Mono-X Searches at CMS and ATLAS

Mario Martínez

(on behalf of CMS and ATLAS Collaborations)

LPC SUSY Workshop, Fermilab, Nov. 2013

Outline

- LHC and ATLAS/CMS
- Introduction/Motivation

- Mono-jets
- Mono-photons
- Mono-W/Z

- Final notes

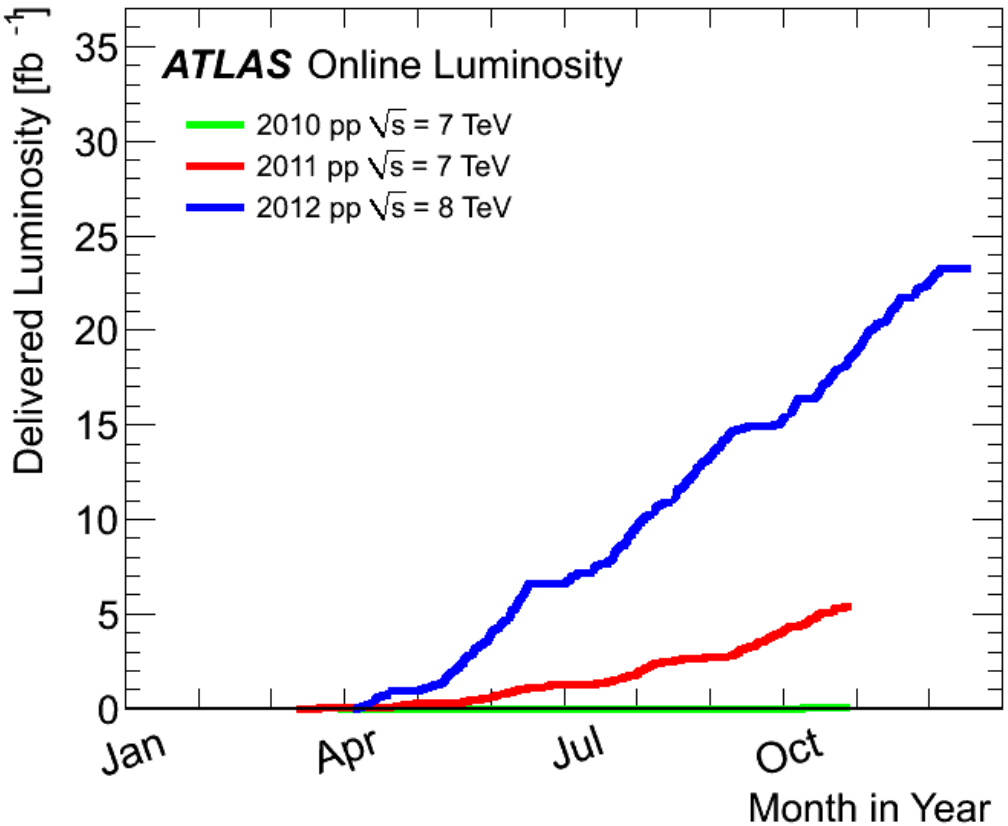
"Particles, particles, particles."

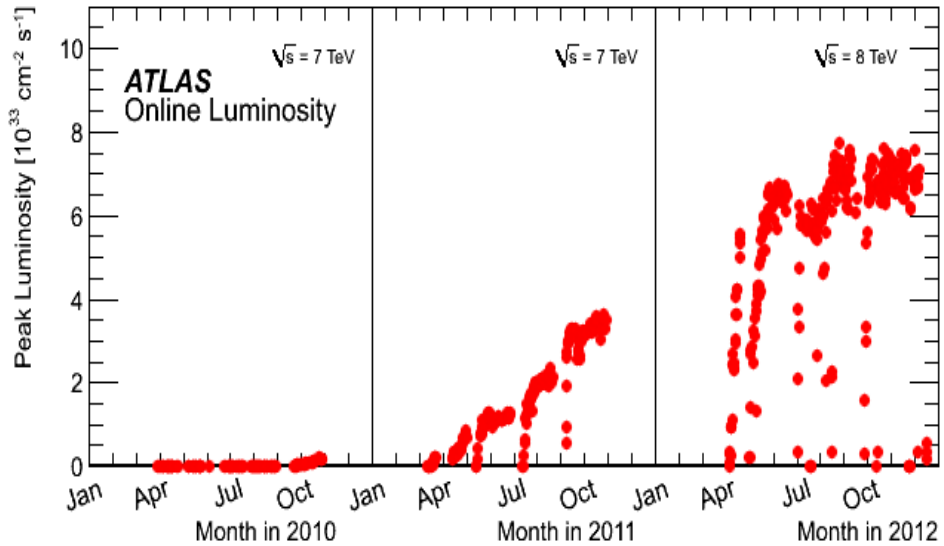
The results are put in terms of searches for

- Dark Matter
- Large Extra Dimensions and unparticles
- Supersymmetry
- *Invisible Higgs*

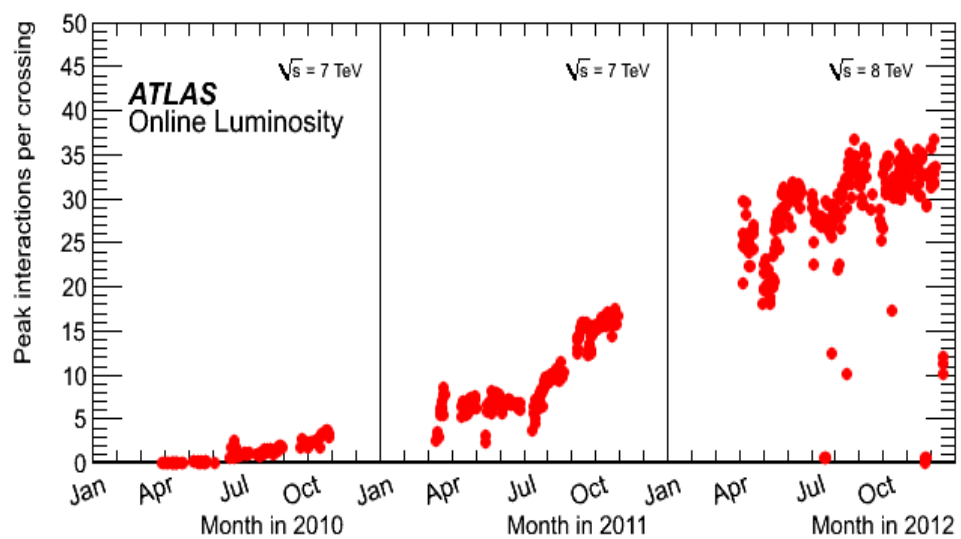
LHC Performance (2010-2012)

Spectacular LHC performance (rapid increase of data samples)



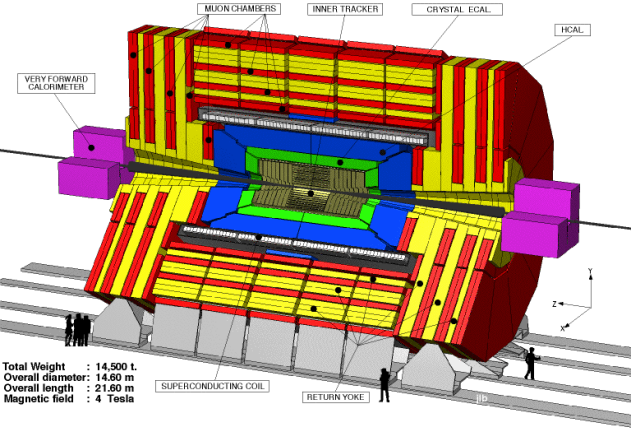


… rapid increase of pile-up conditions

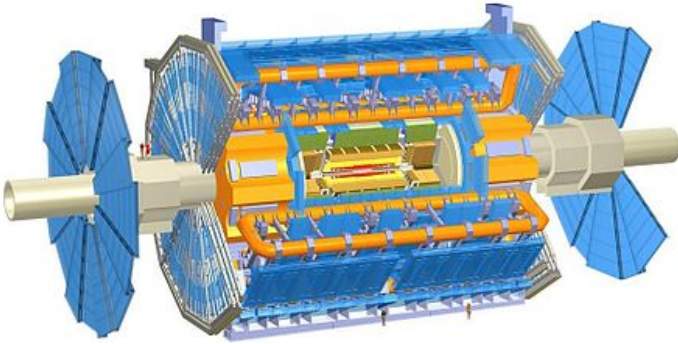


LHC ended pp run at 7+8 TeV after delivering more than 28 fb^{-1}

…will come back in 2015 with 13-14 TeV collisions

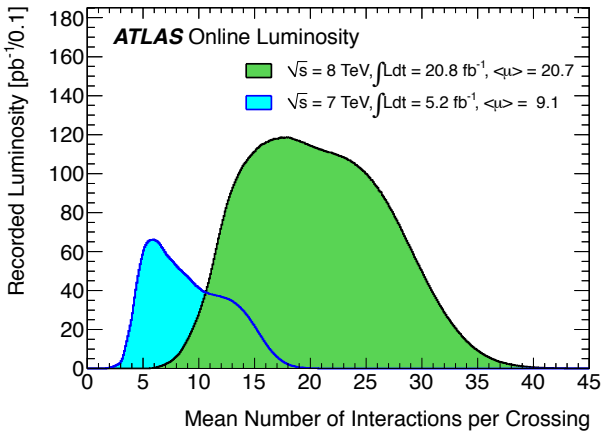


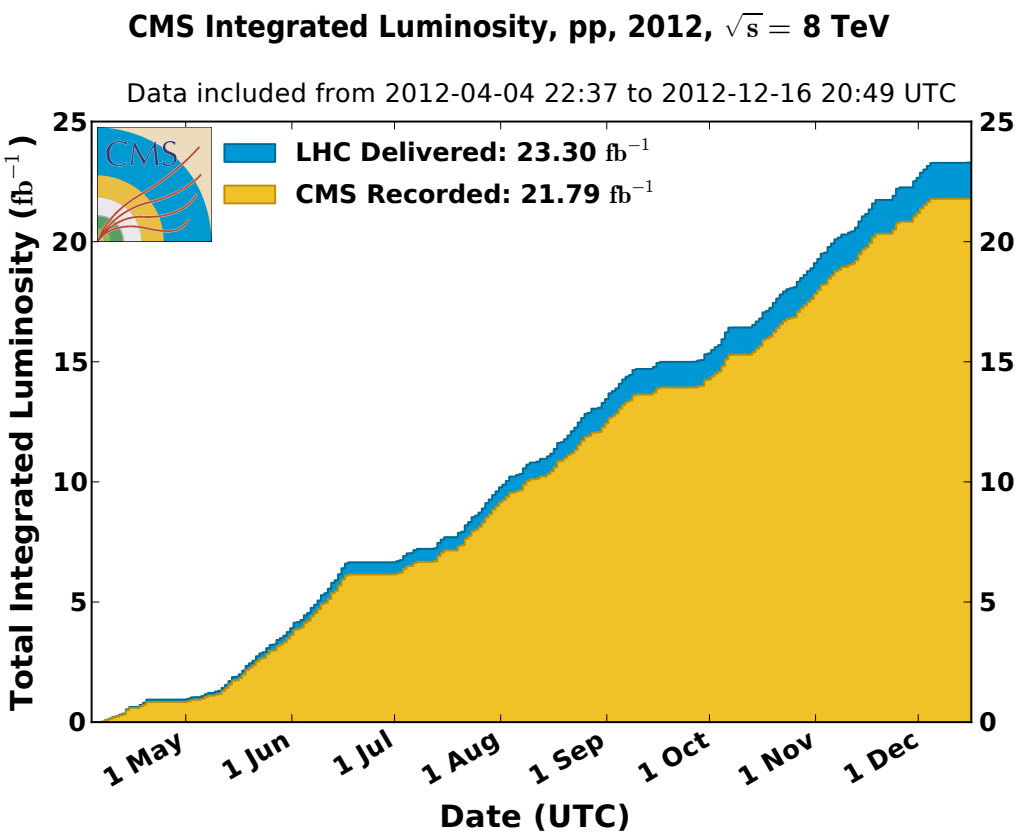
CMS & ATLAS

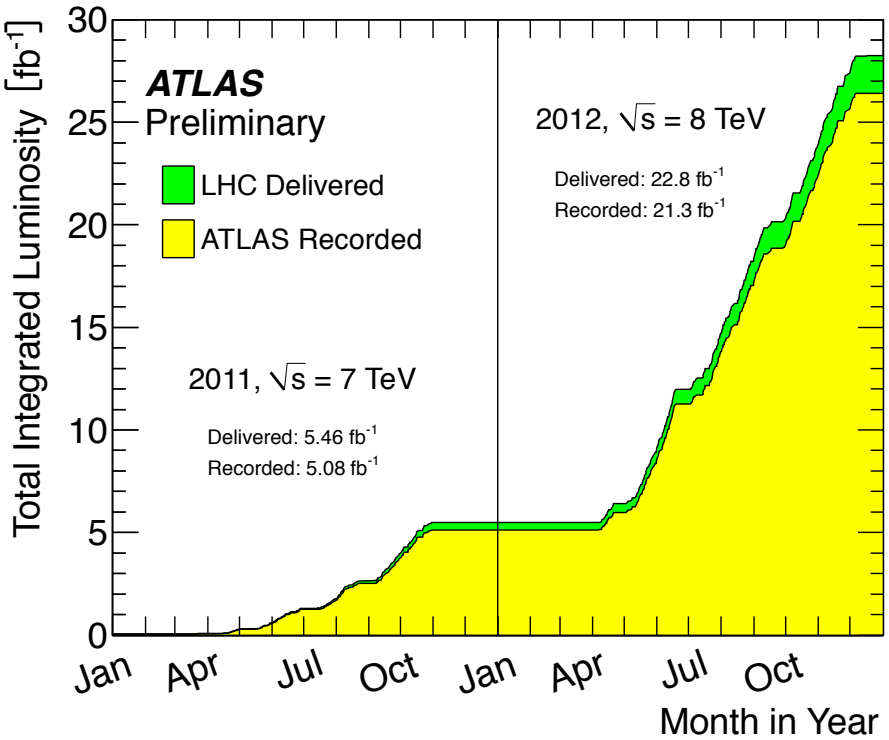


About 5 fb-1 collected by CMS and ATLAS @ 7 TeV
More than 21 fb-1 collected by CMS and ATLAS @ 8 TeV

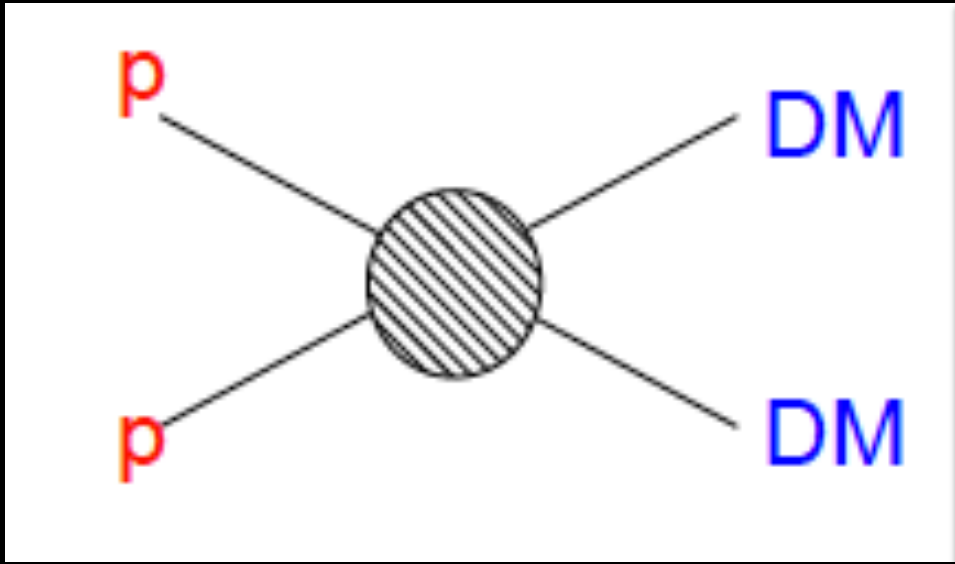
challenging pile up conditions for the physics analysis







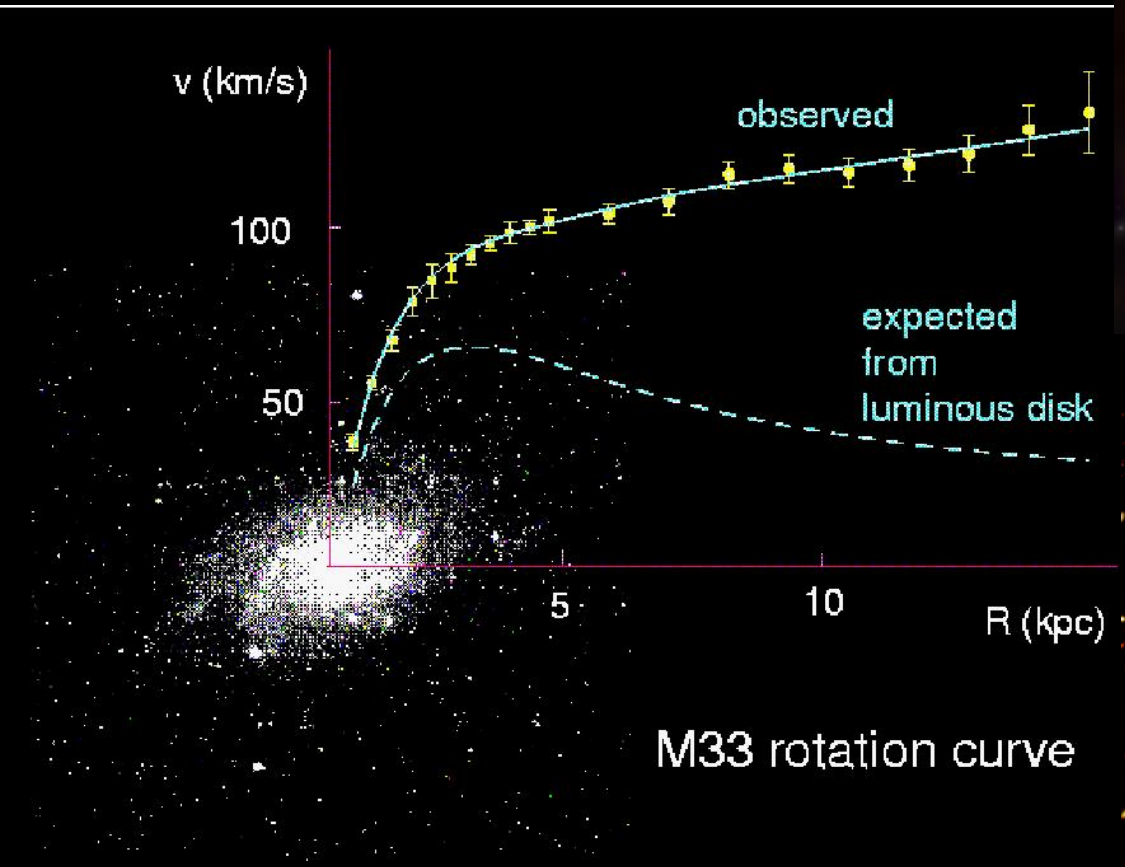
Search for Dark Matter

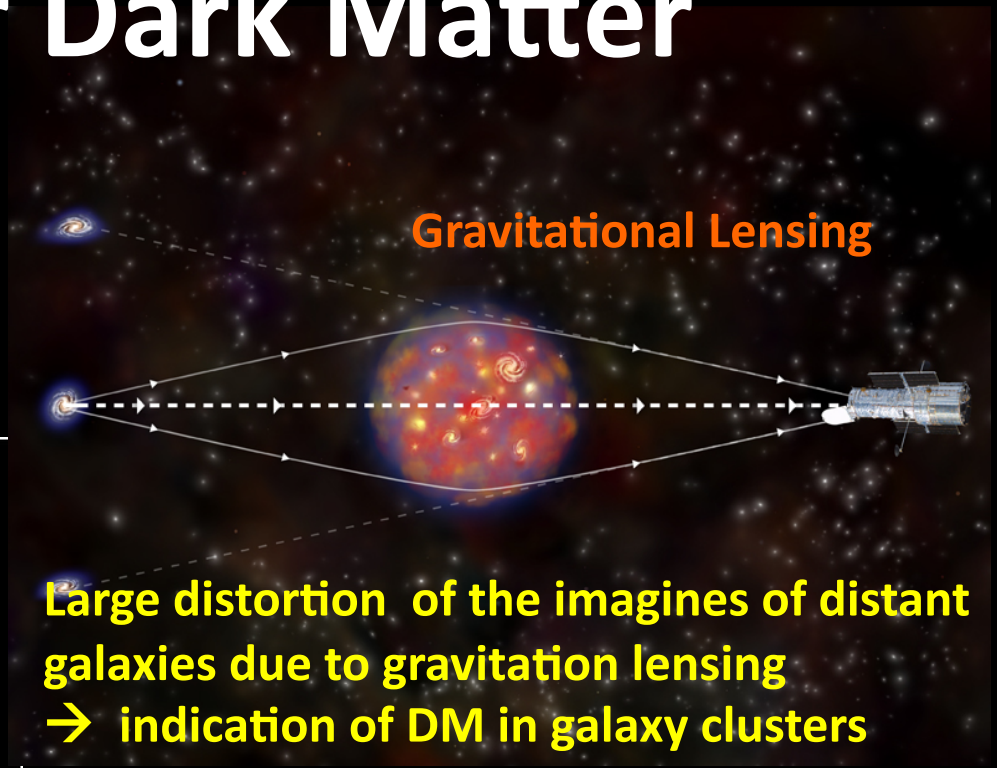


Evidence for Dark Matter

The rotation of the stars around the center of the galaxies is not consistent with the amount of mass observed $(L/M \text{ ratio})_{SUN}$

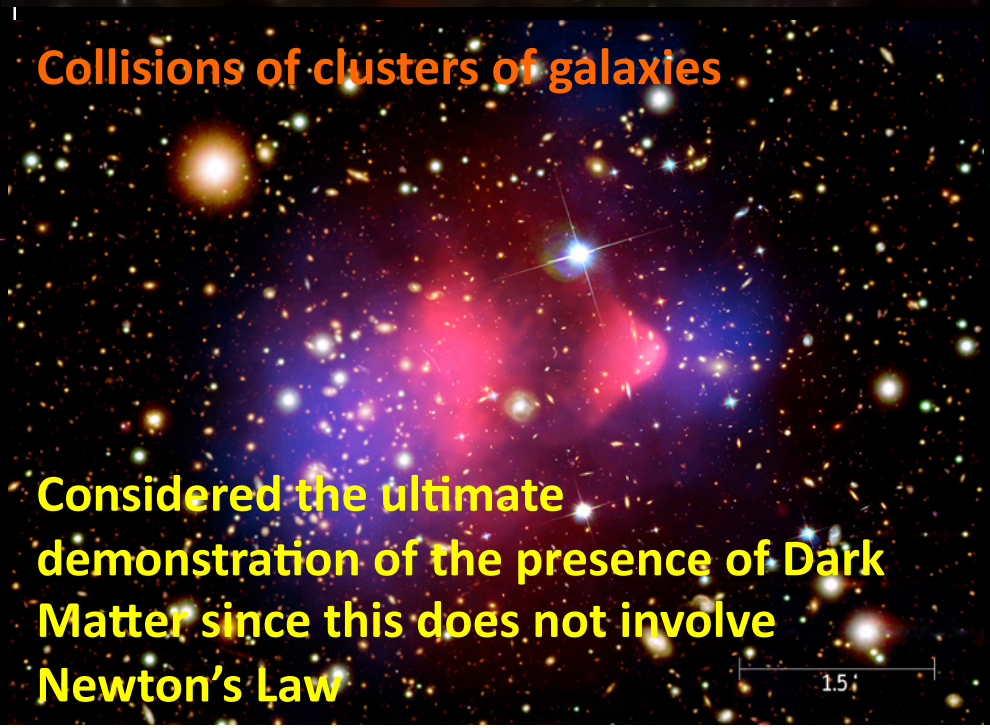
Spherical dark matter halo





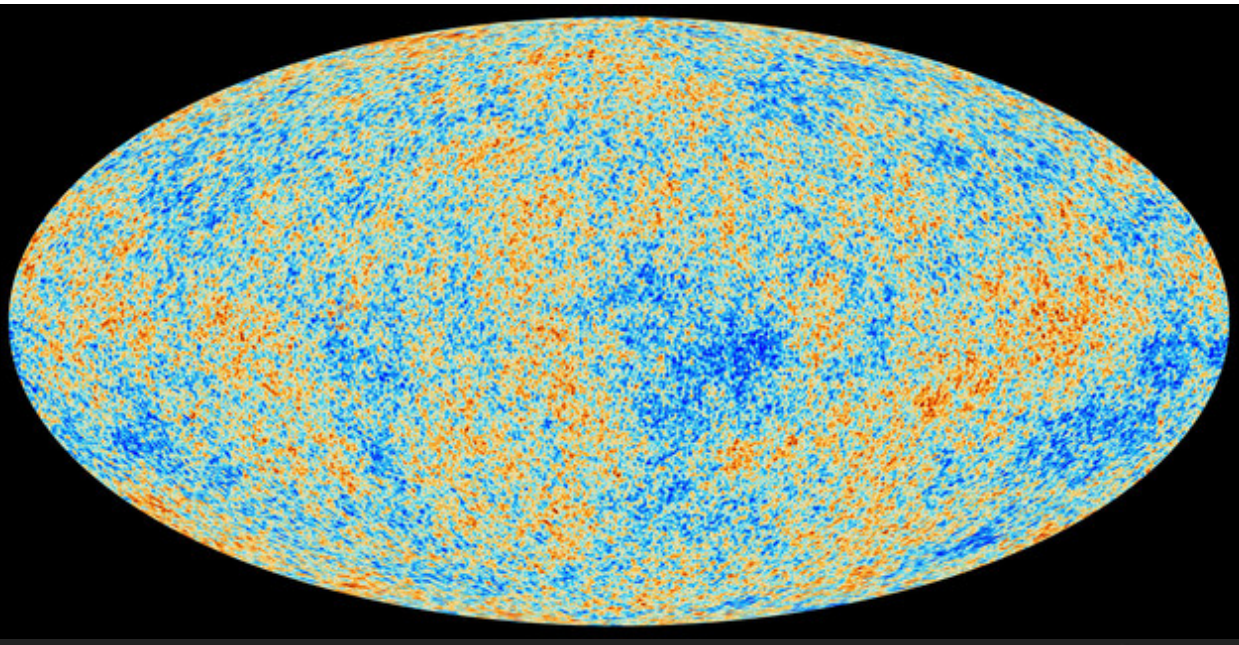
Large distortion of the imagines of distant galaxies due to gravitation lensing
→ indication of DM in galaxy clusters

Collisions of clusters of galaxies

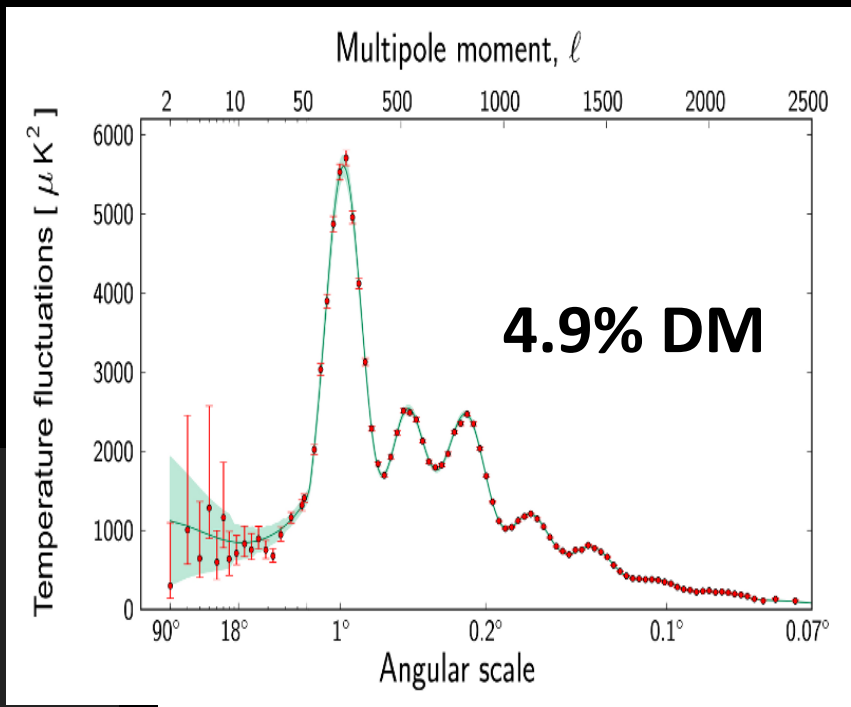


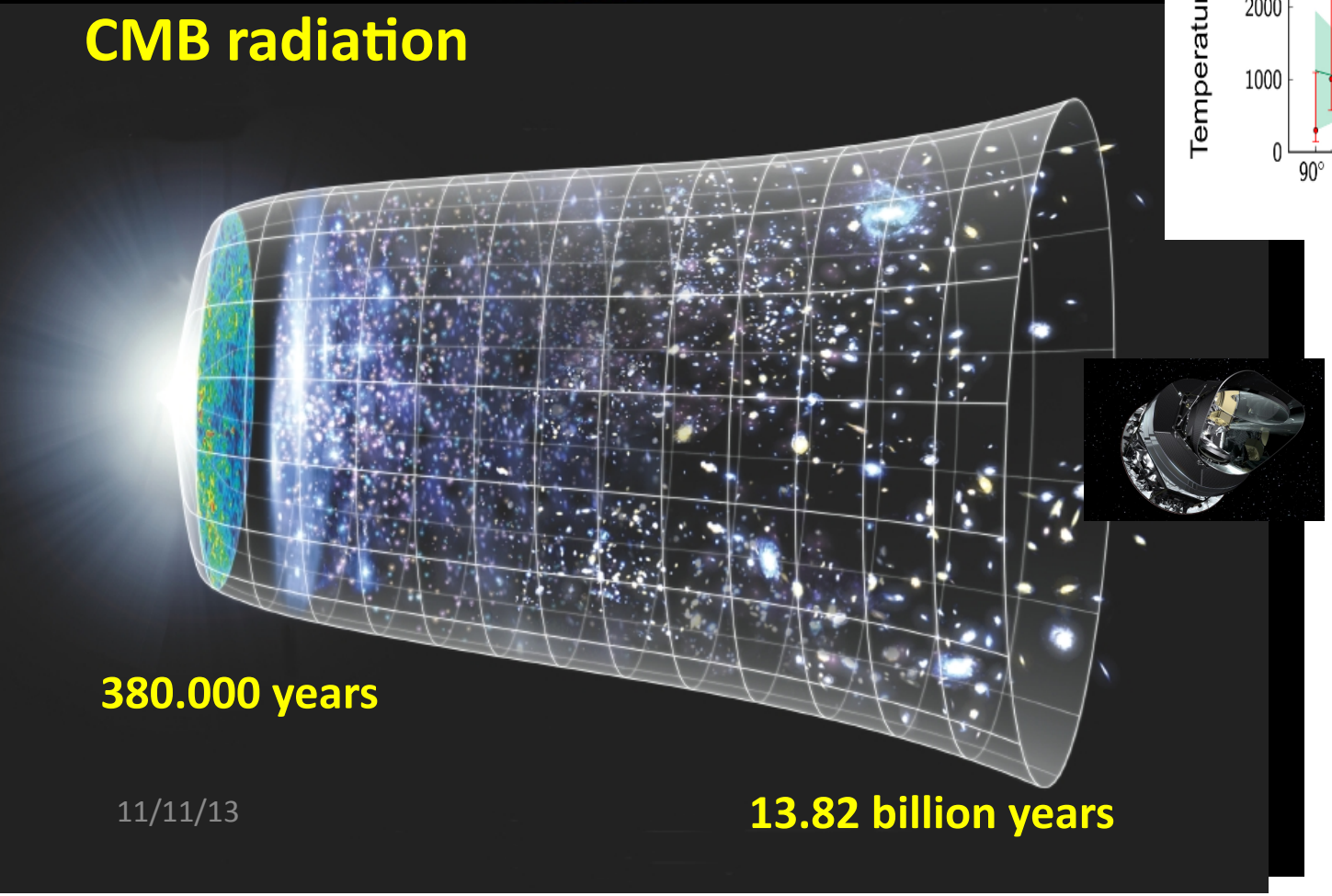
Considered the ultimate demonstration of the presence of Dark Matter since this does not involve Newton's Law

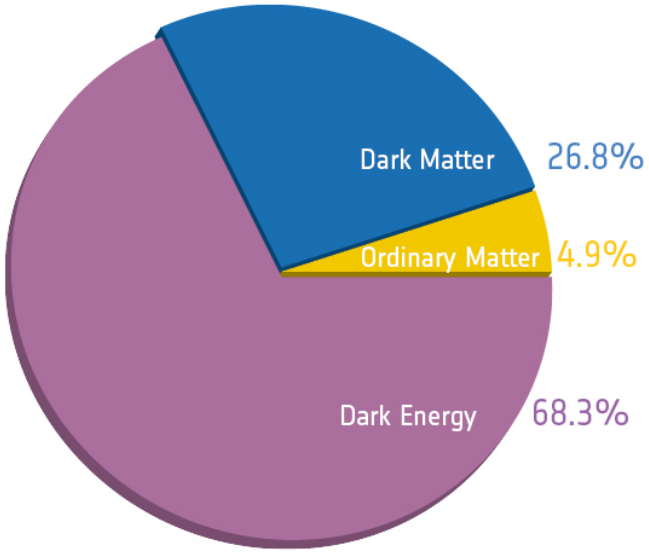
Planck (20 March 2013)
arXiv:1303.5062v1



CMB radiation







After Planck

Dark Matter Candidates

- Neutrinos ? ($\Omega_\nu h^2 < 0.0067$ @ 95%CL)
- Sterile Neutrinos
- Axions
- SUSY particles
  - Lightest neutralino
  - Sneutrinos
  - Gravitinos
  - Axinos
- KK states (UED)
- Wimpzillas
- ……
- ……

General requirements

- Electrically Neutral ("dark")
- Stable (lifetime larger than age of the Universe)
- Massive and Weakly interacting ($\Omega_{CDM} h^2 \sim 0.1$)

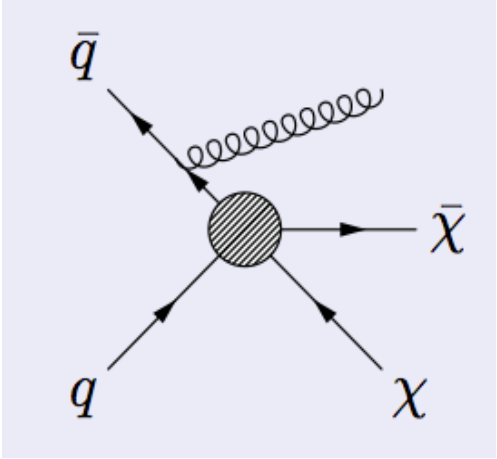
→WIMPS

Note: No reason DM should be made out of a single component (neutrinos exist)

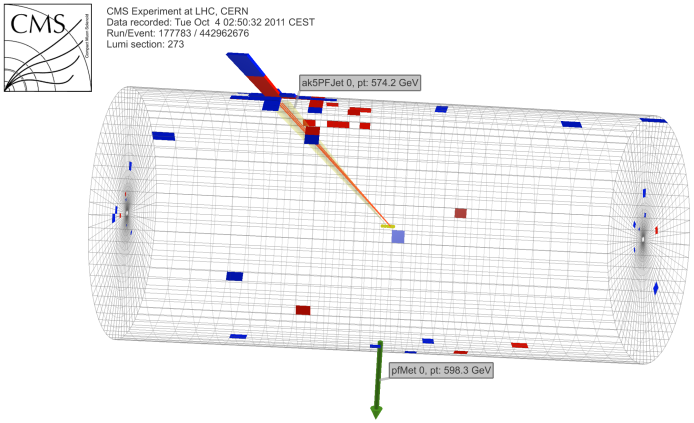
WIMP Pair Production at Hadron Colliders

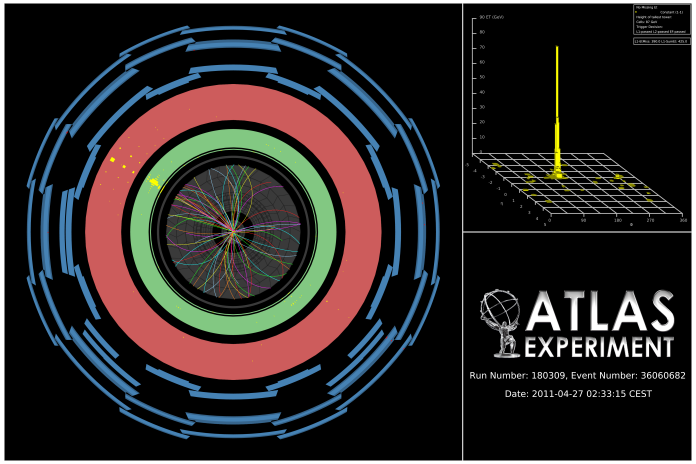
At colliders (LHC) WIMPs can be produced in pairs leading to "nothing to detect" in the final state

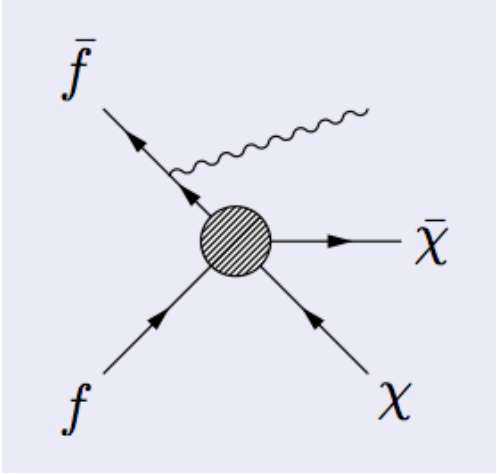
Such events are tagged via the presence of an energetic jet or a photon (or a W/Z) from initial state radiation



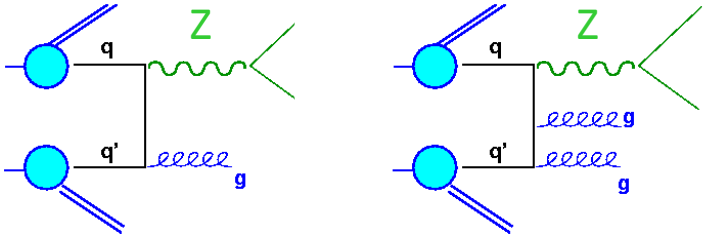
→Mono-jet, Mono-photon, Mono-W/Z





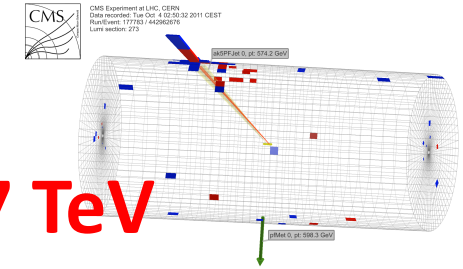


Rather spectacular and distinctive signature to search for new physics



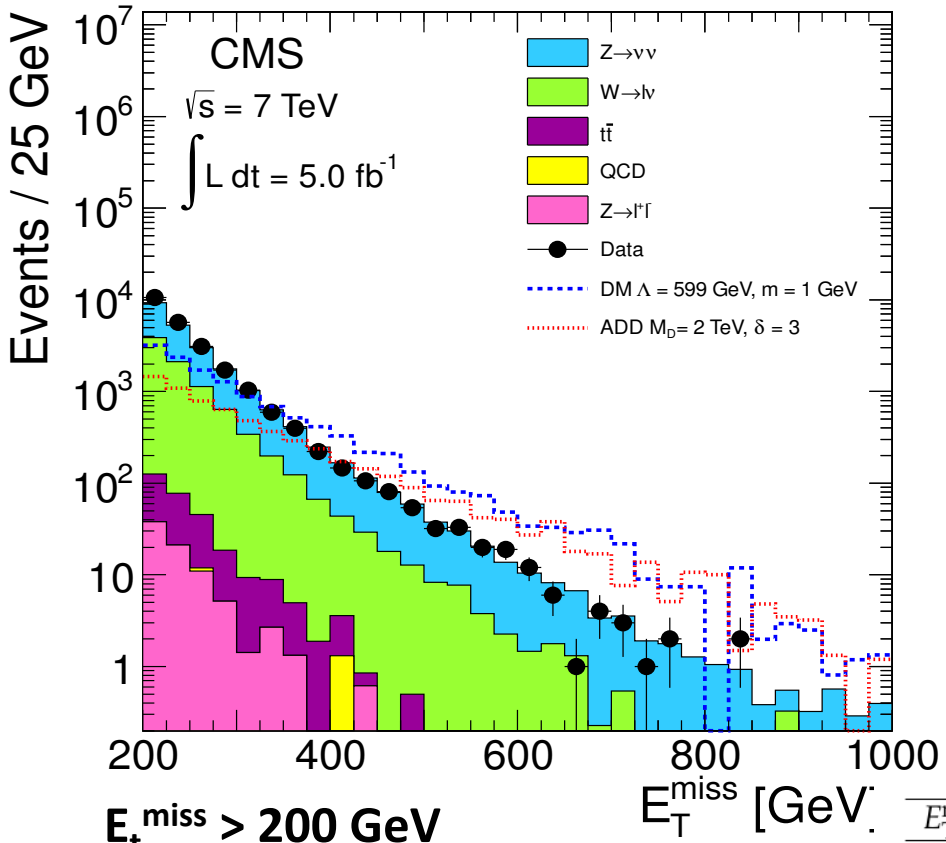
Mono-jets

JHEP09(2012)094

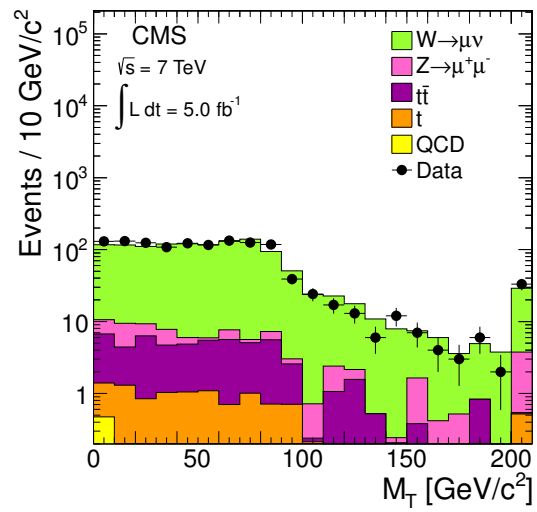


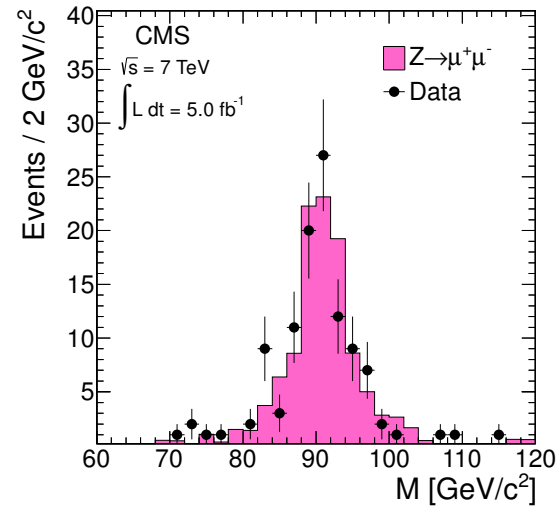
7 TeV

5 fb^{-1}



Data driven estimation of the dominant Z+jets and W+jets background using control regions





E_t^{miss} > 200 GeV

p_T (j1) > 110 GeV

$N_{jet}(p_T >$ 30 GeV) < 3

$\Delta\phi$ (j1,j2) < 2.5

Lepton vetoes

Good agreement with SM

E_T^{miss} (GeV/c) →	≥ 250	≥ 300	≥ 350	≥ 400
Process	Events			
$Z(\nu\bar{\nu})$+jets	5106 ± 271	1908 ± 143	900 ± 94	433 ± 62
W+jets	2632 ± 237	816 ± 83	312 ± 35	135 ± 17
$t\bar{t}$	69.8 ± 69.8	22.6 ± 22.6	8.5 ± 8.5	3.0 ± 3.0
$Z(\ell\ell)$+jets	22.3 ± 22.3	6.1 ± 6.1	2.0 ± 2.0	0.6 ± 0.6
Single t	10.2 ± 10.2	2.7 ± 2.7	1.1 ± 1.1	0.4 ± 0.4
QCD Multijets	2.2 ± 2.2	1.3 ± 1.3	1.3 ± 1.3	1.3 ± 1.3
Total SM	7842 ± 367	2757 ± 167	1225 ± 101	573 ± 65
Data	7584	2774	1142	522
Expected upper limit non-SM	779	325	200	118
Observed upper limit non-SM	600	368	158	95

Mono-jets

7 TeV
4.7 fb^{-1}

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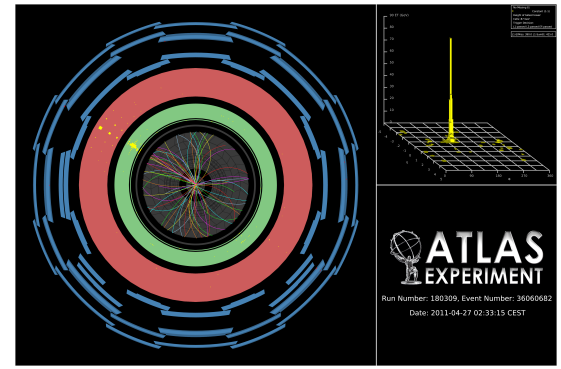

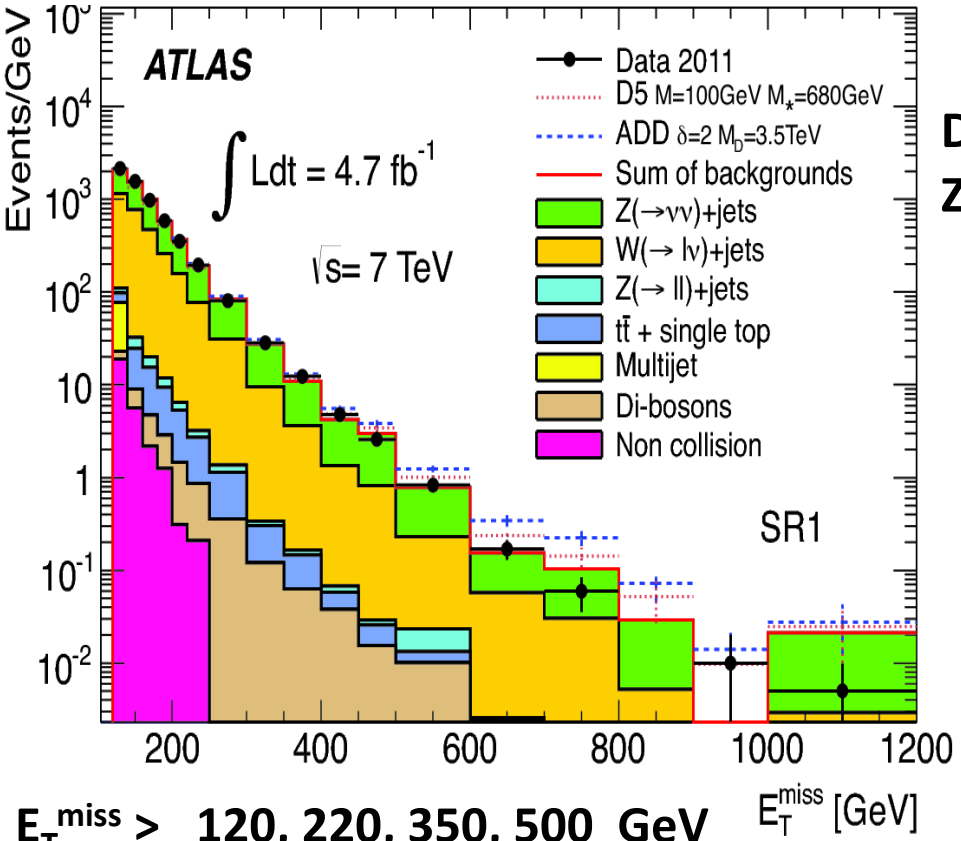

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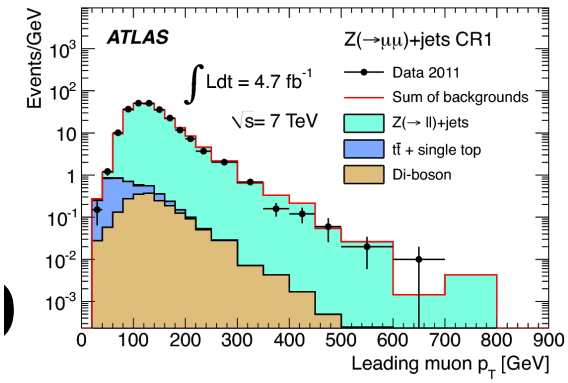
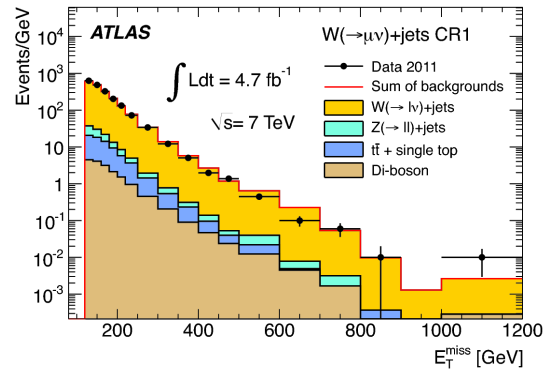




E_T^{miss} > 120, 220, 350, 500 GeV
p_T (j1) > 120, 220, 350, 500 GeV
$N_{jet}(p_T$ > 30 GeV) < 3

$\Delta\phi$ (E_T^{miss}, j2) > 0.5
Lepton vetoes

Good agreement with SM

	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

Effective Theory

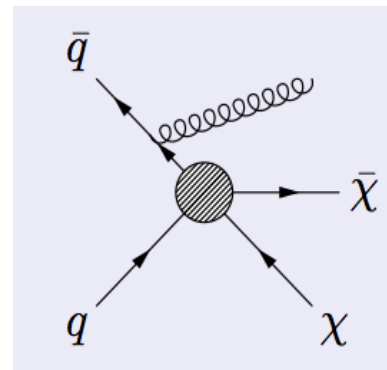
(model independent approach)

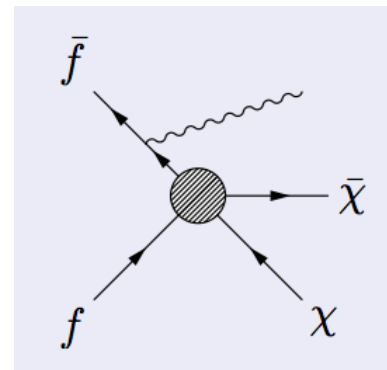
J. Goodman et al., Phys.Rev.D82:116010,2010

Effective Lagrangian approach (contact interaction) with parameters M_* (Λ) and m_χ

$$M_*^2 \sim M^2/g_1 g_2 \qquad [M > 2\ m_\chi\ ,\ g_1 g_2 < (4\pi)^2\ ]$$

assuming the interaction is mediated by a heavy particle with mass M and couplings g_1 and g_2





Different operators are considered with different structures and here χ will be taken as Dirac fermions

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	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

Important note:

Not clear whether the effective approach under- or over-estimates the cross sections since this depends on the details of the unknown UV limit of the theory

Strictly speaking theory only applicable when M is much larger than the energy scale present in the reaction $[Q^2 << (4\pi M_*)^2\ ,\ m_\chi < 2\pi M_*]$

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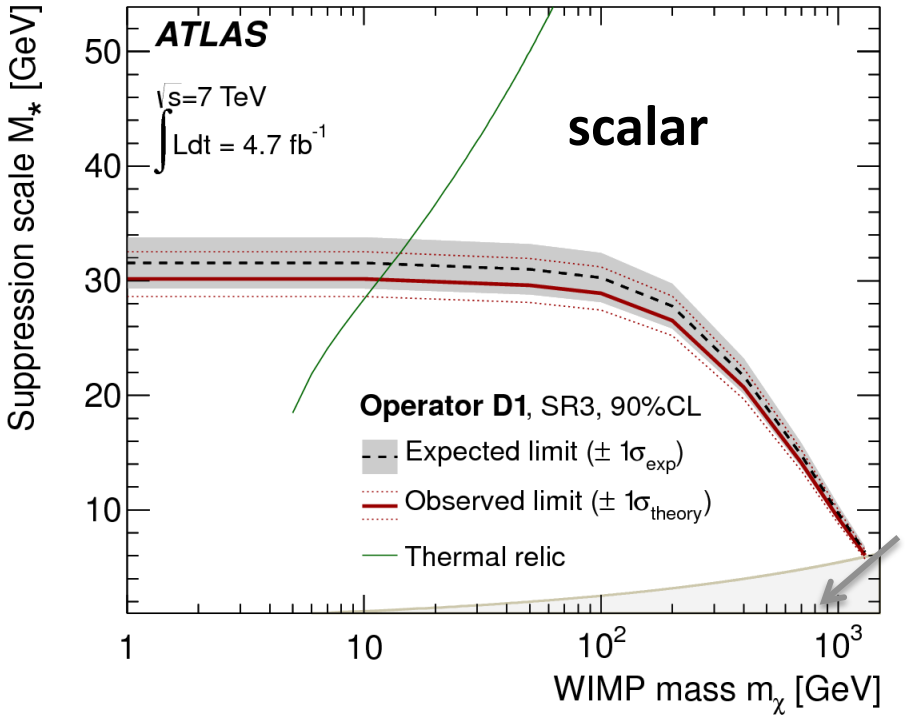
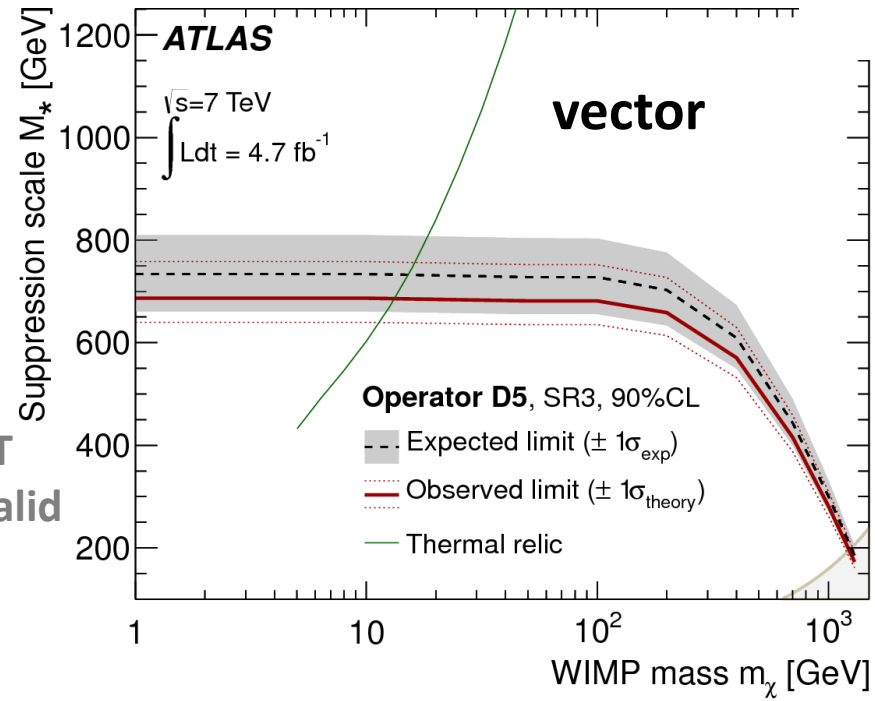
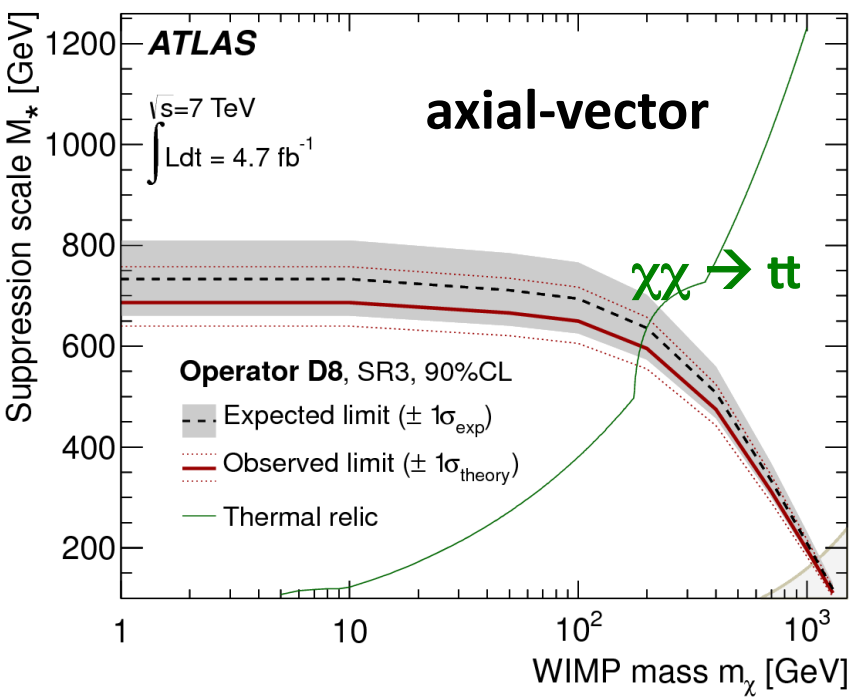
Limits on WIMP production



EFT not valid





90% CL on the visible cross sections for new physics are translated into limits on M_* as a function of the WIMP mass for the different operators

Line indicates the values for M_* and m_χ leading to the proper abundance (WMAP)

WIMP-nucleon cross section

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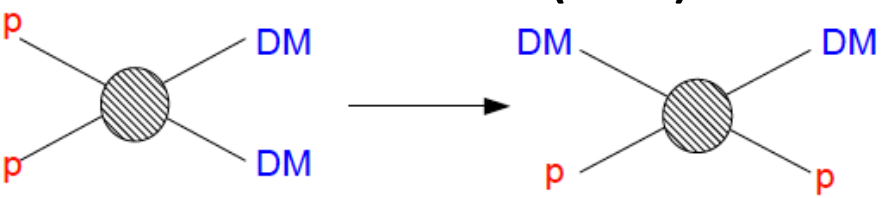
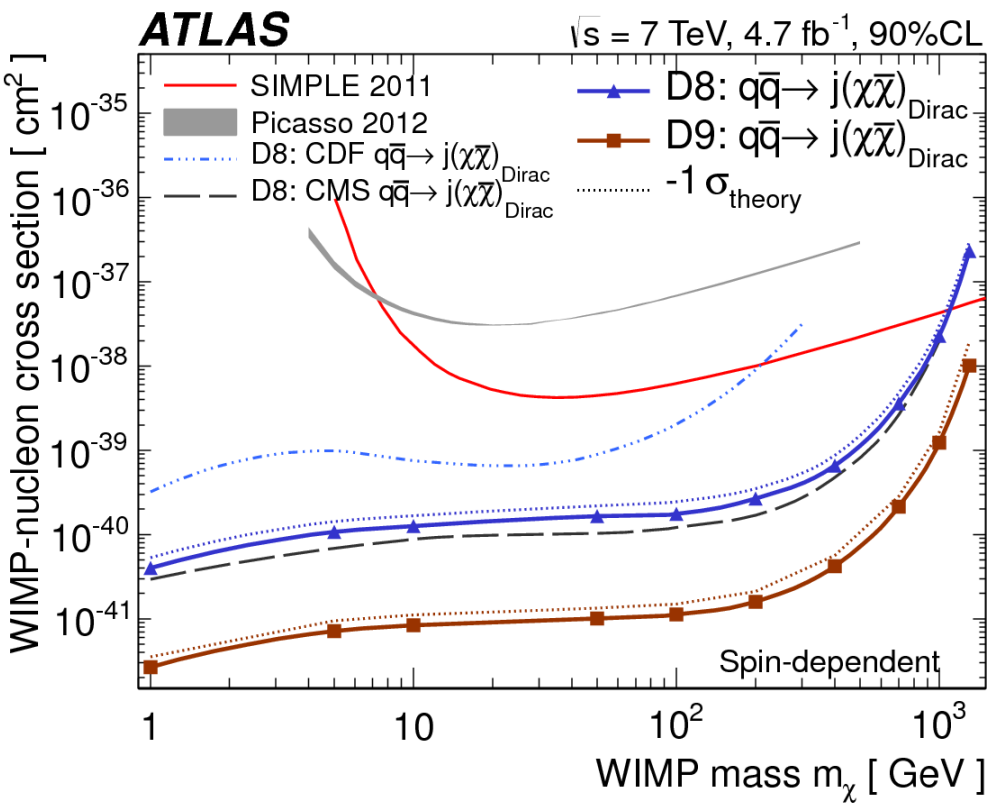
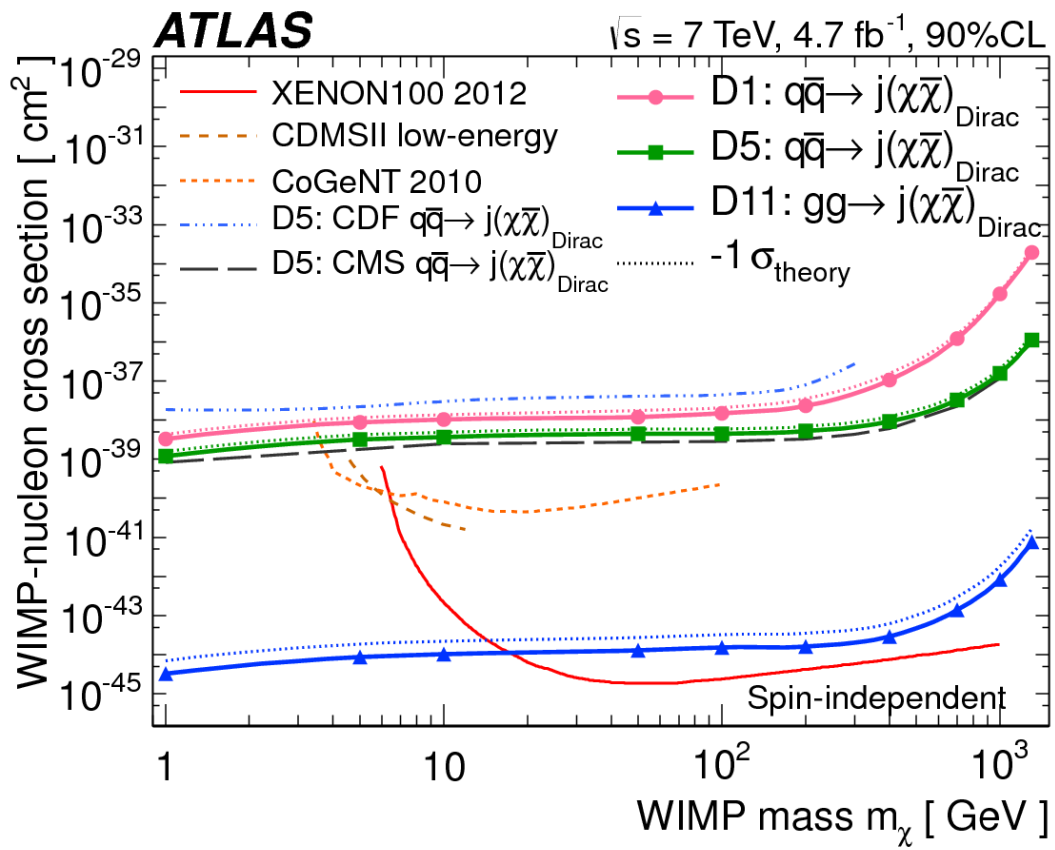


$$\sigma_0^{D1} = 1.60 \times 10^{-37}\mathrm{cm}^2 \left(\frac{\mu_\chi}{1\mathrm{GeV}}\right)^2 \left(\frac{20\mathrm{GeV}}{M_*}\right)^6,$$

$$\sigma_0^{D5,C3} = 1.38 \times 10^{-37}\mathrm{cm}^2 \left(\frac{\mu_\chi}{1\mathrm{GeV}}\right)^2 \left(\frac{300\mathrm{GeV}}{M_*}\right)^4,$$

Different operators contribute either to spin-dependent or spin-independent WIMP-nucleon cross sections





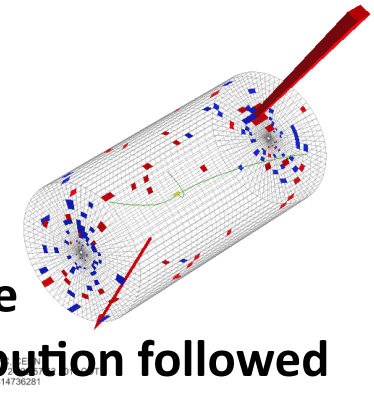
Very strong limits for SD processes

Within the assumption of the validity of the effective theory **the LHC results are competitive to direct detector experiments (particularly relevant at $m_\chi < 10$ GeV)**

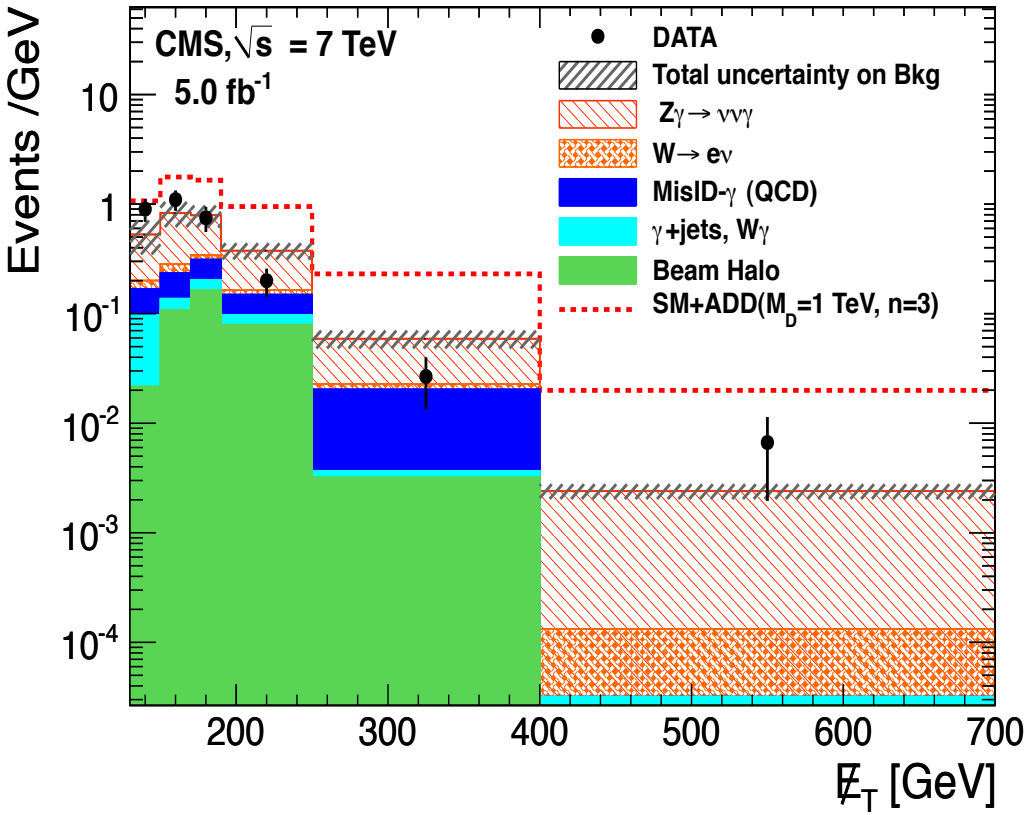
Large sensitivity in case of D11 (gg initiated)

Mono-photons

7 TeV
5 fb^{-1}



Phys. Rev. Lett.108 261803 (2012)



P_t^{γ} >145 GeV, $|\eta^{\gamma}|$ < 1.44, isolated
E_t^{miss} > 130 GeV
Veto on leptons, isolated tracks, jets

Good agreement with SM

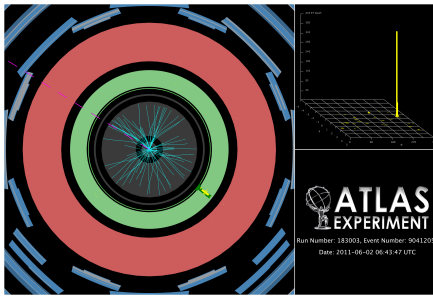
Background dominated by the irreducible Zγ (→ ννγ) contribution followed by photon fakes and non-collision background, plus other small contributions

- **QCD-jet fakes data driven using EM-enriched sample with loose photon requirements**
- **Time distribution of the calorimeter energy deposit used to estimate non-collision background**

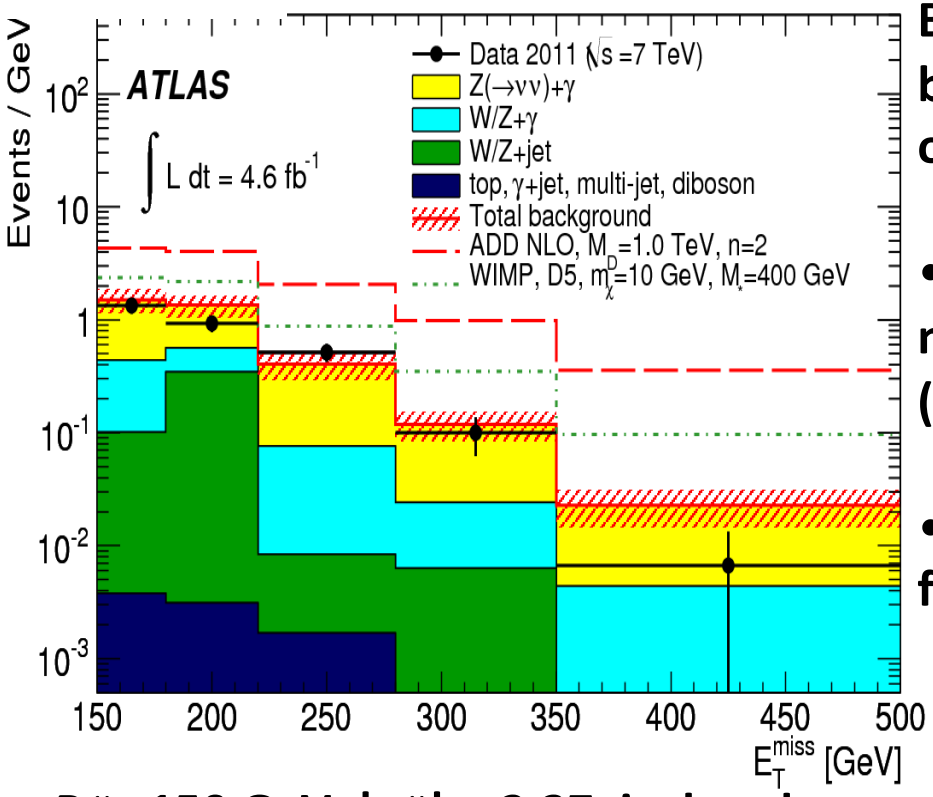
Source	Estimate
Jet Mimics Photon	11.2 ± 2.8
Beam Halo	11.1 ± 5.6
Electron Mimics Photon	3.5 ± 1.5
$W\gamma$	3.0 ± 1.0
γ+jet	0.5 ± 0.2
$\gamma\gamma$	0.6 ± 0.3
$Z(\nu\bar{\nu})\gamma$	45.3 ± 6.9
Total Background	75.1 ± 9.5
Total Observed Candidates	73

Mono-photons

7 TeV
4.6 fb^{-1}

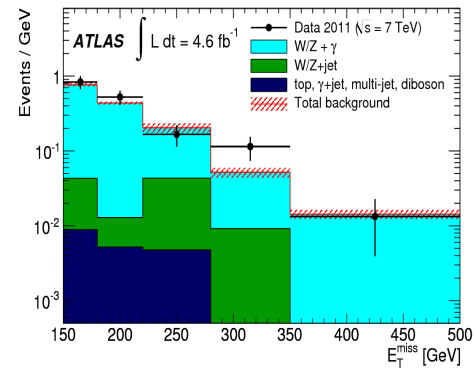


Phys. Rev. Lett 110, 011802 (2013)



Background dominated by Z/W+γ followed by contributions with jets faking photons plus other small contributions

- **Z/W+γ contributions from MC normalized in control regions (γ+ μ + E_t^{miss} control sample)**



- **Jet and electron fakes fully data driven**

σxAxε< 6.8 fb @ 95% CL

Background source	Prediction	± (stat.)	± (syst.)
$Z(\to \nu\bar{\nu}) + \gamma$	93	± 16	± 8
$Z/\gamma^*(\to \ell^+\ell^-) + \gamma$	0.4	± 0.2	± 0.1
$W(\to \ell\nu) + \gamma$	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		

P_t^γ >150 GeV, $|\eta^\gamma|$ < 2.37, isolated
E_t^{miss} > 150 GeV
N^{jet} < 2 (p_T > 30 GeV)
Δφ (γ, E_T^{miss}) >0.4, Δφ (jet, E_T^{miss}) >0.4
Veto on leptons

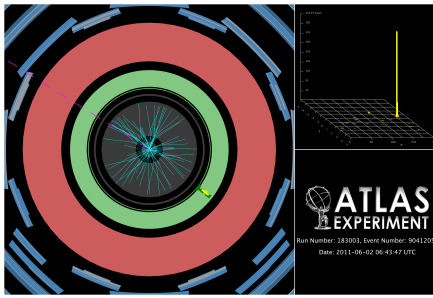
Good agreement with SM

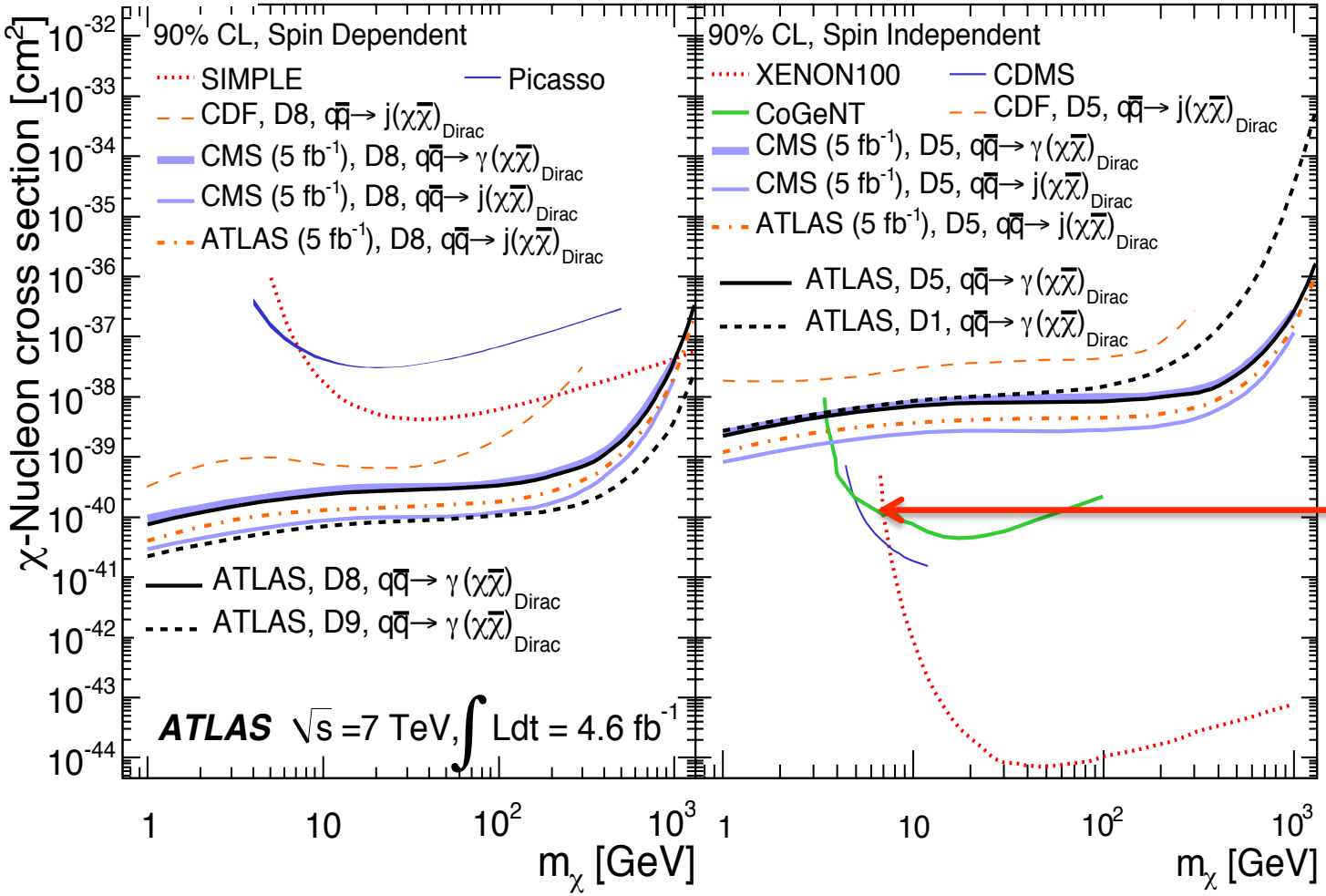
WIMPS

(monojets & monophotons)

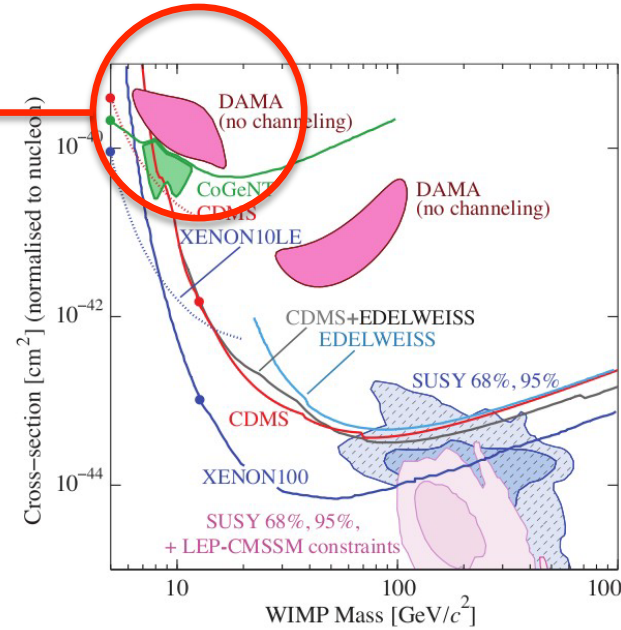
Phys. Rev. Lett 110, 011802 (2013)

7 TeV
5 fb^{-1}





Not enough sensitivity yet to exclude/confirm the CoGeNT/DAMA (*) excess at m_χ~10 GeV in case the of D1/D5 models



Rather strong limits from LHC (dominated by monojets)

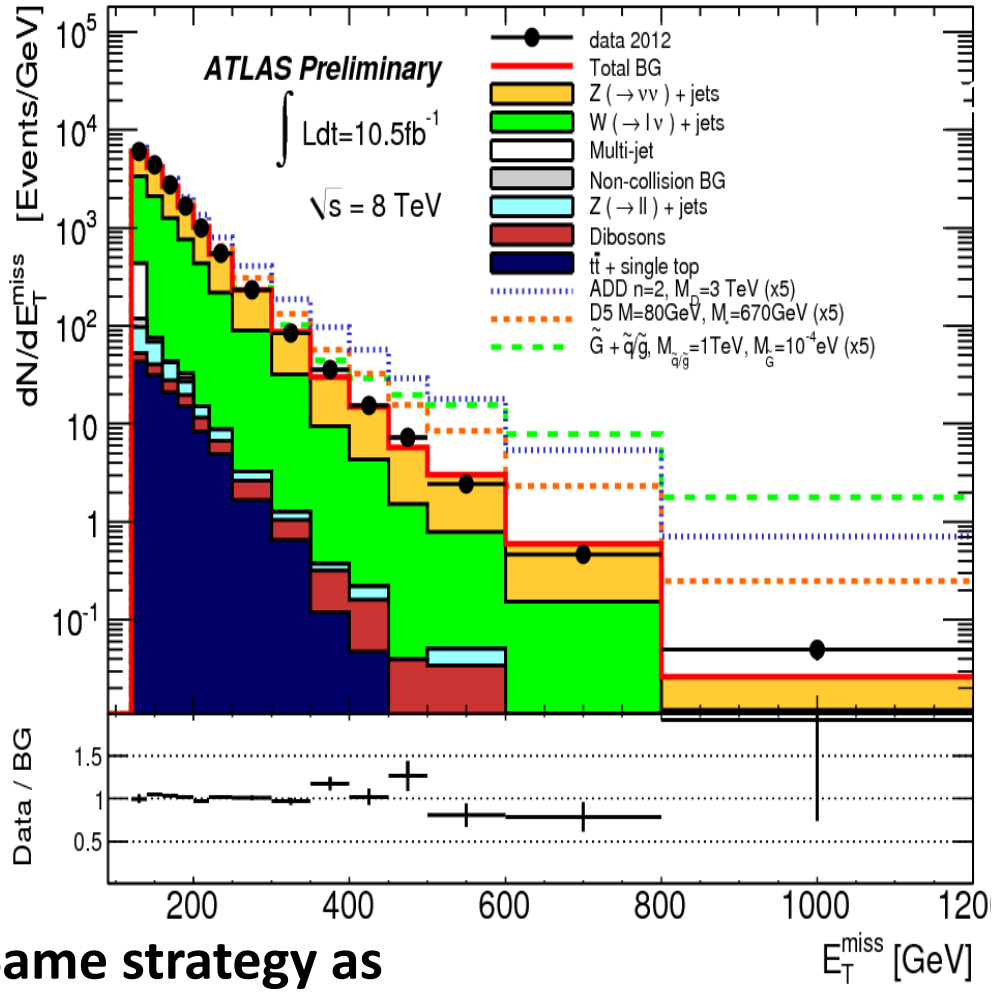
For m_χ < 100 GeV : WIMPS-nucleon cross sections above 3 x10^{-40} cm^2 (10^{-39} cm^2) are excluded for spin –dependent (spin-independent) operators

(*) not confirmed by Xenon100 and LUX results

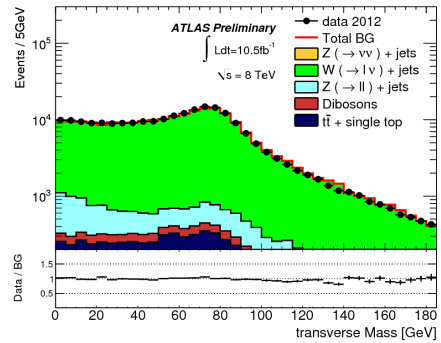
8 TeV 10 fb^{-1}

Mono-jets

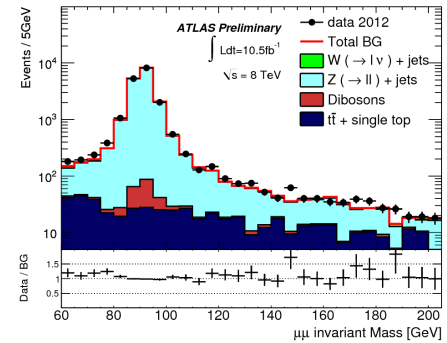
ATLAS-CONF-2012-147

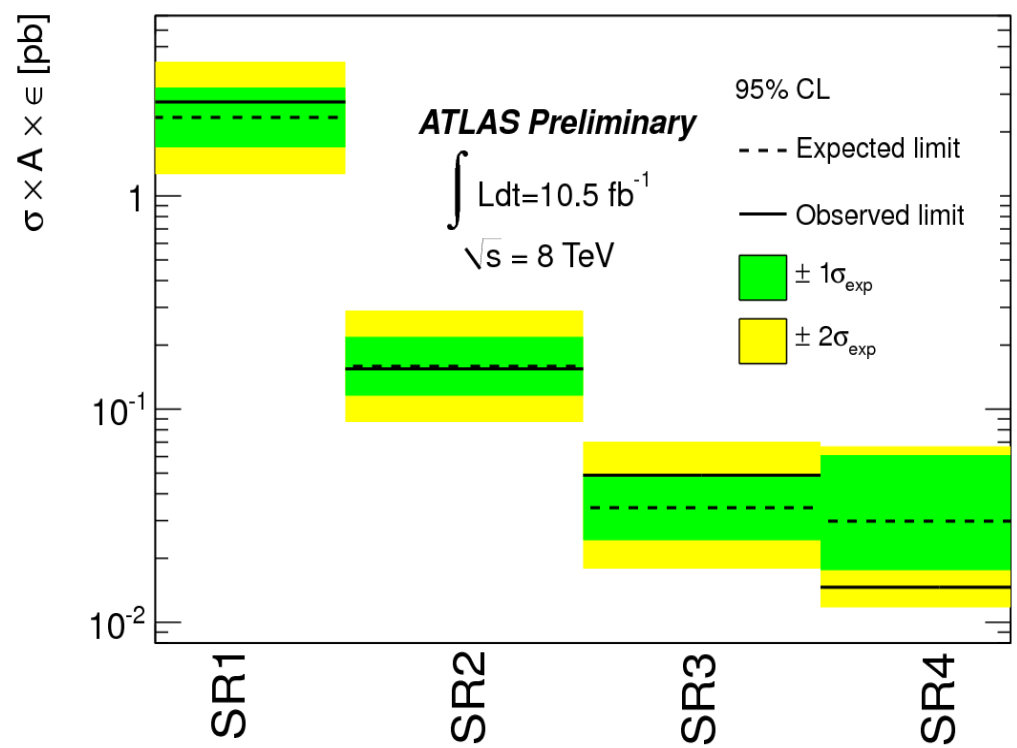


single-muon events



dimuon events





Same strategy as in the 7 TeV analysis

E_T^{miss} > 120, 220, 350, 500 GeV

p_T (j1) > 120, 220, 350, 500 GeV

$N_{jet}(p_T$ > 30 GeV) < 3

$\Delta\phi$ (E_T^{miss}, j2) > 0.5

Lepton vetoes

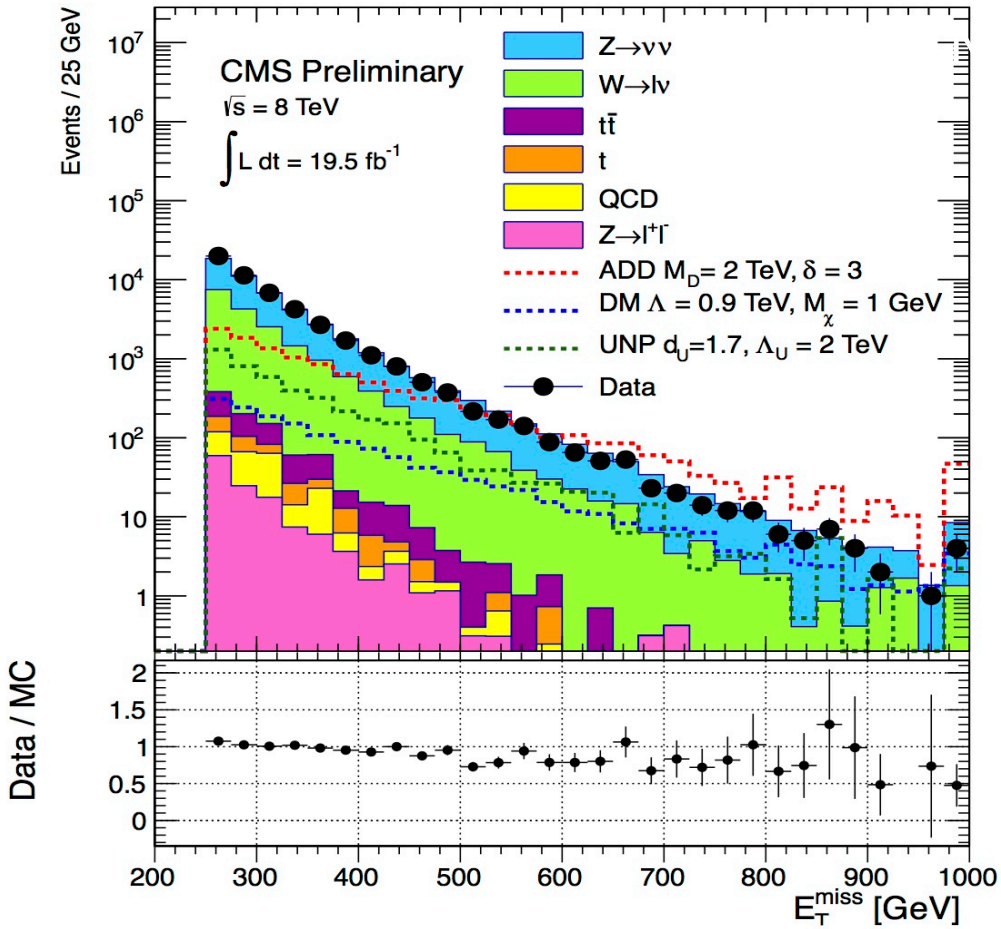
Good agreement with SM predictions

(suffered from lack of MC statistics)

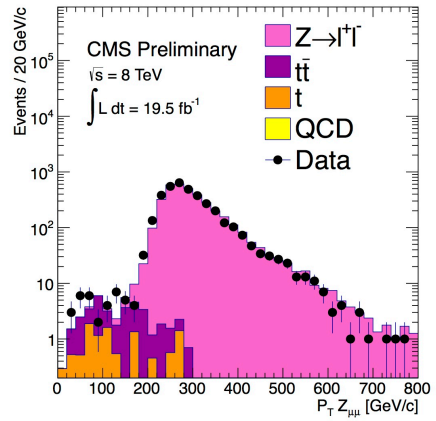
CMS-PAS-EXO-12-048

Mono-jets

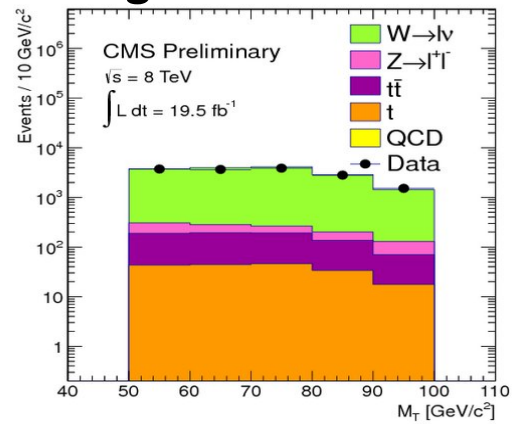
8 TeV 19.5 fb^{-1}

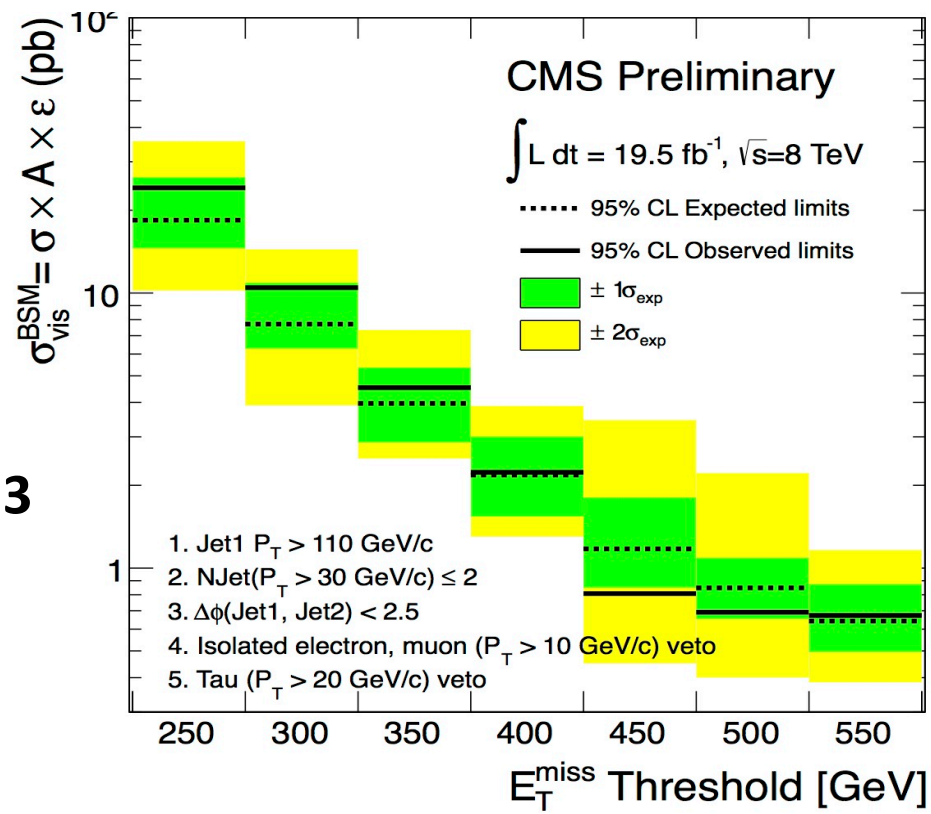


dimuon events



single-muon events





Same strategy as in the 7 TeV analysis

Good agreement with SM predictions

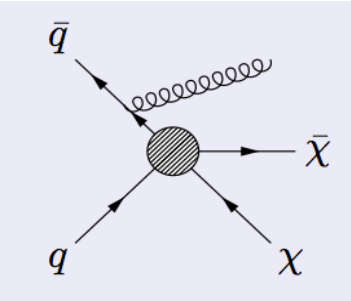
$E_t^{miss} > 200$ GeV

$p_T(j1) > 110$ GeV

$N_{jet}(p_T > 30 \text{ GeV}) < 3$

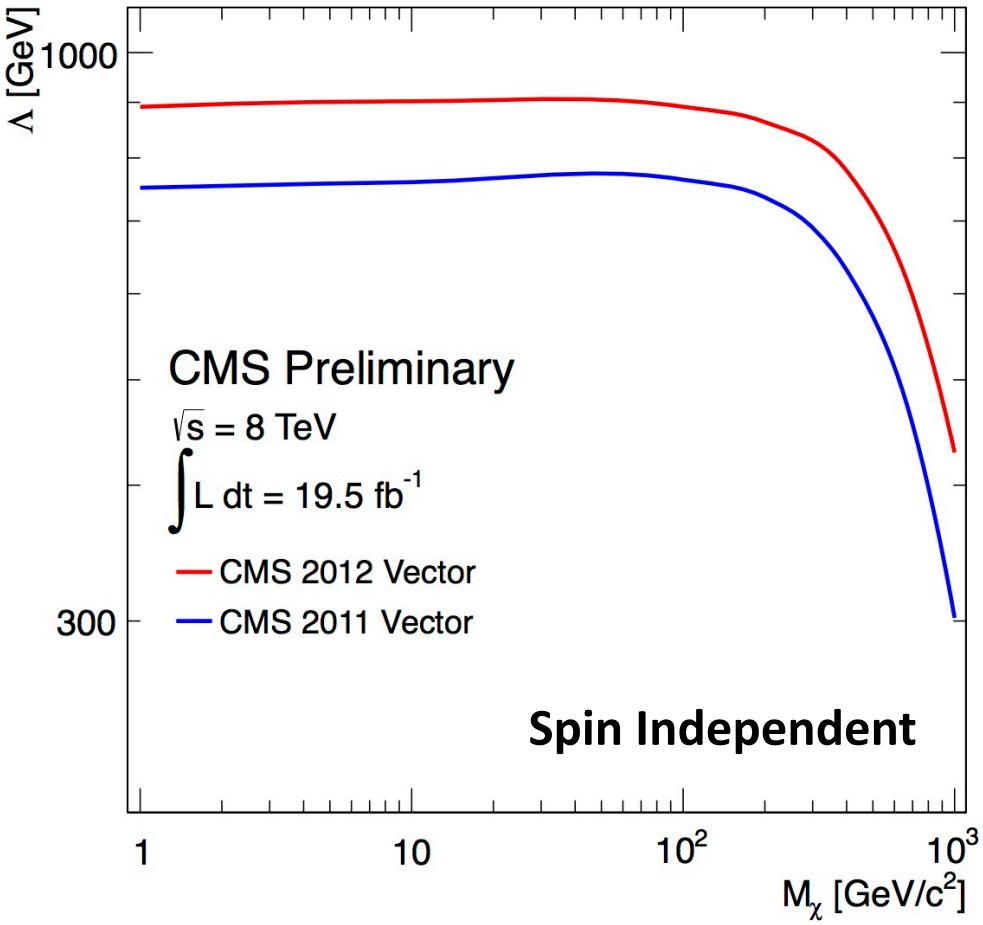
$\Delta\phi(j1,j2) < 2.5$

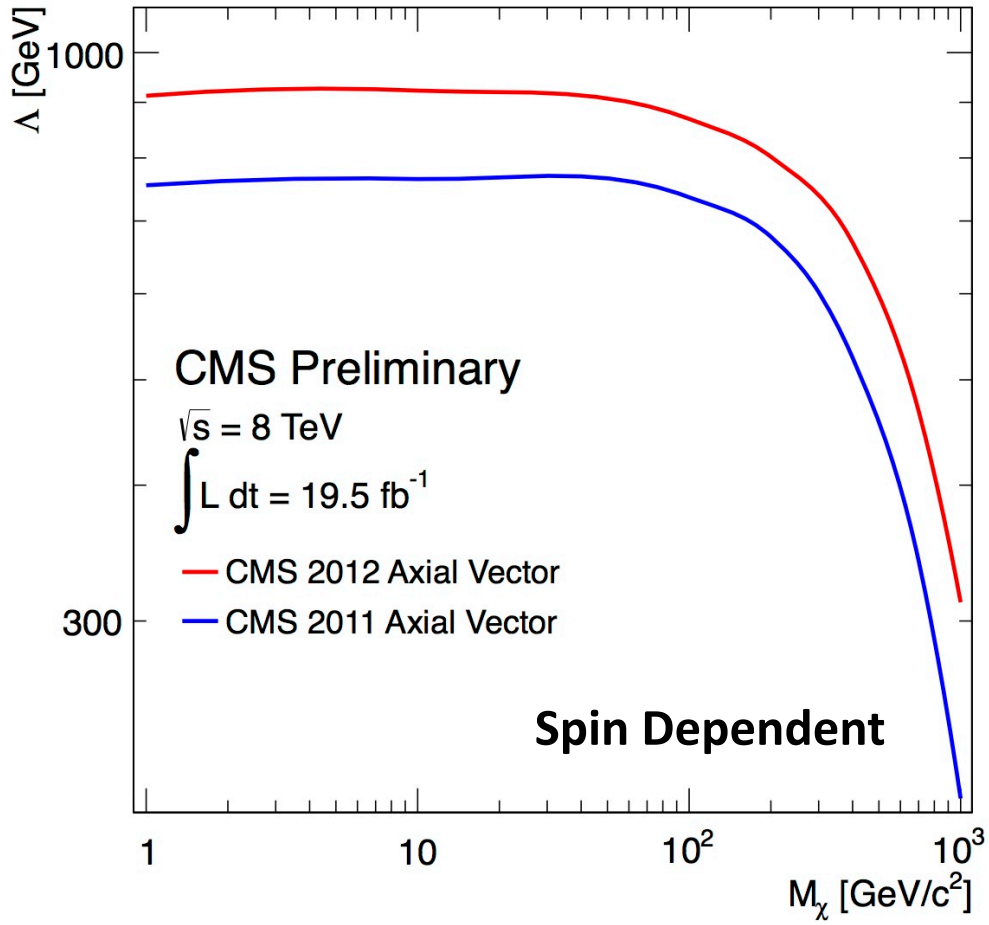
Lepton vetoes



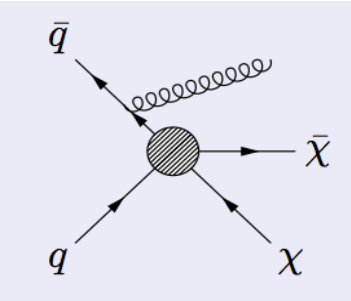
90% CL Limits on suppression scale

CMS-PAS-EXO-12-048



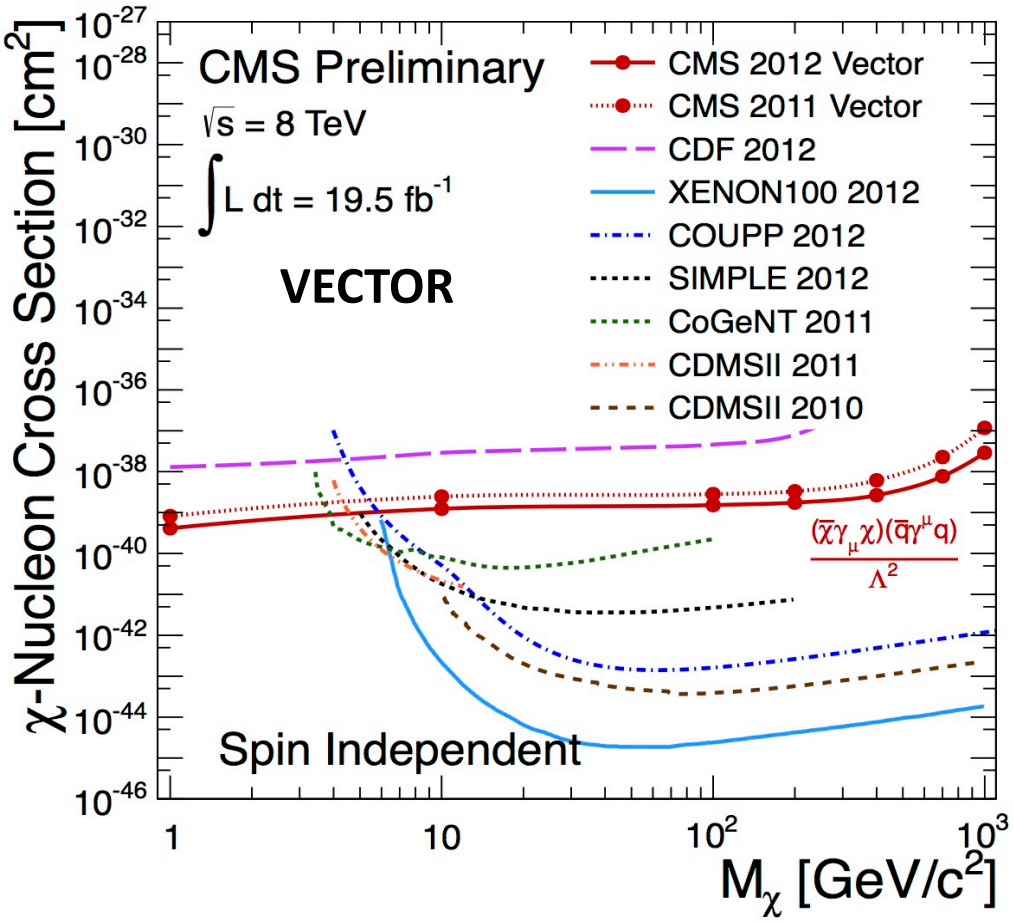


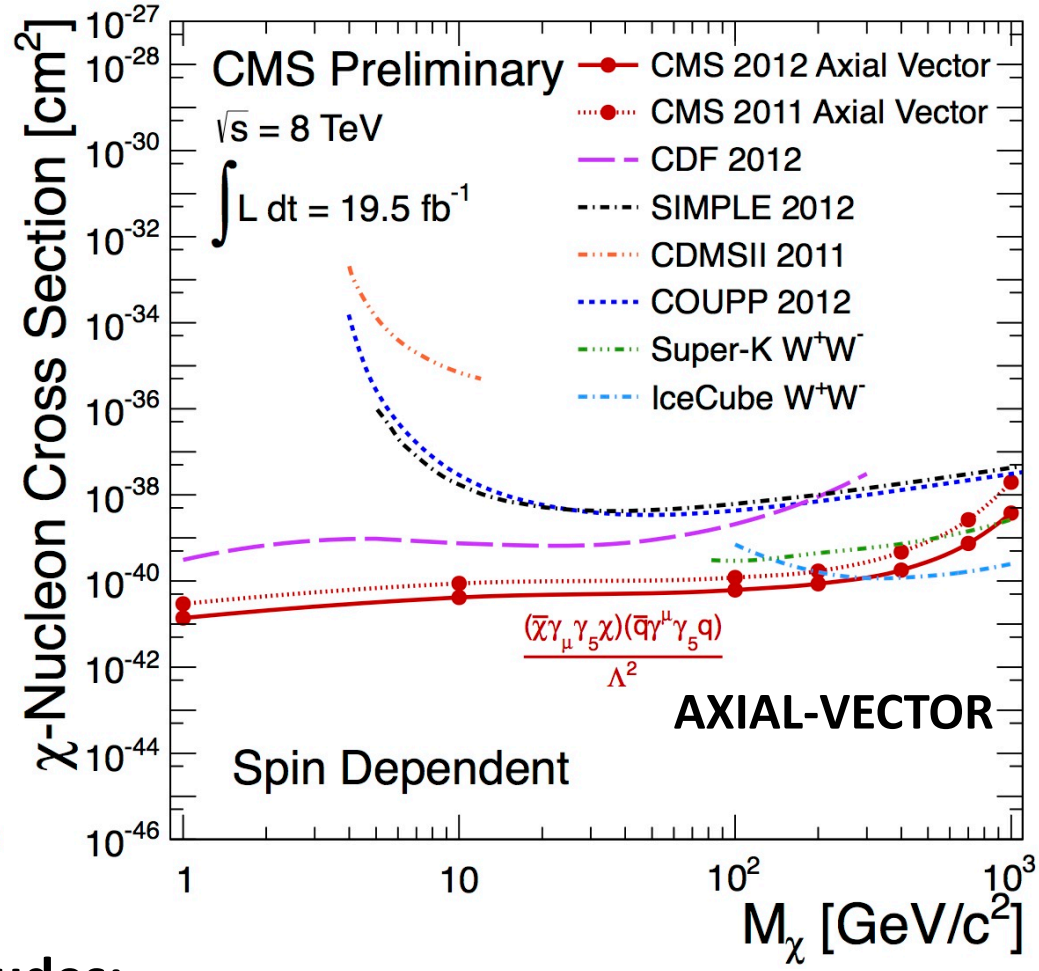
8 TeV data improves previous limits on Λ (M_*) by about 150 GeV (approaching the 1 TeV scale)



90% CL Limits on WIMP-nucleon

CMS-PAS-EXO-12-048

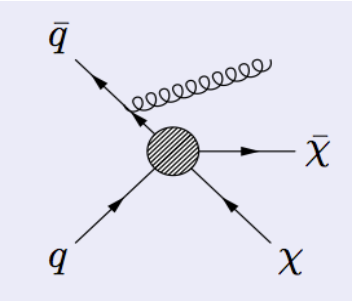




For m_χ ~ 10 GeV the experiment excludes:

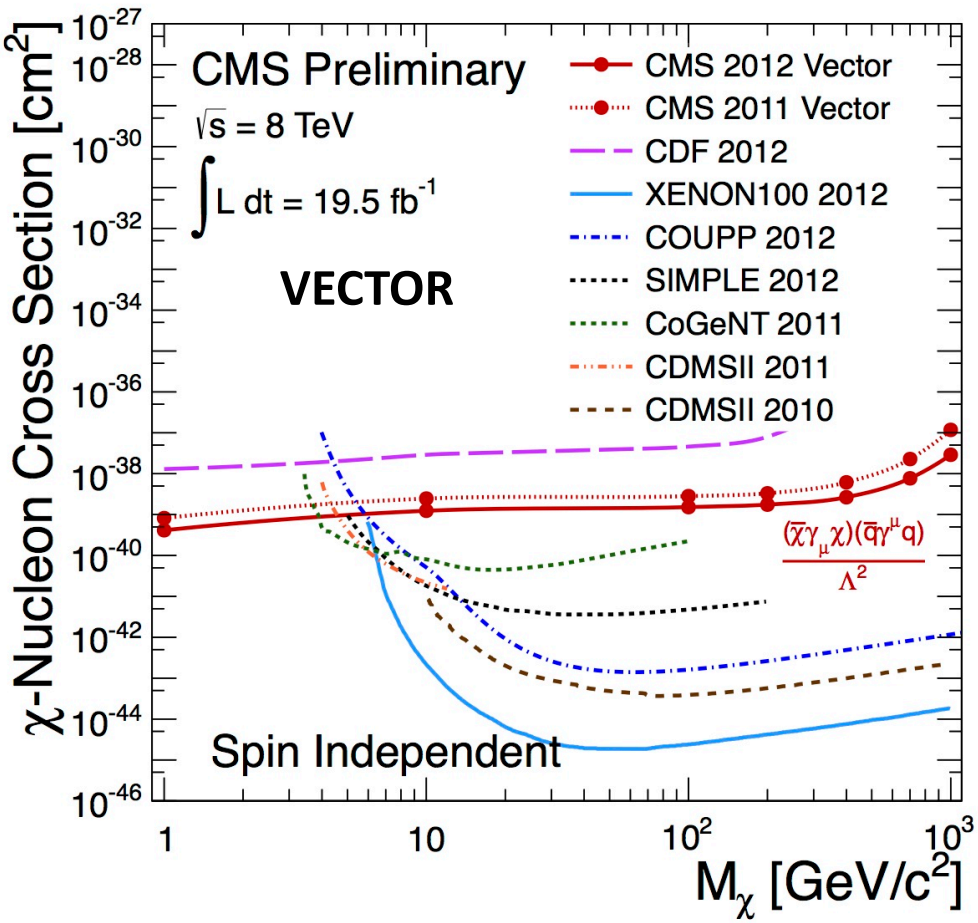
WIMP-nucleon x-section > 1.2 x10^{-39} cm^2 at 90% CL (vector operator)

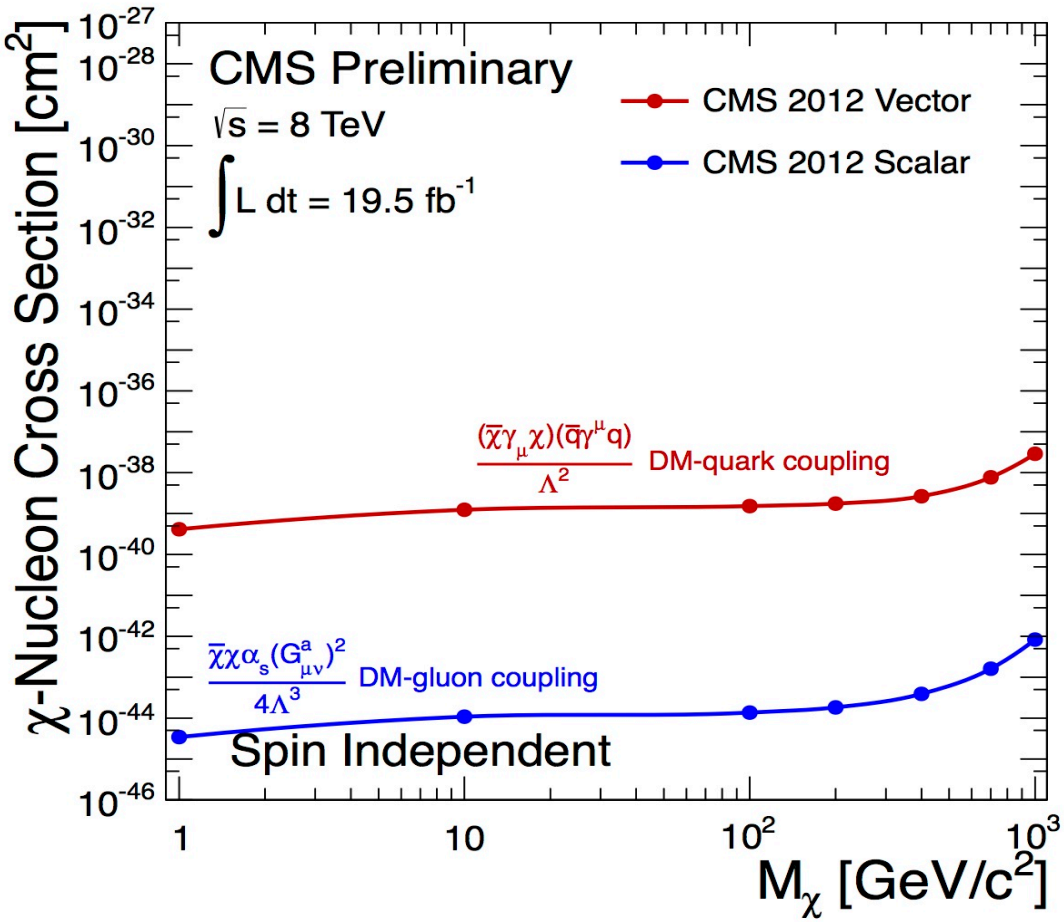
WIMP-nucleon x-section > 4.2 x10^{-41} cm^2 at 90% CL (axial vector operator)



90% CL Limits on WIMP-nucleon

CMS-PAS-EXO-12-048





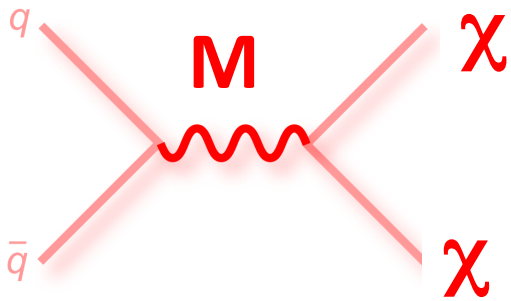
For m_χ ~ 10 GeV the experiment excludes:

WIMP-nucleon x-section > 1.2 x10^{-39} cm^2 at 90% CL (vector operator)

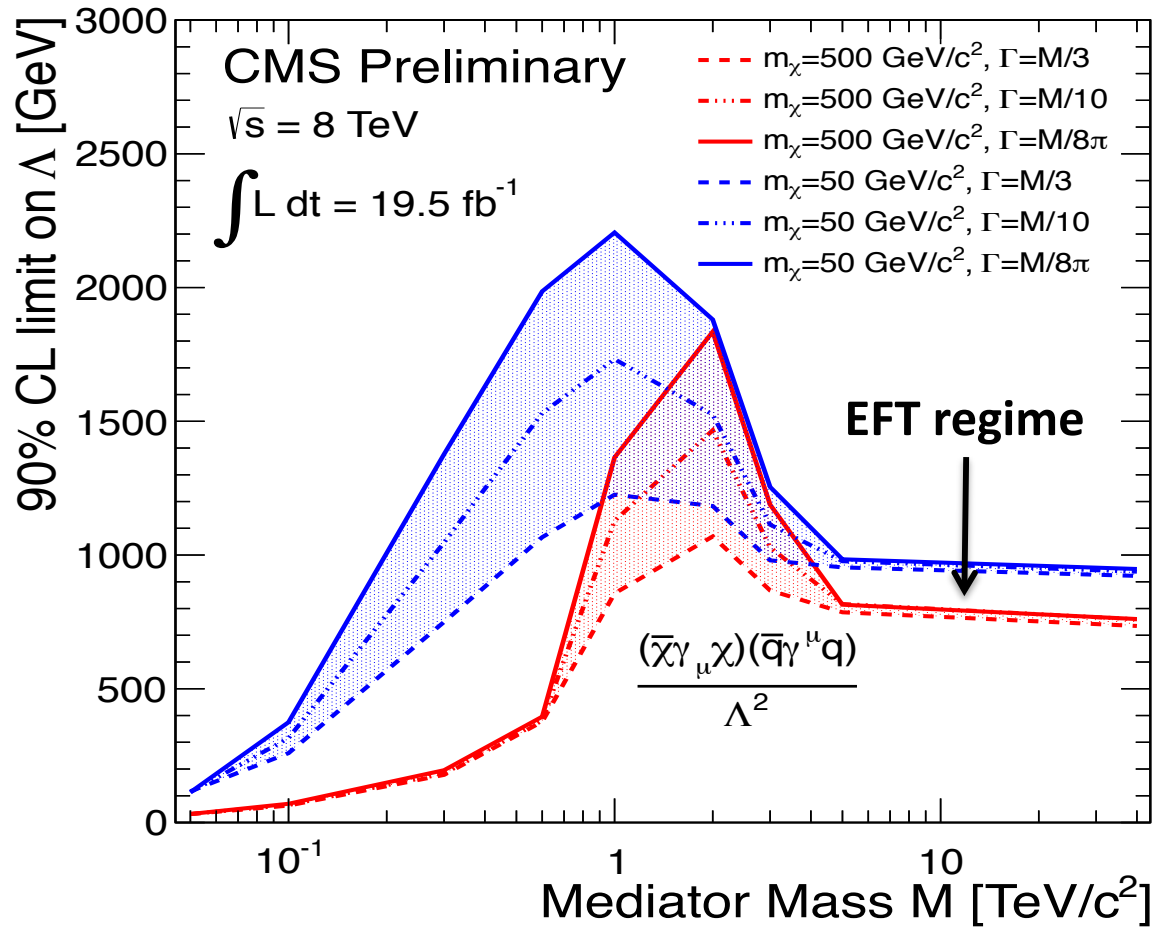
WIMP-nucleon x-section > 1.1 x10^{-44} cm^2 at 90% CL (scalar)

Light Mediator

CMS-PAS-EXO-12-048



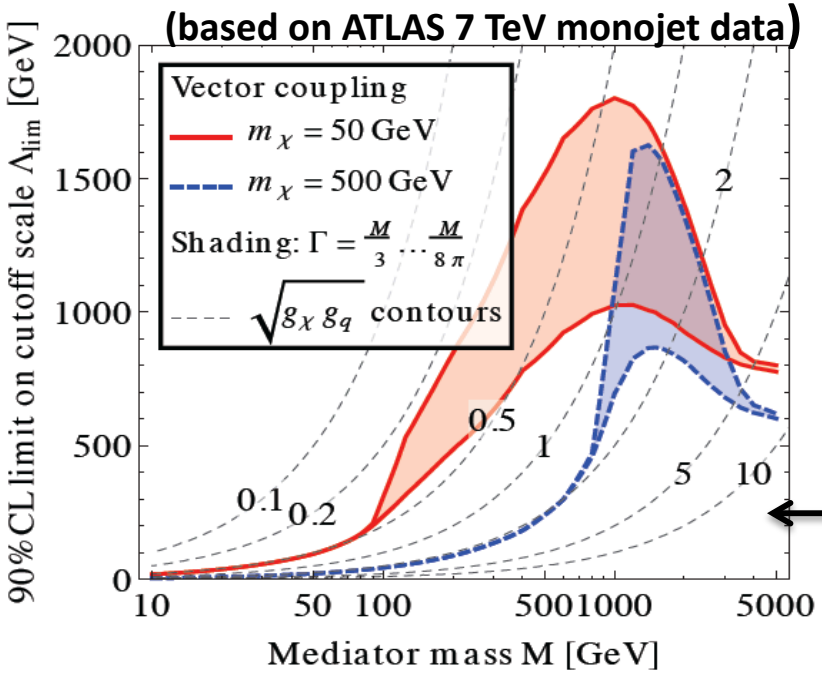
$$\sigma(pp \to \bar{\chi}\chi + X) \sim \frac{g_q^2 g_\chi^2}{(q^2 - M^2)^2 + \Gamma^2/4} E^2$$



Exploring the scenario with a vector-like coupling and a light mediator with given M and Γ and different DM masses

P.J. Fox et al., PhysRevD.85.056011

(based on ATLAS 7 TeV monojet data)



For M > few x 100 GeV the EFT is adequate and somehow conservative in the bounds on Λ (note however the effective couplings become large)

For M < 100 GeV the collider bounds are weakened

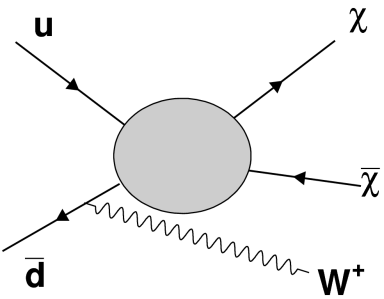
CMS-PAS-EXO-13-004

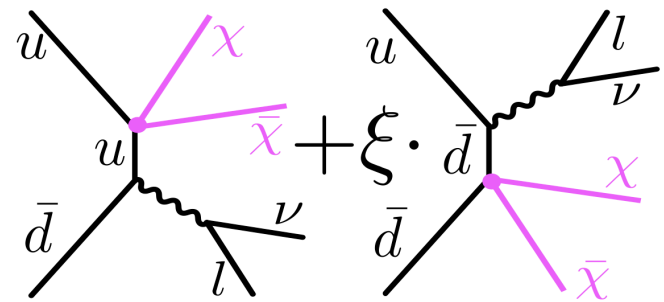
Mono-W

8 TeV

20 fb^{-1}

Search for mono-W (electron/muon)
Interpreted in terms of DM-DM + W



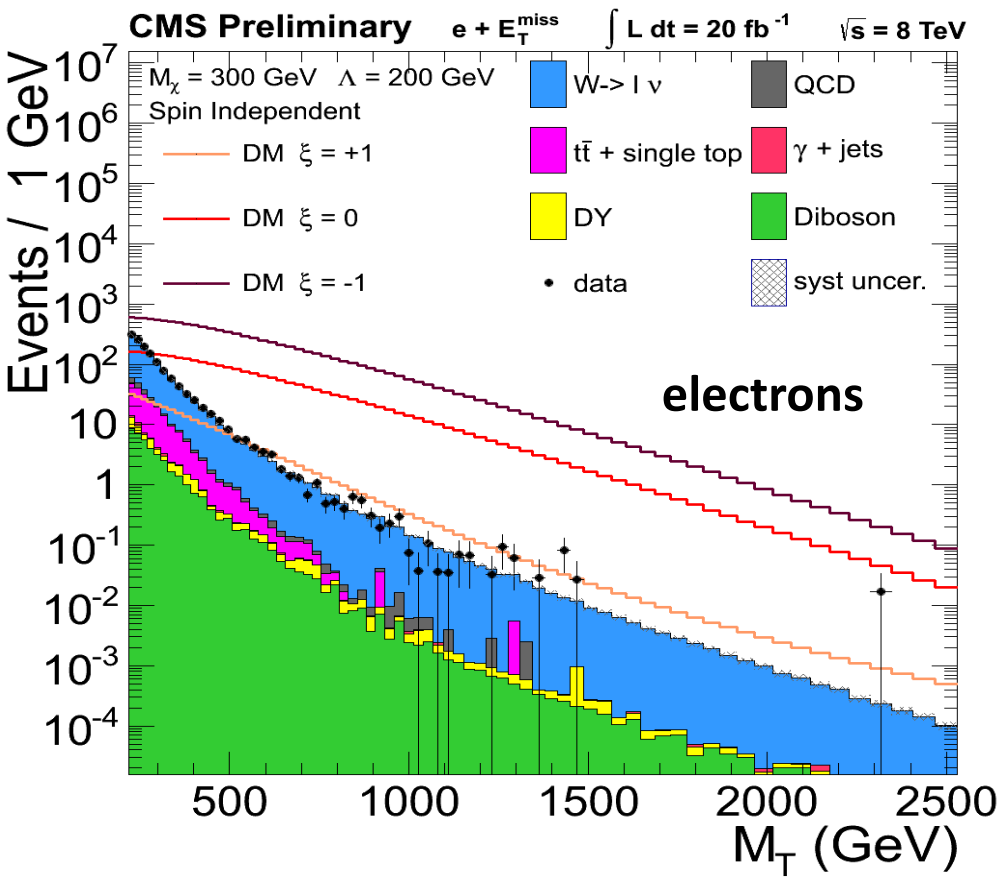


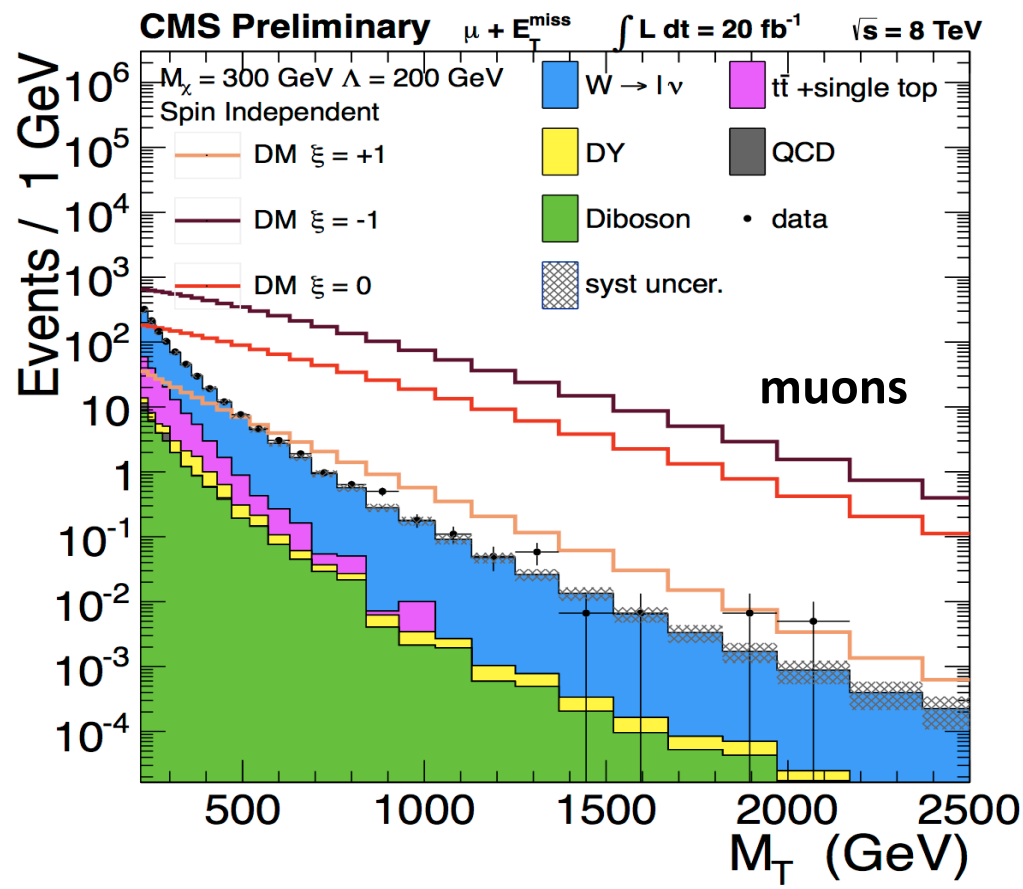
Considering vector and axial-vector operators and interference between different contributions (ξ = +1, -1 , 0)

$$(\mathrm{V})\ \frac{1}{\Lambda^2}\bar{\chi}\gamma^{\mu}\chi \quad \xi_i\bar{q}_i\gamma_{\mu}q_i$$

$$(\mathrm{AV})\ \frac{1}{\Lambda^2}\bar{\chi}\gamma^{\mu}\gamma^5\chi \quad \xi_i\bar{q}_i\gamma_{\mu}\gamma^5 q_i$$

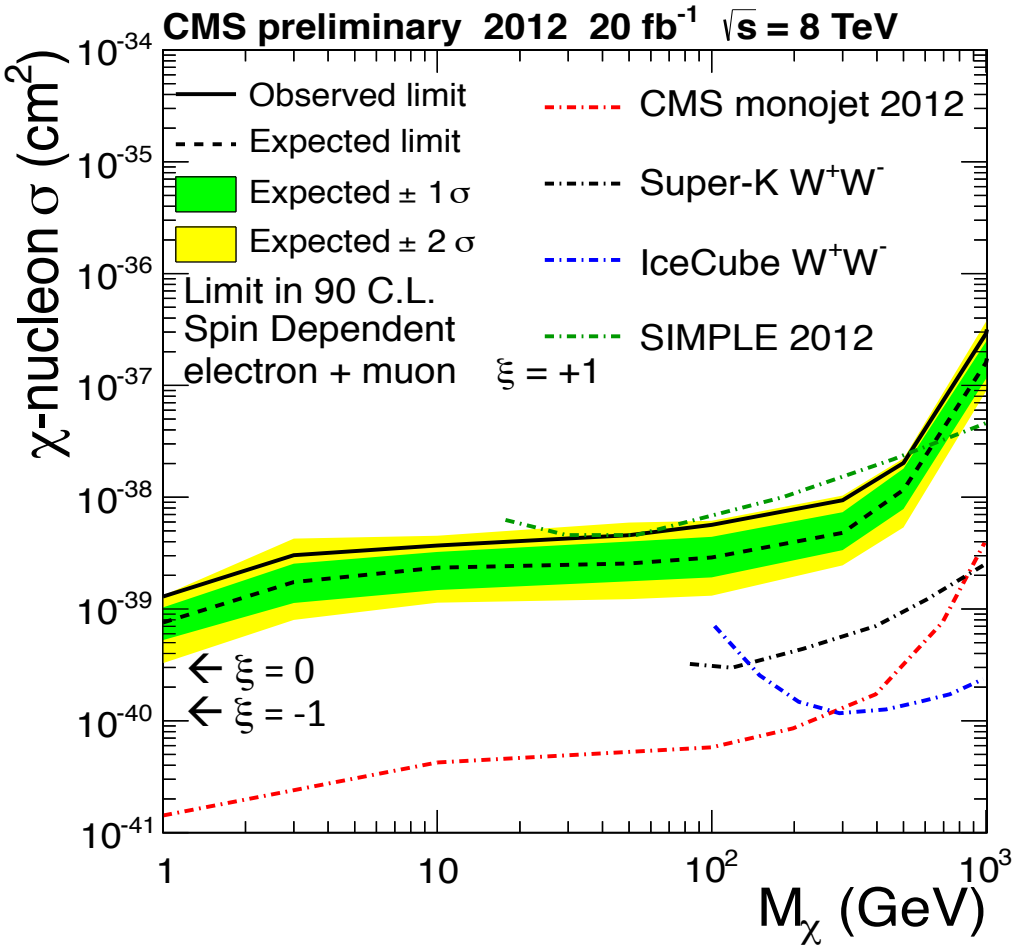
$$M_{\mathrm{T}} = \sqrt{2\cdot p_{\mathrm{T}}^{\ell}\cdot E_{\mathrm{T}}^{\mathrm{miss}}\cdot(1-\cos\Delta\phi_{\ell,\nu})}$$



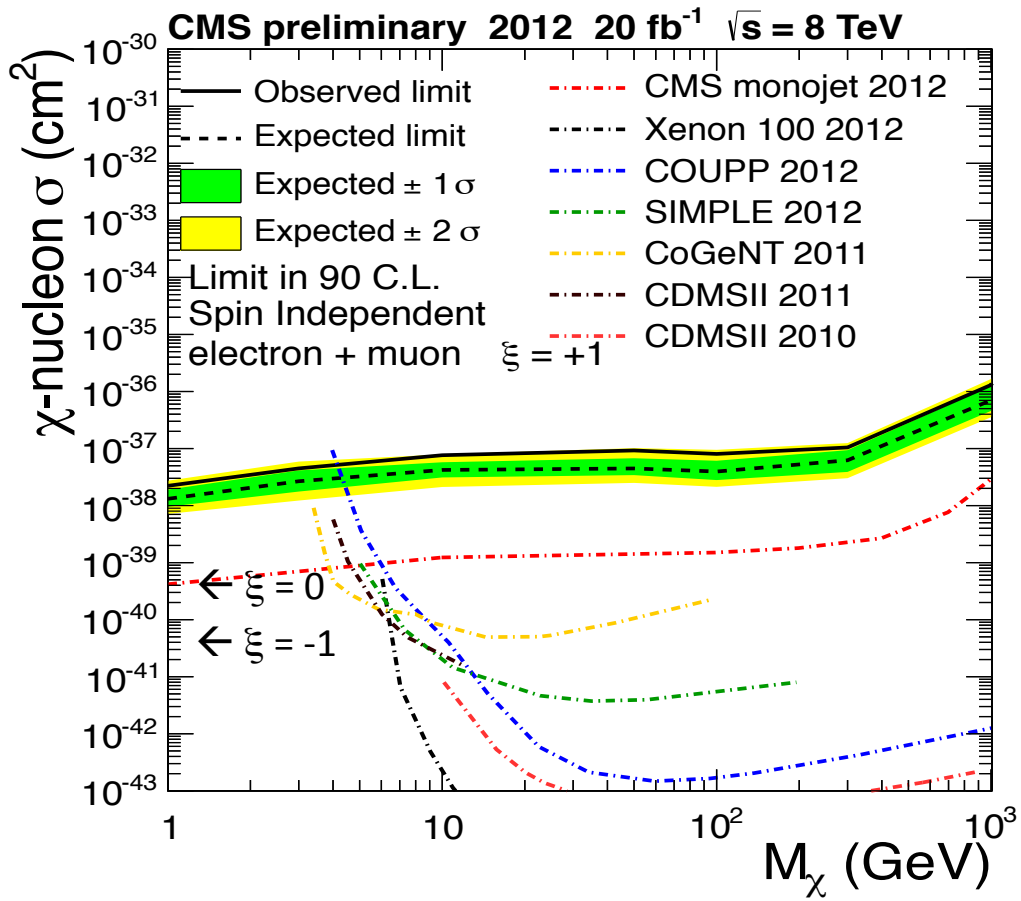


Mono-W (90% CL limits)

CMS-PAS-EXO-13-004



cross section enhancement when interference is constructive : ξ = -1



	$\xi = -1$		$\xi = 0$		$\xi = +1$	
M_χ	Λ[TeV]	$\sigma_{p\chi}$[cm^2]	Λ[TeV]	$\sigma_{p\chi}$[cm^2]	Λ[TeV]	$\sigma_{p\chi}$[cm^2]
1	1.02	1.3×10^{-40}	0.72	2.3×10^{-40}	0.32	1.5×10^{-39}
10	0.10	4.4×10^{-40}	0.72	7.3×10^{-40}	0.32	4.6×10^{-39}
300	0.85	1.0×10^{-39}	0.60	1.7×10^{-39}	0.26	1.1×10^{-38}
1000	0.33	4.4×10^{-38}	0.24	7.6×10^{-38}	0.11	3.6×10^{-37}

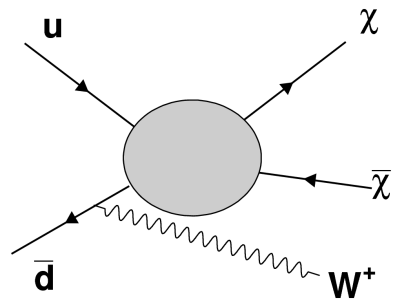
	$\xi = -1$		$\xi = 0$		$\xi = +1$	
M_χ	Λ[TeV]	$\sigma_{p\chi}$[cm^2]	Λ[TeV]	$\sigma_{p\chi}$[cm^2]	Λ[TeV]	$\sigma_{p\chi}$[cm^2]
1	0.95	3.5×10^{-41}	0.68	5.5×10^{-40}	0.31	2.7×10^{-38}
10	0.97	1.0×10^{-40}	0.68	1.7×10^{-39}	0.31	9.0×10^{-38}
300	0.86	1.9×10^{-40}	0.60	3.2×10^{-39}	0.30	1.3×10^{-37}
1000	0.44	3.0×10^{-39}	0.31	4.6×10^{-38}	0.16	1.6×10^{-36}

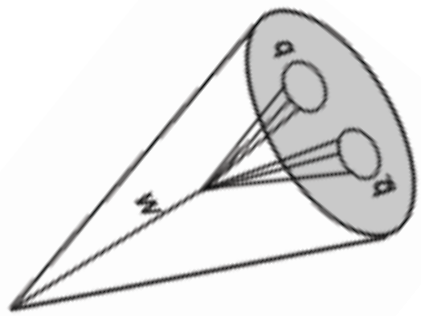
In the case of SI interactions and ξ = -1, 0 the mono-W limits compete with mono-jets

Mono-W/Z

ATLAS-CONF-2013-073
http://arxiv.org/abs/1309.4017

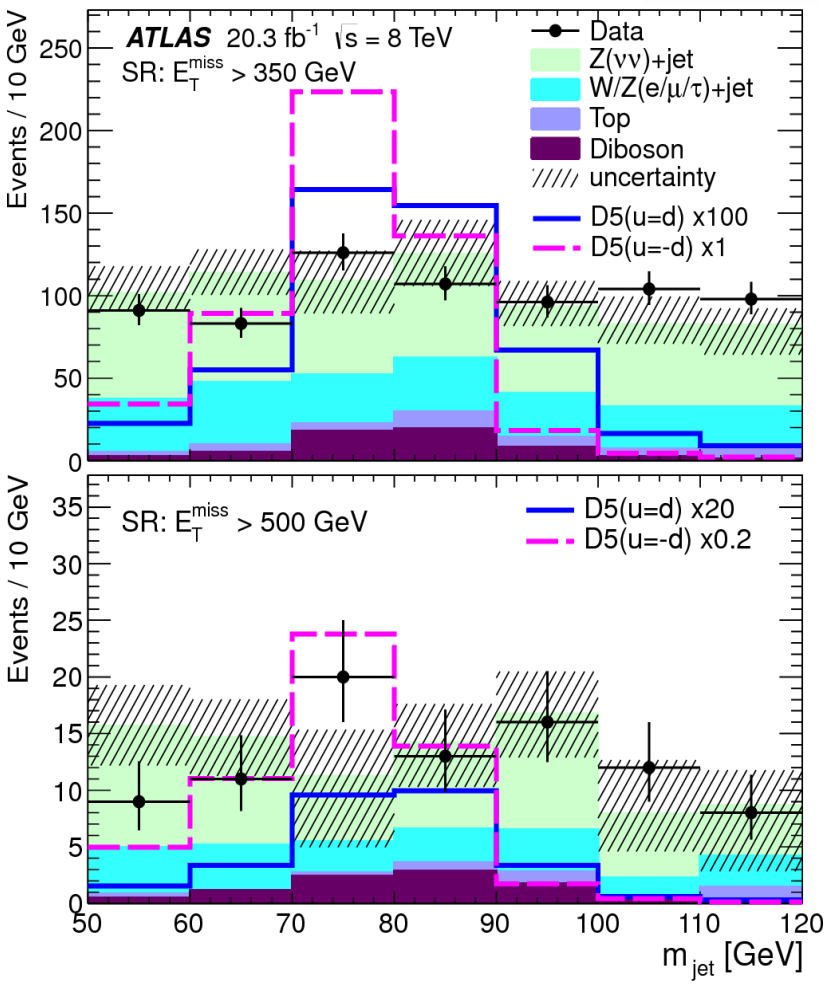
8 TeV
20 fb^{-1}

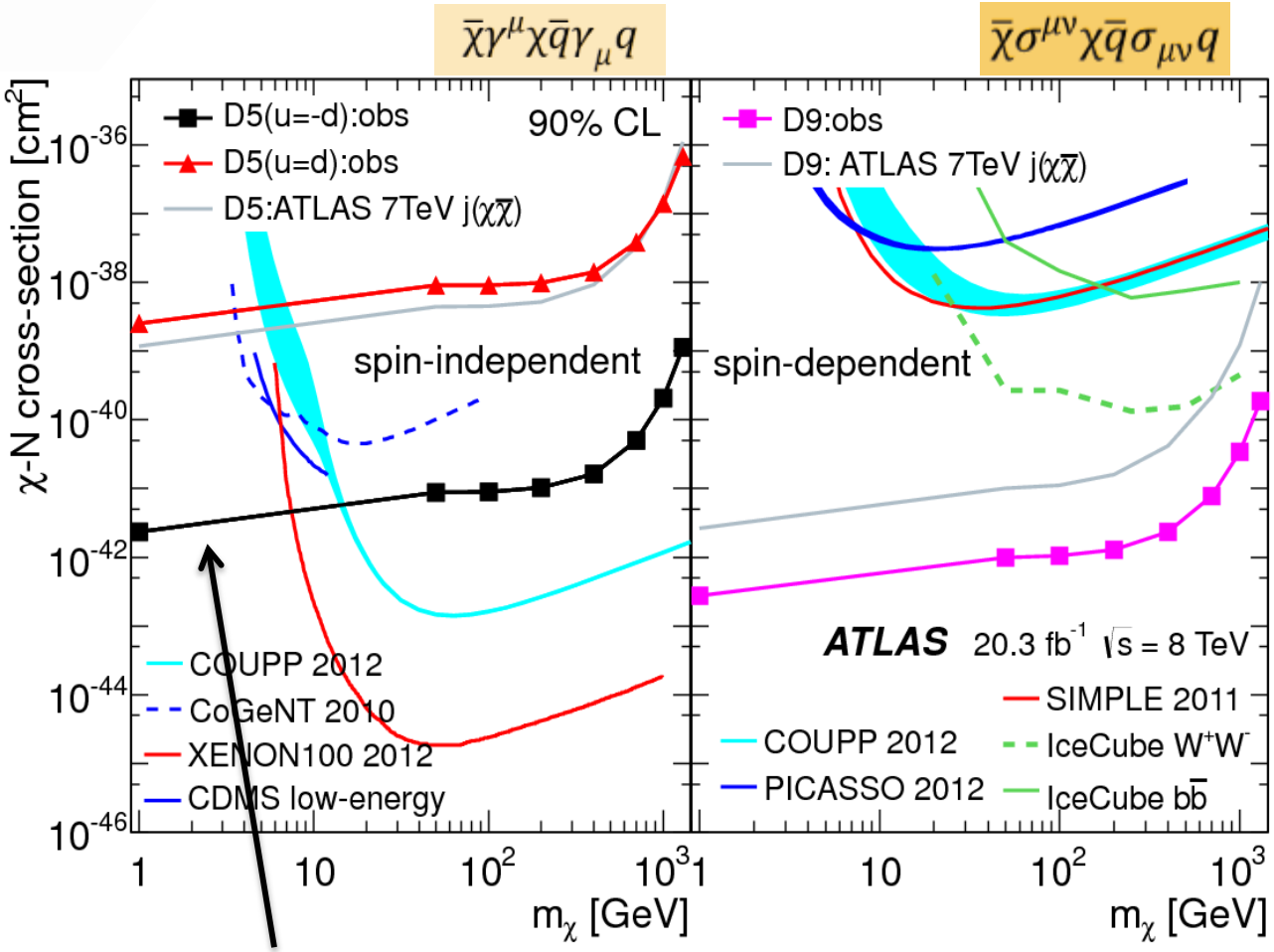




Based on the W/Z hadronic decay products reconstructed as subjets from CA R=1.2 jets
Jet P_t > 250 GeV, $|\eta|$ < 2.1, 50 < M_{jet} < 120 GeV

No additional jet (anti-kT 0.4) with p_T > 40 GeV

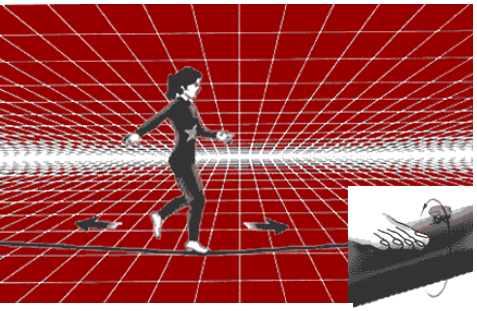




Even stronger limits than those obtained by the mono-W with W→(e,μ)$\nu_{e,\mu}$ analysis

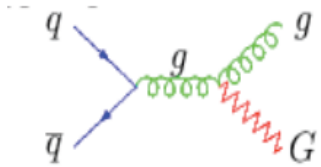
Extra dimensions

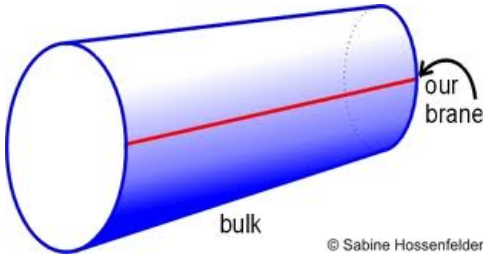
Mono-jets and mono-photons

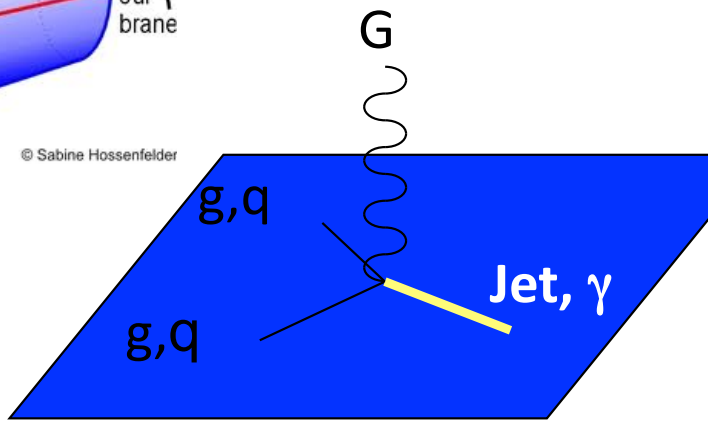


Large Extra Dimensions

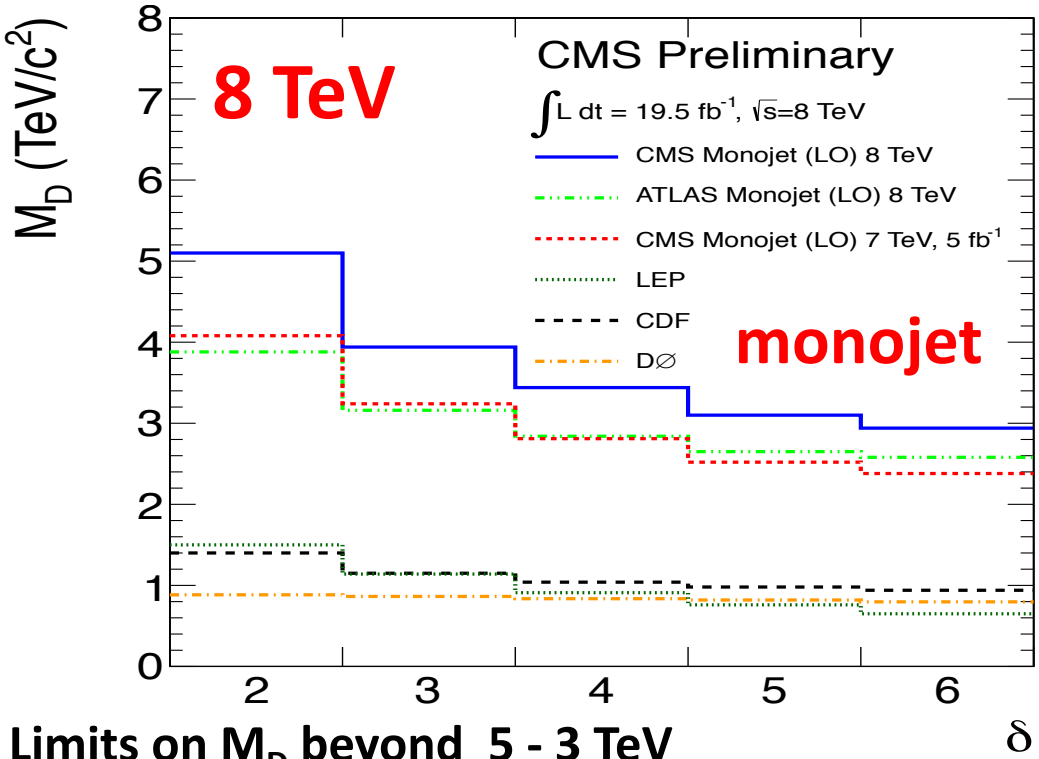
Extra spatial dimensions explain the apparent weakness of Gravity (relevant scale ~TeV)

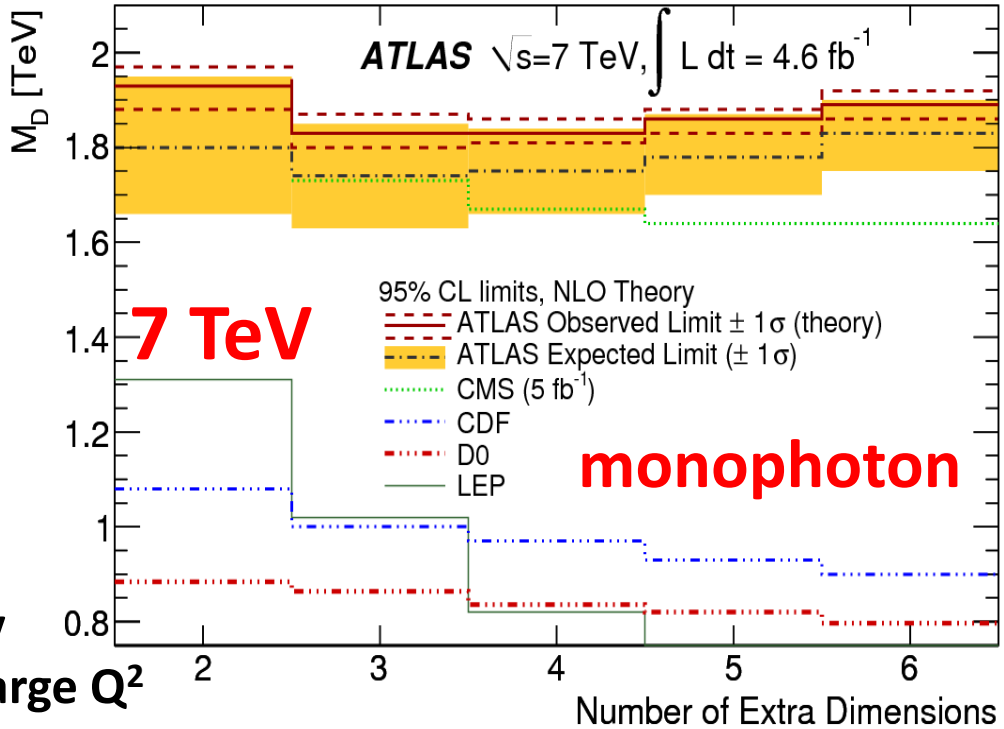






$(M_{PL})^2 \sim R^n (M_D)^{2+n}$





Limits on M_D beyond 5 - 3 TeV
(a real challenge of the model validity)

Note: Limits sensitive to the truncation strategy for s-hat > M_D^2 … LHC probing phase space at large Q^2

Search for SUSY

Very light gravitino (GMSB)
Stop in compressed scenario

GMSB Gravitino

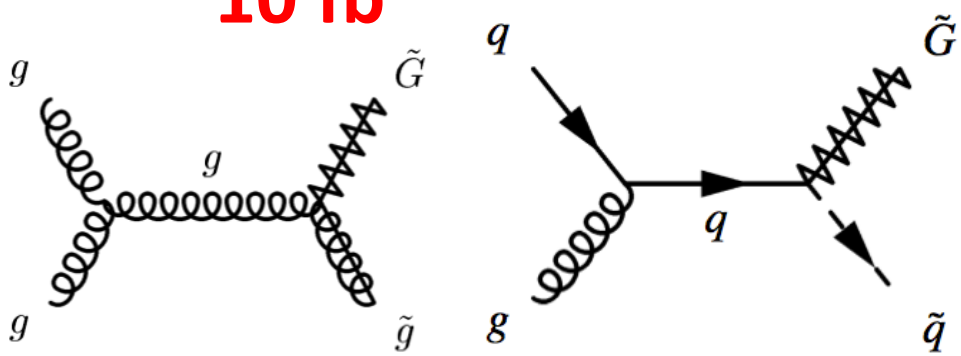
8 TeV
10 fb^{-1}

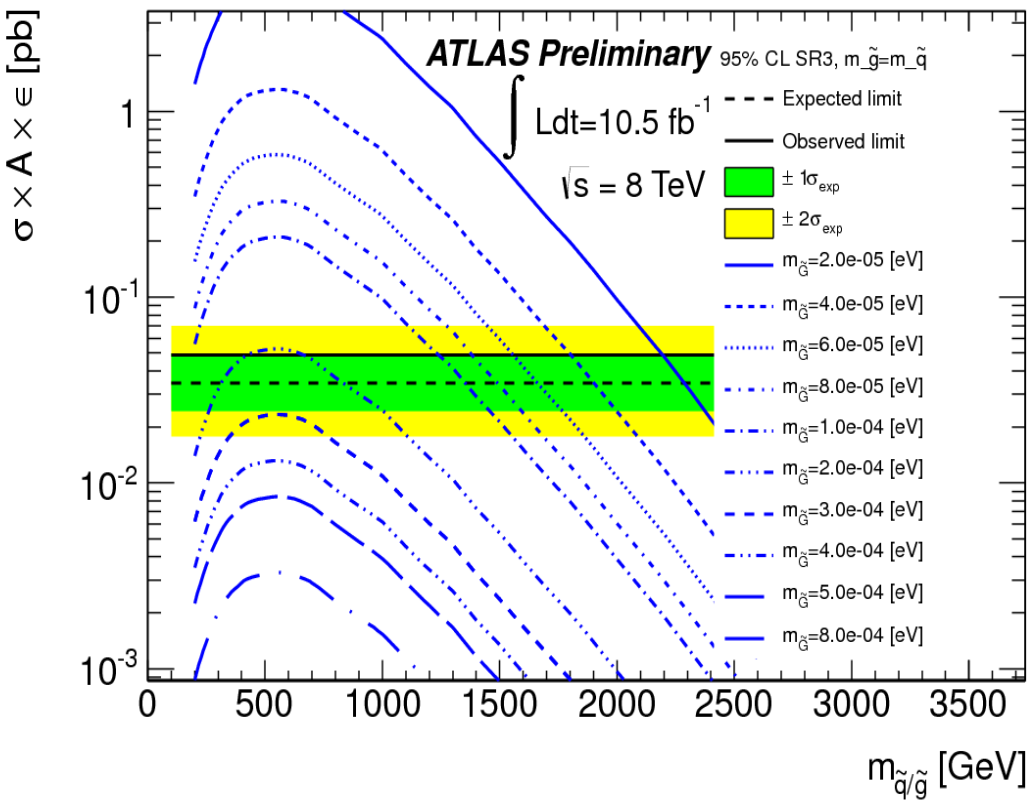
Monojet analysis
ATLAS-CONF-2012-147

$$m_{3/2} = \langle F \rangle / \sqrt{3}\,\overline{M}_{\rm Pl}$$

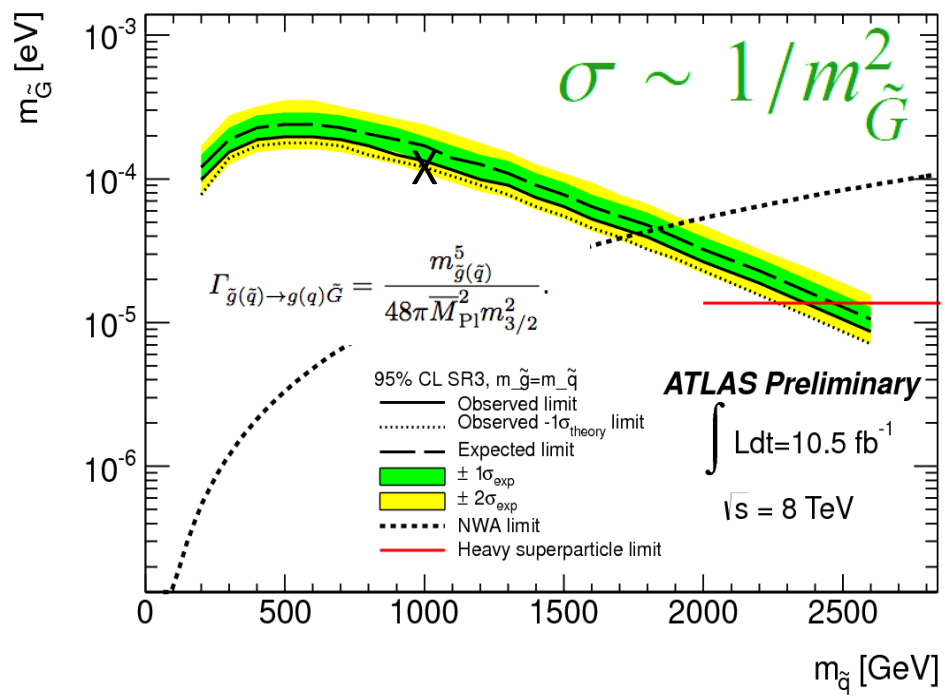
Interpreted in terms of GMSB gravitino+squark/gluino production

gluinos (squarks) decay to gluon (quark) plus Gravitino (100%)





Best limits to date on the gravitino mass



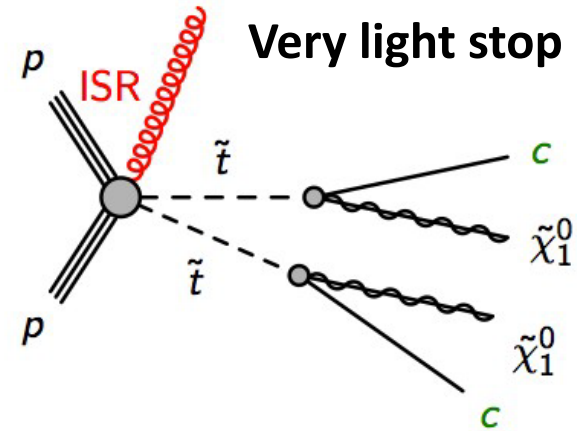
$m_{3/2} > 10^{-4}$ eV → √F > 640 GeV
(LEP limit 240 GeV)

Stop Production

8 TeV
20 fb^{-1}

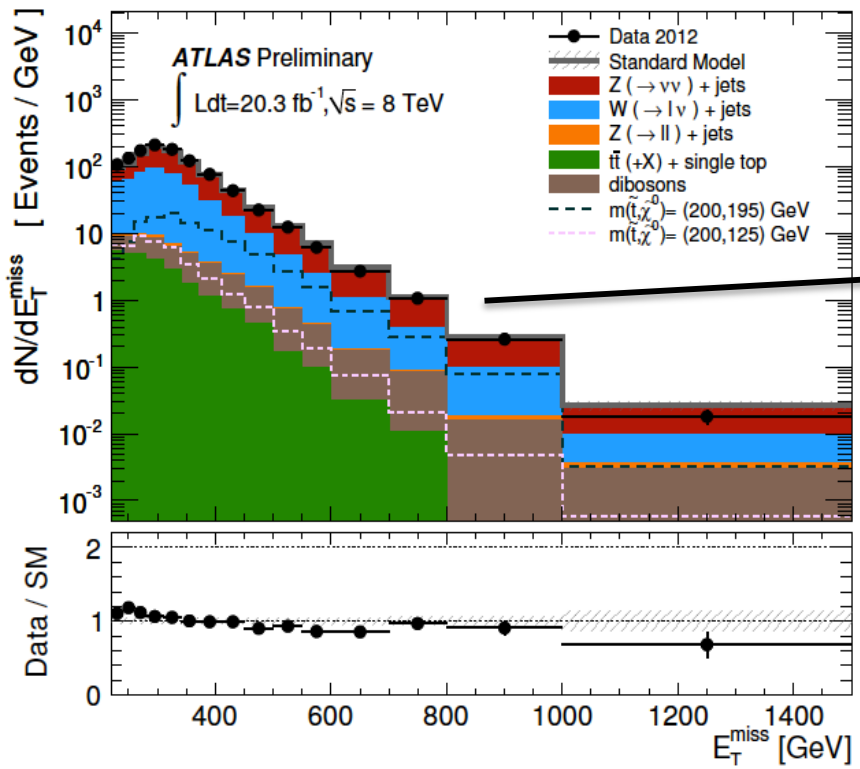
ATLAS-CONF-2013-068

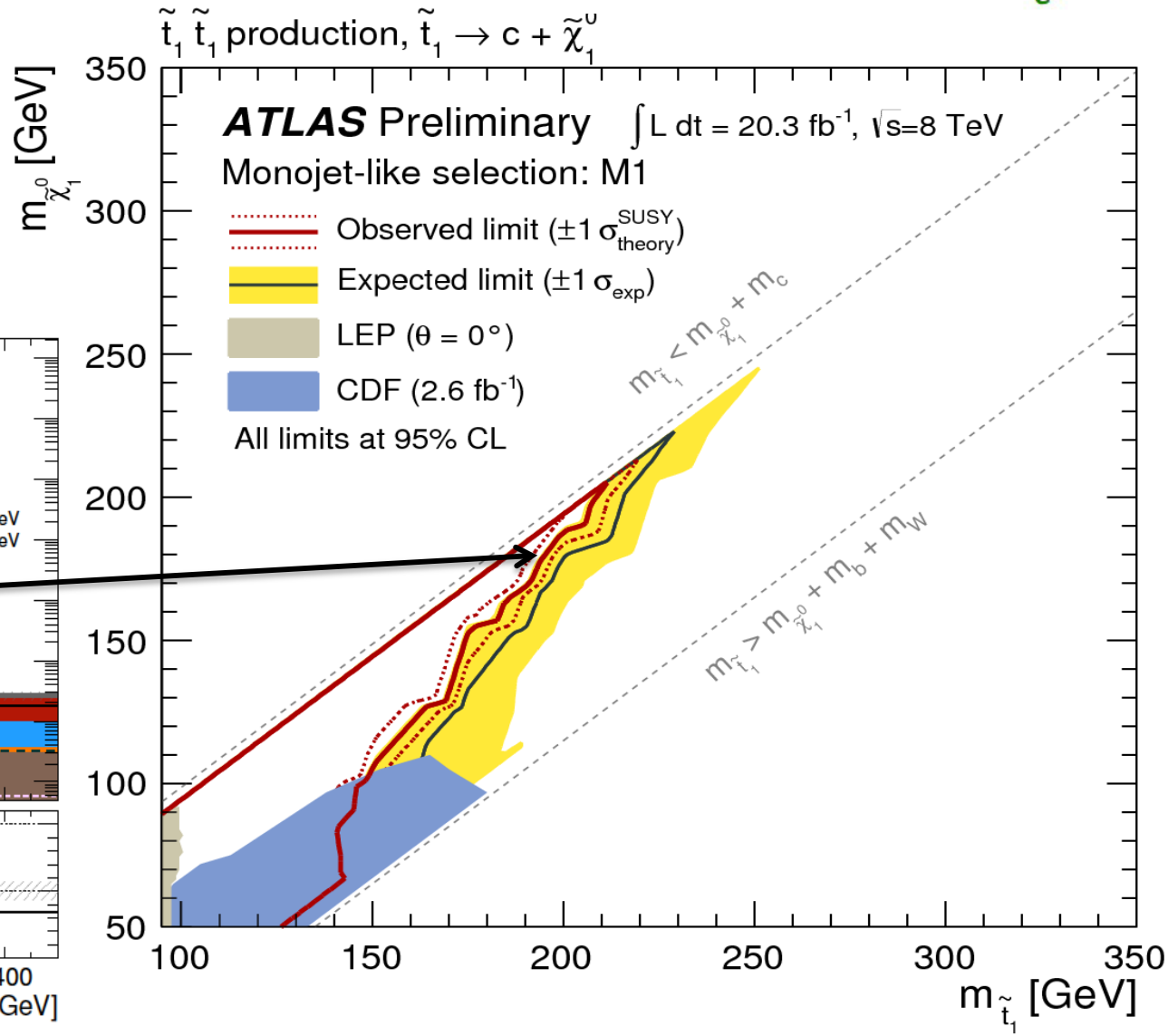
Very light stop



Dedicated monojet analysis
to target compressed scenario

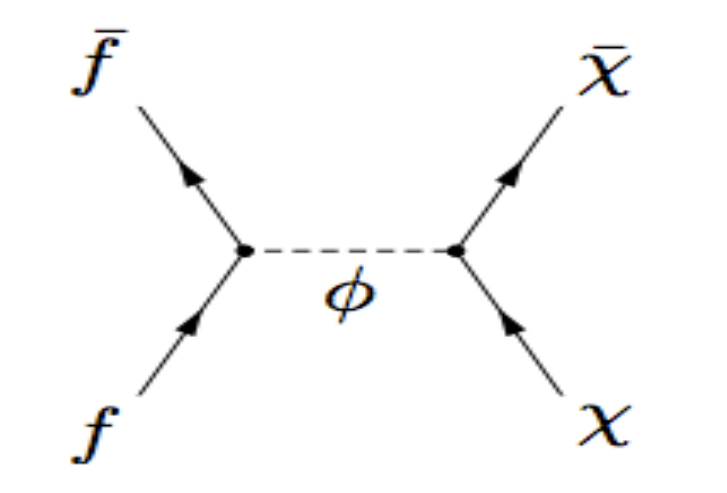
$E_T^{miss} > 220$ GeV
$p_T(j1) > 280$ GeV
$N_{jet}(p_T > 30\text{ GeV}) < 4$
$\Delta\phi(E_T^{miss}, \text{jets}) > 0.4$
Lepton vetoes





Invisible Higgs

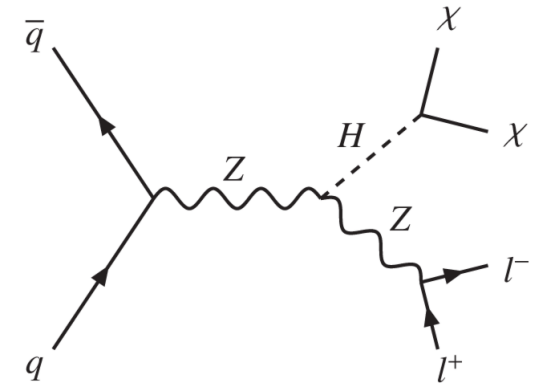
Mono-W/Z



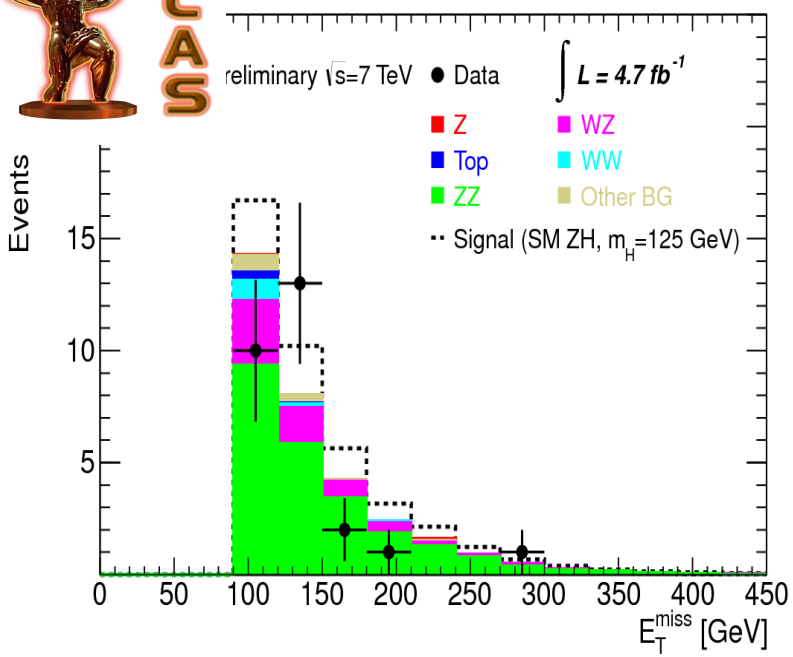
Mono-Z (→ll)

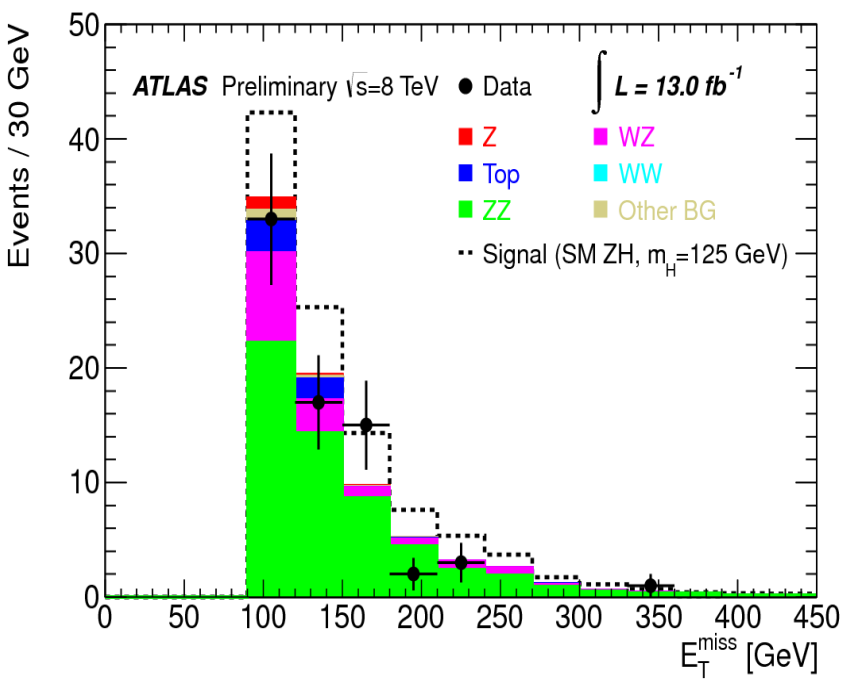
7+ 8 TeV
4.7 + 13.0 fb^{-1}

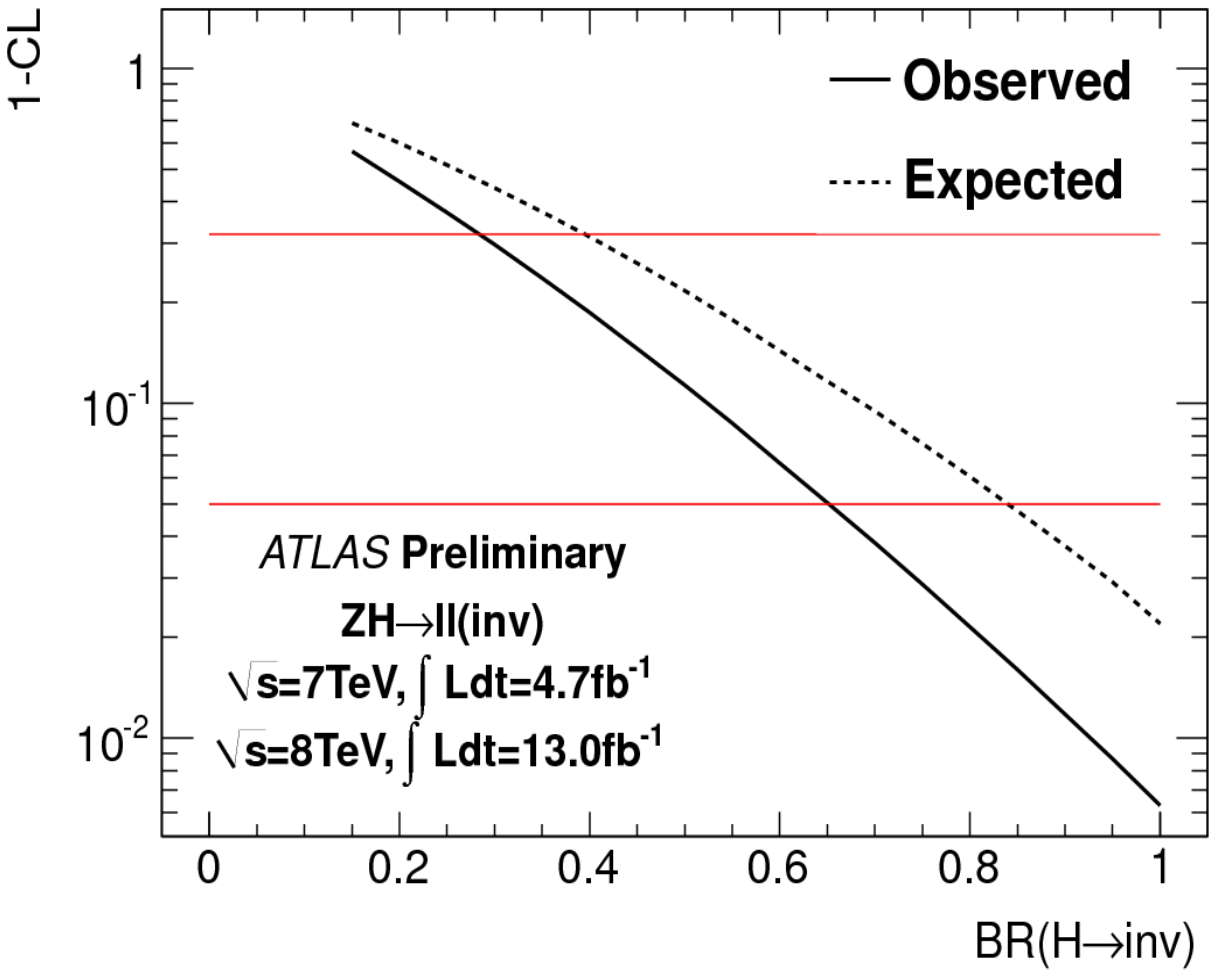
ATLAS-CONF-2013-011



2l + E_T^{miss}







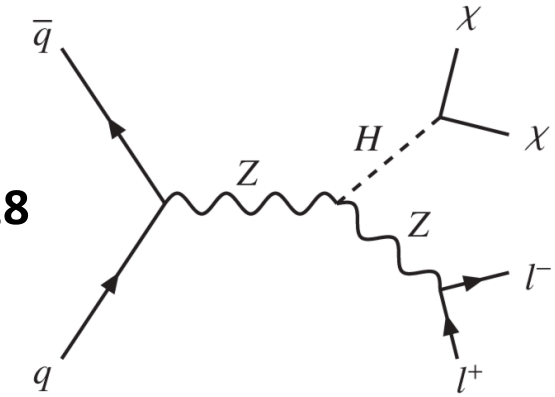
Br (H → invisible) < 65% at 95% CL

Mono-Z (→ll)

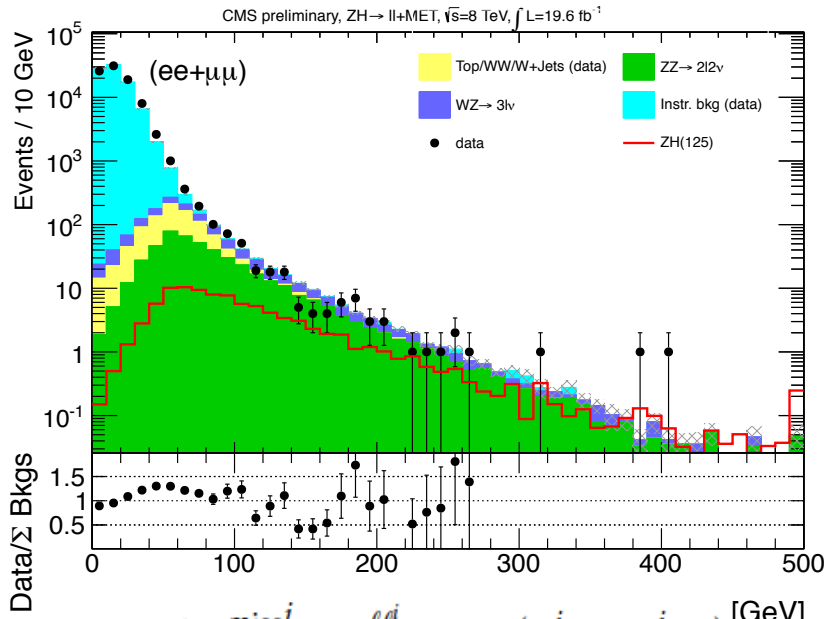
8 TeV

20 fb^{-1}

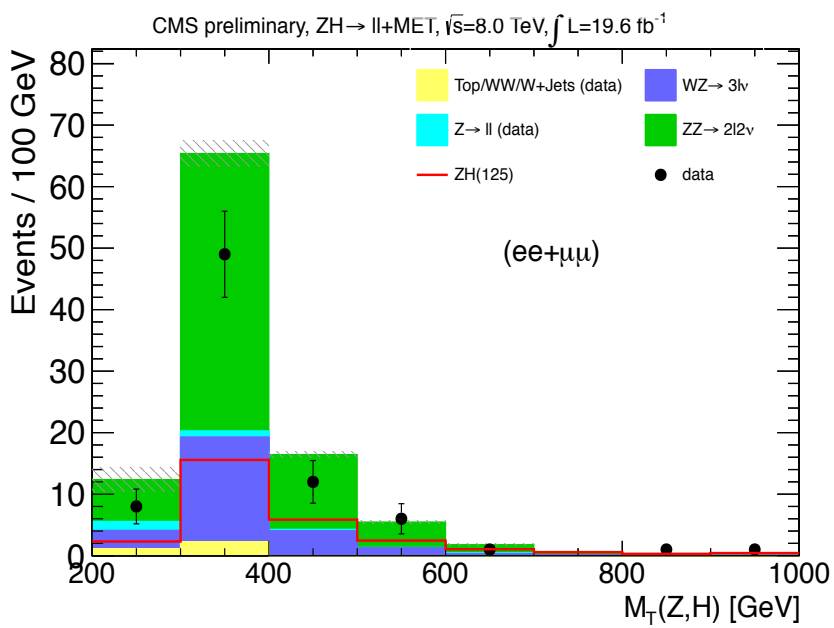
CMS-PAS-HIG-13-018

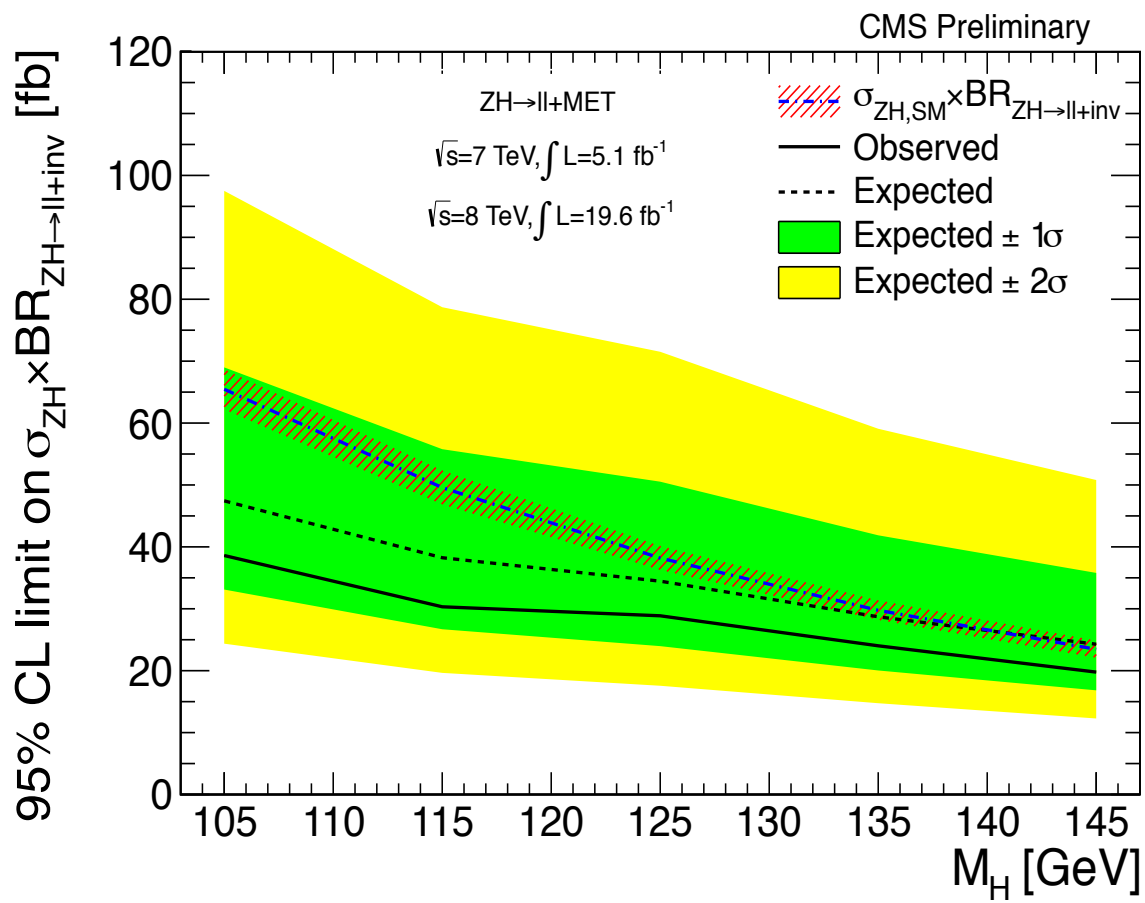


2l + E_T^{miss}



$$\text{red-}E_T^{miss^i} = p_T^{\ell\ell^i} - min(R^i_{clust}, R^i_{uncl})$$





Br (H → invisible) < 75% at 95% CL

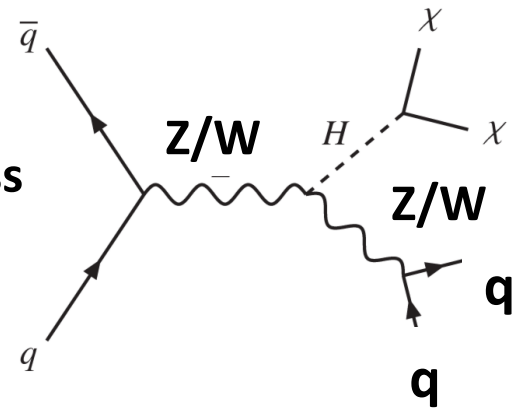
Mono-W/Z (→jj)

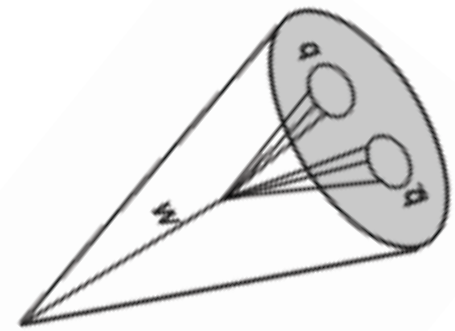
ATLAS-CONF-2013-073

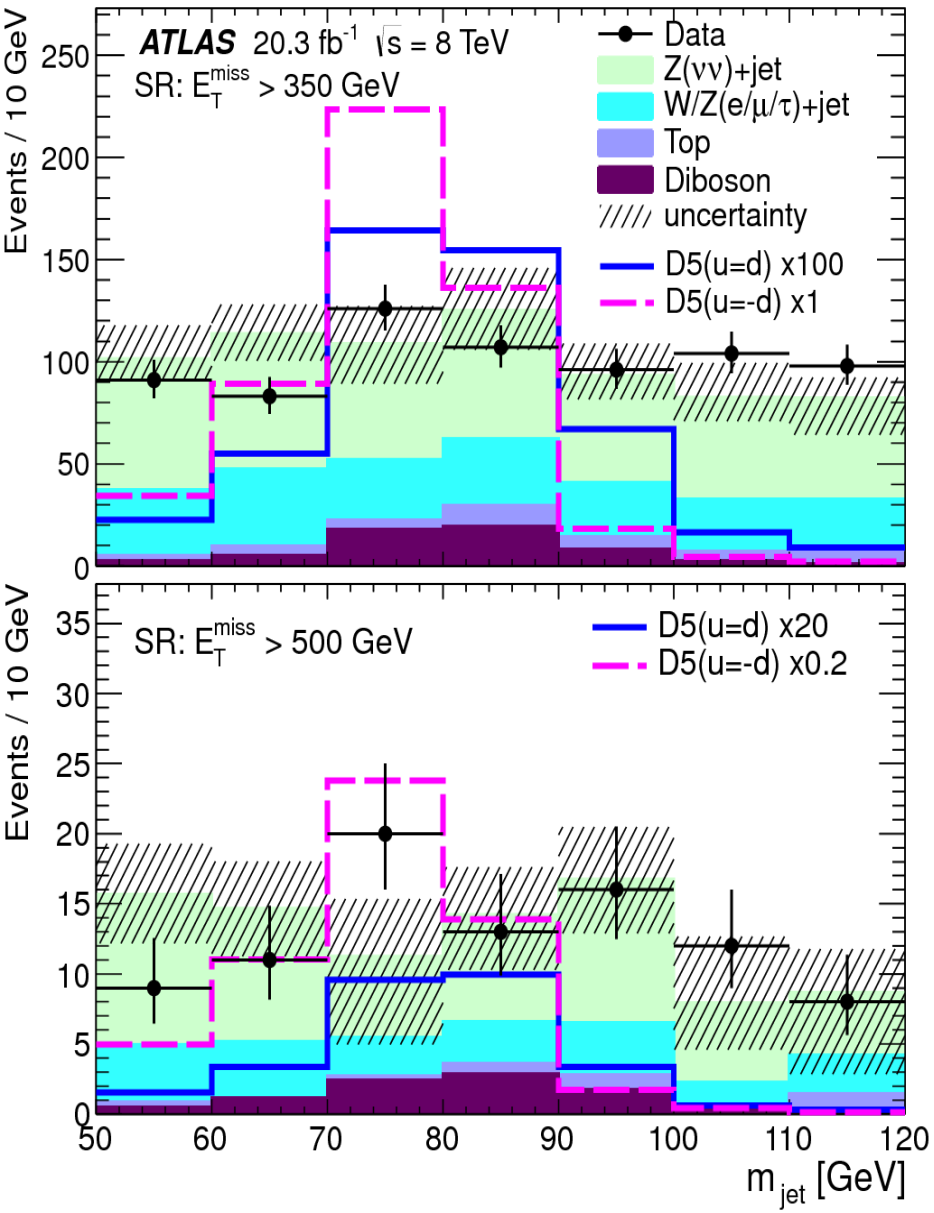
8 TeV

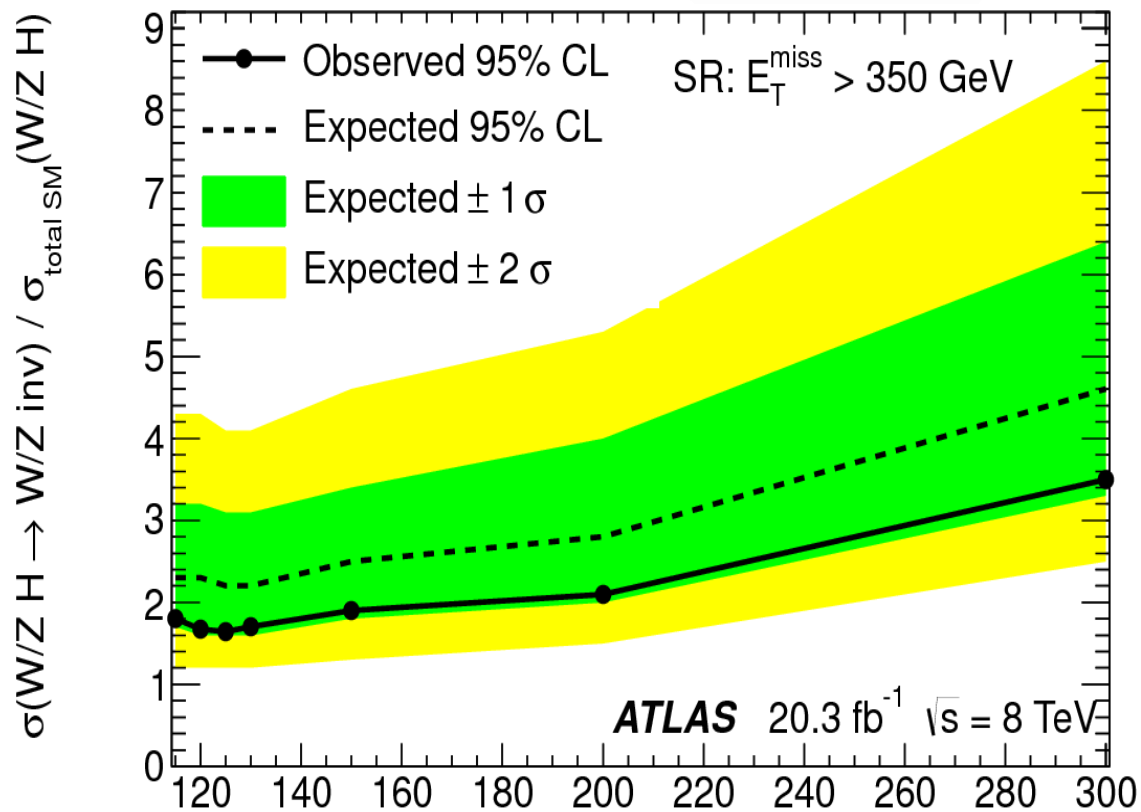
20 fb^{-1}

Mono-W/Z result interpreted
In terms of VH (H→ inv.) process









σ(VH, VH→inv) / σ (VH)$_{SM}$ → 1.6 @ 95% CL
for M_H = 125 GeV

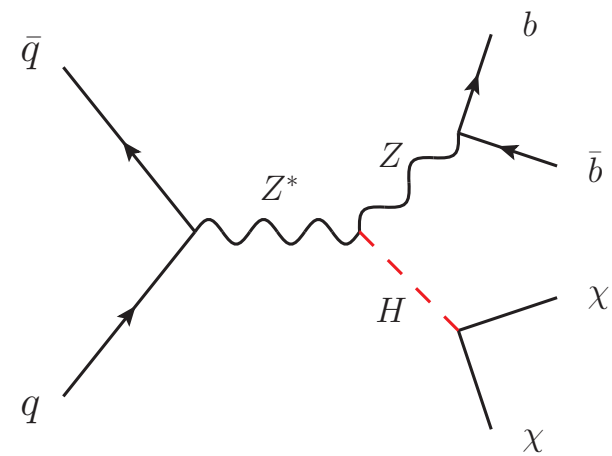
Mono-Z (→ bb)

8 TeV

18.9 fb^{-1}

CMS-PAS-HIG-13-028

Following very closely the CMS ZH (H→ bb) SM analysis



E_t^{miss} bins: (100-130, 130-170, > 170) GeV

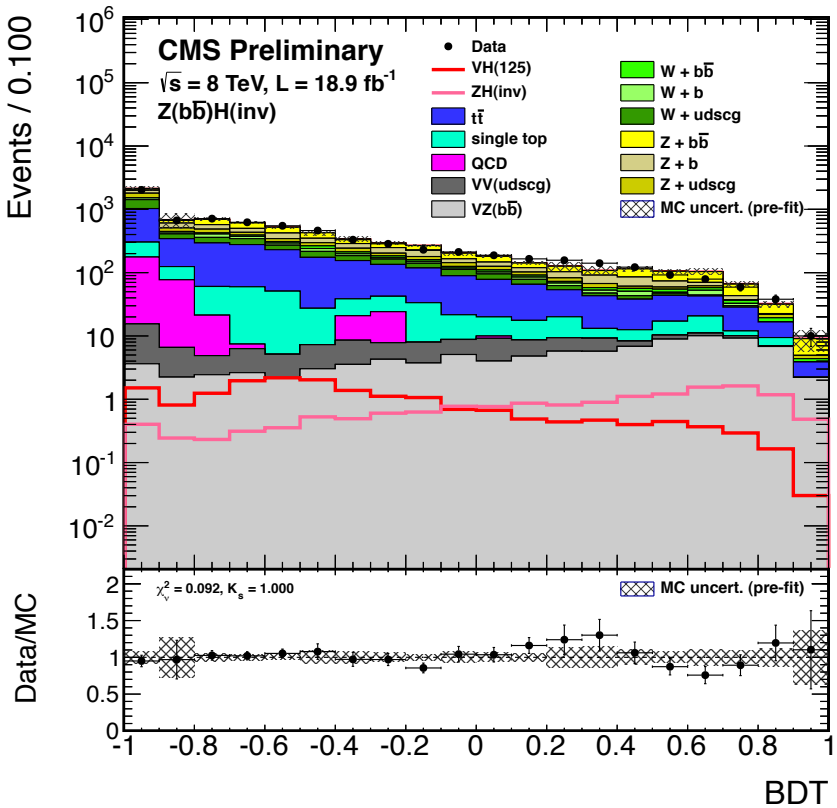
Two b-jets p_T > 25 GeV

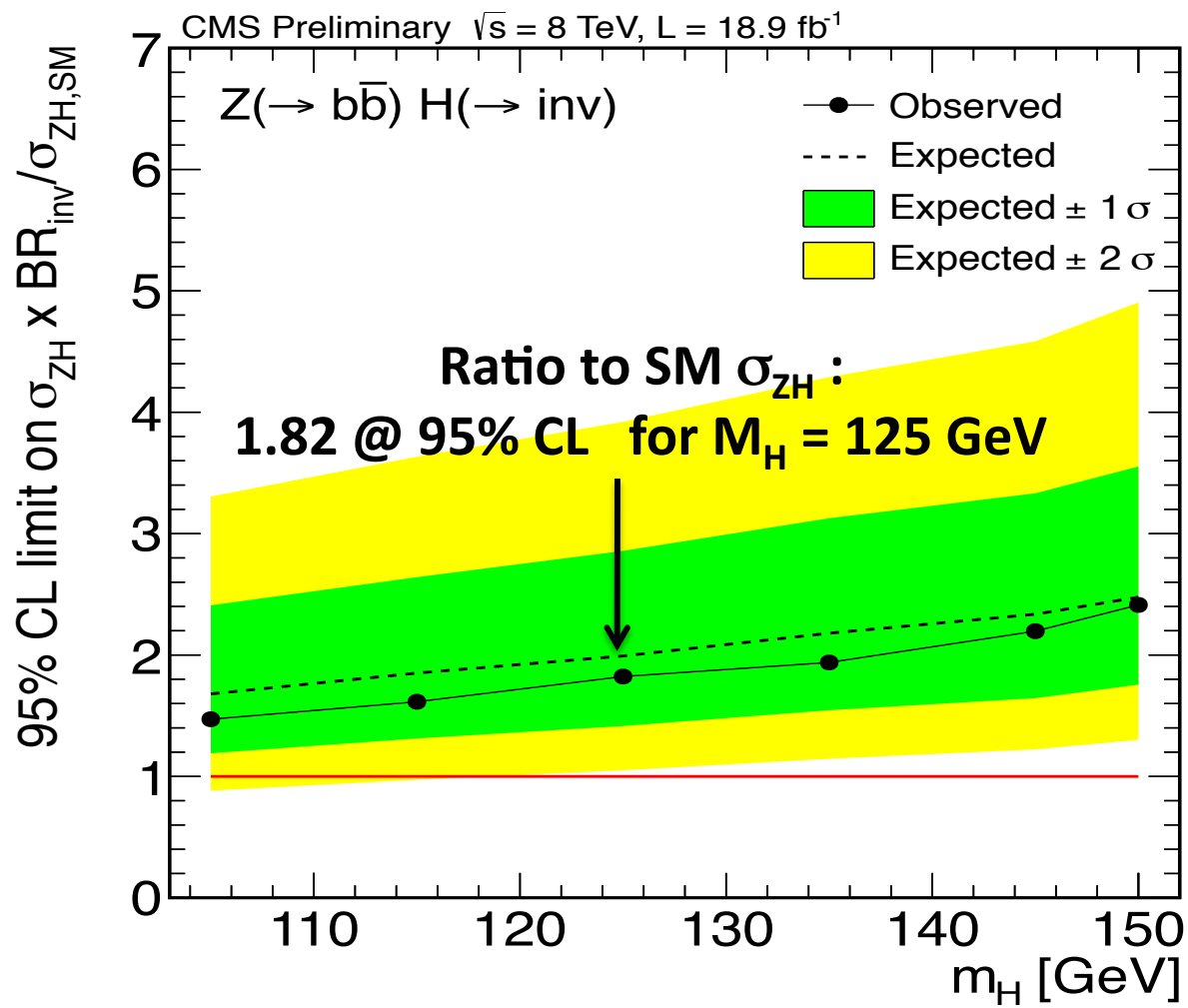
min$\Delta\phi$ (E_T^{miss}, P_T^{miss}) > 0.7 - 0.5

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

Lepton vetoes

Fit to BDT to extract the H→inv signal





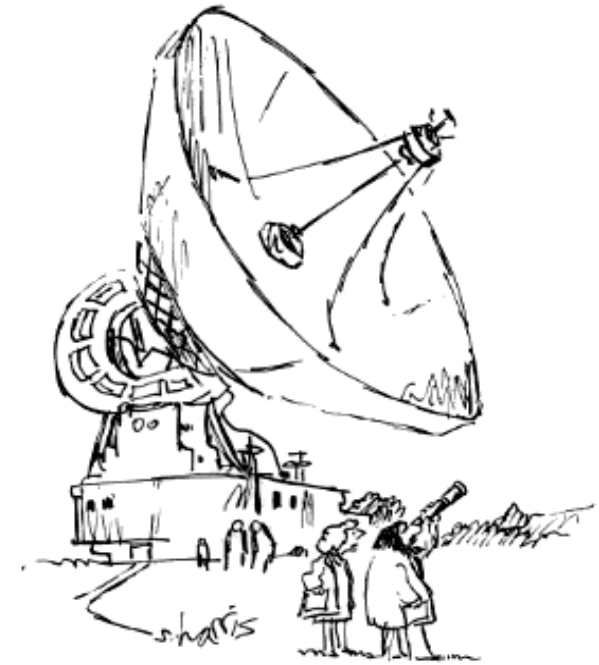
Final Notes

- **Very successful LHC operations during the last 3 years : more than 26 fb-1 of data on tape for ATLAS/CMS (7 TeV & 8 TeV)**

- **Mono-X final states demonstrated to be rather sensitive channels in several searches for physics beyond SM including**
  - ***Dark Matter, Extra Dimensions, SUSY, Higgs…***

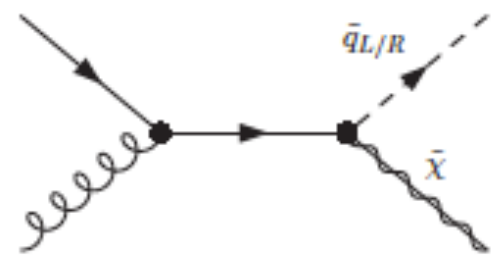
- **Within the effective lagrangian framework the LHC DM searches are rather competitive for low WIMP masses**
  - ***The validity of the EFT approach, the proper comparison with the results from direct detection experiments, the use of simplified models with light mediators, and the Higgs portal, are hot topics in an active field.***

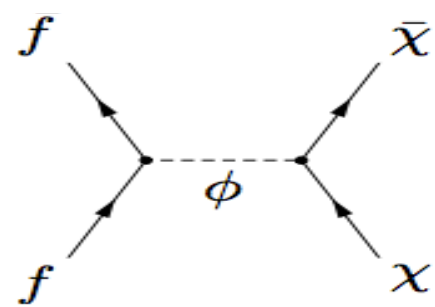
- **Searches continue with the full 2012 dataset but a new discovery might eventually require more energy and more data (coming in 2015)**



"Just checking."

..and more data bring new things and maybe a direct access to DM





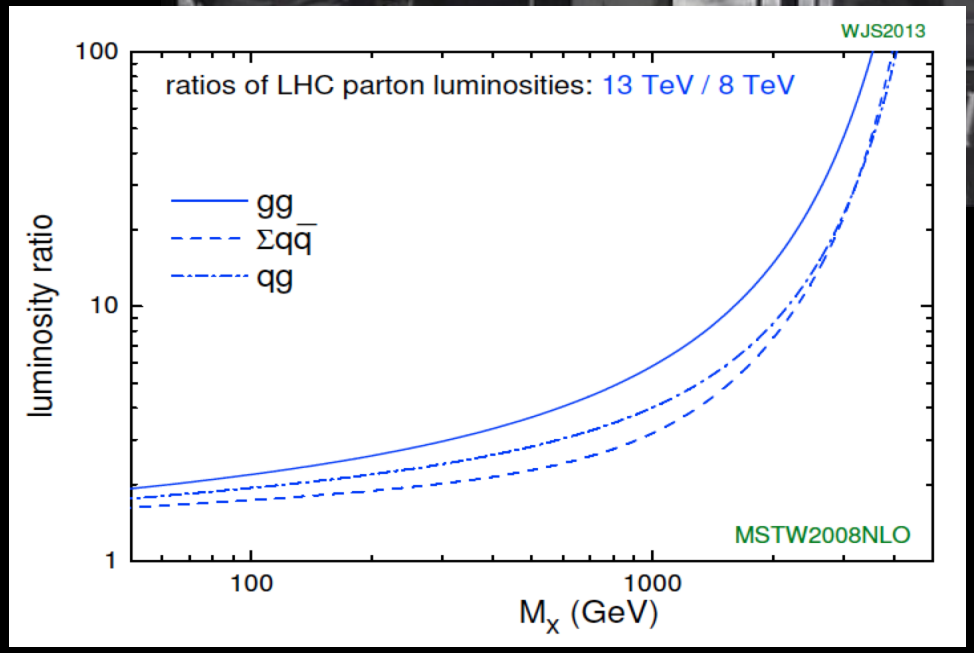
Final Notes

More energy and more data !

El LHC will almost double the centre-of-mass energy in 2015

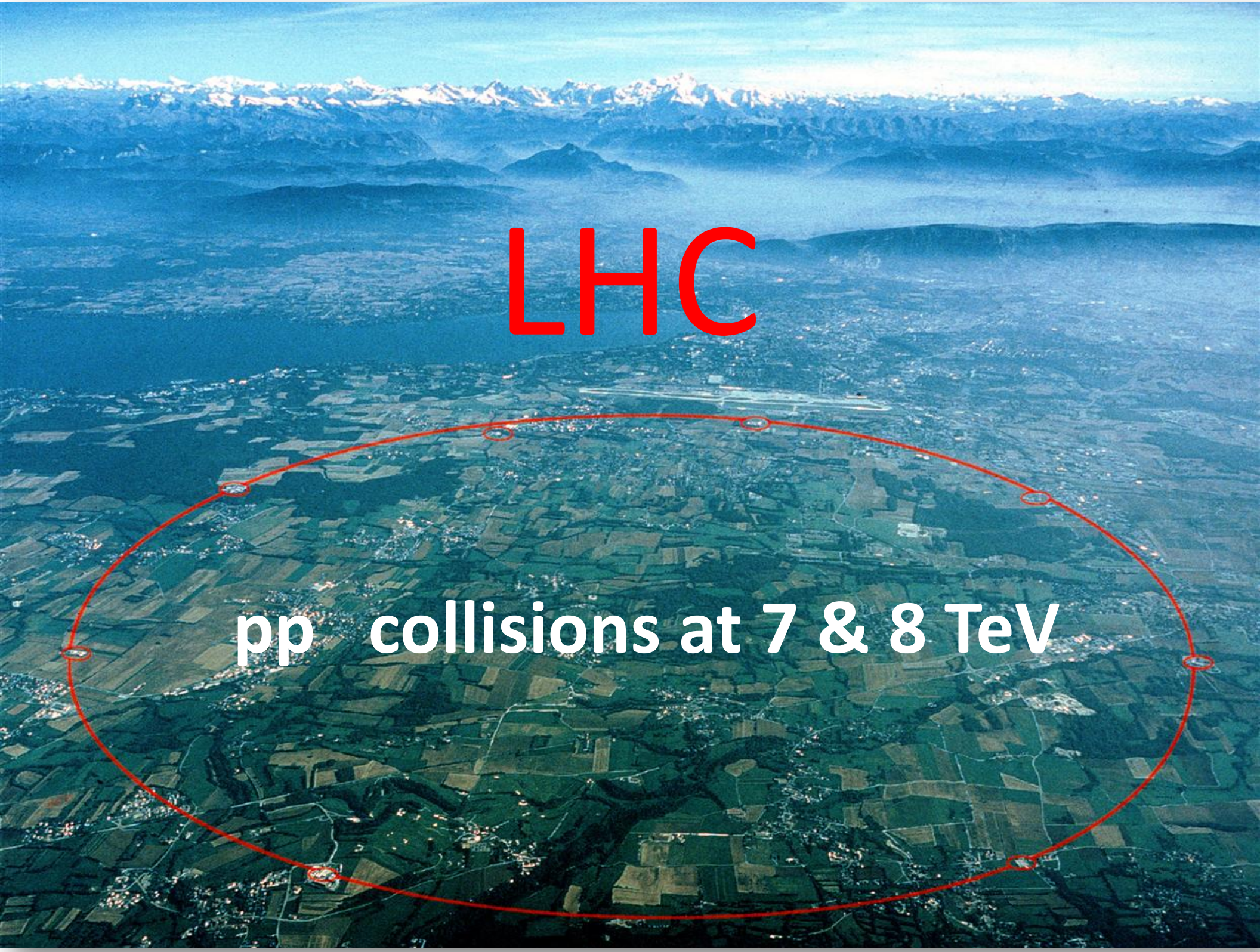
8 TeV → 13 TeV

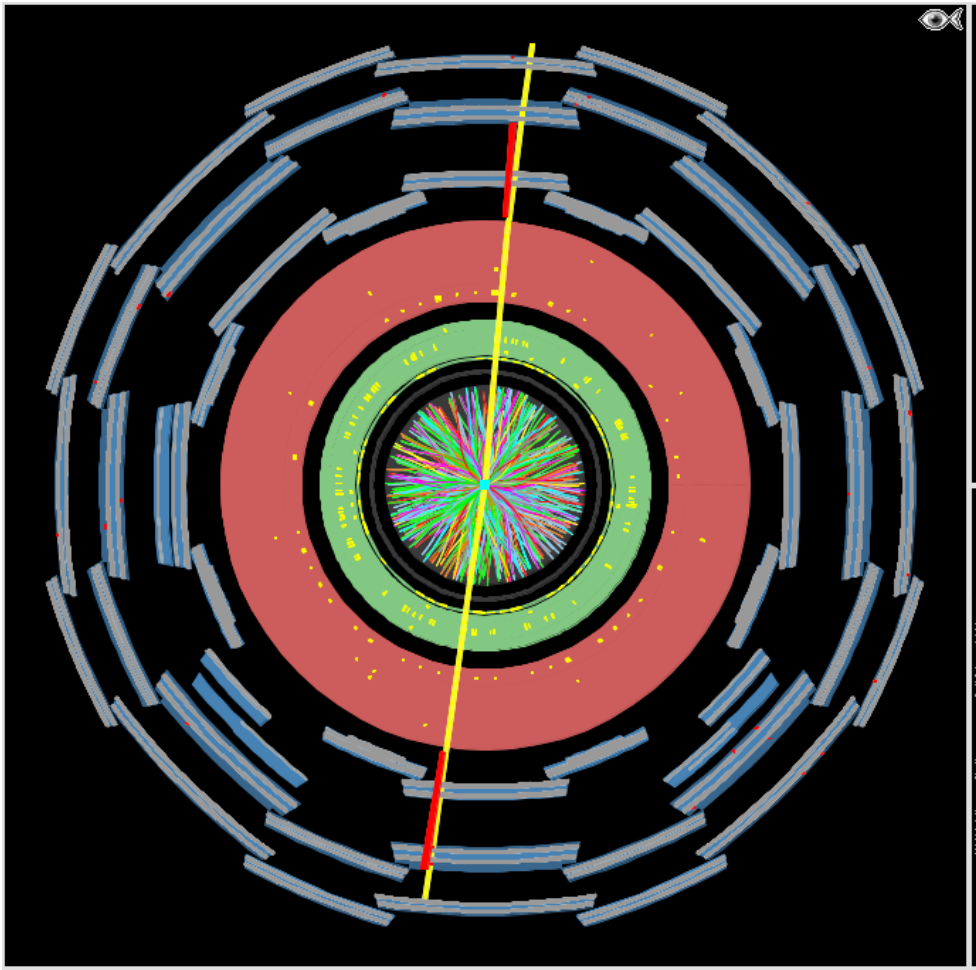
We expect a significant data sample already in 2015 (10-30 fb^{-1}..my guess)

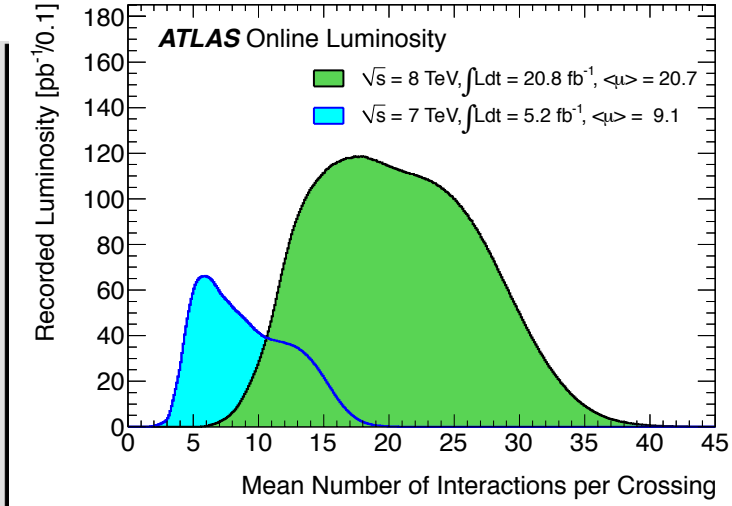


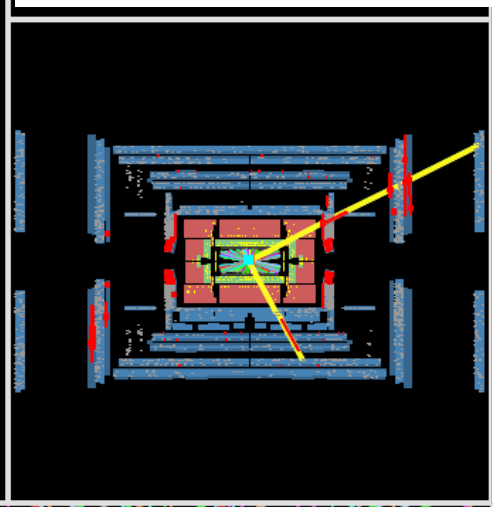
Ready for a new discovery ?

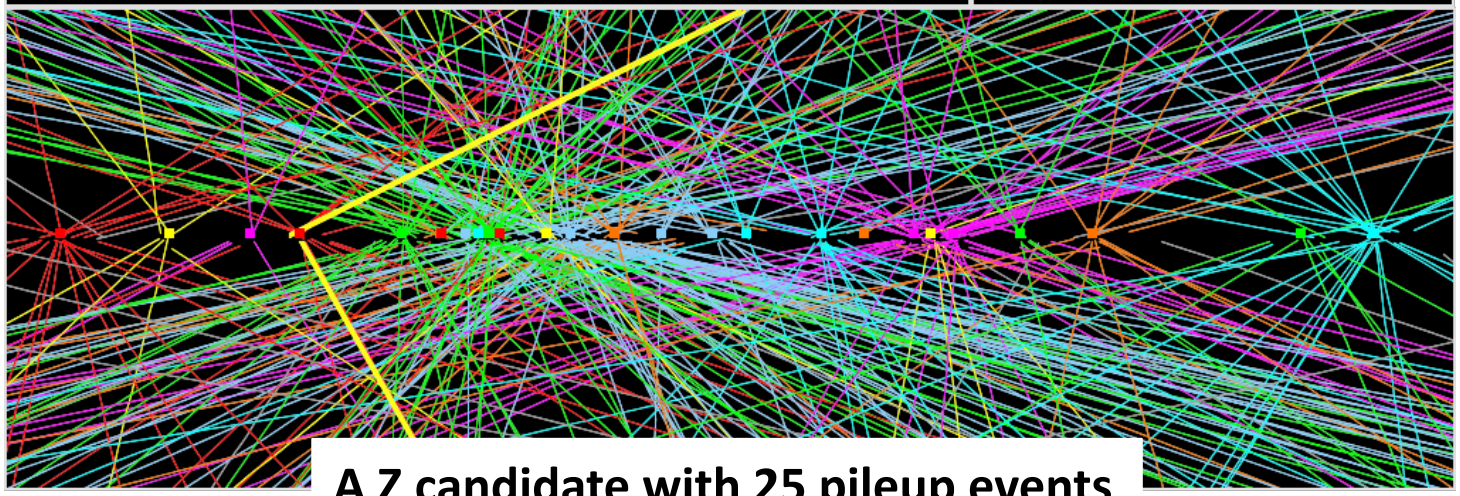
Backup Slides


LHC
pp collisions at 7 & 8 TeV





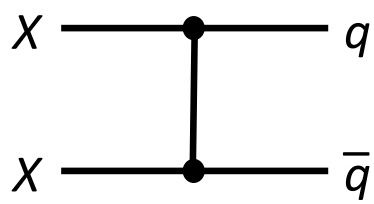




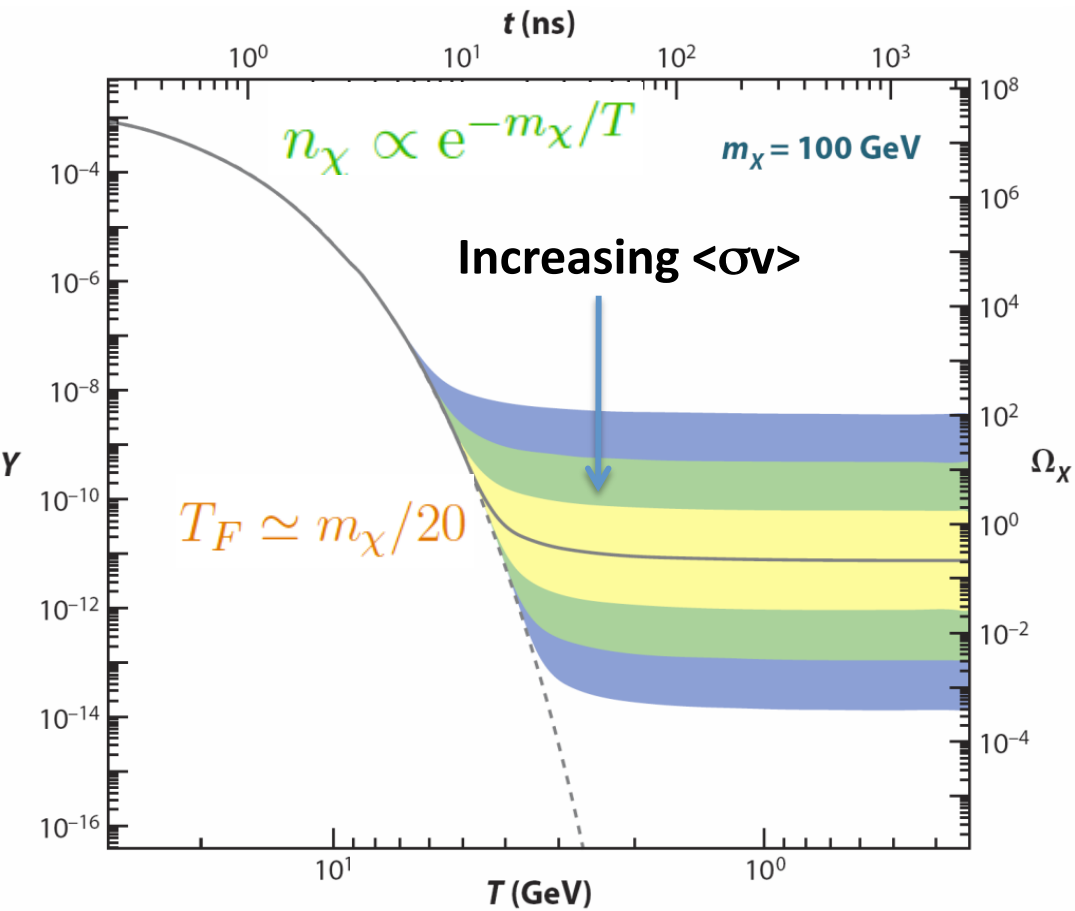
A Z candidate with 25 pileup events

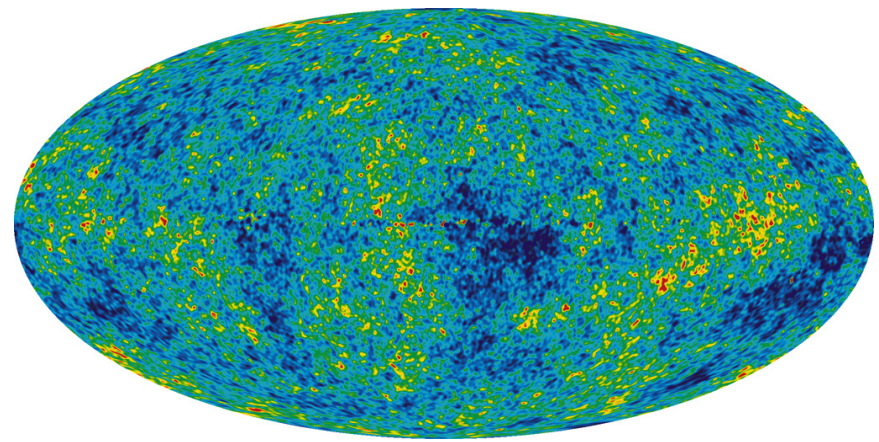
WMAP results

arXiv:1212.5226v2
(January 30th 2013)

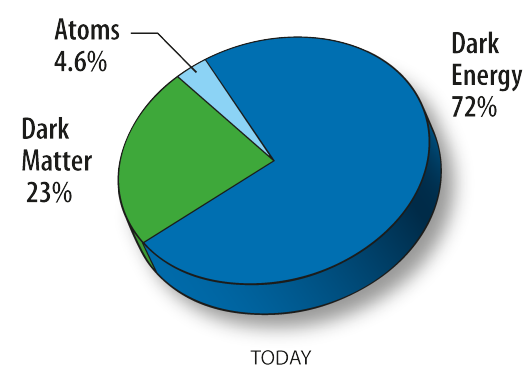


$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$





$$\Omega_\chi h^2 \simeq \frac{0.1\ \mathrm{pb} \cdot c}{\langle \sigma(\chi\chi \to \mathrm{SM}) v \rangle}$$

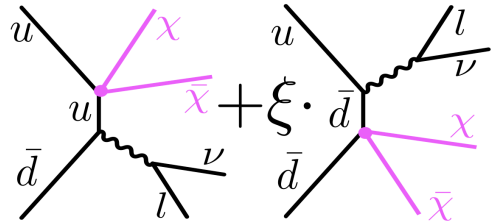


$$\langle \sigma(\chi\chi \to \mathrm{any}) v \rangle \simeq 3 \cdot 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$

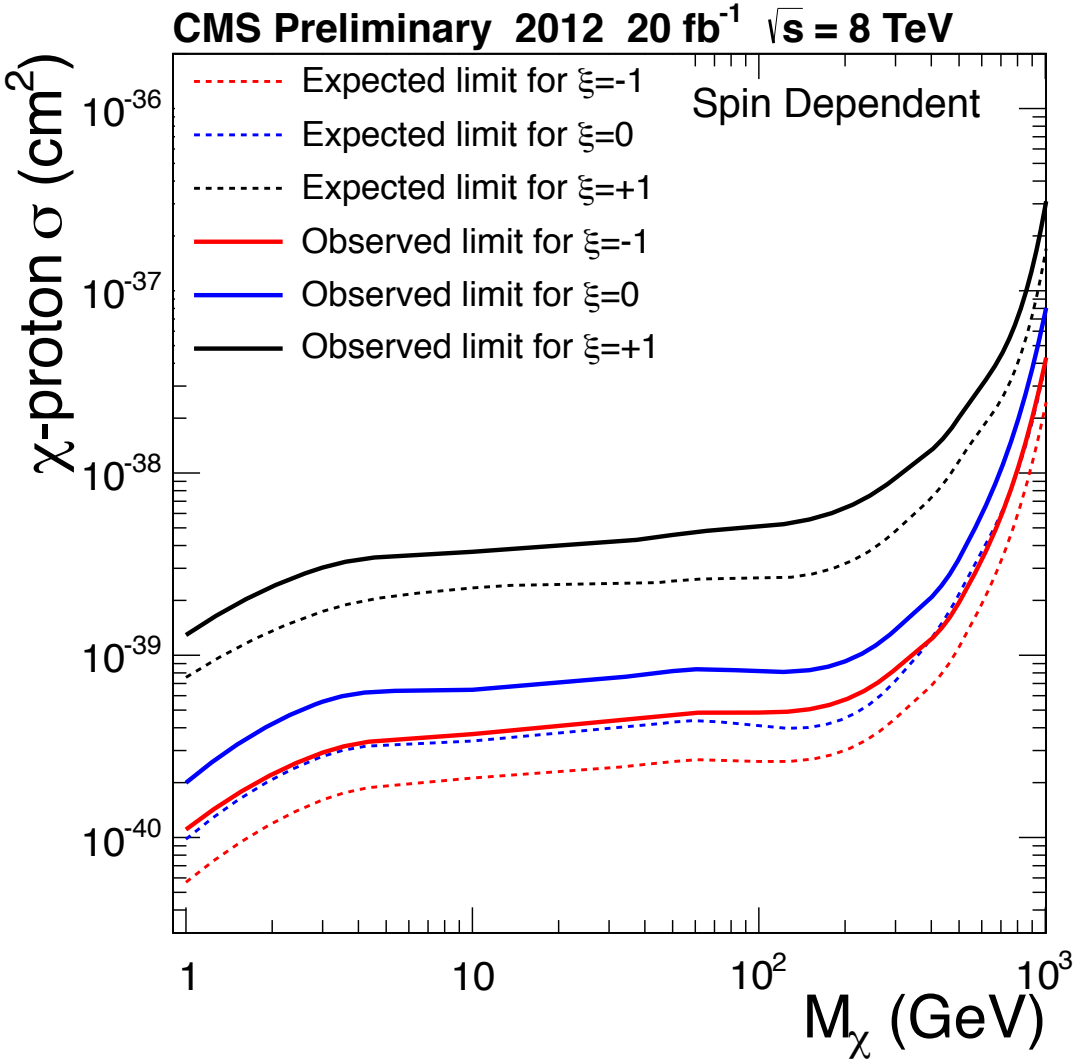
WMAP : $\Omega_{CDM} h^2 \sim 0.1$

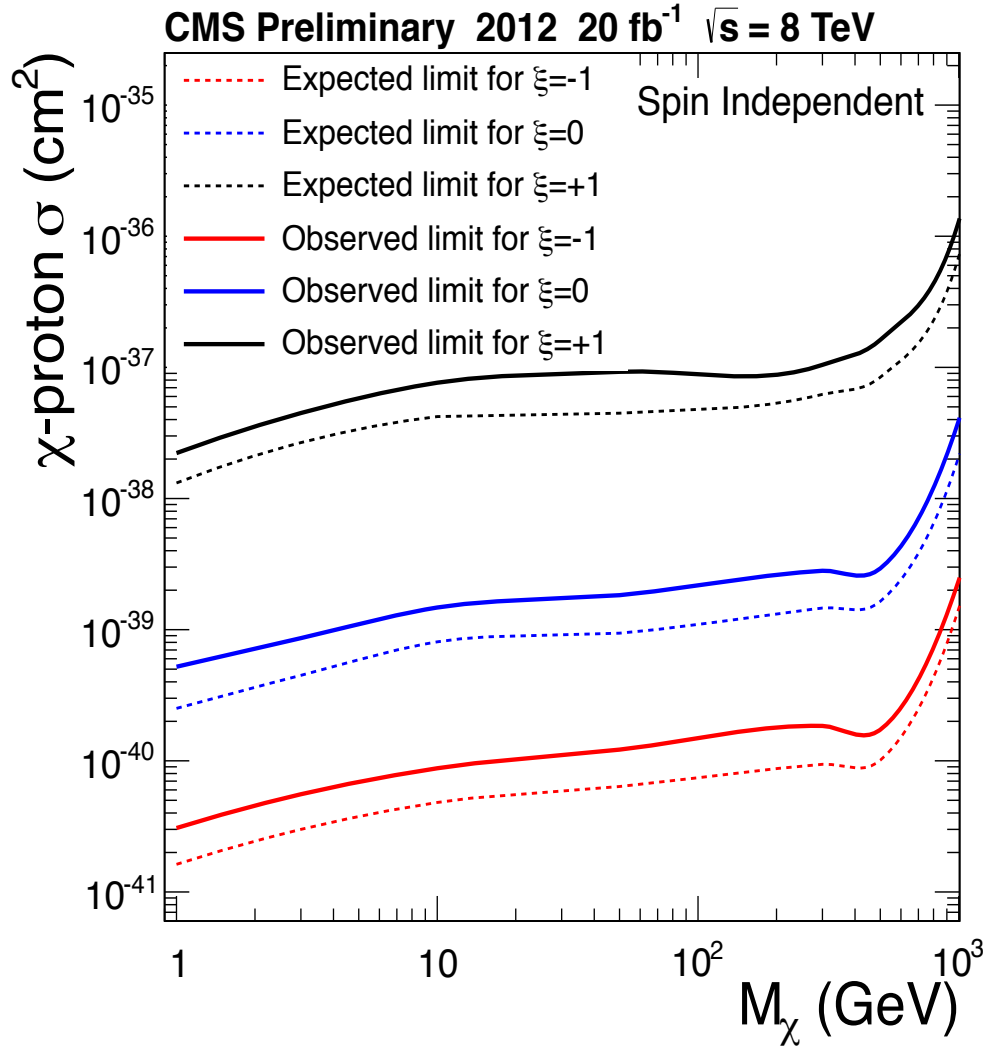
Weak scale for $\chi\chi$ annihilation cross section

Mono-W (90% CL limits)

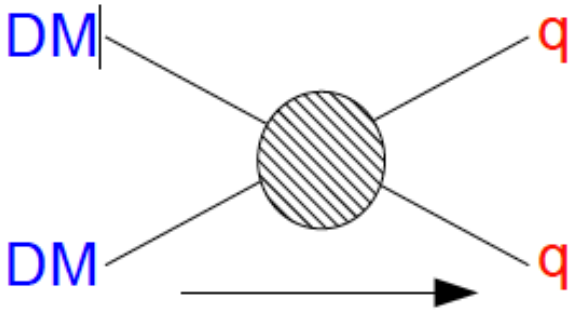


CMS-PAS-EXO-13-004



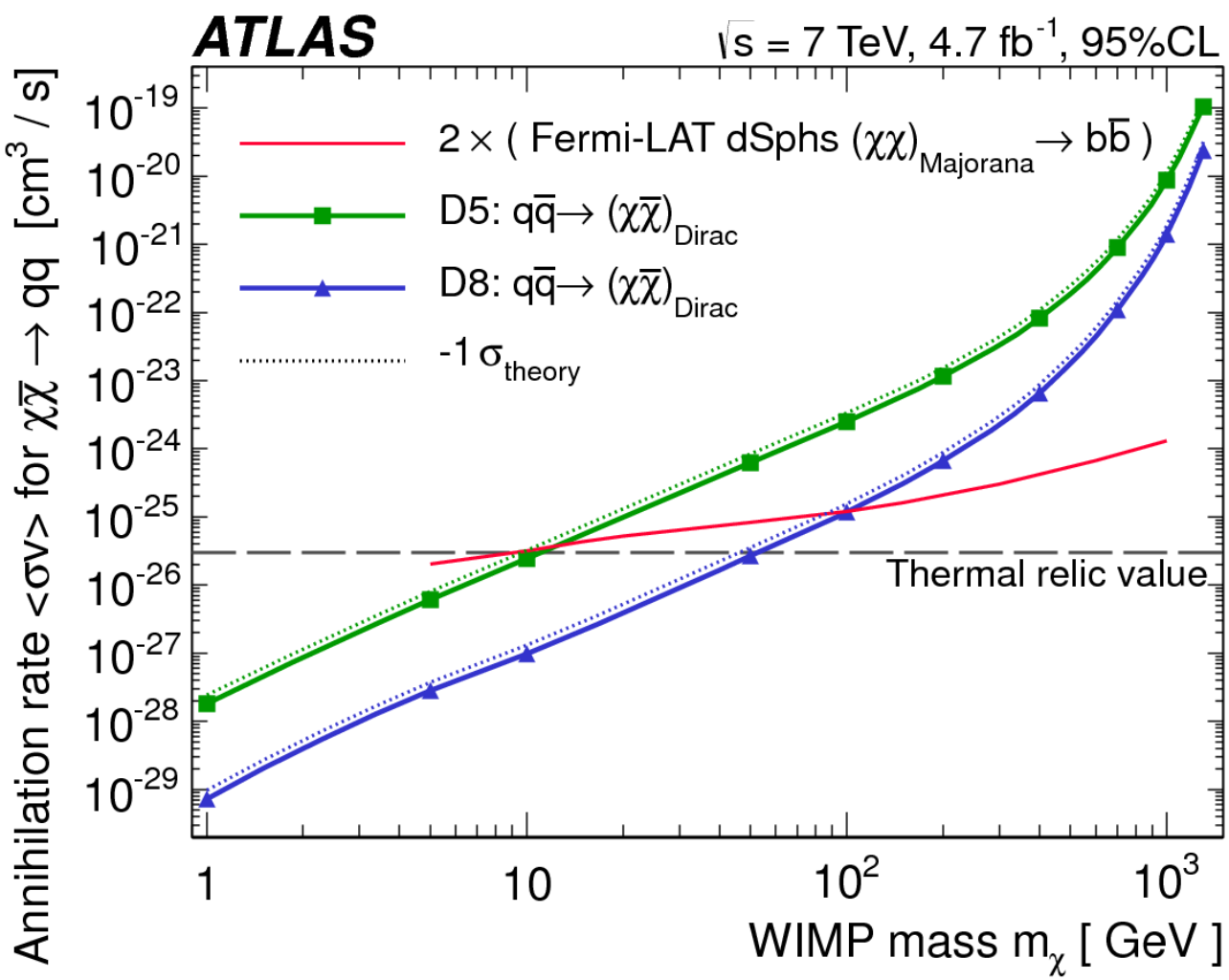


WIMP-WIMP annihilation



$$\sigma_V v_{\rm rel} = \frac{1}{16\pi\Lambda^4}\sum_q \sqrt{1-\frac{m_q^2}{m_\chi^2}}\left(24(2m_\chi^2+m_q^2)+\frac{8m_\chi^4-4m_\chi^2 m_q^2+5m_q^4}{m_\chi^2-m_q^2}\,v_{\rm rel}^2\right),$$

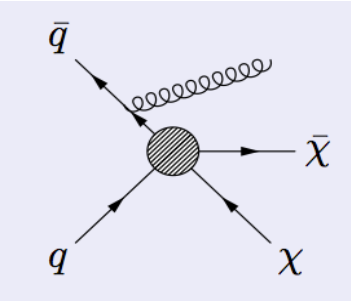
$$\sigma_A v_{\rm rel} = \frac{1}{16\pi\Lambda^4}\sum_q \sqrt{1-\frac{m_q^2}{m_\chi^2}}\left(24m_q^2+\frac{8m_\chi^4-22m_\chi^2 m_q^2+17m_q^4}{m_\chi^2-m_q^2}\,v_{\rm rel}^2\right).$$



Results can be expressed in terms of limits on WIMP-WIMP annihilation cross section (assuming the interaction is dominated by a given operator)

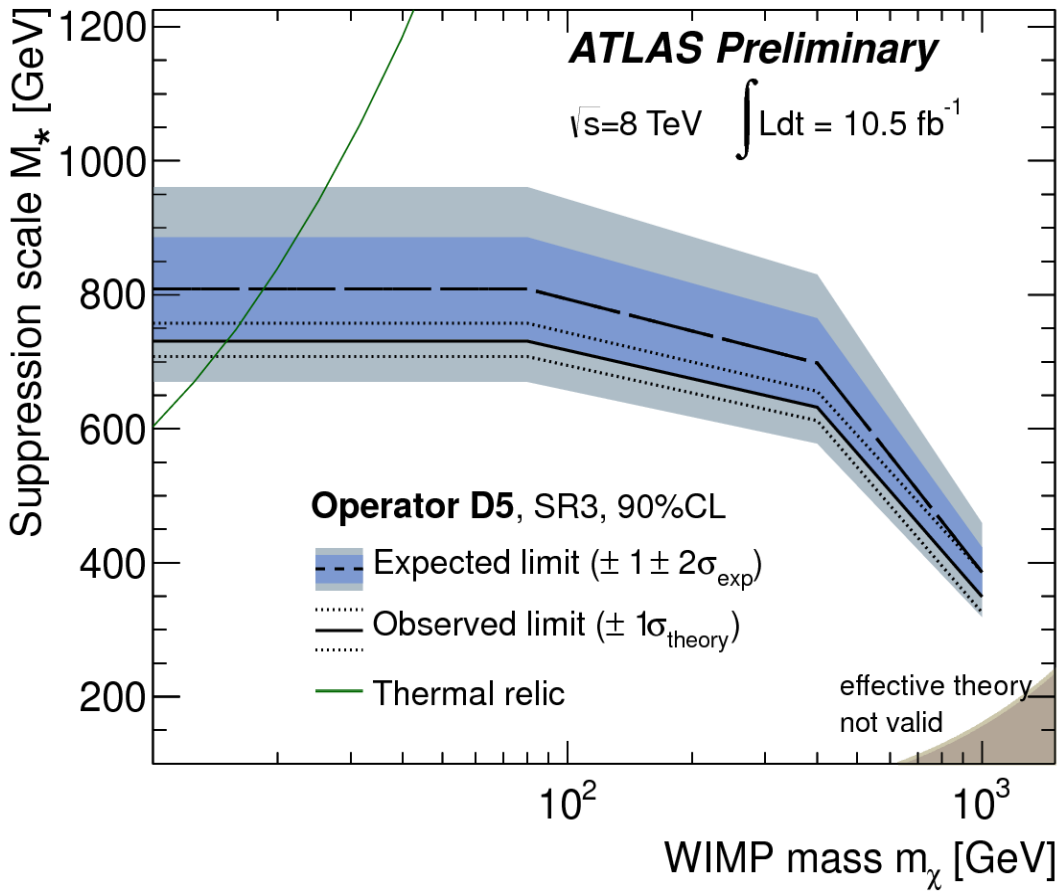
For a given operator, WIMPS are required to have a minimum mass to meet the annihilation rate (and therefore the proper relic abundance)

Alternatively, for light WIMPS more than a single process is needed

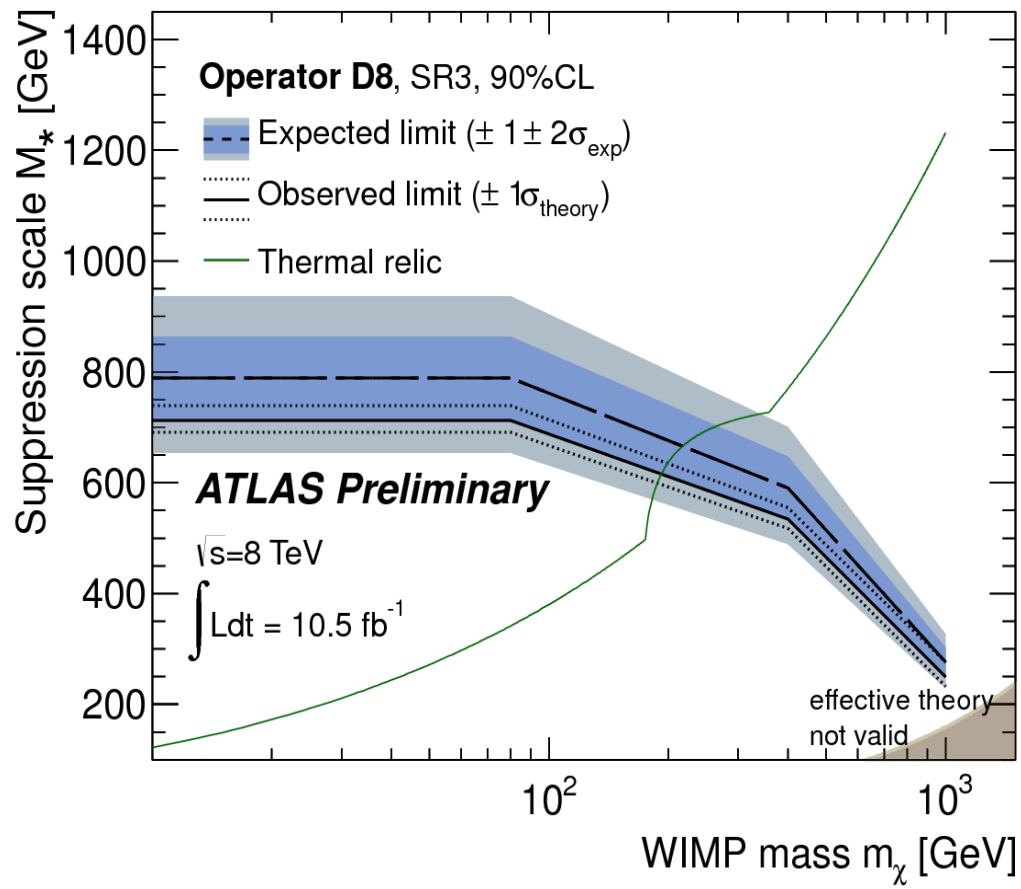


90% CL Limits on suppression scale

VECTOR



AXIAL-VECTOR

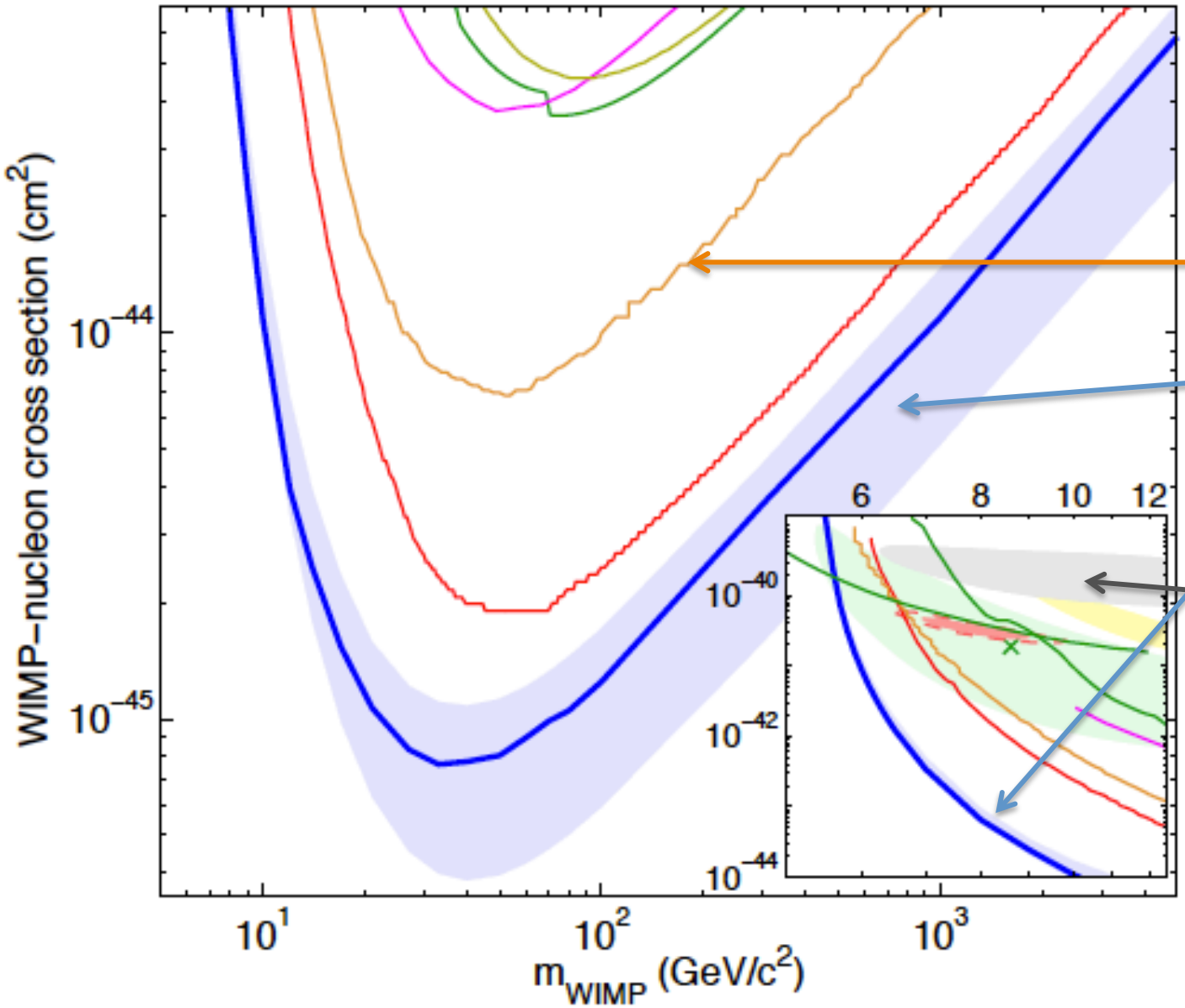


Modest (~10%) improved with respect to 7 TeV limits (due to Backg. MC statistics limitations)

http://arxiv.org/abs/1310.8214

Recent LUX results

minimum 90% CL upper Limit on the cross section of 7.6×10^{-46} cm^2 at a WIMP mass of 33 GeV/c^2



Xenon100

LUX new result

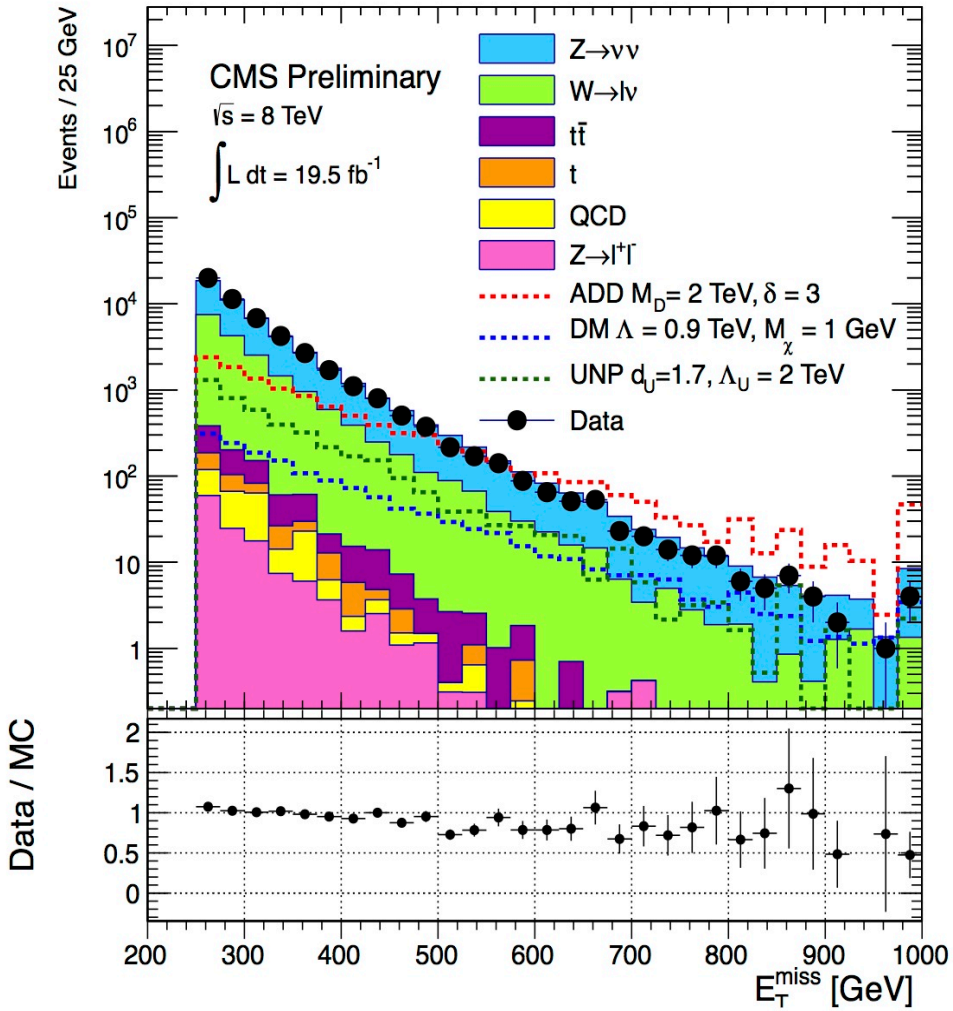
DAMA

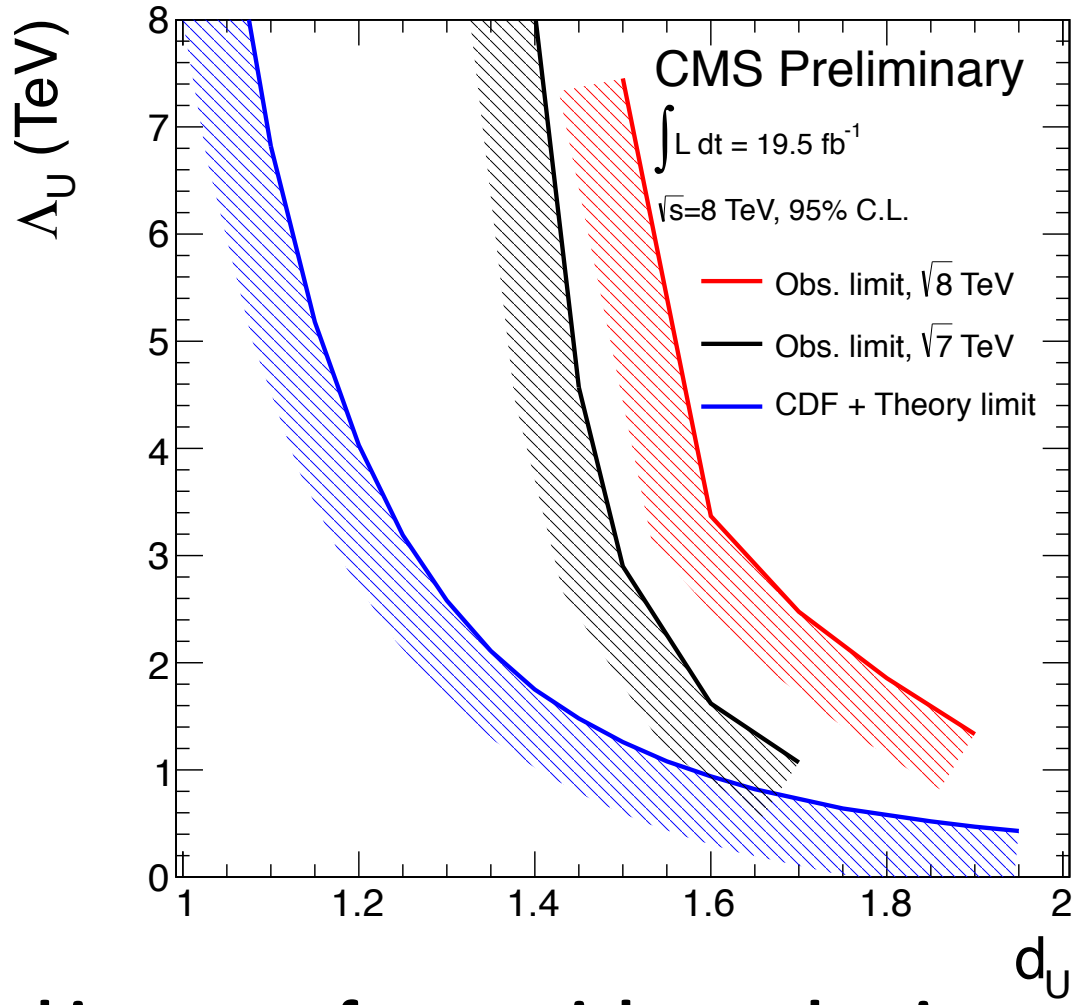
LUX data are in strong disagreement with low-mass WIMP signal interpretations

CMS-PAS-EXO-12-048

Unparticles

Howard Georgi,
Phys Rev Lett. 98, (2007) 221601.





Monojet results also interpreted in term of unparticle production

Limits are set in the scale dimension (d_U) vs mass scale (Λ_U) plane