *ATLAS-CONF-2017-028*

- **Backgrounds (from MC):**
  - Resonant:
    - SM Z(vv)h(bb)
  - Non-resonant (dominant):
    - Z(vv)+jets (30-60%), W+jets (10-25%), tt (15-20%) + rest
- **Overview of signal regions (SR) and control regions (CR):**

0 lepton signal region	1 lepton control region	2 lepton control region
Signal + constrain Z(vv)+jets in m_{bb} sidebands	Constrain tt and W+jets	Constrain Z(vv)+jets using Z($\ell\ell$)+jets

- **Backgrounds (from MC):**
  - Resonant:
    - SM Z(vv)h(bb)
  - Non-resonant (dominant):
    - Z(vv)+jets (30-70%), W+jets (10-20%), tt (10-50%) + rest
- **Overview of signal regions (SR) and control regions (CR):**

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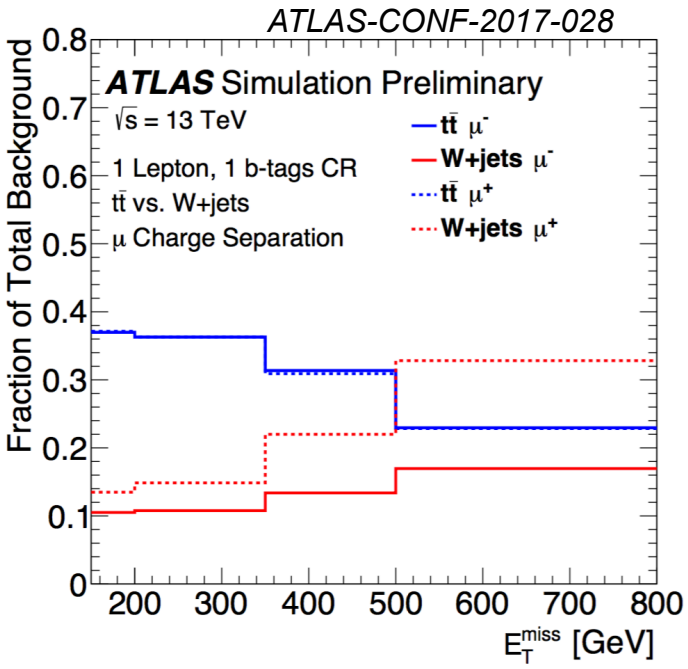
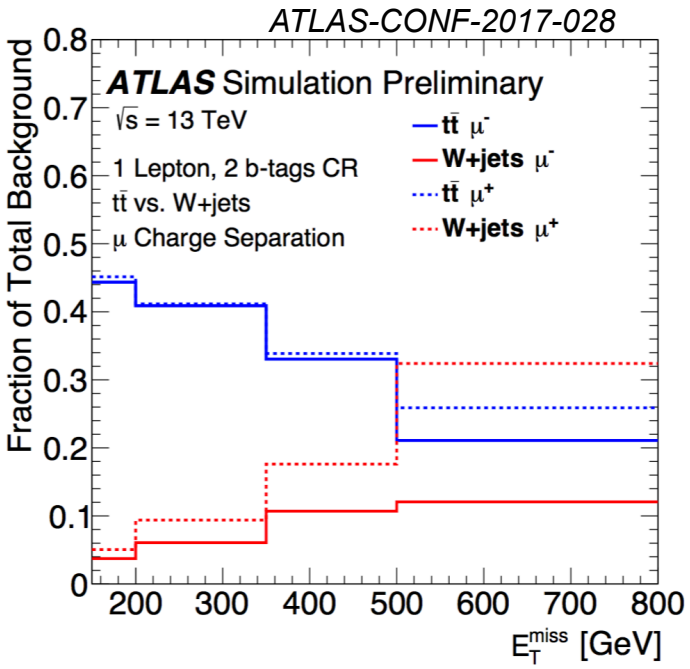
  } $p_T^V > 150$ GeV
  - Most selections identical in SR, 1μCR, 2ℓ-CR

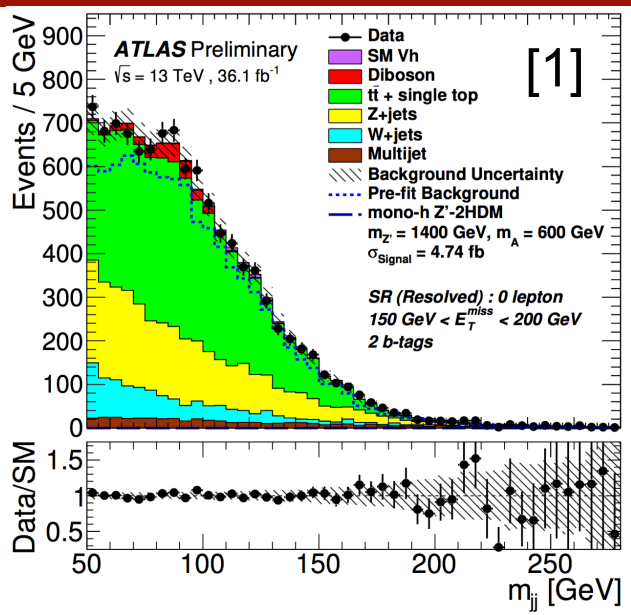
- **Separate tt and W+jets in 1lep CR:**

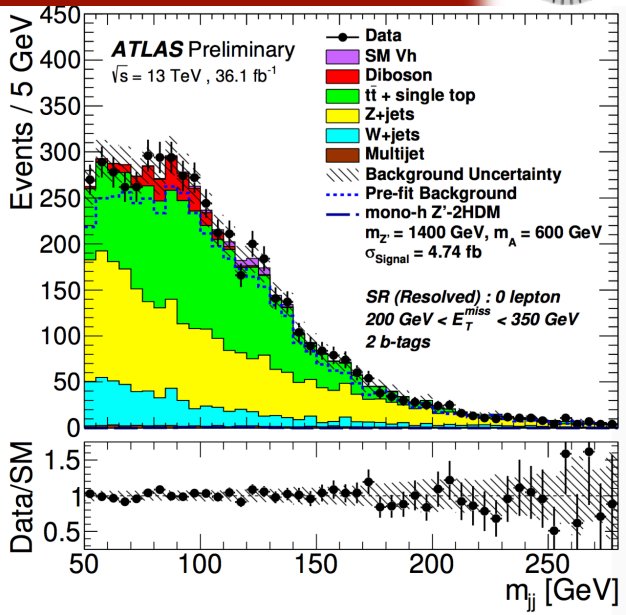


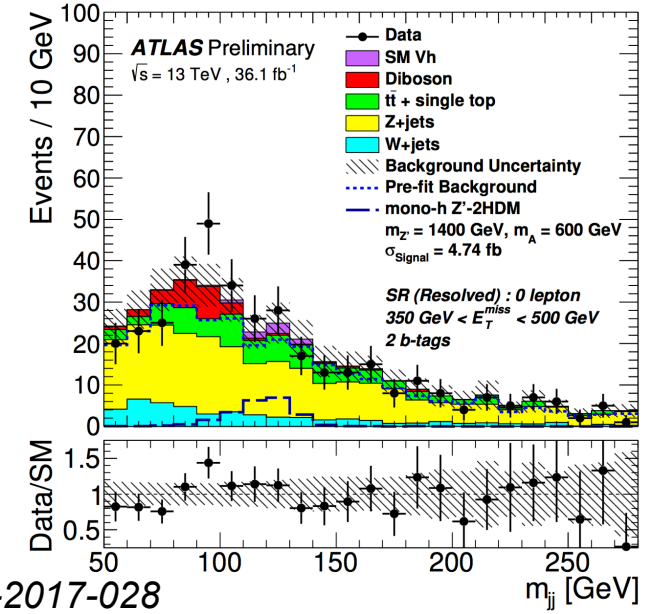


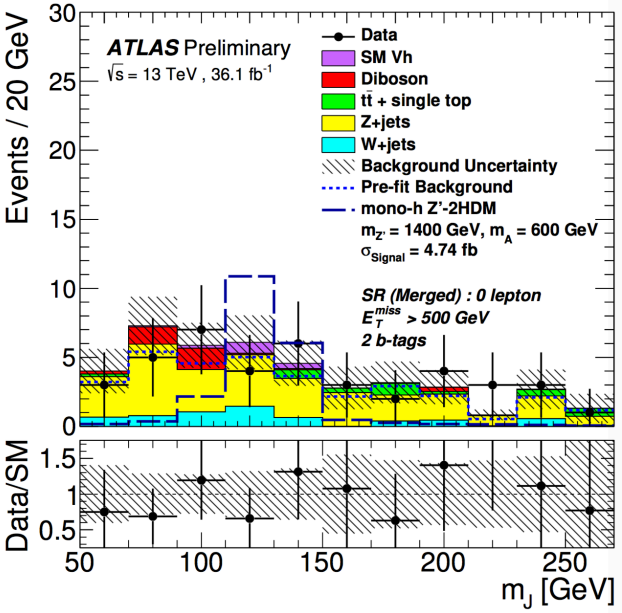
- **Trigger (main challenge):**
  - $E_T^{miss,trig}$ > 70 GeV, plateau starts at E_T^{miss} ≈ 200 GeV → MC correction!
- **B-tagging:**
  - Highest purity in 2 b-tag category
  - High $p_{T,higgs}$: 1 b-tag dominates sensitivity

HIGGS(*bb*) + E_T^{MISS}: RESULTS







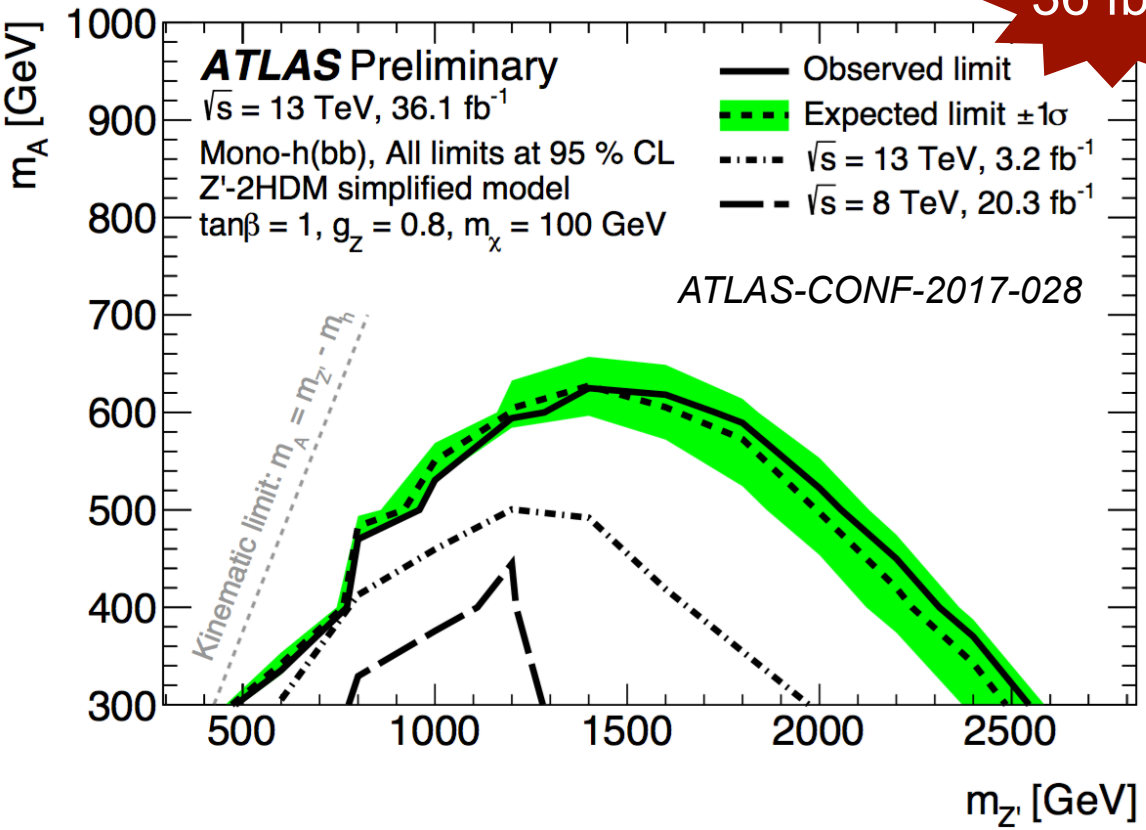


[1] *ATLAS-CONF-2017-028*

- **Results for Z'-2HDM model:**
  - Large portion of parameter space excluded
    - Stronger sensitivity than mono-h($\gamma\gamma$) for $p_{T,h} \gtrsim 150$ GeV
    - Complementarity for $p_{T,h} \lesssim 150$GeV

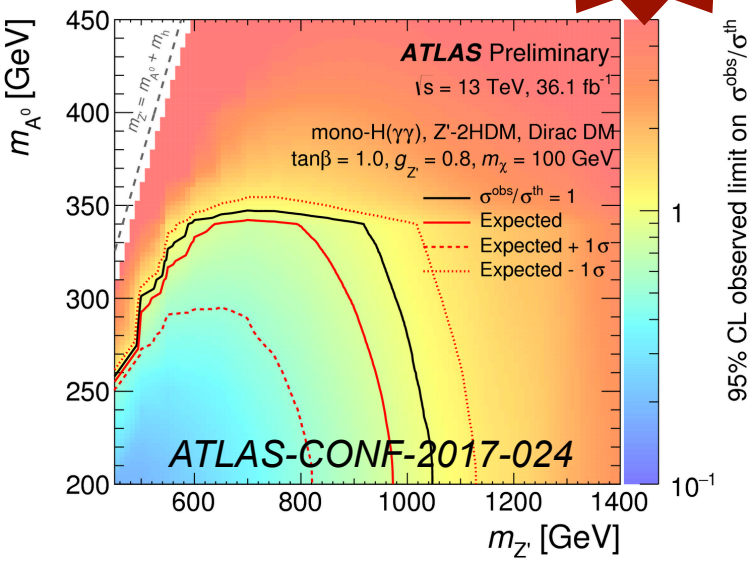
mono-h(bb)

36 fb^{-1}!



mono-h($\gamma\gamma$)

36 fb^{-1}!



HIGGS(*bb*) + E_T^{MISS}: "MODEL-INDEPENDENT" LIMITS

- **Limits on h+DM events with minimal model dependence**
  - Assume SM-like Higgs boson ($m_h \approx 125$ GeV, BR(h→bb) ≈ 58%)
  - Assume back-to-back topology of Higgs and E_T^{miss}
- **Set limits on visible cross section:**

$$\sigma_{\text{vis},h\text{+DM}} \equiv \sigma_{h\text{+DM}} \times BR(h \rightarrow b\bar{b}) \times \mathcal{A} \times \varepsilon$$

- $\mathcal{A} \times \varepsilon$ probability to reconstructed in same E_T^{miss} bin as generated and to pass all selections except b-tagging and $m_{h,reco}$ (measurement-specific)

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- $\mathcal{A} \times \varepsilon$ probability to reconstructed in same E_T^{miss} bin as generated and to pass all selections except b-tagging and $m_{h,reco}$ (measurement-specific)
  - $\sigma_{h+\text{DM}}$ at **parton level** → can compare with $\int_{E_T^{\text{miss}}\ \text{bin}} \mathrm{d}\sigma/\mathrm{d}E_T^{\text{miss}}$

ATLAS-CONF-2017-028

Range in E_T^{miss}/GeV	$\sigma^{\text{obs}}_{\text{vis},h+\text{DM}}$ [fb]	$\sigma^{\text{exp}}_{\text{vis},h+\text{DM}}$ [fb]	$\mathcal{A} \times \varepsilon$ %
[150, 200)	19.1	$18.3^{+7.2}_{-5.1}$	15
[200, 350)	13.1	$10.5^{+4.1}_{-2.9}$	35
[350, 500)	2.4	$1.7^{+0.7}_{-0.5}$	40
[500, ∞)	1.7	$1.8^{+0.7}_{-0.5}$	55

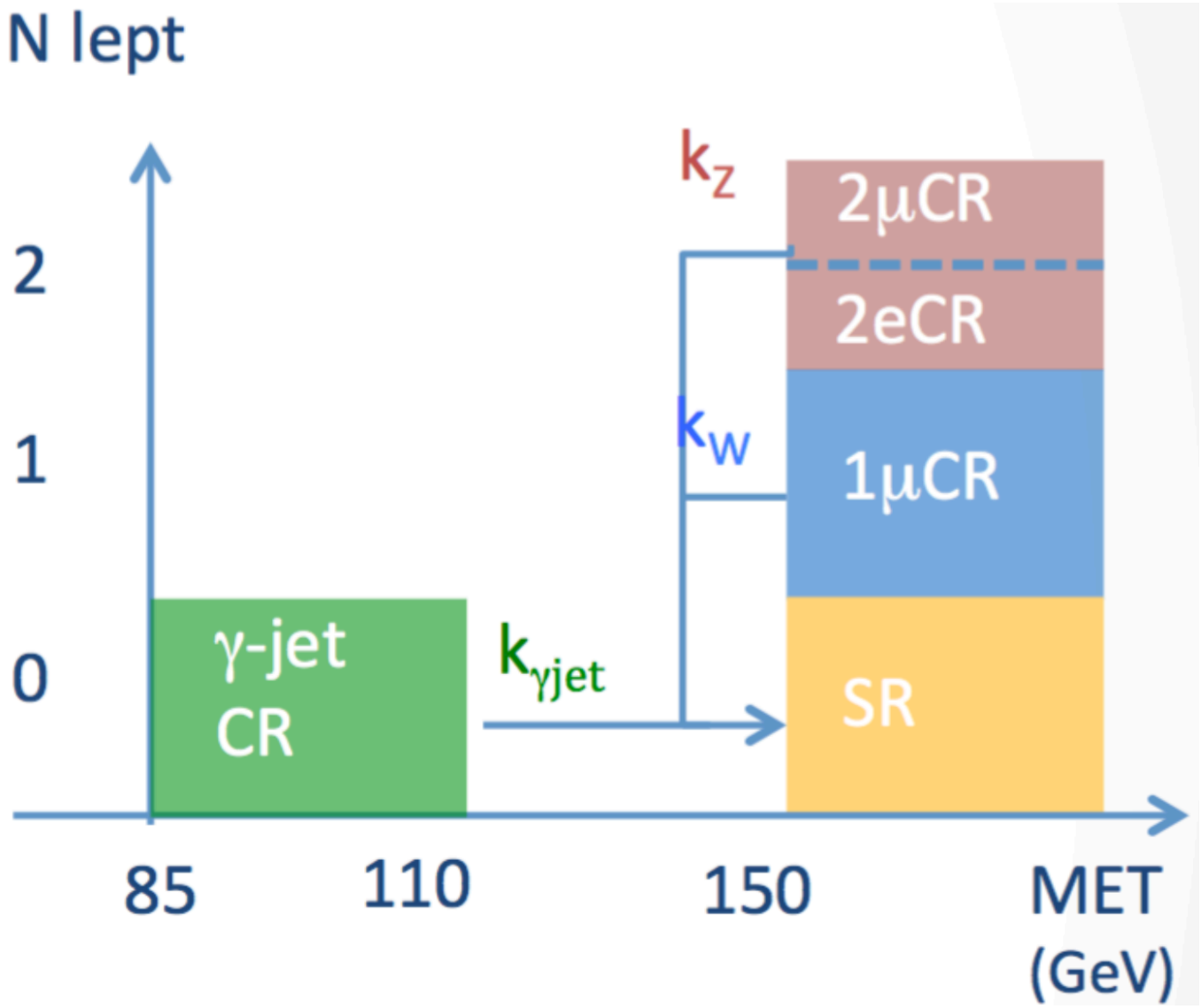
Weakest limit from a range of Z'-2HDM models

Summary + Outlook

- **First searches for Dark Matter using full 36.1 fb^{-1}**
  - **Photon + E_T^{miss}:**
    - Large Z(vv)+γ background, constrain from data
    - Stringent exclusion limits
    - **"Model-independent" limits on:**
      - fiducial cross section σ × A at particle level
        - A, ε provided
  - **Mono-h(bb):**
    - Large backgrounds, constrain from data
    - Superior sensitivity for E_T^{miss} > 150 GeV
      - Statistically limited for E_T^{miss} > 300 GeV
    - **"Model-independent" limits on:**
      - Visible cross section σ × BR(h→bb) x A × ε
        - A × ε provided → translate to parton level
- Will **probe more extreme regions of phase space** with more data + further analysis improvements

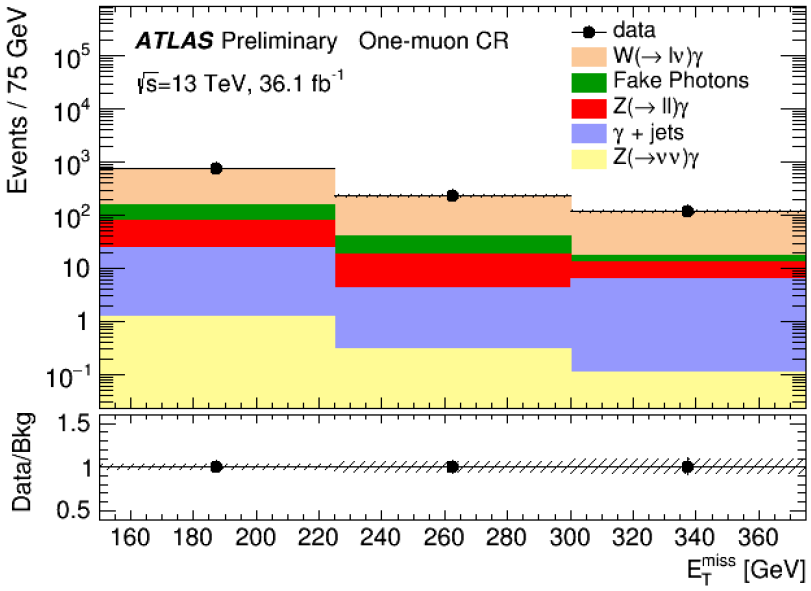
Backup

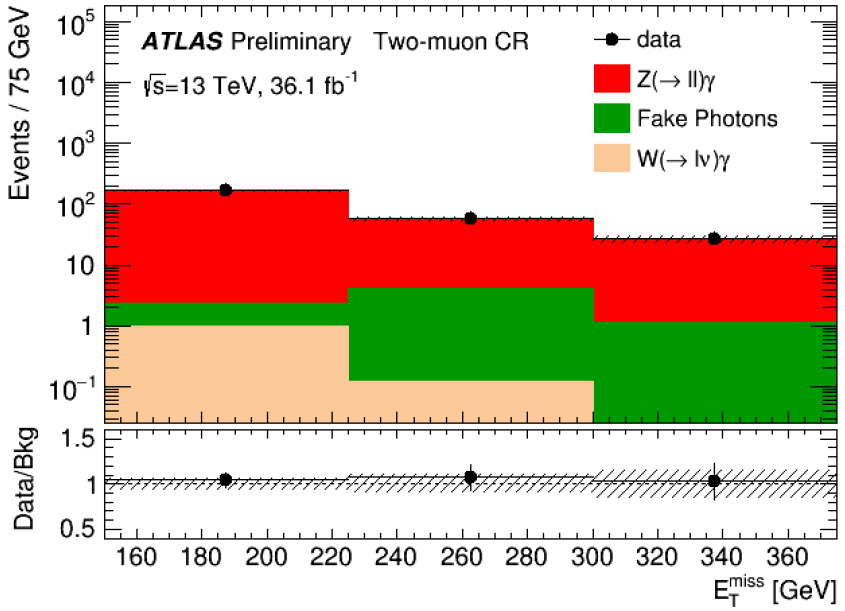
Event cleaning	Quality and Primary vertex				
Leading photon	$E_T^\gamma > 150$ GeV, $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.37$, tight, isolated, $\lvert z\rvert < 0.25$ m, $\Delta\phi(\gamma, \boldsymbol{E}_T^{miss}) > 0.4$				
$E_T^{miss}/\sqrt{\Sigma E_T}$	> 8.5 GeV$^{1/2}$				
Jets	0 or 1 with $p_T > 30$ GeV, $\lvert\eta\rvert < 4.5$ and $\Delta\phi$(jets, $\boldsymbol{E}_T^{miss}$) > 0.4				
Lepton	veto on e and μ				
E_T^{miss} [GeV]	SRI1 > 150	SRI2 > 225	SRI3 > 300	SRE1 150–225	SRE2 225–300
Selected events in data	2400	729	236	1671	493
Events with 0 jets	1559	379	116	1180	263

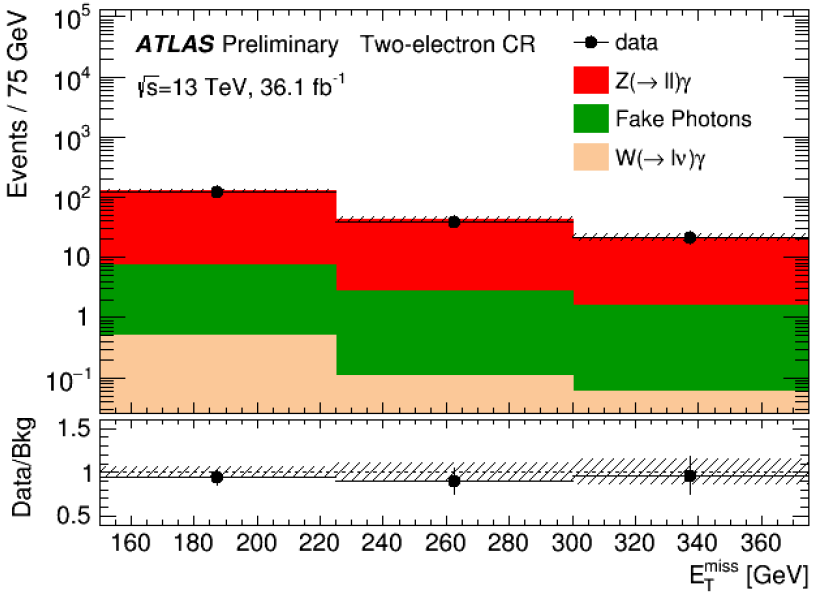

N lept
2
1
0
γ-jet CR
$k_{\gamma jet}$
k_z
k_w
2μCR
2eCR
1μCR
SR
85
110
150
MET (GeV)

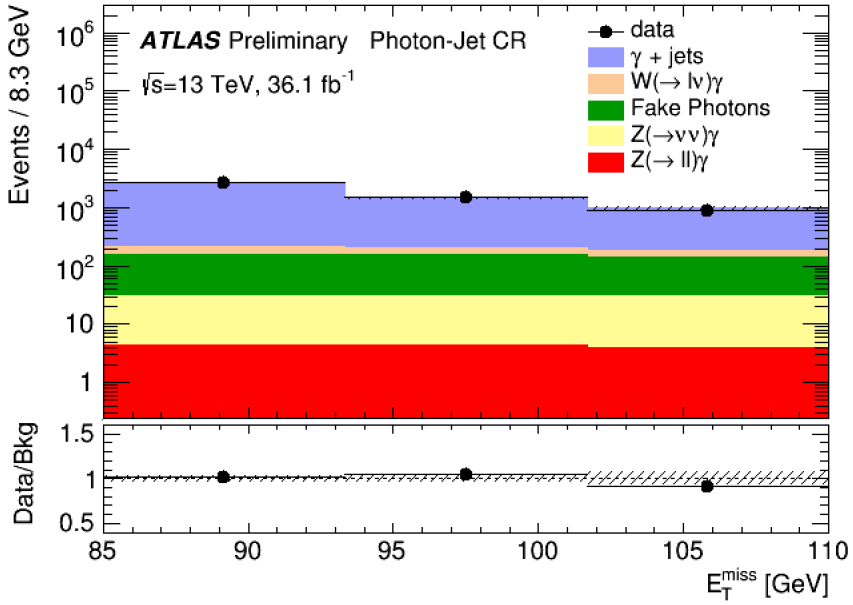
Process	Event generators used	PDF sets	Order	Requirements
DMsimp model	MG5_aMC@NLO v2.4.3 + PYTHIA v8.212	NNPDF30_nlo_as_0118	NLO	$E_T^\gamma > 130$ GeV
EFT model	MG5_aMC@NLO v2.2.3 + PYTHIA v8.186	NNPDF30_lo_as_0130	LO	$E_T^\gamma > 130$ GeV
BSM resonance	POWHEG-Box + PYTHIA v8.210	CT10	NLO	--
$W/Z\gamma$	SHERPA v2.1.1	CT10	LO	for Z: $m_{\ell\ell} > 10$ GeV
γ + jets	SHERPA v2.1.1	CT10	LO	--
W/Z+jets	SHERPA v2.2.0	NNPDF30_nnlo	LO/NLO	--

PHOTON + E_T^{MISS}









<table>
<tr><th>0 lepton
($p_T^V = \not{E}_T$)</th><th>1 lepton
($p_T^V = p_T(\mu, \not{E}_T)$)</th><th>2 lepton
($p_T^V = p_T(l,l)$)</th></tr>
<tr><td colspan="3">$p_T^V > 150$ GeV</td></tr>
<tr><td colspan="2">2015: HLT_xe70
2016: HLT_xe90_mht_L1XE50
2016: HLT_xe{100 OR 110}_mht_L1XE50
2016: HLT_xe110_mht_L1XE50</td><td>lowest unprescaled
single lepton trigger</td></tr>
<tr><td>no loose e
no loose μ</td><td>1 signal μ</td><td>2 signal leptons
opposite-charged $\mu\mu$
71 GeV $< m_{\mu\mu} <$ 106 GeV
83 GeV $< m_{ee} <$ 99 GeV</td></tr>
<tr><td colspan="2">$p_T^{\text{miss}} > 30$ GeV for 0,1 b-tags
$\min(\Delta\phi(p_T^V, j_{1,2,3})) > 20°$
$\Delta\phi(p_T^V, p_T^{\text{miss}}) < 90°$</td><td>$p_T^V / H_T^* < 3.5\sqrt{\text{GeV}}$

$H_T^* = \sum_{\substack{\text{leptons} \\ \text{small-}R\text{jets}}} p_T$</td></tr>
</table>

Resolved $(p_T^V \leq 500)$ GeV	Merged $(p_T^V > 500)$ GeV
$N(\text{small-}R\text{jets}) \geq 2$	$N(\text{large-}R\text{jets}) \geq 1$ $N(\text{track-jets}) \geq 1$
$p_T^{j1} > 45$ GeV —— $p_T^{j2} > 45$ GeV $\sum_{i=1}^{2(3)} p_T(j_i) > 120(150)$ GeV $\Delta\phi(j_1, j_2) < 140°$ $\Delta\phi(p_T^V, j_1 + j_2) > 120°$	
New 2016 optimisation selection (substantial reduction of $t\bar{t}$, significance gain is up to 50%)	
$< 3b-$jets no loose-BDT-ID τ no extended-ID τ $\sum_{i=4}^{\infty} p_T^{j_i} / \sum_{i=1}^{\infty} p_T^{j_i} < 0.37$ $\Delta R(j_1, j_2) < 1.8$	no $b-$tagged track-jet outside J_1 no loose-BDT-ID τ outside J_1 no extended-ID τ outside J_1 $\sum_{i=1}^{\infty} p_T^{j_i \text{ outside } J_1} / (\sum_{i=1}^{\infty} p_T^{j_i \text{ outside } J_1} + p_T^{J_1}) < 0.57$

	0 lepton	**1 muon**	**2 leptons**
Discriminant	m_{bb} distribution	muon charge	m_{bb}, single bin
Aim	signal region	$t\bar{t}$ and W+jets control region	Z+jets control region
b-tag multiplicities	1 and 2		
p_{T}^{V}	$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss,\ no\ mu}}$	$p_{\mathrm{T}}^{\ell\ell}$
	resolved: [150,200], [200,350] and [350,500] GeV merged: more than 500 GeV		

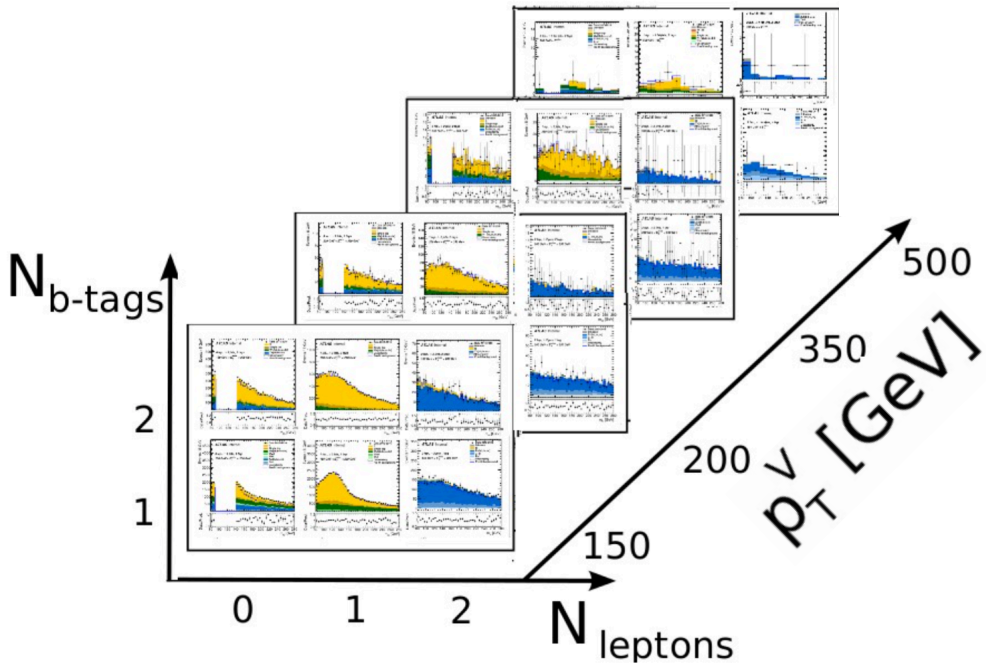
MONO-HIGGS(BB)

- **Trigger (main challenge):**
  - $E_T^{miss,trig}$ > 70 GeV – 110 GeV
  - Plateau starts at E_T^{miss} ≈ 200 GeV → dedicated MC correction!
- **B-tagging:**
  - Reduce non-resonant SM backgrounds
  - Highest purity in 2 b-tag category
- **E_T^{miss}:**
  - p_T^V > 150 GeV
    - Reduce SM backgrounds
  - Reconstruction similar to mono-h($\gamma\gamma$)
- **Additional optimisations:**
  - No isolated τ leptons (tt & W+jets)
  - ΔR(b,b) < 1.8 (tt)
  - No extra b-tags (tt)
  - H_T-ratio (tt):
    - most p_T in Higgs candidate + one extra jet

tt reduced by up to 70%
➔ significance gain up to 50%

- **Binned maximum likelihood fit**
  - Free normalisations for main backgrounds (tt, W+jets, Z+jets)
  - Systematic uncertainties with Gaussian/log-normal priors

- **Analysis regions:**

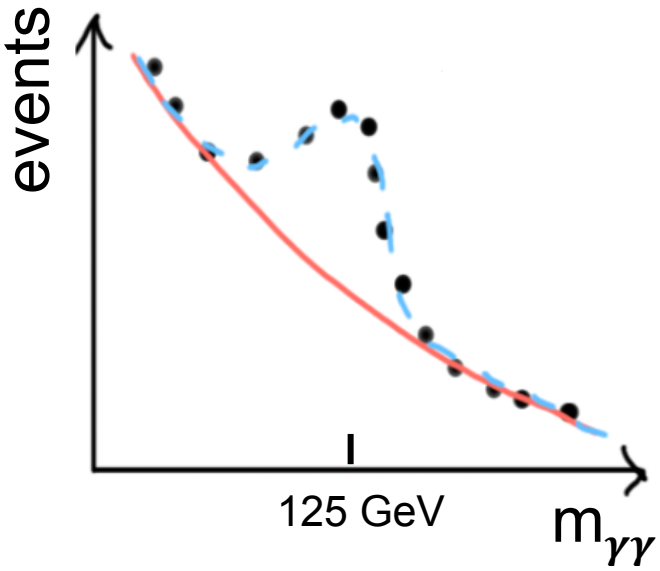


Systematic uncertainties

Source of uncert.	Impact [%] (a)	(b)	(c)
V+jets modeling	5.0	5.7	8.2
Top modeling	3.2	3.0	3.9
SM $Vh(b\bar{b})$ norm.	2.2	6.9	6.9
Signal modeling	3.9	2.9	2.1
MC statistics	4.9	11.3	21.6
Luminosity	3.2	4.5	5.4
b-tagging, track jets	1.4	11.1	17.3
b-tagging, calo jets	5.0	3.4	4.7
Jets $R = 0.4$	1.7	3.8	2.1
Jets $R = 1.0$	<0.1	1.2	4.7
Systematic	10.2	20.9	36.0
Statistical	5.8	37.6	61.5
Total	11.7	43.1	71.3

MONO-HIGGS($\gamma\gamma$) [1]

- **Analysis strategy in a nutshell:**
  - Require E_T^{miss} from χ
  - Look for excess in $m_{\gamma\gamma}$ distribution:

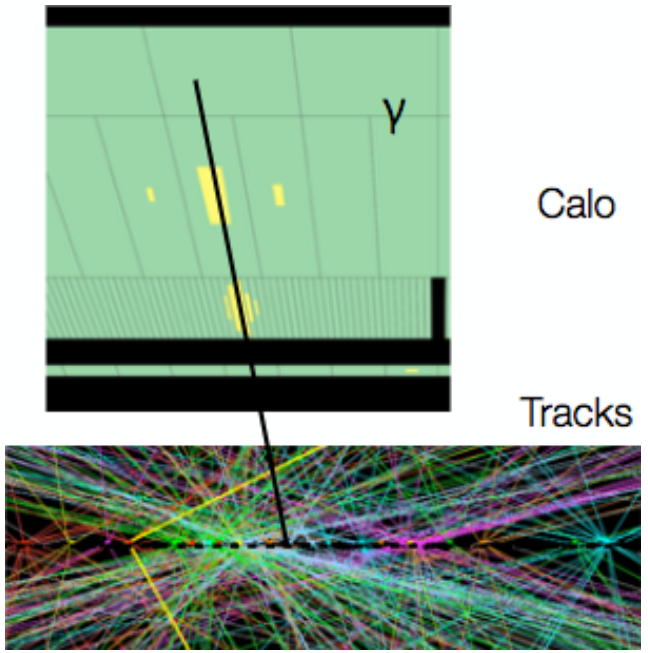


- **Backgrounds:**
  - Resonant (from MC):
    - SM Z(vv)h($\gamma\gamma$)
  - Non-resonant (from data):
    - $\gamma\gamma$ (≈80%), γ+jet (≈20%), Vγ, V$\gamma\gamma$

[1] *ATLAS-CONF-2017-024*

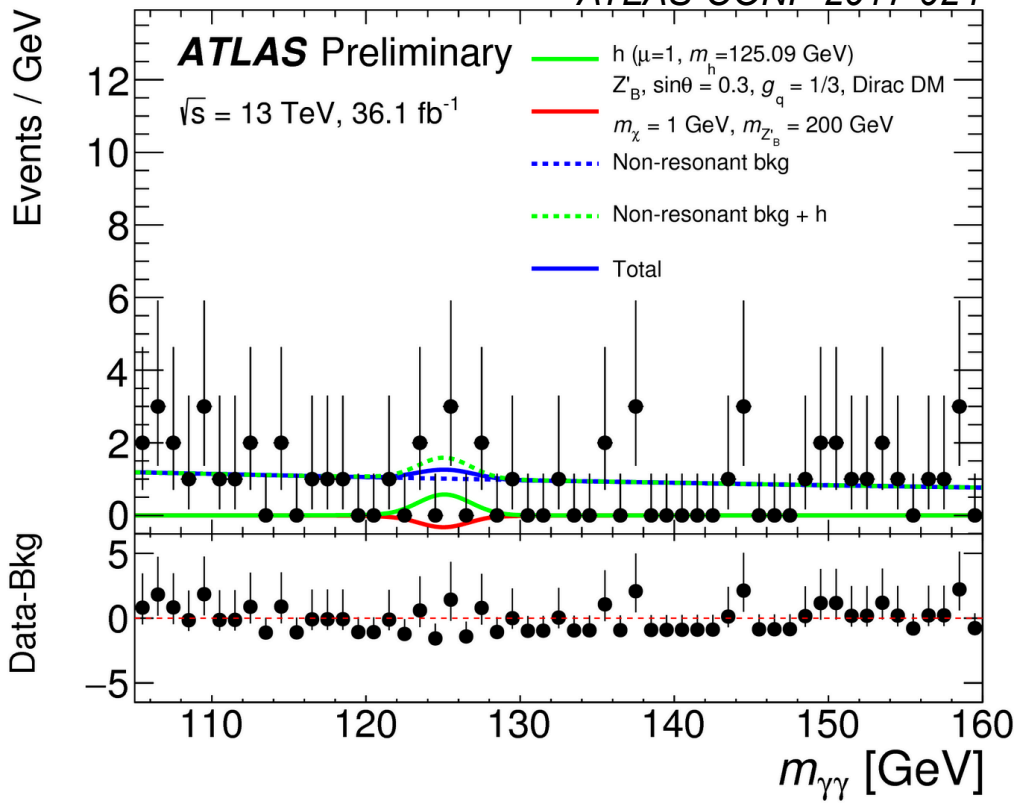
MONO-HIGGS($\gamma\gamma$)

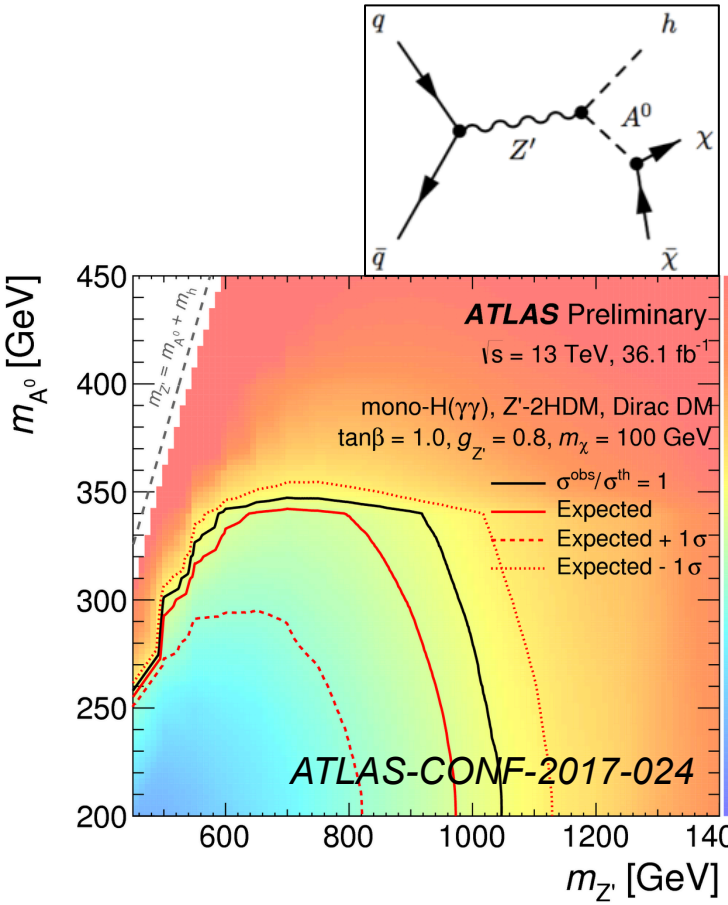
- **Trigger:**
  - Diphoton trigger, $p_T^{\gamma 1\,(\gamma 2)} > 35\ (25)$ GeV
- **Photon ID crucial**
  - Shower shape variables
  - Unconverted photons ($\varepsilon \approx$ 85-95%):
    - No hits in tracker
  - Converted photons ($\varepsilon \approx$ 90-98%):
    - 2 tracks consistent with massless γ
    - 1 track w/o hits in innermost tracker layer
  - Isolated within $\Delta R = 0.2$ ($\varepsilon \approx$ 90%)
  - Matched to primary vertex ($\varepsilon \approx$ 80%):
    - Neural Network
      - Extrapolated γ trajectories from calorimeter clusters, etc…
- **E_T^{miss}:**
  - Reconstructed objects (jets, e, μ)
  - Not reconstructed objects (tracks from same primary vertex)



- **Results:**

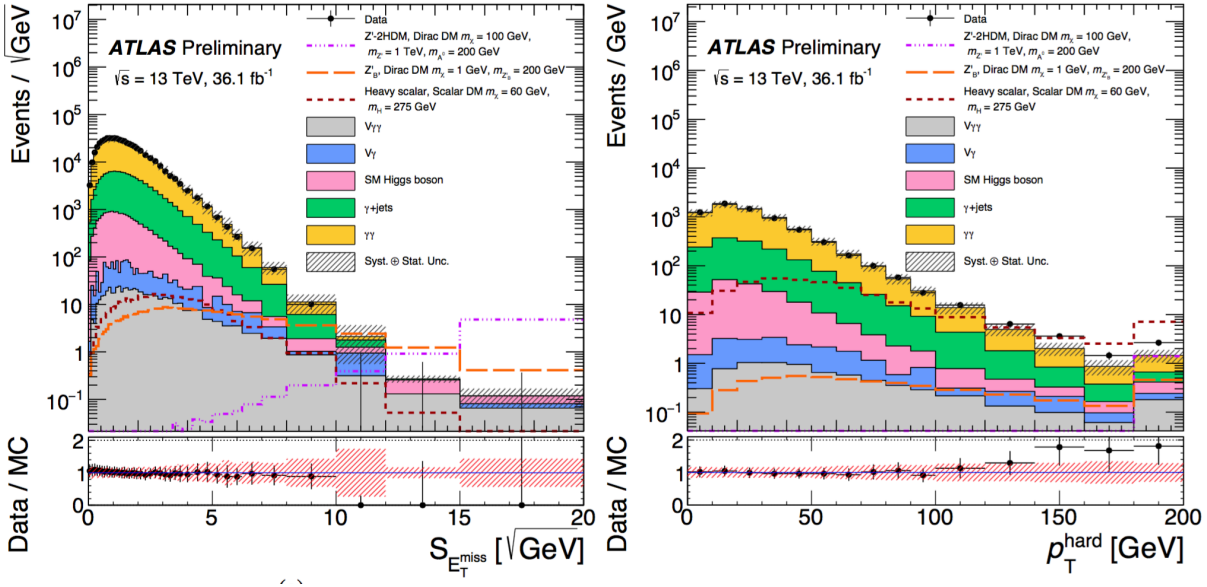
ATLAS-CONF-2017-024





- **Analysis categories:**

Category	Requirements
Mono-Higgs	$S_{E_{\mathrm{T}}^{\mathrm{miss}}} > 7\ \sqrt{\mathrm{GeV}}$, $p_{\mathrm{T}}^{\gamma\gamma} > 90$ GeV, lepton veto
High-$E_{\mathrm{T}}^{\mathrm{miss}}$	$S_{E_{\mathrm{T}}^{\mathrm{miss}}} > 5.5\ \sqrt{\mathrm{GeV}}$, $\lvert z_{PV}^{\mathrm{hard}} - z_{PV}^{\gamma\gamma} \rvert < 0.1$ mm
Intermediate-$E_{\mathrm{T}}^{\mathrm{miss}}$	$S_{E_{\mathrm{T}}^{\mathrm{miss}}} > 4\ \sqrt{\mathrm{GeV}}$, $p_{\mathrm{T}}^{\mathrm{hard}} > 40$ GeV, $\lvert z_{PV}^{\mathrm{hard}} - z_{PV}^{\gamma\gamma} \rvert < 0.1$ mm
Different-Vertex	$S_{E_{\mathrm{T}}^{\mathrm{miss}}} > 4\ \sqrt{\mathrm{GeV}}$, $p_{\mathrm{T}}^{\mathrm{hard}} > 40$ GeV, $\lvert z_{PV}^{\mathrm{hard}} - z_{PV}^{\gamma\gamma} \rvert > 0.1$ mm
Rest	$p_{\mathrm{T}}^{\gamma\gamma} > 15$ GeV



$$S_{E_{\mathrm{T}}^{\mathrm{miss}}} = E_{\mathrm{T}}^{\mathrm{miss}} / \sqrt{\sum E_{\mathrm{T}}}.$$

$$p_T^{\mathrm{hard}} = \left| \sum_{\mathrm{jets},\gamma} \vec{p}_T \right|$$

- First category to search for **vector mediator and Z'-2HDM models**
- All categories to search for heavy scalar model + EFT (low E_T^{miss})

- **Systematic uncertainties** (statistically limited):

Source	SM Higgs boson uncertainty (%)	Signal uncertainty (%)
Experimental		
Luminosity	3.2	
Trigger efficiency	0.4	
Vertex selection (inclusive cat.)	< 0.01	
Photon identification efficiency	2.7 – 3.7	2.9 – 4.3
Photon isolation efficiency	0.8 – 1.6	1.2
Photon energy scale	0.9 – 3.7	0.1 – 2
Photon energy resolution	0.1 – 1.1	0.1 – 0.2
$E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction (diphoton vertex)	2.0 – 10.3	-
$E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction (Jets, Soft term)	5.1 – 48	1.0 – 1.4
Pileup reweighting	0.7 – 11.0	0.2 – 5.6
Spurious signal (ratio with respect to stat. uncertainty from background)	29 – 34	
Theoretical		
Factorisation and renormalisation scale	0.5 – 20	< 11
PDF+α_S	2 – 6	< 25
Multi-parton interactions	0.5 – 31 (on ggF sample)	< 1
BR($H \to \gamma\gamma$)	1.73	

MONO-HIGGS($\gamma\gamma$)

- **Photons**
  - $|\eta| < 2.37$ (exclude crack $1.37 < |\eta| < 1.52$)
  - Leading (subleading) photon : $p_T > 35$ GeV ($p_T > 25$ GeV)
  - Pass Tight Id, e/γ ambiguity and FixedCutTight Iso
  - Relative p_T cuts : $p_T > 0.35(0.25)\, m_{\gamma\gamma}$ for leading (subleading) photon
- **Electrons**
  - $p_T > 10$ GeV and $|\eta| < 2.47$ (exclude crack $1.37 < |\eta| < 1.52$)
  - $|d_0|/\sigma_{d0} > 5$ and $z_0 \sin\theta < 0.5$ mm
  - Pass Medium LH ID and Loose Iso criteria
- **E_T^{miss}**
  - Recalculated w.r.t the diphoton vertex.
  - Using TST soft-terms.
- **Jets**
  - AntiKt4EMTopoJets
  - $p_T > 25$ GeV and $|\eta| < 4.4$
  - JVT > 0.59 for central jets (20 GeV $< p_T <$ 60 GeV , $|\eta| < 2.4$)
- **Muons**
  - Pt > 10 GeV and $|\eta| < 2.7$
  - $|d_0|/\sigma_{d0} > 3$ and $z_0 \sin\theta < 0.5$ mm
  - Pass Medium ID and GradientLoose Iso criteria
- **Event selection**
  - Pass quality cuts
  - Trigger HLT_g_35_loose_g_25_loose
  - Pass jet cleaning : LooseBad WP for jets with $p_T >$ 20 GeV
  - $m_{\gamma\gamma}$ in [105,160] GeV
  - Events weights: HgammaAnalysis:weight()*weightJvt()*lumixsec

6

Category	Mono-Higgs	High-$E_{\mathrm{T}}^{\mathrm{miss}}$	Intermediate-$E_{\mathrm{T}}^{\mathrm{miss}}$	Different-Vertex	Rest
Data	9	72	464	1511	46804
Backgrounds					
SM Higgs boson	2.43 ± 0.22	4.2 ± 0.6	11.9 ± 2.7	44 ± 10	1360 ± 110
Non-resonant	9.9 ± 1.9	62 ± 5	418 ± 10	1490 ± 18	45570 ± 110
Total background	12.3 ± 1.9	67 ± 5	430 ± 10	1535 ± 21	46930 ± 170
Heavy scalar, $m_{\mathrm{H}} = 275$ GeV, $m_{\chi} = 50$ GeV					
Expected yields	9.9 ± 1.3	32 ± 4	52 ± 6	42 ± 6	198 ± 18
$A \times \epsilon$ (%)	1.11 ± 0.07	3.62 ± 0.13	5.81 ± 0.17	4.73 ± 0.17	22.3 ± 0.4
Heavy scalar, $m_{\mathrm{H}} = 275$ GeV, $m_{\chi} = 60$ GeV					
Expected yields	10.9 ± 1.4	23.8 ± 3.2	43 ± 5	33 ± 5	222 ± 20
$A \times \epsilon$ (%)	1.22 ± 0.07	2.67 ± 0.10	4.82 ± 0.14	3.65 ± 0.13	24.9 ± 0.4
Z'_B model, $m_{Z'_B} = 200$ GeV, $m_{\chi} = 1$ GeV					
Expected yields	20.0 ± 4.5	–	–	–	–
$A \times \epsilon$ (%)	17.4 ± 0.2	–	–	–	–
Z'-2HDM model, $m_{Z'} = 1000$ GeV, $m_{A^0} = 200$ GeV, and $m_{\chi} = 100$ GeV					
Expected yields	28.0 ± 5.3	–	–	–	–
$A \times \epsilon$ (%)	70.7 ± 0.2	–	–	–	–