Detecting Fourth Generation Heavy Quarks at The LHC

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Outline

- Why the fourth generation?
  - Baryogenesis
  - Tensions within the CKM paradigm
- Current bounds on fourth generation quarks
- Could a fourth generation be discovered at the LHC
- Conclusions

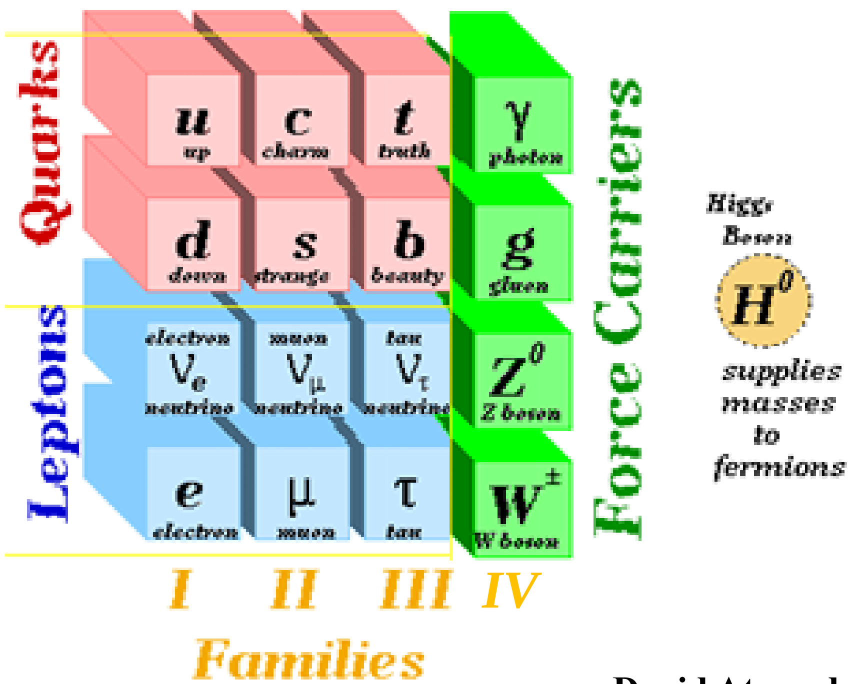
Why the Fourth Generation

What is the Fourth Generation?

- The Standard Model $SU(3) \times SU(2) \times U(1)$ is the simplest renormalizable theory which explains (more or less) all the particles and interactions which have been seen to date.

A Fourth generation of the SM

•Assume the fourth generation is sequential (analogous to the first three generations)



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Sakharov's Conditions

In 1968 Sakharov proved that the CPT theorem implies the following three conditions are required for baryogenesis.

- Baryon number violation
- CP violation
- Thermal non-equilibrium

$$< B >= Tr(e^{-\beta H} B) = Tr(e^{-\beta H}[cpt]B[cpt]^{+}) = - < B >$$

Baryon asymmetry is only 10^{-8} because all the antimatter annihilated 99.999999% of the matter leaving 0.000001% we have today.

Baryogenesis with 3 Generations

- The CP violation needed to drive baryogenesis cannot be provided by the three generation standard model
- The main reason is that the masses of first two generations are so small
- All of the information about CP violation from the quark sector is contained in the mass matrices

$$L_q = -M^d_{ij}\bar{d}_{Li}d_{Rj} - M^u_{ij}\bar{u}_{Li}u_{Rj} + h.c.$$

$$M = \frac{<v>}{\sqrt{2}}\lambda$$

- If there are only 2 generations, then there is a unique CP odd invariant which can be constructed from these matrices and is invariant under field redefinitions (Jarlskog 1987):

$$J = \mathrm{Im}\det[M_u M_u^\dagger M_d M_d^\dagger]$$

$$= 2(m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)$$

$$(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2)A$$

- Where A is the area of the unitarity triangle

Baryogenesis with 3 Generations

- Numerically, this quantity is very small:

$$\frac{J}{<v>^{12}} \sim 10^{-20}$$

- This quantifies the CP violation one has access to during the phase transition.
- Model calculations indicate that this falls short of the needed level of baryogenesis by at least 10 orders of magnitude.

Baryogenesis with 4 Generations

- With four generations, one can construct 3 independent CP odd combinations of the mass matrices, one of which is proportional to two of the bigger masses

$$J_{234} = 2(m_{t'}^2 - m_t^2)(m_{t'}^2 - m_c^2)(m_t^2 - m_c^2)$$
$$(m_{b'}^2 - m_b^2)(m_{b'}^2 - m_s^2)(m_b^2 - m_s^2)A_{234}$$

- From the mass dependence, there is a huge gain over the single three generation invariant just from the mass dependences:

$$\frac{J_{234}}{J} \sim 10^{15-17}$$

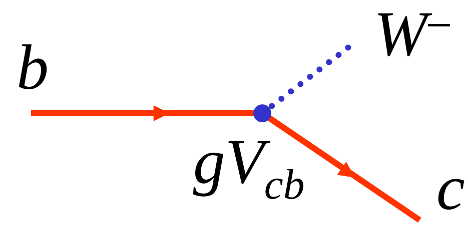
- Baryogenesis now becomes possible [W. S. Hou 2008]
- One advantage of this kind of model over CP viol. from random new physics is that fermion edm's are naturally small.

Phase Transitions

- There is, however the issue of generating a strong enough phase transition.
- Naively with the current higgs mass bounds, it seems not to work because the cubic coupling is too small if m_H >70GeV [e.g. Dine et. al. 2004], however this could change in the following ways:
  - Extra higgs sector [e.g. Dine et al 2004]
  - If the quark masses are on the high side, the large yukawas could lead to the correct kind of phase transition [Carena et. al. 2005]; this has not been proven in a lattice calculation.
- Thus, SM+4 gen might be the simplest model explaining all experiments and baryogenesis.

Consistency of the CKM picture

- The coupling strength at the vertex is given by gV_{ij}
  - g is the universal weak coupling
  - V_{ij} depends on which quarks are involved
  - For leptons, the coupling is just g



- The Standard Model predicts that V_{CKM} is unitary.

$$\mathbf{V}_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Look at unitarity relation for these two columns

- There is only one physical phase in this matrix modulo rephasing of rows and columns which is just the A factor in the Jarlskog invariant.

Consistency of CKM Picture

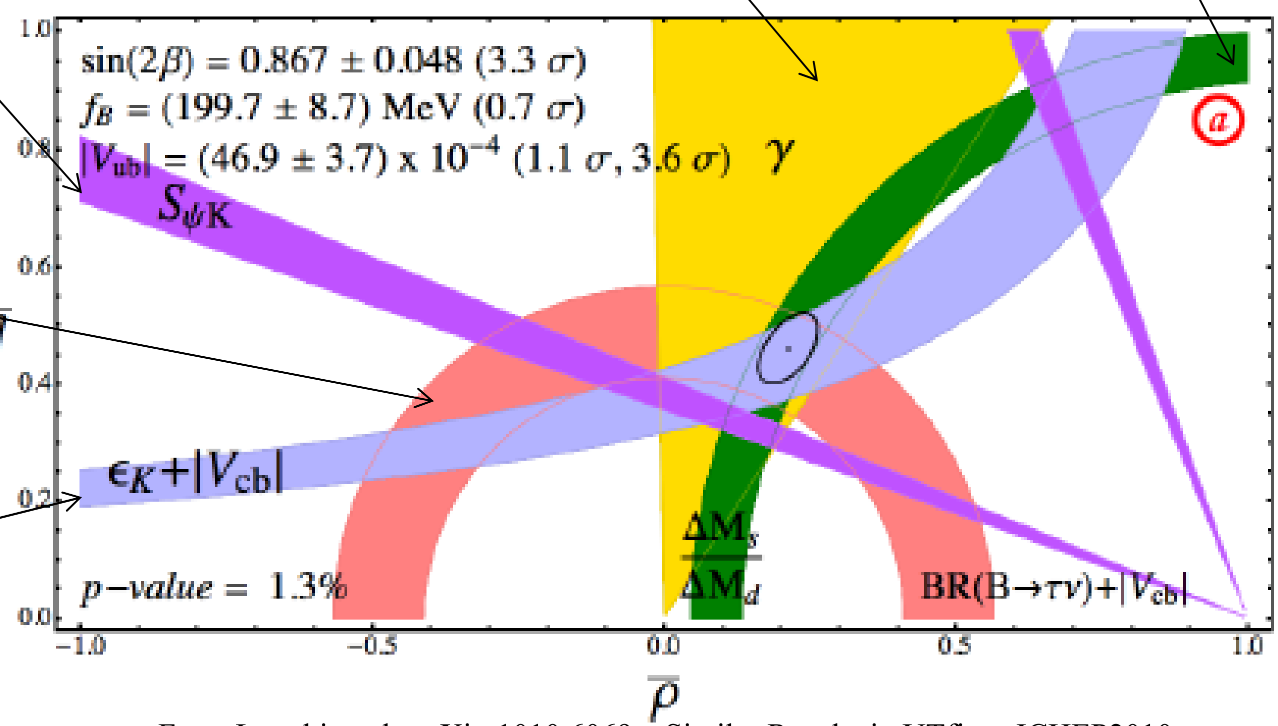
Rate of Bs oscillation

"Gold plated" oscillation in $B \to \psi K_s$.

Determination of γ.

Br($B \to \tau\nu$)

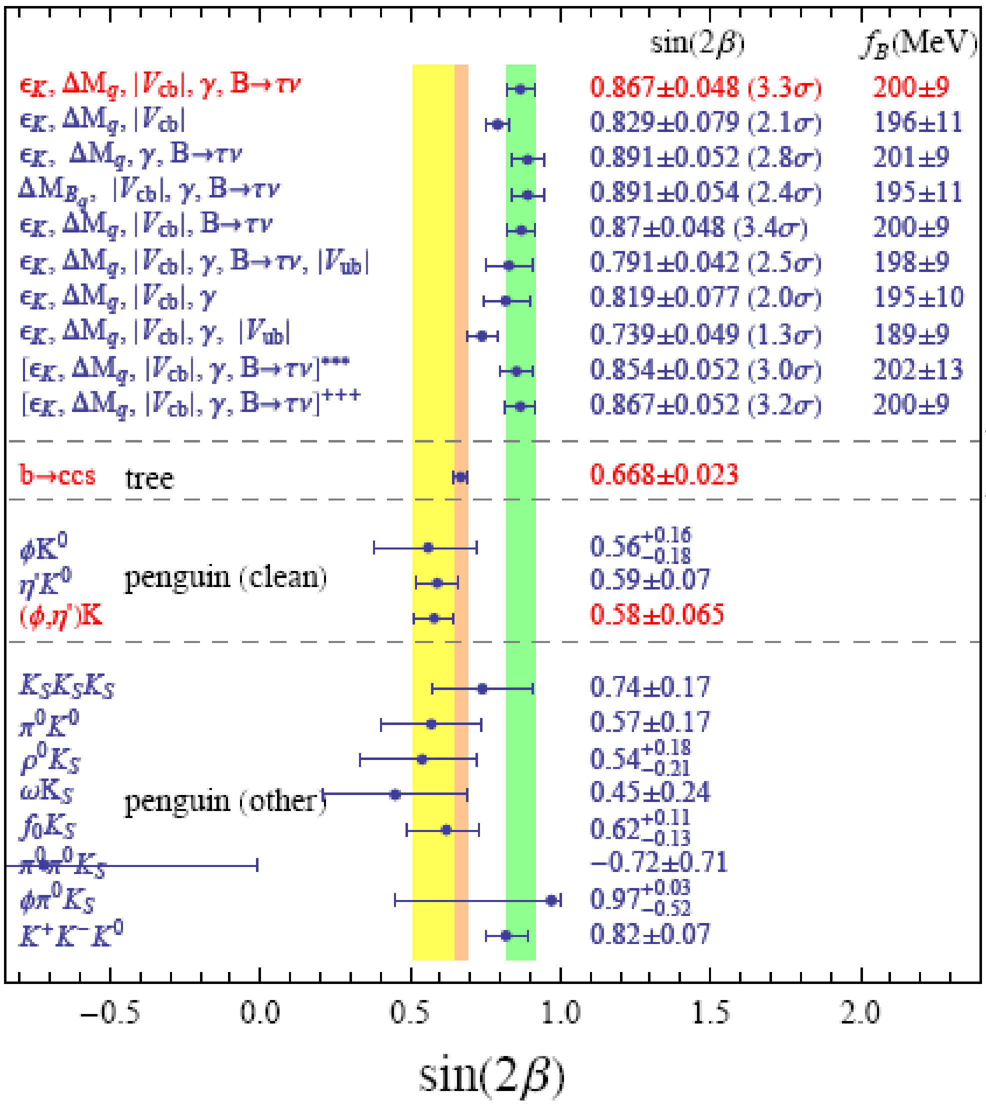
CP Violation in K_L



From Lunghi et al., arXiv:1010.6069 Similar Results in UTfitter ICHEP2010

Consistency of Sin2β Between Modes

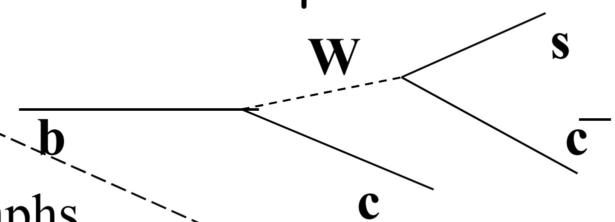
For More details see Soni's talk in the CP section yesterday



From Lunghi et al., arXiv:1010.6069

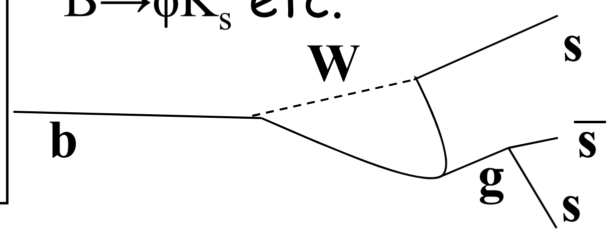
Sin(2β) as inferred from other inputs.

B→ψK_s and related processes



Penguin graphs

B→φK_s etc.



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Current bounds on fourth generation quarks

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The Latest Results from CDF

Bottom Line:

CDF Limits from Luk Talk Tuesday

- **$34pb^{-1} \Rightarrow m_{b}$'>361 GeV (trilepton)**
- **$573pb^{-1}$ (e)+ $821pb^{-1}$ (μ) $\Rightarrow m_{t}$'>450 GeV (single lepton)**

Previous LEP bounds

- **m_L>100GeV (LEP)**
- **m_N>90.3GeV (LEP)**

Could a fourth generation be discovered at the LHC

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Production of Heavy Quarks

Both t' and b' are mostly produced by gluon fusion

In the following we will apply the following assumptions. Note that the conclusions should apply more generally

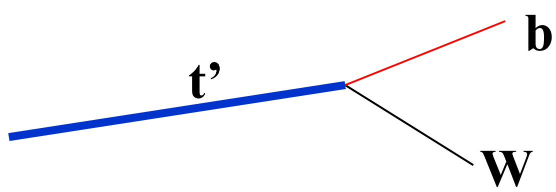
1) **t'-b' Mass splitting < M_W: This is motivated by oblique corrections**

2) **The heavier t' has a large enough CKM (typically >10^{-3}) with lower generations that it undergoes a 2 body decay.**

Atwood, Gupta, Soni arXive 1104:3874

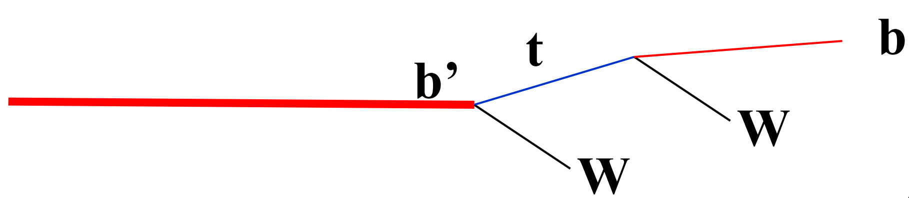
Decays of Heavy Quarks

Following the Assumptions on the last slide



$$t' \to bW$$

Just like a normal top
But more massive



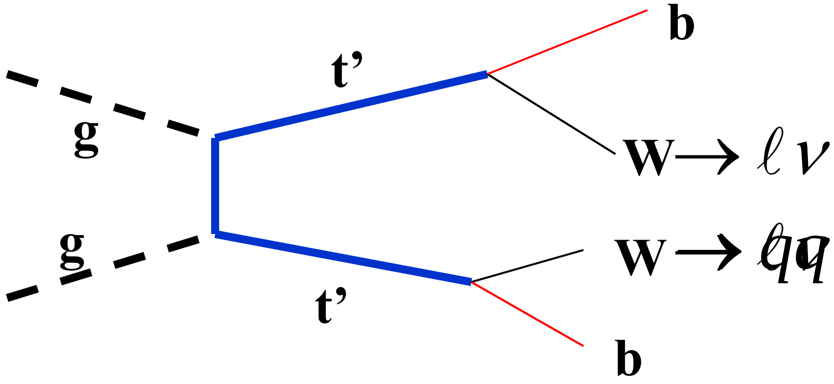
$$b' \to tW \to bWW$$

Assuming Vtb' dominates so the top gives us an extra W

If Vcb' is large enough then the final state is cW which has identical kinematics to bW from t' decay

Overall Signals

Top' Production and Decay



Overall

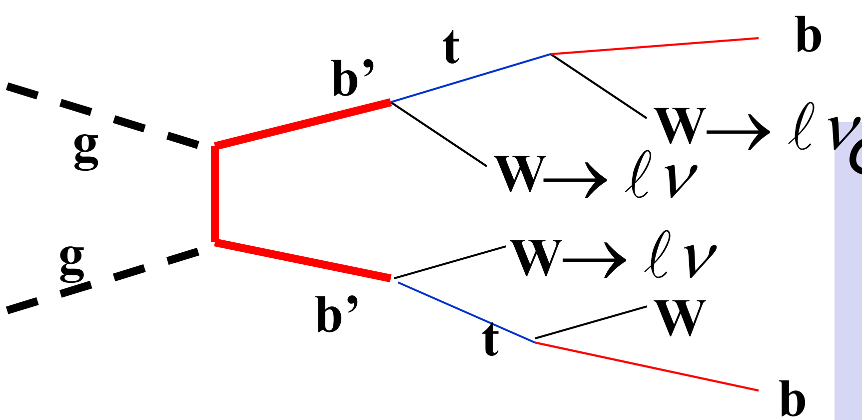
$$g+g \rightarrow t'\,\overline{t'} \rightarrow b\bar{b}W^{+}W^{-}$$

Observable Final States after W Decay

1 Lepton $\rightarrow 4\,jets + \ell + \nu$

2 Lepton $\rightarrow 2\,jets + \ell^{+}\ell^{-} + 2\nu$

Bottom' Production and Decay



Overall

$$g+g \rightarrow b'\,\overline{b'} \rightarrow b\bar{b}\;\; 2W^{+}\;\; 2W^{-}$$

Observable Final States after W Decay

1 Lepton $\rightarrow 8\,jets + \ell + \nu$

2 Lepton $\rightarrow 6\,jets + \ell^{+}\ell^{-} + 2\nu$

2 Lepton $\rightarrow 6\,jets + \ell^{+}\ell^{+} + 2\nu$

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Three Event Samples

- Single Lepton (SL) =1 Lepton + jets + missing P_T.
  - Both b′ and t′ feed into this channel
  - SM3 background: largely from regular top
- Same Sign Dilepton (SSD)= $\ell^+ \ell^+$ + jets + missing P_T.
  - Only b′ feeds into this channel.
  - No significant SM3 background
- Opposite Sign Dilepton (OSD)= $\ell^+ \ell^-$ + jets + missing P_T.
  - Both b′ and t′ feed into this channel
  - SM3 background: largely from regular top.
  - In b′ case there are three distinct scenarios.

Basic Cuts

- In our event selection we use the following cuts

$$P_{T\ell} > 25\text{GeV}; \qquad |\eta_\ell| < 2.7$$

$$P_{Tj} > 25\text{GeV}; \qquad |\eta_j| < 2.7$$

$$\Delta R_{jj}, \Delta R_{j\ell}, \Delta R_{\ell\ell} > 0.4$$

$$\not{E}_T > 30\text{GeV}$$

Basic

$$H_T > 350\text{GeV}$$

Additional

Numbers in Each Channel

In each block the numbers are (SL, OSD, SSD)

Quark	$\sqrt{s}$ (TeV)	cuts	$m_Q = 300$ GeV	$m_Q = 450$ GeV	$m_Q = 600$ GeV	SM background
t'	14	*Basic*	6469, 552, 0	824, 73, 0	170, 15, 0	221833, 16479, 8.8
t'	14	$Basic + H_T > 350$ GeV	5571, 464, 0	809, 71, 0	169, 14, 0	46846, 3472, 6.4
t'	10	*Basic*	2404, 188, 0	272, 22, 0	49, 5, 0	63609, 4467, 4.2
t'	10	$Basic + H_T > 350$ GeV	2074, 158, 0	265, 21, 0	49, 5, 0	12013, 847, 3
t'	7	*Basic*	785, 61, 0	69, 6, 0	10, 1, 0	22847, 1621, 1.7
t'	7	$Basic + H_T > 350$ GeV	668, 50, 0	67, 6, 0	10, 1, 0	4054, 275, 1.2
b'	14	*Basic*	8948, 1210, 625	1092, 166, 86	224, 35, 18	221833, 16479, 8.8
b'	14	$Basic + H_T > 350$ GeV	7293, 960, 582	1057, 159, 84	221, 35, 17	46846, 3472, 6.4
b'	10	*Basic*	3312, 457, 220	370, 54, 28	65, 10, 6	63609, 4467, 4.2
b'	10	$Basic + H_T > 350$ GeV	2654, 358, 212	356, 52, 27	64, 10, 6	12013, 847, 3
b'	7	*Basic*	1060, 145, 74	94, 13, 7	14, 2, 1	22847, 1621, 1.7
b'	7	$Basic + H_T > 350$ GeV	841, 113, 70	90, 13, 7	13, 2, 1	4054, 275, 1.2

TABLE I: Number of signal and background events for a number of scenarios. In each case, the three numbers indicate the single lepton; opposite sign dileptons (OSD) and same sign dileptons (SSD) events from the t'- and b'-pair production at the LHC for $\sqrt{s} = 14$, 10 and 7 TeV and $\int \mathcal{L}dt = 1$ fb^{-1} without the requirement of isolation on jets. The basic cuts are: $p_{T_{l,j}} > 25$ GeV, $|\eta_{l,j}| \leq 2.7$; $\Delta R_{l,l}, \Delta R_{l,j} \geq 0.4$ and $\not{E}_T > 30$ GeV.

Bottom Line: For the SL and OSD case you need to delve into the kinematics to pull out a signal.

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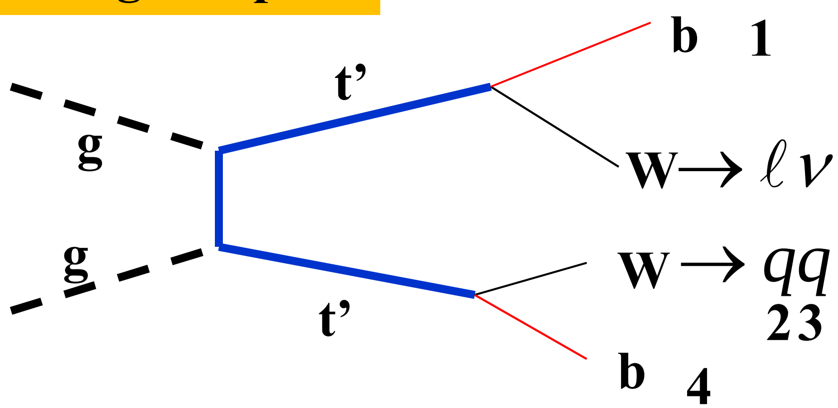
Kinematics of t': Single Lepton

t' /Single Lepton



4 Unknowns

$$p_\nu \to 4?$$

5 Constraints

$$p_{\nu x} = \not{p}_x$$

$$p_{\nu y} = \not{p}_y$$

$$(p_\nu)^2 = 0$$

$$(p_\nu + p_\ell)^2 = m_W^2$$

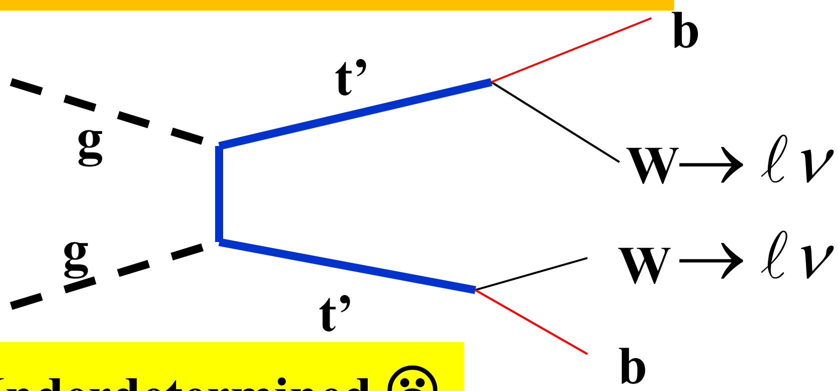
$$(p_\nu + p_\ell + j_1)^2 = (j_2 + j_3 + j_4)^2$$

Overdetermined ☺

Same is true of b' pair to single lepton + jets

Kinematics of t': Opposite Sign Dilepton

t' /Opposite Sign Lepton Pair



Underdetermined ☹

8 Unknowns

$$p_{\nu 1} \to 4?$$
$$p_{\nu 2} \to 4?$$

7 Constraints

$$p_{\nu 1x} + p_{\nu 2x} = \not{p}_x \qquad p_{\nu 1y} + p_{\nu 2y} = \not{p}_y$$

$$(p_{\nu 1})^2 = 0 \qquad (p_{\nu 2})^2 = 0$$

$$(p_{\nu 1} + p_{\ell 1})^2 = m_W^2 \qquad (p_{\nu 2} + p_{\ell 2})^2 = m_W^2$$

$$(p_{\nu 1} + p_{\ell 1} + j_1)^2 = (p_{\nu 2} + p_{\ell 2} + j_2)^2$$

Solution: Use the approximation that the two quarks are at rest wrt each other.

Same is true of b' pair to OSD <u>if the leptons are from prompt W's</u> (case III)

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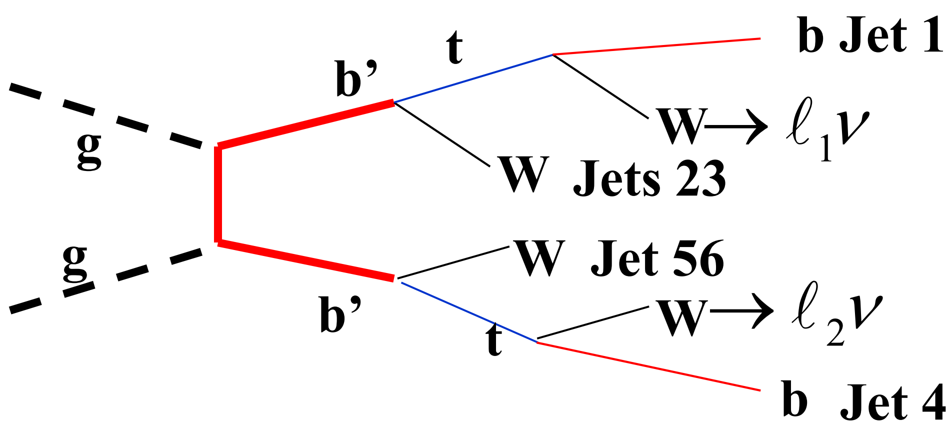
Kinematics of b': Oppsite Sign Dilepton case I

b' /Opposite Sign Dilepton (I)



8 Unknowns

$$p_{\nu 1} \to 4?$$
$$p_{\nu 2} \to 4?$$

9 Constraints

$$p_{\nu 1x} + p_{\nu 2x} = \not{p}_x \qquad p_{\nu 1y} + p_{\nu 2y} = \not{p}_y$$

$$(p_{\nu 1})^2 = 0 \qquad (p_{\nu 2})^2 = 0$$

$$(p_{\nu 1} + p_{\ell 1})^2 = m_W^2 \qquad (p_{\nu 2} + p_{\ell 2})^2 = m_W^2$$

$$(p_{\nu 1} + p_{\ell 1} + j_1)^2 = m_t^2 \qquad (p_{\nu 2} + p_{\ell 2} + j_2)^2 = m_t^2$$

$$(p_{\nu 1} + p_{\ell 1} + j_{123})^2 = (p_{\nu 2} + p_{\ell 2} + j_{456})^2$$

Overdetermined ☺

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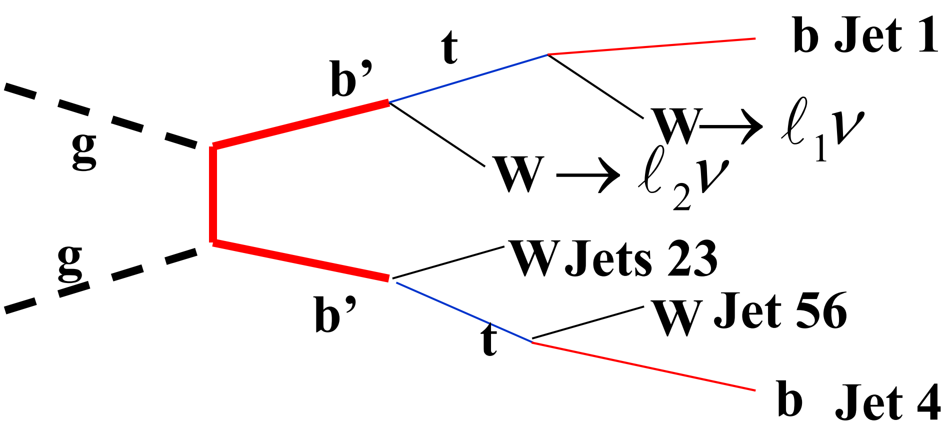
Kinematics of b':Oppsite Sign Dilepton case II

b' /Opposite Sign Dilepton (II)



Determined ☺

8 Unknowns

$$p_{\nu 1} \to 4?$$
$$p_{\nu 2} \to 4?$$

8 Constraints

$$p_{\nu 1x} + p_{\nu 2x} = \not{p}_x \qquad p_{\nu 1y} + p_{\nu 2y} = \not{p}_y$$

$$(p_{\nu 1})^2 = 0 \qquad (p_{\nu 2})^2 = 0$$

$$(p_{\nu 1} + p_{\ell 1})^2 = m_W^2 \qquad (p_{\nu 2} + p_{\ell 2})^2 = m_W^2$$

$$(p_{\nu 1} + p_{\ell 1} + j_1)^2 = m_t^2$$

$$(p_{\nu 1} + p_{\ell 1} + p_{\nu 2} + p_{\ell 2} + j_1)^2 = (j_{23456})^2$$

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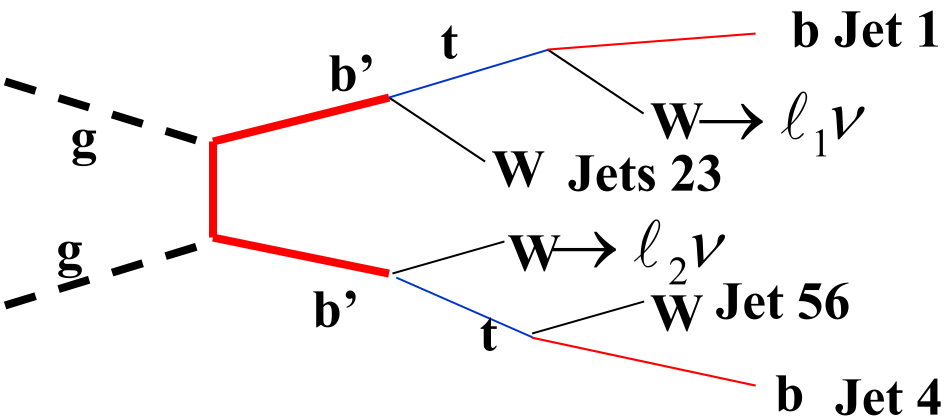
Kinematics of b’: Same Sign Dilepton

b’ /Same Sign Dilepton



Determined 😐

<u>8 Unknowns</u>

$$p_{\nu 1} \rightarrow 4?$$
$$p_{\nu 2} \rightarrow 4?$$

<u>8 Constraints</u>

$$p_{\nu 1x} + p_{\nu 2x} = \not{p}_x \qquad p_{\nu 1y} + p_{\nu 2y} = \not{p}_y$$

$$(p_{\nu 1})^2 = 0 \qquad (p_{\nu 2})^2 = 0$$

$$(p_{\nu 1} + p_{\ell 1})^2 = m_W^2 \qquad (p_{\nu 2} + p_{\ell 2})^2 = m_W^2$$

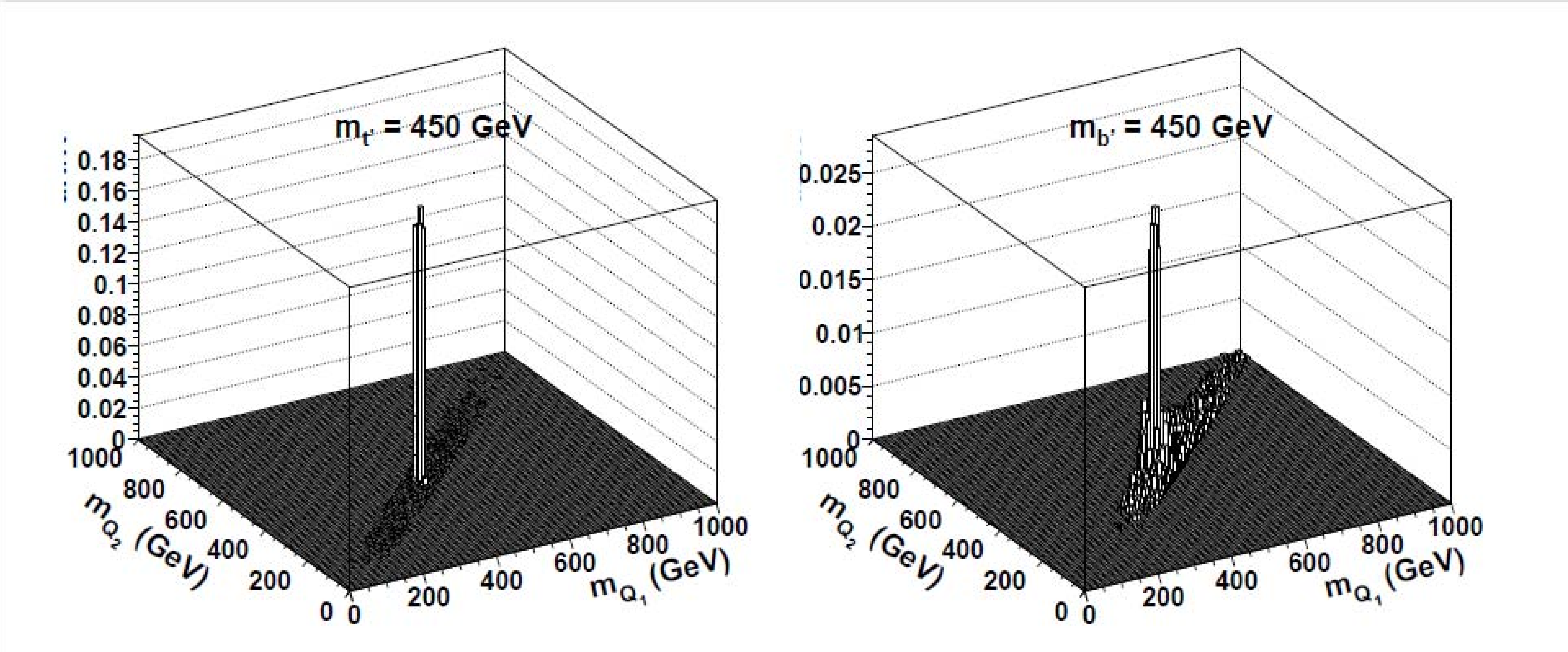
$$(p_{\nu 1} + p_{\ell 1} + j_1)^2 = m_t^2$$

$$(p_{\nu 1} + p_{\ell 1} + j_{123})^2 = (p_{\nu 2} + p_{\ell 2} + j_{456})^2$$

Single Lepton Signal

- Both for t′ and b′
- This case is overdetermined so **<u>if</u>** you have the right jet partition then you can separately reconstruct the mass of each side of the event.
- These two masses should be equal to each other and equal to the heavy quark mass.
- Wrong jet partitions tend to fail to have equal reconstructed masses or do not have physical kinematic solutions.

m1 versus m2 plots

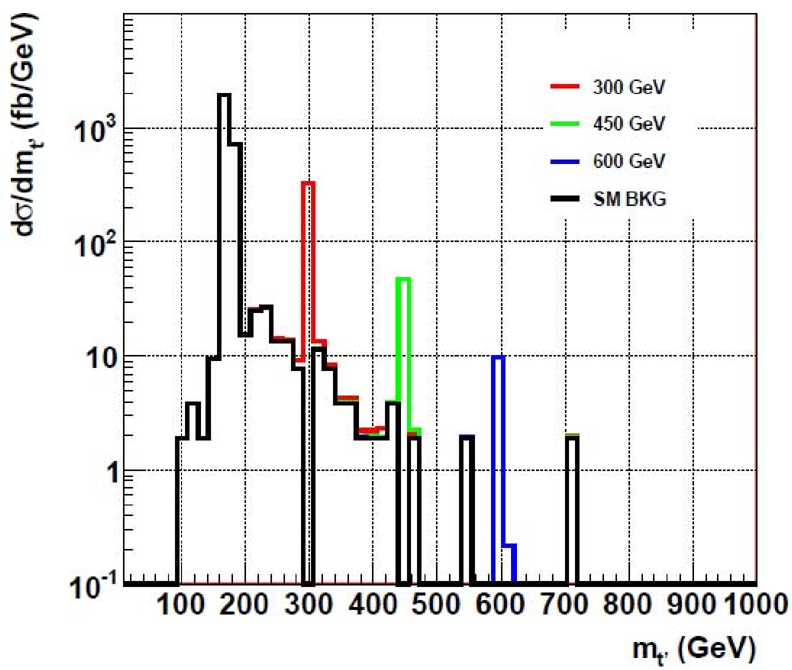


t' case **b' case**

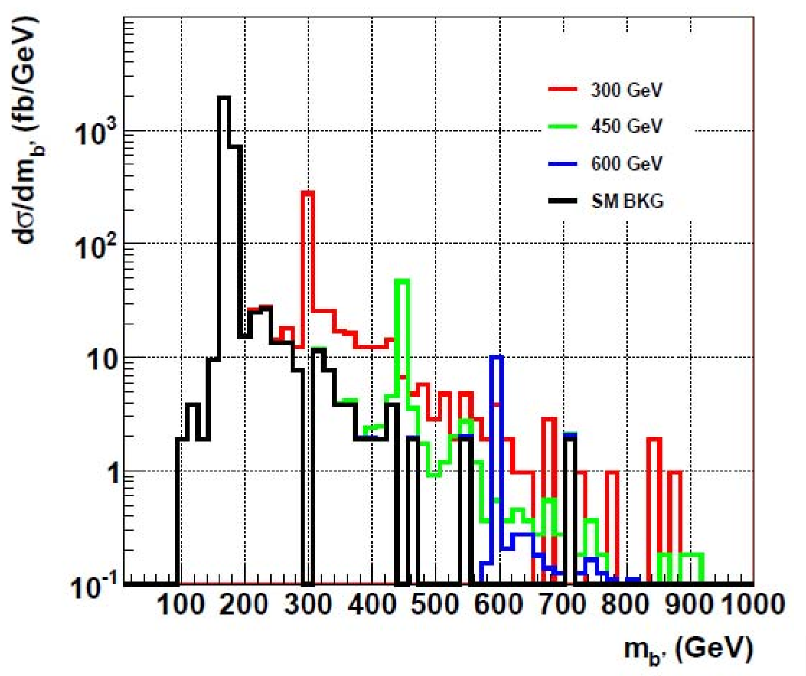
SL Reconstructed Mass Histograms

This is the average of the two masses with the following two cuts imposed:

- **The solution with the smallest mass difference is taken**
- **Only pairs of jets with mass ~M_W must be on the same side of the event.**



t' case



b' case

Same Sign Dilepton Signal

- Only for the b′
- Little SM background so reconstruction is not necessary to find the signal.
- This case is critically determined so there is potentially a 4x ambiguity in reconstruction given the correct jet partition.
- Again, the incorrect jet partitions tend to give unphysical reconstructions.

Mass Distribution of SSL Signal

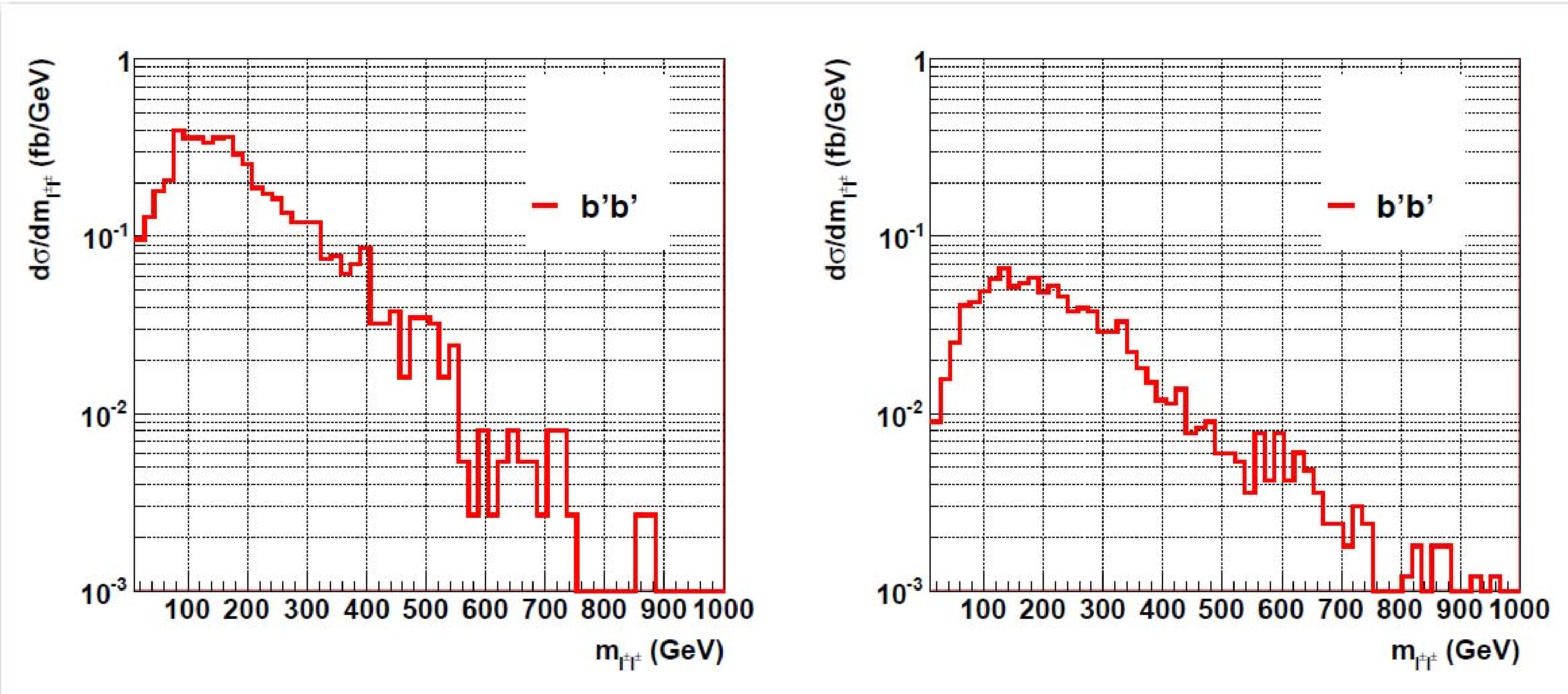


FIG. 10: $m_{l^\pm l^\pm}$ distributions for SSD (same sign dilepton) cases with $m_Q = 450$ (left), $m_Q = 600$ (right).

SSD Reconstructed Mass Histograms

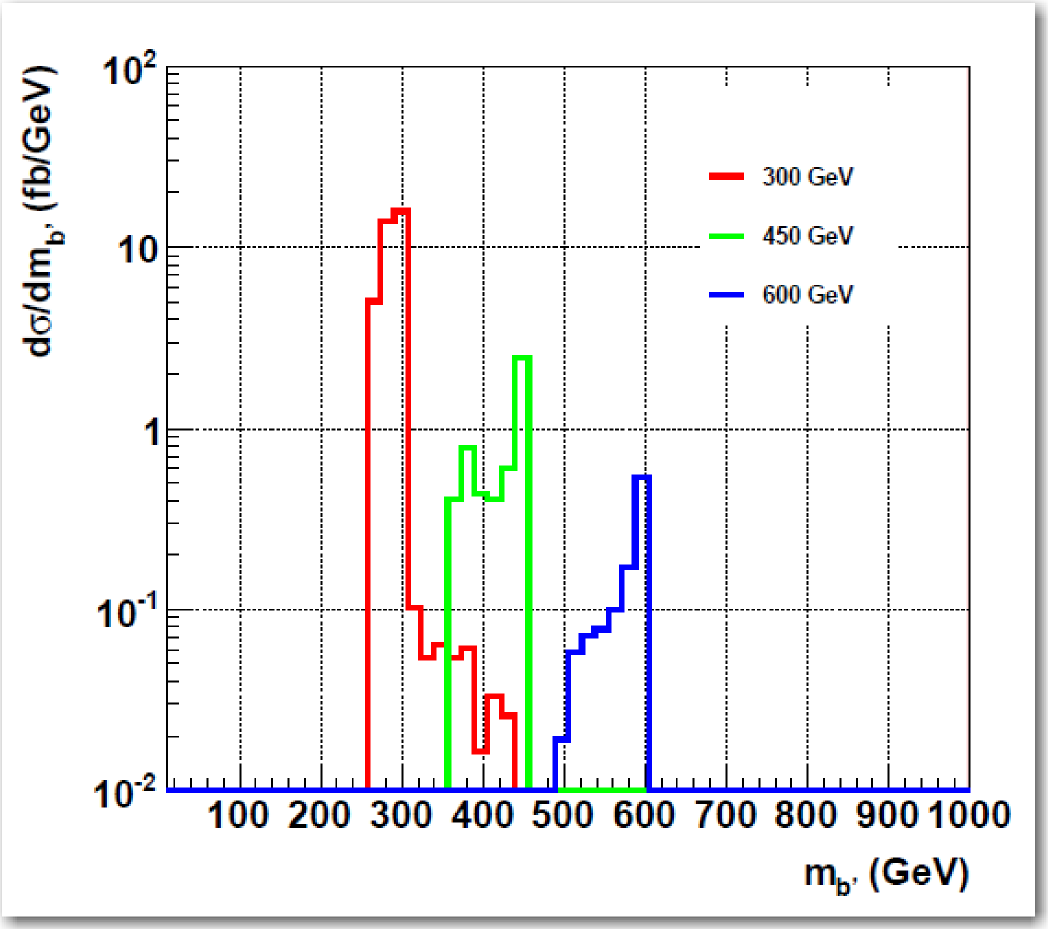


FIG. 11: The reconstructed b' masses from SSD (same sign dilepton) signal case at $\sqrt{s} = 14$ TeV [63].

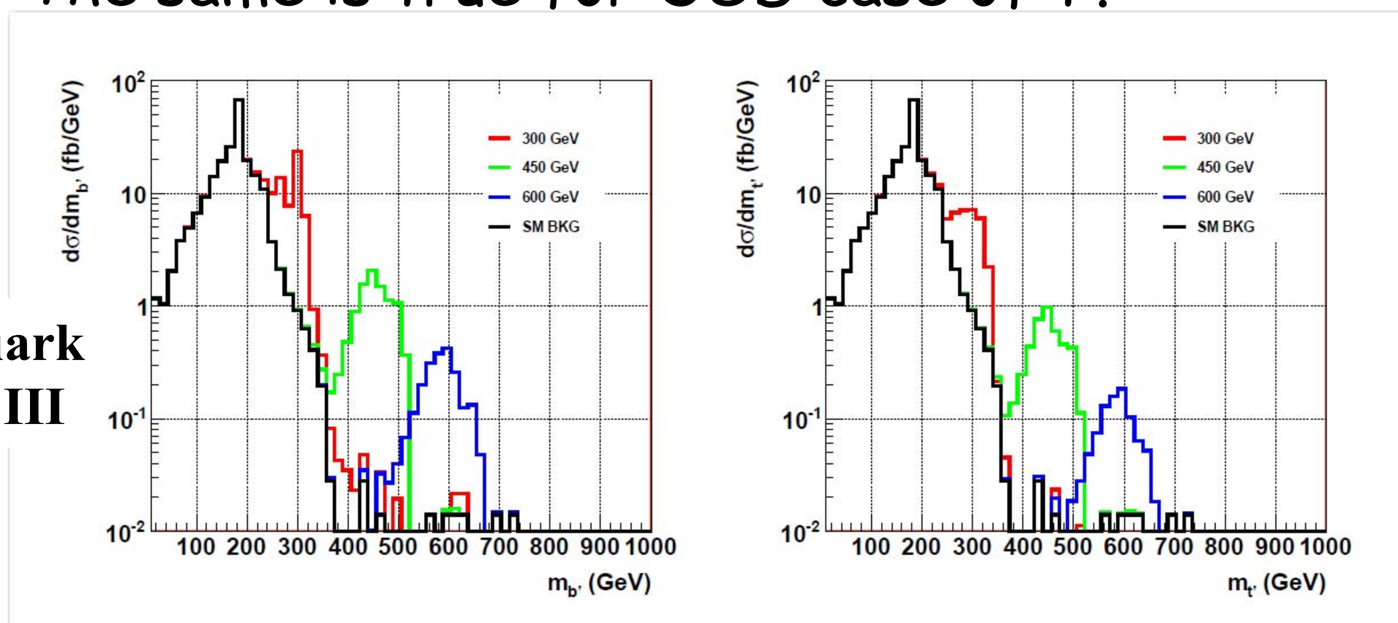
Opposite Sign Dilepton Signal

- This works for both b′ and t′.
- In the b′ case, there are three scenairos but in a given event, we do know which scenario applies nor what the jet partitioning is.
- For the best we can do is to try to reconstruct each event according to each scenario.
- In most cases the wrong assumption or the wrong partition gives unphysical solutions.

OSD III: The underdetermined case

- In this case the system is underdetermined.
- If you "assume" that the two b'-quarks are at rest with each other, the system is determined and the reconstruction gives a reasonable approximation to the true value.
- The same is true for OSD case of t'.

b'-quark OSD III



t'-quark OSD

OSD Signal for b'

- For each event, try to reconstruct it iterating over all jet partitions and all three scenarios (OSD I, II and III).

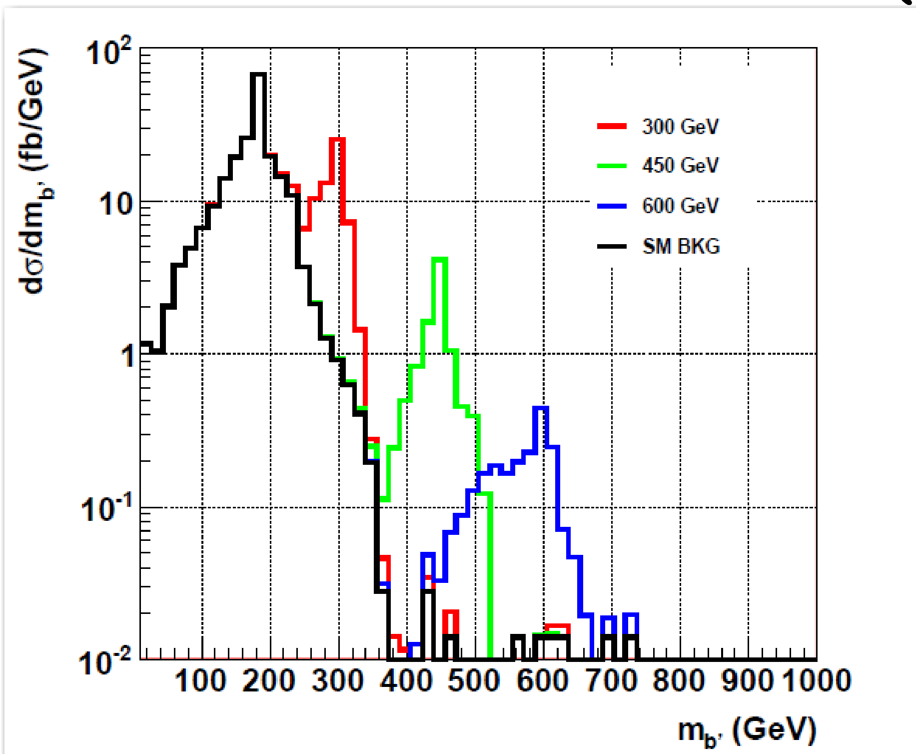


FIG. 15: Reconstructed b' masses where a mixture of OSD1, OSD2 and OSD3 events are analyzed using the three different methods, i.e. assuming that the event has OSD1, OSD2 and OSD3 topology at $\sqrt{s} = 14$ TeV[63]. SM background is also presented.

Conclusions

Conclusions

- A fourth generation can solve some problems with the SM
  - Baryogenesis
  - CKM tensions
- Fourth generation quarks will be produced copiously at the LHC
- Single lepton, and Opposite sign dilepton have bad SM backgrounds that can potentially be managed by reconstruction.
- Same sign dilepton has little SM background
- The kinematics may allow us to sift through the combinatorial backgrounds and come up with a mass peak.