ATLAS Exotics

D. Strom
University of Oregon
on behalf of The ATLAS Collaboration

Outline

Brief overview of 2015 data sample

13 TeV

- Search for quantum gravity and other resonance and structure at high mass 13 TeV
  - Physics motivation:
    - Quantum Black Holes
    - W' and Z' bosons
    - Strong gravity
  - Final states
    - e-μ, γ + jets, Dijets, multi-jets

- Search W' and Z' 13 TeV

- Search for dark matter 13 TeV
  - Mono-Z, W signatures

Other related ATLAS talks:

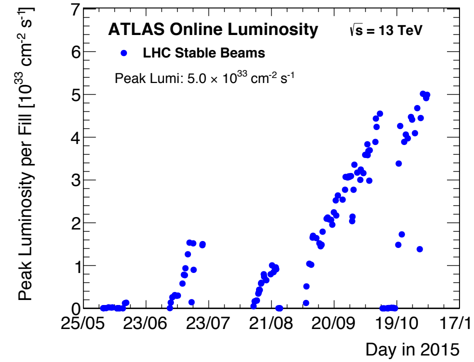
David Lopez:	Dibosons
Christian Ohm:	BSM Higgs
Arely Cortes Gonzalez:	Dark Matter
Lene Bryngemark:	Dijets

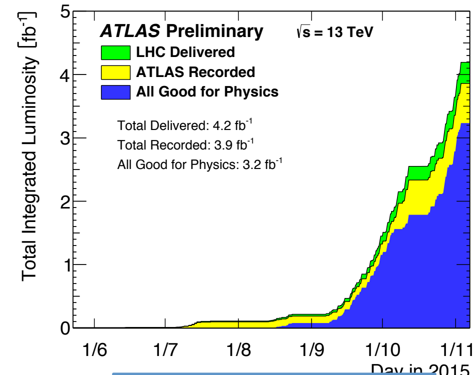
8 TeV (newly submitted for publication)

- Flavor violation $\tau \rightarrow \mu^{-}\mu^{+}\mu^{-}$
- Vector like quarks (from composite theories)

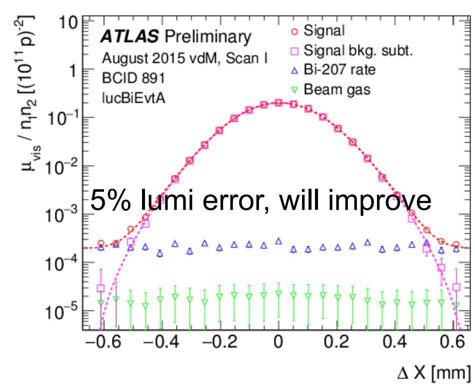
2015 Data

- Cautious ramp up in luminosity $\sqrt{s}$ = 13 TeV
- 3.2 fb^{-1} recorded and good for physics
  - (c.f. 21 fb^{-1} at $\sqrt{s}$ = 8 TeV)
- ATLAS detector and trigger worked well throughout the run
  - New layer of pixels
  - Improved E_t^{miss} hardware trigger
- Cross sections based on luminosity calibrated in a “van der Meer” scan



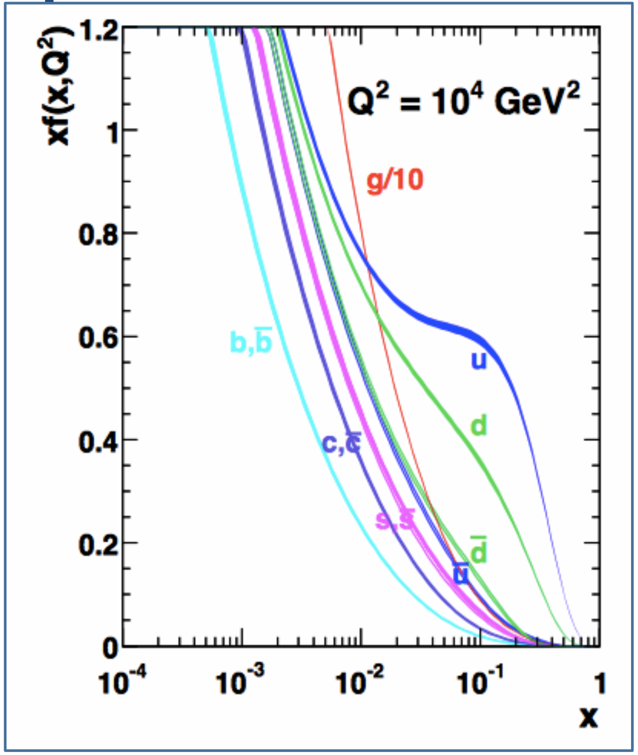


Thanks LHC!



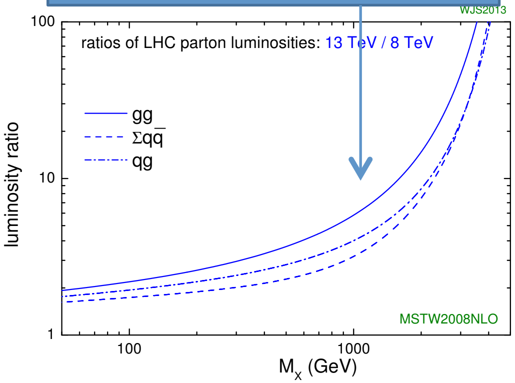
What to expect from 13 TeV data

- PDF are rapidly falling with high x
- Increased center-of-mass energy increases cross sections for heavy particles
- For particles above 1-2 TeV, 13 TeV data is more sensitive, even though luminosity was ~7 times lower.
- With limited luminosity, most interesting searches will depend on processes involving u and d quarks and gluons

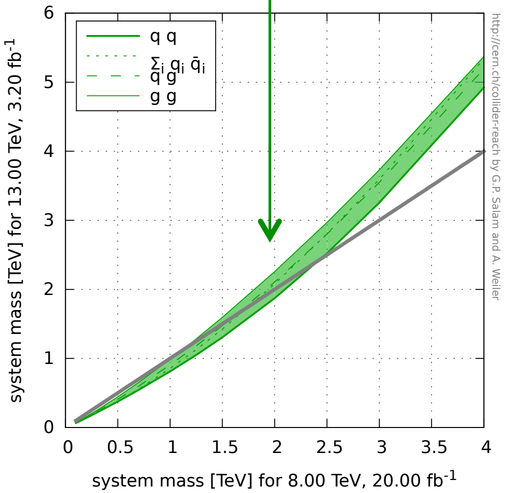


Sterling

Plots of parton luminosity from Sterling



Plot of mass reach equivalence for:
8TeV 21fb^{-1}
13TeV 3.2fb^{-1}

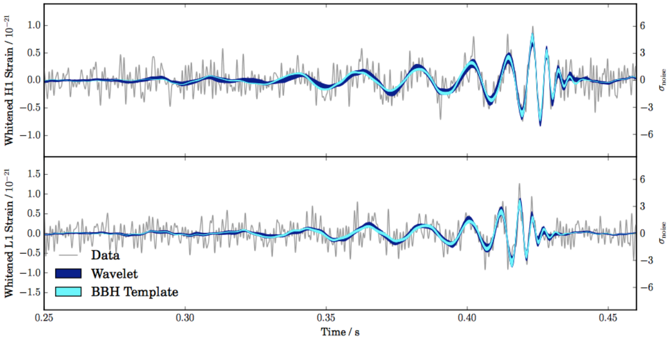


Gavin Salam and Andreas Weiler

http://collider-reach.web.cern.ch/collider-reach/

Search for quantum gravity

- Gravitational waves are now known to be both produced and detected (see talk by Frédérique Marion)
  - No hint of deviations from GR
  - LIGO limit from dispersion:
    $m_g < 1.2 \times 10^{-22}$ eV (PRL 116, 061102 (2016))



- Quantum effects expected near the reduced Planck Scale ~2.4 10^{18} GeV – not accessible in experiments
- In theories with extra dimensions, the Planck Scale can be lower, for example near the GUTS scale
  - CMB observations (see talk by Paolo Natoli) could give us a hint about the scale of quantum gravity from the imprint of gravitational waves on the CMB of the early universe, but dust is major challenge.
  - Improved experiments coming (http://arxiv.org/abs/1502.00612, http://arxiv.org/abs/1601.00125)

- If the extra dimensions are large enough or warped, the scale of quantum gravity can come down to the TeV scale:
  - Quantum Black Holes (low multiplicity final states, like contact interaction, QBH can have color and EM charge)
    - ADD -- Arkani-Hamed, Dimopoulos, Dvali, arXiv:hep-ph/9803315, arXiv:hep-ph/9807344 ``large" extra dimensions
    - RS -- Randall and Sundrum arXiv:hep-ph/9905221
    - Use QBH generator from Gingrich, for most results (arXiv:0911.5370)
      - For ADD models use M_D (gravity scale) = M_{TH} (QBH threshold) and n=6
      - For RS1 use n=1
  - Micro-black holes from strong graviational couplings (multi-jets, leptons, democratic coupling)
  - Expect Kluza-Klein excitations of graviton in ADD, etc.

Other searches

- Contact interactions (e.g. for leptons Phys. Rev. Lett. 50 (1983) 811)

$$\mathcal{L} = \frac{g^2}{\Lambda^2}[\eta_{\rm LL}(\bar{q}_{\rm L}\gamma_\mu q_{\rm L})(\bar{\ell}_{\rm L}\gamma^\mu \ell_{\rm L}) + \eta_{\rm RR}(\bar{q}_{\rm R}\gamma_\mu q_{\rm R})(\bar{\ell}_{\rm R}\gamma^\mu \ell_{\rm R}) + \eta_{\rm LR}(\bar{q}_{\rm L}\gamma_\mu q_{\rm L})(\bar{\ell}_{\rm R}\gamma^\mu \ell_{\rm R}) + \eta_{\rm RL}(\bar{q}_{\rm R}\gamma_\mu q_{\rm R})(\bar{\ell}_{\rm L}\gamma^\mu \ell_{\rm L})],$$

$g^2 = 4\pi$

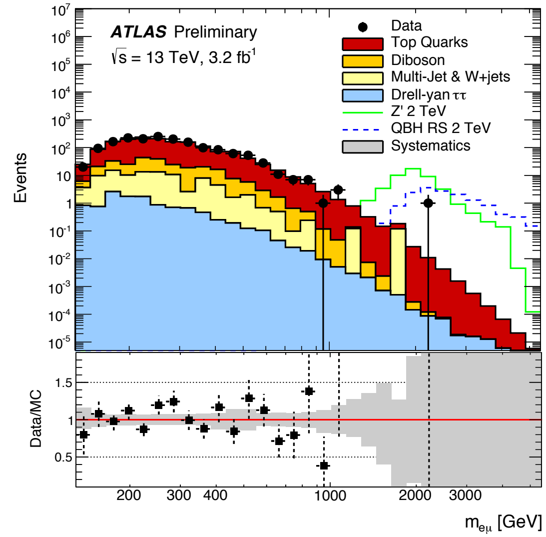
- Excited quarks (e.g. from substructure, KK excitations of quark-gluon resonances, etc.)
  - (Baur, Spira and Zerwas Phys. Rev. D42 (1990) 815)
  - (Bhattacharya, et al Phys. Rev. D80 (2009) 015014)

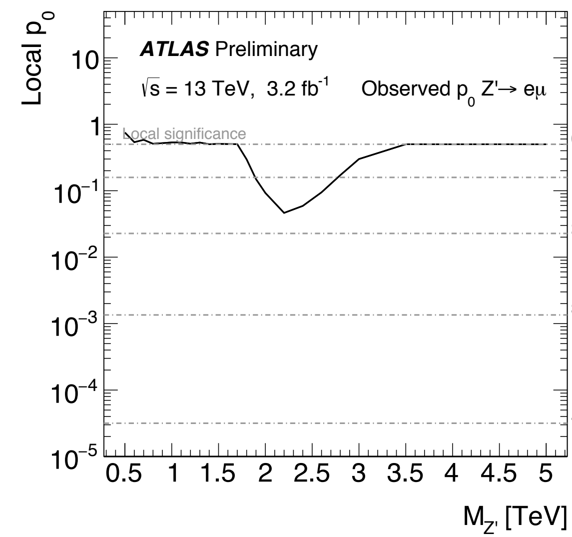
- W' and Z' bosons type depends on final state
  - Sequential Standard Model (SSM)
    - Z' (Langacker Rev.Mod.Phys 81 (2009))1199)
    - W' (Altarelli, Mele, and Ruiz-Altaba Z. Phys. C 45 (1989) 109)
  - Leptophobic (Z' from jets)
    arXiv:1507.00966 [hep-ex] (2015)
  - Z' inspired from GUTS, E6 inspired:
    - London and Rosner, Phys. Rev. D34 (1986) 1530.
    - Langacker, Rev.Mod.Phys 81 (2009))1199.

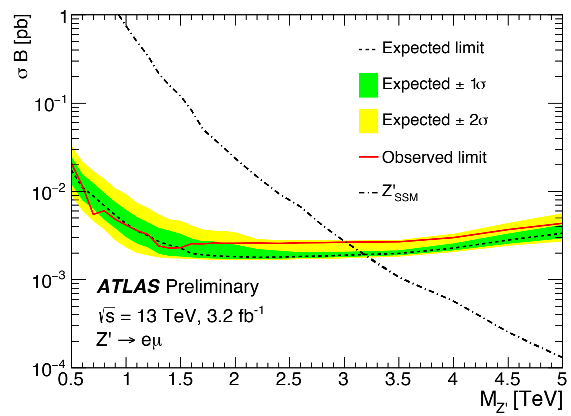
Bench mark models: Reality is probably more interesting

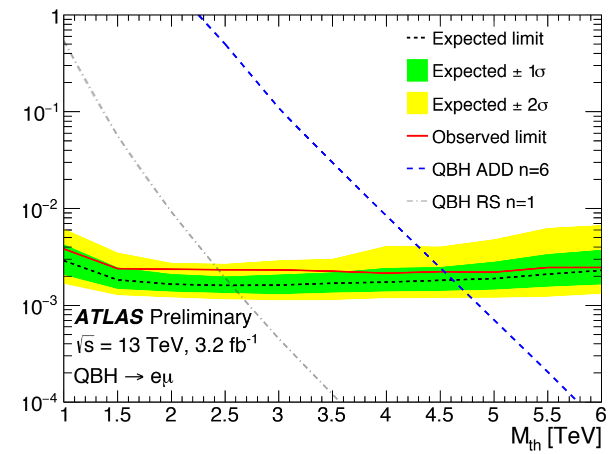
Electron-muon final states

- Resonance in electron-muon final state would be an indictment of the SM
- Background from true leptons is modeled using fits to MC distributions. A data driven measurement of jet→e is used for background from jets
- One event seen in tail, but is not significant
  - Top background dominates
  - Muon resolution spreads signal (and background)
- Limits are shown for Z' and QBH models
- ADD limit 4.6 TeV
  - Branching ratio is small because QBH must be colorless, charge zero
    (http://arxiv.org/pdf/0806.4605v2.pdf)
  - Run 1 Jet+Lepton limit 5.3TeV (PRL 112, 091804)









ATLAS-CONF-2015-072

Background for μe

Process	$m_{e\mu} < 300$ GeV	$300 < m_{e\mu} < 600$ GeV
Top	900 ± 80	404 ± 50
Diboson	116 ± 13	52 ± 7
QCD and W+jets	67 ± 10	17 ± 4
$Z/\gamma^* \to \tau\tau$	9.3 ± 1.3	1.79 ± 0.21
Total background	1092 ± 90	476 ± 50
Data	1164	475

Process	$600 < m_{e\mu} < 1200$ GeV	$1200 < m_{e\mu} < 2000$ GeV
Top	36 ± 4	0.55 ± 0.31
Diboson	2.6 ± 0.4	$(7 \pm 5) \cdot 10^{-3}$
QCD and W+jets	1.0 ± 0.9	0.12 ± 0.35
$Z/\gamma^* \to \tau\tau$	0.13 ± 0.01	$(3.5 \pm 1.4) \cdot 10^{-3}$
Total background	40 ± 4	0.67 ± 0.34
Data	36	0

Process	$2000 < m_{e\mu} < 3000$ GeV	$m_{e\mu} > 3000$ GeV
Top	$(1.7 \pm 3.4) \cdot 10^{-2}$	$(0.3 \pm 2.6) \cdot 10^{-3}$
Diboson	$(4 \pm 6) \cdot 10^{-5}$	$(0.3 \pm 1.5) \cdot 10^{-7}$
QCD and W+jets	0	0
$Z/\gamma^* \to \tau\tau$	$(1.9 \pm 2.6) \cdot 10^{-4}$	$(2 \pm 10) \cdot 10^{-5}$
Total background	$(1.7 \pm 3.4) \cdot 10^{-2}$	$(0.3 \pm 2.7) \cdot 10^{-3}$
Data	1	0

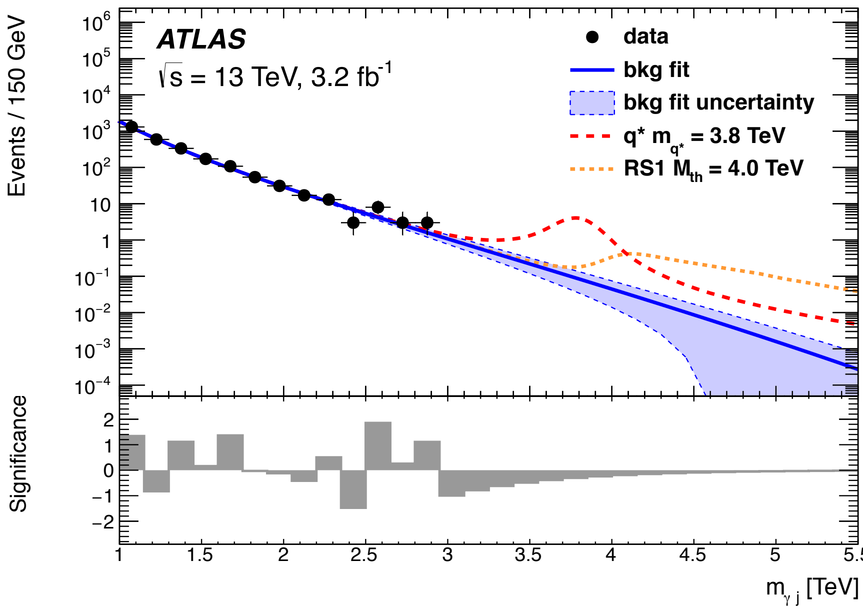
Photon+jet

See YSF talk by Lene Bryngemark

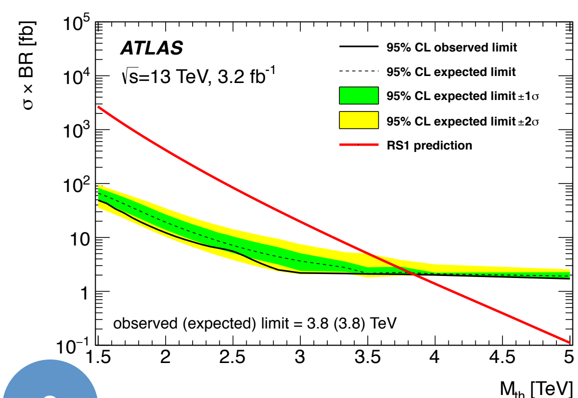
- Use standard fitting function for background:

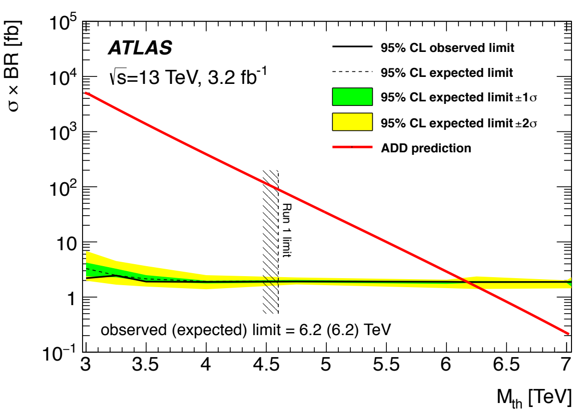
$$f_{\rm bkg}(x \equiv m_{\gamma j}/\sqrt{s}) = p_0(1-x)^{p_1} x^{-p_2-p_3 \log x}$$

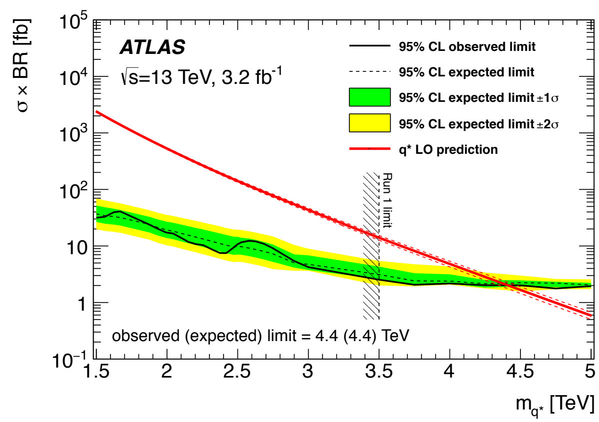
- Likelihood fit to $m_{\gamma j}$ used to extract possible signal
- Models are QBH* and excited quarks, q*
  - ADD (n=6) M_{TH} > 6.2 TeV 95% CL
  - RS (N=1) M_{TH} > 3.8 TeV 95% CL
  - q* M_{q*} > 4.4 TeV 95%CL
- arxiv:1512.05910, accepted by JHEP
- Significant improvement over Run 1, eg ADD limit was 4.6 TeV.



*QBH for photon+jet: Phys.Lett. B668 (2008) 20-23







Di-jet m_{jj}

- Dijets very good for QBH, some sensitivity for q^* and Z', W'
- Search for deviations in m_{jj} for $|y*| < 0.6$
- Background model ($z = m_{jj}/\sqrt{s}$)

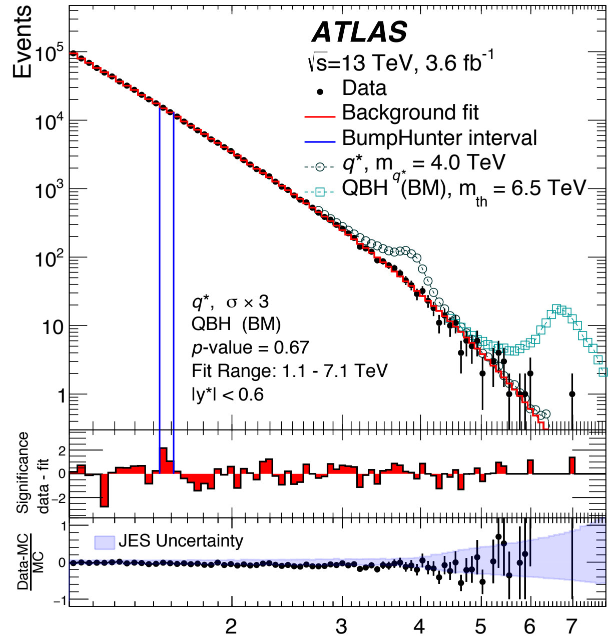
$$f(z) = p_1(1-z)^{p_2} z^{p_3}$$

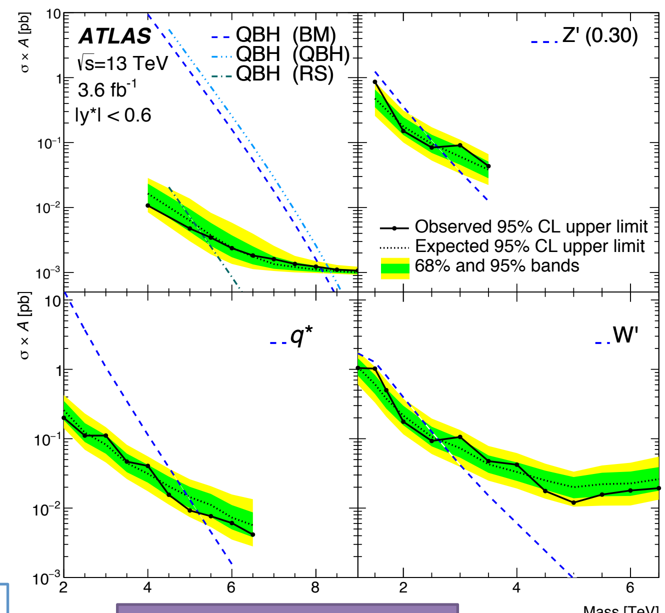
- Background systematic formed by adding terms to model
- Main systematic jet energy scale
- **QBH M_{TH}** limits at 95% CL:

	Run 1	**Obs.**	Expected
ADD(n=6)	5.7 TeV	**8.3 TeV**	8.3 TeV
RS(n=1)		**5.3 TeV**	5.1 TeV

- **q*** limits at 95% CL

	Run 1	**Obs.**	Expected
M_{q^*}	4.1 TeV	**5.2 TeV**	4.9 TeV





[arXiv:1512.01530](https://arxiv.org/abs/1512.01530)
[PLB 754 (2016) 302-322]

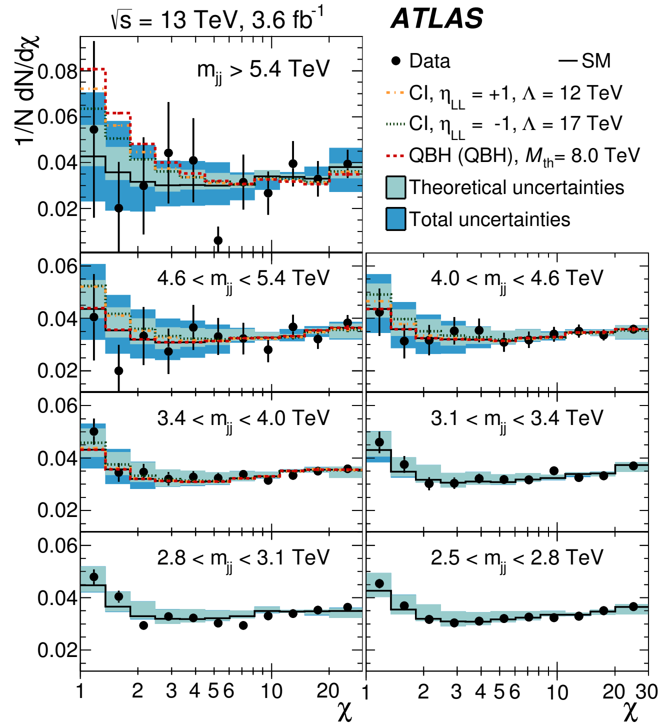
See YSF talk by Lene Bryngemark

Di-jet χ

- Search for deviations in

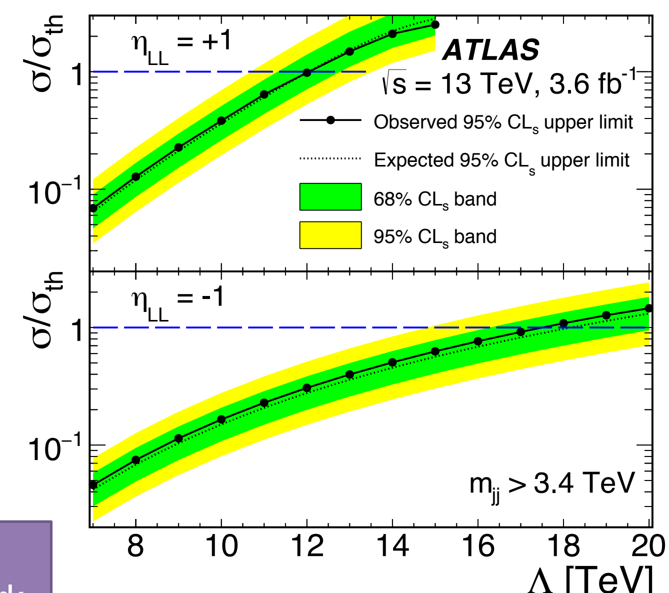
$$\chi = e^{2|y^*|}$$

in bins of in m_{jj}



- Contact interaction limits (95% CL):

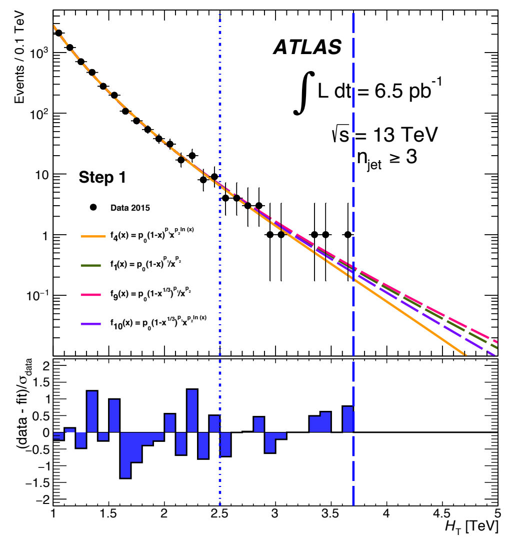
	Run 1 [TeV]	Obs [TeV]	Exp [TeV]
$\eta_{LL} = 1$	8.1	12.0	12.0
$\eta_{LL} = -1$	12.0	17.5	18.1

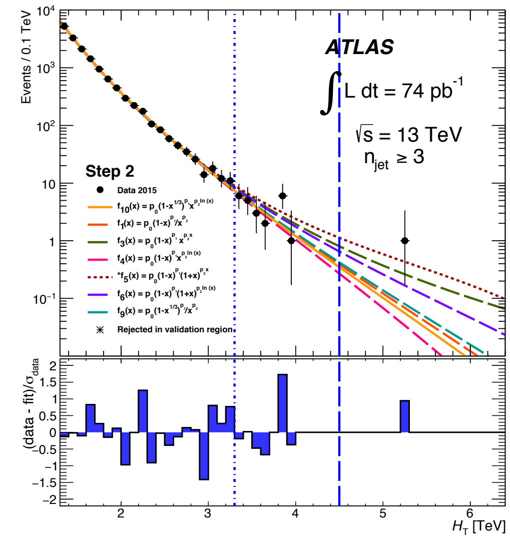


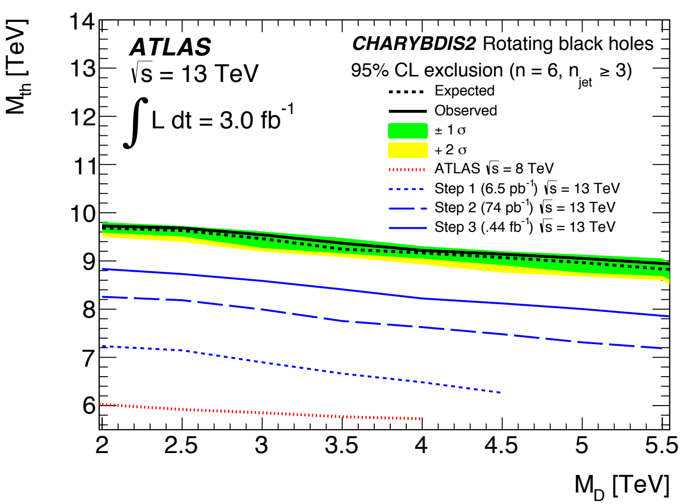
See YSF talk by Lene Bryngemark

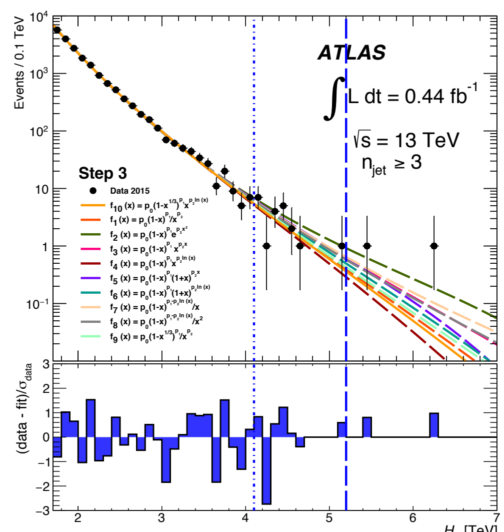
Multi-jet, micro-BH search

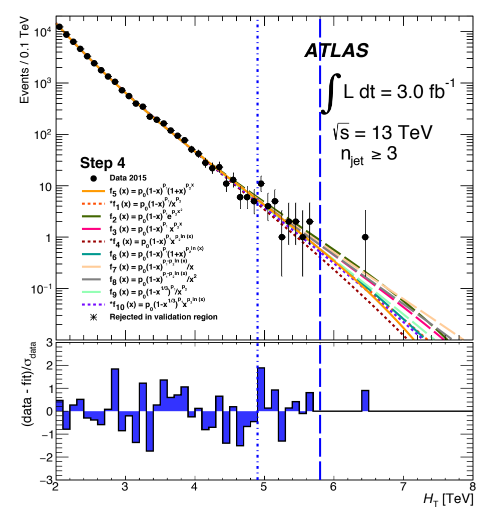
- Extrapolation in H_T extended after each step in luminosity
- Background functions shown on figures
- 95% CL Limits on
  - M_D gravity scale
  - M_{TH} threshold mass







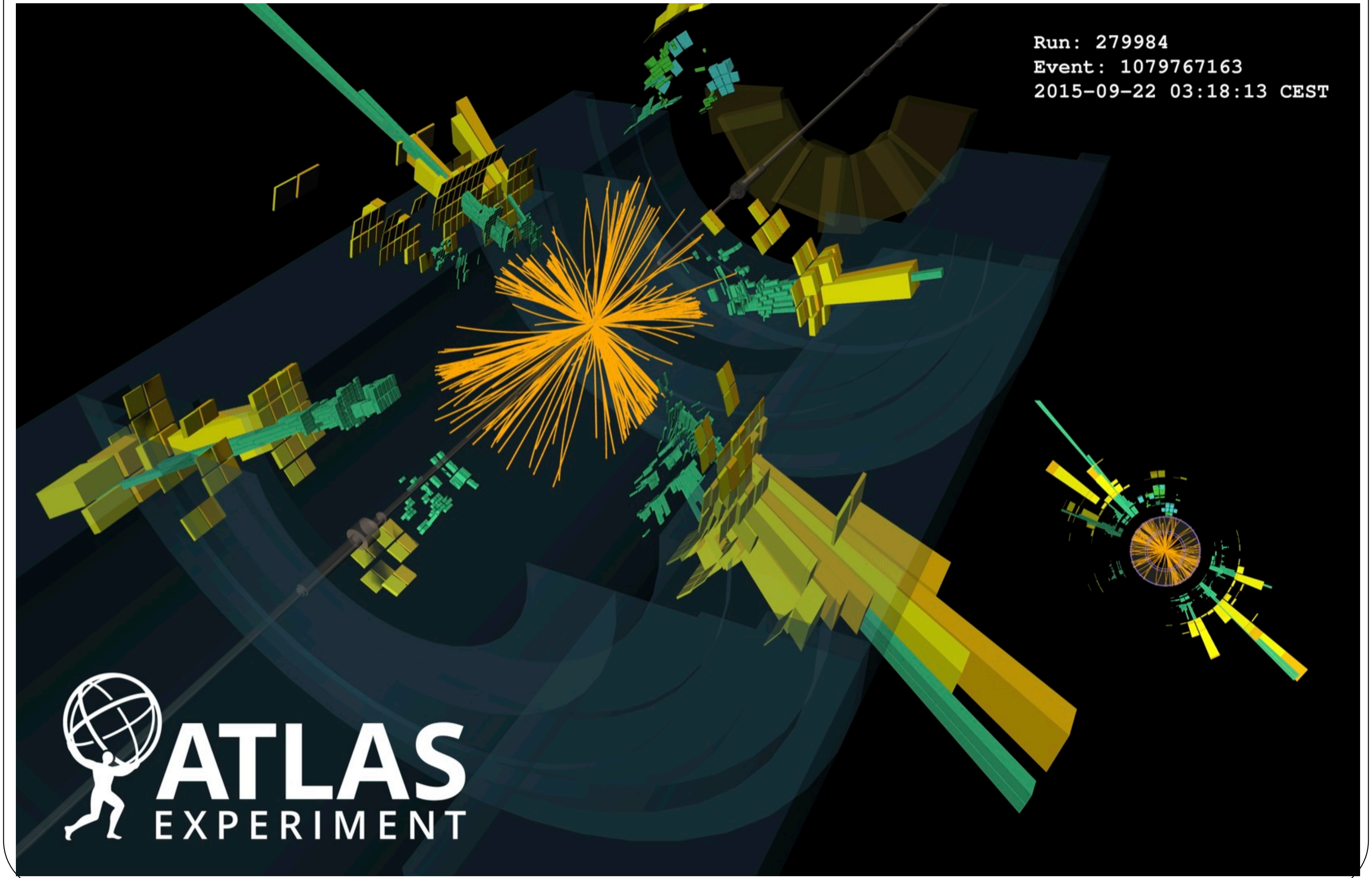




arxiv:1512.02586
Accepted by JHEP

See YSF talk by Lene Bryngemark

Highest mass event:

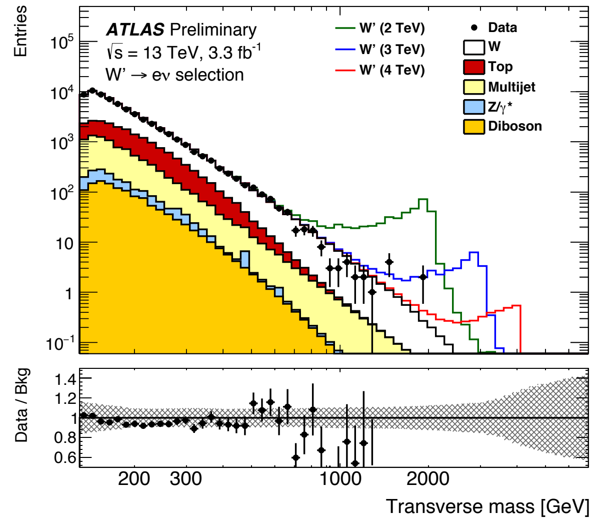


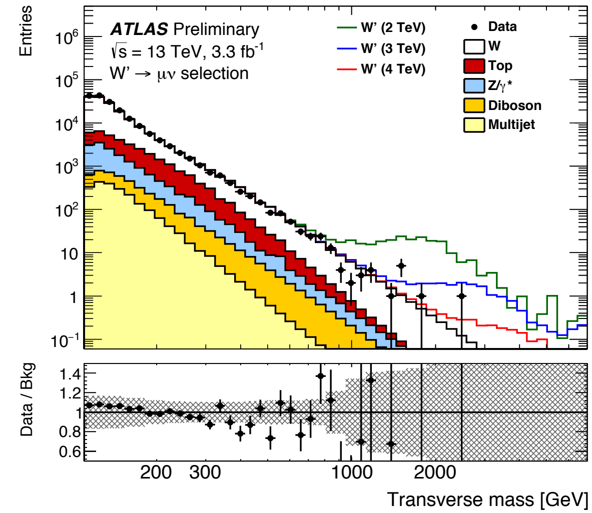
W' (lepton + E_t^{miss})

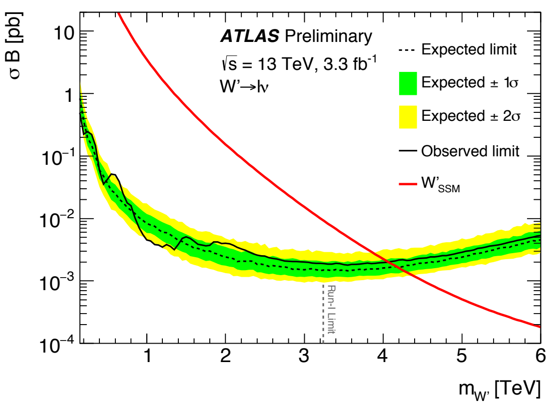
- Leptonic decays:
  W' → e ν
  W' → μ ν

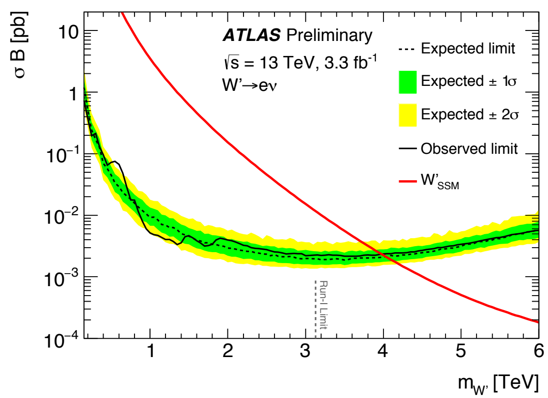
- Background from MC, except multijet (from matrix method)

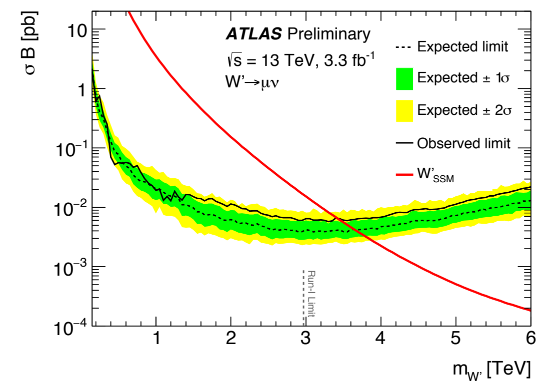
Run 1 [TeV]	Exp [TeV]	Obs [TeV]
3.24	4.18	4.07



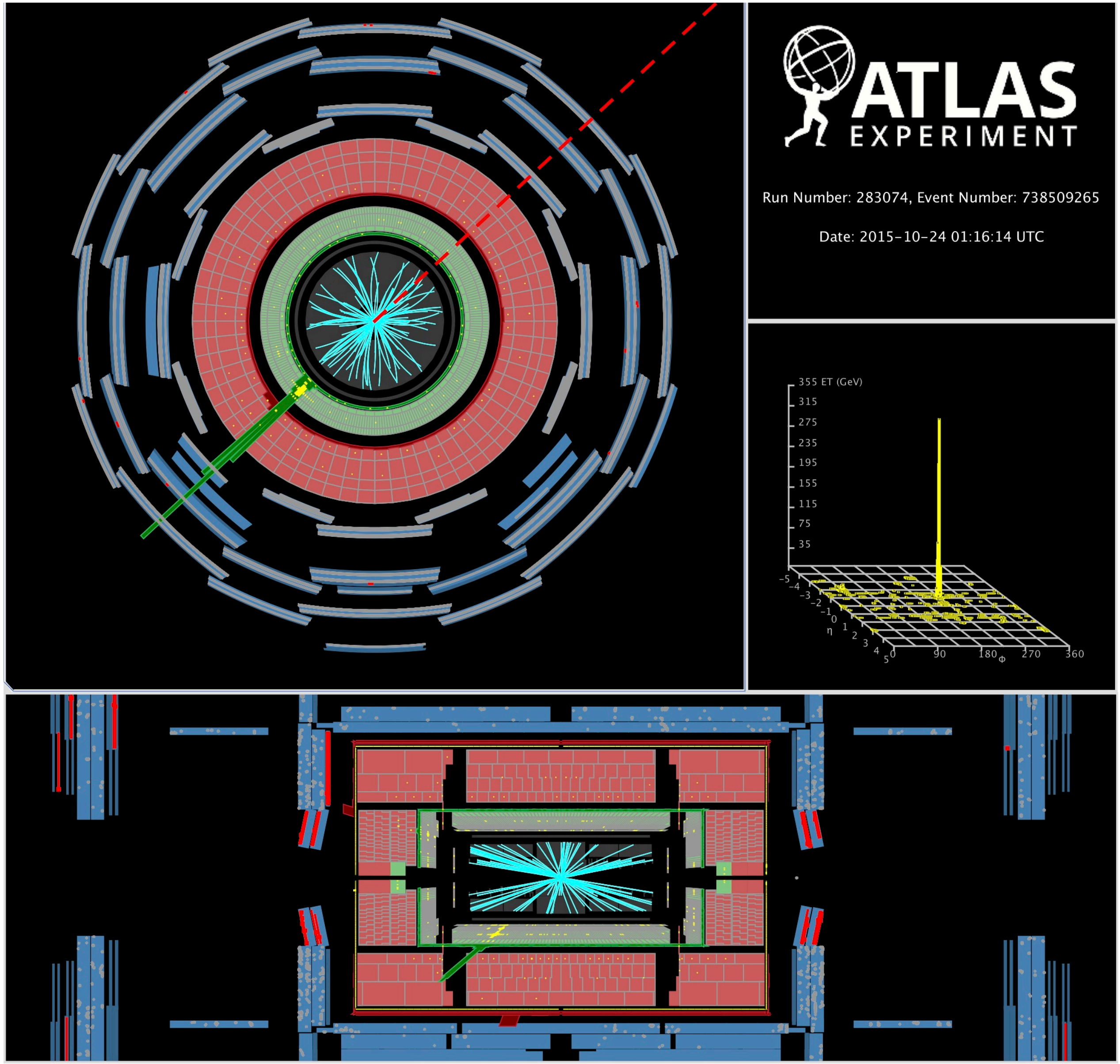




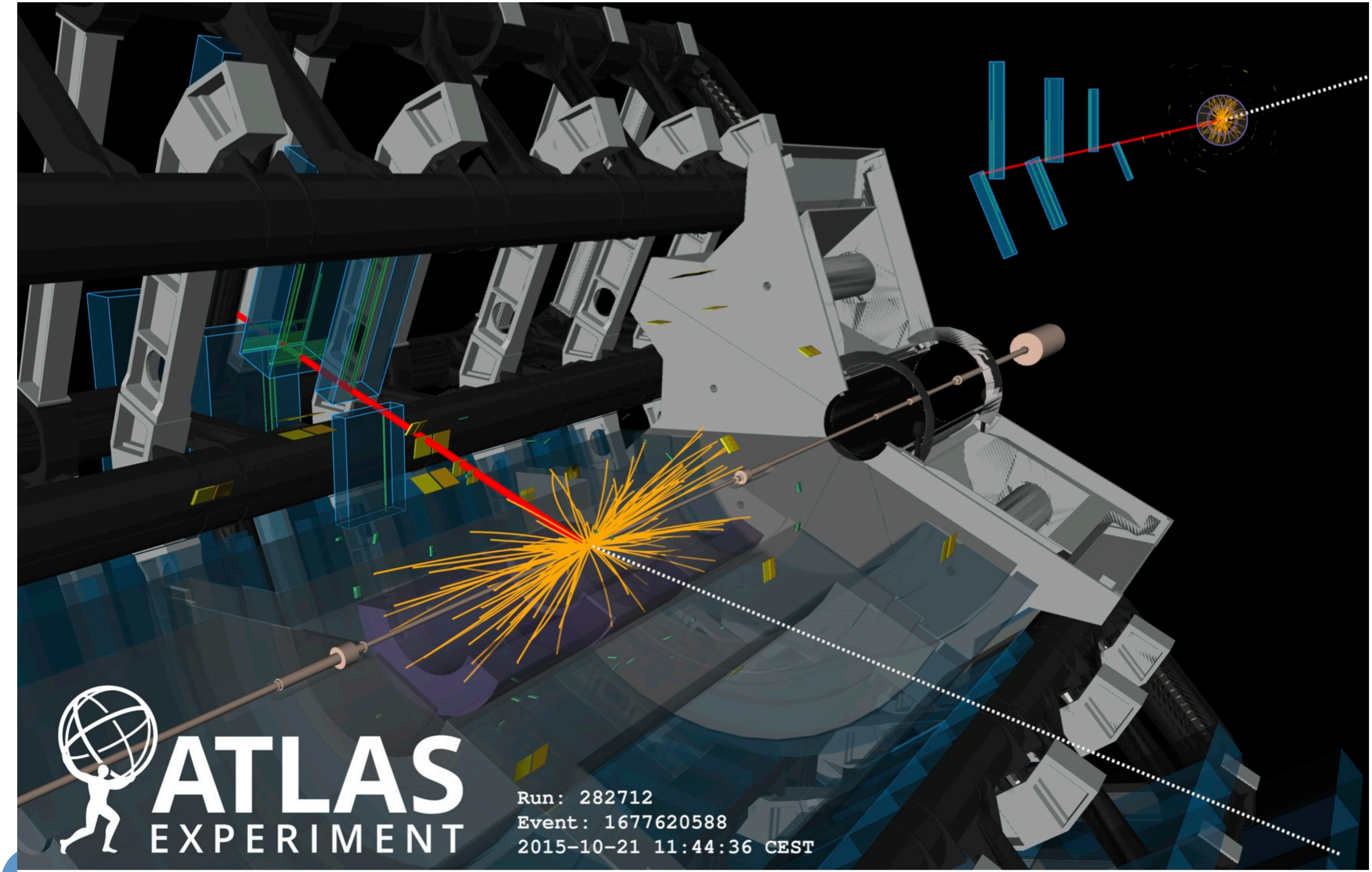




Highest m_T electron event

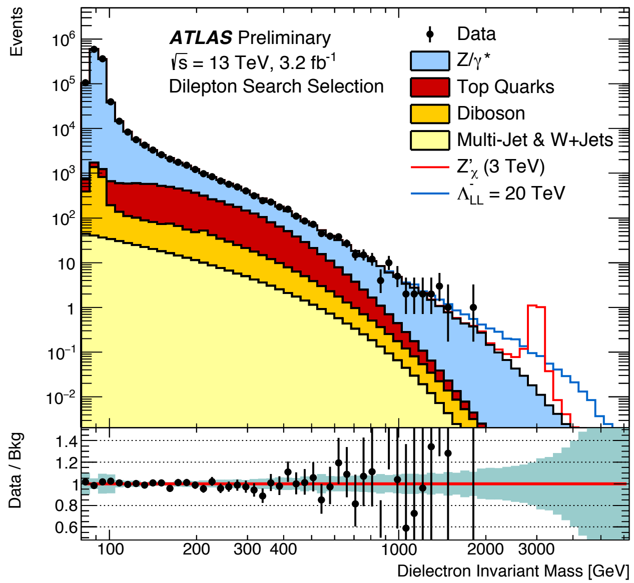


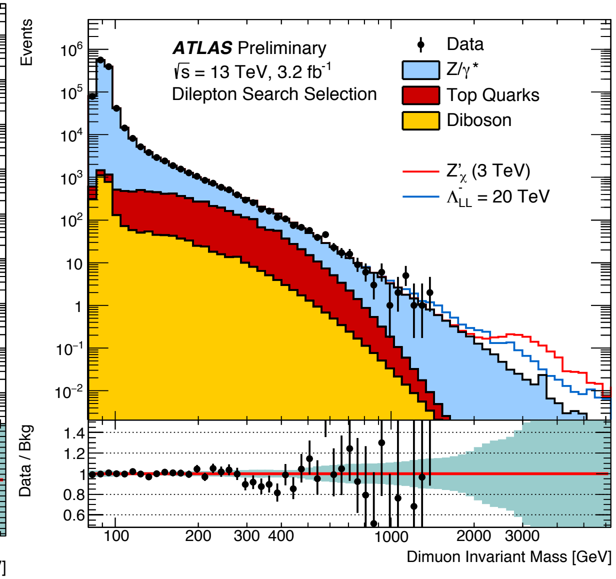
High m_T Muon event

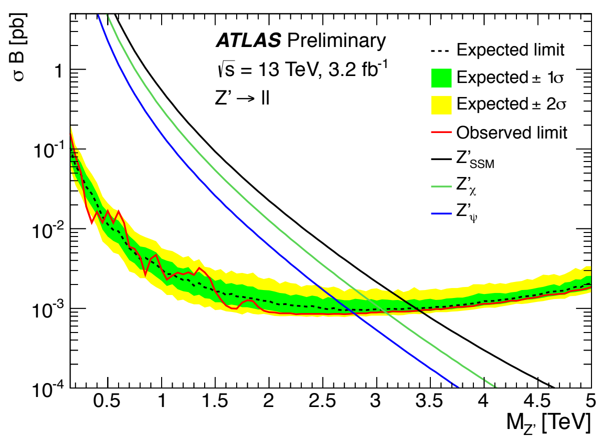


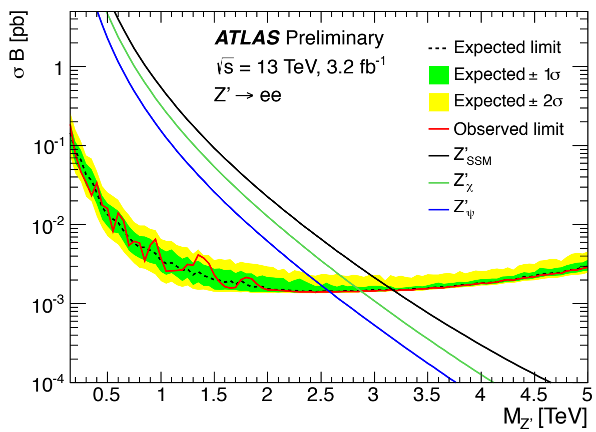
Lepton pairs -- Z' search and CI

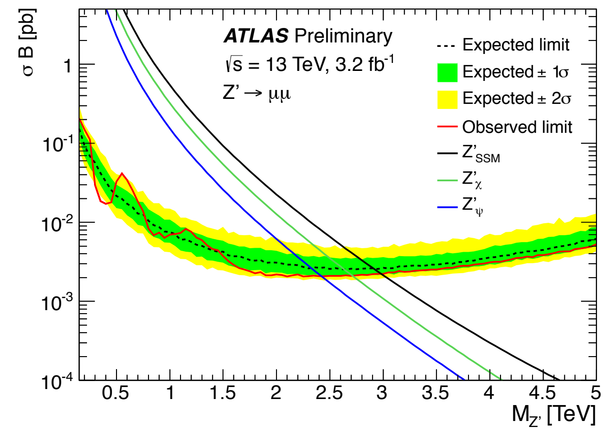
- Leptonic decays:
  $Z' \rightarrow e\, e$
  $Z' \rightarrow \mu\, \mu$
- Careful selection of muons for good resoluton
- MC non-electron background fit to smooth functions.
- Electron background from jets extracted using a matrix method
- Z` limits 2.79 – 3.4 TeV











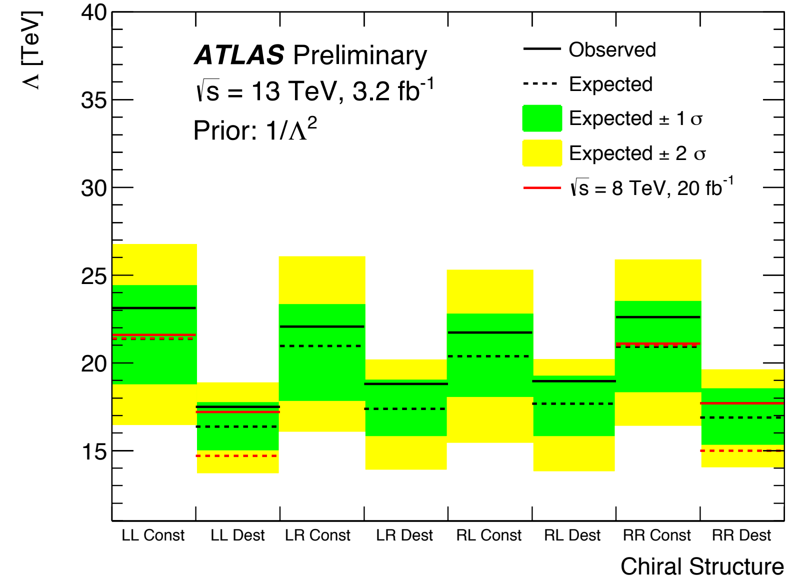
ATLAS-CONF-2015-070

Summary Z' and Contact Interaction limits

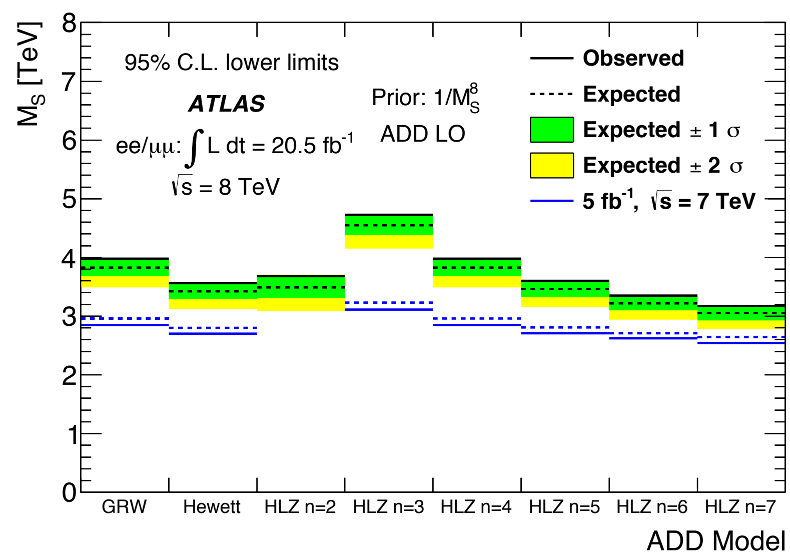
Contact interaction limits are modestly improved over Run 1 data at √s=8TeV

Limits on KK graviton for √s=13 TeV are on the way.

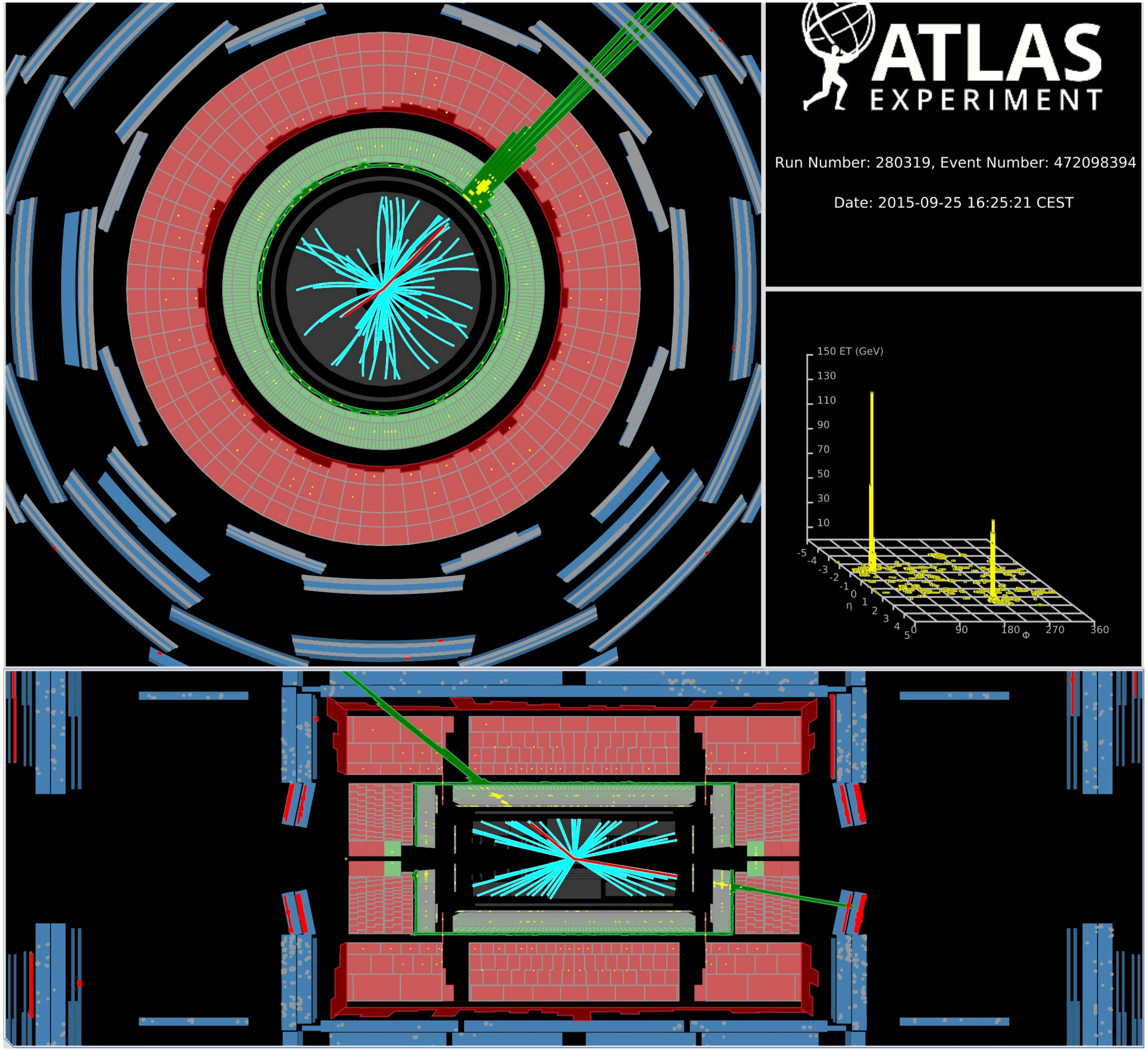
Big improvements are likely with the 2016 data on Contact Interactions and KK gravitons



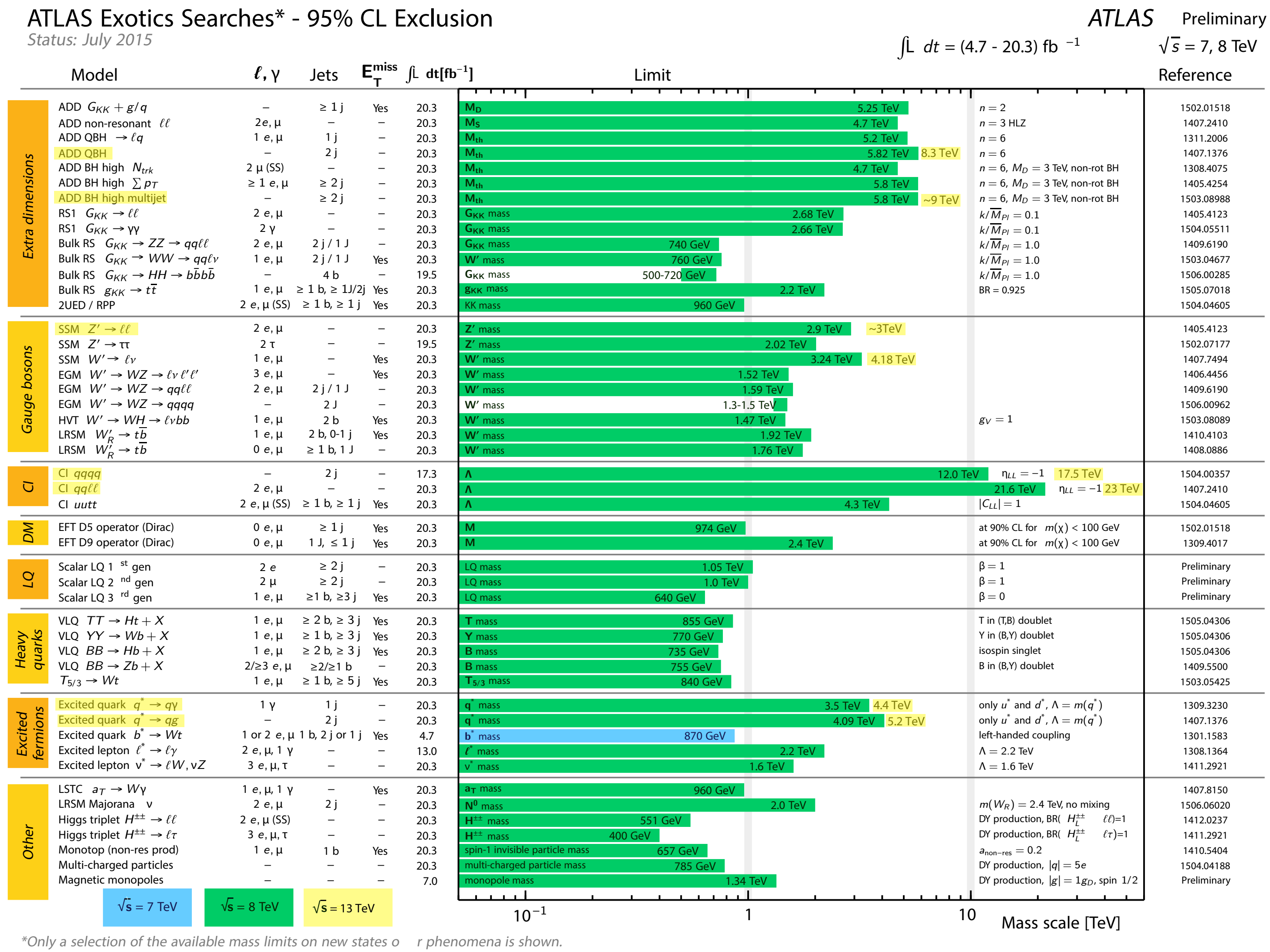
Channel	Prior	Left-Left [TeV]		Left-Right [TeV]		Right-Left [TeV]		Right-Right [TeV]	
		Const.	Destr.	Const.	Destr.	Const.	Destr.	Const.	Destr.
Exp: ee	$1/\Lambda^2$	18.5	15.2	18.1	15.8	17.7	16.1	17.9	15.9
Obs: ee		18.3	15.3	17.6	15.8	17.5	15.9	17.5	15.8
Exp: ee	$1/\Lambda^4$	16.9	14.3	16.6	14.8	16.4	14.8	16.5	14.7
Obs: ee		16.7	14.1	16.2	14.5	16.1	14.6	16	14.6
Exp: $\mu\mu$	$1/\Lambda^2$	18.2	14.5	17.5	15.1	17.4	15.4	18.1	14.5
Obs: $\mu\mu$		20.2	15.8	19.7	17.0	19.4	17.1	20.4	15.8
Exp: $\mu\mu$	$1/\Lambda^4$	16.6	13.8	16.3	14.4	16.1	14.5	16.6	13.9
Obs: $\mu\mu$		18.1	15.0	17.7	15.8	17.4	15.9	18.1	15.0
Exp: $\ell\ell$	$1/\Lambda^2$	21.4	16.4	21.0	17.4	20.4	17.7	20.9	16.9
Obs: $\ell\ell$		23.1	17.5	22.1	18.8	21.7	19.0	22.6	17.7
Exp: $\ell\ell$	$1/\Lambda^4$	19.9	15.6	19.0	16.6	18.7	16.6	19.4	16.0
Obs: $\ell\ell$		20.7	16.4	20.0	17.5	19.8	17.6	20.3	16.6



Di-electron event



Summary of 7 and 8 TeV results



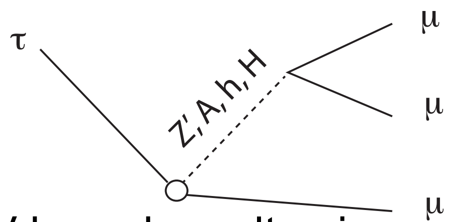
13 TeV updates this talk

Many more exotics results coming soon at 13 TeV

See also results on dibosons from D. Lopez and γγ from C. Ohm

$\tau \rightarrow \mu^- \mu^+ \mu^-$

- Probes LFV, e.g.



- 8 TeV based result using

  $W \rightarrow \tau \nu$

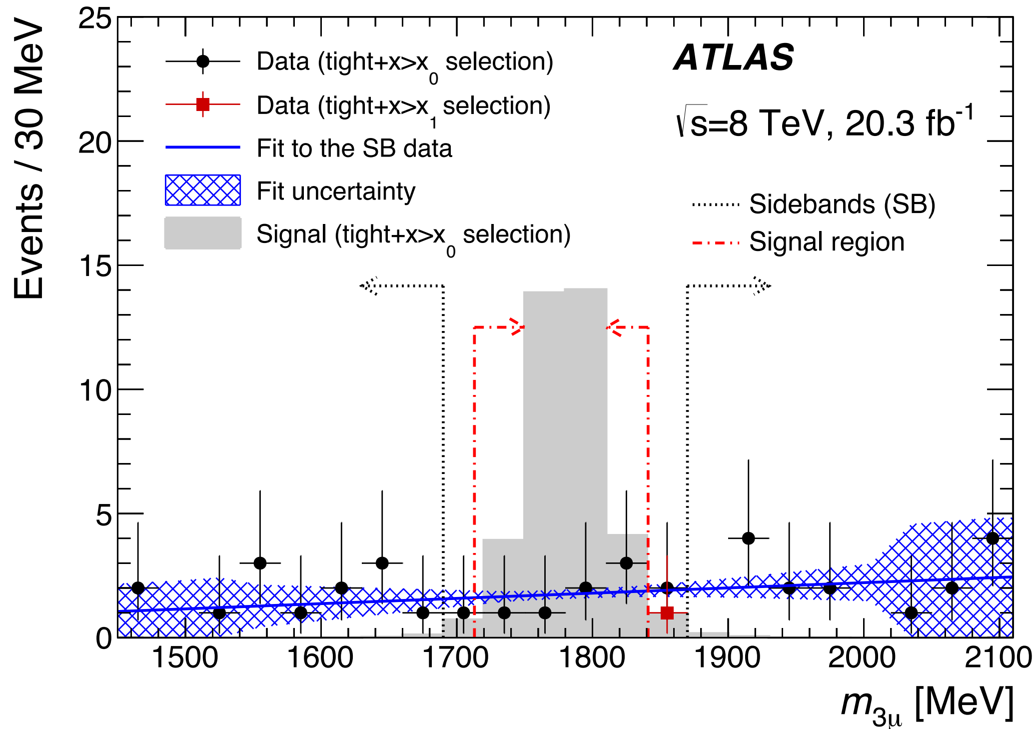
- Acceptance mainly a trigger issue, due to overlap removal, will be improved in future

- ATLAS result

$Br(\tau^- \rightarrow \mu^- \mu^+ \mu^-) < 3.76 \times 10^{-7}$

- PDG (mainly Belle)

$Br(\tau^- \rightarrow \mu^- \mu^+ \mu^-) < 2.1 \times 10^{-8}$

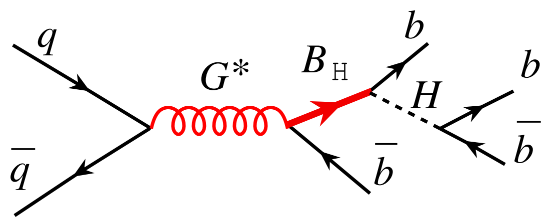


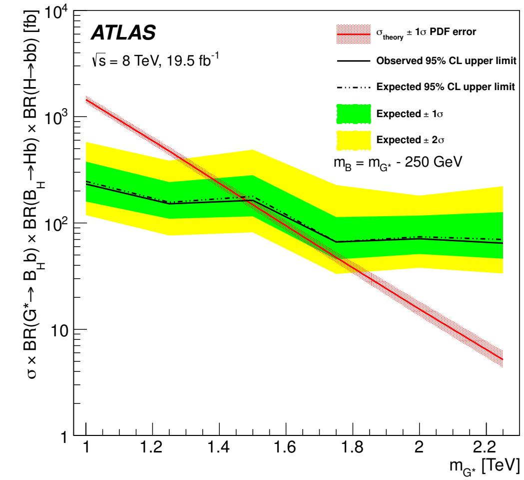
BDT based analysis submitted for publication
http://arxiv.org/pdf/1601.03567.pdf

Only one event survives after the tight selection and it is outside of signal region

Vector like quarks at 8 TeV

- Vector-like quarks can arise in composite Higgs models

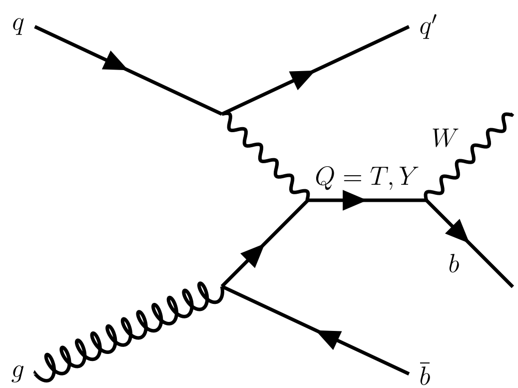


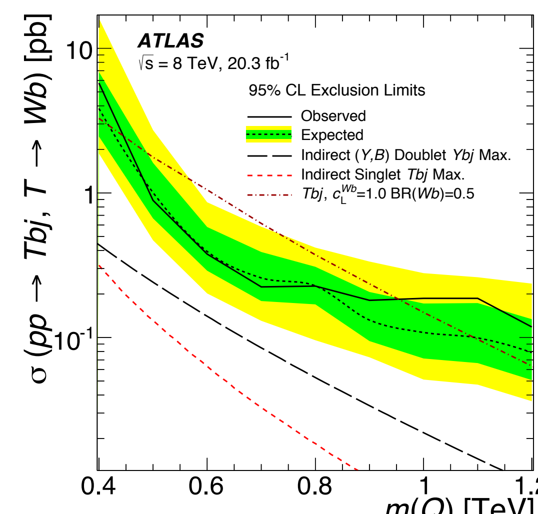


- Boosted jet techniques used

http://arxiv.org/abs/1602.06034

- Two √s =8 TeV results have been recently submitted for publishication

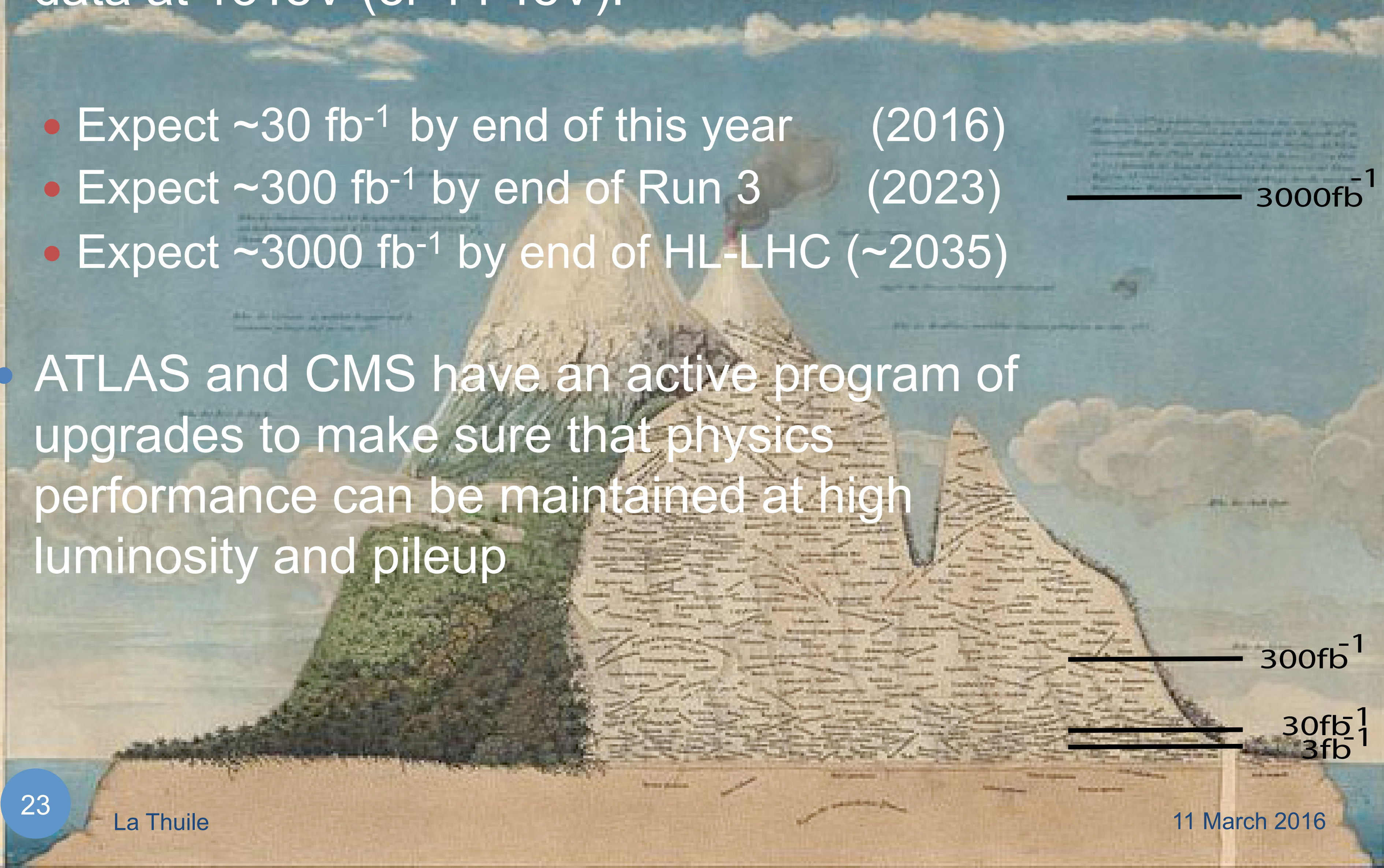




, http://arxiv.org/abs/1602.05606

Exotics Outlook

- Many processes only interesting with more data at 13TeV (or 14 TeV):
  - Expect ~30 fb^{-1} by end of this year (2016)
  - Expect ~300 fb^{-1} by end of Run 3 (2023)
  - Expect ~3000 fb^{-1} by end of HL-LHC (~2035)
- ATLAS and CMS have an active program of upgrades to make sure that physics performance can be maintained at high luminosity and pileup

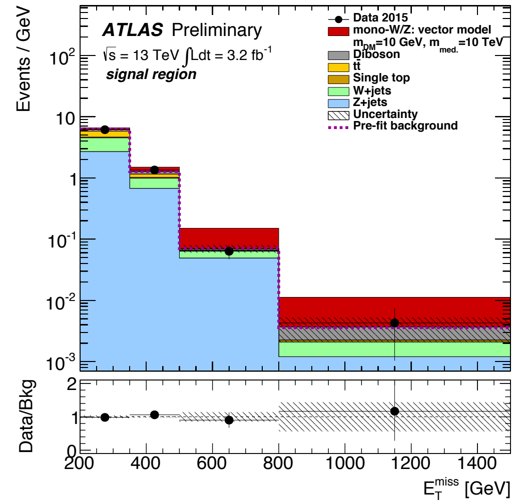


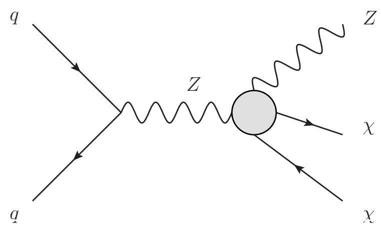
Backup

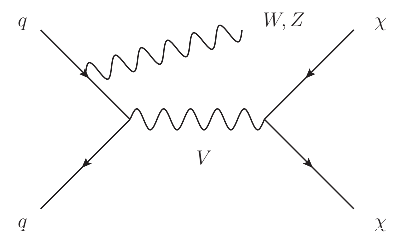
Mono- W and Z

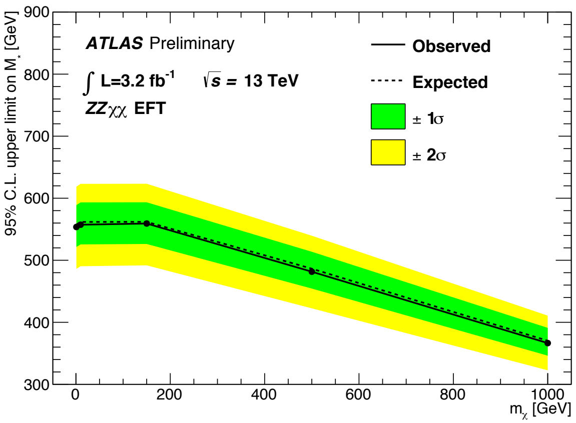
- Hadronically decaying W and Z recoiling against DM
- Two models considered:
  - Effective Field Theory: M_{*}, $m\chi$
  - Vector Mediated simplified model, m_{med}, $m\chi$, μ
- Signature is a large-R jet with missing energy
- Large R boosted techniques described by D. Lopez

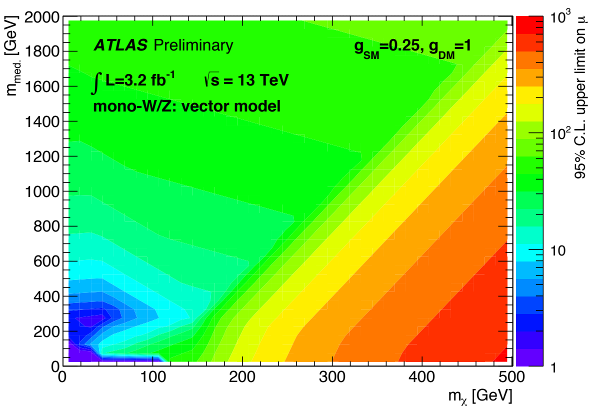
Background dominated by Z + jets and W + jets





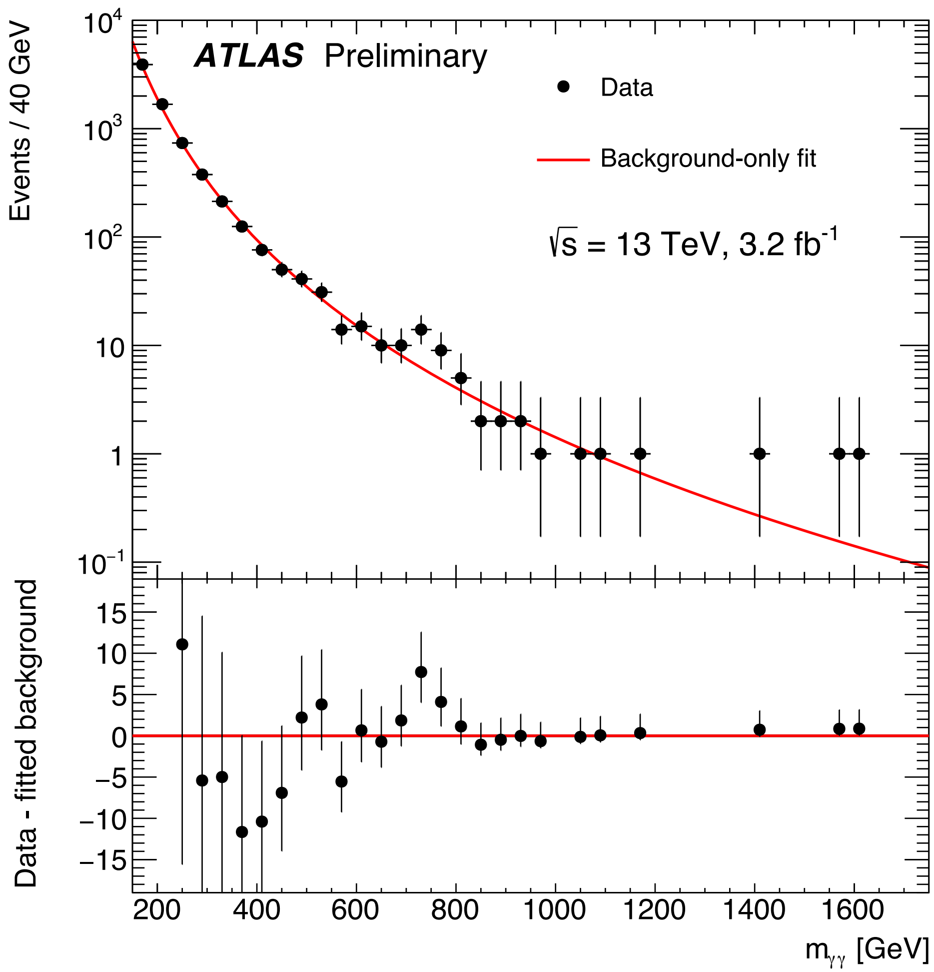


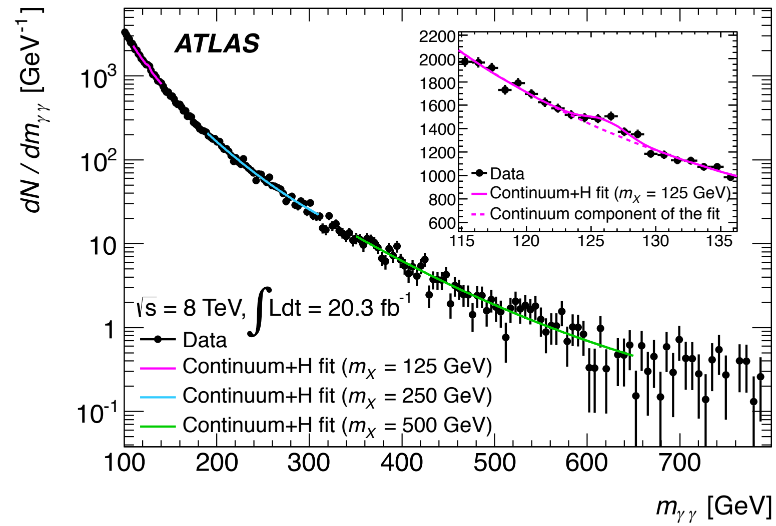




Follows DM form recommendation: http://arxiv.org/abs/1507.00966

750 GeV Photon Pair





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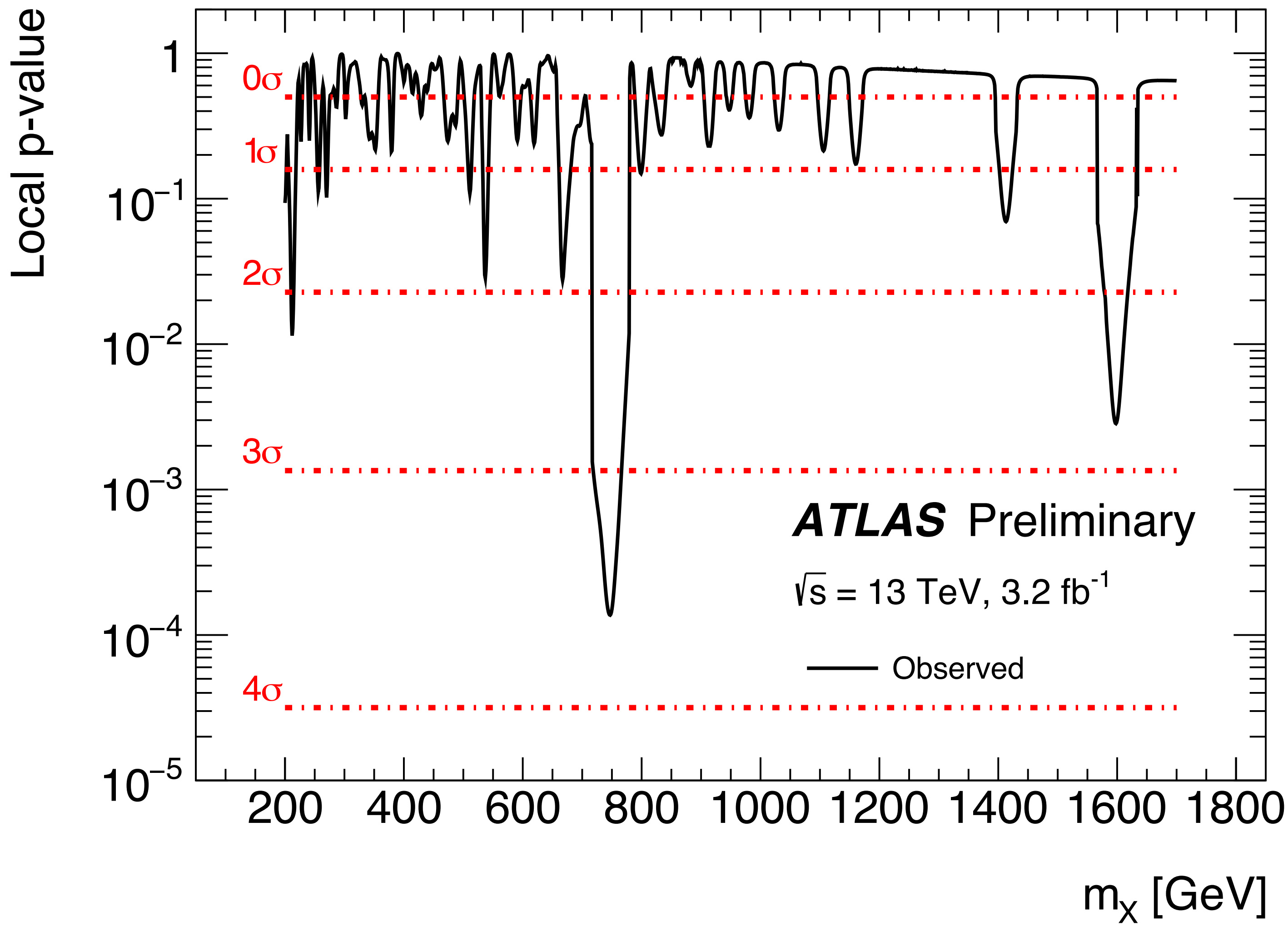
$$E_T^{iso} > 0.022E^\gamma + 2.45GeV$$
$$p_T^{iso} > 0.05E_T^\gamma$$

$$E_T^{\gamma 1}/m_{\gamma\gamma} > 0.4$$
$$E_T^{\gamma 2}/m_{\gamma\gamma} > 0.3$$

M ≈ 750 GeV
α ≈ 6% (Γ ≈ 45 GeV)

Photon pair significance



Assumes narrow width approximation, global significance ~2σ
Local significance increases by 0.3 with variable width fit