Beyond the Standard Model Physics with E_T^{miss} + Photons

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On behalf of the Milano Mono-Photon and Di-Photon groups

X ATLAS ITALIA WORKSHOP - MILANO

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Outline

Motivation of E_T^{miss} + Photons Searches

Run 1 Analyses and Results

Status and plans for Run 2

E_T^{miss} + Photons signatures can probe many BSM scenarios in a unique way:
Dark Matter (DM), SUSY, Large Extra Dimensions.

An excess of events with E_T^{miss} + Photons would signal the presence of **new undetected particles** in ATLAS in a fairly **model-independent** fashion:

- High **E_T^{miss}** = an imbalance in the transverse plane that signals the presence of undetected particles
- High-p_T **Photons** = extremely clean taggers or directly involved in the new physic process searched for

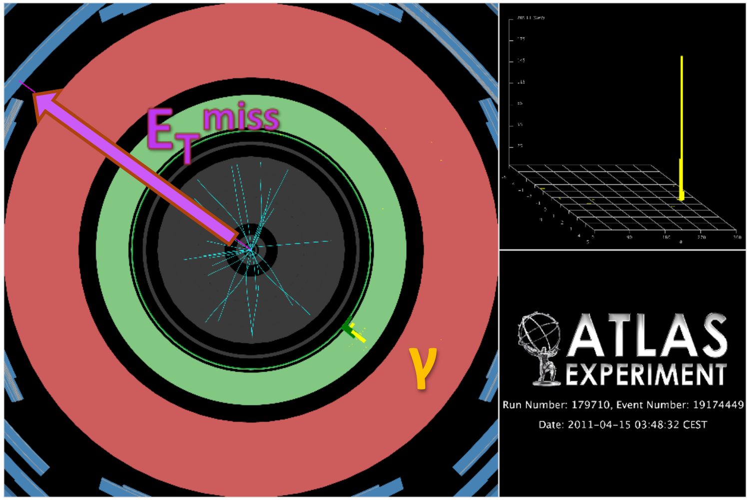
Analyses covered in Italy in E_T^{miss} + Photons searches (Cut&Count) by the Milano Group in Run 2:

- **Mono-Photon + E_T^{miss}** **EXOTICS**
- **Di-photon + E_T^{miss}** **SUSY**

=> Some common Backgrounds and Strategies

People Involved:

4 staff, 1 post-doc, 2 PhD students, 1 Master Student
Donatella Cavalli, Leonardo Carminati, Tommaso Lari, Stefano Manzoni, Silvia Resconi, Maria Giulia Ratti, Ruggero Turra, Giacomo Zecchinelli



Display of a candidate mono-photon event
one photon of p_T = 449.7 GeV E_T^{miss} = 446.9 GeV
$\Delta\varphi(E_T^{miss},\gamma) \approx \pi$

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Run 1 Papers

Mono-Photon 8 TeV Paper:

Phys. Rev. D 91, 012008 (2015) : http://journals.aps.org/prd/abstract/10.1103/PhysRevD.91.012008

Search for new phenomena with the ATLAS detector in monophoton events from proton-proton collisions at $\sqrt{s} = 8$ TeV

Leonardo Carminati[1], Donatella Cavalli[1], Marie-Helene Genest[2], Valerio Ippolito[3], Lashkar Kashif[4], Andrew Nelson[5], Marta Perego[1], Caterina Pizio[1], Maria Giulia Ratti[1], Silvia Resconi[1], Chase Shimmin[5], Fuquan Wang[4], Daniel Whiteson[5], Mengqing Wu[2], Sau Lan Wu[4], Ning Zhou[5]

[1] *Milan*
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[3] *Harvard*
[4] *Wisconsin*
[5] *UCI*

Contact Editor of the Paper

Di-Photon CONF with 8 TeV results:

Search for Diphoton Events with Large Missing Transverse Momentum in 8 TeV pp Collision Data with the ATLAS Detector
ATLAS-CONF-2014-001, http://cds.cern.ch/record/1641169

Combination Paper - SUSY signatures with photons (on-going):

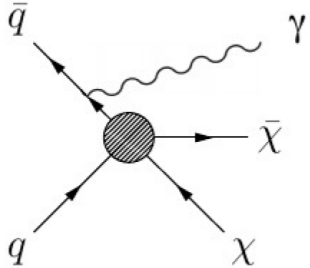
Combination of di-photon, photon+lepton, photon+b, photon+jet Run 1 Results

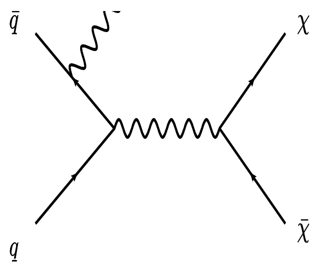
Other analyses with similar signatures:

- Search for Higgs boson decays to neutralinos and gravitino: https://cds.cern.ch/record/1742700/ (not public yet)
- Search for direct pair production of a chargino and a neutralino decaying to the 125 GeV Higgs Boson: http://arxiv.org/abs/1501.07110

Mono-Photons in Run 1: *Signals and Backgrounds*

SIGNAL: Dark Matter WIMP pairs χχ with ISR Photon





What we look for: = High E_T^{miss} recoiling back-to-back against one photon

How it is described:

Effective Field Theory approach

Interaction between WIMPs and SM particles is described effectively, Fermi-like: the mediator is integrated out

- **PRO:** production cross section only depends on m_χ and mediator mass
- **CON:** limited validity regime

Simplified Models approach

Explicit integration of the mediator

- **PRO:** not limited by any validity regime
- **CON:** cross section depends on more parameters (width of mediator and coupling)

Standard Model BACKGROUNDS

Which backgrounds

Z(→νν) + γ	irreducible background	**O(75%)**
W(→lν) + γ	electron or muon not identified	**O(13%)**
Z(→ll) + γ	both leptons not indentified	**O(<1%)**
W/Z + jets	lepton or jet reconstructed as photon	**O(10%)**
ttbar, single top, diboson, multijets		**O(1%)**
γ + jets	badly reconstructed jet causes E_T^{miss}	**O(<1%)**

How they are estimated

- Z(→νν) + γ, W(→lν) + γ, Z(→ll) + γ: from **DATA/MC RATIOS** in appropriate Control Regions
- W/Z + jets; ttbar, single top, diboson, multijets: purely **DATA-DRIVEN** techniques (electron fakes and jet fakes)
- γ + jets: pure MC simulation

Mono-Photons in Run 1: *Analysis*

Signal Region (SR)

- Preselections: GRLs, Good Vertex, data quality, jet cleaning, Trigger E_T^{miss} > 80 GeV
- **E_T^{miss}>150 GeV**
- at least one **photon** with **p_T > 125 GeV**
- well-separated objects: **$\Delta\varphi(\gamma, E_T^{miss}) > 0.4$**
- leading photon **"tight"**, **isolated, $|\eta^\gamma| < 1.37$**
- at most **one jet** p_T>30GeV, $\Delta\varphi(jet, E_T^{miss}) > 0.4$
- **Veto on electrons and muons**

Control Regions (CRs)

- keep the same cuts as SR
- **revert one or more cuts** at a time to define regions enriched in a particular source of background

W/Z + γ Backgrounds

SR Z+γ W+γ	2μ CR Z(μμ)+γ	1μ CR W(μν)+γ	2ele CR Z(ee)+γ

Two k-factors (k_W, k_Z) are determined from data/MC ratios in the CRs, which normalize the MC yields in the SR:

$$N_{SR} = N_{SR}^{MC} \cdot k$$

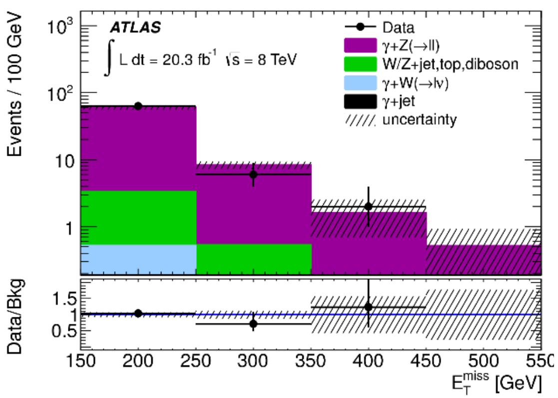
one control region is designed for W+γ estimation

→ two control regions are designed for the main background Z+γ

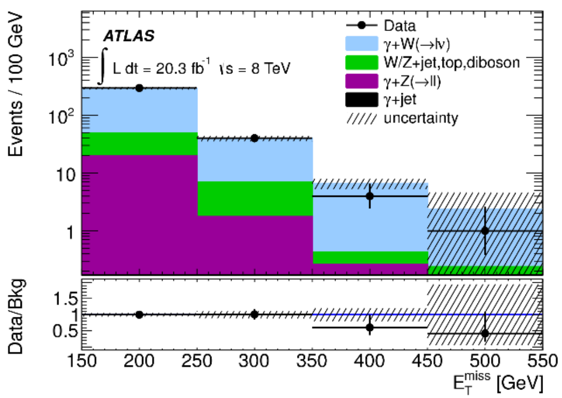
→ 2μ and 2ele control regions alone have low statistics

→ systematic uncertainties can be correlated among CRs and SR

2μ CR



1μ CR



Plots from Phys. Rev. D 91, 012008 (2015)

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- well-separated objects: **$\Delta\varphi(\gamma, E_T^{miss}) > 0.4$**
- leading **photon "tight", isolated**
- at most **one jet** p_T>30GeV, $\Delta\varphi(\text{jet}, E_T^{miss}) > 0.4$
- Veto on **electrons** and muons

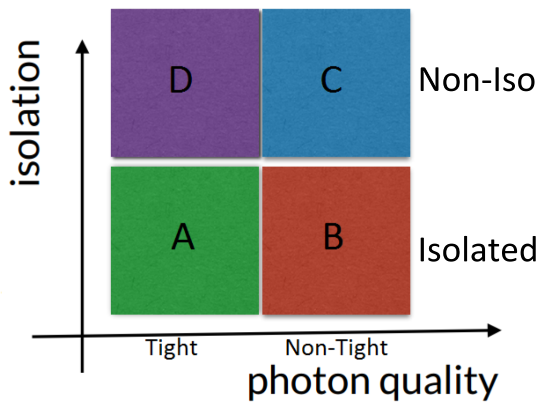
Control Regions (CRs)

- keep the same cuts as SR
- revert one or more cuts at a time to define regions enriched in a particular source of background

Jets Faking Photons

Estimate contribution of **fake photons originated by jets** that pass the identification and isolation criteria of the photon with an ABCD method:

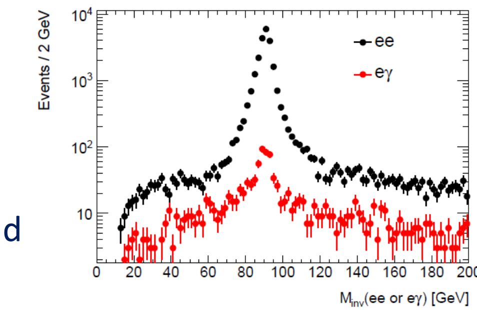
$$N_A^{bkg} = N_B \frac{N_D}{N_C}$$



Electrons Faking Photons

Estimate contribution of **electrons reconstructed as photons in SR**:

1. **Mono-electron CR:** require an isolated tight++ electron of p_T > 125 GeV instead of a photon
2. **EFR** (electron fake rate) with a tag&probe method:
   - tag electron (pT>20 GeV) and probe photon OR electron (pT>125 GeV)
   - invariant mass of the two to be compatible with the Z mass
   - EFR = ratio of number of probe photons and probe electrons



1ele CR no photon × **EFR**

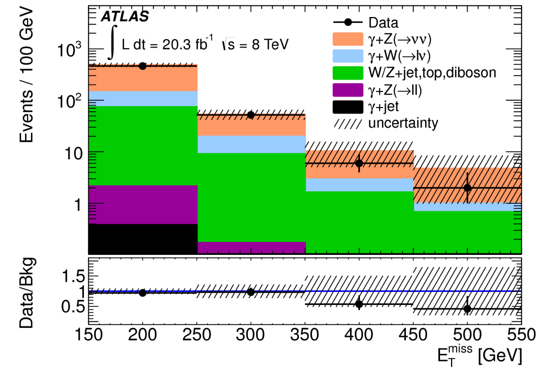
Mono-Photons in Run 1: *Results*

Simultaneous fit in lepton CRs and SRs:

$$L_{reg}[\mu \mid N_{obs}] = Poiss(N_{reg}^{obs} \mid \mu \cdot N_{reg}^{sig} + k_Z \cdot N_{reg}^{Z\gamma} + k_W \cdot N_{reg}^{W\gamma} + N_{reg}^{other})$$

No deviation was found from Standard Model predictions

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

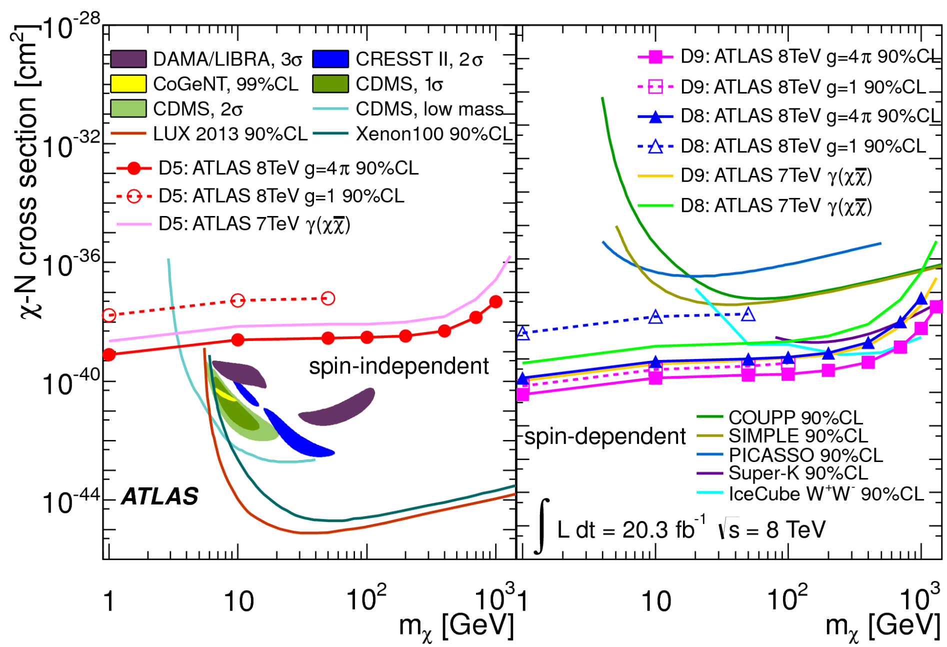


Results interpreted in terms of **exclusion limits** of WIMP-nucleon cross section vs WIMP mass m_χ

- ⇒ can be directly compared to **direct and indirect searches of Dark Matter**
- ⇒ different sensitivities for spin-independent (D5 operator)/dependent (D9 operator) interaction between SM and DM

Good sensitivity to low WIMP mass, where direct experiments are not sensitive

MIND: more results for DM in simplified models and SUSY and LED interpretations in the paper



Plots from Phys. Rev. D 91, 012008 (2015)

Di-Photons in Run 1: *Signals and Backgrounds*

SIGNAL: SUSY in GMSB models

Search for a signal from **GMSB** models
(Gauge-Mediated Supersymmetry Breaking):

- neutralino (NLSP) promptly decaying in γ + Gravitino (LSP)

Two processes are identified with γ γ + E_T^{miss} in the final state :

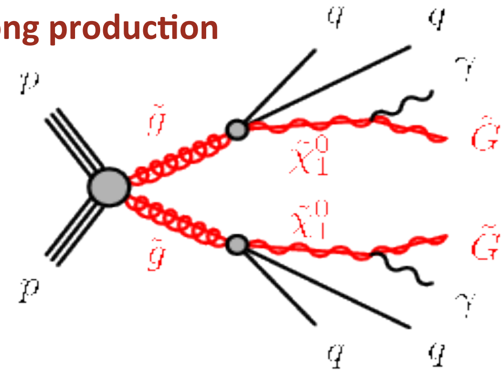
→ **Strong** production:
gluinos -> neutralinos + jets -> photons+Gravitinos+jets

→ **Electroweak** production:
neutralinos are produced via wino triplet

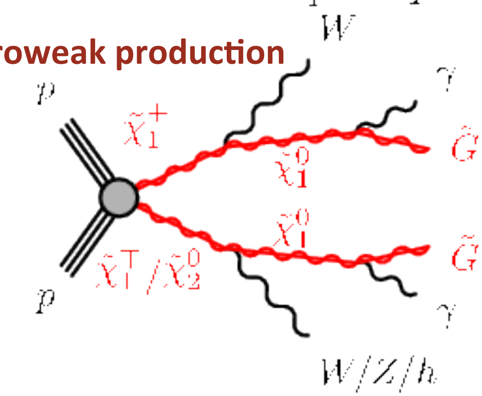
The mass of the neutralino is treated as a free parameter, and varied between 50 GeV and the mass of the gluino/wino

Short-lived neutralino is considered, prompt decay

Strong production



Electroweak production



Standard Model BACKGROUNDS

- **QCD background**, instrumental E_T^{miss}
  SM diphoton, multijet, γ+jet → data-driven

- **EW background**: genuine E_T^{miss}
  V+γ → data-driven

- **Irreducible background**
  W(->lν)+γγ → data/MC ratio
  Z(->νν)+γγ → pure MC

Di-Photons in Run 1: *Analysis*

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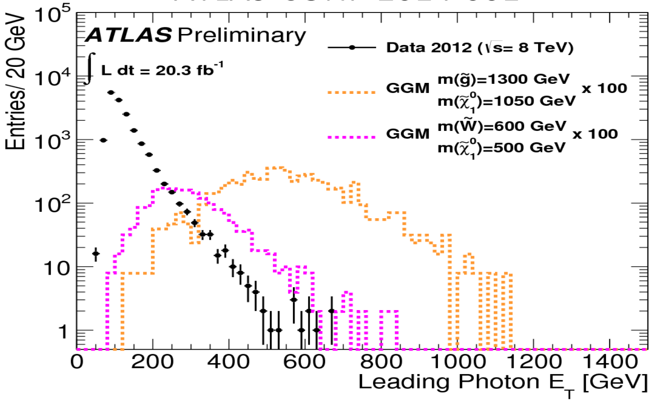

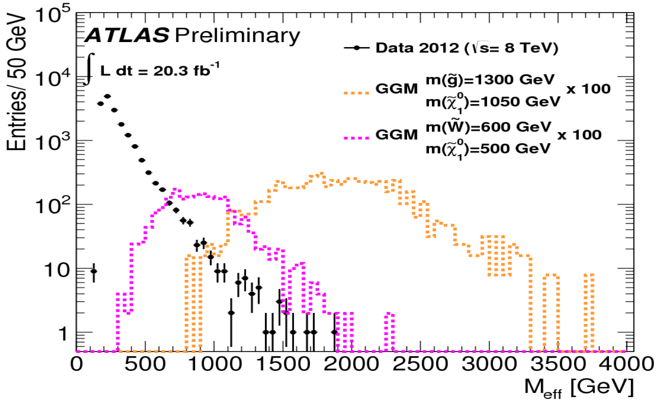

Event selection

- Two tight photons with p_T>75 GeV
- Event Cleaning (jet cleaning, cosmic muon cleaning)

Inclusive signature: no explicit requests on jets, leptons

Five Signal Regions optimized using:

E_T^{miss} , $\Delta\phi(\gamma, E_T^{miss})$, $\Delta\phi(jet, E_T^{miss})$

H_T = total transverse energy of all visible objects, expected to be large for strong production

M_{eff} = scalar sum of H_T and E_T^{miss}

- SP1, SP2 for Strong Production
- WP1, WP2 for Electroweak Production
- MIS, Model Indipendent

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

Di-Photons in Run 1: *Results*

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

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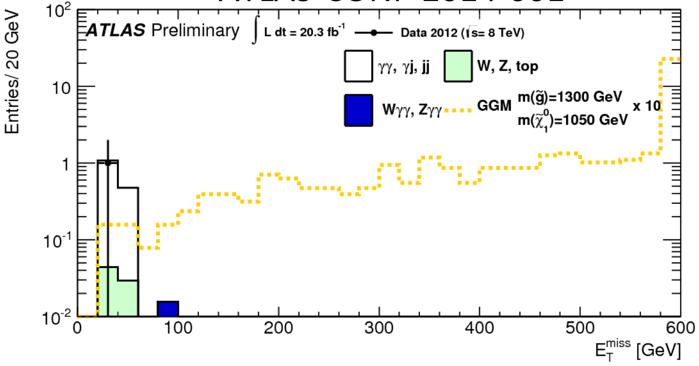

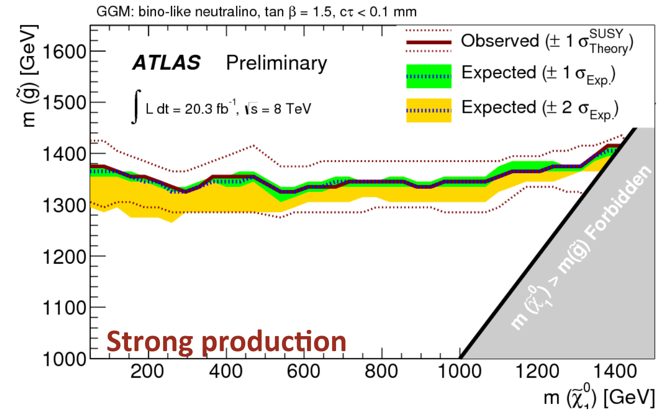

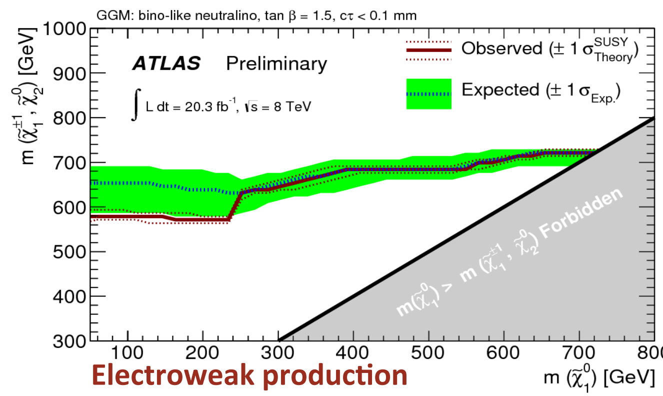

- No statistically significant deviation from the SM is observed
- **SRs have very low background**
- For each signal region 95% CL lower limit is set on the **visible cross section**:
  - SP1 (SP2) 0.15 (0.14) fb
  - WP1 (WP2) 0.19 (0.41) fb
  - MIS 0.23 fb
- 95% CL lower limits (-1 sigma) are set on
  - **Gluino mass** at 1280 GeV
  - **Wino mass** at 570 GeV

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Towards Run 2: *Challenges and Strategies*

Challenges: deal with 13 TeV conditions

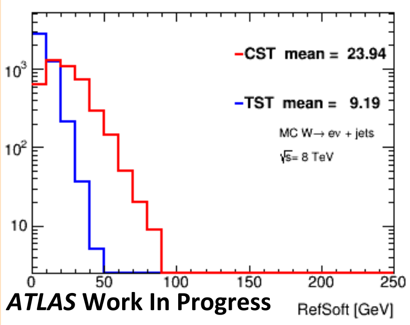
- Higher **center-of-mass energy** → enhanced signal sensitivity
- More dense **PILE-UP** conditions → more difficult **object reconstruction**

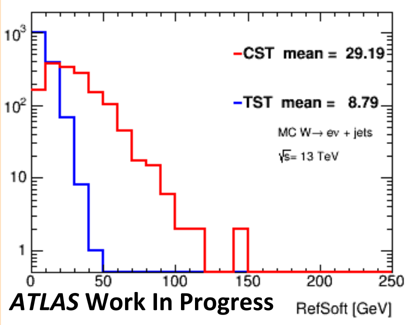
Reconstruction of Photons:

- The new std calibration will be based on Monte Carlo calibration tuned using multivariate techniques
- Photon reconstruction has changed
- New photon ID is being tuned
- Pre-recommendations by extrapolation from Run 1 data (similar or conservative uncertainties)
- Use of first 1 fb^{-1} of 50 ns to update recommendations
- Expected similar to Run 1 perfomance
- See more in Ruggero Turra's talk https://indico.cern.ch/event/371430/session/6/contribution/15/material/slides/0.pdf

Reconstruction of E_T^{miss} and Pile-Up impact

- E_T^{miss} will be rebuilt for each analysis in order to accomodate for the various object selections
  see more in Marianna Testa's talk https://indico.cern.ch/event/371430/session/6/contribution/19/material/slides/0.pdf
- Pile-Up will mostly impact on jets and Soft Term
  - Calorimeter based Soft Term gets worse at 13 TeV
  - Track based Soft Term shows a better and more stable performance going to 13 TeV





Strategies

- **Harmonised objects** will be used in Run 2 analyses
- **Robust** cut & count analyses: start with **Run 1 analysis strategy,** use **common analysis tools**
- keep the analysis as **model-independent** as possible with single SR for **early data**
- Use **multiple SRs** optimized for different models when **more data** becomes available

Mono-Photons in Run 2: *Sensitivity*

Study the analysis sensitivity at 13 TeV

First studies based on PDF reweighting (13 TeV MC samples not yet available):
repeat analysis at 8 TeV and **scale the event yields by the ratio $\sigma_{13TeV}/\sigma_{8TeV}$**

→ Backrounds: all scaled by the ratio of the cross sections of the main process $Z(\rightarrow \nu\nu) + \gamma$
$\sigma_{13TeV}/\sigma_{8TeV}$ ≈2,

→ Signals: 2 signal points for EFT Dark Matter
$\sigma_{13TeV}/\sigma_{8TeV}$ ≈ 4-6

With 1-2 fb^{-1} the analysis can compete with 8 TeV but in a model dependent way:
required luminosity is 1.72 fb^{-1} for D5 50 GeV, 0.96 fb^{-1} for D5 400 GeV.

→ we aim at 2-5 fb^{-1} publication

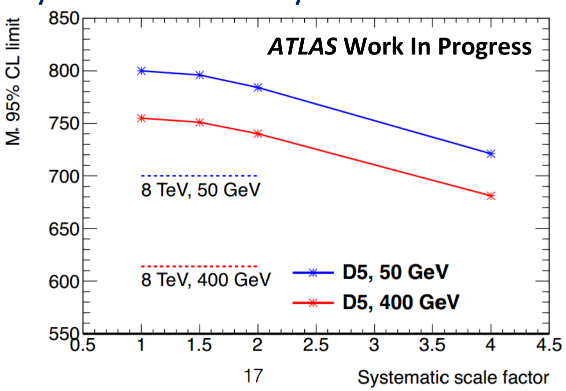
Yields in Signal Region for total background and two benchmark signal points, same cuts as in 8 TeV, same systematics

Process	**8 TeV, 20.3 fb^{-1}**	**13 TeV, 5 fb^{-1}**	**13 TeV, 10 fb^{-1}**
Background	557	290	581
± stat ± syst	± 36 ± 27	± 26 ± 14	± 36 ± 28
D5, 50 GeV	20.7	26.7	53.3
D5, 400 GeV	12.3	21.2	42.4

For the 5 fb^{-1} case, systematic tolerance is studied by scaling the systematics. With as twice as bad systematic error, sensitivity is still better than 8 TeV. Analysis dominated by **statistical error**

Lower Limits on M_* (=suppression scale of the theory) for two benckmark signal points

Process	**8 TeV, 20.3 fb^{-1}**	**13 TeV, 5 fb^{-1}**	**13 TeV, 10 fb^{-1}**
D5, 50 GeV	700 GeV	800 GeV	854 GeV
D5, 400 GeV	614 GeV	755 GeV	806 GeV



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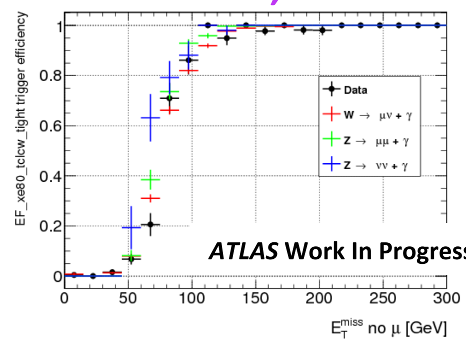
Mono-Photons in Run 2: *Readiness*

Exotic Analysis Walk-Through took place in Geneva last week (4-6 February) aimed at preparing for early Run 2 analysis.

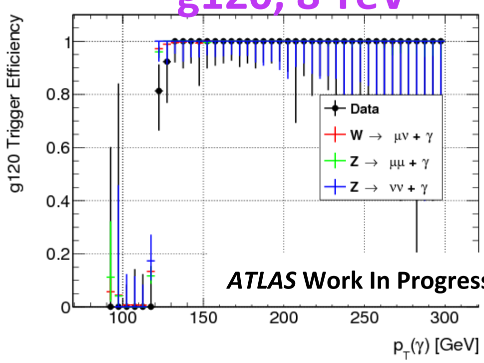
Some important items discussed for the Mono-Photon analysis:

1. **Signal Samples** DC14: full-simulation samples requested for EFT and Simplified Models, in production, close to finish
   MC15: a standardized set of simplified models being discussed in ATLAS+CMS Dark Matter Forum.
2. **Background Samples** DC14: main background requested, just becoming available.
   MC15: backgrounds will be requested with revisited filters.
3. **Derivation:** EXOT6 derivation framework in common with gamma +jet analysis is in place, smart slimming implemented, tests done for interface with xAOD analysis
4. **Trigger:** move from E_T^{miss} trigger to photon trigger, based on Run 1 studies
   - → photon trigger more efficient and with sharper turn-on
   - → photon trigger less sensitive to pile-up
   - → possibility to use a single trigger for the entire analysis
5. **xAOD analysis** being implemented
   Tools: common choices with other mono-X analyses, SUSYTools and HistFitter
   Analysis: optimization of analysis cuts (jet/gamma pT thresholds, MET)
6. **Institutes:** ANL, Harvard, LPSC Grenoble, Milano, Wisconsin

xe 80, 8 TeV



g120, 8 TeV



Mono-Photons in Run 2: *Unblinding strategy*

Run 1

In 8 TeV analysis, a **Validation Region (VR)** was used for checking the consistency and robustness of the background estimation techniques, before unblinding the SR.

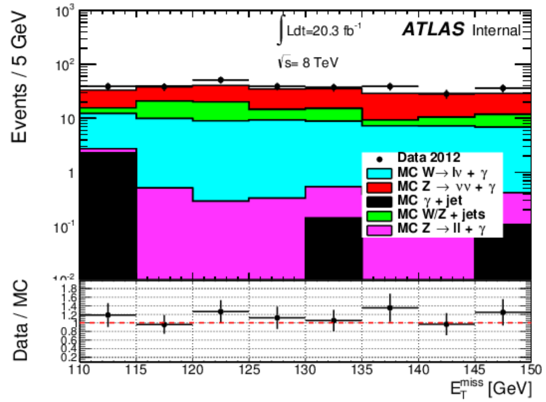
→ Optimize a VR at low E_T^{miss} such that:
1. contamination of signal is low
2. background composition similar to SR
3. statistics is comparable to SR

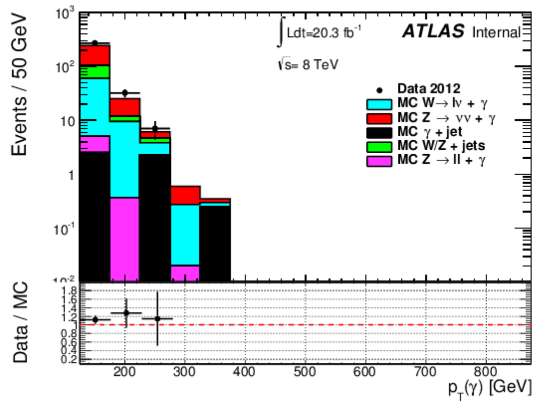
→ Repeat the entire background estimation using the corresponding CRs at low E_T^{miss}

→ Check the data/MC ratio in the VR: if it is 1 within the uncertainties

→ Proceed to unblind the SR (otherwise re-optimize the VR)

Run 1 results in the VR





Run 2

For Run 2 several possibilities are being discussed:

→ same strategy as run 1

→ use as VR either 50 ns data

→ use as VR first fb^{-1} of 25 ns data

In both last two cases there is less sensitivity that 8 TeV

Di-Photons in Run 2: *Sensitivity*

Sensitivity at 13 TeV

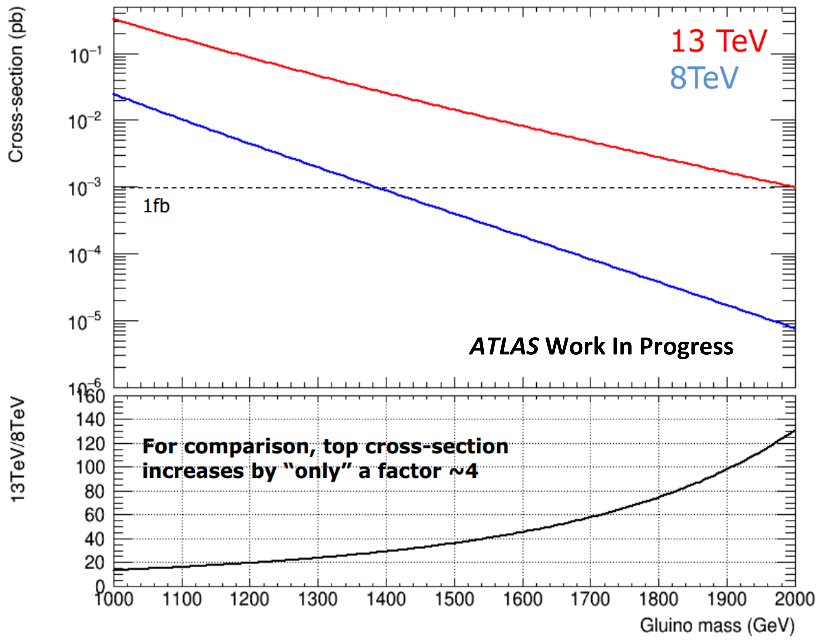
Considering a single signal point,
gluino with mass 1400 GeV, just above the 8 TeV exclusion limit:

- Signal: σ(13TeV)/σ(8TeV) ≈ 30
- Background: σ(13TeV)/σ(8TeV) ≈ 2-3
- **S/√B ≈ 20**

This search will reach the sensitivity of the 8 TeV analysis with **1 fb^{-1}** at 13 TeV

For very early data the analysis will probably consider only the Strong Production SRs and Model Indipendent SR

Signal Cross Section vs Gluino Mass



Di-Photons in Run 2: *Readiness*

Status of the analysis

At the moment di-photon is the **only photon + E_T^{miss} Susy analysis on-going** for Run 2 (no displaced photons, γ+b/lepton/jets+MET)

1. **Signal Samples** DC14: three points in the strong production mode have been requested
   MC15: request will be updated for complete signal grid
2. **Background Samples** DC14: some are alrealdy there, some are being requested.
   MC15: backgrounds will be requested
3. **Derivation:** under evaluation, either EXOT10 , or HGG
4. **Trigger:** 2g50_loose or g35_medium_g25_medium
5. **xAOD analysis** being implemented. Some delay caused by the overlap of the closure of the Run1 analysis and the beginning of the new one

   Tools: SUSYTools and HistFitter
6. **Institutes:** LPNHE Paris, Milano, Santa Cruz, Tokyo

Summary and Conclusions

- E_T^{miss} + Photons searches can provide insight in different BSM scenarios
- **Mono-Photon** and **Di-Photon analyses** have produced interesting results in Run 1, although no excesses were found
- Mono-Photon and Di-Photon searches **have good sensitivity for discovery or exclusion** with early or very early data at 13 TeV

  Di-Photon → very early data

  Mono-Photon → early data

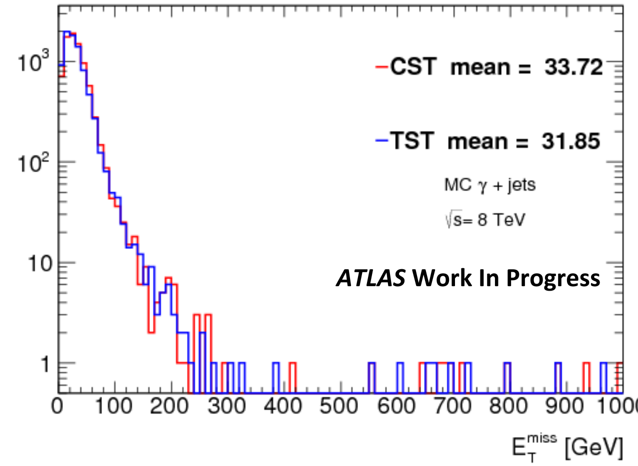
- Run 2 work is on-going and analyses are being implemented: we aim at covering all analyses aspects !

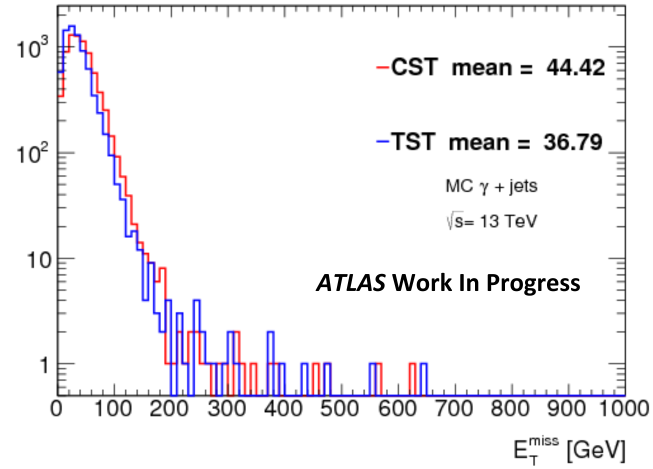
BACK-UP

E_T^{miss} performance in Gamma+Jet

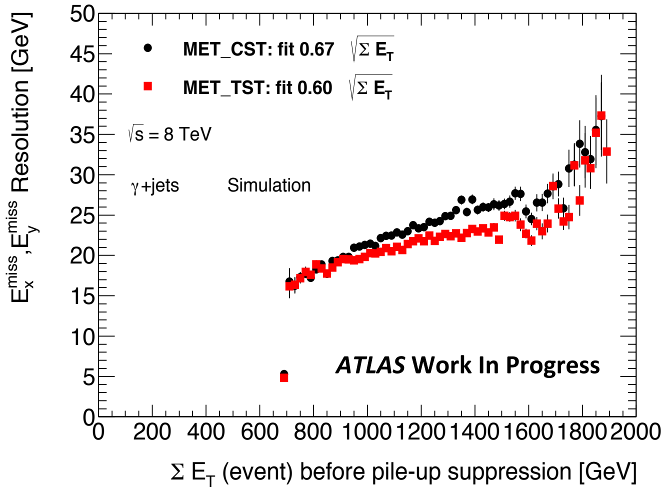
8 TeV | **13 TeV**

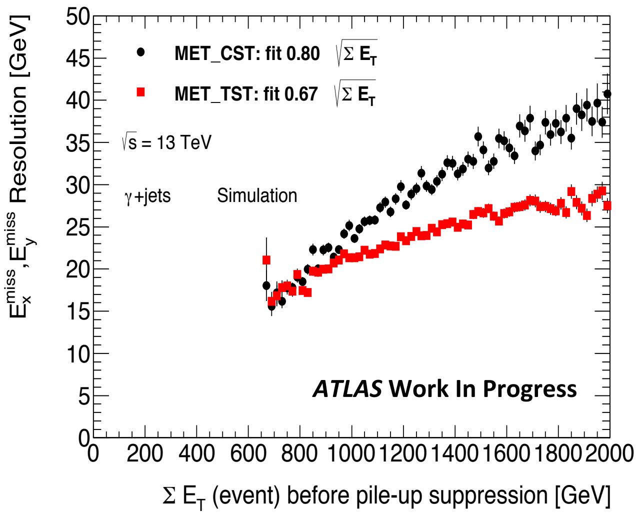
Total E_T^{miss}



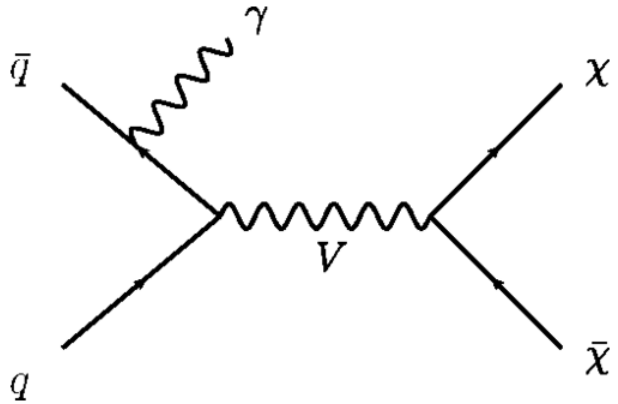


E_T^{miss} Resolution

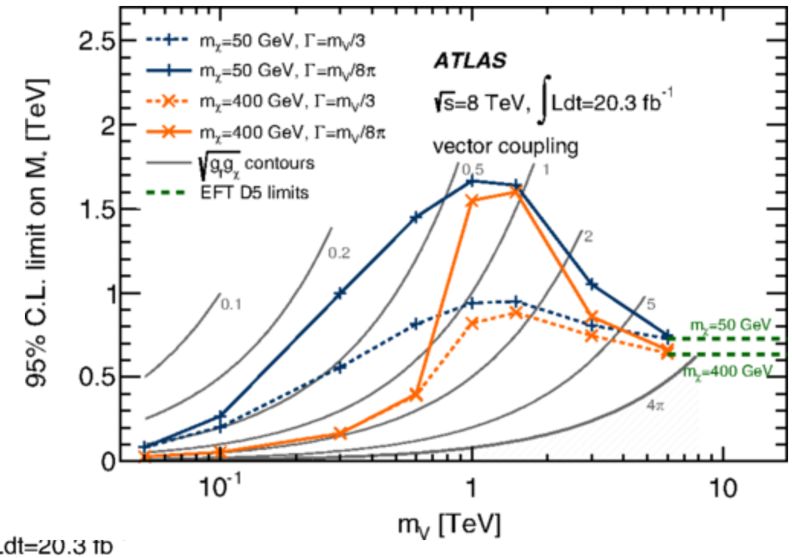


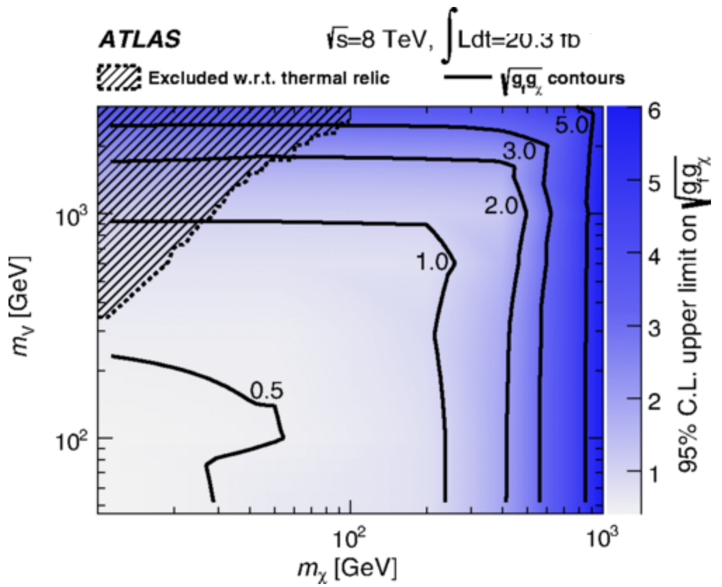


Simplified Z' model



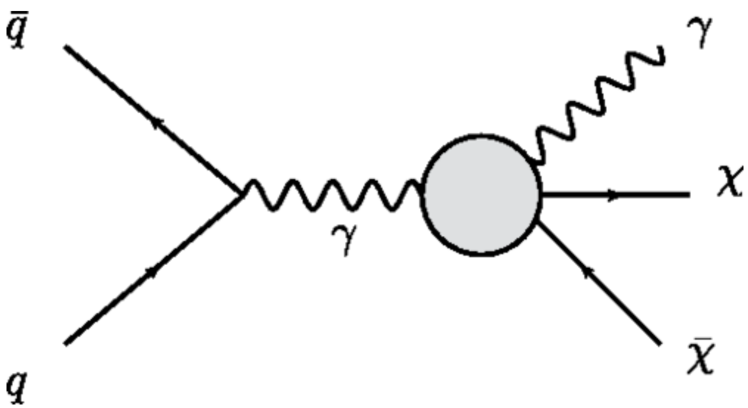
Plots from Phys. Rev. D 91, 012008 (2015)



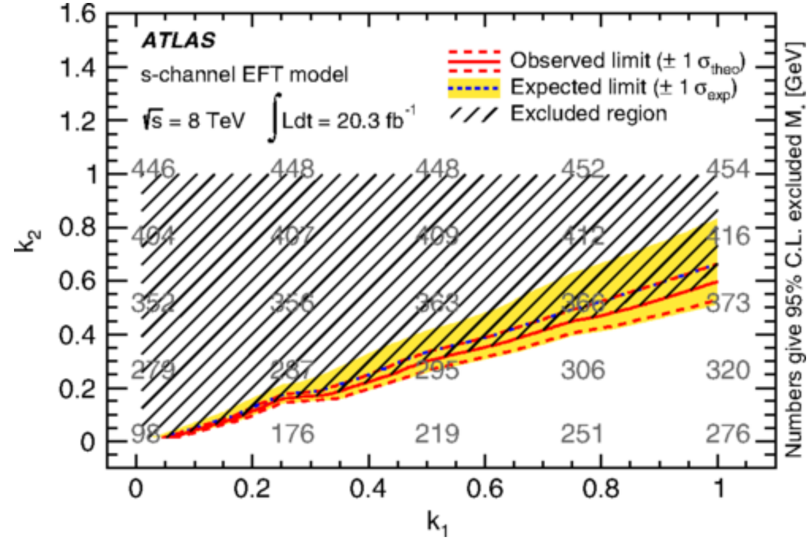


Mono-Photons in Run 1: *More Results*

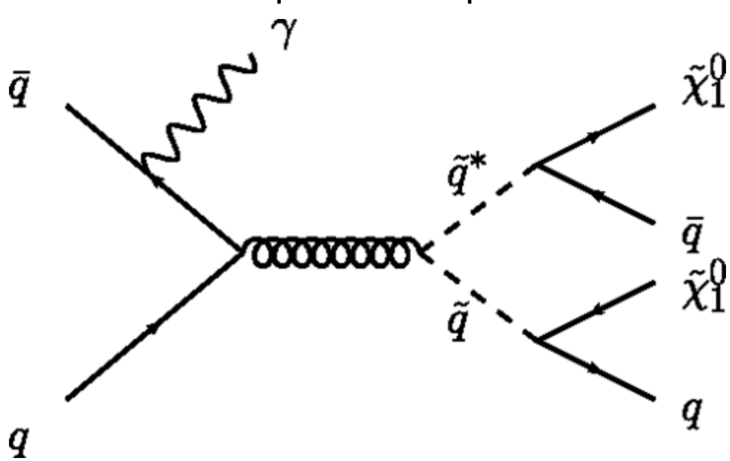
EFT, WIMP coupling to SM gauge bosons

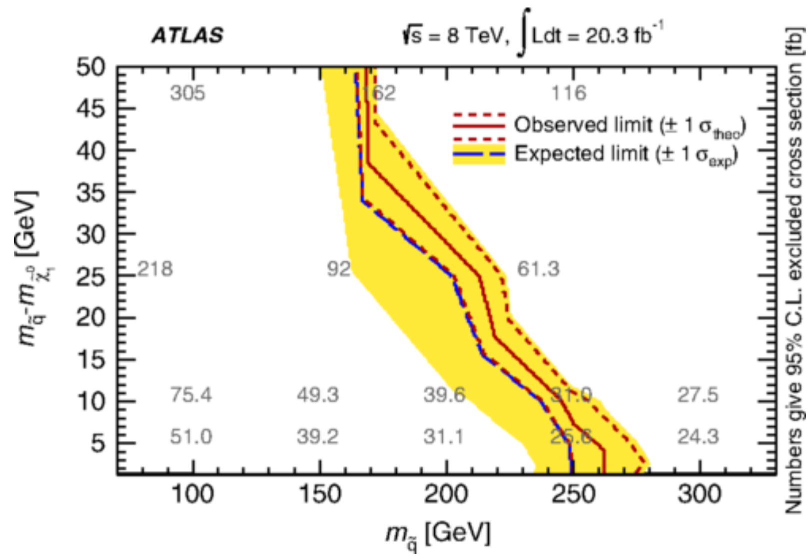


Plots from Phys. Rev. D 91, 012008 (2015)



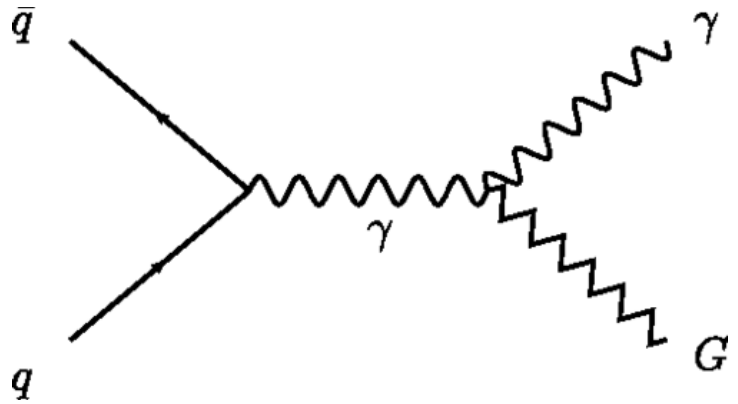
Compressed S-quark





Mono-Photons in Run 1: *More Results*

ADD Large Extra Dimensions



Plots from Phys. Rev. D 91, 012008 (2015)