SM Extensions at CDF

Daniel Whiteson, UC Irvine

BNL 2010

Motivation

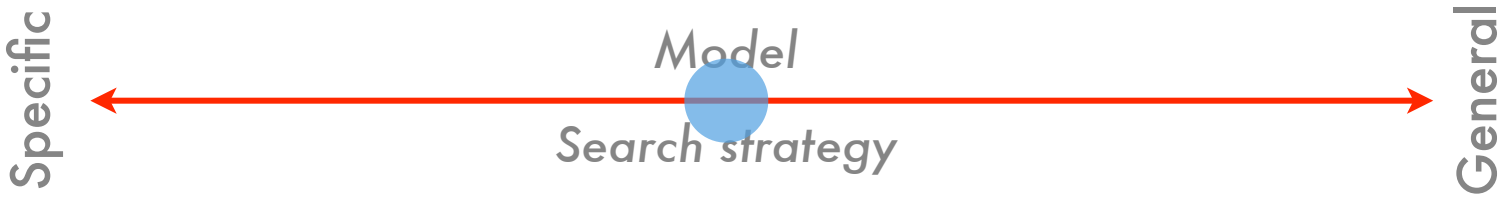
The Standard Model

$$
\begin{gathered}
-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
\tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \\
\tfrac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \tfrac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h [\tfrac{2M^2}{g^2} + \\
\tfrac{2M}{g} H + \tfrac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - \\
W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
\tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \\
\tfrac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2] - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - \\
W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \\
\phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu\phi^- - W^-_\mu\phi^+) + \\
igs_w M A_\mu (W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w} Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + \\
igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2 W^+_\mu W^-_\mu [H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \\
\tfrac{1}{4}g^2\tfrac{1}{c_w^2} Z^0_\mu Z^0_\mu [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w} Z^0_\mu \phi^0 (W^+_\mu\phi^- + \\
W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w} Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu \phi^0 (W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1) Z^0_\mu A_\mu \phi^+\phi^- - \\
g^1 s_w^2 A_\mu A_\mu \phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \\
\bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \\
\tfrac{ig}{4c_w} Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - \\
1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}} W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + \\
(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}} W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1 + \\
\gamma^5)u^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}\tfrac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \\
\tfrac{g}{2}\tfrac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + \\
m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1- \\
\gamma^5)u^\kappa_j] - \tfrac{g}{2}\tfrac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \\
\tfrac{ig}{2}\tfrac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \\
\tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \\
\partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \\
\partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2}\bar{X}^0 X^0 H] + \\
\tfrac{1-2c_w^2}{2c_w} igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] + \tfrac{1}{2c_w} igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \\
igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \tfrac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]
\end{gathered}
$$

Can this be right?

Strategy

Strategy



<u>Need some kind of model</u>

New signal requires a coherent physical explanation, even trivial or effective

<u>Make the model general</u>

Construct simple models that describe classes of new physics, not specific theories

<u>Examples</u>

Simple SM extensions: fourth generation, Z′, resonances (X->tt) etc

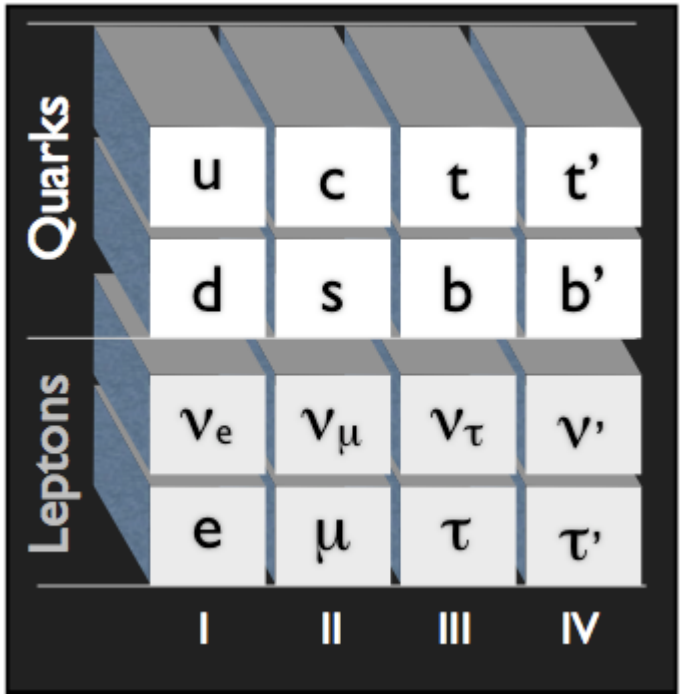
Outline

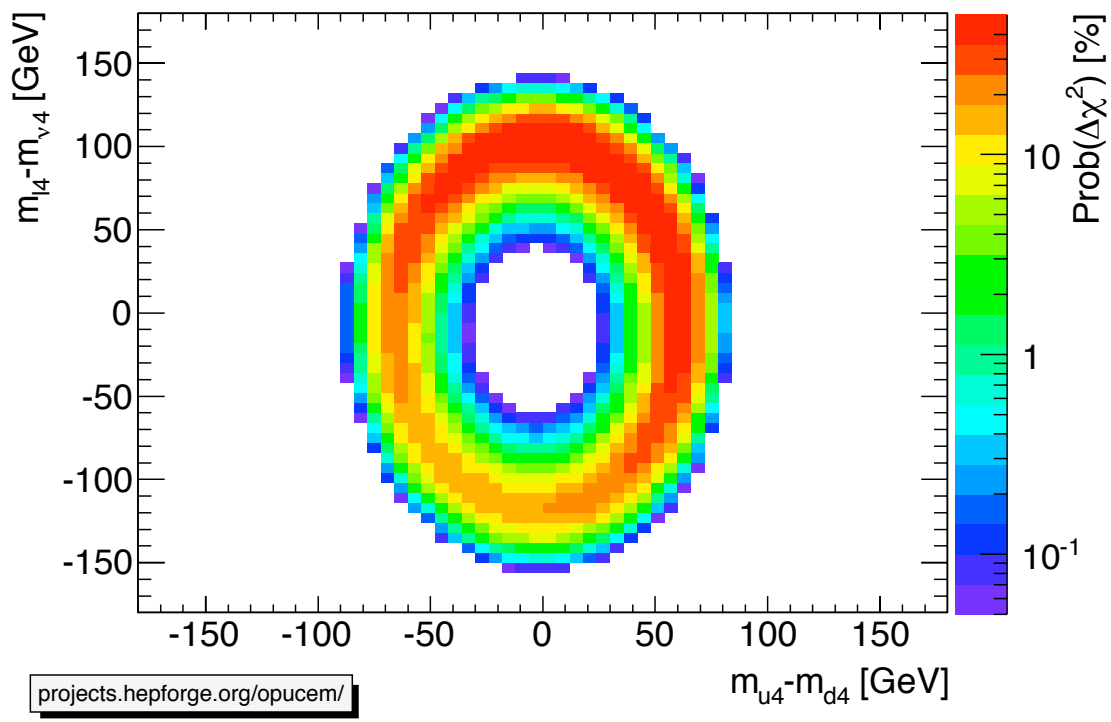
1. 4th generation quarks (Q)
2. Heavy neutrinos (N)
3. Heavy vector bosons (Z′)

4th generation

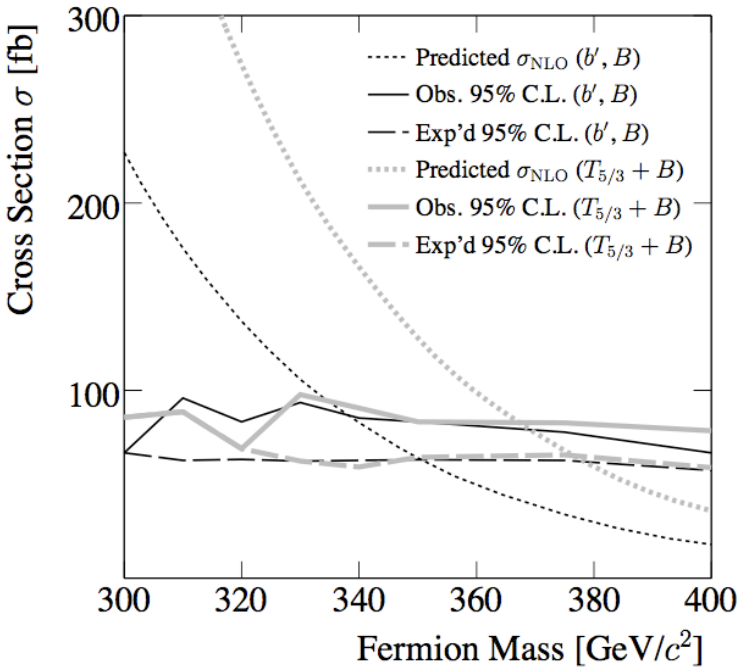
PDG says it's
ruled out to 6σ....

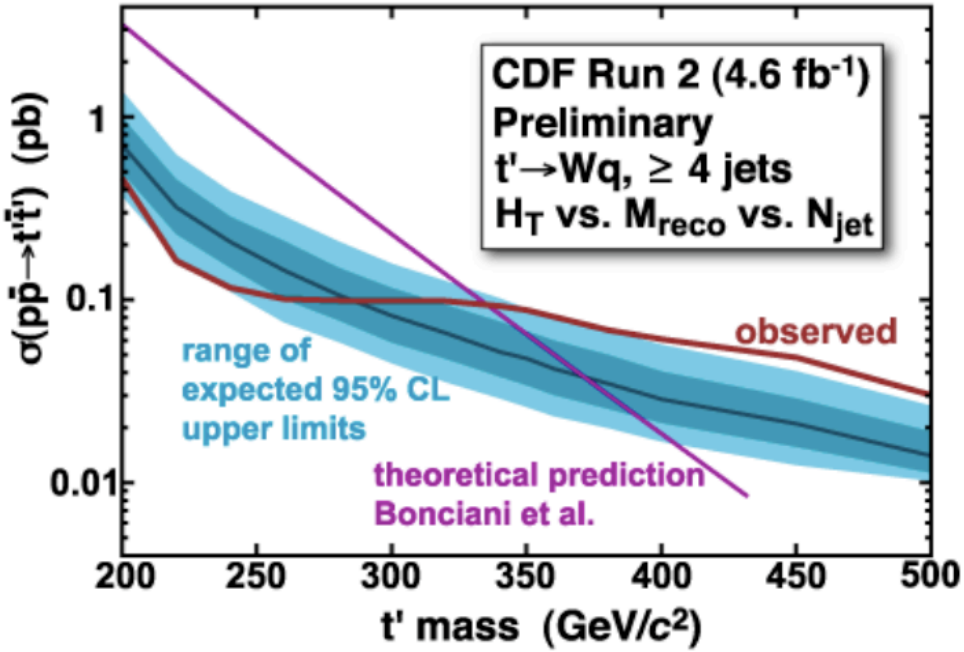
..that's true if the
masses are degenerate





Direct searches

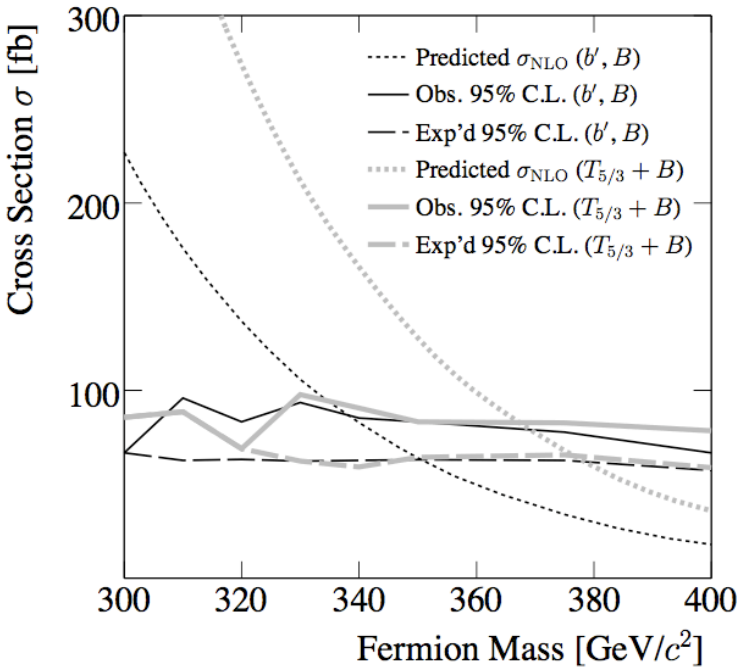


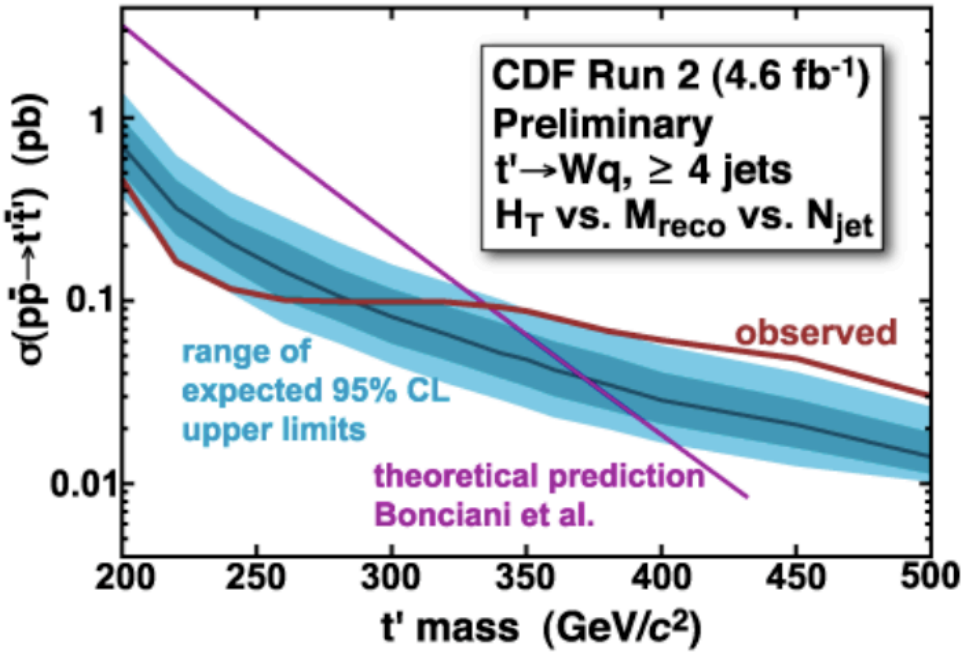


$m_{b'}$ > 338 GeV

$m_{t'}$ > 335 GeV

Direct searches





$m_{b'}$ > 338 GeV

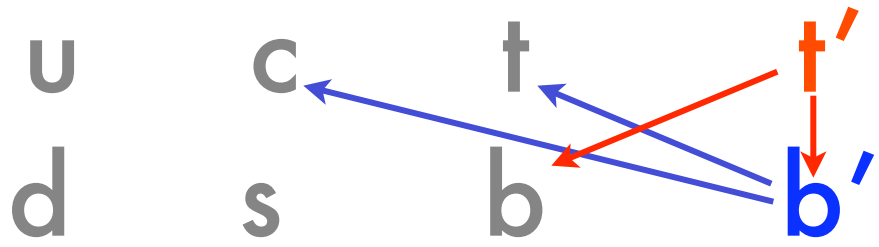
If BR(b′ →Wt)=100%

$m_{t'}$ > 335 GeV

If BR(t′ →Wq)=100%

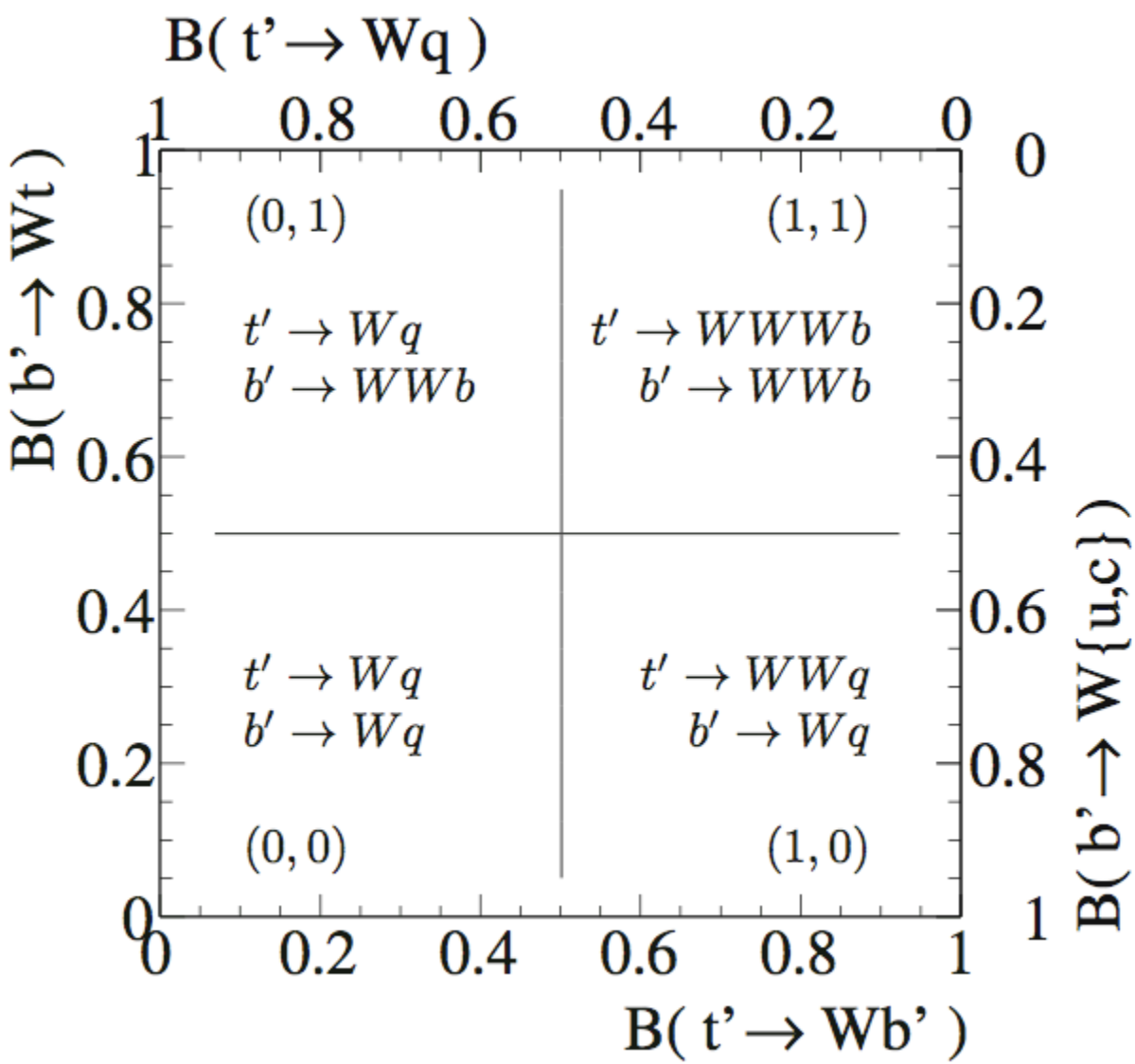
Modes

<u>If $m_{t'} > m_{b'}$</u>

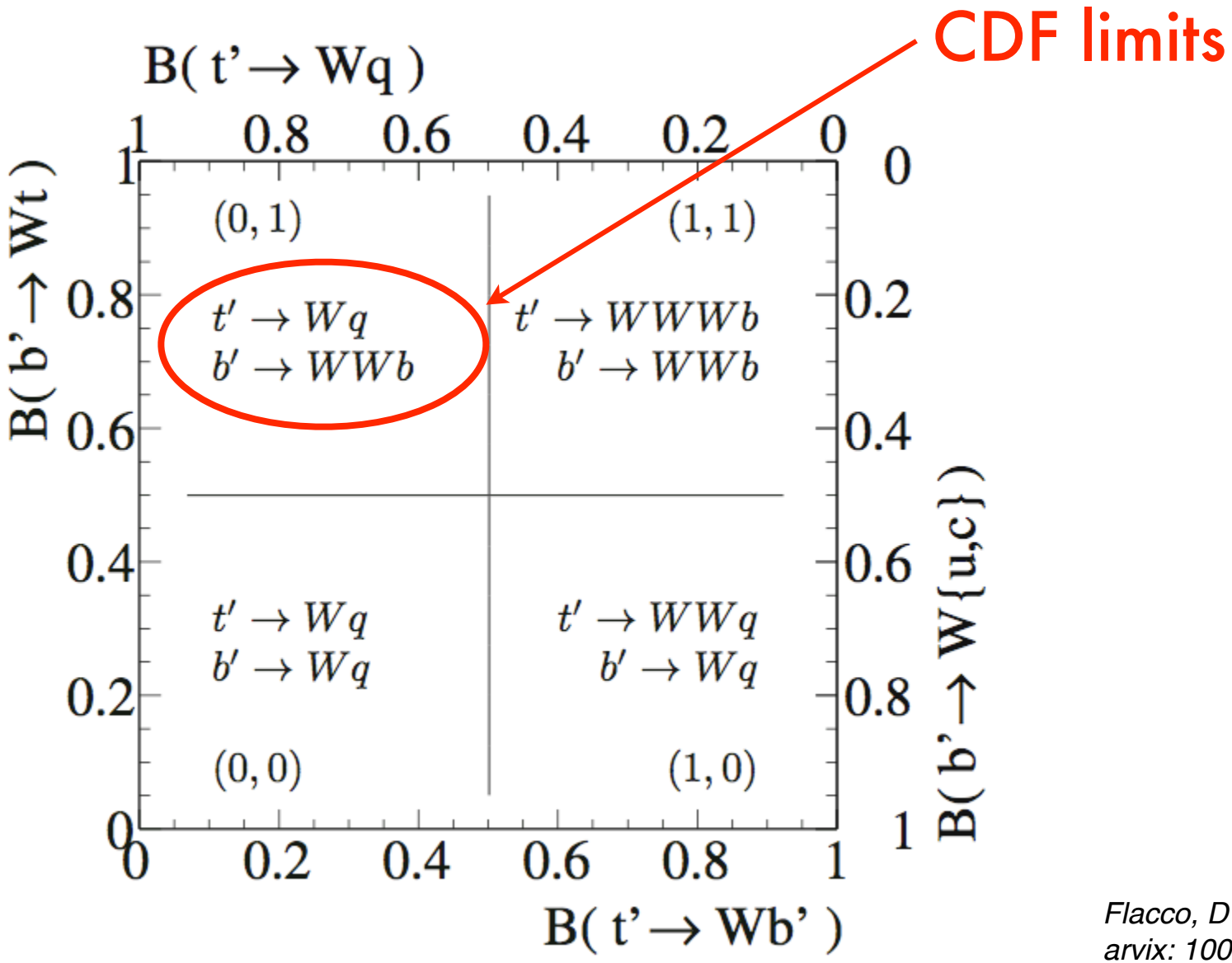


BR space

Flacco, DW, Bar-Shalom & Tait
arvix: 1005.1077

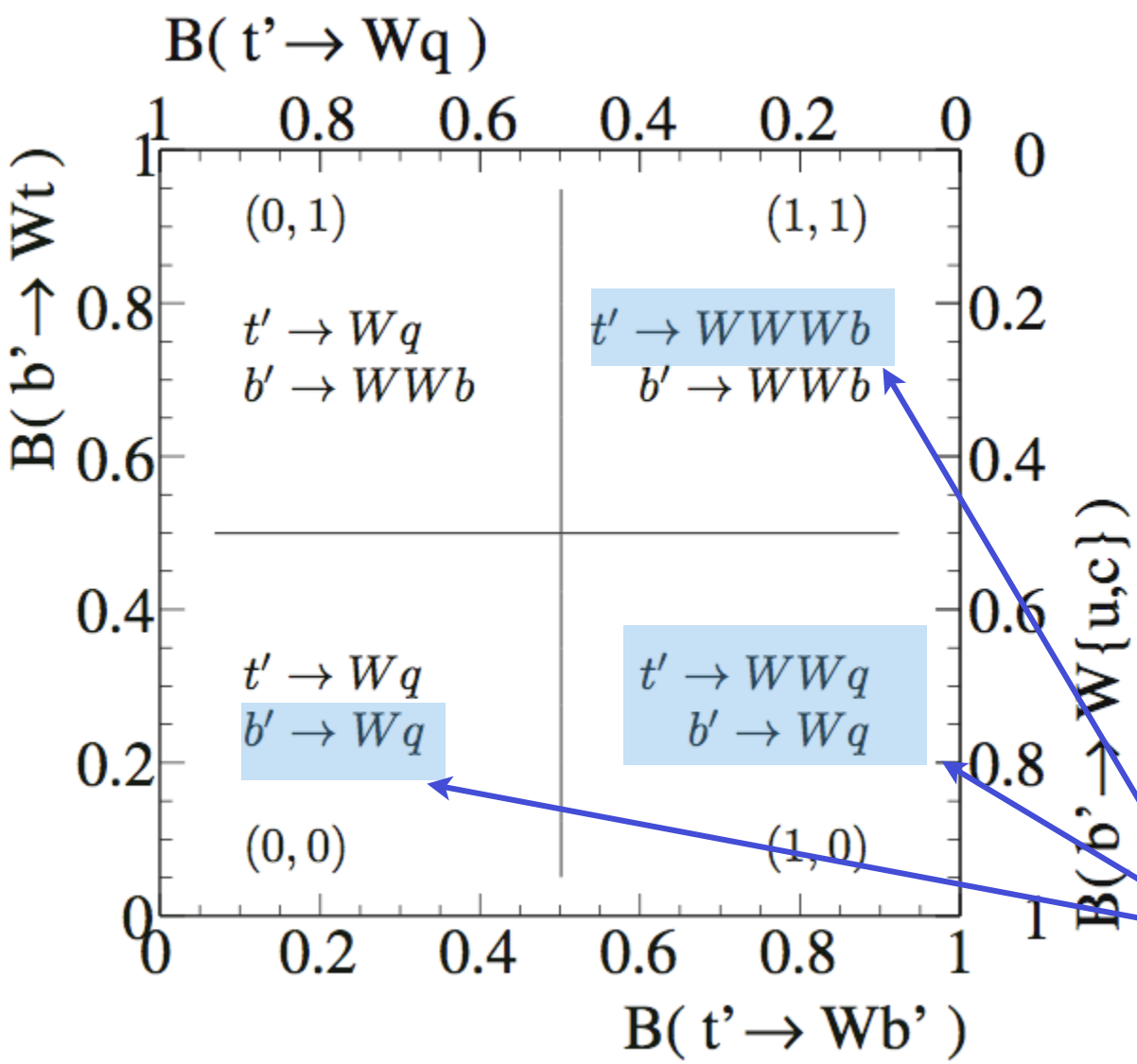


BR space



Flacco, DW, Bar-Shalom & Tait
arvix: 1005.1077

BR space



No direct limits!

Flacco, DW, Bar-Shalom & Tait
arvix: 1005.1077

t′ and b′

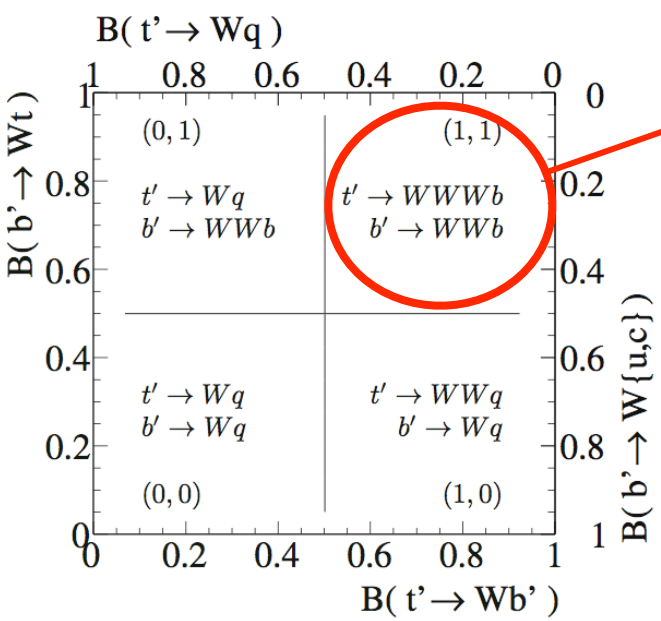
b′ only

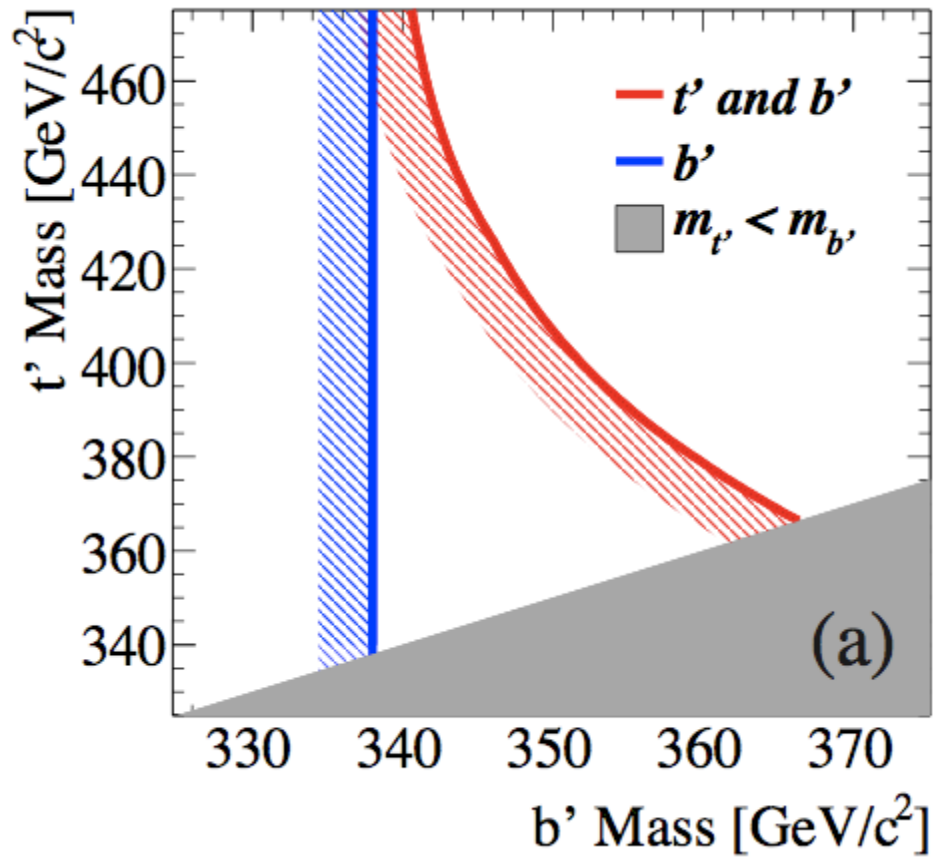
$m_{b'}$ > 335 GeV

b′+t′

$m_{b'}$ > 335-370 GeV

$m_{t'}$ > 360 GeV

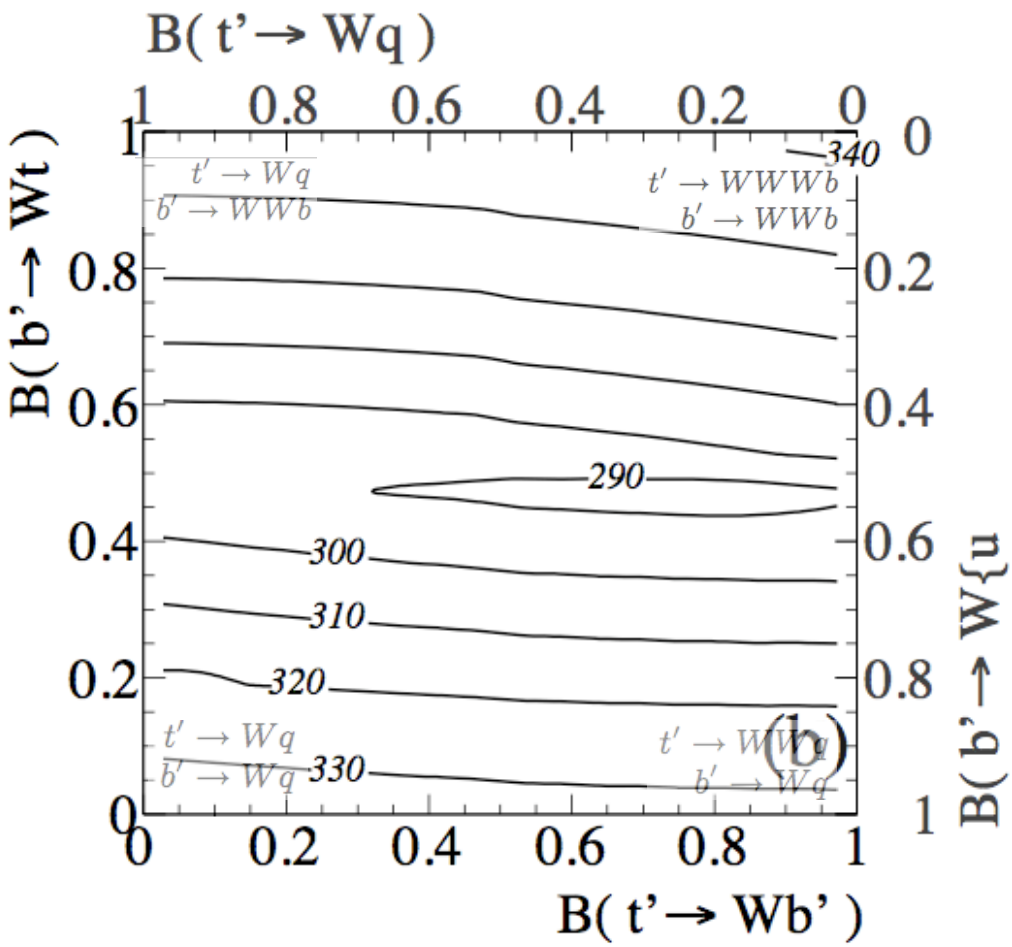


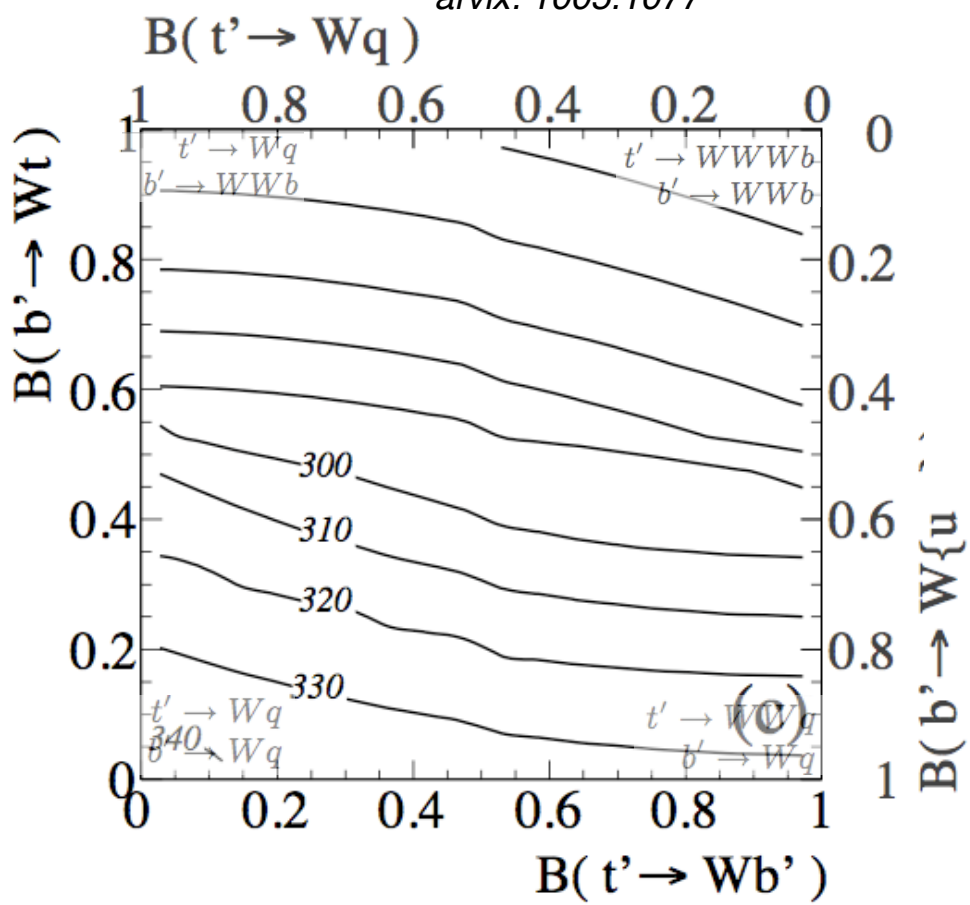


Flacco, DW, Bar-Shalom & Tait
arvix: 1005.1077

Generalized limits

Flacco, DW, Bar-Shalom & Tait
arvix: 1005.1077

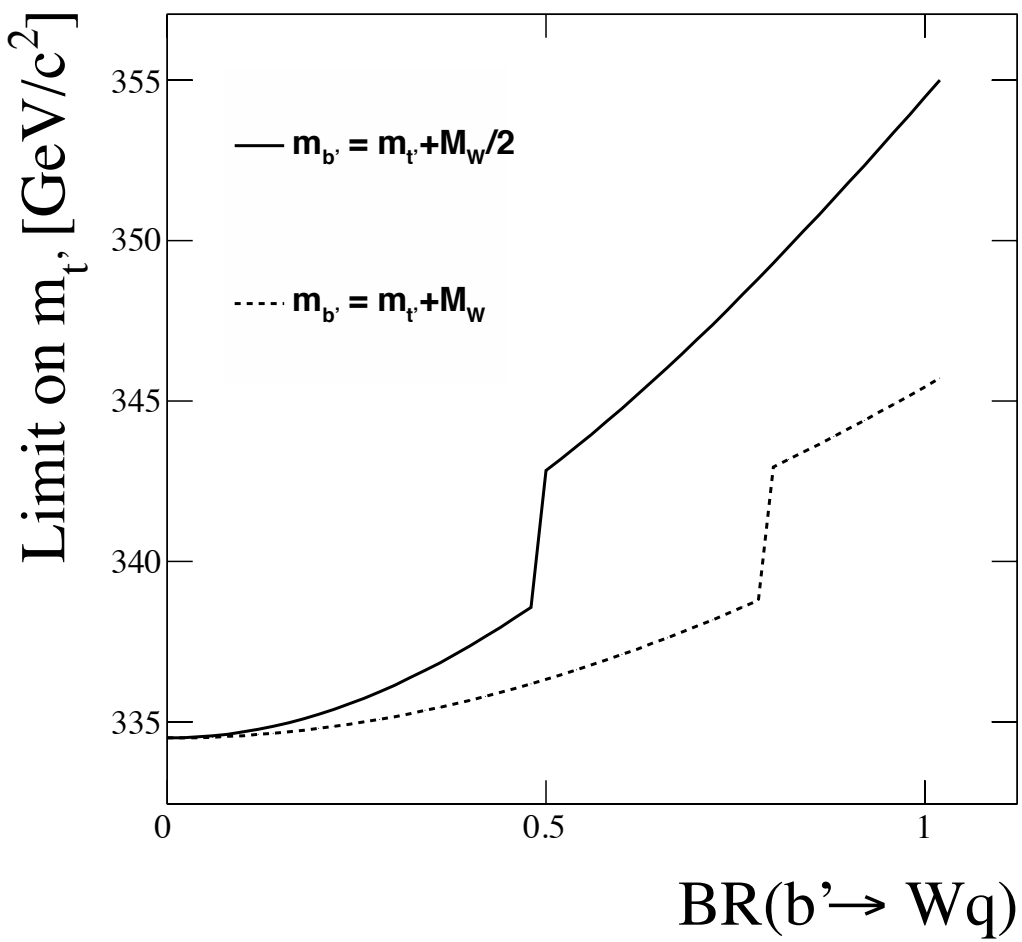




$m_{t'} = m_{b'} + 100$

$m_{t'} = m_{b'} + 50$

b′ heavier than t′?



l+4jets t′→4j search provides strong limits on t′ mass, imply strong limits on b′ if $m_{b'} > m_{t'}$, stronger than limits from WWb data.

Flacco, DW, Bar-Shalom & Tait
arvix: 1005.1077

General Limits

$$m_{Q'} > 290 \text{ GeV}$$

Flacco, DW, Bar-Shalom & Tait
arvix: 1005.1077

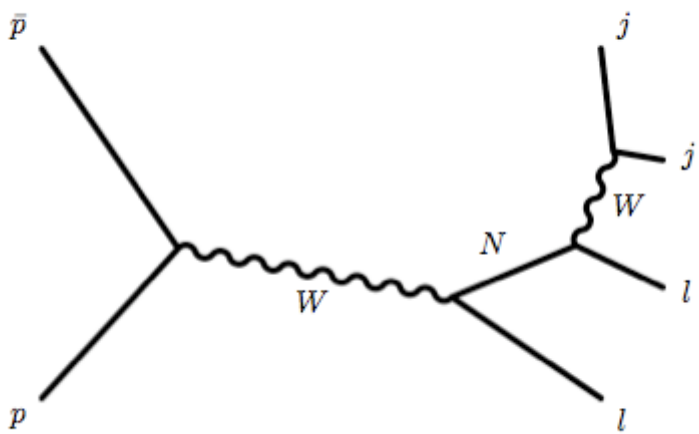
In progress: map to CKM space, apply constraints from other measurements

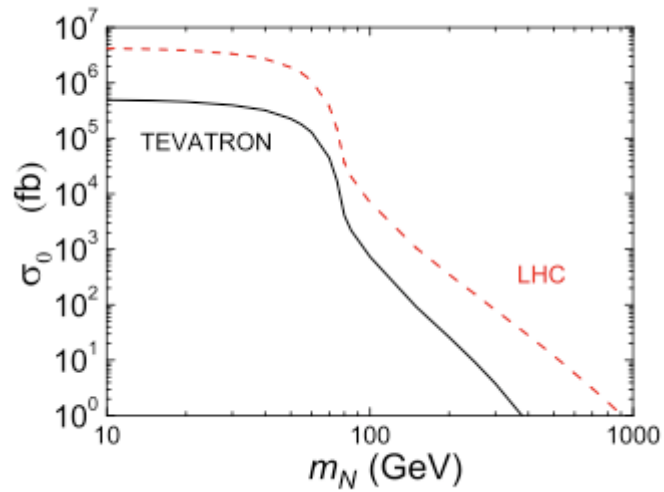
Outline

1. 4th generation quarks (Q)
2. Heavy neutrinos (N)
3. Heavy vector bosons (Z′)

Majorana neutrinos

Production via W has been studied





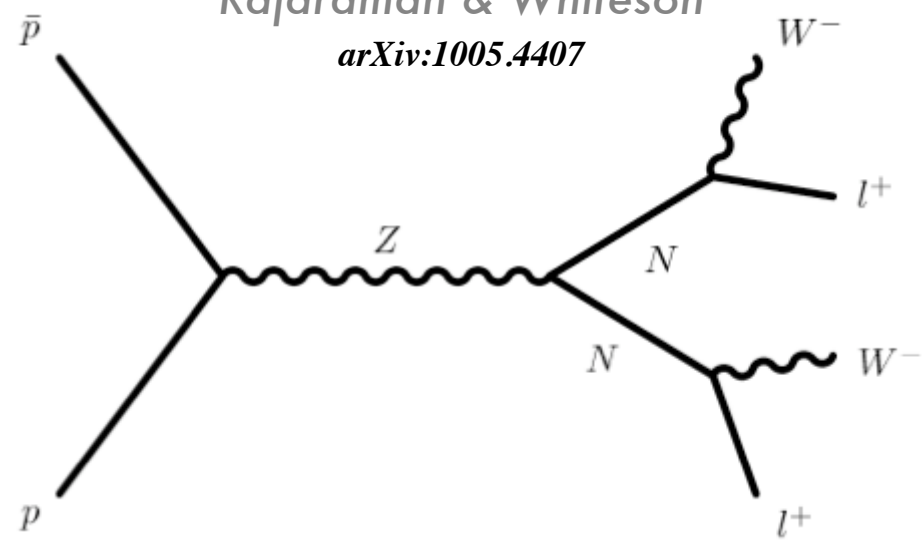
hep-ph/0604064

LEP limits at 90 GeV

4th gen neutrinos

Rajaraman & Whiteson

arXiv:1005.4407



Production via Z

avoids *WlN* vertex in production mechanism

Two mass eigenstates

$$L_m = -\frac{1}{2}\overline{(Q_R^c N_R^c)} \begin{pmatrix} 0 & m_D \\ m_d & M \end{pmatrix} \begin{pmatrix} Q_R \\ N_R \end{pmatrix} + h.c.$$

$$\cos^2\theta = \frac{M_2}{M_2 + M_1}$$

$$pp \to Z \to N_1 N_1 \to lWlW$$

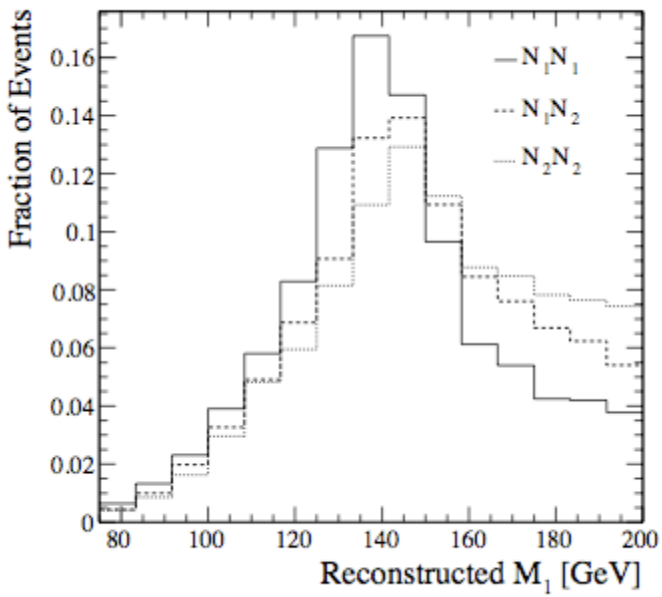
$$pp \to Z \to N_1 N_2 \to lWlWZ$$

$$pp \to Z \to N_2 N_2 \to lWlWZZ$$

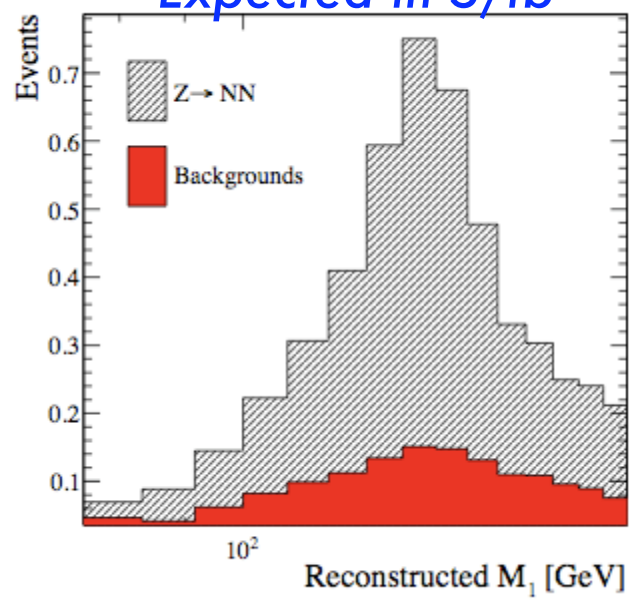
Reconstruction

Rajaraman & Whiteson
arXiv:1005.4407

Selection: two same-sign leptons
at least two jets



Expected in 5/fb

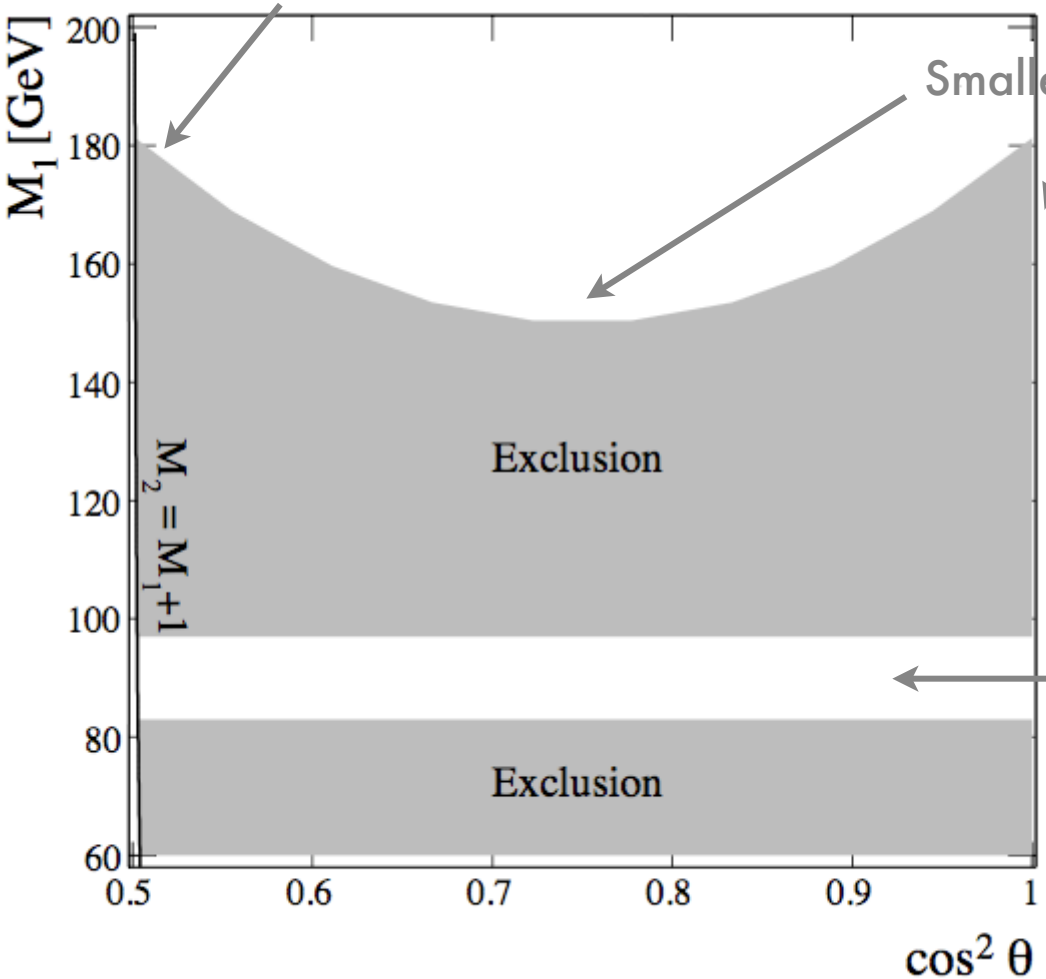


Backgrounds: normalized from 1/fb CDF paper
shapes using fast simulation

Expected exclusion

Smaller θ means smaller N_2 mass (Dirac limit)

Smaller θ means smaller coupling to Z



cosθ =1 means N_2 very massive (Majorana limit)

Leptons from N→lW get too soft

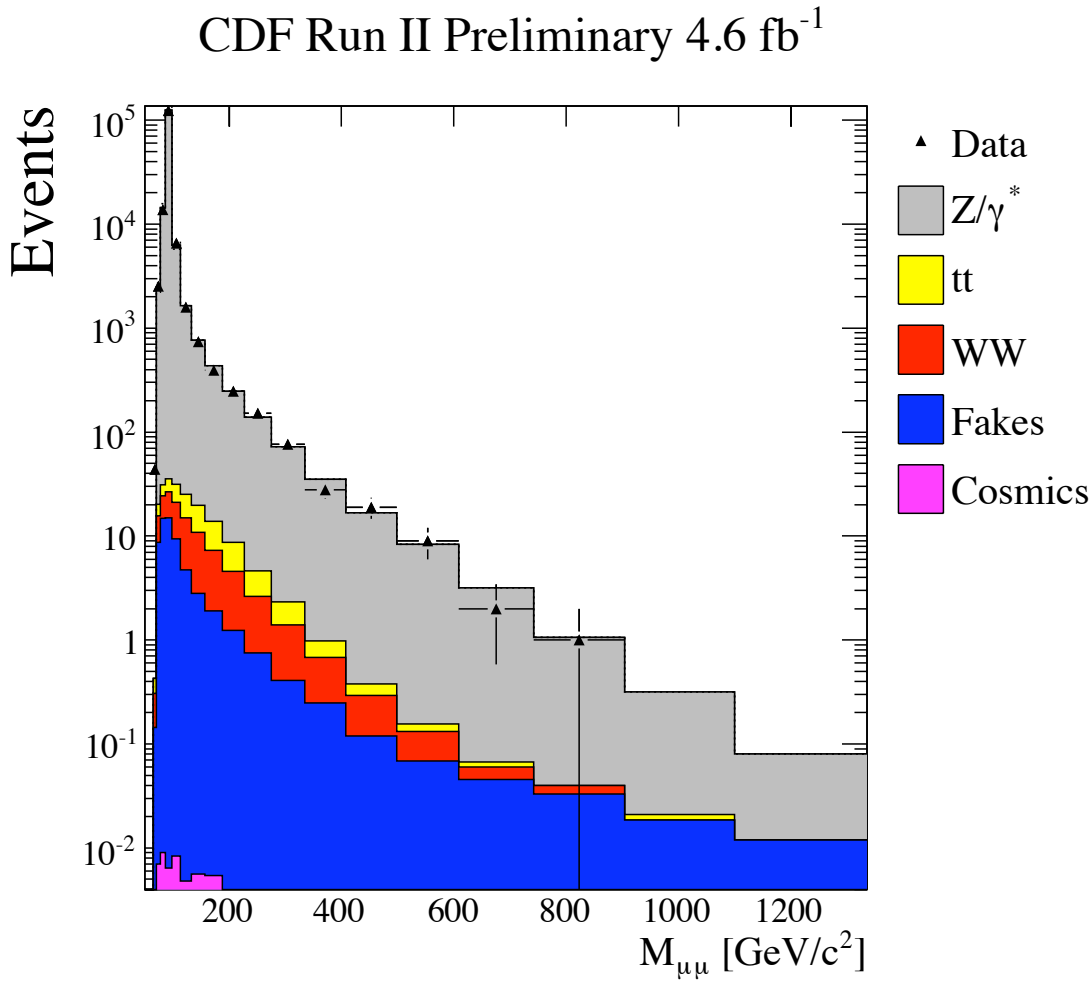
Rajaraman & Whiteson

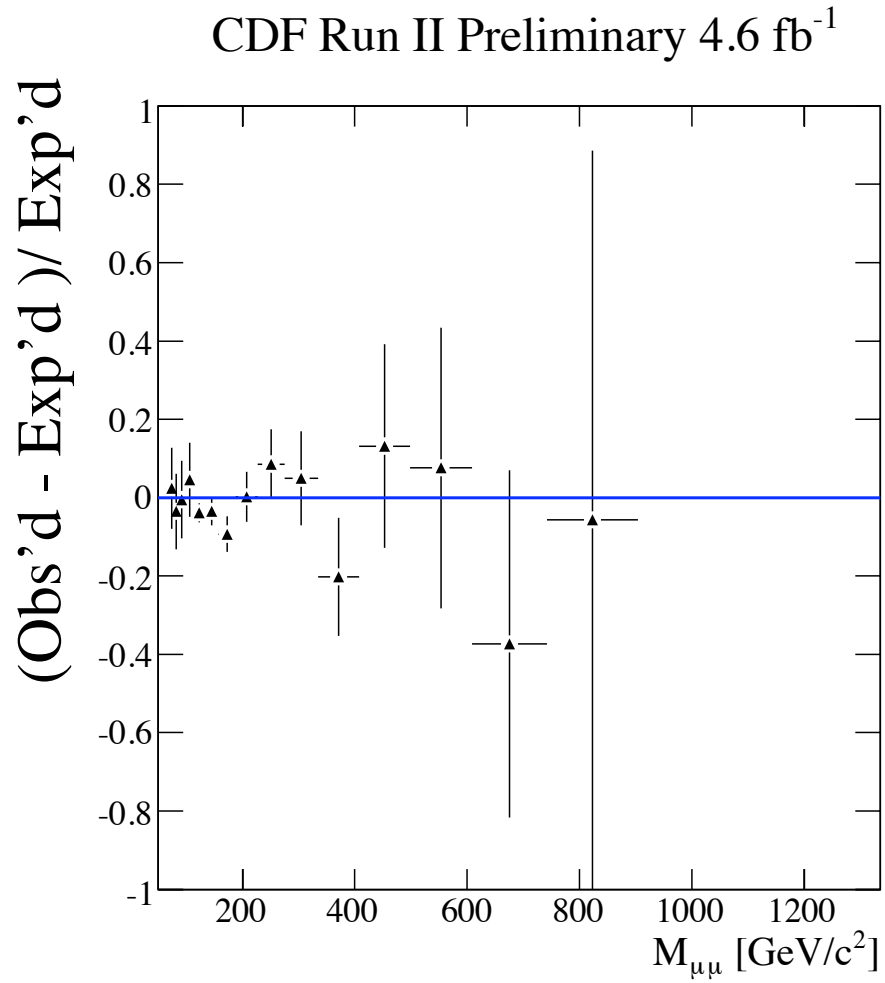
arXiv:1005.4407

Outline

1. 4th generation quarks (Q)
2. Heavy neutrinos (N)
3. Heavy vector bosons (Z′)

Z′ to muons

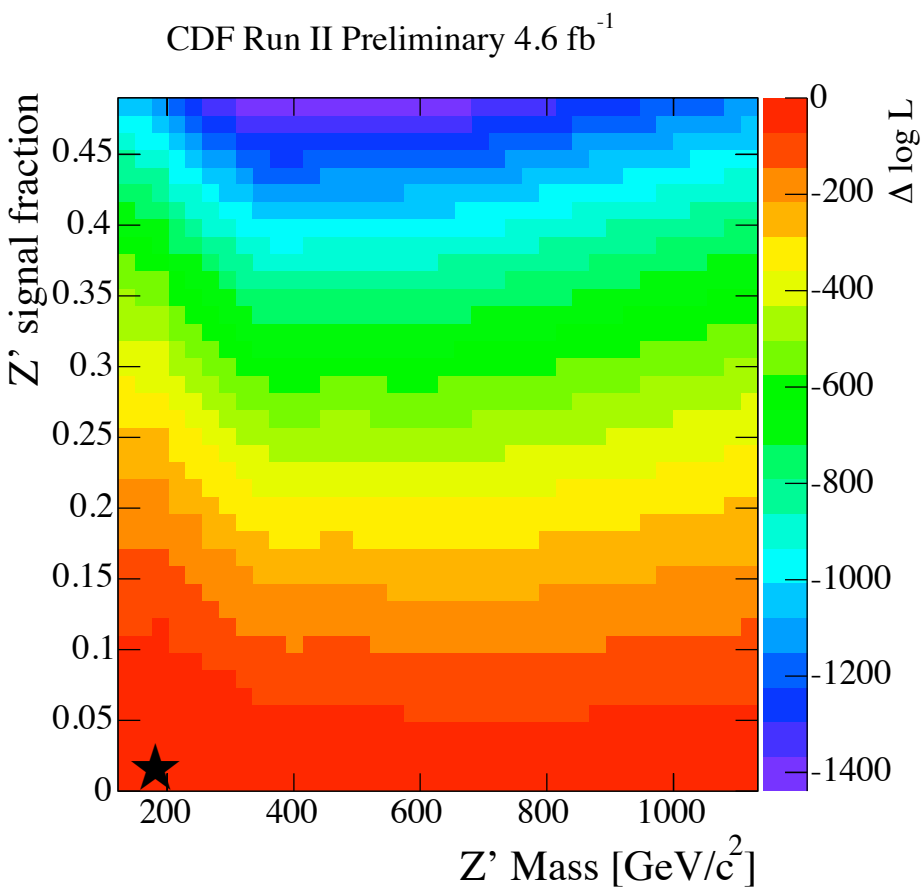

CDF Run II Preliminary 4.6 fb^{-1}
Events
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
200
400
600
800
1000
1200
$M_{\mu\mu}$ [GeV/c^2]
Data
Z/γ^*
tt
WW
Fakes
Cosmics

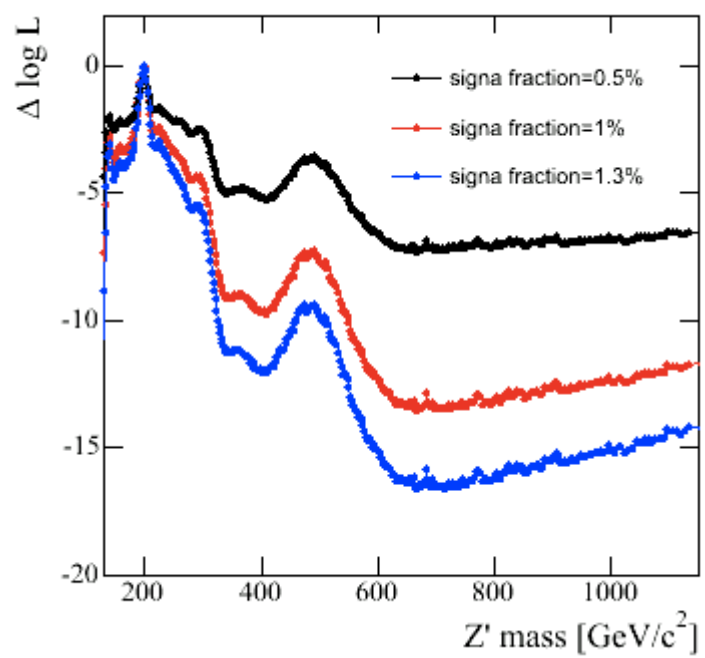

CDF Run II Preliminary 4.6 fb^{-1}
(Obs'd - Exp'd)/ Exp'd
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
200
400
600
800
1000
1200
$M_{\mu\mu}$ [GeV/c^2]

Analysis

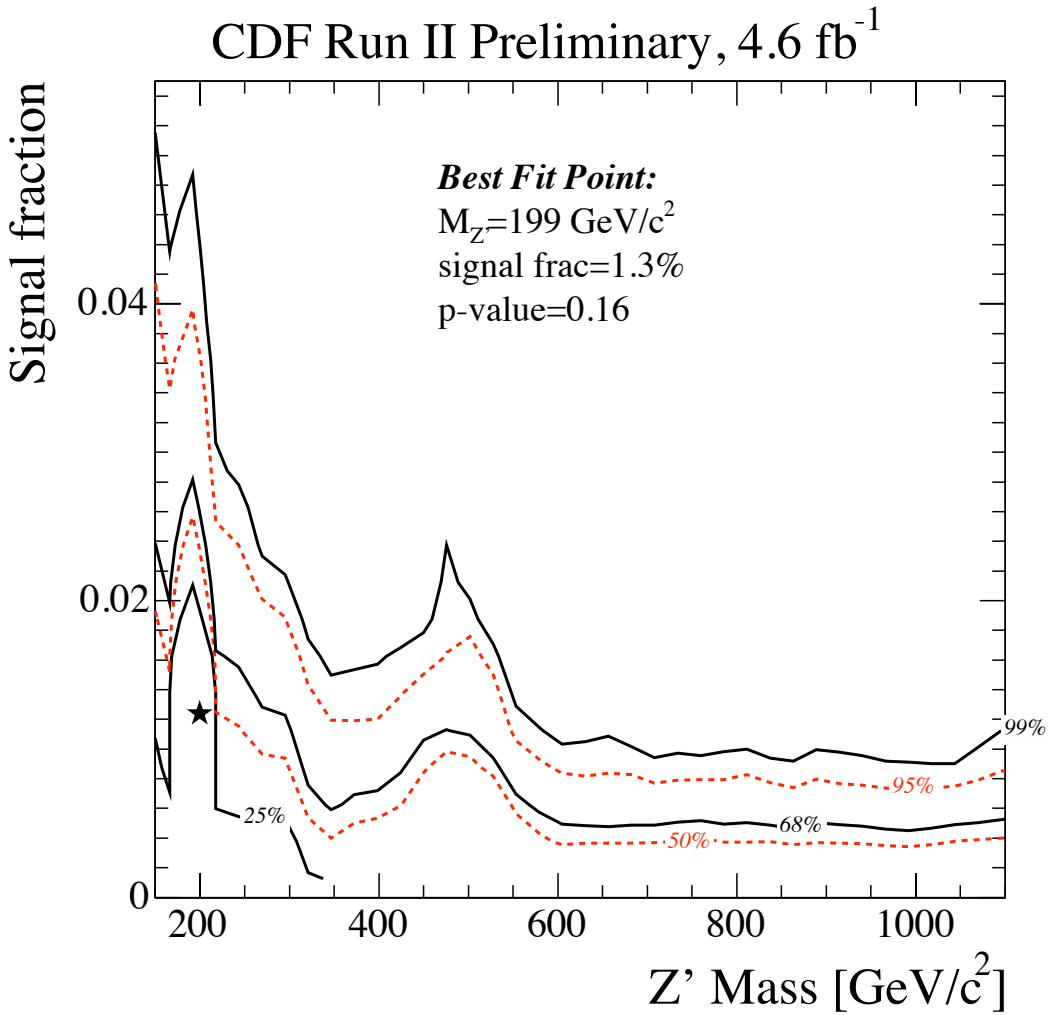
$$P_{Z'}(x_i|M_{Z'}) = \int dq_1 dq_2 |\mathcal{M}_{Z'}(M_{Z'})|^2$$

$$\times f_{PDF}(x_p) f_{PDF}(x_{\bar{p}}) T(p_1, q_1) T(p_2, q_2) P_{PT}(q_1 + q_2, N_{jets})$$

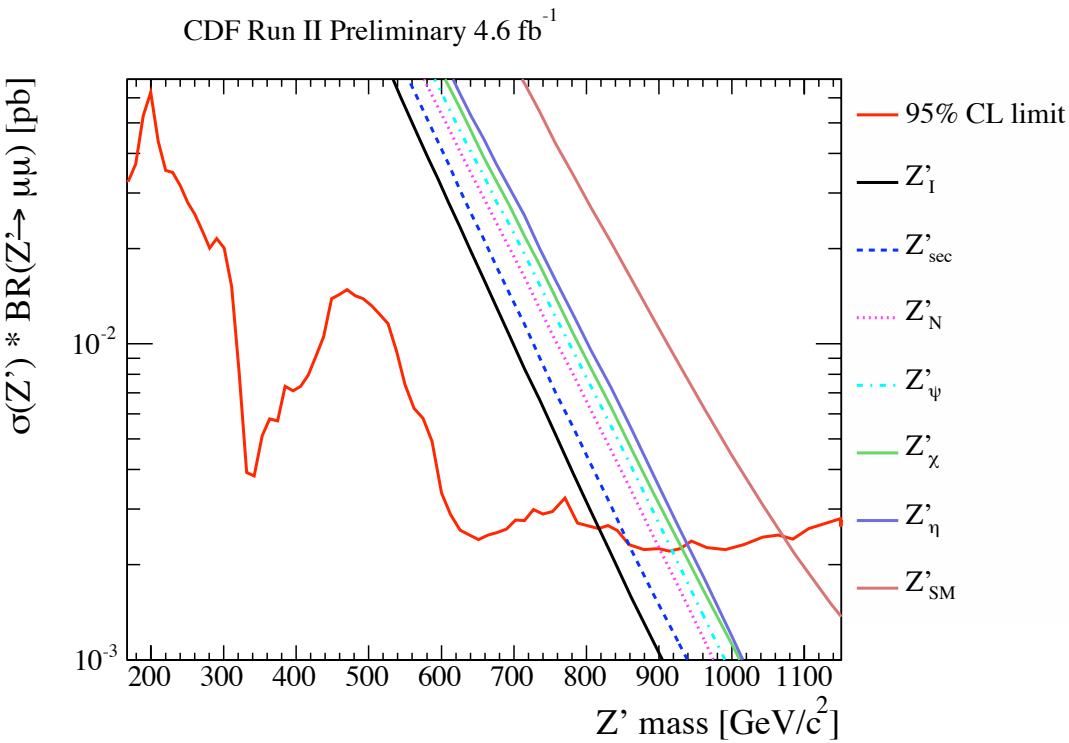




Scan


CDF Run II Preliminary, 4.6 fb^{-1}
Signal fraction
Best Fit Point:
M_Z=199 GeV/c^2
signal frac=1.3%
p-value=0.16
0.04
0.02
0
200
400
600
800
1000
Z' Mass [GeV/c^2]
99%
95%
68%
50%
25%

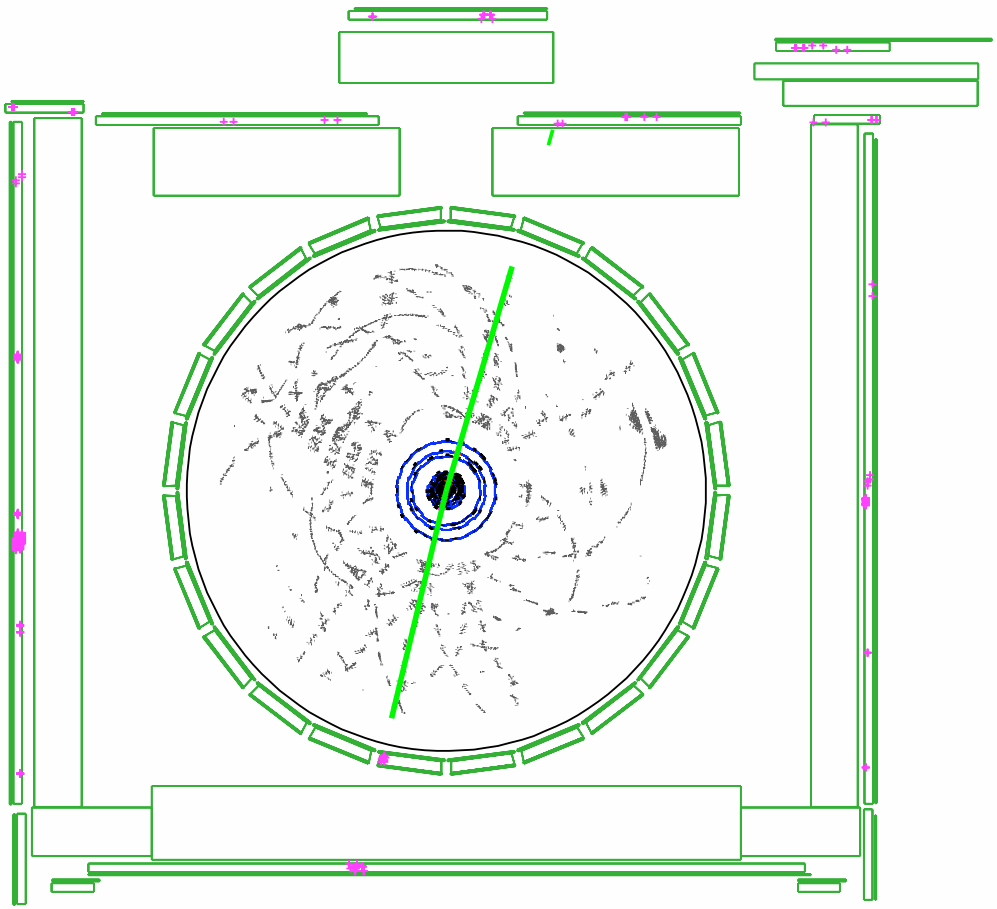
Limits

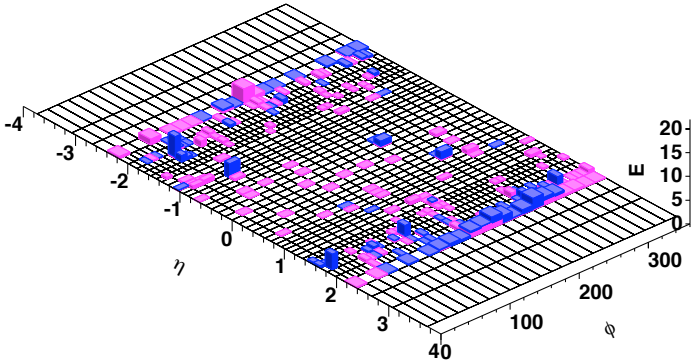


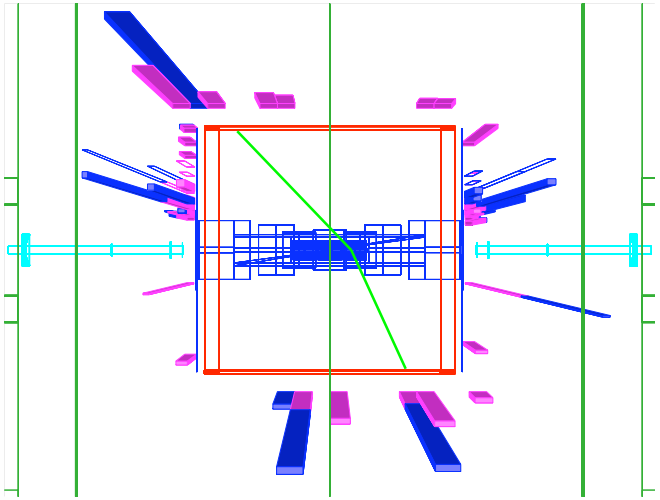
Model	Mass Limit (GeV/c^2)
Z'_I	817
Z'_{sec}	858
Z'_N	900
Z'_ψ	917
Z'_χ	930
Z'_η	938
Z'_{SM}	1071

M_{ll} = 882 GeV

CDF Run II Preliminary







Summary

Searching for SM extensions

From CDF 5/fb of data

$m_Q > 290$ GeV

$m_{Z'} > 1071$ GeV

CDF 5/fb dataset could say:

$m_N > \sim 175$ GeV *(expected)*

.....or discovery! 1/fb saw excess