Searches for Bottom-like 4th Generation Quarks at CMS

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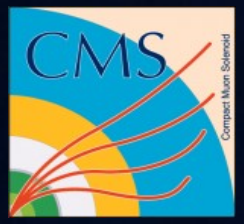

The CMS Collaboration

CERN Theory Institute – From the LHC to Future Colliders
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Introduction: 4th 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.

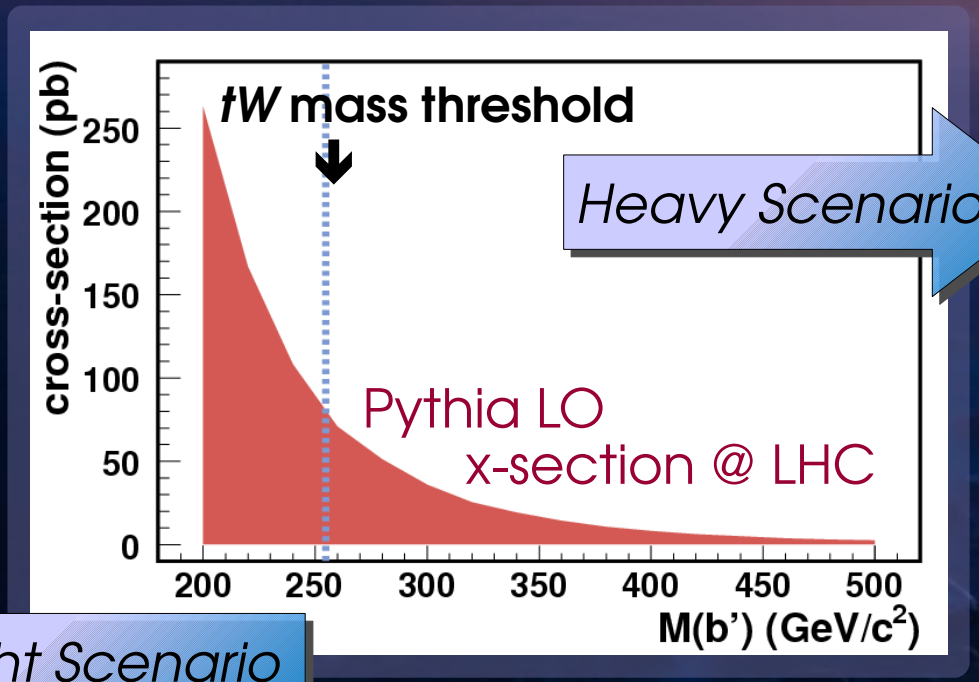
Today we are focusing on the bottom-like 4th generation quark, *b'*.

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:
  $b' \to bZ, bH$



$b' \to tW$ 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.

The Analysis: $b' \rightarrow tW$ 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: $b' \rightarrow tW$ Searches

Expected Yields @ 100/pb

***b'* Signal** *Assuming 100% b'→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**

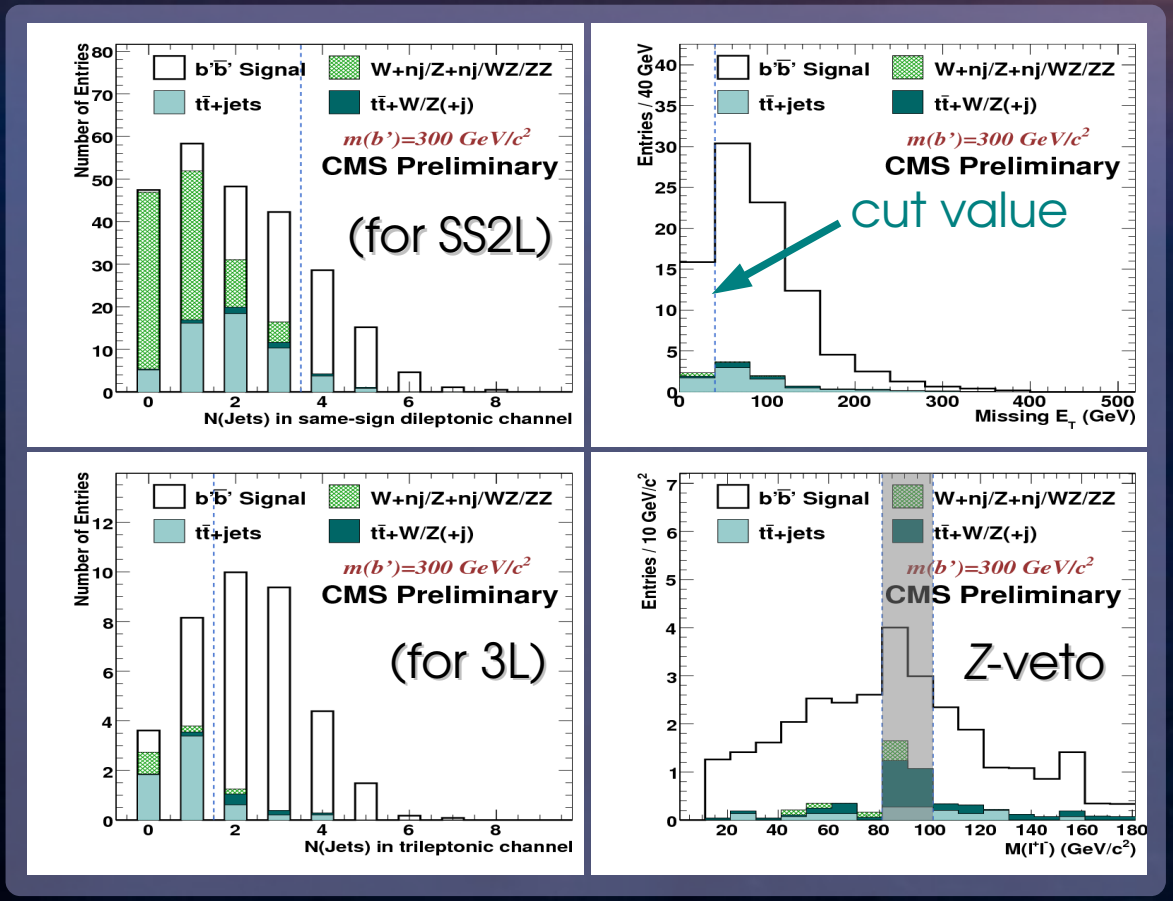
- The signal is very significant, high S/N with 300 GeV/c^2.
- Good sensitivity up to 400 GeV/c^2.
- Background is dominated by the **tt+jets** events.

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)

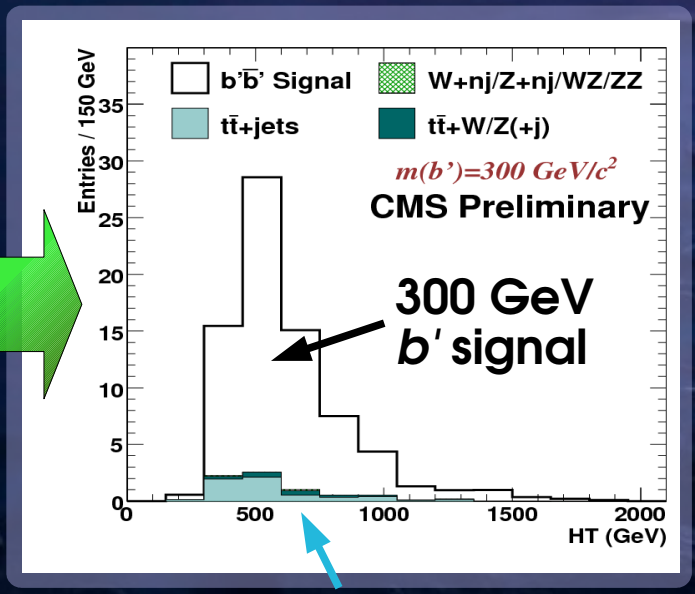
Resulting Figures (for 300 GeV/c^2 b')



Signal observable:

HT = Σp_T(jets) + Σp_T(leps) + MET

(carries mass information!)



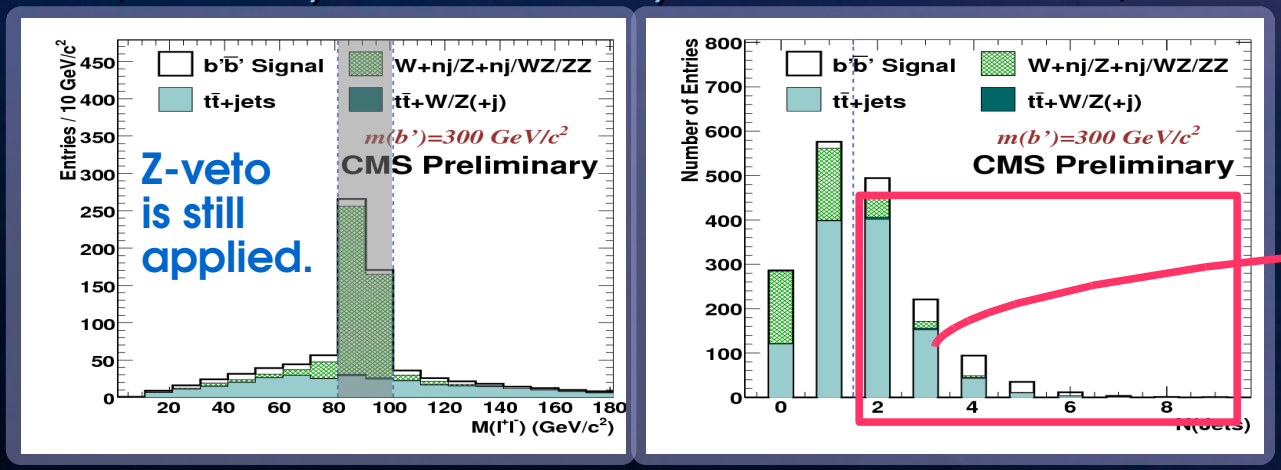
Background, mainly tt+jets

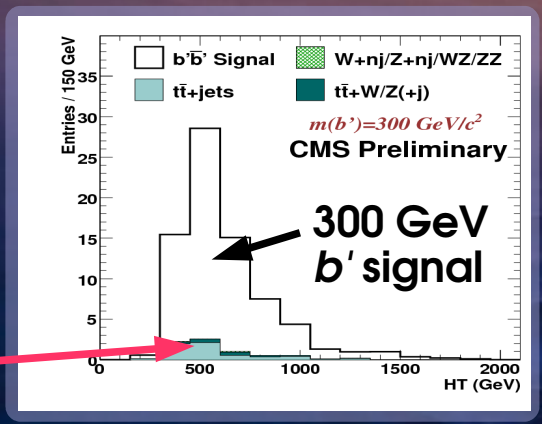
Histograms are normalized to 100/pb luminosity

Background Estimation with Data

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

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



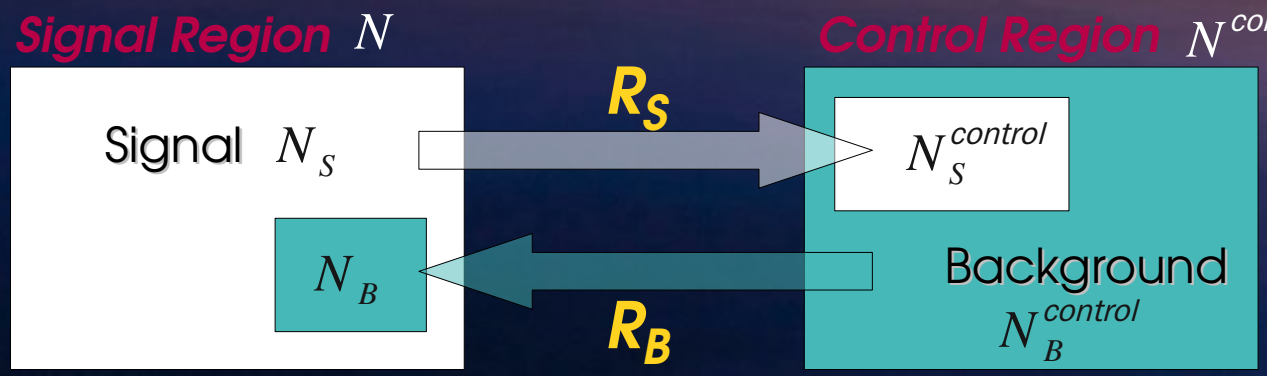


Signal Region

- Governed by the probability to
  - ➔ observe a sign-flipped lepton (become same-sign 2L)
  - ➔ find an extra (fake) lepton (become 3L)
- Signal yield is obtained by an iteration method.
  - ➔ Next slide.

Background Estimation with Data

- Number of signal events is resolved by an iteration method:



- ➔ Attribute all the events in the control region are background.
- ➔ Resolve the signal/background yields in the signal region:

$$N_B = N_B^{control} \times R_B = N^{control} \times R_B \qquad N_S = N - N_B$$

- ➔ If we have signal, calculate the signal yield in the control region with R_S: $N_S^{control} = N_S / R_S$
- ➔ Subtract the signal in the control region, re-calculate the sianal & backaround vields until it converaed.

Systematic Uncertainties

- The ratios (R_S, R_B) used in the background estimation is the dominant systematic source.

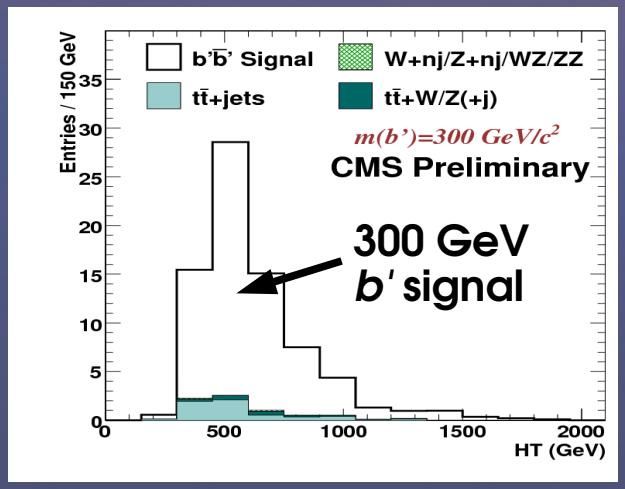
M(b') (GeV)	300	400	500
Integrated luminosity	11%	11%	11%
Non-prompt & fake leptons	+7/–17%	+19/–47%	+51/–124%
Background cross sections	1%	3%	8%
Jet energy scale	11%	14%	27%
Jet efficiency	5%	5%	8%
Missing energy	30%	20%	21%
Leptons	2%	3%	3%
Pile-ups	1%	1%	2%
Parton distribution function	5%	7%	9%
MC statistics	4%	8%	20%
Sum: systematics	**+36/–39%**	**+35/–55%**	**+67/–132%**
Statistics (100 pb^{-1})	**15%**	**28%**	**57%**

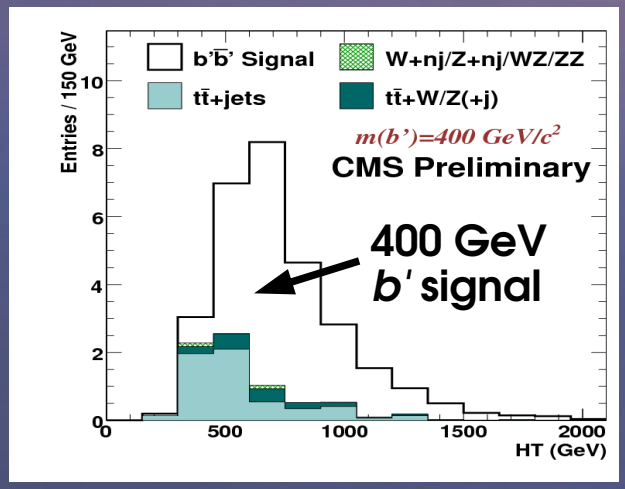
From ensemble tests (toy MC)

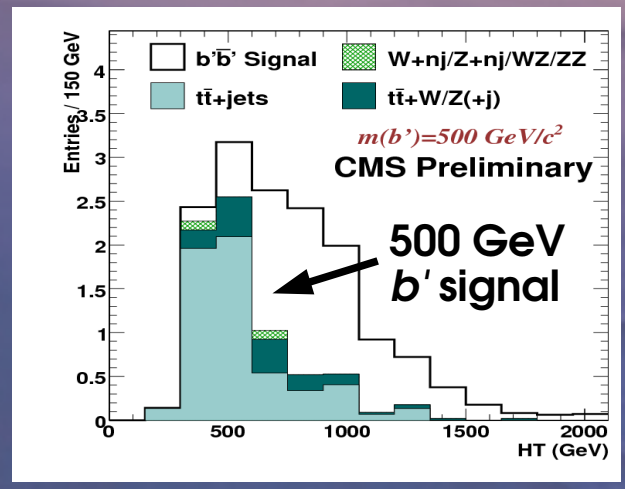
All the systematic uncertainties are determined assuming the early condition.

Counting Significance

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







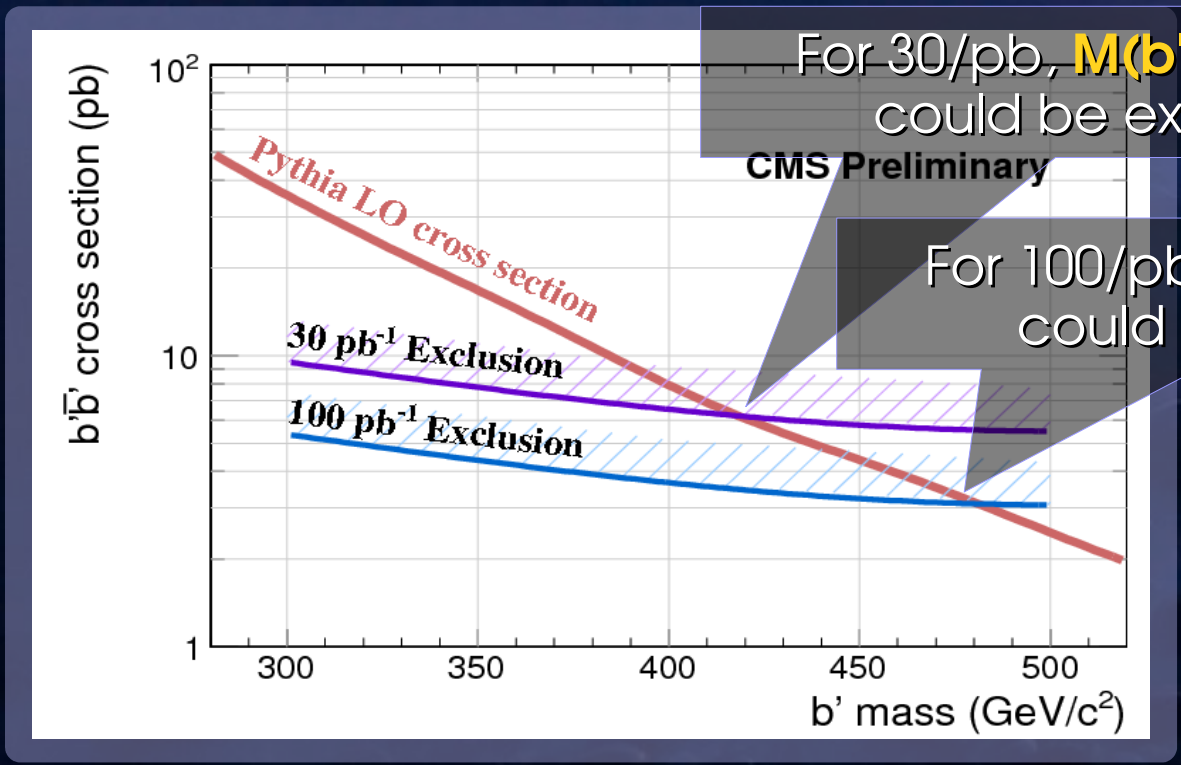
M(b') (GeV)	300	400	500
b'b LO cross section (pb)	34.9	8.05	2.45
Signal Yield	68.2	22.2	8.0
Background Yield	**7.3 +10.5/–4.8** (syst.)		
Significance (stat.+syst.)	**7.5σ**	**2.0σ**	**0.0σ**

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, **M(b')<420 GeV** could be excluded.

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

Summary & Conclusion

- We have performed the feasibility study for a search of **4th generation bottom-like quark, $b' \rightarrow tW$**, assuming a data set of 100 pb^{-1} at 14 TeV at CMS. The systematic uncertainties at early condition are considered:
  - ➔ If the b' quark is as light as 300 GeV/c^2, the expected signal yield is **68** events, against **7.3** background events.
    be made using a simple counting experiment.
  - ➔ A **7.5σ** discovery can be carried out for a 300 GeV/c^2 b' signal, 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.
- Other possible decay channels are working in progress.
- Looking forward to the first data from LHC.