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

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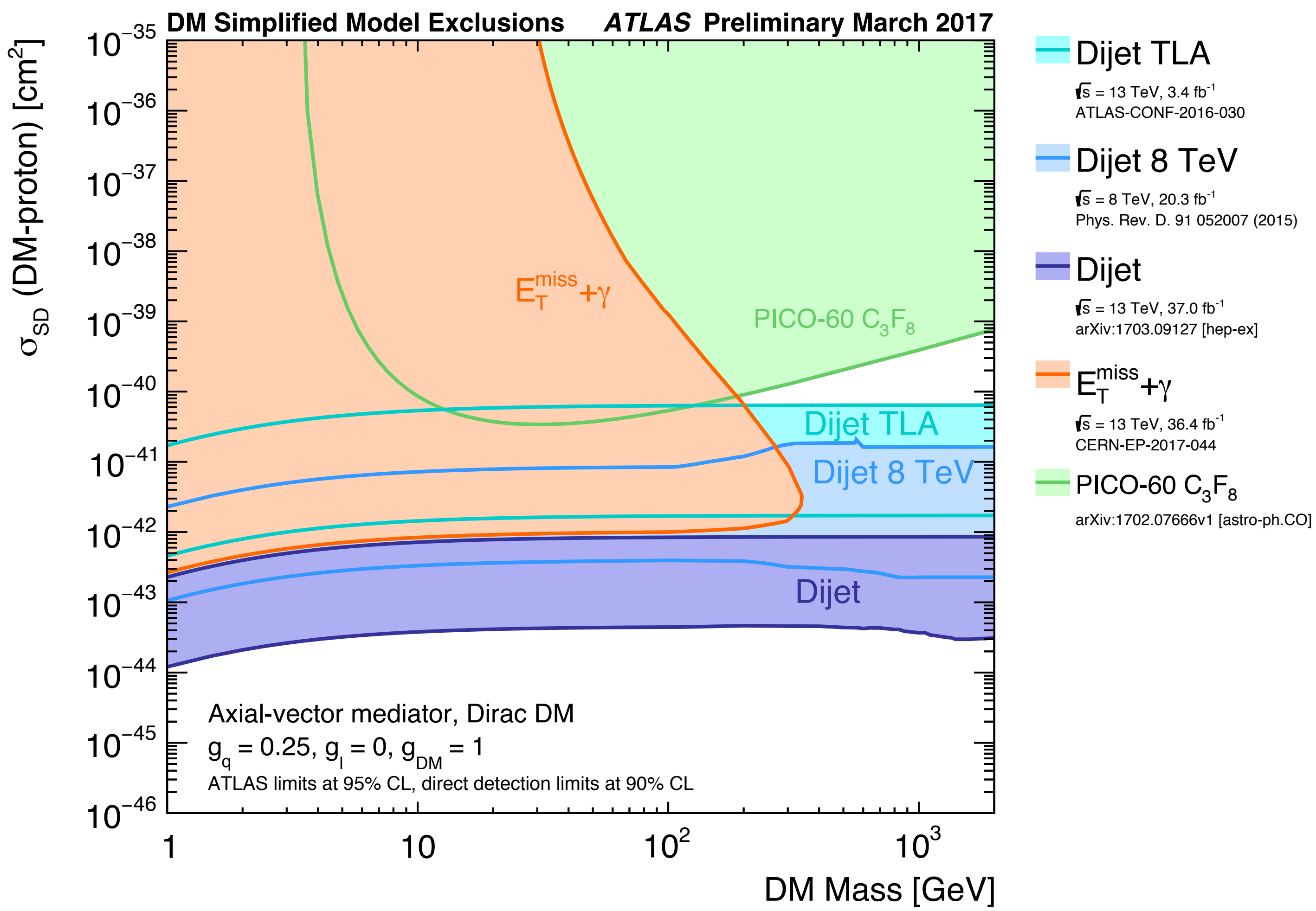
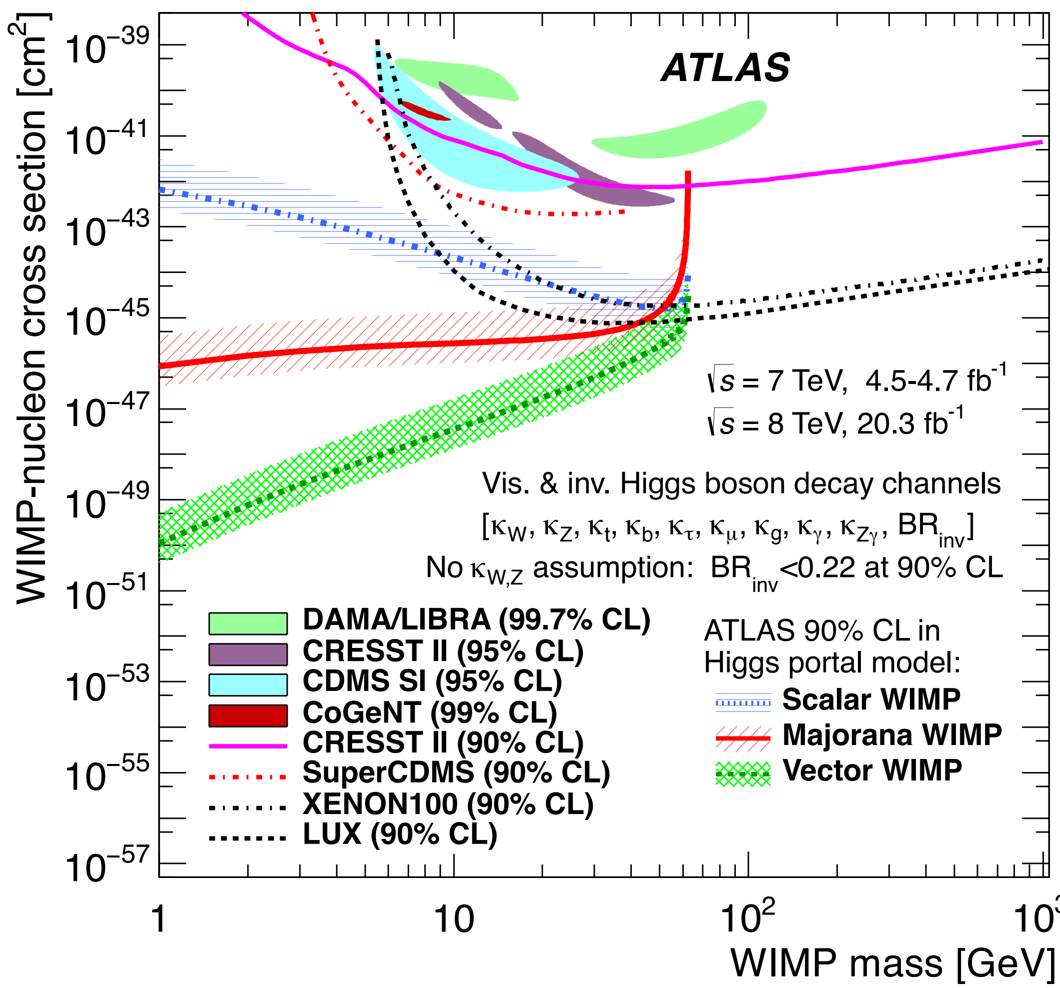
Dark Matter Searches

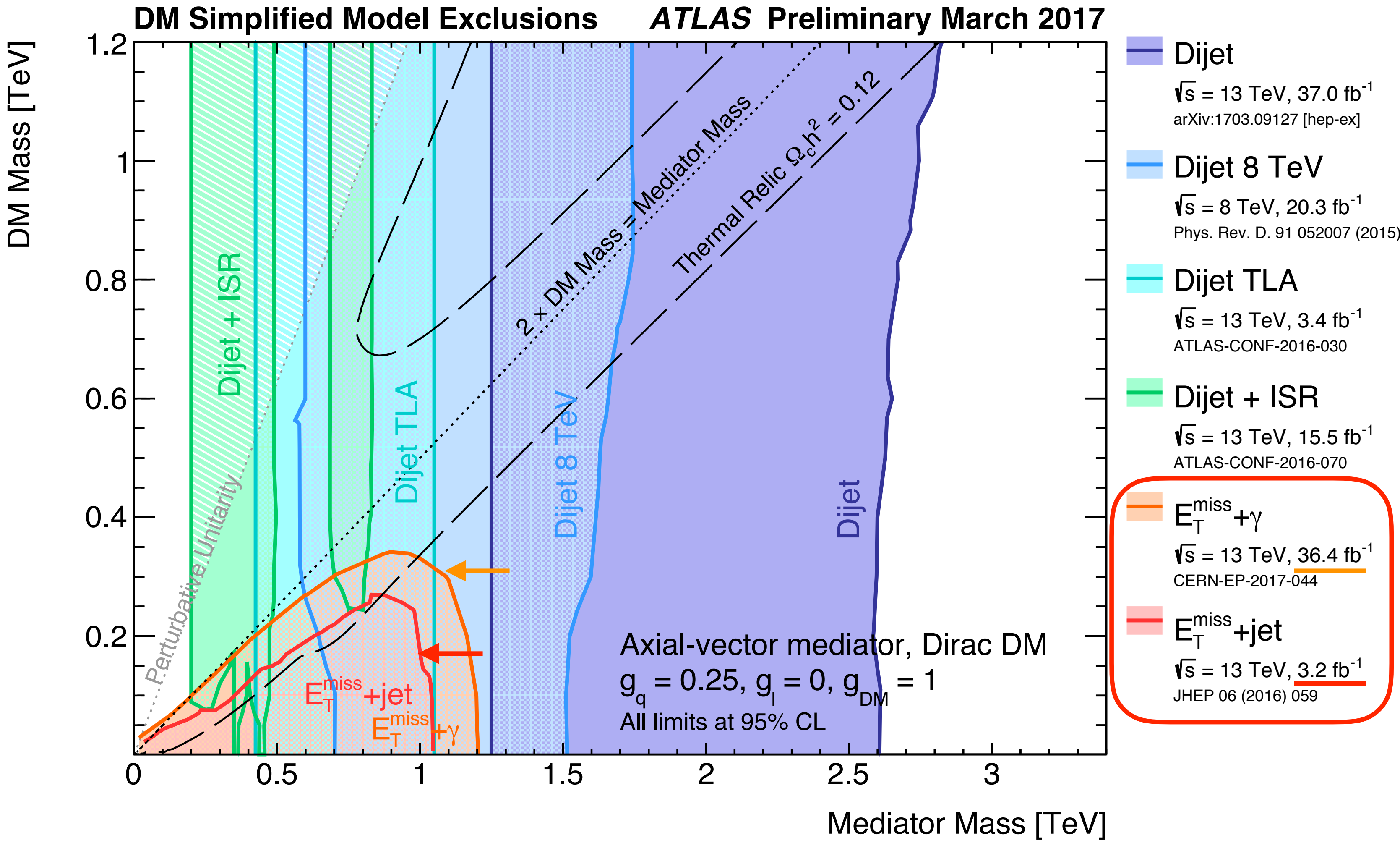
JHEP11(2015)206

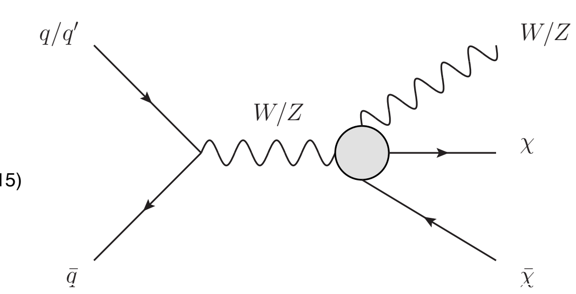


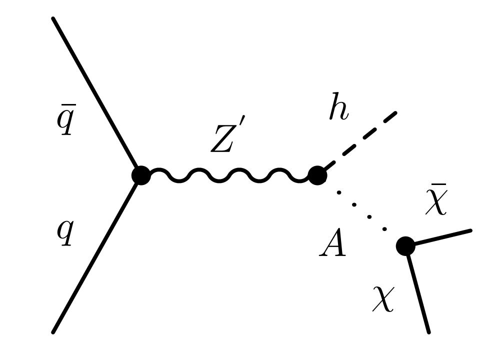


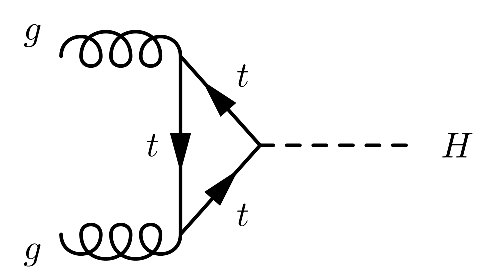
- Dark matter (DM) has been extensively searched by direct, indirect detection and previous collider experiments (e.g. PICO-60 C_3F_8, LUX, PandaX-II, Xenon-100, Tevatron).
  (talks by Graciela Beatriz Gelmini, Florian Reindl)
- LHC offers complementary sensitivities to some specific scenarios (e.g. axial-vector DM mediator, Higgs-portal).
  (talks by Steven Lowette, Patrick Fox)

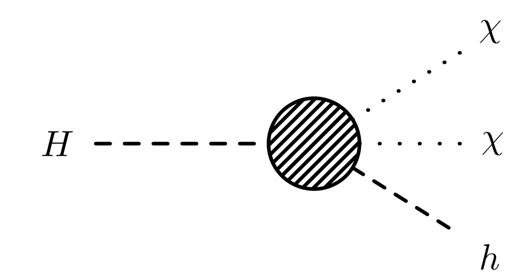
Mono-X Searches











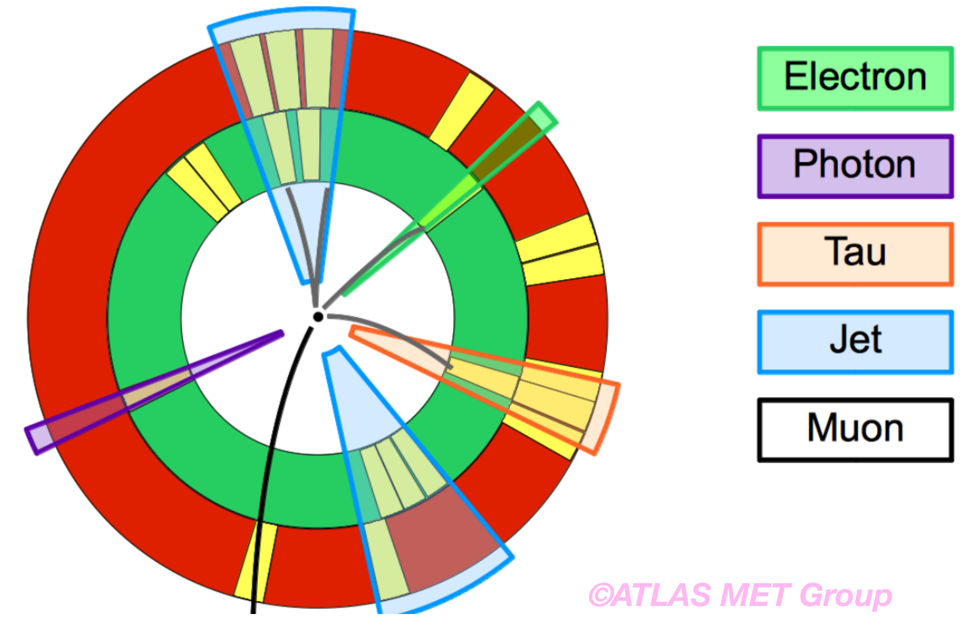
- Among the mono-X searches, the monojet channel is generally the most sensitive channels, followed by the monophoton (talk by William Kalderon).
- Nevertheless, mono-W/Z and mono-H channels are important when the DM or mediator only interacts with the vector bosons or Higgs boson.
- In these searches, **identification/reconstruction of the bosons** & **missing transverse momentum (E_T^{miss}): indirect measurement of $p_T(\chi\chi)$** are the key.

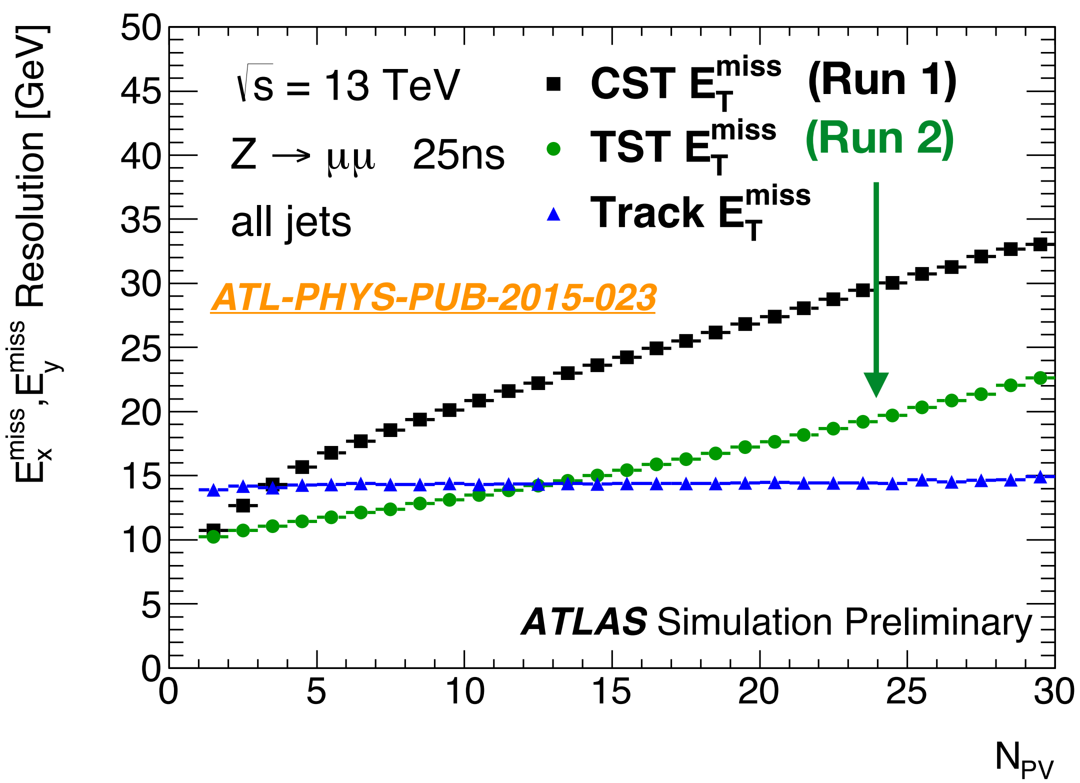
Missing Transverse Momentum

- Missing transverse momentum (E_T^{miss}) is the p_T imbalance of reconstructed physics objects.

$$E_{x(y)}^{\mathrm{miss}} = -p_{x(y)}^{e} - p_{x(y)}^{\gamma} - p_{x(y)}^{\tau_{\mathrm{had,vis}}} - p_{x(y)}^{\mathrm{jets}} - p_{x(y)}^{\mu} - p_{x(y)}^{\mathrm{soft}}$$

- It is <u>**indirect measurement of weakly interacting particle (neutrinos, dark matter) momenta**</u>, so very important for dark matter searches.

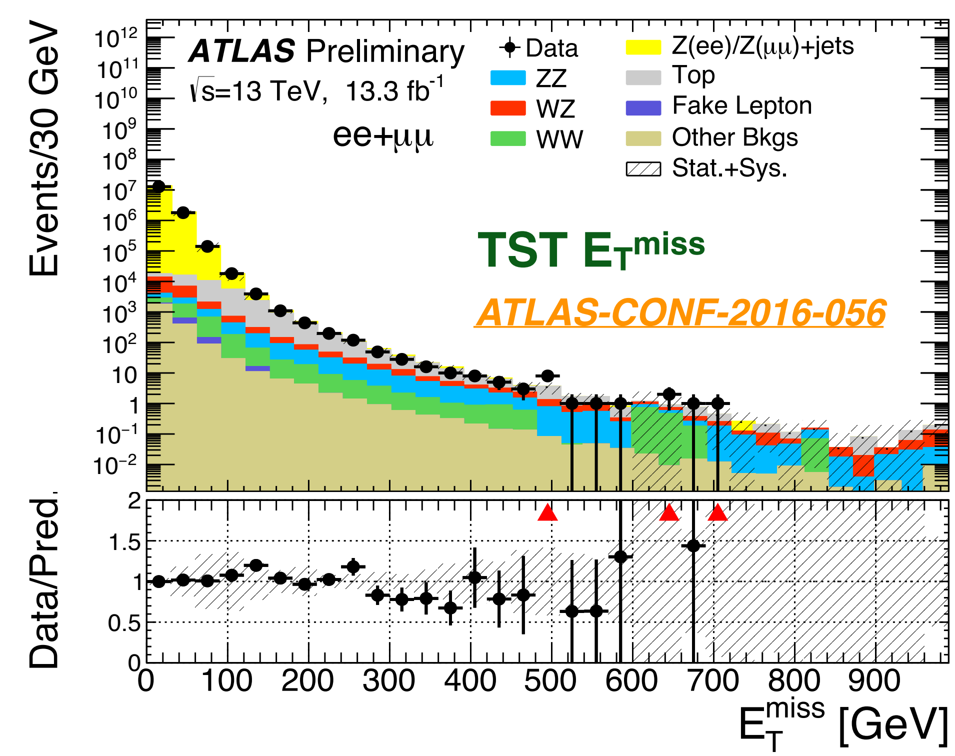




CST E_T^{miss}: Algorithm using Calorimeter Soft Term

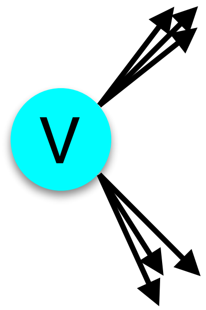
TST E_T^{miss}: Algorithm using Track Soft Term

Track E_T^{miss}: Purely reconstructed from tracks

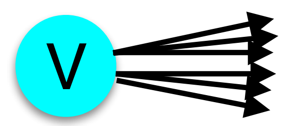


Boosted Boson Tagging

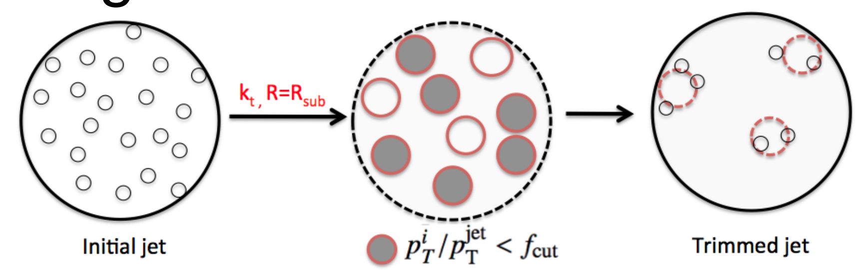
low-p_T V (2 jets)

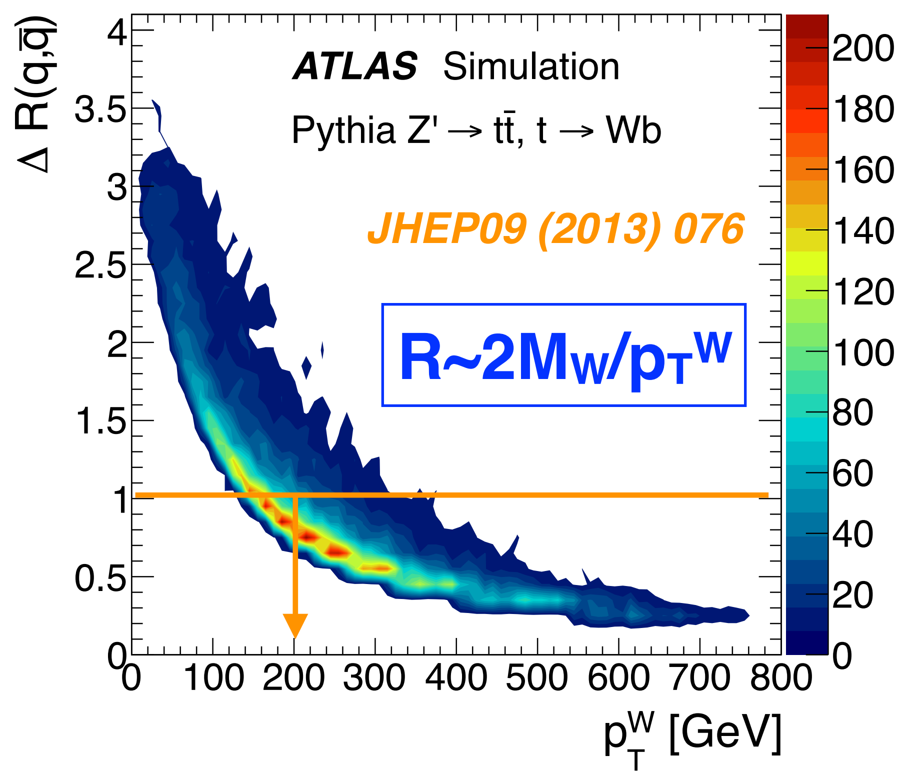


high-p_T V **(1 jet)**



Trimming





- Anti-k_t large-R jet (R=1.0) is used. Trimming is performed to remove pileup contributions.
- Cut on D_2 (energy correlation ratio; offers separation for 1- & 2-prong decays) is applied to reduce the multijet BG.
- Jets with mass consistent with m_V or m_H are selected.
- b-tagging using small-R track jets (R=0.2) is further considered to tag the Higgs bosons.

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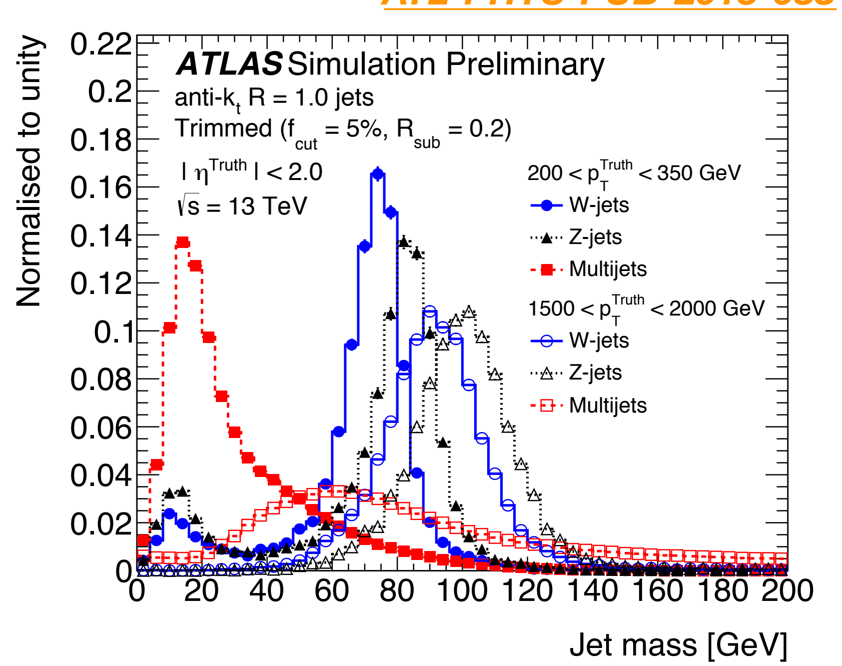

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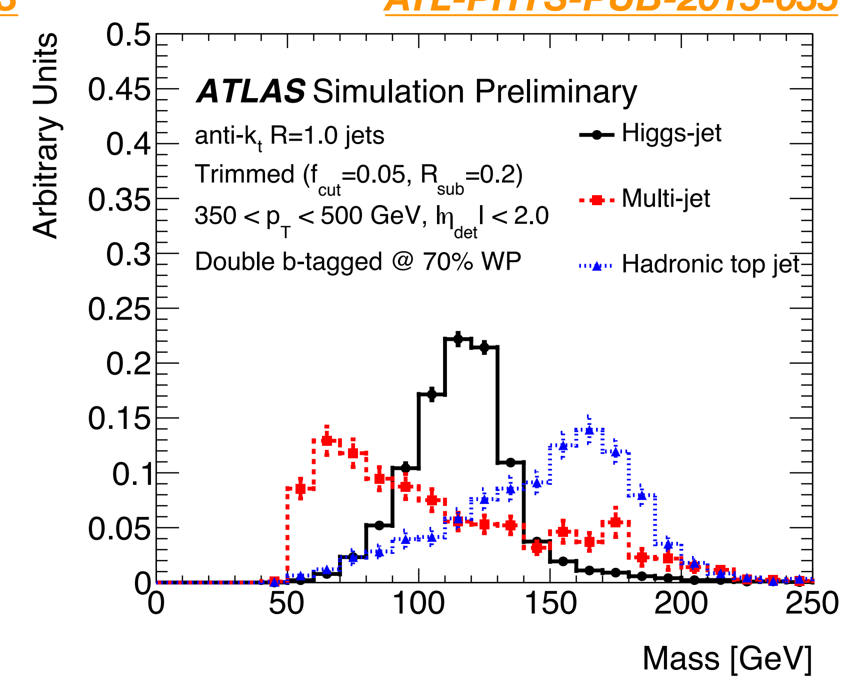

Mono-W/Z(qq)

2015 Data ($3.2\ fb^{-1}$)

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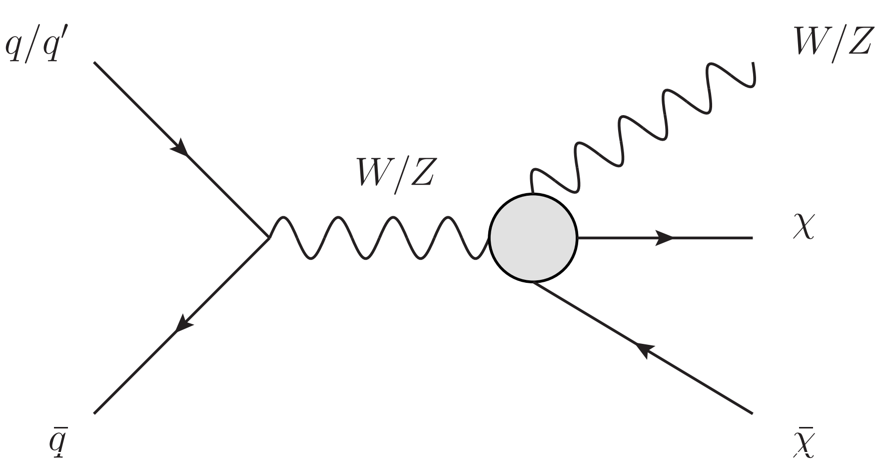
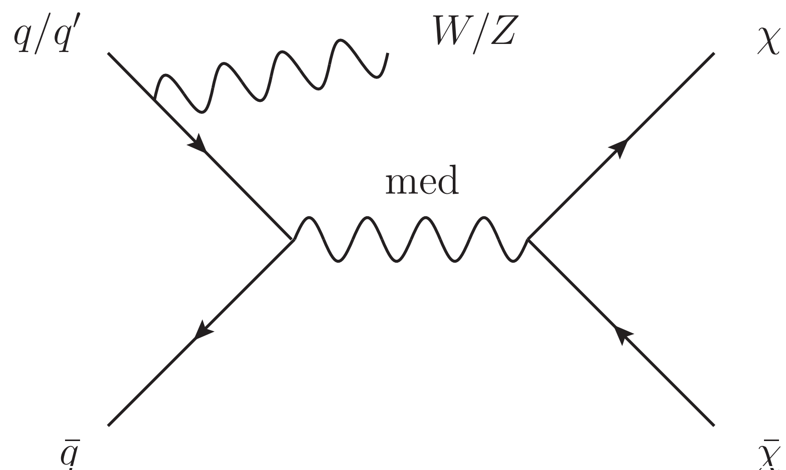
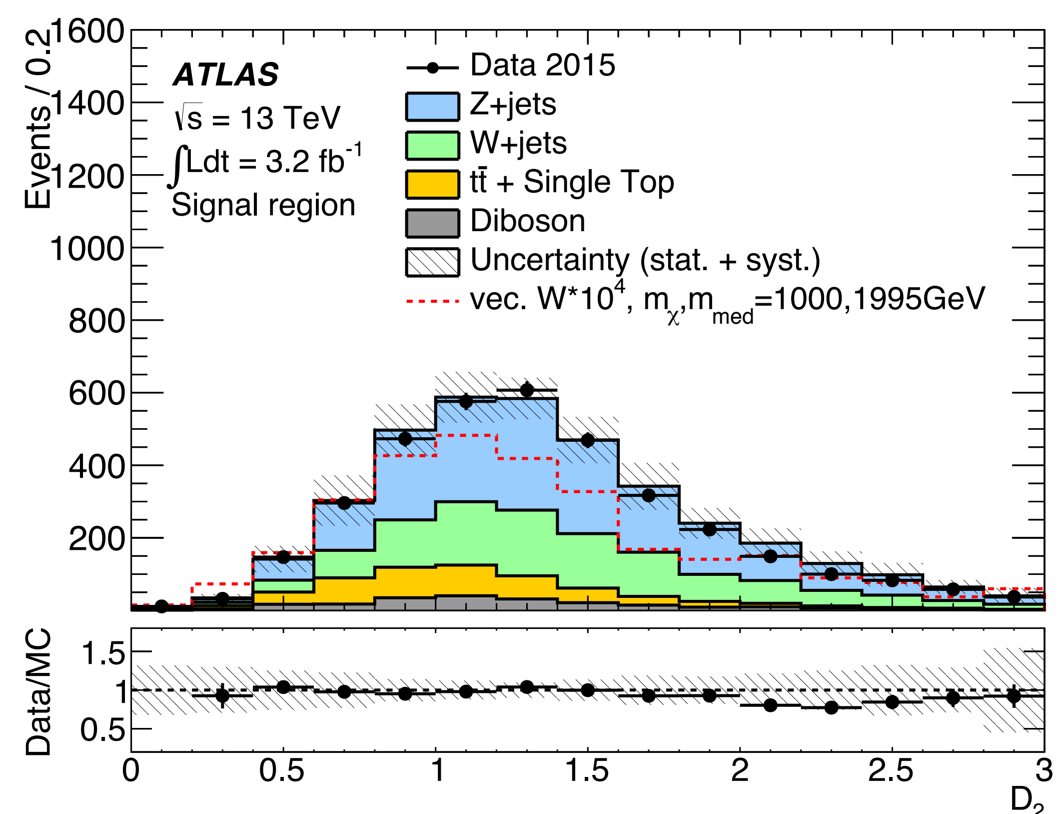




- Hadronic final states have advantage of large yields.
  - BR(W→qq) ~ 3BR(W→eν_e, μν_μ)
  - BR(Z→qq) ~ 10BR(Z→ee, μμ)

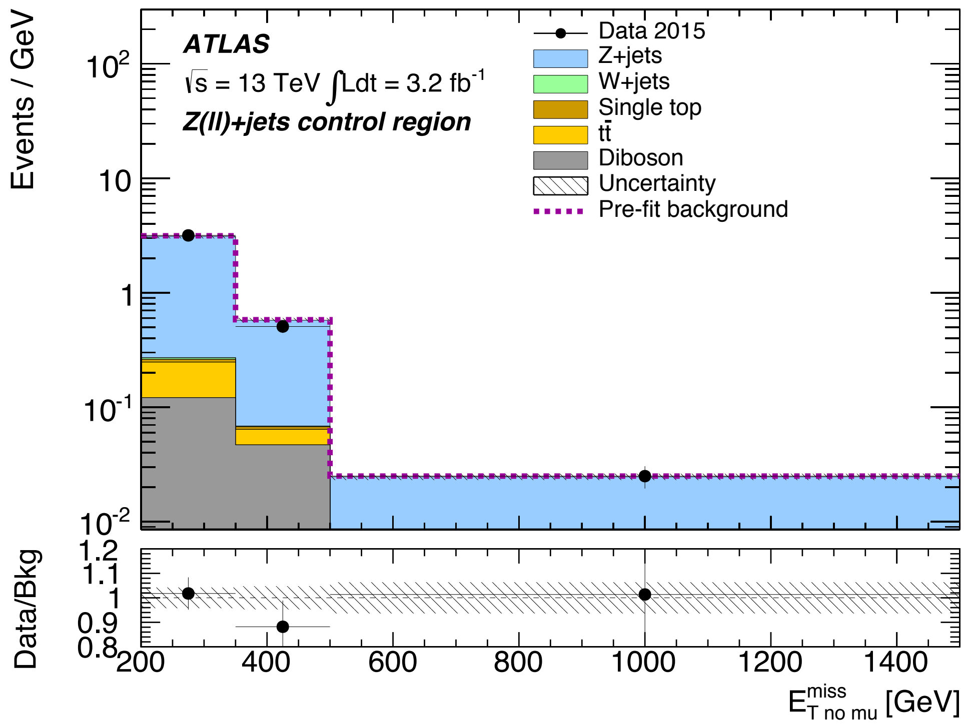
- No lepton.
- E_T^{miss} > 250 GeV & Track E_T^{miss} > 30 GeV.
- dϕ(E_T^{miss}, Track E_T^{miss}) < $\pi/2$.
- Boosted boson tagging:
  - Large-R jet p_T>200 GeV, |η|<2.0. Trimmed.
  - D_2 (2-prong-ness) & jet mass consistent w/ W or Z.
    → p_T-dependent D_2 cut w/ 50% tagging efficiency.

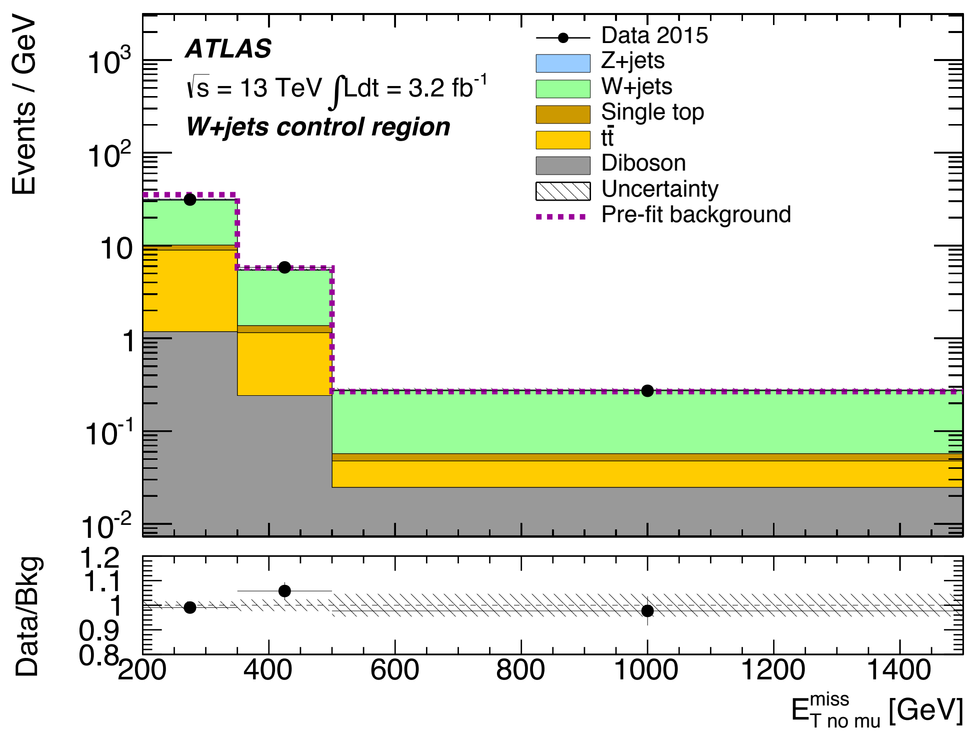


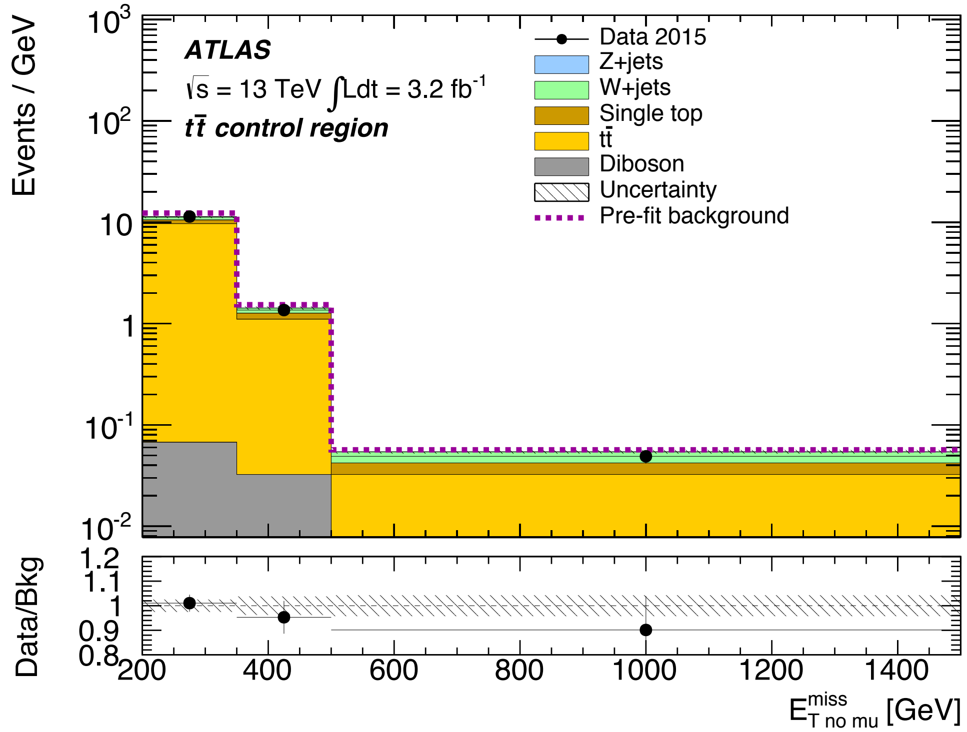
Mono-W/Z(qq)

2015 Data (3.2 fb^{-1})

- Main BGs: Z(νν)+jets, W(ℓν)+jets, Top, dibosons.
- Normalization is taken from control regions for Z(νν)+jets, W(ℓν)+jets & Top.
  - Z control region: 2 muons, 66<$m_{\mu\mu}$<116 GeV.
  - W (Top) control region: 1 muon, 0 b-jet (≥1 b-jets).
  - $E_{T\ no\ \mu}^{miss}$: muon contributions removed from E_T^{miss}.
- Fully MC for shape & dibosons/single-top.

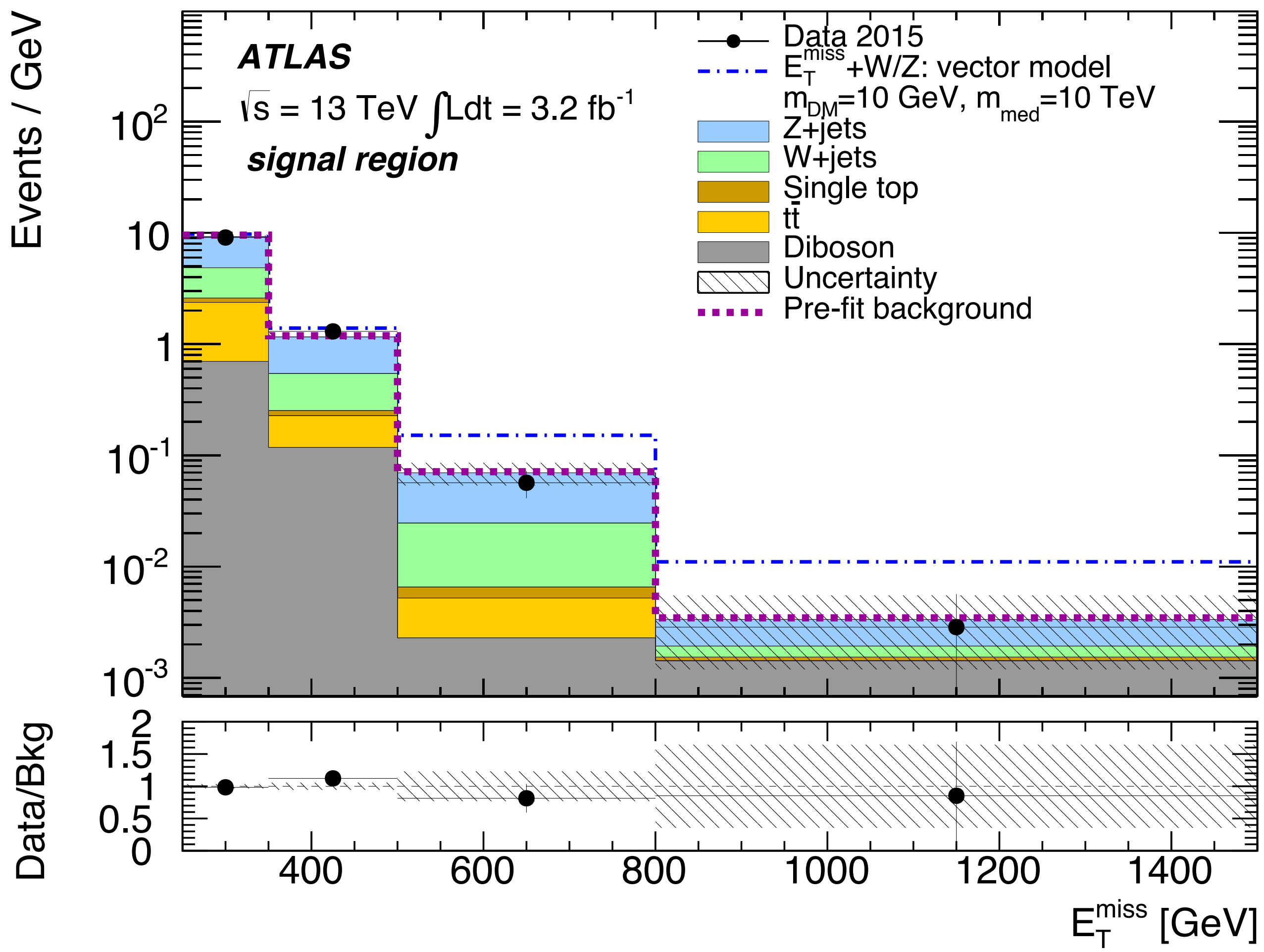


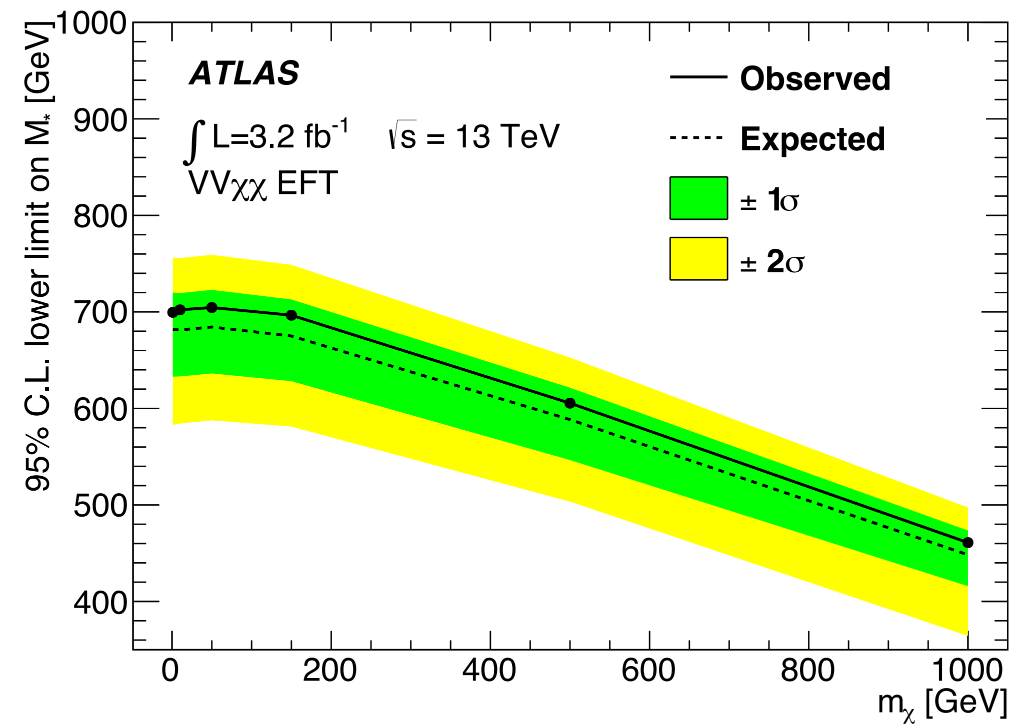


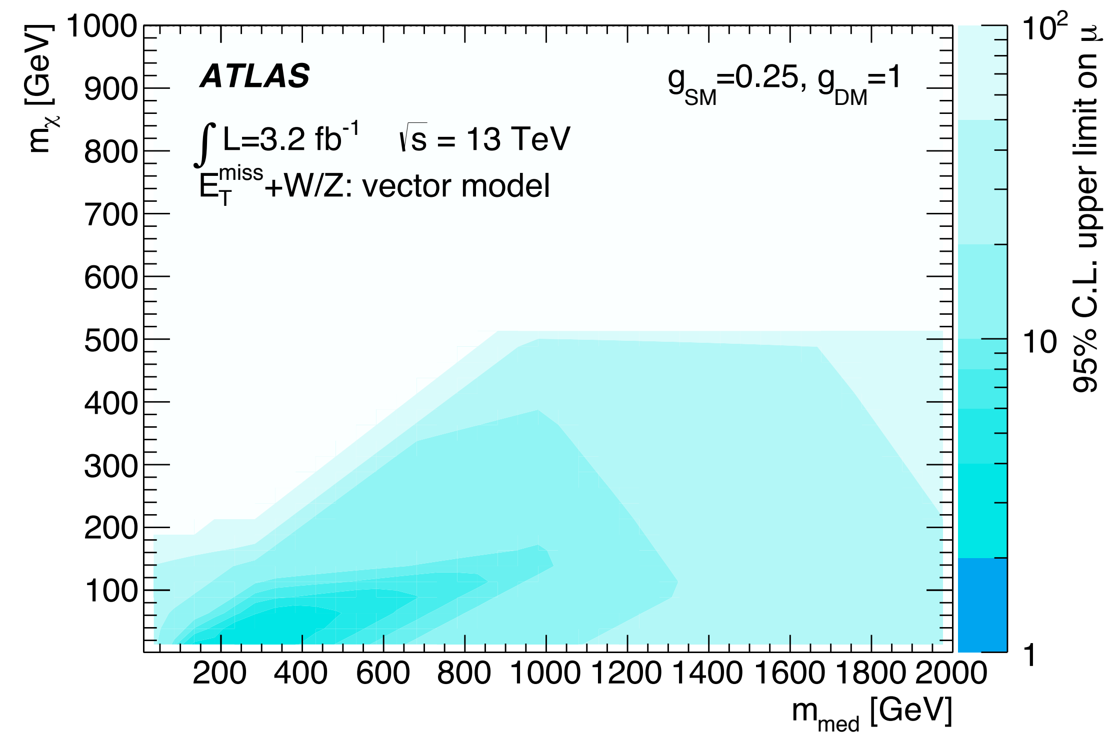


Mono-W/Z(qq)

2015 Data (3.2 fb^{-1})



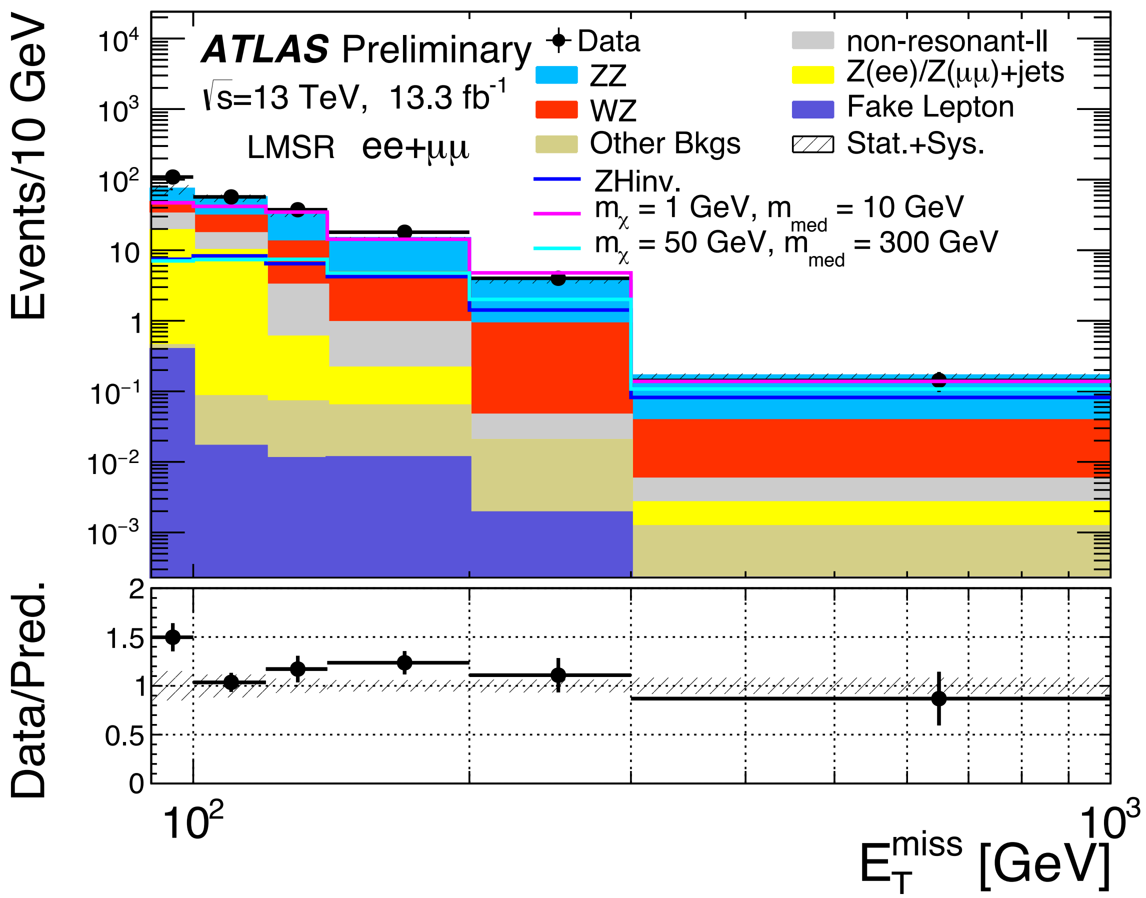




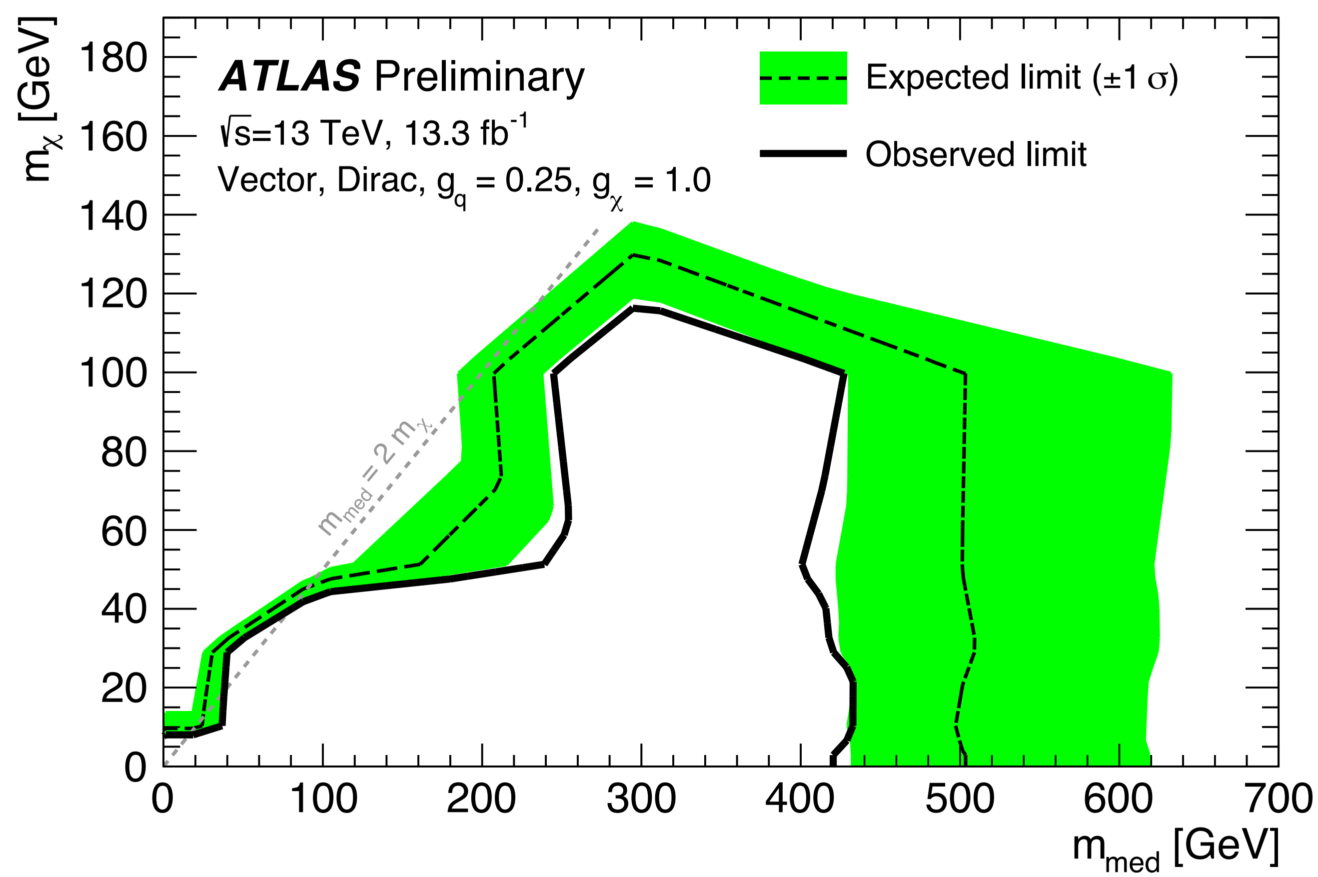
- No deviation from the SM prediction.
- Interpreted with an EFT and simplified vector mediator model.

Mono-Z(ℓℓ)

2015 + 2016 ($13.3\ fb^{-1}$)



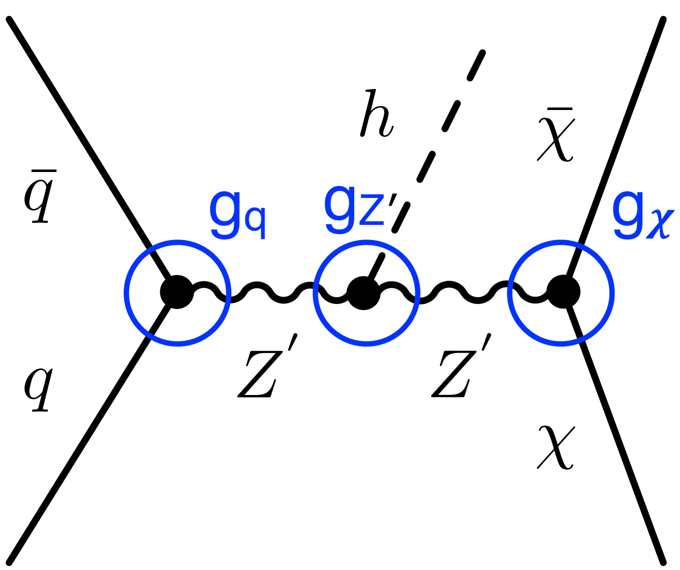
- Clean channel, but lacks in statistics.
- Z+jets BG is highly suppressed by various kinematic selections ($E_T^{miss} > 90$ GeV, etc.). The irreducible ZZ BG is the most dominant.
- No significant excess from the SM prediction.



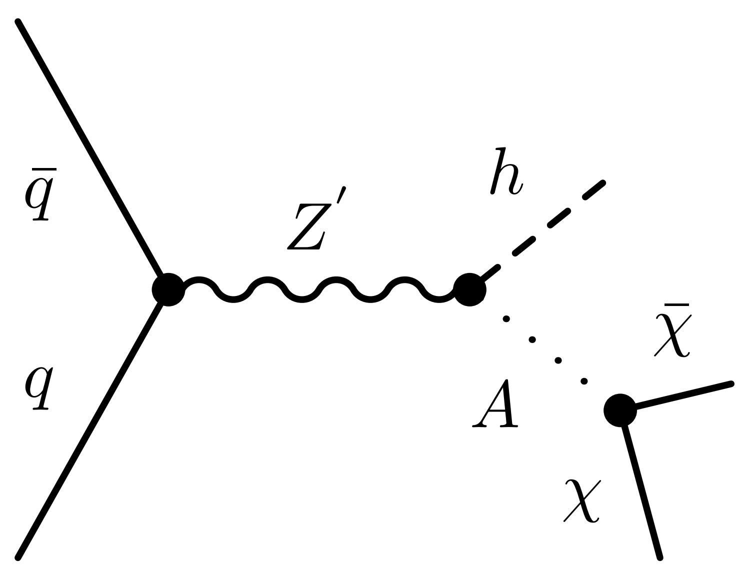
- This channel is also sensitive to the Higgs-portal model.
- **BR(H→inv) < 0.98 [obs], 0.65 [exp] at 95% CL.** Not yet surpassing the Run-1 constraint **(< 0.75 [obs], 0.62 [exp])**.

Mono-H Searches

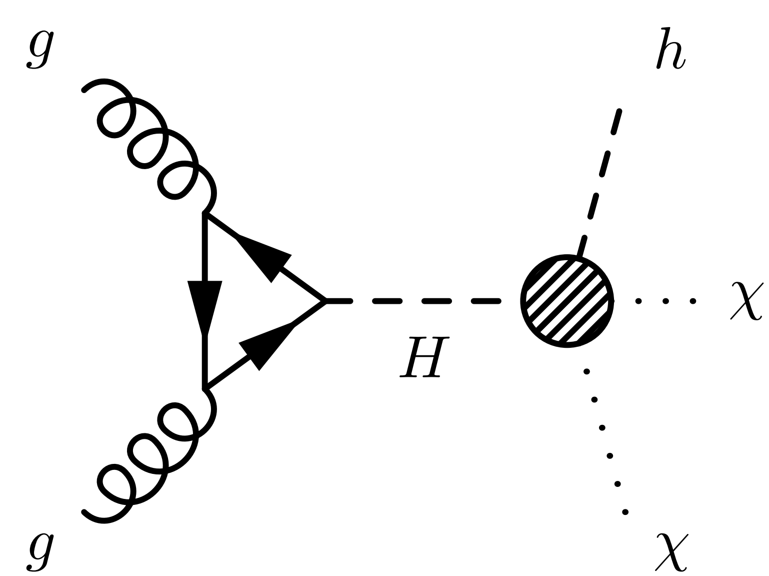
- Higgs-strahlung from initial-state partons is suppressed by the Yukawa coupling.
- **Mono-H searches are direct probes for the DM interactions.**
- Effective Field Theory (Run-1) & various simplified models (Run-2) have been considered in ATLAS.



Vector Mediator Model



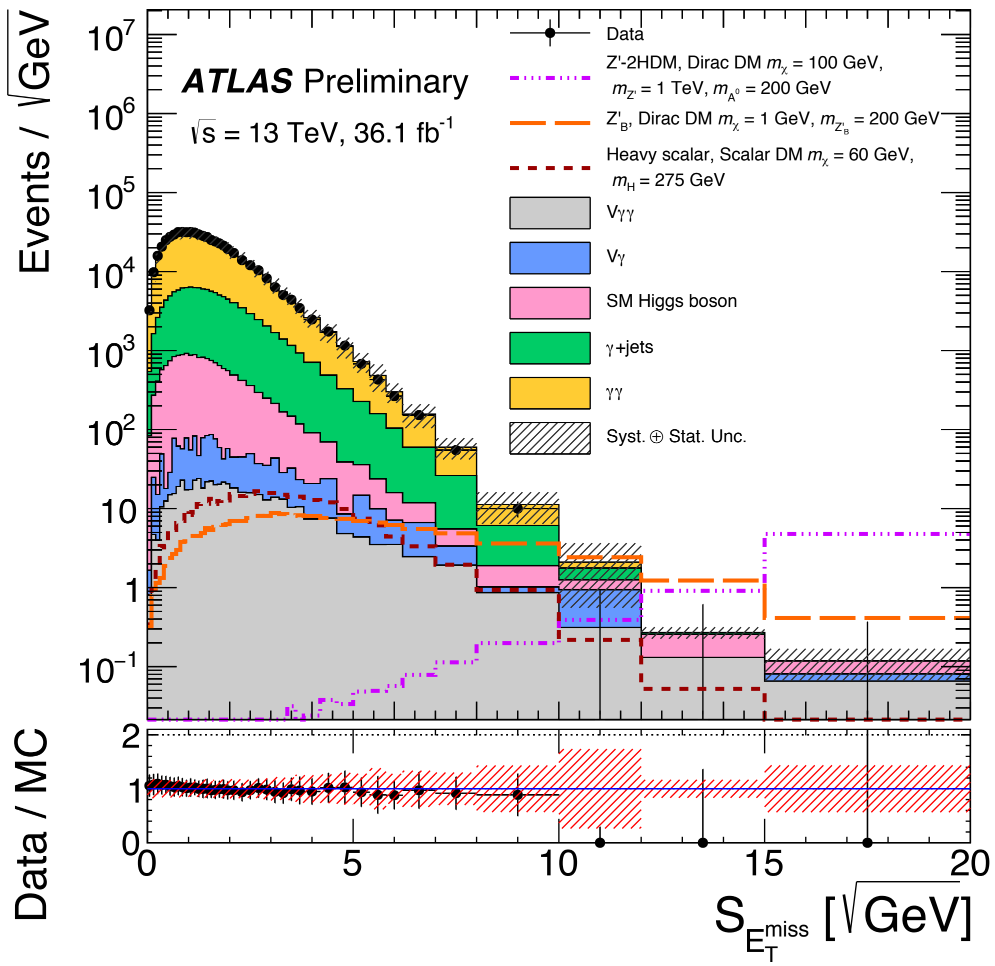
Z′-2HDM Model



Heavy Scalar Model

Mono-H($\gamma\gamma$) NEW!

ATLAS-CONF-2017-024



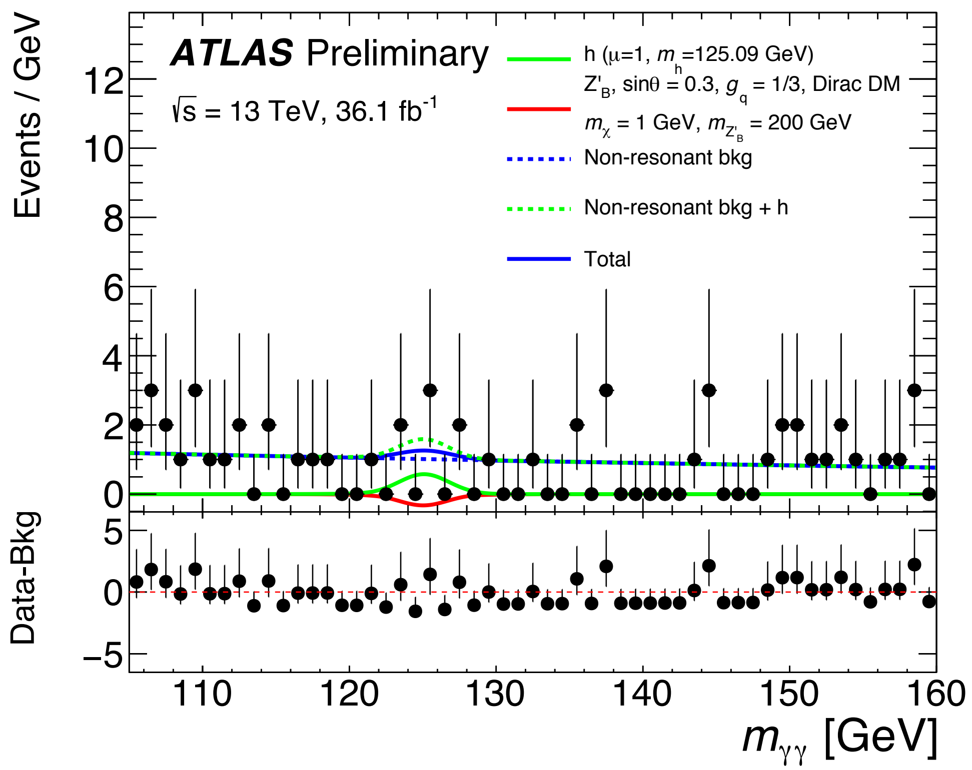
- Low BR, but very clean signature.
- Baseline selection is the same as the SM H→$\gamma\gamma$:
  - At least two photons with p_T>25 GeV.
  - $E_T^{\gamma 1}/m_{\gamma\gamma}$>0.35, $E_T^{\gamma 2}/m_{\gamma\gamma}$>0.25
- $105 < m_{\gamma\gamma} < 160$ GeV
- 5 event categories based on $S_{E_T^{miss}}$, $p_T^{\gamma\gamma}$, p_T^{hard}, # of leptons, $|z_{PV}^{hard} - z_{PV}^{\gamma\gamma}|$
  - First category for vector-mediator & Z′-2HDM.
  - All categories for heavy scalar models.

$$S_{E_T^{miss}} = E_T^{miss} / \sqrt{\sum E_T}$$

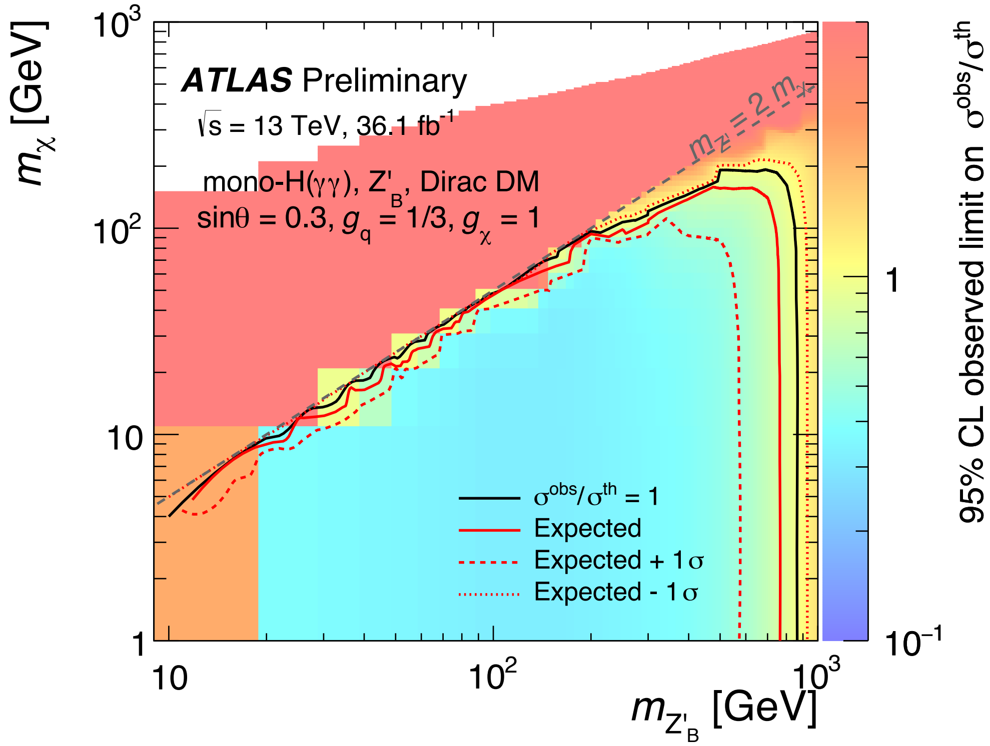
$$p_T^{hard} = \left| \sum \vec{p}_T^{\,\gamma} + \sum \vec{p}_T^{\,jet} \right|$$

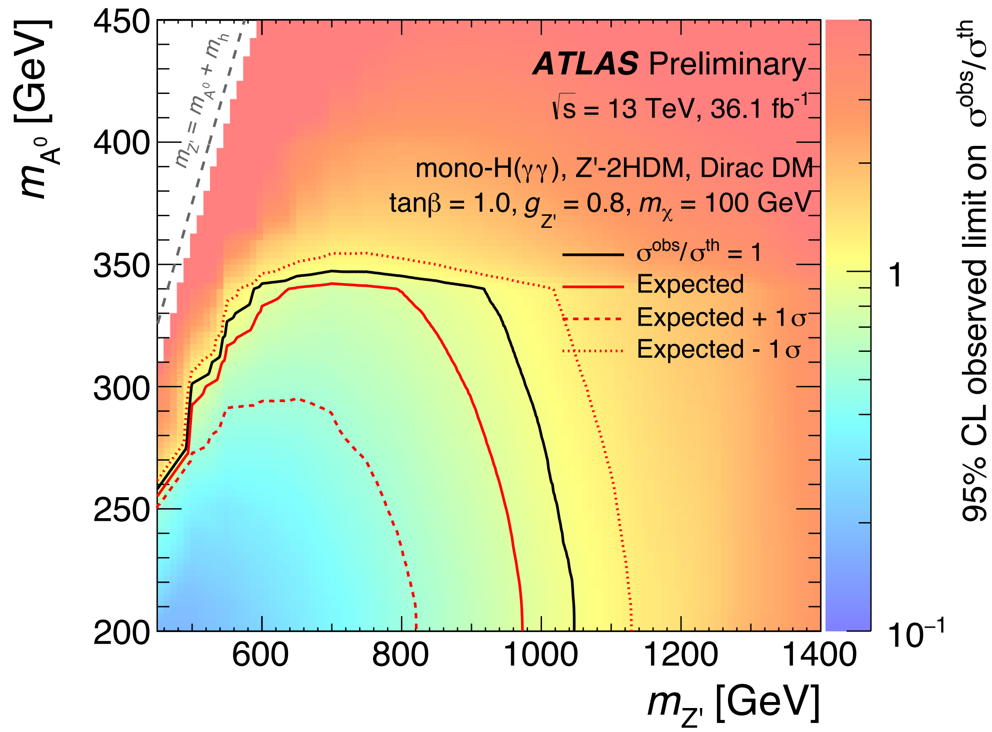
Category	Requirements
Mono-Higgs	$S_{E_T^{miss}} > 7\ \sqrt{\text{GeV}}$, $p_T^{\gamma\gamma} > 90$ GeV, lepton veto
High-E_T^{miss}	$S_{E_T^{miss}} > 5.5\ \sqrt{\text{GeV}}$, $\lvert z_{PV}^{hard} - z_{PV}^{\gamma\gamma}\rvert < 0.1$ mm
Intermediate-E_T^{miss}	$S_{E_T^{miss}} > 4\ \sqrt{\text{GeV}}$,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

Mono-H($\gamma\gamma$) NEW!

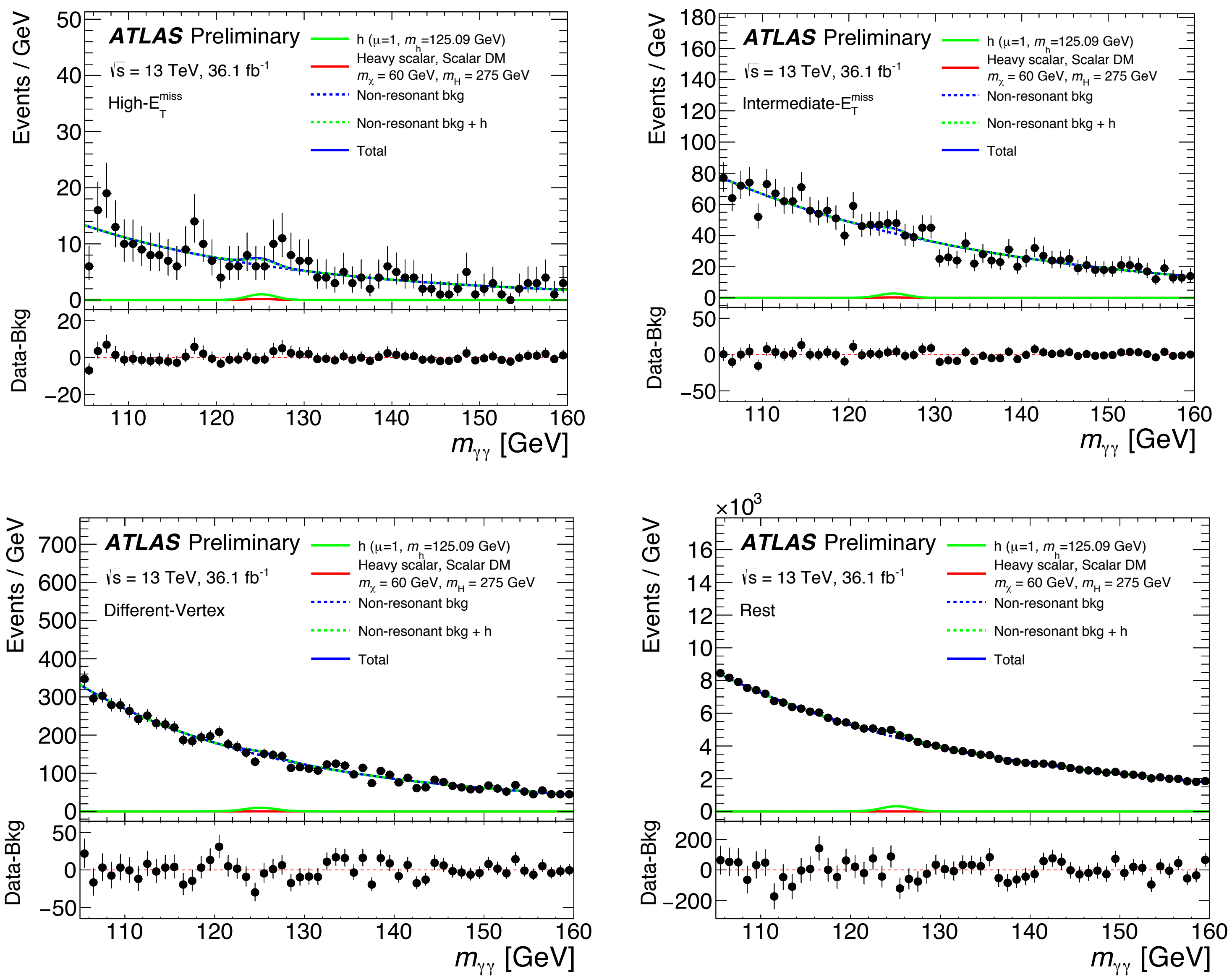


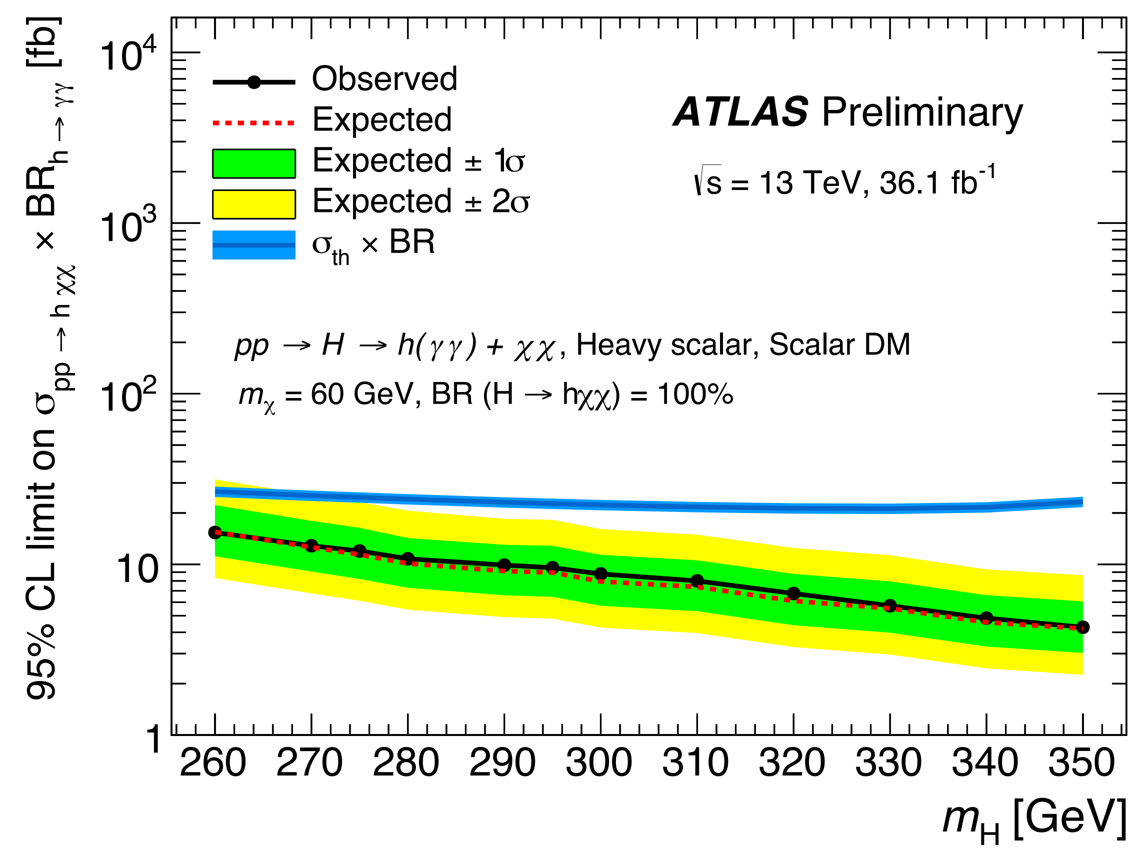
- Non-resonant BG (w/o H): $\gamma\gamma$, γ+jets, Vγ, V$\gamma\gamma$.
- Non-resonant BG (w/ H): Z(νν)H($\gamma\gamma$).
- Likelihood fit in $105 < m_{\gamma\gamma} < 160$ GeV using analytic functions.
  - Double-sided Crystal Ball is used for the signals & Z(νν)H($\gamma\gamma$).
- Consistent with the SM predictions.





Mono-H($\gamma\gamma$) NEW!



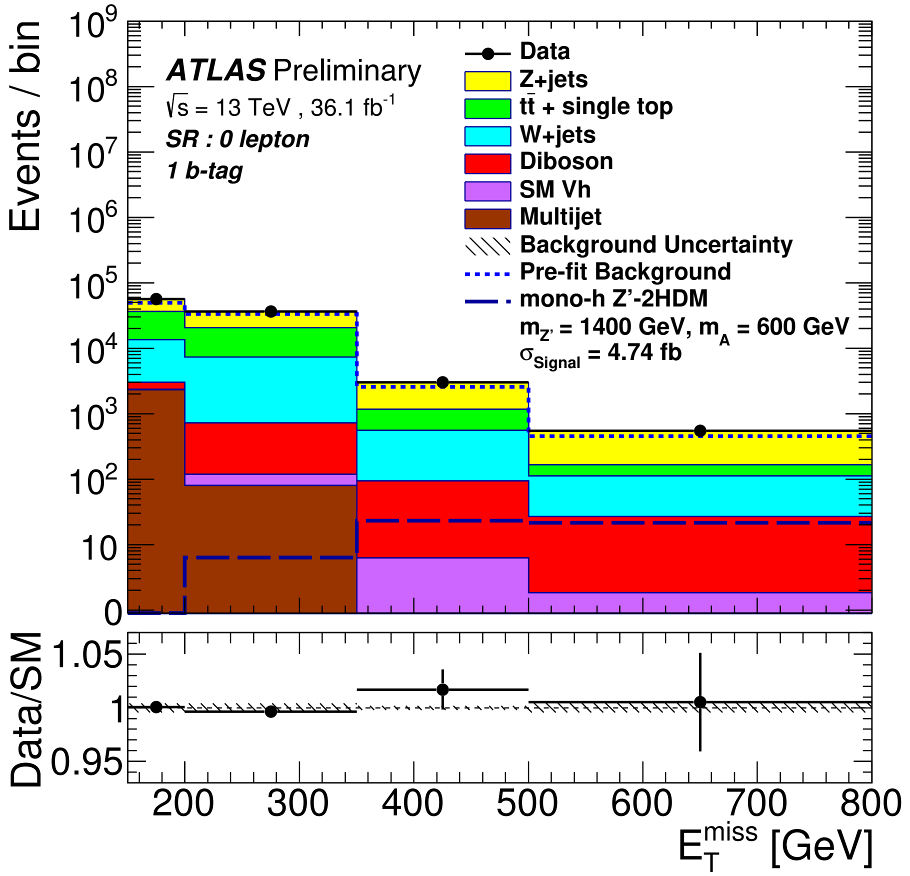


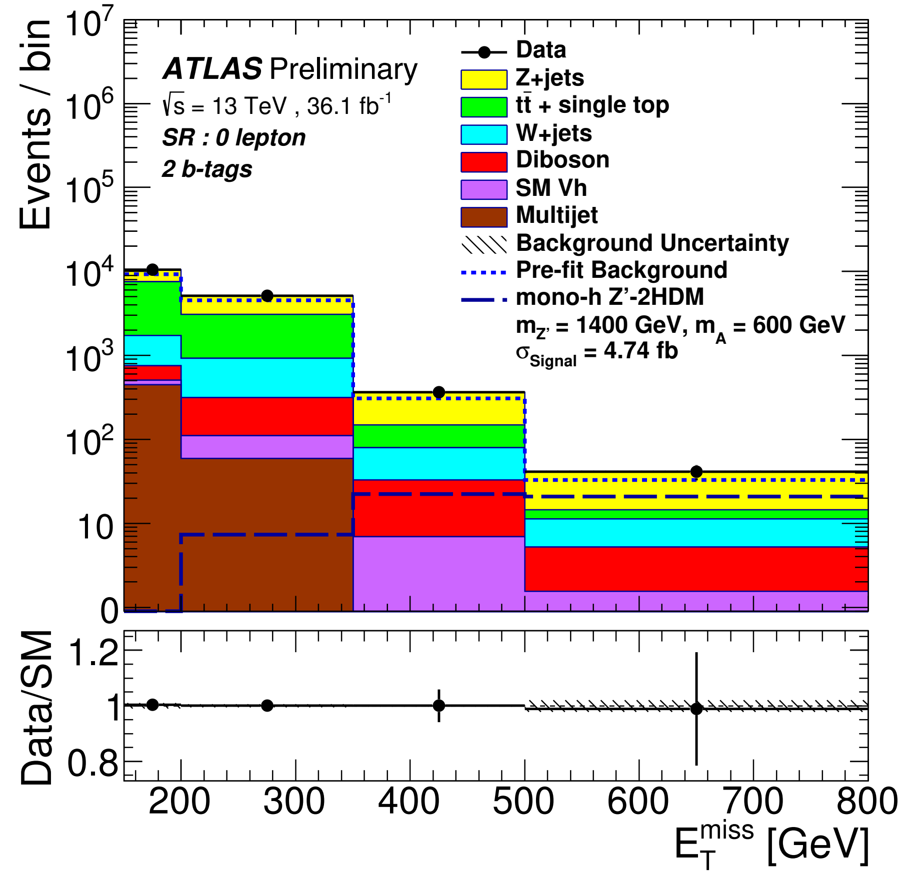
- The same approach for the other 4 categories as well.
- Consistent with the SM prediction.

Mono-H(bb)

NEW!

ATLAS-CONF-2017-028

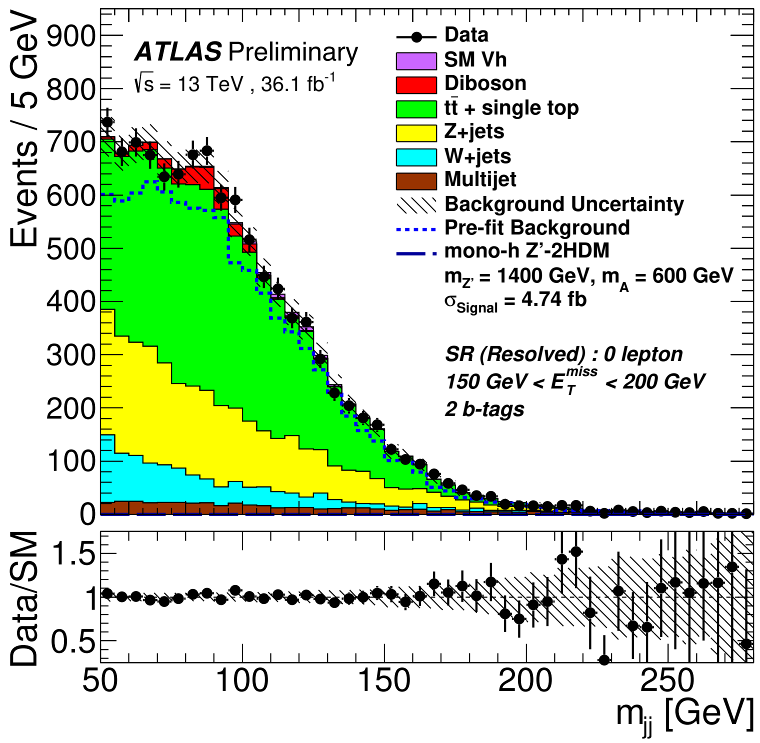


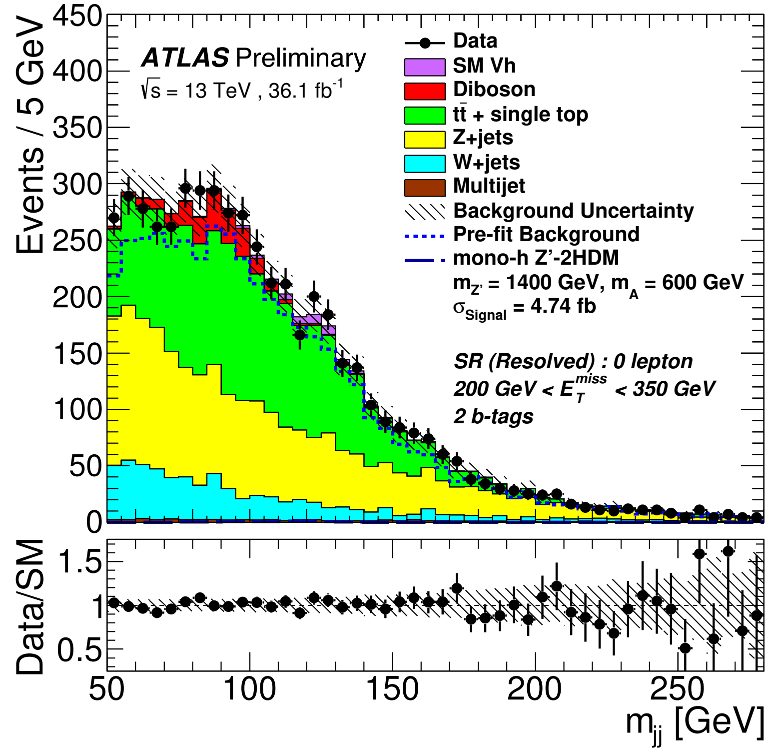


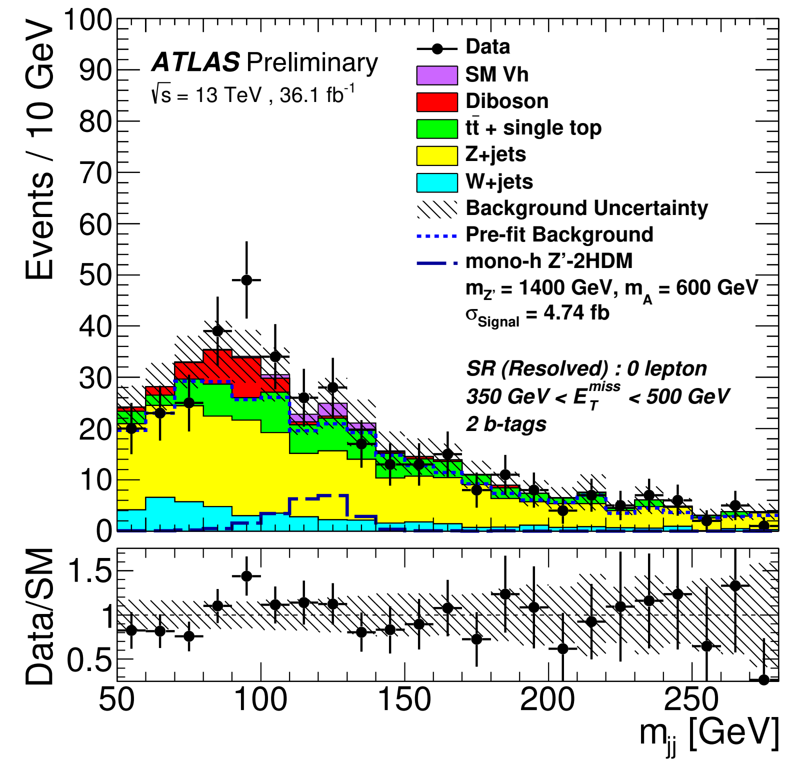
- Advantage due to high BR(H→bb) ~ 58%.
- 8 signal regions categorized with the **b-jet multiplicity (1 or 2 b-tags) & E_T^{miss} bins**.
- Small-R jets (R=0.4) are considered for E_T^{miss} < 500 GeV & large-R jets (R=1.0) for the last bin.

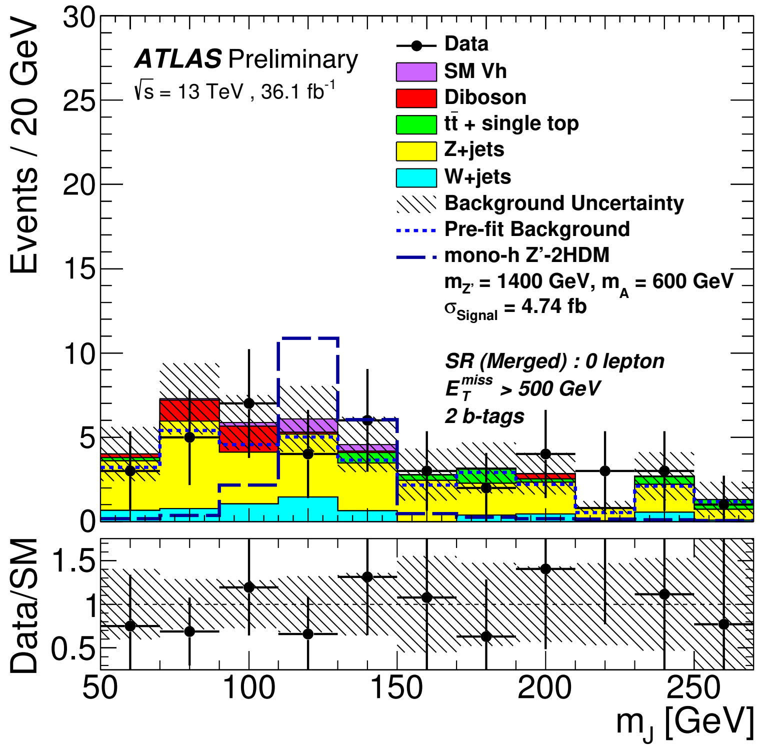
- Veto on τ-leptons & additional b-jets. Some angular cuts for the resolved (using small-R jets) categories & some H_T requirements to reduce BGs.
- Main BGs are Z+jets, W+jets, Top, diboson & Z(vv)H(bb).
- Normalization of Z+jets taken from 2-lepton CR, whereas 1-lepton CR is used for W+jets & Top.

Mono-H(bb) NEW!





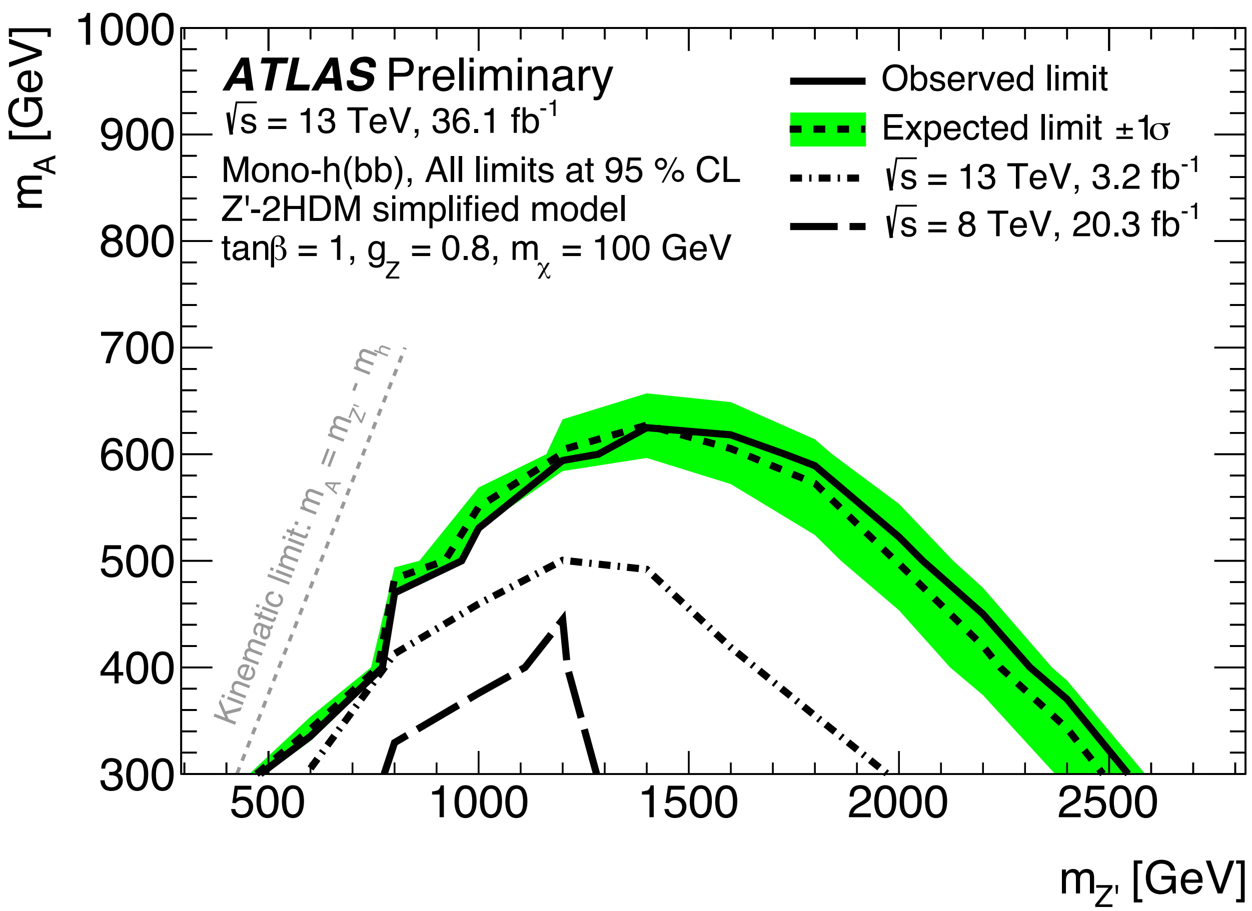


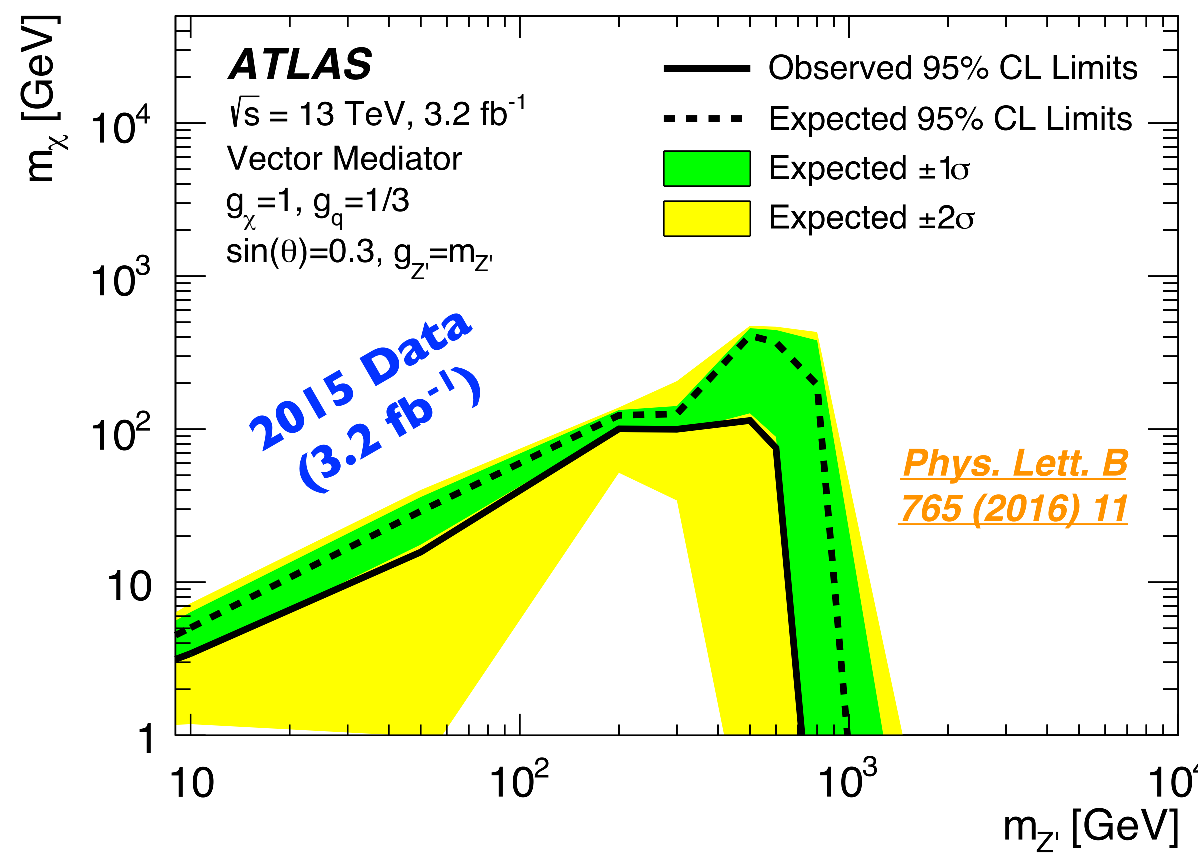


- m_{jj} or m_J is used as the final discriminant.
- No deviation from the SM prediction.
- Main systematics: b-tagging, V+jets modeling, SM VH normalization.

Mono-H(bb)

NEW!





- Mono-H(bb) has the best sensitivity among the Mono-H channels.
- For Z′-2HDM, the exclusion curves are shown with the ATLAS/CMS benchmark parameters of tan β=1, g_Z=0.8, m_χ=100 GeV.
- For vector mediator models, $m_{Z'} <$ ~700 GeV is excluded for g_χ=1, g_q=1/3, sinθ=0.3, $g_{Z'}=m_{Z'}$.

Summary

- Presented the latest results of mono-W/Z and mono-H searches at the ATLAS experiment.
- These searches are direct probes of BSM interactions with the vector bosons/Higgs boson and the dark matter.
- No deviation from the Standard Model predictions at the moment.
- New models (e.g. an extra scalar with H mixing, etc.) are proposed by the LHC DM WG, and are being considered for the near future.
- More results using the full 2015+2016 dataset will follow.


backups

D_2 for Boosted-V Tagging

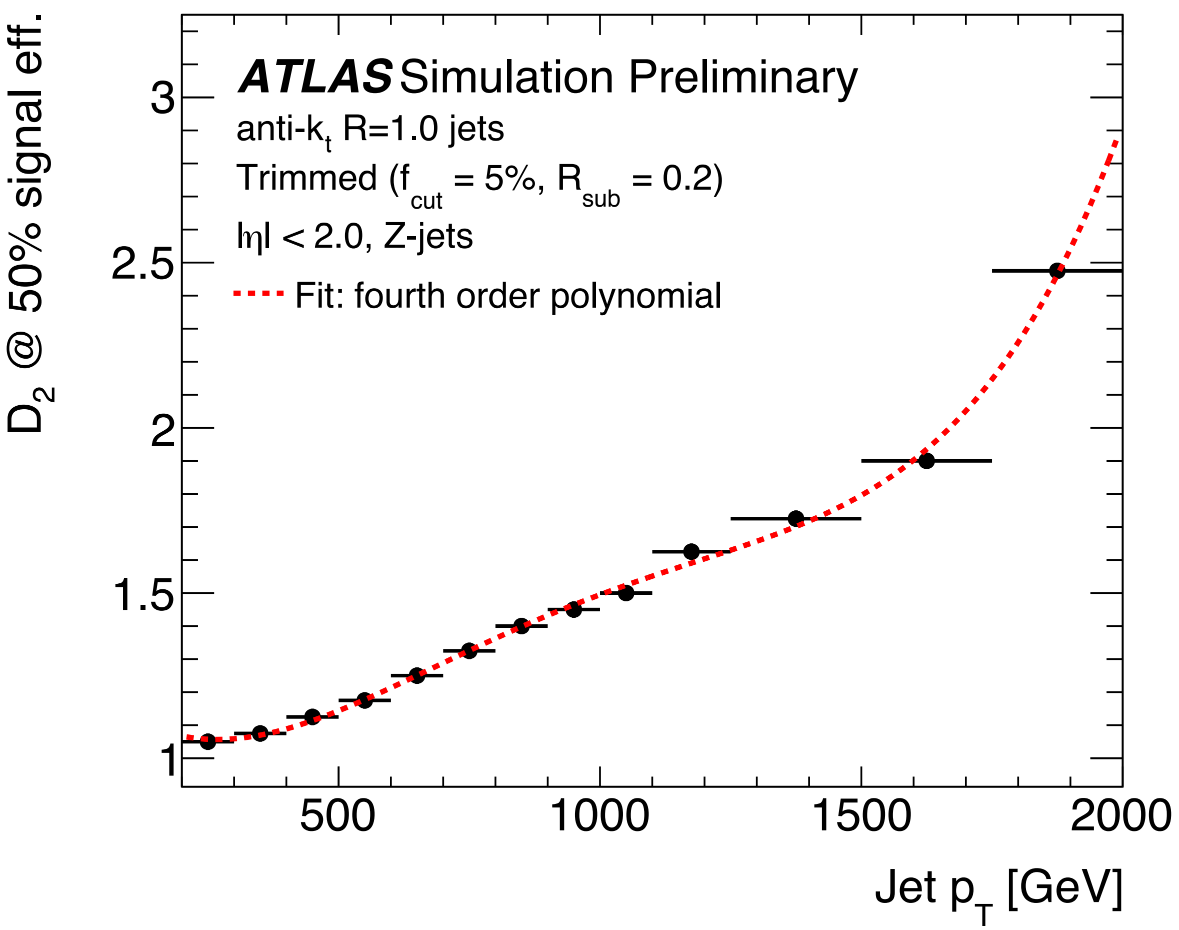
$$E_{CF0}(\beta) = 1,$$
$$E_{CF1}(\beta) = \sum_{i\in J} p_{\mathrm{T}_i},$$
$$E_{CF2}(\beta) = \sum_{i<j\in J} p_{\mathrm{T}_i} p_{\mathrm{T}_j} (\Delta R_{ij})^{\beta},$$
$$E_{CF3}(\beta) = \sum_{i<j<k\in J} p_{\mathrm{T}_i} p_{\mathrm{T}_j} p_{\mathrm{T}_k} (\Delta R_{ij} \Delta R_{ik} \Delta R_{jk})^{\beta},$$

$$e_2^{(\beta)} = \frac{E_{CF2}(\beta)}{E_{CF1}(\beta)^2},$$
$$e_3^{(\beta)} = \frac{E_{CF3}(\beta)}{E_{CF1}(\beta)^3}.$$

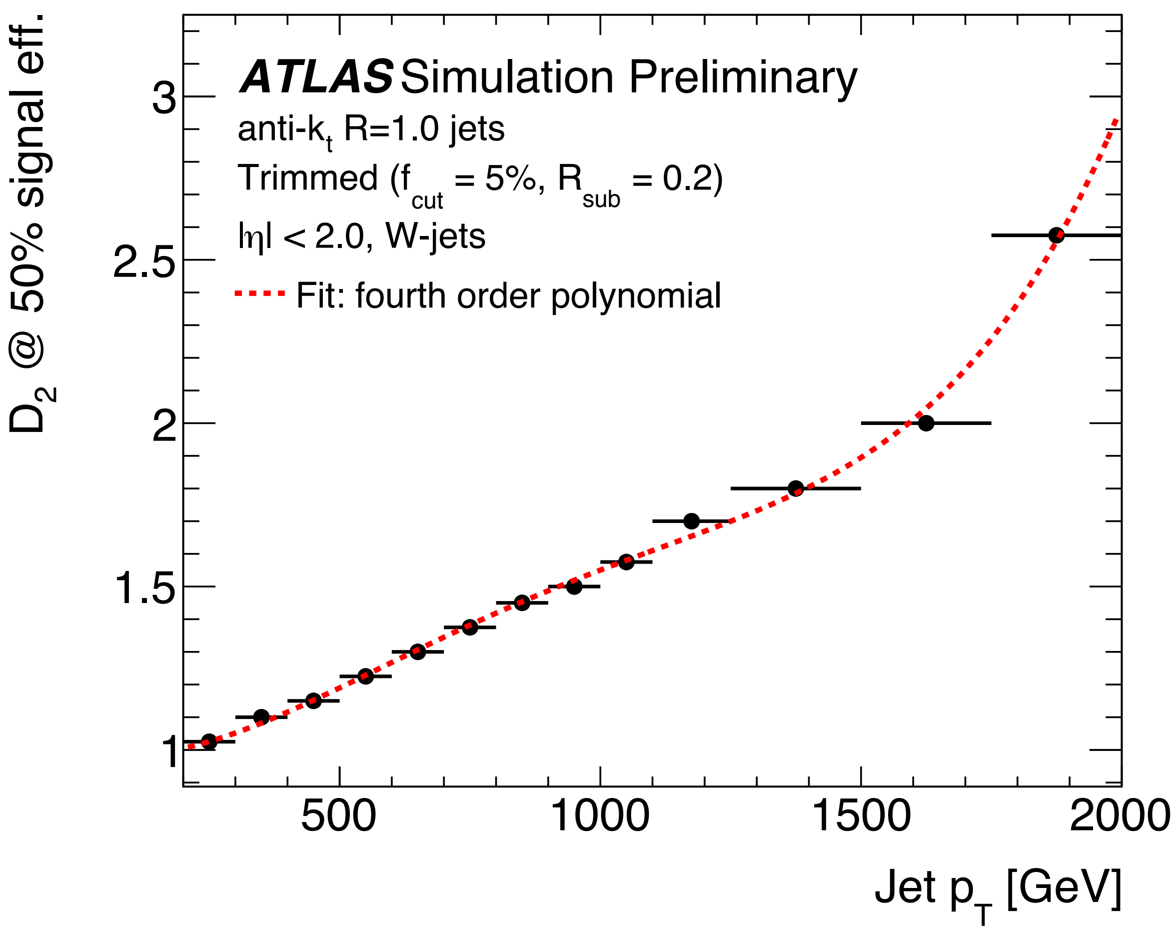
$$D_2^{(\beta)} = \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^3}.$$

β=1 is considered

Boosted-Boson Tagging



(a) *Z*-jets, 'Medium'.



(c) *W*-jets, 'Medium'.

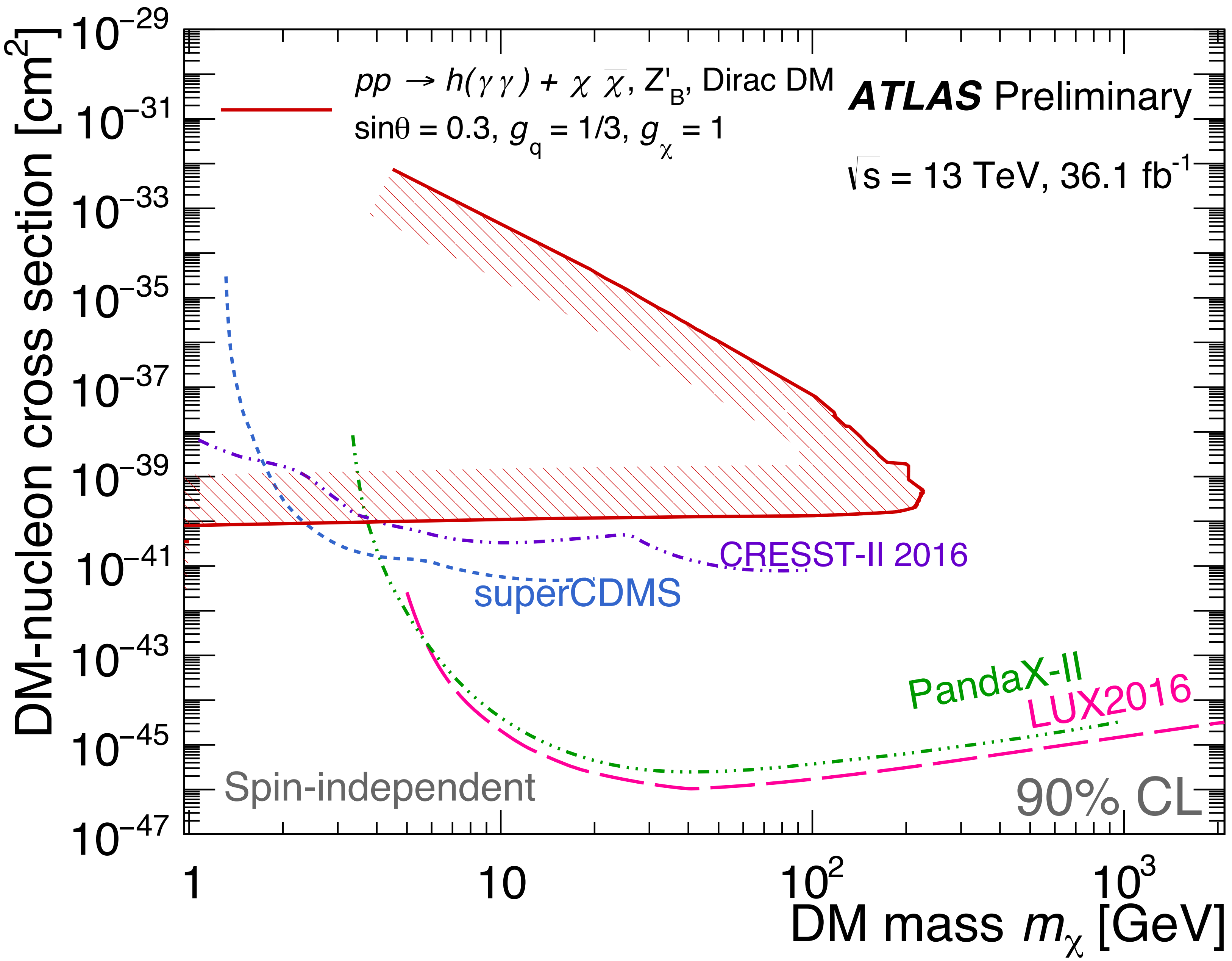
Mono-Z(ℓℓ)

2015 + 2016 (13.3 fb^{-1})

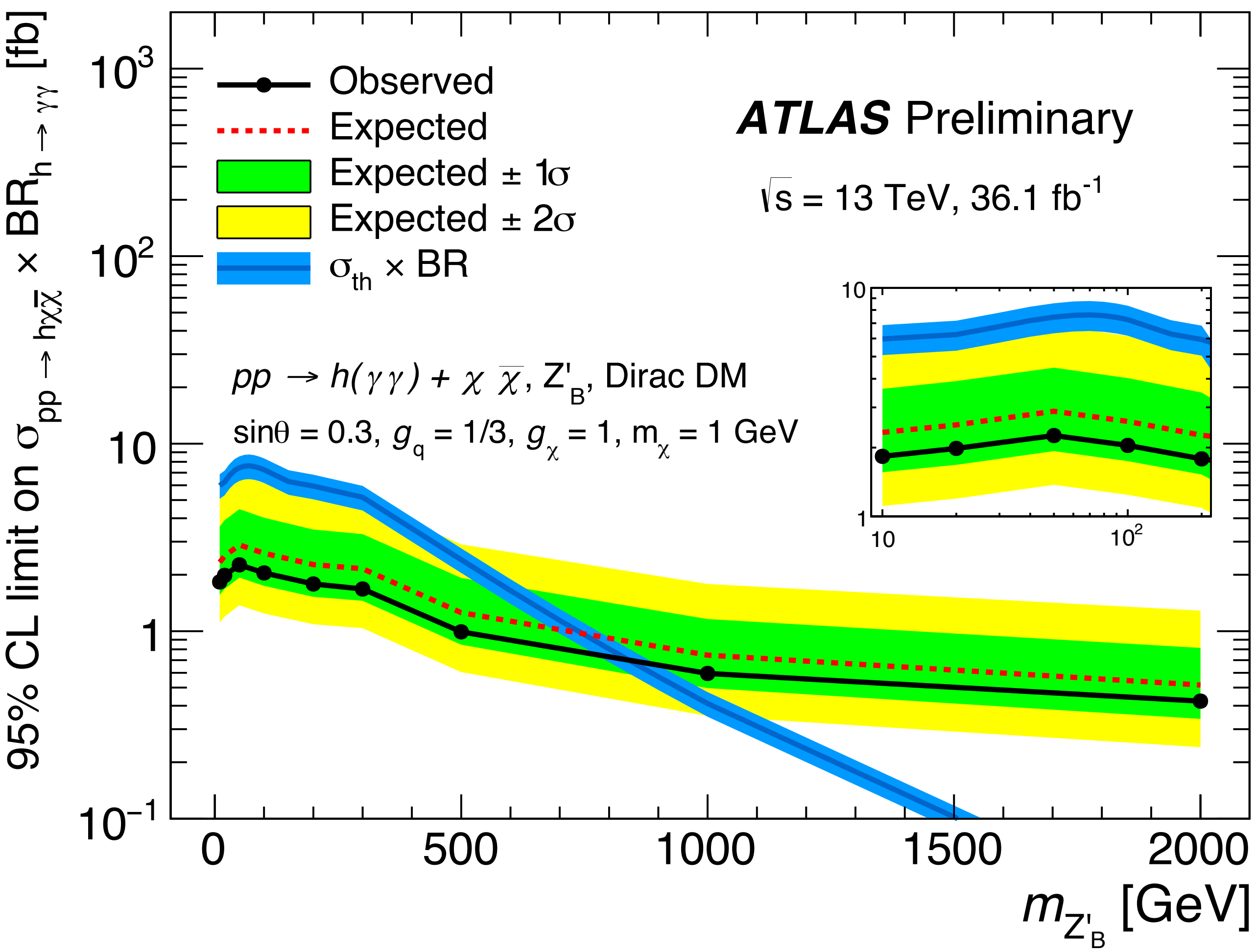
Event Selection		
Exactly one ee or $\mu\mu$ pair		
$p_T(e/\mu) > 30(20)$ GeV for leading (sub-leading) lepton		
Selection	**High Mass**	**Low Mass**
$\|m_{ll} - m_Z\|$	< 15 GeV	
E_T^{miss}	> 120 GeV	> 90 GeV
$\Delta R_{\ell\ell}$	< 1.8	
$\| \Delta\phi(\vec{p}_T^{\ell\ell}, \vec{E}_T^{miss}) \|$	> 2.7	
$\|p_T^{miss,jet} - p_T^{\ell\ell}\|/p_T^{\ell\ell}$	< 0.2	
$\| \Delta\phi(\vec{E}_T^{miss}, jets) \|$	> 0.4 $p_T(jet) > 100$ GeV	> 0.7 $p_T(jet) > 25$ GeV
$p_T^{\ell\ell}/m_T$	< 0.7	< 0.9
Number of b-jets	$= 0$	

Low Mass Signal Region	ee	$\mu\mu$
Data	220	236
Signals		
ZH (m_H = 125 GeV) with BF($H \to$ invisible)=100%	40.5 ± 1.2 ± 4.1	41.7 ± 1.2 ± 4.4
Mono-Z (m_χ = 1 GeV, m_{med} = 10 GeV)	175 ± 24 ± 14	169 ± 21 ± 22
Mono-Z (m_χ = 50 GeV, m_{med} = 300 GeV)	43.7 ± 2.3 ± 2.8	49.1 ± 2.6 ± 4.2
Backgrounds		
$qqZZ$ (MC-based)	95.0 ± 1.5 ± 5.8	102.1 ± 1.6 ± 8.0
$ggZZ$ (MC-based)	5.6 ± 0.1 ± 3.3	5.7 ± 0.1 ± 3.4
WZ (Data-driven)	44.0 ± 1.1 ± 3.3	50.5 ± 1.2 ± 3.3
$Z(\to ee, \mu\mu)$+jets (Data-driven)	23 ± 5 ± 11	16.9 ± 5.2 ± 6.7
non-resonant-$\ell\ell$ (Data-driven)	16.9 ± 2.8 ± 1.0	20.7 ± 3.4 ± 1.2
fake-lepton (Data-driven)	0.18 ± 0.04 ± 0.03	0.36 ± 0.46 ± 0.08
$t\bar{t}V/VVV$ (MC-based)	0.44 ± 0.02 ± 0.06	0.43 ± 0.02 ± 0.06
Total background	185 ± 6 ± 13	196 ± 7 ± 12

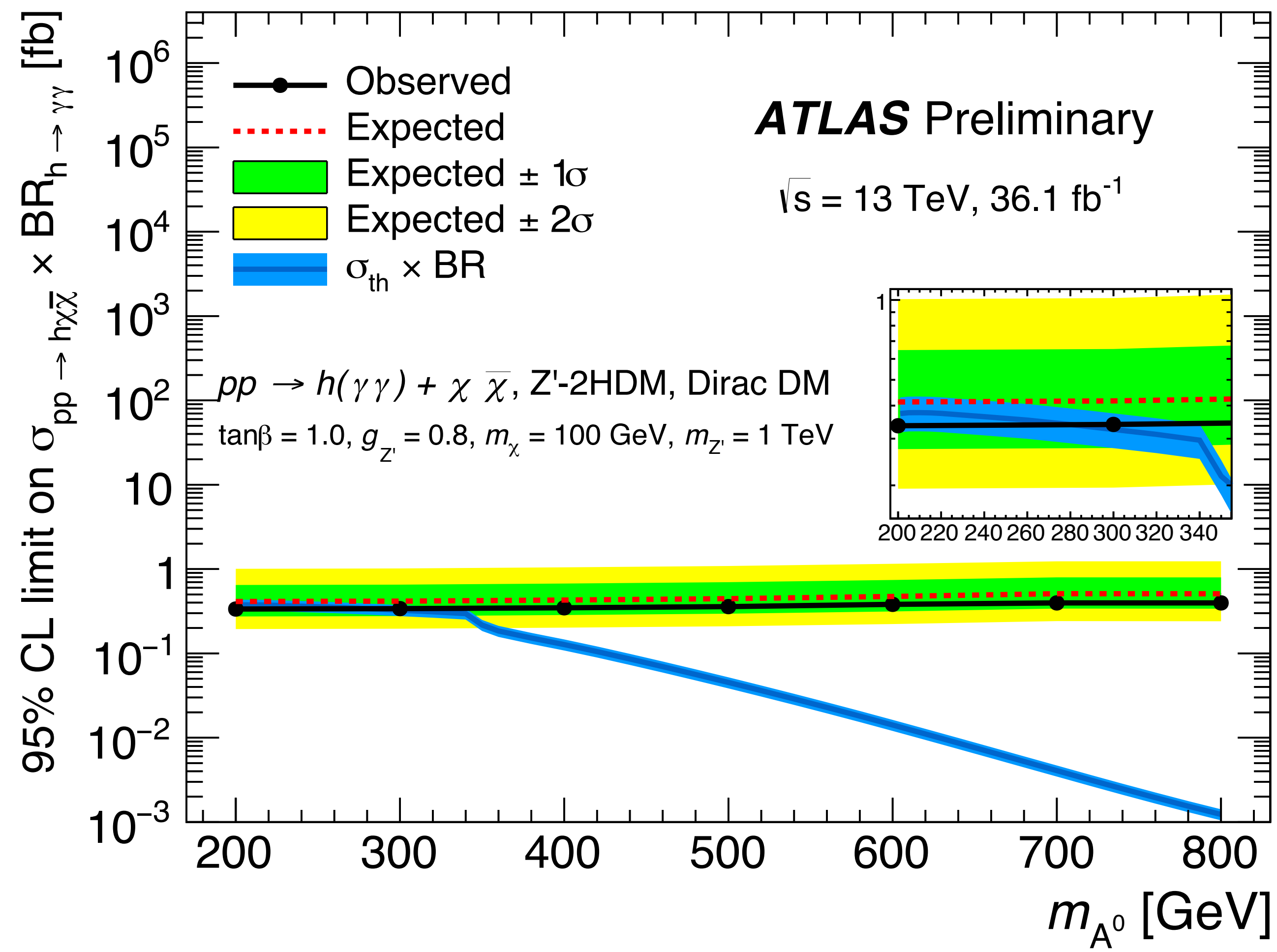
Mono-H($\gamma\gamma$)



Mono-H(γγ)



Observed
Expected
Expected ± 1σ
Expected ± 2σ
σth × BR
ATLAS Preliminary
√s = 13 TeV, 36.1 fb-1
pp → h(γγ) + χ χ̄, Z'B, Dirac DM
sinθ = 0.3, gq = 1/3, gχ = 1, mχ = 1 GeV
95% CL limit on σpp → hχχ̄ × BRh → γγ [fb]
mZ'B [GeV]



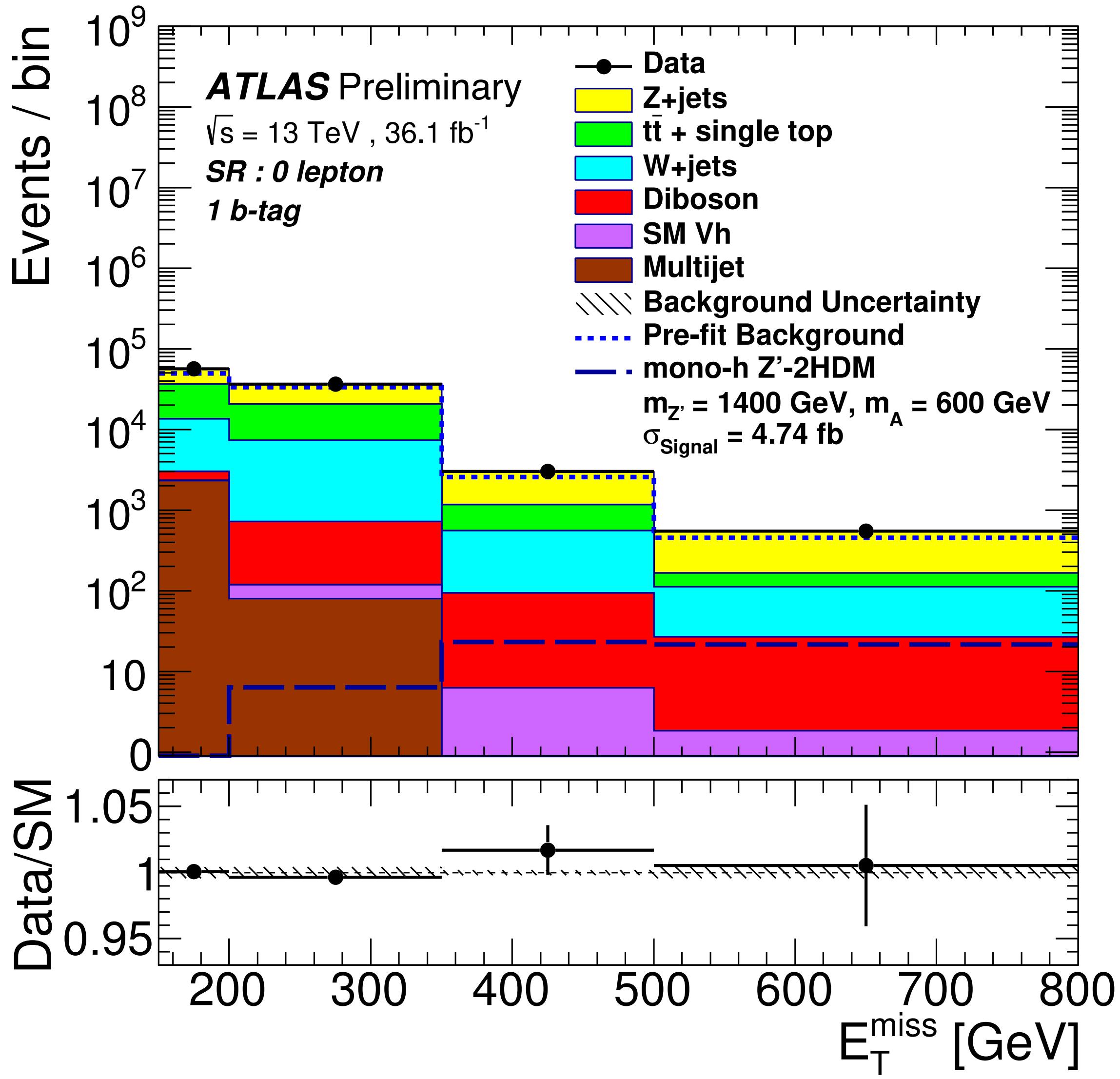
Observed
Expected
Expected ± 1σ
Expected ± 2σ
σth × BR
ATLAS Preliminary
√s = 13 TeV, 36.1 fb-1
pp → h(γγ) + χ χ̄, Z'-2HDM, Dirac DM
tanβ = 1.0, gZ' = 0.8, mχ = 100 GeV, mZ' = 1 TeV
95% CL limit on σpp → hχχ̄ × BRh → γγ [fb]
mA0 [GeV]

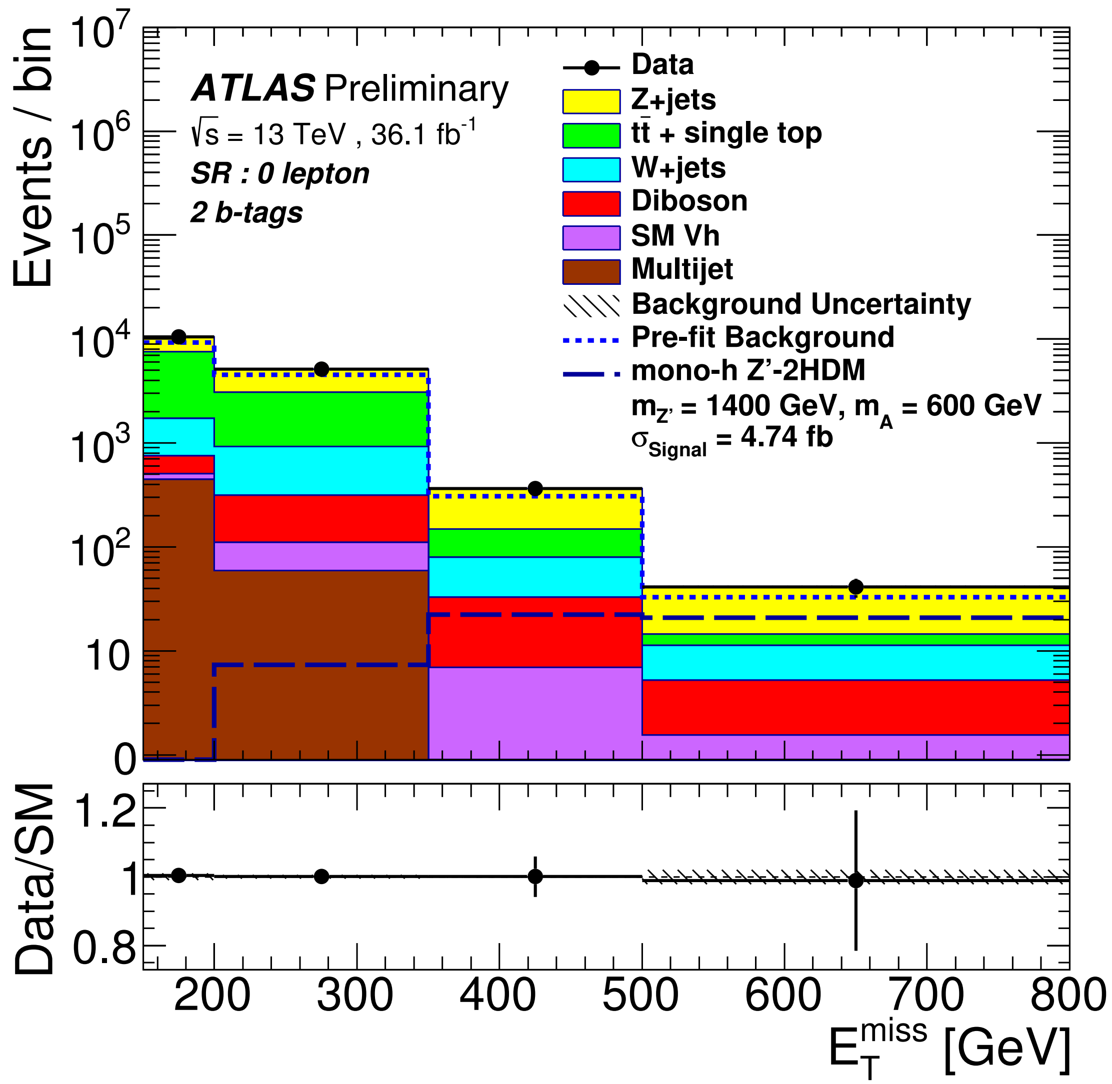
Mono-H(bb)

Table 3: A summary of the main analysis selection criteria. The notation $p_{\mathrm{T}}(A, B)$ used here is defined as the vector sum of the p_{T} for the objects A and B. For detailed descriptions of the selection criteria, please refer to the text body.

Region	SR	1μ-CR	2ℓ-CR
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single lepton
Leptons	No e or μ	Exactly one μ	Exactly two e or μ 83 GeV $< m_{ee} <$ 99 GeV 71 GeV $< m_{\mu^{\pm}\mu^{\mp}} <$ 106 GeV
Resolved	$E_{\mathrm{T}}^{\mathrm{miss}} \in [150, 500]$ GeV	$p_T(\mu, E_{\mathrm{T}}^{\mathrm{miss}}) \in [150, 500]$ GeV	$p_T(\ell, \ell) \in [150, 500]$ GeV
	$p_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV (1 b-tag only)	$p_T(\mu, p_{\mathrm{T}}^{\mathrm{miss}}) > 30$ GeV	–
	$\min\left[\Delta\phi\left(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_T^{\mathrm{jet}}\right)\right] > \pi/9$	$\min\left[\Delta\phi\left(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_T^{\mathrm{jet}}\right)\right] > \pi/9$	–
	$\Delta\phi\left(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}\right) < \pi/2$	$\Delta\phi\left(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}\right) < \pi/2$	–
	–	–	$E_{\mathrm{T}}^{\mathrm{miss}} \times \left(\sum_{\mathrm{jets,leptons}} p_T\right)^{-1/2} < 3.5\ \mathrm{GeV}^{1/2}$
	Number of central small-R jets ≥ 2		
	Leading Higgs candidate small-R jet $p_{\mathrm{T}} > 45$ GeV		
	$H_{T,2\,\mathrm{jets}} > 120$ GeV for 2 jets, $H_{T,3\,\mathrm{jets}} > 150$ GeV for > 2 jets		
	$\Delta\phi\left(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{T,h}\right) > 2\pi/3$		
	Veto on τ-leptons		
	$\Delta R\left(\vec{p}_h^{\mathrm{jet\,1}}, \vec{p}_h^{\mathrm{jet\,2}}\right) < 1.8$		
	Veto on events with > 2 b-tags		
	Sum of p_{T} of two Higgs candidate jets and leading extra jet $> 0.63 \times H_{T,\mathrm{all\,jets}}$		
	b-tagging : one or two small-R calorimeter jets		
	Final discriminant = Dijet mass		
Merged	$E_{\mathrm{T}}^{\mathrm{miss}} > 500$ GeV	$p_T(\mu, E_{\mathrm{T}}^{\mathrm{miss}}) > 500$ GeV	$p_T(\ell, \ell) > 500$ GeV
	$p_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV	$p_T(\mu, p_{\mathrm{T}}^{\mathrm{miss}}) > 30$ GeV	–
	$\min\left[\Delta\phi\left(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_T^{\mathrm{jet}}\right)\right] > \pi/9$	$\min\left[\Delta\phi\left(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_T^{\mathrm{jet}}\right)\right] > \pi/9$	–
	$\Delta\phi\left(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}\right) < \pi/2$	$\Delta\phi\left(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}\right) < \pi/2$	–
	Number of large-R jets ≥ 1		
	Veto on τ-lepton not associated to large-R jet		
	Veto on b-jets not associated to large-R jet		
	H_T-ratio selection ($<$0.57)		
	b-tagging : one or two ID track jets matched to large-R jet		
	Final discriminant = Large-R jet mass		

Mono-H(bb)


ATLAS Preliminary
√s = 13 TeV , 36.1 fb-1
SR : 0 lepton
1 b-tag
Data
Z+jets
tt̄ + single top
W+jets
Diboson
SM Vh
Multijet
Background Uncertainty
Pre-fit Background
mono-h Z'-2HDM
mZ' = 1400 GeV, mA = 600 GeV
σSignal = 4.74 fb
Events / bin
Data/SM
E_T^miss [GeV]


ATLAS Preliminary
√s = 13 TeV , 36.1 fb-1
SR : 0 lepton
2 b-tags
Data
Z+jets
tt̄ + single top
W+jets
Diboson
SM Vh
Multijet
Background Uncertainty
Pre-fit Background
mono-h Z'-2HDM
mZ' = 1400 GeV, mA = 600 GeV
σSignal = 4.74 fb
Events / bin
Data/SM
E_T^miss [GeV]

Mono-H(bb)

Table 2: Upper limits at 95% confidence level on the visible cross-section $\sigma_{\mathrm{vis},h+\mathrm{DM}}$ of h+DM events. The observed $\sigma^{\mathrm{obs}}_{\mathrm{vis},h+\mathrm{DM}}$ is consistent with the expectation $\sigma^{\mathrm{exp}}_{\mathrm{vis},h+\mathrm{DM}}$ within uncertainties. Also shown are the $\mathcal{A} \times \varepsilon$ values to reconstruct and select an event in the same $E_{\mathrm{T}}^{\mathrm{miss}}$ bin as generated.

Range in $E_{\mathrm{T}}^{\mathrm{miss}}$/GeV	$\sigma^{\mathrm{obs}}_{\mathrm{vis},h+\mathrm{DM}}$ [fb]	$\sigma^{\mathrm{exp}}_{\mathrm{vis},h+\mathrm{DM}}$ [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

Mono-H(4ℓ)

2015 Data (3.2 fb^{-1})

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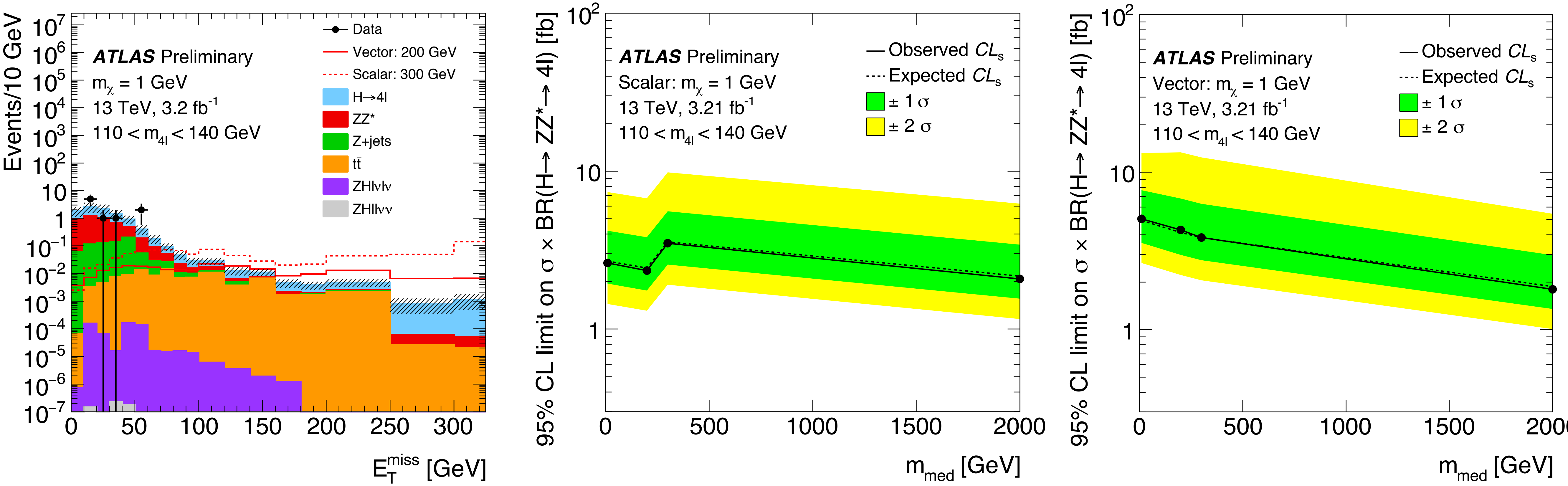

- Mono-H search using the 4ℓ decay. Limited by statistics, but offers a clean signature.
- No deviation from the SM prediction.
- Results are interpreted in terms of scalar/vector DM.