Exotics Searches at ATLAS

Workshop on the
Interplay between Particle and
Astroparticle Physics (IPA)

August 2014

Ruth Pöttgen
on behalf of the
ATLAS Collaboration

Bundesministerium
für Bildung
und Forschung

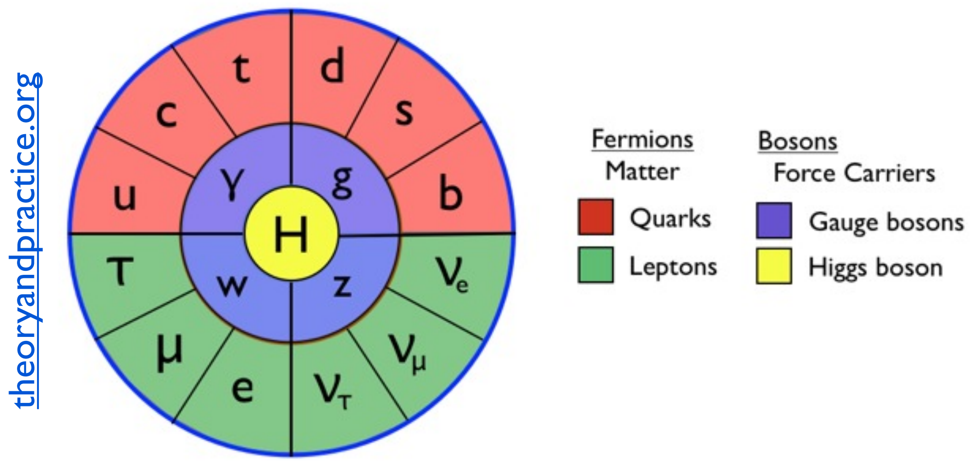
BMBF-Forschungsschwerpunkt
ATLAS Experiment
Physics on the TeV-scale at the Large Hadron Collider

FSP 101
ATLAS

PRiSMA

JOHANNES GUTENBERG
UNIVERSITÄT MAINZ

Motivation



Particles of the Standard Model

- **Standard Model** of particle physics (SM) **confirmed** with great precision in many experiments
  - even more complete with **Higgs**-discovery

- however, many **unresolved questions**
  - matter-antimatter asymmetry
  - hierarchy problem
  - dark matter/dark energy
  - ...

- one possible extension of SM providing solutions to some of the above: **SUSY**
  - not this talk, see **talk by L. Ancu** on Thursday

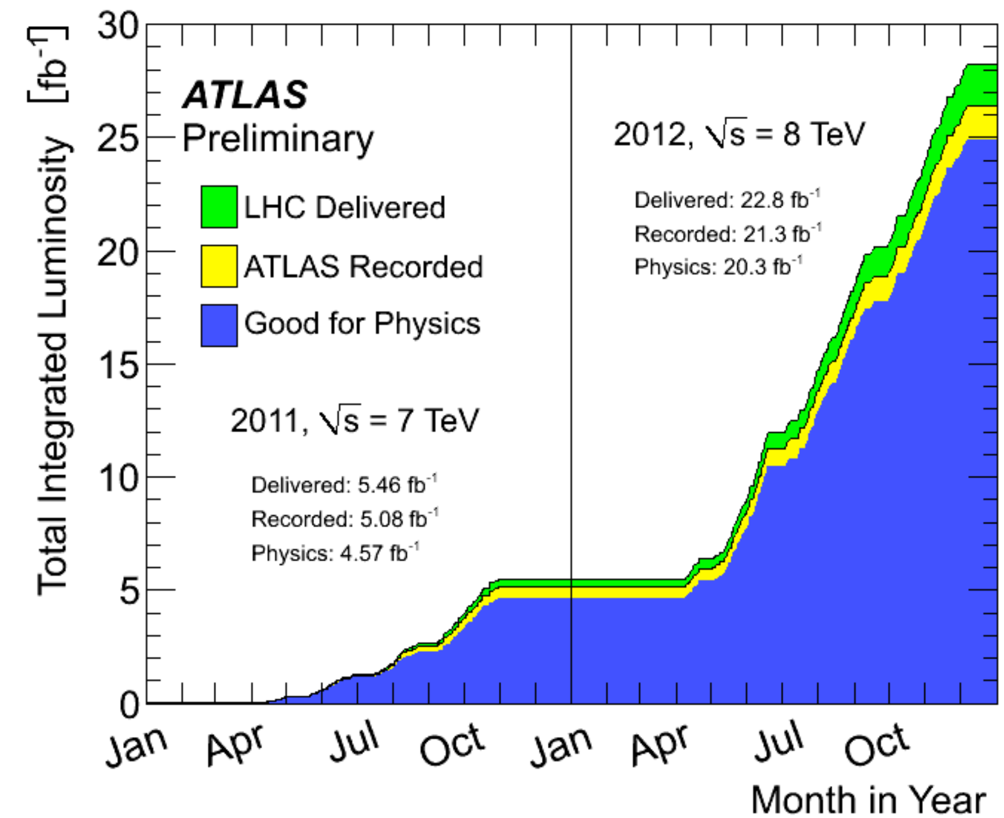
- many other suggestions for 'physics beyond the SM' (BSM): "**exotics**"

Exotics in ATLAS and in this talk

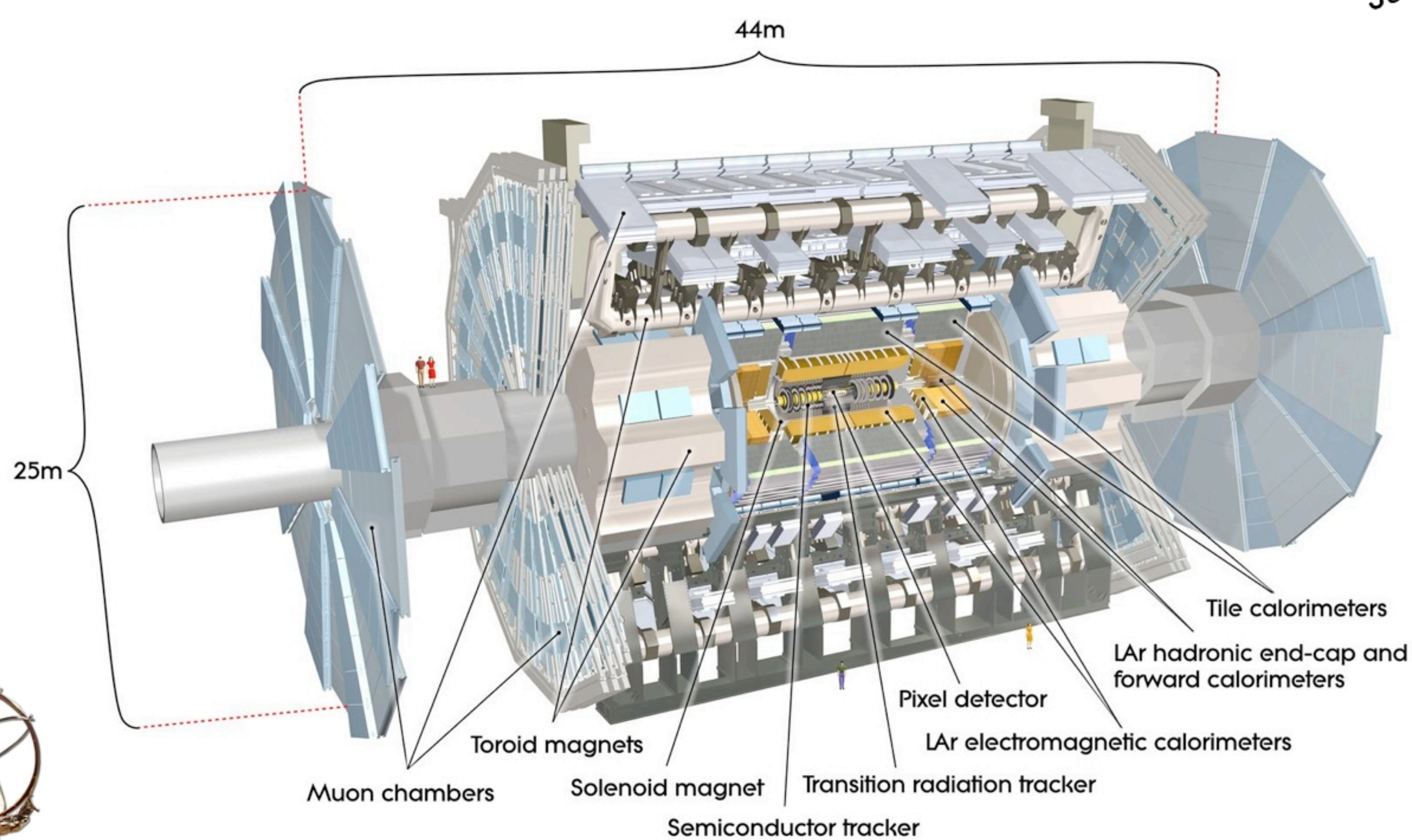
- published results with 2012 data: **14 papers, 17 CONF notes**
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
- large variety of final states/observables/models
- typical strategy:
  - consider some **discriminant variable**
  - search for **excess** above data-driven or MC based background
  - if no excess observed: set **limits**
- in this talk: only **subset** of recent results
  - special focus on mono-X **dark matter** (DM) searches
  - will also flash some of the other results
    - general search
    - new heavy/excited quarks
    - new gauge bosons
    - contact interaction (CI)
    - large extra dimensions/black holes

ATLAS and LHC

- LHC has exceeded expectations
  - ~5/fb at $\sqrt{s}$= 7TeV, ~20/fb at $\sqrt{s}$=8TeV
  - peak instantaneous luminosities of $8\times10^{33}cm^{-2}s^{-1}$
- currently shutdown to prepare for run-II
  - 13-14TeV, $10^{34}cm^{-2}s^{-1}$



- ATLAS one of 4 large experiments at the LHC
- general purpose detector, broad physics programme

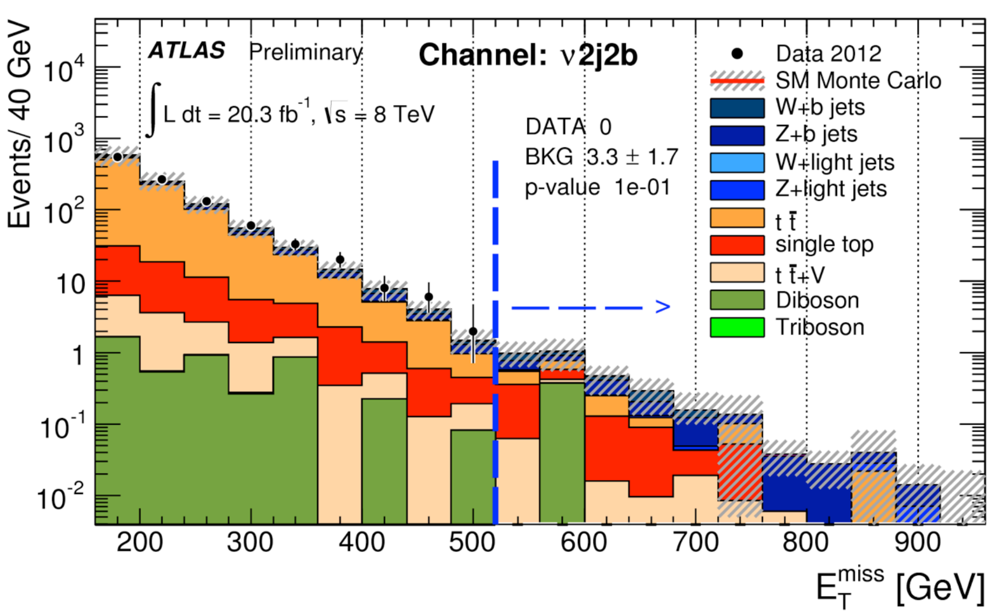


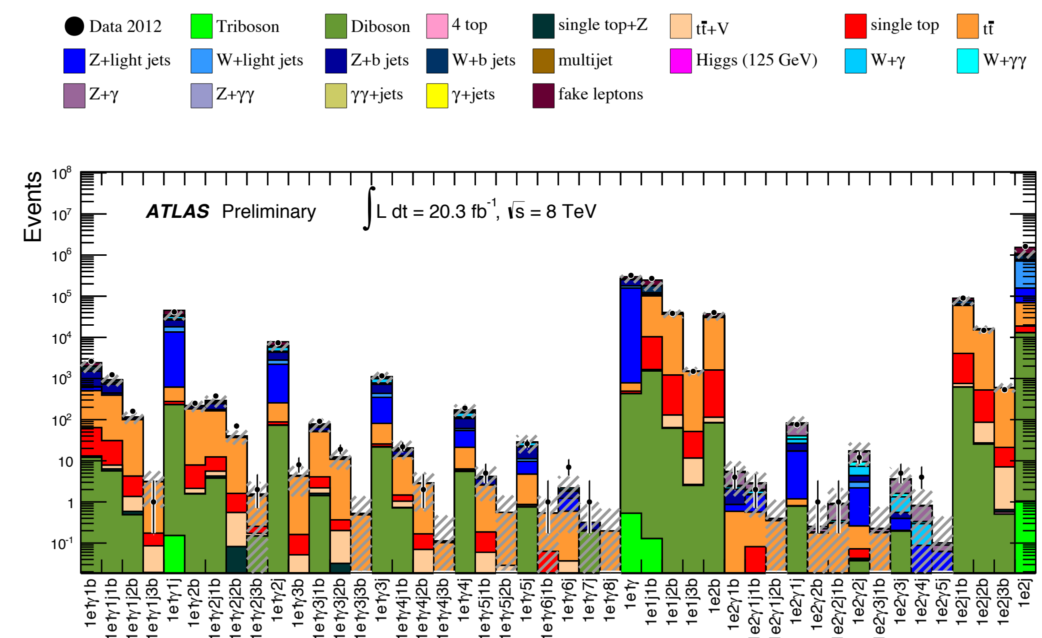
General Search

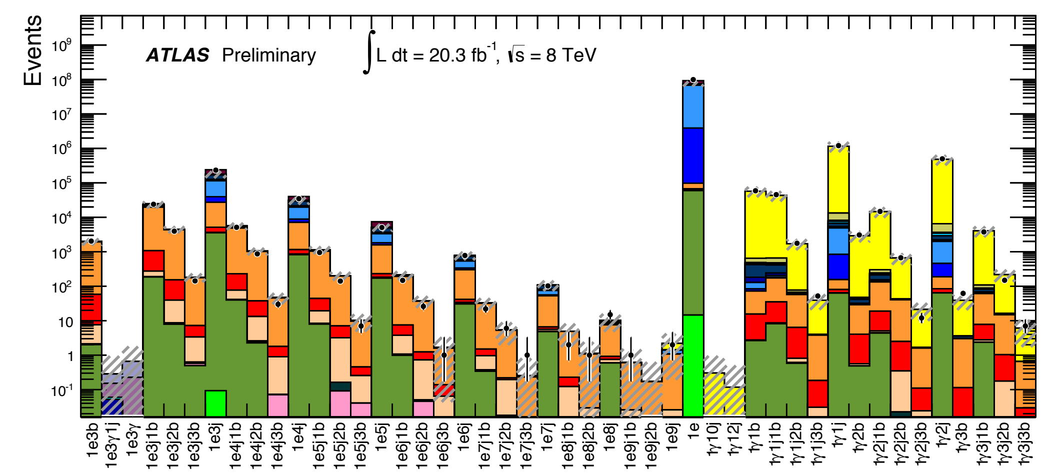
ATLAS-CONF-2014-006

20.3/fb

- no particular model, looking for deviations from SM prediction in many distributions
  - ~700 event classes, categorised based on final states
  - can involve electrons, photons, muons, (b-)jets, E_T^{miss}
  - discriminants: m_{eff}, m_{inv}, E_T^{miss}
    - m_{eff}: scalar p_T sum of all objects including E_T^{miss}
    - m_{inv}: invariant mass of all objects excluding E_T^{miss}
  - algorithm searching for regions with largest deviations







classes for which electron or photon triggers are used

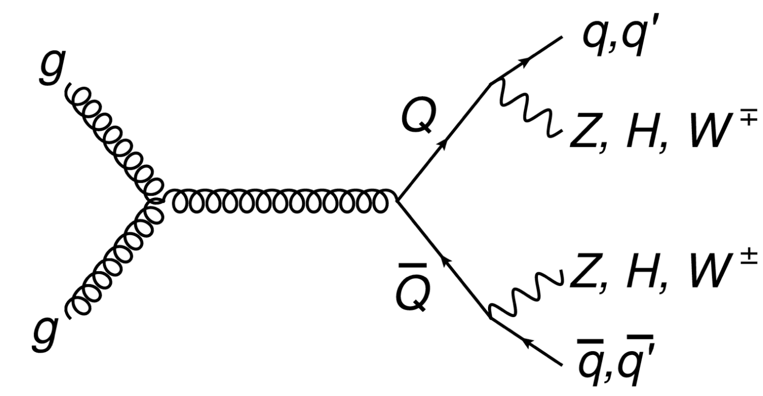
- no significant deviation observed
  - not as sensitive as optimised specific searches
    - but: comprehensive investigation

New Heavy Quarks

ATLAS-CONF-2014-036

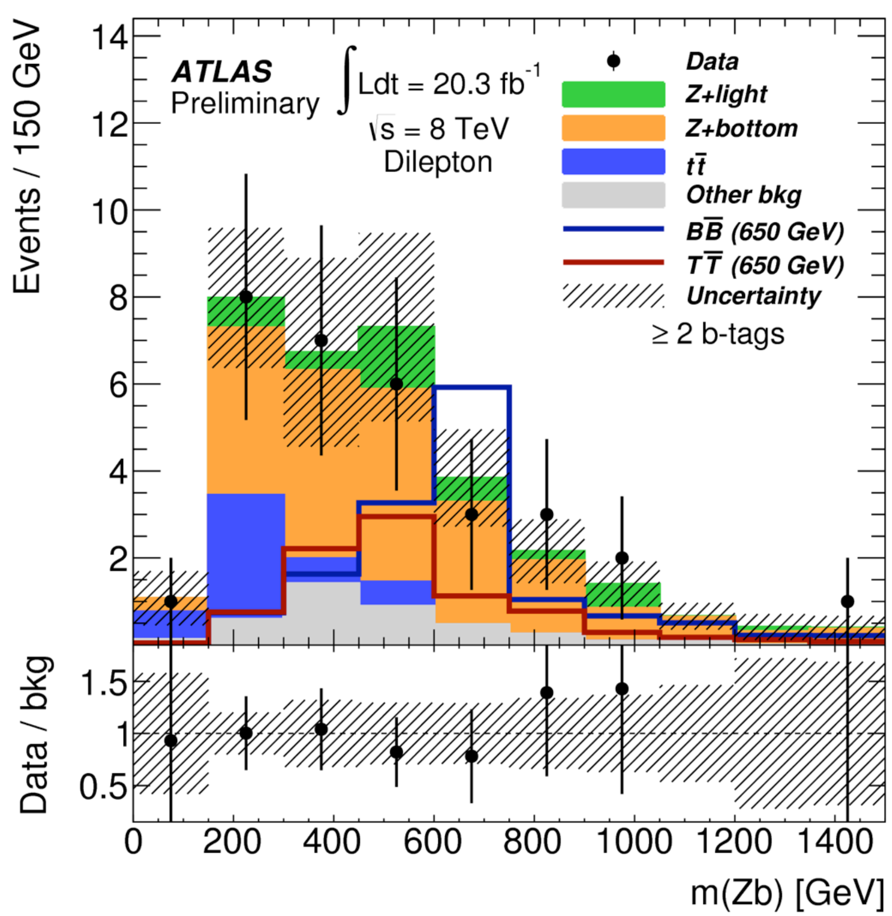
20.3/fb

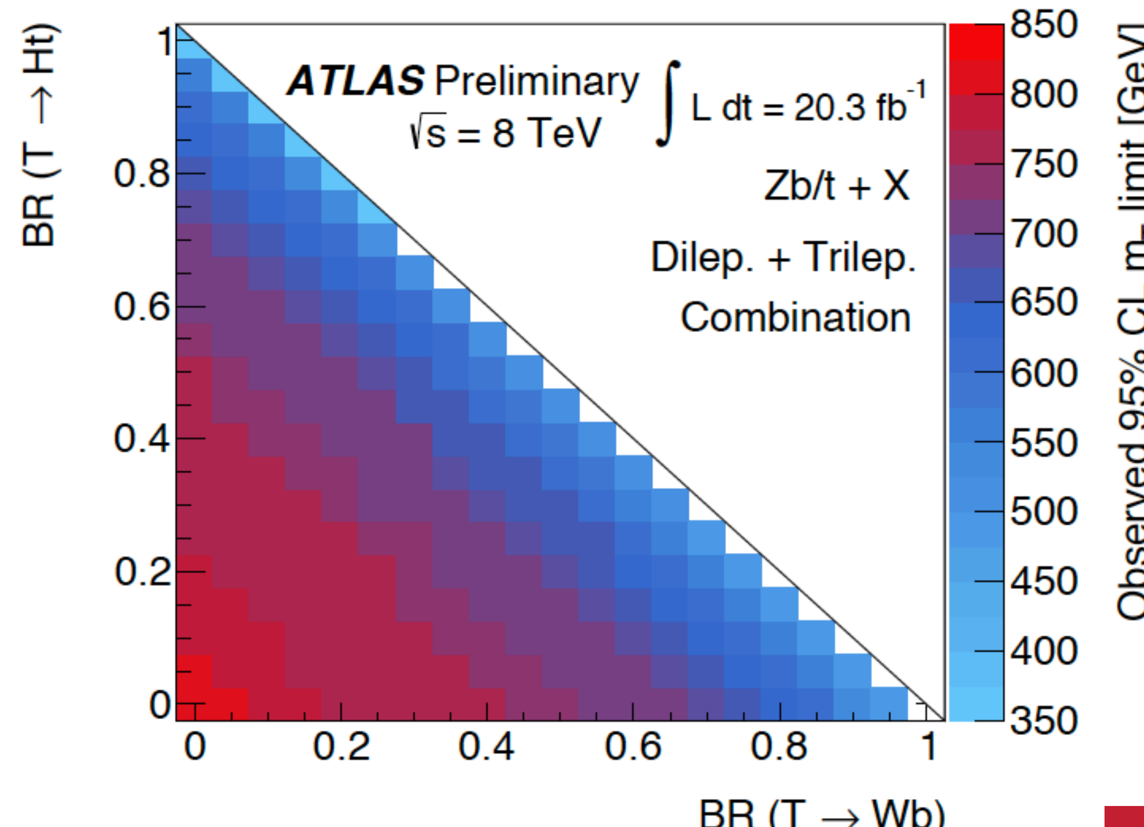
- vector-like quarks part of various non-SUSY natural models
- regulation of quadratic divergence of one-loop contributions to Higgs mass
- here: TT→Zt+X, BB→Zb+X
  (also single production considered in conf note)



here: Q=T or Q=B

- select **high p_T** (>150GeV) **Z** boson (from ee or μμ) + **(b-)jets**
- two categories: exactly 2 or ≥3 leptons
- discriminants: m(Zb) or H_T(jet+leptons) (scalar p_T sum)





New Gauge Bosons - Lepton+E_T^{miss}

arxiv:1407.7494
accepted by JHEP

20.3/fb

- new gauge bosons predicted by many BSM scenarios
- models for GUTs/solutions to hierarchy problem

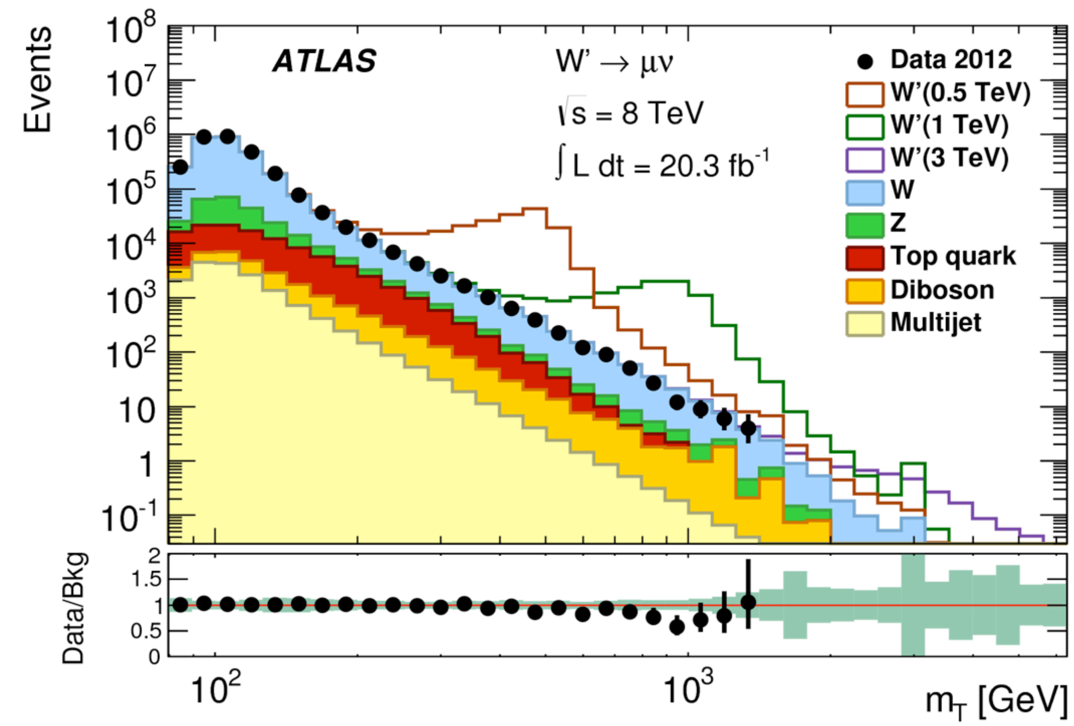
- select exactly one electron or muon
- $p_T^e > 125$GeV, $p_T^\mu > 45$GeV
- same cuts on E_T^{miss}

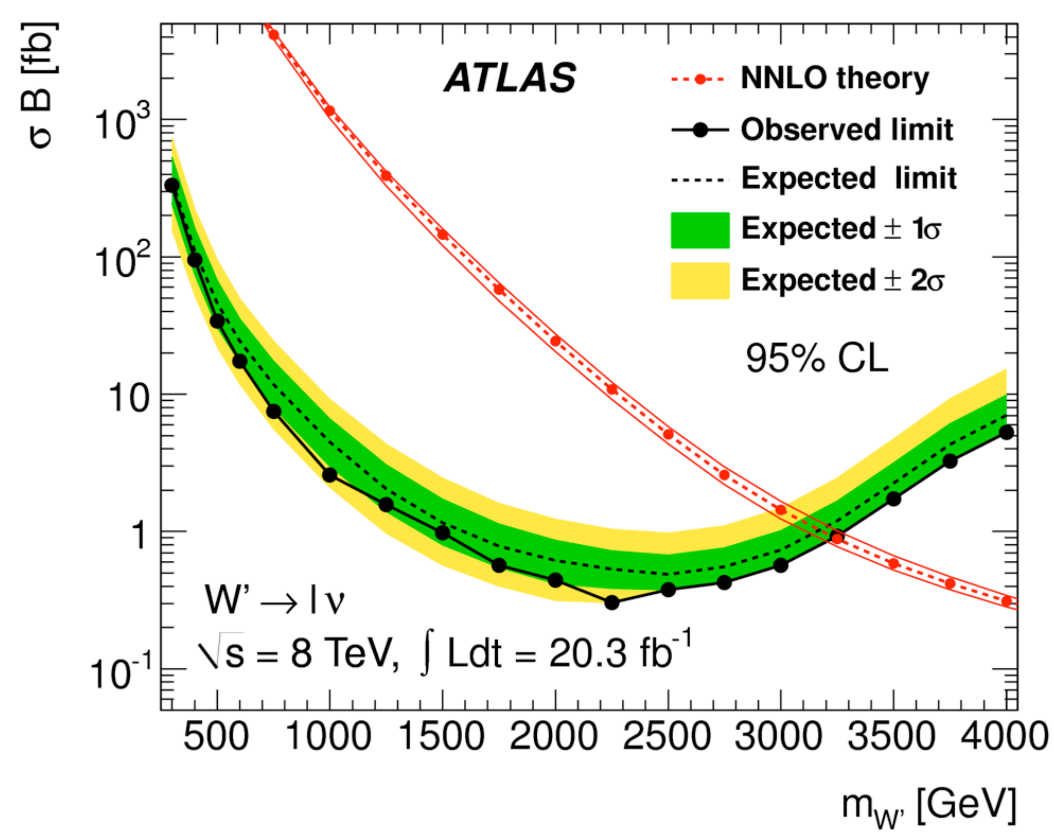
- multi-jet background estimated from data

- discriminant: $m_T = \sqrt{2 p_T E_T^{miss} (1 - \cos\varphi_{\nu\ell})}$

- 95%CL limits

	$m_{W'}$ [TeV]	
Decay	Exp.	Obs.
$e\nu$	3.13	3.13
$\mu\nu$	2.97	2.97
Both	3.17	3.24





New Gauge Bosons - Dilepton

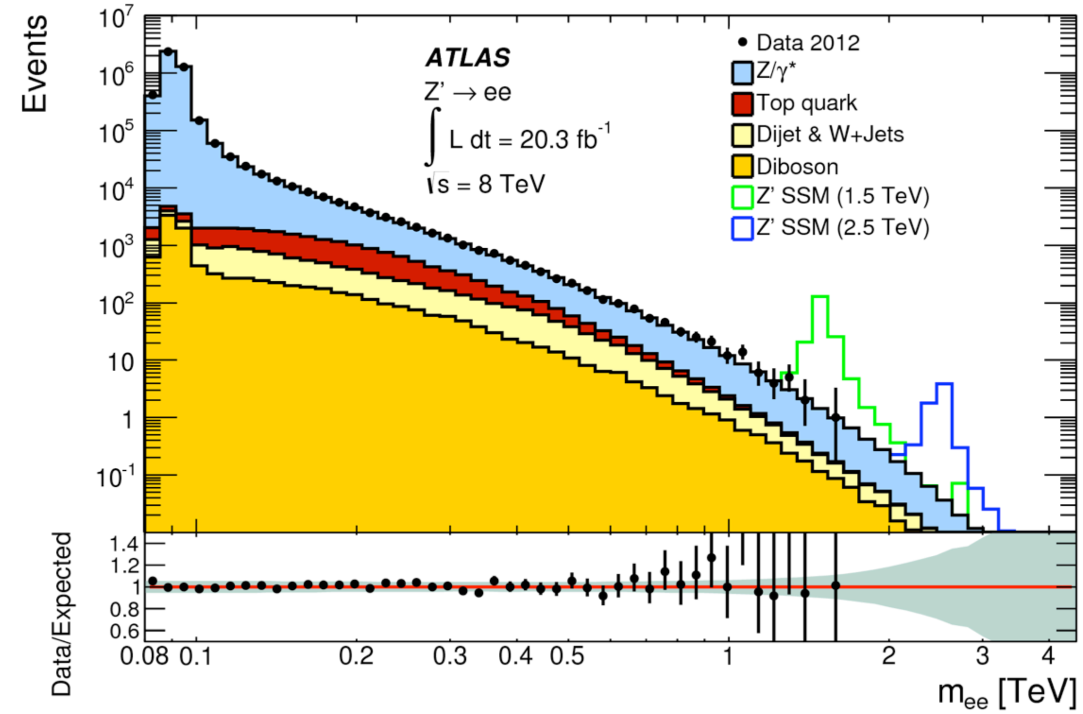
[arxiv:1405.4123](https://arxiv.org/abs/1405.4123)
accepted by PRD

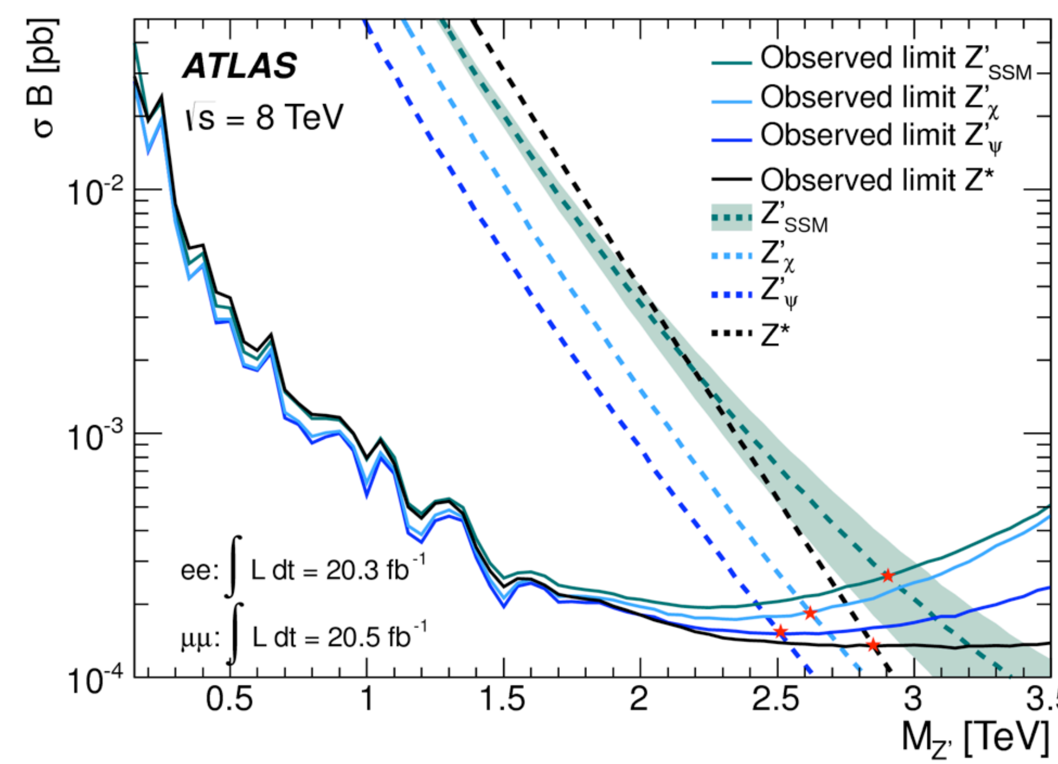
20.3/fb

- dilepton resonances predicted by many BSM scenarios
- e.g. GUTs/solutions to hierarchy problem (many considered in this paper)

> - 2 central electrons, p_T>40 (30) GeV
> - or 2 opposite-sign muons, p_T>25 GeV
> - discriminant: dilepton invariant mass $128\ \text{GeV} < m_{ll} < 4500\text{GeV}$

- dijet and W+jets final states estimated from data
- simulation normalised to data in Z-peak





- 95%CL limits

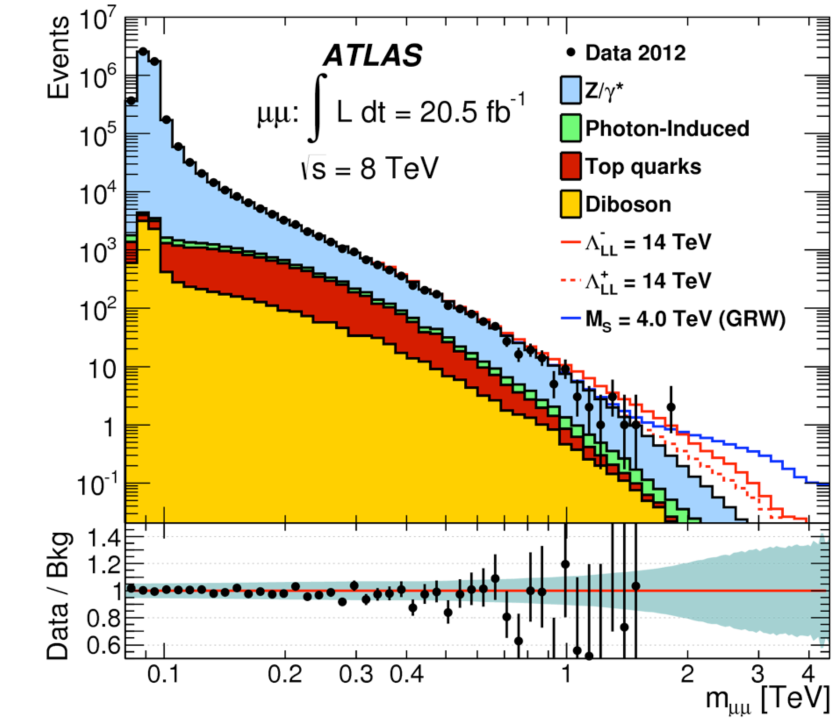
Model	Width [%]	Observed Limit [TeV]	Expected Limit [TeV]
Z'_{SSM}	3.0	2.90	2.87
Z'_{χ}	1.2	2.62	2.60
Z'_{ψ}	0.5	2.51	2.46
Z^*	3.4	2.85	2.82

Contact Interaction (CI)

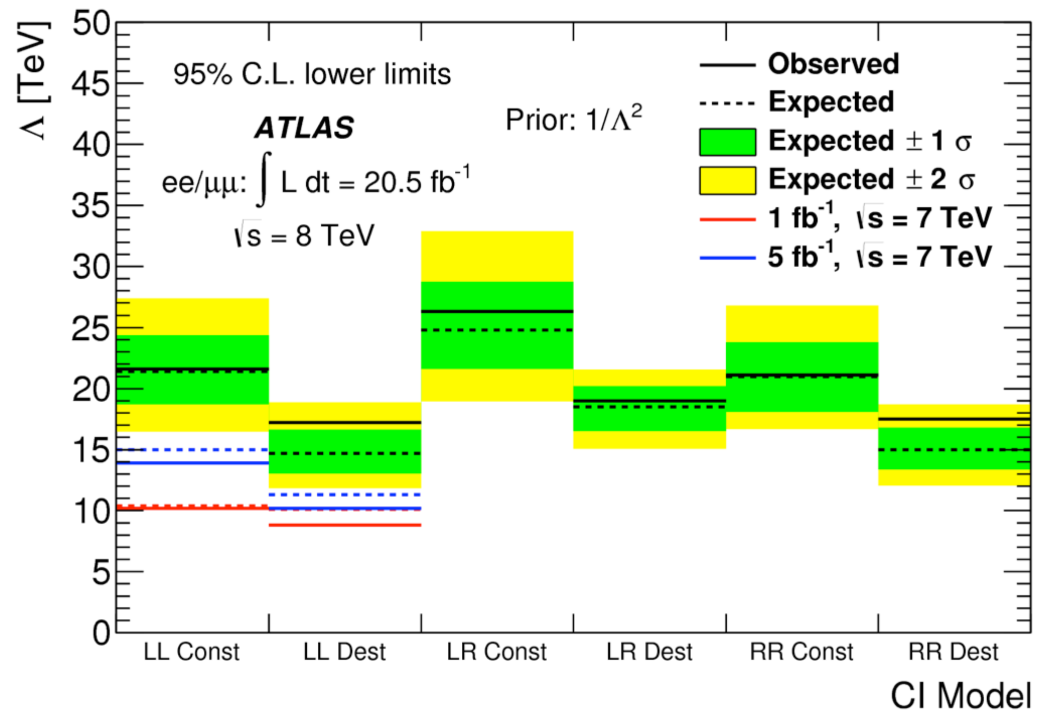
arXiv:1407.2410
submitted to EPJC

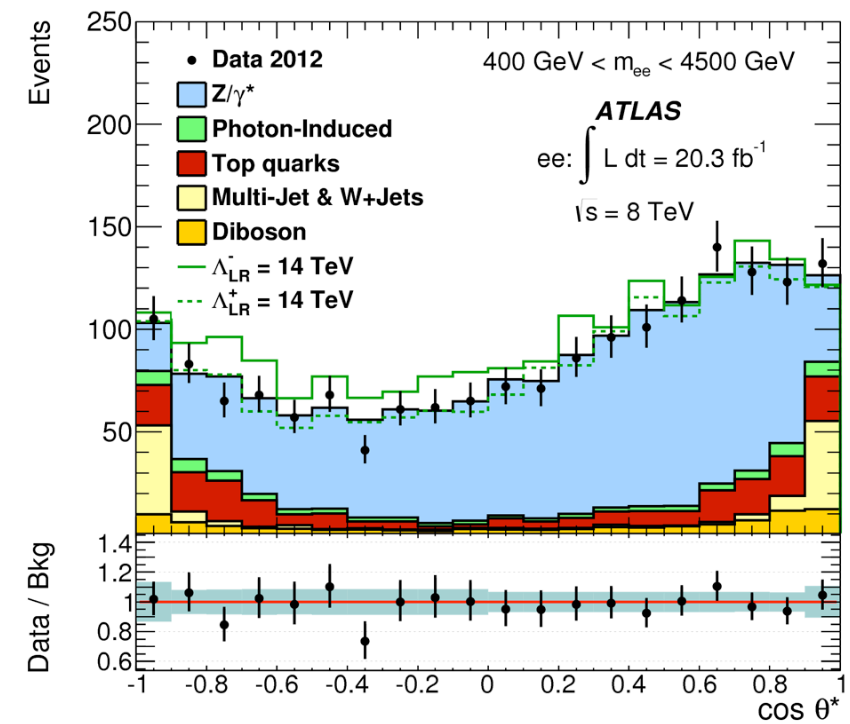
20.5/fb

- search for non-resonant new phenomena in ee and μμ
  - p_T^{e1}>40GeV, p_T^{e2}>30GeV
  - $p_T^{\mu 1,2}$>25GeV
  - opposite sign
  - m_{ll}>80GeV
- accommodate fermion compositeness by 4-fermion CI (similar to Fermi theory of β-decay)
- discriminant: **dilepton mass** and dilepton **decay angle**
- limits on CI scale Λ (binding energy) for different chiral structures
- constructive or destructive interference with DY (η_{ij} , i,j=L,R)



$$\sigma_{tot} = \sigma_{DY} - \eta_{ij}\frac{F_I}{\Lambda^2} + \frac{F_C}{\Lambda^4}$$



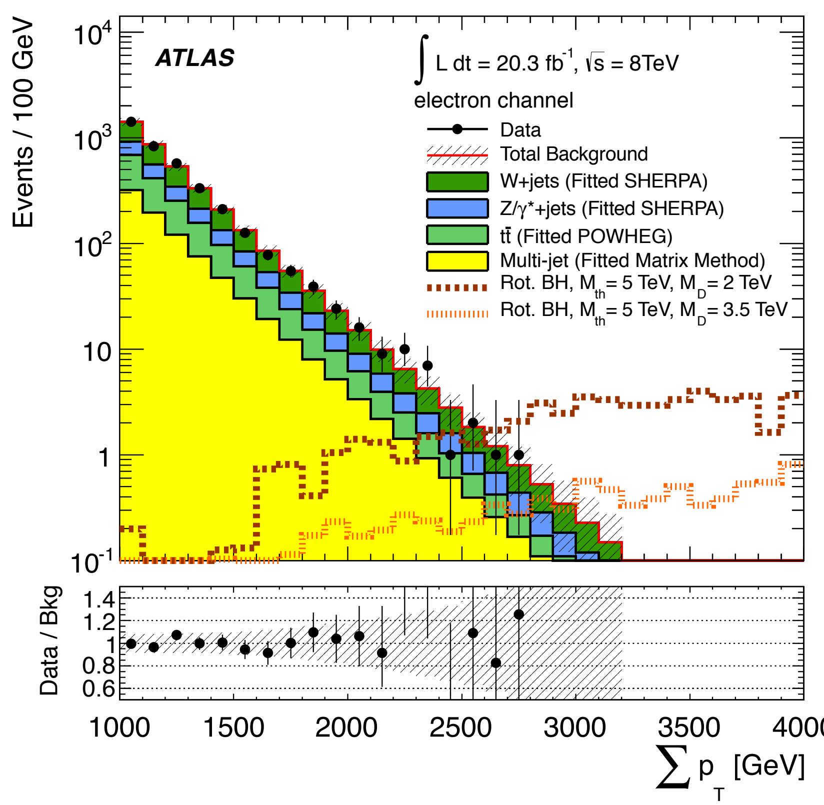


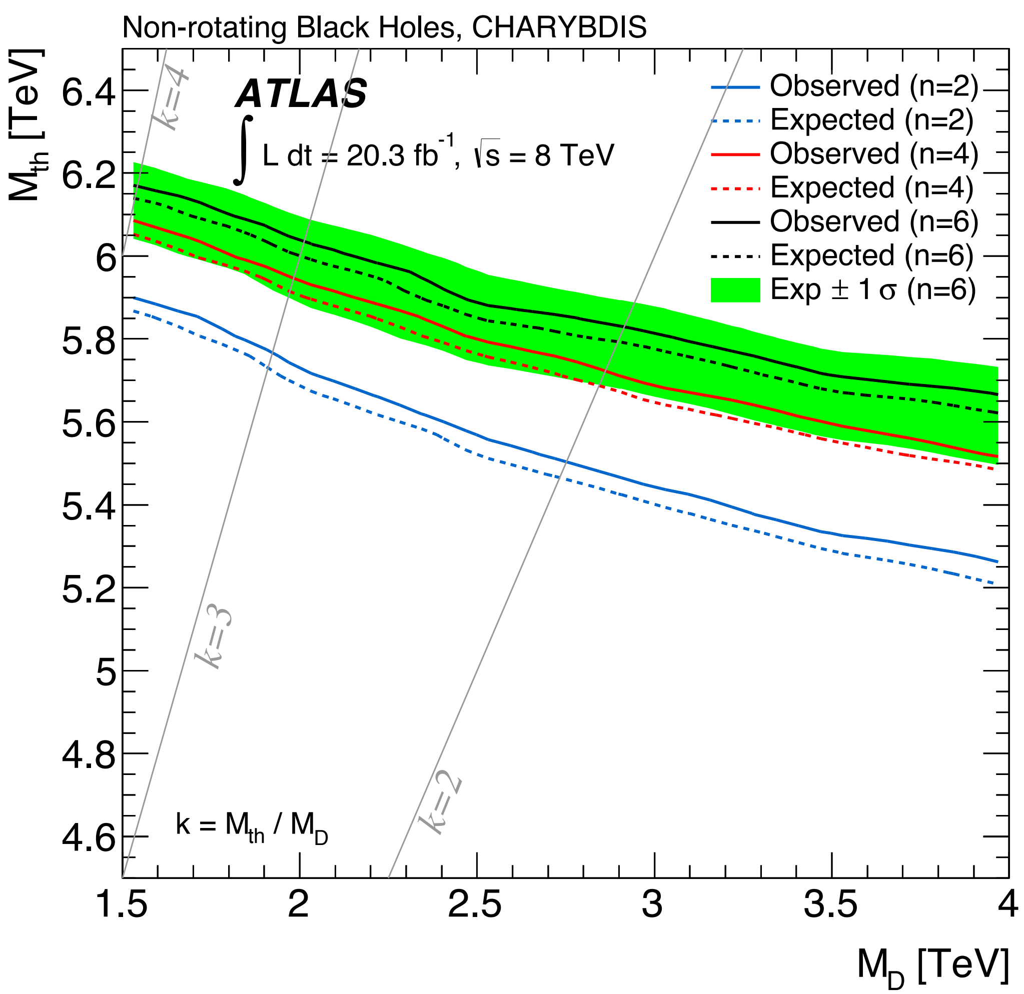
Extra Dimensions

arXiv:1405.4254
accepted by JHEP
20.3/fb

- possible solution to **hierarchy problem**
- often used benchmark model: **ADD** (Arkani-Hamed, Dimopoulos, Dvali)
- propagation of gravitons in **n spacial extra dimensions** of **size R**
- $M_{Pl}^2 = M_D^{n+2} R^n$ => M_D could be in TeV range => **black hole** production at LHC energies

- <u>leptons+jets</u> search
  - ≥3 objects with p_T>100GeV
  - ≥1 lepton (e,μ)
  - production mass threshold M_{th}>M_D
  - discriminant: scalar p_T sum

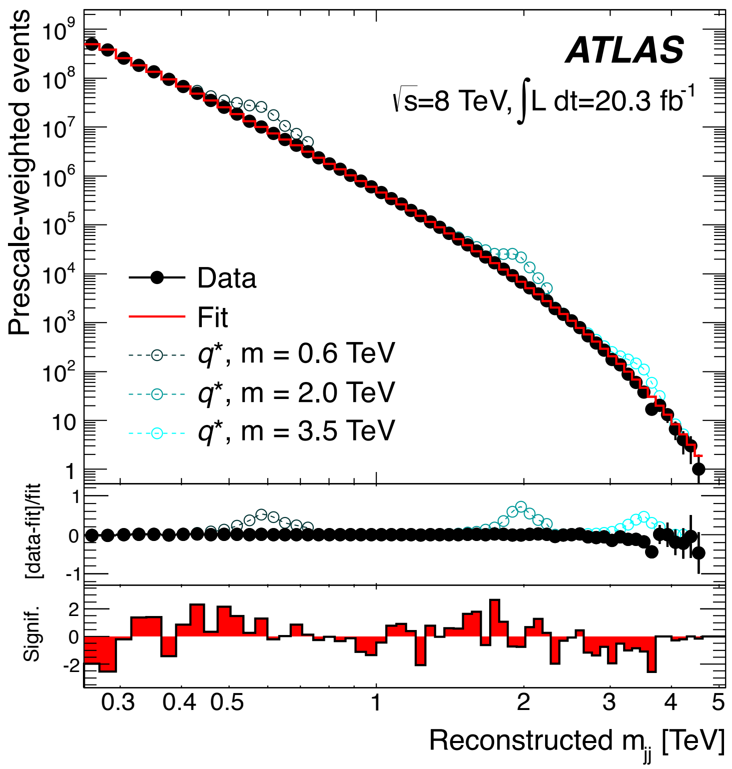




Dijets

arXiv:1407.1376
submitted to PRD

20.3/fb

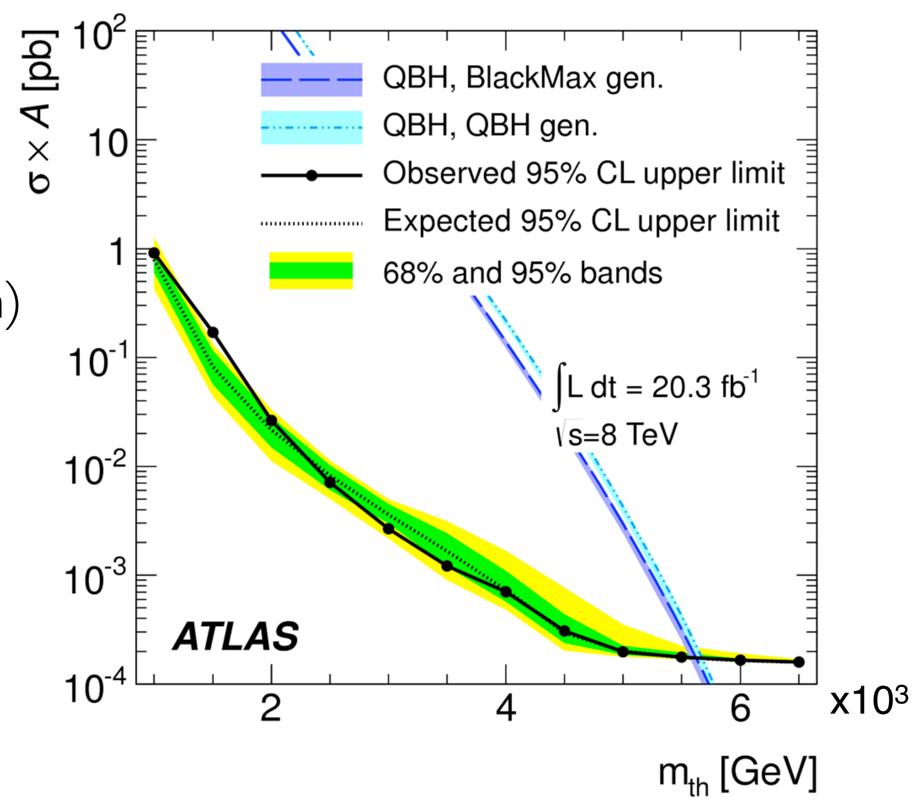


- QCD: **smoothly falling** dijet mass spectrum
- many BSM models predict **narrow resonances**
- => search for **bumps** on top of smooth background
- new trigger strategy
  => reach extended to <1TeV
  wrt 2011 results

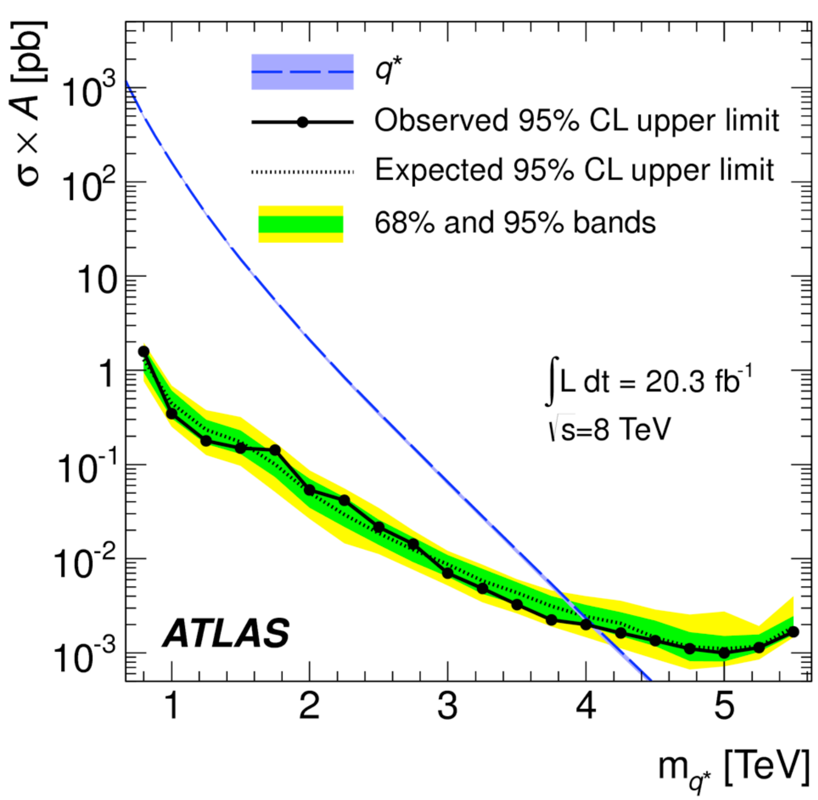
- $\geq$2 jets with p_T>50GeV
- 2 leading jets in $|\eta|$<2.8
- m_{jj}>250GeV
- $|y^*|=1/2|y_1-y_2|$<0.6

2 example interpretations:

- quantum black holes (QBH) in ADD LED
  - n=6
  - $M_D=m_{th}$
    (threshold for
    QBH production)

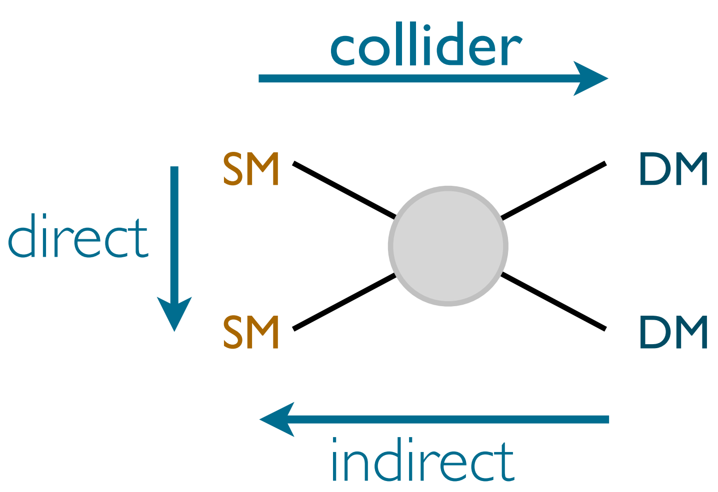


- excited quarks

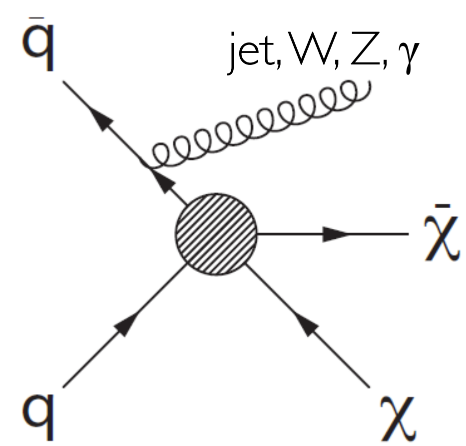


compositeness
of fermions
might explain SM
family structure

Mono-X Searches for Dark Matter



- DM itself **invisible** to detector
  - need something to ‘**tag**’/trigger on



- unbalanced reconstructed object
  => missing transverse energy (**E_T^{miss}**)

What is the ?

- assume: interaction mediated by a new particle
  too heavy to be directly produced @LHC
- effective field theory approach
  (contact interaction)
- suppression scale of effective theory: M_*

$$M_* \sim \frac{M}{\sqrt{g_\chi g_{SM}}}$$

- M: mediator mass
- g_χ : coupling to DM
- g_{SM} : coupling to SM

for Dirac-fermionic DM

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

(some representative examples)

gg-operator only for mono-jet

Mono-jet

ATLAS-CONF-2012-147

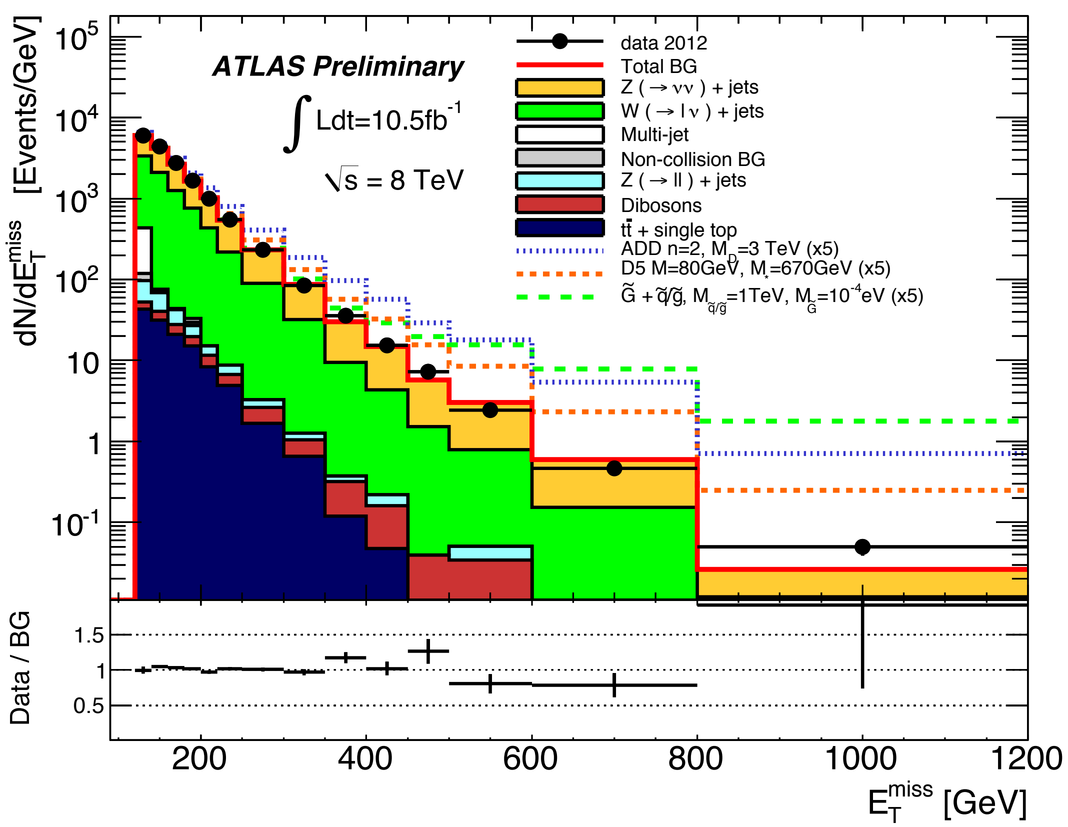
10.5/fb

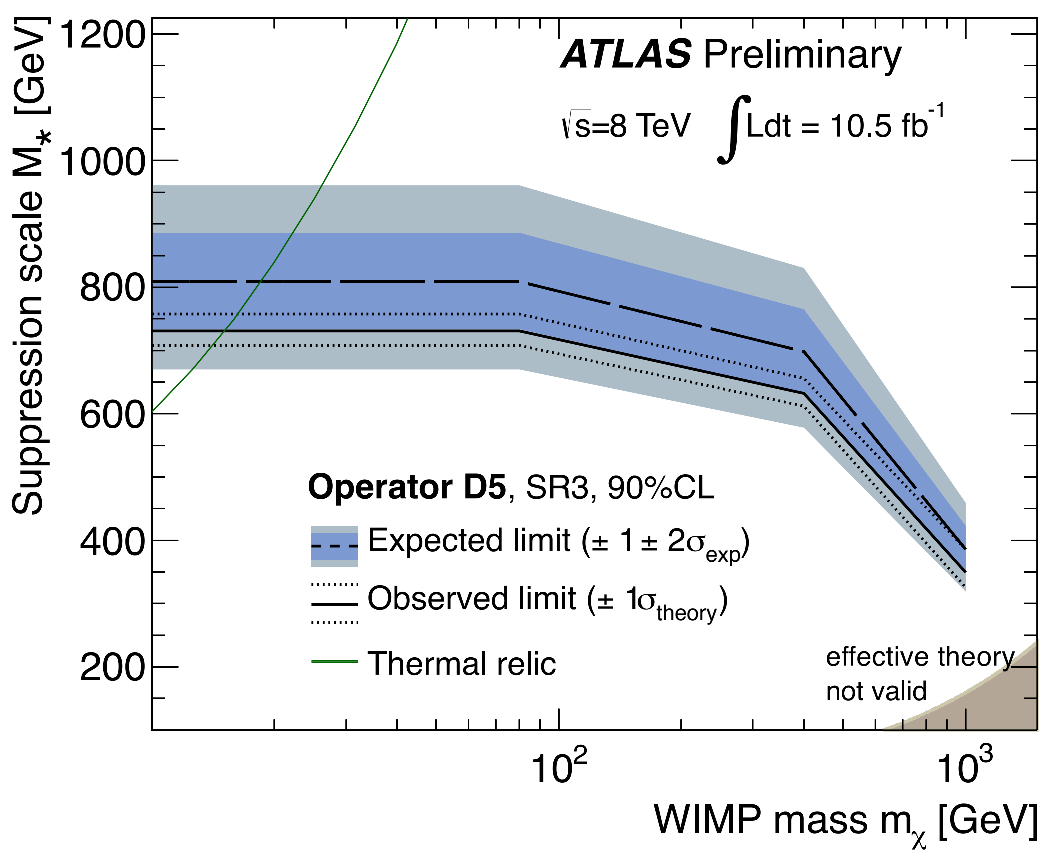
update with full 2012 dataset in preparation

- highest sensitivity to many of the operators due to large cross section
- solely sensitive to gg-operator

- $1 \leq n_{jet} \leq 2$
- lepton veto
- lead. jet p_T>120GeV, $|\eta|$<2.0
- 4 signal regions (SR1-SR4)
  lead jet p_T & E_T^{miss} > [120, 220, 350, 500]GeV

- no significant deviation from SM



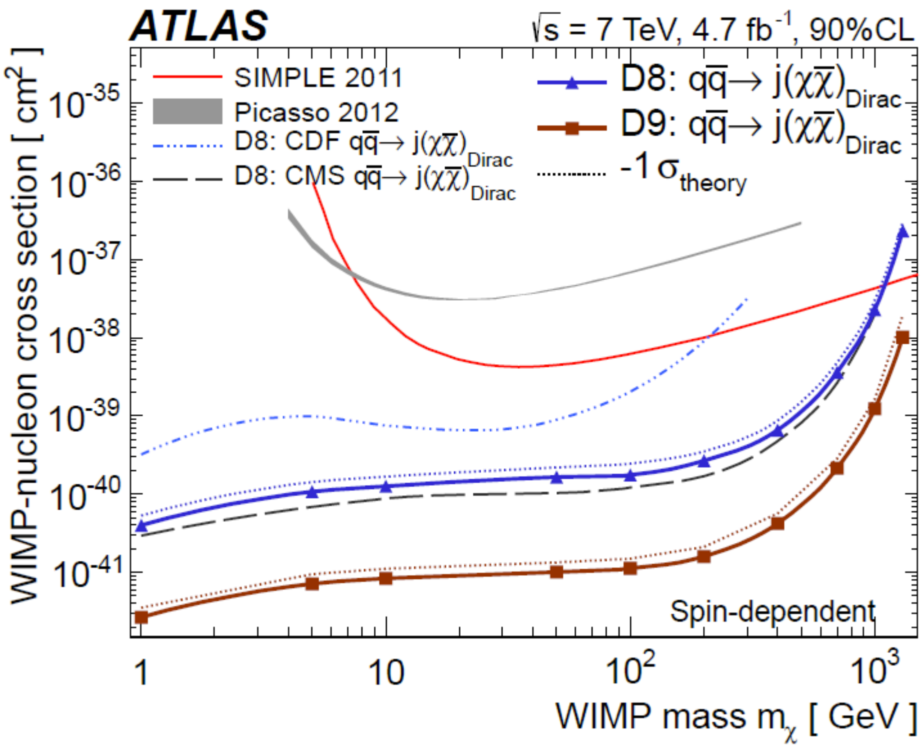


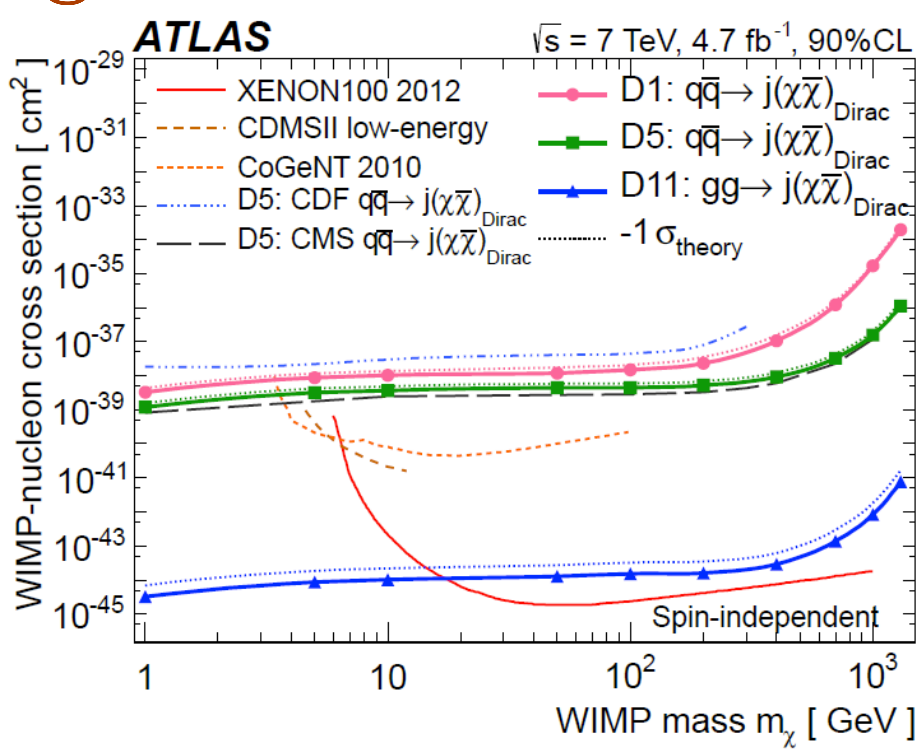
Mono-jet 7TeV

[JHEP 04 (2013) 075]

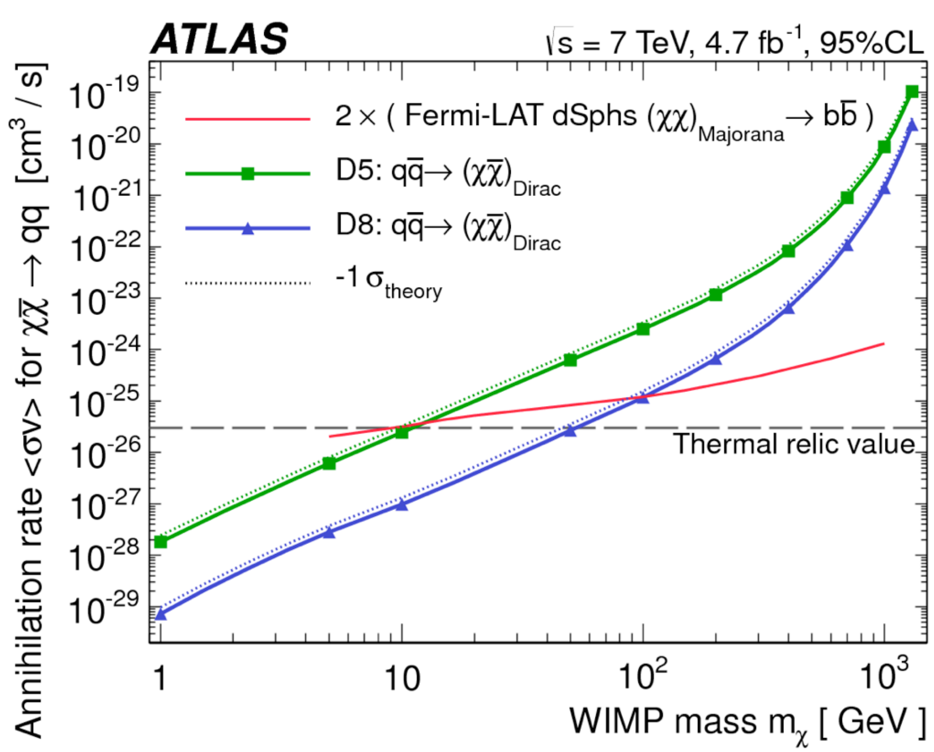
- limits on M* can be translated into (upper) limits on WIMP-Nucleon scattering cross section

Monojet@7TeV





- spin-dependent interaction: collider competitive over large mass region
- spin-independent interaction: collider competitive at small masses



- collider competitive at small masses

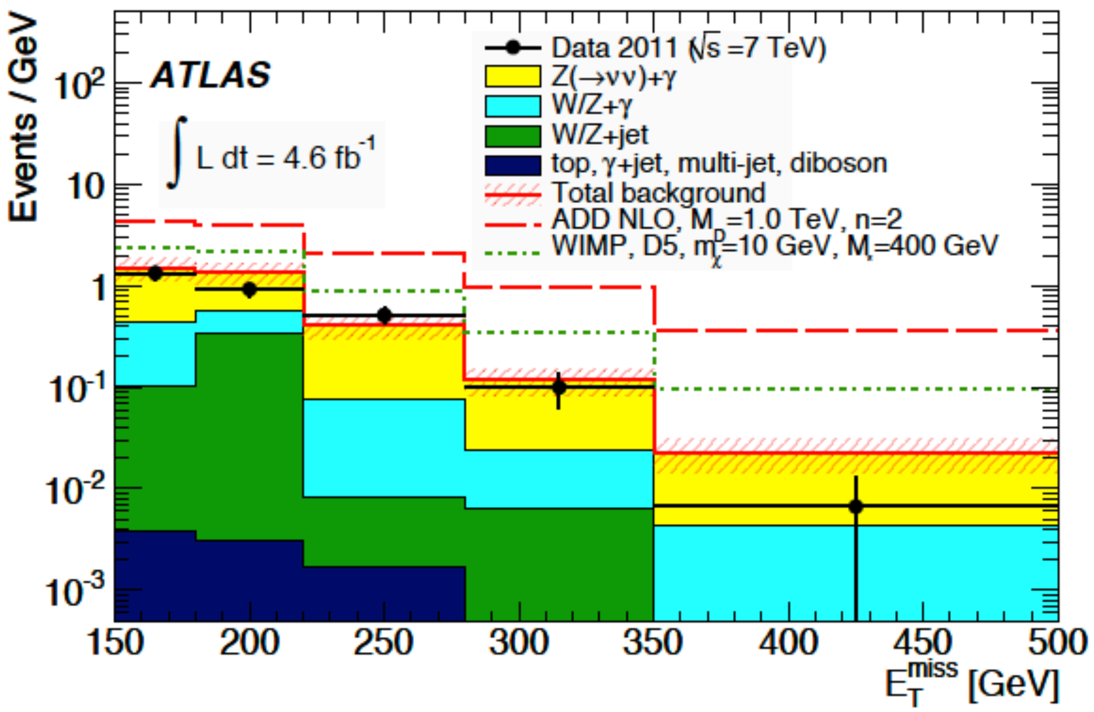
Mono-Photon

PRL 110, 011802 (2013)

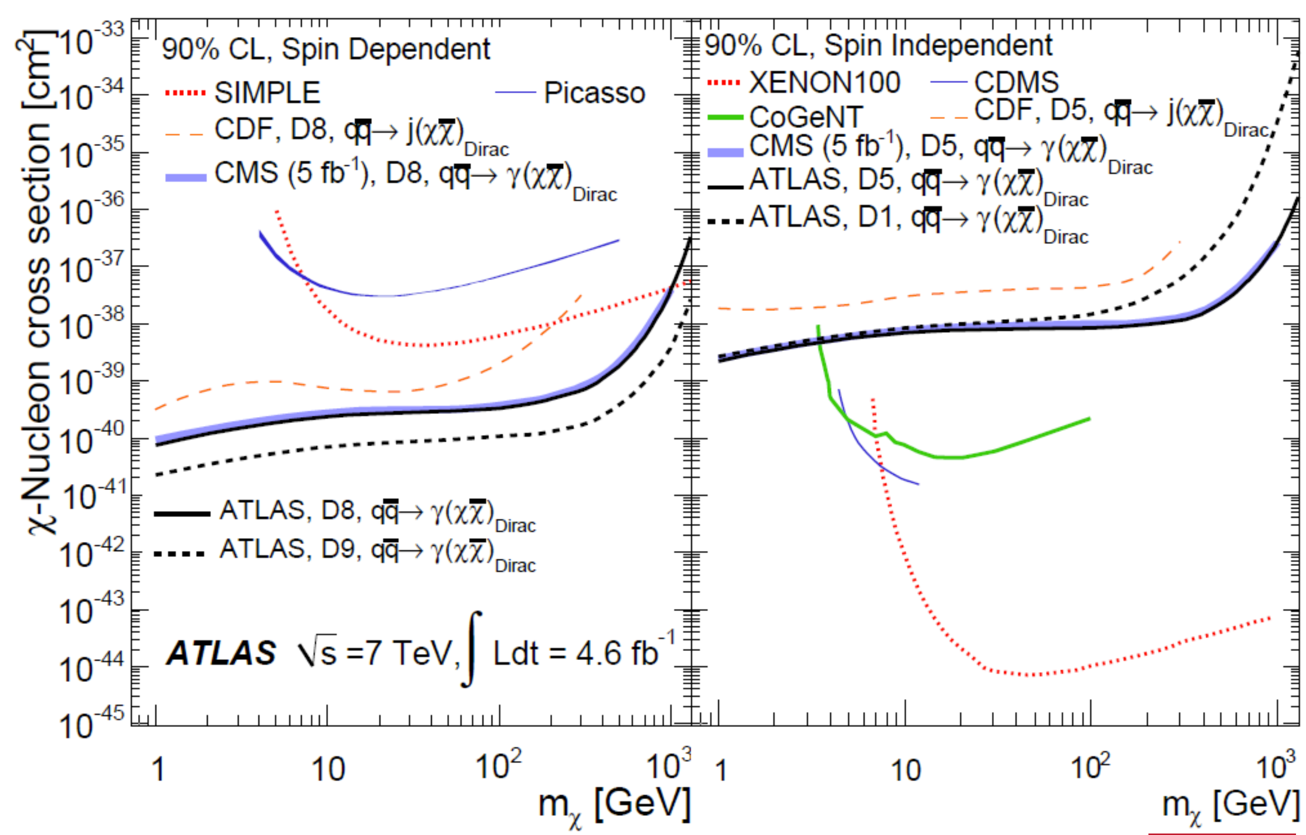
4.6/fb, 7TeV

- photon $|\eta|<2.37$, $p_T>150$GeV
- $E_T^{miss}>150$GeV
- lepton veto, ≤1 jet

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		



no significant deviation from Standard Model prediction



update with full 2012 dataset in preparation

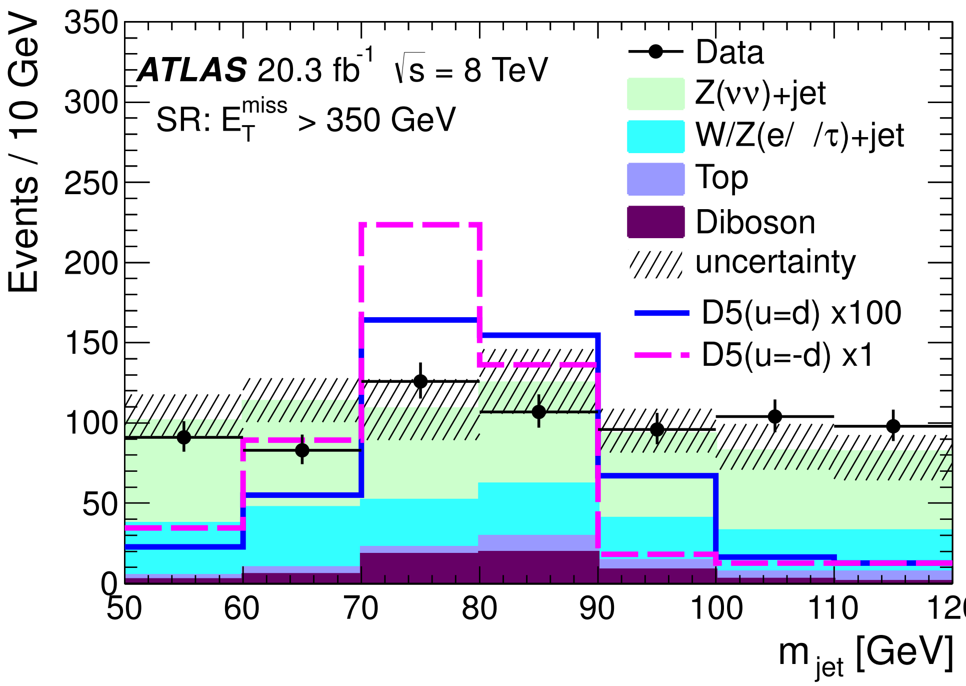
Mono-W/Z (hadronic)

PRL 112, 041802 (2014)

- 1 fat jet (Cambridge-Aachen), R=1.2
- jet p_T > 150GeV, E_T^{miss} >350, 500 GeV
- lepton/γ veto, ≤1 AntiKt jet (R=0.4)

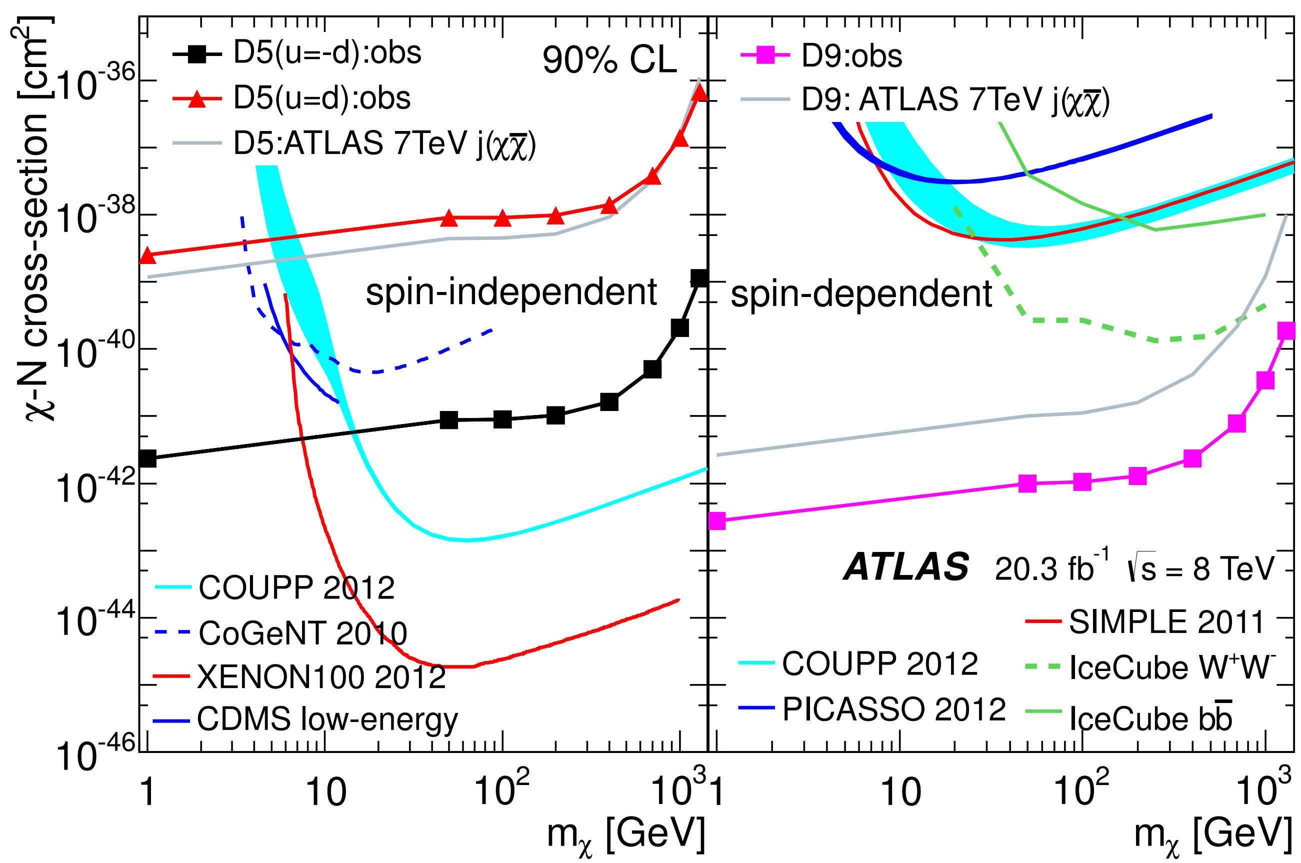
20.3/fb

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



no significant deviation from Standard Model prediction

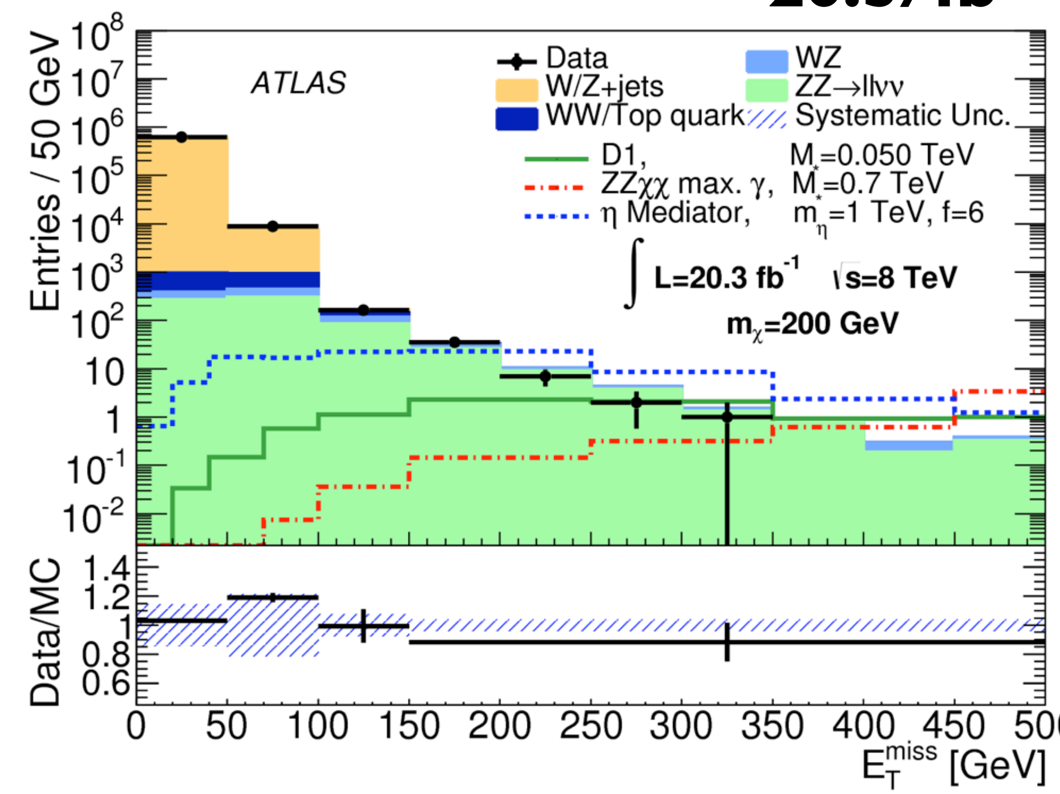
- constructive interference for *W* emission if g_u=-g_d
  - => mono-W dominant process
    - => limits surpass mono-jet by 3 orders of magnitude (for D5)



Mono-Z($\ell\ell$)

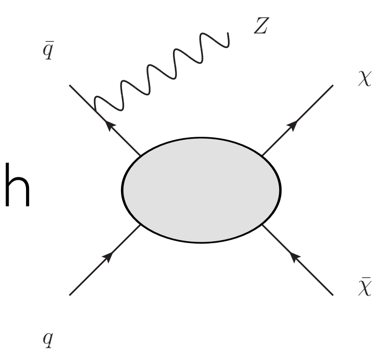
PRD 90, 012004 (2014)

20.3/fb

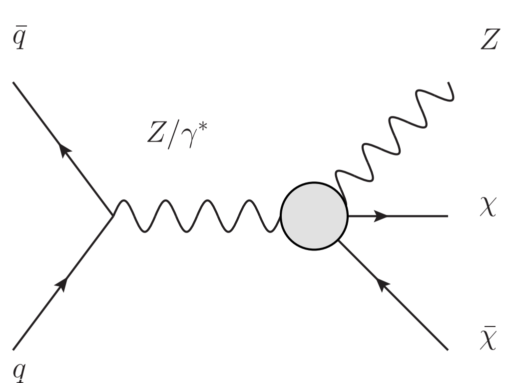


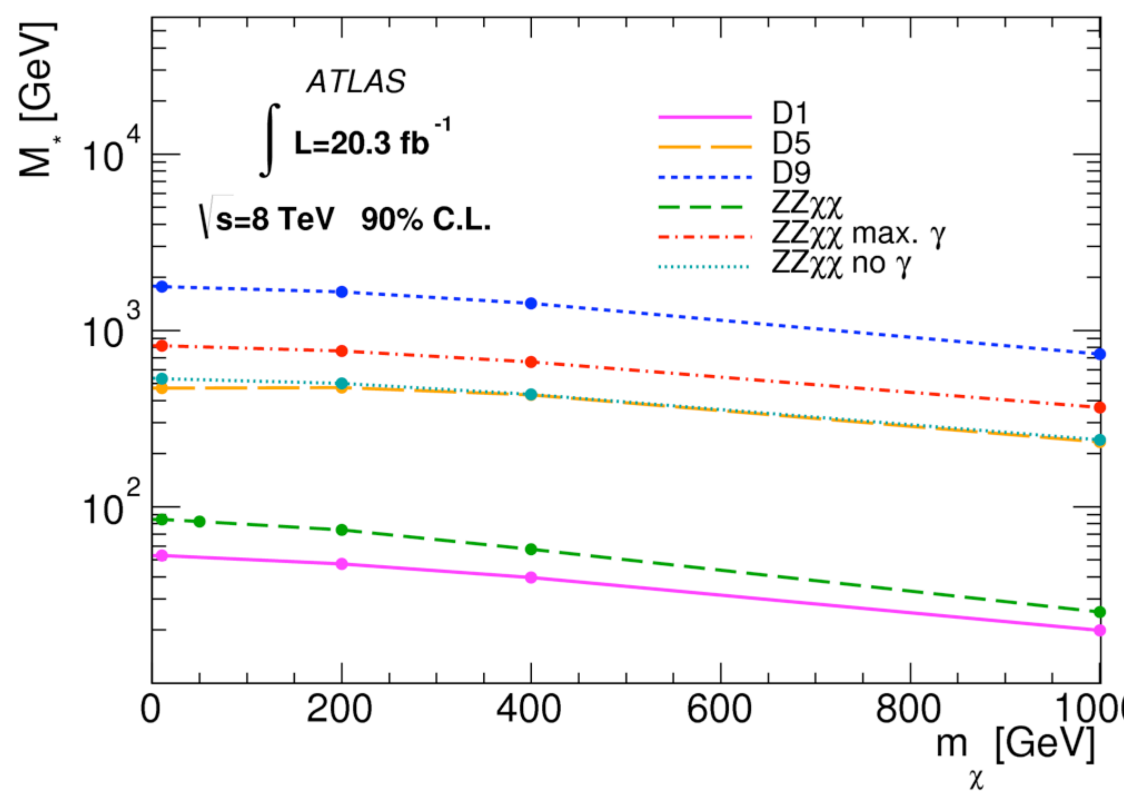
- 2 opposite-sign electrons or muons
- $\Delta\varphi(p_T^{ll}, E_T^{miss})>2.5$, $|\eta^{ll}|<2.5$, $(p_T^{ll} - E_T^{miss})/p_T^{ll} < 0.5$
- veto additional leptons or jets
- SR1-SR4: $E_T^{miss} > 150, 250, 350, 450$ GeV

- in addition to ISR graph



sensitivity to coupling of DM to Z



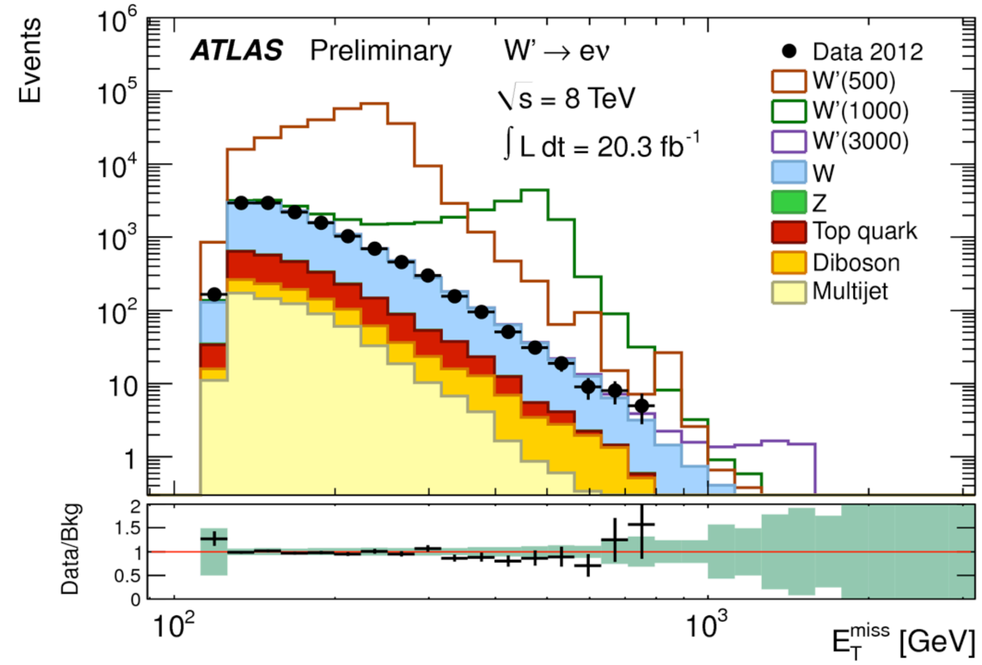


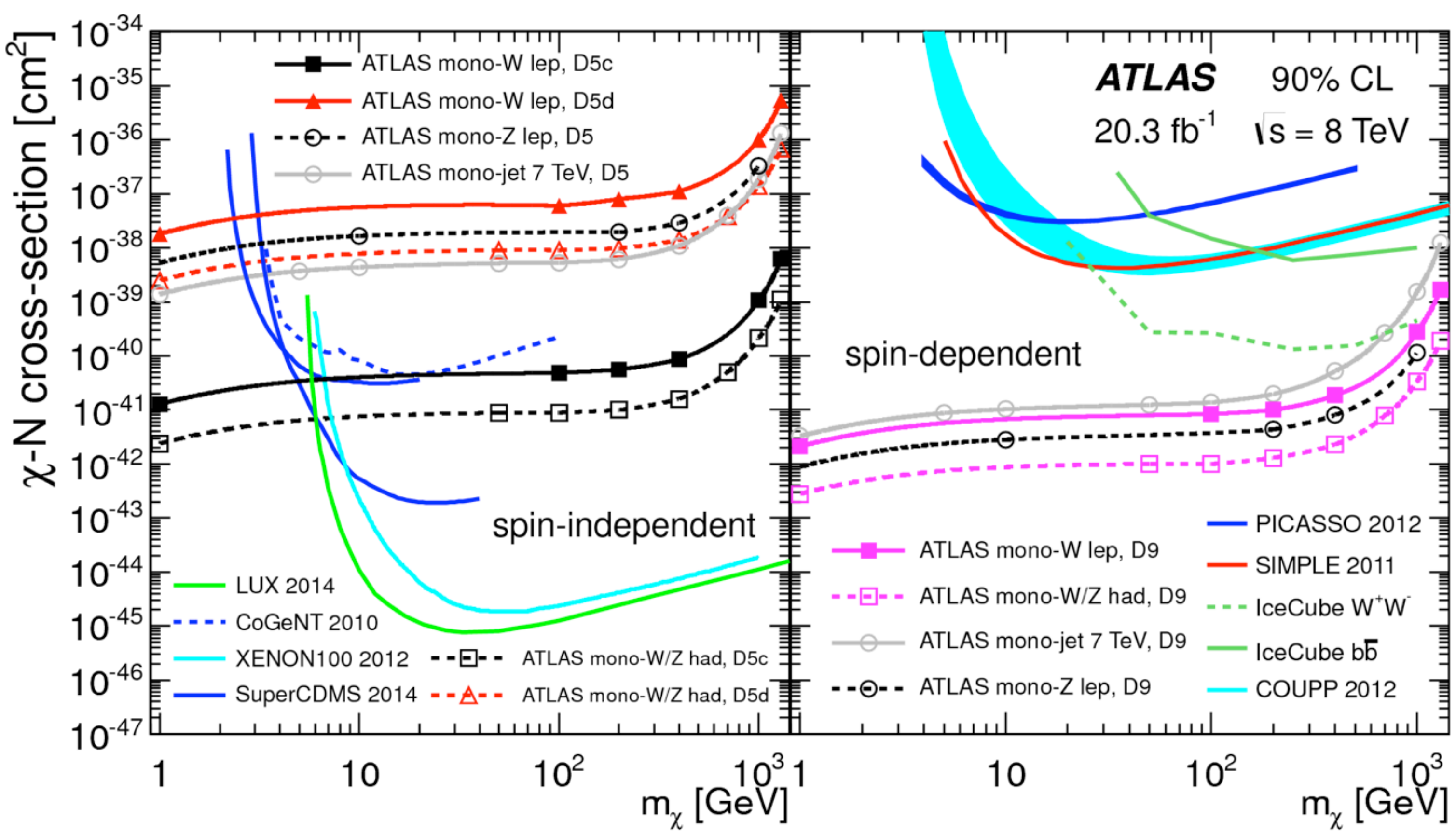
arxiv:1407.7494
accepted by JHEP

Mono-W($\ell\nu$)

20.3/fb

- final state of W' search can also be interpreted as mono-W signal for DM pair production
- discriminant: E_T^{miss}
- reminder: construtive or destructive interference for D5





Beyond the EFT

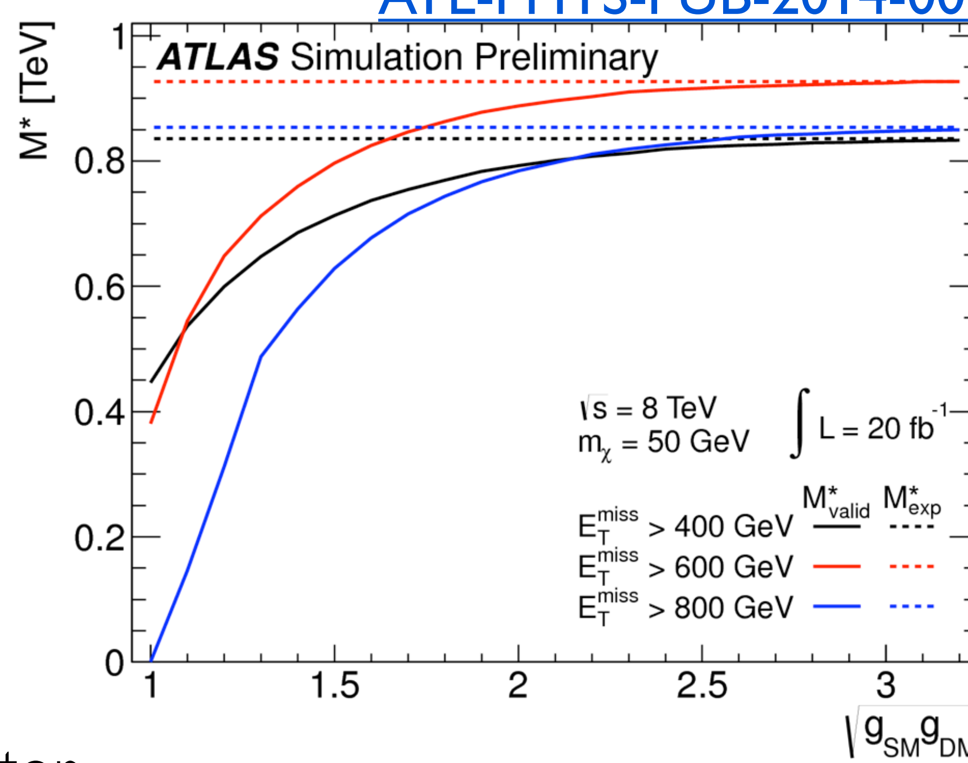
- merit of EFT:
  only 2 parameters,
  independent of details of UV completion,
  directly comparable to (in)direct searches
- however: validity of EFT questionable at LHC energies
- minimal requirement: momentum transfer $Q_{tr} < M_{med} = f(g_{SM}, g_{DM}, M_*)$,
  + couplings bounded from above

coupling to SM particles

coupling to WIMPs

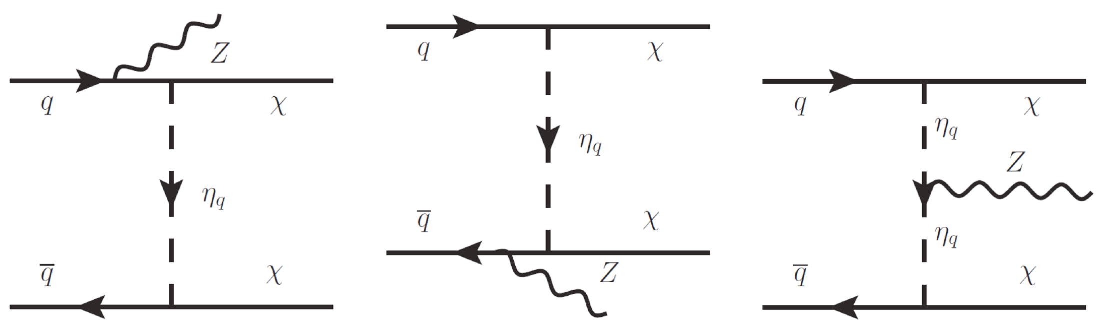
- remove events that do not fulfill the above requirement
  - => limits deteriorate
  - how much, depends on assumed coupling/operator
  - e.g. D5 fully valid wrt this requirement for
    $\pi < \sqrt{(g_{SM}\, g_{DM})} < 4\pi$ ATL-PHYS-PUB-2014-007
  - details depend on UV completion
    - increases number of parameters
    - natural next step: simplified model with a light mediator
      - parameters: WIMP mass, mediator mass and width

ATL-PHYS-PUB-2014-007

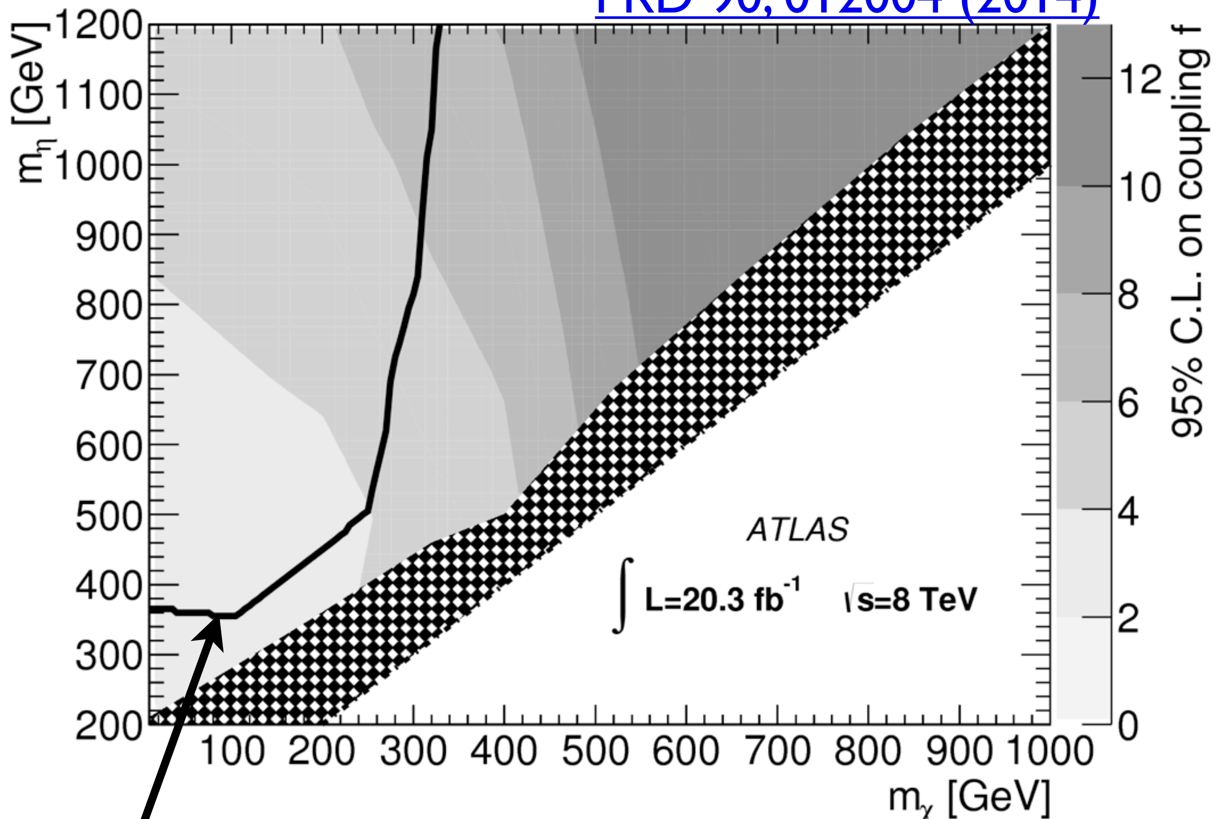


Simplified Models

- **mono-Z**: scalar, coloured t-channel mediator



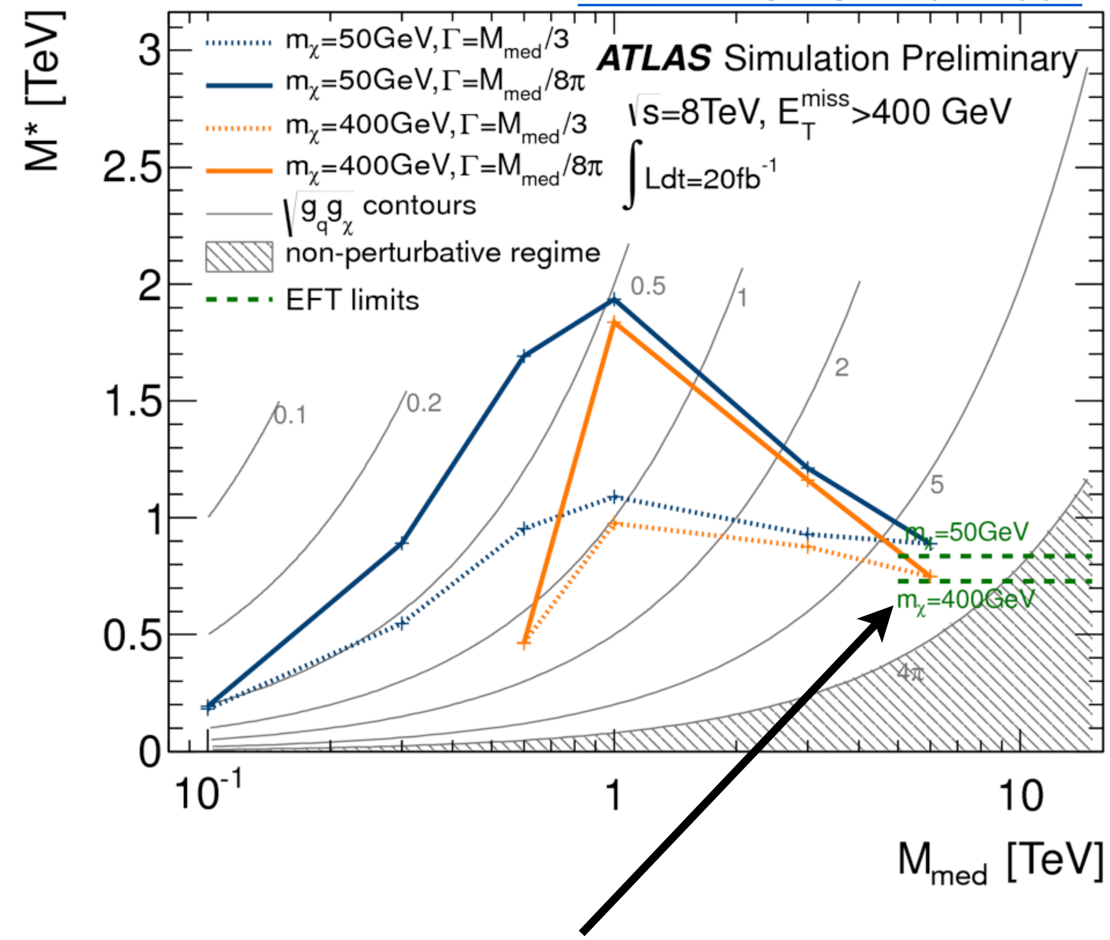
PRD 90, 012004 (2014)



- lower limits from relic density
  => upper left corner in conflict

- mono-jet: vector s-channel mediator

ATL-PHYS-PUB-2014-007

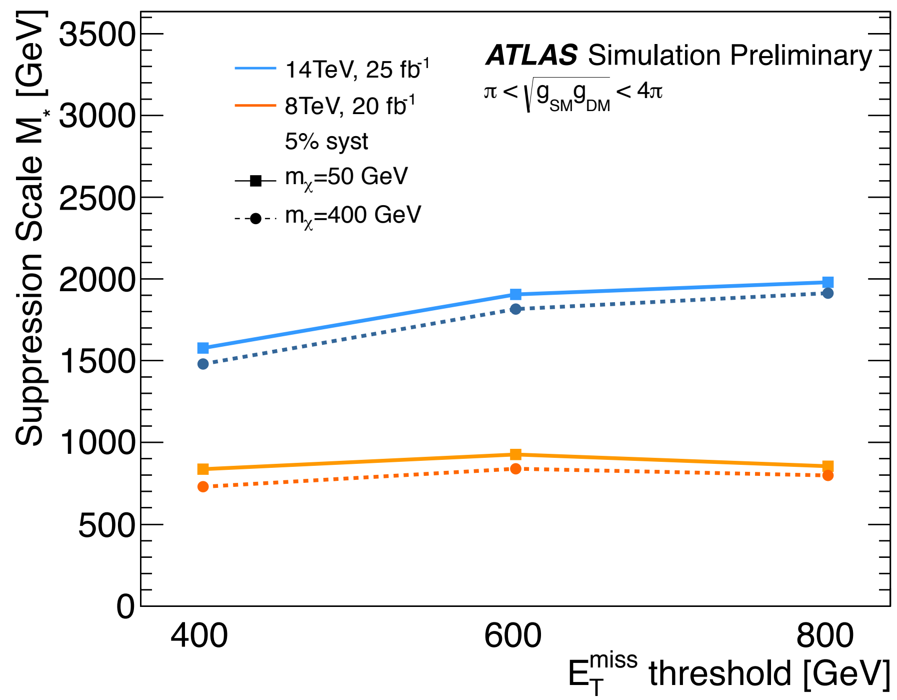


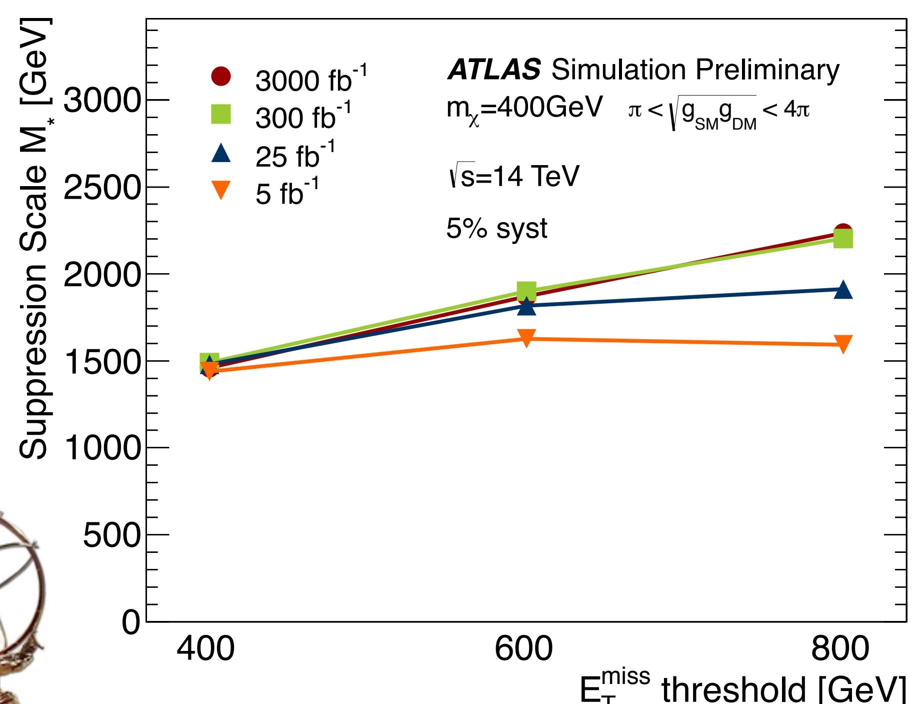
- approaches EFT at high mediator masses
- resonant enhancement at intermediate masses

- $f := \sqrt{(g_q g_\chi)}$
  g_q : coupling to quarks
  g_χ : coupling to WIMPs

14 TeV Prospects

- simulation studies for 14TeV performed for some analyses, here two examples
  - **mono-jet** ATL-PHYS-PUB-2014-007
    - improvement by factor ~2



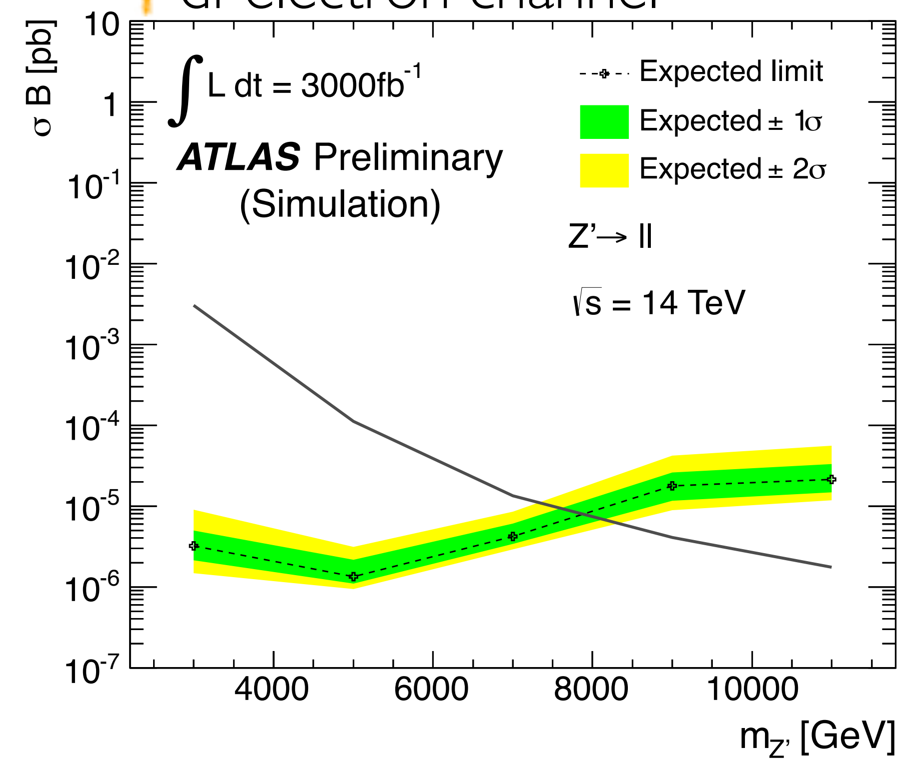


- **di-lepton** ATL-PHYS-PUB-2013-003
  - current limits ~3TeV

95%CL limits in TeV

model	300 fb^{-1}	1000 fb^{-1}	3000 fb^{-1}
$Z'_{SSM} \to ee$	6.5	7.2	7.8
$Z'_{SSM} \to \mu\mu$	6.4	7.1	7.6

- di-electron channel



Astroparticle Forum

- founded April 2012
- forum for discussion of astroparticle physics related issues
- exchange between ATLAS and astroparticle physics experiments and theorists
  - invites speakers from other experiments/theorists
  - input welcome and appreciated
- provide guidance to ATLAS groups for astrophysics related interpretation/analyses
- ATLAS impact for astrophysics and vice versa
- example topics:

  dark matter, EFT validity - covered in this talk

  constraints on hadronic interaction models for comparisons to air shower data

- contact:

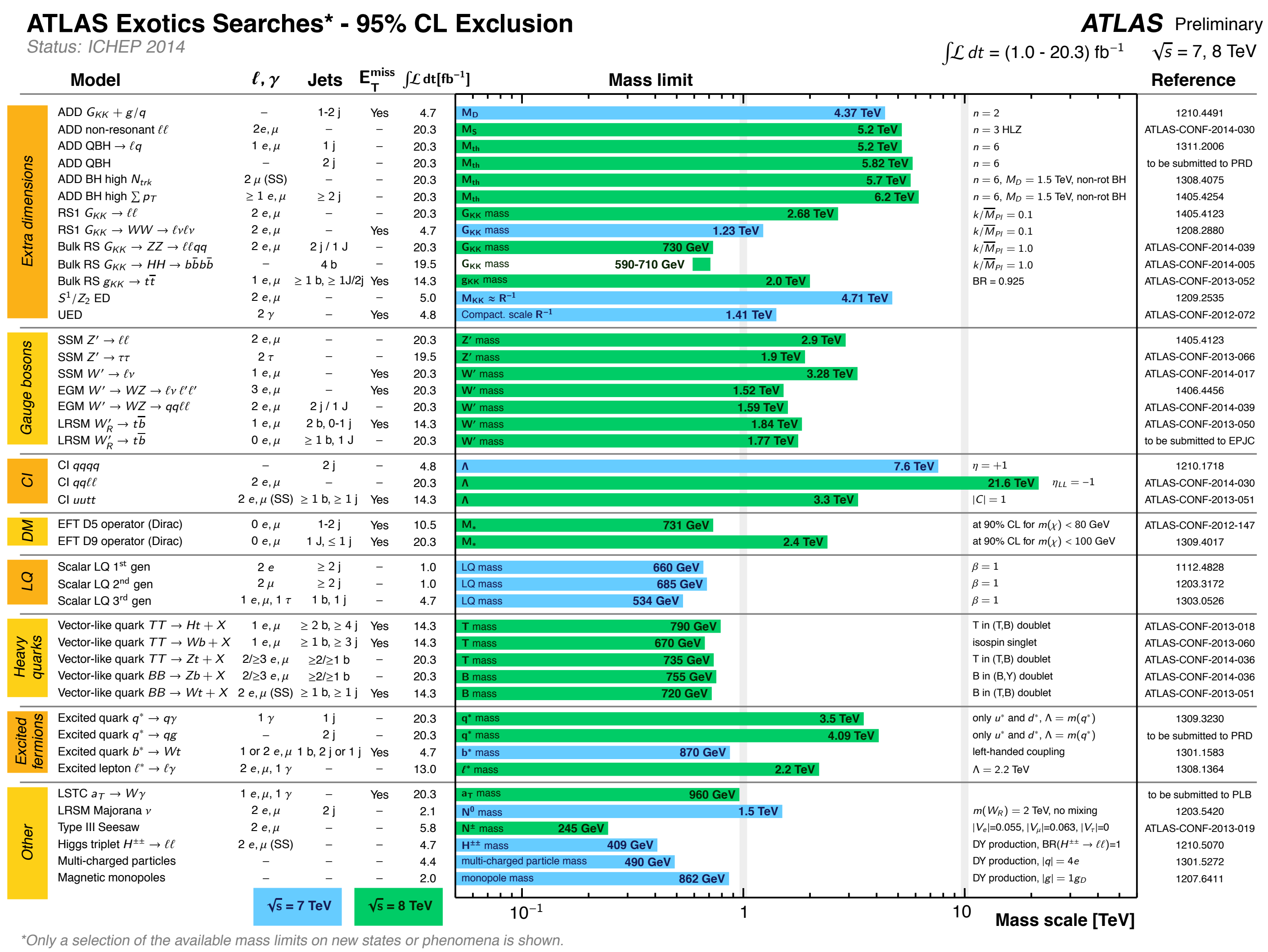
  david.berge@cern.ch stephane.willocq@cern.ch onofrio@cern.ch

  heidi.sandaker@cern.ch tobias.golling@yale.edu jamie.boyd@cern.ch

Summary

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

- large **variety** of exotics BSM searches conducted in ATLAS
- **no excess** over SM expectations observed
- **limits** on large number of model parameters



- **Dark Matter** searches performed in many channels
- mostly use of **EFT** for easy comparison to (in)direct experiments
- in the future: move on to **simplified models**

- LHC **run-II** will start in 2015
  - higher energies, higher luminosity
  - expect many more interesting results
  - **stay tuned! :)**

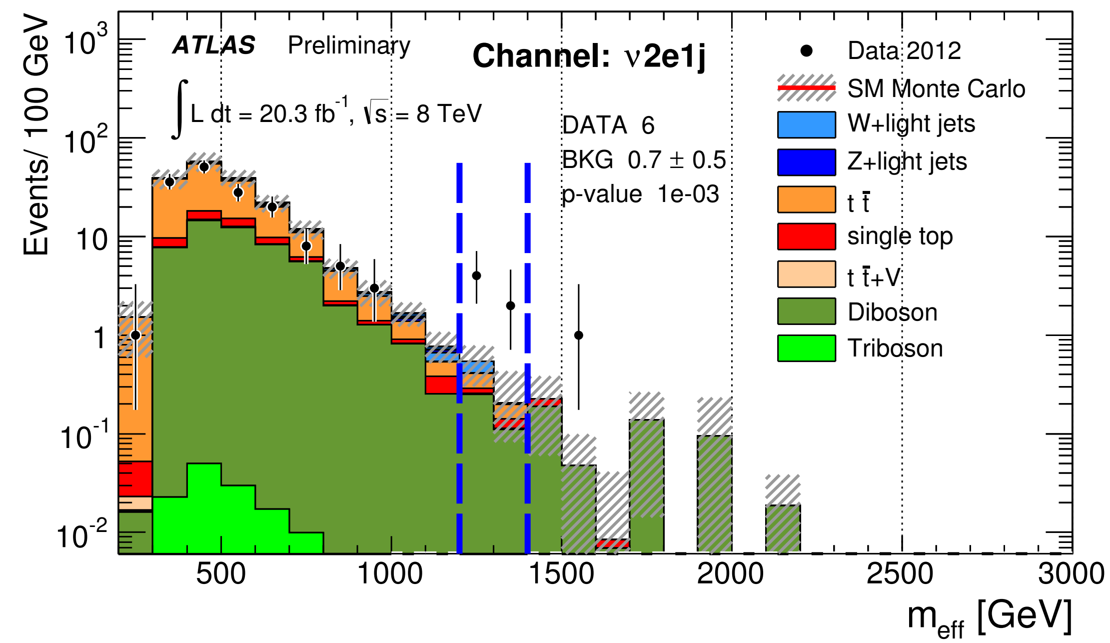
Additional Material

General Search

ATLAS-CONF-2014-006

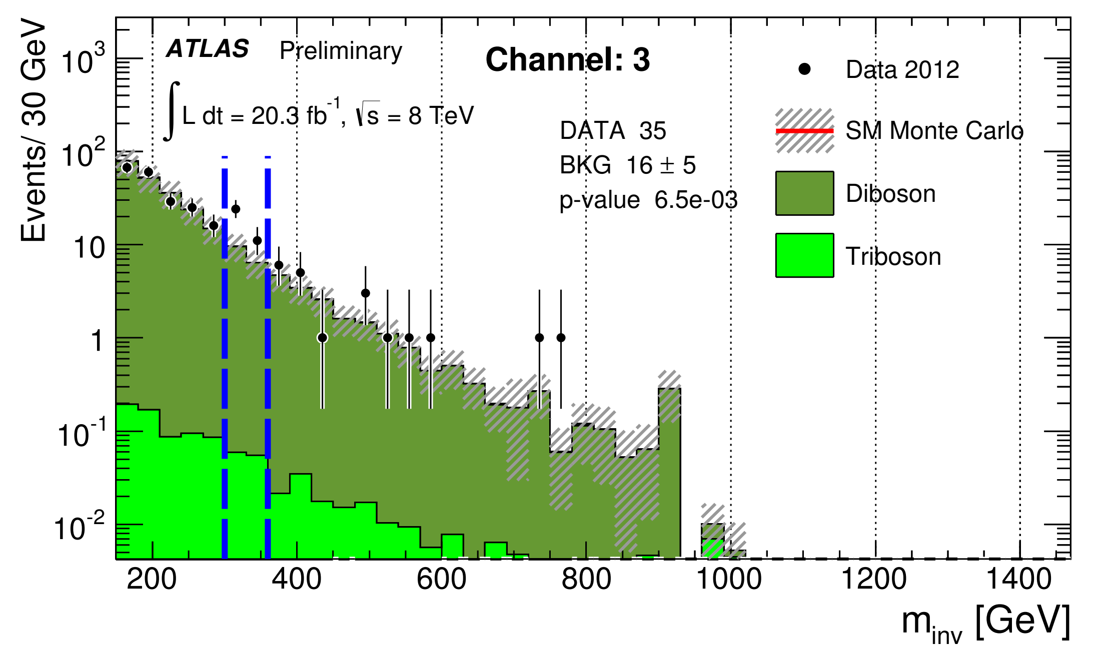
- not sensitive at low p_T or small cross sections
- p_T cuts

Object	jet	*b*-jet	electron	muon	photon	E_T^{miss}
Label	j	b	e	μ	γ	ν
Lower p_T cut	50 GeV	50 GeV	25 GeV	25 GeV	40 GeV	150 GeV



- background systematics

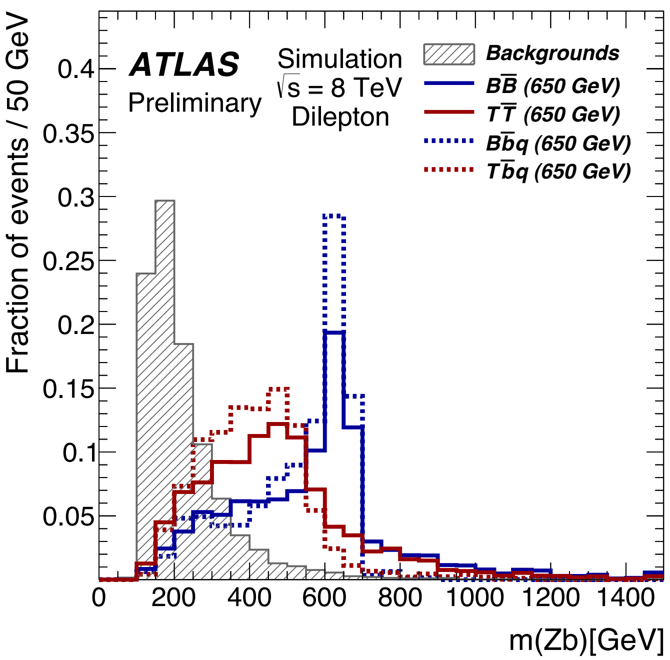
Process	correlated uncertainty (%)	uncorrelated uncertainty (%)
Multijet (normalized to data)	0	30
γ+jets and $\gamma\gamma$+jets	10	30
W/Z + jets production	5	15
W/Z + heavy flavour production	10	30
$t\bar{t}$ and single top	5	20
$t\bar{t}$ + vector boson	10	30
Diboson processes (including W/Z+γ)	10	30
Triboson	20	50
Higgs production	5	20

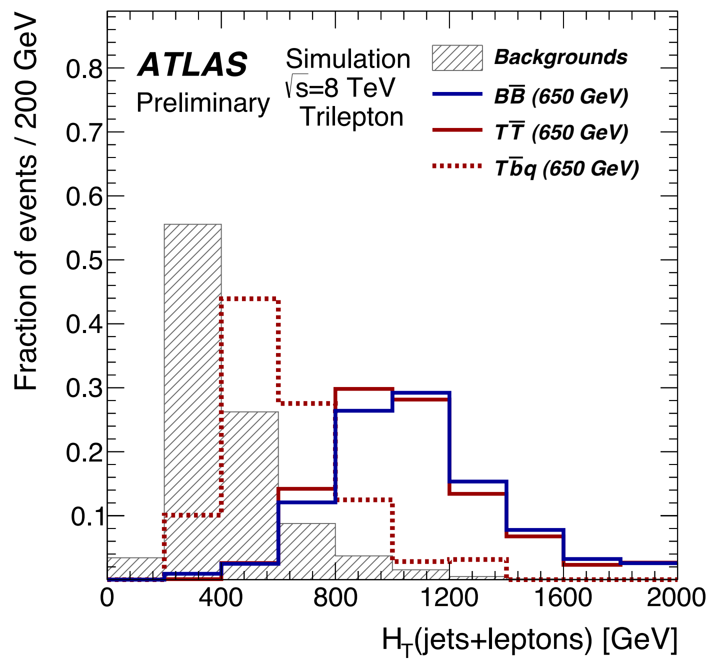


New Heavy Quarks

ATLAS-CONF-2014-036

Event selection			
Z boson candidate preselection ≥ 2 central jets $p_T(Z) \geq 150$ GeV			
Dilepton channel		**Trilepton channel**	
$= 2$ leptons		≥ 3 leptons	
≥ 2 b-tagged jets		≥ 1 b-tagged jet	
Pair production	**Single production**	**Pair production**	**Single production**
$H_T(\text{jets}) \geq 600$ GeV	≥ 1 fwd. jet	–	≥ 1 fwd. jet
Final discriminant			
$m(Zb)$		H_T(jets+leptons)	





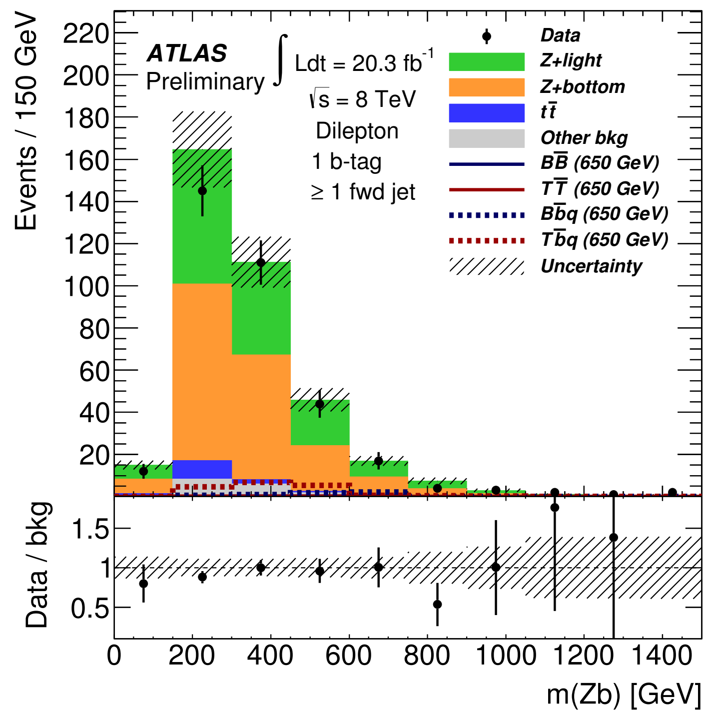
Fractional uncertainties (%): dilepton channel

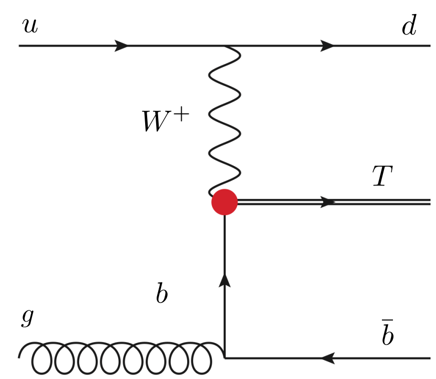
	Z+jets	$t\bar{t}$	Other bkg.	Total bkg.	$B\bar{B}$	$T\bar{T}$
Luminosity	1.4	2.8	2.8	0.3	2.8	2.8
Cross section	5.5	6.4	29	0.7	-	-
Jet reconstruction	13	10	14	11	2.0	2.1
b-tagging	9.1	13	9.9	5.7	7.2	5.9
e reconstruction	2.9	16	5.9	4.6	2.5	1.5
μ reconstruction	3.8	7.8	7.2	4.2	3.2	1.3
Z+jets $p_T(Z)$ correction	9.0	-	-	6.5	-	-
Z+jets rate correction	6.9	-	-	5.0	-	-
MC statistics	5.0	25	12	5.4	2.4	2.9

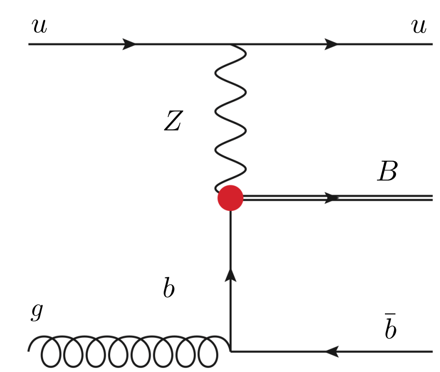
Fractional uncertainties (%): trilepton channel

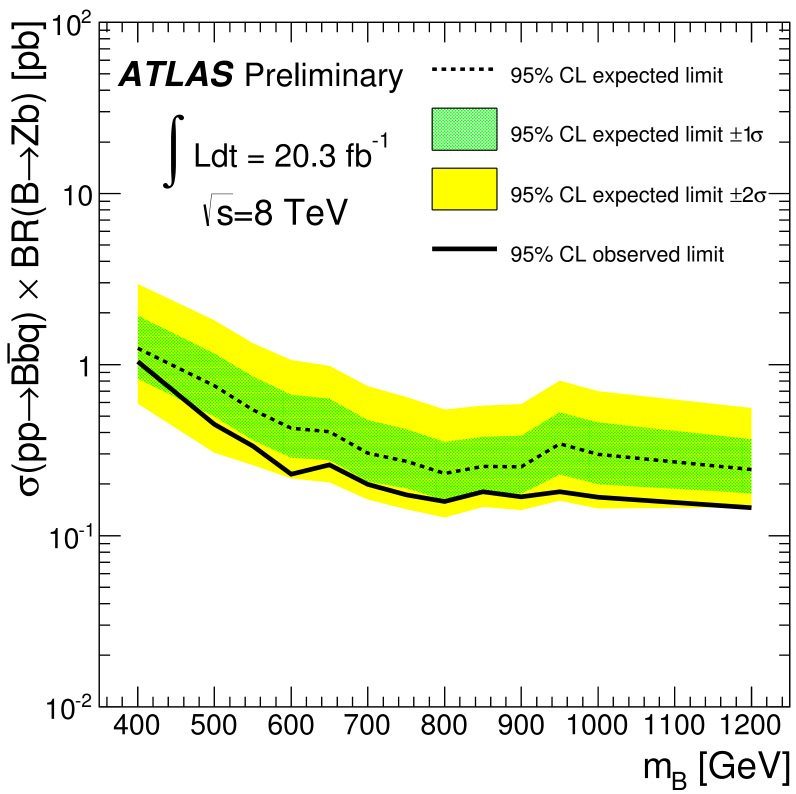
	WZ	$t\bar{t}+V$	Other bkg.	Total bkg.	$B\bar{B}$	$T\bar{T}$
Luminosity	2.8	2.8	2.8	2.8	2.8	2.8
Cross section	17	30	8.9	21	-	-
Jet reconstruction	5.4	1.2	8.1	3.1	4.0	1.8
b-tagging	13	3.6	13	6.7	5.6	5.5
e reconstruction	9.3	3.9	37	11	5.9	12
μ reconstruction	14	3.9	18	4.2	6.2	5.7
MC statistics	11	3.1	27	6.6	4.8	8.3

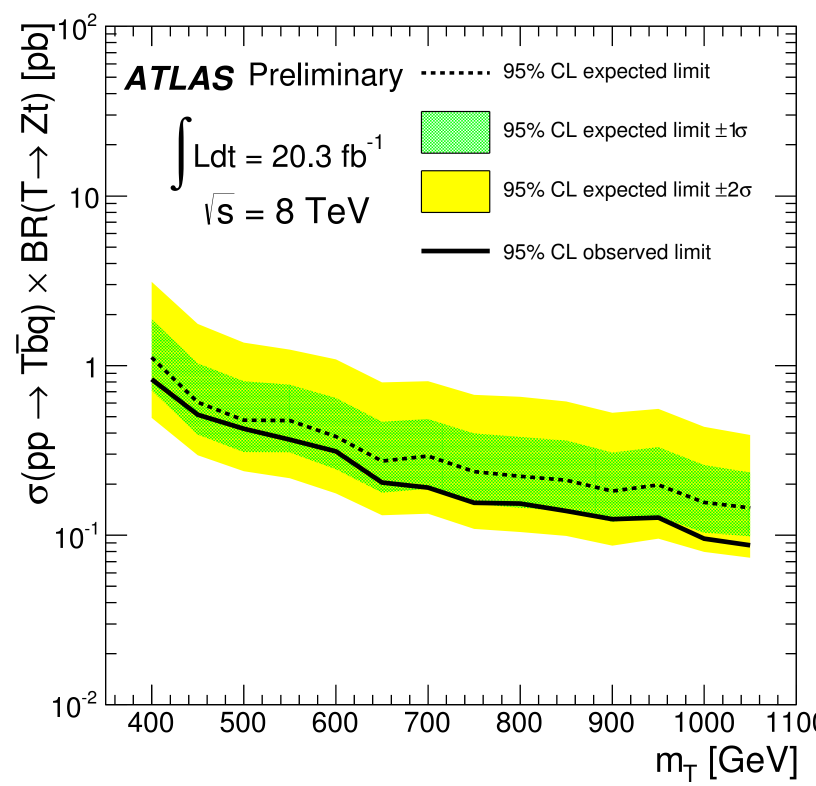
- electroweak single production











New Gauge-Bosons - Dilepton

m_{ee} [GeV]	110–200	200–400	400–800	800–1200	1200–3000	3000–4500
Z/γ^*	122000 ± 7000	14000 ± 800	1320 ± 70	70 ± 5	10.0 ± 1.0	0.008 ± 0.004
Top	8200 ± 700	2900 ± 500	200 ± 80	3.1 ± 0.8	0.16 ± 0.08	< 0.001
Diboson	1880 ± 90	680 ± 40	94 ± 5	5.9 ± 0.4	1.03 ± 0.06	< 0.001
Dijet & W+jet	3900 ± 800	1290 ± 320	230 ± 70	9.0 ± 2.3	0.9 ± 0.5	0.002 ± 0.004
Total	136000 ± 7000	18800 ± 1000	1850 ± 120	88 ± 5	12.1 ± 1.1	0.011 ± 0.005
Observed	136200	18986	1862	99	9	0

$m_{\mu\mu}$[GeV]	110–200	200–400	400–800	800–1200	1200–3000	3000–4500
Z/γ^*	111000 ± 8000	11000 ± 1000	1000 ± 100	49 ± 5	7.3 ± 1.1	0.034 ± 0.022
Top	7100 ± 600	2300 ± 400	160 ± 80	3.0 ± 1.7	0.17 ± 0.15	< 0.001
Diboson	1530 ± 180	520 ± 130	64 ± 16	4.2 ± 2.1	0.69 ± 0.30	0.0024 ± 0.0019
Total	120000 ± 8000	13700 ± 1100	1180 ± 130	56 ± 6	8.2 ± 1.2	0.036 ± 0.023
Observed	120011	13479	1122	49	8	0

TABLE III. Summary of systematic uncertainties on the expected numbers of events at a dilepton mass of $m_{\ell\ell} = 2$ TeV, where N/A indicates that the uncertainty is not applicable. Uncertainties $< 3\%$ for all values of m_{ee} or $m_{\mu\mu}$ are neglected in the respective statistical analysis.

Source ($m_{\ell\ell} = 2$ TeV)	Dielectrons		Dimuons	
	Signal	Backgr.	Signal	Backgr.
Normalization	4%	N/A	4%	N/A
PDF variation	N/A	11%	N/A	12%
PDF choice	N/A	7%	N/A	6%
α_s	N/A	3%	N/A	3%
Electroweak corr.	N/A	2%	N/A	3%
Photon-induced corr.	N/A	3%	N/A	3%
Beam energy	$< 1\%$	3%	$< 1\%$	3%
Resolution	$< 3\%$	$< 3\%$	$< 3\%$	3%
Dijet and $W +$jets	N/A	5%	N/A	N/A
Total	4%	15%	4%	15%

New Gauge-Bosons - Dilepton

arxiv:1405.4123
submitted to PRD

Table 4. Expected numbers of events from the various background sources in each decay channel for $m_{\mathrm{T}} > 1500$ GeV, the region used to search for a W' with a mass of 2000 GeV. The $W \to \ell\nu$ and $Z \to \ell\ell$ rows include the expected contributions from the τ-lepton. The uncertainties are statistical.

	$e\nu$	$\mu\nu$
$W \to \ell\nu$	2.65 $\pm$ 0.10	2.28 $\pm$ 0.21
$Z \to \ell\ell$	0.00163 $\pm$ 0.00022	0.232 $\pm$ 0.005
Diboson	0.27 $\pm$ 0.23	0.46 $\pm$ 0.23
Top	0.0056 $\pm$ 0.0009	0.0017 $\pm$ 0.0001
Multi-jet	0.066 $\pm$ 0.020	0.046 $\pm$ 0.039
Total	2.99 $\pm$ 0.25	3.01 $\pm$ 0.31

Table 5. Relative uncertainties on the selection efficiency $\varepsilon_{\mathrm{sig}}$ and expected number of background events N_{bkg} for a W' (upper part of the table) and W^* (lower part of the table) with a mass of 2000 GeV. The efficiency uncertainties include contributions from the trigger, reconstruction and event selection. The last row gives the total relative uncertainties.

	$\varepsilon_{\mathrm{sig}}$		N_{bkg}	
Source	$e\nu$	$\mu\nu$	$e\nu$	$\mu\nu$
$W' \to \ell\nu$				
Reconstruction and trigger efficiency	2.5%	4.1%	2.7%	4.1%
Lepton energy/momentum resolution	0.2%	1.4%	1.9%	18%
Lepton energy/momentum scale	1.2%	1.8%	3.5%	1.5%
$E_{\mathrm{T}}^{\mathrm{miss}}$ scale and resolution	0.1%	0.1%	1.2%	0.5%
Beam energy	0.5%	0.5%	2.8%	2.1%
Multi-jet background	-	-	2.2%	3.4%
Monte Carlo statistics	0.9%	1.3%	8.5%	10%
Cross-section (shape/level)	2.9%	2.8%	18%	15%
Total	4.2%	5.6%	21%	27%
$W^* \to \ell\nu$				
Reconstruction and trigger efficiency	2.7%	4.1%	2.6%	4.0%
Lepton energy/momentum resolution	0.4%	0.9%	3.0%	17%
Lepton energy/momentum scale	2.4%	2.4%	3.1%	1.5%
$E_{\mathrm{T}}^{\mathrm{miss}}$ scale and resolution	0.1%	0.4%	3.1%	0.6%
Beam energy	0.1%	0.1%	2.5%	1.9%
Multi-jet background	-	-	1.8%	2.6%
Monte Carlo statistics	1.2%	1.8%	6.7%	8.6%
Cross-section (shape/level)	0.2%	0.2%	17%	15%
Total	3.9%	5.1%	19%	25%

Contact Interaction

arXiv:1407.2410

- calculation of decay angle in Collins-Soper frame
  - z-acis bisecting angel between incoming partons
  - x-axis perpendicular to plane of incoming parton momenta

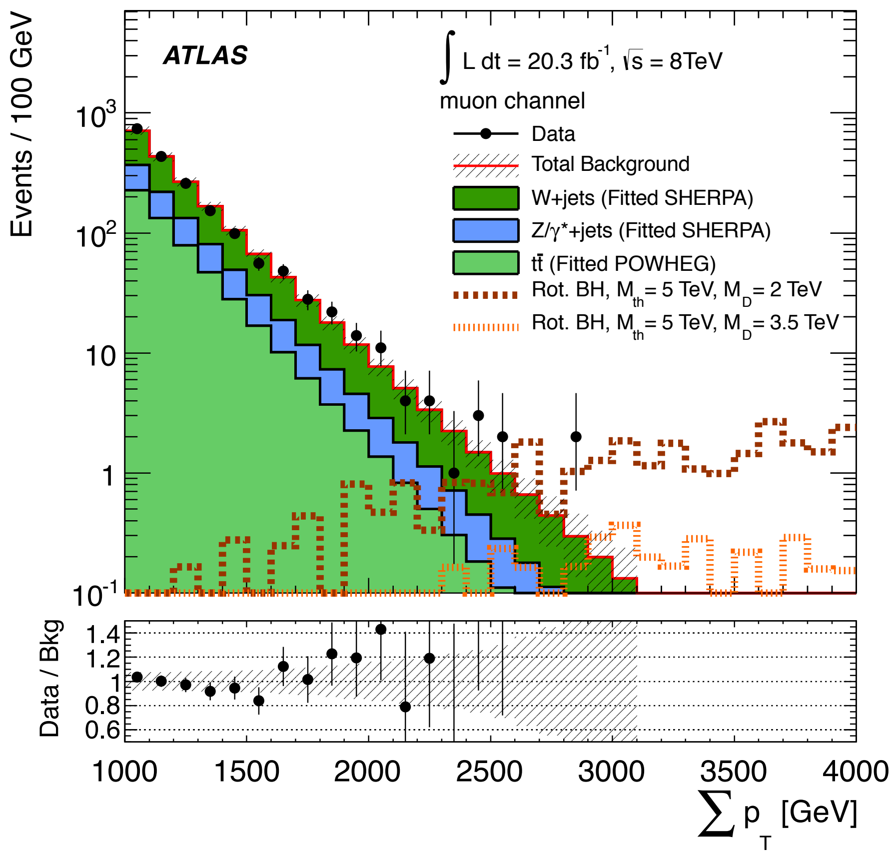
$$\cos\theta^* = \frac{p_z(\ell^+\ell^-)}{|p_z(\ell^+\ell^-)|}\frac{2(p_1^+p_2^- - p_1^-p_2^+)}{m(\ell^+\ell^-)\sqrt{m(\ell^+\ell^-)^2 + p_T(\ell^+\ell^-)^2}}$$

- $p^{+/-}=E+/-p_z$

  - angle between z-axis and outgoing negatively charged lepton

Leptons+Jets Extra Dimensions

arXiv:1405.4254
accepted by JHEP



Min. $\sum p_T$ [GeV]	Electron Channel Expected Background	Electron Channel Data	Muon Channel Expected Background	Muon Channel Data
2000	44 ± 12	47	22.8 ± 5.4	27
2200	19 ± 7	22	10.1 ± 3.2	12
2400	8.2 ± 3.7	5	4.5 ± 1.9	7
2600	3.5 ± 2.1	2	2.0 ± 1.3	2
2800	1.5 ± 1.2	0	0.89 ± 0.82	2
3000	$0.65^{+0.69}_{-0.65}$	0	$0.40^{+0.53}_{-0.40}$	0
3200	$0.28^{+0.40}_{-0.28}$	0	$0.18^{+0.34}_{-0.18}$	0

Angular Mom.	Description	Excluded M_{th} value [TeV] for: $M_D = 1.5$ TeV	Excluded M_{th} value [TeV] for: $M_D = 4$ TeV
Non-rotating	Black holes: High multiplicity remnant	6.2	5.7
Rotating	Black holes: High multiplicity remnant	6.0	5.4
Rotating	Black holes: Low multiplicity remnant	6.0	5.2
Rotating	Production loss model (gravitons)	5.5	4.8

Mono-Z

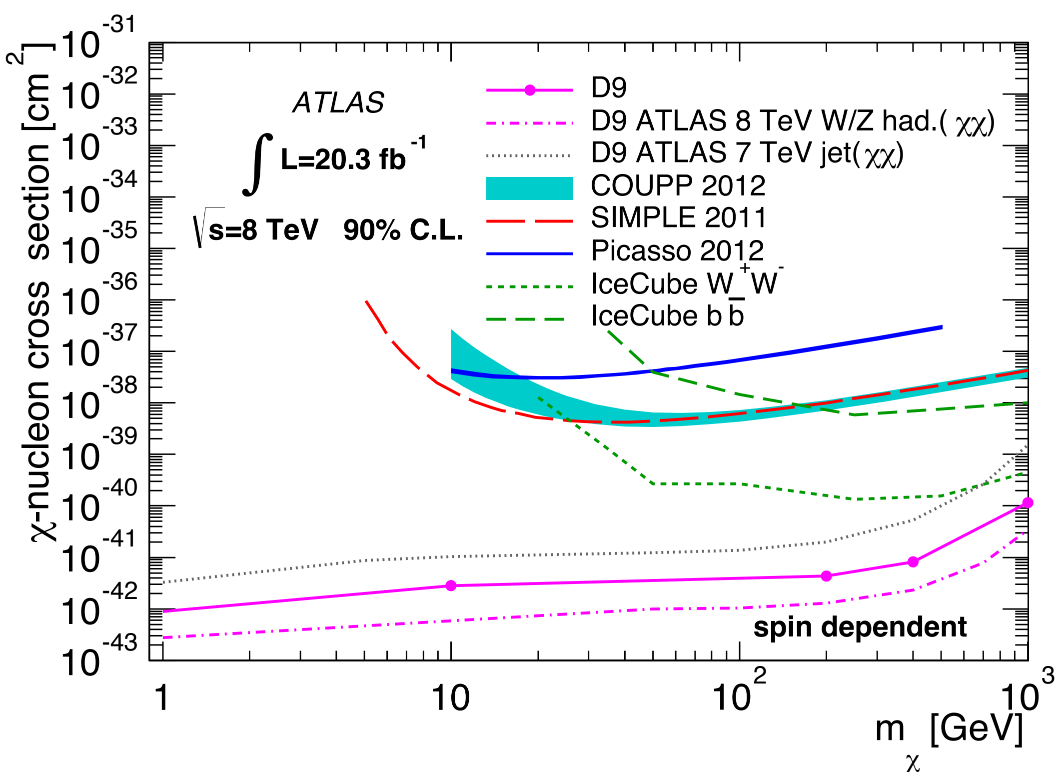
PRD 90, 012004 (2014)

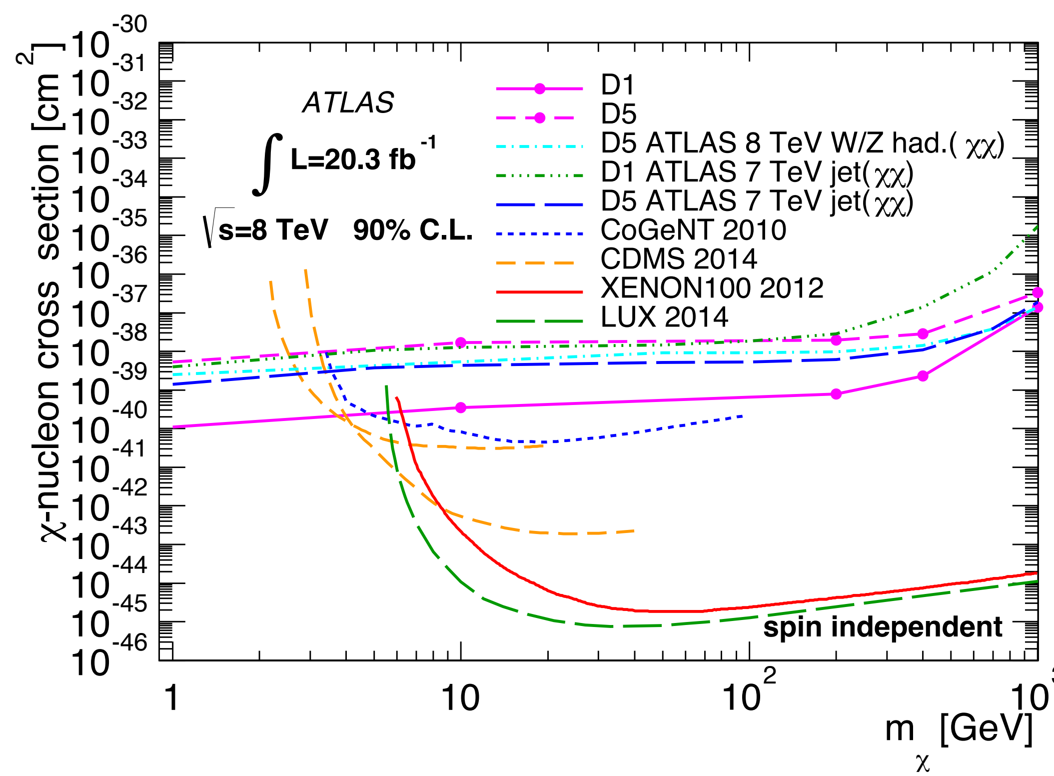
event numbers

Process	E_T^{miss} threshold [GeV] 150	250	350	450
ZZ	41 ± 15	6.4 ± 2.4	1.3 ± 0.5	0.3 ± 0.1
WZ	8.0 ± 3.1	0.8 ± 0.4	0.2 ± 0.1	0.1 ± 0.1
WW, $t\bar{t}$, $Z \to \tau^+\tau^-$	1.9 ± 1.4	$0^{+0.7}_{-0.0}$	$0^{+0.7}_{-0.0}$	$0^{+0.7}_{-0.0}$
Z+jets	0.1 ± 0.1	–	–	–
W+jets	0.5 ± 0.3	–	–	–
Total	52 ± 18	7.2 ± 2.8	1.4 ± 0.9	$0.4^{+0.7}_{-0.4}$
Data	45	3	0	0

systematic uncertainties

Uncertainty Source	E_T^{miss} threshold [GeV] 150	250	350	450
Statistical [%]	2	6	13	24
Experimental [%]	3	6	9	8
Theoretical [%]	35	35	35	35
Luminosity [%]	3	3	3	3
Total [%]	35	36	38	43





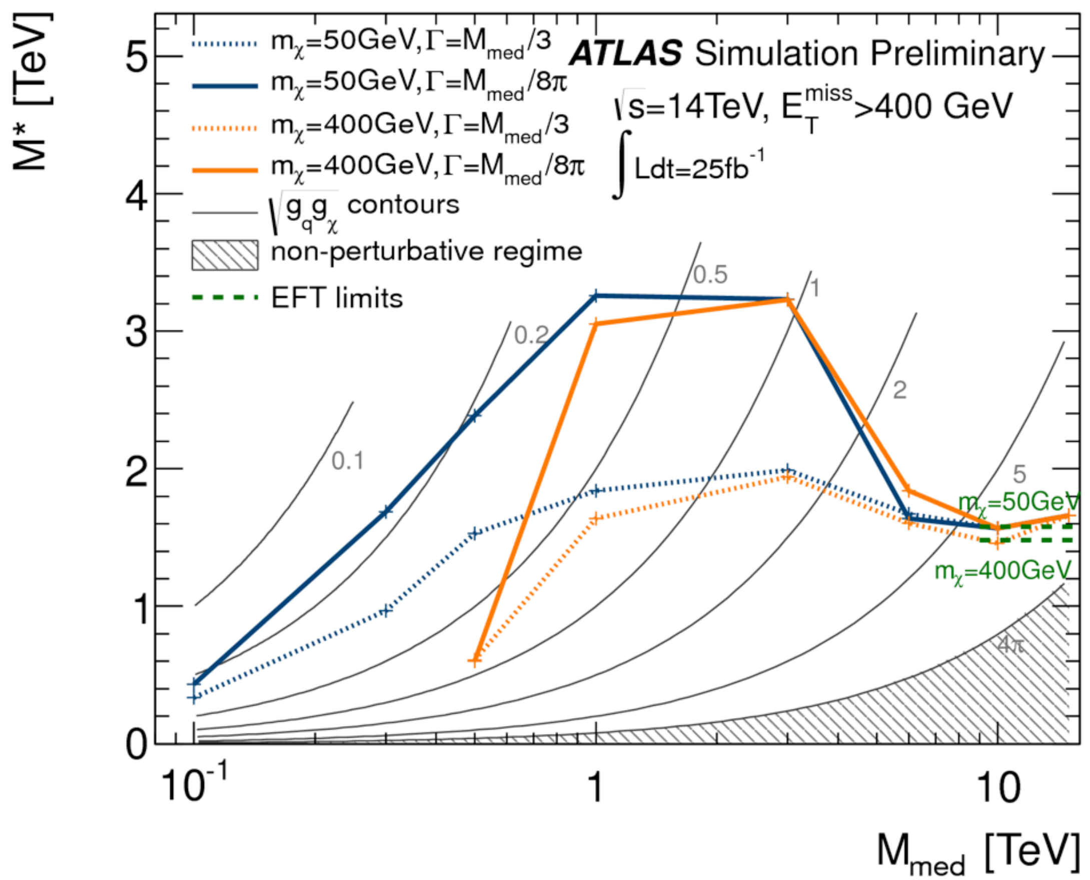
Mono-jet, 8TeV

ATLAS-CONF-2012-147

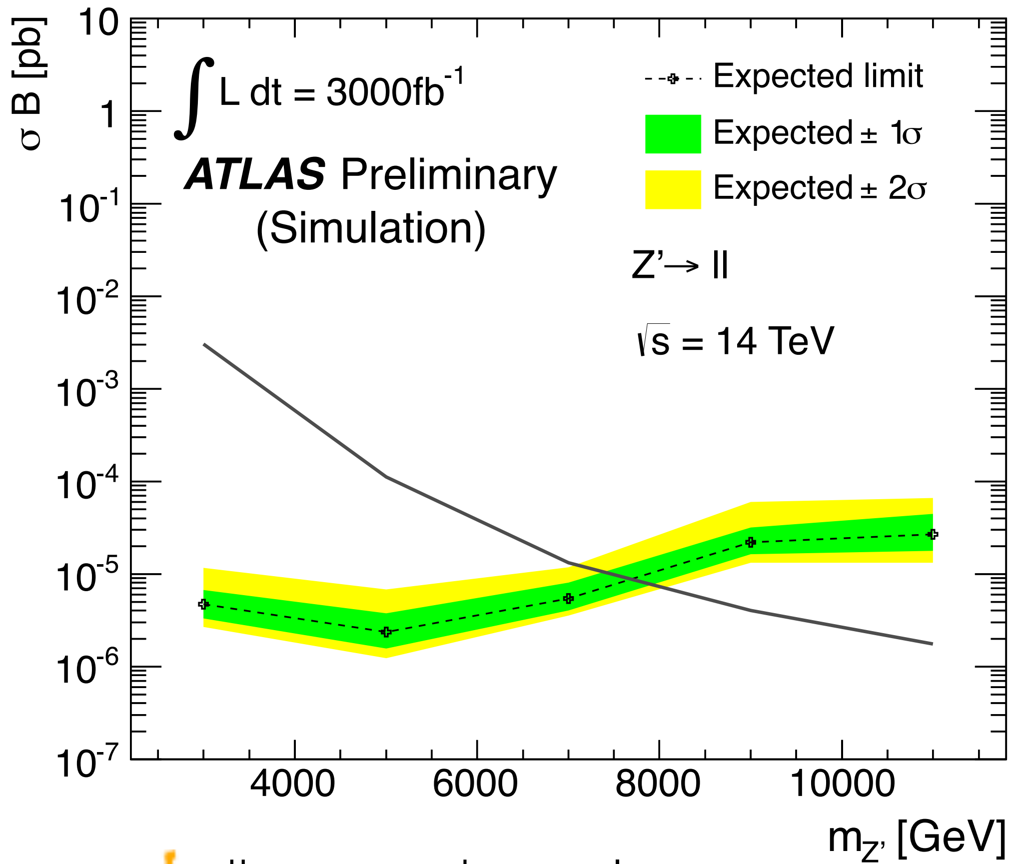
Background Predictions ± (stat.data)± (stat.MC) ± (syst.)				
	SR1	SR2	SR3	SR4
$Z(\to \nu\bar{\nu})$+jets	173600 ± 500 ± 1300 ± 5500	15600 ± 200 ± 300 ± 500	1520 ± 50 ± 90 ± 60	270 ± 30 ± 40 ± 20
$W \to \tau\nu$+jets	87400 ± 300 ± 800 ± 3700	5580 ± 60 ± 190 ± 300	370 ± 10 ± 40 ± 30	39 ± 4 ± 11 ± 2
$W \to e\nu$+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

More 14TeV Prospects

ATLAS-CONF-2012-147



ATL-PHYS-PUB-2013-003



- di-muon channel