Vrije
Universiteit
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Searches for new fermions and bosons

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On behalf of the CMS and ATLAS collaborations

Physics In Collision 2012 – September, 12 – 15

This talk is complementary to
“Exotic Phenomena Searches”
(Francesco Santanastasio)

Setting the scene

Many exotic models:

→ new particles!?
→ this talk: searches for new fermions and new bosons
→ other recent searches covered by Francesco Santanastasio

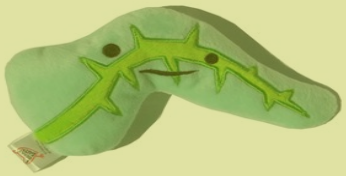
There are many searches for new fermions and new gauge bosons (but less searches than models)

→ excluding parts of the allowed parameter space

Focus on most recent/stringent results

Many (new) searches – preview

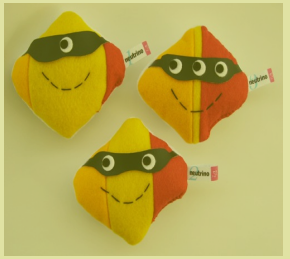
New bosons



$Z' \rightarrow ee/\mu\mu$ *
$Z' \rightarrow \tau\tau$
$Z' \rightarrow qq$ *
$Z' \rightarrow bb$

$W' \rightarrow l\nu$ *
$W' \rightarrow tq$
$W' \rightarrow qq$

New fermions



$N\ (+W_R)$

$t' \rightarrow bW$
$b' \rightarrow tW$
$B \rightarrow bZ$
$T \rightarrow tZ$
$T^{5/3} \rightarrow tW$

Searches are performed in different final states depending on the model and assumed couplings:
→ (same-sign) dileptons
→ (di)jets
→ lepton+jets
→ ...

* (also) 8 TeV result

Z' searches

(Narrow) resonances are predicted by several extensions of the Standard Model:

- Z'_{SSM} (sequential SM → same couplings to fermions as Z)
- Z'_{ψ} / Z'_{χ} ($E_6 \rightarrow SU(5) \times U(1)_{\chi} \times U(1)_{\psi}$ or $E_6 \rightarrow SO(10) \times U(1)_{\psi}$)
- Z* (technicolor gauge bosons)

Search strategies:

- Z' → ee/μμ:

2 oppositely charged, isolated, high-momentum leptons

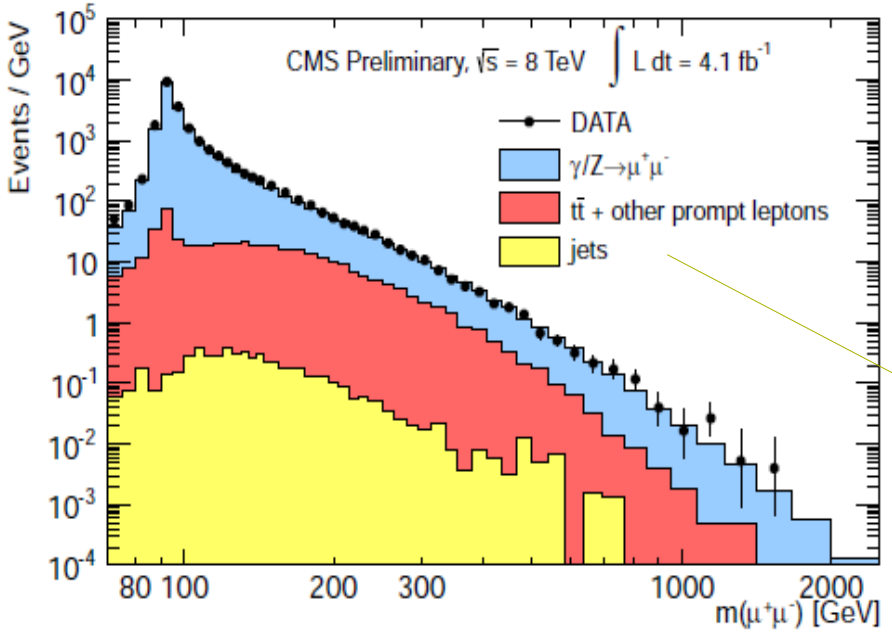
- Z' → ττ:

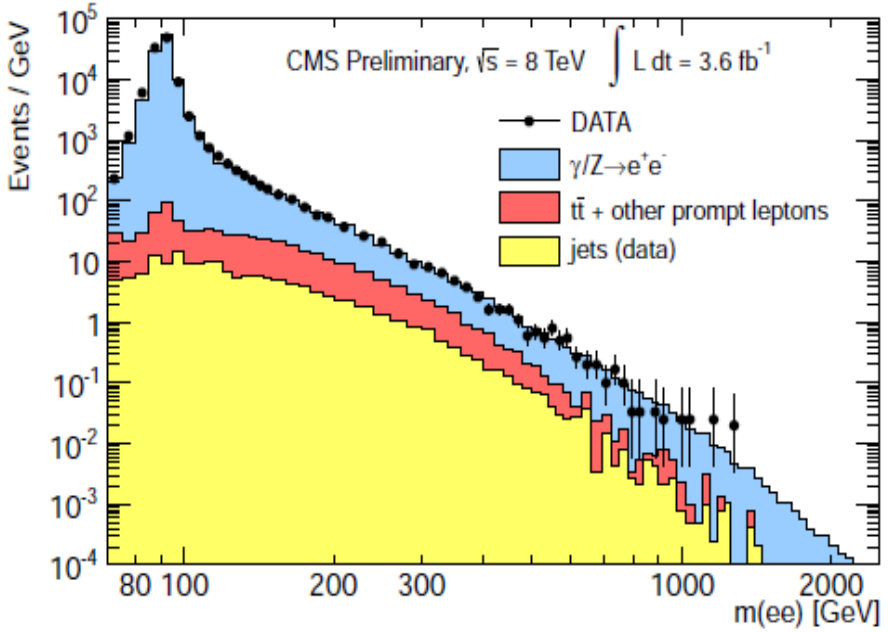
different subsamples depending on the τ decay

- Z' → qq

Dijet reconstruction (with or without b-tagging, fat/wide jets)

Z' → ee / μμ – analysis strategy





For each selected event, m_{ee} or $m_{\mu\mu}$ is reconstructed

"jets": events with at least 1 jet misreconstructed as lepton

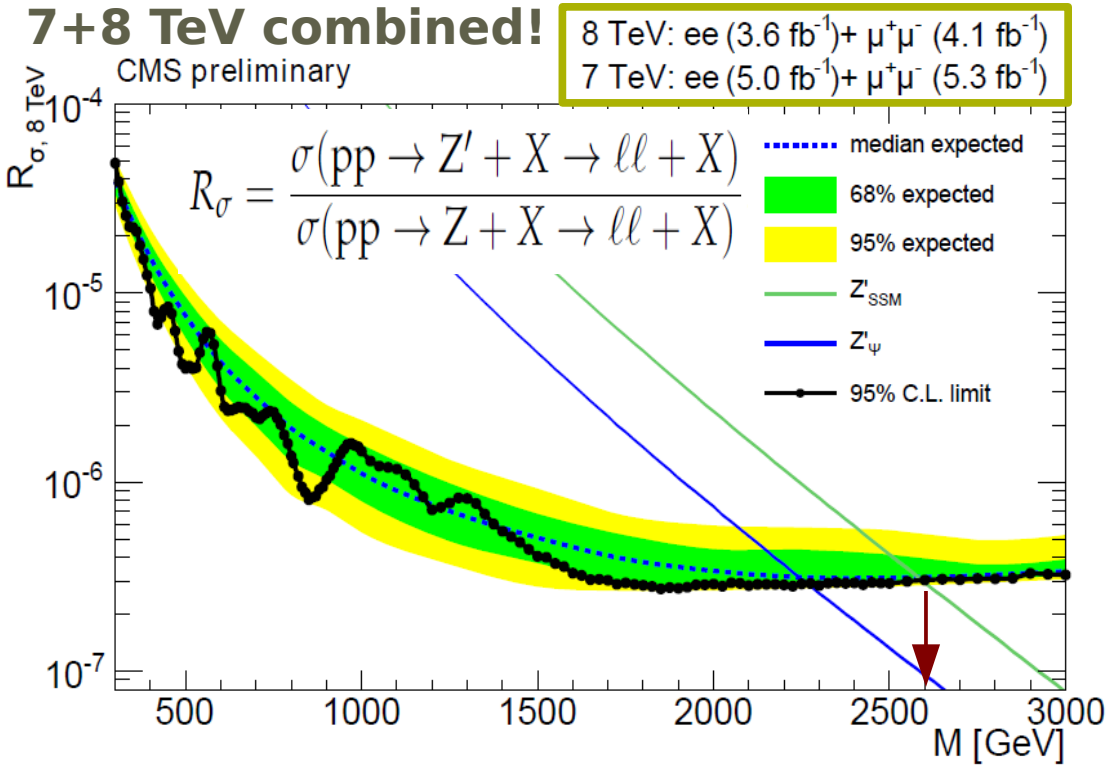
- Relative fractions fixed by theory cross sections
- The total background contribution is normalized to the data in a window around m_Z (CMS: $60 < m_{ll} < 120$ GeV)

Z' → ee / μμ – lower limits on the mass of the Z'

The m_{ll} distribution is fitted for the presence of a resonance to determine upper limits on

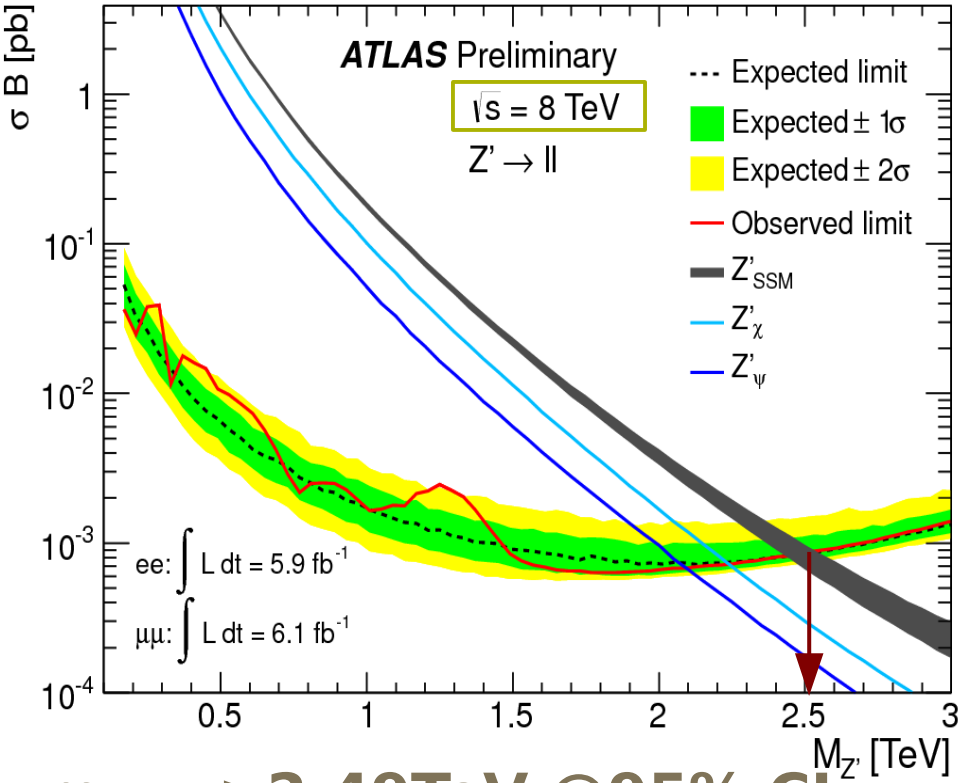
- the cross section times branching ratio (σB) → ATLAS
- the ratio of σB for signal and σB for SM Z boson → CMS

CMS-PAS-EXO-12-015



$m_{Z'_{SSM}}$>2.59TeV @95% CL

ATLAS-CONF-2012-007



$m_{Z'_{SSM}}$>2.49TeV @95% CL

$Z' \rightarrow \tau\tau$ – analysis strategy

$\tau \rightarrow e/\mu + \nu + \nu$

$\tau \rightarrow$ 1/3 charged hadrons + ν (+ neutral hadrons)

Mass reconstruction difficult due to presence of neutrino's

CMS

Decay channels:

$\tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$, $e\mu$

Effective visible mass:

$$M(\tau_1, \tau_2, E_T^{miss}) = \sqrt{(E_{\tau_1} + E_{\tau_2} + E_T^{miss})^2 - (\overrightarrow{p_{\tau_1}} + \overrightarrow{p_{\tau_2}} + \overrightarrow{E_T^{miss}})^2}$$

Fit the expected mass spectrum → limit

ATLAS

Decay channels:

$\tau_h\tau_h$, $\mu\tau_h$, $e\mu$

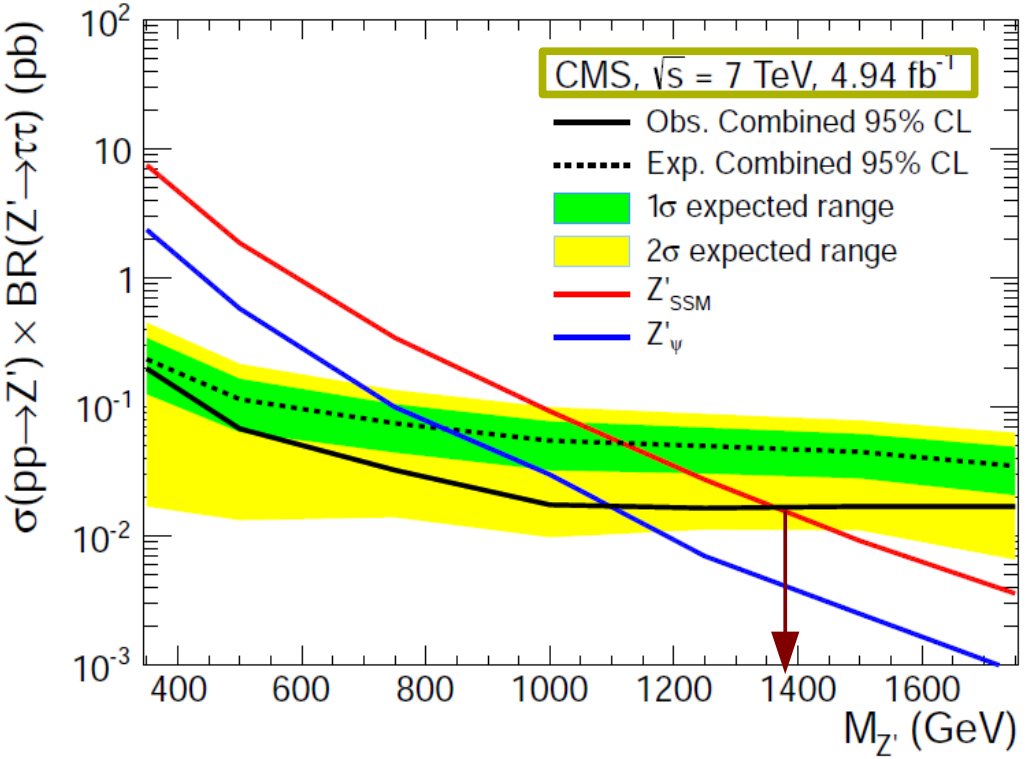
Transverse mass M_T*

Count events with M_T above threshold (optimized for each signal mass) → limit

* $$M_T = \sqrt{2p_{T,1}p_{T,2}(1-\cos\Delta\phi_{1,2}) + 2E_T^{miss}p_{T,1}(1-\cos\Delta\phi_{1,Miss}) + 2E_T^{miss}p_{T,2}(1-\cos\Delta\phi_{2,Miss})}$$

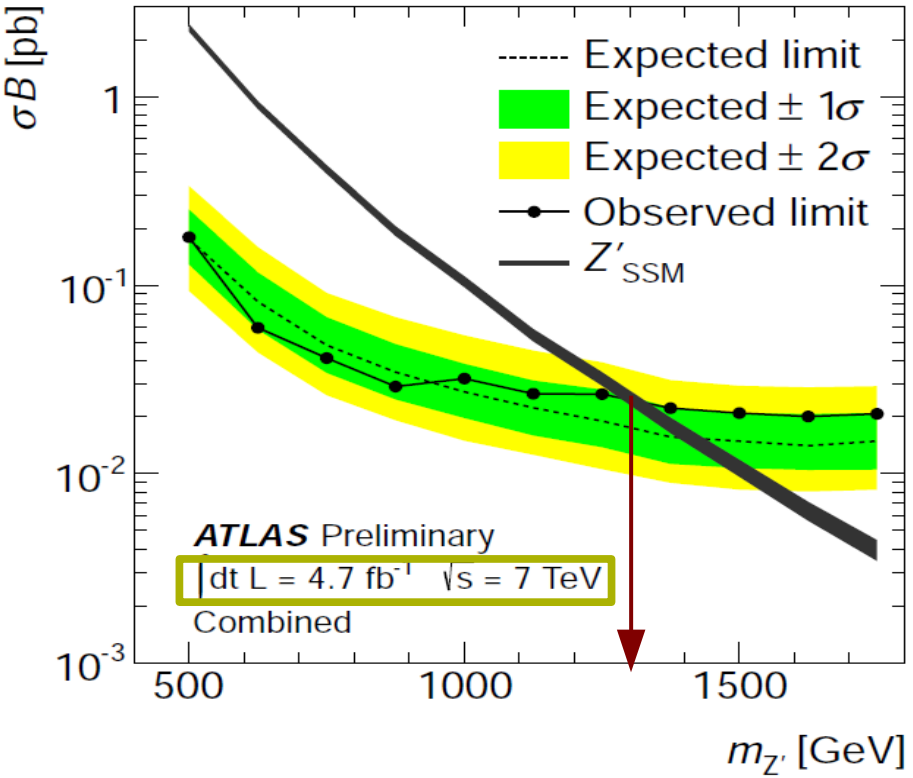
$Z' \to \tau\tau$ – lower limits on the mass of the Z'

arXiv:1206.1725



$m_{Z'_{SSM}}$>1.4 (1.15)TeV @95%CL

ATLAS-CONF-2012-067

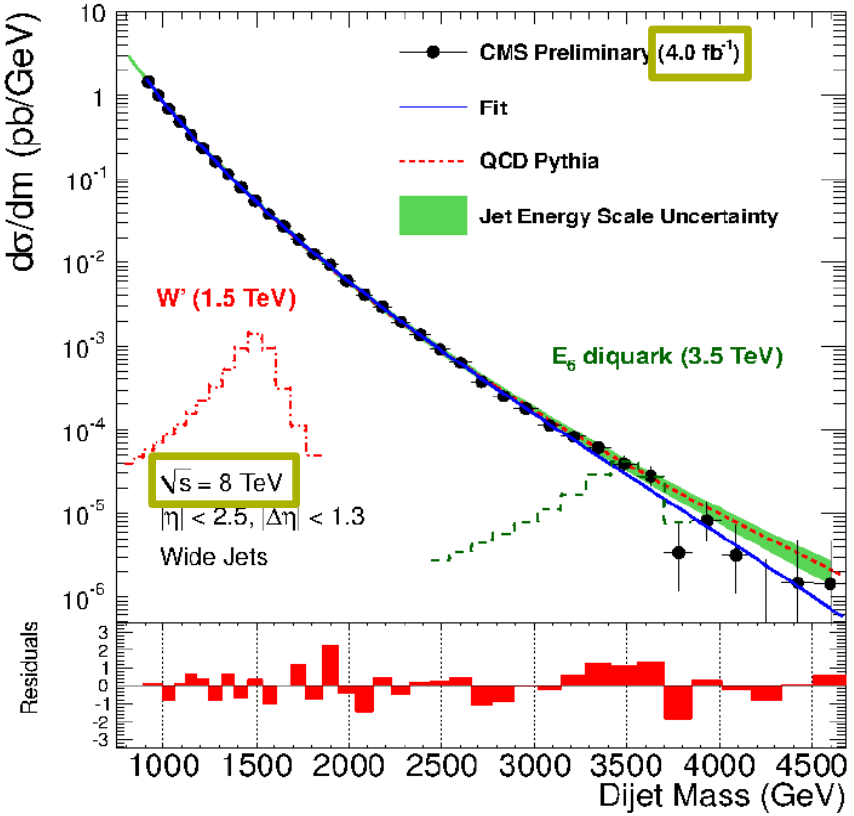


$m_{Z'_{SSM}}$>1.3 (1.4)TeV @95%CL

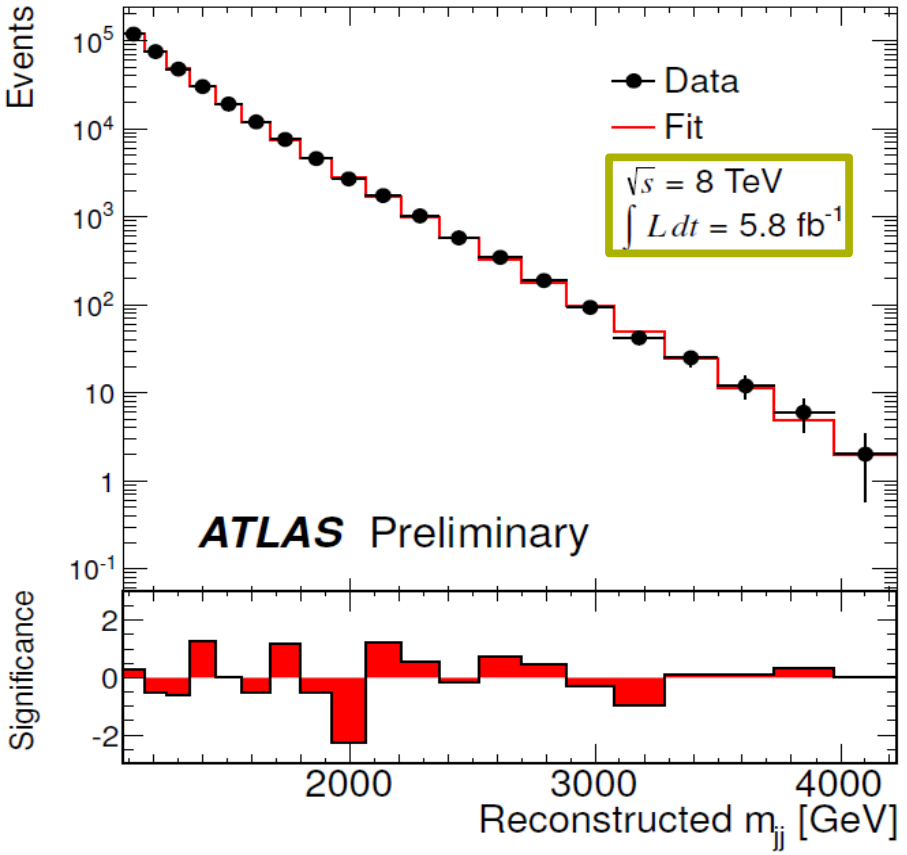
Dijet resonances, e.g. Z' → qq

Require 2 well-separated high-pT jets
CMS: reconstruct 2 'wide' jets using the two highest p_T jets and merge jets closer than R = 1.1

CMS-PAS-EXO-2012-016



ATLAS-CONF-2012-088

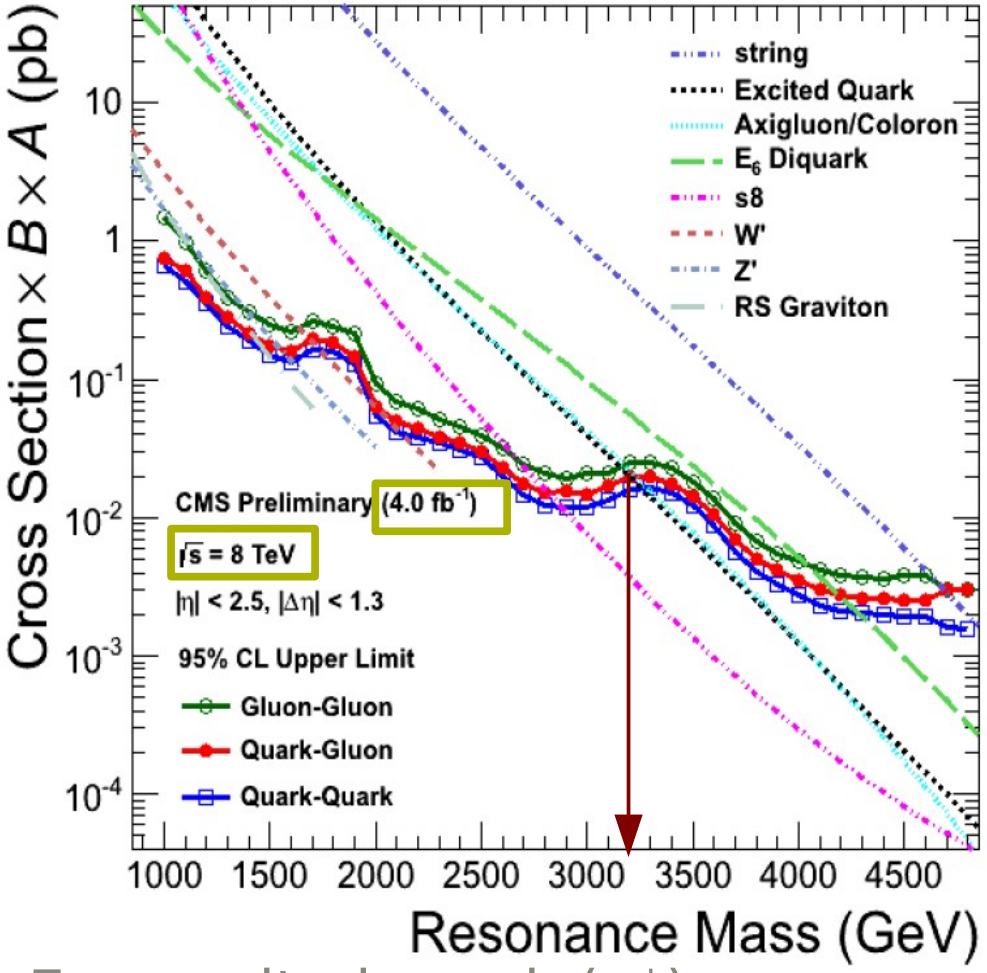


Fit with smooth functional form:

$$f(x) = p_1(1-x)^{p_2} x^{p_3 + p_4 \ln x} \qquad x \equiv m_{jj}/\sqrt{s}$$

Dijet resonances

CMS-PAS-EXO-2012-016



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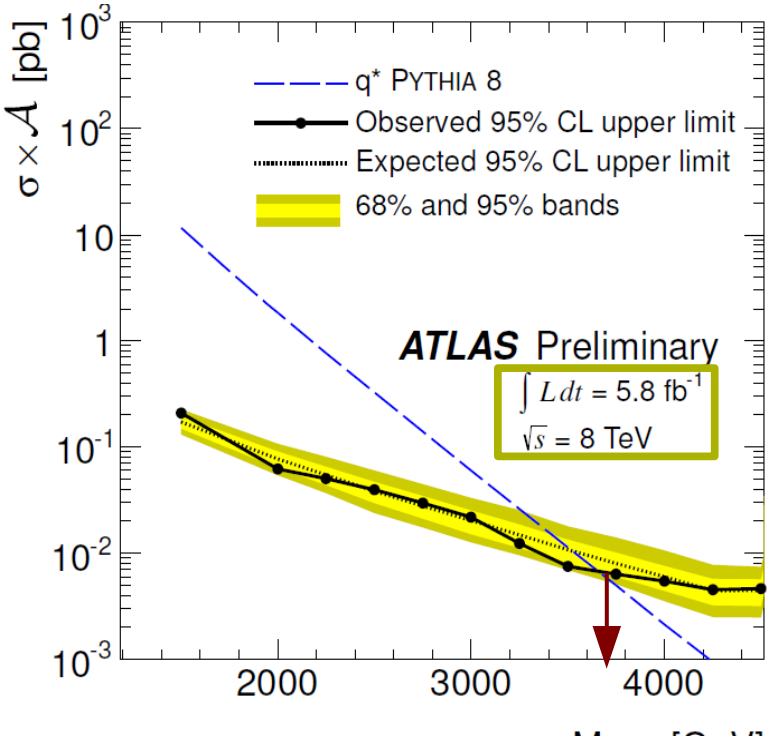
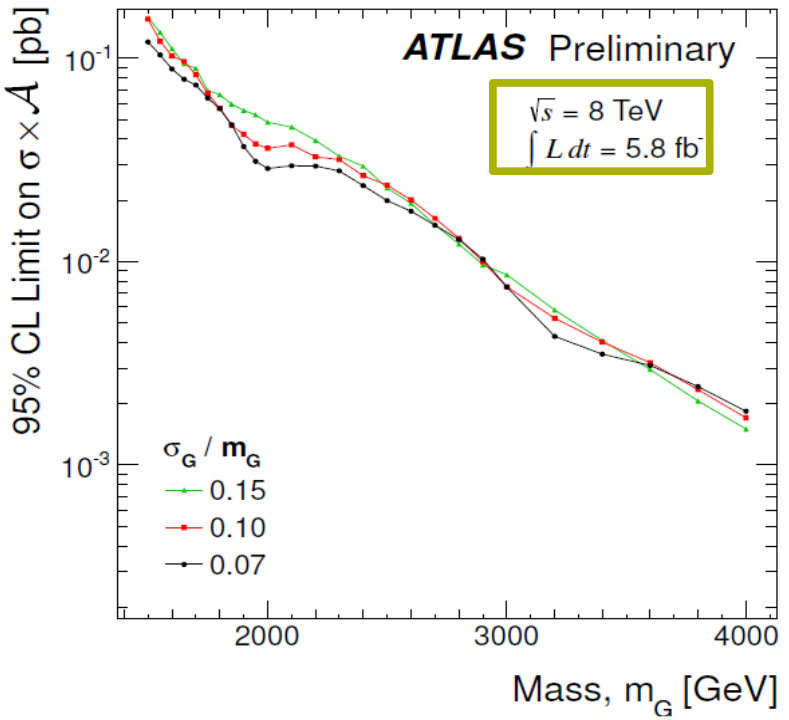




E.g. excited quark (q*)

ATLAS: $m_{q^*} > 3.79$ TeV (3.66)

@ 95% CL using Pythia 6 (8)

CMS: $m_{q^*} > 3.19$ TeV @ 95%CL

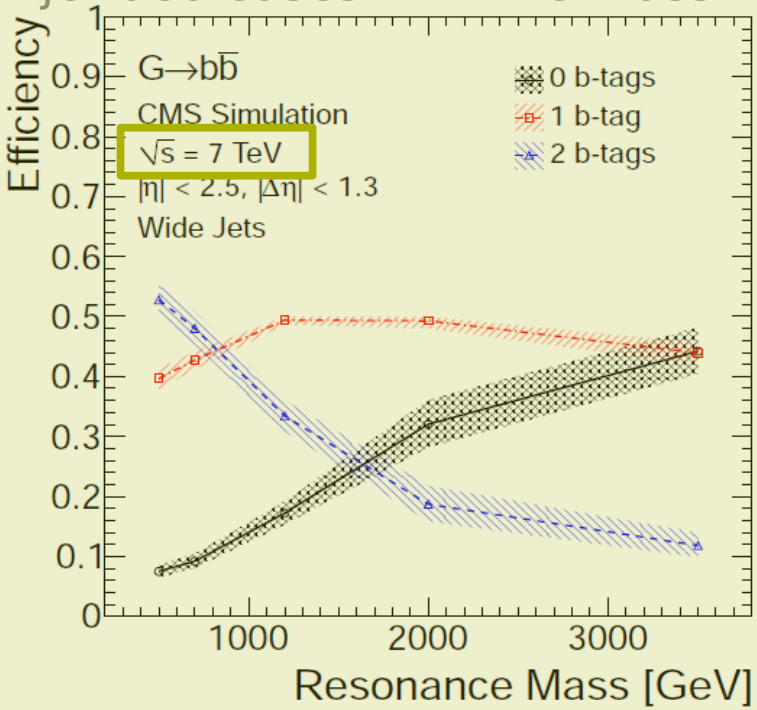
$1.0 < m_{Z'} < 1.6$ TeV excluded

b-jet resonances

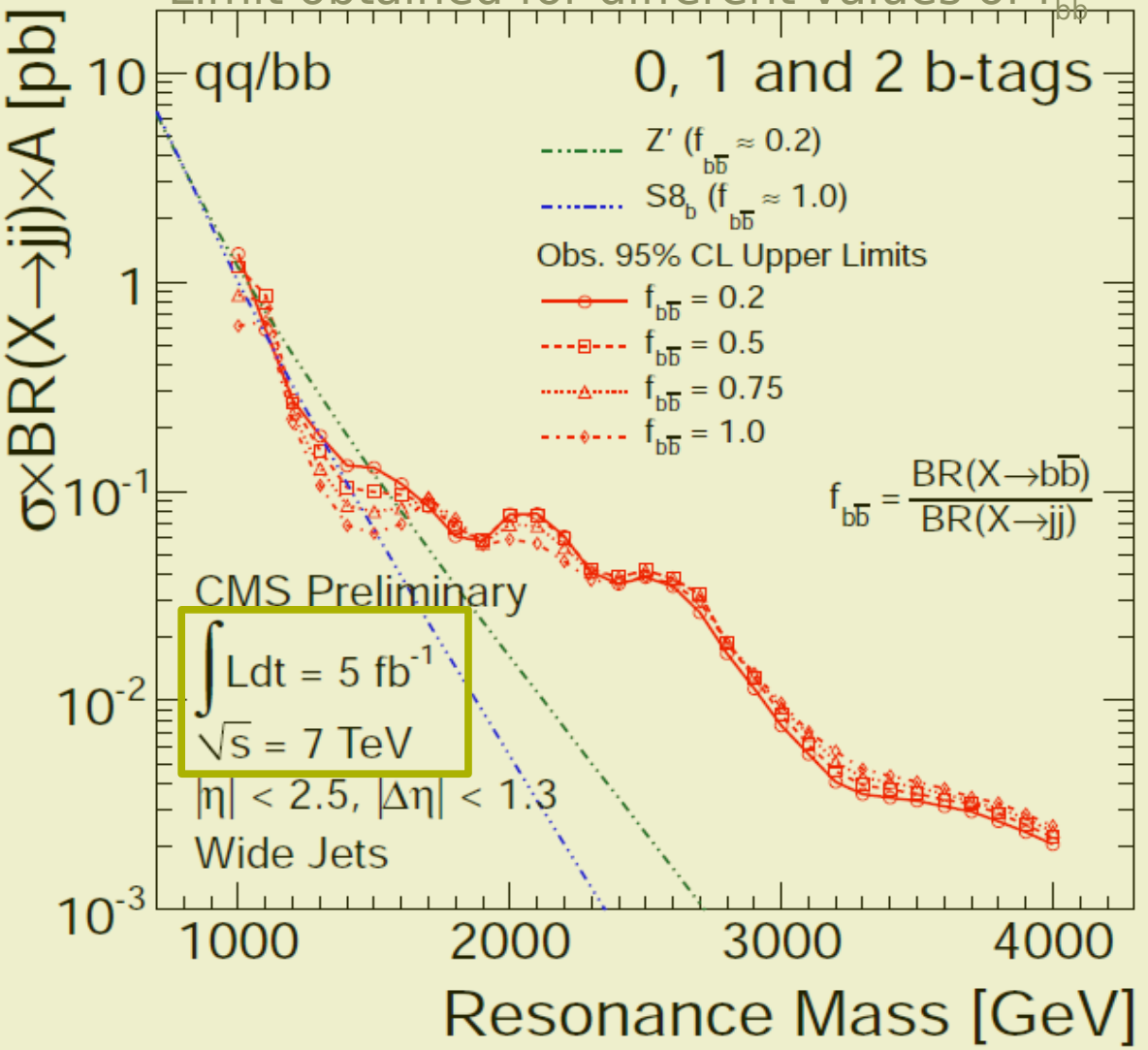
Require 2 'wide' jets

Only leading jet in each of the 2 wide jets is used for b-tagging → 3 subsamples (0,1,2)

Efficiency to correctly tag a b-jet decreases with the mass



Limit obtained for different values of $f_{b\bar{b}}$



1.04 < $m_{Z'}$<1.49 TeV excluded @ 95%CL

For large f_{bb}, upper limits < 2 TeV improve by up to 70%

W' models

Scenarios that involve a W' boson are:
- a left-right symmetric model
- model based on a new SU(2) sector
- W' as the lowest Kaluza-Klein mode of the W boson

Forward-backward asymmetry measured in ttbar events @ Tevatron
→ discrepancy with the SM expectation
→ could be explained by top-flavor-violating process, e.g. pp → W't → (tbarq)t (produced in association with top!)

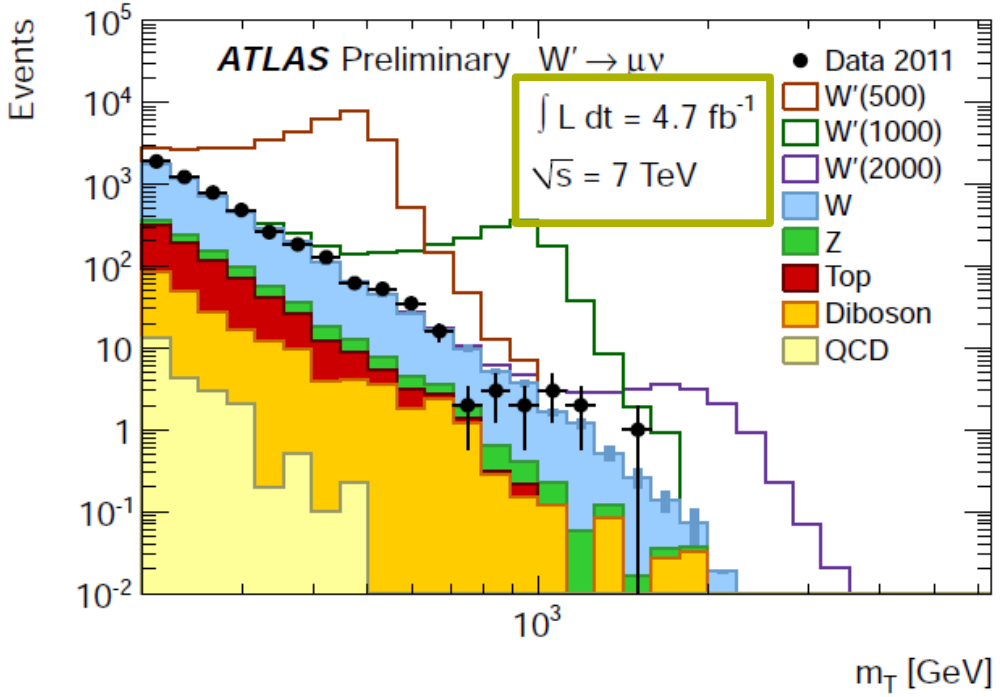
Sequential SM, assuming the same coupling with the fermions as in the SM:
→ search for e.g. W' → lν or W' → qq

W' → lν – strategy

Counting experiment after cut on transverse mass
(optimized for best expected exclusion limit vs signal mass)

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

ATLAS-CONF-2012-086



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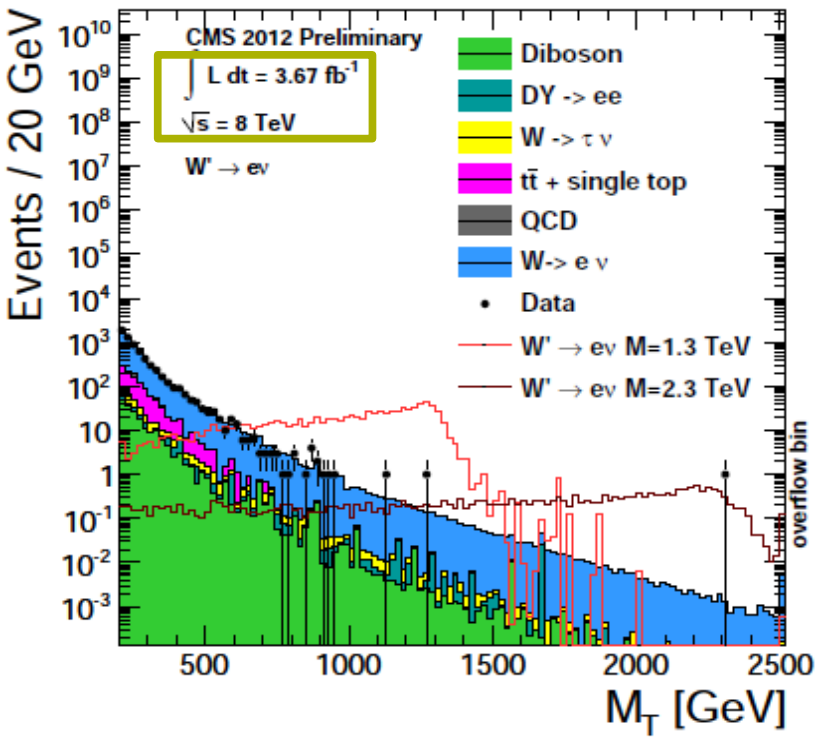
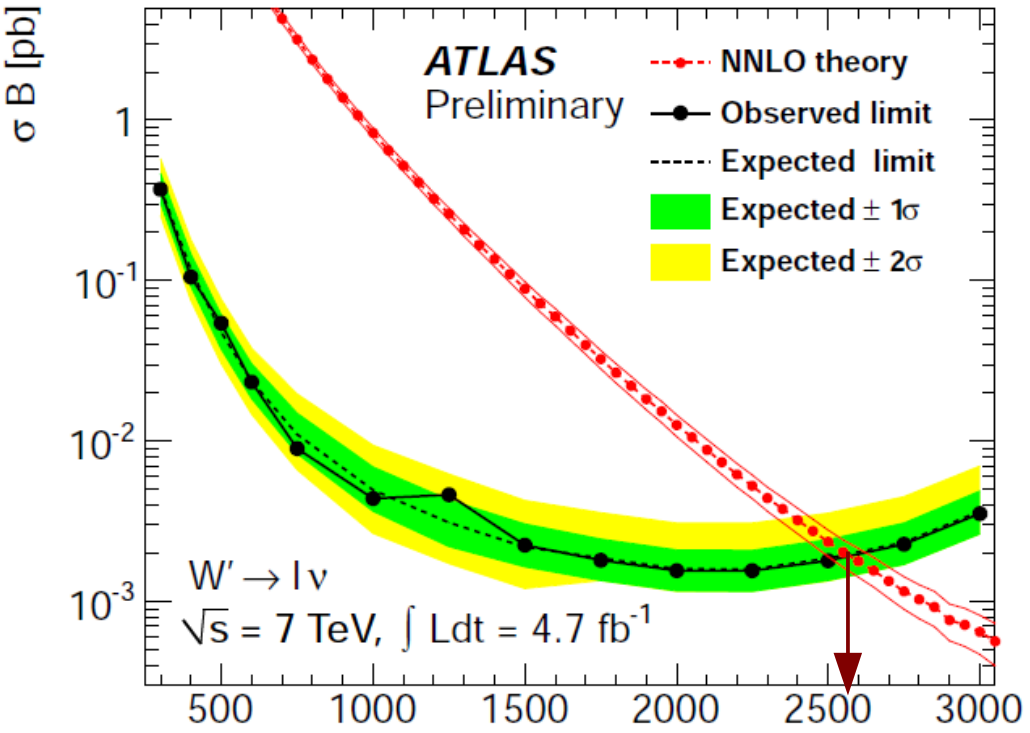


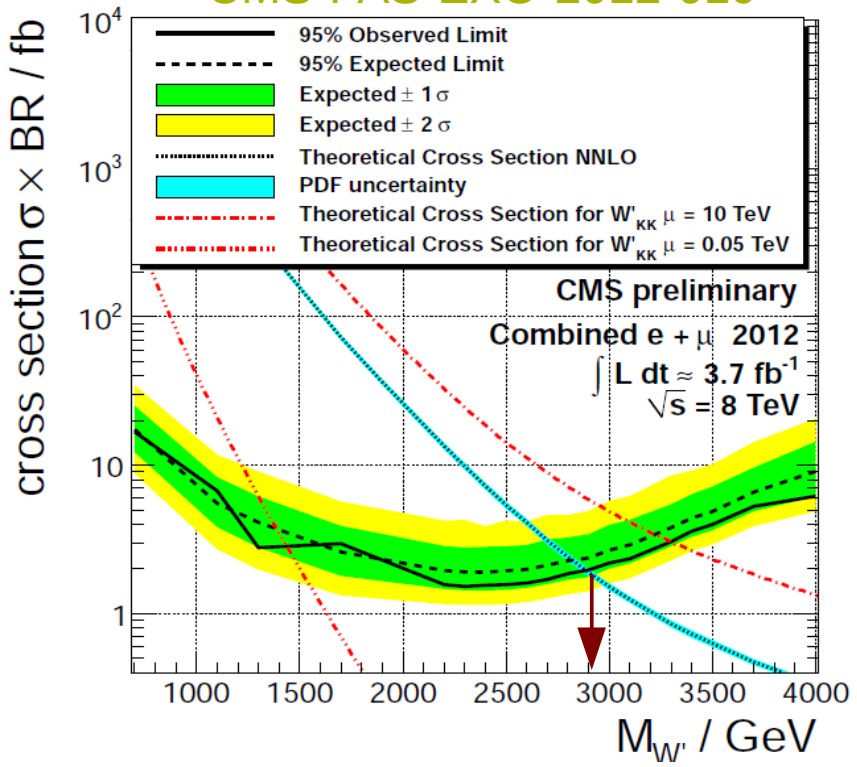
W' → lν – lower limits

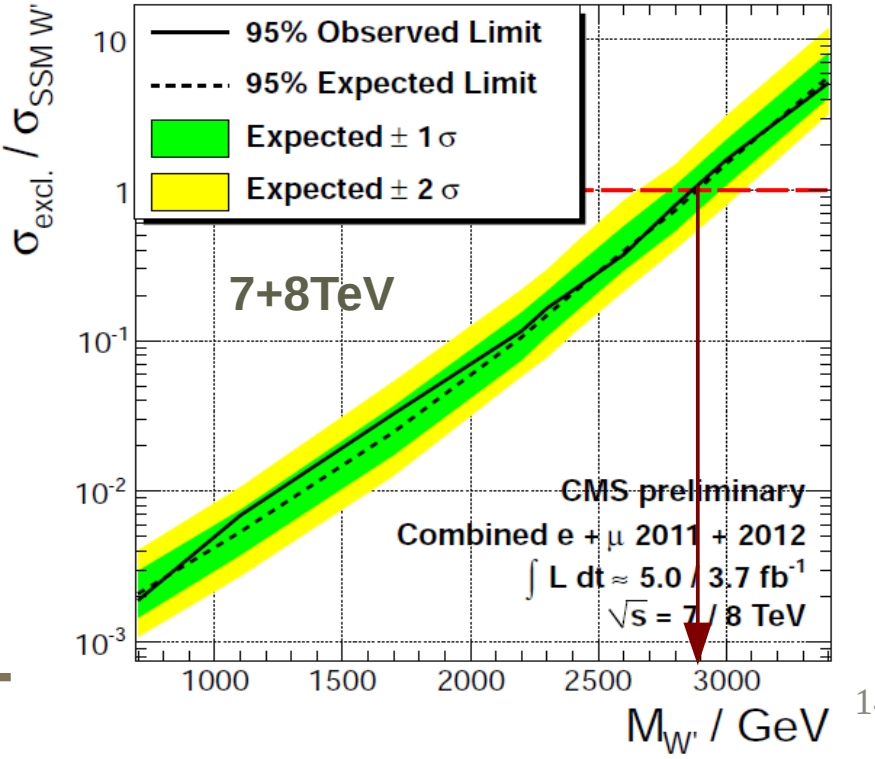
ATLAS-CONF-2012-086



$m_{W'SSM}$>2.55TeV @95%CL

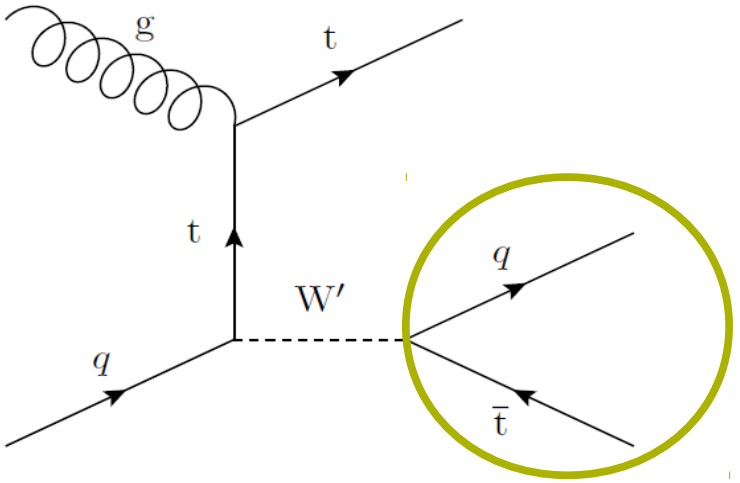
CMS-PAS-EXO-2012-010



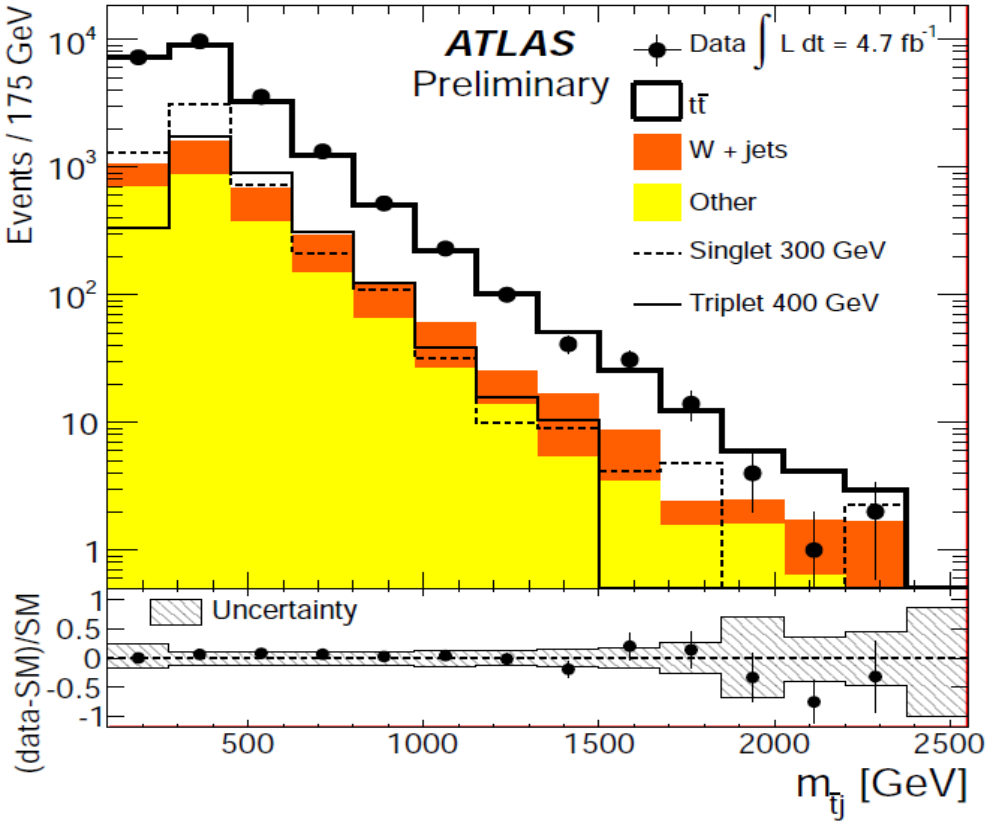


$m_{W'SSM}$>2.85TeV @95%CL

W' → tq – search strategy (e/μ + 5 jets)



ATLAS-CONF-2012-096



Reconstruct m_{tj}:
jet-quark assignment!

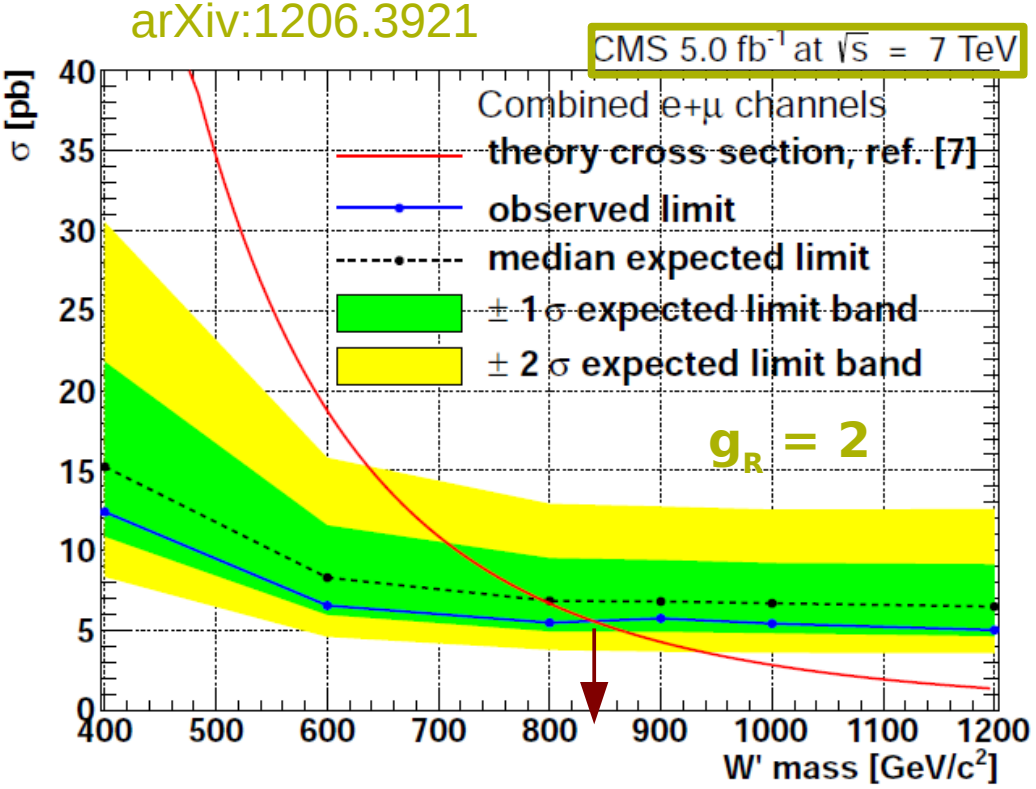
ATLAS:
- kinematic likelihood fitter using m_W & m_t
- remaining jets are paired with top quark
→ combinations with largest masses chosen

CMS:
- chose jets with mass closest to (m_W and)m_t
- highest p_T jet combined with t and tbar

W' → tq – lower limits

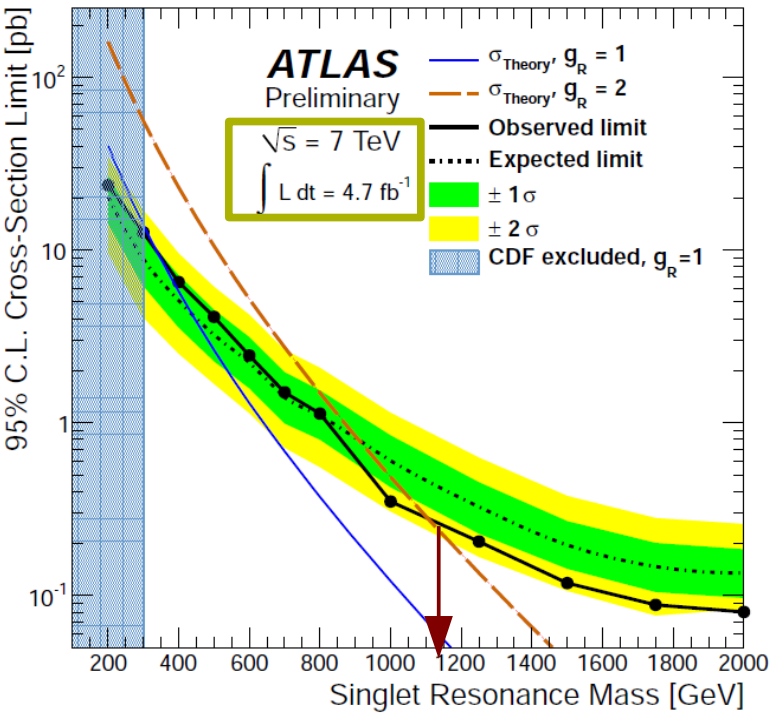
Counting experiment
after cut on m_{tj}

arXiv:1206.3921

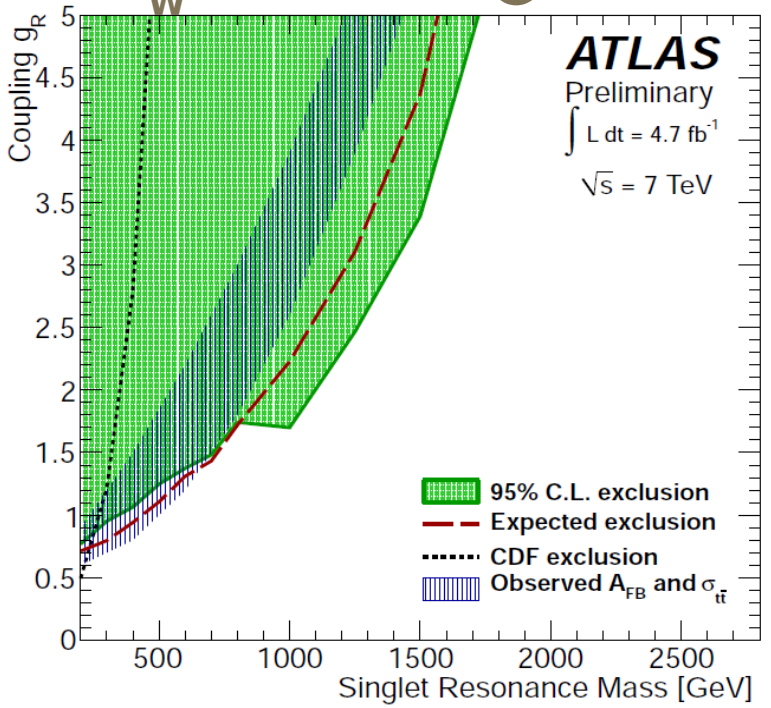


$m_{W'}$>840GeV @95%CL

ATLAS-CONF-2012-096



$m_{W'}$>1.1TeV @95%CL



Heavy neutrino models

Neutrino oscillations → $m_\nu \neq 0$

→ clear indication of physics beyond the Standard Model

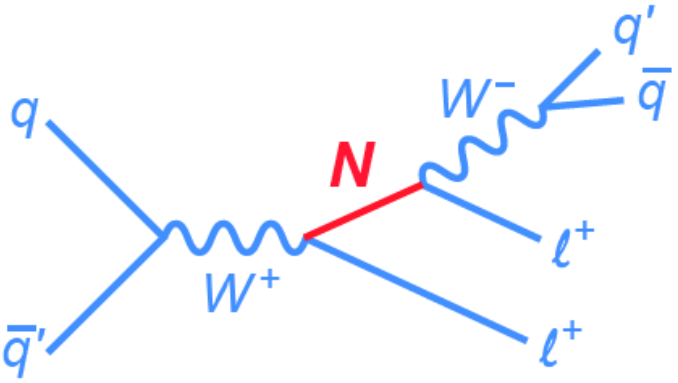
GUT models predict at least 1 heavy Majorana neutrino
→ neutrino mass through see-saw mechanism

Majorana neutrino's allow interactions violating lepton and lepton-flavour numbers → same-sign leptons!

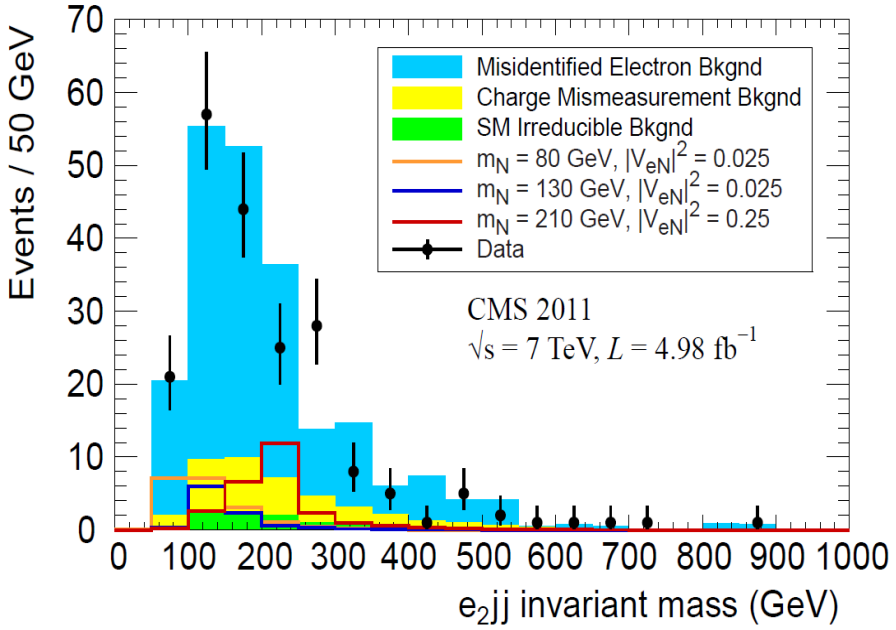
Different models:
- Left-right symmetric model (LRSM) → right-handed W boson (W_R) from new gauge group
- Isosinglet Majorana N

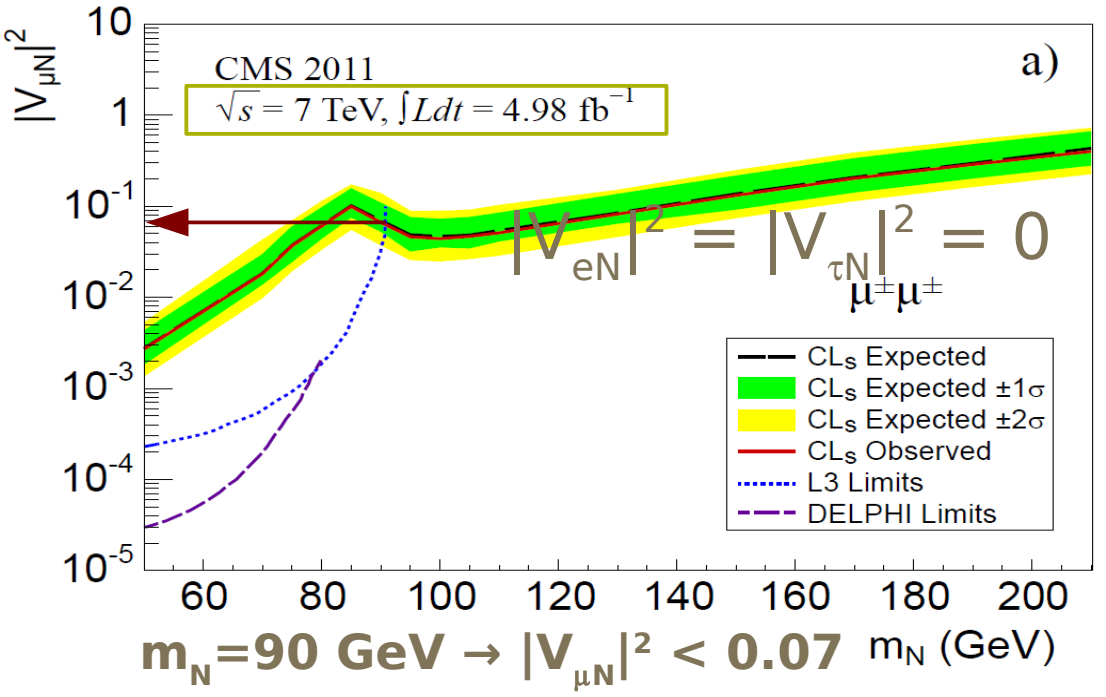
Signature: 2 leptons + at least 2 jets

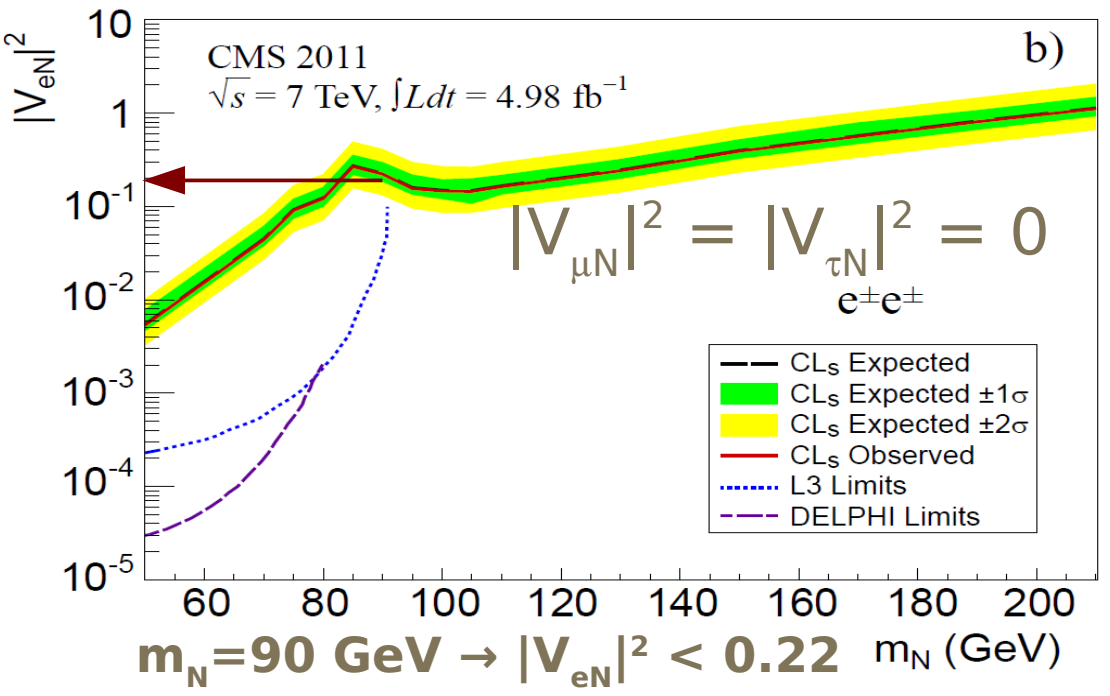
Heavy isosinglet Majorana neutrino



Model-independent:
→ m_N and V_{lN}







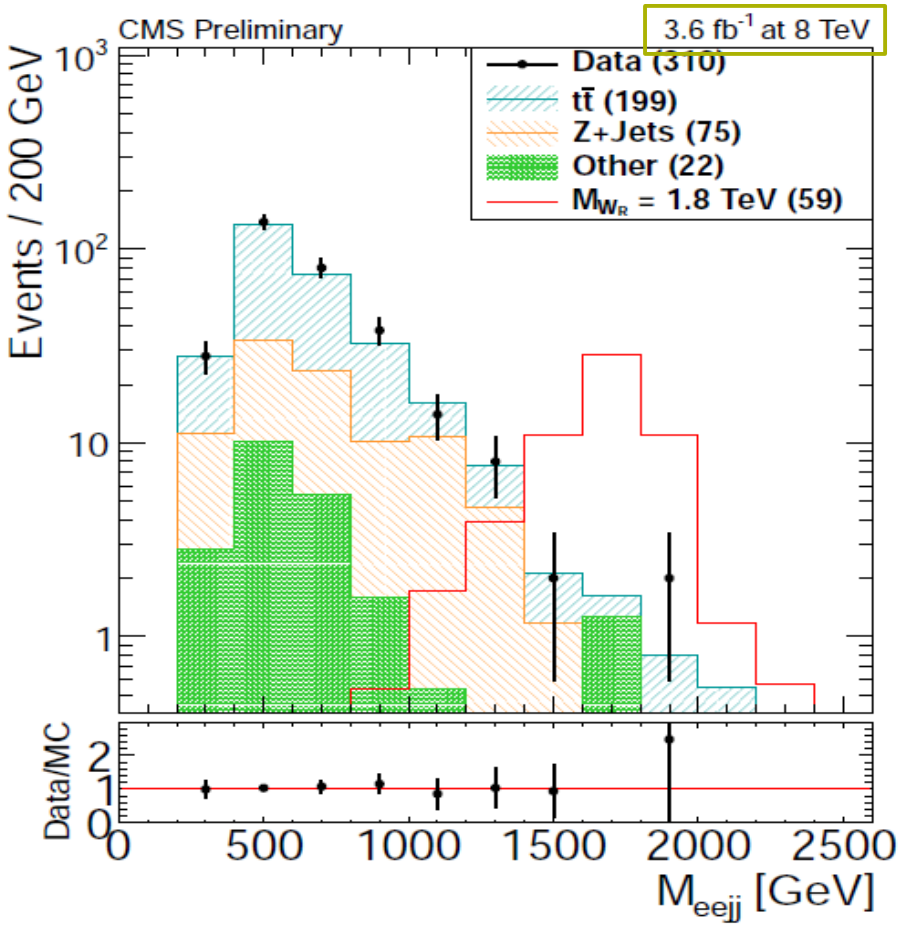
Heavy neutrino + W_R

$$W_R \to \ell_1 N_\ell \to \ell_1 \ell_2 W_R^* \to \ell_1 \ell_2 q q' \to \ell_1 \ell_2 jj$$

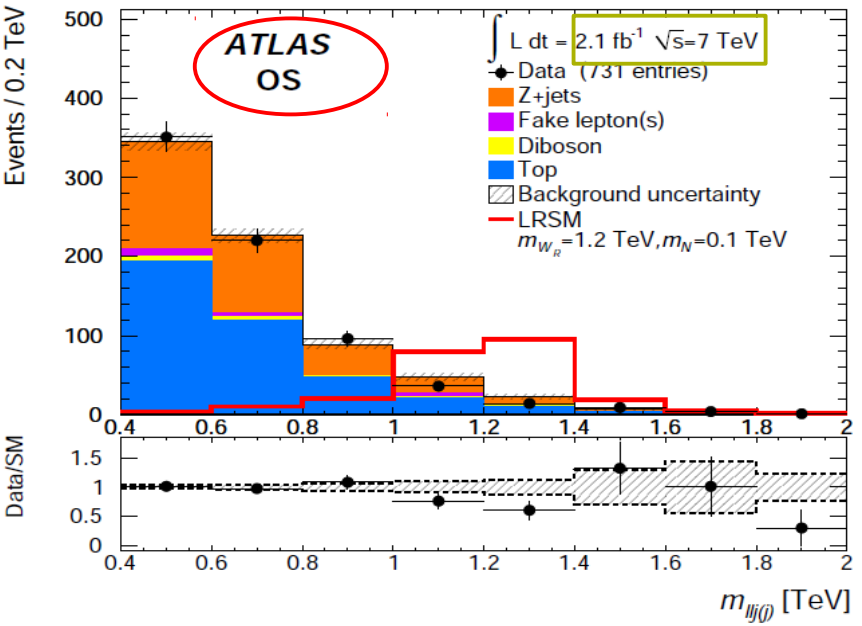
Reconstruct m_{W_R} and m_N:

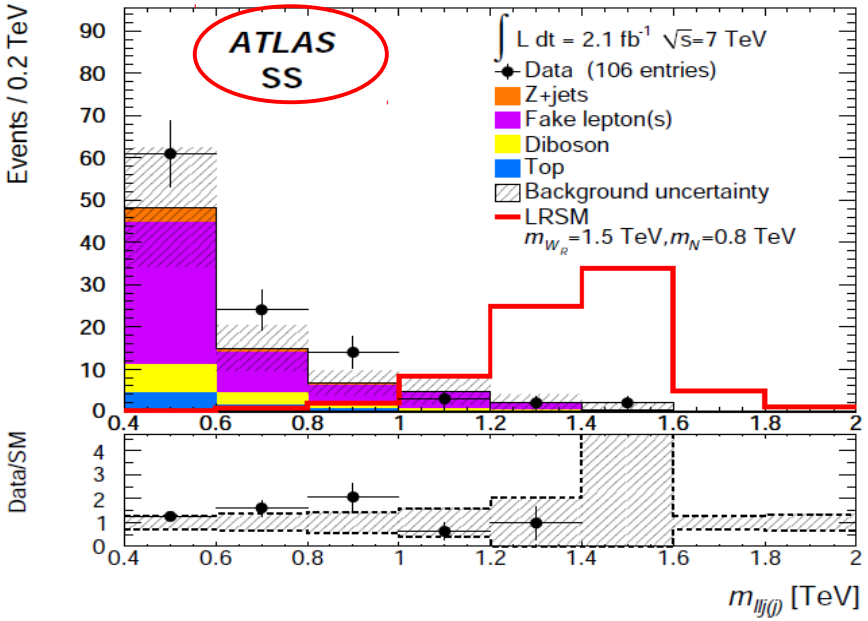
2 leptons + 2(1) highest p_T jet(s)

CMS-PAS-EXO-2012-017



arXiv:1203.5420



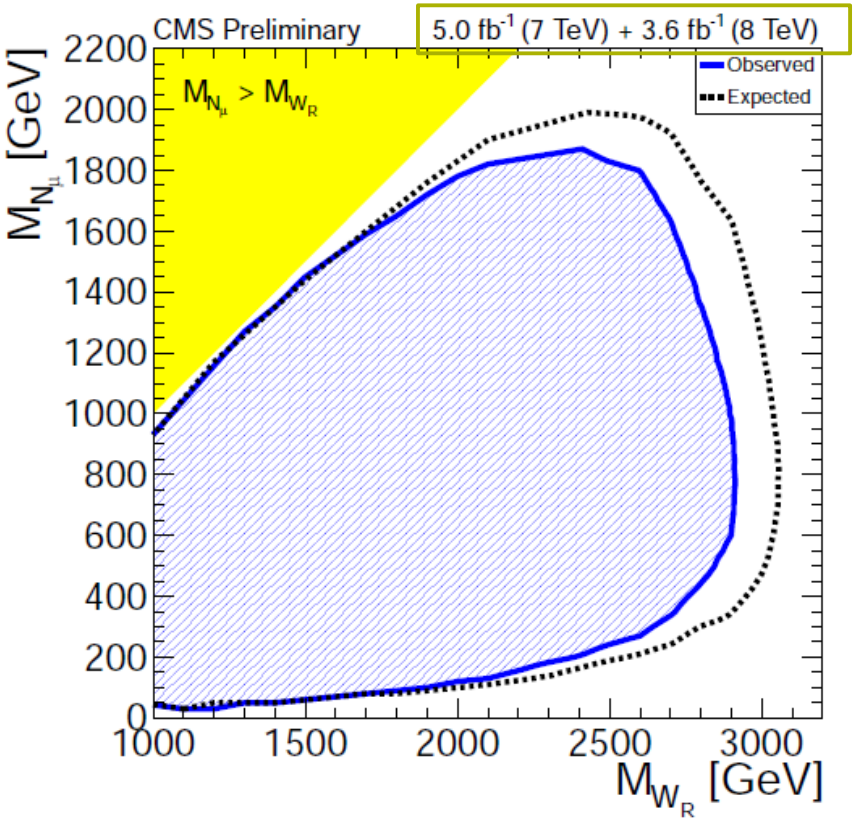


Heavy neutrino + W_R

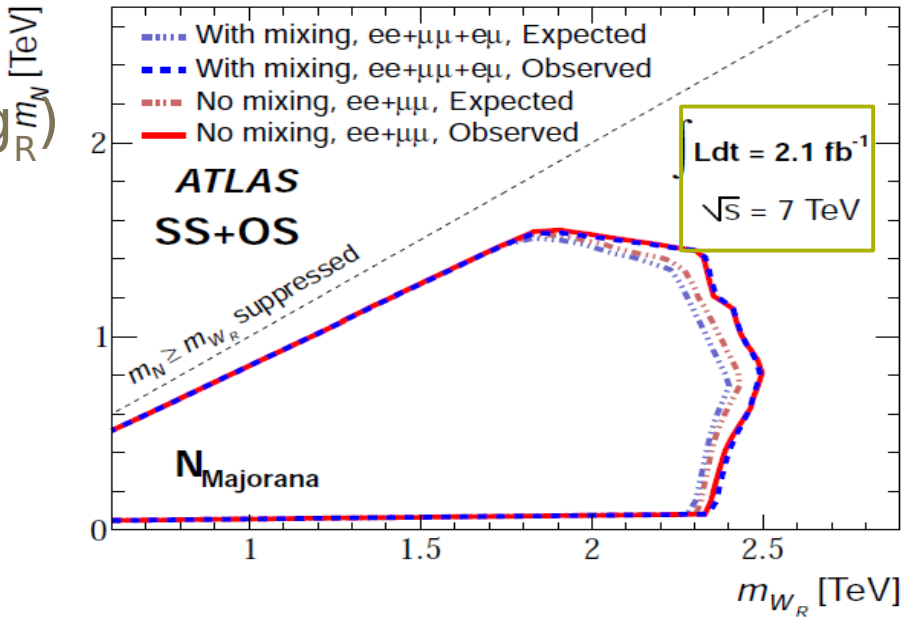
Left-right symmetric model ($g_L = g_R$)

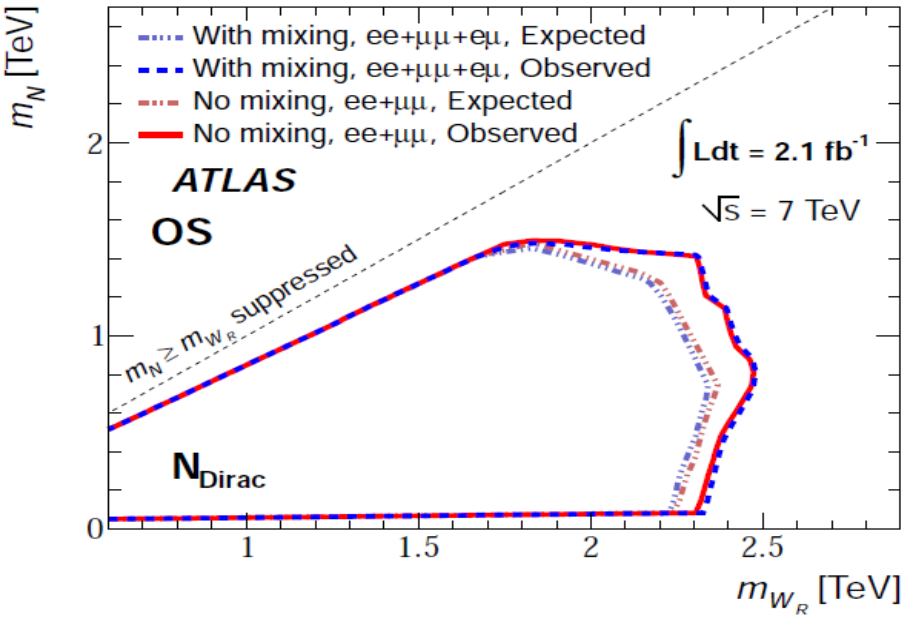
Template fitting of m_{W_R} and m_N

CMS-PAS-EXO-2012-017



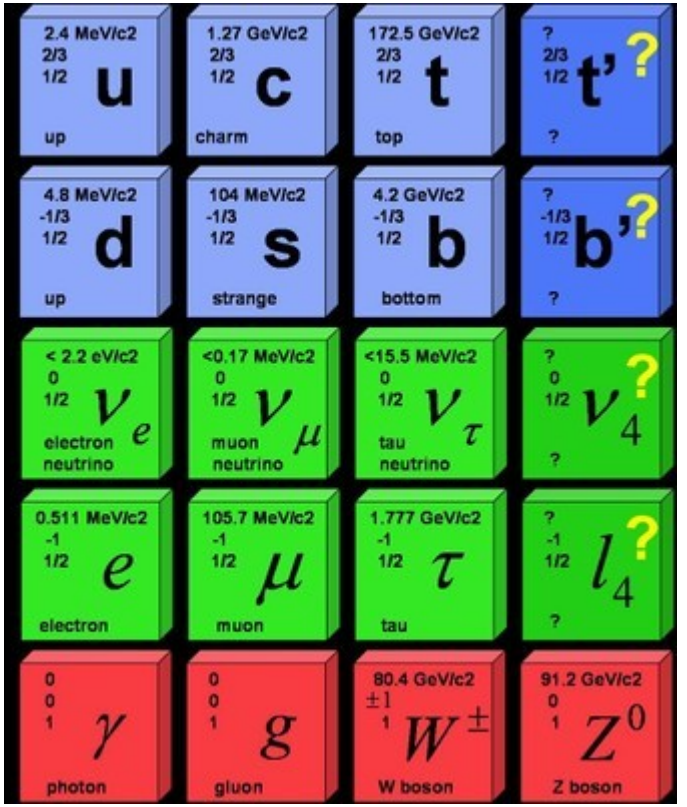
arXiv:1203.5420





A fourth generation of quarks

3 generations of fermions → fourth?
→ sequential fourth generation
→ vector-like quarks (T→tZ or B→ bZ)



until recently allowed by electroweak precision measurements

New results:
→ combined search for singly and pair-produced quarks (t'→bW, b'→tW)
→ search for B→bZ, dilepton channel
→ sequential-fourth generation down-type quark (b'→tW) and vector-like up-type quarks (T→tZ), single lepton channel
→ heavy partner of the top quark with charge 5/3

Search for single & pair-produced t' and b'

arXiv:1209.1062

$$V_{CKM}^{4\times4} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{ub'} \\ V_{cd} & V_{cs} & V_{cb} & V_{cb'} \\ V_{td} & V_{ts} & V_{tb} & V_{tb'} \\ V_{t'd} & V_{t's} & V_{t'b} & V_{t'b'} \end{pmatrix} = \begin{pmatrix} \mathcal{O}(1) & \mathcal{O}(0) & \mathcal{O}(0) & 0 \\ \mathcal{O}(0) & \mathcal{O}(1) & \mathcal{O}(0) & 0 \\ \mathcal{O}(0) & \mathcal{O}(0) & \sqrt{A} & \sqrt{1-A} \\ 0 & 0 & -\sqrt{1-A} & \sqrt{A} \end{pmatrix}$$

Signal processes

- $t'b \to bWb$;
- $t'\bar{t}' \to bWbW$;
- $b't \to tWbW \to bWWbW$;
- $b't' \to tWbW \to bWWbW$;
- $b'\bar{b}' \to tWtW \to bWWbWW$

→ Require at least 1 W → lν (l = e,μ)
Reconstruct W → qq

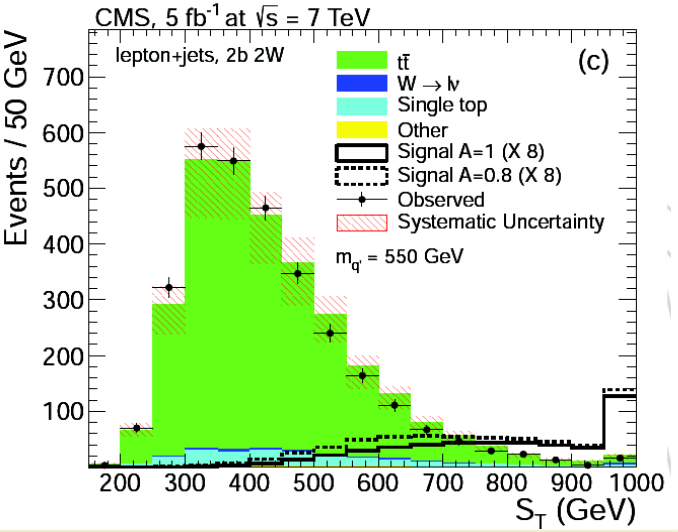
subsample	observable
single-lepton 1W	S_T
single-lepton 2W	S_T and m_{bW}
single-lepton 3W	S_T
single-lepton 4W	event yield
same-sign dilepton	event yield
trilepton	event yield

$$S_T = \not{E}_T + p_T^{\ell} + p_T^{b} + p_T^{j} + \sum_{i=0}^{N} p_T^{W_{q\bar{q}}^{i}}$$

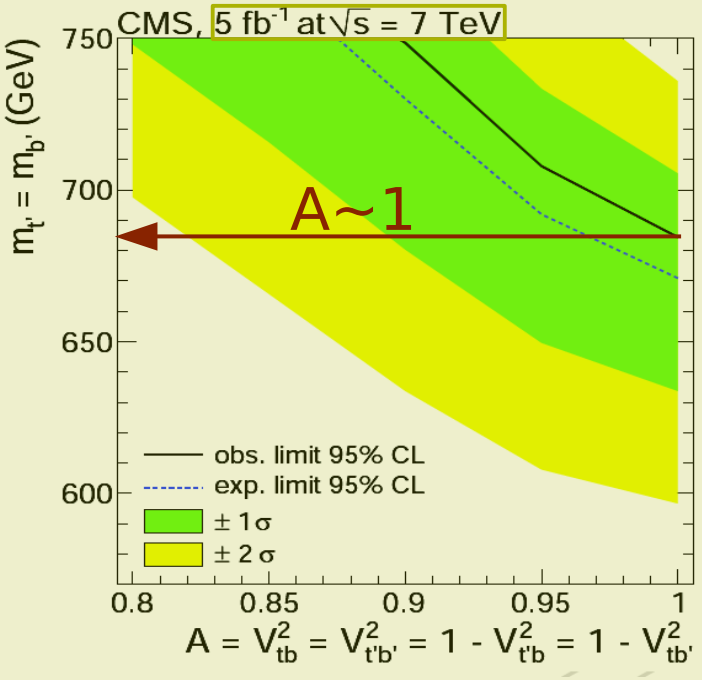
Limit for single & pair-produced t' and b'

Example of S_T distribution for single-lepton 2b 2W subsample

Calculate limit for all subsamples combined (template fitting)



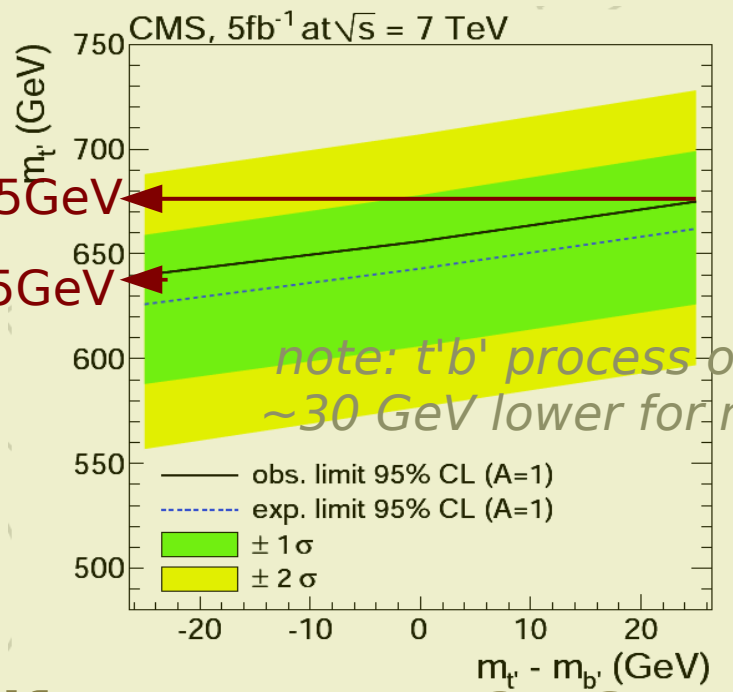
degenerate mass versus A



$m_{t'} = m_{b'} + 25\text{GeV}$

$m_{t'} = m_{b'} - 25\text{GeV}$

$m_{t'}$ versus $m_{t'} - m_{b'}$ (A=1)



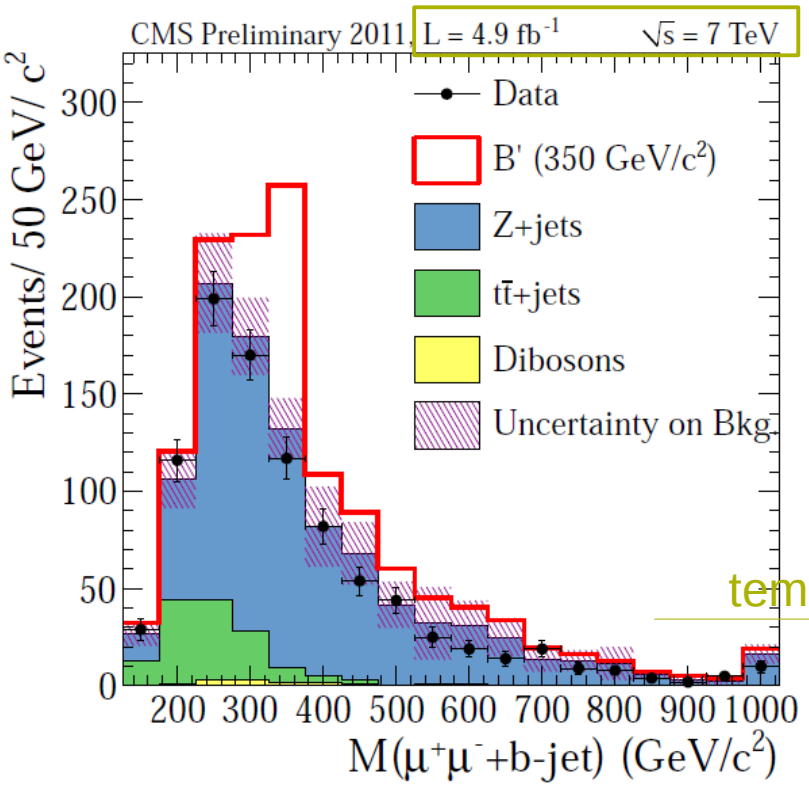
note: t'b' process omitted
~30 GeV lower for $m_{t'}=m_{b'}$

For A~1:
$m_{t'} = m_{b'} > 685$ GeV @ 95% CL

if $m_{t'} - m_{b'} = \pm 25$ GeV
→ limit shifts ± 20 GeV

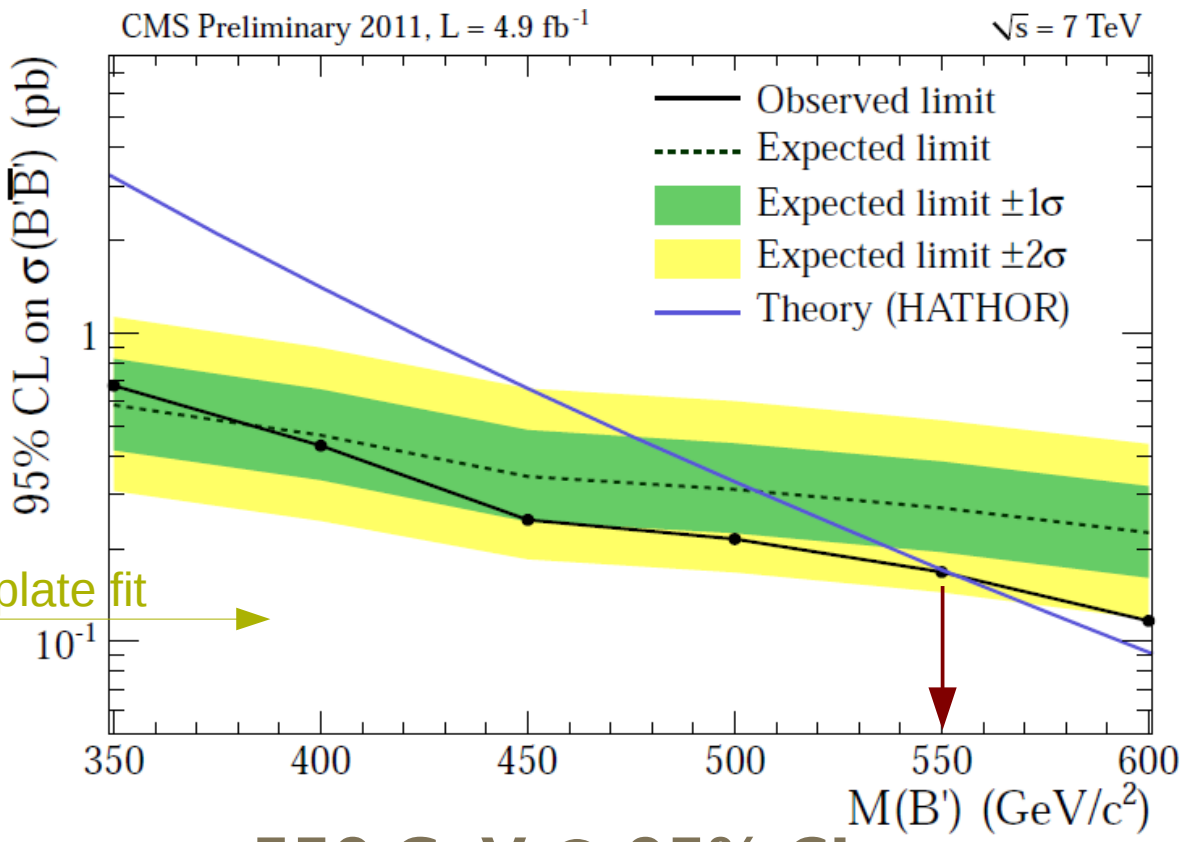
B'B' → bZbZ (Z → ee/μμ)

- Assume BF(B' → bZ) = 100%
- Z boson: lepton pair with same flavour, opposite charge and 60 GeV < m_{ll} < 120 GeV
- ≥ 1 b-tagged jet, p_T > 65 GeV & ≥ 1 Z boson, p_T > 95 GeV



highest p_T Z and b-jet

template fit



$m_{B'}$>550 GeV @ 95% CL

b' → tW and T → tZ

CMS-PAS-B2G-12-004

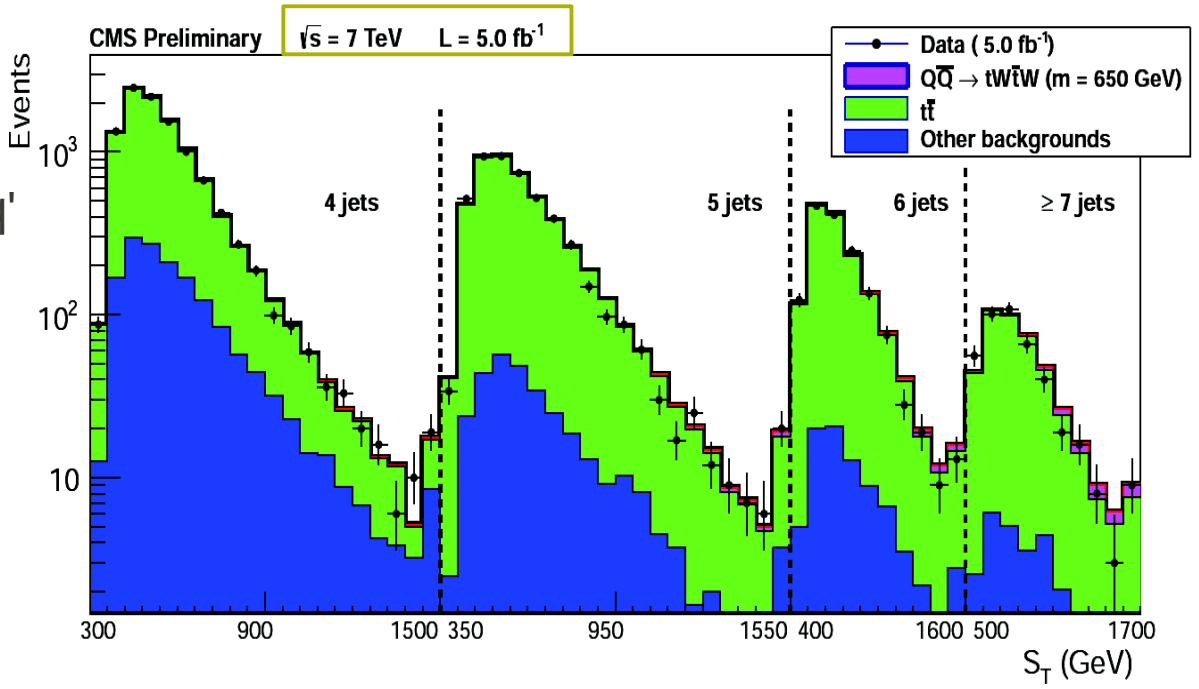
$TT \to tZtZ \to bWZbWZ \to b\ l\nu\ qq'\ b\ qq'\ qq'$

$b'b' \to tWtW \to bWWbWW \to b\ qq'\ l\nu\ b\ qq'\ qq'$

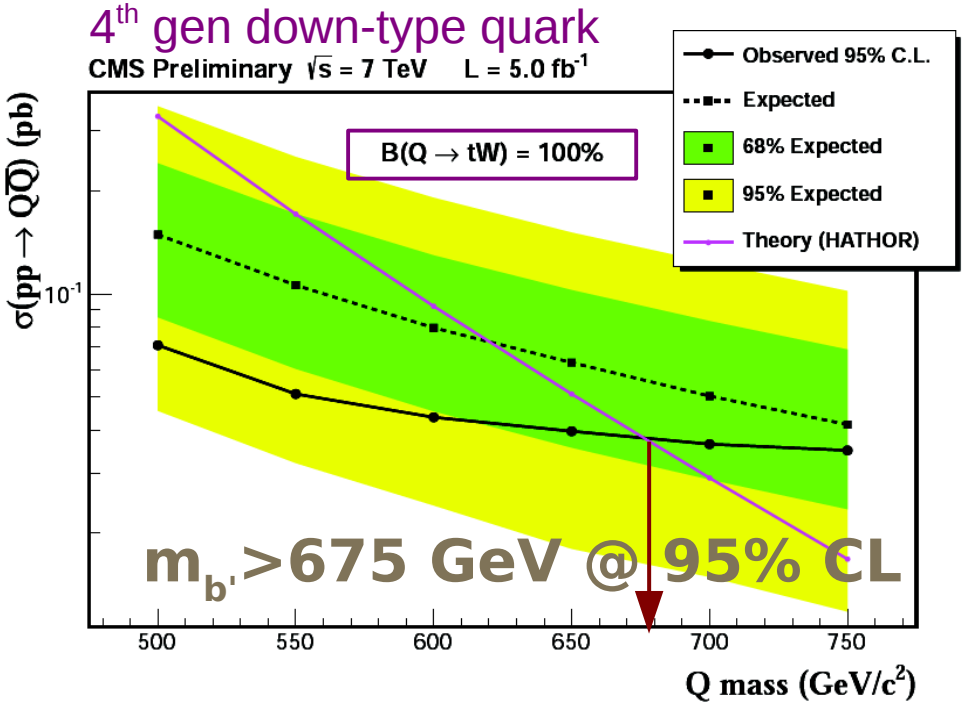
=1 lepton (e or μ)

≥ 4 jets (≥ 1 b-tag)

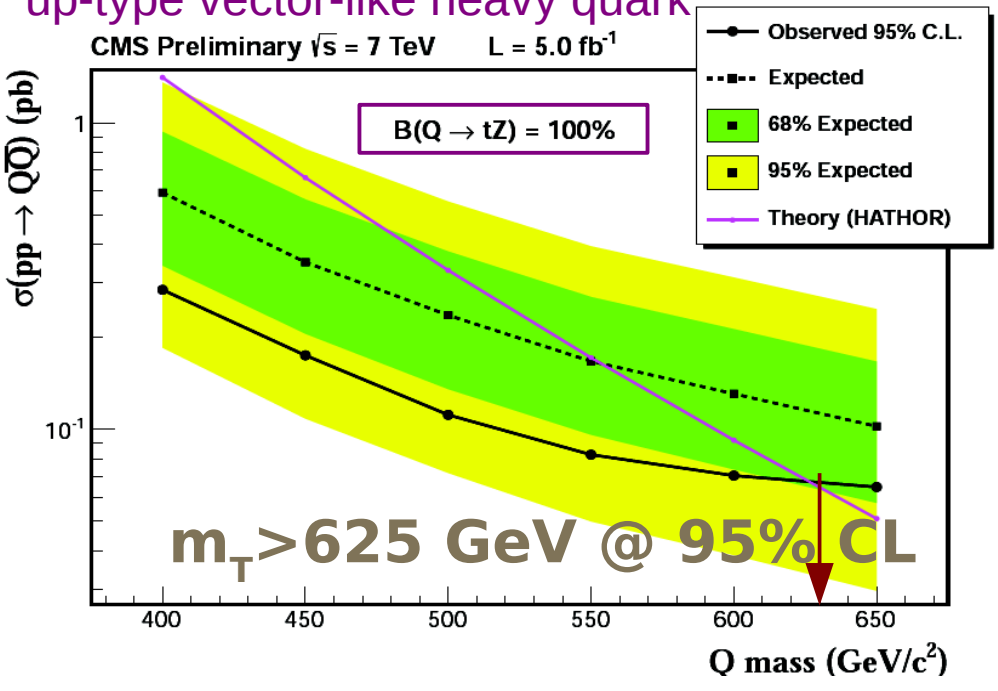
Reconstruct S_T and perform a template fit to calculate the limit



4th gen down-type quark



up-type vector-like heavy quark

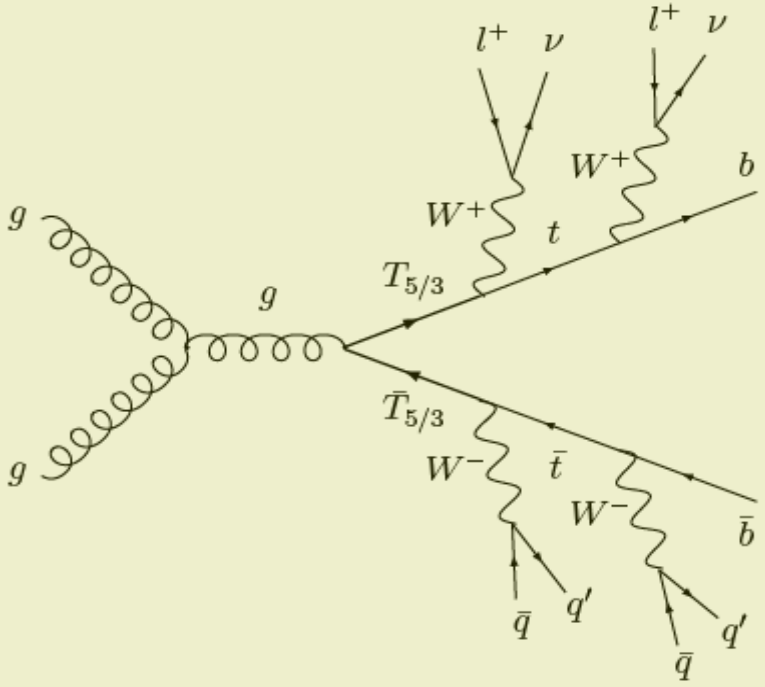


Heavy partner of top quark with charge 5/3

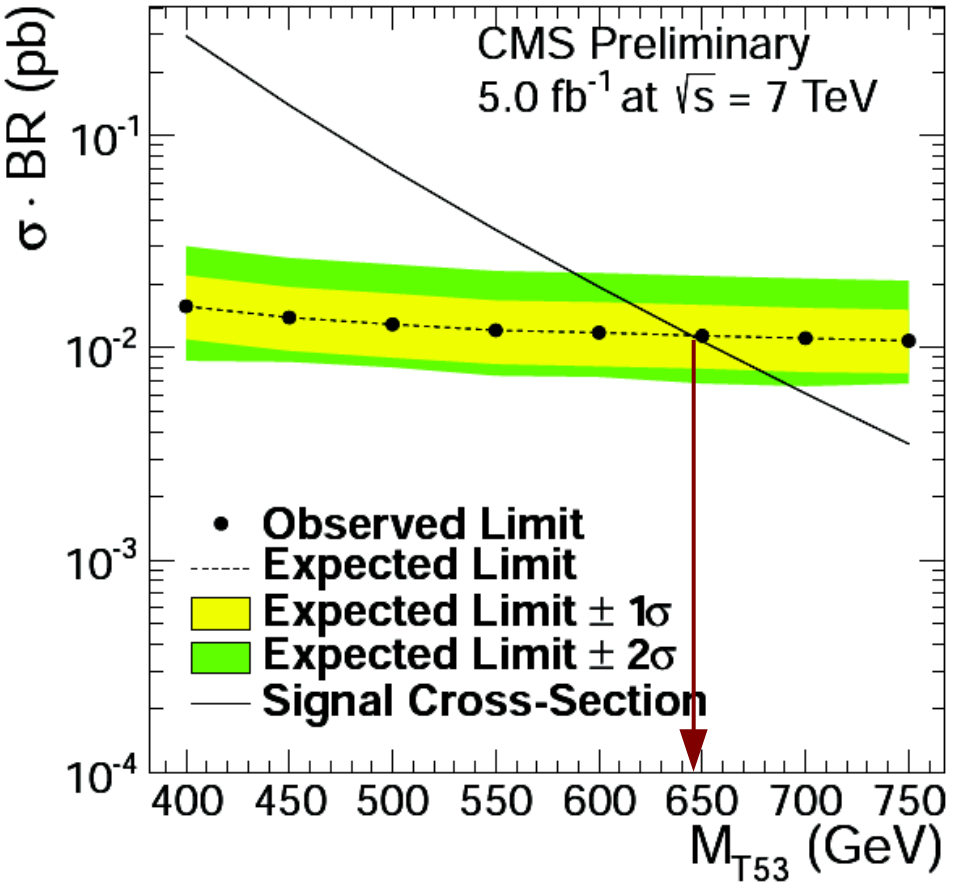
Assumptions:

- $m_B > m_{T5/3}$ (Mrazek & Wulzer)
- $BF(T^{5/3} \rightarrow tW) = 100\%$

Upper limits on σ*BR are derived using the event yields from the ee, eμ, μμ subsamples



2 same-sign leptons + 6 jets

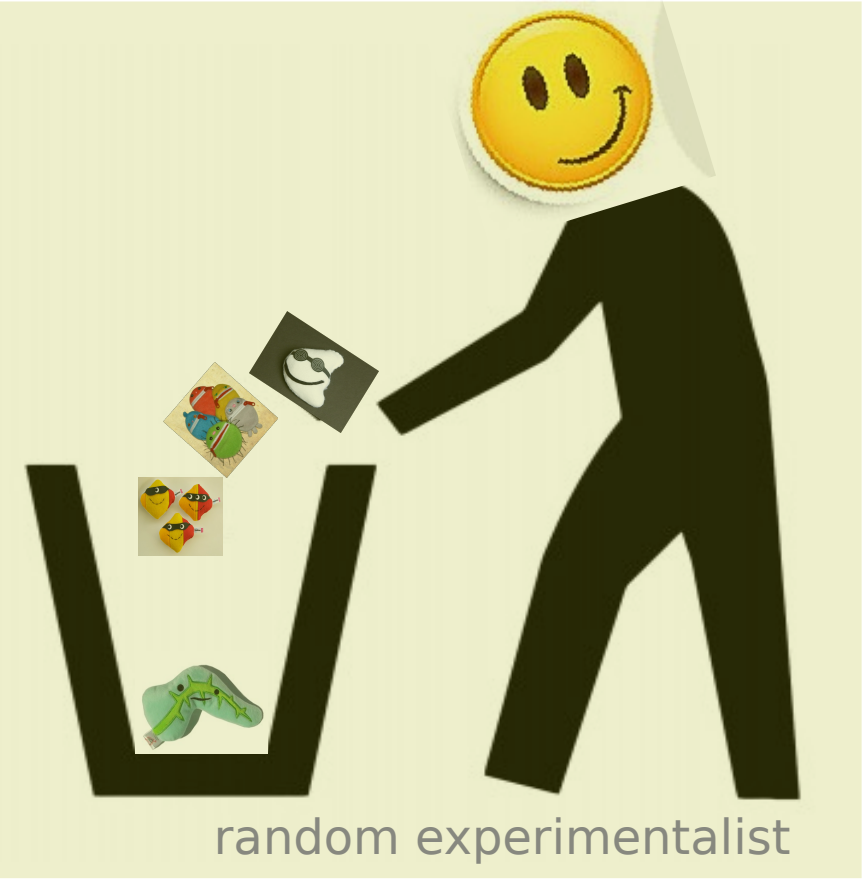


$m_{T5/3}$ > 645 GeV @ 95% CL

We are not there yet!

Only the latest-greatest results presented, there is much more!

Searches are ongoing, we are starting to exclude some models

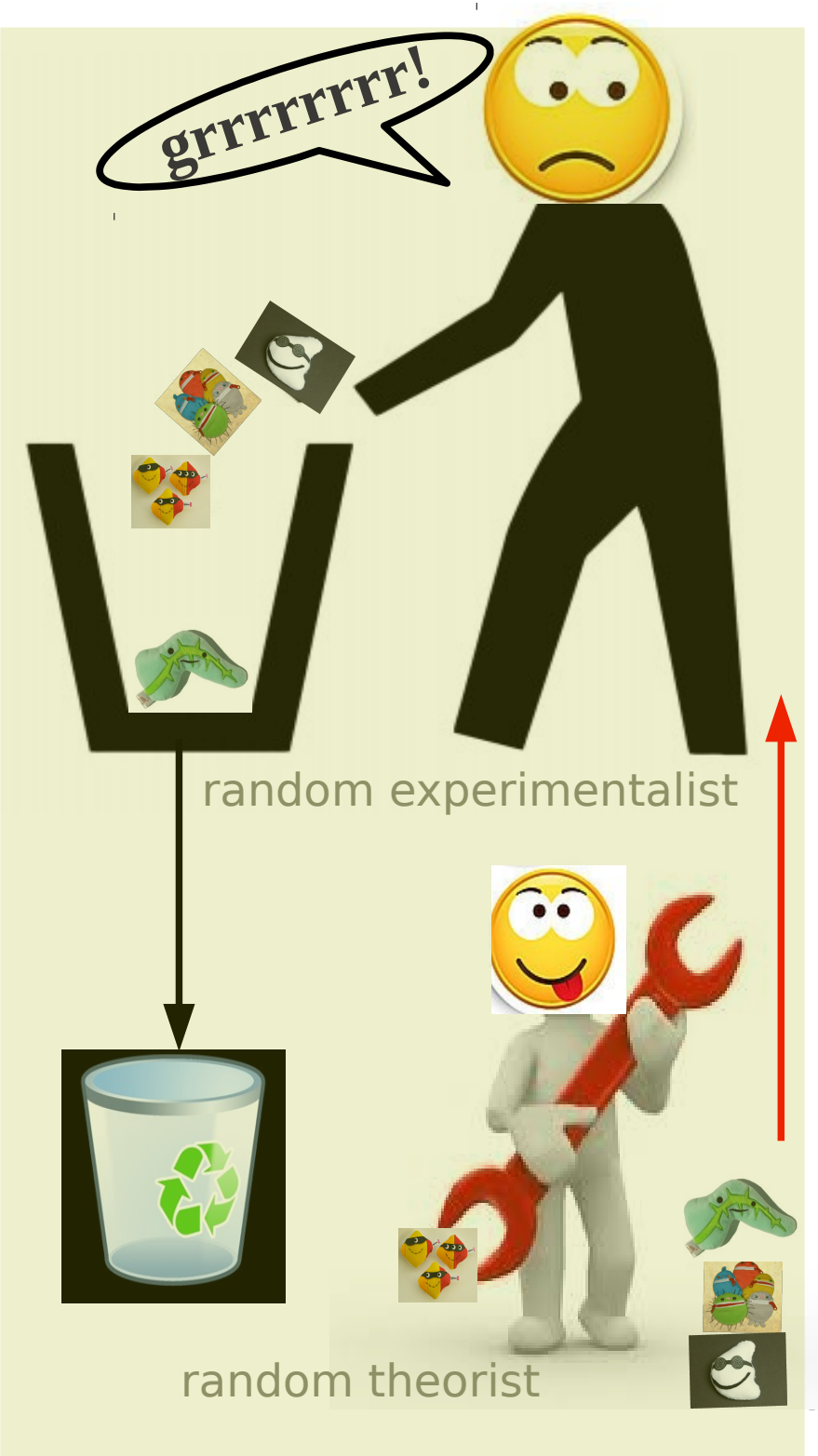


We are not there yet!

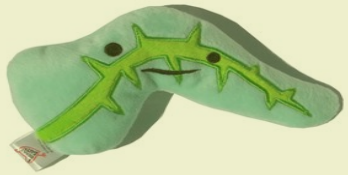
Only the latest-greatest results presented, there is much more!

Searches are ongoing, we are starting to exclude some models

But we are not done yet, theorists tend to reanimate their favorite models...



Grand summary for new fermions and bosons



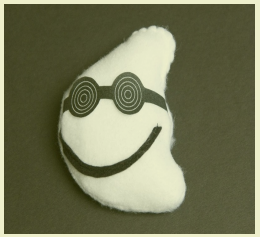
$Z' \to ee/\mu\mu$: $m_{Z'_{SSM}} > 2.6$ TeV @95%CL

$Z' \to \tau\tau$: $m_{Z'_{SSM}} > 1.4$ TeV @95%CL

$Z' \to qq$: $m_{Z'} > 1.6$ TeV @95%CL

$Z' \to bb$: $m_{Z'} > 1.5$ TeV @95%CL

$Z' \to tt$: $m_{Z'} > 1.55$ TeV @95%CL (not shown)



$W' \to l\nu$: $m_{W'_{SSM}} > 2.85$TeV @95%CL

$W' \to tq$: $m_{W'} > 1.1$TeV @95%CL

$m_N = 90$ GeV $\to |V_{\mu N}|^2 < 0.07$ & $|V_{eN}|^2 < 0.22$

$t' \to bW$ & $b' \to tW$: $m_{t'} = m_{b'} > 685$ GeV @95%CL

$B \to bZ$: $m_{B'} > 550$ GeV @ 95% CL

$T \to tZ$: $m_T > 625$ GeV @ 95% CL

$T^{5/3} \to tW$: $m_{T5/3} > 645$ GeV @ 95% CL

Additional material

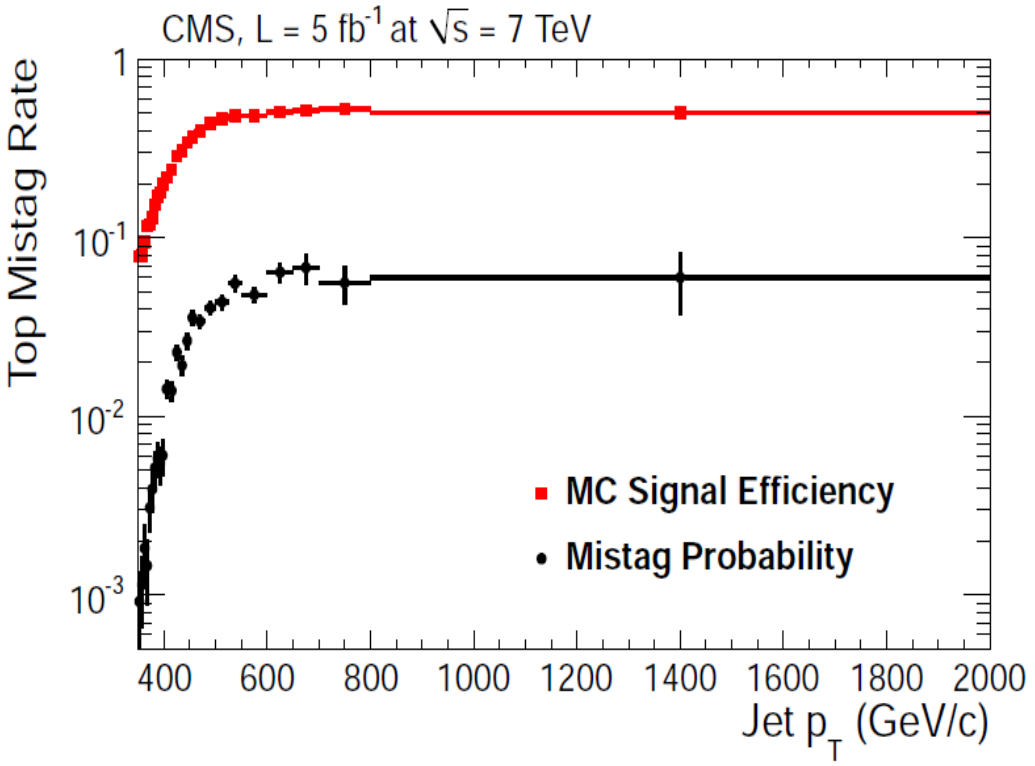
Z' → tt (boosted tops)

CMS arXiv:1204.2488

all hadronic final state

jets with R=0.8 and substructure

Use mistag probability to estimate the non-top multijet background

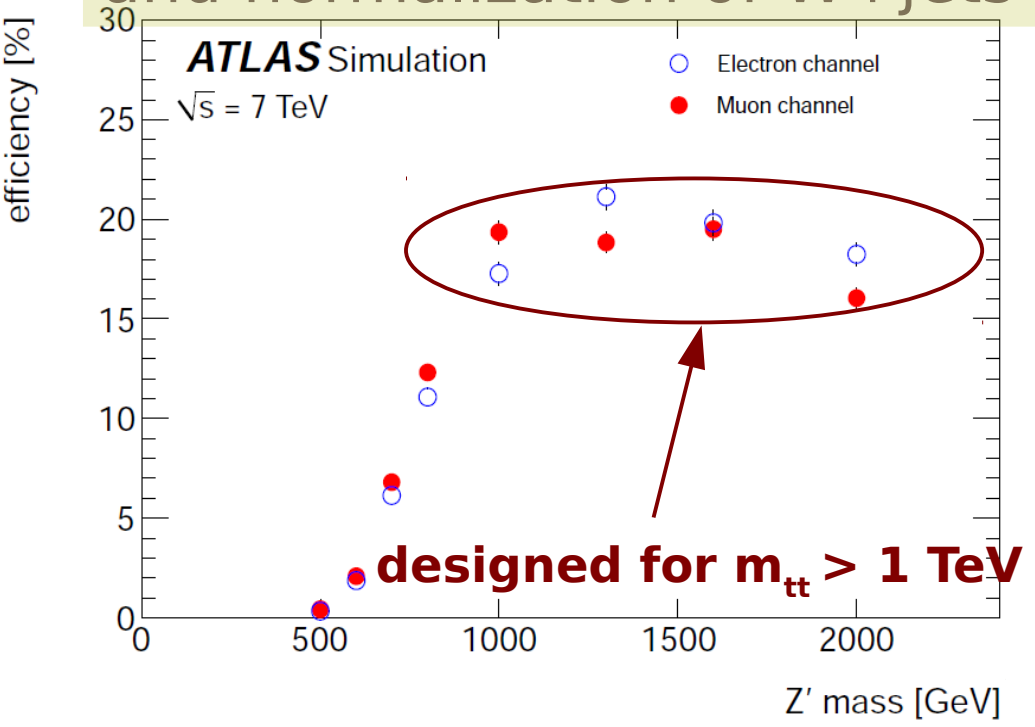


ATLAS arXiv:1207.2409

lepton + jets

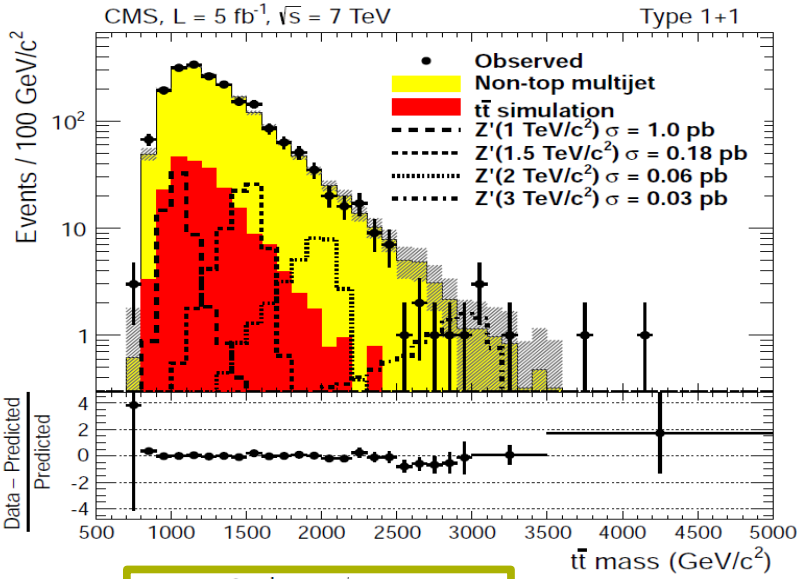
2 jet types:
- normal with R = 0.4
- fat jets using R = 1.0

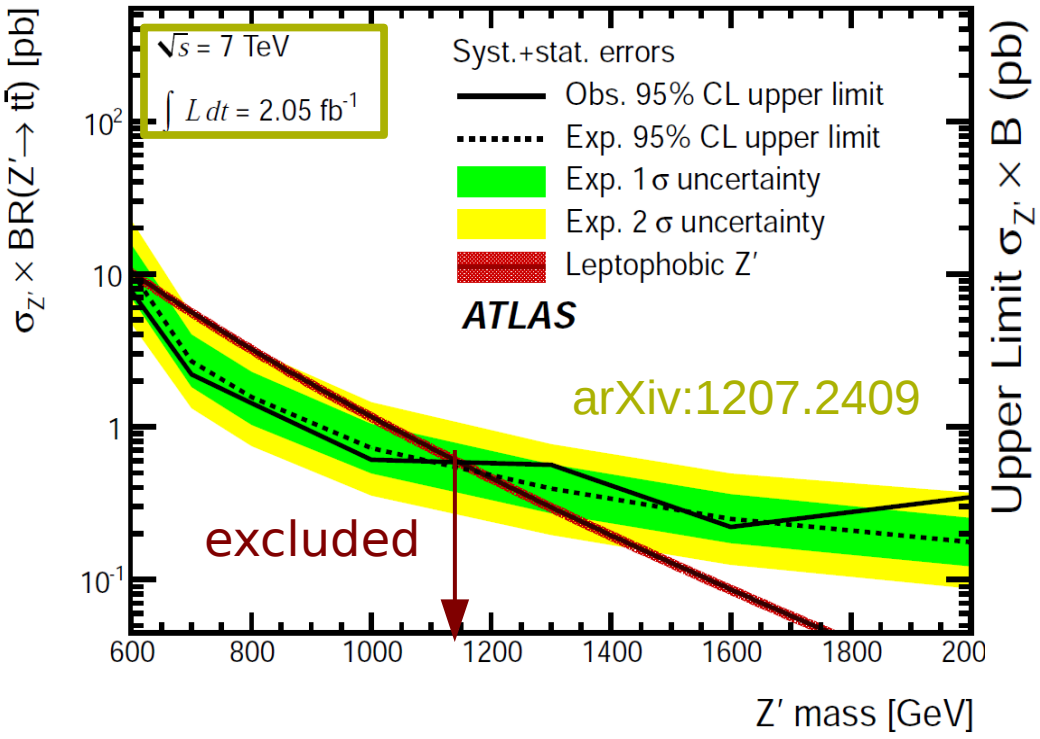
Data-driven estimation for non-top QCD background and normalization of W+jets

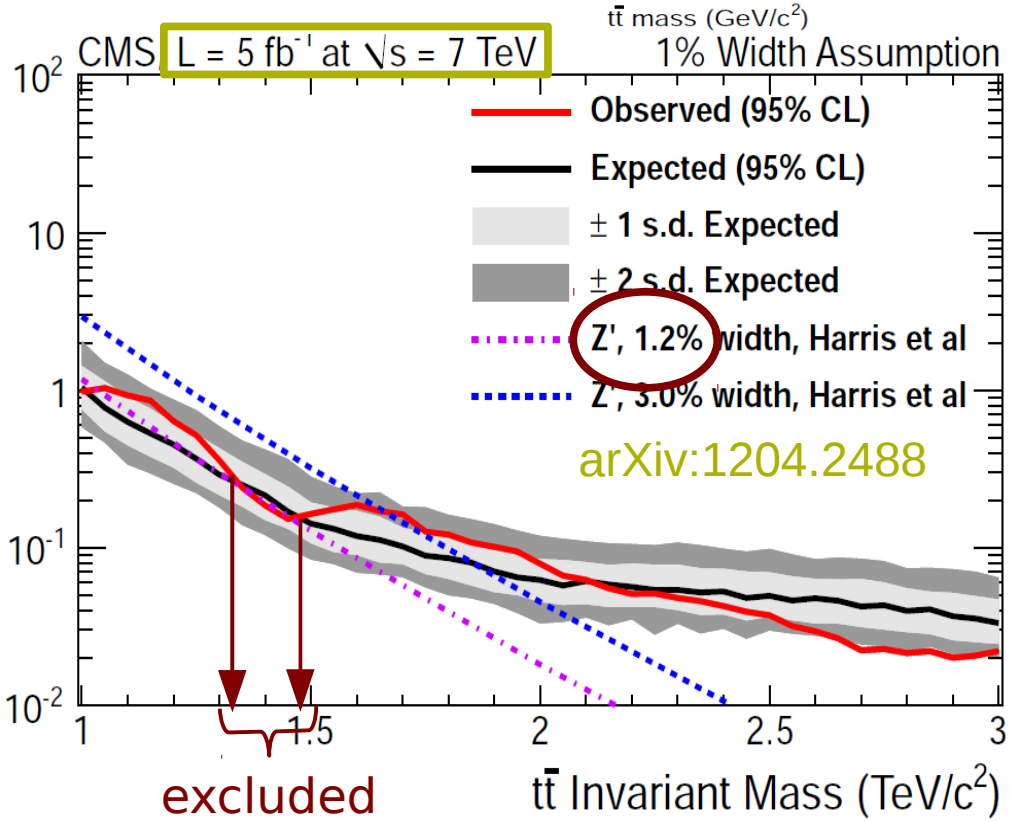


Z' → tt (boosted tops)

Reconstruct m_{tt}
→ fit the mass spectrum
to obtain upper limits on
σxBR







CMS analysis using lepton+jets & b-tagging
→ χ^2 method for the reconstruction of the top quarks
$m_{Z'}$>1.55 TeV@95%CL for Z' with Γ/m=1.2% CMS-PAS-EXO-11-093

Search for single & pair-produced t' and b'

arXiv:1209.1062

$$V_{CKM}^{4\times4} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{ub'} \\ V_{cd} & V_{cs} & V_{cb} & V_{cb'} \\ V_{td} & V_{ts} & V_{tb} & V_{tb'} \\ V_{t'd} & V_{t's} & V_{t'b} & V_{t'b'} \end{pmatrix} = \begin{pmatrix} \mathcal{O}(1) & \mathcal{O}(0) & \mathcal{O}(0) & 0 \\ \mathcal{O}(0) & \mathcal{O}(1) & \mathcal{O}(0) & 0 \\ \mathcal{O}(0) & \mathcal{O}(0) & \sqrt{A} & \sqrt{1-A} \\ 0 & 0 & -\sqrt{1-A} & \sqrt{A} \end{pmatrix}$$

Signal processes

- $t'b \to bWb$;
- $t'\bar{t}' \to bWbW$;
- $b't \to tWbW \to bWWbW$;
- $b't' \to tWbW \to bWWbW$;
- $b'\bar{b}' \to tWtW \to bWWbWW$

→ Require at least 1 W → lν (l = e,μ)
Reconstruct W → qq

single-lepton decay channel			
1 W	2 W	3 W	4 W
= 2 jets	≥ 4 jets	≥ 6 jets	≥ 8 jets
= 2 b jets	either = 1 or ≥ 2 b jets		
$\Delta\phi(j_1, j_2)$ requirement	1 W → qq̄	2 W → qq̄	3 W → qq̄

same-sign dilepton	trilepton
= 2 isolated leptons with same sign	= 3 isolated leptons
≥ 4 jets ($p_T > 30$ GeV, $\|\eta\| < 2.4$)	≥ 2 jets ($p_T > 30$ GeV, $\|\eta\| < 2.4$)
≥ 1 b jet	≥ 1 b jet

subsample	observable
single-lepton 1W	S_T
single-lepton 2W	S_T and m_{bW}
single-lepton 3W	S_T
single-lepton 4W	event yield
same-sign dilepton	event yield
trilepton	event yield

$$S_T = \not{E}_T + p_T^{\ell} + p_T^{b} + p_T^{j} + \sum_{i=0}^{N} p_T^{W_{q\bar{q}}^{i}}$$