“Beyond 3 Gen Standard Model”

2nd Workshop – NTU, Taiwan, Jan 14-16 2010

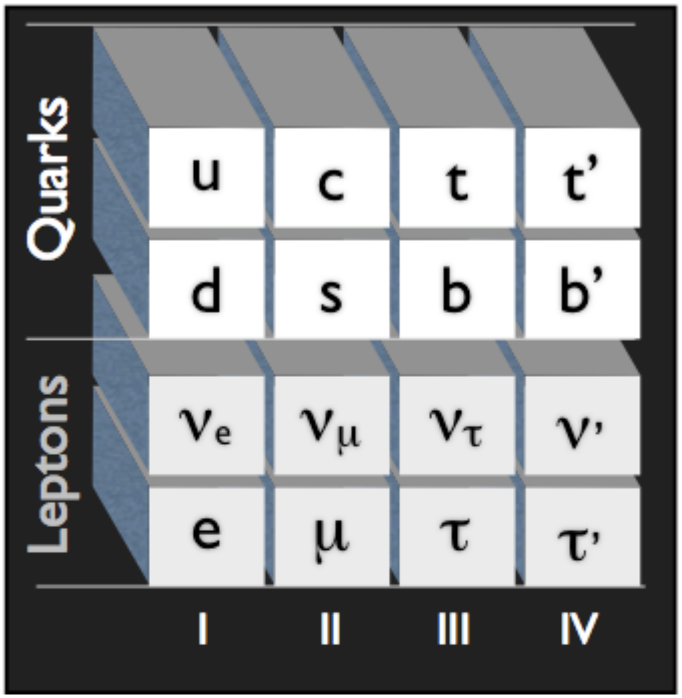
Full agenda:
http://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=68036

Daniel Whiteson, UC Irvine

Outline

- Introduction/Motivation
- Constraints
  - *Electroweak constraints*
  - *Mixing constraints*
  - *Heirarchy problem*
  - *Strong coupling/dynamics*
- Searches
  - *Tevatron Direct Searches*
    - *Followup: updated t′ result*
    - *Followup: limits as function of BRs*
  - *Tevatron Indirect Searches*
  - *LHC prospects*
- Dark Matter connections
- Clues from meson mixing?

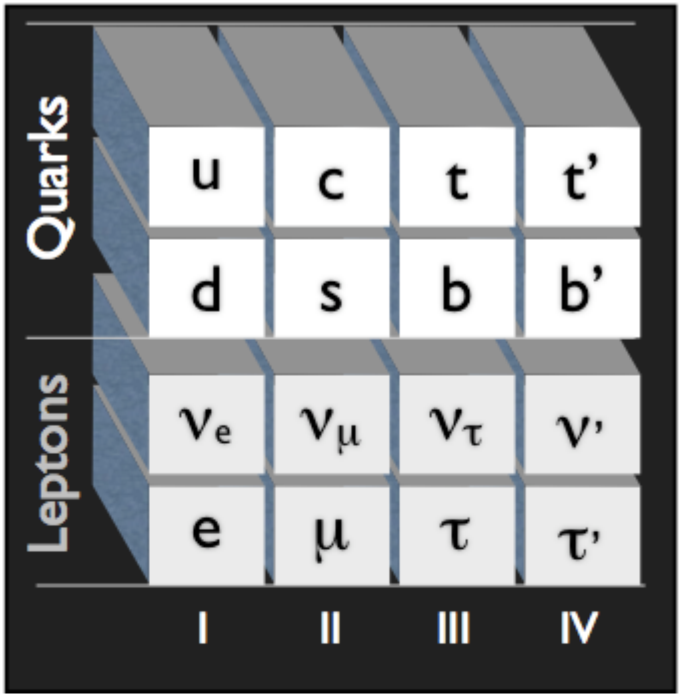
Motivation



4th generation

A Natural SM extension.

Motivation



4th generation

A Natural SM extension.

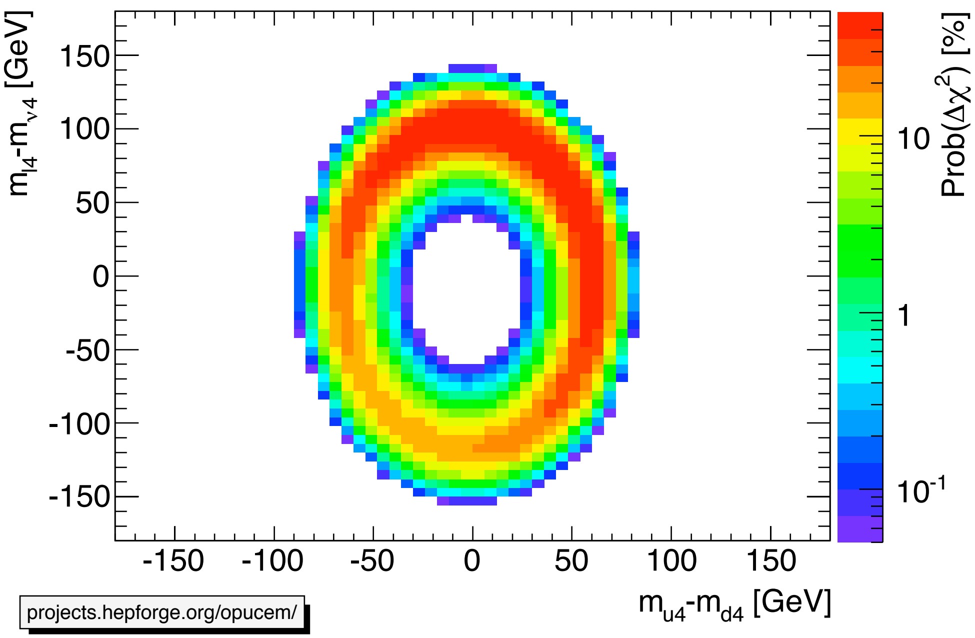
Note

PDG says it's ruled out
to 6 sigma....

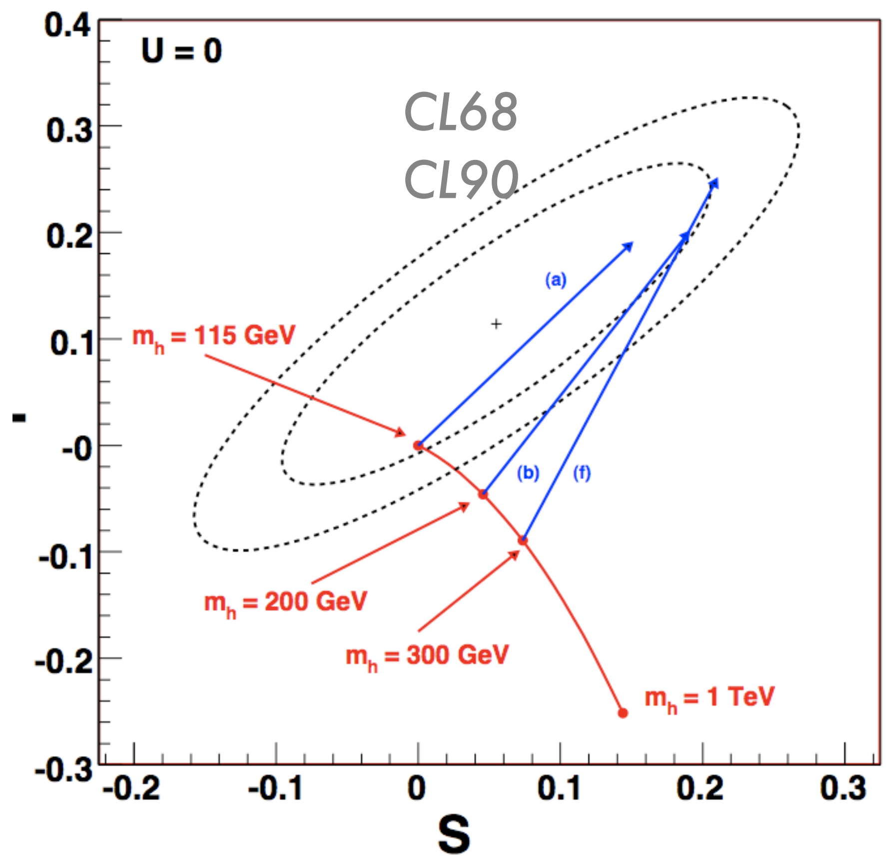
... assuming degenerate masses

Electroweak Constraints

Erkcan showed a general tool for EW oblique parameters.



4th gen allows heavier higgs to be consistent with EW precision



CKM mixing constraints

$$V_{CKM4} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{ub'} \\ V_{cd} & V_{cs} & V_{cb} & V_{cb'} \\ V_{td} & V_{ts} & V_{tb} & V_{tb'} \\ V_{t'd} & V_{t's} & V_{t'b} & V_{t'b'} \end{pmatrix}$$

V_{ud}	$=$	0.97418	$\pm$	0.00027	Nuclear Beta decay
V_{us}	$=$	0.2255	$\pm$	0.0019	Semileptonic K-decay
V_{ub}	$=$	0.00393	$\pm$	0.00036	Semileptonic B-decay
V_{cd}	$=$	0.230	$\pm$	0.011	Semileptonic D-decay
V_{cs}	$=$	1.04	$\pm$	0.06	Semi- /Leptonic D-decay
V_{cb}	$=$	0.0412	$\pm$	0.0011	Semileptonic B-decay
V_{tb}	$>$	0.74			Single Top-production

Lenz

CKM mixing constraints

$$V_{CKM4} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{ub'} \\ V_{cd} & V_{cs} & V_{cb} & V_{cb'} \\ V_{td} & V_{ts} & V_{tb} & V_{tb'} \\ V_{t'd} & V_{t's} & V_{t'b} & V_{t'b'} \end{pmatrix}$$

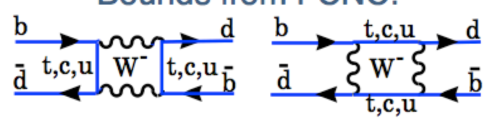
$$\begin{aligned}
|V_{ub'}|^2 &= 0.0001 \pm 0.0014 \\
&\Rightarrow \text{Error: } 0.037 \approx 0.74 \cdot \lambda^2 \approx 3.3 \cdot \lambda^3 \\
|V_{td}|^2 + |V_{t'd}|^2 &= -0.0020 \pm 0.0055 \\
&\Rightarrow \text{Error: } 0.074 \propto 1.5 \cdot \lambda^2 \\
|V_{ts}|^2 + |V_{t's}|^2 &= -0.13 \pm 0.13 \\
&\Rightarrow \text{Error: } 0.36 \approx 1.6 \cdot \lambda^1 \\
|V_{cb'}|^2 &= -0.14 \pm 0.18 \\
&\Rightarrow \text{Error: } 0.42 \approx 1.9 \cdot \lambda^1 \\
|V_{t'b}|^2 &< 0.45 \\
&\Rightarrow |V_{t'b}| < 0.67 = 0.67 \cdot \lambda^0
\end{aligned}$$

Lenz

CKM mixing constraints

$$V_{CKM4} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{ub'} \\ V_{cd} & V_{cs} & V_{cb} & V_{cb'} \\ V_{td} & V_{ts} & V_{tb} & V_{tb'} \\ V_{t'd} & V_{t's} & V_{t'b} & V_{t'b'} \end{pmatrix}$$

Bounds from FCNC:



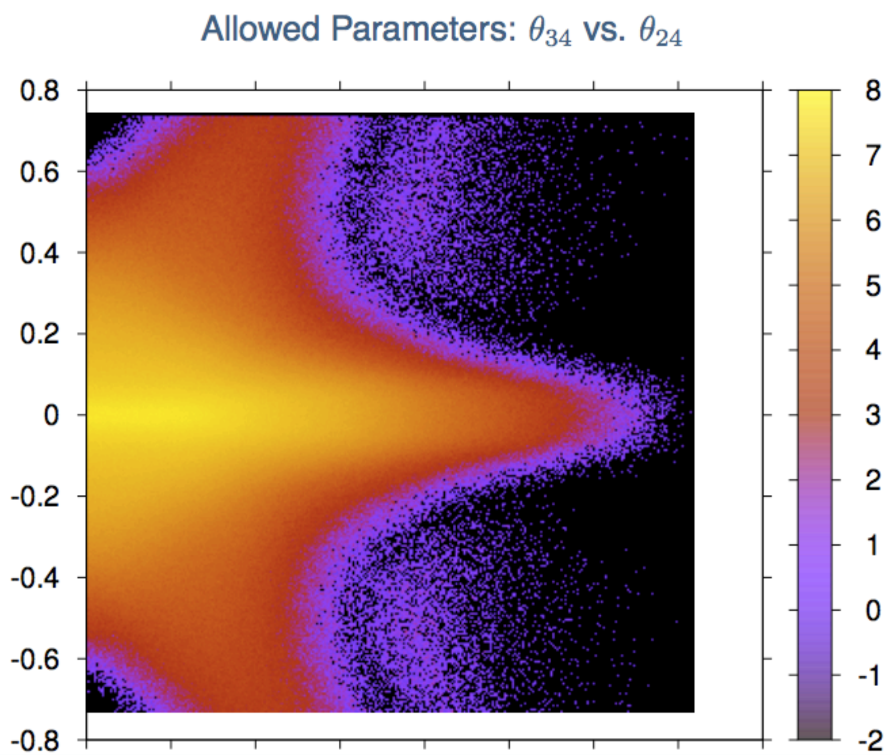
$$\Delta_X := \frac{X_{SM4}}{X_{SM3}}$$

- K-Mixing: $Re(\Delta_K) = 1 \pm 0.5\,(0.25)$ $\quad Im(\Delta_K) = 0 \pm 0.3\,(0.15)$
- B_d-Mixing: $|\Delta_{B_d}| = 1 \pm 0.3\,(0.1)$ $\quad Arg(\Delta_{B_d}) = 0 \pm 10^\circ\,(5^\circ)$
- B_s-Mixing: $|\Delta_{B_s}| = 1 \pm 0.3\,(0.1)$ $\quad Arg(\Delta_{B_s}) =$ free
- $b \to s\gamma$ $\quad \Delta_{b \to s\gamma} = 1 \pm 0.15\,(0.07)$

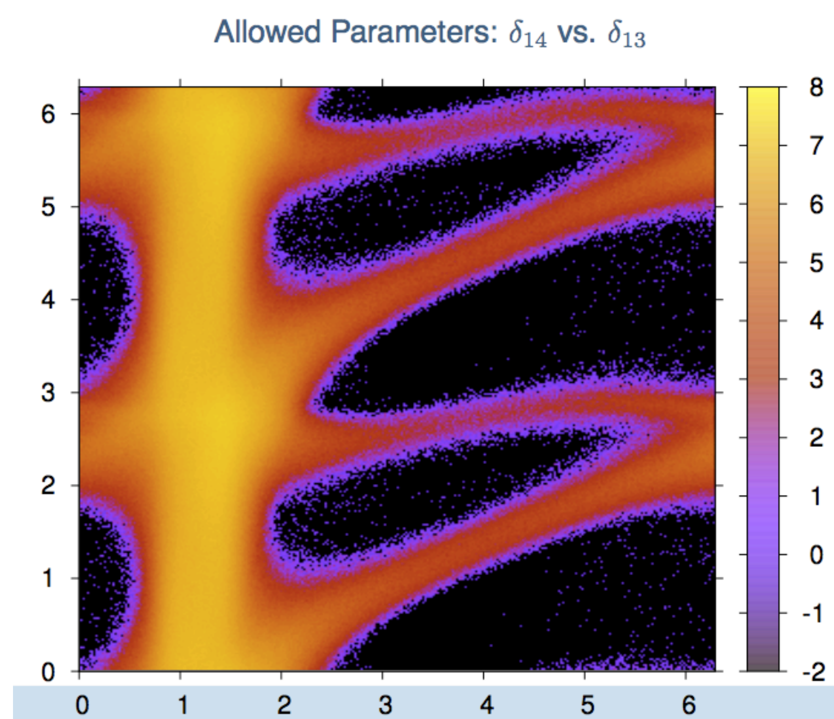
Lenz

CKM constraints

Angles



CP-violating phases



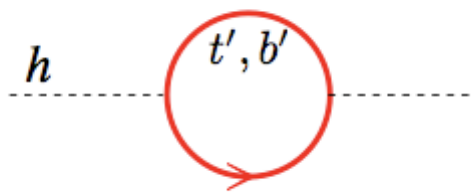
Combined CKM+EW constraints underway

Lenz

Heirarchy Problem

If 4th family is fairly light (200-300 GeV)

Then can co-exist with Higgs, but doesn't make heirarchy problem any easier.



(for simplest Higgs sector with one scalar. See Bar-Shalom's talk on composite Higgs & the 4th gen)

(Unless we make other modifications. See PQ Hung talk on a fixed point....)

Strong dynamics

If 4th family is fairly heavy their yukawa couplings get very large, and there may be new strong dynamics.

Good:
No need for a Higgs, replaced by fermion condensate

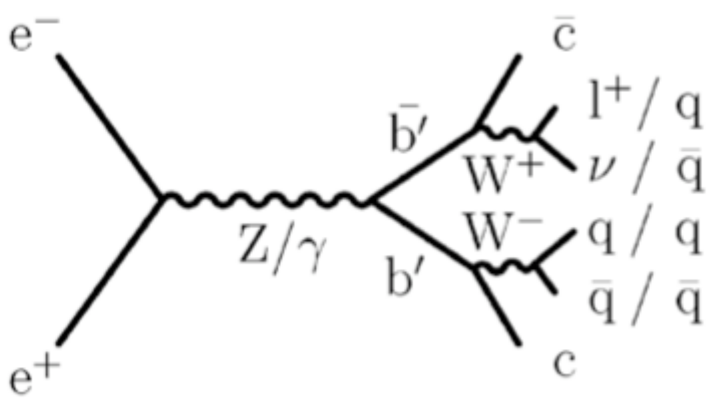
Bad: If they're very heavy (>600 GeV) then can't use perturbative calculations, worry about partial wave unitarity.

Direct Searches

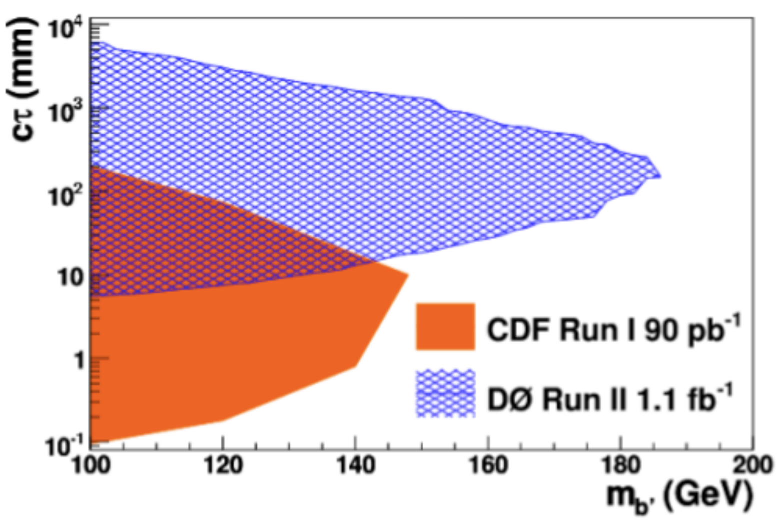
"It ain't murder until you've found the body..."

Direct b′ limits: low mass

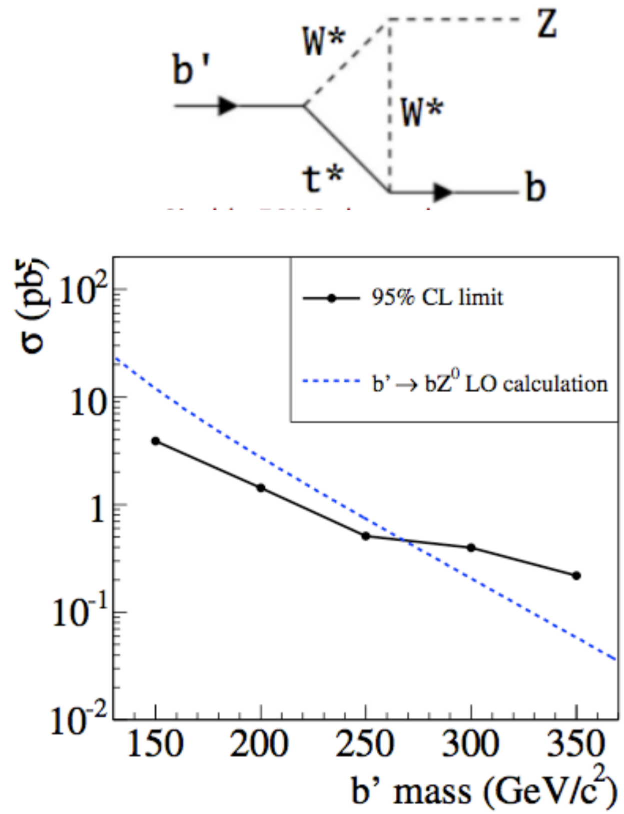
LEP: $m_{b'}$ > ~90 GeV



CDF/D0: long lived b′



CDF: $m_{b'}$ > ~255 GeV



CDF b′ search

<u>Selection</u>

2 like-signed leptons

pt>20 GeV

at least one isolated

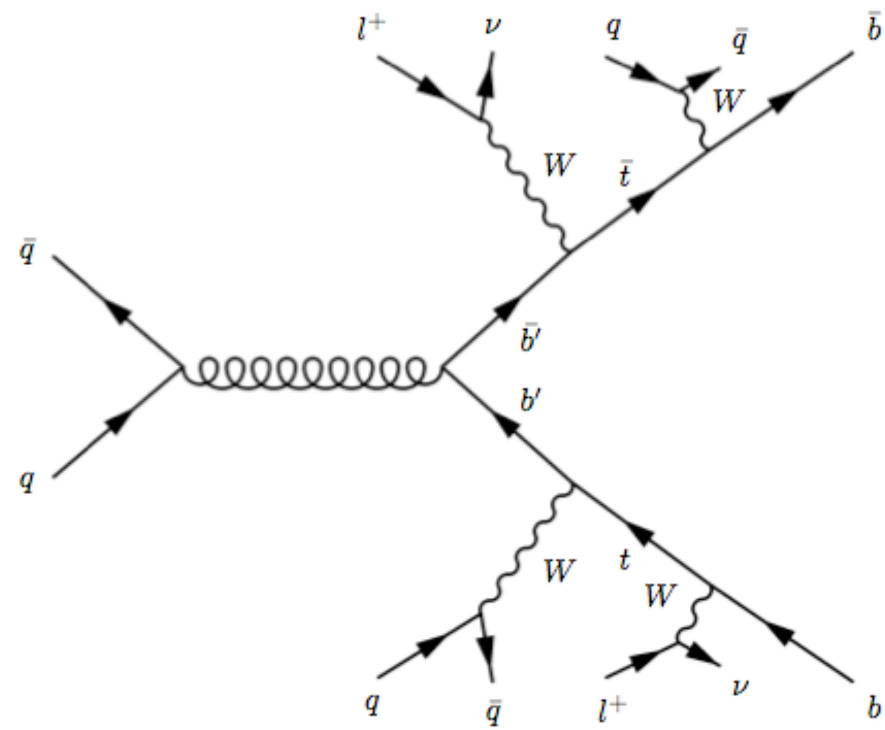
2 jets

pt>20 GeV

>=1 btags

Missing transverse energy

>20 GeV



<u>Sample</u>

2.7/fb

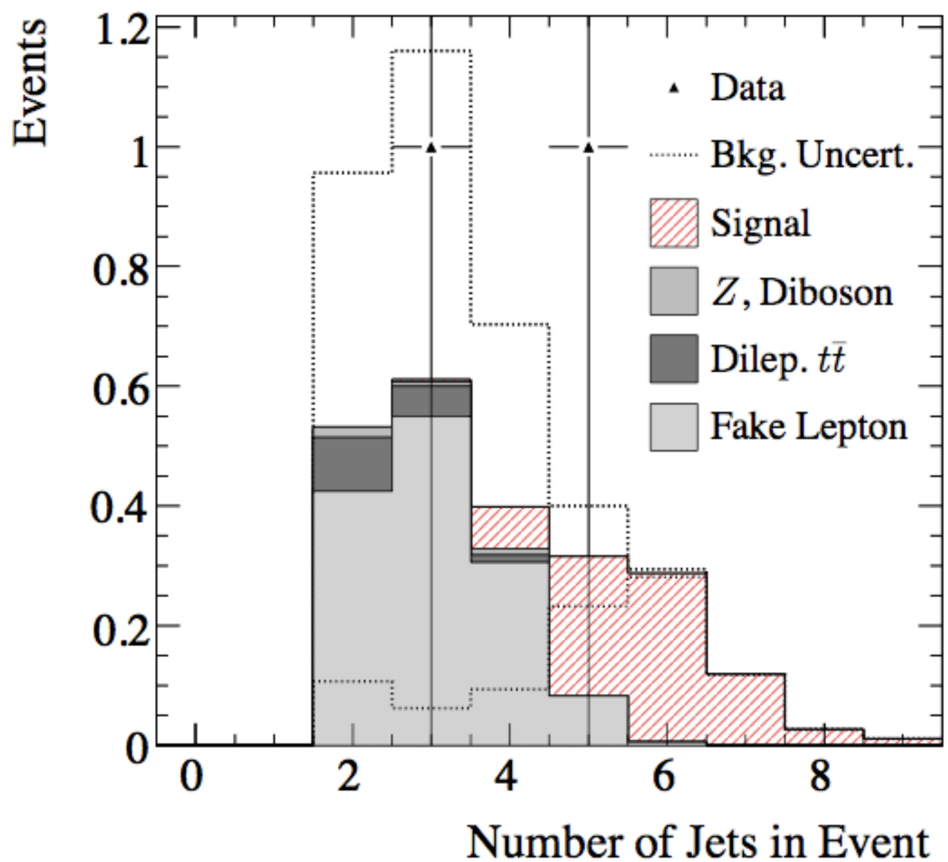
Data (2.7/fb)

<u>Final selection</u>

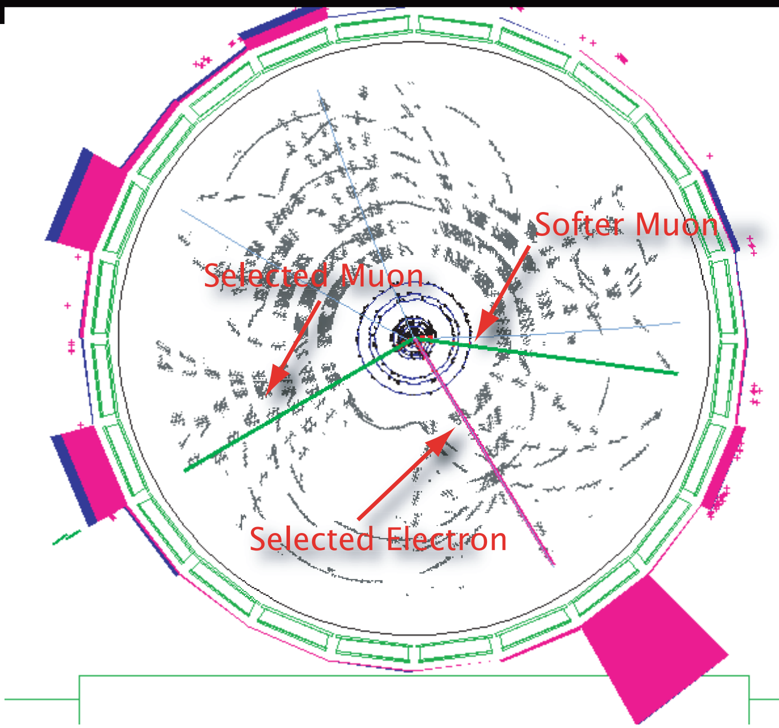
2 like-signed leptons

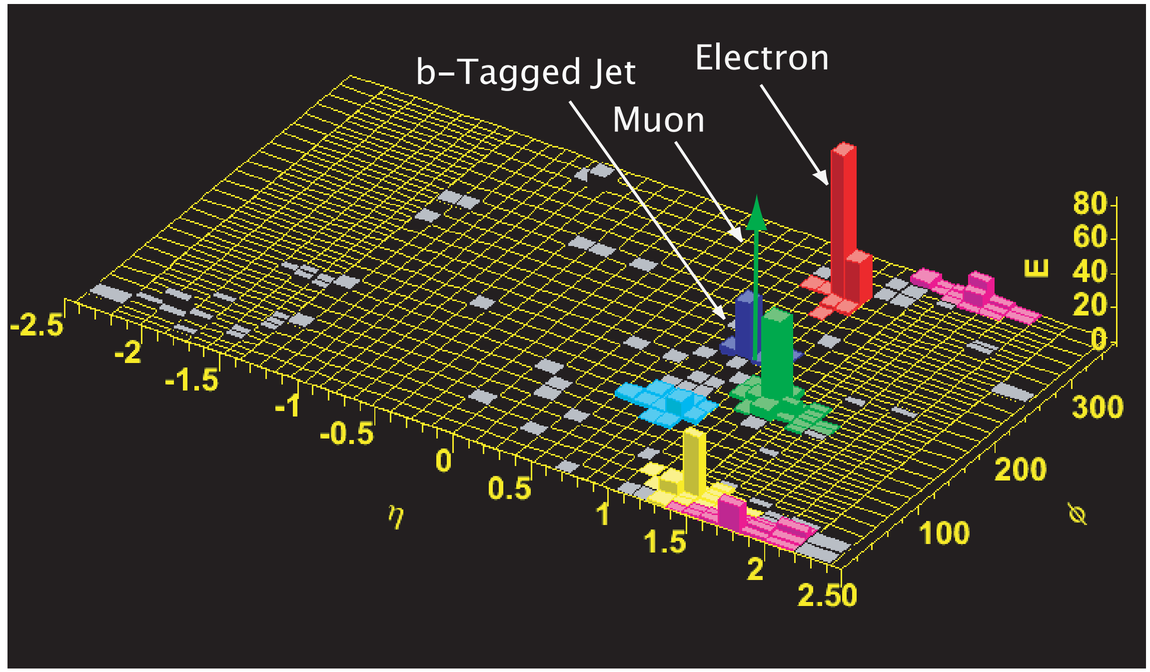
2 jets *>=1 btags*

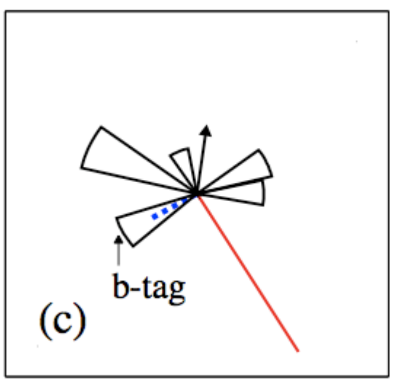
Missing transverse energy

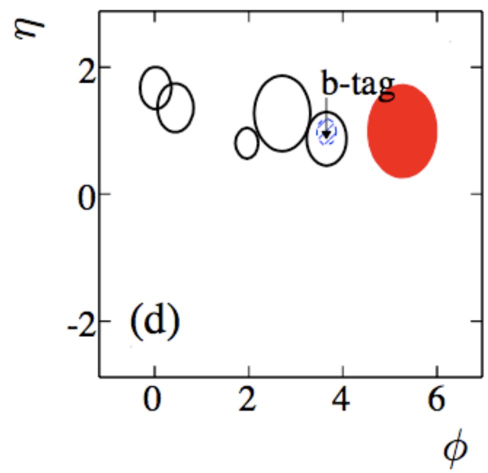


5-jet $e^+\mu^+$ event









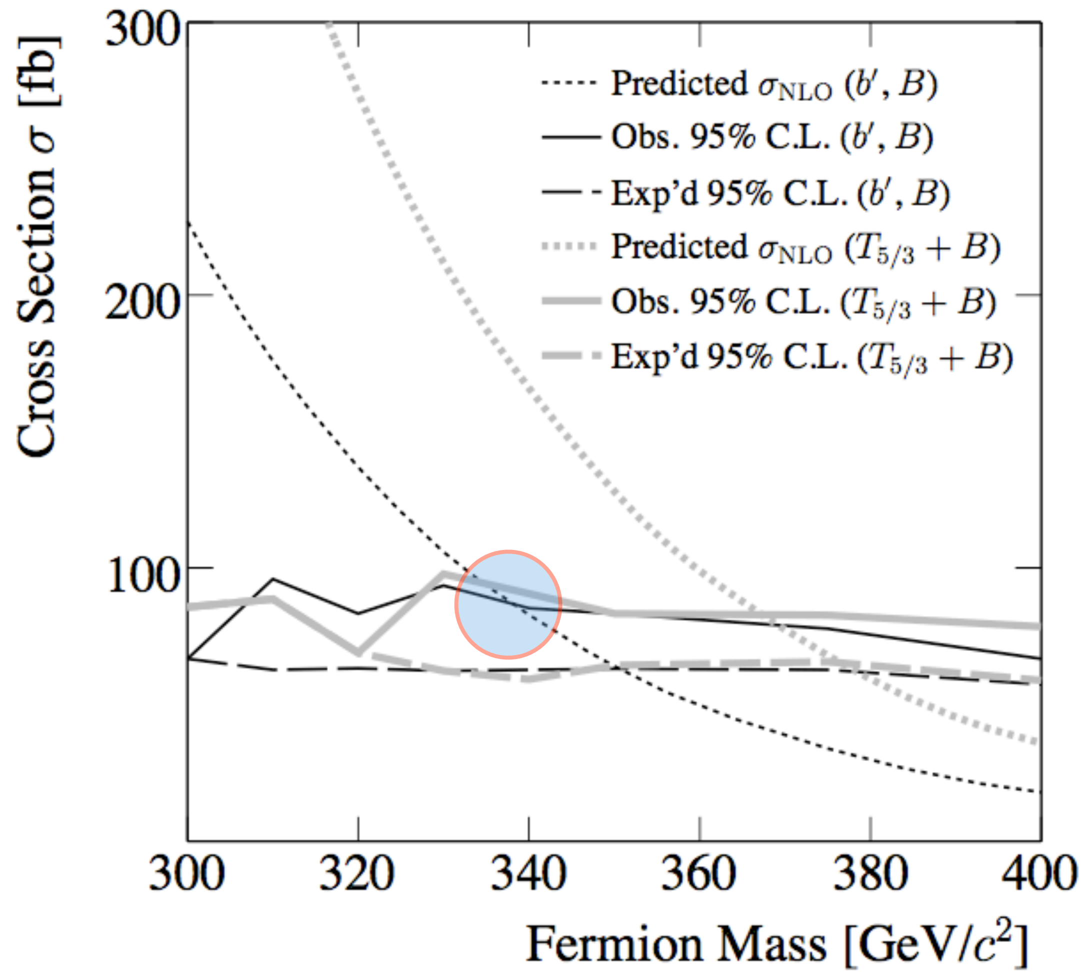
r-ϕ Projection

Jet
Electron
Muon

Limits

Limit

$m_{b'}$ > 338 GeV



CDF t′ search

Selection

1 lepton

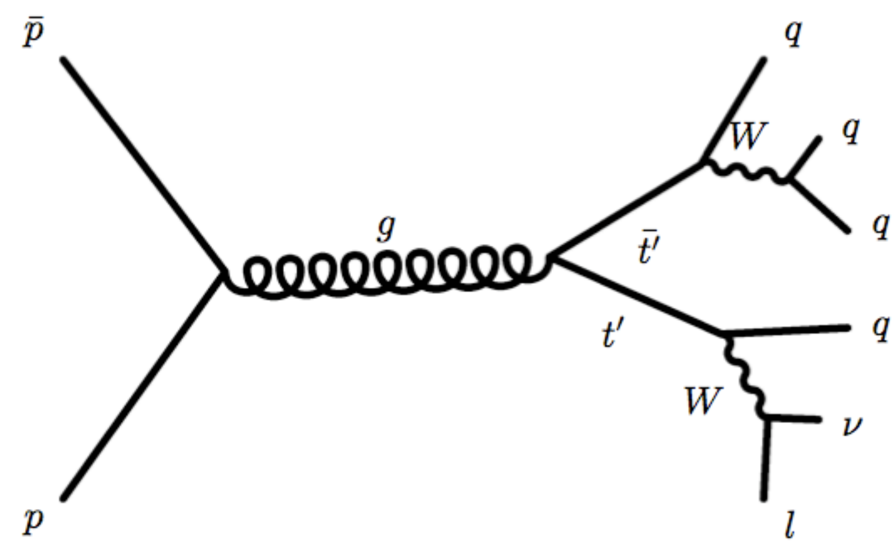
pt>20 GeV

4 jets

pt>20 GeV

Missing transverse energy

>20 GeV

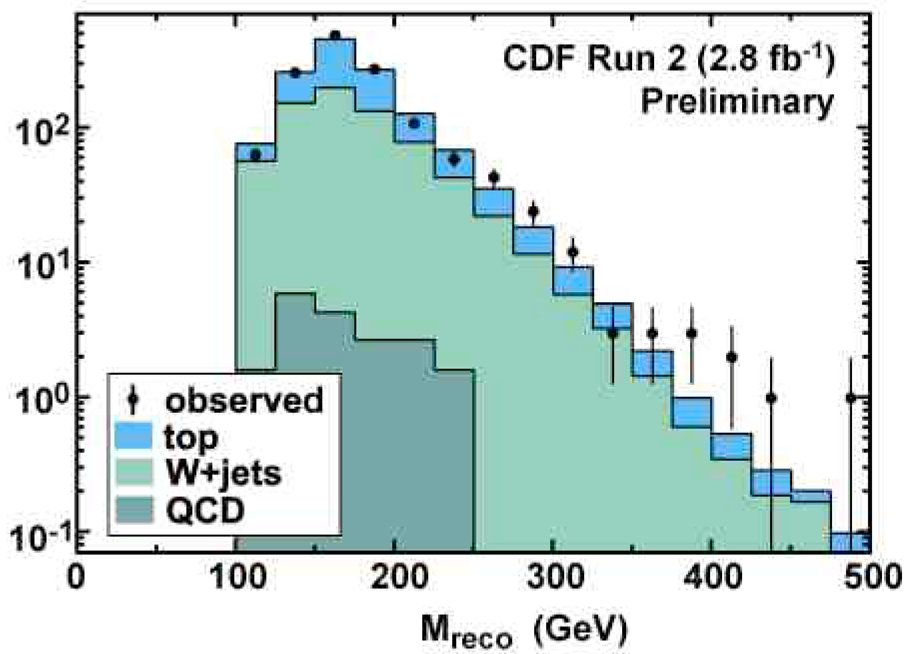


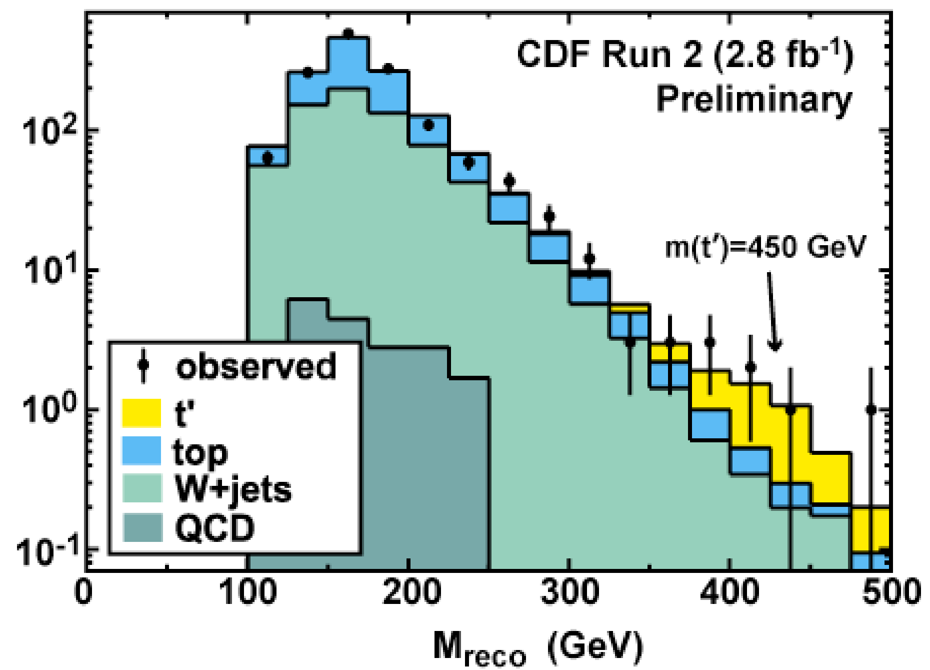
Sample

2.8/fb

Mass fit

Fit mass of each event

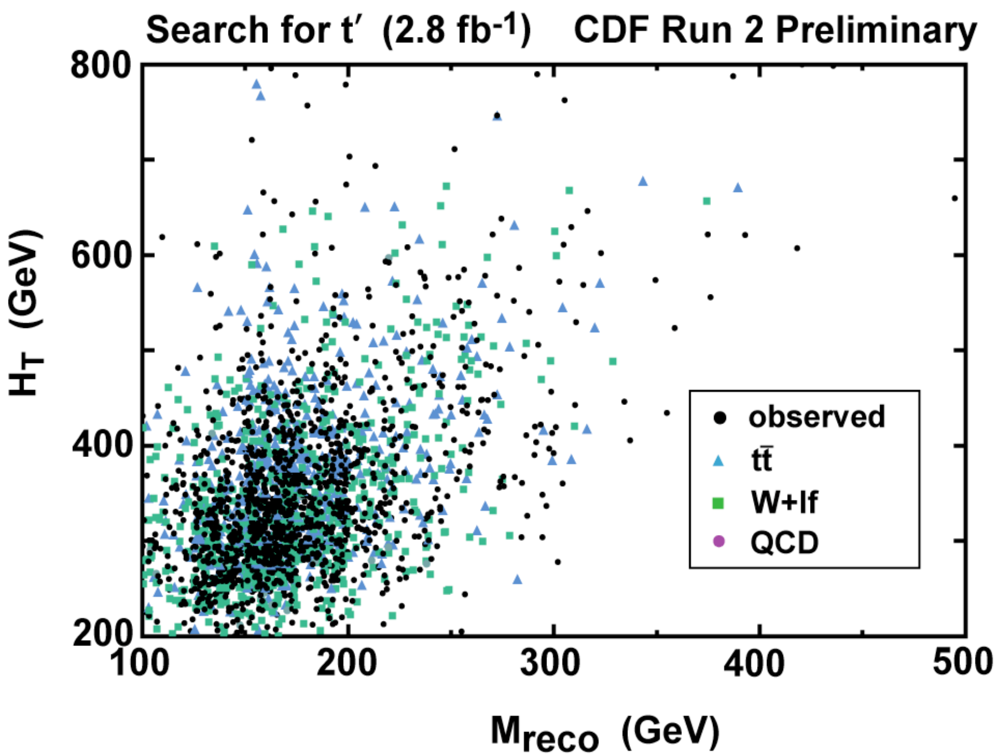




Room on tail for signal events

Events

Total scalar energy



Fitted mass

t′

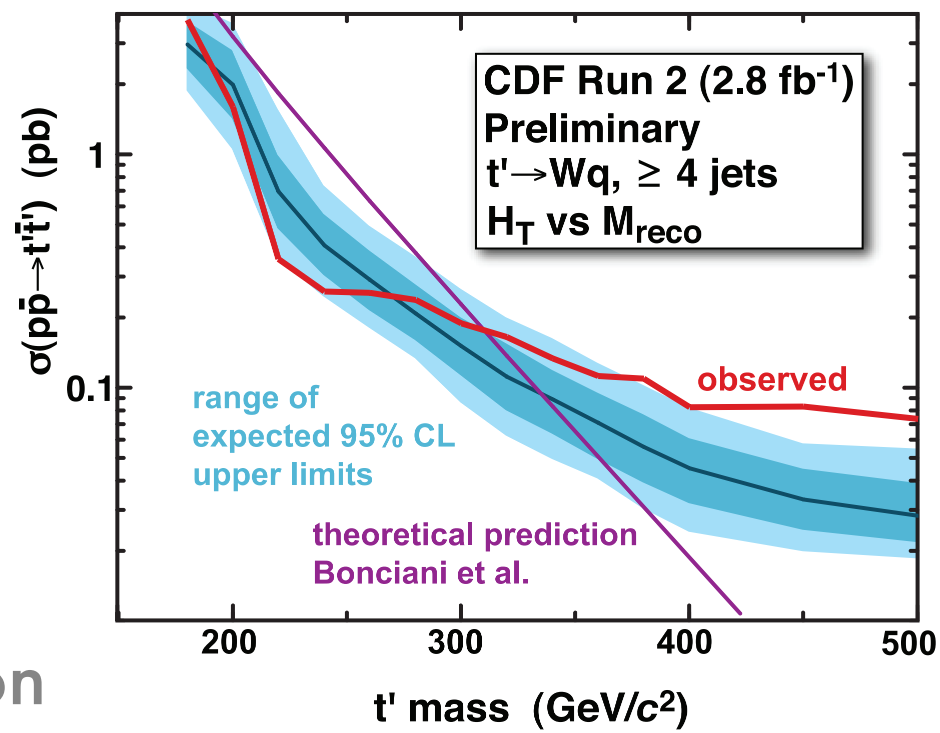
Limit

$m_{t'} > 311$ GeV

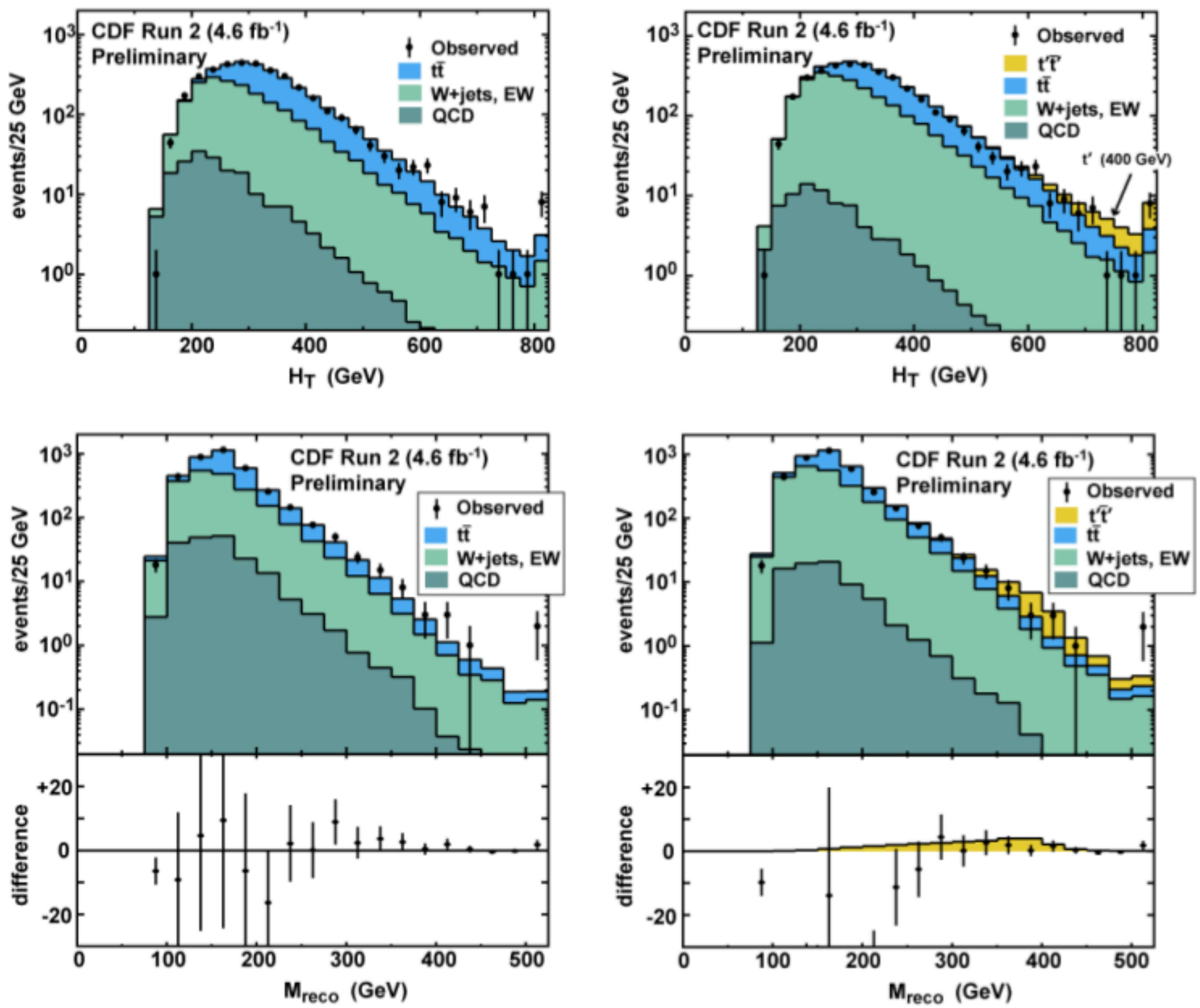
Plans

Study WbWb→l+jets mode

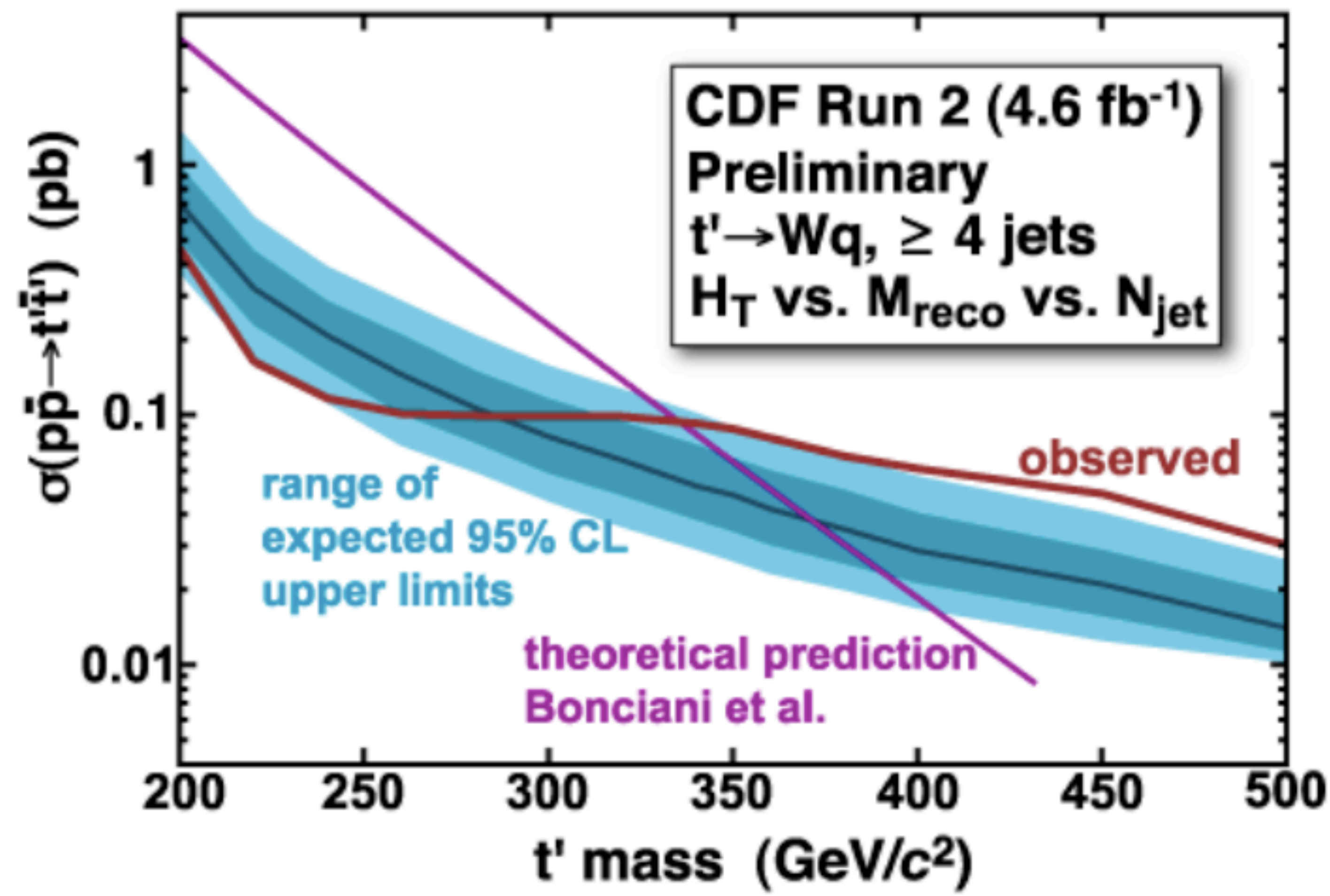
New mode WqWq→ dilepton



Followup: t′ result

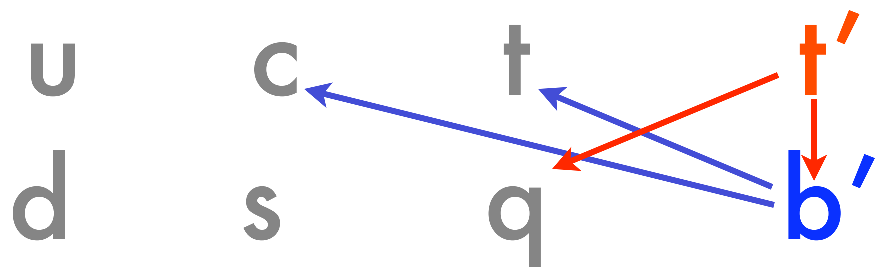


Followup: t′ result



Followup: BRs

If $m_{t'} > m_{b'}$



	Decay Modes	
BR($t' \to Wb'$)	BR($b' \to Wt$) = 0	BR($b' \to Wt$) = 1
0	$t' \to Wq$	$t' \to Wq$
	$b' \to Wq$	$b' \to WWb$
1	$t' \to WWq$	$t' \to WWWb$
	$b' \to Wq$	$b' \to WWb$

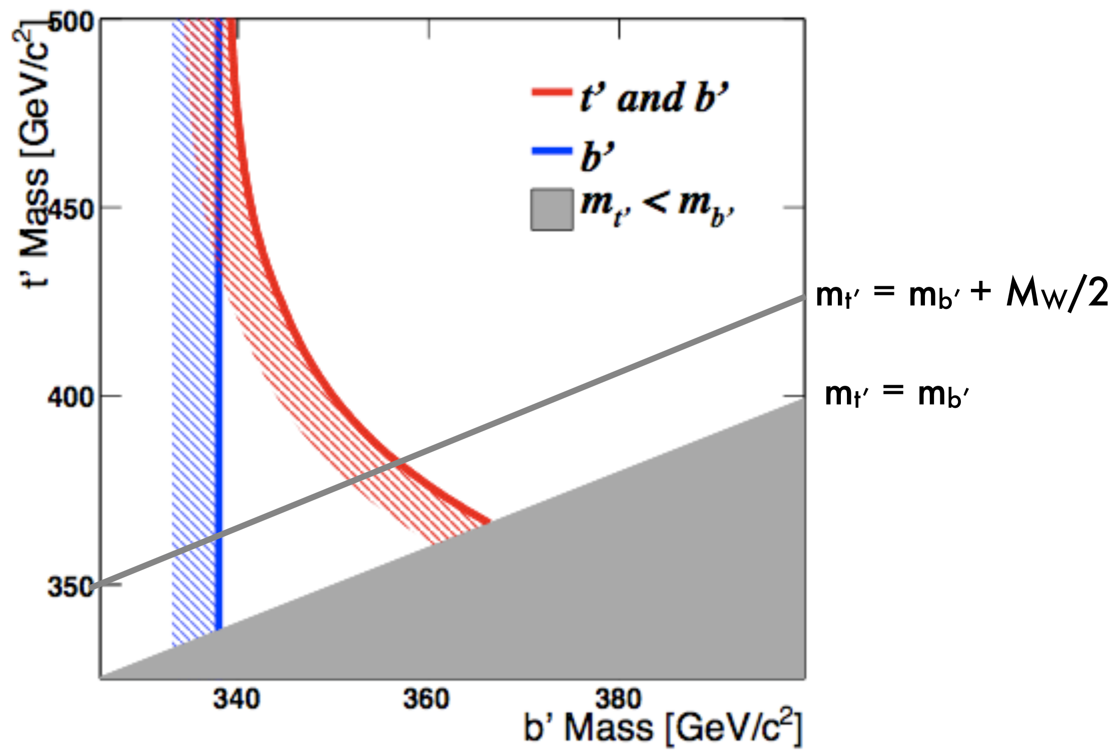
No direct limits!

Old data, new modes

WWb data sensitive to both

$b' \rightarrow Wt \rightarrow WWb$

$t' \rightarrow Wb' \rightarrow WWt \rightarrow WWWb$

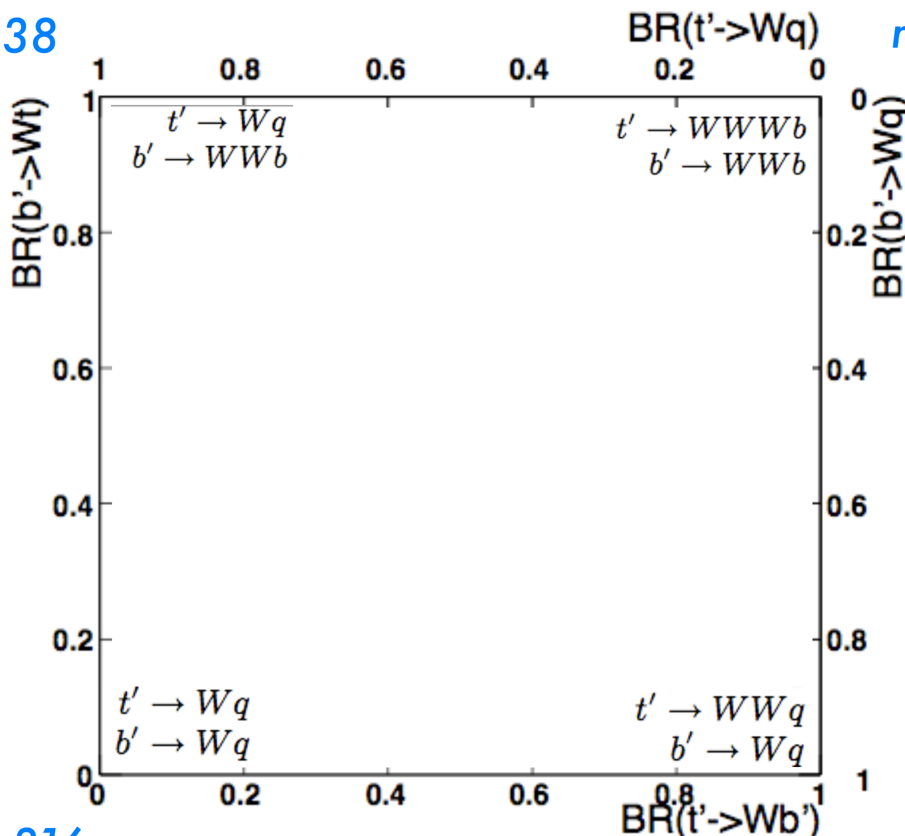


DW et al, to appear

Four corners

$m_{t'} > 311$
$m_{b'} > 338$

$m_{t'} > 426$
$m_{b'} > 345$



$m_{t'} > 316$
$m_{b'} > 235$

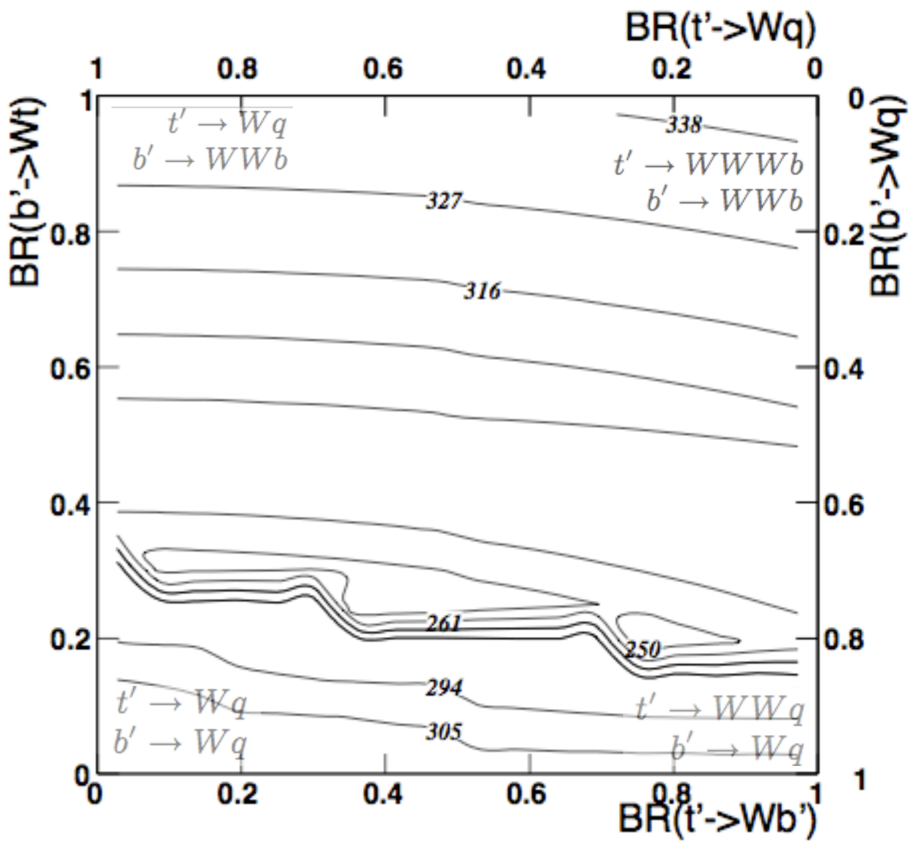
$m_{t'} > 285$
$m_{b'} > 311$

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

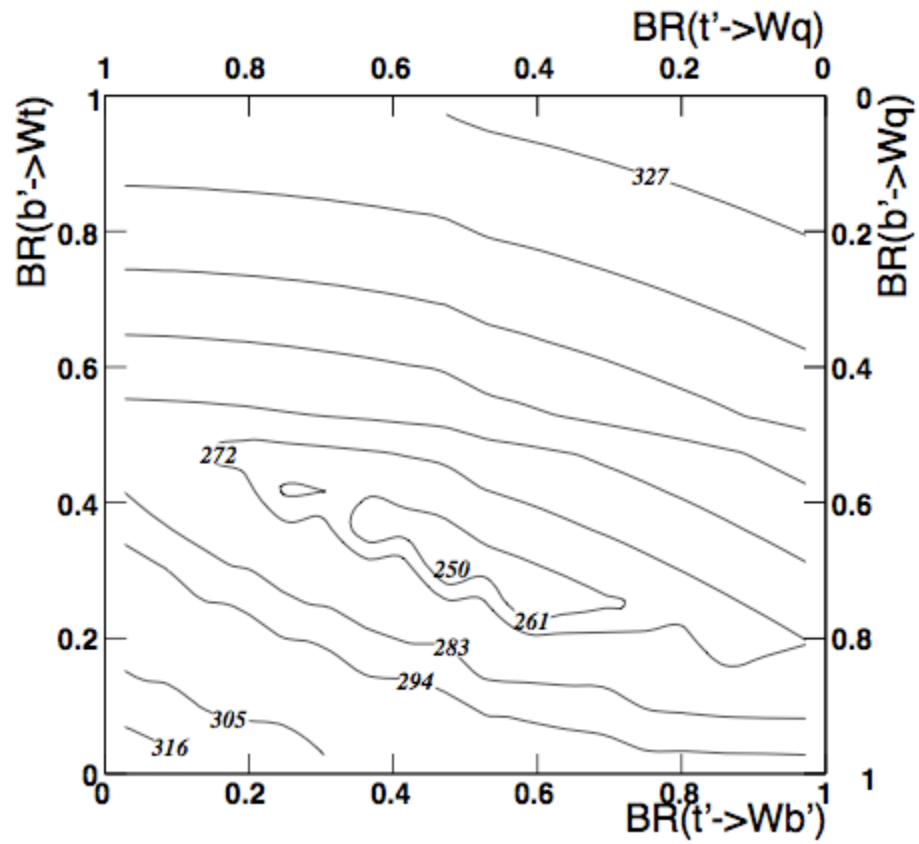
DW et al, to appear

All data

Limits on lighter quark mass (b′)



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

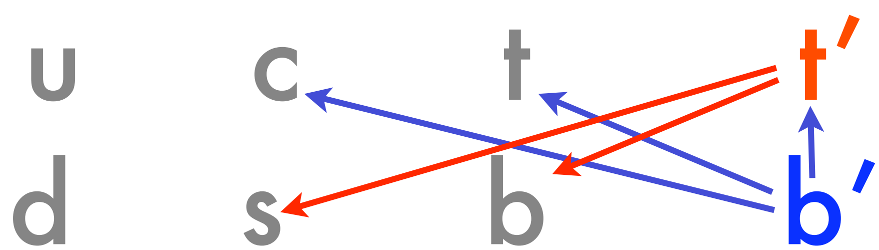


$m_{t'} = m_{b'} + M_W/2$

DW et al, to appear

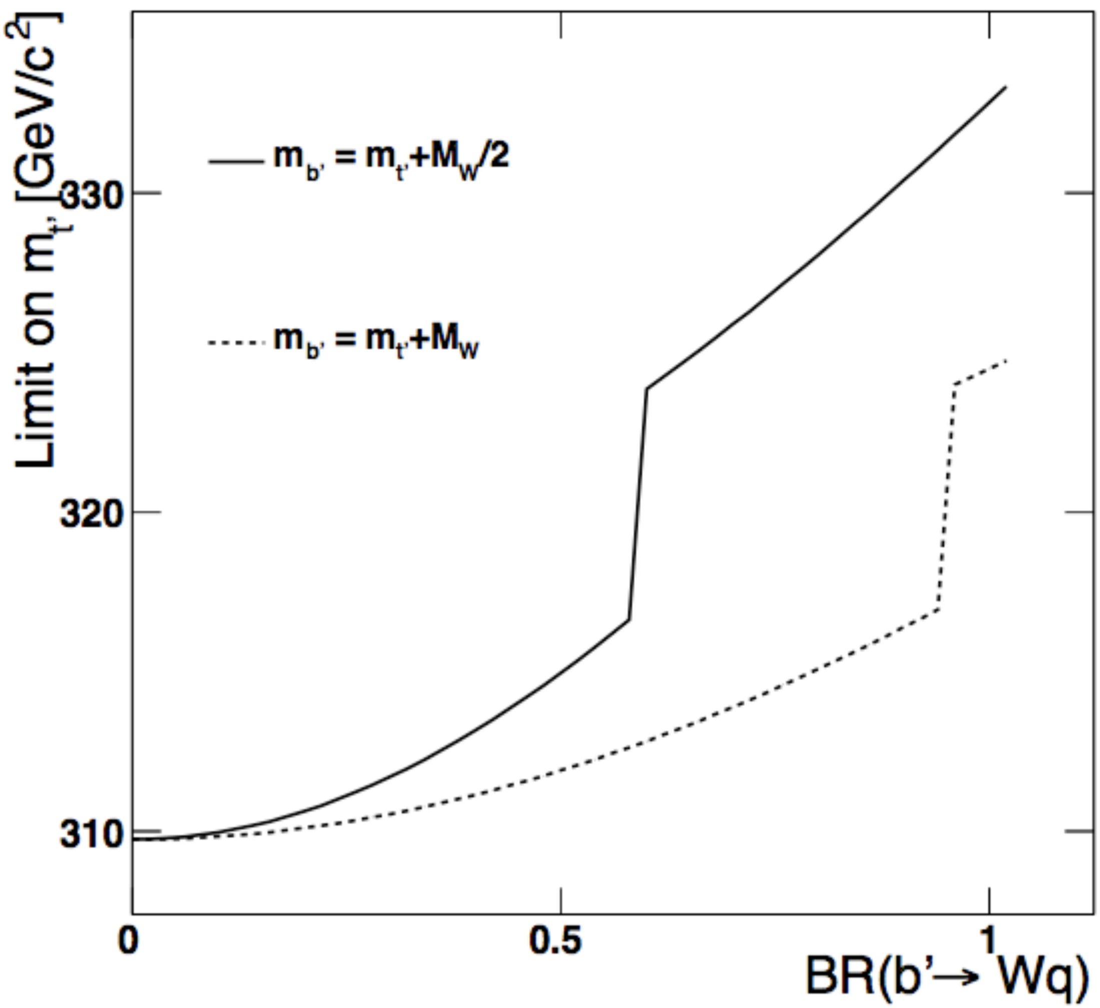
Modes

If $m_{b'} > m_{t'}$



Decay Modes			
$BR(t' \to Wb)$	$BR(b' \to Wt') = 1$	$BR(b' \to Wt) = 1$	$BR(b' \to W\{q = u, c\}) = 1$
0	$b' \to Wt' \to WW\{q = d, s\}$	$b' \to Wt \to WWb$ $t' \to W\{q = d, s\}$	$b' \to W\{q = u, c\}$
1	$b' \to Wt' \to WWb$	$b' \to Wt \to WWb$ $t' \to Wb$	$b' \to W\{q = u, c\}$

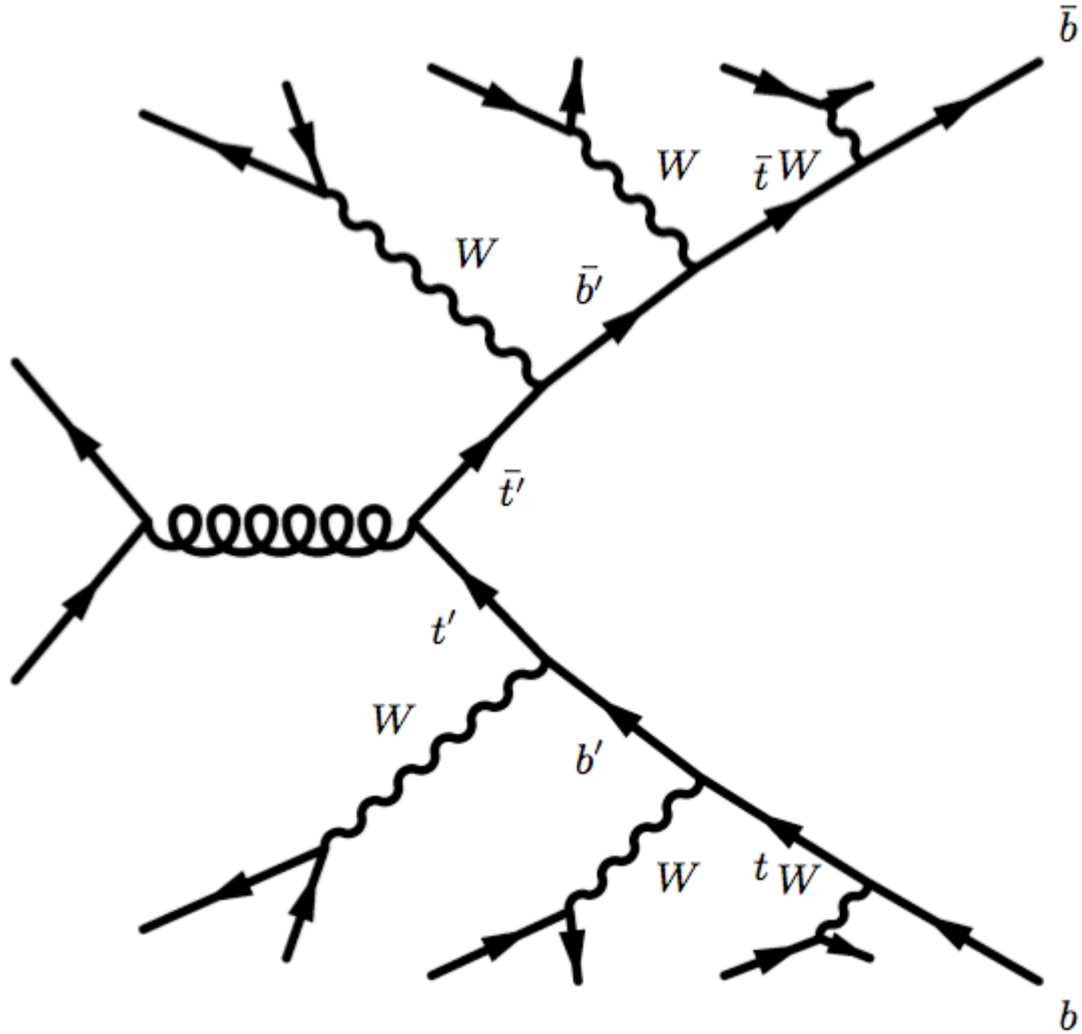
Wq data



Wq data provides strong limits on t′ mass, imply strong limits on b′ if $m_{b'} > m_{t'}$, stronger than limits from WWb data.

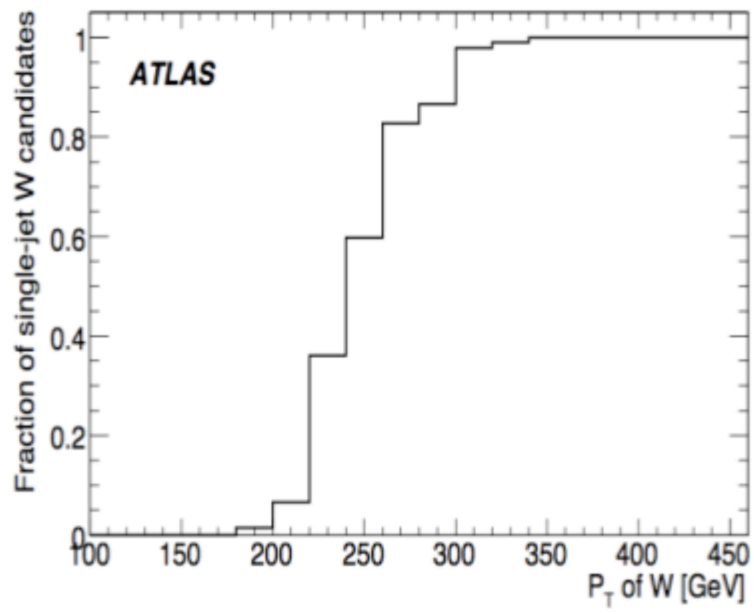
DW et al, to appear

WWWbWWWb



Boosted Ws?

Angles between decay products becomes small



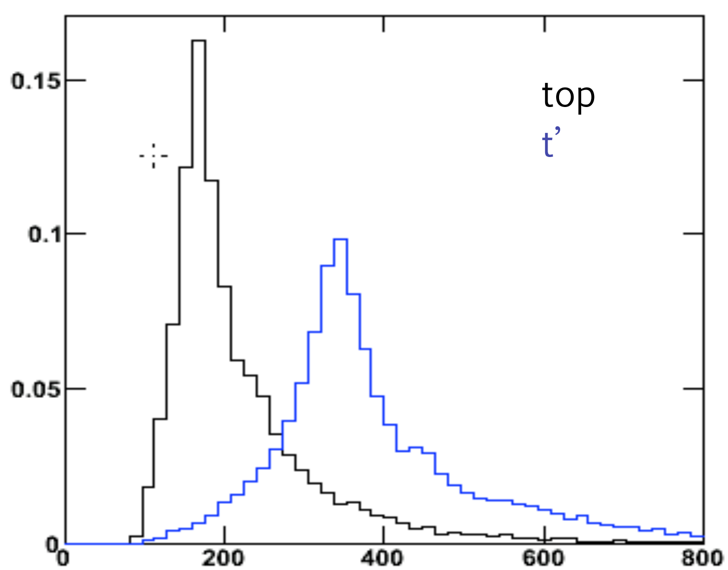
From arXiv:0901.0512
CERN-OPEN-2008-020

In hadronic mode, jets merge into one.

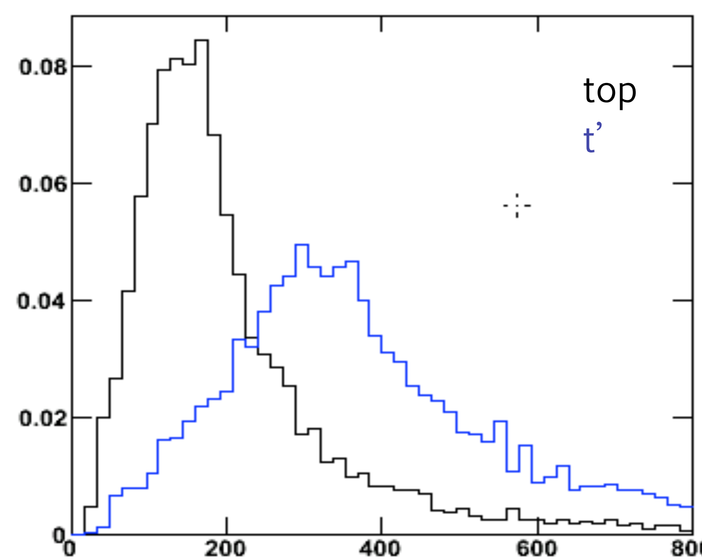
Collinear approximation

Use lepton angle to resolve t′ mass under-constraint in dilepton channel

lepton+jets



dileptons

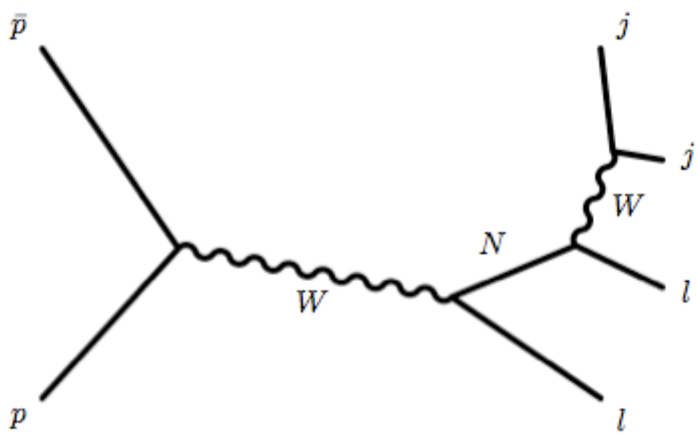


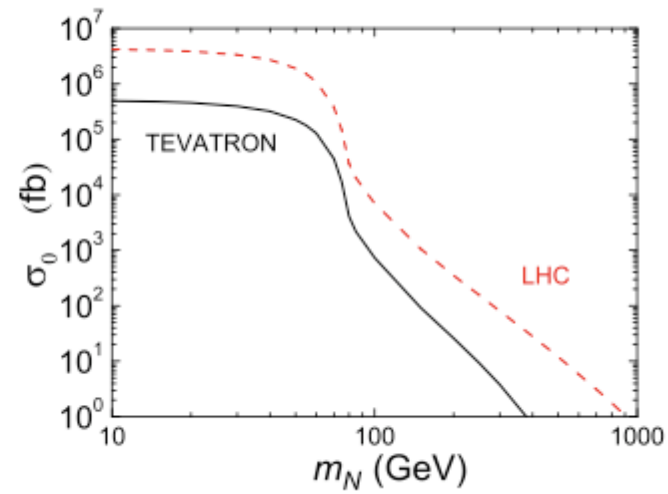
CompHEP 350 GeV t′
10 TeV pp
PGS detector simulation

Speaker's own plots
Not ATLAS result

CDF: Majorana neutrinos

Production via W has been studied





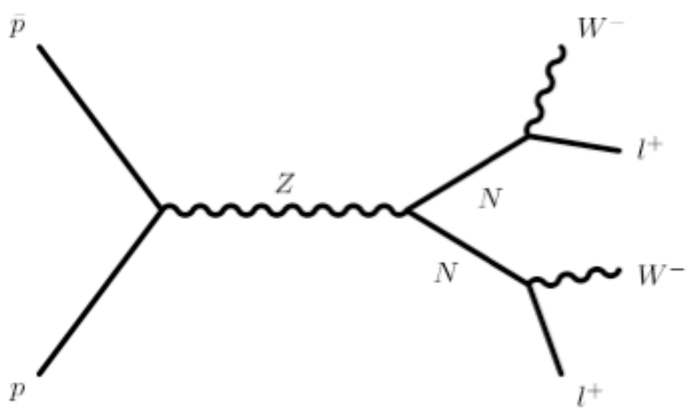
hep-ph/0604064

LEP limits at 90 GeV

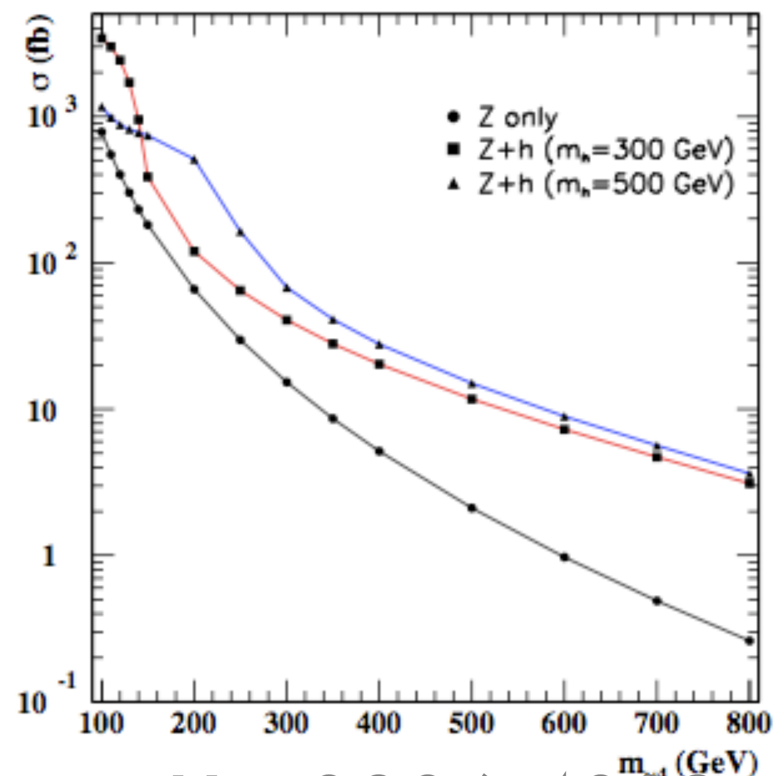
Majorana neutrinos

<u>Production via Z</u>

avoids *WIN* vertex in production mechanism

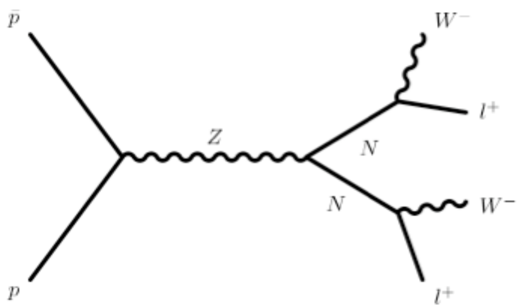


One mass point studied for LHC



arXiv:0806.4003

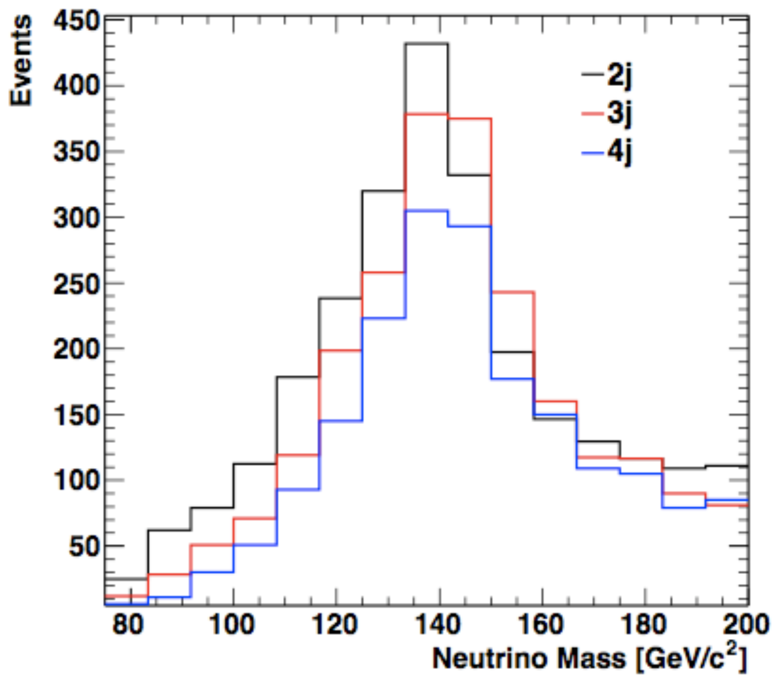
Reconstruction



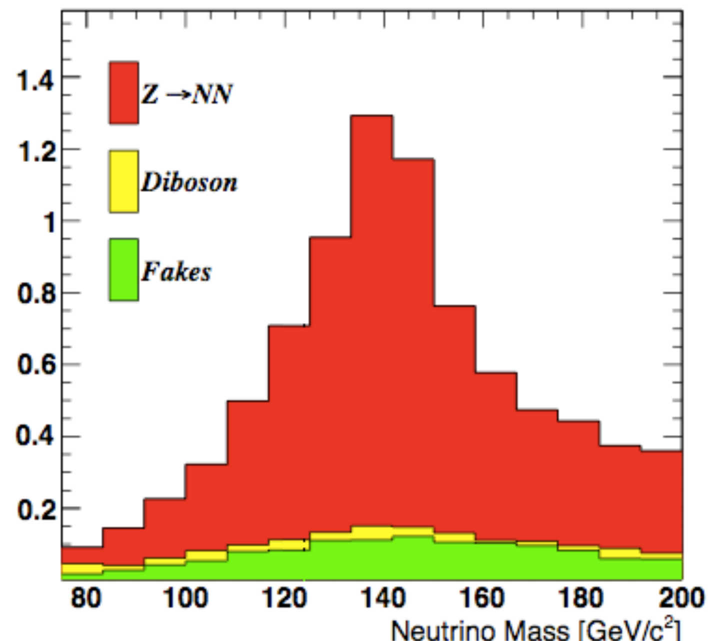
arXiv:1001.1229

Reconstruct N mass as M_{ljj}

Mass reconstruction



Signal and backgrounds

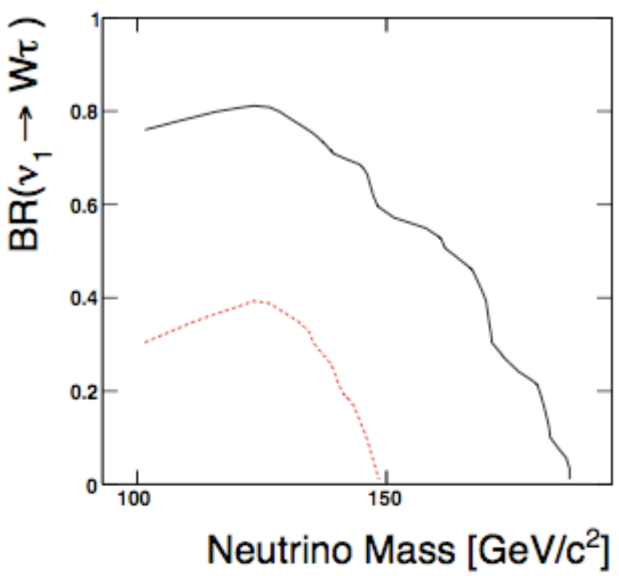


Study using parametric detector sim (PGS)
Not official CDF results

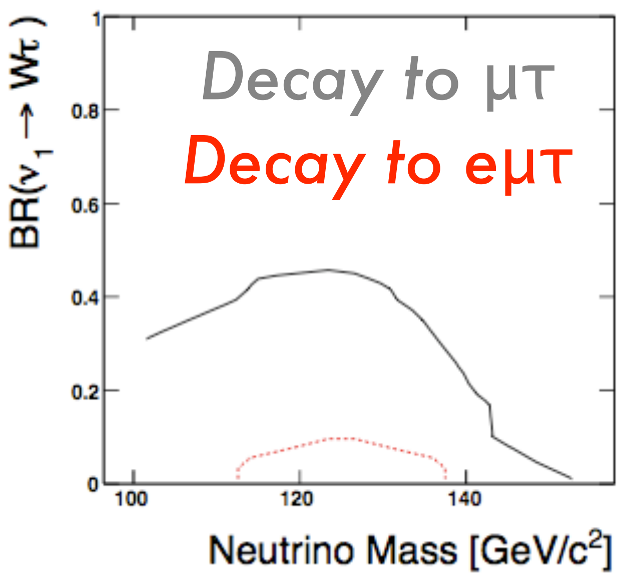
Tevatron Power

arXiv:1001.1229

95% Exclusion



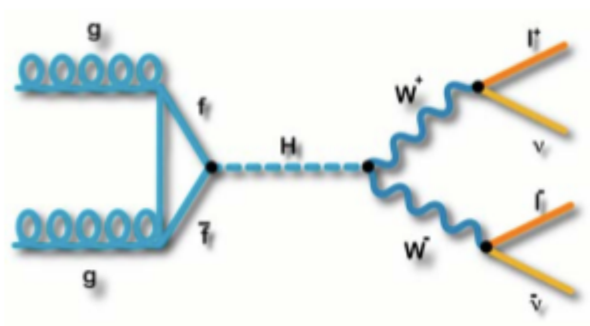
3σ evidence

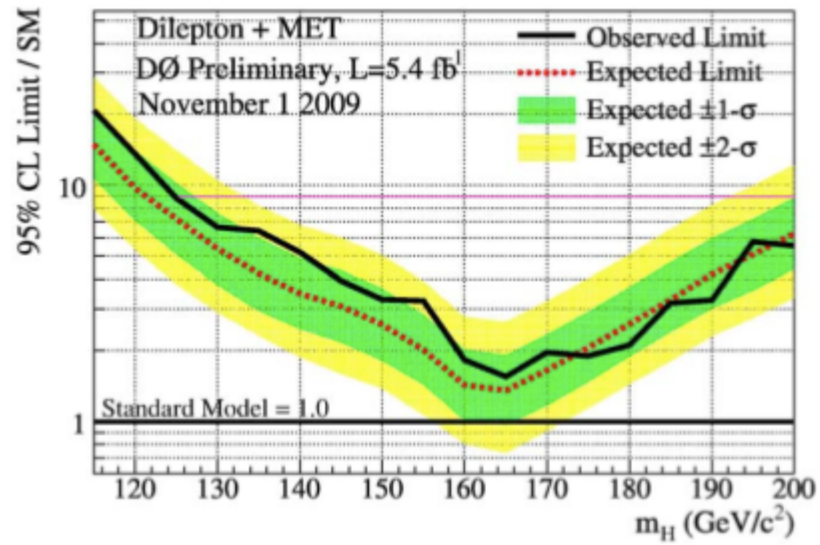


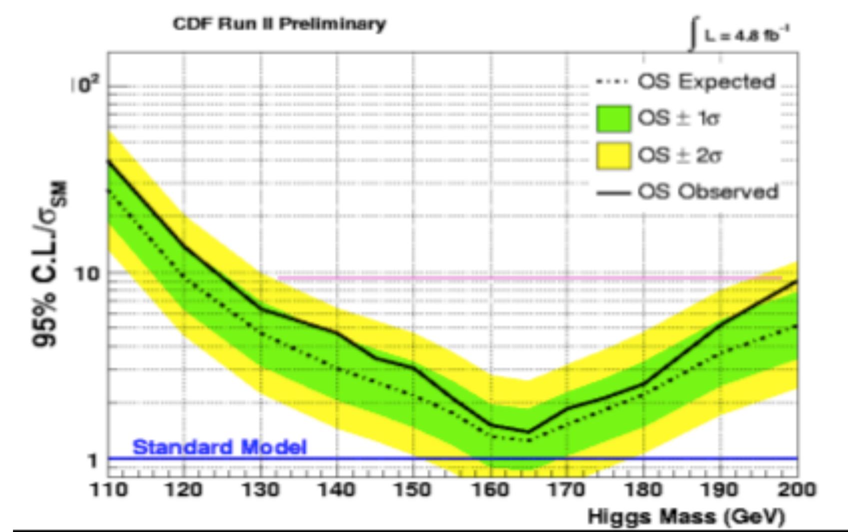
Study using parametric detector sim (PGS)
Not official CDF results

Indirect H->WW

4th family increases production rate of H by factor of 9

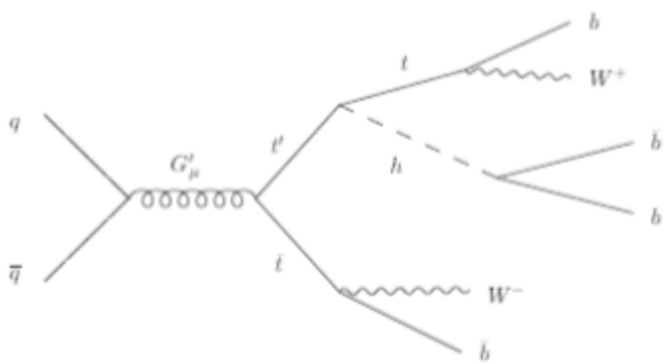


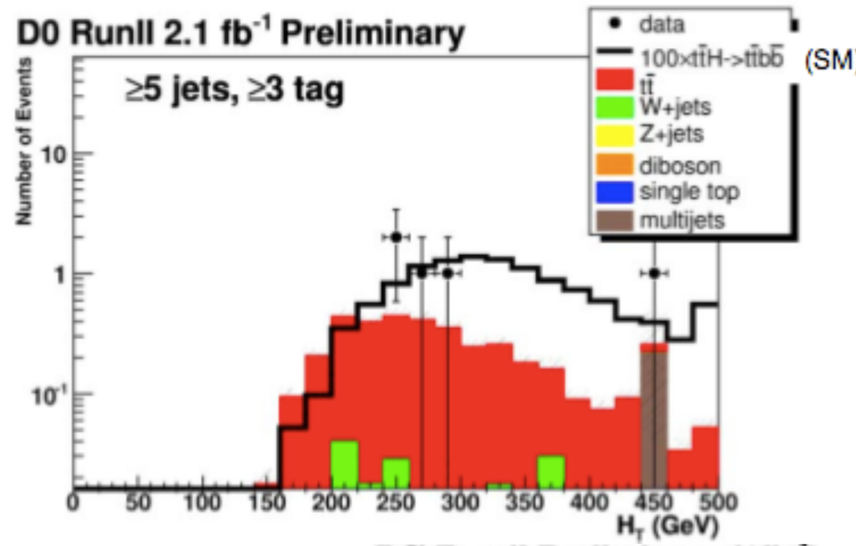


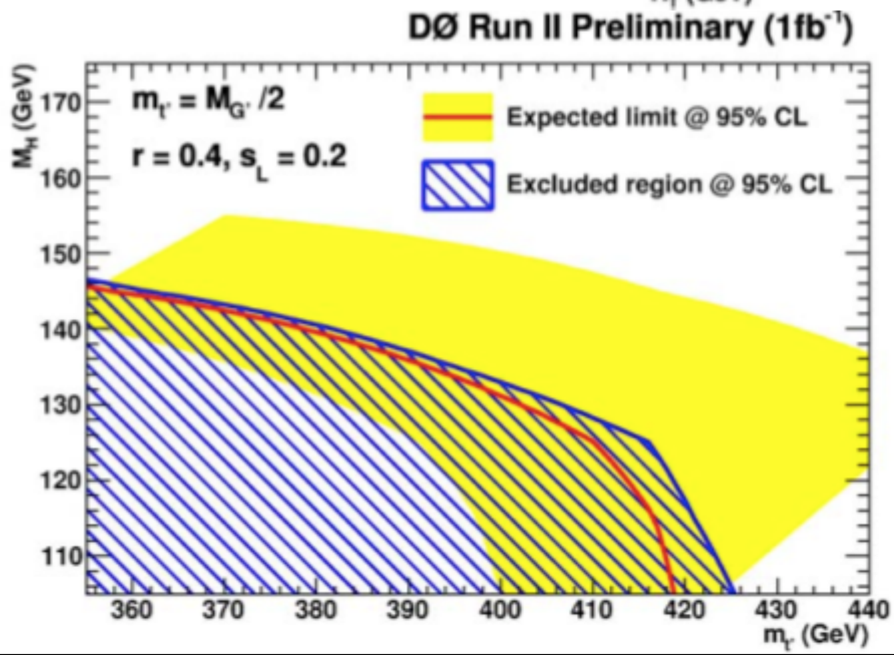


Indirect t′ -> th

JHEP 0906:001,2009, arXiv:0902.0792v2







Selection

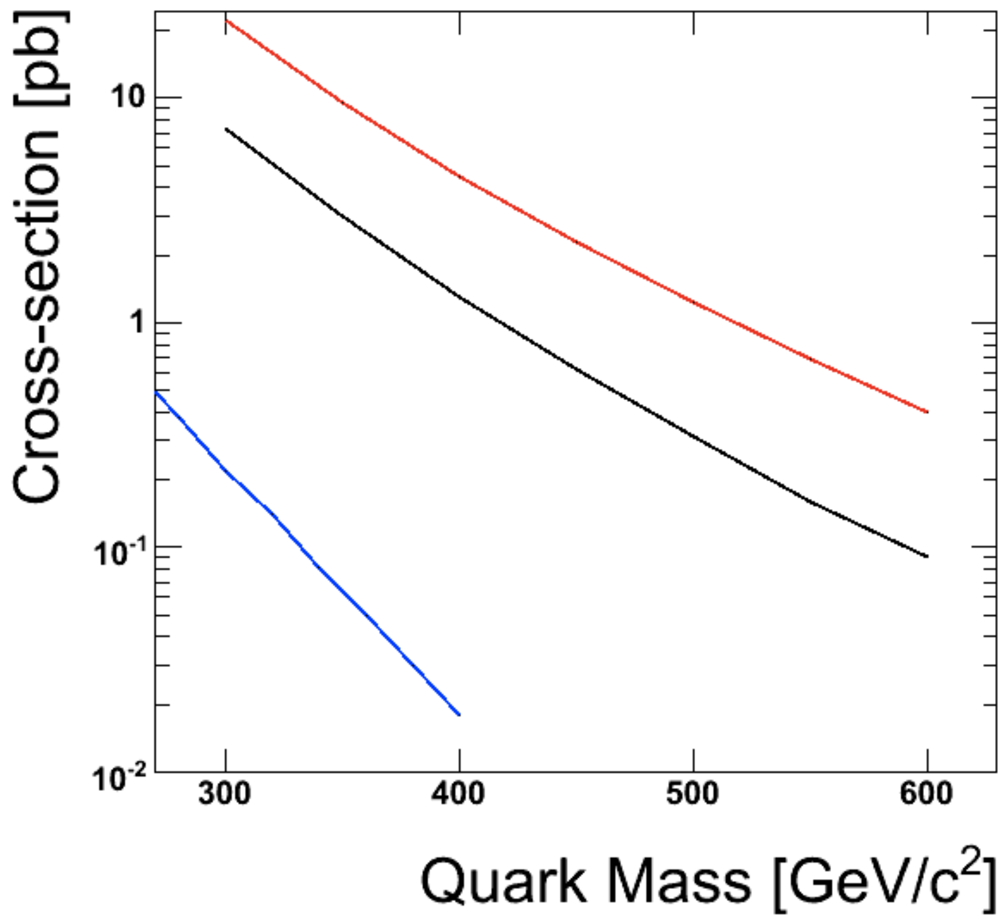
1 lepton

5+ jets

3+ btags

LHC prospects

LHC has much larger rates for heavy quarks

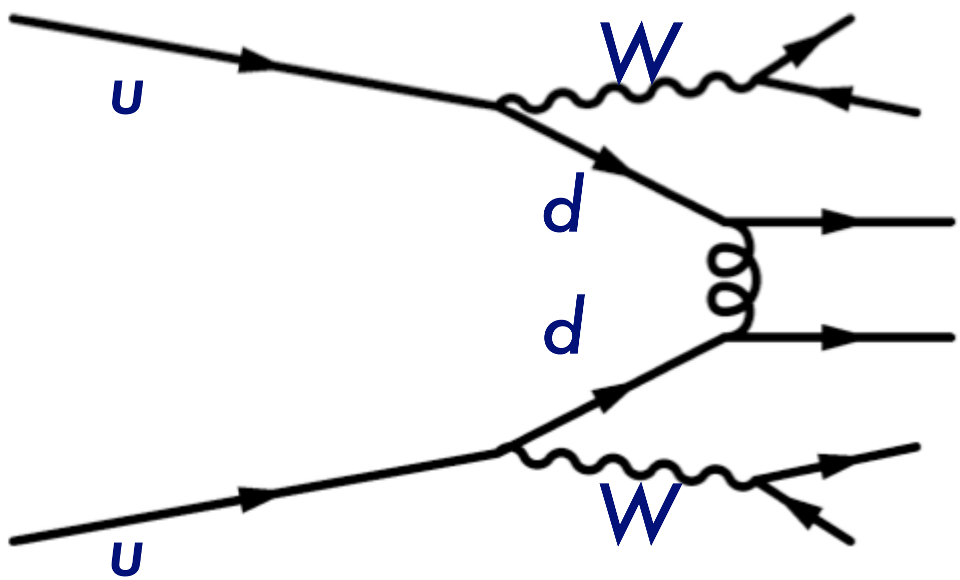


pp 10 TeV
pp 7 TeV
$p\bar{p}$ 2 TeV

From
arXiv: 0804.2800v1

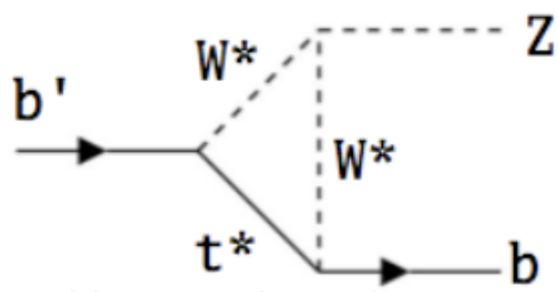
LHC-specific backgrounds

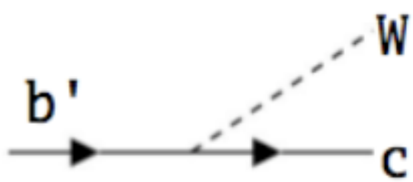
At Tevatron, true same-charge leptons are rare
Primarily from trilepton processes

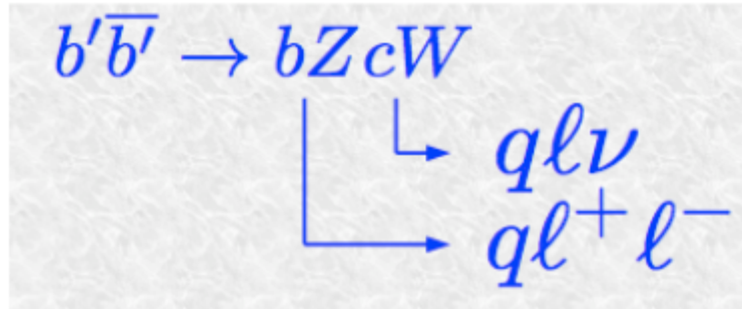


pp nature of LHC beams offers new background
with true same-sign dileptons

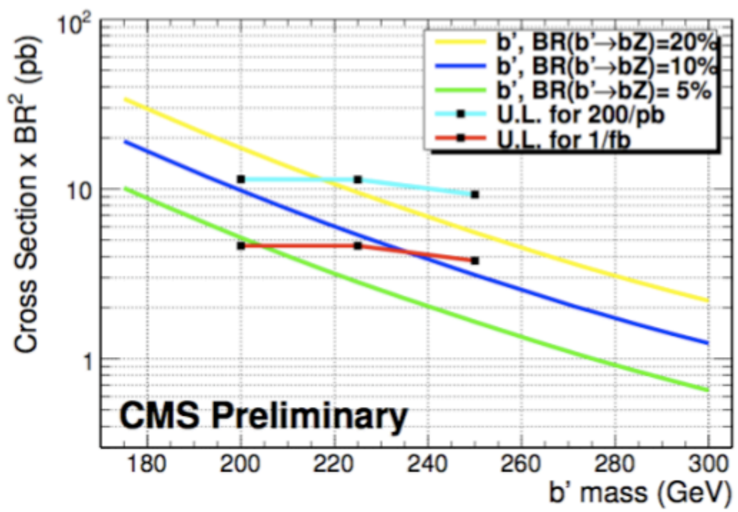
CMS light b′



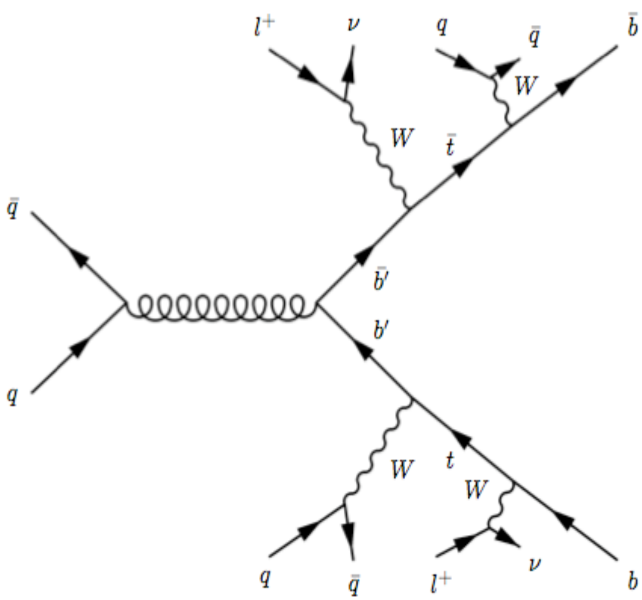




m(b′) @ 1 fb^{-1}	200 GeV	225 GeV	250 GeV
Cross-section	113 pb	65 pb	11 pb
Expected Yields	29.9	16.7	11.4
Background	13.8	13.8	13.8
Significance	3.8 σ	1.9 σ	1.1 σ

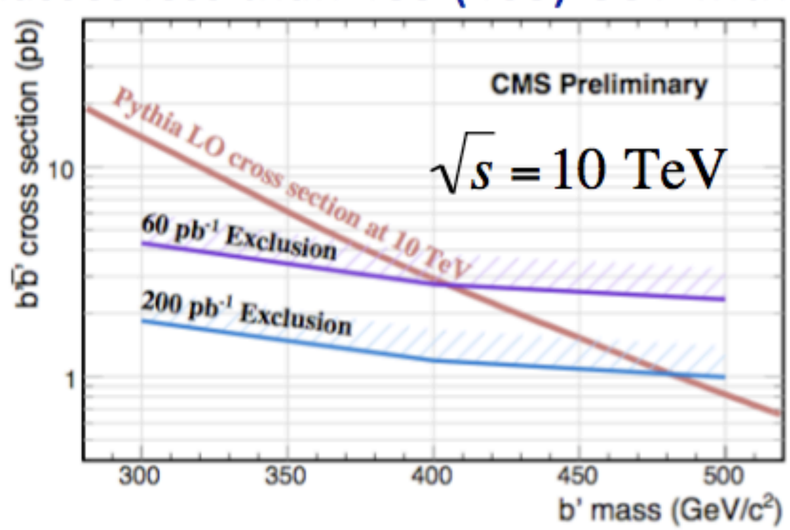


CMS heavy b’

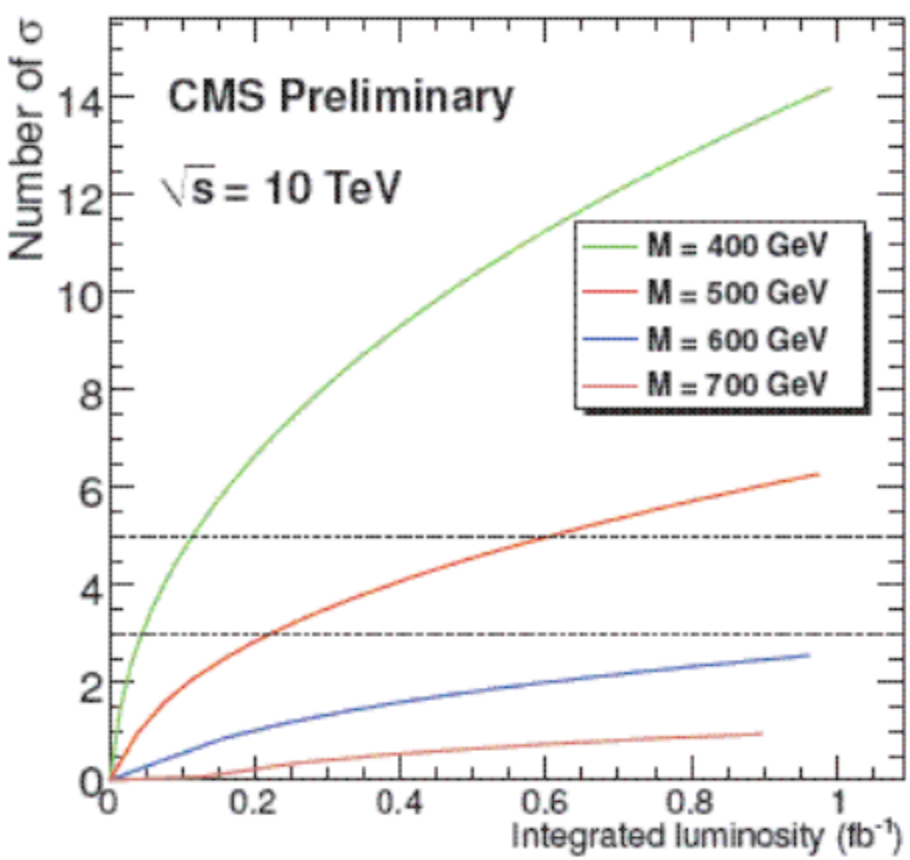


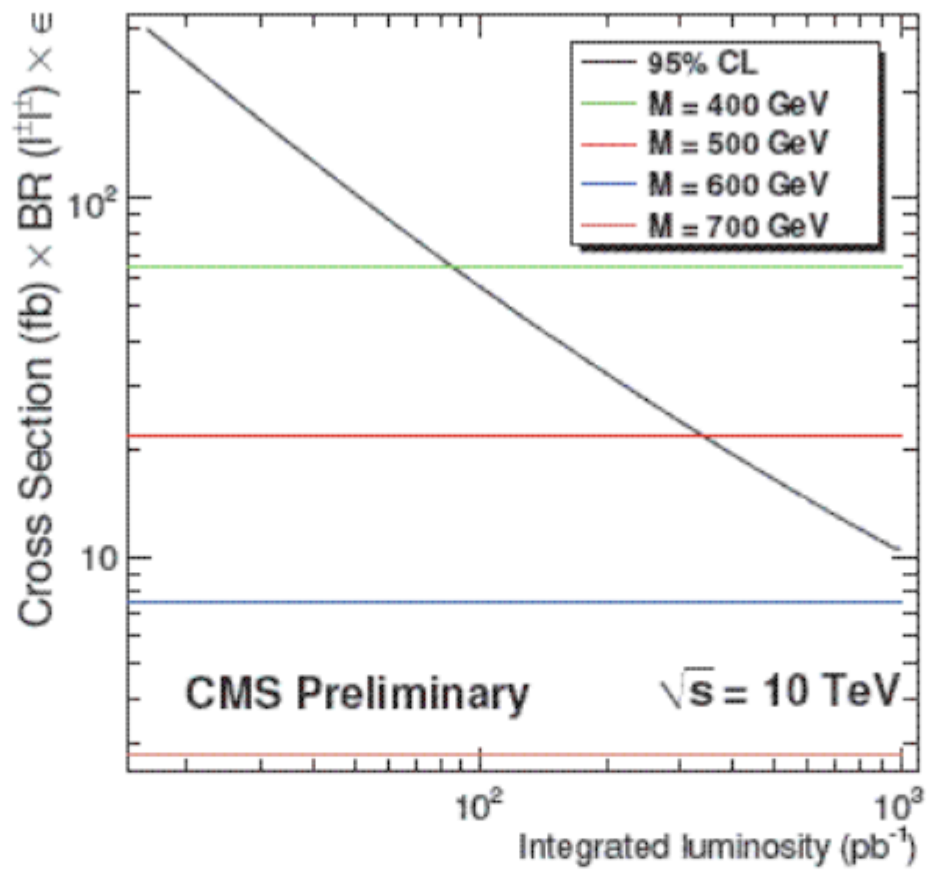
m(b’) @ 200pb^{-1}	300 GeV	400 GeV	500 GeV
Cross-section	13.6 pb	2.8 pb	0.78 pb
Expected Yields	34.08	10.58	3.52
Background	1.08	1.08	1.08
Significance	9.0 σ	3.7 σ	1.4 σ

ude b’ masses less than 485 (405) GeV with 200 (60) pb

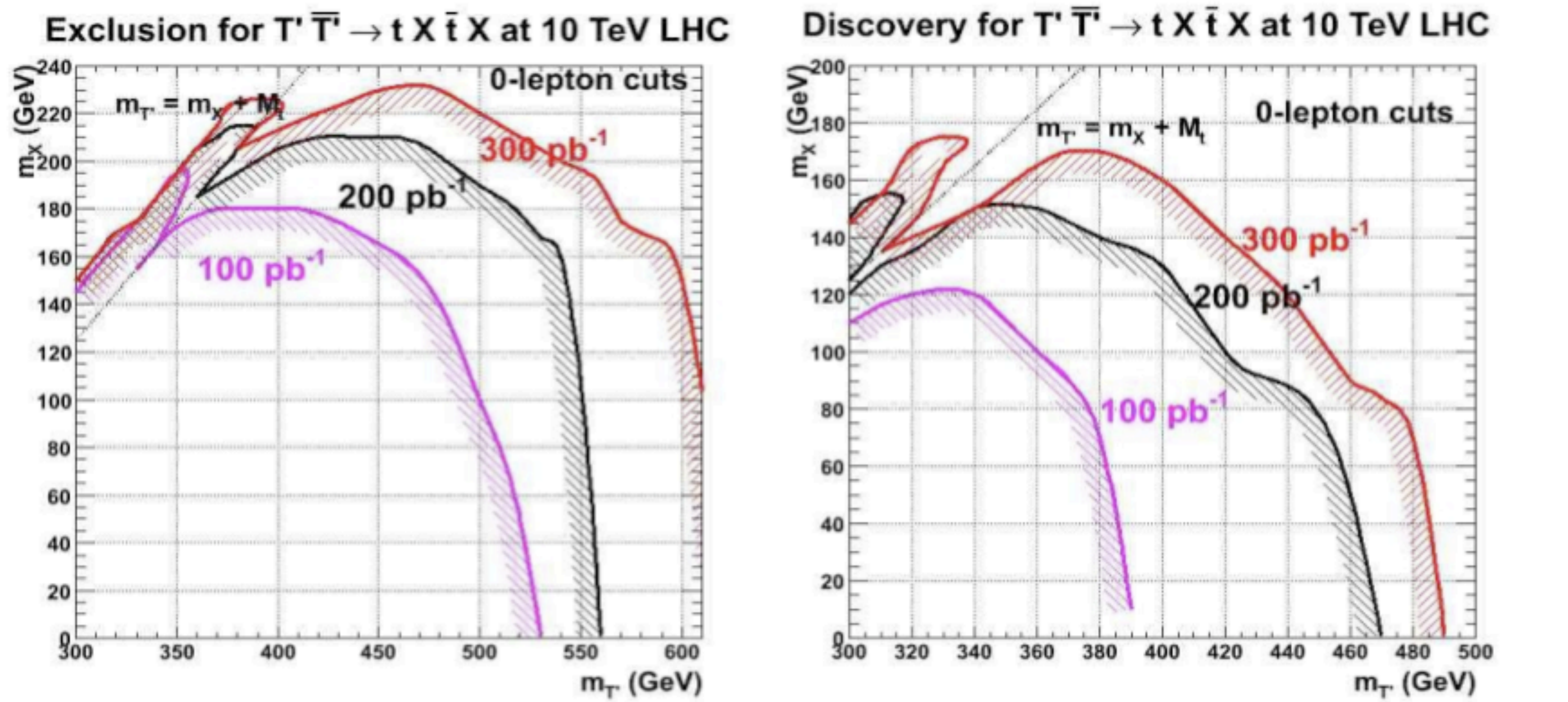


CMS $T_{5/3}$

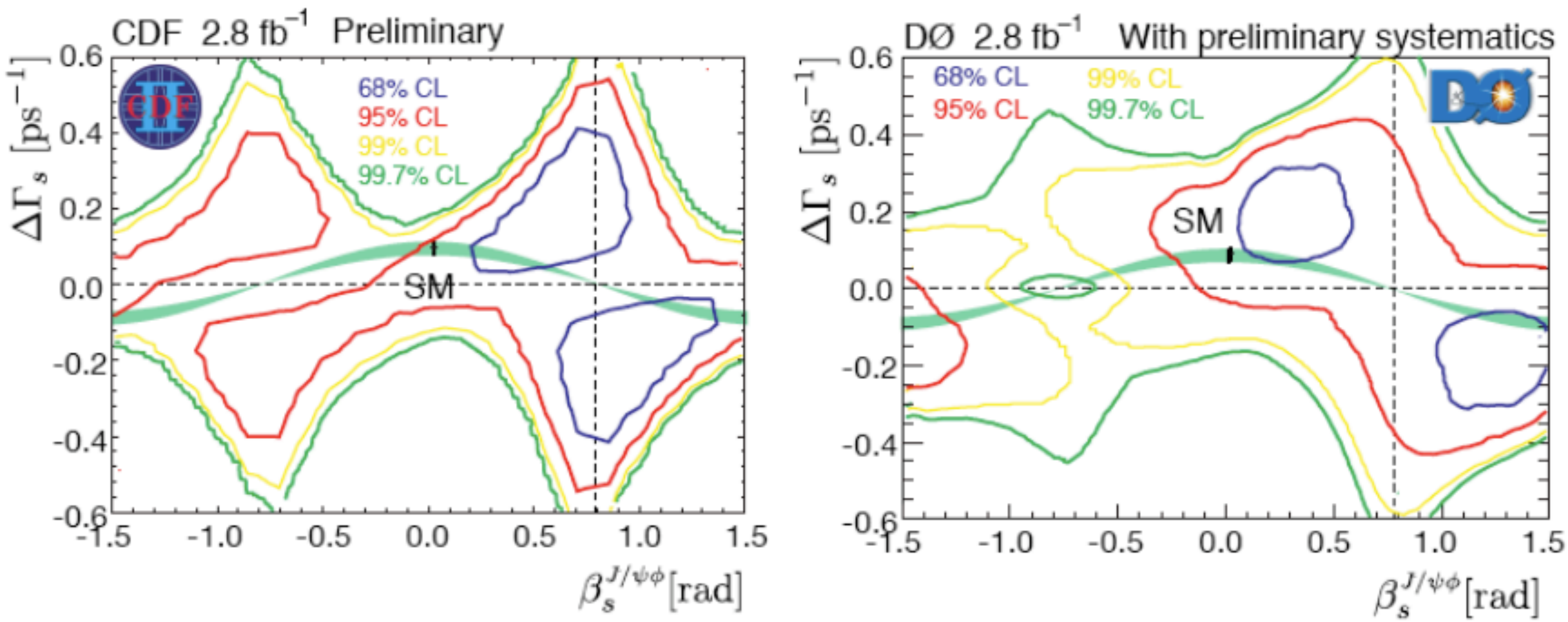

CMS Preliminary
√s = 10 TeV
M = 400 GeV
M = 500 GeV
M = 600 GeV
M = 700 GeV
Number of σ
Integrated luminosity (fb⁻¹)


95% CL
M = 400 GeV
M = 500 GeV
M = 600 GeV
M = 700 GeV
CMS Preliminary
√s = 10 TeV
Cross Section (fb) × BR (l±l±) × ε
Integrated luminosity (pb⁻¹)

Darkmatter

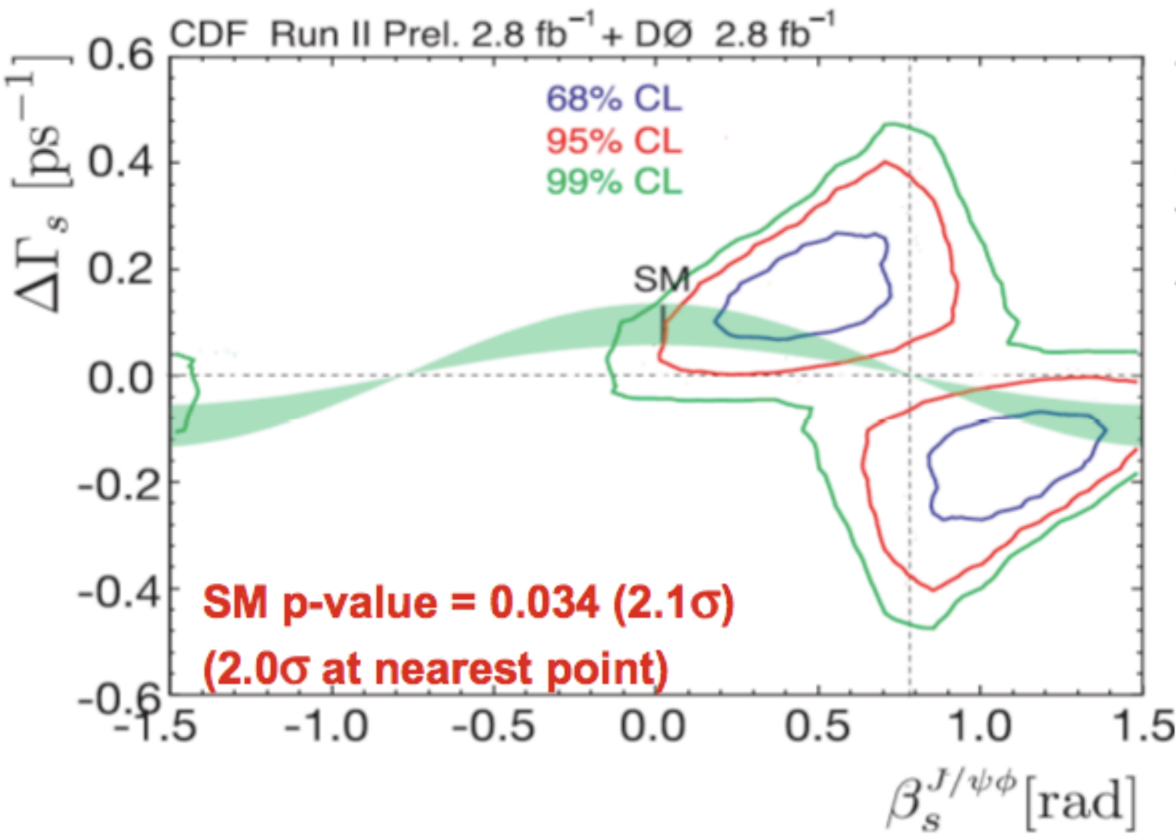

Exclusion for T' $\overline{T'}$ → t X $\bar{t}$ X at 10 TeV LHC
0-lepton cuts
$m_{T'} = m_X + M_t$
300 pb^{-1}
200 pb^{-1}
100 pb^{-1}
m_X (GeV)
$m_{T'}$ (GeV)
Discovery for T' $\overline{T'}$ → t X $\bar{t}$ X at 10 TeV LHC
0-lepton cuts
$m_{T'} = m_X + M_t$
300 pb^{-1}
200 pb^{-1}
100 pb^{-1}
m_X (GeV)
$m_{T'}$ (GeV)

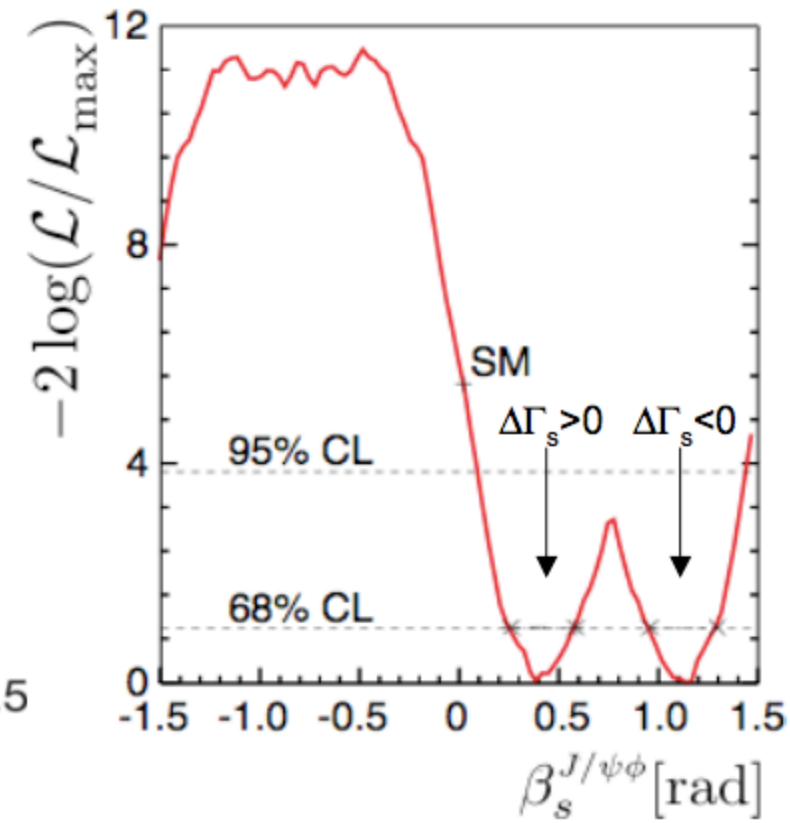
Clues?



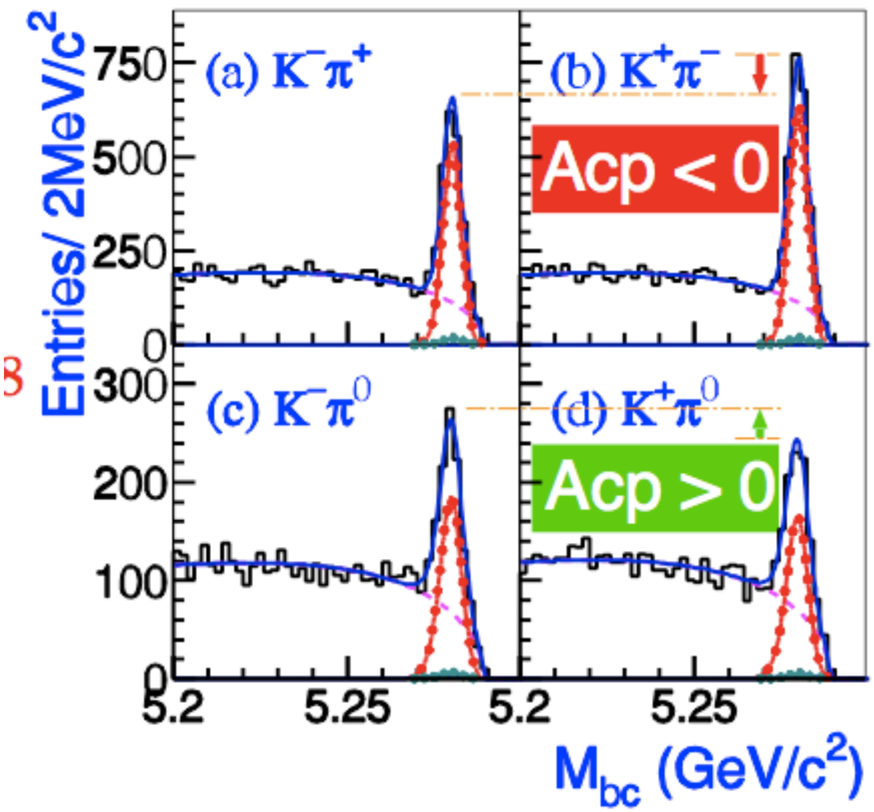
Combining with additional external constraints gives smaller SM p-value.

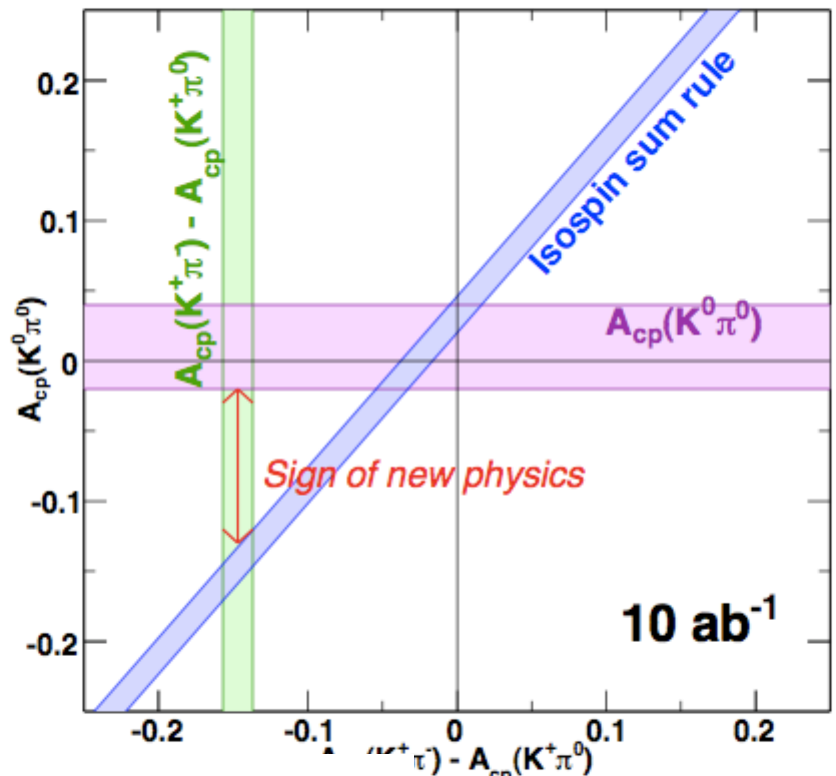
CDF/D0 combined

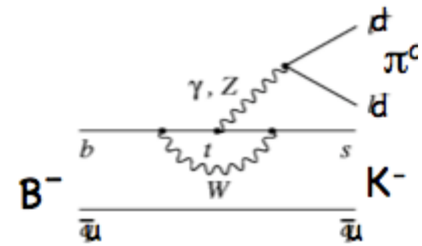




hints from B factories







$$\Delta A_{K\pi} = A_{cp}(K^+\pi^-) - A_{cp}(K^+\pi^0)$$
$$= -0.147 \pm 0.028 \ @\ 5.3\sigma$$

Fun theory

arXiv:hep-ph/0611107v2

Fourth Generation CP Violation Effect on $B \to K\pi$, ϕK and ρK in NLO PQCD

Wei-Shu Hou[1], Hsiang-nan Li[2,3], Satoshi Mishima[4], and Makiko Nagashima[5]

We study the effect from a sequential fourth generation quark on penguin-dominated two-body nonleptonic B meson decays in the next-to-leading order perturbative QCD formalism. With an enhancement of the color-suppressed tree amplitude and possibility of a new CP phase in the electroweak penguin, we can account better for $A_{CP}(B^0 \to K^+\pi^-) - A_{CP}(B^+ \to K^+\pi^0)$. Taking $|V_{t's}V_{t'b}| \sim 0.02$ with phase just below 90°, which are consistent with the $b \to s\ell^+\ell^-$ rate and the B_s mixing parameter Δm_{B_s}, we find a downward shift in the mixing-induced CP asymmetries of $B^0 \to K_S\pi^0$ and ϕK_S. The predicted behavior for $B^0 \to \rho^0 K_S$ is opposite.

arXiv:hep-ph/0610385v4

Large Time-dependent CP Violation in B_s^0 System and Finite D^0-$\bar{D}^0$ Mass Difference in Four Generation Standard Model

Wei-Shu Hou[a], Makiko Nagashima[b], and Andrea Soddu[c]

Combining the measured B_s mixing with $b \to s\ell^+\ell^-$ rate data, we find a sizable 4 generation t' quark effect is allowed, for example with $m_{t'} \sim 300$ GeV and $V^*_{t's}V_{t'b} \sim 0.025\, e^{\pm i\, 70^\circ}$, which could underly the new physics indications in CP violation studies of $b \to s\bar{q}q$ transitions. With positive phase, large and negative mixing-dependent CP violation in B_s system is predicted, $\sin 2\Phi_{B_s} \sim -0.5$ to -0.7. This can also be probed via width difference methods. As a corollary, the short distance generated D^0-$\bar{D}^0$ mass difference is found to be consistent with, if not slightly higher than, recent B factory measurements, while CP violation is subdued with $\sin 2\Phi_D \sim -0.2$.

Summary

A lot of experiment and theoretical activity

Much I didn't mention:

- Reinterpret observables for CKM triangle in 4th gen mode
- Understand CP violation in presence of 4th gen
- explore Higgs sectors motivated by condensates of 4th gen fermions

LHC should discover or exclude up to large masses