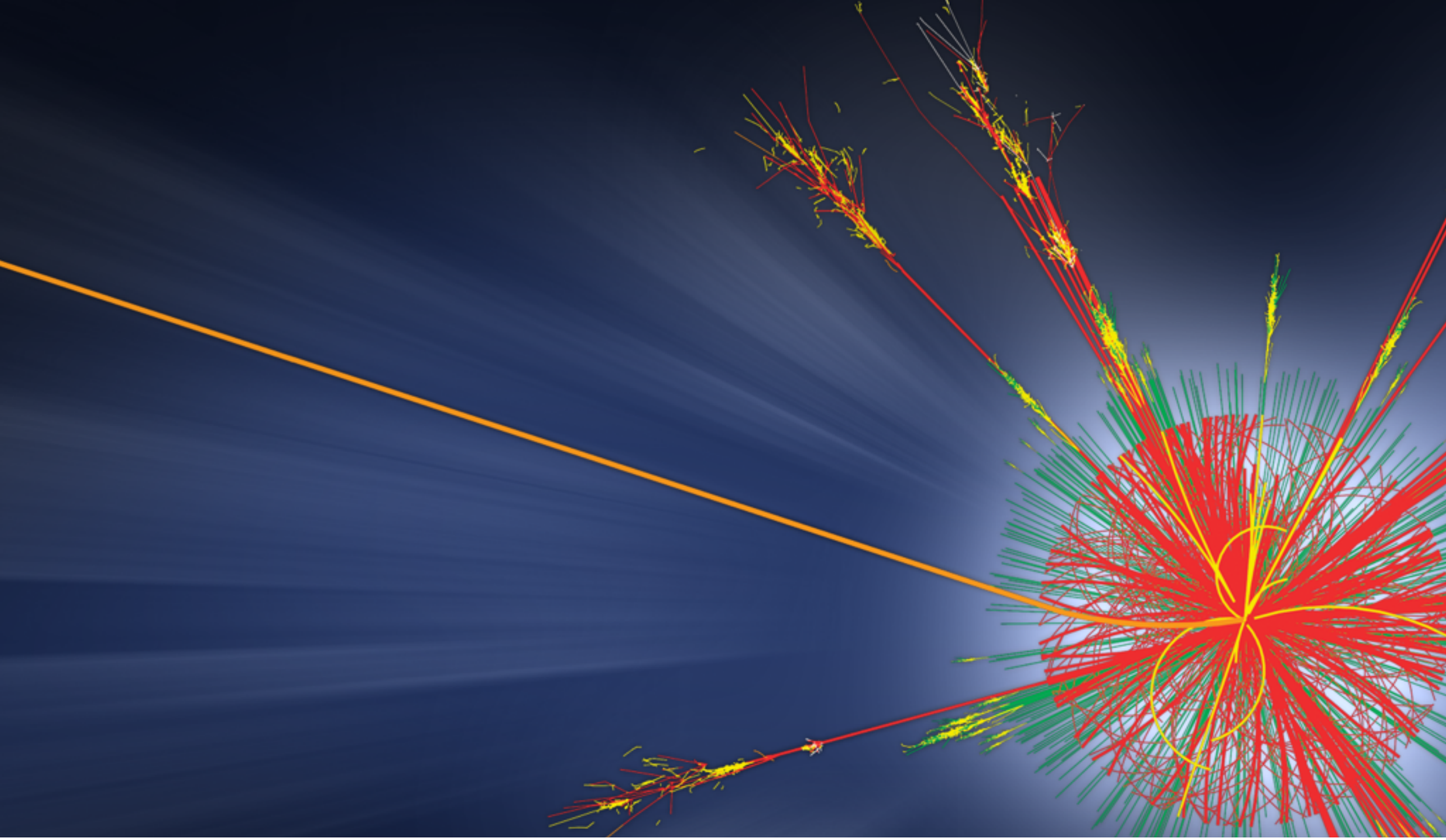


Searches for new exotic phenomena at the LHC

Kate Pachal
for the ATLAS and CMS collaborations
ICNFP 2016

Introduction

The Standard Model has so far done remarkably well at withstanding experimental tests

- Higgs discovery of 2012 marked last piece of the SM
- No meaningful deviations from SM predictions observed by end of Run I

But many questions indicate there must still be new physics beyond the Standard Model!

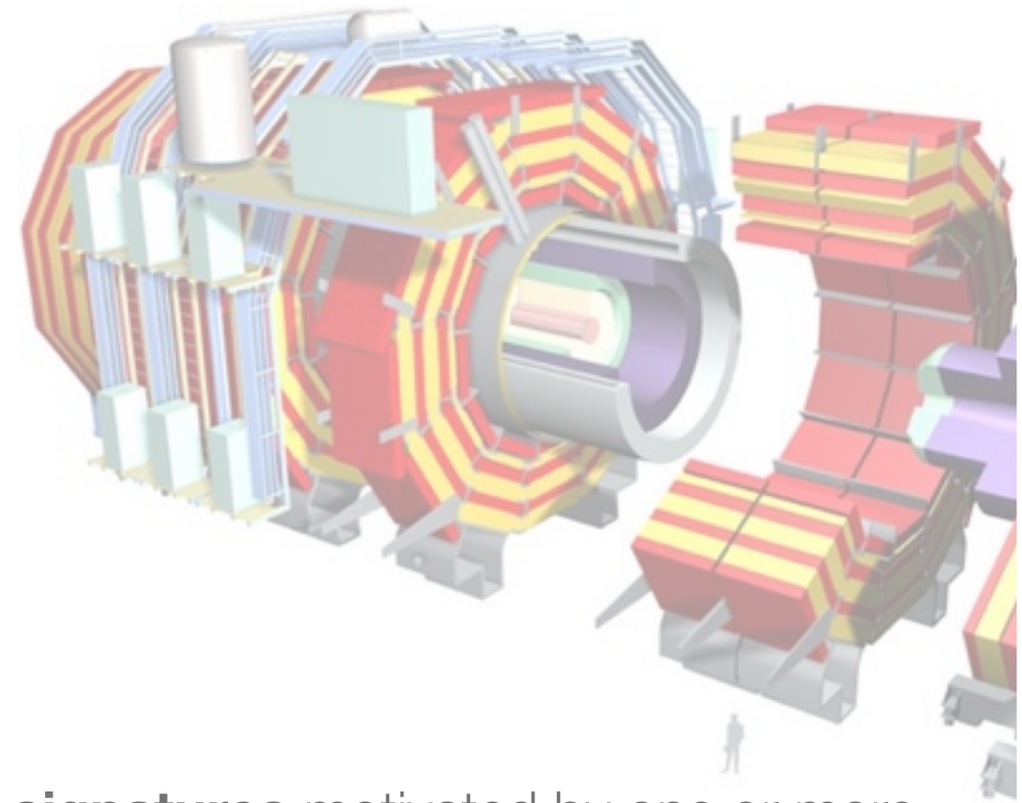
Dark matter	What is it? Is it a particle?
Hierarchy problem	Why is gravity so weak? Can extra dimensions explain it?
Gauge unification	Is there a unified theory connecting fundamental forces?
Higgs fine-tuning	How do we account for large, fine-tuned Higgs mass corrections?
....	Why 3 generations? Why 4 forces? Matter-antimatter asymmetry?

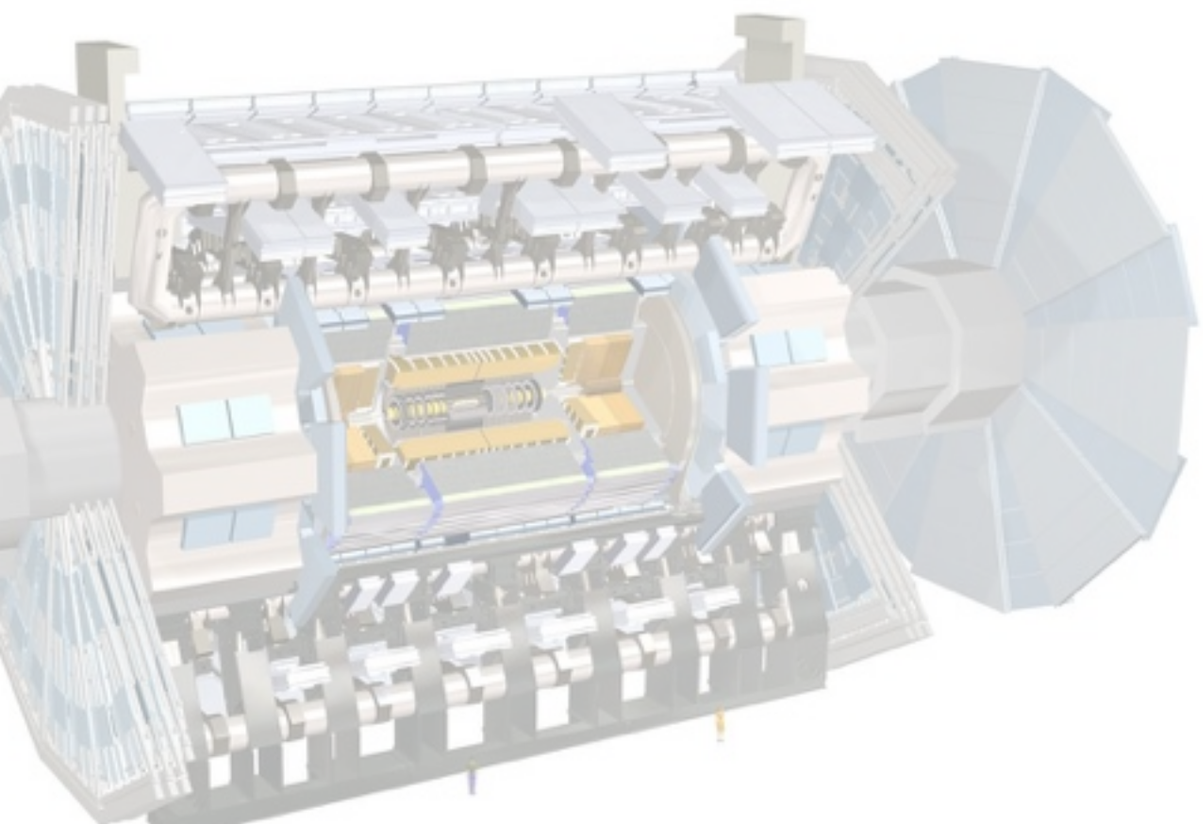
Searching for BSM physics with ATLAS and CMS

- Two **all-purpose detectors** at the LHC allow examination of any high-energy final state

- Enormous overlap between models and signatures, with each final state corresponding to numerous theories and vice versa

- To ensure we don't miss anything, focus on signatures in broad classes of analyses and search for any signs of deviation from a SM prediction





- Select **signatures** motivated by one or more theories

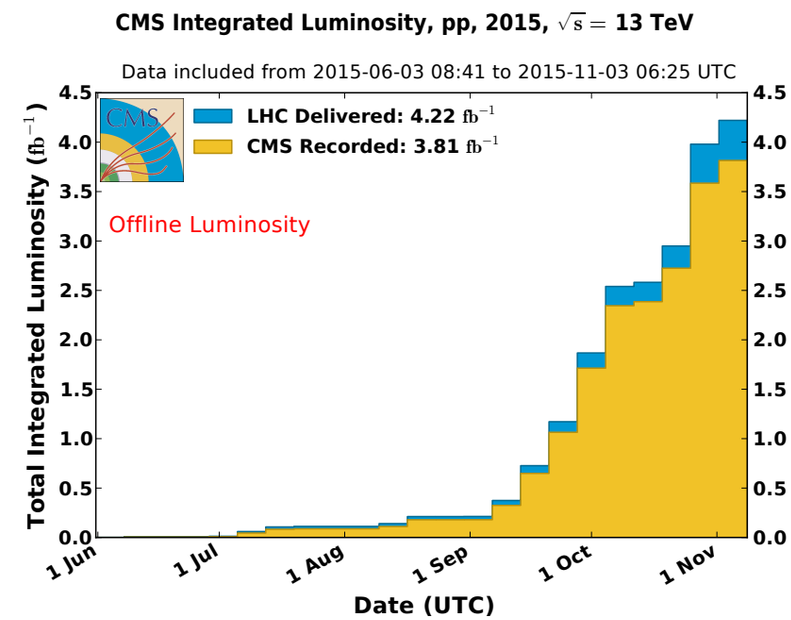
- Use handful of **benchmark models** to define limits on mass or cross section of possible new particles

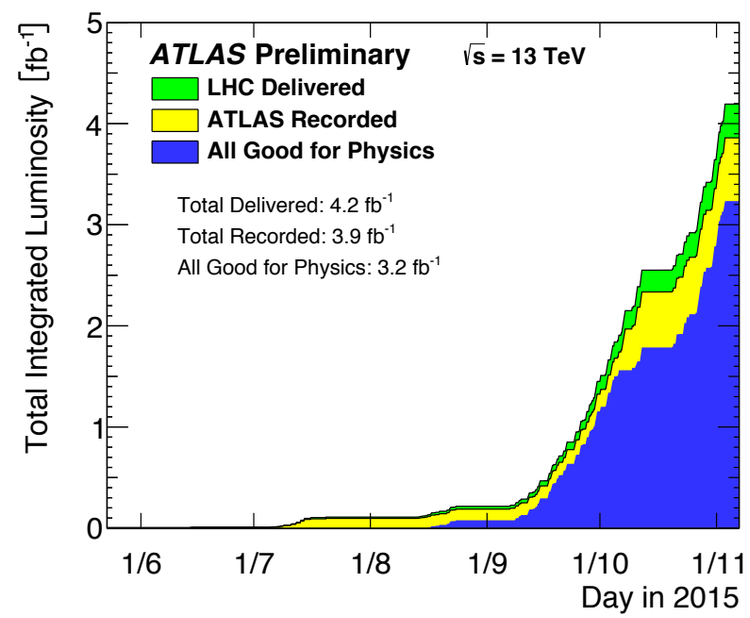
- Today: searches for (non-SUSY) physics **beyond the Standard Model** in 13 TeV data

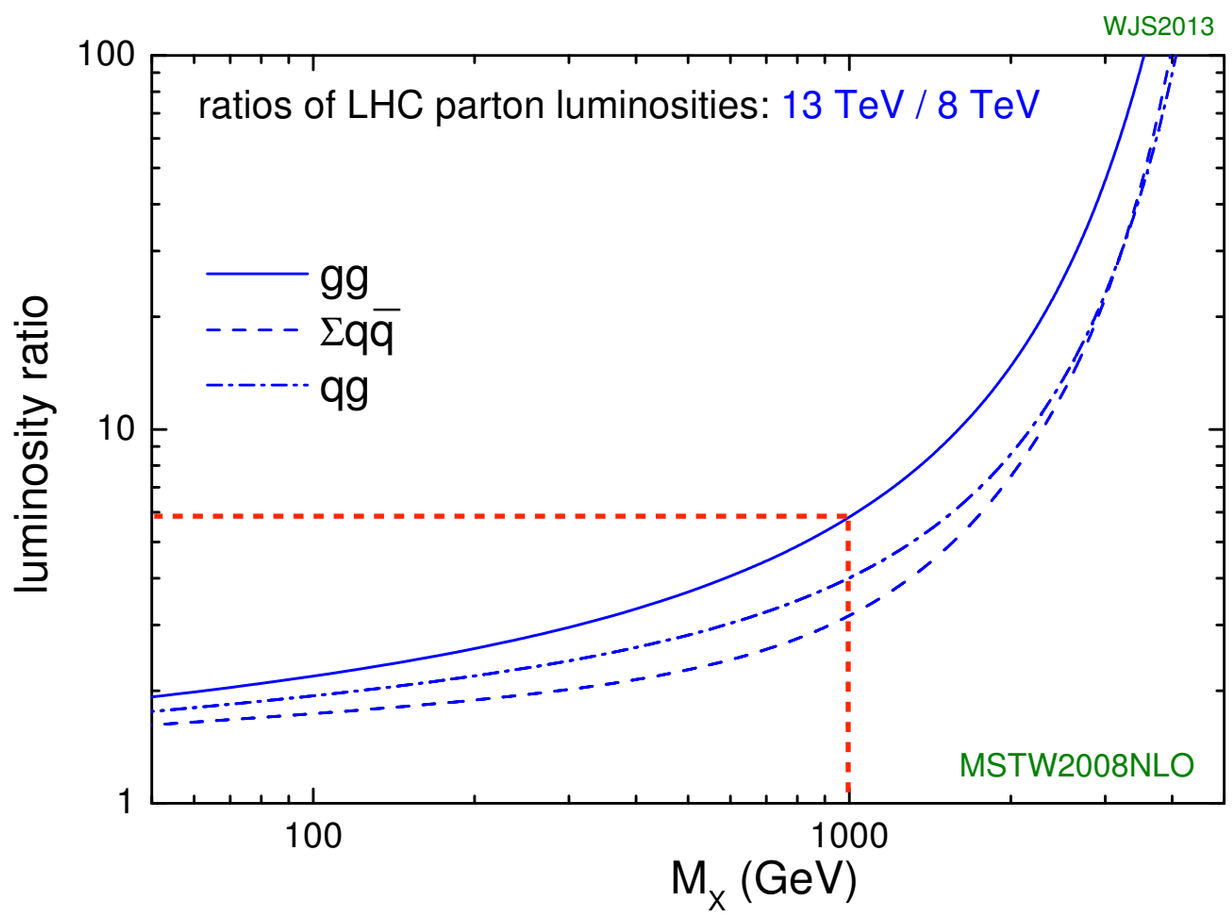
The 2015 data-taking period

Integrated luminosity delivered: 4.2/fb

- ATLAS Recorded: 3.9/fb (IBL on: 3.2/fb)
- CMS Recorded: 3.8/fb (toroid on: 2.7/fb)







Since cross-section increase over Run I corresponds to dramatic increase in parton luminosities at high mass, sensitivity to exotic signatures improves even with much less than the 20/fb of luminosity used in 2012

ADD $G_{KK} + g/q$	–	≥ 1 j	Yes	20.3	M_D	5.25 TeV	$n = 2$
ADD non-resonant $\ell\ell$	$2e, \mu$	–	–	20.3	M_S	4.7 TeV	$n = 3$ HLZ
ADD QBH $\to \ell q$	$1\ e, \mu$	1 j	–	20.3	M_{th}	5.2 TeV	$n = 6$
ADD QBH	–	2 j	–	20.3	M_{th}	5.82 TeV	$n = 6$
ADD BH high N_{trk}	$2\ \mu$ (SS)	–	–	20.3	M_{th}	4.7 TeV	$n = 6$, $M_D = 3$ TeV, non-ro
ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	20.3	M_{th}	5.8 TeV	$n = 6$, $M_D = 3$ TeV, non-ro
ADD BH high multijet	–	≥ 2 j	–	20.3	M_{th}	5.8 TeV	$n = 6$, $M_D = 3$ TeV, non-ro
RS1 $G_{KK} \to \ell\ell$	$2\ e, \mu$	–	–	20.3	G_{KK} mass	2.68 TeV	$k/\overline{M}_{Pl} = 0.1$
RS1 $G_{KK} \to \gamma\gamma$	$2\ \gamma$	–	–	20.3	G_{KK} mass	2.66 TeV	$k/\overline{M}_{Pl} = 0.1$
Bulk RS $G_{KK} \to ZZ \to qq\ell\ell$	$2\ e, \mu$	2 j / 1 J	–	20.3	G_{KK} mass	740 GeV	$k/\overline{M}_{Pl} = 1.0$
Bulk RS $G_{KK} \to WW \to qq\ell\nu$	$1\ e, \mu$	2 j / 1 J	Yes	20.3	W' mass	760 GeV	$k/\overline{M}_{Pl} = 1.0$
Bulk RS $G_{KK} \to HH \to b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass	500-720 GeV	$k/\overline{M}_{Pl} = 1.0$
Bulk RS $g_{KK} \to t\bar{t}$	$1\ e, \mu$	≥ 1 b, $\geq$ 1J/2j	Yes	20.3	g_{KK} mass	2.2 TeV	BR = 0.925
2UED / RPP	$2\ e, \mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	20.3	KK mass	960 GeV	
SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	20.3	Z' mass	2.9 TeV	
SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	19.5	Z' mass	2.02 TeV	
SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	20.3	W' mass	3.24 TeV	
EGM $W' \to WZ \to \ell\nu\ \ell'\ell'$	$3\ e, \mu$	–	Yes	20.3	W' mass	1.52 TeV	
EGM $W' \to WZ \to qq\ell\ell$	$2\ e, \mu$	2 j / 1 J	–	20.3	W' mass	1.59 TeV	
EGM $W' \to WZ \to qqqq$	–	2 J	–	20.3	W' mass	1.3-1.5 TeV	
HVT $W' \to WH \to \ell\nu bb$	$1\ e, \mu$	2 b	Yes	20.3	W' mass	1.47 TeV	$g_V = 1$
LRSM $W'_R \to t\bar{b}$	1 e, μ	2 b, 0-	–	20.3	W'_R mass	1.92 TeV	
LRSM $W'_R \to t\bar{t}$	0 e, μ	$\geq$ [illegible]	–	20.3	W'_R mass	1.76 TeV	
CI $qqqq$	–	2 j	–	17.3	Λ	12.0 TeV	$\eta_{LL} = -1$
CI $qq\ell\ell$	–	–	–	20.3	Λ	21.6 TeV	$\eta_{LL} = -1$
CI $uutt$	$2\ e, \mu$ (SS)	≥ 1 b, $\geq$ [illegible]	Yes	20.3	Λ	4.3 TeV	$\lvert C_{LL}\rvert = 1$
EFT D5 operator (Dirac)	$0\ e, \mu$	≥ 1 j	Yes	20.3	M_*	974 GeV	at 90% CL for $m(\chi) < 100$ G
EFT D9 operator (Dirac)	$0\ e, \mu$	1 J, ≤ 1 j	Yes	20.3	M_*	2.4 TeV	at 90% CL for $m(\chi) < 100$ G
Scalar LQ 1st gen	$2\ e$	≥ 2 j	–	20.3	LQ mass	1.05 TeV	$\beta = 1$
Scalar LQ 2nd gen	$2\ \mu$	≥ 2 j	–	20.3	LQ mass	1.0 TeV	$\beta = 1$
Scalar LQ 3rd gen	$1\ e, \mu$	$\geq$1 b, $\geq$3 j	Yes	20.3	LQ mass	640 GeV	$\beta = 0$
VLQ $TT \to Ht + X$	$1\ e, \mu$	≥ 2 b, ≥ 3 j	Yes	20.3	T mass	855 GeV	T in (T,B) doublet
VLQ $YY \to Wb + X$	$1\ e, \mu$	≥ 1 b, ≥ 3 j	Yes	20.3	Y mass	770 GeV	Y in (B,Y) doublet
VLQ $BB \to Hb + X$	$1\ e, \mu$	≥ 2 b, ≥ 3 j	Yes	20.3	B mass	735 GeV	isospin singlet
VLQ $BB \to Zb + X$	$2/\geq 3\ e, \mu$	$\geq$2/$\geq$1 b	–	20.3	B mass	755 GeV	B in (B,Y) doublet
$T_{5/3} \to Wt$	$1\ e, \mu$	≥ 1 b, ≥ 5 j	Yes	20.3	$T_{5/3}$ mass	840 GeV	
Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	20.3	q^* mass	3.5 TeV	only u^* and d^*, $\Lambda = m(q^*)$
Excited quark $q^* \to qg$	–	2 j	–	20.3	q^* mass	4.09 TeV	only u^* and d^*, $\Lambda = m(q^*)$
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
Excited lepton $\ell^* \to \ell\gamma$	$2\ e, \mu, 1\ \gamma$	–	–	13.0	ℓ^* mass	2.2 TeV	$\Lambda = 2.2$ TeV
Excited lepton $\nu^* \to \ell W, \nu Z$	$3\ e, \mu, \tau$	–	–	20.3	ν^* mass	1.6 Te[illegible]	$\Lambda = 1.6$ Te[illegible]
LSTC $a_T \to W\gamma$	$1\ e, \mu, 1\ \gamma$	–	Yes	20.3	a_T mass	960 GeV	
LRSM Majorana ν	$2\ e, \mu$	2 j	–	20.3	N^0 mass	2.0 TeV	$m(W_R) = 2.4$ TeV, no mixin
Higgs triplet $H^{\pm\pm} \to \ell\ell$	$2\ e, \mu$ (SS)	–	–	20.3	$H^{\pm\pm}$ mass	551 GeV	DY production, BR($H_L^{\pm\pm} \to$
Higgs triplet $H^{\pm\pm} \to \ell\tau$	$3\ e, \mu, \tau$	–	–	20.3	$H^{\pm\pm}$ mass	400 GeV	DY production, BR($H_L^{\pm\pm} \to$
Monotop (non-res prod)	$1\ e, \mu$	1 b	Yes	20.3	spin-1 invisible particle mass	657 GeV	$a_{\text{non-res}} = 0.2$
Multi-charged particles	–	–	–	20.3	multi-charged particle mass	785 GeV	DY production, $\lvert q\rvert = 5e$
Magnetic monopoles	–	–	–	7.0	monopole mass	1.34 TeV	DY production, $\lvert g\rvert = 1g_D$, s

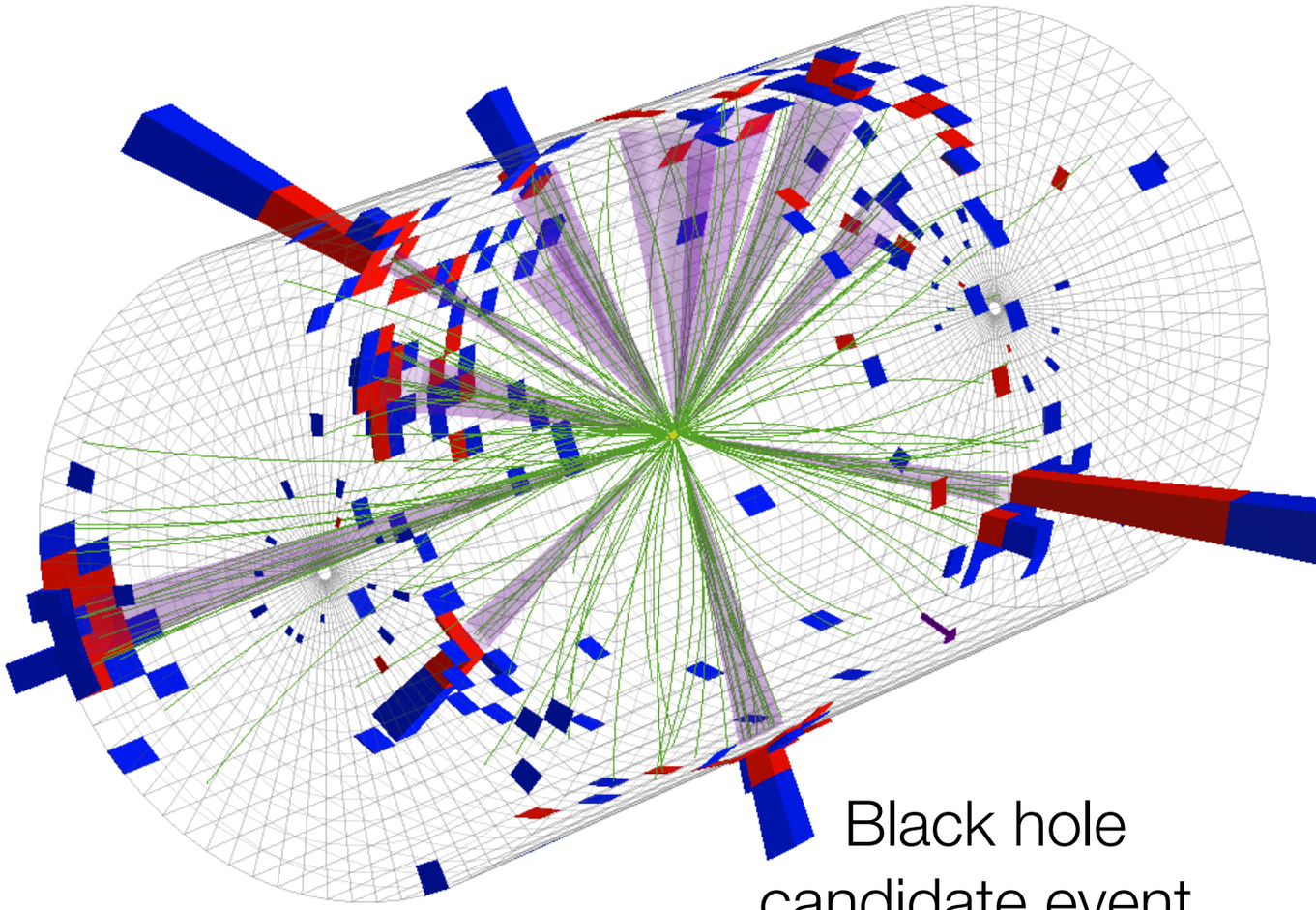
Enormous number of exotic limits at the end of Run I...

Where to next?

Black hole searches

- Models assuming a higher-dimensional universe allow strong gravity on the same scale as the other fundamental forces

- Consequence is production of microscopic black holes above fundamental gravity scale M_D



Black hole candidate event, CMS EXO-15-007

- Decays of semiclassical microscopic black holes are “democratic”: equally likely to produce any particle, and give high multiplicity final states

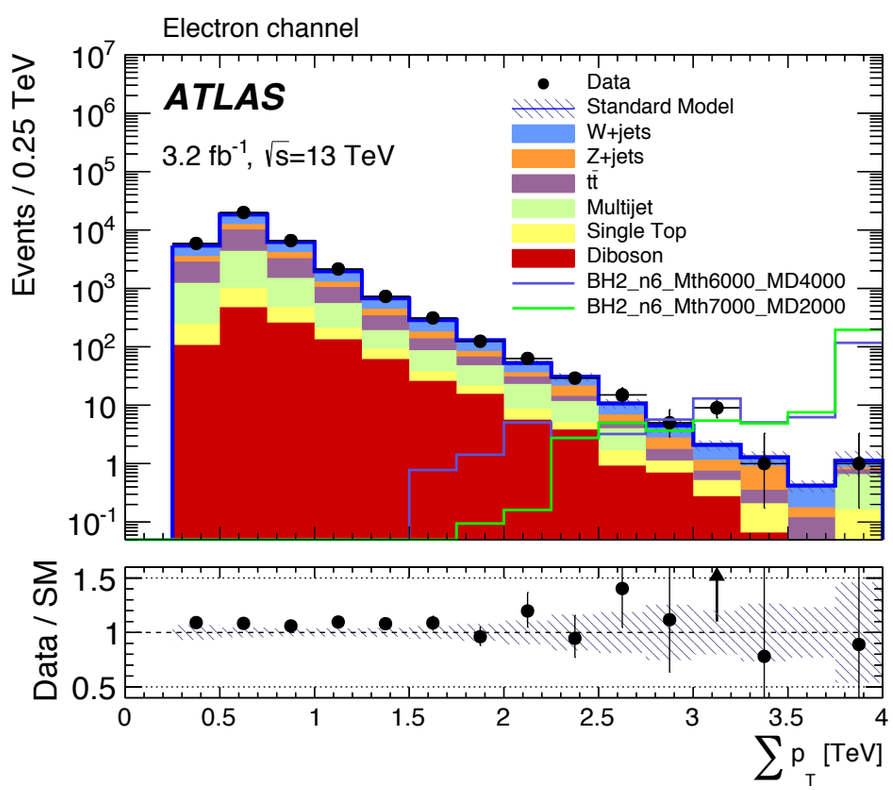
- Decays of quantum black holes are dominated by 2-body final states, especially jets at the LHC

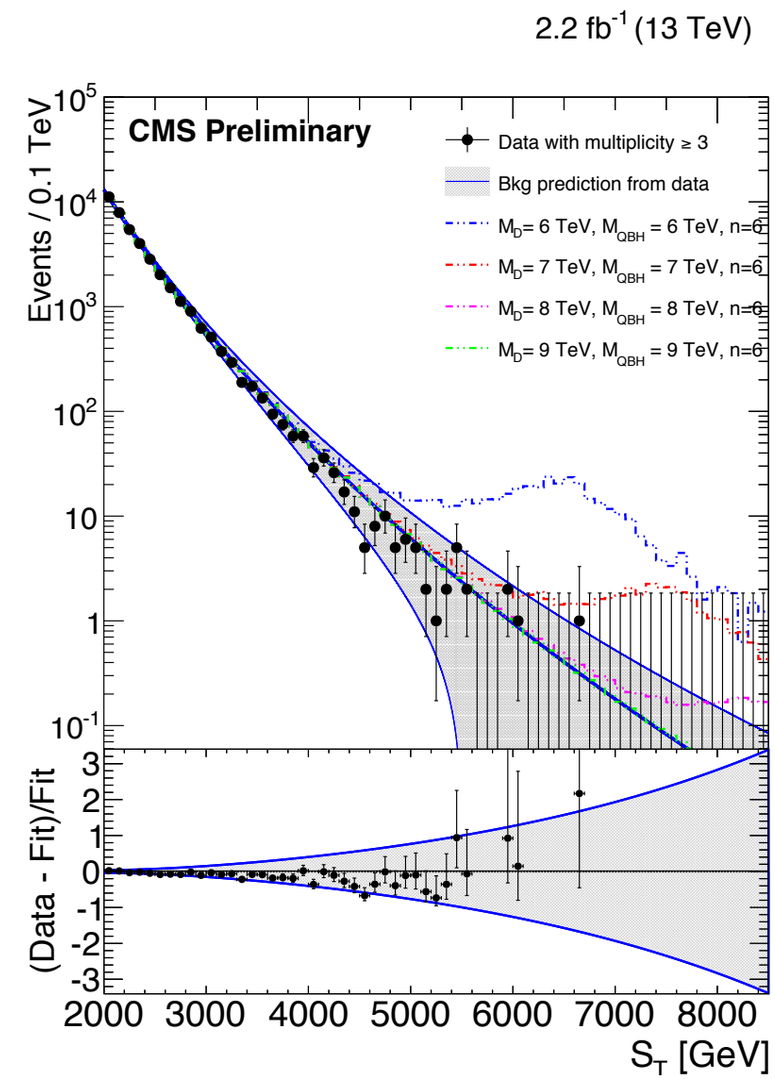
- Primary backgrounds: QCD multijet production. Secondary: V+jets, γ+jets, tt

Black holes in multi-particle final states

- Discriminating variable: $S_T = \Sigma p_T$ (ΣE_T) of **all objects**. Include jets, e, μ, (γ, MET in CMS) > 60/50 GeV
- Selection: S_T > 2 TeV. CMS accepts any event of mult. ≥ 2; ATLAS requires ≥ 1 lepton, mult. ≥ 3
- Background estimation
  - ATLAS: **W/Z+jets** dominant with ttbar, di-boson, single-top contribs. Estimate from MC.
  - CMS: dominated by **QCD multijets**. Since shape of S_T dist. constant, scale from fit to dijet events with low S_T

CMS PAS EXO-15-007
ATLAS CERN-EP-2016-109

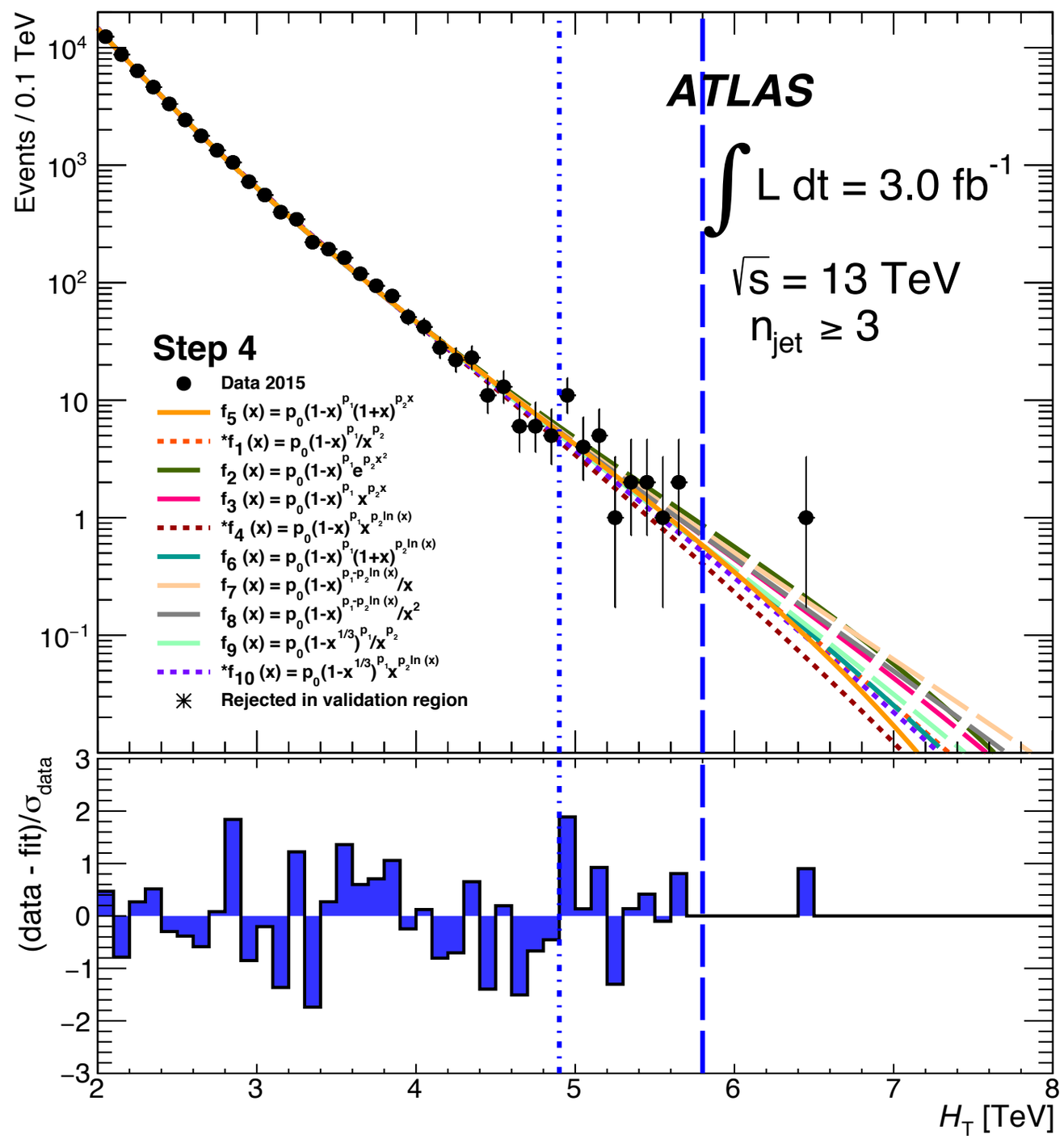




Black holes in multi-particle final states

ATLAS CERN-PH-EP-2015-312

- ATLAS covers **non-leptonic** states with multiplicity ≥ 3 by **fit** extrapolated in H_T
- Evaluate in exclusive luminosity steps to ensure low contamination of CR & VR
- 10 fit functions examined in data and MC.
  - Baseline = highest performing
  - Uncertainty = envelope of other acceptable function predictions



Limits

Semi-classical BH, n=6

CMS (non-rotating), @ MD = 4 TeV:
8.7 TeV using all final states

ATLAS (rotating), @ MD = 5 TeV:
7.4 TeV for lepton+jets
9 TeV for multijets

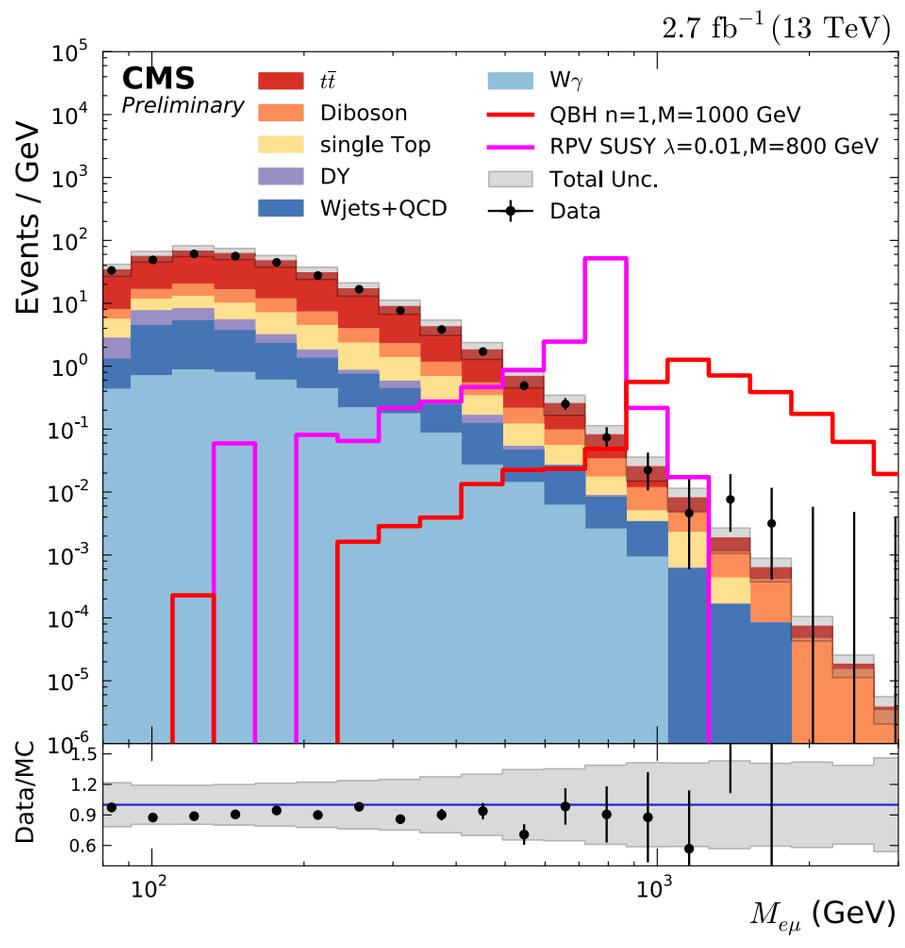
Black holes decaying to different-flavour leptons

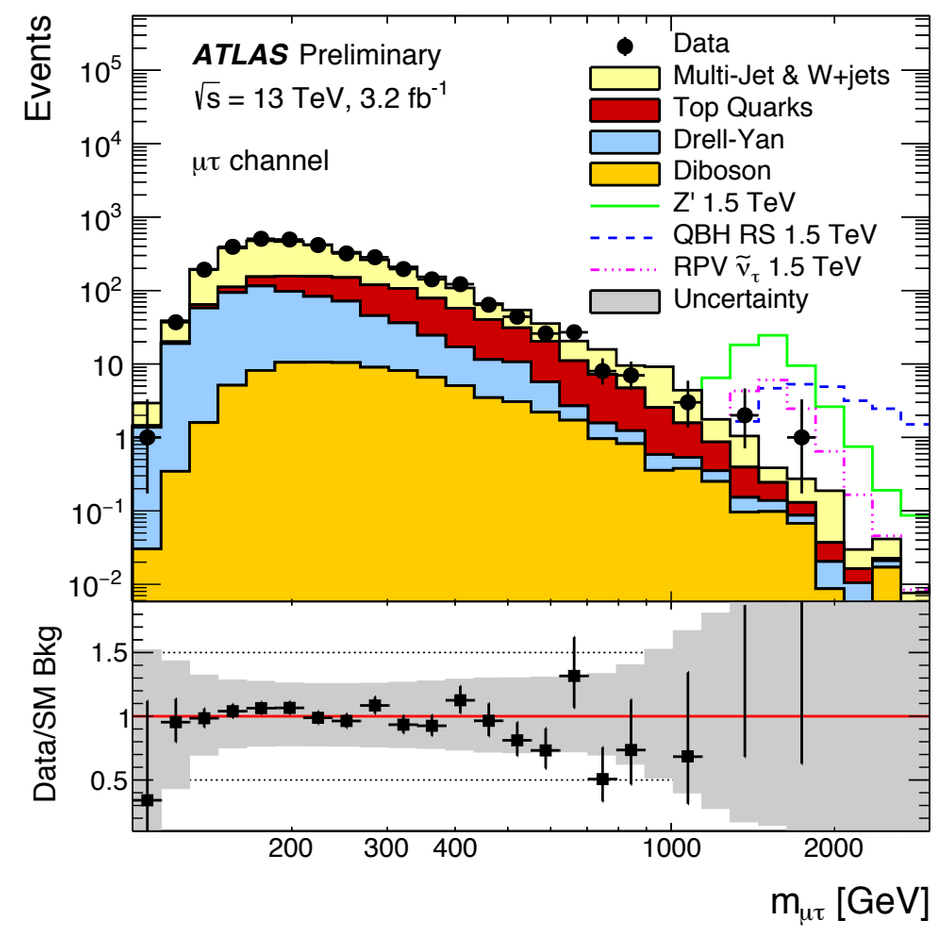
Limits

ADD QBH, n=6:
4.5 TeV for both ATLAS, CMS
Comparison: dijet analysis sets limits at 8.1 TeV

- Quantum black holes favour **two-body production** and often support **flavour violation**.
- Selection: exactly 1 e and 1 mu (**new** ATLAS analysis also covers eτ, μτ!)
- Low SM background to mixed lepton flavours.
- ttbar dominant dilepton background; single-top, Drell-Yann, diboson also contribute. Take from MC. In ATLAS, use fit to top and diboson backgrounds to extend shape where stats are low
- W+jet and multijet processes with a fake electron: use data-driven estimation

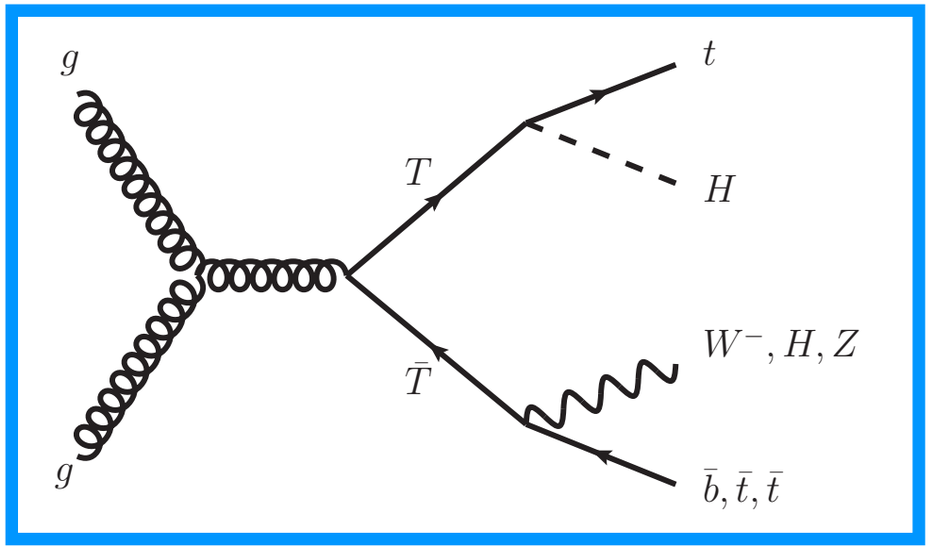
CMS PAS EXO-16-001
ATLAS EXOT-2015-20

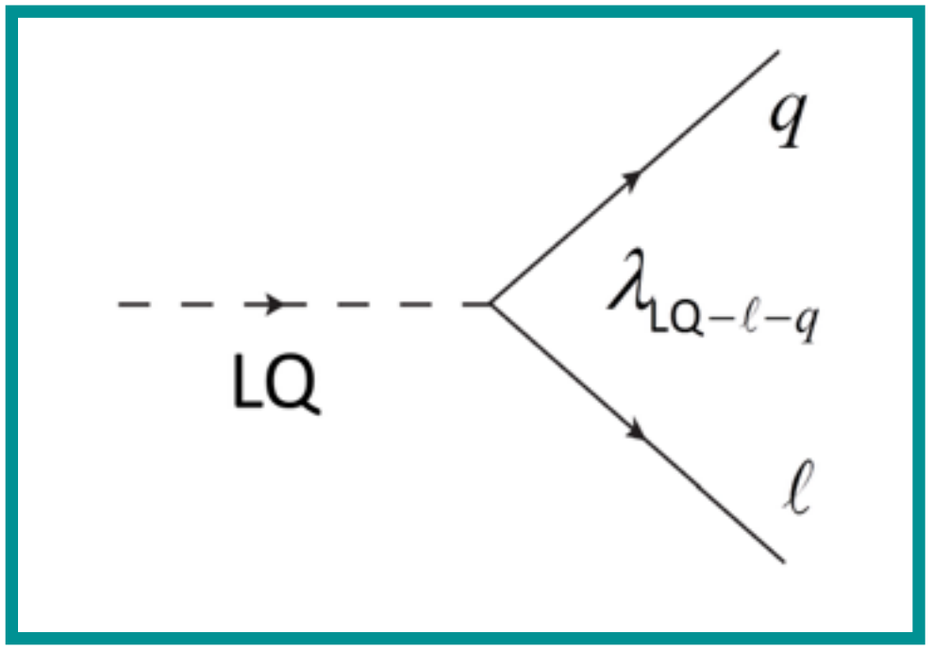




Vector-like quarks, leptoquarks, simple SM extensions

- Compositeness models remain among the few naturally motivated models not yet excluded. One prediction is **vector-like quarks**
  - Couple to 3rd generation quarks
  - Permit flavour-changing neutral current decays
- Second potential consequence (also consequence of GUTs) is **leptoquarks**
  - Essentially fill in the holes of the SU(5) matrix. Mediate interactions between leptons & quarks of same generation.
  - Pair-produced at LHC; decay gives lq
- Another GUT consequence is additional standard-model like **heavy vector bosons**, W' and Z'
  - Simplest are "sequential standard model" SSM: same couplings as SM W and Z with larger masses

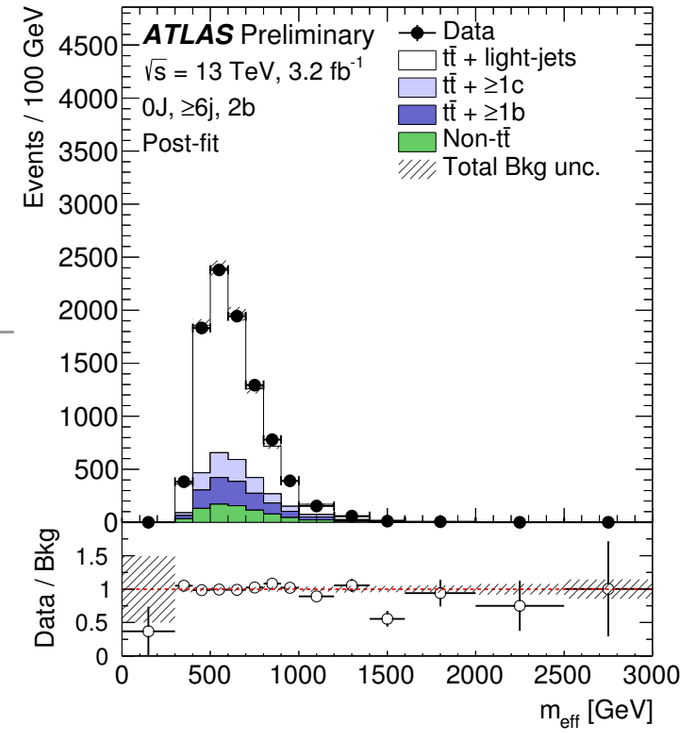


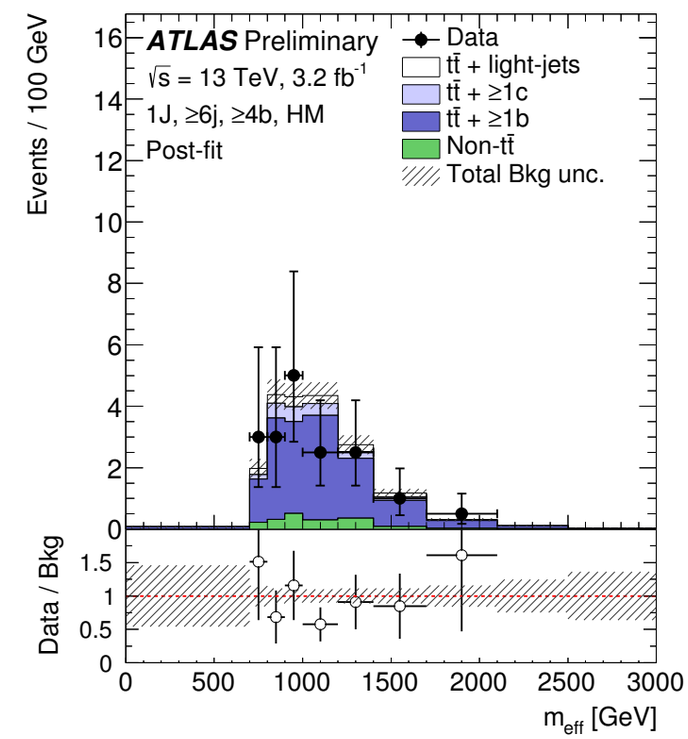


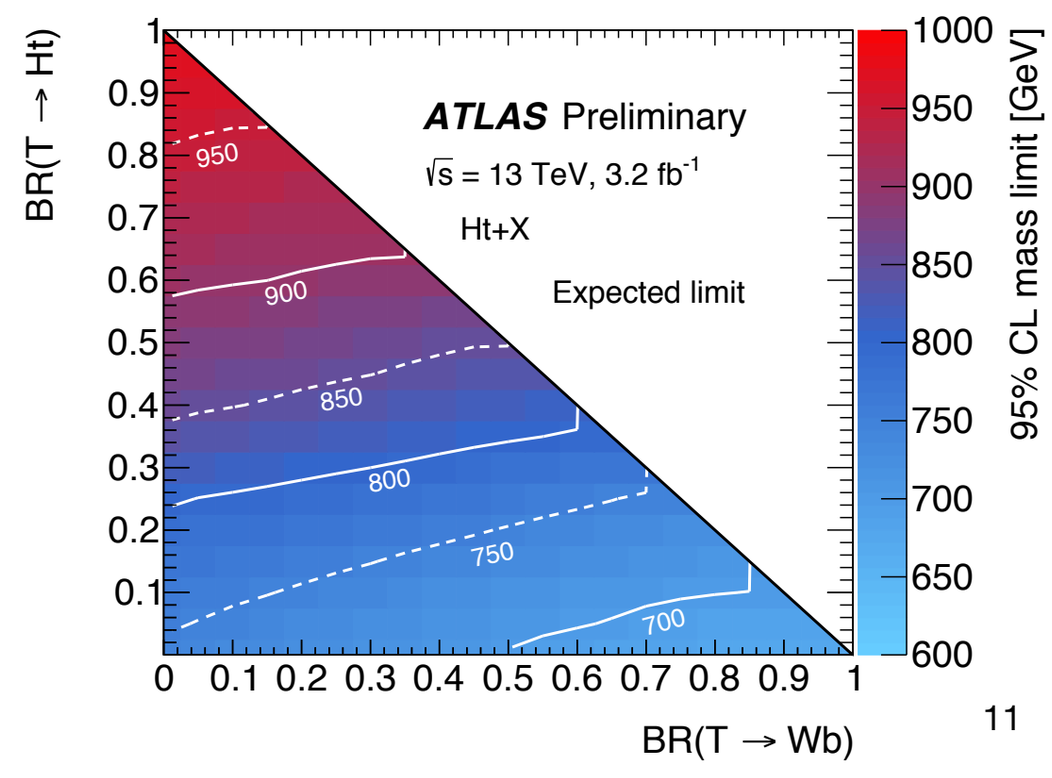
VLQ to lepton+jets

ATLAS-CONF-2016-013

- Model: pair production of up-type vector quarks T to Wb, Zt, and Ht
  - **One lepton**, high MET, and **plenty of jet activity** including several b-tagged jets from H->bb
  - Also sensitive to SM tttt production
- Selection: isolated leptons, all objects' p_T > 30 GeV. Sort by N(jets), N(b-tagged jets), and number of large-R jets passing n-subjet requirements (and in some cases jet mass cuts). Define 11 search channels with ≥ 6 j and 9 validation channels with exactly 5 j
- Backgrounds: mainly tt + bosons or jets inc. heavy flavour, also W/Z+jets, single top, diboson
- Uncertainties: tt cross section, generator choice, ISR/FSR, normalisation uncertainties



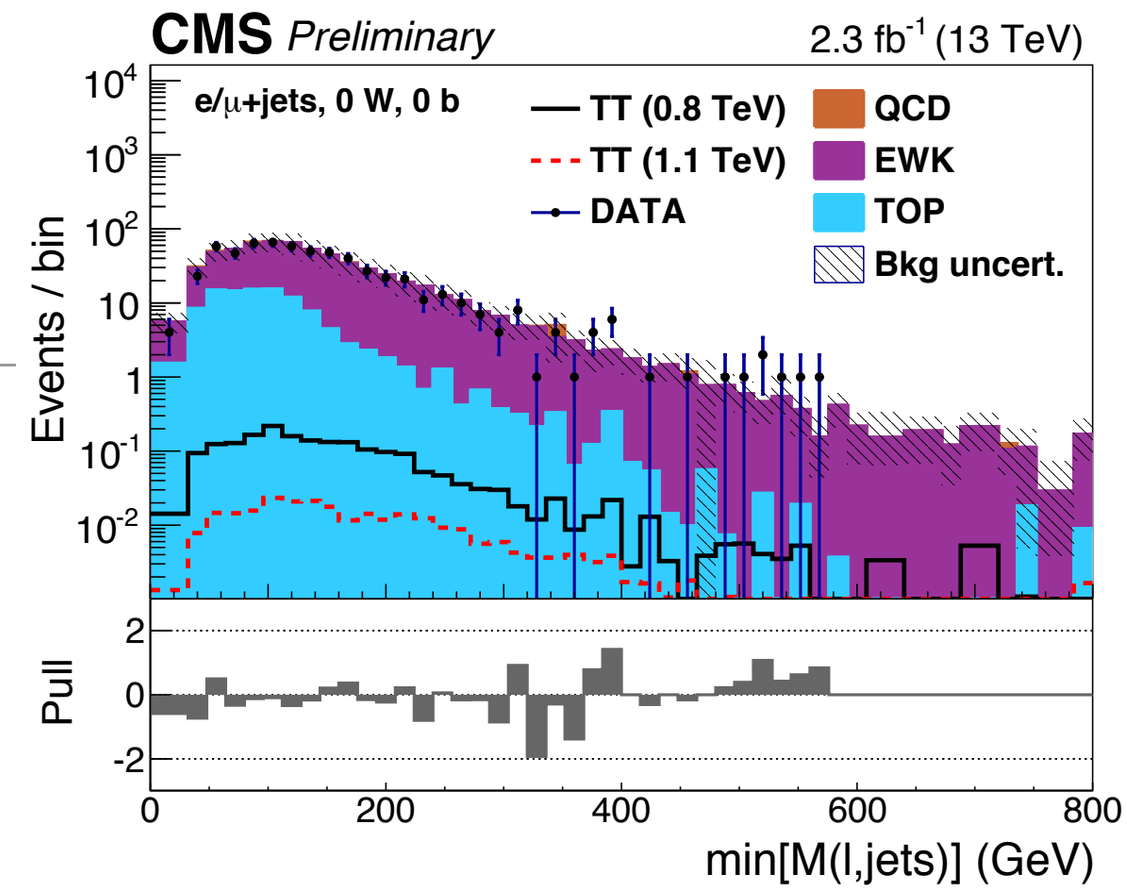


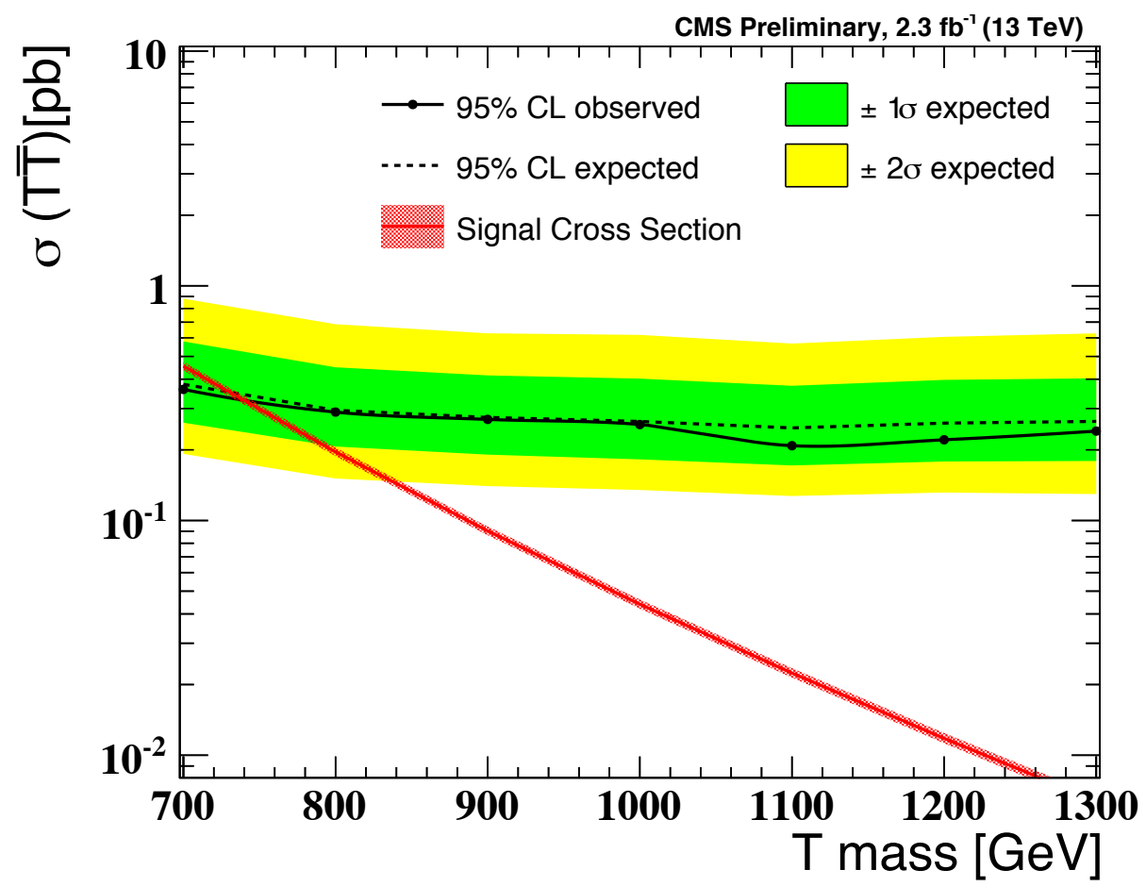


VLQ to lepton+jets, cont'd

- **CMS analysis** of VLQ pair production: T to Wb, Zt, and Ht
  - One lepton, high MET, ≥ 3 high-pT jets
  - Divide into regions by lepton flavour, N(b-tagged jets), N(W-tagged large-R jets). 16 signal regions.
  - Same background contributions as ATLAS
- Uncertainties: reweighting of MC distributions to match data add additional uncertainty to background
- Analyses give **results** sorted by **BR assumption**. Nominal assumption used in CMS limit plot: B(T->bW) = 0.5, B(T->tH) = 0.25, B(T->tZ) = 0.25

CMS-PAS-B2G-16-002

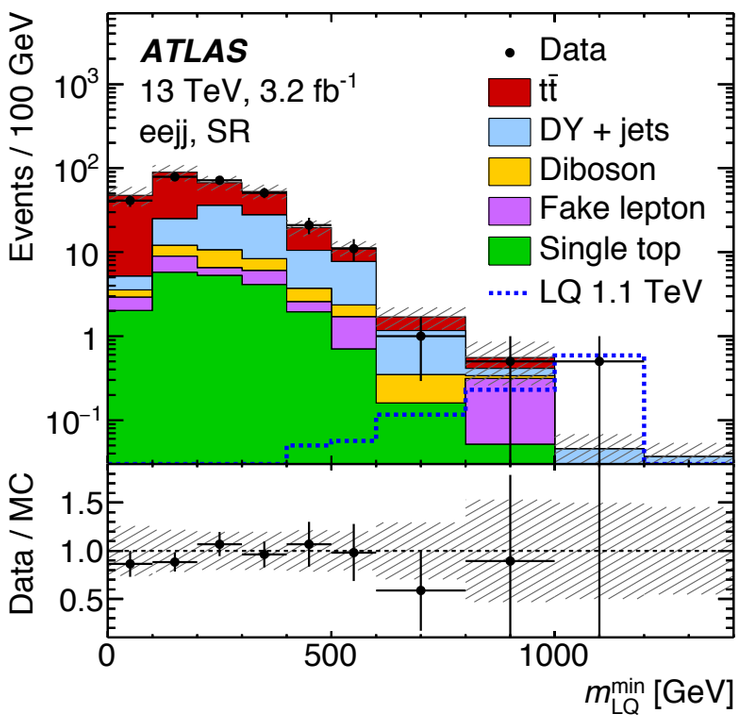


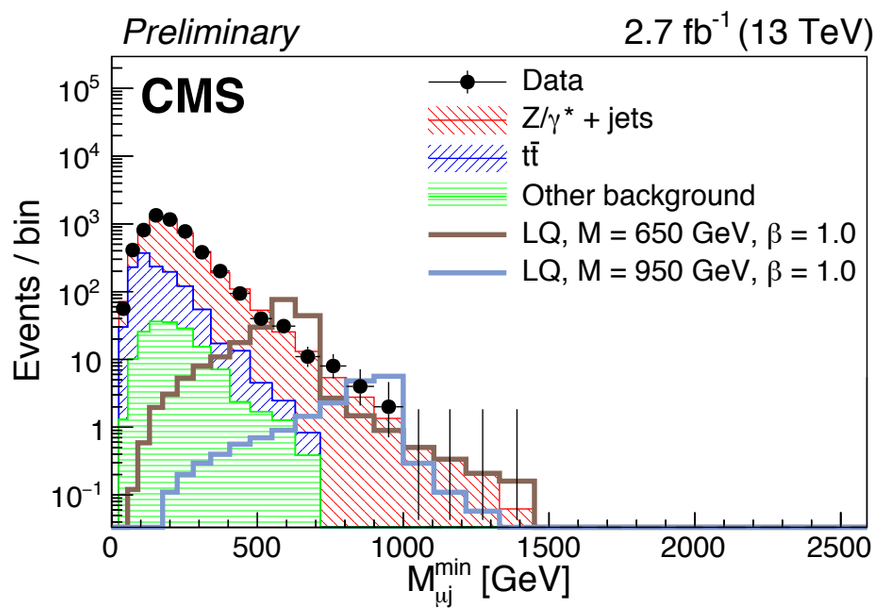


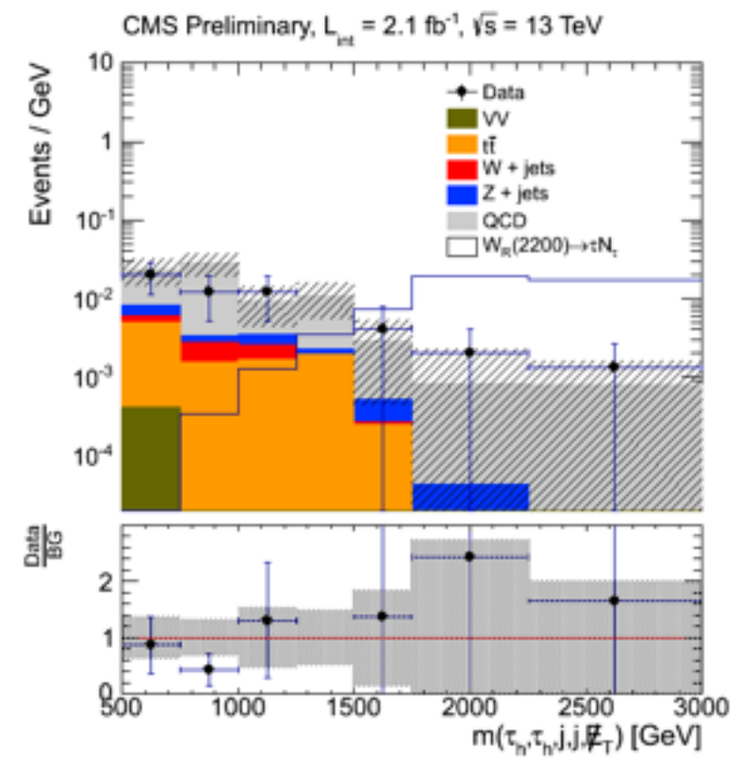
Leptoquarks at ATLAS and CMS

Limits

Observed limits, β=1
LQ1 to 1100 GeV (ATLAS)
LQ2 to 1165 GeV (CMS)
LQ3 to 740 GeV (CMS)







- LQ **pair production**: 2 leptons (ATLAS: exactly 2 e or μ, CMS: ≥ 2 μ) and ≥ 2 jets
- Backgrounds: tt, Drell-Yann+jets, diboson, W+t
- Systematics: JES, lumi, MC shape and norm. (CMS), PDF acceptance & cross section, showering & hadronisation (ATLAS)

- Signal regions **cut in m_{ll} and S_T**. Discriminating variable: **minimum m_{LQ}**, pairs chosen for smallest mass difference
- CMS also searches in hadronic tau channel.

ATLAS CERN-EP-2016-074
CMS PAS EXO-16-007
CMS PAS EXO-16-016

CMS PAS EXO-15-006
ATLAS CERN-PH-2016-143

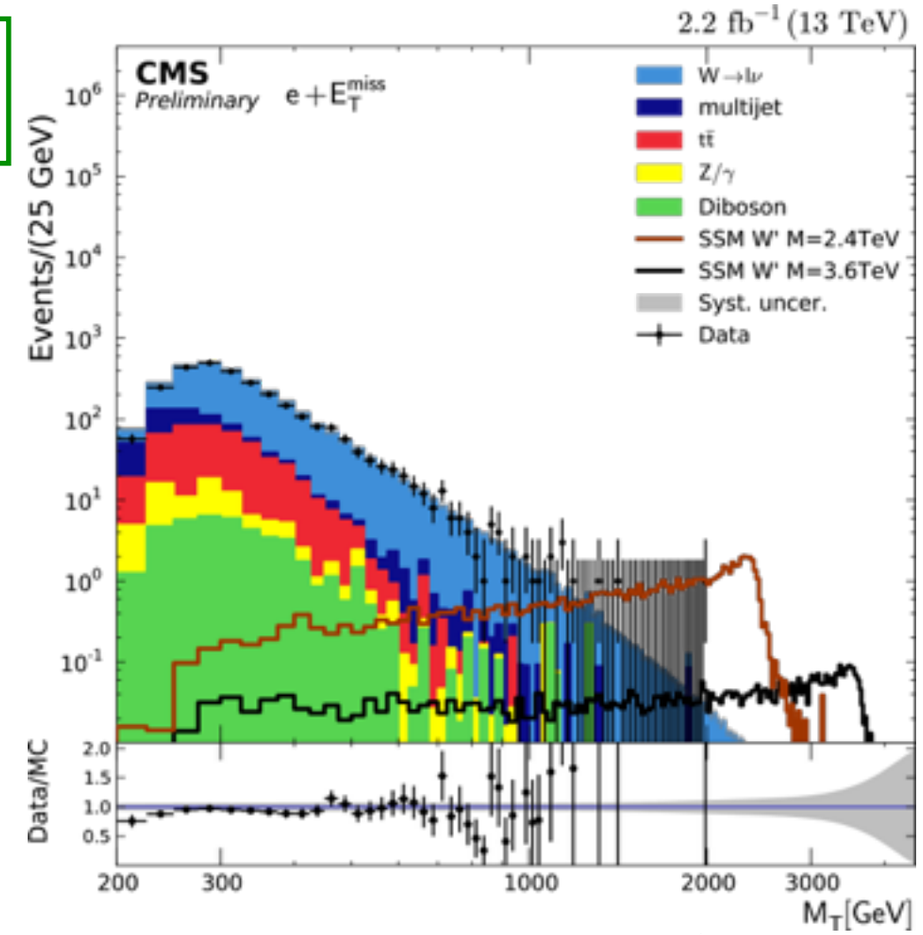
W' to lepton + MET

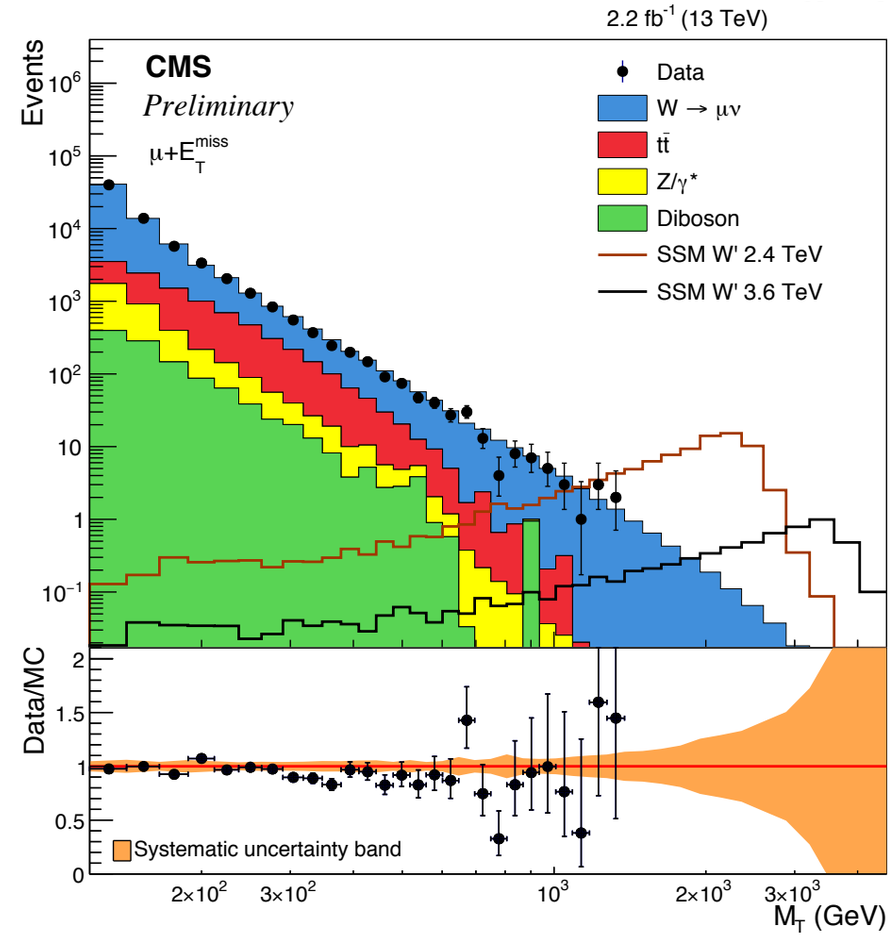
- Kinematic variable:

$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos \phi_{\ell\nu})}$$

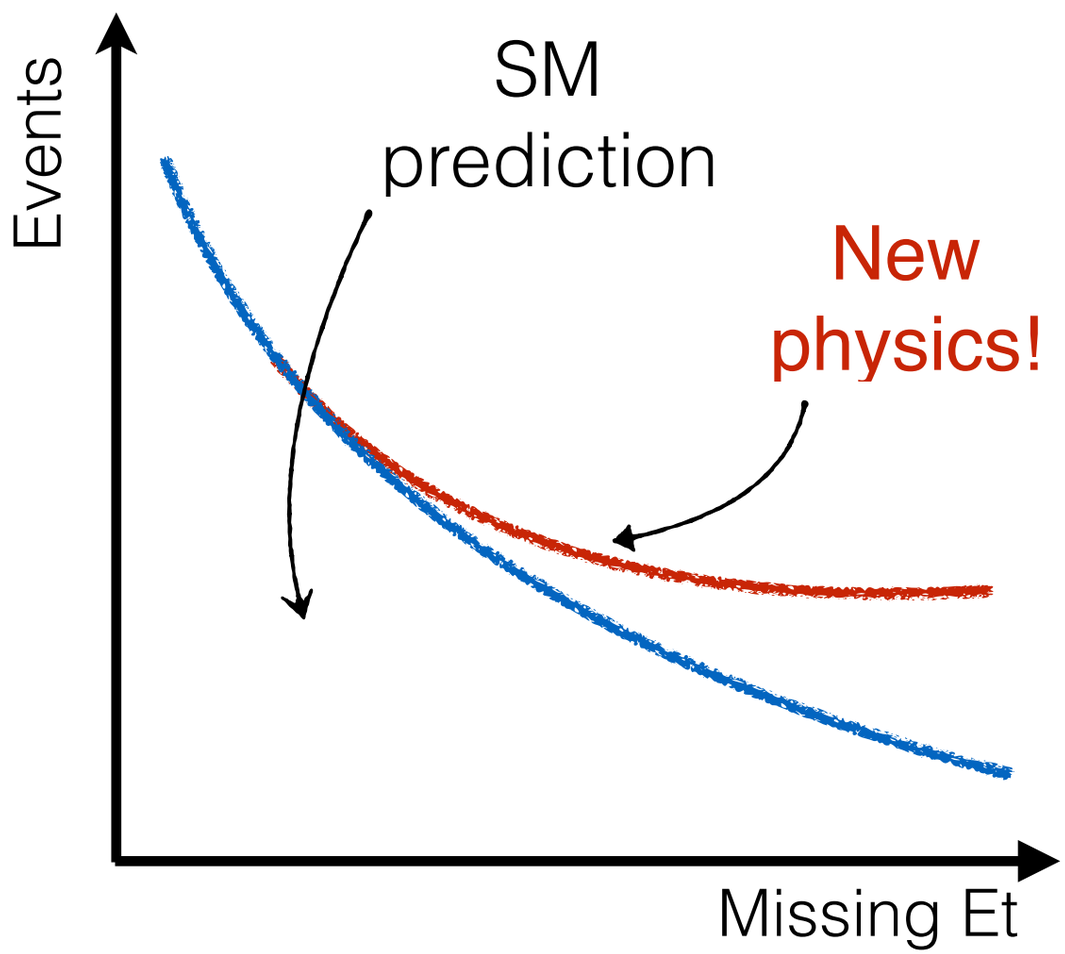
- Selection: exactly **1 e** > 55 (53) GeV **or μ** > 55 (130) GeV
  - ATLAS ensures MET > 55 GeV, m_T > 110 GeV
  - CMS requires 0.4 < pT/MET < 1.5, lepton and MET back-to-back
- Backgrounds: **W->lν**, Drell-Yann, tt, single-top, diboson. Estimated using MC. Fake lepton contrib. estimated from data
- Systematics: muon scale factors, pT/E scales, MET uncertainties, K factors, PDF

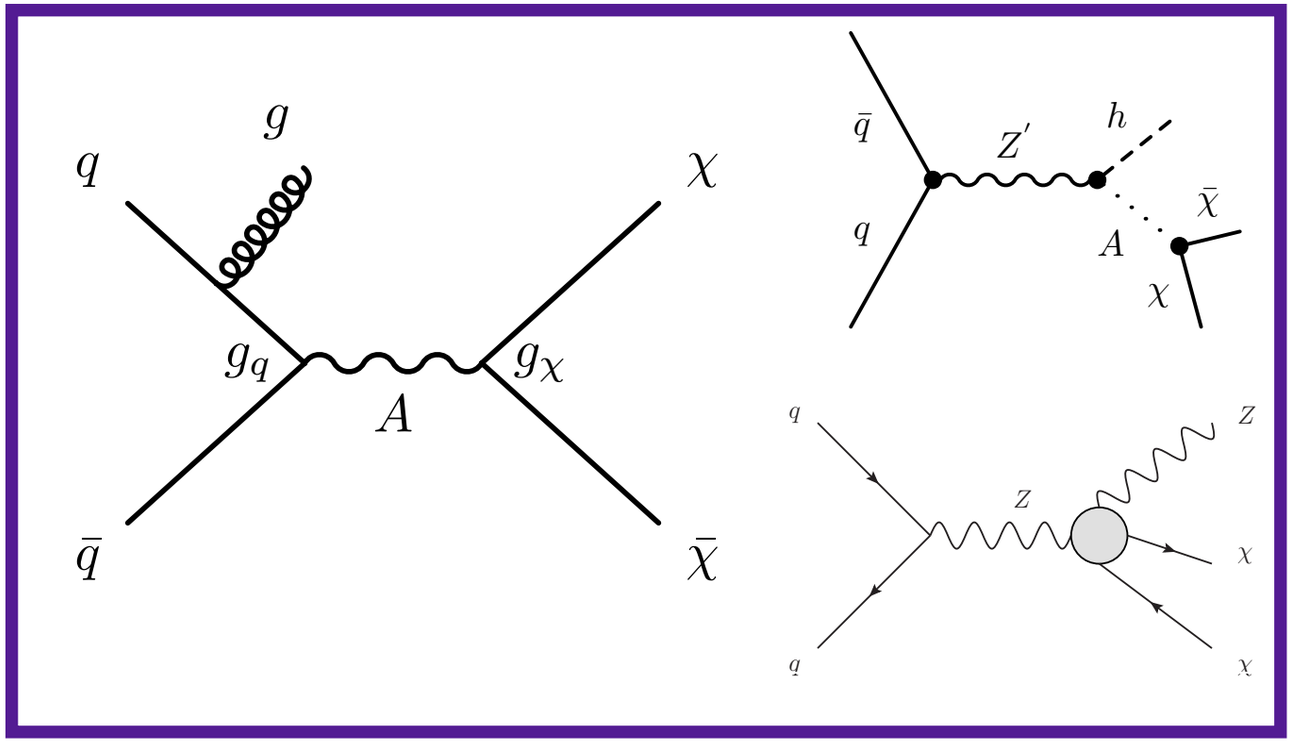
Limits
SSM W'
4.07 TeV (ATLAS)
4.4 TeV (CMS)





Dark matter searches: mono-X





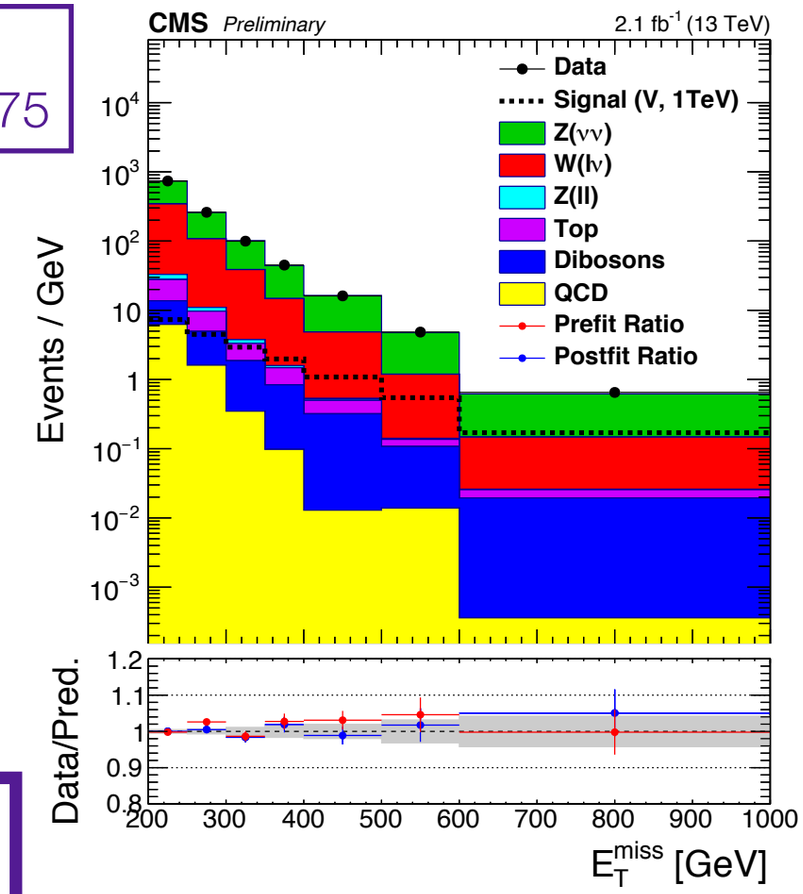
- Search for DM mediator to MET plus any object on which to trigger
- **Simplified model** uses mediator explicitly. Usually SM object produced in conjunction with mediator or as ISR

- **EFT** uses contact operators for DM to SM vertex
- Harmonisation of WIMP models a big focus of CMS and ATLAS for Run II. **Dark Matter Forum** targets include (arXiv:1507.00966v1, arXiv: 1506.03116v3):
  - Unify simplified models and implementations between analyses
  - Ensure effective field theory models only used within valid regimes (very heavy mediators)
  - Help LHC results to complement direct detection searches

CMS PAS EXO-15-003
ATLAS CERN-EP-2016-075

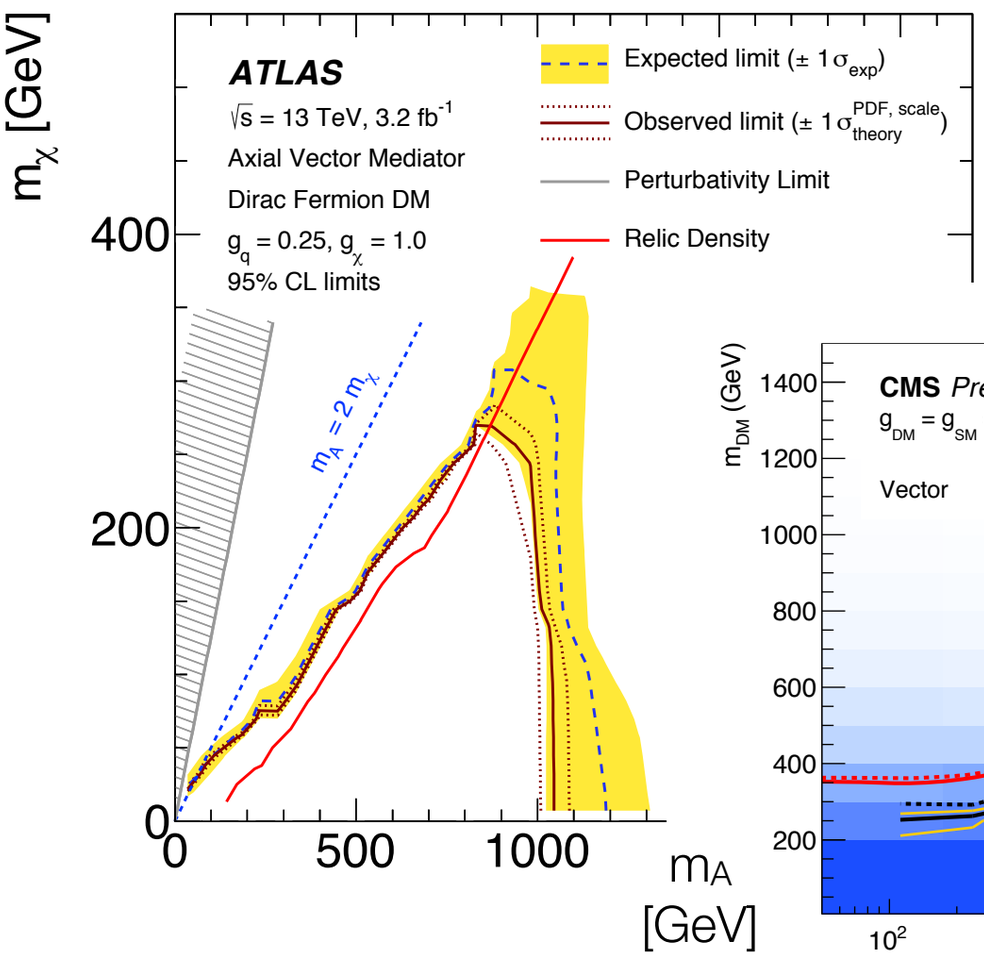
Jet + MET signatures

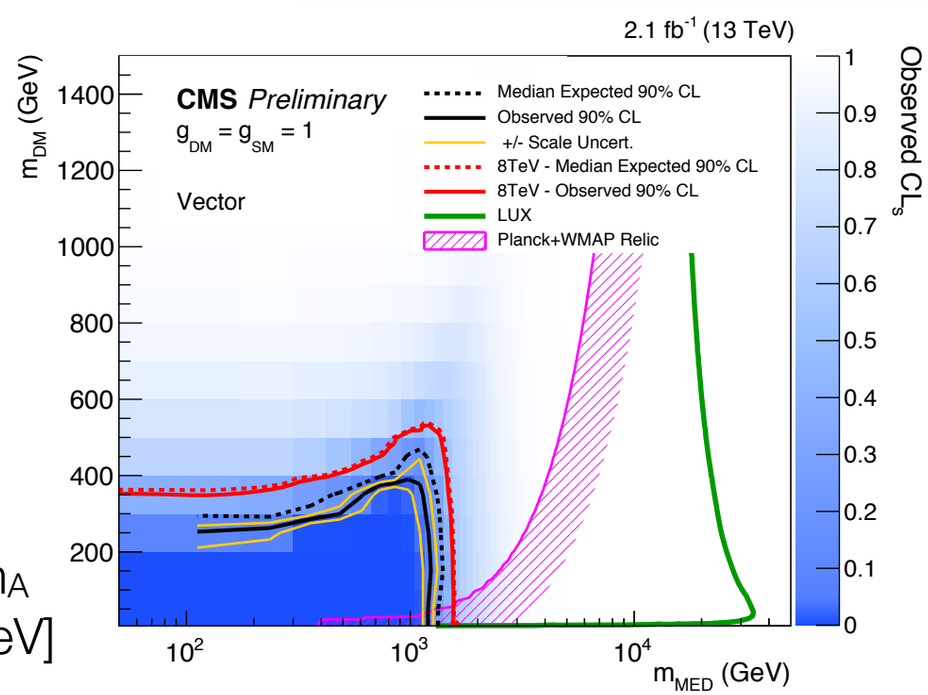
- **Lead jet pT > 250** (100) GeV, up to 4 jets (ATLAS), MET > 250 (200) GeV isolated from 4 lead jets.
- **Leptons vetoed**. CMS rejects events with b-jets.
- Z(vv)/W(lv)+jets contributions calculated from simultaneous fit to control regions



Limits

Mediator mass
1.3 TeV, g_q=1, 90% CL (CMS)
1 TeV, g_q=0.25, 95% CL (ATLAS)





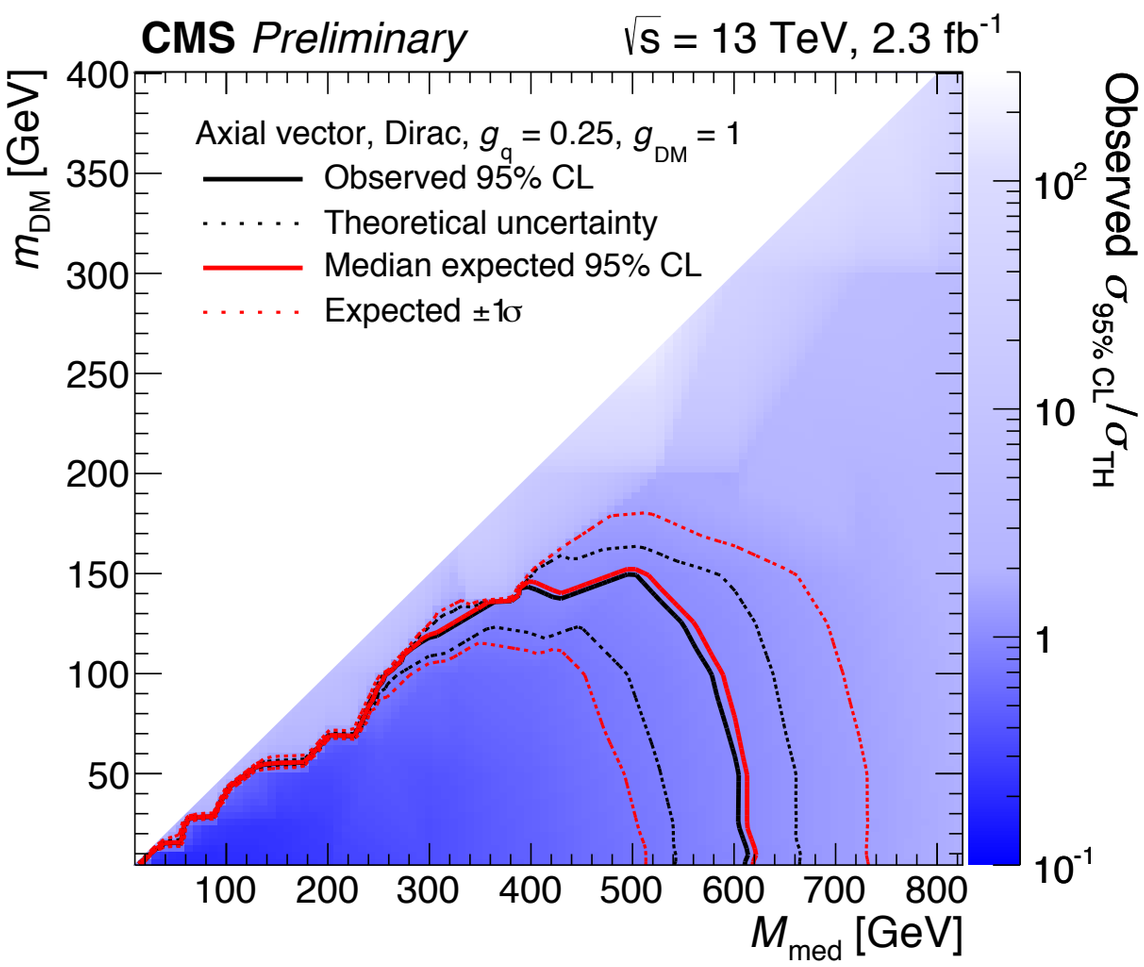
- Top and diboson backgrounds taken from simulation
- Systematics: normalisation/ factorisation σ effects, PDF unc., NLO correction, MET, lumi, selection/background estimation uncertainties

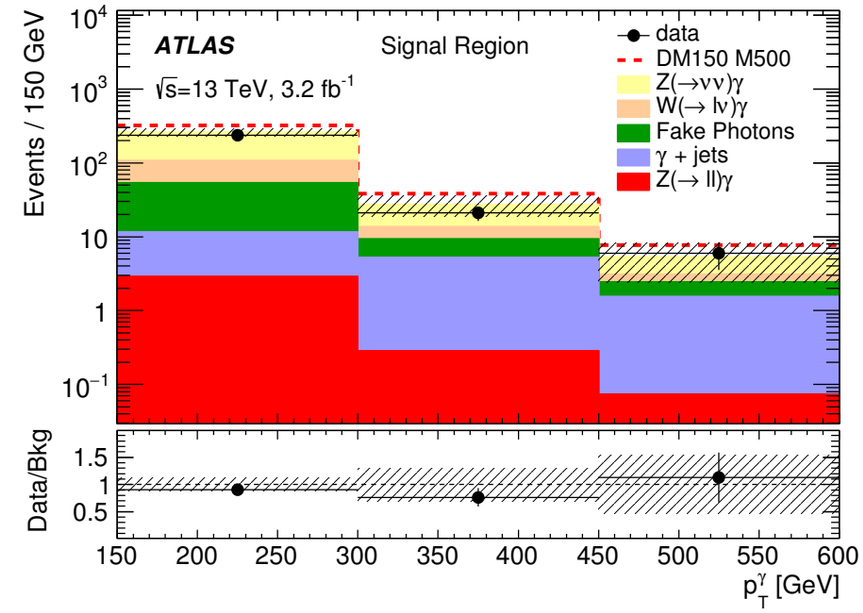
Photon + MET

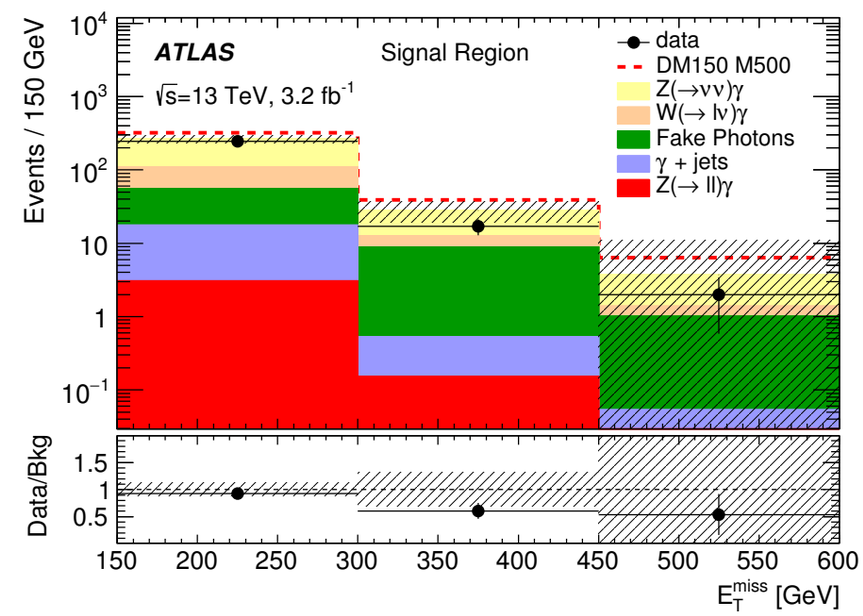
Limits

Axial-vector mediator
710 GeV (ATLAS)
600 GeV (CMS)

- Leading **isolated photon** with pT > 150 (175) GeV, MET > 150 (170) GeV and not near photon. **Leptons vetoed.**
  - ATLAS vetoes if > 1 jet, or jet is near photon.
  - CMS rejects if photon near any of 4 leading jets







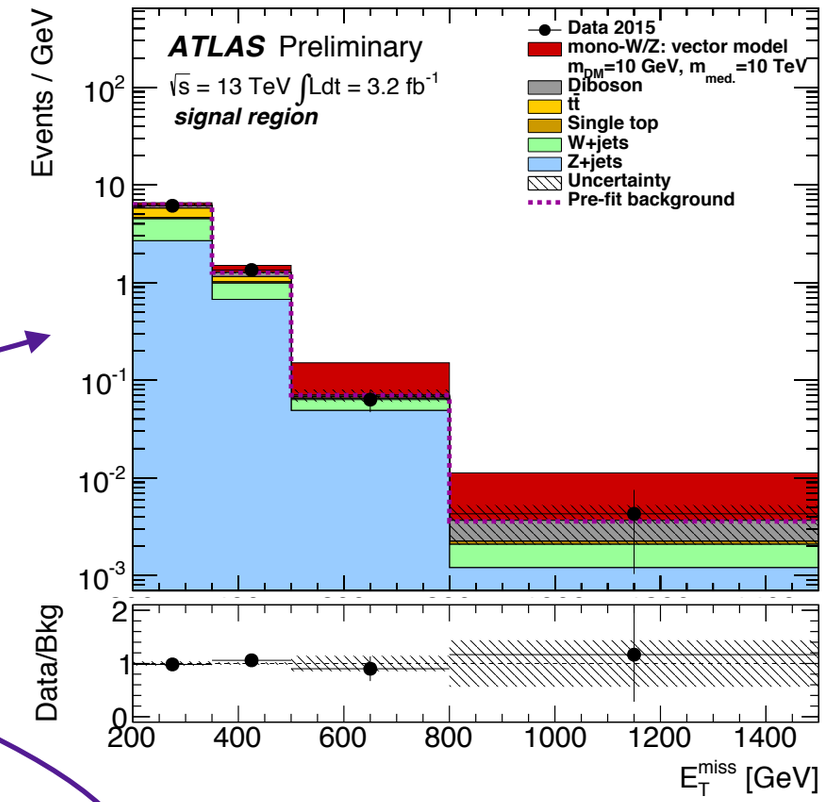
- Backgrounds: ATLAS takes Z/W+γ from simultaneous fit to control regions; CMS directly from MC. γ+jets from MC. Fake photons estimated from data.

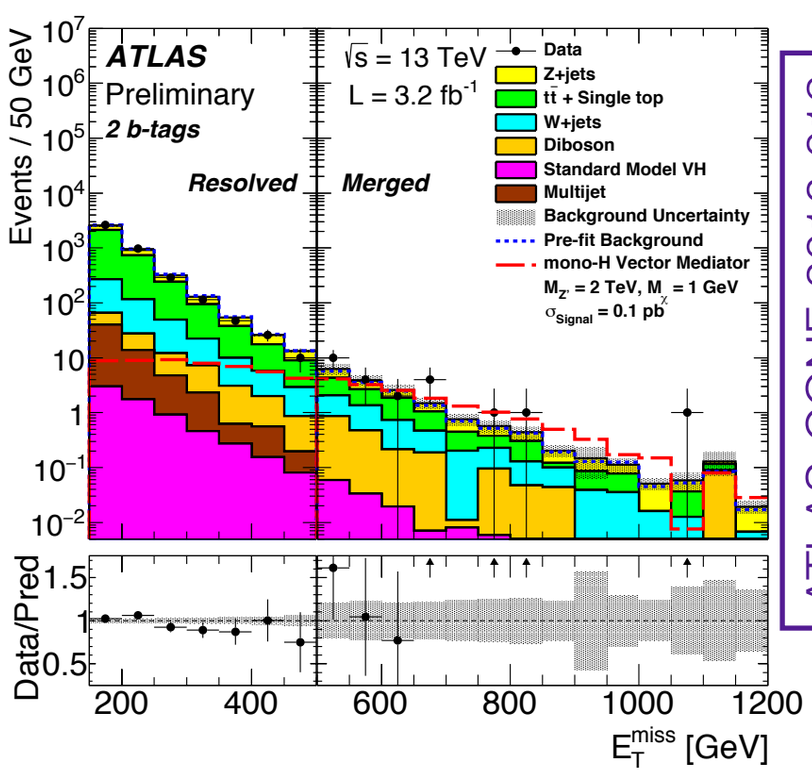
CMS PAS EXO-16-014
ATLAS CERN-EP-2016-060

Heavy boson + MET signatures

- (ATLAS) **W/Z hadronic + MET**
  - 1 large-R jet, high MET, no leptons
- (CMS) **Multijet** (W/Z hadronic) **+ MET** includes the above + mono-jet channel
- **Higgs + MET** (ATLAS)
  - H(bb) High MET, no leptons, two small or one large jet, 2 b-tags
  - Also H(γγ), H to four leptons. See ATLAS-CONF-2016-011, ATLAS-CONF-2015-059

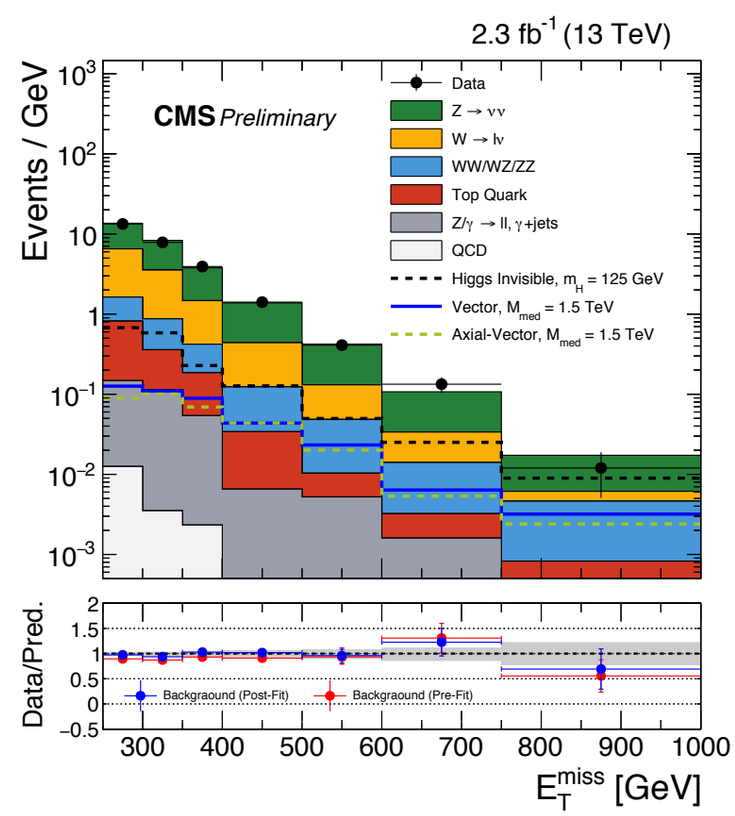
ATLAS-CONF-2015-080





ATLAS-CONF-2016-019

CMS PAS EXO-16-013



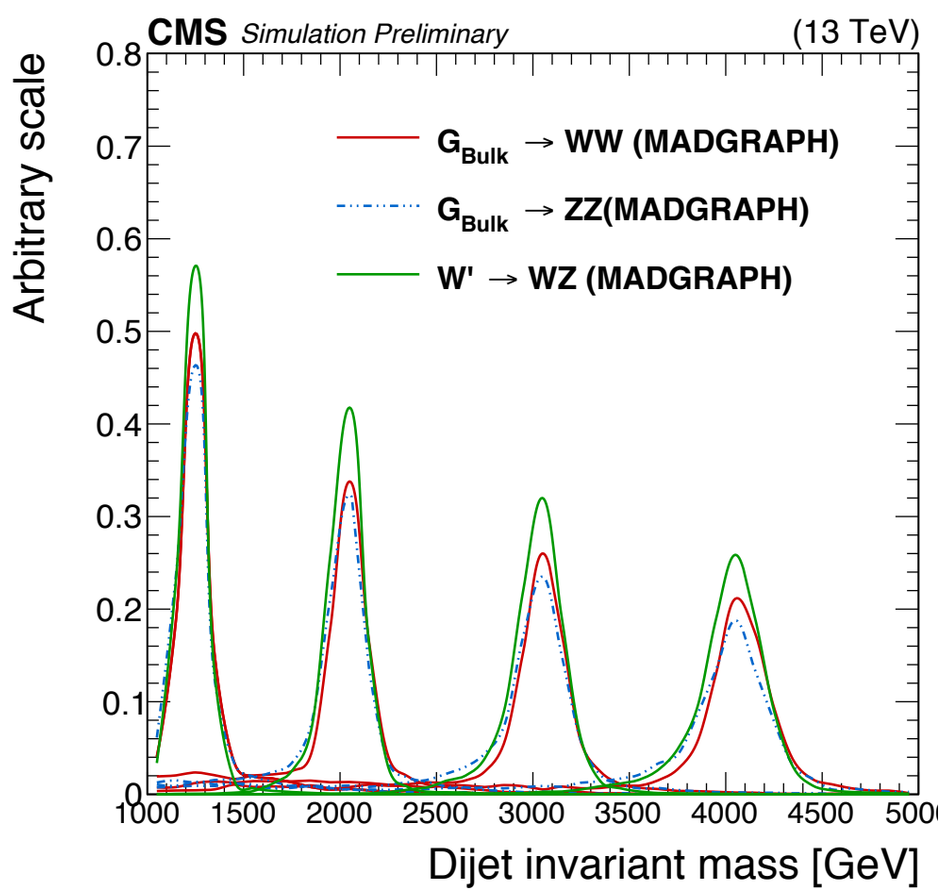
General resonance searches

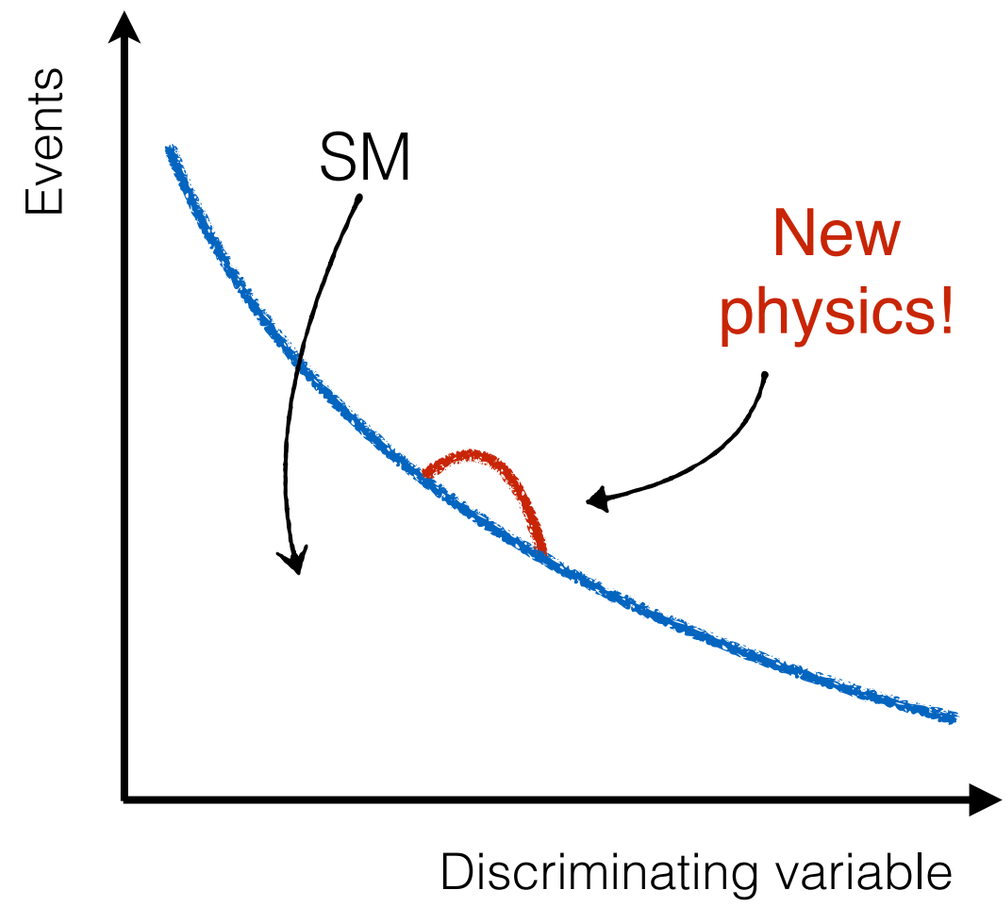
Heavy particles with short lifetimes appear as **narrow resonances**

$$f(E) = \frac{k}{(E^2 - m^2)^2 + M^2\Gamma^2}$$

where M is resonance mass and Γ is decay width.

This appears as a **bump** on a smooth, well-understood background:

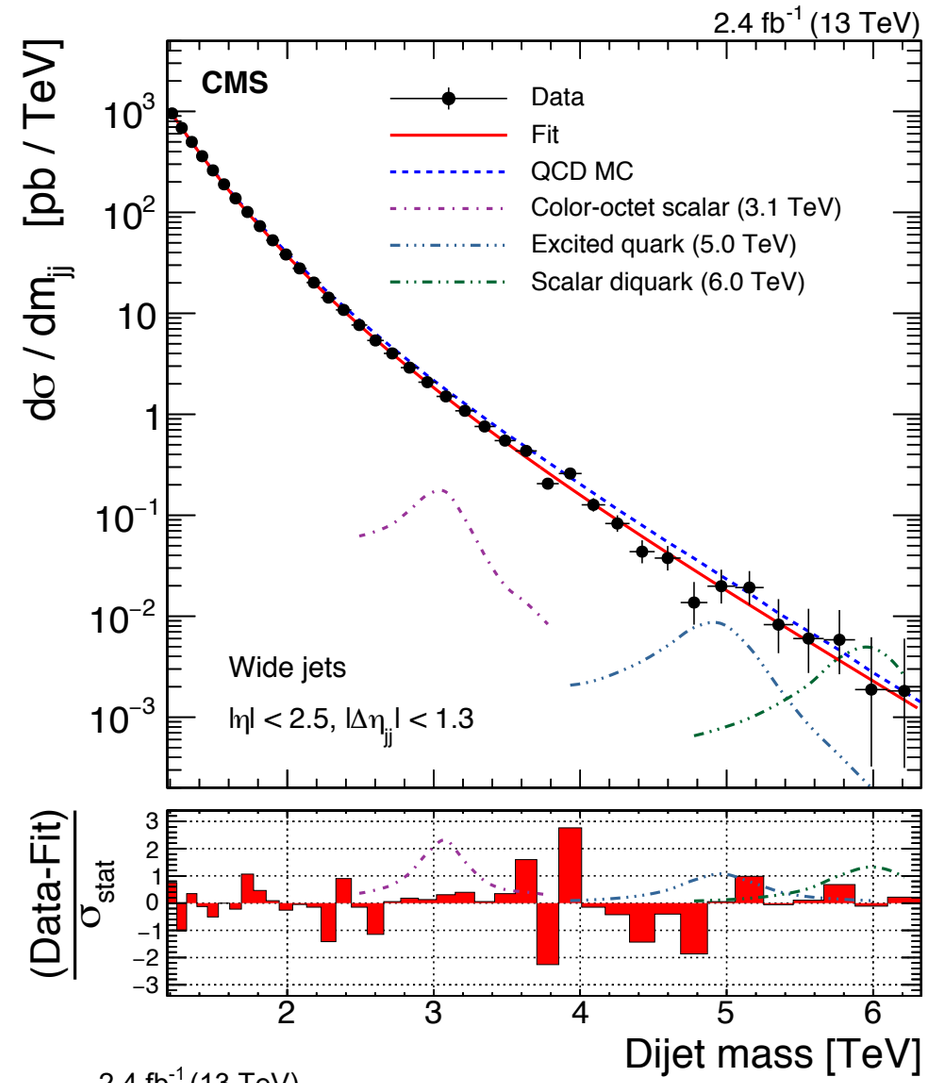


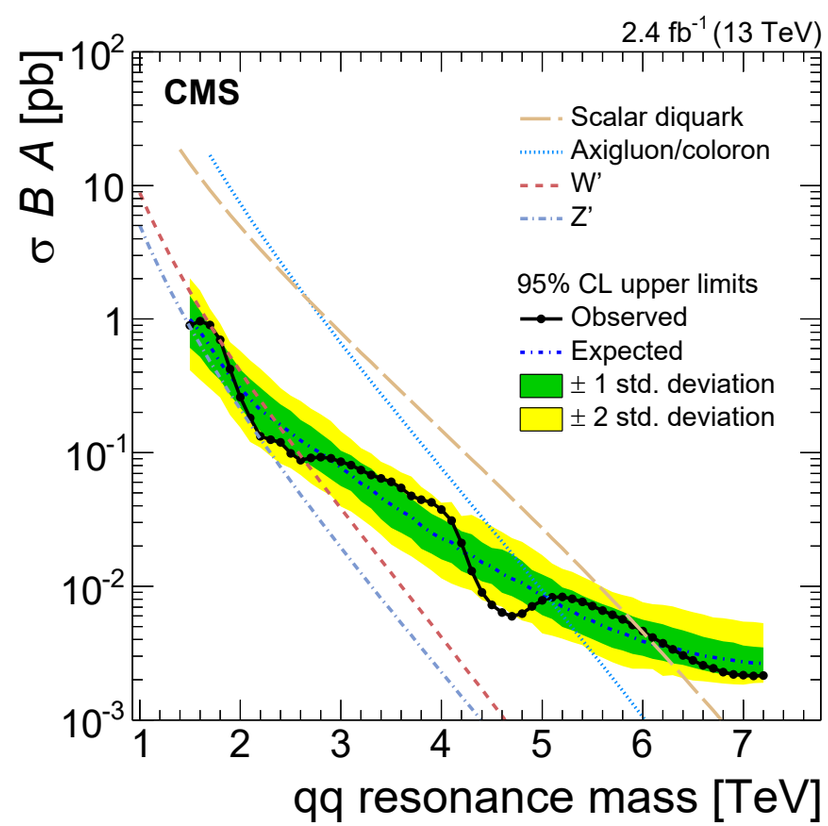


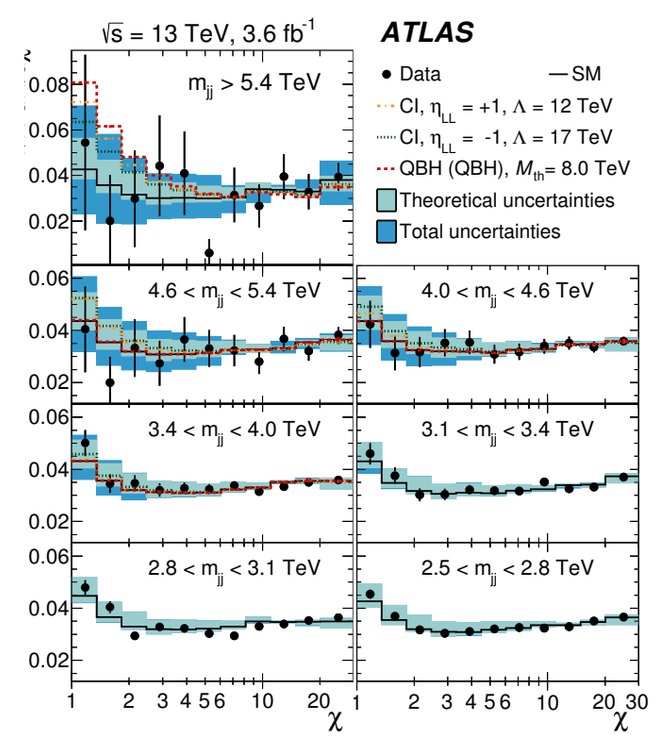
Dijet resonance search

- Search dijet events above unprescaled trigger turn-on
  - **Resonance analysis** uses invariant mass m_{jj}
  - **Angular analysis** uses rapidity difference in jet CMF
- ATLAS: ≥2 jets, $|y^*| < 0.6$ ($\chi < 30$), $m_{jj} > 1$ (2.5) TeV
- CMS: ≥2 jets, $|\Delta\eta_{jj}| < 1.3$ ($\chi < 16$), $m_{jj} > 1.2$ (1.9) TeV. Uses wide jets to account for gluon FSR
- Background estimate taken from smooth parameterised **fit (resonance)** or from **MC (angular)**
- ATLAS also explores m_{jj} with ≥1 b-tag

CERN-PH-EP-2015-311, CMS-EXO-15-001, CMS PAS EXO-15-009, CERN-EP-2016-066







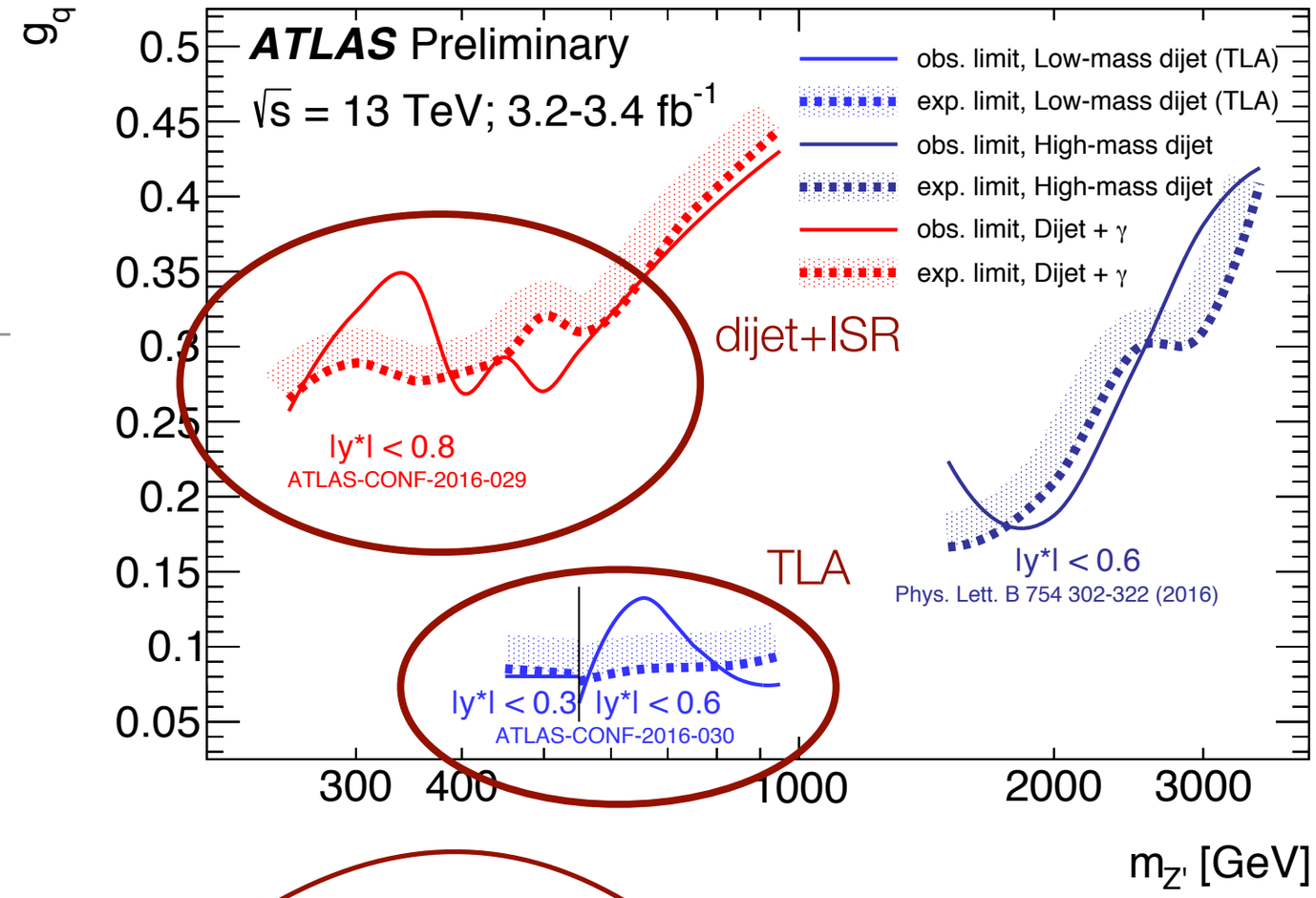
Limits

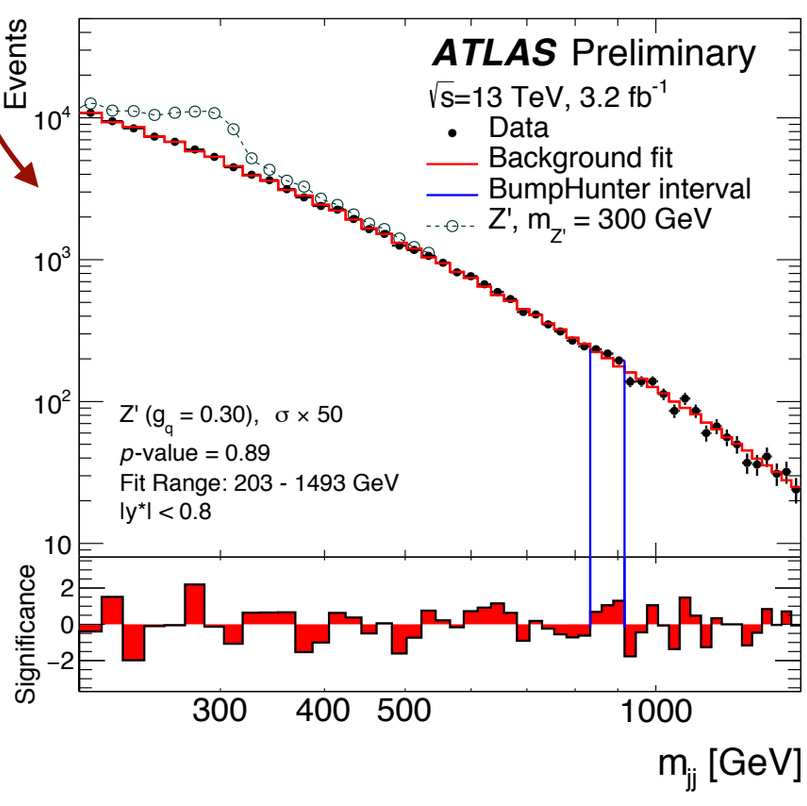
q*	CI n_{LL} = +1
5.2 TeV (ATLAS)	12.0 TeV (ATLAS)
5.0 TeV (CMS)	12.1 TeV (CMS)

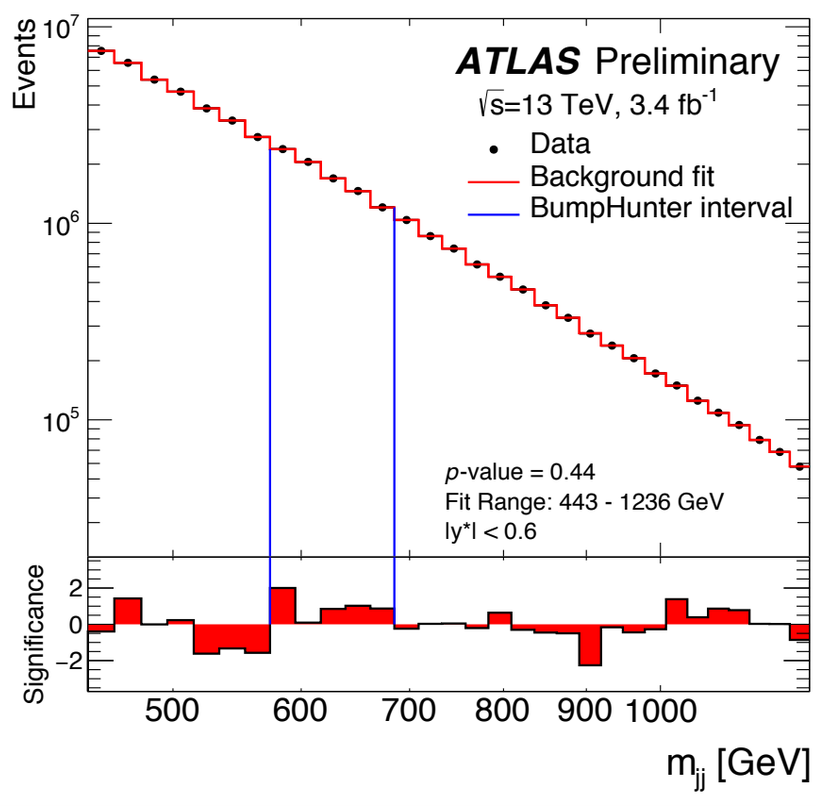
See Garabed's talk for more details!

Dijets at low masses

- Challenge in dijet analysis **below 1 TeV** is strong trigger prescales
- Wish to access this region for low-cross section, low-mass signals (Z')
- Solution 1: look for **dijet + ISR** (jet or γ) events and trigger on the ISR object



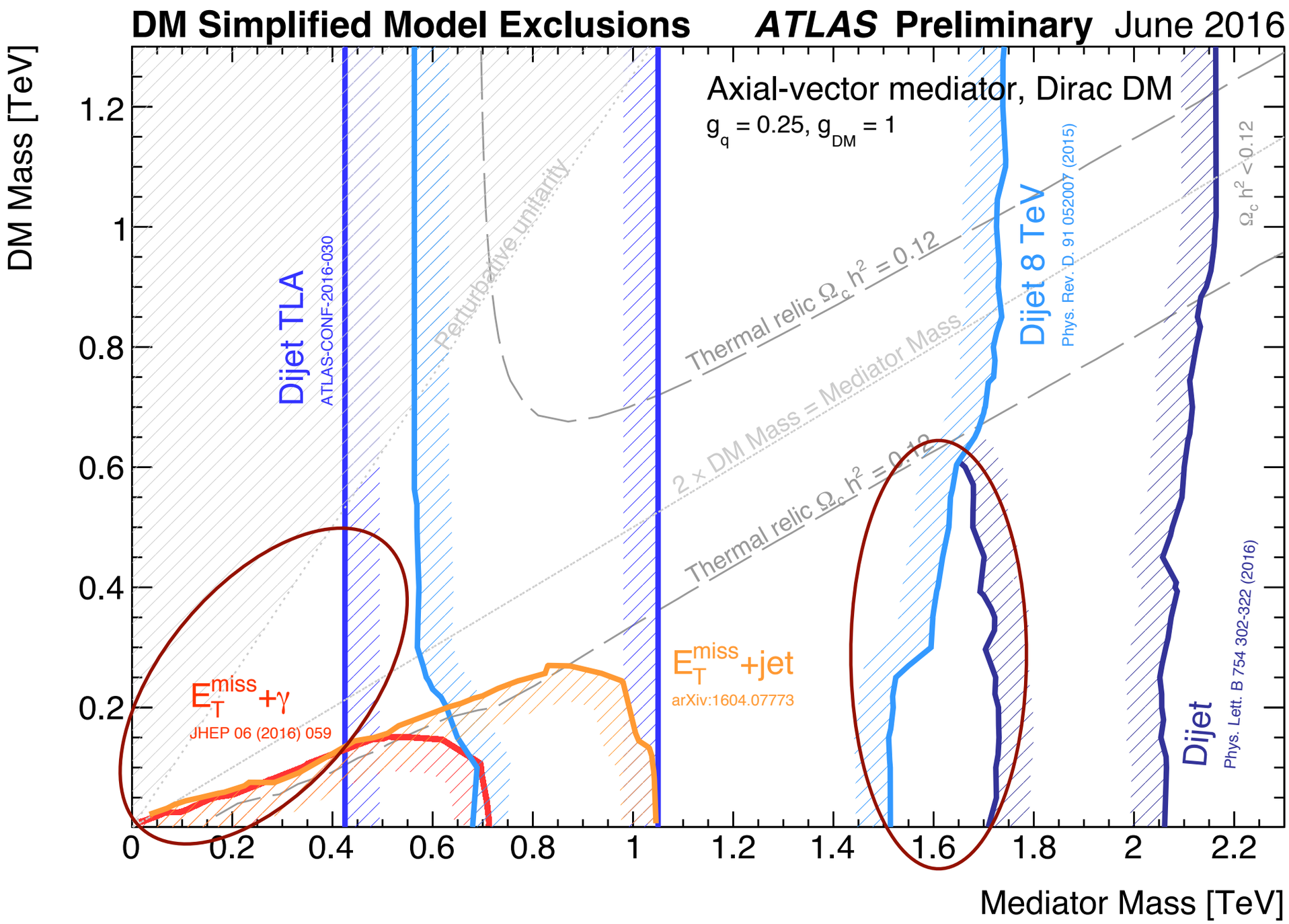




- Solution 2: **"Trigger level analysis"**. Save only partial event data to increase statistics.
  - Challenging! Requires special jet calibration for jets with only calorimeter level information
  - CMS used same strategy in 8 TeV

ATLAS-CONF-2016-029, ATLAS-CONF-2016-030, ATLAS-CONF-2016-031

DM including dijet limits: where do we stand?



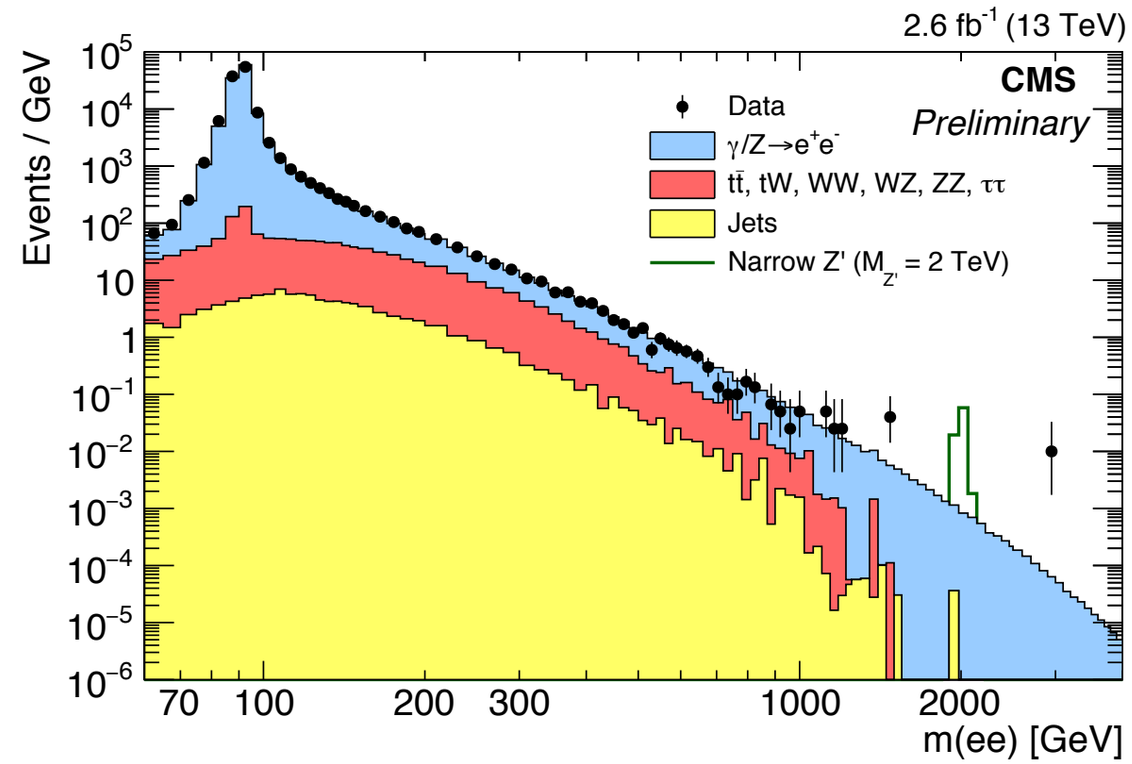
Limits on simplified DM are filling in remaining holes

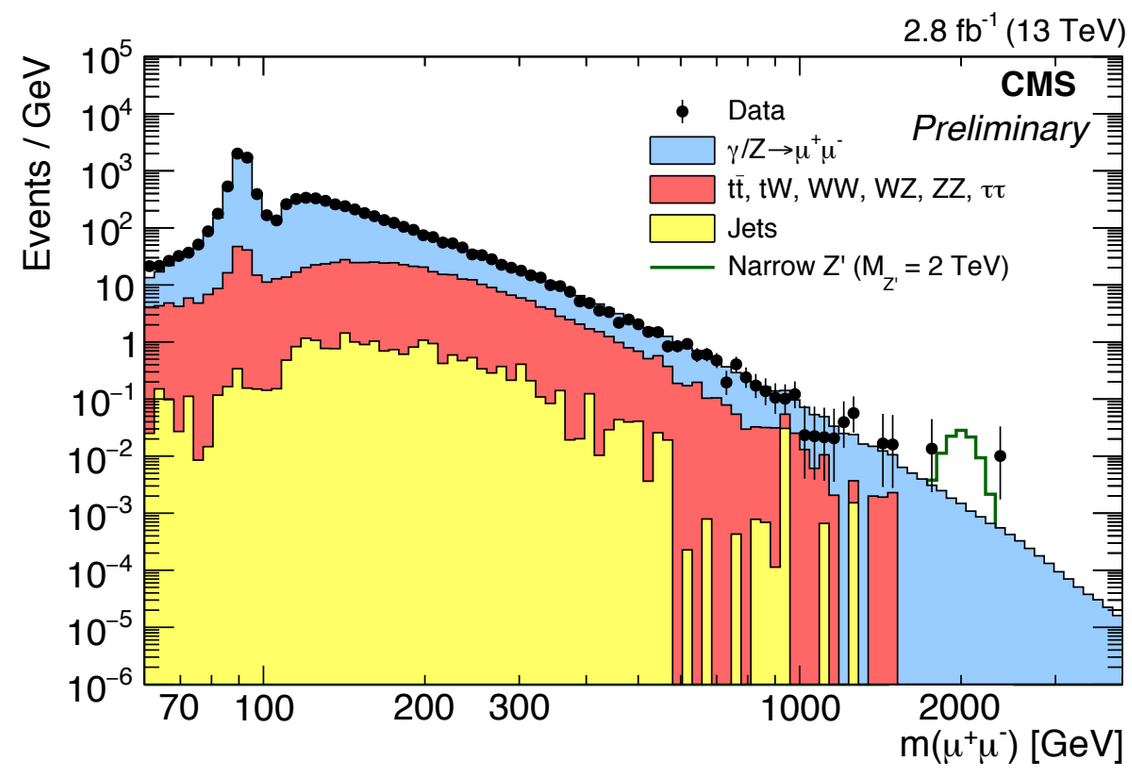
Most limits dramatically improved from 8 TeV!

CMS PAS EXO-15-005, ATLAS-CONF-2015-070

Di-lepton final states

- Models: **SSM Z'**, six narrow E6 gauge group model Z's
- Selection:
  - ATLAS: ≥2 **same-flavour isolated leptons**, p_T > 30 GeV; opposite-sign if μ. Select highest scalar sum-p_T lepton pair
  - CMS: Dedicated ee selection algorithm. Require isolated muons > 53 GeV of opposite sign.
- Systematics: Z/γ cross-section (PDF etc), lepton energy scale, trigger, reco., isolation efficiencies, MC stats. Data driven bkg estimation in ee.
- CMS also publishes analysis in di-τ channel



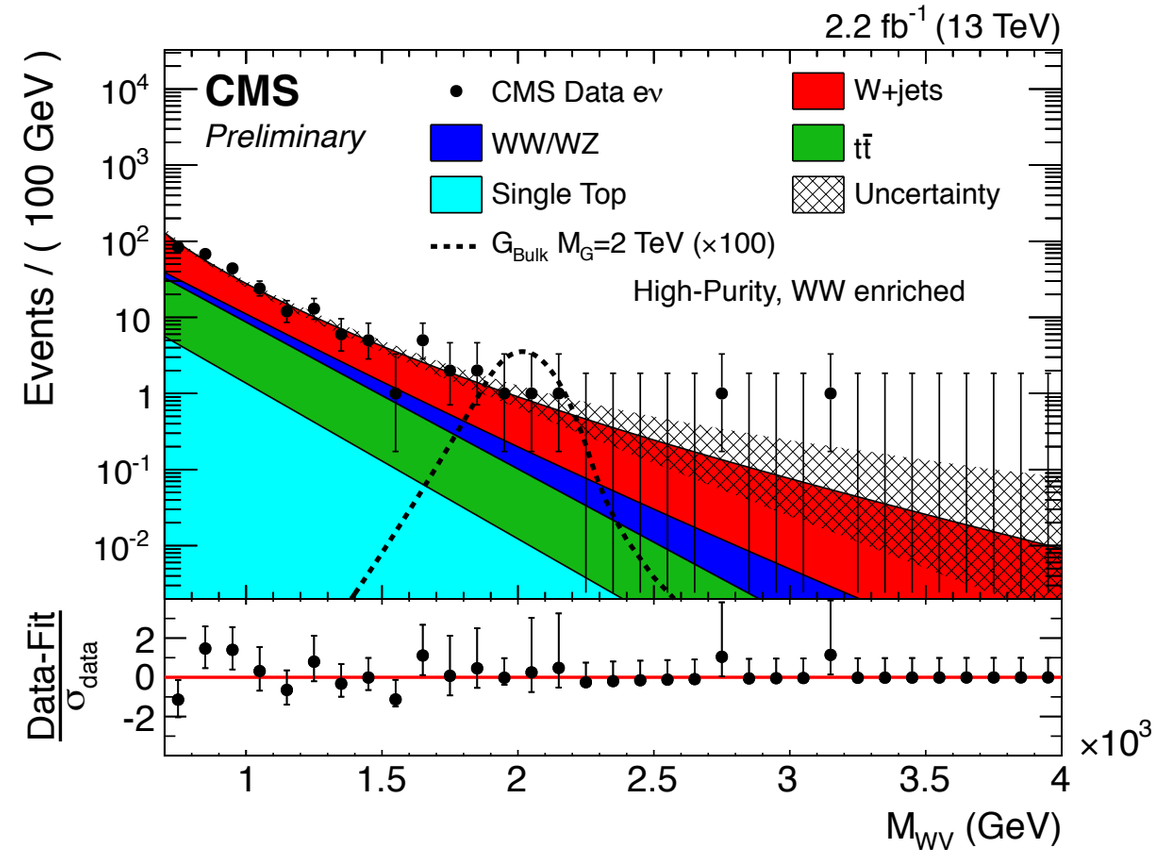


Limits

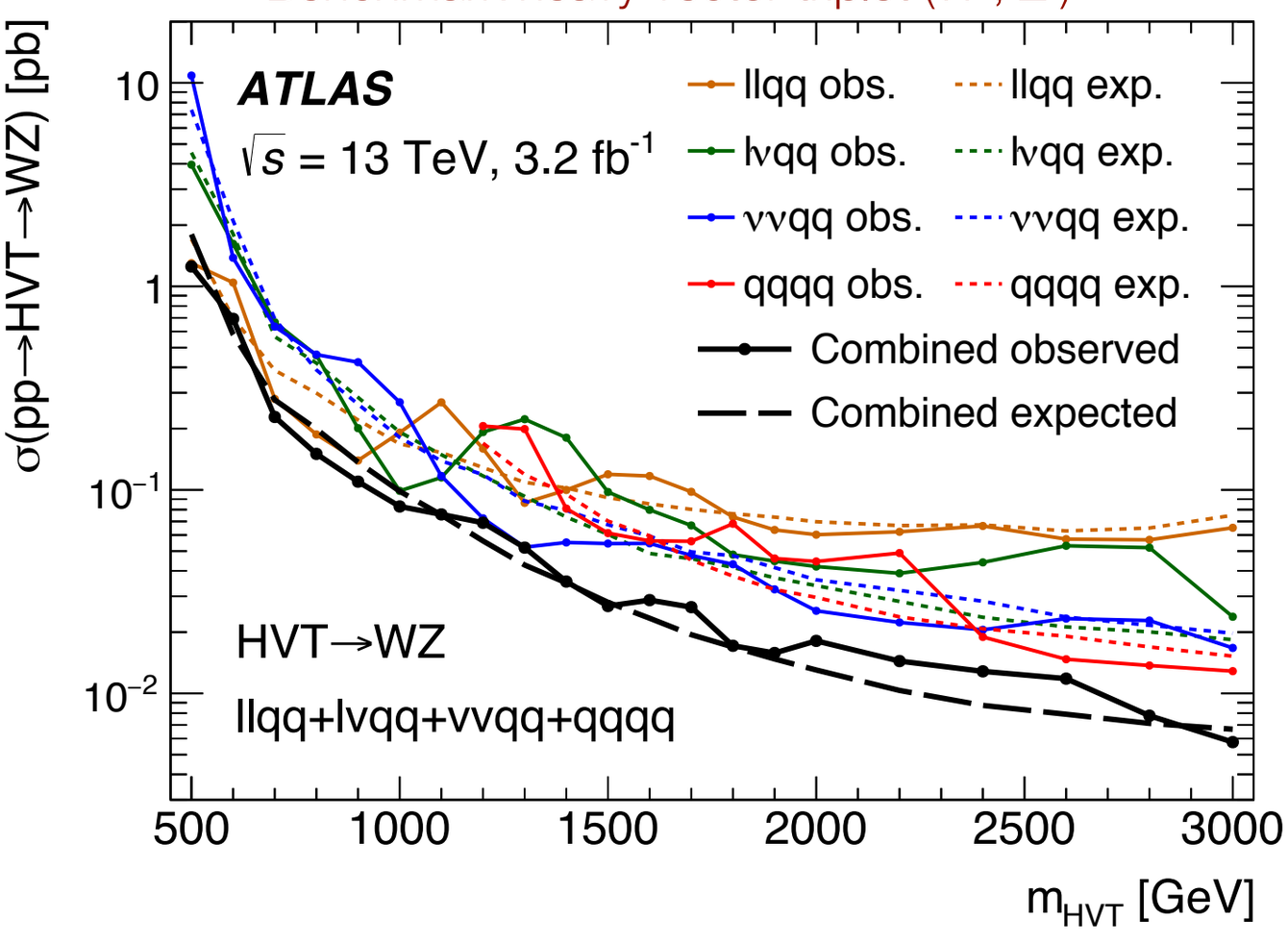
Z'_{ψ}	Z'_{SSM}
2.8 TeV (ATLAS)	3.4 TeV (ATLAS)
2.6 TeV (CMS)	3.15 TeV (CMS)

Resonances in diboson final states

- **W(lν)+jj, Z(ll)+jj, Z(νν)+jj** final states reconstructed by using single large-R jet plus isolated, high pT leptons and/or large MET.
- **W/Z->qqqq** reconstructed as 2 large-R boson-tagged jets



Benchmark heavy vector triplet (W', Z')

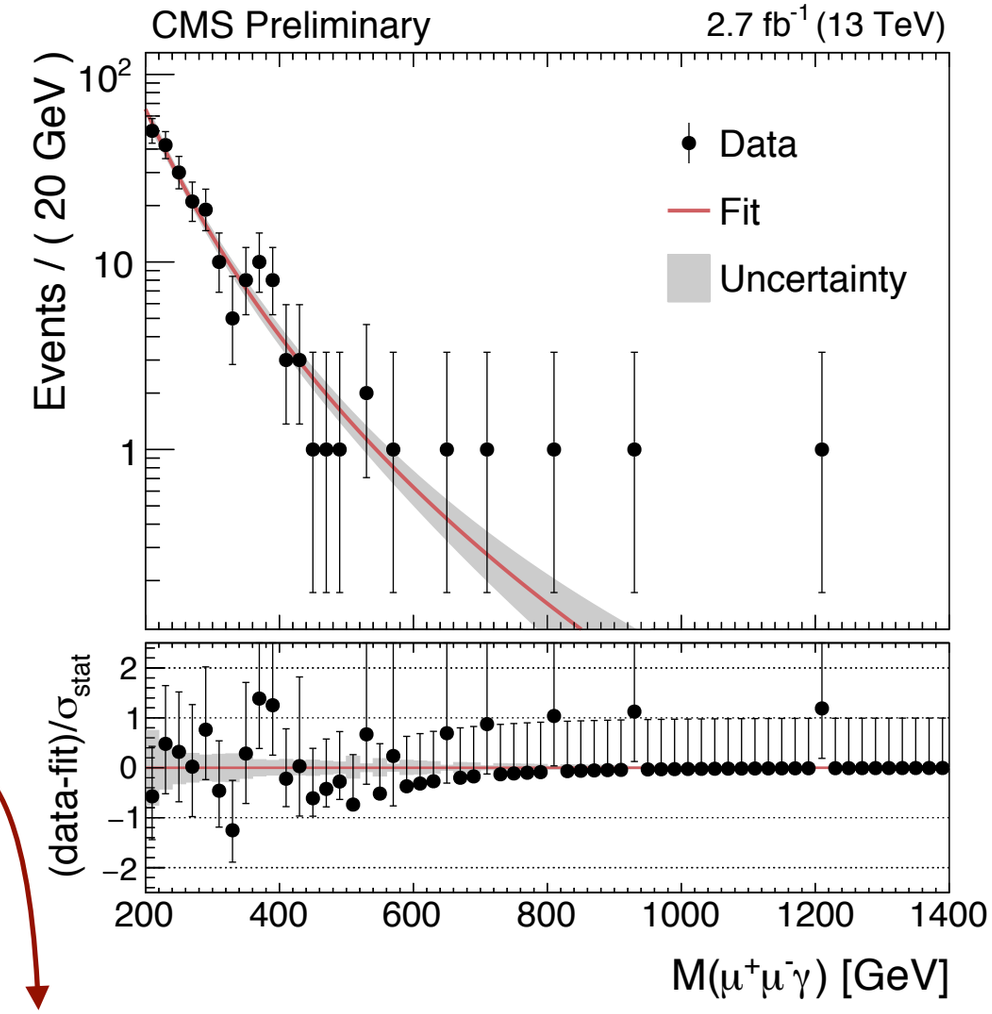


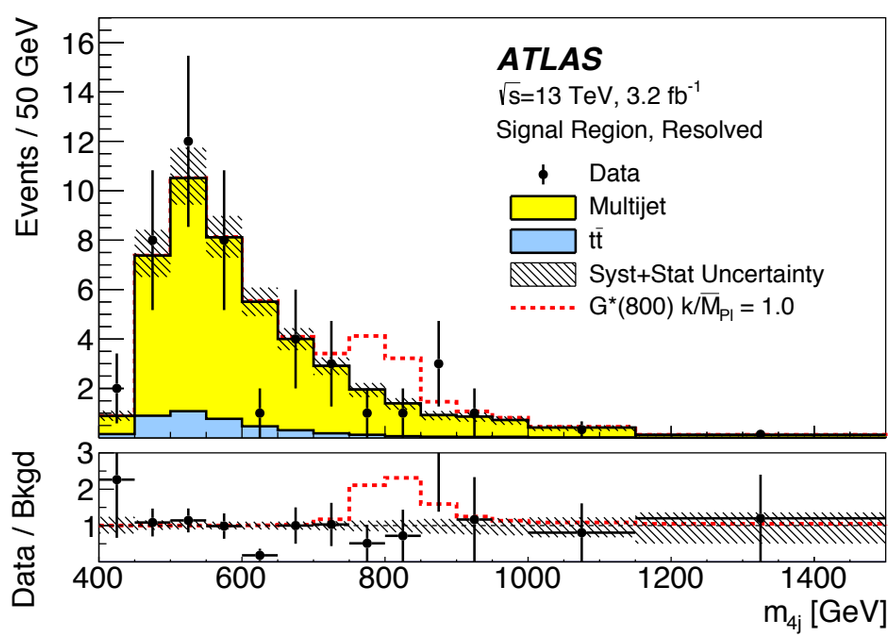
- Backgrounds for semileptonic channels: SM diboson and W/Z+jets, ttbar, mis-ID'd jets and photons.
- Estimate qqqq bkg with **dijet fit** to data
- Estimate semileptonic backgrounds by combined fit of **MC** across control regions

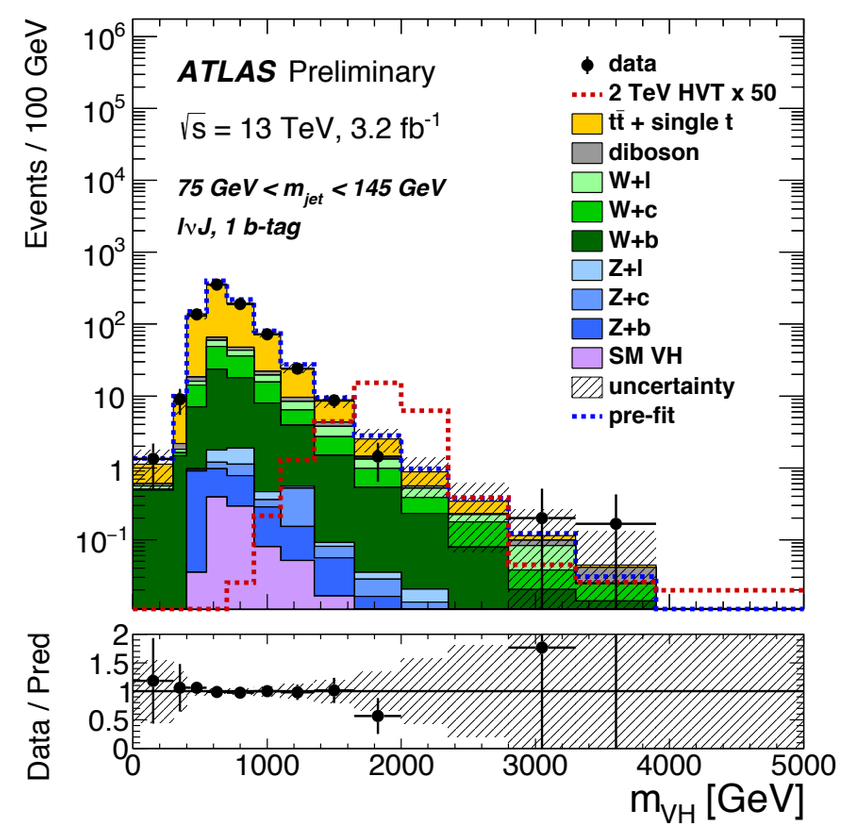
ATLAS CERN-EP-2016-106, CMS PAS EXO-15-002

Other heavy diboson signatures

- **Z+γ** sets limits on generic signals of varying widths
  - Z(ee,μμ). CMS includes Z(ττ) analysis, ATLAS includes Z(qq).
  - Background taken from fit
- **W/Z+h** constrains W' and Z' models plus generic resonances
- **X->hh->(bb)(bb)** constrains KK gravitons
  - Resolved analysis: ≥ 4 b-tagged jets in two nearby, high-pT dijet pairs. Boosted analysis: ≥2 large-R jets with 3 or 4 b-tags



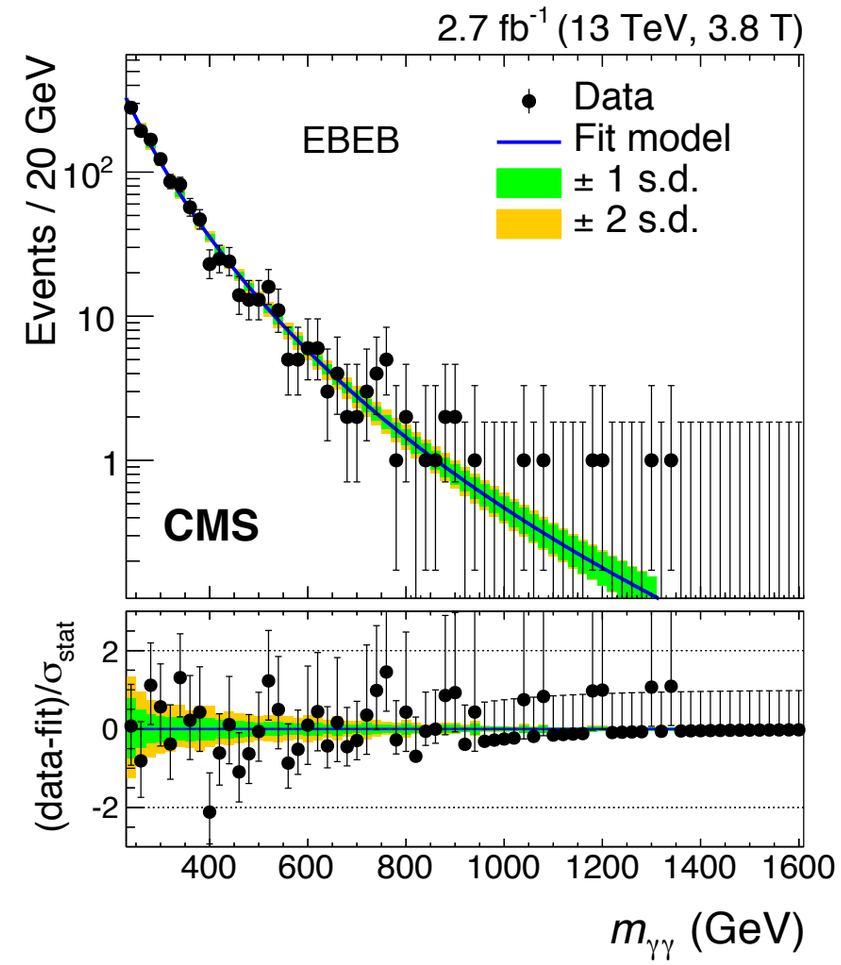


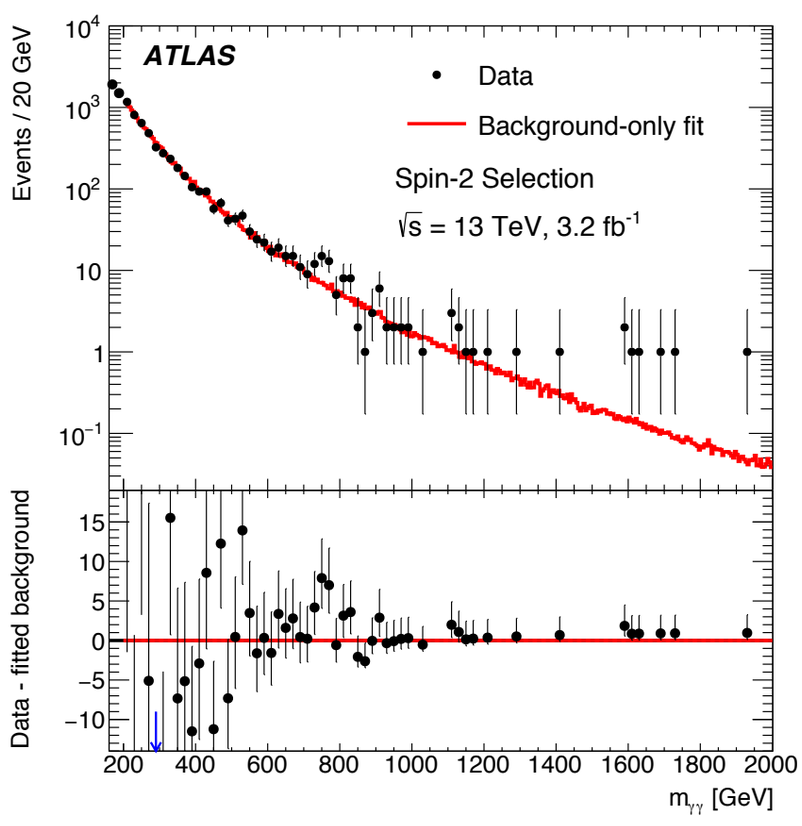


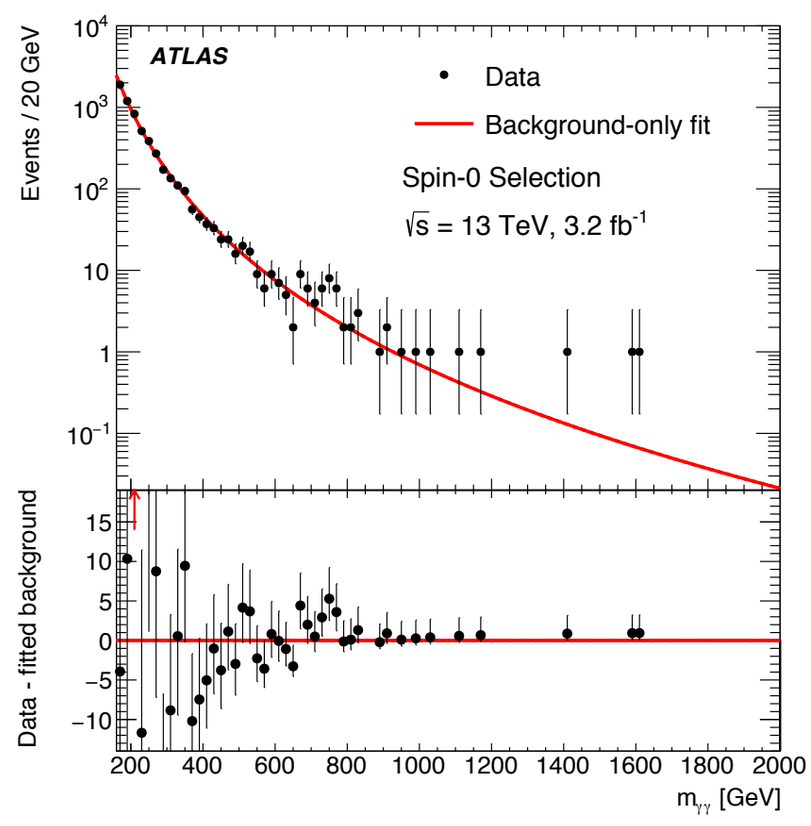
CMS PAS EXO-16-019,
ATLAS CERN-EP-2016-142,
ATLAS EXOT-2015-18

The diphoton final state

- Caused a great deal of fervour in the community with these results!
- **Pairs of isolated photons** passing cleaning cuts are parameterised by a smooth fit
  - In CMS, divide into separate spectra by detector region
  - In ATLAS, fits include signal template and therefore 2 distinct results







- Constrain spin-0, spin-2 RS gravitons
- **Excess at 750 GeV** has global significance 2.1σ in ATLAS and 1.6σ in CMS. Require 2016 data to confirm or deny the presence of interesting physics!

ATLAS CERN-EP-2016-120
CMS-EXO-16-018

… and a whole host of other exotic searches

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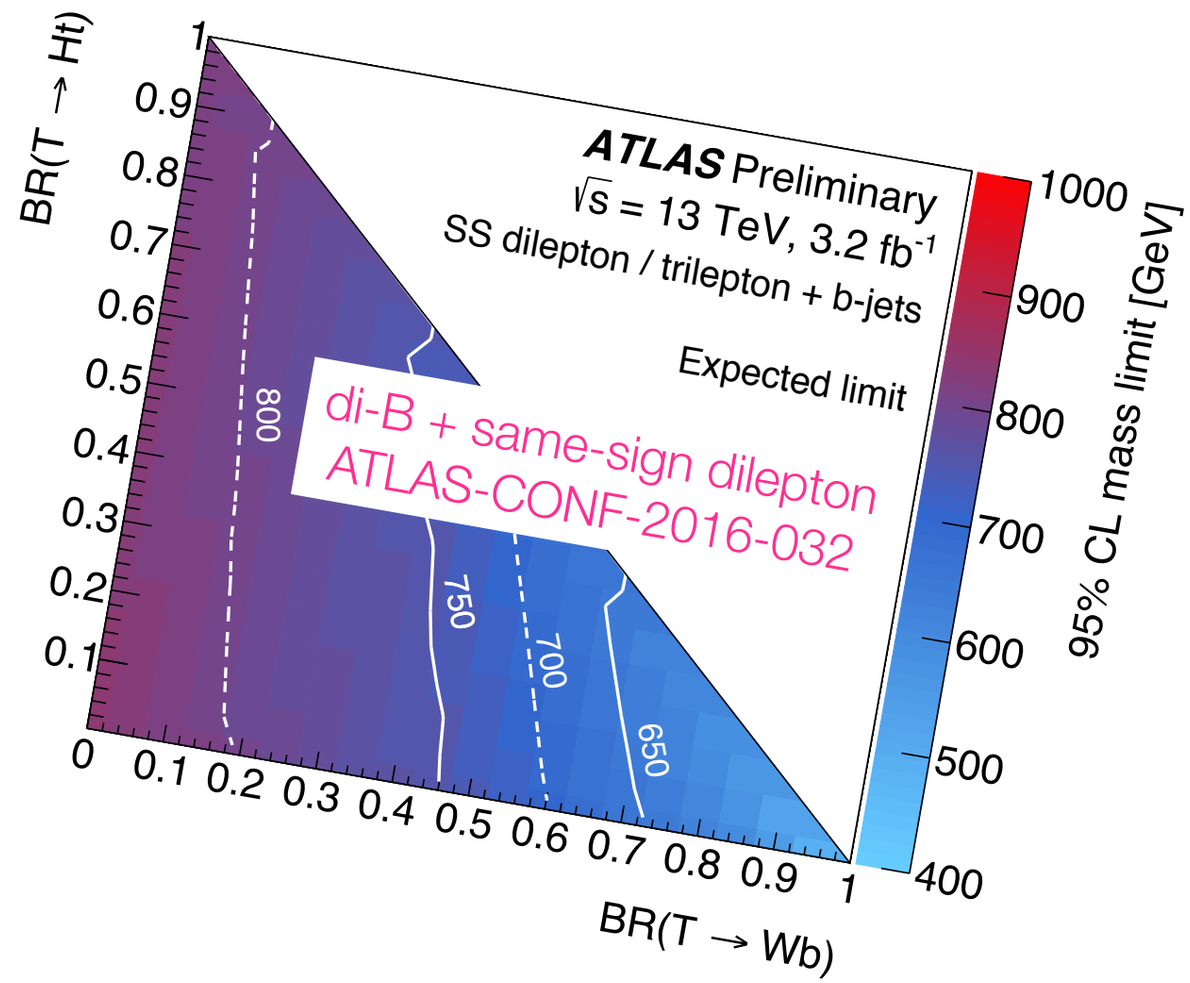
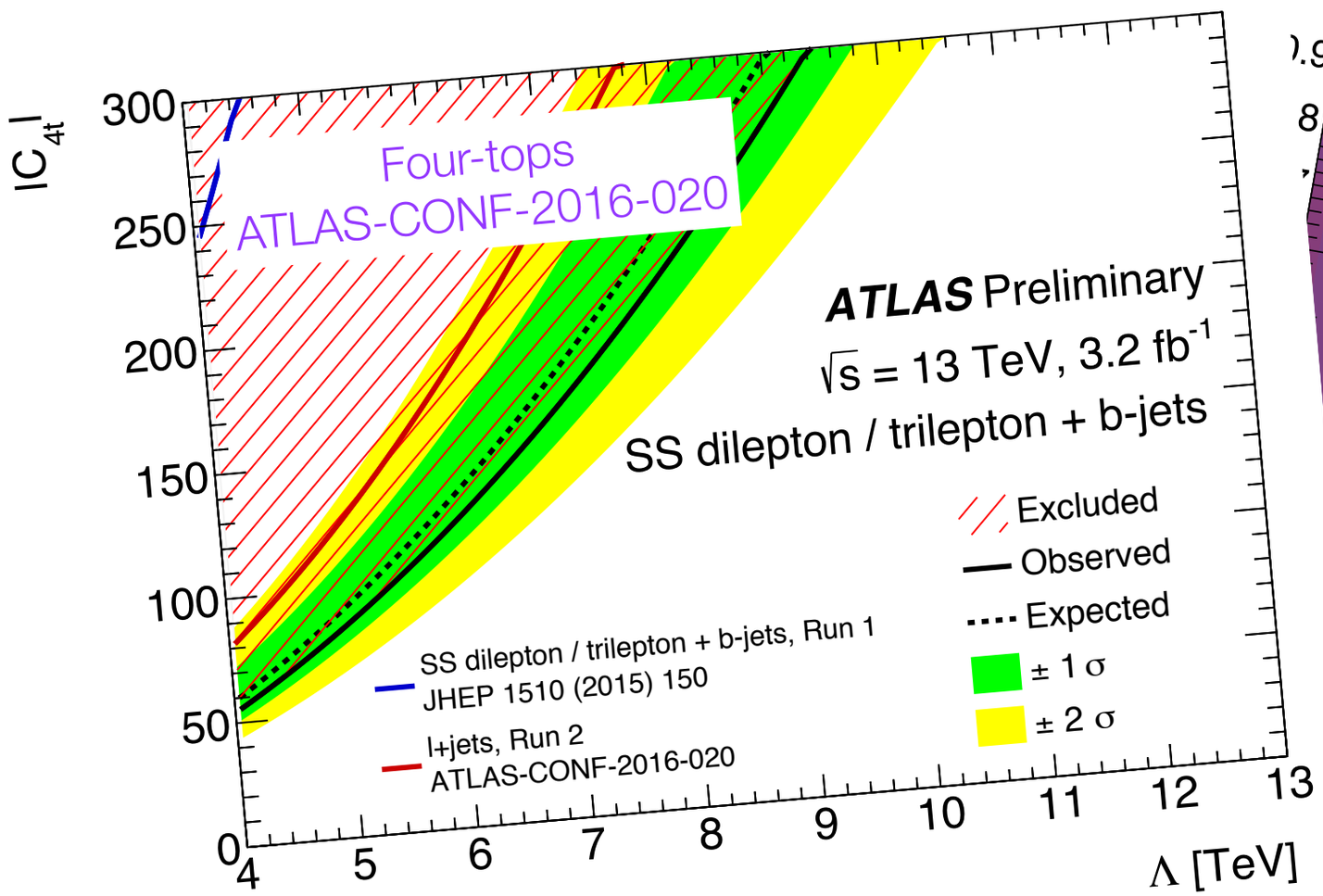
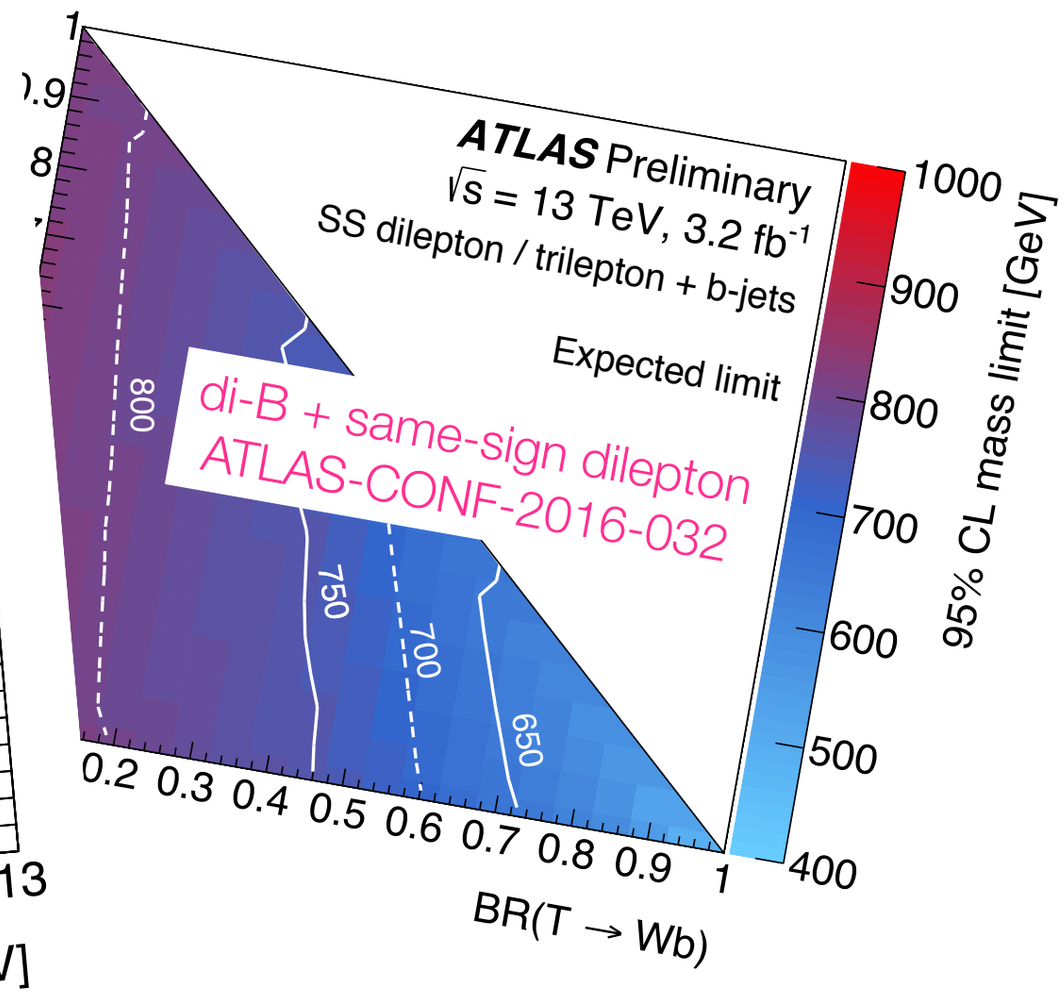
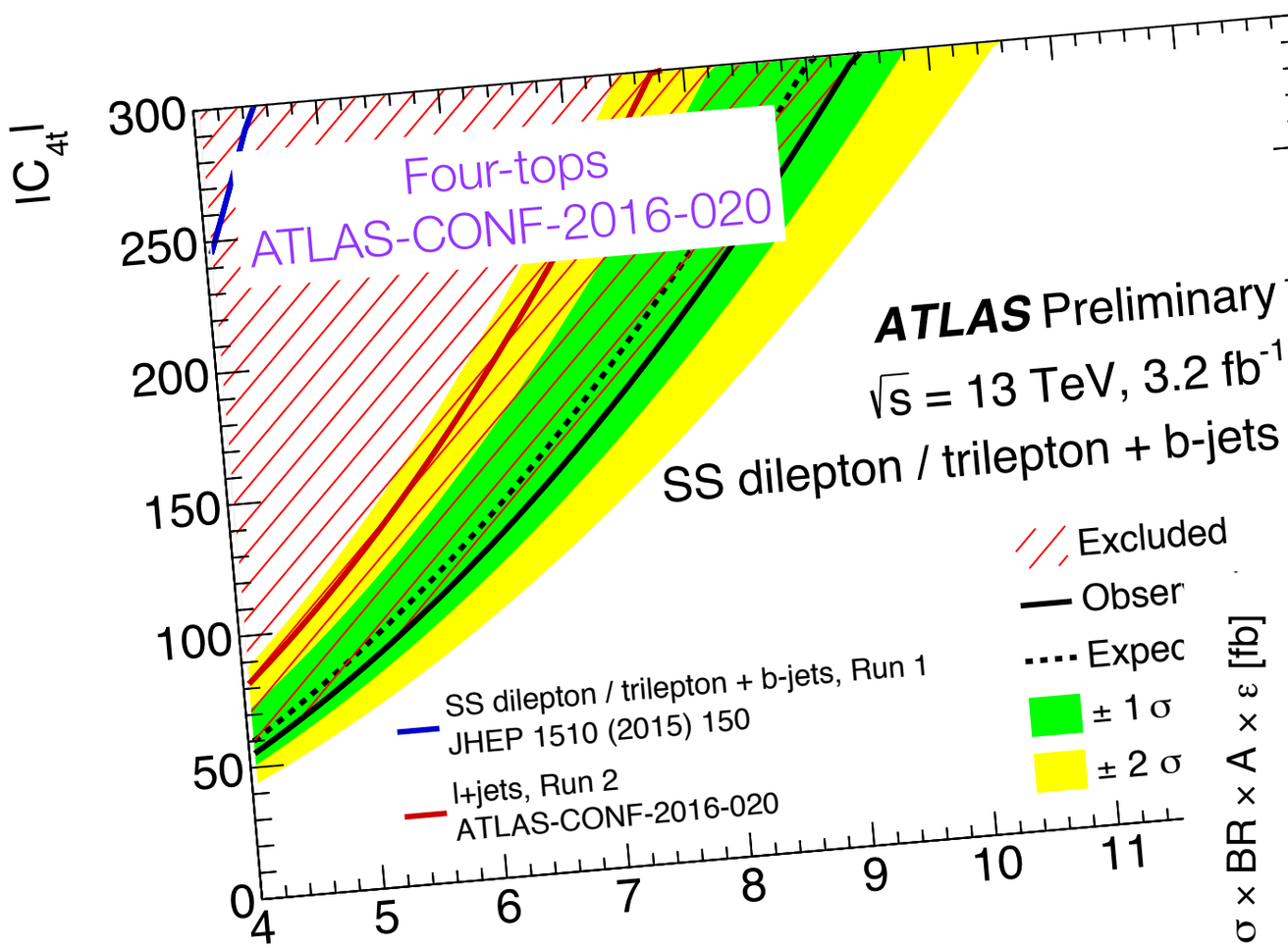


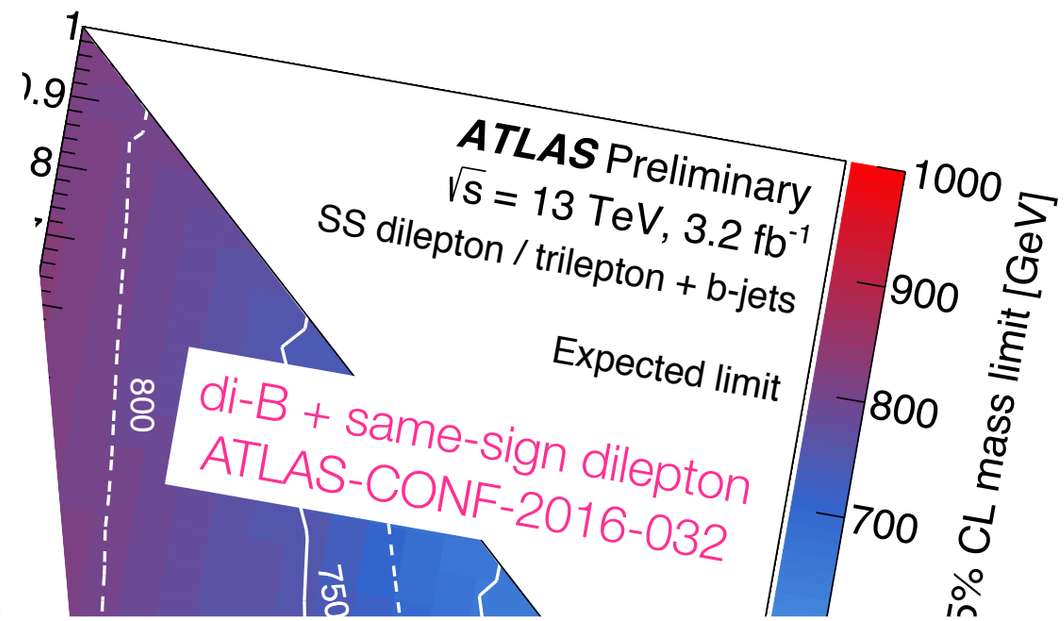
… and a whole host of other exotic searches

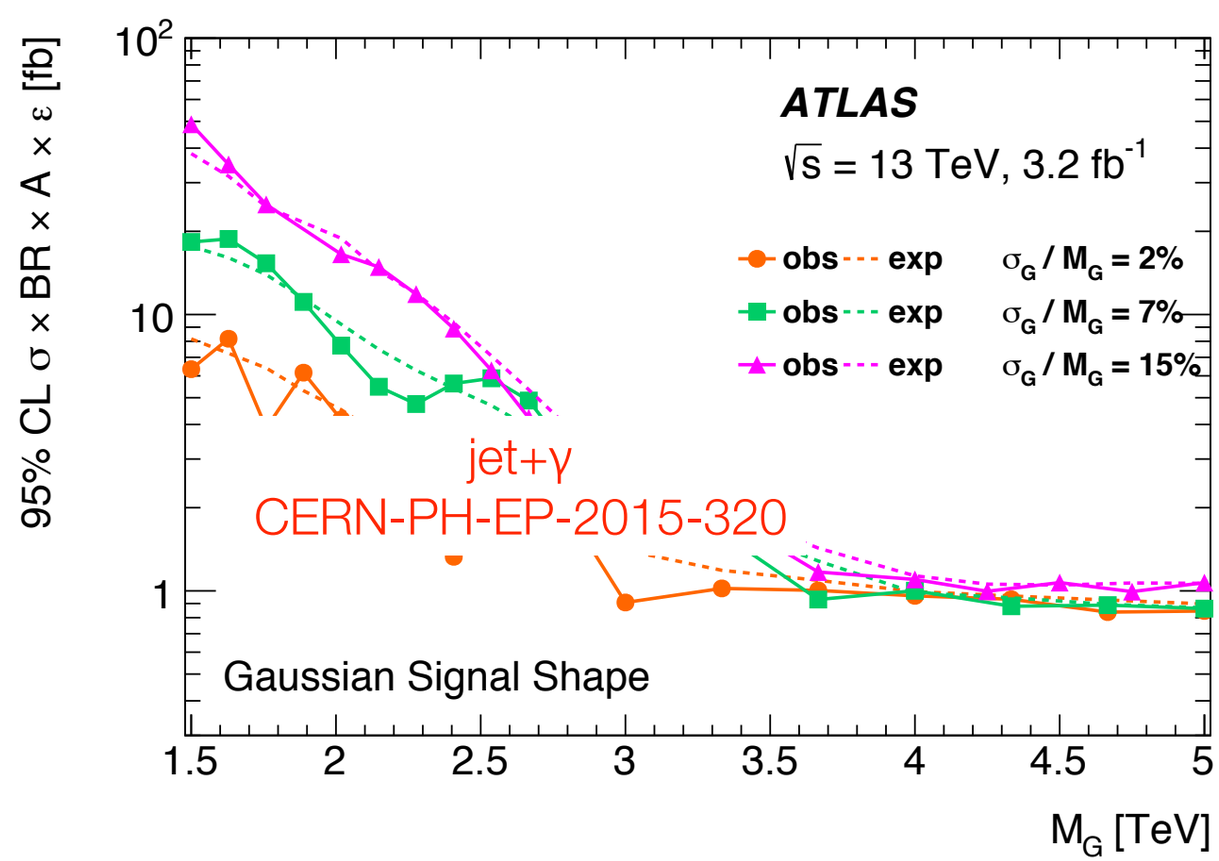




… and a whole host of other exotic searches







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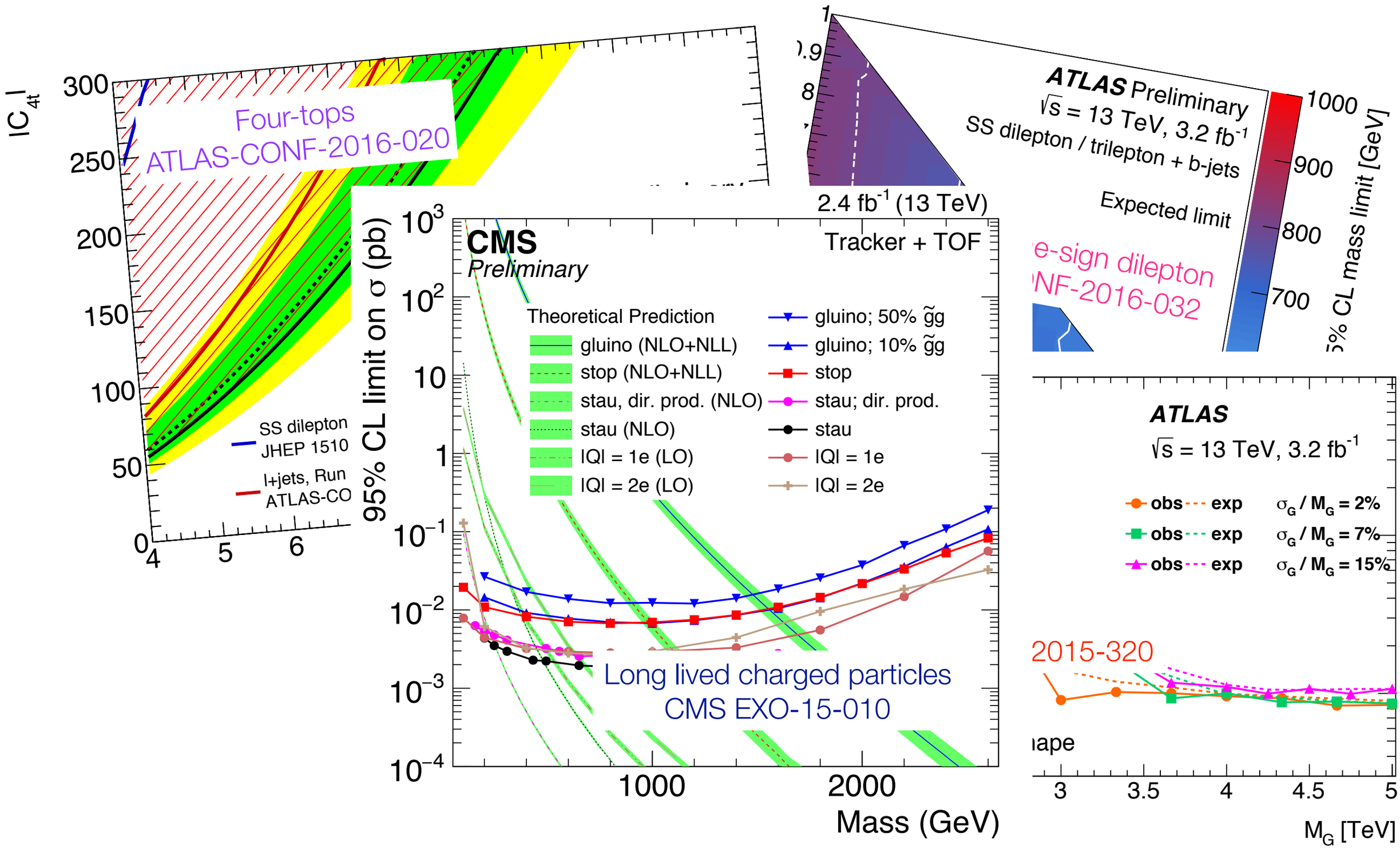
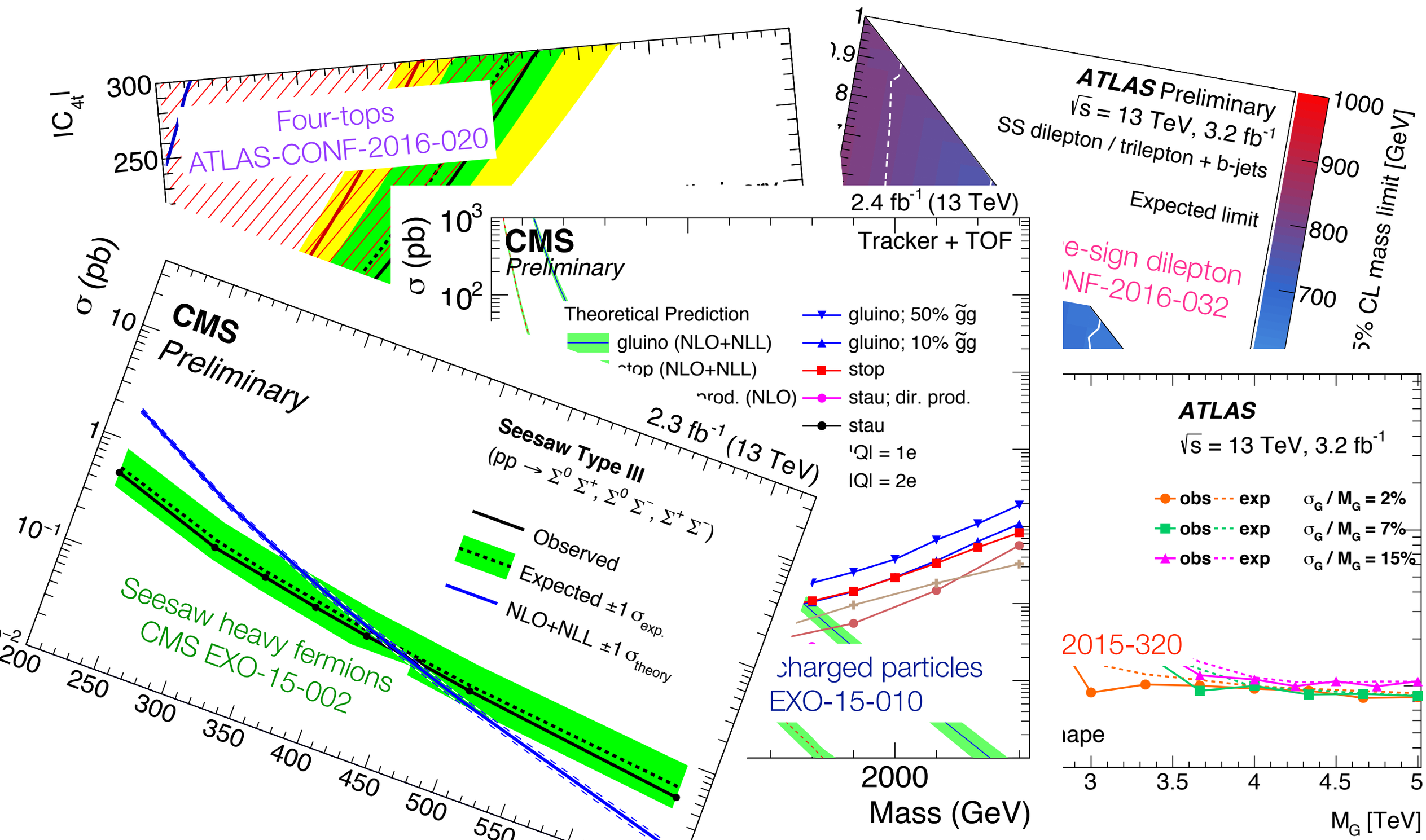


… and a whole host of other exotic searches



The exotic landscape at 13 TeV

Empty and desolate, yet still fun to explore!

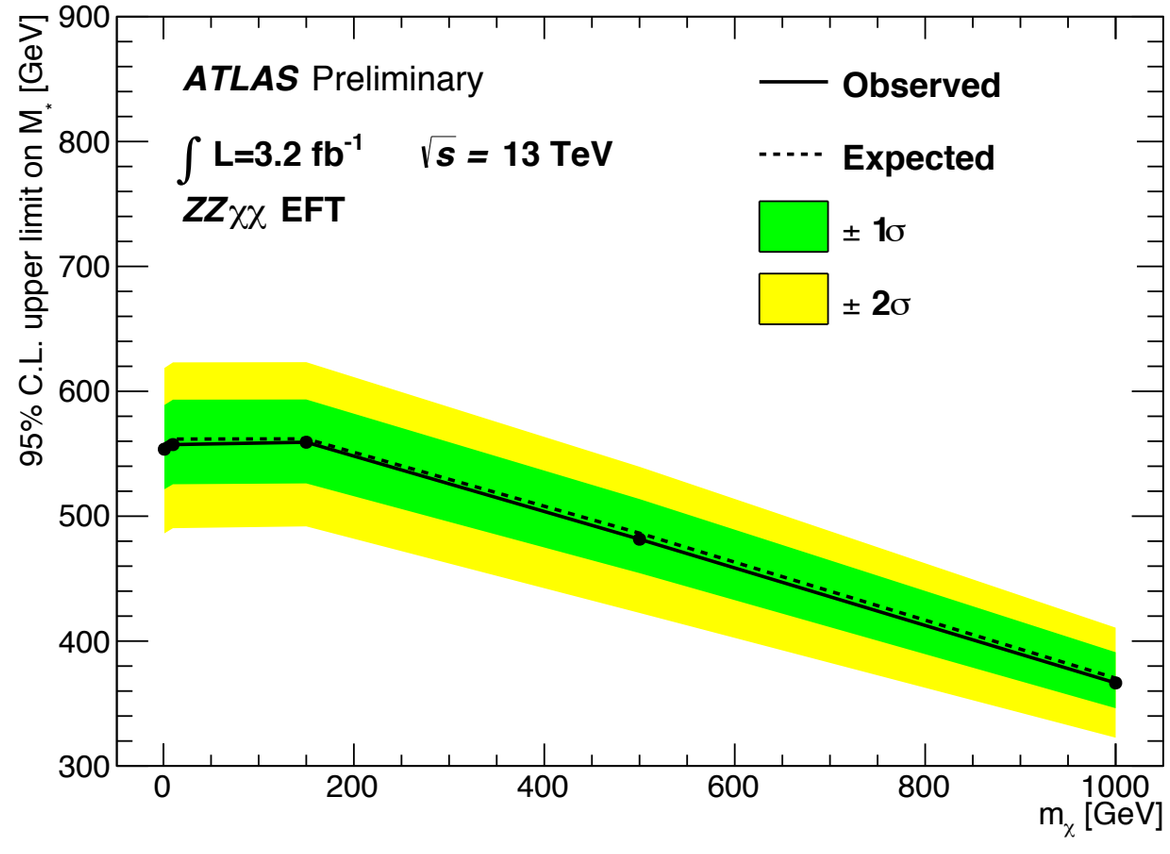
Does the diphoton analysis offer excitement on the horizon?

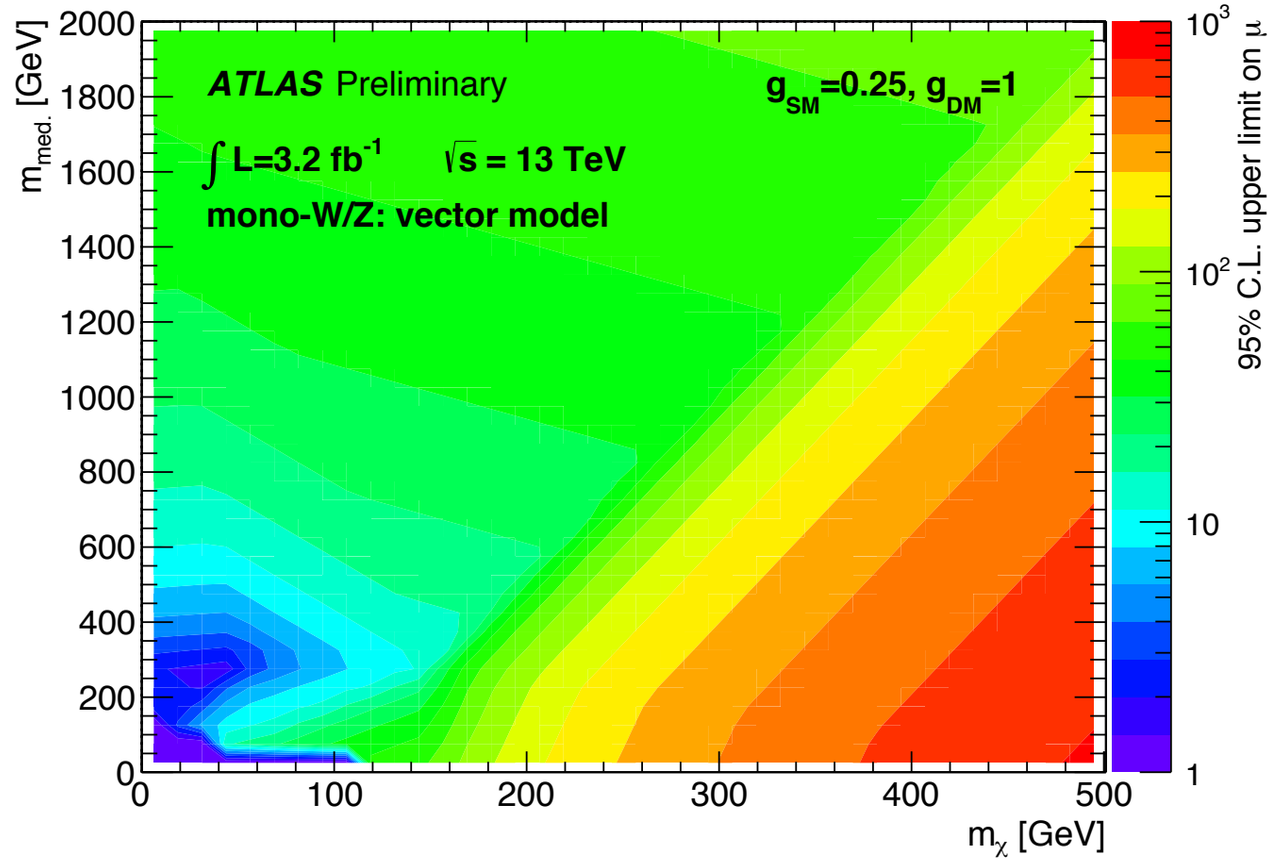
Backup

W/Z hadronic + MET

- Selection
  - 1 large-R jet, MET > 250 GeV isolated from all small-R jets, no leptons
  - Large-R jets reclustered, selected by jet mass and D_2 substructure variable
- Systematics:
  - Dominant: modelling of large-R jet parameters (D2, mass, energy)
  - Other: small-R JES, lumi, reconstruction and ID efficiency for leptons
- Backgrounds: ttbar, W+jets, Z+jets, single-top

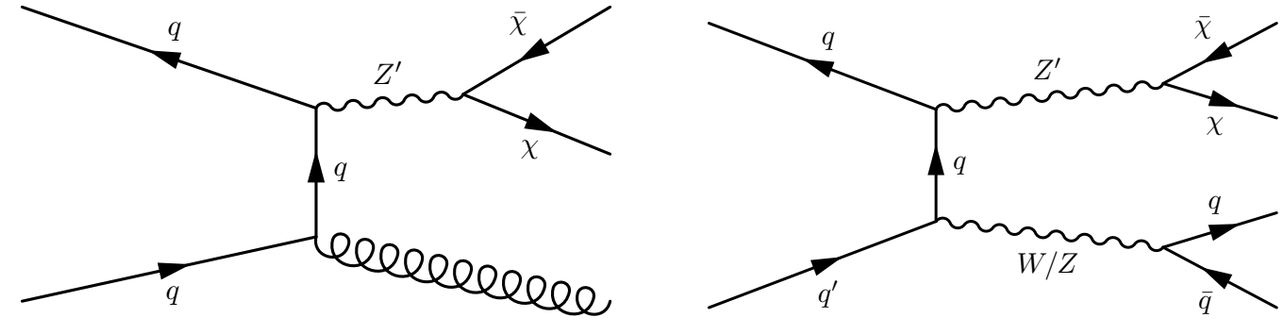
ATLAS-CONF-2015-080

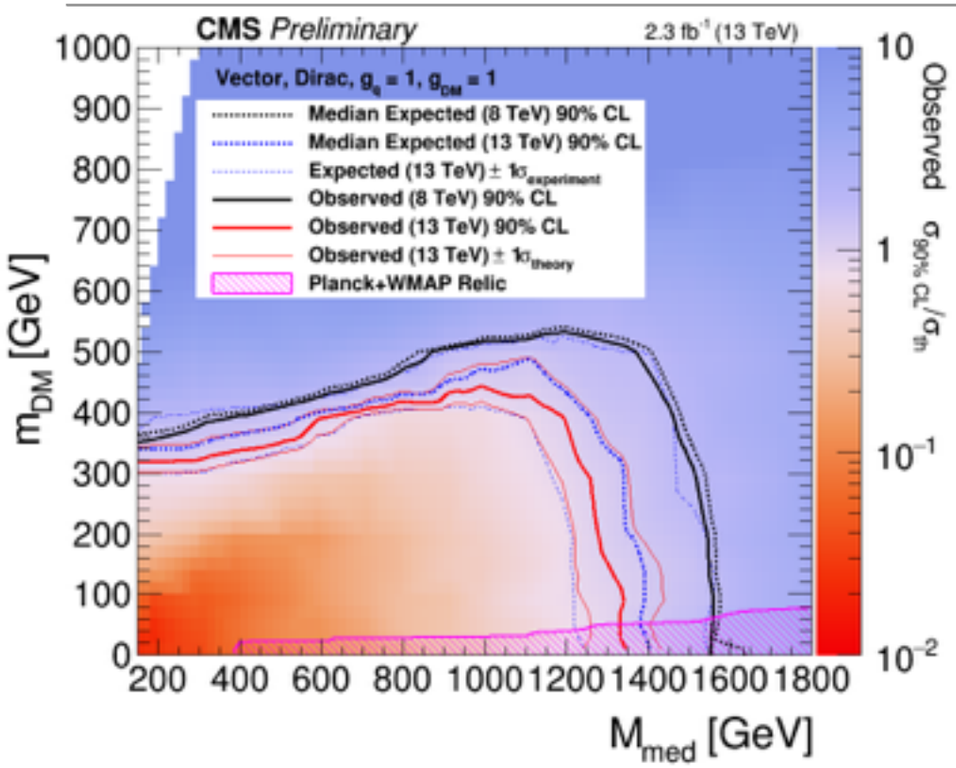


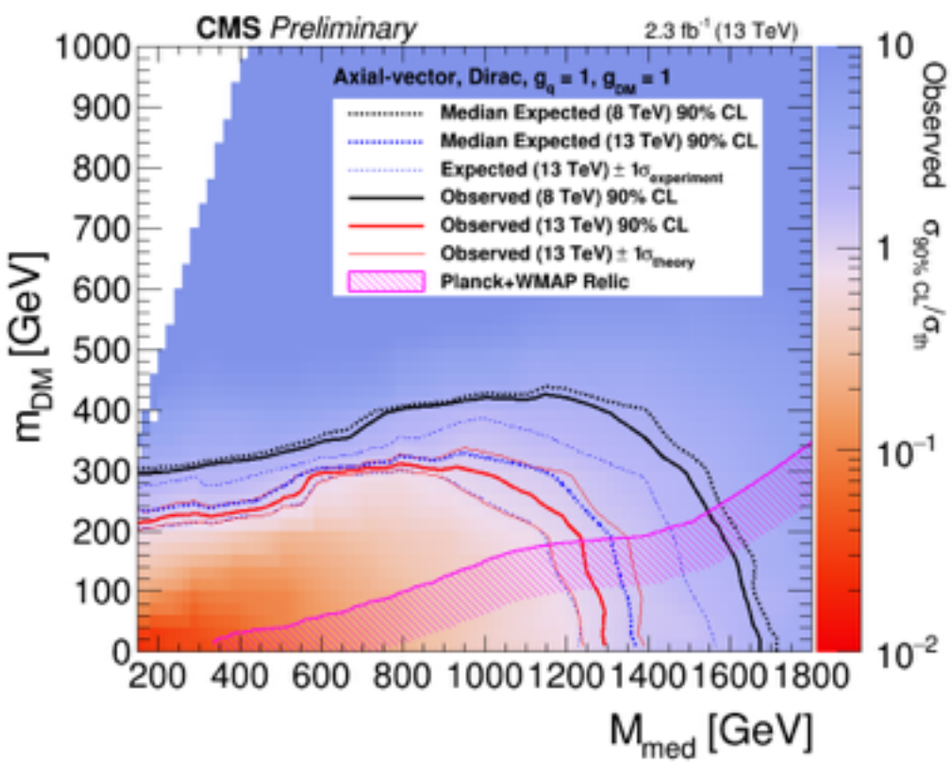


CMS PAS EXO-16-013

Multijet + MET







- ≥ 2 jets and high MET. Lepton veto. MET is kinematic variable
  - For mono-V look at AKT8 jets with n-subjettiness cut
  - Includes mono jet (top left) and mono-vector boson hadronic (top right) signatures
- Backgrounds: Z(vv)+jets, W(vl)+jets dominant & taken from data control regions. Top and diboson subdominant and taken from MC.
- Systematics: V-tagging in large-R jets, normalisation of top & diboson background, luminosity, b jet veto efficiency
- Consider vector, axial-vector simplified models

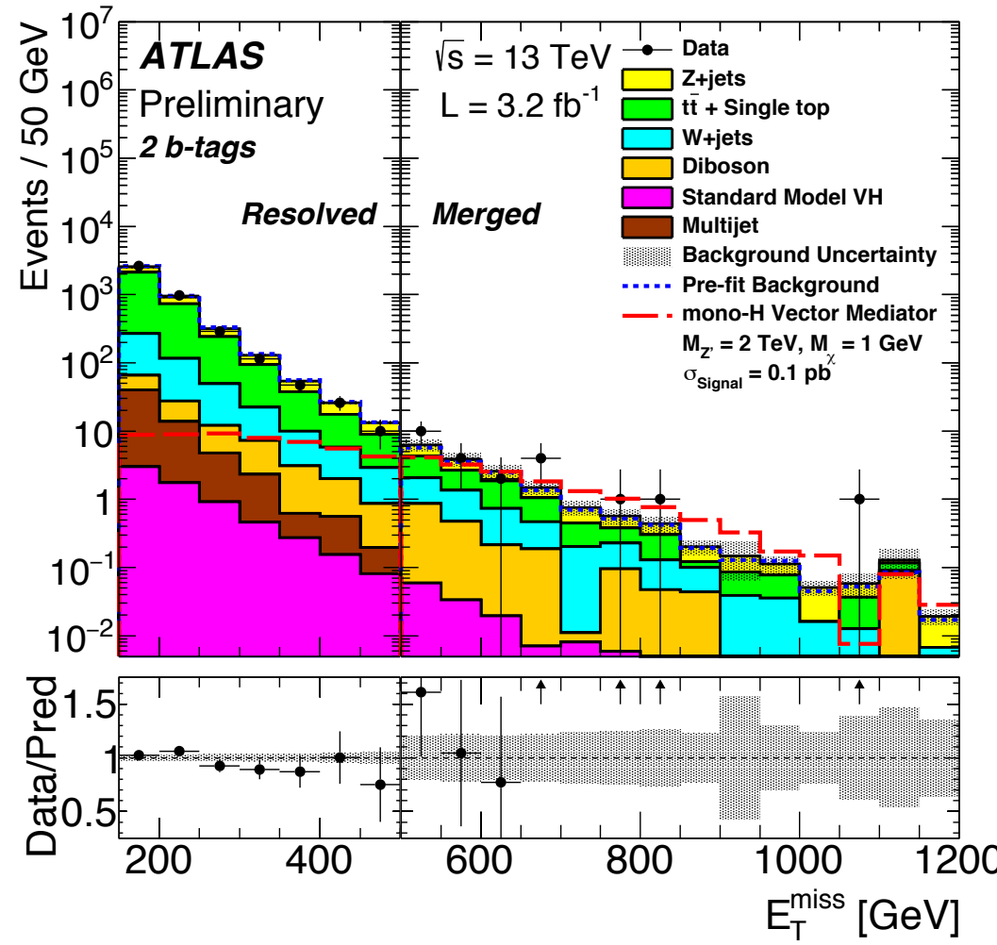
Limits

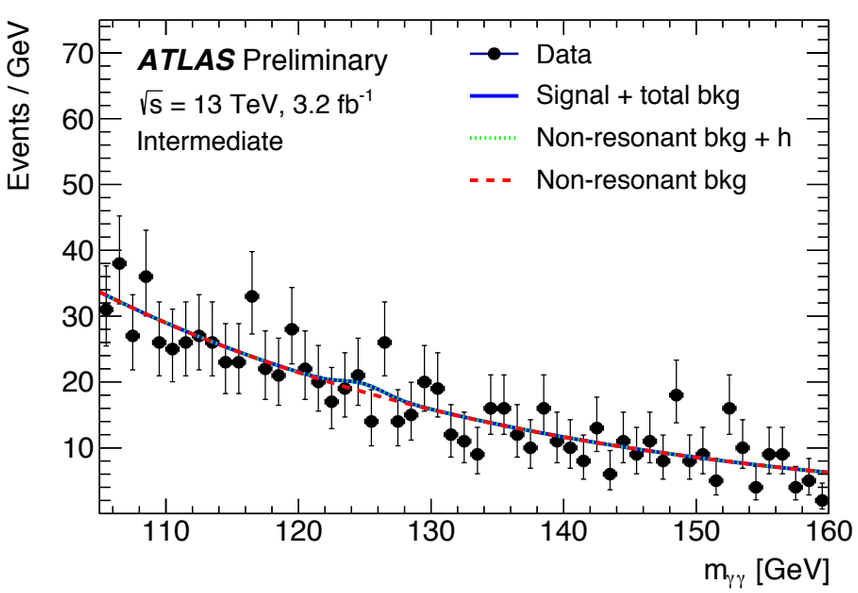
Vector, axial-vector mediators @ 90% CL: 1.3 TeV

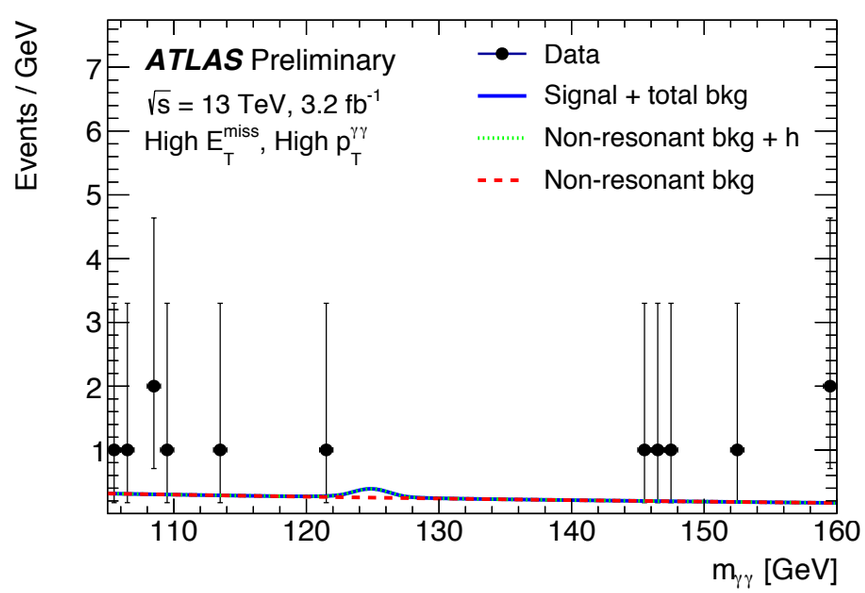
Higgs + MET

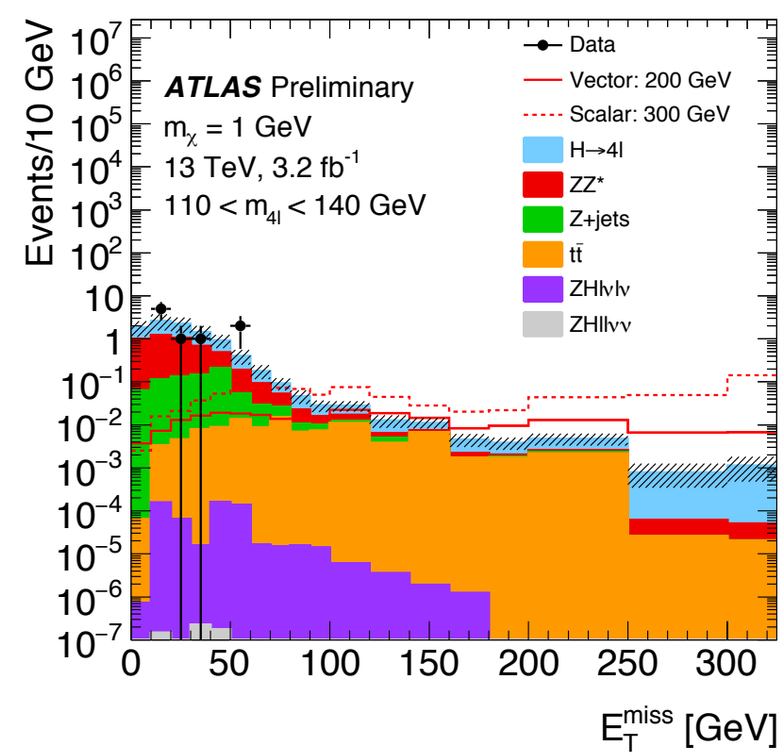
ATLAS-CONF-2016-019
ATLAS-CONF-2016-011
ATLAS-CONF-2015-059

- All s-channel vector mediators Z' with higgs as ISR/FSR
- **H(bb)+MET**: High MET, no leptons, resolved (2 small-R jets) and boosted (large-R jet with 2 ass. track jets) channels
- **H(γγ)+MET**: 2 central isolated photons. High MET. Modelled with fit; count number of events with mγγ in Higgs mass window.
- **H(llll)+MET**: reinterpretation of measurement results extended to high-MET region

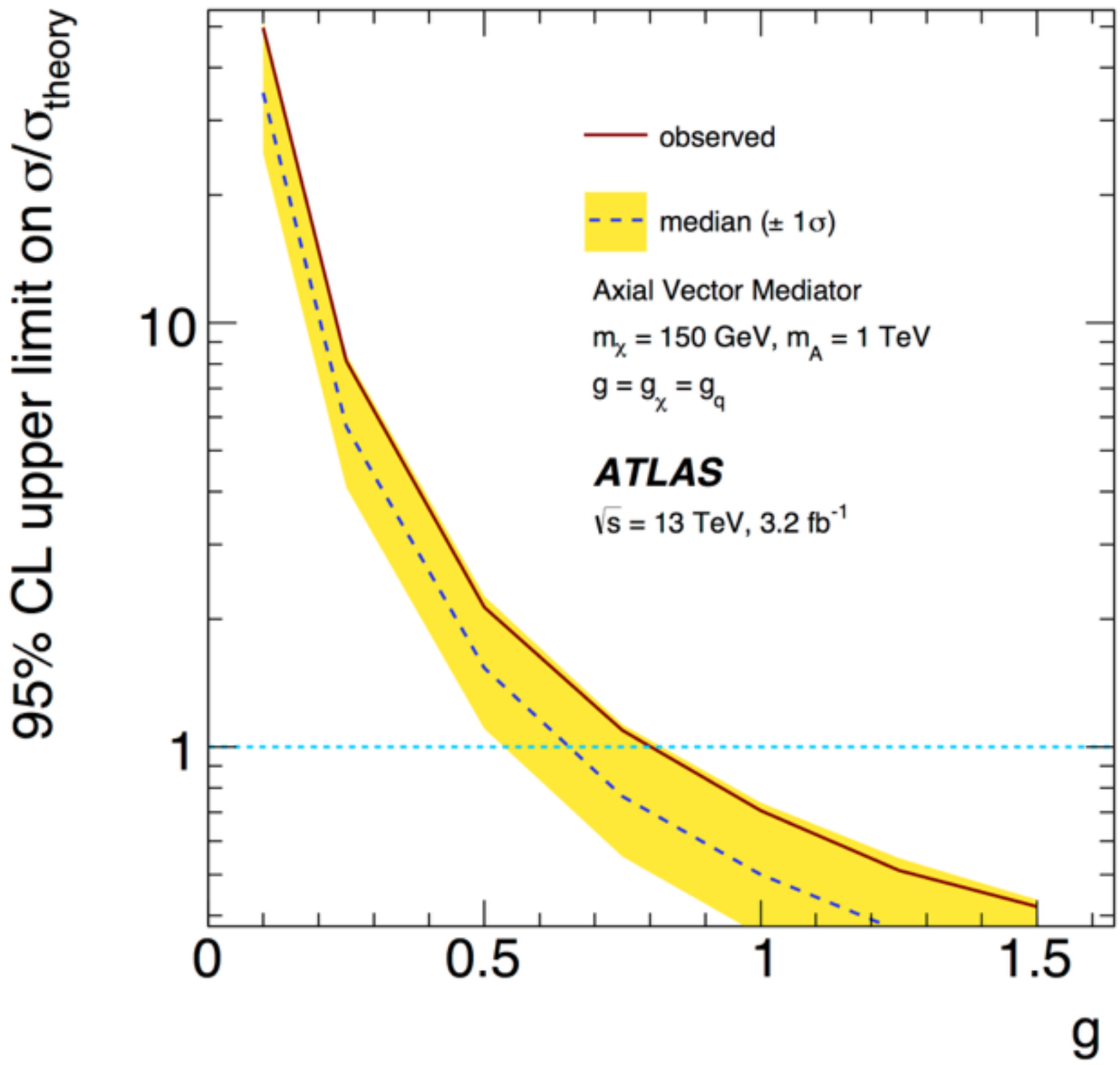




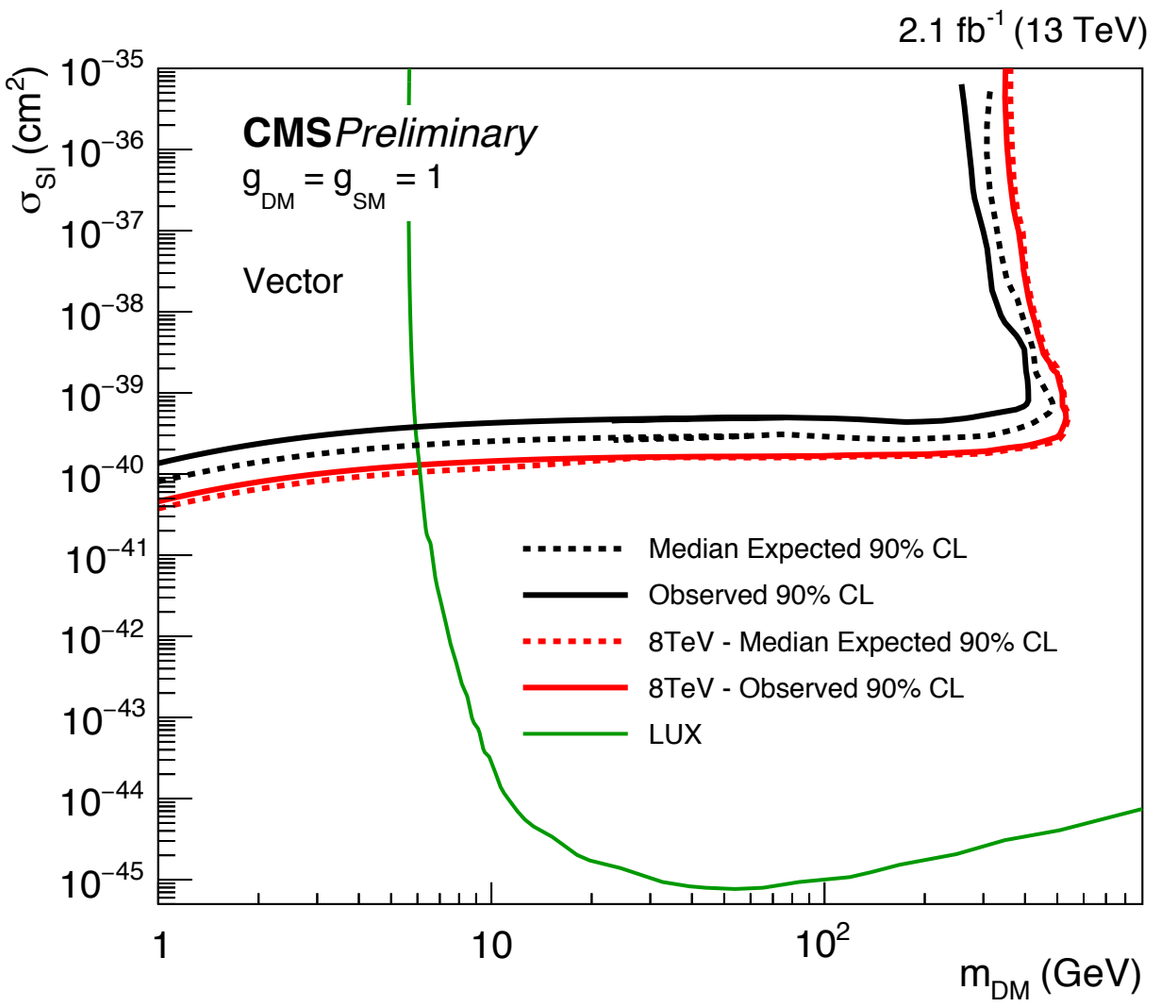


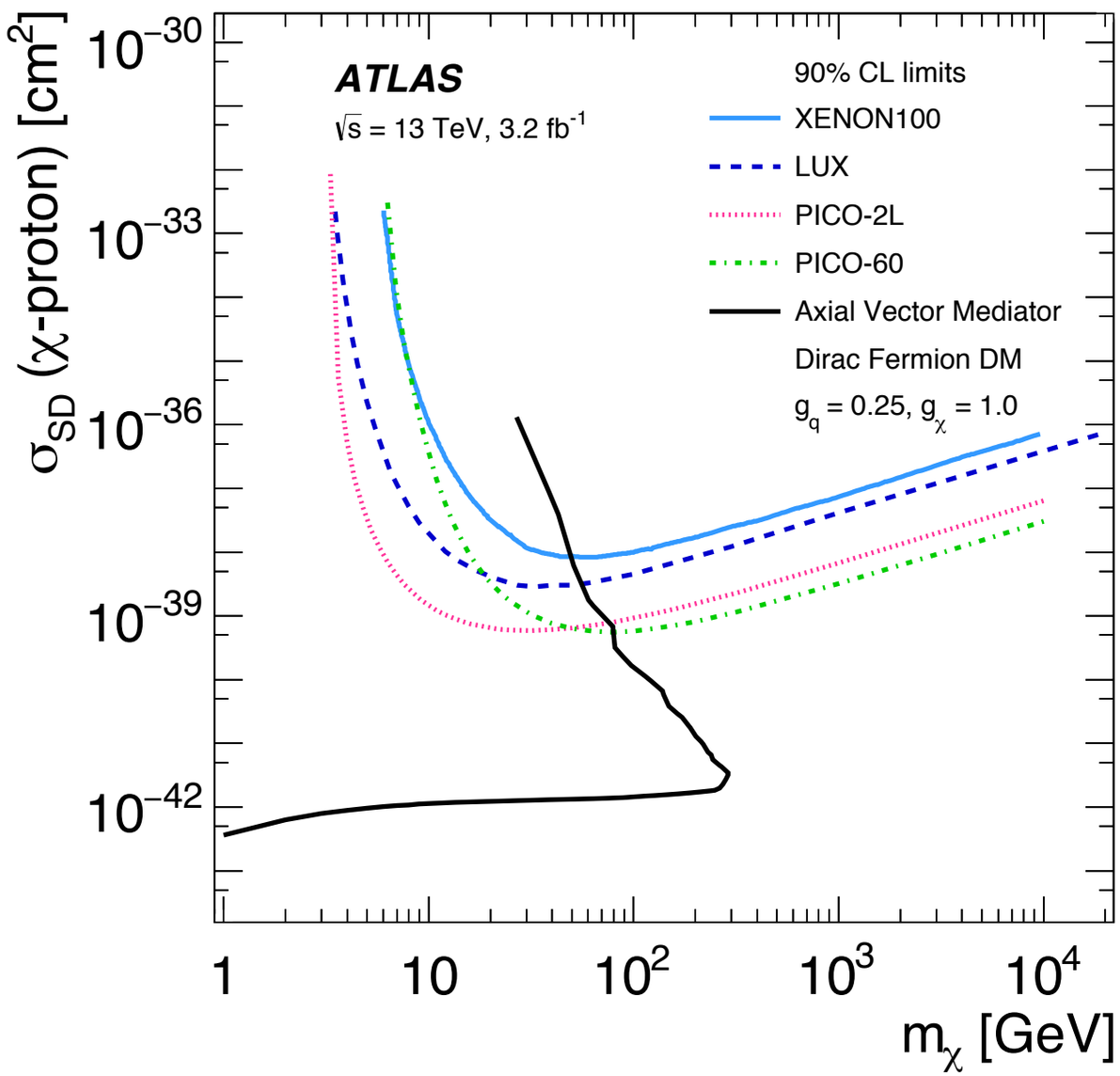


Monojet further information I: limit vs. coupling



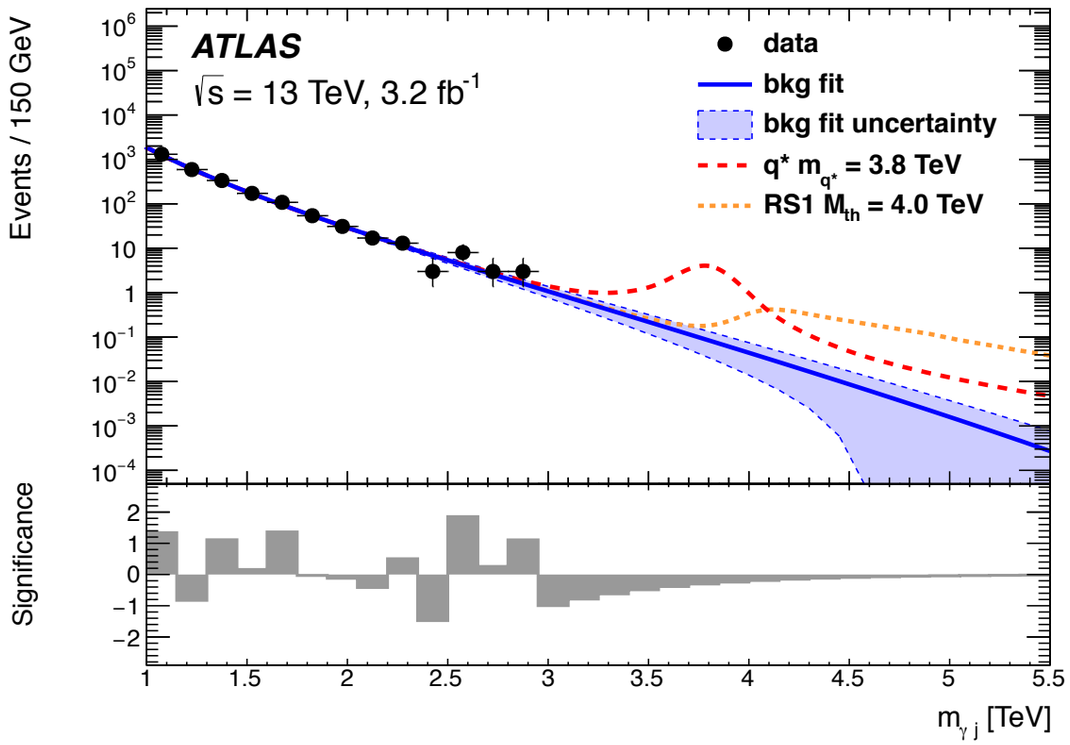
Monojet further information II: WIMP-proton scattering cross-section limits

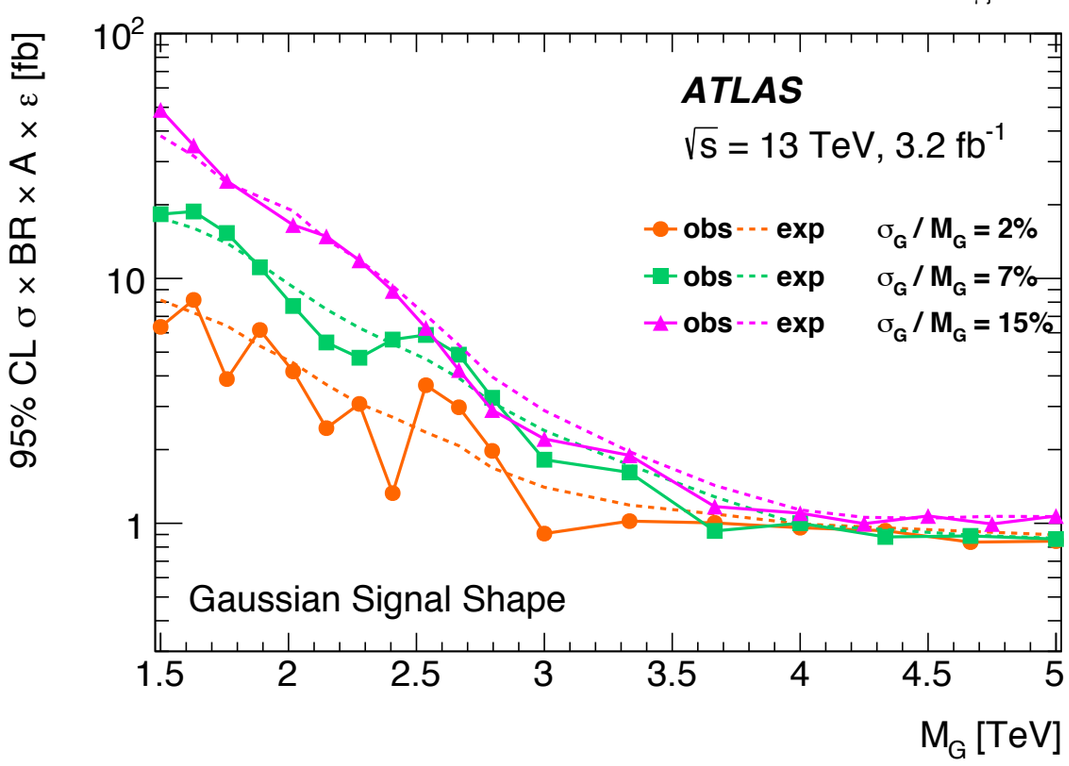




The jet+γ final state

Limits
q* 4.4 TeV
RS1 QBH 3.8 TeV
ADD QBH 6.2 TeV



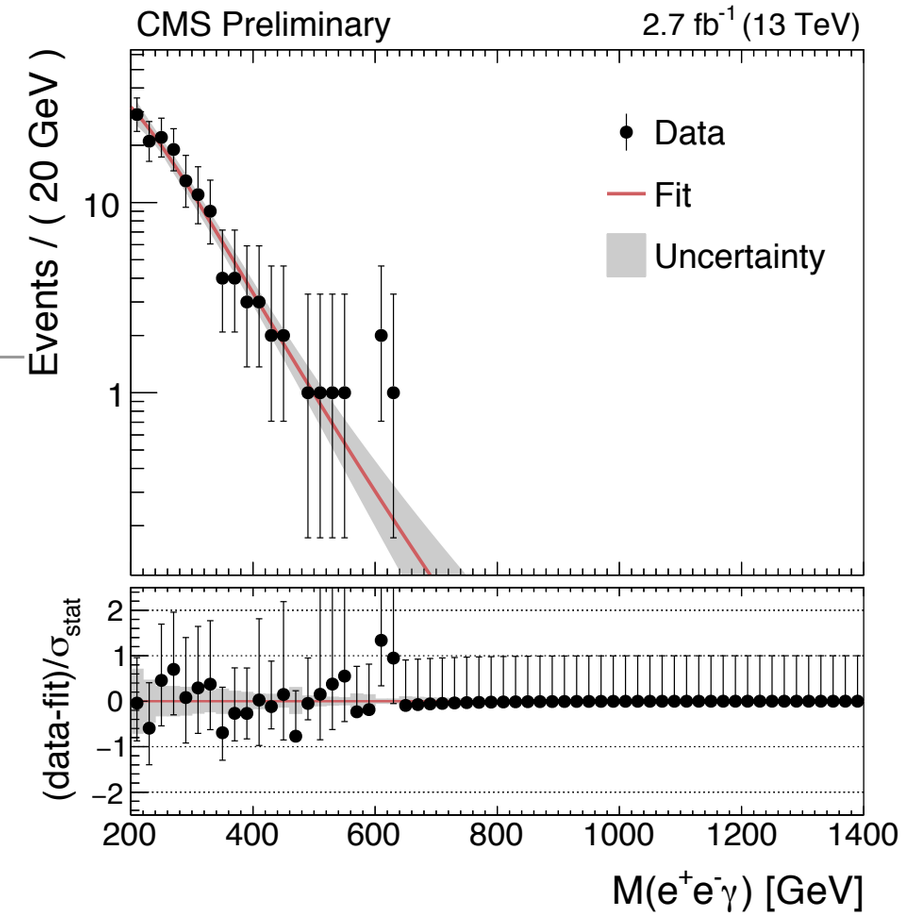


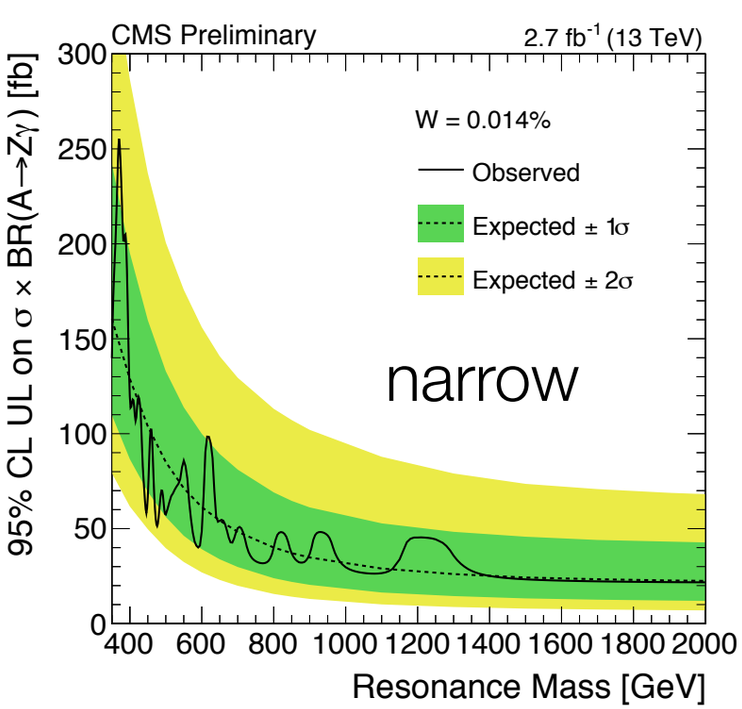
- ATLAS uses jet+γ events to set limits on excited quarks, RS1 and ADD quantum black holes, generic resonances
- Selection: at least 1 each of an isolated photon and a jet, both pT > 150 GeV. |Δη| < 1.6 between the lead jet and photon, and photon is not near any jet.
- Data-driven background estimate from fit.
  - Fit above 1 TeV for all signals but ADD QBH
  - Fit for ADD QBH from 2 TeV
- Systematics: jet and γ energy scales, γ trigger, ID, and isolation efficiencies, function choice.
  - Here function choice modelled by testing spurious signal for each mass point and range of MC settings, taking result as uncertainty

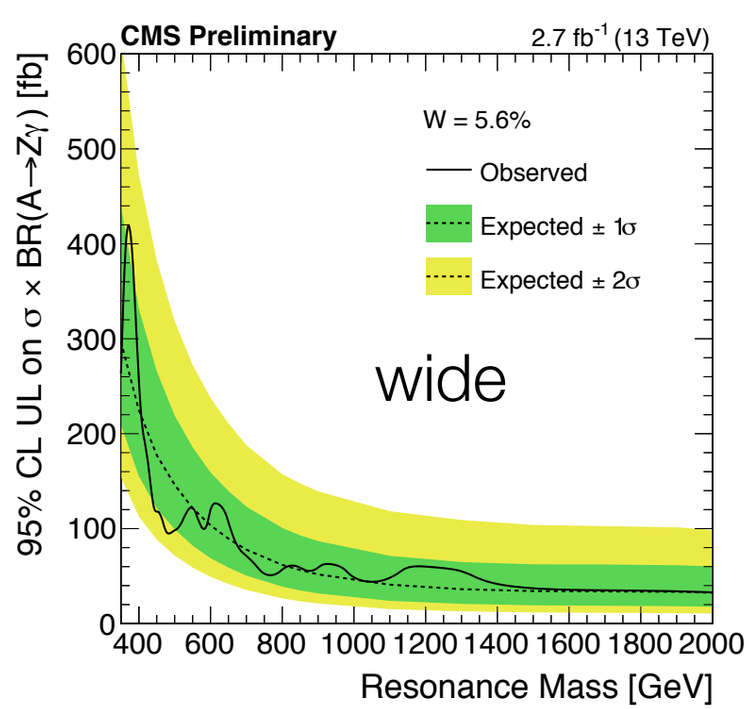
Z+γ search

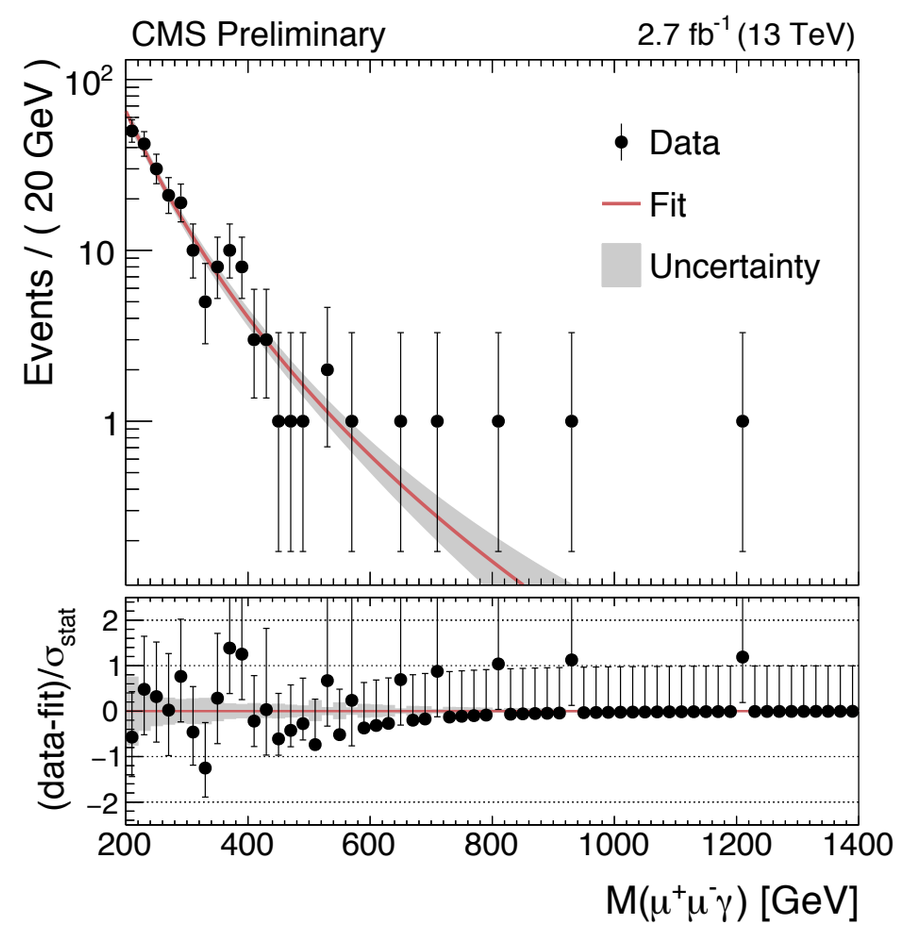
CMS PAS EXO-16-019

- Z(ee) or Z(μμ) + photon
- Require exactly 2 opposite-sign leptons, at least 1 photon isolated from leptons and with significant fraction of energy in Zγ system
- Search in $m_{Z\gamma}$ > 200 GeV for localised excesses. Background described by parametric fit.
- Signal shape is generic based on the crystal ball function





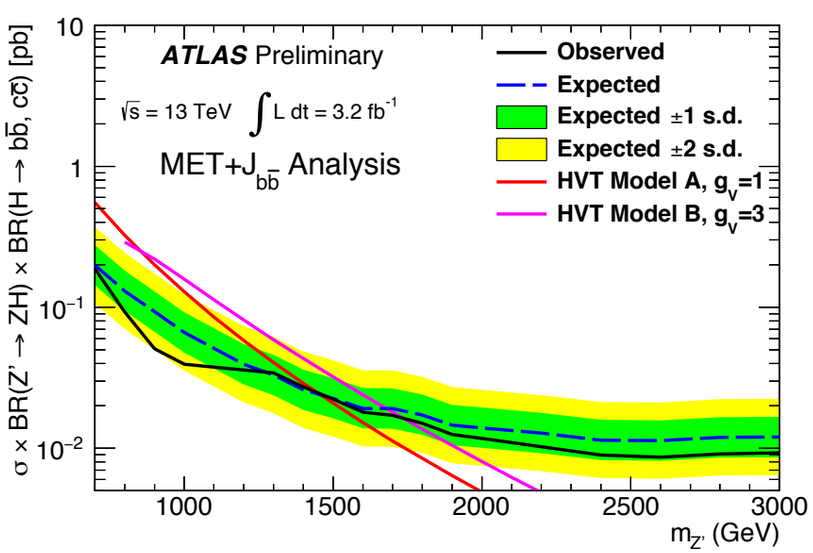


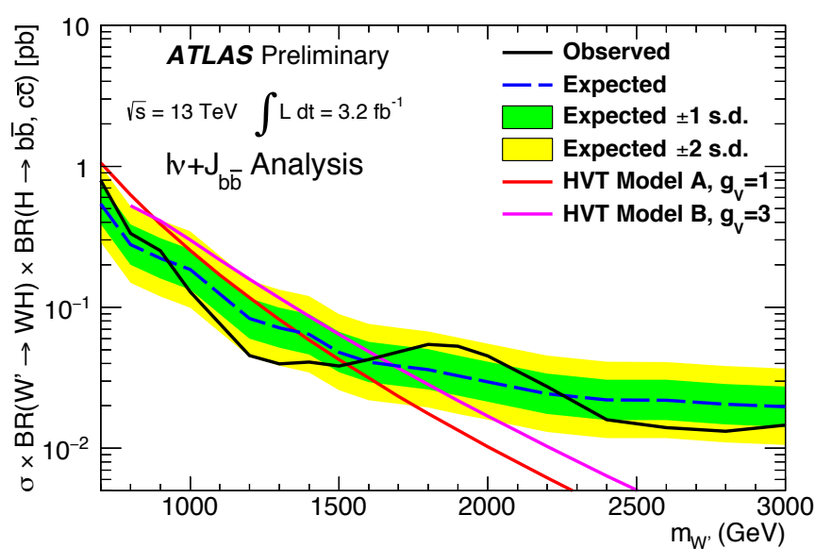


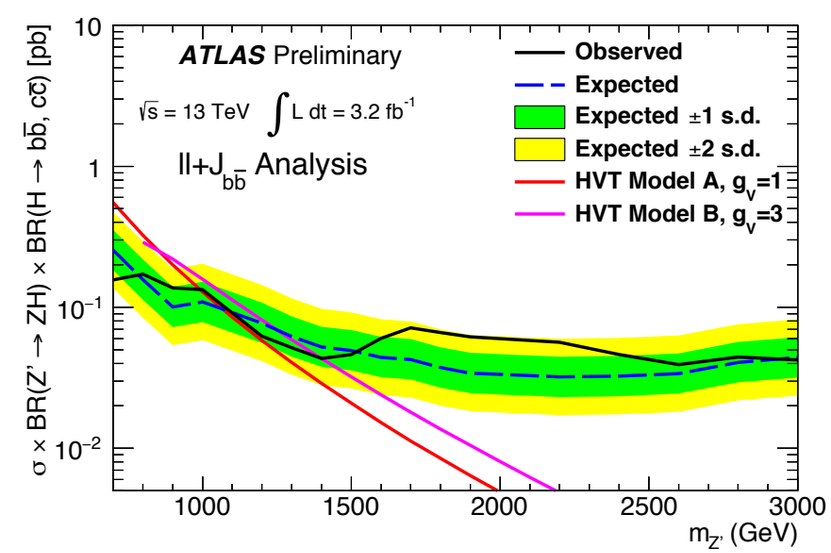
ATLAS CERN-EP-2016-142

W/Z+higgs final state

- Signature: Z(ll),W(lv), or Z(vv) plus h(bb)
- Reconstruct higgs candidate with large-R jet associated to b-tagged track jets and within selected mass window
- Use simplified model of heavy vector triplets as benchmark: V couples to higgs and SM bosons
- Use transverse mass as discriminant in 0-lepton channel; m_{VH} in other channels
- Background modelling taken from MC







X->hh->bbbb

- Resolved analysis: search for 4 b-tagged small-R jets. Reconstruct as 2 dijet pairs with small ΔR within pair
- Boosted: 2 large-R jets each with associated b-tagged track jets (3 or 4 tags overall)
- Switch at resonance masses of 1100 GeV
- Compare dijet/fatjet masses to top quark mass and higgs mass using probability variable. Use for ttbar veto and to define signal region near Higgs mass

ATLAS EXOT-2015-18