Search for Extra Dimensions, Dark Matter & New Interactions with Leptons and Bosons using the ATLAS detector

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PRiSMA

Motivation

- SM impressively consistent
  (even after discovery of Higgs) ➔

Still open questions…and no favorite solution !

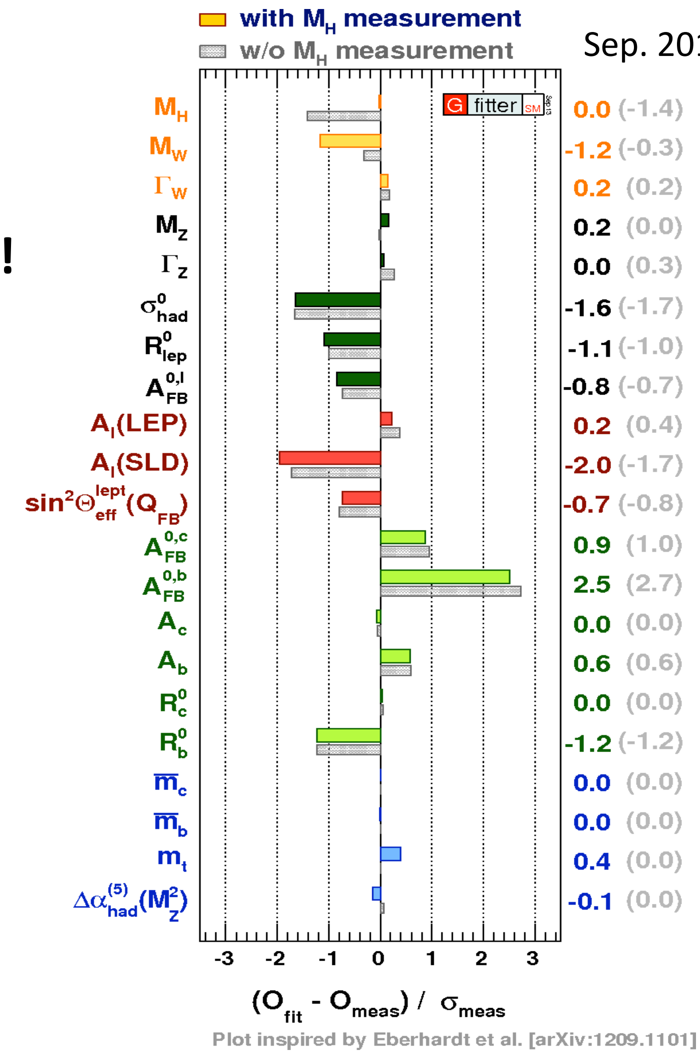
<u>Focus of this talk:</u>

- Hierarchy problem:
  - New TeV scale interactions/particles
  - Extra dimensions
  - Composite Higgs
- WIMPs as dark matter candidates ?

<u>Signatures/objects involved:</u>

- Search for new (heavy) objects.
- High-p_T leptons/jets
- Large E_T^{miss}

Sep. 2013



http://gfitter.desy.de/

Baak et al., Eur. Phys. J. C72 (2012) 2205

No deviations > 3 σ !

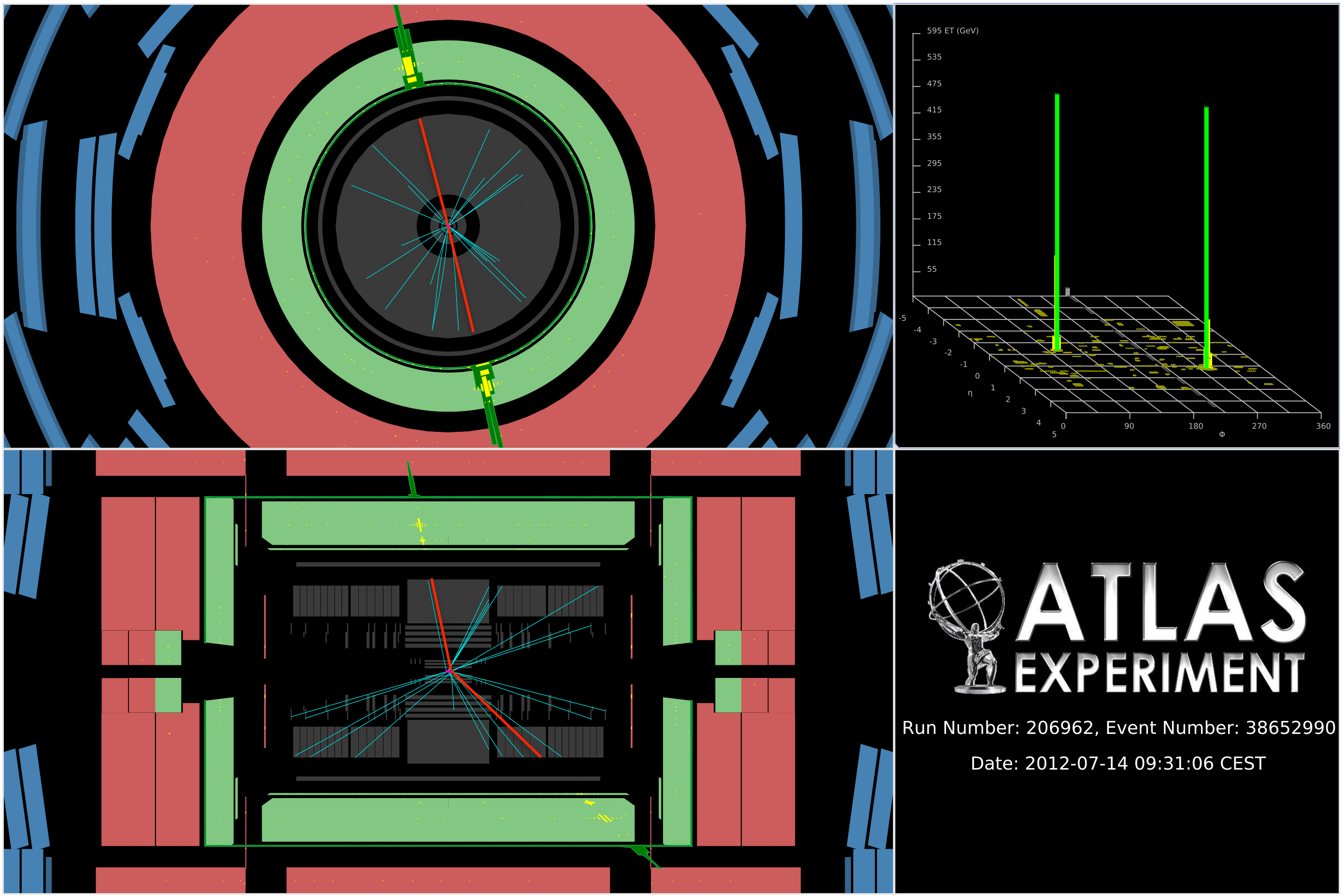
➔ SM consistent!

The results (full 8 TeV data set):

- New Spin-1 resonances
  - Dilepton: Methods and techniques -> one example in detail (ATLAS-CONF-2013-017)
  - Lepton plus E_T^{miss} (ATLAS-CONF-2014-017)
  - WZ (ATLAS-CONF-2014-015)
- Extra-Dimensions: Randall-Sundrum
  - Dileptons (ATLAS-CONF-2013-017 + prelim. updates)
  - Dihiggs -> 4b (ATLAS-CONF-2014-005)
- Extra-Dimensions: (Quantum) Black Holes
  - Lepton + jet (PRL 112, 091804 (2014))
  - Photon + jet (PLB 728, 562 (2013))
  - Dilepton (ATLAS-CONF-2013-017 + prelim. updates/reinterpretation)
  - Multi-Object (leptons, jets) (ATLAS-CONF-2014-016)
- Dark Matter
  - Mono-W, Mono-Z, hadronic decay (PRL 112, 041802 (2014))
  - Mono-W, Lepton + E_T^{miss} (ATLAS-CONF-2014-017)
- Composite Higgs in Minimal Walking Technicolor
  - Dilepton (ATLAS-CONF-2013-017 + prelim. updates/reinterpretation)

New for today

HowTo ? Example: Dileptons



Two electrons:
p_T > 40 GeV
p_T > 30 GeV

Highest m_{ll} event 8 TeV:
p_T = 588 GeV
p_T = 584 GeV
m_{ll} = 1.54 TeV

Two isolated leptons -> Clean signature with low background

➔ Also used for NP searches with small BR to dilepton final states

Background and Signal

Background estimate from MC in dilepton channel

Drell-Yan: Powheg-Pythia 8 (binned in invariant mass) scaled (mass-dependent) to FEWZ calculation (NNLO pQCD, NLO EW, no FSR) using MSTW2008NNLO plus photon induced and real W/Z contribution, FSR from Photos

Diboson: Herwig scaled to NLO cross section

$t\bar{t}$ & tW: MC@NLO, scaled to approx. NNLO, extrapolation to high-mass via fits

Signal MC:

Pythia 8: scaled (mass-dependent) to same FEWZ calculation not including EW, photon-induced and real W,Z radiation, FSR from Photos

Data driven background estimate:

Events with one or more misidentified jets etc. from data (negligible for muons)

➔ Electron channel: Veto on MC events with less than 2 real electrons

➔ "Fake background": Mainly Dijet & W+jet

Data driven (Matrix-Method) background

- Real quantities: $N_{RR}, N_{RF}, N_{FR}, N_{FF}$
- Measurable quantities: $N_{TT}, N_{TL}, N_{LT}, N_{LL}$
- Method based on different probabilities of fake electrons and real electrons for moving from a "loose" selection into a "tight" selection
- Measure relative probability of real electrons $r = N_{real}^{tight} / N_{real}^{loose}$ to do this transition in MC
- Measure the relative probability of fakes $f = N_{fakes}^{tight} / N_{fakes}^{loose}$ in a jet enriched control region from data

$$\begin{pmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{pmatrix} = \begin{pmatrix} r_1 r_2 & r_1 f_2 & f_1 r_2 & f_1 f_2 \\ r_1(1-r_2) & r_1(1-f_2) & f_1(1-r_2) & f_1(1-f_2) \\ (1-r_1)r_2 & (1-r_1)f_2 & (1-f_1)r_2 & (1-f_1)f_2 \\ (1-r_1)(1-r_2) & (1-r_1)(1-f_2) & (1-f_1)(1-r_2) & (1-f_1)(1-f_2) \end{pmatrix} \begin{pmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{pmatrix}$$

$$N_{di-jet\,\&\,W+Jets} = N_{TT}^{fake} = r_1 f_2 N_{RF} + f_1 r_2 N_{FR} + f_1 f_2 N_{FF}$$

Default method: Replace real quantities (N_{RF}, …) by inverting matrix
Default calculation of f (η, p_T) on jet triggered sample

Fake BG sys. (dominant exp.unc.)

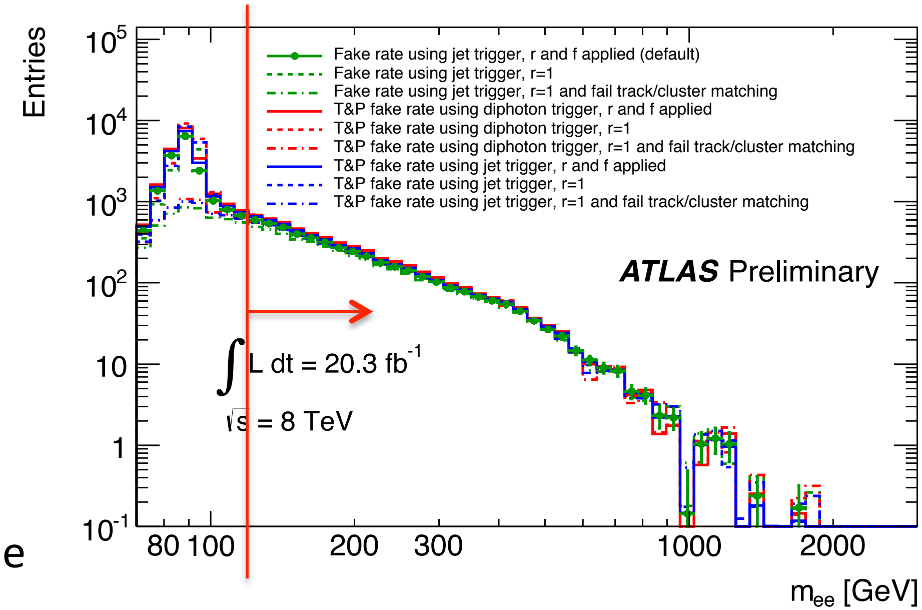
Three “matrix” methods:

- Full matrix (prev. slide, default)
- Assume $r_1 = r_2 = 1$, account for identification inefficiencies with MC
- different “loose” definition/sample

Three measurements of f_1, f_2:

- jet triggered sample (default)
- jet trigger, enrich jets by Tag & Probe
- diphoton trigger, enrich jets by Tag & Probe

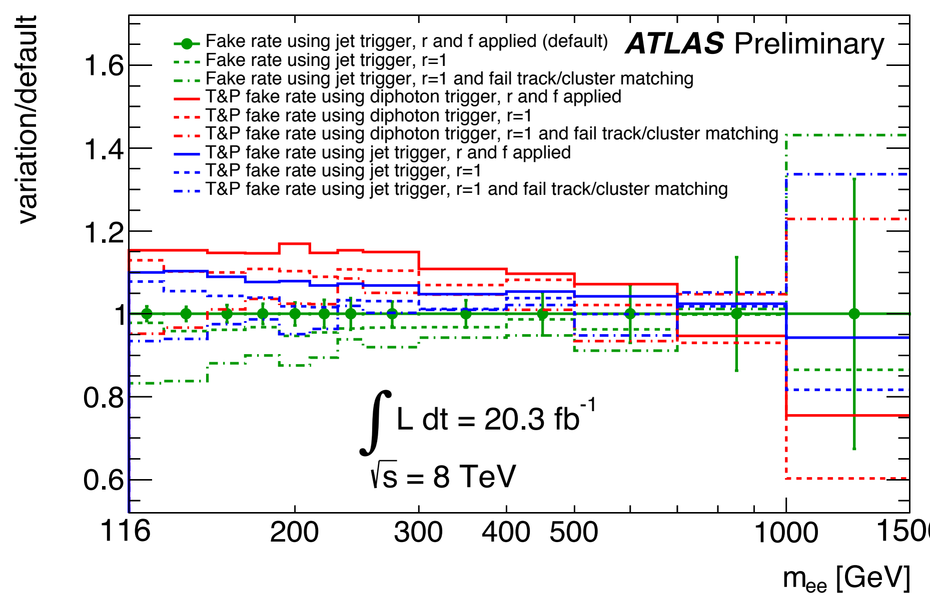
➔ 9 different estimates -> +/- 18%



In addition:

- Cut variations in determination of f -> 5%
- Statistical uncertainty of f -> 5%
- Background composition -> negligible

➔ 20 % overall systematic uncertainty



Systematic uncertainties

Systematic uncertainty on expected number of events @ 3 TeV:

Source	Dielectrons		Dimuons	
	Signal	Background	Signal	Background
Normalization	4%	N/A	4%	N/A
PDF variation	N/A	30%	N/A	17%
PDF choice	N/A	22%	N/A	12%
α_s	N/A	5%	N/A	4%
Electroweak corrections	N/A	4%	N/A	3%
Photon-induced corrections	N/A	6%	N/A	4%
Beam energy	$< 1\%$	5%	$< 1\%$	3%
Resolution	$< 3\%$	$< 3\%$	$< 3\%$	8%
Dijet and $W +$ jets	N/A	21%	N/A	N/A
Total	4%	44%	4%	23%

These updated systematics (w.r.t. ATLAS-CONF-2013-17) used in new interpretations later in this talk…

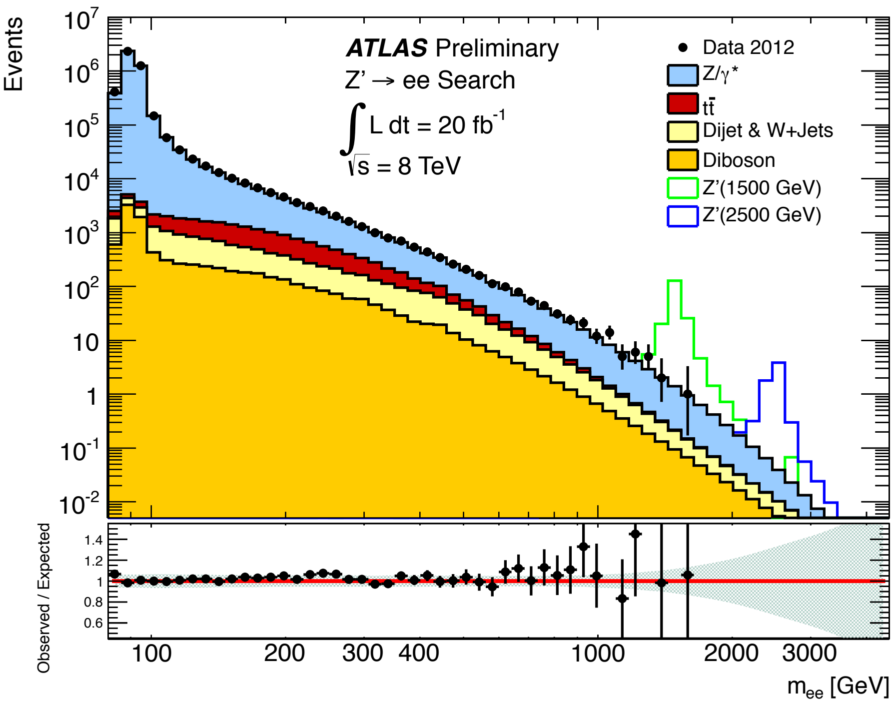
<u>Dominant systematics:</u>

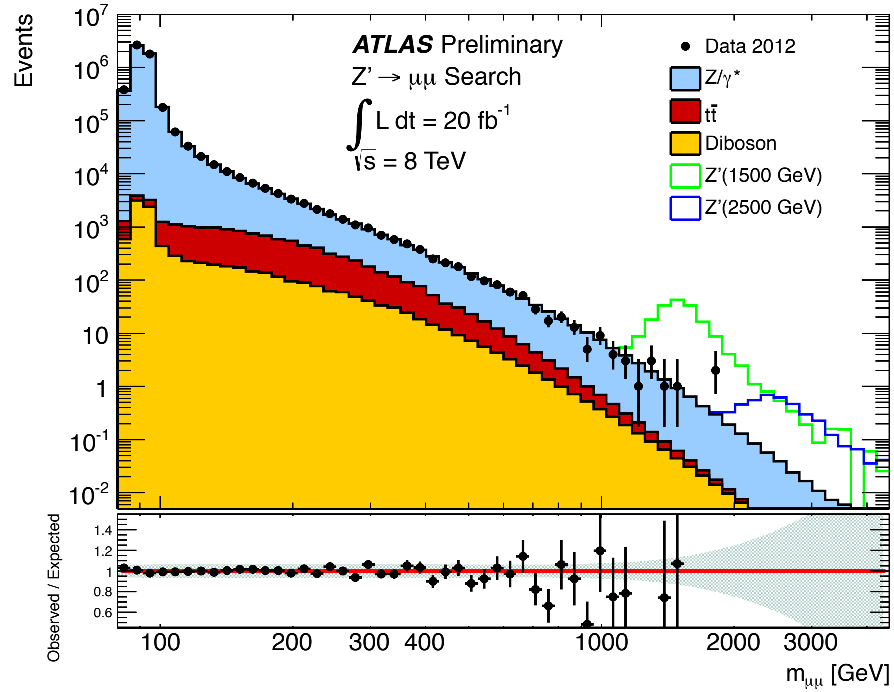
- PDF variation: 90% CL MSTW2008NNLO PDF error set
- PDF choice: Central values of other PDFs outside MSTW error set ?
  (CT10NNLO, NNPDF2.3, ABM11, HERAPDF1.5)
  ➔ ABM 11 is outside…
- Dijet & W+Jets (electrons)

Comparison: Data-Expectation

Sum of MCs scaled to data (minus Dijets & W+Jets) in 80 GeV < m_{ll} < 110 GeV
➔ Scale factors approx. unity

ATLAS-CONF-2013-017





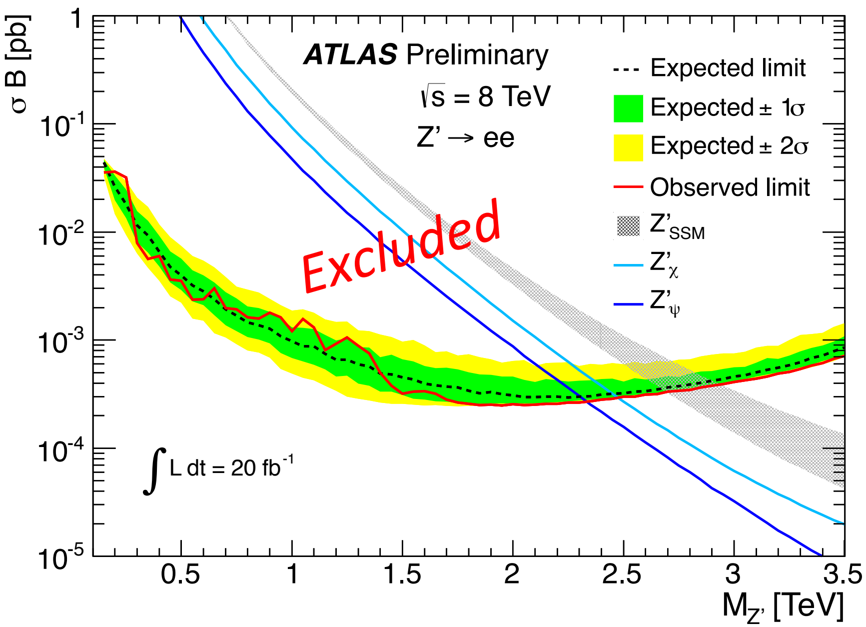
- Better resolution for electrons
- (+ Better efficiency for electrons)

➔ Electron limits dominate (more or less)

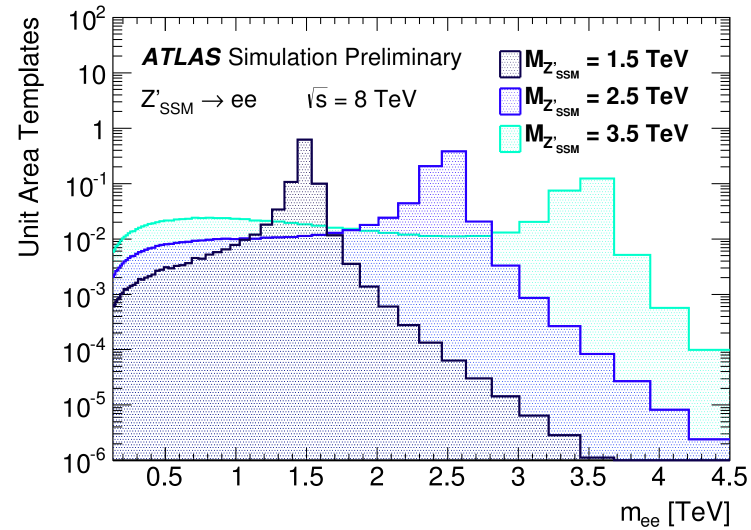
Signal:
Additional neutral gauge bosons Z'_{SSM}
(couplings same as for Z, benchmark model)

Good agreement of data with expectation !
➔ Set limits…

Limits



Limits set using MC templates taking into account actual signal shape on reconstruction level:

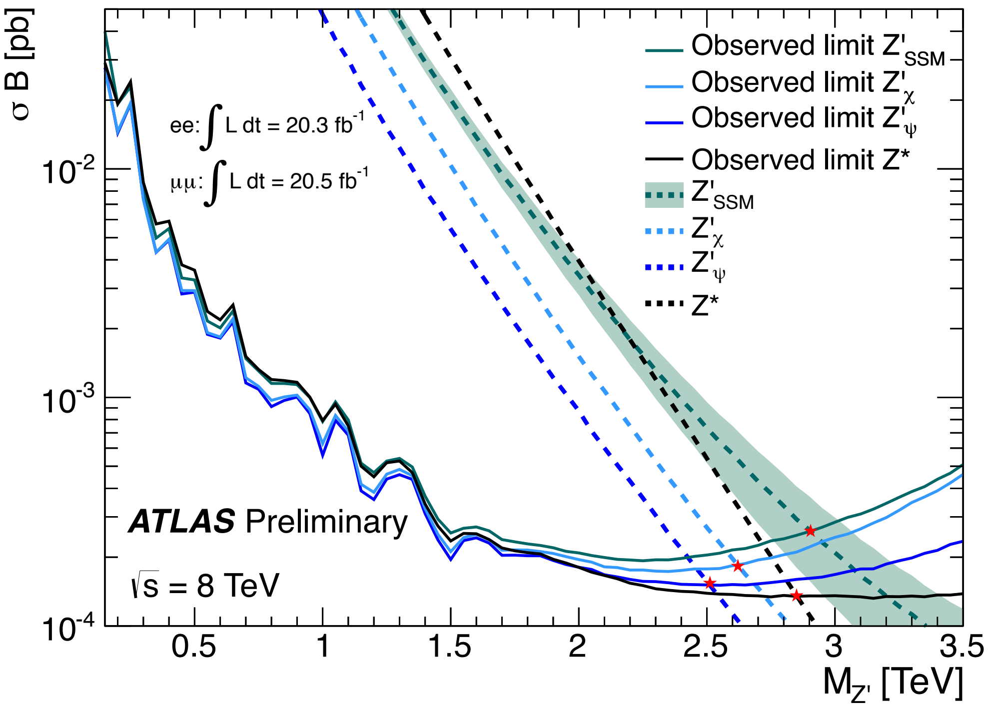


➔ Upper limit (95% CL) on σB.

➔ Lower mass limit (95% CL) on Z'_{SSM} is 2.8 TeV (2.9 TeV when combined with muons)

Large off-shell production
➔ Limit degrades for high masses
➔ Time for higher beam energy!

Discussion limits



Additional neutral gauge bosons:

- Z'_{SSM}
- E6 Z'_χ and Z'_ψ, GUT motivated
- Z*, appear as doublet (Z*,W*) in various solutions to hierarchy problem, anomalous couplings to fermions

Model	Width [%]
Z'_{SSM}	3.0
Z'_χ	1.2
Z'_ψ	0.5
Z^*	3.4

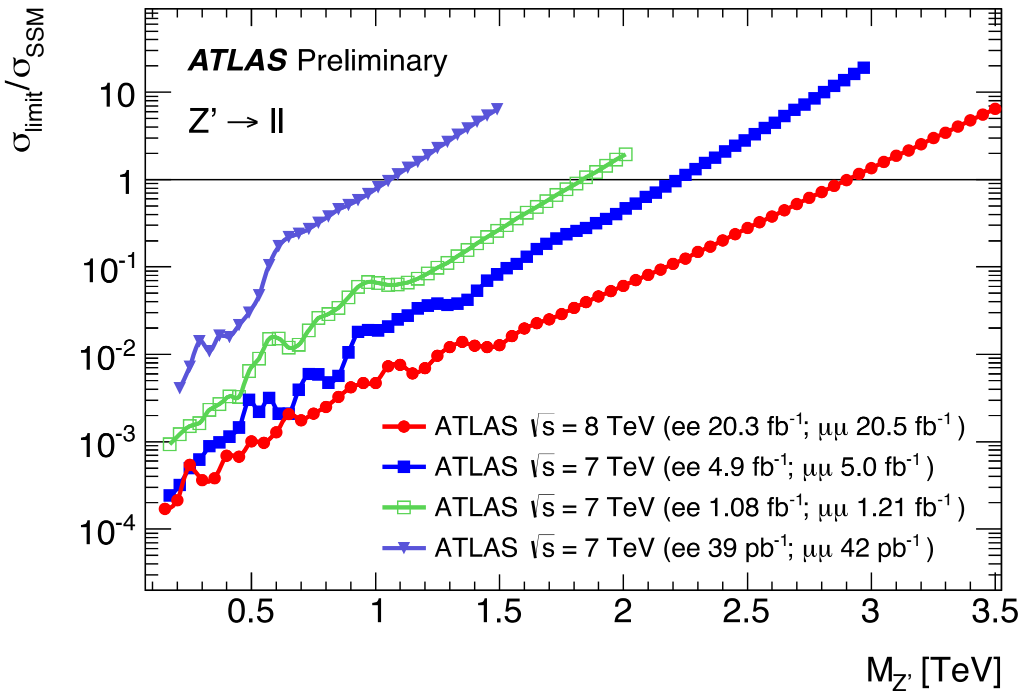
Low mass:

- Limits get stronger with decreasing width, but effect small…

High mass:

- Off-shell production leads to weaker limits
- Off-shell production increases with increasing width
- Z'_{SSM} mass limit would increase by 0.3 TeV if suppressed off-shell production (Z*)

Development over recent years



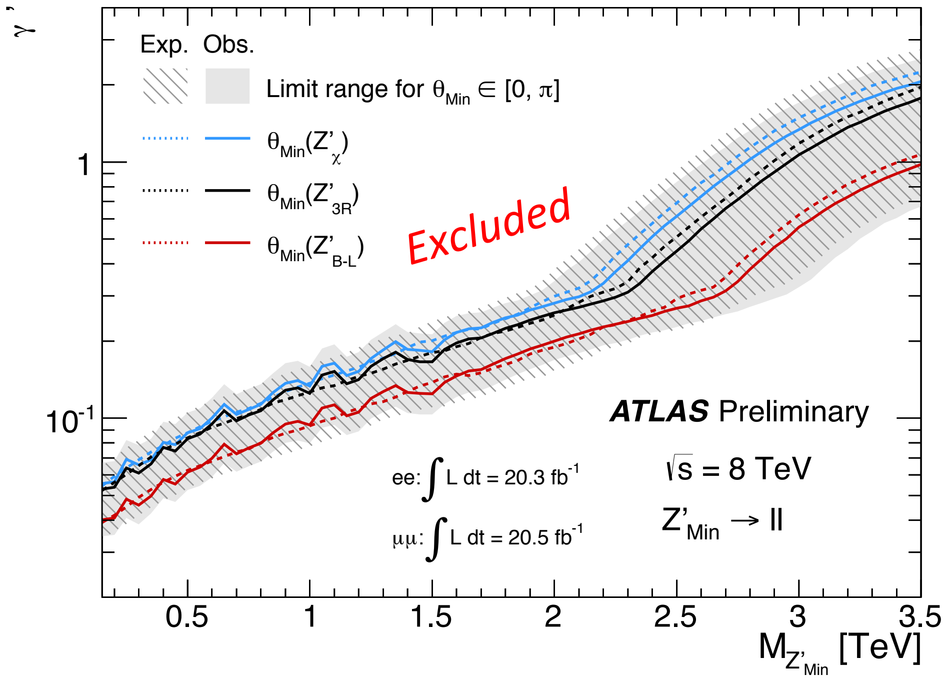
- Tevatron limits (approx. 1 TeV) reached with 2010 data
- 2011 data ➔ 2.2 TeV limit
- 2012 data ➔ 2.9 TeV limit

Fast increase in limits (1TeV->3TeV) in short period of time !

Also, narrow resonances with 100 times smaller cross section than SSM excluded up to 1.4 TeV

Minimal Z‘ Model

Minimal Z’ model (Salvioni et al., JHEP 0911 068) with only two parameters in addition to mass:
γ': Z’ coupling strength relative to Z coupling strength
θ_{min}: mixing between weak hypercharge and (B-L) gauge groups



➔ Encompasses many models, also Z'_χ

	$Z'_{\rm B-L}$	Z'_χ	$Z'_{\rm 3R}$
γ'	$\sqrt{\frac{5}{8}}\sin\theta_W$	$\sqrt{\frac{41}{24}}\sin\theta_W$	$\frac{5}{\sqrt{12}}\sin\theta_W$
$\cos\theta_{\rm Min}$	1	$\sqrt{\frac{25}{41}}$	$\frac{1}{\sqrt{5}}$
$\sin\theta_{\rm Min}$	0	$-\sqrt{\frac{16}{41}}$	$-\frac{2}{\sqrt{5}}$

Templates take into account varying width of Z’ (varies with coupling) and interference

➔ Limits less model-dependent…

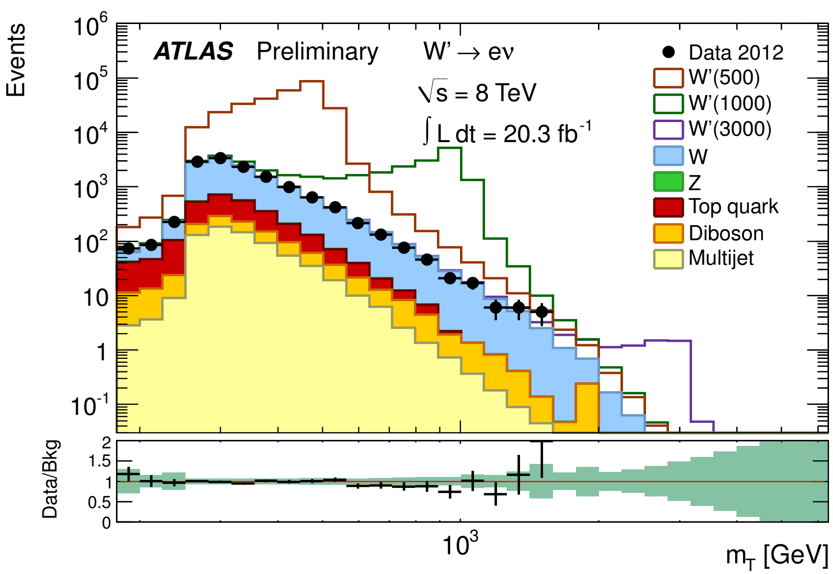
Search in lepton plus E_T^{miss}

Additional charged (Spin-1) gauge bosons:

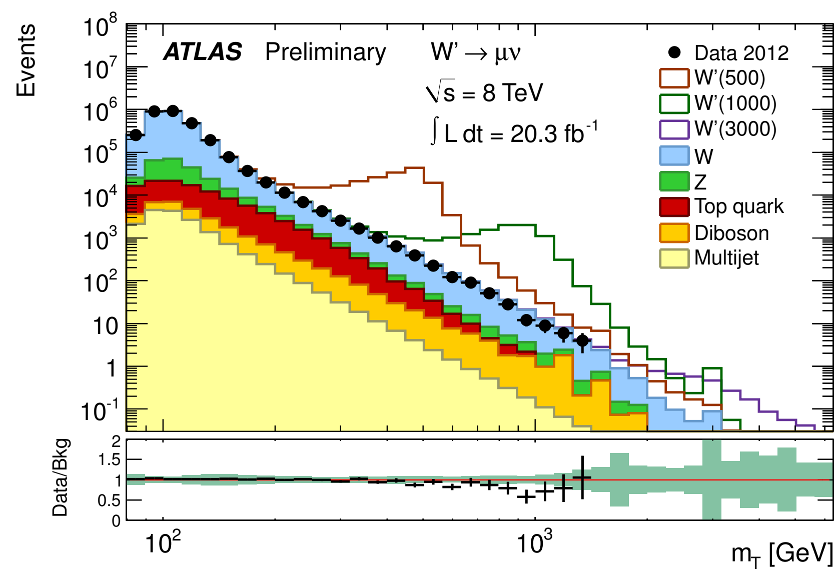
- W'_{SSM}, same couplings as W, benchmark model
- W*, appear as doublet (Z*,W*), anomalous couplings to fermions

ATLAS-CONF-2014-017

Electron $p_T > 125$ GeV
$E_T^{miss} > 125$ GeV



Muon $p_T > 45$ GeV
$E_T^{miss} > 45$ GeV



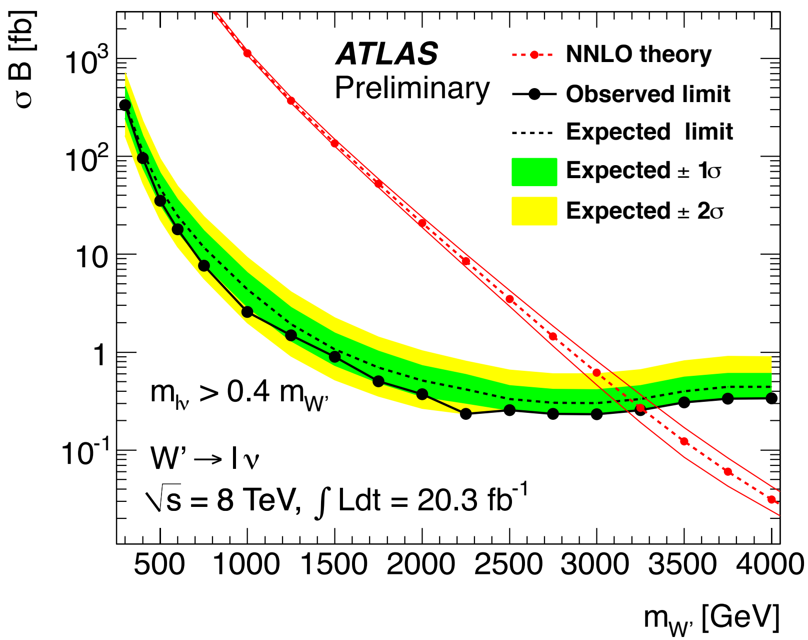
$$m_T = \sqrt{2 p_T E_T^{miss} (1 - \cos \varphi_{\ell\nu})}$$

- EW backgrounds from MC
- “QCD” from data driven matrix-method

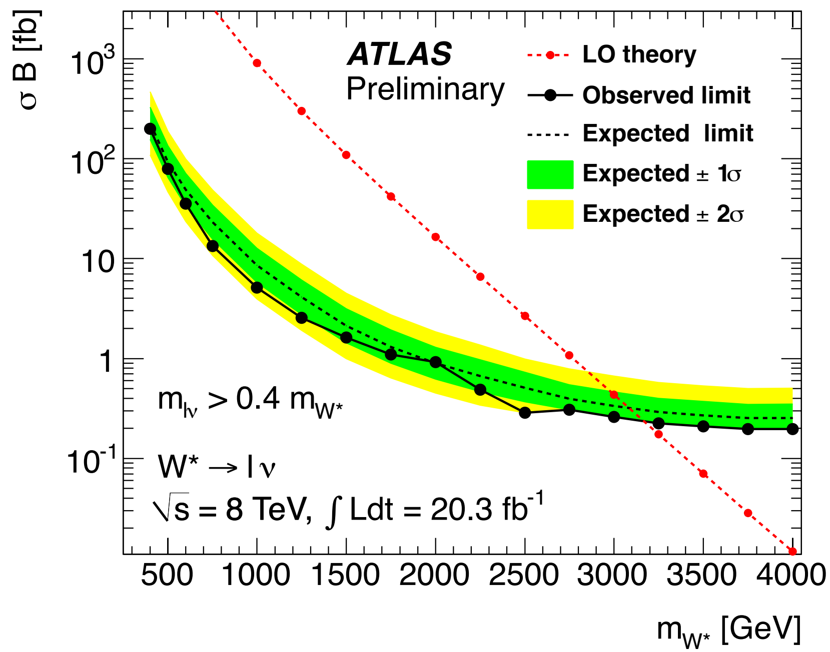
Limits: W‘ and W*

ATLAS-CONF-2014-017

W’



W*



Upper 95% CL limits on σ Br in kinematical region ($m_{l\nu} > 0.4\ m_{W'}$)

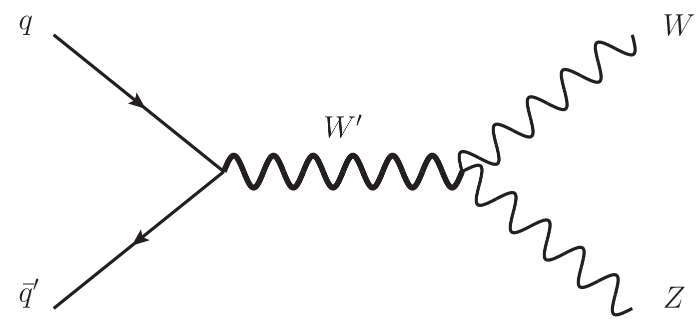
➔ Only small degradation of limits observed

➔ Lower 95% CL limit on mass does not depend on acceptance definition (restricted versus total)

	$m_{W'}$ [TeV]		m_{W^*} [TeV]	
decay	Exp.	Obs.	Exp.	Obs.
$e\nu$	3.15	3.15	3.04	3.04
$\mu\nu$	2.98	2.98	2.80	2.80
both	3.19	3.27	3.08	3.17

W‘ -> WZ -> 3l + ν

ATLAS-CONF-2014-015



Benchmark model:

W’ (extended gauge model): same couplings as W, except suppressed coupling to WZ by $(m_W/m_{W'})^2$

- Narrow resonance (5-70 GeV for masses of 0.2-2 TeV) compared to resolution (100 GeV for 1 TeV W’)
  ➔ can be used for reinterpretation

Basic selection:

- Exactly three leptons
- Z: 2 opposite-sign same flavor leptons within 20 GeV of Z peak
- W: E_T^{miss} > 25 GeV
- Δy (W,Z) < 1.5

Two signal regions:

- Low mass: $\Delta\phi$ (l, E_T^{miss}) > 1.5
- High mass: $\Delta\phi$ (l, E_T^{miss}) < 1.5

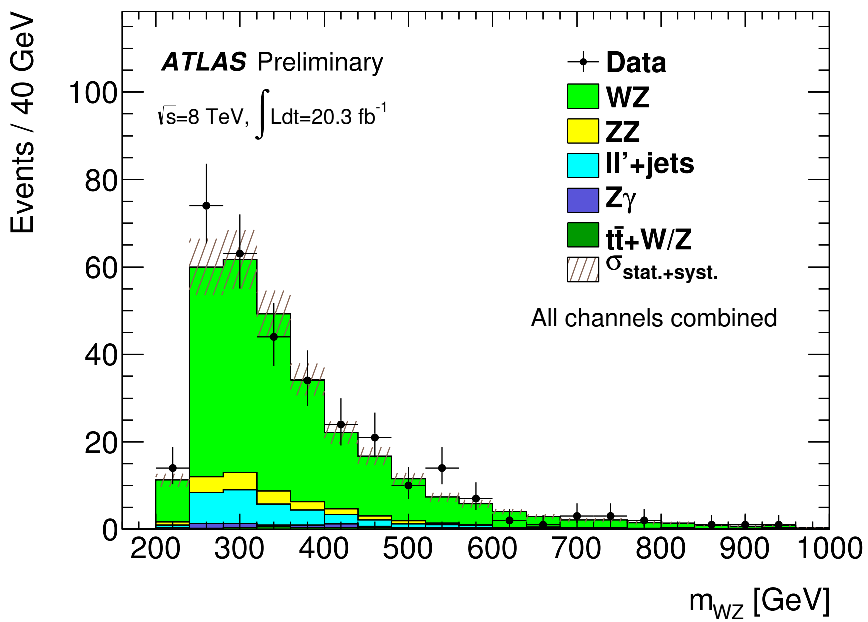
Background to WZ

- p_z of neutrino ? -> use W mass to constrain
  ➔ Calculate mass of WZ system

ATLAS-CONF-2014-015

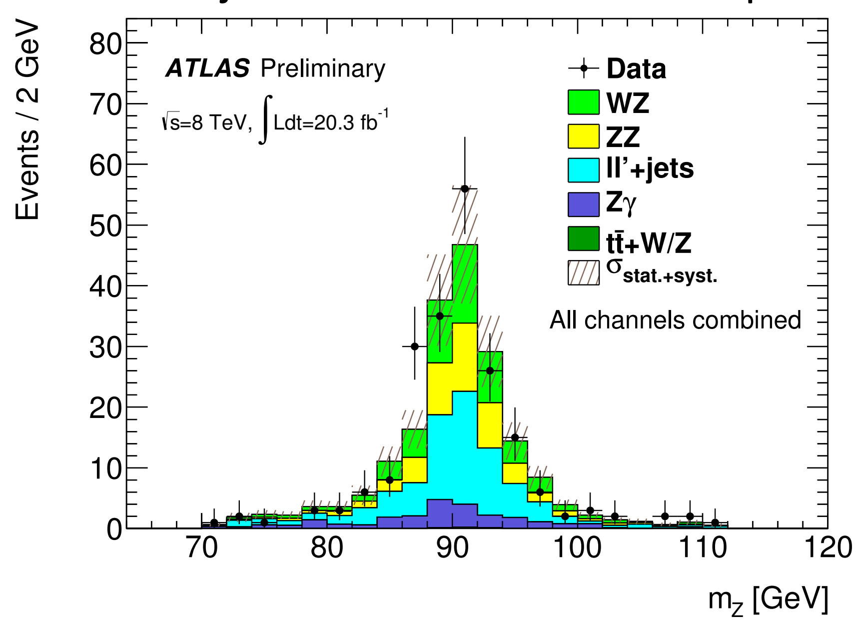
- Background from MC if 3 or more prompt leptons (WZ, ZZ, …) and for Zγ
- Fake factor (matrix) method for fake leptons from jets (Z+jets, $t\bar{t}$,…) -> "ll+jets"

WZ control region



- Δy (W,Z) > 1.5 (reverted)
- No ϕ requirement

Ll+jets CR: at least one fake lepton

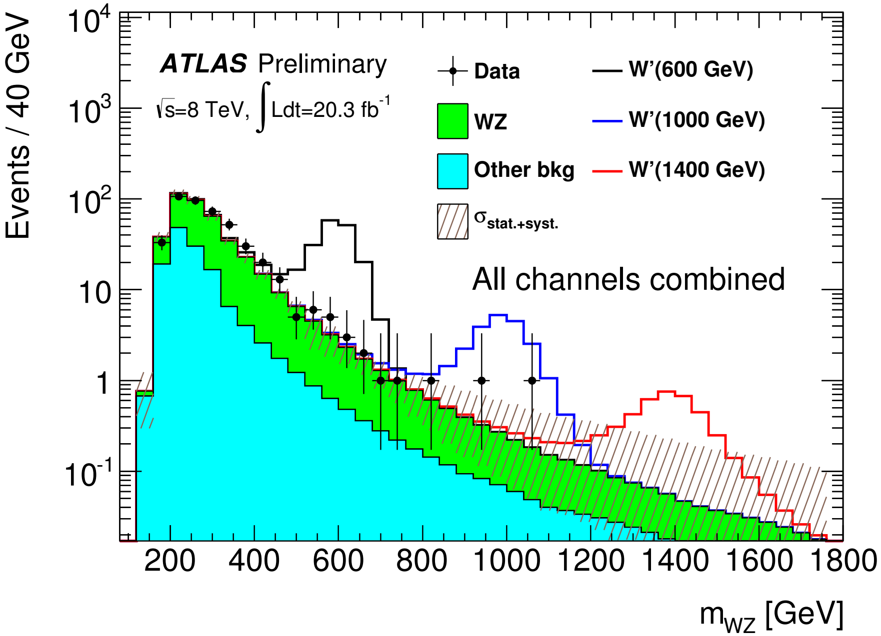


- E_T^{miss} < 25 GeV (reverted)
- W boson m_T < 25 GeV

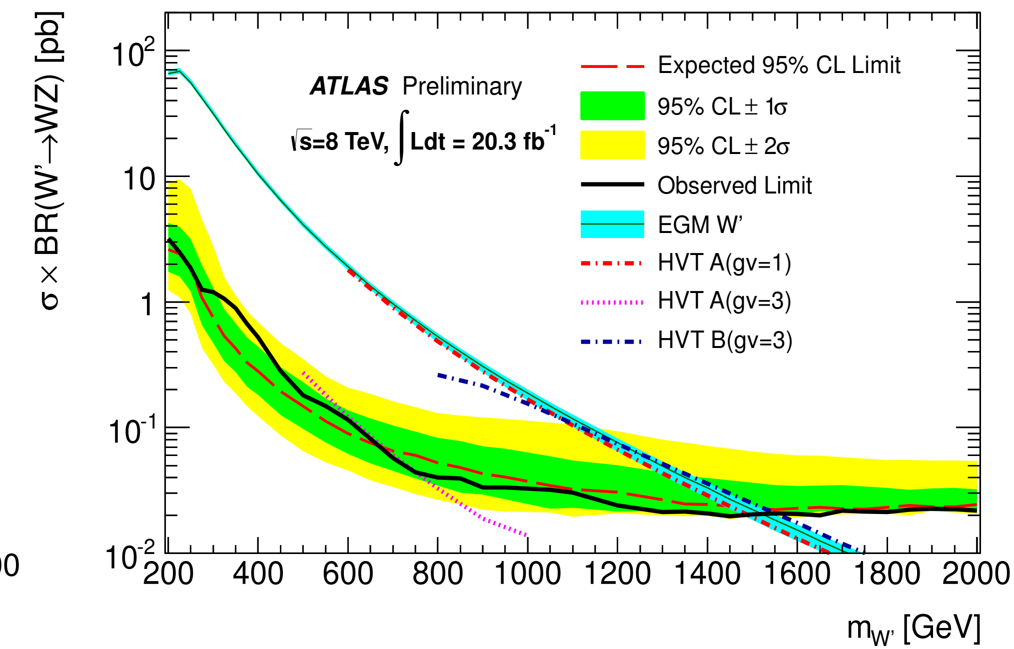
Limits on resonances decaying to WZ

ATLAS-CONF-2014-015

Signal region: high mass



Combined limit from both signal regions



	Excluded EGM W' mass (TeV)				
	$e\nu ee$	$\mu\nu ee$	$e\nu\mu\mu$	$\mu\nu\mu\mu$	combined
Expected	1.21	1.16	1.17	1.16	1.49
Observed	1.20	1.19	1.06	1.17	1.52

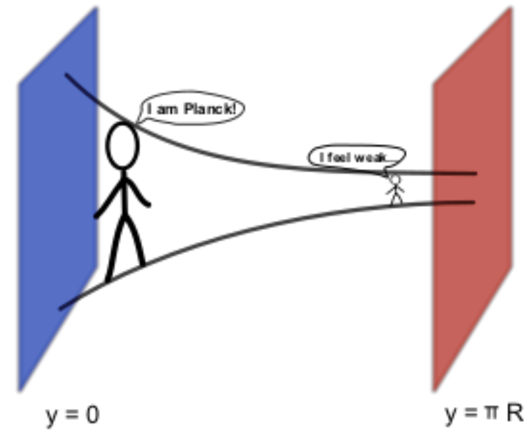
This channel could be interesting if new object is leptophobic
or if decay to heavy objects preferred (bulk RS) ➔

Randall-Sundrum: Dilepton

Hierarchy problem: Planck scale @ 10^{16} TeV much higher than our usual mass scales

Basic idea: more than 3+1 dimensions ?

➔ higher-dim Planck mass could be TeV scale



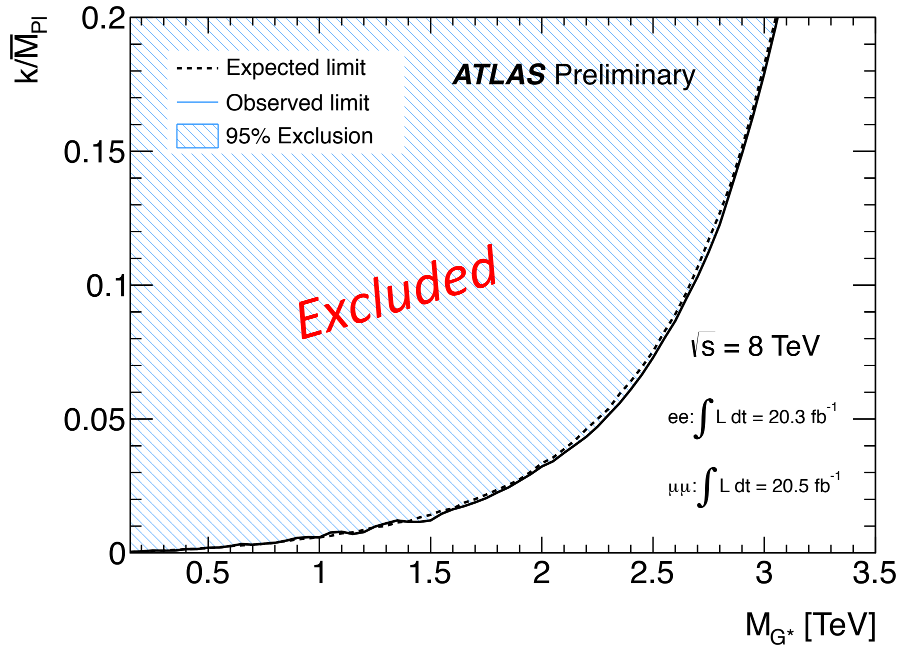
Randall-Sundrum (RS):

- one warped extra dimension
- Gravity originates on Planck brane and can propagate through bulk
- SM confined to 3+1 dimensional brane (RS-1)

➔ Narrow resonances in dilepton, diphoton (lightest excitation of Graviton, G*)

➔ Search for Spin-2 resonances (decay to leptons not favored)

- Further improvement (≈10%) expected when adding diphotons



G*-> HH-> 4b

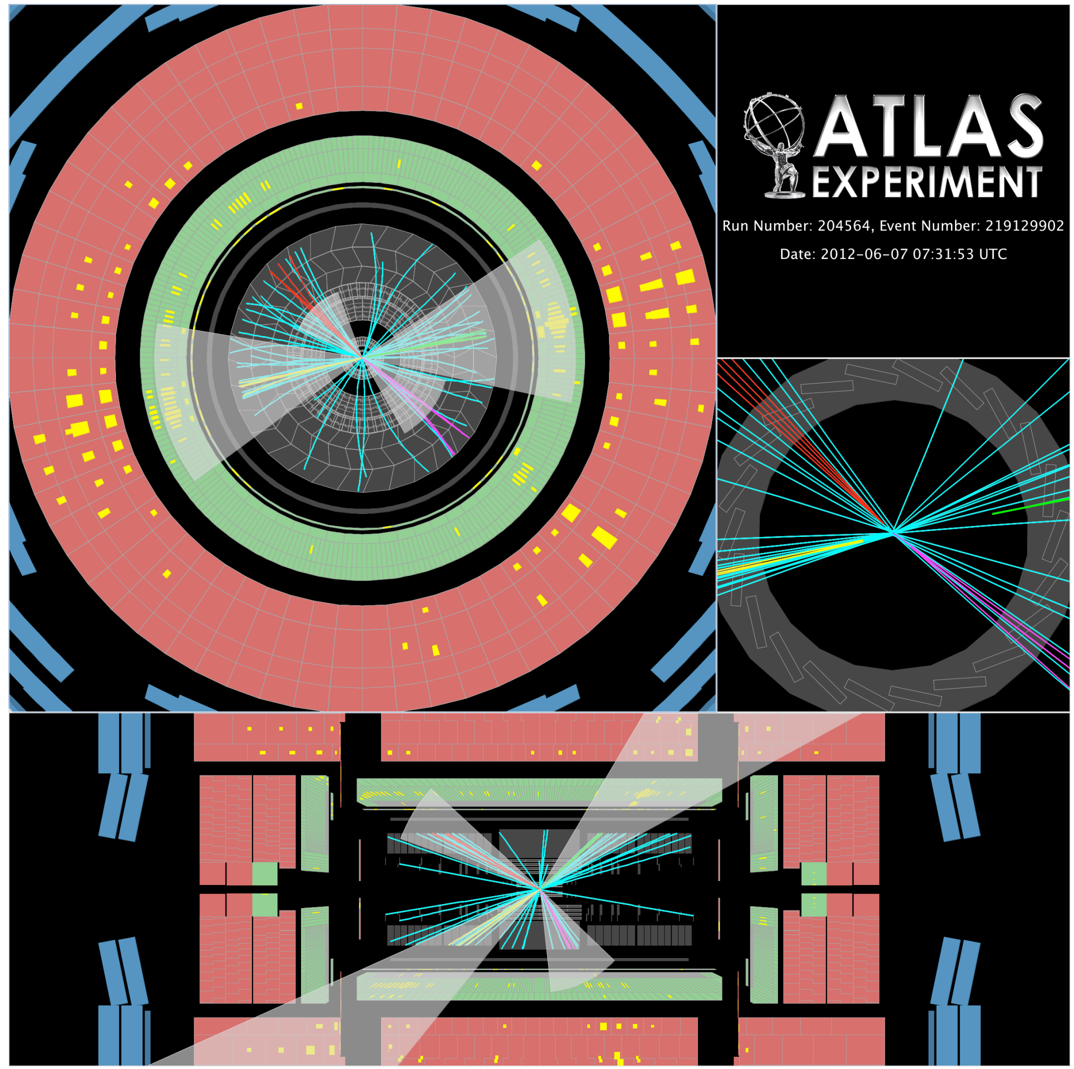
ATLAS-CONF-2014-005

<u>Bulk RS model:</u>
(fermion and boson fields can
can propagate into ED)
➔ Decay to heavy objects favored

➔ Narrow resonance: G*-> HH
(G*, first excitation of graviton)

- BR: G*->HH about 7%
- Resonance narrower than m_{4j} resolution (approx 15%)

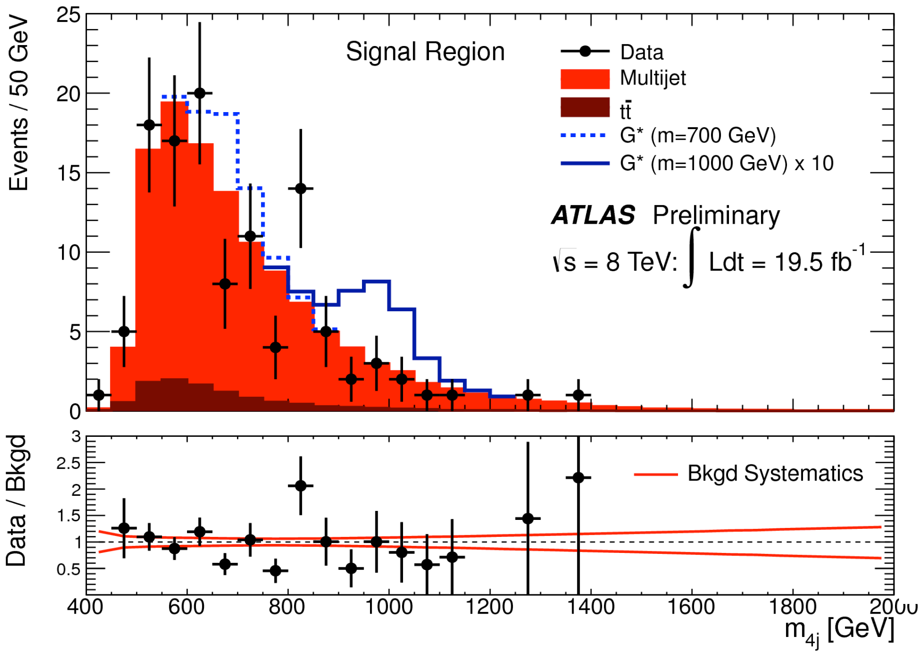
- 4 b-jets (70% eff., anti-k_T, R = 0.4)
- p_T > 40 GeV
- p_T (jet, jet) > 200 GeV
- ΔR(jet, jet) < 1.5
- m_{jj} approx m_H

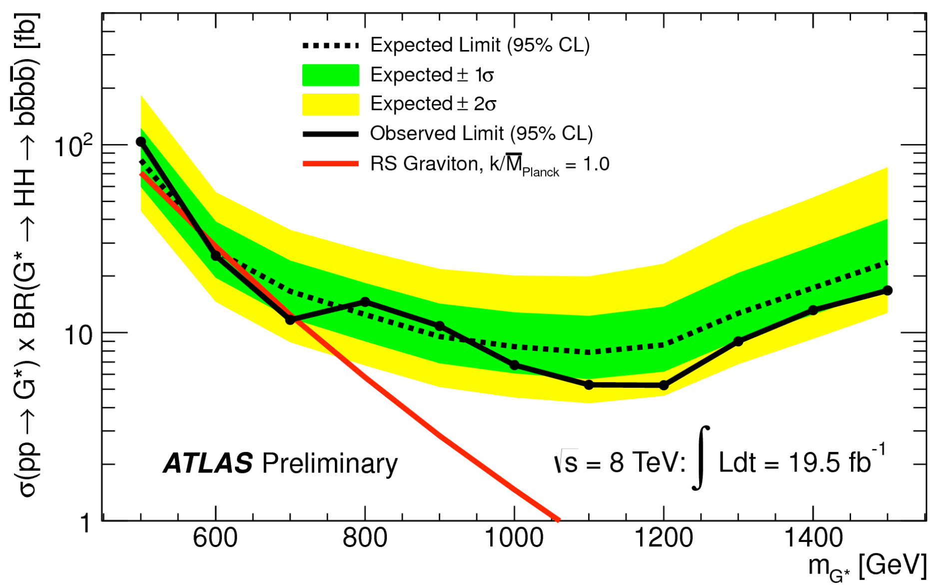


Mass of dijets: 112 GeV and 115 GeV

G*-> HH->4b

ATLAS-CONF-2014-005





Backgrounds:

- Multi-jet (90%): data-driven method
- $t\bar{t}$ (10%): Shape from MC, normalization from data
- Z+Jets (<1%): MC

- RS graviton (k/M_{PL} = 1) excluded at 95% CL for masses between 590 GeV and 710 GeV
- Upper 95% CL limits on σ BR between 100fb (@ 500GeV) and 7fb (@ 1 TeV).

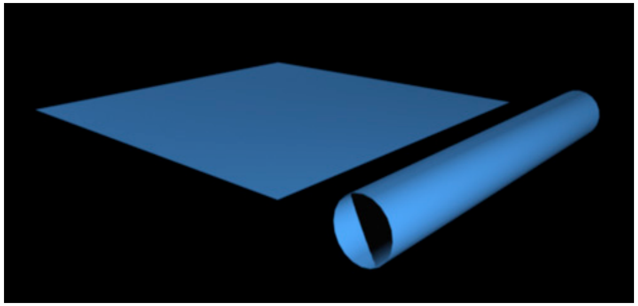
ADD and Quantum Black Holes

ADD: Arkani-Hamed, Dimopoulos, Dvali

- Hierachy problem
- n >= 1 additional flat extra dimensions, compactified
- If higher-dim Planck scale (M_D) about 1 TeV:

  N = 1 -> r = 10^8 km

  N = 2 -> r = 1mm

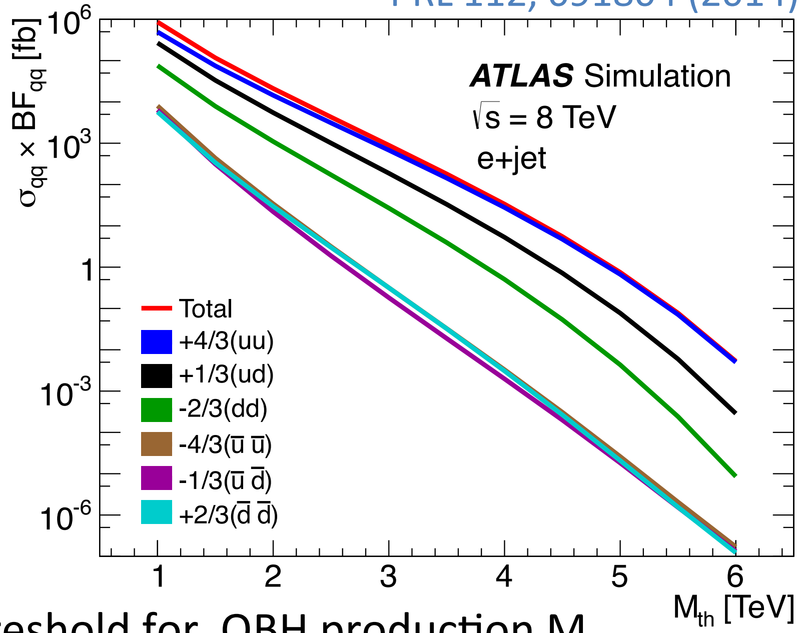


If collision energy -> higher-dim Planck mass M_D

➔ Quantum Black Holes can be produced

- QBH can decay to lepton+jet
  (violation of lepton and baryon number conserv.)
- Cross section dominated by uu (charge 4/3) with e,μ+jet BR of 11% and ud (BR: 6%) ➔
- Model used here assumed to conserve total angular momentum, color and charge

PRL 112, 091804 (2014)

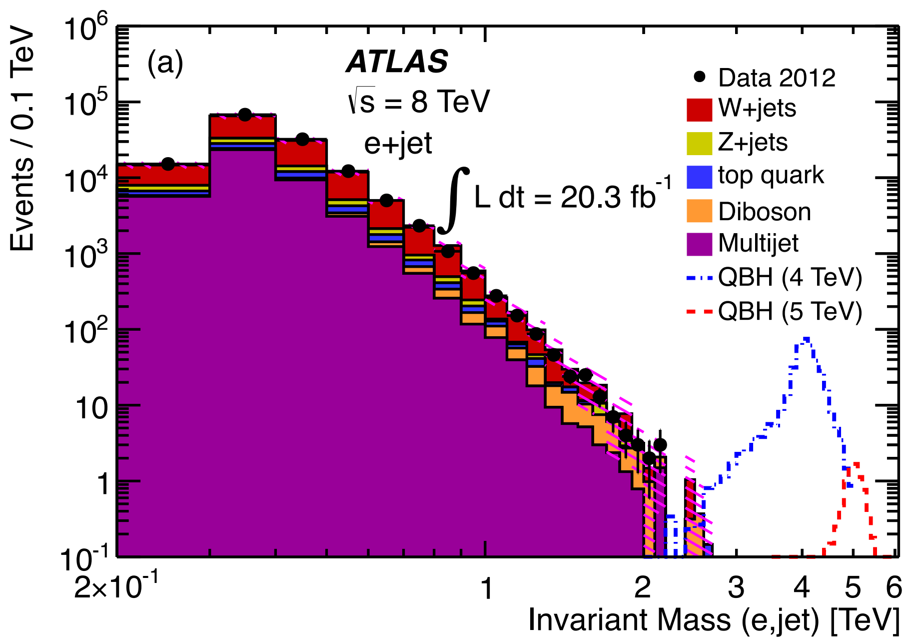


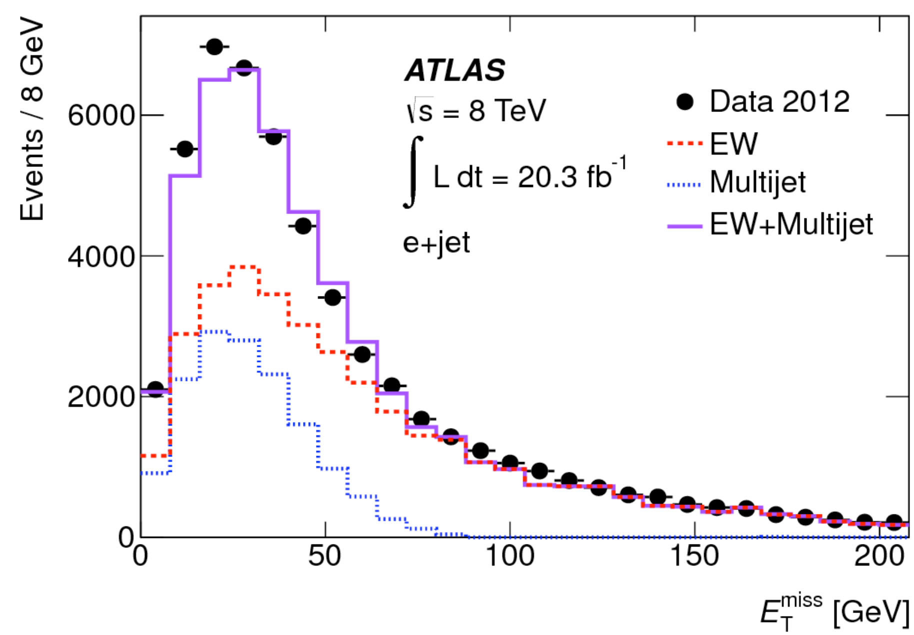
Threshold for QBH production M_{th}
(assumed to be approx equal to M_D)

Quantum Black holes: l+jet

Lepton p_T (e, μ) > 130 GeV
Jet p_T > 130 GeV (anti-k_T, R = 0.4)

PRL 112, 091804 (2014)

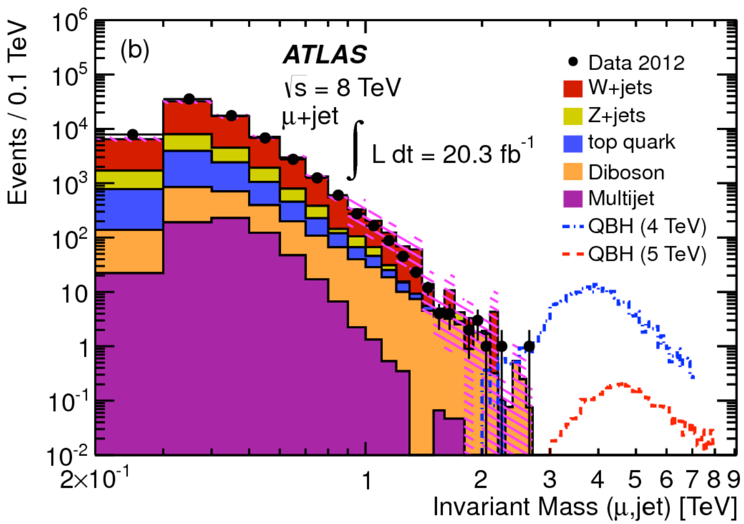


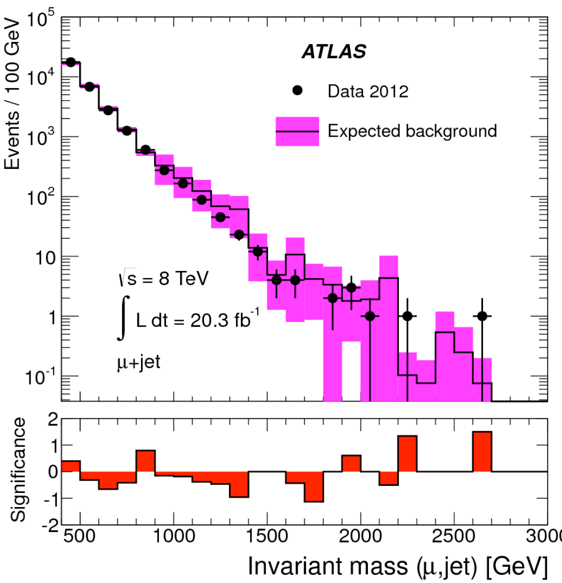


- EW background from MC
- Multijet data driven using templates derived by reversing criteria
- Normalization of MC and data-driven BG using data control regions (440 < m_{ej} < 900 GeV) in E_T^{miss} spectrum
- Extrapolation of background to high-mass done via fits (dominating systematic uncertainty, similar to PDF uncertainty)

QBH: lepton + jet

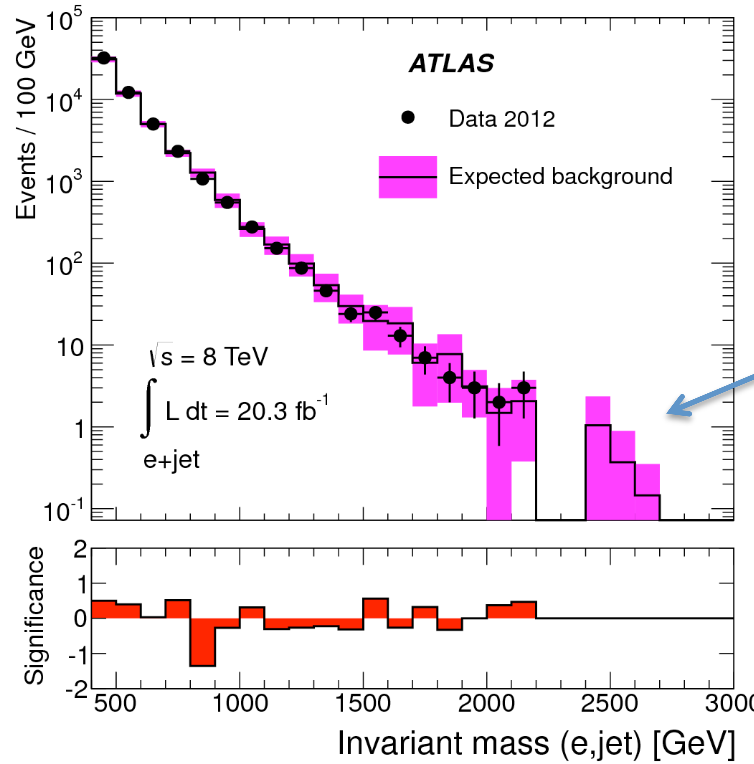
Similar analysis for muon + jet:





electron + jet

PRL 112, 091804 (2014)

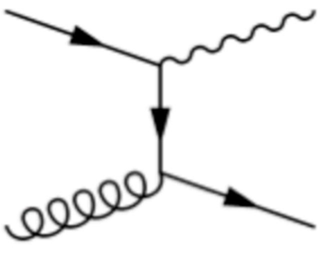


BG with stat. + sys. uncertainties

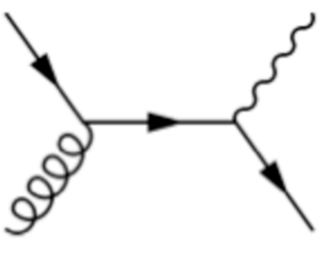
No significant deviations found ➔ γ+jets ?

QBH: Photon+jet

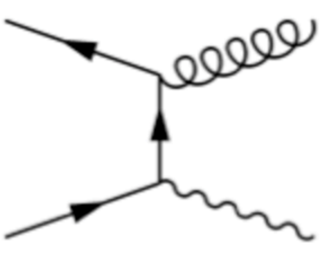
tree-level γ+jet:



(a)



(b)



(c)

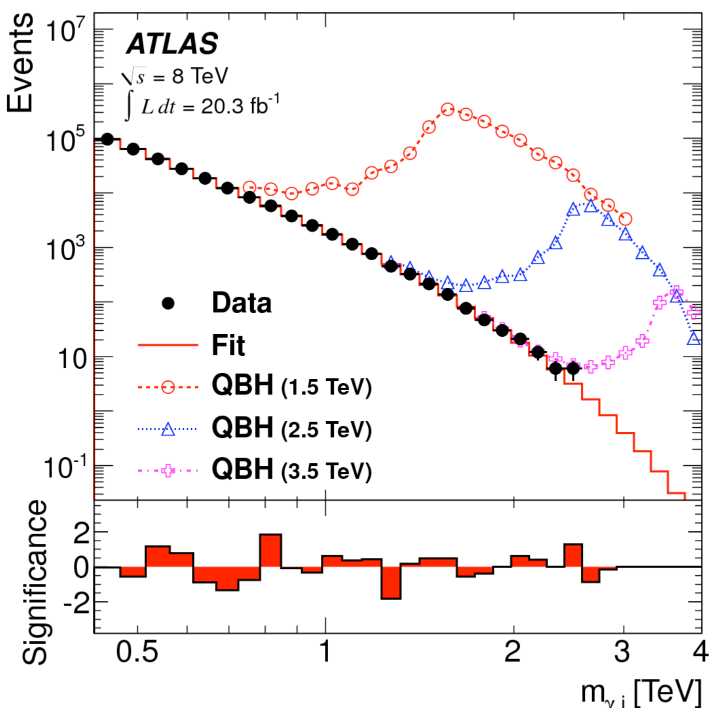
Photon p_T > 125 GeV
Jet pT (anti-k_T, R = 0.6) > 125 GeV

PLB 728, 562 (2013)

Dijet background dominated by t-channel
➔ Enhance s-channel
- Photon in barrel
- $\Delta\eta\ (\gamma,j) < 1.6$

Background:
- Determined by fitting the $m_{\gamma j}$ spectrum

$$f(x \equiv m_{\gamma j}/\sqrt{s}) = p_1(1-x)^{p_2} x^{-(p_3+p_4 \ln x)}$$



Functional form tested with various MCs and control samples (reversing photon ID criteria)

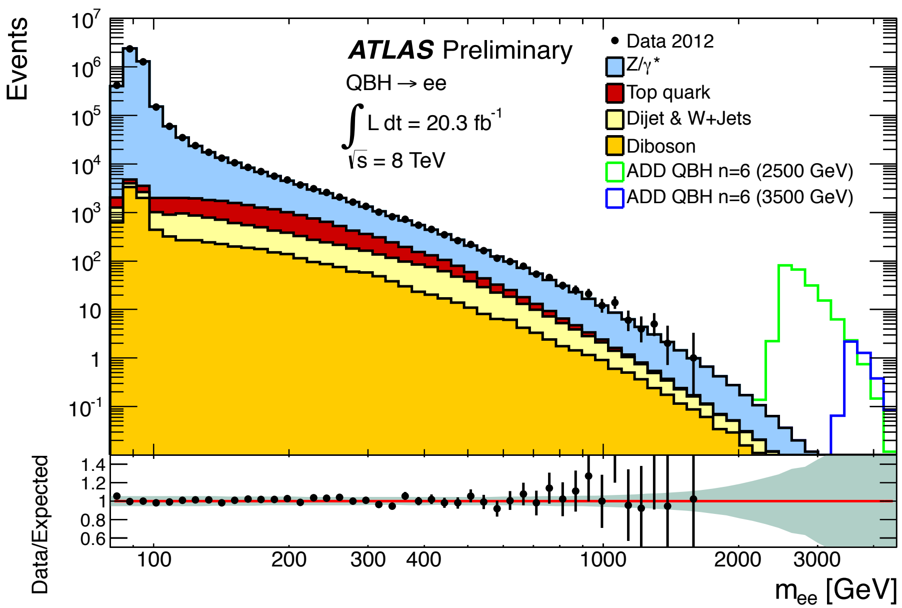
Also here no significant deviation …

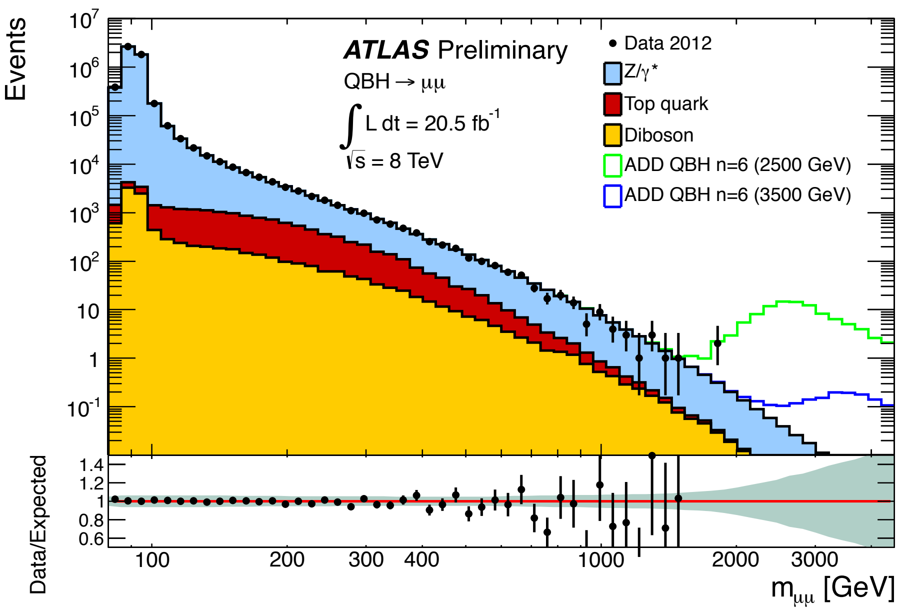
QBH dileptons

Another interpretation of dilepton resonance search:

➔ QBH can decay to dileptons (no violation of lepton and baryon number)

- QBH with neutral charge
- $q\bar{q}$ or gg production

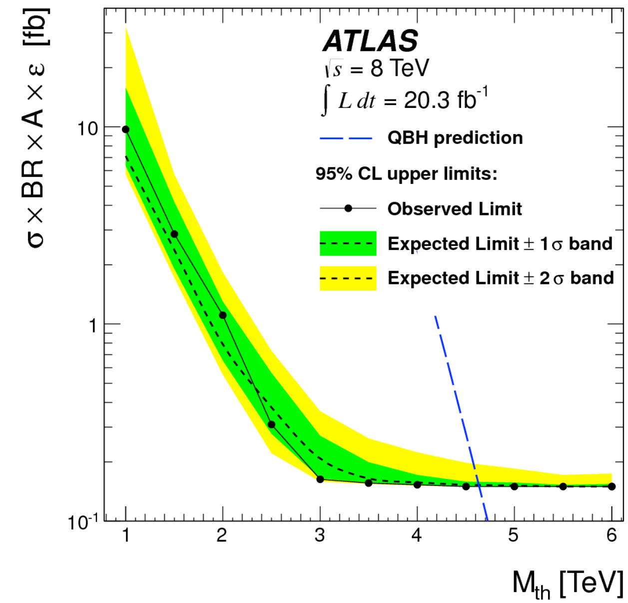




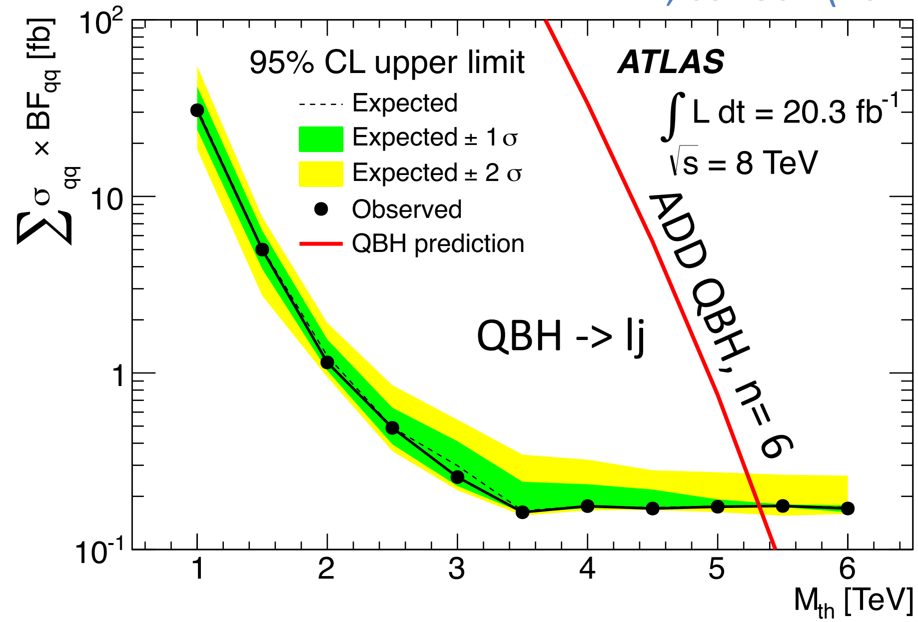
Finally, all the limits ➔

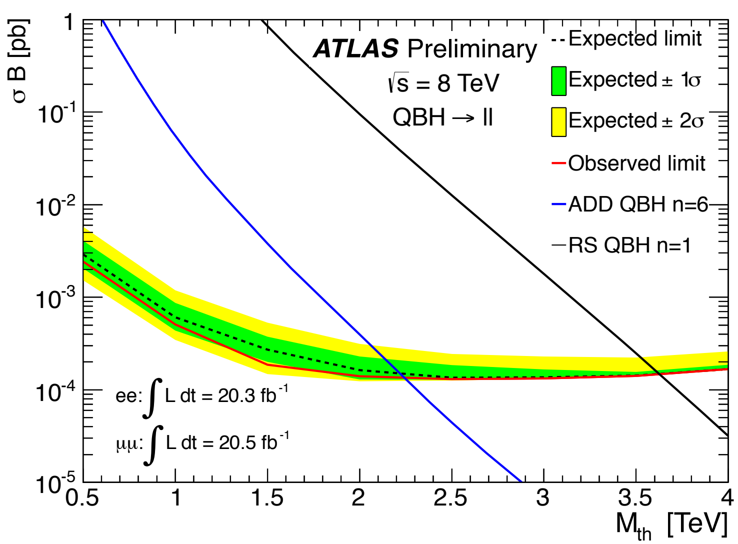
Quantum Black holes

PLB 728, 562 (2013) QBH -> γj



PRL 112, 091804 (2014)





ADD, n= 6 lower limit on M_{th} is 5.3 TeV
(5.2/5.1 TeV for electrons/muons)
ADD, n= 2 lower limit on M_{th} is 4.7 TeV

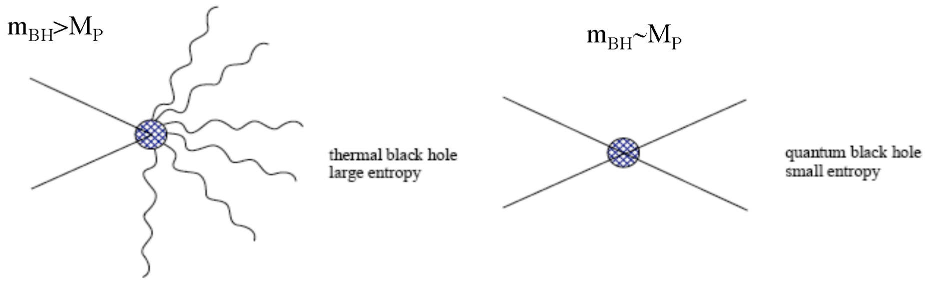
Limits on QBH set in various decay channels
(and with different assumptions)
➔ Masses up to 5 TeV excluded

Black Holes

<u>Hierarchy problem</u>: gravitational (Planck) scale <-> EW scale

- (Semi classical) BH production: $M_{th} > M_D$ (higher dim. gravitational scale) (QBH have mass closer to M_D)
- Loose mass and angular momentum by Hawking radiation
- Once mass close to M_D, decay to small number of SM states (large theor. uncertainties)

Semi-classical versus quantum (non-thermal) black hole:



<u>Experimental signature:</u>

➔ Ensemble of high-energy particles (very model dependent)

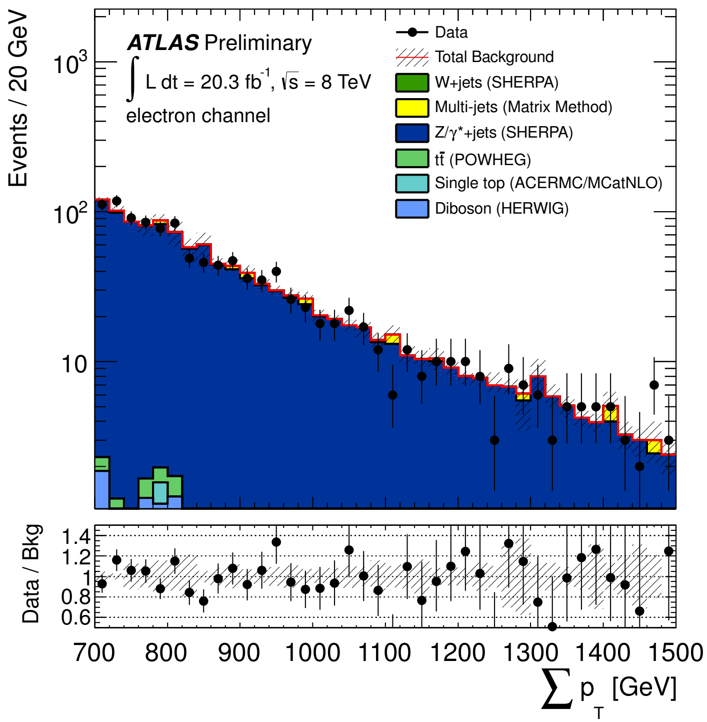
- Rotating BH has less but higher energy particles compared to non-rotating BH
- Decay BR to lepton+X is 15-50 % (depends on M_D, M_{th}, model)

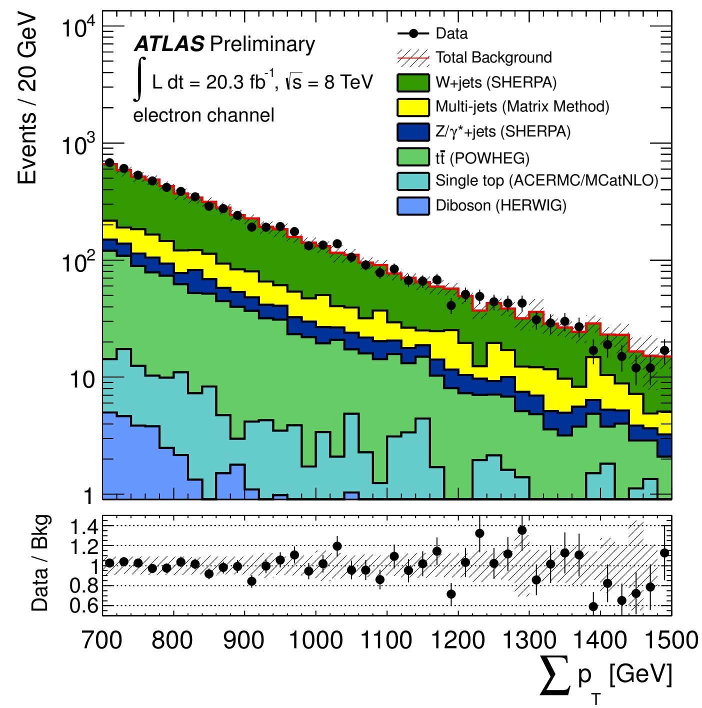
Black Holes

Search for excess in sum p_T of at least one lepton and at least three objects (l, jets)

- Dominant backgrounds (MC): W+jets, Z+Jets, $t\bar{t}$, normalized to data in control regions
- Mulitjets: Data-driven (matrix method)

ATLAS-CONF-2014-016





Z+Jets control region:

- Exactly 2 leptons, same flavor, opposite charge
- $80 < m_{ll} < 100$ GeV

W+Jets control region:

- Exactly one lepton
- $E_T^{miss} > 60$ GeV

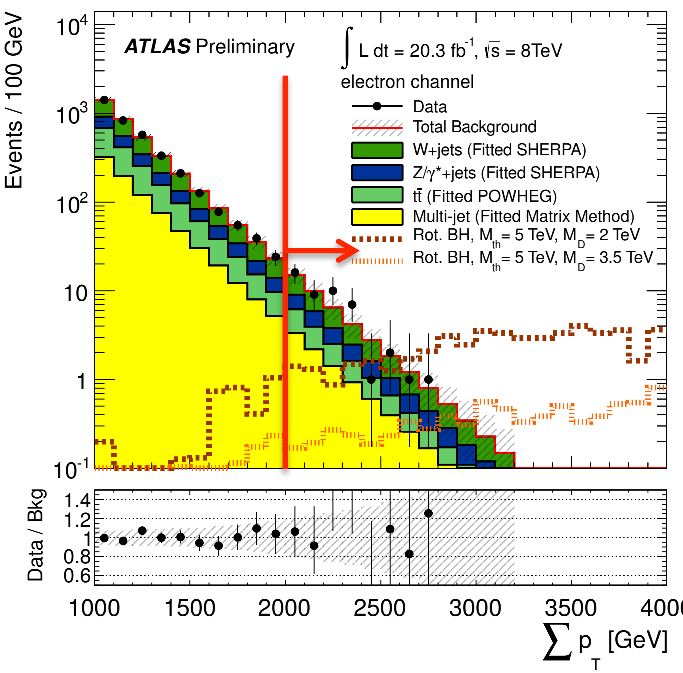
Black Holes

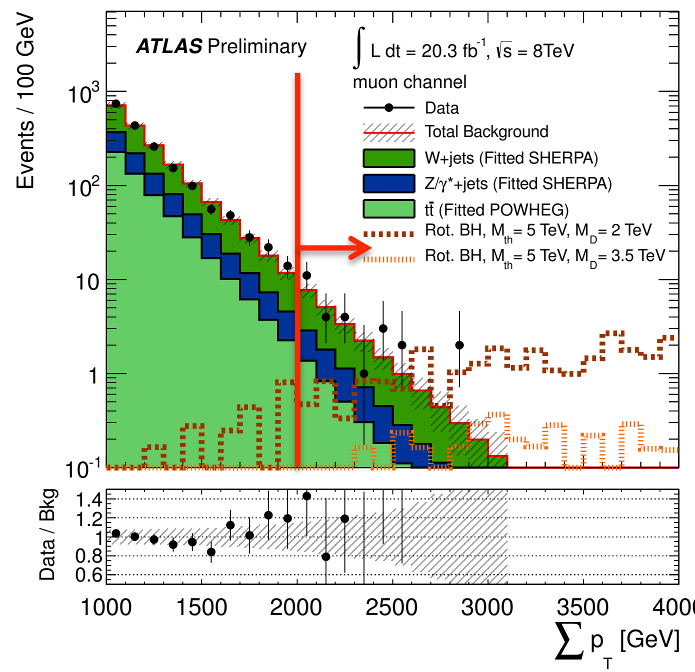
Quantity	Region	
	Sideband	Signal
$\sum p_{\mathrm{T}}$	1000–2000 GeV	$>$ 2000 GeV
nObjects	at least 3 objects above 100 GeV	
leading lepton	at least 1 lepton with $p_{\mathrm{T}} > 100$ GeV	

ATLAS-CONF-2014-016

Background extrapolated to high sum p_T via fits: $\mathcal{F} = (1-x)^{p_0}\, x^{p_1}\, x^{p_2 \log(x)}$

$$\mathcal{F}_{\mathrm{alt}} = \frac{p_0}{x}(1 - p_1 x)^{p_2} \qquad x = \sum p_{\mathrm{T}} / \sqrt{s}$$

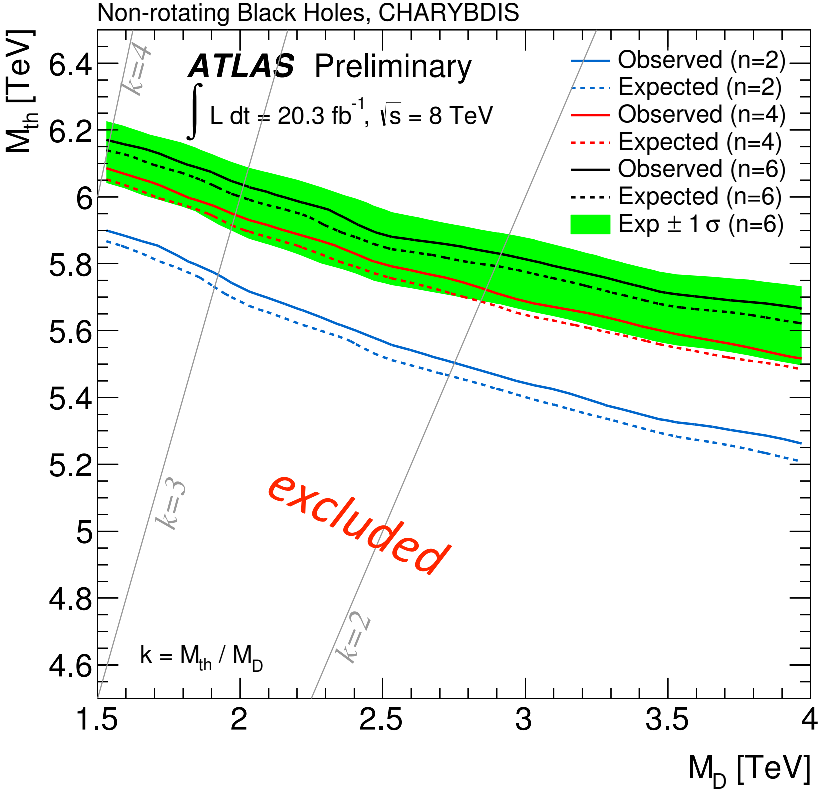


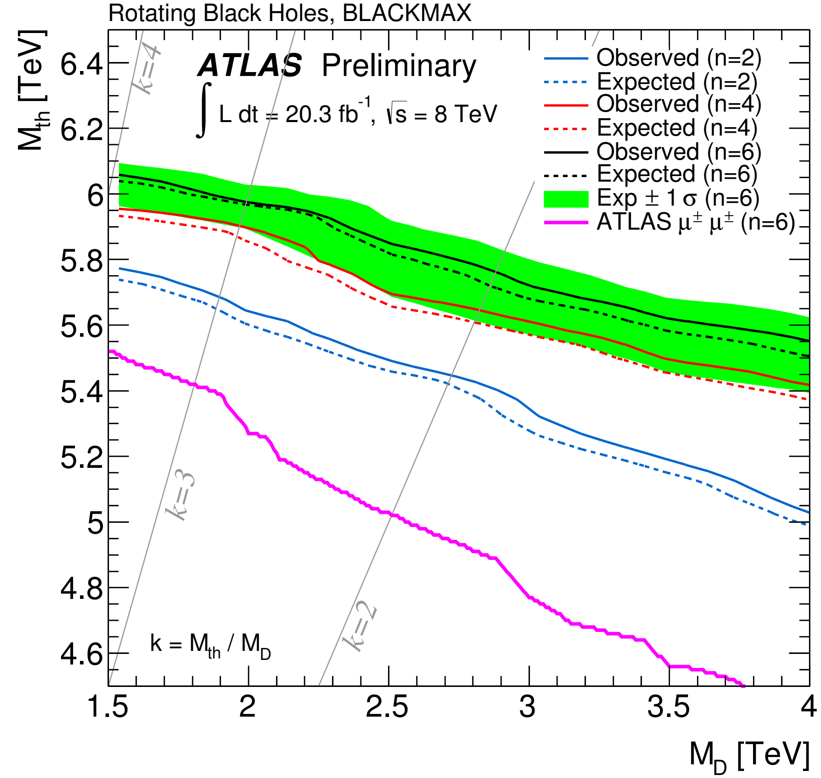


No sign of excess…➔

Black Holes

ATLAS-CONF-2014-016





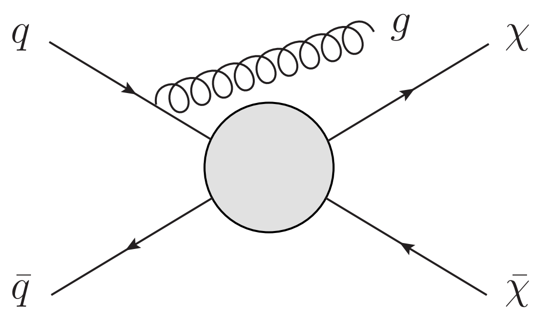
- Stronger limits with higher number of extra dimensions due to larger cross section
- Stronger limits compared to ATLAS (full 8 TeV data set) limits using same sign dimuons (PRD 88 (2013) 072001)

Black hole mass thresholds are above 5.5 TeV for six extra dimensions

Dark Matter

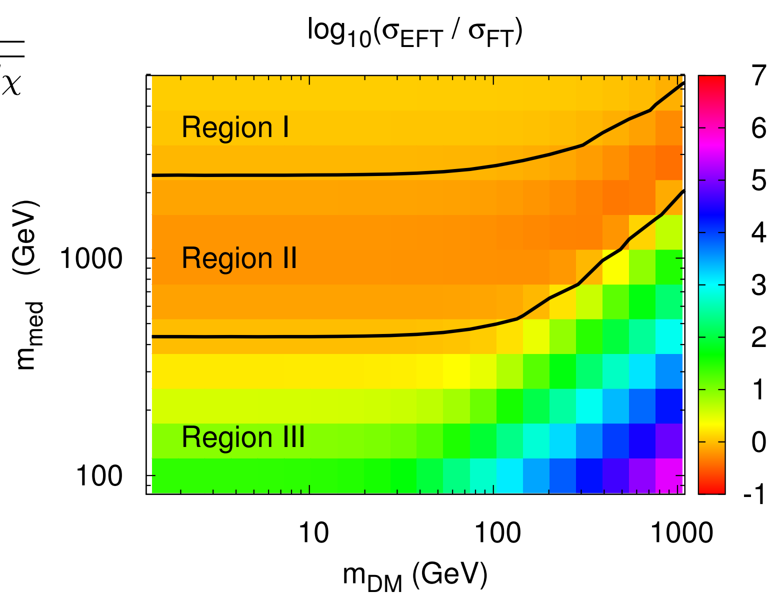
Popular dark matter candidate ➔ Weakly Interacting Massive Particle (WIMP)

Production and detection at LHC (also gg)



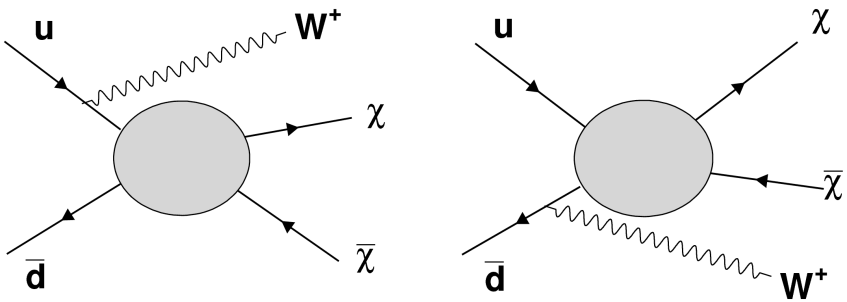
Strongest limits from monojets, assuming equal coupling of dark matter particles to up and down type quarks

- Interpretation in context of EFT assuming contact interaction (CI) between quarks and DM particles
- Modeled in EFT with mass scale $M_* \sim \frac{M_{med}}{\sqrt{g_{SM} g_\chi}}$
- Low mass WIMPs difficult to detect in direct (WIMP-nucleon scattering) searches➔ Complementary search !
- Problem: EFT not valid at low mediator mass

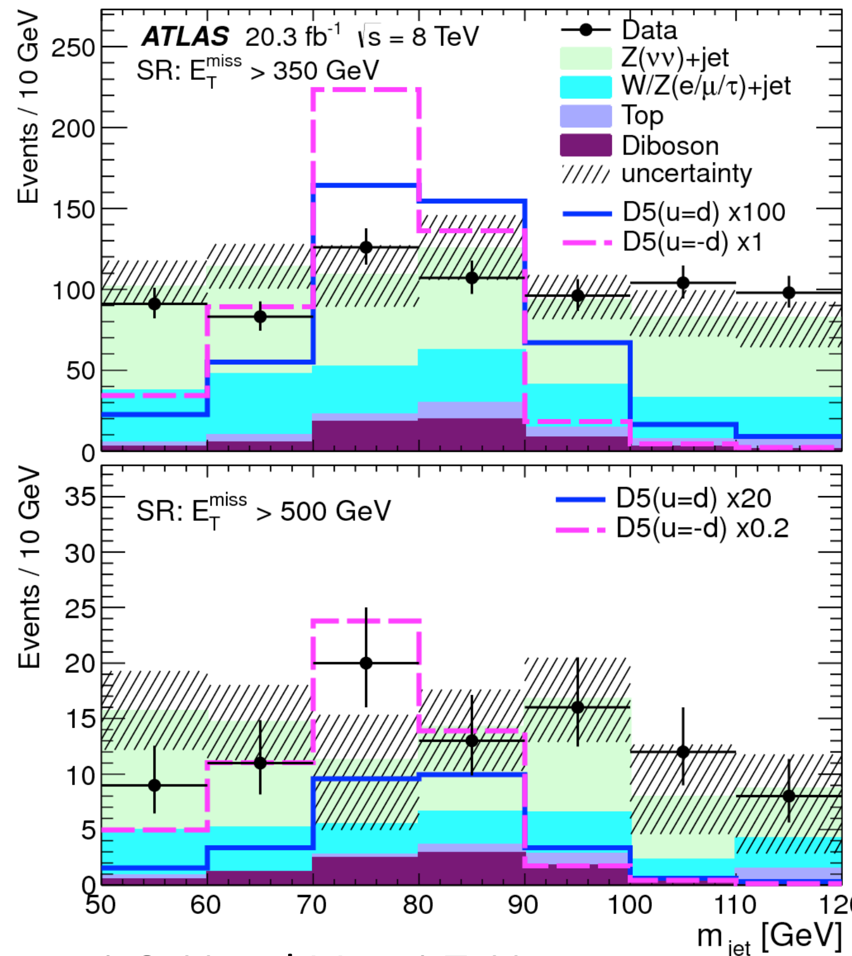


Buchmueller et al., arXiv:1308.6799

W or Z hadronic decay



PRL 112, 041802 (2014)



Mono-W :

- Interference between radiation from u and d quarks
- Destructive if equal couplings→small signal
- If opposite sign: mono-W could be most sensitive channel

Selection:

- Large radius (R=1.2) jet assumed to capture jets from both quarks-> substructure
- Jet with p_T > 250 GeV
- Large E_T^{miss} :
  SR1: E_T^{miss} > 350 GeV
  SR2: E_T^{miss} > 500 GeV

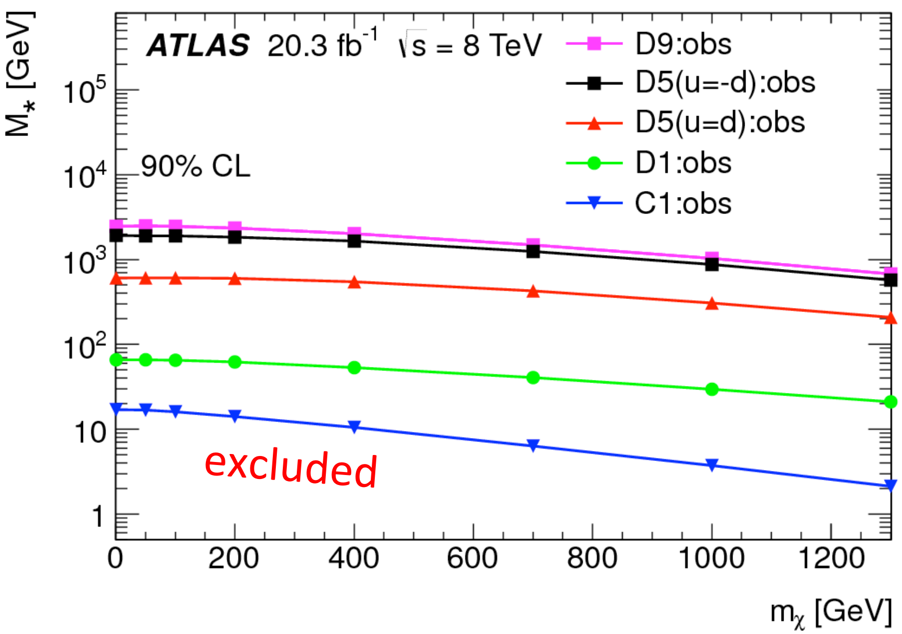
Signals for m_χ = 1 GeV and M_* = 1 TeV,
with constructive (u=-d) and destructive (u=d) interference and WIMP being Dirac fermion

Limits

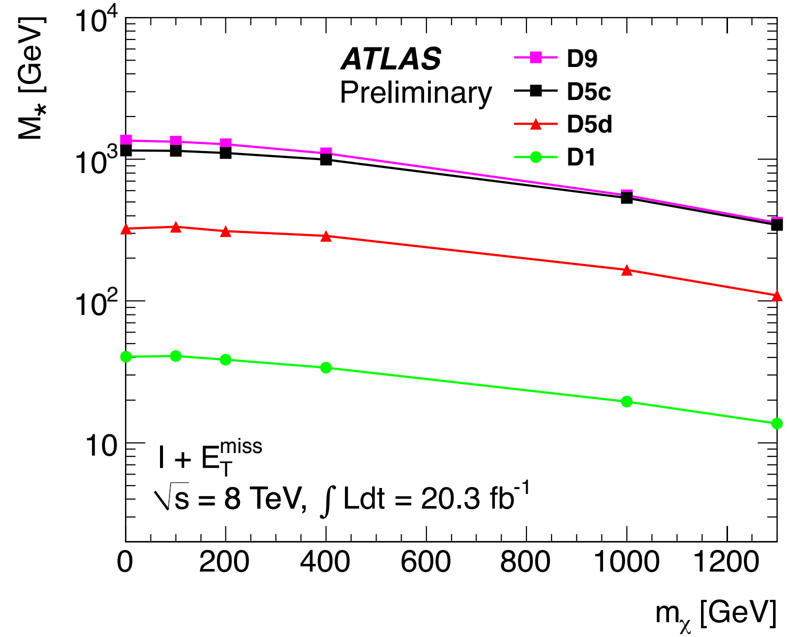
PRL 112, 041802 (2014)

ATLAS-CONF-2014-017

W/Z hadronic decay:



W' -> l ν reinterpretation, using m_T as search variable



Exclusion regions at 90% CL for various operators coupling WIMPs to SM particles

Exclusion regions at 95% CL for various operators:

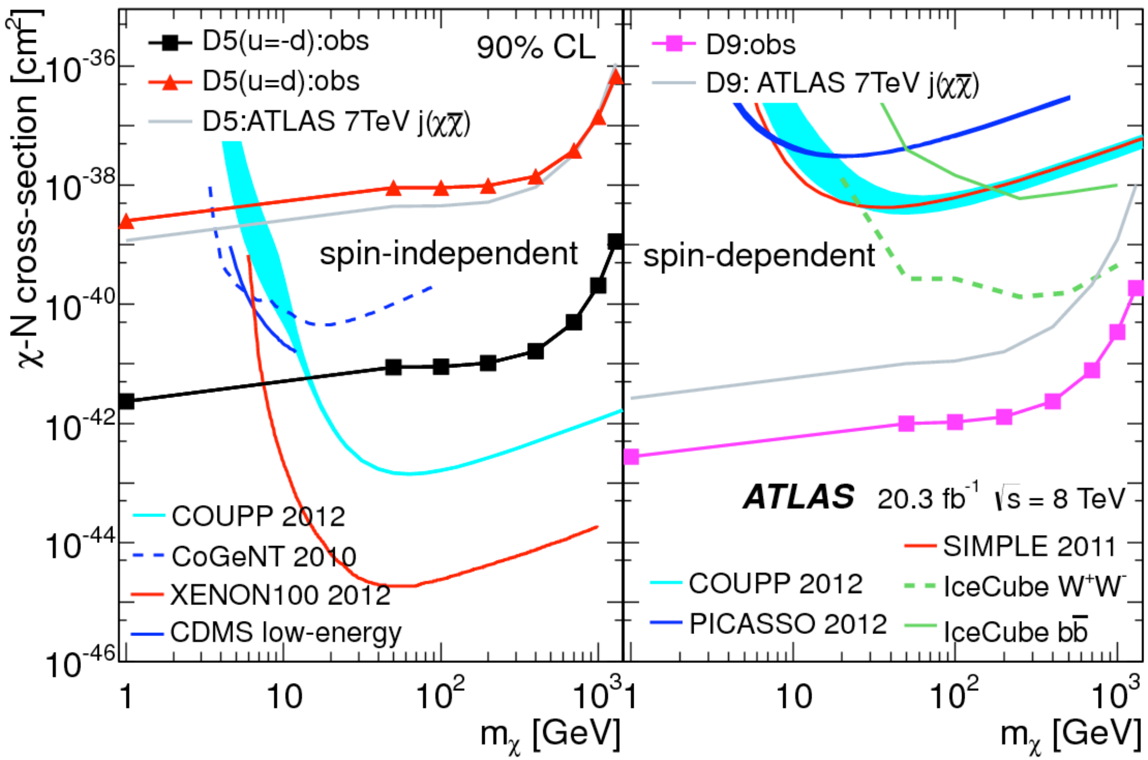
➔ Limits in hadronic channel dominate

Limits on WIMP-Nucleon cross section

Lower limits on M_* can be converted into upper limits on WIMP-Nucleon scattering cross section:

PRL 112, 041802 (2014)

W/Z hadronic ➔

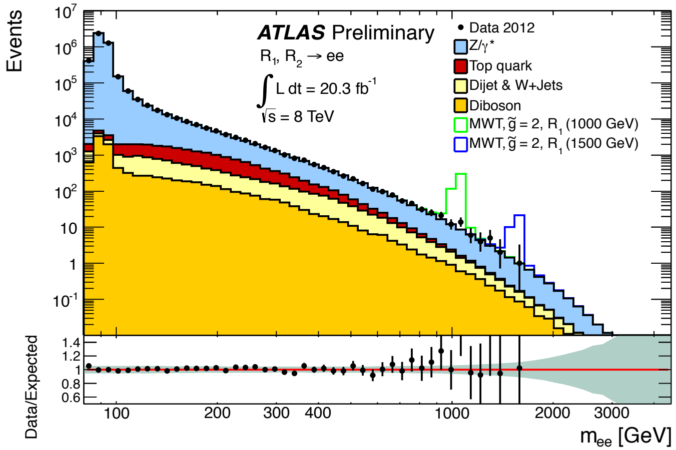


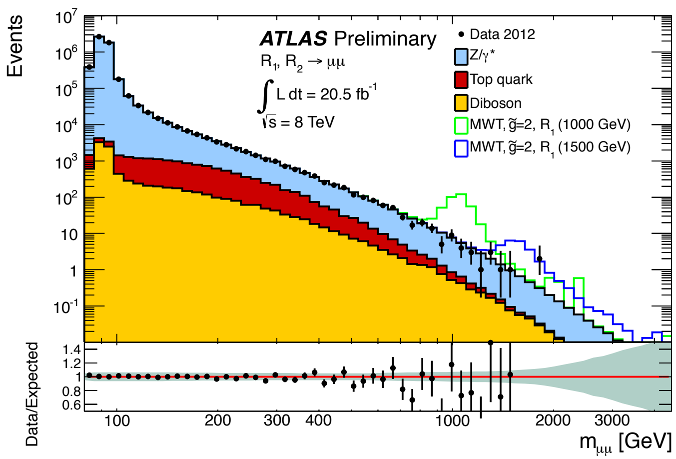
- Constructive interference ➔ 3 orders of magnitude better than mono-jet @ 7 TeV
- Complementary sensitivity to direct detection exp., but model dependent…

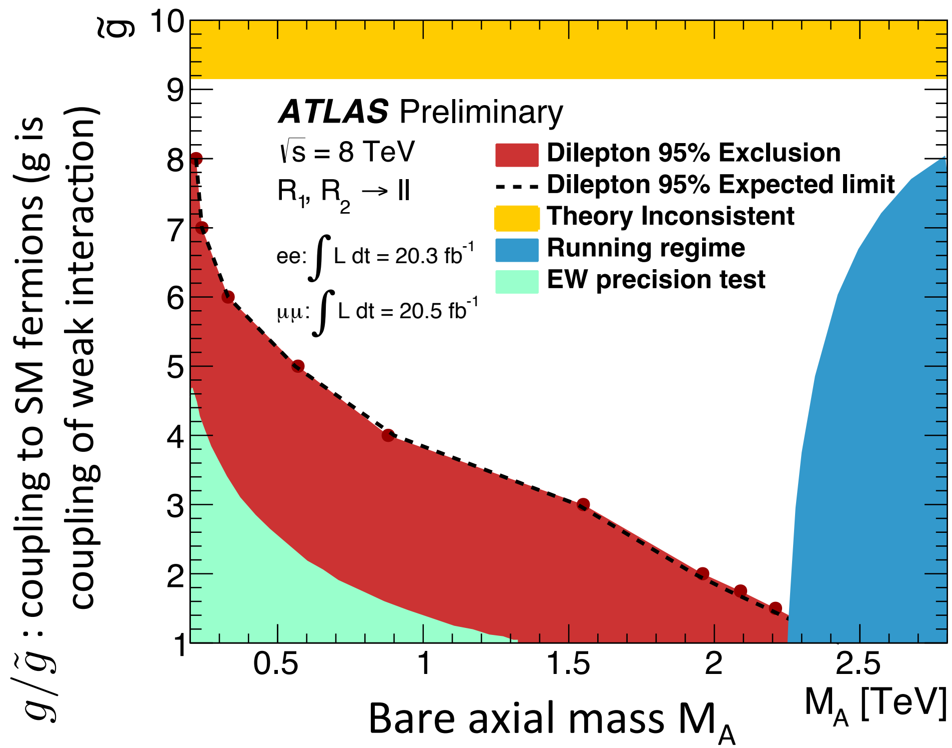
Technicolor

Minimal Walking Technicolor with composite Higgs, bound by (strong force) technicolor

➔ New narrow resonances (technimesons) decaying to dilepton final states







$\tilde{g}$	1.5	2	3	4	5	6	7	8
Observed limit on M_{R_1} [TeV]	2.27	1.99	1.57	0.89	0.57	0.33	0.24	0.22
Expected limit on M_{R_1} [TeV]	2.24	1.96	1.54	0.90	0.56	0.33	0.24	0.22
Observed limit on M_A [TeV]	2.21	1.96	1.55	0.88	0.57	0.33	0.24	0.22
Expected limit on M_A [TeV]	2.18	1.93	1.53	0.90	0.56	0.33	0.24	0.22

ATLAS Exotics Searches* - 95% CL Exclusion

Status: April 2014

ATLAS Preliminary

$\int \mathcal{L}\, dt = (1.0 - 20.3)\ \mathrm{fb}^{-1}$ $\sqrt{s}$ = 7, 8 TeV

	Model	ℓ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt [\mathrm{fb}^{-1}]$	Mass limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	1-2 j	Yes	4.7	M_D 4.37 TeV	$n = 2$	1210.4491
	ADD non-resonant $\ell\ell/\gamma\gamma$	2γ or $2e, \mu$	–	–	4.7	M_S 4.18 TeV	$n = 3$ HLZ NLO	1211.1150
	ADD QBH $\to \ell q$	$1\ e, \mu$	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD BH high N_{trk}	$2\ \mu$ (SS)	–	–	20.3	M_{th} 5.7 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	20.3	M_{th} 6.2 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	ATLAS-CONF-2014-016
	RS1 $G_{KK} \to \ell\ell$	$2\ e, \mu$	–	–	20.3	G_{KK} mass 2.47 TeV	$k/\overline{M}_{Pl} = 0.1$	ATLAS-CONF-2013-017
	RS1 $G_{KK} \to ZZ \to \ell\ell qq/\ell\ell\ell\ell$	2 or 4 e, μ	2 j or –	–	1.0	G_{KK} mass 845 GeV	$k/\overline{M}_{Pl} = 0.1$	1203.0718
	RS1 $G_{KK} \to WW \to \ell\nu\ell\nu$	$2\ e, \mu$	–	Yes	4.7	G_{KK} mass 1.23 TeV	$k/\overline{M}_{Pl} = 0.1$	1208.2880
	Bulk RS $G_{KK} \to HH \to b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass 590-710 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-005
	Bulk RS $g_{KK} \to t\bar{t}$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	14.3	g_{KK} mass 0.5-2.0 TeV	BR = 0.925	ATLAS-CONF-2013-052
	S^1/Z_2 ED	$2\ e, \mu$	–	–	5.0	$M_{KK} \approx R^{-1}$ 4.71 TeV		1209.2535
	UED	$2\ \gamma$	–	Yes	4.8	Compact. scale R^{-1} 1.41 TeV		ATLAS-CONF-2012-072
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	20.3	Z' mass 2.86 TeV		ATLAS-CONF-2013-017
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	19.5	Z' mass 1.9 TeV		ATLAS-CONF-2013-066
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	20.3	W' mass 3.28 TeV		ATLAS-CONF-2014-017
	EGM $W' \to WZ \to \ell\nu\ \ell'\ell'$	$3\ e, \mu$	–	Yes	20.3	W' mass 1.52 TeV		ATLAS-CONF-2014-015
	LRSM $W'_R \to t\bar{b}$	$1\ e, \mu$	2 b, 0-1 j	Yes	14.3	W' mass 1.84 TeV		ATLAS-CONF-2013-050
CI	CI $qqqq$	–	2 j	–	4.8	Λ 7.6 TeV	$\eta = +1$	1210.1718
	CI $qq\ell\ell$	$2\ e, \mu$	–	–	5.0	Λ 13.9 TeV	$\eta_{LL} = -1$	1211.1150
	CI $uutt$	$2\ e, \mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	Λ 3.3 TeV	$\lvert C \rvert = 1$	ATLAS-CONF-2013-051
DM	EFT D5 operator	–	1-2 j	Yes	10.5	M_* 731 GeV	at 90% CL for $m(\chi) < 80$ GeV	ATLAS-CONF-2012-147
	EFT D9 operator	–	1 J, ≤ 1 j	Yes	20.3	M_* 2.4 TeV	at 90% CL for $m(\chi) < 100$ GeV	1309.4017
LQ	Scalar LQ 1^{st} gen	$2\ e$	≥ 2 j	–	1.0	LQ mass 660 GeV	$\beta = 1$	1112.4828
	Scalar LQ 2^{nd} gen	$2\ \mu$	≥ 2 j	–	1.0	LQ mass 685 GeV	$\beta = 1$	1203.3172
	Scalar LQ 3^{rd} gen	$1\ e, \mu$, $1\ \tau$	1 b, 1 j	–	4.7	LQ mass 534 GeV	$\beta = 1$	1303.0526
Heavy quarks	Vector-like quark $TT \to Ht + X$	$1\ e, \mu$	≥ 2 b, ≥ 4 j	Yes	14.3	T mass 790 GeV	T in (T,B) doublet	ATLAS-CONF-2013-018
	Vector-like quark $TT \to Wb + X$	$1\ e, \mu$	≥ 1 b, ≥ 3 j	Yes	14.3	T mass 670 GeV	isospin singlet	ATLAS-CONF-2013-060
	Vector-like quark $BB \to Zb + X$	$2\ e, \mu$	≥ 2 b	–	14.3	B mass 725 GeV	B in (B,Y) doublet	ATLAS-CONF-2013-056
	Vector-like quark $BB \to Wt + X$	$2\ e, \mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	B mass 720 GeV	B in (T,B) doublet	ATLAS-CONF-2013-051
Excited fermions	Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	20.3	q^* mass 3.5 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1309.3230
	Excited quark $q^* \to qg$	–	2 j	–	13.0	q^* mass 3.84 TeV	only u^* and d^*, $\Lambda = m(q^*)$	ATLAS-CONF-2012-148
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2 j or 1 j	Yes	4.7	b^* mass 870 GeV	left-handed coupling	1301.1583
	Excited lepton $\ell^* \to \ell\gamma$	$2\ e, \mu$, $1\ \gamma$	–	–	13.0	ℓ^* mass 2.2 TeV	$\Lambda = 2.2$ TeV	1308.1364
Other	LRSM Majorana ν	$2\ e, \mu$	2 j	–	2.1	N^0 mass 1.5 TeV	$m(W_R) = 2$ TeV, no mixing	1203.5420
	Type III Seesaw	$2\ e, \mu$	–	–	5.8	$N^{\pm}$ mass 245 GeV	$\lvert V_e \rvert$=0.055, $\lvert V_\mu \rvert$=0.063, $\lvert V_\tau \rvert$=0	ATLAS-CONF-2013-019
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	$2\ e, \mu$ (SS)	–	–	4.7	$H^{\pm\pm}$ mass 409 GeV	DY production, BR($H^{\pm\pm} \to \ell\ell$)=1	1210.5070
	Multi-charged particles	–	–	–	4.4	multi-charged particle mass 490 GeV	DY production, $\lvert q \rvert = 4e$	1301.5272
	Magnetic monopoles	–	–	–	2.0	monopole mass 862 GeV	DY production, $\lvert g \rvert = 1g_D$	1207.6411

$\sqrt{s}$ = 7 TeV $\sqrt{s}$ = 8 TeV

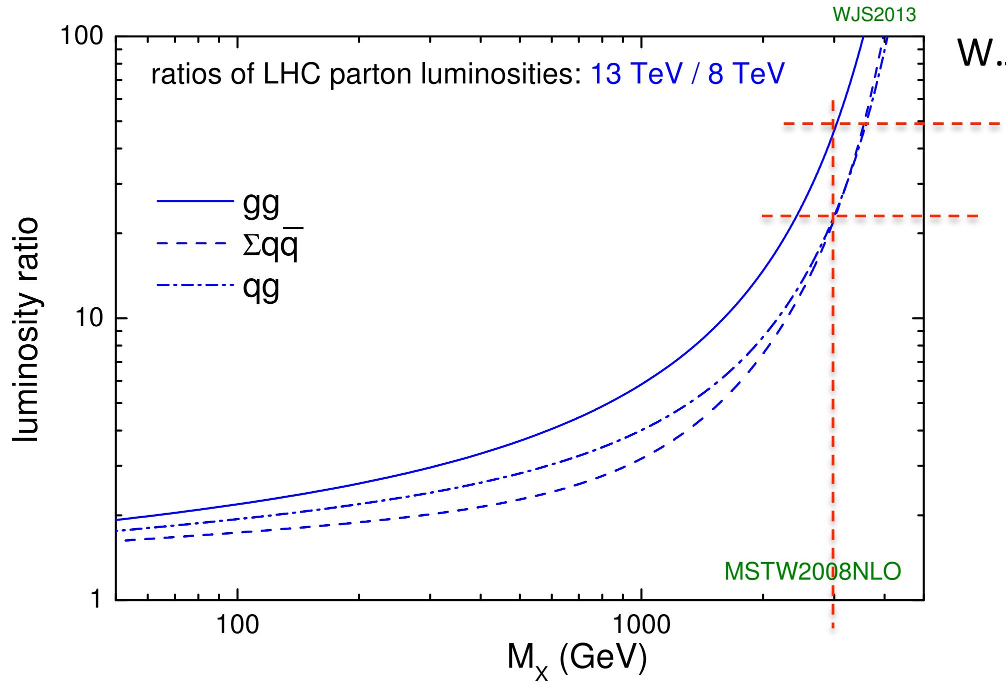
Mass scale [TeV]: 10^{-1}, 1, 10

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

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/

Outlook 2015 data @ 13/14 TeV

Extrapolation via scaling of parton luminosities



W.J. Stirling 2013

➔ $q\bar{q}$ yield of signal @ 3 TeV 20 times higher at 13 TeV compared to 8 TeV !
(unfortunately background yield higher as well)

➔ Limits (around 3 TeV) with 1-3/fb @ 13/14 TeV are comparable to present limits

....eagerly awaiting 2015 data !

Summary

LHC Run-1 explored new territory

➔ nothing (unexpected) found yet...

- SM impressively consistent (even after discovery of Higgs)
- Direct searches: Much progress (in terms of reach) !
- Starting from 1/fb of 2015 data some analyses surpass current sensitivity !

➔ Eagerly awaiting the new data ...

backup

Operators

scalar

D1: scalar
D5: vector
D9: tensor
C1: complex scaler

vector

Spin-dependent, axial-vector

Spin-dependent, tensor

gg scalar

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu} q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta} q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

TABLE I: Operators coupling WIMPs to SM particles. The operator names beginning with D, C, R apply to WIMPS that are Dirac fermions, complex scalars or real scalars respectively.

arXiv:1008.1783

Operators

lower limits on M_* can be converted into upper limits on WIMP-Nucleon scattering cross section

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

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

$$\sigma_0^{D8,D9} = 9.18 \times 10^{-40}\text{cm}^2 \left(\frac{\mu_\chi}{1\text{GeV}}\right)^2 \left(\frac{300\text{GeV}}{M_*}\right)^4,$$

$$\sigma_0^{D11} = 3.83 \times 10^{-41}\text{cm}^2 \left(\frac{\mu_\chi}{1\text{GeV}}\right)^2 \left(\frac{100\text{GeV}}{M_*}\right)^6,$$

$$\sigma_0^{C1,R1} = 2.56 \times 10^{-36}\text{cm}^2 \left(\frac{\mu_\chi}{1\text{GeV}}\right)^2 \left(\frac{10\text{GeV}}{m_\chi}\right)^2 \left(\frac{10\text{GeV}}{M_*}\right)^4$$

arXiv:1008.1783

$$\sigma_0^{C5,R3} = 7.40 \times 10^{-39}\text{cm}^2 \left(\frac{\mu_\chi}{1\text{GeV}}\right)^2 \left(\frac{10\text{GeV}}{m_\chi}\right)^2 \left(\frac{60\text{GeV}}{M_*}\right)^4$$

G*-> HH->4b: Multijet BG

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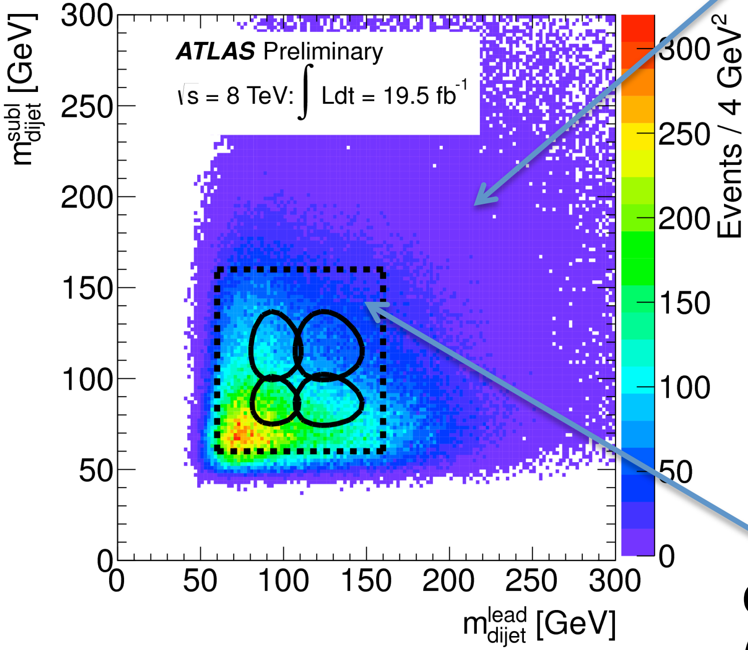
Alternative sample with same selection, except only one of the dijets is b-tagged
➔ 300k events, 2-tag sample

Normalize and reweight 2-tag to 4-tag (sideband)

2-tag sample



Check afterwards (control region)

4-tag sample