Searches for New Phenomena with ATLAS at $\sqrt{s} = 8$ TeV

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CAP Congress
Edmonton, Alberta
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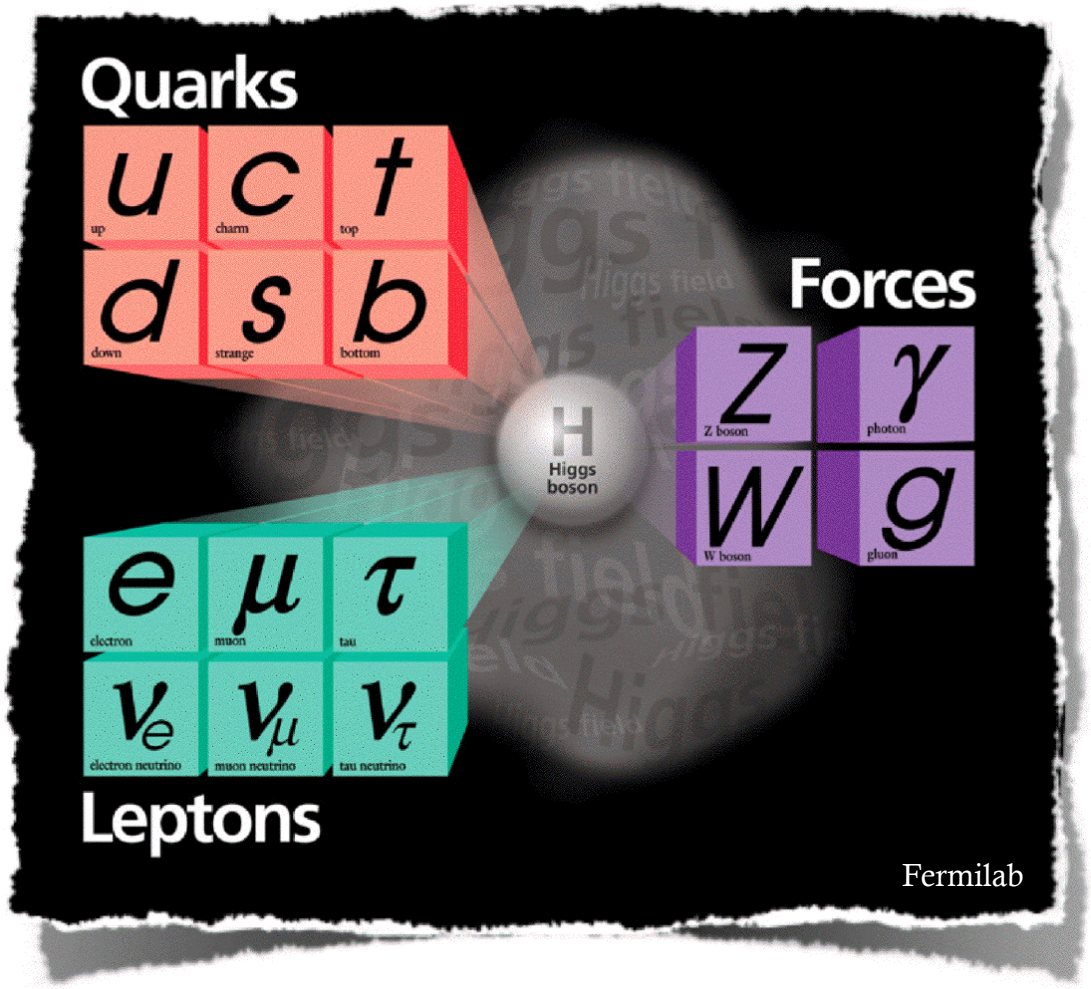
YORK UNIVERSITÉ UNIVERSITY

2012: Higgs Boson

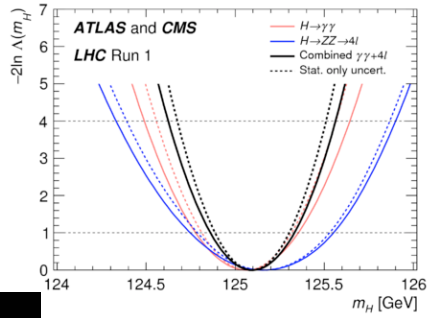


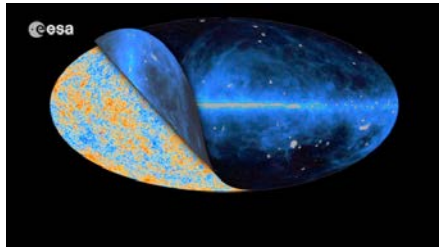
Standard Model Woes

Questions that SM fails to answer

- Why is gravity so weak?
- Why is the Higgs mass so low?
- What is dark matter?
- Where happened to all the antimatter?
- Why are there three fermion families?

PRL 114, 191803





CERN

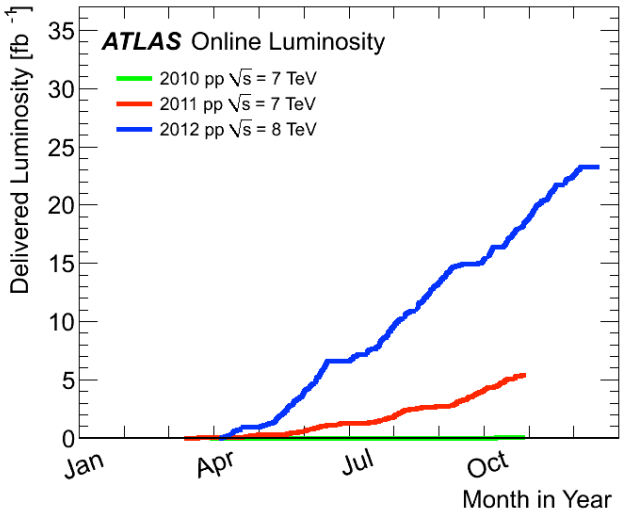
New Phenomena as a Cure

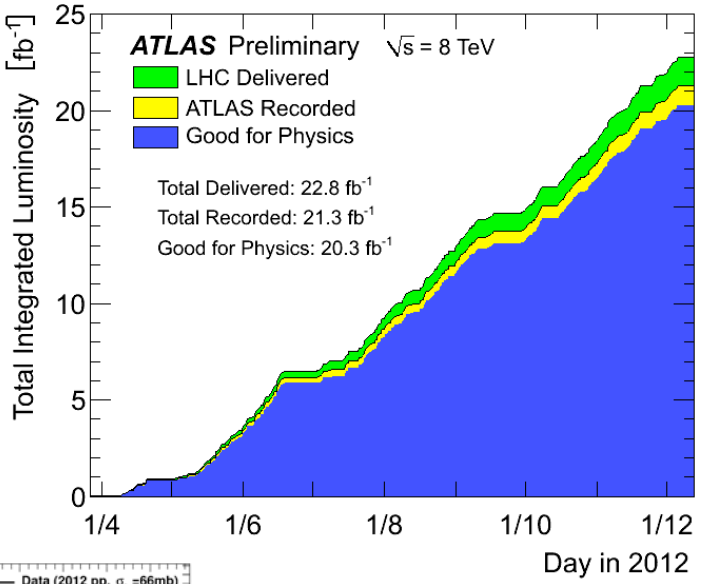
- Hierarchy Problem

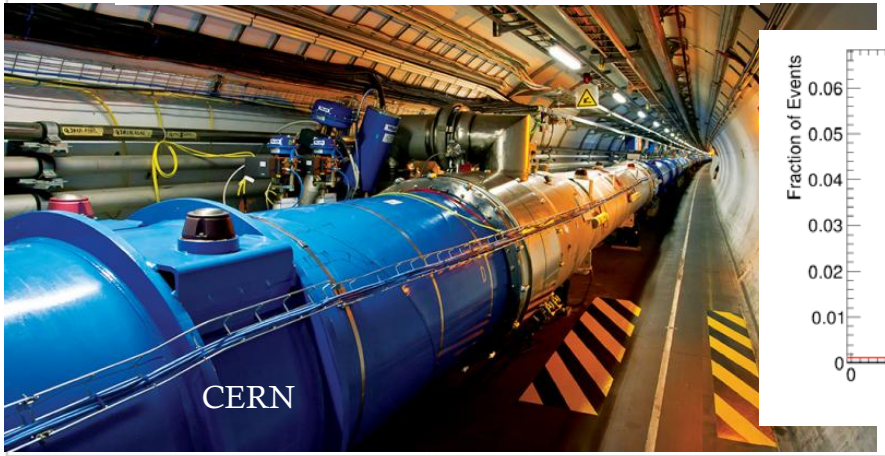
  $O_{EW}(10^2\,\mathrm{GeV}) << O_{Pl}(10^{19}\,\mathrm{GeV})$

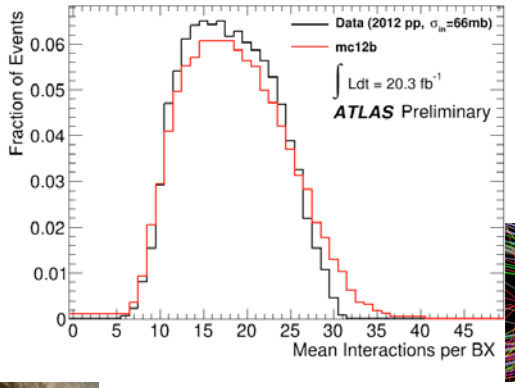
  ⇒ extreme fine-tuning of Higgs mass
  - NP: GUT → heavy gauge bosons
  - NP: Composite Higgs/Little Higgs → vector-like quarks (T/B)
- Weak force of gravity
  - NP: GUT → heavy gauge bosons
  - NP: gravity permeates into extra dimensions → Randall-Sundrum gravitons, microscopic black holes and string balls
- Blue sky searches for exotic particles
  - Multicharged particles (particles with electric charge >1e)
  - Magnetic monopoles and high electric charge objects (see G. Palacino's talk)

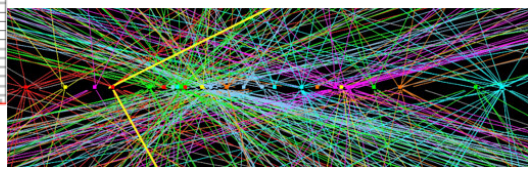
LHC Run 1


ATLAS Online Luminosity
2010 pp √s = 7 TeV
2011 pp √s = 7 TeV
2012 pp √s = 8 TeV
Delivered Luminosity [fb⁻¹]
Jan
Apr
Jul
Oct
Month in Year

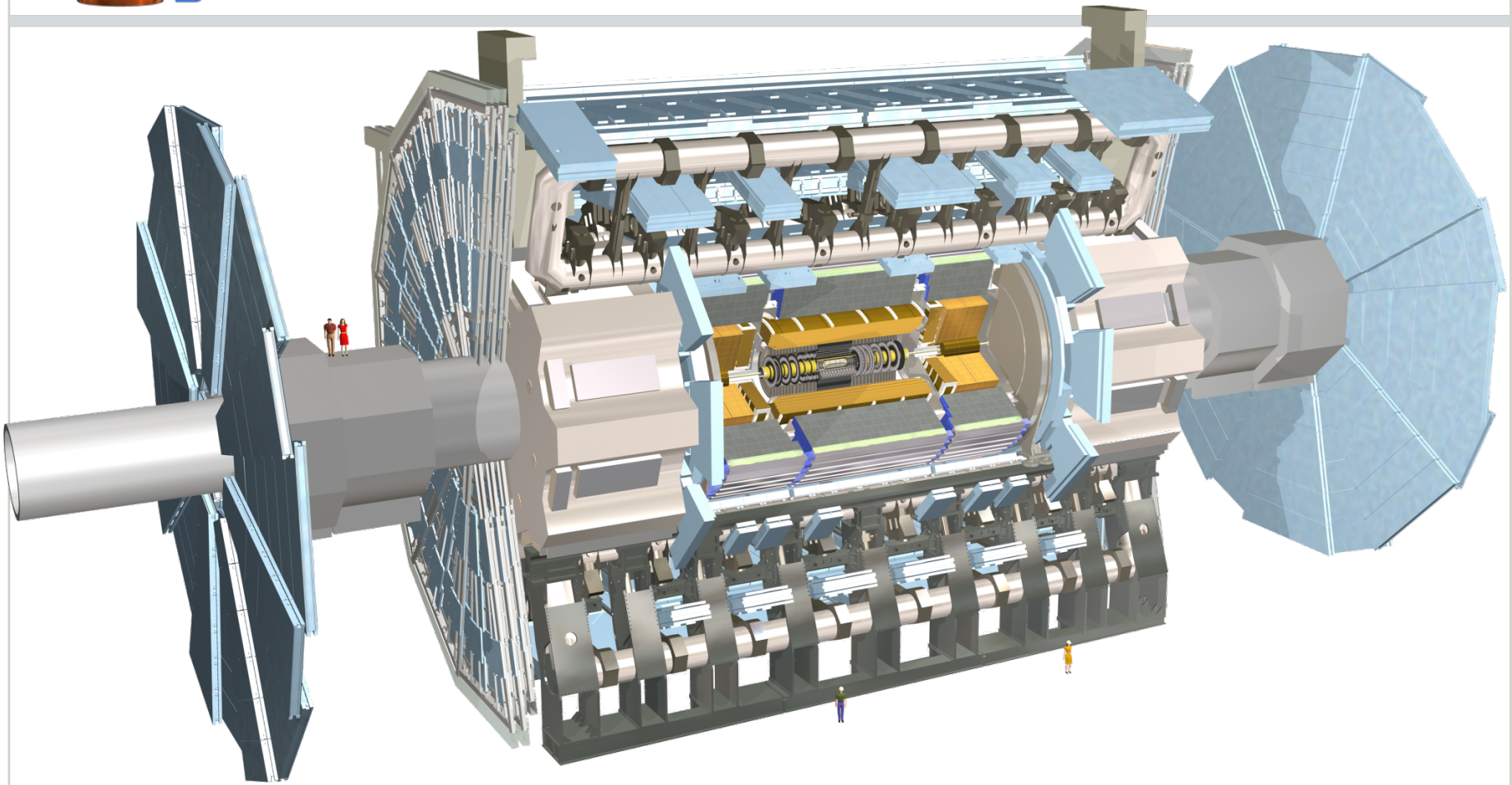

ATLAS Preliminary √s = 8 TeV
LHC Delivered
ATLAS Recorded
Good for Physics
Total Delivered: 22.8 fb⁻¹
Total Recorded: 21.3 fb⁻¹
Good for Physics: 20.3 fb⁻¹
Total Integrated Luminosity [fb⁻¹]
Day in 2012


CERN


Data (2012 pp, σin=66mb)
mc12b
∫ Ldt = 20.3 fb⁻¹
ATLAS Preliminary
Fraction of Events
Mean Interactions per BX

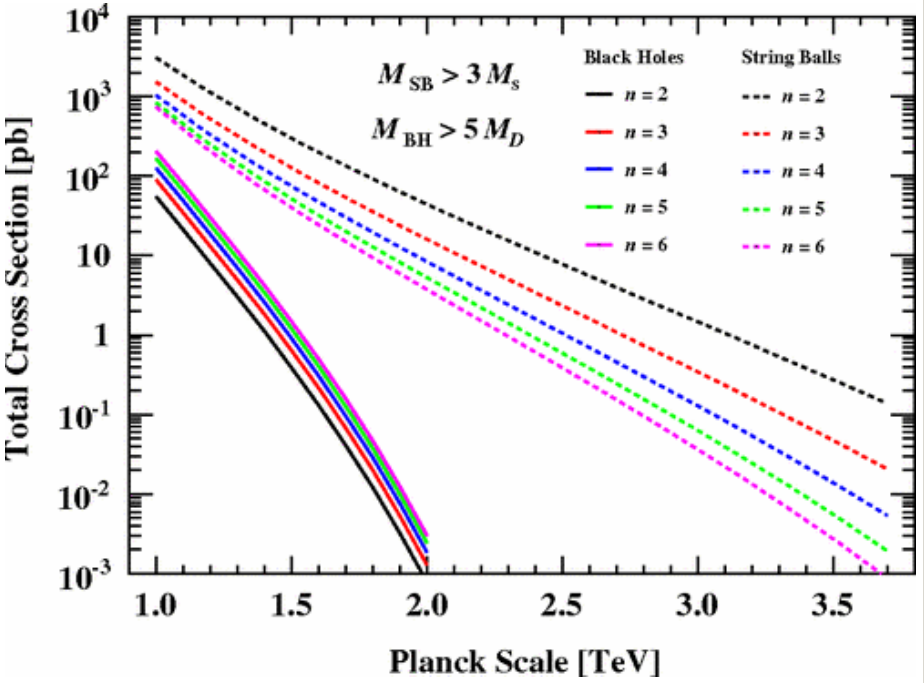


ATLAS multipurpose detector



Low-Scale Quantum Gravity

- Models with extra spatial dimensions can resolve the Hierarchy Problem
  - True gravitational scale is comparable to electroweak scale
  - Effective gravitational strength is weakened by volume of extra dimensions
- A weakly coupled string theory model incorporating extra dimensions → non-perturbative strong gravitational states: microscopic black holes and string balls (highly excited string states)

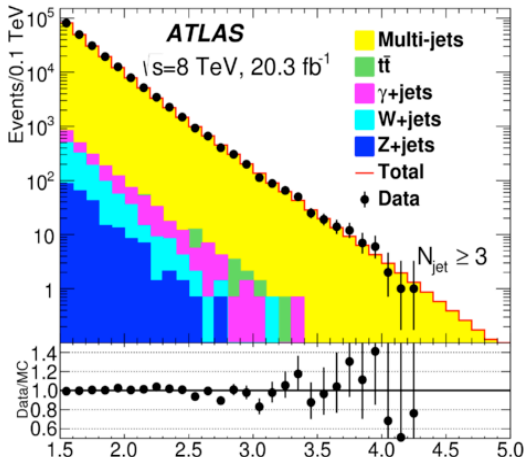


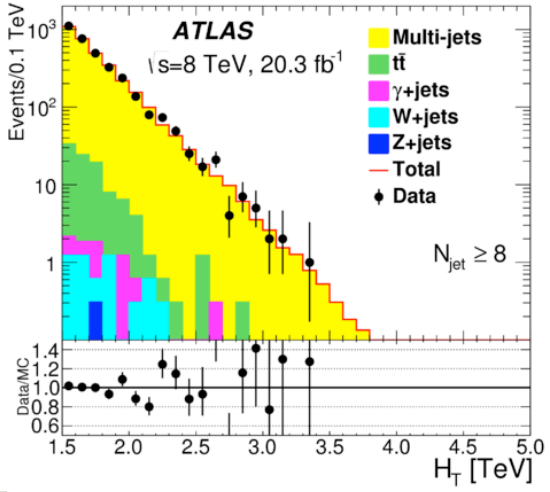
Gingrich and Martell, Phys.Rev.D78.115009

Black Holes and String Balls

arXiv:1503.08988

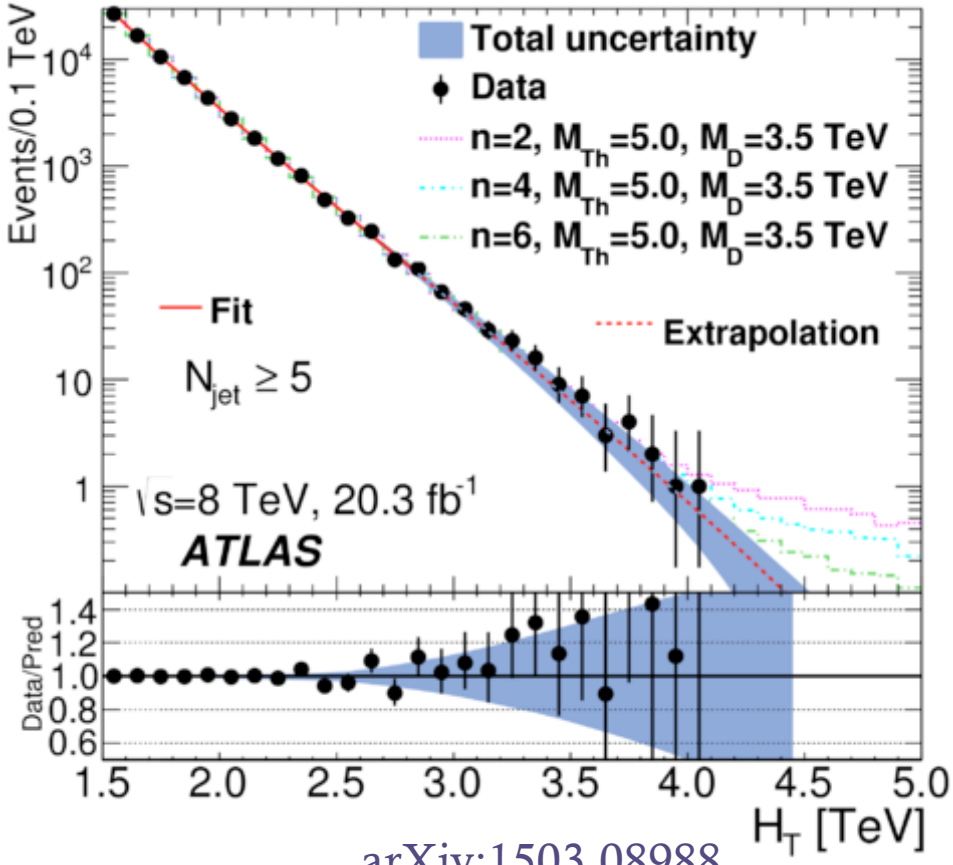
- Decay via Hawking evaporation to large multiplicity of high-p_T particles (mostly quarks and gluons) → multijet events
- Complementary to dilepton and lepton+jets searches
- Search variable: $H_T = \sum_{N_{jet}} p_T^{jet}$
- Consider bins $N_{jet} \geq 3-8$





Black Holes and String Balls

- H_T distribution is extrapolated from control region $1.5<H_T<2.9$ TeV to signal region $H_T>3.0$ TeV
- No event observed for $H_T>4.3$ TeV, in agreement with background estimate

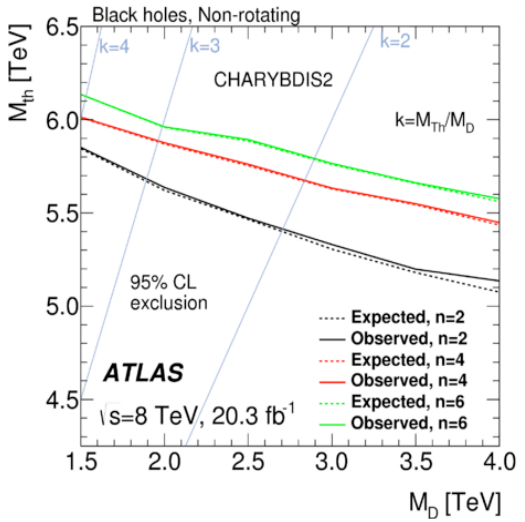


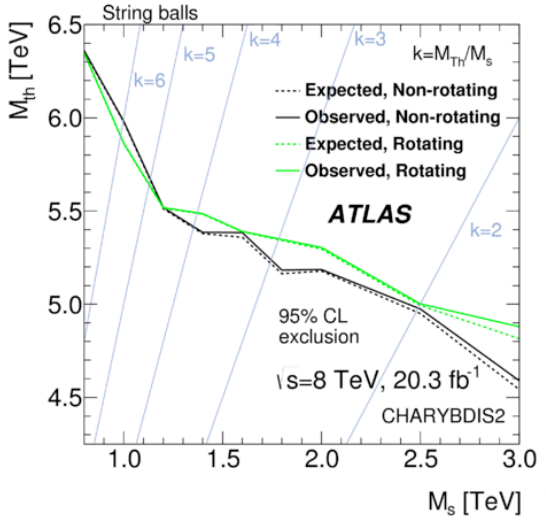
arXiv:1503.08988

Black Holes and String Balls

- Cross-section limits obtained for a variety of models
- Lower-mass limits on black hole and string ball masses range from 4.6 to 6.2 TeV

arXiv:1503.08988





Heavy Dilepton Resonances

- Additional neutral spin-1 vector gauge bosons
  - Due to existence of larger symmetry groups that break to yield the SM gauge group and additional U(1) gauge groups
  - Predicted by various extensions of the Standard Model
    - Grand Unified Theories
      - Sequential Standard Model (SSM) Z'_{SSM} has same couplings to fermions as Z_{SM}
      - E_6-based GUT-inspired theory: Z'_χ, Z'_ψ

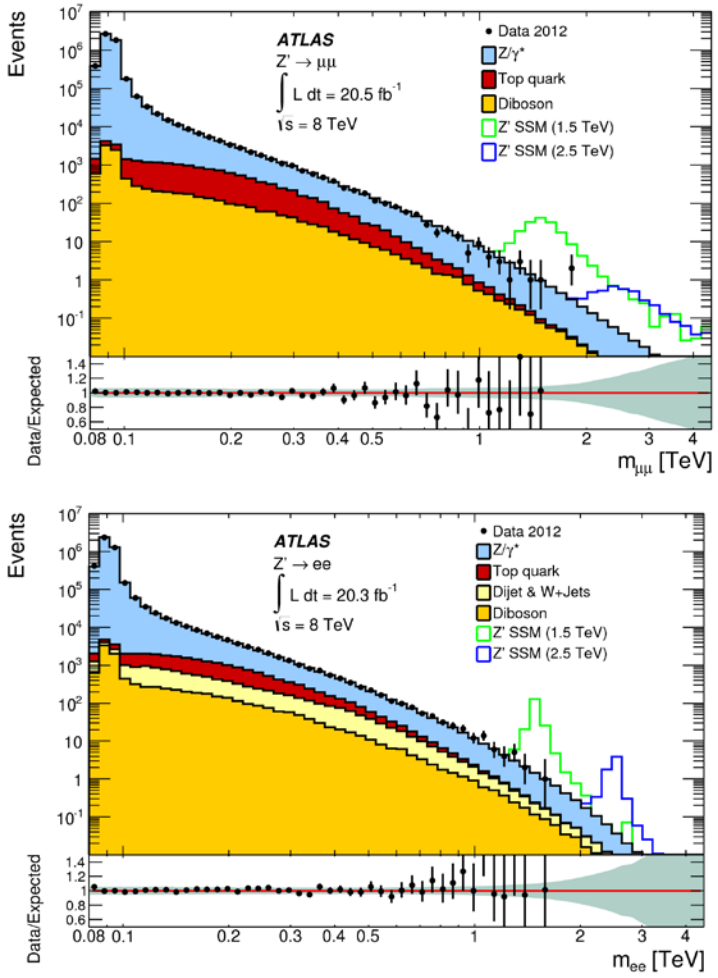
Heavy Dilepton Resonances

- Other dilepton resonances that address hierarchy problem
  - Z*: couplings and kinematics differ from Z_{SM}
  - Spin-2 graviton excitations G*: Randall-Sundrum extra dimensions (PRL 83.3370 (1999))
  - Quantum black holes (QBH): low-scale gravity
  - Technimesons in Minimal Walking Technicolor model with composite Higgs boson (PRD71, 051901 (2005), PRD72, 055001 (2005), PRD76, 055005 (2007))

Heavy Dilepton Resonances

Phys. Rev. D90, 052005 (2014)

- Two opposite-charge muons or two electrons (opposite charge not required)
- New for 8 TeV analysis: improved electron reconstruction
  - Higher efficiency
  - Track pattern recognition accounts for bremsstrahlung
- Main electron backgrounds are photons/jets
- Data-driven background determination



$Z' \rightarrow l^+l^-$ Resonances

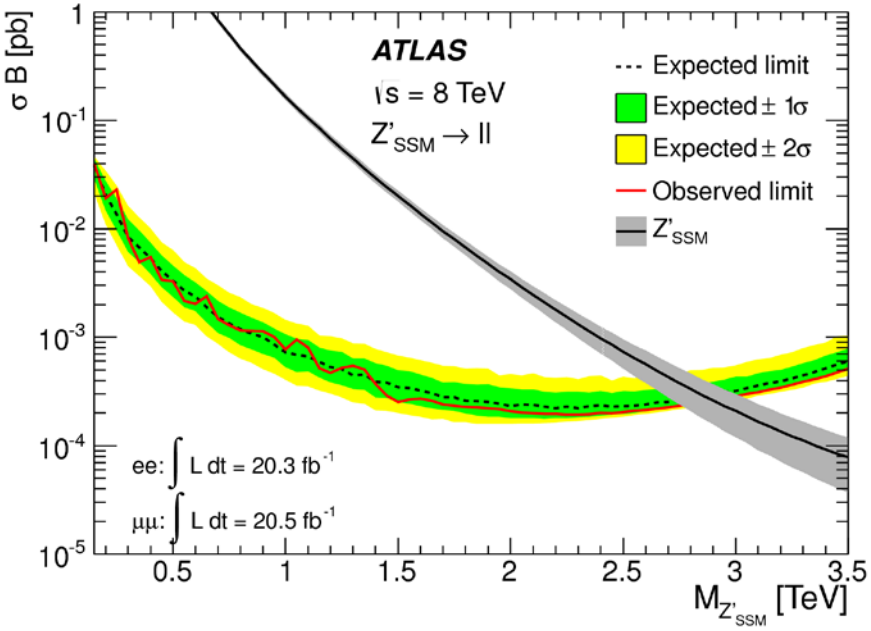
95% CL upper limits on cross section times branching fraction

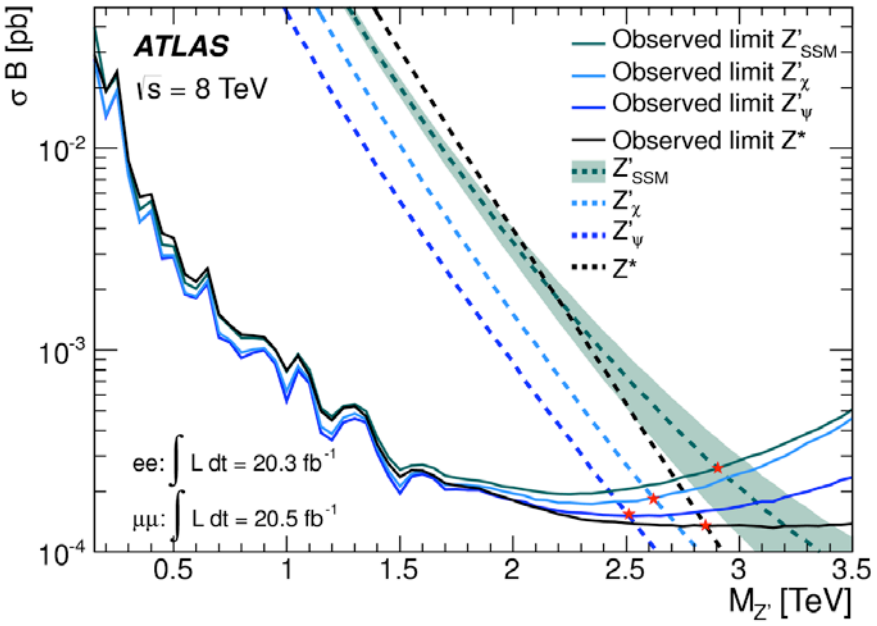
$m(Z'_{SSM}) > 2.9$ TeV

$m(Z'_{\chi}) > 2.62\,\text{TeV}$

$m(Z'_{\psi}) > 2.51\,\text{TeV}$

$m(Z^{*}) > 2.85\,\text{TeV}$





Phys. Rev. D90, 052005 (2014)

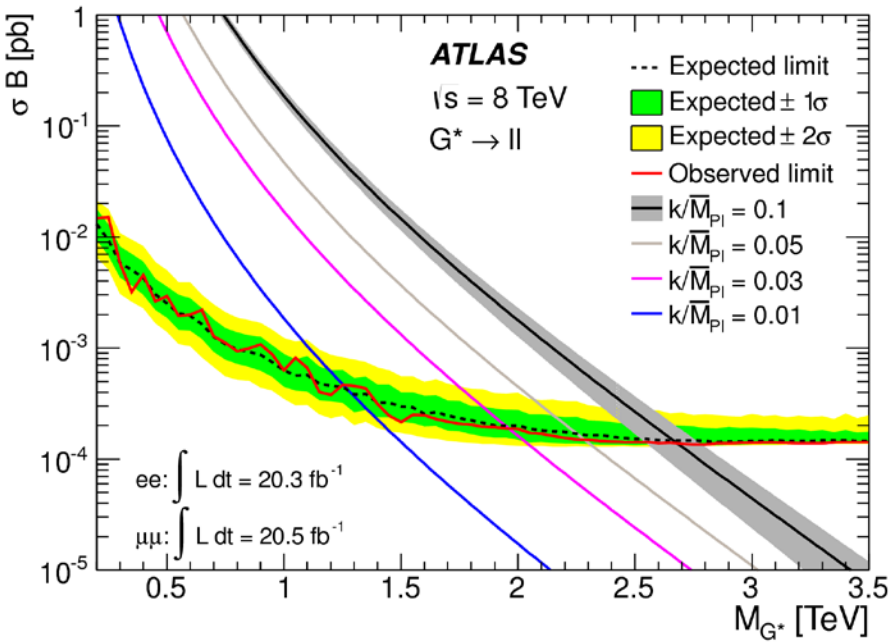
$G^* \rightarrow l^+l^-$ Resonances

- Randall-Sundrum model invokes extra dimension with curvature k that warps spacetime
  (PRL 83.3370 (1999))
  - Observed strength of gravity is suppression of true strength

  ⇒ Bridges large hierarchy

  ⇒ Predicts excited spin-2 gravitons (G*) that decay into dileptons

95% CL upper limits on cross section times branching fraction



Phys. Rev. D90, 052005 (2014)

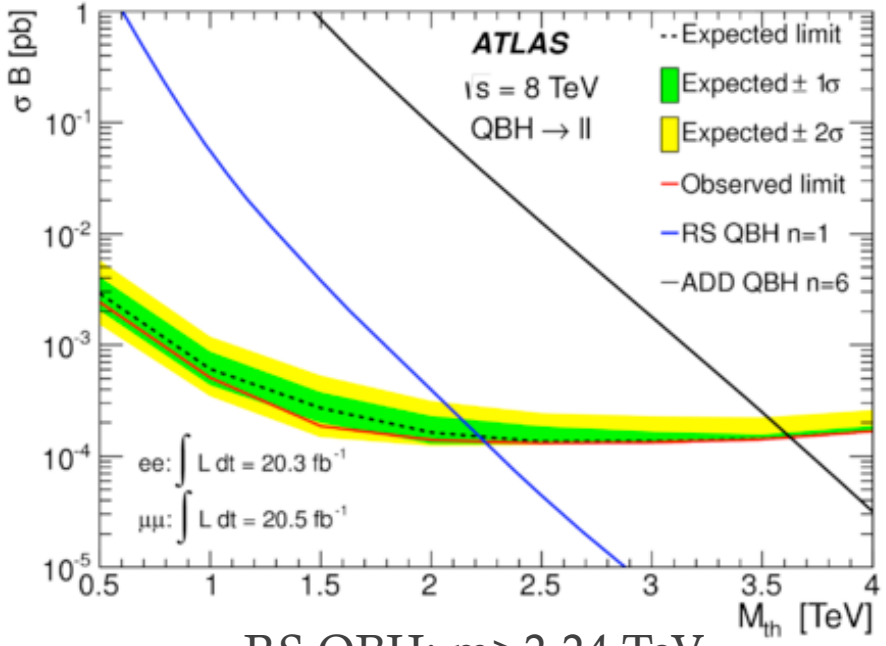
RS graviton (k/M_{Pl}=0.1): m>2.68 TeV

QBH $\rightarrow l^+l^-$ Resonances

Quantum Black Holes

Phys. Rev. D90, 052005 (2014)

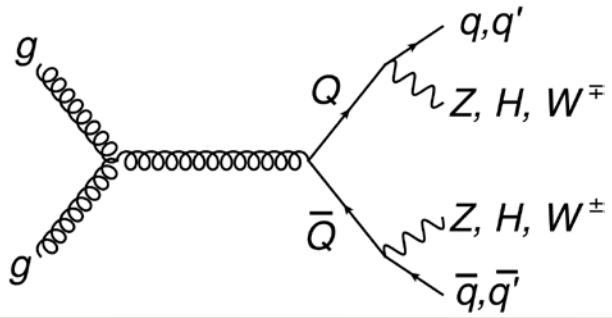
- Production models include
  - RS: PRL 83.3370 (1999)
  - Arkani-Hamed Dimopoulos Dvali ADD: PLB 429, 263 (1998)



RS QBH: m>2.24 TeV
ADD QBH: m>3.65 TeV

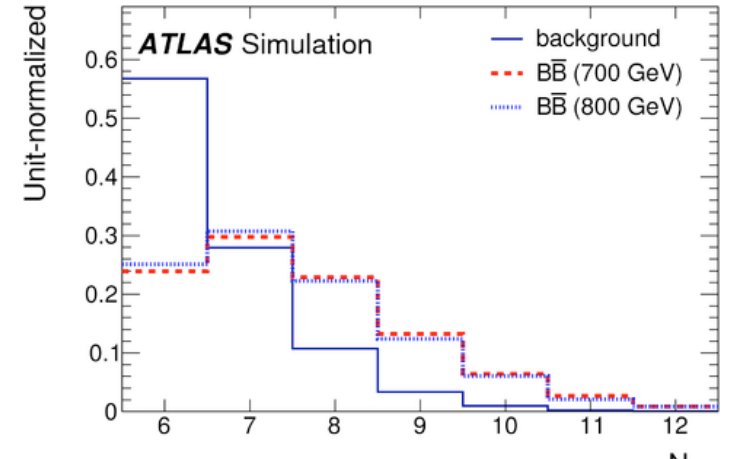
Vector-like Quarks (T/B)

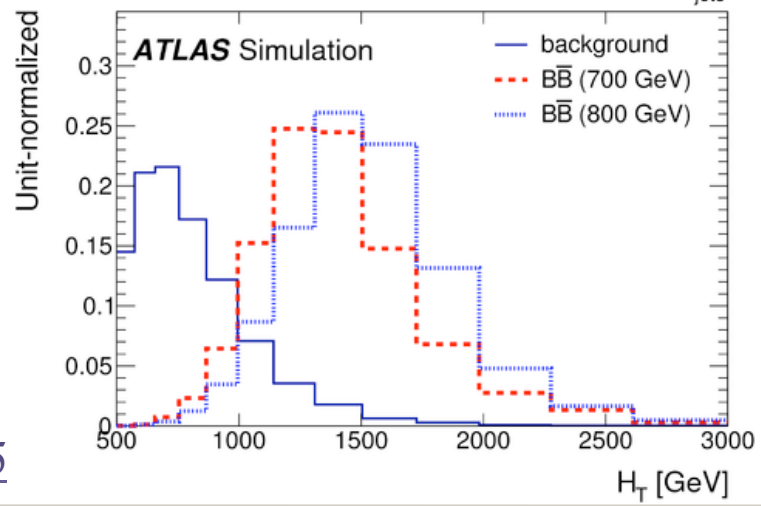
- Vector-like quarks (VLQ) are additional fermions from BSM models that can
  - Provide new sources of CP violation
  - Cancel Higgs mass divergence from top loops → would solve Hierarchy Problem
  - Unify gauge couplings
- Can arise in "Little Higgs"models and models with composite Higgs
- More viable than fourth-generation quarks
  - Colour-triplet spin-1/2 fermions
  - Left- and right-handed under SU(2)
- Signature: leptons, jets, MET



Vector-like Down-type (B) Quarks

- *B*: vector-like down-type quark of charge -1/3
- (Frédérick Dallaire's talk in T1-5: $pp \rightarrow Bb \rightarrow H(\rightarrow bb)bb$)
- Here: $B \rightarrow Zb$, $B \rightarrow Hb$, $B \rightarrow Wt$
- Lepton+jets+MET final state
- Boosted decision tree used for event selection:
  - $N_{\text{jets}} \geq 6$
  - $N_{\text{b-jets}} \geq 1$
  - $N_{\text{Vertices}} \geq 1$
  - $H_T > 500$ GeV



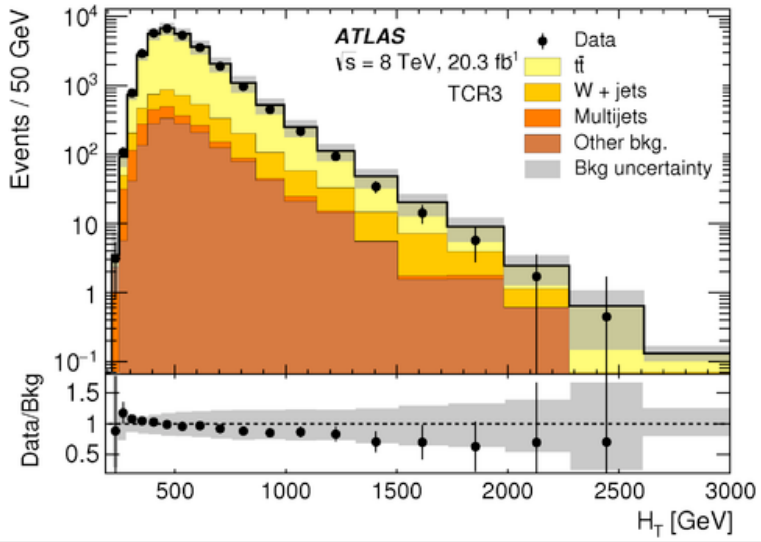


arXiv:1503.05425

Vector-like Down-type (B) Quarks

- Main backgrounds: *t*-*t*bar, *W*+jets, multijets (with lepton mis ID)
- Dominant uncertainty in signal yield is *b*-tagging efficiency (6%)
- Dominant uncertainty in background yield is Jet Energy Scale (15%)

arXiv:1503.05425

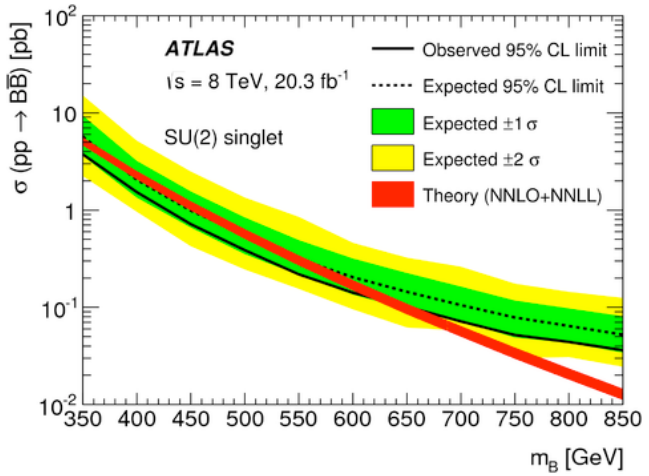


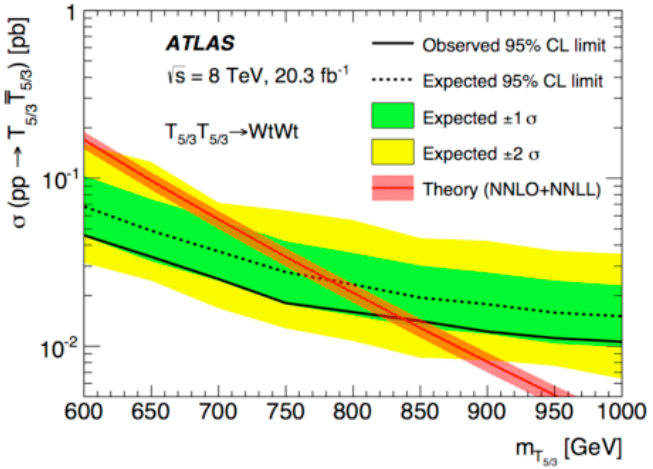
Physics process	Event yield [±(stat)±(syst)]
700 GeV VLQ B; BR($B \to Wt$) = 1	$164 \pm 2 \pm 13$
$t\bar{t}$	$10800 \pm 100 \pm 2800$
W+jets	$1020 \pm 30 \pm 630$
Single top	$490 \pm 20 \pm 300$
Z+jets	$180 \pm 30 \pm 120$
$t\bar{t} + V$	$147 \pm 1 \pm 47$
Diboson	$66 \pm 5 \pm 42$
Multijets	$183 \pm 9 \pm 92$
Total background	$12900 \pm 100 \pm 3100$
Observed in data	12235

Vector-like Down-type (B) Quarks

- No signal observed
- Excludes *B* below 810 GeV
- Another interpretation: coloured charge +5/3 exotic fermion $T_{5/3}$: m>840 GeV

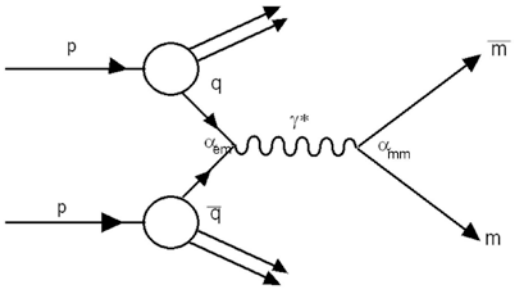
arXiv:1503.05425





Multi-charged Particles

- Fundamental particle with charge $2 \leq |z| \leq 6$
- Predicted by models such as Walking Technicolor and Left-Right Symmetric Model
- Drell-Yan pair production with purely QED coupling proportional to $|z|$



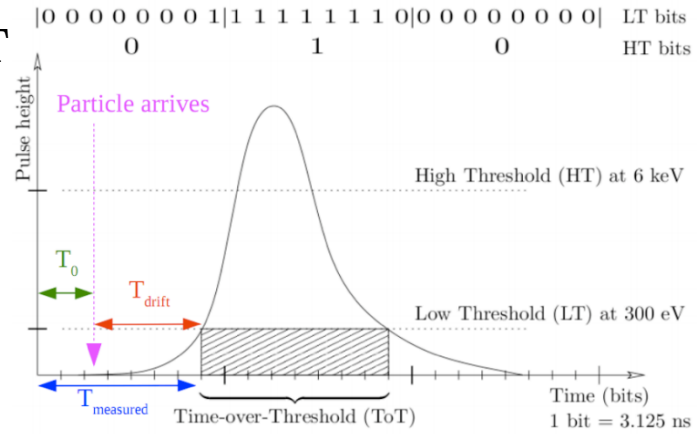
- Consider long-lived scenario, where particle traverses and exits ATLAS
- High ionization (dE/dx) in pixel detector, transition radiation tracker (TRT) and muon system (MDT)
- Charged-particle trajectory reconstructed using standard algorithms (p_T underestimated by factor z, since tracking assumes $|z|=1$)

arXiv:1504.04188

Multi-charged Particles

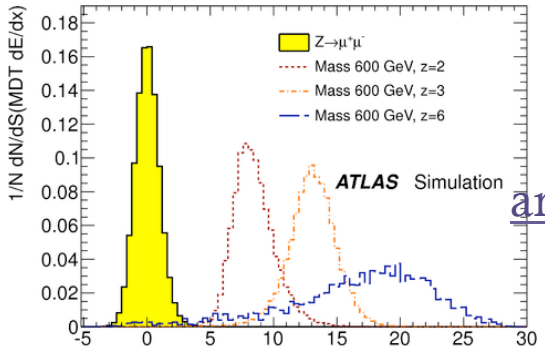
- dE/dx measurement based on "time-over-threshold"

TRT



- Compare to that expected for a high-β muon

$$S(dE/dx) = \frac{dE/dx_{track} - \langle dE/dx_{\mu} \rangle}{\sigma(dE/dx_{\mu})}$$



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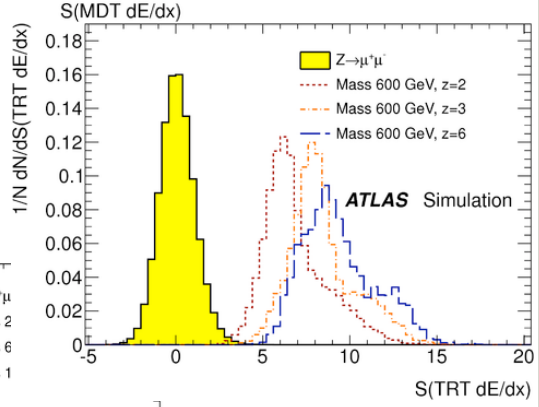
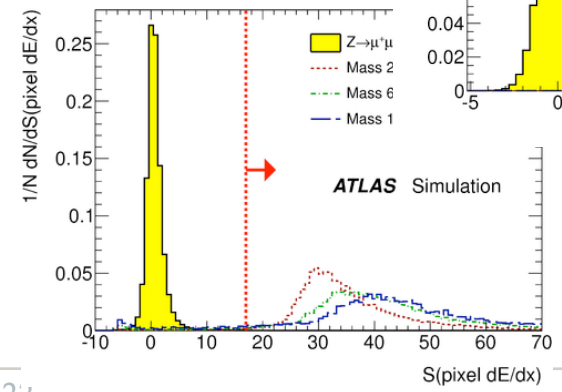
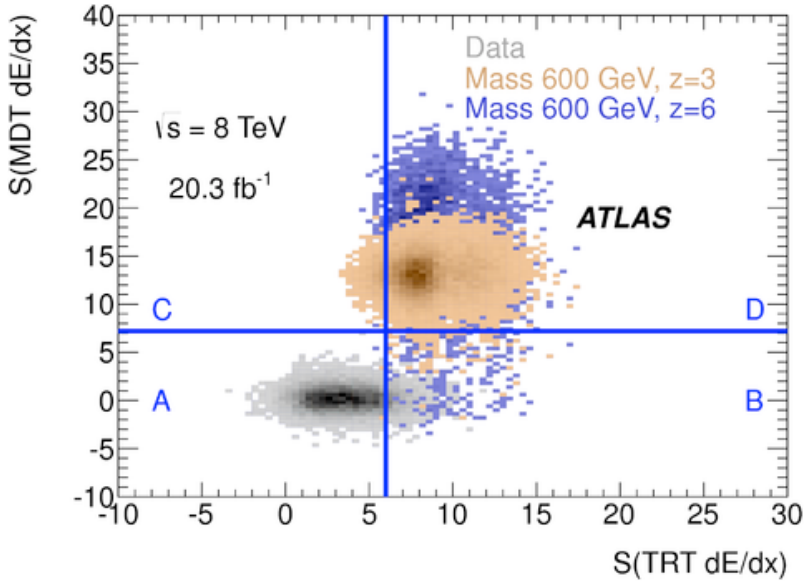


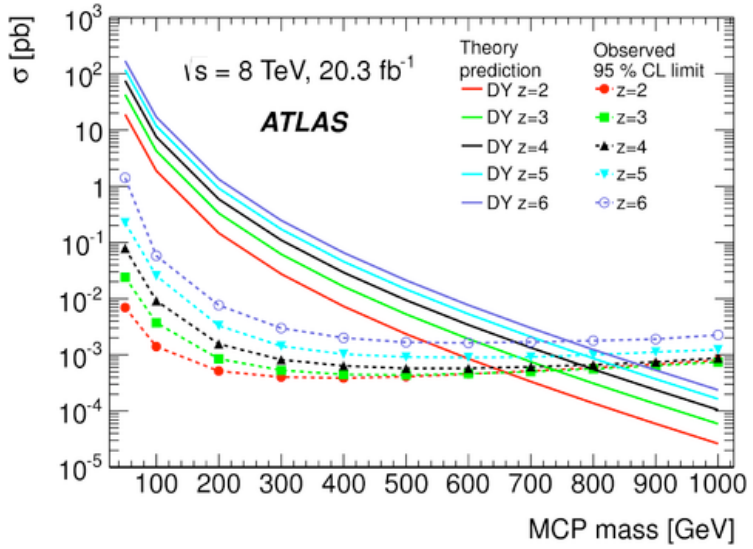


Multi-charged Particles



	N^{B}_{obs}	f	N^{D}_{exp}	N^{D}_{obs}
$z = 2$	76	1.8×10^{-4}	0.013±0.002	0
$z \geq 3$	1251	2.1×10^{-5}	0.026±0.003	0

arXiv:1504.04188



|z|	2	3	4	5	6
Mass limit [GeV]	660	740	780	758	760

Summary

- In the absence of observation of new phenomena, set mass limits

New Phenomenon	Lower Limit (95% C.L.)
Z' (dilepton (SSM))	2.9 TeV
RS graviton (k/M_{Pl}=0.1) (dilepton)	2.68 TeV
Quantum black hole (dilepton) (RS/ADD)	2.24/3.65 TeV
Microscopic black hole/string ball	4.6-6.2 TeV
Vector-like down-type quark B	810 GeV
Multi-charged particle $2 \leq \lvert z \rvert \leq 6$	660/740/780/758/760 GeV

- Many 8 TeV ATLAS new phenomena searches published
- Many more to be published in the coming months
- Discovery potential improves at $\sqrt{s} = 13$ TeV!

ATLAS Exotics Searches* - 95% CL Exclusion

Status: March 2015

ATLAS Preliminary

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

	Model	ℓ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt$[fb^{-1}]	Mass limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	≥ 1 j	Yes	20.3	M_D 5.25 TeV	$n = 2$	1502.01518
	ADD non-resonant $\ell\ell$	2 e, μ	–	–	20.3	M_S 4.7 TeV	$n = 3$ HLZ	1407.2410
	ADD QBH $\rightarrow \ell q$	1 e, μ	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	20.3	M_{th} 5.82 TeV	$n = 6$	1407.1376
	ADD BH high N_{trk}	2 μ (SS)	–	–	20.3	M_{th} 4.7 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	20.3	M_{th} 5.8 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	1405.4254
	ADD BH high multijet	–	≥ 2 j	–	20.3	M_{th} 5.8 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	Preliminary
	RS1 $G_{KK} \rightarrow \ell\ell$	2 e, μ	–	–	20.3	G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2 γ	–	–	20.3	G_{KK} mass 2.66 TeV	$k/\overline{M}_{Pl} = 0.1$	Preliminary
	Bulk RS $G_{KK} \rightarrow ZZ \rightarrow qq\ell\ell$	2 e, μ	2 j / 1 J	–	20.3	G_{KK} mass 740 GeV	$k/\overline{M}_{Pl} = 1.0$	1409.6190
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\ell\nu$	1 e, μ	2 j / 1 J	Yes	20.3	W' mass 700 GeV	$k/\overline{M}_{Pl} = 1.0$	1503.04677
	Bulk RS $G_{KK} \rightarrow HH \rightarrow bbbb$	–	4 b	–	19.5	G_{KK} mass 590-710 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-005
	Bulk RS $g_{KK} \rightarrow t\bar{t}$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	20.3	g_{KK} mass 2.2 TeV	BR = 0.925	ATLAS-CONF-2015-009
	2UED / RPP	2 e, μ (SS)	≥ 1 b, ≥ 1 j	Yes	20.3	KK mass 960 GeV		Preliminary
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	2 e, μ	–	–	20.3	Z' mass 2.9 TeV		1405.4123
	SSM $Z' \rightarrow \tau\tau$	2 τ	–	–	19.5	Z' mass 2.02 TeV		1502.07177
	SSM $W' \rightarrow \ell\nu$	1 e, μ	–	Yes	20.3	W' mass 3.24 TeV		1407.7494
	EGM $W' \rightarrow WZ \rightarrow \ell\nu\,\ell'\ell'$	3 e, μ	–	Yes	20.3	W' mass 1.52 TeV		1406.4456
	EGM $W' \rightarrow WZ \rightarrow qq\ell\ell$	2 e, μ	2 j / 1 J	–	20.3	W' mass 1.59 TeV		1409.6190
	HVT $W' \rightarrow WH \rightarrow \ell\nu bb$	1 e, μ	2 b	Yes	20.3	W' mass 1.47 TeV	$g_V = 1$	Preliminary
	LRSM $W'_R \rightarrow t\bar{b}$	1 e, μ	2 b, 0-1 j	Yes	20.3	W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \rightarrow t\bar{b}$	0 e, μ	≥ 1 b, 1 J	–	20.3	W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	17.3	Λ 12.0 TeV	$\eta_{LL} = -1$	Preliminary
	CI $qq\ell\ell$	2 e, μ	–	–	20.3	Λ 21.6 TeV	$\eta_{LL} = -1$	1407.2410
	CI $uutt$	2 e, μ (SS)	≥ 1 b, ≥ 1 j	Yes	20.3	Λ 4.35 TeV	$\lvert C_{LL} \rvert = 1$	Preliminary
DM	EFT D5 operator (Dirac)	0 e, μ	≥ 1 j	Yes	20.3	M_* 974 GeV	at 90% CL for $m(\chi) < 100$ GeV	1502.01518
	EFT D9 operator (Dirac)	0 e, μ	1 J, ≤ 1 j	Yes	20.3	M_* 2.4 TeV	at 90% CL for $m(\chi) < 100$ GeV	1309.4017
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	1.0	LQ mass 660 GeV	$\beta = 1$	1112.4828
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	1.0	LQ mass 685 GeV	$\beta = 1$	1203.3172
	Scalar LQ 3rd gen	1 e, μ, 1 τ	1 b, 1 j	–	4.7	LQ mass 534 GeV	$\beta = 1$	1303.0526
Heavy quarks	VLQ $TT \rightarrow Ht + X, Wb + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	20.3	T mass 785 GeV	isospin singlet	ATLAS-CONF-2015-012
	VLQ $TT \rightarrow Zt + X$	2/≥3 e, μ	≥2/≥1 b	–	20.3	T mass 735 GeV	T in (T,B) doublet	1409.5500
	VLQ $BB \rightarrow Zb + X$	2/≥3 e, μ	≥2/≥1 b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	1409.5500
	VLQ $BB \rightarrow Wt + X$	1 e, μ	≥ 1 b, ≥ 5 j	Yes	20.3	B mass 640 GeV	isospin singlet	Preliminary
	$T_{5/3} \rightarrow Wt$	1 e, μ	≥ 1 b, ≥ 5 j	Yes	20.3	$T_{5/3}$ mass 840 GeV		Preliminary
Excited fermions	Excited quark $q^* \rightarrow q\gamma$	1 γ	1 j	–	20.3	q^* mass 3.5 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1309.3230
	Excited quark $q^* \rightarrow qg$	–	2 j	–	20.3	q^* mass 4.09 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1407.1376
	Excited quark $b^* \rightarrow Wt$	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 $\ell^* \rightarrow \ell\gamma$	2 e, μ, 1 γ	–	–	13.0	ℓ^* mass 2.2 TeV	$\Lambda = 2.2$ TeV	1308.1364
	Excited lepton $\nu^* \rightarrow \ell W, \nu Z$	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LSTC $a_T \rightarrow W\gamma$	1 e, μ, 1 γ	–	Yes	20.3	a_T mass 960 GeV		1407.8150
	LRSM Majorana ν	2 e, μ	2 j	–	2.1	N^0 mass 1.5 TeV	$m(W_R) = 2$ TeV, no mixing	1203.5420
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2 e, μ (SS)	–	–	20.3	$H^{\pm\pm}$ mass 551 GeV	DY production, BR($H_L^{\pm\pm} \rightarrow \ell\ell$)=1	1412.0237
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, BR($H_L^{\pm\pm} \rightarrow \ell\tau$)=1	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{non-res} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $\lvert q \rvert = 5e$	Preliminary
	Magnetic monopoles	–	–	–	2.0	monopole mass 862 GeV	DY production, $\lvert g \rvert = 1 g_D$	1207.6411

2015-06-16

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

10^{-1} 1 10 **Mass scale [TeV]**

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

LHC Plans

2011 – 2012: 25 fb^{-1}
√s = 7,8 TeV
$\mathcal{L}$=6.8×10^{33} cm^{-2} s^{-1}

2013 – 2014: LS1

2015 – 2016 – 2017: ~75-100 fb^{-1}
√s = 13,14 TeV
$\mathcal{L}$=1×10^{34} cm^{-2} s^{-1}

2018: LS2

2019 – 2020 – 2021: ~350 fb^{-1}
√s = 14 TeV
$\mathcal{L}$=2×10^{34} cm^{-2} s^{-1}

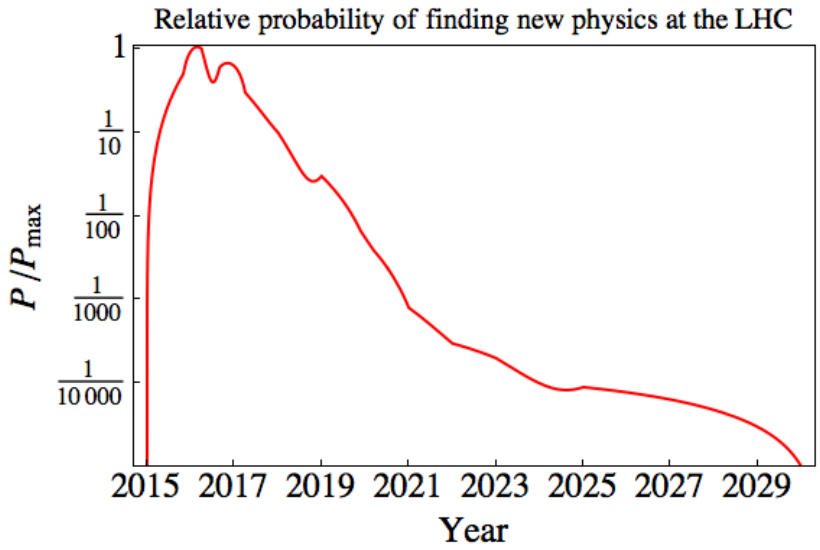
2022: LS3

2023 …
√s = 14 TeV
$\mathcal{L}$=5×10^{34} cm^{-2} s^{-1}

Expected ATLAS *Z'* mass limit prospects (TeV):

	20.3 fb^{-1} √s = 8 TeV	**300 fb^{-1}** √s = 13 TeV	**1000 fb^{-1}** √s = 14 TeV	**3000 fb^{-1}** √s = 14 TeV
Z'_{SSM}-> e^+e^-	2.9	6.5	7.2	7.8

ATL-PHYS-PUB-2013-007



http://resonaances.blogspot.ca

13 TeV Event Displays

Record energy *pp* collisions
on May 21, 2015