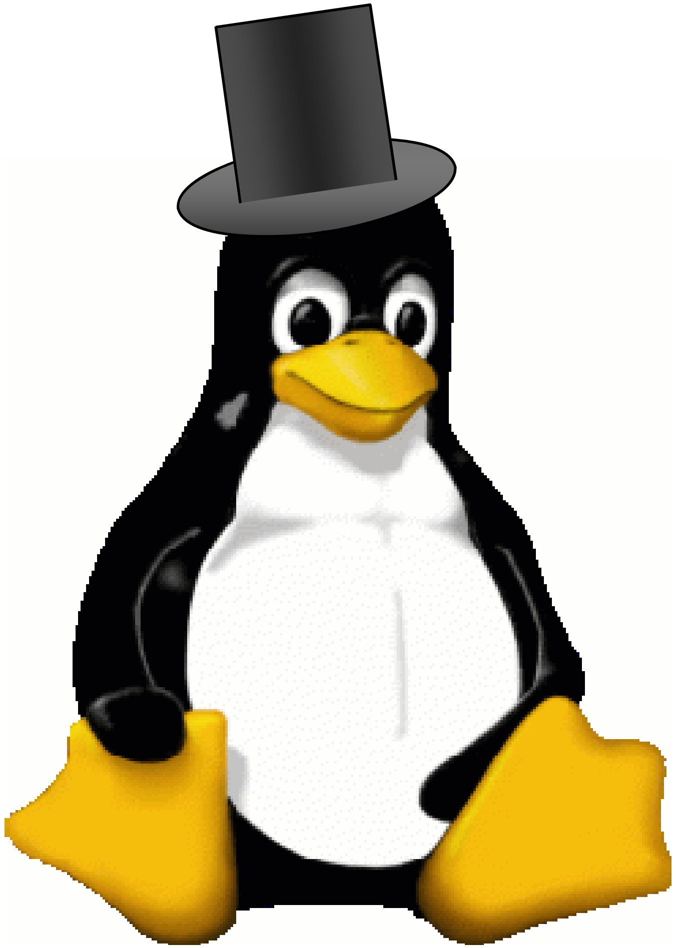


How Charming is the Truth?

The Search for Top Flavor Changing Neutral Currents $t \rightarrow Z\,c$ at CDF Run II

***Charles Plager*, UCLA**

On behalf of the CDF Collaboration

CERN Seminar

July 2nd, 2008

Outline

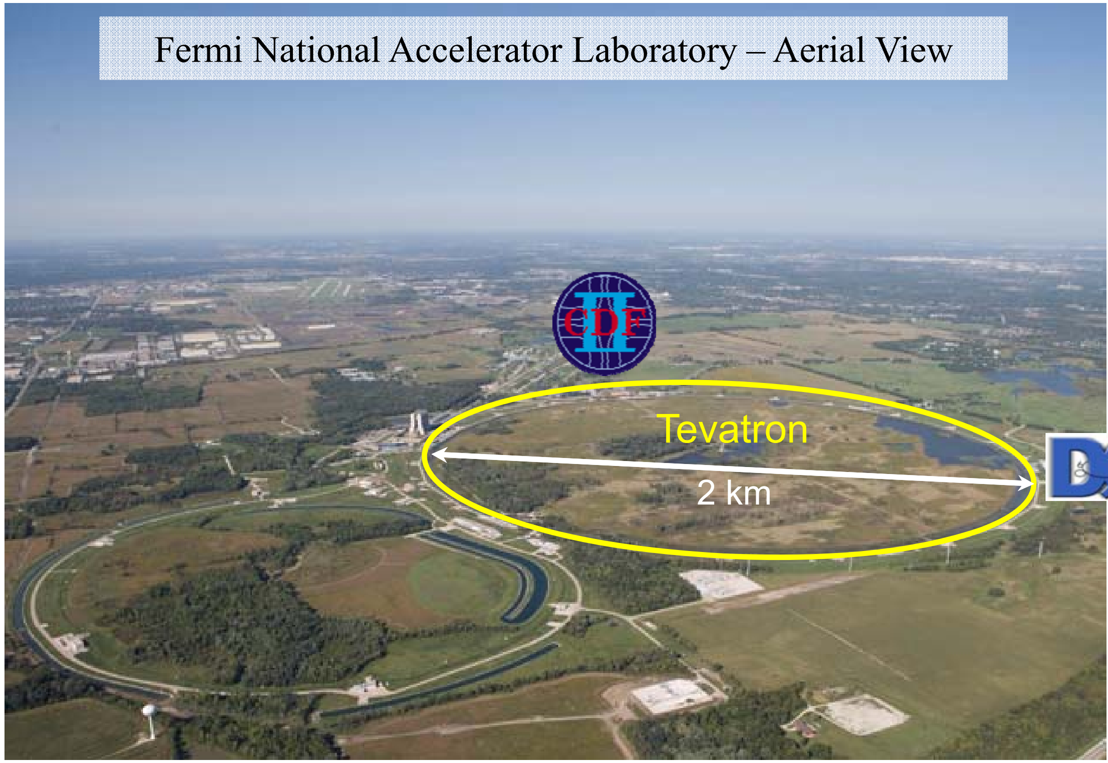
The Tevatron and the CDF Experiment

Top Quark Physics

The Search for Top FCNC Decay

Summary

Tevatron Run II: 2001–2009 (2010?)



- Proton-antiproton collider: $\sqrt{s}$ = 1.96 TeV.
- 36×36 bunches, collisions every 396 ns.
- Record instantaneous peak luminosity:

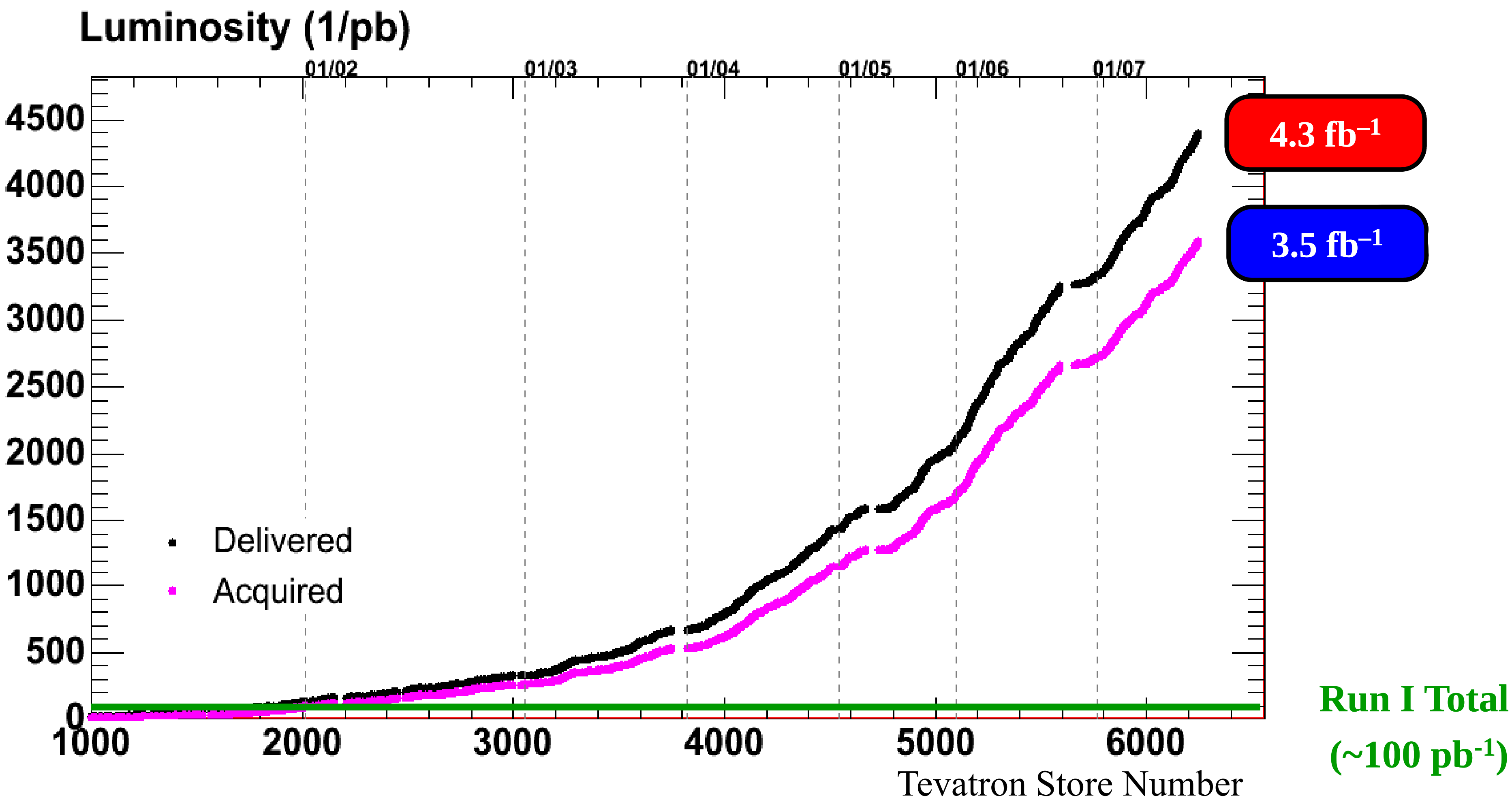
$315 \cdot 10^{30}$ cm^{-2} s^{-1}!

- Luminosity goal: 5.5 – 6.5 fb^{-1} of integrated luminosity by 2009, running in 2010 currently under discussion.
- Two multi-purpose detectors: CDF and DØ.

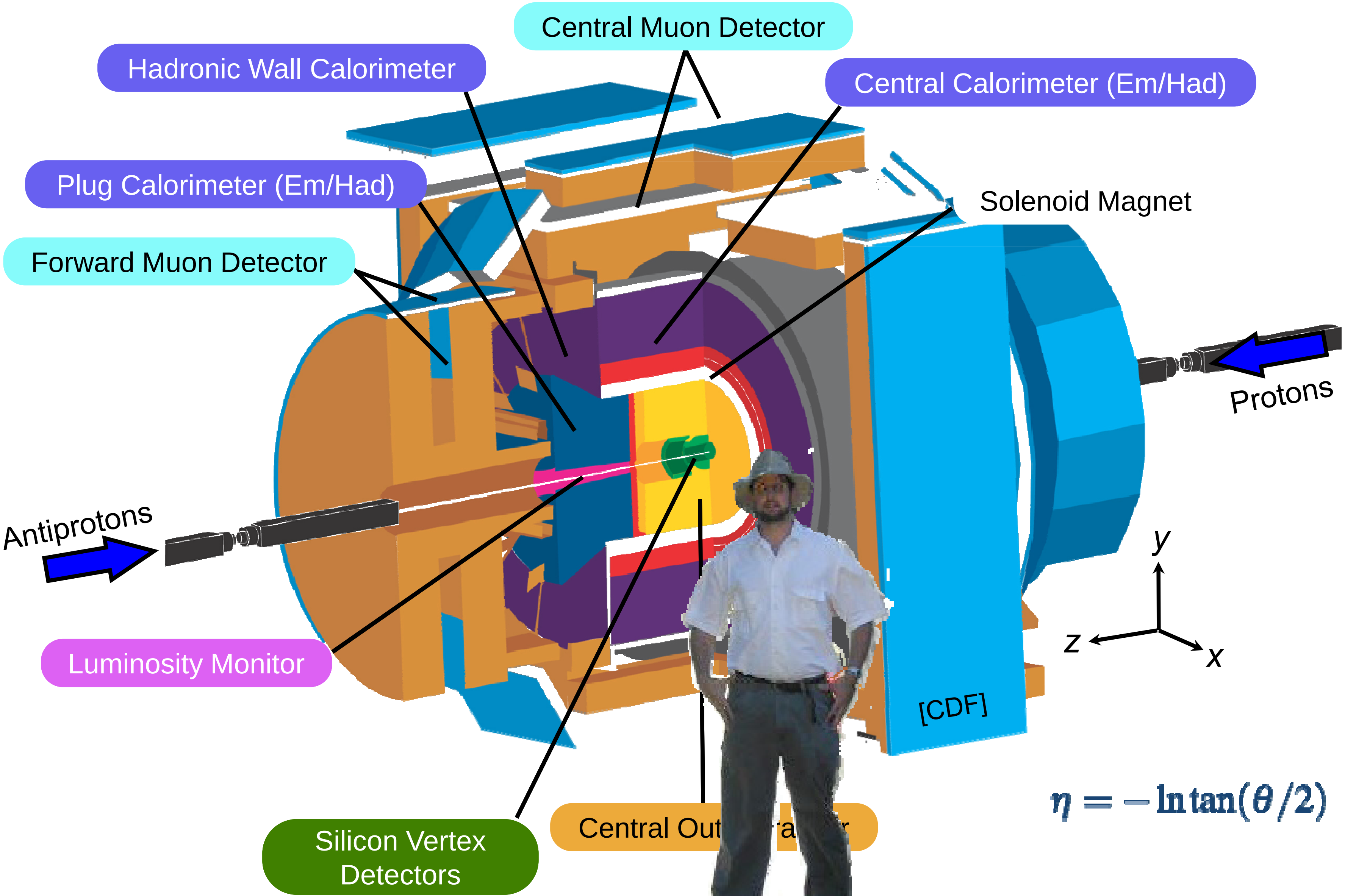
Tevatron Performance

- Tevatron continues to perform **very** well:
  - More than 4.3 fb^{-1} delivered.
  - More than 3.5 fb^{-1} recorded by CDF.

The Tevatron just delivered 56 pb^{-1} in ***single week!***



The CDF II Detector



$$\eta = -\ln \tan(\theta/2)$$

Outline

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Top Quark History

- CDF and DØ Run I announced the top quark discovery March, 1995.

- This discovery did not "*just happen*":
  - Other experiments had been looking for the previous 20 years with no (real) top quark discovery.
    - PETRA (DESY): e^+e^-
    - $Sp\bar{p}S$ (CERN): $p\,\bar{p}$
    - LEP I (CERN): e^+e^-
  - Run I was in its fourth year (after three years of Run 0 and many years of designing, building, and commissioning the detectors).

A Quick Note About Scale

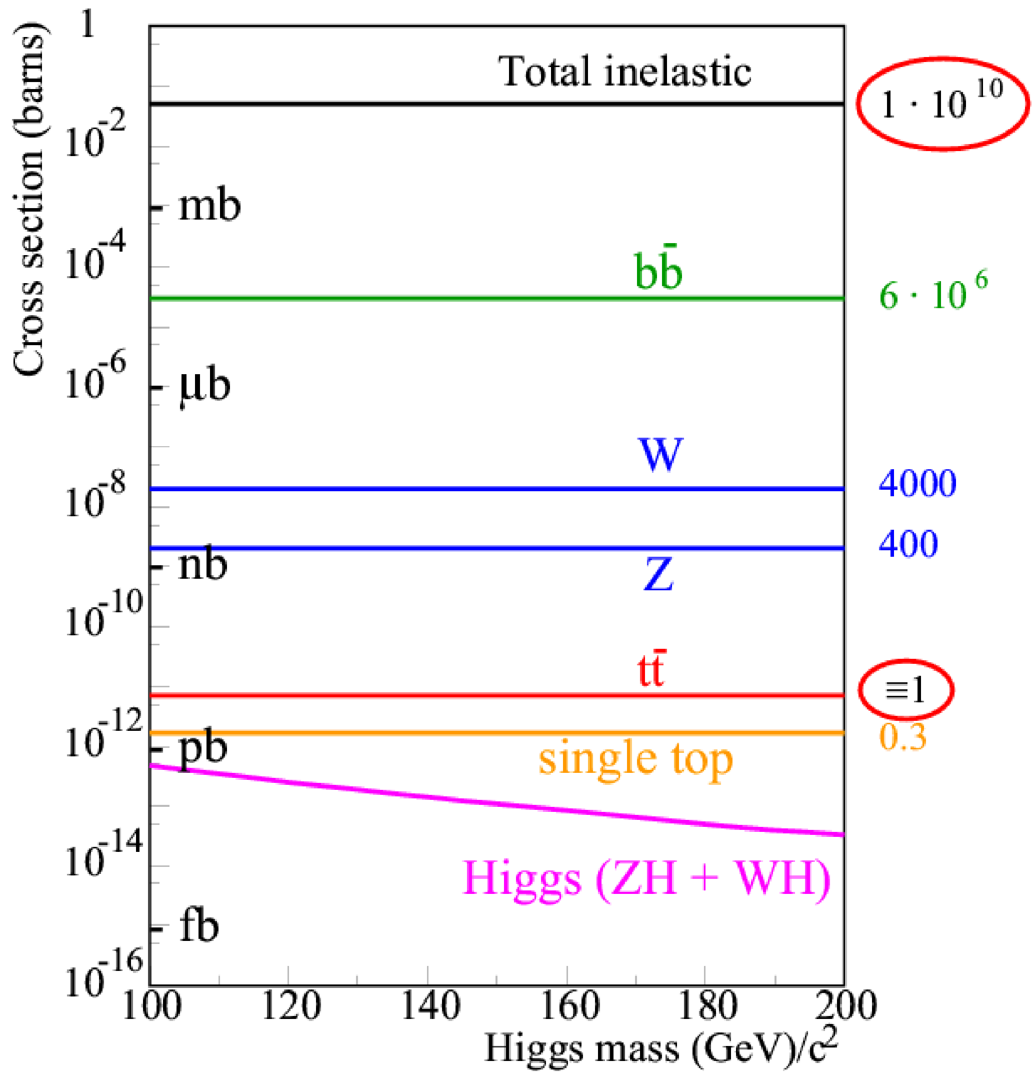
For those not intimately familiar with Tevatron high p_T Physics:

Top:

1 in **10 Billion**

Reducing and understanding backgrounds is the key.

Cross Sections at $\sqrt{s}$ = 1.96 TeV

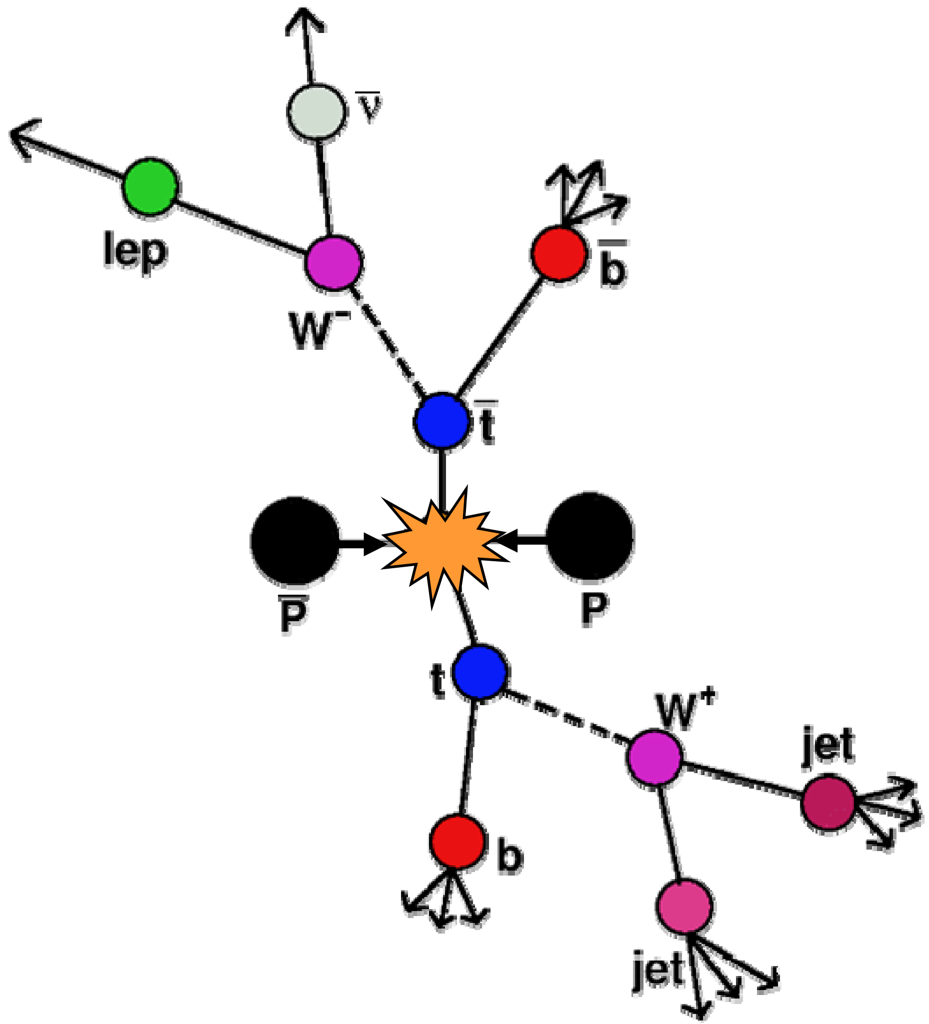


Top Quark Review

- Top: the **Golden** quark (~ 175 GeV/c^2)
  - Only fermion with mass near EW scale.
  - 40 times heavier than the bottom quark.
- Very wide (1.5 GeV/c^2)
  - The top quarks decay before they can hadronize.
    - We can study the decay of the bare quark.
- Usually observed in pairs.
- Fundamental question:

  Is it the truth, the Standard Model (SM) truth, and nothing but the truth?
  - Did we really find the top quark?
  - Is it the SM top quark?
  - Is it only the SM top quark?
- The top quark is an ideal place to look for Beyond the Standard Model Physics!

$t\bar{t}$ Pair Lepton + Jets Decay



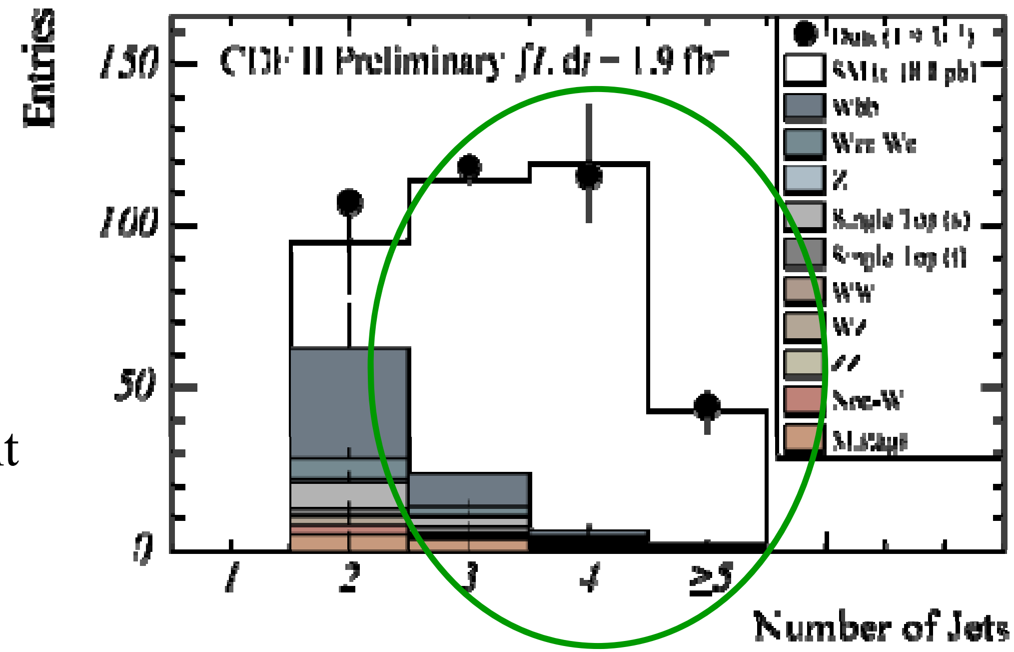
New Era of Top Precision Physics!

- CDF and DØ now have more than thirty (**30** !!!) times as much integrated luminosity as we did when they discovered the top quark in Run I!

- With the data we have recorded, we are now able to have large, ***very pure*** top samples.

- Of the almost 50 results that CDF sent to the winter conferences, ***more than half*** were in top physics!

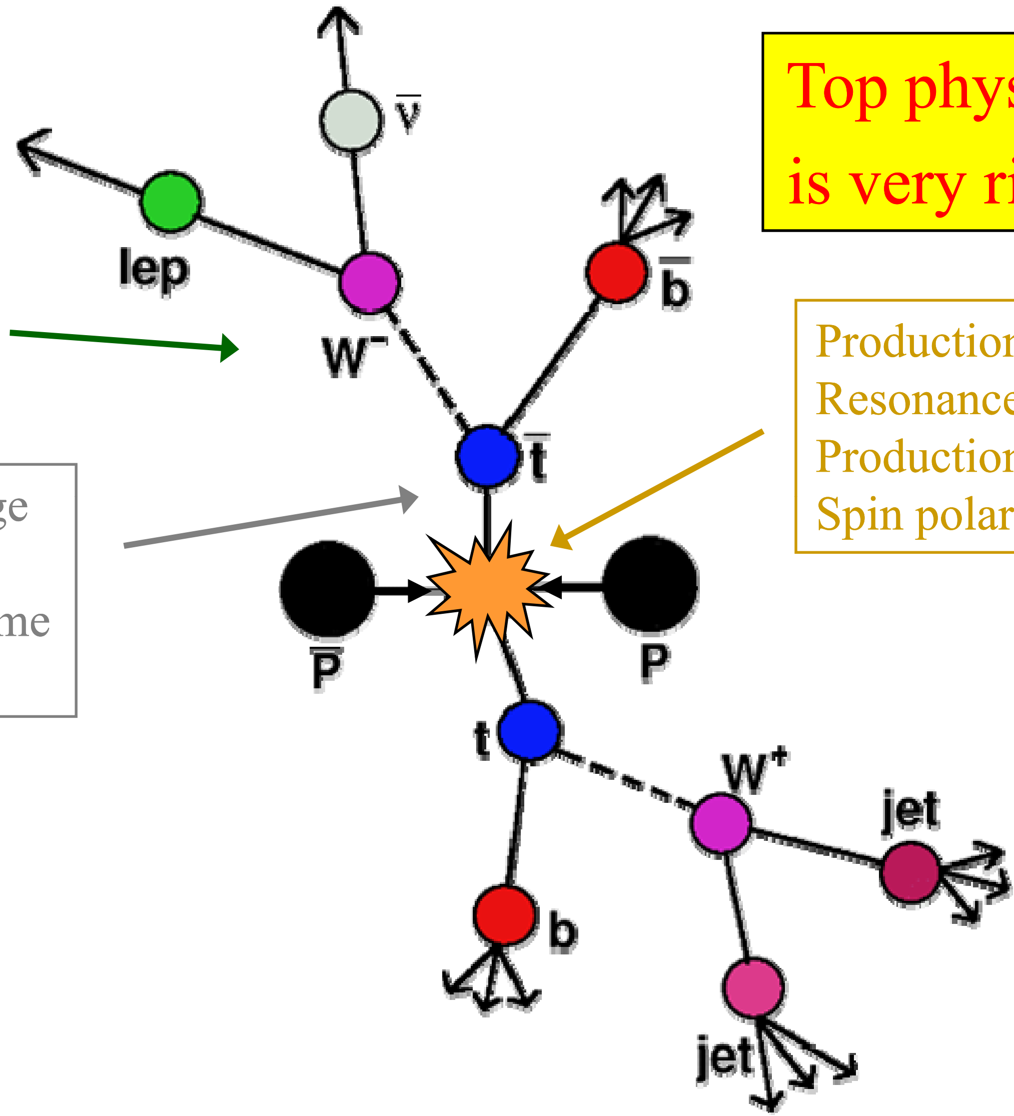
Double B-Tag W + Jets Candidates



What Can We Study About Top Quarks?

Branching ratios
Rare decays
Non-SM decays
Decay kinematics
W helicity
$|V_{tb}|$

Top charge
Top spin
Top lifetime
Top mass

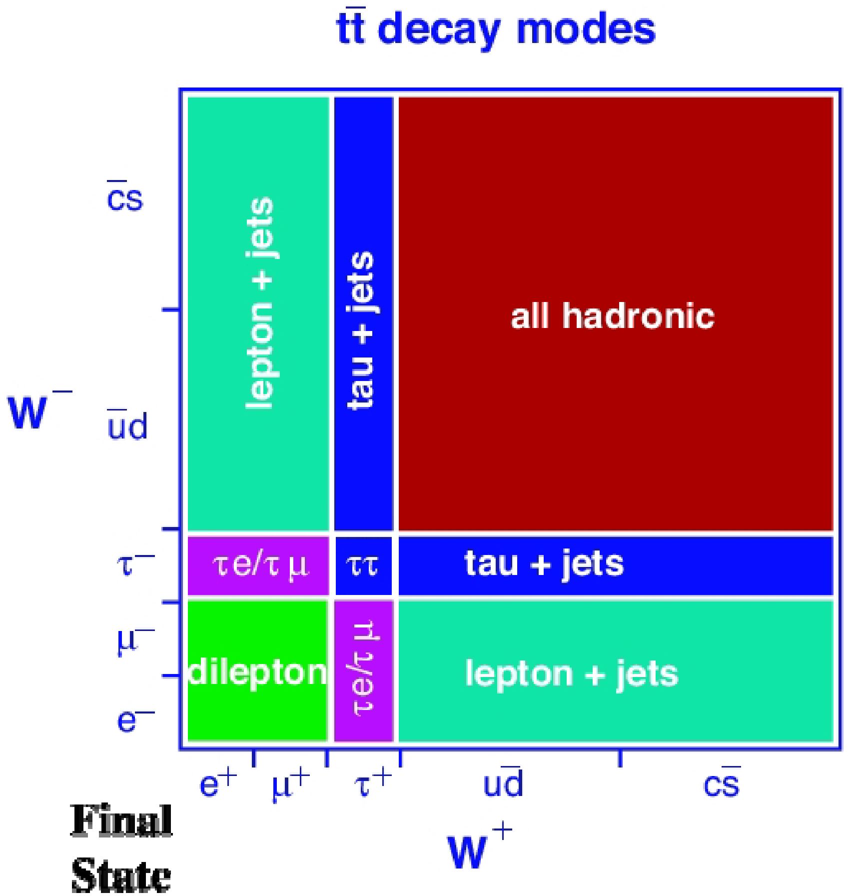


Top physics is very rich.

Production cross section
Resonance production
Production kinematics
Spin polarization

Top Pair Decay Modes

- According to the SM, top quarks almost (?) always decay to Wb.
- When classifying the decay modes, we use the W decay modes:
  - Leptonic
    - Light leptons (e or μ)
    - Tauonic (τ)
  - Hadrons

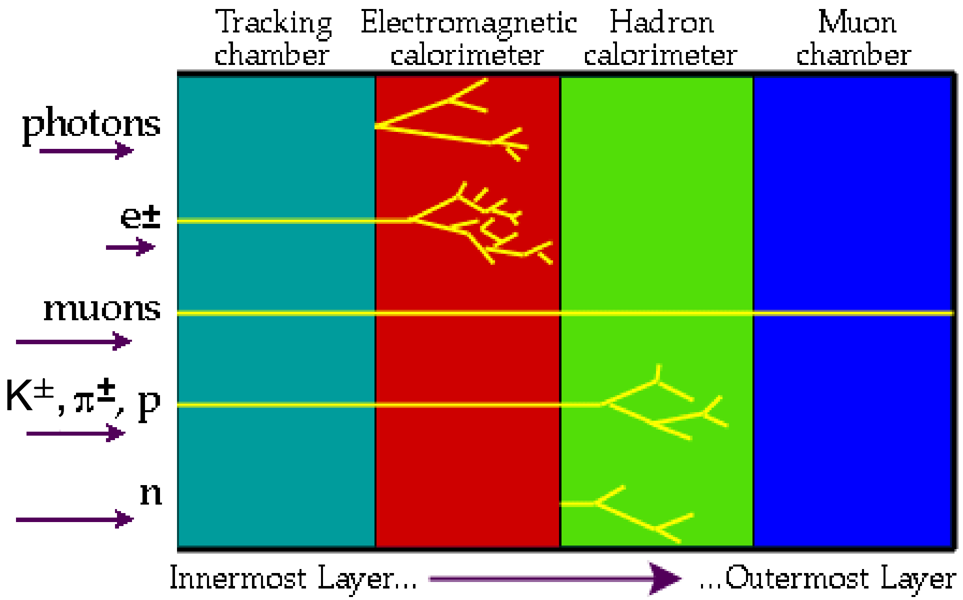


Decay Mode	Branching Fraction	Relative Background	Final State
Dilepton - no τs	~ 5%	Low	$\ell\ell\,\nu\nu$ bb
Lepton + Jets - no τs	~ 30%	Medium	$\ell\,\nu$ bb jj
All Hadronic	~ 45%	High	bb jjjj
Tauonic	~ 20%	High	

Important Tool: Lepton ID

- For many analyses, we need a very pure set of high p_T electrons and muons.

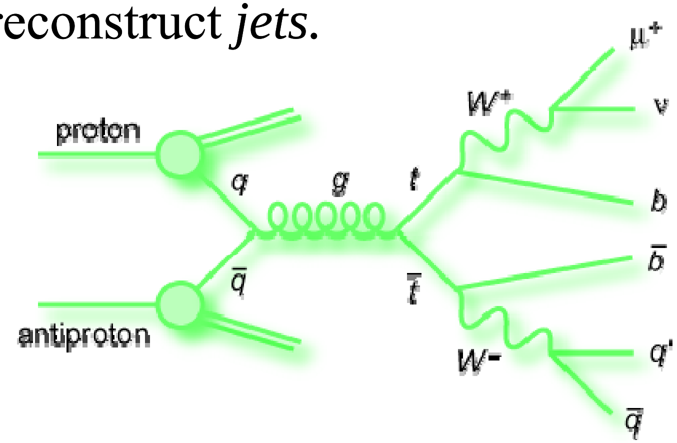
- Electrons (as we reconstruct them):
  - Have charged particle track.
  - Leave almost all of their energy in the electromagnetic calorimeter.
  - Ask for no other nearby tracks.
    - We do not want leptons from (heavy flavor) jets.



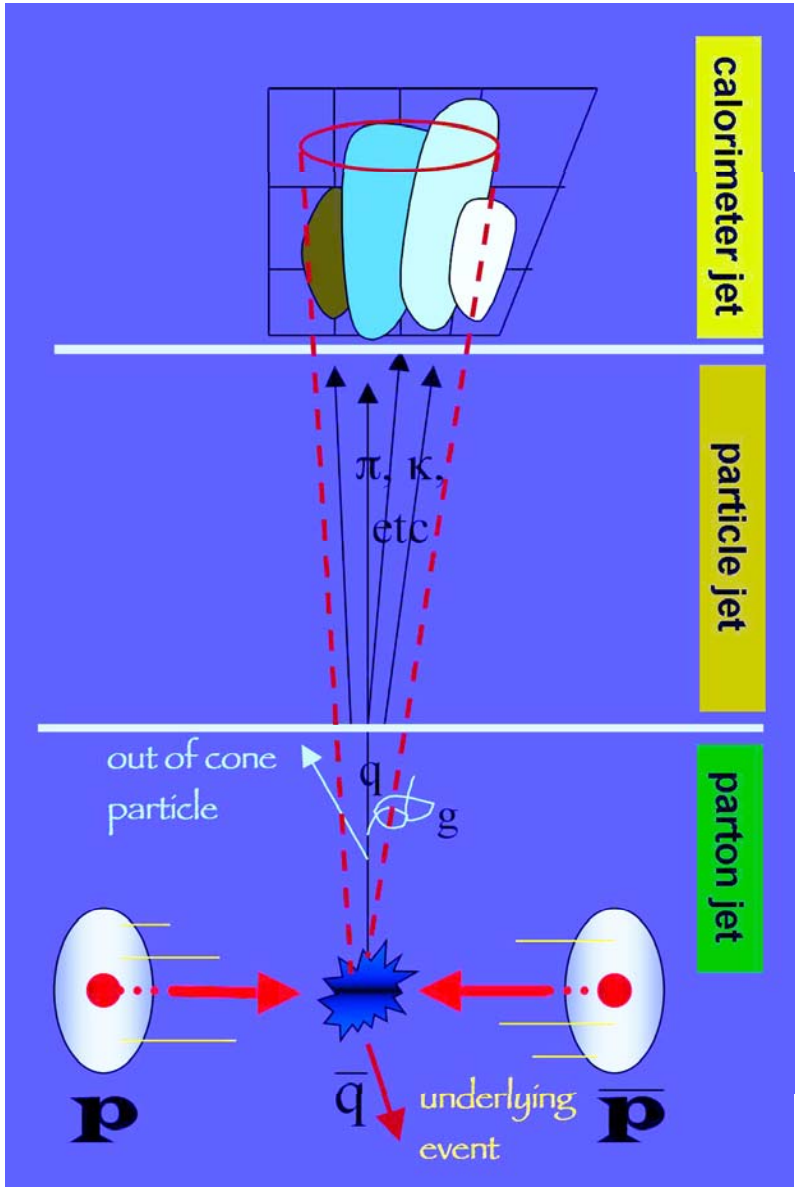
- Muons:
  - Have charged particle track.
  - ~ Minimum ionizing (leave little energy in either the electromagnetic or hadronic calorimeter)
  - Find a "stub" of a track in dedicated muon detector systems on outside of CDF.
  - Ask for no other nearby tracks.

Important Tool: Jet Reconstruction

- We think of *partons*, but we reconstruct *jets*.

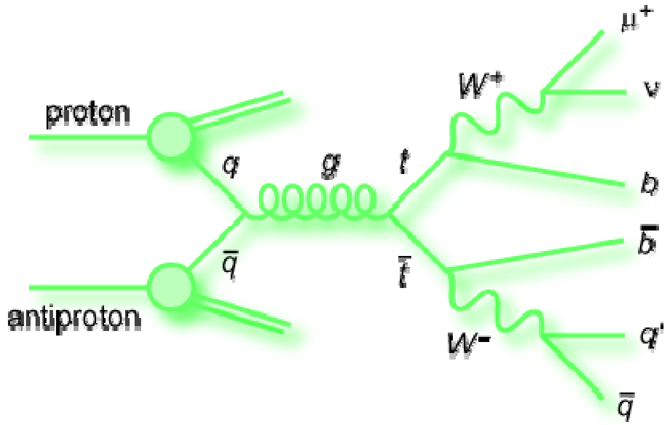


- We need to convert "*raw*" jets to "*corrected*" jets - Jet Energy Scale (JES) correction.
  - Takes into account detector effects, neutral particles in jets, particles outside of the jet cone, underlying events, multiple interactions, …



Important Tool: B Jet Tagging

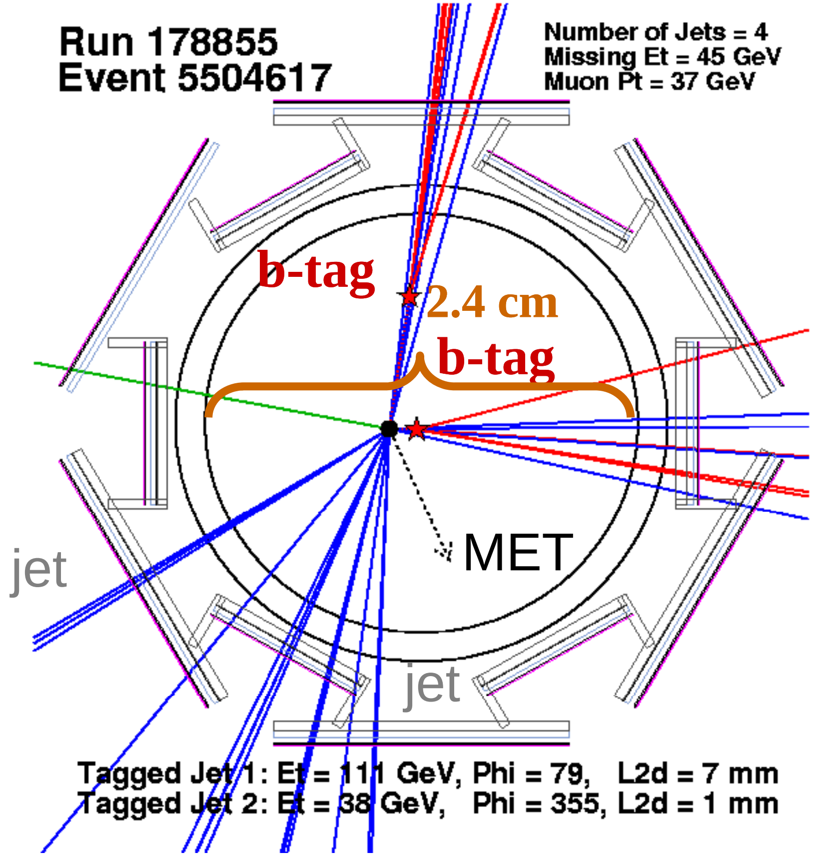
- Since we (often) expect $t \rightarrow W\, b$, b jet tagging is a very important tool.
  - Most backgrounds do not have bottom quark jets.



- We rely on the long b quark lifetime.
  - B hadrons can travel several millimeters before decaying.
  - Use displaced vertices or many displaced tracks (impact parameter).

CDF Event:

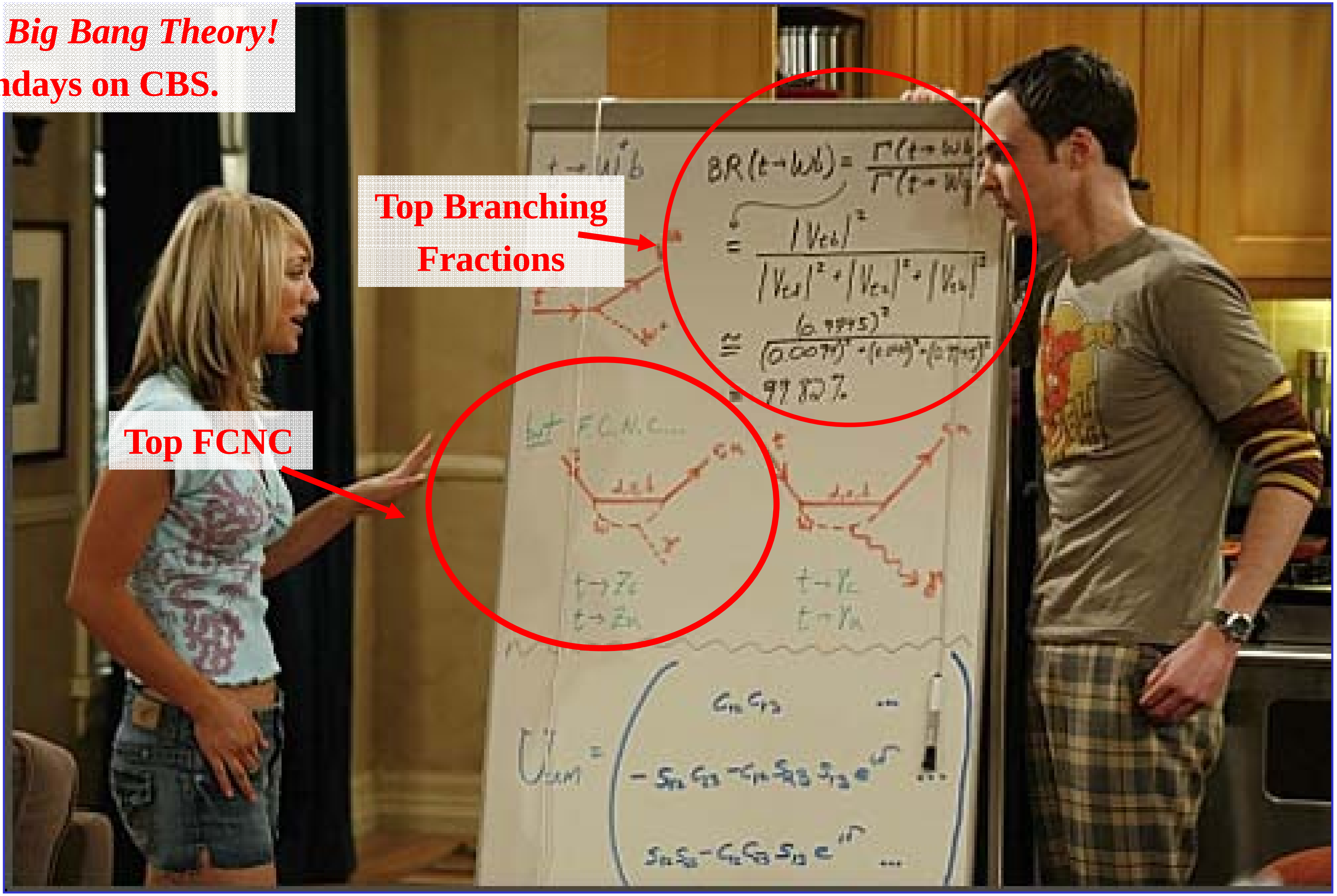
Close-up View of Layer 00 Silicon Detector



Top Physics *Finally* Makes Prime Time

The Big Bang Theory!

Mondays on CBS.



Outline

The Tevatron and the CDF Experiment

Top Quark Physics

The Search for Top FCNC Decay

Summary

Top FCNC Outline

The Search for Top FCNC Decay

Introduction

Search For Invisible Top Decays

Direct FCNC Search

Acceptances

Backgrounds

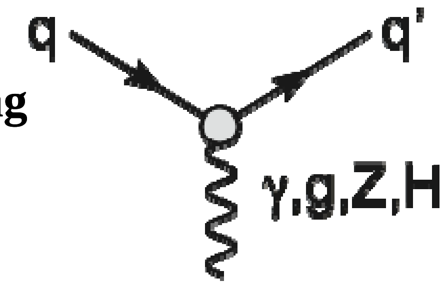
Unblinding

Fitting For Everything

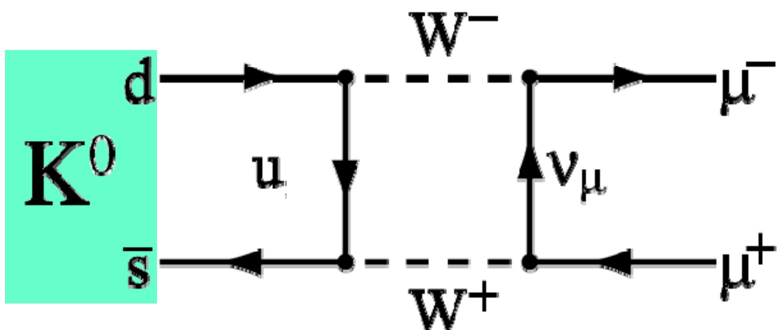
Flavor Changing Neutral Currents

- Flavor changing neutral current (FCNC) interactions:
  - Transition from a quark of flavor A and charge Q to quark of flavor B with the same charge Q.
  - Examples: $b \rightarrow s\gamma$, $t \rightarrow Hc$, …

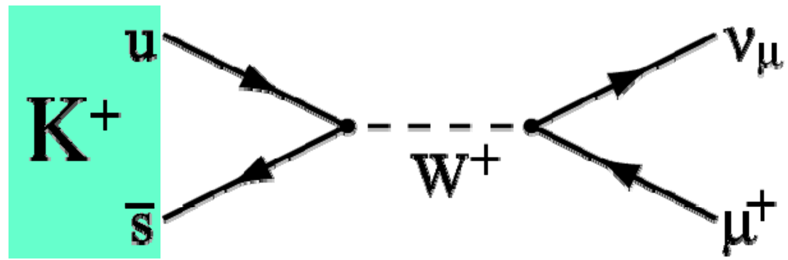
Flavor Changing Neutral Current



- 1960s: only three light quarks (u,d,s) known, mystery in kaon system:



10^8 times smaller than…?

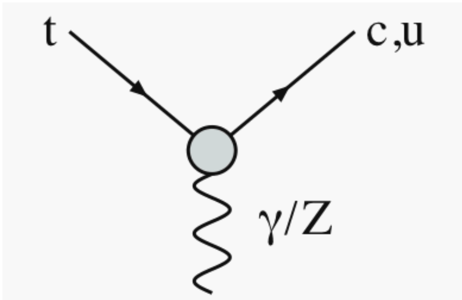


- Solution: "GIM Mechanism" (Glashow, Iliopoulos, Maiani, 1970)
  - Fourth quark needed for cancellation in box diagram: prediction of charm quark.
  - Cancellation would be exact if all quarks had the same mass: estimate of charm quark mass.

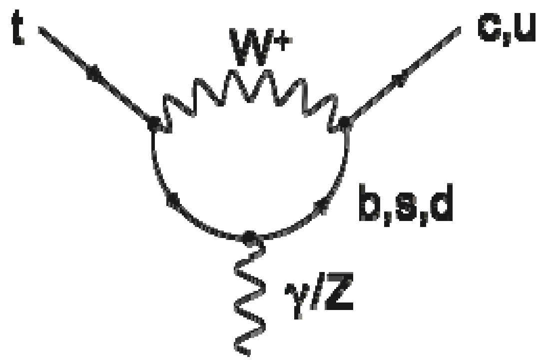
Top Flavor Changing Neutral Currents

- SM Higgs mechanism: weak neutral currents (NC) do not change the flavor of quarks/leptons ("flavor-diagonal")
  ⇒ no FCNC at "tree level."
- FCNC possible e.g. via penguin diagrams.
- Suppression of this mode:
  - GIM mechanism
  - Cabibbo suppression
- Expected SM branching fraction (Br) for $t \rightarrow Zc$ as small as 10^{-14} .
- Any signal at the Tevatron or LHC: New Physics.

Generic FCNC

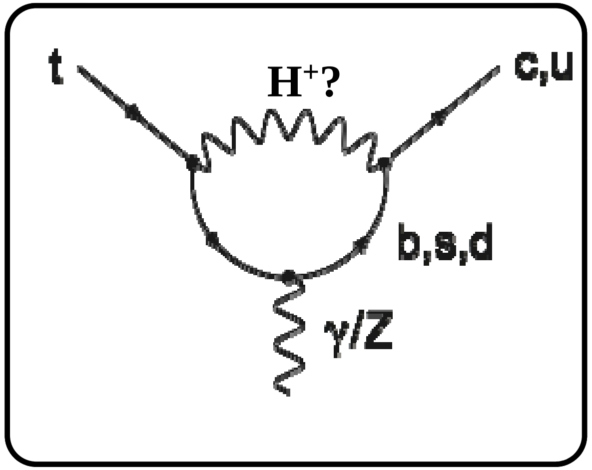


Penguin Diagram



Top FCNC & New Physics

- FCNC are enhanced in many models of physics beyond the SM.
- Enhancement mechanisms:
  - FCNC interactions at tree level.
  - Weaker GIM cancellation by new particles in loop corrections.
- Examples:
  - New quark singlets: Z couplings not flavor-diagonal → tree level FCNC.
  - Two Higgs doublet models: modified Higgs mechanism.
- Flavor changing Higgs couplings allowed at tree level.
- Virtual Higgs in loop corrections.
  - Supersymmetry: gluino/neutralino and squark in loop corrections.

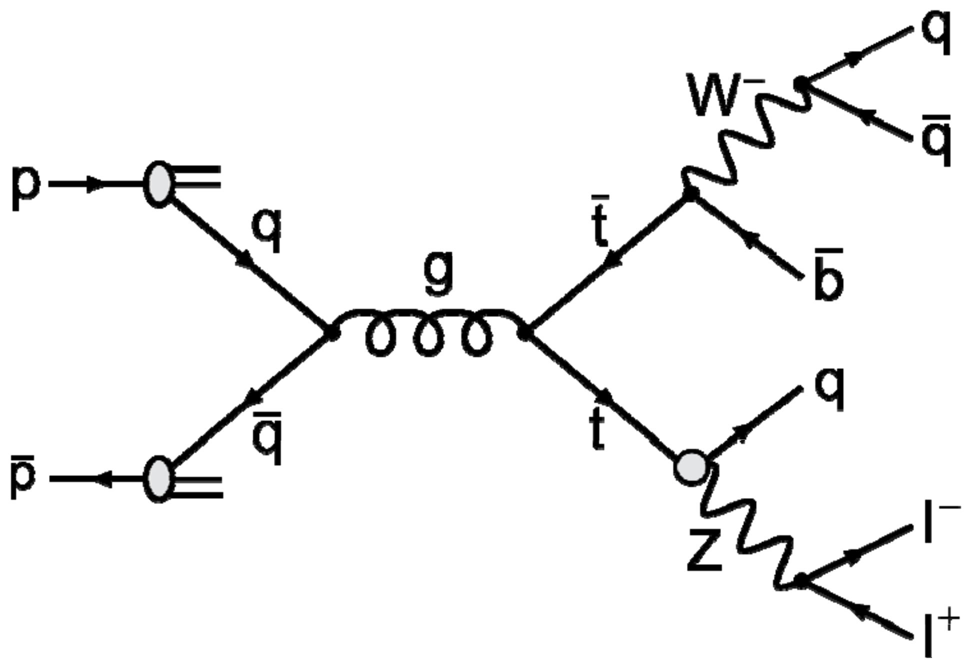


Model	BR($t \to Zq$)
Standard Model	$\mathcal{O}(10^{-14})$
$q = 2/3$ Quark Singlet	$\mathcal{O}(10^{-4})$
Two Higgs Doublets	$\mathcal{O}(10^{-7})$
MSSM	$\mathcal{O}(10^{-6})$
R-Parity violating SUSY	$\mathcal{O}(10^{-5})$

[after J.A. Aguilar-Saavedra, Acta Phys. Polor **B35** (2004) 2695]

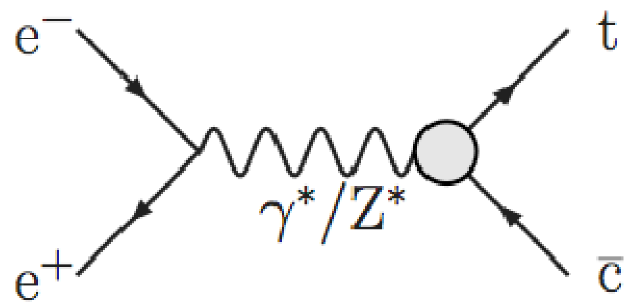
Previous Limits

- Run I Search:
  - 110 pb^{-1} of data
  - $t\bar{t} \rightarrow Zc\ Wb \rightarrow Z+\geq 4j$
  - Limit: Br $(t \rightarrow Zc) < 33\%$ at 95% C.L.



- Limit from LEP II
  - search for single top production:

$$e^+ e^- \rightarrow t\,\bar{c}$$



  - 634 pb^{-1}
  - Limit: Br $(t \rightarrow Zc) < 13.7\%$ at 95% C.L.

  ⇒ Best limit so far with **Z bosons**.

Top FCNC Outline

The Search for Top FCNC Decay

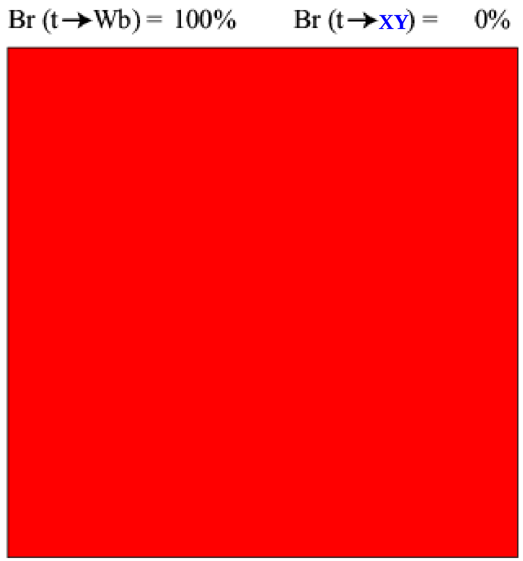
- Introduction
- Search For Invisible Top Decays
- Direct FCNC Search
- Acceptances
- Backgrounds
- Unblinding
- Fitting For Everything

Search for Invisible Top Decays

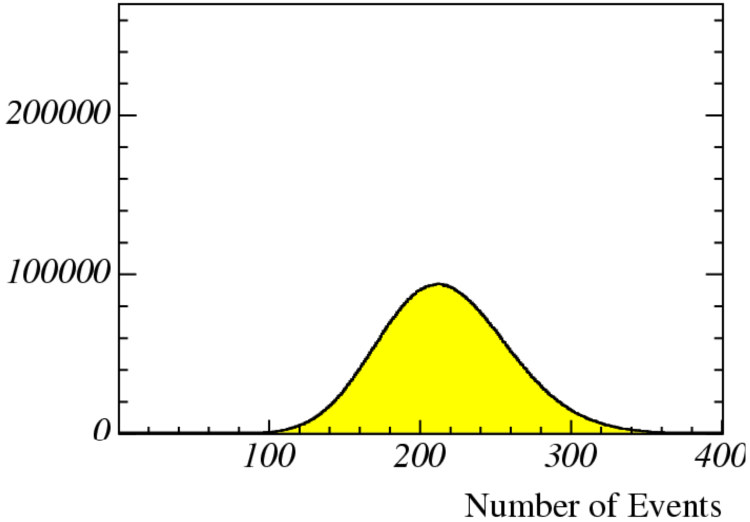
- It is the *relative* reconstruction efficiency ⊗ acceptance that determines the relative yield.
  - $\mathscr{R}_{wx/ww}$ is the relative acceptance when one top decays to the *Wb* while the other decays to the new decay, *XY*.
  - $\mathscr{R}_{xx/ww}$ is the relative acceptance when both top quarks decays to the new decay, *XY*.

$$\text{Yield} \propto \mathscr{P}(t\bar{t} \to Wb\,Wb) + \mathscr{P}(t\bar{t} \to Wb\,XY)\cdot\mathscr{R}_{wx/ww}\ \mathscr{P}(t\bar{t} \to XY\,XY)\cdot\mathscr{R}_{xx/ww}$$

- Compare expected yield to observed number of candidate events.
  - Create Feldman-Cousins acceptance bands using number of observed events.
  - t → Zc, t → gc, t → γc, t → Invisible.

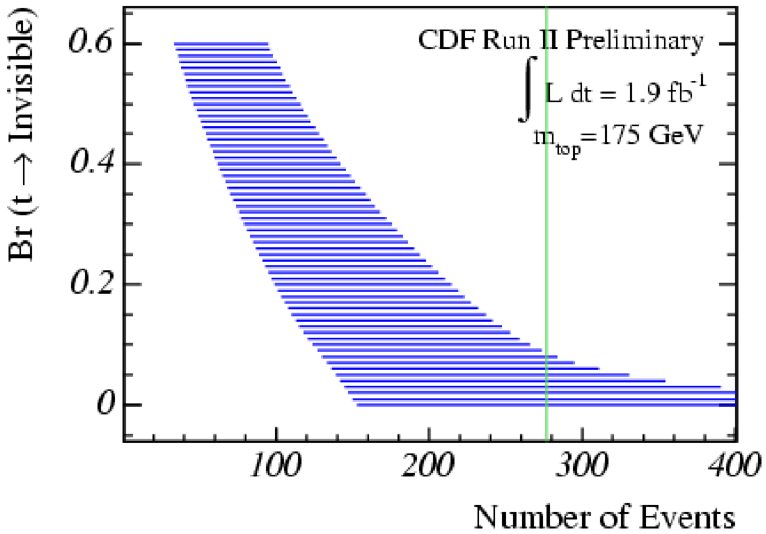


t → Invisible PEs for 0% Branching Fraction

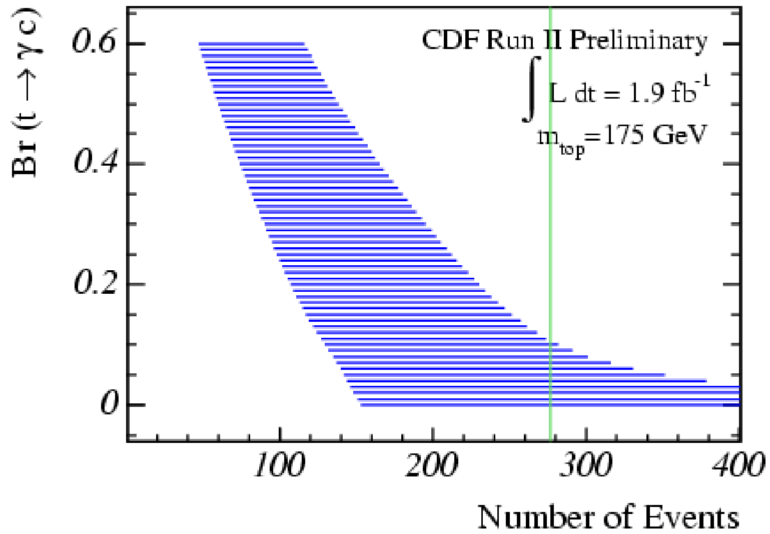


Feldman-Cousins Acceptance Bands

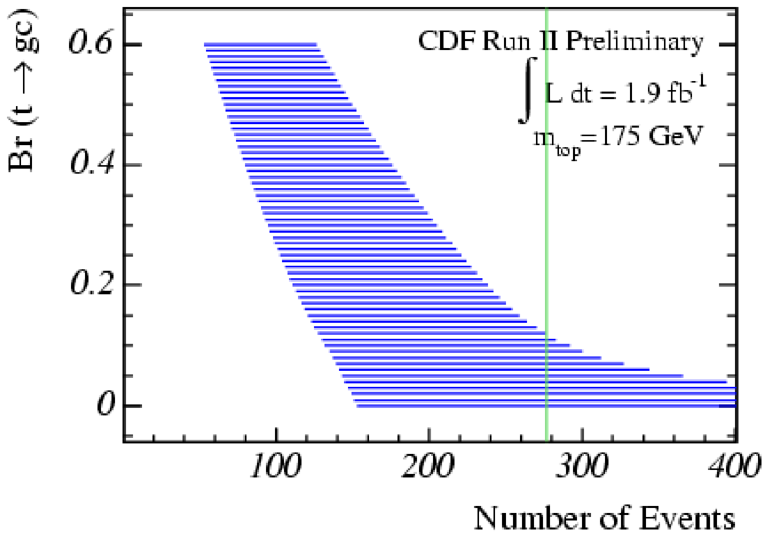
FC Bands for t → Invisible



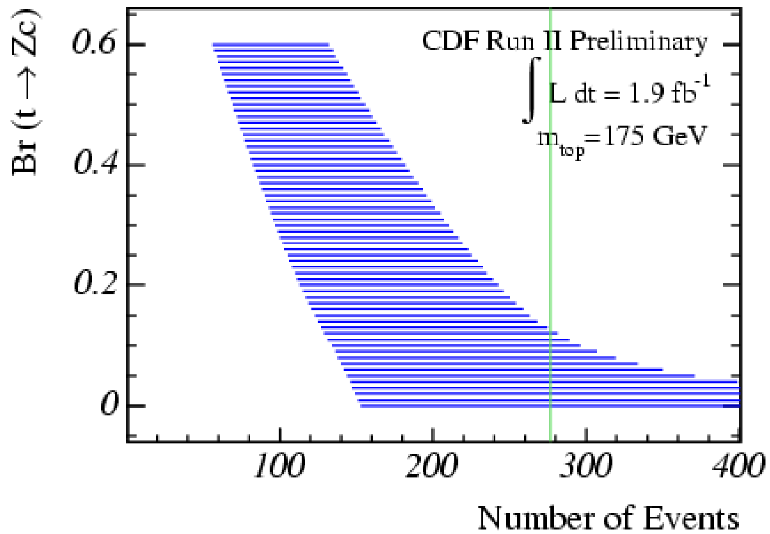
FC Bands for t → γ c



FC Bands for t → gc



FC Bands for t → Zc



Search for Invisible Top Decays, cont.

- From Cacciari et al. (hep-ph: 0804.2800) assuming CTEQ PDFs.
- Expected Limits:

CDF Run II Preliminary 1.9 fb^{-1}

Decay	$\mathscr{R}_{wx/ww}$ (%)	175 GeV (%)
$t \to Zc$	32	28^{-14}_{-12}
$t \to gc$	27	26^{-14}_{-11}
$t \to \gamma c$	13	24^{-12}_{-10}
$t \to$ invisible	0	20^{-10}_{-8}

$$\int \mathscr{L}\,dt = 1.9\ \text{fb}^{-1}$$

Better Than L3's Published Limit!

- Observed Limits:

CDF Run II Preliminary 1.9 fb^{-1}

Decay	$\mathscr{R}_{wx/ww}$ (%)	Upper Limit (%) (175 GeV)	Upper Limit (%) (172.5 GeV)
$\mathscr{B}(t \to Zc)$	32	13	15
$\mathscr{B}(t \to gc)$	27	12	14
$\mathscr{B}(t \to \gamma c)$	18	11	12
$\mathscr{B}(t \to \text{invisible})$	0	9	10

World's First Measurement!

Top FCNC Outline

The Search for Top FCNC Decay

Introduction

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Direct FCNC Search

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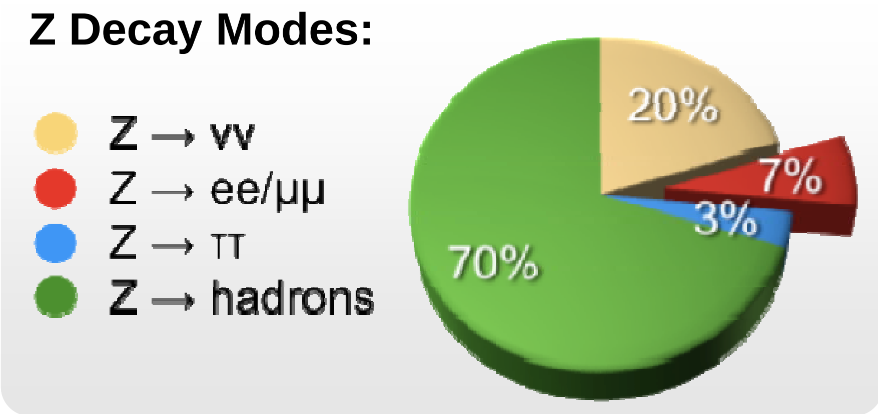
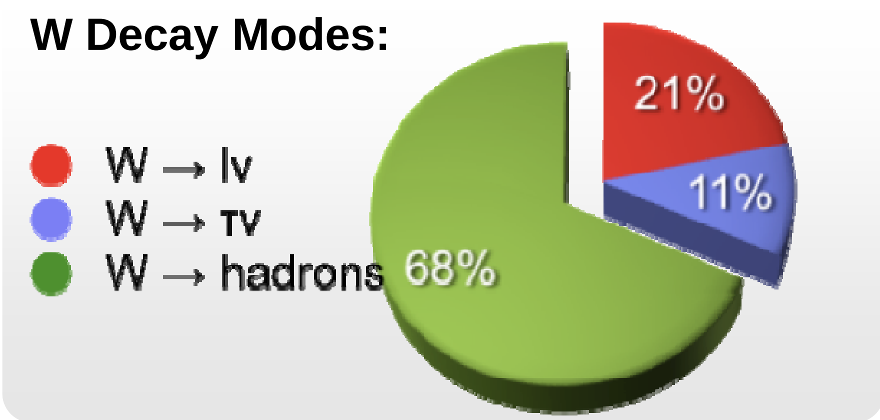
Top FCNC Direct Search: Roadmap

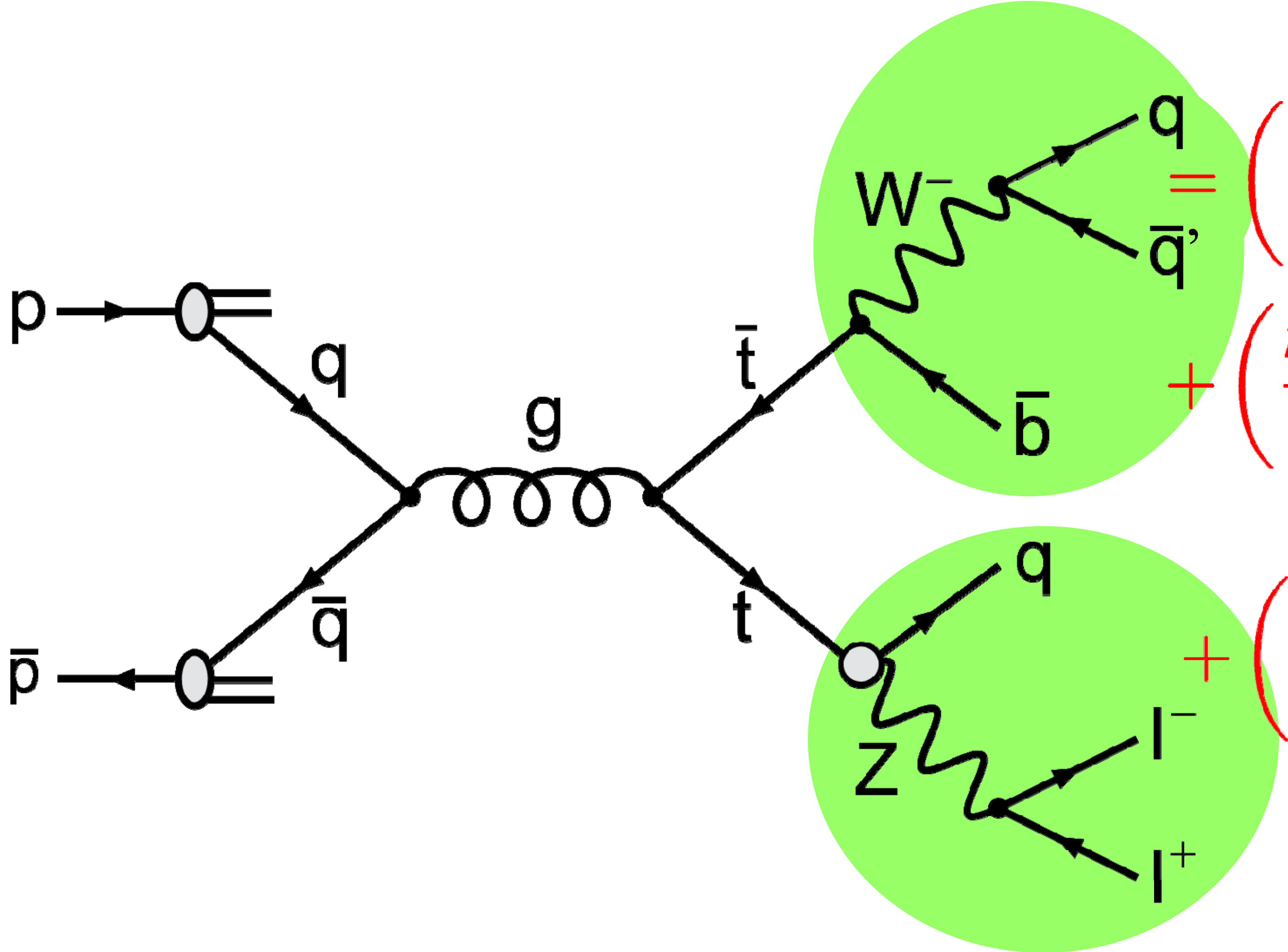
- Basic question: how often do top quarks decay into Zc?
  - Measure (or set limit) on branching fraction, Br ($t \rightarrow Zc$).
  - Normalize to lepton + jets top pair decays.



- Selection of decay channels for $tt \rightarrow Zc\ Wb$:
  - $Z \rightarrow$ charged leptons: very clean signature, lepton trigger.
  - $W \rightarrow$ hadrons: large branching fractions, no neutrinos .
    $\Rightarrow$ Event can be fully reconstructed
  - Final signature: $Z + \geq 4$ jets.



Search for FCNC: Ingredients



$$\chi^2_{\text{mass reconstruction}} = \left(\frac{m_{W\ \text{recon}} - m_W}{\sigma_W}\right)^2 + \left(\frac{m_{tWb\ \text{recon}} - m_t}{\sigma_{tWb}}\right)^2 + \left(\frac{m_{tZc\ \text{recon}} - m_t}{\sigma_{tZc}}\right)^2$$

Top Mass Reconstruction

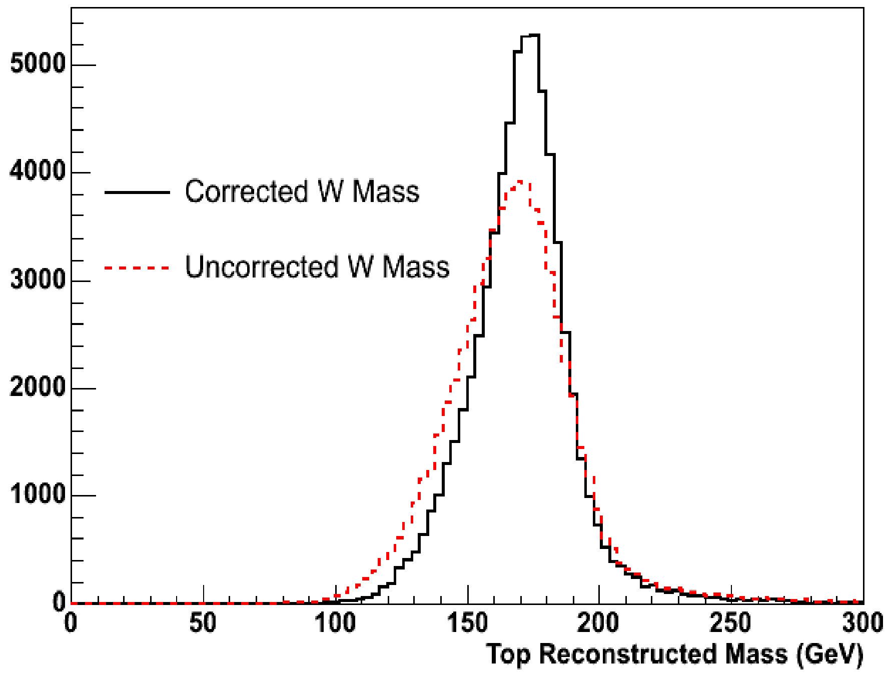
- For our signal, we have three hadronic masses to reconstruct:
  - W mass
  - $t \to Wb$ mass
  - $t \to Zc$ mass

$t \to Wb$ mass resolution:

20 GeV ⇒ 16 GeV!

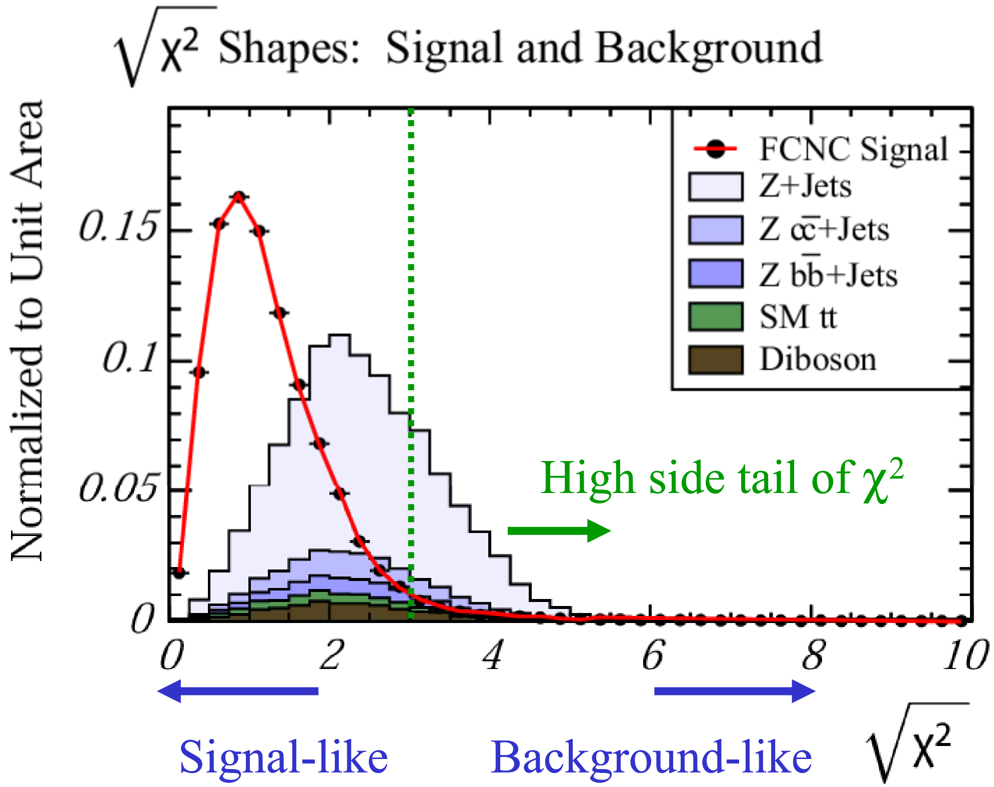
Signal MC with partons correctly matched to reconstructed objects.

- To improve resolution, we correct the W and Z daughters so that the masses are correct.
  - Rescale the daughters within their resolutions.
  - Smaller mass resolution ⇒ Better signal separation.



Mass χ^2

- We do not know which partons are reconstructed as which jets.
  $\Rightarrow$ Loop over all 12 permutations and take lowest χ^2 value.



Round 1: Blind Analysis

- Event signature: $Z \rightarrow l^+ l^- + 4$ jets.
- Motivation for blind analysis: Avoid biases by looking into the data too early.
- Blinding & unblinding strategy:
  - Initial blinded region: $Z + \geq 4$ jets.
  - Later: add control region in $Z + \geq 4$ jets from high side tail of mass χ^2.
  - Optimization of analysis on data control regions and Monte Carlo (MC) simulation only.
  - Very last step: "opening the box", *i.e.*, look into signal region in data.
  - Counting experiment:

    ⇒ Compared expected background to observed events.

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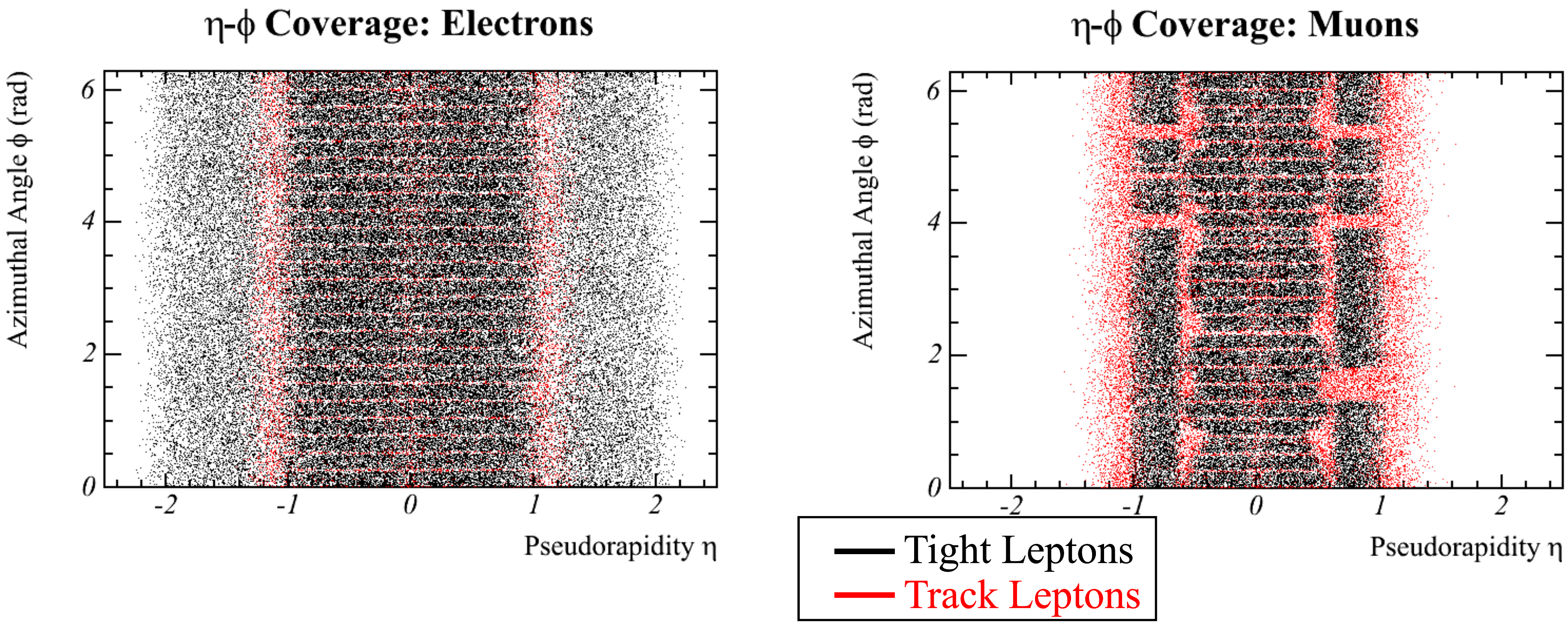
Lepton + Track Z Candidates



- Use isolated track (instead of tight lepton) for second lepton.
  - Doubles acceptance.
  - Almost all backgrounds have real leptons.

- Base Event Selection:
  - Tight lepton + track lepton Z candidate.
  - At least four jets ($|\eta| < 2.4$, corrected $E_T > 15$ GeV).

To B-Tag or not to B-Tag?

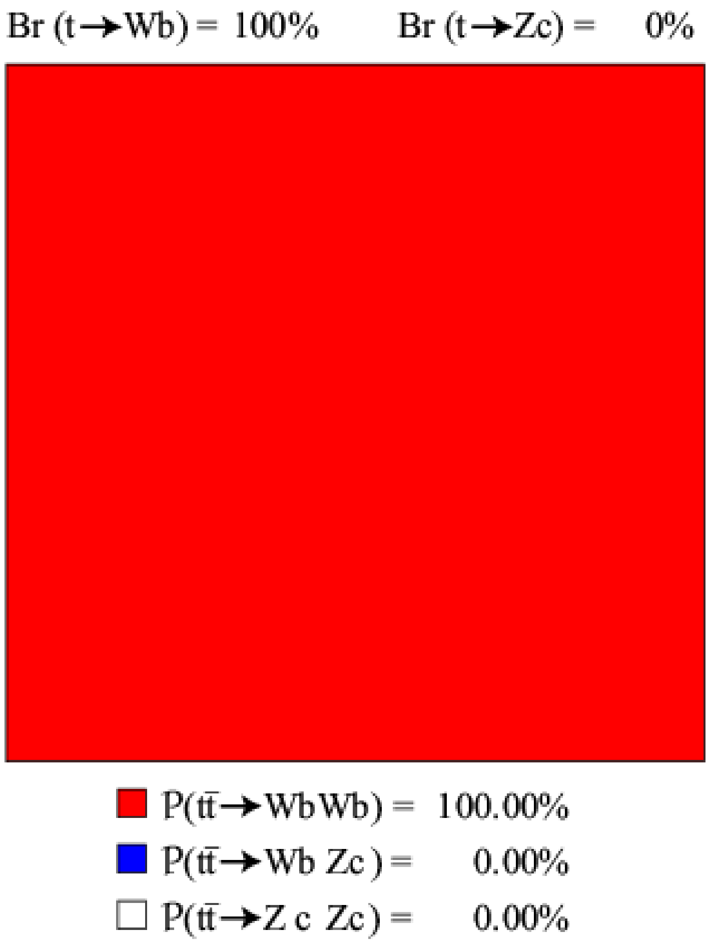
- Advantage of requiring b-tag:
  ⇒ Better discrimination against main background (Z + jets).
- Disadvantage:
  ⇒ Reduction of data sample size.

Sample	Before tagging	At least 1 b-tag
Background	130 (100%)	20 (15%)
Relative Signal Acceptance	100%	50%

- Solution: Use both!
  - Split sample in ***tagged*** (at least one tagged jet) and ***anti-tagged*** (no tagged jets).
  - Optimize cuts individually for tagged and anti-tagged samples.
  - Combine samples in limit calculation.

Acceptance Calculation: Catch 22?

$$\mathcal{N}_{\text{signal}} = [(\mathcal{P}(t\bar{t} \rightarrow WbZc) \cdot \mathcal{A}_{WZ}) + (\mathcal{P}(t\bar{t} \rightarrow ZcZc) \cdot \mathcal{A}_{ZZ})] \cdot \sigma_{t\bar{t}} \cdot \int \mathcal{L}\, dt$$



Solution: Running Acceptance

$$\mathcal{N}_{\text{signal}} = [(\mathcal{P}(t\bar{t} \to WbZc) \cdot \mathcal{A}_{WZ}) + (\mathcal{P}(t\bar{t} \to ZcZc) \cdot \mathcal{A}_{ZZ})] \cdot \sigma_{t\bar{t}}(\mathcal{B}_Z) \cdot \int \mathcal{L}\,dt$$

... 1/2 page of algebra ...

$$= \mathcal{B}_Z \cdot (\mathcal{N}_{LJ} - B_{LJ}) \cdot \frac{\mathcal{A}_{WZ}}{\mathcal{A}_{LJ\,\mathrm{ww}}} \cdot \frac{(2 \cdot (1-\mathcal{B}_Z) + K_{ZZ/WZ} \cdot \mathcal{B}_Z)}{(1-\mathcal{B}_Z)^2 + 2 \cdot \mathcal{B}_Z (1-\mathcal{B}_Z) \cdot \mathcal{R}_{\mathrm{wz/ww}} + \mathcal{B}_Z^2 \cdot \mathcal{R}_{\mathrm{zz/ww}}}$$

L+J yield | Acc. Ratio | "Running" Acceptance Correction

- Acceptance and σ_{tt} depend on $\mathcal{B}_Z$
- Our limit code recalculates acceptance as a function of branching fraction.
- Normalization to double-tagged top pair cross section measurement:
  - Smallest overlap ($\mathcal{R}_{\mathrm{wz/ww}}$) between acceptances.

$\mathcal{B}_Z$	$\equiv$	$Br(t \to Zc) = 1 - Br(t \to Wb)$
$\mathcal{A}_{WZ}$	$\equiv$	FCNC acceptance
$\mathcal{A}_{ZZ}$	$\equiv$	Double FCNC acceptance
$\mathcal{A}_{LJ\,\mathrm{ww}}$	$\equiv$	L+J acceptance for SM $t\bar{t}$
$\mathcal{A}_{LJ\,\mathrm{wz}}$	$\equiv$	L+J acceptance for FCNC
$\mathcal{A}_{LJ\,\mathrm{zz}}$	$\equiv$	L+J acceptance for FCNC
$K_{ZZ/WZ}$	$\equiv$	$\mathcal{A}_{ZZ}/\mathcal{A}_{WZ}$
$\mathcal{R}_{\mathrm{wz/ww}}$	$\equiv$	$\mathcal{A}_{LJ\,\mathrm{wz}}/\mathcal{A}_{LJ\,\mathrm{ww}}$
$\mathcal{R}_{\mathrm{zz/ww}}$	$\equiv$	$\mathcal{A}_{LJ\,\mathrm{zz}}/\mathcal{A}_{LJ\,\mathrm{ww}}$

Top FCNC Outline

The Search for Top FCNC Decay

- Introduction
- Search For Invisible Top Decays
- Direct FCNC Search
- Acceptances
- **Backgrounds**
- Unblinding
- Fitting For Everything

Expected Backgrounds

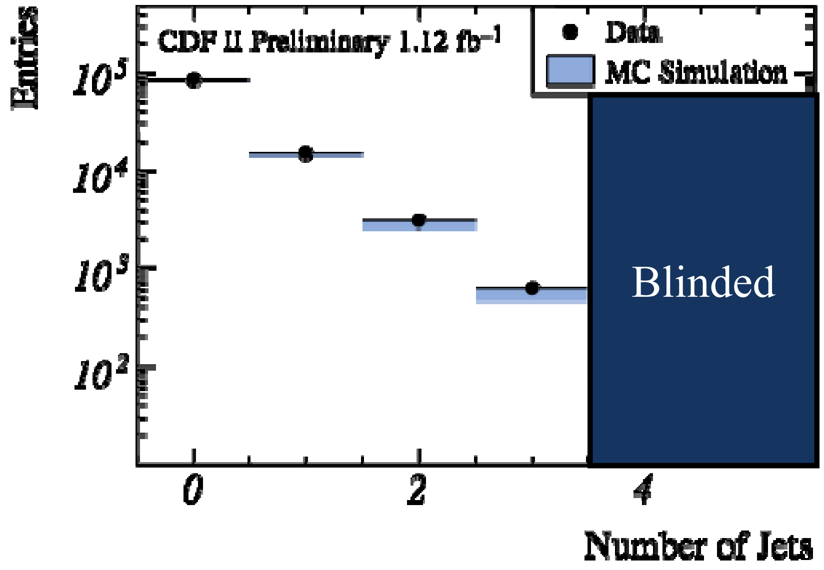
- How do you search for a signal that is likely not there? Understand the background!

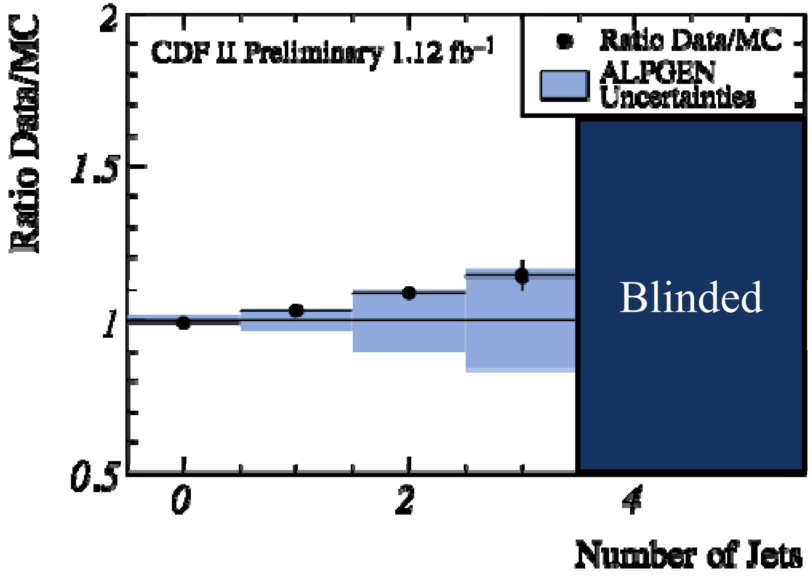
- Standard model processes that can mimic Z + ≥4 jets signature:
  - Z+Jets: Z boson production in association with jets → dominant background for top FCNC search, most difficult to estimate
  - Standard model top pair production → small background
  - Dibosons: WZ and ZZ diboson production → small background
  - W+Jets, WW: negligible

- Top FCNC background estimate: mixture of data driven techniques and MC predictions

Z+Jets Production

- MC tool for Z+Jets: ALPGEN
  - Modern MC generator for multiparticle final states
  - "MLM matching" prescription to remove overlap between jets from matrix element and partons showers
- Comparing ALPGEN with data:
  - Leading order generator: no absolute prediction for cross section.
  - After normalization to total Z yield, still underestimates of number of events with large jet multiplicities.
- Our strategy: only shapes of kinematic distributions from MC, normalization from control samples in data.
  - Normalize to the high side tail of mass χ^2 in data.





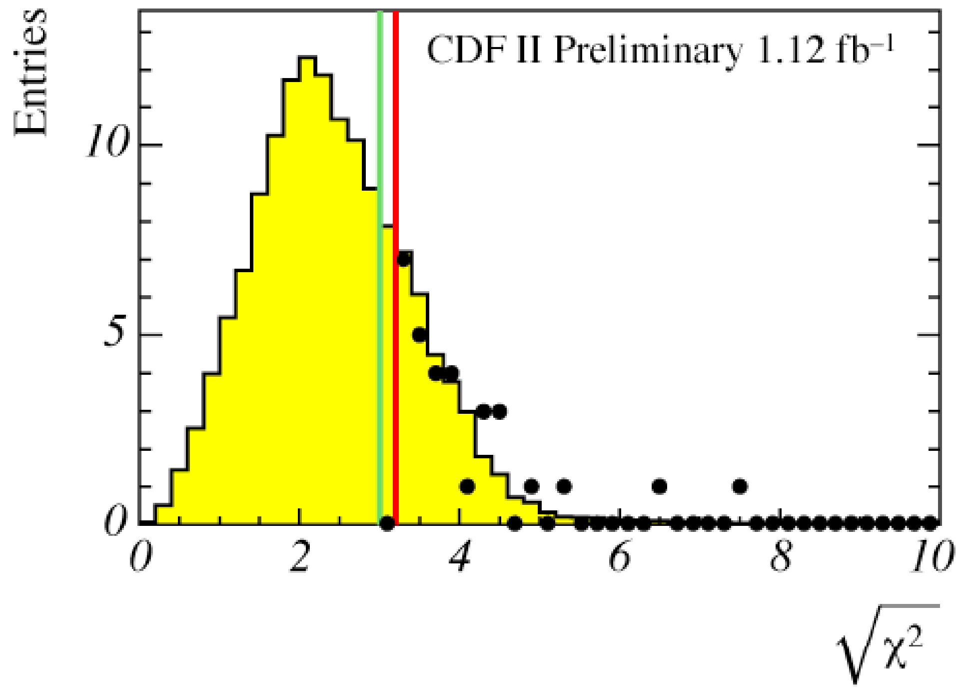
Base Selection Background Estimate

- Fit from high side of χ^2 tail :
  130 ± 28 total background events.

- Background tagging rate:
  - 5 of 31 events are tagged.
  - Combine with data-based method in lower jet bins.

  ⇒ **15% ± 4% background event tag rate.**

Fit to High χ^2 Tail



Selection	Expected
Base Selection	130±28
Base Selection (Tagged)	20±6

Optimized Signal Region Selection

- Optimized for best average expected limit.

Kinematic Variable	Optimized Cut
Z Mass	$\in [76,106]$ GeV$/c^2$
Leading Jet E_T	≥ 40 GeV
Second Jet E_T	≥ 30 GeV
Third Jet E_T	≥ 20 GeV
Fourth Jet E_T	≥ 15 GeV
Transverse Mass	≥ 200 GeV
$\sqrt{\chi^2}$	< 1.6 (b-tagged)
	< 1.35 (anti-tagged)

Selection	Expected
Anti-Tagged Selection	7.7±1.8
Tagged Selection	3.2±1.1

Expected Limit:
6.8% ± 2.9%

- Systematic uncertainties are taken into account, but do not affect limit very strongly.

Top FCNC Outline

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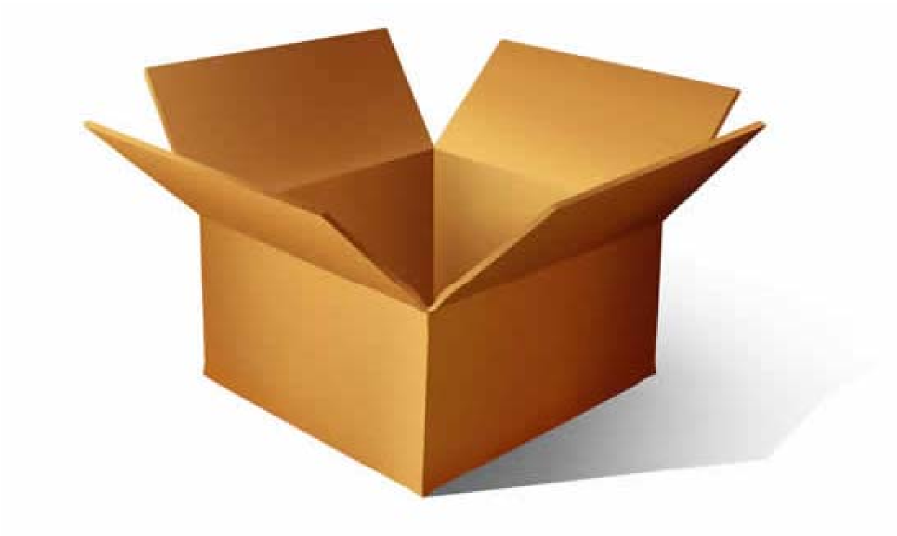
First Look

- Before we unblind the signal regions, we want to check our base predictions:

Selection	Observed	Expected
Base Selection	141	130±28
Base Selection (Tagged)	17	20±6

- So far, so good… Let's open the box!



Open the Signal Box

- Opening the box with 1.1 fb^{-1}
  - Event yield consistent with background only.
  - Fluctuated about 1σ high: slightly *"unlucky."*
  - ***Or is it the first hint of a signal?!***

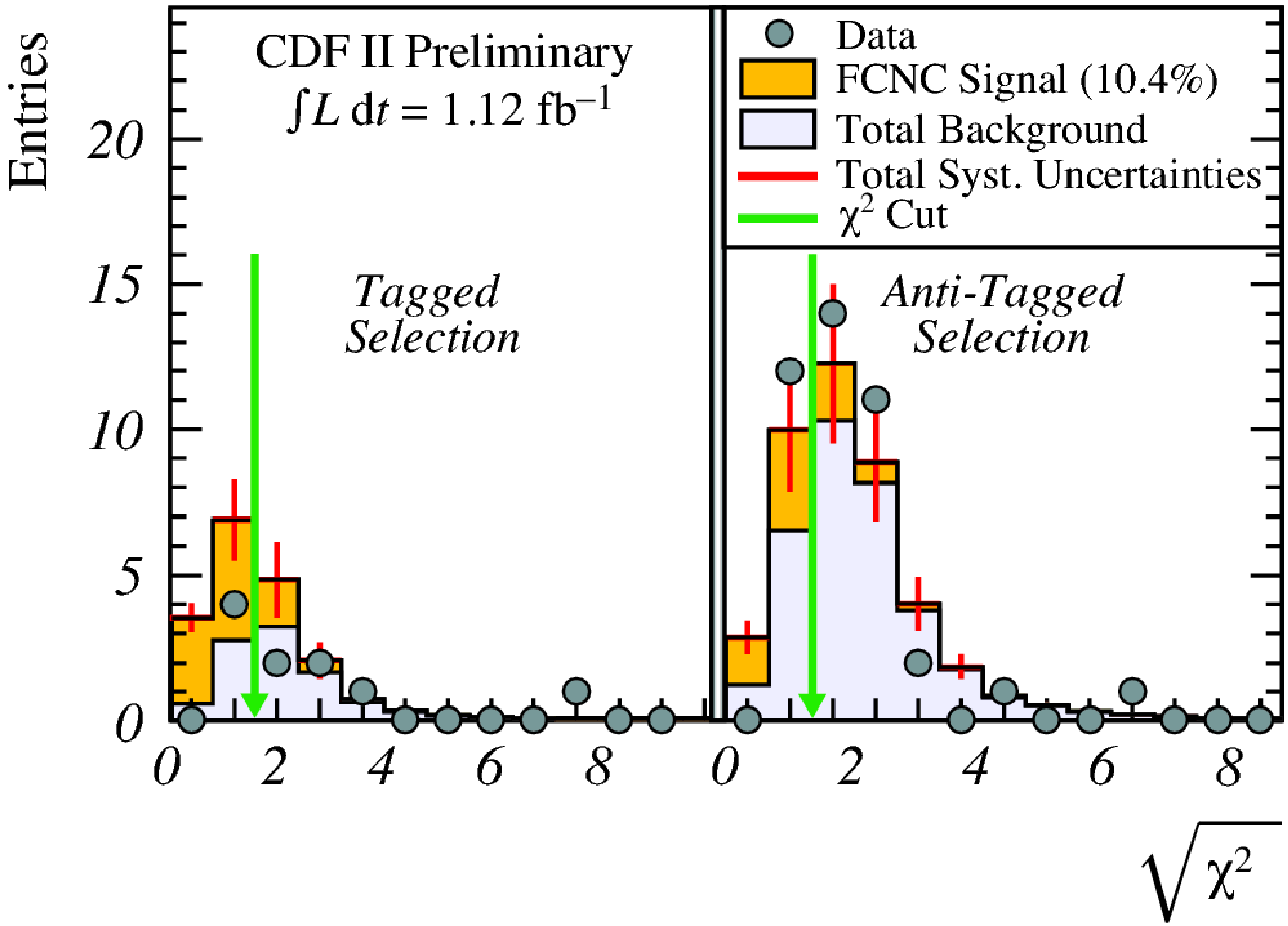
Selection	Observed	Expected
Base Selection	141	130±28
Base Selection (Tagged)	17	20±6
Anti-Tagged Selection	12	7.7±1.8
Tagged Selection	4	3.2±1.1

- Result:

$$\mathcal{B}(t \rightarrow Zq) < 10.4\% \text{ @ } 95\%\text{C.L.}$$

  - Expected limit: 6.8% ± 2.9%.

Mass χ^2 (95% C.L. Upper Limit)




The World's Is Not Enough
Best
Limit

Top FCNC Outline

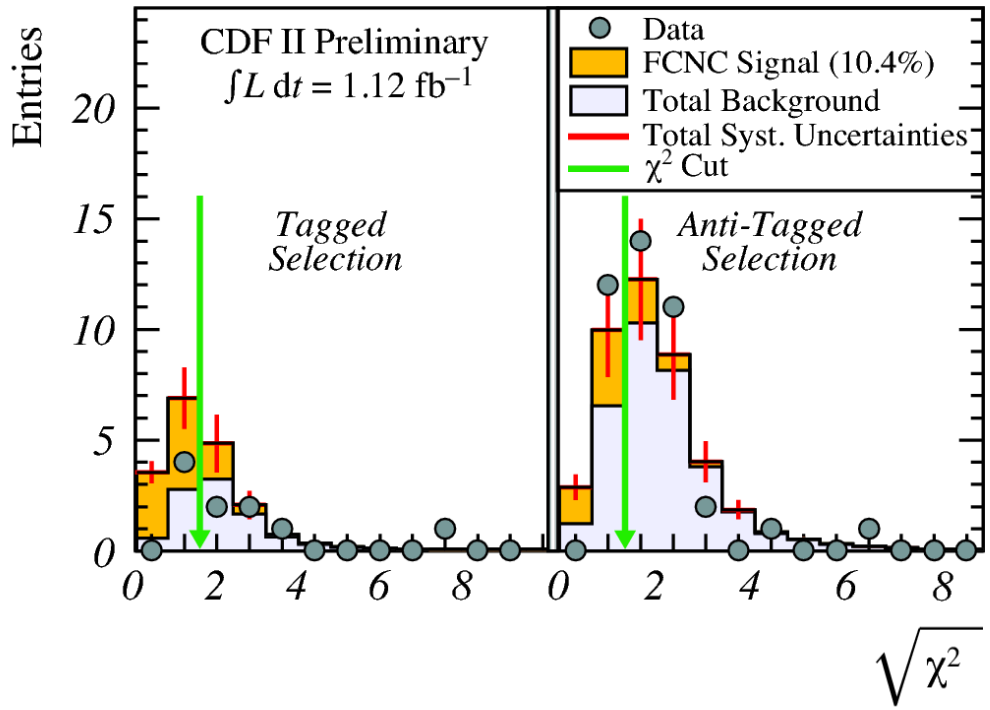
The Search for Top FCNC Decay

- Introduction
- Search For Invisible Top Decays
- Direct FCNC Search
- Acceptances
- Backgrounds
- Unblinding
- **Fitting For Everything**

Round 2: Is That The Best We Can Do?

- More $\int \mathscr{L} dt$:
  - Add 70% more data (1.9 fb^{-1}).
- Fit χ^2 Shape:
  - Previous version: counting experiment.
  - Template fit to $\sqrt{\chi^2}$ shape: exploit full shape information, less sensitive to background normalization.
- Build on previous experience:
  - Same event selection
  - Same acceptance algebra
  - Same method of calculating (most) systematic uncertainties

Mass χ^2 (95% C.L. Upper Limit)



Differences From Counting Experiment

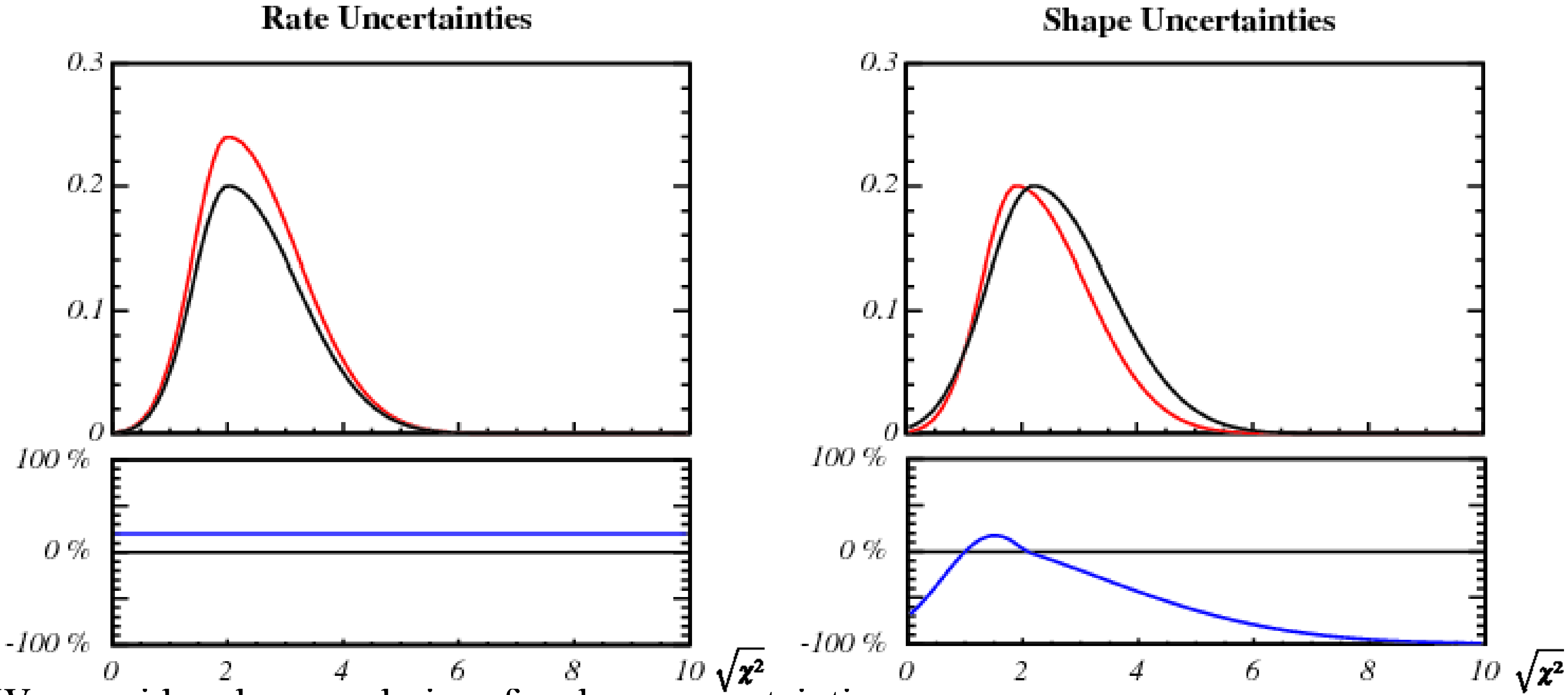
- Advantages:
  - Absolute estimation of Z + jets background is difficult. This drove the counting experiment.
  - Since we are fitting:
    - No absolute Z + jets background estimation needed.
    - No estimate of Z + jets tagging fraction needed.

  ⇒ Let these both float in the fit.
    - Smaller backgrounds are fixed to SM expectations.

- Disadvantages:
  - Counting experiment does not have shape systematic uncertainties.
    - Counting experiment: Only worry about ratios of acceptances.
    - Fit χ^2: We need to understand and account for this.

Shape Uncertainties

- What do we mean by *"shape uncertainties"*?



- We considered many choices for shape uncertainties.
- The two dominant effects were much larger than all others.
  - Factorization/Renormalization (Q^2) scale for Z + jets MC.
  - Jet energy scale uncertainties.

Shape Uncertainties: Q^2

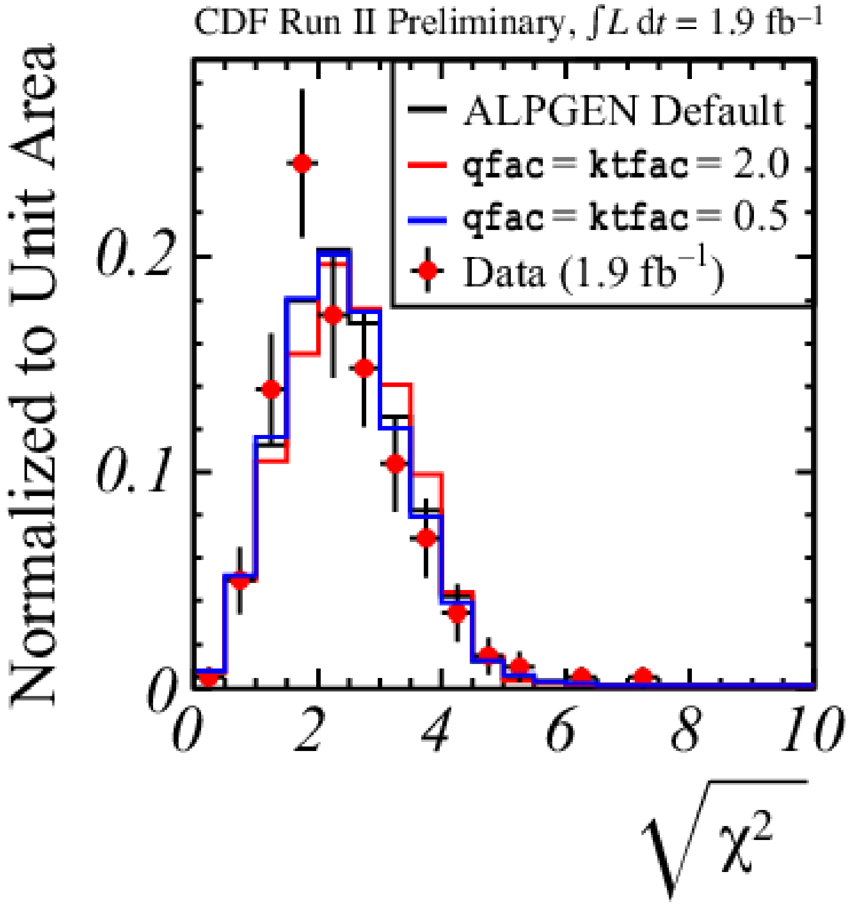
- ALPGEN: two Q^2 "knobs" to turn.
  - Factorization/renormalization scale:

    $$Q = \mathrm{qfac} \times \sqrt{M_Z^2 + \sum p_T^2(p)}$$

  - Vertex Q^2 (for evaluation of α_S):

    $$Q = \mathrm{ktfac} \times p_T$$

  - We turn both at the same time.
  - Not enough to explain data.

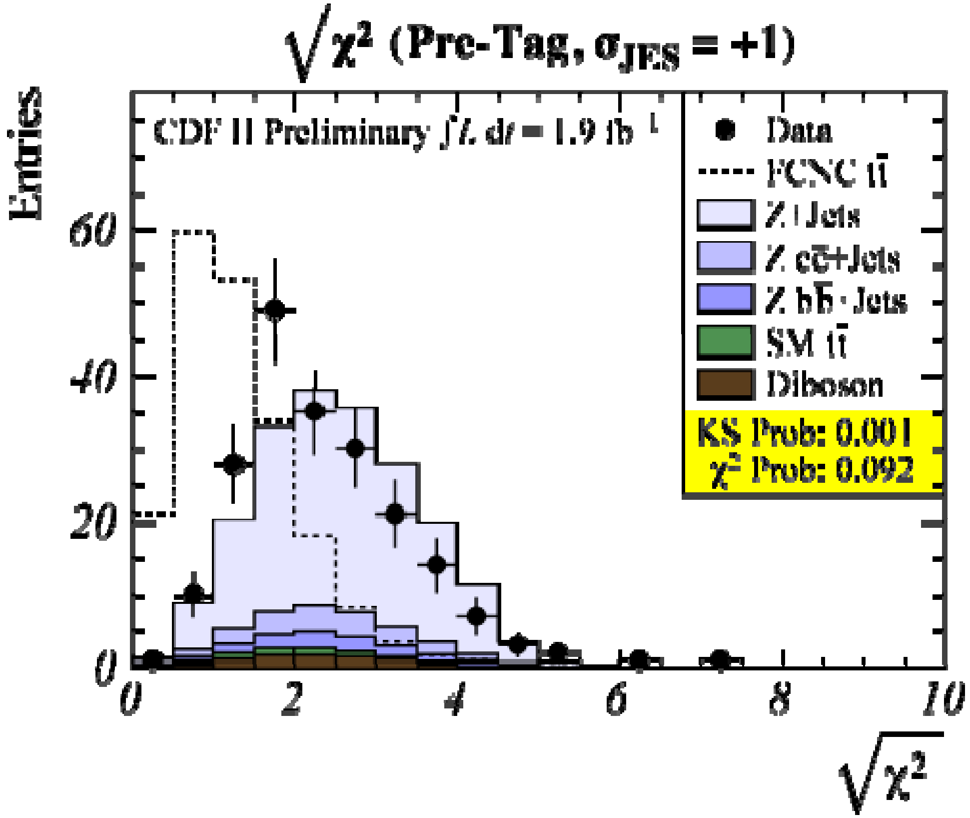


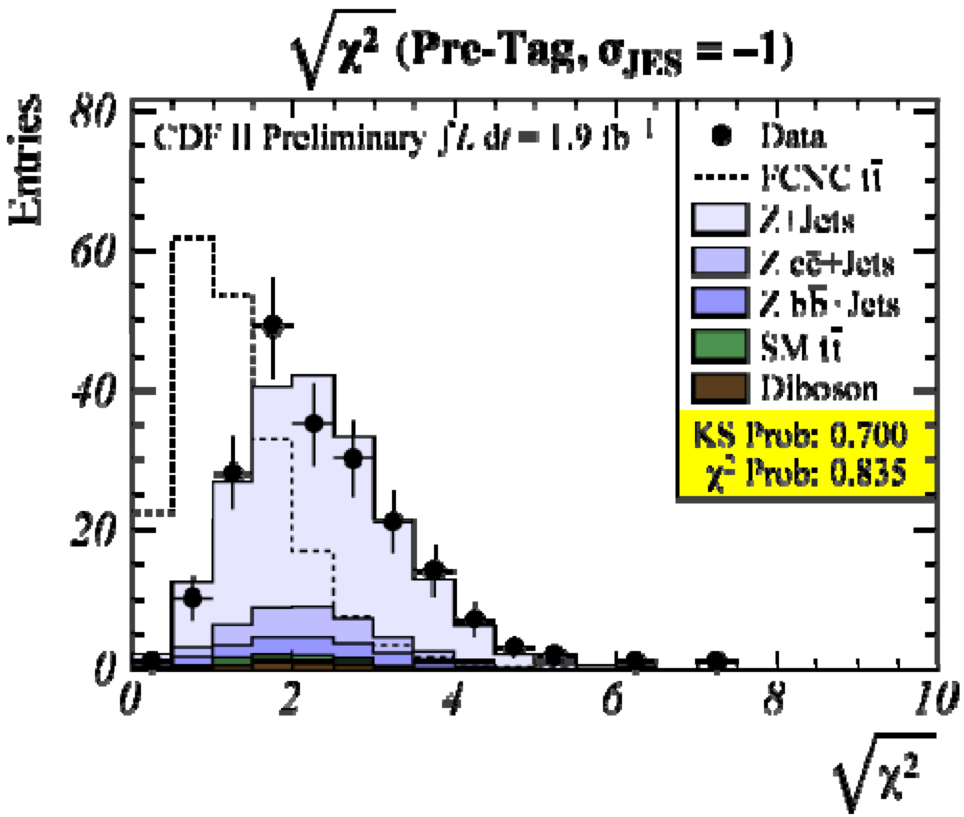
Shape Uncertainties: JES

- We need to convert "*raw*" jets to *"corrected"* jets

  ⇒ Jet Energy Scale correction (JES)

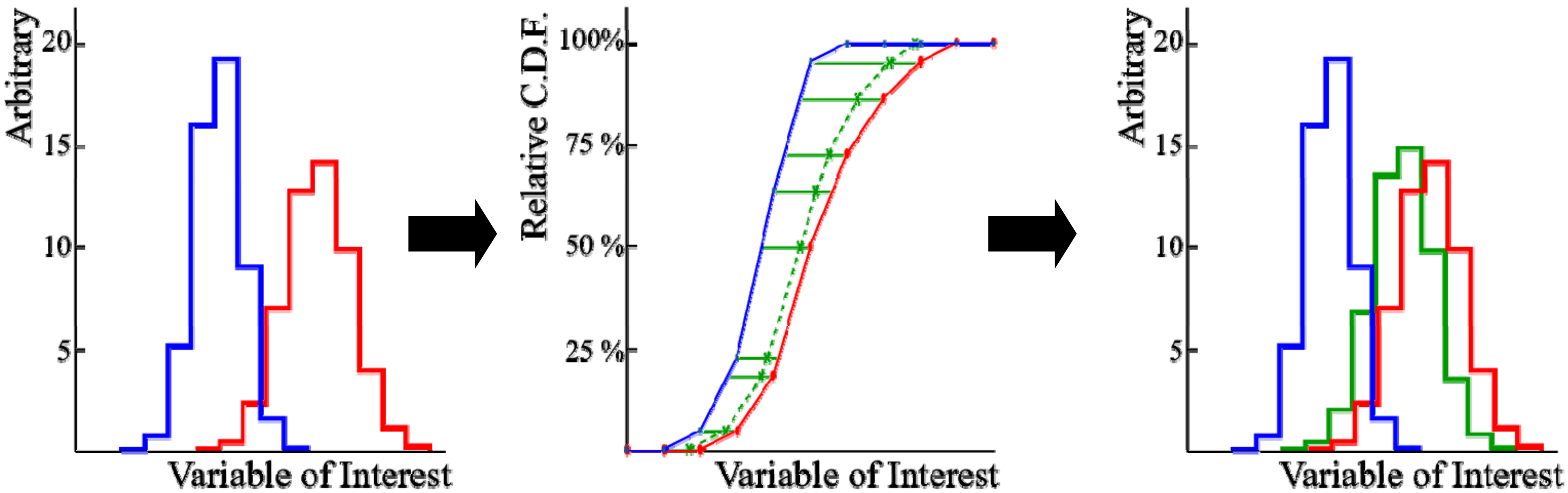
  – Takes into account detector effects, neutral particles in jets, particles outside of the jet cone, underlying events, multiple interactions, …





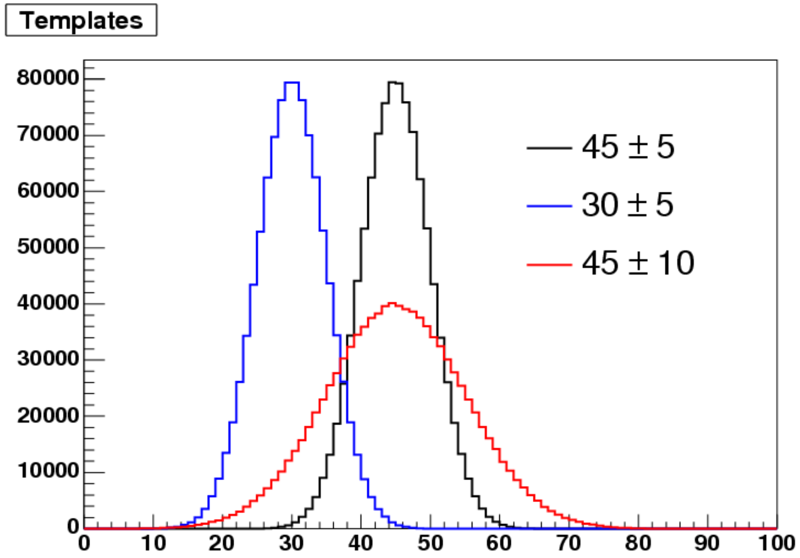
- Now that we have JES shifts, how do we incorporate this in our machinery?
  ⇒ Implemented *compound horizontal template morphing*.

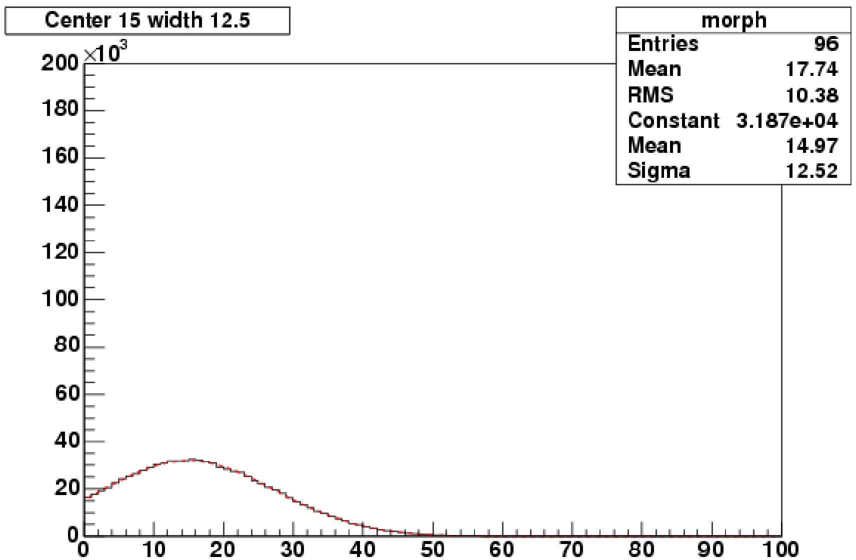
- Horizontal morphing is simply interpolating between two normalized cumulative distribution functions (*i.e.*, the normalized integral of the histogram).
  - The **green** C.D.F. curve is the 75% interpolation between the **blue** and **red** C.D.F. curves.

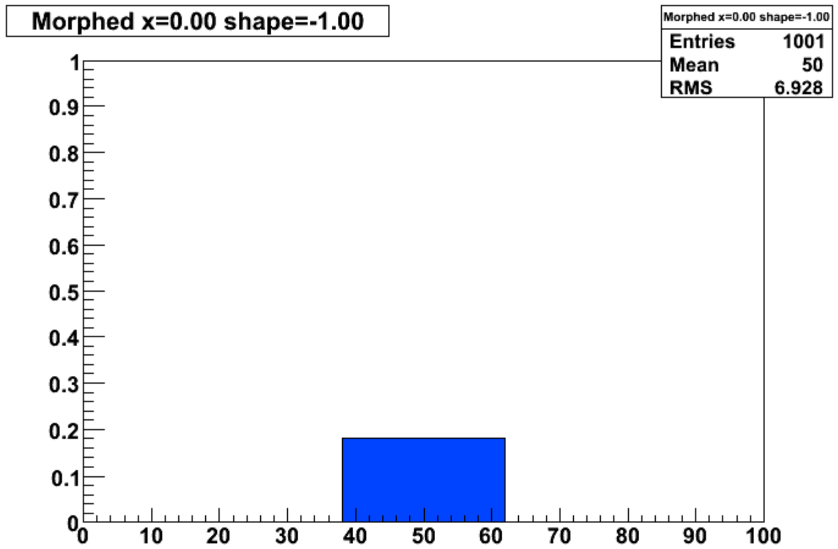


Does Morphing Work?

- Test with Gaussians
  - Easy to verify it is working as expected.
- Works on much more complicated shapes.
  - Squares
  - Half-circles
  - mass χ^2 shapes



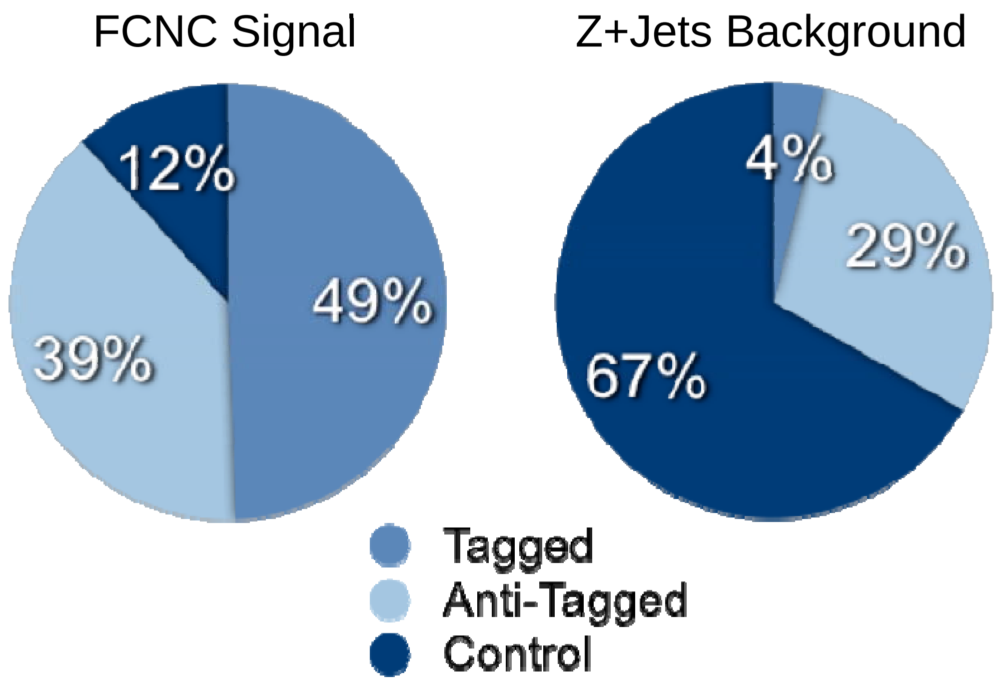




Signal and Control Regions

- *"How do we control shape uncertainties without hiding a small signal?"*
- Solution: add control region with little signal acceptance:
  - Constrain shape uncertainties without "morphing away" signal.
  - Definition: At least one optimized E_T or m_T cut failed (do not look at any b-tagging information).

Kinematic Variable	Optimized Cut
Transverse Mass	$\geq$ 200 GeV
Leading Jet	$\geq$ 40 GeV
Second Jet	$\geq$ 30 GeV
Third Jet	$\geq$ 20 GeV
Fourth Jet	$\geq$ 15 GeV



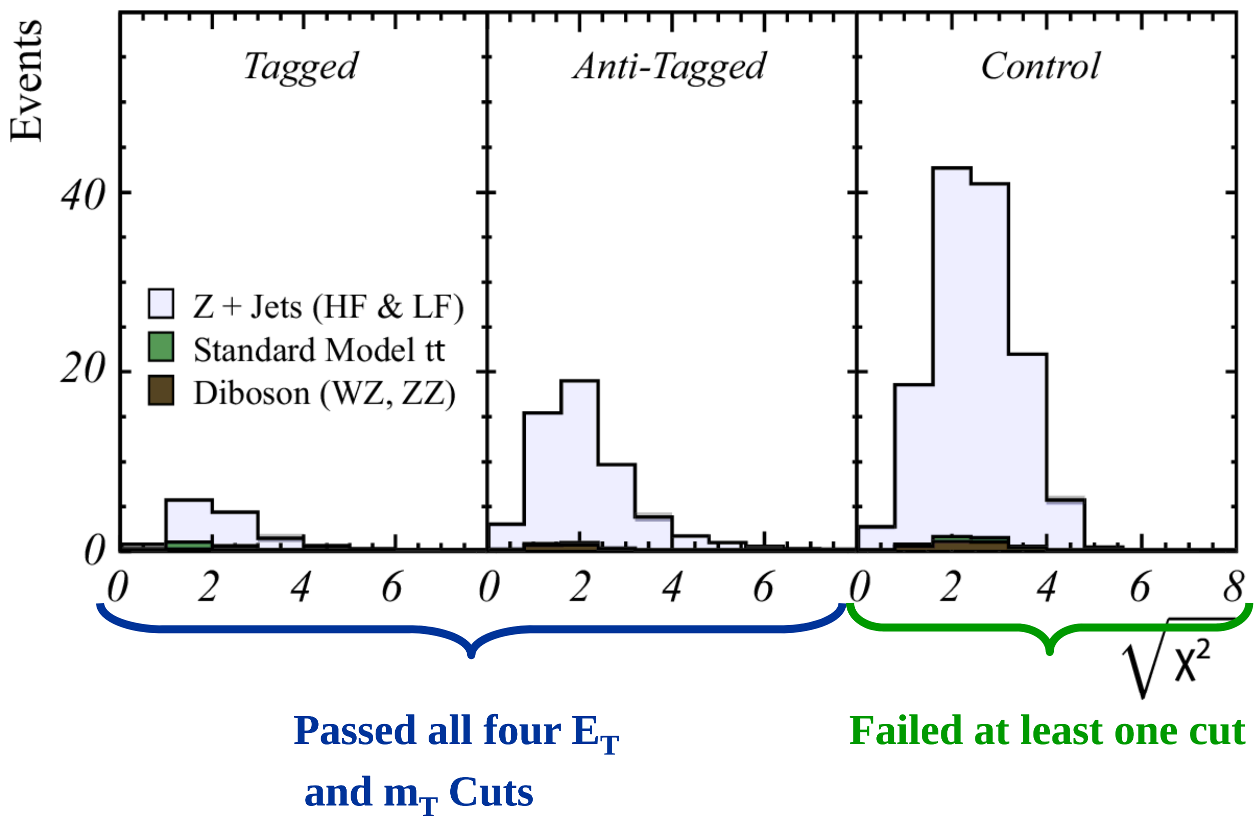
Constraining Z + Jets Background

- We have validated that the MC works fairly well in a jet bin, but we do not trust it across jet bins.

  ⇒ No absolute Z + jet constraints.

- Use MC to predict the ratio of Z + jets acceptance in the two signal regions to the control region.

Expected Background Distributions



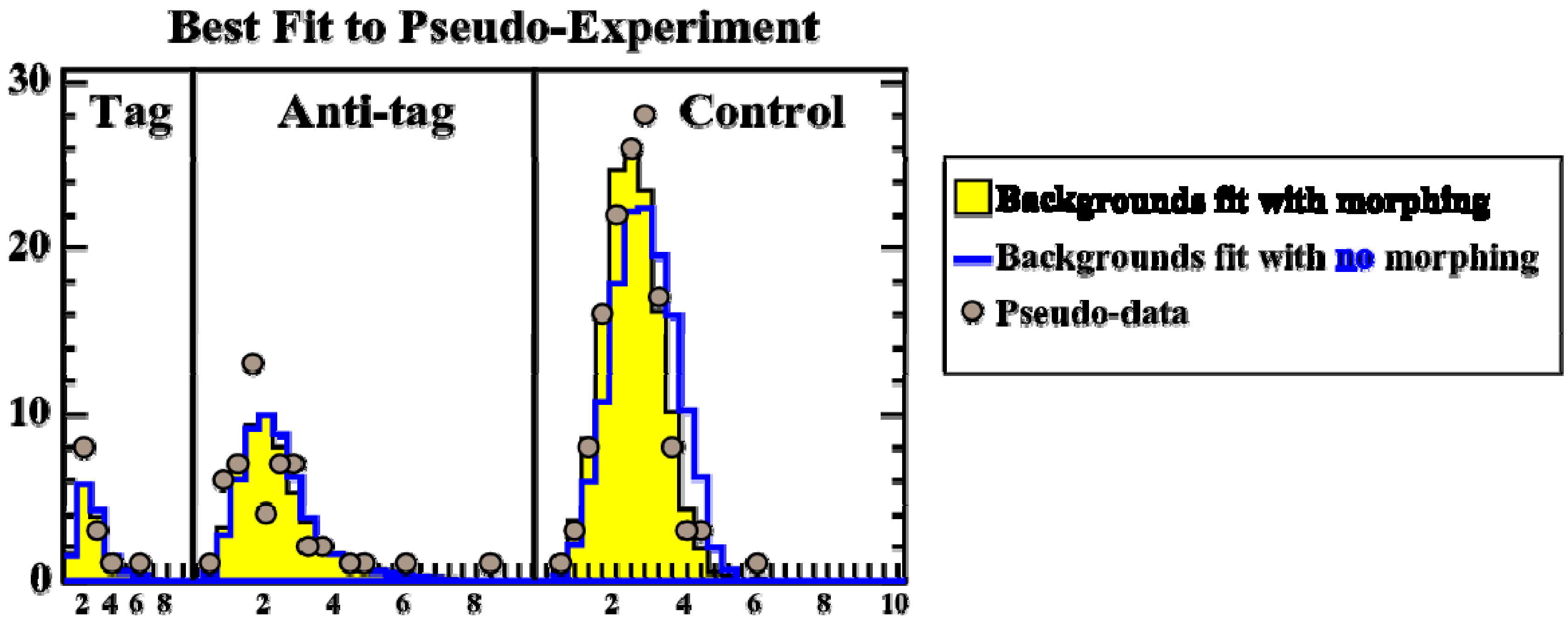
$\mathcal{R}_{sig}$ ≡ Ratio of Z + jets in the signal regions to the control region.

⇒ 20% constraint

⇒ No constraint!

Fitting χ^2 Roundup

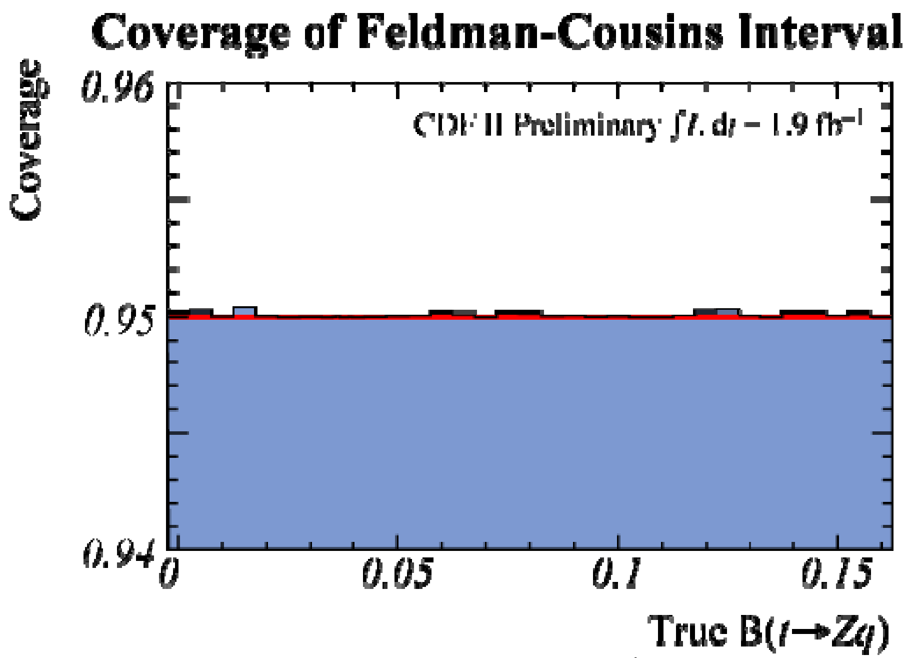
- No absolute Z + jet background estimate needed.
- For the template fit, we need to deal with shape uncertainties.
  - Find dominant sources ⇒ JES
  - Morphing of JES templates in fitter.
- Do not want to *"morph away"* a real signal ⇒ Control region.
  - Use control region also for Z + jet constraints.
- Investigated effect of shape **not** being from JES ⇒ Small effect.



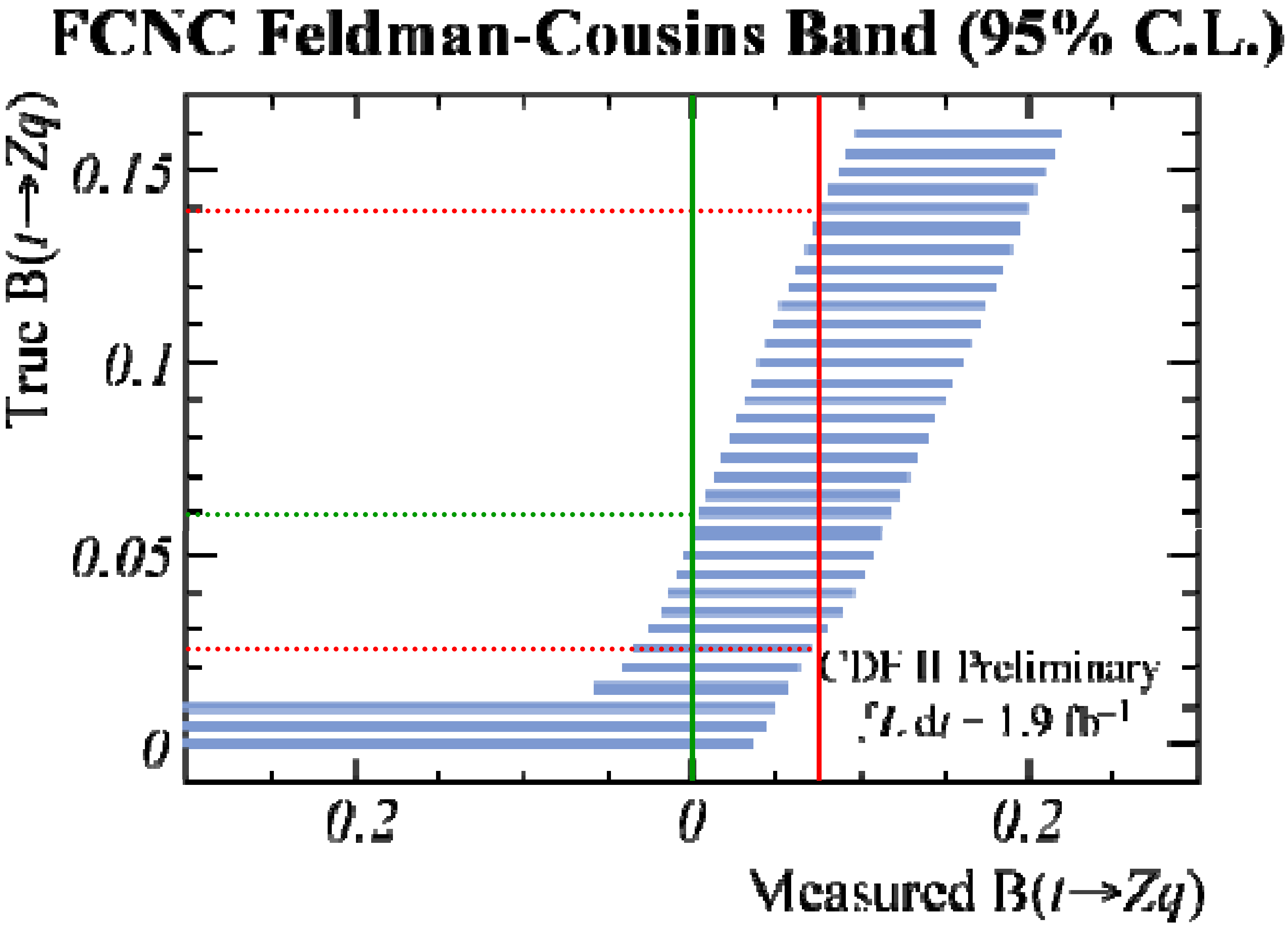
Feldman-Cousins in Five Minutes

- How are we going to interpret our results?
- Feldman-Cousins answers the question:

  "What range of true values are likely to lead to this measured value?"
- Why use Feldman-Cousins?
  - Guarantees coverage.
  - Data tell us whether we should report a measurement or a limit.
  - Our method incorporates systematic uncertainties easily.



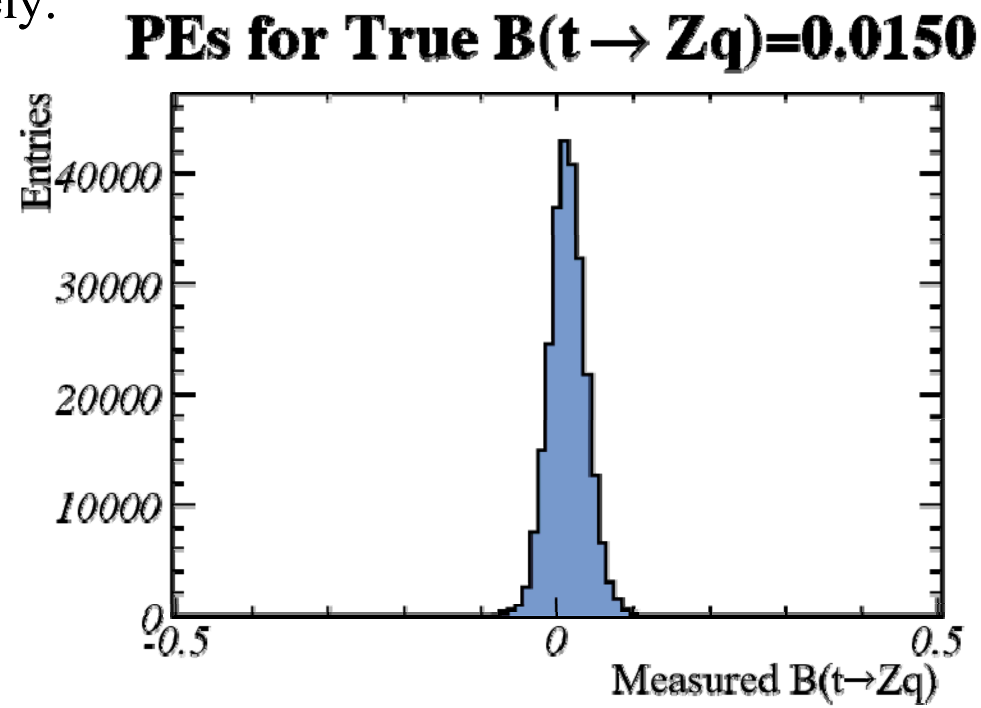
Top FCNC Feldman-Cousins Bands



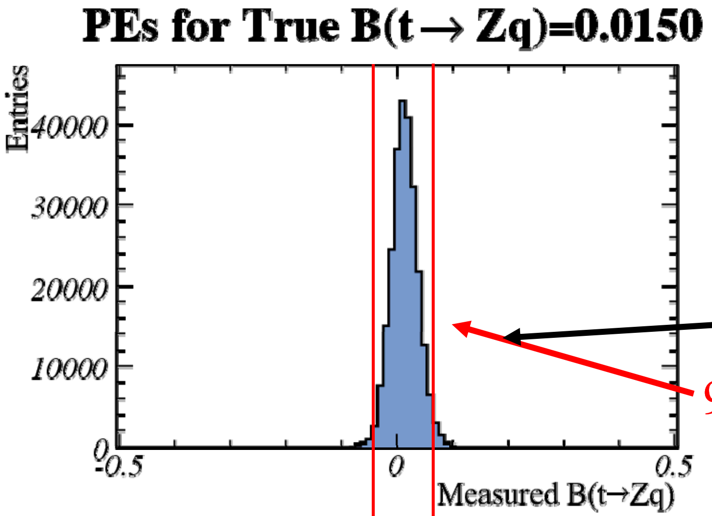
Pseudo-Experiments (PEs)

Pseudo-experiment: Generate all necessary numbers/templates to emulate data from an experiment.

1. Generate random numbers to simulate all systematic uncertainties.
   - Pay attention to correlations.
   - Vary **all** systematic uncertainties.
   - Verify all numbers are physical.
   - Morph all templates appropriately.
2. Generate numbers of background and signal events.
3. For each type of event, use templates to generate mass χ^2.
4. Fit as if data.
5. Repeat!



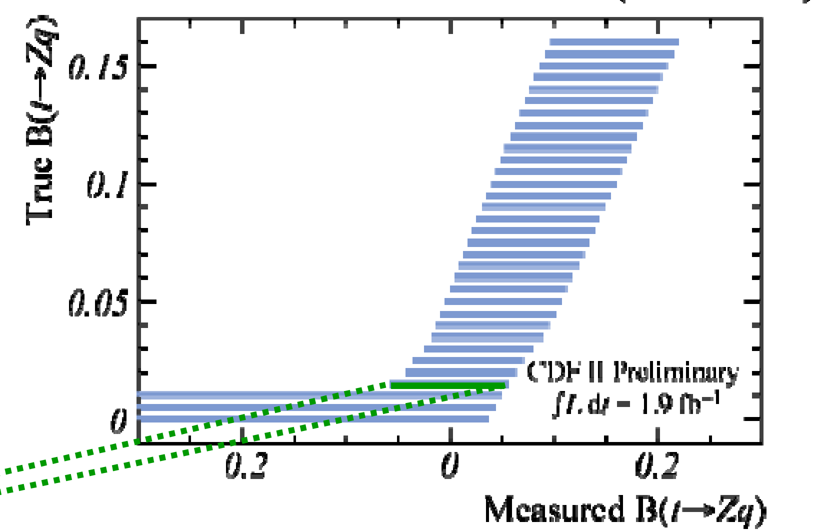
FC Band Construction In A Nutshell



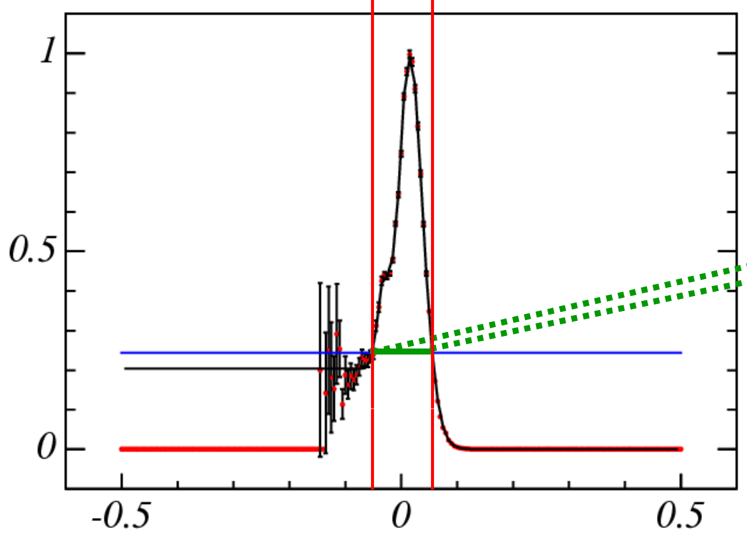
- Use *Likelihood Ratio Ordering Principle*:

$$\text{Likelihood Ratio}(\mu_{\text{meas}}) = \frac{P(\mu_{\text{meas}}|\mu_{\text{true}})}{P(\mu_{\text{meas}}|\mu_{\text{best}})}$$

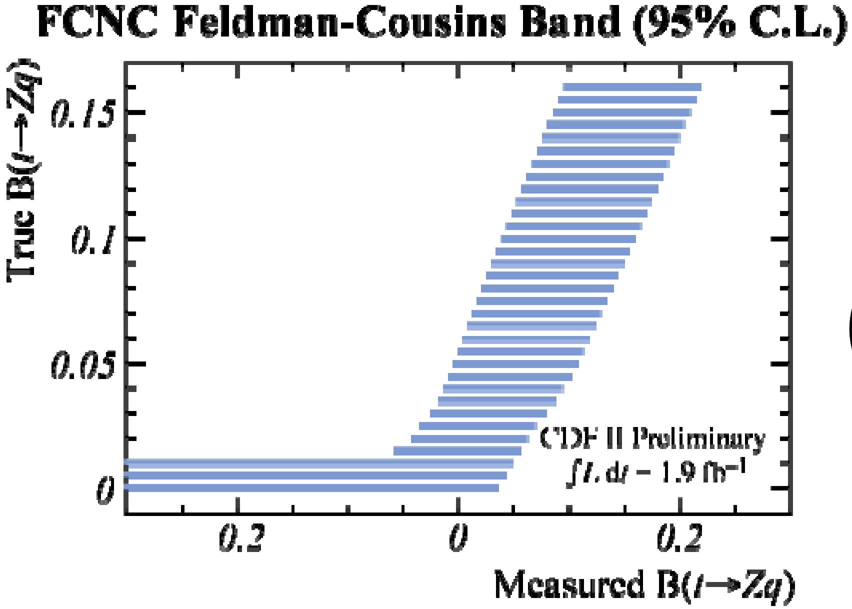
PEs generated with all statistical and systematic uncertainties.



Likelihood Ratio for B(t → Zq) = 0.0150



Expected Limit



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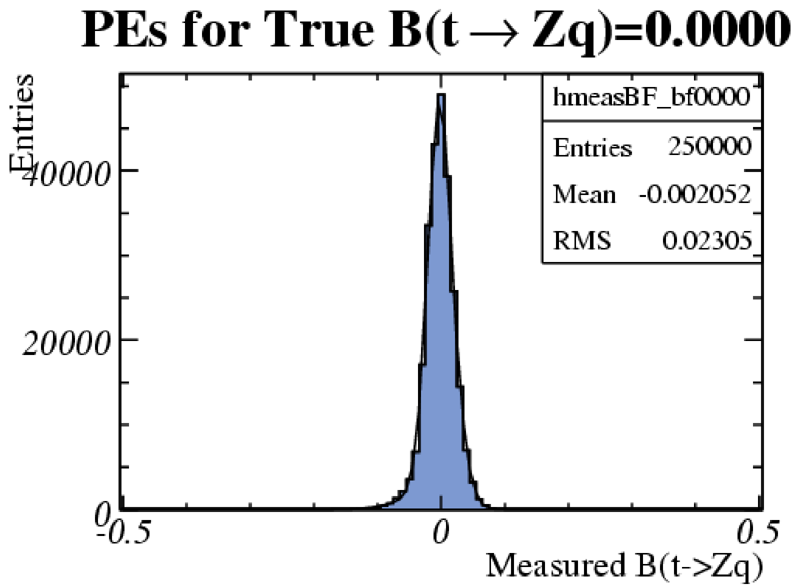

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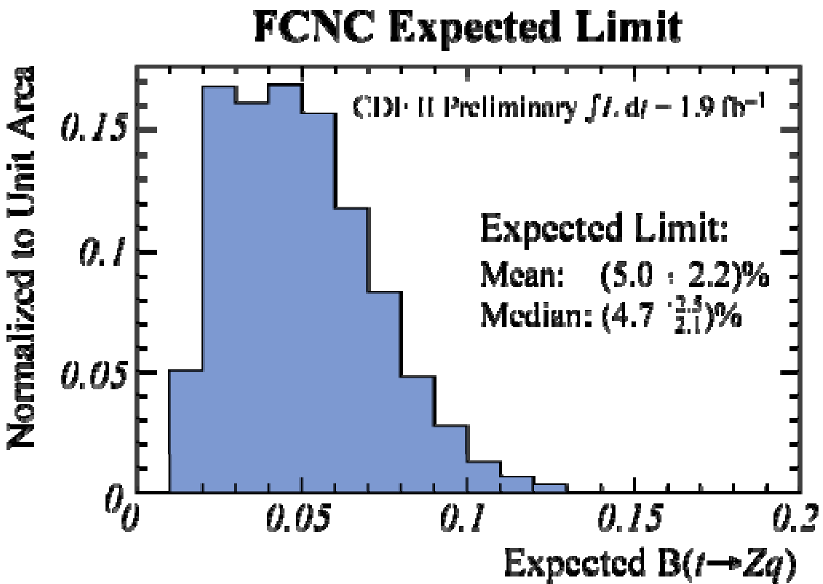
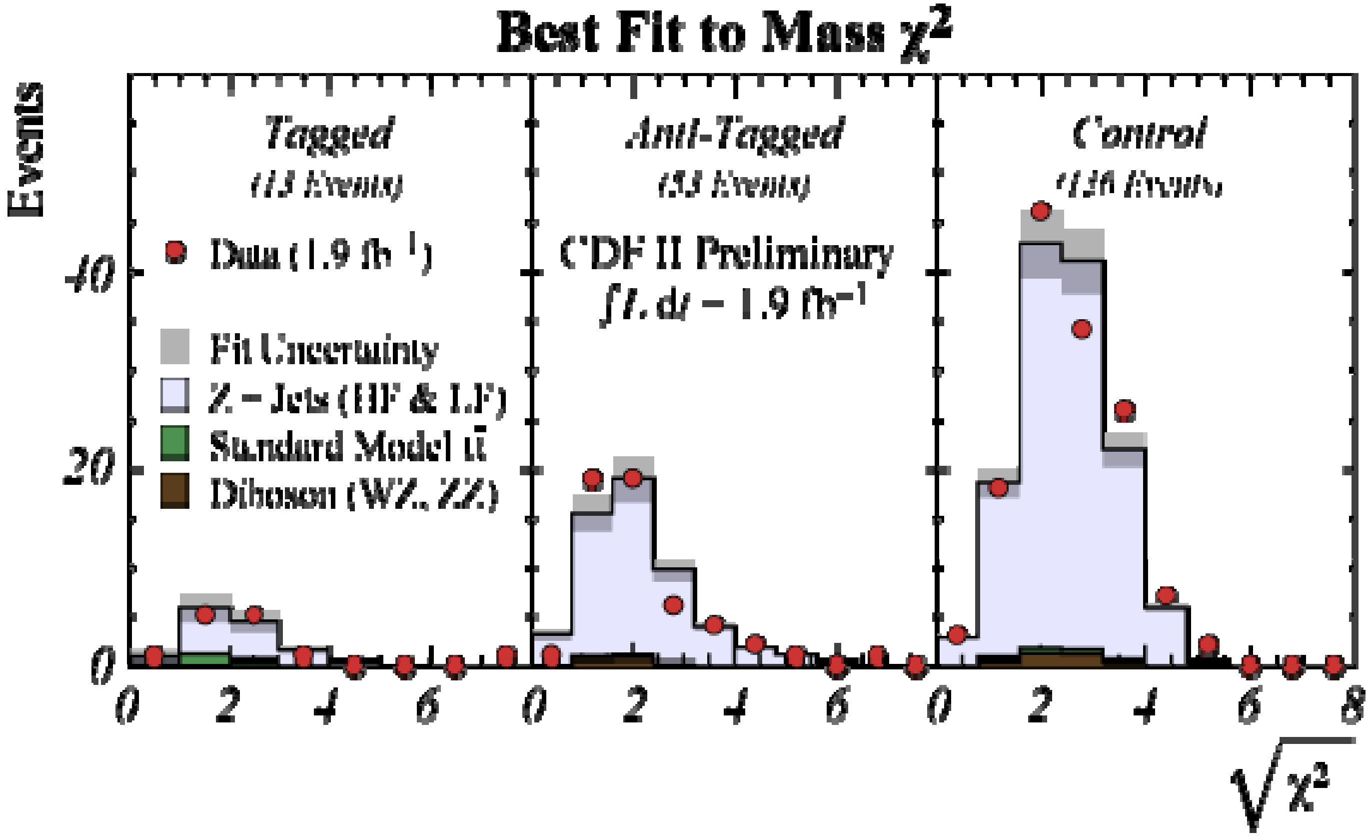
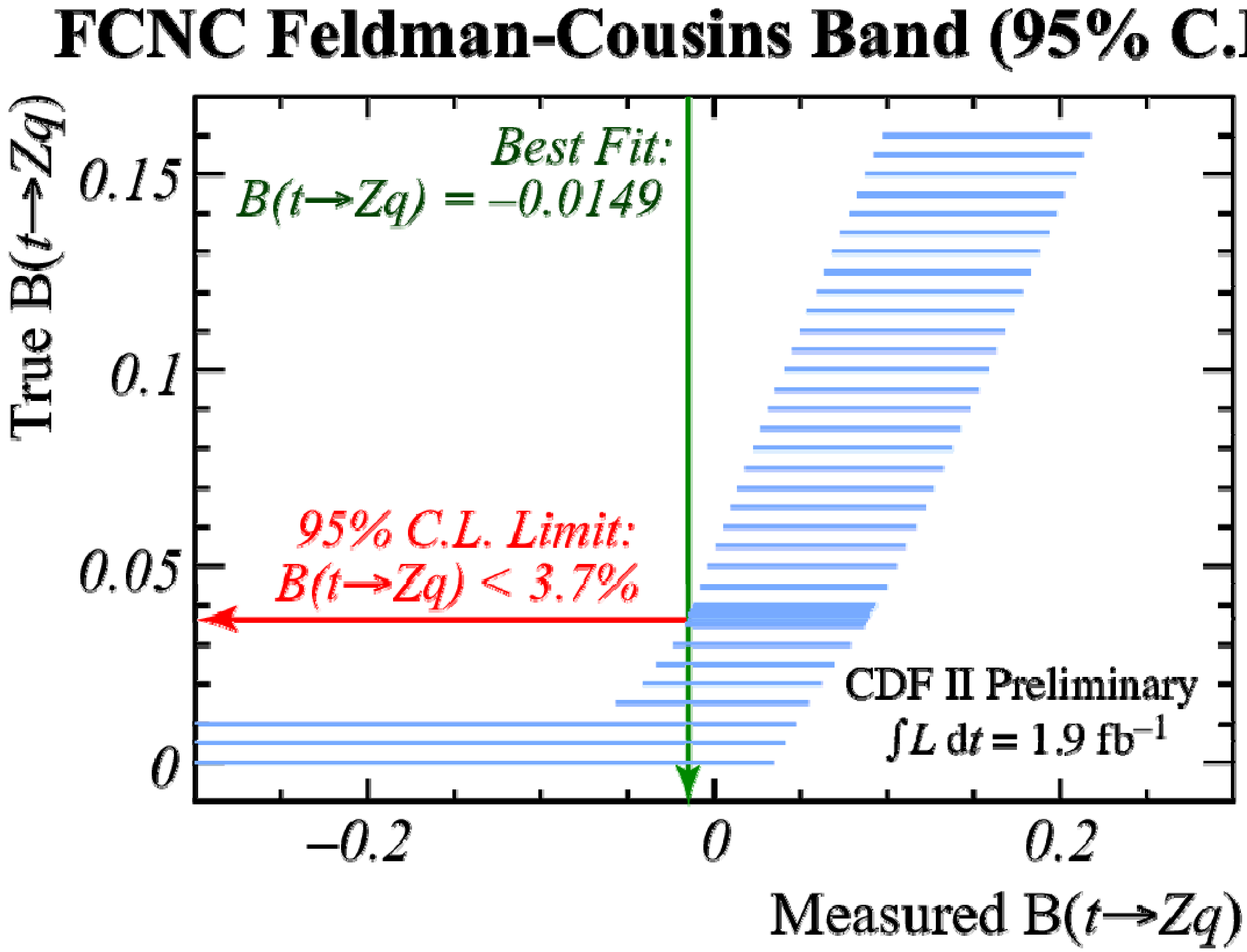


The Fit to the Data



Fit Parameter ($\int \mathscr{L} dt = 1.9\text{fb}^{-1}$)	Value		
Branching Fraction, $\mathscr{B}(t \to Zq)$ (%)	−1.49	±	1.52
Z+Jets Events in Control Region, Z_{control}	129.0	±	11.1
Ratio Signal/Control Region, $\mathscr{R}_{\text{sig}}$	0.52	±	0.07
Tagging Fraction, f_{tag} (%)	20.0	±	5.9
Jet Energy Scale Shift, σ_{JES}	−0.74	±	0.43

F.C. 95% C.L. Limit



Outline

The Tevatron and the CDF Experiment

Top Quark Physics

The Search for Top FCNC Decay

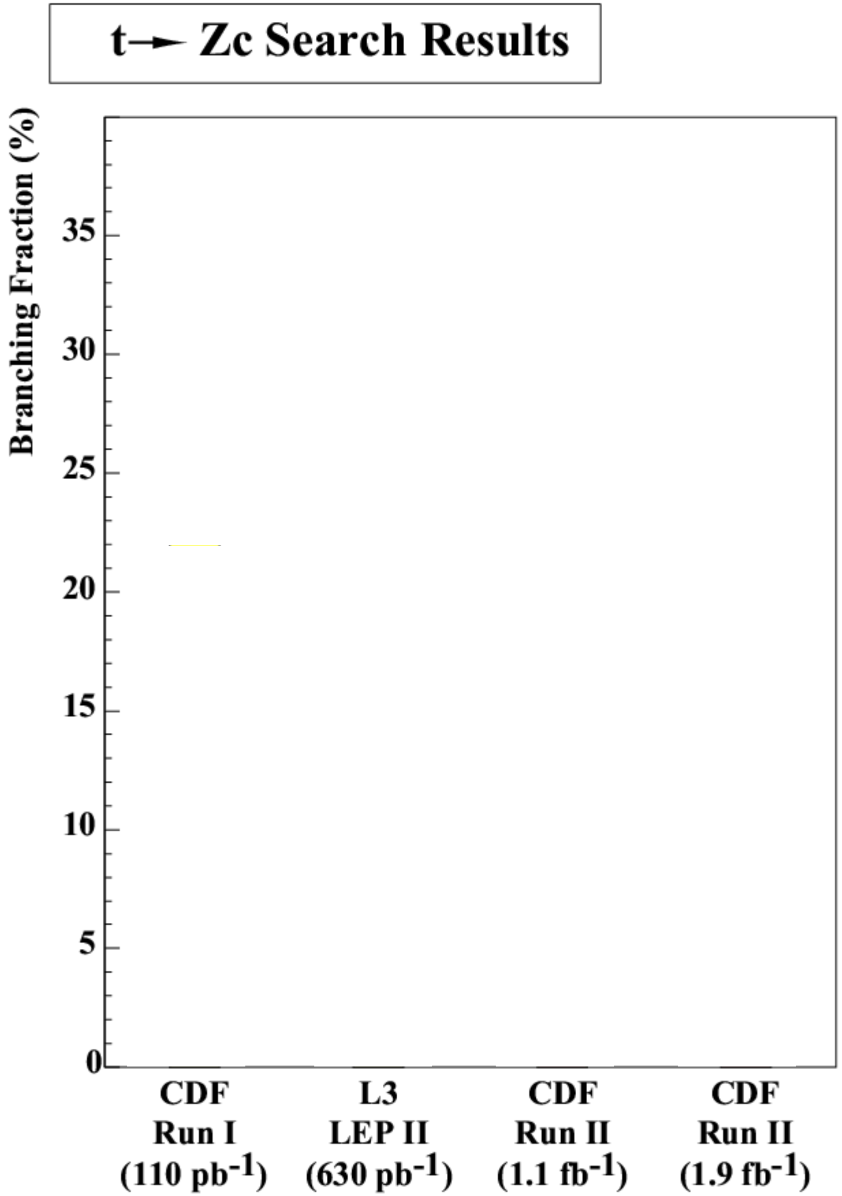
Summary

Summary

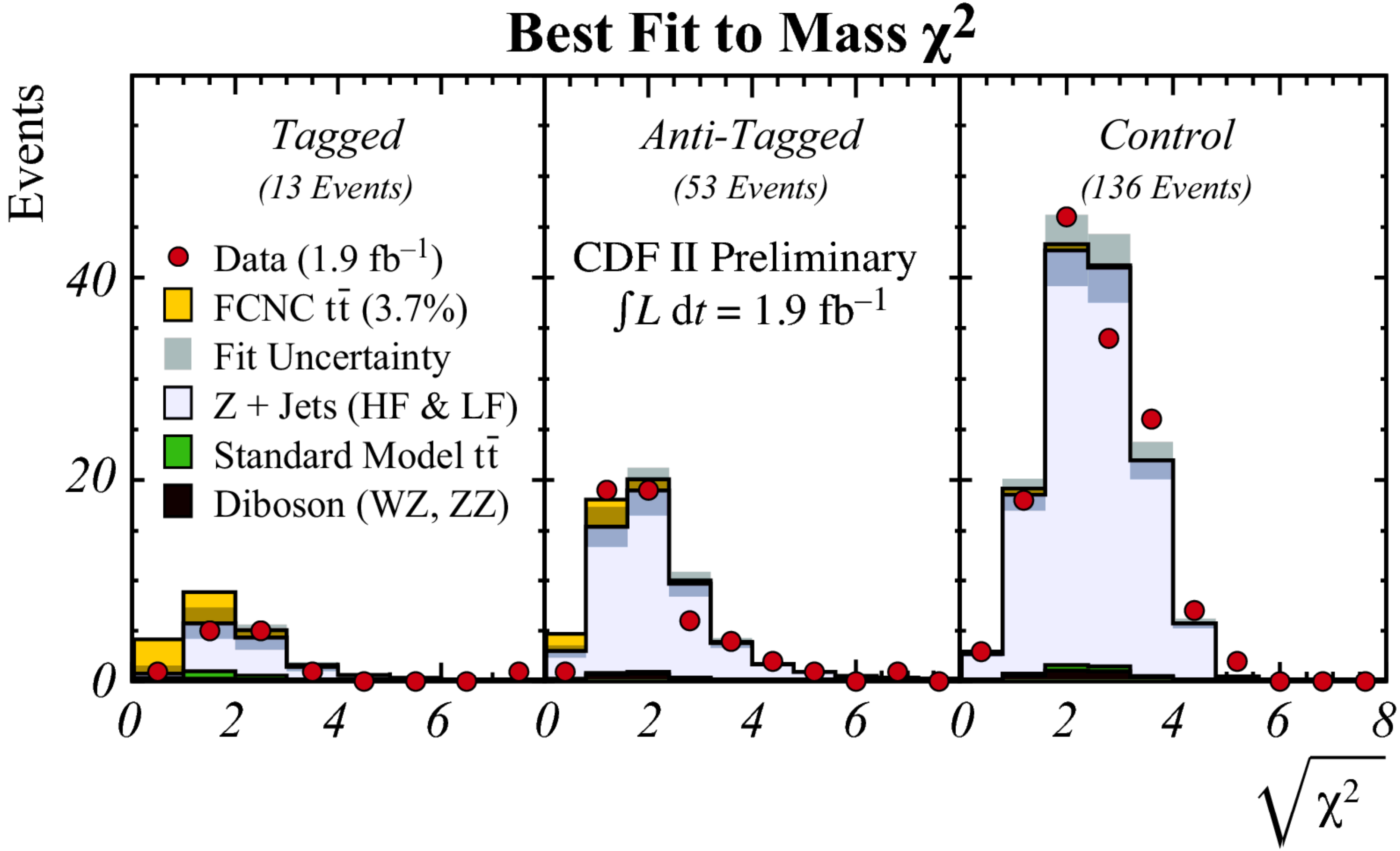
- CDF and the Tevatron are running very well.
  - Thanks Tevatron!
- We just finished Run II's first search for Top FCNC $t \to Z\ c$.
  - Using **1.9 fb^{-1}**,

    we have the world's best limit:

    Br ($t \to Z\ c$) < 3.7% at 95% C.L.
- Using data-based background techniques will be very important for the LHC.



Money Plot



Best Fit to Mass χ²
Events
Tagged
(13 Events)
Anti-Tagged
(53 Events)
Control
(136 Events)
Data (1.9 fb⁻¹)
FCNC tt̄ (3.7%)
Fit Uncertainty
Z + Jets (HF & LF)
Standard Model tt̄
Diboson (WZ, ZZ)
CDF II Preliminary
∫L dt = 1.9 fb⁻¹
0
20
40
0
2
4
6
0
2
4
6
0
2
4
6
8
√χ²

2010 PDG Top Entry

t

$I(J^P) = 0(\frac{1}{2}^+)$

Charge = $\frac{2}{3}$ e Top = +1

Mass $m = 172.6 \pm 1.4$ GeV [b] (direct observation of top events)
Mass $m = 172.3^{+10.2}_{-7.6}$ GeV (Standard Model electroweak fit)

t DECAY MODES			Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$W q (q = b, s, d)$					–
$W b$					–
$\ell \nu_\ell$ anything		[c,d]	(9.4±2.4) %		–
$\tau \nu_\tau b$					–
$\gamma q (q=u,c)$		[e]	< 5.9 × 10^{-3}	95%	–
$\Delta T = 1$ weak neutral current ($T1$) modes					
$Z q (q=u,c)$	$T1$	[f]	< 3.7 %	95%	–

γq (q = u,c)
$g q$ (q = u,c)
5σ Evidence for single top production
...
(Your analysis here?!)

Thank You!

Best Fit to Mass χ^2