SEARCH workshop
18 March, 2012

Searches for New Particles in Multilepton and Diboson Final States at ATLAS

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on behalf of the ATLAS Collaboration

Outline

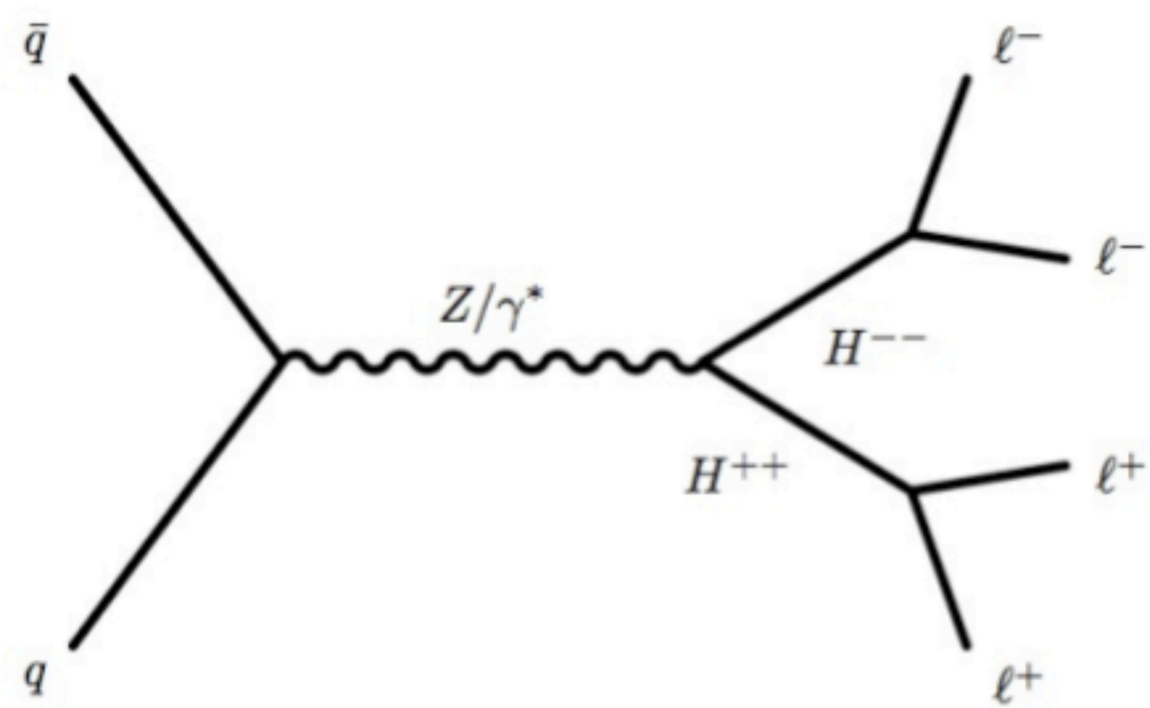
Review and discuss ATLAS results on the search for new particles in multi-lepton and diboson (and similar) final states using 1~2 fb^{-1} data

- Inclusive 3 or more leptons
- Heavy neutrino and right-handed W boson
- Leptoquark
- Diboson resonances
  - ZZ → 4-lepton, and 2-lepton + 2-jet
  - WZ → 3-lepton + E_T^{Miss}

Multi-lepton Searches

ATLAS-CONF-2011-158 (1.0 fb^{-1})

Inclusive search for new physics signature with ≥3 high p_T leptons
Not necessarily involving Z's, E_T^{miss} or jets in the final state
Veto events with OS SF lepton pair in Z mass window



Benchmark :
- Doubly charged Higgs
- Excited neutrinos

Also sensitive to
- SUSY multi-lepton
- Seesaw mechanism
- 4th gen. *b'b'*→*WtWt*, *ZbZb*, *etc*.
- 4-tops from composite top
- ...

Multi-lepton : Selection

	Electron	Muon
p_T	> 20 GeV	> 20 GeV
$\|\eta\|$	< 2.47*	< 2.5

Isolation : $p_T^{Cone0.2}/p_T < 0.1$
* crack removed

Selection Cuts

- Single lepton triggers
- ≥3 good leptons
- No OS-SF pair lepton with $|M_{ll}-M_Z|<10$ GeV or $M_{ll}<20$ GeV
  → Nominal signal region
- Additionally require $p_T^l>30$ GeV
  → Tight signal region

Process	Nominal	Tight
Z+jets	7.9 ± 3.2 ± 2.4	1.0 ± 1.5
tt + e-fake	3.9 ± 1.6 ± 0.5	1.1 ± 0.5 ± 0.2
tt + μ-fake	4.8 ± 0.6 ± 0.2	0.9 ± 0.1 ± 0.1
Double Fakes	$5.1 \pm 1.1^{+1.7}_{-1.4}$	0.2 ± 0.2 ± 0.0
Diboson	3.6 ± 0.4	1.5 ± 0.2
Single Top	0.1 ± 0.1	0.0 ± 0.0
tt + W/Z	0.5 ± 0.0	0.3 ± 0.0
Total BG	**25.9 ± 3.8 ± 4.3**	**4.9 ± 1.6 ± 0.9**
Signal ($M_{H^{++}}$=200GeV)	4.5 ± 0.2	4.2 ± 0.2
Data	**31**	**6**

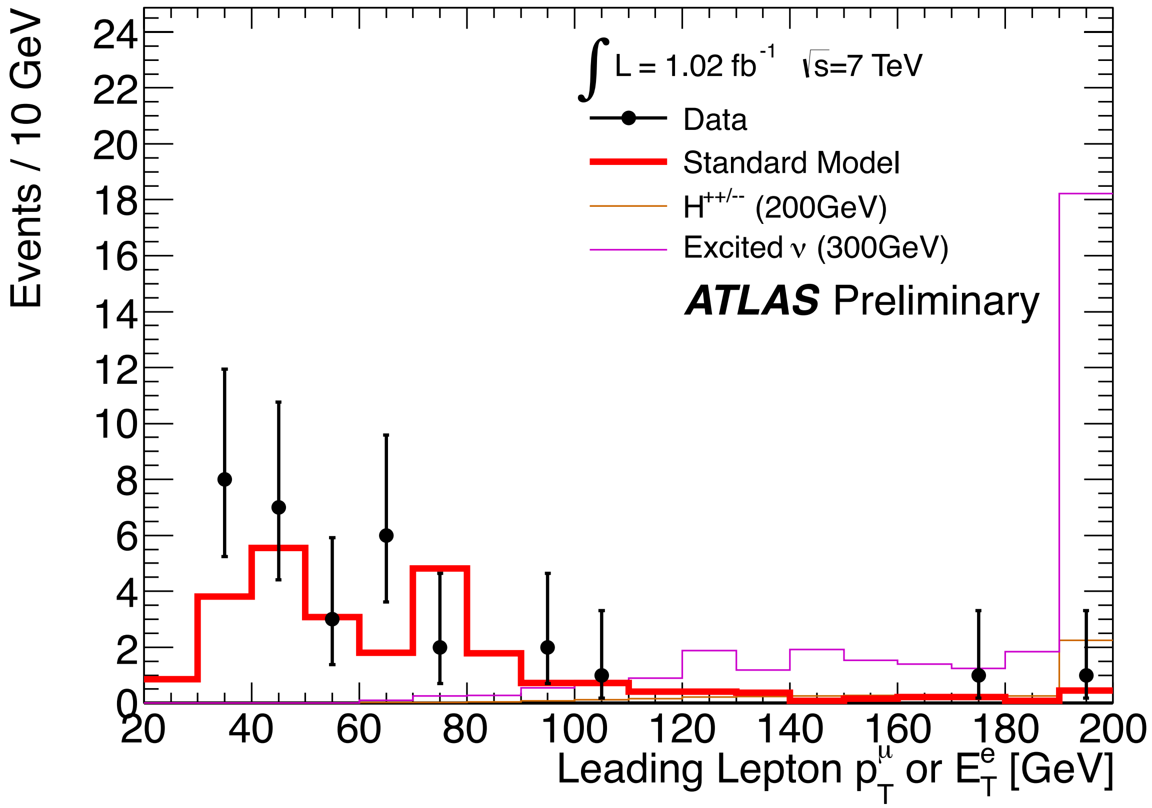
Background

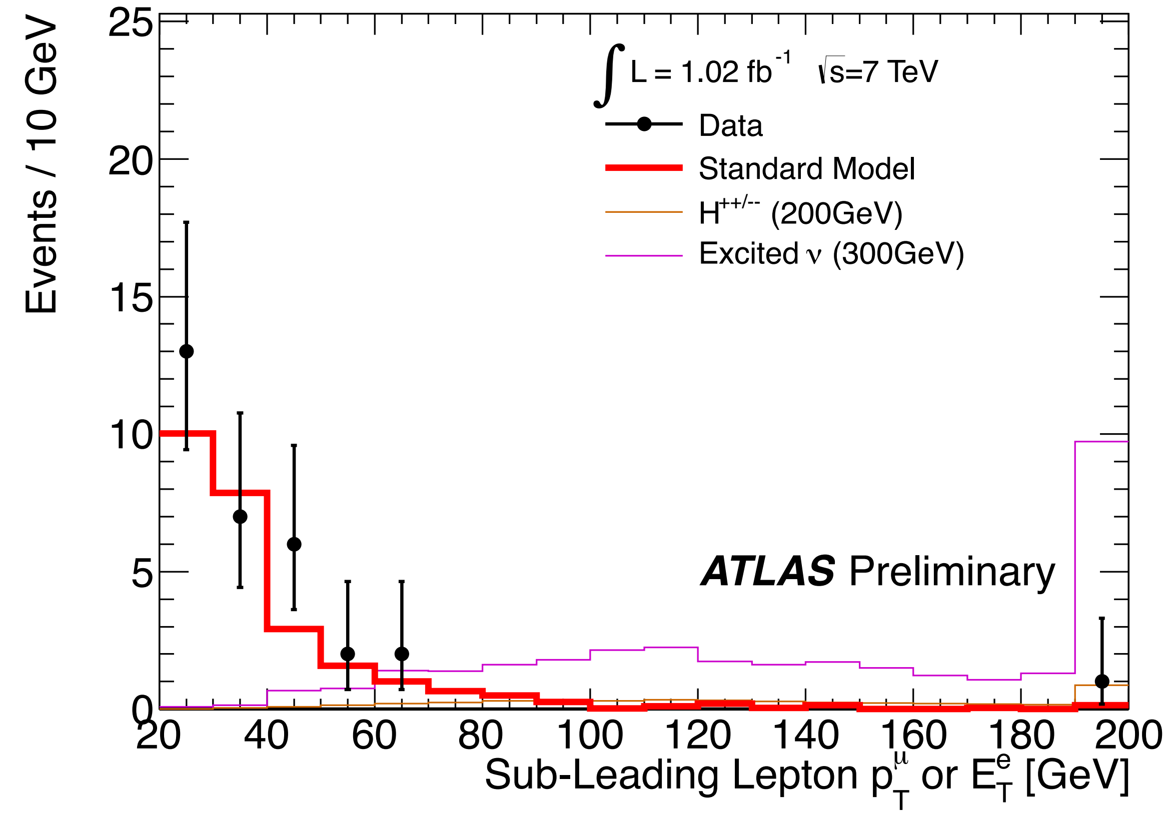
Jet-faking lepton background dominant outside the Z mass region

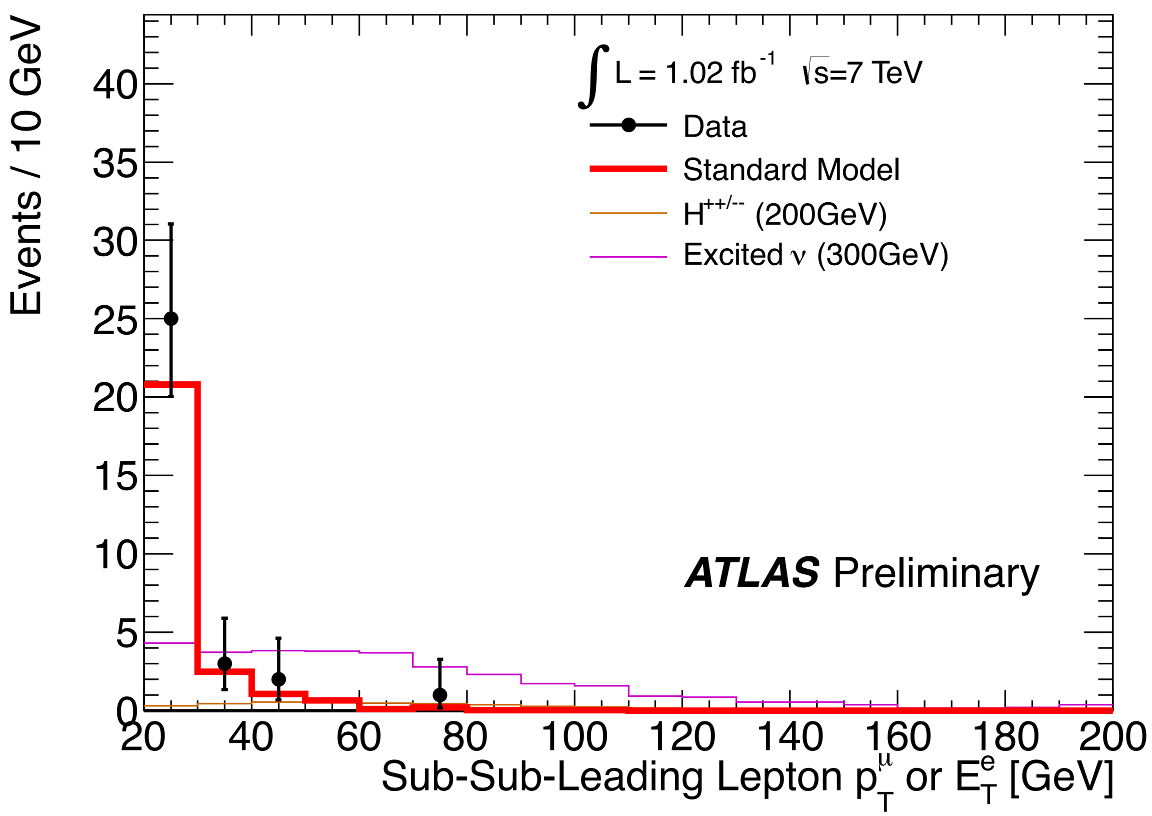
- (off-shell) Z + jets
- tt
- Double fakes (e.g, W+bb)

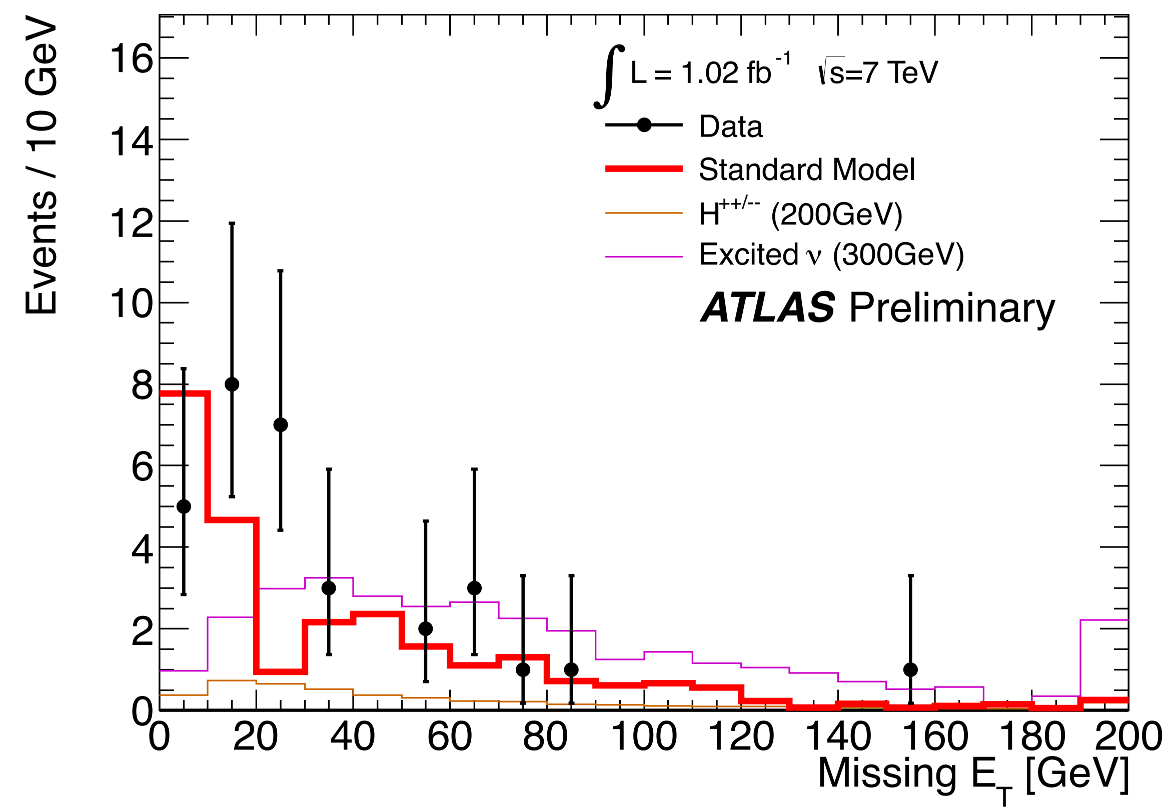
⇒ Use data-driven estimation
(see backup for more details)

Multi-lepton : Data









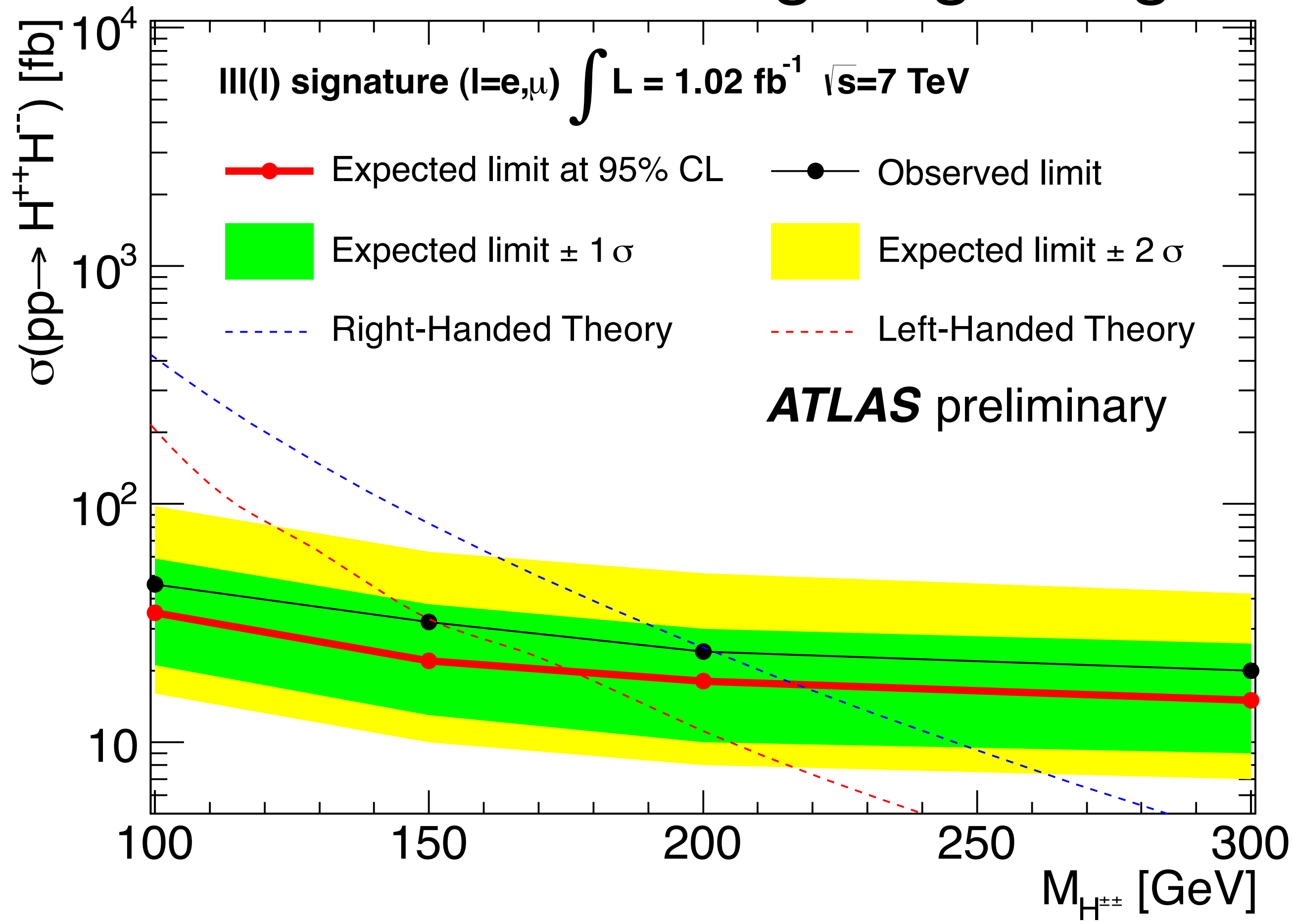
➔ No significant excess found at high lepton p_T or E_T^{Miss}

Multi-lepton : Limits

Set 95% CL limits on fiducial cross section

- *using MCLIMIT package*

Tight signal region



Fiducial Region

- p_T>20(or 30) GeV, $|\eta|$<2.5
- ≥3 leptons (e, μ)
- No OS SF pair lepton with 81 < M_{ll} < 101 GeV

Observed (expected) limits :

σ^{Fid} < 38 (28) fb for p_T>20 GeV

< 14 (11) fb for p_T>30 GeV

σ < 41 (34) pb for 200 (300) GeV excited ν_e

	Outside fiducial region		Inside fiducial region	
Signal	Fraction	Sel. Efficiency	Fraction	Sel. Efficiency
$H^{++/--}$ (100GeV)	0.68	0.02	0.32	0.57
$H^{++/--}$ (150GeV)	0.53	0.02	0.47	0.61
$H^{++/--}$ (200GeV)	0.44	0.03	0.56	0.63
$H^{++/--}$ (300GeV)	0.36	0.03	0.64	0.66
Excited ν_e (200GeV)	0.61	0.02	0.39	0.49
Excited ν_e (300GeV)	0.55	0.02	0.45	0.52

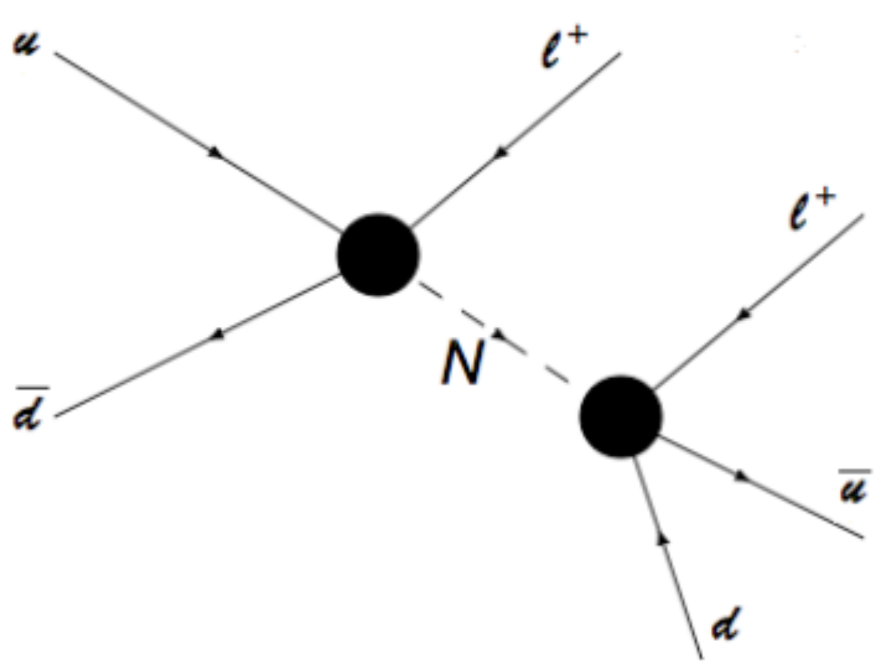
Heavy Neutrino / W_R

Non-zero masses for SM neutrinos
➔ Evidence for new physics

ATLAS Preliminary (2.1 fb^{-1})

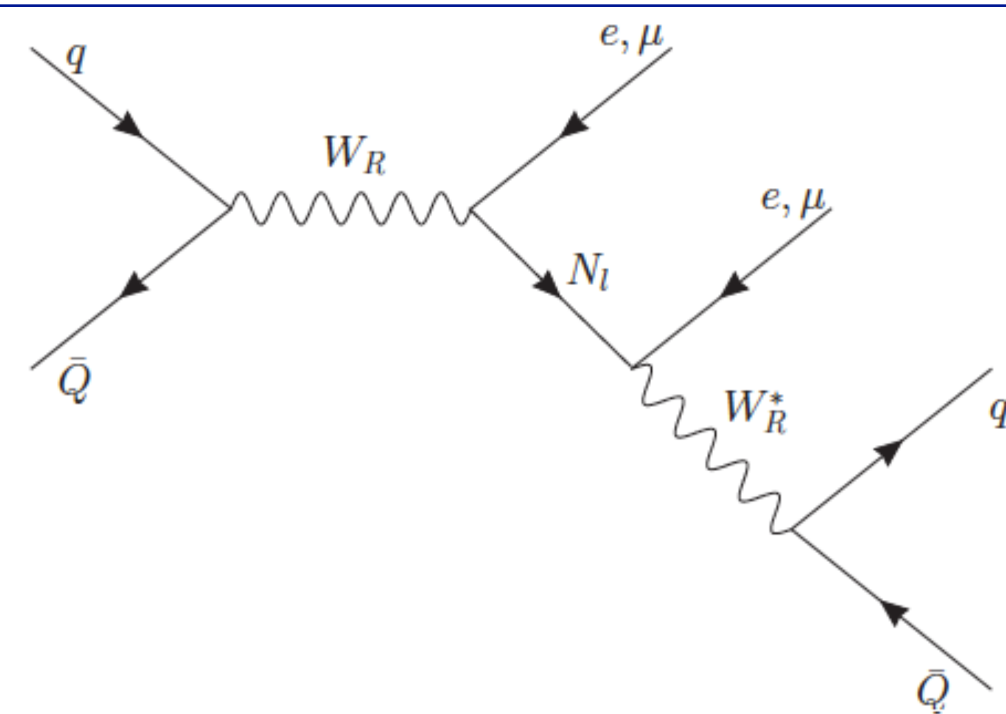
Possible explanation : Seesaw mechanism

- light neutrino mass $m_\nu \approx m_D^2/m_N$ given by *heavy neutrino* N via m_D
- *Majorana* nature for light and heavy neutrino → same-sign leptons



Lagrangian of Effective Operator (HNEO)

- Based on effective operators
  - *Vector (V), Scalar (S1, S2 and S3)*
- Sensitivity varies with $\alpha^{-1/2}\Lambda$ vs N mass
  - α = *heavy N - lepton coupling*
  - Λ = *new physics scale*



Left-Right Symmetric Model (LRSM)

- Extend SM EW gauge group
  - *new force carriers : W_R, Z'*
- Heavy N produced in decay of W_R
- mixing and no-mixing scenarios
  - *only electron and muon considered*

➔ Signature : SS (Majorana) or OS (Majorana, Dirac) lepton pair with ≥1 jet

N_H / W_R : Selection

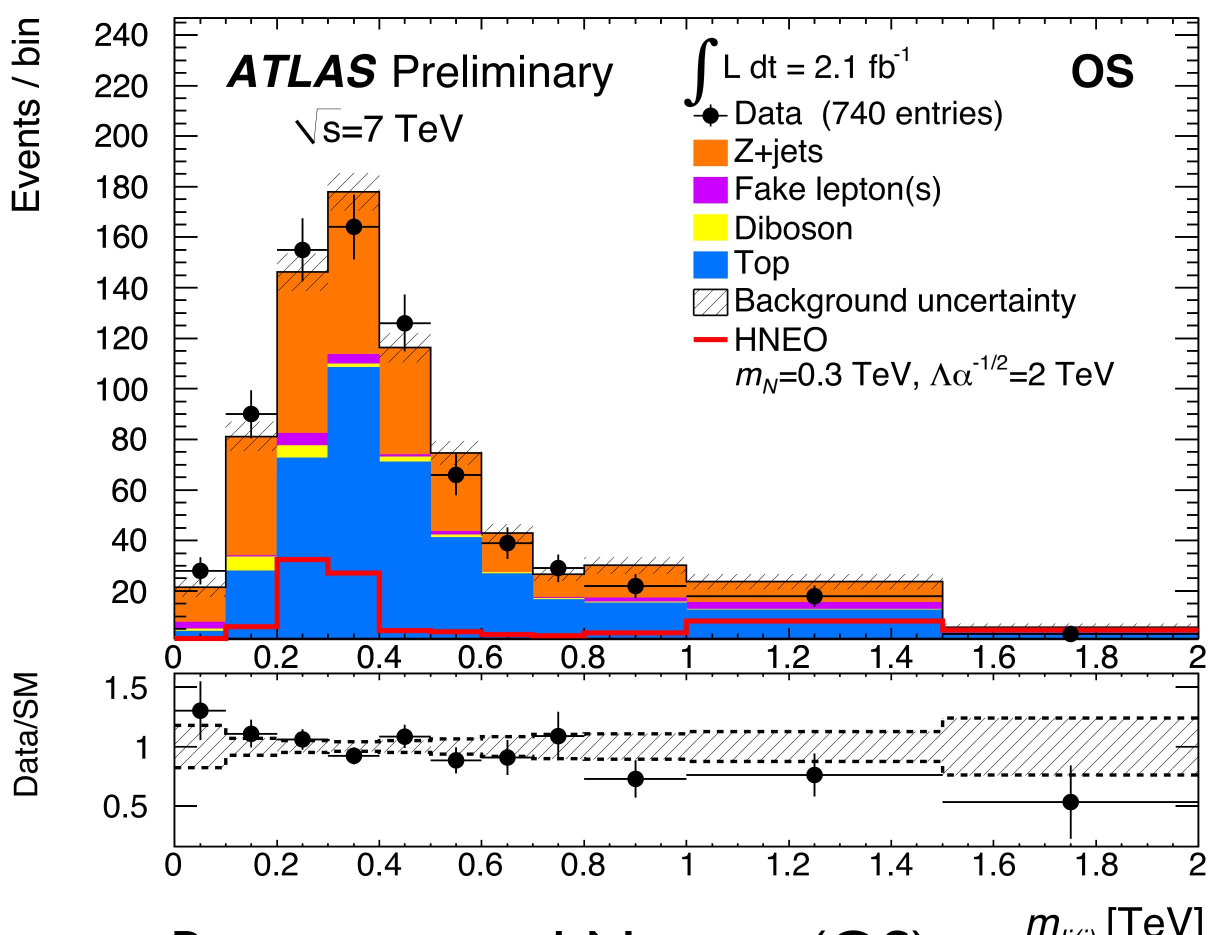
	Electron	Muon	Jet
p_T	> 25 GeV	> 25 GeV	> 20 GeV
$\|\eta\|$	< 2.47*	< 2.4	< 2.8

Isolation required for both e and μ

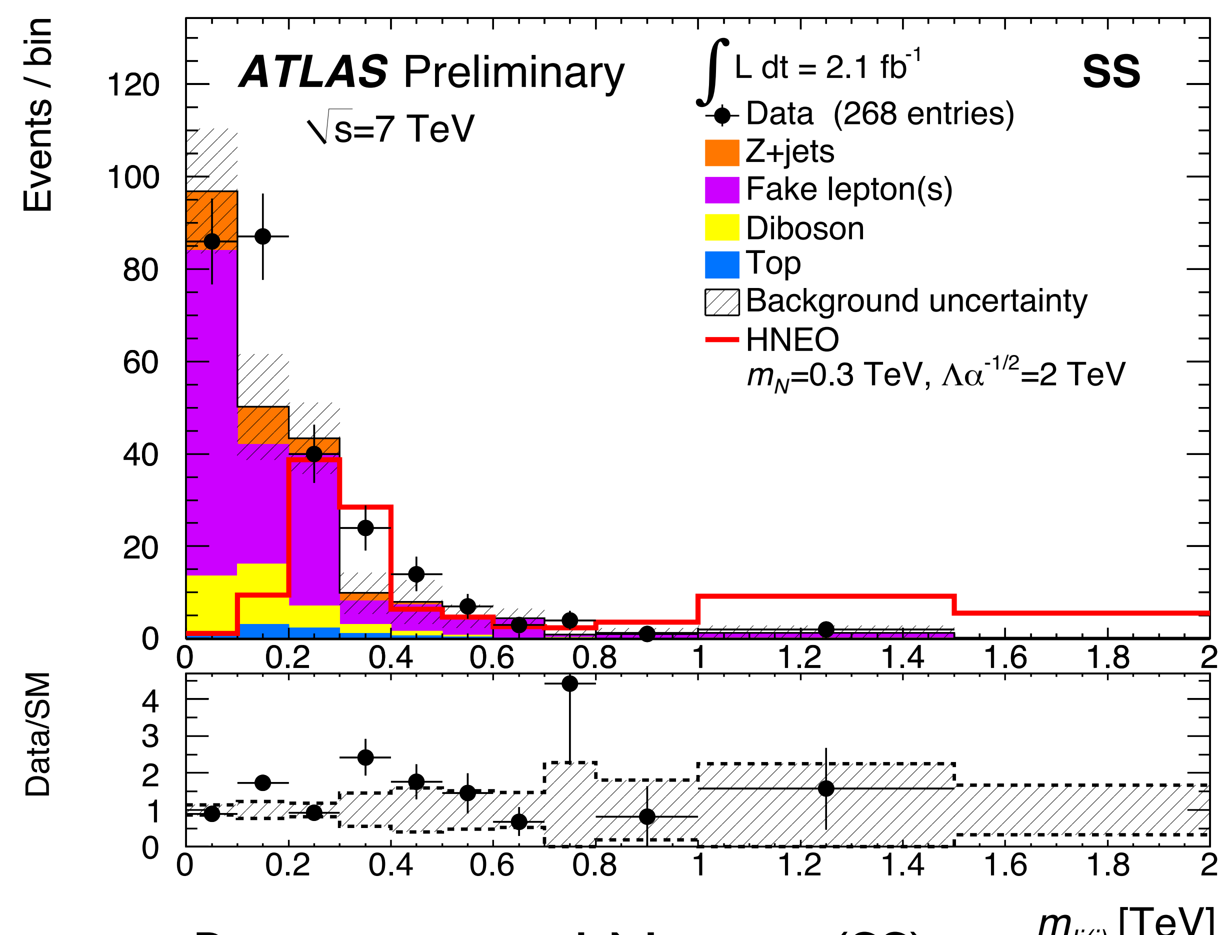
* crack removed

Selection Cuts

- 2 leptons and ≥ 1 jets
- M_{ll} > 110 GeV
- Scaler p_T sum of leptons and up to 2 jets : S_T > 400 GeV (OS only)
- LRSM search : $M_{llj(j)}$ > 400 GeV



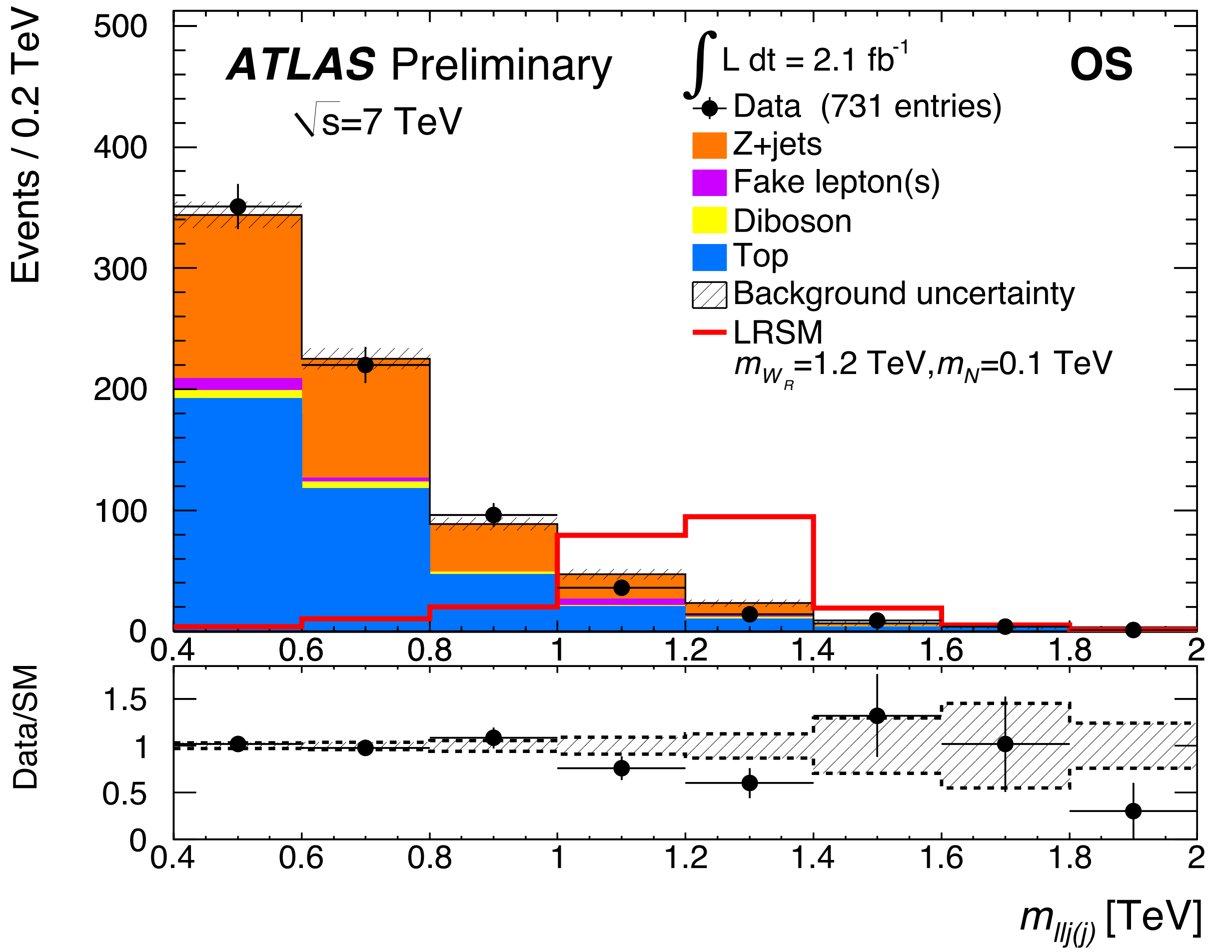
Reconstructed N mass (OS)



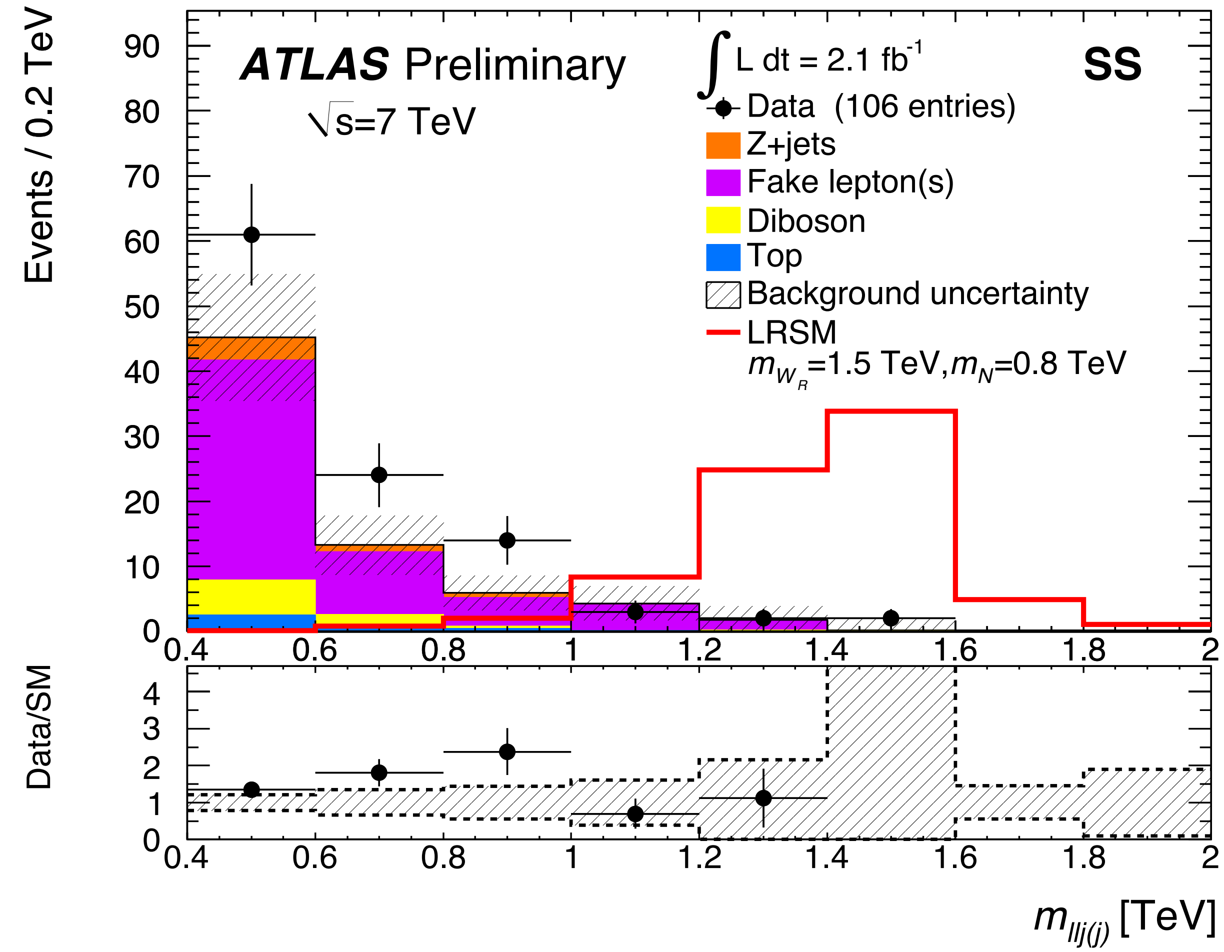
Reconstructed N mass (SS)

N_H / W_R : Background and Systematics

Reconstructed W_R mass (OS)



Reconstructed W_R mass (SS)



Background

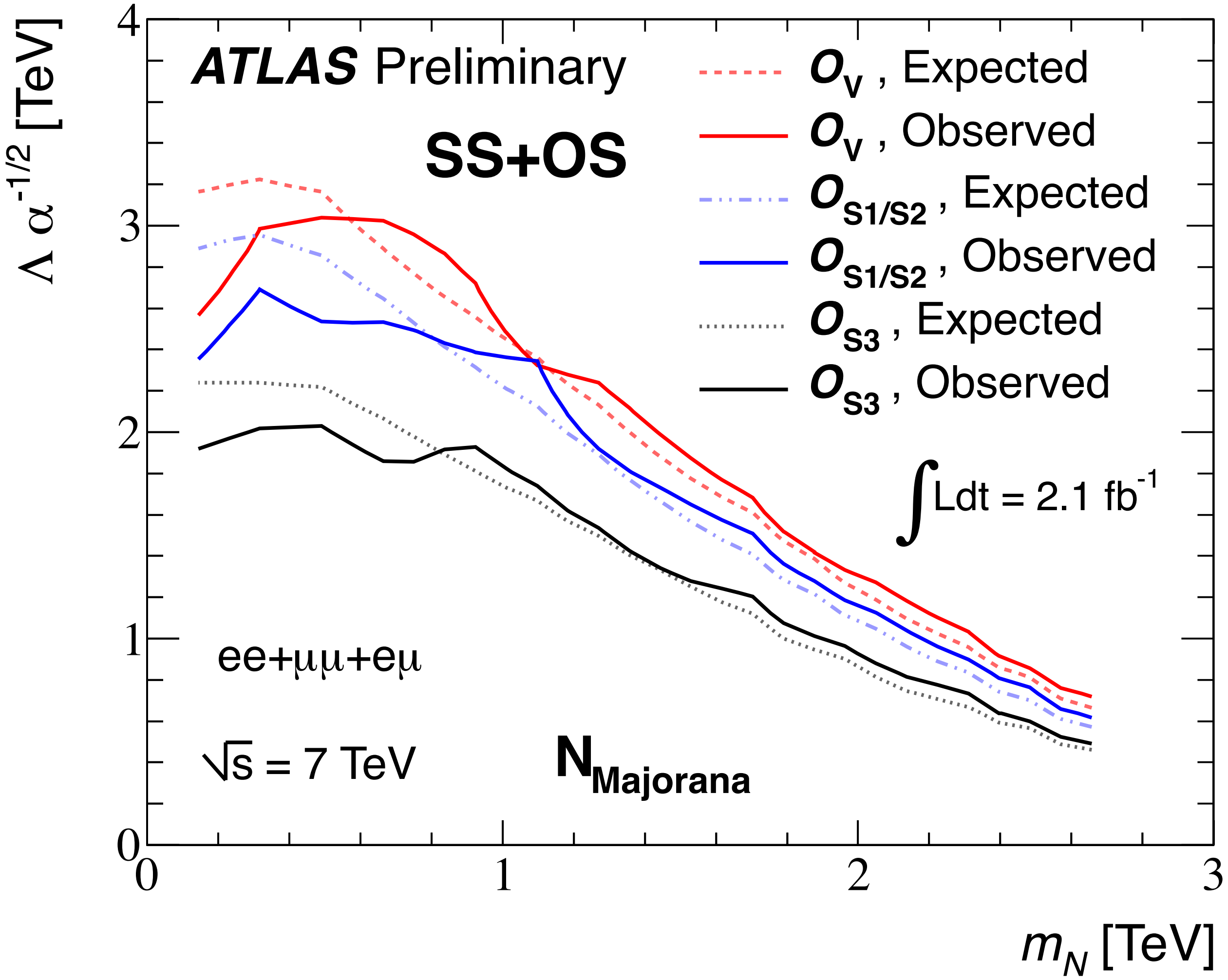
- SS final states
  - Misidentified leptons (W+jets, tt, QCD)
  - Electron charge misID due to hard brem
  - Diboson from MC
- OS final states
  - Z/γ^*+jets (MC scaled to data)
  - tt, single-top, diboson from MC

Systematics

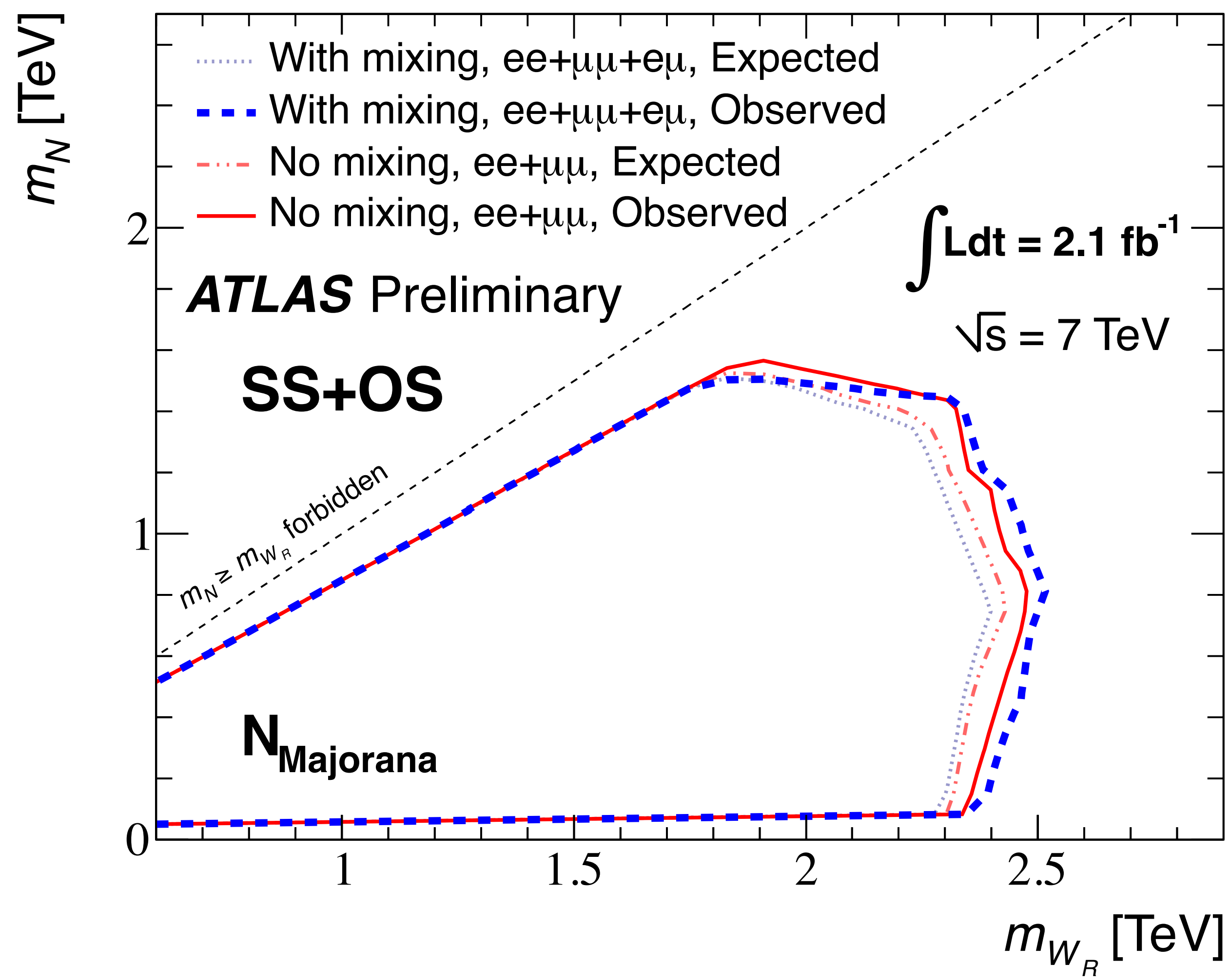
- Misidentified leptons
- Electron charge misID
- For both signal and background:
  - Lepton efficiency, energy scale & resolution
  - JES, JER
  - PDF (signal)

N_H / W_R : Limits

HNEO model



LRSM model



Set 95% CL limits on $\alpha^{-1/2}\Lambda$ vs M_N for HNEO and excluded mass region in (M_{WR}, M_N) for LRSM

- *Bayesian approach with nuisance parameters for systematics*

➔ M ≲ 1.8(2.3) TeV excluded for W_R with $\Delta M(W_R, N) > 0.3(0.9)$ TeV

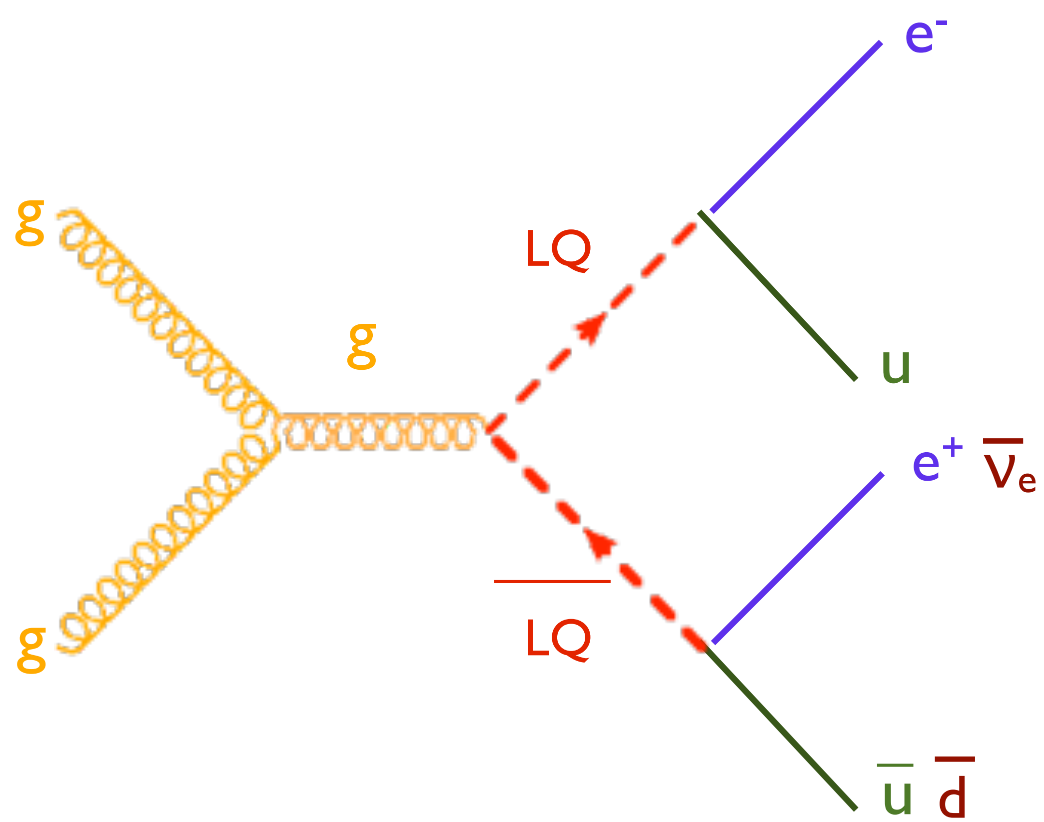
Similar limits for Dirac neutrino (in backup)

Leptoquarks

Quarks and leptons look similar ➔ New symmetry at high energy scale?

Could be mediated by new gauge boson :“Leptoquark”

- *Baryon and lepton quantum numbers, colored and fractional electric charge*
- *Predominantly produced in pairs via gg or $q\bar{q}$*
- *Usually assumed to couple within generations (FCNC)*



2 leptons (lν, ll) + 2 jets in the final state

- 1st generation : eeqq, eνqq
  Phys. Lett. B 709, 158 (2012) (1 fb^{-1})
- 2nd generation : μμqq, μνqq
  Submitted to EPJC (1 fb^{-1})
  arXiv:1203.3172

Analysis strategy

- Data-driven estimation for major backgrounds (W/Z+jets, tt, QCD)
- Form log-likelihood ratio from signal-sensitive variables to look for data excess
- Results combined to set limits on M_{LQ} vs β (= Br(LQ→$l^{\pm}$q))

Leptoquarks : Analysis

	Electron	Muon	Jet
p_T	> 30 GeV	> 30 GeV	> 30 GeV
$\lvert\eta\rvert$	< 2.47*	< 2.4	< 2.8
Isolation	$E_T^{Cone0.2}/E_T < 0.1$	$p_T^{Cone0.2}/p_T < 0.2$	

* crack removed

Selection Cuts

- Exactly 1 or 2 charged leptons
- At least 2 jets
- E_T^{Miss} > 30 GeV ($l\nu qq$)
- $M_T(l, E_T^{Miss})$ > 40 GeV ($l\nu qq$)
- M_{ll} > 40 GeV ($llqq$)

Construct likelihood for signal and background hypotheses :

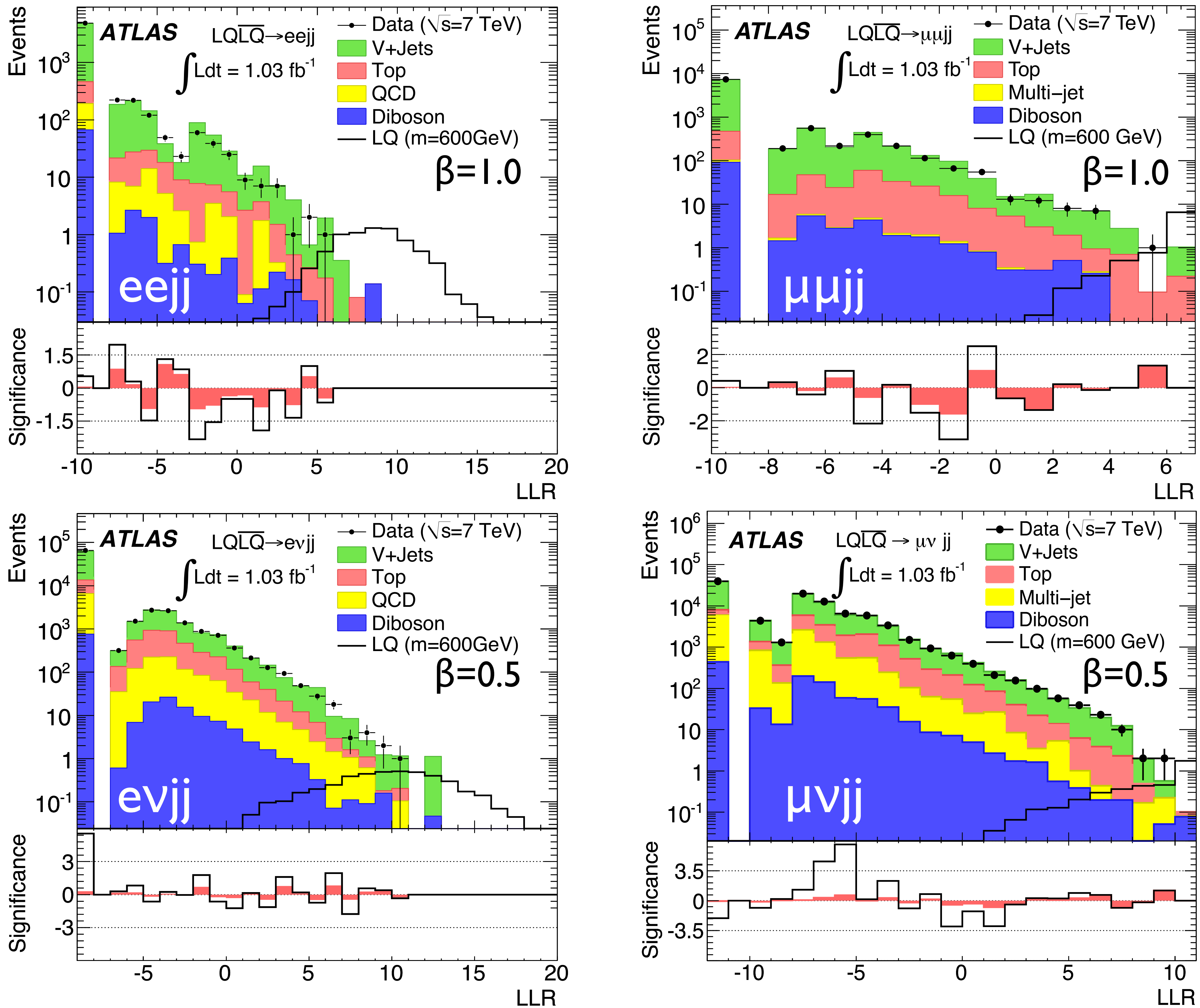
$L_B = \prod b_i(x_{ij})$ and $L_S = \prod s_i(x_{ij})$ with
- M_{ll}, S_T, $\overline{M}_{LQ}$ for lljj channel
- M_T(l,MET), S_T, M_T^{LQ}(jet,MET), M_{LQ} for $l\nu jj$ channel

as input variables

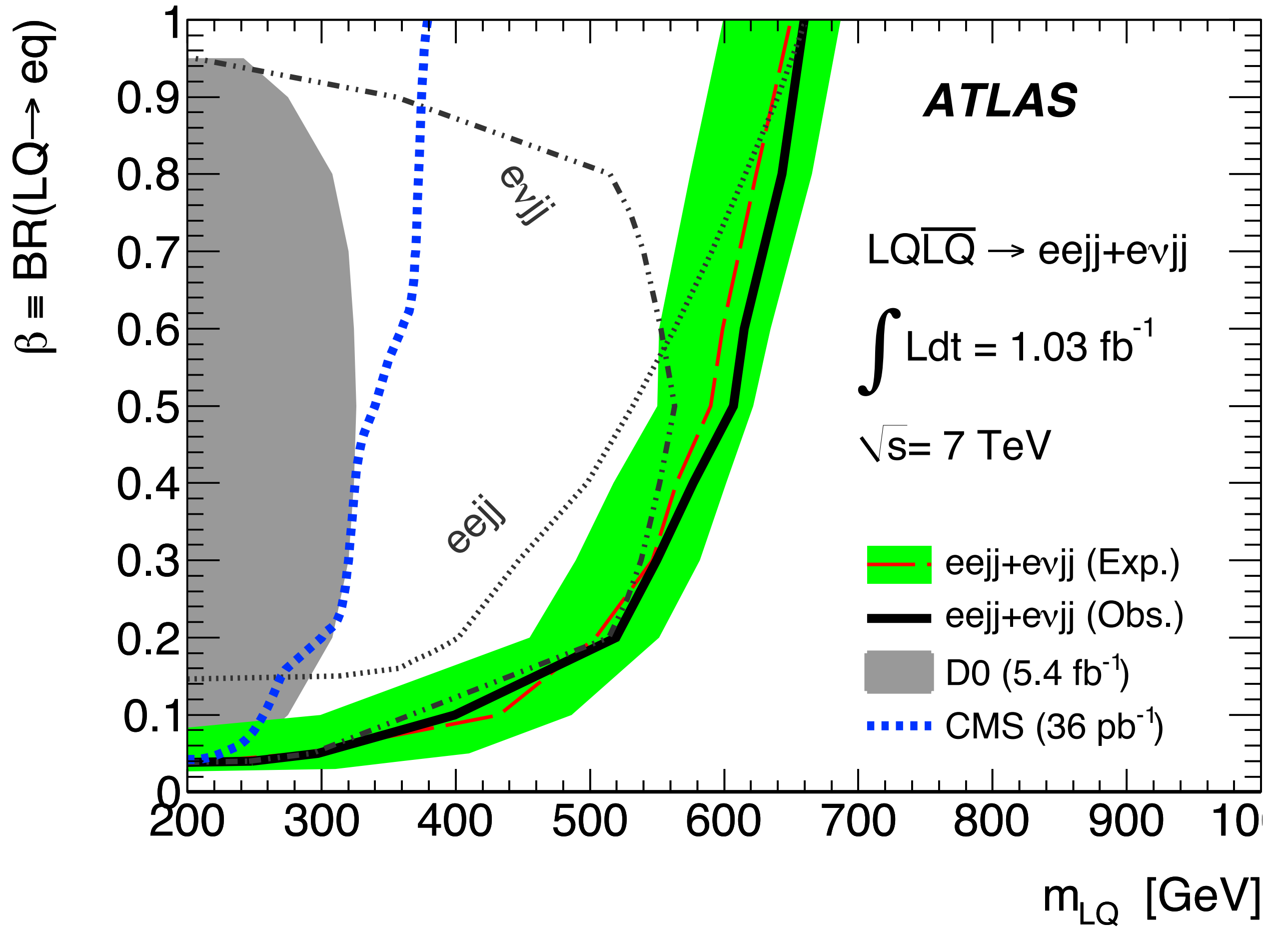
Use LLR = $\log(L_S/L_B)$ as a final variable

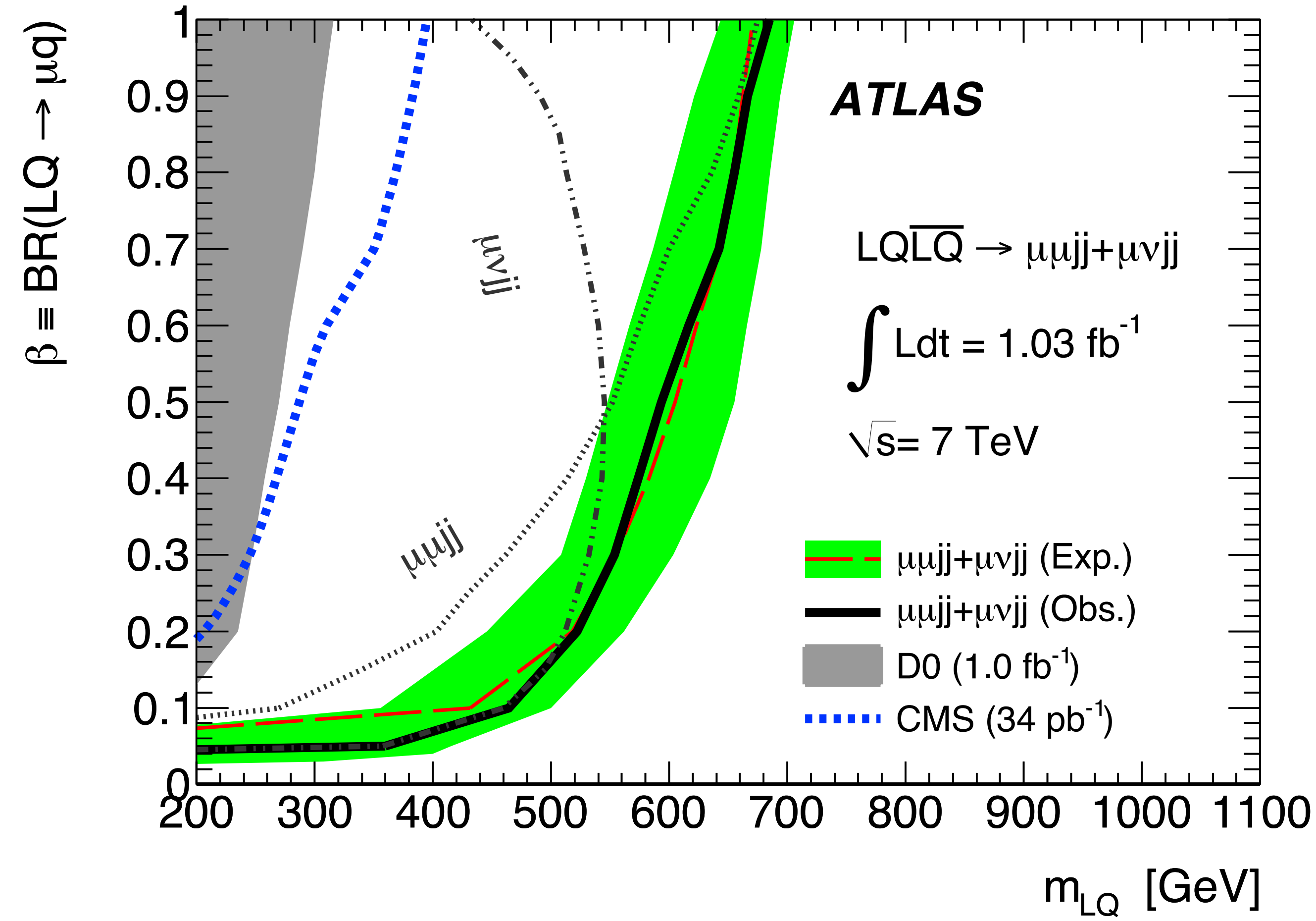
	LLR > 0		No cut on LLR	
Process	eejj	eνjj	$\mu\mu$jj	$\mu\nu$jj
V+jets	26 ± 14	688 ± 210	8500±3400	74000±17000
Top	5.3 ± 2.2	173 ± 38	590 ± 240	11600±1900
Diboson	0.7 ± 0.3	11 ± 2	120 ± 30	1020 ± 180
Multijet	2.3 ± 1.5	75 ± 15	130 ± 120	9690 ± 230
Total BG	**34 ± 14**	**950 ± 220**	**9300±3400**	**96000±17000**
LQ (600GeV)	7.5 ± 0.5	4.5 ± 0.2	8.2 ± 0.4	3.9 ± 0.2
Data	**22**	**900**	**9254**	**97113**

Leptoquarks : Data



Leptoquarks : Limits





Set 95% CL limits on LQ pair production cross section and exclusion regions in (M_{LQ}, β) plane

- *Modified frequentist approach with LLR test statistic*

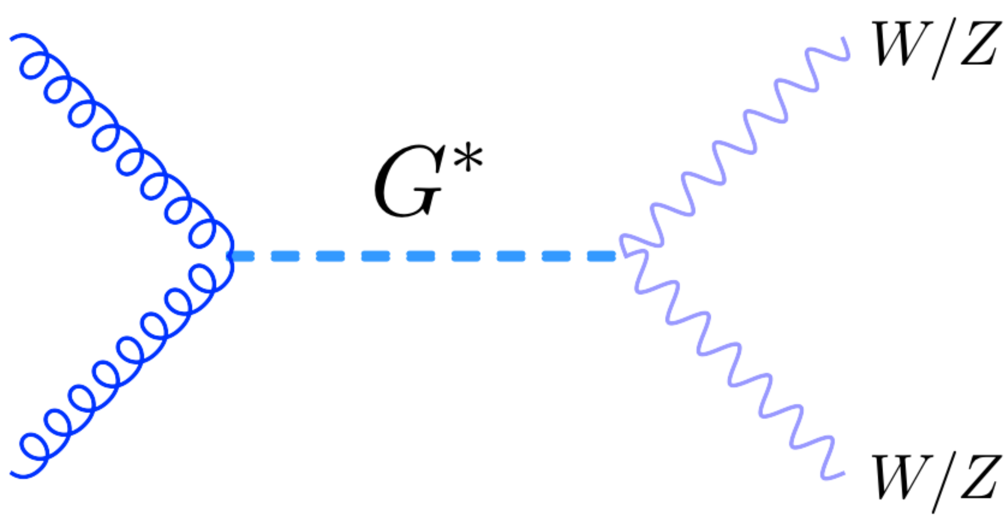
Observed (expected) limits on LQ mass

1st Gen. LQ		2nd Gen. LQ	
β = 0.5	β = 1.0	β = 0.5	β = 1.0
607 (587)	**660** (650)	**594** (605)	**685** (671)

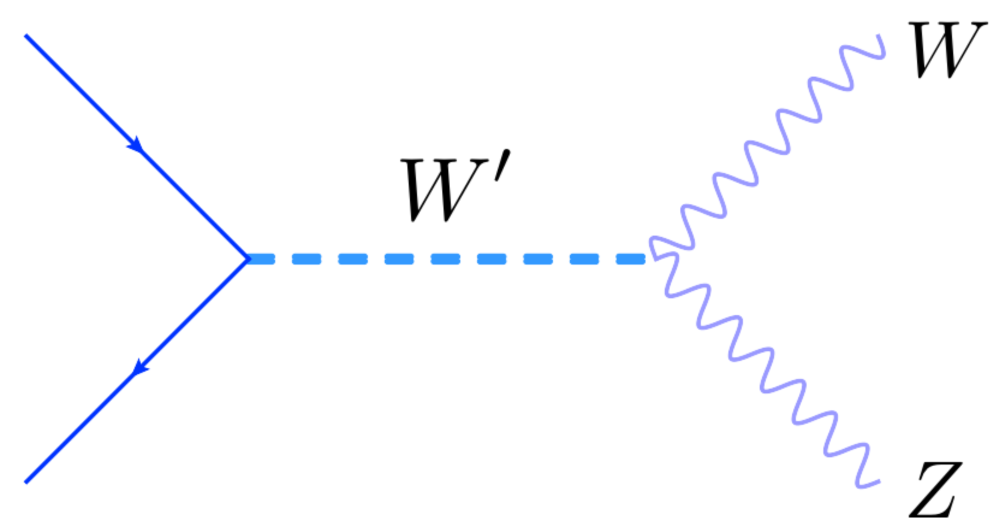
Diboson Searches

Look for "narrow" resonances decaying to WW/WZ/ZZ and Wγ/Zγ

Two benchmark models in Pythia as a baseline



Spin-2 RS1 Graviton → WW/ZZ



Spin-1 SSM W'-boson → WZ

Other interesting models that predict diboson final states

- RS with "SM fields in the bulk" : G^* → WW, ZZ, KK Z' → WW
- Low-scale technicolor : ρ_T/a_T → WZ, WW, Wγ/Zγ
- Minimum walking technicolor : R → WZ, Wh, Zh

For a longer term :

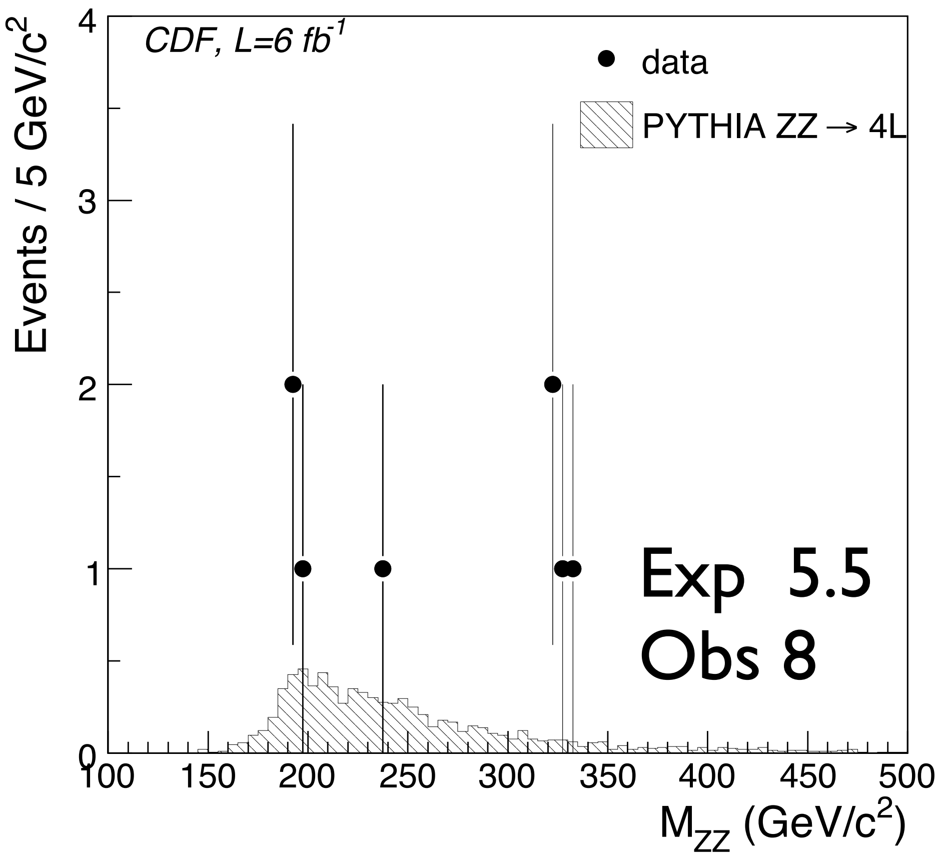
- VV resonances in Vector Boson Scattering : e.g, qq → qqWW

ZZ (→ ll + ll / ll + qq) Resonance

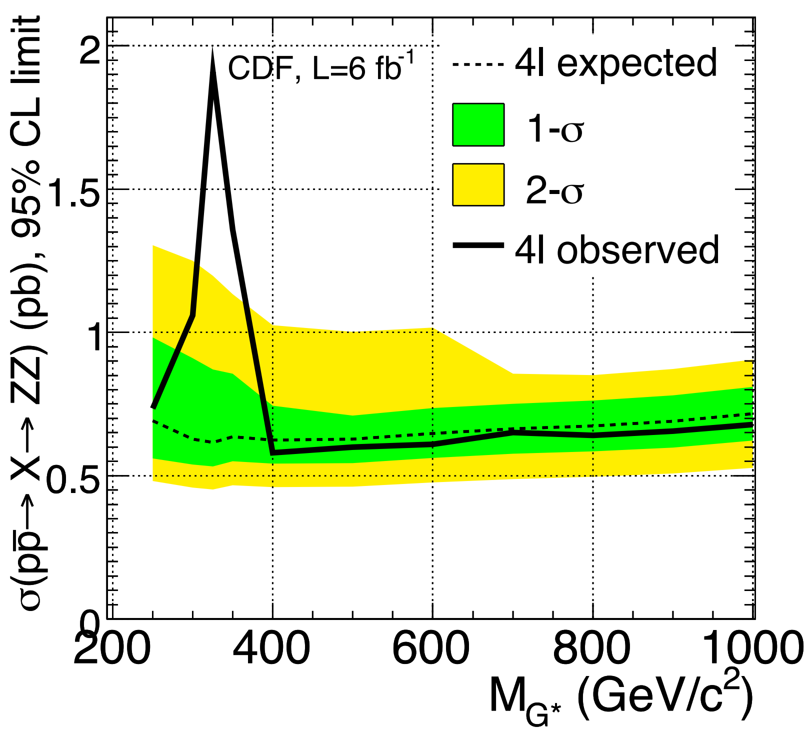
Sensitive to high-mass ZZ resonances over wide mass range

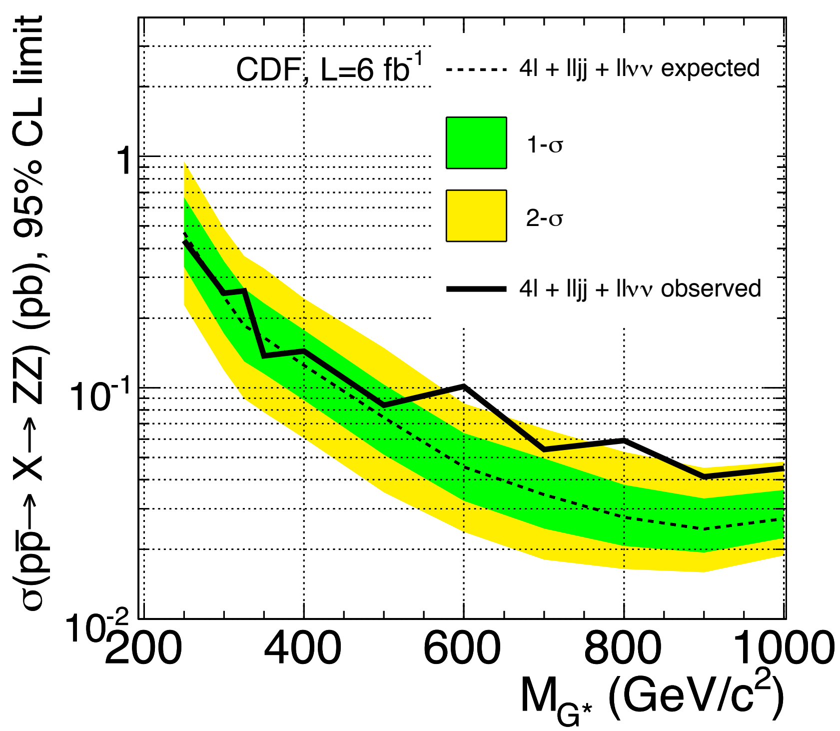
Motivated by CDF 4l events at ~325 GeV (not confirmed by other channels)

M_{ZZ}



CDF 6 fb^{-1} : PRD 85, 012008 (2012)





ZZ → ll+ll ➔ Clean signal; very small background; sensitive at low mass

ZZ → ll+qq ➔ Larger branching fraction; sensitive at high mass

RS1 Graviton → ZZ as a benchmark

Fiducial cross section limits for ZZ → ll+ll

Submitted to PLB (1 fb^{-1})

arXiv : 1203.0718

ll + ll : Selection

Selection Cuts

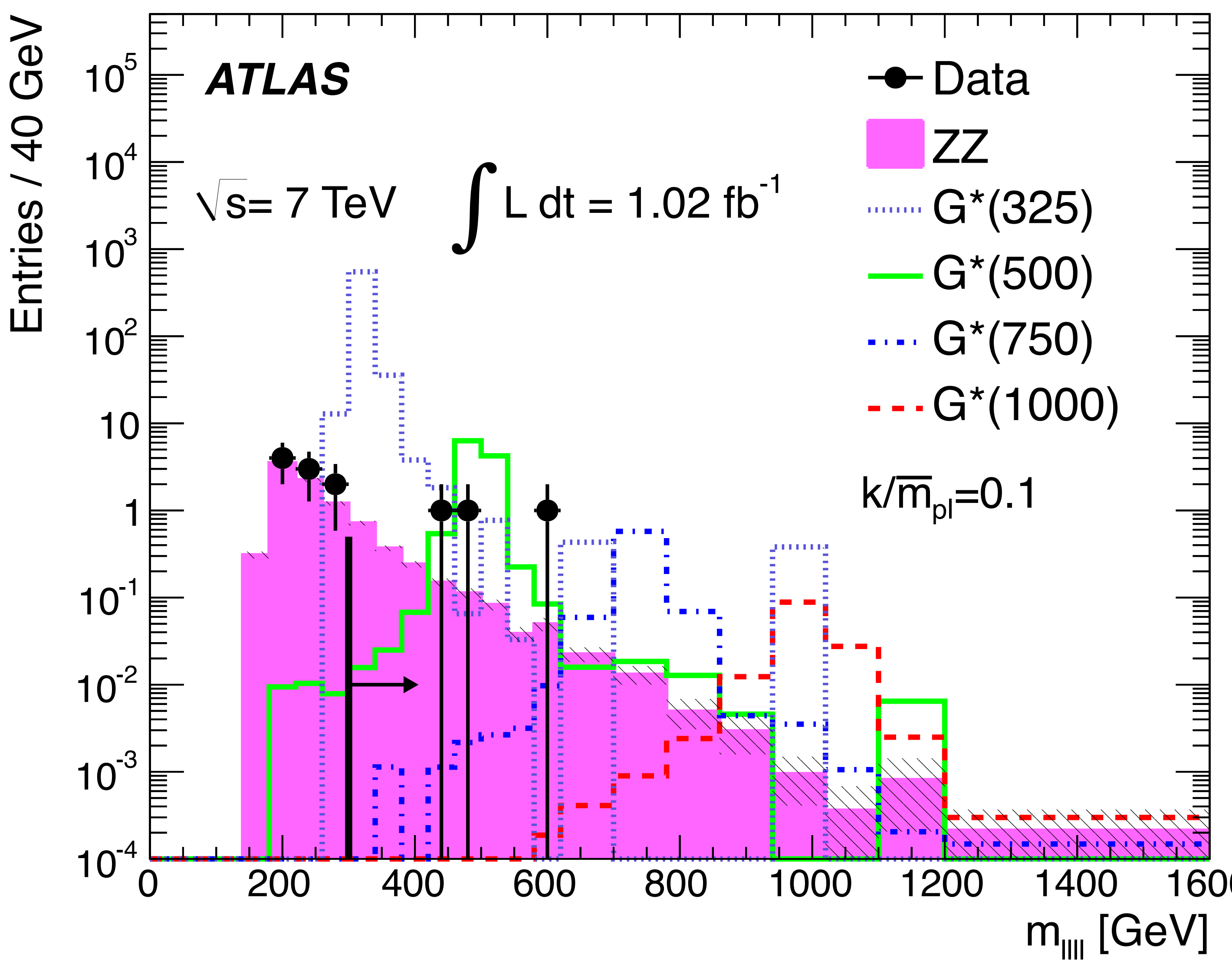
- 2 OS SF pairs (eeee, eeμμ, μμee, μμμμ)
- $|M_{ll} - M_Z| < 25$ GeV
- $M_{ZZ} > 300$ GeV

	Electron	Muon
p_T	> 15 GeV	> 15 GeV
$\|\eta\|$	< 2.47*	< 2.5

Isolation : $p_T^{Cone0.2}/p_T < 0.15$

* crack removed

Process	Events
ZZ	1.9 ± 0.1 ± 0.1
Fake Leptons	$0.02\ ^{+1.0}_{-0.01}\ ^{+0.8}_{-0.02}$
Total BG	$\mathbf{1.9\ ^{+1.0}_{-0.1}\ ^{+0.8}_{-0.1}}$
Signal	
M_{G*} = 325 GeV	590 ± 40 ± 30
500 GeV	71 ± 3 ± 4
750 GeV	12 ± 0.5 ± 0.6
1000 GeV	1.5 ± 0.1 ± 0.1
Data	**3**



ll + ll : Background and Systematics

Background

- SM ZZ from MC
- Misidentified leptons from data
  - WZ+jets
  - Z+X (jets or photons)
  - tt → bb+lνlν

Systematics

- Luminosity
- Lepton efficiency : 3-6% for e, 1-2% for μ
- Misidentified leptons
  - Limited WZ(→3l)+jets sample
  - heavy vs light flavor jets

Misidentified lepton background estimated by

- selecting events with 3 real leptons + "lepton-like" jet
- applying *fake factor* = *Prob(jet → lepton cut) / Prob.(jet → "lepton-like" jet cut)* obtained from jet-dominant control sample
- correcting for real lepton contamination and double counting

ZZ background modeling checked at M_{ZZ} < 300 GeV

Process	eeee	μμμμ	eeμμ
ZZ	$1.3 \pm 0.1 \pm 0.1$	$2.5 \pm 0.1 \pm 0.1$	$3.6 \pm 0.1 \pm 0.1$
Fake Leptons	$0.01\ ^{+0.02}_{-0.01}\ ^{+0.02}_{-0.01}$	$0.3\ ^{+0.9}_{-0.3} \pm 0.2$	$0.0\ ^{+1.0}_{-0.0}\ ^{+0.8}_{-0.0}$
Total BG	$\mathbf{1.3 \pm 0.1 \pm 0.1}$	$\mathbf{2.7\ ^{+0.9}_{-0.3} \pm 0.3}$	$\mathbf{3.6\ ^{+1.0}_{-0.1}\ ^{+0.8}_{-0.1}}$
Data	**2**	**6**	**1**

ll + jj : Selection

Selection Cuts

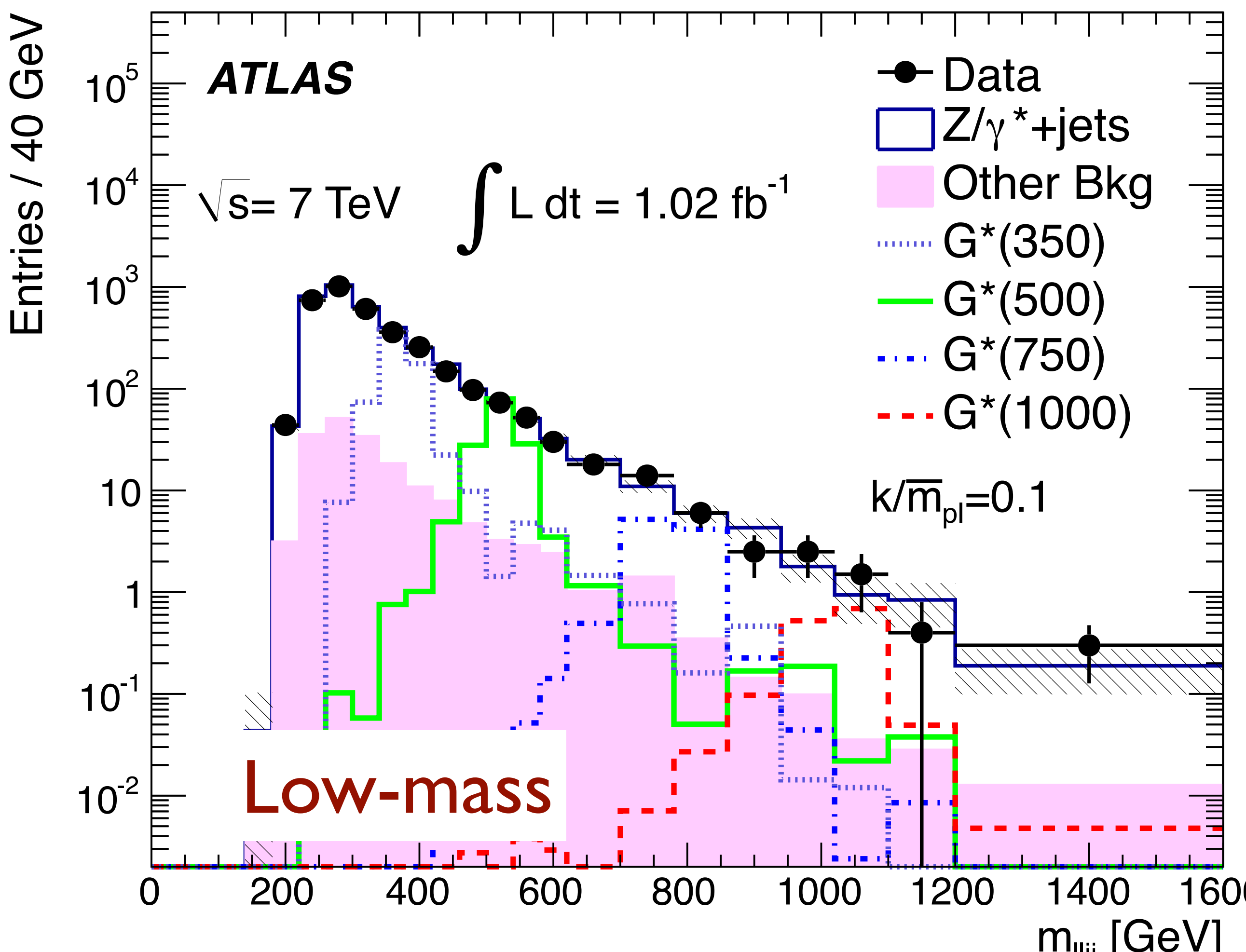
- 2 SF leptons with $|M_{ll} - M_Z| < 25$ GeV
- $65 < M_{jj} < 115$ GeV
- Low-mass selection =
  $p_T^{ll}>50$ GeV + $p_T^{jj}>50$ GeV
- High-mass selection =
  $p_T^{ll}>200$ GeV + $p_T^{jj}>200$ GeV

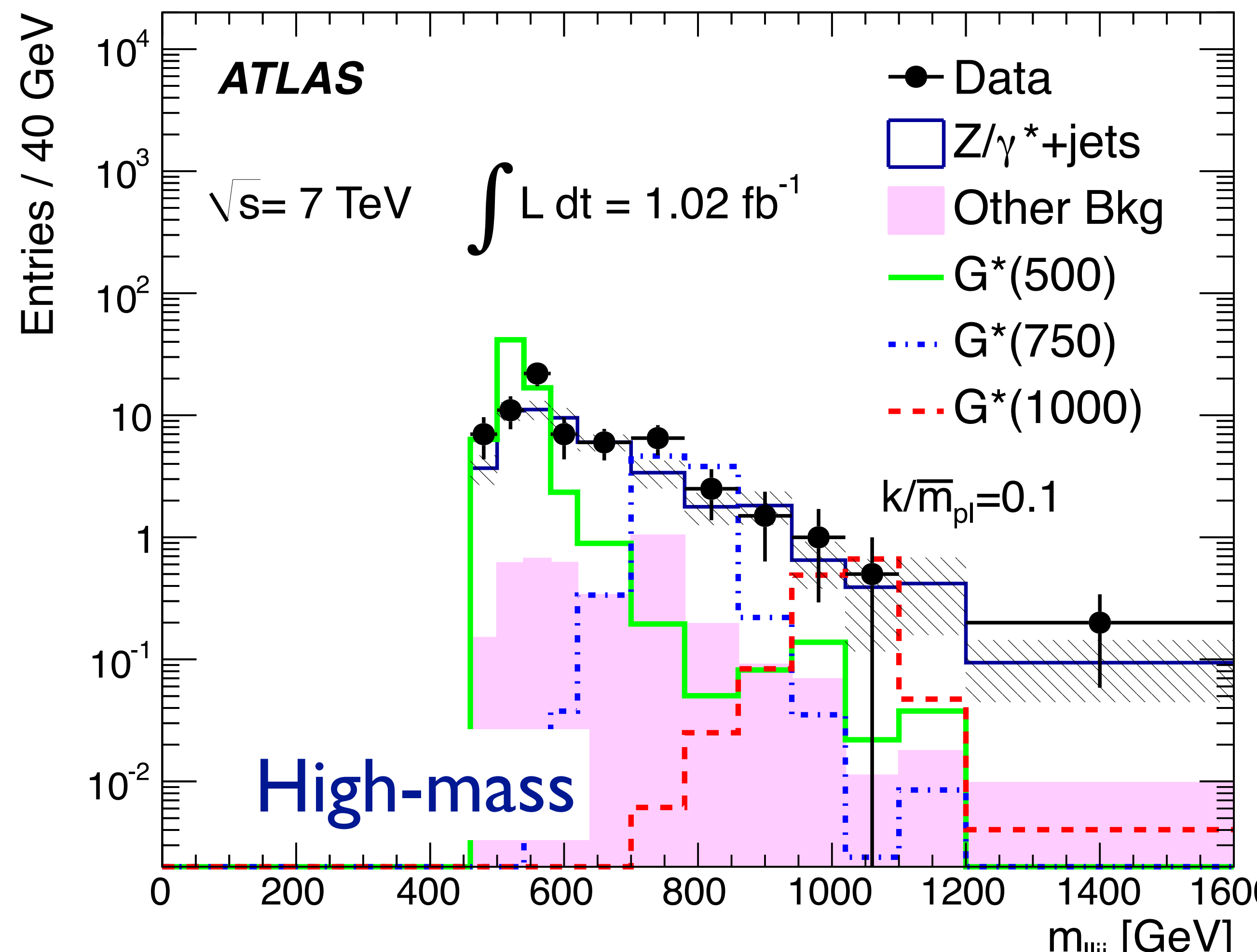
	Electron	Muon	Jet
p_T	> 20 GeV	> 20 GeV	> 25 GeV
$\|\eta\|$	< 2.47*	< 2.4	< 2.8

Isolation : $p_T^{Cone0.2}/p_T < 0.1$

* crack removed

➔ Also sensitive to WZ→jjll





ll + jj : Background and Systematics

Background

- Z+jets from data-driven method
  - Define control regions :
    M_{jj}<65 GeV or M_{jj}>115 GeV
  - Use M_{jj} sidebands to determine MC (ALPGEN) normalization
  - Systematic uncertainty estimated from normalization difference between Mjj sidebands
  - Cross check with SHERPA and MCFM
- Top, Diboson, W+jets from MC

Process	Low-mass	High-mass
Z+jets	3530 ± 190	60 ± 27
Top	81 ± 25	0.4 ± 0.3
Diboson	92 ± 14	4 ± 1
W + jets	9 ± 5	1 ± 1
Multijet	14 ± 14	0.2 ± 0.2
Total BG	**3720 ± 200**	**66 ± 27**
Signal	680 ± 120 (M_{G*} = 350 GeV)	21 ± 4 (M_{G*} = 750 GeV)
Data	**3515**	**85**

Systematics

- Z+jets background modeling (~40%)
- Top (~25%), Diboson (7%), W+jets (40%)
- JES (~13%)
- Lepton efficiency, scale & resolution (1-2%)
- PDF, ISR/FSR (signal)

⇨ Statistical analysis details for ll+ll and ll+jj in backup

ll + ll : Fiducial Limits

Signal acceptance and selection efficiency to get limits on new theory

Fiducial Region
- p_T>15 GeV, |η|<2.5
- 2 OS SF pairs leptons (e, μ)
- 66 < M_{ll} < 116 GeV
- M_{ZZ} > 300 GeV

Cross section limits within fiducial region

$$\sigma_{ZZ}^{Fid} < \frac{N_{ZZ}}{\varepsilon_{ZZ} \times Br(ZZ \rightarrow llll) \times L}$$

$$= \frac{5.7}{0.61 \times 0.01 \times 1.02} = 0.92 \text{ pb}$$

Reco & ID efficiency
- Largely process independent

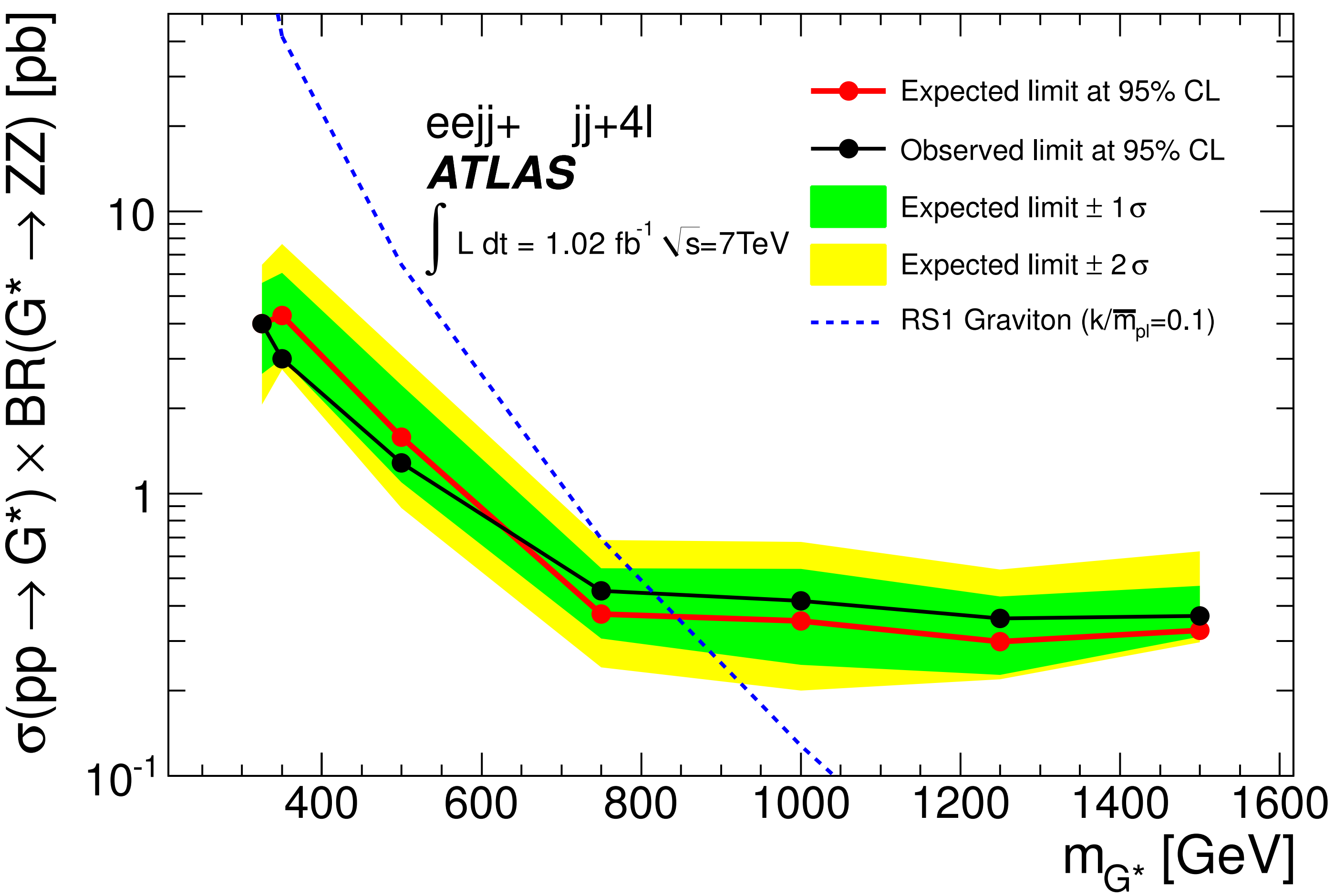
Graviton Mass [GeV]	Theory [pb]	Fid. Acceptance	Sel. Efficiency	Exp. Limit [pb]	Obs. Limit [pb]
325	950	23%	61%	4.0	4.0
350	42	27%	61%	3.3	3.3
500	6.5	28%	63%	3.2	3.2
750	0.69	31%	66%	2.9	2.9
1000	0.13	32%	66%	2.8	2.8
1250	0.03	33%	67%	2.7	2.7
1500	0.01	35%	66%	2.6	2.6

Need parton-level fiducial acceptance for new theory

$ZZ \rightarrow ll + ll$ / $ll + jj$: Limits

95% CL observed limits on σ·Br

Graviton Mass [GeV]	eejj [pb]	μμjj [pb]	lljj [pb]	llll [pb]	llll + lljj [pb]
325	-	-	-	4.0	4.0
350	8.9	11.6	10.9	3.3	3.0
500	2.3	1.8	2.1	3.3	1.3
750	0.9	0.5	0.5	2.9	0.5
1000	0.6	0.7	0.5	2.8	0.4
1250	0.7	0.6	0.4	2.8	0.4
1500	0.7	0.9	0.4	2.6	0.4



Set 95% CL limits on σ·Br for the RS1 G^* signal ($k/\overline{m}_{pl} = 0.1$)

- *Modified frequentist approach with LLR test statistic*

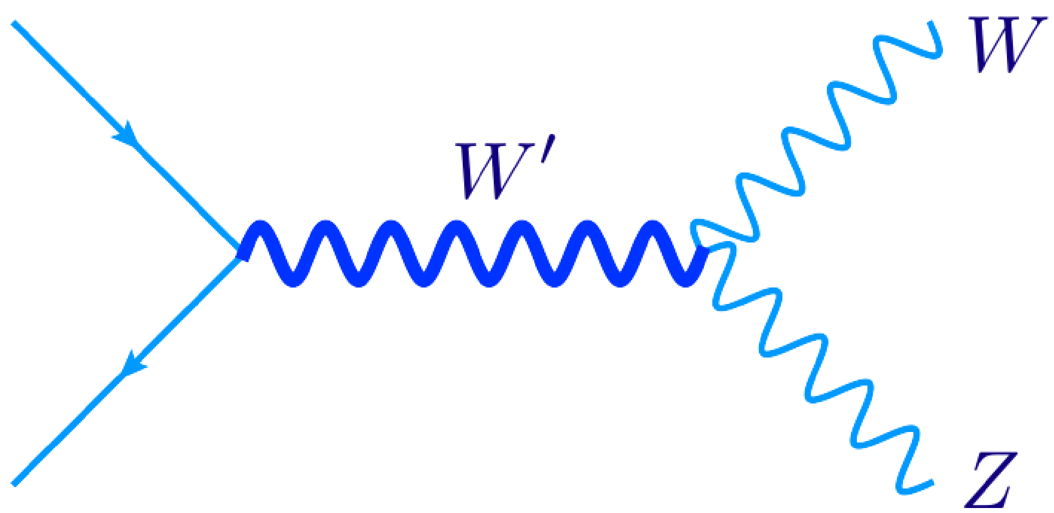
RS1 Graviton ($k/\overline{m}_{pl} = 0.1$) excluded within 325-845 GeV at 95% CL

WZ ($\rightarrow l\nu + ll$) Resonance

ATLAS Preliminary (1.0 fb^{-1})

Resonance search in WZ → 3 lepton final state

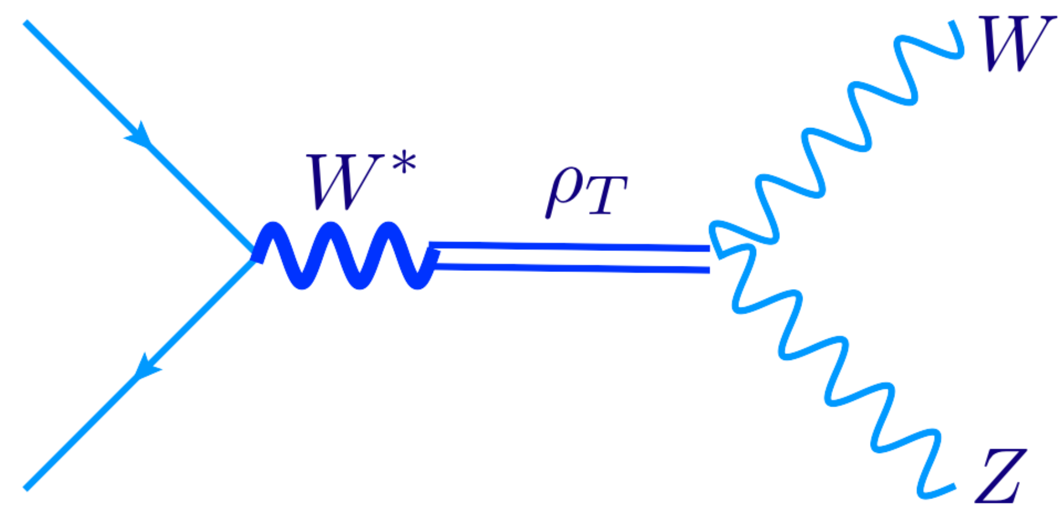
Small branching fraction but also small background (dominated by SM WZ)



G. Altarelli et al., Z. Phys. C 45, 109 (1989)

EGM W' → WZ

- Predominantly longitudinal W/Z
- W'→WZ coupling w.r.t SM W→WZ coupling given by $M_W \cdot M_Z / M_{W'}^2$



LSTC ρ_T/a_T → WZ

W/Z polarization not accounted for in ρ_T decay in PYTHIA
➔ slightly lower A×ε than W'

Analysis strategy

- Select events with 3 leptons and E_T^{Miss}
- Background modeling checked in control region data
- Look for excess events in M_T^{WZ}

WZ → lν + ll : Selection

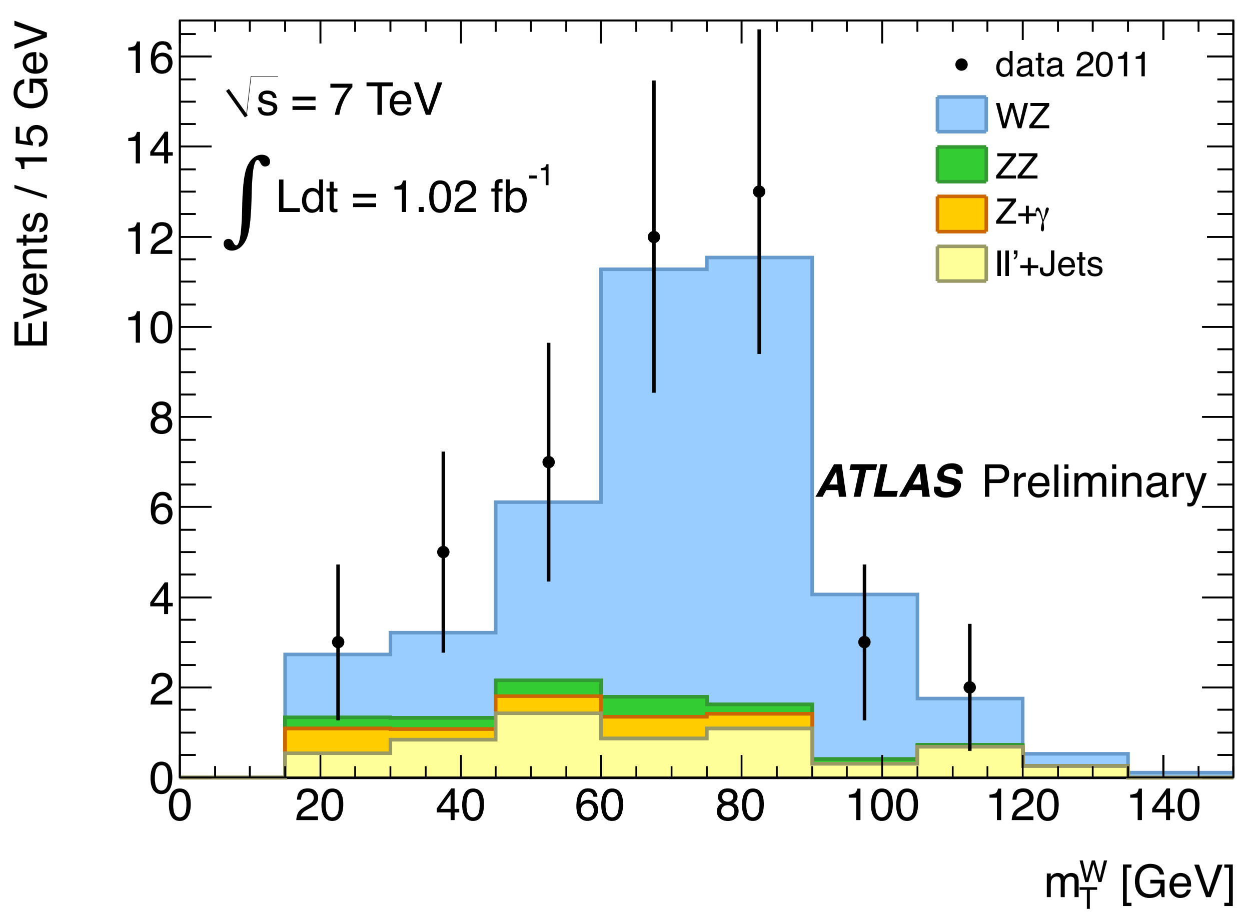
	Electron	Muon
p_T	> 25 GeV	> 25 GeV
$\lvert\eta\rvert$	< 2.47*	< 2.4
Isolation	$E_T^{Cone0.3}$ < 4GeV	$p_T^{Cone0.2}/p_T$ < 0.1

* crack removed

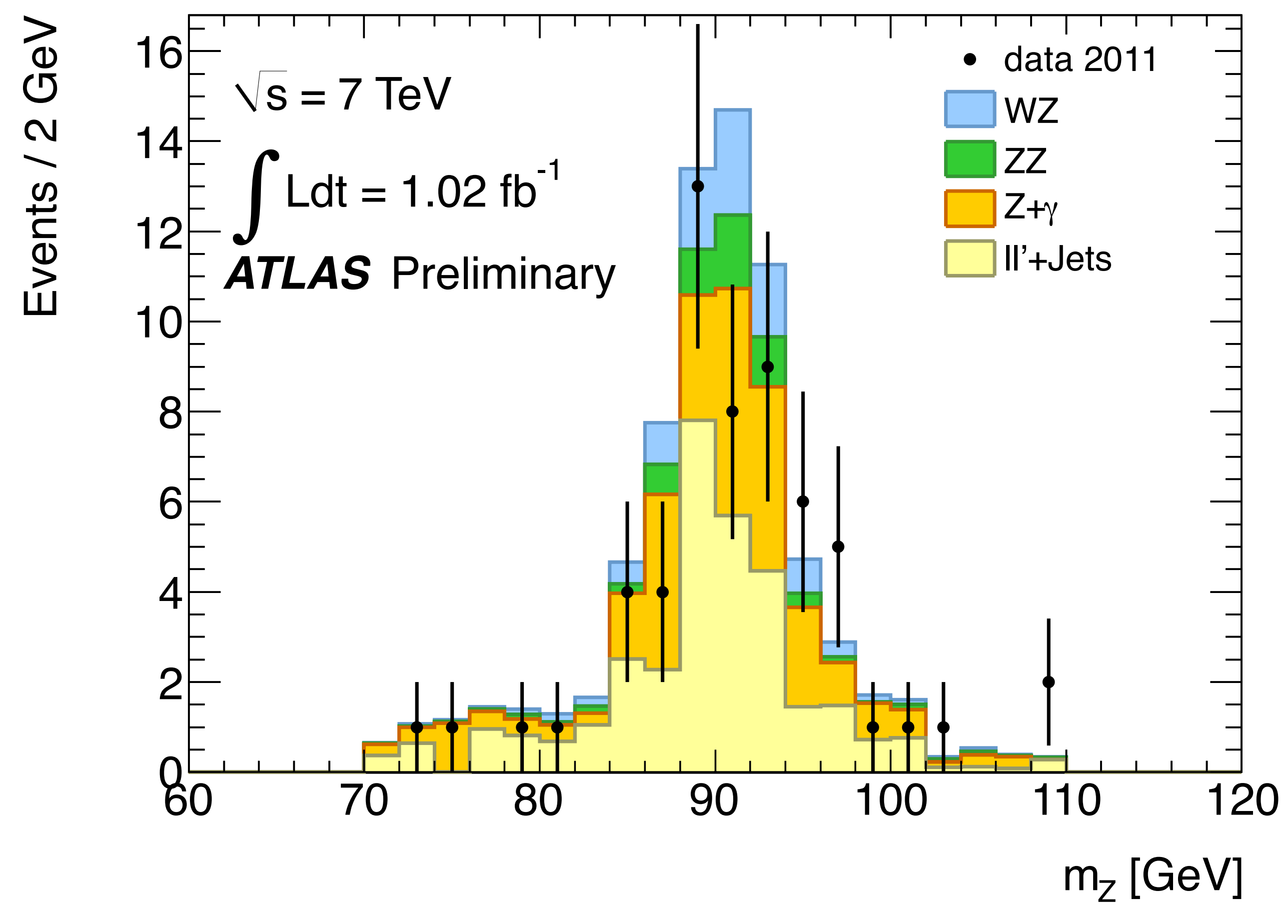
Selection Cuts

- Exactly 3 leptons (veto 4th one)
- At least one pair of $|M_{ll} - M_Z| < 20$ GeV
- $E_T^{Miss} > 25$ GeV
- $M_T^W > 15$ GeV

Background modeling checked in control regions



WZ background (MC@NLO)
control region = $M_T^{WZ} < 300$ GeV



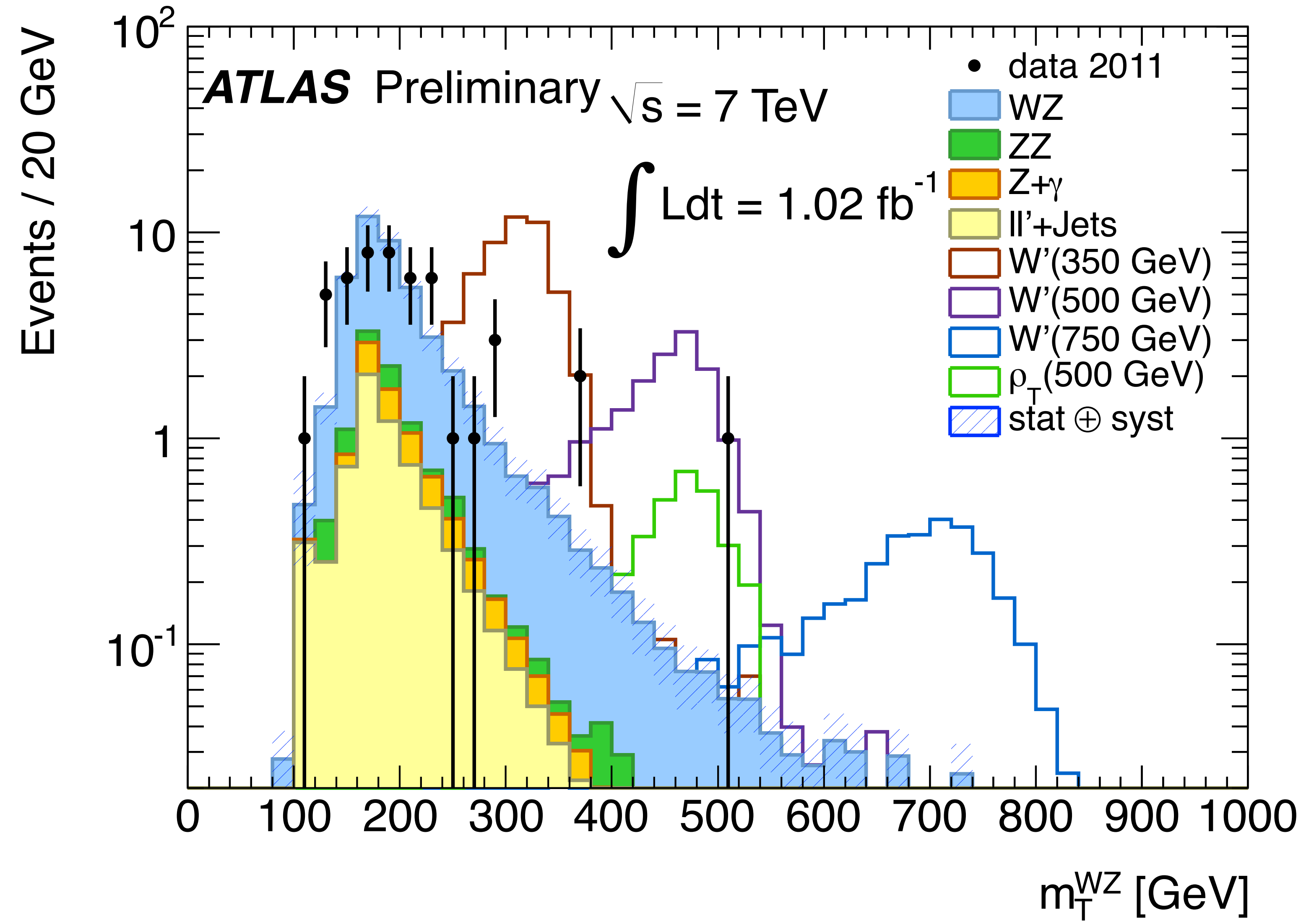
ll'+jets background (data-driven)
control region = $E_T^{Miss} < 25$ GeV

WZ → lν + ll : Data

Statistical significance of data assessed using log-likelihood ratio built from M_T^{WZ} and pseudo-experiments

Lowest p-value (= 1 − CL_b) = 0.19 at M_T^{WZ} = 550 GeV

➔ No significant excess found in data



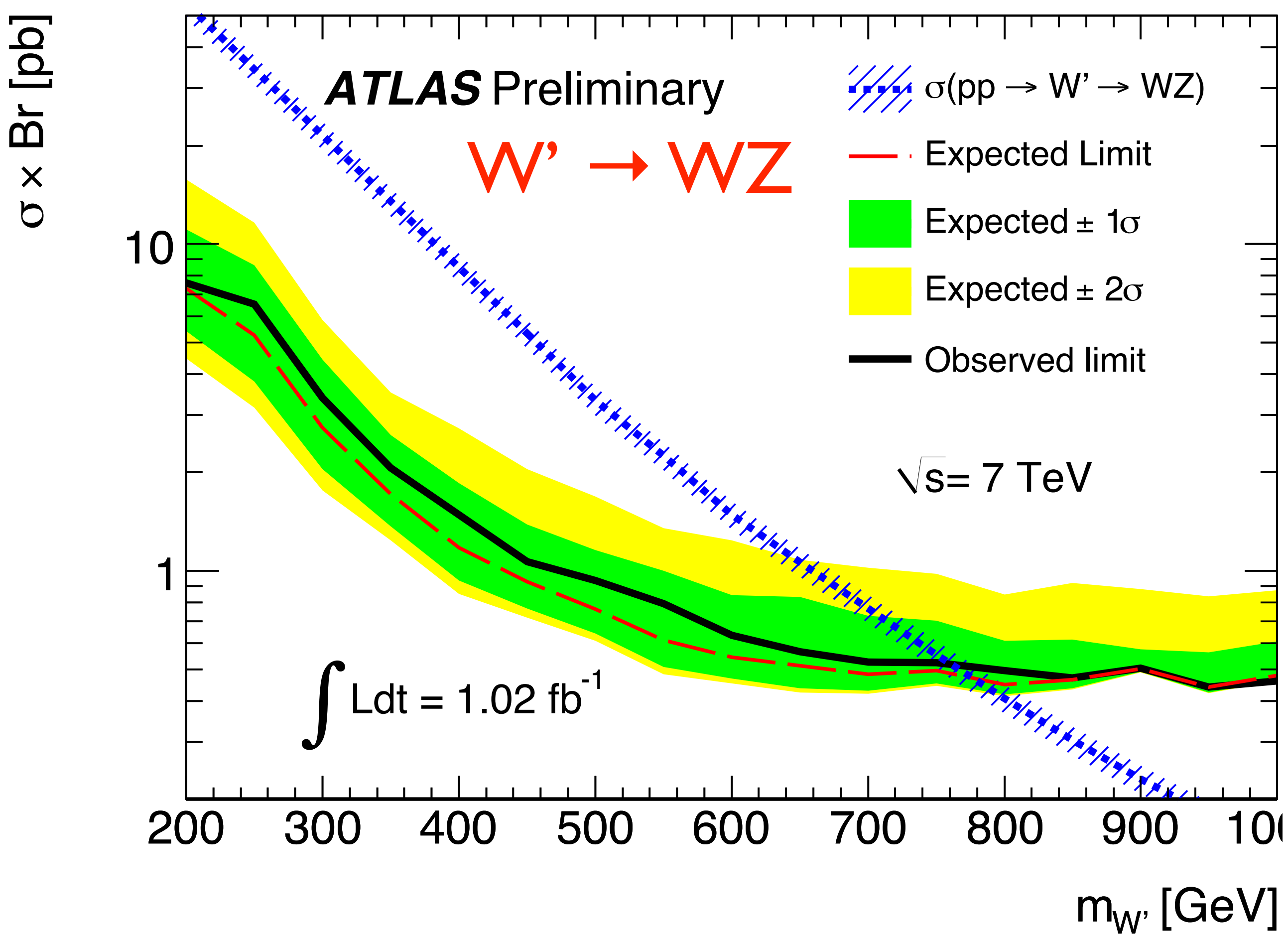
Process	eνee	μνee	eνμμ	μνμμ	Combined
WZ	6.2 ± 0.2 ± 0.5	7.6 ± 0.2 ± 0.5	9.2 ± 0.2 ± 0.5	11.6 ± 0.2 ± 0.6	34.6 ± 0.4 ± 1.9
ZZ	$0.25 \pm 0.06^{+0.04}_{-0.09}$	$0.48 \pm 0.09^{+0.11}_{-0.09}$	$0.37 \pm 0.07^{+0.13}_{-0.09}$	$0.63 \pm 0.10^{+0.13}_{-0.04}$	$1.7 \pm 0.2^{+0.4}_{-0.2}$
Zγ	1.3 ± 0.6 ± 0.4	-	1.0 ± 0.4 ± 0.8	-	$2.3 \pm 0.7^{+1.1}_{-0.6}$
ll'+jets	1.1 ± 0.4 ± 0.7	$1.3 \pm 0.5^{+0.6}_{-0.8}$	$3.0 \pm 0.7^{+1.6}_{-1.9}$	$1.0 \pm 0.4^{+0.5}_{-0.6}$	$6.4 \pm 1.0^{+3.2}_{-4.0}$
Total BG	**8.9±0.8±1.0**	$\mathbf{9.3 \pm 0.5^{+0.8}_{-1.0}}$	$\mathbf{13.6 \pm 0.8^{+2.0}_{-2.2}}$	$\mathbf{13.2 \pm 0.5^{+0.9}_{-1.0}}$	$\mathbf{45.0 \pm 1.3^{+4.2}_{-4.7}}$
Data	**9**	**7**	**16**	**16**	**48**

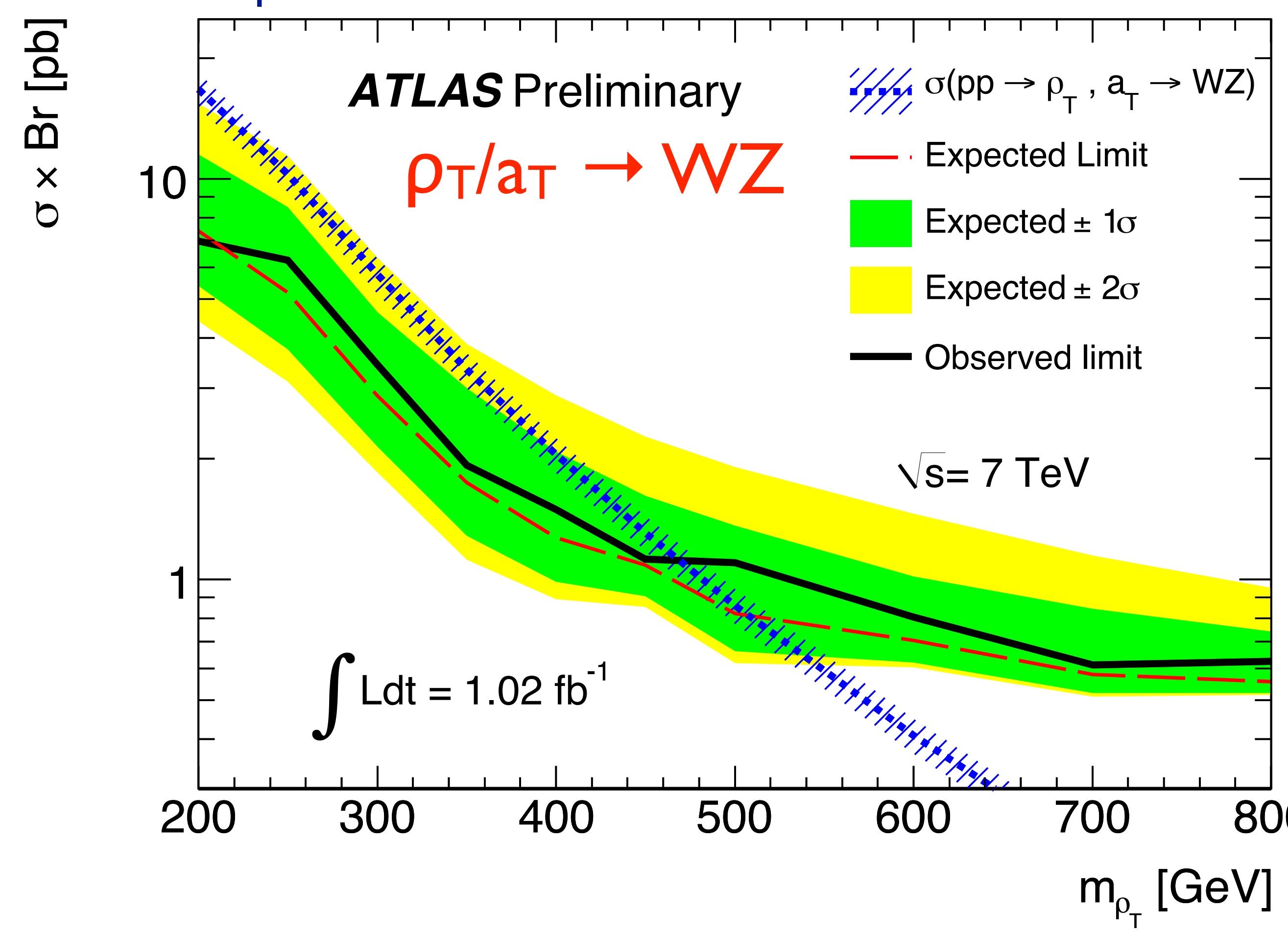
WZ → lν + ll : Limits

$\rho_T(A\times\varepsilon)$ as implemented in PYTHIA

$M_{aT} = 1.1 M_{\rho T}$

$M_{\rho T} = M_{\pi T} + M_W$



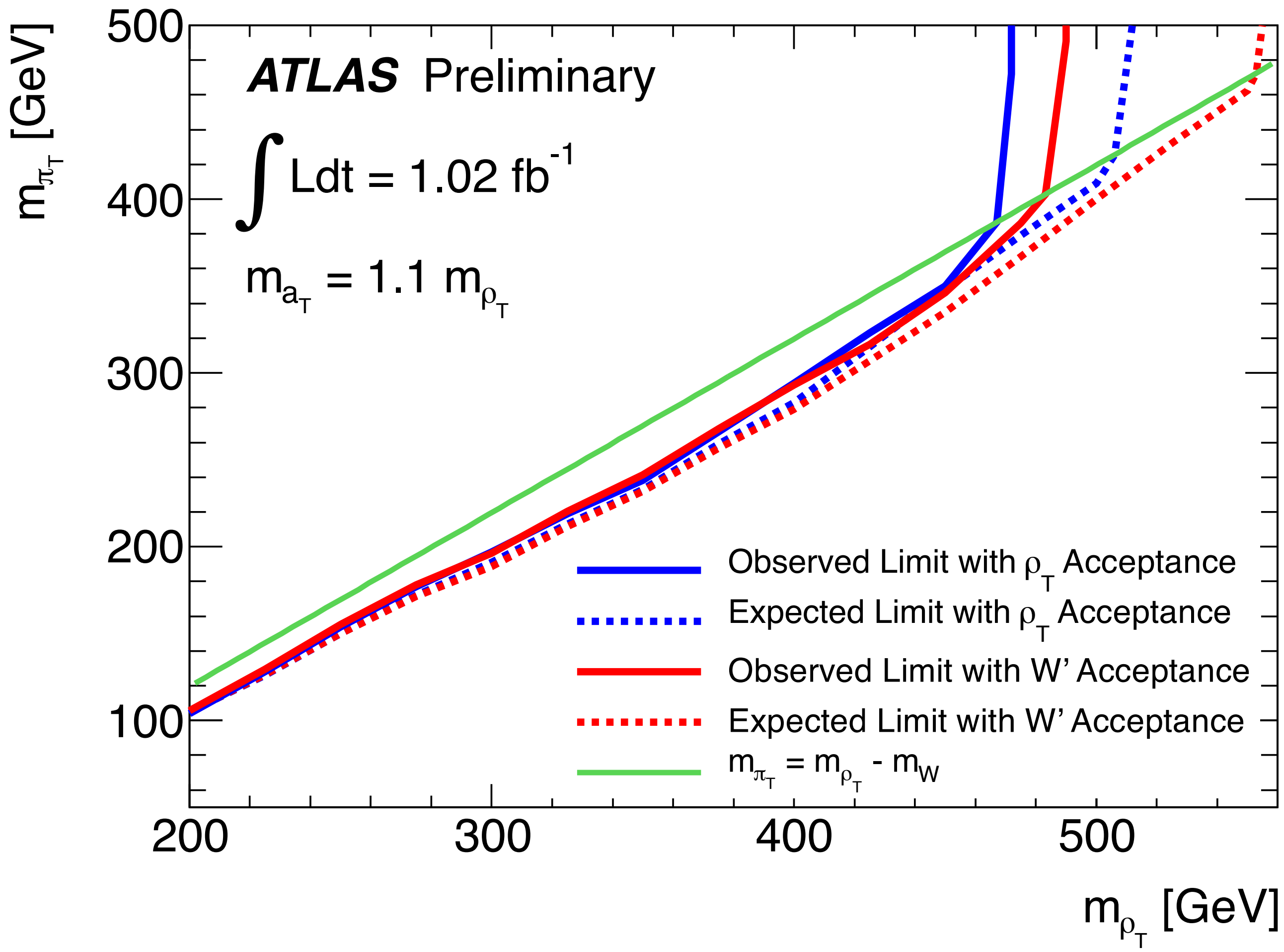


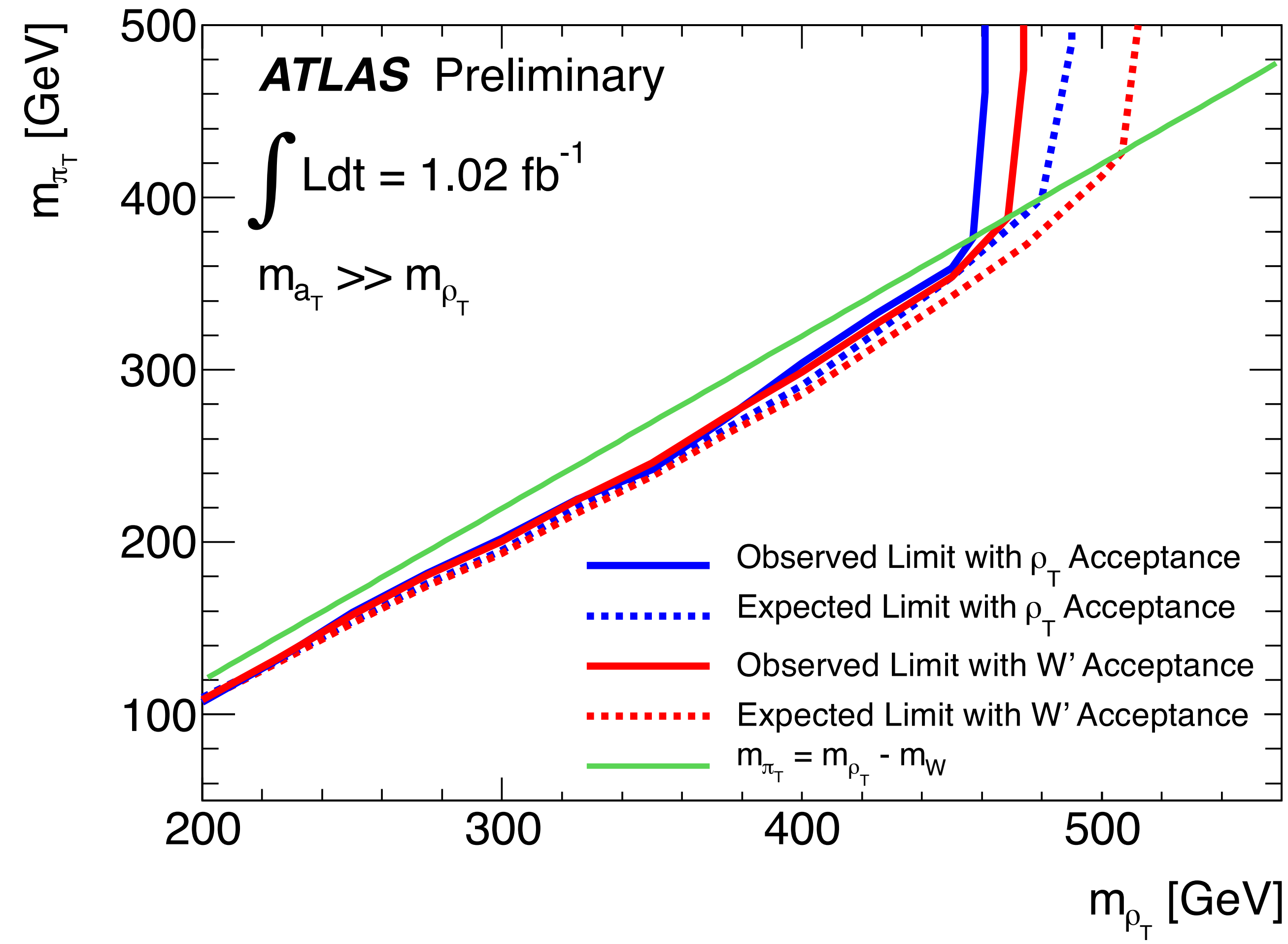
Set 95% CL limits on σ·Br for the W' and ρ_T signal using

- *Finely binned signal templates*
- *Modified frequentist approach with LLR test statistic*

σ·Br < 0.5 pb for $M_{W'}$=800 GeV, < 0.6 pb for $M_{\rho T}$ =700 GeV

WZ → lν + ll : Limits on ($M\rho_T$, $M\pi_T$)





95% CL excluded mass regions in ($M_{\rho T}$, M_{aT}) plane assuming acceptance for W' and ρ_T as implemented in PYTHIA

- *with 2 mass assumptions for a_T and ρ_T*

$M_{\rho T} = M_{\pi T} + M_W$

Acceptance × Efficiency from	$M_{aT} = 1.1 M_{\rho T}$	$M_{aT} >> M_{\rho T}$
EGM W'	**483** (553)	**469** (507)
LSTC ρT (PYTHIA)	**467** (506)	**456** (482)

Summary

Reviewed ATLAS results on the search for new particles in multi-lepton and diboson final states with 1~2 fb^{-1} data

Haven't seen hints for new physics yet ...

Inclusive 3 or more leptons

➡ *Preliminary limits on σ(fiducial) for ≥3 non-Z leptons, and σ for $H^{\pm\pm}$ and ν^**

Heavy neutrino and W_R

➡ *Preliminary limits on effective Lagrangian and (M_{WR}, M_N) for LRSM*

Leptoquark

➡ *Limits on σ(LQ-pair) for 1st generation LQ and mass*

➡ *Limits on σ(LQ-pair) for 2nd generation LQ and mass*

ZZ resonance → 4-lepton, and 2-lepton + 2-jet

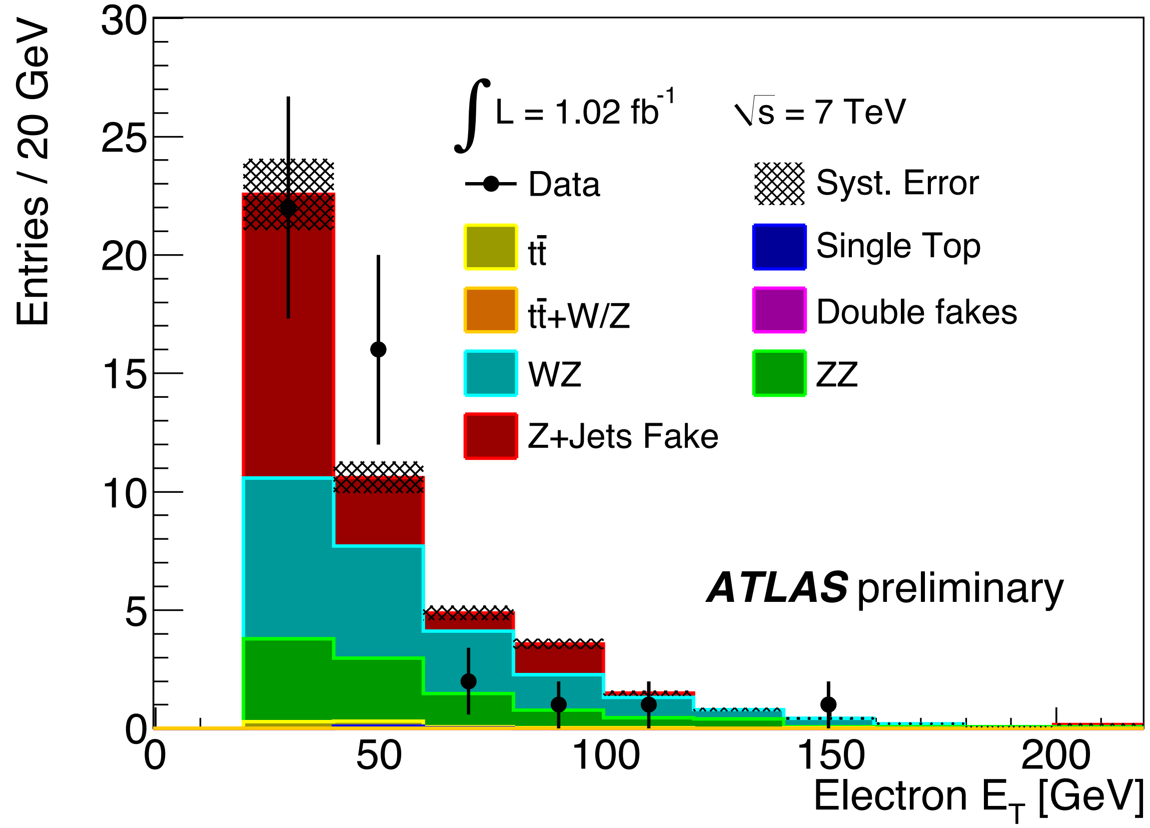
➡ *Limits on σ(RS1 $G^* \to ZZ$) and G* mass*

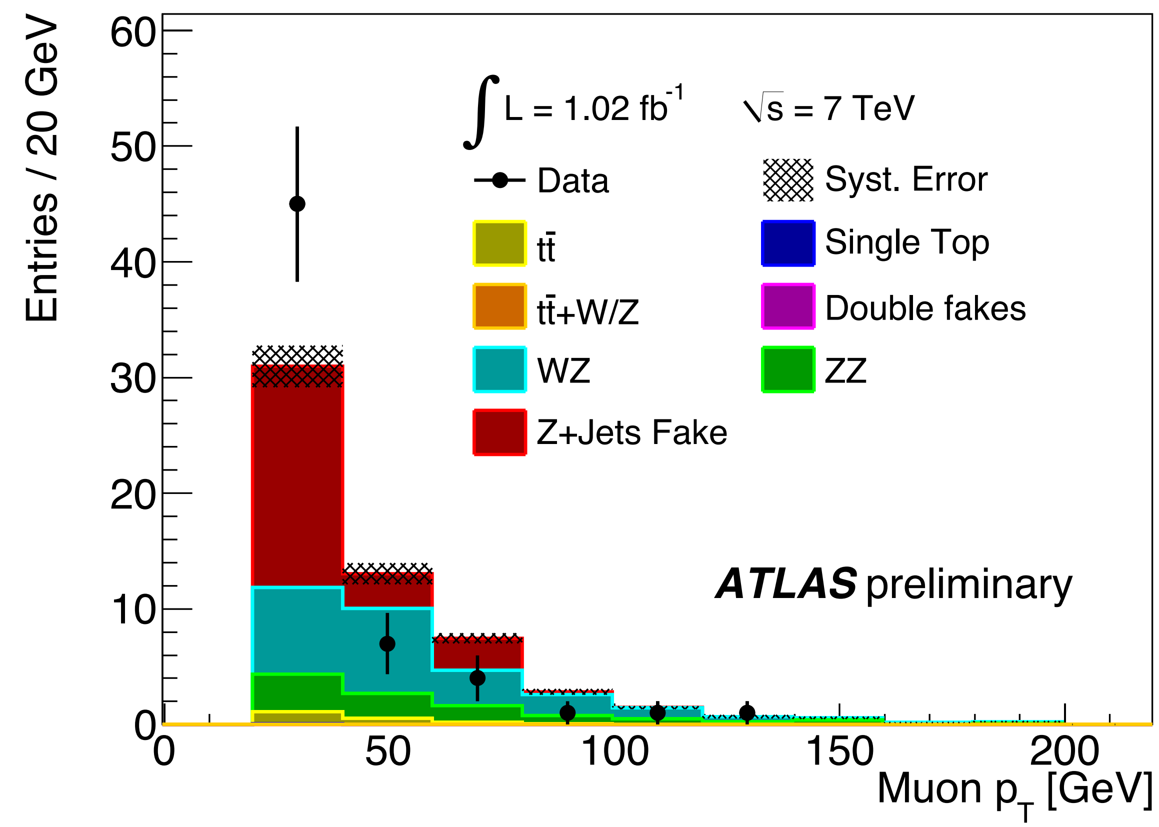
WZ resonance → 3-lepton + E_T^{Miss}

➡ *Preliminary limits on σ(W'→WZ), σ($\rho_T/a_T \to WZ$) and ($M_{\rho T}$, $M_{\pi T}$) for LSTC*

Backup

Multi-lepton : Z+jets Background





Estimated from fakes inside Z mass window by

- loosing isolation (0.5) to enhance Z+jets fakes
- anti-E_T^{Miss} cut (<50 GeV) to reject WZ
- Subtracting non-Z background with MC
- Scaling to outside Z window

$$N^{SR}_{Z,Est.} = R_{iso} \cdot R_{MET} \cdot R_{m_{ll}} \cdot (N^{CR-Z}_{Obs.,Data} - N^{CR-Z}_{BG,MC})$$

$$R_{MET} = \frac{N^{SR}_{Z,MC}}{N^{SR,MET}_{Z,MC}}$$

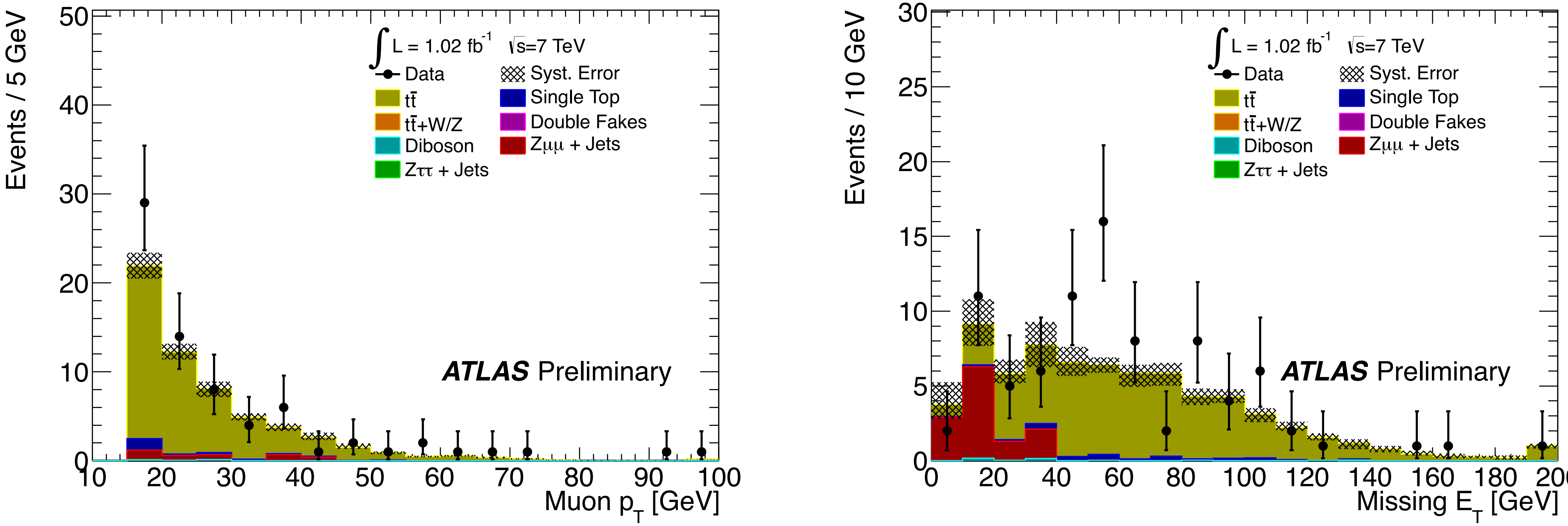
$$R_{m_{ll}} = \frac{N^{SR}_{Z,MC}}{N^{SR,m_{ll}}_{Z,MC}}$$

Nominal signal region

	Z + e-fake	Z + μ-fake
$N_{Z,MC}^{SR}$	5.8	1.9
$N_{BG,MC}^{CR\text{-}Z}$	27.7	32.2
$N_{Data}^{CR\text{-}Z}$	43	59
$N_{Z,MC}^{SR,\ MET}$	5.8	1.9
$N_{Z,MC}^{SR,Mll}$	8.4	5.5
R_{iso}	0.53	0.24
$N_{Z,Est}^{SR}$	**5.6 ± 3.1**	**2.3 ± 0.8**

Multi-lepton : tt Background

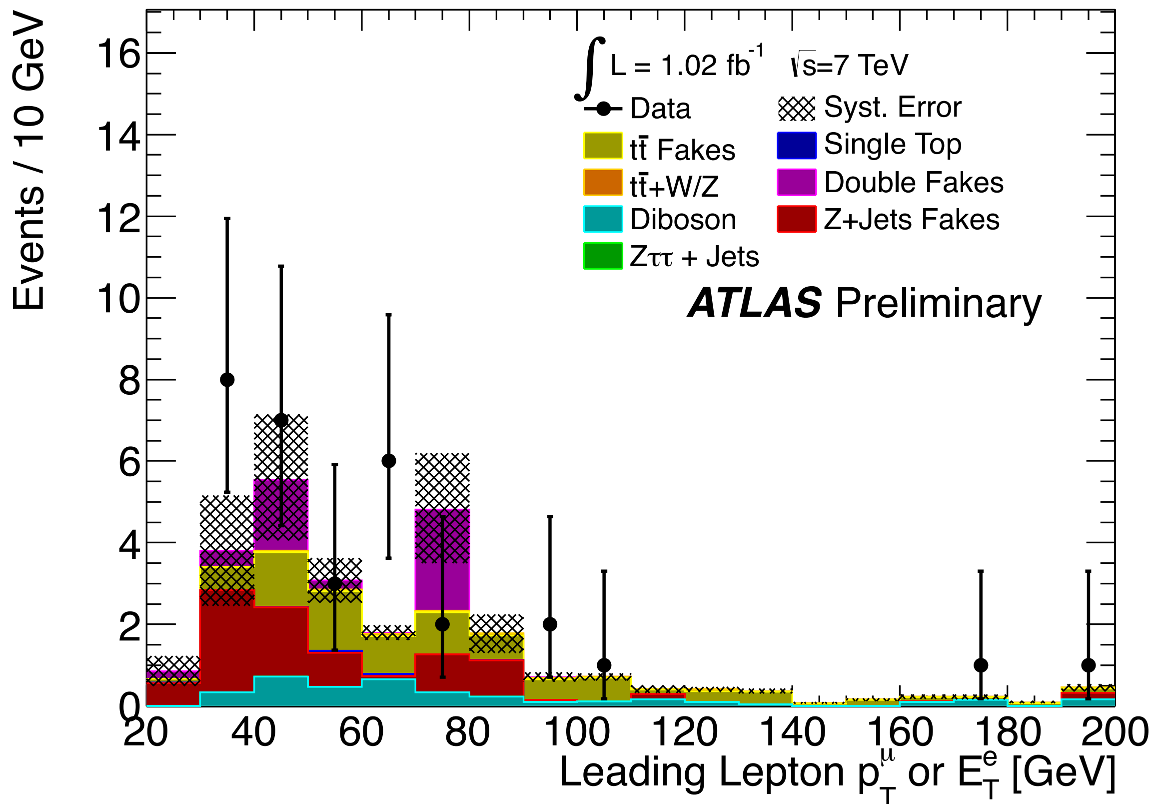
- Estimated from e + μ + 3rd lepton failing isolation cut
- Increase top purity with $E_T^{Miss} > 20$ GeV
- Fake e and μ contributions estimated separately

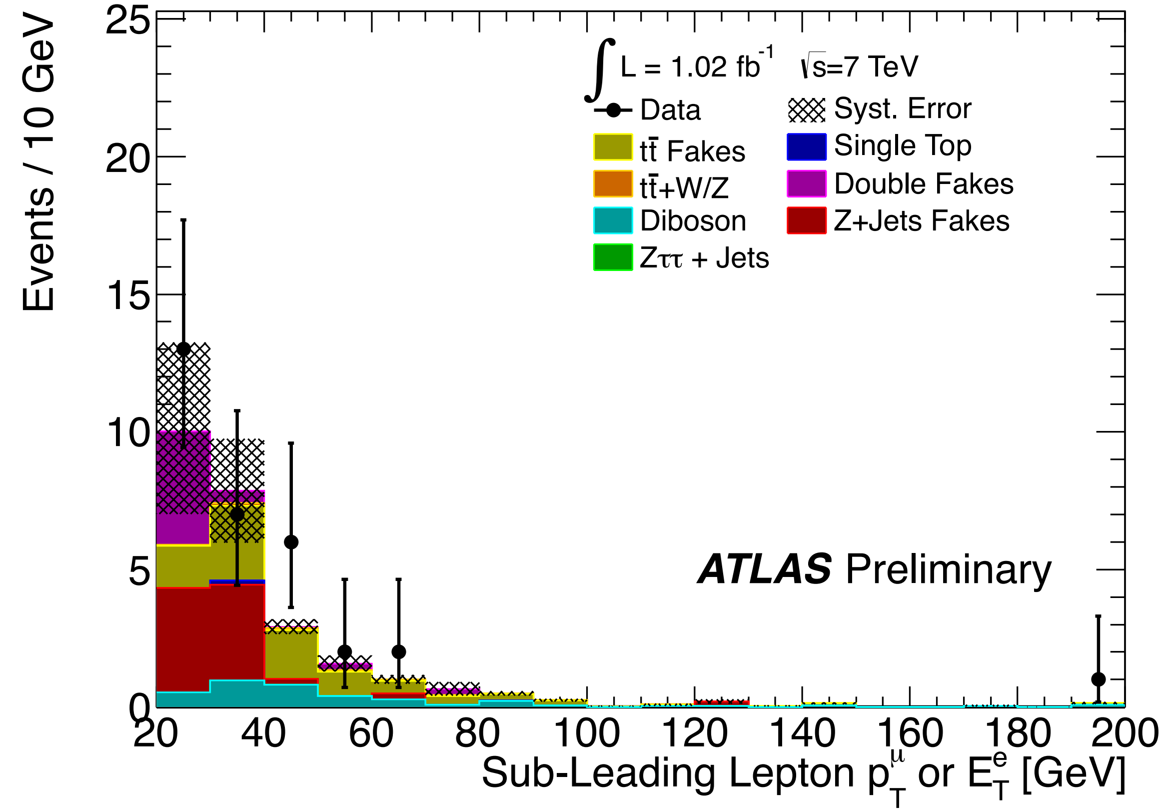


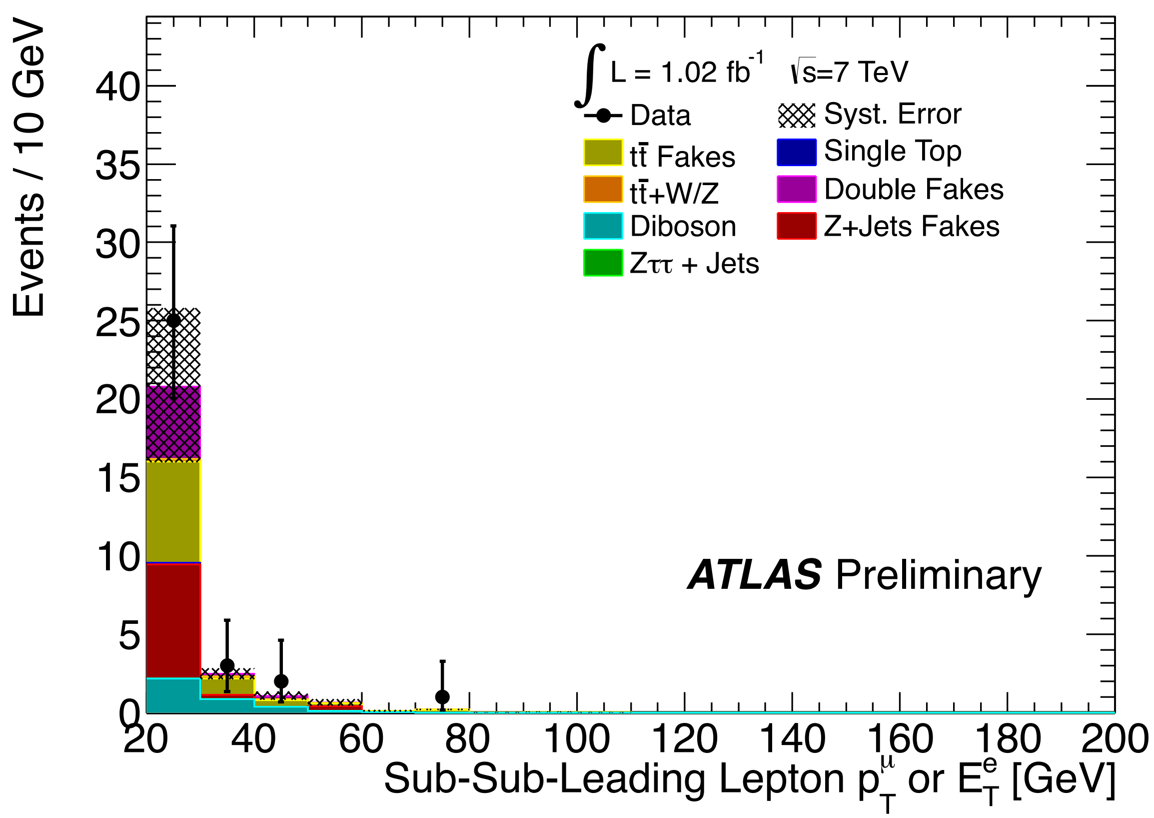
		Nominal signal region		Tight signal region	
		Electron	Muon	Electron	Muon
N_{tt}^{SR}	MC	2.3 ± 0.3	3.8 ± 0.3	0.7 ± 0.1	0.7 ± 0.1
N_{tt}^{CR}	MC	4.0 ± 0.5	54.8 ± 3.2	4.0 ± 0.5	54.8 ± 3.2
N^{CR}	Data	8	76	8	76
N_{BG}^{CR}	MC	1.2 ± 0.3	7.4 ± 1.3	1.2 ± 0.3	7.4 ± 1.3
Estimated N_{tt}^{SR}		**3.9 ± 1.6 ± 0.5**	**4.8 ± 0.6 ± 0.2**	**1.1 ± 0.5 ± 0.2**	**0.9 ± 0.1 ± 0.1**

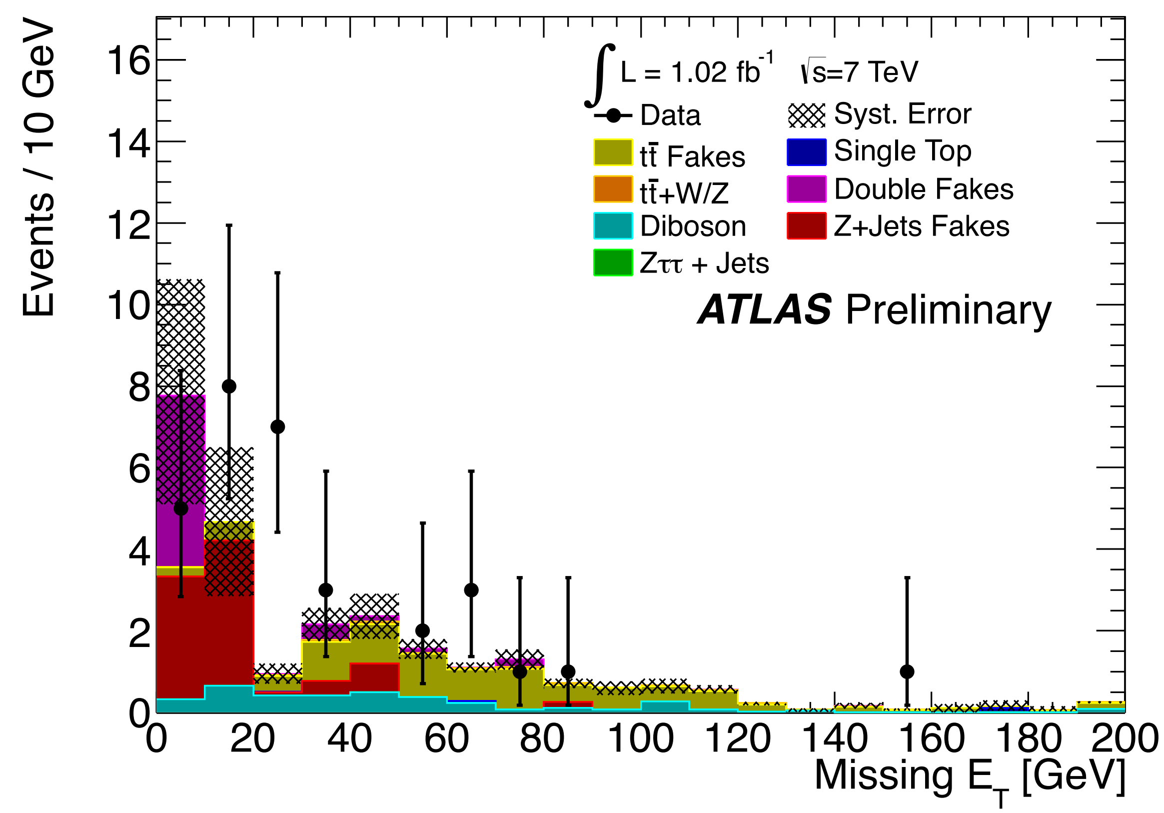
Multi-lepton : Data

Background composition after all cuts applied



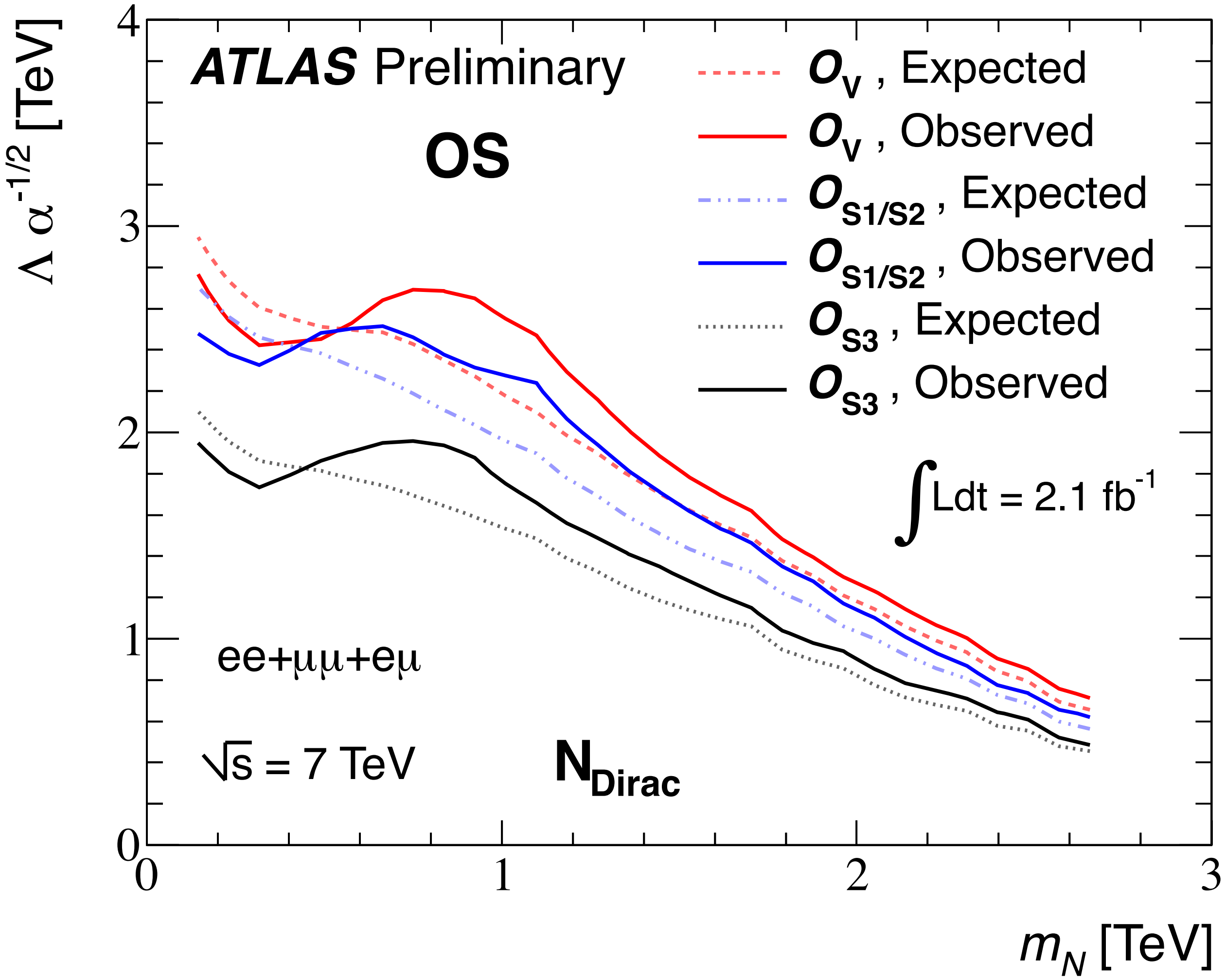




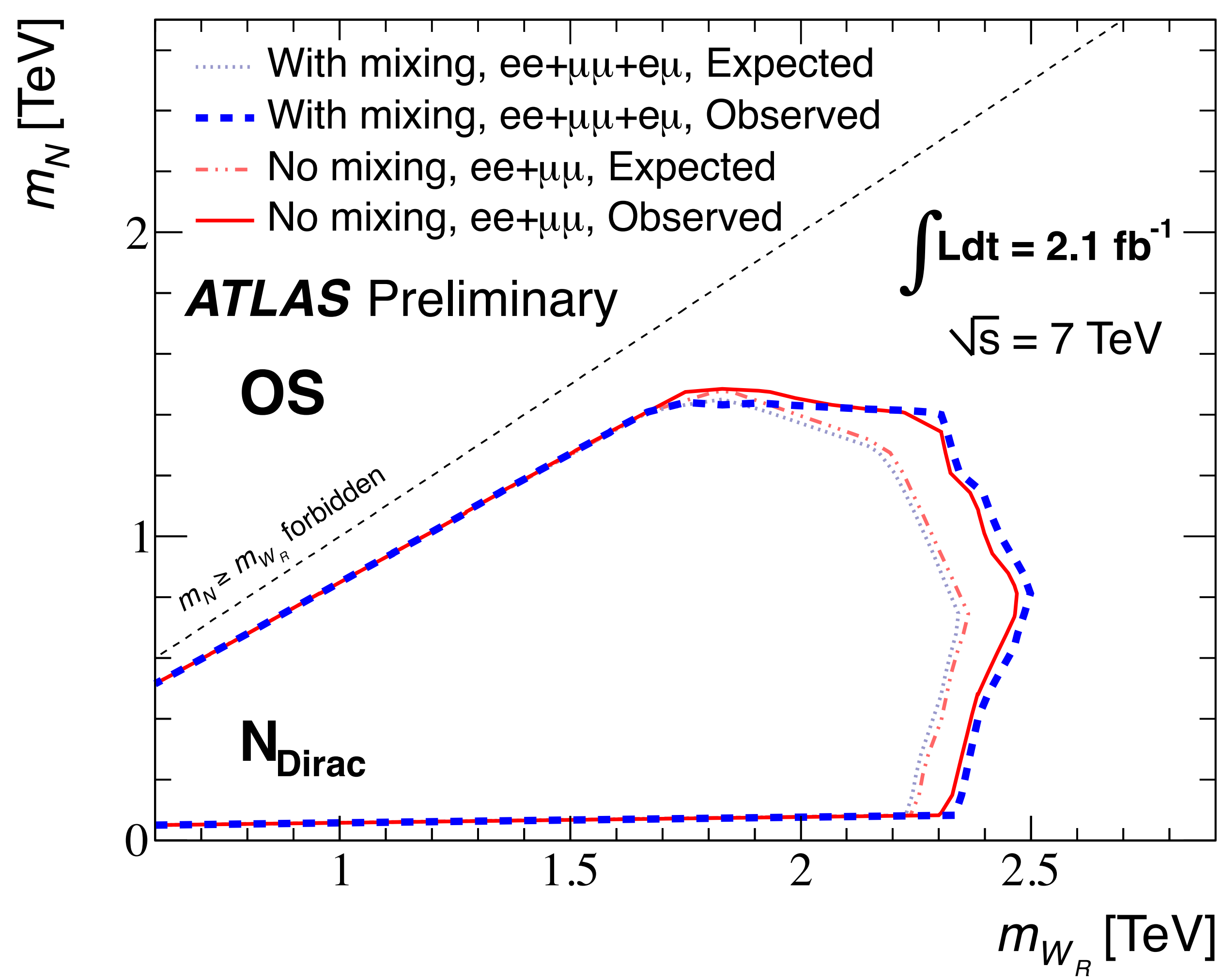


N_H / W_R : Limits

HNEO model



LRSM model



95% CL limits on $\alpha^{-1/2}\Lambda$ vs M_N for HNEO and excluded mass region in (M_{WR}, M_N) for LRSM with Dirac-type neutrinos

➔ Similar to those with Majorana-type neutrino

ll + ll / ll + jj : Statistical Analysis

Perform counting experiments inside mass windows (M_{ZZ}>300 GeV for ll+ll)
Mass windows optimized using signal predictions
Identical systematics taken to be correlated across channels

Res. Mass [GeV]	Mass Window [GeV]		Expected Background	Expected Signal	Obs
350	330-360	eejj	116^{+20}_{-15}	161^{+36}_{-14}	109
		μμjj	163^{+28}_{-23}	165^{+19}_{-16}	147
500	480-530	eejj	6^{+4}_{-2}	27^{+3}_{-4}	8
		μμjj	8^{+5}_{-2}	23^{+2}_{-3}	6
750	730-830	eejj	4^{+2}_{-1}	$6.5^{+0.6}_{-0.9}$	6
		μμjj	$1.2^{+0.9}_{-0.5}$	$6.9^{+0.6}_{-0.7}$	2
1000	900-1090	eejj	$2.1^{+1.3}_{-0.9}$	1.2±0.2	2
		μμjj	$1.2^{+0.8}_{-0.5}$	1.2±0.1	3
1250	1150-∞	eejj	$0.4^{+0.4}_{-0.3}$	0.18±0.01	1
		μμjj	$0.5^{+0.5}_{-0.4}$	0.21±0.01	1
1500	1300-∞	eejj	0.1±0.1	0.04±0.01	0
		μμjj	0.4±0.4	0.04±0.01	1

Look for bumps in full mass spectrum using BUMPHUNTER algorithm

➔ Most significant excess

	p-value	Significance
llll	0.07	1.5σ
lljj (Low-mass)	0.08	1.4σ
lljj (High-mass)	0.08	1.4σ

WZ → lν + ll : M_T^{WZ} = 506 GeV