



Search for high mass resonances with ATLAS

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On behalf of the ATLAS Collaboration

Rencontre de Moriond: QCD and High Energy Interactions

La Thuile 25 March-1 April 2017

Introduction

- After Higgs discovery, the Standard Model (SM) is a self-consistent theory
- So far in good agreement with data

- Many *experimental* observations not explained in the SM

- Nature of Dark Matter/Energy
- Baryon asymmetry
- neutrino masses

- *Theory* problems:

- Hierarchy problem: $m_{EW}/M_{Pl} \sim 10^{-16}$
- How to accomodate gravity
- Unexplained hierarchical structure of Yukawa couplings

Model and ideas to address them:

- SUSY
- (*)• Compositeness, Extra dimensions
- Extended Higgs Sector
- Top Partner
- (*)• W'/Z'
- Minimal Dark Matter
- Hidden Sectors

(*) in this talk

Search of physics beyond the SM is well motivated

Introduction

ATLAS has an extensive search program to prove or discard models

ATLAS Exotics Searches* - 95% CL Exclusion
 Status: August 2016

ATLAS Preliminary
 $\sqrt{s} = 8, 13 \text{ TeV}$

$$\int \mathcal{L} dt = (3.2 - 20.3) \text{ fb}^{-1}$$

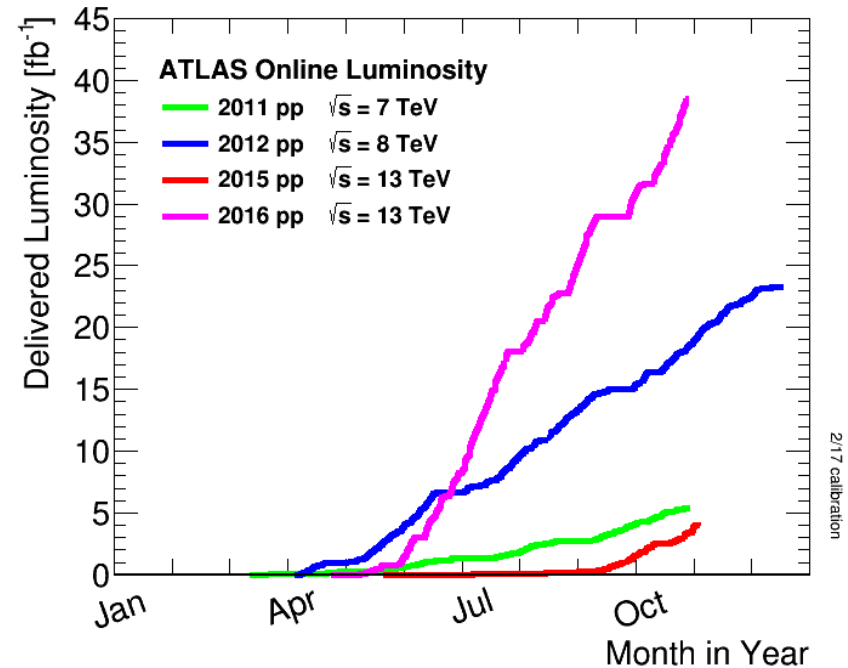
Model	ℓ, γ	Jets [†]	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference	
(*) Extra dimensions	ADD $G_{KK} + g/q$	-	$\geq 1j$	Yes	3.2	M_D 6.58 TeV	$n = 2$ 1604.07773
	ADD non-resonant $\ell\ell$	$2 e, \mu$	-	-	20.3	M_S 4.7 TeV	$n = 3 \text{ HLZ}$ 1407.2410
	ADD CBH $\rightarrow \ell q$	$1 e, \mu$	$1j$	-	20.3	M_{BH} 5.2 TeV	1311.2006
	ADD CBH	-	$2j$	-	-	M_{BH} 8.7 TeV	$n = 6$ ATLAS-CONF-2016-069
	ADD BH high Σp_T	$\geq 1 e, \mu$	$\geq 2j$	-	-	M_{BH} 8.2 TeV	$n = 6, M_D = 3 \text{ TeV, rot BH}$ 1606.02265
	ADD BH multijet	-	$\geq 3j$	-	-	M_{BH} 9.55 TeV	$n = 6, M_D = 3 \text{ TeV, rot BH}$ 1512.02586
	RS1 $G_{KK} \rightarrow \ell\ell$	$2 e, \mu$	-	-	20.3	$G_{KK} \text{ mass}$ 2.68 TeV	$k/\bar{M}_{Pl} = 0.1$ 1405.4123
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ	-	-	3.2	$G_{KK} \text{ mass}$ 3.2 TeV	$k/\bar{M}_{Pl} = 0.1$ 1606.03833
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\ell\nu$	$1 e, \mu$	$1j$	Yes	13.2	$G_{KK} \text{ mass}$ 1.24 TeV	$k/\bar{M}_{Pl} = 1.0$ ATLAS-CONF-2016-062
	Bulk RS $G_{KK} \rightarrow HH \rightarrow bbbb$	-	$4b$	-	13.3	$G_{KK} \text{ mass}$ 360-860 GeV	$k/\bar{M}_{Pl} = 1.0$ ATLAS-CONF-2016-049
	Bulk RS $G_{KK} \rightarrow tt$	$1 e, \mu$	$\geq 1b, \geq 1J/2j$	Yes	20.3	$R_{KK} \text{ mass}$ 2.2 TeV	$BR = 0.925$ 1505.07018
	2UED / RPP	$1 e, \mu$	$\geq 2b, \geq 4j$	Yes	3.2	$KK \text{ mass}$ 1.46 TeV	Tier (1,1), $BR(A^{(1,1)} \rightarrow t\bar{t}) = 1$ ATLAS-CONF-2016-013
(*) Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	-	13.3	$Z' \text{ mass}$ 4.05 TeV	ATLAS-CONF-2016-045
	SSM $Z' \rightarrow \tau\tau$	2τ	-	-	19.5	$Z' \text{ mass}$ 2.02 TeV	1502.07177
	Leptophobic $Z' \rightarrow bb$	-	$2b$	-	3.2	$Z' \text{ mass}$ 1.5 TeV	1603.08791
	SSM $W' \rightarrow \ell\nu$	$1 e, \mu$	-	Yes	13.3	$W' \text{ mass}$ 4.74 TeV	ATLAS-CONF-2016-061
	HVT $W' \rightarrow WZ \rightarrow qq\nu\nu$ model A	$0 e, \mu$	$1j$	Yes	13.2	$W' \text{ mass}$ 2.4 TeV	$g_V = 1$ ATLAS-CONF-2016-082
	HVT $W' \rightarrow WZ \rightarrow qqqq$ model B	-	$2j$	-	15.5	$W' \text{ mass}$ 3.0 TeV	$g_V = 3$ ATLAS-CONF-2016-055
(*) CI	HVT $V' \rightarrow WH/ZH$ model B	multi-channel	-	-	3.2	$V' \text{ mass}$ 2.31 TeV	$g_V = 3$ 1607.05621
	LRSM $W'_R \rightarrow tb$	$1 e, \mu$	$2b, 0-1j$	Yes	20.3	$W' \text{ mass}$ 1.92 TeV	1410.41103
	LRSM $W'_R \rightarrow tb$	$0 e, \mu$	$\geq 1b, 1j$	-	20.3	$W' \text{ mass}$ 1.76 TeV	1408.0886
DM	CI $qqqq$	-	$2j$	-	15.7	A 19.9 TeV	$\eta_{LL} = -1$ ATLAS-CONF-2016-069
	CI $\ell\ell qq$	$2 e, \mu$	-	-	3.2	A 25.2 TeV	$\eta_{LL} = -1$ 1607.03669
	CI $uutt$	$2(SS) \geq 3 e, \mu \geq 1b, \geq 1j$	Yes	20.3	A 4.9 TeV	$ C_{RR} = 1$ 1504.04605	
LQ	Axial-vector mediator (Dirac DM)	$0 e, \mu$	$\geq 1j$	Yes	3.2	μA 1.0 TeV	$g_\tau = 0.25, g_\ell = 1.0, m(\chi) < 250 \text{ GeV}$ 1604.07773
	Axial-vector mediator (Dirac DM)	$0 e, \mu, 1 \gamma$	$1j$	Yes	3.2	μA 710 GeV	$g_\tau = 0.25, g_\ell = 1.0, m(\chi) < 150 \text{ GeV}$ 1604.01306
	$ZZ\chi\chi$ EFT (Dirac DM)	$0 e, \mu$	$1j, \leq 1j$	Yes	3.2	M_χ 550 GeV	$m(\chi) < 150 \text{ GeV}$ ATLAS-CONF-2015-080
Heavy quarks	Scalar LQ 1 st gen	$2 e$	$\geq 2j$	-	3.2	LQ mass 1.1 TeV	$\beta = 1$ 1605.06035
	Scalar LQ 2 nd gen	2μ	$\geq 2j$	-	3.2	LQ mass 1.05 TeV	$\beta = 1$ 1605.06035
	Scalar LQ 3 rd gen	$1 e, \mu$	$\geq 1b, \geq 3j$	Yes	20.3	LQ mass 640 GeV	$\beta = 0$ 1508.04735
Excited fermions	VLQ $TT \rightarrow Ht + X$	$1 e, \mu$	$\geq 2b, \geq 3j$	Yes	20.3	T mass 855 GeV	T in (TB) doublet 1505.04306
	VLQ $YY \rightarrow Wb + X$	$1 e, \mu$	$\geq 1b, \geq 3j$	Yes	20.3	Y mass 770 GeV	Y in (B,Y) doublet 1505.04306
	VLQ $BB \rightarrow Hb + X$	$1 e, \mu$	$\geq 2b, \geq 3j$	Yes	20.3	B mass 735 GeV	isospin singlet 1505.04306
	VLQ $BB \rightarrow Zb + X$	$2/\geq 3 e, \mu$	$\geq 2/\geq 1b$	-	20.3	B mass 755 GeV	B in (B,Y) doublet 1409.5500
	VLQ $QQ \rightarrow WqWq$	$1 e, \mu$	$\geq 4j$	Yes	20.3	Q mass 690 GeV	1509.04261
	VLQ $T_{5/3} T_{5/3} \rightarrow WtWt$	$2(SS) \geq 3 e, \mu \geq 1b, \geq 1j$	Yes	3.2	$T_{5/3} \text{ mass}$ 990 GeV	ATLAS-CONF-2016-032	
Other	Excited quark $q^* \rightarrow q\gamma$	1γ	$1j$	-	3.2	$q^* \text{ mass}$ 4.4 TeV	only u' and d' , $\Lambda = m(q')$ 1512.05910
	Excited quark $q^* \rightarrow qg$	-	$2j$	-	15.7	$q^* \text{ mass}$ 5.6 TeV	only u' and d' , $\Lambda = m(q')$ ATLAS-CONF-2016-069
	Excited quark $b^* \rightarrow bg$	-	$1b, 1j$	-	8.8	$b^* \text{ mass}$ 2.3 TeV	ATLAS-CONF-2016-060
	Excited quark $b^* \rightarrow Wt$	$1 \text{ or } 2 e, \mu$	$1b, 2-0j$	Yes	20.3	$b^* \text{ mass}$ 1.5 TeV	$f_\ell = f_\tau = f_R = 1$ 1510.02664
	Excited lepton ℓ^*	$3 e, \mu$	-	-	20.3	$\ell^* \text{ mass}$ 3.0 TeV	$\Lambda = 3.0 \text{ TeV}$ 1411.2921
	Excited lepton ν^*	$3 e, \mu, \tau$	-	-	20.3	$\nu^* \text{ mass}$ 1.6 TeV	$\Lambda = 1.6 \text{ TeV}$ 1411.2921
Other	LSTC $a_T \rightarrow W\gamma$	$1 e, \mu, 1 \gamma$	-	Yes	20.3	$a_T \text{ mass}$ 960 GeV	1407.8150
	LRSM Majorana ν	$2 e, \mu$	$2j$	-	20.3	$N^0 \text{ mass}$ 2.0 TeV	1506.06020
	Higgs triplet $H^{\pm\pm} \rightarrow ee$	$2 e$ (SS)	-	-	13.9	$H^{\pm\pm} \text{ mass}$ 570 GeV	$m(W_R) = 2.4 \text{ TeV, no mixing}$ DY production, $BR(H^{\pm\pm} \rightarrow ee) = 1$ ATLAS-CONF-2016-051
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3 e, \mu, \tau$	-	-	20.3	$H^{\pm\pm} \text{ mass}$ 400 GeV	DY production, $BR(H^{\pm\pm} \rightarrow \ell\tau) = 1$ 1411.2921
	Monotop (non-res prod)	$1 e, \mu$	$1b$	Yes	20.3	spin-1 invisible particle mass 657 GeV	$\alpha_{\text{non-res}} = 0.2$ 1410.5404
	Multi-charged particles	-	-	-	20.3	multi-charged particle mass 785 GeV	DY production, $ gl = 5e$ 1504.04188
Magnetic monopoles	-	-	-	7.0	monopole mass 1.34 TeV	DY production, $ gl = 1g_D, \text{spin } 1/2$ 1509.08059	

*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

†Small-radius (large-radius) jets are denoted by the letter j (J).

Outline

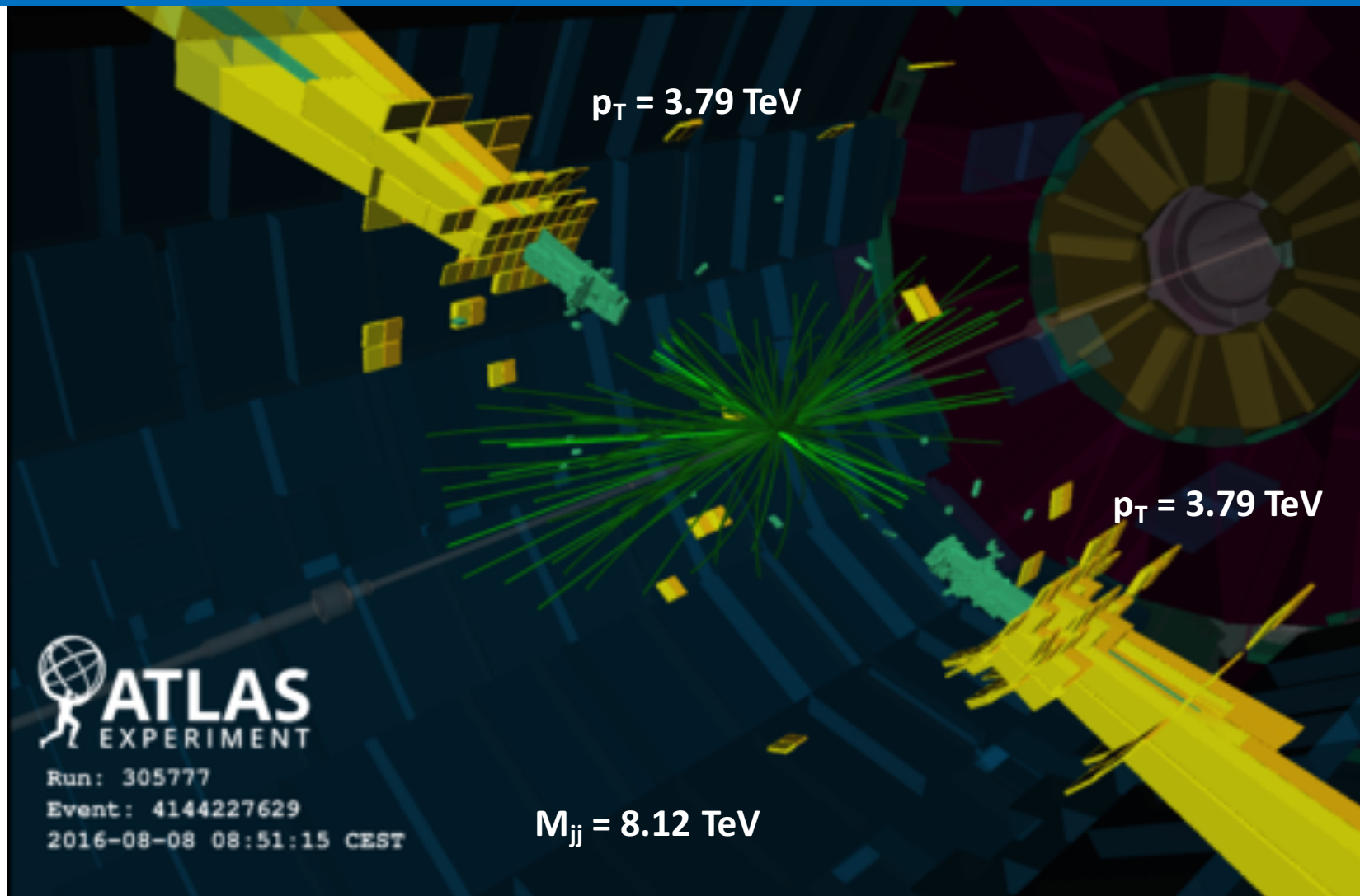
- Searches of new phenomena with di-jet final states
full 2015+2016 dataset **NEW**
- Search for new resonances decaying to a charged lepton and a neutrino
full 2015+2016 dataset **NEW**
- Search for new high-mass resonances in the dilepton final state with 13.3 fb^{-1} and 3.2 fb^{-1}



Excellent performance of LHC in Run 2:

- Center-of-mass energy: $\sqrt{s} = 13 \text{ TeV}$
- Collected good data: 36.1 fb^{-1}
 3.2 fb^{-1} in 2015, 32.9 fb^{-1} in 2016

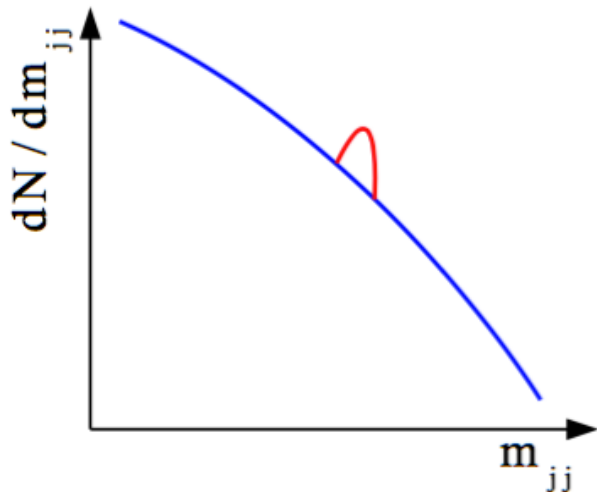
Search for new phenomena in di-jets



Search for new phenomena in di-jets

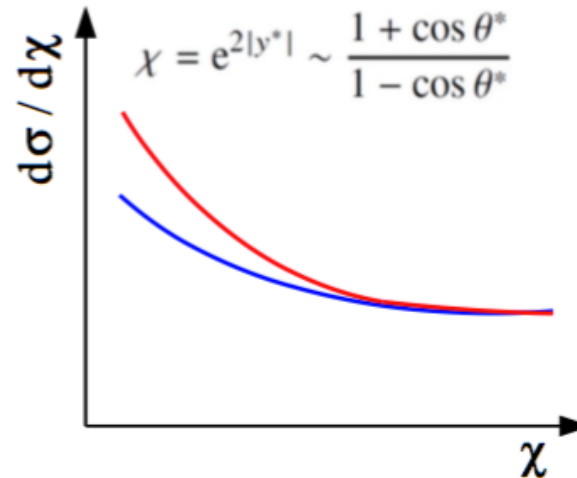
Di-jets final states sensitive to a broad class of new phenomena, through **generic** features of Beyond Standard Models (BSM) signals

Resonances searches



- localized excess in the m_{jj} distribution
- Sensitive to narrow resonance:
 - Quantum Black Hole (QBH),
 - Excited quark (q^*), W' ,
 - excited W^*

Di-jets angular distributions anomalies:

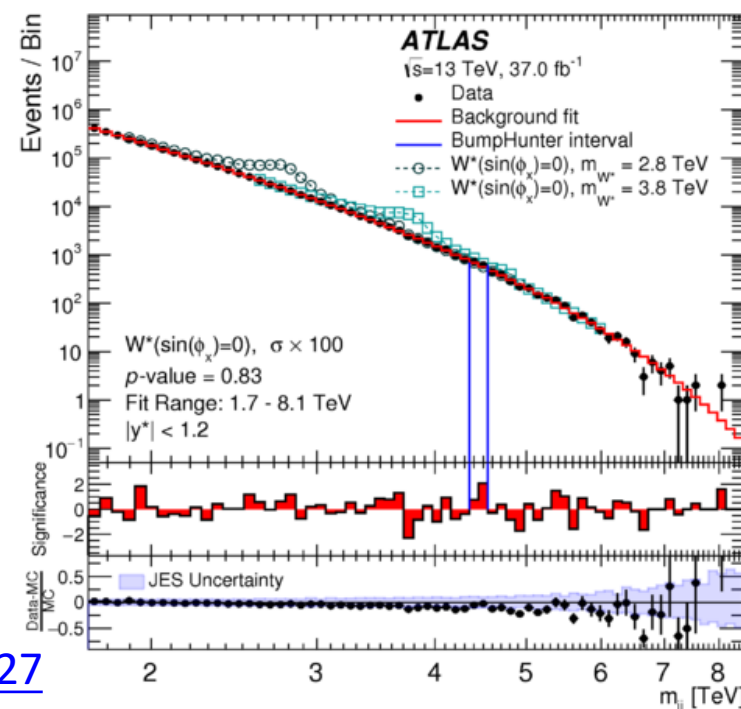
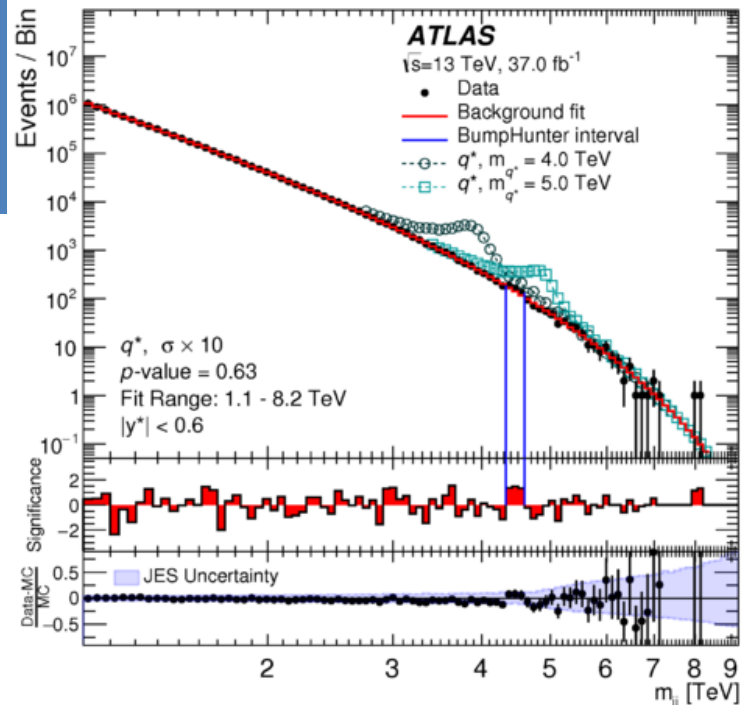


- BSM give more isotropic signature wrt to QCD
- More Sensitive to non-resonant signals
 - Contact interactions at compositeness scale Λ

Resonance Search in di-jets

- Single jet trigger $p_T > 380$ GeV
- $p_T^{\text{lead(sub)}} > 440$ (60) GeV
- To suppress t-channel scattering:
 - $y^* < 0.6(1.2)$, $y^* = |y_{\text{lead}} - y_{\text{sublead}}| / 2$
 - $m_{jj} > 1.1(1.7)$ TeV (for W^*)
 - fully efficient trigger selection
 - Smooth QCD background from a Sliding Window Fit
- BumpHunter algorithm to scan for excesses
 - Most discrepant interval: 4326 – 4595 GeV
 - global significance of 0.63 (0.83 for W^*)

No evidence of a localized contribution from BSM phenomena



[arXiv:1703.09127](https://arxiv.org/abs/1703.09127)

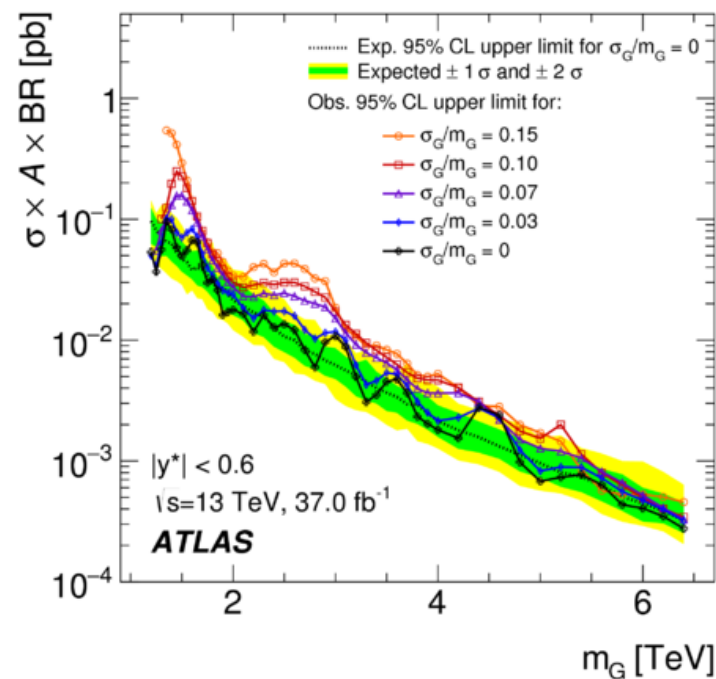
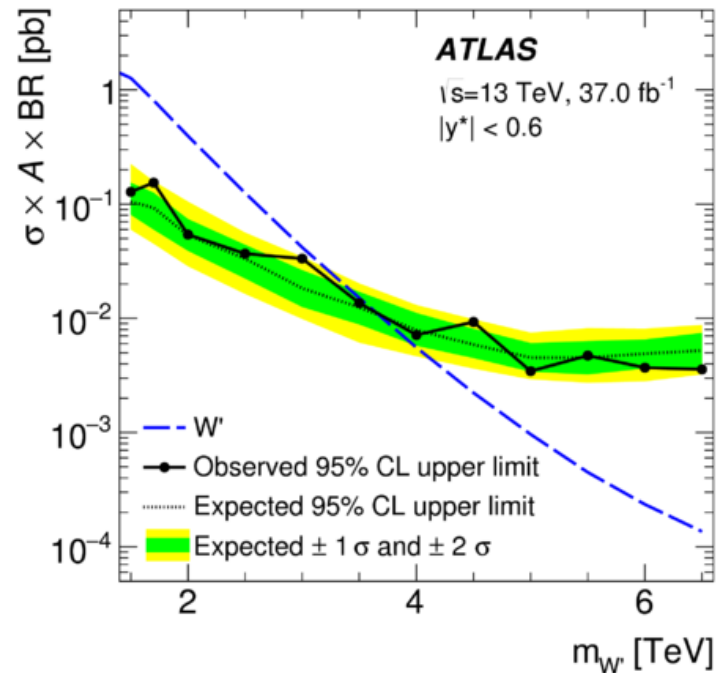
Resonance Search in di-jets: Exclusion limits

95 %CL exclusion limit		
Model	Observed	Expected
Quantum Black Hole, ADD	8.9 TeV	8.9 TeV
Excited quark	6.0 TeV	5.8 TeV
W'	3.7 TeV	3.7 TeV
W^*	3.4 TeV, 3.8-3.9 TeV	3.6 TeV

Improved limits from 7% to 40% wrt analysis based on 3.2 fb⁻¹

Limits on generic Gaussian signals

- can be re-interpreted with various signal models
- MC-based folding methods to factorize physics & detector effects
- Excluded at 95% CL effective cross-sections from 20–50 fb at $m_G < 2$ TeV to 0.2-0.4 fb for $m_G > 6$ TeV



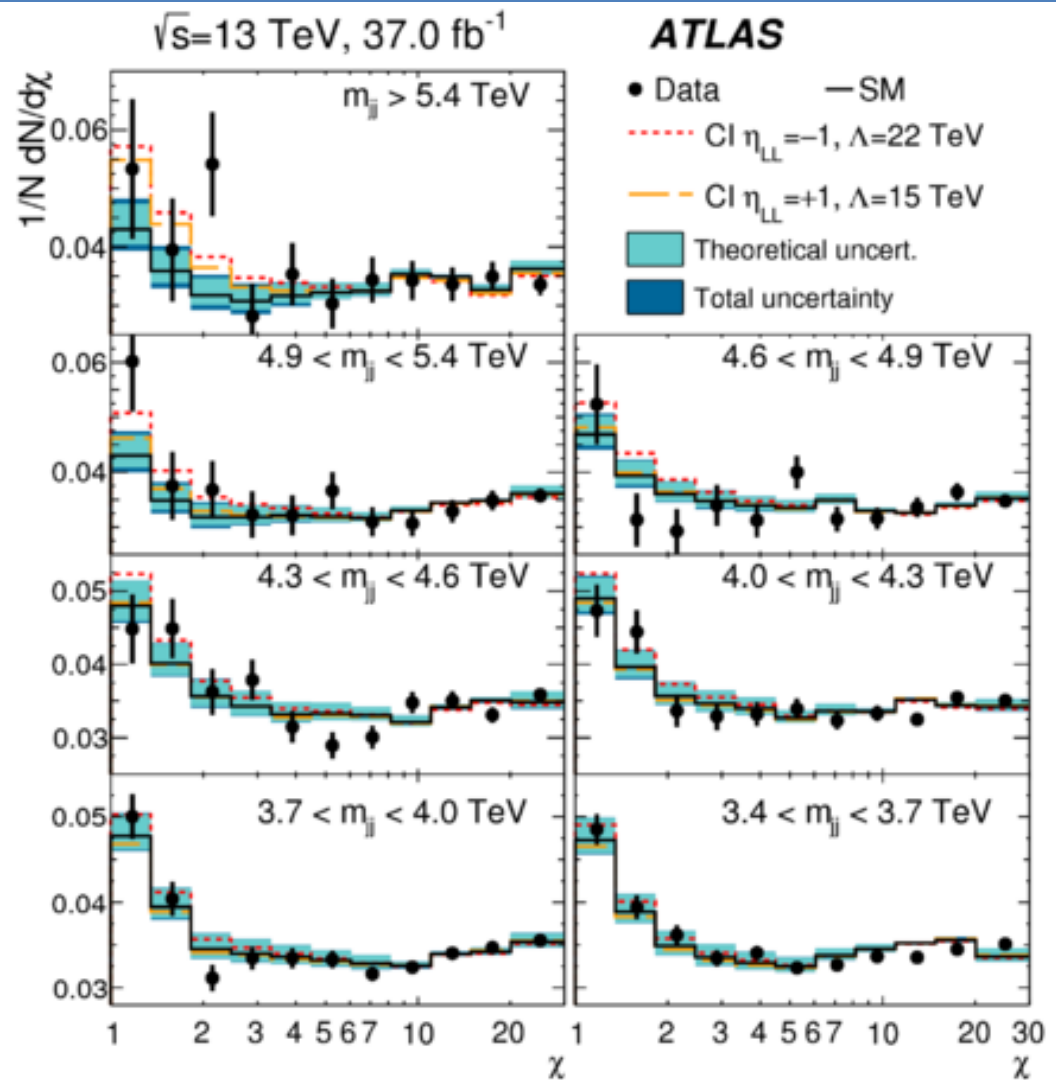
Angular Searches in di-jets

- Single jet trigger $p_T > 380$ GeV, $p_T^{\text{lead(sub)}} > 440(60)$ GeV
- $y^* < 1.7$, $y_B < 1.1$, $m_{jj} > 2.5$ TeV, y_B semi-sum of rapidities
- Signal: Contact interactions at compositeness scale Λ

$$L_{qq} = \frac{2\pi}{\Lambda^2} \left[\eta_{LL} (\bar{q}_L \gamma^\mu q_L) (\bar{q}_L \gamma_\mu q_L) + \eta_{RR} (\bar{q}_R \gamma^\mu q_R) (\bar{q}_R \gamma_\mu q_R) + 2\eta_{RL} (\bar{q}_R \gamma^\mu q_R) (\bar{q}_L \gamma_\mu q_L) \right],$$

$$\eta_{LL} = \pm 1, \eta_{RR} = \eta_{RRL} = 0$$

- QCD background described by MC, normalized to data in each m_{jj} bin
- Dominant Uncertainty:
 - Jet energy scale (exp) and renormalization/factorization scales (theory)



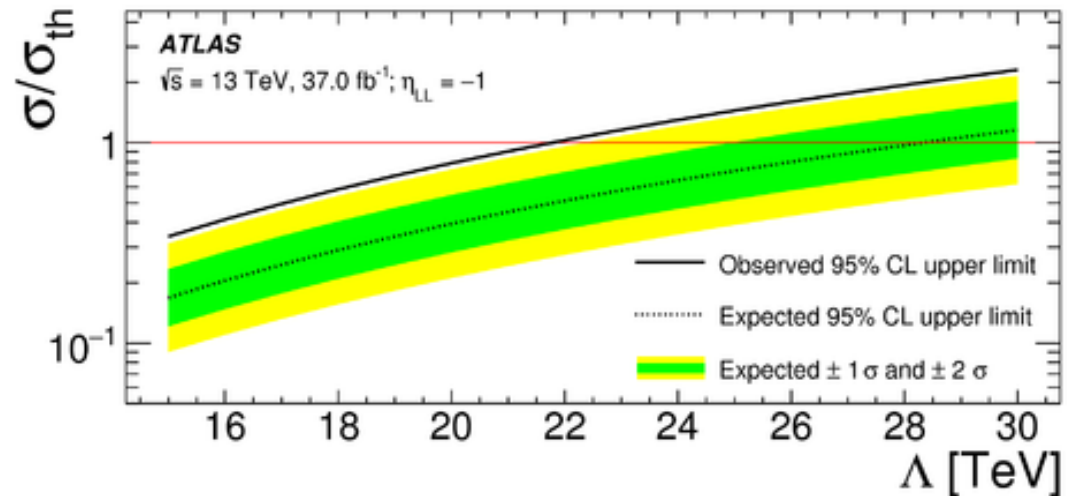
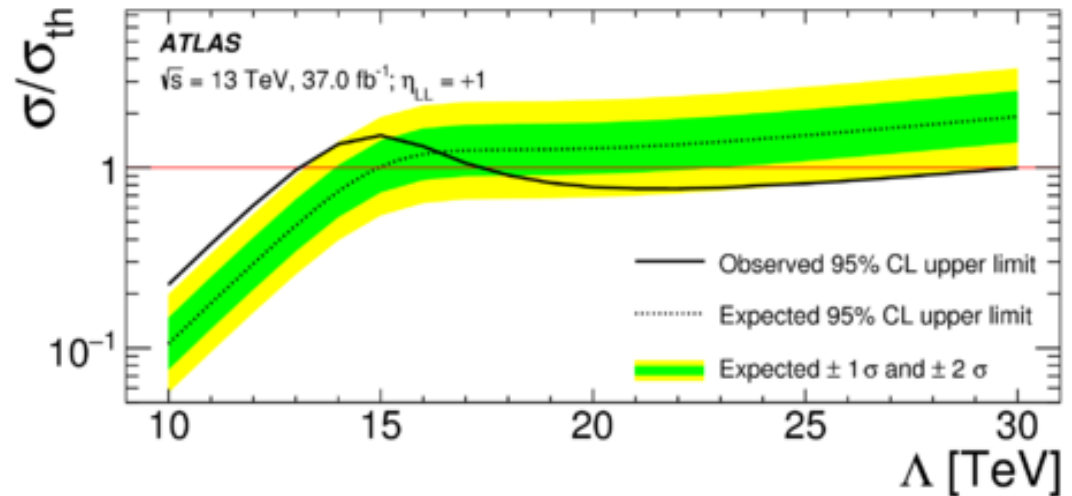
$$\chi = e^{y^*} \sim \frac{1 + \cos \theta^*}{1 - \cos \theta^*}$$

Angular Searches in di-jets: Exclusion limits on contact interactions

**No deviations from
background expectations**

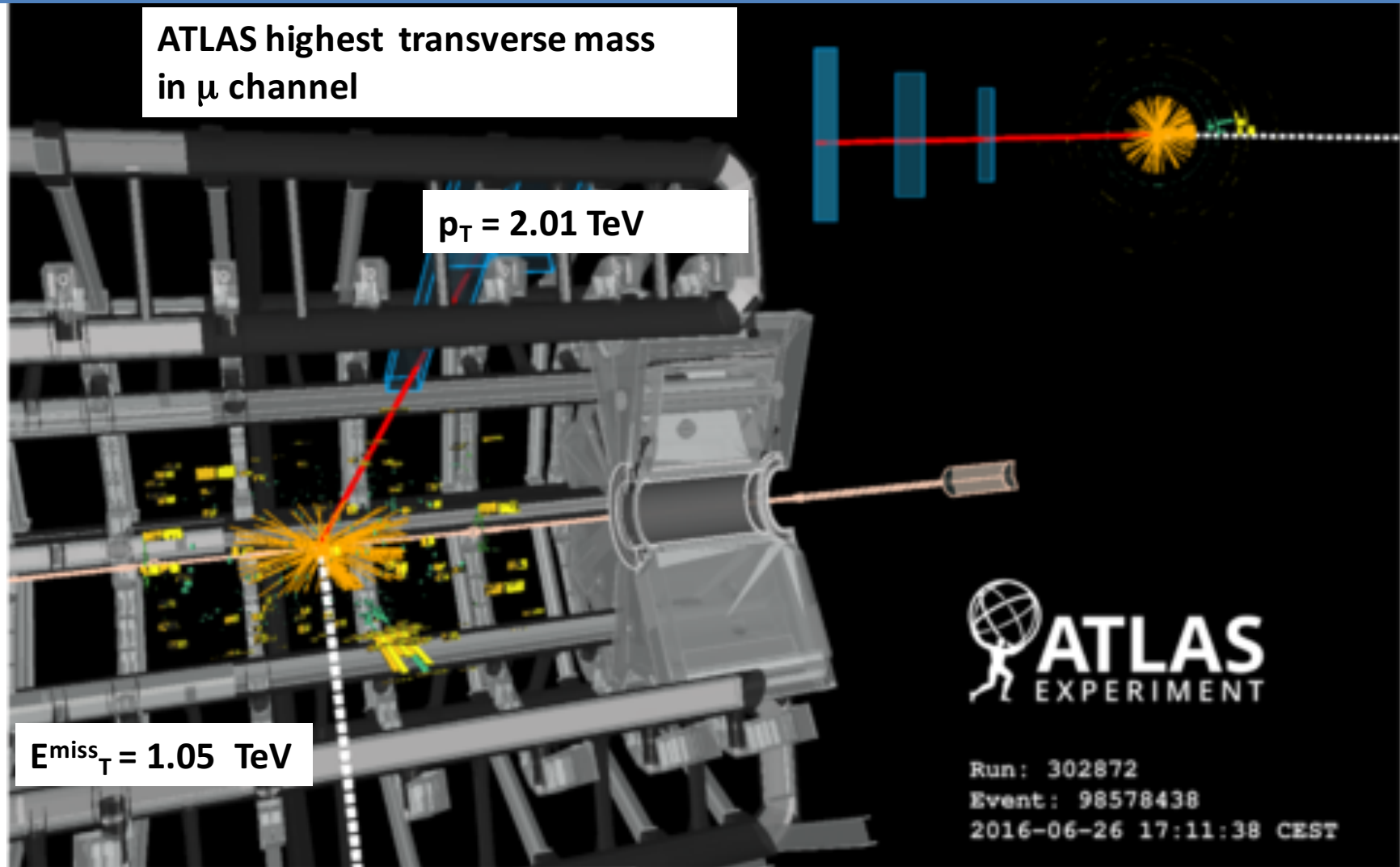
95 %CL exclusion limit on Λ		
Model	Observed	Expected
$\eta_{LL}=-1$	21.8 TeV	28.3 TeV
$\eta_{LL}=+1$	13.1 TeV 17.4-29.5 TeV	15.0 TeV

-10% less sensitivity to other benchmark models compared to resonance search



Negative (positive) interference of signal model $\eta_{LL} = +1(-1)$ with SM QCD

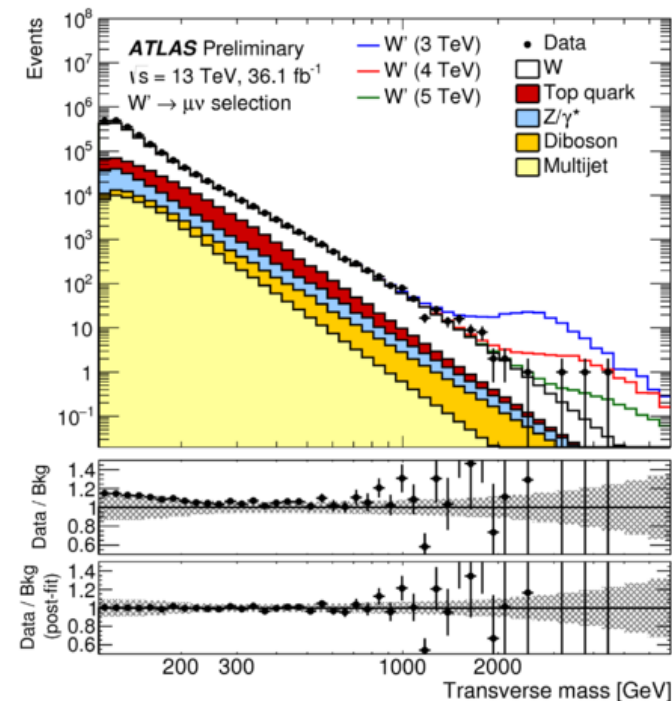
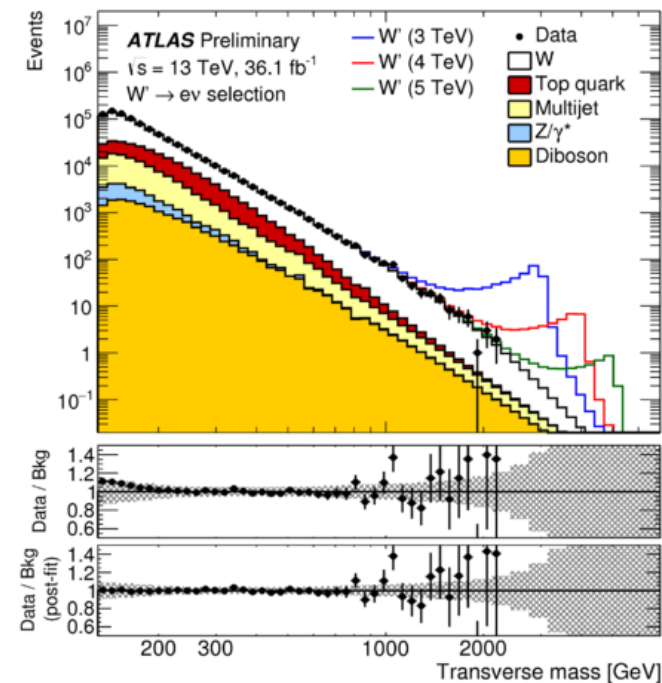
Search for new resonances decaying to a charged lepton and a neutrino



Search for new resonances decaying to a charged lepton and a neutrino

- BSM models introduce new heavy charged Spin-1 gauge-bosons W'
- $W' \rightarrow l\nu$ experimental signature
- Benchmark model: Sequential Standard Model (SSM)
 - Same fermion coupling as the SM W
 - no coupling to W, Z
 - Interference between W and W' neglected
- Analysis Strategy:
 - exactly one high- p_T lepton and large missing transverse energy
 - Compare transverse mass distribution to SM predictions

$$m_T = \sqrt{2p_T E_T^{miss} \cdot (1 - \cos \Delta\phi)}$$



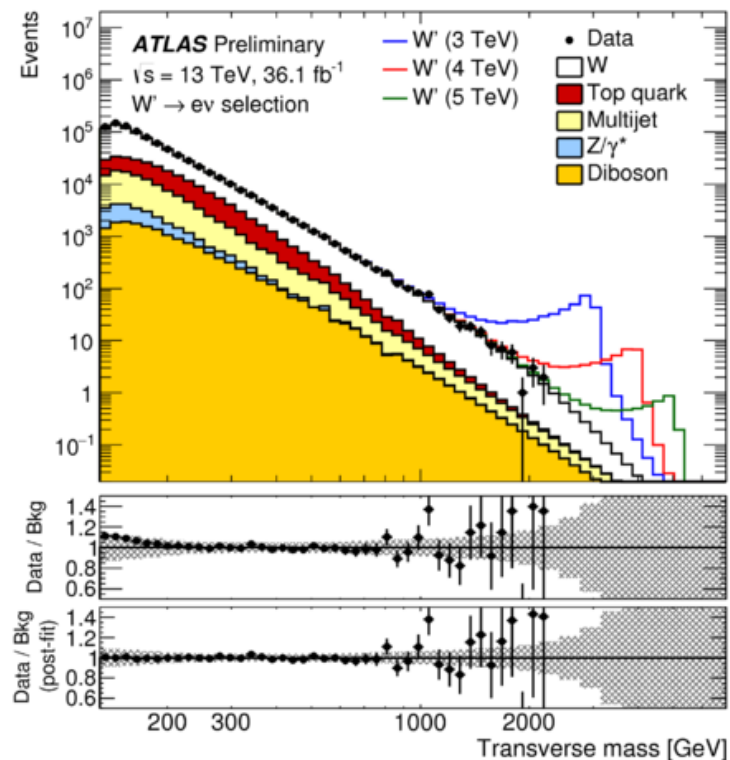
Search of $W' \rightarrow e \nu$: event yield

- Tight ID electron $p_T > 65$ GeV
- $E_T^{\text{miss}} > 65$ GeV, $m_T > 130$ GeV
- Bkg with “real” leptons estimated with MC
 - Largest from W Drell-Yan production
- Bkg from misidentified object: data-driven
- $\text{Acc} \times \varepsilon = 81\%$ (77%) @ $m_{W'} = 2$ TeV (4 TeV)

m_{ll} (TeV)	0.6-1	1-2	2-3	3-7
Obs	1931	246	4	0
Exp SM	1960 ± 140	224 ± 23	5.7 ± 1.4	0.4 ± 0.4
SM+ W' 2 TeV	2260 ± 160	3930 ± 80	380 ± 80	1.4 ± 0.4

No significant excess is observed

most significant excess at $m_{W'} = 1.1$ TeV:
local (global) significance of 2.3 (0.6)



- Syst. Uncertainty for Bkg and Signal:
7% (115%) and 21% (10%)
 $m_T = 2$ TeV (4 TeV)

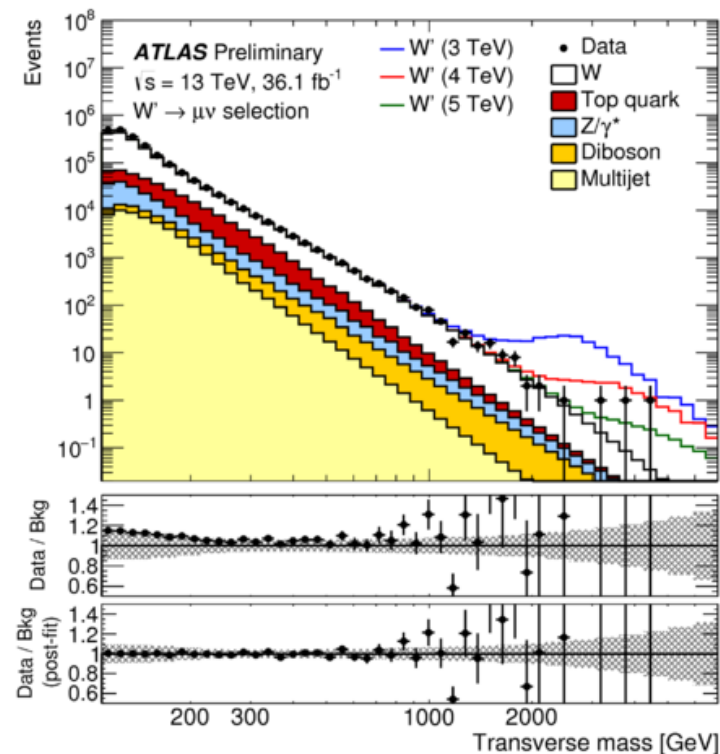
Search of $W' \rightarrow \mu \nu$: event yield

- Tight ID muon $p_T > 55$ GeV
- $E_T^{\text{miss}} > 55$ GeV, $m_T > 130$ GeV
- Bkg with “real” leptons estimated with MC
 - Largest from W Drell-Yan production
- Bkg from misidentified objet: data-driven
- $\text{Acc} \times \varepsilon = 50\%$ (46%) @ $m_{W'} = 2$ TeV (4 TeV)

m_{\parallel} (TeV)	0.6-1	1-2	2-3	3-7
Obs	1392	177	3	3
Exp SM	1320 ± 90	150 ± 13	4.7 ± 0.6	0.63 ± 0.13
SM+ W' 2 TeV	1740 ± 100	1870 ± 90	374 ± 28	18 ± 4

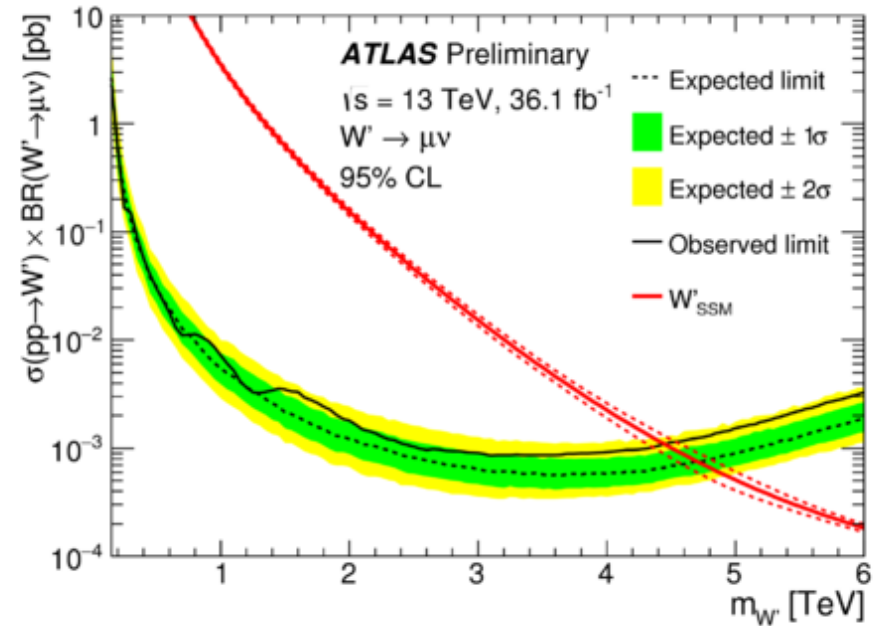
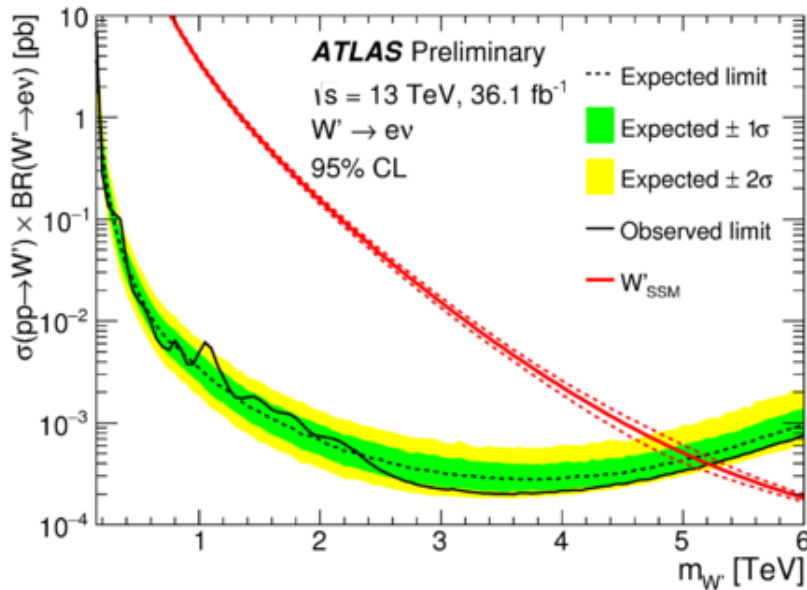
No significant excess is observed

most significant excess at $m_{W'} \sim 5$ TeV:
local (global) significance of 1.8 (0.1)



- Syst. Uncertainty for Bkg and Signal:
12% (21%) and 6% (8%)
 $m_T = 2$ TeV (4 TeV)

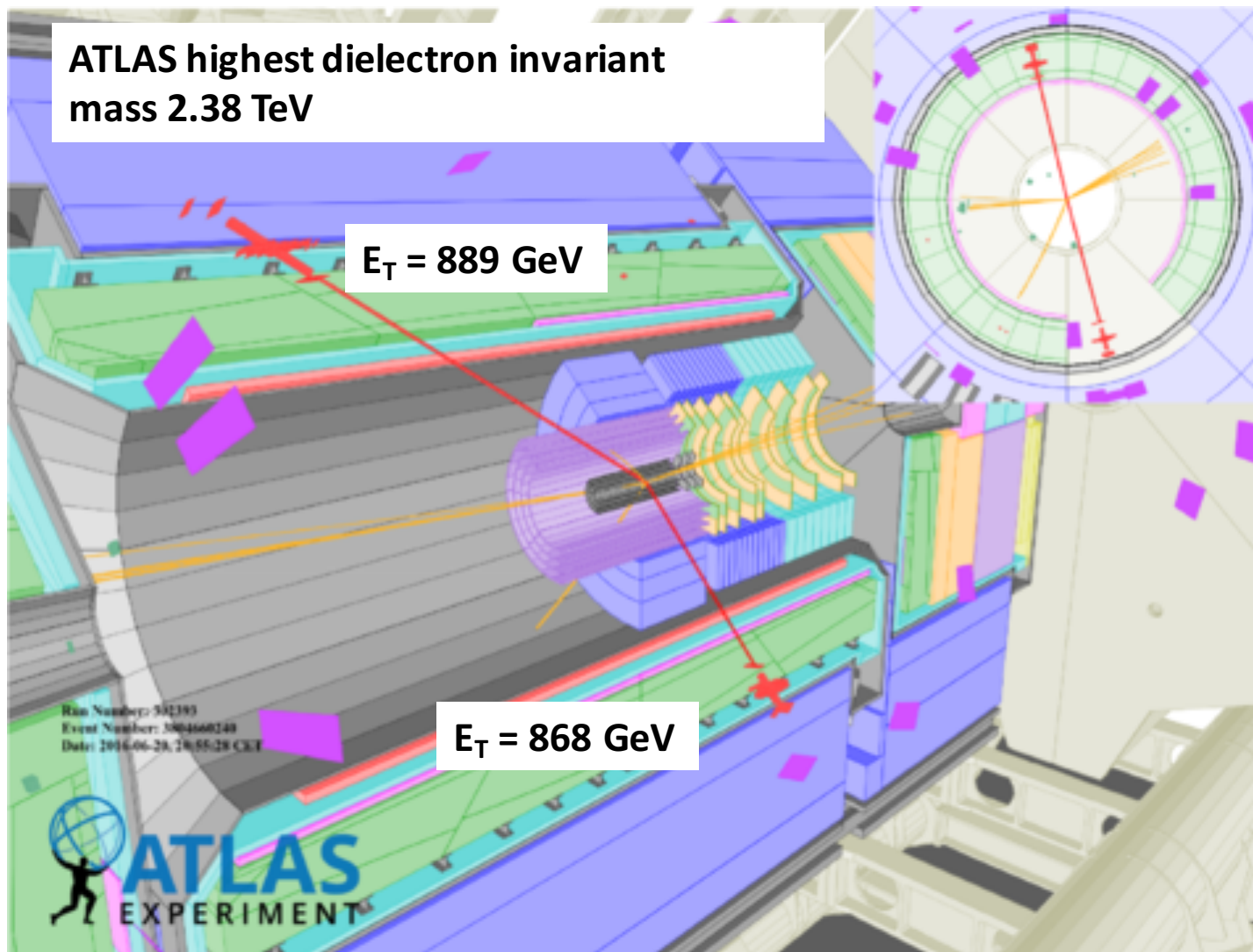
Search of $W' \rightarrow l\nu$: Limits on $\sigma \cdot \text{BR}$



- **Observed (Exp) limits on $m W'_{\text{SSM}}$**
 - 5.22 (5.10) TeV for e channel
 - 4.45 (4.71) TeV for μ channel
 - 5.11 (5.24) TeV combined

Limits improved by $\sim 1 \text{ TeV}$ wrt previous analysis based on 3.2 fb^{-1}

Search of high-mass resonances in the dilepton final state

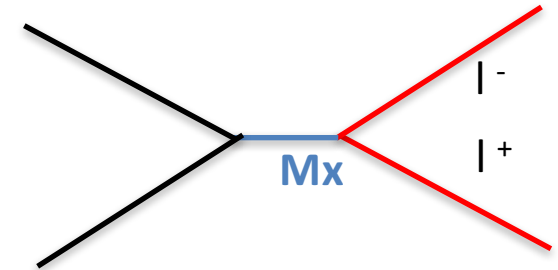


Search of high-mass resonances in the dilepton final state

Di-lepton final states sensitive to a broad class of new phenomena

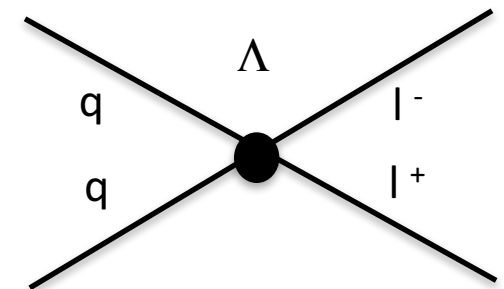
1. Direct search of narrow new heavy resonances

- Sequential Standard Model (SSM):
 Z' with same couplings to fermions as Z
- Grand unified Theories (GUT) inspired E_6 gauge group:
 - predicts two neutral gauge bosons mixing to
 $Z'(\theta_{E6}) = Z'_\psi \cos(\theta_{E6}) + Z'_\chi \sin(\theta_{E6})$
 - Signals considered for 6 values of θ_{E6}



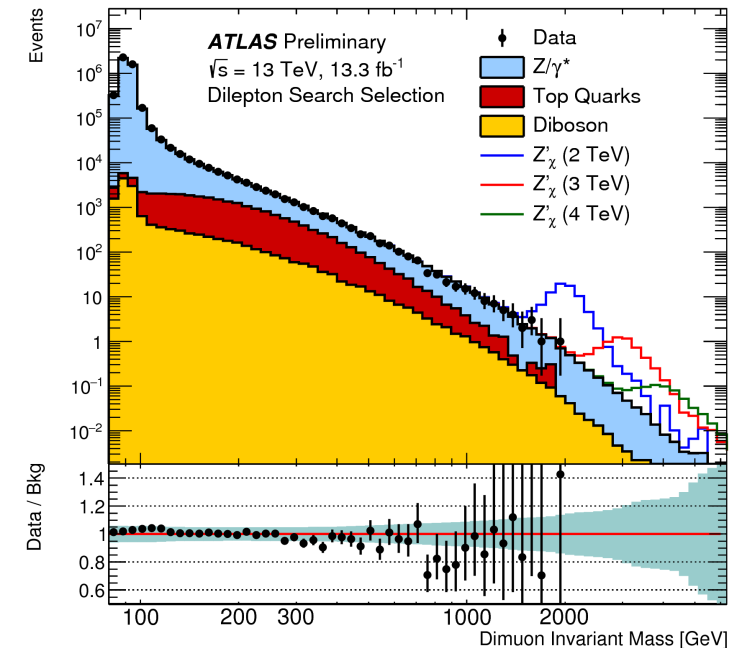
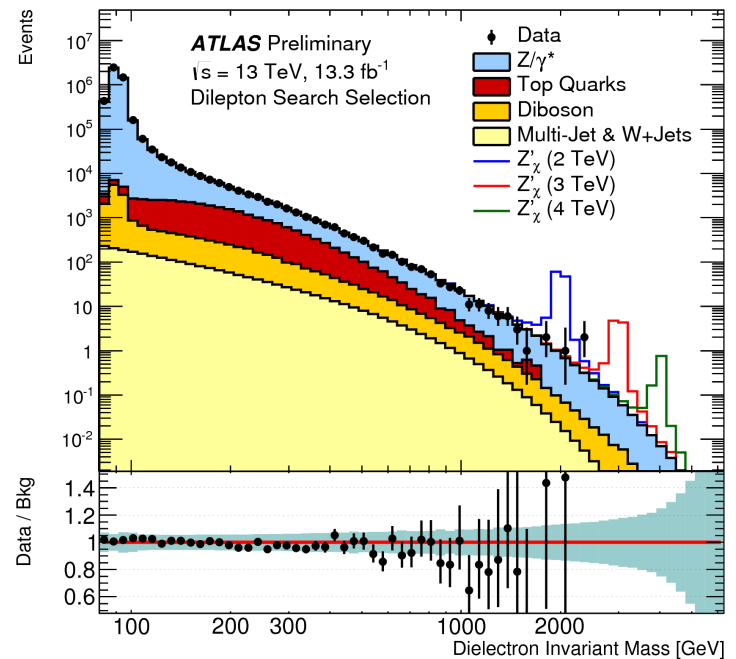
2. Non-resonant deviations from predicted SM dilepton mass spectrum.

- new interactions or compositeness in $qq \rightarrow l^+l^-$
- contact interaction representation



Search of $Z' \rightarrow ll$: Analysis strategy

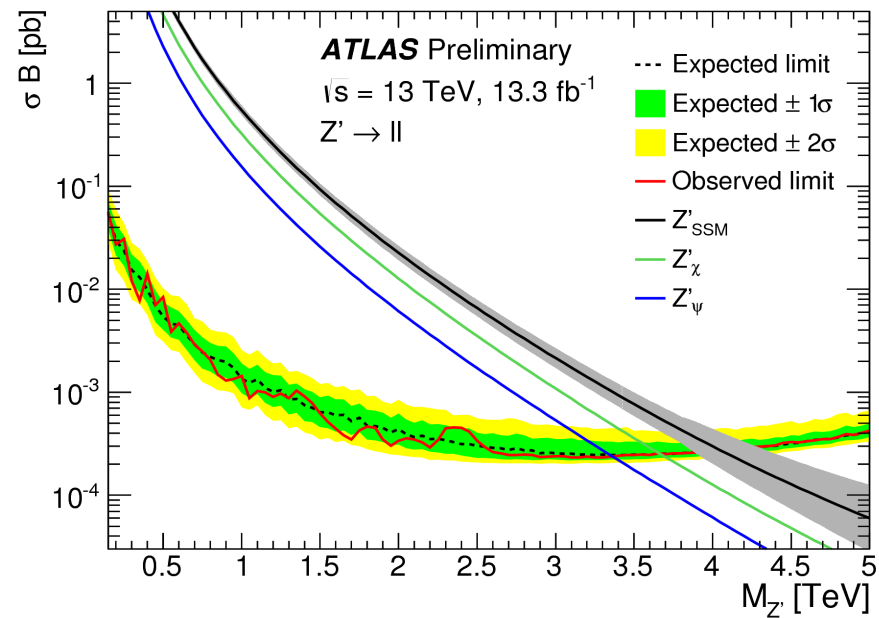
- **Trigger:** $2e$ with $E_T > 17$ GeV
 1μ -iso $p_T > 26$ GeV OR $1 \mu p_T > 50$ GeV
- **Selection:**
 - $\geq e$ (μ) with E_T (p_T) > 30 GeV
 - Isolation and quality criteria
 - $\epsilon^{\text{tot}} = 73\%$ (44%) for ee ($\mu\mu$) channel for $m_{Z'} = 3$ TeV
- **Backgrounds** with two real leptons:
 - Drell-Yan (dominant), $t\bar{t}$, single-top, WW , WZ , and ZZ by MC
- **Background** due to jet faking electrons:
 - W +jets and multi-jet events estimated from data
- Syst. Uncertainties for bkg at $m_{ll} \sim 4$ TeV:
 - e (μ) efficiency: 5% (17%)
 - e or μ energy scale and resolution: $\sim 10\%$



Search of $Z' \rightarrow ll$: Limits on $\sigma \cdot BR$

No significant excess is observed

Limit increased by 700 GeV wrt
limit obtained with 3.2 fb^{-1}

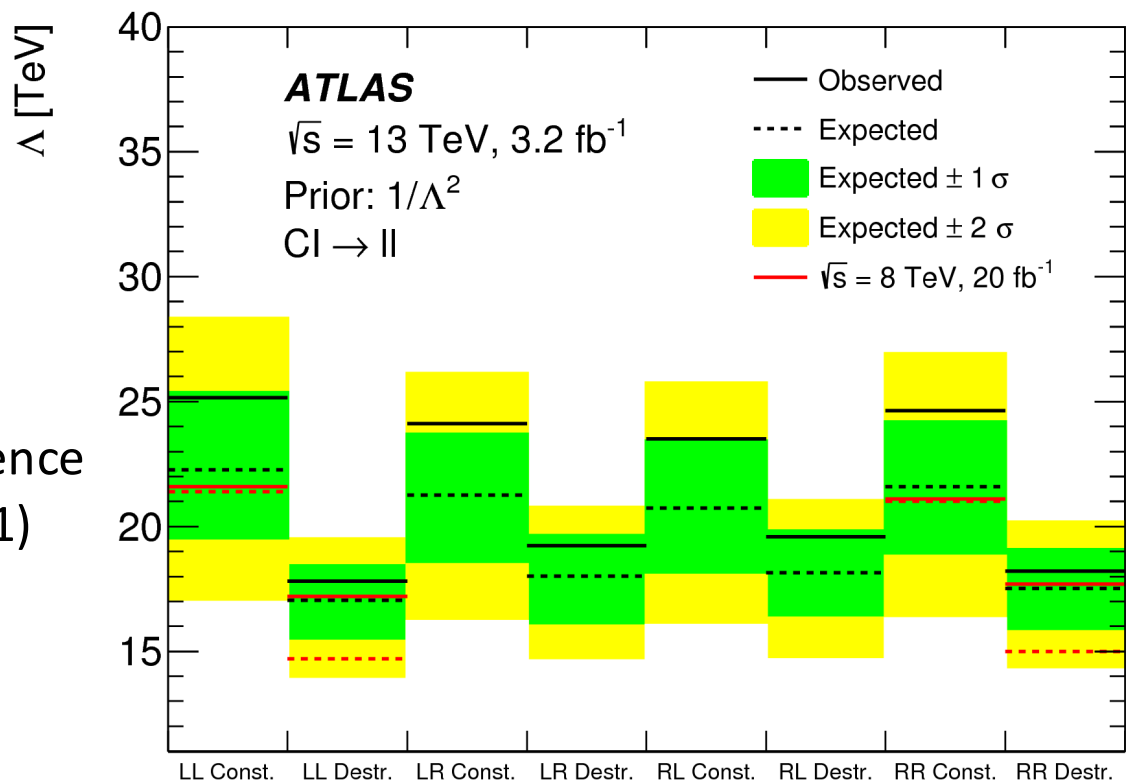


Model	Width [%]	θ_{E_6} [Rad]	Lower limits on $m_{Z'}$ [TeV]					
			ee		$\mu\mu$		ll	
			Obs	Exp	Obs	Exp	Obs	Exp
Z'_{SSM}	3.0	-	3.85	3.86	3.49	3.53	4.05	4.06
Z'_{χ}	1.2	0.50	3.48	3.49	3.18	3.19	3.66	3.67
Z'_S	1.2	0.63π	3.43	3.44	3.14	3.14	3.62	3.61
Z'_I	1.1	0.71π	3.37	3.37	3.08	3.08	3.55	3.55
Z'_η	0.6	0.21π	3.25	3.25	2.96	2.94	3.43	3.42
Z'_N	0.6	-0.08π	3.23	3.23	2.95	2.94	3.41	3.41
Z'_ψ	0.5	0π	3.18	3.18	2.90	2.88	3.36	3.35

Search of $Z' \rightarrow \ell\ell$: Exclusion limits on contact interactions

- Based on only 3.2 fb^{-1} of data collected in 2015
- Different chiral structures tested:
 - Left-right, left-left, right-rights
 - $\eta_{LR(RL)} = \pm 1$
 - $\eta_{LL(RR)} = \pm 1$
 - the others to zero
- (con)destructive interference of signal model $\eta_{ij} = -1(+1)$ with SM QCD
- Limits on Λ between 16.7 and 25.2 TeV

$$\mathcal{L} = \frac{g^2}{\Lambda^2} [\eta_{LL} (\bar{q}_L \gamma_\mu q_L) (\bar{\ell}_L \gamma^\mu \ell_L) + \eta_{RR} (\bar{q}_R \gamma_\mu q_R) (\bar{\ell}_R \gamma^\mu \ell_R) + \eta_{LR} (\bar{q}_L \gamma_\mu q_L) (\bar{\ell}_R \gamma^\mu \ell_R) + \eta_{RL} (\bar{q}_R \gamma_\mu q_R) (\bar{\ell}_L \gamma^\mu \ell_L)]$$



[Phys. Lett. B 761 \(2016\)](#)

Chiral Structure

Conclusions

Search for new physics has been performed using full 2015+2016 dataset

No deviations from SM expectations are observed

- **Di-jets final states**
 - Limits on resonances masses between 3.4 and 8.9 TeV
 - contact interactions scale $\Lambda > 13 - 29$ TeV
 - New techniques to fit background and new folding methods
- **lepton+neutrino final state:** $M_{W'} > 5.1$ TeV
- **dilepton final state:**
 - $M_{Z'} > 3.4 - 4.1$ TeV
 - contact interactions scale $\Lambda > 17-25$ TeV

Improved limits on many signal scenarios compared to previous results

Backup

Limits on Z'

Z' model:
axial-vector couplings to all SM quarks and to Dirac fermion dark matter

Assume decay to DM negligible:

→ rate and resonance width depend only on the coupling to quarks, g_q , and the mass of the resonance $m_{Z'}$

