Anomalous resonant production of fourth family quarks at the LHC

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Overview

- A Fourth Family
- SM Interactions
- Anomalous Interactions
- Decay widths and branchings
- Resonant production
- Signal and Backgrounds
- Conclusion

A fourth family

The most recent analyses indicate that an additional family of heavy fermions is not inconsistent with the precision electroweak data at the available energies [holdom, hung, kribs, okun, murdock].

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 structure of the standard model.** Additional fermions can also be accommodated in many models beyond the SM.

Limits

- The upper limit on the number of flavour from QCD asymptotic freedom is eighteen [TH]
- The upper limit on mass from partial wave unitarity is about 1 TeV [TH]
- A recent lower limit on the mass of the fourth family quark b' quark is $m_{b'}>256$ GeV from Tevatron experiments [EXP]
- A most recent limit on the mass of t' quark is $m_{t'}>311$ GeV from CDF experiment [EXP].
- $|V_{tb}|>0.74$ from the single top production at Tevatron [EXP]
- $R=|V_{tb}|^2/\sum_q|V_{tq}|^2>0.79$ from top pair production at Tevatron [EXP].

Motivations

- Due to their expected large mass fourth family quarks could have different dynamics than the quarks of three families of the SM. For example, dynamical models of fermion mass generation.

- Anomalous magnetic moments of the quarks are proportional to the mass ratio $\sim m_q/m_t$ [Fritzsch]. Arguments discussed for the top quarks can be well applied to the fourth family quarks since they are expected to be heavier than top quark.

- We follow similar steps given in the previous study [Arik&Cakir&Sultansoy].

Mixing with the 4th SM

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

- Experimental inputs
- Unitarity

Our parametrizations:

PI: $V_{qb'}=V_{t'q}=0.01$

PII: $V_{qb'}=V_{t'q}=A_q\lambda^{(4-n)}$

with $A_q=1$ and $\lambda=0.1$

PIII: $V_{ub'}=0.044$, $V_{cb'}=0.46$, $V_{tb'}=0.47$, $V_{t'd}=0.063$, $V_{t's}=0.46$.

Erkcan's talk

Interactions

$$L' = -g_e \sum_{Q'_i=b',t'} Q_{ei}\overline{Q_i}'\gamma^\mu Q'_i A_\mu - g_s \sum_{Q'_i=b',t'} \overline{Q_i}' T^a \gamma^\mu Q'_i G^a_\mu$$
$$- \frac{g_e}{2\cos\theta_w \sin\theta_w} \sum_{Q'_i=b',t'} \overline{Q}'_i\gamma^\mu (g^i_V - g^i_A\gamma_5) Q'_i Z^0_\mu$$
$$- \frac{g_e}{2\sqrt{2}\sin\theta_w} \sum_{Q'_{i\neq j}=b',t'} V_{ij}\overline{Q}'_i\gamma^\mu (1-\gamma_5) q_j W^\pm_\mu + h.c.$$

SM

Interactions

Implemented in the program CompHEP to study in a framework.

$$L = \sum_{q_i=u,c,t} \frac{\kappa^{q_i}_\gamma}{\Lambda} Q_{q_i} g_e \overline{t}'\sigma_{\mu\nu} q_i F^{\mu\nu} + \sum_{q_i=u,c,t} \frac{\kappa^{q_i}_z}{2\Lambda} g_z \overline{t}'\sigma_{\mu\nu} q_i Z^{\mu\nu}$$
$$+ \sum_{q_i=u,c,t} \frac{\kappa^{q_i}_g}{2\Lambda} g_s \overline{t}'\sigma_{\mu\nu}\lambda_a q_i G^{\mu\nu}_a + h.c.$$
$$+ \sum_{q_i=d,s,b} \frac{\kappa^{q_i}_\gamma}{\Lambda} Q_{q_i} g_e \overline{b}'\sigma_{\mu\nu} q_i F^{\mu\nu} + \sum_{q_i=d,s,b} \frac{\kappa^{q_i}_z}{2\Lambda} g_z \overline{b}'\sigma_{\mu\nu} q_i Z^{\mu\nu}$$
$$+ \sum_{q_i=d,s,b} \frac{\kappa^{q_i}_g}{2\Lambda} g_s \overline{b}'\sigma_{\mu\nu}\lambda_a q_i G^{\mu\nu}_a + h.c.$$

Anomalous

Interactions

Decay widths and branchings

$$\Gamma(Q' \to Wq) = \frac{1}{16}\frac{\alpha_e |V_{Q'q}|^2 m_{Q'}^3}{\sin^2\theta_W m_W^2}\lambda_W\sqrt{\lambda_r}$$

$$\lambda_r = (1 + m_W^4/m_{Q'}^4 + m_q^4/m_{Q'}^4 - 2m_W^2/m_{Q'}^2 - 2m_q^2/m_{Q'}^2 - 2m_W^2 m_q^2/m_{Q'}^4)$$

$$\lambda_W = \left(1 + m_W^2/M_{Q'}^2 - 2m_q^2/m_{Q'}^2 + m_q^4/m_{Q'}^4 + m_q^2 m_W^2/m_{Q'}^4 - 2m_W^4/m_{Q'}^4\right)$$

SM decay widths

Checked by hand calculations..

Anomalous decay widths

$$\Gamma(Q' \to gq) = \frac{2}{3}\left(\frac{\kappa_q^g}{\Lambda}\right)^2 \alpha_s m_{Q'}^3 \lambda_0$$

$$\lambda_0 = \left(1 - 3m_q^2/m_{Q'}^2 + 3m_q^4/m_{Q'}^4 - m_q^6/m_{Q'}^6\right)$$

t'

$$\Gamma(Q' \to \gamma q) = \frac{2}{9}\left(\frac{\kappa_\gamma^q}{\Lambda}\right)^2 \alpha_e m_{Q'}^3 \lambda_0$$

$$\Gamma(Q' \to Zq) = \frac{1}{16}\left(\frac{\kappa_Z^q}{\Lambda}\right)^2 \frac{\alpha_e m_{Q'}^3}{\sin^2\theta_W \cos^2\theta_W}\lambda_Z\sqrt{\lambda_r}$$

$$\lambda_Z = \left(2 - m_Z^2/m_{Q'}^2 - 4m_q^2/m_{Q'}^2 + 2m_q^4/m_{Q'}^4 - 6m_q m_Z^2/m_{Q'}^3 - m_Z^2 m_t^2/m_{Q'}^4 - m_Z^4/m_{Q'}^4\right)$$

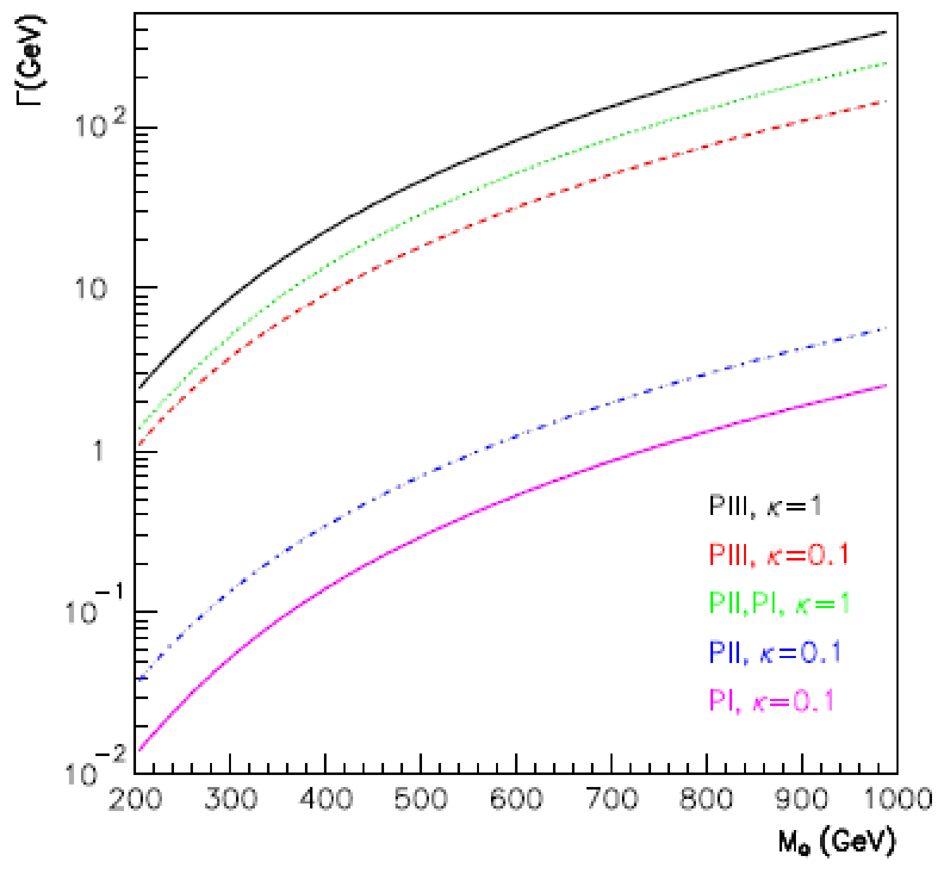
Branching ratios and decay widths for the PI parametrization

	t'			b'		
Mass (GeV)	300	500	700	300	500	700
Wq_1	0.017(1.6)	0.014(1.4)	0.014(1.3)	0.013(1.3)	0.013(1.3)	0.013(1.3)
Wq_2	0.017(1.6)	0.014(1.4)	0.014(1.3)	0.013(1.3)	0.013(1.3)	0.013(1.3)
Wq_3	0.017(1.6)	0.014(1.4)	0.014(1.3)	0.003(0.34)	0.009(0.86)	0.011(1.0)
$Zq_{1,2}$	2.5(2.3)	2.3(2.2)	2.2(2.1)	1.9(1.8)	2.1(2.0)	2.1(2.1)
Zq_3	0.27(0.26)	1.4(1.4)	1.8(1.7)	1.9(1.8)	2.1(2.0)	2.1(2.1)
$\gamma q_{1,2}$	0.9(0.86)	0.76(0.73)	0.72(0.69)	0.17(0.17)	0.17(0.17)	0.17(0.17)
γq_3	0.26(0.25)	0.52(0.5)	0.6(0.57)	0.17(0.17)	0.17(0.17)	0.17(0.17)
$gq_{1,2}$	40(39)	34(33)	32(31)	31(30)	31(30)	31(30)
gq_3	12(11)	23(22)	27(26)	31(30)	31(30)	31(30)
Γ_{tot}(GeV)	5.21(0.055)	28.47(0.297)	82.58(0.859)	6.75(0.069)	31.43(0.325)	86.39(0.895)

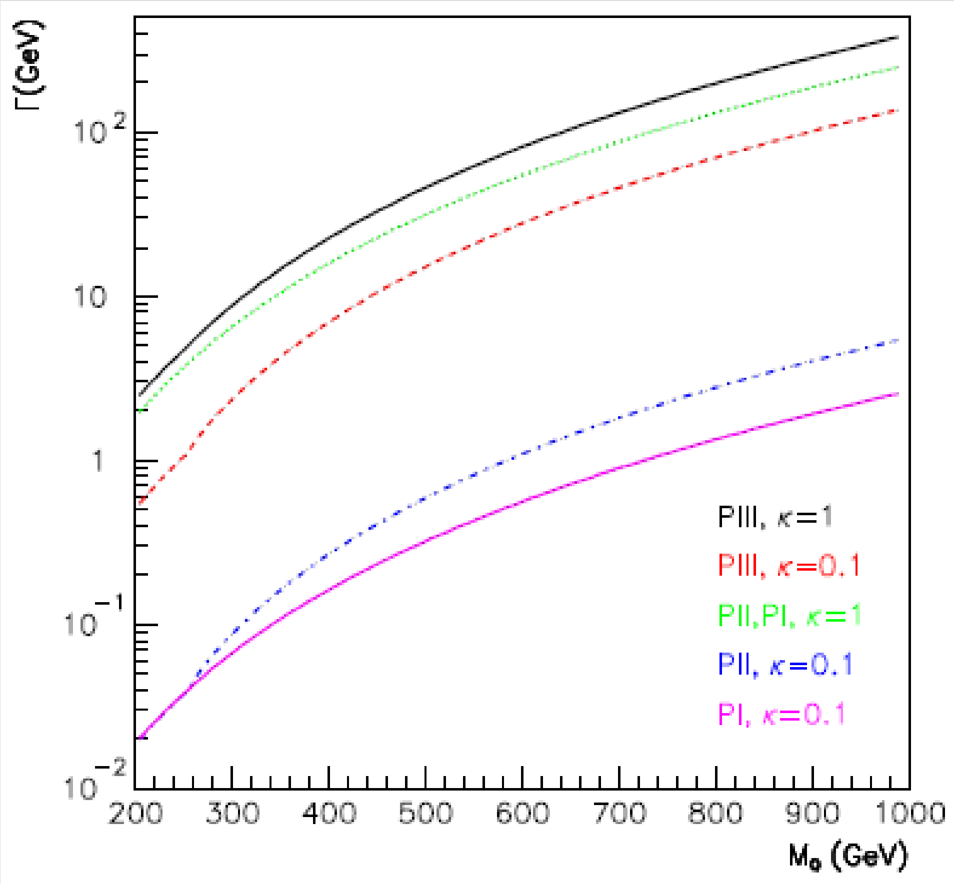
BR and Γ for PIII parametrization

	t'			b'		
Mass (GeV)	300	500	700	300	500	700
Wq_1	0.39(0.9)	0.35(0.9)	0.34(0.89)	0.19(0.69)	0.17(0.52)	0.17(0.48)
Wq_2	21.0(48)	19.0(48)	18.0(48)	20.0(75)	19.0(57)	18.0(52)
Wq_3	21.0(50)	20.0(50)	19.0(50)	5.7(21)	13.0(40)	16.0(45)
$Zq_{1,2}$	1.4(0.033)	1.4(0.036)	1.4(0.037)	1.4(0.052)	1.4(0.043)	1.4(0.04)
Zq_3	0.16(0.0036)	0.89(0.023)	1.1(0.03)	1.4(0.052)	1.4(0.043)	1.4(0.04)
$\gamma q_{1,2}$	0.52(0.012)	0.47(0.012)	0.45(0.012)	0.13(0.0048)	0.12(0.0036)	0.11(0.0033)
γq_3	0.52(0.0035)	0.32(0.008)	0.37(0.0098)	0.13(0.0048)	0.12(0.0035)	0.11(0.0033)
$gq_{1,2}$	23.0(0.54)	21.0(0.53)	20.0(0.53)	23.0(0.86)	21.0(0.64)	20.0(0.59)
gq_3	6.8(0.16)	14.0(0.36)	20.0(0.44)	23.0(0.85)	21.0(0.64)	20.0(0.59)
Γ_{tot}(GeV)	9.05(3.89)	46.46(18.29)	132.04(50.30)	9.14(2.46)	46.39(15.29)	131.23(45.74)

Decay widths are important for the resonance !

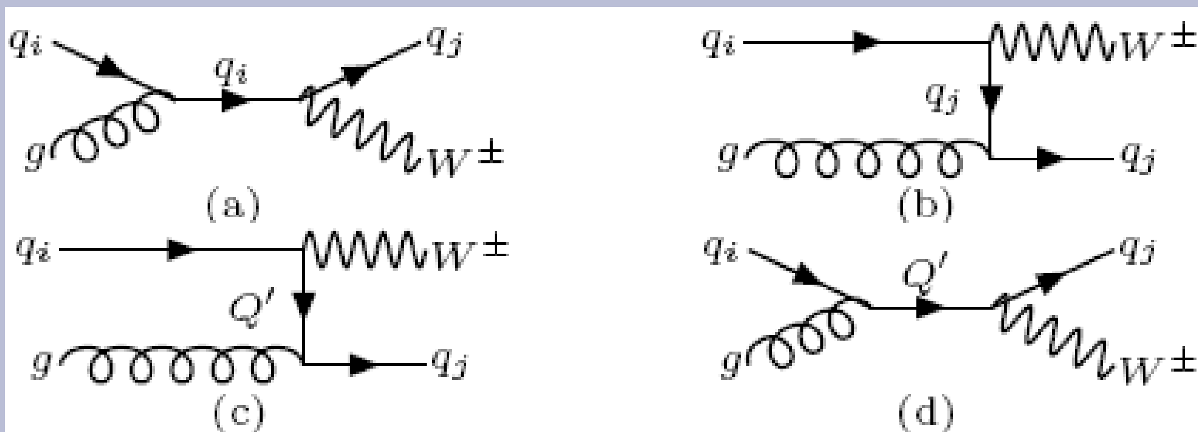


We find the width Γ=6.74(129.01) GeV for $m_{b'}$=300(800) GeV



We find the width Γ=5.21(125.06) GeV for $m_{t'}$=300(800) GeV

Q’ Production



$$
\begin{aligned}
pp \rightarrow\ & t' \quad X \\
& \hookrightarrow W^+ \quad b_{jet} \\
& \hookrightarrow W^+ \quad j
\end{aligned}
$$

$$
\begin{aligned}
pp \rightarrow\ & b' \quad X \\
& \hookrightarrow W^- \quad W^+ \quad b_{jet} \\
& \hookrightarrow W^- \quad W^+ \quad j \\
& \hookrightarrow W^- \quad j
\end{aligned}
$$

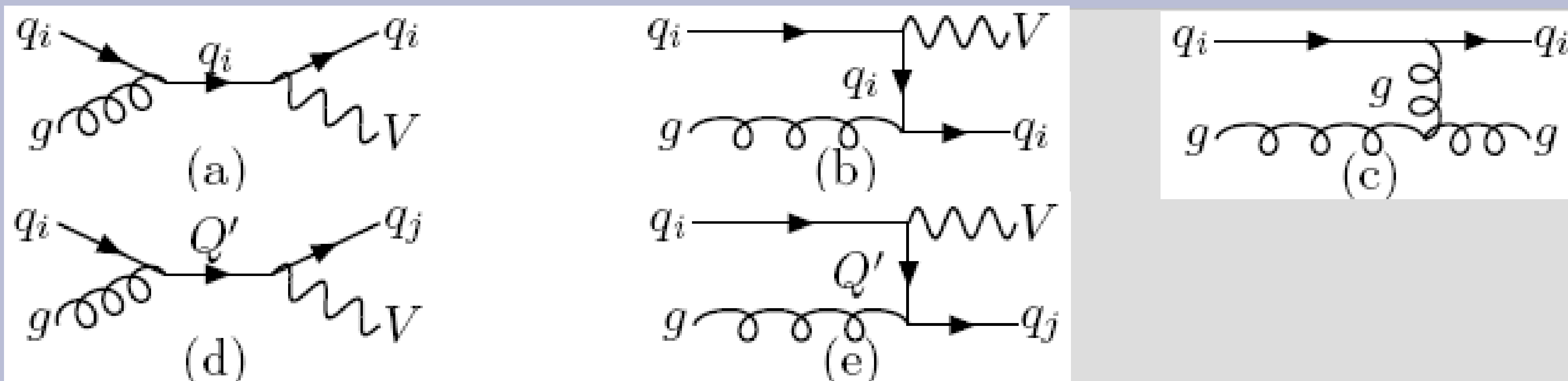
$$\sigma = \int_{\tau_{min}}^{1} d\tau \int_{\tau}^{1} \frac{dx}{x} f_q(x, Q^2) f_g\left(\frac{\tau}{x}, Q^2\right) \hat{\sigma}(\tau s)$$

PI parametrization with $\kappa/\Lambda = 1\ \mathrm{TeV}^{-1}$

Mass(GeV)→	200	300	400	500	600	700	800	900	1000
$\sigma(pp \to t'X \to W^+bX)$	5.07	2.55	1.43	0.903	0.608	0.429	0.311	0.232	0.174
$\sigma(pp \to \bar{t}'X \to W^-\bar{b}X)$	1.76	0.744	0.360	0.198	0.119	0.075	0.049	0.034	0.023
$\Gamma_{t'}$(GeV)	1.35	5.21	13.74	28.46	50.91	82.59	125.06	179.82	248.43
$\sigma(pp \to b'X \to W^-tX)$	0.027	0.405	0.455	0.366	0.275	0.204	0.151	0.113	0.085
$\sigma(pp \to \bar{b}'X \to W^-tX)$	0.012	0.231	0.241	0.181	0.127	0.089	0.062	0.044	0.032
$\Gamma_{b'}$(GeV)	1.97	6.74	16.07	31.43	54.37	86.39	129.01	183.73	252.08

$\sqrt{s}$=14 TeV

Anomaolus production and anomalous decay

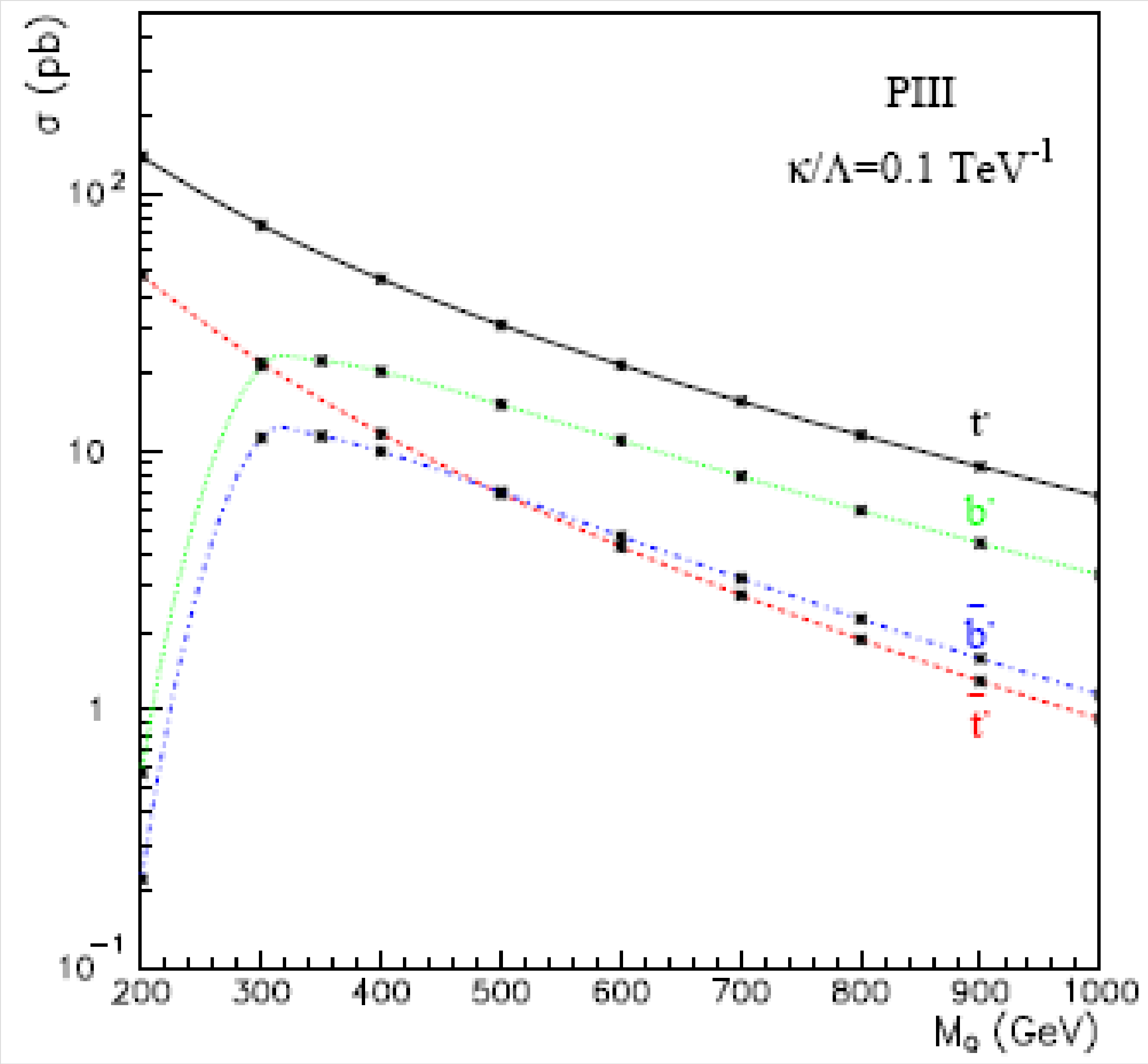


$$
\begin{aligned}
pp \rightarrow \; & b' \quad X \\
& \hookrightarrow \; V \quad b_{jet} \\
& \hookrightarrow \; V \quad j
\end{aligned}
$$

Zb+Z $\bar{b}$ cross sections, where PIII parametrization is used

σ(pb)	300	400	500	600	700	800
κ/Λ=1/TeV	2.14×10^{2}	1.55×10^{2}	1.10×10^{2}	8.27×10^{1}	6.53×10^{1}	5.40×10^{1}
κ/Λ=0.1/TeV	3.15×10^{1}	3.08×10^{1}	3.04×10^{1}	2.99×10^{1}	2.96×10^{1}	2.93×10^{1}

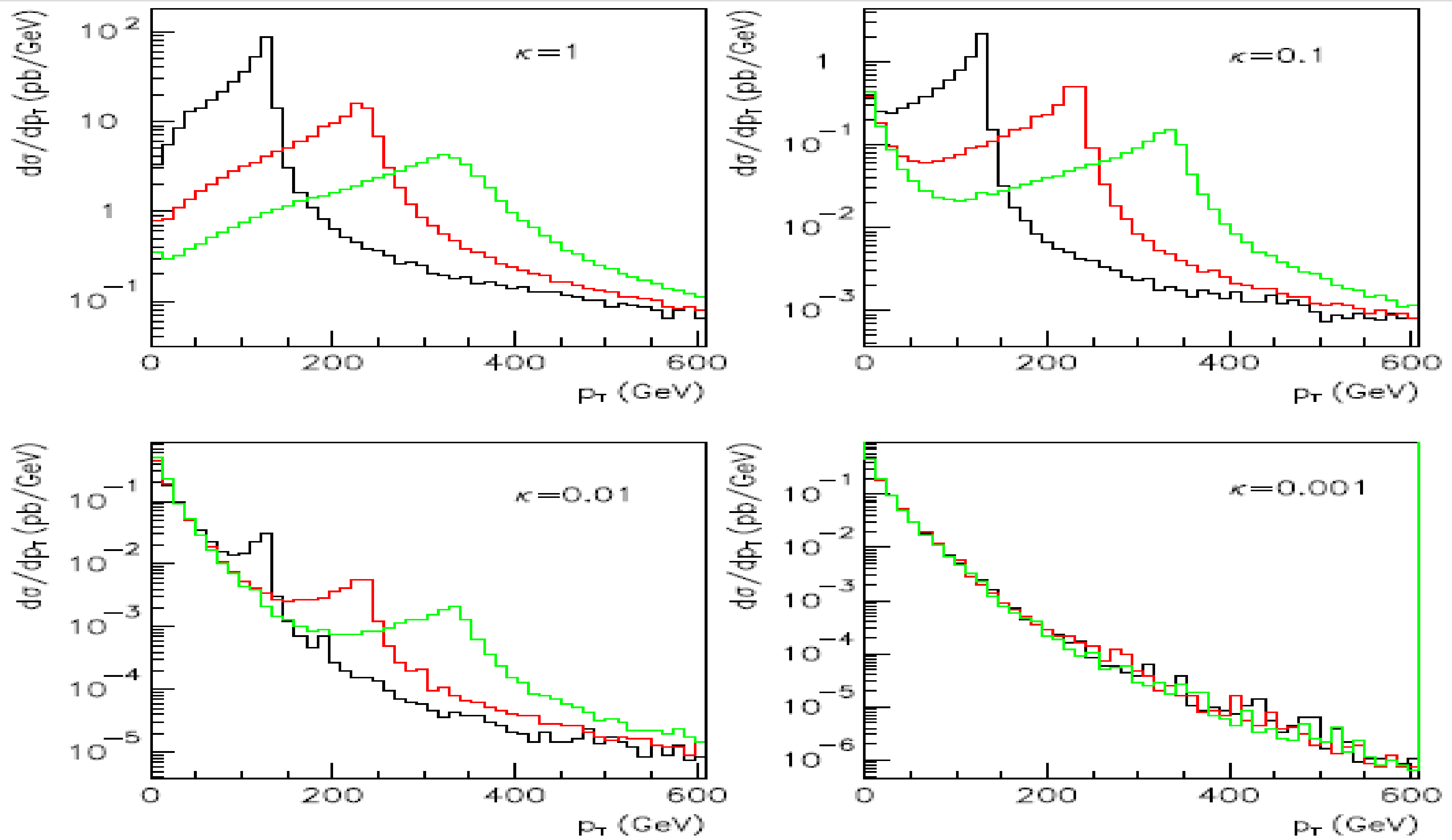
Resonant cross section for $pp \rightarrow t'(b')X \rightarrow W^{+}b(W^{-}t)X$



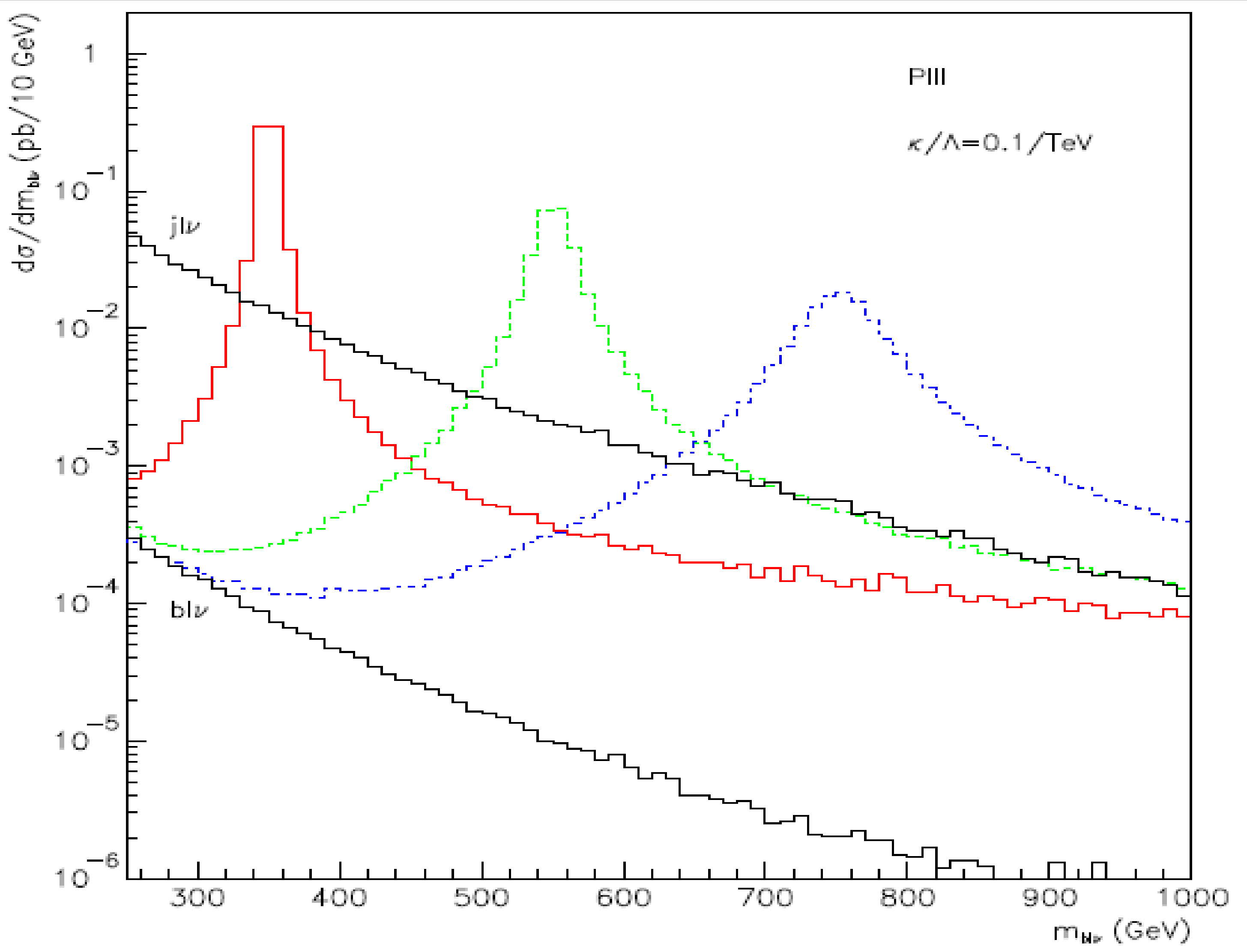
The resonance cross sections for t'($\bar{t}$') and b'($\bar{b}$') depending on the mass. We use the parametrization PIII and take κ/Λ=0.1/TeV.

Decrease due to the tW channel for $m_{b'}$<300 GeV.

p_T distribbution of b-jets



Invariant mass distributions for the signal and background (blν)



Background study,

Cuts:

p_T>50 GeV

1 b-jet

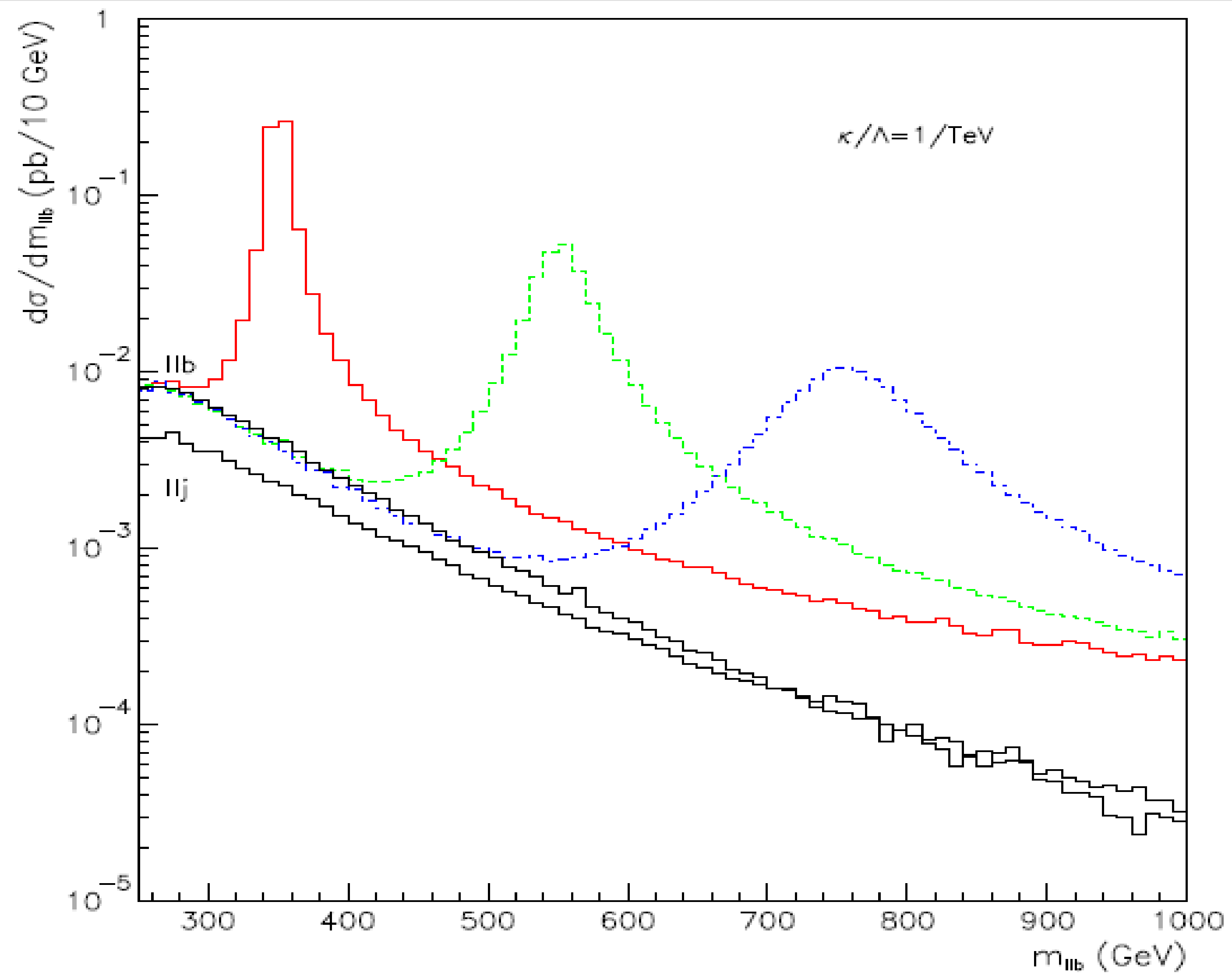
eff (b) 60% ,

rej(j)~100,

rej(c)~10

- we count events in the mass intervals Δm.

Invariant mass distributions for the signal and background (llb)



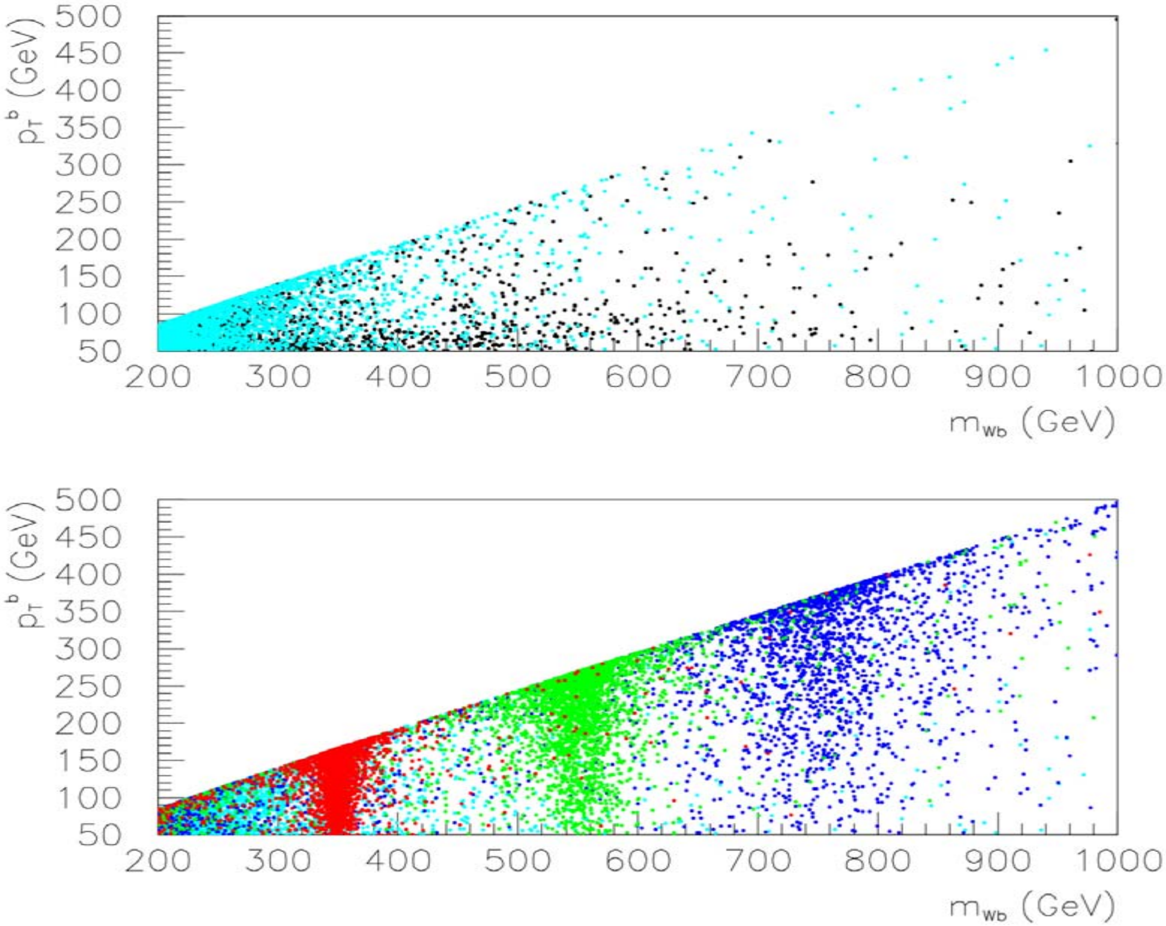
Signal:
pp→b'X→ZbX

Background:

pp→llbX and
pp→lljX

Distributions

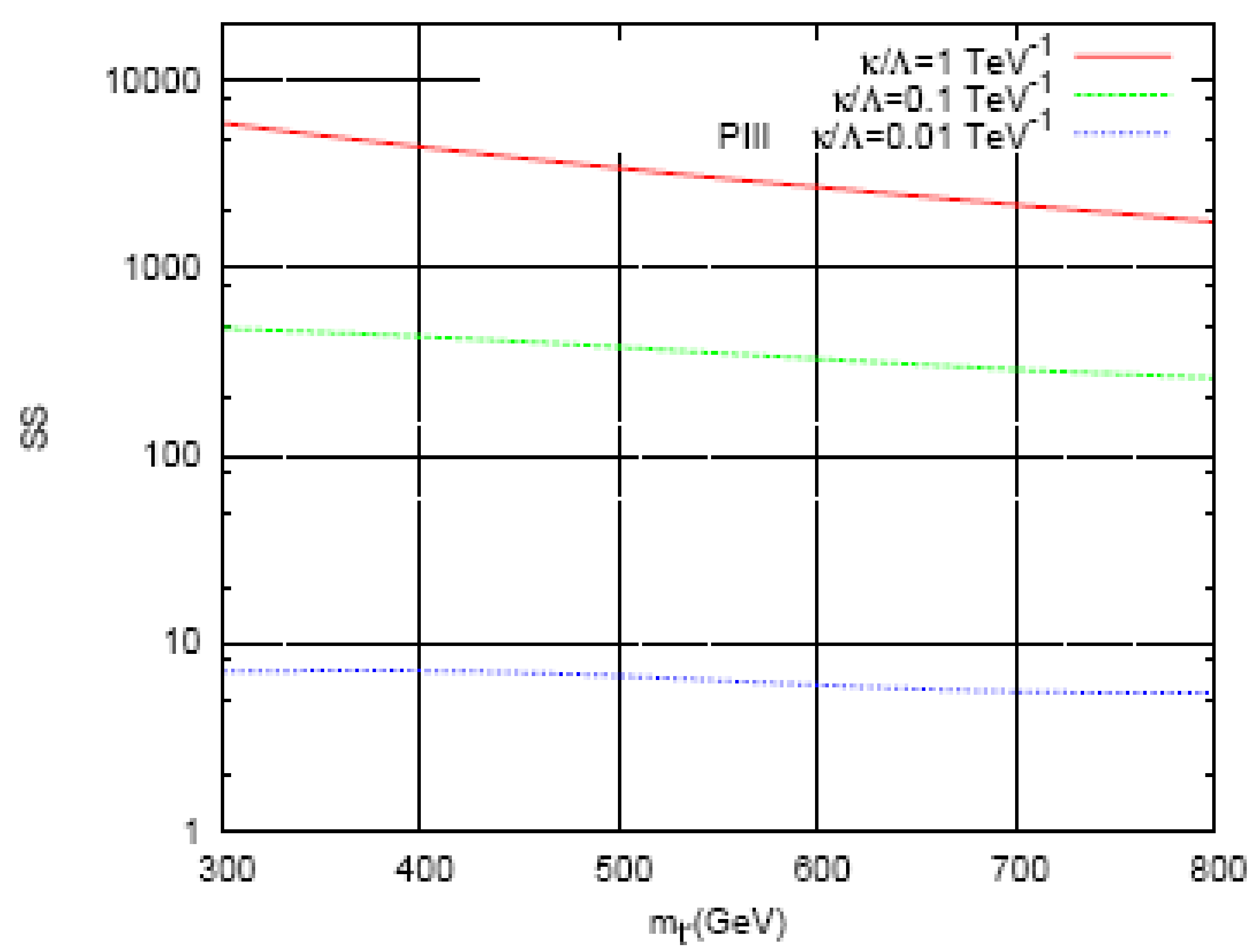
- Kinematical distributions of background events Wb and Wj(b)
- Signal and background events are shown on the same plot



Backgrounds relevant to the resonant t’ and b’ production

Backgrounds	$p_T > 20\text{GeV}$	$p_T > 50\text{GeV}$	$p_T > 100\text{GeV}$
$W^+b(W^-\bar{b})$	$2.79(2.71)$	$6.98\times10^{-1}(6.71\times10^{-1})$	$1.16\times10^{-1}(1.09\times10^{-1})$
$W^+j(W^-j)$	$2.22\times10^4(1.64\times10^4)$	$5.37\times10^3(3.87\times10^3)$	$1.02\times10^3(6.92\times10^2)$
$W^+W^-b(W^-W^+\bar{b})$	$2.20\times10^1(2.12\times10^1)$	$1.60\times10^1(1.42\times10^1)$	$4.27(3.08)$
$tj(\bar{t}j)$	$1.43\times10^2(8.41\times10^1)$	$8.61\times10^1(4.84\times10^1)$	$3.02\times10^1(1.54\times10^1)$
$Zb,Z\bar{b}$	3.41×10^2	9.19×10^1	1.64×10^1
$\gamma b,\gamma\bar{b}$	2.34×10^3	9.48×10^1	6.67
$bj,\bar{b}j$	8.42×10^6	3.12×10^5	2.12×10^4
Zj	1.24×10^4	3.23×10^3	6.52×10^2
γj	1.49×10^5	7.67×10^3	7.22×10^2
$2j$	4.6×10^8	1.8×10^7	1.4×10^6

Significance for pp→W⁺bX



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

We calculate the statistical significance for L=10 fb^{-1} .

We conclude that SS>5 if κ/Λ>0.01/TeV.

Conclusion

The fourth family quarks can be produced with large numbers if their anomalous interactions dominate over the SM interactions. Following the results from the signal significance for t’ and b’ anomalous production, the sensitivity to anomalous coupling $\kappa/\Lambda=0.01$ TeV^{-1} providing an optimal parametrization for the extended CKM elements. If found at the LHC the fourth family quarks will change our perspective on the flavor an the mass.