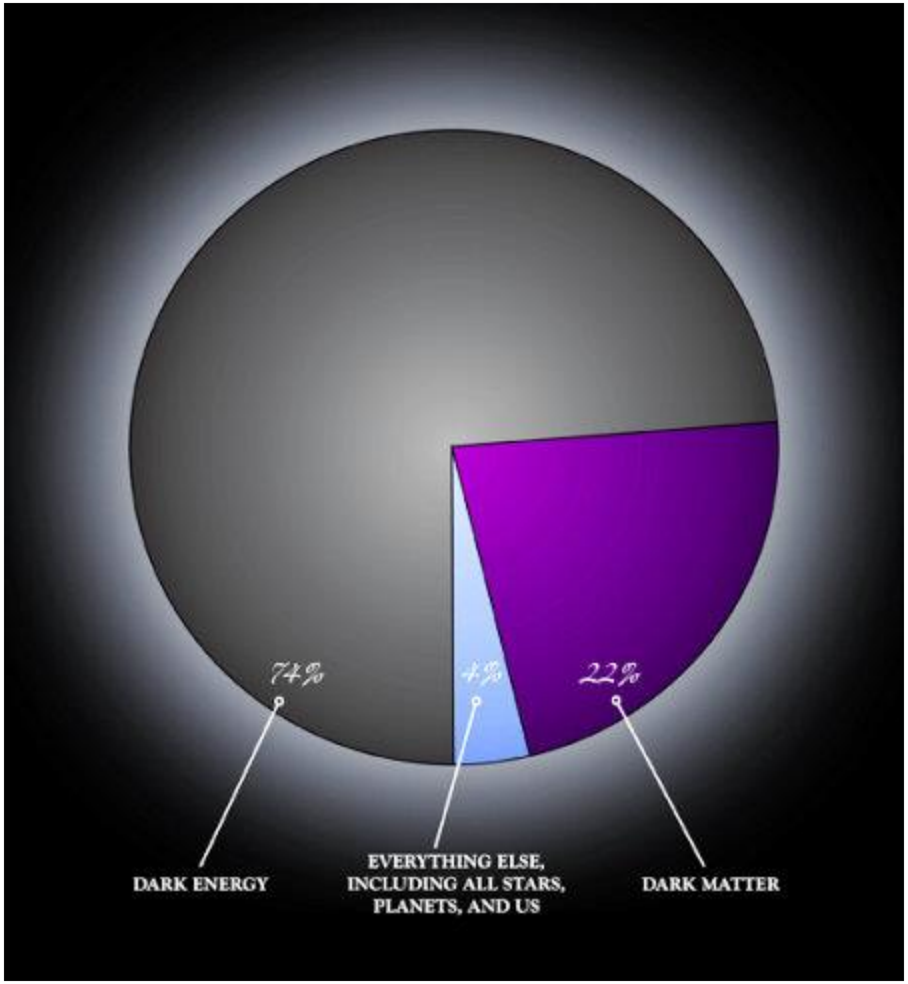
W' searches at Colliders:
Results & Prospects

THE UNIVERSITY *of* EDINBURGH

Christos Leonidopoulos

From Majorana to LHC: Workshop on the Origin of Neutrino Mass
Trieste – 2-5 October 2013


74%
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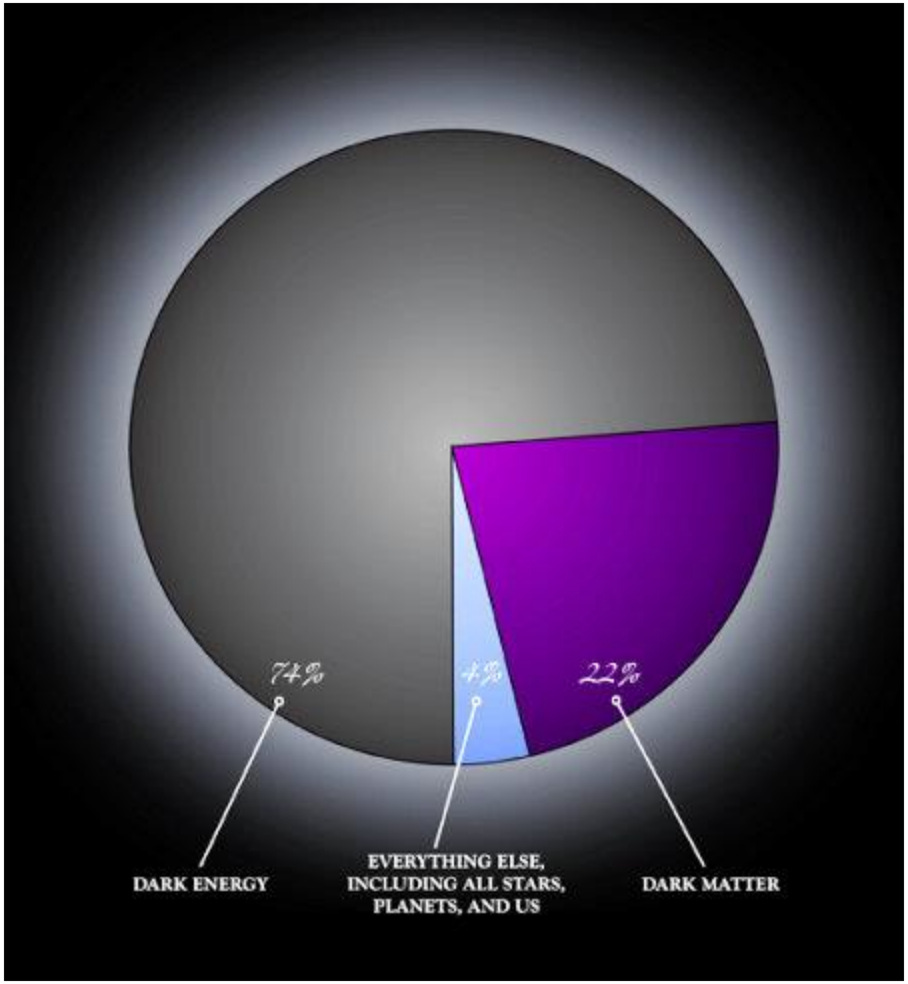
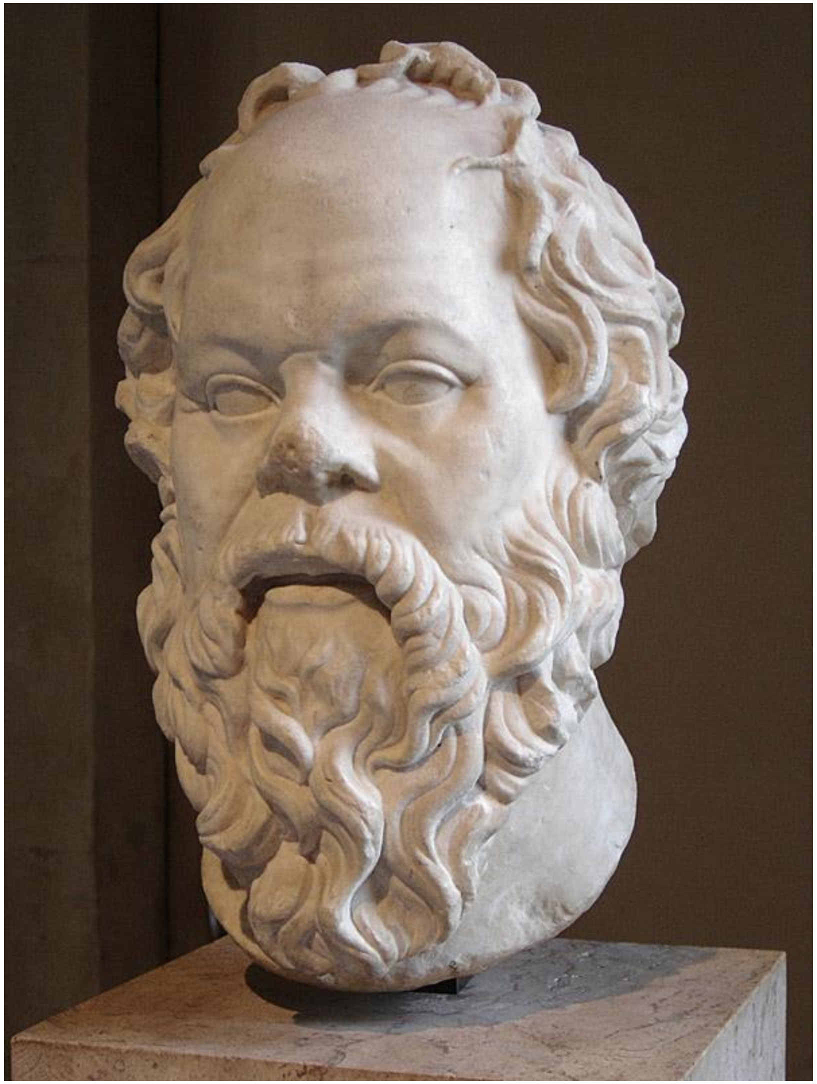
DARK ENERGY
EVERYTHING ELSE, INCLUDING ALL STARS, PLANETS, AND US
DARK MATTER





"I know nothing except the fact of my ignorance"

Majorana neutrino $\leftrightarrow W_R$

Majorana neutrino $\leftrightarrow$ W_R $\leftrightarrow$ General W' searches

- Review of recent (and not so recent) W' searches
- How well have we explored the full mass range?
- All W' signatures relevant to some extent for right-handed W and (by association) new types of neutrinos

Majorana neutrino $\leftrightarrow W_R \leftrightarrow$ General W' searches

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Experimentalists should follow ~~agnostic~~ holistic approach

- Go beyond SSM limits, ie. provide limits on cross section × branching fractions
- Direct searches: allow for the unexpected to be discovered
- Consider as many final states as possible

W': experimental signatures

W' searches

- W' Signatures
  - Leptonic: $e+\nu, \mu+\nu, \tau+\nu$
  - Bosonic: WZ
  - Hadronic: qq', $t\bar{b}$, ℓN_ℓ $(N_\ell \rightarrow qq'\ell')$ $\ell = e$, μ

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- Large W' mass opens up new channels
- Channels that are favored/suppressed: model-dependent

General W' searches and W_R

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- $m(N_\ell) \to 0$, ie. $m(N_\ell) << m(W_R)$
- $m(N_\ell) \sim$ "few tens of GeV"
- $m(N_\ell) >$ 80-100 GeV"
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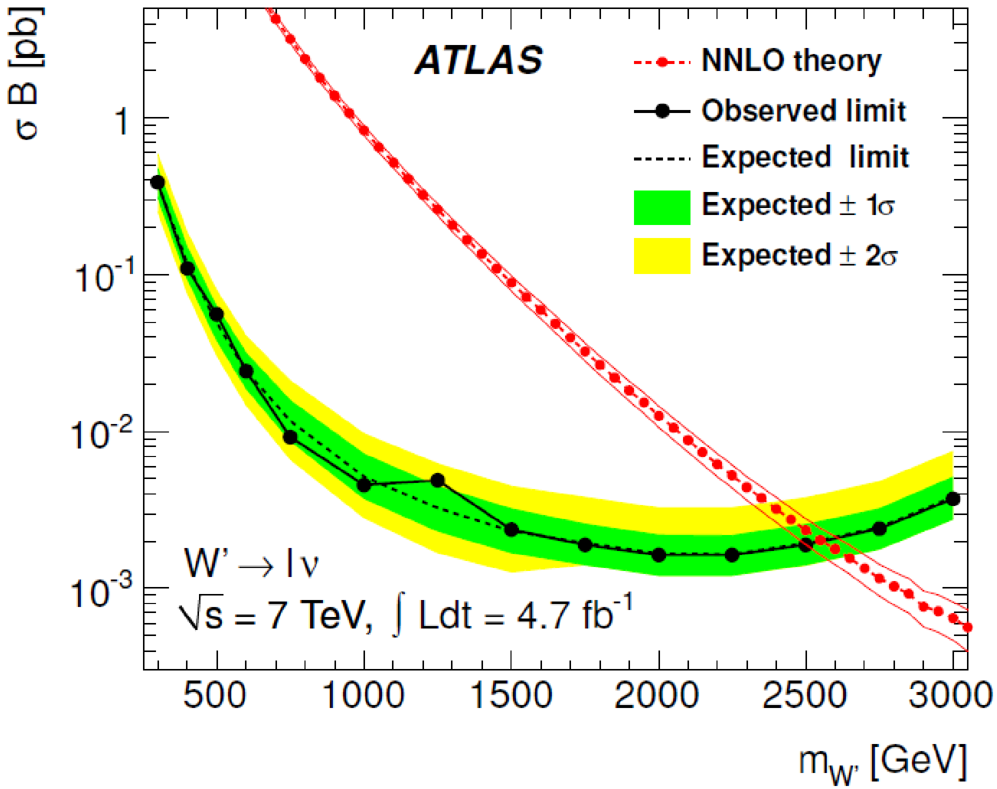
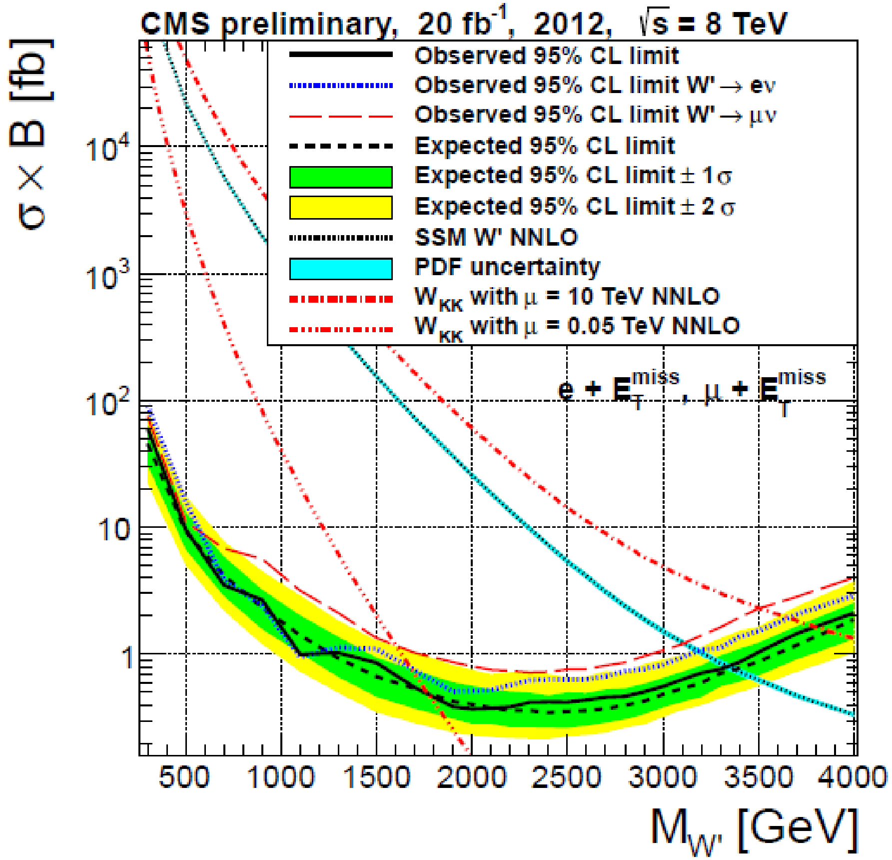
$$W' \to \ell\nu$$

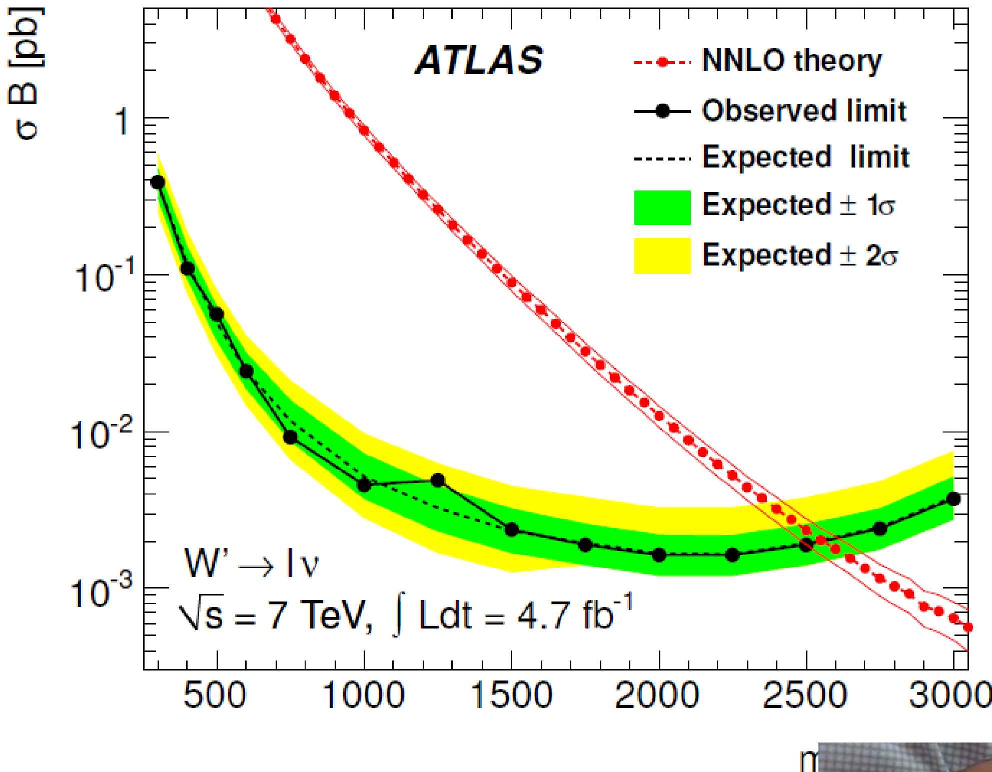
$W' \to \ell\nu$: ATLAS & CMS

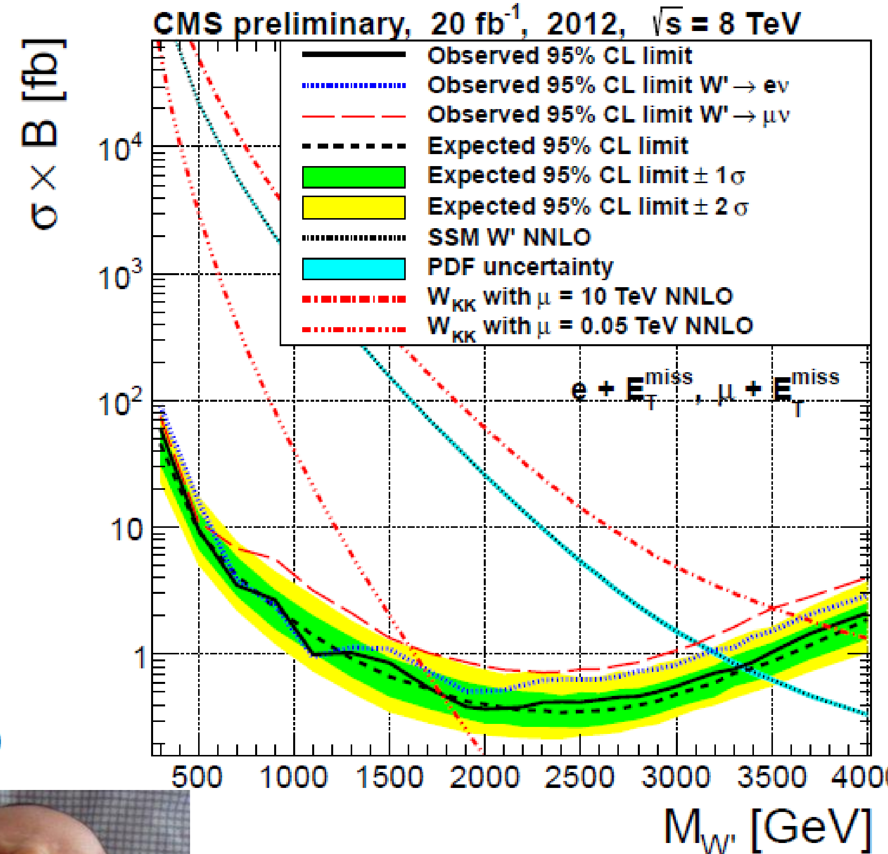




ATLAS: 7 TeV, 4.7 fb^{-1}, EXOT-2012-02 CMS: 8 TeV, 20 fb^{-1}, EXO12060

$W' \to \ell\nu$: ATLAS & CMS





ATLAS: 7 TeV, 4.7 fb^{-1}, EXOT- S: 8 TeV, 20 fb^{-1}, EXO12060

W' searches: Overview

Channel	Experiment	Search range (TeV)	σ ×B Limits (fb)	SSM limit (TeV)
e+MET	CMS, 20 fb^{-1}, 8 TeV	0.4-4.0	0.5-90	0.4-3.20
μ+MET	CMS, 20 fb^{-1}, 8 TeV	0.4-4.0	0.8-70	0.4-3.10
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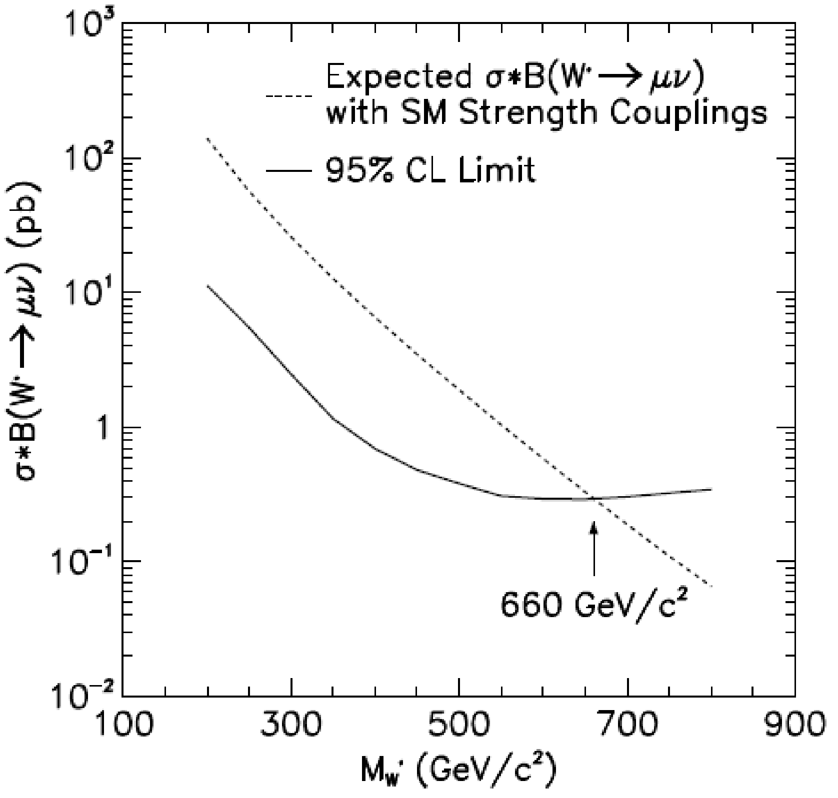
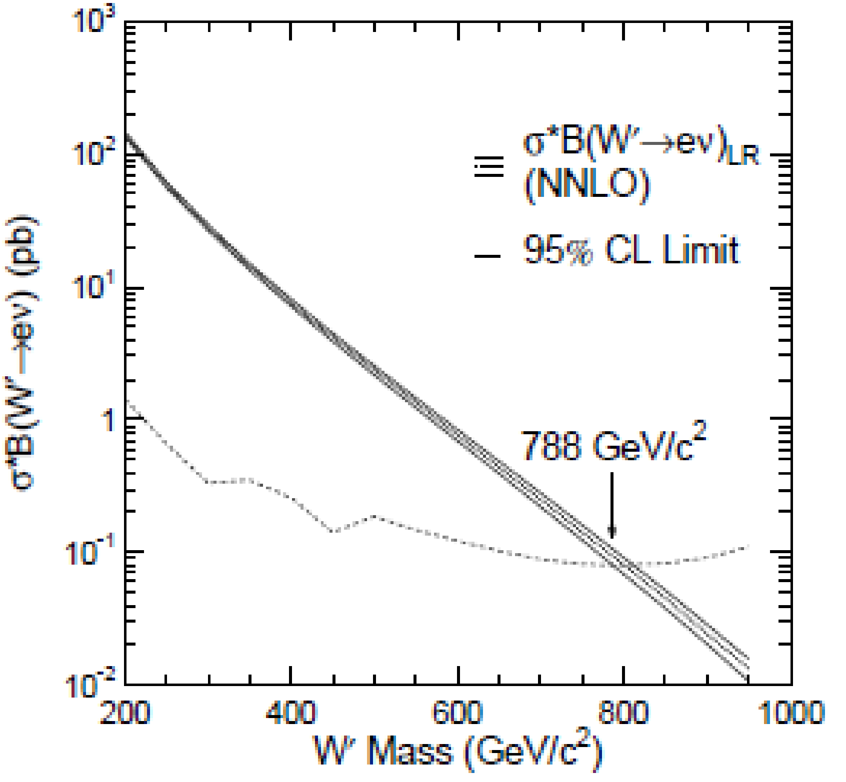
$W' \rightarrow \ell\nu$: CDF

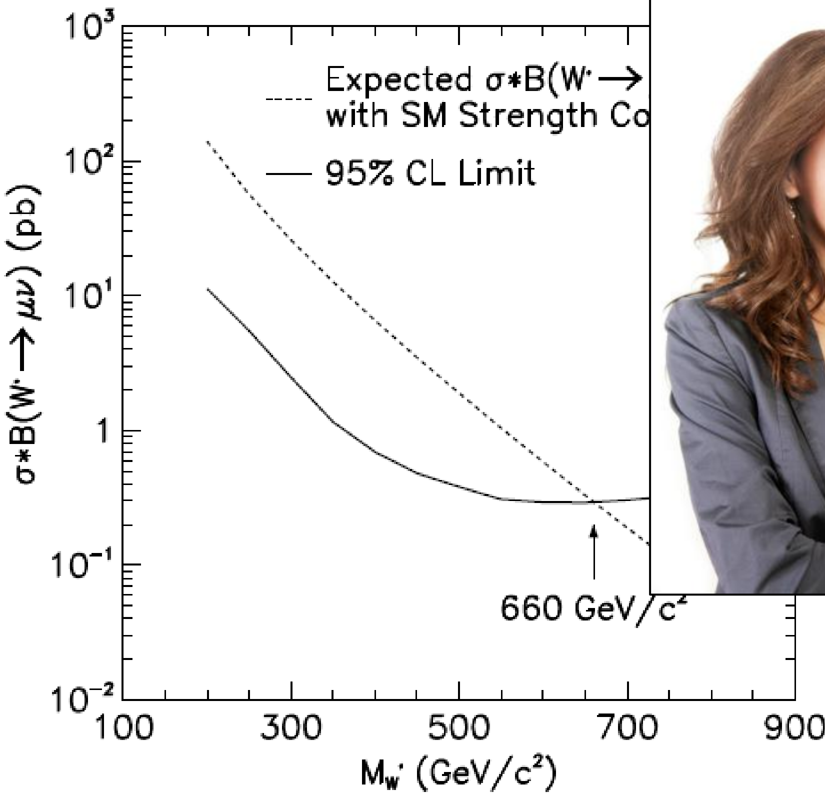


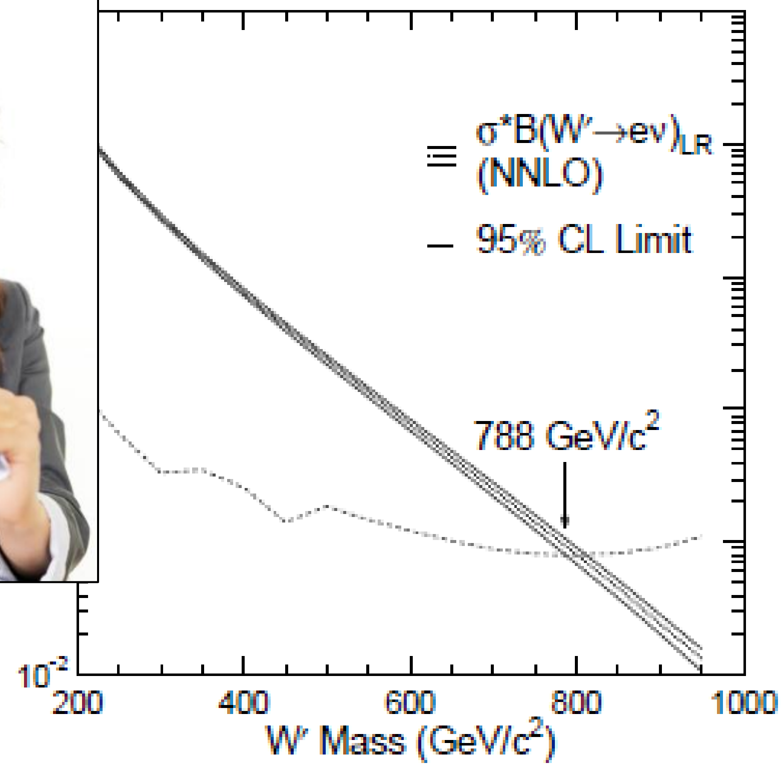


CDF: 1.8 TeV, 107 pb^{-1}, arXiv9910004

CDF: 1.96 TeV, 205 pb^{-1}, arXiv0611022

$W' \rightarrow \ell\nu$: CDF





CDF: 1.8 TeV, 107 pb^{-1}, arXiv9910004

CDF: 1.96 TeV, 205 pb^{-1}, arXiv0611022

Exclusion limits much closer to theoretical curve here: weak limits

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ℓ+MET		0.1-0.2	???	???

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τ+MET		---	---	---

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ℓ+MET		0.1-0.2	???	???
τ+MET		---	---	

- Direct searches between 105 and 200 GeV?
- Tau searches?

General W' searches and W_R

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- As its mass increases, neutrino decay gradually moves inside detector, but not necessarily at IP
- Non-IP activity may/may not be compatible with ℓ+MET signature
- Dedicated searches (displaced vertices, etc), but not comprehensive!
- Not discussed today

General W' searches and W_R

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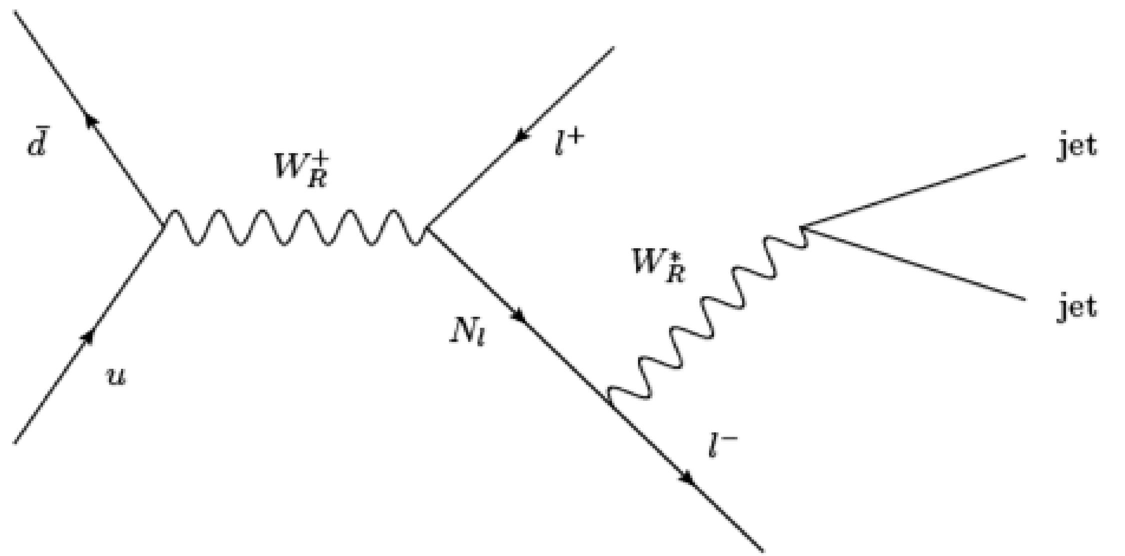
$$W' \rightarrow \ell\, N_\ell\,, N_\ell \rightarrow q q' \ell'$$

$W' \to \ell\, N_\ell\, (qq'\ell')$

Search for W' decaying to heavy neutrino plus lepton



- No L-R mixing: heavy neutrino decays via W_R'
- Cross-section: depends on W_R', N_ℓ masses (assuming W_L' couplings)
- Final state: two (same-flavor) leptons plus two jets

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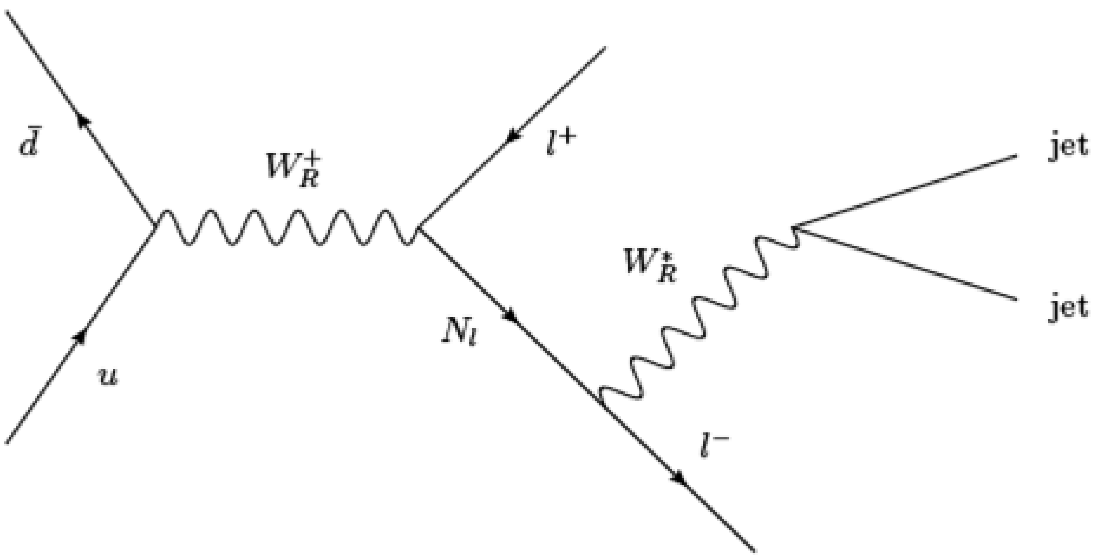
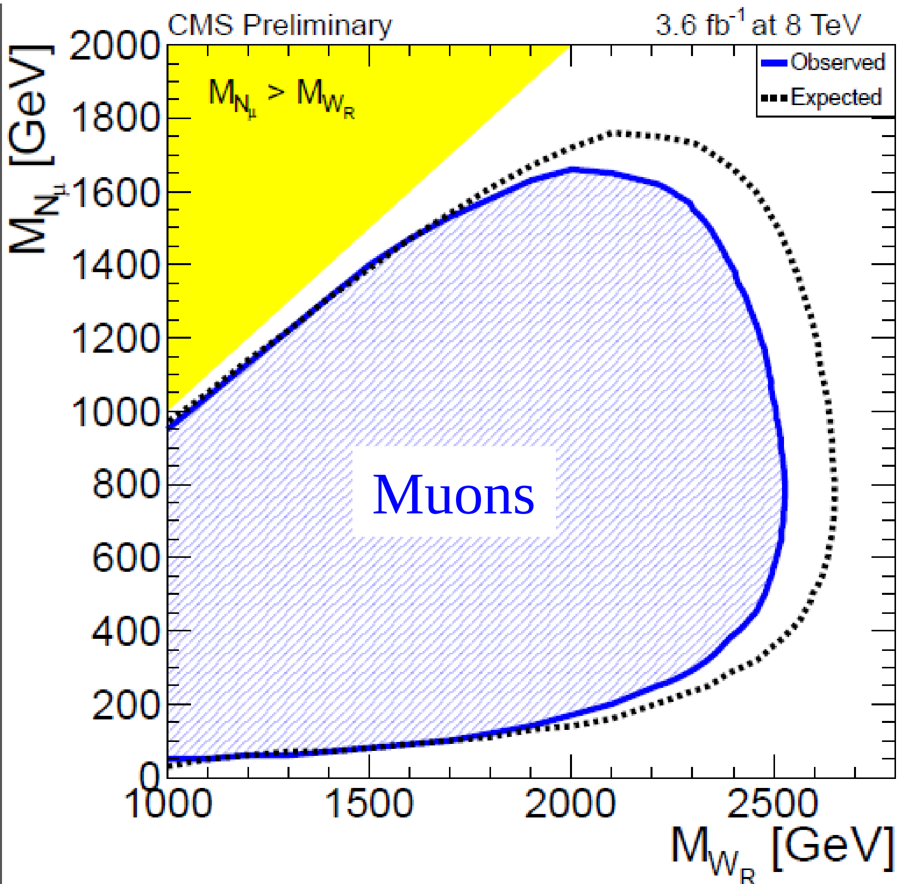
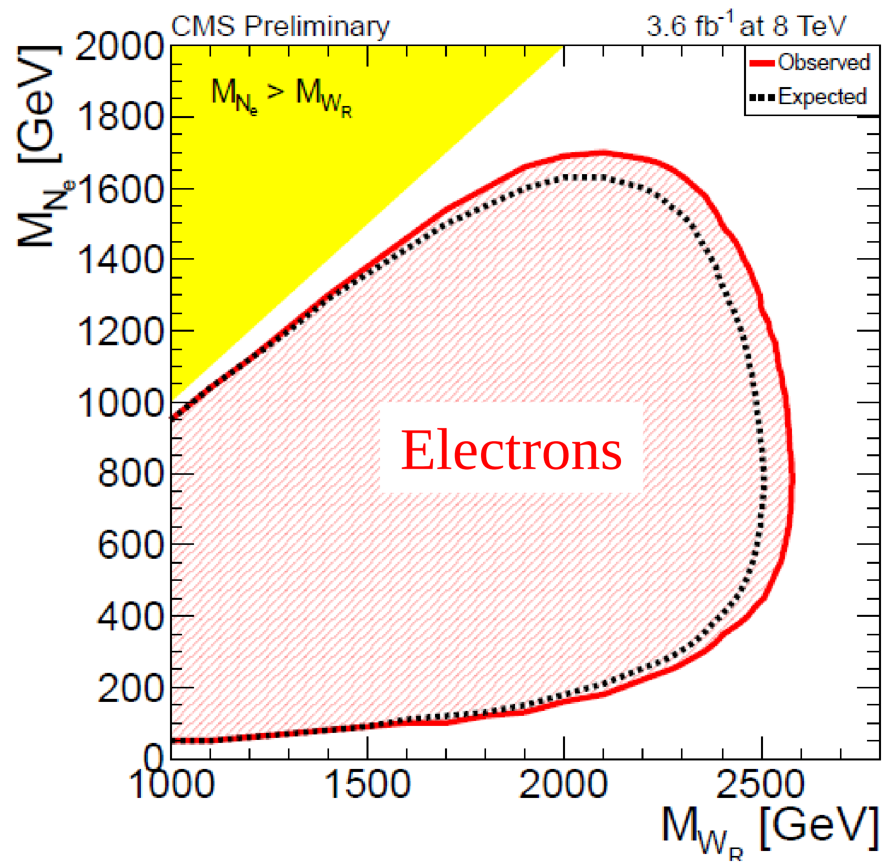


- Discovery #1: mass of two jets & lepton = neutrino mass
- Discovery #2: mass of neutrino + lepton = W_R mass
- Discovery #3: compare lepton charges (Majorana vs Dirac)
- Discovery #4: compare lepton flavors (LFV)

$W' \to \ell\, N_\ell\, (qq'\ell')$: ~~ATLAS~~(*) & CMS





$M_{\ell\ell} > 200$ GeV

CMS: 8 TeV, 3.6 fb^{-1}, EXO120017

(*) See V. Savinov's talk for ATLAS results

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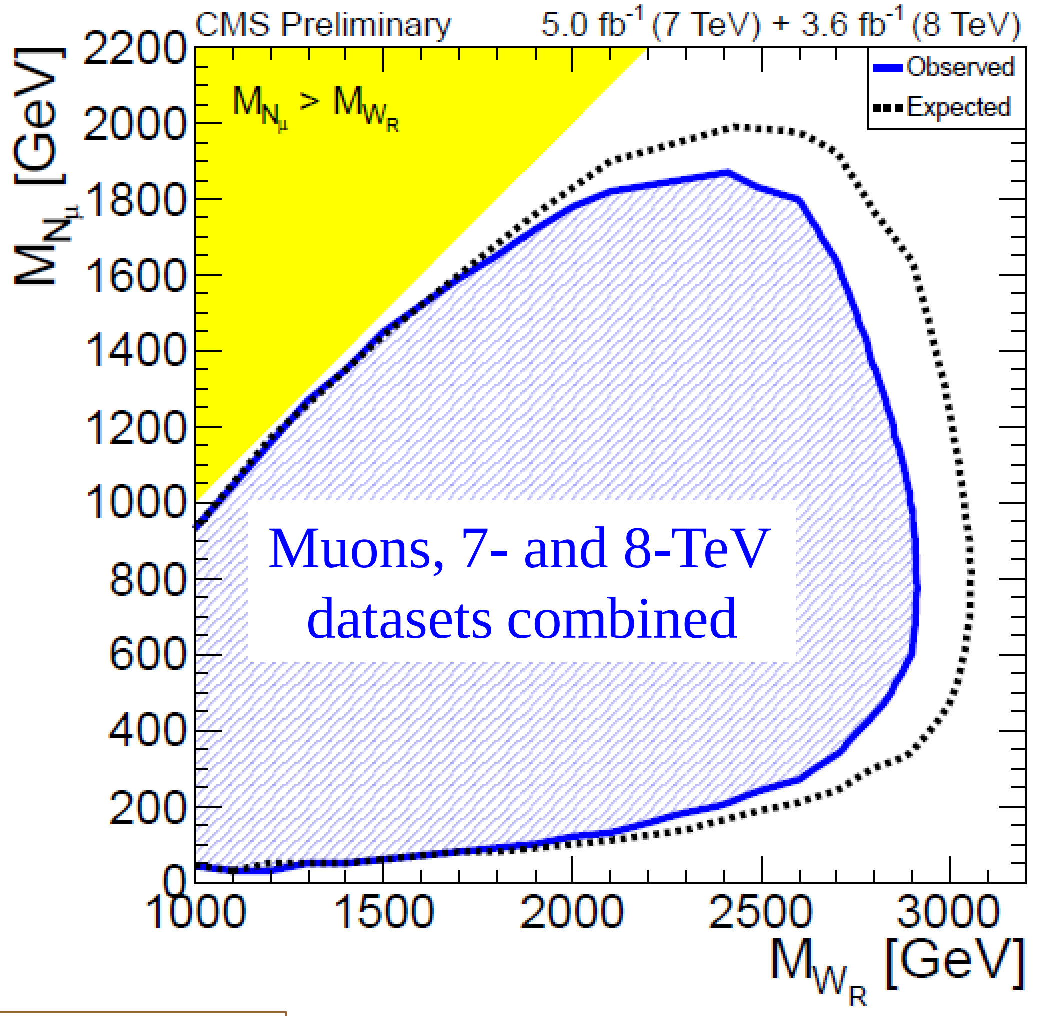
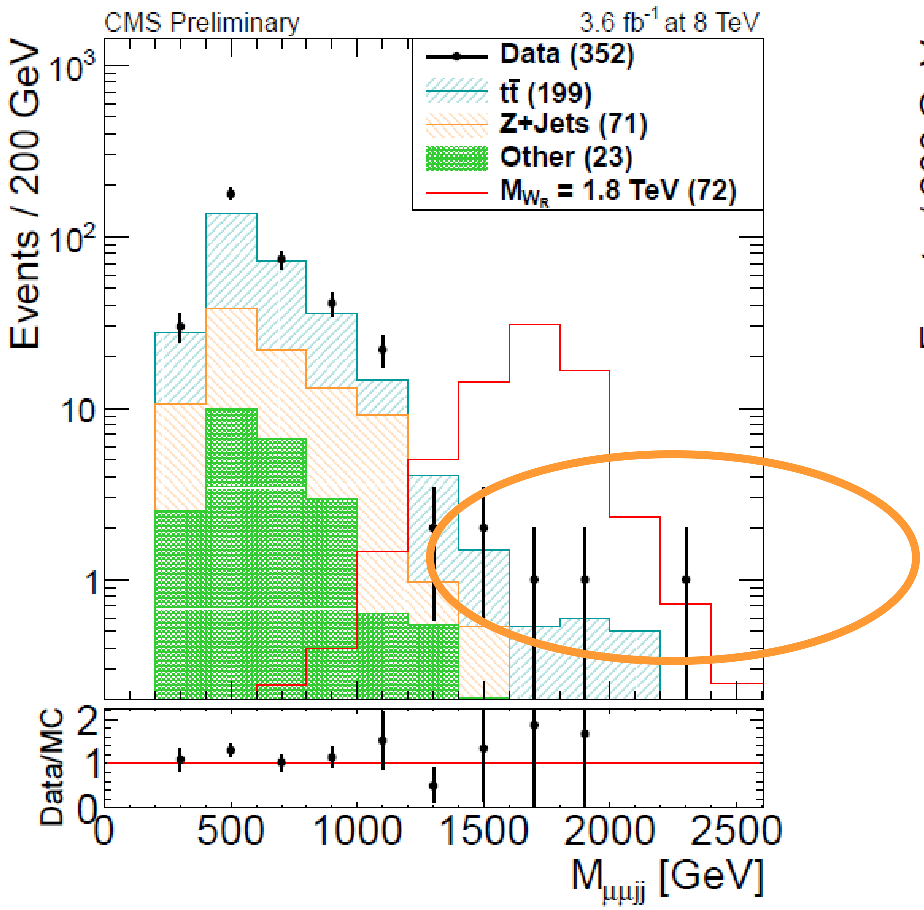


$M_{\ell\ell} > 200$ GeV

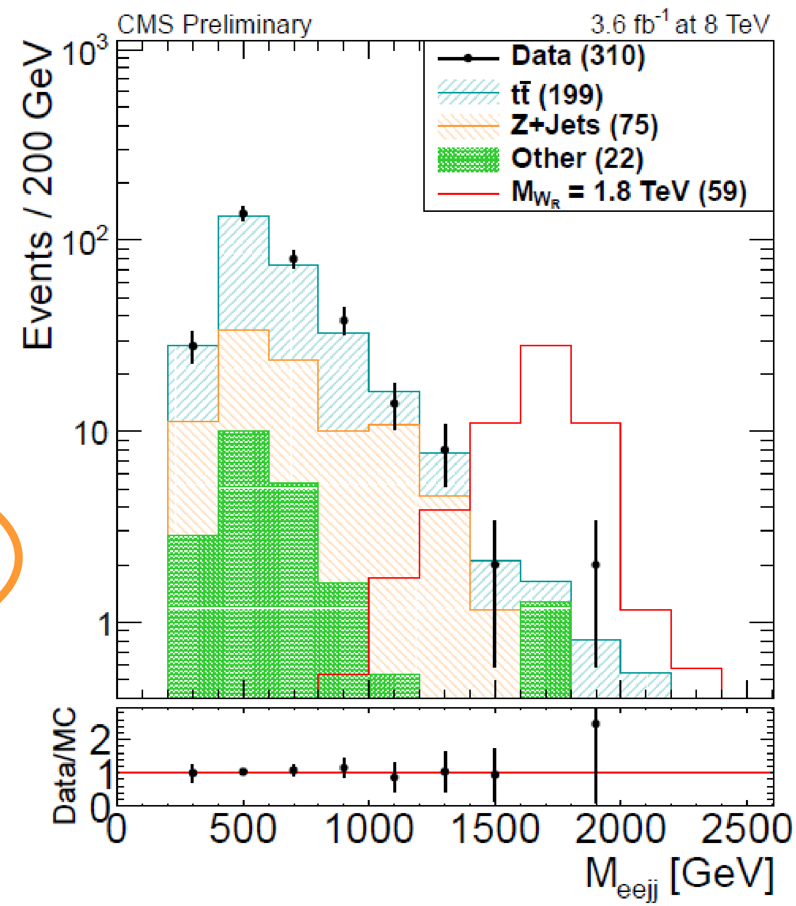
CMS: 7 TeV, 5.0 fb^{-1} & 8 TeV, 3.6 fb^{-1}

$W' \rightarrow \ell\, N_\ell\, (qq'\ell')$: CMS

Muons



Electrons



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ℓ+MET		0.1-0.2	???	???
τ+MET		---	---	---
ℓℓjj	CMS, 3.6 fb^{-1}, 8 TeV	1.0-3.0		

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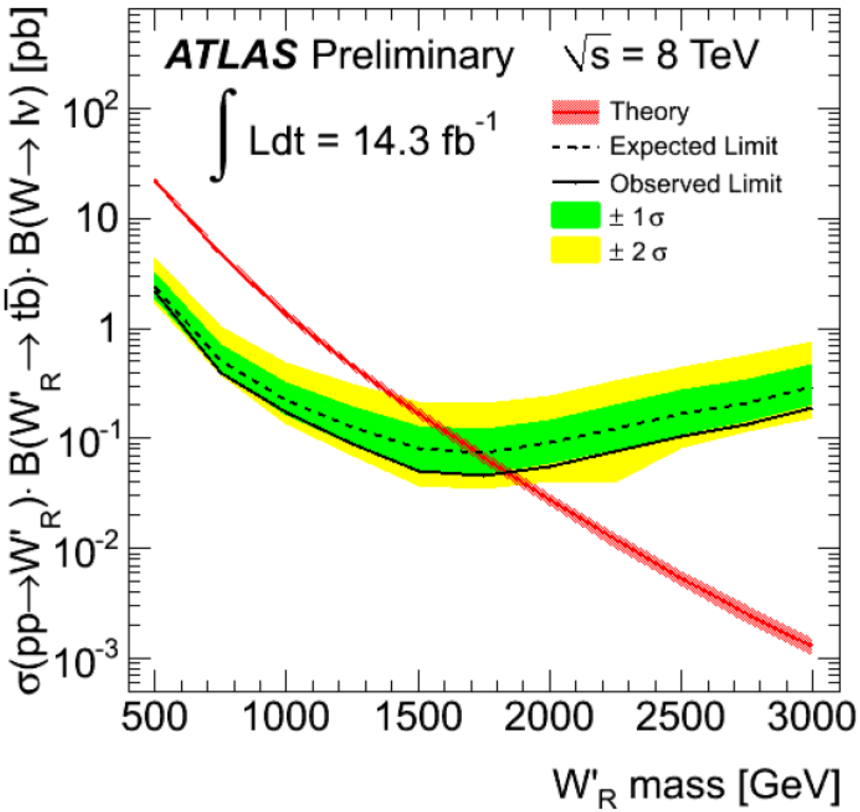
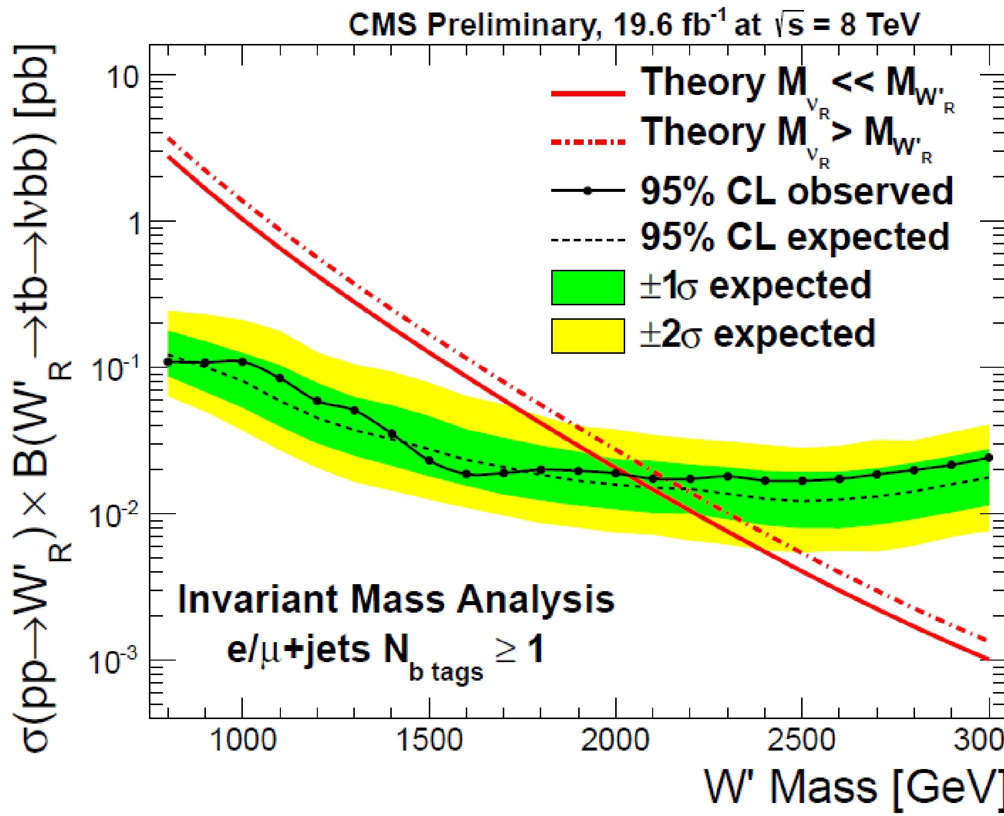
$$W' \rightarrow t\bar{b}$$

$W' \to t\bar{b}$: ATLAS & CMS

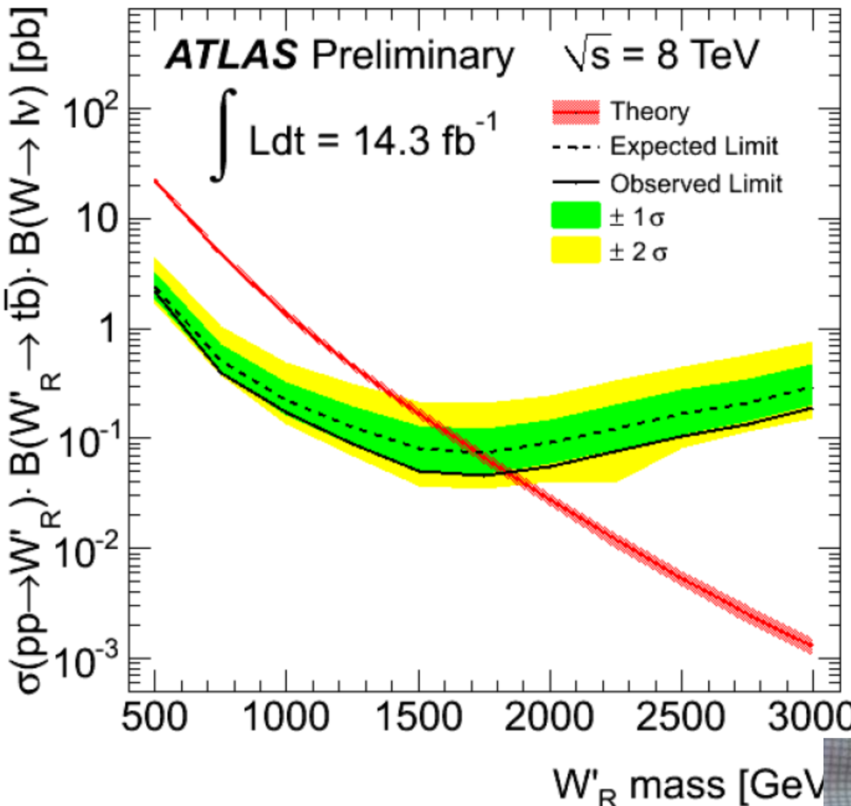


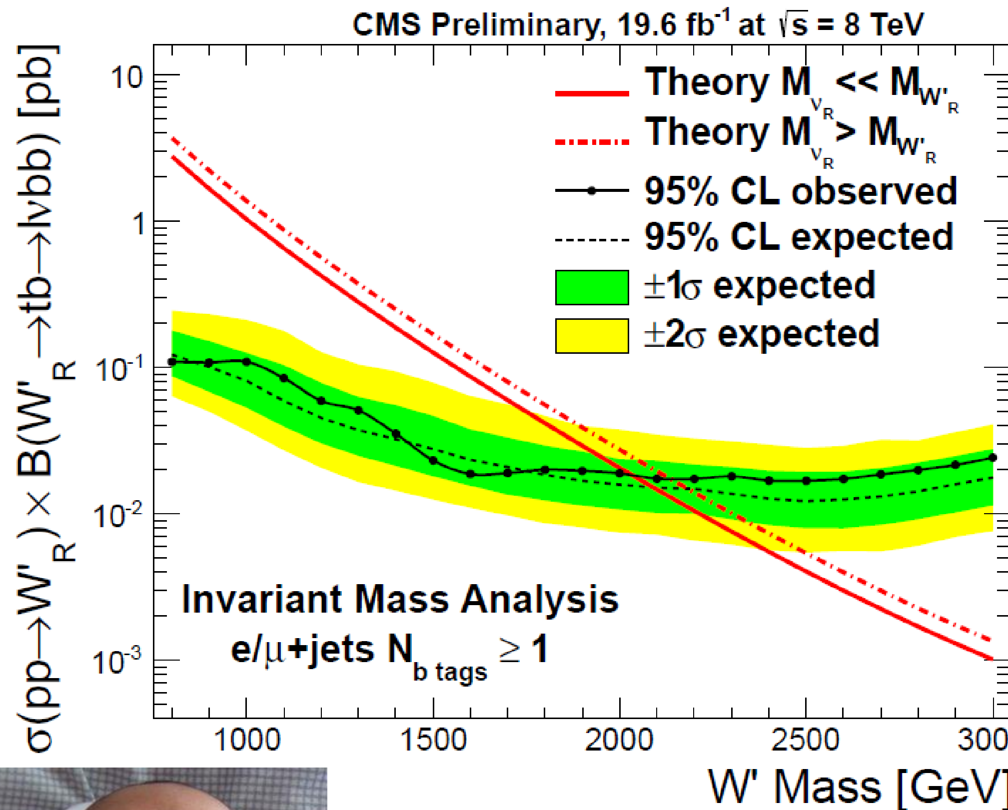


ATLAS assumes neutrino too heavy to produce

ATLAS: 8 TeV, 14.3 fb^{-1}, CONF-2013-050 CMS: 8 TeV, 20 fb^{-1}, B2G12010

$W' \to t\bar{b}$: ATLAS & CMS





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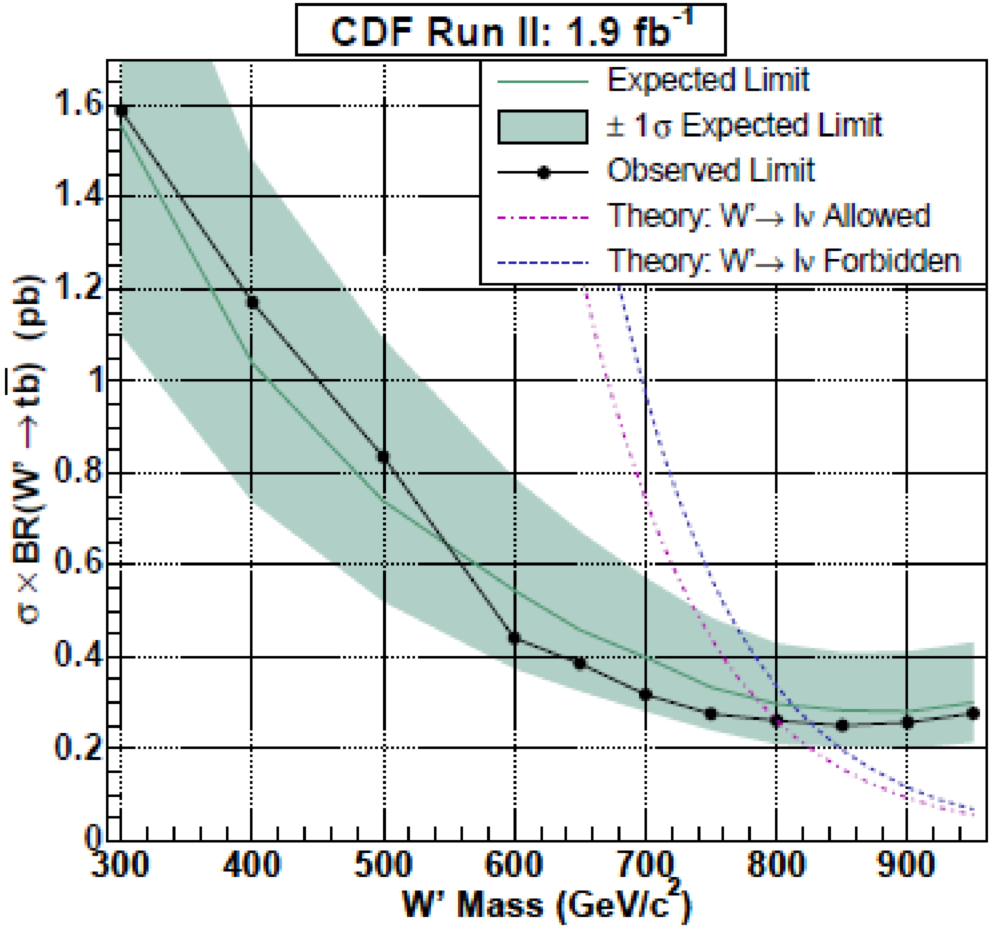
e+MET	CDF, 205 pb^{-1},2 TeV	0.2-1.0	100-1000	0.2-0.8
μ+MET	CDF, 107 pb^{-1}, 1.8 TeV	0.2-0.8	400-10000	0.2-0.7
ℓ+MET	LEP	0-0.105	10^{-3} × SSM?	0-0.105
ℓ+MET		0.1-0.2	???	???
τ+MET		---	---	---
ℓℓjj	CMS, 3.6 fb^{-1}, 8 TeV	1.0-3.0		
tb	CMS, 20 fb^{-1}, 8 TeV	0.8-3.0	20-100	0.8-2.05(2.15)

$W' \rightarrow t\bar{b}$: CDF



CDF: 1.96 TeV, 1.9 fb^{-1}, arXiv: 0902.3276

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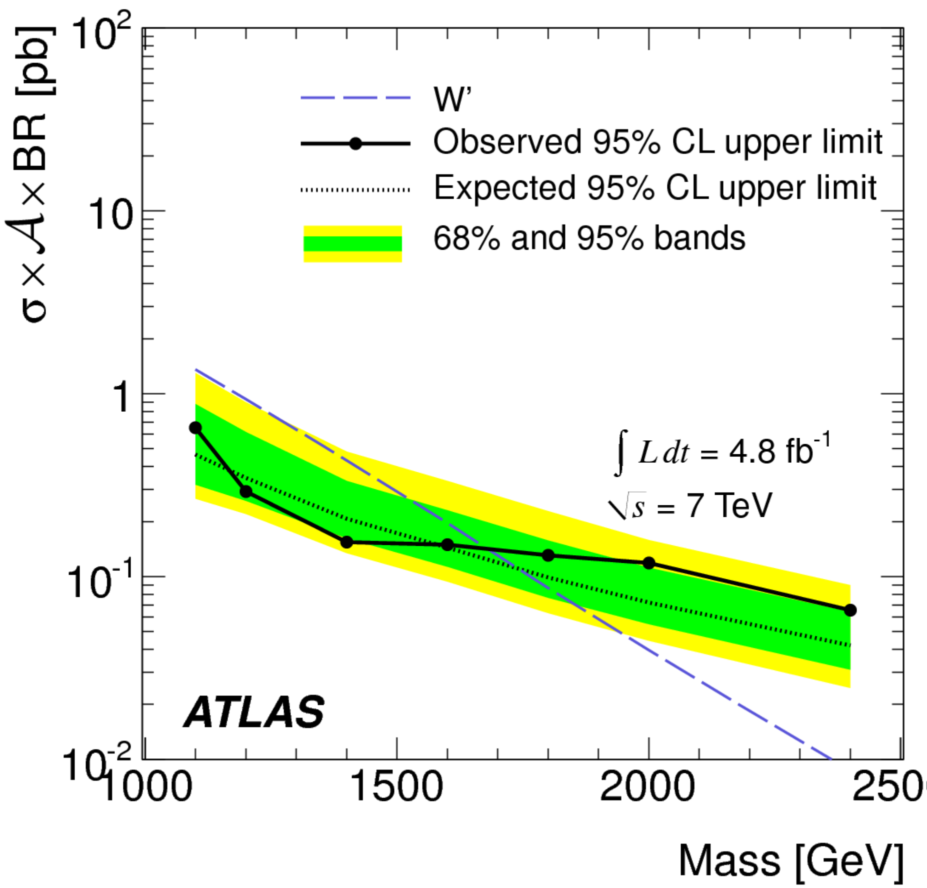
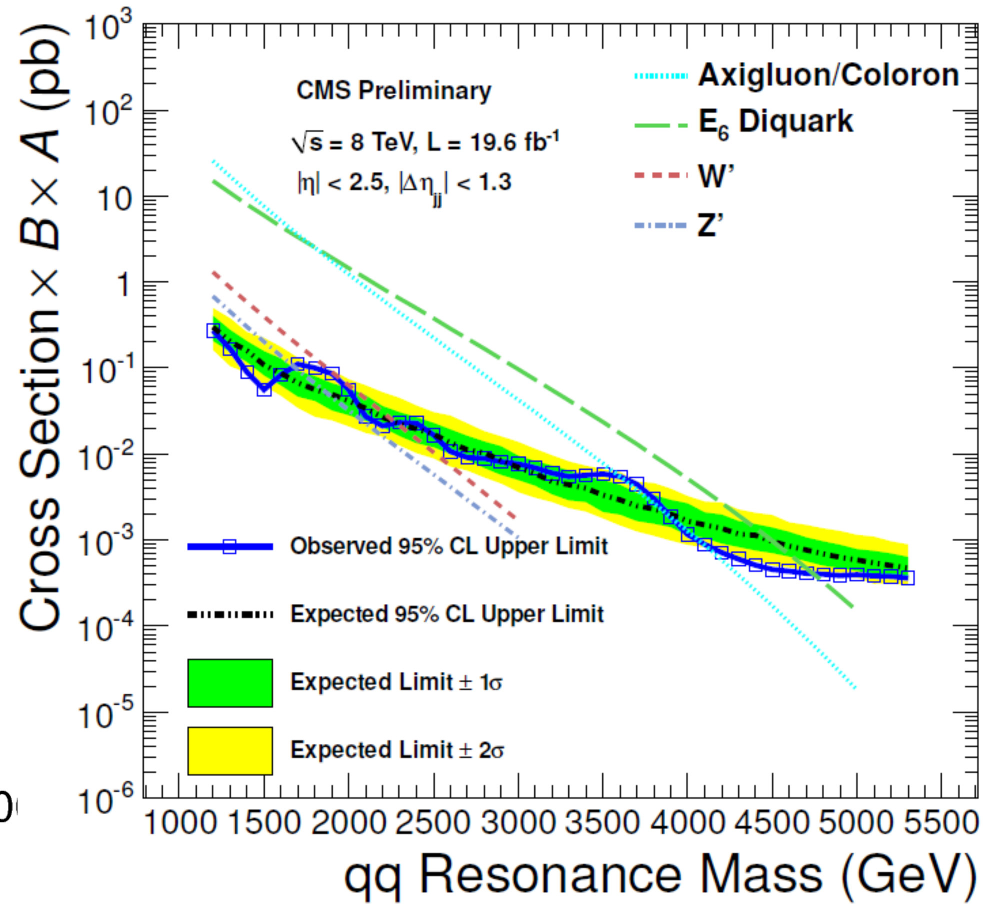
tb	CMS, 20 fb^{-1}, 8 TeV	0.8-3.0	20-100	0.8-2.05(2.15)
tb	CDF, 1.9 fb^{-1}, 2 TeV	0.3-0.9	300-1600	0.3-0.8

$$W' \rightarrow qq'$$

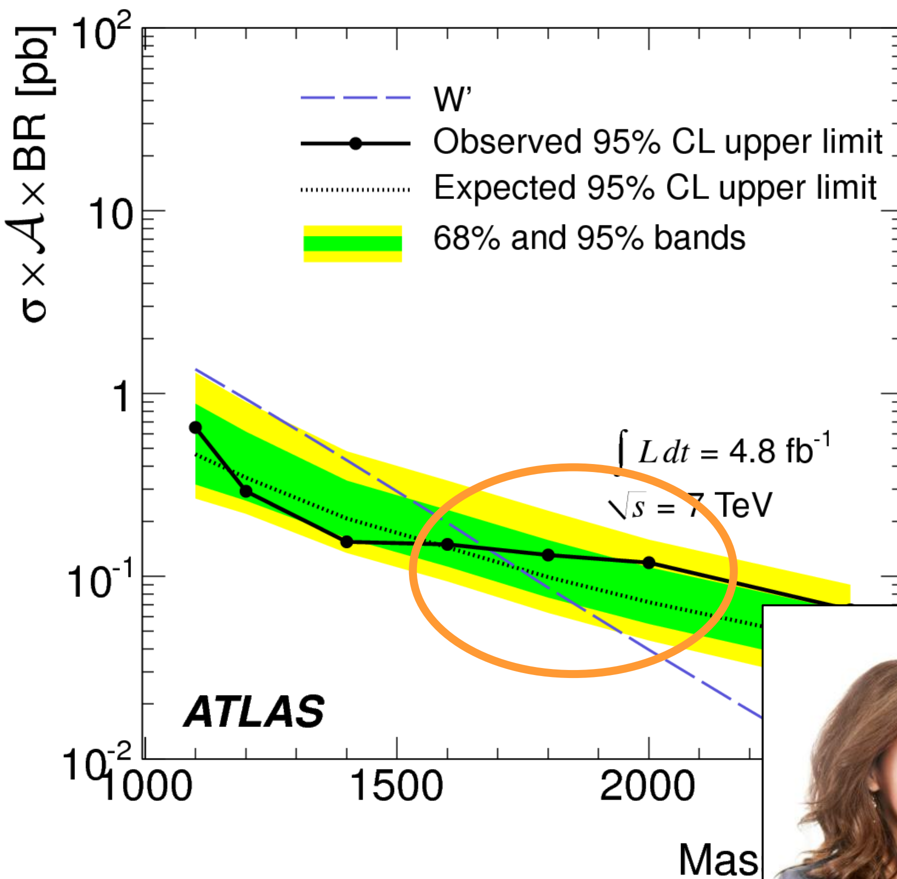
$W' \to qq'$: ATLAS & CMS

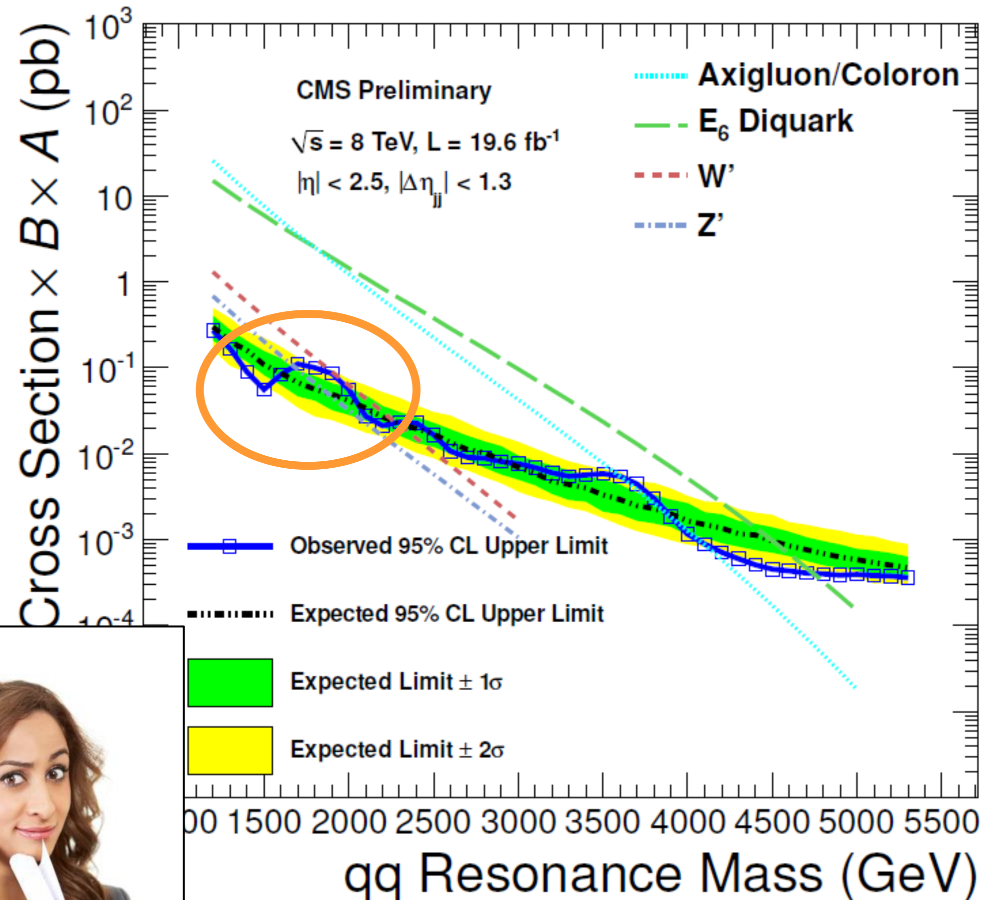




ATLAS: 7 TeV, 4.8 fb^{-1}, EXOT-2011-021 CMS: 8 TeV, 20 fb^{-1}, EXO12059

$W' \to qq'$: ATLAS & CMS





ATLAS: 7 TeV, 4.8 fb^{-1}, EXOT-2011-021

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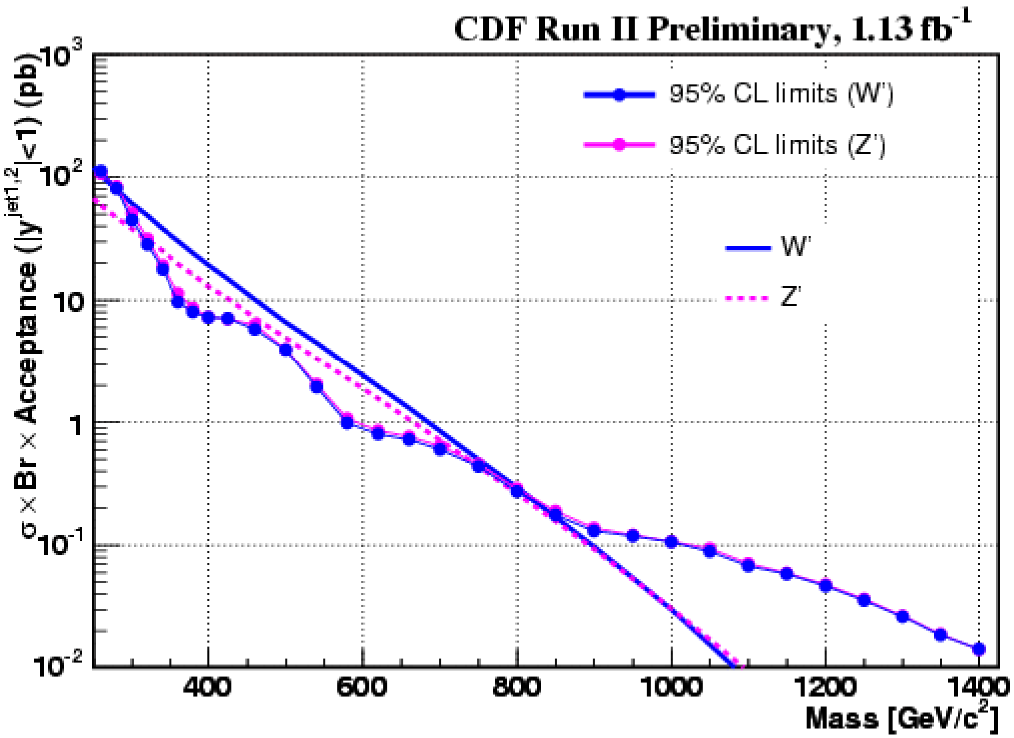
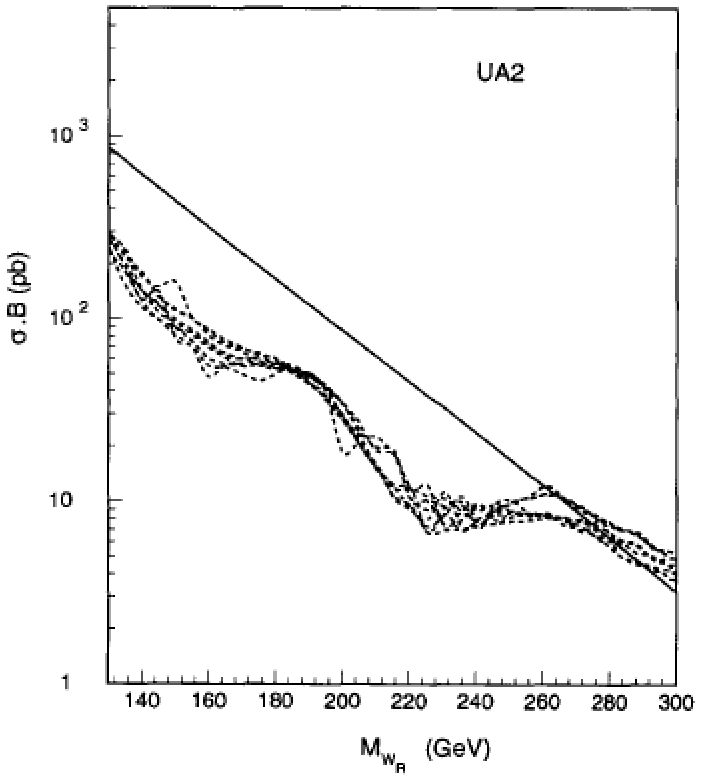
$W' \rightarrow qq'$: CDF & UA2





CDF: 1.96 TeV, 1.13 fb^{-1}, arXiv:0812.4036

UA2: 0.45 TeV, 11 pb^{-1}, Nucl. Physics B400 (1993), 3-22

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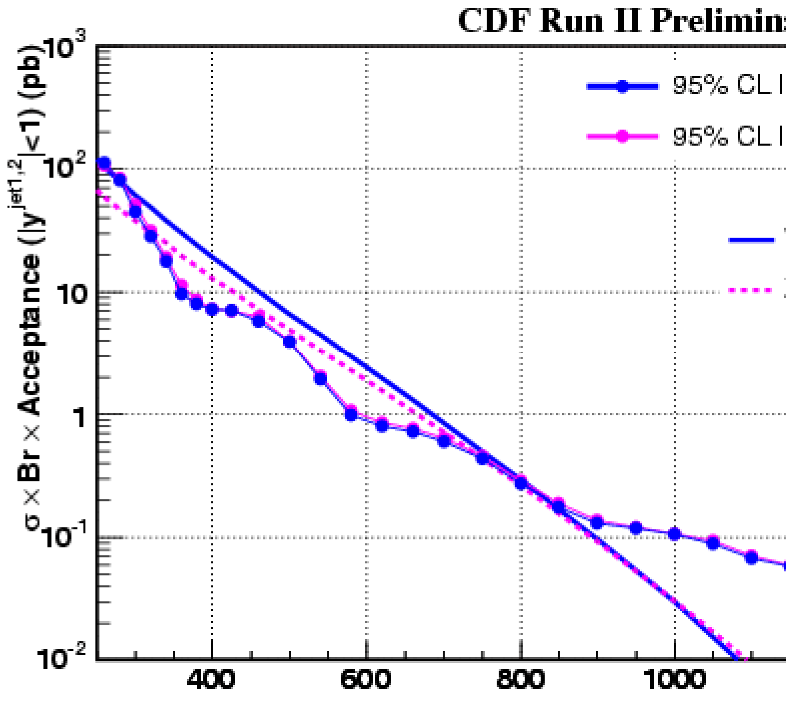

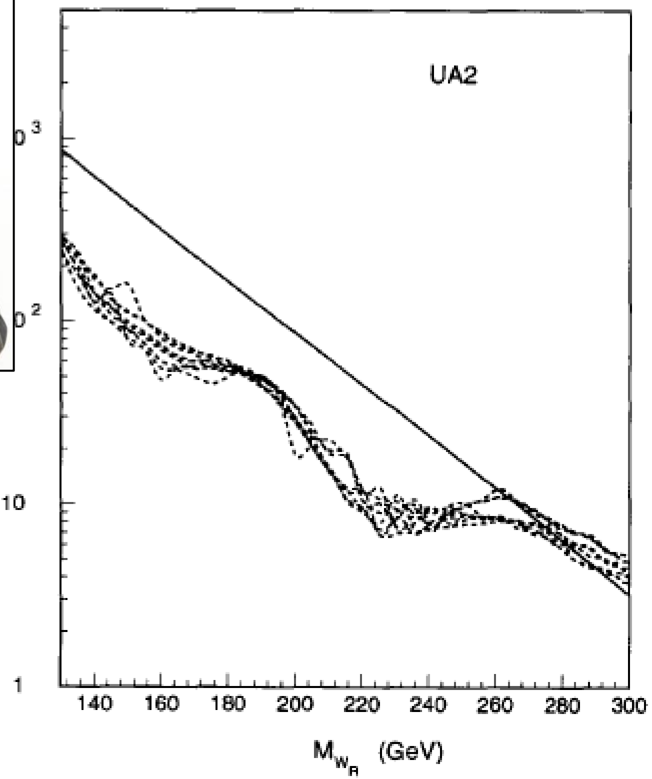

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- Exclusion limits much closer to theoretical curve here: weak limits
- No 1/2 σ "brazilian flag" bands: impossible to judge significance of fluctuations

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e+MET	CMS, 20 fb^{-1}, 8 TeV	0.4-4.0	0.5-90	0.4-3.20
μ+MET	CMS, 20 fb^{-1}, 8 TeV	0.4-4.0	0.8-70	0.4-3.10
e/μ+MET	CMS, 20 fb^{-1}, 8 TeV	0.4-4.0	0.5-70	0.4-3.35
e+MET	CDF, 205 pb^{-1},2 TeV	0.2-1.0	100-1000	0.2-0.8
μ+MET	CDF, 107 pb^{-1}, 1.8 TeV	0.2-0.8	400-10000	0.2-0.7
ℓ+MET	LEP	0-0.105	10^{-3} × SSM?	0-0.105
ℓ+MET		0.1-0.2	???	???
τ+MET		---	---	---
ℓℓjj	CMS, 3.6 fb^{-1}, 8 TeV	1.0-3.0		
tb	CMS, 20 fb^{-1}, 8 TeV	0.8-3.0	20-100	0.8-2.05(2.15)
tb	CDF, 1.9 fb^{-1}, 2 TeV	0.3-0.9	300-1600	0.3-0.8
jj	CMS, 20 fb^{-1}, 8 TeV	1.2-5.0	1-300	1.2-2.29
jj	CDF, 1.9 fb^{-1}, 2 TeV	0.3-1.4	1E2-1E5	0.35-0.75
jj	UA2, 11 pb^{-1}, 0.45 TeV	0.13-0.30	3E3-2E5	0.13-0.26

- Weak limits at low masses
- Holes in mass spectrum coverage?

What about the WZ?

General W' searches and W_R

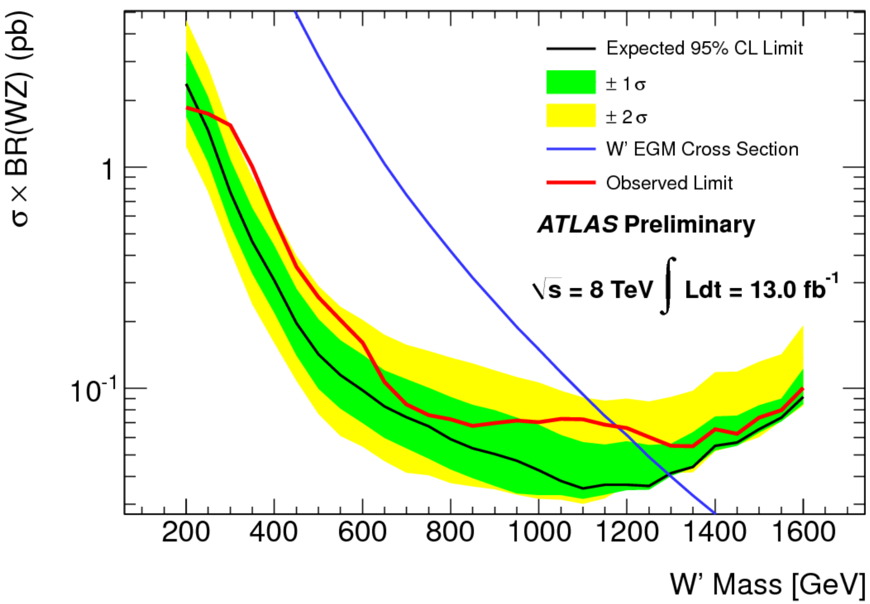
- W' Signatures
  - Leptonic: $e+\nu, \mu+\nu, \tau+\nu$
  - Bosonic: $WZ(3\ell\nu$ or $qq'\ell\ell$ or qq'), $\ell = e, \mu$
  - Hadronic: qq', $t\bar{b}$, ℓN_ℓ ($N_\ell \to qq'\ell'$) $\ell = e, \mu$

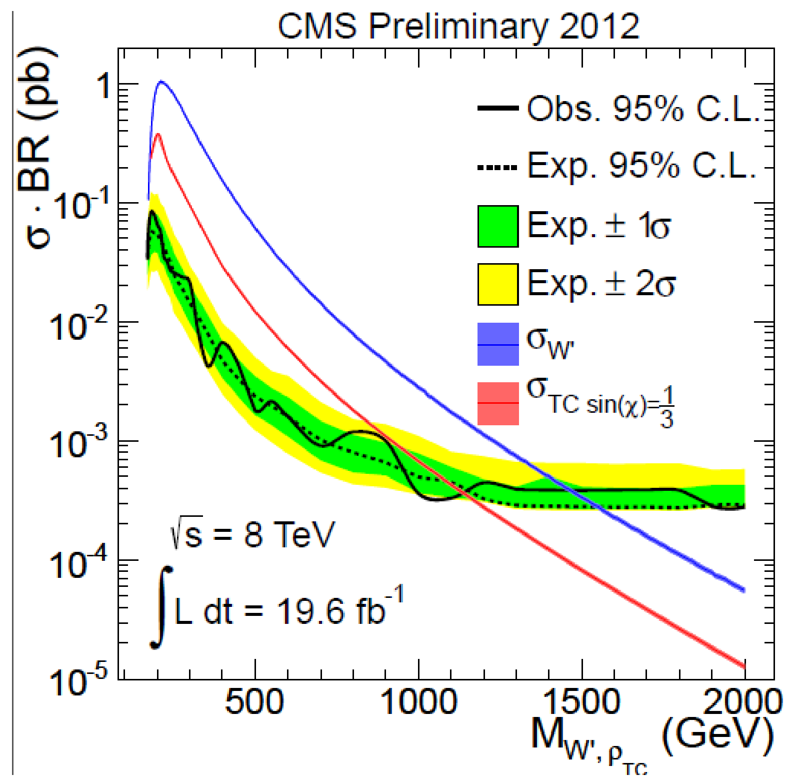
- $m(N_\ell) \to 0$, ie. $m(N_\ell) << m(W_R)$

- The fully leptonic channel is not exciting in terms of L-R models
- But: semi-leptonic (plus hadronic) channel very similar to the "traditional" W_R channel: two leptons + two jets
- W_R analysis typically includes some (kind of) Z-veto (cut on dilepton mass) WZ analysis reverses this cut, offering complementarity in phase space

$$W' \rightarrow WZ \rightarrow 3\ell\nu$$

$W' \to WZ \to 3\ell\nu$: ATLAS & CMS





ATLAS: 8 TeV, 13 fb^{-1}, CONF-2013-015

CMS: 8 TeV, 20 fb^{-1}, EXO12025

W' searches: Overview

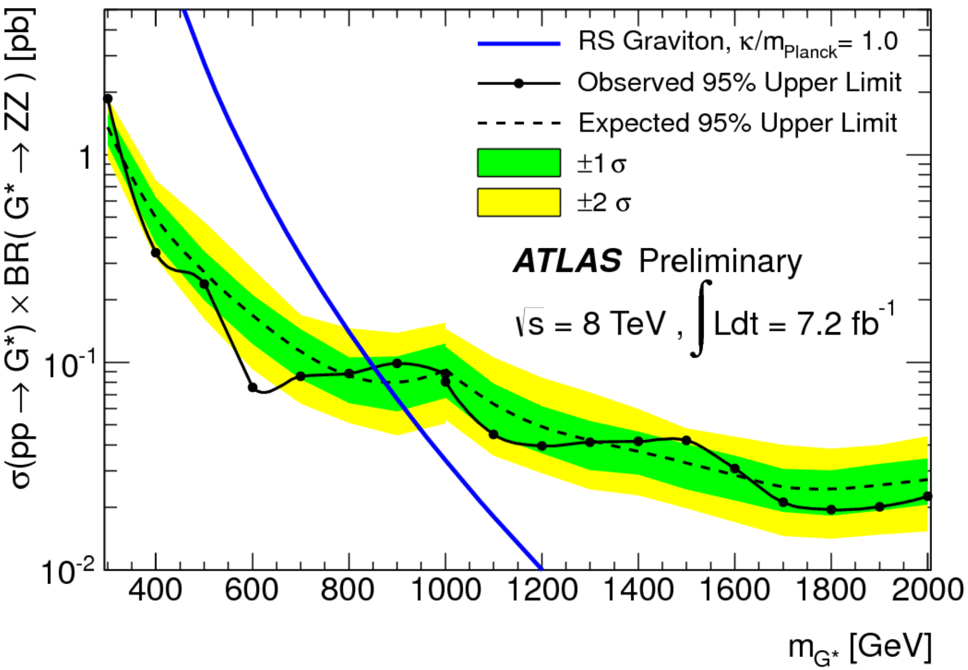
Channel	Experiment	Search range (TeV)	σ ×B Limits (fb)	SSM limit (TeV)
e+MET	CMS, 20 fb^{-1}, 8 TeV	0.4-4.0	0.5-90	0.4-3.20
μ+MET	CMS, 20 fb^{-1}, 8 TeV	0.4-4.0	0.8-70	0.4-3.10
e/μ+MET	CMS, 20 fb^{-1}, 8 TeV	0.4-4.0	0.5-70	0.4-3.35
e+MET	CDF, 205 pb^{-1},2 TeV	0.2-1.0	100-1000	0.2-0.8
μ+MET	CDF, 107 pb^{-1}, 1.8 TeV	0.2-0.8	400-10000	0.2-0.7
ℓ+MET	LEP	0-0.105	10^{-3} × SSM?	0-0.105
ℓ+MET		0.1-0.2	???	???
τ+MET		---	---	---
ℓℓjj	CMS, 3.6 fb^{-1}, 8 TeV	1.0-3.0		
tb	CMS, 20 fb^{-1}, 8 TeV	0.8-3.0	20-100	0.8-2.05(2.15)
tb	CDF, 1.9 fb^{-1}, 2 TeV	0.3-0.9	300-1600	0.3-0.8
jj	CMS, 20 fb^{-1}, 8 TeV	1.2-5.0	1-300	1.2-2.29
jj	CDF, 1.9 fb^{-1}, 2 TeV	0.3-1.4	1E2-1E5	0.35-0.75
jj	UA2, 11 pb^{-1}, 0.45 TeV	0.13-0.30	3E3-2E5	0.13-0.26
3ℓ+MET	CMS, 20 fb^{-1}, 8 TeV	0.17-2.0	0.3-100	0.17-1.45

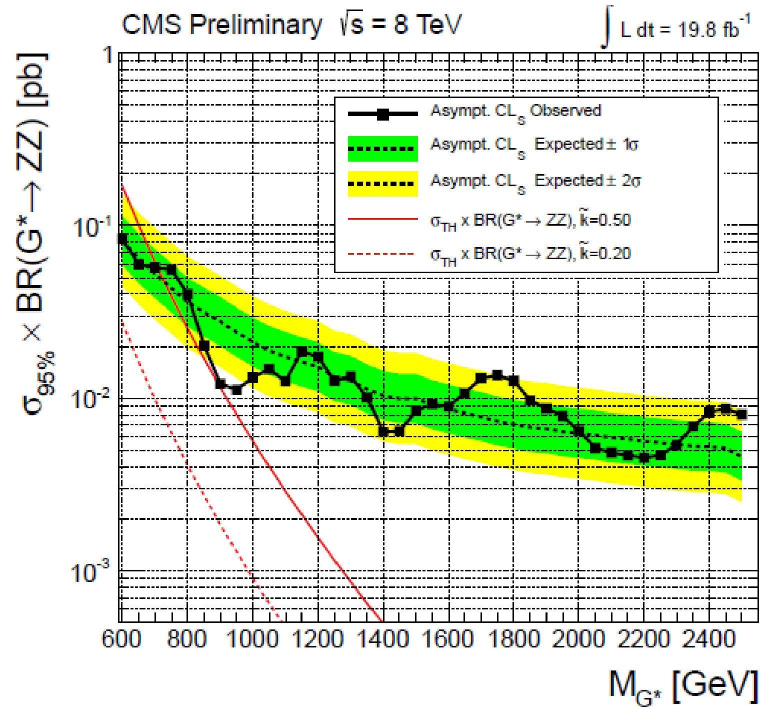
$$W' \to WZ \to qq'\ell\ell$$

$B(WZ \to 3\ell\nu) \sim 1.5\%$

$\mathrm{B}(WZ \to qq'\ell\ell) \sim 5\%$

$W' \to WZ \to qq'\ell\ell$: ATLAS &CMS

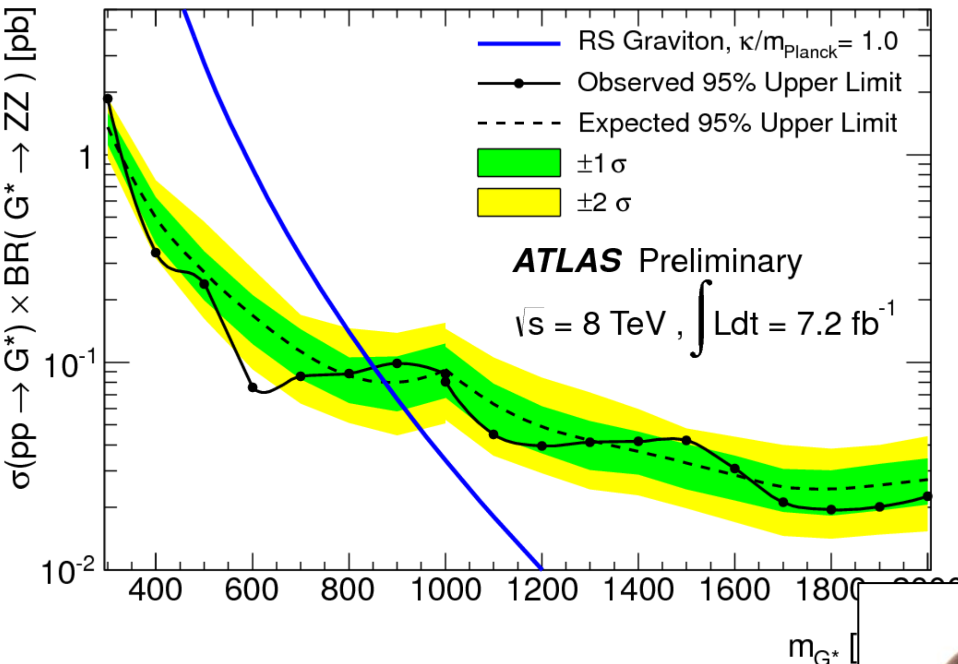


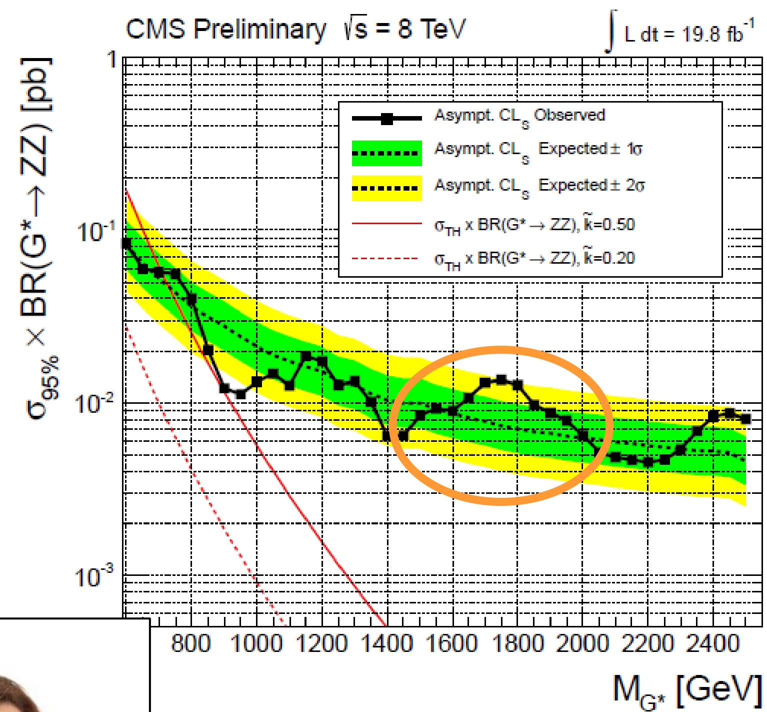


- Interpretation of results assumes ZZ final state.
- Cannot use results to extract W' limits

ATLAS: 8 TeV, 7 fb^{-1}, CONF-2012-150 CMS: 8 TeV, 20 fb^{-1}, EXO12022

$W' \to WZ \to qq'\ell\ell$: ATLAS &CMS





- Interpretation of results assur tate.
- Cannot use results to extract

ATLAS: 8 TeV, 7 fb^{-1}, CONF-2012-1 8 TeV, 20 fb^{-1}, EXO12022

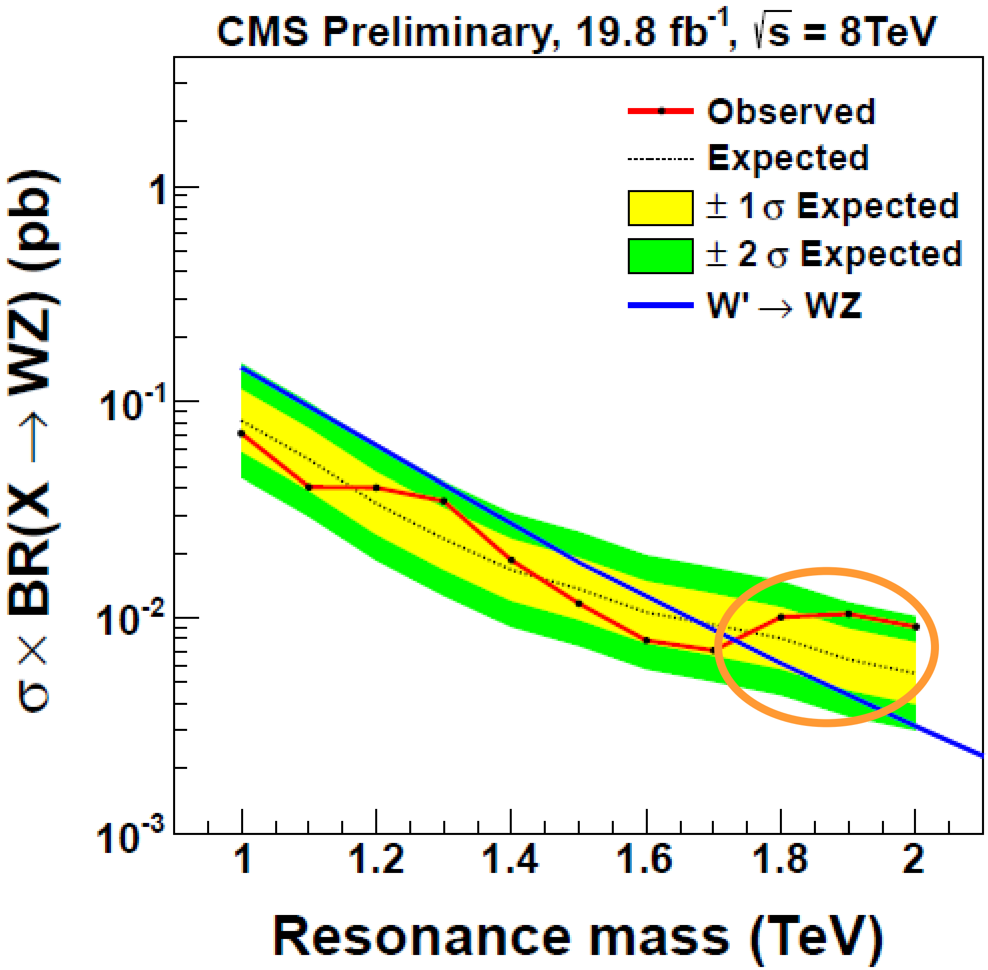
$$W' \rightarrow WZ \rightarrow (qq')(qq')$$

$$B(WZ \rightarrow 3\ell\nu) \sim 1.5\%$$

$$B(WZ \rightarrow qq'\ell\ell) \sim 5\%$$

$$B\left(WZ \rightarrow (qq')(qq')\right) \sim 48\%$$

$W' \to WZ \to (qq')(qq')$: CMS



CMS: 8 TeV, 20 fb^{-1}, EXO12024

W' searches: Overview

Channel	Experiment	Search range (TeV)	$\sigma \times B$ Limits (fb)	SSM limit (TeV)
e+MET	CMS, 20 fb^{-1}, 8 TeV	0.4-4.0	0.5-90	0.4-3.20
μ+MET	CMS, 20 fb^{-1}, 8 TeV	0.4-4.0	0.8-70	0.4-3.10
e/μ+MET	CMS, 20 fb^{-1}, 8 TeV	0.4-4.0	0.5-70	0.4-3.35
e+MET	CDF, 205 pb^{-1},2 TeV	0.2-1.0	100-1000	0.2-0.8
μ+MET	CDF, 107 pb^{-1}, 1.8 TeV	0.2-0.8	400-10000	0.2-0.7
ℓ+MET	LEP	0-0.105	10^{-3} × SSM?	0-0.105
ℓ+MET		0.1-0.2	???	???
τ+MET		---	---	---
ℓℓjj	CMS, 3.6 fb^{-1}, 8 TeV	1.0-3.0		
tb	CMS, 20 fb^{-1}, 8 TeV	0.8-3.0	20-100	0.8-2.05(2.15)
tb	CDF, 1.9 fb^{-1}, 2 TeV	0.3-0.9	300-1600	0.3-0.8
jj	CMS, 20 fb^{-1}, 8 TeV	1.2-5.0	1-300	1.2-2.29
jj	CDF, 1.9 fb^{-1}, 2 TeV	0.3-1.4	1E2-1E5	0.35-0.75
jj	UA2, 11 pb^{-1}, 0.45 TeV	0.13-0.30	3E3-2E5	0.13-0.26
3ℓ+MET	CMS, 20 fb^{-1}, 8 TeV	0.17-2.0	0.3-100	0.17-1.45
W(jj)Z(jj)	CMS, 20 fb^{-1}, 8 TeV	1.0-2.0	10-80	1.00-1.73

Summary

First Summary

- LHC W' searches:
  - ➢ No smoking gun, but not all data analyzed yet (esp. ATLAS)
  - ➢ A handful of deviations to keep an eye on

- Low-mass region not very well explored
  - ➢ Additionally, certain final states and mass regions have been overlooked completely

First Summary

- Comprehensive search approach
  - ➢ Allows comparison of deviations in different final states
  - ➢ Helps reduce holes in phasespace coverage

TLEP: a Physics Study

First Look at the Physics Case of TLEP

The TLEP Design Study Working Group
(See next pages for the list of authors)

arXiv: 1308.6176

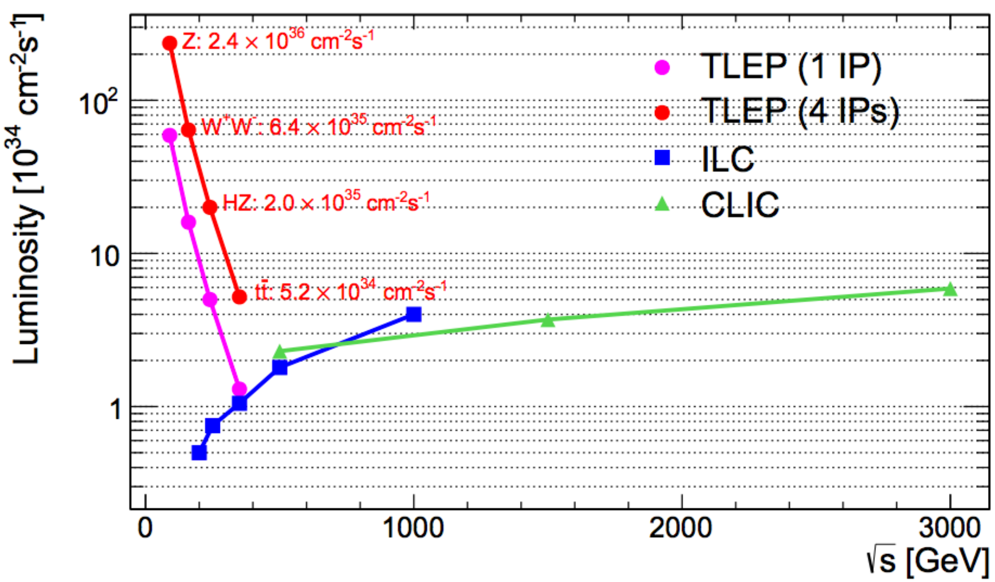
Abstract
The discovery by the ATLAS and CMS experiments of a new boson with mass around 125 GeV and with measured properties compatible with those of a Standard-Model Higgs boson, coupled with the absence of discoveries of phenomena beyond the Standard Model up to scales of several hundred GeV, has triggered interest in ideas for future Higgs factories. A new circular e^+e^- collider hosted in a 80 to 100 km tunnel, TLEP, is among the most attractive solutions proposed so far. It has a clean experimental environment, produces high luminosity for top-quark, Higgs boson, W and Z studies, accommodates multiple detectors, and can reach energies up to the $t\bar{t}$ threshold and beyond. It will enable measurements of the Higgs boson properties and of Electroweak Symmetry-Breaking (EWSB) parameters with unequalled precision, offering exploration of physics beyond the Standard Model in the multi-TeV range. Moreover, being the natural precursor of the VHE-LHC, a 100 TeV hadron machine in the same tunnel, it builds up a long-term vision for particle physics. Altogether, the combination of TLEP and the VHE-LHC offers, for a great cost effectiveness, the best precision and the best search reach of all options presently on the market. This paper presents a first appraisal of the salient features of the TLEP physics potential, to serve as a baseline for a more extensive design study.

TLEP: a Physics Study

	TLEP-Z	TLEP-W	TLEP-H	TLEP-t
$\sqrt{s}$ (GeV)	90	160	240	350
L (10^{34} $cm^{-2}s^{-1}$)	56	16	5	1.3
# bunches	4400	600	80	12
RF Gradient (MV/m)	3	3	10	20
Vertical beam size (nm)	270	140	140	100
Total AC Power (MW)	250	250	260	284
L_{int} (ab^{-1}/year/IP)	5.6	1.6	0.5	0.13

Table 2: Indicative costs for the main cost drivers of the TLEP collider.

Item	Cost (Million CHF)
RF system	900
Cryogenics system	200
Vacuum system	500
Magnets systems for the two rings	800
Pre-injector complex	500
Total	**2,900**



arXiv: 1308.6176

Epilogue

Backup

W_R (Right-Handed W Boson) MASS LIMITS

Assuming a light right-handed neutrino, except for BEALL 82, LANGACKER 89B, and COLANGELO 91. $g_R = g_L$ assumed. [Limits in the section MASS LIMITS for W' below are also valid for W_R if $m_{\nu_R} \ll m_{W_R}$.] Some limits assume manifest left-right symmetry, *i.e.*, the equality of left- and right Cabibbo-Kobayashi-Maskawa matrices. For a comprehensive review, see LANGACKER 89B. Limits on the W_L-W_R mixing angle ζ are found in the next section. Values in brackets are from cosmological and astrophysical considerations and assume a light right-handed neutrino.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
> 592	90	[1] BUENO	11	TWST	μ decay
> 715	90	[2] CZAKON	99	RVUE	Electroweak
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 245	90	[3] WAUTERS	10	CNTR	^{60}Co β decay
> 180	90	[4] MELCONIAN	07	CNTR	^{37}K β^+ decay
> 290.7	90	[5] SCHUMANN	07	CNTR	Polarized neutron decay
[> 3300]	95	[6] CYBURT	05	COSM	Nucleosynthesis; light ν_R
> 310	90	[7] THOMAS	01	CNTR	β^+ decay
> 137	95	[8] ACKERSTAFF	99D	OPAL	τ decay
>1400	68	[9] BARENBOIM	98	RVUE	Electroweak, Z-Z' mixing
> 549	68	[10] BARENBOIM	97	RVUE	μ decay
> 220	95	[11] STAHL	97	RVUE	τ decay
> 220	90	[12] ALLET	96	CNTR	β^+ decay
> 281	90	[13] KUZNETSOV	95	CNTR	Polarized neutron decay
> 282	90	[14] KUZNETSOV	94B	CNTR	Polarized neutron decay
> 439	90	[15] BHATTACH...	93	RVUE	Z-Z' mixing
> 250	90	[16] SEVERIJNS	93	CNTR	β^+ decay
		[17] IMAZATO	92	CNTR	K^+ decay
> 475	90	[18] POLAK	92B	RVUE	μ decay
> 240	90	[19] AQUINO	91	RVUE	Neutron decay
> 496	90	[19] AQUINO	91	RVUE	Neutron and muon decay
> 700		[20] COLANGELO	91	THEO	$m_{K^0_L} - m_{K^0_S}$
> 477	90	[21] POLAK	91	RVUE	μ decay
[none 540–23000]		[22] BARBIERI	89B	ASTR	SN 1987A; light ν_R
> 300	90	[23] LANGACKER	89B	RVUE	General
> 160	90	[24] BALKE	88	CNTR	$\mu \rightarrow e\nu\overline{\nu}$
> 406	90	[25] JODIDIO	86	ELEC	Any ζ
> 482	90	[25] JODIDIO	86	ELEC	$\zeta = 0$
> 800		MOHAPATRA	86	RVUE	$SU(2)_L \times SU(2)_R \times U(1)$
> 400	95	[26] STOKER	85	ELEC	Any ζ
> 475	95	[26] STOKER	85	ELEC	ζ <0.041
		[27] BERGSMA	83	CHRM	$\nu_\mu e \rightarrow \mu\nu_e$
> 380	90	[28] CARR	83	ELEC	μ^+ decay
>1600		[29] BEALL	82	THEO	$m_{K^0_L} - m_{K^0_S}$

[1] The quoted limit is for manifest left-right symmetric model.

[2] CZAKON 99 perform a simultaneous fit to charged and neutral sectors.

[3] WAUTERS 10 limit is from a measurement of the asymmetry parameter of polarized