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Searches for Dark Matter and Extra Dimensions with the ATLAS detector

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On Behalf of the ATLAS Collaboration

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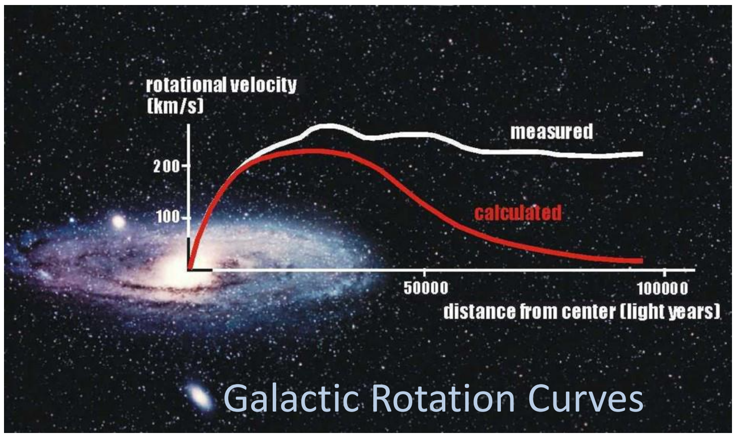
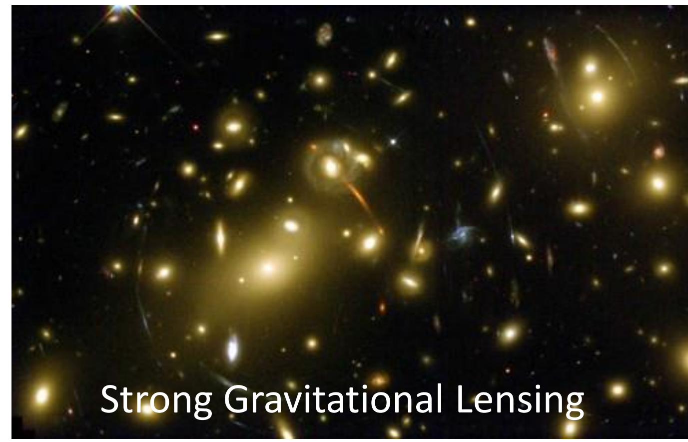
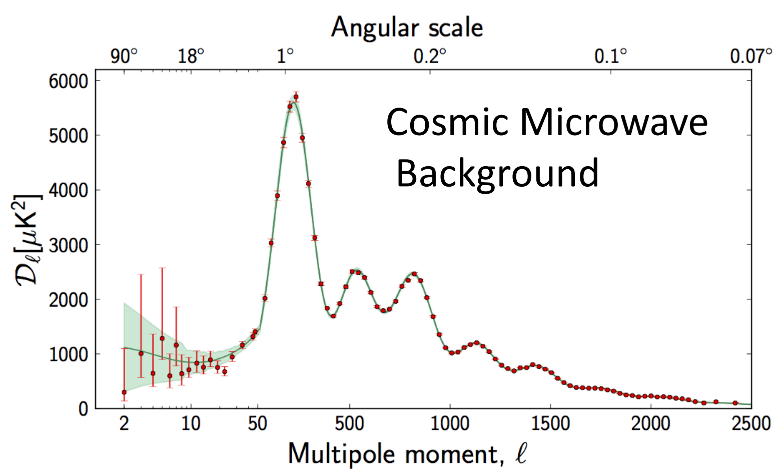
Dark Matter Motivations

- Numerous astrophysical observations of galaxies, gravitational lensing and cosmic microwave background indicate that **26.8%** of the energy density (**84.2%** of the mass) of the universe exists as **Dark Matter**, **detectable (so far) only by gravitational effects**.

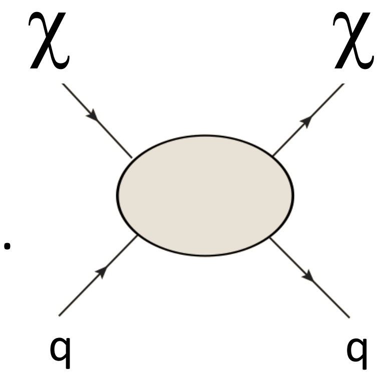




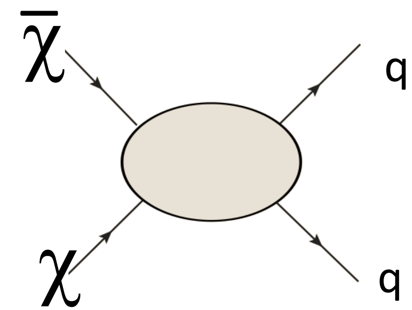


Non-Gravitational Dark Matter Detection

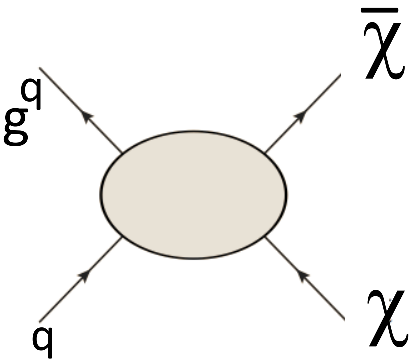
- **Direct detection from astrophysical sources:**
  Nuclear recoil from DM particle interactions
  Experiments: LUX,DAMA,COGENT/LIBRA08,CDMS…



- **Indirect astrophysical detection**
  Search for products of **WIMP annihilation**
  Cosmic-ray observations: HEAT, PAMELA, AMS…
  DM WIMP-WIMP annihilation to SM particles



- **Production of Dark Matter in LHC collisions**
  Model-dependent signatures typically involving missing energy with trigger/tag particles

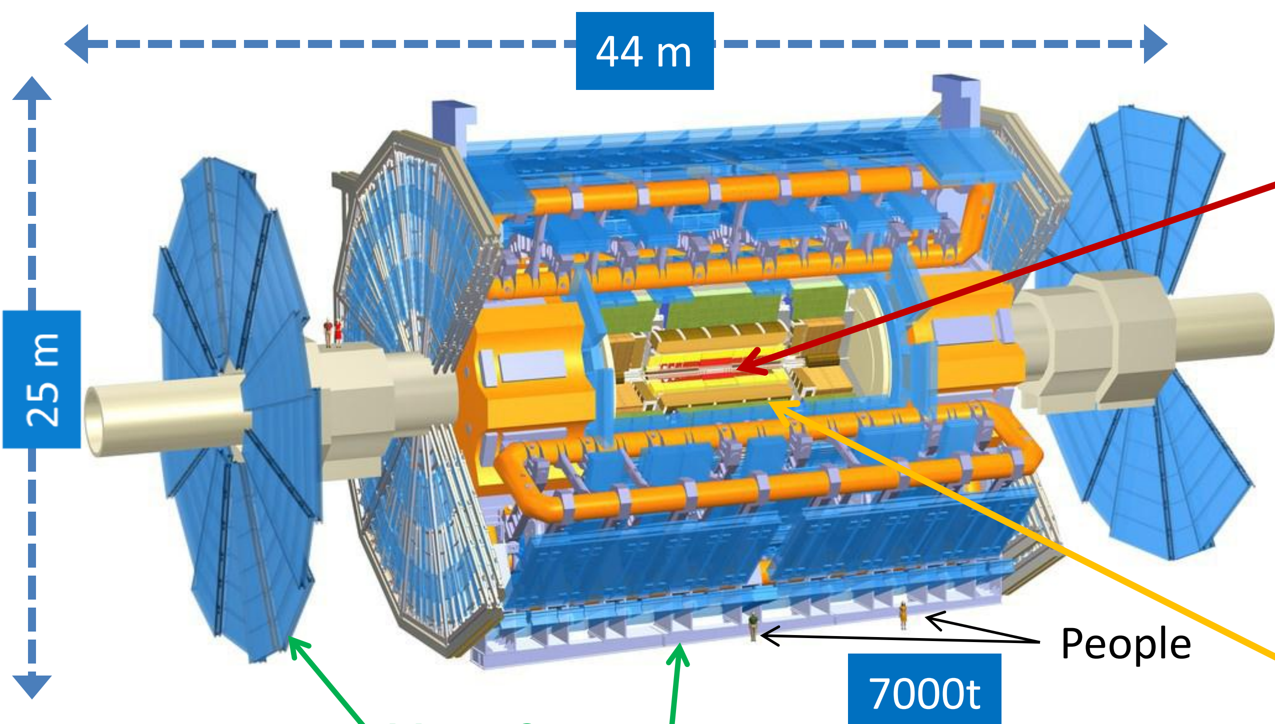


Known Dark Matter Properties

1. It's electrically **neutral**, since it does not produce photons.
2. It's **stable**, or at least has a lifetime on cosmological scales.
3. It's **non-baryonic**, to preserve the success of CDM.
4. It's density (**relic abundance) is consistent with weak scale** mass and interactions.

- The best candidate for dark matter is a new type of particle with weak-scale interactions – the so-called **WIMP** (**W**eakly **I**nteracting **M**assive **P**article).
- WIMPs with mass between **1-100 GeV** would have significant relic densities from the Big Bang and hence would be cosmologically significant dark matter.
- Particle physics theory provides many possible WIMP-like particles (potentially a whole sector) which may be produced at the LHC.
- If the Dark Matter is a yet-undiscovered particle, not only is it possible the LHC is producing it but ATLAS could be measuring it; **we need to look carefully!**

ATLAS Experiment



JINST 3 (2008) S08003

Inner Detector:

- 2T solenoid
- Silicon pixel & strip detectors
- Transition radiation tracker
- Interaction vertex
- |η| < 2.5
- Several hundred tracks per collision

Muon Spectrometer:

- 0.5-1T torroidal magnetic field
- Resistive Plate Chambers & Thin Gap Chambers for trigger
- Monitored Drift Tubes & Cathode Strip Chambers measure sagitta
- Δp/p 3% @ 100 GeV rising to 10% at 1TeV
- |η| < 2.7

Calorimeters:

- Liquid argon electromagnetic calorimeter
- Tile hadronic calorimeter
- |η| < 4.9
- 9.7 interaction lengths at η=0

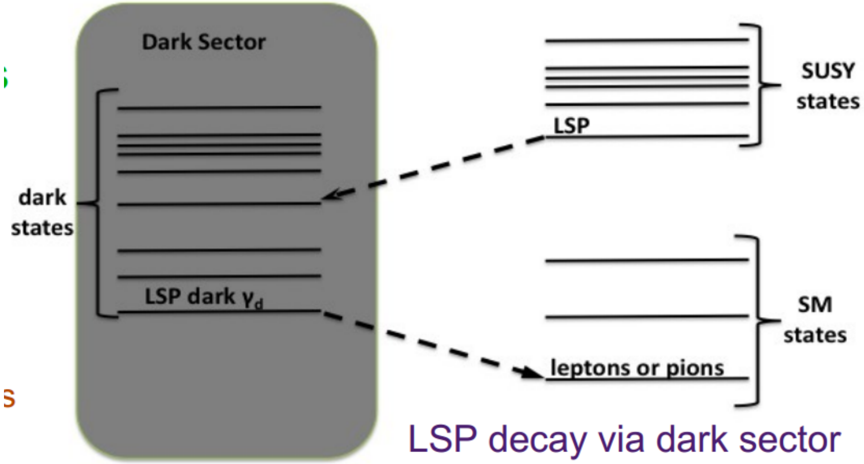
ATLAS Exotic Searches in This Talk

- Lepton-jet signatures
  - Search for dark-sector particles; set limits on x-sect x BR
- Searches with large missing transverse momentum plus ‘X’:
  - Mono-jet
  - Mono-photon
  - Mono-W/Z
- Other related topics
  - Extra-dimensions (ADD, RS)
  - Searches for microscopic black holes (Semi-classical, Quantum)

Lepton-Jets from Dark Matter

PLB 79, 599, arxiv1212.5409

- **Lepton-jets are bundles of tightly-collimated, high-pt leptons – unique experimental signature.**
- Lepton-jets result from dark matter models motivated by astrophysical observations (such as possible e+/e- excess in cosmic rays) and combine SUSY with a Hidden Valley ("Dark Sector").
- SUSY LSP may decay to dark sector particles ending in light, highly-boosted dark photons which decay into lepton pairs.
- Dark photon mass < 2 GeV preventing decay to protons (since no cosmic p-bar excess has been observed)
- **Signatures considered:**
  - Single muon-jet with ≥ 4 muons
  - Pairs of muon-jets with ≥ 2 muons each
  - Pairs of electron-jets with ≥ 2 electrons each



LSP decay via dark sector in a Hidden Valley model

Lepton-jet Results

Phys. Lett. B 719 (2013) 299-317

- Used model from **arXiv:0909.0290** with main parameters dark sector gauge coupling, $\boldsymbol{\alpha_d}$ and dark photon mass $\mathbf{m_{\gamma D}}$
- **No excess over SM background seen** and set limits on cross section x branching ratio for several values of $\boldsymbol{\alpha_d}$ and $\mathbf{m_{\gamma D}}$

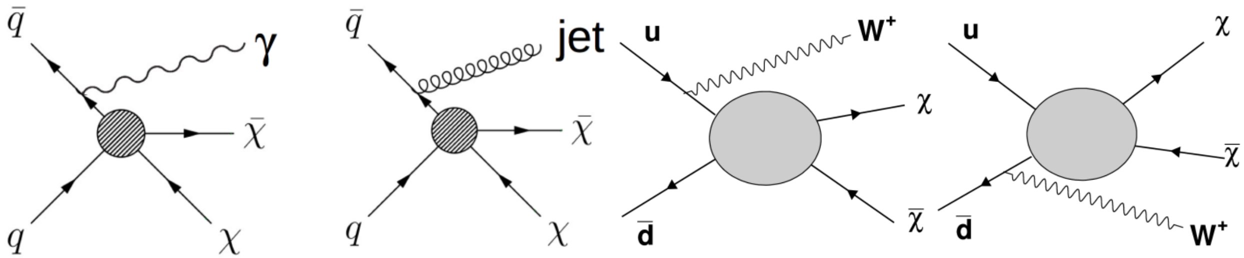
.

Signal Parameters α_d	m_{γ_D} [MeV]	Electron LJ Obs (Exp) pb	1 Muon LJ Obs (Exp) pb	2 Muon LJ Obs (Exp) pb
0.0	150	0.082 (0.082)	-	-
0.0	300	0.11 (0.11)	0.060 (0.035)	0.017 (0.011)
0.0	500	0.20 (0.21)	0.15 (0.090)	0.019 (0.012)
0.10	150	0.096 (0.10)	-	-
0.10	300	0.37 (0.37)	0.064 (0.036)	0.018 (0.011)
0.10	500	0.39 (0.39)	0.053 (0.035)	0.018 (0.011)
0.30	150	0.11 (0.11)	-	-
0.30	300	0.40 (0.40)	0.099 (0.055)	0.020 (0.012)
0.30	500	1.2 (1.2)	0.066 (0.043)	0.022 (0.015)

Dark Matter Approach with Effective Field Theory

We can use an Effective Field Theory(**EFT**) to model what we know about **DM**, without resorting to any one specific UV complete theory (eg. **SUSY**, **LED**, etc.)

- Direct production of Dark Matter at colliders is complementary to direct and indirect detection methods (different technologies; different uncertainties)
  - Produced WIMPS escape the detector giving **MET (they recoil off photon/jet/W/Z)**
  - Events are **tagged by** ISR **photon**, **jet** or **W/Z** ; clean final states+understood backgrounds



Two possible diagrams lead to interference for W:

C(u)=-C(d) : signal enhanced

C(u)=C(d): signal suppressed

- New physics is expressed with a contact interaction (g, q, χ) and we use **EFT** to describe the interaction in a model independent way.
  - **Valid when the scale of the interaction is less than the mediator mass (m < 2πM*)**
- WIMPs assumed to be Dirac fermions[Goodman et al., Phys. Rev. D82, 116010] (2010); Results described by WIMP mass **m** and mass scale ***M****, Operators of interest are **D1**(scalar), **D5**(vector), **D8**(axial-vector), **D9**(tensor)
- Limits on **σ(pp→χχ)** can be converted to elastic scattering x-section **σ(χp→χp)** to compare with direct searches.

Mono-'X' Methodology

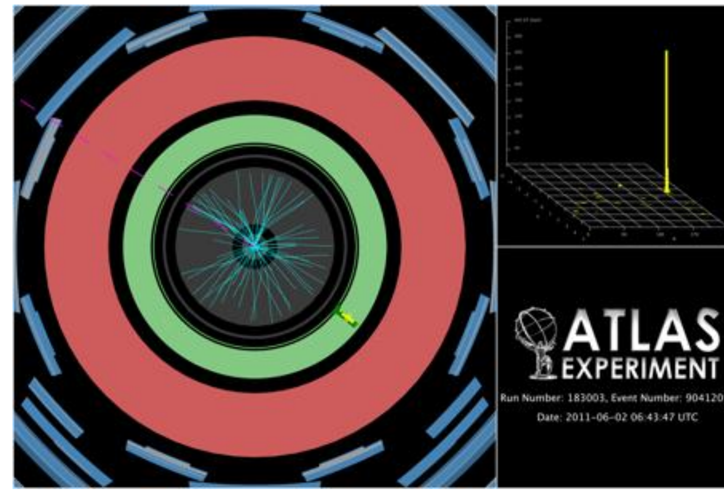
- Select events with a high p_T ***X*** (***X***=jet,γ,W/Z) and large missing energy
  - Veto on leptons to get rid of electro-weak backgrounds
  - Veto events where the MET is in the direction of a secondary jet in the event to get rid of MET from jet mis-measurement
  - Veto events with > 1 extra jet for top, multi-jet backgrounds
- Remaining backgrounds are
  - Irreducible, real MET + jet:
    - Dominant: $Z \to \nu\nu$ + X
    - $W \to l\nu$, $Z \to ll$ where l is not measured
  - Reducible, estimated from data: Beam-backgrounds, multi-jet
  - MC driven: top, diboson
- Estimate backgrounds from data using signal & control regions:

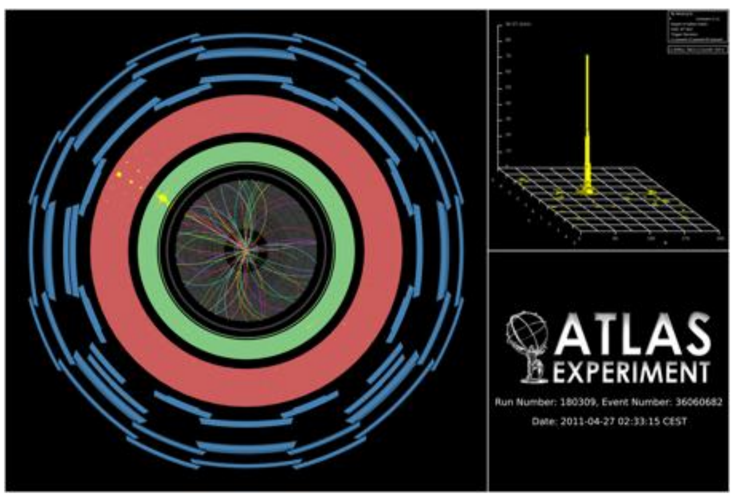
$$N_b{}^{SR} = N_{meas}{}^{CR} \times C \times \frac{N_{MC.b}{}^{SR}}{N_{MC.b}{}^{CR}}$$

- Then count N^{SR} events and look for SM deviations

Monojet and Monophoton Analysis

- Mono-jet: require R = 0.4 antikT jet with pT > 120 GeV, MET > 120 GeV
  - 4 signal regions with symmetric jet p_T and MET cuts: >120 GeV, > 220 GeV, > 350 GeV and > 500 GeV
  - Results from 8 TeV, 10.5 fb^{-1}

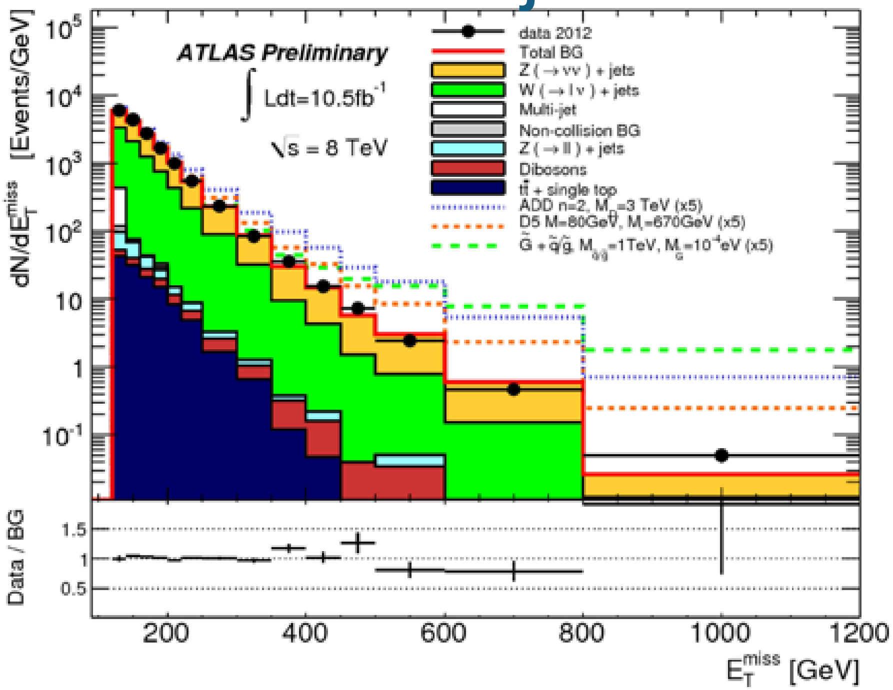




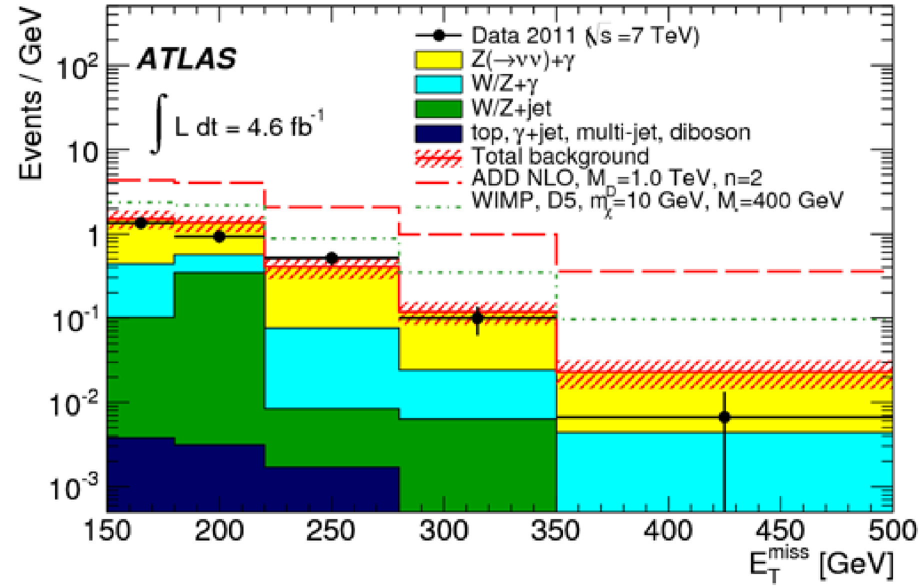
- Mono-photon: require high pT, isolated photon with pT > 150 GeV, MET > 150 GeV
  - Results from 7 TeV, 4.6 fb^{-1}

Monojet and Monophoton Results

Monojet



Monophoton

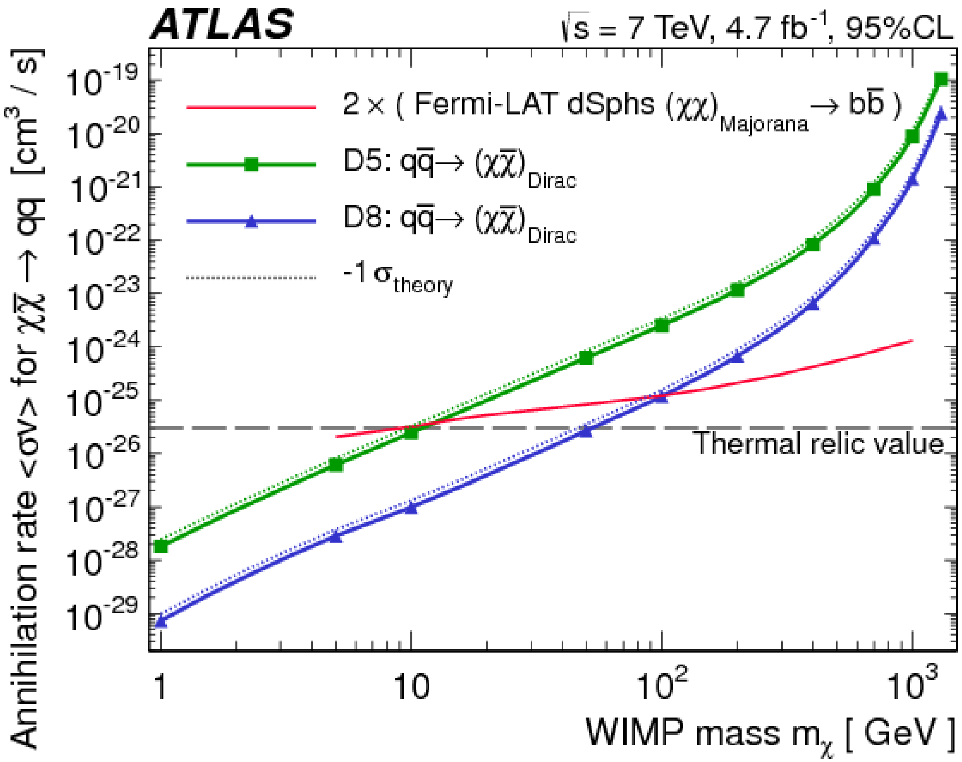


Good agreement with Standard Model seen for both analyses in all signal regions

- Monojet (SR3): Exp. **2180±170**, Obs. **2353**
- Monophoton: Exp. **137±20**, Obs. **116**

WIMP Annihilation Limits (EFT)

Comparison with FERMI-LAT is possible through our EFT.
(Note FERMI-LAT looks at astrophysical gamma-rays)



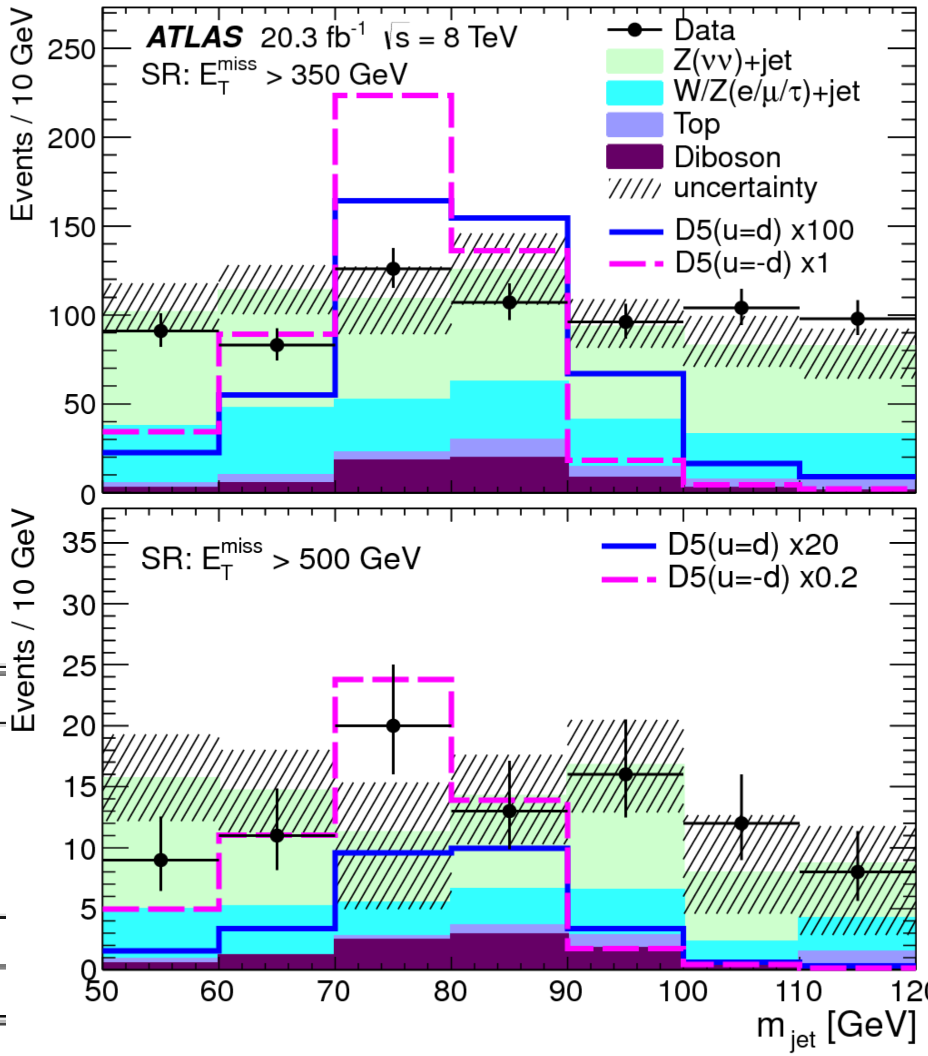
- The results can also be interpreted in terms of limits on WIMPs annihilating to light quarks.
- All limits shown here assume **100% branching fractions** of WIMPs annihilating to quarks.
- Below **10 GeV** for **D5** and **70 GeV** for **D8** the ATLAS limits are below the values needed for WIMPs to make up the DM relic abundance.

ATLAS Mono-W Results

arXiv:1309.4017

Selection:

- Trigger: $E_{T\ Miss}$ > 80 GeV
- **Fat jet**: Cambridge-Aachen algorithm, R = 1.2, first two sub-jets balanced (p_y > 0.4), p_T > 250 GeV, $|\eta|$< 1.2, m_{jet} = 50-120 GeV
- Veto leptons (e,μ) and photons
- tt_{bar} supression: **veto** if >= 2 AntiKt4 jets with R(jet_{Fat}, $jet_{AntiKt4}$) > 0.9 OR ($E_{T\ Miss}$, jet) < 0.4 for any AntiKt4 jets.
- SR: $E_{T\ Miss}$ > {350, 500} GeV



Results agree with SM

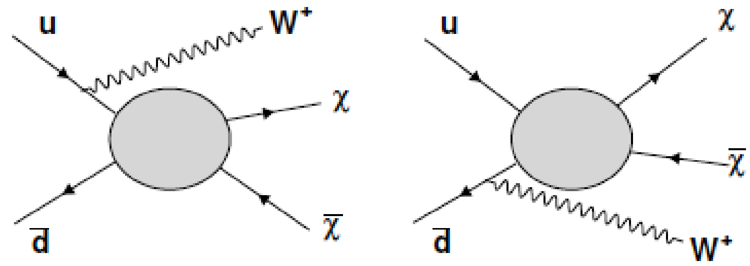
Process	$E_T^{miss} > 350$ GeV	$E_T^{miss} > 500$ GeV
$Z \to \nu\bar{\nu}$	400^{+39}_{-34}	54^{+8}_{-10}
$W \to \ell^{\pm}\nu, Z \to \ell^{\pm}\ell^{\mp}$	210^{+20}_{-18}	22^{+4}_{-5}
WW, WZ, ZZ	57^{+11}_{-8}	$9.1^{+1.3}_{-1.1}$
$t\bar{t}$, single t	39^{+10}_{-4}	$3.7^{+1.7}_{-1.1}$
Total	710^{+48}_{-38}	89^{+9}_{-12}
Data	705	89

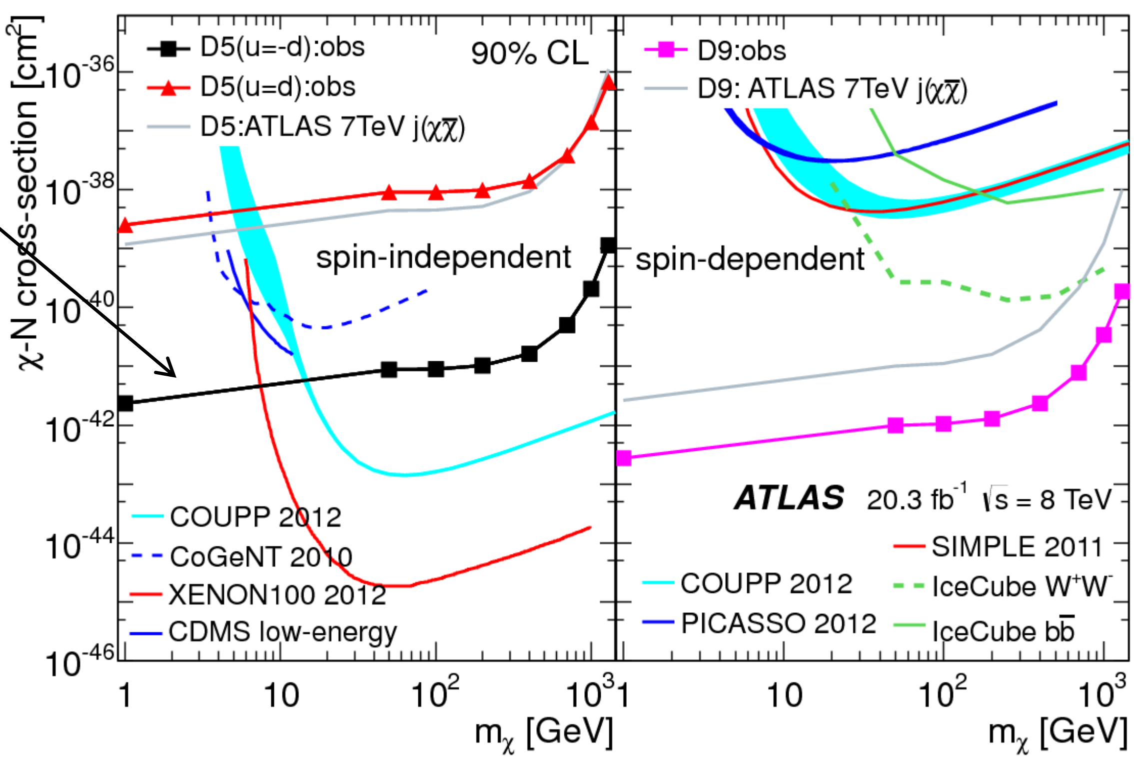
Mono-W/Z Limits

- Limits expressed in terms of m χ , χ-n cross section and M*
- Set strong spin-dependent limits
  - Tensor operator (**D9**)
- Vector operator (**D5**) spin-independent limits also **very strong when u & d have opposite coupling**

- LUX just reported about a factor 3 lower limit than Xenon100 (spin-independent)

- **Note** XENON/LUX and D5(u=-d) exclude low WIMP mass results from COGENT/DAMA/CRESST

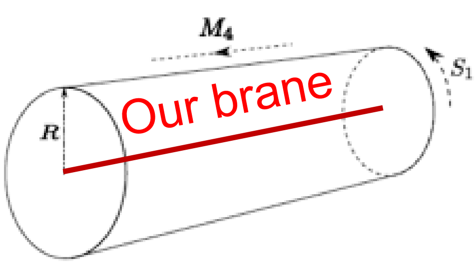




Large Extra Dimensions

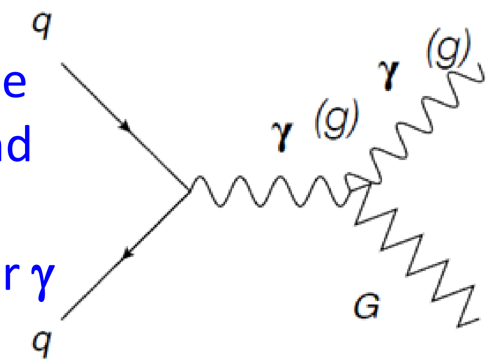
- Large Extra Dimensions (LED) are a proposed solution the hierarchy problem
  - Gravity exists in the other dimensions "diluting" it
  - ADD model (Phys. Lett. B429 1998) has compact new dimensions
    - Leads to massive gravitons which can be radiated by gluons or quarks
- Introduces new fundamental scales to explain Planck mass for n extra dimensions:

$$M^2_{Pl} = M^{2+n}_D R^n \text{ (from generalized Gauss' Law)}$$



Compactified dimensions

At LHC **graviton** modes may be excited in extra dimensions and appear as non-interacting particles in 4 –space plus **jet** or γ

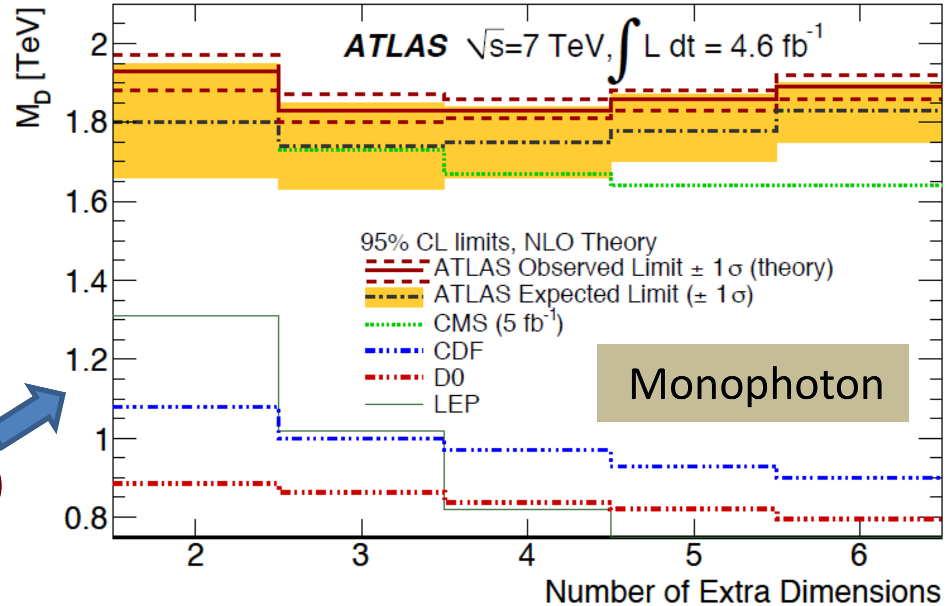


ADD Model Limits from Mono-[jet,γ]

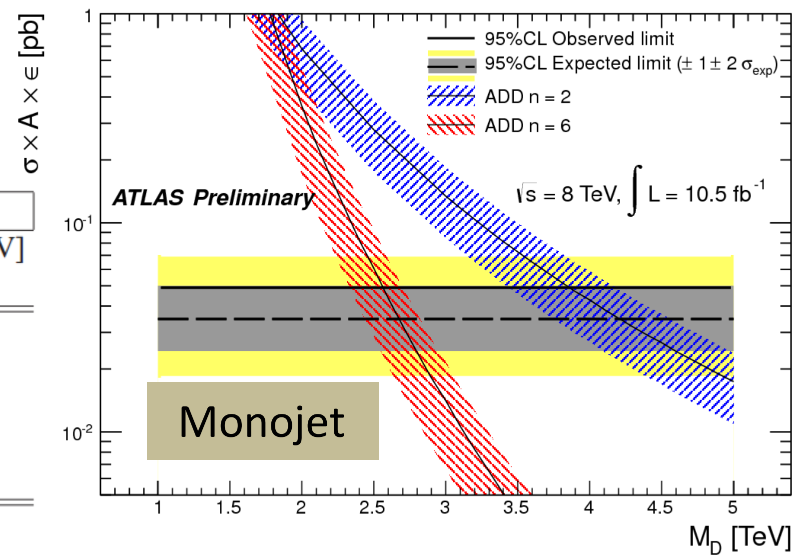
$$M^2_{Pl} = M^{2+n}_D R^n$$

Both analyses set limits up to n = 6 for **M_D**

- Monophoton 7 TeV limits (5 fb^{-1})
  - **1.8-1.9 TeV**
- Monojet 8 TeV limits (10 fb^{-1}):
  - **2.5-3.9 TeV**



95% CL limits on ADD model using LO signal cross sections						
n extra-dimensions	95% CL observed limit on M_D [TeV] +1σ(theory)	Nominal	−1σ(theory)	95% CL expected limit on M_D [TeV] +1σ	Nominal	−1σ
2	+0.32	3.88	−0.42	−0.36	4.24	+0.39
3	+0.21	3.16	−0.29	−0.24	3.39	+0.46
4	+0.16	2.84	−0.27	−0.16	3.00	+0.20
5	+0.16	2.65	−0.27	−0.13	2.78	+0.15
6	+0.13	2.58	−0.23	−0.11	2.69	+0.11



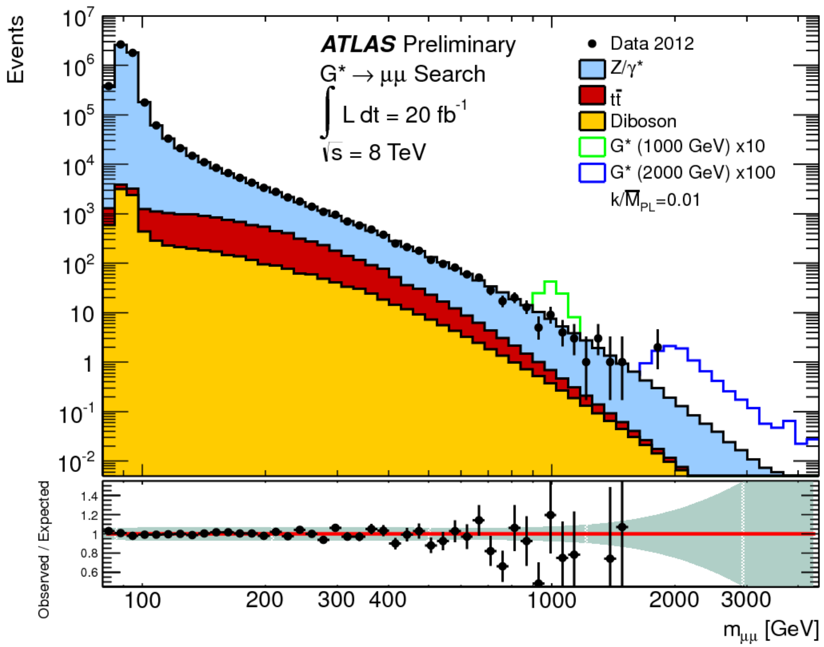
Graviton Limits (Extra Dimensions)

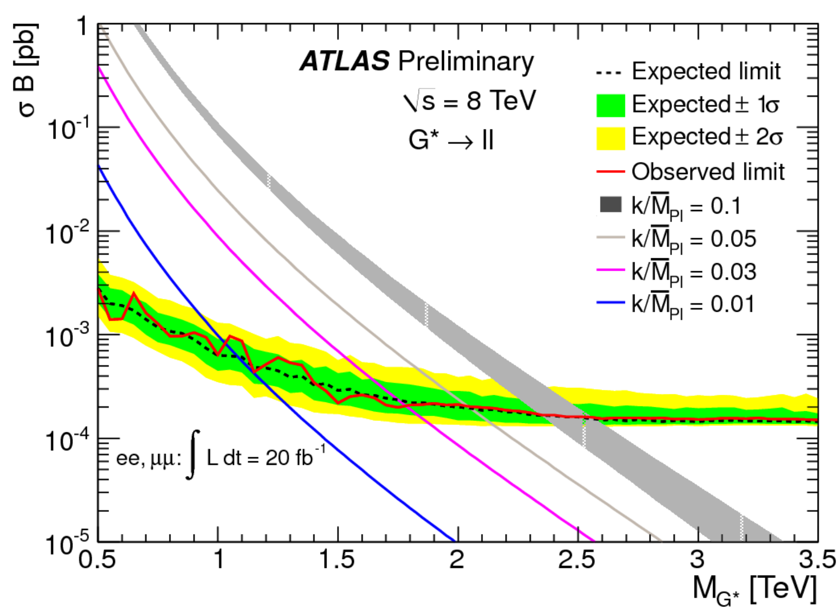
[ATLAS-CONF-2013-017]

ATLAS searches for high-mass dilepton resonances can be used to search for excited graviton production.

Below are two plots from ATLAS-CONF-2013-017

- First shows the dimuon invariant mass with two selected graviton (G*) signals (uses **Randall-Sundrum** model with one warped extra dimension)
- Second shows the 95% C.L. on σB and the expected σB for G* production





Black Holes

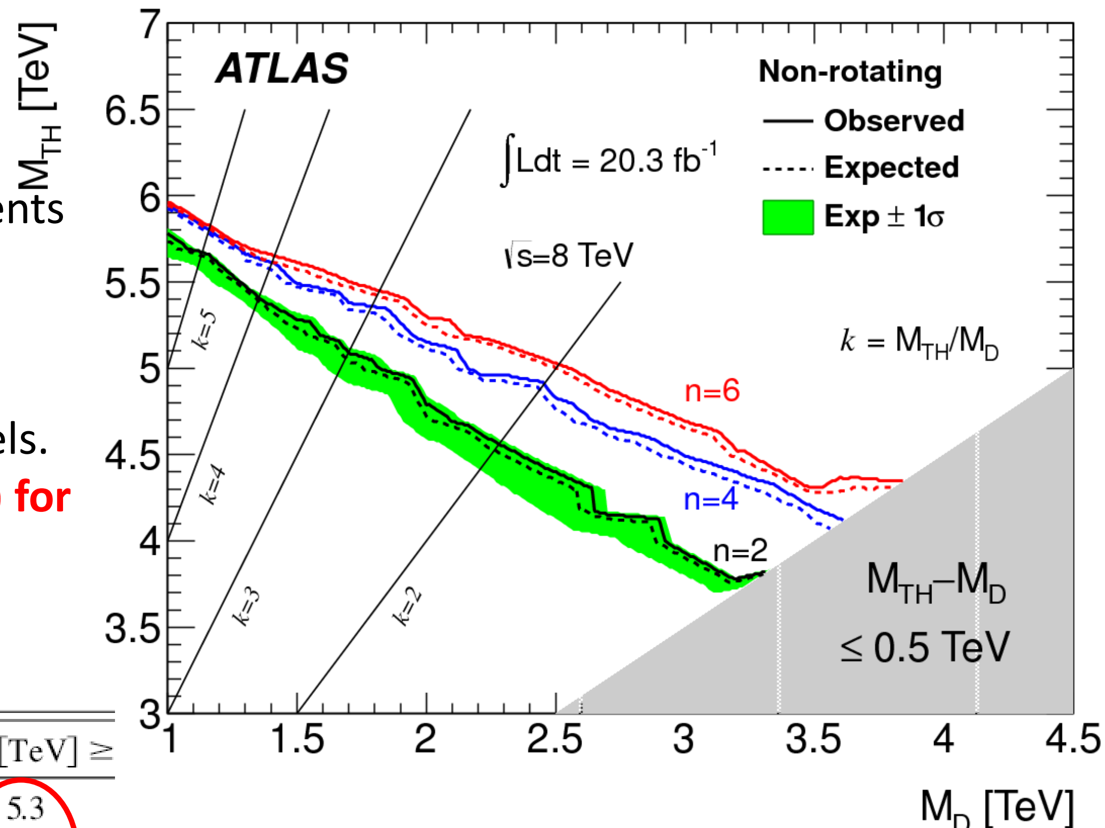
- Microscopic Black Holes of mass $\mathbf{M_{BH}}$ produced if the impact parameter of the colliding partons is below the Schwarzschild radius ($\mathbf{r_s}$)
  – ADD: $r_S = \frac{1}{\sqrt{\pi} M_D} \left[\frac{M_{\mathrm{BH}}}{M_D} \frac{8\Gamma\left(\frac{n+3}{2}\right)}{n+2} \right]^{\frac{1}{n+1}}$
- **Semi-classical black holes** ($M_{BH} > 3\text{-}5M_D$):
  – Decay thermally via Hawking radiation "democratically"
  – Large multiplicities of energetic particles
- **Quantum black holes** ($M_{BH} \sim M_D$):
  – Decay before thermalizing to low multiplicities of energetic particles (dijet final states dominate).
  – Inherit color, electric charge and angular momentum from the parton pair.

Search for Semi-classical BH

- General idea: search for excess of events at high p_T sum or invariant masses and large multiplicity

- Most recent search (PRD 88, 072001 (2013)) looks for **like-sign di-muon events**
- Predict **0.6 +- 0.2** background events from Standard Model processes.
- **None observed**.
- This result is interpreted in the context of low-scale gravity models.
- **Current limits (M_D set at 1.5 TeV) for M_{TH}** (BH mass threshold)

Model	n	M_{TH}[TeV] $\geq$
Nonrotating black hole	2	5.3
Nonrotating black hole	4	5.6
Nonrotating black hole	6	5.7

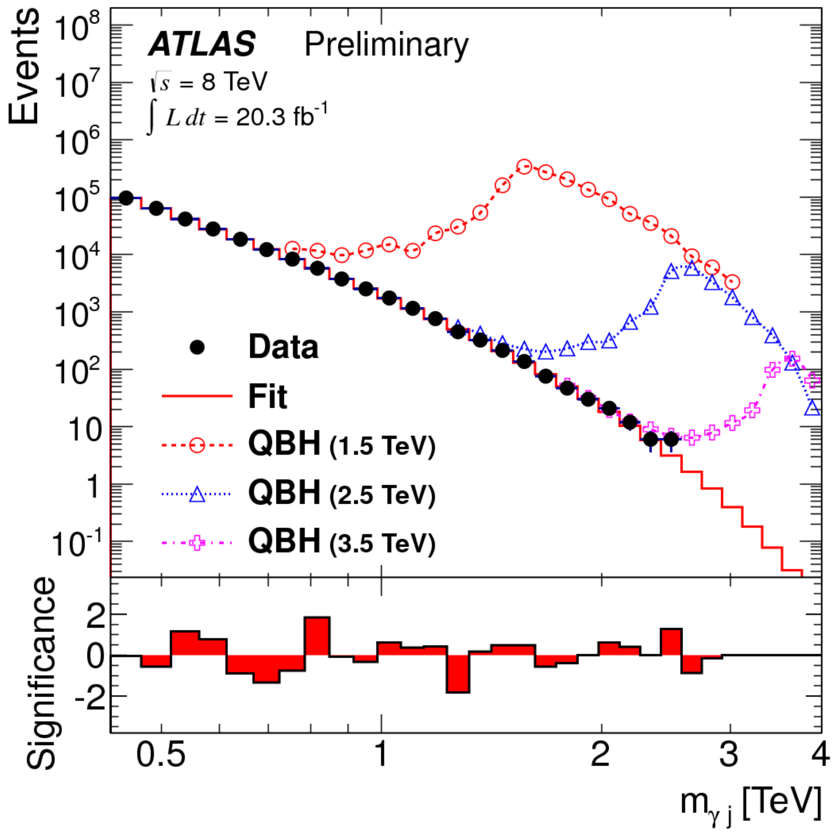


Quantum Black Hole Search

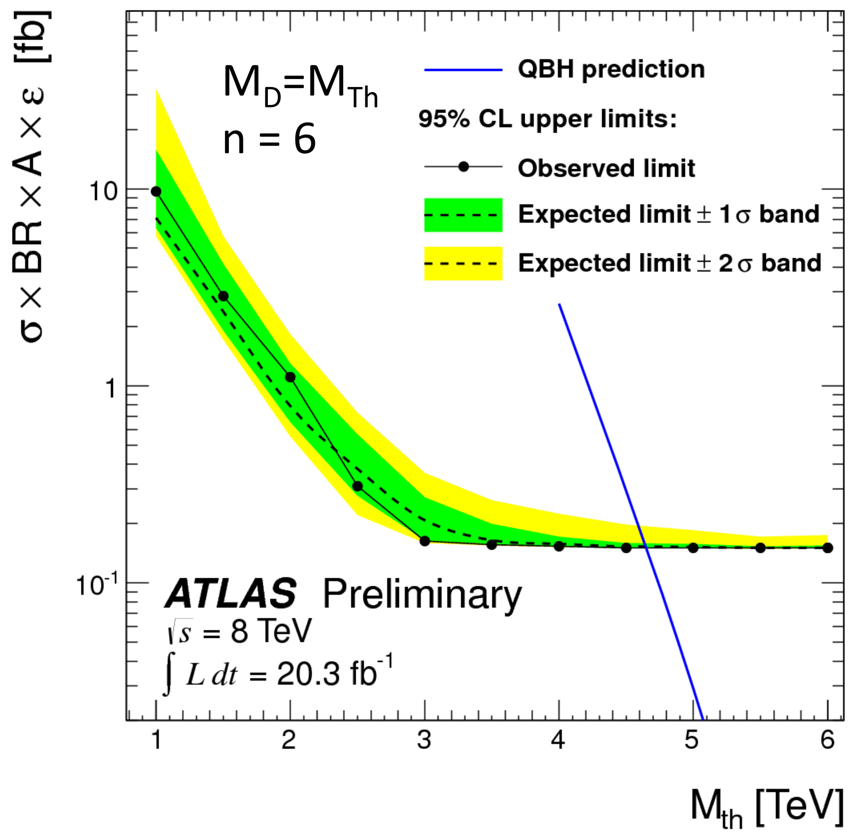
arXiv:1309.3230 Photon+jet

- Quantum BH production would result in a broad excess at high invariant mass. Limit: excluded below **4.6 TeV**

Photon + Jet



Photon + Jet

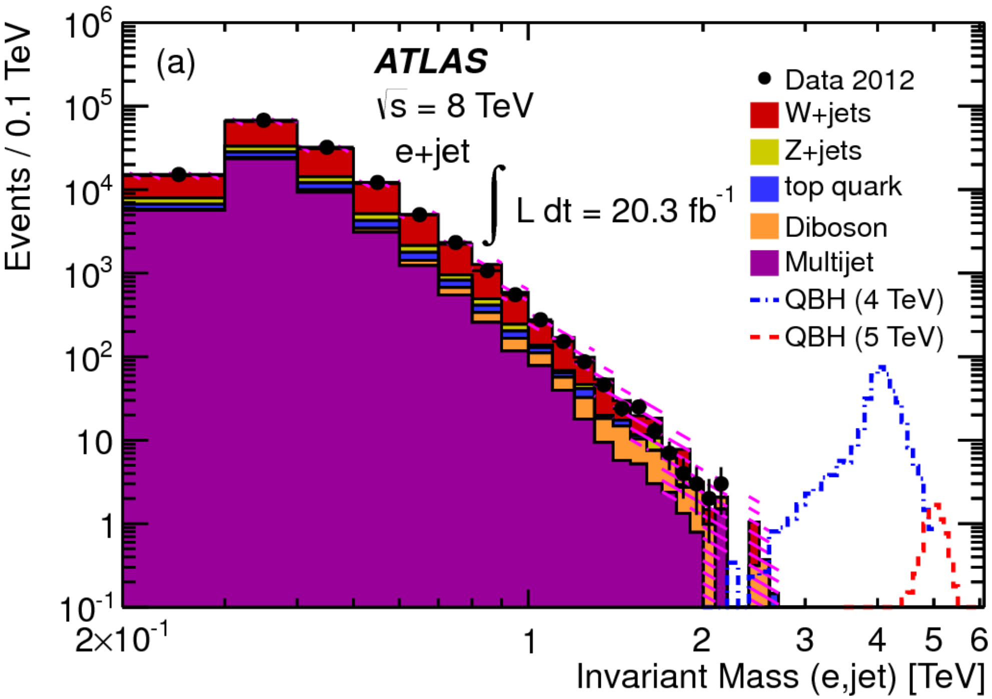


Quantum Black Hole Search

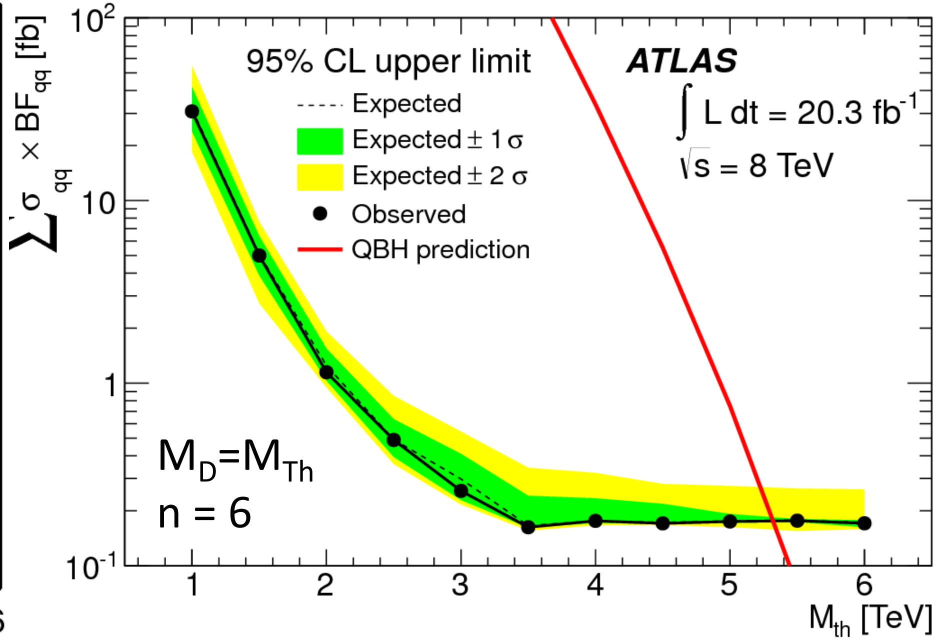
arXiv:1311.2006 Lepton+jet

- New result but for Lepton+jet instead of Photon+jet. Limit: QBH excluded below **5.3 TeV**

Electron + Jet



Lepton + Jet



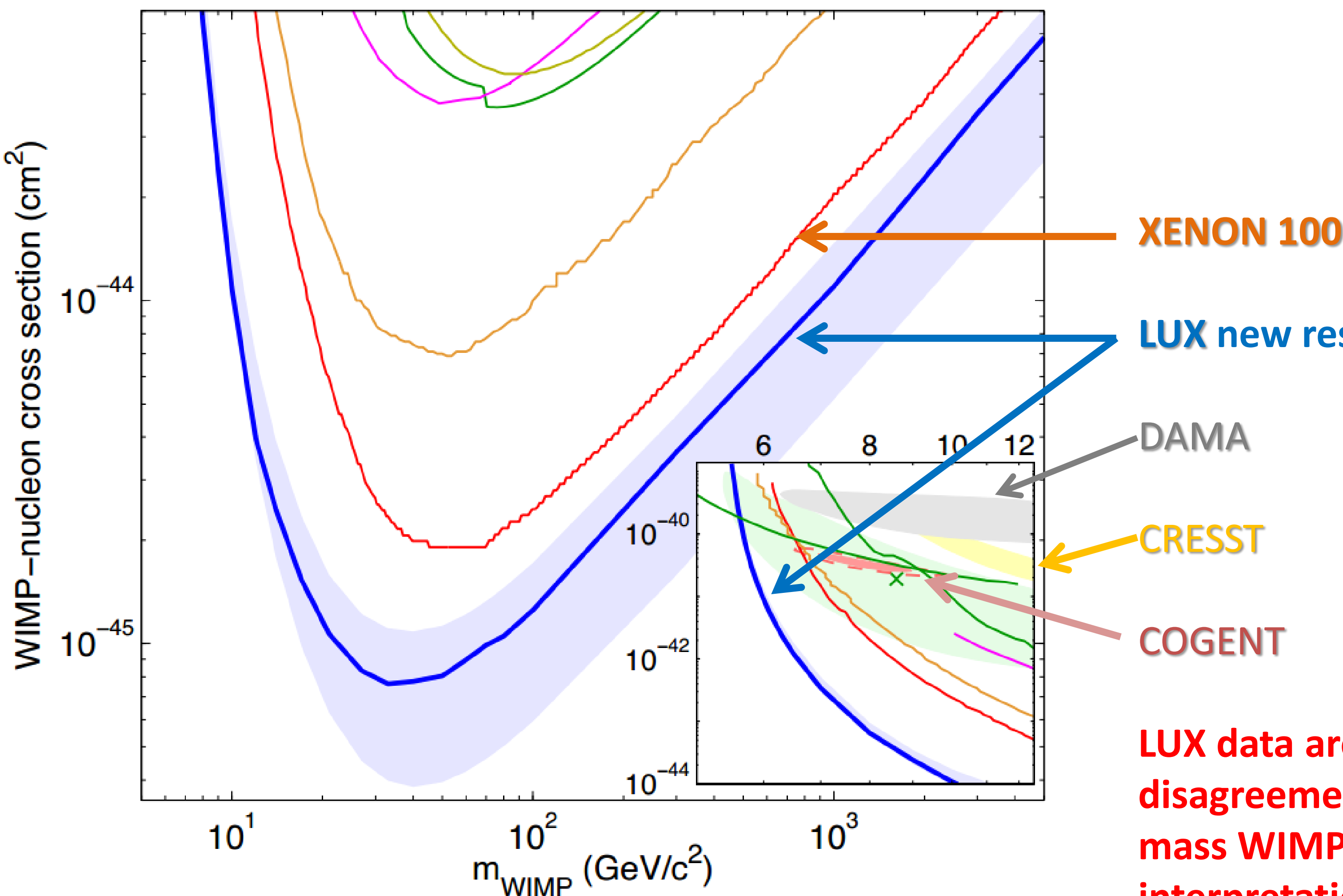
Conclusions

- **Great Run 1 for the LHC and ATLAS!**
- LHC searches for DM are complementary to direct and indirect search experiments.
- Everything we expected was confirmed/found…
  - Standard Model, Higgs, …
- Unfortunately nothing beyond the standard model was found (at least not yet):
  - **no Dark Matter, no Extra Dimensions, no Black Holes**
  - **However, we probed new kinematic regions and set strong constraints on many models predicting new phenomena.**
- Restart in 2015 at sqrt(s)=13-14 TeV. **Much more to come**, especially for searches limited in center-of-mass energy.

Questions?

http://arxiv.org/pdf/1310.8214v1.pdf

LUX Limits



LUX data are in <u>strong</u> disagreement with low-mass WIMP signal interpretations