Spin-3/2 quarks at the LHC

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Outline

- Introduction & Motivation
- Feynman Rules for spin-3/2 particle
- Cross section Calculation
- Signals at the LHC
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  b. Two-b jets & two light jets
  c. Two-t and two light jets
- Conclusions

Introduction & Motivation

Colored particles in the SM: Quarks & Gluons

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BSM: Exotic particles

Many extensions of the SM predict new colored states :

SUSY : squarks & sgluons
Extra Dimensions: KK excitations of SM quarks & gluons
Extended Gauge Symmetries: scalar diquarks, colorons etc.
4^{th} Generation Quarks : (eg. t`, b`)

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Possible experimental signature :

- New resonances decaying two-jet, three-jet etc.
- Multijet +/ multi-lepton final state
- Missing E_T with high jet multiplicity

Introduction & Motivation

It is possible to have a spin-3/2 quark by

- Bound states of quarks & gluons
- Bound states of three heavy quarks (Taylor, 1979)
- Higher spin excitations of the SM fields in warped extra dimension models (Hassanain + , 2008)
- Effects of excited top on t tbar production (Stirling +, 2012)

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We consider the pair production of spin-3/2 quark each decaying to quark and gluon.

Feynman rules for spin-3/2 particles

Lagrangian for spin-3/2 particles:

on-shell

$$\mathcal{L} = \bar{\psi}_\alpha \Lambda^{\alpha\beta} \psi_\beta$$

$$\gamma^\alpha \psi_\alpha = 0$$

$$\partial^\alpha \psi_\alpha = 0.$$

where

$$\Lambda_{\alpha\beta} = (i\partial\!\!\!/ - M) g_{\alpha\beta} + iA(\gamma_\alpha \partial_\beta + \gamma_\beta \partial_\alpha) + \frac{iB}{2} \gamma_\alpha \partial\!\!\!/ \gamma_\beta + CM \gamma_\alpha \gamma_\beta$$

with $B \equiv 3A^2 + 2A + 1$ and $C \equiv 3A^2 + 3A + 1$

A is an arbitary parameter :

$$\psi_\alpha \to \psi'_\alpha = \psi_\alpha + d\gamma_\alpha \gamma_\lambda \psi^\lambda$$

$$A \to A' = \frac{A - 2d}{1 + 4d}$$

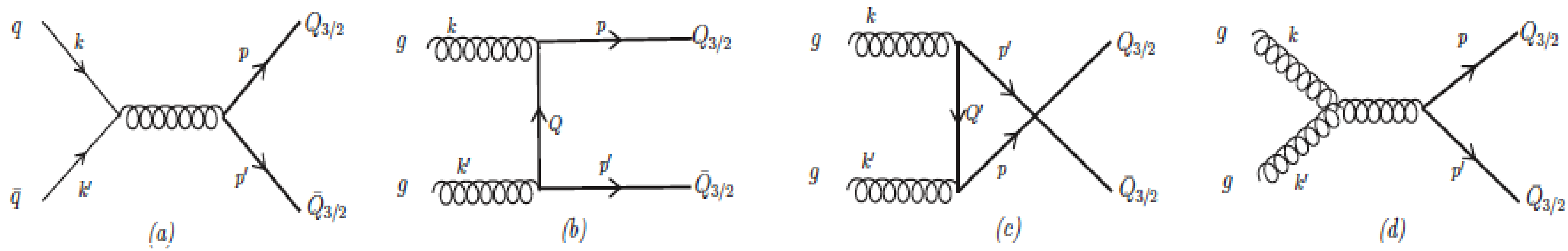
where $d \neq -\frac{1}{4}$.

The interaction of spin-3/2 quarks with gluons :

$$\mathcal{L}_I = g\bar{\psi}_\alpha \left(\frac{B}{2} \gamma^\alpha \gamma^\mu \gamma^\beta + A g^{\alpha\mu} \gamma^\beta + A \gamma^\alpha g^{\mu\beta} + g^{\beta\alpha} \gamma^\mu \right) T_a \psi_\beta A^a_\mu$$

Cross section calculation

$$pp \to Q_{3/2}\bar{Q}_{3/2} + X$$



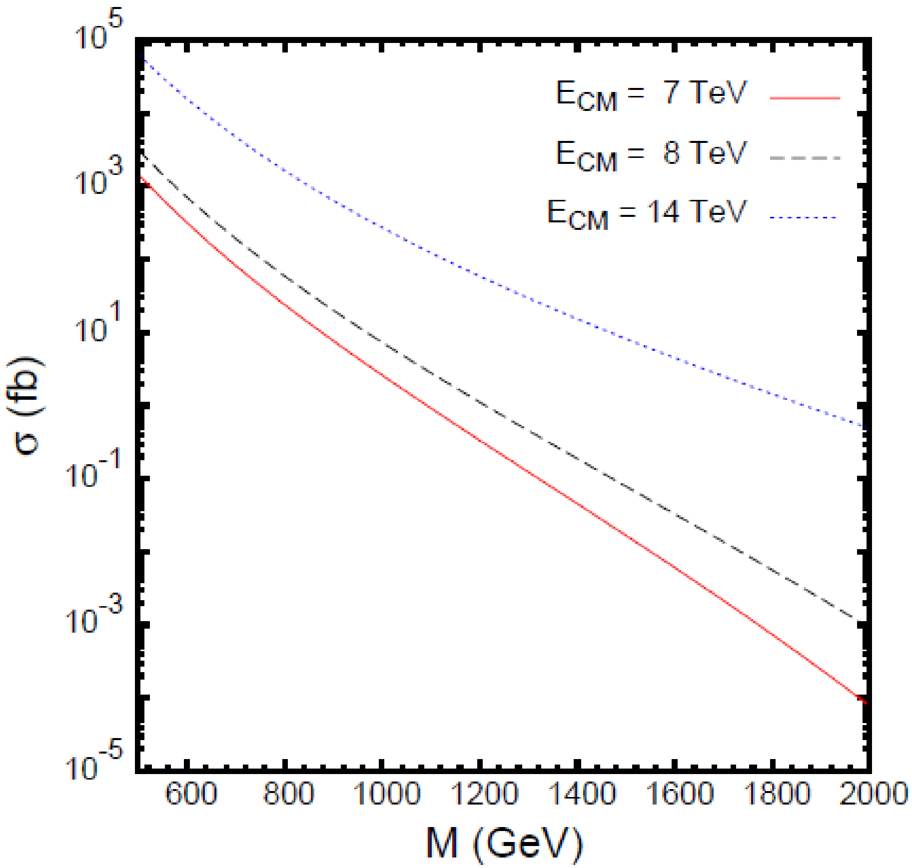
$$\hat{\sigma}(gg \to Q_{3/2}\bar{Q}_{3/2}) = \frac{\pi\alpha_s^2}{116640\ \hat{s}} \left\{ 60\ \ln\left(\frac{1+\beta}{1-\beta}\right)\left[66y^2 + 8y + 886 + 5184\frac{1}{y} + 1296\frac{1}{y^2}\right] + \beta\left[24y^4 + 1178y^3 - 13626y^2 + 11380y - 97200 - 602640\frac{1}{y}\right]\right\}$$

where $\alpha_s \equiv g_s^2/4\pi$, $y \equiv \hat{s}/M^2$ and $\beta \equiv \sqrt{1-4/y}$.

We used A independence as a check in cross section calculation.

For quark-antiquark process:

$$\hat{\sigma}(q\bar{q} \to Q_{3/2}\bar{Q}_{3/2}) = \frac{\pi\alpha_s^2}{81\hat{s}}\beta\left[\frac{8}{3}y^2 - \frac{16}{3}y - \frac{16}{3} + 96\frac{1}{y}\right]$$



Leading-order pair production cross section for spin-3/2 quarks.

Signals at the LHC

- Higher dimension-five operators would lead to interactions between spin-3/2 quarks and SM quarks :

$$\mathcal{L}_{dim-5} = i\frac{g_s}{\Lambda}\bar{\psi}_\alpha \left(g^{\alpha\beta} + A\gamma^\alpha\gamma^\beta\right)\gamma^\nu T^a \frac{(1\pm\gamma_5)}{2}\xi F^a_{\beta\nu} + H.C.$$ (Stirling+, 12)

- We assume that the colored spin-3/2 quark will decay promptly to a gluon and spin-1/2 SM quark with 100% branching probability.

Possible decays :

a light SM quark and a gluon $(Q_{3/2} \to qg)$

or

$(Q_{3/2} \to bg$ or $Q_{3/2} \to tg)$

Four-jet final state

If the spin-3/2 quark decays to light quark and a gluon:

- Four jets in the final state
- All jets carry large transverse momenta
- Huge QCD background (sensitive to p_T requirement of jets)
- Resonance in a pair of dijet invariant mass distribution

Kinematic Cuts :

$|y_j| < 2.5$

$M_{jj} > 10$ GeV

$\Delta R_{ij} > 0.5$

	Signal cross-section (fb)						
	M (GeV)						
p_T cut (GeV)	500	600	700	800	900	1000	SM background (fb)
	$\sqrt{s} = 7$ TeV						
200	326.	124.	48.6	18.8	7.2	2.8	11900.
250	134.	51.9	24.9	11.5	5.1	2.1	2420.
300	65.2	21.0	10.1	5.7	3.0	1.5	577.
	$\sqrt{s} = 8$ TeV						
300	194.	61.2	27.6	15.1	8.1	4.1	1270.
350	106.	32.2	12.6	6.6	4.1	2.4	377.
400	58.1	17.6	6.5	3.0	1.8	1.2	118.
	$\sqrt{s} = 14$ TeV						
400	4842.	1549.	569.4	242.2	120.8	69.7	3013.
450	3271.	1074.	399.7	167.6	79.5	43.3	1315.
500	2184.3	746.9	280.8	117.6	54.9	28.4	609.2

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- Significant improvement in sensitivity when strong p_T cuts are used

- for p_T > 200 GeV on the jets and for M_Q = 500 GeV

$S/\sqrt{B} \equiv L\sigma_s/\sqrt{L\ \sigma_b}$ is about 4.4

- Signal will exhibit peak in the invariant mass distribution of a pair of jets

  - CMS analysis with 2.2 fb^{-1} integrated luminosity @ 7 TeV run of LHC exclude coloron mass < 580 GeV.

(CMS-PAS-EXO-11-016)

  - Corresponding bounds on spin-3/2 quarks mass > 490 GeV.

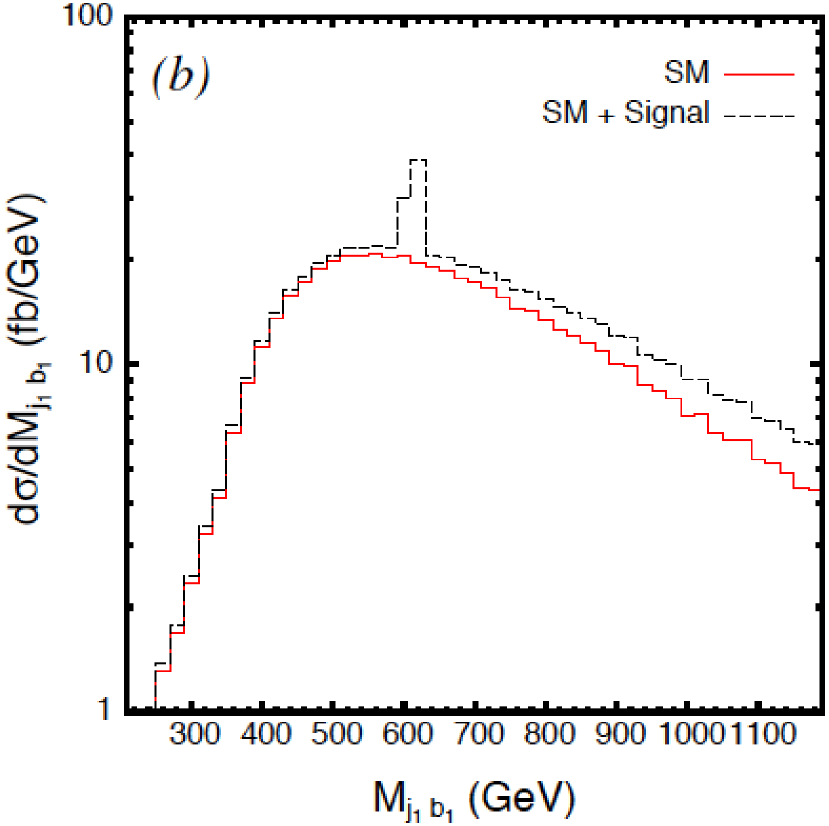
Two-b jets & two light jets

- If the spin-3/2 quark decays to a bottom quark and gluon :

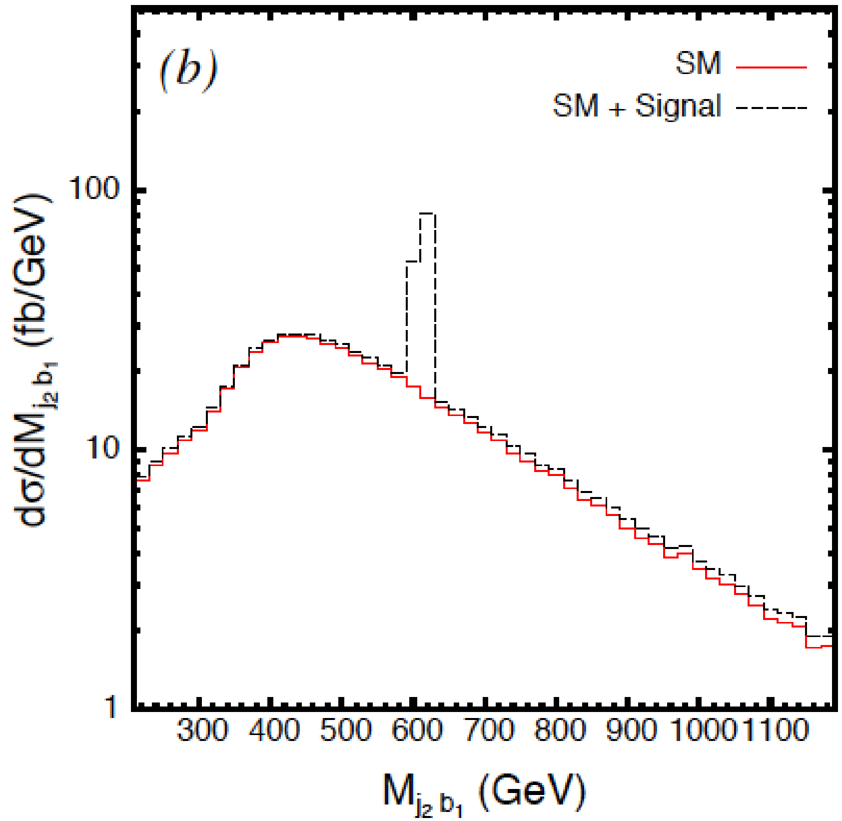
  - 2 b-jets in the final state and 2 light jets *(2b2j)*
  - all jets carry large transverse momenta (p_T)
  - flavor tagging helps to reduce QCD background significantly
  - resonance in the invariant mass of light jet and b-jet

Kinematic cuts:

- $p_T > 150$ GeV on all jets and $|y| < 2.5$
- $\Delta R_{ij} > 0.7$



Invariant mass distribution of the leading b-jet and leading light jet



Invariant mass distribution of the leading b-jet and sub-leading light jet

$M_{3/2}$ = 600 GeV, LHC @ 8 TeV

- As in the 4-jet analysis, stronger p_T cut on the jets will be useful in improving the signal to background ratio.

$pp \to 2b2j$	Signal cross-section (fb)						SM background (fb)
	M (GeV)						
	500	600	700	800	900	1000	
$\sqrt{s} = 7\ TeV$	182.5	55.0	17.6	5.9	2.1	0.7	351.3
$\sqrt{s} = 8\ TeV$	403.0	124.8	41.6	14.7	5.5	2.1	608.9
$\sqrt{s} = 14\ TeV$	584.8	275.4	123.4	57.6	29.7	17.1	12.9

We have used b-tag efficiency of 0.5, while mistag of 0.1 for c-jet tagged as b-jet and 0.01 for light jet tagged as b-jet.

Sensitivity is significantly improved in the 2b2j mode for larger mass spin-3/2 quarks.

Two-t & two light jets

- If the spin-3/2 quark decays to a top quark and gluon :

$$pp \longrightarrow Q_{3/2}\bar{Q}_{3/2} \longrightarrow t\bar{t}gg$$

- New physics signal is more pronounced when the additional jets with high p_T are triggered upon

  - SM background generated using Madgraph 5

  - Sensitivity is improved for higher center-of-mass energies

- Let us consider the full semileptonic decay of top quarks to analyze the signal :

$$
\begin{aligned}
pp \longrightarrow & (Q_{3/2} \to tg) \longrightarrow (t \to bW^+)g \longrightarrow (W^+ \to \ell^+\nu_\ell)bg \\
& \hookrightarrow (\bar{Q}_{3/2} \to \bar{t}g) \longrightarrow (\bar{t} \to \bar{b}W^-)g \longrightarrow (W^- \to \ell^-\bar{\nu}_\ell)\bar{b}g \\
& \hookrightarrow \ell^+\ell^- b\bar{b}jj\not{E}_T
\end{aligned}
$$

Choose two different set of cuts (differing mainly in p_T of the jets)

Variable	Cut $\mathcal{C}_1$	Cut $\mathcal{C}_2$
$p_T^{\ell,b}$	$> 10, 20$ GeV	$> 10, 20$ GeV
p_T^j	> 50 GeV	> 200 GeV
$\|\eta\|$	< 2.5	< 2.5
$\boldsymbol{\Delta R_{jj}}$	> 0.4	> 0.7
$\Delta R_{\ell\ell,\ell j,\ell b,bj}$	> 0.2	> 0.2

$pp \to \ell^+\ell^- bbjj\not{E}_T$	Signal cross-section (fb)			SM background (fb)
	M (GeV)			
	500	800	1000	
$\sqrt{s} = 8\ TeV$	20.1 (7.8)	0.4 (0.3)	0.055 (0.045)	93.2 (2.9)
$\sqrt{s} = 14\ TeV$	385.9 (186.1)	11.2 (8.2)	1.9 (1.6)	522.8 (26.7)

cuts $\mathcal{C}_1(\mathcal{C}_2)$

Stronger cuts on the jet transverse momenta help more in improving S/B for larger values of spin-3/2 quark mass .

If the top decays hadronically, one can reconstruct the spin-3/2 mass from the 3-jet invariant mass distribution.

t* > 790 GeV L = 9.6 fb^{-1} @ 8 TeV. (CMS PAS B2G-12-014)

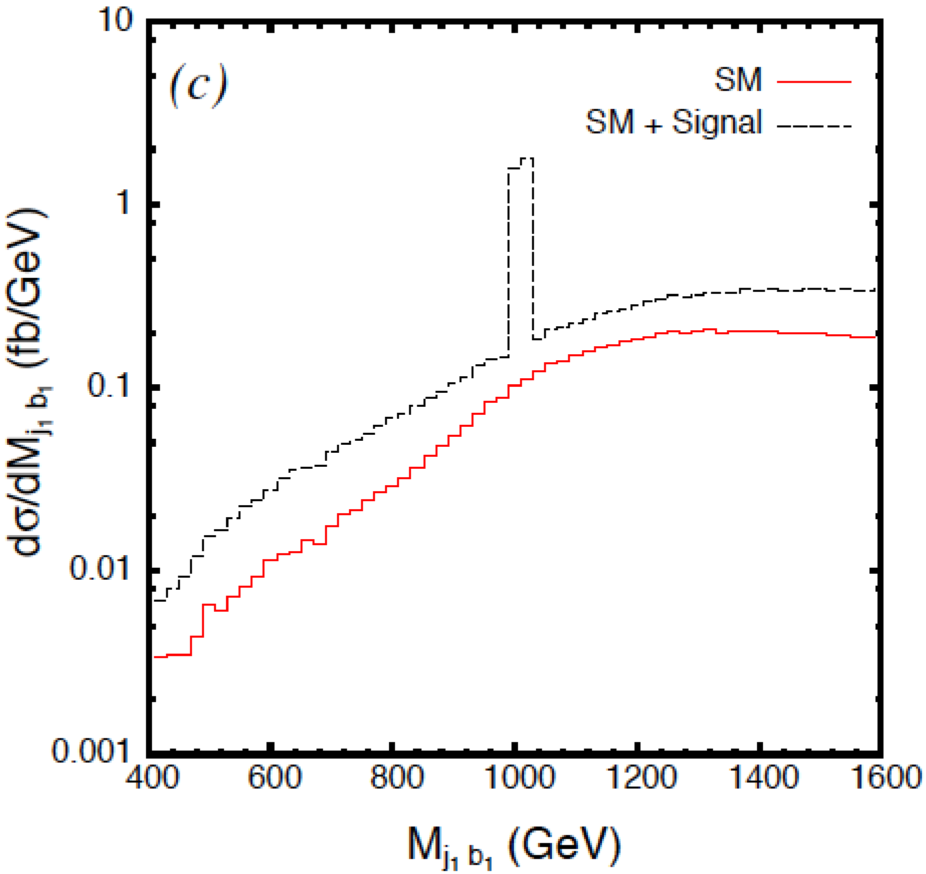
Conclusions

- We studied the interesting resonant signals coming from the decay of spin-3/2 quark.
- Use of specific selection cuts on the kinematics helps to increase the LHC sensitivity to heavier spin-3/2 quark mass.
- Spin-3/2 quarks can lead to resonant signals in the 2-jet and 3-jet invariant mass distributions
- Existing LHC studies can be extended and/or applied to search for spin-3/2 quarks.

THANK YOU

Extras

$pp \to t\bar{t}jj$ ($p_T^j > 100$ GeV)	Signal cross-section M (GeV) 500	800	1000	SM background
$\sqrt{s} = 7\ TeV$	1.11 pb	21.7 fb	2.4 fb	2.12 pb
$\sqrt{s} = 8\ TeV$	2.38 pb	53.4 fb	6.8 fb	3.55 pb
$\sqrt{s} = 14\ TeV$	49.4 pb	1.46 pb	249. fb	24.7 pb



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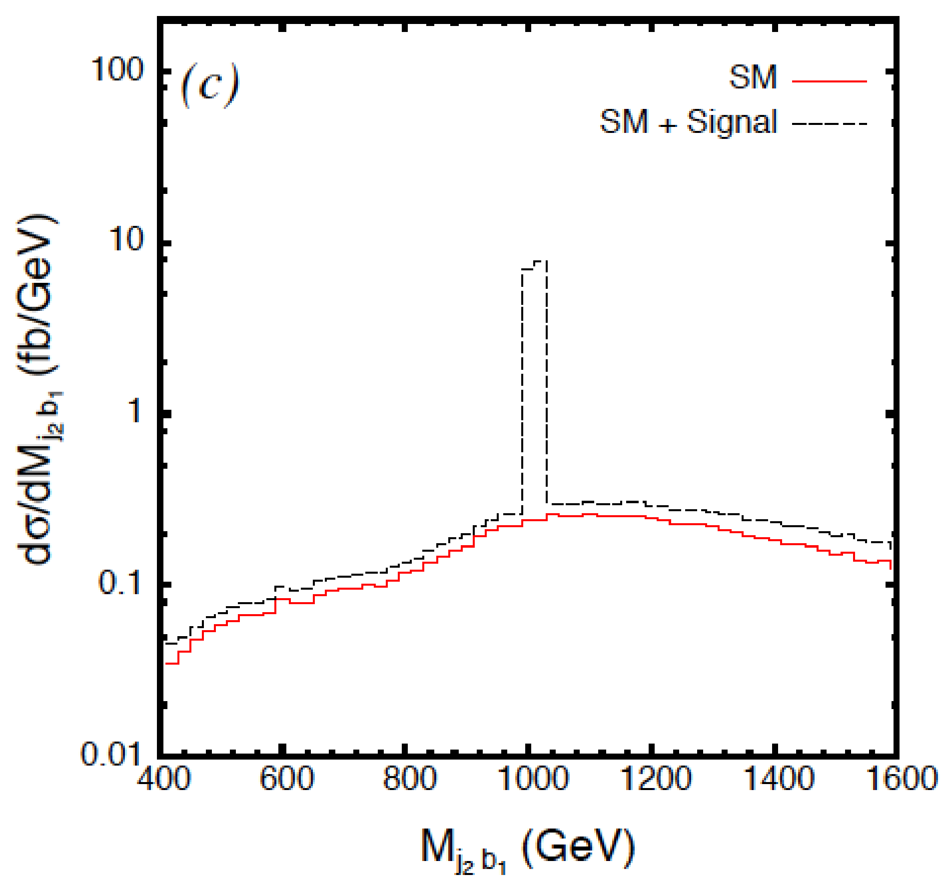

Invariant mass distribution of the leading b-jet and sub-leading light jet

$M_{3/2}$ = 1 TeV, LHC @ 14 TeV