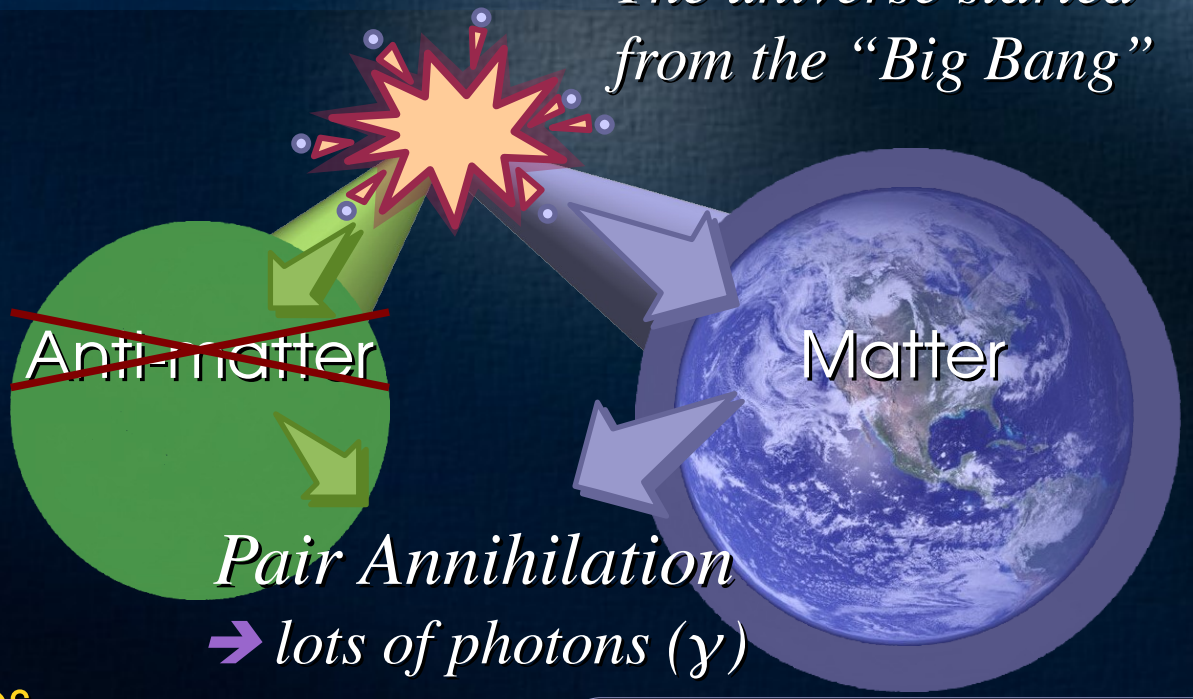
4th Generation Quarks: CMS Sensitivities

Kai-Feng Chen
National Taiwan University

The CMS Collaboration

SM and BSM physics at the LHC, August 21st, 2009

Motivation: the Grand Puzzle



- Although, the known baryon-antibaryon asymmetry is already quite small (10^{-10}).

Kobayashi-Maskawa phase only contributes $\sim 10^{-20}$

$$\frac{n(\bar{B})}{n(\gamma)} \simeq 0$$

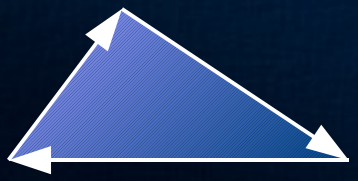
$$\frac{n(B)}{n(\gamma)} = (5.1^{+0.3}_{-0.2}) \times 10^{-10}$$ (WMAP)

- The *CP* violation in the Standard Model is far too small for accommodating the "matter-dominated" Universe!

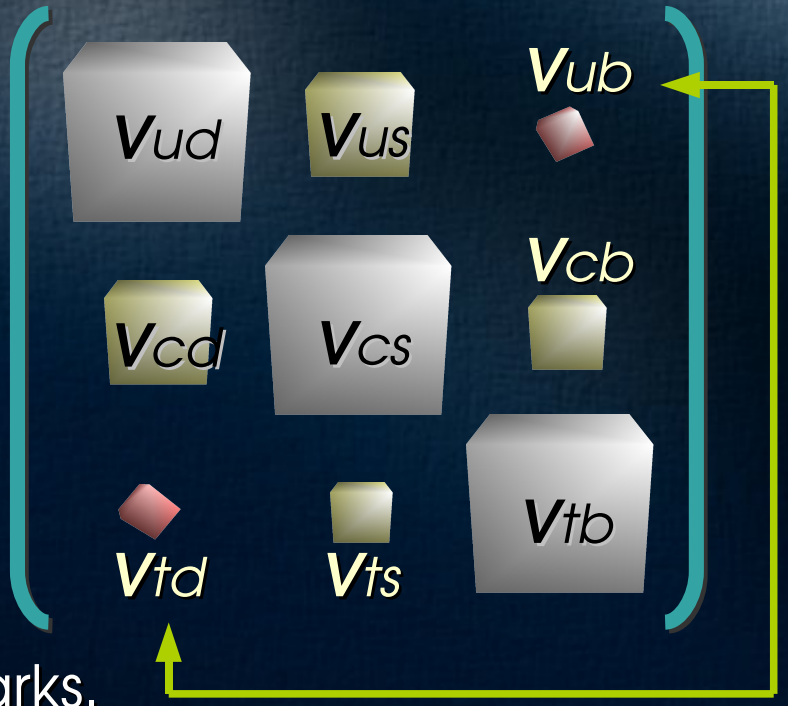
"Something" is definitely necessary to enlarge the asymmetry by ***O(10^10)!***

Ingredients in the SM

- **KEY1**: At least **THREE** generations!
- **KEY2**: Non-trivial *CP* phase,
  Non-trivial unitarity triangle.



$$V_{ud}V^*_{ub}+V_{cd}V^*_{cb}+V_{td}V^*_{tb} = 0$$



- **KEY3**: Non-degenerate like-charge quarks.
- **Jarlskog Invariant**: prop. to quark masses and triangle area *A*.

$$J = (m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2)A$$

$J/T^{12} \sim 10^{-20}$

How could we boost *J* by O(10^{10})?
Adding one more generation of heavy quark is one of the low-cost solutions!

A Low-Cost Solution

See W.S.Hou arXiv:0803.1234 for details.

- If we simply shift the invariant by one generation:

$$\begin{bmatrix} u & c & t \\ d & s & b \end{bmatrix} t' \quad \Rightarrow \quad u \begin{bmatrix} c & t & t' \\ s & b & b' \end{bmatrix}$$

$$J' \sim (m_{t'}^2 - m_c^2)(m_{t'}^2 - m_t^2)(m_t^2 - m_c^2)(m_{b'}^2 - m_s^2)(m_{b'}^2 - m_b^2)(m_b^2 - m_s^2)A'$$

$$\frac{J'}{J} \simeq \frac{m_{t'}^2}{m_c^2}\left(\frac{m_{t'}^2}{m_t^2} - 1\right)\frac{m_{b'}^4}{m_b^2 m_s^2}\frac{A'}{A}$$

The area contributes only a factor of ~30.

For $m(b',t') = 300 \sim 600$ GeV/c^2

already gives us a huge boost of **O(10^{13}~10^{15})** on J!

- Also resolves some known NP hints (e.g. B_s mixing phase).
- A strong motivation for a carpet search at LHC!

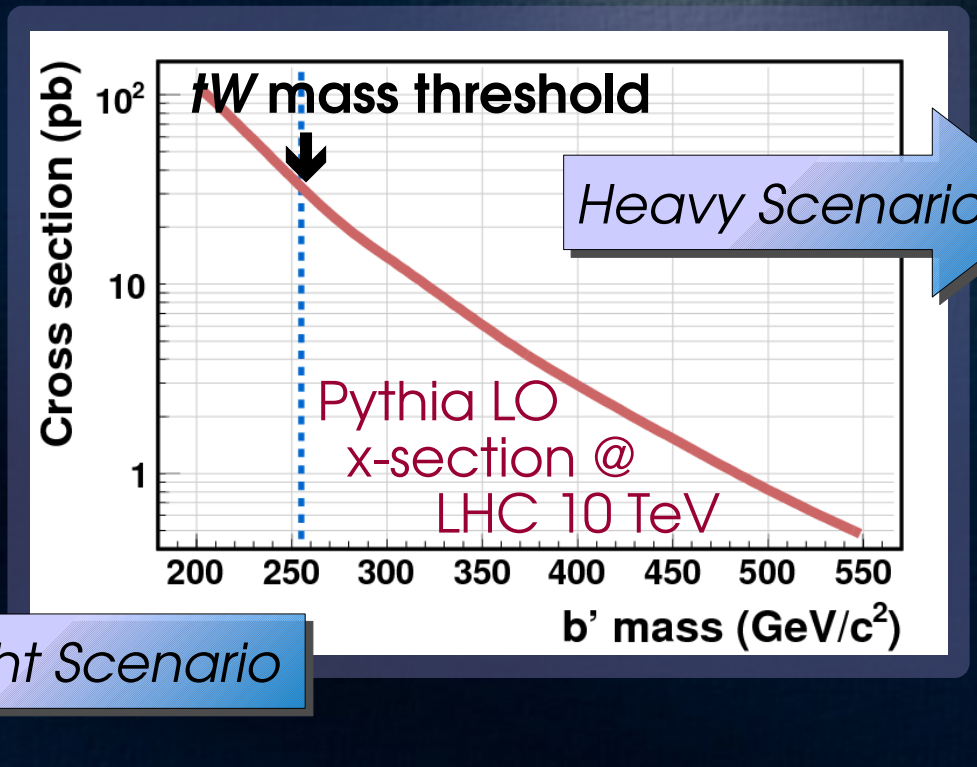
Today we are focusing on the **bottom-like 4th generation quark, *b'*.**

(t' analysis is also working in progress.)

The Decay Pattern of b'

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' → tW dominance

- Lower x-sec.
- Large mass coverage.

Tevatron limits:

M($b' \to tW$) > 325 GeV/c^2.
M($t' \to qW$) > 311 GeV/c^2.
M($b' \to bZ$) > 268 GeV/c^2
(assuming 100% $b' \to bZ$, so it's not really firm).

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

b'/t' Searching Scenarios at CMS

- The searching scenarios:
  based on the combination of decay modes and signature.

Scenario #1
Low mass, decaying into *cWcW*

How to disentangle *b'* form top would be the critical issue.

Scenario #2
Low mass, decaying into *bZcW*

Clear signature, fight for low *bZ* branching fraction, seek for a early discovery.

Scenario #3
High mass, decaying into *qWqW*

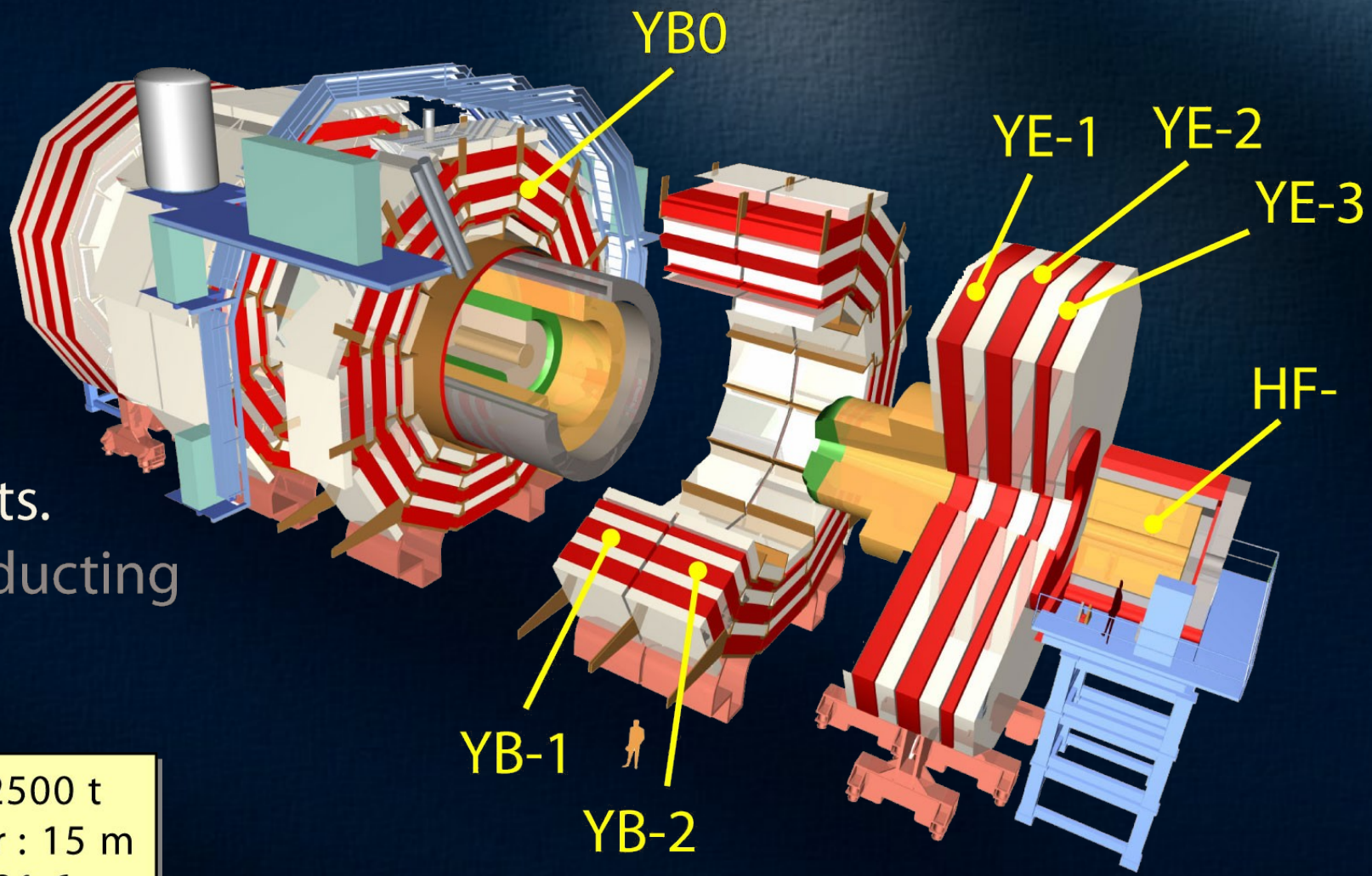
Include possible *t'* and the case of *b'* which is not decaying into tW.

Scenario #4
High mass, decaying into *tWtW*

Composite signature, seek for a method to observe the signal with early data.

#1 and #3 are working in progress, #2 and #4 will be shown today.

The CMS Detector



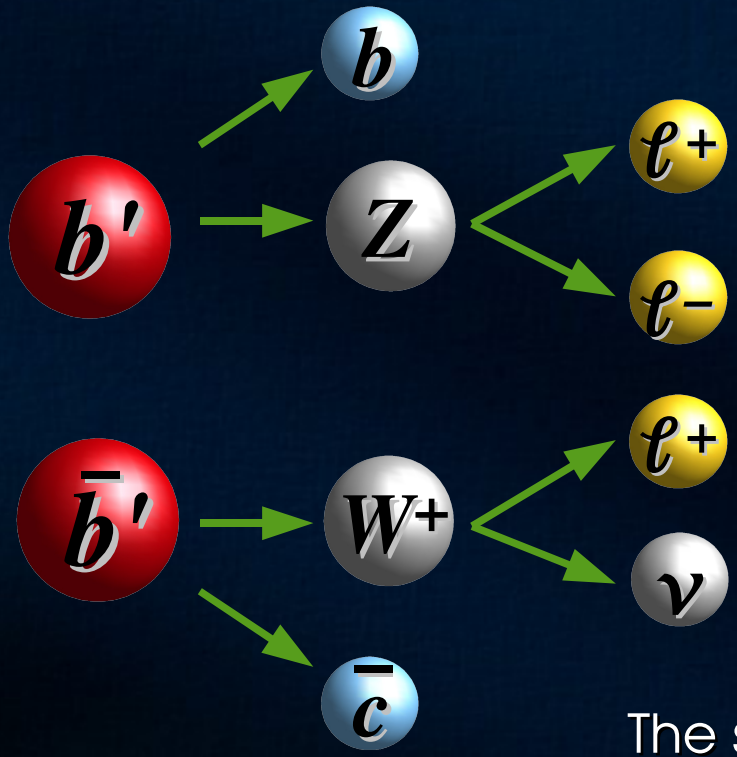
- Pixels
- Tracker
- ECAL
- HCAL
- MUON Dets.
- Superconducting Solenoid

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

A general purpose detector
Acceptance: Calorimetry $|\eta| < 5.0$, Tracking $|\eta| < 2.4$

The Analysis: Light b'b'→bZcW

- Looking for ***b'b'*** → ***cW bZ*** → ***2 jets + 3 leptons + MET*** signature



FCNC *b'→bZ*
10% branching fraction assumed.

Dominate *b'→cW*
90% branching fraction assumed.

The study is looking for a very clean final state with 3 leptons and a constraint of *Z* boson.
But more data is required for the low branching function of ***b'→bZ***.

The Analysis: Light b'b'→bZcW

- **Data set assumption:**
  1 fb^{-1} at 10 TeV recorded by the CMS detector.
- **Trigger:** single electron trigger or single muon trigger.
- **Lepton selections:**
  - ➔ Electrons: isolated from tracks and EM/Hadron clusters, cut-based ID, p_T> 20 GeV/c.
  - ➔ Muons: isolated from tracks and EM/Had. clusters, p_T> 20 GeV.
- ***Z* selection:** 80 < $M(\ell\ell)$ < 100 GeV/c^2, and no other candidate between 60~120 GeV/c^2.
- ***W* selection:** 30 < $M_T = \sqrt{2\,MET\,E_T^l(1-\cos\Delta\phi)}$ < 120 GeV/c^2, daughter charged lepton p_T> 30 GeV.
- **Jet selections:** Iterative cone algorithm of 0.5 radius
  - ➔ At least 2 jets with p_T> 30 GeV/c.

The Analysis: Light b'b'→bZcW

Expected Yields @ 10 TeV 1/fb

b' Signal

Assuming 10% b'→bZ x 90% b'→cW

Process	Yield	S/N
b'b', *M*=200 GeV	29.9	2.2
b'b', *M*=225 GeV	16.7	1.2
b'b', *M*=250 GeV	11.4	0.8

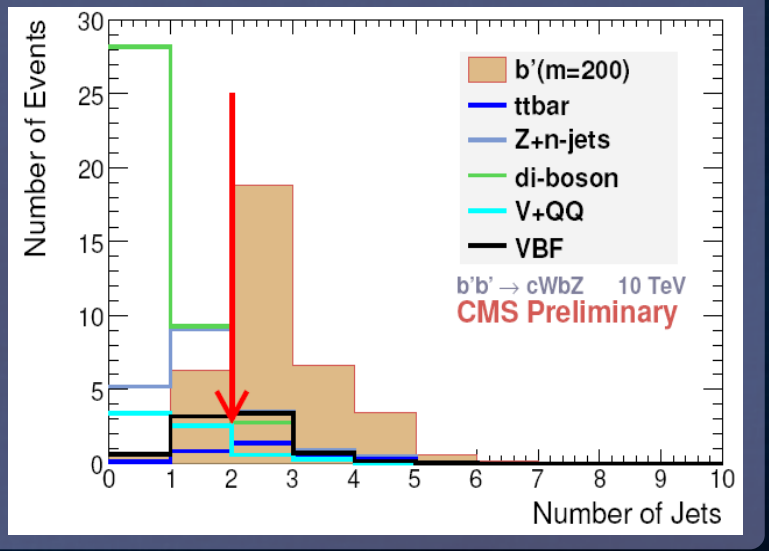
- The signal is clear if *M*(b')~200 GeV or with a larger *bZ* branching fraction.
- Non-trivial background from ***Z+jets*** and ***WZ*** events.

Background Sources

Process	Yield
tt+jets	1.3
Z+jets	4.8
W+jets	<1.1
W/Z+*QQ* (*Q*=*b*,*c*)	0.9
WW	0.1
WZ	2.3
WZ+2*j* VBF	4.1
ZZ	0.3
Sum	**13.8**

QCD background expectation is also small (<1.3 events).

Resulting Figures (200 GeV b')



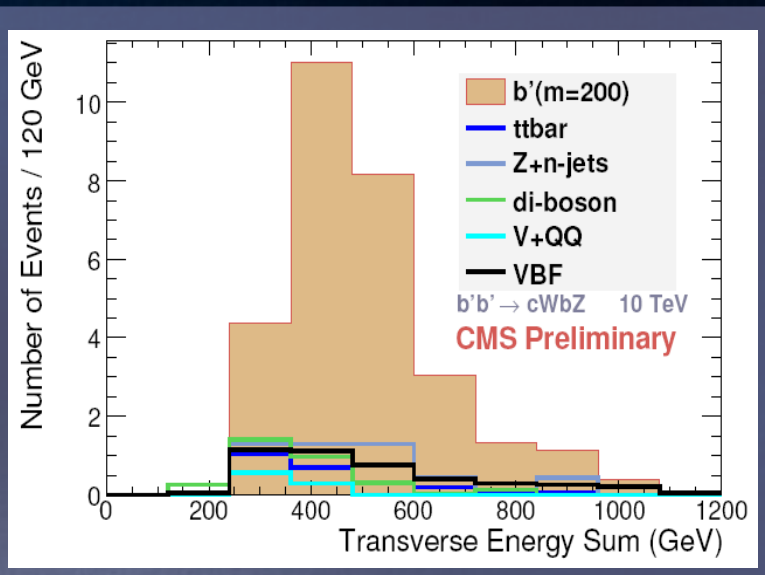
Histograms are normalized to 1/fb luminosity

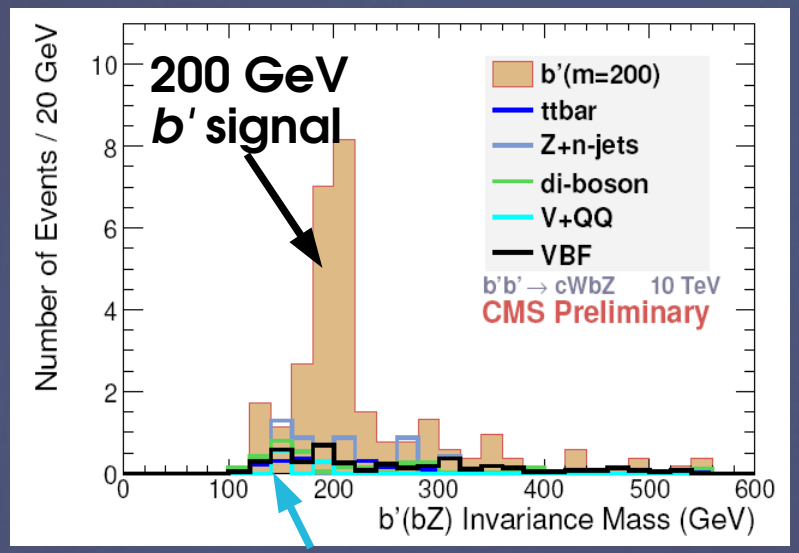
Signal observable(s):

HT = Σp_T(jets) + Σp_T(leps) + MET

and *M(bZ)*

- Pairing by making balanced *bZ* and *cW* in ϕ direction



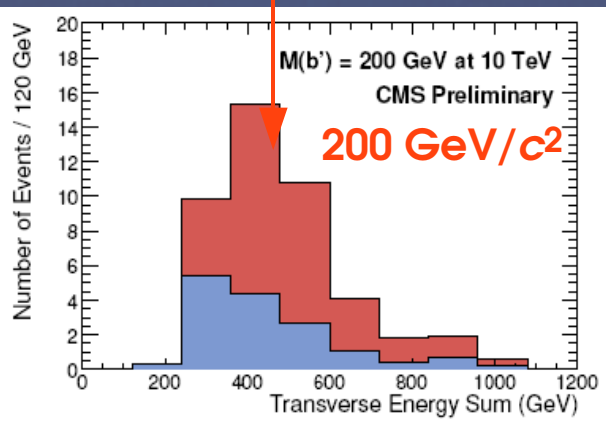


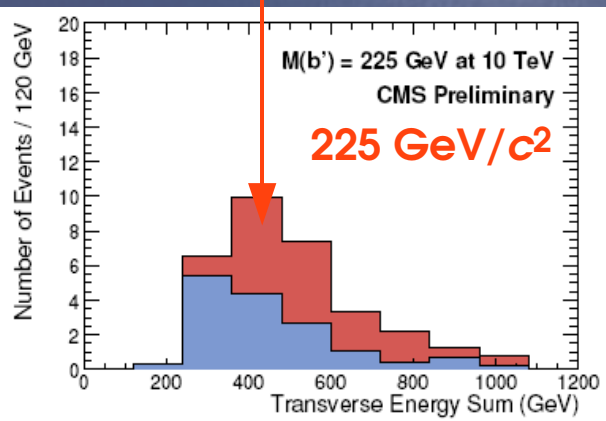
Background, mainly from Z+jets and WZ

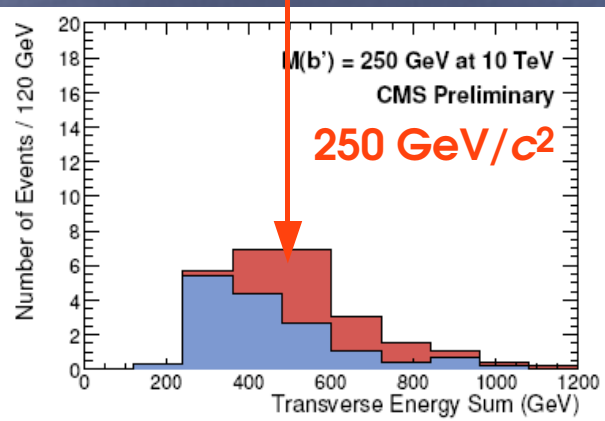
Resulting Figures (Various b' masses)

b' signal, vary with different masses:

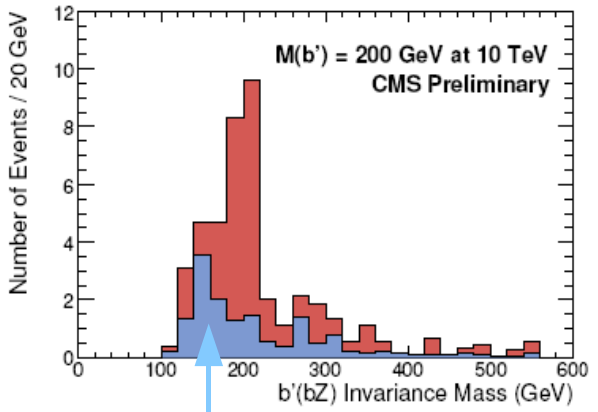
HT:

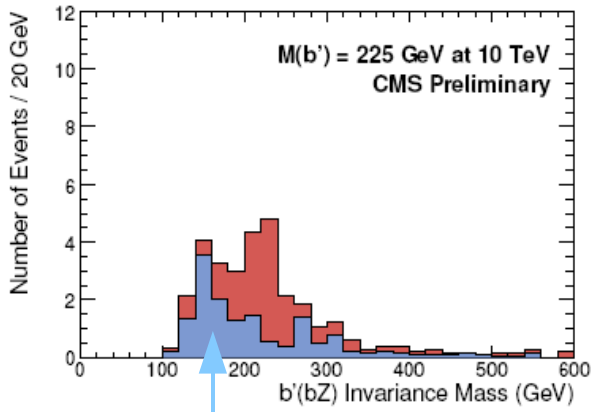


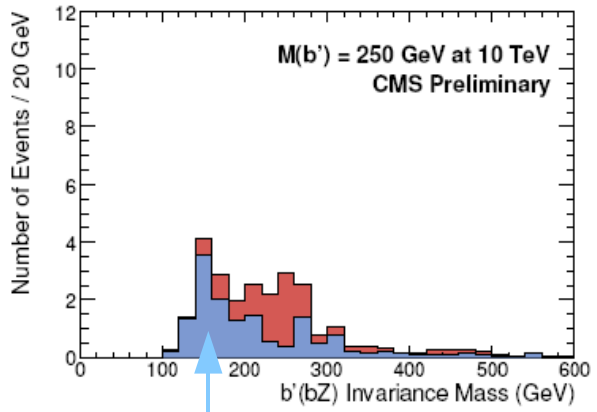




M(bZ):







Background, independent of *b'* assumption

Z+jets & WZ events are normalized using control regions with loser lepton isolation requirements.

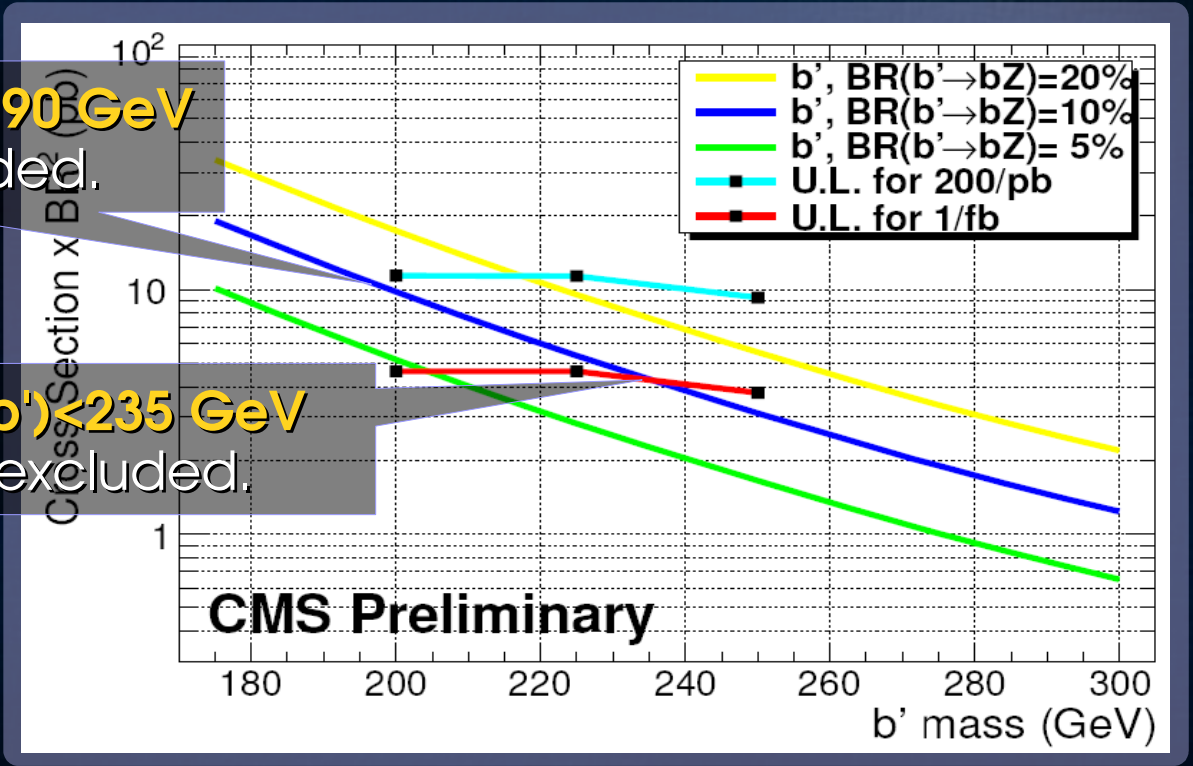
Discovery Potential & Exclusion Limit

M(*b'*) (GeV)	200	225	250
Signal Yield	29.9	16.7	11.4
Background Yield		**13.8**	
Significance	**3.8σ**	**1.9σ**	**1.1σ**

Assuming:
10% b'→bZ x 90% *b'→cW*
1 fb^{-1} data at 10 TeV

For 200/pb, **M(b')<190 GeV** could be excluded.

For 1/fb, **M(b')<235 GeV** could be excluded.



The discovery potential & exclusion limit depend on *b'→bZ* branching fraction.

The Analysis: Heavy b'→tW

- Full decay chain: $b'b' \rightarrow tW\,tW \rightarrow bbW^+W^-W^+W^-$ (4 *W*-bosons!)

Possible final states:

L: Lepton **J**: Jet,
MET: Missing energy

0L + 10J
1L + 8J + MET
2L + 6J + MET
3L + 4J + MET
4L + 2J + MET

5 possibilities in total

Look for **Same-sign dileptons** and **Trileptons** for the first probing of the signal

The Analysis: Heavy b'→tW

- **Data set assumption:**
  200 pb^{-1} at 10 TeV recorded by the CMS detector.
- **Trigger:** single electron trigger or single muon trigger.
- **Lepton selections:**
  - Electrons: cut-based ID, isolated from tracks, p_T> 25 GeV/c.
  - Muons: isolated from tracks and EM clusters, 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:**
  - At least one jet > 85 GeV/c, at least one lepton > 35 GeV/c.
  - 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: Heavy b'→tW

Expected Yields @ 10 TeV 200/pb

b' Signal *Assuming 100% b'→tW*

M(*b'*) (GeV)	300	400	500
N(3L)	8.56	2.75	0.79
N(same-sign 2L)	25.52	7.84	2.72
Sum	**34.08**	**10.58**	**3.52**
S/N	**32**	**9.8**	**3.2**

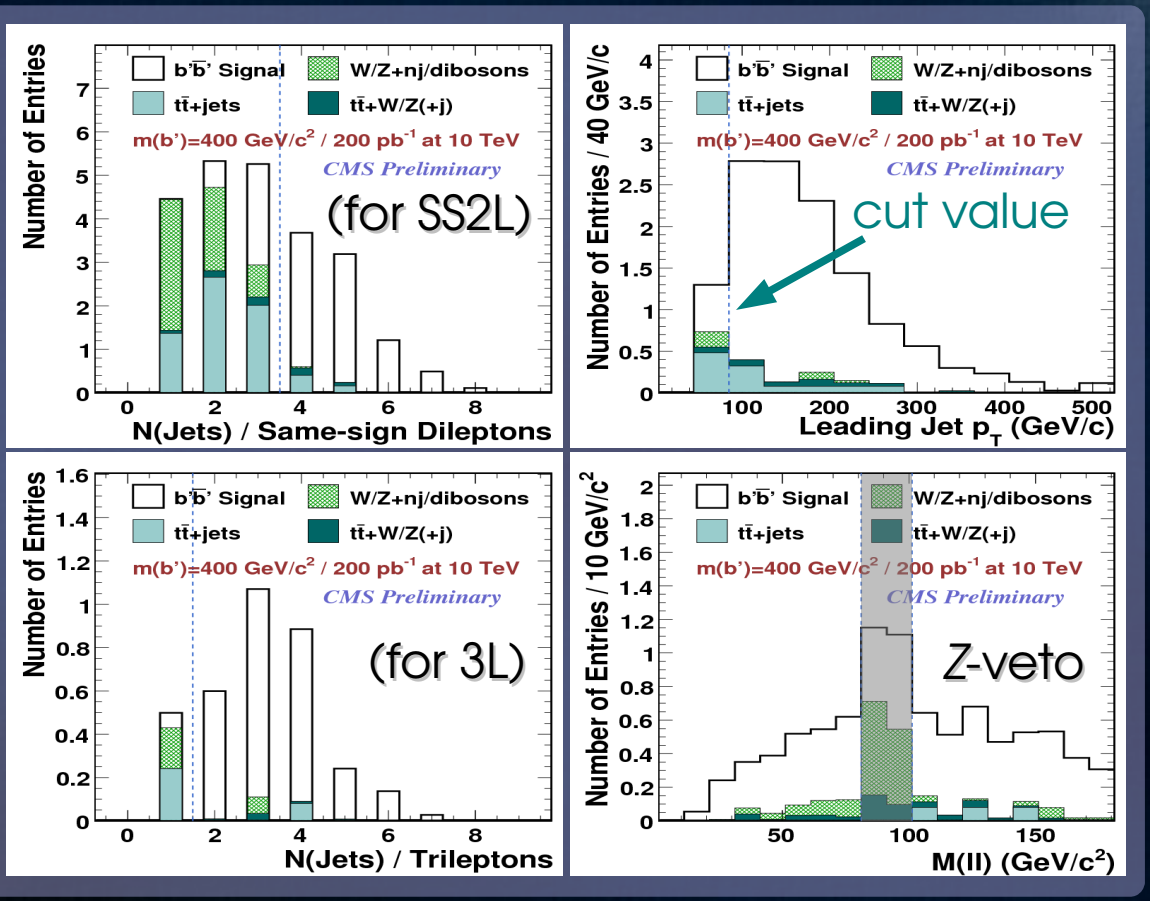
- The signal is very significant with high S/N, up to 300~400 GeV/c^2 *b'*.
- Background is dominated by the **tt+jets** events.

Background Sources

Process	tt+nj	ttZ+j	ttW+j	ttWW	Z/W+nj	dibosons	All
N(3L)	0.08	0.02	0.03	0.004	0.08	<0.08	0.22
N(same-sign 2L)	0.56	0.10	0.17	0.007	<0.11	0.04	0.87
Sum	**0.64**	**0.12**	**0.20**	**0.010**	**0.08**	**0.04**	**1.08**

QCD events are negligible (<0.11 events)

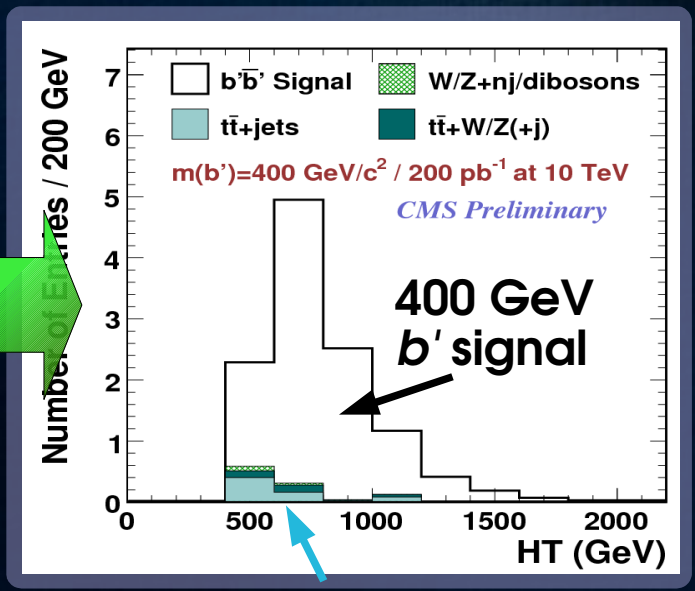
Resulting Figures (300 GeV b')



Signal observable:

HT = Σp_T(jets) + Σp_T(leps) + MET

(carries mass information!)



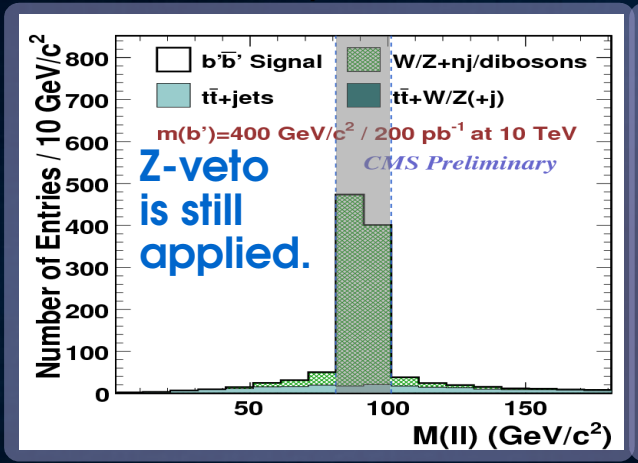
Background, mainly tt+jets

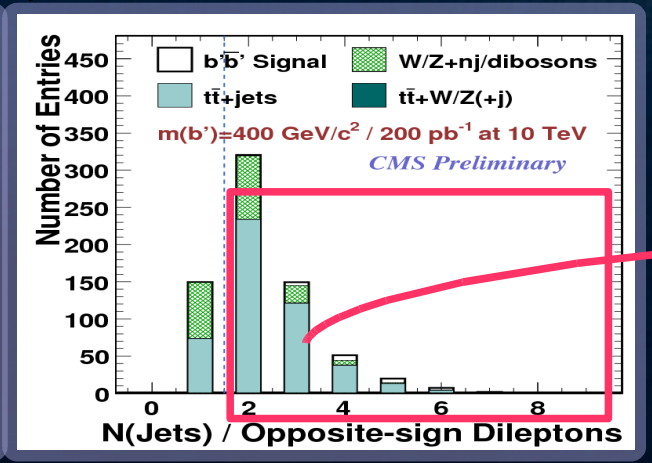
Histograms are normalized to 200/pb luminosity

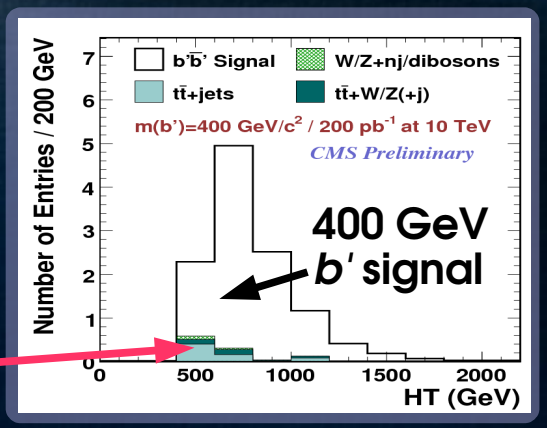
Background Estimation with Data

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

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







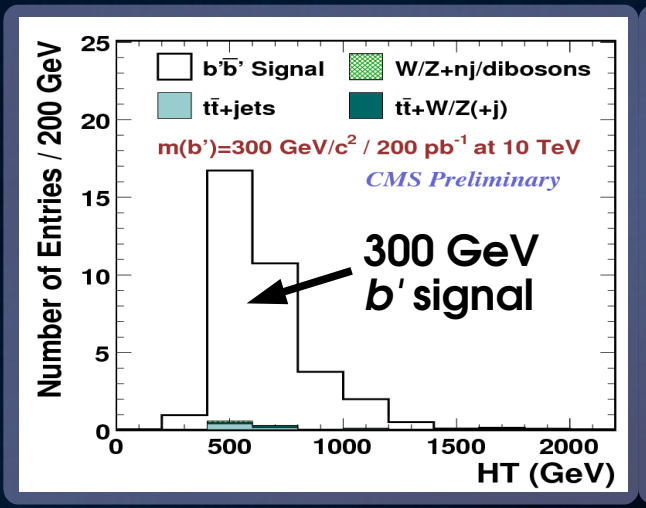
Signal Region

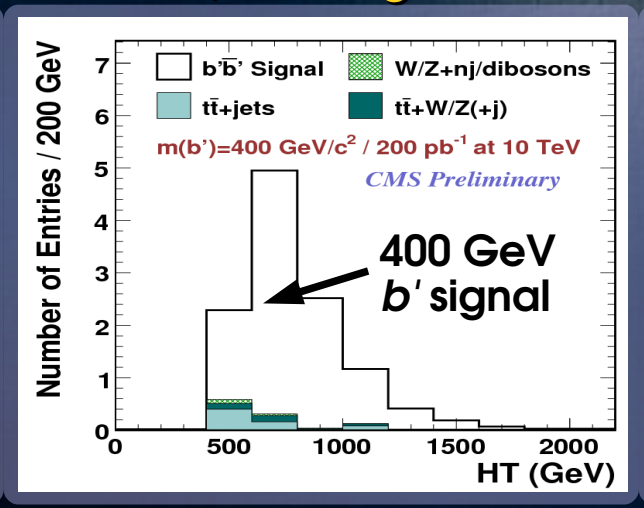
- Governed by the probability to
  - ➔ observe a sign-flipped lepton (become same-sign 2L)
  - ➔ find an extra (fake) lepton (become 3L)

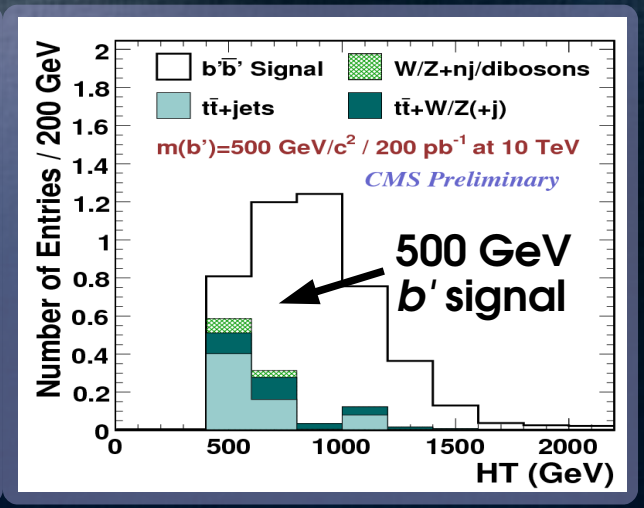
This is the dominant systematic error (6%~34%, depends on b' mass).
Other big errors are Jet energy scale (14%~20%), PDF (7%~11%).
All the systematic uncertainties are determined assuming the early condition.

Significance Calculation

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







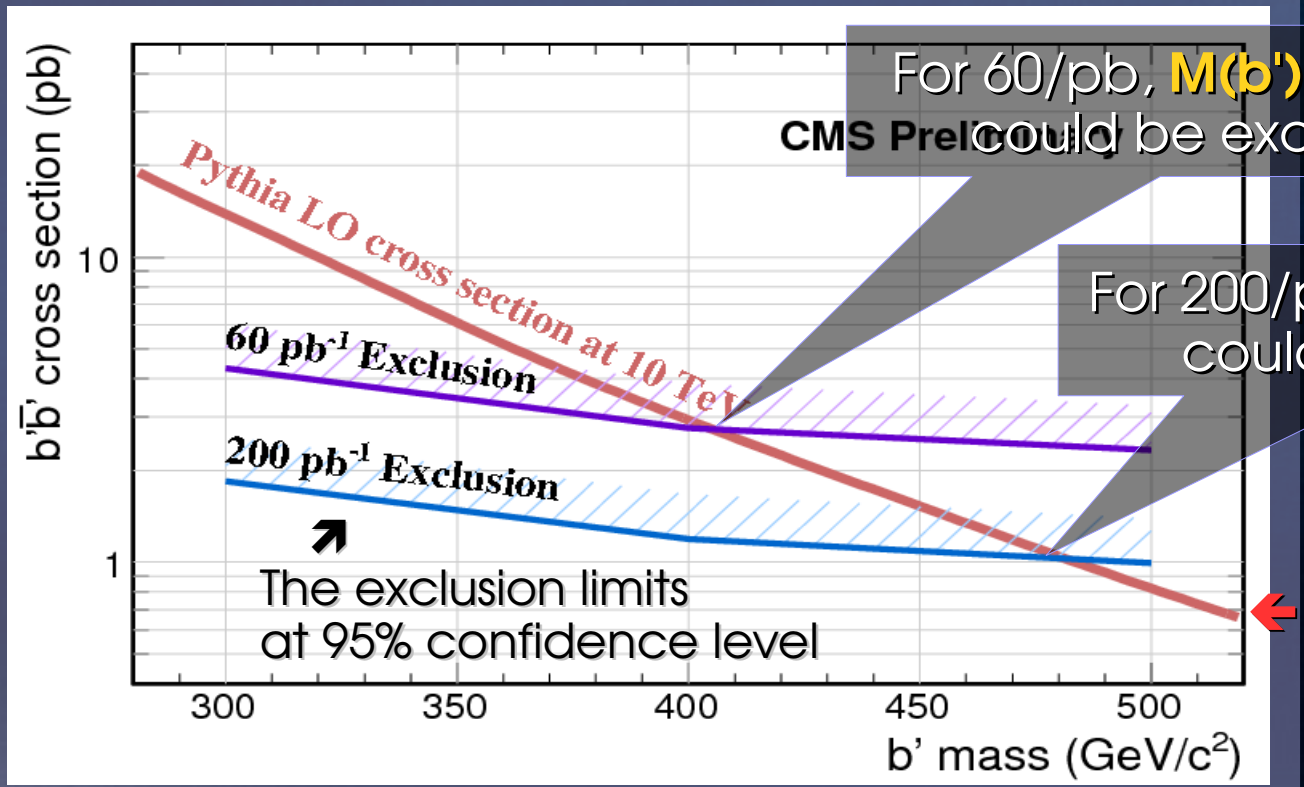
M(b') (GeV)	300	400	500
$b'b'$ LO cross section (pb)	13.6	2.80	0.78
Signal Yield	34.08	10.58	3.52
Background Yield		**1.08 +1.23/–0.72**	
Significance (stat.+syst.)	**9.0σ**	**3.7σ**	**1.4σ**

Background is independent of b' mass.

*Quite significant (**3.7σ**) even if M(b') = 400 GeV/c^2.*
Not significant at all for 500 GeV/c^2, need more data and/or tighter cuts.

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:

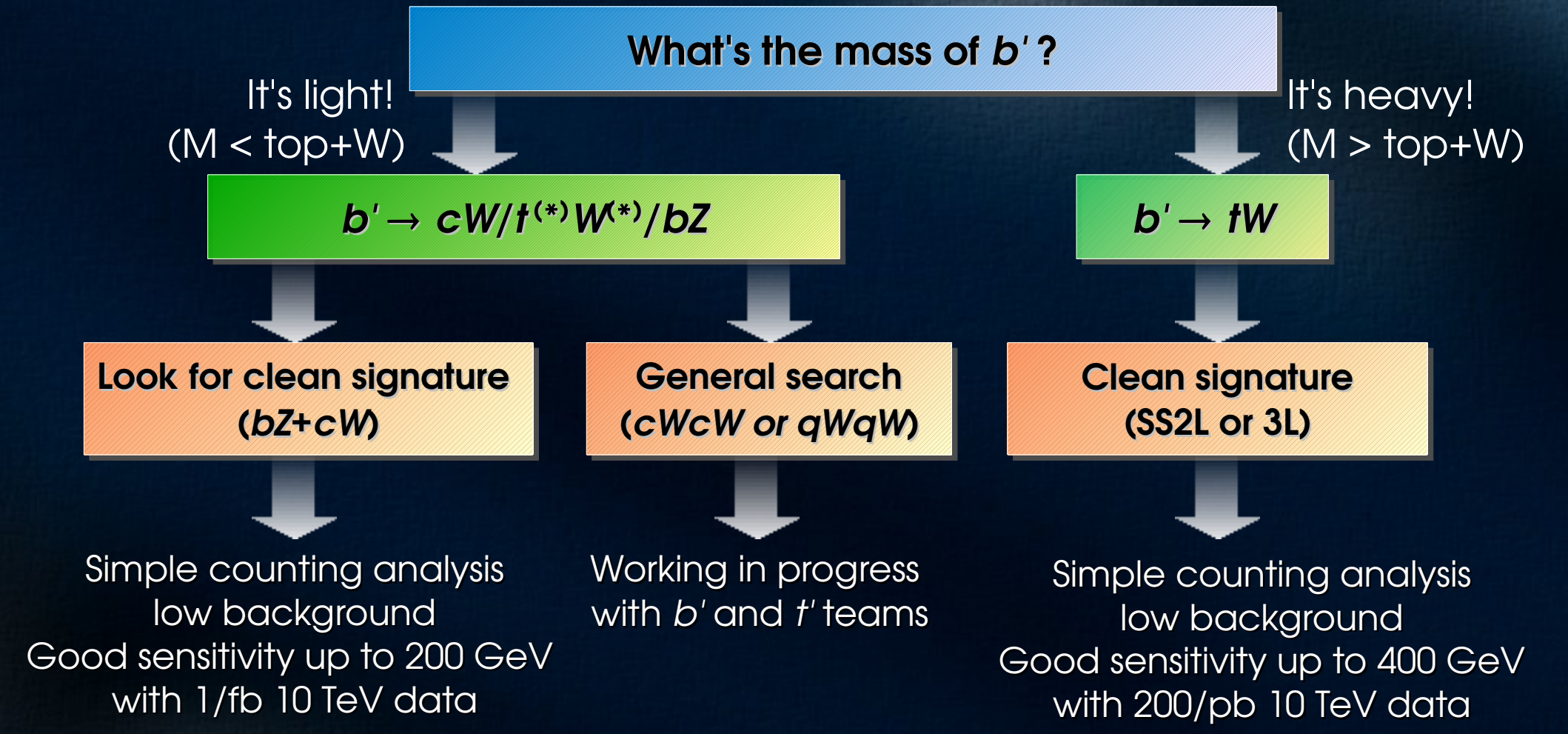


For 60/pb, **M(b')<405 GeV** could be excluded.

For 200/pb, **M(b')<485 GeV** could be excluded.

***b'* production cross section as a function of its mass at LHC (leading-order).**

Summary: b' Searches Roadmap



Let's wait for the first data from LHC!