BSM searches with photons

Workshop on Photon Physics at the LHC

LPNHE

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CNRS IN2P3 Les deux infinis

Overview

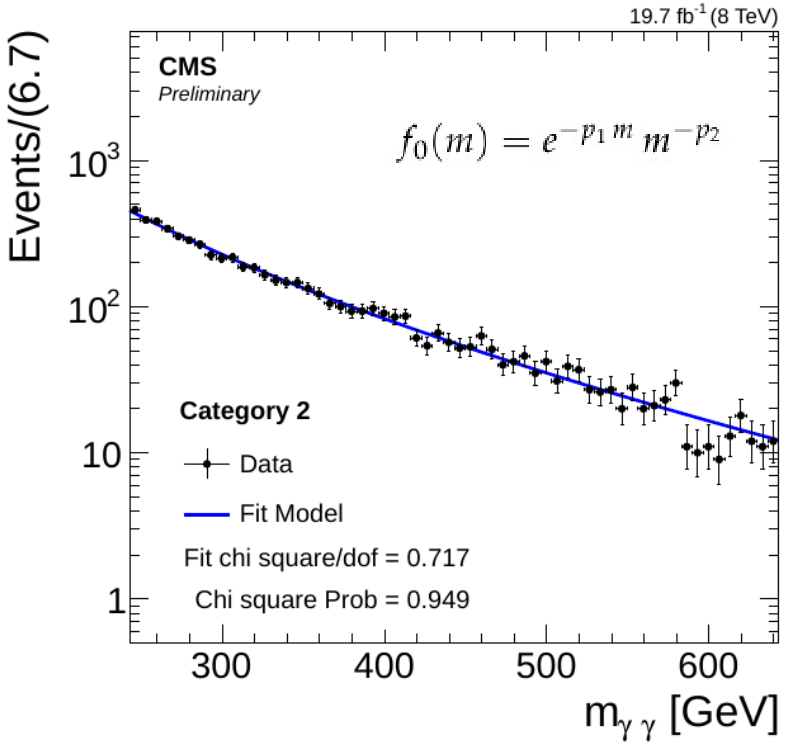
- Photon-based BSM analyses (based on the 8 TeV run-1 data):
  - γ + X resonance searches
  - γ + X searches
  - BSM through $H \rightarrow \gamma X$
  - Non-pointing γ
- Using the photon as a tool in other BSM searches: an example
- Summary and perspectives

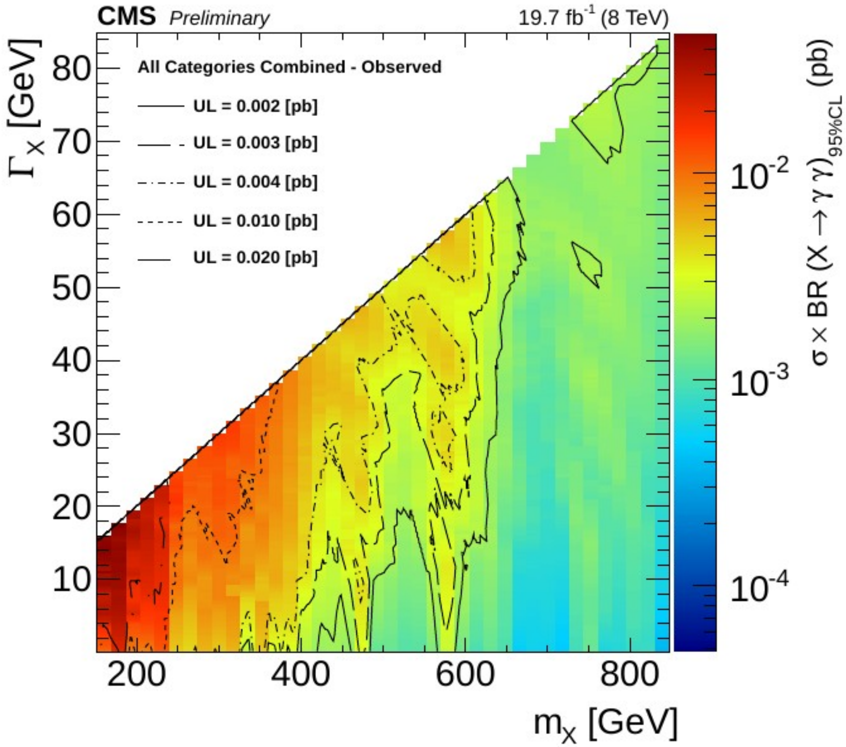
γ+X resonance searches

$\gamma\gamma$ resonance in CMS in the 150 - 850 GeV mass range

CMS-PAS-HIG-14-006

- Based on the SM-like Higgs boson search
- At least two photons with $E_T/m_{\gamma\gamma}$ > 1/3 (1/4)
- Increase sensitivity by subdividing the events into classes (different mass resolution and predicted S/B):
  - Minimum R9 (Sum E of 3x3 crystals centered on the most energetic one divided by the energy of the supercluster)
  - Maximum η of the photons
- Describe BG using a functional form (can't go to higher masses as too few events)





Phys. Rev. Lett. 113, 171801

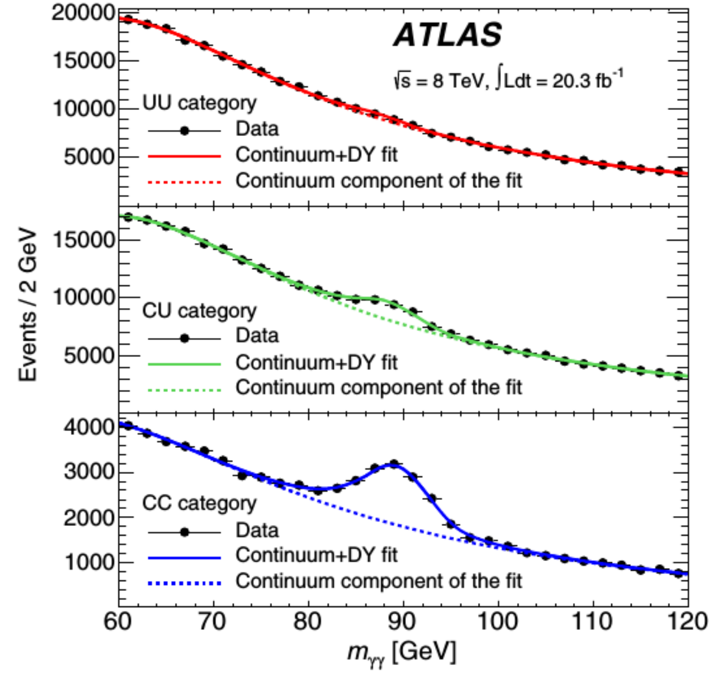
- ≥2 tight photons with E_T > 22 GeV
- Two analyses:

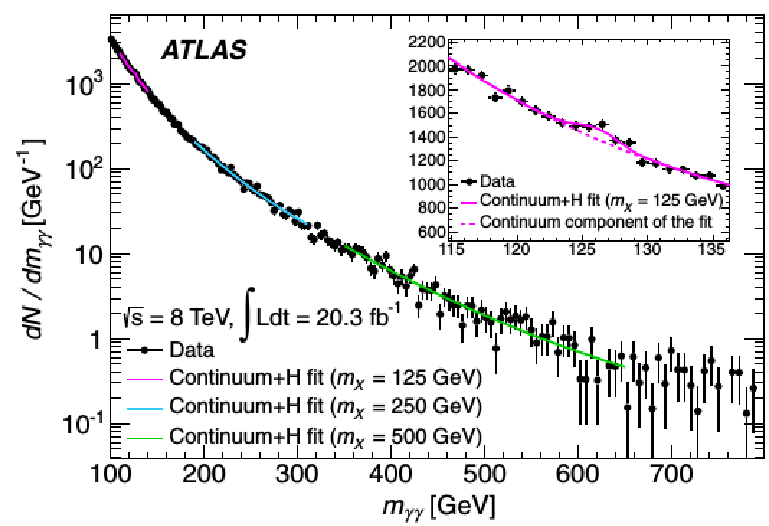
Low mass: 65-110 GeV

  - 3 categories (converted / unconverted combinations)
  - Z peak: Z(ee) + e→γ corrections, normalized with e→γ rate (eγ/ee in Z(ee) peak)
  - Fit of the continuum with a functional form

High-mass analysis: 110-600 GeV

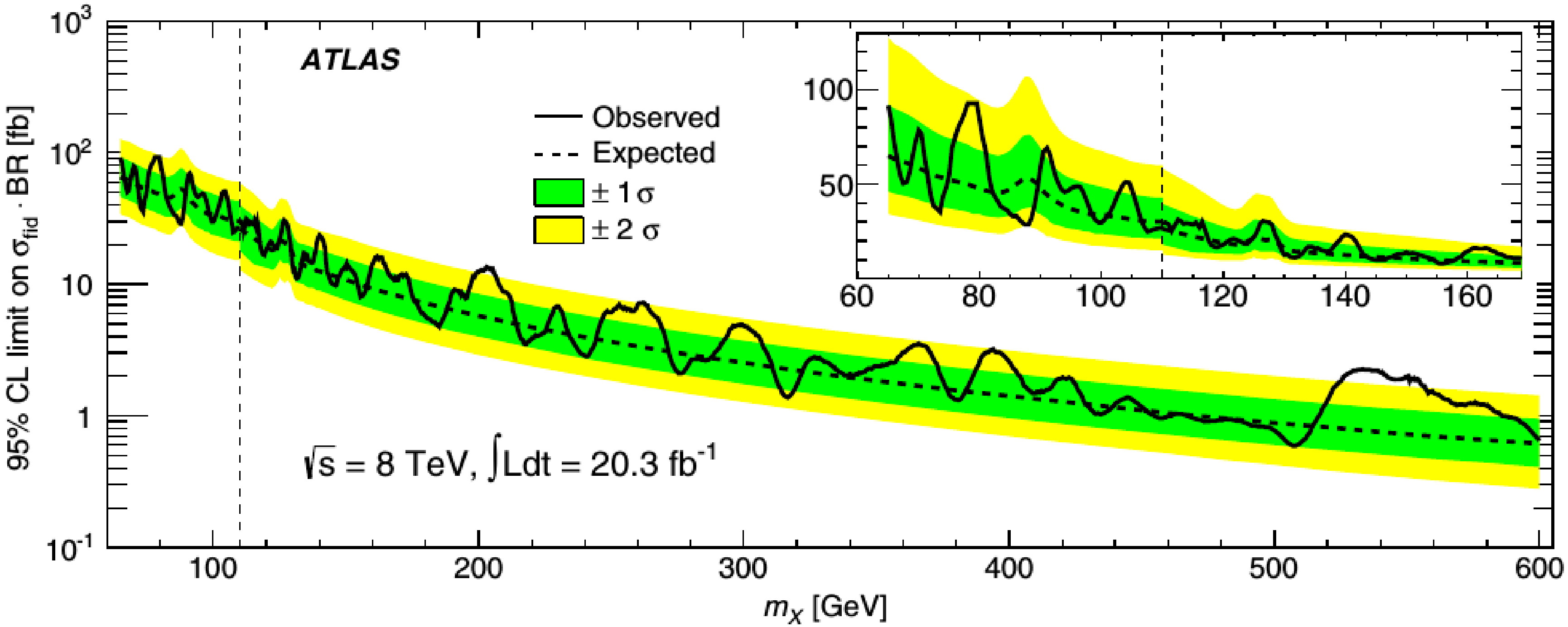
  - $E_{T,1(2)}/m_{\gamma\gamma}$ > 0.4 (0.3)
  - Higgs peak: double-sided Crystal Ball (m=125.9 GeV) + SM cross section
  - Fit of the continuum with a functional form





$\gamma\gamma$ resonance in ATLAS in the 65 - 600 GeV mass range

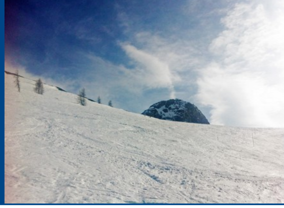
Phys. Rev. Lett. 113, 171801



$$\sigma_{\text{fid}} BR(X \to \gamma\gamma) = \frac{N_{\text{data}}}{C_X \mathcal{L}} \quad \text{with} \quad C_X = \frac{N^{\text{reco}}_{\text{MC}}}{N^{\text{fid}}_{\text{MC}}}$$

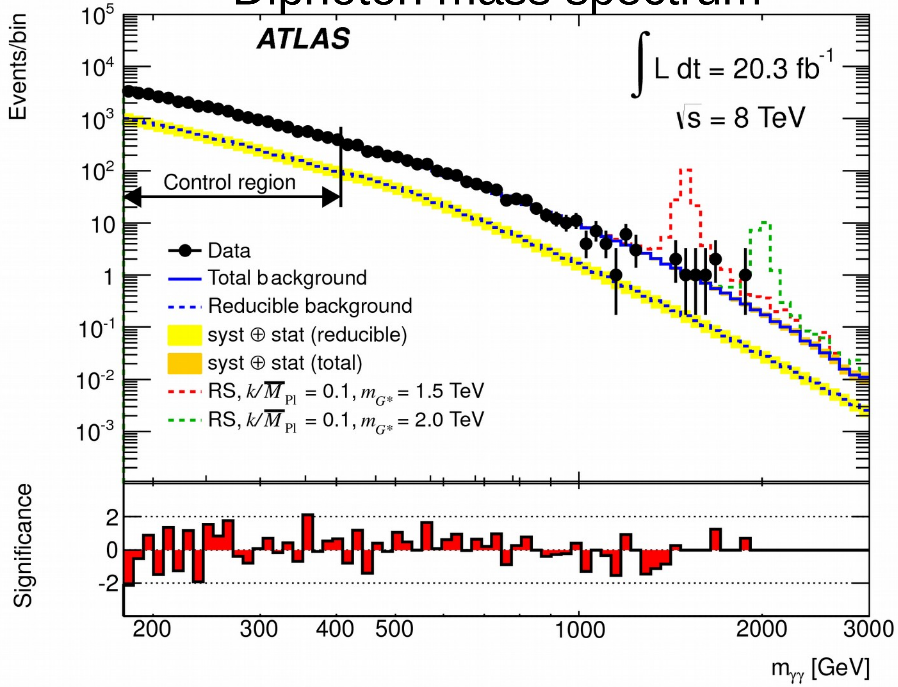
High-mass $\gamma\gamma$ resonance in ATLAS

arxiv:1504.05511 submitted to PRD



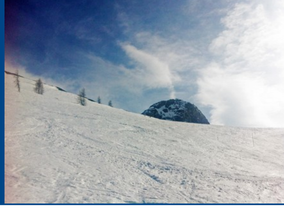
- At least two tight photons with E_T>50 GeV
- Use the two leading photons
- Isolated photons:
  - The expected contribution from photon leakage outside the central core is subtracted, but fluctuations around the expected leakage grows with ET
  - Significant inefficiencies if using a fixed cut on the isolation:
  - Vary the isolation requirement with E_T, from <8 GeV to <13 GeV at 1 TeV

Diphoton mass spectrum



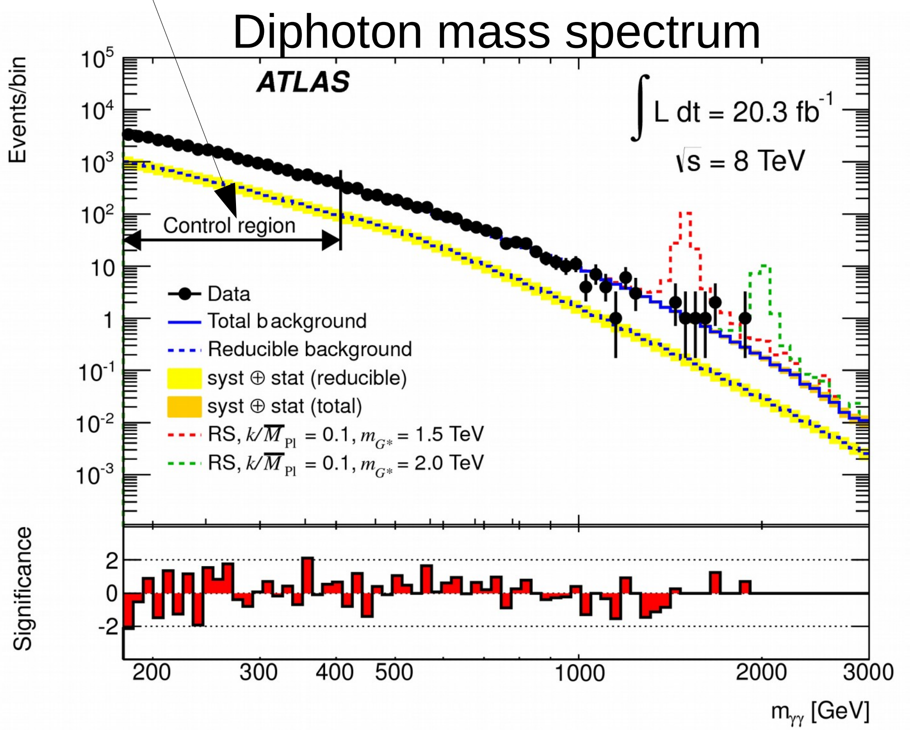
High-mass γγ resonance in ATLAS

arxiv:1504.05511 submitted to PRD



- Main BG: SM diphoton, Pythia (LO) + DIPHOX (NLO + fragmentation)
- Normalized to data in the low-mass region

In lower-mass analyses, it is more accurate to rely on sidebands, but this can't be done here, as insufficient event yields...



High-mass γγ resonance in ATLAS

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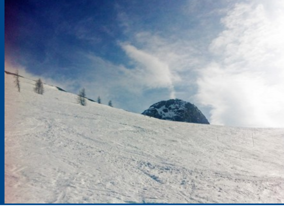
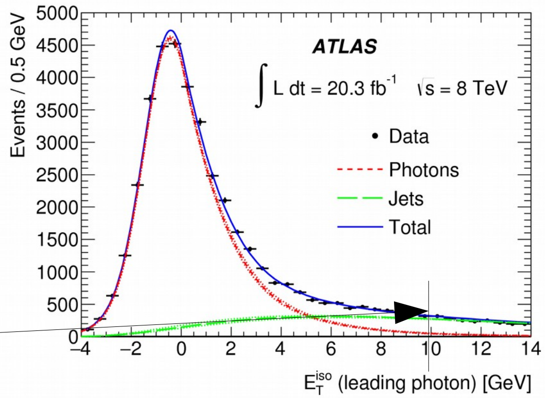
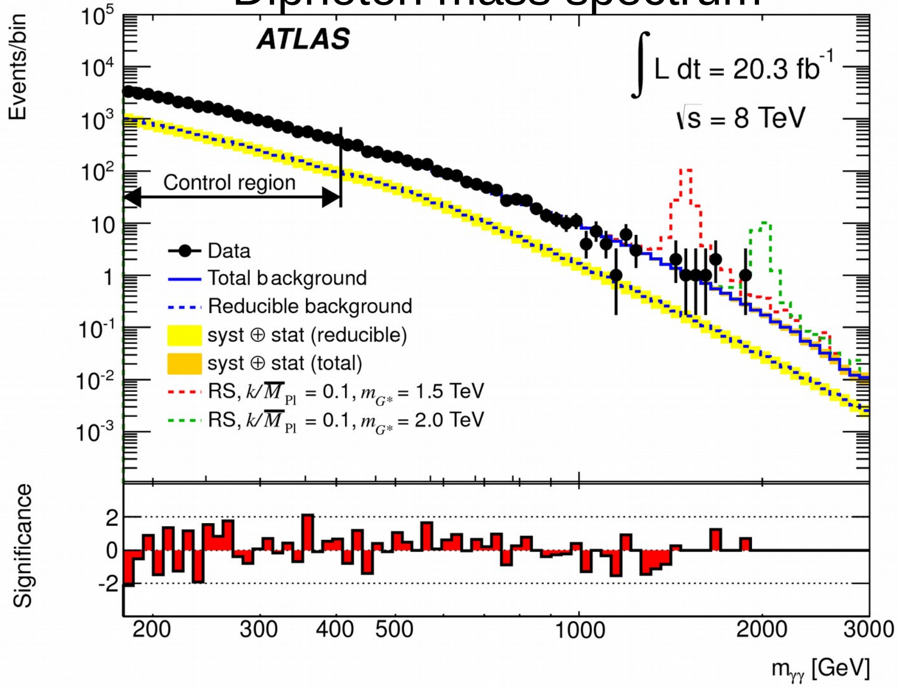
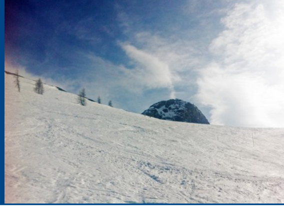


- Main BG: SM diphoton, Pythia (LO) + DIPHOX (NLO + fragmentation)
- Normalized to data in the low-mass region
- Need to know the reducible (gamma+jet, dijet) BG component in this region:
  - Template fit to the isolation energy distribution
  - Fake template: loose but not tight photons
  - True template: tight - fake contribution normalized in the E_T^{iso}>10 GeV region

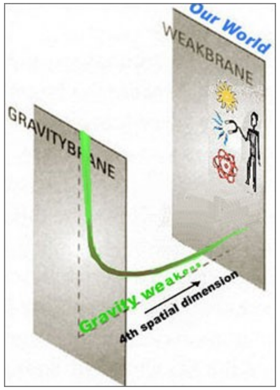


Diphoton mass spectrum

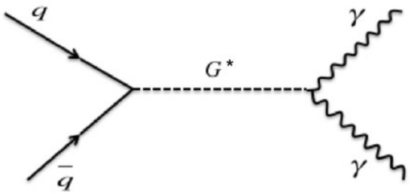


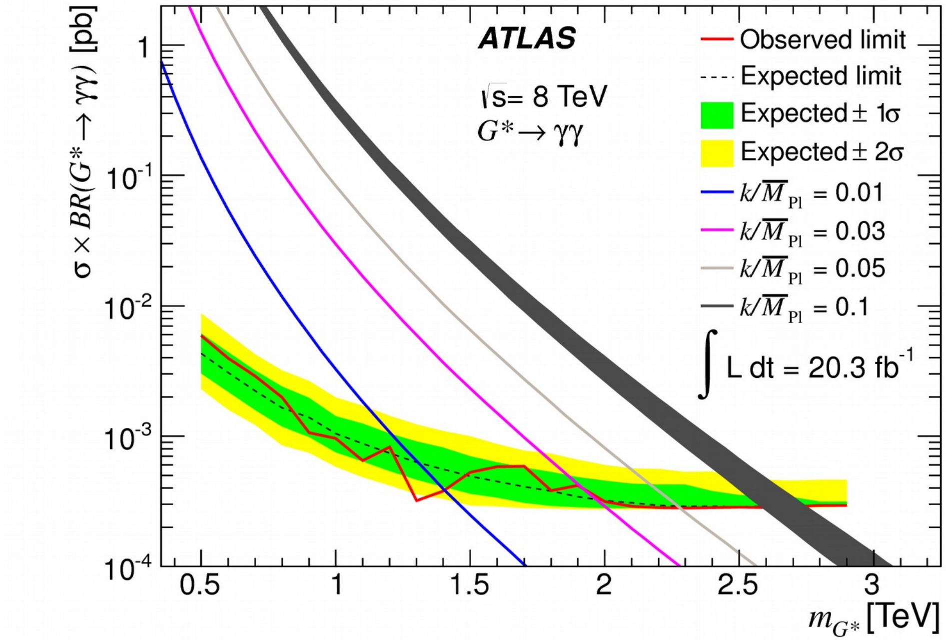


- Interpretation:
  - Randall-Sundrum (RS) model of extra dimension
  - Can address the hierarchy problem as gravity can propagate in extra dimension, diluting it

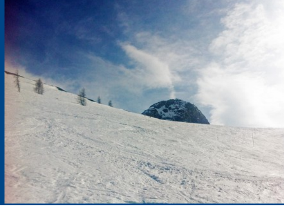


Limits on the lightest Kaluza-Klein graviton for different coupling strenghts :





Phys.Lett.B 728 C (2014) 562-578(ATLAS), Phys. Lett. B 738 (2014) 274-293 (CMS)



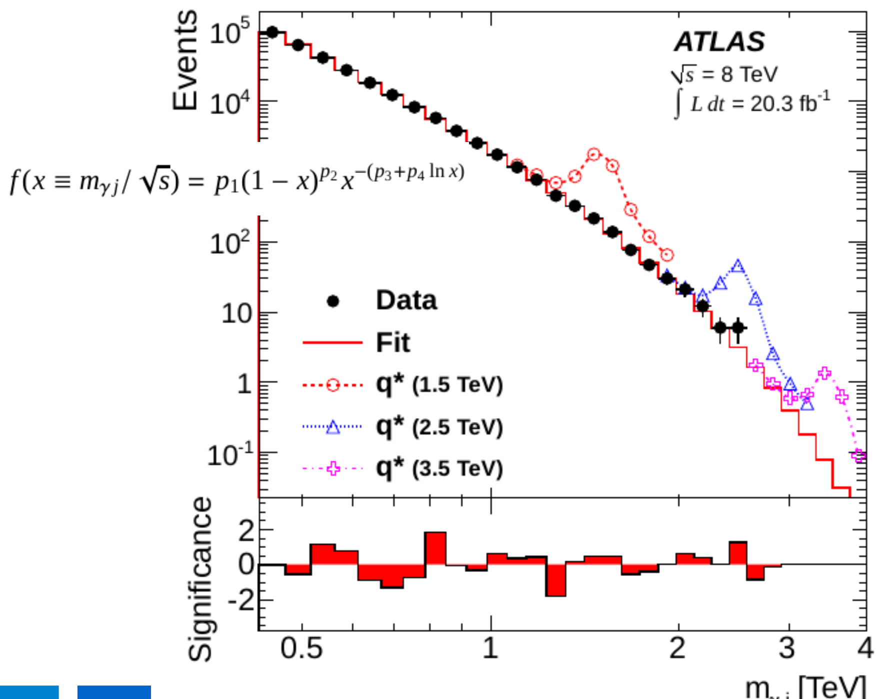
One advantage of the γ + jet search is that it can be sensitive in a lower mass region with respect to dijet searches (higher hadronic trigger thresholds)

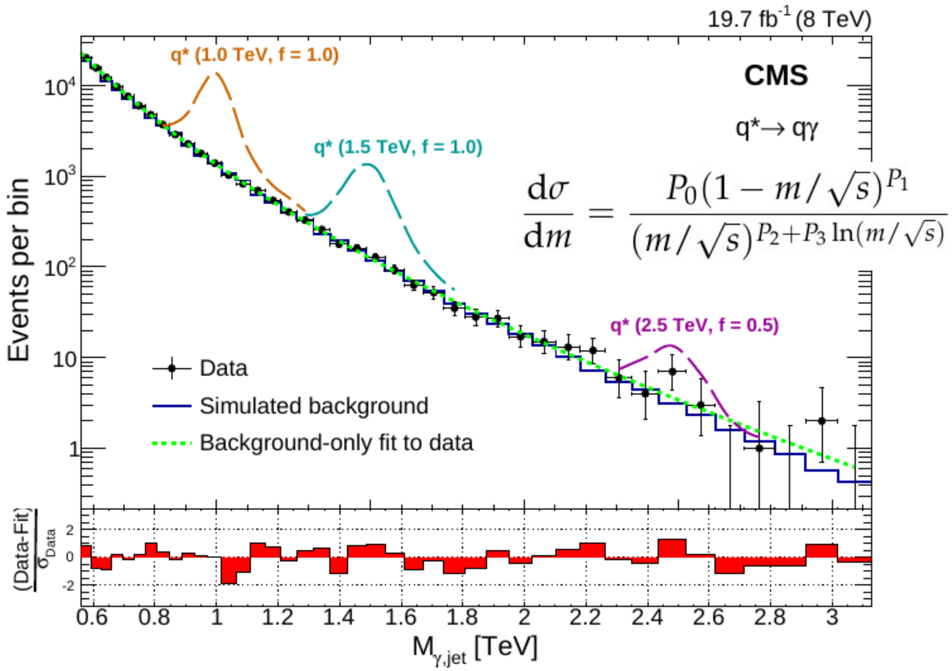
ATLAS

- ≥ 1 photon E_T>125 GeV, |η|< 1.37
- E_T^{iso}I(0.4) < 0.011 $E_{T\gamma}$ + 3.65 GeV
- ≥ 1 AKt6 jet, |η|<2.8, p_T> 125 GeV, ΔR(γ,j)>1.0
- Δη(γ,j)<1.6
- Functional form for background

CMS

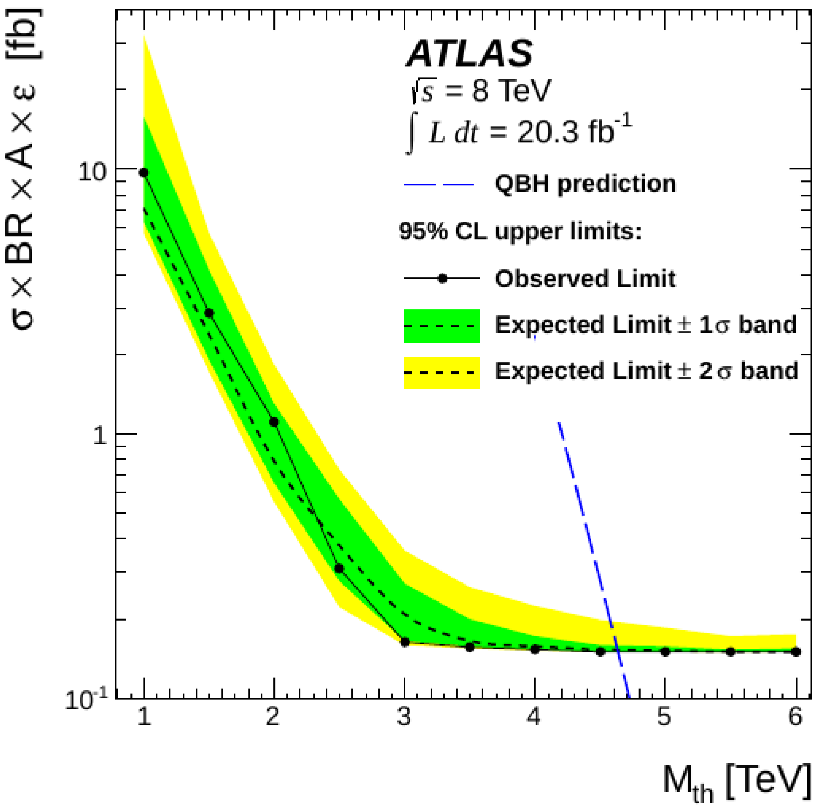
- ≥ 1 photon E_T>170 GeV, |η|< 1.37
- E_T-dependent iso ΔR=0.3 (γ,charged/neutral hadrons)
- ≥ 1 AKt5 jet, |η|<3.0, p_T> 170 GeV, ΔR(γ,j)>0.5
- Δη(γ,j)<2.0, Δφ(γ,j)>1.5, $m_{\gamma j}$>560 GeV
- Functional form for background

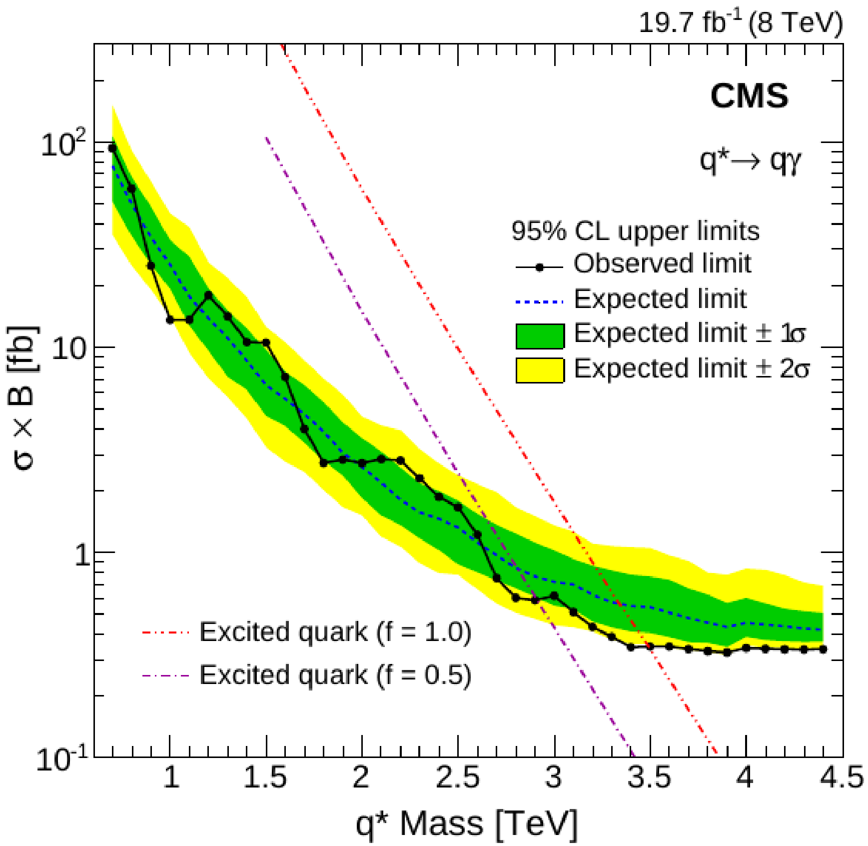




photon+jet

Phys.Lett.B 728 C (2014) 562-578(ATLAS), Phys. Lett. B 738 (2014) 274-293 (CMS)





Non-thermal quantum black hole (QBH):

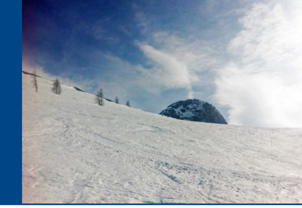
- Extra dimensions model lowers the Planck mass to M_D : possibility to create QBH.
- The ones produced near M_D would evaporate faster than they thermalize: decay into a few particles rather than high-multiplicity final states.

Excited quarks

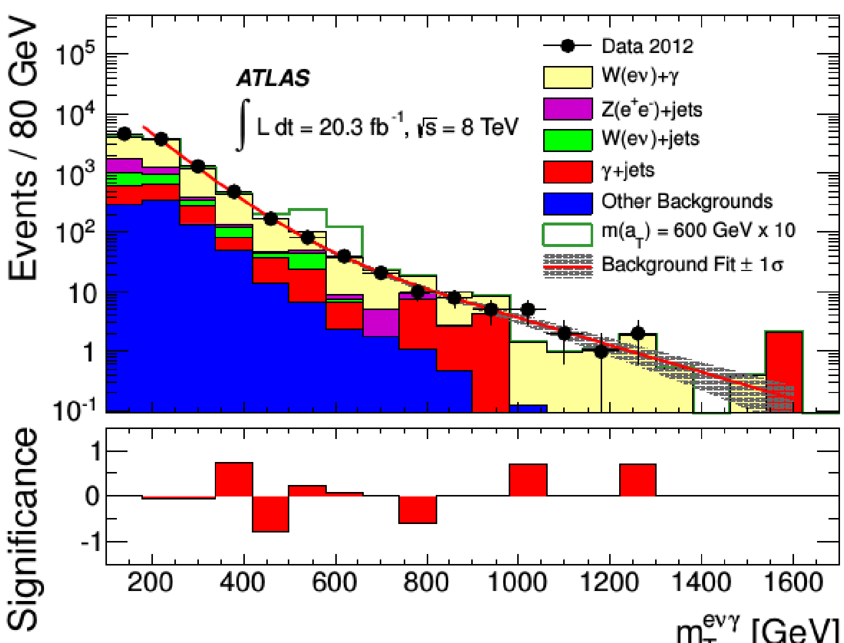
(same limit in ATLAS)

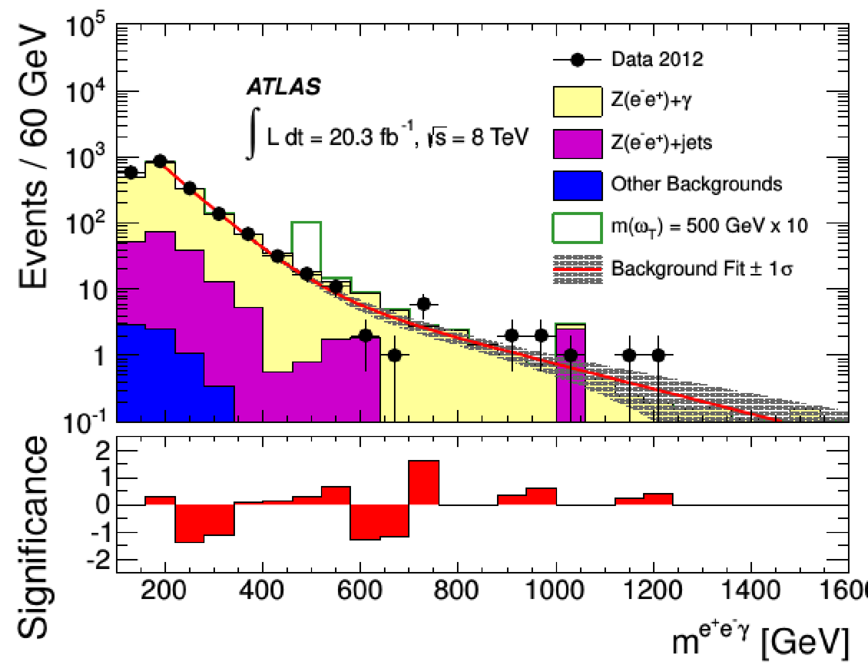
photon+W/Z(leptonic)

Phys. Lett. B 738 (2014) 428-447



- At least one tight photon E_T>40 GeV, E_T^{iso}(0.4)<4 GeV
- Isolated electons and muons p_T>25 GeV, $\Delta R(l,\gamma)$>0.7
- **W SR**: 1 lepton, MET>35 GeV, $m_{e\gamma}$!= Z mass (±15 GeV)
- **Z SR**: 2 leptons SFOS m_{ll} in 65-115 GeV
- Functional form for BG (sum of two exponentials) between 180 and 1600 GeV





photon+W/Z(leptonic)

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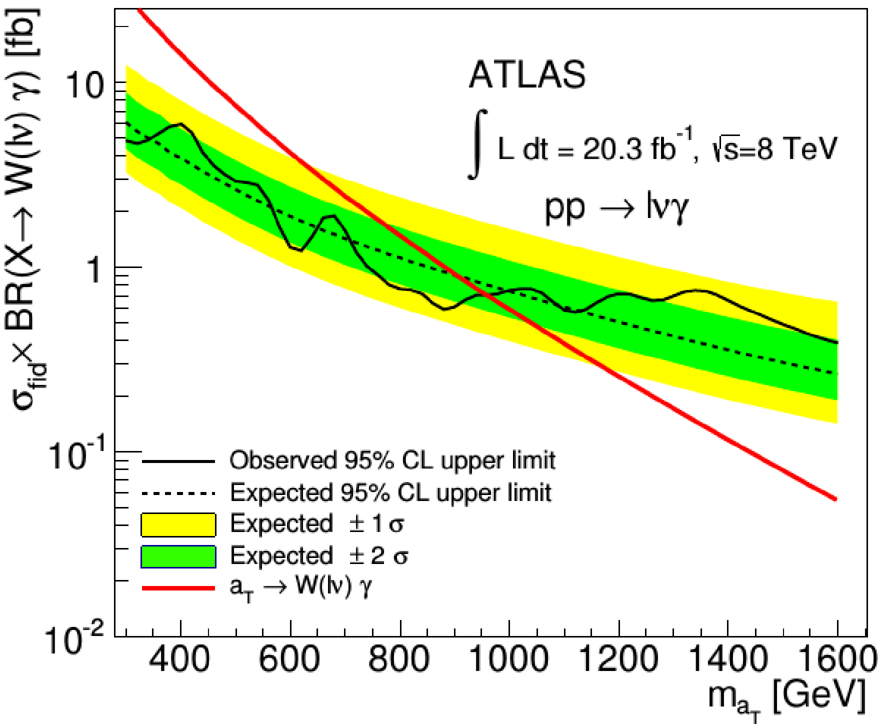
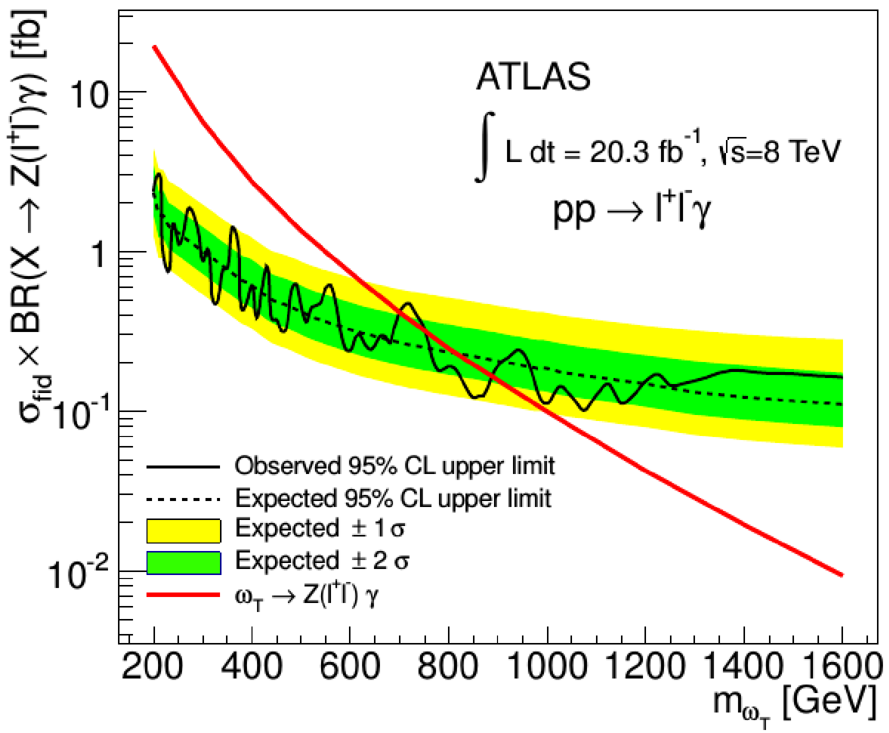
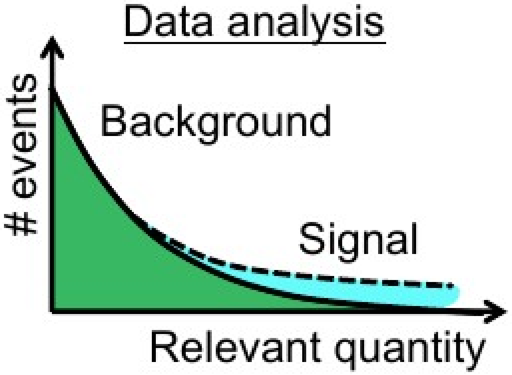




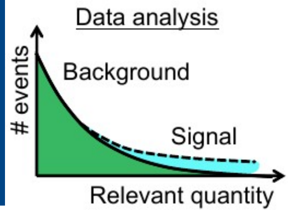
Limits on narrow technimeson resonances in a model of low scale technicolour

Photon + X searches



Photon + MET

Phys. Rev. D 91, 012008 (2015) (ATLAS) , arxiv:1410.8812 Submitted to Phys. Lett. B (CMS)



ATLAS

Selection:

- ≥ 1 photon E_T>125 GeV, $|\eta|$<1.37, E_T^{iso}(0.4)<5 GeV
- MET>150 GeV, $\Delta\varphi$(MET,γ)>0.4
- ≤ 1 jet p_T>30 GeV, $\Delta\varphi$(j,MET)>0.4
- Veto e(μ) p_T>7(6) GeV

Background estimation:

- Z($\nu\nu$)γ and W($l\nu$)γ normalized using a fit to data in multiple CR (Z(ee)γ, Z($\mu\mu$)γ, W($\mu\nu$)γ)
- Jet fake using isolation / ID
- Electron fake using tag & probe method on Z(ee) applied on a W(eν) CR

Cut and count

CMS

Selection:

- ≥ 1 photon E_T>145 GeV, $|\eta|$<1.44, E_T-dependent iso ΔR=0.3 (γ,charged/neutral hadrons)
- MET>140 GeV, $\Delta\varphi$(MET,γ)>2.0
- ≤ 1 jet p_T>30 GeV
- Veto e,μ p_T>10 GeV

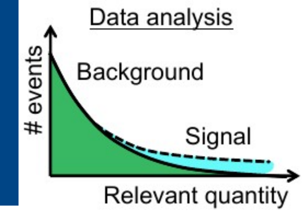
Background estimation:

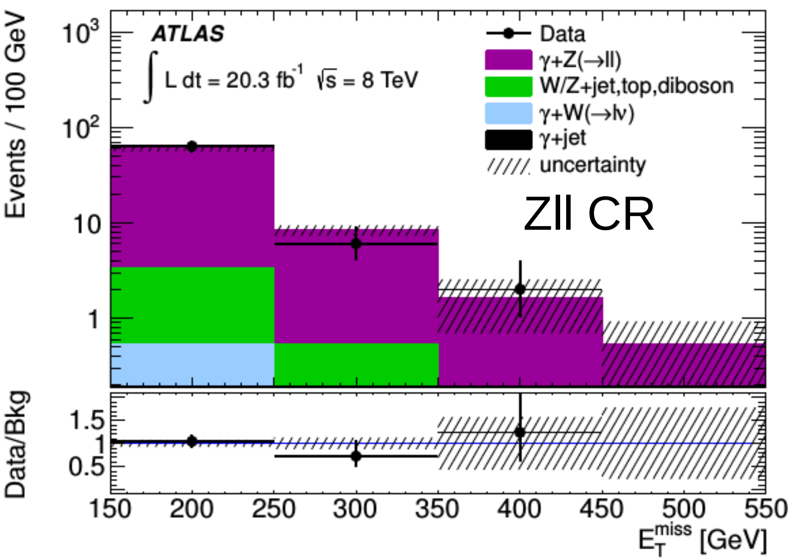
- Z($\nu\nu$)γ, W($l\nu$)γ from MC (cross checked in Z(ll)γ)
- Jet fake using isolation / ID (shower width)
- Electron fake using tag & probe method on Z(ee) applied on a W(eν) CR
- Non-collision BG: reverting the beam halo tag (evidence in ECAL of a MIP roughly parallel to the beam axis)

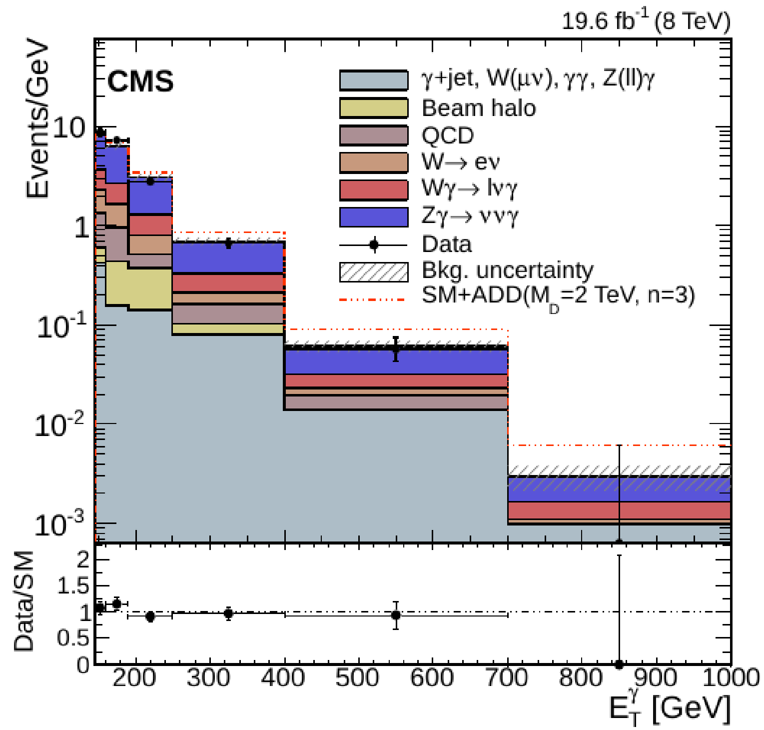
Limits using a shape fit to $E_{T\gamma}$

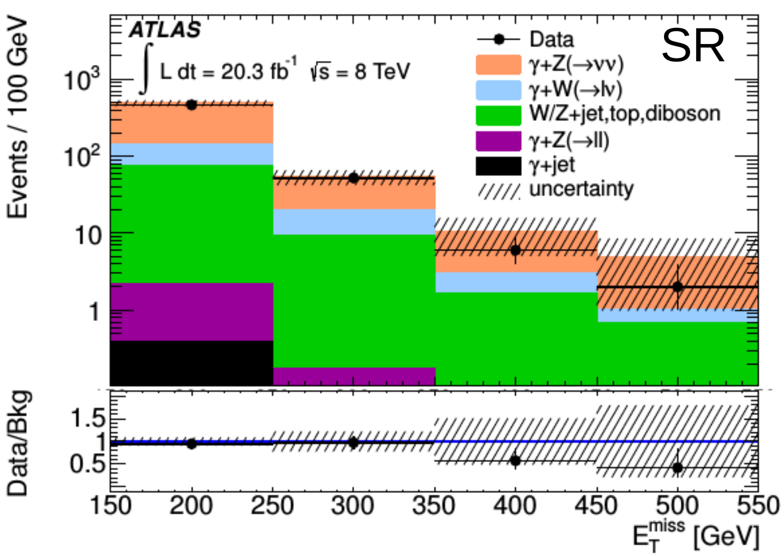
Photon + MET

Phys. Rev. D 91, 012008 (2015) (ATLAS) , arxiv:1410.8812 Submitted to Phys. Lett. B (CMS)







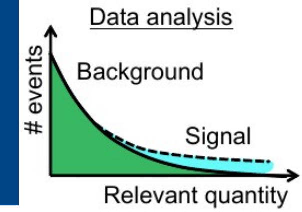


Process	Event yield (SR)
$Z(\to \nu\nu) + \gamma$	$389 \pm 36 \pm 10$
$W(\to \ell\nu) + \gamma$	$82.5 \pm 5.3 \pm 3.4$
W/Z + jet, $t\bar{t}$, diboson	$83 \pm 2 \pm 28$
$Z(\to \ell\ell) + \gamma$	$2.0 \pm 0.2 \pm 0.6$
γ + jet	$0.4^{+0.3}_{-0.4}$
Total background	$557 \pm 36 \pm 27$
Data	521

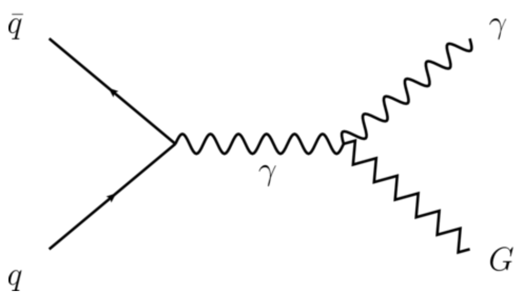
Process	Estimate
$Z(\to \nu\bar{\nu}) + \gamma$	345 ± 43
$W(\to \ell\nu) + \gamma$	103 ± 21
W $\to$ eν	60 ± 6
jet $\to \gamma$ MisID	45 ± 14
Beam halo	25 ± 6
Others	36 ± 3
Total background	614 ± 63
Data	630

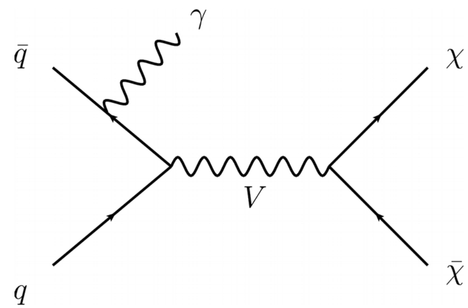
Photon + MET

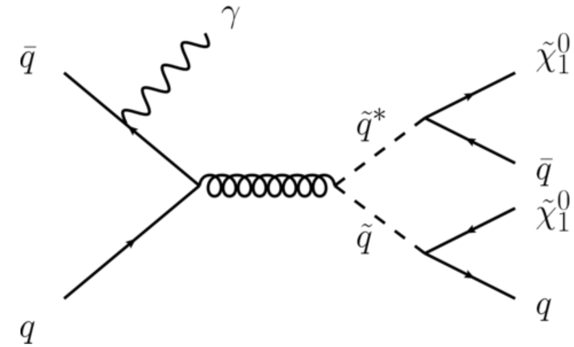
Phys. Rev. D 91, 012008 (2015) (ATLAS) , arxiv:1410.8812 Submitted to Phys. Lett. B (CMS)

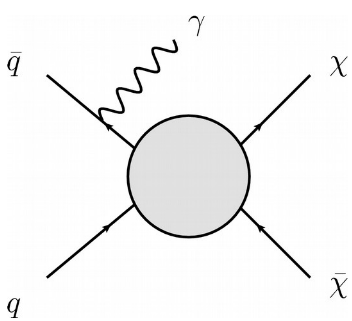


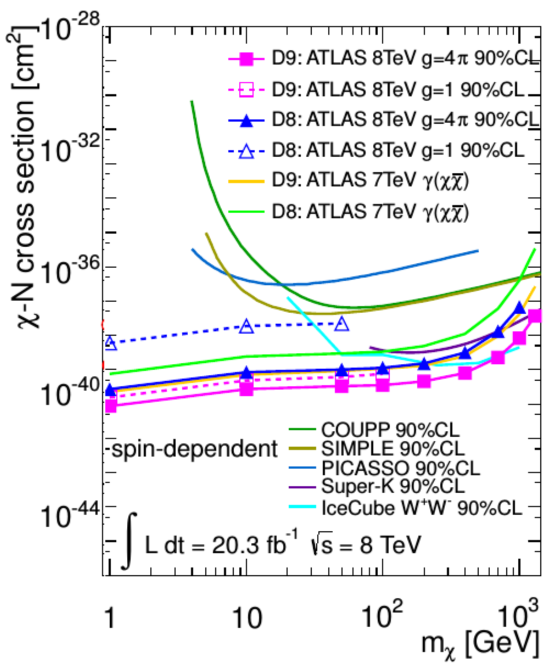
Many interpretations: dark matter (EFT, simplified models), ADD, compressed SUSY scenario

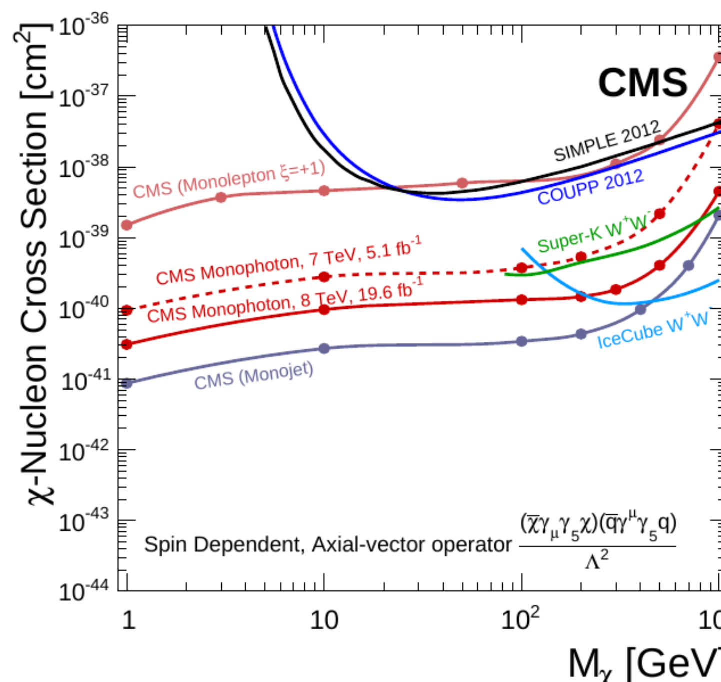




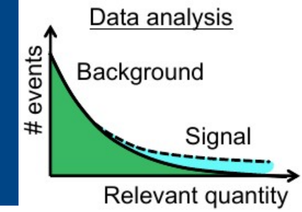






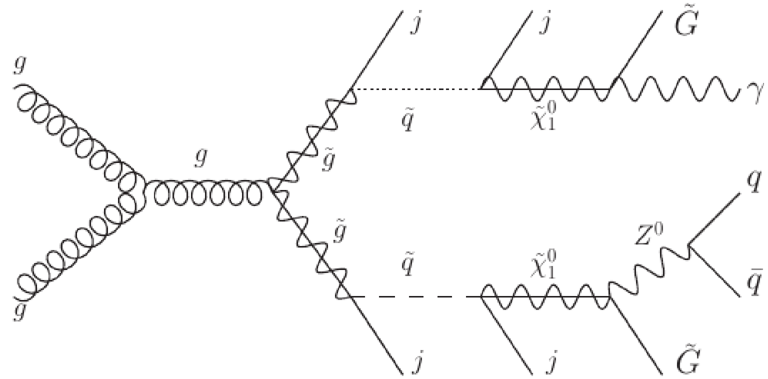


Similar limits on Dark Matter EFT, slightly better for ATLAS at lower masses and for CMS at large masses



Selection:

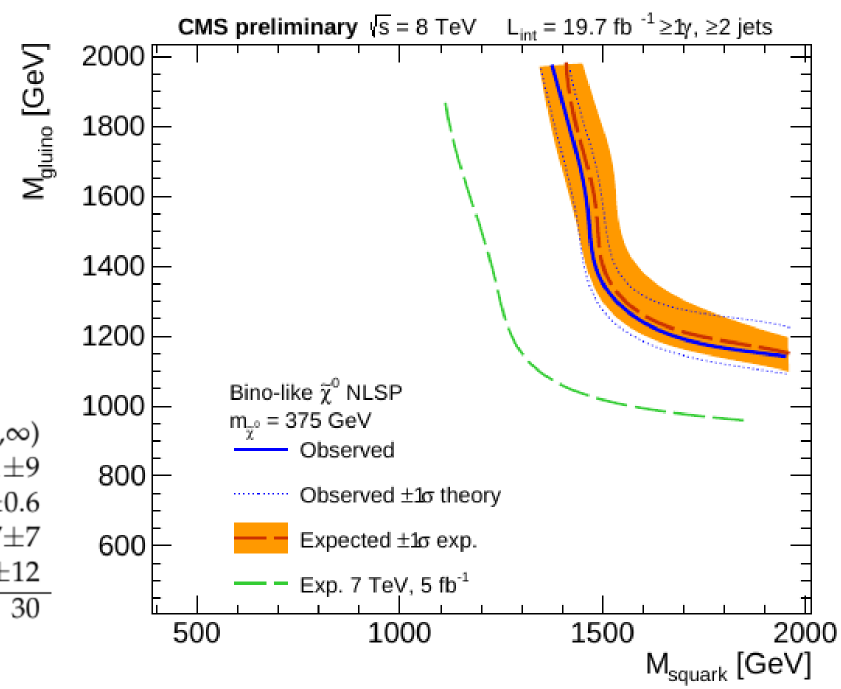
Trigger	γ-H_T trigger with $p_T^\gamma \geq 70$ GeV, $H_T \geq 400$ GeV (using $p_T^{\text{jets}} \geq 40$ GeV, $\lvert\eta\rvert < 3.0$)
Photon(s)	$\geq 1, p_T^{*\,\gamma} \geq 110$ GeV, $\lvert\eta\rvert < 1.4442$
Jet(s)	$\geq 2, p_T^{\text{jets 1,2}} \geq 30$ GeV, $\lvert\eta\rvert < 2.5$
H_T	≥ 500 GeV (using $p_T^{\text{jets},\,\gamma} \geq 40$ GeV, $\lvert\eta\rvert < 3.0$)
isolated e,μ	veto, $p_T > 15$ GeV, $\lvert\eta^{e(\mu)}\rvert < 2.5(2.4)$
$\not{E}_T$	$\not{E}_T \geq 100$ GeV (six intervals in $\not{E}_T$)



Background estimation:

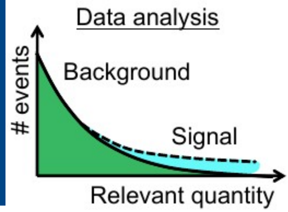
- Zγ, Wγ and γtt from MC
- QCD from a loose γ CR
- EW from t&p in Zee on CR

$\not{E}_T$ Range [GeV]	[100,120)	[120,160)	[160,200)	[200,270)	[270,350)	[350,∞)
QCD	991±164	529±114	180±69	95.6±45	11.7±12	9.1±9
EWK	37.3±4	42.5±5	23.0±3	19.2±2	7.7±1.0	4.1±0.6
ISR/FSR	53.6±27	72.5±36	44.9±23	40.1±20	19.7±10	14.7±7
Background	1082±166	644±119	248±73	155±50	39.0±16	27.8±12
Data	1286	774	232	136	46	30



Search for supersymmetry in diphoton+MET

ATLAS-CONF-2014-001



Selection:

- Two tight photons with E_T>75 GeV, $E_T^{iso}(0.4)$<4 GeV
- 5 different SR (strong/weak production for high/low mass bino and a model-independent SR)

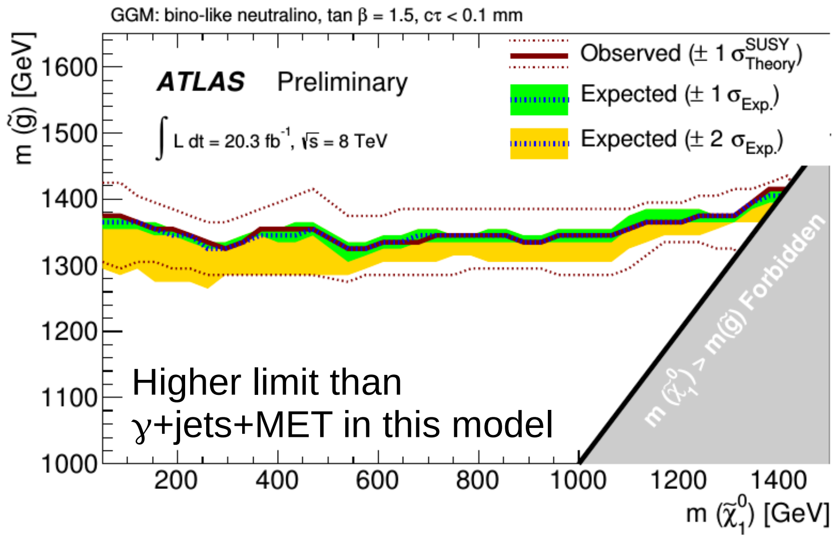
Background estimation:

- Z(νν)γγ from MC
- W(lν)γγ from MC normalized in a W(lν)γγ CR at lower MET
- QCD BG (γγ, γ+j): MET template in tight-nontight sample, normalised in MET<60 GeV.
  - SP1 and SP2: too low stat, so made in bins of M_{eff} and extrapolated to SR
- EW BG: from eγ CR scaled with e→γ probability from t&p in Z(ee)

	SP1	SP2	WP1	WP2	MIS
$\Delta\phi_{\gamma}^{\rm min}$ >	0.5	0.0	0.5	0.0	0.0
$\Delta\phi_{\rm jet}^{\rm min}$ >	0.5	0.5	0.5	0.5	0.5
$M_{\rm eff}$ > ($H_{\rm T}$ >) (GeV)	1500	1800	(400)	(600)	0
$E_{\rm T}^{\rm miss}$ > (GeV)	250	150	200	150	250

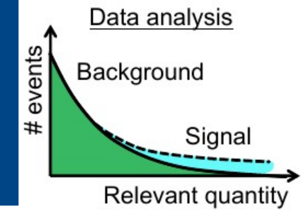
Δφ w.r.t MET. M_{eff}: scalar sum p_T's + MET

Background	SP1	SP2	WP1	WP2	MIS
QCD	$0.00^{+0.20}_{-0.00}$	$0.22^{+0.53}_{-0.22}$	0.29 ± 0.29	0.89 ± 0.60	0.73 ± 0.53
Electroweak	< 0.02	0.02 ± 0.02	0.15 ± 0.07	0.67 ± 0.22	0.24 ± 0.10
$W(\to \ell\nu) + \gamma\gamma$	0.03 ± 0.02	0.02 ± 0.01	0.44 ± 0.18	0.74 ± 0.27	0.47 ± 0.19
$Z(\to \nu\bar{\nu}) + \gamma\gamma$	< 0.01	< 0.01	0.13 ± 0.07	0.08 ± 0.04	0.15 ± 0.08
Total	$0.03^{+0.20}_{-0.02}$	$0.26^{+0.53}_{-0.22}$	1.01 ± 0.36	2.38 ± 0.69	1.59 ± 0.58
Observed events	0	0	1	5	2



Supersymmetry in diphoton + razor

SUS-14-008



- At least two photons with p_T> 30,22 GeV and at least one jet p_T>40 GeV
- Use the razor to describe a two-megajet topology coming from the pair production of sparticles each decaying into X + neutralino
  - Form two mega-jets by chosing the ones with lowest sum squared masses

$$M_R = \sqrt{(|\vec{p}_{j_1}| + |\vec{p}_{j_2}|)^2 - (p_z^{j_1} + p_z^{j_2})^2}$$

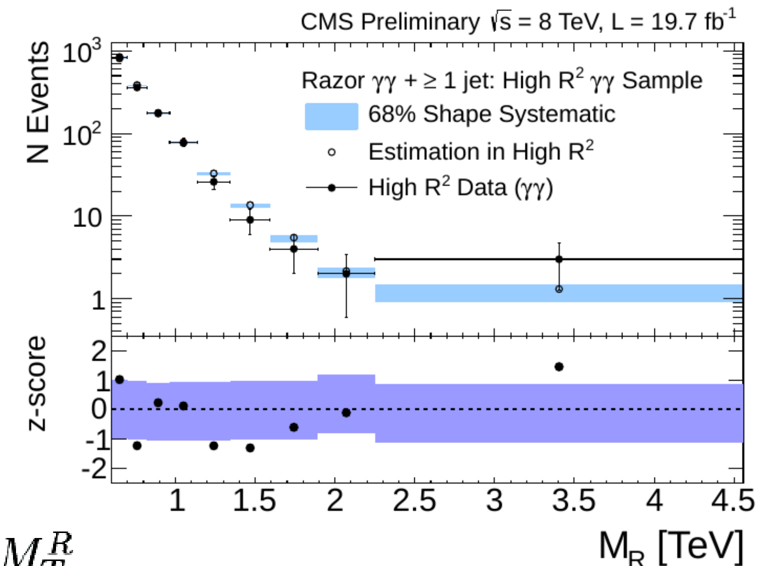
Peaks at

$$M_\Delta = \frac{M_S^2 - M_{LSP}^2}{M_S}$$

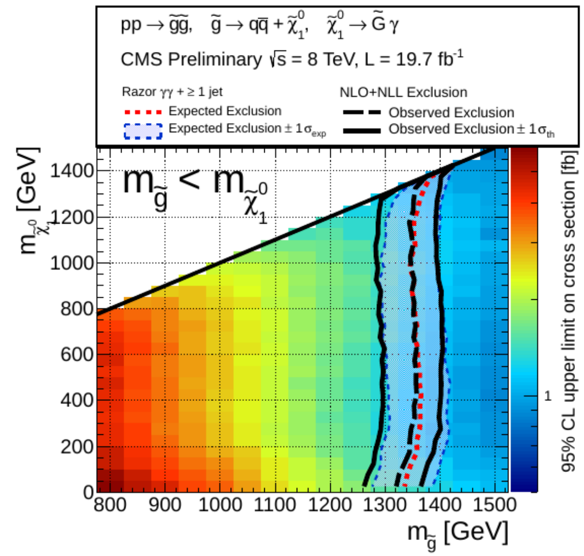
$$M_T^R = \sqrt{\frac{E_T^{miss}(p_T^{j_1} + p_T^{j_2}) - \vec{E}_T^{miss} \cdot (\vec{p}_T^{j_1} + \vec{p}_T^{j_2})}{2}} \quad R = \frac{M_T^R}{M_R}$$

Edge at M_Δ

$$R = \frac{M_T^R}{M_R}$$



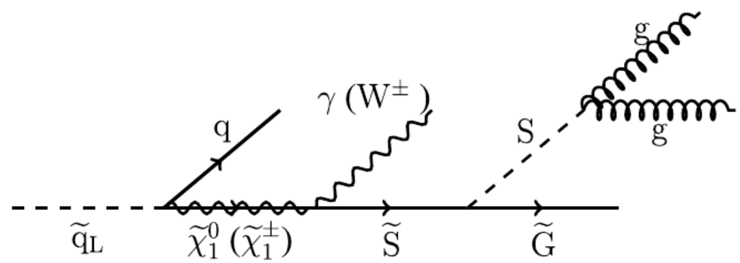
- Divide the (M_R, R^2) plane:
  - Signal region: M_R > 600 GeV and R^2 > 0.02
  - Control region: M_R > 600 GeV and 0.01 < $R^2 \leq$ 0.02.
- Fit the BG in the CR and apply in the SR (normalized to yield)

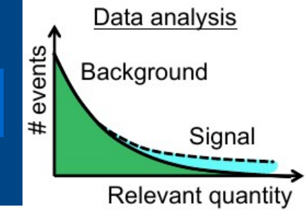


Limit similar to diphoton + MET in this model

Stealth SUSY in diphoton events

Phys. Lett. B 743 (2015) 503–525



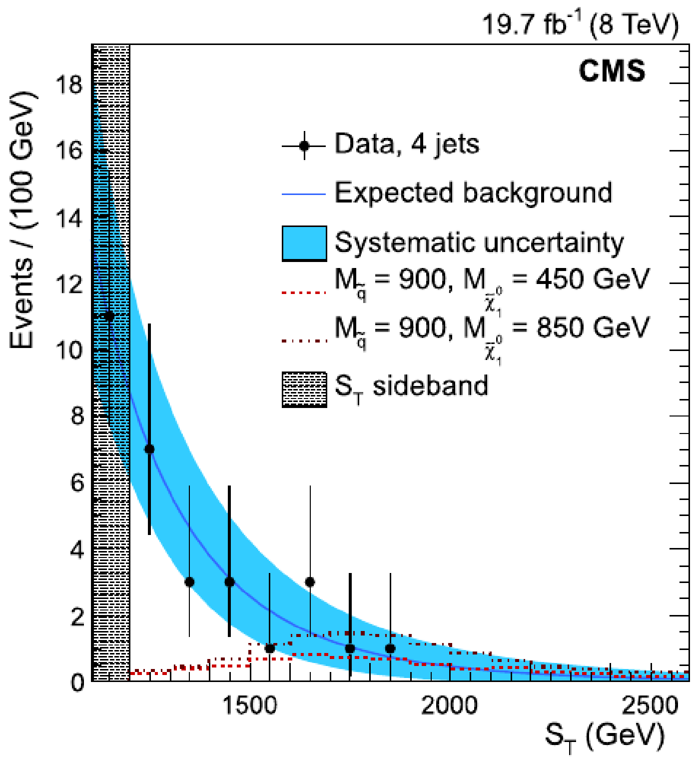


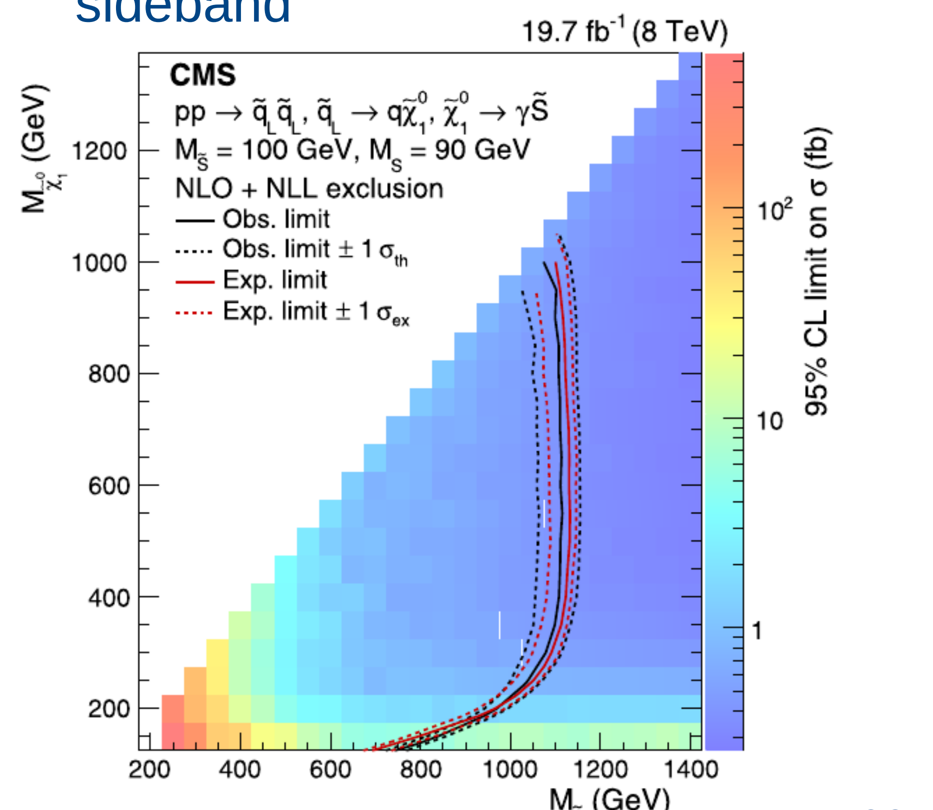
Selection:

- 4 jets or ≥5 jets p_T>30 GeV
- ≥2 photons with E_T>40, 25 GeV
- H_T>60 GeV, S_T(H_T+MET)>1200 GeV

Background estimation:

- Fit S_T distribution in Njet=3 sideband
- Normalize in 1100<S_T<1200 GeV sideband





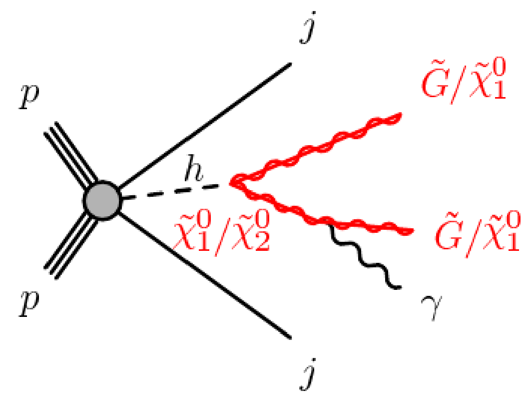
BSM through $H \rightarrow \gamma X$

Higgs to photon +MET (VBF) [GMSB, NMSSM]

ATLAS-CONF-2015-001

Selection:

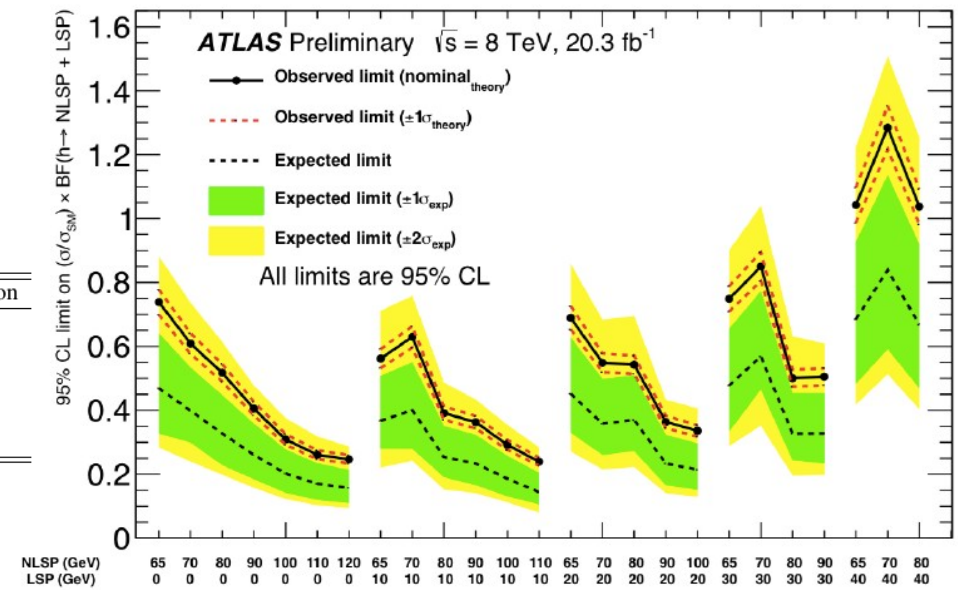
- VBF: ≥2 jets p_T>40 GeV, m_{jj}>600 GeV, $\Delta\eta_{jj}$>4.0
- ≥1 photon E_T>40 tight photon
  - unconverted (to reduce e→γ)
  - $E_T^{iso}(0.4)$<5 GeV + $p_T^{tracks}(0.2)<0.05E_T$
  - Between the VBF jets in η
- MET>50 GeV, $\Sigma p_T^{vec}(\gamma$+jets)>50 GeV
- $\Delta\varphi$(VBF j, MET)>1.4, $\Delta\varphi(\gamma$,MET)<1.8
- Veto lepton, ≤ 1 non-VBF jet p_T>30 GeV

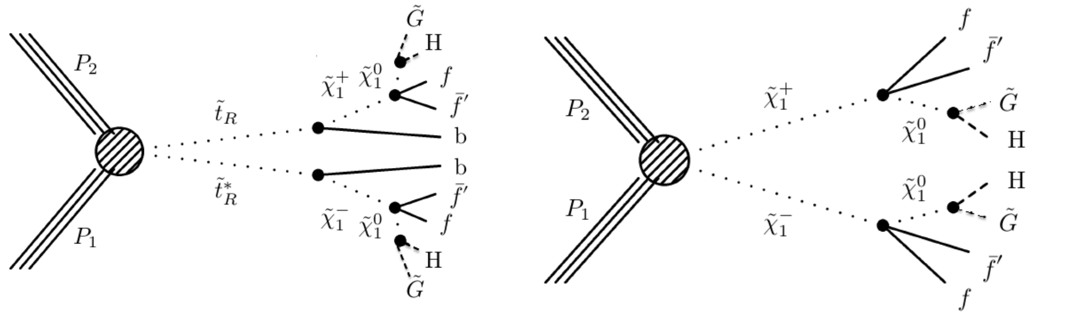


Background estimation:

Background	Distributions	Normalization
$W(\to e\nu)$	$W(\to e\nu)$ MC with $e\to\gamma$ misidentification rate from data	Data CR
W/Z + jets	W/Z + jets MC with jet$\to\gamma$ misidentification rate from MC	Data CR
$W\gamma/Z\gamma$	MC	Data CR
Top and diboson	MC	MC
γ + jets and multijet	Data CR	Data CR

Total background	38.0 ± 2.2 ± 4.5
Data	50





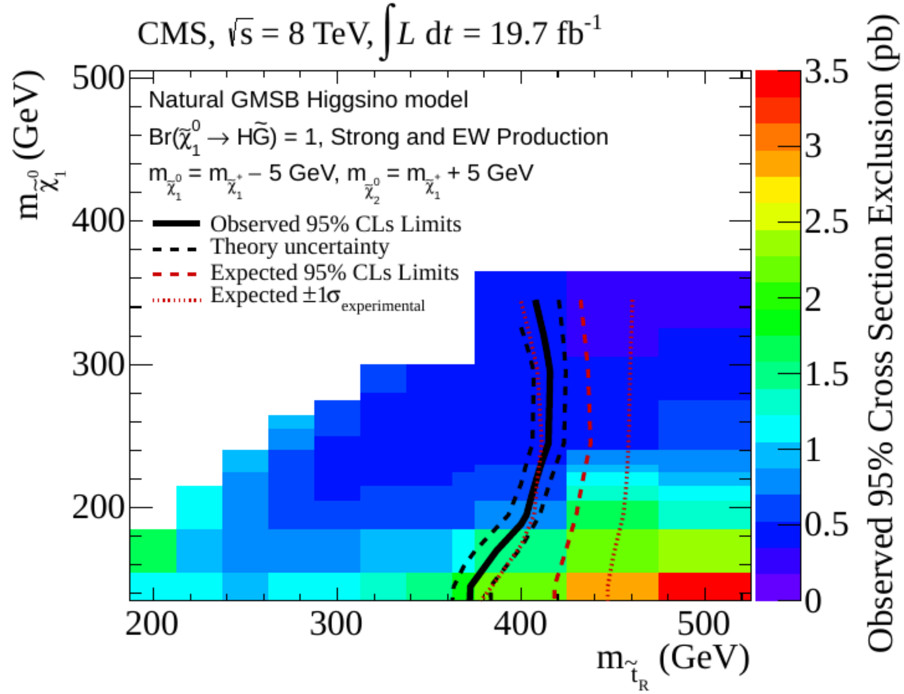
Selection:

- ≥2 photons E_T>40, 25 GeV
- 120<$m_{\gamma\gamma}$<131 GeV
- ≥2 jets p_T>30 GeV
  - loose(80-85%)+medium(50-75%) b-tag
- 3 categories:
  1. Additional loose b-tagged jet
  2. 95<m_{bb}<155 GeV
  3. Others

Categories	1	2	3
expected background	6.7 ± 1.4	10.5 ± 1.8	29.7 ± 2.8
observed	6	7	33

Background estimation:

- Fit in sidebands:
  - 103<$m_{\gamma\gamma}$<118 GeV
  - 133<$m_{\gamma\gamma}$<163 GeV



Can be greatly enhanced by new physics like heavy vector-like quarks (quark-singlet model) or models of two Higgs doublets with/without flavour conservation:

Process	SM	QS	2HDM-III	FC-2HDM	MSSM
$t \to u\gamma$	$3.7 \cdot 10^{-16}$	$7.5 \cdot 10^{-9}$	—	—	$2 \cdot 10^{-6}$
$t \to uZ$	$8 \cdot 10^{-17}$	$1.1 \cdot 10^{-4}$	—	—	$2 \cdot 10^{-6}$
$t \to uH$	$2 \cdot 10^{-17}$	$4.1 \cdot 10^{-5}$	$5.5 \cdot 10^{-6}$	—	10^{-5}
$t \to c\gamma$	$4.6 \cdot 10^{-14}$	$7.5 \cdot 10^{-9}$	$\sim 10^{-6}$	$\sim 10^{-9}$	$2 \cdot 10^{-6}$
$t \to cZ$	$1 \cdot 10^{-14}$	$1.1 \cdot 10^{-4}$	$\sim 10^{-7}$	$\sim 10^{-10}$	$2 \cdot 10^{-6}$
$t \to cH$	$3 \cdot 10^{-15}$	$4.1 \cdot 10^{-5}$	$1.5 \cdot 10^{-3}$	$\sim 10^{-5}$	10^{-5}

ATLAS

- Two tight isolated photons
- **Hadronic 2nd top:**
  - ≥4 jets, ≥1 b-tagged
  - M_{jjj}, $m_{\gamma\gamma j}$ ~ top mass
- **Leptonic 2nd top:**
  - ≥2 jets, ≥ 1 b-tagged
  - m_T>30 GeV
  - $m_{\gamma\gamma j}$ and $m_{l\nu j}$ ~ the top mass
- Fit $m_{\gamma\gamma}$

B(t → cH)<0.83(0.53)%

CMS

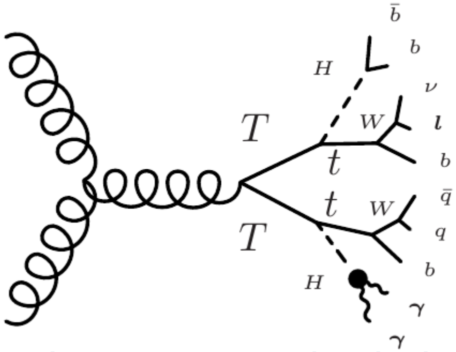
- Analysis also looking for additional Higgses : multiple SRs (multilepton, diphoton+leptons, diphoton+dilepton…)
- Two photons
- 1 lepton (including tau)
- 120<$m_{\gamma\gamma}$<130 GeV
- ≥ 1 b-tagged
- Split in MET bins
- Fit $m_{\gamma\gamma}$ sidebands

B(t → cH)<0.56(0.65)%

Vector-like top through H→γγ

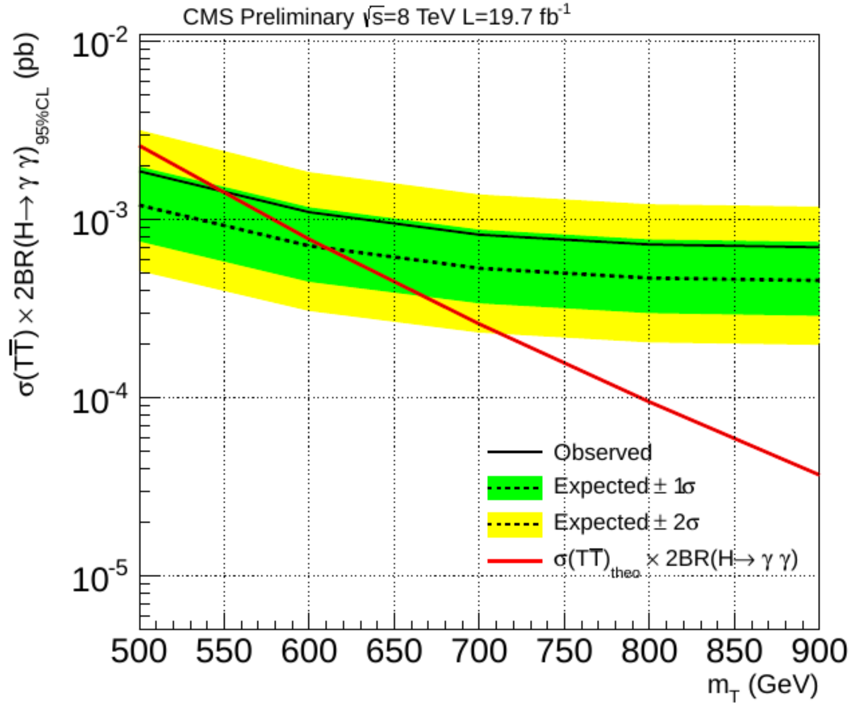
CMS-PAS-B2G-14-003

Variable	Hadronic channel	Leptonic channel
$p_T(\gamma_1)$	$> \frac{3}{4} m_{\gamma\gamma}$ GeV	$> \frac{1}{2} m_{\gamma\gamma}$ GeV
$p_T(\gamma_2)$	35 GeV	25 GeV
n_{jets}	≥ 2	≥ 2
H_T	≥ 1000 GeV	≥ 770 GeV
leptons	0	≥ 1
b tags	≥ 1	-



Vector-like top: left- and right-handed transform in the same way under SU(2)

- **Advantage of γγ channel: can precisely measure $m_{\gamma\gamma}$**
  - Search for a narrow resonance centered around the Higgs mass
  - Estimate BG from data sidebands (ttH taken from MC)

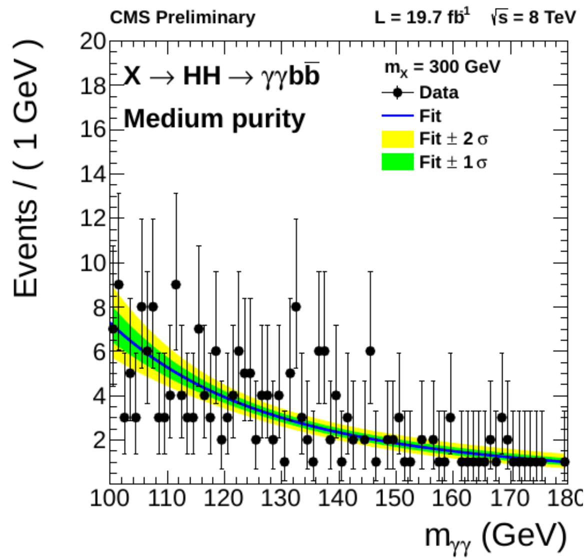


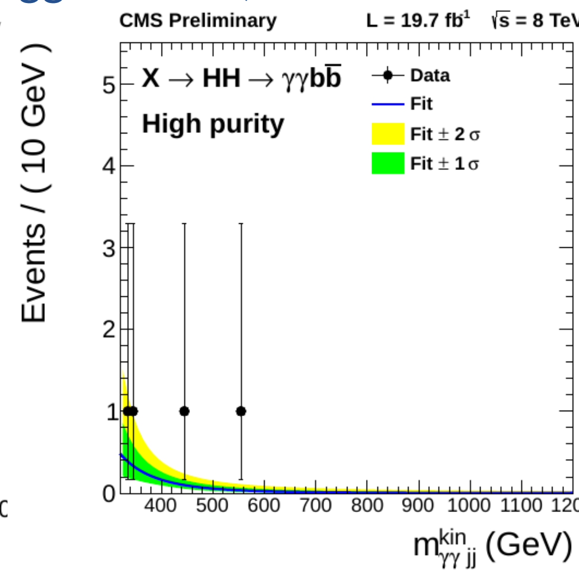
Process	Hadronic	Leptonic
$T\bar{T}(m_T = 700$ GeV$)$	1.05	0.43
$t\bar{t}H$	0.042	0.039
Background	$0.65^{+0.16}_{-0.13}$	$0.11^{+0.07}_{-0.03}$
Observed Data	2	0

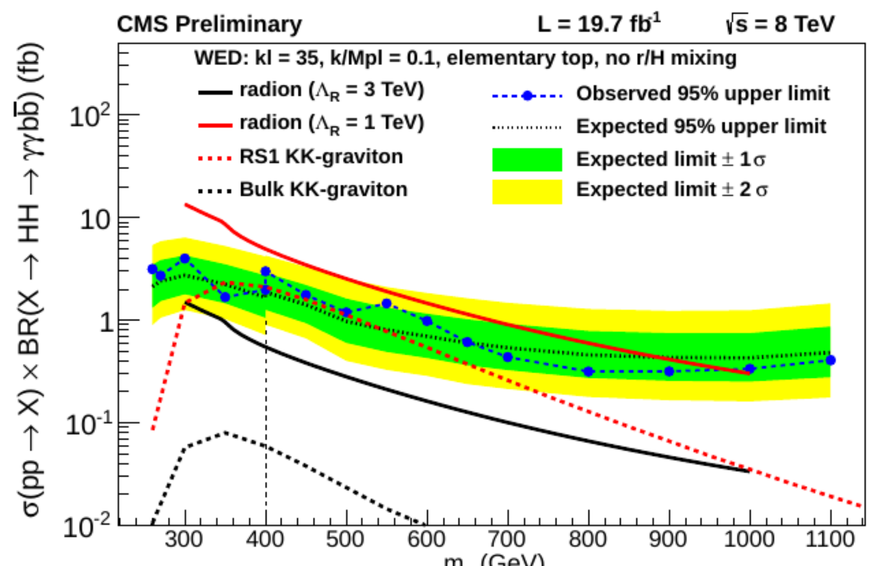
- X : graviton in extra dimension models, heavy additional Higgs in SUSY,...

Selection:

- ≥ 2 photons
- $100<m_{\gamma\gamma}<180$ GeV
- At least two jets with:
  - 1b-tagged jet (“medium purity”)
  - 2 b-tagged jets (“high purity”)
- Two strategies:
  - Low-mass region:
    - $260 < m_X < 400$ GeV:
    - Use $m_{\gamma\gamma}$ shape
    - Mass-dependent m_{jj} and $m_{\gamma\gamma jj}$ cuts (BG has a peak ~ $m_{\gamma\gamma bb} \approx 300$ GeV
  - High-mass region:
    - $400 < m_X < 1100$ GeV:
    - Use $m_{\gamma\gamma bb}$ shape







Non-pointing photons

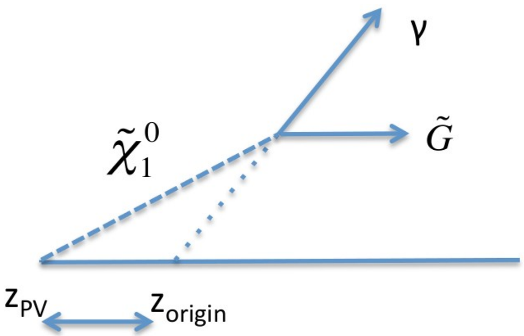
Non-pointing photons in supersymmetry

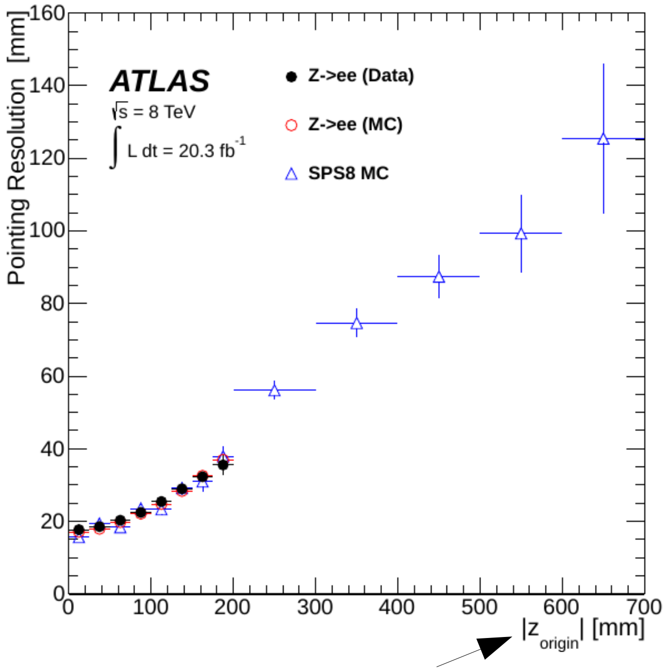
Phys. Rev. D 90, 112005 (2014)

- GMSB can have a neutralino NLSP with a finite lifetime before decaying into a photon and a gravitino
- The photons appear delayed and may not point back to the PV

Idea:

- Use the finely segmented ATLAS LAr EM calorimeters:
  - Flight direction using shower spread in the first two layers
  - Measure $|\Delta z_\gamma| = z_{origin} - z_{PV}$
    - Only barrel photons (resolution worse in the end-caps)
  - Loose photon ID efficiency for signal:
    - 95% for $|z_{origin}|<250$ mm down to 75% at $|z_{origin}|= 700$ mm
- Also use the photon arrival time t_γ at the calorimeter
  - From pulse-shape of the 2nd-layer cell with max. energy
  - $t_\gamma=0$: prompt photon from the hard collision
  - Time resolution for large energy deposits is 256 ps
    - ≈ 220 ps due to LHC bunch-spread along the beamline (so LAr contribution to the time resolution is ≈ 130 ps)
  - Concentrate on lifetimes above 250 ps





Z_{PV} for Z(ee)

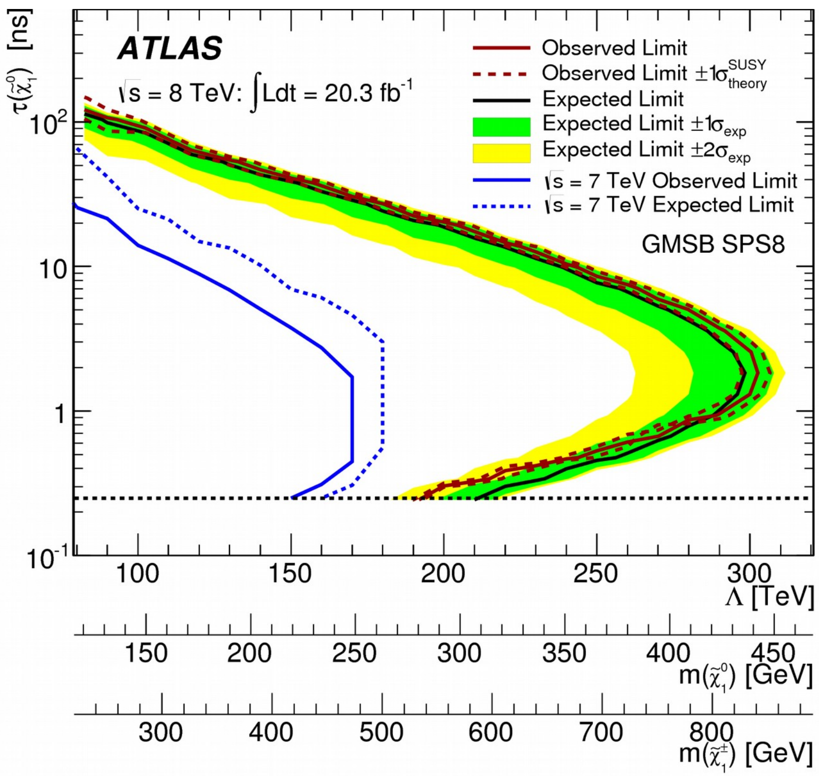
Non-pointing photons in supersymmetry

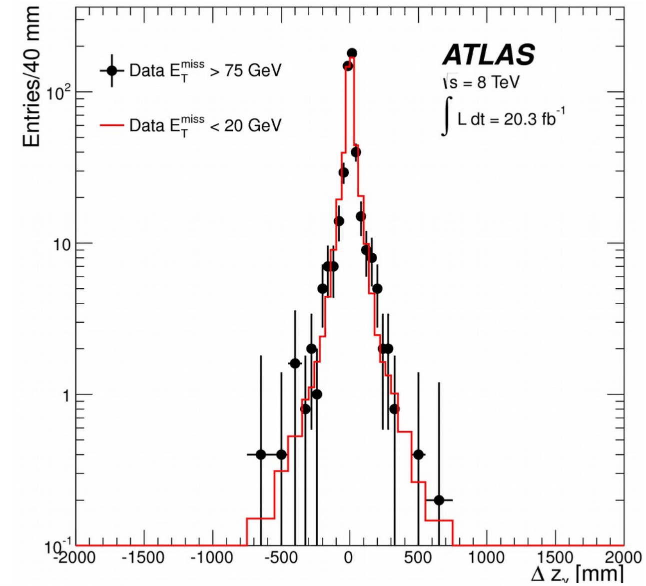
Phys. Rev. D 90, 112005 (2014)

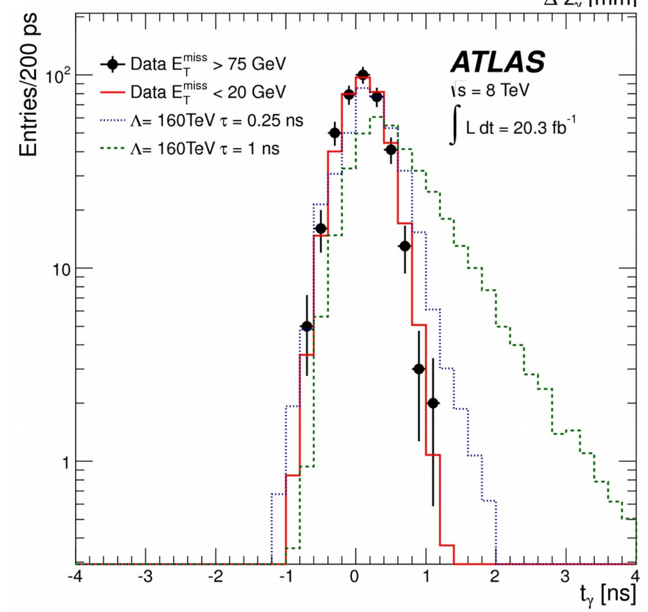
Selection:

- 2 loose isolated photons E_T>50 GeV, one in $|\eta|$<1.37
- MET>75 GeV
- 2D search in $|\Delta z_\gamma|$and t_γ of the barrel photon (or largest value)
  - Almost completely uncorrelated for prompt backgrounds

BG estimation: Templates from low-MET region



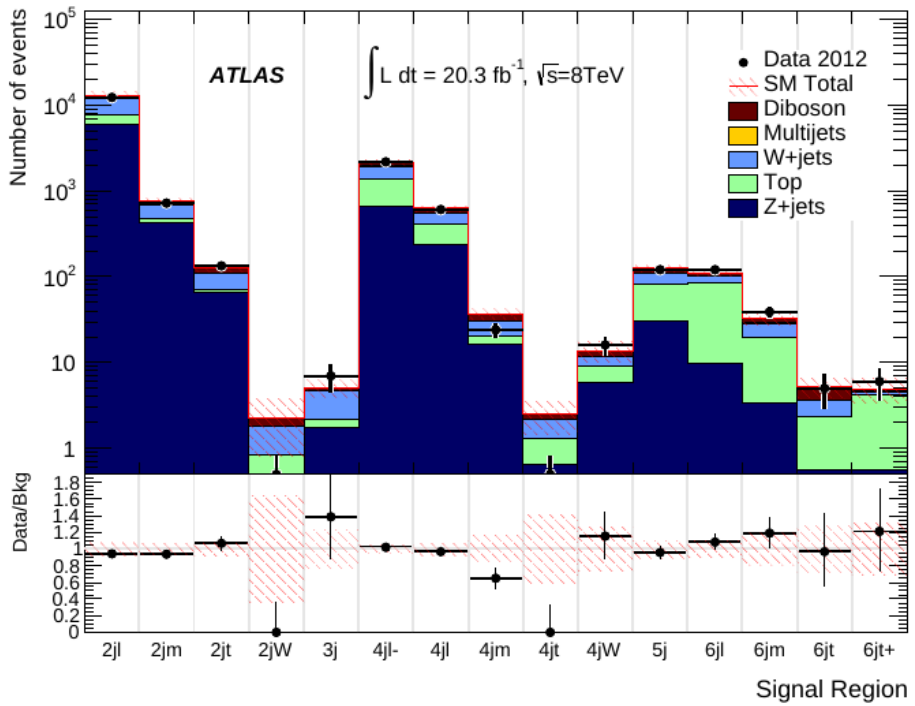




Photons as a tool for other BSM searches

An example: the jets+MET SUSY analysis

- Search for squarks and gluinos in 0-lepton+jets+MET channel
- How to estimate the Z(νν)+jets BG?
  - Select a sample of γ+jets events with E_T>130 GeV
  - Treat the reconstructed photon as contributing to MET
  - For $E_{T,\gamma}$>m_Z kinematics very similar to Z+jets
  - Cross section (x BR) ratio N(photon CR)→N(Z, SR): $$R_{Z/\gamma} = \frac{d\sigma(Z+\text{jets})/dp_T}{d\sigma(\gamma+\text{jets})/dp_T}$$
- More stats than Z(ll) CR…



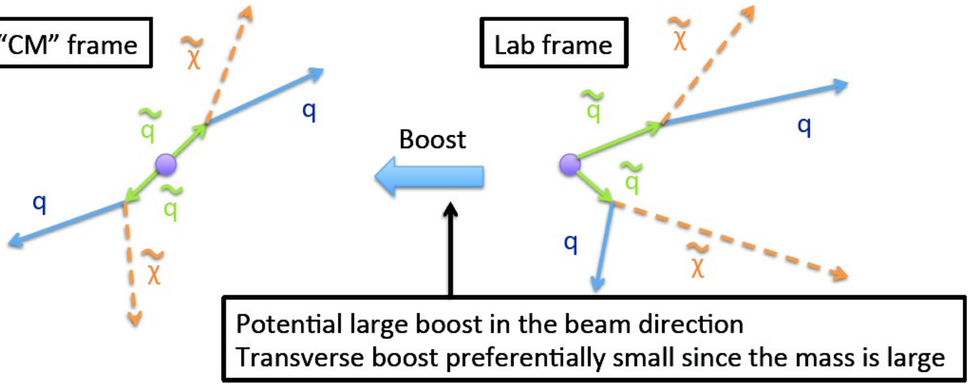
Summary

- Very many models of new physics can be probed using photons:
  - supersymmetry, extra dimensions, dark matter, vector-like quarks, technicolour, FCNC, excited quarks, ...
- BSM searches use photons from ~20 GeV up to the TeV scale, converted and unconverted, timing and pointing info, ...
- Many data-driven background estimates: functional form fits, ABCD methods on ID/isolation, t&p on Z(ee) + CR(e), SR variable side-band,...
- They can also be used to control the BG in other BSM searches
- No new physics discovered yet, but run-2 is looming...
- Many analyses will become more sensitive than run-1 very quickly : expect many new results during the next year!

Isolation CMS

- **Pflow isolation criteria photon + jet:**
  - the energy deposited in the single HCAL tower closest to the supercluster position, inside a cone of $\Delta R = 0.15$ centered on the photon direction, must be less than 5% of the energy deposited in that ECAL supercluster;
  - the total pT of photons within a cone of $\Delta R = 0.3$, excluding strips of width $\Delta\eta=0.015$ on each side of the supercluster, must be less than 0.5 GeV + 0.005pT
  - the total pT of all charged hadrons within a hollow cone of $0.02 < \Delta R < 0.3$ about the supercluster must be less than 0.7 GeV
  - the total pT of all neutral hadrons within a cone of $\Delta R = 0.3$ must be less than 0.4 GeV + 0.04pT
- **Pflow isolation criteria photon + MET within a cone of $\Delta R = 0.3$:**
  - E_T^{iso}(additional photons) < $(0.7 + 0.005E_T)$ GeV
  - E_T^{iso}(neutral hadrons) < $(1.0 + 0.04E_T)$GeV
  - E_t^{iso}(charged hadrons)<1.5 GeV

More on razor



$$M_R = \sqrt{(|\vec{p}_{j_1}| + |\vec{p}_{j_2}|)^2 - (p_z^{j_1} + p_z^{j_2})^2}$$

$$M_T^R = \sqrt{\frac{E_T^{miss}(p_T^{j_1} + p_T^{j_2}) - \vec{E}_T^{miss} \cdot (\vec{p}_T^{j_1} + \vec{p}_T^{j_2})}{2}}$$

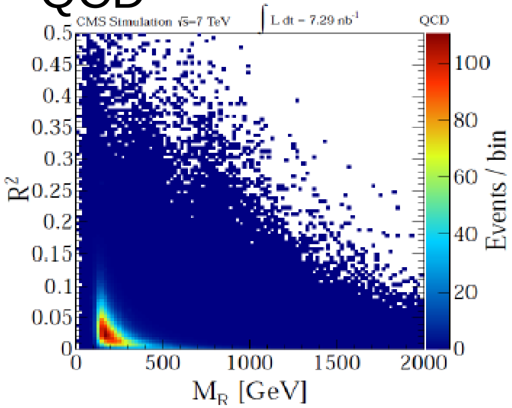
$$R = \frac{M_T^R}{M_R}$$

Peaks at

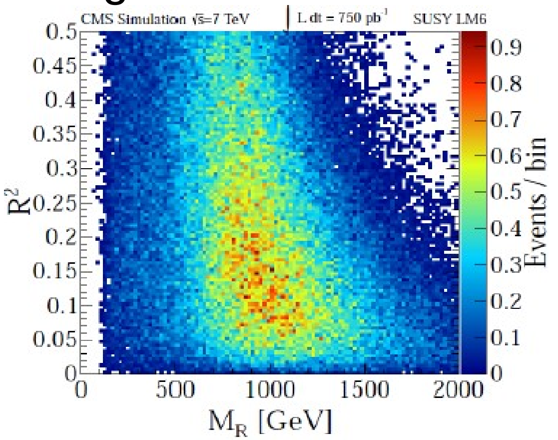
$$M_\Delta = \frac{M_S^2 - M_{LSP}^2}{M_S}$$

Edge at M_Δ

QCD



Signal



- ATLAS:
  - https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2013-05/
  - http://www.sciencedirect.com/science/article/pii/S0370269314001713
- CMS:
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13006PubTWiki
  - http://arxiv.org/pdf/1307.5515.pdf