Searches for dark matter and extra dimensions with the ATLAS detector

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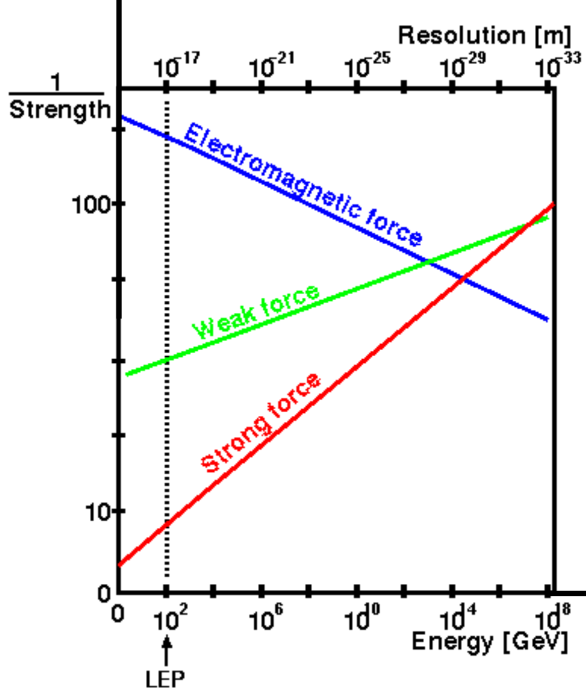
on behalf of the ATLAS Collaboration

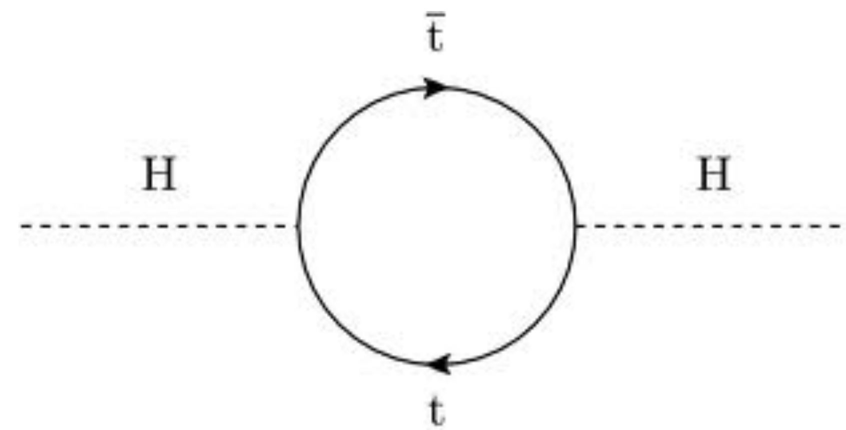
Questions I will attempt to address in this talk:

what are our problems?
what did we ~~expect~~ ~~believe~~ hope to see?
how well did we exclude it?

$$F = \frac{GM_1M_2}{r^2}$$

Big Hierarchy Problem
(not to scale)



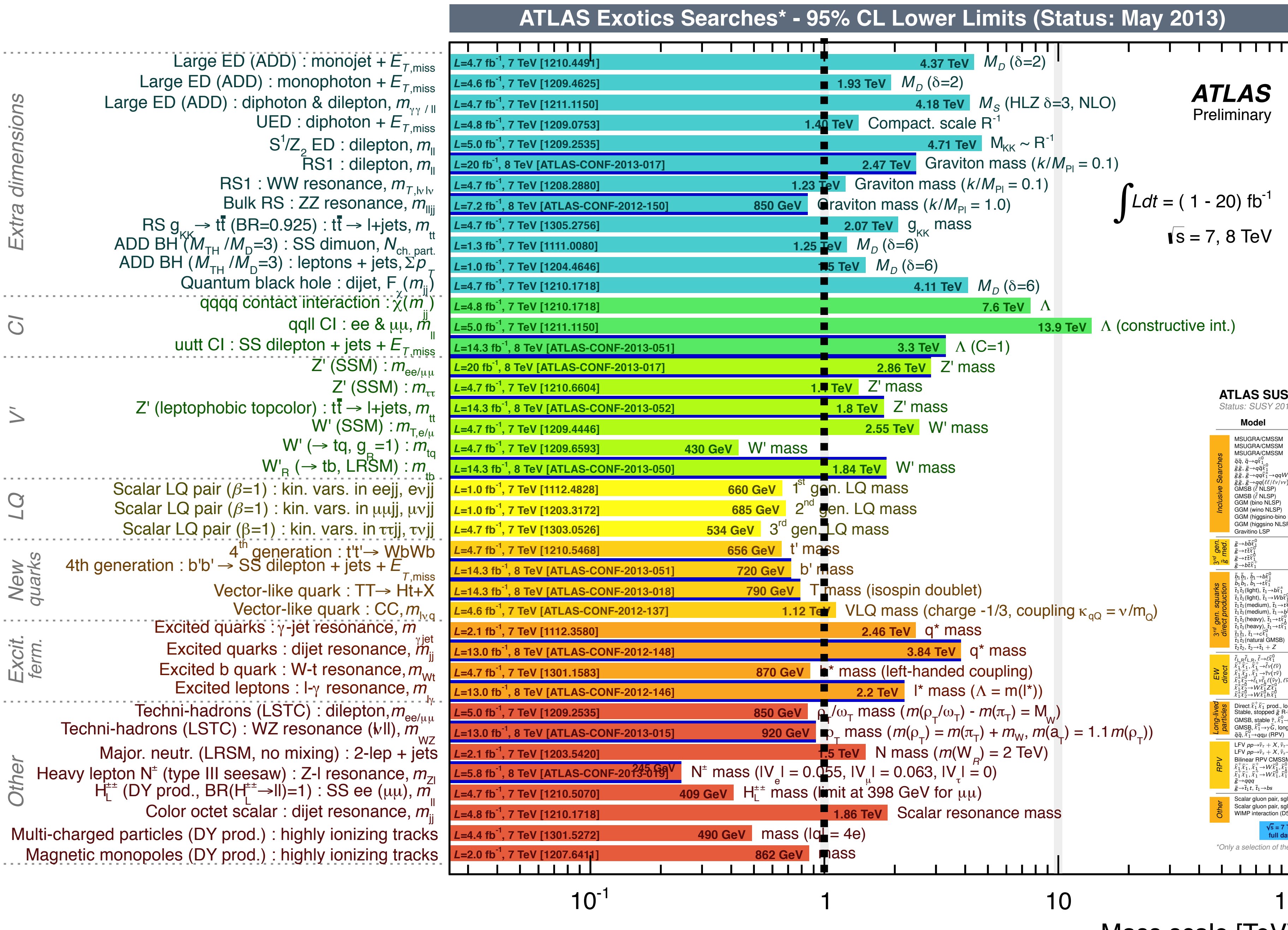


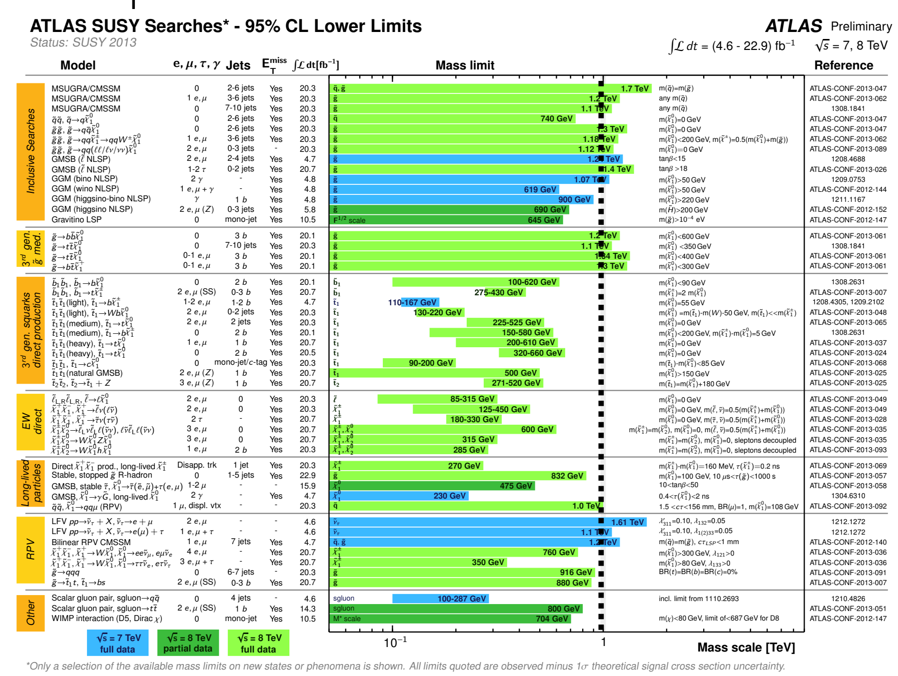
Little Hierarchy Problem *

$$\underbrace{m^2_{physical}}_{what\ we\ measure} = \underbrace{m^2_h}_{free\ parameter} + \frac{3\lambda}{8\pi}\underbrace{\Lambda^2}_{theory\ cutoff} - \frac{3\lambda}{8\pi} m^2_h \log\left(\frac{\Lambda^2 + m^2_h}{m^2_h}\right)$$

* whether the little hierarchy problem is indeed a problem in a matter of debate, depending on philosophical opinions on naturalness, amongst others…

Many results out on BSM physics





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

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/

Herculean tasks: killing hydras and finding a golden apple

Dark Matter:
Hunting down the Stymphalian Bird(s)

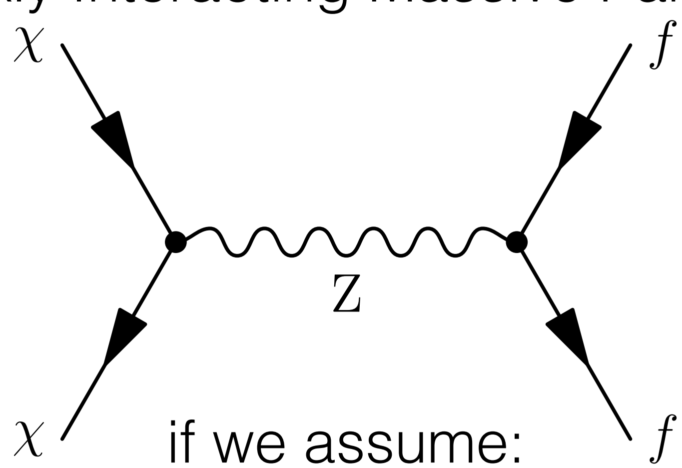
Generic requirements of Dark Matter (DM)

time passes

<u>DM freeze out:</u>
expansion rate = annihilation rate

What we know about Dark Matter:	
does not couple to:	E&M
does couple to:	Gravity
decouples at certain temperature	
<u>very</u> light < m_χ < 10^{18} GeV	

No statement about the weak force - let's try
WIMPs
(Weakly Interacting Massive Particles)



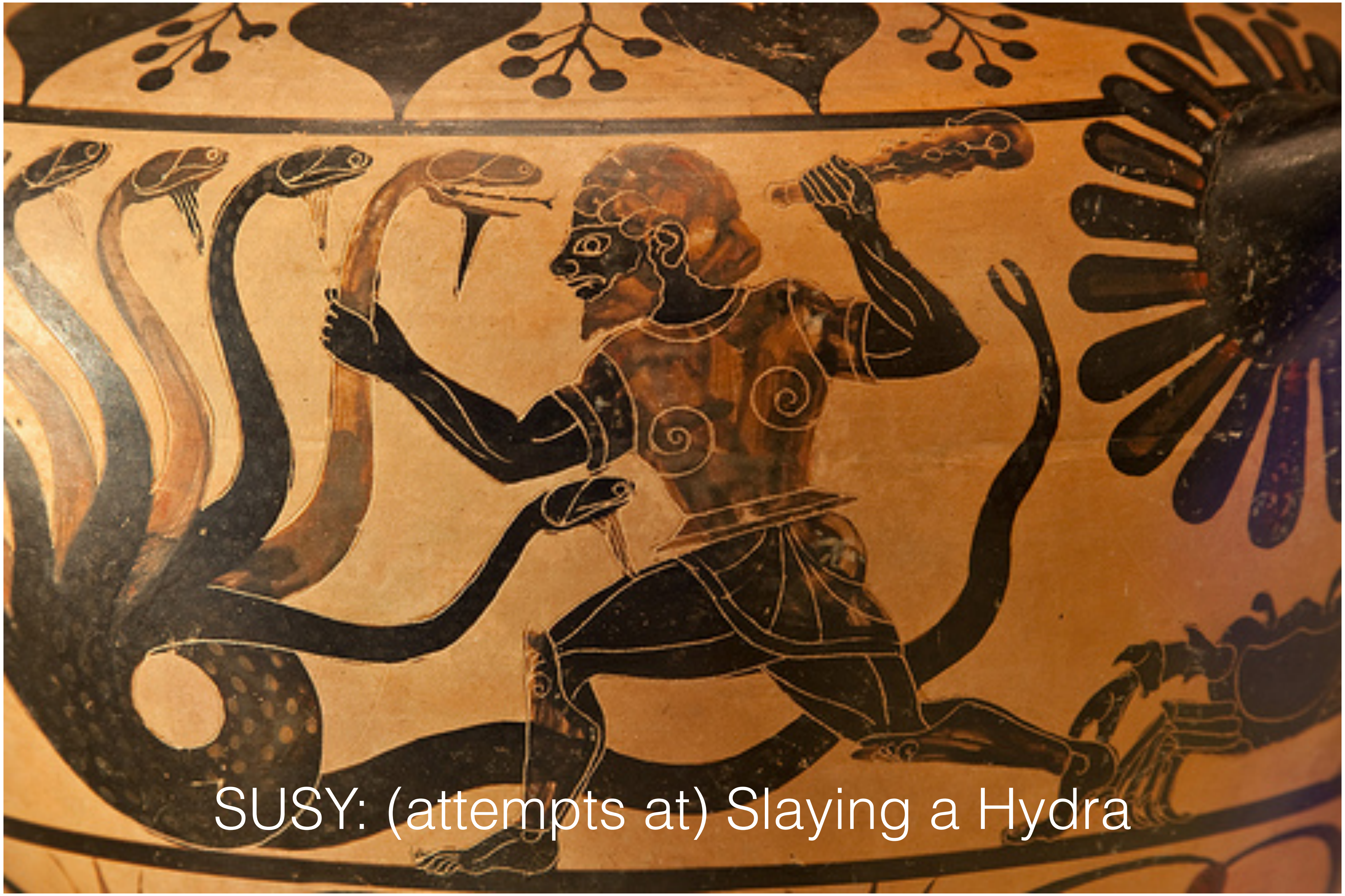
if we assume:

$\sigma \approx \sigma_{Weak} = (\alpha_{Weak} / m_\chi)^2$

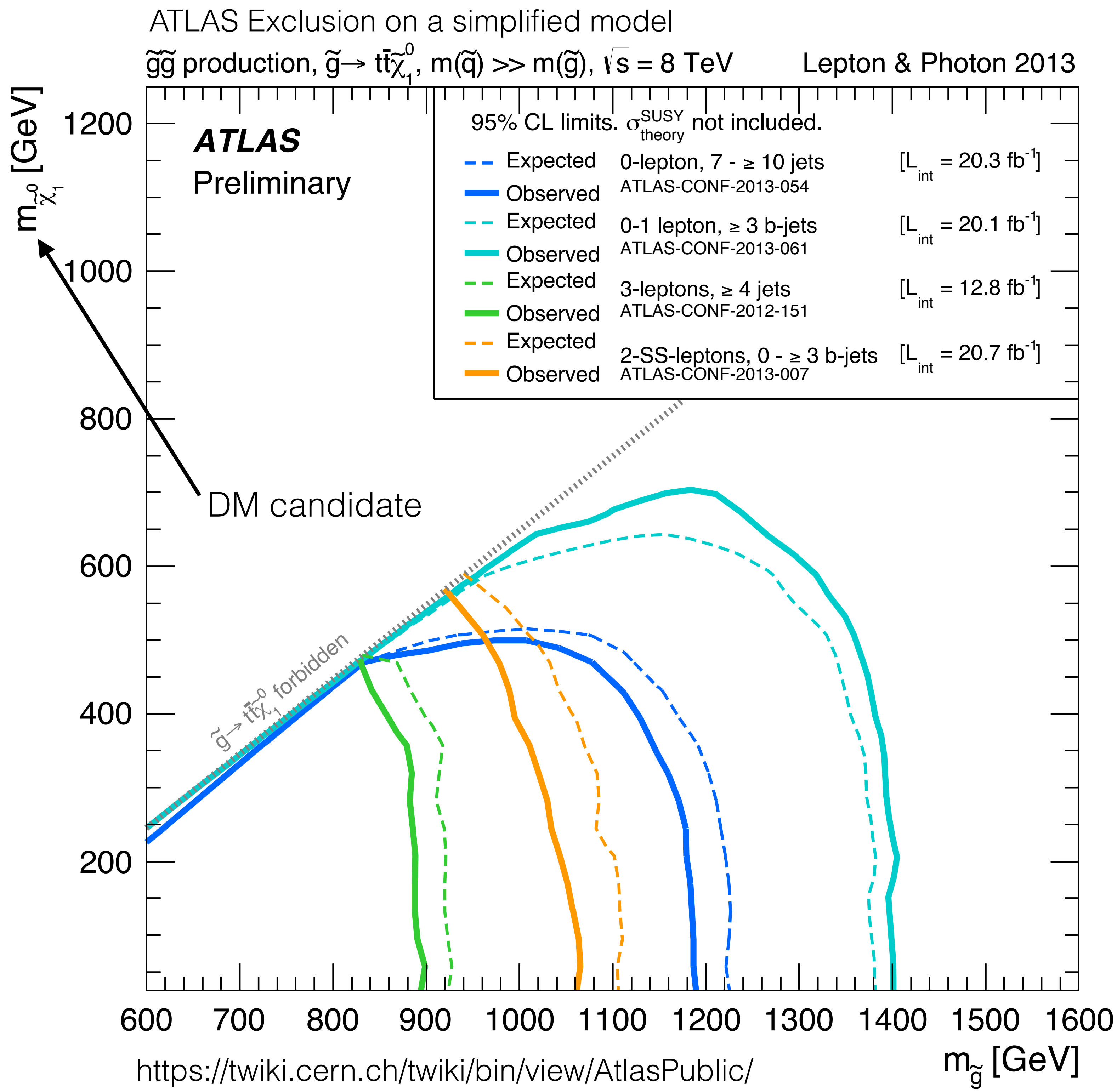
$m_\chi \approx 100$ GeV

We get: $\rho_{DM} \approx 0.23$
The correct relic density!

It’s a (WIMP) miracle!


SUSY: (attempts at) Slaying a Hydra

The retreat of “natural” SUSY



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- SUSY both solves the little hierarchy problem and gives a DM candidate
- to be considered “natural”, i.e. have low fine-tuning, SUSY particles should be light
- limits on natural SUSY DM candidate pushed to hundreds of GeVs
- can have many, many SUSY paradigms - can always hide it

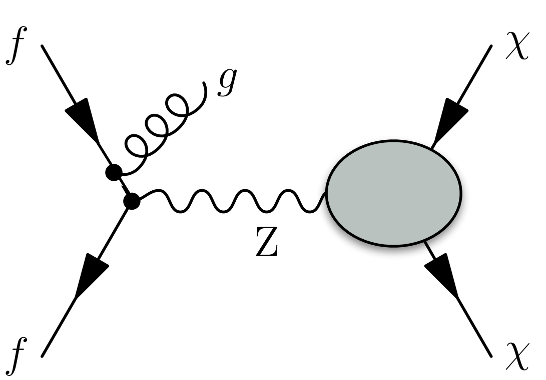
ATLAS Exotics approach:

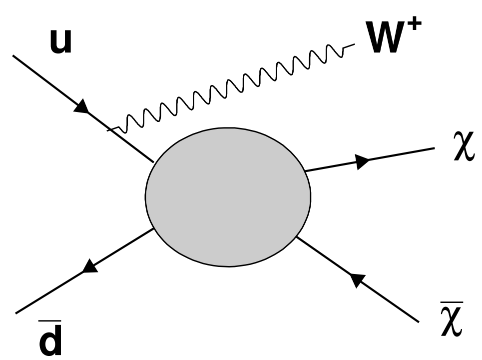
Use an effective field theory: reduce number of parameters to m_χ and suppression scale M*

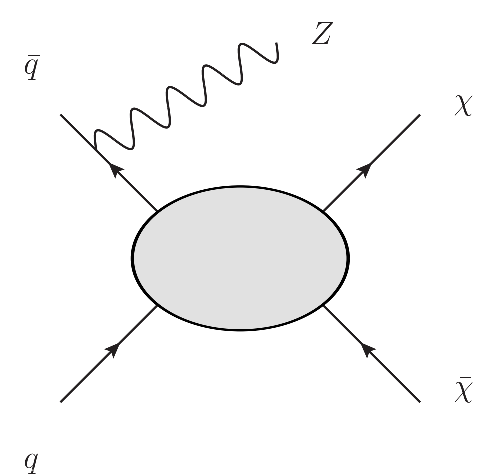
Define a series of possible operators

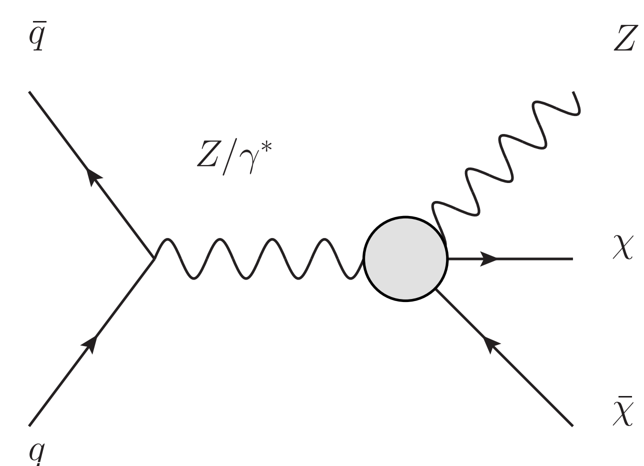
Agnostic to model, just look for massive particle interacting weakly

for example:





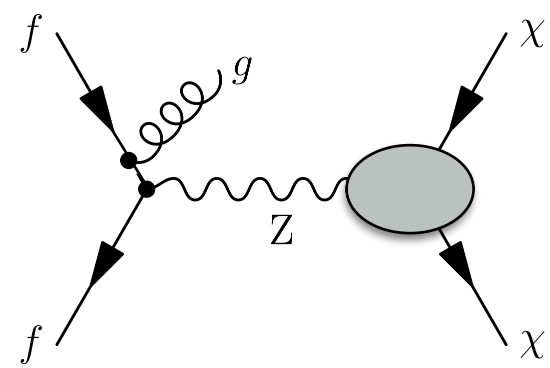




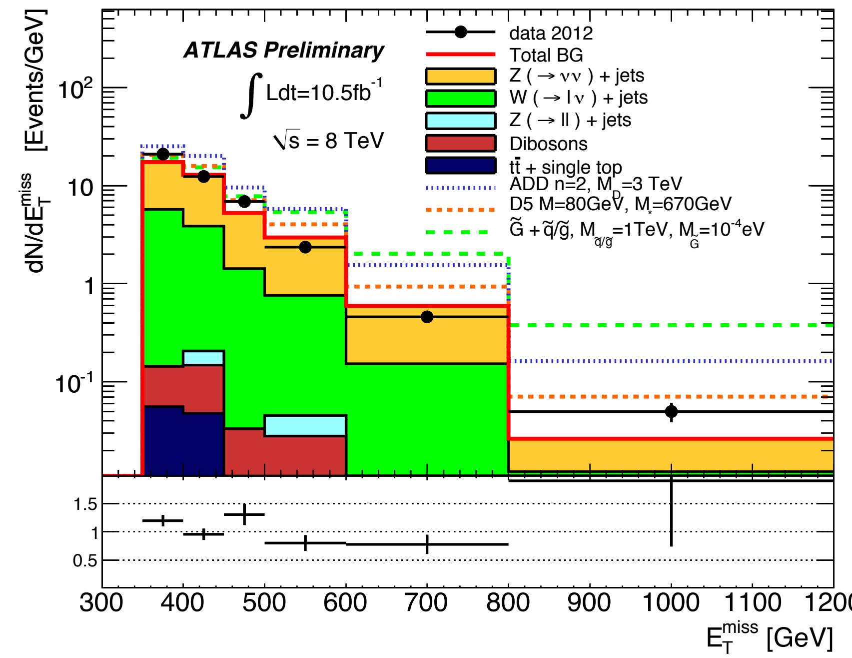
See nice phenomenology paper summarising the models: PRD 82, 116010 (2010)

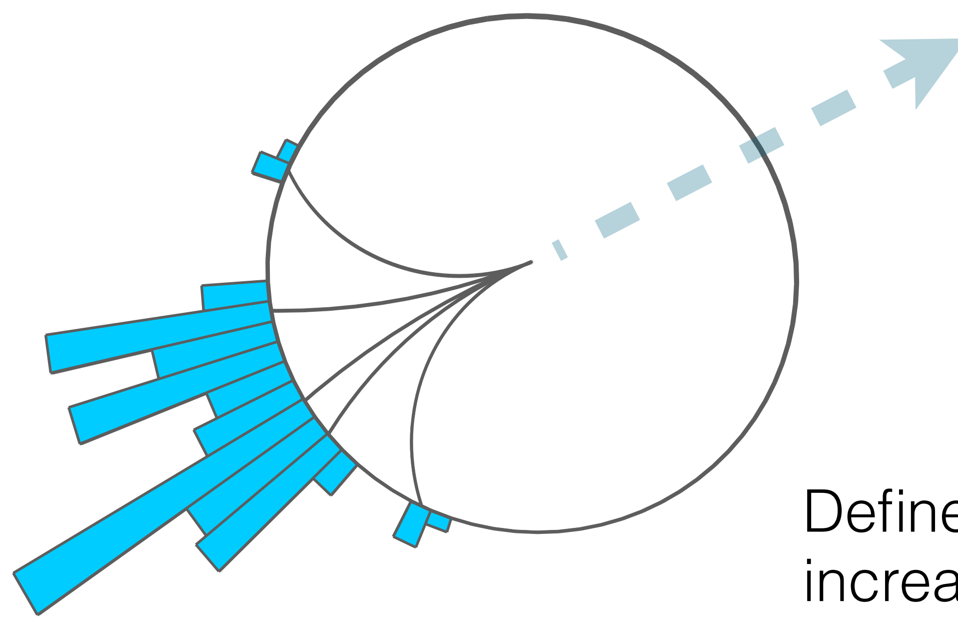
Monojets

- look at events with only **one jet and E_T^{miss}**.
  - veto leptons and more than one additional jet

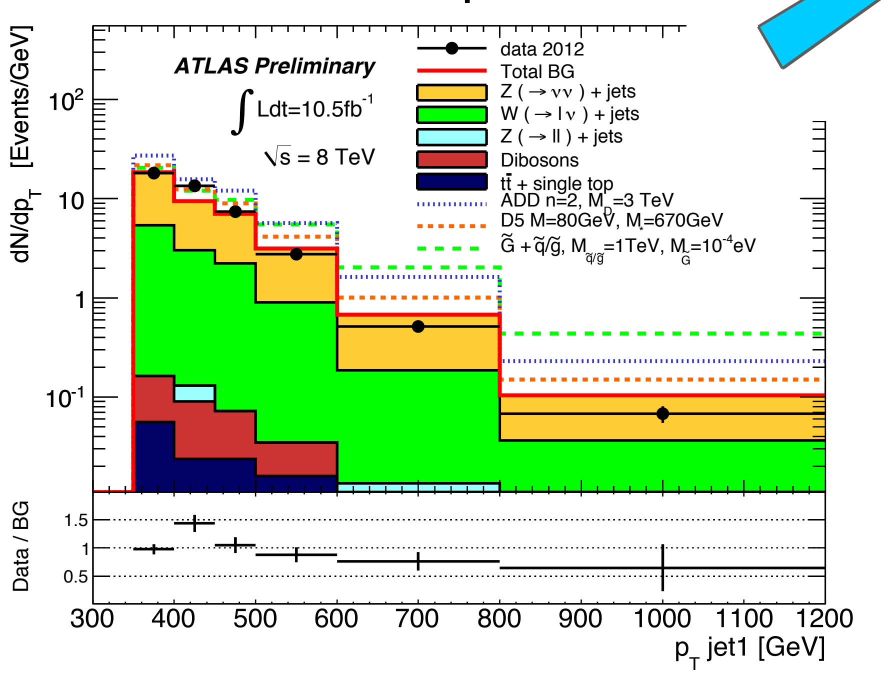


E_T^{miss}





Jet p_T



Define four signal regions with increasingly tighter jet p_T and E_T^{miss} cuts.

Signal region shown requires:

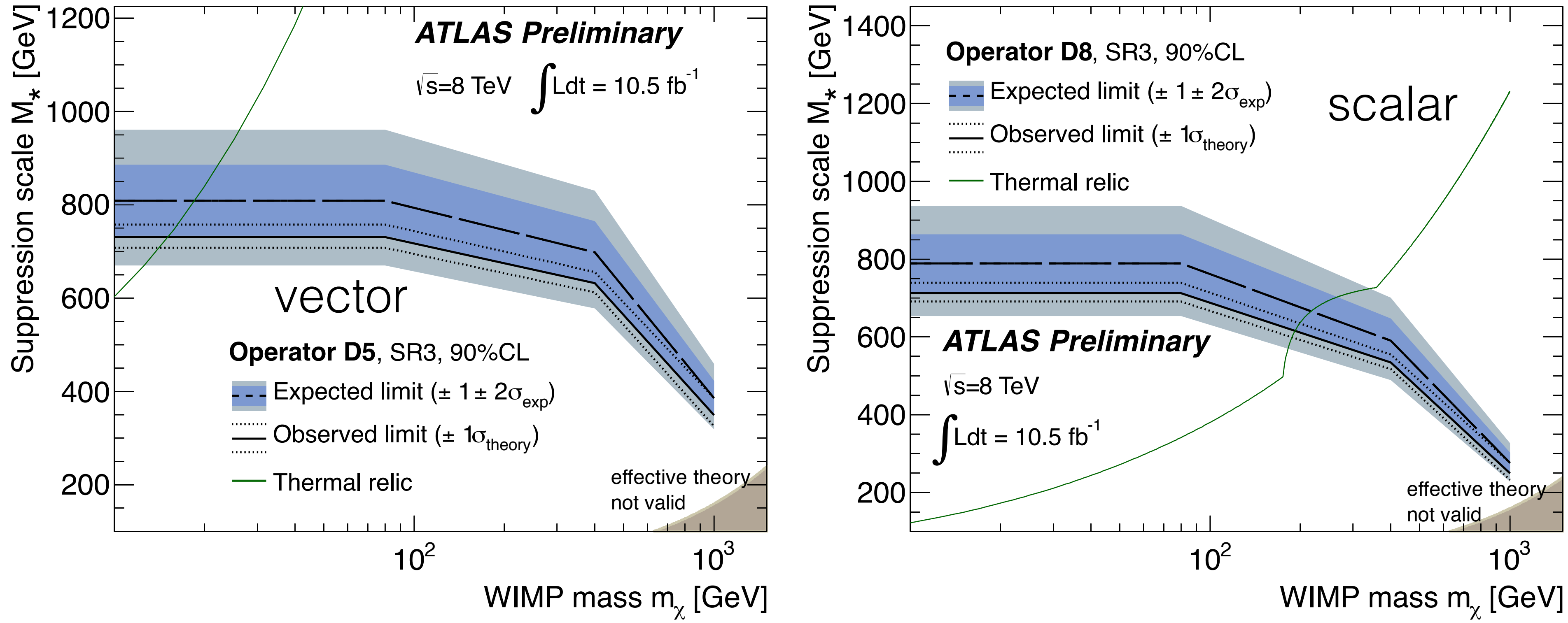
- jet p_T > 350 GeV
- E_T^{miss} > 350 GeV

ATLAS-CONF-2012-147

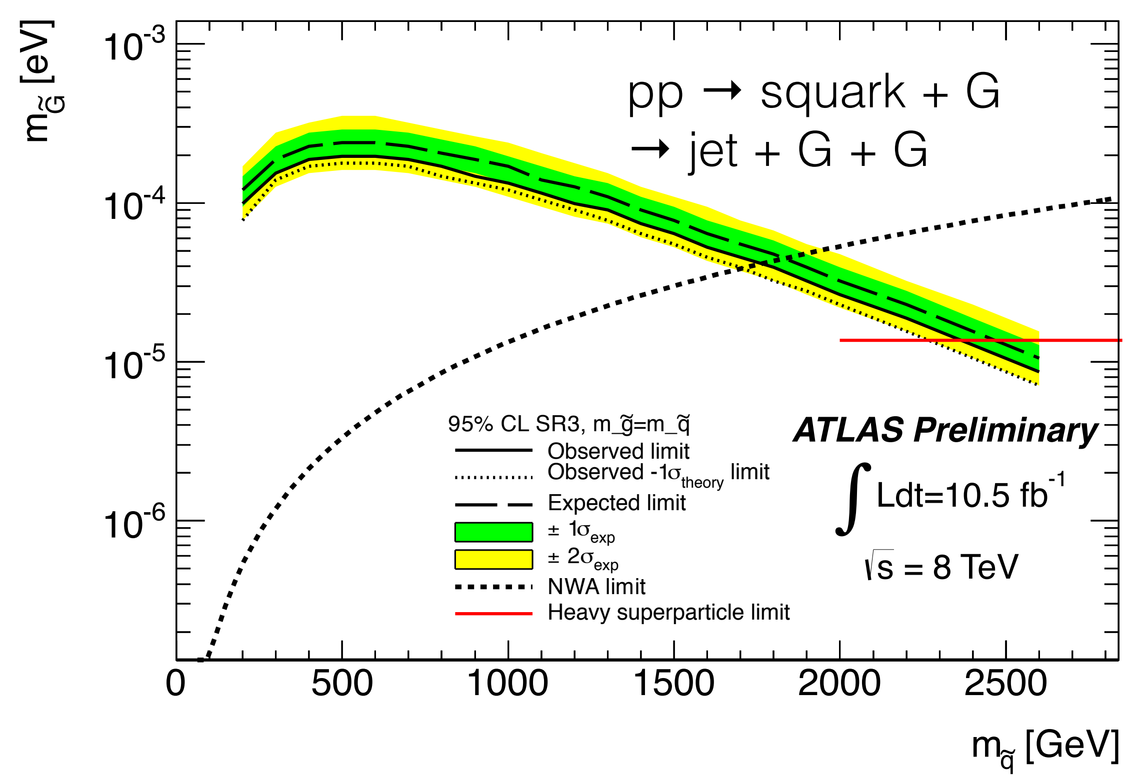
Diagram borrowed from Tai Sakuma

Monojets: WIMP interpretation

ATLAS-CONF-2012-147



Exclusions for generic WIMP model

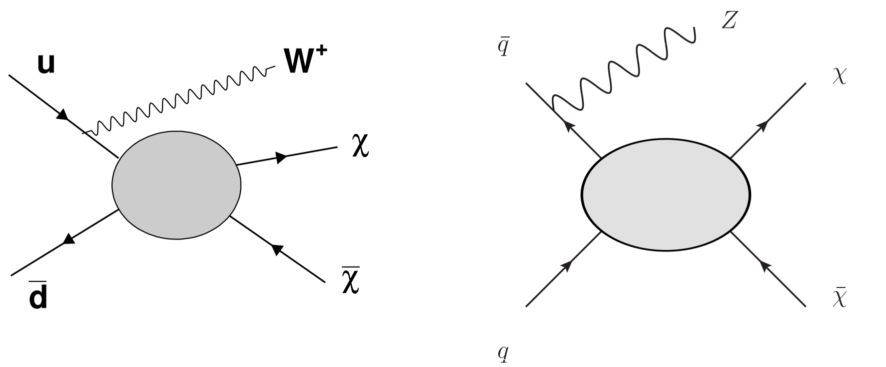


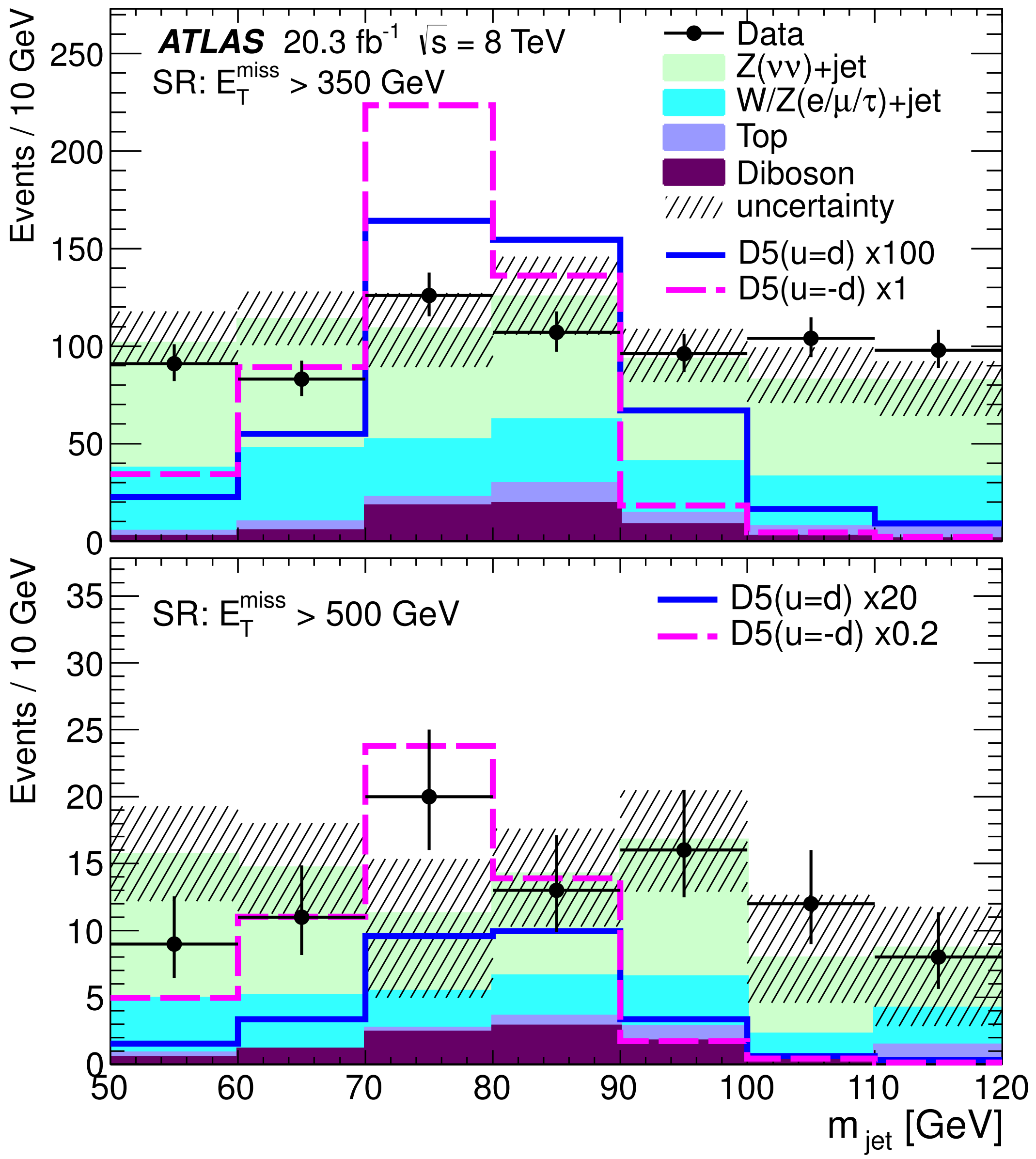
Exclusion in the GMSB SUSY paradigm

DM production in association with hadronically decaying W/Z

arXiv:1309.4017

similar to Monojet, but specific to associated W/Z production:



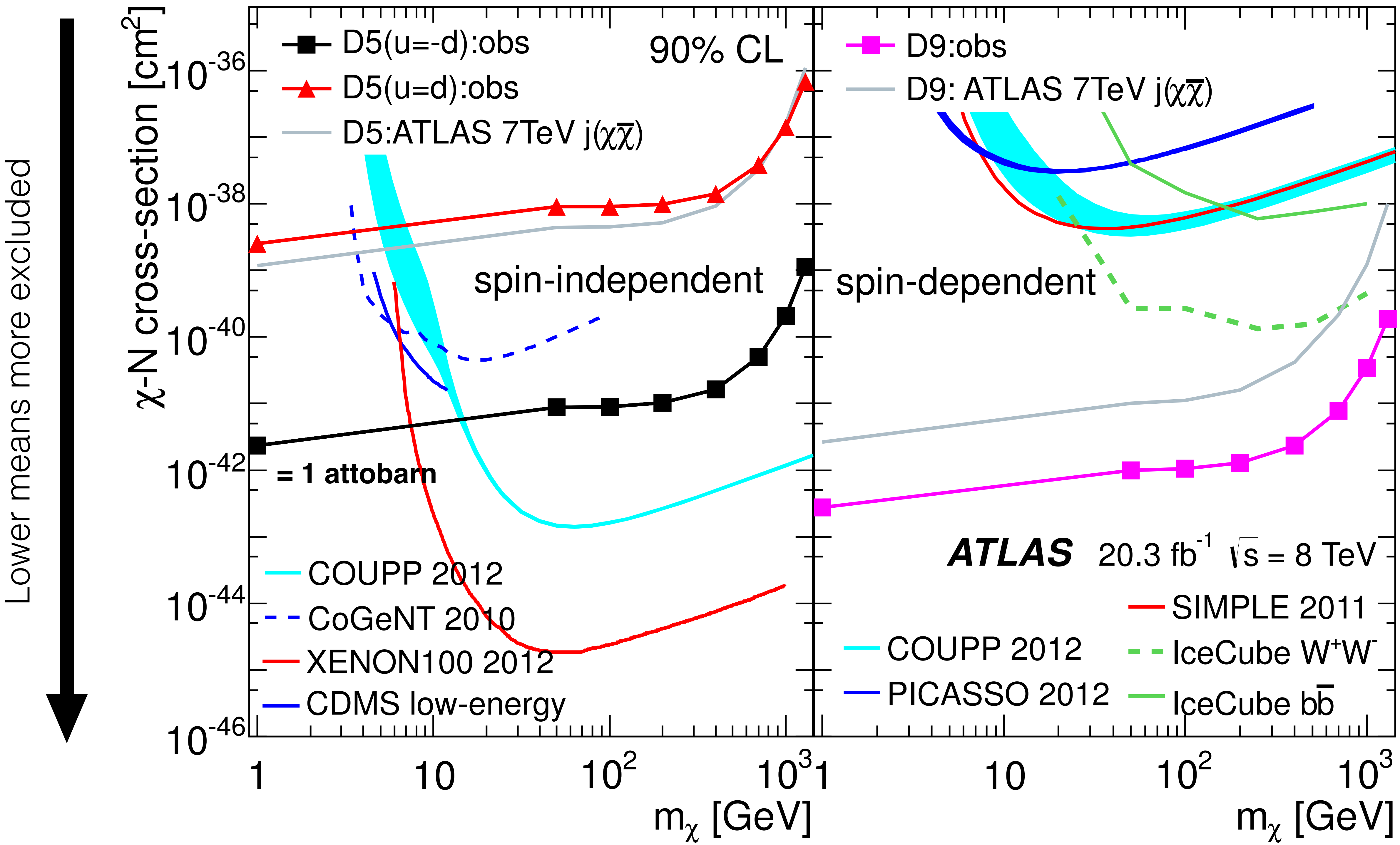


Use jet substructure techniques to reconstruct the W or Z:

- Cambridge-Aachen jet, R = 1.2, with:
  - $p_T > 250$ GeV
  - $|\eta| < 1.2$
  - $50 < m_{jet} < 120$ GeV
- reject additional leptons/jets
- two signal regions:
  - $E_T^{miss} > 350$ GeV
  - $E_T^{miss} > 500$ GeV

Interpreting the results: ATLAS competitive at low WIMP mass

Naive SUSY neutralino lsp WIMP miracle cross-section around **~ 10^{-39} cm^{-2}**
Slightly more acrobatics with Higgs couplings puts it at ~10^{-44} cm^{-2}



arXiv:1309.4017

State of WIMP Dark Matter

“WIMP miracle” would have been nice - no sign of it so far.

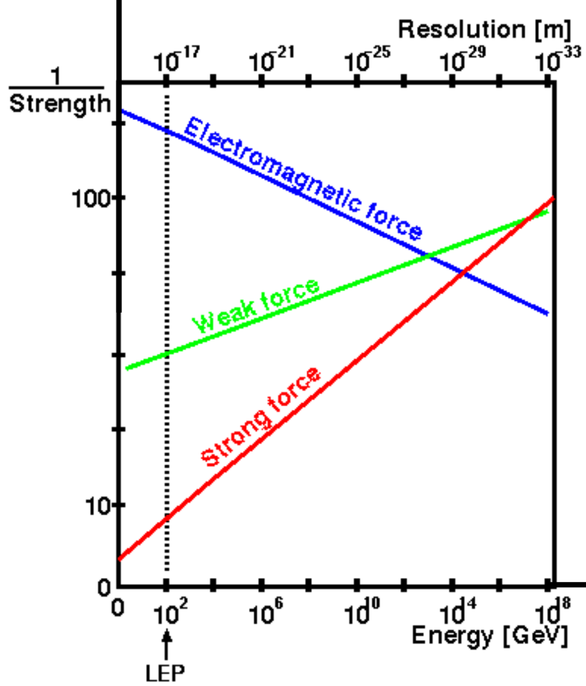
WIMP could still hide in fancier SUSY models
- or something more exotic

Extra Dimensions and Black Holes: Descent into Hades

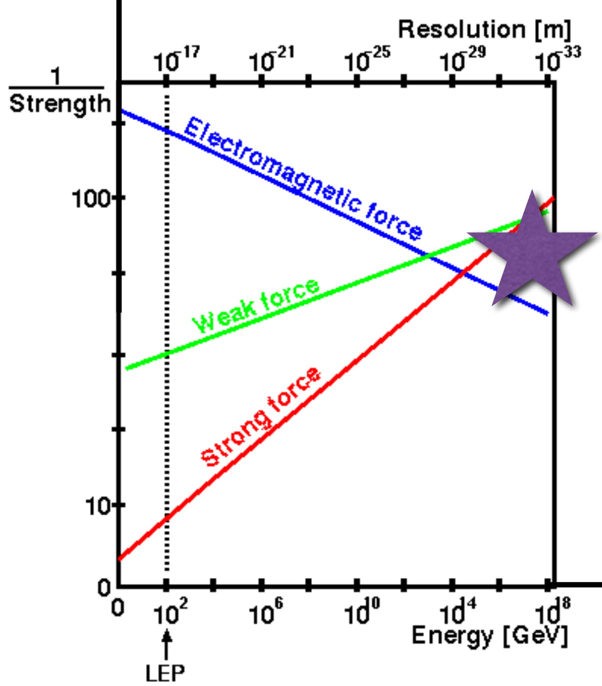
$$F = \frac{GM_1M_2}{r^2}$$

Big Hierarchy Problem

(not to scale… t'is pretty big)



No Hierarchy Problem?



Extra Dimensional Models

If $M_{Planck} \approx m_{EW}$, most of gravity must be going somewhere else

Assume there exist one or several **small extra dimensions** of **radius R**.

At large distances, they are closed and do not appear to exist.

$$V(r) \sim \frac{m_1 m_2}{\underbrace{M_{Pl(4+n)}^{n+2} R^n}} \frac{1}{r}, \; (r \gg R)$$

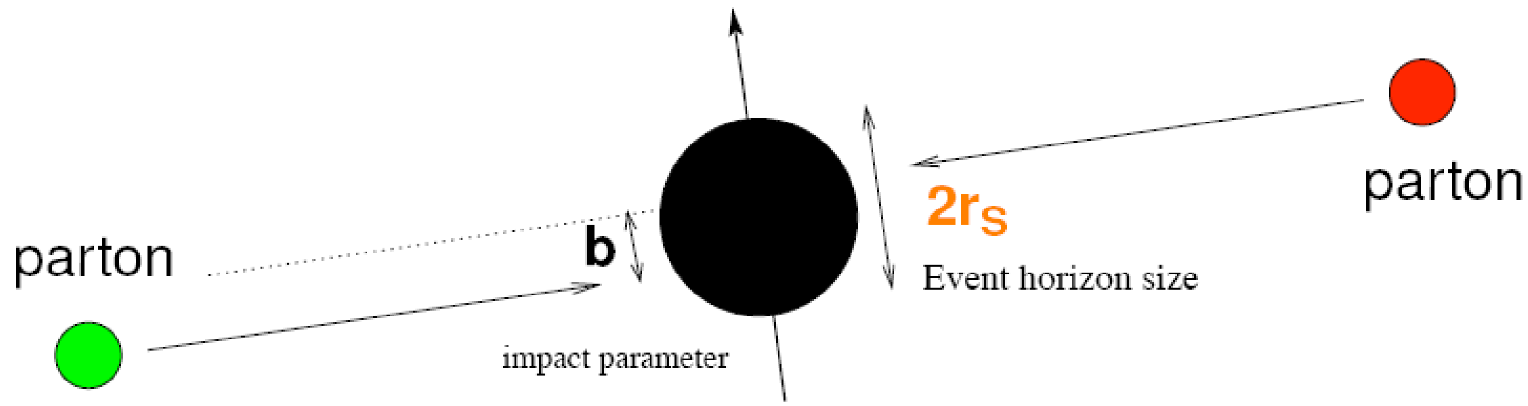
Our "normal" M_{Planck} $\longrightarrow$ $M_{Pl}^2 \sim M_{Pl(4+n)}^{2+n} R^n$

At small distances, they change the potential of gravity:

Modified M_{Planck} (now referred to as M_D)

$$V(r) \sim \frac{m_1 m_2}{M_{Pl(4+n)}^{n+2}} \frac{1}{r^{n+1}}, \; (r \ll R). \qquad M_{Pl(4+n)} \sim m_{EW}$$

Exciting consequence: Black Holes



Randall-Sundrum	ADD Models	
one warped dimension	several flat dimensions	
	Classical Black Holes	Quantum Black Holes
current energies too low to produce Black Holes	$M_{th} > M_D$ required	$M_{th} = M_D$
probed indirectly in resonance searches	semi-classical decay via Hawking radiation	non-classical decays
	high object multiplicty	usually 2-body decay

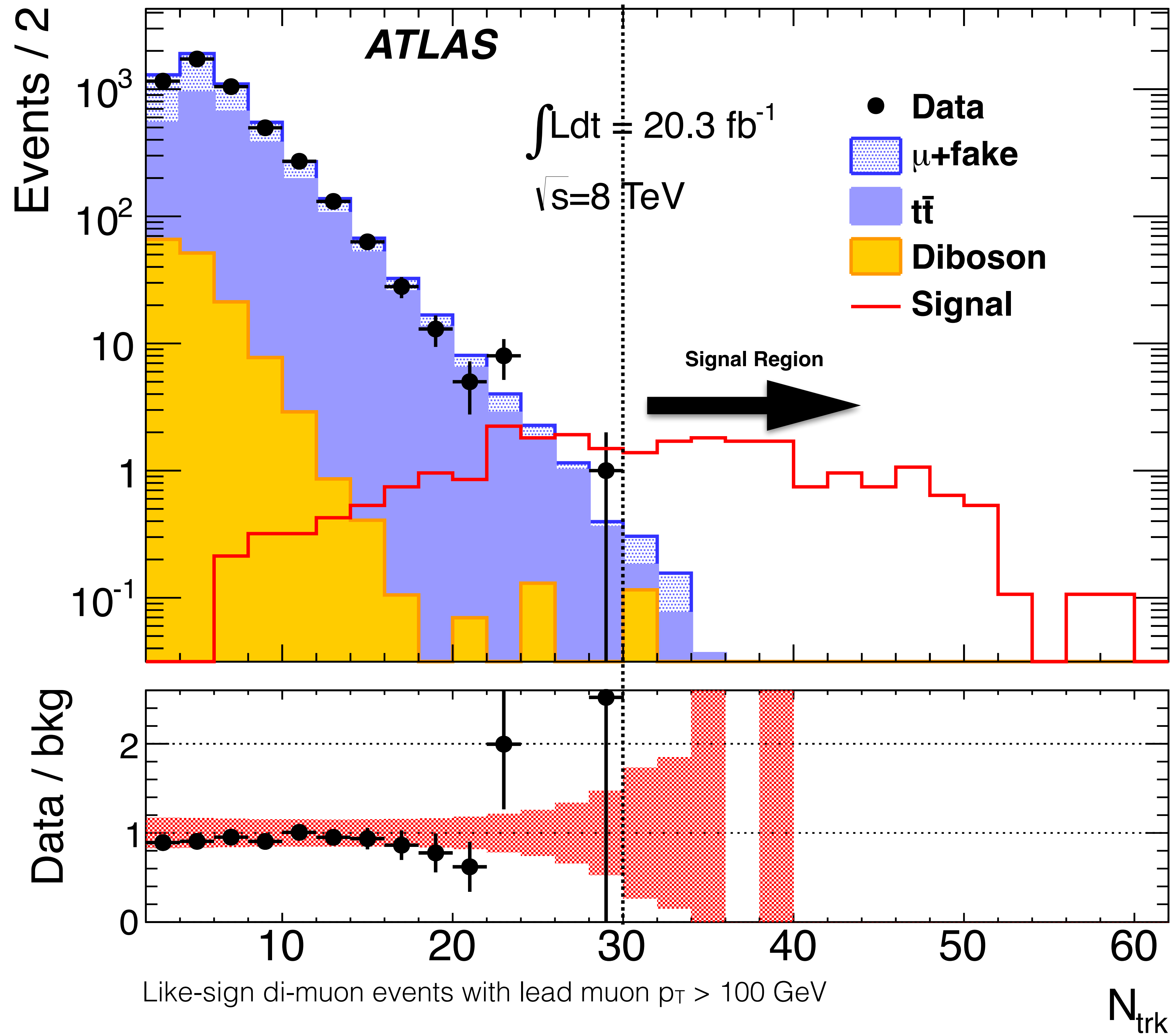
Diagram borrowed from James Frost

Classical black holes in $\mu\mu$-final state

arXiv:1308.4075

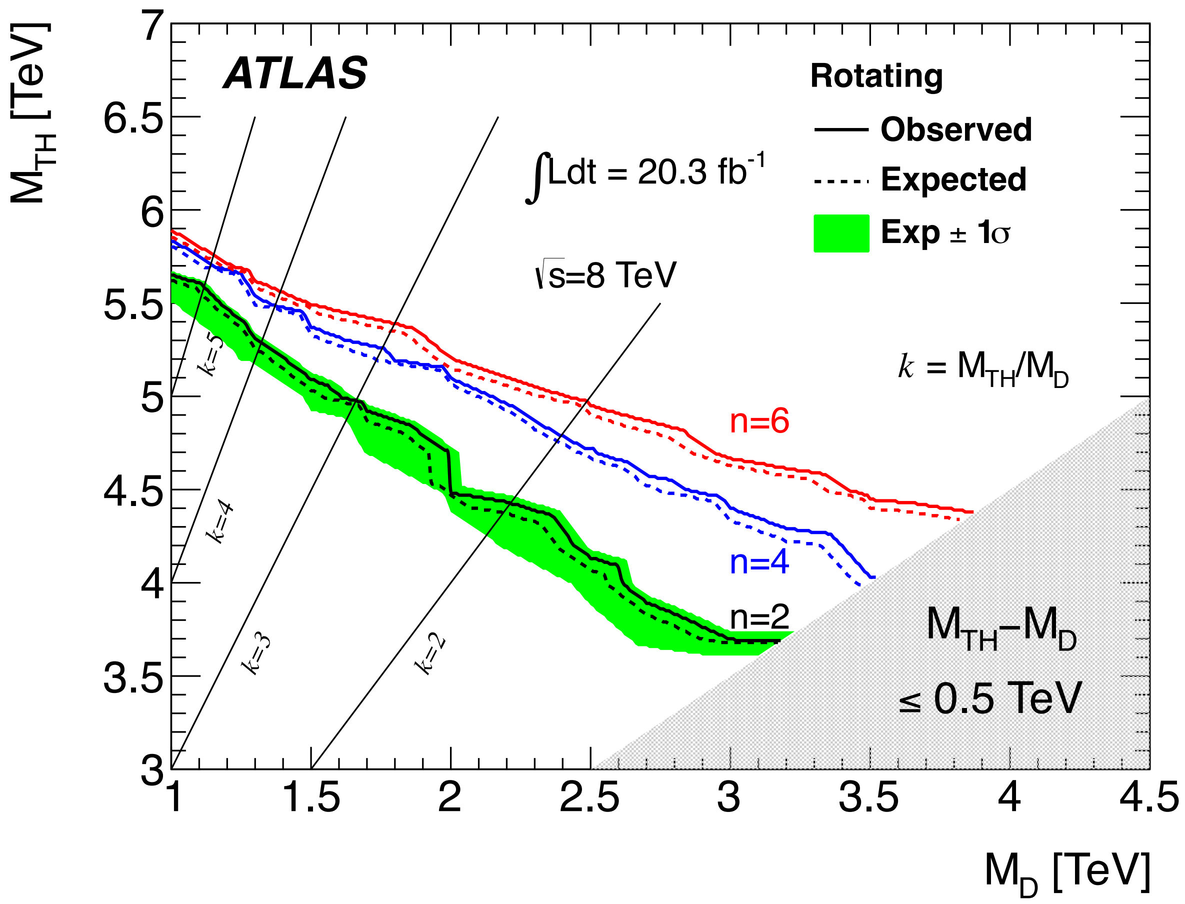
- two same-sign muons
  - lead muon p_T > 100 GeV
- nTracks (above 10 GeV) ≥ 30

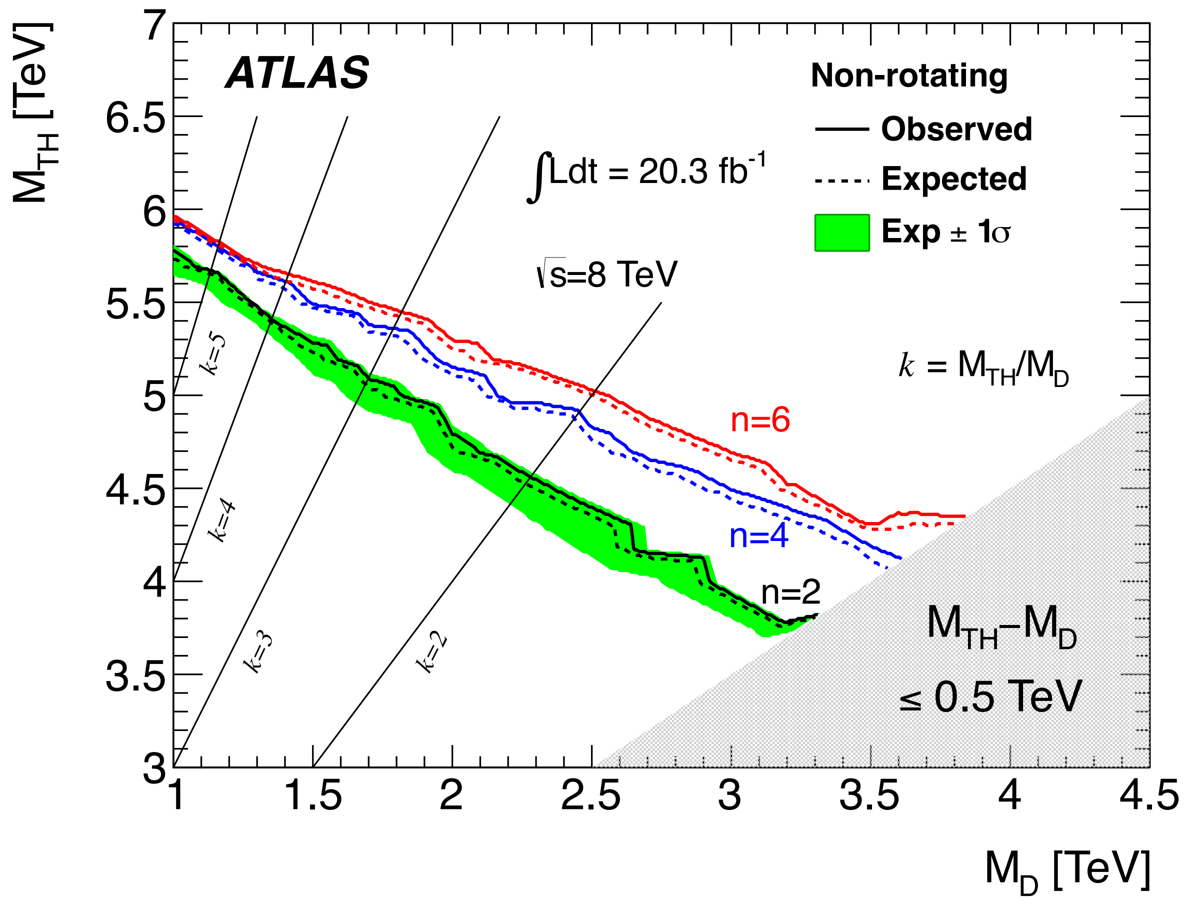
Signal acceptance: 0.2% - 11%



Like-sign di-muon events with lead muon p_T > 100 GeV

Classical Black Holes interpretation





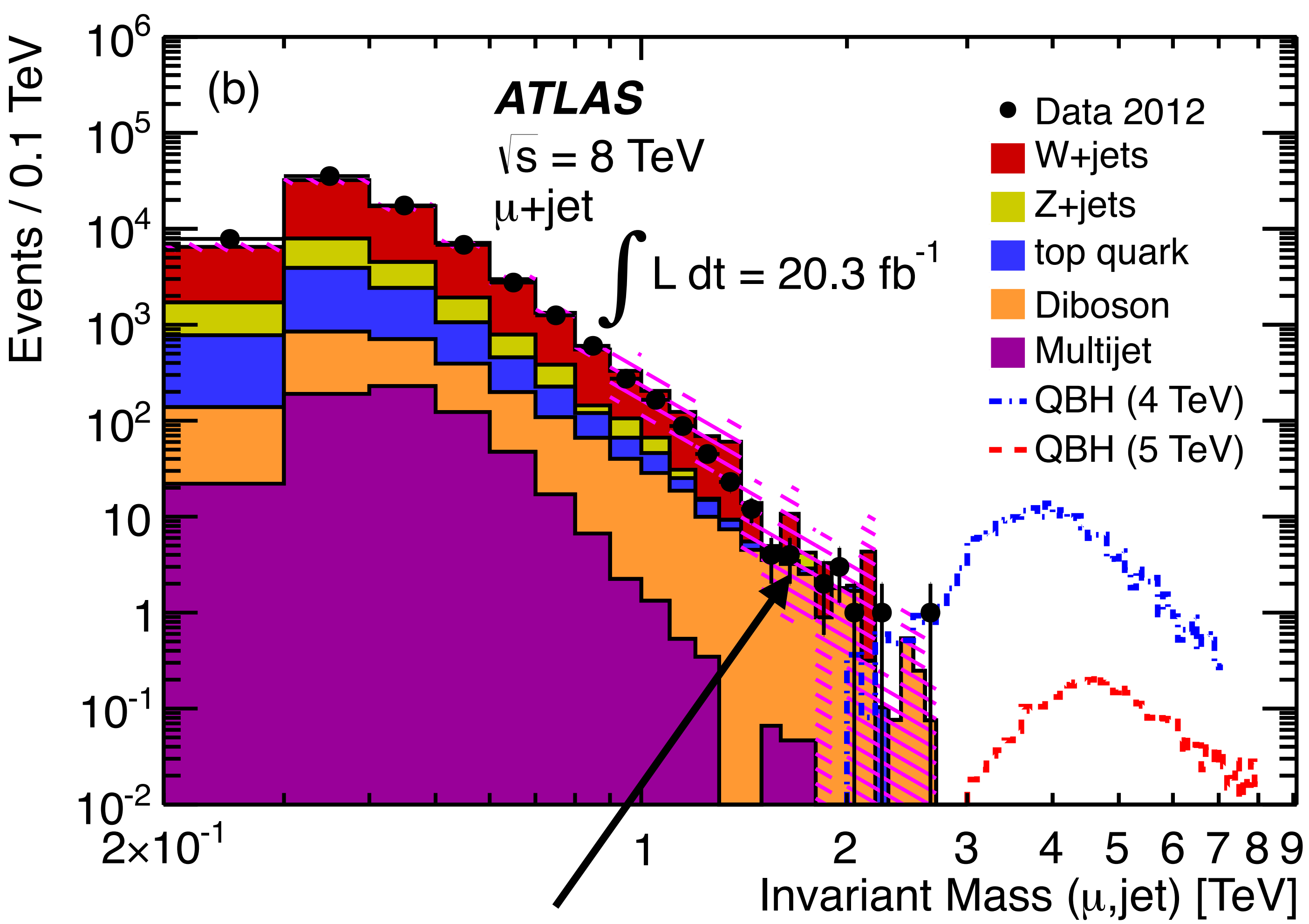
arXiv:1308.4075

Quantum Black Holes in the Lepton + Jets Final State

arXiv:1311.2006

Stage I: Monte Carlo Driven

- require exactly 1 lepton with $p_T > 130$ GeV
- construct invariant mass with hardest jet



Low Monte Carlo statistics in tail

Stage II: Fits

Smooth out statistical variations by fitting the invariant mass distribution to an analytic function.

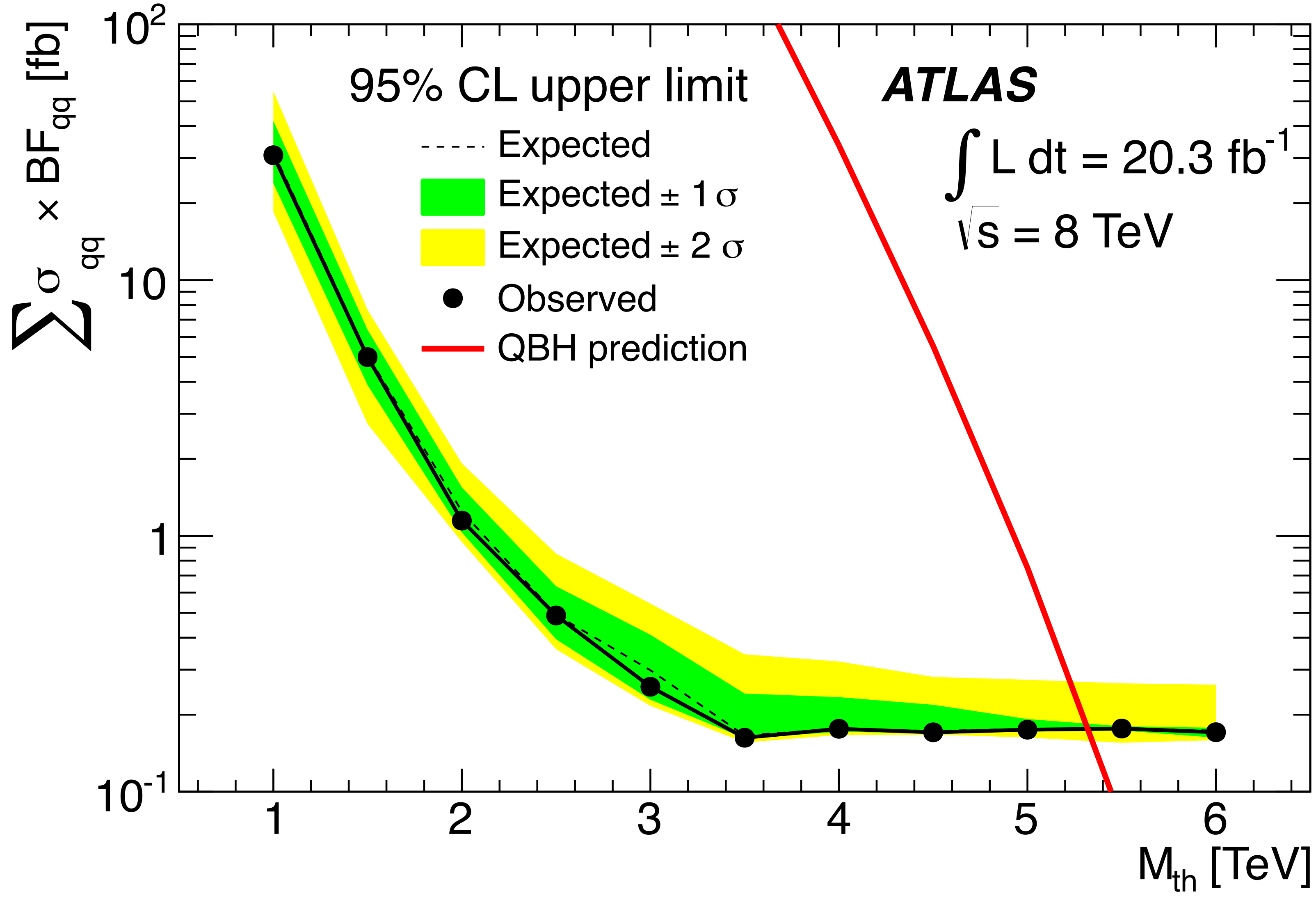
$f(x) = p_1\, x^{p2+p3\,\ln(x)}\, (1-x)^{p4}$

Largest uncertainty is choice of fit function — order 100 %

Define several signal regions in slices of invariant mass

Quantum Black Hole Interpretation

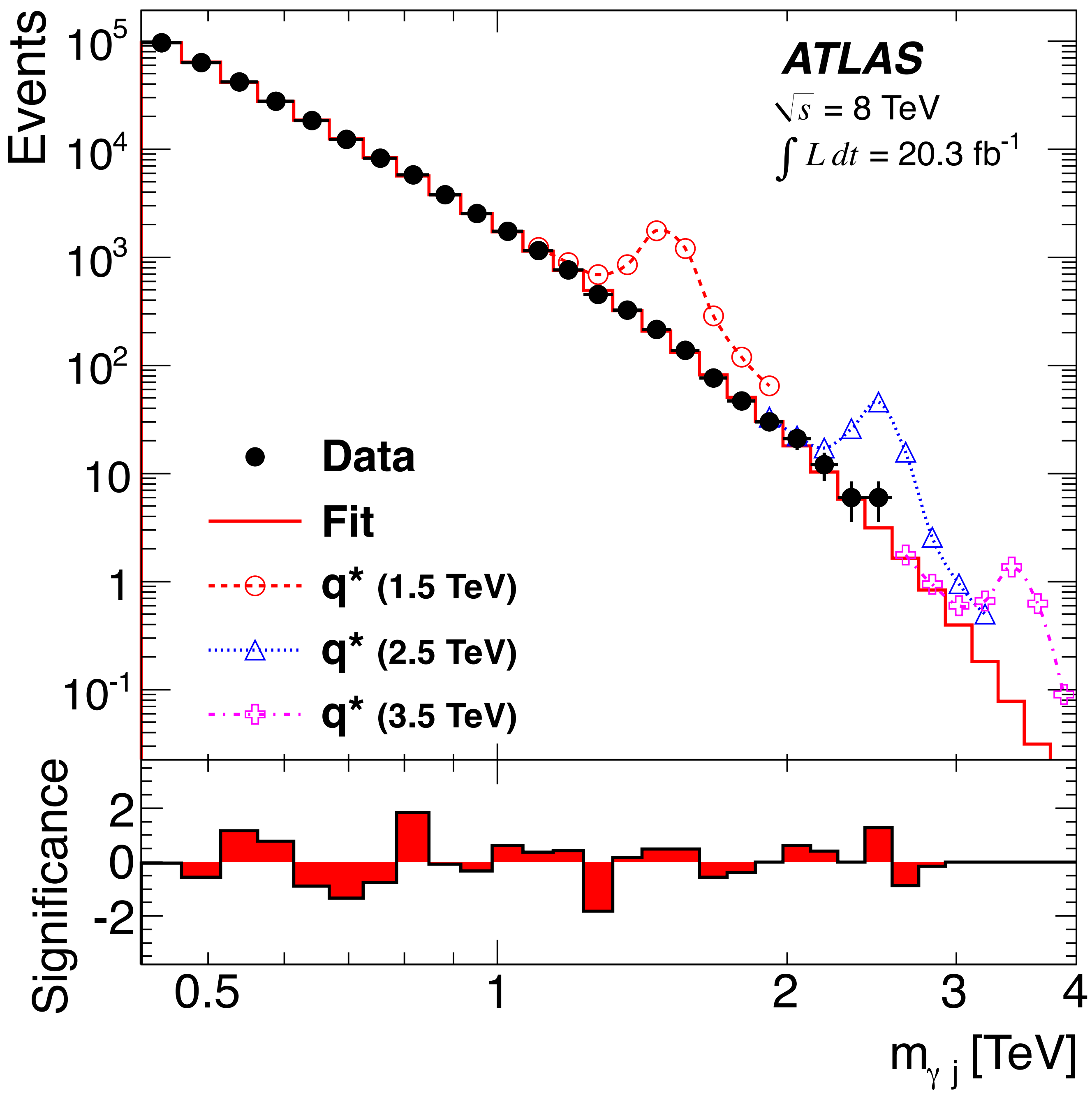
$M_D = M_{th}$ and $n = 6$



arXiv:1311.2006

Photon + Jets

- select events with photon and jet, each with p_T > 125 GeV
- construct invariant mass
- fit to function: $f(x) = p_1 x^{p_2+p_3 \ln(x)} (1-x)^{p_4}$
- hunt for bumps

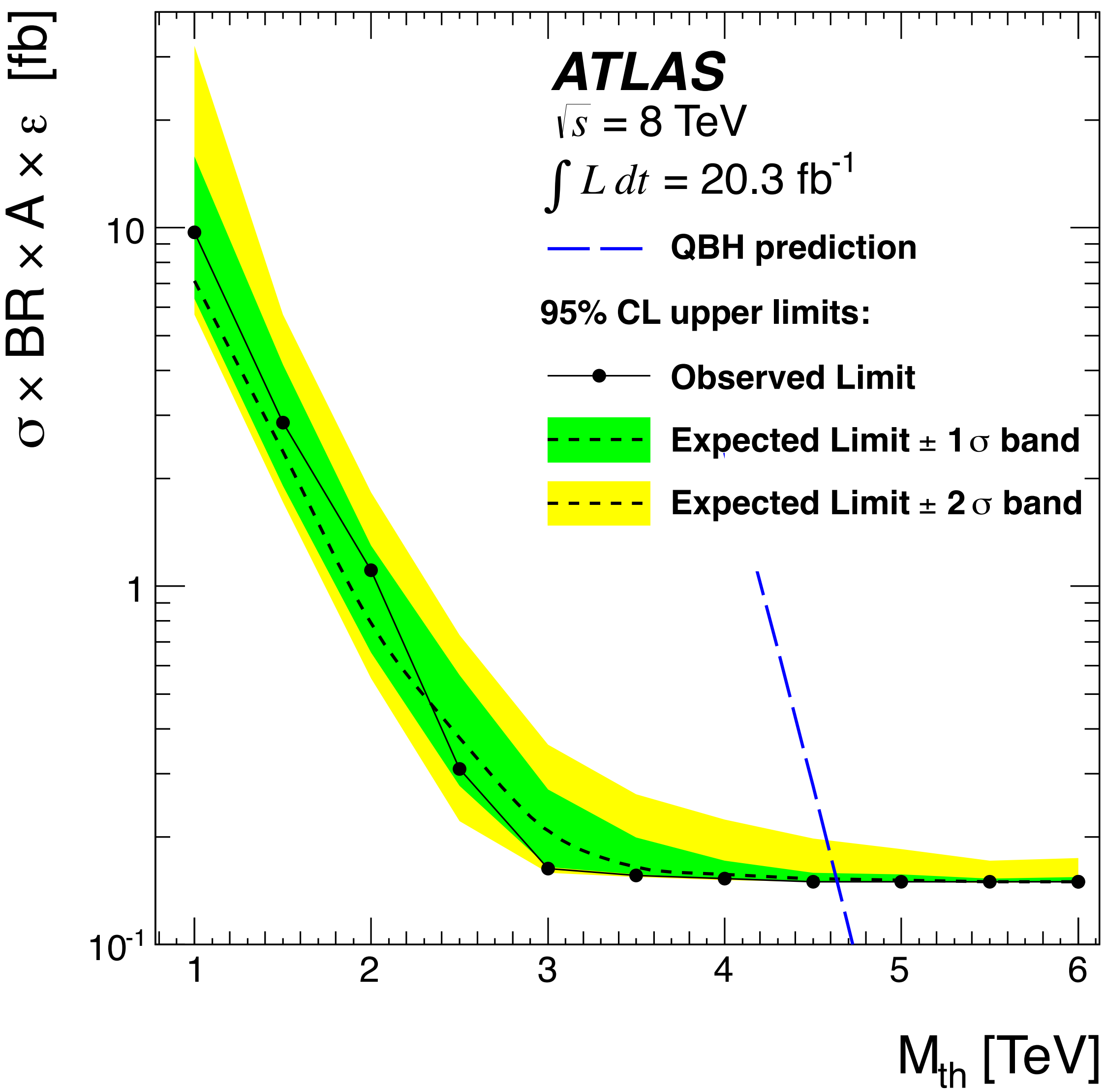


arXiv:1309.3230

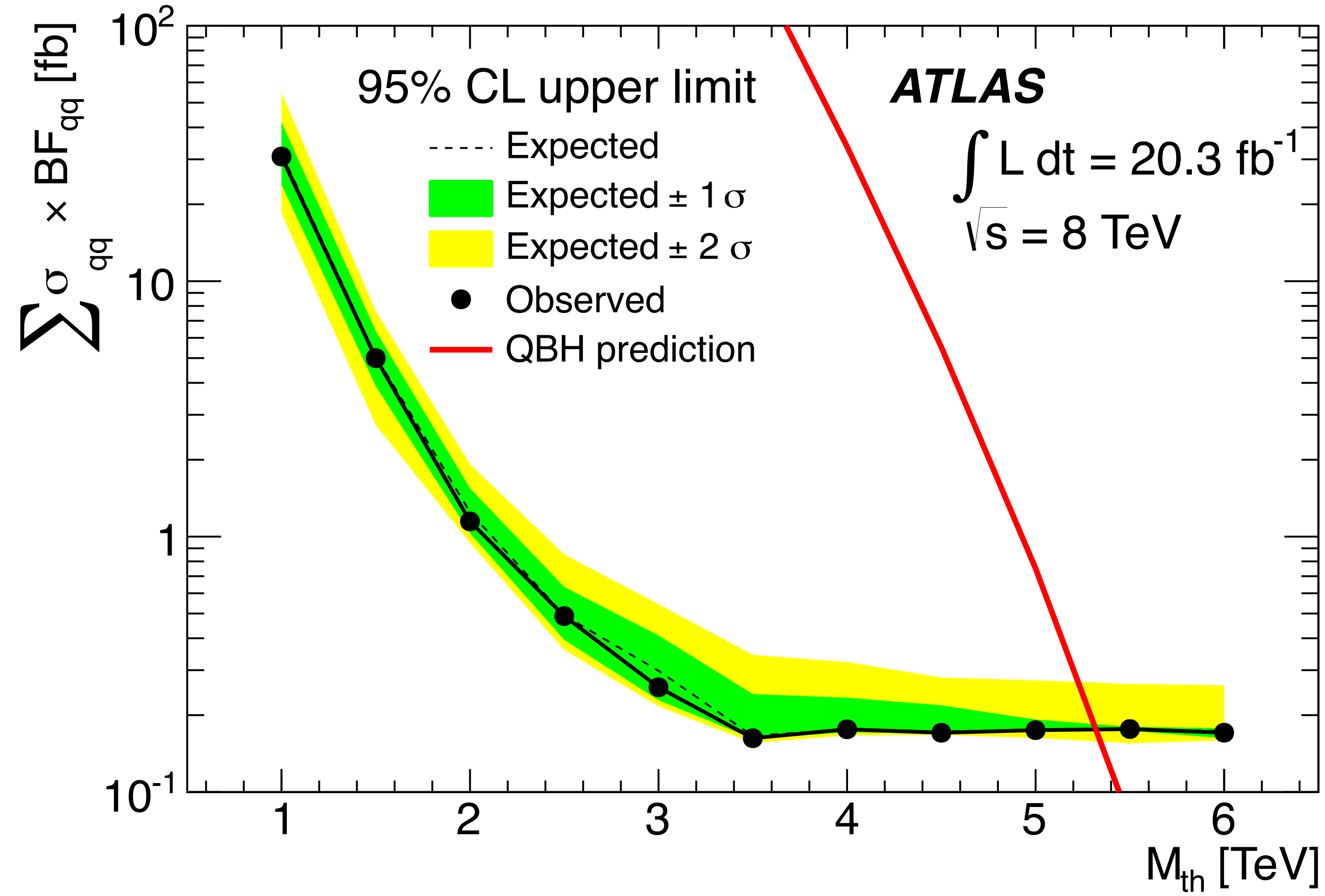
Quantum Black Hole interpretations

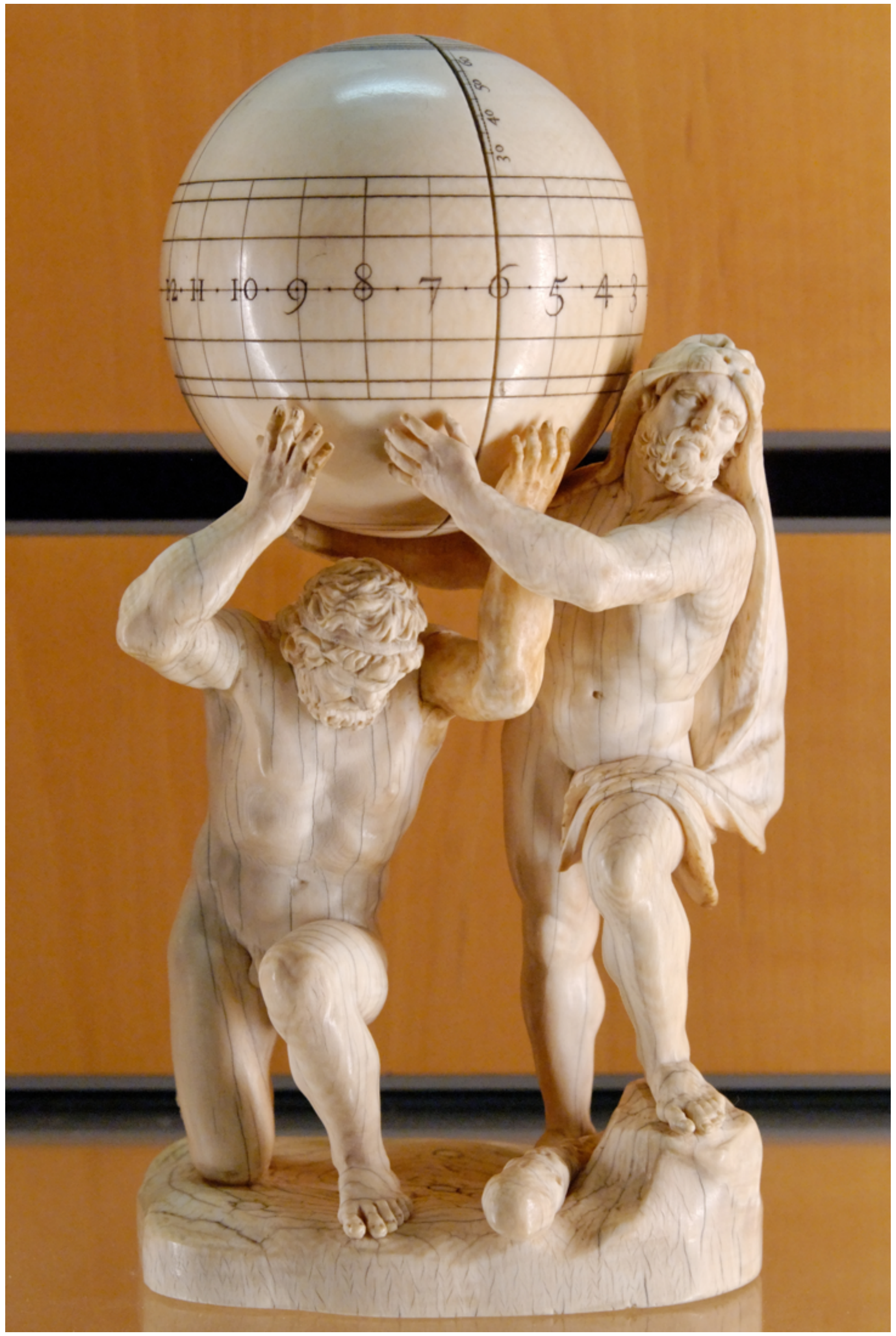
$M_D = M_{th}$ and n = 6

Photon + Jets



QBH Analysis





We looked very hard, and saw nothing

Considered a wide spectrum of search methods and final states

Run II at 13 TeV will be very exciting

Atlas did get the golden apples for Hercules…

Backup

Dark matter pair production - additional material

- C1 scalar, D1 scalar, D5 vector (both the constructive and destructive interference cases), and D9 tensor.
- In each case, mχ = 1, 50, 100, 200, 400, 700, 1000 and 1300 GeV are used.
- simulated with MG

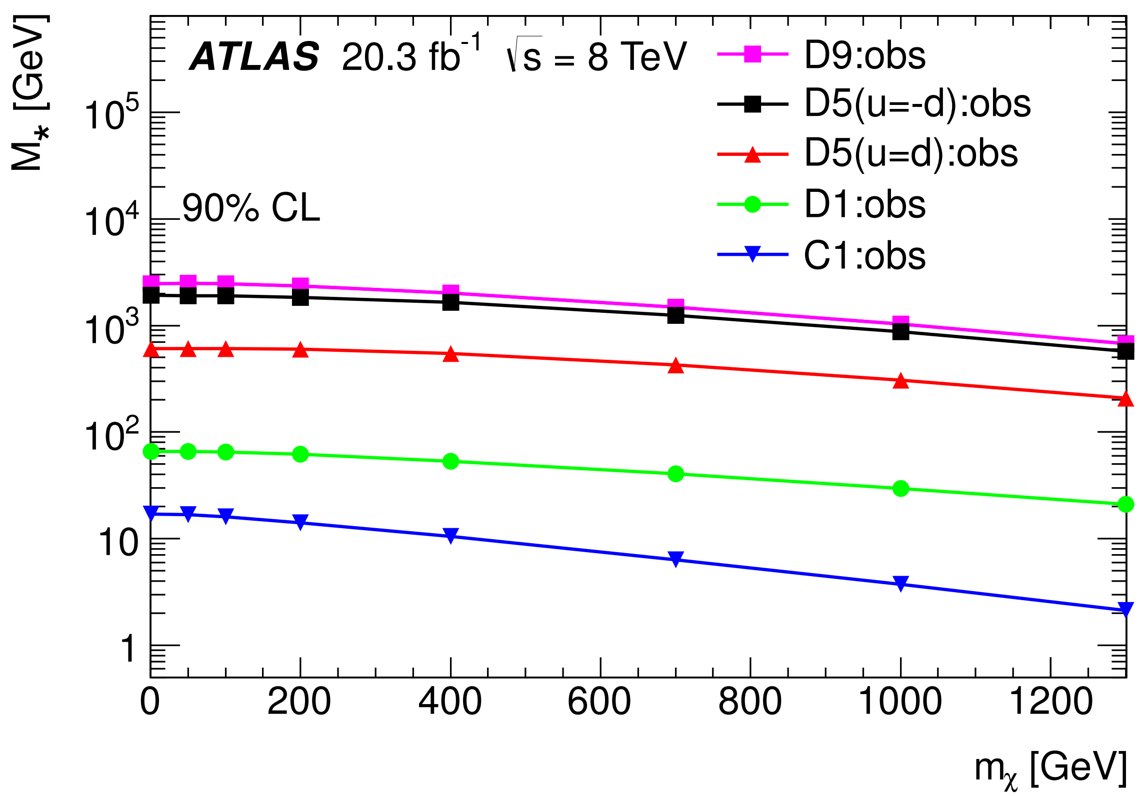
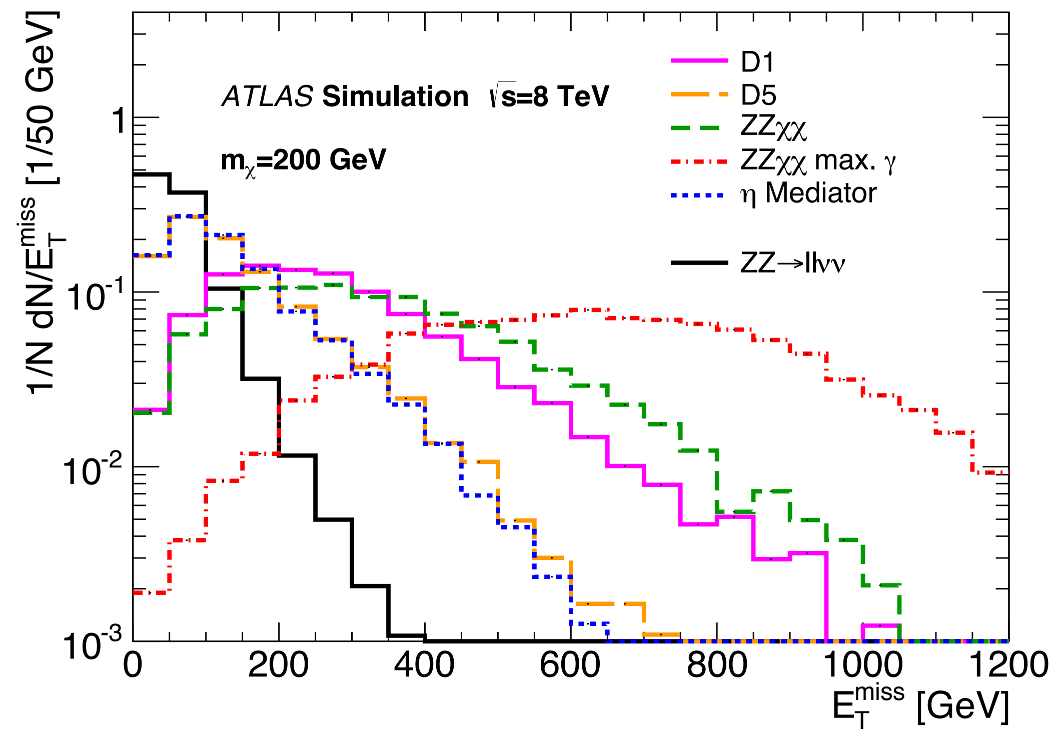


TABLE I: Data and estimated background yields in the two signal regions. Uncertainties include statistical and systematic contributions.

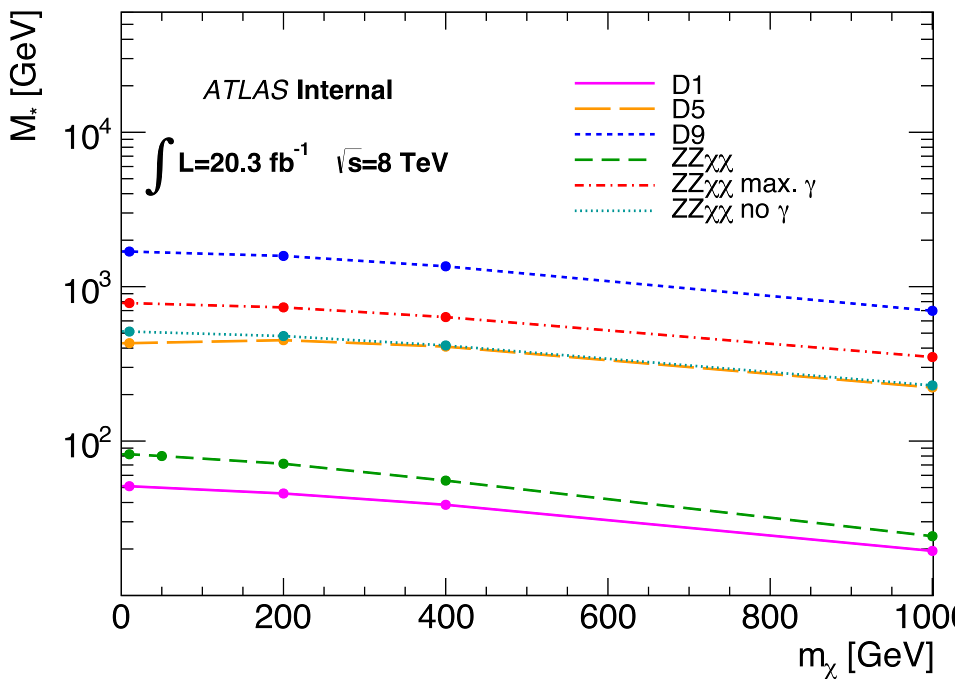
Process	$E_T^{miss} > 350$ GeV	$E_T^{miss} > 500$ GeV
$Z \to \nu\bar{\nu}$	402^{+39}_{-34}	54^{+8}_{-10}
$W \to \ell^\pm\nu$, $Z \to \ell^\pm\ell^\mp$	210^{+20}_{-18}	22^{+4}_{-5}
WW, WZ, ZZ	57^{+11}_{-8}	$9.1^{+1.3}_{-1.1}$
$t\bar{t}$, single t	39^{+10}_{-4}	$3.7^{+1.7}_{-1.3}$
Total	707^{+48}_{-38}	89^{+9}_{-12}
Data	705	89

Dark Matter with Z

- ZZ background dominant
  - estimated via ABCD method
- WZ estimated via fit and extrapolated



Process	$E_{\mathrm{T}}^{\mathrm{miss}}$ threshold [GeV] 150	250	350	450
ZZ	41.4 ± 7.1	6.4 ± 1.5	1.3 ± 0.7	0.3 ± 0.3
WZ	8.0 ± 1.7	$0.8^{+1.5}_{-0.8}$	$0.2^{+0.3}_{-0.2}$	$0.1^{+0.1}_{-0.1}$
WW, $t\bar{t}$, $Z \to \tau^+\tau^-$	1.9 ± 1.4	–	–	–
Z+jets	0.1 ± 0.1	–	–	–
W+jets	0.5 ± 0.3	–	–	–
Total	51.9 ± 8.7	7.2 ± 3.0	1.4 ± 1.2	$0.4^{+0.8}_{-0.4}$
Data	45	3	0	0



Monojets - EW background prediction

- use data-driven method for determining Z ➞ νν + Jets and W ➞ lν + Jets backgrounds

- the Alpgen MC prediction for these backgrounds is scaled by a transfer factor determined in a control region that is enriched in W ➞ μν or in W ➞ eν events .

$$N(Z(\to \nu\bar{\nu}) + jets)_{signal} = (N^{data}_{W\to\mu\nu,control} - N^{background}_{W,control}) \times \frac{N^{MC}(Z(\to \nu\bar{\nu}) + jets)_{signal}}{N^{MC}_{W\to\mu\nu,control}},$$

- other backgrounds, including multijet is estimated from simulation.

Monojet - background yields

	Background Predictions ± (stat.data)± (stat.MC) ± (syst.)			
	SR1	SR2	SR3	SR4
$Z (\to \nu\bar{\nu})$+jets	173600 ± 500 ± 1300 ± 5500	15600 ± 200 ± 300 ± 500	1520 ± 50 ± 90 ± 60	270 ± 30 ± 40 ± 20
$W \to \tau\nu$+jets	87400 ± 300 ± 800 ± 3700	5580 ± 60 ± 190 ± 300	370 ± 10 ± 40 ± 30	39 ± 4 ± 11 ± 2
$W \to e\nu$+jets	36700 ± 200 ± 500 ± 1500	1880 ± 30 ± 100 ± 100	112 ± 5 ± 18 ± 9	16 ± 2 ± 6 ± 2
$W \to \mu\nu$+jets	34200 ± 100 ± 400 ± 1600	2050 ± 20 ± 100 ± 130	158 ± 5 ± 21 ± 14	42 ± 4 ± 13 ± 8
$Z \to \tau\tau$+jets	1263 ± 7 ± 44 ± 92	54 ± 1 ± 9 ± 5	1.3 ± 0.1 ± 1.3 ± 0.2	1.4 ± 0.2 ± 1.5 ± 0.2
$Z/\gamma^*(\to \mu^+\mu^-)$+jets	783 ± 2 ± 35 ± 53	26 ± 0 ± 6 ± 1	2.7 ± 0.1 ± 1.9 ± 0.3	–
$Z/\gamma^*(\to e^+e^-)$+jets	–	–	–	–
Multijet	6400 ± 90 ± 5500	200 ± 20 ± 200	–	–
$t\bar{t}$ + single t	2660 ± 60 ± 530	120 ± 10 ± 20	7 ± 3 ± 1	1.2 ± 1.2 ± 0.2
Dibosons	815 ± 9 ± 163	83 ± 3 ± 17	14 ± 1 ± 3	3 ± 1 ± 1
Non-collision background	640 ± 40 ± 60	22 ± 7 ± 2	–	–
Total background	344400 ± 900 ± 2200 ± 12600	25600 ± 240 ± 500 ± 900	2180 ± 70 ± 120 ± 100	380 ± 30 ± 60 ± 30
Data	350932	25515	2353	268

Table 2: Number of observed events and predicted background events, including statistical and systematic uncertainties. The statistical uncertainties for data and MC simulation are shown separately. In the total background prediction the first quoted uncertainty reflects the contribution from the statistical uncertainty in the data in the control regions affecting the electroweak background estimation, the second represents the MC statistical uncertainty, and the third includes the rest of systematic uncertainties. In SR3 and SR4 selections the MC statistical uncertainty dominates. The background uncertainties in SR1 and SR2 selections are dominated by the rest of systematic uncertainties.

Classical Black Holes - background estimation

- ttbar, VV and W+jets background largest.
- track multiplicity: number of ID tracks with $p_T > 10$ GeV and $|\eta| < 2.5$ that pass quality and z_0 cuts.
- fake muon background estimated using a matrix method.

TABLE I: The systematic uncertainties on the event yields in the signal region for the different backgrounds and sources, in percent. The uncertainties on signal acceptance are also summarized in the table.

Source	μ+fake	$t\bar{t}$	Diboson	Signal
Fake rate measurement	34			
Photon trigger	13			
Prompt correction	18			
ISR/FSR		0.7		
Parton showering		9		
Generator		11	24	
Cross section		10	6	
Muon trigger		1.2	1.3	1.3
Muon reconstruction		2.0	1.2	2.3
Luminosity		2.8	2.8	2.8
Tracking efficiency		10	10	10
Fiducial efficiency				15
PDF (Acceptance)				5
Total	41	21	27	19

Source	Signal Region
μ+fake	$0.21 \pm 0.09 \pm 0.09$
$t\bar{t}$	$0.22 \pm 0.08 \pm 0.04$
Diboson	$0.12 \pm 0.08 \pm 0.03$
Total	$0.55 \pm 0.15 \pm 0.10$
Data	0
Signal	$14.2 \pm 1.3 \pm 2.7$

Signal Point: rotating BH, n=4, M_{TH} =5 TeV, M_D = 1.5 TeV

Quantum Black Hole selection

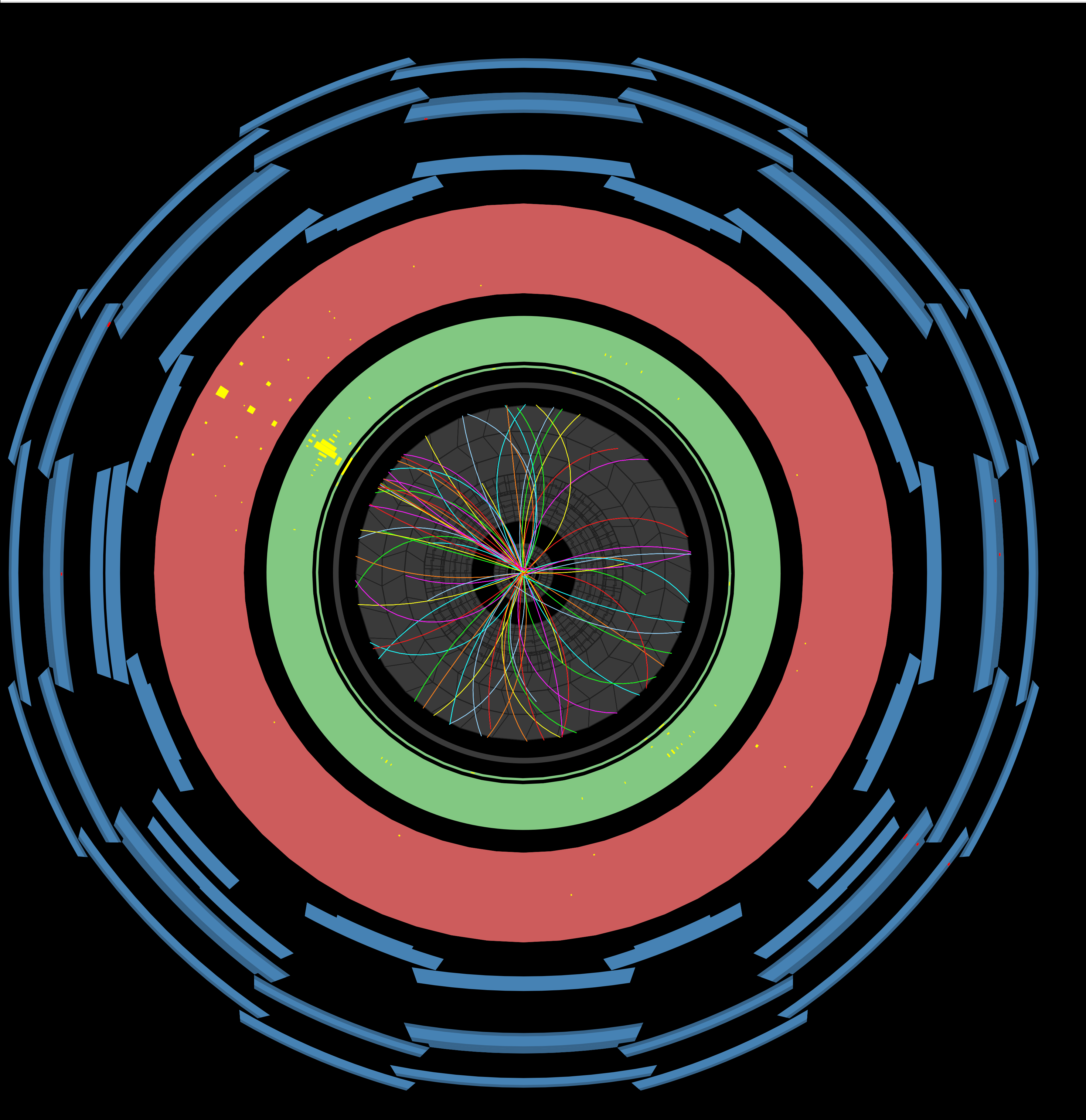
- Exactly one lepton:
  - electron: p_T > 130 GeV, |η| < 2.47
  - muon: p_T > 130 GeV, |η| < 2.4
- Jets: p_T > 50 GeV, |η| < 2.5
- construct invariant mass with lepton and highest p_T jet.
- signal acceptance is very high, ranging from 50-90 %.

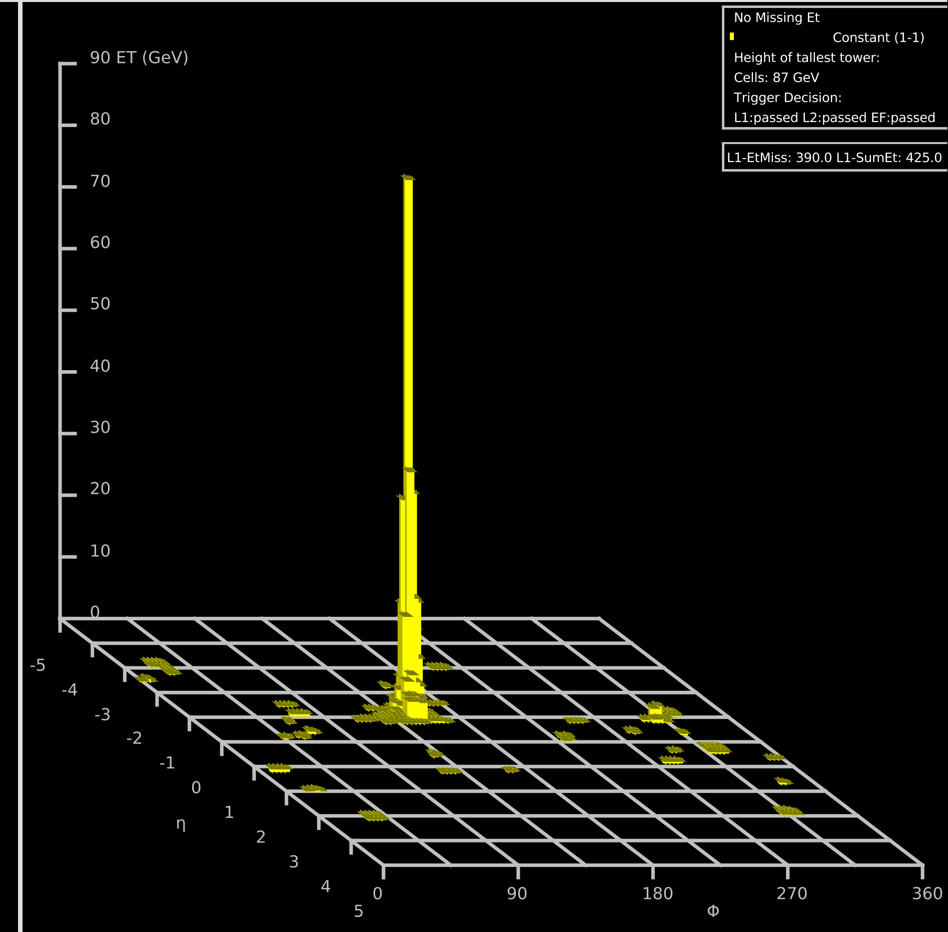
Table of relative systematic uncertainties

Source	Electron+jet %	Muon+jet %
Lepton reconstruction, scale and resolution	$^{+2}_{-1}$	$^{+30}_{-7}$
Jet reconstruction, scale and resolution	$^{+31}_{-15}$	$^{+5}_{-5}$
Multijet modeling	$^{+27}_{-27}$	-
PDF	$^{+52}_{-33}$	$^{+100}_{-69}$
Fit	$^{+77}_{-77}$	$^{+130}_{-71}$
Total	$^{+100}_{-89}$	$^{+170}_{-100}$

- Fit function: $p_1 x^{p_2 + p_3 \ln(x)} (1-x)^{p_4}$
  (with $x = m_{\text{inv}}/\sqrt{s}$ and fit parameters p_1–p_4)

Monojet event display (2011 data)





ATLAS EXPERIMENT

Run Number: 180309, Event Number: 36060682

Date: 2011-04-27 02:33:15 CEST