Workshop on Photon Physics and Simulation at Hadron Colliders

INFN Frascati, June 6-7, 2019

Dark Matter and Supersymmetry with Photons

Bruce A. Schumm

Santa Cruz Institute for Particle Physics

University of California, Santa Cruz

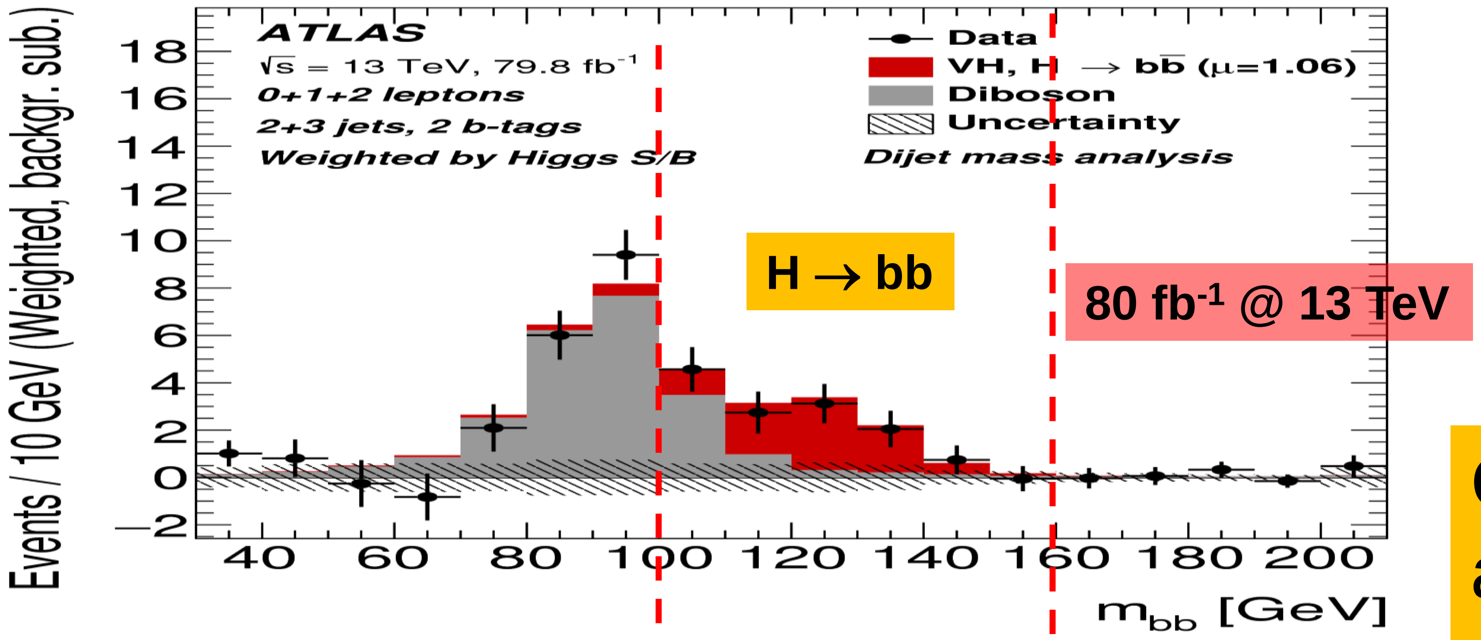
On behalf of the

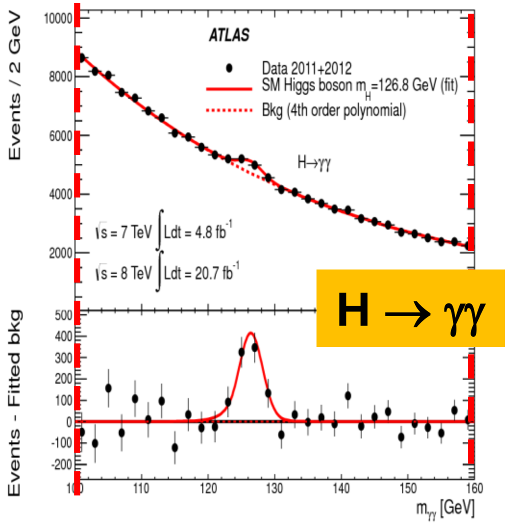
ATLAS and CMS Collaborations

Preamble

- Many models motivate photonic searches
  - GMSB SUSY
  - Compositeness
  - Kaluza-Klein towers
  - Channels with intermediate Higgs
  - Generic dark matter
  - …
- Talk will be organized more by signature than by models
- Although generally we asked that models be motivated by signatures (but finding a signal (!) in a signature motivated by a model won't confirm the model…)
- Will spend a moment on the advantages of photons
- Analyses will be presented in roughly inverse order of "subtlety" of signature (in my estimation)

The Beauty of Photons: Clean and precise





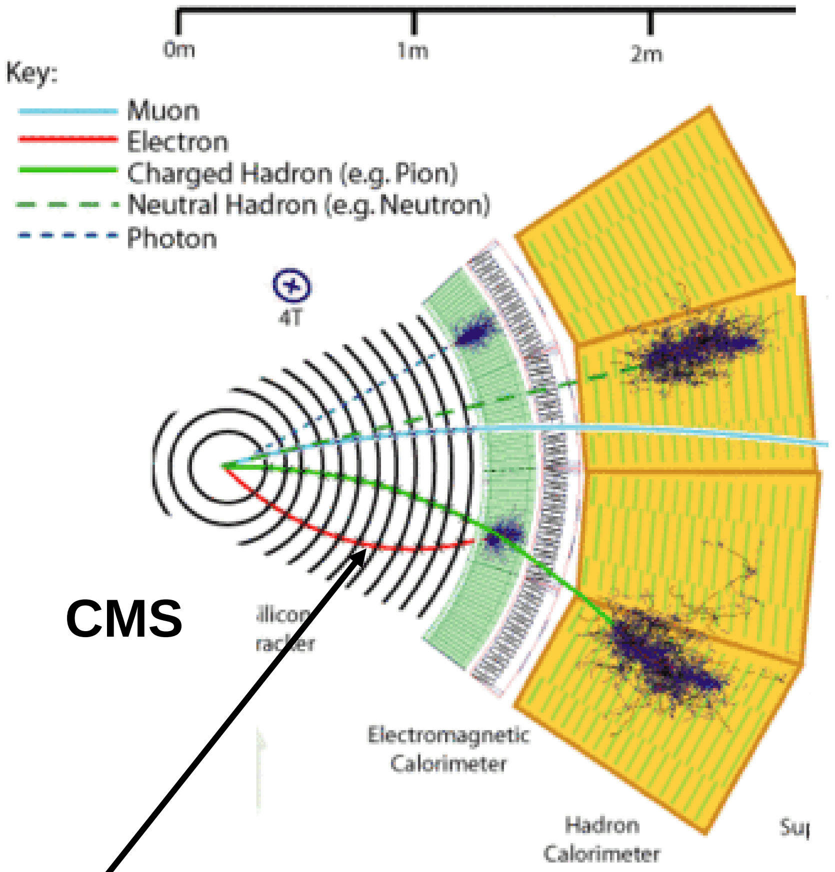
25 fb^{-1} @ 7-8 TeV

Most signals involve EW couplings in the production/decay chain ➔ isolated photons

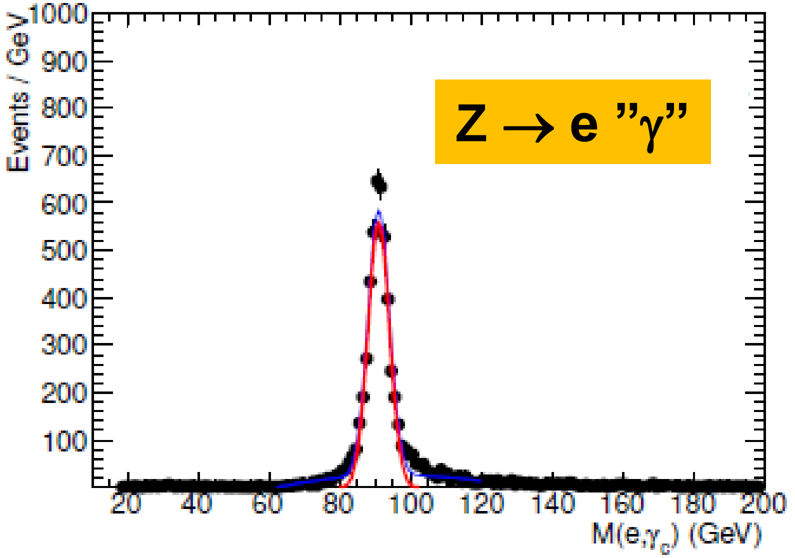
Clarity of reconstruction allows for extraction of clear signal, even over large physics backgrounds

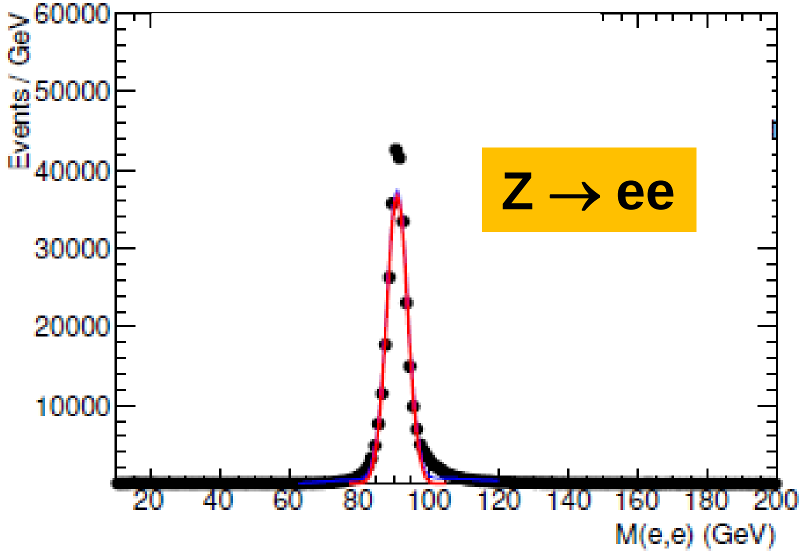
e.g. Higgs discovery B(H→γγ) ≅ 2x10^{-3} but primary contribution to discovery

Backgrounds Relatively Easily Modeled



Missed track ➔ reconstructed as photon





Mis-ID rate 1-5% depending on energy, angle

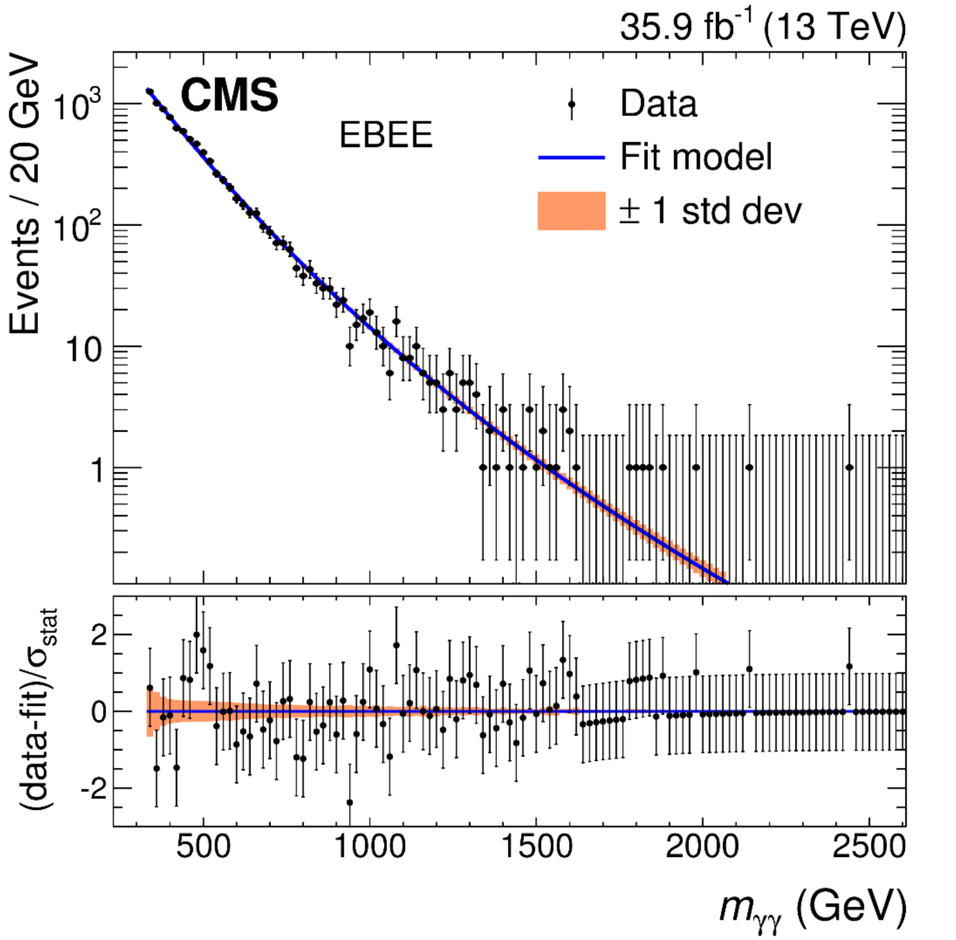
= $e^- \rightarrow \gamma$ mis-ID rate from ratio

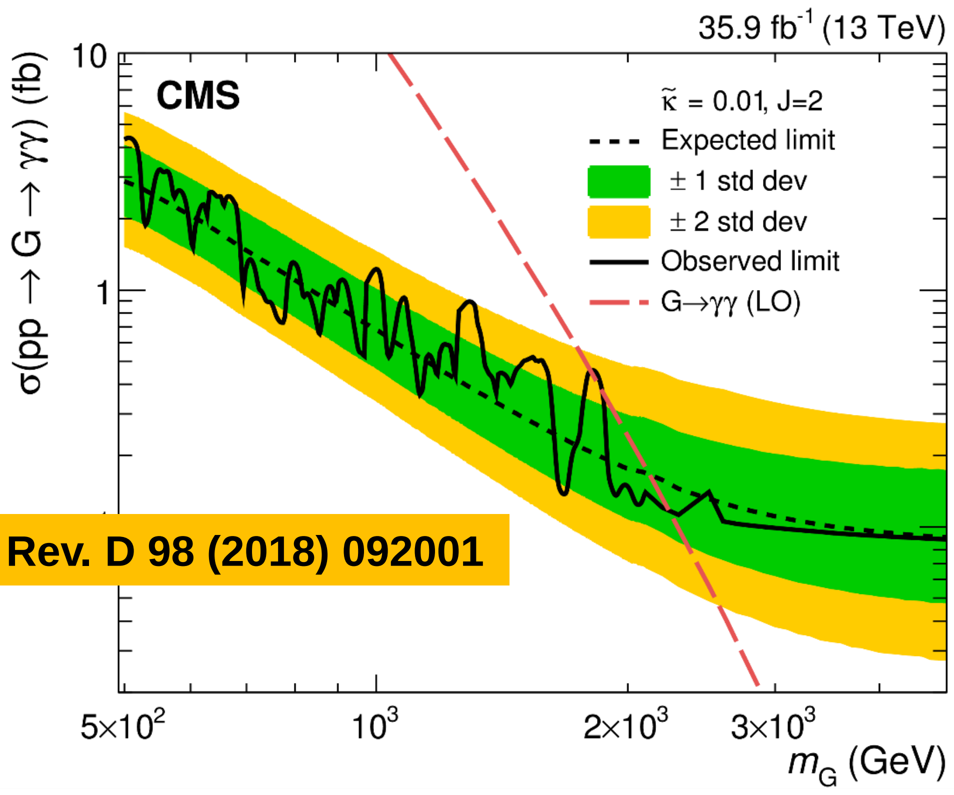
Control sample with signal photon replaced by electron with identical kinematics then establishes background rate

The Analyses

Basic Photonic Search: High Mass Diphoton Resonance

- Motivations: Higgs Multiplets, Extra dimensions, generic scalar resonances
- Event selection essentially just two energetic photons





Phys. Rev. D 98 (2018) 092001

Also ATLAS: Phys. Lett. B 775 (2017) 105

GMSB: Direct Photonic Signatures within SUSY

SUSY is a **broken** symmetry between fermions and bosons…

SUGRA: Local supersymmetry broken by **supergravity** interactions

Phenomenology: LSP (usually χ_1^0) carries **E_t^{miss}**.

GMSB: Explicit couplings to intermediate-scale ($M_{EW} < \Lambda < M_{GUT}$) "messenger" **gauge** interactions **mediate** SUSY breaking.

Phenomenology: Gravitino ($\tilde{G}$) LSP (**E_t^{miss}**); NLSP is χ_1^0 or slepton $\tilde{\tau}$. χ_1^0 tends to be bino-like ➔ **photonic signatures**.

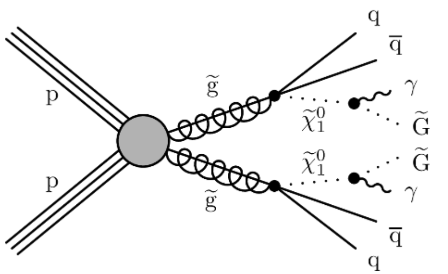
AMSB: Higher-dimensional SUSY breaking communicated to 3+1 dimensions via "Weyl **anomaly"**.

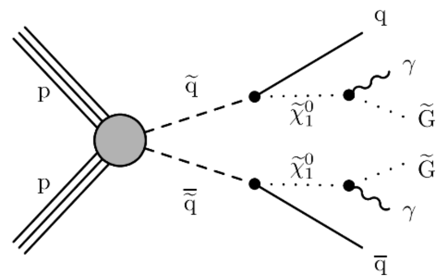
Phenomenology: LSP tends to be $\tilde{W}$, with χ_1^+, χ_1^0 nearly degenerate.

GMSB scenarios supply the inspiration for direct photons signatures

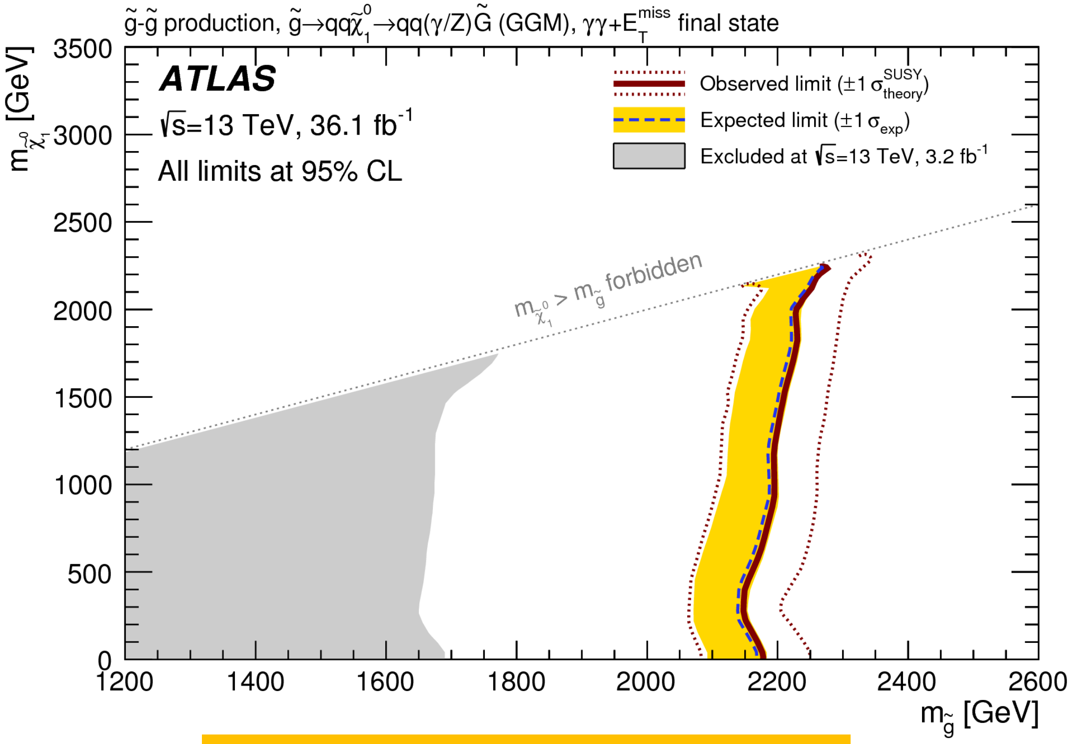
(**SUGRA** inspires intermediate-Higgs scenarios)

GMSB: Strong Production





Signal Region	$SR^{\gamma\gamma}_{S-L}$	$SR^{\gamma\gamma}_{S-H}$
Number of photons	≥ 2	≥ 2
E_T^{γ} [GeV]	> 75	> 75
Number of jets	...	...
Number of leptons	...	...
E_T^{miss} [GeV]	> 150	> 250
H_T [GeV]	> 2750	> 2000
m_{eff} [GeV]	...	...
R_T^4	...	...
$\Delta\phi_{min}(\text{jet}, E_T^{miss})$	> 0.5	> 0.5
$\Delta\phi_{min}(\gamma, E_T^{miss})$ $(\Delta\phi(\gamma, E_T^{miss}))$	...	> 0.5



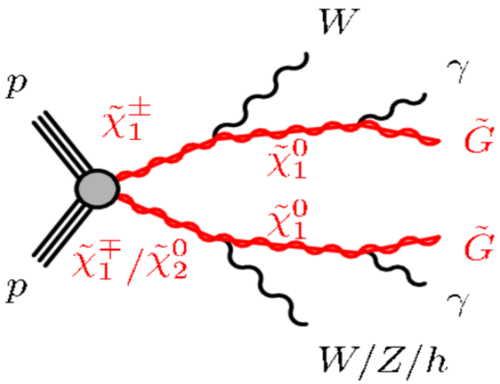
Signal Region	$SR^{\gamma\gamma}_{S-L}$	$SR^{\gamma\gamma}_{S-H}$
Jet $\to \gamma$	$0.19^{+0.21}_{-0.19}$	$0.19^{+0.21}_{-0.19}$
QCD diphoton	$0.00^{+0.17}_{-0.00}$	$0.00^{+0.17}_{-0.00}$
EW background	0.08 ± 0.04	0.06 ± 0.04
$(W \to \ell\nu)\gamma\gamma$	0.22 ± 0.14	0.21 ± 0.13
$(Z \to \nu\nu)\gamma\gamma$	0.01 ± 0.01	0.03 ± 0.02
Expected background events	$0.50^{+0.30}_{-0.26}$	$0.48^{+0.30}_{-0.25}$
Observed events	0	0

Phys. Rev. D 97 (2018) 092006

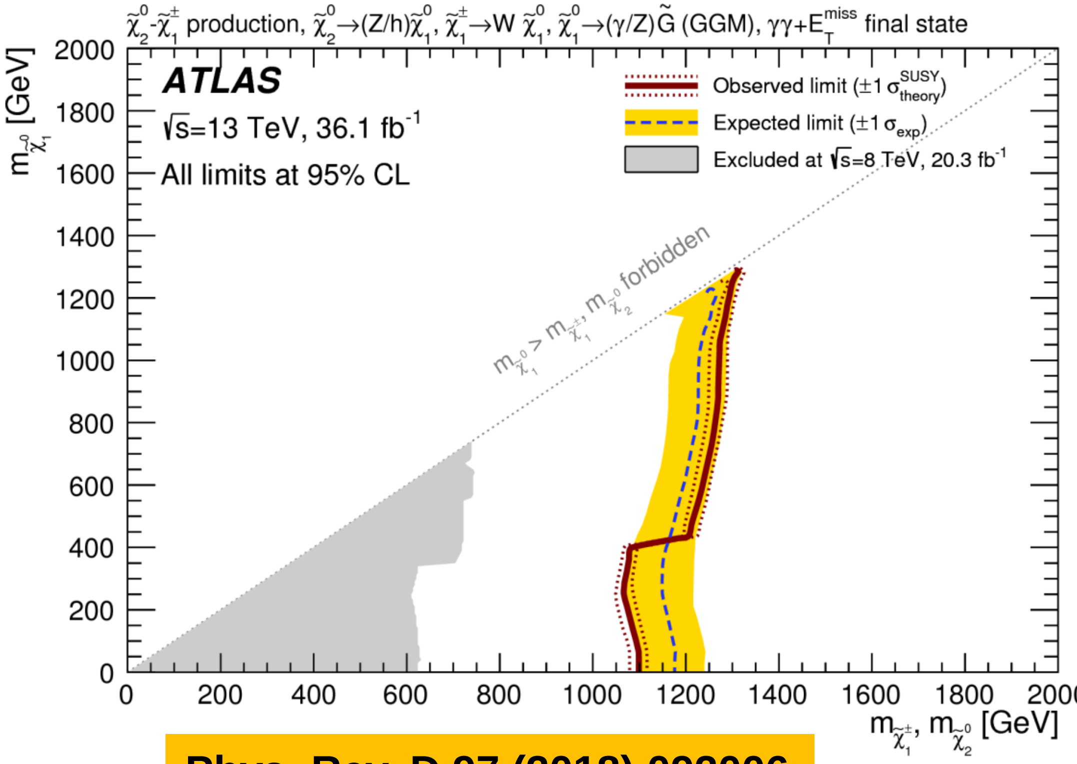
$$\frac{d\sigma}{dM_{\tilde{g}}}(M_{\tilde{g}} = 2200) \propto M_{\tilde{g}}^{-9}$$

Also CMS: arXiv:1903.07070; submitted to JHEP

GMSB: Electroweak Production



Signal Region	$\mathrm{SR}^{\gamma\gamma}_{\mathrm{W-L}}$	$\mathrm{SR}^{\gamma\gamma}_{\mathrm{W-H}}$
Number of photons	≥ 2	≥ 2
E_{T}^{γ} [GeV]	> 75	> 75
Number of jets	...	...
Number of leptons	...	...
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 150	> 250
H_{T} [GeV]	> 1500	> 1000
m_{eff} [GeV]	...	...
R_{T}^4	...	...
$\Delta\phi_{\mathrm{min}}(\mathrm{jet}, E_{\mathrm{T}}^{\mathrm{miss}})$	> 0.5	> 0.5
$\Delta\phi_{\mathrm{min}}(\gamma, E_{\mathrm{T}}^{\mathrm{miss}})$ $(\Delta\phi(\gamma, E_{\mathrm{T}}^{\mathrm{miss}}))$	...	> 0.5

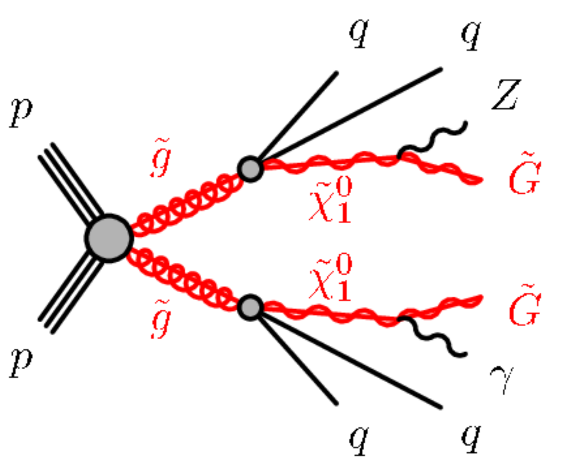


Phys. Rev. D 97 (2018) 092006

Signal Region	$\mathrm{SR}^{\gamma\gamma}_{\mathrm{W-L}}$	$\mathrm{SR}^{\gamma\gamma}_{\mathrm{W-H}}$
Jet $\rightarrow \gamma$	0.93 ± 0.67	$0.19^{+0.21}_{-0.19}$
QCD diphoton	$0.15^{+0.17}_{-0.15}$	$0.00^{+0.17}_{-0.00}$
EW background	0.88 ± 0.23	0.51 ± 0.15
$(W \rightarrow \ell\nu)\gamma\gamma$	1.55 ± 0.78	1.08 ± 0.56
$(Z \rightarrow \nu\nu)\gamma\gamma$	0.15 ± 0.08	0.27 ± 0.13
Expected background events	3.7 ± 1.1	$2.05^{+0.65}_{-0.63}$
Observed events	6	1

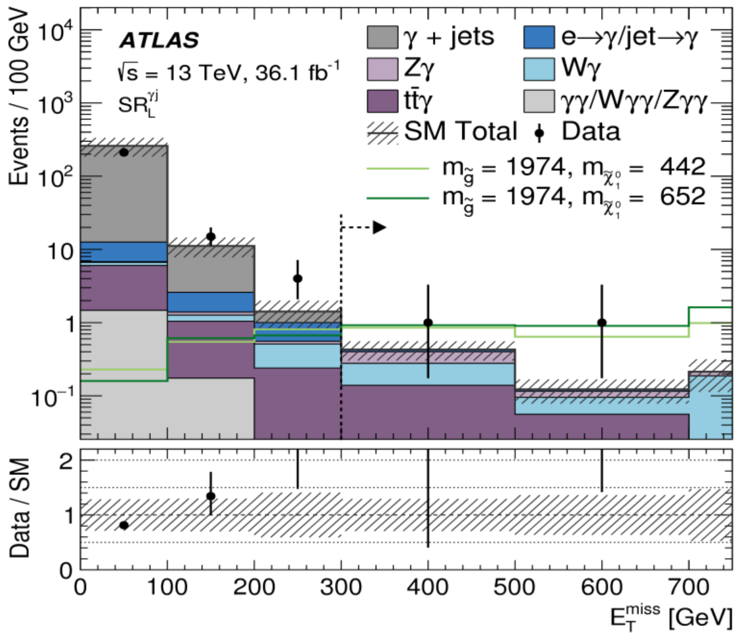
- Lower production cross section: somewhat more challenging to separate from backgrounds
- Can benefit from increased statistics

GMSB: Can you find it with just one photon?



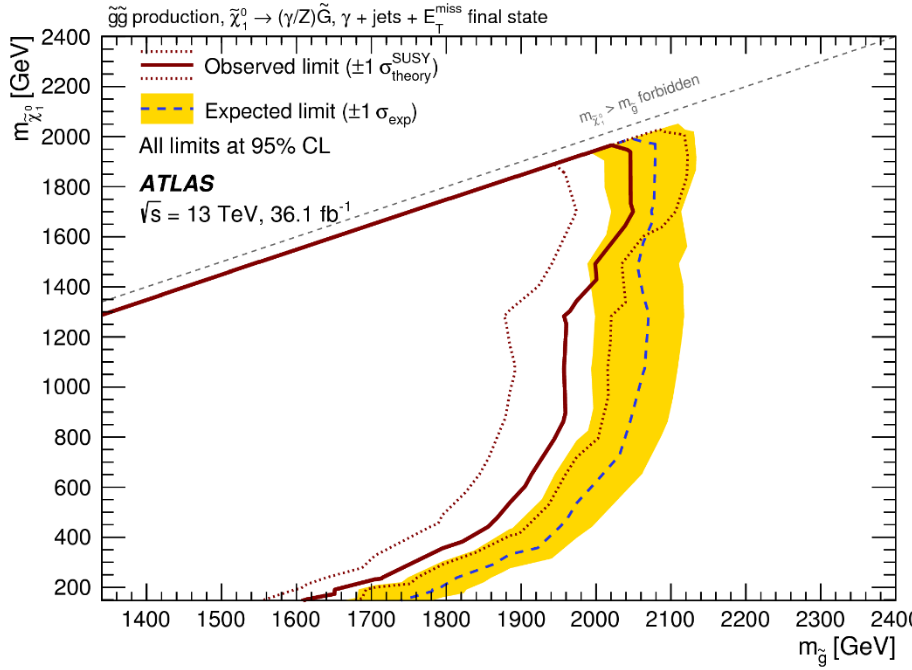
- Mixed NLSP can lead to limited γ production
- High backgrounds in single-photon samples
- Suppress with large MET, extensive jet activity
- Becomes model specific (models provide more discriminators, at cost of generality)
- Possibility of missing signals (ideas needed!)

Signal Region	$\mathrm{SR}^{\gamma j}_{\mathrm{L200}}$	$\mathrm{SR}^{\gamma j}_{\mathrm{H}}$
Number of photons	≥ 1	≥ 1
E_{T}^{γ} [GeV]	> 145	> 400
Number of jets	≥ 5	≥ 3
Number of leptons	0	0
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 200	> 400
H_{T} [GeV]	...	...
m_{eff} [GeV]	> 2000	> 2400
R_{T}^4	< 0.90	...
$\Delta\phi_{\mathrm{min}}(\mathrm{jet}, E_{\mathrm{T}}^{\mathrm{miss}})$	> 0.4	> 0.4
$\Delta\phi_{\mathrm{min}}(\gamma, E_{\mathrm{T}}^{\mathrm{miss}})$ $(\Delta\phi(\gamma, E_{\mathrm{T}}^{\mathrm{miss}}))$	(> 0.4)	(> 0.4)



- After all other cuts, look for signal at high E_T^{miss}
- Small excess observed

Phys. Rev. D 97 (2018) 092006

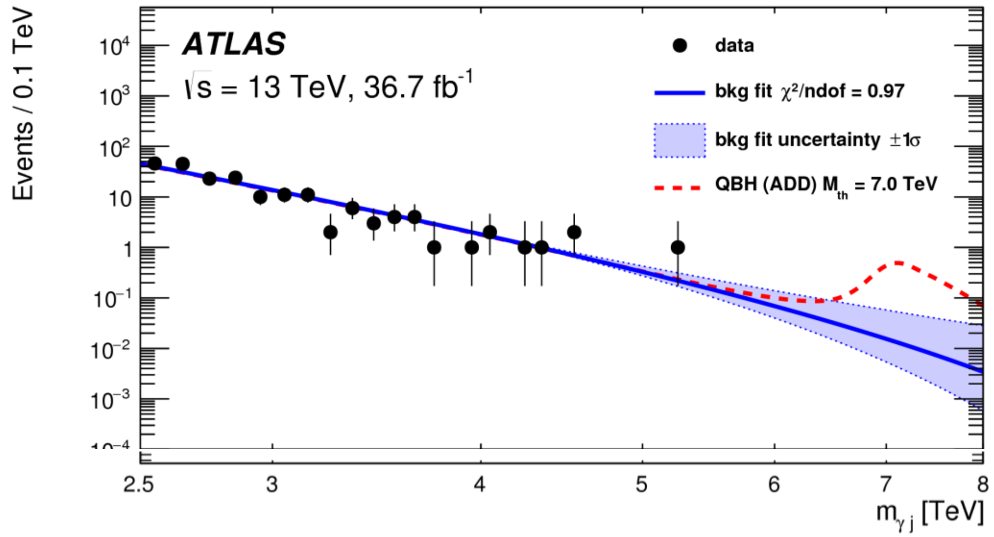


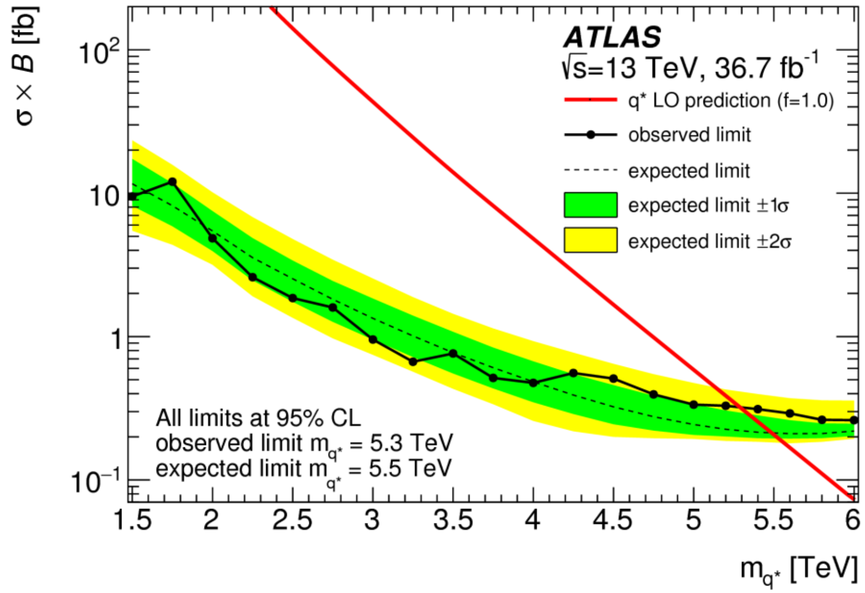
Or: Single Photon, but Paired to Form Exotic Resonance

- De-excitation of exited strong states can be reconstructed as relatively narrow states ("γ-jet resonance")
- Excited composite quarks ($q^* \rightarrow q\gamma$)
- Kaluza-Klein de-excitation
- Set limits on compositeness scale Λ or size of extra dimensions

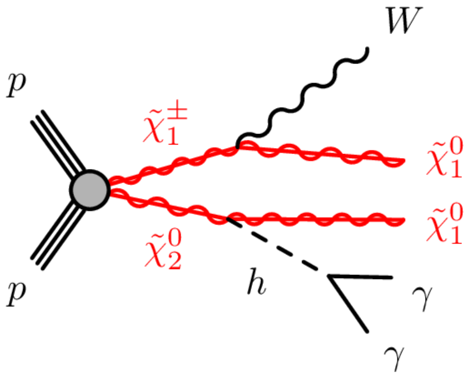
Particle-level selection for fiducial region
Photon : $E_T^{\gamma} > 150$ GeV, $\lvert\eta^{\gamma}\rvert < 1.37$ Jet : $p_T^{jet} > 60$ GeV, $\lvert\eta^{jet}\rvert < 4.5$ Photon–Jet η separation : $\lvert\Delta\eta_{\gamma j}\rvert < 1.6$ No jet with $p_T^{jet} > 30$ GeV within $\Delta R < 0.8$ around the photon
Detector-level selection for selection efficiency
Tight photon identification Photon isolation Jet identification including quality and pile-up rejection requirements

Eur. Phys. J. C (2018) 102





SUSY: $\chi_2^0\chi_1^\pm$ production; $\chi_1^\pm \rightarrow W\chi_1^0$ and $\chi_2^0 \rightarrow h\chi_1^0$; $h \rightarrow \gamma\gamma$

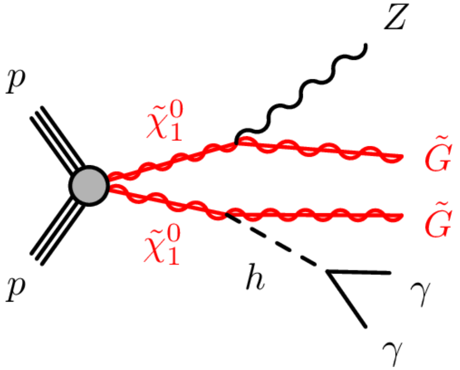


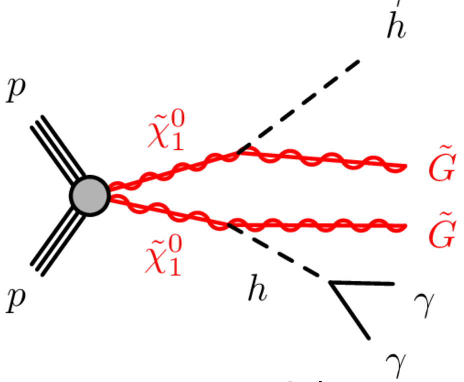
Channels	Names	Selection
Leptonic	Category 1	$0 < S_{E_T^{miss}} \leq 2,\ N_\ell \geq 1$
	Category 2	$2 < S_{E_T^{miss}} \leq 4,\ N_\ell \geq 1$
	Category 3	$4 < S_{E_T^{miss}} \leq 6,\ N_\ell \geq 1$
	Category 4	$S_{E_T^{miss}} > 6,\ N_\ell \geq 1$
Hadronic	Category 5	$5 < S_{E_T^{miss}} \leq 6,\ N_\ell = 0,\ N_j \geq 2,\ M_{jj} \in [40, 120]\ GeV$
	Category 6	$6 < S_{E_T^{miss}} \leq 7,\ N_\ell = 0,\ N_j \geq 2,\ M_{jj} \in [40, 120]\ GeV$
	Category 7	$7 < S_{E_T^{miss}} \leq 8,\ N_\ell = 0,\ N_j \geq 2,\ M_{jj} \in [40, 120]\ GeV$
	Category 8	$S_{E_T^{miss}} > 8,\ N_\ell = 0,\ N_j \geq 2,\ M_{jj} \in [40, 120]\ GeV$
Rest	Category 9	$6 < S_{E_T^{miss}} \leq 7,\ N_\ell = 0,\ N_j < 2$ or $(N_j \geq 2,\ M_{jj} \notin [40, 120]\ GeV)$
	Category 10	$7 < S_{E_T^{miss}} \leq 8,\ N_\ell = 0,\ N_j < 2$ or $(N_j \geq 2,\ M_{jj} \notin [40, 120]\ GeV)$
	Category 11	$8 < S_{E_T^{miss}} \leq 9,\ N_\ell = 0,\ N_j < 2$ or $(N_j \geq 2,\ M_{jj} \notin [40, 120]\ GeV)$
	Category 12	$S_{E_T^{miss}} > 9,\ N_\ell = 0,\ N_j < 2$ or $(N_j \geq 2,\ M_{jj} \notin [40, 120]\ GeV)$

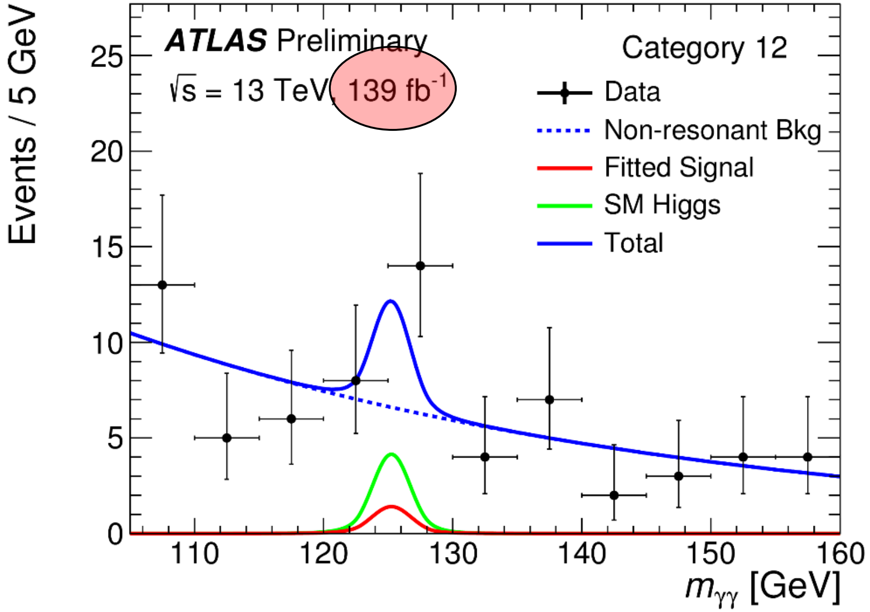
- Good examples of an Intermediate Higgs channel
- Main (continuum) background constrained by sidebands

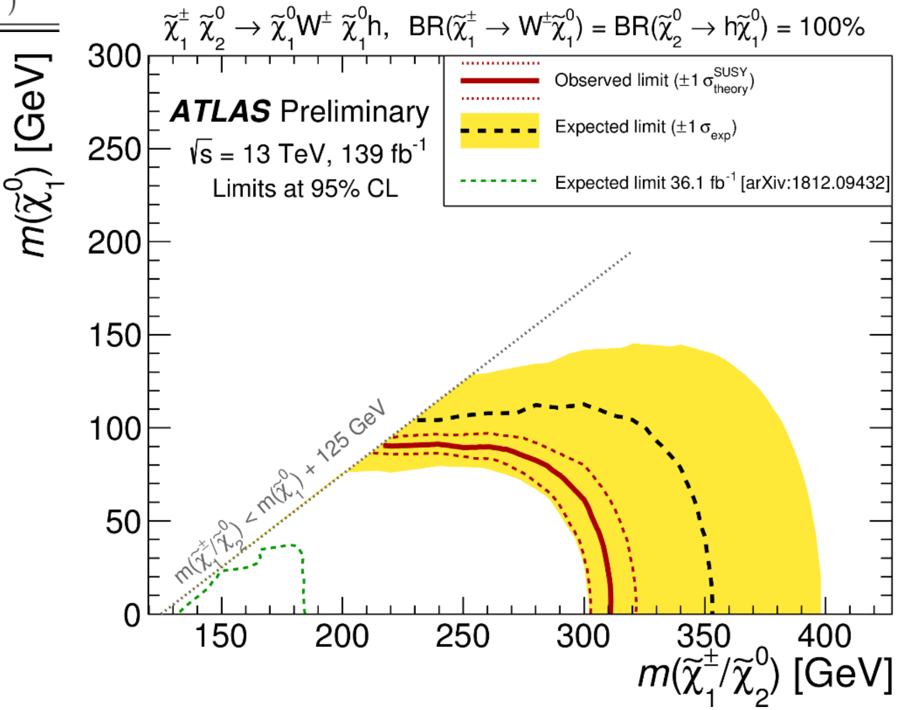
ATLAS-CONF-2019-019; May 2017

Also:

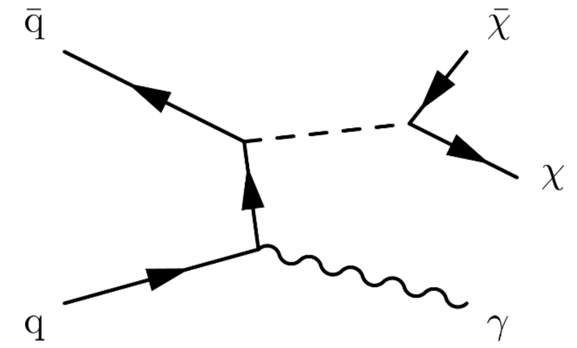




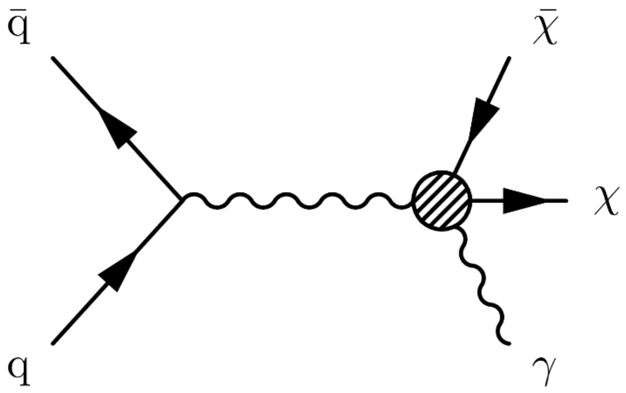


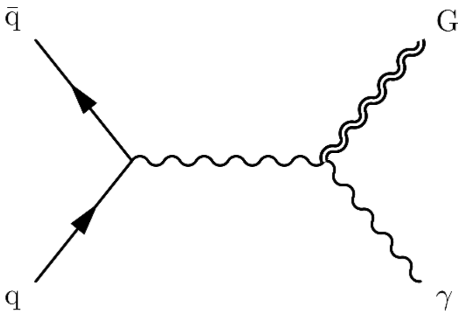


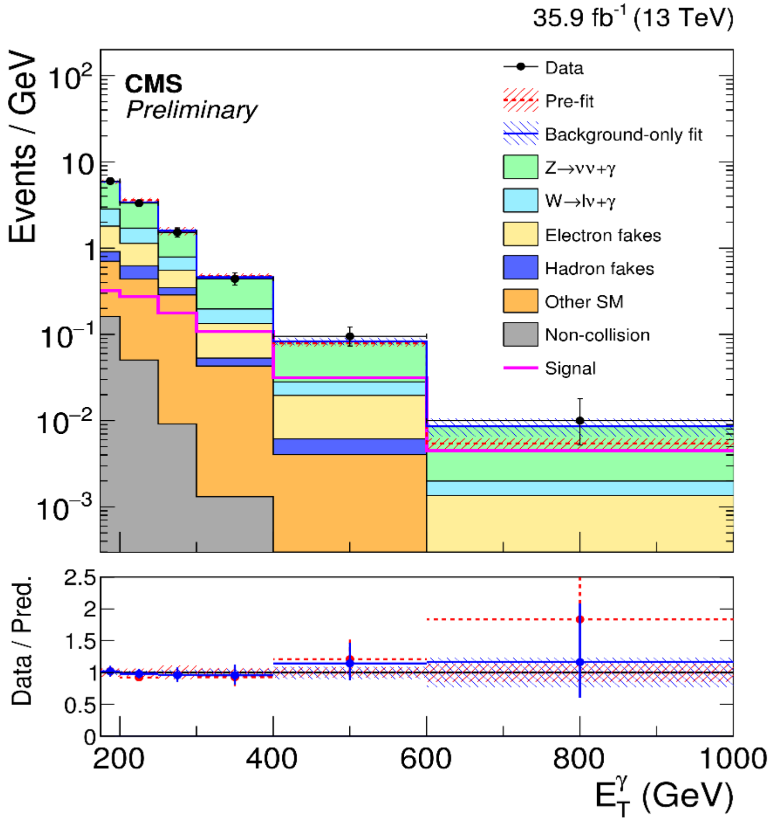
Monophoton: Generic Production of Invisible States



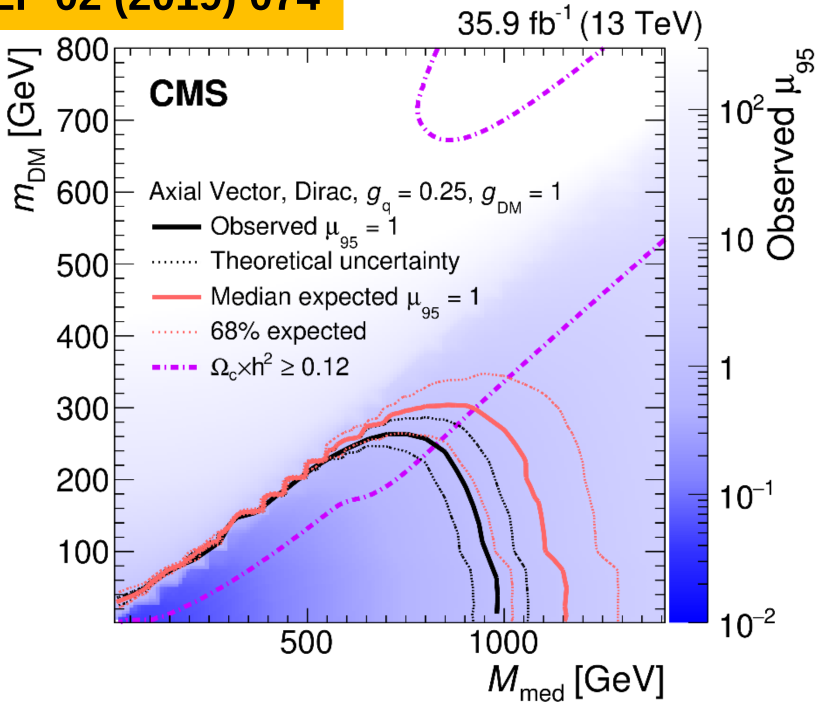
- Produced state is invisible; can only be detected in recoil against SM parton (photon, jet)
- Photons produced via ISR, or in effective contact interaction
- Recoil produces significant E_t^{miss}
- $E_T^{miss} > 170$, $E_T^{\gamma} > 175$, and $E_T^{\gamma} / E_T^{miss} < 1.4$ to protect against mis-measurement







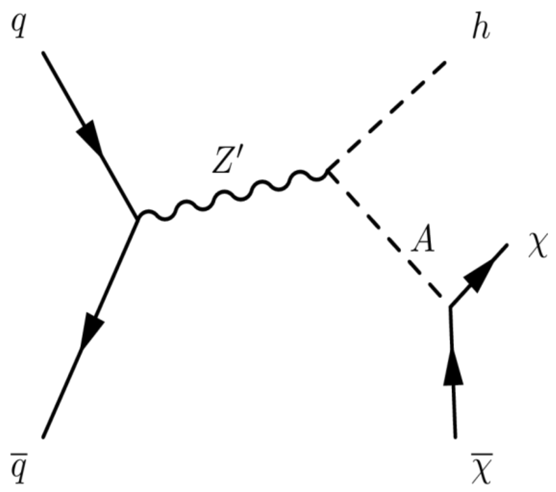
JHEP 02 (2019) 074

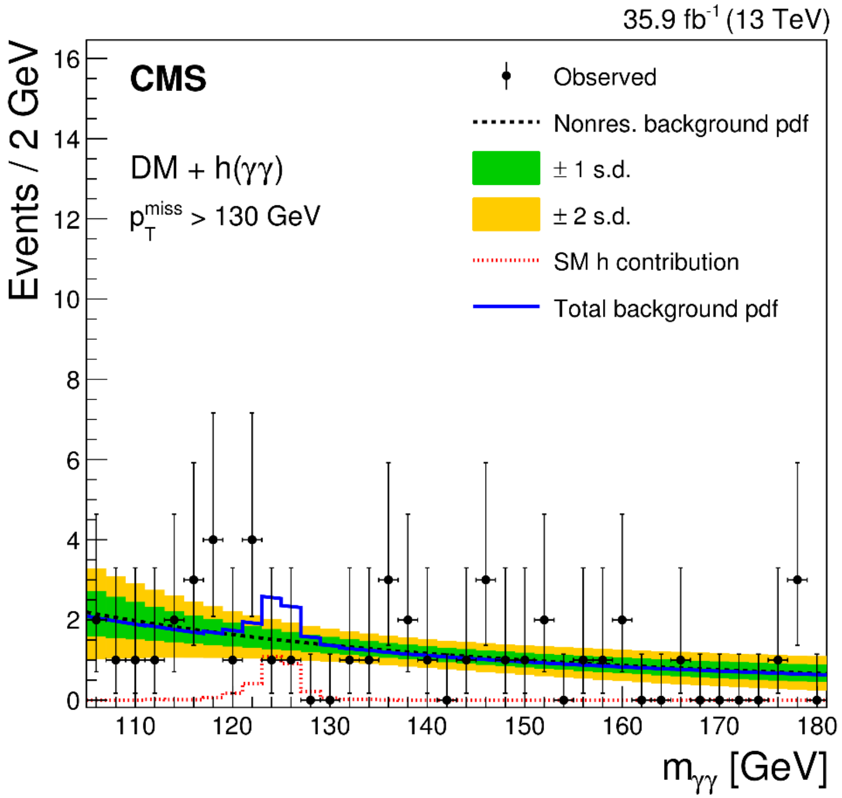


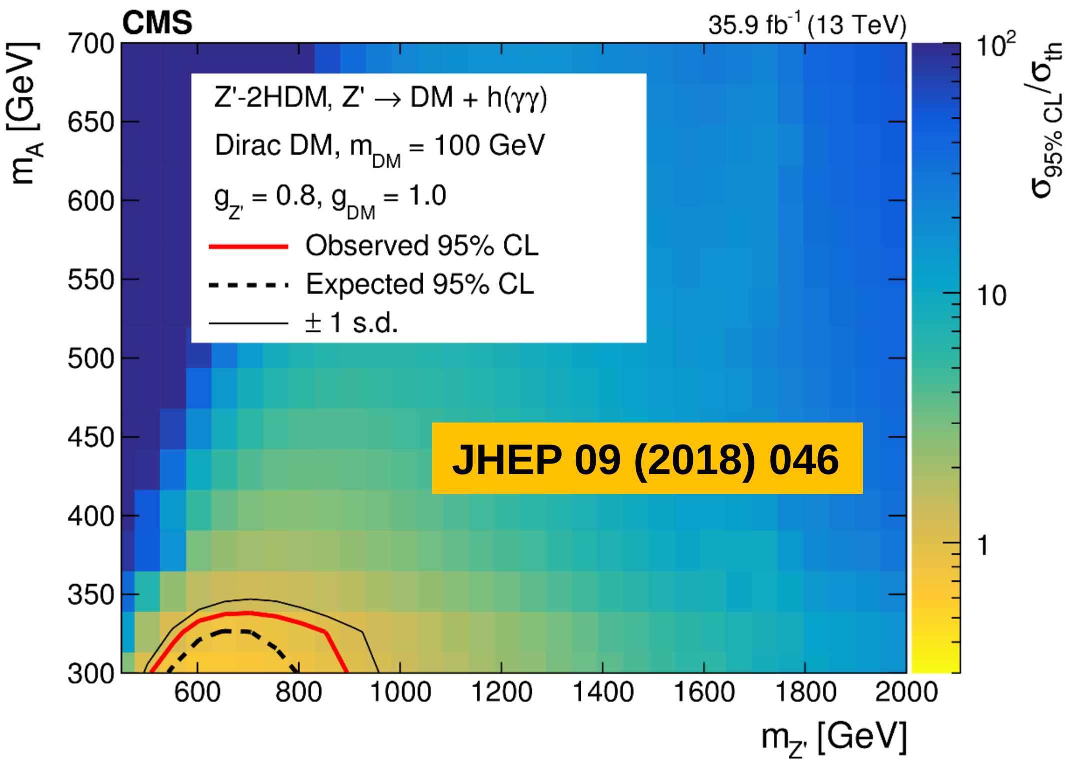
Also ATLAS: Eur. Phys. J. C 77 (2017) 393

Higgstrahlung: Another Use of Photons in DM Searches

- Radiative search, but with two photons forming h_{125}
- Very low backgrounds
- Pay price of branching rate (~2×10^{-3})







JHEP 09 (2018) 046

Most sensitive analysis for low-mass Z' propagator

Anomalous Couplings (First, $Q^2 = 0$; proton moment μ_p)

$$\mu_N = \frac{e}{2 m_N}$$

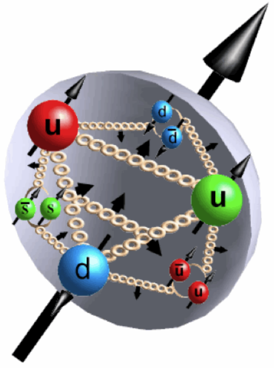
Nuclear magneton μ_N arises for point-like states (pre-1950s proton) in the Dirac theory, but:

$$\mu_p = \text{measured} = 2.793\,\mu_N$$

$$|p\rangle = \text{octet uud} = \frac{1}{\sqrt{2}}\left\{(8_{MS}, 2_{MS}) + (8_{MA}, 2_{MA})\right\}$$

$$= \frac{1}{\sqrt{18}}\,\big|\,2u\uparrow u\uparrow d\downarrow + 2d\downarrow u\uparrow u\uparrow + 2u\uparrow d\downarrow u\uparrow - u\downarrow u\uparrow d\uparrow - u\uparrow u\downarrow d\uparrow - d\uparrow u\uparrow u\downarrow - d\uparrow u\downarrow u\uparrow - u\downarrow d\uparrow u\uparrow - u\uparrow d\uparrow u\downarrow \,\big\rangle$$

But there's more going on… **new physics** leads to **anomalous photonic couplings** that provide essential clues to the deeper under-standing of nature (e.g. SU(3) quark model)

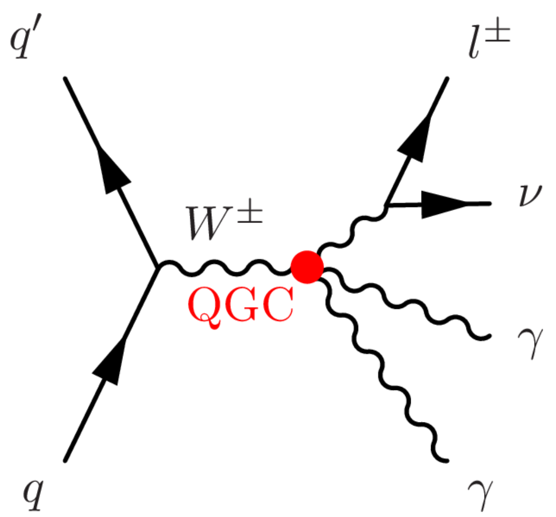


Proton's SU(3) Wavefunction → → →

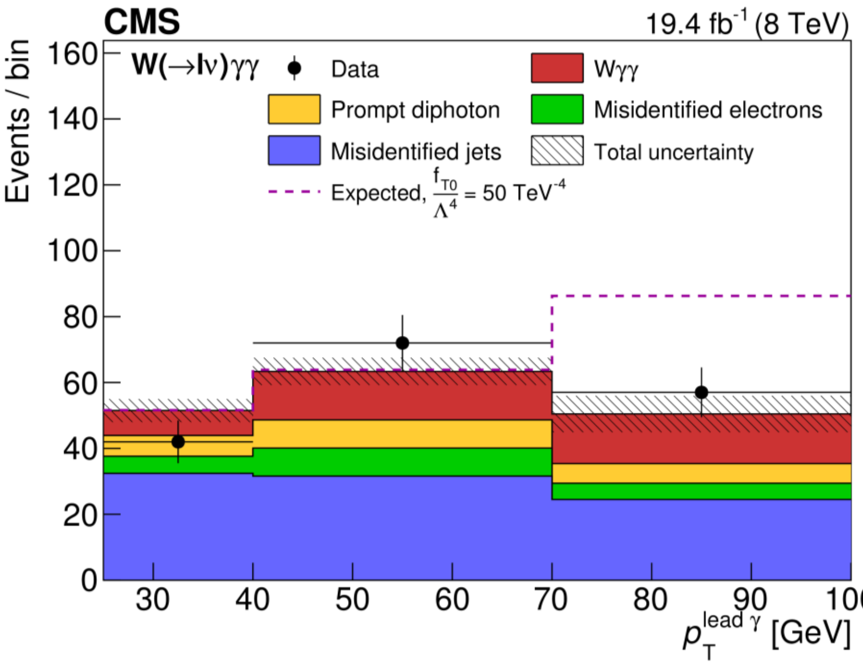
$$\mu_p = \frac{1}{3}(4\mu_u - \mu_d) = 2.79\,\mu_N \qquad \text{measured} = 2.793\,\mu_N$$

REMARKABLE!!

Radiative Behavior (Anomalous Couplings at $Q^2 > 0$)

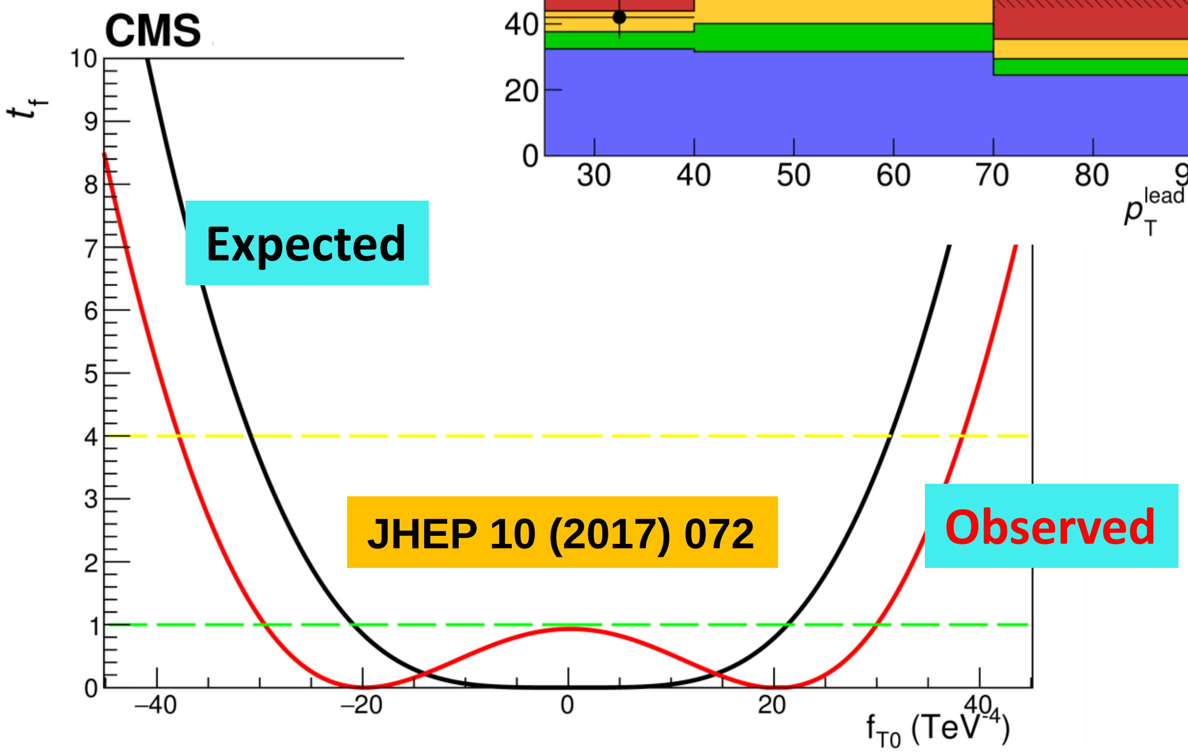


- Anomalous couplings change the rate of photon emission (“radiation”) by SM objects
- Substructure, non-standard quantum numbers, new forces



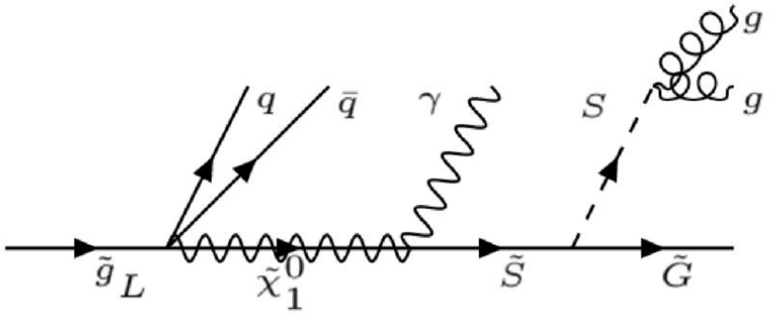
Definition of $W^{\pm}\gamma\gamma$ Fiducial Region

$p_T^{\gamma} > 25\,\text{GeV}$, $\lvert\eta^{\gamma}\rvert < 2.5$ $p_T^{\ell} > 25\,\text{GeV}$, $\lvert\eta^{\ell}\rvert < 2.5$
Exactly one candidate muon and two candidate photons $m_T(\ell, \nu_{(s)}) > 40\,\text{GeV}$ $\Delta R(\gamma,\gamma) > 0.4$ and $\Delta R(\gamma,\ell) > 0.4$



Also ATLAS: JHEP 12 (2018) 010

“Stealth” SUSY with **Non-Isolated** Photons

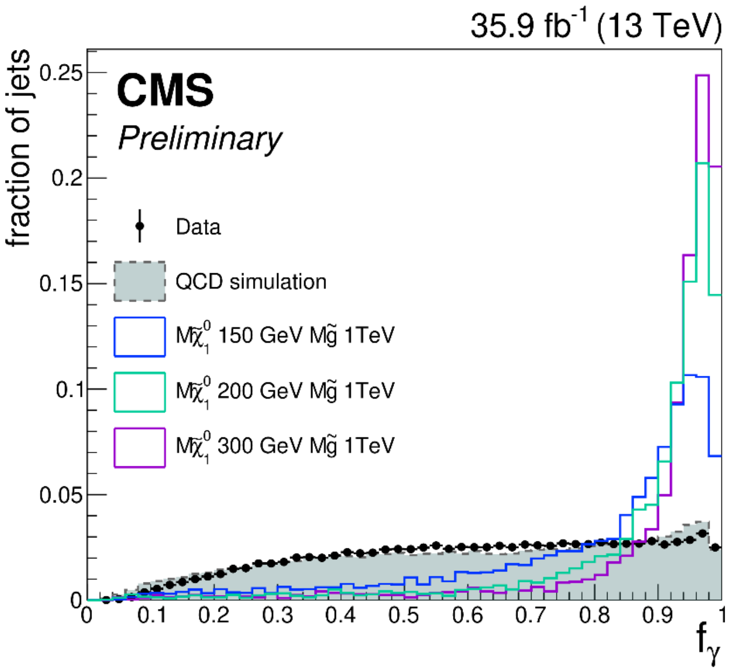


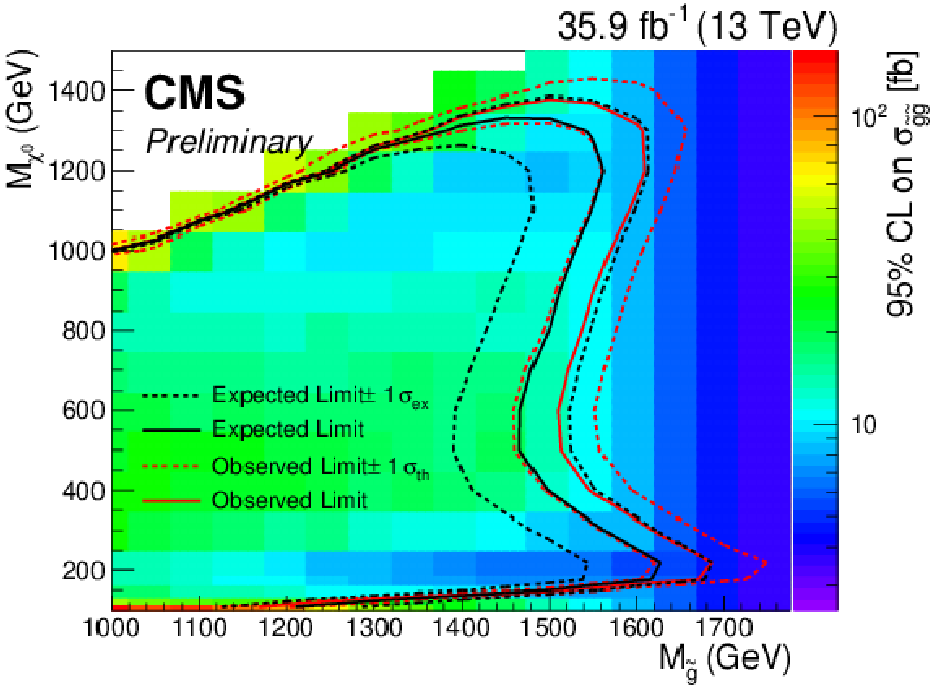
S, $\tilde{S}$ are lightly-couple, degenerate hidden sector bosons

➔ $\tilde{G}$ produced with little momentum, so event has limited missing energy

Photon buried in jet ➔ challenging, requires sophisticated jet substructure tools

- 3+ jets
- One subjet with high photon energy fraction f_y
- Large total visible energy (H_T ~ 2 TeV)





CMS-PAS-B2G-18-007

Summary/Conclusion/Exhortation

PHOTONS offer a clean, powerful and often low-background approach to searching for new physics

Their **unique, relatively strong coupling** to SM fermions and bosons allow for the development of many promising signatures, motivated by some of the most promising BSM hypothesis (especially SUSY)

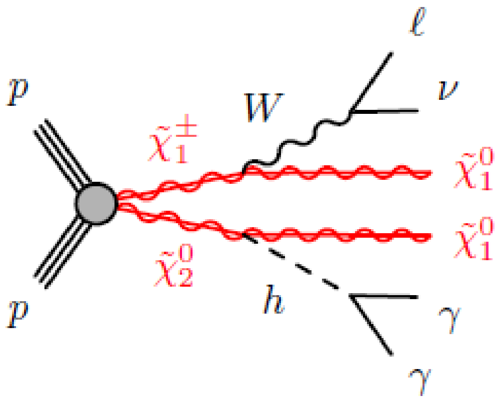
The **intermediate Higgs channels**, while suffering a bit from the low $H \to \gamma\gamma$ branching fraction, offer a clean approach with excellent control of backgrounds that competes well with and complements other approaches.

Some of the **highest-mass limits** are established with photonic searches ($M_{\tilde{g}}$>2200 GeV in bino-like NLSP scenario)

Subtle signatures that might hold the key to breakthrough discoveries (e.g. Stealth SUSY) **remain under development**!

BACKUP

SUSY: $\chi_2^0\chi_1^\pm$ production; $\chi_1^\pm \to W\chi_1^0$ and $\chi_2^0 \to h\chi_1^0$; $h \to \gamma\gamma$

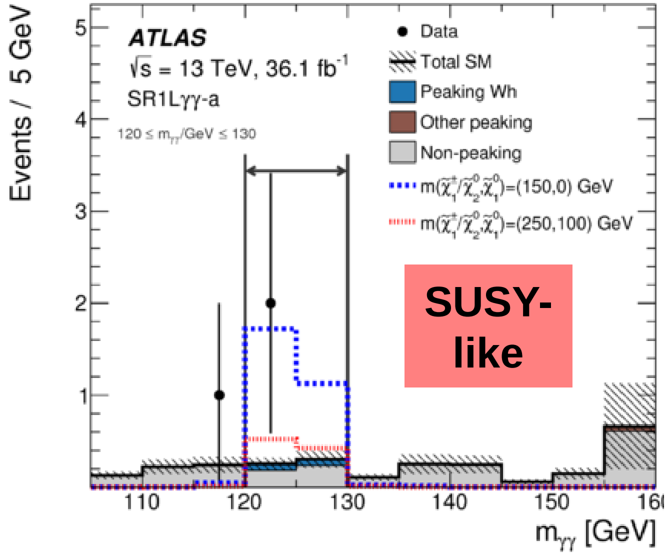


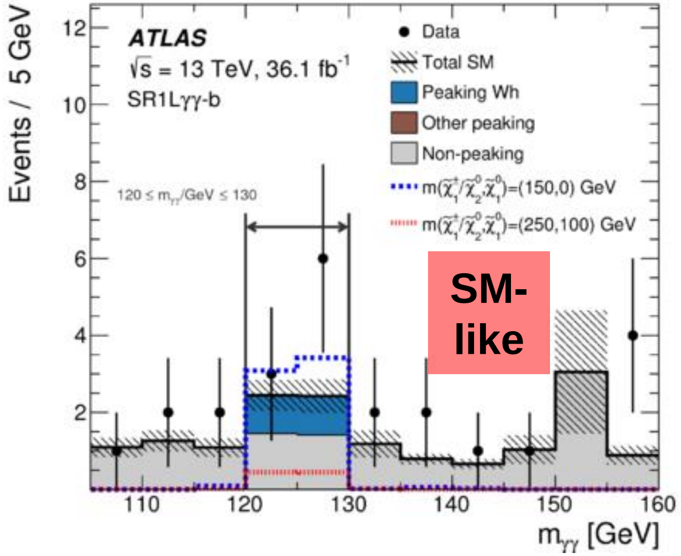
Variable	SR1Lγγ-a	SR1Lγγ-b
N_γ	$= 2$	
p_T^γ [GeV]	$> (40, 31)$	
N_{lepton}	$= 1$	
p_T^ℓ [GeV]	> 25	
E_T^{miss} [GeV]	> 40	
$\Delta\phi_{W,h}$	> 2.25	
$m_{\gamma\gamma}$ [GeV]	$\in [120, 130]$	
$N_{b\text{-jet}}$ ($p_T > 30$ GeV)	$= 0$	
$m_T^{W\gamma_1}$ [GeV]	≥ 150	
$m_T^{W\gamma_2}$ [GeV]	> 140	$\in [80, 140]$
m_T [GeV]	> 110	< 110

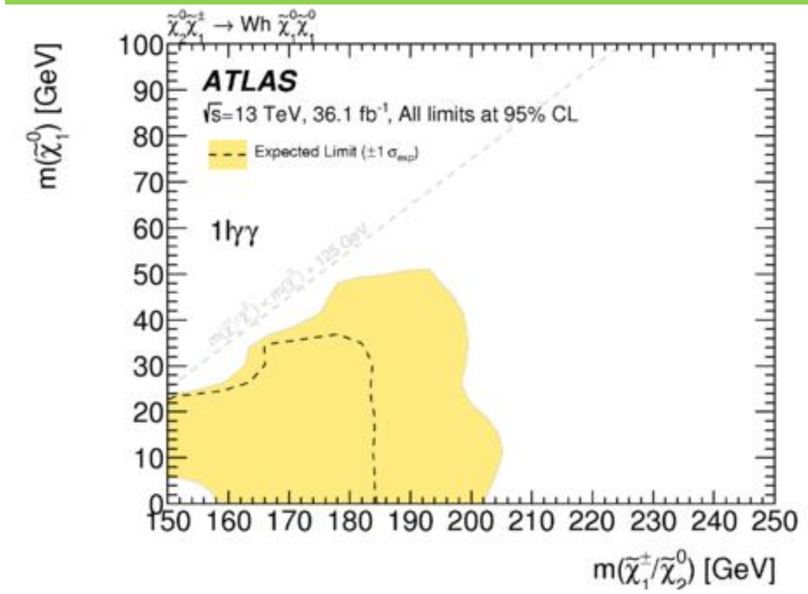
SUSY-like (SR1Lγγ-a) **SM-like** (SR1Lγγ-b)

- Good examples of an Intermediate Higgs channel
- Main (continuum) background constrained by sidebands
- Fake lepton background removed by requiring l-γγ vertex consistency

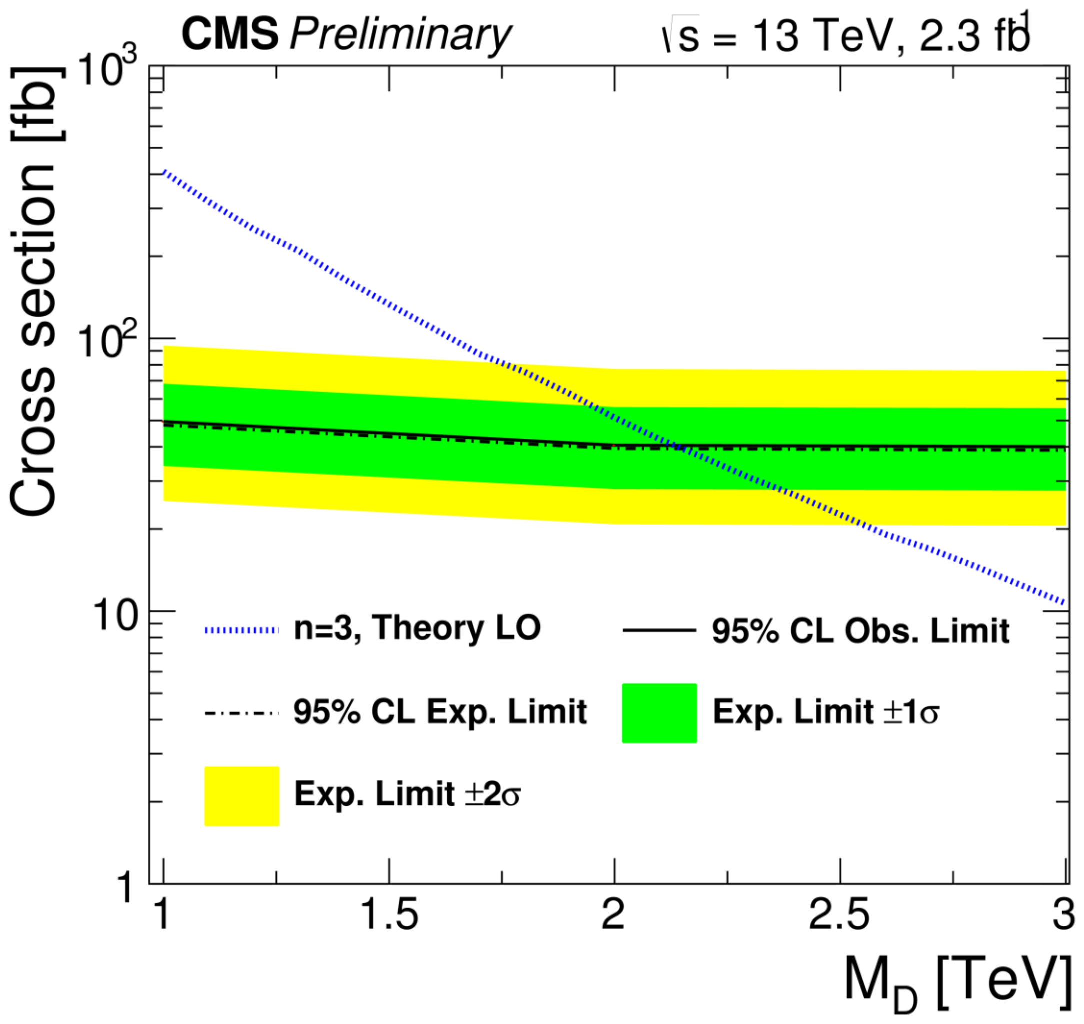
arXiv:1812.09432; Submitted to Phys. Rev.D



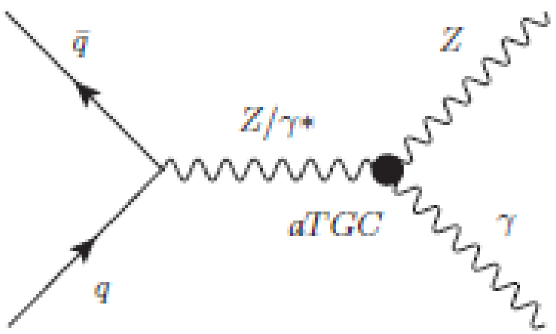


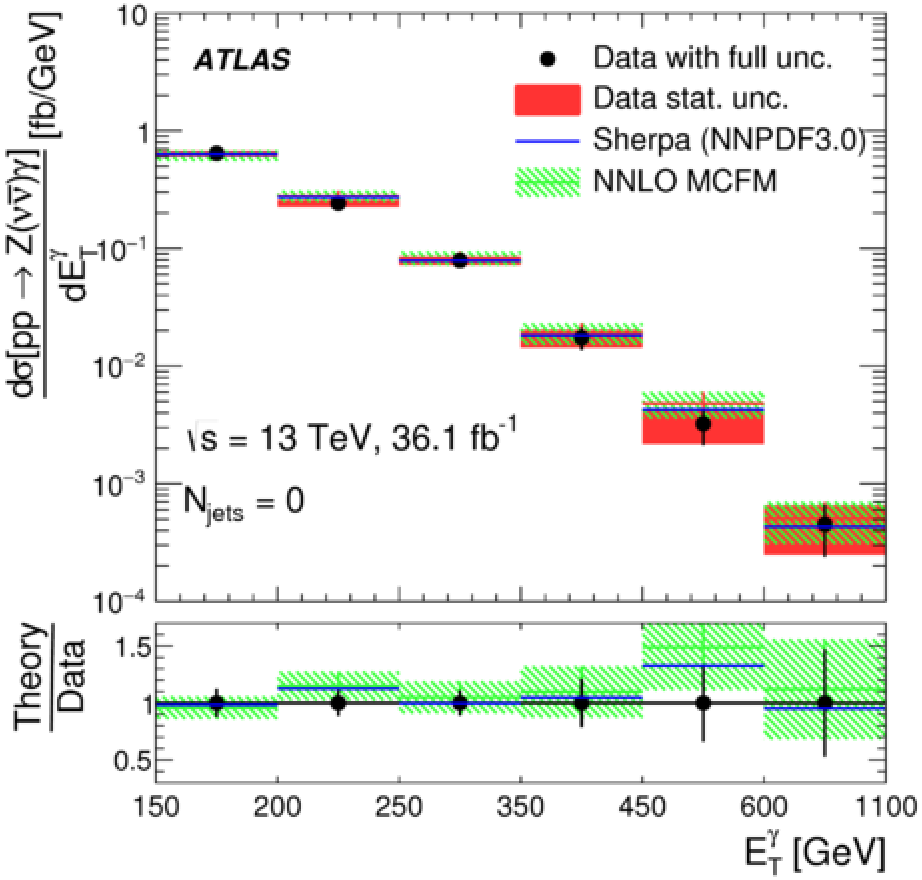


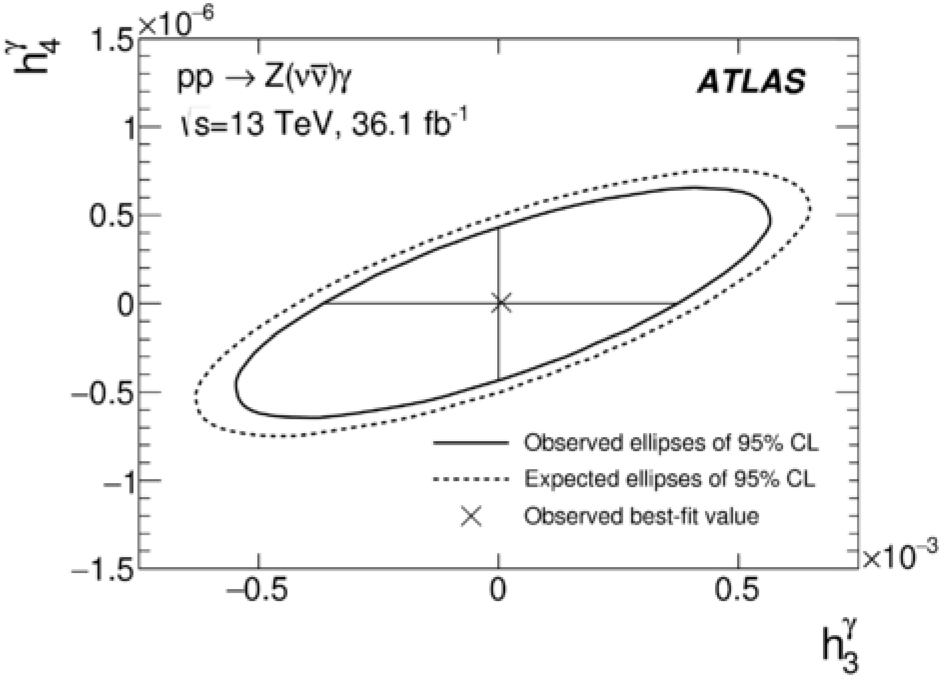
Small excess observed; update soon!


CMS Preliminary
√s = 13 TeV, 2.3 fb⁻¹
Cross section [fb]
M_D [TeV]
n=3, Theory LO
95% CL Obs. Limit
95% CL Exp. Limit
Exp. Limit ±1σ
Exp. Limit ±2σ

Radiative Behavior (Anomalous Couplings at $Q^2 > 0$)







CMS SUSY:
http://cms-results.web.cern.ch/cms-results/public-results/publications/SUS/index.html
And then just click on the link for final states with photons

CMS mainstream photon Moriond result: arXiv:1903.07070

CMS Exotica
http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/index.html
11 results with “photon” in title

ATLAS: Just see
https://twiki.cern.ch/twiki/bin/view/AtlasPublic
And search for “photon” results. Note there’s no SUSY selector (?!) so just search for all photon results.

Pseuso-Goldstini analysis (Dodsworth): Nov 12 Photons+X meeting (no ref for model though; but I dug up https://arxiv.org/abs/1312.1698

Higgs decays to neutralinos (Khilesh): see Nov 22 2017 meeting in OLD groupings of meetings. References on signal model page.