Summary on 4th generation part of Helmholtz alliance Workshop on single top physics and fourth generation quarks

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Helmholtz alliance meeting
DESY, November 11, 2009

1. H. Lacker: Overview talk (constraints etc.)
2. T. Plehn: 4th generation theory and relation to LHC physics
3. A. Lenz: Constraints from Flavour Physics
4. M. Felcini: Trigger for top and 4th generation at ATLAS & CMS

1. Theoretical Features of a 4th generation

- 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)

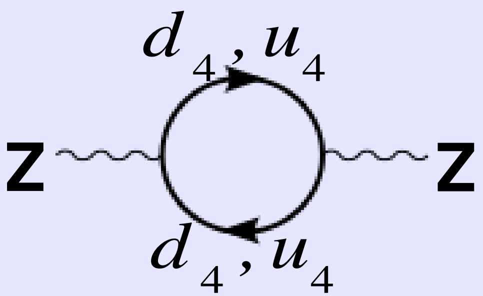
- EWSB w/o Higgs: Heavy Quark condensate (Holdom)

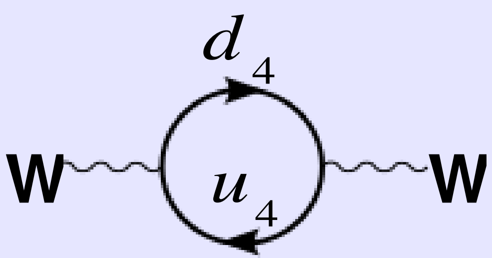
- SU(5) gauge coupling unification w/o SUSY possible (Hung, PRL80, 3000, 1998)

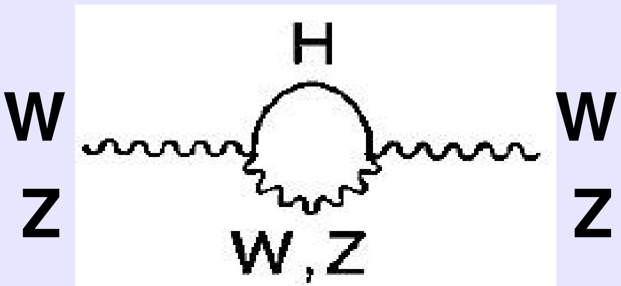
2. Fourth generation not excluded by e.w. precision fit

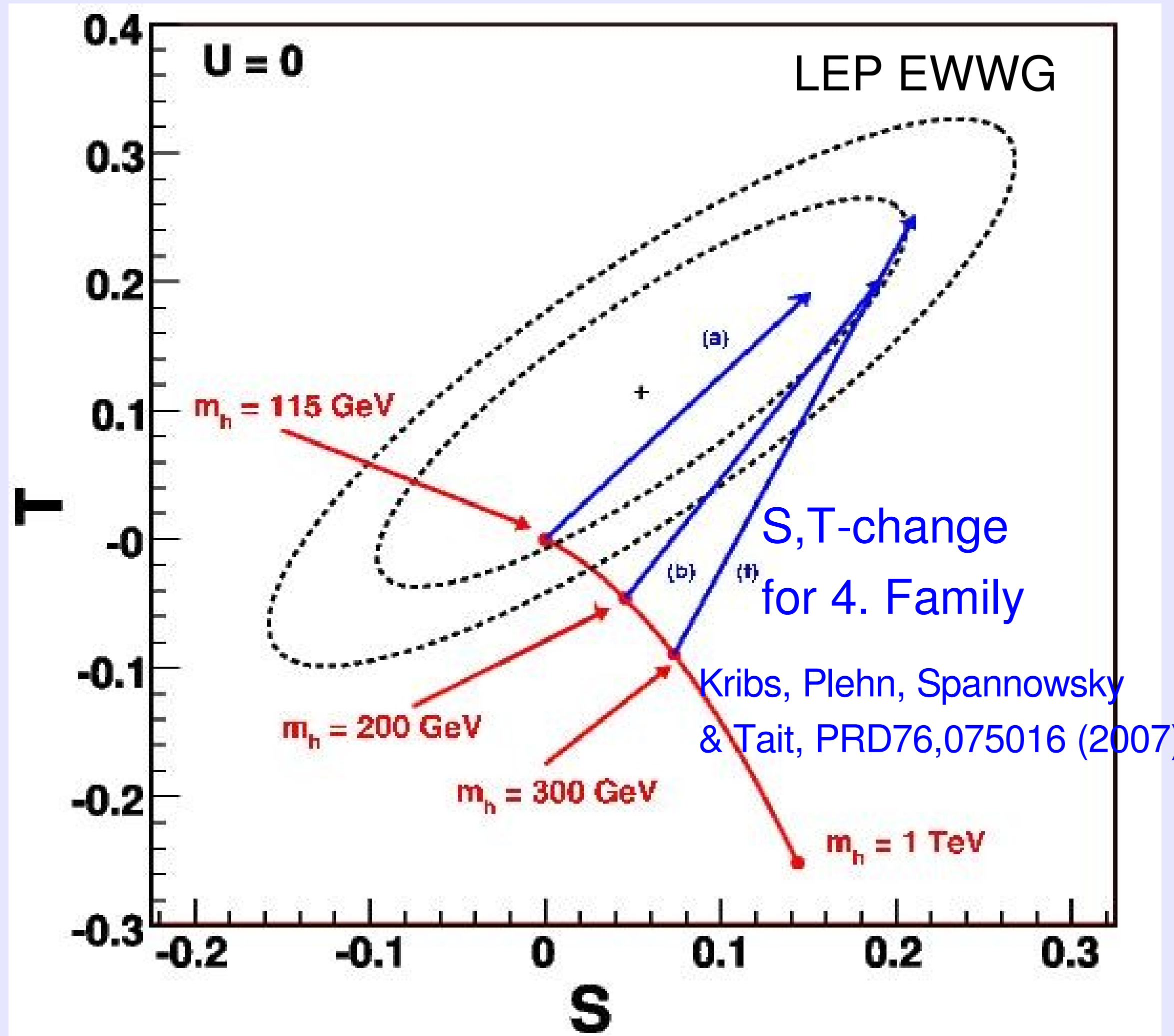
$$S = \frac{1}{6\pi}\left(1 - 2Y \ln \frac{m_{l_4}^2}{m_{\nu_4}^2}\right) + \frac{N_c}{6\pi}\left(1 - 2Y \ln \frac{m_{u_4}^2}{m_{d_4}^2}\right) \qquad Y = 1/6(\text{quarks}), -1/2(\text{leptons})$$

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

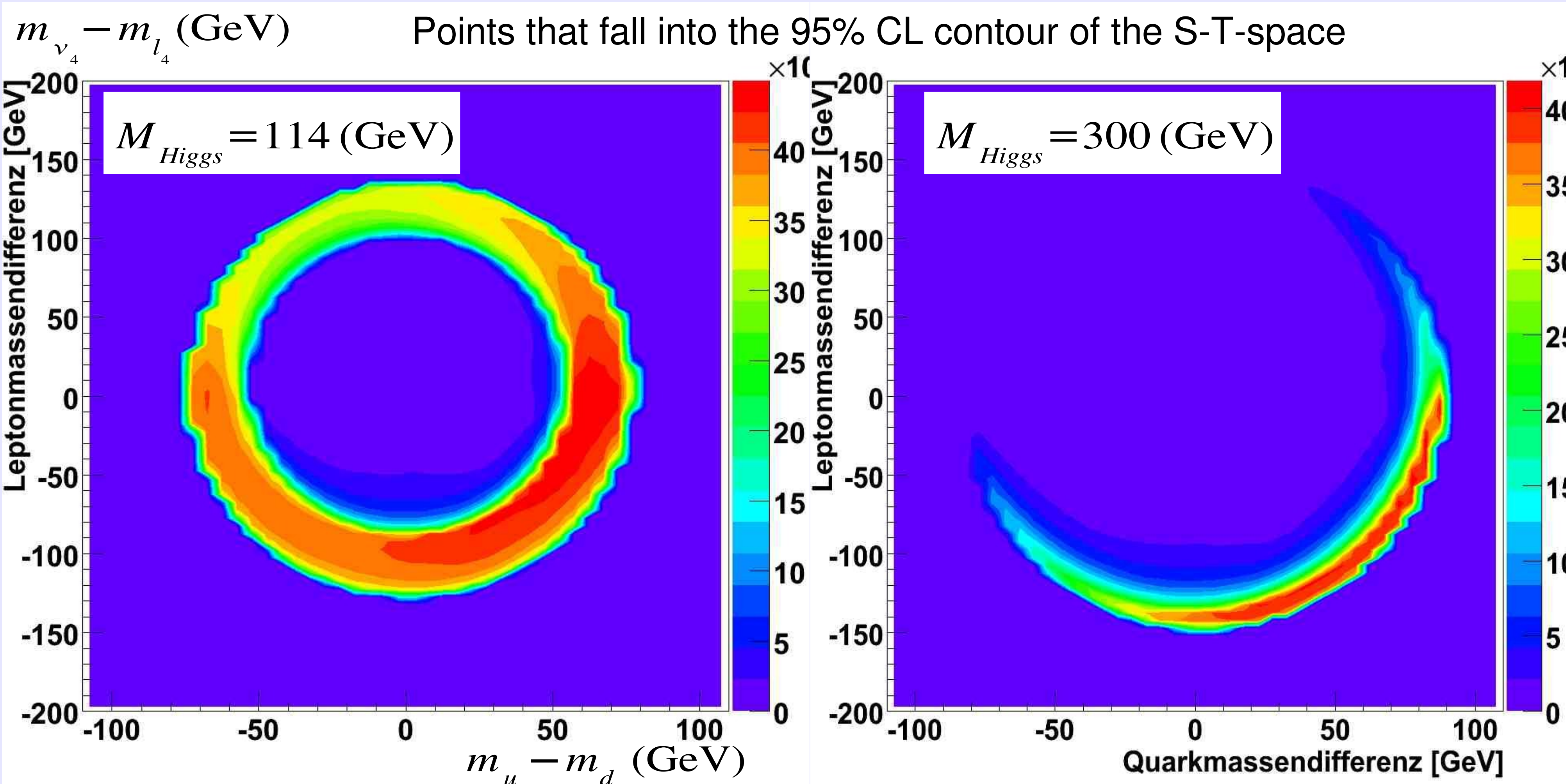








M_{Higgs} ~ O(750 GeV) possible



- $m(u_4) > m(d_4)$ 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 with support from T. Plehn and M. Spannowsky: D. Wendland & M. Mamach (HUB))

- PDG statement about exclusion of 4[th] generation assumes mass degeneracy

  1. assumption not needed   2. Is the 3[rd] generation mass-degenerate?

3. Higgs phenomenology @ LHC (T. Plehn)

$$\Gamma_{H\to\gamma\gamma} = \frac{G_\mu \alpha^2 m_H^3}{128\sqrt{2}\pi^3} \left| \sum_f N_c Q_f^2 A_f(\tau_f) + A_W(\tau_W) \right|^2$$

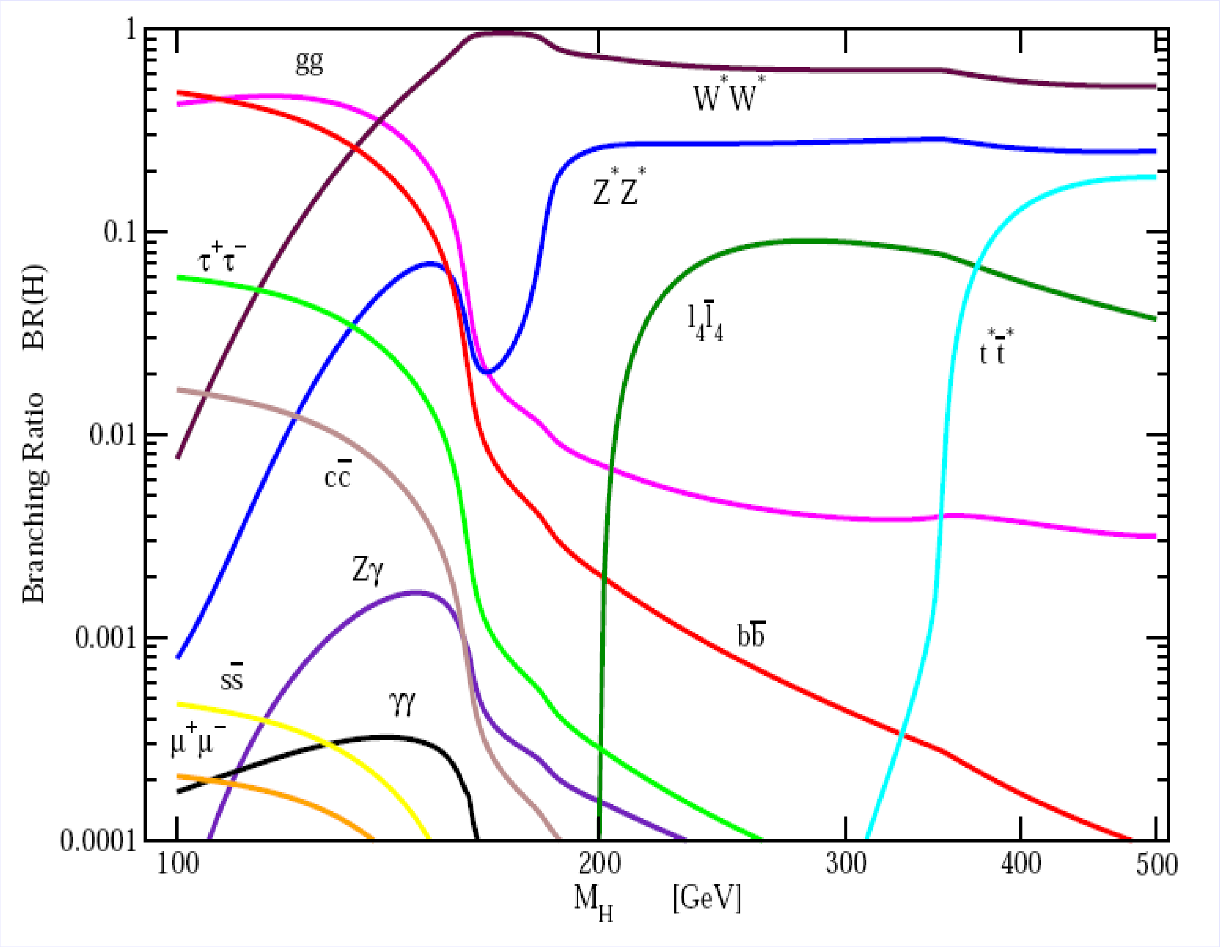
$$\Gamma_{H\to gg} = \frac{G_\mu \alpha_s^2 m_H^3}{36\sqrt{2}\pi^3} \left| \frac{3}{4} \sum_f A_f(\tau_f) \right|^2 \quad \text{with} \quad \tau_i = \frac{m_H^2}{4m_i^2}$$

Kribs, Plehn, Spannowsky & Tait, PRD76,075016 (2007)

ggH-coupling enhancement: 3

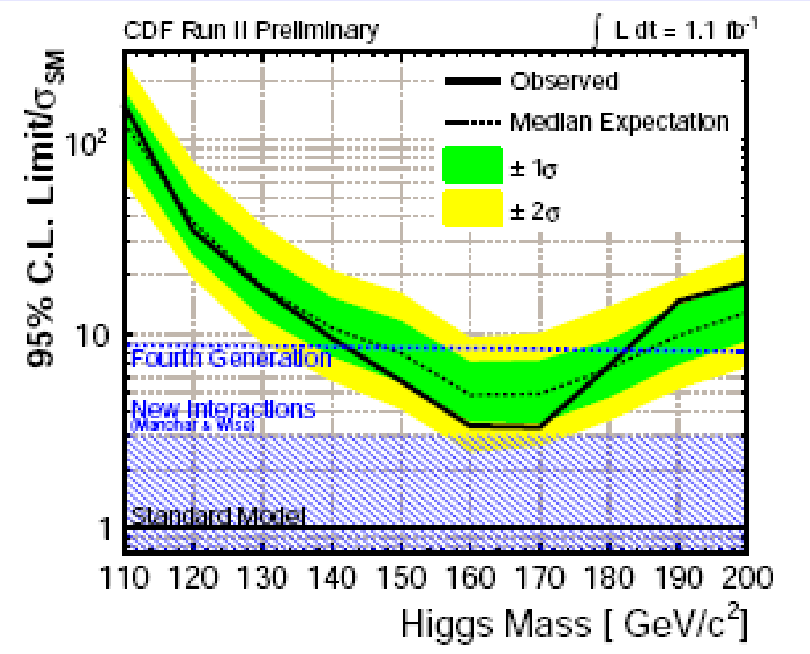
γγH-coupling decrease: 1/3

$$\sigma_{gg}\,\mathrm{BR}_{\gamma\gamma} \to \sigma_{gg}\,\mathrm{BR}_{\gamma\gamma}$$
$$\sigma_{gg}\,\mathrm{BR}_{ZZ} \to (5\cdots 8)\,\sigma_{gg}\,\mathrm{BR}_{ZZ}$$



E.g. CDF exclusion @ 95% CL:

$$H \to W\,W^*$$

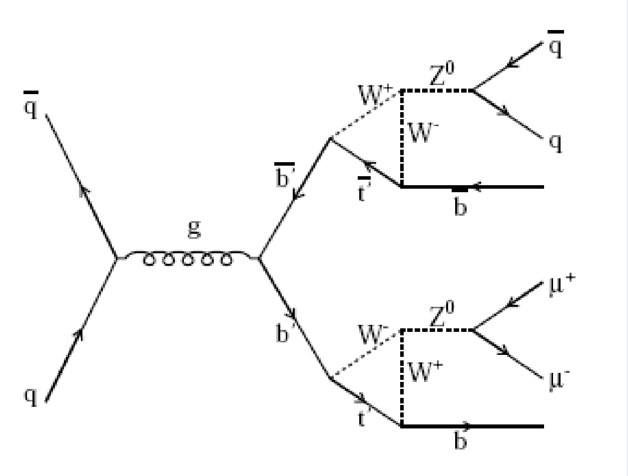


4. Limits: FCNC decay (D0)

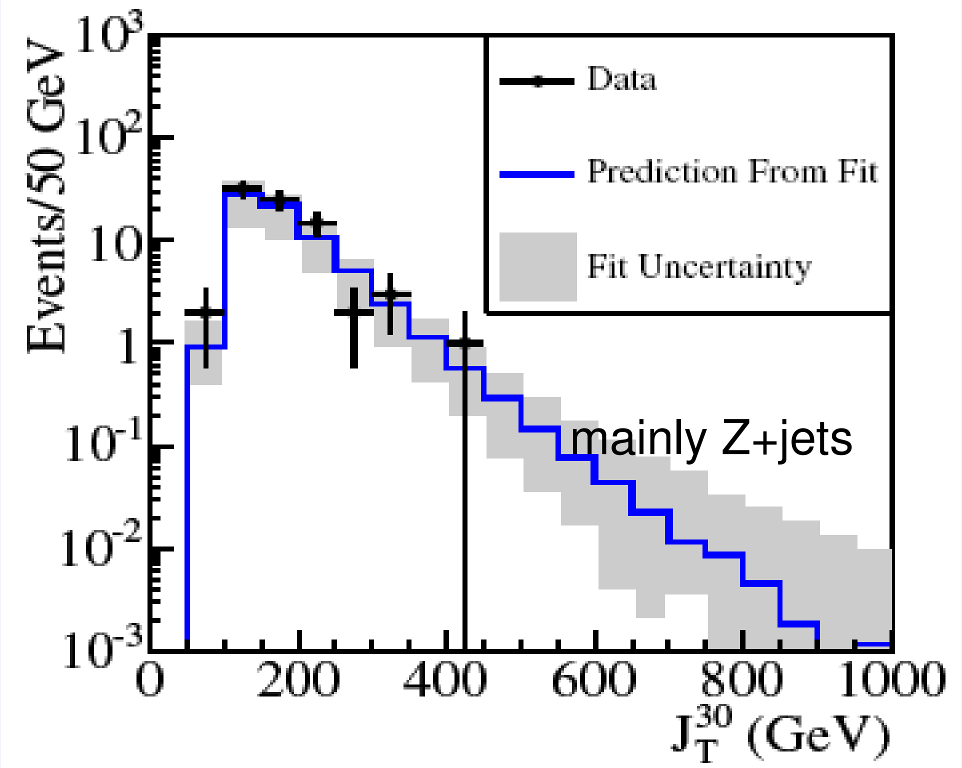
CDF (1.06 fb^{-1}), PRD 76, 072006 (2007):

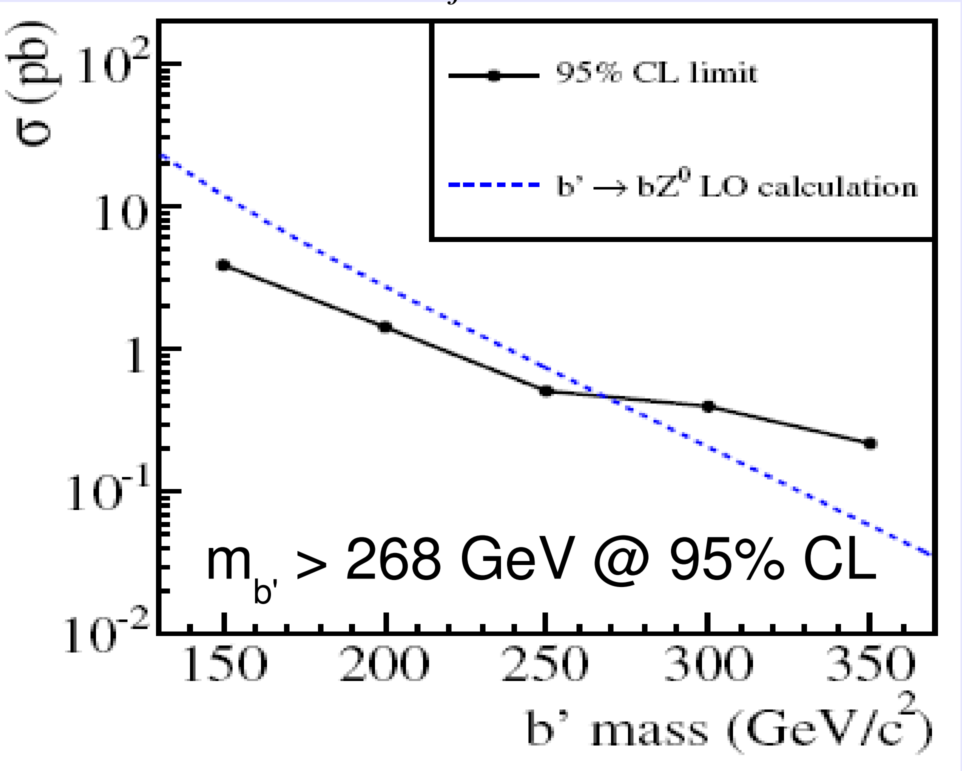
$$p\,\bar{p} \rightarrow b'\bar{b}',\, b'(d_4) \rightarrow b + Z$$

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



$$Z \rightarrow e^+e^-, \mu^+\mu^- \quad N_{jet}^{30} \geq 3\,(30 \equiv E_{T,\,jet} \geq 30\ \mathrm{GeV}) \quad J_T^{30} = \sum_{jets} E_T\,(E_T > 30\,GeV)$$



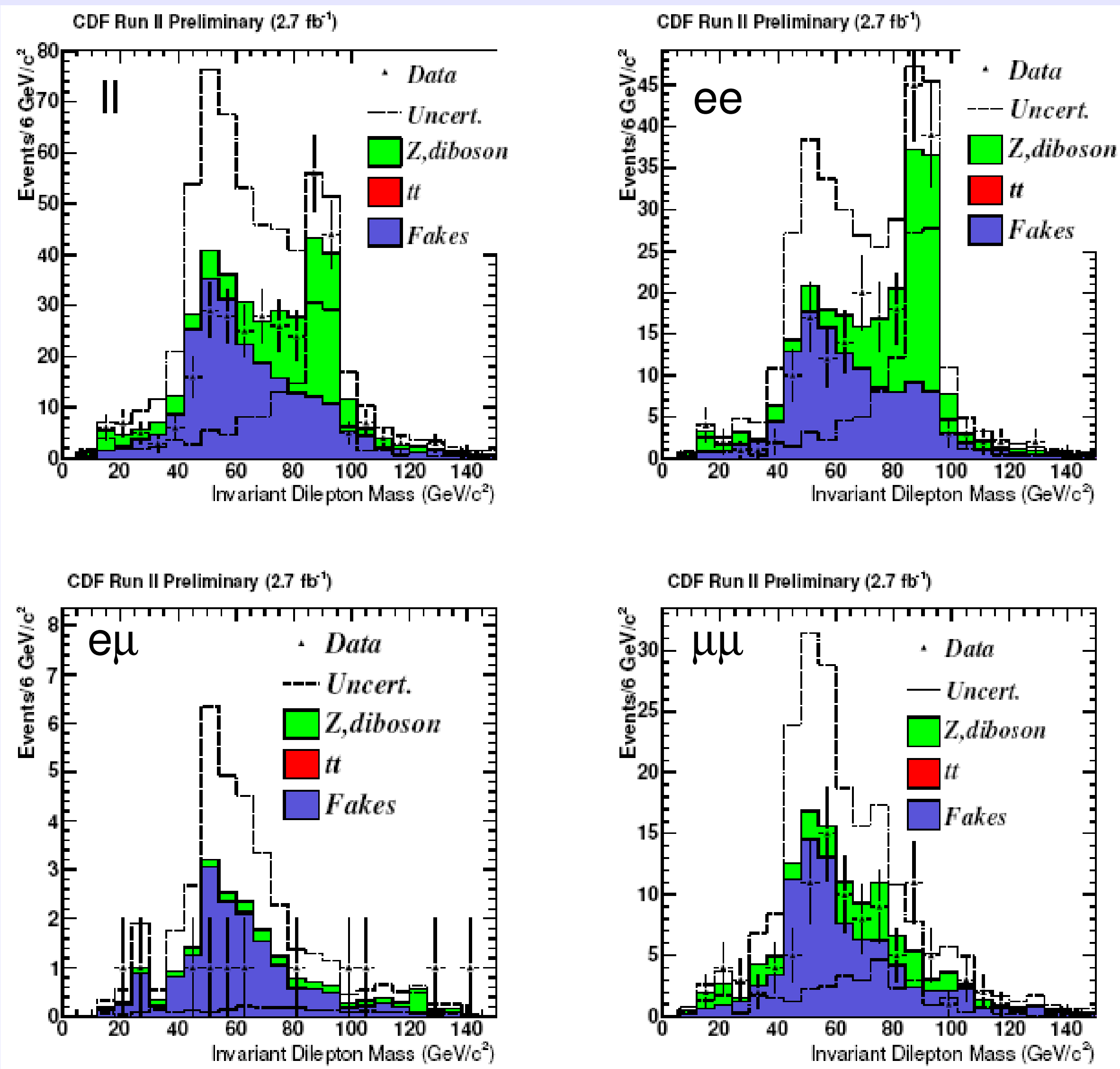


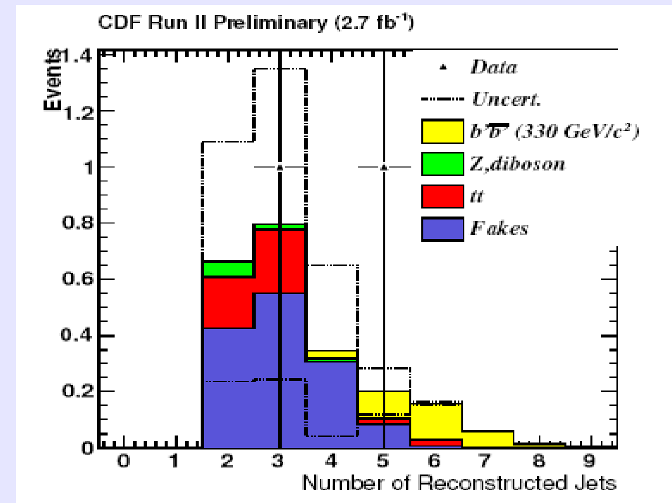
4. Limits: same-sign dilepton (CDF)

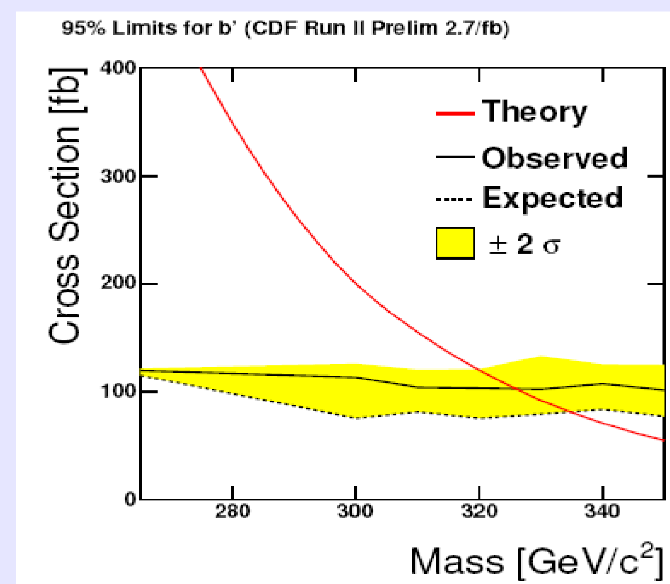
In many mass/CKM scenarios: $p\,\bar{p} \to b'\bar{b}' + X,\ b' \to W + t\,(\to b + W)$

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

CDF, note 9759, 2.7 fb-1:







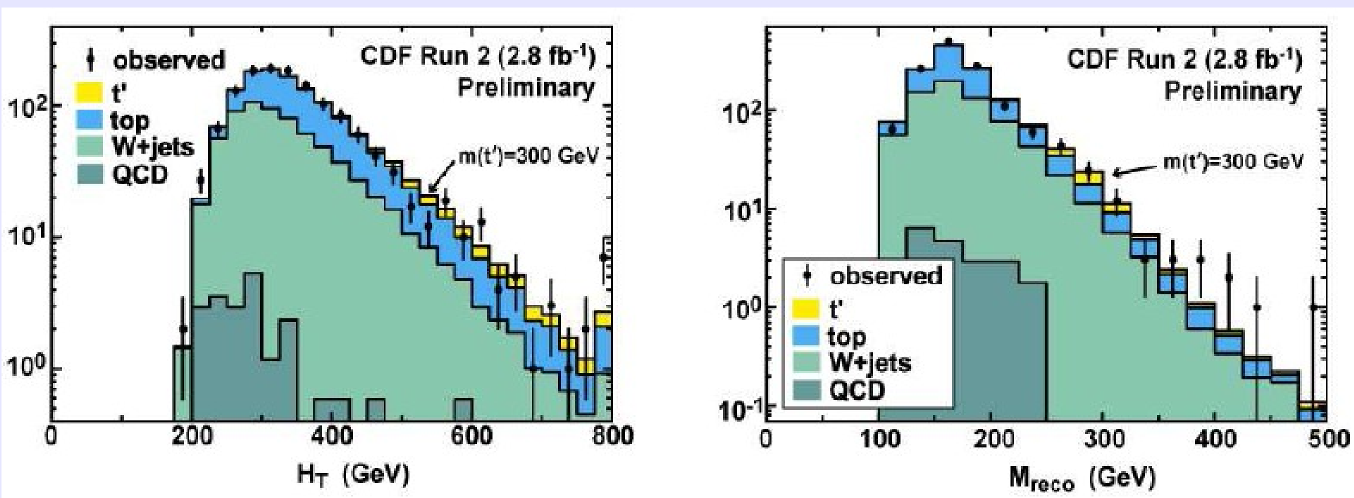
4. Limits: top-like search (CDF)

CDF note 9446, 2.8 fb^{-1}

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

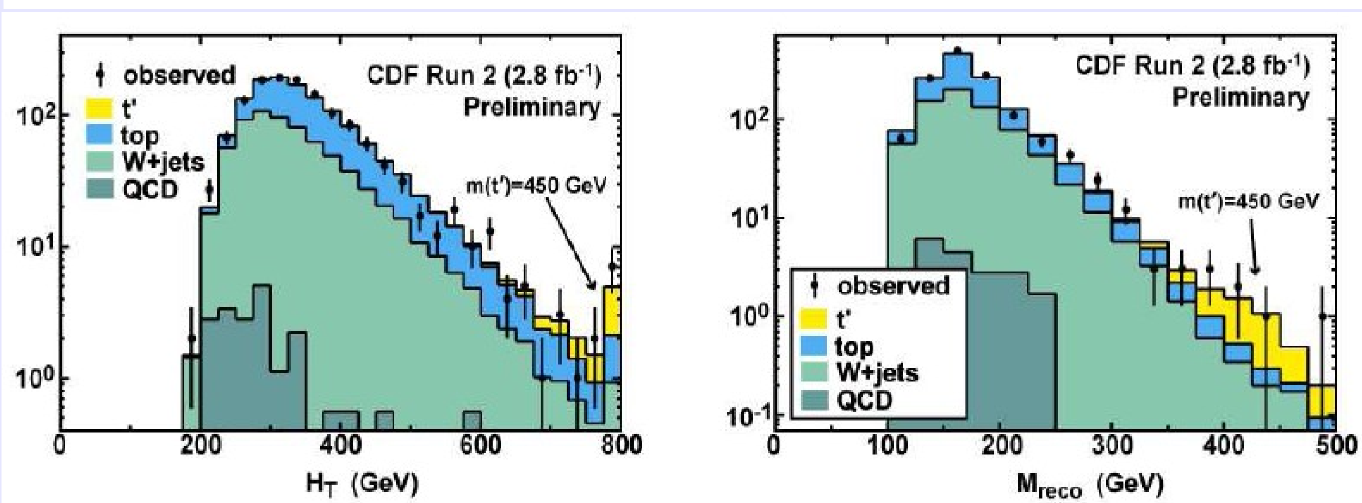
Note:
no distinction between
t' and b' possible

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



Kinematic fit like in
top reconstruction

No b-tagging



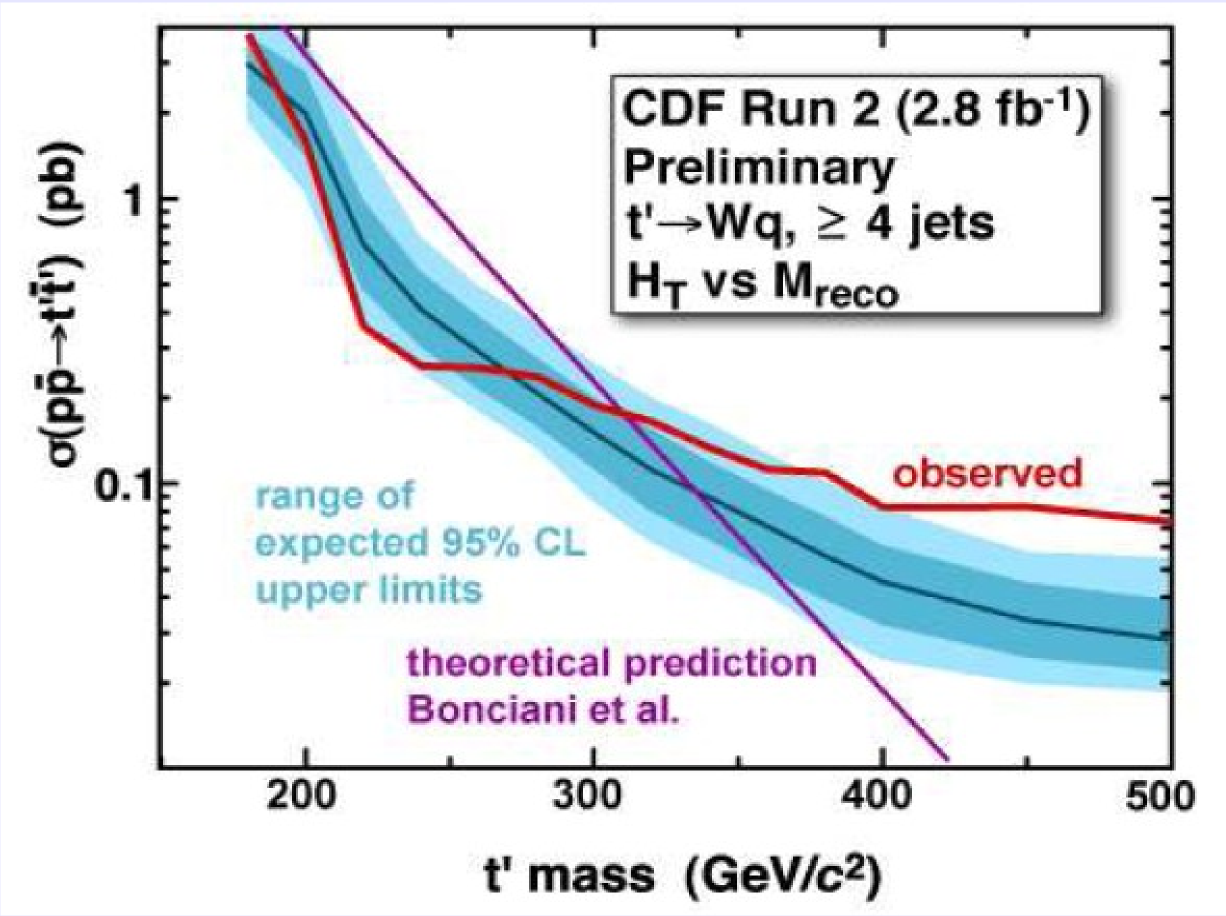
$$M_{reco} = M_{bjj} = M_{bl\nu}$$

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

=> Likelihood fit

4. Limits: top-like search (CDF)

- 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 4[th] gen. quark
    - b) 4[th] gen.: contributions from t' <u>and</u> b' decays ?

4. Limits depend on assumptions

Hung & Sher, PRD77, 037302 (2008):

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

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

m_W > $m_{t'}$-$m_{b'}$ > 0: t'→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 $V_{t'q}$ in a non-trivial way

Similar in line for other constraints (for b' limit even more involved)

5. CKM and PMNS sector

Directly measured matrix elements:

at ~2σ

$$\left|V_{CKM}^{4\times4}\right|=\begin{pmatrix} 0.97418 & 0.2246 & 0.0039 & <0.038 \\ 0.22 & >0.84 & 0.041 & <0.51 \\ <0.06 & <0.26 & >0.78 & <0.62 \\ <0.105 & <0.51 & <0.62 & >0.74 \end{pmatrix}$$

my numbers

Limiting factors: * $|V_{tb}|$ from single top (+ $R=\frac{\Gamma(t\to W+b)}{\Gamma(t\to W+q)}=\frac{|V_{tb}|^2}{|V_{td}|^2+|V_{ts}|^2+|V_{tb}|^2}$)

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

* $|V_{cs}|$ from semileptonic D-decays: form factor

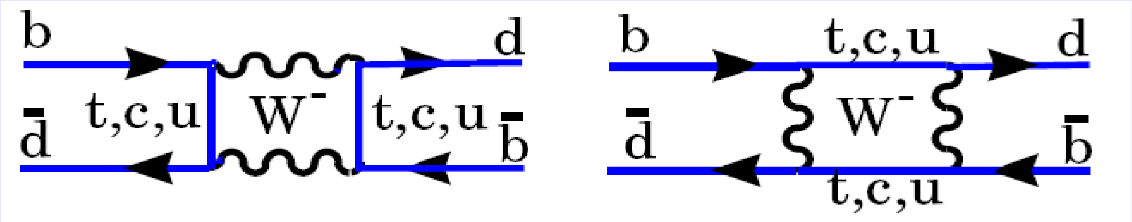
- $|V_{cs}|$ constraint significantly improved when using BF(W-> l ν)

$$\left|V_{CKM}^{4\times4}\right|=\begin{pmatrix} 0.97418 & 0.2246 & 0.0039 & <0.038 \\ 0.22 & 0.97 & 0.041 & <0.2 \\ <0.04 & <0.125 & >0.78 & <0.62 \\ <0.07 & <0.20 & <0.62 & >0.78 \end{pmatrix}$$

- Currently, a consistent extraction of $|V_{tb}|$ (together with $|V_{ts}|$ and $|V_{td}|$) missing.

5. CKM and PMNS sector (A. Lenz)

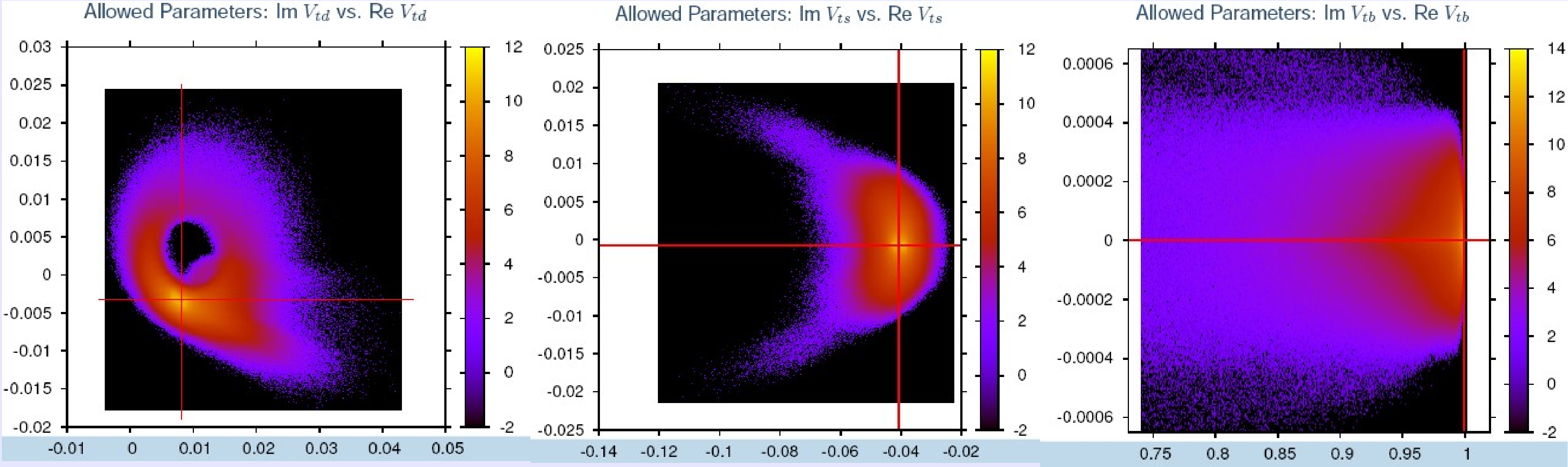
Most recent work on CKM constraints for 4th generation CKM matrix using loop-induced processes (Bobrowski et al., Phys.Rev.D79:113006, 2009):



$$\Delta m_d, \Delta m_s, \epsilon_K, BF(B \to X_s \gamma)$$

$$300\,\mathrm{GeV} \le m_{t'} \le 650\,\mathrm{GeV}$$

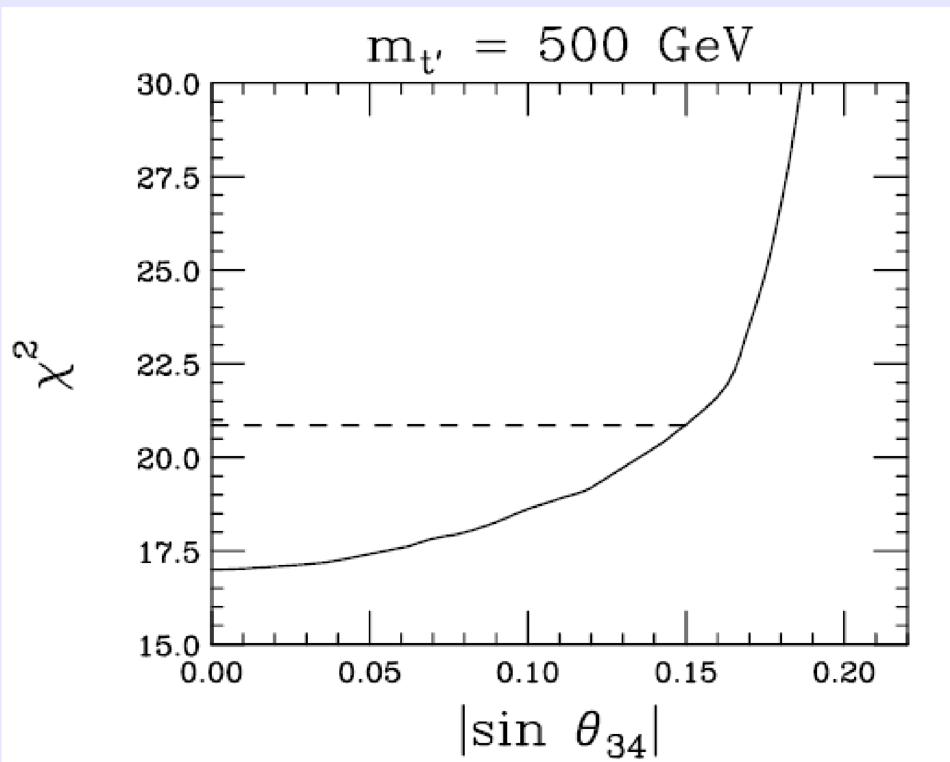
- Improved constraints on $|V_{td}|$, $|V_{ts}|$ and $|V_{tb}|$(?) but at the same time still significantly different values possible compared to 3x3 unitarity:



5. CKM and PMNS sector

Funny enough but only recently taken into account (Chanowitz,):
e.w. precision fit incl. a 4th generation can not rely on 3x3 unitarity

$$T_4 = \frac{1}{8\pi x_W(1-x_W)}\left\{3\left[F_{t'b'} + s_{34}^2(F_{t'b} + F_{tb'} - F_{tb} - F_{t'b'})\right] + F_{l_4\nu_4}\right\} \qquad F_{12} = \frac{x_1+x_2}{2} - \frac{x_1 x_2}{x_1 - x_2}\ln\frac{x_1}{x_2}$$



=> Seems to improve constraints on 4th gen. CKM elements over Bobrowski et al.

E.g. $|V_{tb}| \geq 0.95$ @ 95% CL
(for $m_{t'}$=326 GeV)

=> However, combined CKM & e.w. precision fit is still missing

5. CKM and PMNS sector

$$\Gamma(\tau^- \to l^- \bar{\nu}_l \nu_\tau) \propto G_F^2 \sum_{i=1,2,3} |U_{\tau i}|^2 \sum_{k=1,2,3} |U_{lk}|^2$$ => No strong constraint on G_F

$$\Gamma(\mu^- \to e^- \bar{\nu}_e \nu_\mu) \propto G_F^2 \sum_{i=1,2,3} |U_{\mu i}|^2 \sum_{k=1,2,3} |U_{ek}|^2$$ => CKM & e.w. precision fit?!

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

With 4[th] 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} & $K_{\mu 3}$ $\to \sum_{i=1,2,3} |U_{\mu i}|^2 / \sum_{k=1,2,3} |U_{ek}|^2$

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

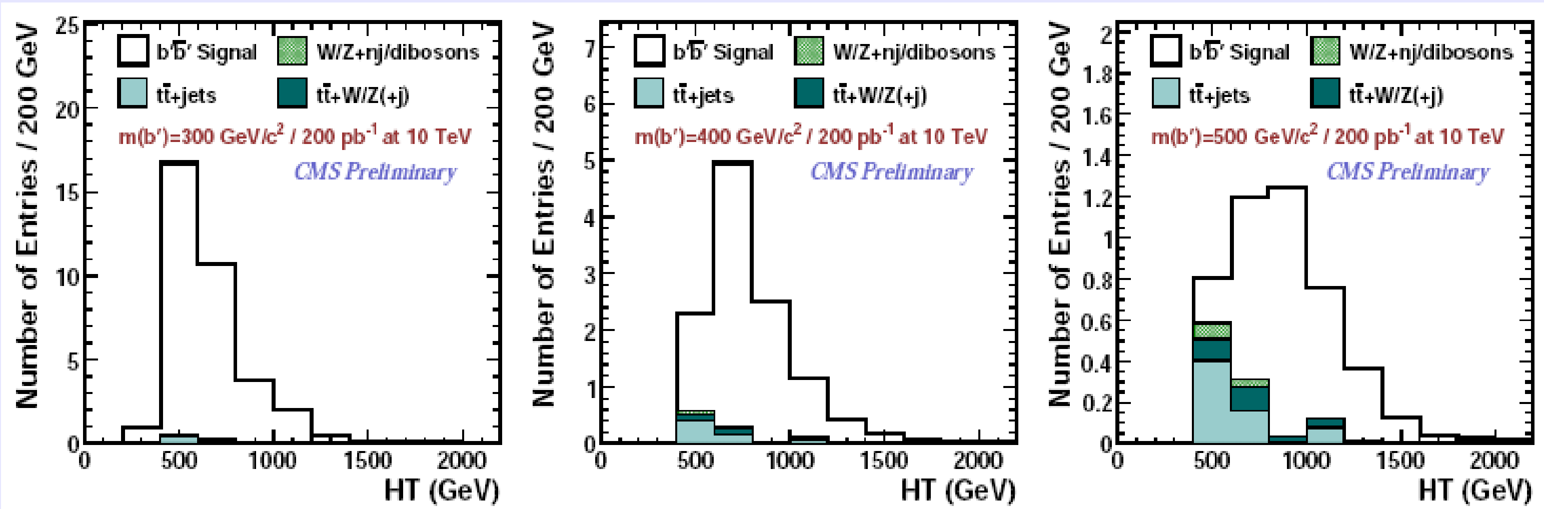
- Possibility to determine G_F by avoiding this problem to leading order:

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

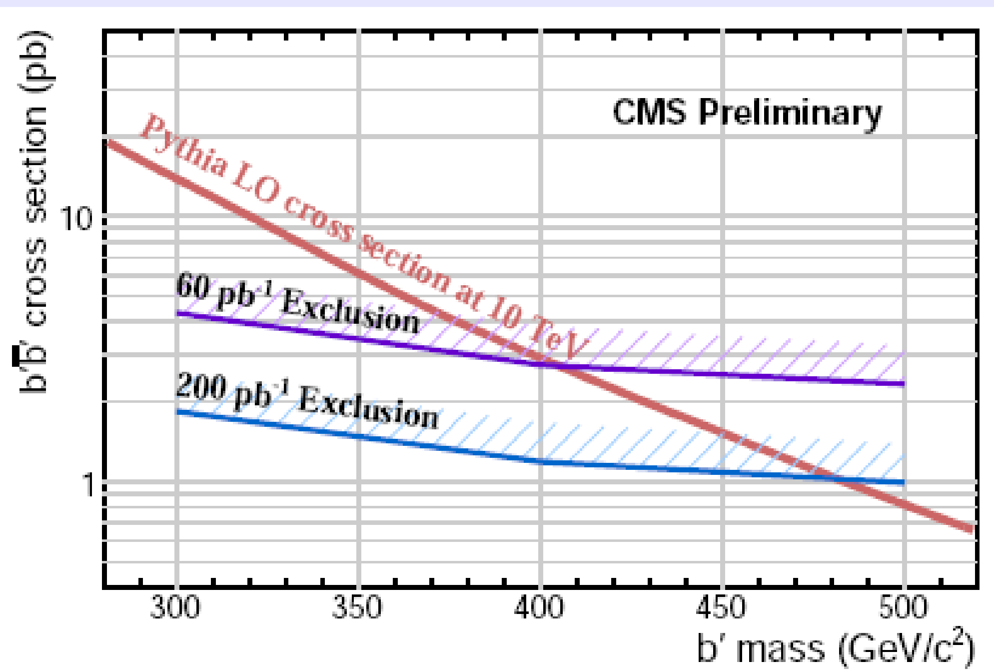
=> Combined CKM, PMNS and e.w. precision fit required

6. 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

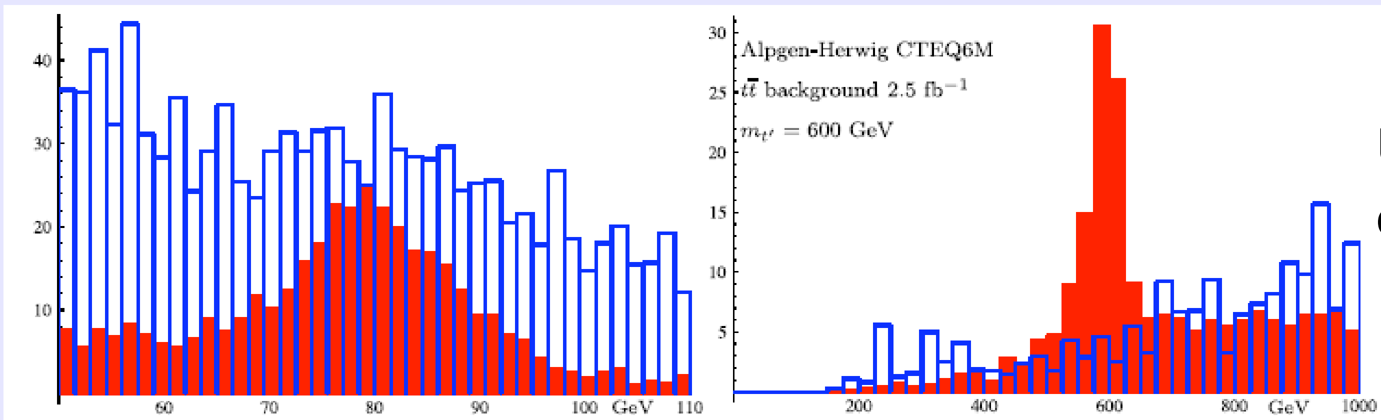
6. Search strategies @ LHC: t'->W+q

- 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



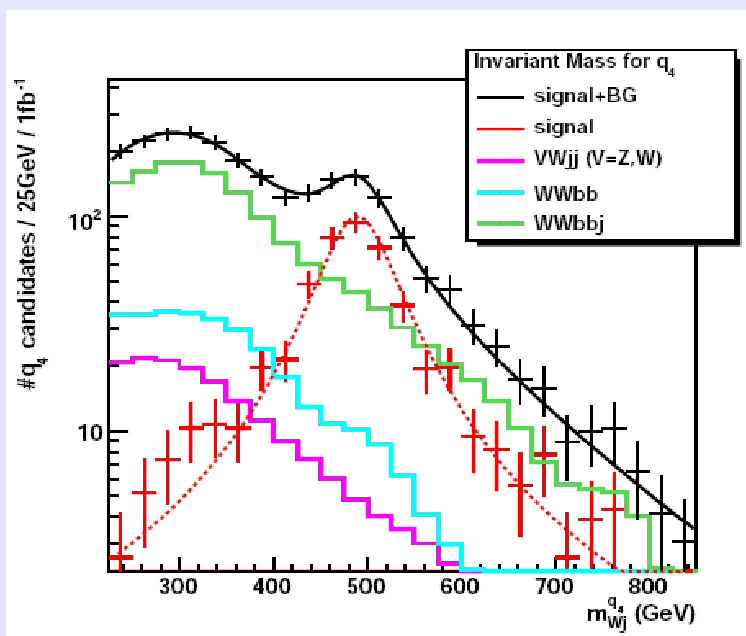
Understanding of high-p_T top's?

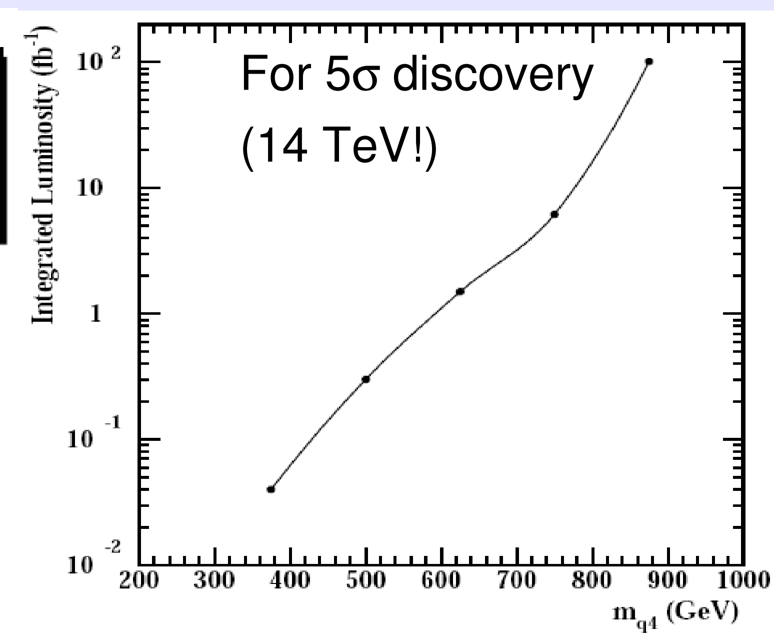
Özcan, Sultansoy and Ünel (ATLAS) EPJ C57, 621 (2008):

Assumption primarly mixing with first two families => b'→W+q

If not: t'→W+b

Problem: BF(t'→W+b) might be small





SUMMARY OF THE SUMMARY

1. 4th generation has several attractive theoretical features

2. In contrast to PDG: 4th generation not excluded by e.w. precision fit

3. If existing: very different Higgs phenomenology possible

4. Current mass limits should be interpreted with care

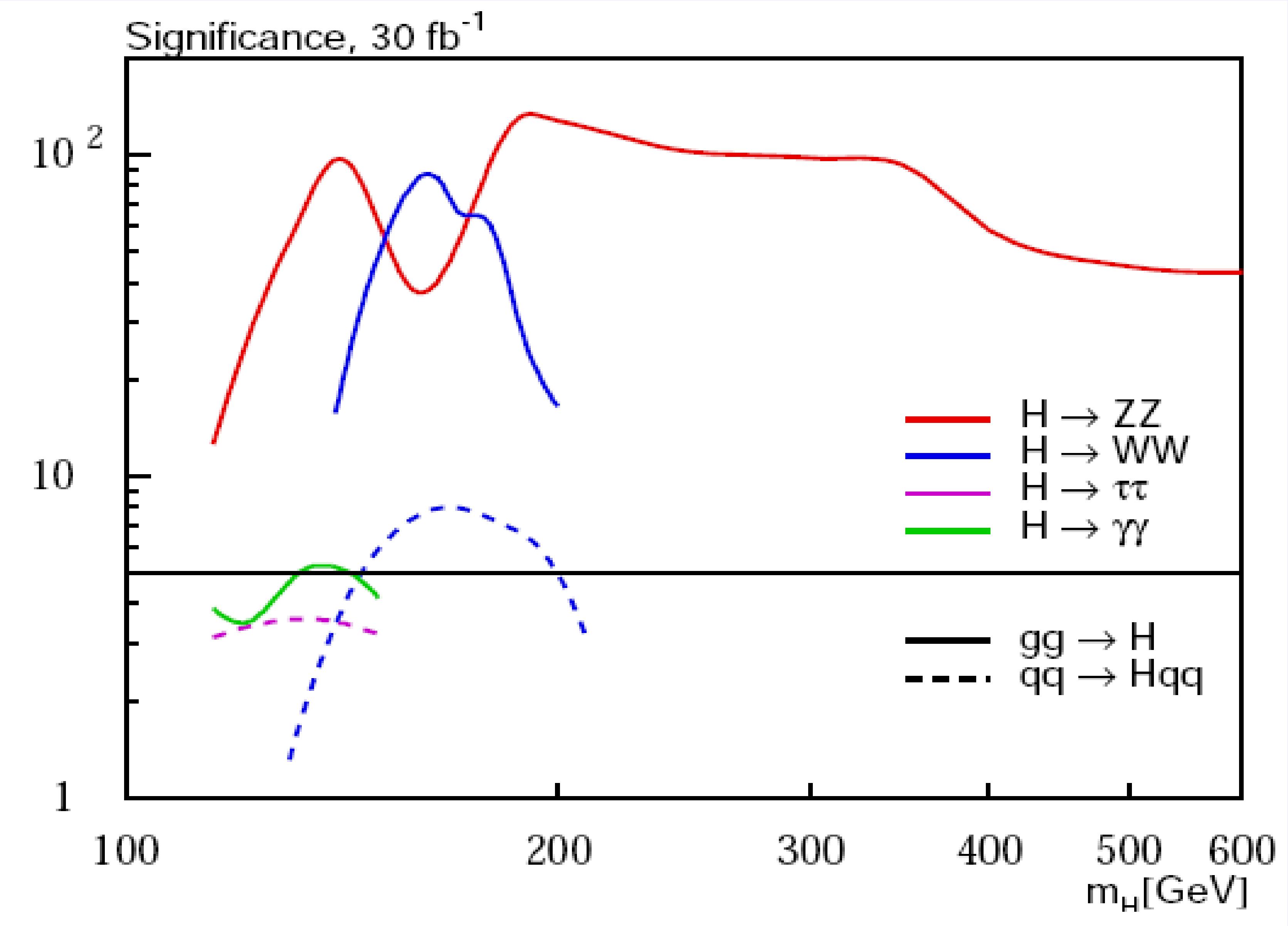
5. Phenomenology quite involved and correlations between CKM, PMNS & e.w. precision fit still to be studied

6. Experimental activities inside CMS & ATLAS starting to rise

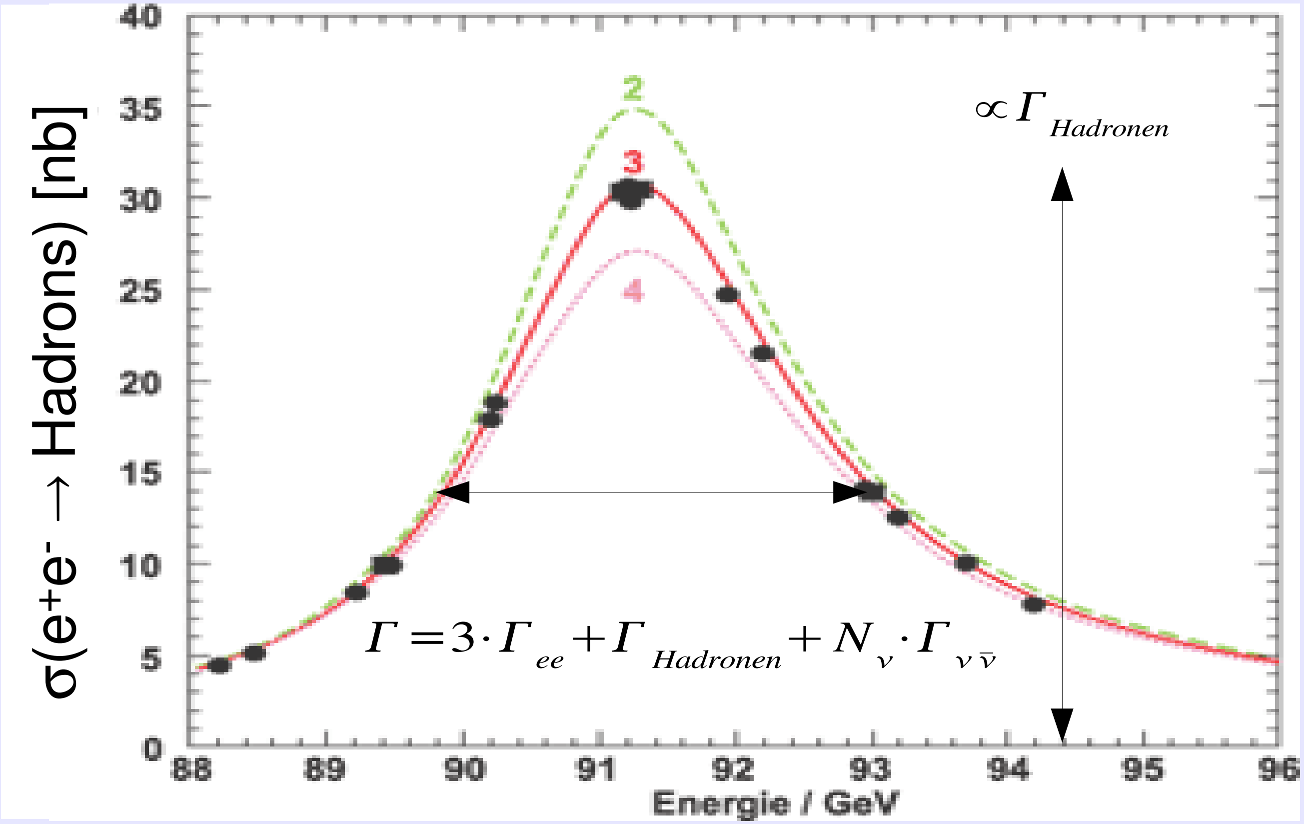
=> There is still a lot to discover in the land of four generations

BACKUP

3. Higgs phenomenology @ LHC (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:

$m_{\nu_4} > M_Z / 2$

LEP2: $m_{l_4} > 100.8$ GeV

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

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

All limits for unstable heavy leptons

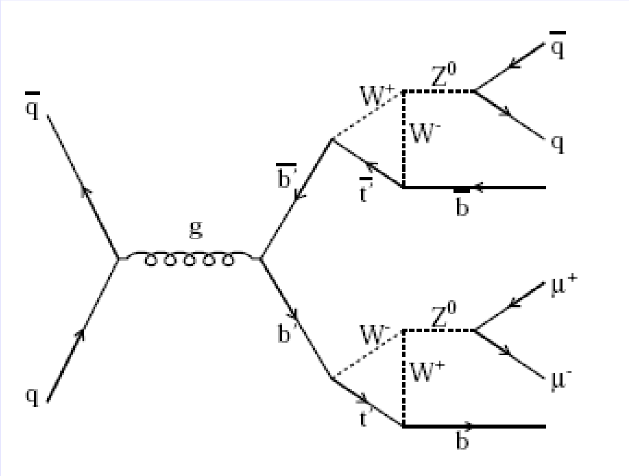
2.2 TEVATRON constraints: FCNC decay

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

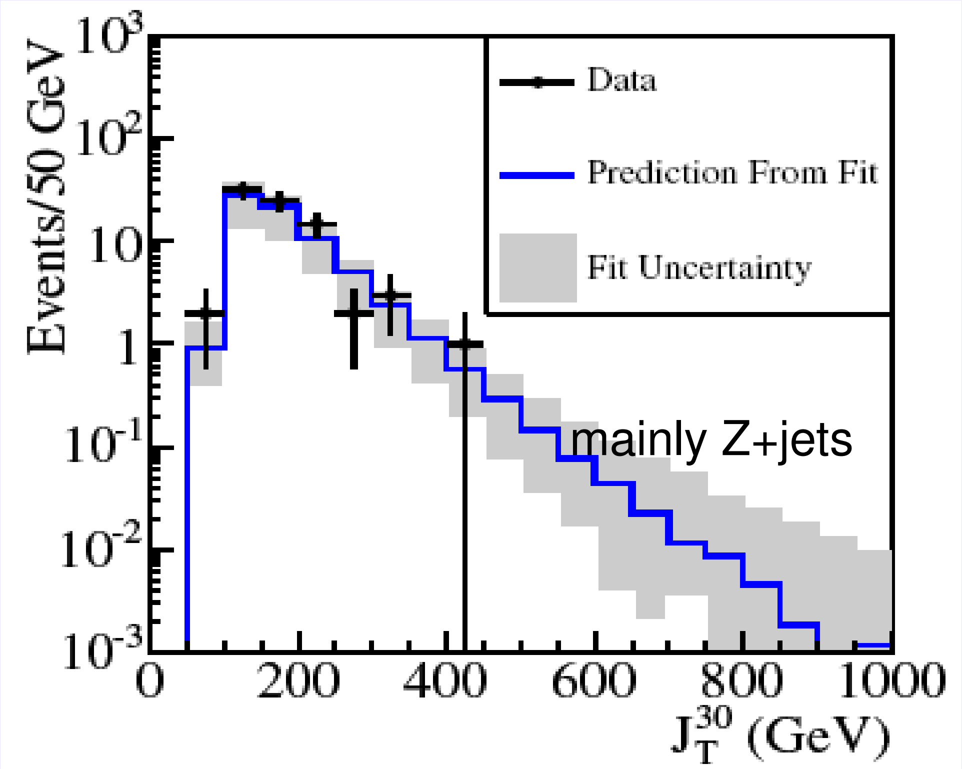
$$p\bar{p} \to b'\bar{b}', b'(d_4) \to b + Z$$

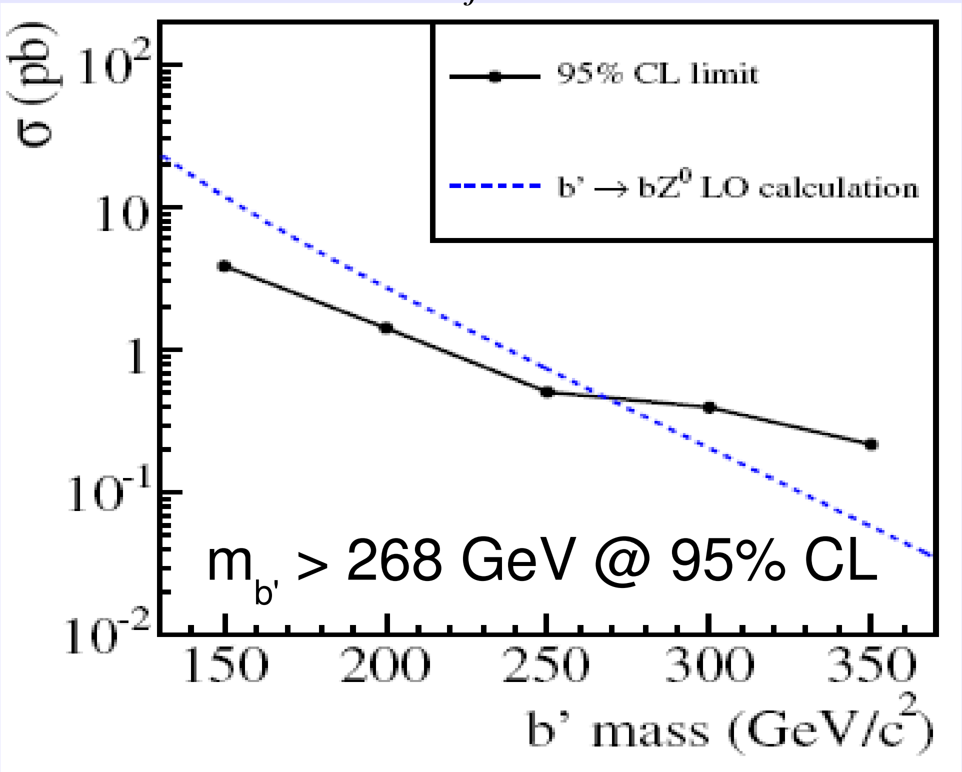
assumption:

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



$$Z \to e^+ e^-, \mu^+ \mu^- \quad N_{jet}^{30} \geq 3 (30 \equiv E_{T,jet} \geq 30\,\text{GeV}) \quad J_T^{30} = \sum_{jets} E_T (E_T > 30\,GeV)$$





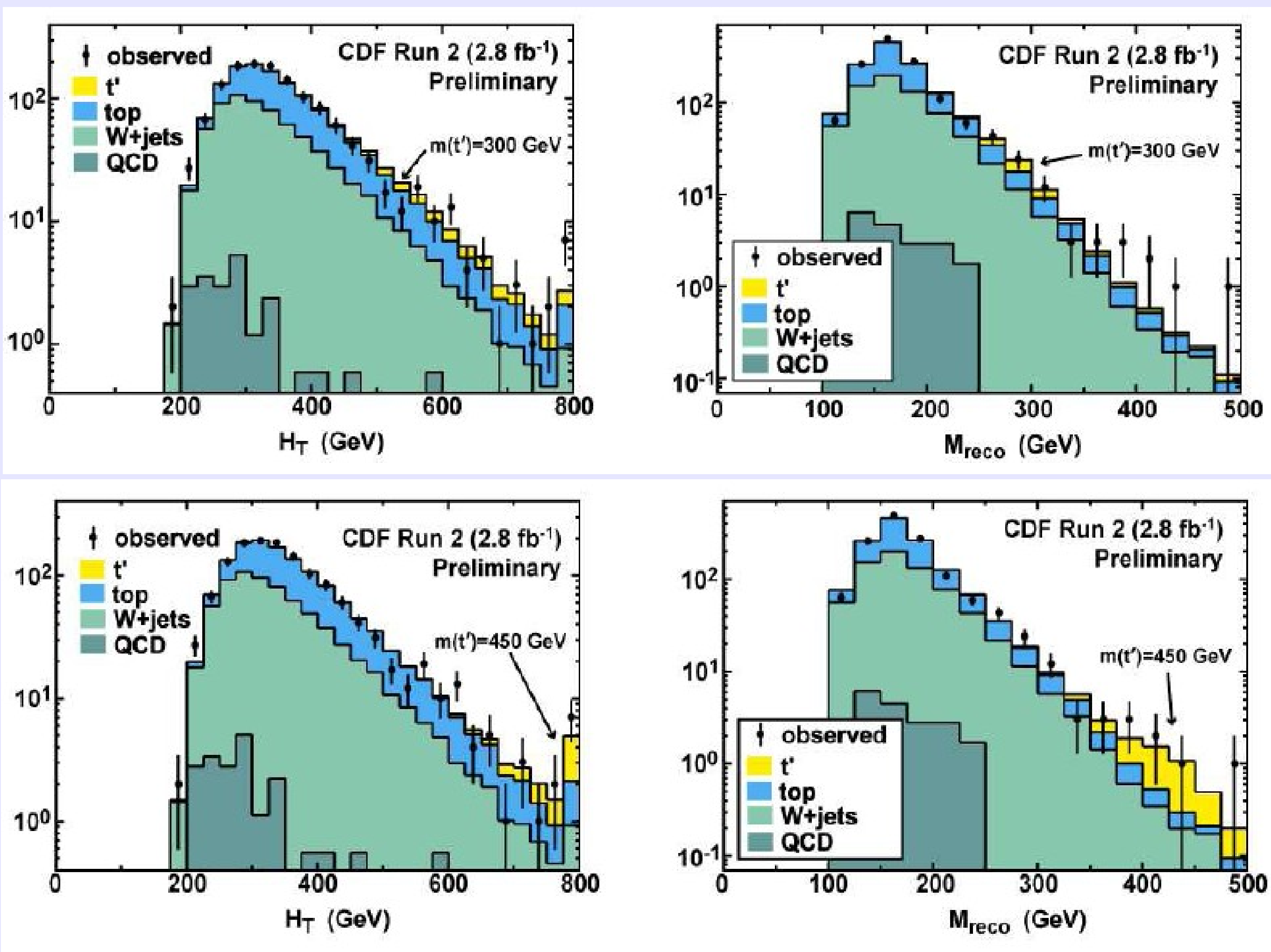
2.3 TEVATRON constraint: top-like search

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

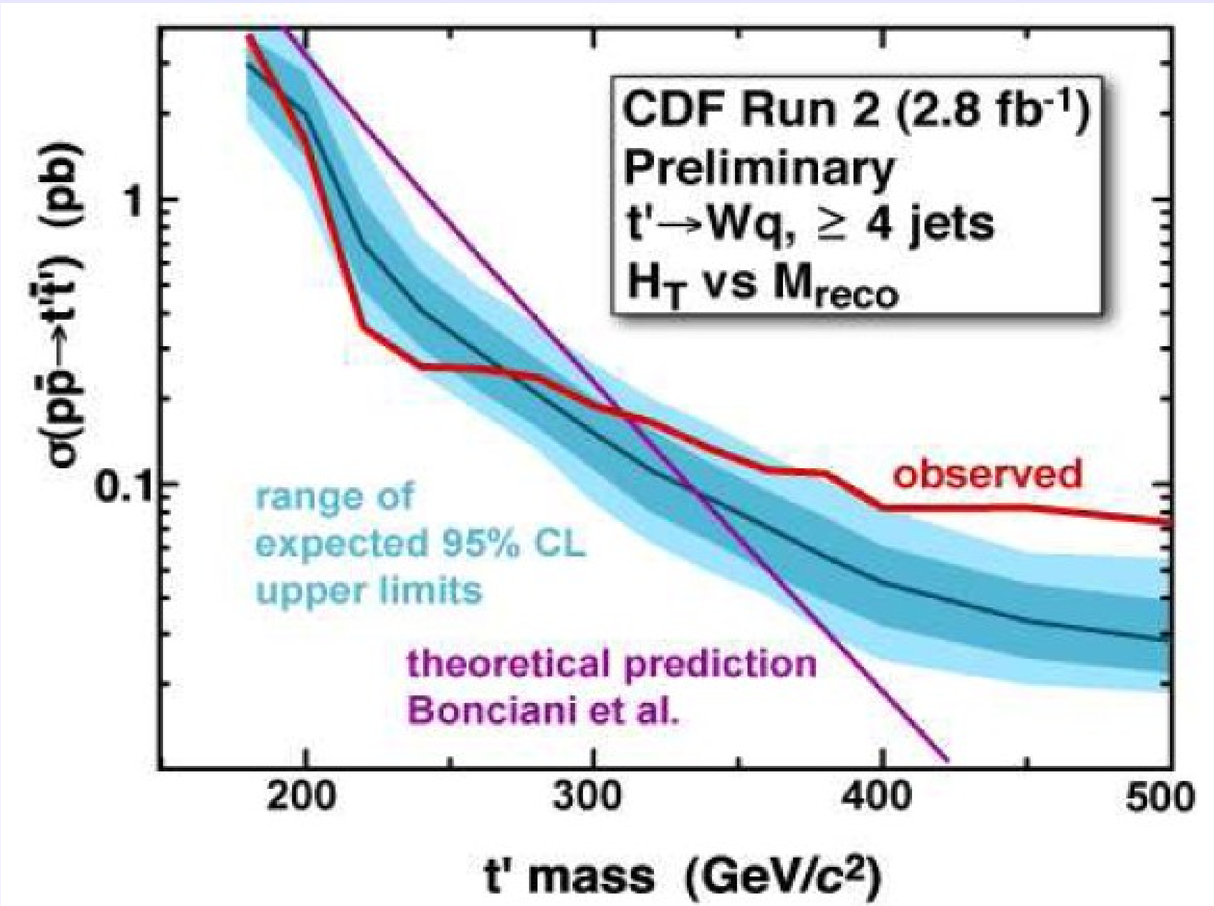
$$M_{reco} = M_{b\,j\,j} = M_{b\,l\,\nu}$$

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

=> 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' <u>and</u> 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: $p\,\bar{p} \rightarrow b'\,\bar{b}' + X\,,\; b' \rightarrow W + t\,(\rightarrow b + W)$

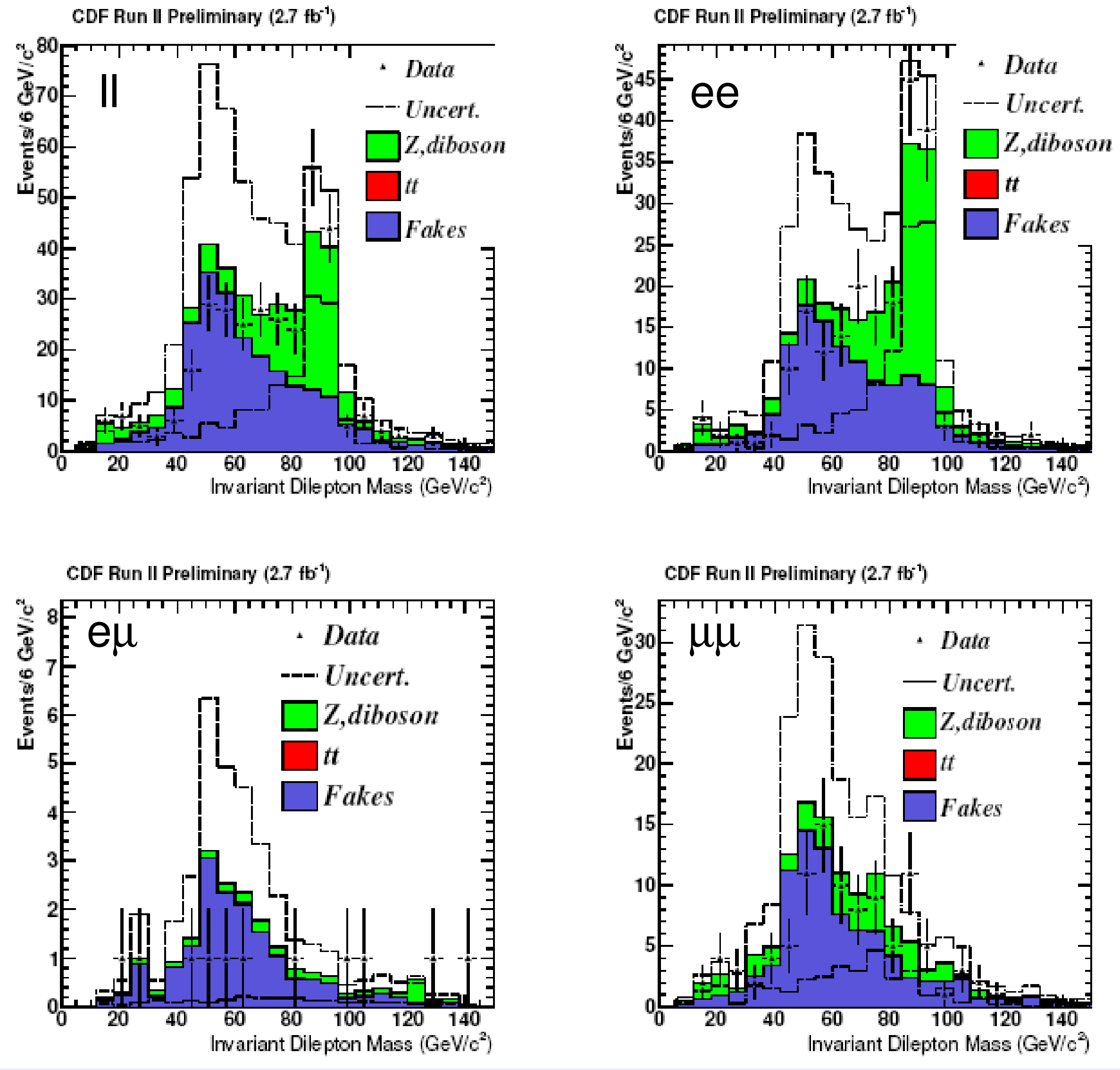
Striking search scenario: same-sign dilepton final state + high jet multiplicity

CDF, note 9759, 2.7 fb-1:

same-sign dilepton
invariant mass

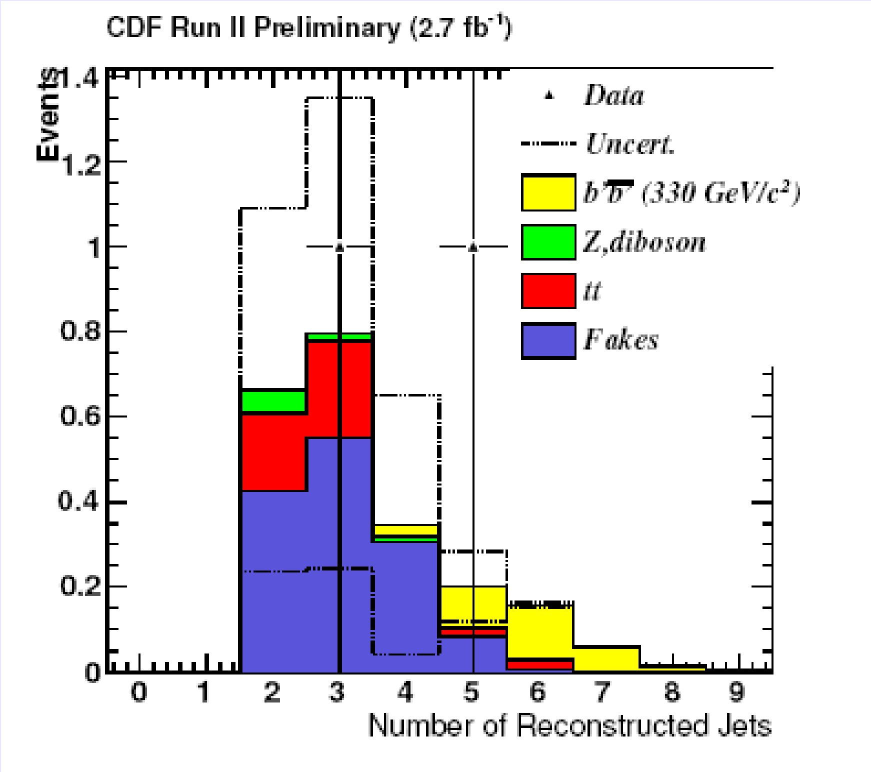
- **Fakes: mainly W+jets**

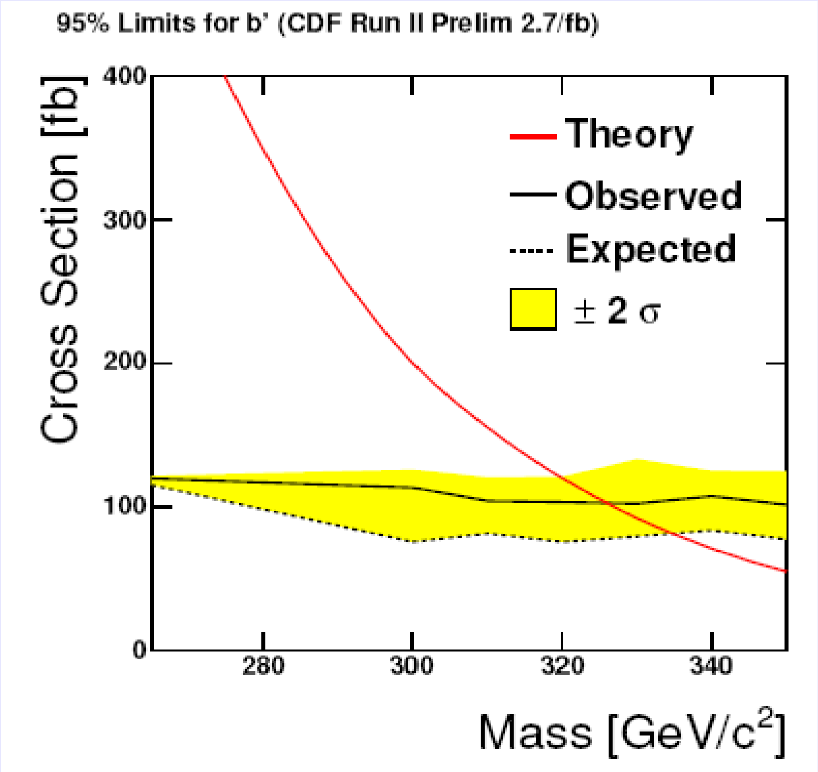
- **Z+jets:**
  $Z \rightarrow e^+e^-$ with hard bremsstr.
  + asymmetric conversion
  $\gamma \rightarrow e^+e^-$



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'→W+q)=100% & prompt t' decay

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

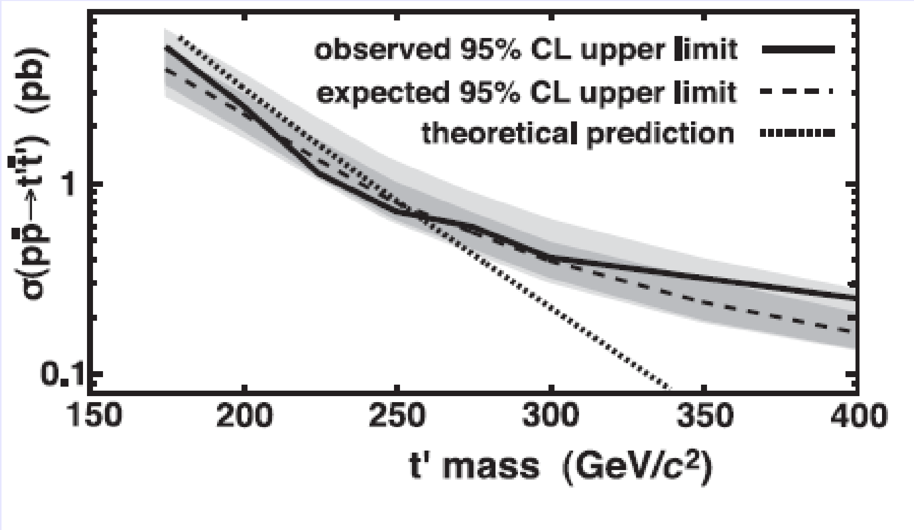
0 < $m_{t'}$-$m_{b'}$ < m_W: t'→W* + b' can still dominate for small $V_{t'q}$

$m_{t'}$-$m_{b'}$ < 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)

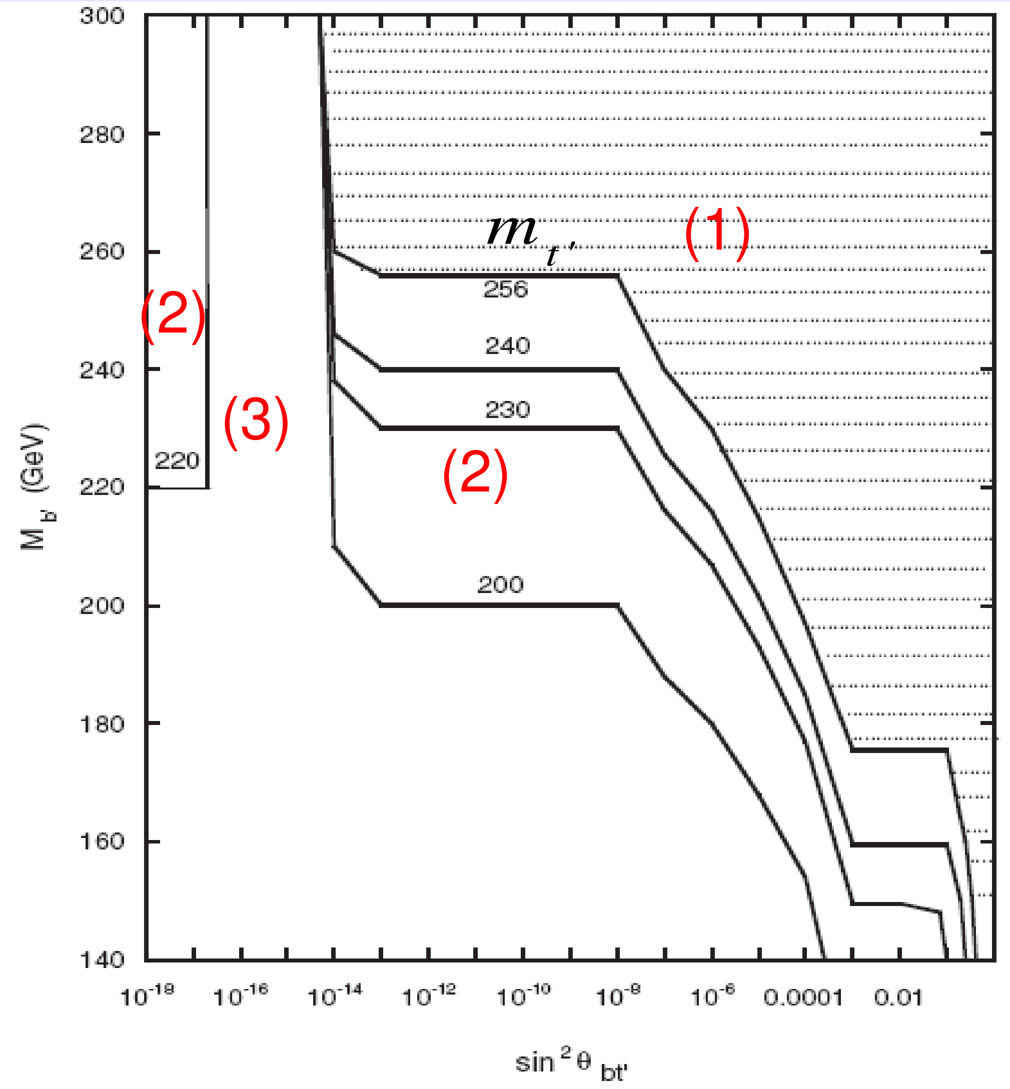
=> Constraint dependent on $m_{b'}$ and $V_{t'q}$

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

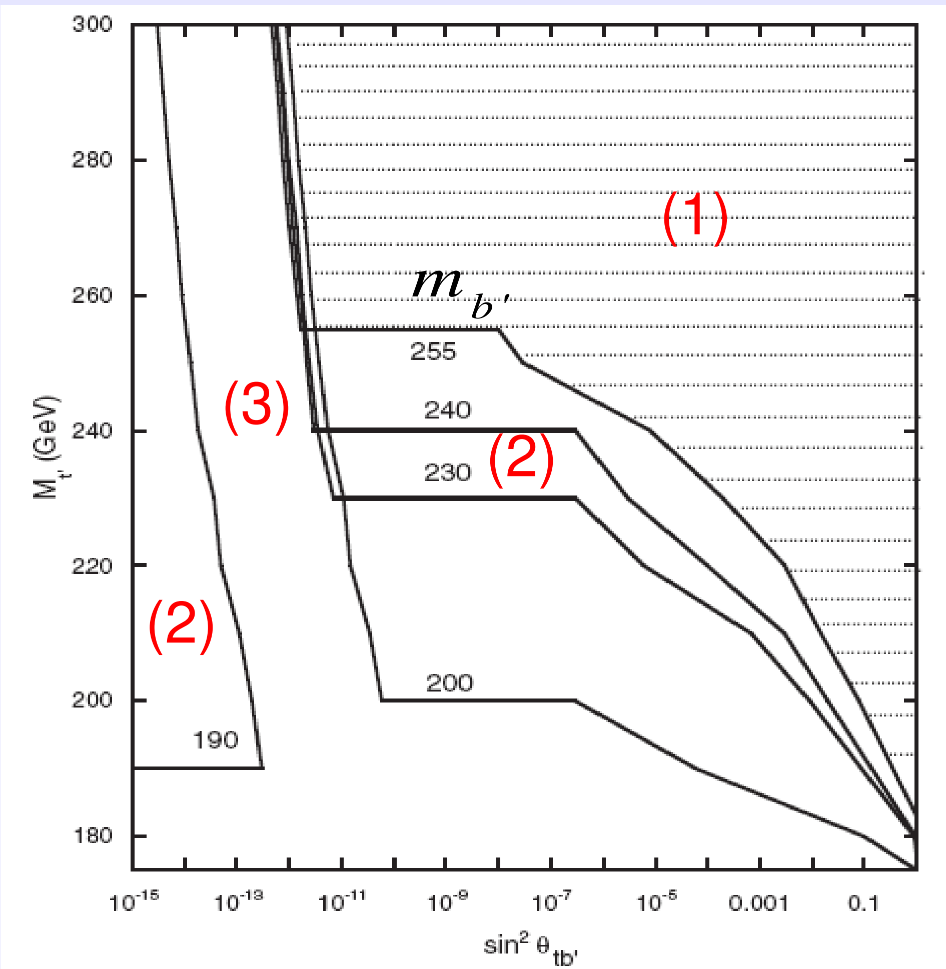
(3) lifetime region: no mass limit

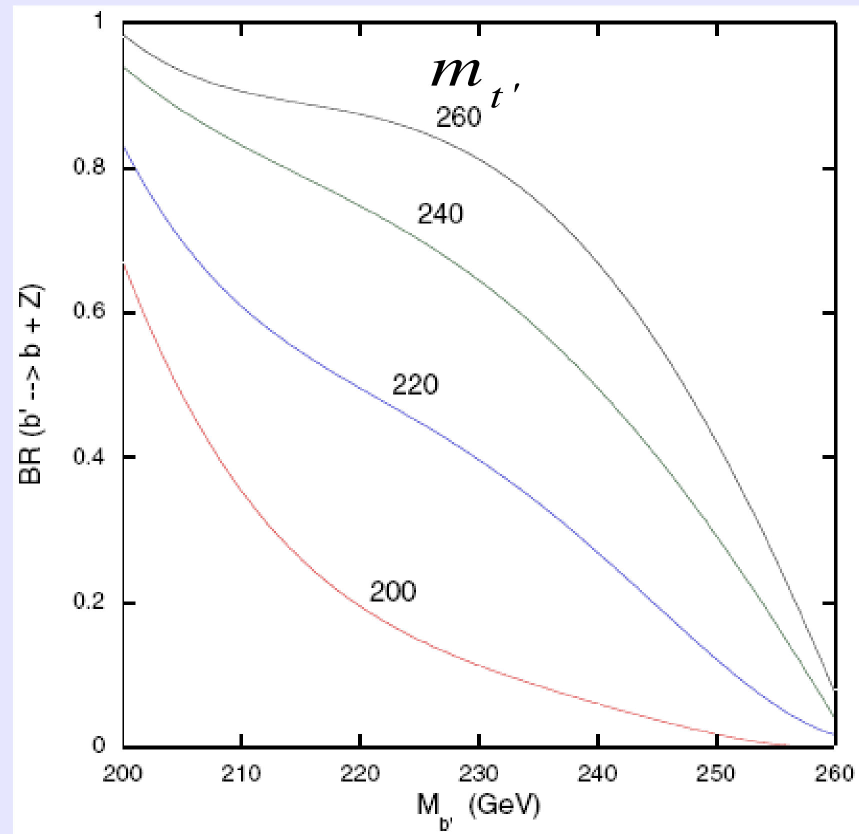
2.5 TEVATRON constraints: assumptions

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):





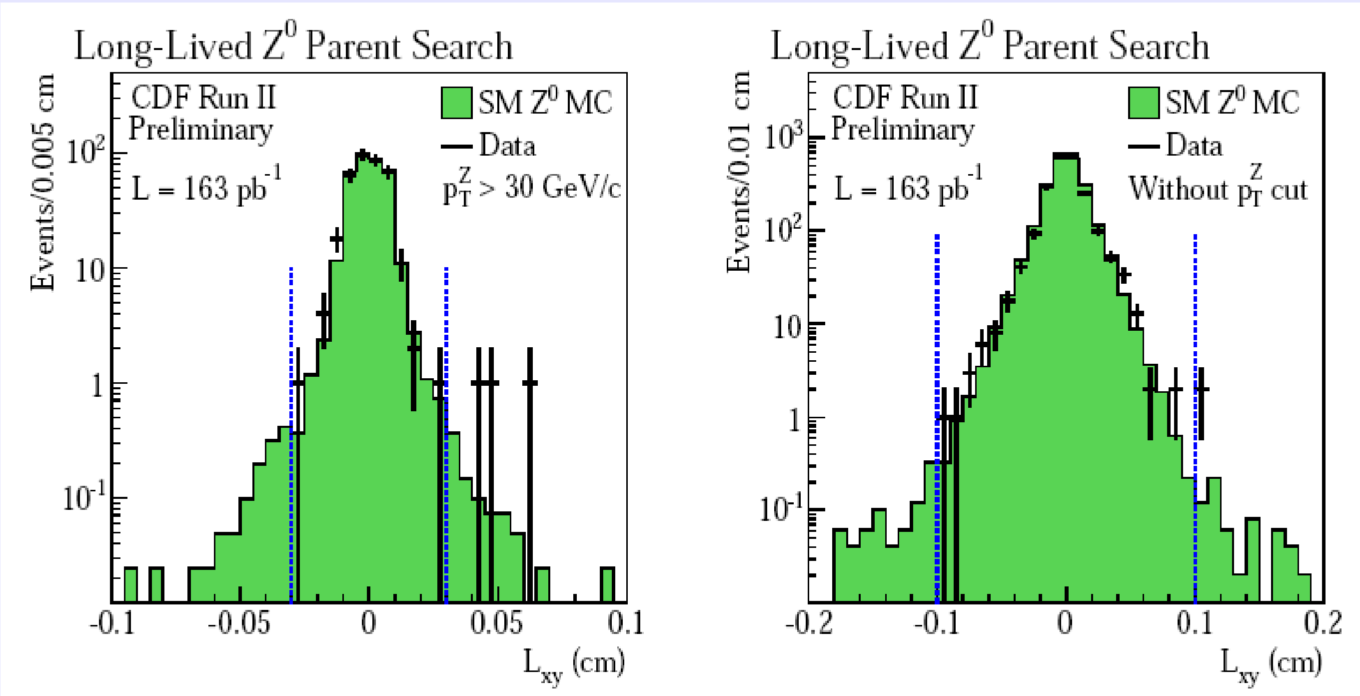
BF(b'→Z+b)=100% for

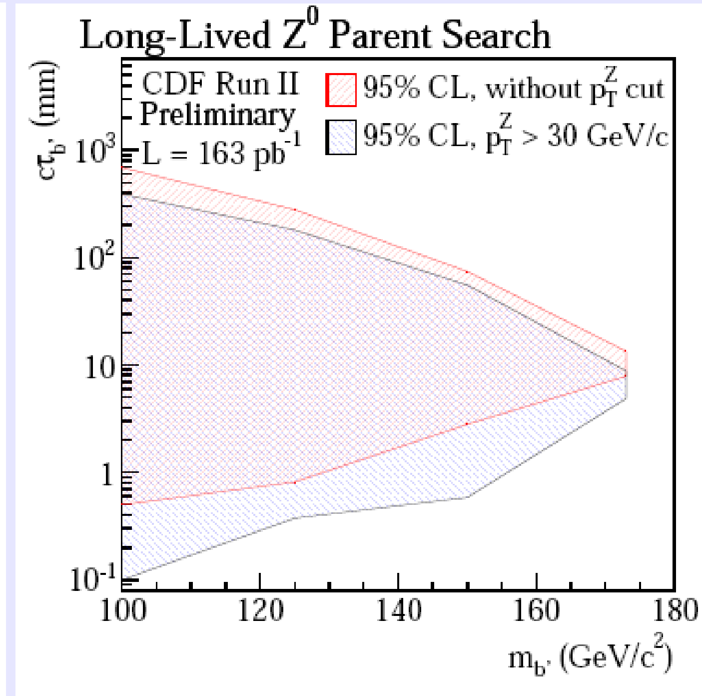
$m_{b'}$ > 255 GeV never met:

b'→W + t threshold opens

2.5 TEVATRON constraints: long-lived b'

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

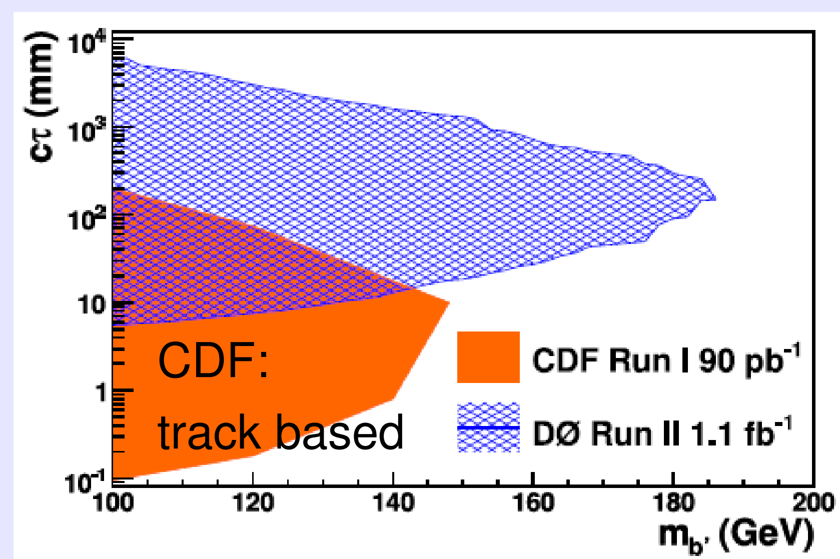




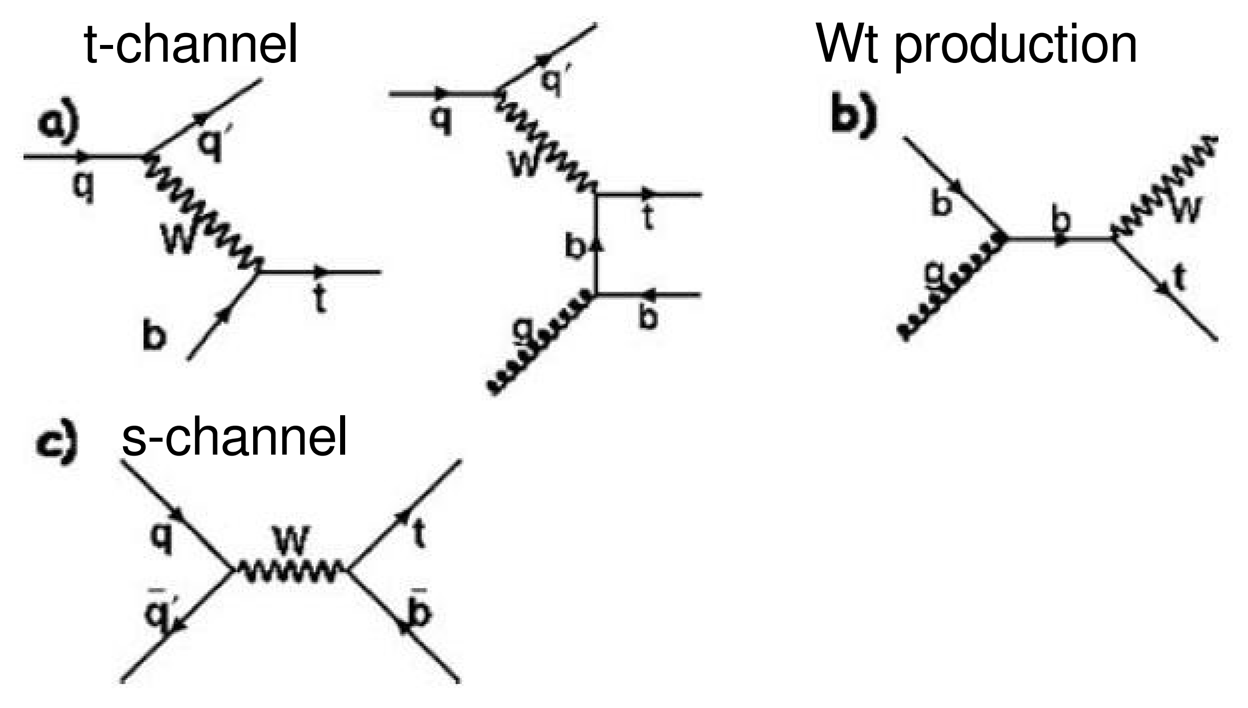
D0, PRL 101, 111802 (2008) with 1.1 fb^{-1}

$b' \rightarrow Z + b$

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



3.1 Effects of a 4th generation on Single Top production



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

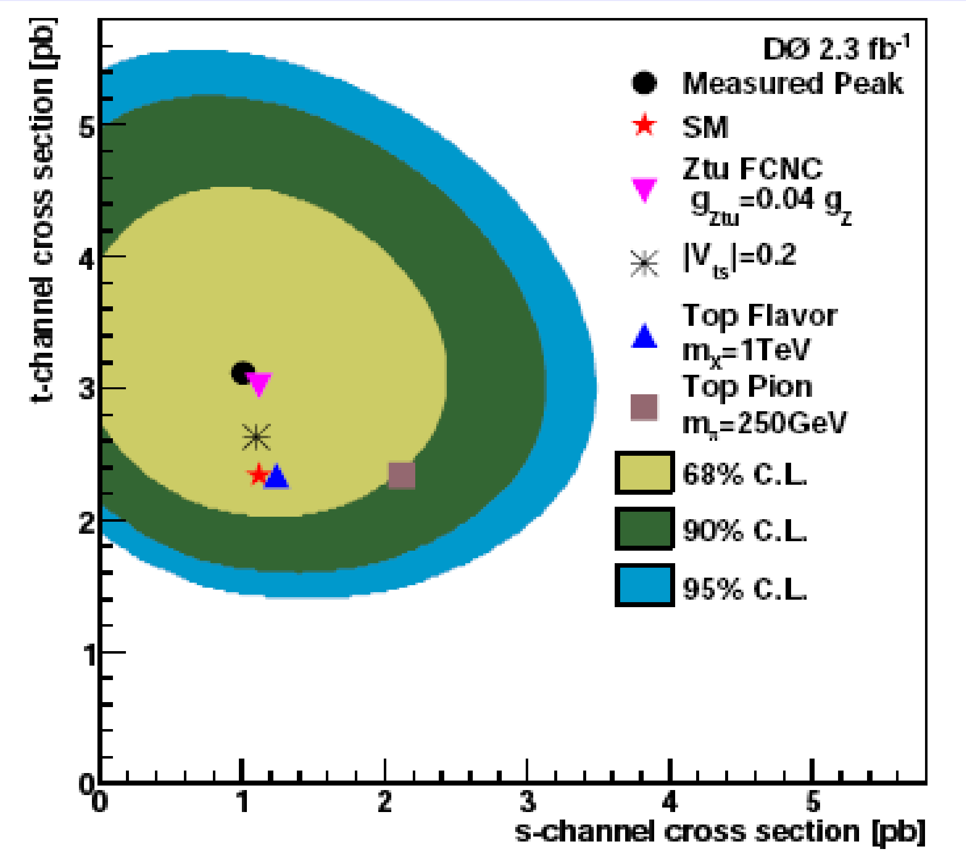
If $\sigma_{meas} \neq \sigma_{theo}$:

$|V_{tb}|<1$ (=> 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

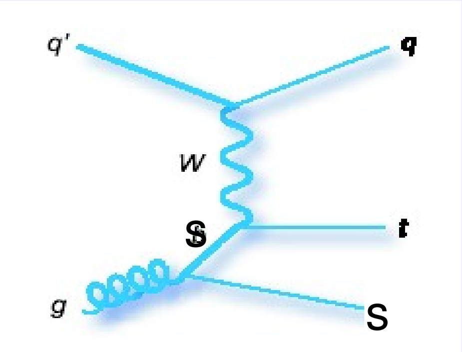


$\sigma_{SingleTop} \sim |V_{tb}|^2$ in N_{gen}=3-SM

Nonetheless, it is possible to have:

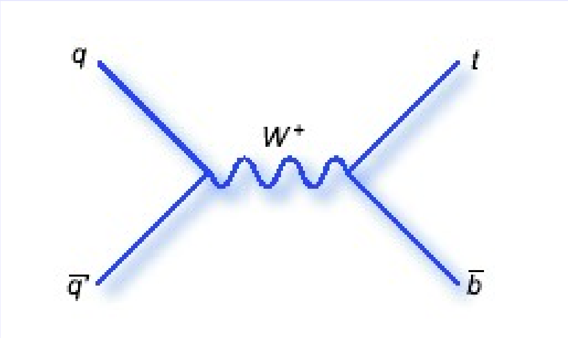
$\sigma_{SingleTop}(N_{gen}=4) > \sigma_{SingleTop}(N_{gen}=3)$

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



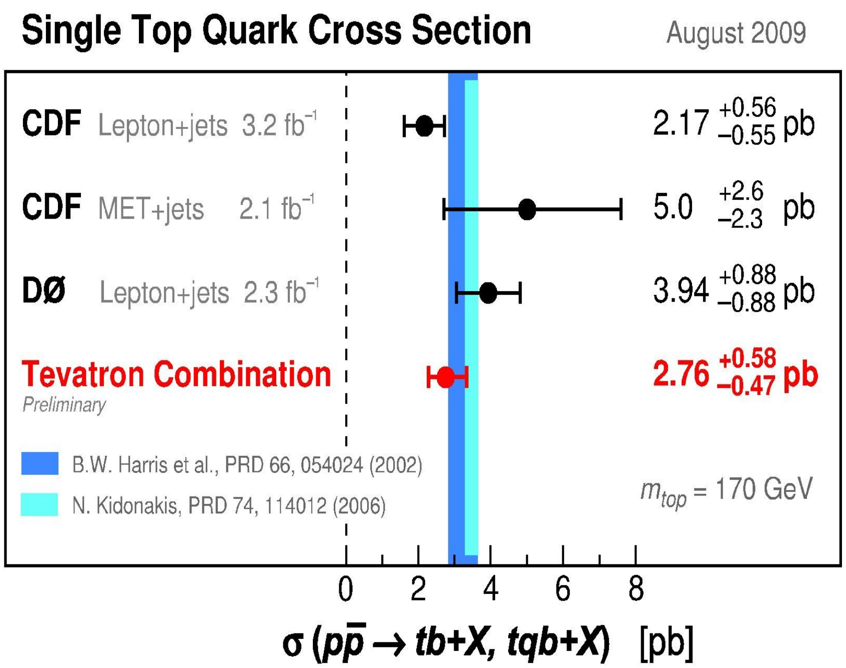
t-channel enhanced

PDF(s) >> PDF(b)



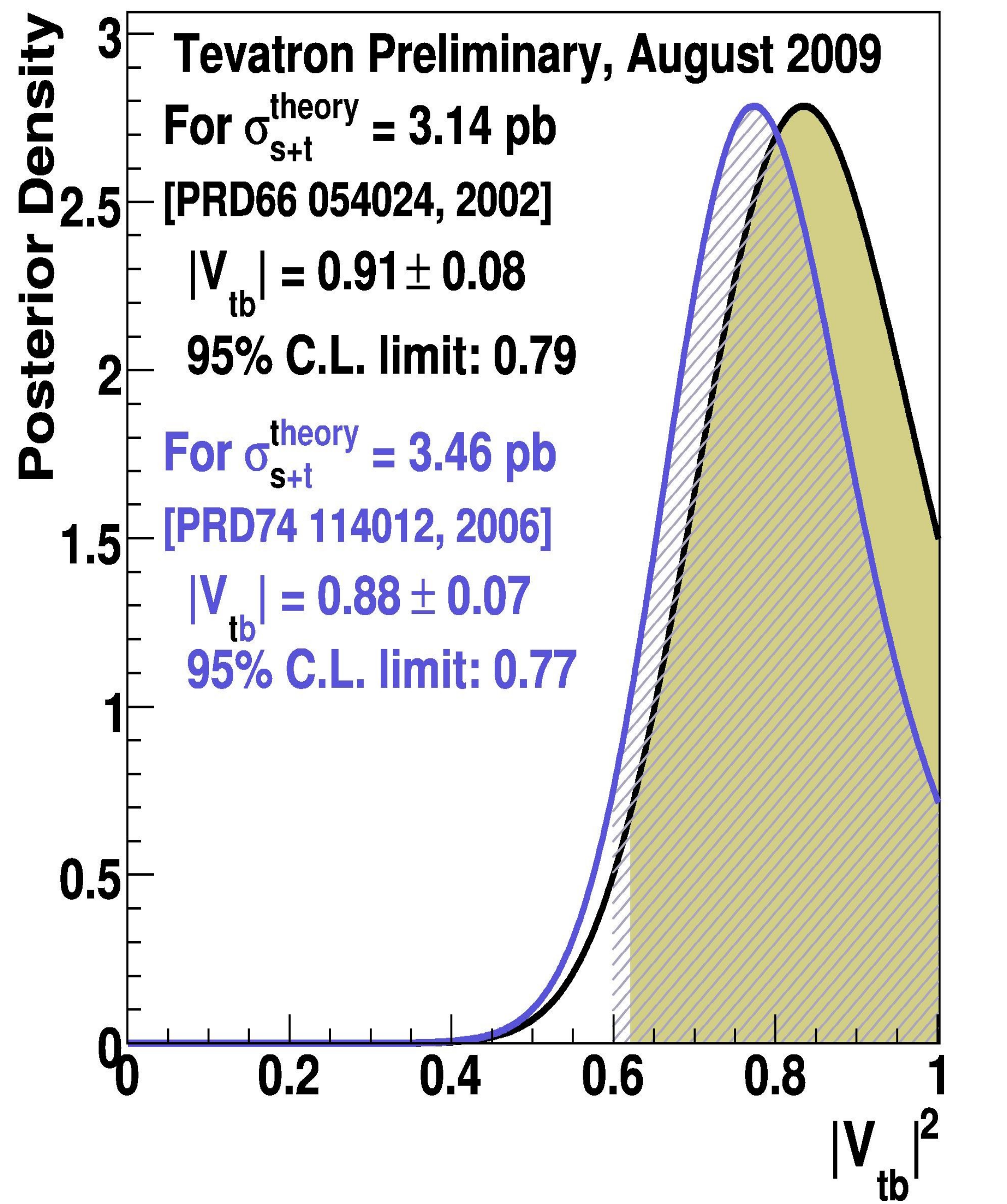
s-channel suppressed: $|V_{tb}| <1$

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: $R = \frac{\Gamma(t \rightarrow W+b)}{\Gamma(t \rightarrow W+q)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$

  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: $|V_{tb}| \frac{|V_{tb}|}{\sqrt{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}}$

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

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: $\mu \to e\gamma$, $\mu \to e$ conversion

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

   CKM-Treelevel + K-, D-, B-mixing & $b \to s\gamma$ ---> 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

$$\left|V_{CKM}^{4\times4}\right| = \begin{pmatrix} 0.97418 & 0.2246 & 0.0039 & <0.038 \\ 0.22 & >0.84 & 0.041 & <0.51 \\ <0.06 & <0.26 & >0.78 & <0.62 \\ <0.105 & <0.51 & <0.62 & >0.74 \end{pmatrix}$$

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:

$$\left|V^{4\times4}_{CKM}\right| = \begin{pmatrix} 0.97418 & 0.2246 & 0.0039 & <0.038 \\ 0.22 & >0.84 & 0.041 & <0.51 \\ <0.06 & <0.26 & >0.78 & <0.62 \\ <0.105 & <0.51 & <0.62 & >0.74 \end{pmatrix}$$

my numbers

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

  * $|V_{tb}|$

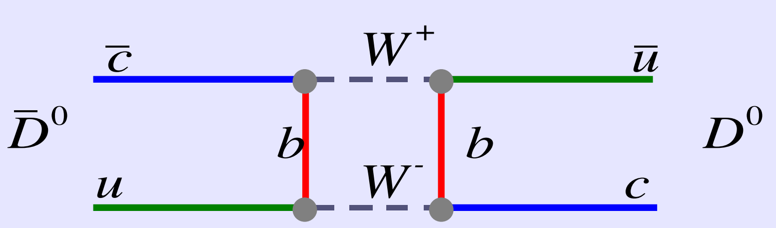
  * $\Gamma(W\rightarrow had)$

$$\left|V^{4\times4}_{CKM}\right| = \begin{pmatrix} 0.97418 & 0.2246 & 0.0039 & <0.038 \\ 0.22 & 0.97 & 0.041 & <0.2 \\ <0.04 & <0.125 & >0.78 & <0.62 \\ <0.07 & <0.20 & <0.62 & >0.78 \end{pmatrix}$$

  * D-mixing (Golowich et al., PRD76:095009, 2007) $\rightarrow \left|V_{u d_4} V^*_{c d_4}\right| < 0.002$

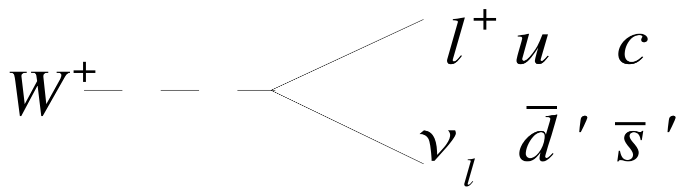
  Limit depends on d_4 mass (200 GeV used)

  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:

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

=> 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 $\rightarrow \sin\theta = 0$

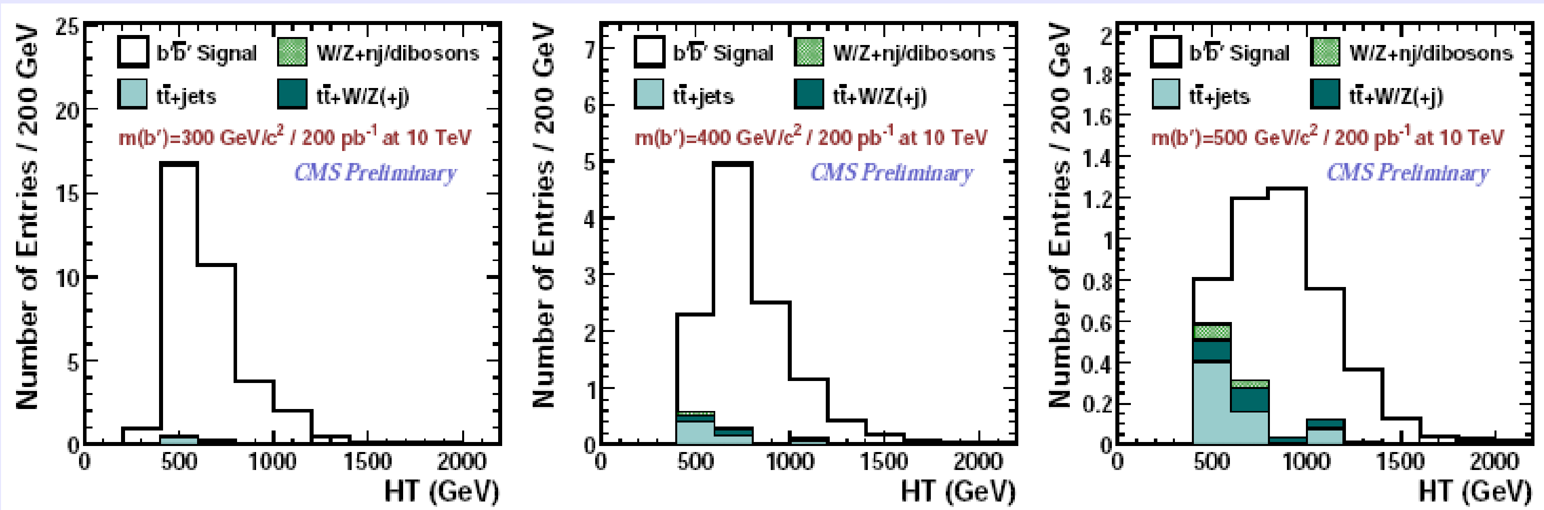
  by Planck scale effects
- Flavor democracy $\rightarrow U_{l_4 i} \approx 10^{-5} - 10^{-4} \quad (V_{t'q} \approx 10^{-4} - 10^{-3}, V_{qb'} \approx 10^{-4} - 10^{-3})$
- Benchmark: $|U_{\mu 4}|$ ~ 0.023 corresponds to a $|V_{ud}|$ change of 1σ

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

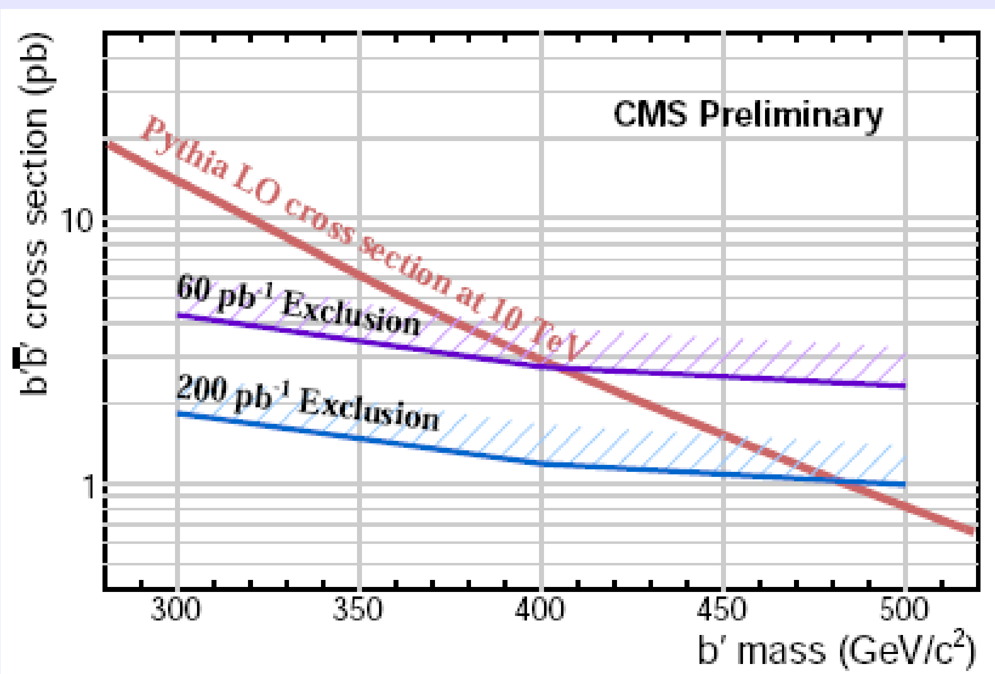
  Scenario already excluded? $\dfrac{g_\tau}{g_\mu} = 0.9976 \pm 0.0022 \stackrel{?}{=} \dfrac{\cos\theta_{34}}{\cos\theta_{24}} \approx 0.9911$

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

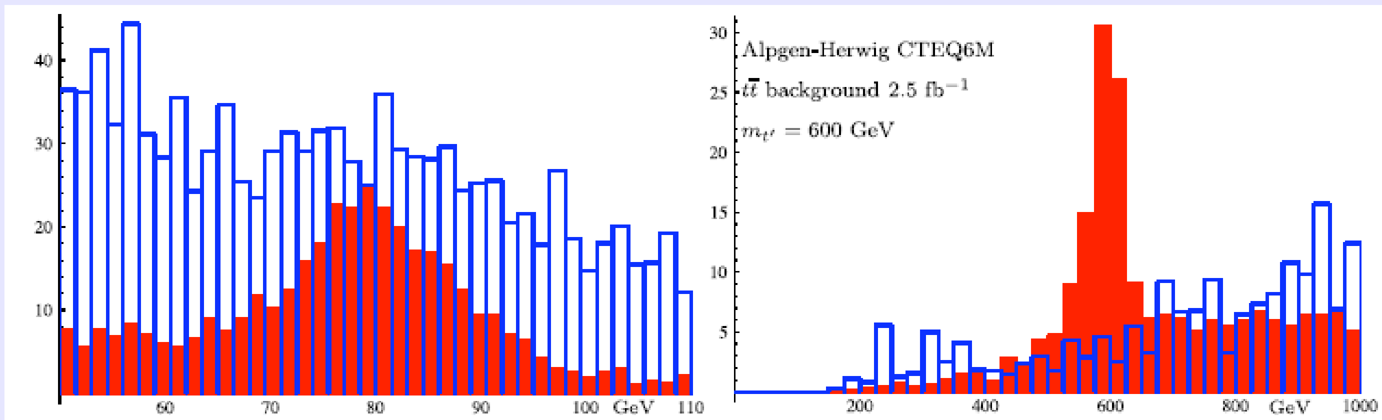
6.2 Search strategies @ LHC: t'->W+q

- 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

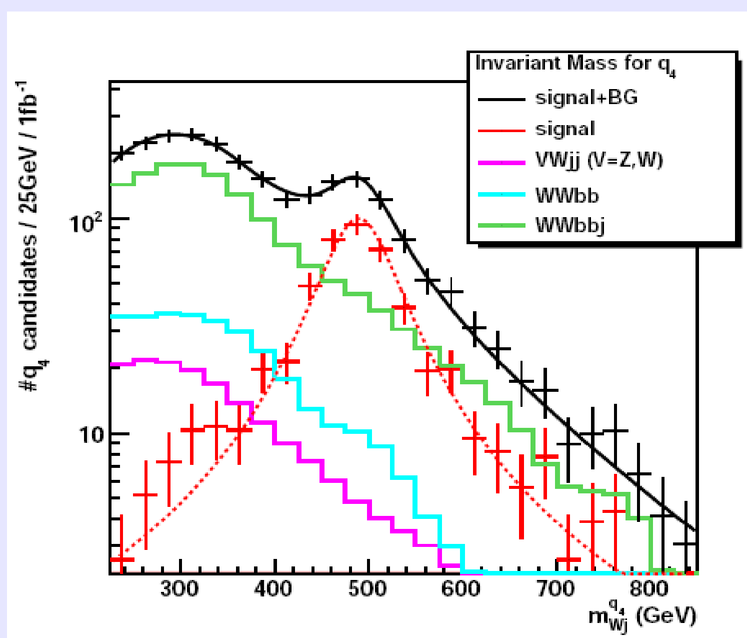


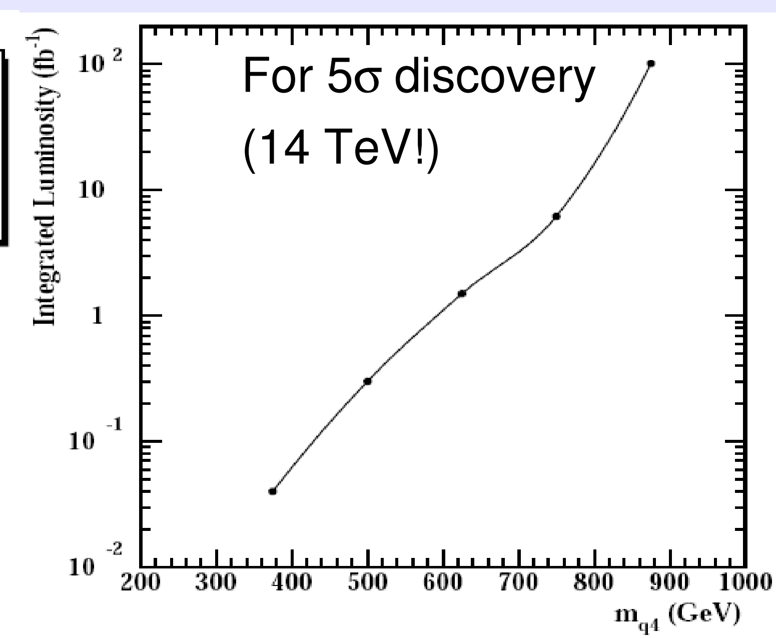
Understanding of high-p_T top's?

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 4^{th} 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)

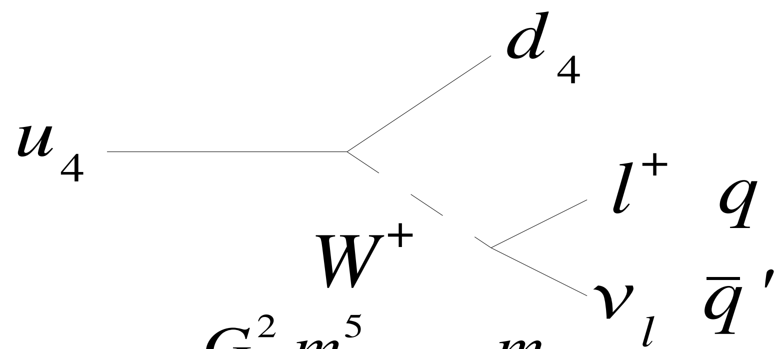
3. * 3x3 unitarity in lepton sector assumed in all analyses (CKM, ...) so far
   * Combined analysis of CKM-, PMNS-, & e.w. precision fit required

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

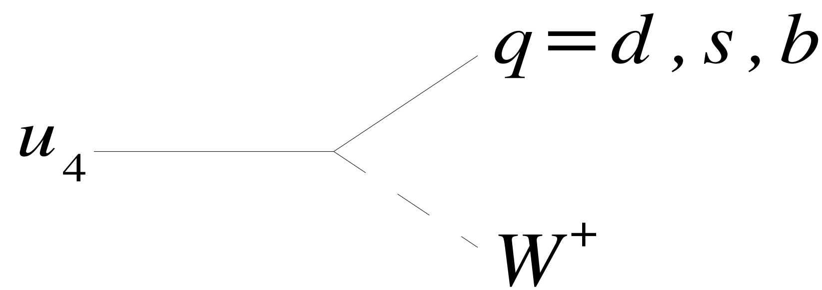
5. LHC: * excellent place for discovery 4^{th} ($M \leqslant 1$ TeV→partial wave unitarity)
   Complementary search scenarios: b'(t')→W+q(b) ↔ b'→W+t
   * BG-suppression with single jet invariant mass (→boosted W's)
   (also interesting for other channels)
   * Heavy quark with long lifetime searches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

Decays

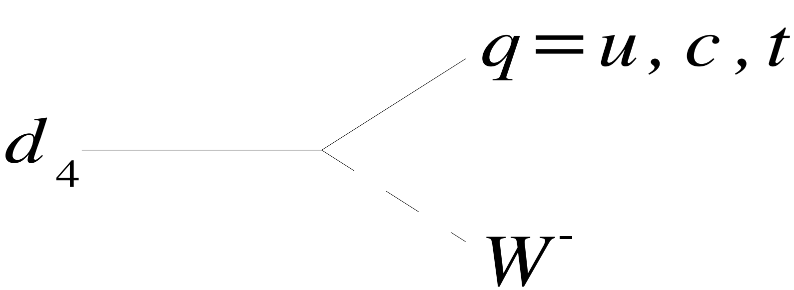
Ex.: $0 < m_{u_4} - m_{d_4} < M_W$



$$|V_{u_4 d_4}|^2 \cdot \frac{G_F^2 m_{u_4}^5}{192\pi^3} f_3\left(\frac{m_{d_4}}{m_{u_4}}\right)$$



$$|V_{u_4 q}|^2 \cdot \frac{G_F m_{u_4}^3}{8\pi\sqrt{2}} f_2(M_W, m_{u_4}, m_q)$$



$$|V_{d_4 q}|^2 \cdot \frac{G_F m_{d_4}^3}{8\pi\sqrt{2}} f_2(M_W, m_{d_4}, m_q)$$

for $m_{d_4} - m_q > M_W$

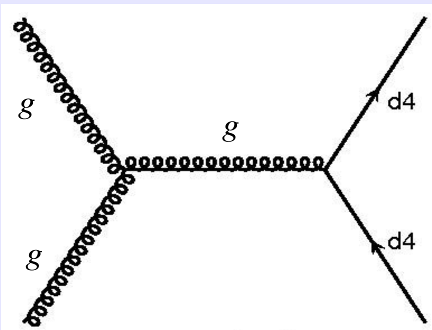
else: 3-body decay rate

(only for top possible)

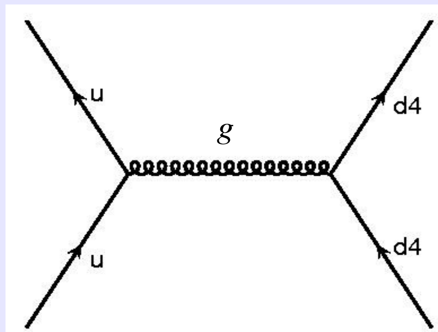
4^{th} Generation Pair production (w/o Higgs) at LHC

$$p\,p \rightarrow f\,\bar{f}\,X \;\; (14\ \text{TeV})$$

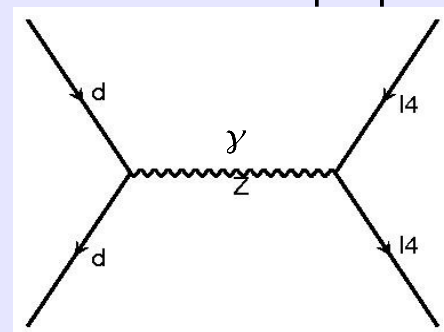
$g\,g \rightarrow q_4\,\bar{q}_4$



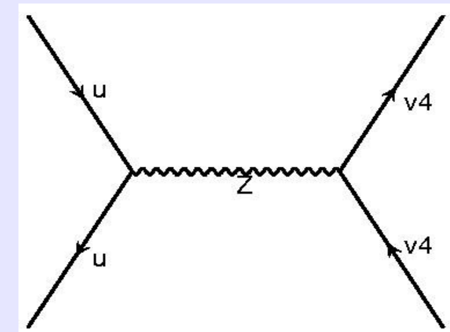
$q\,\bar{q} \rightarrow q_4\,\bar{q}_4$

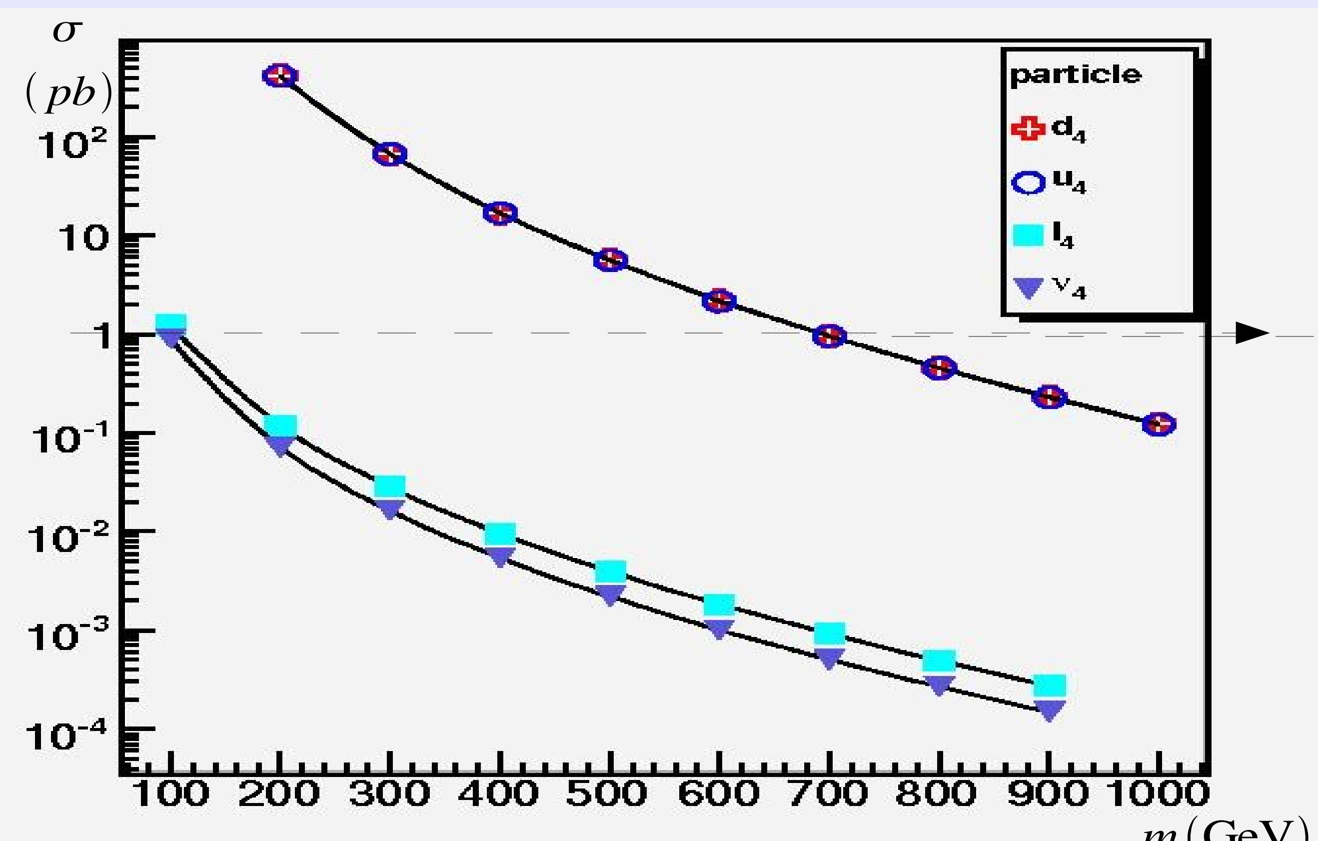


$q\,\bar{q} \rightarrow l_4^+\,l_4^-$



$q\,\bar{q} \rightarrow \nu_4\,\bar{\nu}_4$





L=1-10 fb^{-1}

N = σ L = 10^3 - 10^4 events (w/o acceptance, BF's & efficiency)

2.2 Cosmological constraints: heavy neutrino

1) $m_{\nu_4} < m_{l_4}$ **preferred (e.w. precision fit)**

=> ν_4 **could have long lifetime => Dark Matter candidate !?**

2) Direct searches for Dark Matter

Big bang: $n_{\nu_4}(m_{\nu_4})$

If neutrinos clump together like baryons do:

m > 500 GeV, since no signal observed by CDMS II

3) Argument can be circumvented, if:

*** Neutrinos do not clump together like baryons (=> m > 100 GeV)**

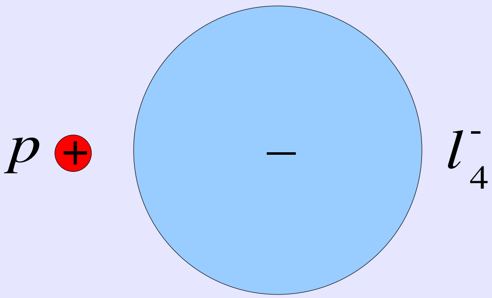
*** Lifetime significantly smaller than age of the universe**

(BTW: Cosmological neutrino mass bound only valid for “light” neutrinos)

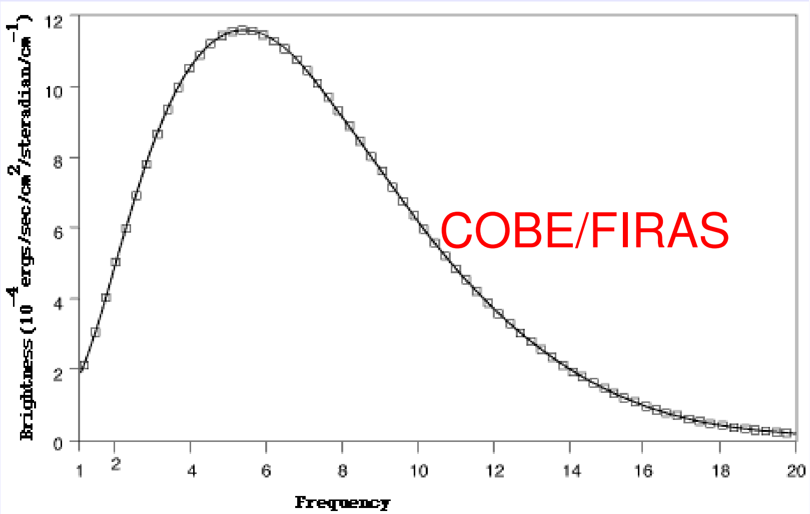
2.3 Lifetimes: Example of heavy charged lepton

1) No heavy hydrogen found

=> cannot be nicht quasistable



2) Finite lifetime cosmological constrained:



a) CMB

Perfect black-body spectrum

$$\Rightarrow \tau(l_4^-) < 10^9 - 10^{11}\,\mathrm{s}$$

b) Primordial nucleosynthesis

Photons from decay products would break up D (He)

=> decrease (increase) of deuteron abundance

D/He compatible with standard nucleosynthesis

$$\Rightarrow \tau(l_4^-) < 10^7 - 10^8\,\mathrm{s}$$

5.1 Mixing in quark sector

Directly measured matrix elements:

$$\left|V_{CKM}^{4\times4}\right| = \begin{pmatrix} 0.97418 & 0.2246 & 0.0039 & <0.04 \\ 0.22 & >0.75 & 0.041 & <0.6 \\ <0.08 & <0.40 & >0.78 & <0.65 \\ <0.1 & <0.60 & <0.65 & >0.78 \end{pmatrix}$$

- Constraints discussed by Kribs et al.:

* $|V_{tb}|$

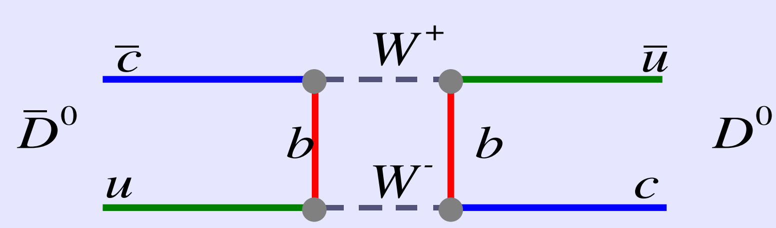
* $\Gamma(W\rightarrow\text{had})$

$$\left|V_{CKM}^{4\times4}\right| = \begin{pmatrix} 0.97418 & 0.2246 & 0.0039 & <0.04 \\ 0.22 & 0.965 & 0.041 & <0.2 \\ <0.08 & <0.15 & >0.78 & <0.65 \\ <0.09 & <0.17 & <0.65 & >0.78 \end{pmatrix}$$

* 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



CKM & PMNS-matrix: W→lep & τ-/μ-decays

Constraints on PMNS elements:

$$\left|U^{4\times4}\right| = \begin{pmatrix} * & * & * & <0.2 \\ * & * & * & <0.2 \\ * & * & * & <0.2 \\ <0.25 & <0.25 & <0.25 & >0.9 \end{pmatrix}$$

IF G_F is constrained to vary by 5% around its standard value

PMNS constraints are sufficiently strong to improve CKM constraints from $\Gamma(W\rightarrow l\nu)$ but less constraining compared to constraint assuming lepton universality in such a case

Constraints on CKM elements:

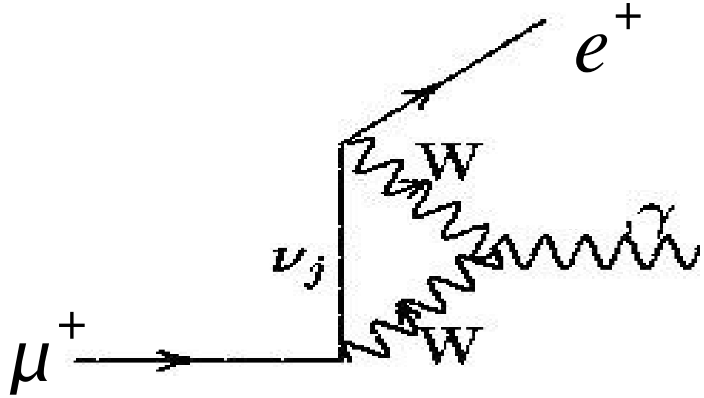
$$\left|V_{CKM}^{4\times4}\right| = \begin{pmatrix} 0.97418 & 0.2246 & 0.0039 & <0.04 \\ 0.22 & 0.965 & 0.041 & <0.3 \\ <0.08 & <0.3 & >0.78 & <0.65 \\ <0.09 & <0.3 & <0.65 & >0.78 \end{pmatrix}$$

CKM & PMNS matrix: W→lep & μ→eγ

Constraints on PMNS elements:

$$|U^{4\times4}| = \begin{pmatrix} * & * & * & <0.1 \\ * & * & * & <0.1 \\ * & * & * & <0.1 \\ <0.1 & <0.1 & <0.1 & >0.99 \end{pmatrix}$$

Similar constraints



$$BF(\mu \to e\gamma) < 1.2 \cdot 10^{-11}$$

$$\Rightarrow \frac{|U_{e4} U_{\mu4}^*|}{\left(\sqrt{\sum_{i=1,2,3} |U_{\mu i}|^2 \sum_{k=1,2,3} |U_{ek}|^2}\right)} < 4 \cdot 10^{-4}$$

Kribs et al.

w/o ()

$m_{\nu_4} > 100\, GeV$

Constraints on CKM elements:

$$|V_{CKM}^{4\times4}| = \begin{pmatrix} 0.97418 & 0.2246 & 0.0039 & <0.04 \\ 0.22 & 0.965 & 0.041 & <0.2 \\ <0.08 & <0.15 & >0.78 & <0.65 \\ <0.09 & <0.17 & <0.65 & >0.78 \end{pmatrix}$$