Searches for 4th Generation Particles & Heavy Neutrinos at CMS

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Introduction: 4^{th} Generation Quarks

- The Standard Model: At least three generations of quarks are required for *CP* violation, however...
  - ➔ CPV is far too small by 10 orders of magnitude.
  - ➔ An extra family of quarks may resolve this big gap.
    (Hou, arXiv:0803.1234)
- Direct measurement of Invisible *Z* width: $N\nu = 2.92 \pm 0.05$, but
  - ➔ It does not guarantee that N(gen) = 3 exactly, e.g. heavy neutrino with mass > $0.5M_Z$.
- Experimental limits from Tevatron direct searches:
  - ➔ $M(t'\to qW) > 311$ GeV/c^2.
  - ➔ $M(b'\to bZ) > 268$ GeV/c^2 *(assuming 100% b'→bZ, so it's not really firm).*
    Also there are some searches for long lived b' decay, with 2D limits on M(b') and cτ plane.

Today we are focusing on the bottom-like 4^{th} generation quark, *b'*.

Introduction: 4th Generation Quarks

Decay "pattern" of the *b'* quark

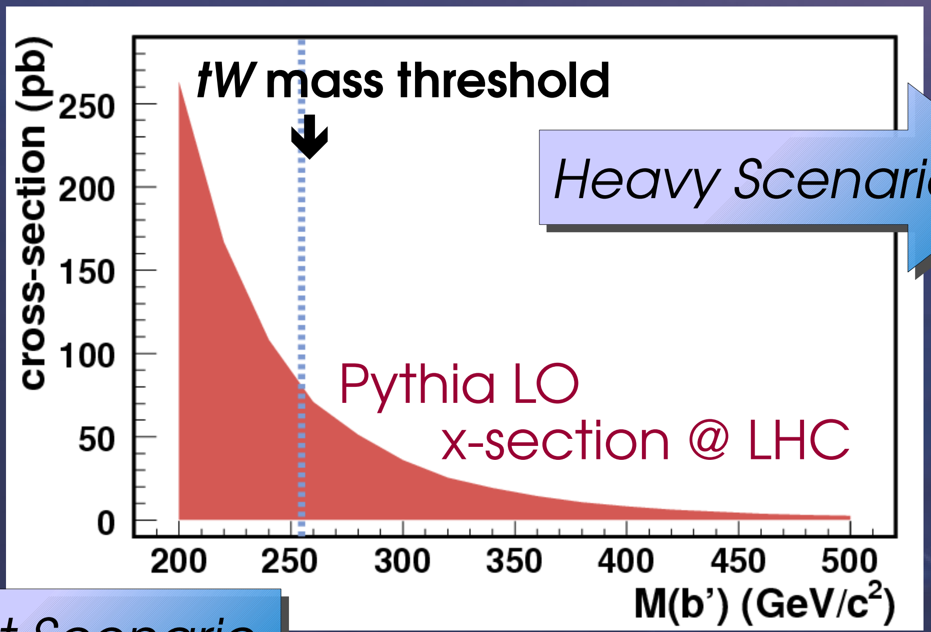
Rich Signatures

- Larger x-sec.
- For sizable $|V_{cb'}|$:

  $b' \to cW \gg t^{(*)}W^{(*)}$
- Suppressed $|V_{cb'}|$:

  $b' \to cW \ll t^{(*)}W^{(*)}$
- FCNC:

  $b' \to bZ, bH$



Heavy Scenario

Light Scenario

$b' \to tW$ dominance

- Lower x-sec.
- Large mass coverage.

LHC provides the chance for direct searches, from light to heavy!

(⇧ *today's topic*)

Introduction: 4th Generation Quarks

Heavy b' = A bottom-like quark that decays to top and W. (Mass > 255 GeV)

- Full decay chain: $b'b' \rightarrow tW\,tW \rightarrow bbW^+W^-W^+W^-$ (4 W-bosons!)
- Possible final states: 4L+2J, 3L+4J, 2L+6J, 1L+8J, 0L+10J

(clean & large modes first)

Production yields @ 100/pb

M(b') (GeV)	300	350	400	450	500
N(4L)	38	18	9	5	3
N(3L)	307	143	71	38	22
N(2L)	920	429	212	115	65
➔same-sign 2L	307	143	71	38	22
N(1L)	12.3k	572	283	153	86

BR($W \rightarrow l\nu$) = 1/3

BR($W \rightarrow jj$) = 2/3

Smaller Standard Model background is expected for same-sign 2L.

Introduction: Heavy Neutrinos

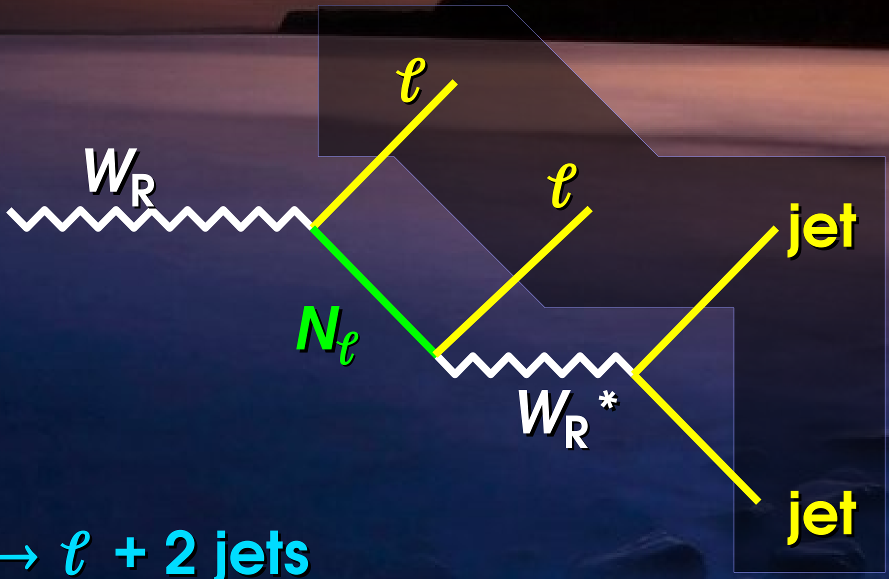
- Heavy Majorana neutrinos: predicted by many models, particularly, the Left-Right Symmetry Model:
  - ➔ Incorporates right-handed gauge bosons W_R, or Z', and the heavy right-handed Majorana neutrinos, N_ℓ ($\ell = e, \mu, \tau$), which can be the partners of the light neutrinos.
  - ➔ Light neutrino masses are generated via SeeSaw mechanism: *Neutrino oscillation indicates $M(\nu) > 0$, but this is not in the SM!*
  - ➔ Explains parity violation in weak interactions.
  - ➔ Includes SM at ~1 TeV scale.
- In many SM extensions, **$M(N_\ell)$ ~ 0.1 – 1 TeV**.

Perfect for searching these new particles at LHC & CMS!

Introduction: Heavy Neutrinos

The Model Parameters

- The key parameters: masses
  - ➔ $M(W_R)$ & $M(N_\ell)$ (ℓ = e, μ, τ).
- Possible reaction:
  - ➔ $pp \rightarrow W_R + X \rightarrow N_\ell + \ell + X$
    $\hookrightarrow \ell + W_R^* \rightarrow \ell$ + 2 jets



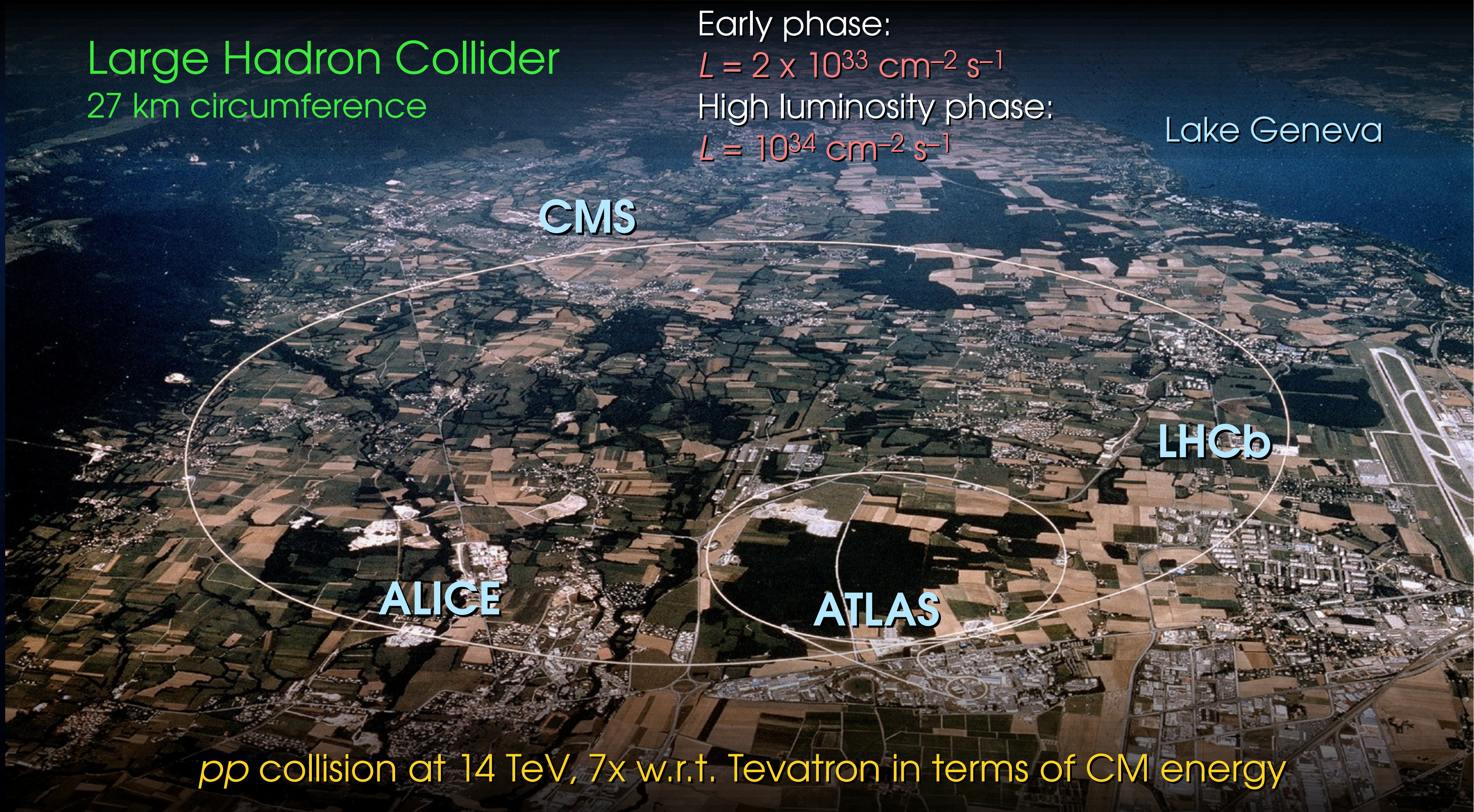
  - ➔ Produce a signature of a high p_T lepton pair (same flavor!) plus two high p_T jets.
- Best limit from D0: (Phys. Rev. Lett.100:211803,2008)
  - ➔ $M(W_R) > 739$ GeV/c^2, if W_R decays to leptons + quarks
  - ➔ $M(W_R) > 768$ GeV/c^2, if W_R decays to only quarks

The best limit on $M(W' \rightarrow e\nu)$ is 1.0 TeV from D0 direct searches.

The LHC

Large Hadron Collider
27 km circumference

Early phase:
$L = 2 \times 10^{33}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
High luminosity phase:
$L = 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$



pp collision at 14 TeV, 7x w.r.t. Tevatron in terms of CM energy

The CMS Experiment

180 institutions
38 countries
~2000 authors

- Pixels
- Tracker
- ECAL
- HCAL
- MUON Dets.
- Superconducting Solenoid

Total weight : 12500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

Acceptance: Calorimetry $|\eta|<5.0$, Tracking $|\eta|<2.4$

The Analysis: $b' \to tW$ Searches

- **Data set assumption:**
  100 pb^{-1} at 14 TeV recorded by the CMS detector.
- **Trigger:** single "relax" electron trigger + single loose muon trigger.
- **Lepton selections:**
  - Electrons: cut-based ID, isolated from tracks, $p_T > 20$ GeV/c.
  - Muons: must be isolated from tracks, $p_T > 20$ GeV/c.

  Requiring exact **2L with the same charge**, or **3L** in the final state.
- **Jet selections:** Iterative cone algorithm of 0.5 radius
  - Same-sign 2L: at least 4 or more jets $p_T > 35$ GeV/c.
  - 3L: at least 2 or more jets $p_T > 35$ GeV/c.
- **Other requirements:**
  - Missing ET: MET > 40 GeV.
  - A Z-boson veto: $|M(\ell^+\ell^-)-M_Z| > 10$ GeV/c^2.
  - Objects isolation: $\Delta R(\ell,\ell) > 0.3$ & $\Delta R(\ell,\text{jet}) > 0.3$

The Analysis: $b' \to tW$ Searches

Expected Yields @ 100/pb

b' Signal *Assuming 100% $b' \to tW$*

M(*b'*) (GeV)	300	400	500
N(3L)	23.6	7.6	2.9
N(same-sign 2L)	44.7	14.6	5.1
Sum	**68.2**	**22.2**	**8.0**
S/N	**9.3**	**3.0**	**1.1**

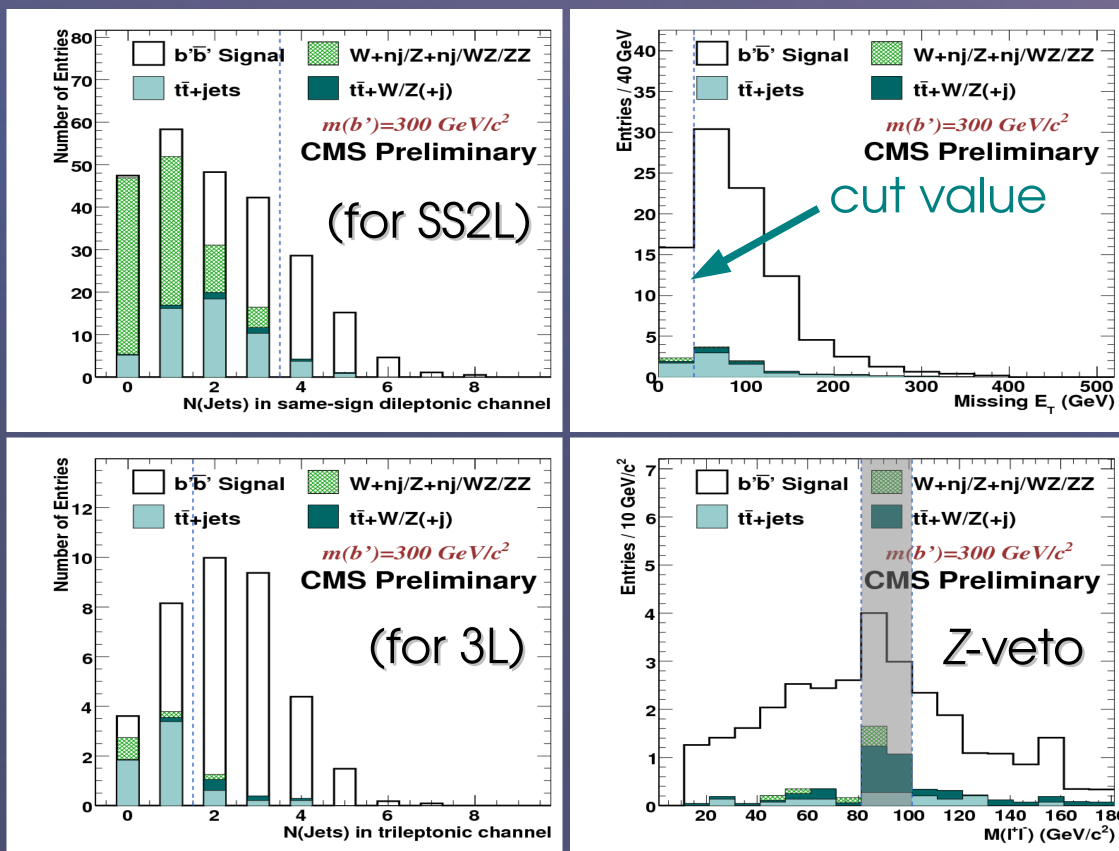
- The signal is very significant, high S/N with 300 GeV/c^2.
- Good sensitivity up to 400 GeV/c^2.
- Background is dominated by the **tt+jets** events.

Background Sources

Process	tt+nj	ttZ(+j)	ttW(+j)	ttWW	Z/W+nj	WZ/ZZ	All
N(3L)	1.0	0.38	0.31	0.014	<1.4	0.21	1.9
N(same-sign 2L)	4.7	0.31	0.43	0.020	<1.4	<0.11	5.4
Sum	**5.7**	**0.69**	**0.74**	**0.035**	**<1.4**	**0.21**	**7.3**

QCD events are negligible (<0.3 events)

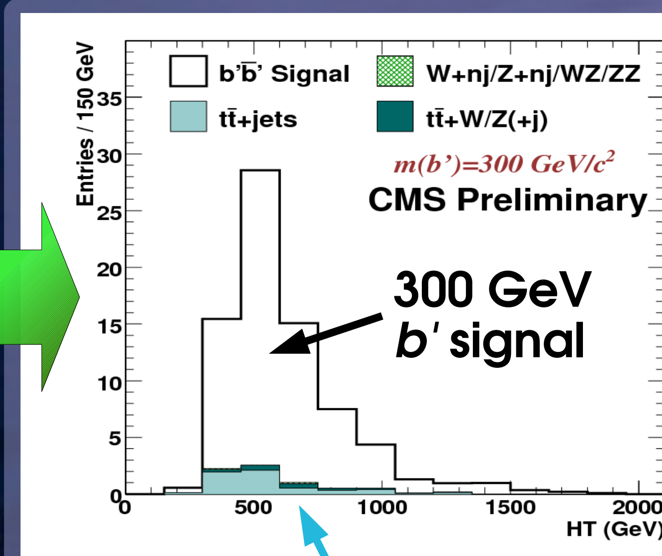
Resulting Figures (for 300 GeV/c^2 b')



Signal observable:

HT = Σp_T(jets) + Σp_T(leps) + MET

(carries mass information!)



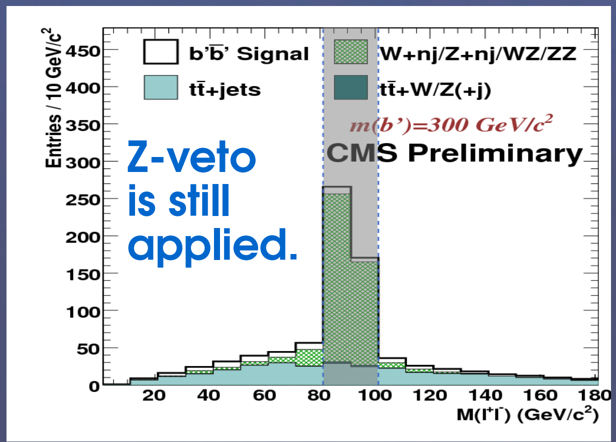
Background, mainly tt+jets

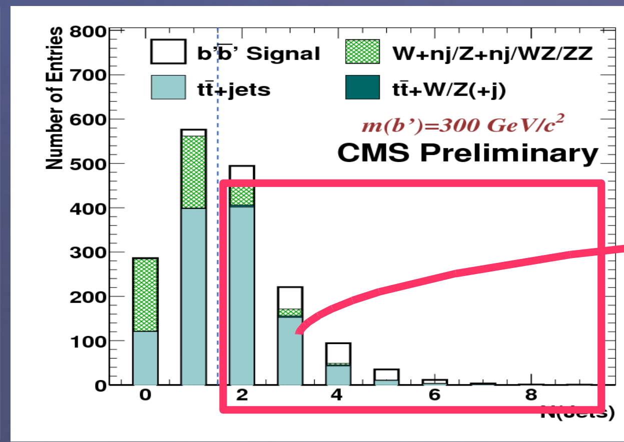
Histograms are normalized to 100/pb luminosity

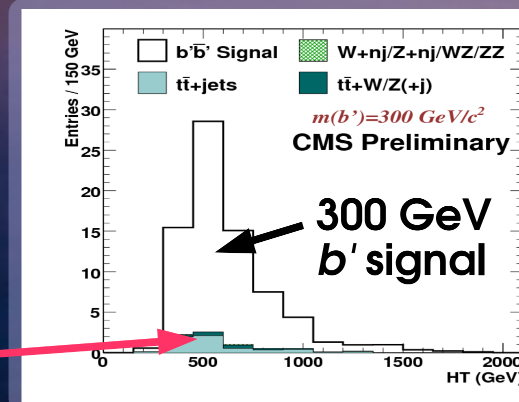
Background Estimation with Data

- Background is normalized by the control sample:
  <u>Opposite sign</u> 2L w/ the same jet requirement

  (It's totally dominated by ttbar – as our wish!)







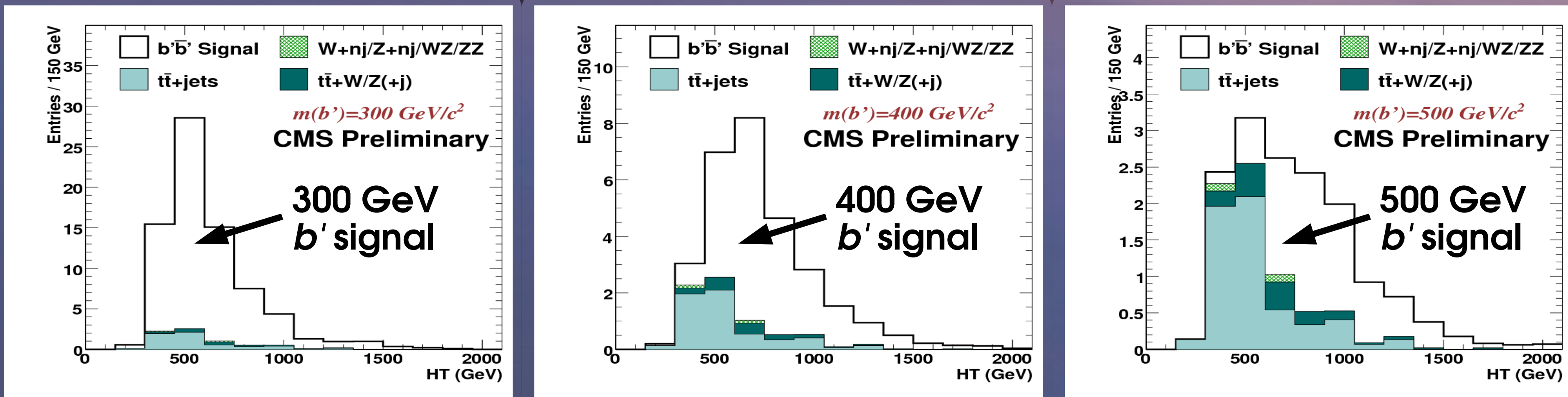
Signal Region

- Governed by the probability to
  - ➔ observe a sign-flipped lepton (become same-sign 2L)
  - ➔ find an extra (fake) lepton (become 3L)

This is the dominant systematic error (17%~124%, depends on b' mass).
Other big errors are MET (21%~30%), Jet energy scale (11%~27%).
All the systematic uncertainties are determined assuming the early condition.

Counting Significance

HT Distributions for 300, 400, 500 GeV/c^2 b' signals



M(b') (GeV)	300	400	500
b'b LO cross section (pb)	34.9	8.05	2.45
Signal Yield	68.2	22.2	8.0
Background Yield		**7.3 +10.5/-4.8**	
Significance (stat.+syst.)	**7.5σ**	**2.0σ**	**0.0σ**

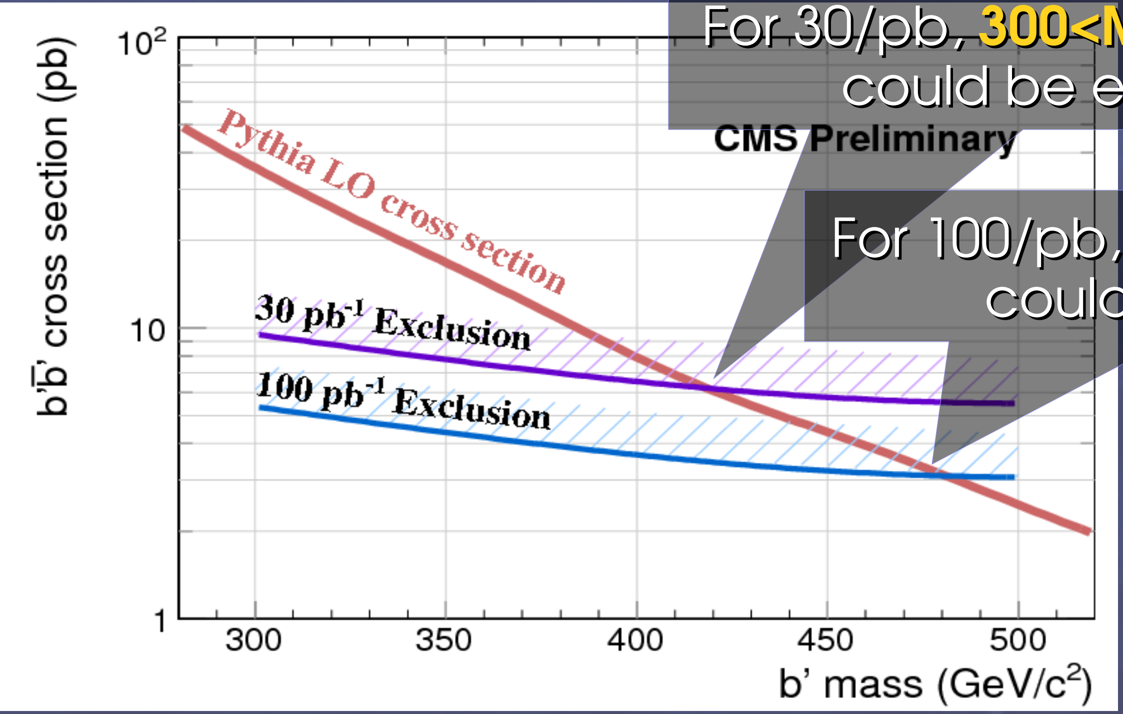
Background is independent of b' mass.

Very significant (7.5σ) if M(b') = 300 GeV/c^2.

Not significant at all for 500 GeV/c^2, since background error > signal.

Exclusion Limit

- In the case of no signal observed in data, we could set the exclusion limit accordingly at 95% C.L.
- We use a Bayesian limit for null hypothesis tests, with all the systematic effects are included. By comparing to the Pythia LO X-secs:



For 30/pb, **300<M(b')<420 GeV** could be excluded.

For 100/pb, **300<M(b')<480 GeV** could be excluded.

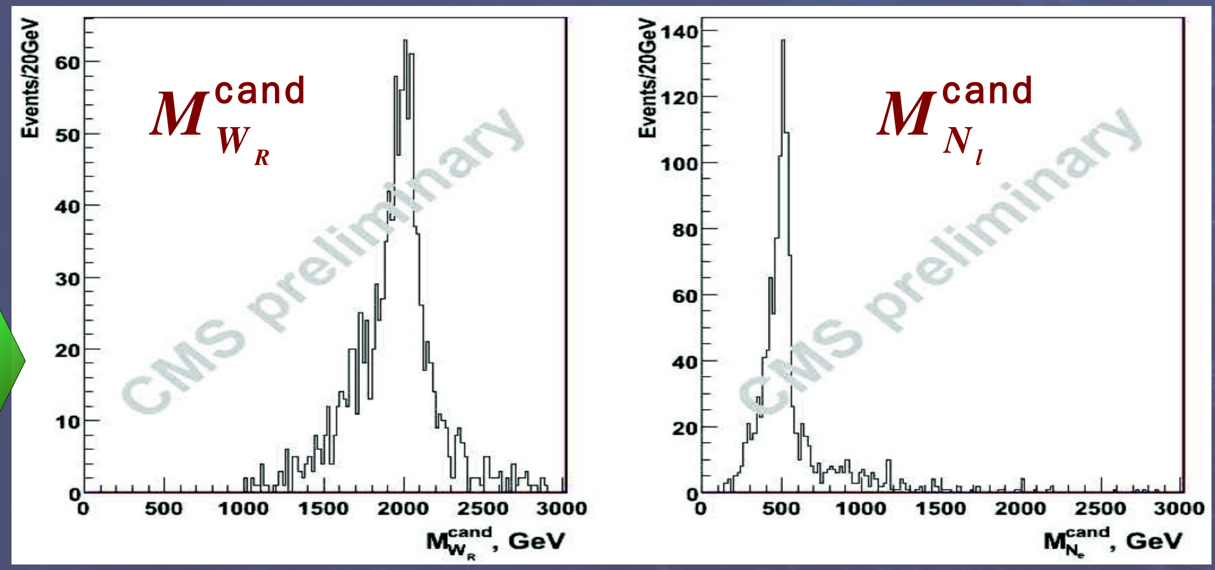
The Analysis: Heavy Neutrinos

- **Data set assumption:**
  100 pb^{-1} at 14 TeV recorded by the CMS detector.
- **Trigger:**
  - ➔ Electron channel:
    high p_T electron (80 GeV) or very high p_T electron (120 GeV).
  - ➔ Muon channel:
    Isolated muon trigger.
- **Lepton selections:**
  Requiring at least 2 electrons or 2 muons, $M(\ell\ell) > 200$ GeV/c^2.
  (one with $p_T > 80$ GeV/c, one with $p_T > 20$ GeV/c.)
  - ➔ Electrons: cut-based ID, isolation using tracker & calorimeter.
  - ➔ Muons: track quality cuts, isolation using tracker & calorimeter.
- **Jet selections:** Iterative cone algorithm of 0.5 radius
  Requiring at least 2 jets, $p_T > 40$ GeV/c.

The Analysis: Heavy Neutrinos

- **Reconstructed kinematic variables:**
  - ➔ Right-handed W_R boson mass, $M_{W_R}^{\text{cand}}$:
    The invariant mass of the combination, $\ell_1\ell_2 J_1 J_2$.
  - ➔ Heavy neutrino mass, $M_{N_l}^{\text{cand}}$:
    The invariant mass of $\ell_2 J_1 J_2$, where ℓ_2 is the "softer" lepton.

Example signal distributions simulated with $M(W_R) = 2$ TeV & $M(N_\ell) = 500$ GeV, (electron channel)



The Analysis: Heavy Neutrinos

Expected Yields @ 100/pb

Signal reference point:
$M(W_R) = 1.5$ TeV, $M(N_\ell) = 500$ GeV

Electron channel

Process	Signal	tt	Z+nj	W+nj	γ+nj	QCD	WW	WZ	Others
Grand region	**23**	19	7.2	2.1	0.68	0.23	2.27	0.56	0.85
2D peak region	**14**	0.44	0.15	0.31	0	0	0.084	0	0.1

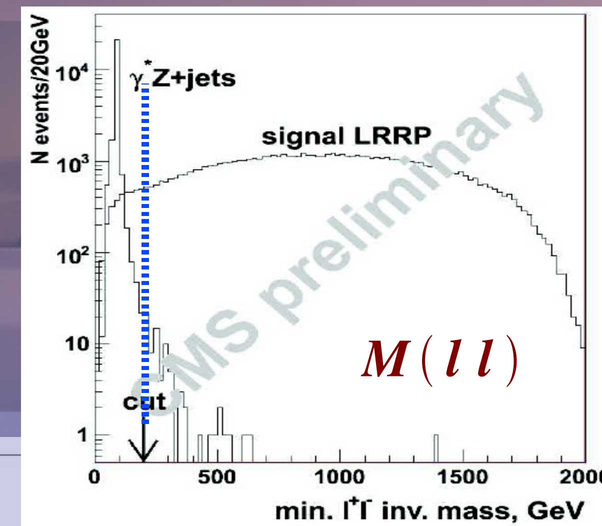
Muon channel

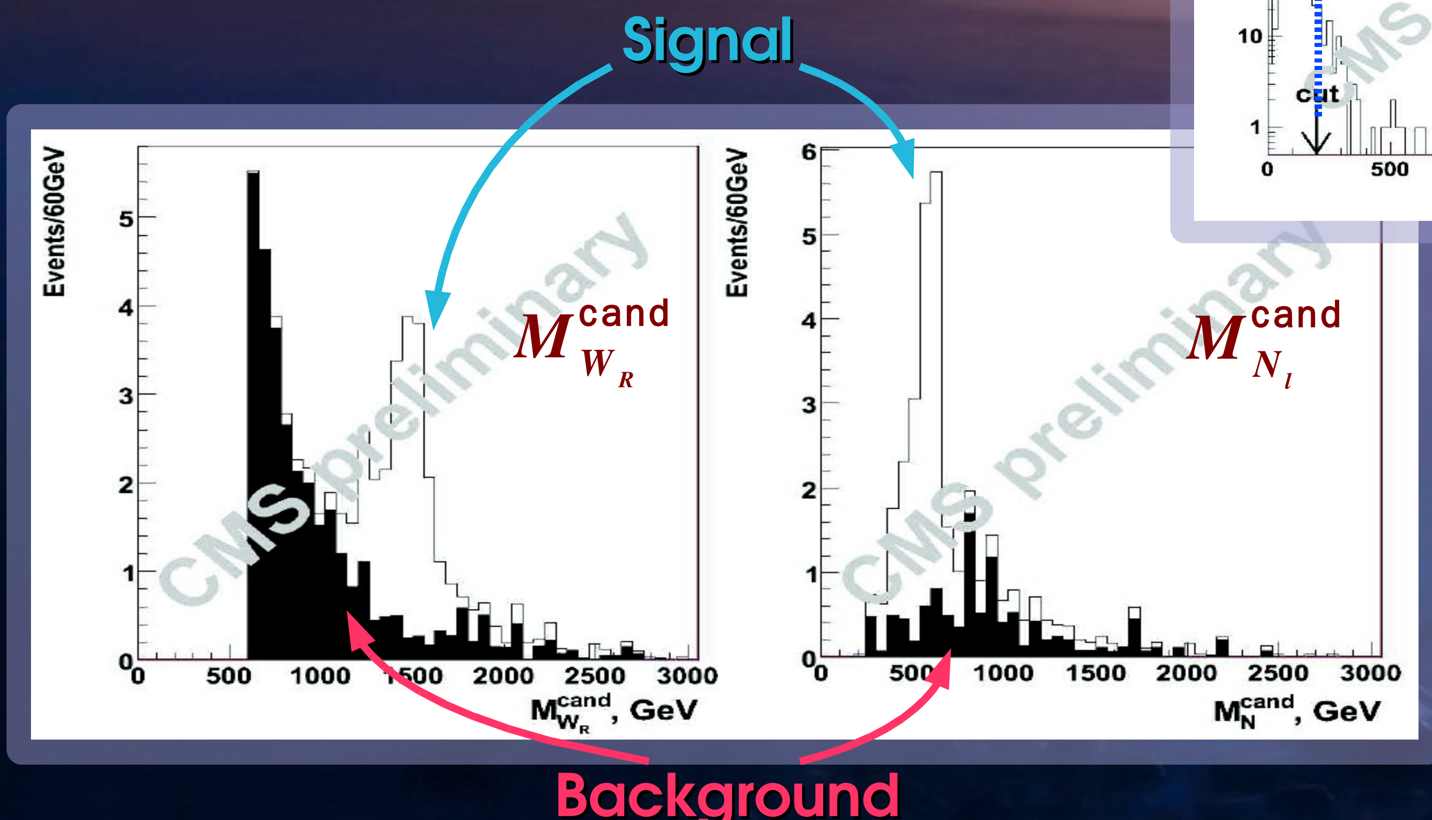
Process	Signal	tt	Z+nj	W+nj	γ+nj	QCD	WW	WZ	Others
Grand region	**23**	22	8.7	0.025	0	3.4	2.6	0.57	0.32
2D peak region	**17.6**	0.57	0.16	0	0	0	0.19	0	0

Grand region: $M_{W_R}^{\text{cand}} > 600\ \text{GeV}/c^2$

2D peak region: $1250 < M_{W_R}^{\text{cand}} < 1720\ \text{GeV}/c^2,\ 480 < M_{N_l}^{\text{cand}} < 710\ \text{GeV}/c^2$

Resulting Figures





- Background is checked by the control samples:
  - ➔ top events: selecting the cross flavor e-μ events.
  - ➔ Z+jets: relax the M($\ell\ell$) cut to 80 GeV/c^2.

The Fits & Results

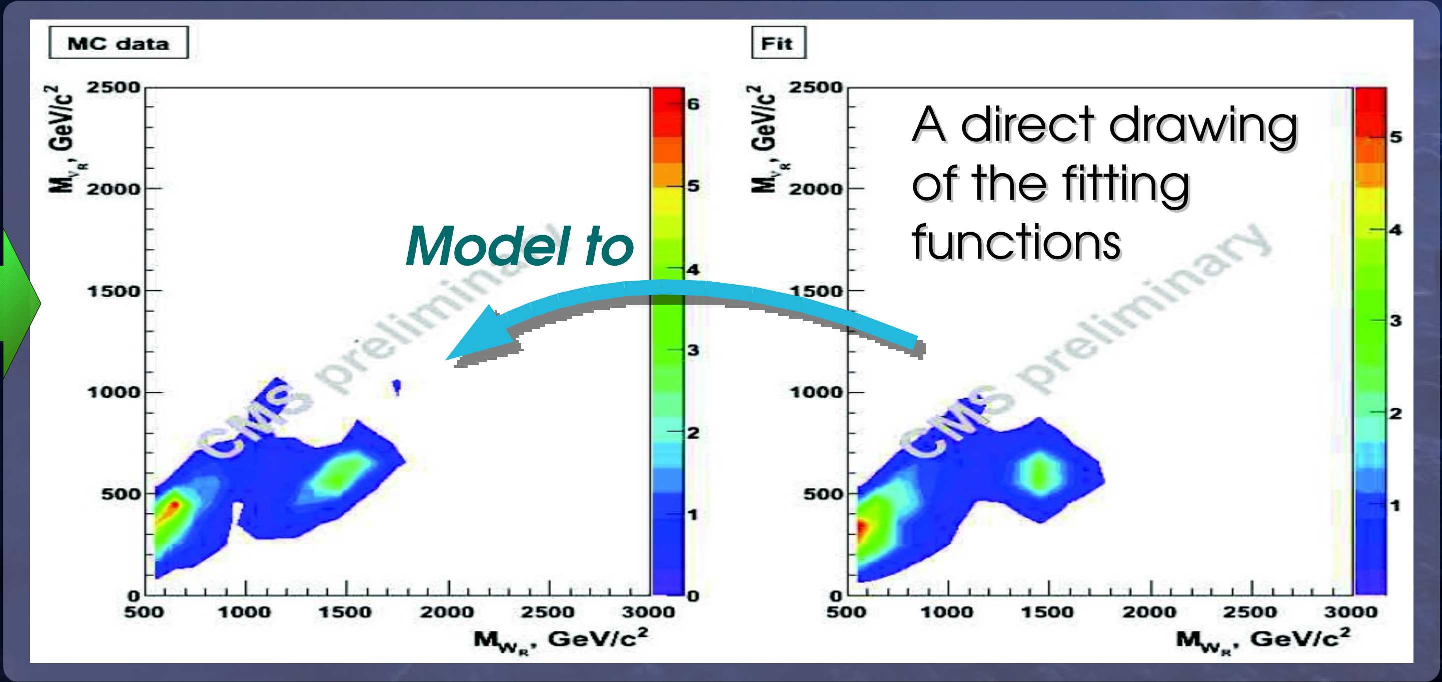
- Signal is extracted by a maximum likelihood fit in 2 dimensions:

$$P(M_{W_R}, M_{N_l}) = N_S \times BW(M_{W_R}) \times BW(M_{N_l}) + N_B \times P_B(M_{W_R}, M_{N_l})$$

The signal is modeled by two Breit-Wigners.
(mean are free, widths are quasi-free in the fits)

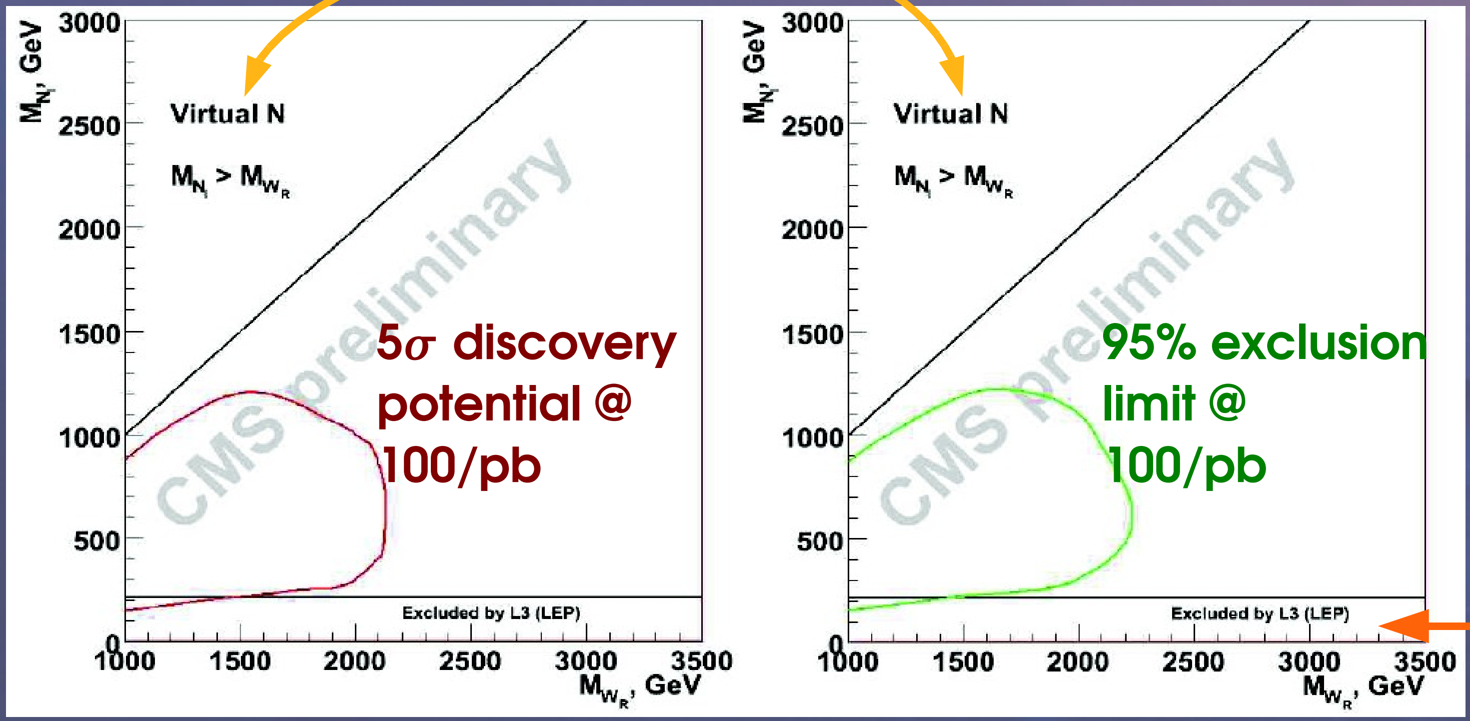
2D Background shape from smooth histograms

Weighted sample (a mixture of signal and background MC events)



The Fits & Results

We only consider $M(N_\ell) < M(W_R)$ at this moment.



Exclusion by LEP searches

- The limit is obtained by pseudo experiments.
- For the exclusion limit, systematic uncertainties are included in the consideration.

Summary & Conclusion

- We have performed two feasibility studies, assuming a data set of 100 pb^{-1} at 14 TeV at CMS. The systematic uncertainties at early condition are considered.
- **Search for a 4th generation bottom-like quark, $b' \rightarrow tW$:**
  - ➔ If the b' quark is as light as 300 GeV/c^2, a **7.5σ** discovery can be made using a simple counting experiment.
  - ➔ Or, we could exclude such $b' \rightarrow tW$ signal up to $M(b')<480$ GeV at 95% confidence level if only SM processes observed.
- **The study for right-handed *W*-boson & heavy neutrinos:**
  - ➔ We analyzed the possibility of two leptons & two jets final states.
  - ➔ These new particles can be observed at the level of **5σ** in the mass region that goes up to $M(W_R) = 2.1$ TeV, $M(N_\ell) = 1.2$ TeV.
- Looking forward to the first data from LHC.