Search for dark photon from a heavy Higgs Boson decay in events with a photon and missing transverse momentum in *pp* collisions at a center-of-mass energy of 13 TeV with the ATLAS detector

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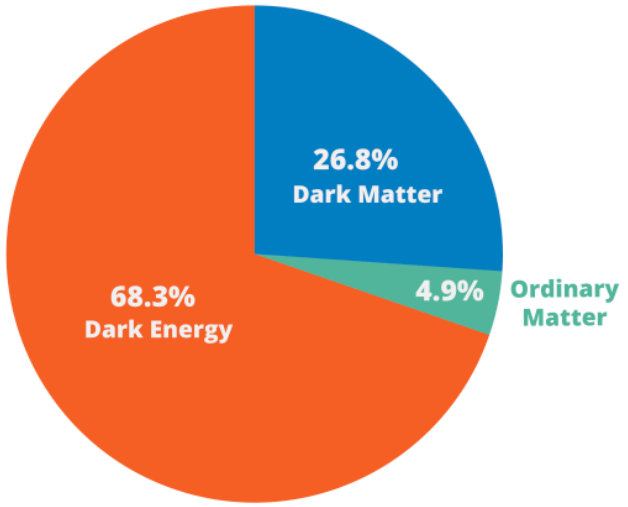
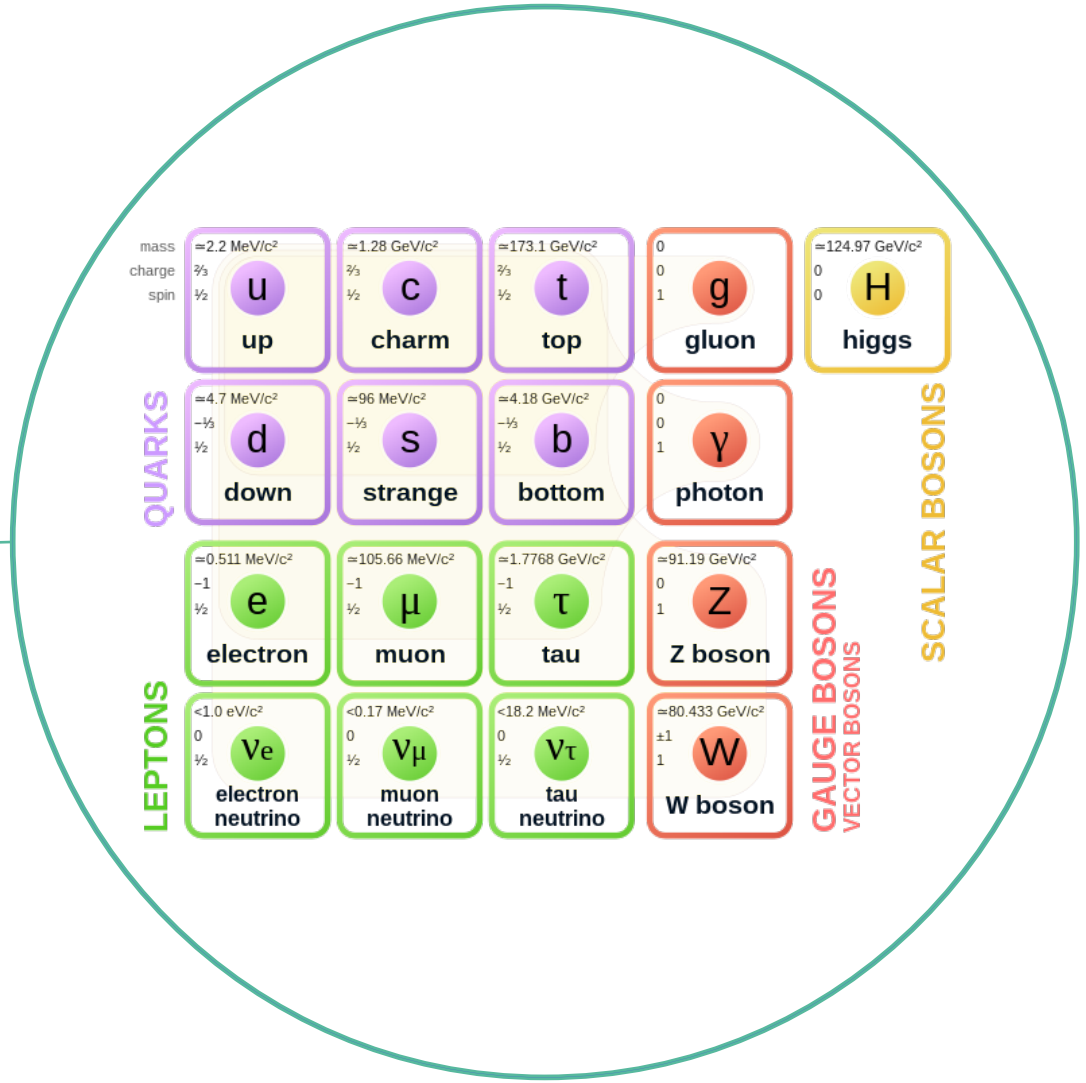
The Standard Model (SM)

- Description of elementary particles and their interactions:
  - Fermions: constituents of matter (quarks and leptons)
  - Bosons: gauge bosons (interactions mediators) and Higgs boson
- Accounts only for the 5% of the matter-energy content of the universe





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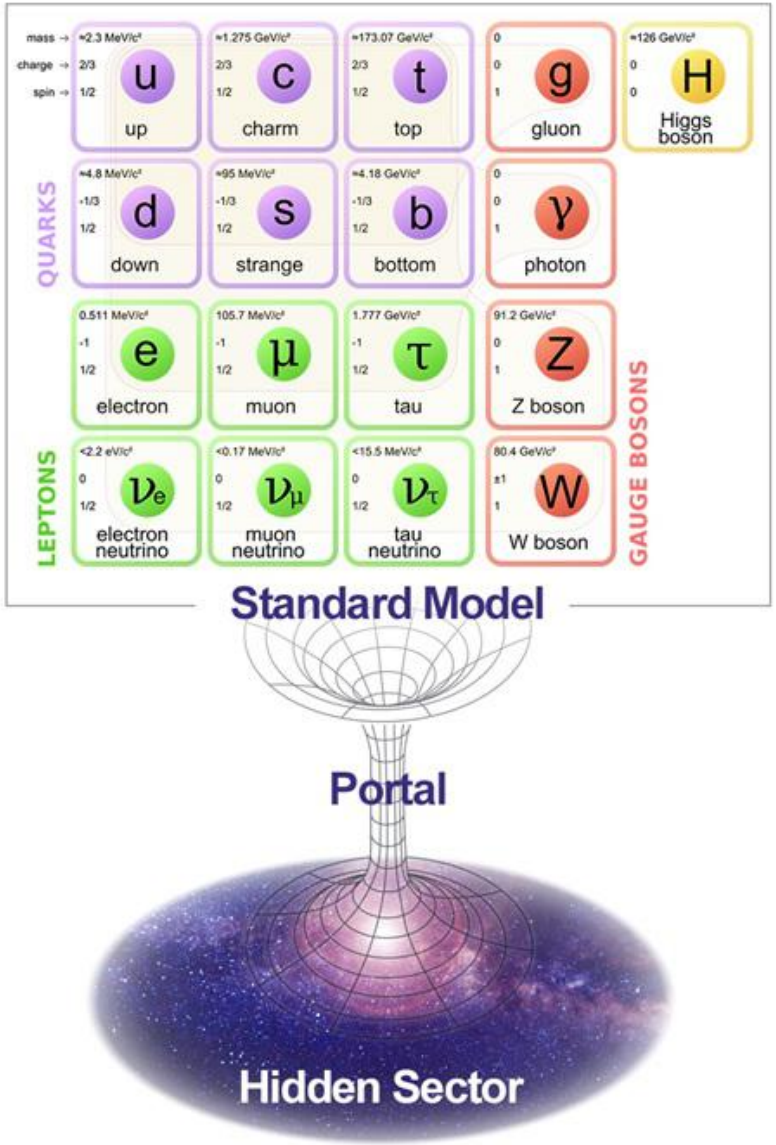
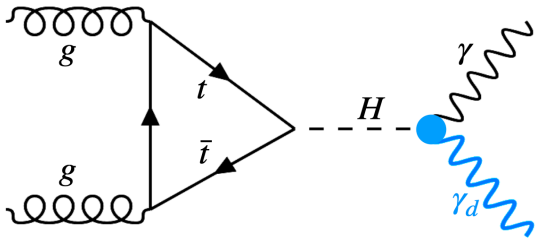
Higgs portal

- Dark or Hidden Sector:
  - Dark matter candidates
  - Dark gauge bosons (e.g. dark photon γ_d)
  - Potentially observable decay $H \longrightarrow \gamma\gamma_d$



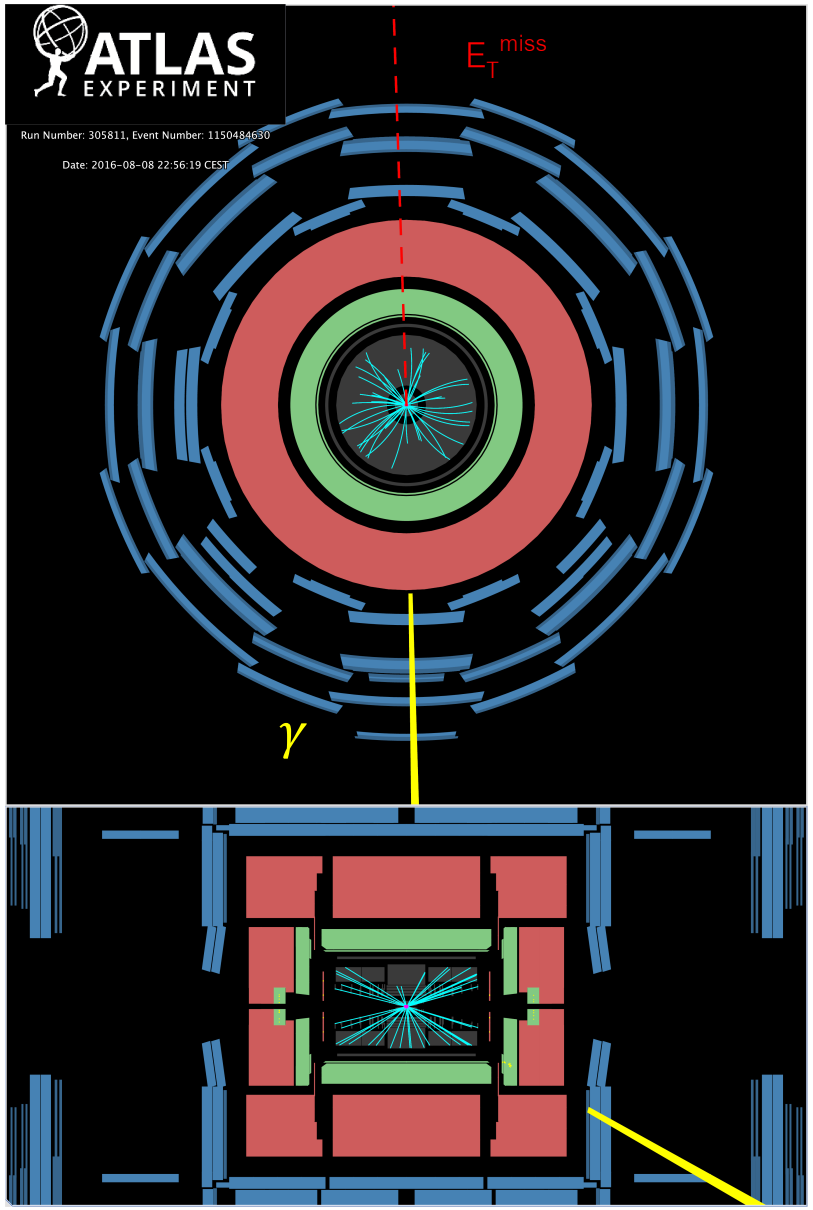
The mono-photon signature

- Mono-photon signature:
  - Production of a weakly- or non-interacting particle (e.g. the dark photon)
  - photon + E_T^{miss} in the final state:



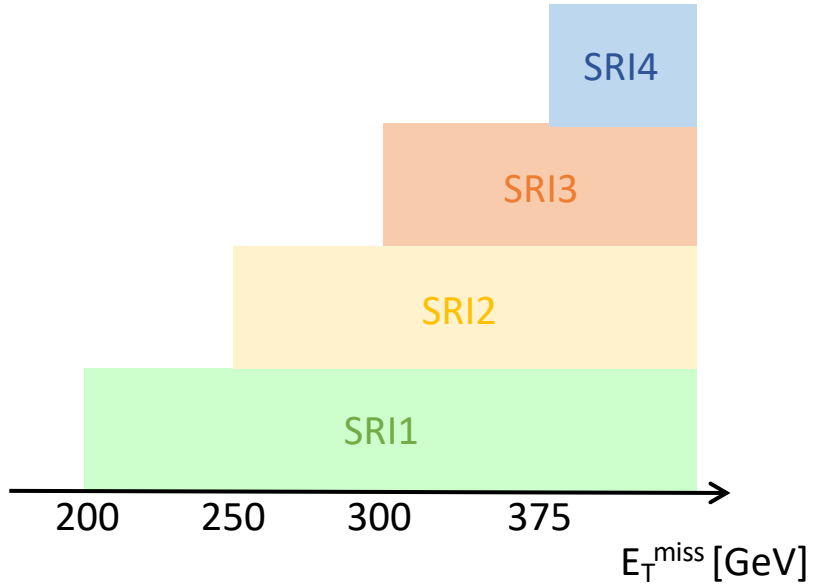
- **Momentum conservation**: in the plane transverse to the beam axis, the momenta of all particles in the final state should sum to zero
  - Imbalance in the transverse momentum

$$\vec{E_T}^{miss} = -\underbrace{\sum_{e} \vec{p_T}^{e} - \sum_{\gamma} \vec{p_T}^{\gamma} - \sum_{\mu} \vec{p_T}^{\mu} - \sum_{\tau} \vec{p_T}^{\tau} - \sum_{jet} \vec{p_T}^{jet}}_{\text{reconstructed objects}} - \sum_{soft} \vec{p_T}^{soft}$$



The mono-photon analysis

- Search for dark matter performed by ATLAS at the LHC, published using the full Run 2 dataset (2015-2018), corresponding to an integrated luminosity L = 139 fb^{-1}
- **Mono-photon signature**: photon + E_T^{miss} in the final state
- Definition of **Signal Regions (SRs):**
  1. E_T^{miss} selection: inclusive SRs and exclusive SRs
  2. Leading photon with pT > 150 GeV
  3. DeltaPhi(photon, E_T^{miss}) > 0.4
  4. E_T^{miss} significance > 8.5
  5. At most 1 jet with DeltaPhi(jet, E_T^{miss}) > 0.4
  6. No electron and no muon



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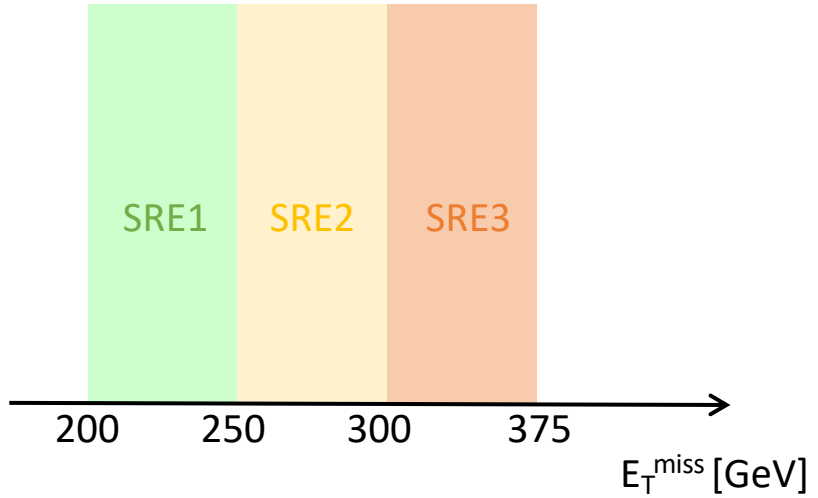

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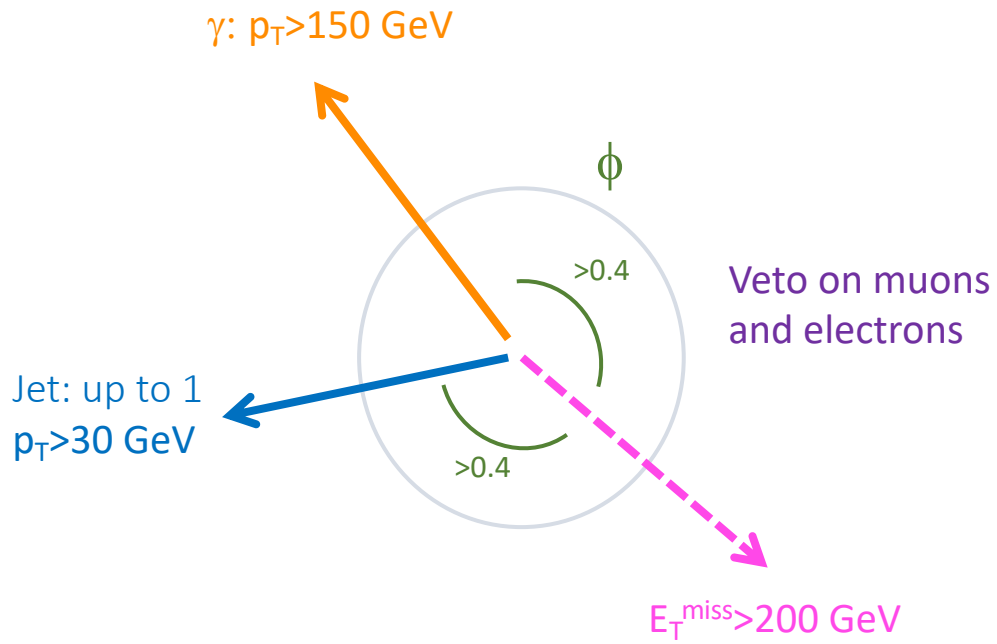

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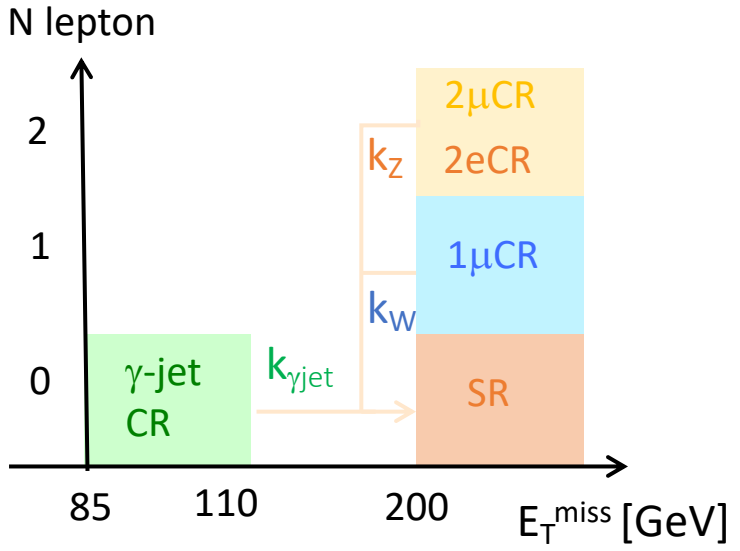
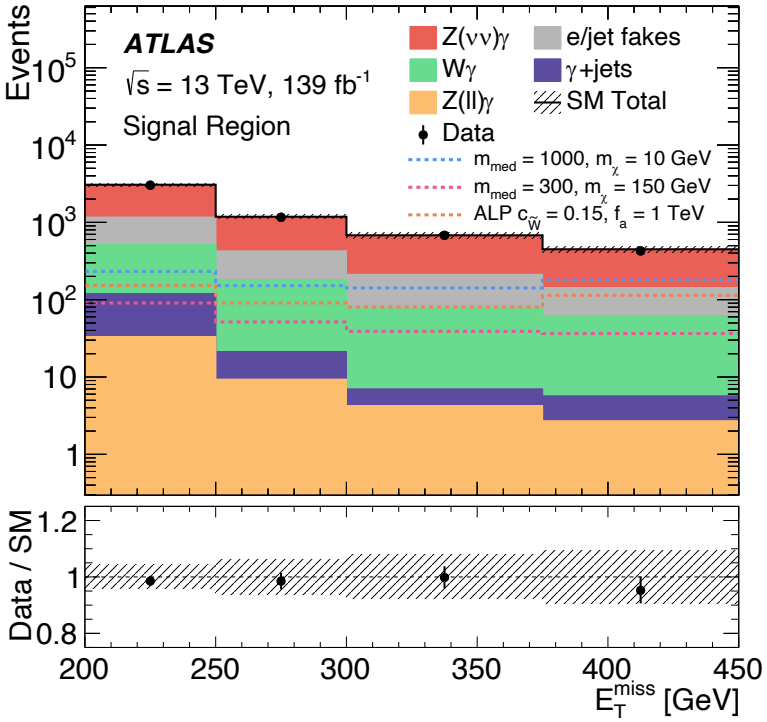
- **Mono-photon signature**: photon + E_T^{miss} in the final state
- Definition of **Control Regions (SRs)**:
  - Complementary to SRs, defined inverting one selection criteria
  - PhJetCR: γ+jet
  - 1MuCR: γ+W($\rightarrow l\nu$)
  - 2MuCR / 2EleCR: γ+Z($\rightarrow \nu\nu$), γ+Z($\rightarrow ll$)



- Simultaneous likelihood fit in CRs to extract normalization factors k_{yjet} , k_W , k_Z and propagate them in SRs

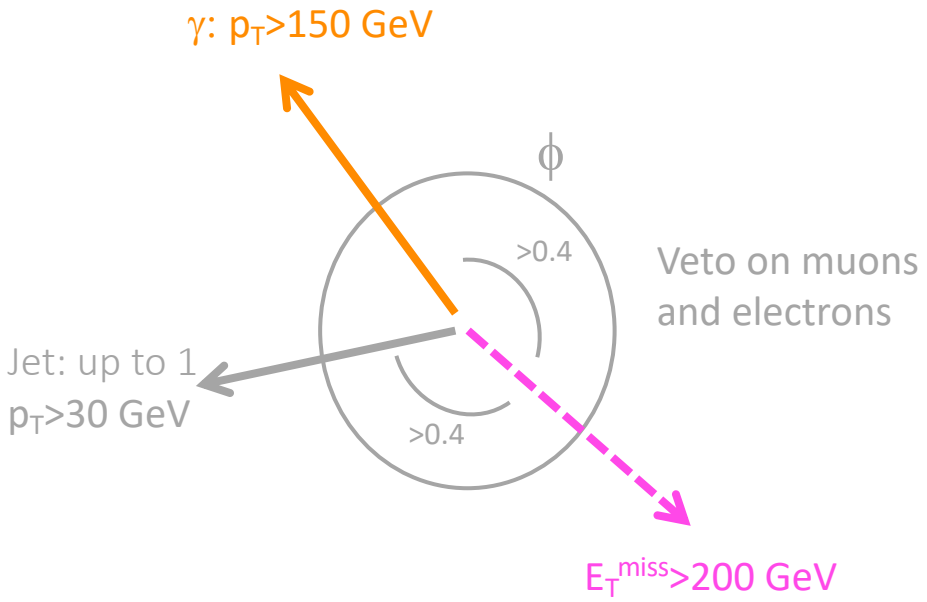
The mono-photon analysis

- Simultaneous shape-fit in CRs and SRs:
  - Exclusive SRs and last inclusive (SRI4)
  - Better reproduce the E_T^{miss} distribution
- No significant event excess was observed in the SRs
  - Exclusion limits in models predicting weakly interacting dark-matter candidates
  - Model-independent limits are also provided for possible reinterpretation in other theoretical models



Reinterpretation

- Reinterpretation of the mono-photon analysis in searches for dark photon
- **Higgs boson** decay into a **photon** and a **dark photon**: $H \longrightarrow \gamma\gamma_d$
  - Beyond SM heavy **Higgs boson** (due to mono-photon selection)



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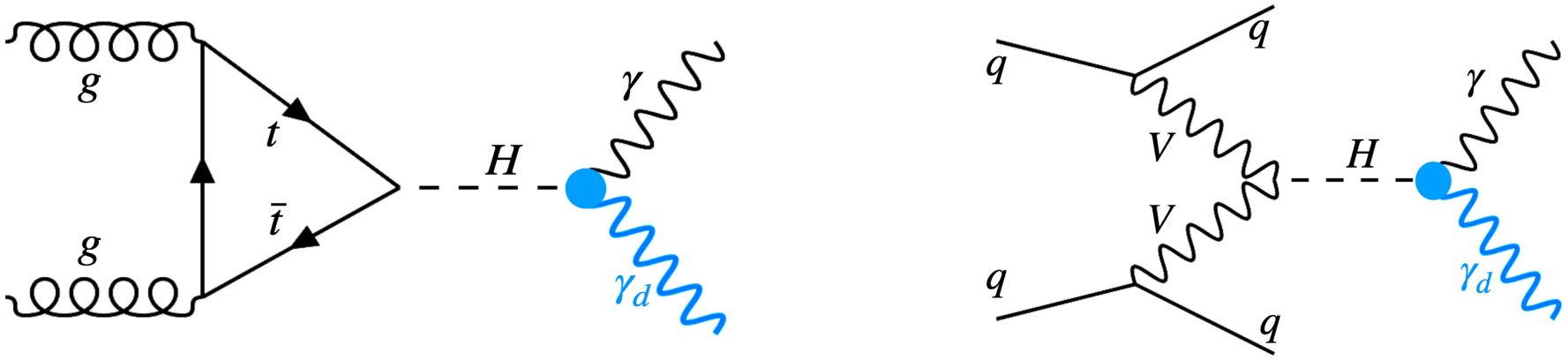
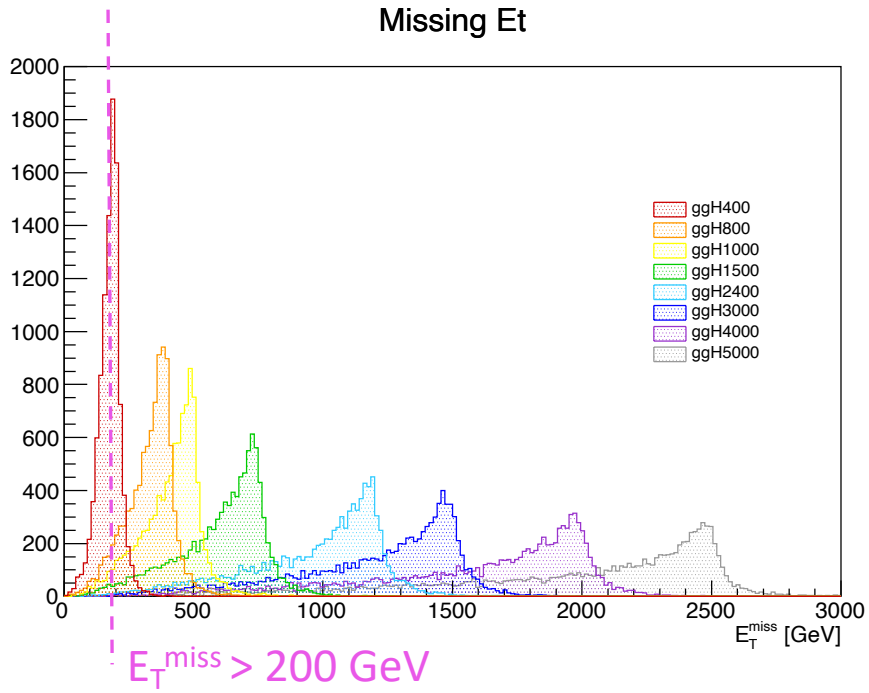
- **Higgs boson** decay into a **photon** and a **dark photon**: $H \longrightarrow \gamma\gamma_d$
  - Beyond SM heavy **Higgs boson** (due to mono-photon selection)
  - Produced via guon gluon fusion (**ggF**) and vector boson fusion (**VBF**)

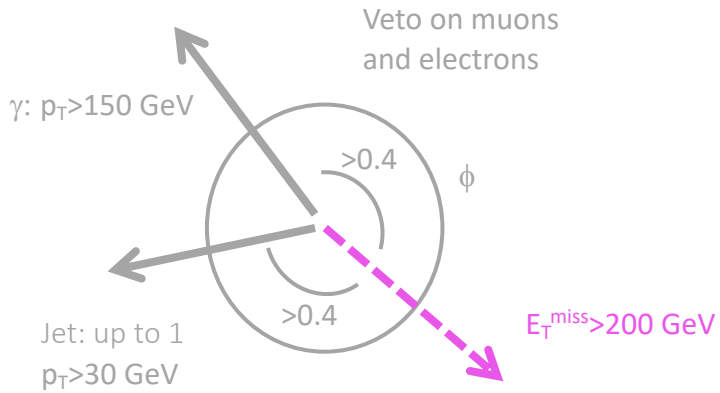


First reinterpretation approach

- From mono-photon model-independent limits
- 8 ggF Higgs MC truth-samples:
  - The detector response is not take into account
  - 400, 800, 1000, 1500, 2400, 3000, 4000, 5000 GeV
  - Statistics of N = 10000 events each



- Mono-photon selection:



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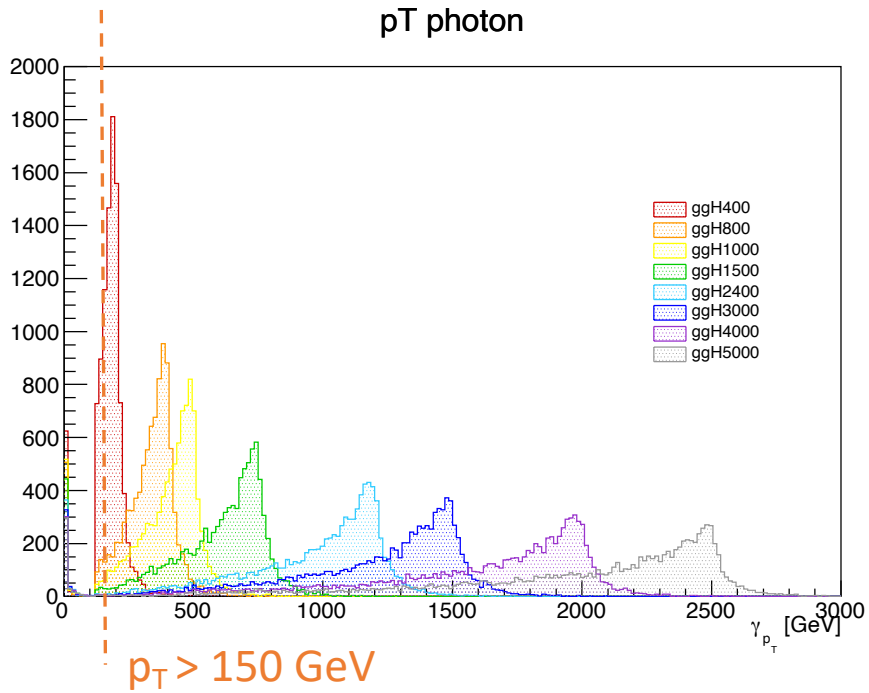

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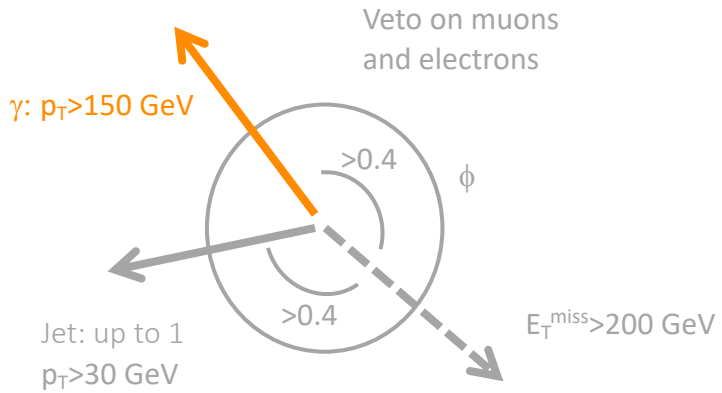
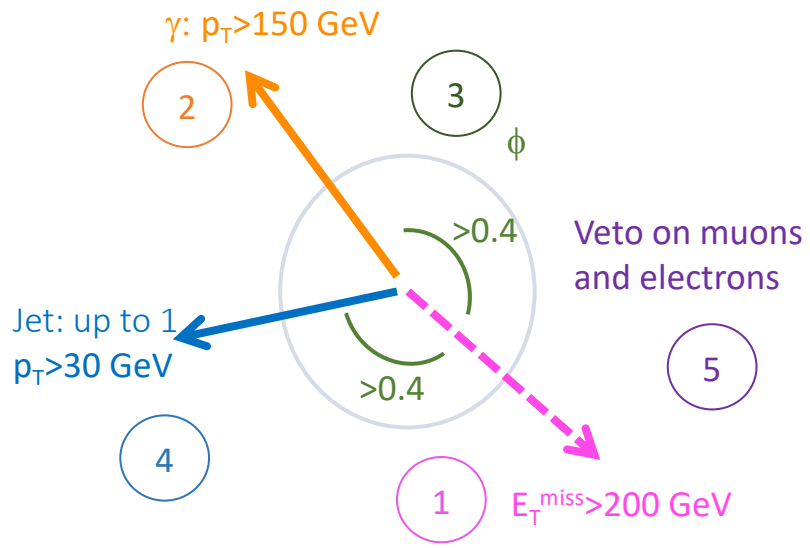
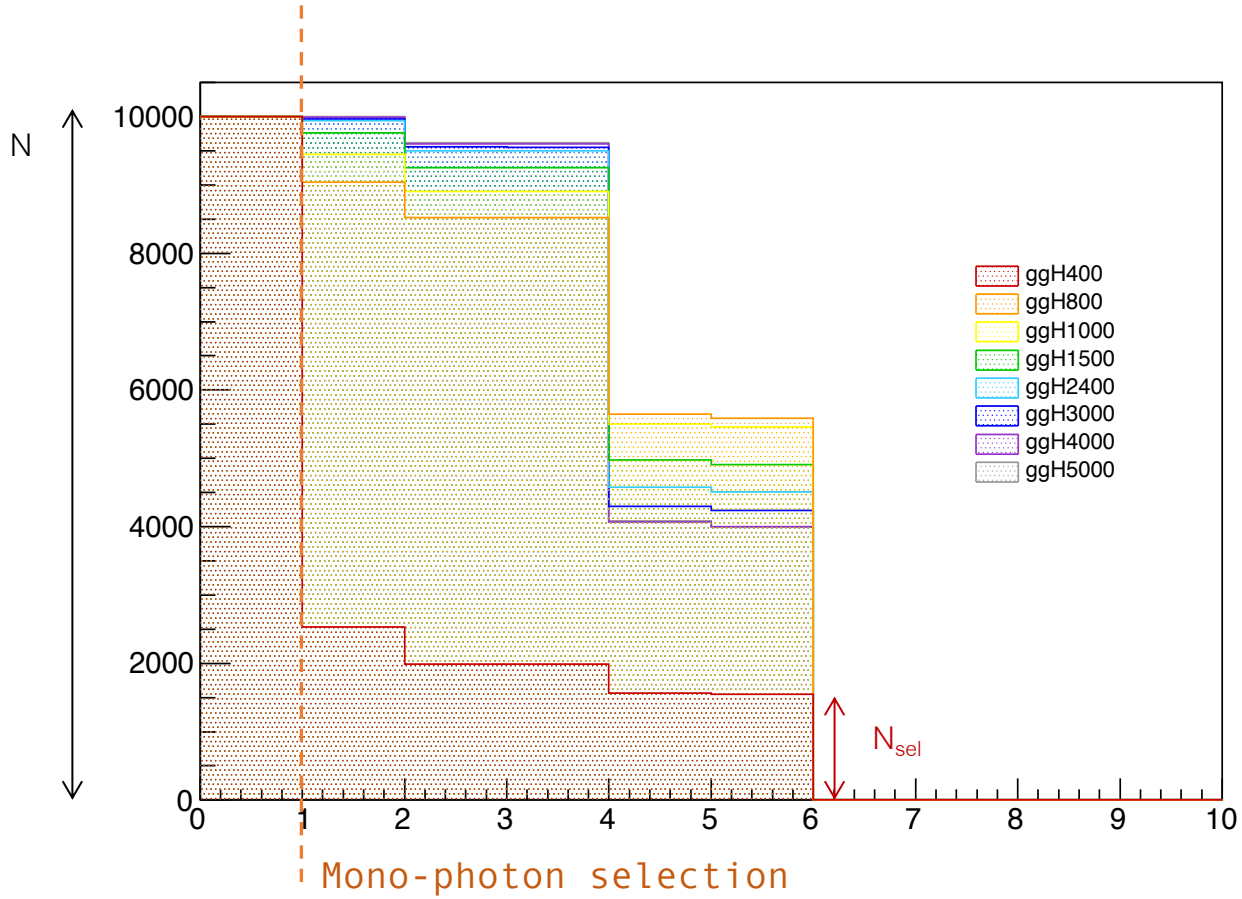


Cut flow

- Mono-photon selection:





- The **fiducial acceptance** is the fraction of events that pass the selection: $A_{fid} = \frac{N_{sel}}{N}$

Model-independent limits

- Fiducial upper limits on xsec x A:
  - Do not depend on the signal model
  - provided by the mono-photon analysis
- Can be exploited to estimate first exclusion limits dividing by the fiducial acceptance: $\sigma_{lim} = \frac{\sigma_{fid}}{A_{fid}}$

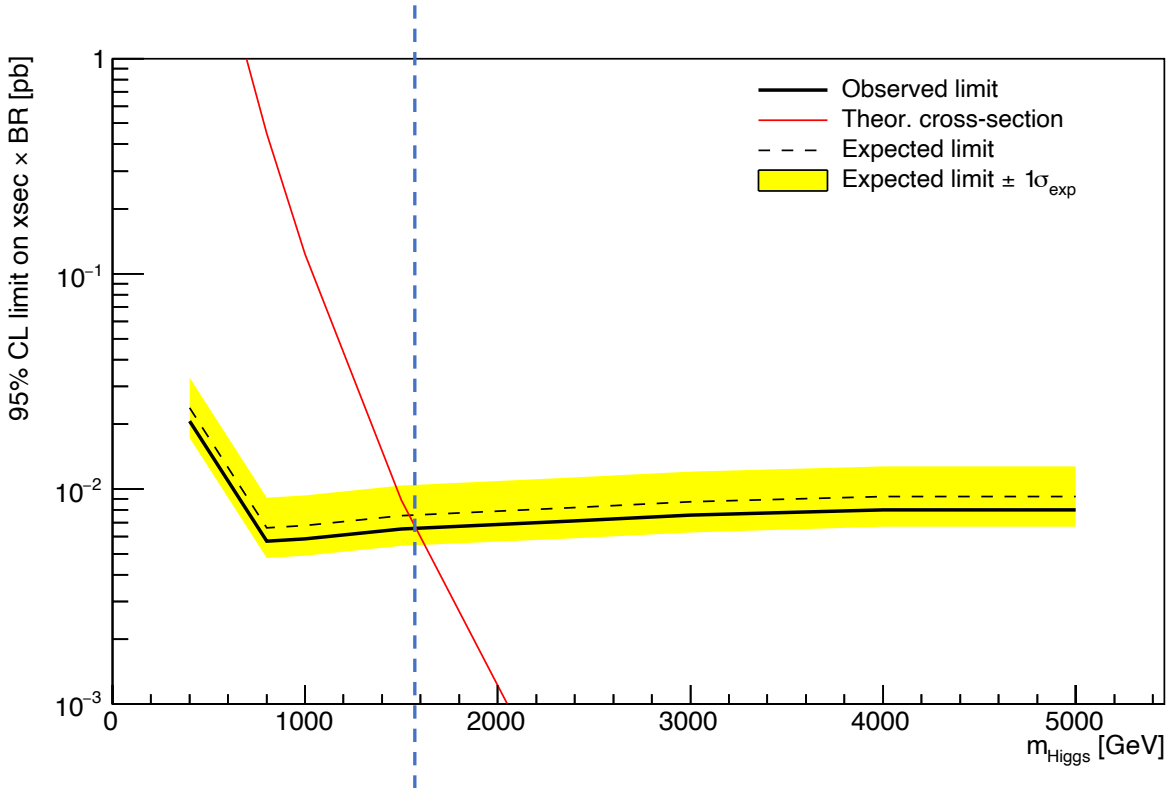
m_H	$E_T^{miss} > 200$ GeV A_{fid}	$E_T^{miss} > 250$ GeV A_{fid}	$E_T^{miss} > 300$ GeV A_{fid}	$E_T^{miss} > 375$ GeV A_{fid}
400 GeV	0.155 ± 0.004	0.007 ± 0.001	0.0004 ± 0.0002	–
800 GeV	0.56 ± 0.01	0.51 ± 0.01	0.44 ± 0.01	0.23 ± 0.01
1 TeV	0.55 ± 0.01	0.52 ± 0.01	0.48 ± 0.01	0.40 ± 0.01
1.5 TeV	0.49 ± 0.01	0.48 ± 0.01	0.47 ± 0.01	0.45 ± 0.01
2.4 TeV	0.45 ± 0.01	0.45 ± 0.01	0.45 ± 0.01	0.44 ± 0.01
3 TeV	0.42 ± 0.01	0.42 ± 0.01	0.42 ± 0.01	0.42 ± 0.01
4 TeV	0.40 ± 0.01	0.40 ± 0.01	0.40 ± 0.01	0.40 ± 0.01
5 TeV	0.40 ± 0.01	0.40 ± 0.01	0.40 ± 0.01	0.40 ± 0.01

Signal channel	$\langle\sigma\rangle_{obs}^{95}$[fb]	$\langle\sigma\rangle_{exp}^{95}$[fb]
$E_T^{miss} > 200$ GeV	3.20	$3.69^{+1.41}_{-1.02}$
$E_T^{miss} > 250$ GeV	1.91	$2.26^{+0.85}_{-0.62}$
$E_T^{miss} > 300$ GeV	1.26	$1.46^{+0.55}_{-0.40}$
$E_T^{miss} > 375$ GeV	0.78	$0.93^{+0.34}_{-0.25}$
$200 < E_T^{miss} < 250$ GeV	2.30	$2.60^{+0.98}_{-0.71}$
$250 < E_T^{miss} < 300$ GeV	1.37	$1.52^{+0.57}_{-0.41}$
$300 < E_T^{miss} < 375$ GeV	1.09	$1.13^{+0.43}_{-0.31}$

https://cds.cern.ch/record/2689095/files/ATL-COM-PHYS-2019-1162.pdf

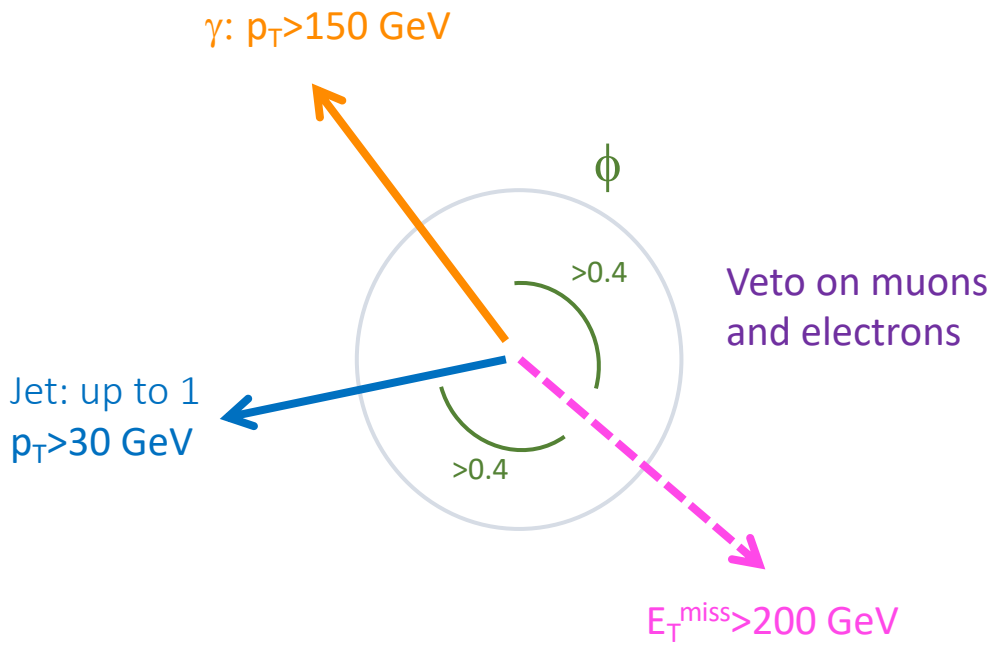
Limit plot for E_T^{miss} > 200 GeV

- Limit plot at 95% CL (Confidence Level):
  - Observed upper limit (solid line)
  - Expected upper limit (dashed line)
  - 68% confidence band (yellow band)
- A BR = 100% is used for theoretical prediction
- For high masses (m_H > 1500 GeV) the upper limits exceed the theoretical prediction
  - Non-sensitivity region of the mono-photon analysis



Second reinterpretation approach

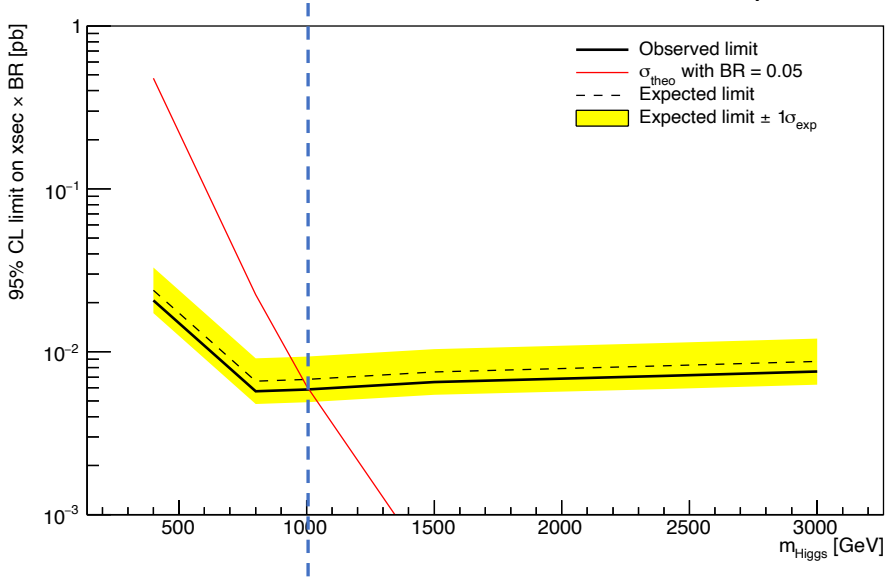
- Same simultaneous fit strategy of the mono-photon analysis
  - Same number of events observed in the CRs and simulated in SRs /CRs for each background process
  - Dark photon signal
  - Signal uncertainties are taken into account
- 8 ggF and VBF Higgs reconstructed samples:
  - The detector response is simulated
  - 400, 600, 800, 1000, 1500, 2000, 2500, 3000 GeV
  - Statistics of N = 10000 events each
- Mono-photon selection



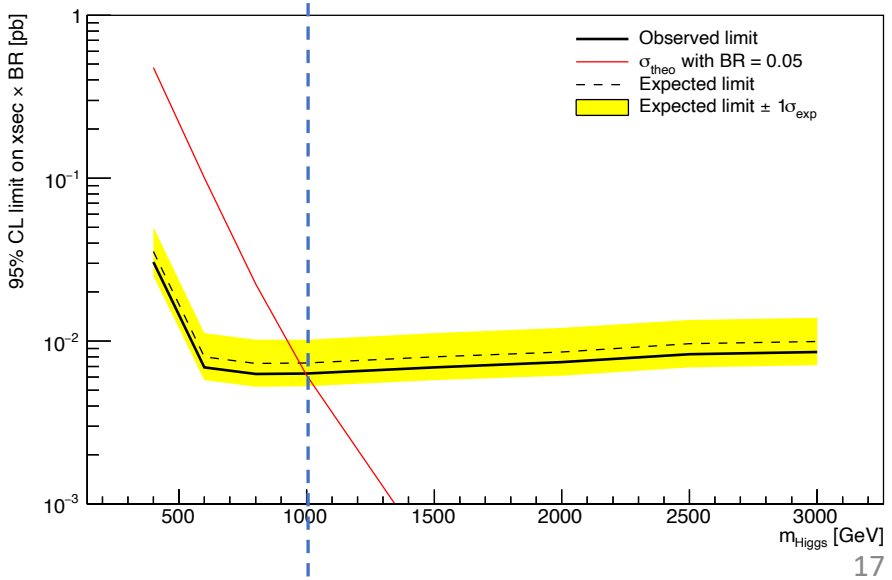
ggF comparison

- Two strategies are adopted in inclusive SRs for the ggF production channel
- The compared results are shown for SRI1 (E_T^{miss} > 200 GeV)
- A BR = 5% is assumed for theoretical prediction, due to present constraints

From model-independent



From model-dependent fit

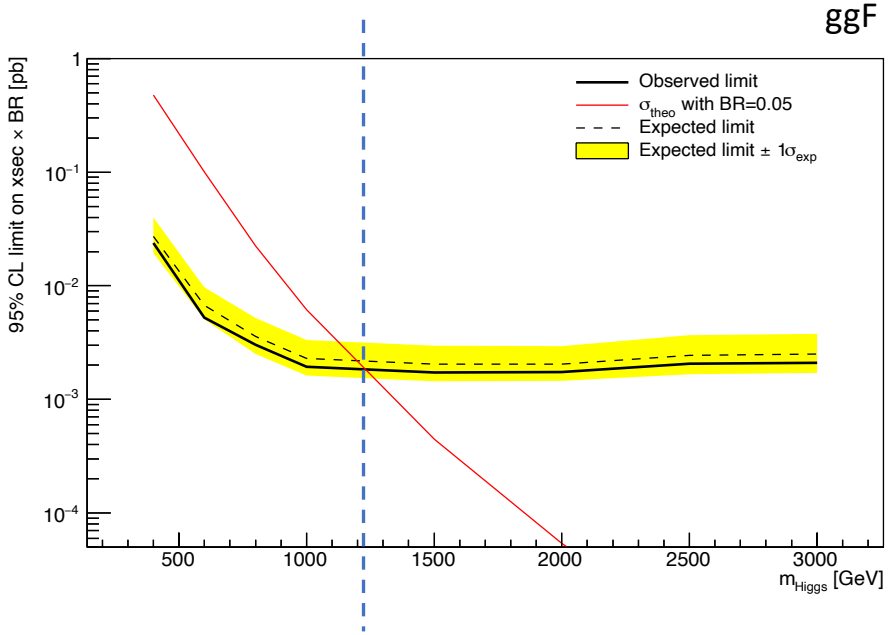


ggF and VBF shape-fit

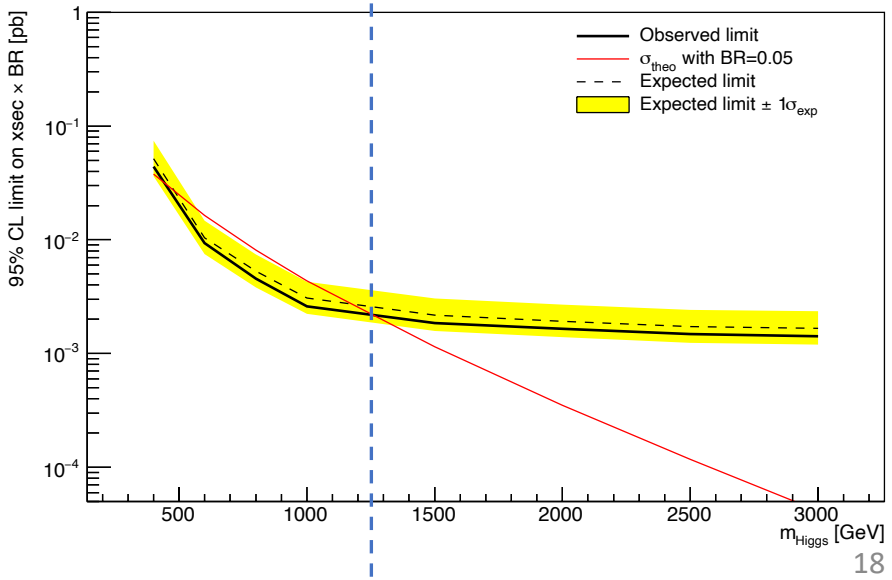
- The shape fit provides best limits, as it exploits the E_T^{miss} information at best
- The compared results are shown for both production processes (ggF and VBF)
- A BR = 5% is assumed for theoretical prediction, due to present constraints

95% CL Limits	$\sigma_{ggF} \times BR$		$\sigma_{VBF} \times BR$	
m_H	Obs. (fb)	Exp. $^{+1\sigma}_{-1\sigma}$ (fb)	Obs. (fb)	Exp. $^{+1\sigma}_{-1\sigma}$ (fb)
400 GeV	23.3	$27.1\ ^{+12.5}_{-8.03}$	44.1	$51.6\ ^{+22.8}_{-15.4}$
600 GeV	5.08	$5.72\ ^{+2.6}_{-1.65}$	9.33	$10.45\ ^{+4.32}_{-2.97}$
800 GeV	3.04	$3.56\ ^{+1.63}_{-1.06}$	4.55	$5.29\ ^{+2.16}_{-1.47}$
1 TeV	1.93	$2.30\ ^{+1.02}_{-0.68}$	2.60	$3.08\ ^{+1.21}_{-0.85}$
1.5 TeV	1.73	$2.04\ ^{+0.93}_{-0.60}$	1.86	$2.18\ ^{+0.86}_{-0.59}$
2 TeV	1.74	$2.05\ ^{+0.88}_{-0.60}$	1.64	$1.92\ ^{+0.78}_{-0.52}$
2.5 TeV	2.06	$2.44\ ^{+1.24}_{-0.77}$	1.48	$1.73\ ^{+0.70}_{-0.49}$
3 TeV	2.10	$2.48\ ^{+1.28}_{-0.75}$	1.42	$1.66\ ^{+0.69}_{-0.46}$

ggF



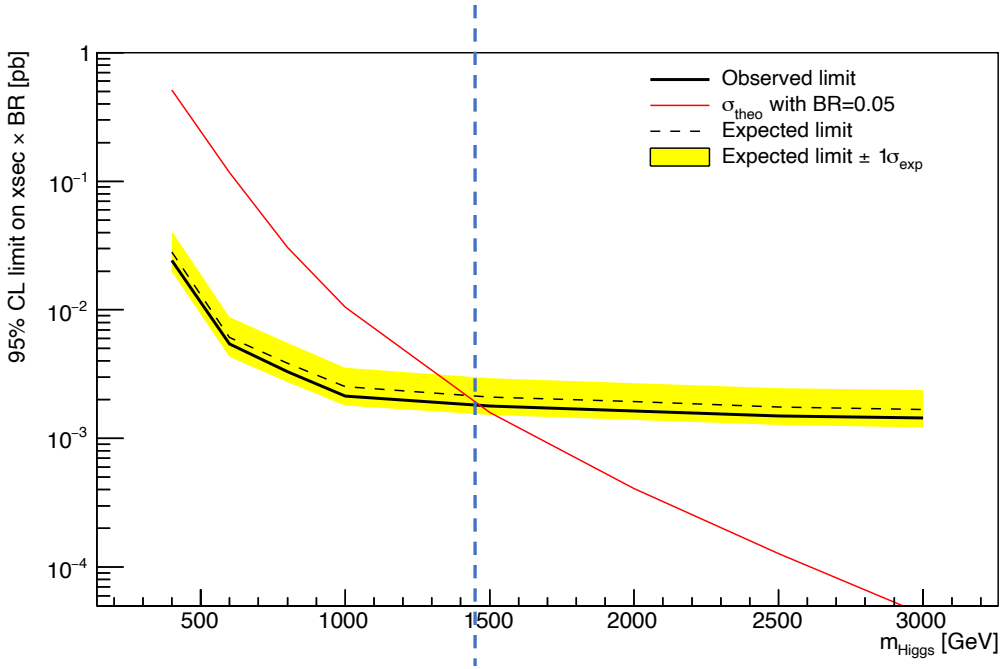
VBF



Combined limits

- Combined exclusion limits are obtained from the shape-fit
- Two production processes are combined proportionally to their relative theoretical cross-section
- A BR = 5% is assumed for theoretical prediction, due to present constraints

95% CL Limits	$\sigma_{ggF} \times BR$		$\sigma_{VBF} \times BR$		$\sigma_{(ggF+VBF)} \times BR$	
m_H	Obs. (fb)	Exp. $^{+1\sigma}_{-1\sigma}$ (fb)	Obs. (fb)	Exp. $^{+1\sigma}_{-1\sigma}$ (fb)	Obs. (fb)	Exp. $^{+1\sigma}_{-1\sigma}$ (fb)
400 GeV	23.3	$27.1\ ^{+12.5}_{-8.03}$	44.1	$51.6\ ^{+22.8}_{-15.4}$	24.2	$28.1\ ^{+12.7}_{-8.30}$
600 GeV	5.08	$5.72\ ^{+2.6}_{-1.65}$	9.33	$10.45\ ^{+4.32}_{-2.97}$	5.45	$6.10\ ^{+2.66}_{-1.80}$
800 GeV	3.04	$3.56\ ^{+1.63}_{-1.06}$	4.55	$5.29\ ^{+2.16}_{-1.47}$	3.31	$3.86\ ^{+1.69}_{-1.13}$
1 TeV	1.93	$2.30\ ^{+1.02}_{-0.68}$	2.60	$3.08\ ^{+1.21}_{-0.85}$	2.14	$2.52\ ^{+1.04}_{-0.71}$
1.5 TeV	1.73	$2.04\ ^{+0.93}_{-0.60}$	1.86	$2.18\ ^{+0.86}_{-0.59}$	1.79	$2.09\ ^{+0.84}_{-0.57}$
2 TeV	1.74	$2.05\ ^{+0.88}_{-0.60}$	1.64	$1.92\ ^{+0.78}_{-0.52}$	1.64	$1.93\ ^{+0.76}_{-0.54}$
2.5 TeV	2.06	$2.44\ ^{+1.24}_{-0.77}$	1.48	$1.73\ ^{+0.70}_{-0.49}$	1.50	$1.75\ ^{+0.71}_{-0.48}$
3 TeV	2.10	$2.48\ ^{+1.28}_{-0.75}$	1.42	$1.66\ ^{+0.69}_{-0.46}$	1.44	$1.68\ ^{+0.69}_{-0.46}$



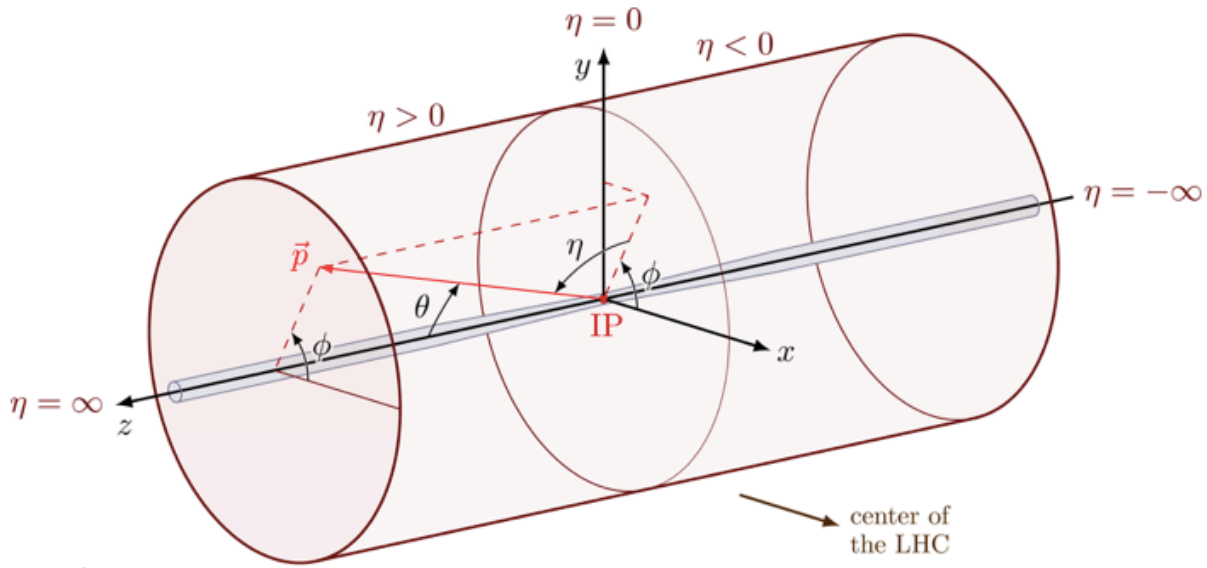
Conclusions

- **Reinterpretation** of mono-photon results in the context of **dark photon** searches, in order to obtain **exclusion limits** on cross section times branching ratio of the process $H \longrightarrow \gamma\gamma_d$
- **Heavy Higgs boson** mass range: 400 GeV – 3000 GeV
- **Two approaches** adopted for the **ggF** production channel:
  - Using model-indipendent limits of the mono-photon analysis
  - Performing the model-dependent fit
- Best exclusion limits combining **ggF** and **VBF** channels, compatible with other ATLAS results
- Results will be included in an **ATLAS publication** soon!

Thank you for your attention!

Coordinate system

- Origin in the interaction point IP
  - z-axis: along the beam direction
  - x-axis: towards ring center
  - y-axis: upwards
- Polar angle θ on the y-z plane
- Azimuthal angle ϕ on the x-y plane (transverse plane)
- Pseudorapidity: $\eta = -ln\, tan\frac{\theta}{2}$
- angular separation: $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$



Photon reconstruction

- Topo-clusters:
  - clusters of energy deposits in connected cells of the EM
  - Matched to Inner Detector (ID) tracks and to conversion vertices
- Photon candidates:
  - converted photons (energy clusters matched to a conversion vertex)
  - unconverted photons (energy clusters that do not match a track or a reconstructed conversion vertex)
- Identification Working Points (WP):
  - Loose WP: $p_T > 10$ GeV and $|\eta| < 2.37$
  - Tight WP: $p_T > 10$ GeV and $|\eta| < 2.37$, not in $1.37 < |\eta| < 1.52$
- FixedCutTight Isolation WP : $E_T^{cone40} < 0.022 E_T^{y} + 2.45$ GeV and $p^{cone20} < 0.05 p_T^{y}$
- Selected photons are required to satisfy the Tight Identification WP and the FixedCutTight Isolation WP

Electron reconstruction

- Topo-clusters:
  - clusters of energy deposits in connected cells of the EM
  - Matched to Inner Detector (ID) tracks and to conversion vertices
- Electron candidates: no conversion vertex is found, but the clusters match a track consistent with originating from an electron produced in the beam interaction region.
- Medium Working Points (MediumLLH): pT > 7 GeV and |eta| < 2.47
- FCLoose Isolation WP: : $E_T^{cone20} < 0.02 p_T^{y}$ and $p^{varcone30} < 0.15 p_T^{y}$
- Transverse impact parameter d_0: significance < 5.0
- Longitudinal impact parameter z_0: $|z_0| \sin(\text{theta}) < 0.05$ mm

Mono-photon event selection

- Pre-selection:
  - data quality: the event must be in the good run list (GRL)
  - HLT g140 loose trigger: at least one photon candidate with Loose WP and p_T> 140 GeV
  - good vertex: primary vertex reconstructed with at least two good-quality tracks with p_T > 0.5 GeV and |eta| < 2.5
  - jet cleaning: no LooseBad jet with p_T > 20 GeV overlapping with leptons or photons
- Selected objects:
  - Photon: pT > 10 GeV and |eta| < 2.37, not in 1.37 < |eta| < 1.52 (crack region)
  - Electron: pT > 7 GeV and |eta| < 2.47
  - Muon: pT > 6 GeV and |eta| < 2.5
  - Jet: pT > 30 GeV and |eta| < 4.5, not overlapping with an electron or photon by DeltaR > 0.4

Simultaneous fitting technique

- Simultaneous likelihood: $\mathcal{L}(data|\bar{k},\bar{\theta}) = \prod_R \mathrm{Pois}(N_R^{obs}|N_R^{bkg}(\bar{k},\bar{\theta})) \times f(\bar{\theta})$
- The free parameters of the fit are the signal yield and three k-factors: k_{yjet} , k_W , k_Z

  $N_{SR}=k_{Z\gamma}N_{SR}^{MC}(Z+\gamma)+ k_{W\gamma}N_{SR}^{MC}(W+\gamma)+ k_{\gamma jet}N_{SR}^{MC}(\gamma +jet)$
- Background uncertainties: nuisance parameters and a Gaussian constraint term
- Background-only fit:
  - Background samples
  - estimation the k-factors
- Model-dependent fit:
  - signal sample
  - set exclusion limits