CDF in its prime

Searching for b′,ν′,Z′, and friends

Daniel Whiteson, UC Irvine

RAL HEP Seminar

Feb 3, 2010

Outline

I. General strategy
II. 4th-gen down quark: $b' \rightarrow Wt$
III. Limits on b′ and t′ for all decay modes
IV. Majorana neutrino ν′ (N)
V. Z′ search

Searching for New Physics

Goals:

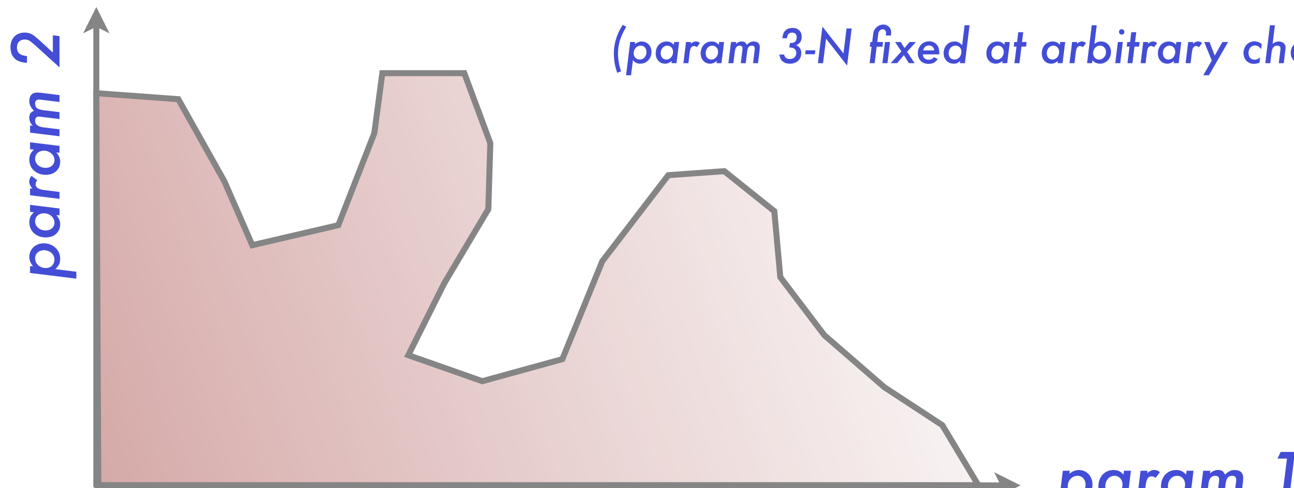
1) Maximize possibility for discovery

2) Learn something no matter what we see

Traditional approach

Bet on a specific full theory

Optimize analysis to squeeze out maximal sensitivity to new physics.



Strengths

Can be very sensitive to this 2D subspace of this full theory

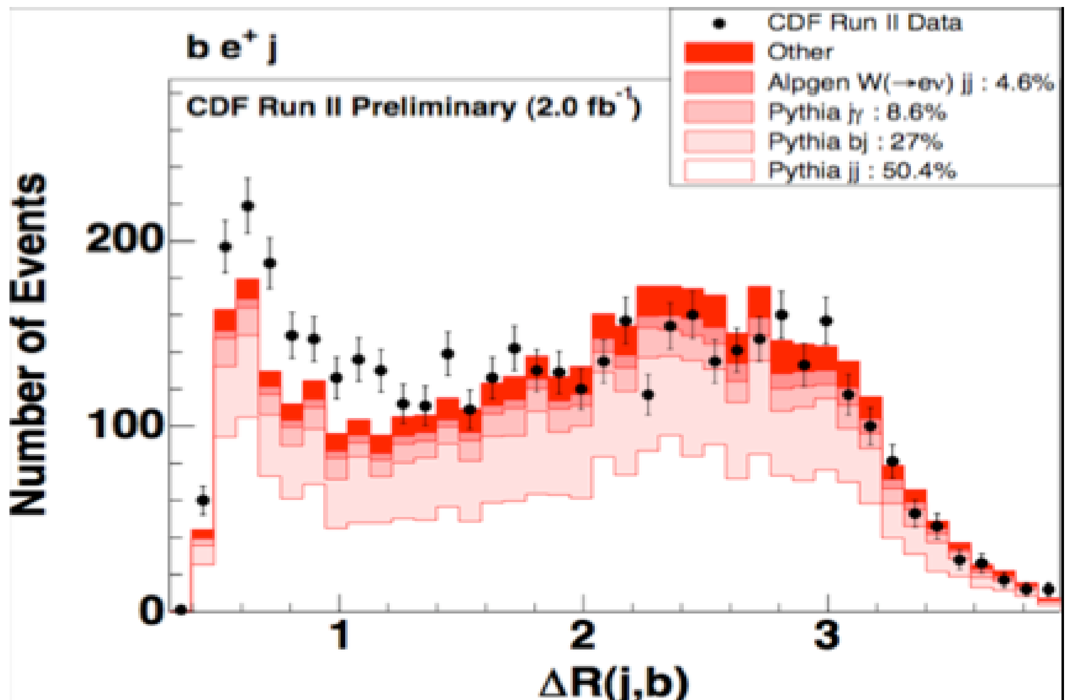
Weaknesses

If many parameters, can only search a subspace
Sensitivity is very narrow
Learn little if you don't discover – did you think the theory was true?

Model independent search

Discard the model

compare data to standard model



Strengths

Broad sensitivity

Weaknesses

Sensitivity is shallow

Discrepancies are hard to interpret

Lack of discrepancies is hard to interpret

Compromise

<u>A necessary step</u>

New signal requires a coherent physical explanation, even trivial

<u>Generalize the model</u>

Focus on the general experimental sensitivity

Construct simple models that describe classes of new physics

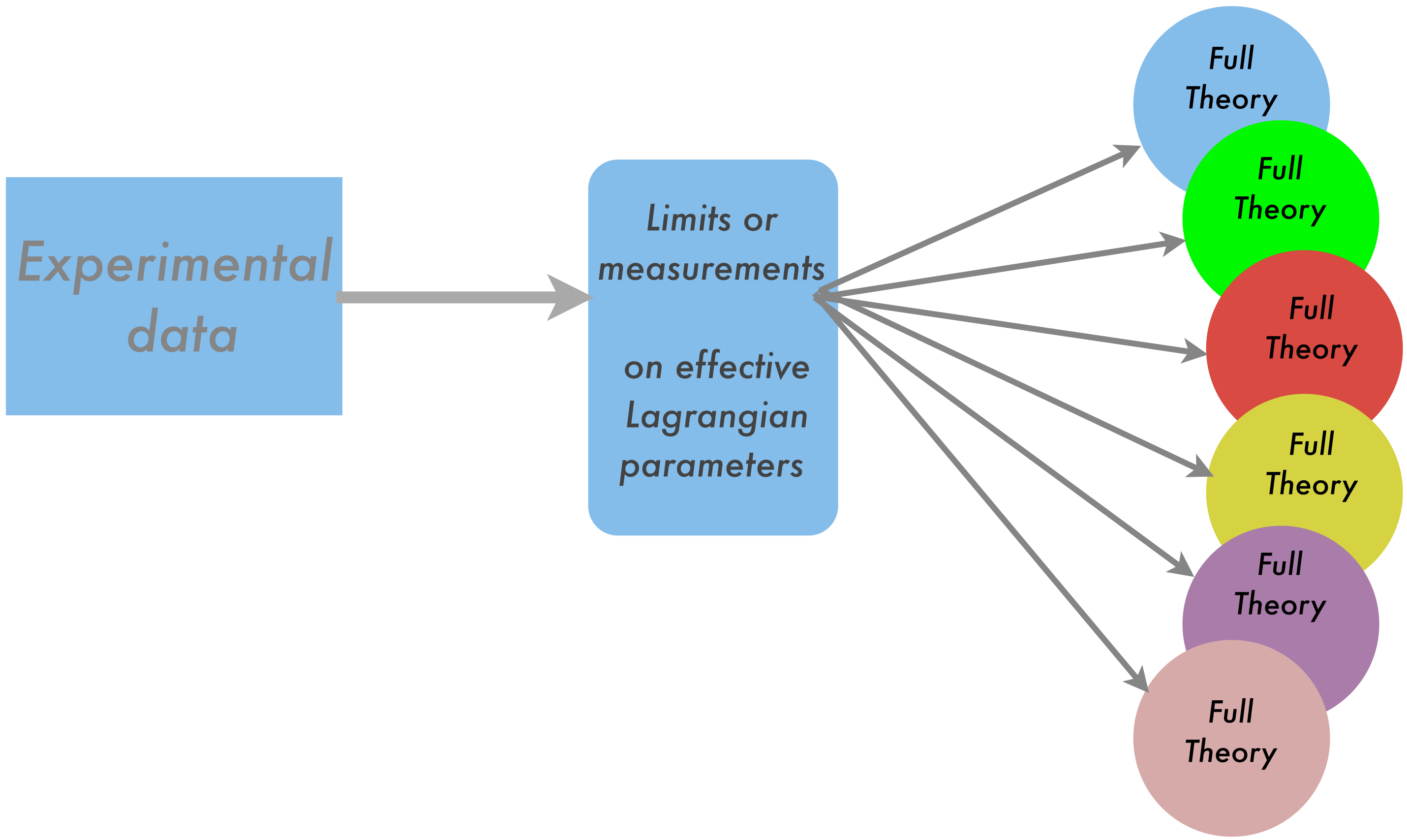
Do it in advance to allow us to think about how & where to look

<u>Examples</u>

Simple SM extensions: b', t', $\nu'(N)$, Z', etc

Effective Lagrangian

A natural, compact language for communication between theory and experiment.



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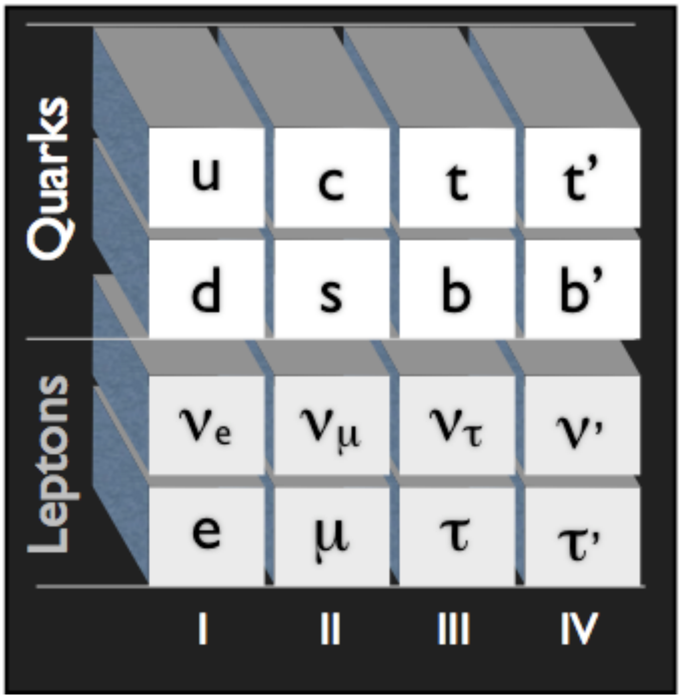
b′



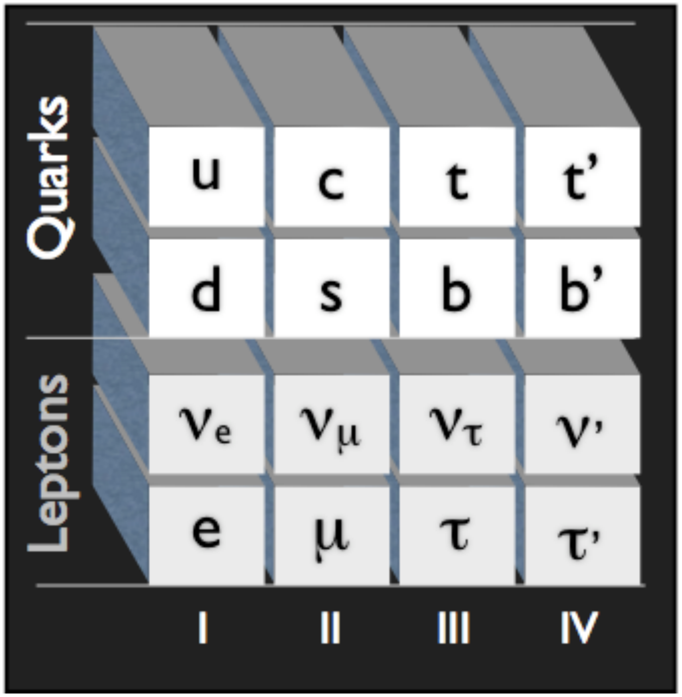
<u>4th generation</u>

Why not?

Natural extension.

PDG says it's excluded to 6σ

b′



<u>4th generation</u>

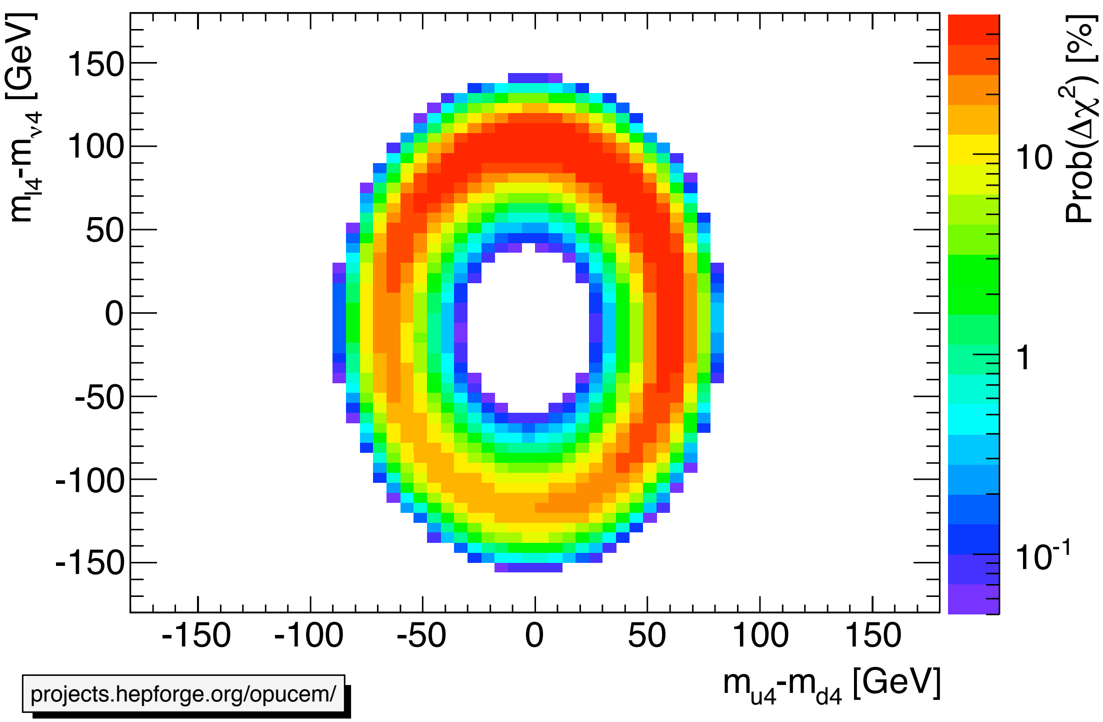
Why not?

Natural extension.

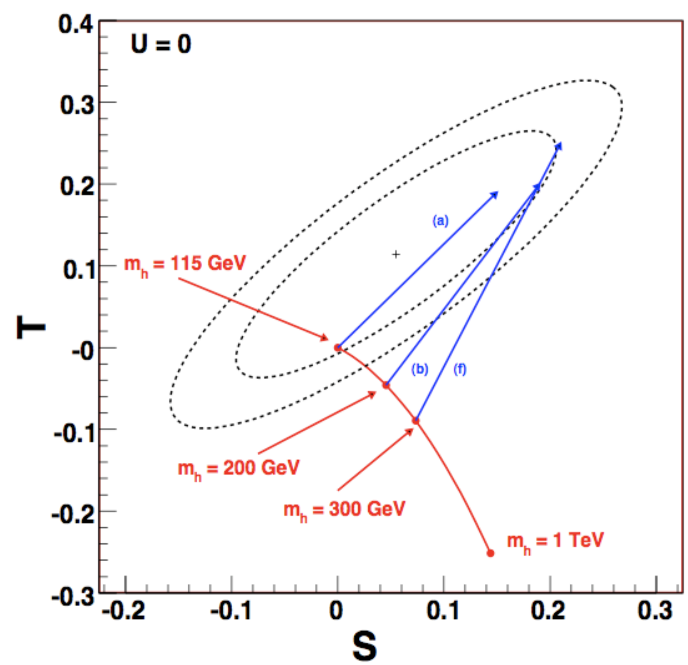
PDG says it′s excluded to 6σ … if masses are degenerate

Masses

Consistency with EW S+T parameters requires mass splitting



4th gen allows a heavier Higgs to be consistent with S+T



Mixing

4x4 unitarity gives

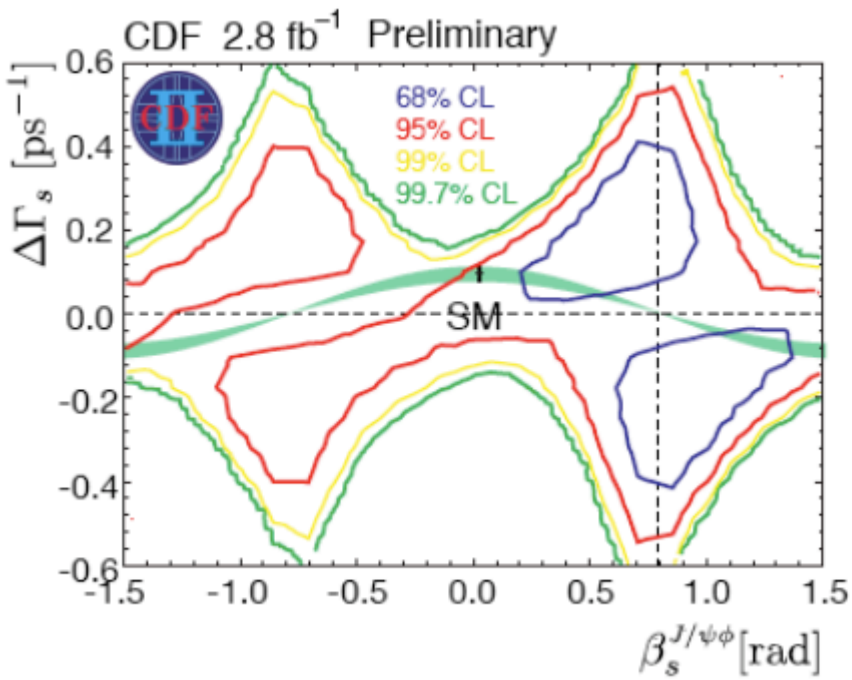
$$|V_{ud_4}| \lesssim 0.04$$
$$|V_{u_4 d}| \lesssim 0.08$$
$$|V_{cd_4}| \lesssim 0.17$$

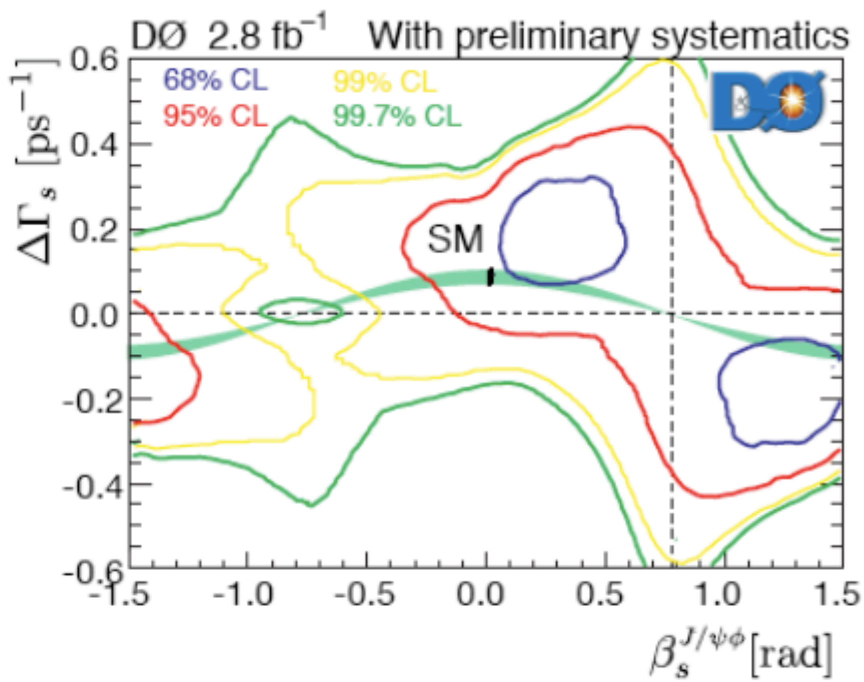
Kribs, Plehn, Spannowsky, Tait
arXiv/0706.3718

Single top gives
$|V_{tb}| \gtrsim 0.68$

Deviations

B_s mixing at the Tevatron





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.

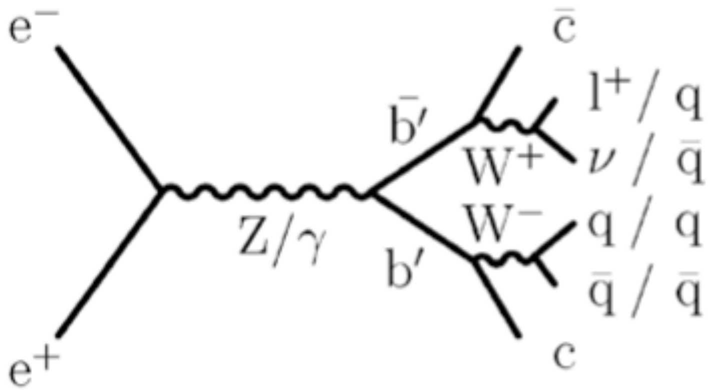
arXiv:hep-ph/0610385v4

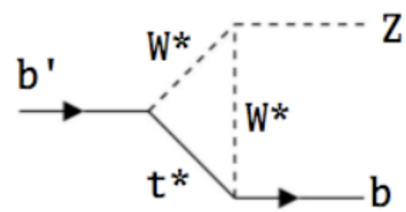
Large Time-dependent CP Violation in B_s^0 System and Finite D^0-$\bar{D}^0$ Mass Difference in Four Generation Standard Model

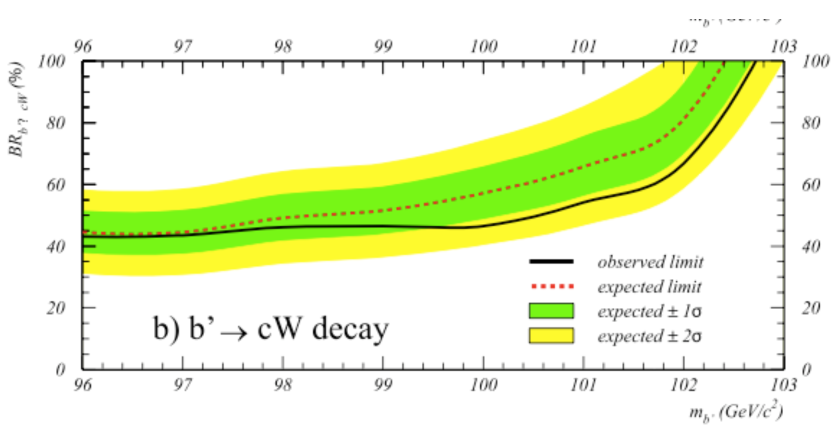
Wei-Shu Hou[a], Makiko Nagashima[b], and Andrea Soddu[c]

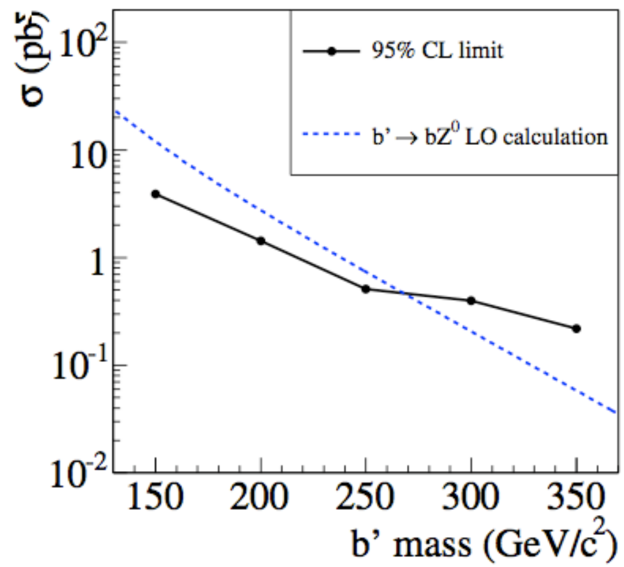
Combining the measured B_s mixing with $b \to s\ell^+\ell^-$ rate data, we find a sizable 4 generation t' quark effect is allowed, for example with $m_{t'} \sim 300$ GeV and $V^*_{t's}V_{t'b} \sim 0.025\, e^{\pm i\, 70^\circ}$, which could underly the new physics indications in CP violation studies of $b \to s\bar{q}q$ 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 $\sin 2\Phi_D \sim -0.2$.

Direct limit









<u>$m_{b'}$ > 268 GeV</u>

If BR(b′→bZ=100%)

Unlikely for $m_{b'} > m_W + m_{top}$ = 255

Signal & Selection

<u>Selection</u>

2 like-signed leptons

pt>20 GeV

at least one isolated

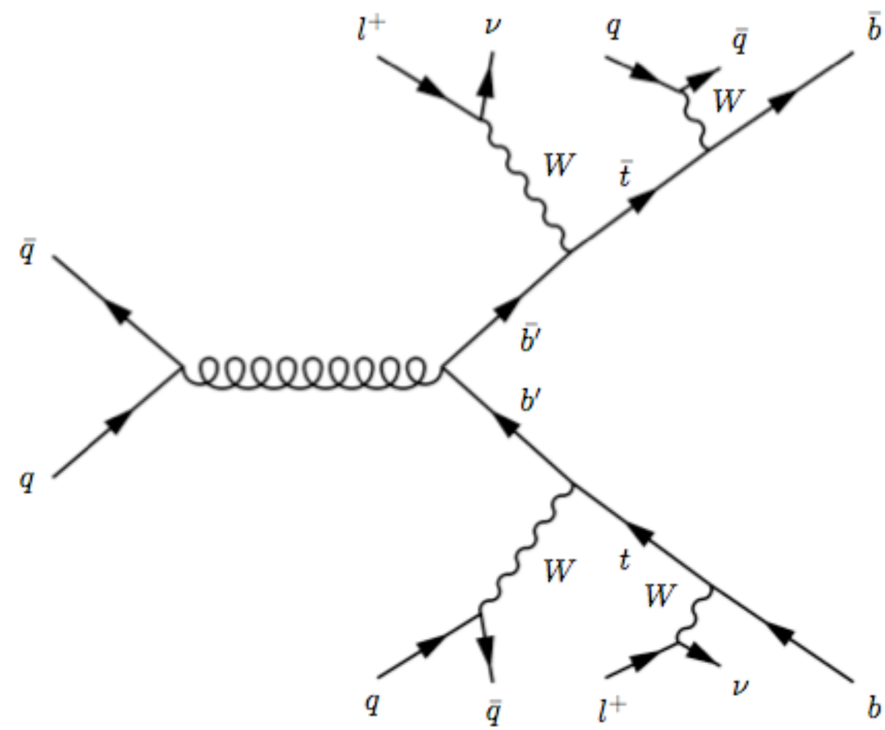
2 jets

pt>20 GeV

>=1 btags

Missing transverse energy

>20 GeV

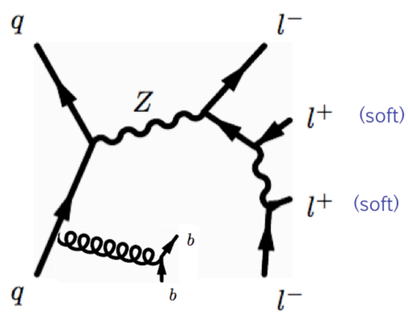


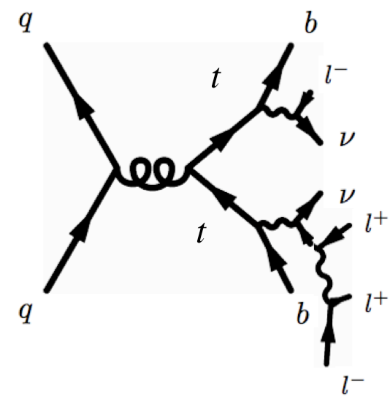
<u>Sample</u>

2.7/fb

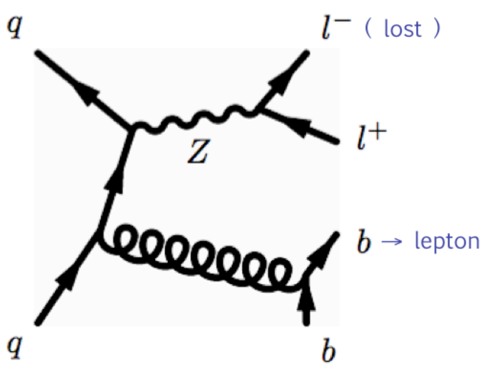
Strategy

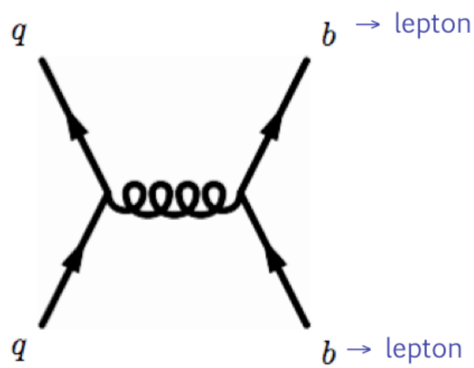
Tridents: use simulated events

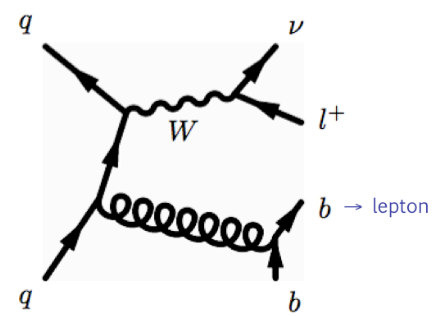


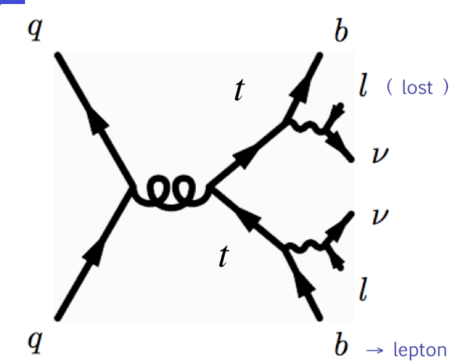


Fake leptons: use a data-driven strategy









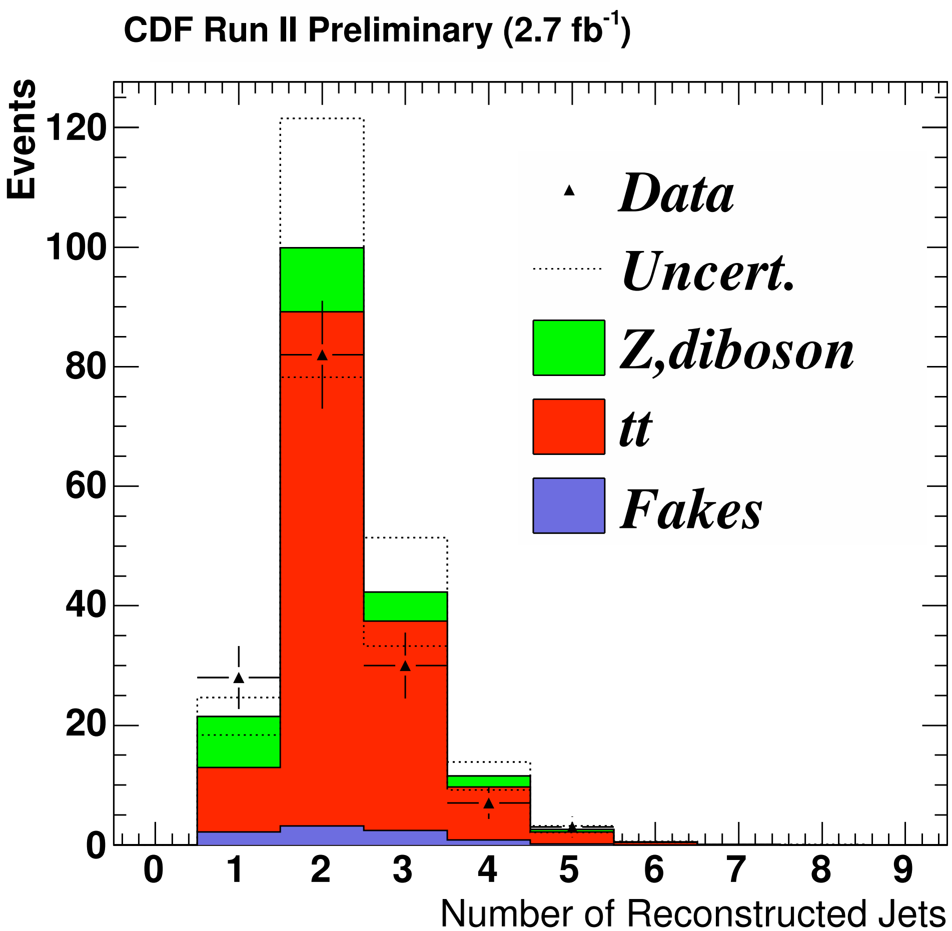
top quark pairs (2.7/fb)

<u>Cross-check</u>

2 opposite-signed leptons

>=1 jet *>=1 btags*

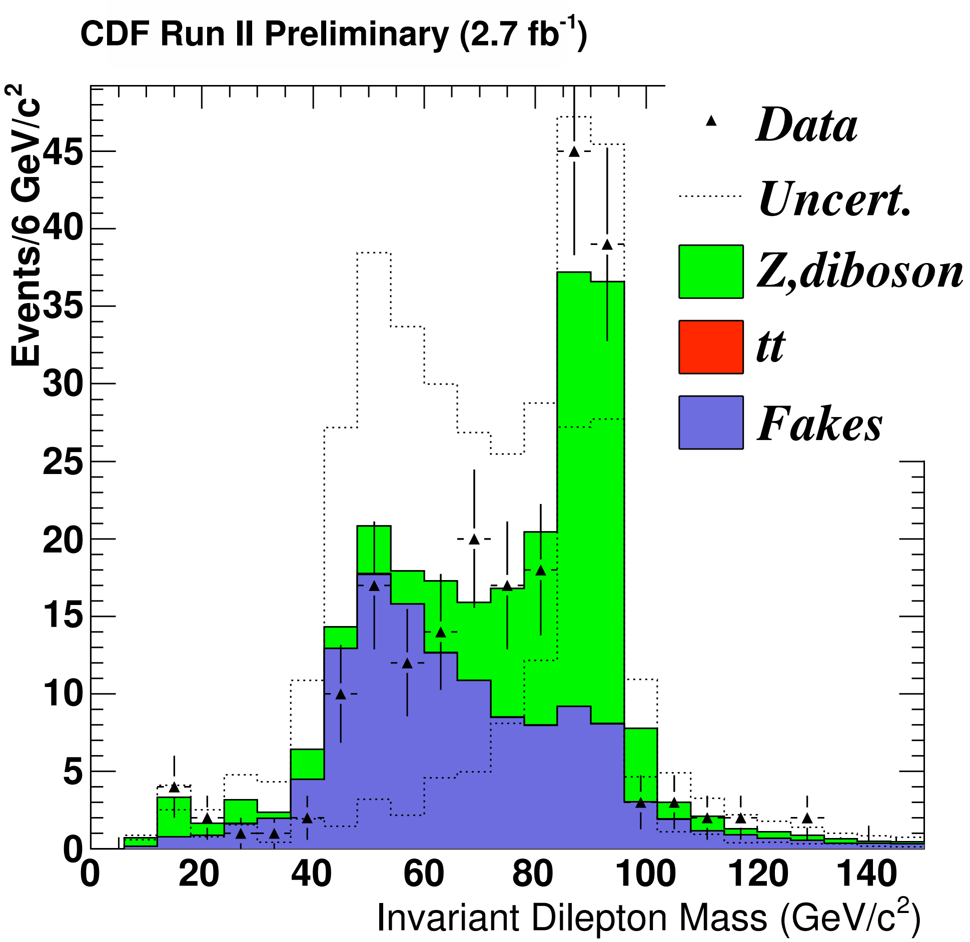
Missing transverse energy



Same-sign leptons (2.7/fb)

Cross-check

2 like-signed leptons



Final selection (2.7/fb)

Final selection
2 like-signed leptons
2 jets *>=1 btags*
Missing transverse energy

Source	*ee*	*μμ*	*eμ*	*ll*
Z	0.01 ± 0.01	0	0.02 ± 0.02	0.03 ± 0.03
top dilep	0.06 ± 0.04	0	0.09 ± 0.03	0.15 ± 0.05
Fakes	0.6 ± 0.6	0.3 ± 0.3	0.5 ± 0.5	1.4 ± 1.4
Total	0.7 ± 0.6	0.3 ± 0.3	0.6 ± 0.5	1.6 ± 1.4
Data	0	1	1	2

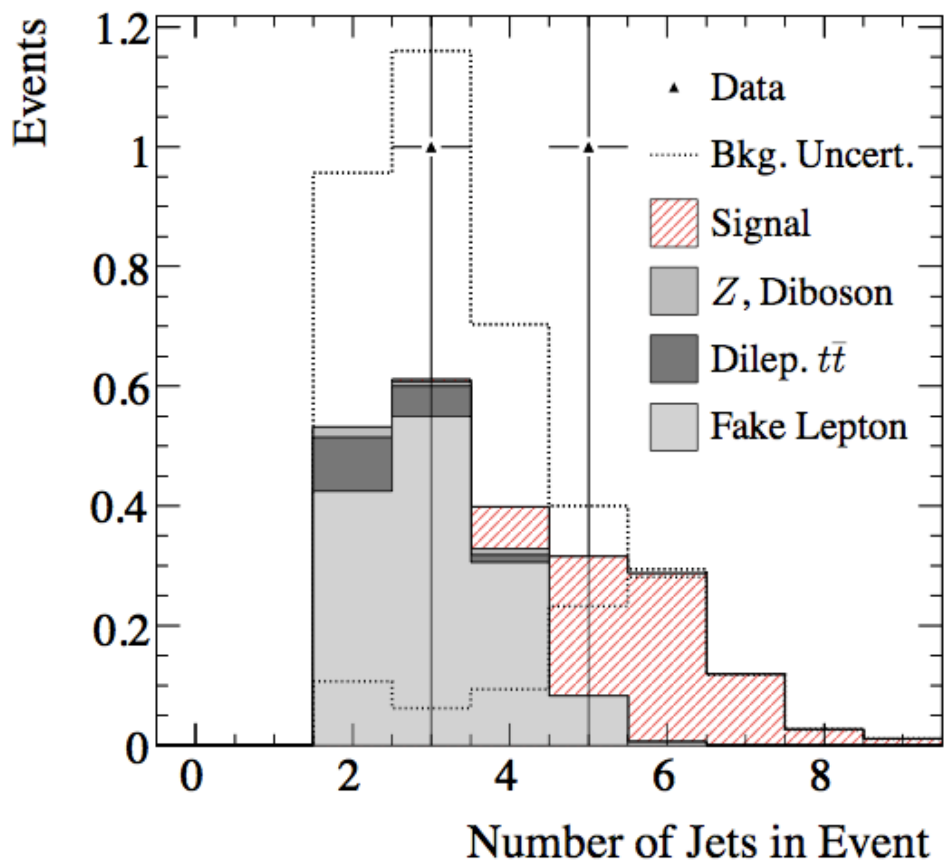
Final selection (2.7/fb)

<u>Final selection</u>

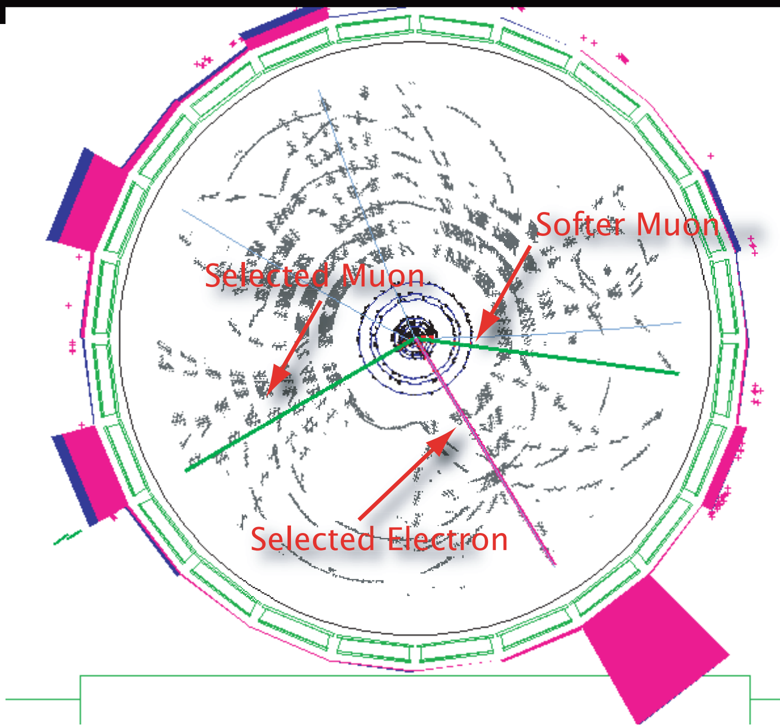
2 like-signed leptons

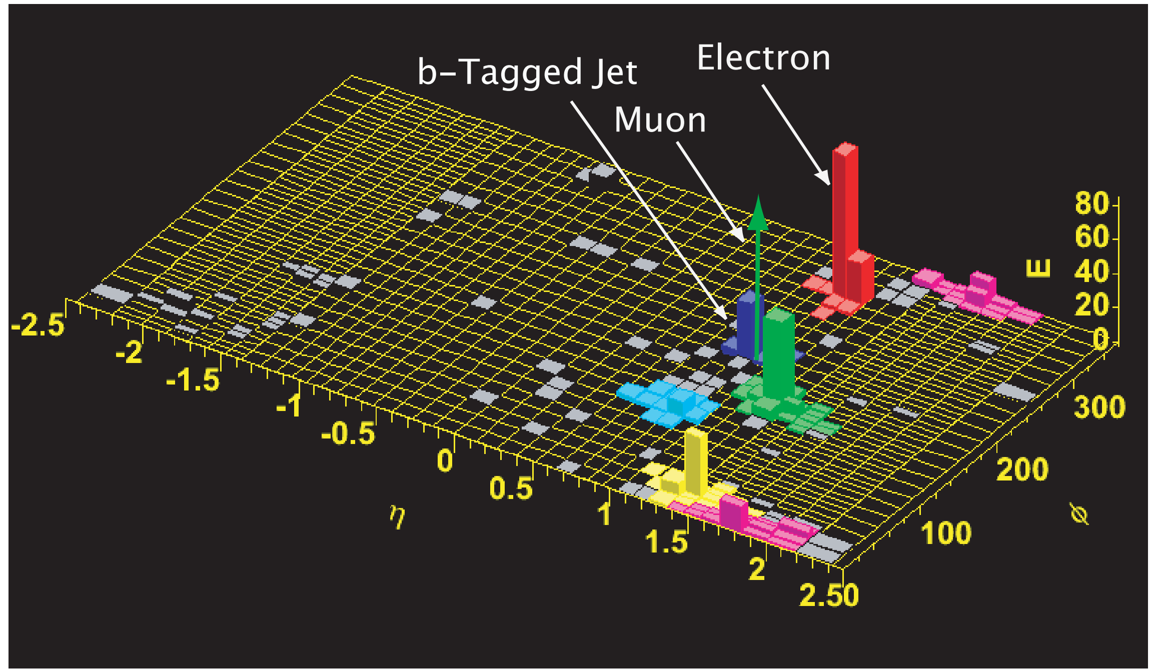
2 jets *>=1 btags*

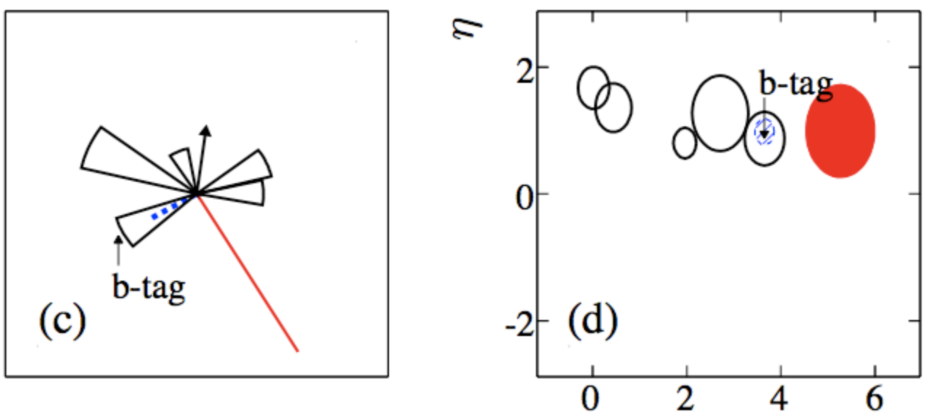
Missing transverse energy



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







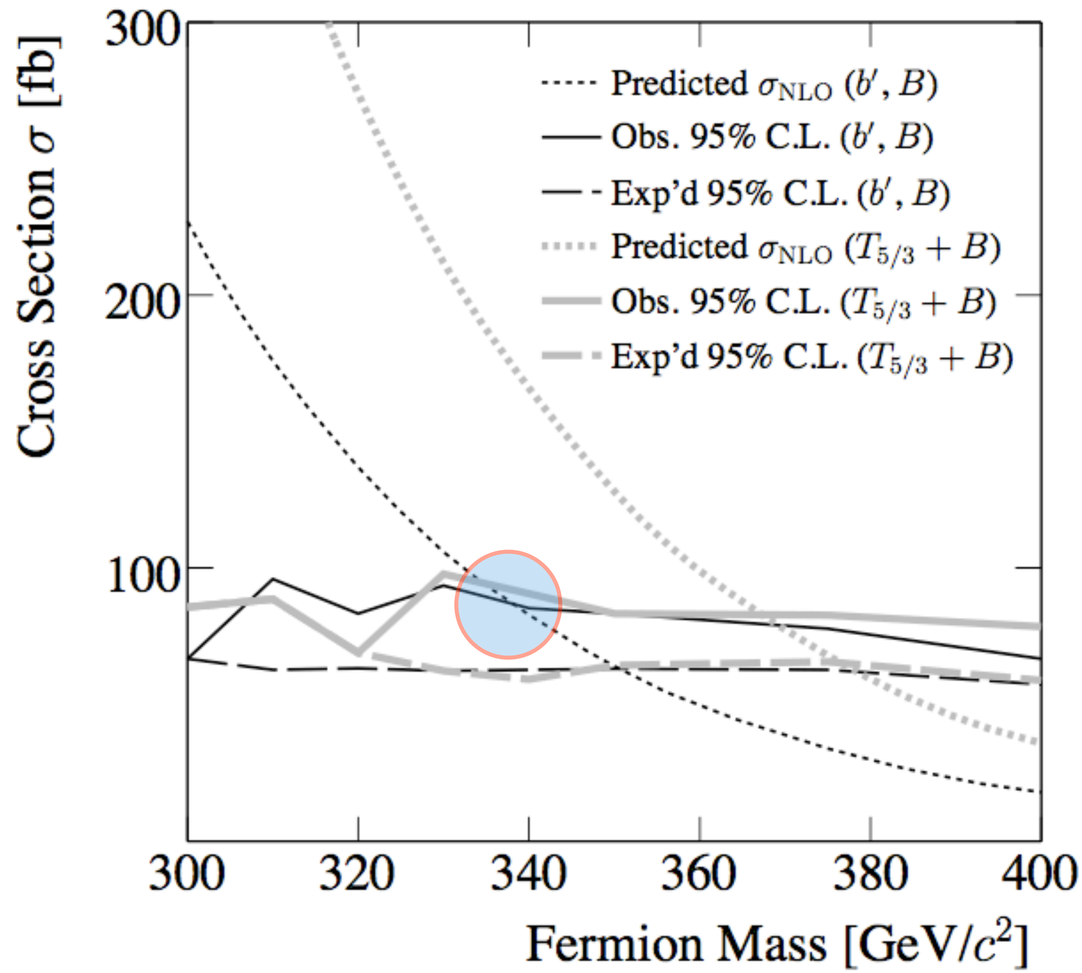
r-ϕ Projection

Jet
Electron
Muon

Limits

Limit

$m_{b'}$ > 338 GeV



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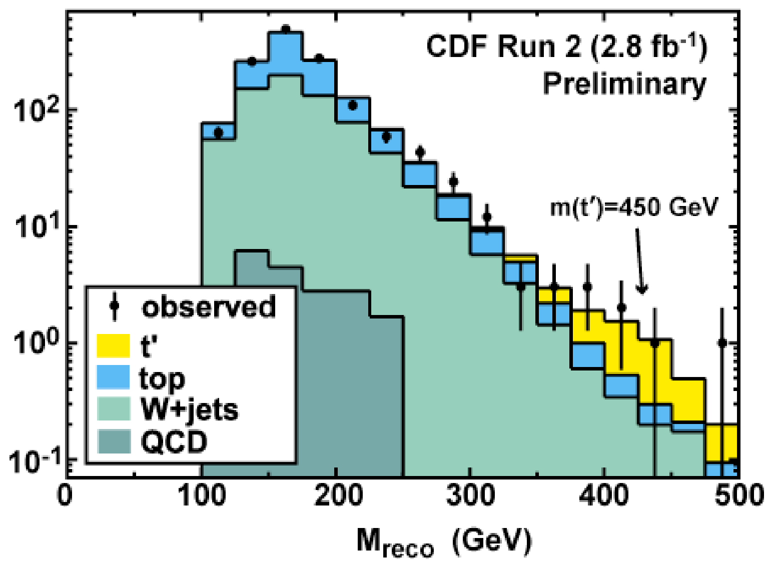
Tevatron Direct searches

t′

m > 311 GeV

If t′→Wq

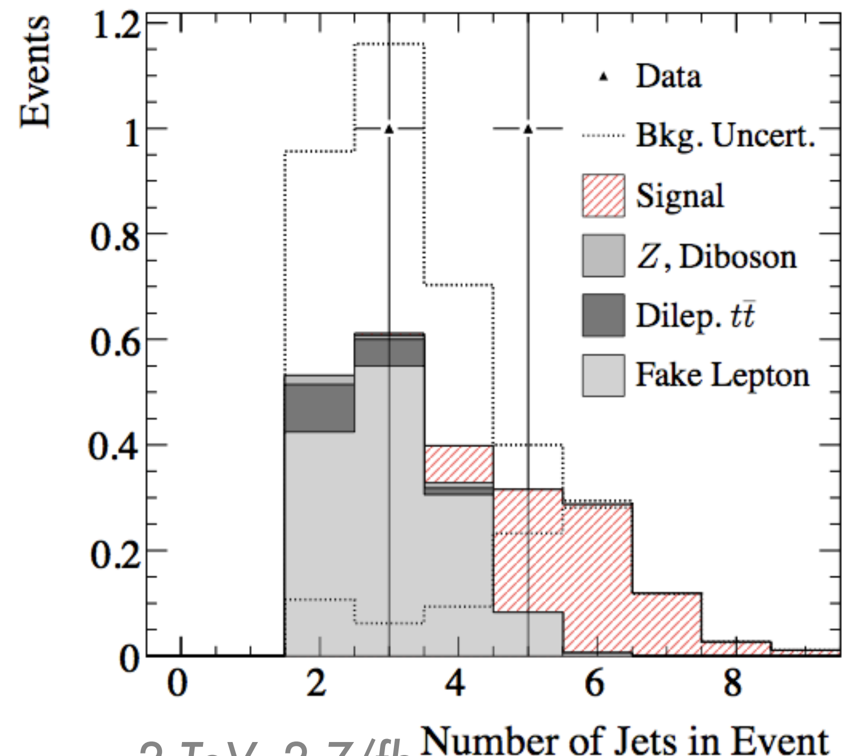


2 TeV, 2.8/fb
CDF9446

b′

m > 338 GeV

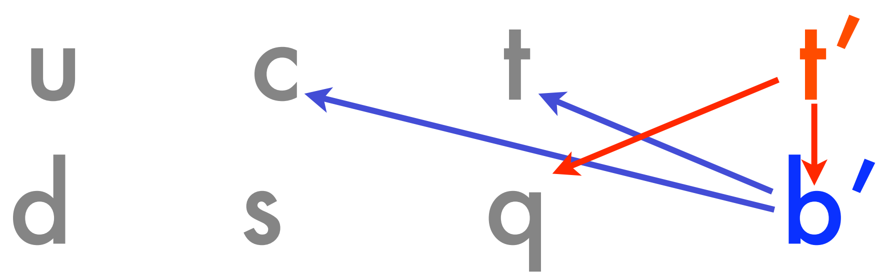
if b′→Wt



2 TeV, 2.7/fb
arxiv:0912.1057

Modes

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	$t' \to WWq$	$t' \to WWWb$
	$b' \to Wq$	$b' \to WWb$

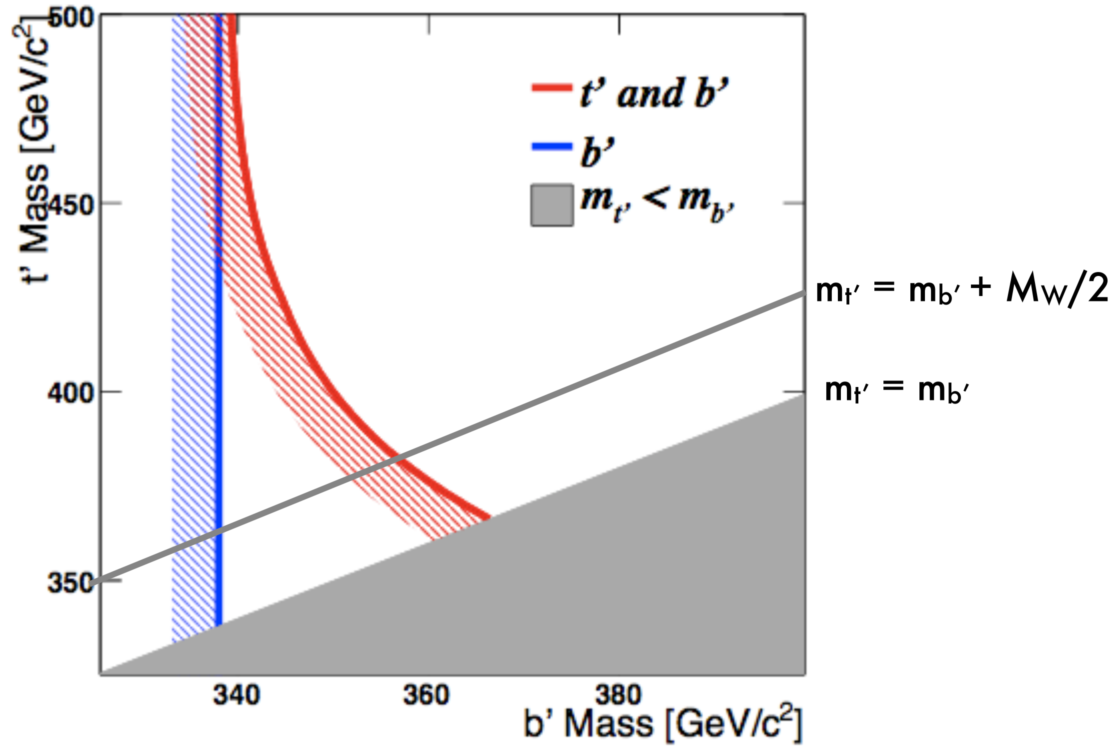
No direct limits!

Old data, new modes

<u>WWb data sensitive to both</u>

b′→Wt →WWb

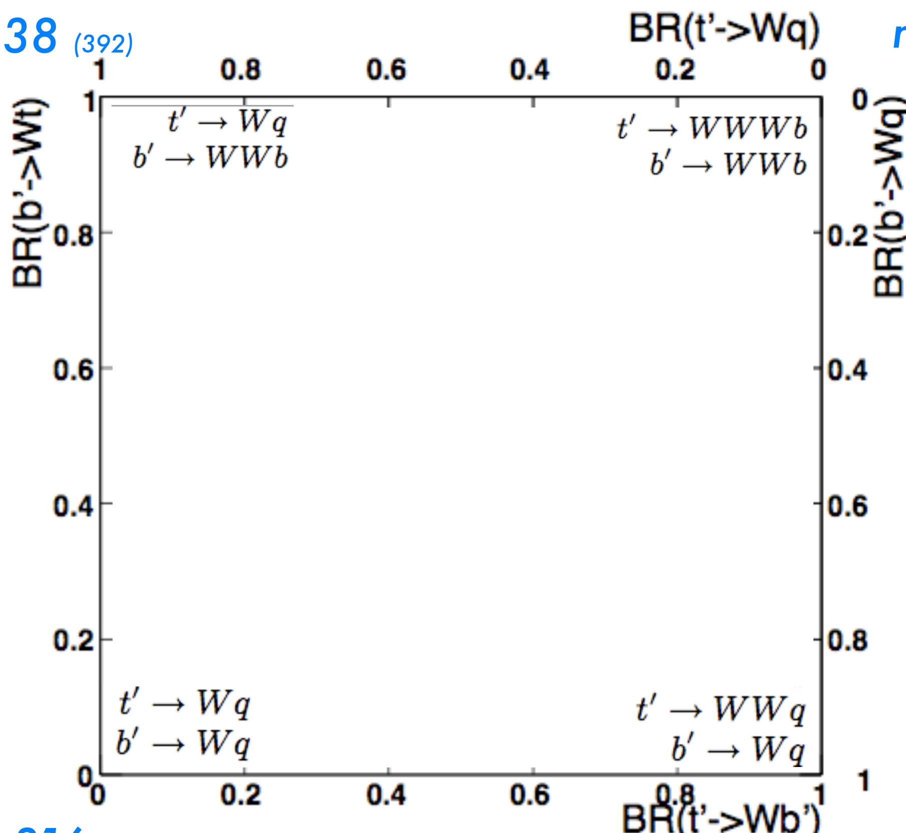
t′→Wb′→WWt →WWWb



Four corners

$m_{t'} > 311$
$m_{b'} > 338$ (392)

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



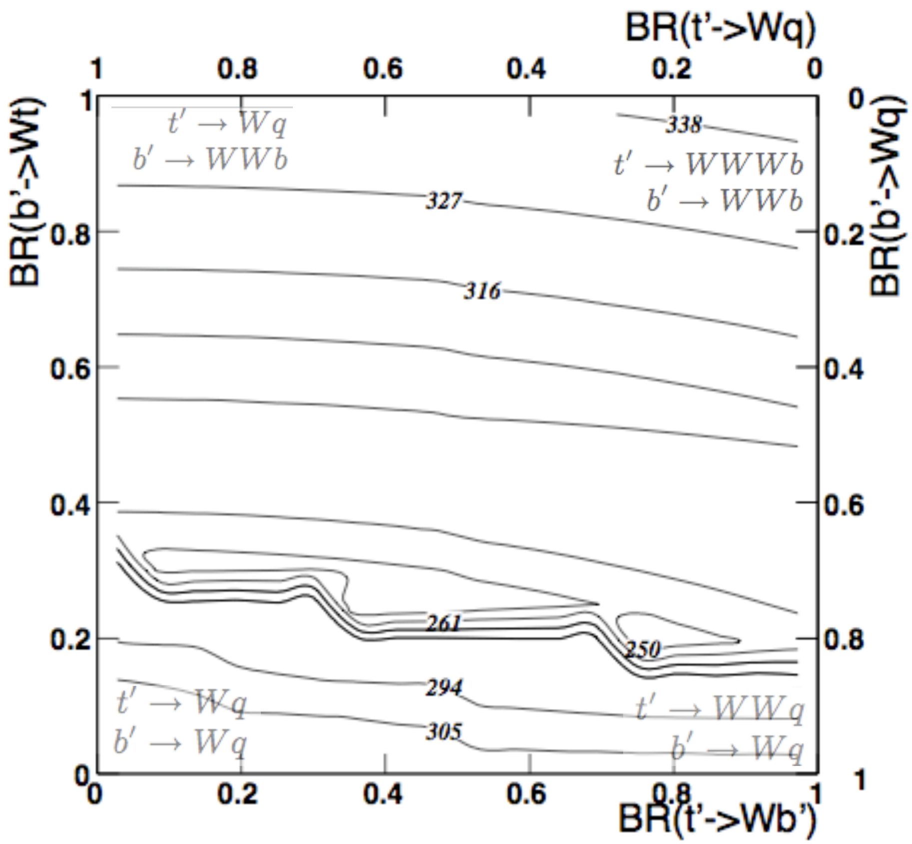
$m_{t'} > 316$
$m_{b'} > 397$

$m_{t'} > 285$ (392)
$m_{b'} > 311$

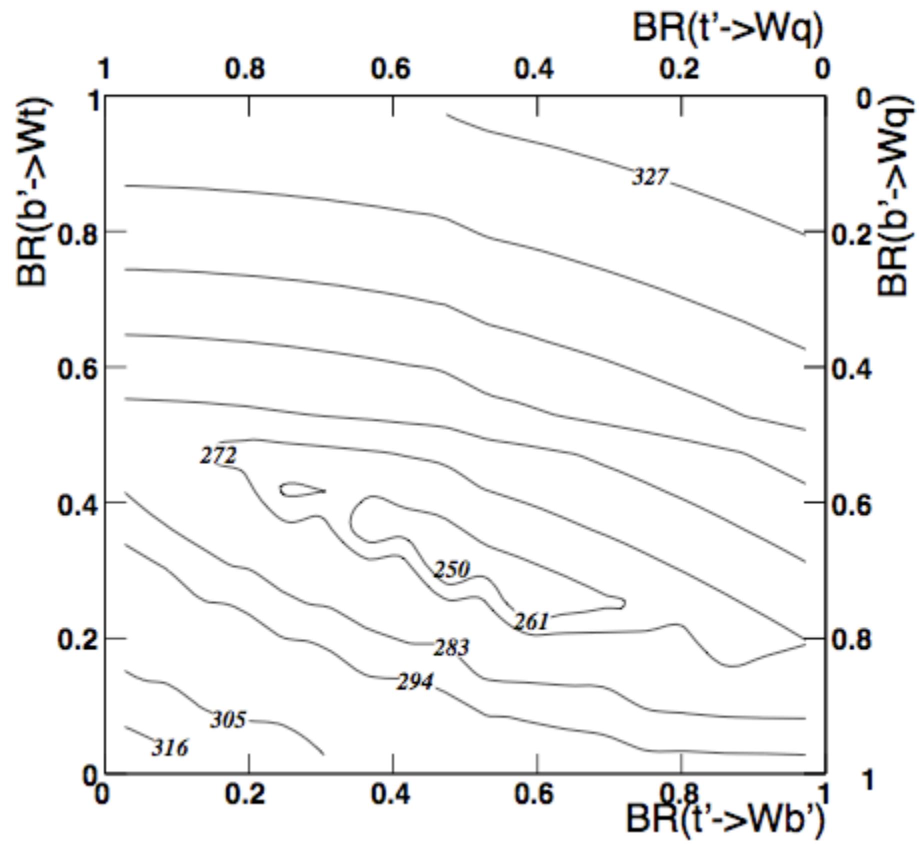
$$m_{t'} = m_{b'} + M_W$$

All data

Limits on lighter quark mass (b′)



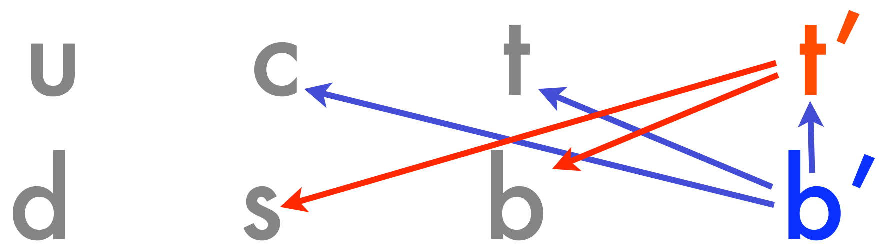
$m_{t'} = m_{b'} + M_W$



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

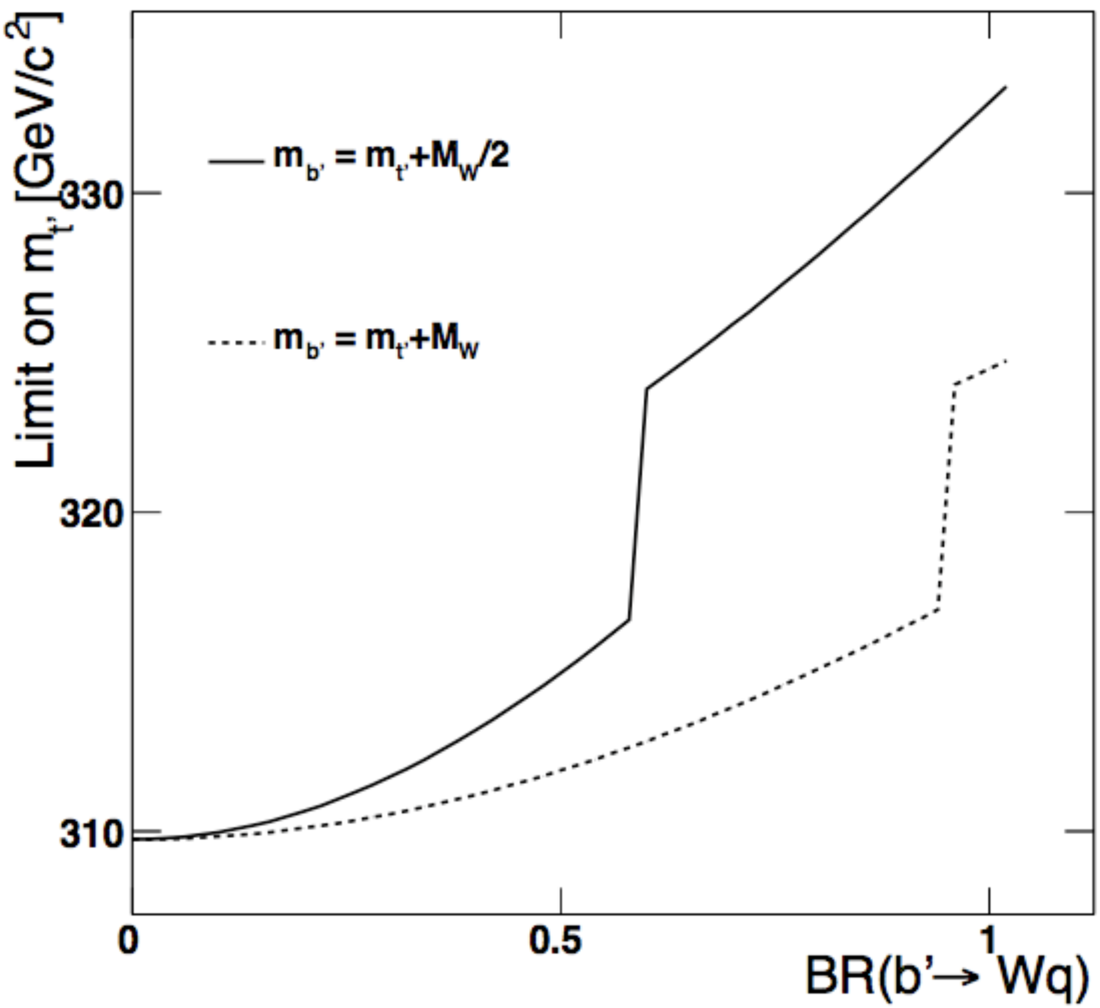
Modes

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.

Conclusions

Specific searches can be broadly interpreted

Two datasets (Wq and WWb) largely complementary.

Limits can be placed in almost all of mixing space.

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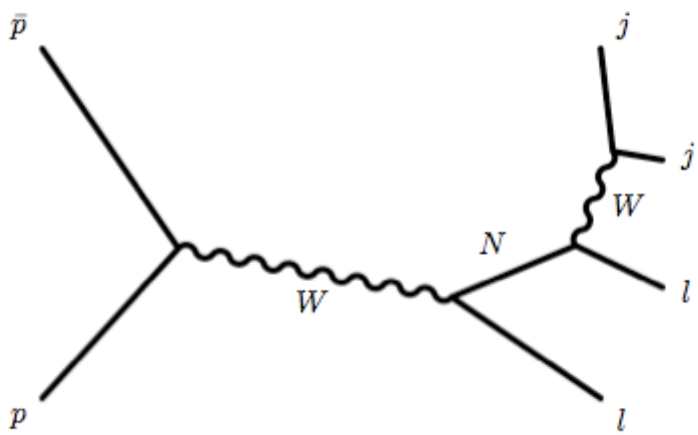
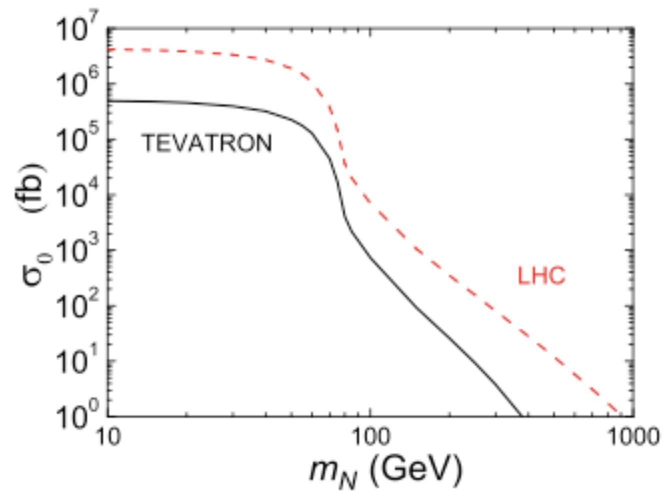
Majorana neutrinos

Production via W has been studied





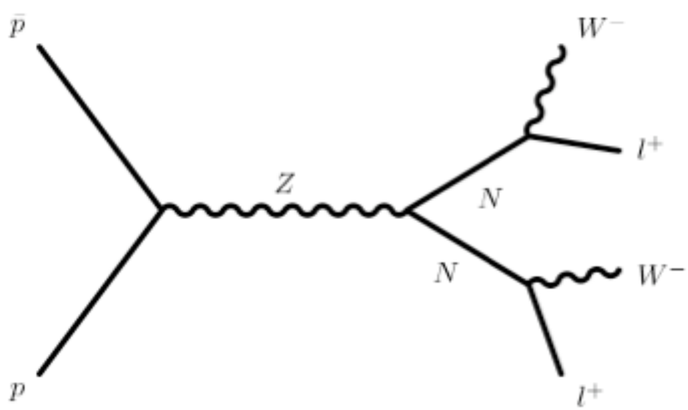
hep-ph/0604064

LEP limits at 90 GeV

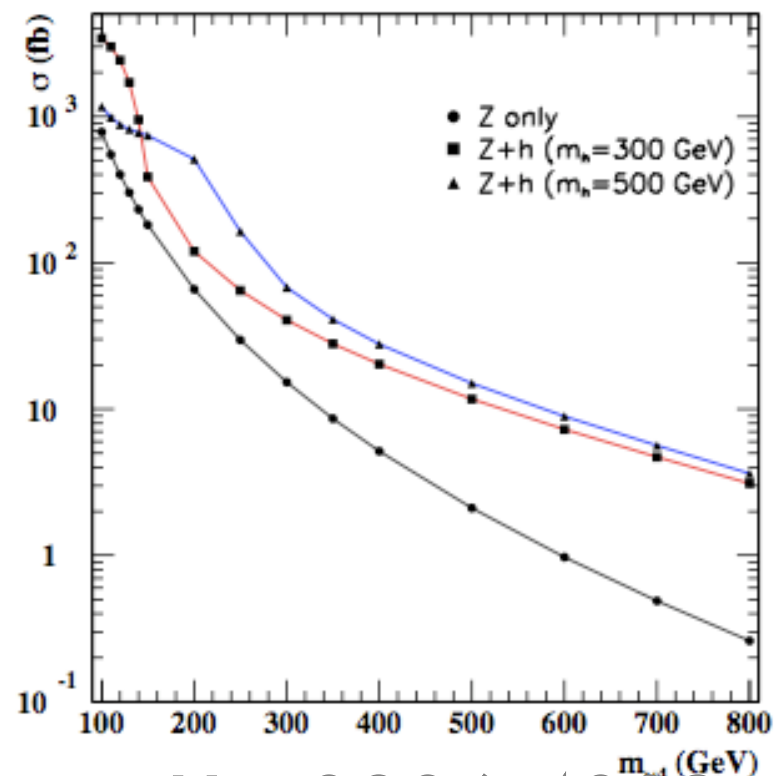
Majorana neutrinos

Production via Z

avoids *WIN* vertex in production mechanism

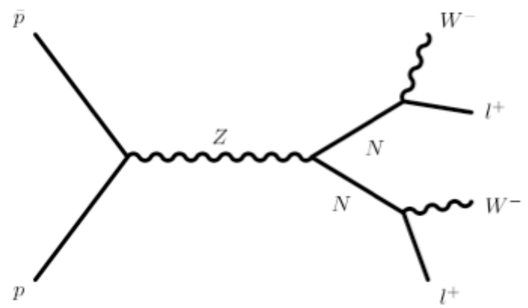


One mass point studied for LHC



arXiv:0806.4003

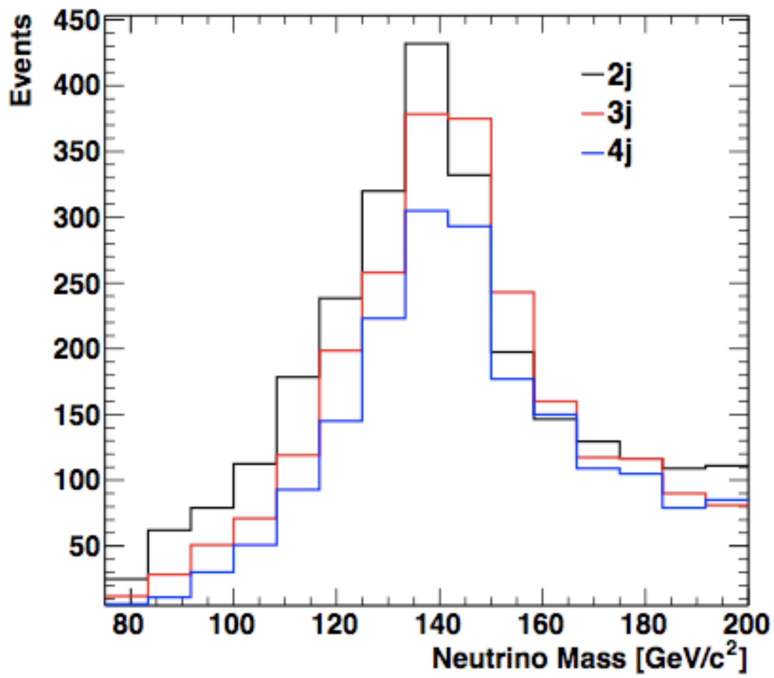
Reconstruction



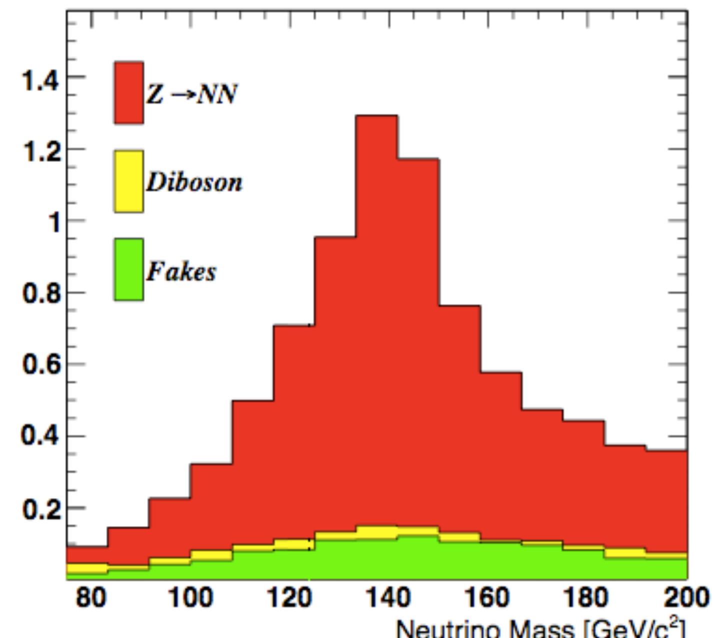
arXiv:1001.1229

Reconstruct N mass as M_{ljj}

Mass reconstruction



Signal and backgrounds



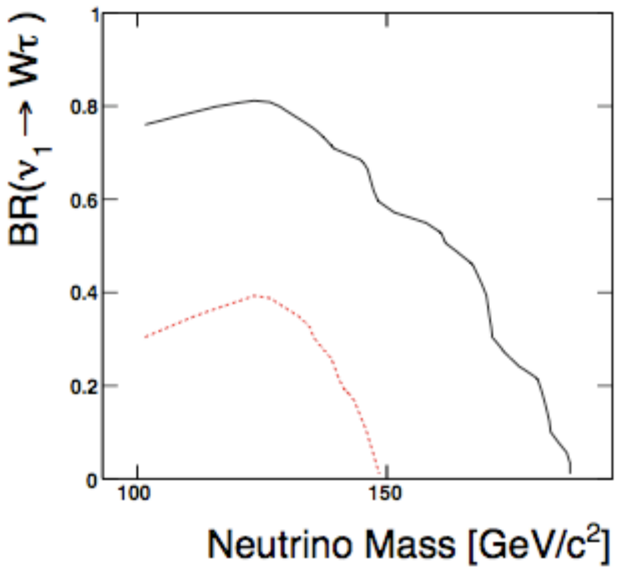
Study using parametric detector sim (PGS)

Not official CDF results

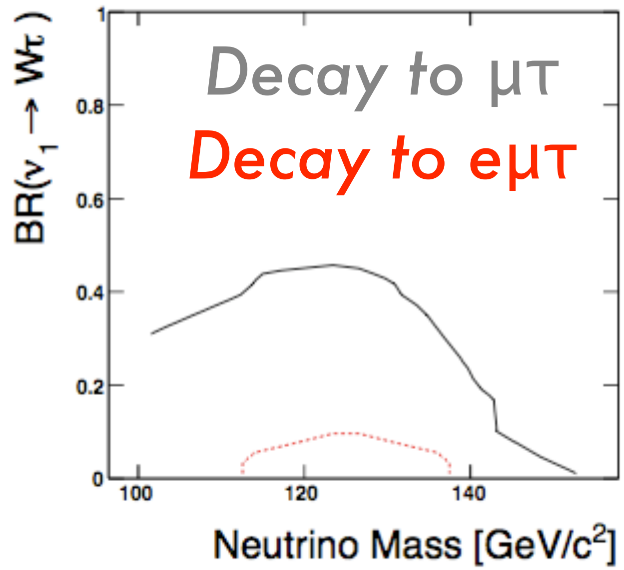
Power

arXiv:1001.1229

95% Exclusion



3σ evidence



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

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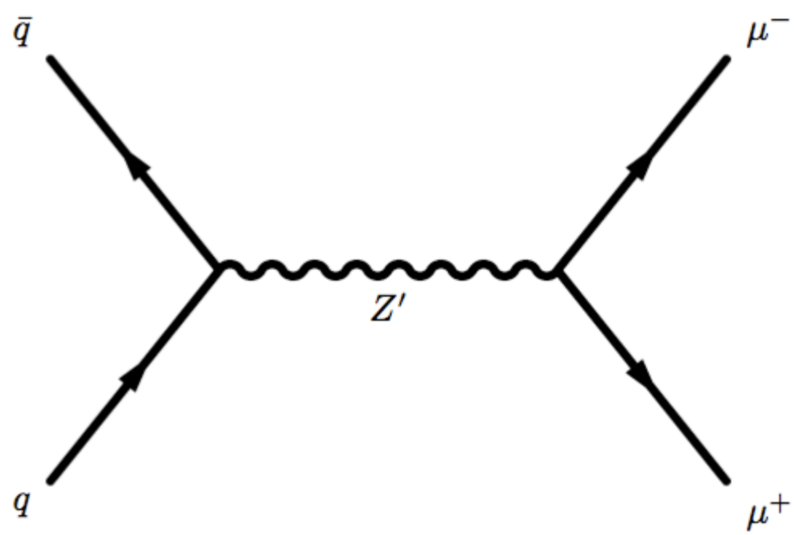
Z'



New heavy boson

Simple extension

Z could be spin 0,1,2

Many models

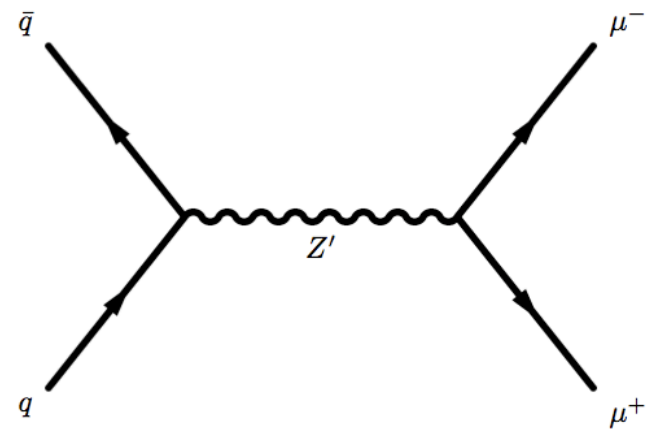
We'll use an effective Lagrangian with a new added particle.

Sample & Selection

Selection

2 opp.-signed muons

p_T > 20 GeV



Target sample

5/fb

(plots are my personal projections)

Calibration sample

2.3/fb

(previous search, today's data plots)

Backgrounds (2.3/fb)

<u>Selection</u>

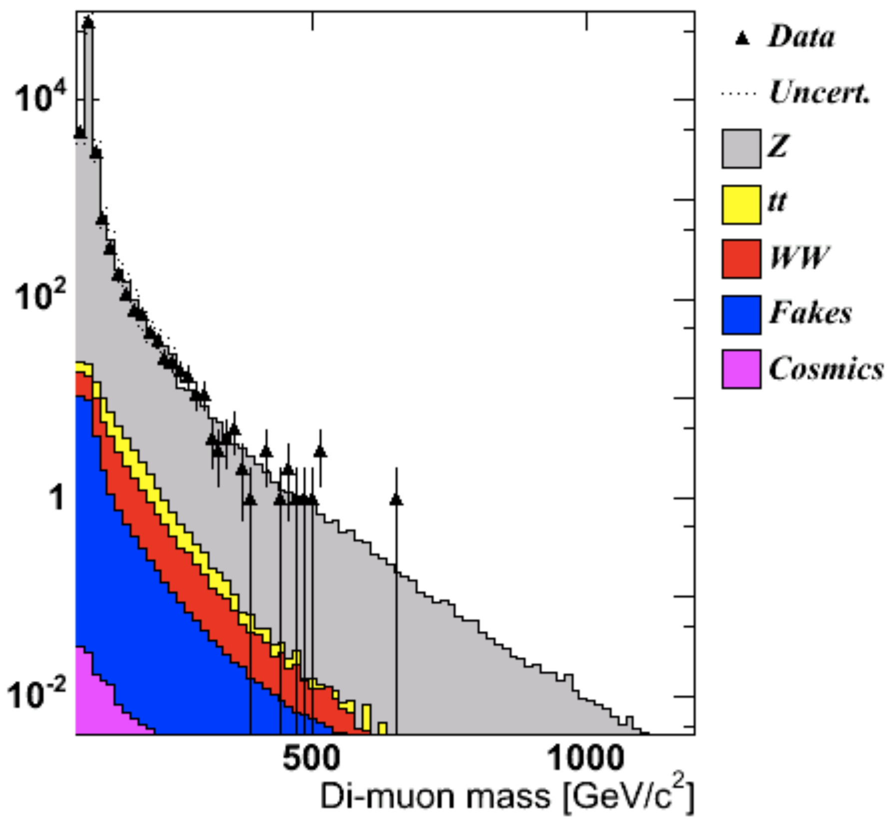
2 opp.-signed muons

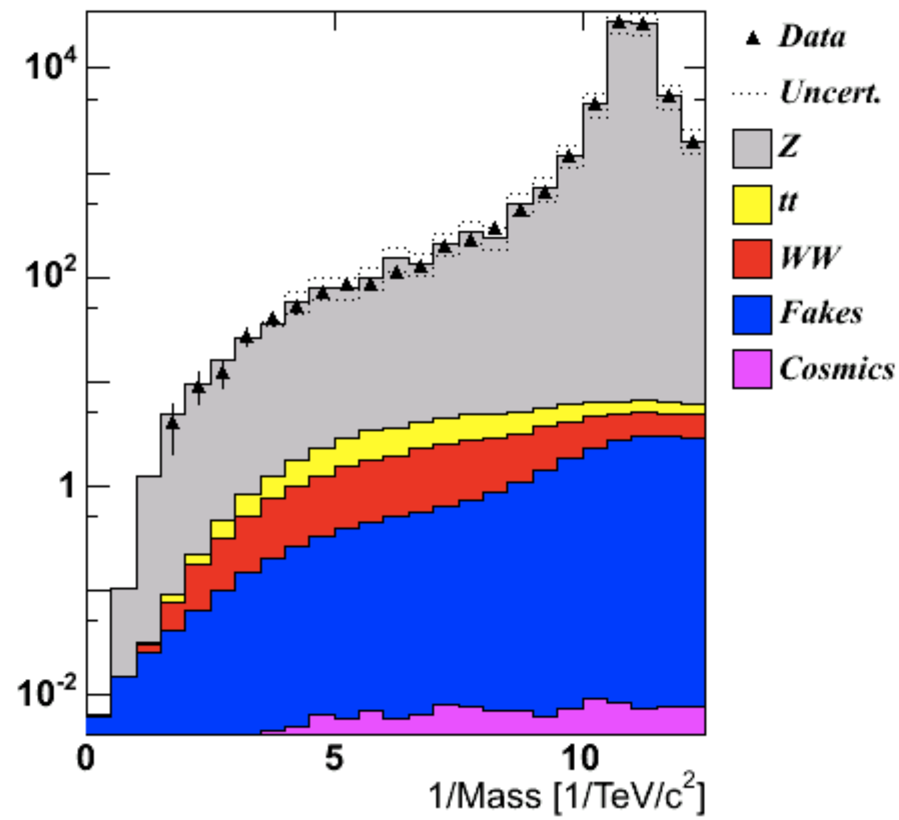
Source	Events ($M_{\mu\mu} > 70$)	Events ($M_{\mu\mu} > 250$)
Z	73983.2	89.6
WW	36.1	1.3
$t\bar{t}$	31.8	1.1
Fakes	32.0	0.3
Cosmics	0.2	0.02
Total	74083.2	92.2
Data	73732	92

Data (2.3/fb)

<u>Selection</u>

2 opp.-signed muons





Measuring mass & cross-sec

Per-event likelihood *L(M,s)*

Function of Z' mass *M* and signal fraction *s*

Calculated from the matrix-element for Z' convoluted with detector resolutions

Sample likelihood

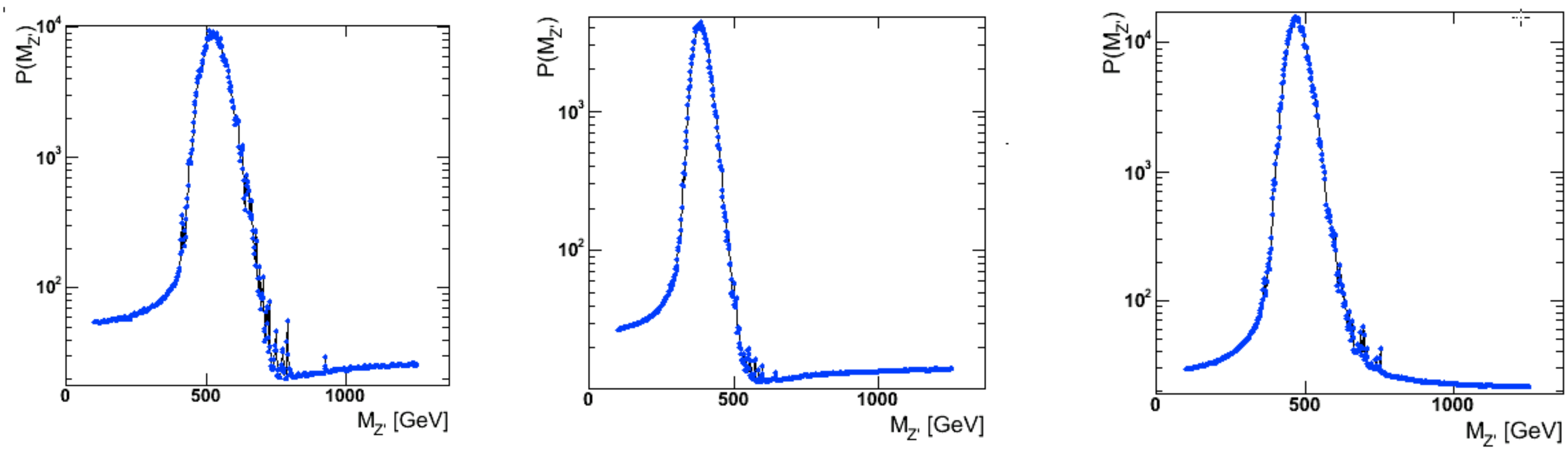
Joint likelihood over events

Find *M,s* which maximize

Why ME likelihood?

<u>More power</u>

Matrix-element-based likelihood provides different mass dependence for well-measured and poorly-measured events (more or less information)



$$\frac{d\sigma(M_{Z'})}{d\mathbf{x}} = \frac{1}{N}\int d\Phi |\mathcal{M}_{Z'}(p_i; M_{Z'})|^2 \prod W(p_i, \mathbf{x}) f_{PDF}(q_1) f_{PDF}(q_2)$$

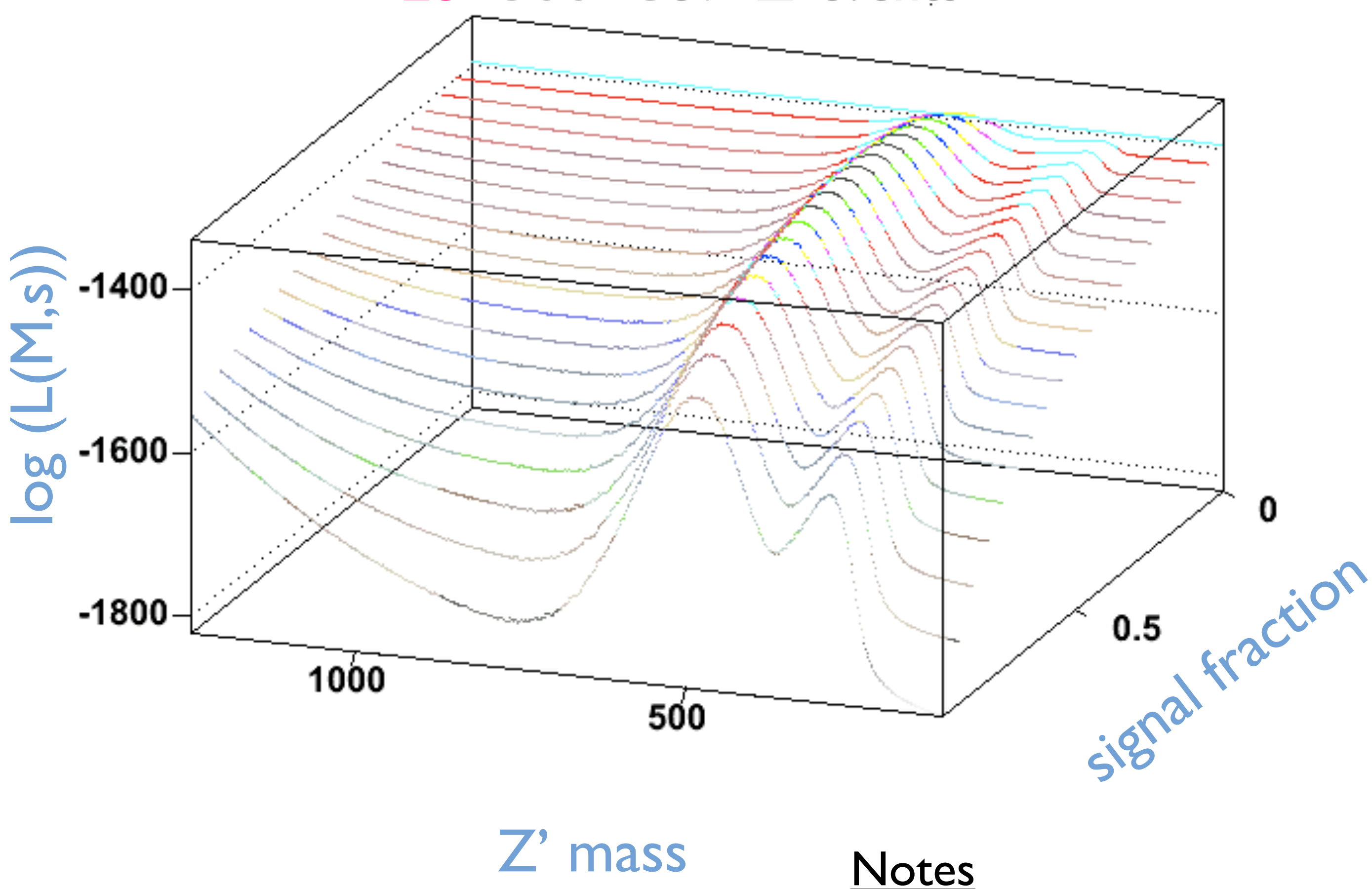
My personal toy pseudo-exp. Unofficial

2D example

Single example pseudo-experiment

92 background events,

25 500 GeV Z' events



My personal toy pseudo-exp. Unofficial

Notes

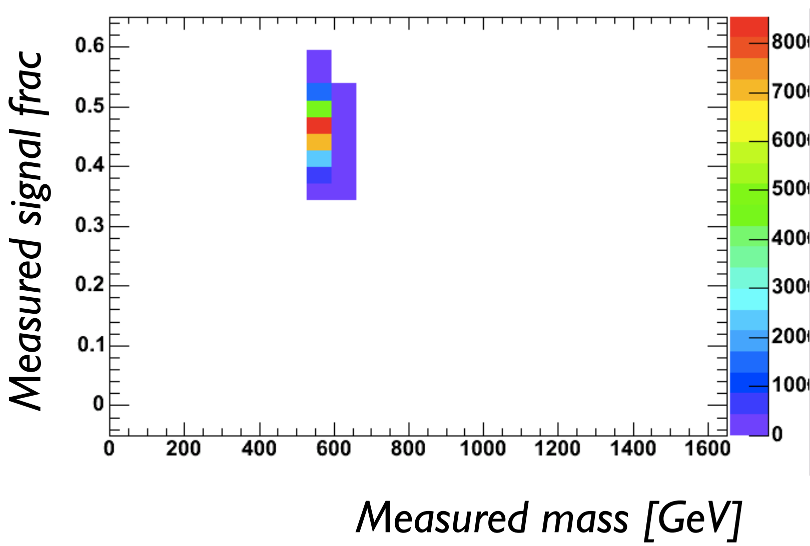
for s=0, $P_{Z'}$ has no effect, L no longer function of M

for s=1, P_Z has no effect, shape of $P_{Z'}$ is seen

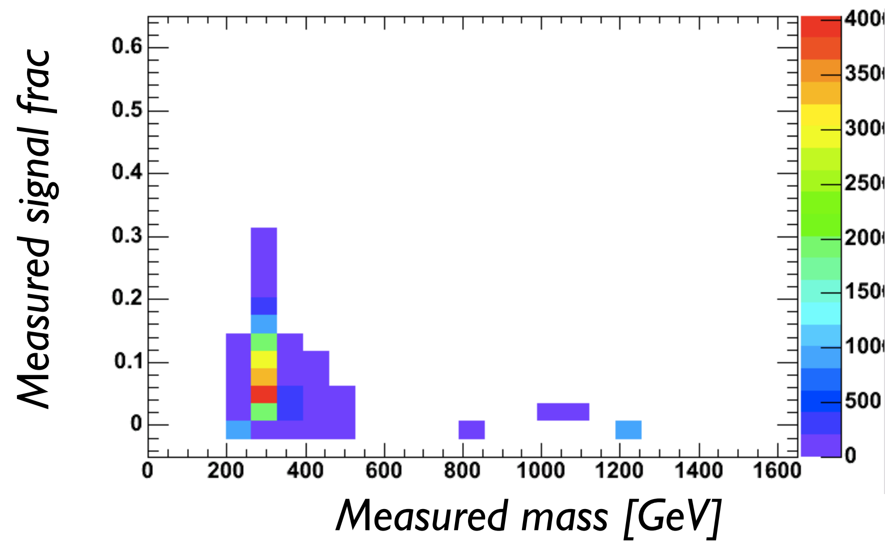
2D examples

Distribution of measured values
for specific true values of *M,s*

600 GeV Z' mass at s=0.475



s=0

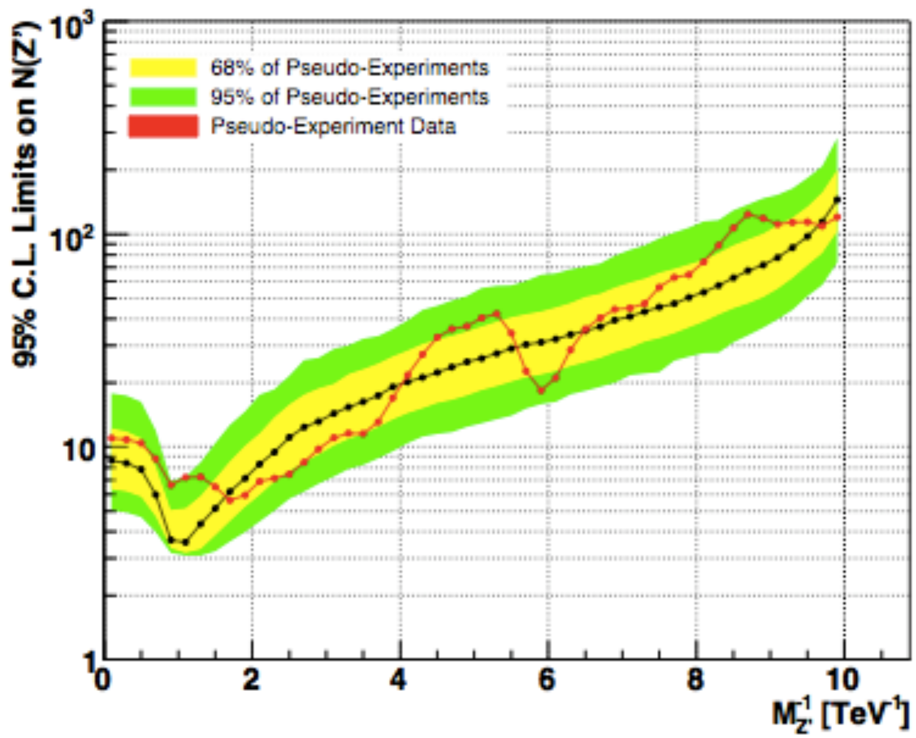


My personal toy pseudo-exp. Unofficial

Why 2D?

<u>Improve on current statistical approach</u>

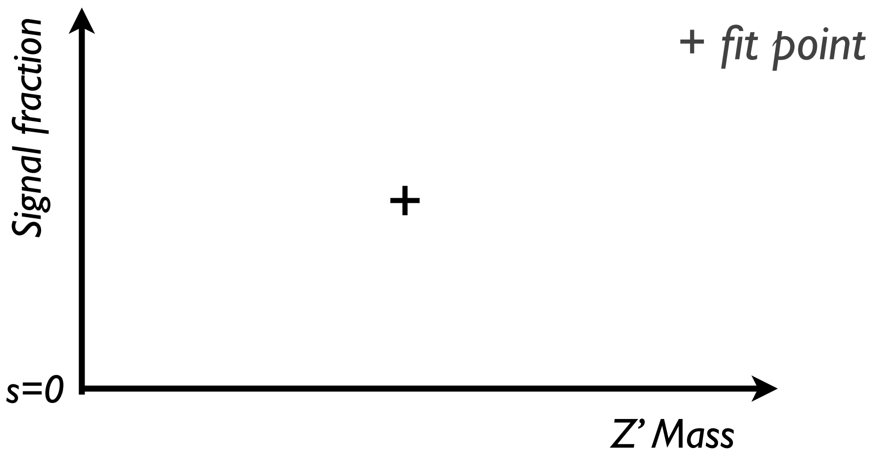
Set of cross-section limits at different masses (“raster scan”) are correlated in a non-trivial way.



Mechanics

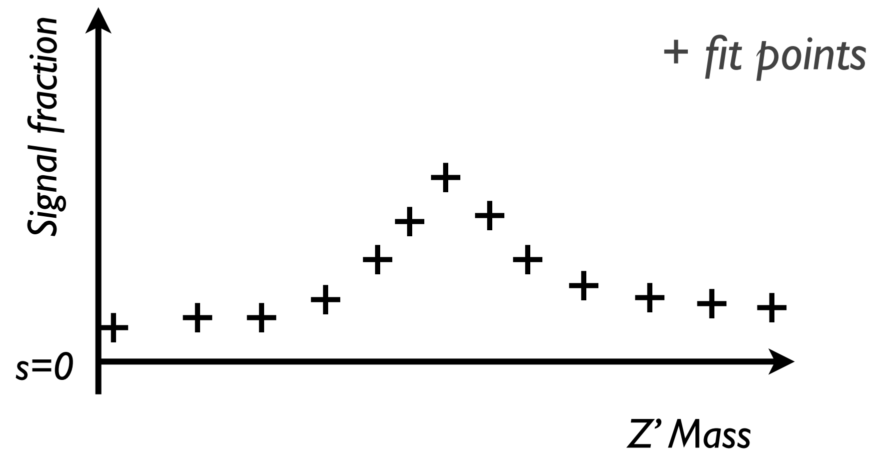
vs

Mass & rate analysis



Finds single point which maximizes L(M,s)

raster scan in mass



Finds set of points which maximize L(s) at each M.

Intervals

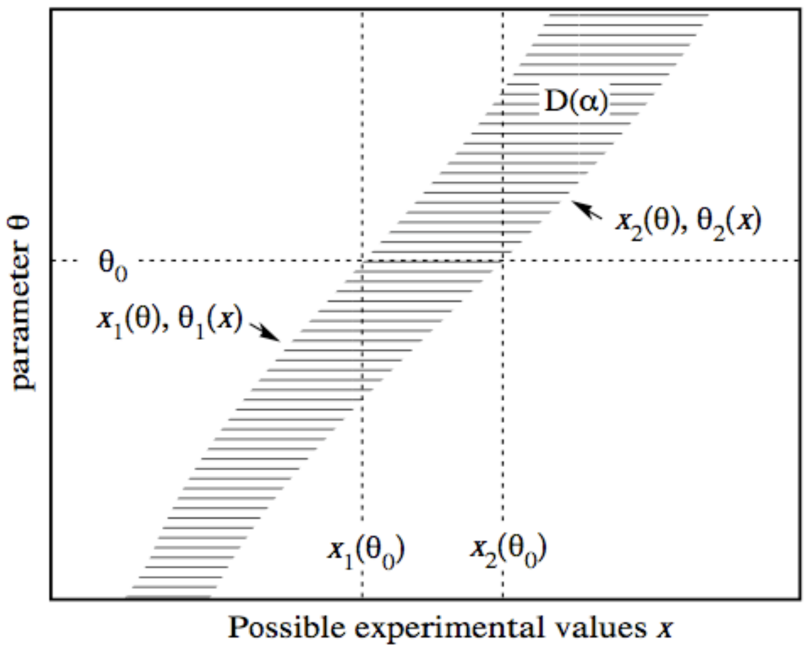
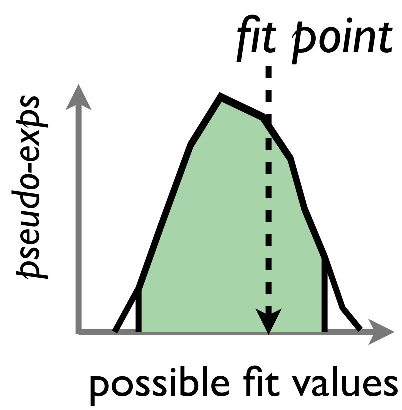


Figure 32.3: Construction of the confidence belt (see text).

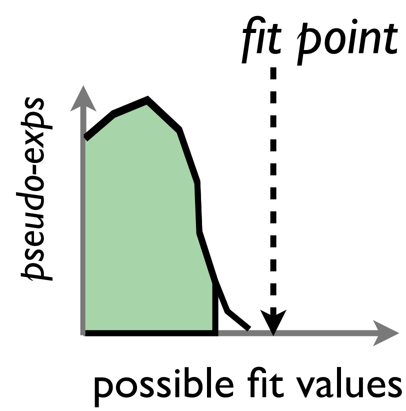
<u>95% intervals in parameter θ</u>

Do pseudo-experiments at varying θ values
Form bands containing 95% of possible measured values
Infer interval from measured value

<u>*Inside interval*</u>

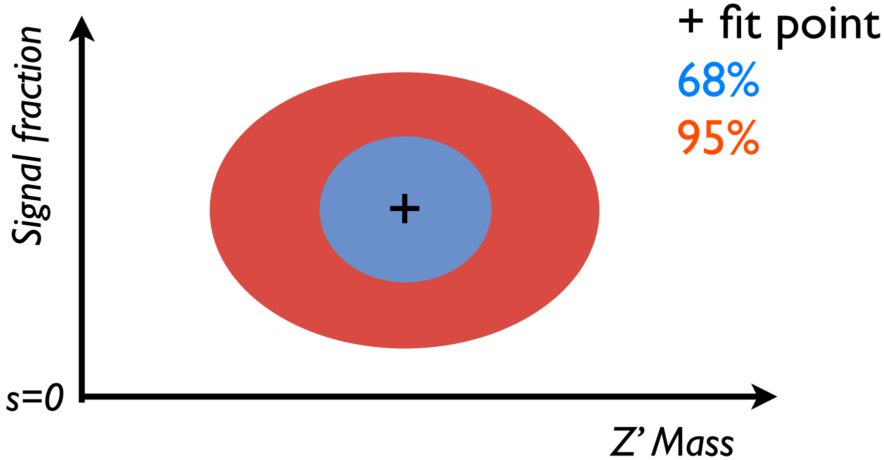


<u>*Outside interval*</u>



What does discovery look like?

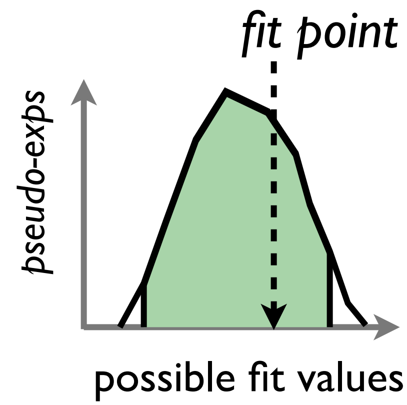
Mass & rate analysis



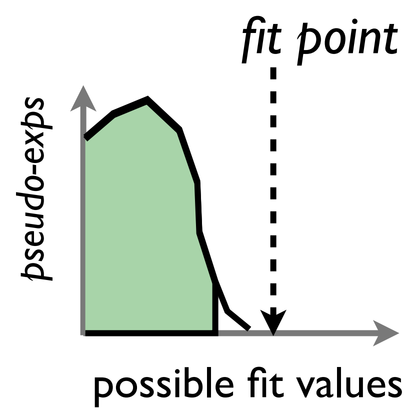
Compare fit point with distribution of fit points for varying *mass and signal*

Discovery if result inconsistent with s=0 for every mass

Inside interval



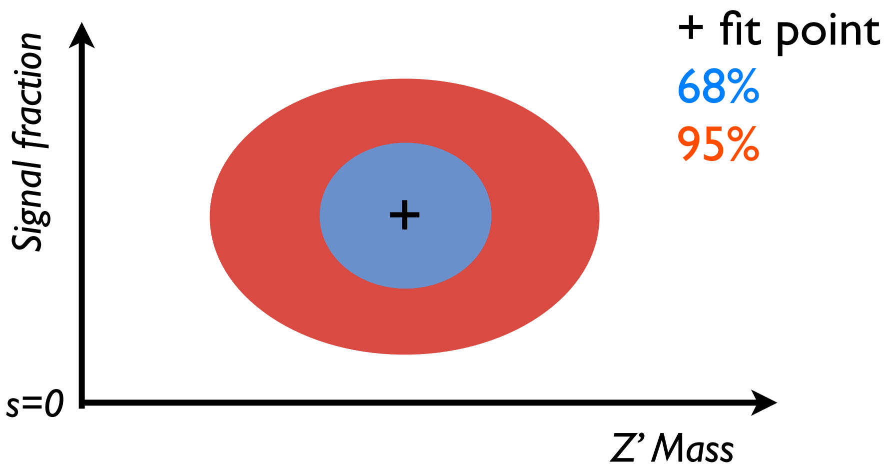
Outside interval



What does discovery look like?

vs

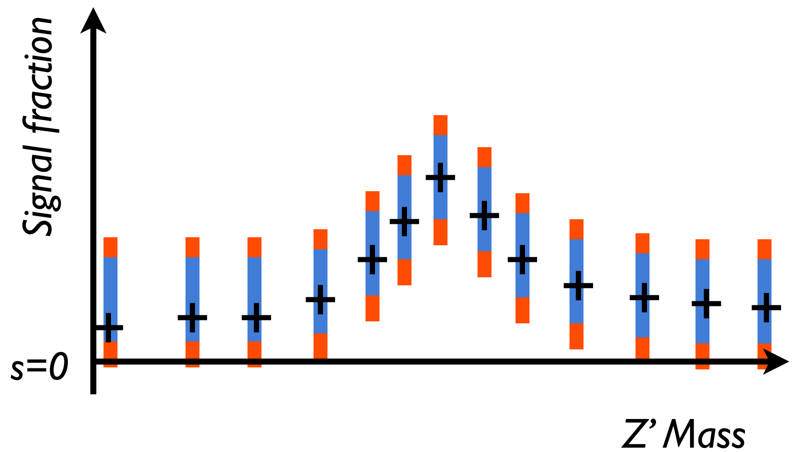
Mass & rate analysis



Compare fit point with distribution of fit points for varying *mass and signal*

Discovery if result inconsistent with s=0 for every mass

raster scan in mass



Compare *each* fit point with distribution of fit points for varying *signal at that mass*

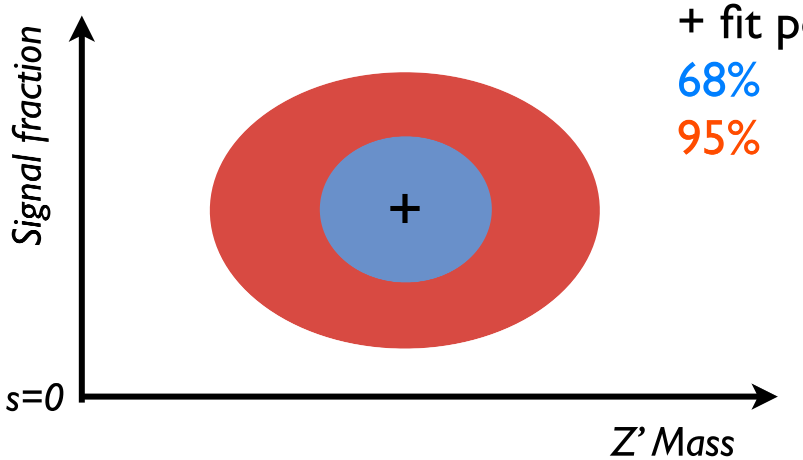
Discovery if result inconsistent with s=0 for any mass??

Curious: line at s=0 is really a point, since mass is not defined for no signal.

What does discovery look like?

vs

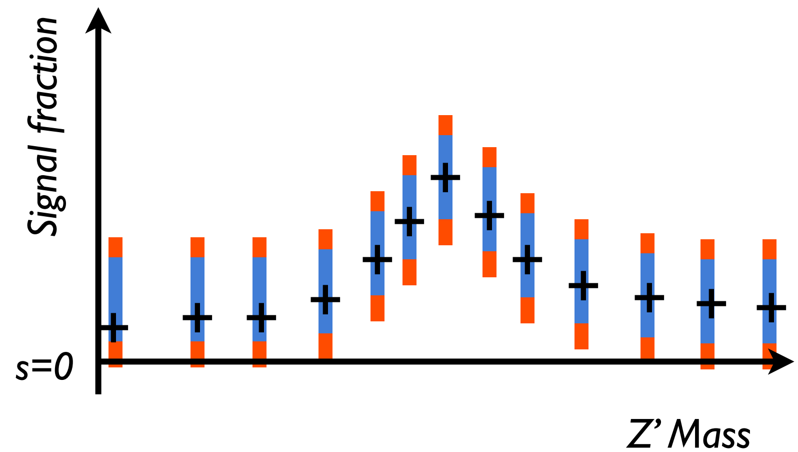
<u>Mass & rate analysis</u>



Intervals based on comparison to fluctuations at all masses.

Look-elsewhere effect naturally accounted for.

<u>raster scan in mass</u>



<u>Each 1D analysis interval</u> based on comparison to fluctuations at *one* mass.

<u>Analysis is really 2D</u>: accept bump at any mass. Look-elsewhere effect requires additional dilution of claimed sensitivity here.

(eg CDF Z'->ee bump at ~250 GeV)

Moral of the story

<u>If you know the mass in advance</u>

1D (cross-section) search is more powerful

can ignore bg fluctuations at other points

<u>If you don't know the mass in advance</u>

You're doing a 2D analysis (mass vs cross-section)

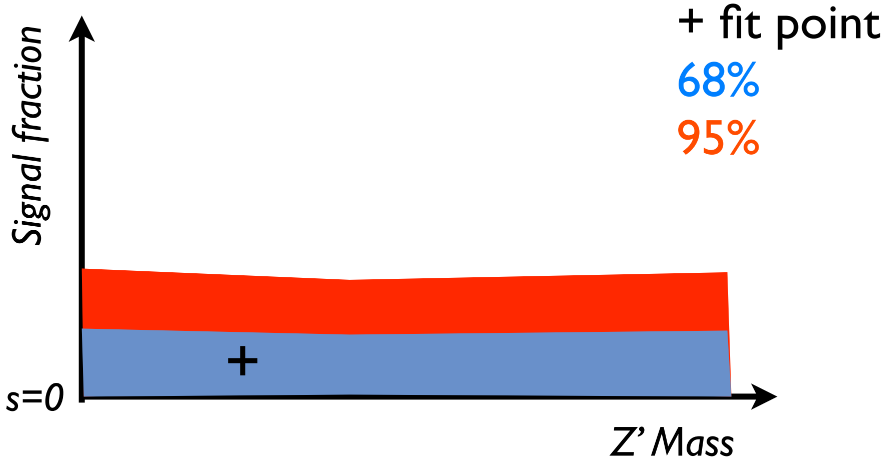
need to stitch 1D analyses together somehow into 2D plane.

<u>For discovery</u>: new pseudo-exps that accept bg fluctuations at any point...*Look-elsewhere effect*

What do limits look like?

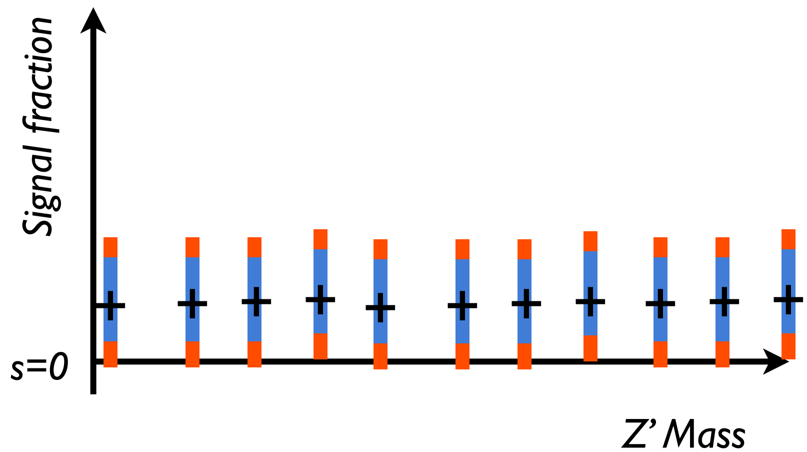
vs

<u>Mass & rate analysis</u>



Result consistent with s=0 at every mass

<u>raster scan in mass</u>



Result consistent with s=0 at every mass

Is there a look-elsewhere effect here?

Mass limits

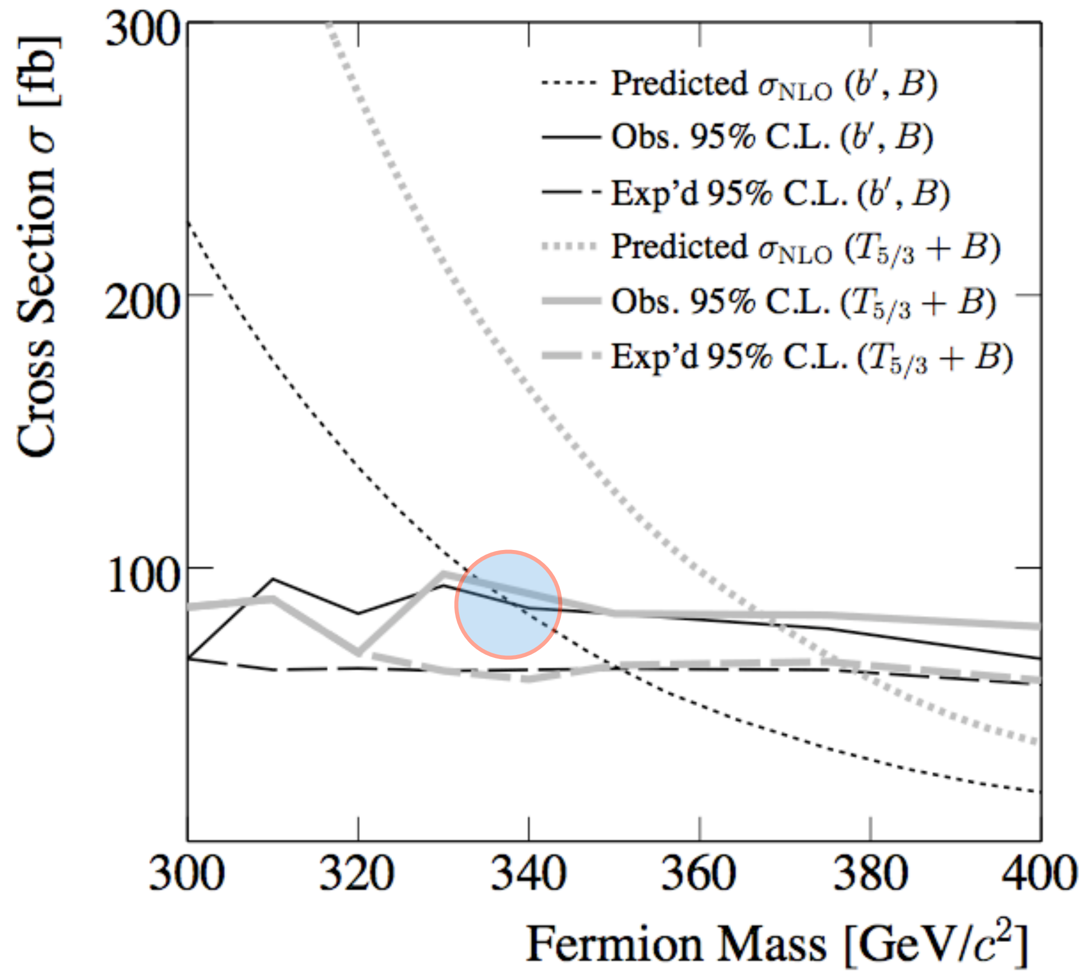
1D limits

$\sigma < \sigma_X$ at 95% C.L.
for mass M

The largest M for which
$\sigma_X < \sigma_{Theory}$ is M_Y

2D limits

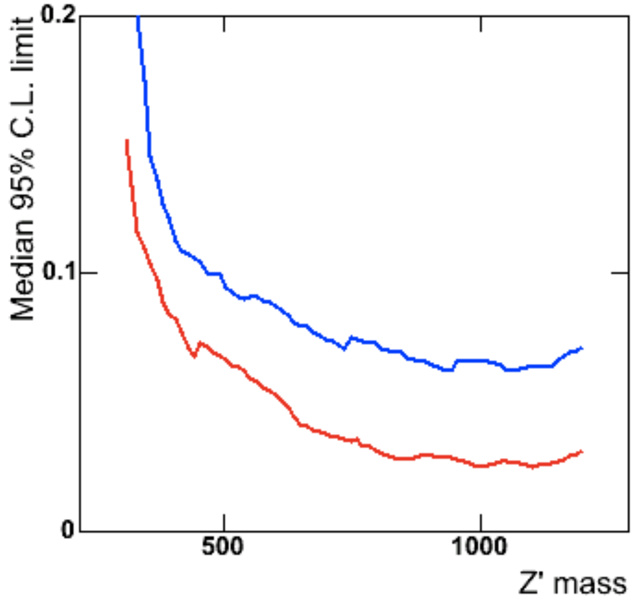
$M > M_Y$ at 95% C.L.



How big an effect?

1D limits are ~30-50% stronger at individual mass

My personal toy pseudo-exp. Unofficial



Background-only

2D limits

1D limits

Look elsewhere effect for limits?

Knowing the mass in advance makes you more sensitive, because your intervals are formed by comparing to background fluctuations at one mass, rather than at many masses.

Can we combine the individual results at each mass into information about the mass? (mass limits) without paying a price? Is that kosher?

Coverage

<u>A 95% claim:</u>

For 95% of pseudo-experiments, quoted interval contains true point

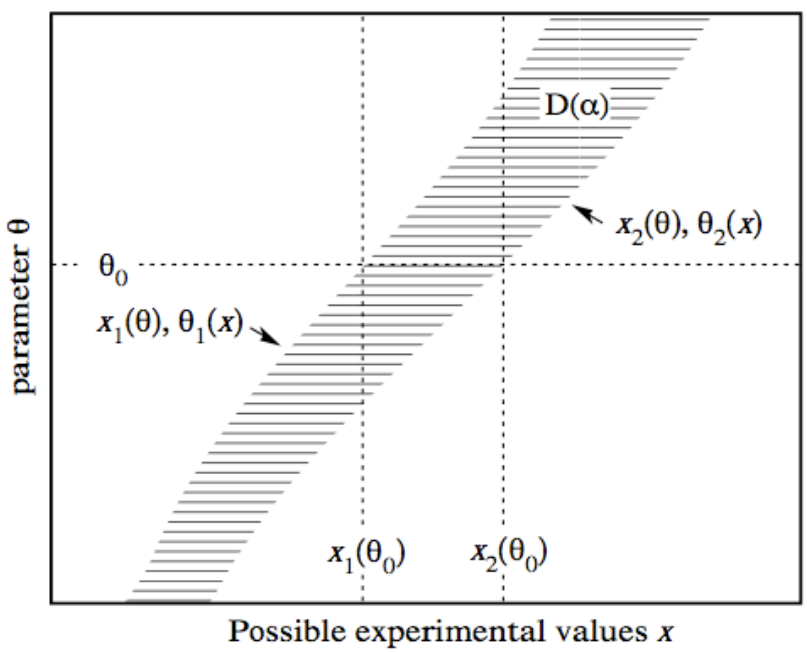


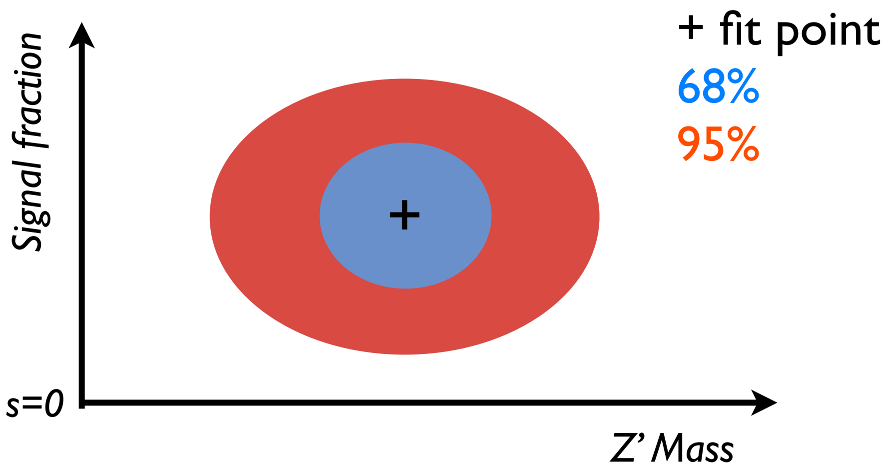
Figure 32.3: Construction of the confidence belt (see text).

True by construction if the pseudo-experiments used to make the bands describe the all expected fluctuations.

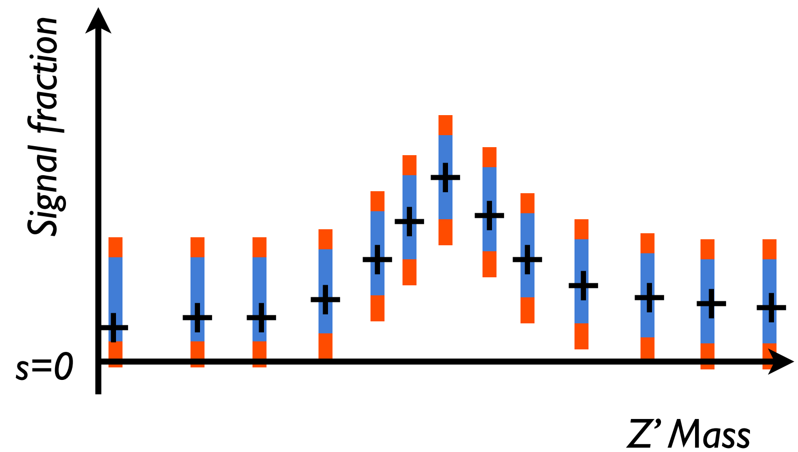
If there is a signal...

vs

Mass & rate analysis



raster scan in mass



Coverage

Both have coverage
For set of rate analyses, only need to consider coverage for single limit at true mass point

Power

2D analysis has smaller intervals

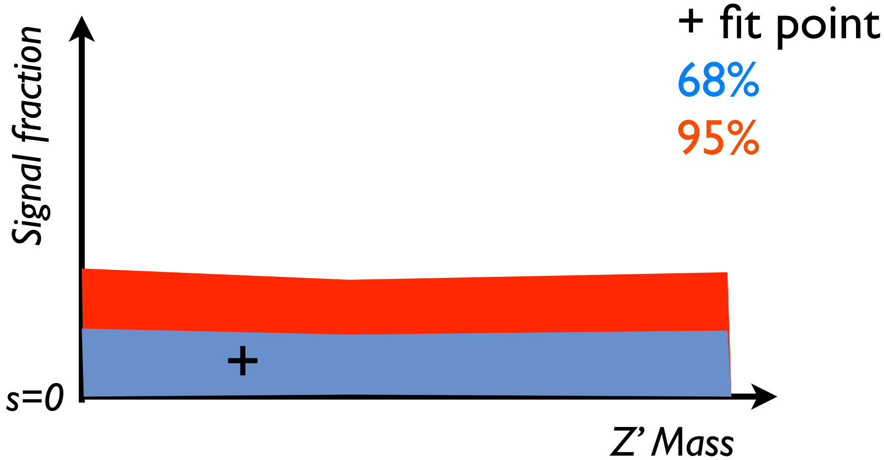
Note

For set of rate analyses, inconsistent statements at different masses for s=0 (which are all the same point)

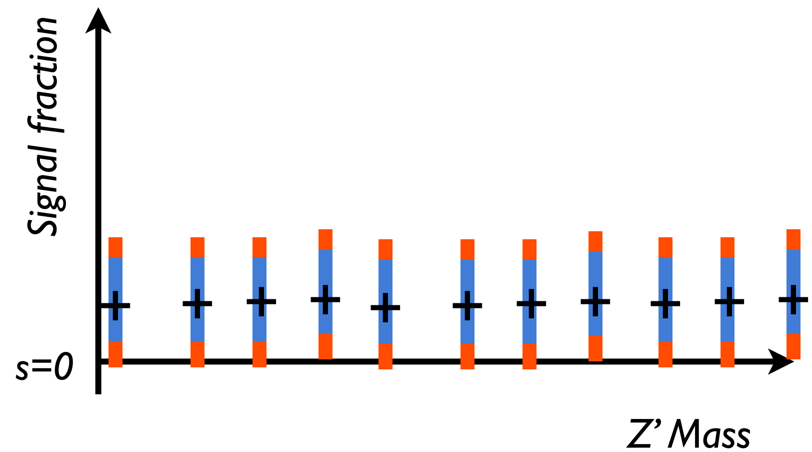
If there is no signal

vs

Mass & rate analysis



raster scan in mass



Coverage

What fraction of the time does the *set of rate* results include s=0 everywhere? < 95%!

Power

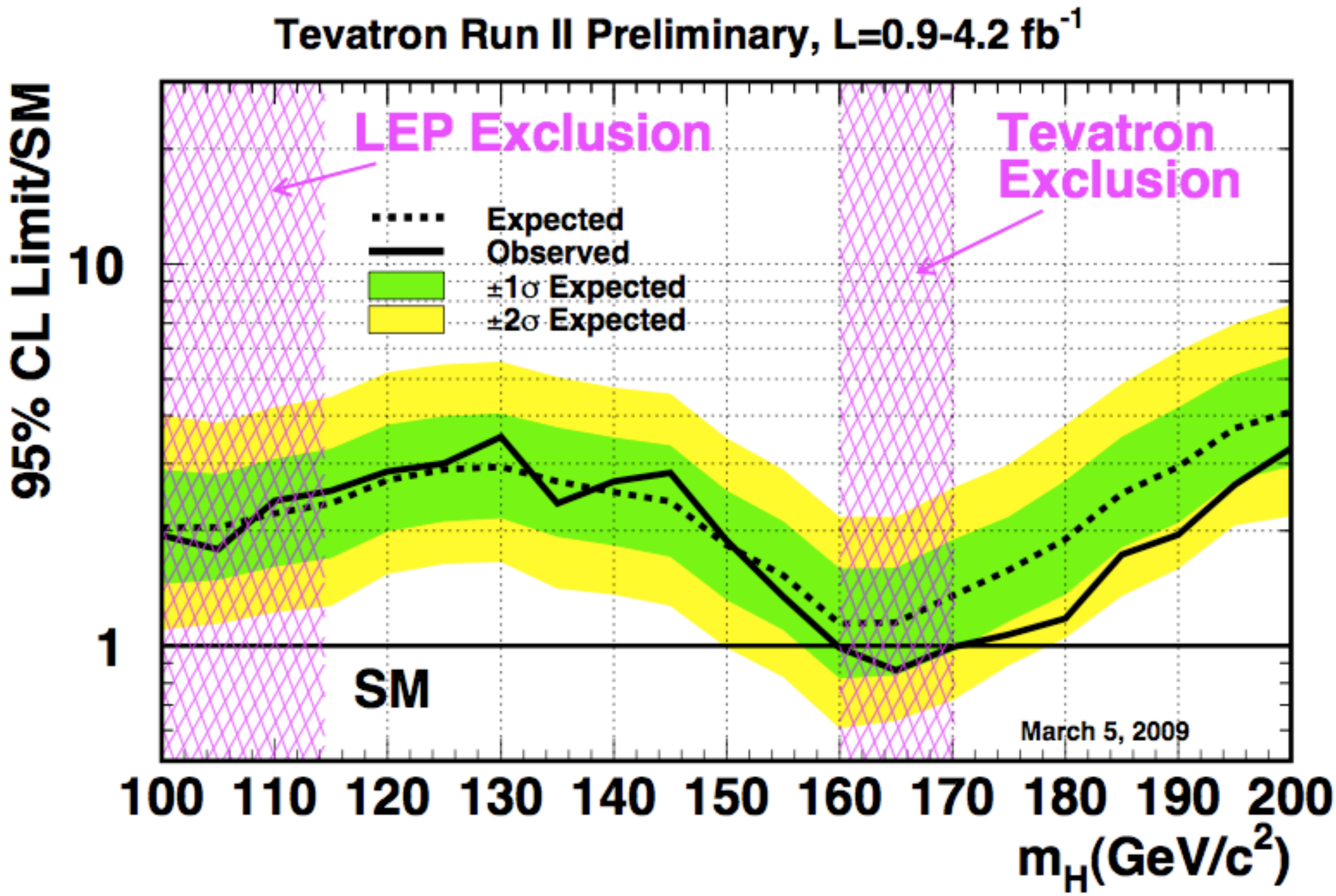
Set of rate analyses appears to set stronger limits: *artifact of ignoring fluctuations at other masses?*

Why not interpolate?

1D analyses have mutually inconsistent assumptions (mass), and so inconsistent s=0 cases.

General problem?

1D raster scan technique is widely used.....



Not persuaded?

<u>Ask yourself these questions:</u>

1) Why do 1D analyses appear to be stronger than 2D?

2) Can an analysis that doesn't know the mass(set of 1D analyses) be as powerful as one that does (single 1D analysis)?

Same-sign plans

Physics

Is there anything hiding in the same-sign lepton sample?

Sample

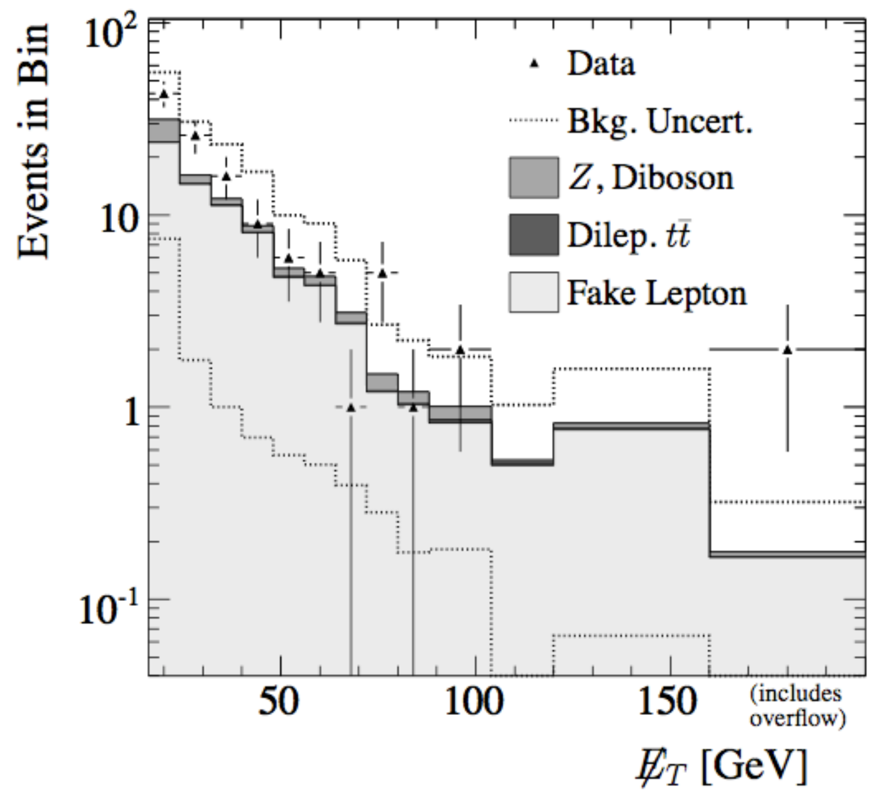
5/fb

Strategy

Inclusive search, few subsets (w/btag, w/looser lepton)

Technicalities

More robust mis-identification model: account for heavy-flavor dependence & multiple sources



Summary

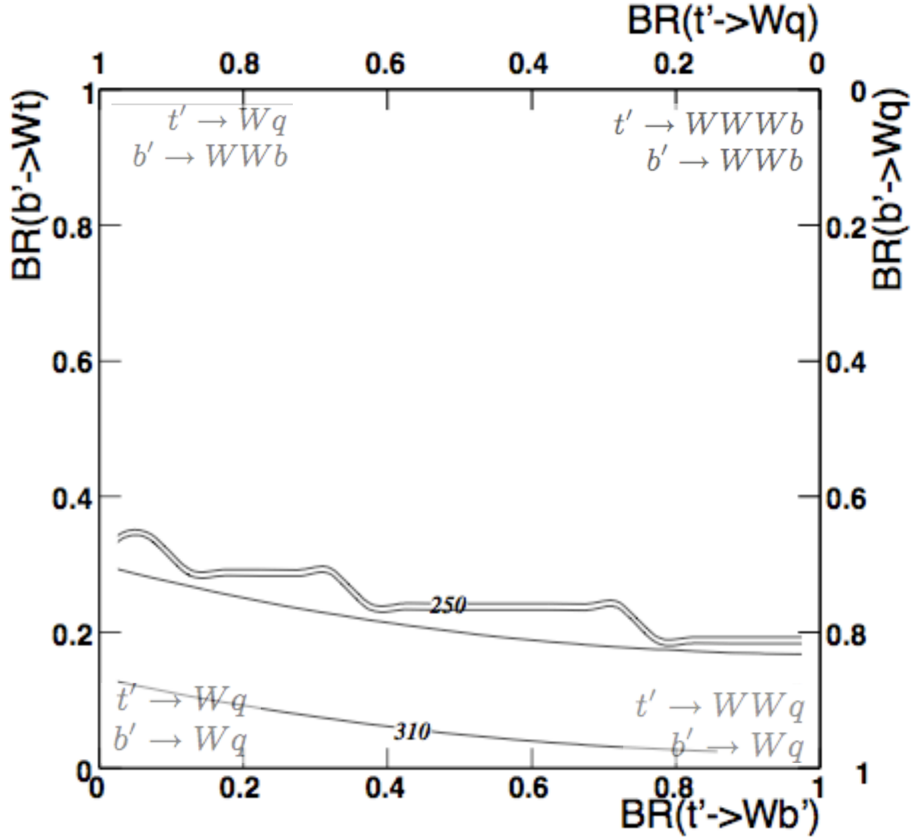
<u>Searches</u>
Try to maximize potential by generalizing models

<u>Limits</u>
New limit on heavy quark masses.

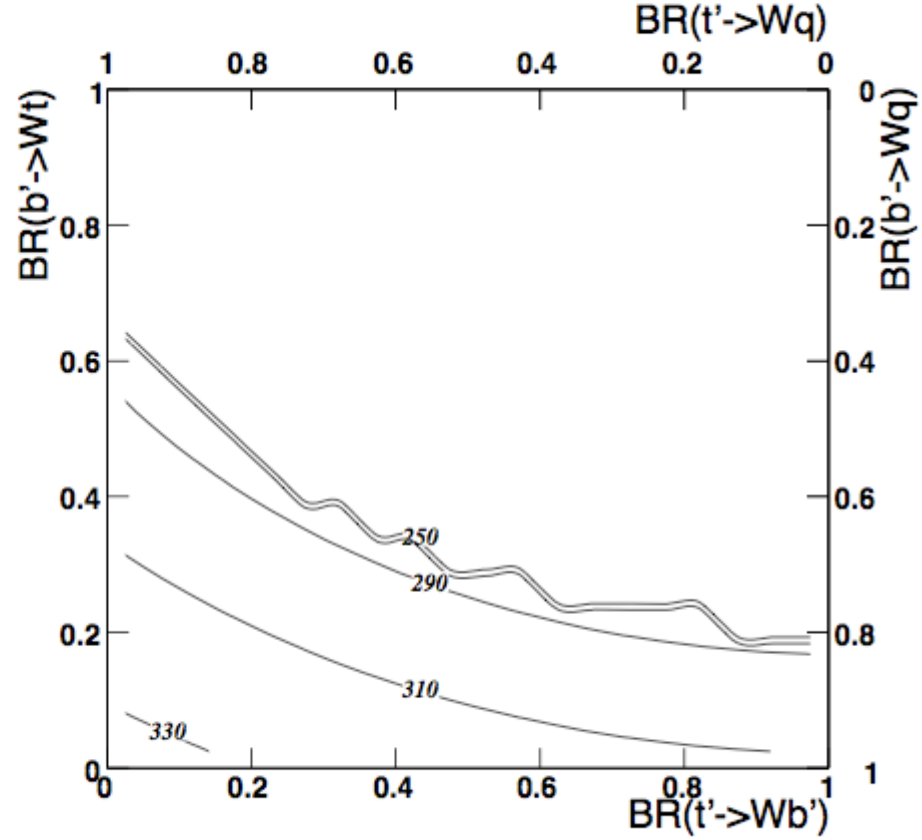
<u>Soon</u>:
New limit on heavy bosons
New limits on Majorana neutrinos
Inclusive study of same-sign leptons

Wq data

Limits on lighter quark mass (b′)

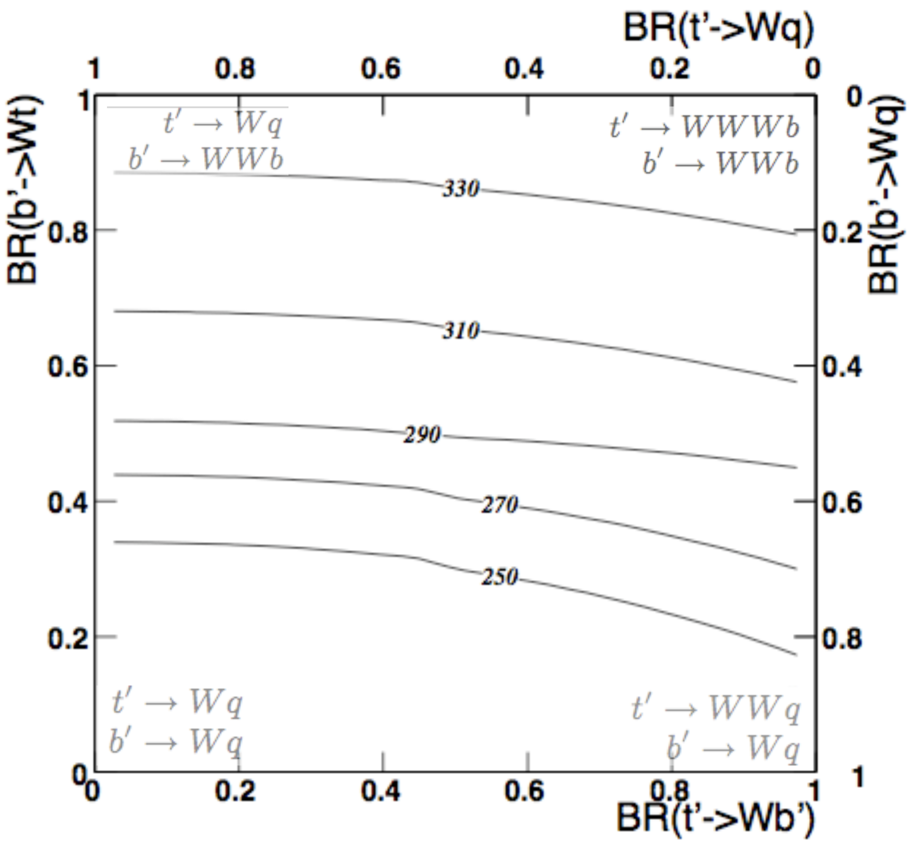


$m_{t'} = m_{b'} + M_W$

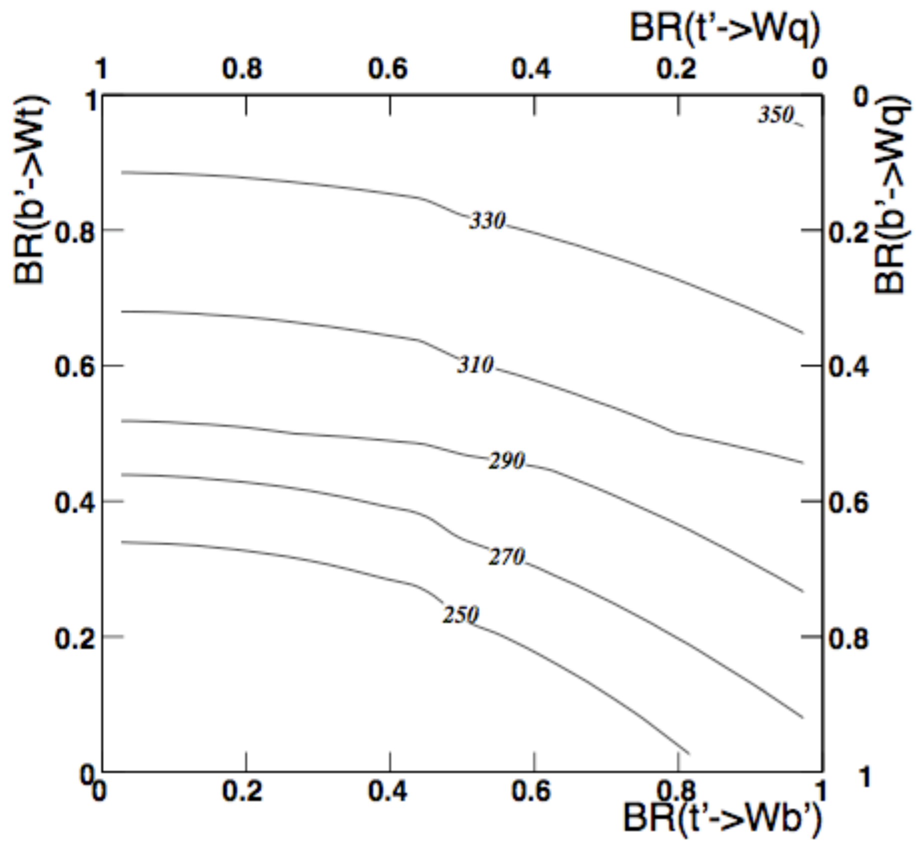


$m_{t'} = m_{b'} + M_W/2$

WWb data



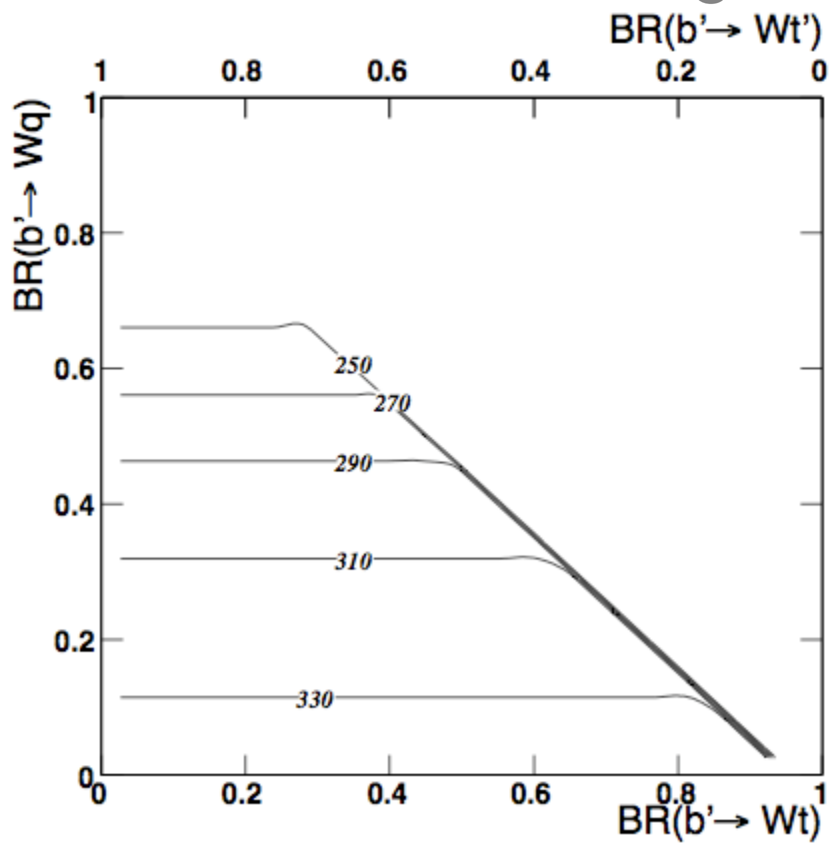
$m_{t'} = m_{b'} + M_W$



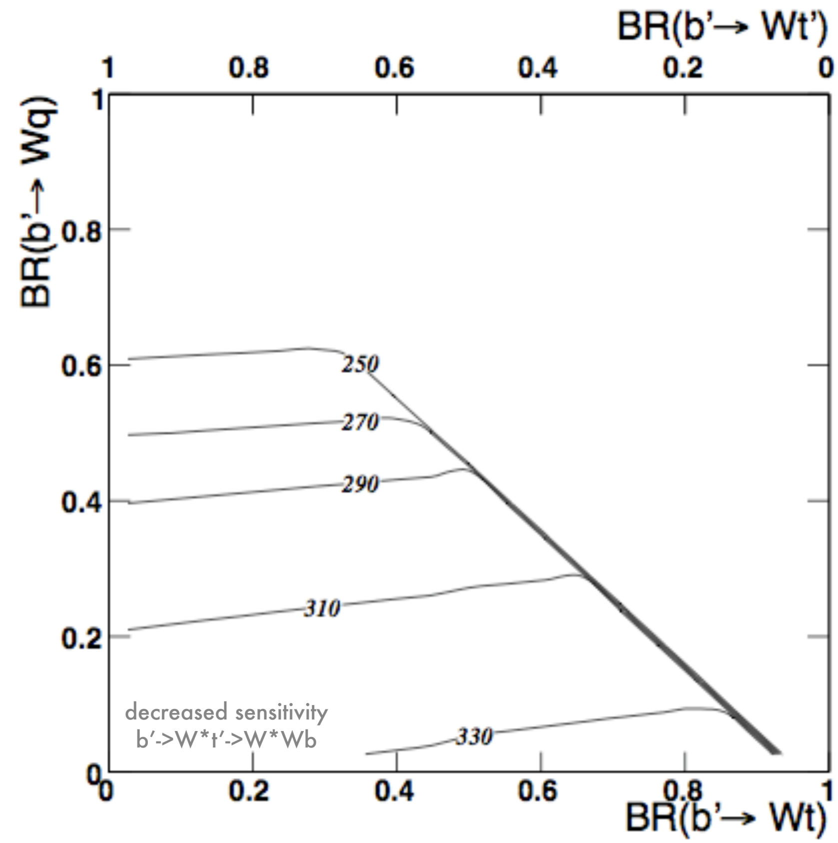
$m_{t'} = m_{b'} + M_W/2$

WWb data

Assuming BR(t'->Wb)=1



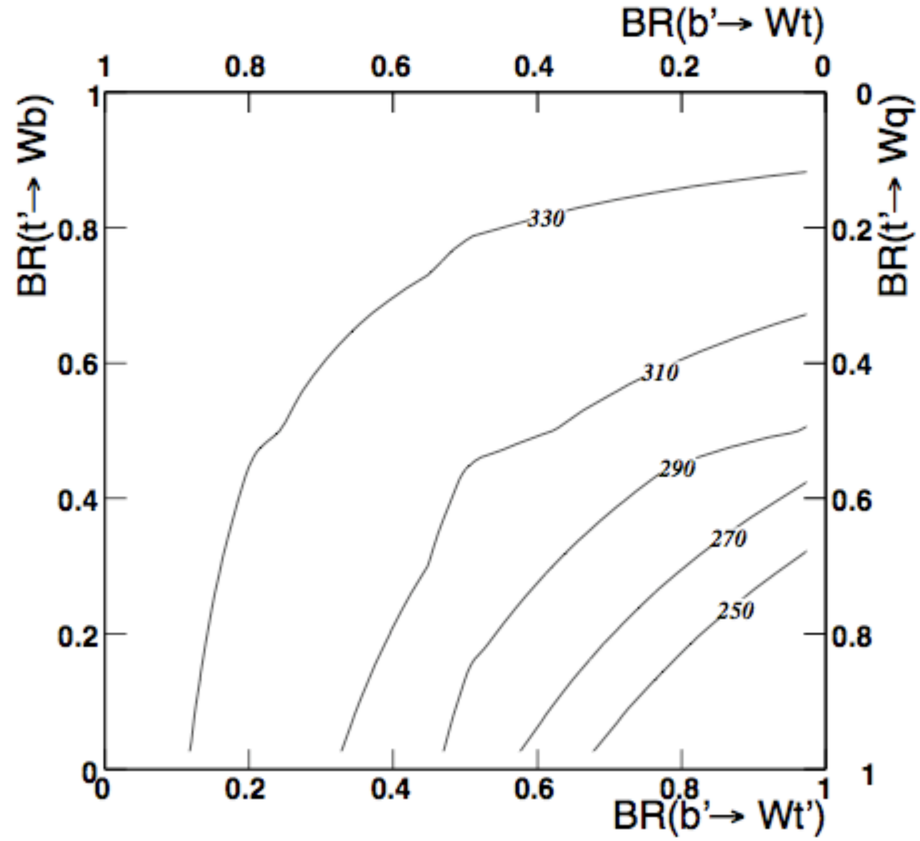
$m_{b'} = m_{t'} + M_W$



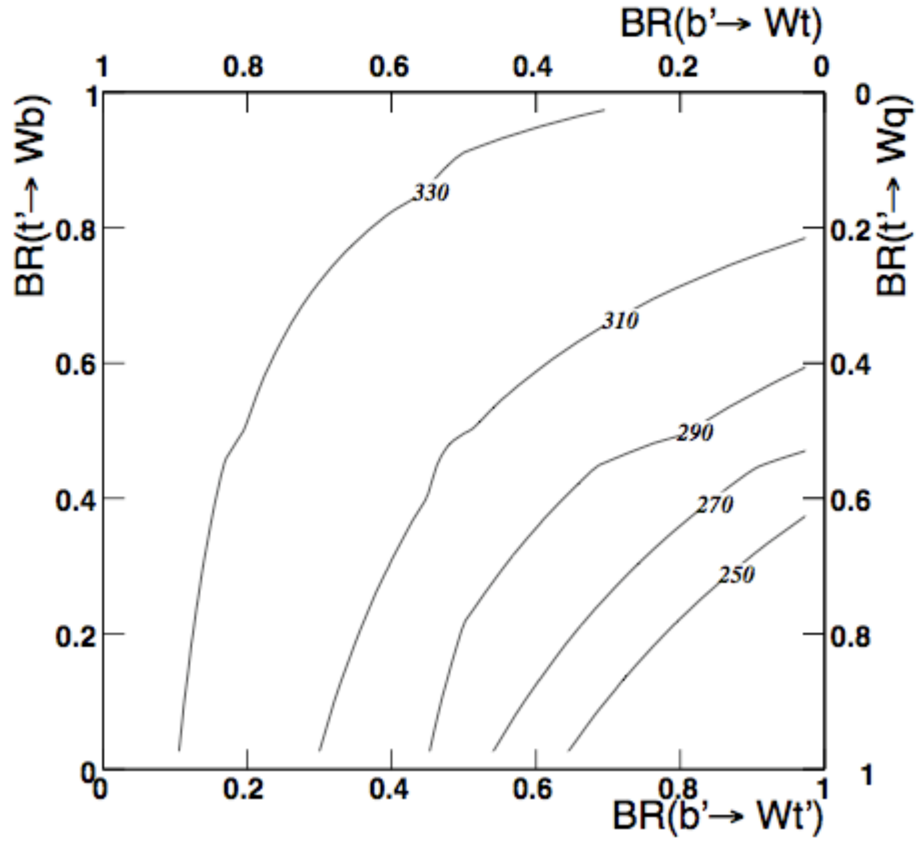
$m_{b'} = m_{t'} + M_W/2$

WWb data

Assuming BR(b′->Wq)=0



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



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

Same-sign leptons (2.7/fb)

Cross-check

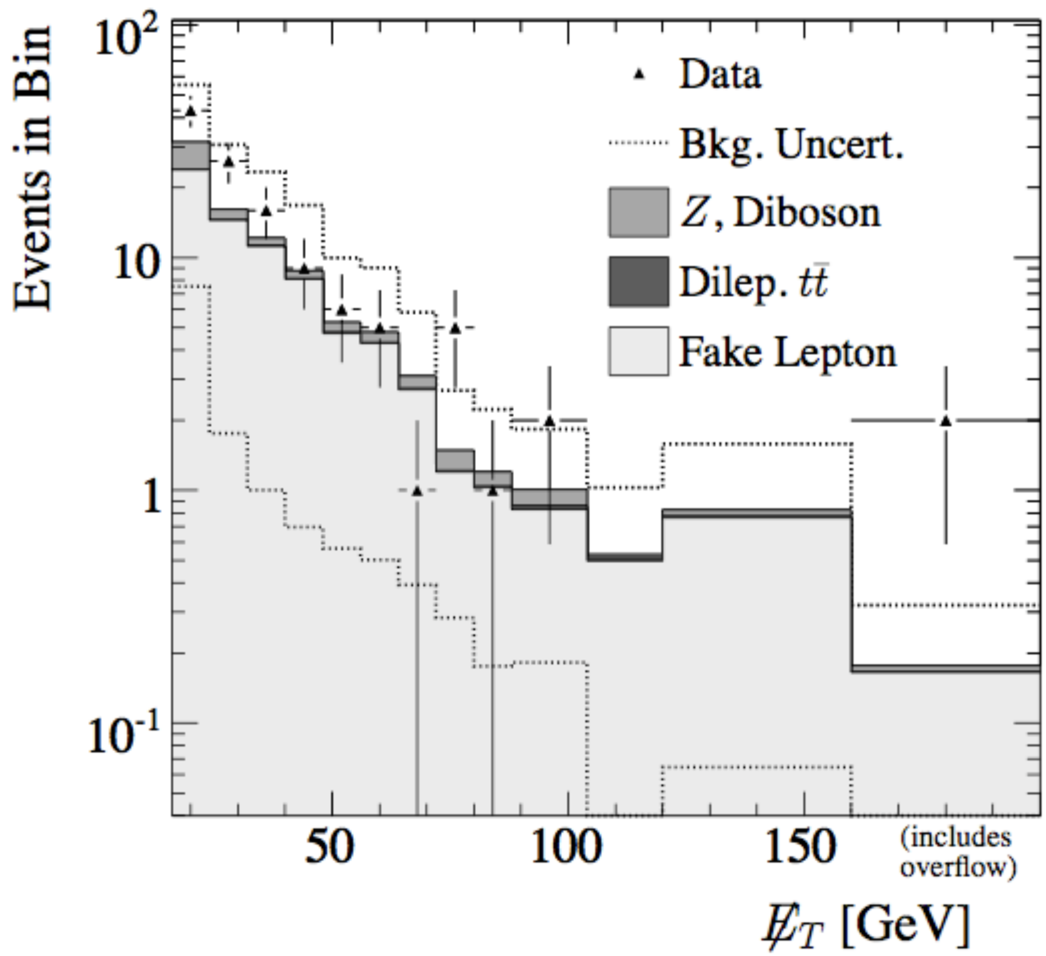
2 like-signed leptons

Source	ee	μμ	eμ	ll
Z	111.2 ± 55	~0	35.0 ± 18	146 ± 75
top dilep	0.3 ± 0.05	~0	0.5 ± 0.05	0.8 ± 0.06
Fake lep	124.5 ± 124.5	17.2 ± 17.2	86.0 ± 86.0	227.6 ± 227.6
Total	236 ± 136	17.2 ± 17.2	121.3 ± 88	374.4 ± 239
Data	220	12	102	334

Same-sign leptons (2.7/fb)

<u>Cross-check</u>

2 like-signed leptons



Backgrounds

<u>Z/γ^*</u>

Describe with simulation, normalized to data in low mass window

<u>top quark pairs & WW</u>

Describe with simulation, normalized to NLO calc.

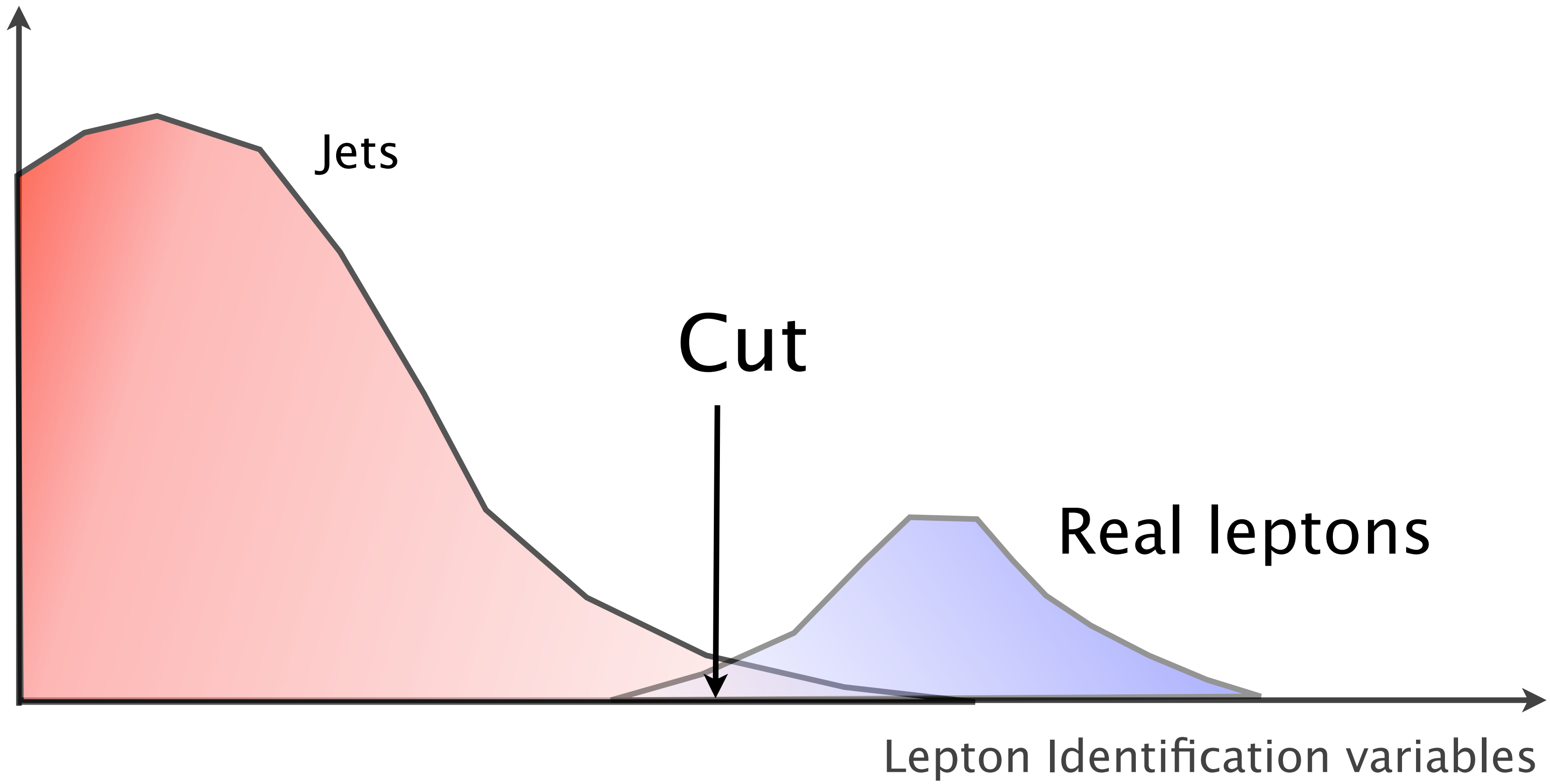
<u>Fake lepton</u>

Use same jet-fake model as b' analysis

<u>Cosmics</u>

Use real high-mass cosmic events flagged by cosmic finder,.
Normalize rate in low-mass region

Lepton fakes

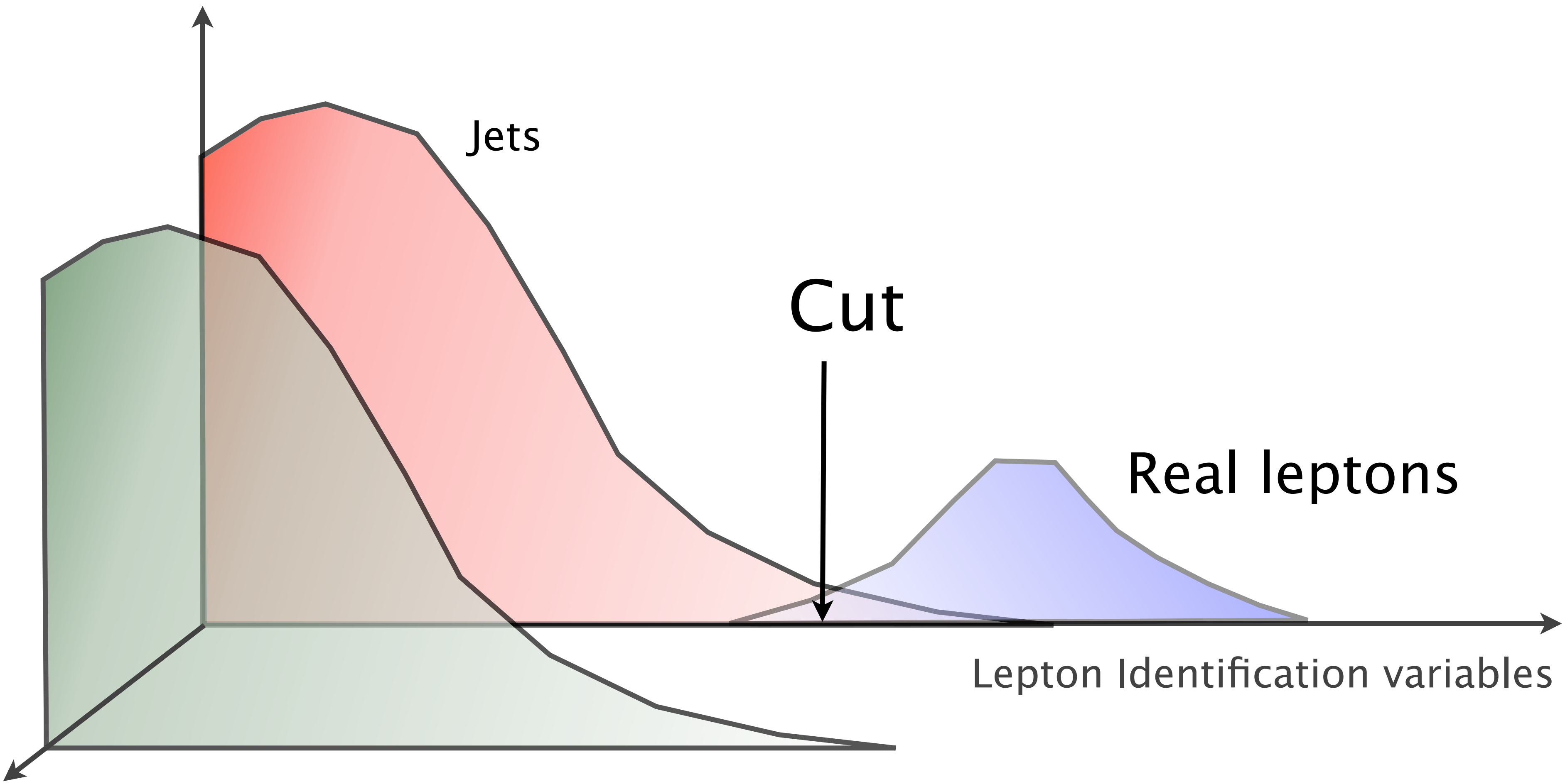


<u>Rate of jets passing lepton cuts</u>

Functional form unknown

Simulation not reliable

Lepton fakes



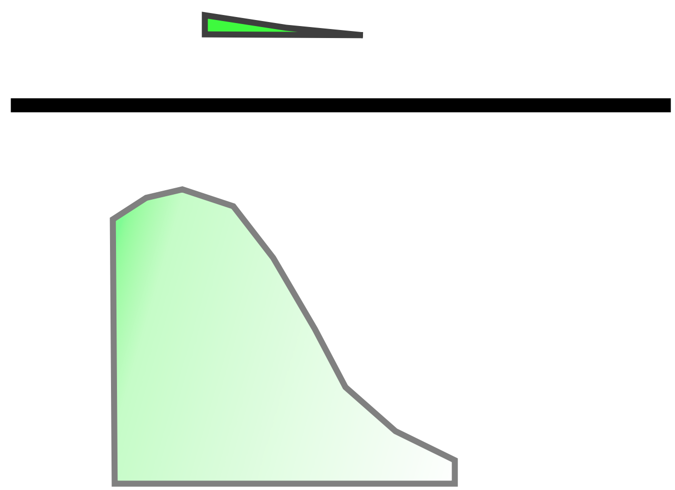
Orthogonal selection (jet triggers)

Background dominated

Measure rate for jets to pass selection

Fake lepton rate

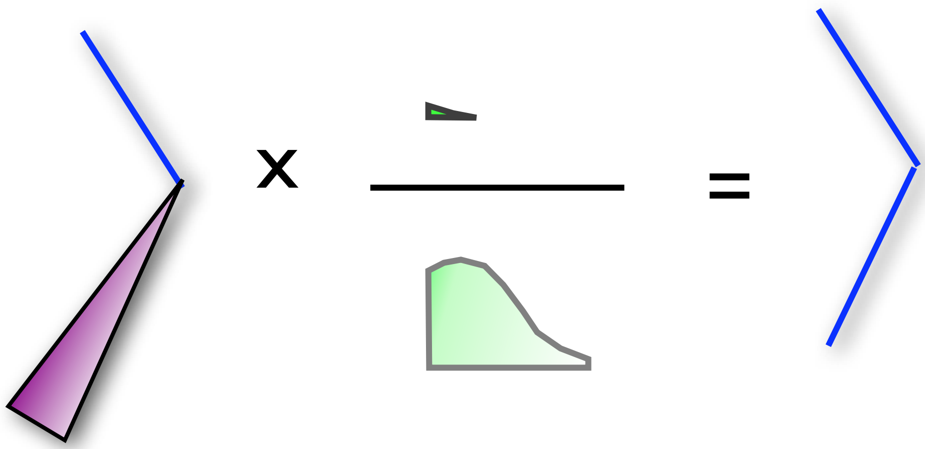
Fake rate =



Event rate estimate

For W/Z+ jets:

N_{l+j} x f = N_{ll}



Complications

<u>Different jets with different rates</u>

Light & heavy flavor jets
Quark and gluon jets

<u>Multiple sources need different calculations</u>

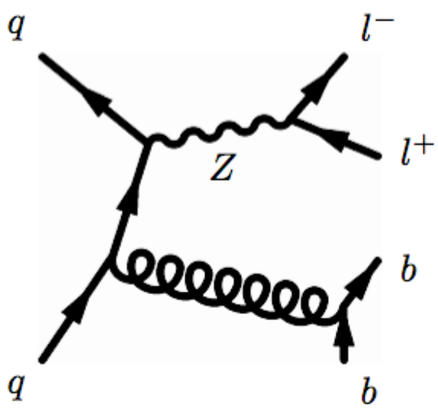
1 fake (W/Z+jets)
2 fakes (dijets)

<u>Current approach</u>

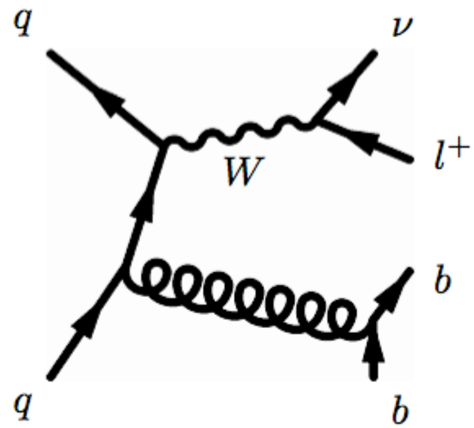
Assume all fakes from W/Z+jets
Assume light/heavy flavor mixture is the same where we measure and apply fake rate.
Use generous systematic uncertainties (~100%)

Backgrounds

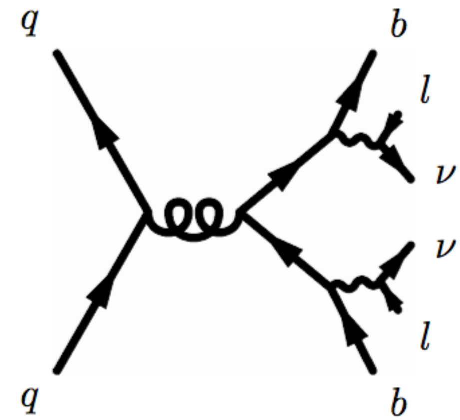
Three largest backgrounds



Z + jets



W + jets

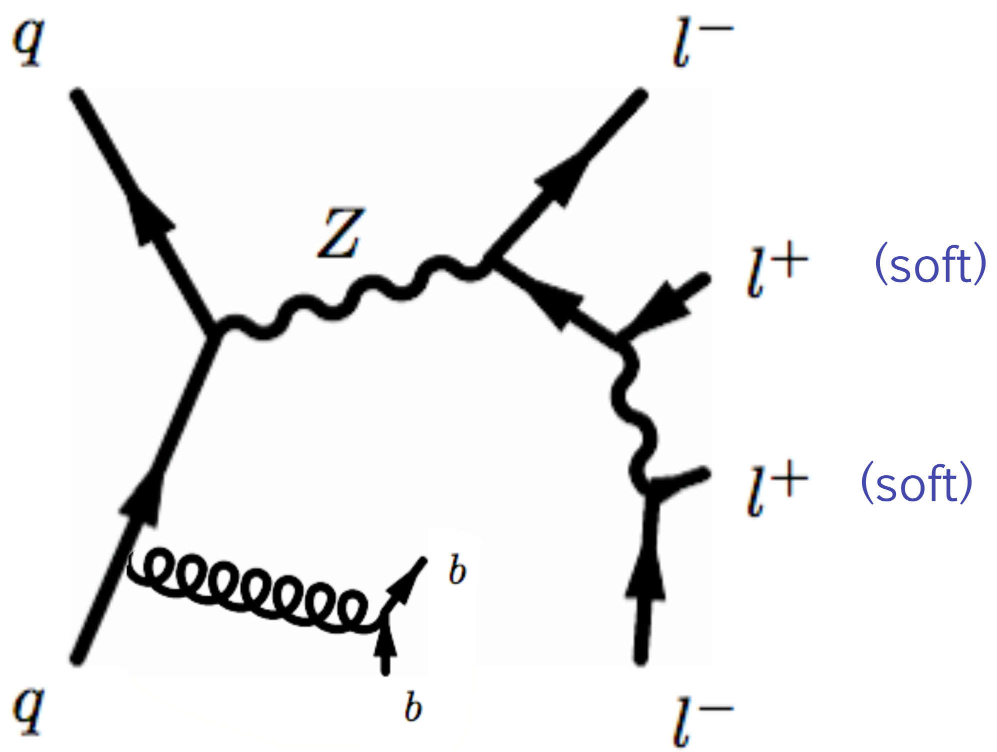


top quark pairs

<u>Dibosons</u>

WZ,ZZ,Wγ, Zγ negligible due to b-tag, jet requirements

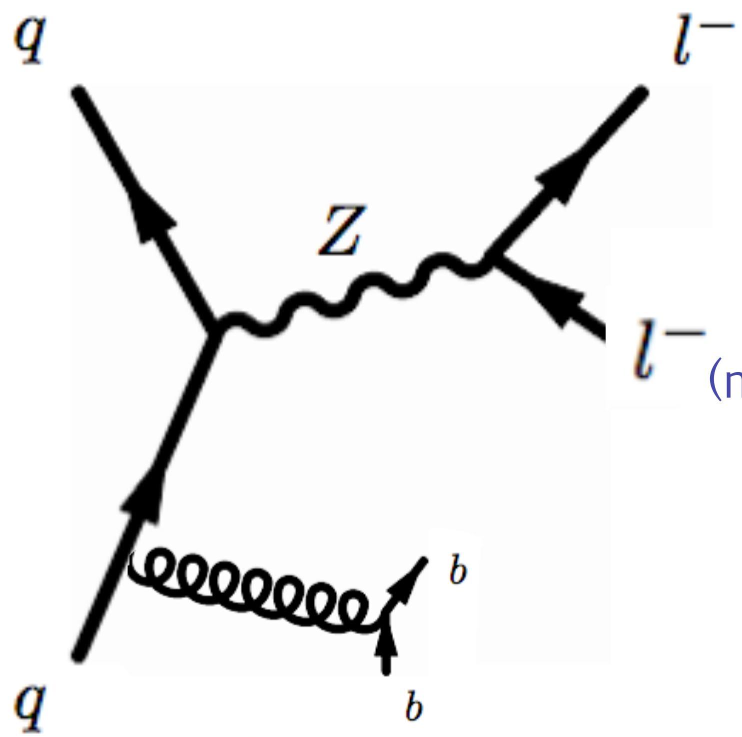
Z + jets



Trident

Bremstrahlung with asymmetric pair production ("trident")

Z + jets

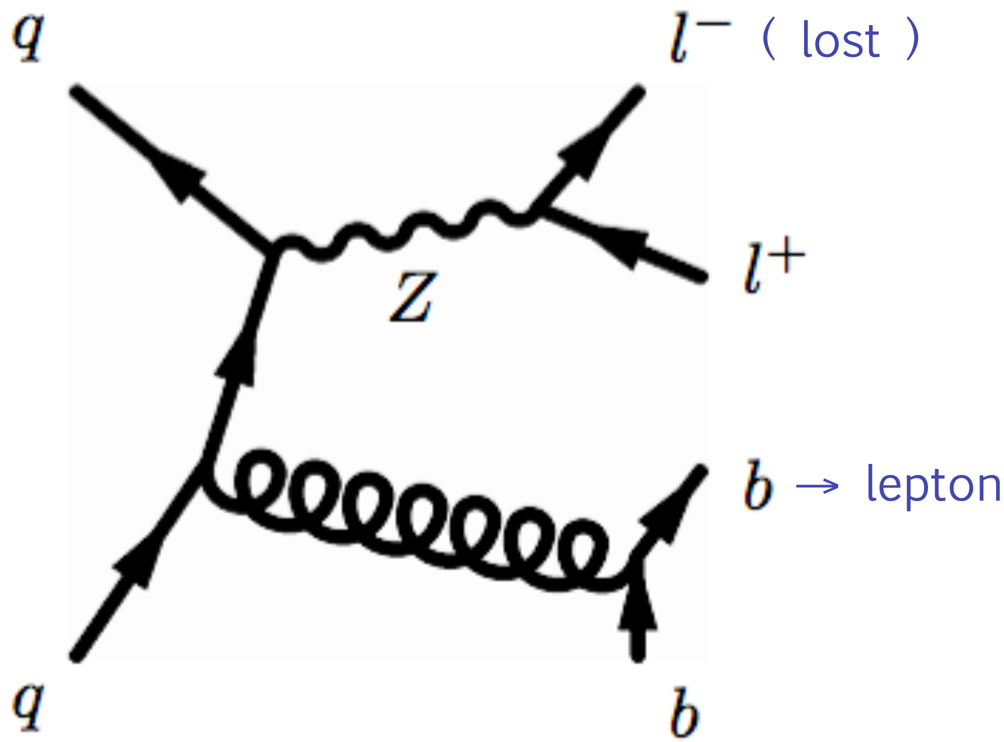


Charge misidentification

High p_T tracks can have the wrong sign charge

This is almost negligible at p_T <= 100 GeV

Z + jets

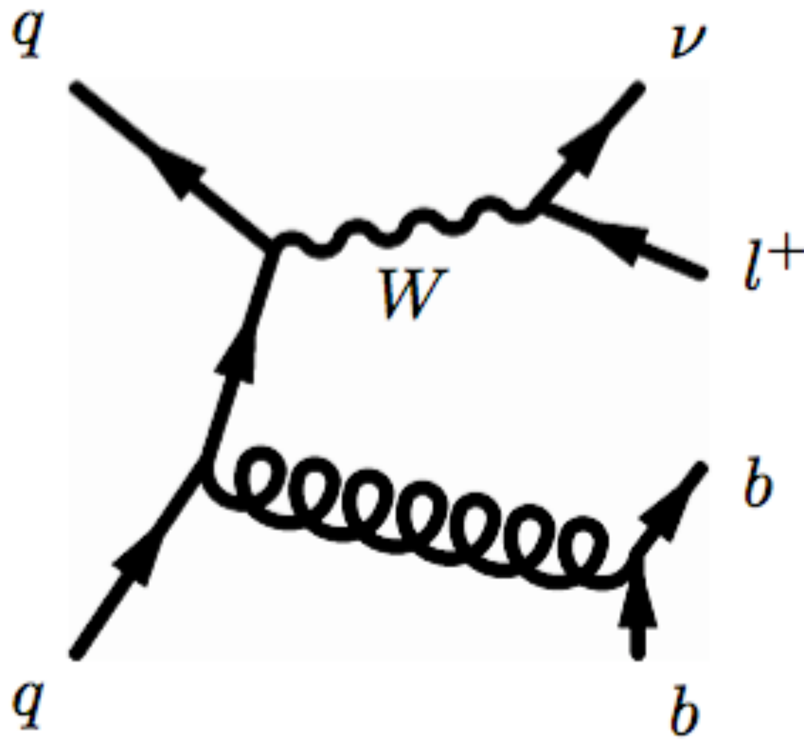


Z with radiated jets

Lose one Z lepton

Fake lepton from (b) jet

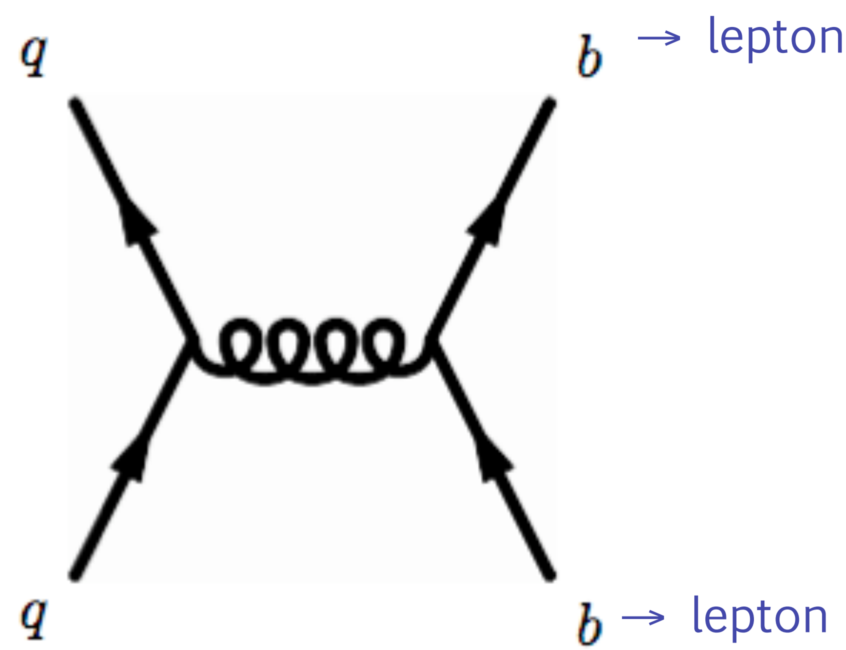
W+jets



→ lepton

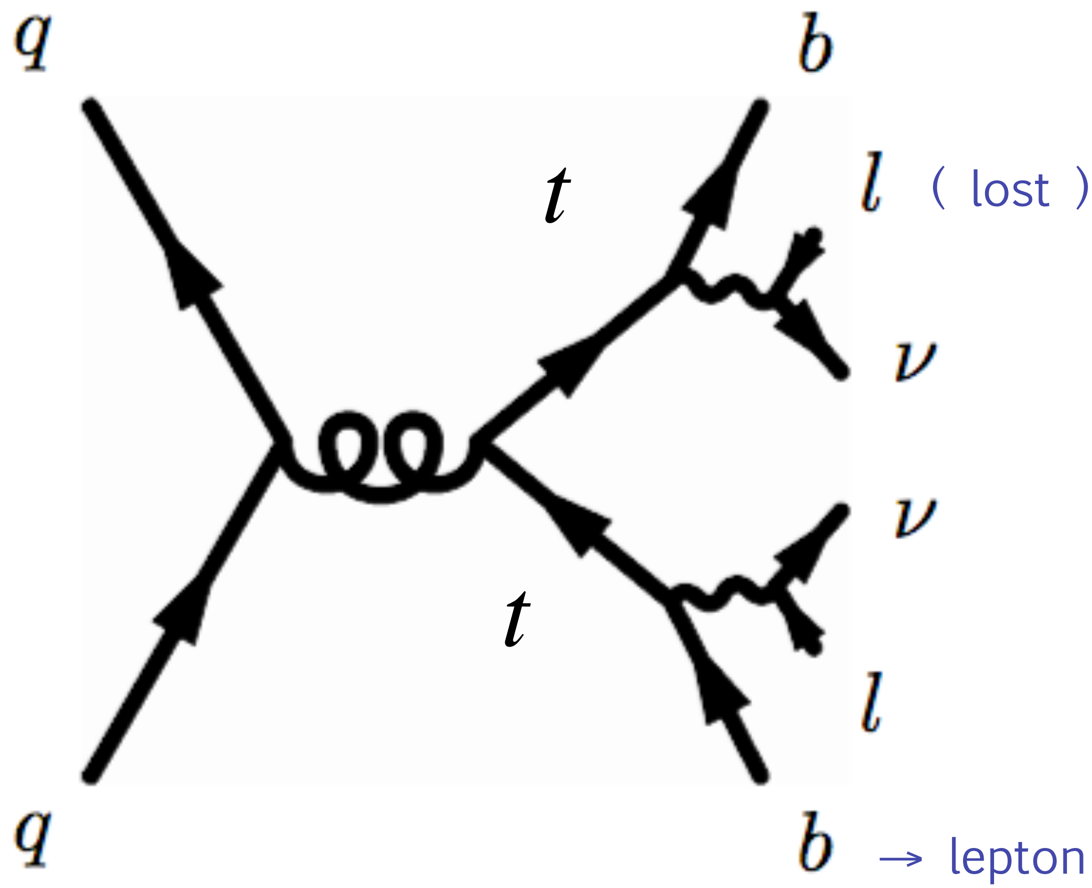
W+jets
Fake lepton from (b) jet

dijets



Di-jets
2 leptons from (b) jets
Some contribution -- suppressed by missing energy requirement

top quark pairs

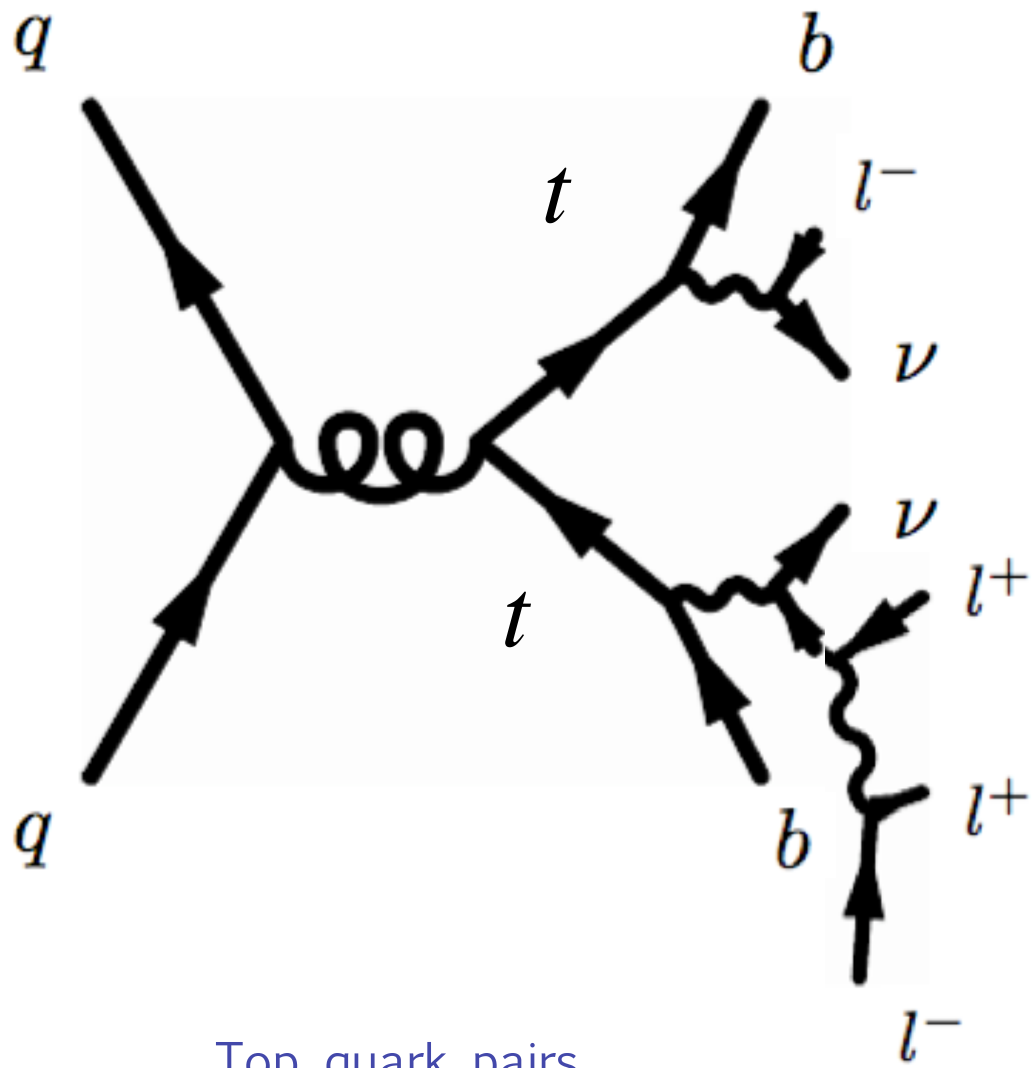


Top quark pairs

Lose W lepton

Fake lepton from (b) jet

top quark pairs



Top quark pairs
Trident from one lepton