Single and anomalous productions of fourth family up type quarks at the LHC

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based on recent studies:
e-Print: arXiv:0908.0123 [hep-ph]
e-Print: arXiv:0801.0236 [hep-ph]

CERN TH Institute, SM and BSM physics at the LHC, 21 August 2009, CERN

Overview

- A fourth family
- Single production
- Parametrizations
- Cross sections @ PI-PIII
- Signal and background
- Anomalous production
- Branching ratios
- Cross sections @ κ=0.1-1
- Conclusion

A fourth family

- For a model with fourth family, the 4x4 quark mixing matrix becomes unitary, where the 3x3 sub matrix loses its unitary properties while the new quarks mix with the ordinary ones.

- The most recent analyses indicate that an additional family of heavy fermions is not inconsistent with the precision electroweak data at the available energies.

- The repetition of quark and lepton families remain a mystery as part of the flavor problem. A possible fourth family may play an important role in our understanding of the flavor physics.

- Due to expected large mass of fourth family quarks they could have different dynamics than the quarks of three families of the Standard Model.

- Additional fermions can also be accommodated in many models beyond the SM. Yet, we have enough space for a new family of fermions.

Present bounds on the parameters

From the searches at Tevatron, $m_{t'} > 311$ GeV[1] and $m_{b'} > 325$ GeV [2].

The electroweak (S,T) parameters are within the experimentally allowed regions if the fourth family quark masses are in $\Delta m' \sim 50\text{-}55$ GeV [3]. From the unitary requirement of 4x4 CKM, the first column element $|V_{t'd}|<0.04$.

Related top quark bounds:

- From the single production of top quarks $|V_{tb}|>0.89$ at 95%CL[4].
- Top quark FCNC couplings $\kappa_{utg}/\Lambda<0.037$ TeV^{-1} and $\kappa_{ctg}/\Lambda<0.15$ TeV^{-1} [5]

If originates from the mass/magnetic moments:

- $\kappa_{tt'g}<(m_t/m_{t'})^{1/2} \dashrightarrow \kappa_{tt'g}<0.5$ **and** $\kappa_{ct'g}<(m_c/m_{t'})^{1/2} \dashrightarrow \kappa_{ct'g}<0.04$

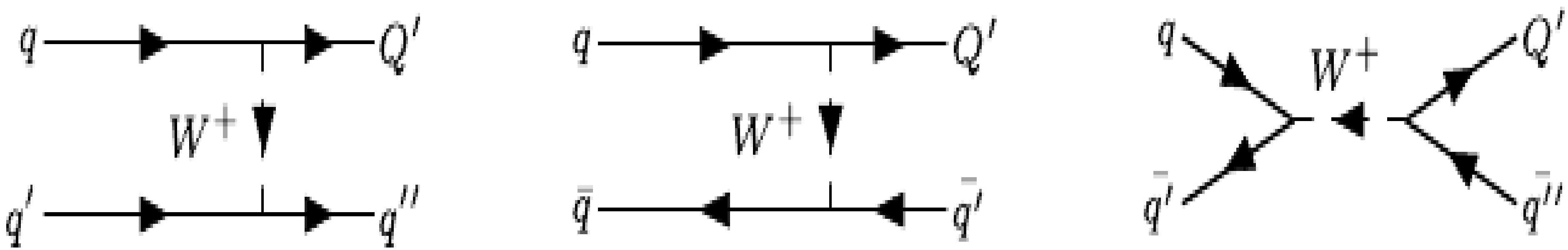
[1]CDF, PRL100, 2008; [2]CDF/PHYS/EXO/PUBLIC/9759; [3]G.D.Kribs et al., PRD76, 2008; [4] D0, PRL100, 2008; [5]D0, PRL 99, 2008

Single production

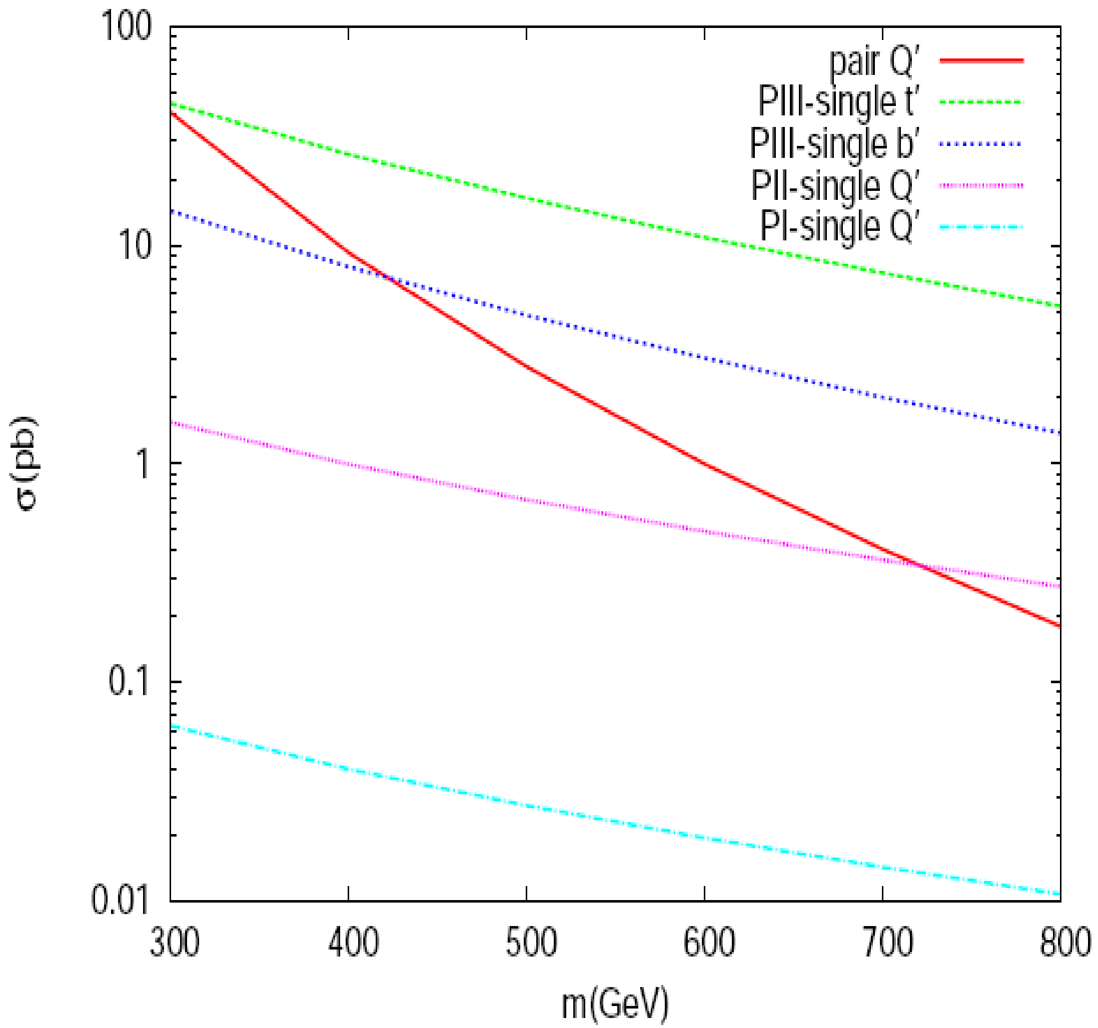
$$L = -g_e \sum_{Q'_i=b',t'} Q_{ei}\overline{Q}'_i\gamma^\mu Q'_i A_\mu$$
$$- g_s \sum_{Q'_i=b',t'} \overline{Q}'_i T^a \gamma^\mu Q'_i G^a_\mu$$
$$- \frac{g}{2\cos\theta_W} \sum_{Q'_i=b',t'} \overline{Q}'_i \gamma^\mu (g^i_V - g^i_A \gamma^5) Q'_i Z^0_\mu$$
$$- \frac{g}{2\sqrt{2}} \sum_{Q'_{j\neq i}=b',t'} V_{ij}\overline{Q}'_i \gamma^\mu (1-\gamma^5) q_j W^\pm_\mu ,$$

The single production cross section depends on the mass of the fourth family quarks and the 4x4 CKM elements.

$$\mathbf{V} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{ub'} \\ V_{cd} & V_{cs} & V_{cb} & V_{cb'} \\ V_{td} & V_{ts} & V_{tb} & V_{tb'} \\ V_{t'd} & V_{t's} & V_{t'b} & V_{t'b'} \end{pmatrix}$$



Parametrizations



Comparison of the single and pair production cross sections at 14 TeV.

4x4 CKM Parametrizations:

Preserving the unitary bounds, three different parametrizations for the 4th row and column of the mixing matrix (4x4 CKM) are assumed:

PI: Vt'q=Vqb'=0.01
PII: Vt'q=Vqb'=0.05
PIII: Vt'd=0.063, Vt's=0.46, Vt'b=0.47, Vub'=0.044, Vcb'=0.46, Vtb'=0.47 [*]

[*] V.E.Ozcan et al, EPJC57

Cross sections

Process →	$pp \to t'(\bar{t}')\, j\, X$		
Mass (GeV)	PI	PII	PIII
300	0.06(0.02)	1.58(0.58)	44.56(25.70)
400	0.04(0.01)	1.00(0.33)	26.06(14.44)
500	0.03(0.01)	0.68(0.20)	16.36(8.75)
600	0.02(0.01)	0.48(0.13)	10.82(5.59)
700	0.01(0.003)	0.35(0.09)	7.42(3.71)
800	0.01(0.002)	0.27(0.06)	5.25(2.54)

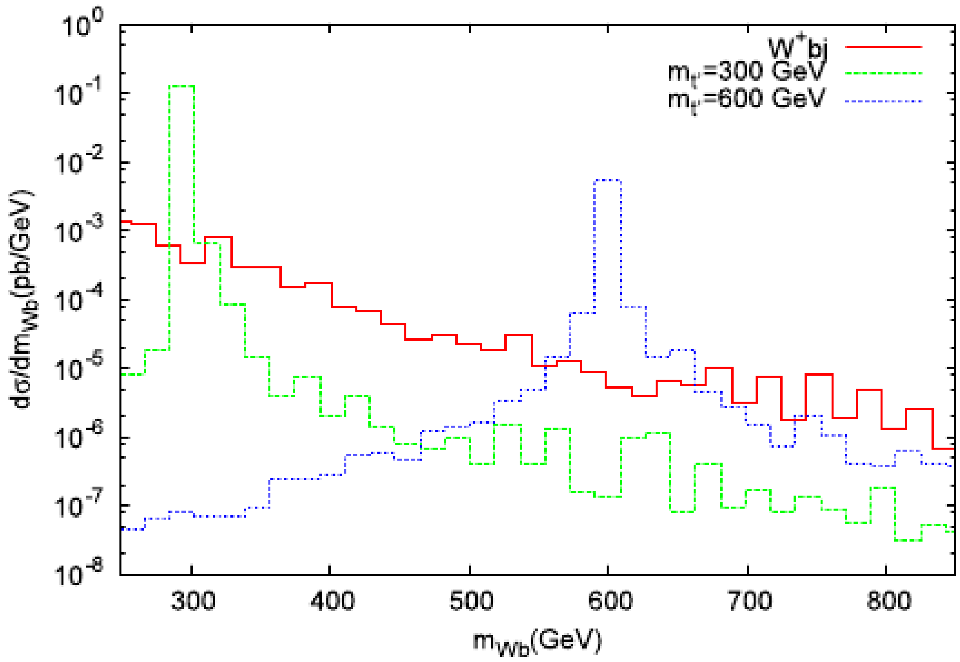
The signal cross sections (in pb) for different parametrizations, $\sqrt{s}$=14 TeV.

Background	$\sigma\,(pb)$
ZZZ	1.111×10^{-2}
ZZW^+	2.050×10^{-2}
ZZW^-	1.091×10^{-3}
$W^+W^-W^+$	8.826×10^{-2}
$W^+W^-W^-$	4.463×10^{-2}
W^+W^-Z	1.033×10^{-1}
W^+Z	1.868×10^{1}
W^-Z	1.169×10^{1}
W^+W^-	8.367×10^{1}

The background cross sections (in pb) are calculated for the cuts p_T^{bj} >20(50) GeV and in the Δm invariant mass intervals (in GeV).

Process	No cut	290–310	390–410	485–515	585–615	680–720	780–820
$pp \to W^+ b j X$	240.34	1.37(0.62)	0.28(0.19)	0.21(0.16)	0.12(0.08)	0.05(0.06)	0.05(0.04)
$pp \to W^- \bar{b} j X$	180.29	0.97(0.43)	0.23(0.18)	0.22(0.16)	0.18(0.12)	0.09(0.09)	0.05(0.02)

Signal signifcance



Invariant mass distributions of the $W^{+}b$ system for two mass values of t' quarks (300,600 GeV), and the corresponding background.

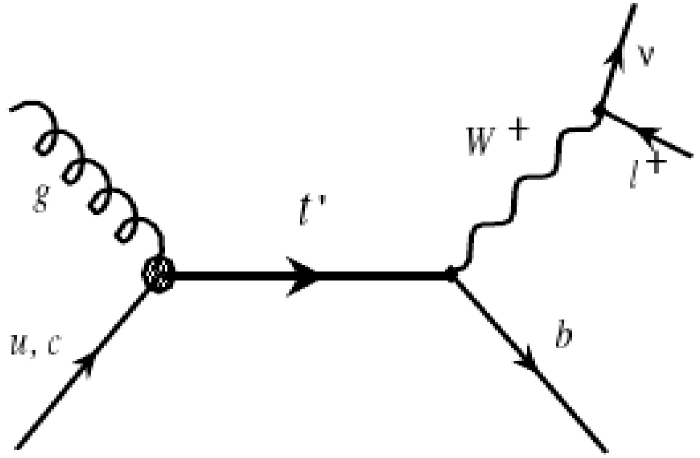
Signal significance (SS) achievable at the LHC with 10^5 pb^{-1}.

•**Providing the parametrization PII-PIII, single t' signal (300-800 GeV) could be observed at LHC.**

SS	t' ($\bar{t}'$) quark		
Mass (GeV)	PI	PII	PIII
300	2.94(1.31)	73.67(32.86)	3184.04(2211.22)
400	3.34(1.17)	83.57(29.22)	3325.72(1928.79)
500	2.49(0.75)	62.26(18.83)	2290.62(1225.12)
600	2.43(0.56)	60.73(14.13)	2079.25(909.39)
700	2.13(0.44)	53.48(11.00)	1707.09(696.92)
800	2.07(0.62)	51.97(15.41)	1559.32(965.05)

Anomalous production

Interested in the process $pp \to W^+ bX$ for anomalous production of t' quark and SM decay at LHC.



$$
\begin{aligned}
L = & \sum_{q_i=u,c,t} \frac{\kappa_\gamma^{q_i}}{\Lambda} Q_{q_i} g_e \bar{t}' \sigma_{\mu\nu} q_i F^{\mu\nu} + \sum_{q_i=u,c,t} \frac{\kappa_z^{q_i}}{2\Lambda} g_z \bar{t}' \sigma_{\mu\nu} q_i Z^{\mu\nu} \\
& + \sum_{q_i=u,c,t} \frac{\kappa_g^{q_i}}{2\Lambda} g_s \bar{t}' \sigma_{\mu\nu} \lambda_a q_i G_a^{\mu\nu} + h.c. \\
& + \sum_{q_i=d,s,b} \frac{\kappa_\gamma^{q_i}}{\Lambda} Q_{q_i} g_e \bar{b}' \sigma_{\mu\nu} q_i F^{\mu\nu} + \sum_{q_i=d,s,b} \frac{\kappa_z^{q_i}}{2\Lambda} g_z \bar{b}' \sigma_{\mu\nu} q_i Z^{\mu\nu} \\
& + \sum_{q_i=d,s,b} \frac{\kappa_g^{q_i}}{2\Lambda} g_s \bar{b}' \sigma_{\mu\nu} \lambda_a q_i G_a^{\mu\nu} + h.c.
\end{aligned}
$$

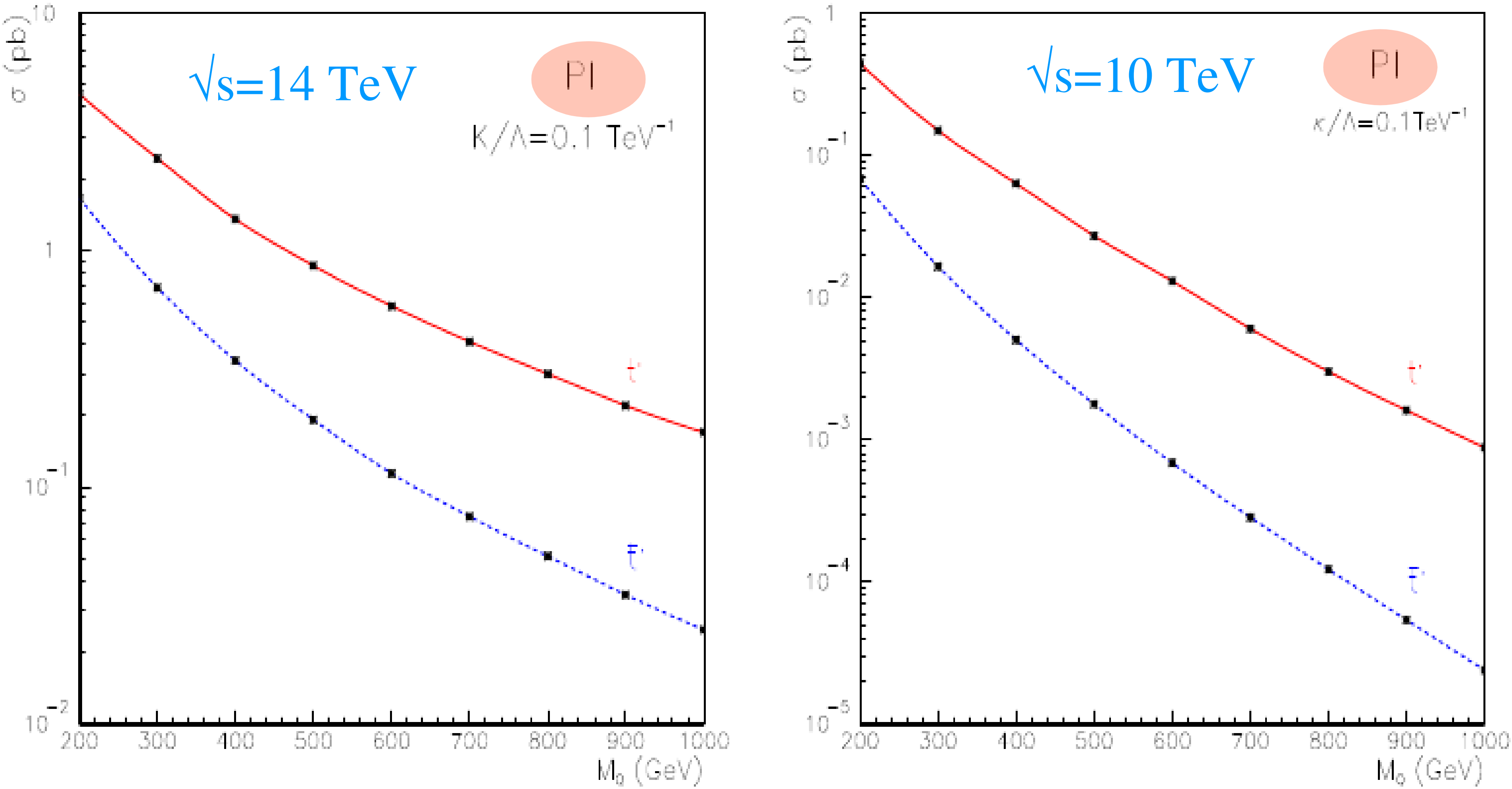
- One could have experimental allowed parameter sets, having a sizable mixing with the fourth family.
- The FCNC could appear without violating the existing bounds.

Branching ratios

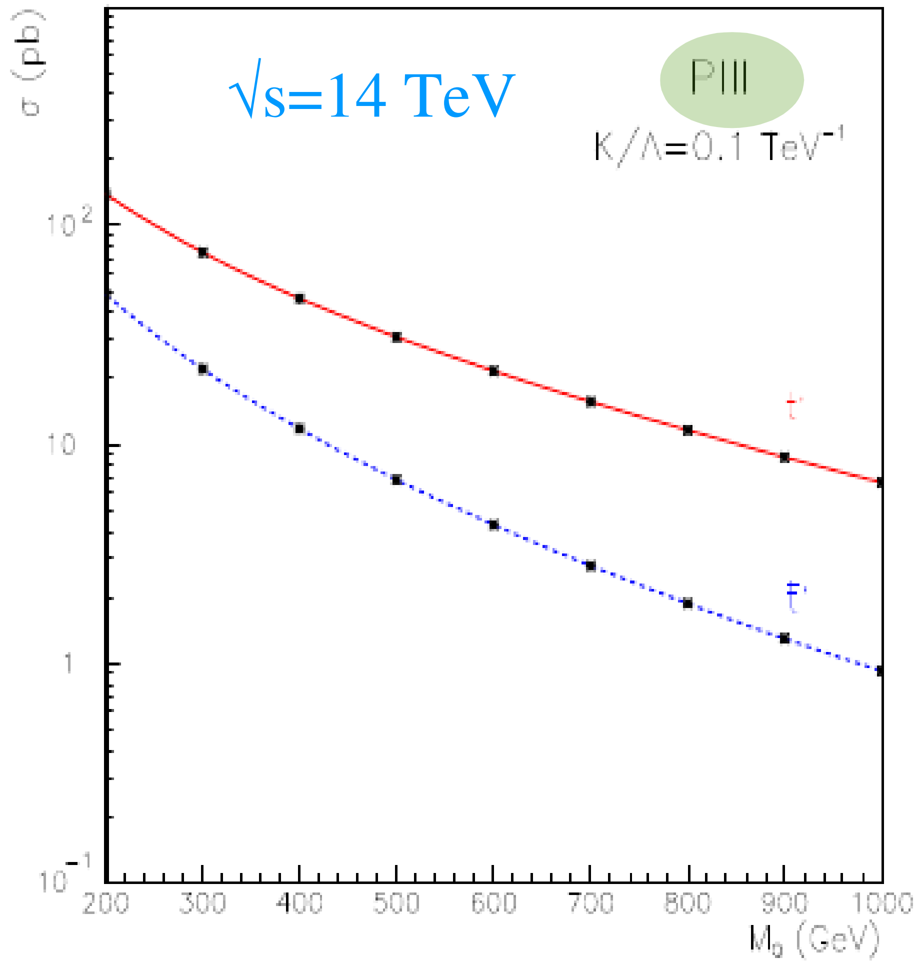
Fourth generation up type quark decays via charged current interactions and anomalous interactions with the redefinition of PII as $V_{t'q}=A_q\lambda^{4-n}$. Here, PI–PII anomalous dominated, PIII has comparable effects.

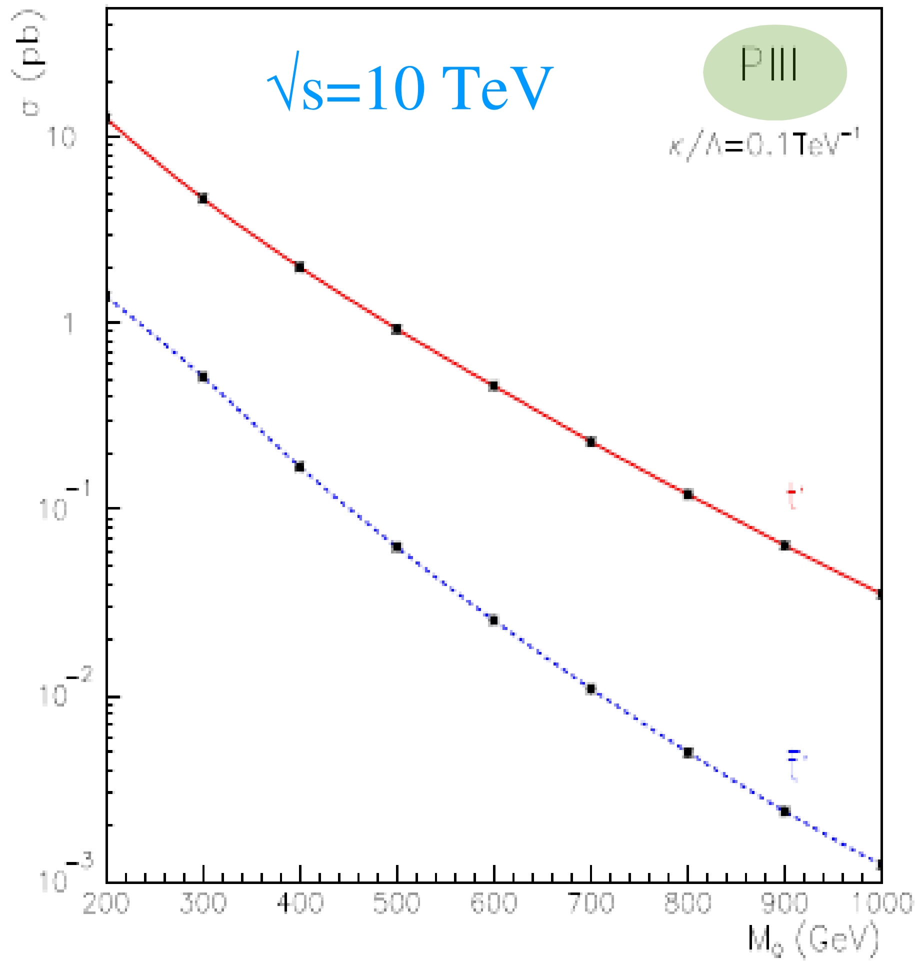
	PI			PII			PIII		
$m_{t'}$(GeV)	300	500	700	300	500	700	300	500	700
Wq_1	0.017(1.6)	0.014(1.4)	0.014(1.3)	0.0002(0.0062)	0.0001(0.0059)	0.0001(0.0058)	0.39(0.9)	0.35(0.9)	0.34(0.89)
Wq_2	0.017(1.6)	0.014(1.4)	0.014(1.3)	0.017(0.62)	0.014(0.59)	0.014(0.58)	21.0(48)	19.0(48)	18.0(48)
Wq_3	0.017(1.6)	0.014(1.4)	0.014(1.3)	1.7(62)	1.4(59)	1.4(58)	21.0(50)	20.0(50)	19.0(50)
$Zq_{1,2}$	2.5(2.3)	2.3(2.2)	2.2(2.1)	2.4(0.91)	2.3(0.93)	2.2(0.93)	1.4(0.033)	1.4(0.036)	1.4(0.037)
Zq_3	0.27(0.26)	1.4(1.4)	1.8(1.7)	0.27(0.1)	1.4(0.59)	1.8(0.75)	0.16(0.0036)	0.89(0.023)	1.1(0.03)
$\gamma q_{1,2}$	0.9(0.86)	0.76(0.73)	0.72(0.69)	0.89(0.33)	0.75(0.31)	0.71(0.3)	0.52(0.012)	0.47(0.012)	0.45(0.012)
γq_3	0.26(0.25)	0.52(0.5)	0.6(0.57)	0.26(0.097)	0.51(0.21)	0.59(0.25)	0.52(0.0035)	0.32(0.008)	0.37(0.0098)
$gq_{1,2}$	40(39)	34(33)	32(31)	40(15)	34(14)	32(14)	23.0(0.54)	21.0(0.53)	20.0(0.53)
gq_3	12(11)	23(22)	27(26)	12(4.4)	23(9.4)	26(11)	6.8(0.16)	14.0(0.36)	20.0(0.44)
Γ_{tot}(GeV)	5.21(0.055)	28.47(0.297)	82.58(0.859)	5.298(0.141)	28.871(0.701)	83.71(1.97)	9.05(3.89)	46.46(18.29)	132.04(50.30)

Cross sections at PI

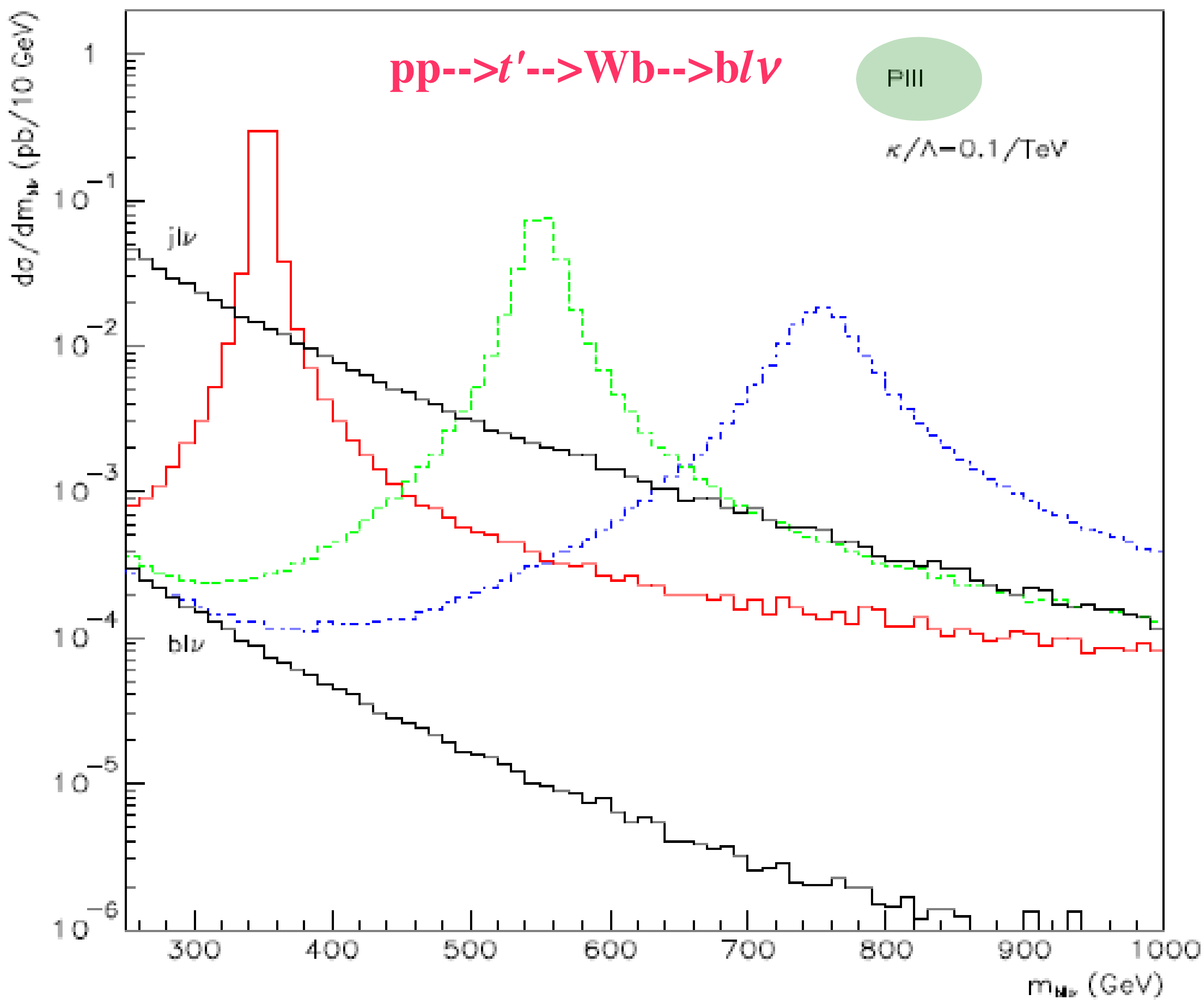


Cross sections at PIII





Signal and background



Background study,

Cuts:

p_T>50 GeV

1 b-jet

eff (b) 60% ,

rej(j)~100,

rej(c)~10

- we count events in the mass intervals Δm.

Simulation with PGS4

Events are simulated with the CompHEP4.5(generation) +PYTHIA6.4(hadronization)+PGS4(simulation) program chain.

Requirements:

b-jet having p_T>50 GeV, $|\eta|<2$

Lepton having p_T>20 GeV, $|\eta|<2.5$

Missing E_T>20 GeV

Reconstruction:

W boson is reconstructed from its leptonic decay

t' quark mass is reconstructed from $bl\nu$ system

Analysis:

ExRootAnalysis package is used to PGS4 data

Output analyzed and histogrammed with ROOT macro

Significance:

$$SS = \sqrt{2\left[(S+B)\ln(1+\frac{S}{B}) - S\right]}$$

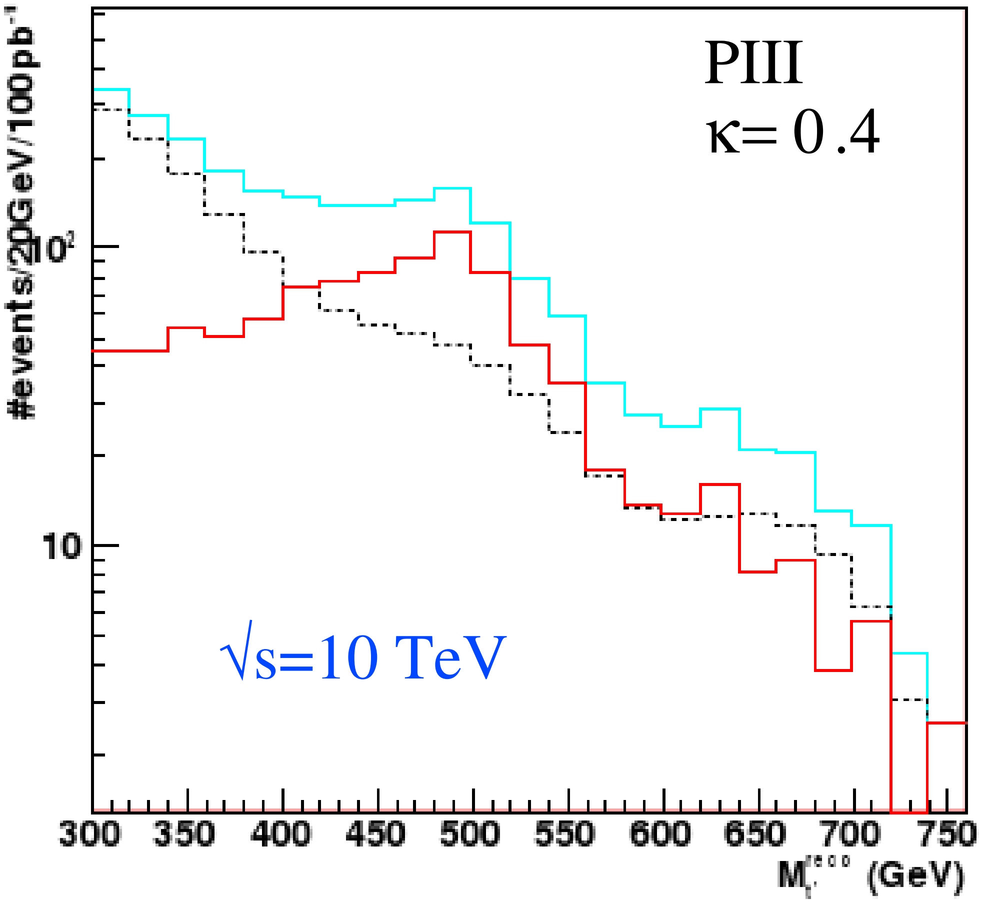
Results

With the early LHC data *t′* quarks can be discovered if there is large anomalous coupling (κ/Λ>0.15 TeV^{-1}) with the other up type quarks.

The signal significance of t' quark at 100 pb^{-1}.

SS	$m_{t'} = 500$ GeV
$\kappa/\Lambda = 0.1\ TeV^{-1}$	1.99
$\kappa/\Lambda = 0.2\ TeV^{-1}$	7.19
$\kappa/\Lambda = 0.4\ TeV^{-1}$	21.40
$\kappa/\Lambda = 0.6\ TeV^{-1}$	38.51
$\kappa/\Lambda = 0.8\ TeV^{-1}$	53.05
$\kappa/\Lambda = 1\ TeV^{-1}$	63.14

Mass reconstruction of *t′* signal and the corresponding background at $\sqrt{s}$=10 TeV.



Conclusion

Fourth family *t′* and *b′* quarks could be pair produced with large numbers ($5\text{x}10^5$ events for $m_{Q'}$=500 GeV) at the LHC with $\sqrt{s}$=14 TeV.

The single production is also important to measure their mixings with the other families, and this become comparable with the pair production in the higher mass region for the maximal parameters of the 4x4 CKM.

If their anomalous interactions dominate or compare the SM interactions, possible resonant productions could appear and give enough signal statistics to measure these couplings.

Simulation results for PIII show that κ/Λ=0.15 TeV^{-1} is reachable at the mass range of 400-600 GeV.

If discovered at the LHC experiments, fourth family quarks will change our perspective on the flavor and the mass.