Search for 4th generation fermions: Motivation, status and prospects

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Workshop on single top physics and fourth generation quarks
DESY, 14th and 15th September, 2009

CONTENT

(only covering an additional Dirac generation)

1. Why is it interesting?

2. Mass constraints (Γ_Z, Direct searches @ LEP2 &Tevatron)

3. Effects of/constraints on a 4th generation:

   Flavour physics: ---> Alexander Lenz

   Higgs prod. & decays: ---> Tilman Plehn

   Single Top production: ---> Fabio Maltoni

4. Constraints on masses from electroweak precision fit

5. What do we know about the CKM and PMNS matrix elements?

6. Search strategies @ LHC

7. Summary

1. Why is it interesting?

- No good argument yet for only N_{gen}=3 (Why generations at all?)

  $N_{gen} \geq 3$ => CP violation in CKM matrix, but N_{gen}=3 not sufficient for baryogenesis

- N_{gen}=4: sufficient CP violation for SM baryogenesis in e.w. symmetry breaking (EWSB) due to large quark masses (Hou, Chin. J. Phys.47:134, 2009)

- Heavy 4th gen. quark masses => strong EWSB

  --> 2nd problem with N_{gen}=3 baryogenesis (M_{Higgs} too large) possibly solvable (Carena et al., NPB 716, 319, 2005)

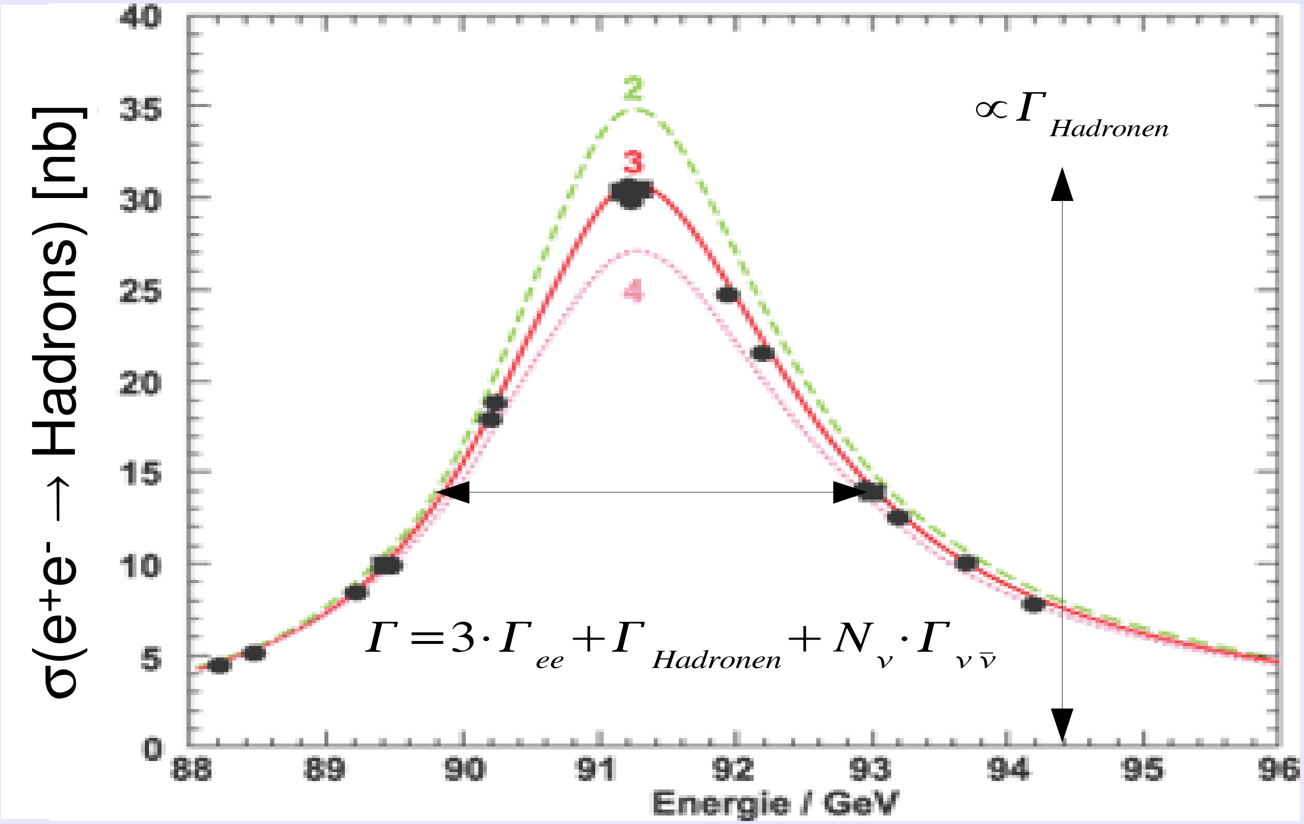
- SU(5) gauge coupling unification w/o SUSY possible (Hung, PRL80, 3000, 1998)

- E.w. precision fit: 4th gen. not excluded (e.g. Kribs et al., PRD76:075016, 2007)

  => significantly larger Higgs mass (up to ~600 GeV) allowed

  => Quite different Higgs phenomenology possible (--> T. Plehn)

2.1 Constraints on a 4th generation: Γ_Z



$$N_\nu = 2{,}984 \pm 0{,}008$$

in agreement with primordial nucleosynthesis

In case of a 4. generation:

$$m_{\nu_4} > M_Z / 2$$

$$\text{LEP2:} \quad m_{l_4} > 100.8 \text{ GeV}$$

$$m_{\nu_4} > 90.3 \text{ GeV (Dirac)}$$

$$m_{\nu_4} > 80.5 \text{ GeV (Majorana)}$$

All limits for unstable heavy leptons

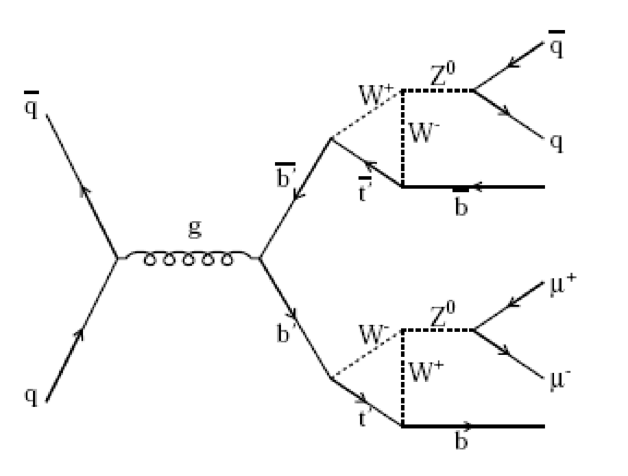
2.2 TEVATRON constraints: FCNC decay

CDF (1.06 fb^{-1}), PRD 76, 072006 (2007):

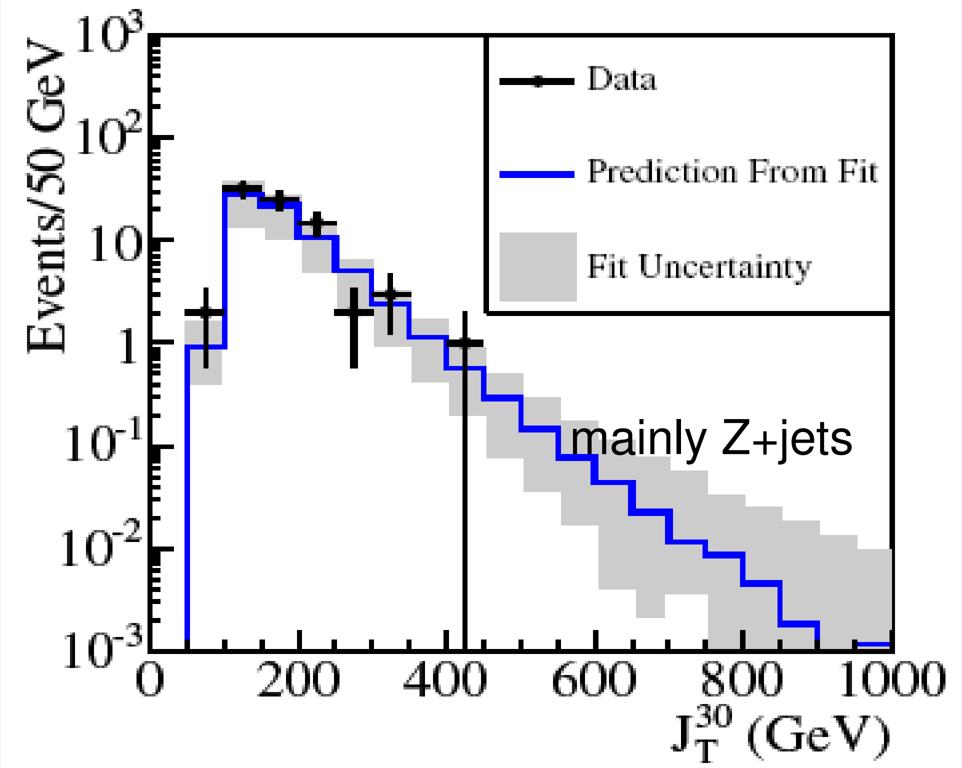
$$p\bar{p} \rightarrow b'\bar{b}', b'(d_4) \rightarrow b + Z$$

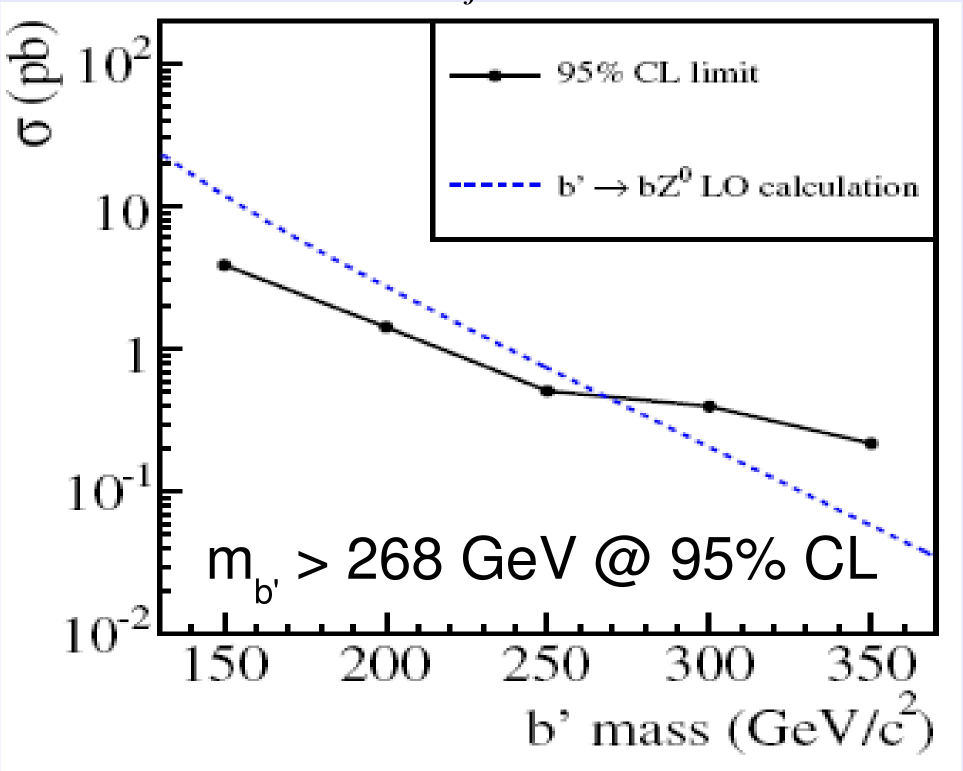
assumption:

BF(b'->Z+b)=100% & prompt b' decay



$$Z \rightarrow e^+e^-, \mu^+\mu^- \quad N^{30}_{jet} \geq 3 (30 \equiv E_{T,jet} \geq 30\,\text{GeV}) \quad J^{30}_T = \sum_{jets} E_T (E_T > 30\,GeV)$$





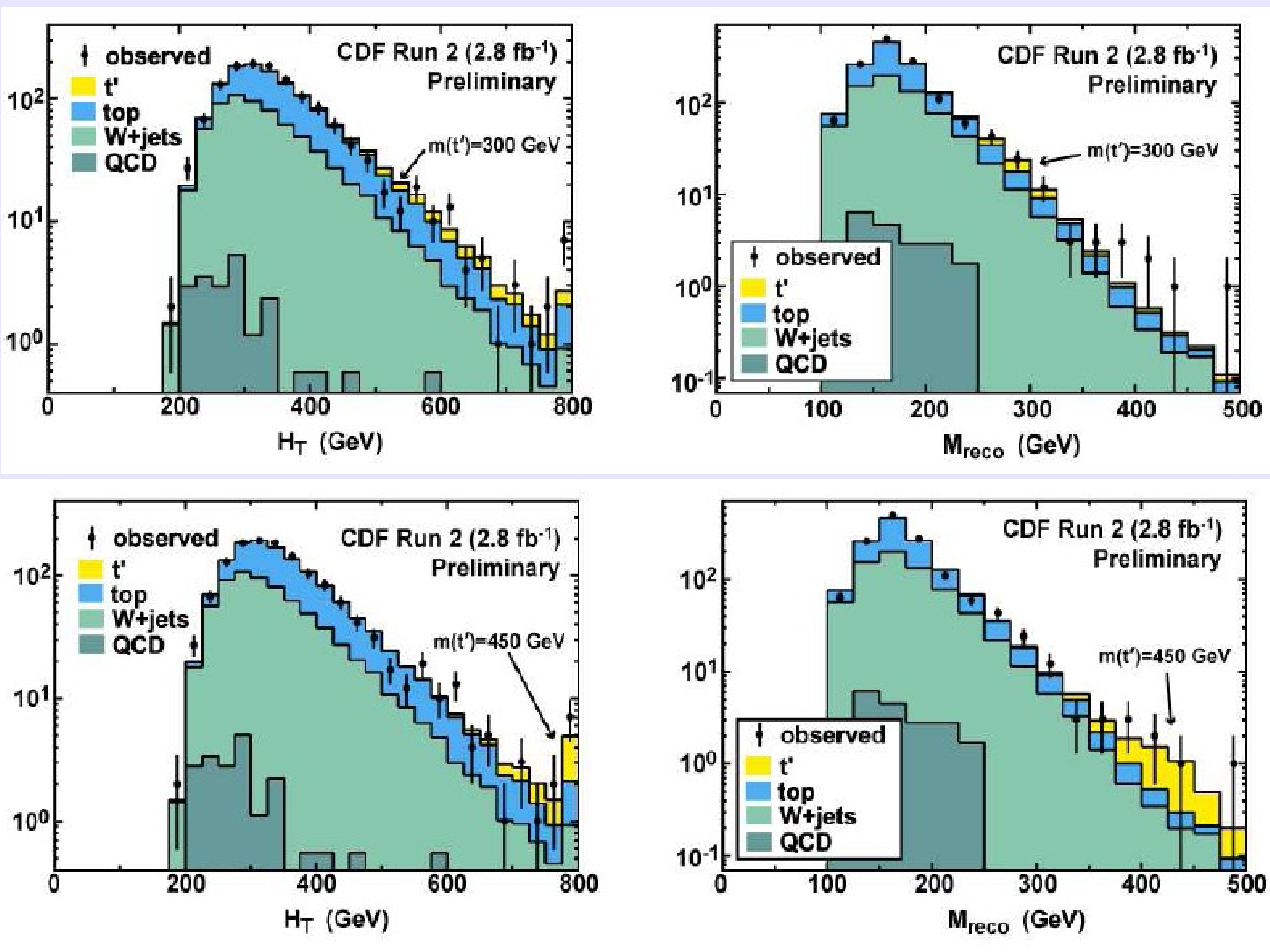
2.3 TEVATRON constraint: top-like search

CDF note 9446, 2.8 fb^{-1}

$$p\,\bar{p} \rightarrow t'\,\bar{t}' + X\,,\;\; t' \rightarrow W + q\,,\, W \rightarrow l\,\nu\,,\, W \rightarrow q\,\bar{q}$$

Note:
no distinction between
t' and b' possible

N_{lepton}=1, at least 4 jets with E_T>20 GeV



Kinematic fit like in
top reconstruction

No b-tagging

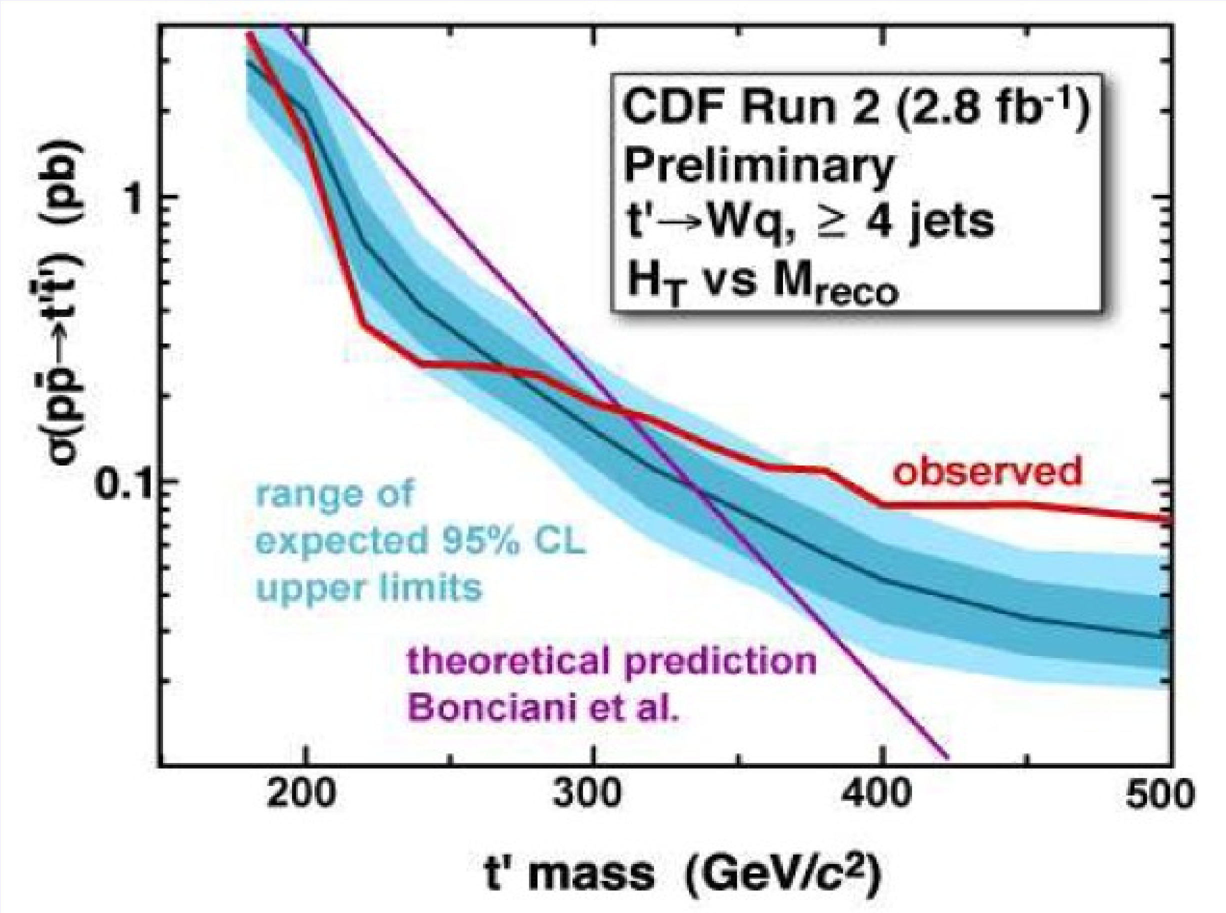
$$M_{reco} = M_{b\,j\,j} = M_{b\,l\,\nu}$$

$$H_T = \sum_{jets} E_T + E_{T,l} + E_{T,miss}$$

=> Likelihood fit

2.3 TEVATRON constraint: top-like search

- Limit: $m_{t'}$ > 311 GeV @ 95% C.L.



- Excess @ 450 GeV?
  P-value=0.01 for SM hypthesis

- $\sigma_{observed} > \sigma_{expected}$!

- Possibilities for excess:
  - * fluctuation
  - * badly understood SM BG
  - * NP signal:
    - a) no 4th gen. quark
    - b) 4th gen.: contributions from t' and b' decays ?

- Caveat: exclusion limit assumes
  - a) final state BF of 100% => mass limit could be lower
  - b) short lifetime => no limit for very small CKM elements

2.4 TEVATRON constraint: same-sign dilepton

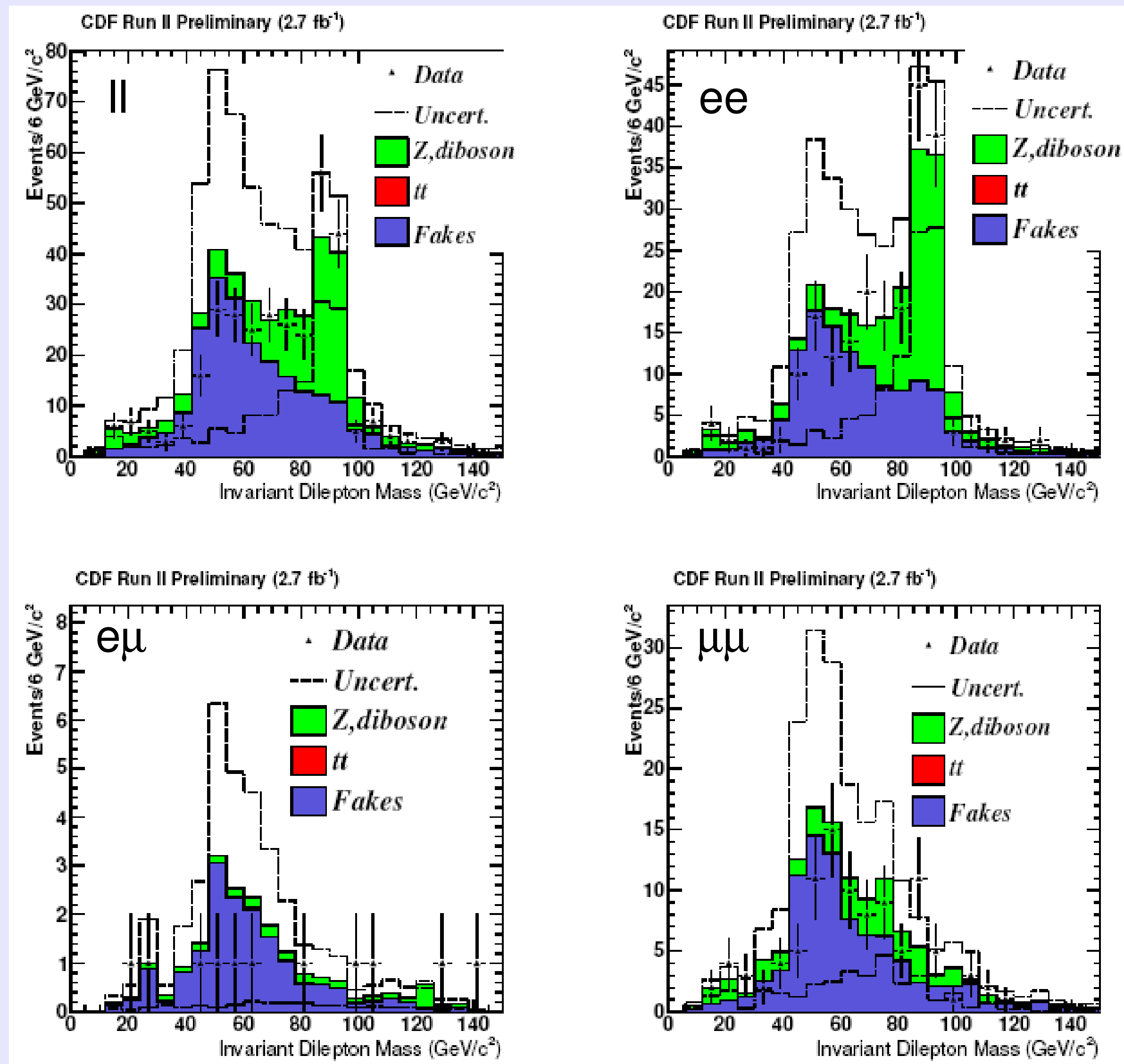
In many mass/CKM scenarios: $p\bar{p} \to b'\bar{b}' + X\,,\; b' \to W + t(\to b + W)$

Striking search scenario: same-sign dilepton final state + high jet multiplicity

CDF, note 9759, 2.7 fb-1:

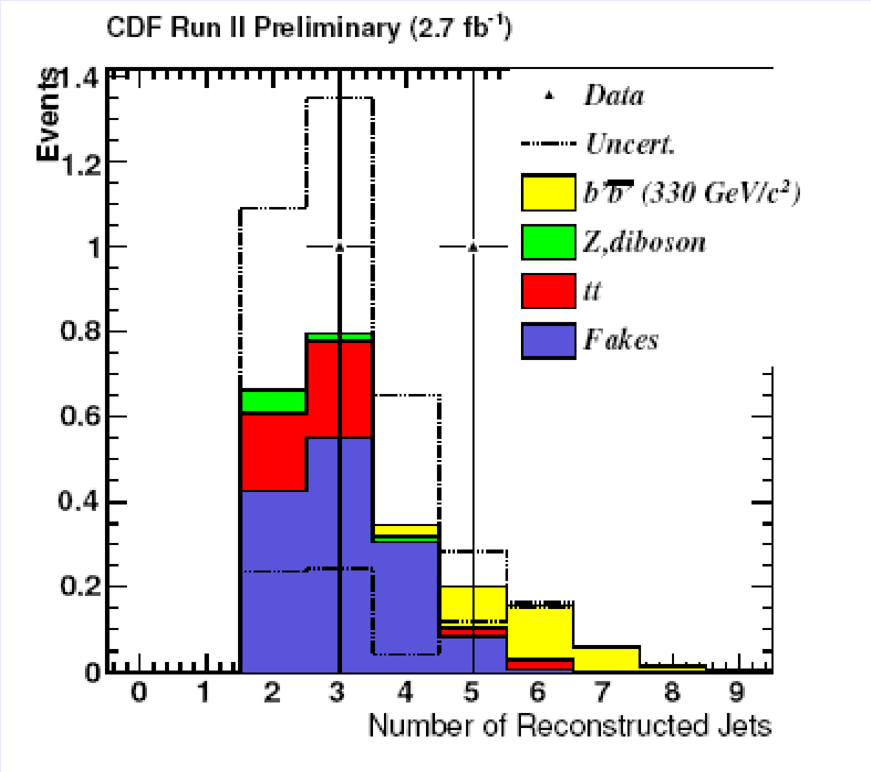
same-sign dilepton invariant mass

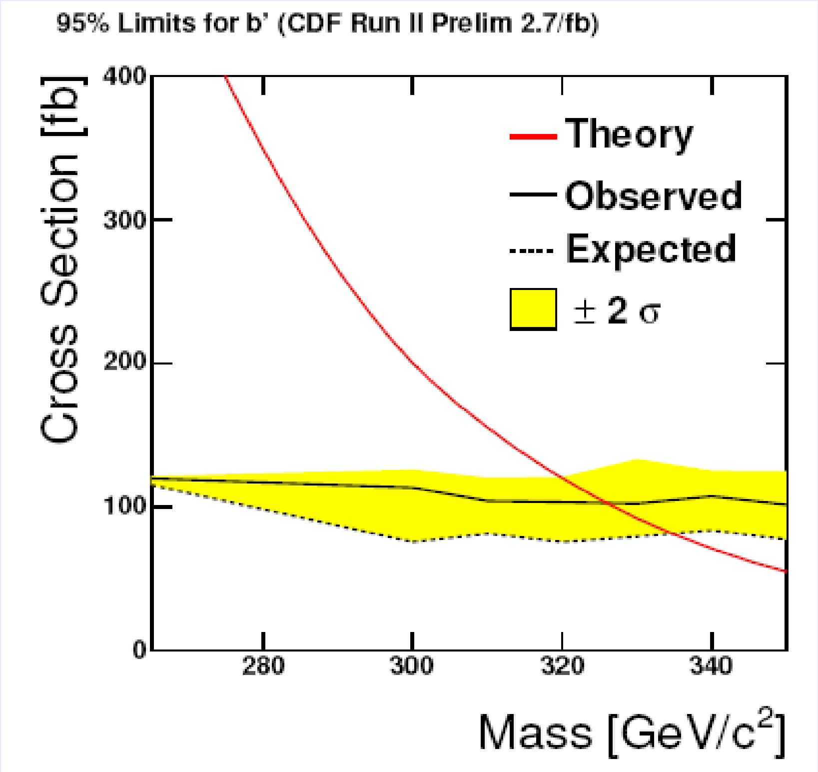
- **Fakes: mainly W+jets**
- **Z+jets:**
  $Z \to e^+e^-$ with hard bremsstr.
  + asymmetric conversion
  $\gamma \to e^+e^-$



2.4 TEVATRON constraint: same-sign dilepton

Extraction method: likelihood fit in jet multiplicity





Usual caveat: CDF assumes BF(b'→W+t)=100% & prompt b' decay

2.5 TEVATRON constraints: assumptions

The following is based on Hung & Sher, PRD77, 037302 (2008)

$t' \to W + q$: CDF assumes BF($t' \to W+q$)=100% & prompt t' decay

$m_{t'}$-$m_{b'}$ > m_W: BF($t' \to W+b'$) dominant => BF($t' \to W+q$) small

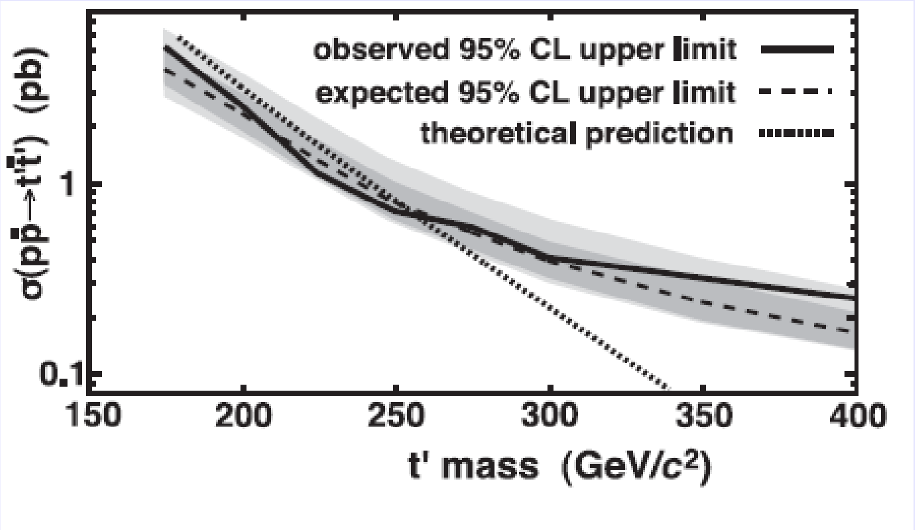
0 < $m_{t'}$-$m_{b'}$ < m_W: $t' \to W^* + b'$ can still dominate for small $V_{t'q}$

$m_{t'}$-$m_{b'}$ < 0: $\tau_{t'}$ could be so small (for tiny $V_{t'q}$) that quark could transverse cm-m before decaying (stable quark searches exclude more than ~3 m)

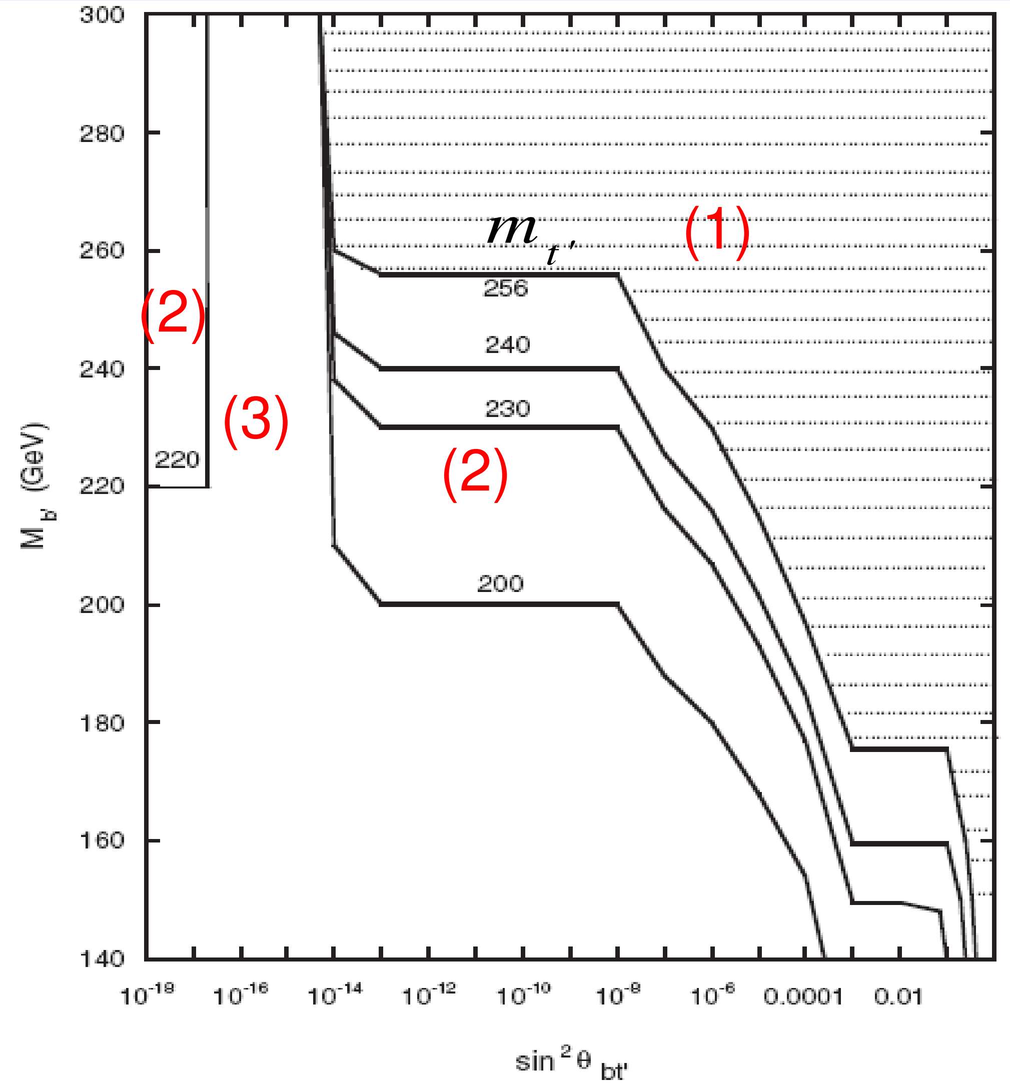
=> Constraint dependent on $m_{b'}$ and $V_{t'q}$

2.5 TEVATRON constraints: assumptions

First CDF result (760 pb^{-1}), PRL 100, 161803 (2008): $m_{t'}$>256 GeV, 95% CL



Hung & Sher, PRD77, 037302 (2008):



(1) Region where CDF limit applies

(2) Region where a smaller mass limit is obtained requiring BF(t'→W+q) still being dominant

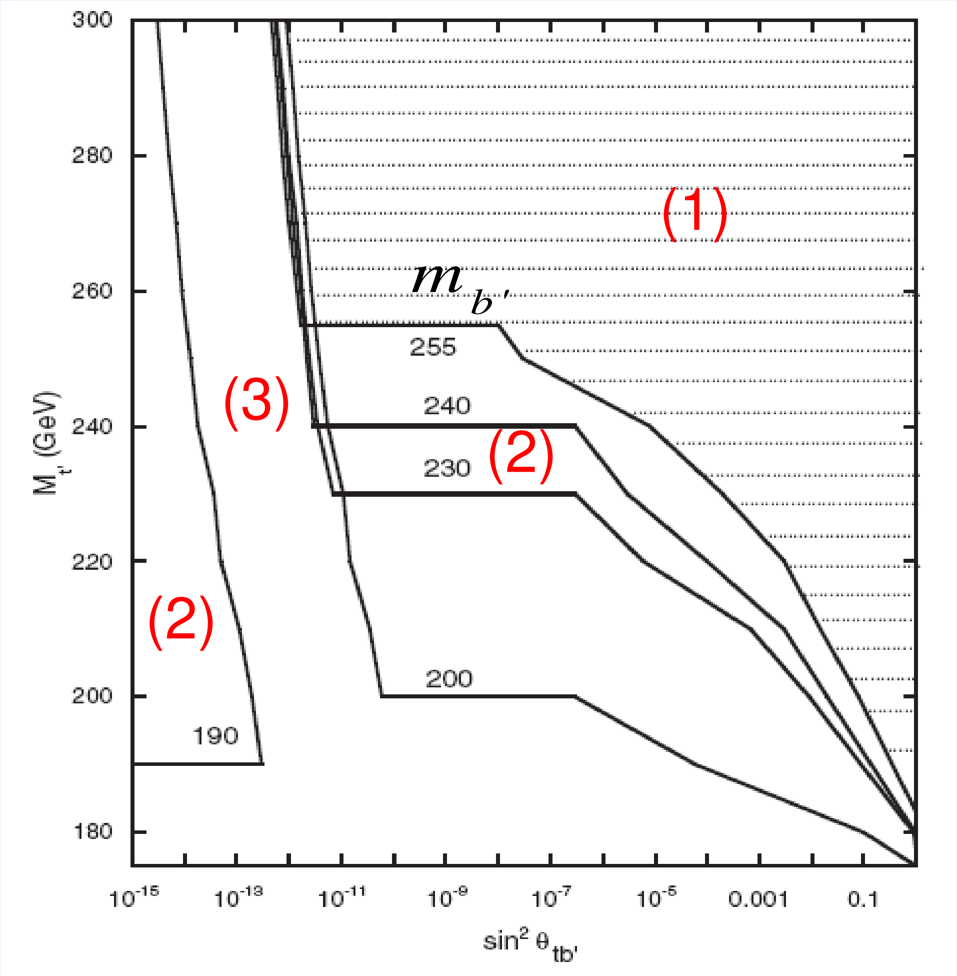
(3) lifetime region: no mass limit

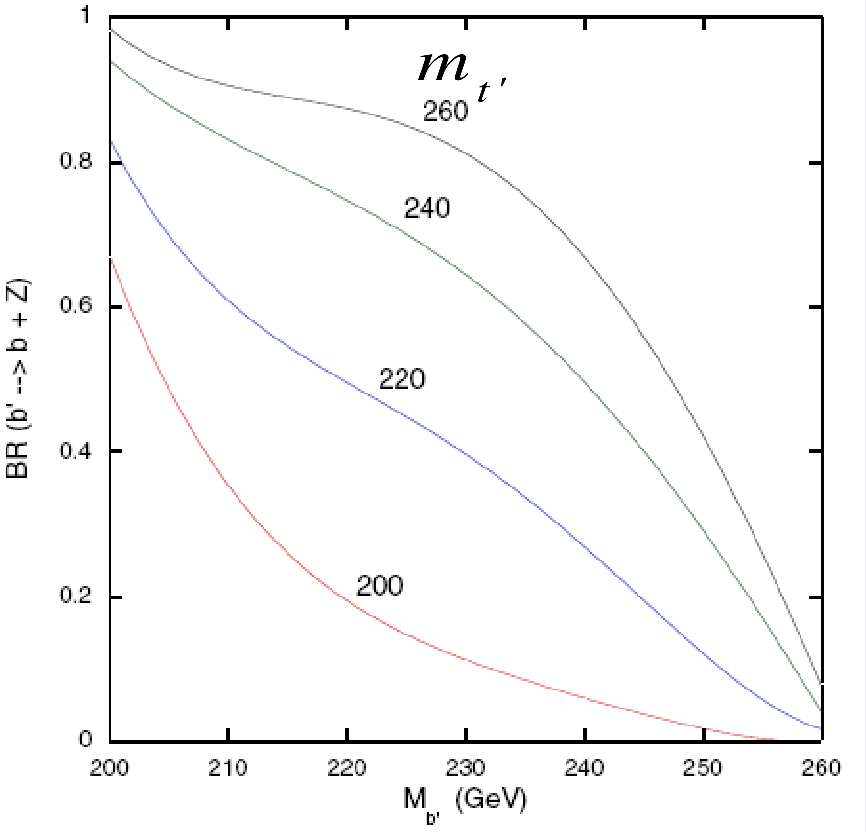
2.5 TEVATRON constraints: assumptions

CDF ($1.06\ fb^{-1}$), PRD 76, 072006 (2007): $p\bar{p} \rightarrow b'\bar{b}', b'(d_4) \rightarrow b + Z$

$m_{b'} > 268$ GeV @ 95% CL

Hung & Sher, PRD77, 037302 (2008):





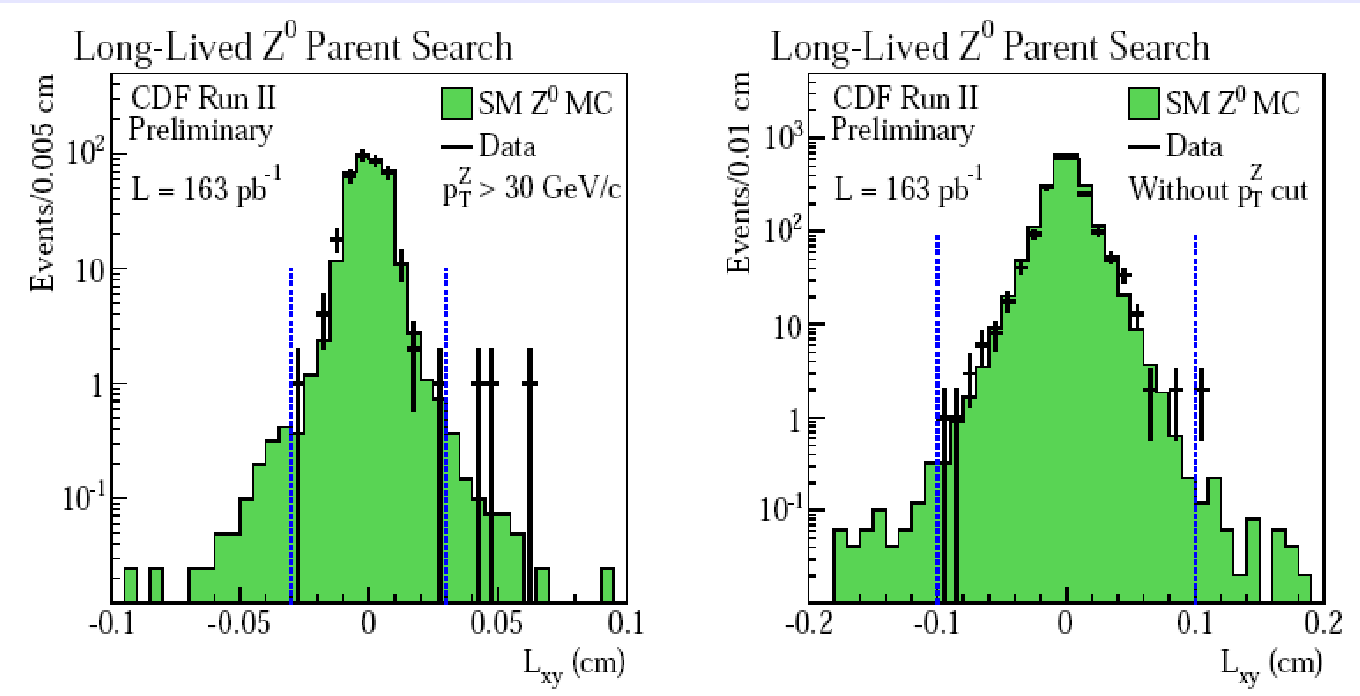
BF(b'→Z+b)=100% for

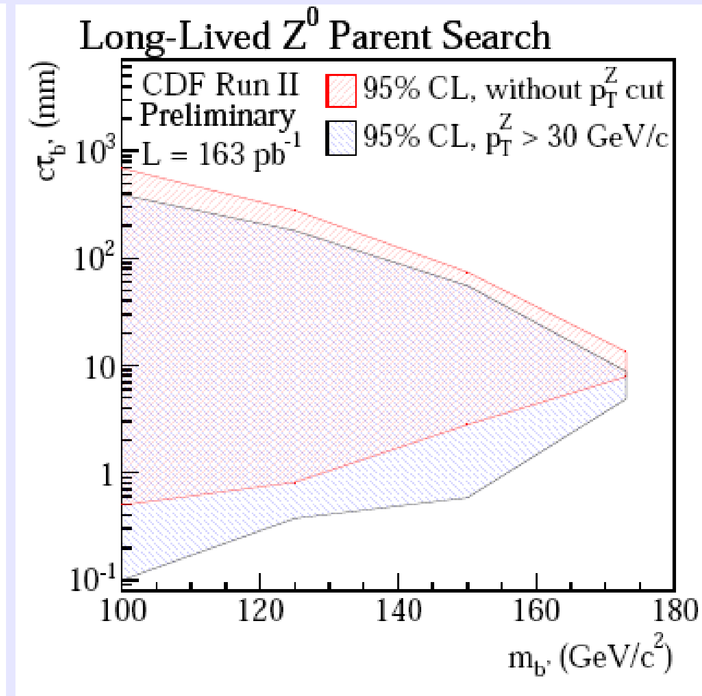
$m_{b'} > 255$ GeV never met:

b'→W + t threshold opens

2.5 TEVATRON constraints: long-lived b'

CDF note 7244 (163 pb^{-1}): $b' \rightarrow Z + b$

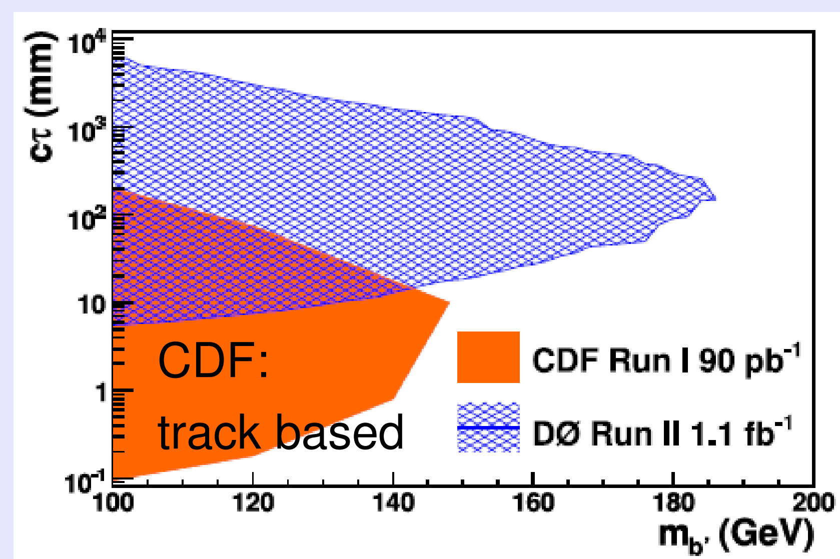




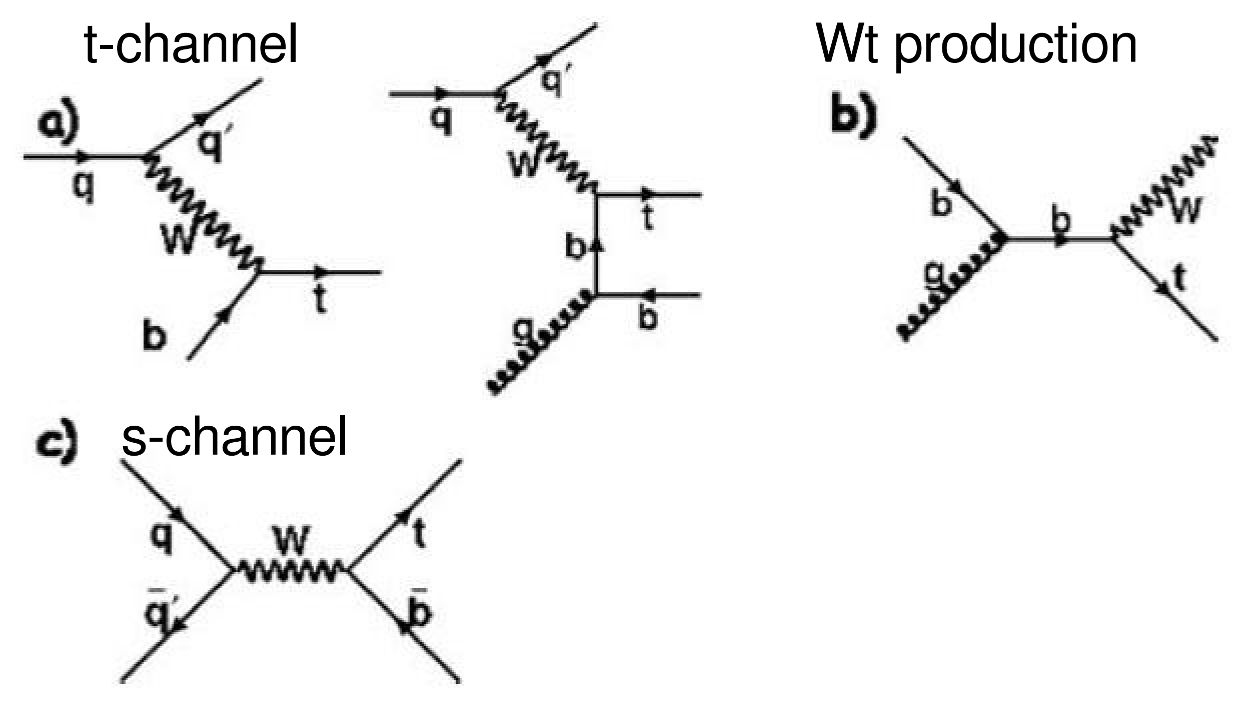
D0, PRL 101, 111802 (2008) with 1.1 fb^{-1}

$b' \rightarrow Z + b$

Search channel: $Z \rightarrow e^+ e^- + X$



3.1 Effects of a 4th generation on Single Top production



Gives direct info on $|V_{tb}|$

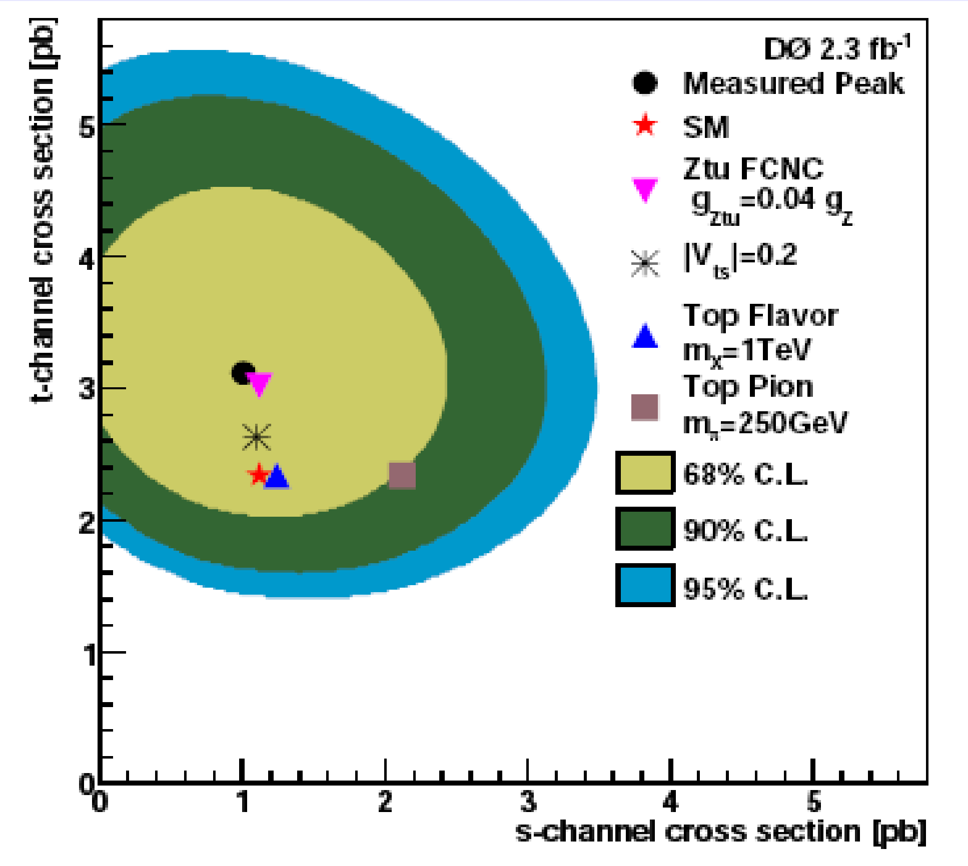
If $\sigma_{meas} \neq \sigma_{theo}$:

$|V_{tb}|<1$ (=> 4th gen.)

or other NP

	t-channel	Wt production	s-channel
TEVATRON($\sqrt{s} = 1.8$ TeV, $p\bar{p}$)	1.98 ± 0.30 pb [149, 161]	≈ 0 pb	0.88 ± 0.14 pb [149, 161]
LHC ($\sqrt{s} = 14$ TeV, pp)	245 ± 27 pb [161, 162]	$62.2^{+16.6}_{-3.7}$ pb [145]	10.2 ± 0.7 pb [144, 161]

3.1 Effects of a 4th generation on Single Top production

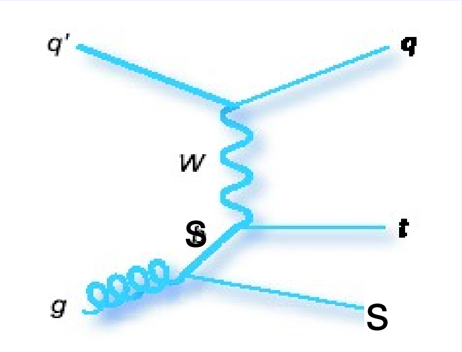


$\sigma_{SingleTop} \sim |V_{tb}|^2$ in N_{gen}=3-SM

Nonetheless, it is possible to have:

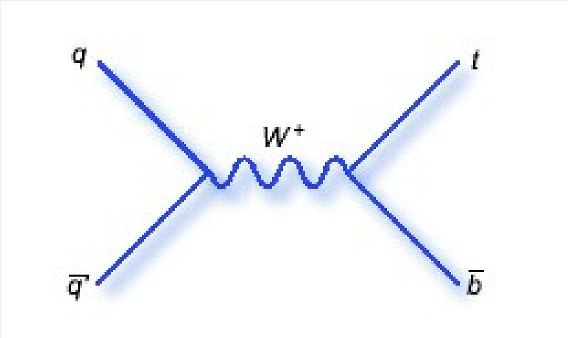
$\sigma_{SingleTop}(N_{gen}=4) > \sigma_{SingleTop}(N_{gen}=3)$

although $|V_{tb}|<1$ if e.g. $|V_{ts}|$ is sizeable



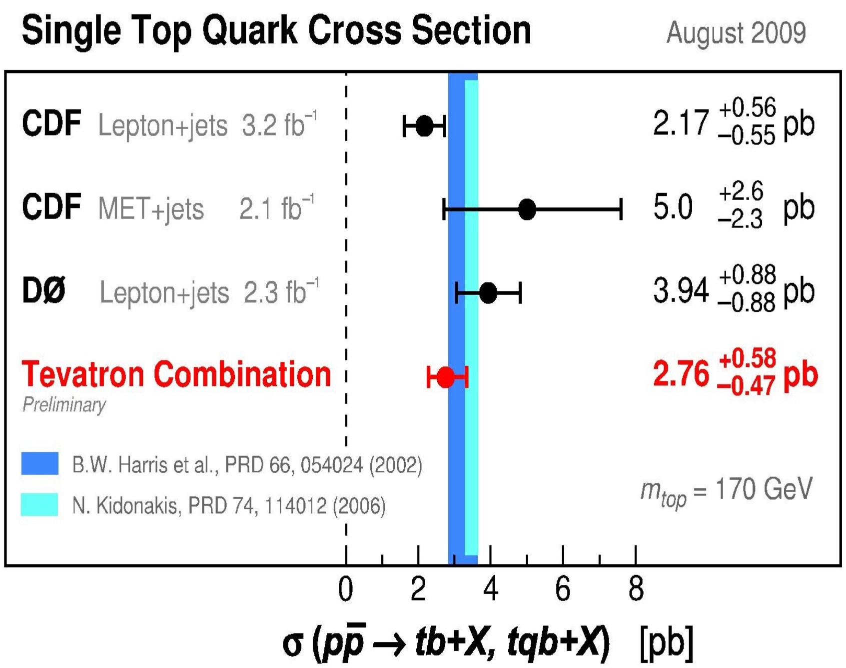
t-channel enhanced

PDF(s) >> PDF(b)



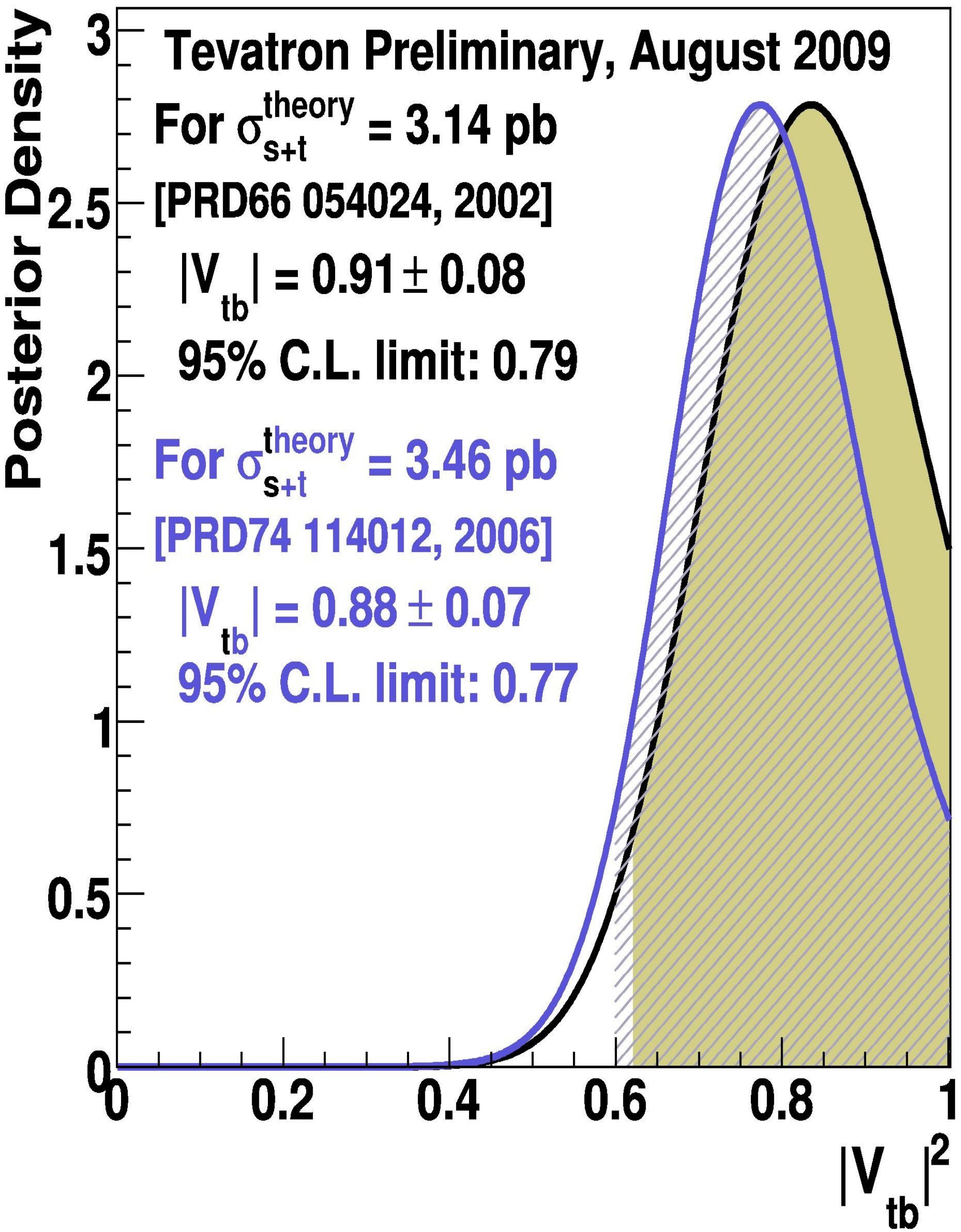
s-channel suppressed: $|V_{tb}| <1$

3.1 Effects of a 4th generation on Single Top production



D0: 0903.0850 [hep-ex]

CDF: 0903.0885 [hep-ex]



3.1 Effects of a 4th generation on Single Top production

- Final remark: Cross section measurement, respectively, extraction of $|V_{tb}|$

  assumes t→Wb to be dominant (--> b-tagging)

- Relevant branching ratio: $R = \dfrac{\Gamma(t \to W + b)}{\Gamma(t \to W + q)} = \dfrac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$

  determined in ttbar events by measuring 0, 1, ≥2 tagged b-jet rates

  BF(t→Wb) dominant fulfilled in N_{gen}=3-SM: $|V_{tb}| = 0.999142^{+0.000021}_{-0.000014}$ (CKMfitter)

- However, best measurement by D0: $R = 0.97^{+0.09}_{+0.08}$

- Most often not taken into account => Single top: $|V_{tb}| \to \dfrac{|V_{tb}|}{\sqrt{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}}$

  It's even more involved (pdf effect!) --> see F. Maltoni's talk

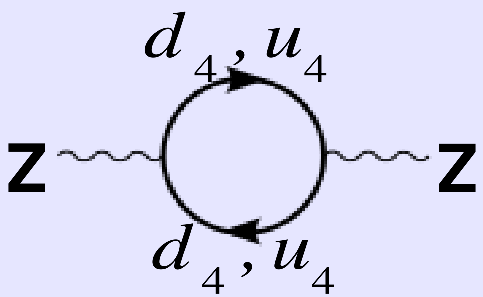
4. Mass splitting within a 4. Generation

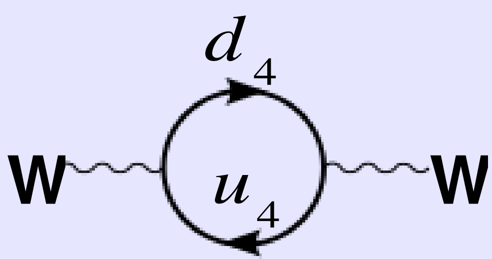
$$S = \frac{1}{6\pi}\left(1 - 2Y \ln \frac{m_{l_4}^2}{m_{\nu_4}^2}\right) + \frac{N_c}{6\pi}\left(1 - 2Y \ln \frac{m_{u_4}^2}{m_{d_4}^2}\right)$$

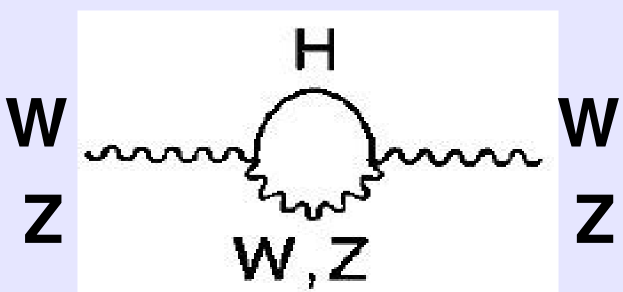
$$Y = 1/6(\text{quarks}), -1/2(\text{leptons})$$

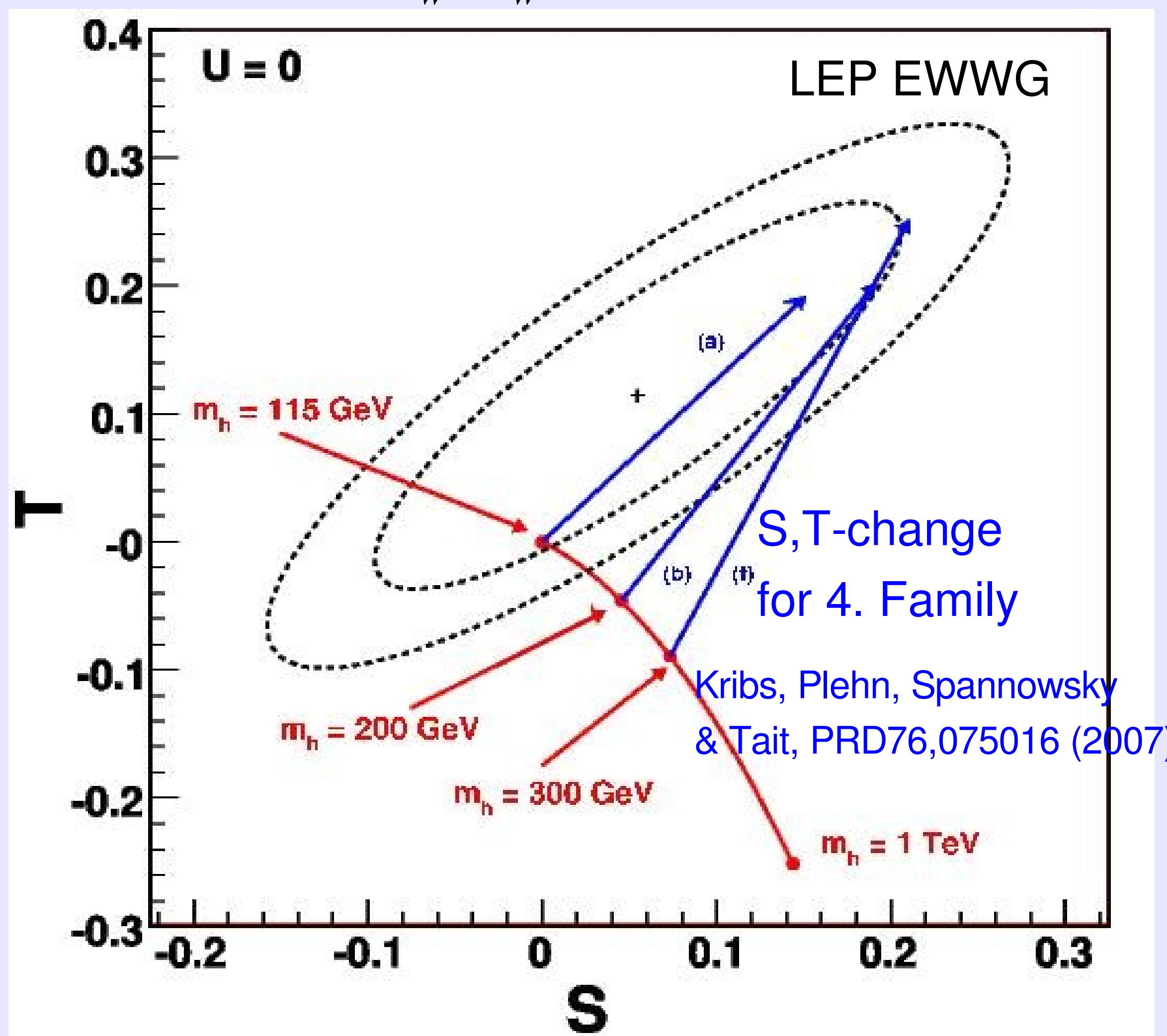
$$T = \frac{1}{12\pi \sin^2\theta_W M_W^2}\left(N_c \left|m_{u_4}^2 - m_{d_4}^2\right| + \left|m_{l_4}^2 - m_{\nu_4}^2\right|\right)$$

Self-energy diagrams:





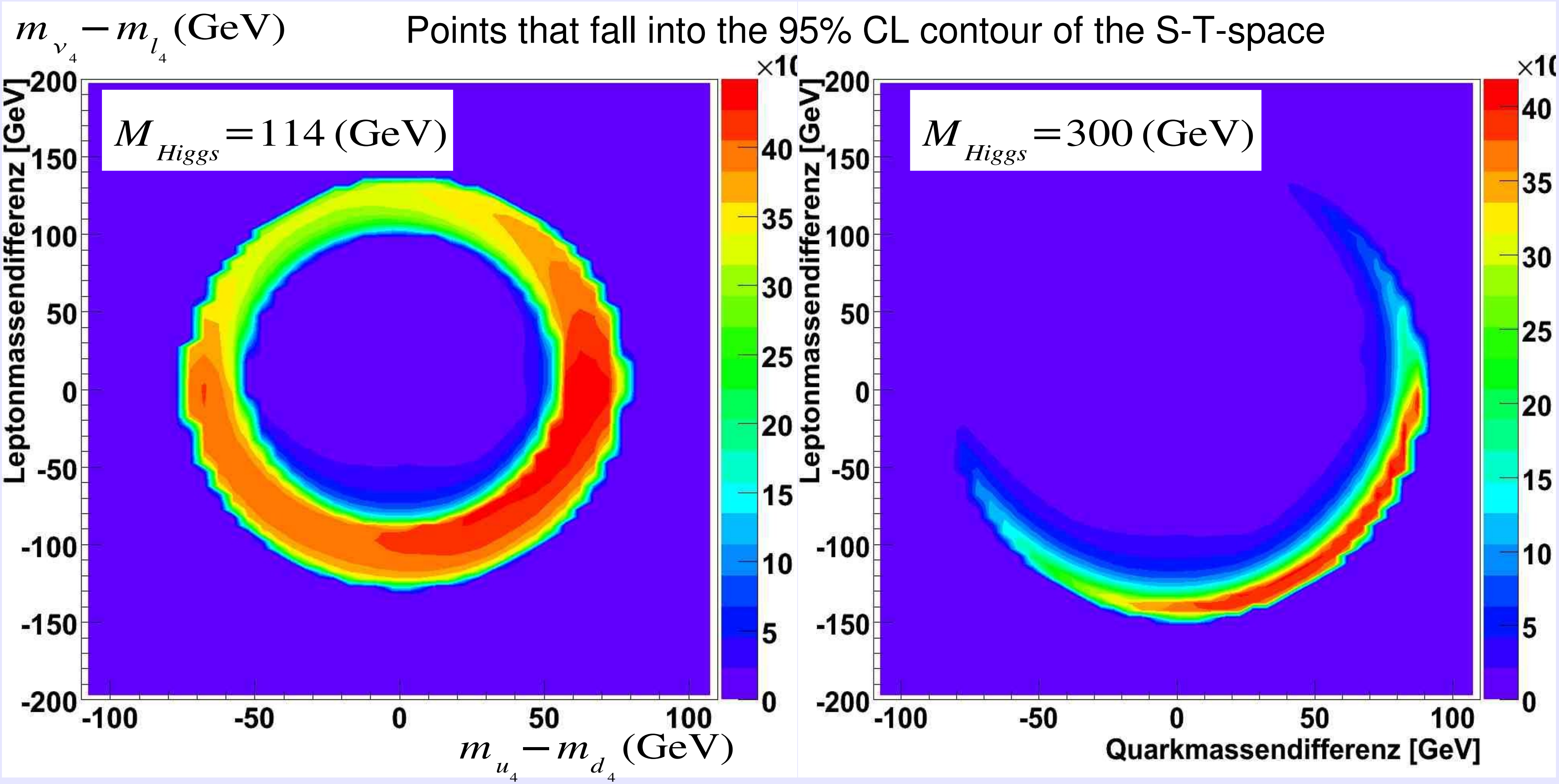




Four Generations:

M_{Higgs} ~ 600 GeV possible

4. Mass splitting within a 4. Generation



- $m(u_4) > m(d_4)$ preferred but opposite not excluded, $m(u_4) - m(d_4) > M_W$ not excluded
- $m(l_4) > m(\nu_4)$ preferred but opposite not excluded

(Study done by HUB bachelor students based on code from Kribs et al.
Thanks for the support provided by T. Plehn and M. Spannowsky)

5. What do we know about the CKM & PMNS matrix elements?

- Recent discussion of constraints on 4x4 CKM- & PMNS-elements:

1. Kribs et al., PRD76, 075016, 2007 ---> See talk by T. Plehn

   CKM: CKM-Treelevel + W-decays + D-mixing

   PMNS: $\mu \rightarrow e\gamma$, $\mu \rightarrow e$ conversion

2. Bobrowski et al., PRD79, 113006, 2009

   CKM-Treelevel + K-, D-, B-mixing & $b \rightarrow s\gamma$ ---> See talk by A. Lenz

3. Chanowitz, PRD79, 113008 (2009)

   e.w. precision fit: taking into account CKM elements in T

Caveat: All studies here assume lepton universality and, implicitely,

U_{E4}=1 in all observables and also in the e.w. precision fit.

In presence of a 4th generation: maybe not justified

5.1 Mixing in quark sector

Directly measured matrix elements:

at ~2σ

$$\left|V_{CKM}^{4\times 4}\right| = \begin{pmatrix} 0.97418 & 0.2246 & 0.0039 & <0.038 \\ 0.22 & >0.84 & 0.041 & <0.51 \\ <0.06 & <0.26 & >0.78 & <0.62 \\ <0.105 & <0.51 & <0.62 & >0.74 \end{pmatrix}$$

my numbers

- Limiting factors:

  * $|V_{tb}|$ from single top + $R = \frac{\Gamma(t \to W+b)}{\Gamma(t \to W+q)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$ not well constrained yet

    (Please note: $|V_{tb}|$ constraint does not take into account R info)

  * $|V_{cs}|$ from semileptonic D-decays: still large theoretical error

    (form factor, decay constant)

5.1 Mixing in quark sector

Directly measured matrix elements:

$$\left|V^{4\times 4}_{CKM}\right| = \begin{pmatrix} 0.97418 & 0.2246 & 0.0039 & <0.038 \\ 0.22 & >0.84 & 0.041 & <0.51 \\ <0.06 & <0.26 & >0.78 & <0.62 \\ <0.105 & <0.51 & <0.62 & >0.74 \end{pmatrix}$$

my numbers

- Constraints discussed by Kribs et al. (my numbers):

  * $|V_{tb}|$

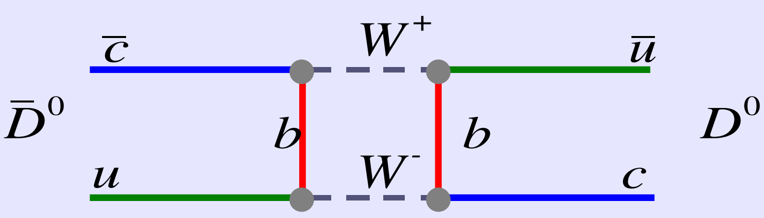
  * $\Gamma(W \to \text{had})$

$$\left|V^{4\times 4}_{CKM}\right| = \begin{pmatrix} 0.97418 & 0.2246 & 0.0039 & <0.038 \\ 0.22 & 0.97 & 0.041 & <0.2 \\ <0.04 & <0.125 & >0.78 & <0.62 \\ <0.07 & <0.20 & <0.62 & >0.78 \end{pmatrix}$$

  * D-mixing (Golowich et al., PRD76:095009, 2007) $\rightarrow \left|V_{ud_4} V^*_{cd_4}\right| < 0.002$

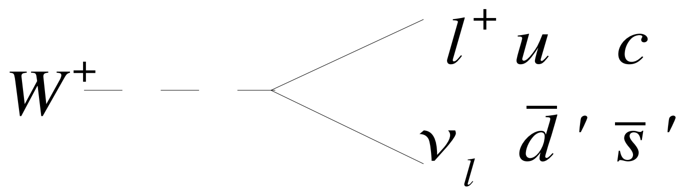
Limit depends on d_4 mass (200 GeV used)

See talk by A. Lenz concerning uncertainties in predicting D-mixing



5.2 Constraint from W-decays

* BF(W→had) used by Kribs et al. calculated from measured BF(W → l ν) !



$$\frac{\Gamma(W\to l\,\nu)}{\Gamma(W\to All)} \approx \frac{1}{3+3\sum_{i=u,c}\;\sum_{j=d,s,b}|V_{ij}|^2(1+\alpha_s(M_W)/\pi)}$$

* Unitarity check in the first place

* N_{gen}>3: Strengthen constraint on $|V_{cs}|$ and, consequently, on $|V_{ts}|$, $|V_{t's}|$ and $|V_{cb'}|$!

* Consistent with 3x3-Unitarity: $\sum_{j=d,s,b}|V_{uj}|^2+\sum_{j=d,s,b}|V_{cj}|^2=2.002\pm0.027$

* However: formula assumes lepton universality

N_{gen}=4: lepton universality possibly violated

and $|U_{l4}|$ >0 possible for l = e, μ, τ

$$BF(W\to e\,\nu)=0.1075\pm0.0013$$
$$BF(W\to \mu\,\nu)=0.1057\pm0.0015$$
$$BF(W\to \tau\,\nu)=0.1125\pm0.0020$$

$$\frac{\Gamma(W\to l\,\nu)}{\Gamma(W\to All)} \approx \frac{\sum_{k=1,2,3}|U_{lk}|^2}{\sum_{l=e,\mu,\tau}\;\sum_{k=1,2,3}|U_{lk}|^2+3\sum_{i=u,c}\;\sum_{j=d,s,b}|V_{ij}|^2(1+\alpha_s(M_W)/\pi)}$$

5.3 Mixing in lepton sector: τ- and μ-decays

Constraints on 4th generation from τ mass & (leptonic) BF's:

* Dova, (Swain & Taylor), NP Proc.Suppl.76:133,1999; (hep-ph/9712383; PRD55:1,1997)

1) Since then: Significant improvements in m_τ & BF measurements

2) Assumption: Only significant mixing between 3rd and 4th family

W/o this assumption:

$$\Gamma(\tau^- \to l^- \bar{\nu}_l \nu_\tau) \propto G_F^2 \sum_{i=1,2,3} |U_{\tau i}|^2 \sum_{k=1,2,3} |U_{lk}|^2 \qquad l = e/\mu$$

$$\Gamma(\tau^- \to h \nu_\tau) \propto G_F^2 f_h^2 |V_{uj}|^2 \sum_{i=1,2,3} |U_{\tau i}|^2 \qquad j = d(\pi)/s(K)$$

$$\Gamma(h^- \to \mu^- \nu_\mu) \propto G_F^2 f_h^2 |V_{uj}|^2 \sum_{i=1,2,3} |U_{\mu j}|^2 \qquad j = d(\pi)/s(K)$$

$$\Gamma(\mu^- \to e^- \bar{\nu}_e \nu_\mu) \propto G_F^2 \sum_{i=1,2,3} |U_{\mu i}|^2 \sum_{k=1,2,3} |U_{ek}|^2$$

=> No strong constraint any more on G_F => CKM & e.w. precision fit?!

5.4 Combining CKM, PMNS and e.w. precision fit

- $|V_{ud}| = 0.97418 \pm 0.00026$ (superallowed β-decays)

With 4th generation: $\Gamma(\beta\text{-}decay) \propto G_F^2 \; |V_{ud}|^2 \sum_{k=1,2,3} |U_{ek}|^2$

$$\Gamma(\mu^- \to e^- \bar{\nu}_e \nu_\mu) \propto G_F^2 \sum_{i=1,2,3} |U_{\mu i}|^2 \sum_{k=1,2,3} |U_{ek}|^2$$

- $|V_{us}|$: 1. Consider separate averages for K_{e3} & $K_{\mu 3}$ $\rightarrow \sum_{i=1,2,3} |U_{\mu i}|^2 / \sum_{k=1,2,3} |U_{ek}|^2$

  2. $K_{\mu 2}/\pi_{\mu 2}$: dependency on lepton sector cancels $\rightarrow |V_{us}|^2 / |V_{ud}|^2$

- Single top and R not affected!

- Possibility to determine G_F by avoiding this problem in leading order:

$$\Gamma(Z \to l^+ l^-) \propto G_F^2 (\text{3-gen. SM} + \text{Loop Contr. from 4th family})$$

=> Need to combine CKM-, PMNS- and e.w precision fit

Work started @ HU Berlin (A. Menzel & H. Lacker) within CKMfitter

5.5 Theoretical prejudice: U_{E4} how close to 1 ?

Consider e.g. mixing angle θ between 3rd and 4th generation:

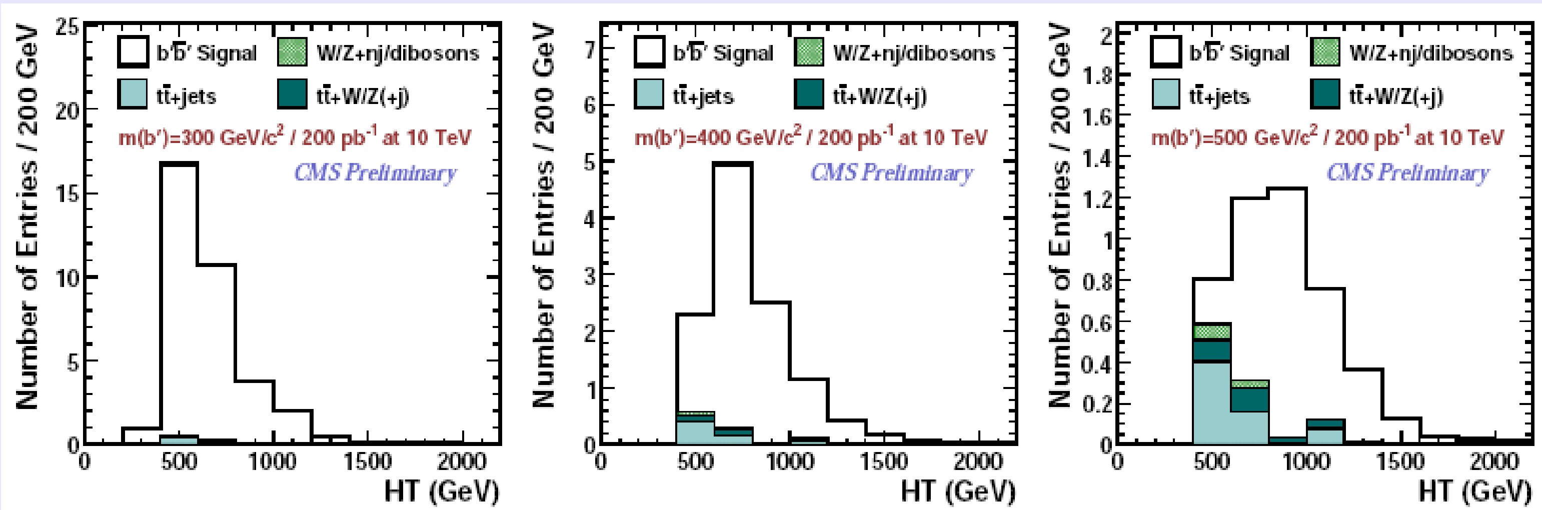
- **Seesaw models** $\rightarrow \sin\theta = \sqrt{m_\tau / m_E} \approx 0.13$
- **Mixing only in neutrino mass matrix** $\rightarrow \sin\theta = \sqrt{m_{\nu_3} / m_{\nu_4}} \approx 5\times 10^{-6}$
- **Global or discrete family symmetries realized that are**
  broken $\rightarrow \sin\theta = m_W / m_{Planck} \approx 10^{-17}$
  unbroken $\rightarrow \sin\theta = 0$
  by Planck scale effects
- **Flavor democracy** $\rightarrow U_{l_4 i} \approx 10^{-5} - 10^{-4} \quad (V_{t'q} \approx 10^{-4} - 10^{-3},\, V_{qb'} \approx 10^{-4} - 10^{-3})$
- **Benchmark: $|U_{\mu 4}|$ ~ 0.023 corresponds to a $|V_{ud}|$ change of 1σ**

  (possible for $\sin\theta_{24} = \sqrt{m_\mu / m_E} \approx 0.03$**)**

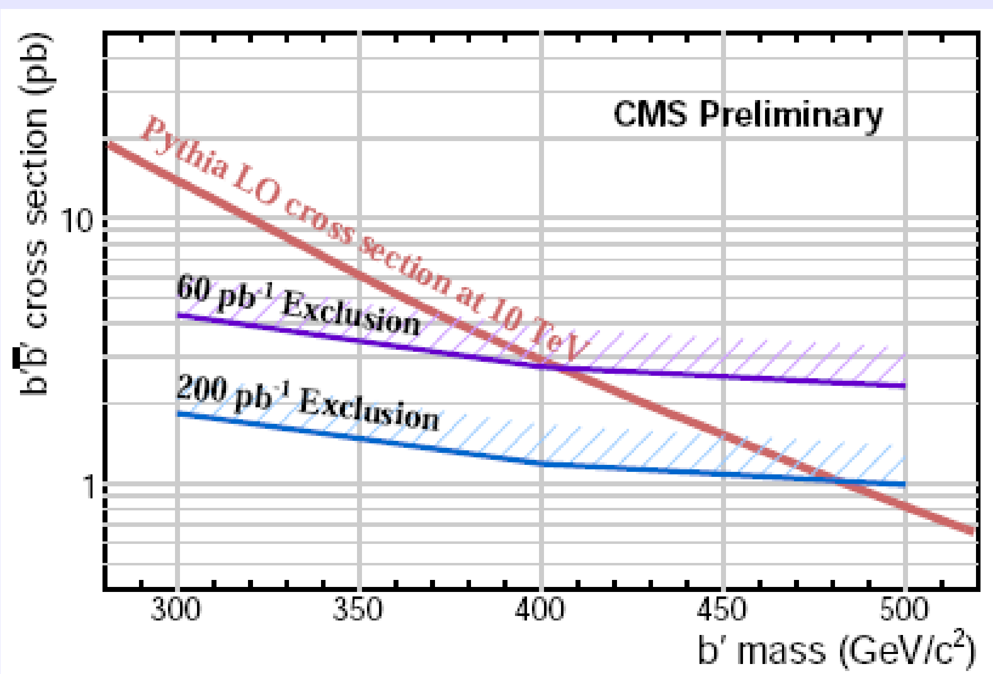
Scenario already excluded? $\dfrac{g_\tau}{g_\mu} = 0.9976 \pm 0.0022 \overset{?}{=} \dfrac{\cos\theta_{34}}{\cos\theta_{24}} \approx 0.9911$

6.1 Search strategies @ LHC: same-sign dileptons

CMS, PAS EXO-09-012 (200 pb^{-1}, 10 TeV)



Same-sign dileptons (N_{jet}>3) + trileptons (N_{jet}>1)



Ideal for searches with early data

Caveat: usual assumptions

Also studied by ATLAS groups HU Berlin, UCI & SLAC

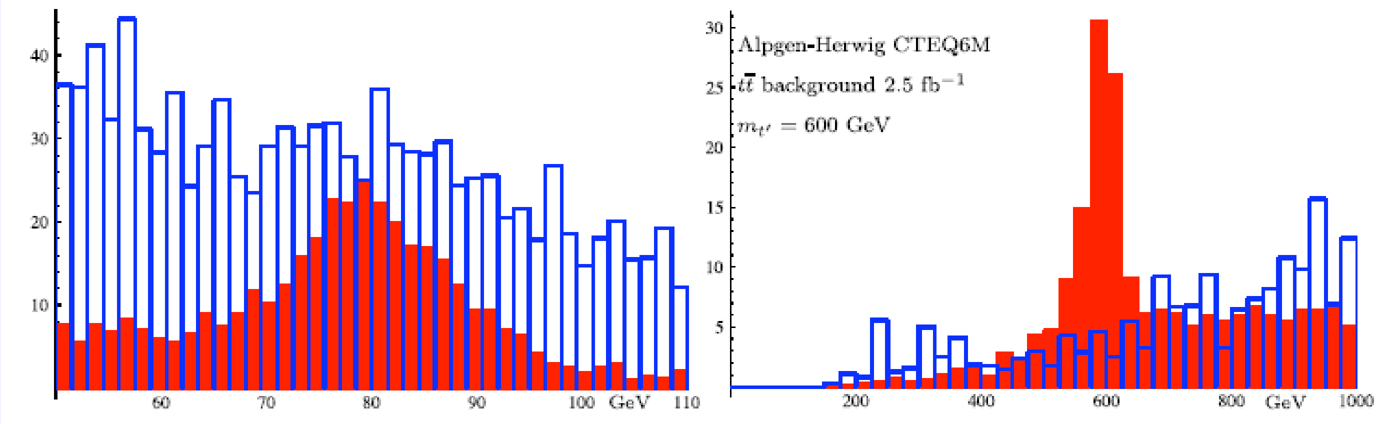
6.2 Search strategies @ LHC: t'->W+q

- BG: ttbar+jets

Idea: W from t'(b') decays have large boost for high t' (b') masses
jets from hadr. W-decays tend to merge => look for single jet invariant mass

B. Holdom JHEP 0708, 069 (2007);

Skiba,Tucker-Smith, hep-ph/0701247

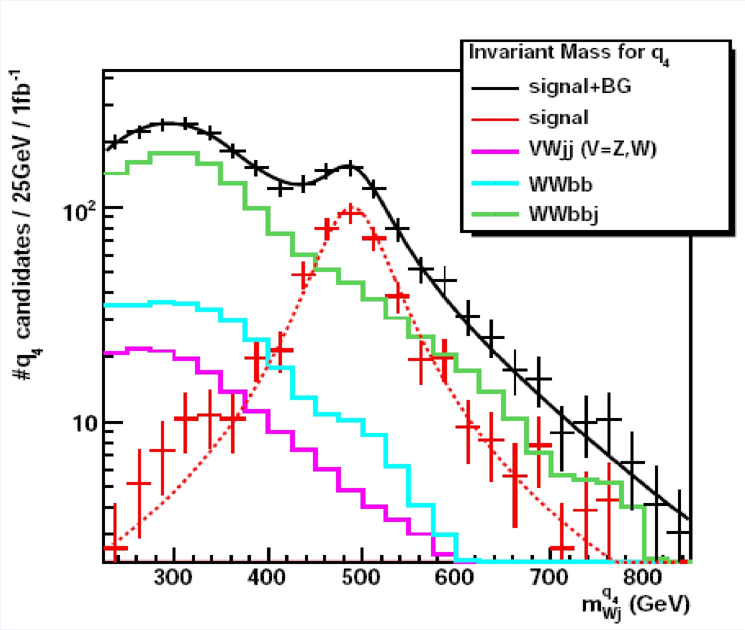


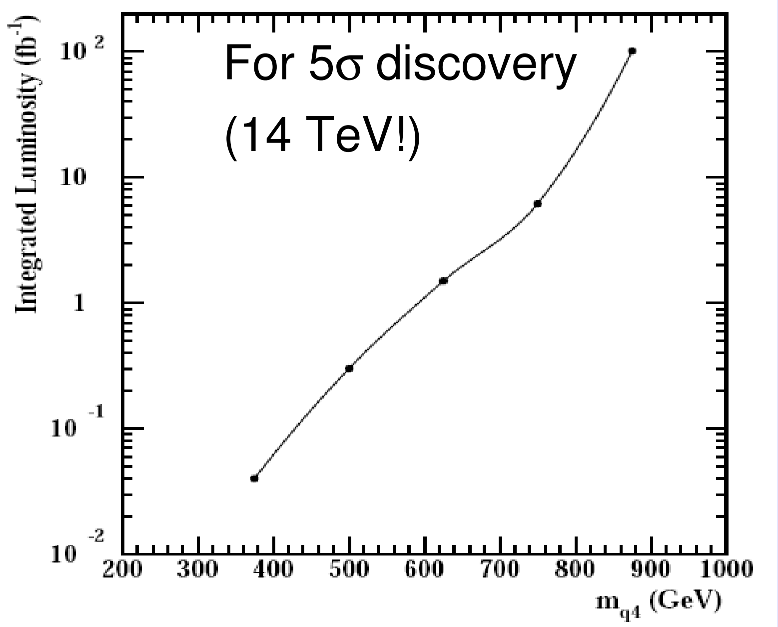
Understanding of high-p_T top's?

Özcan, Sultansoy and Ünel (ATLAS) EPJ C57, 621 (2008):

Assumption:
primarily mixing with first two families => b'→W+q
If not: t'→W+b

Problem: BF(t'→W+b) might be small





7. Summary

1. A 4th generation has several attractive theoretical features:
   special role in EWSB, baryogenesis, unification w/o SUSY, ...

2. E.w. prec. fit prefers: small Δm ($\Delta m > m_W$ not excluded)
   $m(u_4) > m(d_4)$, $m(l_4) > m(\nu_4)$ (opposite not excluded)

3. * 3x3 unitarity in lepton sector assumed in all analyses (CKM, ...) so far
   * Combined analysis of CKM-, PMNS-, & e.w. precision fit required

4. Current limits depend on assumptions concerning τ/BF's!
   => Correct constraints: functions on masses & mixing angles

5. LHC: * excellent place for discovery 4th ($M \leqslant 1$ TeV$\rightarrow$partial wave unitarity)
   Complementary search scenarios: $b'(t') \rightarrow W+q(b) \leftrightarrow b' \rightarrow W+t$
   * BG-suppression with single jet invariant mass ($\rightarrow$boosted W's)
   (also interesting for other channels)
   * Heavy quark with long lifetime searches need more attention