Search for invisible particle production in monojet and monophoton events with missing transverse momentum with the ATLAS detector

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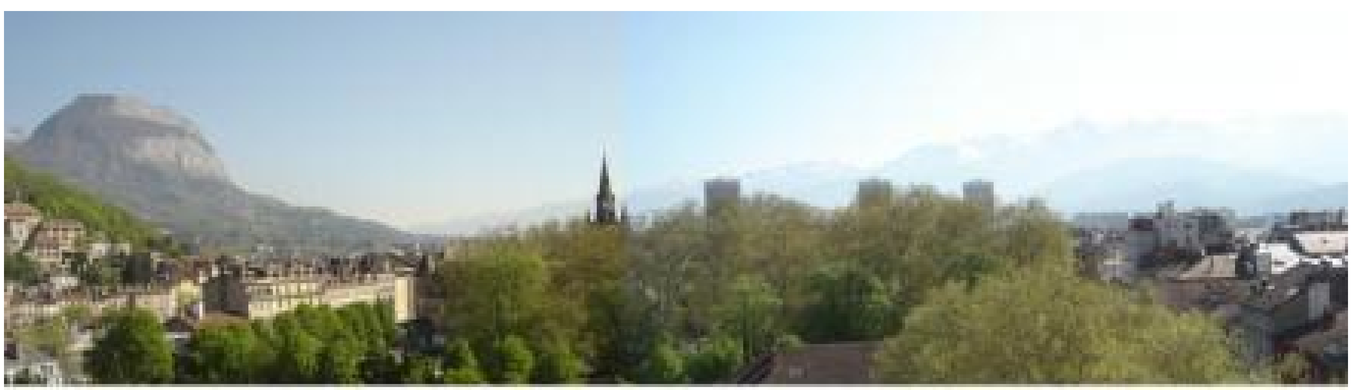


Dark Forces at Accelerators, Oct 2012, Frascati

Evidence for dark matter (DM)

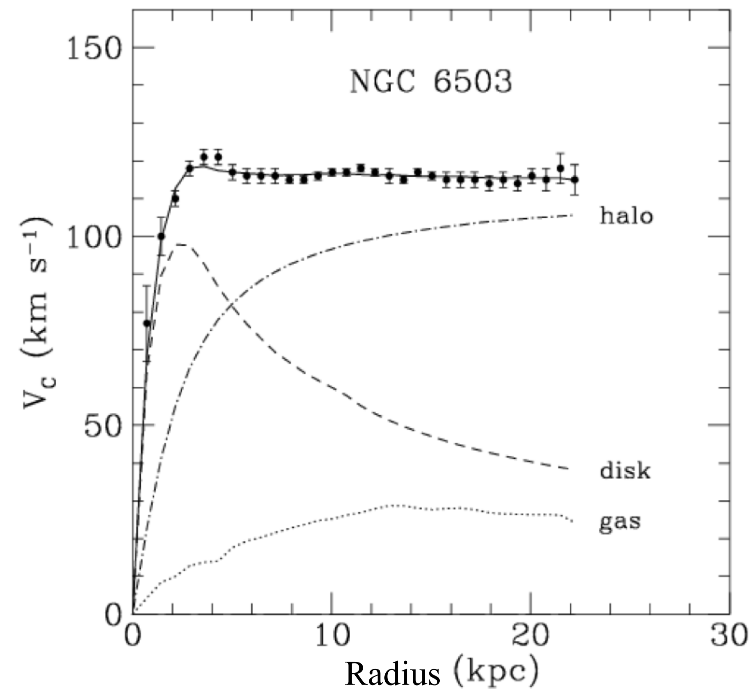
We have evidence for the existence of DM
from observations at quite different length-scales.

<u>"Locally":</u>

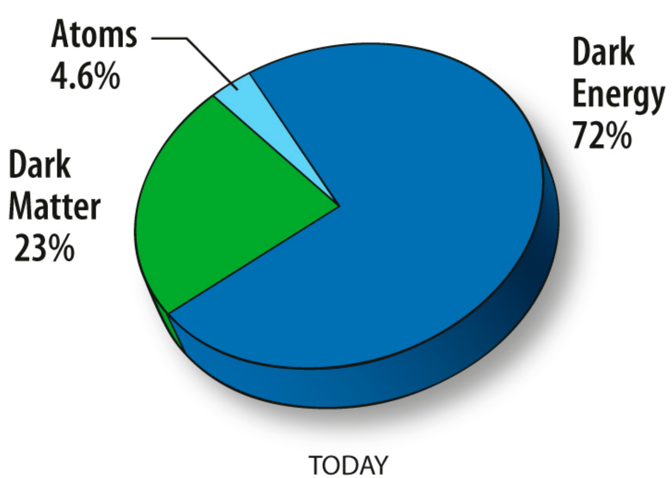
- rotation curves of spiral galaxies
  (checked for over 1000 galaxies, including our own)

- velocity dispersion of galaxies in clusters

Not consistent with gravitation from visible objects.
Consistent with DM with density of ~ 0.1 – 0.2 critical density



Energy budget of the Universe:



<u>Cosmological scales:</u>

- Study of Cosmic Microwave Background (CMB)

- global fits of cosmological parameters to data
  on CMB, Type Ia supernovae, Baryonic Acoustic
  Oscillations, ...

Dark matter candidates

Massive Astrophysical Compact Halo Object (MACHO) ?

Mass of Standard Model neutrinos ?

These are strongly constrained, and cannot account for all of the DM.

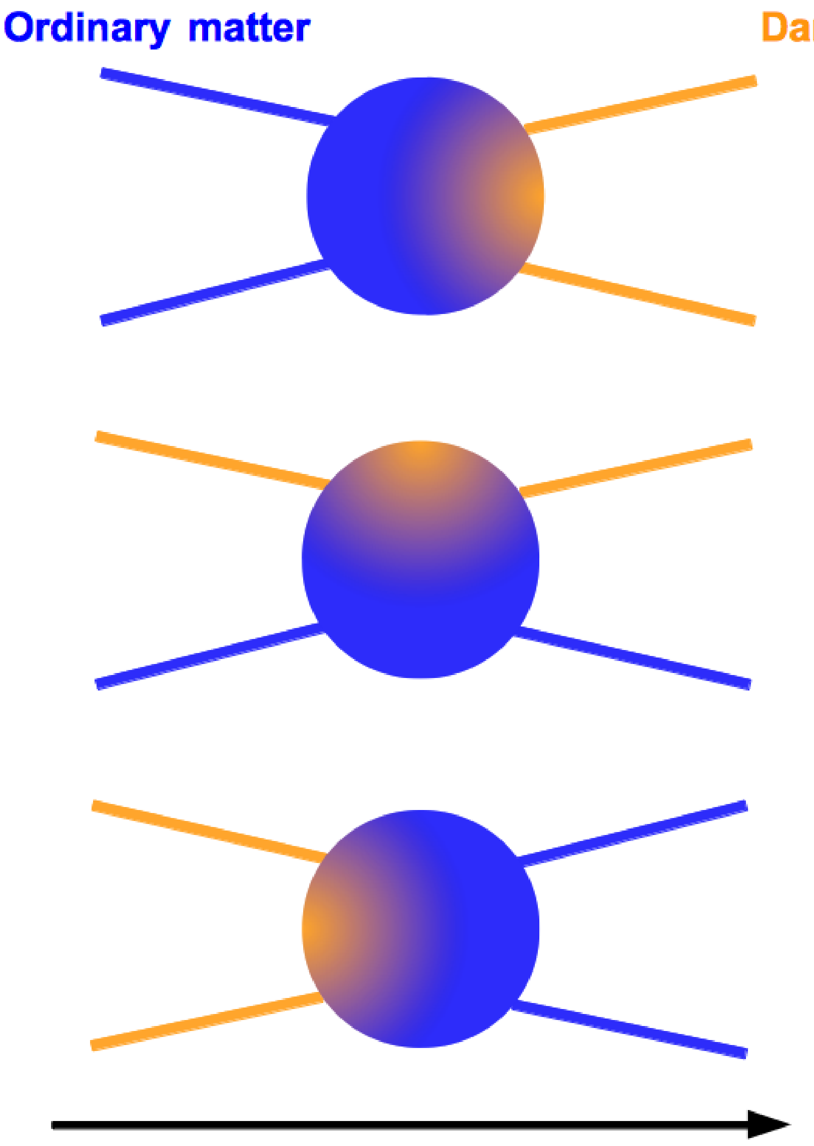
Various extensions to the Standard Model of particle physics provide candidates for non-baryonic DM:

- sterile neutrinos
- axions
- lightest supersymmetric particle (with conservation of R-parity)
- lightest Kaluza-Klein state (extra dimension models)
- …

In general, the "ideal DM candidate" appears to be a Weakly Interacting Massive Particle (WIMP):

no EM or strong interaction, stable enough to still be present in Universe today,
massive enough [O(10) keV] to be non-relativistic during formation of structures in the Universe,
right (consistent with DM seen today) relic density → points to interactions with strength of the weak force

Different approaches to DM search



LHC

Direct detection

Indirect detection
Astrophysics

Direct / indirect searches for WIMPs

WIMPs trapped inside galaxies/massive objects

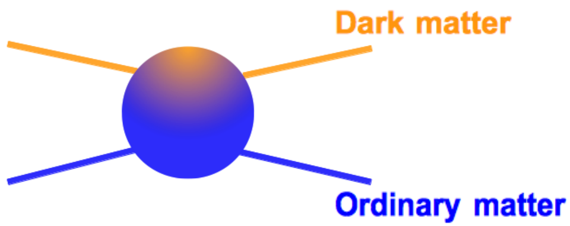
- local density of DM near solar system:

  ~ 0.2 – 0.8 GeV/cm^3

- average velocity w.r.t. Earth:

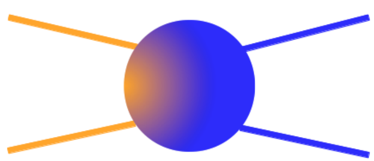
  ~ 270 km/s

Direct search:



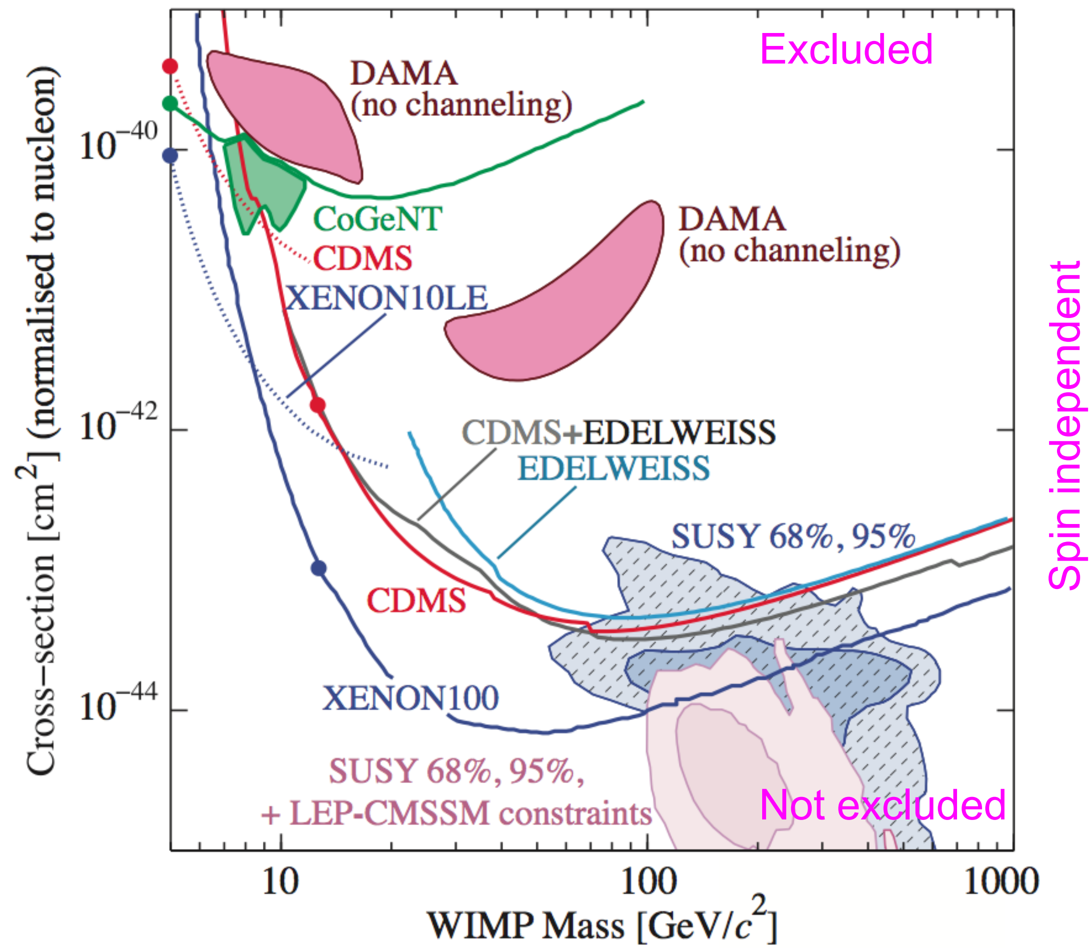
Elastic scattering WIMP-nucleon
in Earth-based detectors
(measurement of nuclear recoil)

Indirect search:



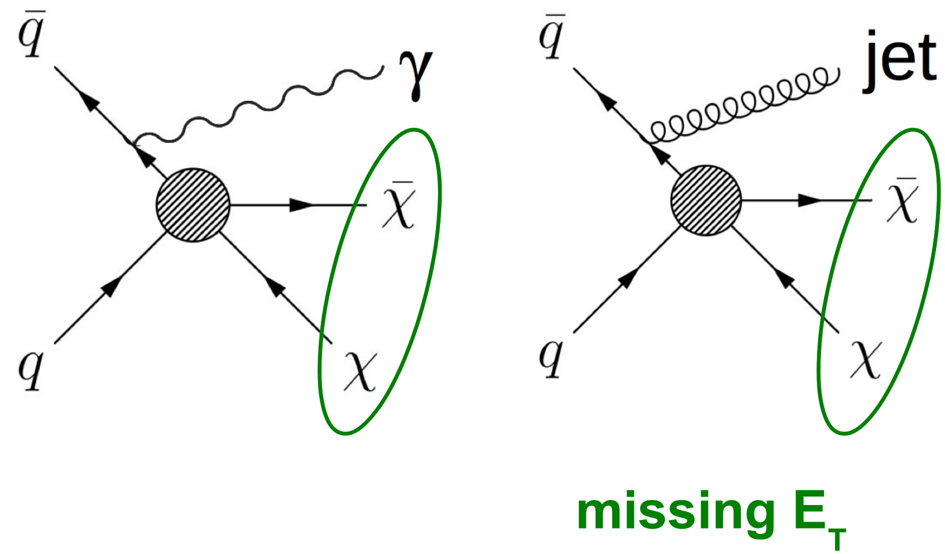
WIMP annihilation products (e.g. photons)
coming to us from celestial objects or from
the galactic halo

Experimental constraints on WIMP-nucleon scattering cross-section as a function of WIMP mass (summary plot from PDG):



Searches for DM candidates at LHC

WIMP pair production on pp collisions
in association with a jet or a photon.



The WIMPs escape detection.

"Need something else in the event to observe."
We get it (the γ or the jet) from QED or QCD radiation.

γ + missing E_T and jet + missing E_T are clean final states with well-understood backgrounds.
They are therefore promising channels in the search for new physics.

Independent verification of results from "direct searches", sensitive to low masses
(where direct searches are blind).

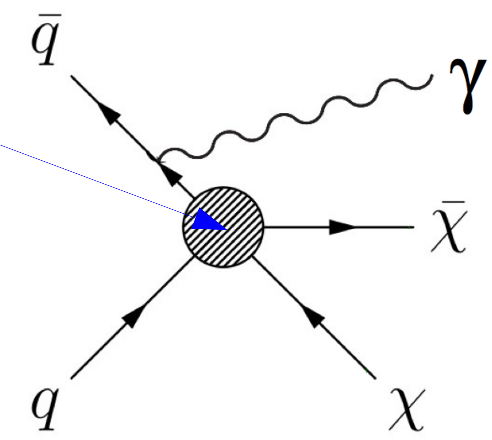
Limits on $\sigma(pp \rightarrow \chi\chi)$ are converted into elastic scattering cross section $\sigma(\chi p \rightarrow \chi p)$
for comparison with direct searches (nuclear recoil).

Effective operators

Parameterise interactions of WIMPs and quarks/gluons using effective operators:

- WIMPs assumed to be Dirac fermions.
- Interaction treated as point interaction with interaction strength M_*

  i.e. all new particles mediating the interaction are too heavy to be produced directly.



Follow the naming scheme of Goodman *et al.*, Phys. Rev. **D82**, 116010 (2010).

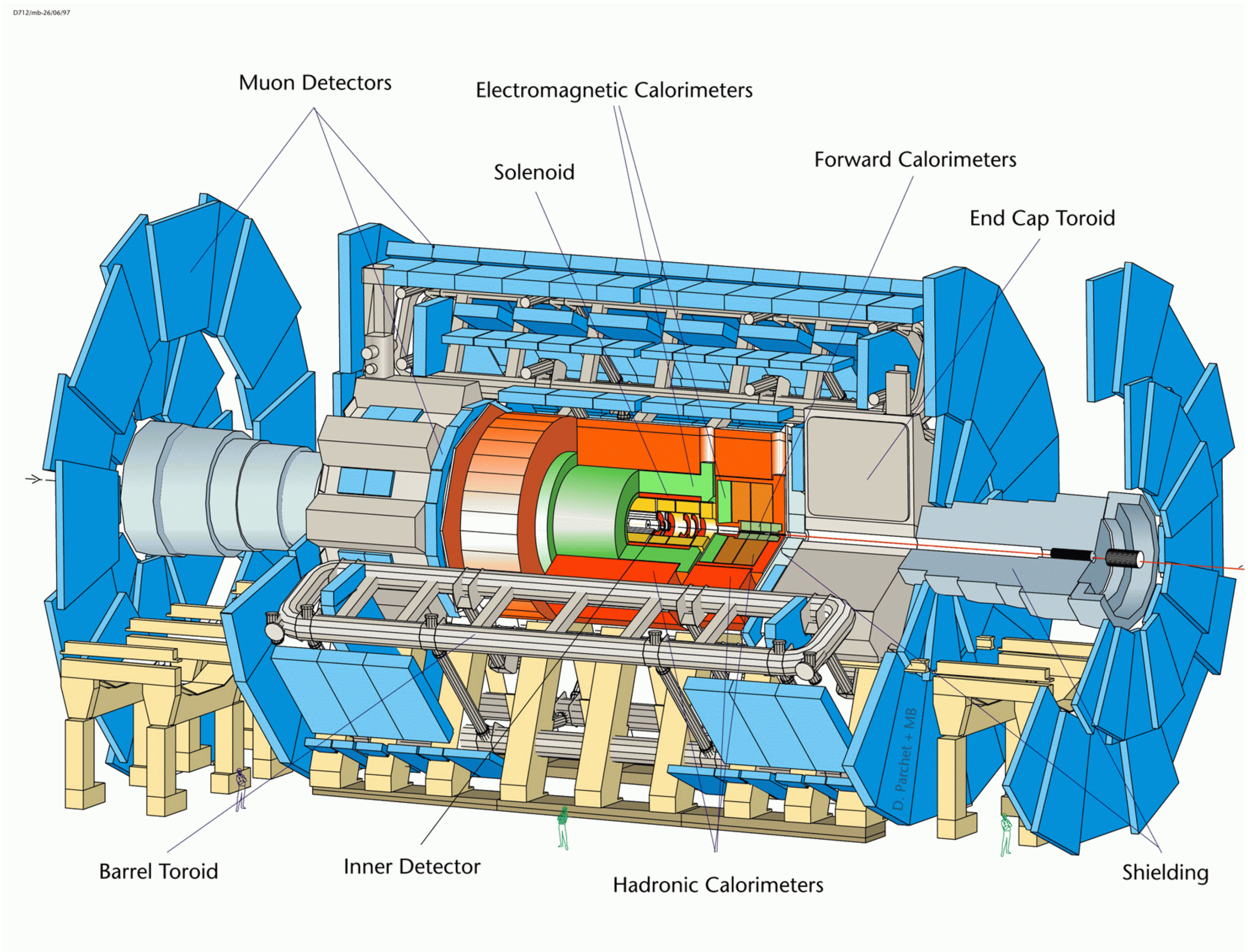
Implemented in the MADGRAPH5 event generator.

spin independent interaction

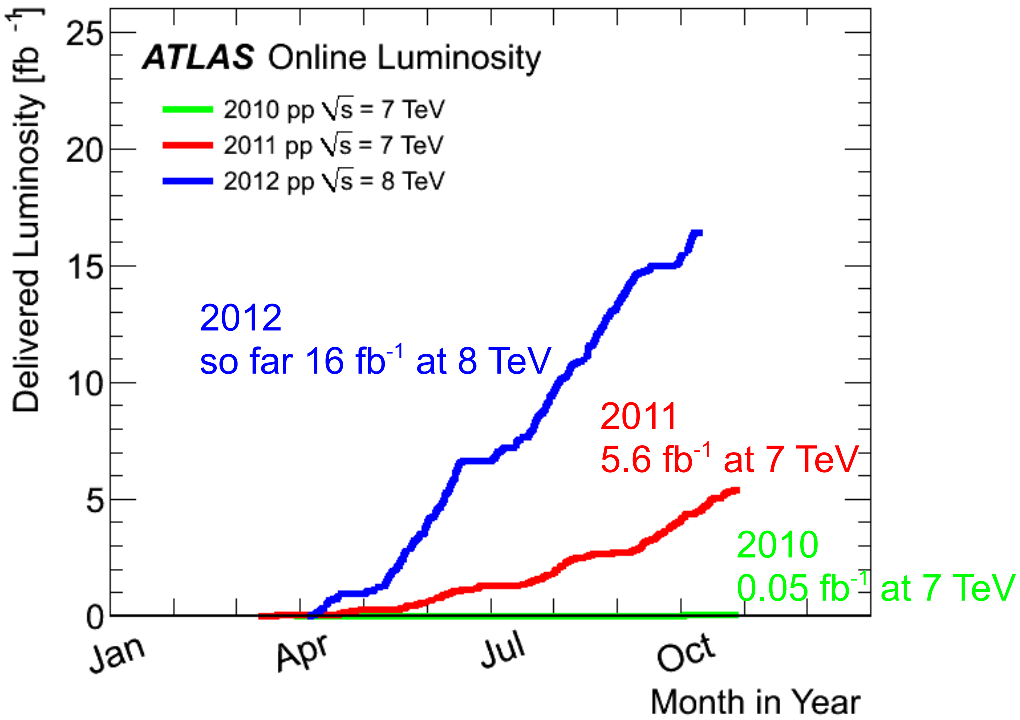
spin dependent interaction

Name	Initial state	Type	Operator
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

ATLAS detector



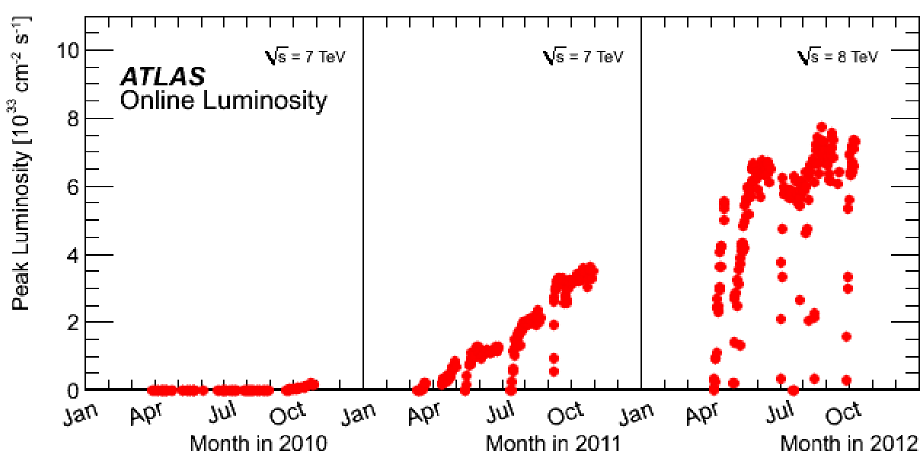
Data taking



expect >20 fb^{-1} by early 2013

$\sqrt{s}$ of 13 – 14 TeV after 2014

The results in this presentation are based on the full 2011 dataset.



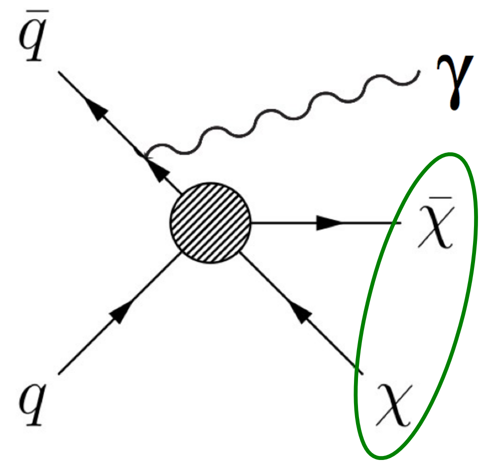
Peak luminosity:

7.7×10^{33} $cm^{-2}s^{-1}$

(~30 interactions per crossing)

Monophoton: event selection

arXiv:1209.4625 (September 2012)
submitted to *Phys. Rev. Lett.*

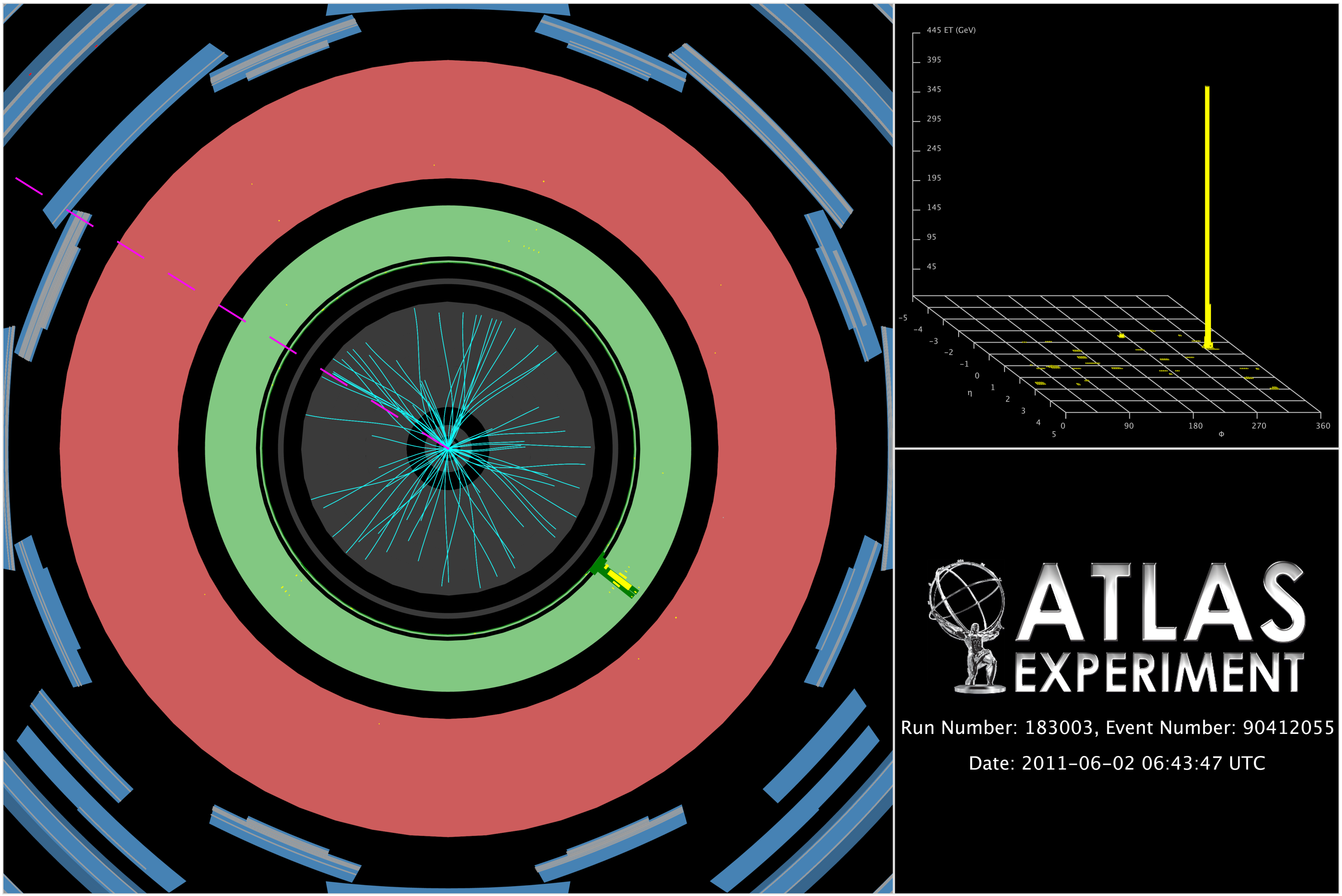


Trigger: $E_T^{miss} > 70$ GeV

Analysis selection:

- Large missing transverse energy:
  $E_T^{miss} > 150$ GeV
- One high-p_T photon:
  p_T(photon) > 150 GeV
- Allow at most one jet with $p_T > 30$ GeV, $|\eta| < 4.5$
- Photon and (possible) jet far away from missing E_T direction:
  $\Delta\phi(\gamma, E_T^{miss}) > 0.4$ $\Delta\phi(\text{jet}, E_T^{miss}) > 0.4$ $\Delta R(\gamma,\text{jet}) > 0.4$
- Veto events with leptons (electrons with $p_T > 20$ GeV, muons with $p_T > 10$ GeV)
- Quality criteria to suppress fake calorimeter signals (noise spikes), cosmic rays (ATLAS-CONF-2012-020)

Monophoton: candidate event



missing E_T:

446.9 GeV

photon p_T:

449.7 GeV

Monophoton: backgrounds

dominant, irreducible background

hadronic τ decay, non-reconstructed e/μ

fake photon / non-reconstructed e/μ

Background source	Prediction	± (stat.)	± (syst.)
$Z(\rightarrow \nu\bar{\nu}) + \gamma$	93	± 16	± 8
$Z/\gamma^*(\rightarrow \ell^+\ell^-) + \gamma$	0.4	± 0.2	± 0.1
$W(\rightarrow \ell\nu) + \gamma$	24	± 5	± 2
W/Z + jets	18	–	± 6
Top	0.07	± 0.07	± 0.01
$WW, WZ, ZZ, \gamma\gamma$	0.3	± 0.1	± 0.1
γ+jets and multi-jet	1.0	–	± 0.5
Total background	137	± 18	± 9
Events in data (4.6 fb^{-1})	116		

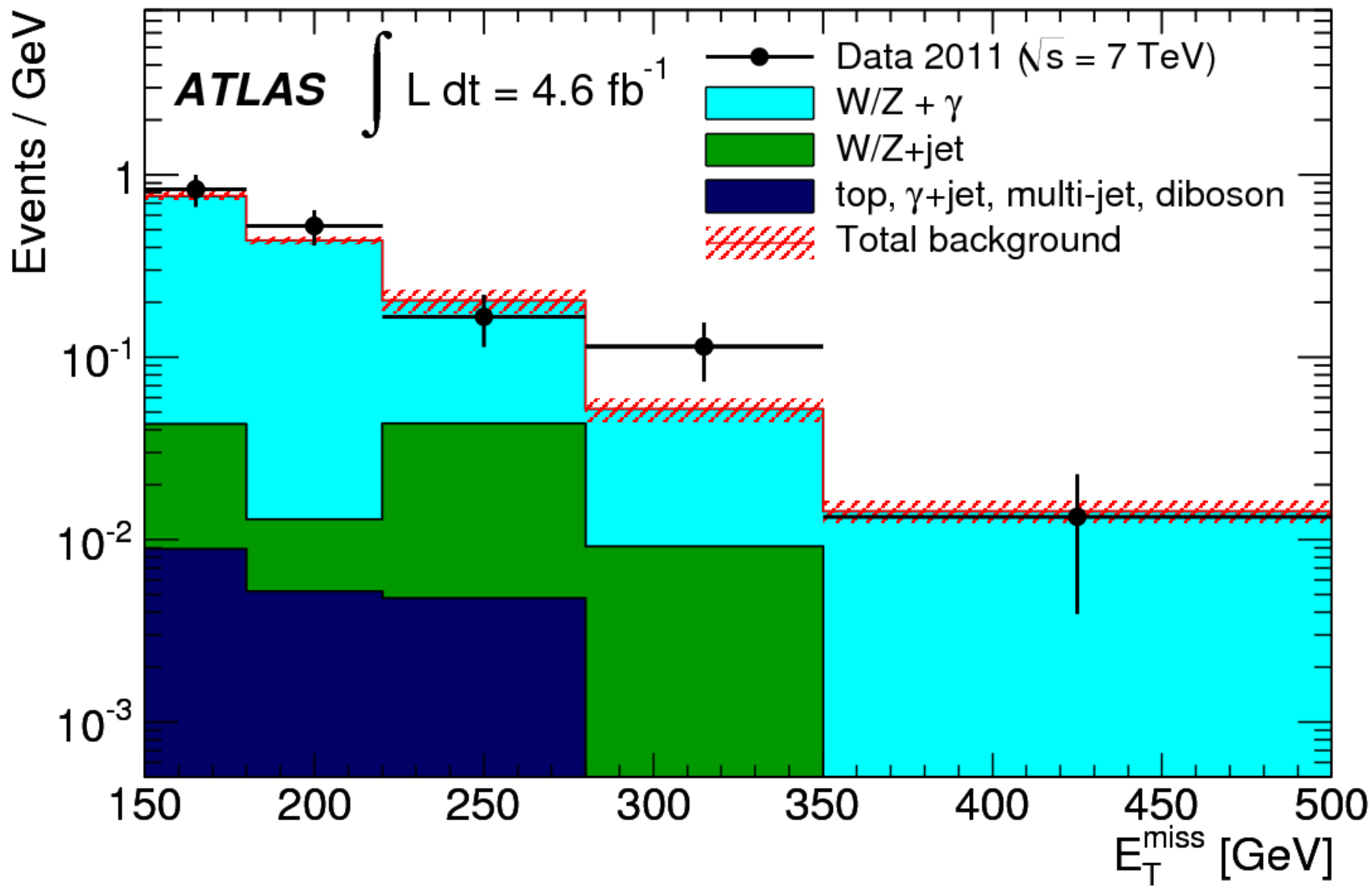
No evidence for excess over expected background in the data.
Will present limits on DM production.

Monophoton: backgrounds

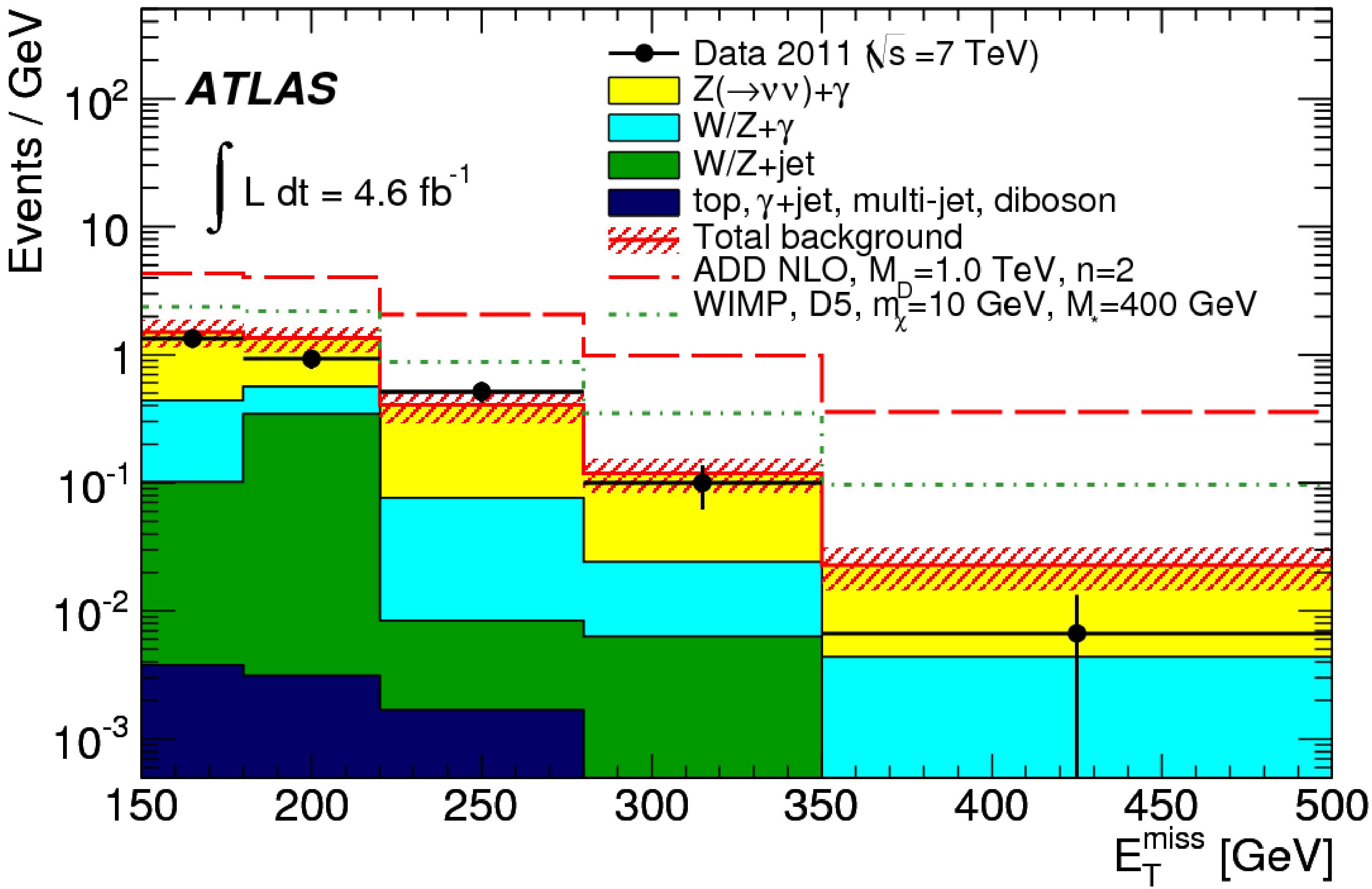
($e \rightarrow \gamma$) and (jet $\rightarrow \gamma$) fakes measured using data-driven method

$Z(\rightarrow \nu\nu, \ell\ell) + \gamma$ and $W(\rightarrow \ell\nu) + \gamma$ background obtained using MC simulations, plus normalisation in a $\mu+\gamma+E_T^{miss}$ data control sample (μ counted as missing E_T)

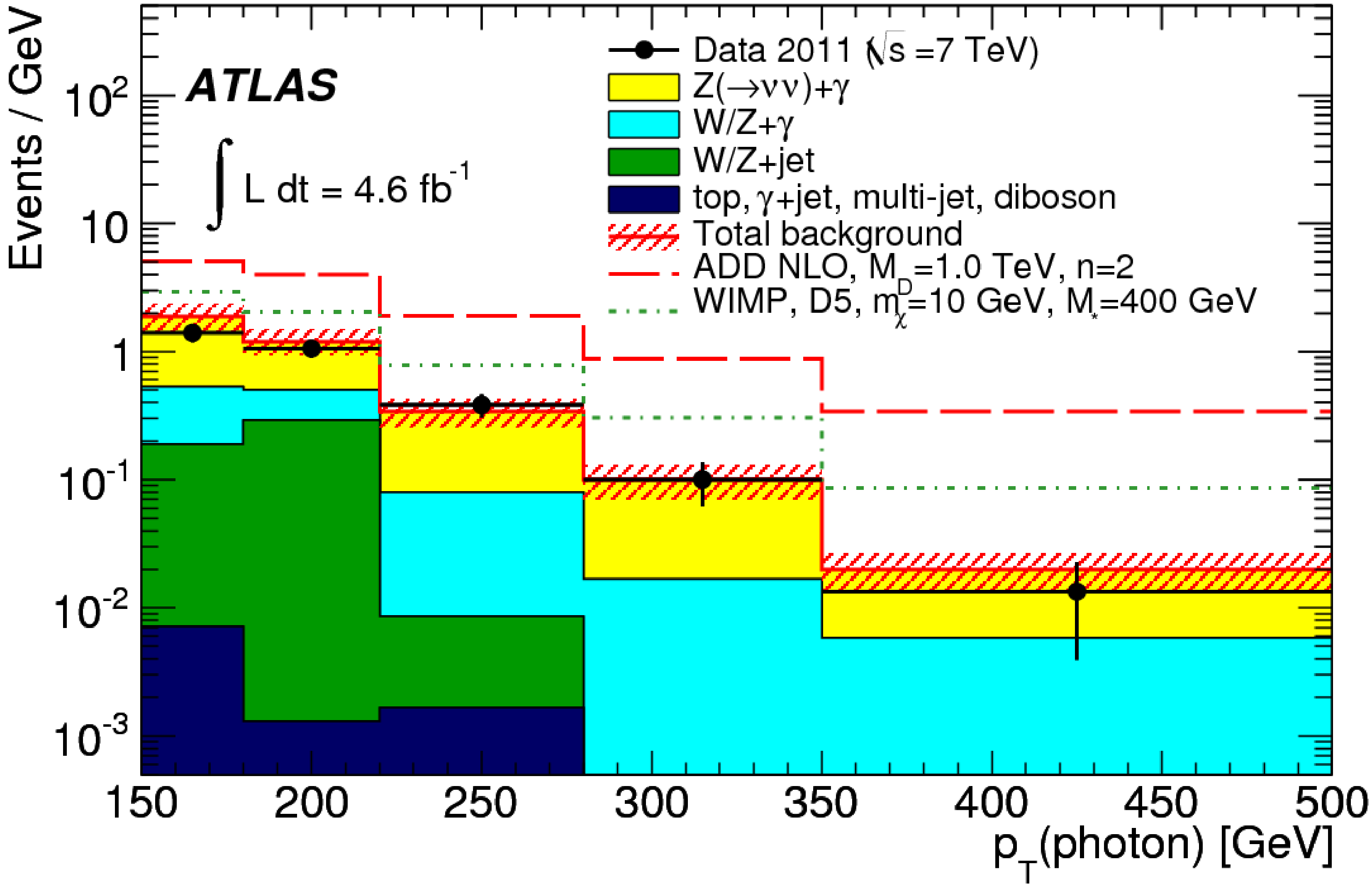
Plot shows E_T^{miss} in the $\mu+\gamma+E_T^{miss}$ data control sample



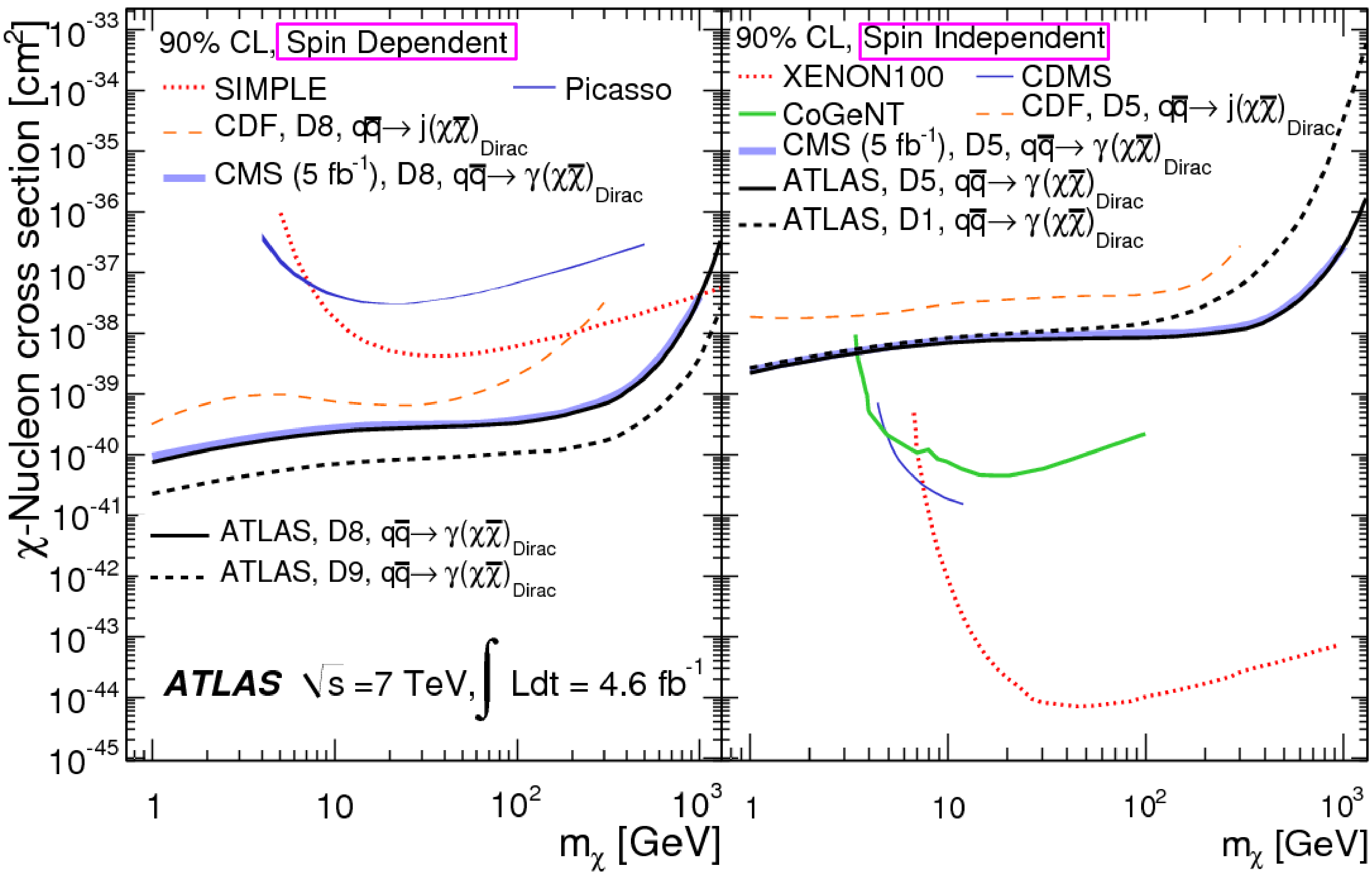
Monophoton: missing E_T spectrum



Monophoton: photon p_T spectrum



Monophoton: WIMP interpretation

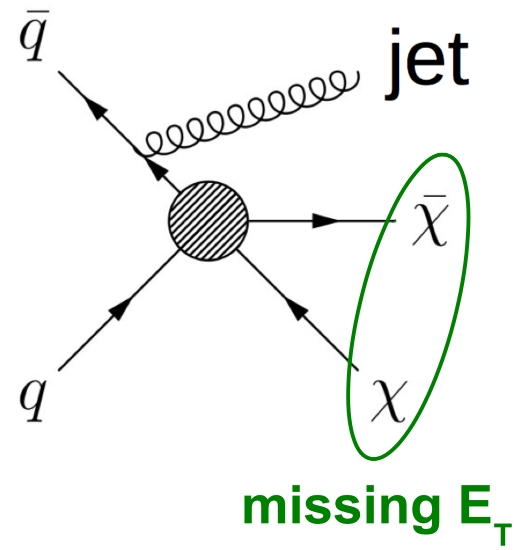


Monojet: event selection

arXiv:1210.4491 (October 2012)
submitted to *JHEP*

NEW

Trigger: $E_T^{miss} > 70$ GeV



Analysis selection:

- Large missing transverse energy:

  $E_T^{miss} > 120$ GeV

- One high-p_T jet:

  p_T(jet) > 120 GeV , $|\eta| < 2$

- Reconstructed primary vertex

- Allow at most two more jets with $p_T > 30$ GeV, $|\eta| < 4.5$

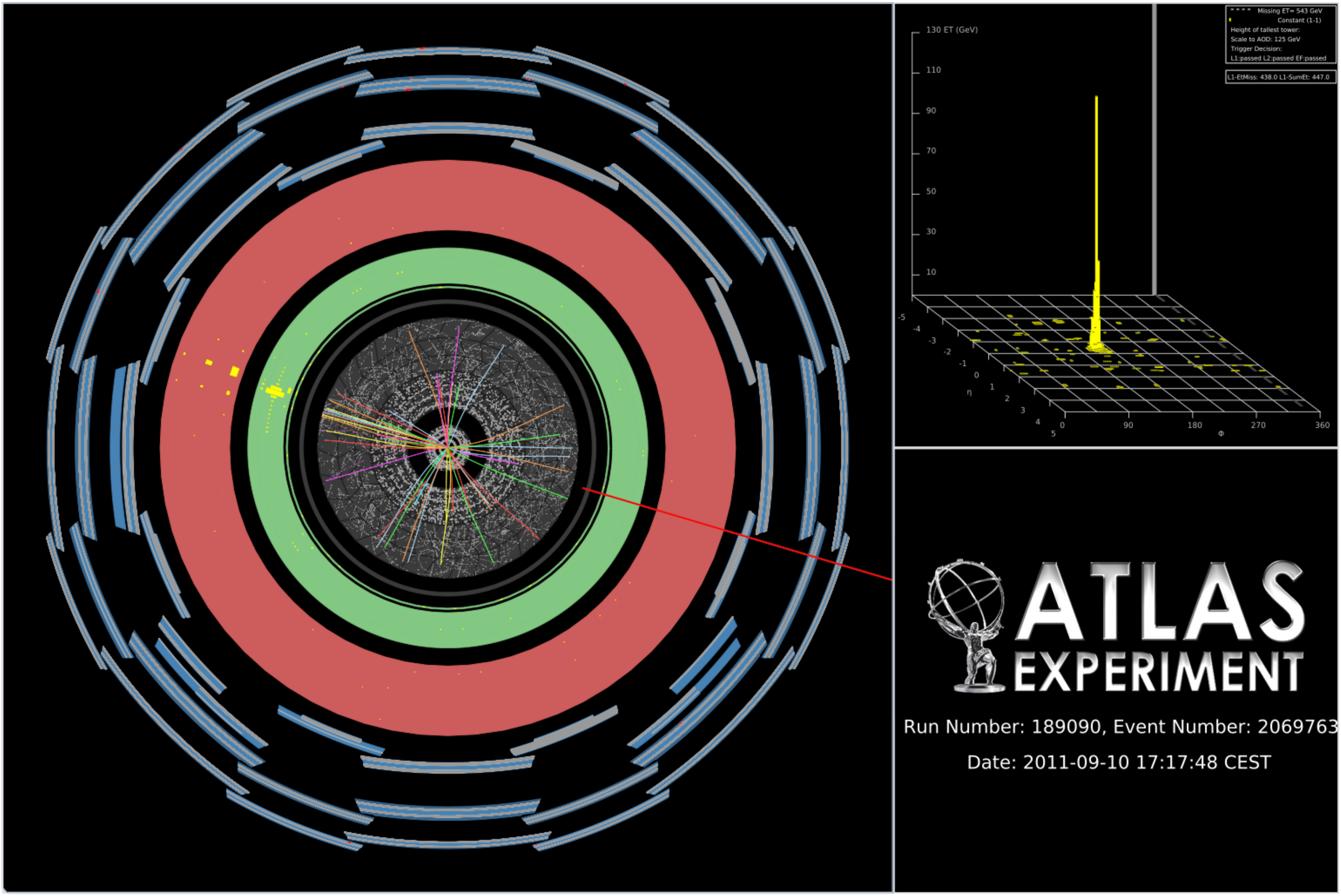
- Subleading jet far away from missing E_T direction:

  $\Delta\phi(\text{jet 2}, E_T^{miss}) > 0.5$

- Veto events with leptons (electrons with $p_T > 20$ GeV, muons with $p_T > 7$ GeV)

- Quality criteria to suppress fake calorimeter signals (noise spikes), cosmic rays (ATLAS-CONF-2010-038)

Monojet: candidate event



missing E_T:

542 GeV

jet p_T:

551 GeV

Monojet: backgrounds

Signal regions	SR1	SR2	SR3	SR4
Common requirements	Data quality + trigger + vertex + jet quality + $\lvert\eta^{\text{jet1}}\rvert < 2.0 + \lvert\Delta\phi(\mathbf{p}_{\text{T}}^{\text{miss}}, \mathbf{p}_{\text{T}}^{\text{jet2}})\rvert > 0.5 + N_{\text{jets}} \leq 2 +$ lepton veto			
$E_{\text{T}}^{\text{miss}}$, $p_{\text{T}}^{\text{jet1}} >$	120 GeV	220 GeV	350 GeV	500 GeV

dominant, irreducible background

hadronic τ decay, non-reconstructed e/μ

	SR1	SR2	SR3	SR4
$Z \to \nu\bar{\nu}$+jets	63000 ± 2100	5300 ± 280	500 ± 40	58 ± 9
$W \to \tau\nu$+jets	31400 ± 1000	1853 ± 81	133 ± 13	13 ± 3
$W \to e\nu$+jets	14600 ± 500	679 ± 43	40 ± 8	5 ± 2
$W \to \mu\nu$+jets	11100 ± 600	704 ± 60	55 ± 6	6 ± 1
$t\bar{t}$ + single t	1240 ± 250	57 ± 12	4 ± 1	-
Multijets	1100 ± 900	64 ± 64	8^{+9}_{-8}	-
Non-coll. Background	575 ± 83	25 ± 13	-	-
$Z/\gamma^* \to \tau\tau$+jets	421 ± 25	15 ± 2	2 ± 1	-
Di-bosons	302 ± 61	29 ± 5	5 ± 1	1 ± 1
$Z/\gamma^* \to \mu\mu$+jets	204 ± 19	8 ± 4	-	-
Total Background	124000 ± 4000	8800 ± 400	750 ± 60	83 ± 14
Events in Data (4.7 fb^{-1})	124703	8631	785	77

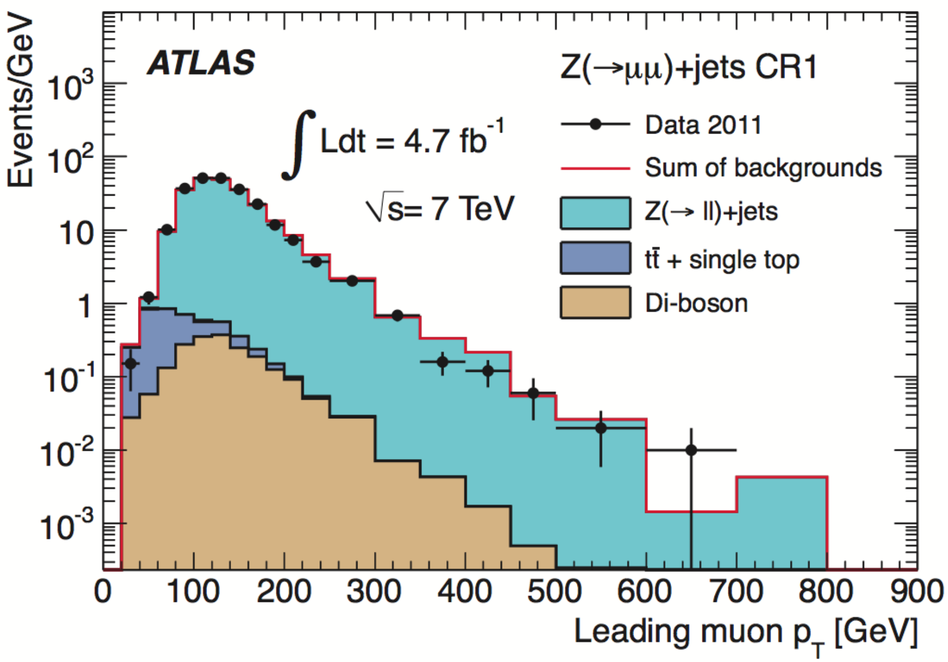
No evidence for excess over expected background in the data. Will present limits on DM production.

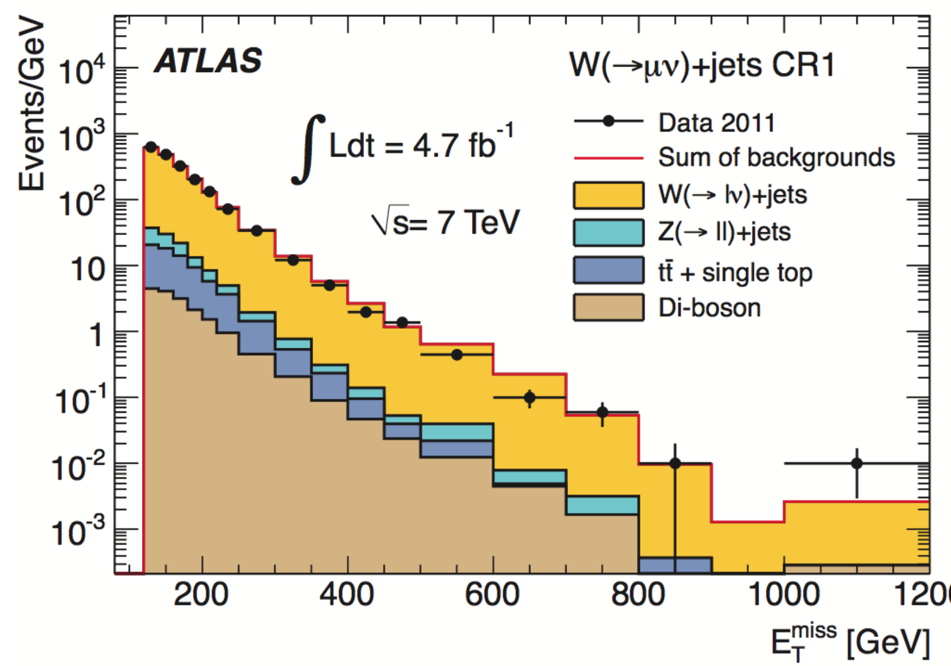
Monojet: backgrounds

For main W/Z + jets background: use data control regions (CR) to correct the background normalisation/shape in the signal region (SR):

- same kinematic selection as SR + requirement of lepton (e,μ)

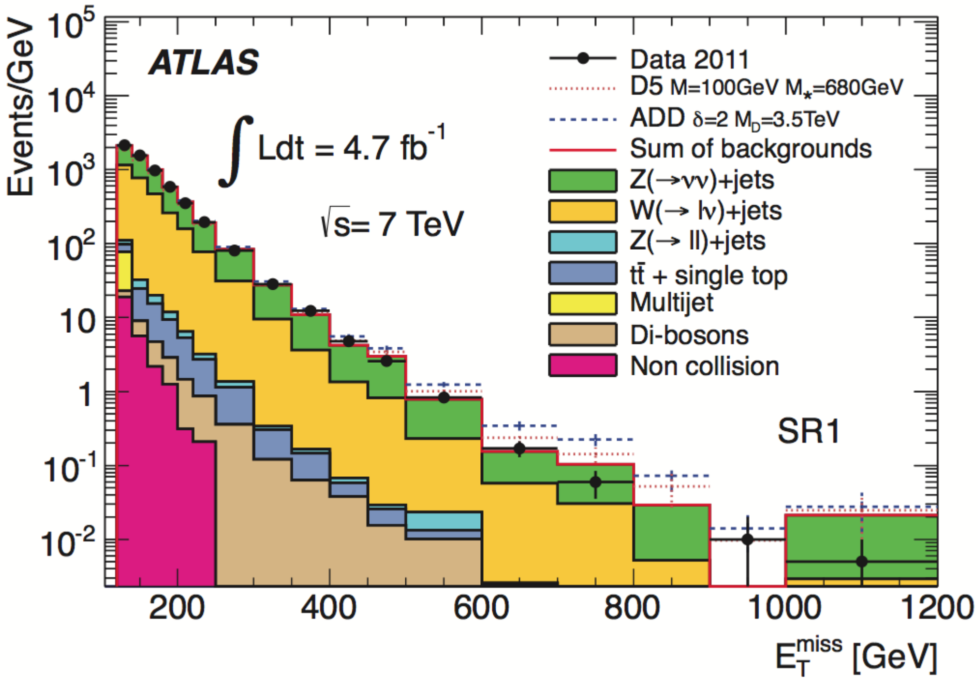
- quite well modelled → corrections applied to MC are small



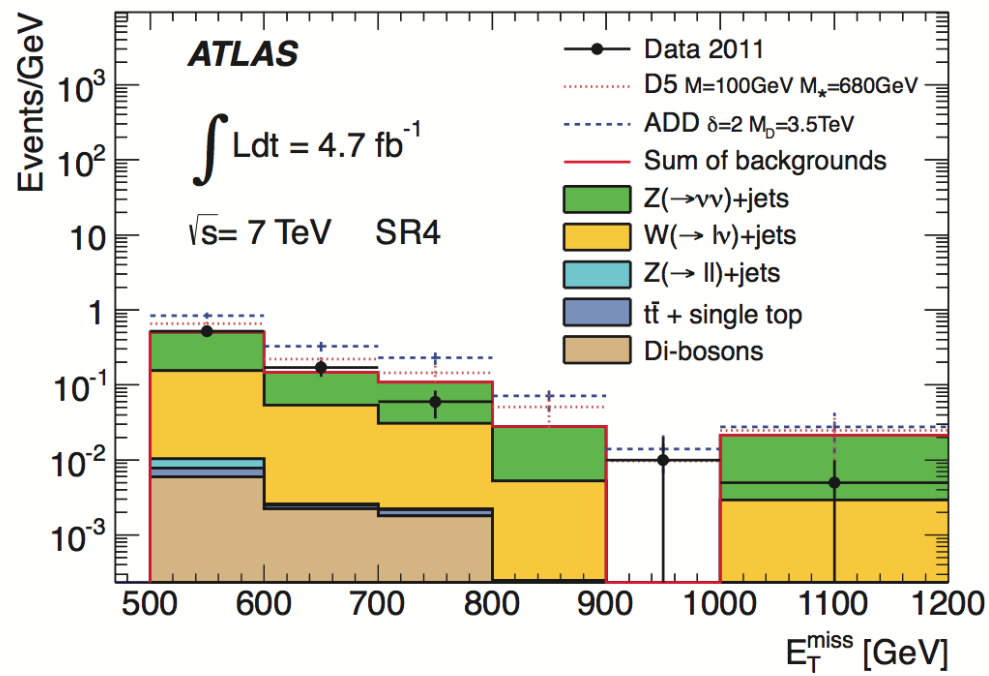


Monojet: missing E_T spectrum

Signal region SR1

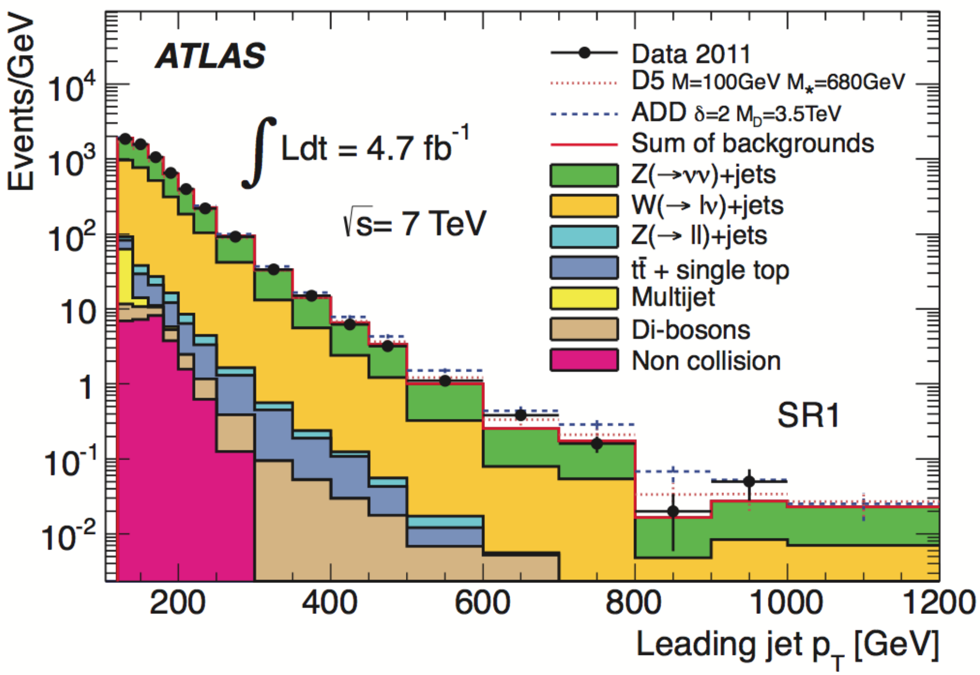


Signal region SR4

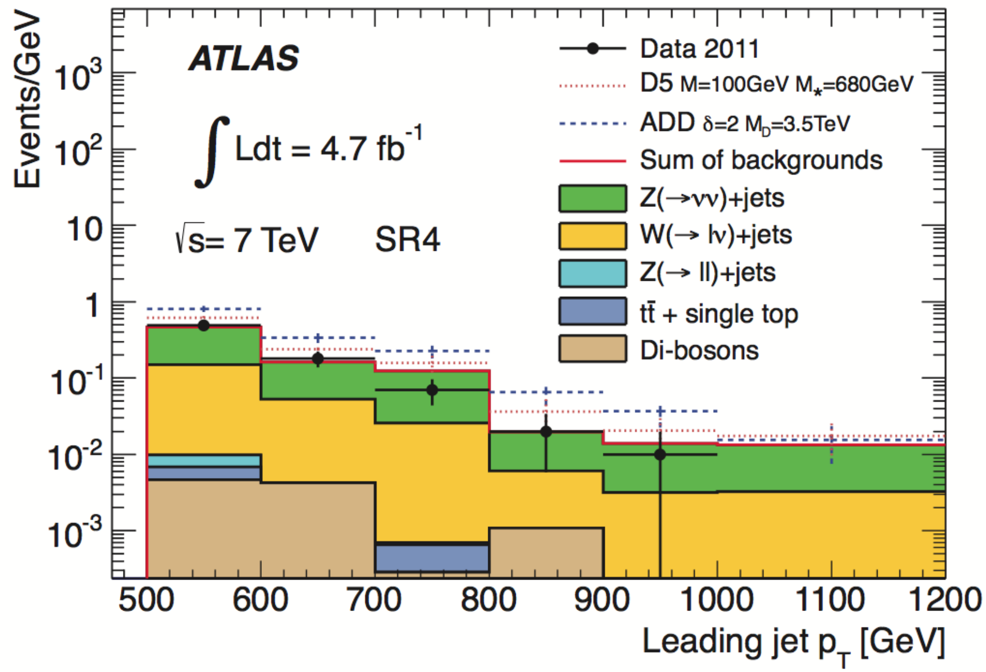


Monojet: jet p_T spectrum

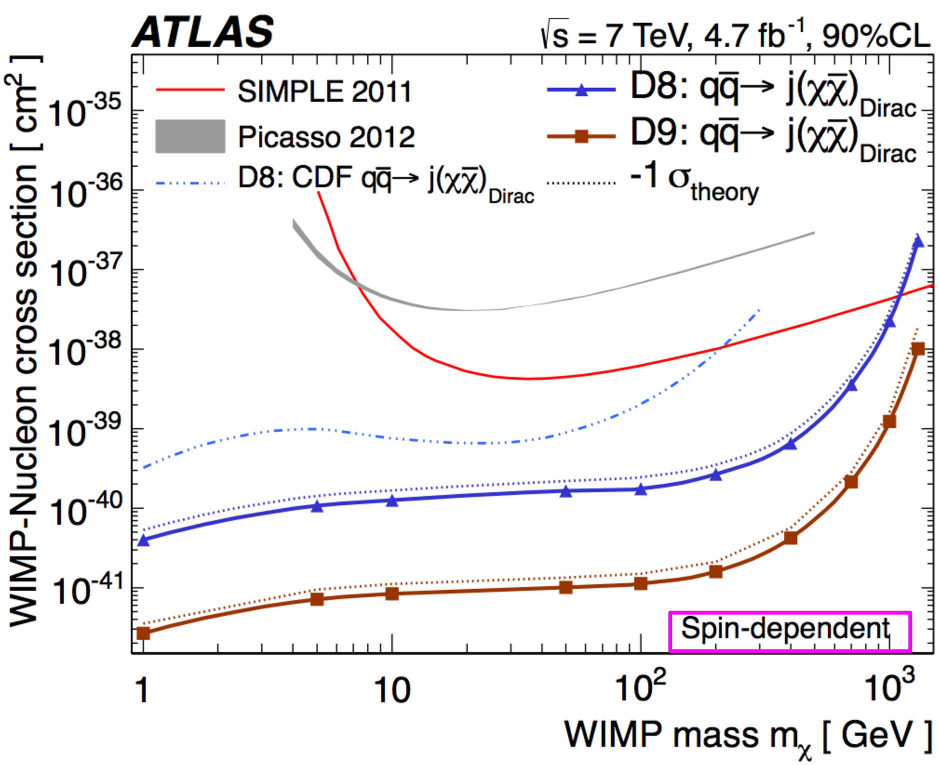
Signal region SR1

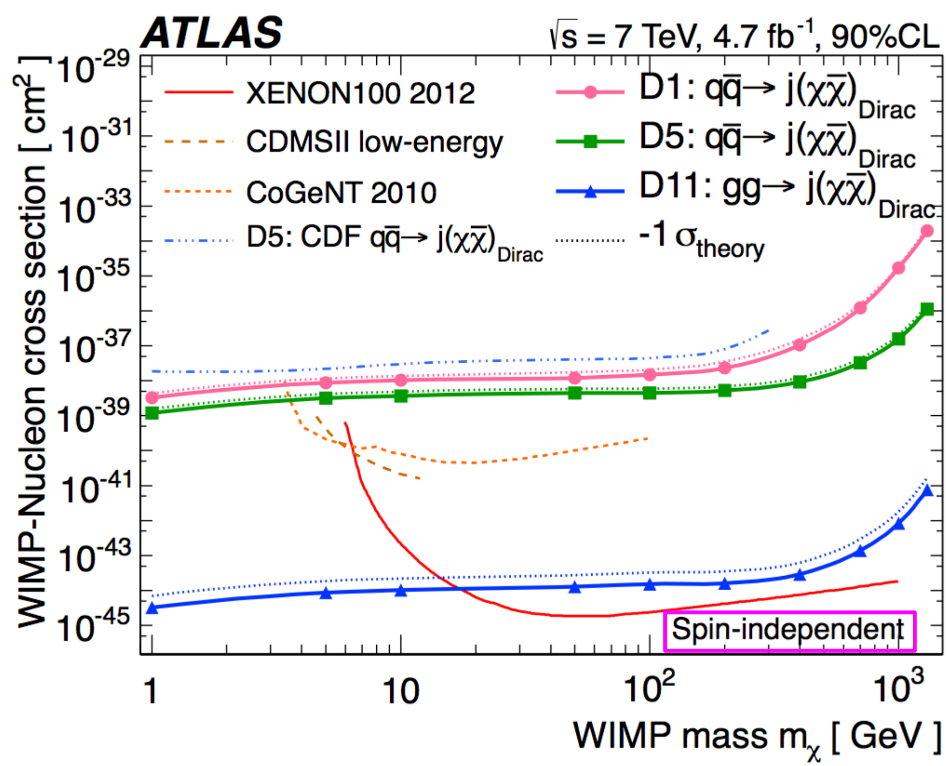


Signal region SR4



Monojet: WIMP interpretation





ADD interpretation

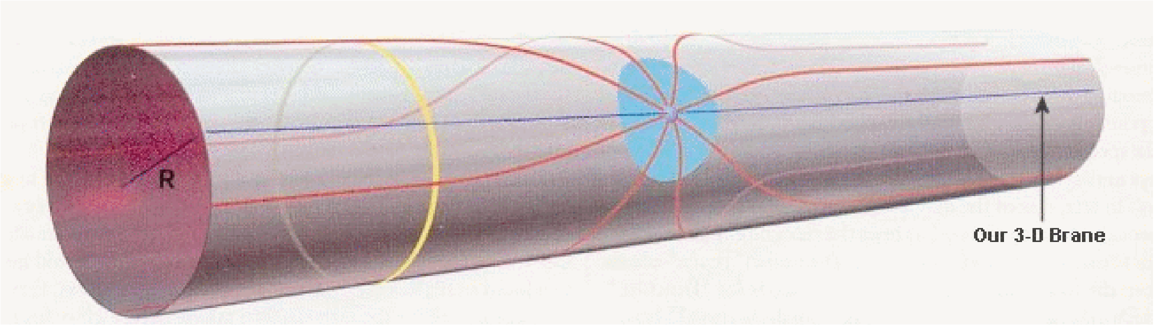
Results of monophoton and monojet searches can also be interpreted in context of **ADD model**:

- Origin of the weakness of gravitation: n warped extra spatial dimensions in which only gravity propagates

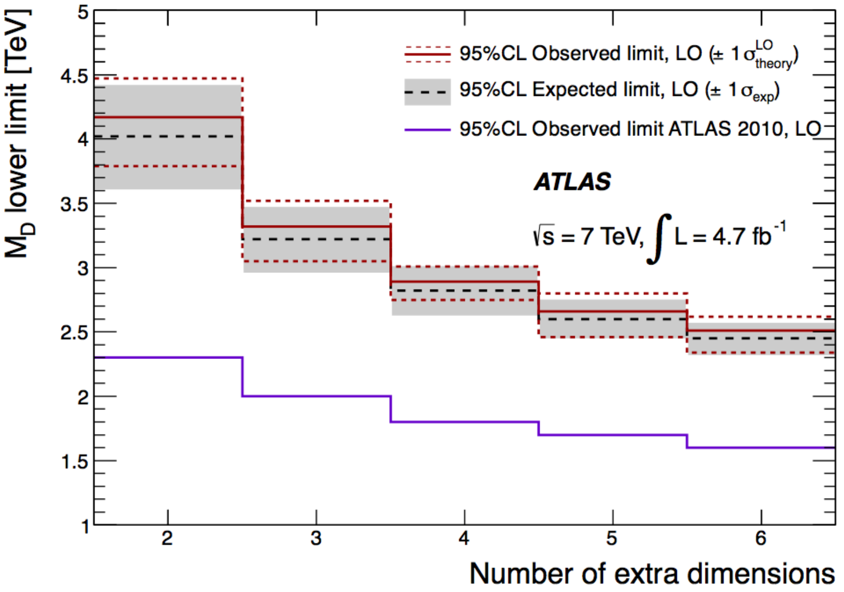
- 4D Planck scale M_{Pl} linked to fundamental Planck scale M_D in 4+n dimensions:

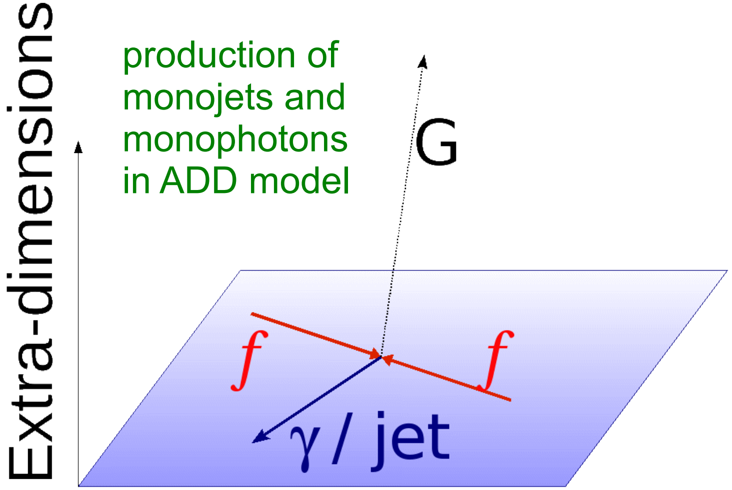
$$M_{Pl}{}^2 \sim M_D{}^{2+n} R^n$$

- $M_D << M_{Pl}$ if R is of O(mm), "solves" hierarchy problem

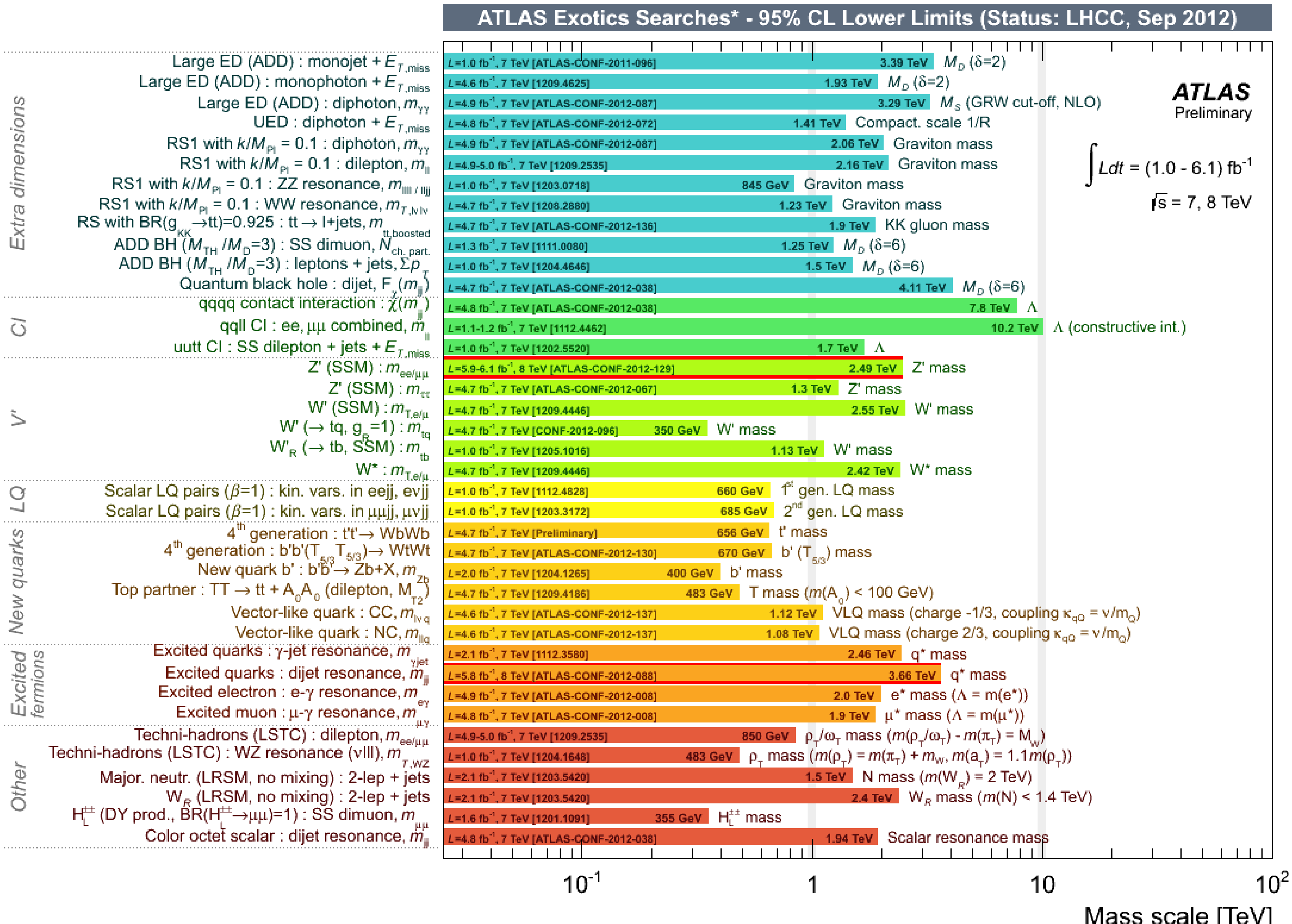


Limits on parameters of the ADD model from the monojet search:





Summary: ATLAS exotics searches



*Only a selection of the available mass limits on new states or phenomena shown

Conclusions

High-p_T jet/γ + large missing E_T are striking signatures of new physics

– backgrounds are small and well understood

Presented analyses based on the full ATLAS dataset from 2011 (~5 fb^{-1} at $\sqrt{s}$ = 7 TeV)

– recently submitted for publication

No significant excess w.r.t. the Standard Model expectation for either final state

– Set model-independent limits on the maximum fiducial cross section for new physics events

– Interpret results in the context of search for WIMPs and in the context of ADD model

In this presentation, focussed on WIMP results

– Depending on the nature of the interaction between DM and ordinary matter, the limits can be very competitive with limits from direct detection

– Complementary to direct detection at low WIMP mass, where direct detection is difficult (kinematic cut-off)

By early 2013, expect at least 4 times more data, at $\sqrt{s}$ = 8 TeV.

Backup Slides

Monojet: backgrounds

Source	SR1	SR2	SR3	SR4
JES/JER/E_T^{miss}	1.0	2.6	4.9	5.8
MC Z/W modelling	2.9	2.9	2.9	3.0
MC statistical uncertainty	0.5	1.4	3.4	8.9
$1 - f_{EW}$	1.0	1.0	0.7	0.7
Muon scale and resolution	0.03	0.02	0.08	0.61
Lepton scale factors	0.4	0.5	0.6	0.7
Multijet BG in electron CR	0.1	0.1	0.3	0.6
Di-boson, top, multijet, non-collisions	0.8	0.7	1.1	0.3
Total systematic uncertainty	3.4	4.4	6.8	11.1
Total data statistical uncertainty	0.5	1.7	4.3	11.8

Table 4. Relative systematic uncertainties for all signal regions (in percent). Individual contributions are summed in quadrature to derive the total numbers. The MC statistical uncertainty is included in the total systematic uncertainty.