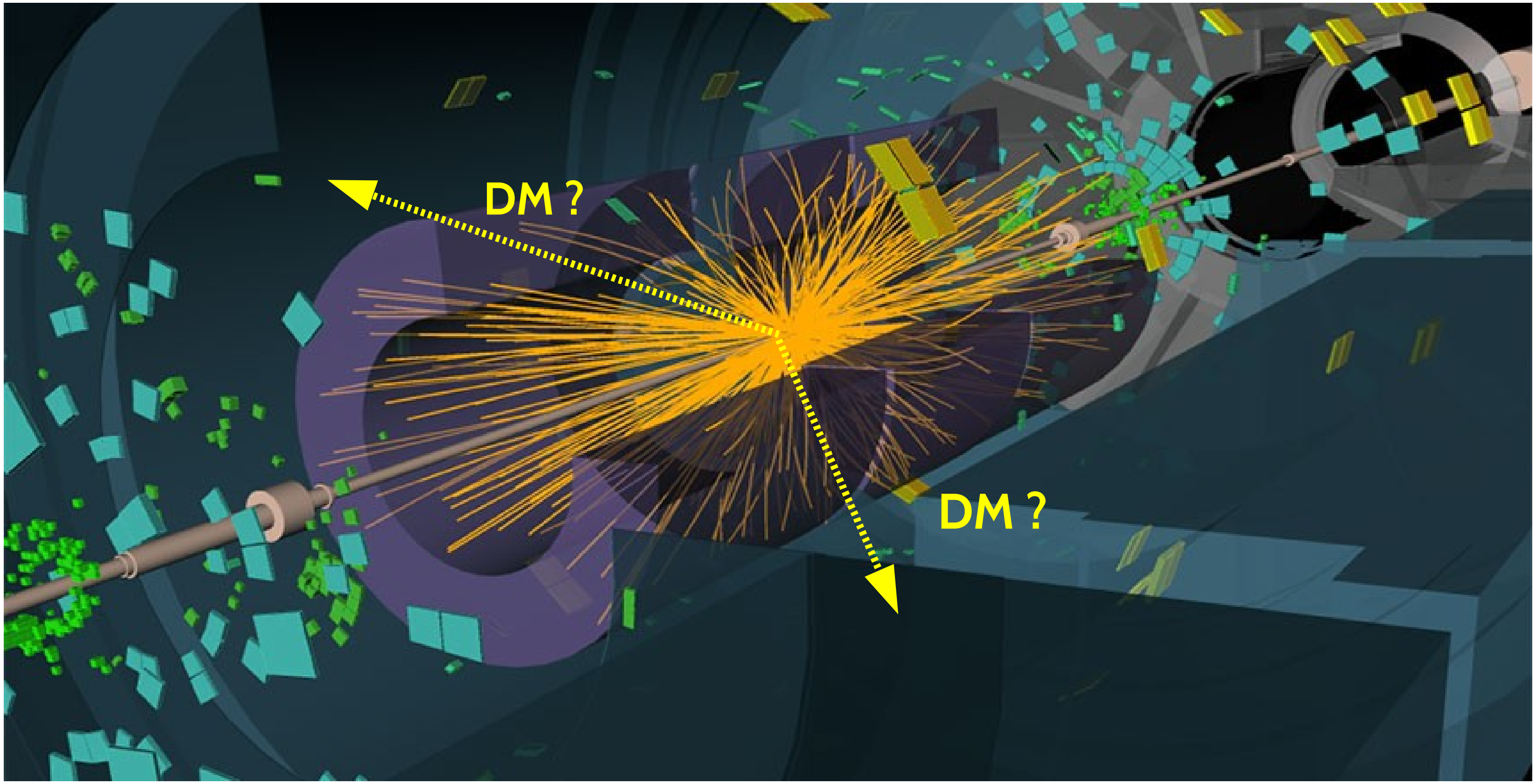
Mono-Higgs searches with the ATLAS detector



Alvaro Lopez Solis

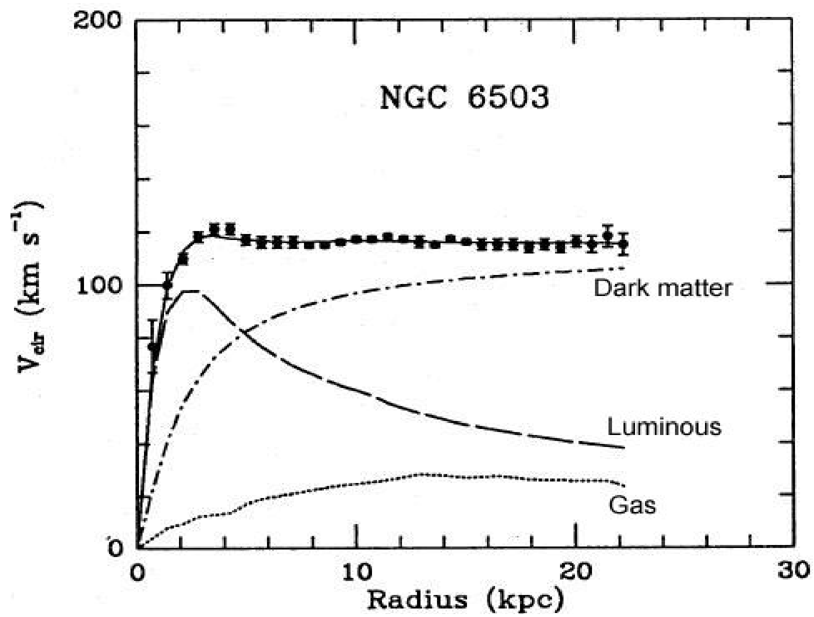
IRN Terascale - Marseille 2017

14th December 2017

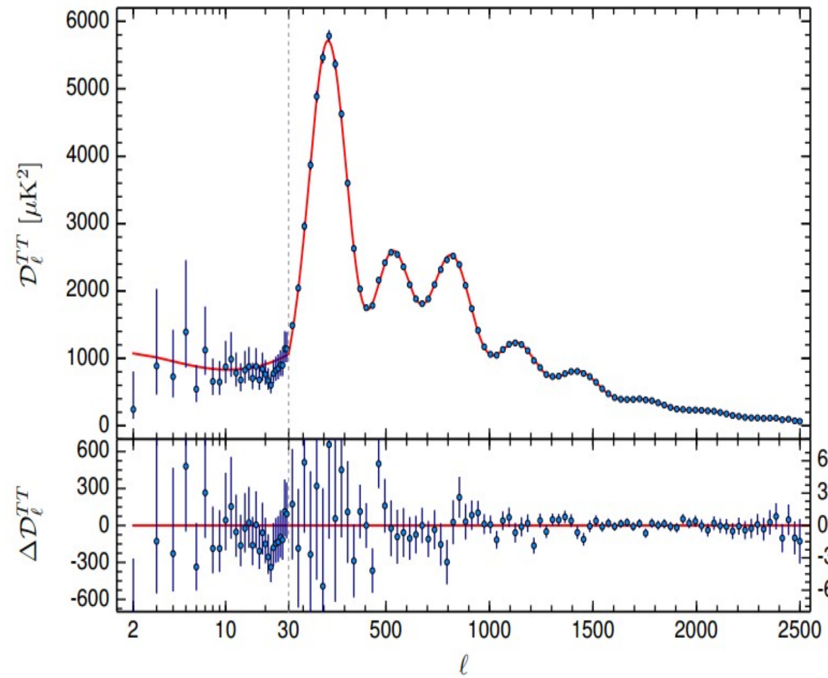
Dark matter

Expected from its gravitational influence observed at cosmological and galactic scale.

Rotation velocity in Andromeda



CMB temperature fluctuations



Bullet cluster

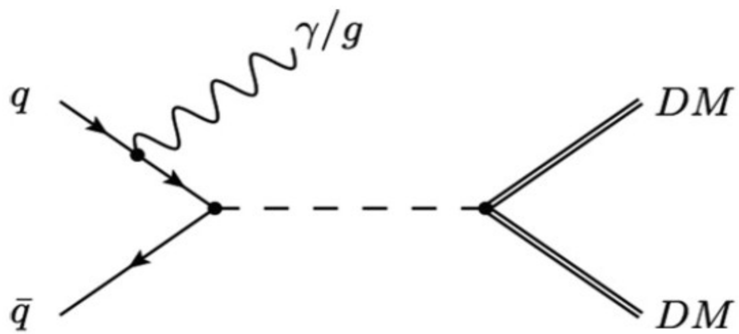
- Microscopic structure is unrevealed.
- Is it a particle? Primordial black holes? Large dark structures?

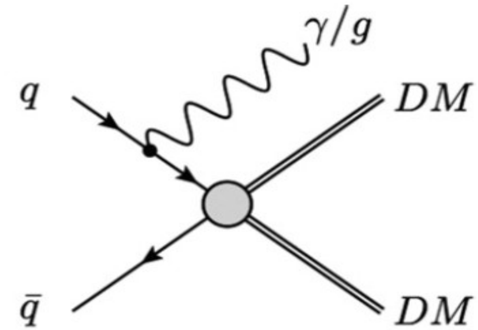
DM production at LHC: Mono-X

Signature: SM particles + large missing transverse momentum.

- Missing transverse momentum → Imbalance in transverse momentum distribution.
- SM particles: gluons, quarks, photons, Z, W and Higgs boson

- Mono-X production: one SM particle as tag of the interaction.
- Two possible interpretations: Effective field theories or simplified models.





$$\frac{g_q g_\chi}{Q_{tr}^2 - M^2} \approx -\frac{g_q g_\chi}{M^2}\left(1 + \frac{Q_{tr}^2}{M^2} + \mathcal{O}\left(\frac{Q_{tr}^4}{M^4}\right)...\right) \overset{M^2 \gg Q_{tr}^2}{\approx} -\frac{g_q g_\chi}{M^2} = -\frac{1}{\Lambda^2}$$

Simplified models: DM-SM interaction through a mediator:
→ Predictions are valid up to high energies.
→ Model-dependent results

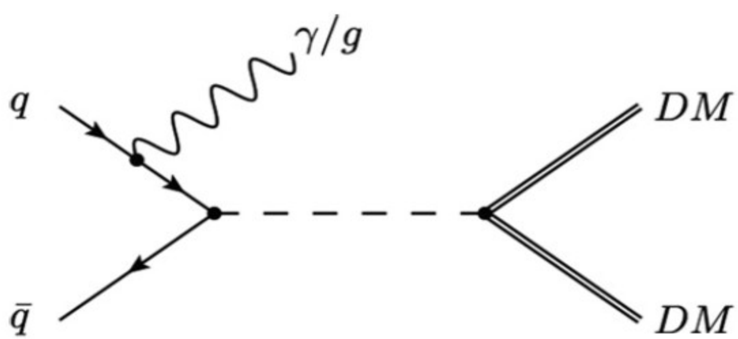
EFT: contact interaction (neglecting terms in expansion beyond scale Λ)
→ Predictions valid at collision energies below Λ.
→ Model-independent results

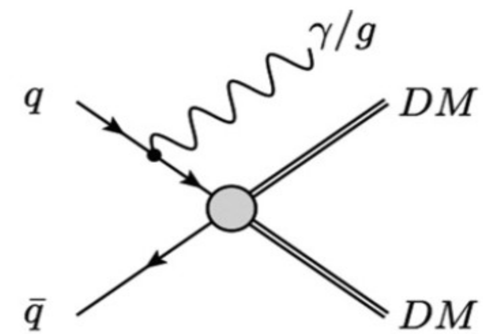
DM production at LHC: Mono-X

Signature: SM particles + large missing transverse momentum.

- Missing transverse momentum → Imbalance in transverse momentum distribution.
- SM particles: gluons, quarks, photons, Z, W and Higgs boson

- Mono-X production: one SM particle as tag of the interaction.
- In Run I, effective field theories and simplified models were used.





$$\frac{g_q g_\chi}{Q_{tr}^2 - M^2} \approx -\frac{g_q g_\chi}{M^2}\left(1+\frac{Q_{tr}^2}{M^2}+\mathcal{O}\left(\frac{Q_{tr}^4}{M^4}\right)\ldots\right) \overset{M^2 \gg Q_{tr}^2}{\approx} -\frac{g_q g_\chi}{M^2} = -\frac{1}{\Lambda^2}$$

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- SM particles: gluons, quarks, photons, Z, W and Higgs boson

- Mono-X production: one SM particle as tag of the interaction.
- In Run II, Dark Matter Forum defining benchmark simplified models.

arXiv:1507.00966v1 [hep-ex] 3 Jul 2015

Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum

July 6, 2015

Daniel Abercrombie *MIT, USA*
Nural Akchurin *Texas Tech University, USA*
Ece Akilli *Université de Genève, DPNC, Switzerland*
Juan Alcaraz Maestre *Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Spain*
Brandon Allen *MIT, USA*
Barbara Alvarez Gonzalez *CERN, Switzerland*
Jeremy Andrea *Institut Pluridisciplinaire Hubert Curien/Département Recherches Subatomiques, Université de Strasbourg/CNRS-IN2P3, France*
Alexandre Arbey *Université de Lyon and Centre de Recherche Astrophysique de Lyon, CNRS and Ecole Normale Supérieure de Lyon, France and CERN Theory Division, Switzerland*
Georges Azuelos *University of Montreal and TRIUMF, Canada*
Patrizia Azzi *INFN Padova, Italy*
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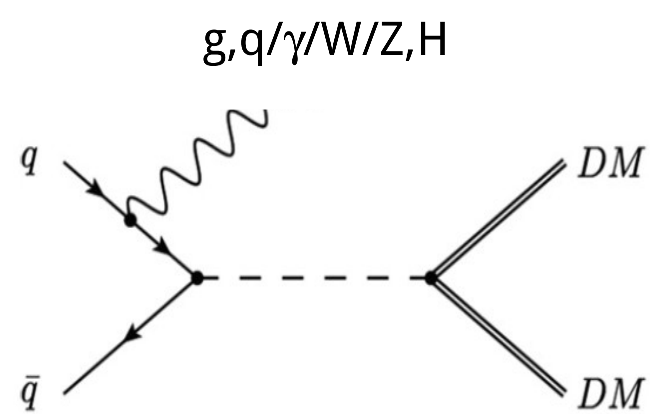
Yangyang Cheng *University of Chicago, USA*
John Paul Chou *Rutgers University, USA*
Arely Cortes Gonzalez *IFAE Barcelona, Spain*

SM particles produced as ISR.



arXiv:1507.00966

DM production at LHC: Mono-Higgs

Signature: SM particles + large missing transverse momentum.

- Missing transverse momentum → Imbalance in transverse momentum distribution.
- SM particles: gluons, quarks, photons, Z, W and Higgs boson

- Mono-X production: one SM particle as tag of the interaction.
  - SM particles produced as ISR.
  - Higgs boson couplings to quarks are weak

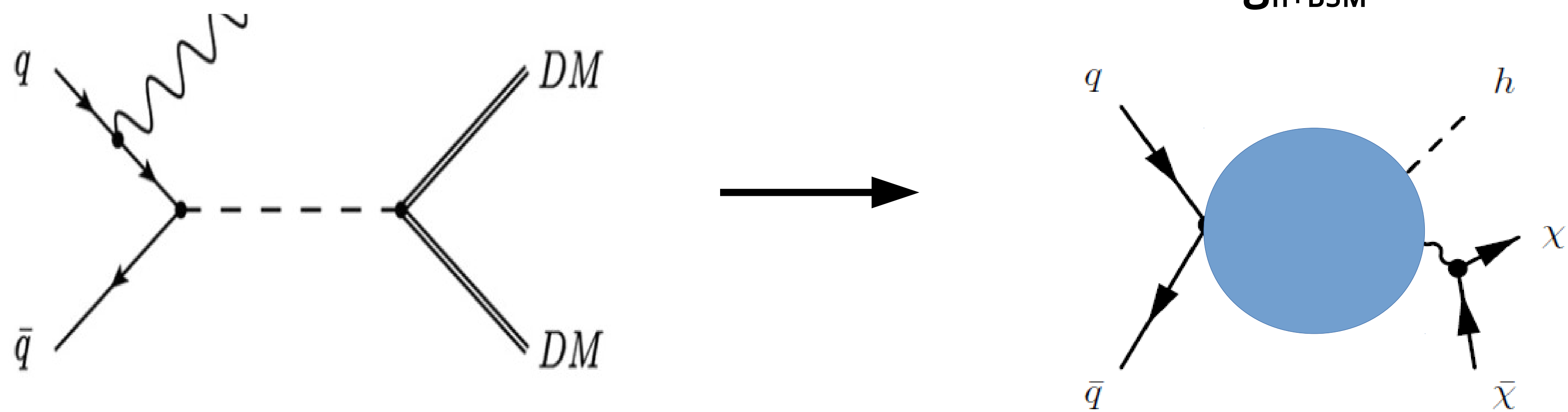
→ Direct probe of the Higgs+BSM interaction.

g/q/γ/W/Z,~~H~~

Suppressed

cross-section

g_{h+BSM} ?

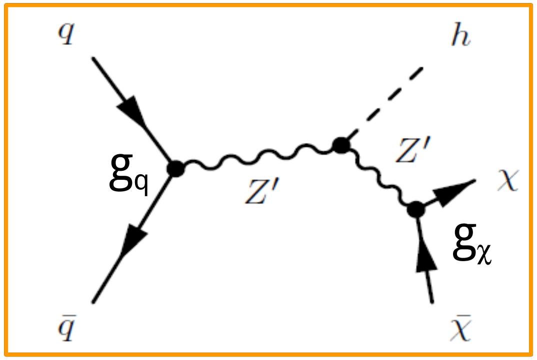


Two Higgs decays studied in ATLAS by now: h → γγ and h → $b\bar{b}$

Mono-Higgs searches: Simplified models

Three simplified models considered in the Mono-Higgs analyses:

- Vector mediator (Z'$_B$ model)



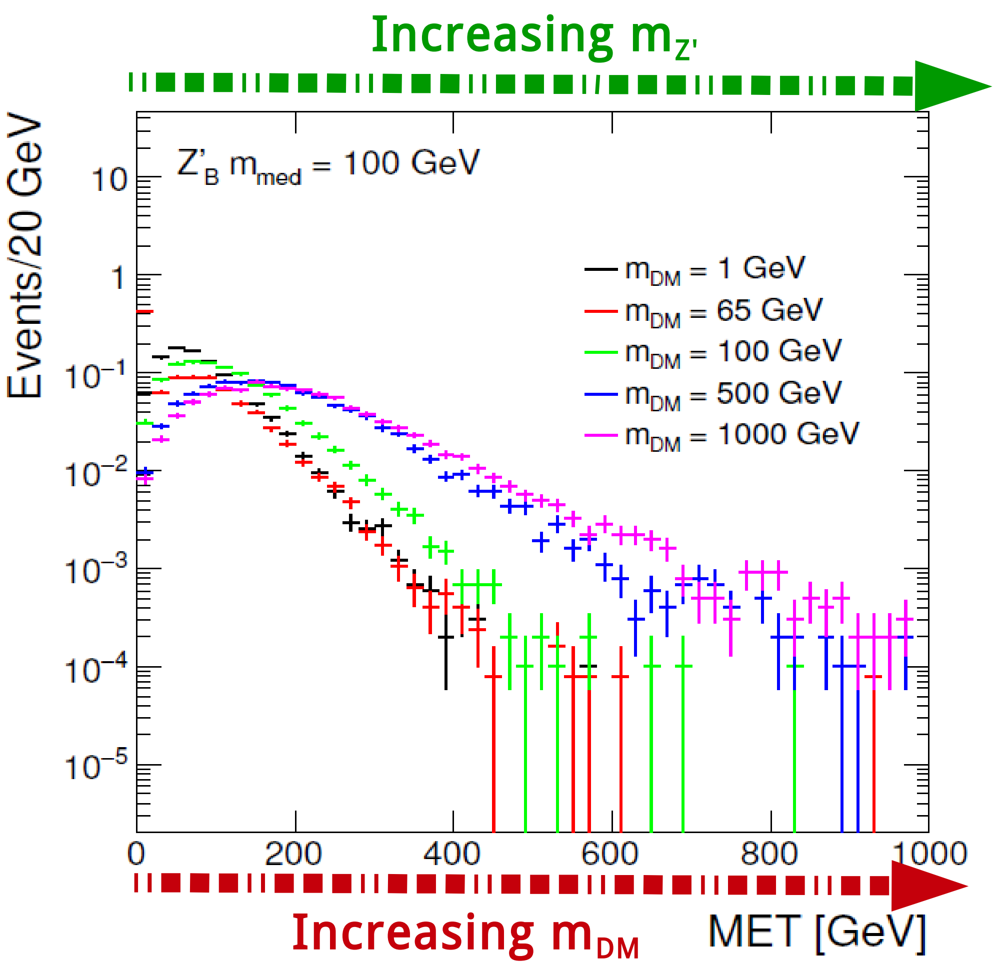
$$\mathcal{L} \supset \begin{array}{l} g_q \bar{q}\gamma^\mu q Z'_\mu + g_\chi \bar{\chi}\gamma^\mu \chi Z'_\mu . \\ + \frac{1}{2}\left(1 + \frac{h_B}{v_B}\right) Z'_{B,\mu} Z'^{\mu}_{B} \; m^2_{Z'_B} \end{array}$$

Relevant parameters

- Mass of the DM particle (m_{DM}).
- Mass of the mediator Z' ($m_{Z'}$).

Other parameters

- g_q = 1/3, g_χ=1 sinθ=0.3

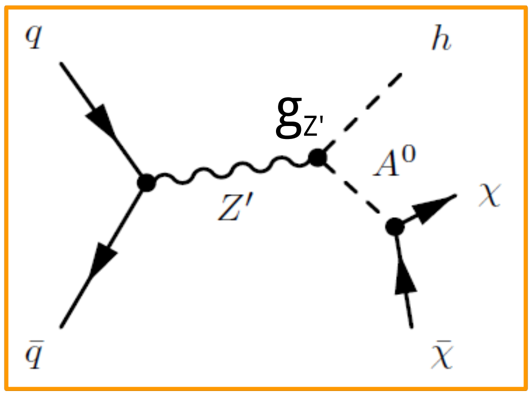


Phys Rev D.89.075017

Mono-Higgs searches: Simplified models

Three simplified models considered in the Mono-Higgs analyses:

- Vector mediator (Z'$_B$ model)
- Vector+Pseudoscalar (Z'-2HDM)



$$\mathcal{L} \supset y_u Q\tilde{\Phi}_u \bar{u} + y_d Q\tilde{\Phi}_d \bar{d} + y_e L\tilde{\Phi}_d \bar{e} + \mathrm{h.c.}$$

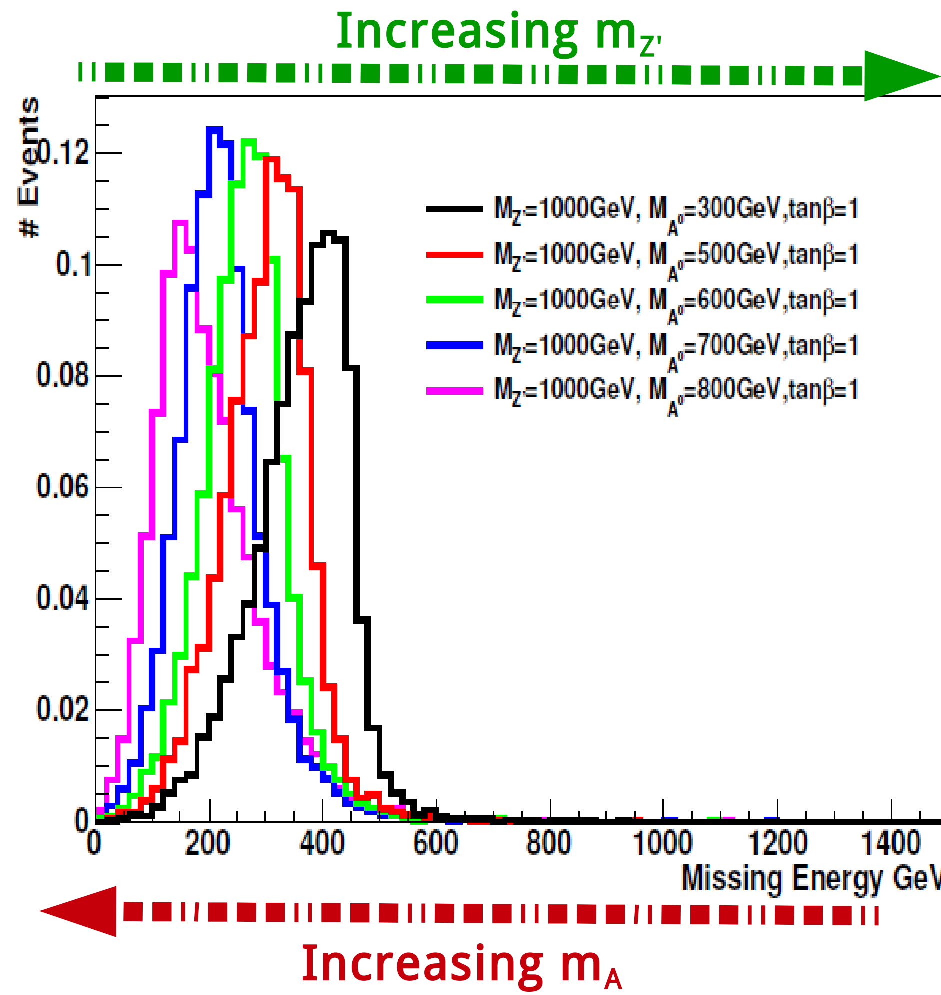
Type-II 2HDM

Relevant parameters

- Mass of the A boson (m_A).
- Mass of the mediator Z' ($m_{Z'}$).

Other parameters

- $g_{Z'}$ = 0.8., tanβ=v_u/v_d = 1, mDM = 100 GeV



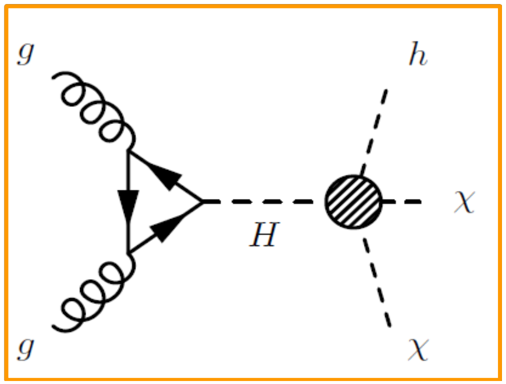
JHEP 06 (2014) 078

Mono-Higgs searches: Simplified models

Three simplified models considered in the Mono-Higgs analyses:

- Vector mediator (Z'$_B$ model)
- Vector+Pseudoscalar (Z'-2HDM)

In addition, a third model is considered with heavy scalar (HS) and an effective interaction.



$$\mathcal{L}_H = -\frac{1}{4}\beta_g \kappa_{hgg}^{SM} G_{\mu\nu}G^{\mu\nu}\mathrm{H} + \beta_V \kappa_{hVV}^{SM}\mathrm{H}V_\mu V^\mu$$

$$\mathcal{L}_Q = -\frac{1}{2}\lambda_{\mathrm{H}h\chi\chi}\mathrm{H}h\chi\chi$$

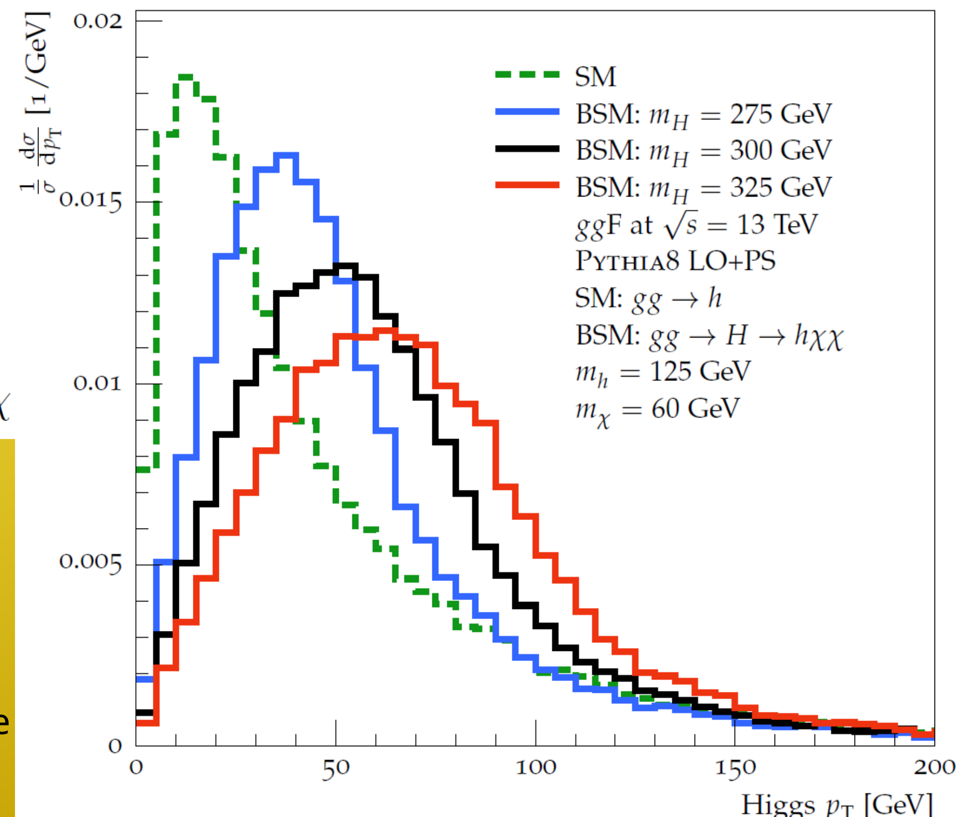
Relevant parameters

- Mass of the DM particle (m_{DM}).
- Mass of the mediator H (m_H).

Produced on ggF channel

Avoid invisible Higgs decays and H → tt to saturate decay width:

→ $2*m_h < m_H < 2*m_t$



EPJC. s10052-016-4435-8

PhysRevD.96.112004 (2017)

Mono-Higgs ($h \rightarrow \gamma\gamma$)

Diphoton decays of the Higgs boson:

- ATLAS good photon resolution
  - Allowing to use diphoton triggers
- Relatively low background.
- But, small branching ratio of the Higgs →
  Strong cuts for evidence

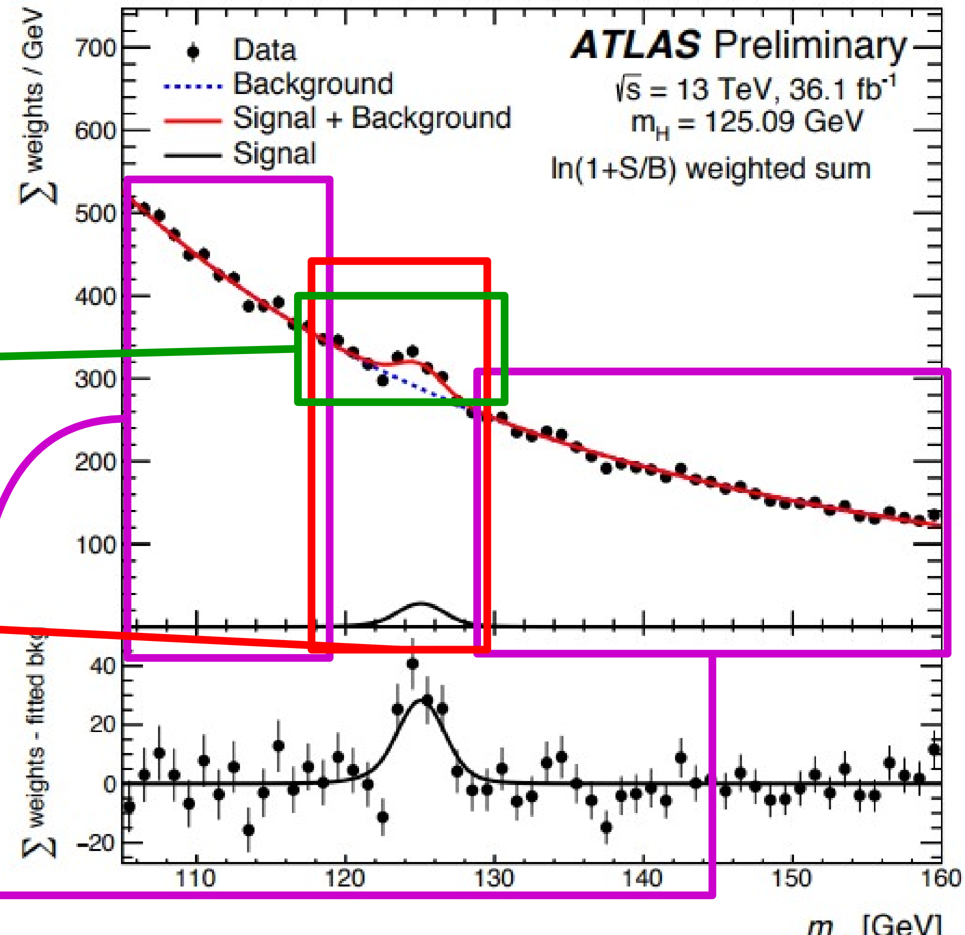
Signals using three Mono-Higgs models

- Z'_B and Z'-2HDM → boosted topologies (high $p_T^{\gamma\gamma}$ and high E_T^{miss})
- Heavy scalar, intermediate $p_T^{\gamma\gamma}$ and E_T^{miss}

DM+Higgs signal: excess of events beyond SM bkg around 125 GeV.

Resonant background (SM Higgs): peak around $m_{\gamma\gamma}$ = 125 GeV.

Non-resonant background ($\gamma\gamma$, γj, $V\gamma$, $V\gamma\gamma$): decreasing contribution along $m_{\gamma\gamma}$



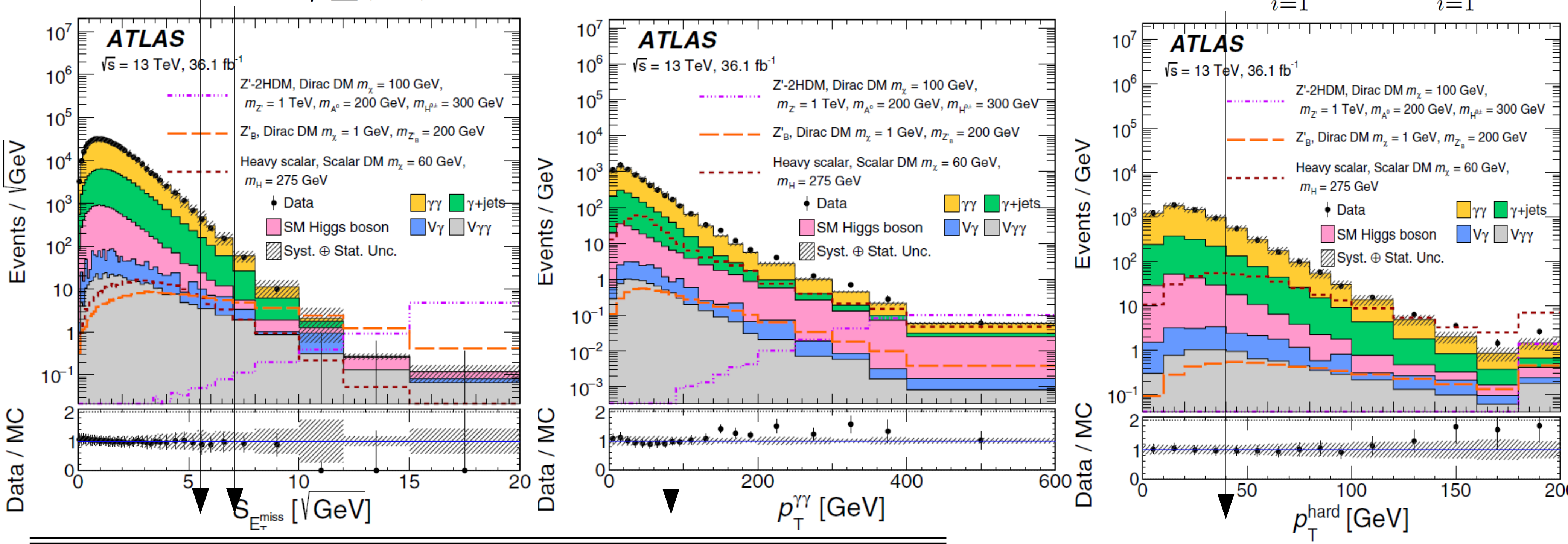
Mono-Higgs ($h\to\gamma\gamma$): Categorization

- Fake E_T^{miss} ($\gamma\gamma$, γj) backgrounds are highly reduced at large E_T^{miss} → Cut on E_T^{miss} significance.
- $V\gamma$, $V\gamma\gamma$ and VH backgrounds become important → Apply lepton veto
- Optimized cuts with $p_T^{\gamma\gamma}$ (boosted large p_T photons) and p_T^{hard} (sum of photons and jets p_T)

$$S_{E_T^{\rm miss}} = \frac{E_T^{\rm miss}}{\sqrt{\sum |E_T|}}$$

$$p_T^{\gamma\gamma} = |\vec{p}_T^{\,\gamma \rm lead} + \vec{p}_T^{\,\gamma \rm sublead}|$$

$$p_T^{\rm hard} = |\sum_{i=1}^{N_\gamma=2} \overrightarrow{p_{\rm T,i}}^{\gamma} + \sum_{i=1}^{N_{\rm jets}} \overrightarrow{p_{\rm T,i}}^{j}|$$



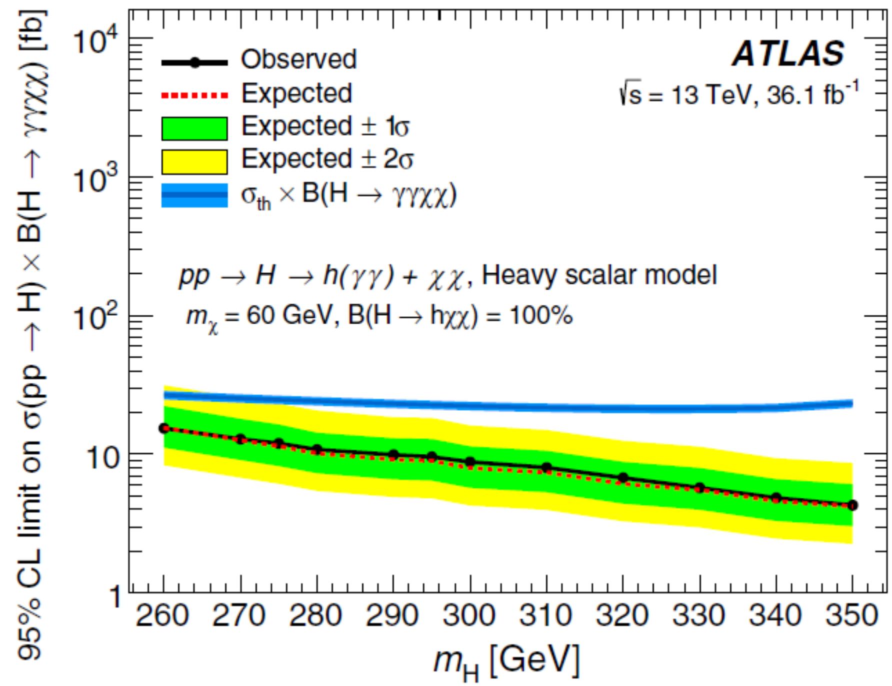
Category	Requirements
Mono-Higgs	$S_{E_T^{\rm miss}} > 7\ \sqrt{\rm GeV}$, $p_T^{\gamma\gamma} > 90$ GeV, lepton veto
High-$E_T^{\rm miss}$	$S_{E_T^{\rm miss}} > 5.5\ \sqrt{\rm GeV}$, $\lvert z_{\rm PV}^{\rm highest} - z_{\rm PV}^{\gamma\gamma}\rvert < 0.1$ mm
Intermediate-$E_T^{\rm miss}$	$S_{E_T^{\rm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

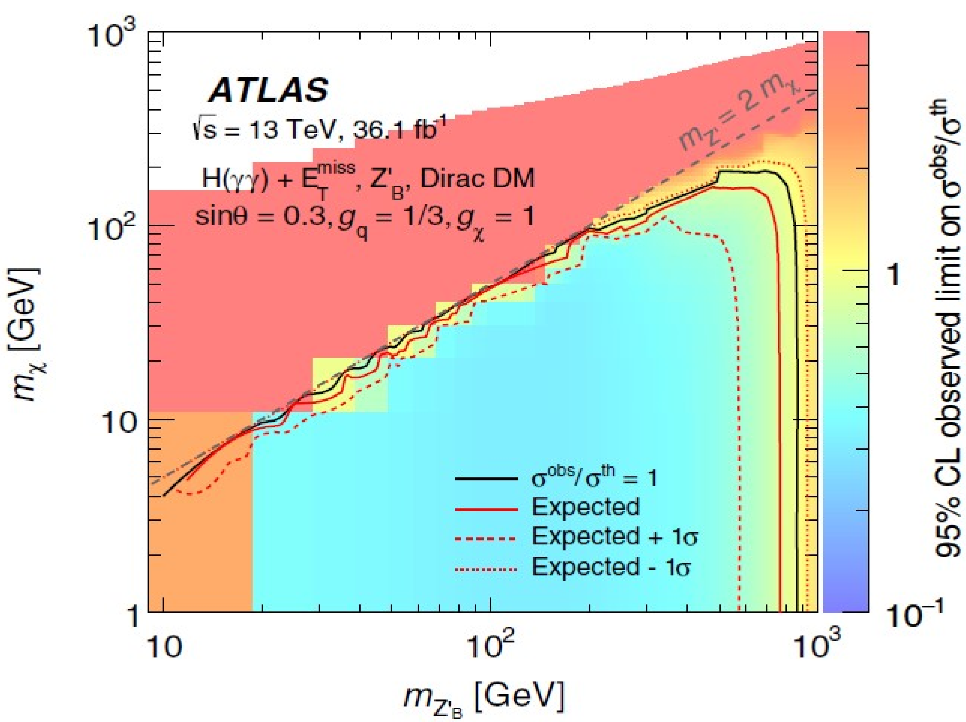
- Results from fits in these categories

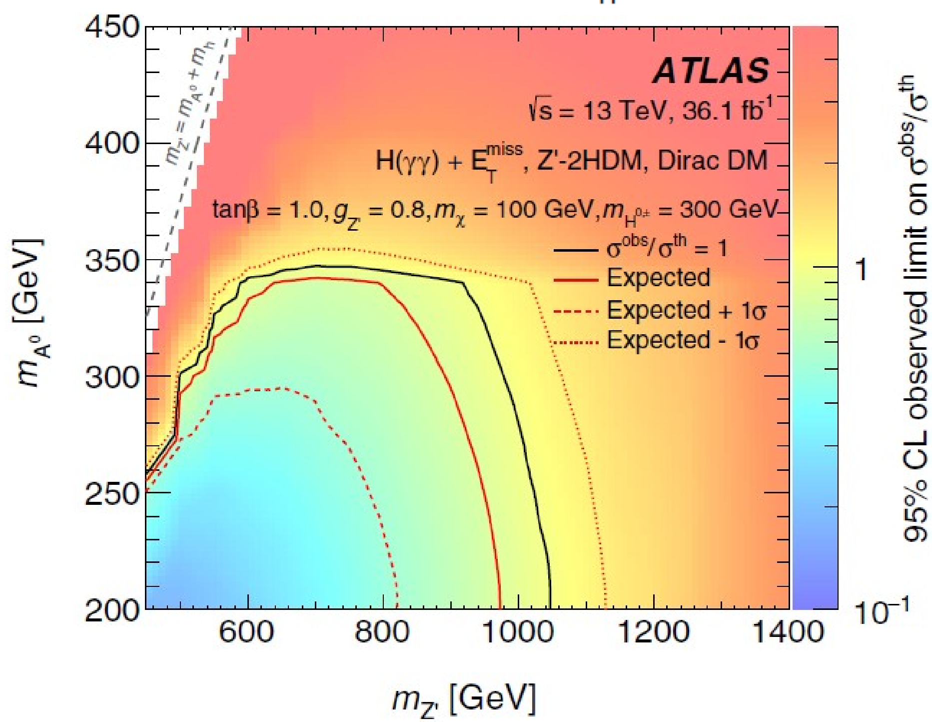
PhysRevD.96.112004 (2017)

Mono-Higgs ($h \rightarrow \gamma\gamma$): Results

- Results are derived from unbinned fit to the $m_{\gamma\gamma}$ distribution in categories
  - Fit on Mono-Higgs category for Z'_B and Z'-2HDM limits.
  - Simultaneous fit on all categories for HS limits.
- No significant excess is observed beyond the SM predictions
  - 95 %CL limits on the $\sigma^{exp}/\sigma^{theo}$ of models.
  - On-shell regions are constrained
  - HS model is fully excluded in the region considered







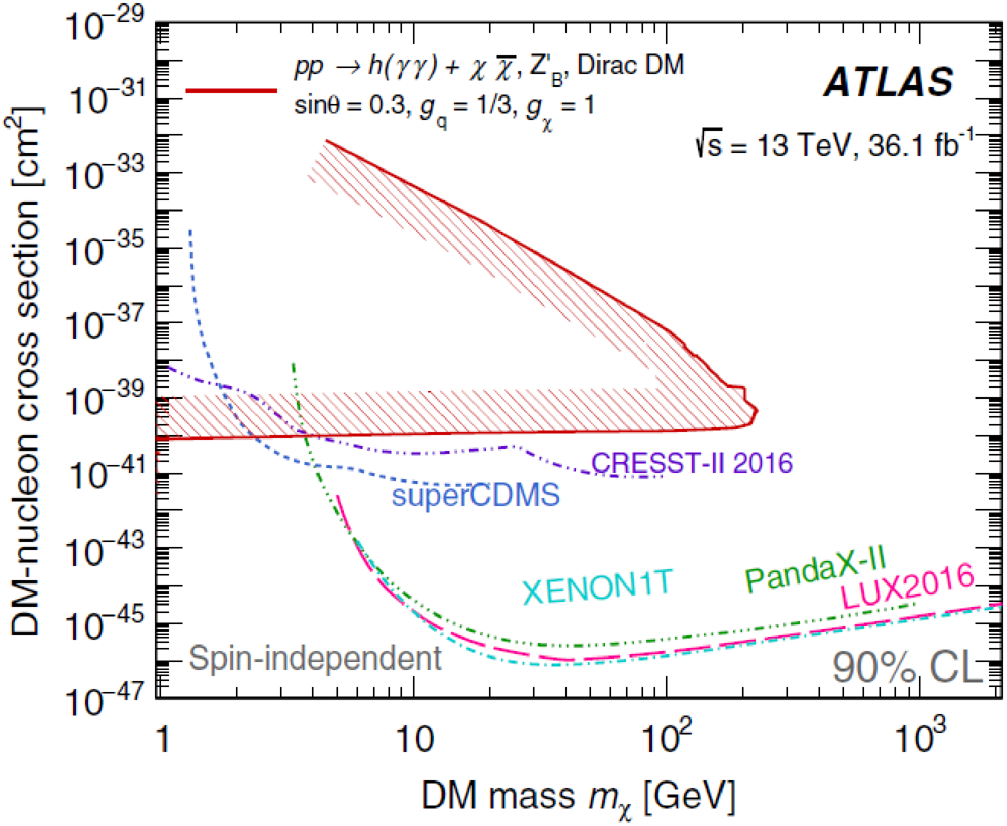
Mono-Higgs ($h \to \gamma\gamma$): Additional material

Z'_B model are translated into 90 % CL spin-independent limits.

- Sensitivity to low DM mass (if DM – SM governed by Z'_B)

Visible cross-section ($\sigma * \mathcal{A} * \varepsilon * \mathcal{B}r$) limits on the BSM signal are set

- Allow a better translation of limits to other theories.



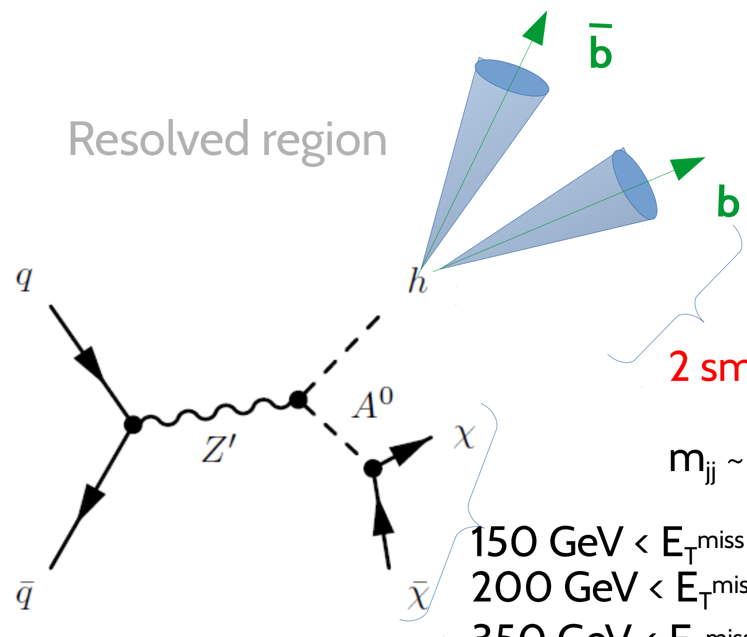
	σ_{vis}^{BSM} [fb]		$\mathcal{A} \times \epsilon$ [%]		
Category	Observed	Expected	Z'-2HDM	Z'_B	Heavy scalar
Mono-Higgs	0.19	$0.23^{+0.11}_{-0.07}$	53–74	15–63	1.0–4.0
High-E_T^{miss}	0.67	$0.52^{+0.23}_{-0.15}$	0.2–12	1.3–7.1	1.8–8.4
Intermediate-E_T^{miss}	1.6	$1.2^{+0.5}_{-0.3}$	0.05–5.0	0.6–5.5	3.9–6.6
Different-vertex	1.5	$2.5^{+1.1}_{-0.7}$	0.04–11	0.9–10	2.5–7.4
Rest	11	15^{+6}_{-4}	0.06–5.5	1.1–22	14–27

Phys Rev Lett.119.181804

Mono-Higgs($h \rightarrow b\bar{b}$)

Dominant decay of the Higgs boson:

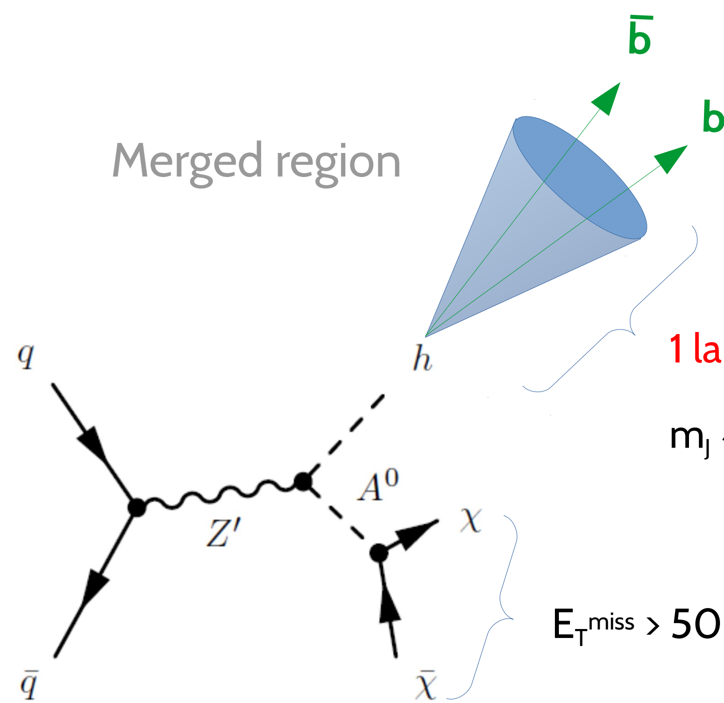
- Significant number of events is expected.
- Large QCD background → Trigger based on E_T^{miss}
  - $E_{T,onl}^{miss}$ > 110 GeV in most of data
- Using Z'-2HDM model (Z'$_B$ included in next results)



2 small-R jets

m_{jj} ~ 125 GeV

150 GeV < E_T^{miss} < 200 GeV
200 GeV < E_T^{miss} < 350 GeV
350 GeV < E_T^{miss} < 500 GeV



1 large-R jet

m_J ~ 125 GeV

E_T^{miss} > 500 GeV

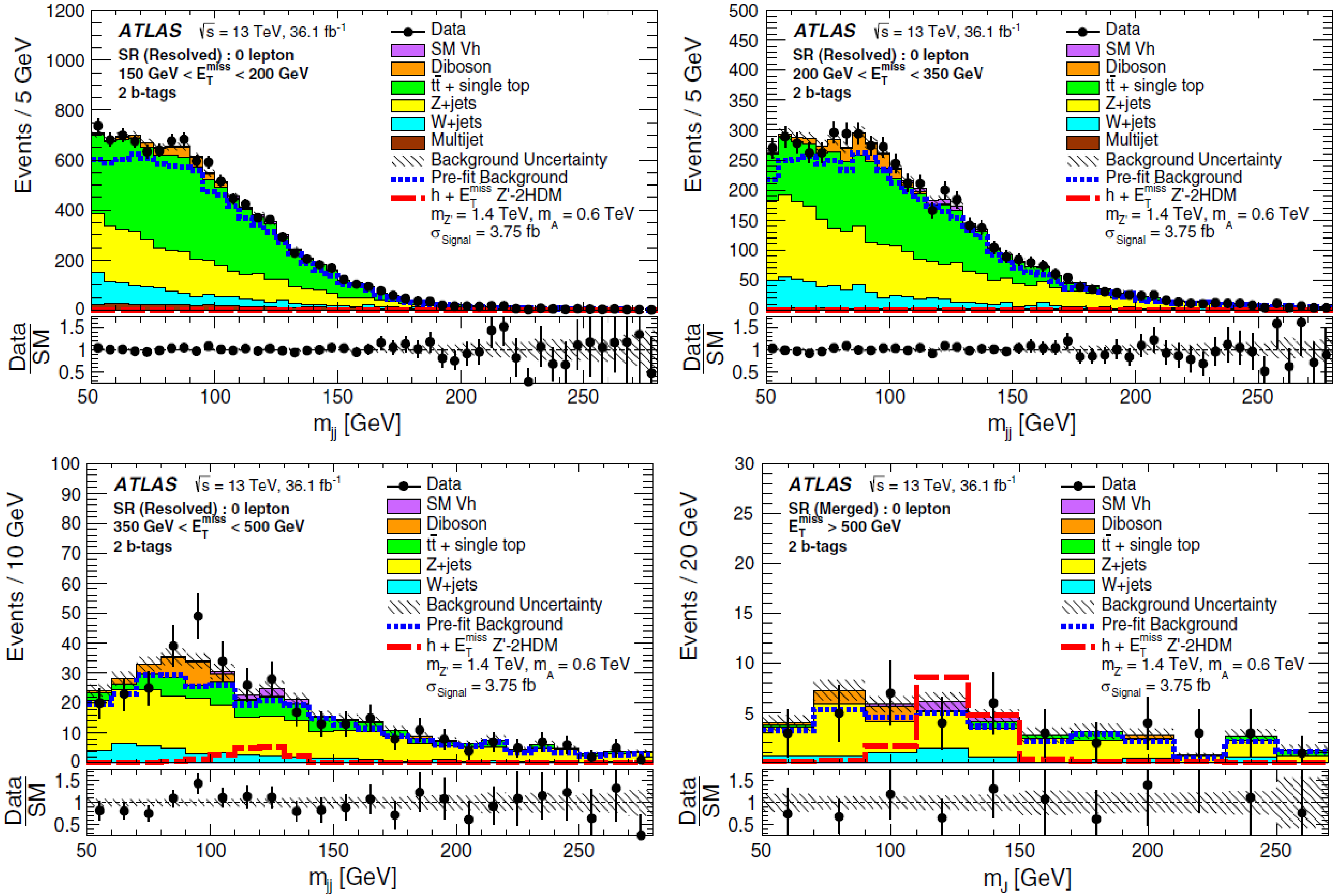
Using control regions (1-μ and 2-leptons) to get the different backgrounds:

- Z+jets (2-lepton CR)
- *tt*, W+jets (1-μ CR)
- Single top, VV, multijet backgrounds, Vh

Phys Rev Lett.119.181804

Mono-Higgs($h \to b\bar{b}$): Fit

- Simultaneous binned likelihood fit of signal regions and control regions.
- No excess over the SM is found.

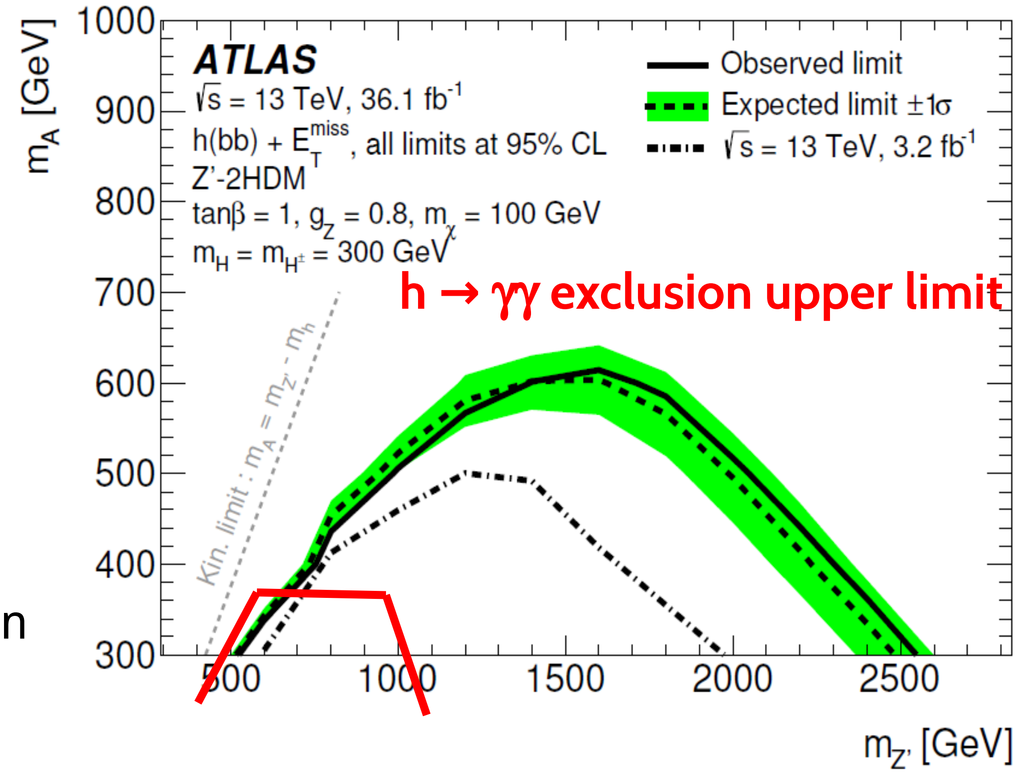


Mono-Higgs($h \to b\bar{b}$): Results

Phys Rev Lett.119.181804

95 % CL limits are set in the Z'-2HDM

- Larger region of the parameter space is excluded
  - Larger branching ratio and fit technique.
- Less sensitivity at low masses (E_T^{miss} trigger)
- Visible cross-section ($\sigma * \mathcal{A} * \varepsilon * \mathcal{B}r$) limits on the BSM signal are set



Range in E_T^{miss} [GeV]	$\sigma^{obs}_{vis,h(b\bar{b})+DM}$ [fb]	$\sigma^{exp}_{vis,h(b\bar{b})+DM}$ [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

Summary

The mono-Higgs results obtained by analyzing events collected by ATLAS have been presented

- Using pp collision taken during LHC Run II in 2015-2016 at 13 TeV of center-of-mass energy.

  Mono-Higgs to diphoton

  - No BSM excess is observed.
  - Limits are set in three benchmark models considered for interpretation.
  - Limits on the spin-independent WIMP-proton cross-section are also set, showing larger sensitivity than DD at low DM mass.

  Mono-Higgs to bb

  - No BSM excess is observed.
  - Limits are set on Z'-2HDM model. Large region of the parameter space below $m_{Z'} < 2.5$ TeV can be rejected.
  - In general, more sensitive than diphoton decay channel → Less sensitive at low $m_{Z'}$-m_A masses.
- Visible cross-section limits are set → Can be used to constrain other type of models.

Waiting for the 2017 data !

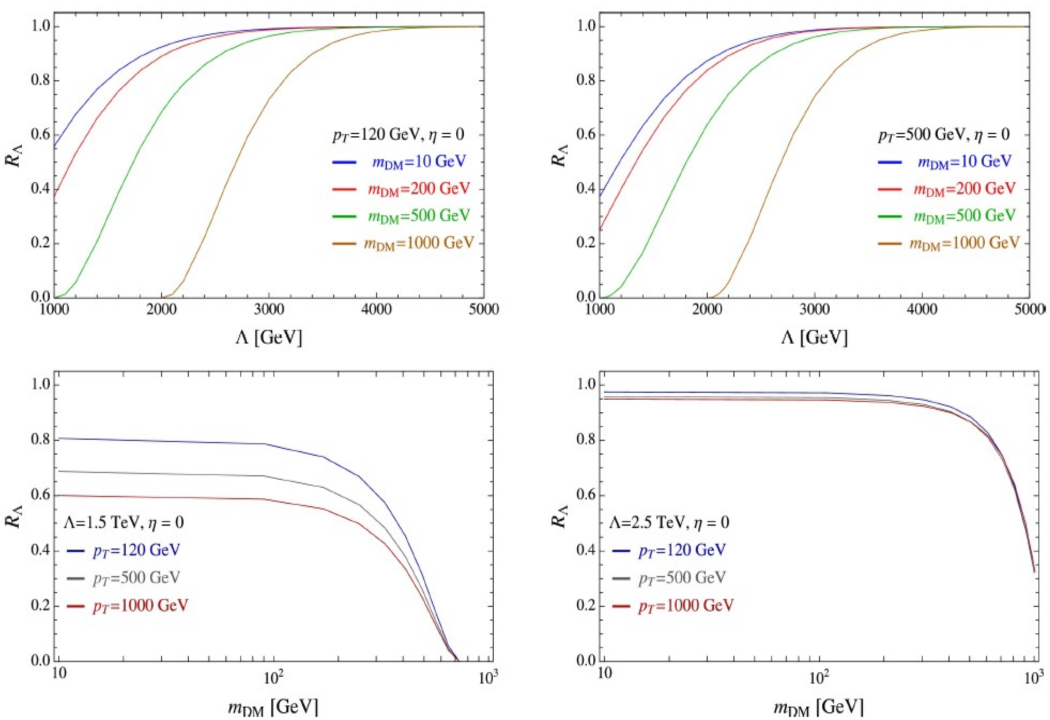
Thank you very much for your attention

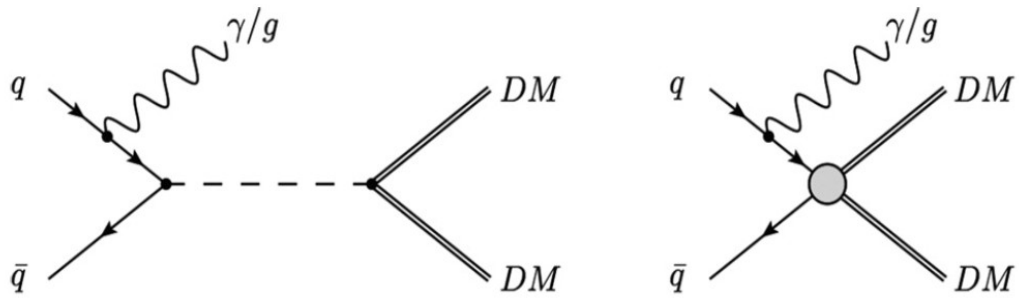
Back-up

Effective field theories vs simplified models

There are two ways to provide an extension to SM:

1. Effective field theories: direct interaction between SM and DM.
   1. Usually, non-renormalizable operators and valid up to a certain scale Λ → Theories valid at low energy.
   2. No assumption of the type of interaction between SM and DM → Model-independent results.
2. Simplified models: interaction of DM with SM is done either directly or through a mediator:
   1. Usually, renormalizable theories and UV-complete theories → Predictions are valid up to high energies.
   2. Interactions between DM, SM and mediators must be assumed → results are model-dependent.
3. Simplified models can be rewritten as EFTs by integrating out the mediator → These EFTs are valid for interactions at energies lower than the mediator mass.





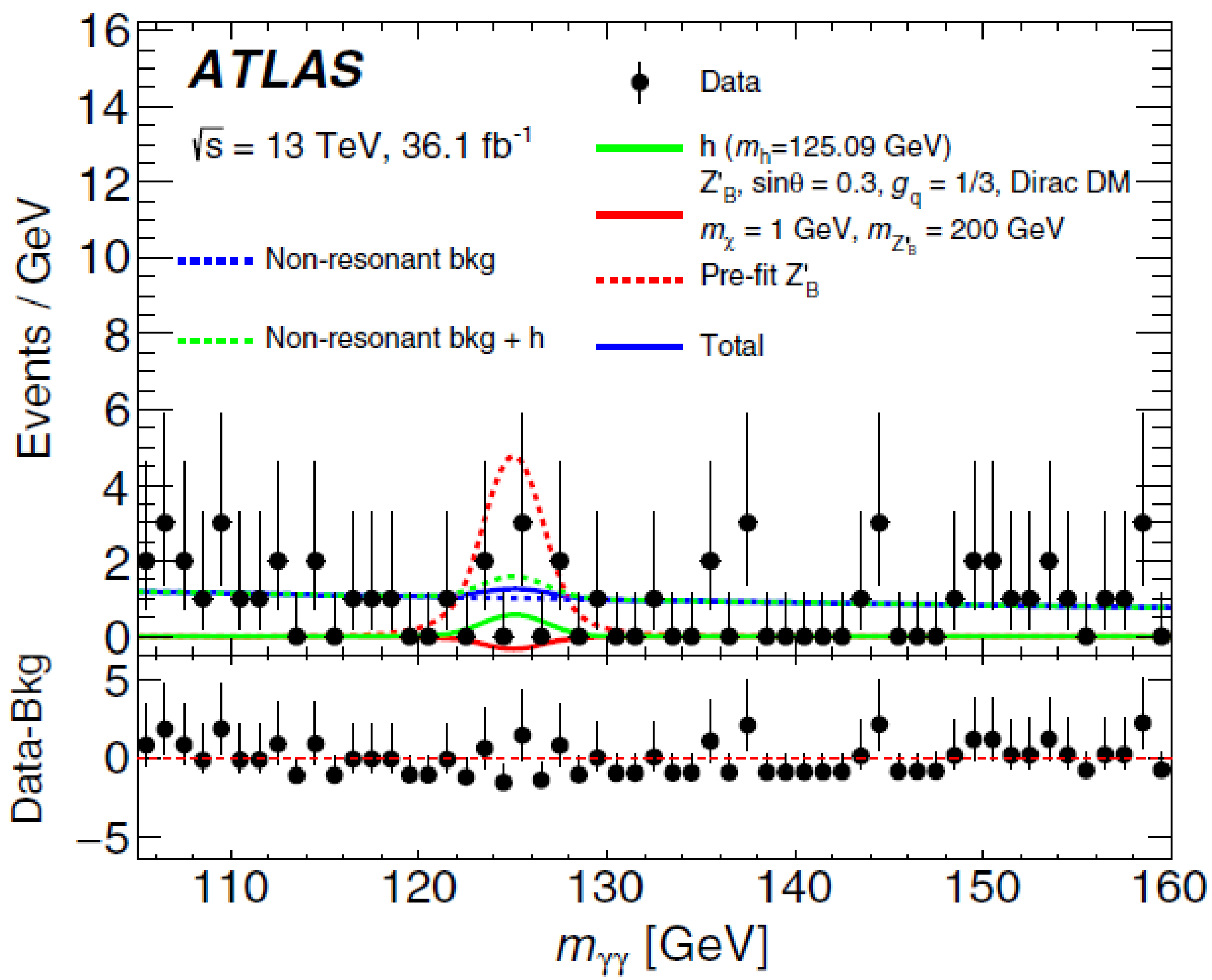
$$\frac{g_q g_\chi}{Q_{tr}^2 - M^2} \approx -\frac{g_q g_\chi}{M^2}\left(1+\frac{Q_{tr}^2}{M^2}+\mathcal{O}\left(\frac{Q_{tr}^4}{M^4}\right)\ldots\right) \overset{M^2 \gg Q_{tr}^2}{\approx} -\frac{g_q g_\chi}{M^2} = -\frac{1}{\Lambda^2}$$

$$R_\Lambda = \frac{\frac{d\sigma_{\mathrm{eff}}}{dp_{\mathrm{T}}\,d\eta}\Big|_{Q_{tr}<\Lambda}}{\frac{d\sigma_{\mathrm{eff}}}{dp_{\mathrm{T}}\,d\eta}}$$

Fit results: Mono-Higgs models

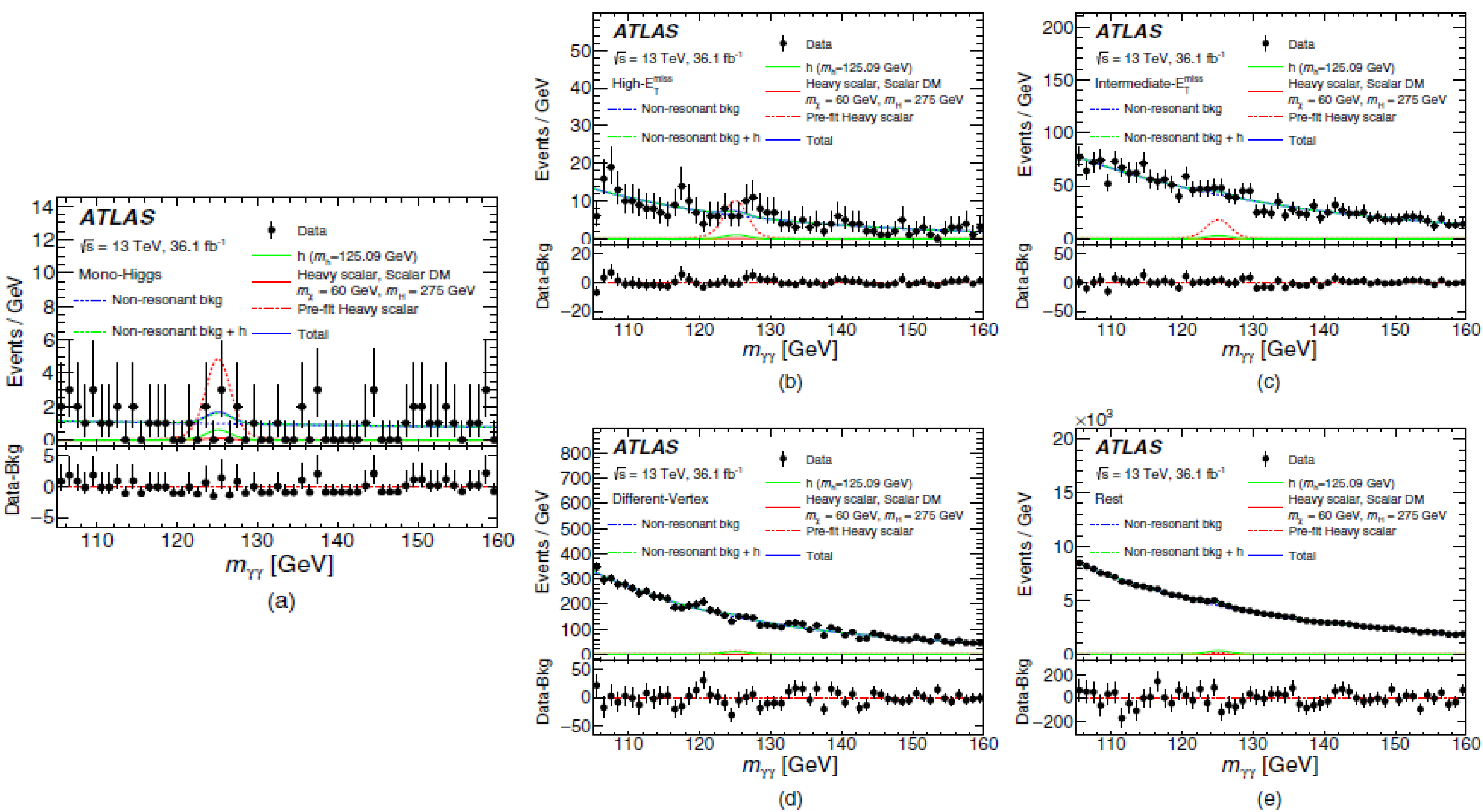
No significant excess is observed beyond the SM predictions

- Negative DM + Higgs contribution coming from a fluctuation of data.



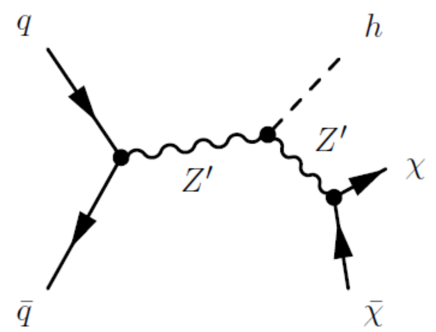
Fit results: Heavy scalar models

No significant excess is observed beyond the SM predictions

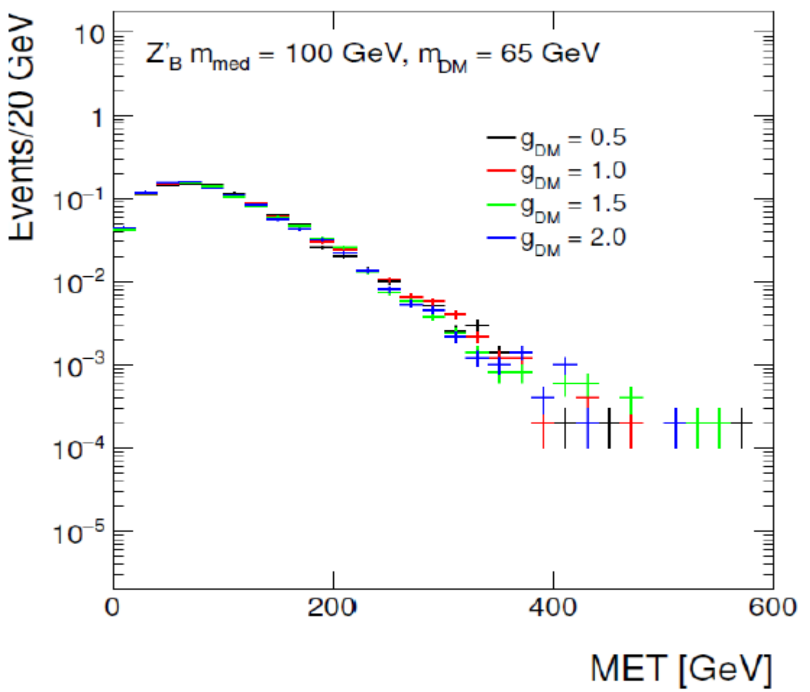


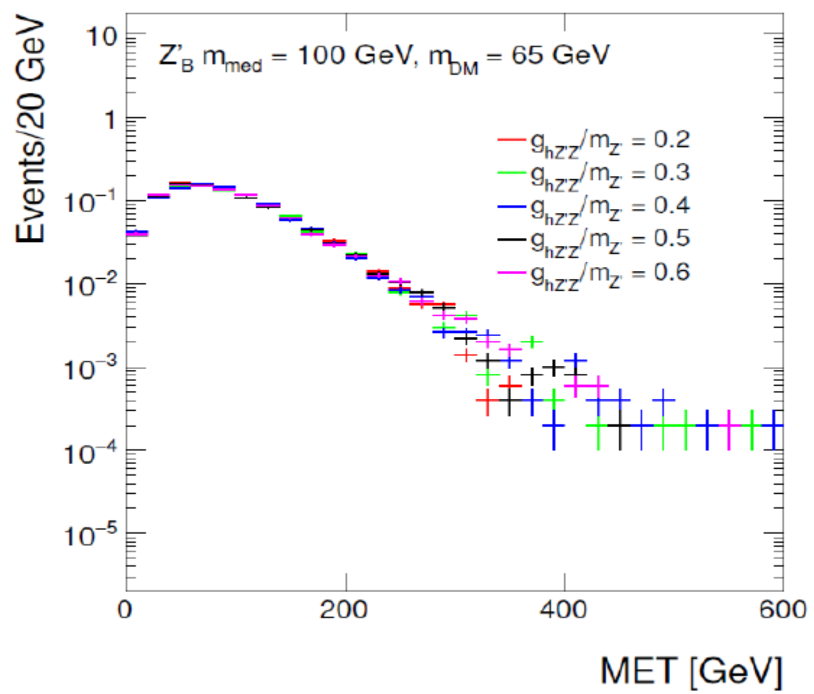
Z'$_B$ model

Vector mediator (Z'$_B$ model)



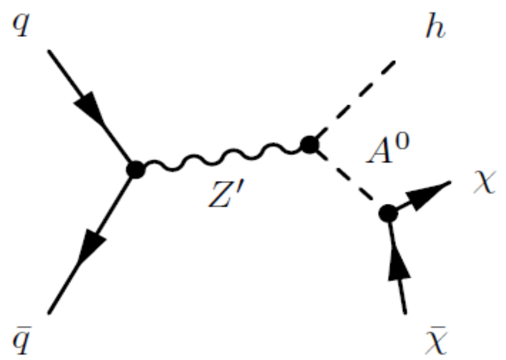
$$\mathcal{L} \supset g_q q \gamma^\mu q Z'_{B,\mu} + g_\chi \bar{\chi} \gamma^\mu \chi Z'_{B,\mu} + \frac{1}{2}\left(1 + \frac{h_B}{v_B}\right) Z'_{B,\mu} Z'^{\mu}_{B}\, m^2_{Z'_B}$$





Z'-2HDM model

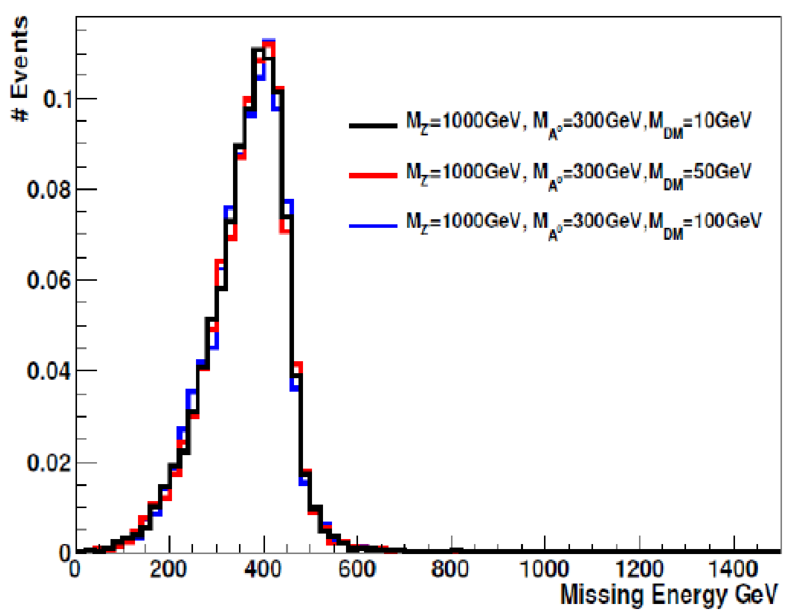
Vector+Pseudoscalar (Z'-2HDM)

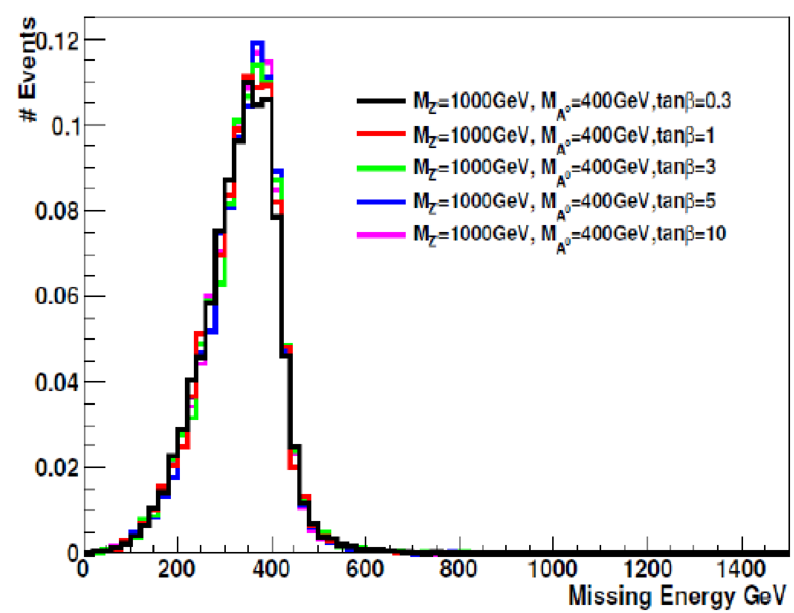


$$\Phi_{\rm u} = \frac{1}{\sqrt{2}}\begin{pmatrix} \cos\beta H^+ \\ v_u + \cos\alpha h + \sin\alpha H^0 + i\cos\beta A^0 \end{pmatrix}$$

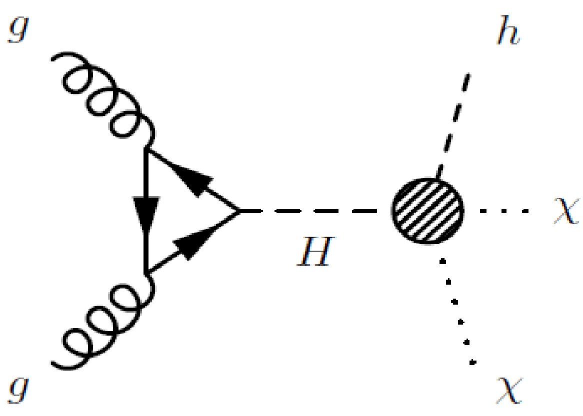
$$\Phi_{\rm d} = \frac{1}{\sqrt{2}}\begin{pmatrix} -\sin\beta H^+ \\ v_d - \sin\alpha h + \cos\alpha H^0 - i\sin\beta A^0 \end{pmatrix}$$

$$\mathcal{L} \supset y_u Q\tilde{\Phi}_u \bar{u} + y_d Q\tilde{\Phi}_d \bar{d} + y_e L\tilde{\Phi}_d \bar{e} + \text{h.c.}$$





Heavy scalar model

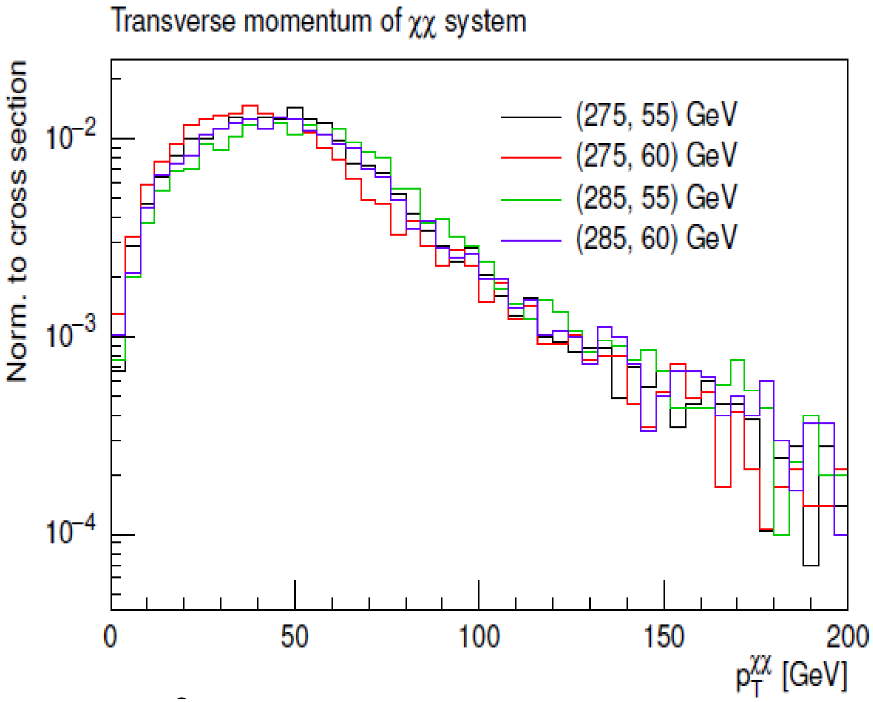


$$\mathcal{L}_H = -\frac{1}{4}\beta_g \kappa_{hgg}^{SM} G_{\mu\nu} G^{\mu\nu} \mathrm{H} + \beta_V \kappa_{hVV}^{SM} \mathrm{H} V_\mu V^\mu$$

$$\mathcal{L}_Y = -\frac{1}{\sqrt{2}} [g_{\mathrm{H}t\bar{t}} \mathrm{H} t\bar{t} + g_{\mathrm{H}b\bar{b}} \mathrm{H} b\bar{b}]$$

$$\mathcal{L}_T = -\frac{1}{\sqrt{2}} v [\lambda_{\mathrm{H}hh} \mathrm{H} hh + \lambda_{h\chi\chi} h\chi\chi + \lambda_{\mathrm{H}\chi\chi} \mathrm{H}\chi\chi]$$

$$\mathcal{L}_Q = -\frac{1}{2}\lambda_{\mathrm{H}h\chi\chi} \mathrm{H} h\chi\chi - \frac{1}{4}[\lambda_{\mathrm{HH}\chi\chi} \mathrm{HH}\chi\chi + \lambda_{hh\chi\chi} hh\chi\chi + \lambda_{\mathrm{HH}hh} \mathrm{HH}hh]$$



Object and event selection

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

Final categorization

After the optimization study, five categories are defined

Category	Requirements
Mono-Higgs	$S_{E_T^{miss}} > 7\sqrt{\text{GeV}}$, $p_T^{\gamma\gamma} > 90\,\text{GeV}$, lepton veto
High-E_T^{miss}	$S_{E_T^{miss}} > 5.5\sqrt{\text{GeV}}$, $\text{PV}^{\text{highest}} = \text{PV}^{\gamma\gamma}$
Intermediate-E_T^{miss}	$S_{E_T^{miss}} > 4\sqrt{\text{GeV}}$, $p_T^{\text{hard}} > 40\,\text{GeV}$, $\text{PV}^{\text{highest}} = \text{PV}^{\gamma\gamma}$
Different-Vertex	$S_{E_T^{miss}} > 4\sqrt{\text{GeV}}$, $p_T^{\text{hard}} > 40\,\text{GeV}$, $\text{PV}^{\text{highest}} \neq \text{PV}^{\gamma\gamma}$
Rest	$p_T^{\gamma\gamma} > 15$ GeV

Z'B and Z'-2HDM models: they present large significance in the Mono-Higgs category

1. Results are derived by fits only on this category

Heavy scalar model: it presents a significant number of events in all categories

1. Largest significance in the Intermediate-E_T^{miss} and High-E_T^{miss} category.
2. Results are derived by a simultaneous fit in all categories.

Expected and observed signals

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
Nonresonant	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
			Z'_B model, $m_{Z'_B} = 200$ GeV, $m_\chi = 1$ GeV		
Expected yields	20.0 ± 4.5	...	...	...	...
$\mathcal{A} \times \epsilon$ [%]	17.4 ± 0.2	...	...	...	...
			Z'-2HDM model, $m_{Z'} = 1000$ GeV, $m_{A^0} = 200$ GeV, $m_{H^{0,\pm}} = 300$ GeV, and $m_\chi = 100$ GeV		
Expected yields	28.0 ± 5.3	...	...	...	...
$\mathcal{A} \times \epsilon$ [%]	70.7 ± 0.2	...	...	...	...
			Heavy-scalar model, $m_H = 275$ GeV, $m_\chi = 60$ GeV		
Expected yields	10.9 ± 1.4	23.8 ± 3.2	43 ± 5	33 ± 5	222 ± 20
$\mathcal{A} \times \epsilon$ [%]	1.22 ± 0.07	2.67 ± 0.10	4.82 ± 0.14	3.65 ± 0.13	24.9 ± 0.4

Non-resonant background fitting functions

Category	Function	$\Delta N_{\text{bkg}}^{\text{nonres}}$	$\Delta N_{\text{bkg}}^{\text{nonres}}/N_{\text{bkg}}^{\text{nonres}}$ [%]	$\Delta N_{\text{bkg}}^{\text{nonres}}/N_{\text{signal}}$ [%]
Mono-Higgs	$\exp(a \cdot x)$	1.2	9.8	6.0
High-$E_{\text{T}}^{\text{miss}}$	$(1 - x^{1/3})^{b} \cdot x^{a}$	2.7	4.0	11
Intermediate-$E_{\text{T}}^{\text{miss}}$	$\exp(a \cdot x + b \cdot x^{2})$	5.8	1.3	14
Different-vertex	$\exp(a \cdot x + b \cdot x^{2})$	8.4	0.5	26
Rest	$\sum_{j=0}^{3} C_{3}^{j} x^{j} (1 - x)^{3-j} b_{j,3}$	61	< 0.1	28

Systematics

		Backgrounds [%]	
Source	Signals [%]	SM Higgs boson	Non-resonant background
Experimental			
Luminosity	3.2		⋯
Trigger efficiency	0.4		⋯
Vertex selection	< 0.1		⋯
Photon energy scale	0.1–2.0	0.1–1.4	⋯
Photon energy resolution	0.1–0.2	0.1–1.1	⋯
Photon identification efficiency	2.9–4.3	1.9–3.8	⋯
Photon isolation efficiency	1.2	0.8–1.6	⋯
$E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction (diphoton vertex)	< 0.1	0.5–1.9	⋯
$E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction (jets, soft term)	1.0–1.4	0.8–23	⋯
Diphoton vertex with largest Σp_{T}^2	< 0.1–1.9	< 0.1–6.0	⋯
Pileup reweighting	0.2–5.6	0.7–11	⋯
Non-resonant background modeling	⋯	⋯	0.1–9.8
Theoretical			
Factorization and renormalization scale	0.6–11	2.5–6.0	⋯
PDF + α_{S}	11–25	1.2–2.9	⋯
Multiple parton-parton interactions	< 1	0.4–5.8	⋯
$\mathcal{B}(H \to \gamma\gamma)$	1.73		⋯

Statistical analysis

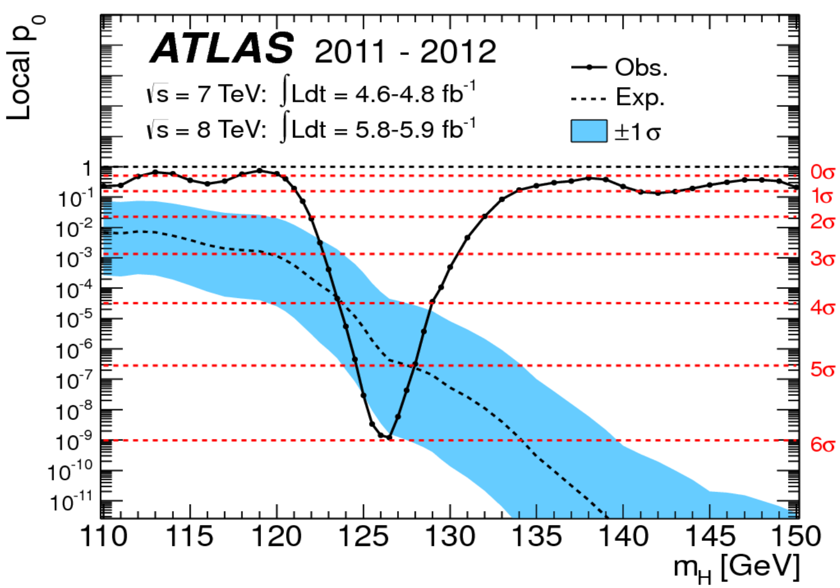
Unbinned likelihood fit on the different categories $t_\mu = -2\ln\lambda(\mu) \quad \lambda(\mu) = \frac{L(\mu,\hat{\hat{\theta}})}{L(\hat{\mu},\hat{\theta})}$

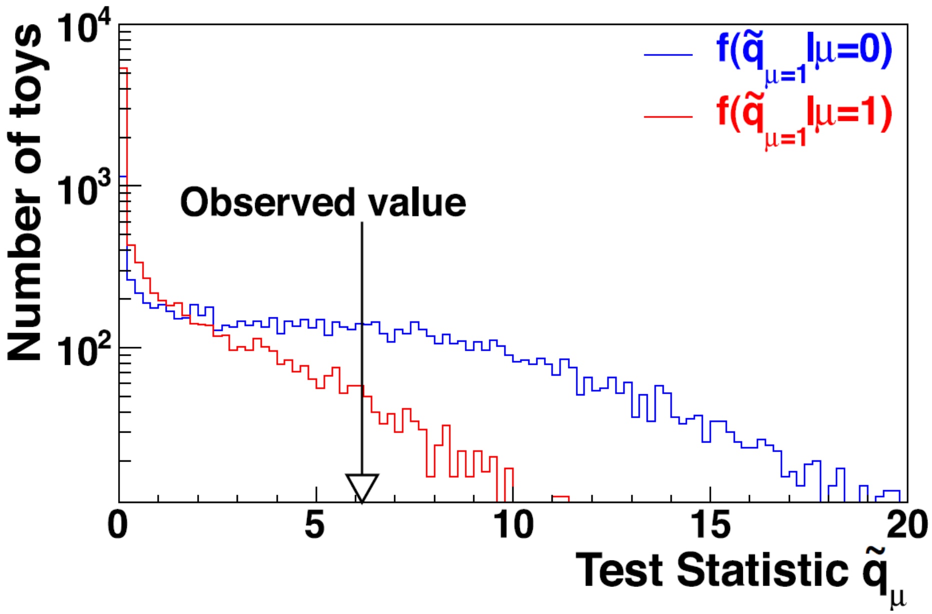
- Statistical test t_μ based on $\lambda(\mu)$ where μ is the signal strength ($\mu=\sigma^{signal}/\sigma^{signal}_{MC}$)
- Nuisance parameters θ are constrained using Gaussian distributions (profiling).

$$L\,(\mu,\theta) = \mathrm{Pois}(n|N) \cdot \prod_{i=1}^{n} F(m^i_{\gamma\gamma};\mu,\langle\theta\rangle \left(\prod_{j=1}^{N_{syst.source}} e^{\epsilon_j}\right)) \cdot G(\epsilon_j)$$

Two possible outcomes:

- Discovery: reject the background-only hypothesis
- CLs technique: set limits on the magnitude of the possible new physics.





Complementary results

Z'$_B$ model can be translated into spin-independent limits.

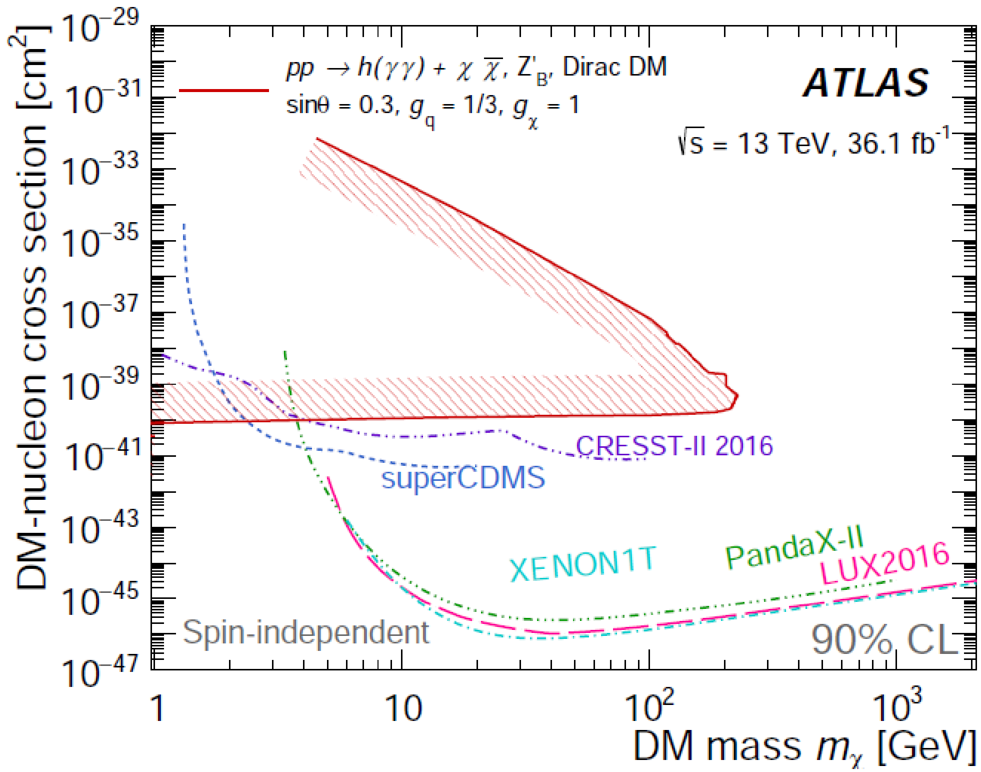
- 90 % CL limits on the WIMP-nucleon cross-section are estimated using the following cross-section formula:

$$\sigma^{\mathrm{SI}}_{N\chi} = \frac{\mu^2_{N\chi}}{\pi A^2}\left[Zf_p - (A-Z)f_n\right]^2$$

$$\mu_{N\chi} = m_\chi m_N/(m_\chi + m_N)$$

$$f_{p,n} = 3g_q g_\chi / m^2_{Z'_B}$$

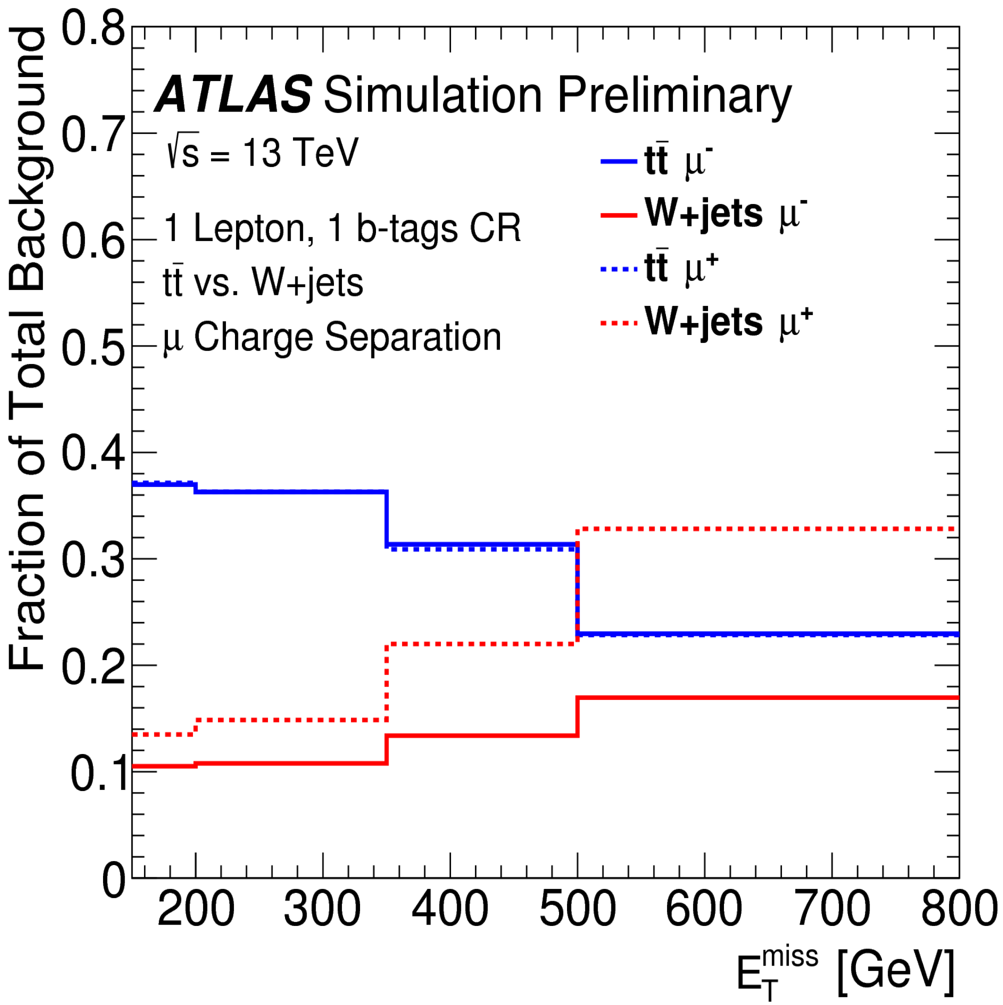
- Limits are compared to most recent direct detection limits.

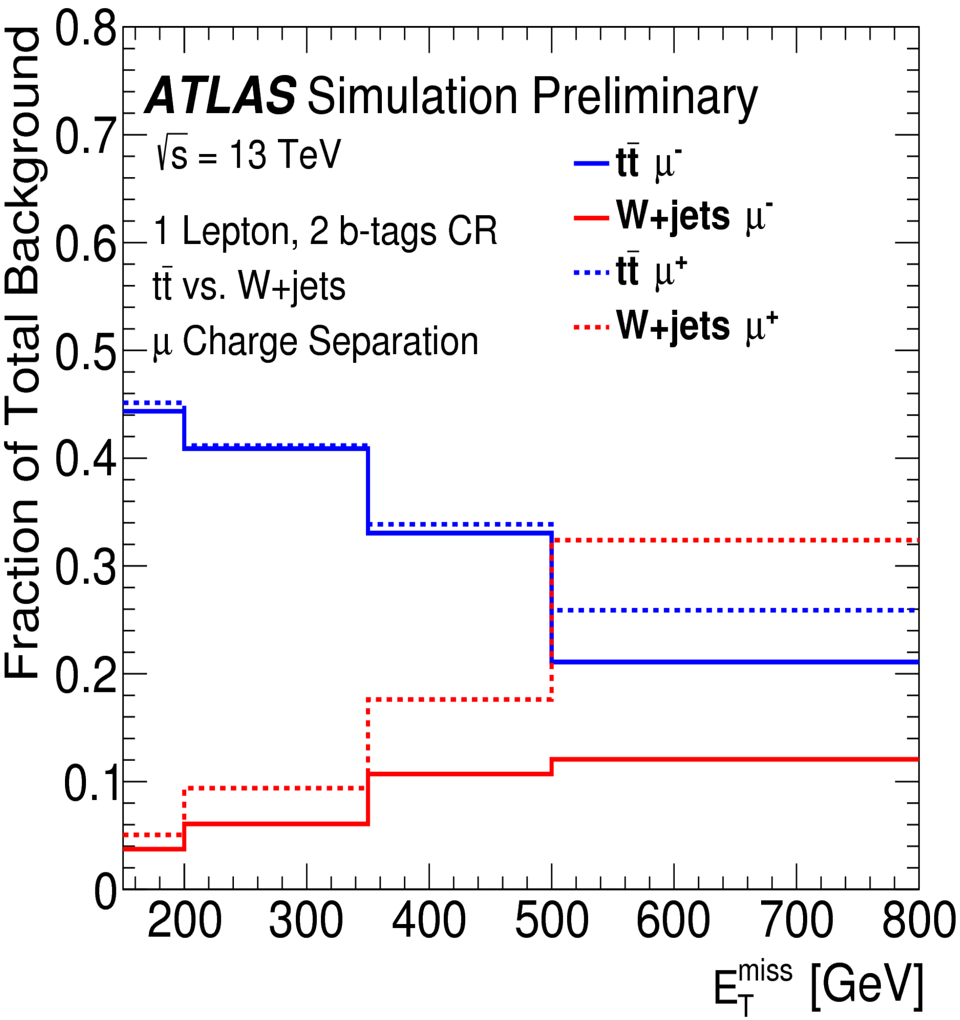


DM production in association to $h \rightarrow b\bar{b}$ (selection)

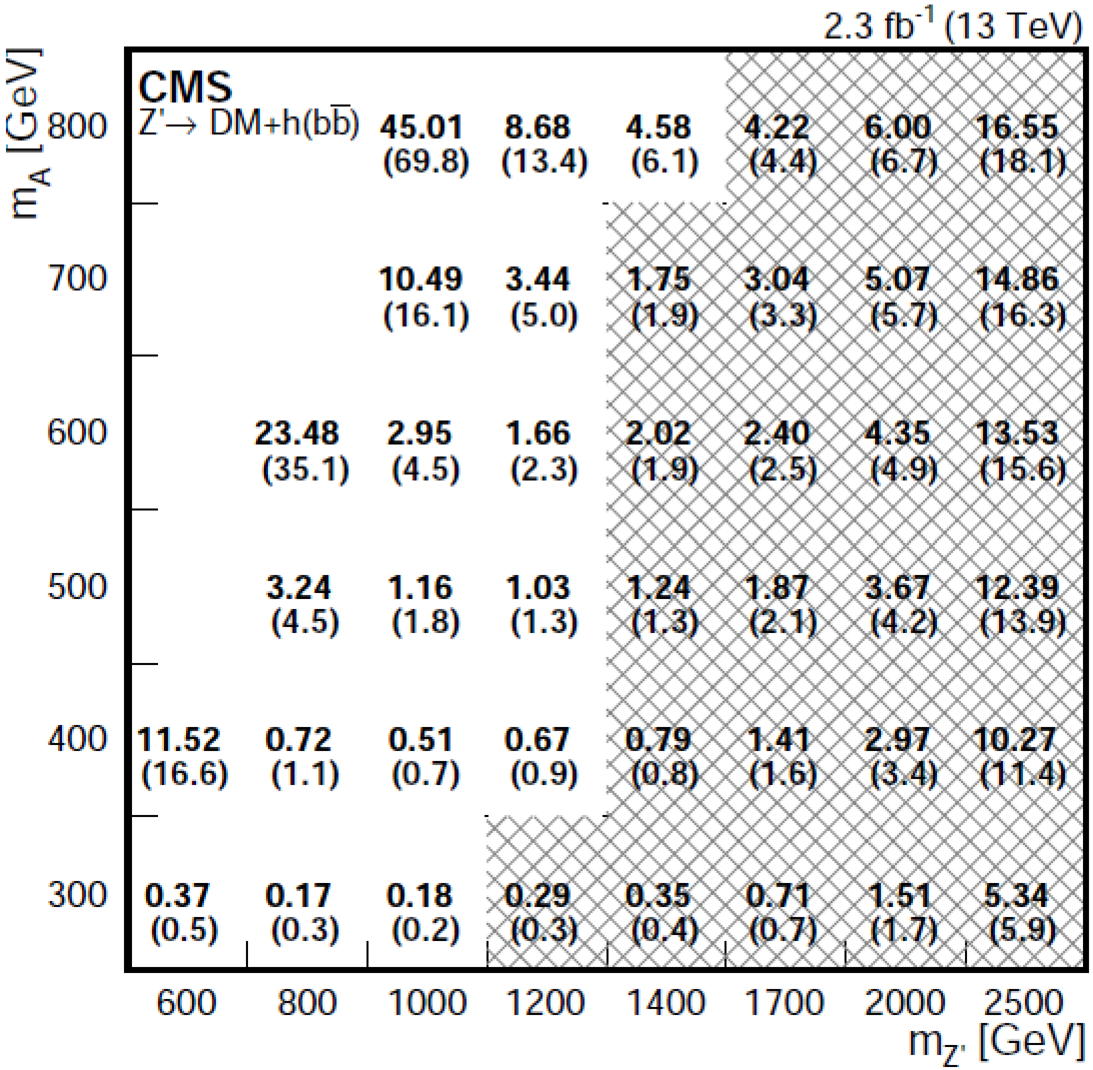
<table>
<tr><th>Region</th><th>SR</th><th>1μ-CR</th><th>2ℓ-CR</th></tr>
<tr><td>Trigger</td><td>$E_{\mathrm{T}}^{\mathrm{miss}}$</td><td>$E_{\mathrm{T}}^{\mathrm{miss}}$</td><td>Single lepton</td></tr>
<tr><td>Leptons</td><td>No e or μ</td><td>Exactly one μ</td><td>Exactly two e or μ
83 GeV $< m_{ee} <$ 99 GeV
71 GeV $< m_{\mu^{\pm}\mu^{\mp}} <$ 106 GeV</td></tr>
<tr><td rowspan="2">Resolved</td><td>$E_{\mathrm{T}}^{\mathrm{miss}} \in [150, 500)$ GeV
$p_{\mathrm{T}}^{\mathrm{miss,trk}} > 30$ GeV (1 b-tag only)
$\min\left[\Delta\phi\left(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{j}\right)\right] > \pi/9$
$\Delta\phi\left(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss,trk}}\right) < \pi/2$
–</td><td>$p_{\mathrm{T}}(\mu, E_{\mathrm{T}}^{\mathrm{miss}}) \in [150, 500)$ GeV
$p_{\mathrm{T}}(\mu, \vec{p}_{\mathrm{T}}^{\mathrm{miss,trk}}) > 30$ GeV
$\min\left[\Delta\phi\left(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{j}\right)\right] > \pi/9$
$\Delta\phi\left(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss,trk}}\right) < \pi/2$
–</td><td>$p_{\mathrm{T}}(\ell, \ell) \in [150, 500)$ GeV
–
–
–
$E_{\mathrm{T}}^{\mathrm{miss}} \times \left(\sum_{\mathrm{jets,leptons}} p_{\mathrm{T}}\right)^{-1/2} < 3.5\ \mathrm{GeV}^{1/2}$</td></tr>
<tr><td colspan="3">Number of central small-R jets ≥ 2
Leading Higgs candidate small-R jet $p_{\mathrm{T}} > 45$ GeV
$H_{\mathrm{T},2j} > 120$ GeV for 2 jets, $H_{\mathrm{T},3j} > 150$ GeV for > 2 jets
$\Delta\phi\left(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T},h}\right) > 2\pi/3$
Veto on τ-leptons
$\Delta R\left(\vec{p}_{h}^{\,j_1}, \vec{p}_{h}^{\,j_2}\right) < 1.8$
Veto on events with > 2 b-tags
Sum of p_{T} of two Higgs candidate jets and leading extra jet $> 0.63 \times H_{\mathrm{T,all\,jets}}$
b-tagging : one or two small-R calorimeter jets
Final discriminant = Dijet mass</td></tr>
<tr><td rowspan="2">Merged</td><td>$E_{\mathrm{T}}^{\mathrm{miss}} \geq 500$ GeV
$p_{\mathrm{T}}^{\mathrm{miss,trk}} > 30$ GeV
$\min\left[\Delta\phi\left(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{j}\right)\right] > \pi/9$
$\Delta\phi\left(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss,trk}}\right) < \pi/2$</td><td>$p_{\mathrm{T}}(\mu, E_{\mathrm{T}}^{\mathrm{miss}}) \geq 500$ GeV
$p_{\mathrm{T}}(\mu, \vec{p}_{\mathrm{T}}^{\mathrm{miss,trk}}) > 30$ GeV
$\min\left[\Delta\phi\left(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{j}\right)\right] > \pi/9$
$\Delta\phi\left(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss,trk}}\right) < \pi/2$</td><td>$p_{\mathrm{T}}(\ell, \ell) \geq 500$ GeV
–
–
–</td></tr>
<tr><td colspan="3">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</td></tr>
</table>

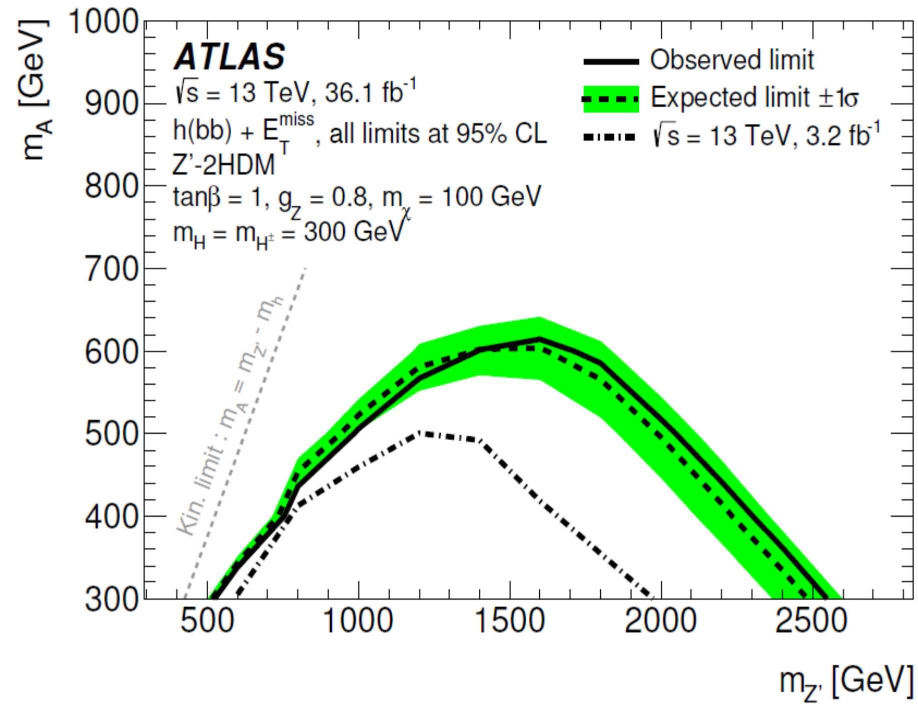
MonoHiggs (h → bb)





MonoHiggs (h → bb)





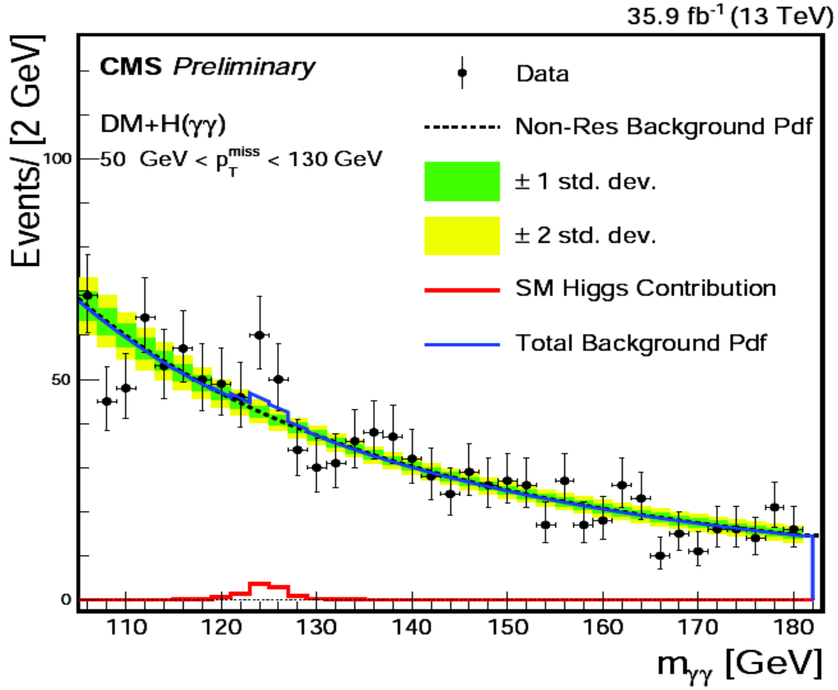
CMS analysis strategy

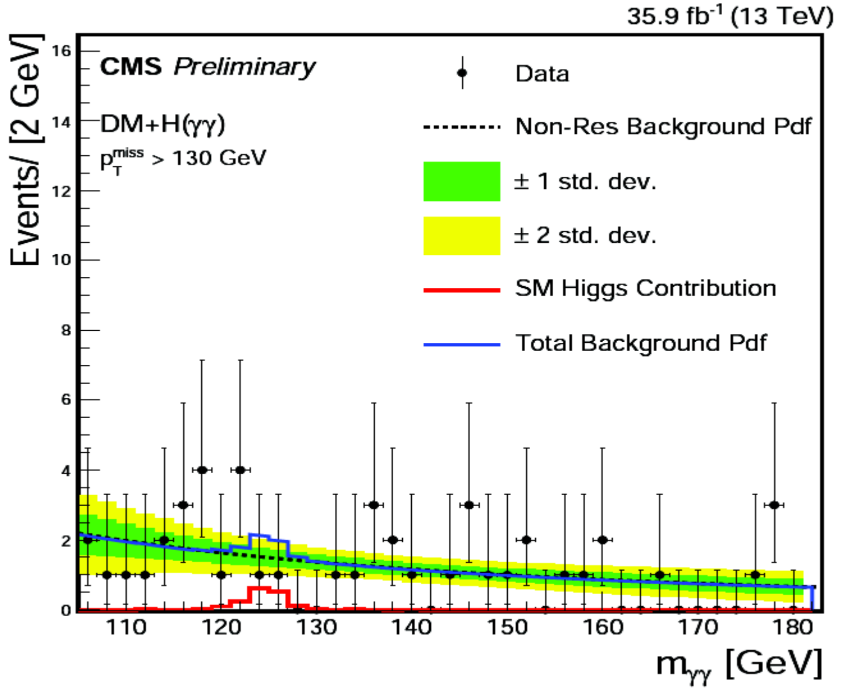
Data is selected and divided into two categories:

1. Results are derived by unbinned fits of a signal + background function to the $m_{\gamma\gamma}$ in those categories.
2. The choice of the background function is performed by studying the bias on the number of events on toy simulated samples. Function presenting a bias lower than 0.2 (N_{fit} – N_{sim}/ σ_{fit}) is used:

$$P(x) = \sum_{i=1}^{N} \beta_i x^{-\alpha_i}$$

3. Dominant uncertainties are the statistical uncertainties





2 σ excess if fitted intermediate p_T^{miss} category. Simultaneous fit, no excess

CMS signal acceptance

Low-p_T^{miss} Efficiencies [%]						
m_A [GeV] / $m_{Z'}$ [GeV]	300	400	500	600	700	800
600	2.9 ± 2.0	11.3 ± 3.7	-	-	-	-
800	0.4 ± 0.7	0.7 ± 1.0	2.0 ± 1.6	7.2 ± 3.0	-	-
1000	0.1 ± 0.4	0.2 ± 0.5	0.3 ± 0.6	0.6 ± 0.9	1.7 ± 1.5	4.7 ± 2.5
1200	/	/	0.1 ± 0.4	0.1 ± 0.4	0.2 ± 0.6	0.5 ± 0.9
1400	/	/	/	/	0.1 ± 0.3	0.1 ± 0.4
1700	/	/	/	/	/	/
2000	/	/	/	/	/	/
2500	/	/	/	/	/	/

High-p_T^{miss} Efficiencies [%]						
m_A [GeV] / $m_{Z'}$ [GeV]	300	400	500	600	700	800
600	28.9 ± 5.4	14.9 ± 4.2	-	-	-	-
800	38.8 ± 5.8	37.0 ± 5.7	32.4 ± 5.5	23.0 ± 5.0	-	-
1000	42.6 ± 5.8	41.6 ± 5.8	40.4 ± 5.8	38.4 ± 5.7	35.0 ± 5.6	29.3 ± 5.4
1200	45.2 ± 5.9	44.8 ± 5.9	43.5 ± 5.9	43.1 ± 5.9	41.8 ± 5.8	39.6 ± 5.8
1400	46.6 ± 5.9	46.5 ± 5.9	45.8 ± 5.9	45.9 ± 5.9	44.6 ± 5.9	43.9 ± 5.9
1700	48.0 ± 5.9	48.2 ± 5.9	47.8 ± 5.9	47.7 ± 5.9	47.2 ± 5.9	47.0 ± 5.9
2000	47.4 ± 5.9	47.7 ± 5.9	47.5 ± 5.9	47.7 ± 5.9	47.9 ± 5.9	48.5 ± 5.9
2500	45.9 ± 5.9	45.8 ± 5.9	45.9 ± 5.9	46.5 ± 5.9	46.9 ± 5.9	46.7 ± 5.9

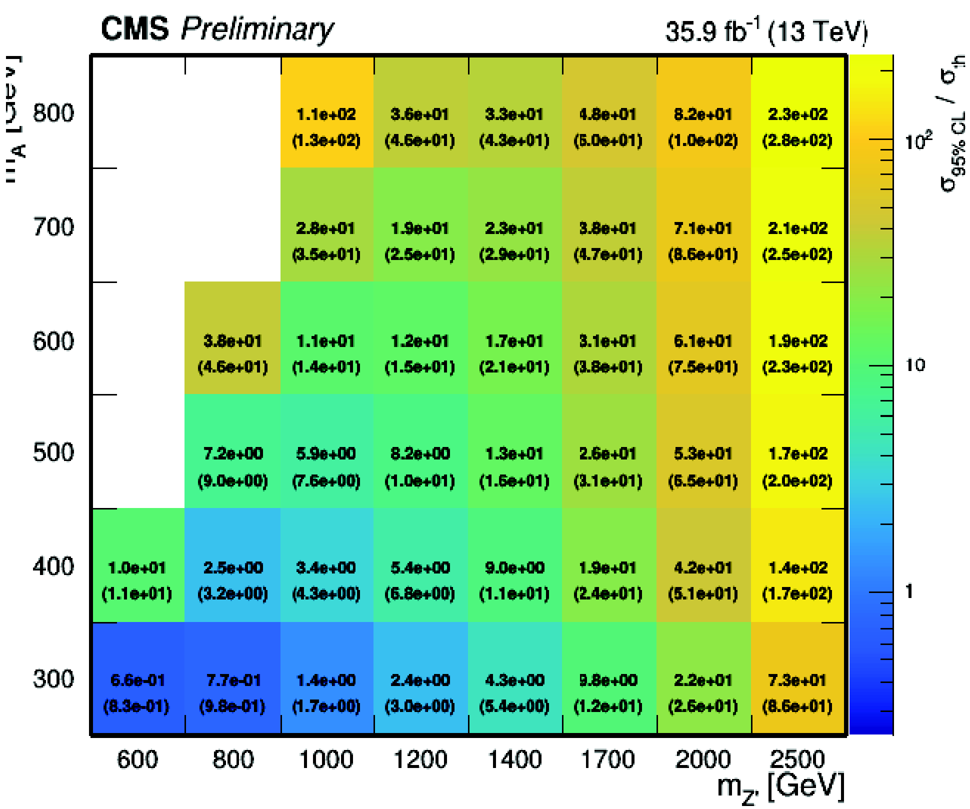
m_χ = 1 GeV

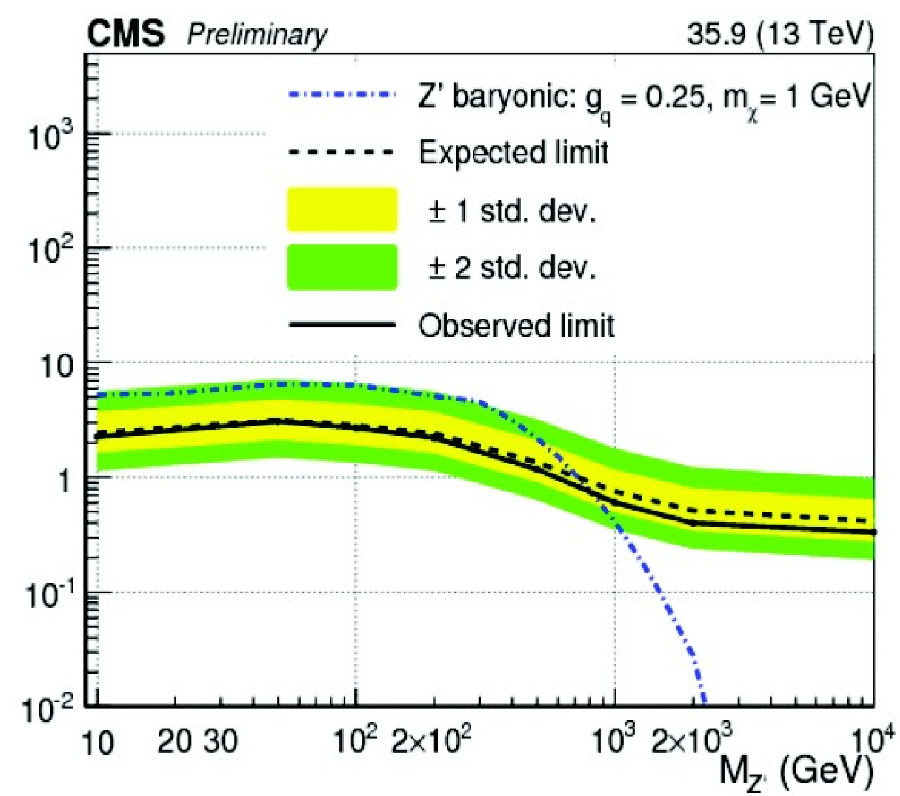
$m_{Z'}$ [GeV]	Low-p_T^{miss} Efficiencies [%]	High-p_T^{miss} Efficiencies [%]
10	6.6 ± 2.9	7.0 ± 3.0
50	6.0 ± 2.8	5.6 ± 2.7
100	6.4 ± 2.9	5.9 ± 2.8
200	6.1 ± 2.8	7.1 ± 3.0
500	7.5 ± 3.1	12.6 ± 3.9
1000	5.4 ± 2.7	22.6 ± 4.9
2000	3.1 ± 2.1	32.0 ± 5.5
10000	1.0 ± 1.2	40.1 ± 5.8

CMS results

No BSM signal is observed → 95 % CL limits are derived

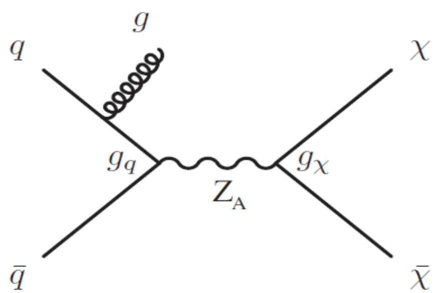
1. Z'-2HDM and Z'_B model are tested.
2. Z'-2HDM: $m_{Z'} <$ 800 GeV and $m_A <$ 300 GeV are excluded.
3. Z'_B: $m_{Z'} <$ 800 GeV are excluded for m_{DM}=1 GeV

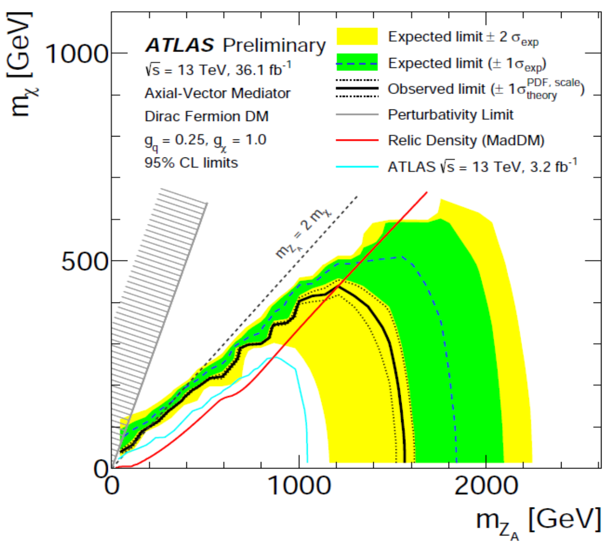


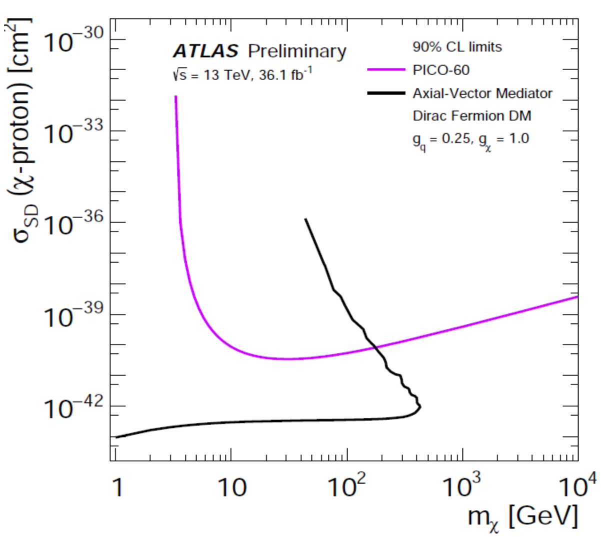


Other mono-X searches

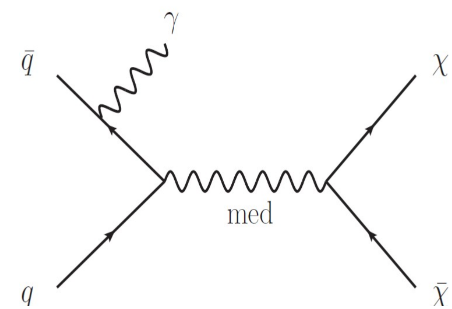
Mono-jet

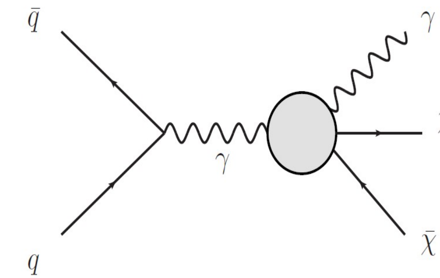


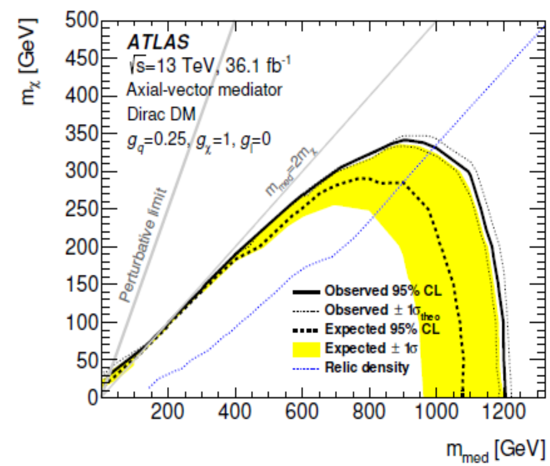


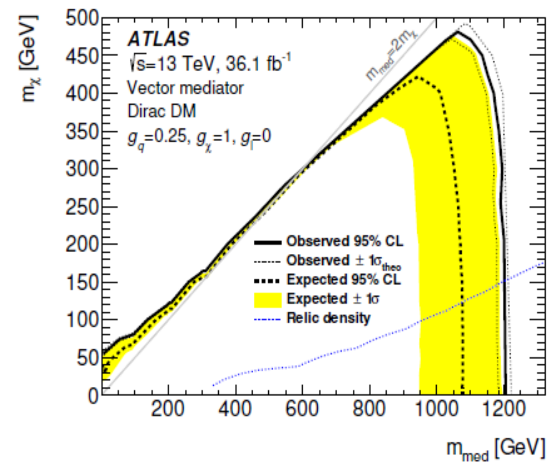


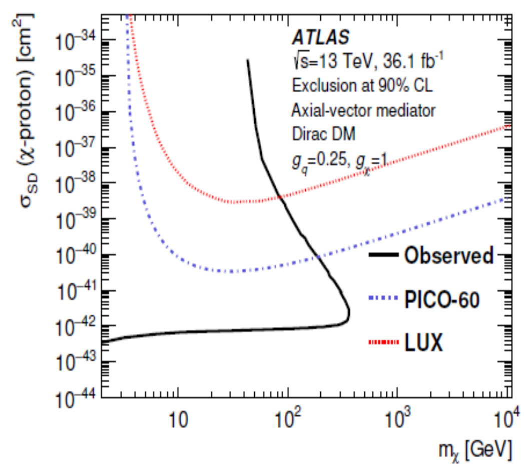
Mono-photon

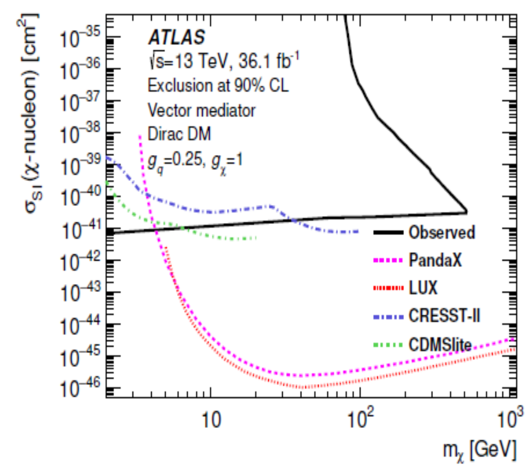












Pseudo-scalar+2HDM

$$V_H = \mu_1 H_1^\dagger H_1 + \mu_2 H_2^\dagger H_2 + \left(\mu_3 H_1^\dagger H_2 + \text{h.c.}\right) + \lambda_1 \left(H_1^\dagger H_1\right)^2 + \lambda_2 \left(H_2^\dagger H_2\right)^2$$

$$+ \lambda_3 \left(H_1^\dagger H_1\right)\left(H_2^\dagger H_2\right) + \lambda_4 \left(H_1^\dagger H_2\right)\left(H_2^\dagger H_1\right) + \left[\lambda_5 \left(H_1^\dagger H_2\right)^2 + \text{h.c.}\right] .$$

$$V_P = \frac{1}{2} m_P^2 P^2 + P\left(i b_P H_1^\dagger H_2 + \text{h.c.}\right) + P^2\left(\lambda_{P1} H_1^\dagger H_1 + \lambda_{P2} H_2^\dagger H_2\right)$$