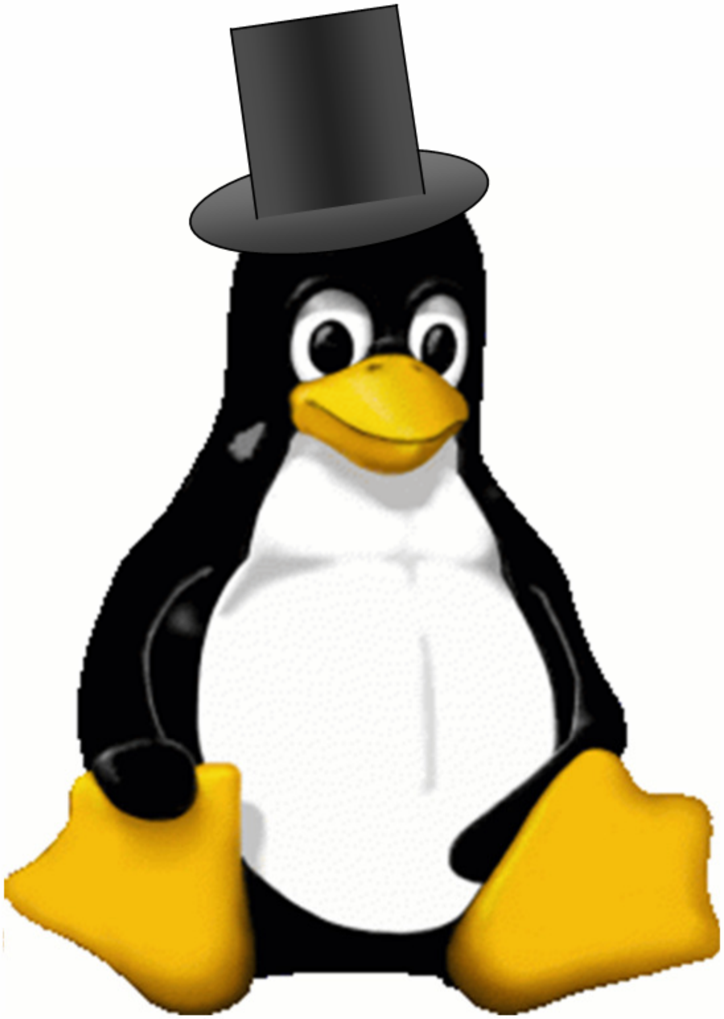

Z(ee) Charming Top Quark: The Search for Top Flavor Changing Neutral Currents $t \rightarrow Z\, c$ at CDF Run II

***Charles Plager*, UCLA**

On behalf of the CDF Collaboration

LPNHE Paris Seminar

July 4th, 2008

Outline

The Tevatron and the CDF Experiment

Top Quark Physics

The Search for Top FCNC Decay

Summary

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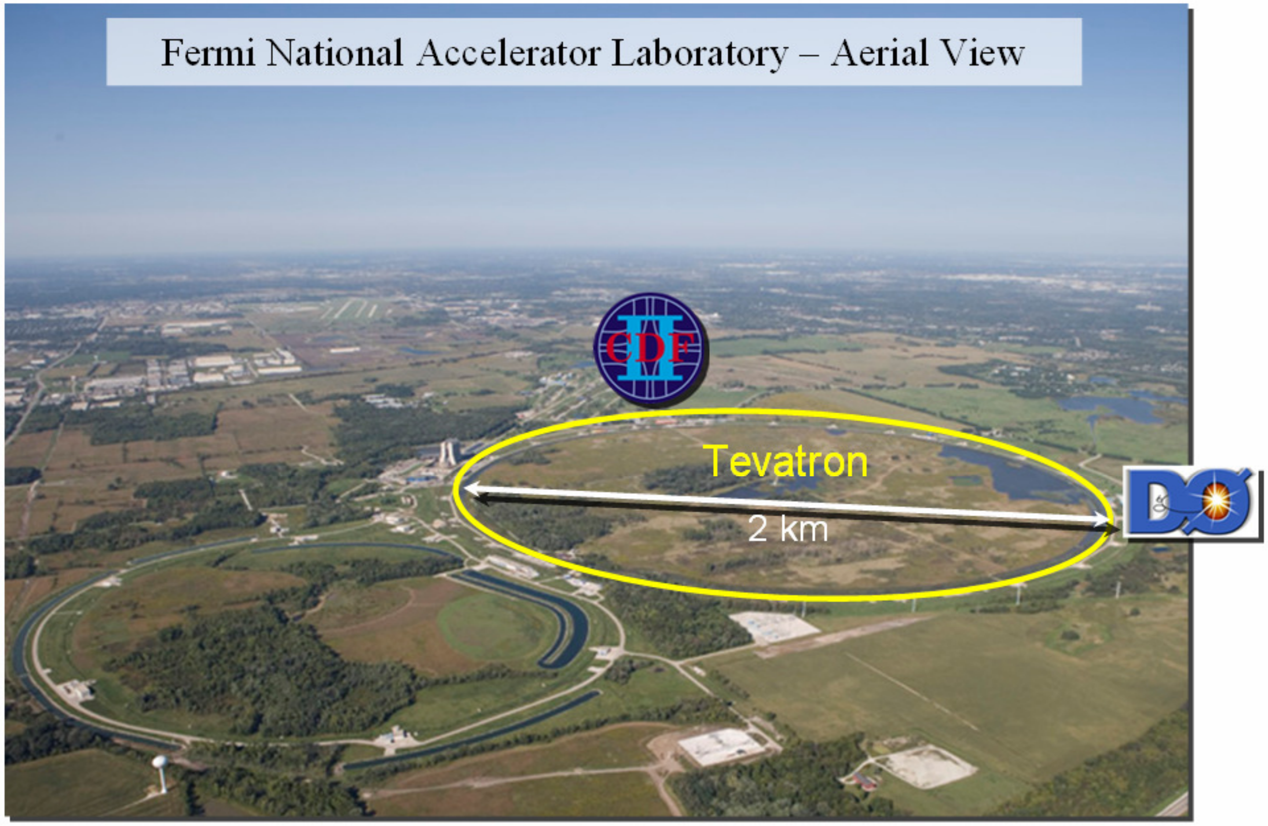
Tevatron Run II: 2001–2009 (2010?)



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

  $290 \cdot 10^{30}$ 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.

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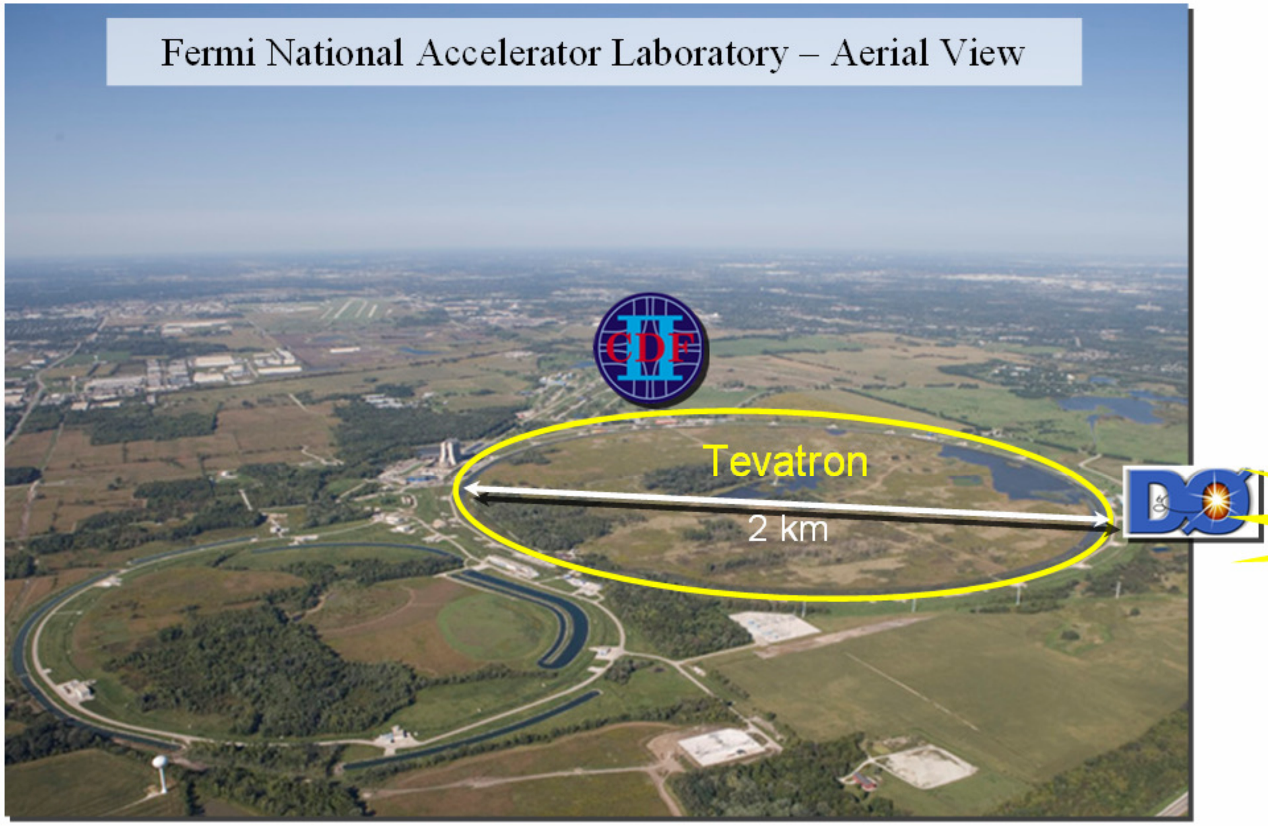

- Proton-antiproton collider: $\sqrt{s}$ = 1.96 TeV.
- 36×36 bunches, collisions every 396 ns.
- Record instantaneous peak luminosity:

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

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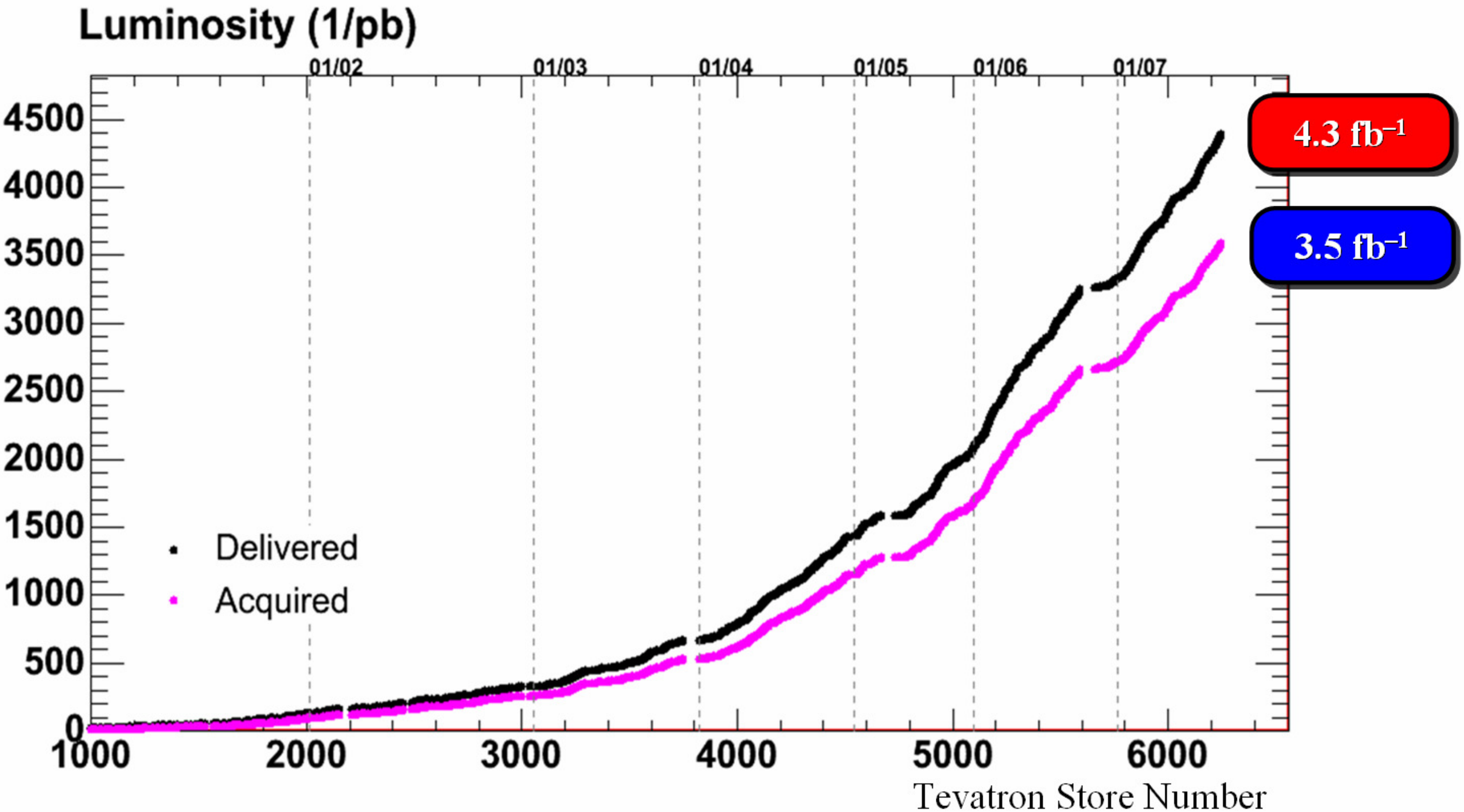
Tevatron Performance

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



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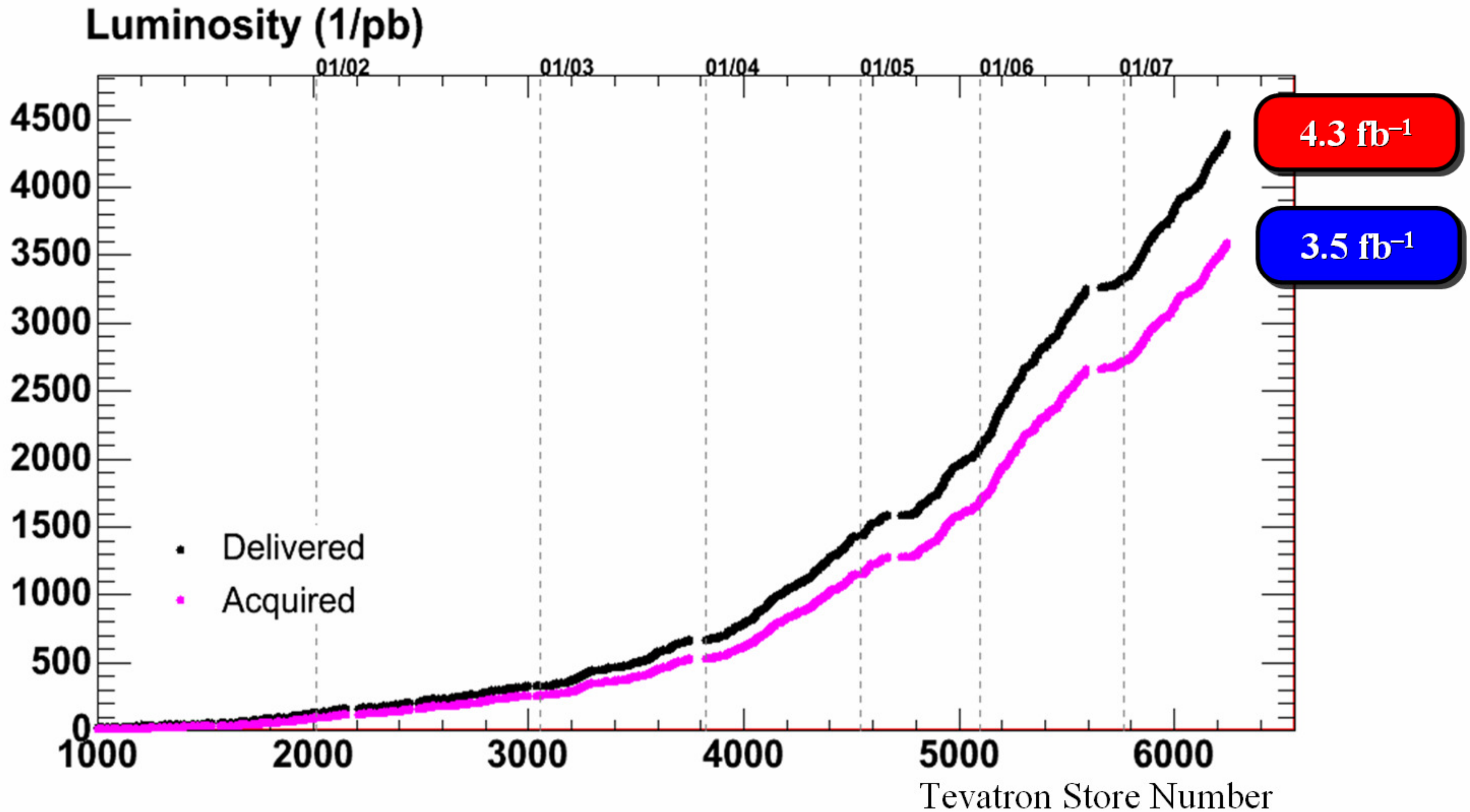

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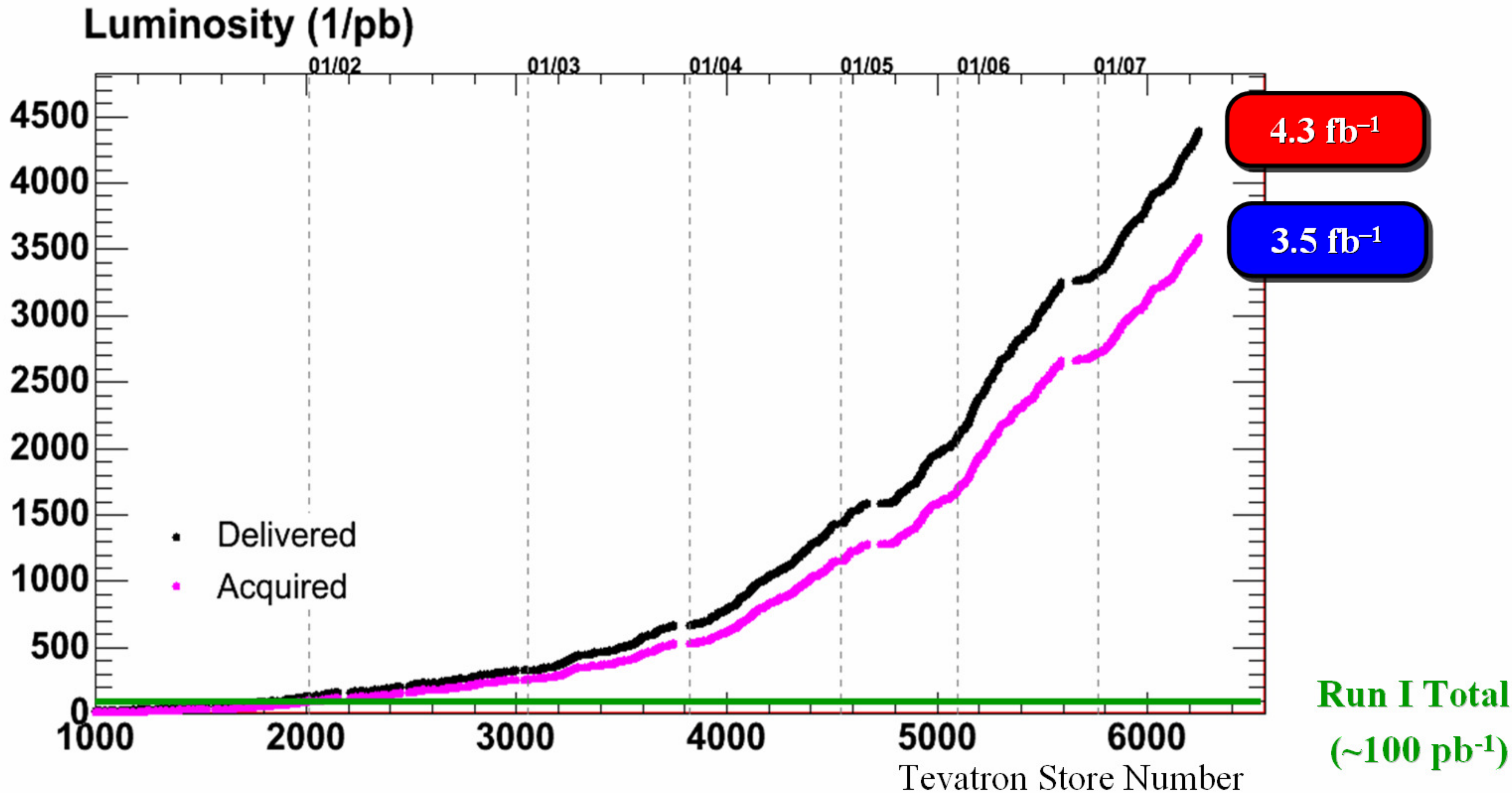
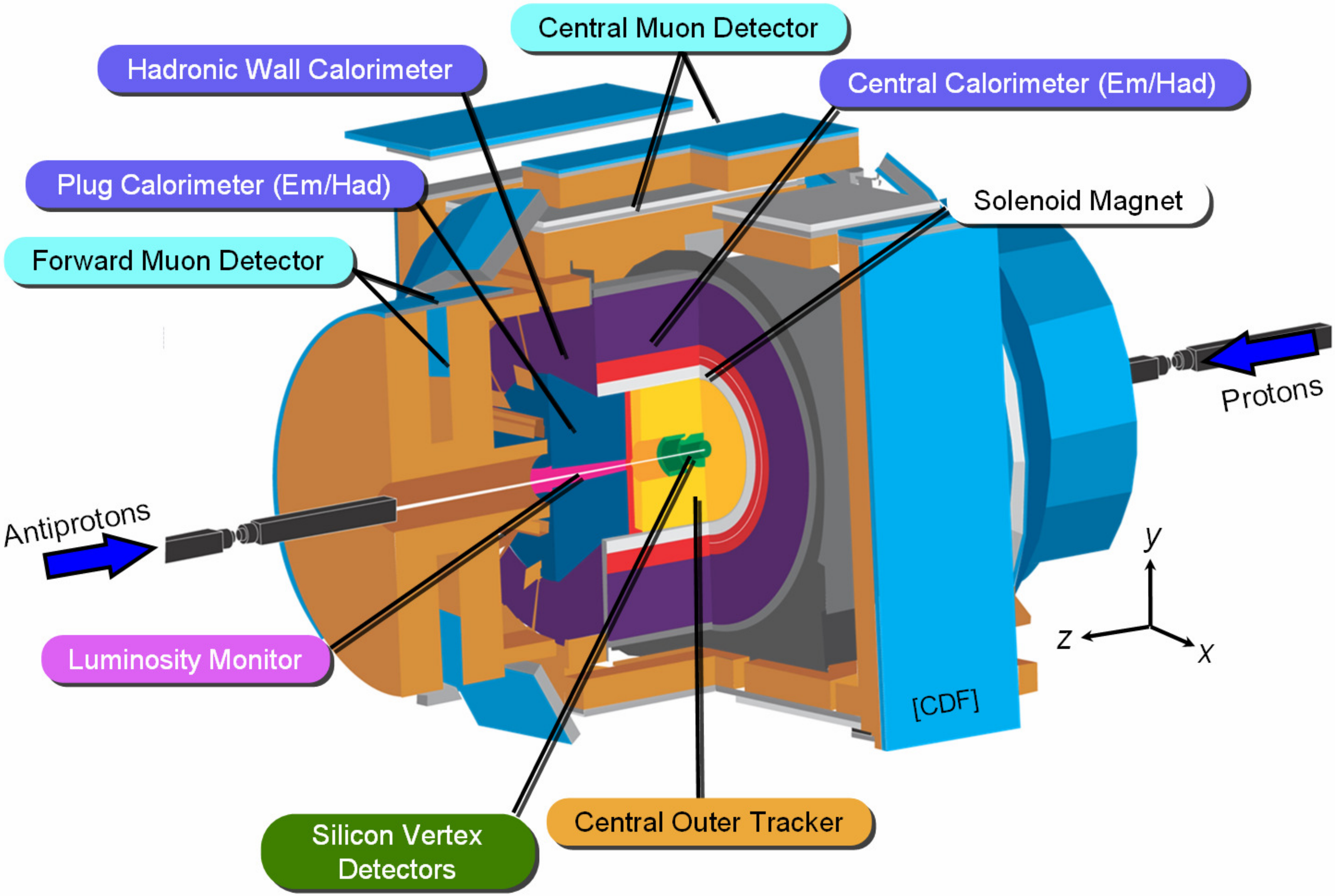


The CDF II Detector



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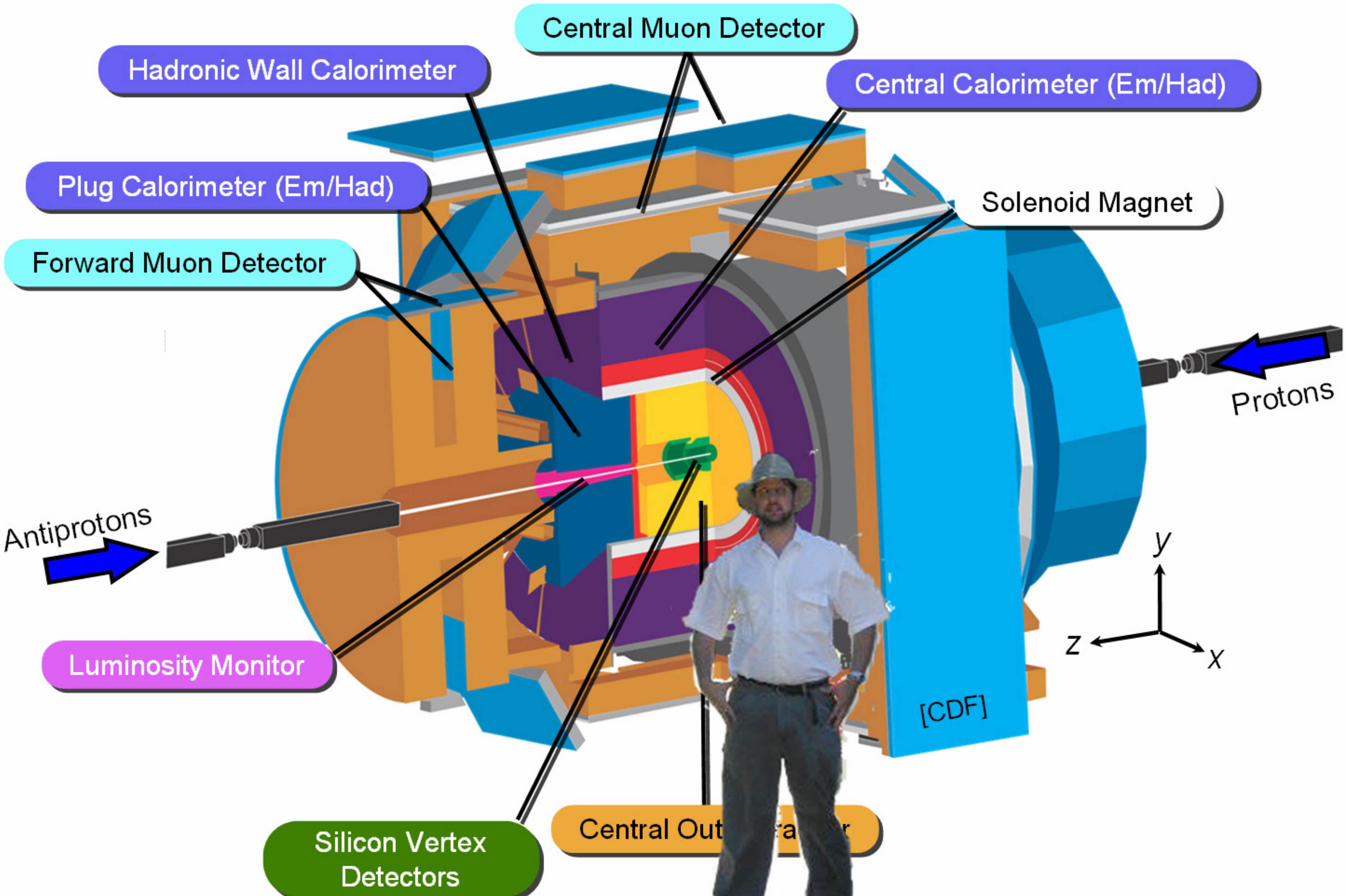

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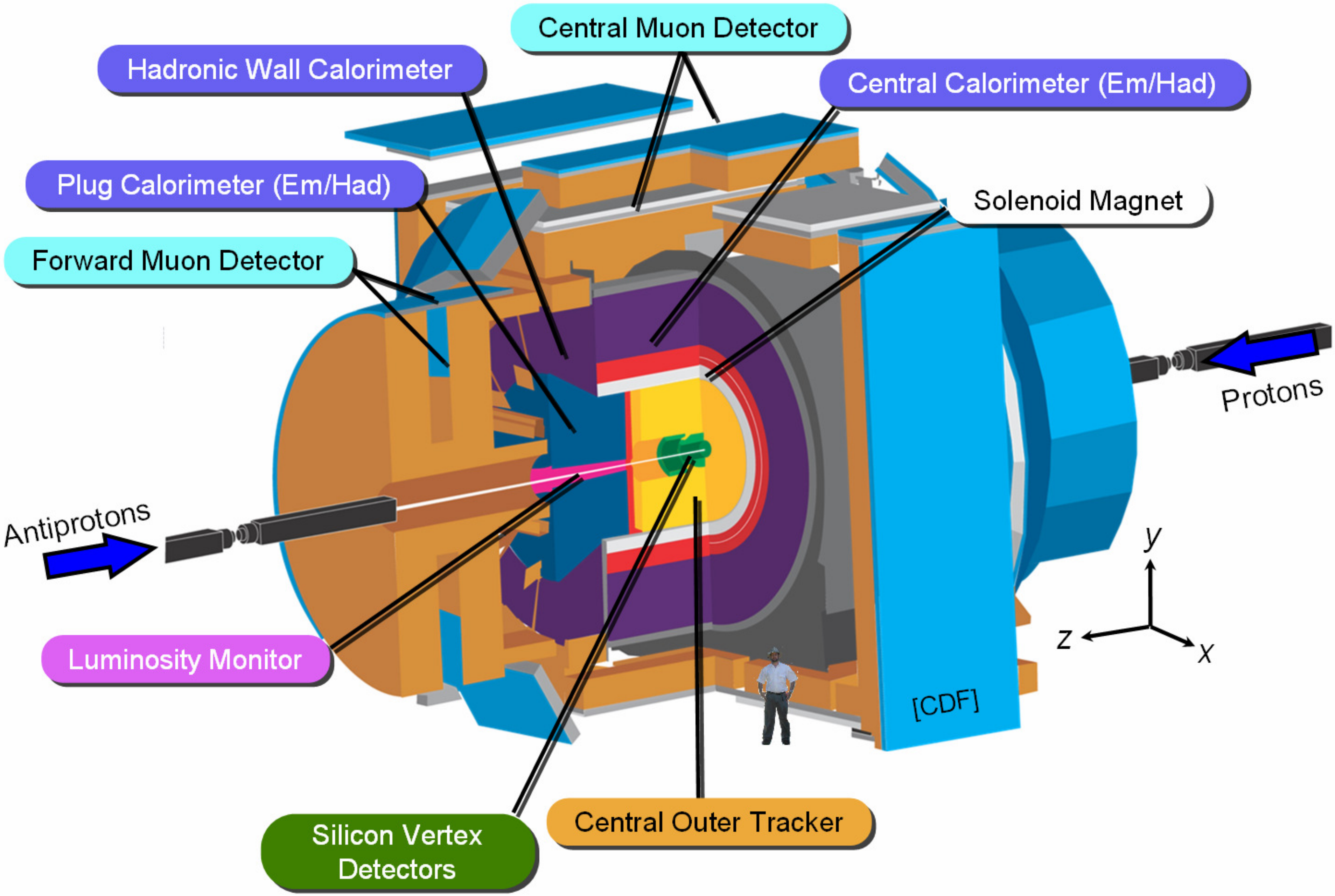

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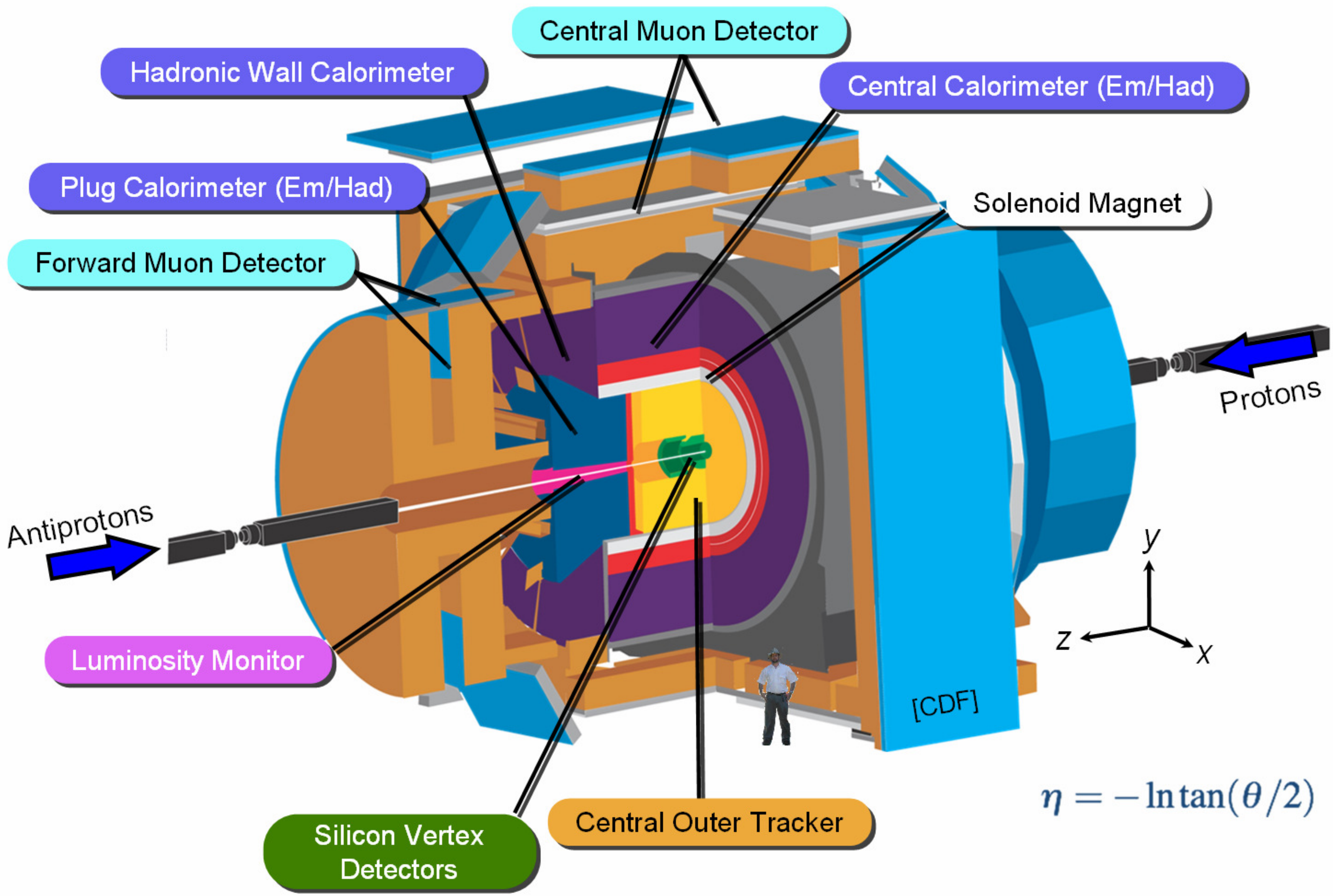

$$\eta = -\ln \tan(\theta/2)$$

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The Search for Top FCNC Decay

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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): $p\,\bar{p}$
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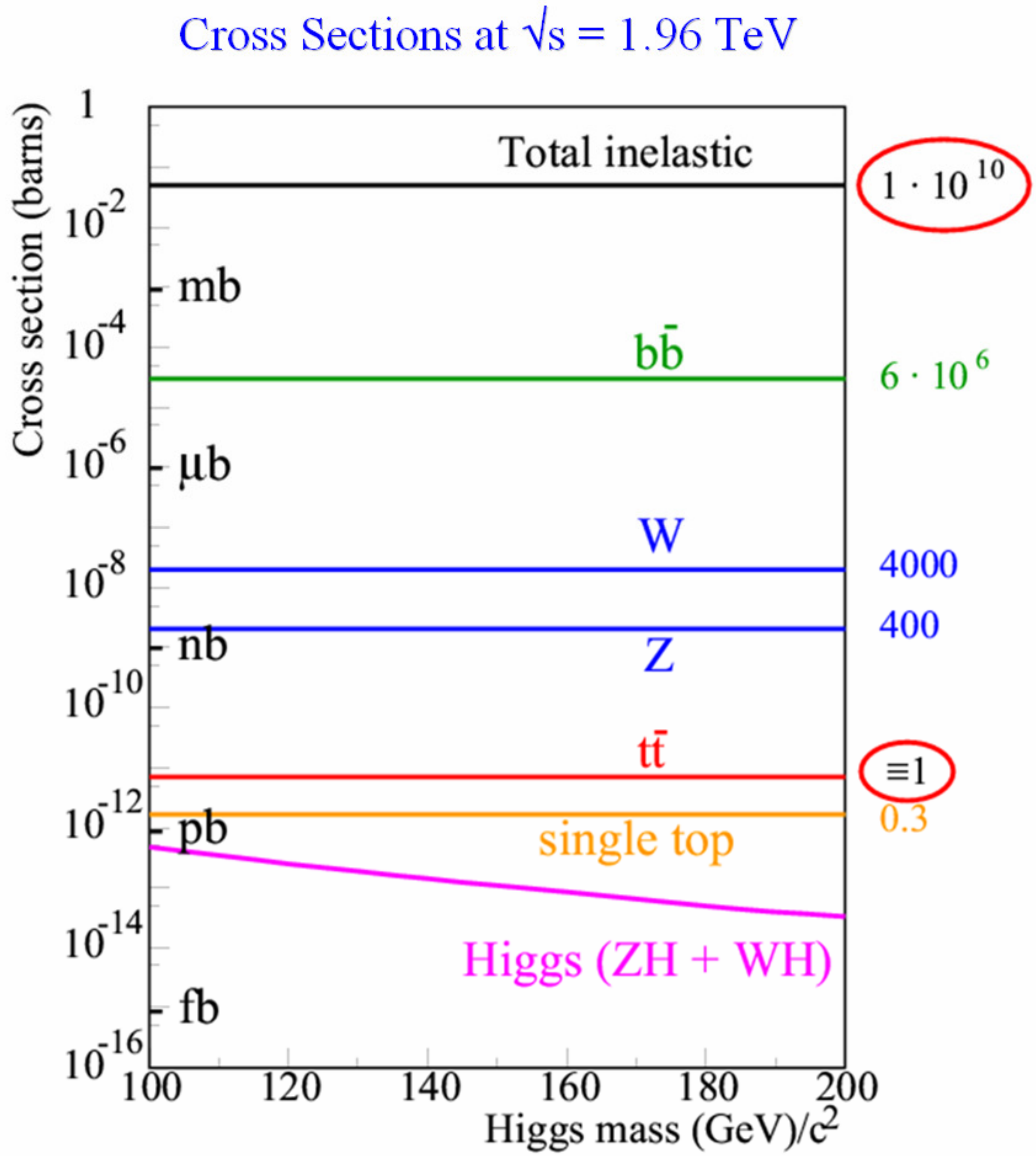
A Quick Note About Scale

For those not
intimately familiar
with Tevatron
high p_T Physics:

Top:

1 in 10 Billion

Reducing and understanding
backgrounds is the key.

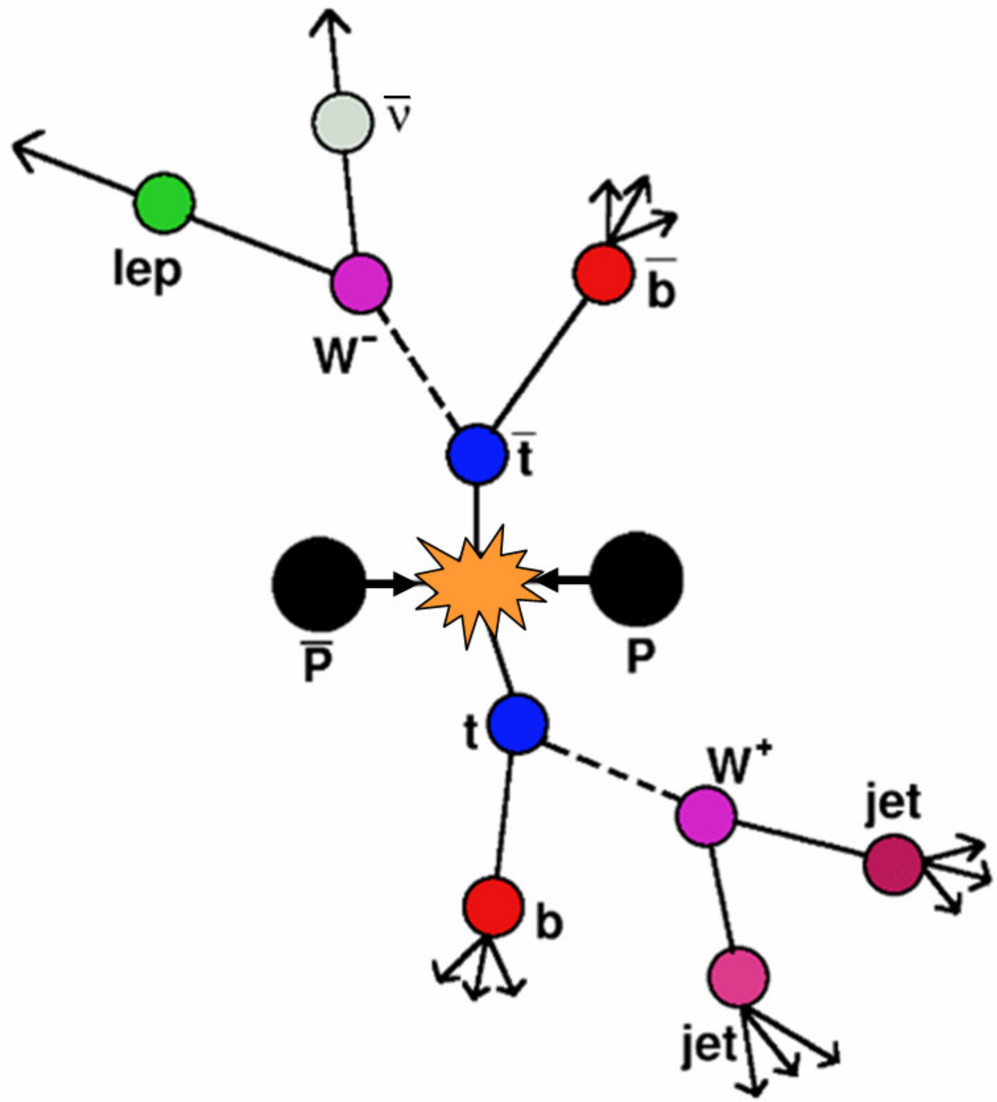


Top Quark Review

- 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



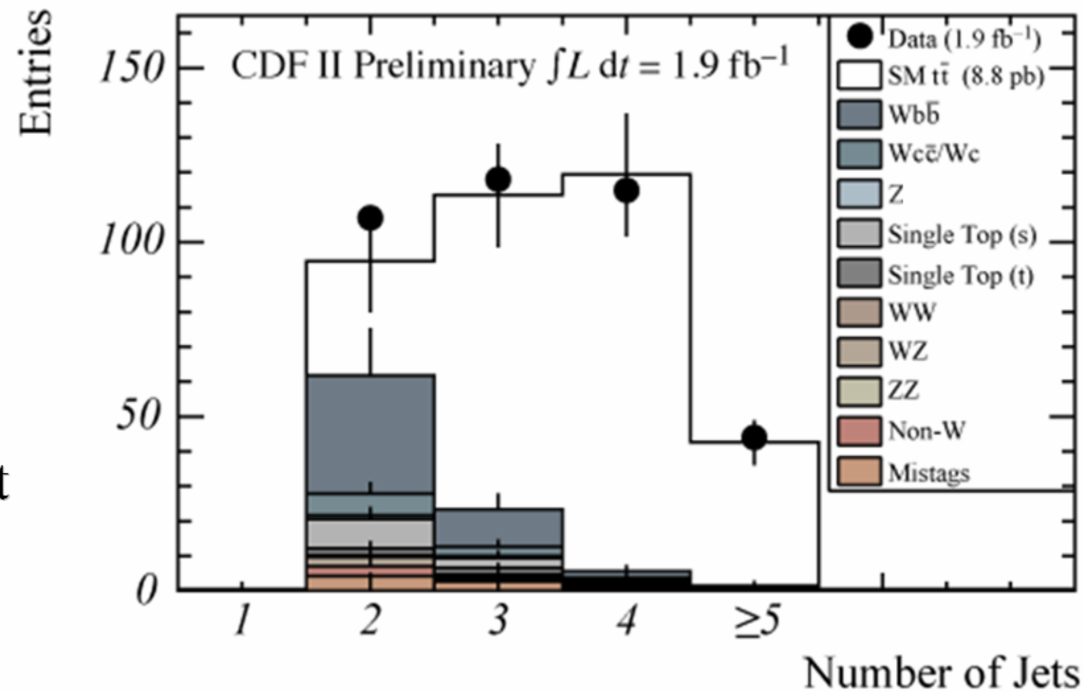
New Era of Top Precision Physics!

- CDF and DØ now have more than thirty (**30** !!!) times as much integrated luminosity as we did when we 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



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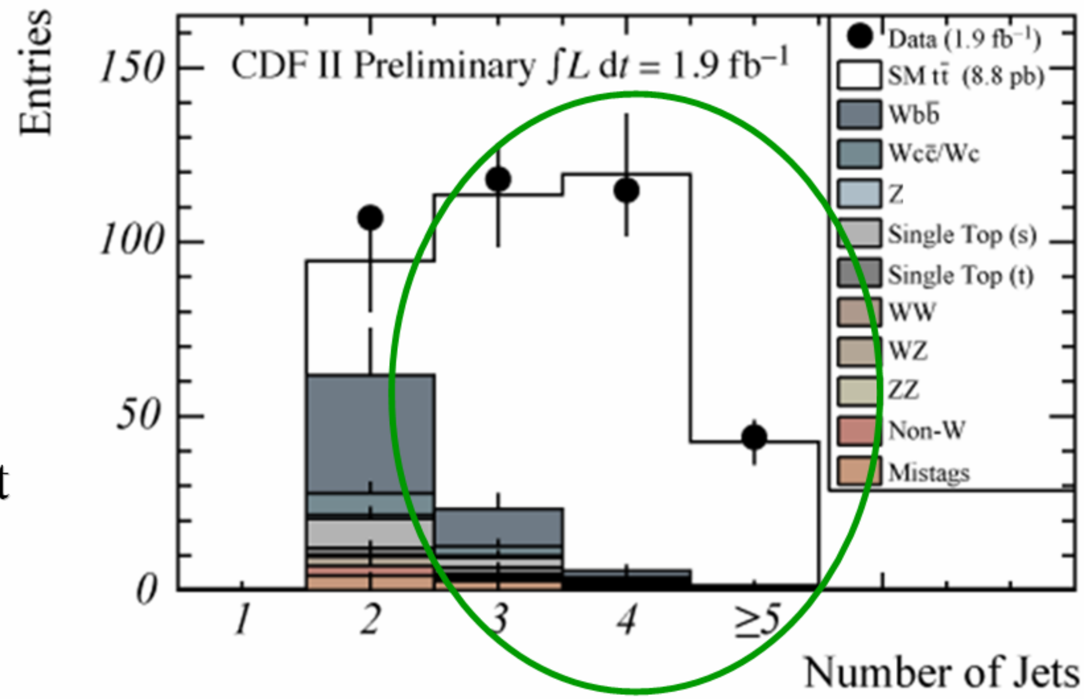
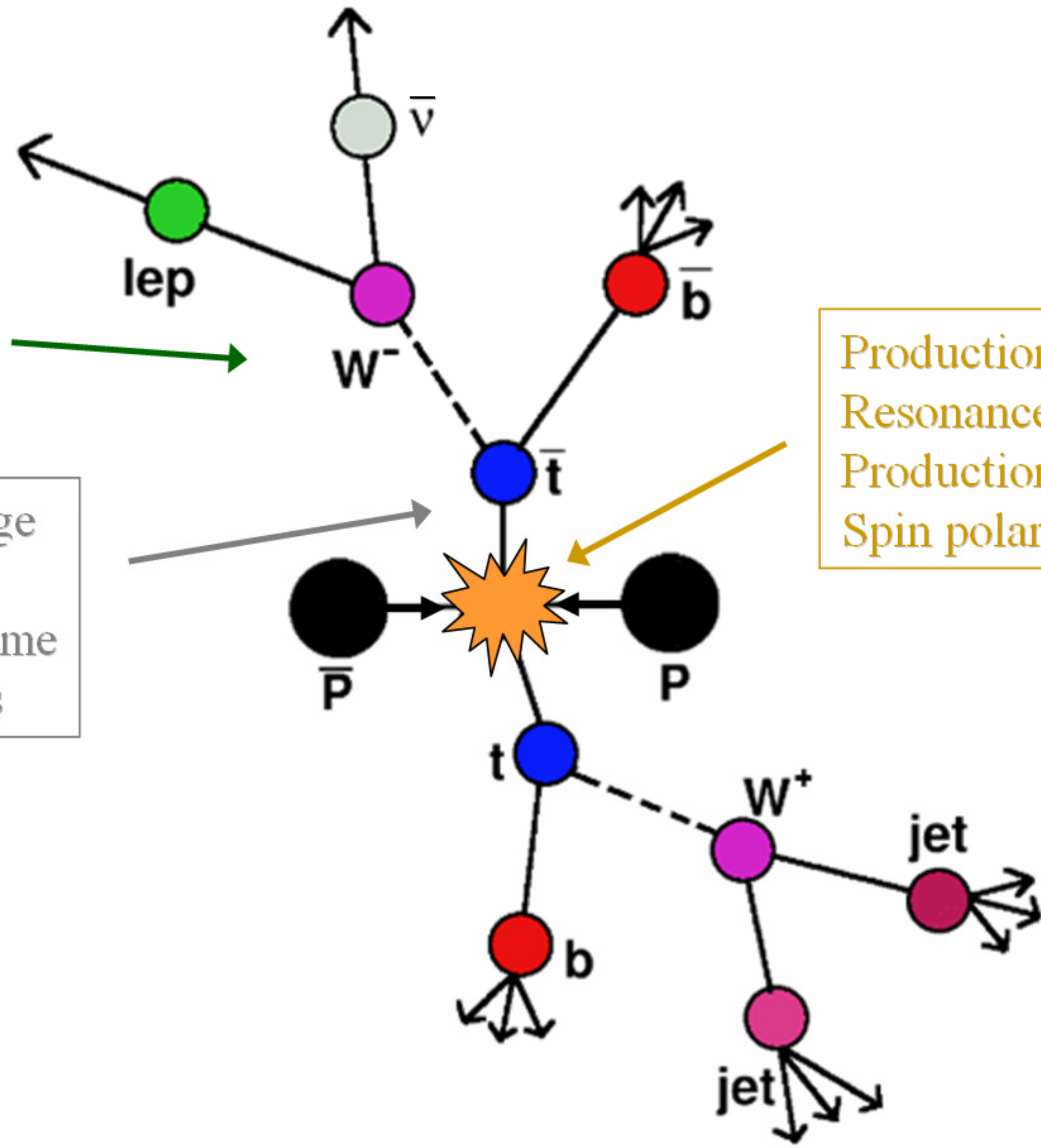


What Can We Study About Top Quarks?

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

Top charge
Top spin
Top lifetime
Top mass

Production cross section
Resonance production
Production kinematics
Spin polarization



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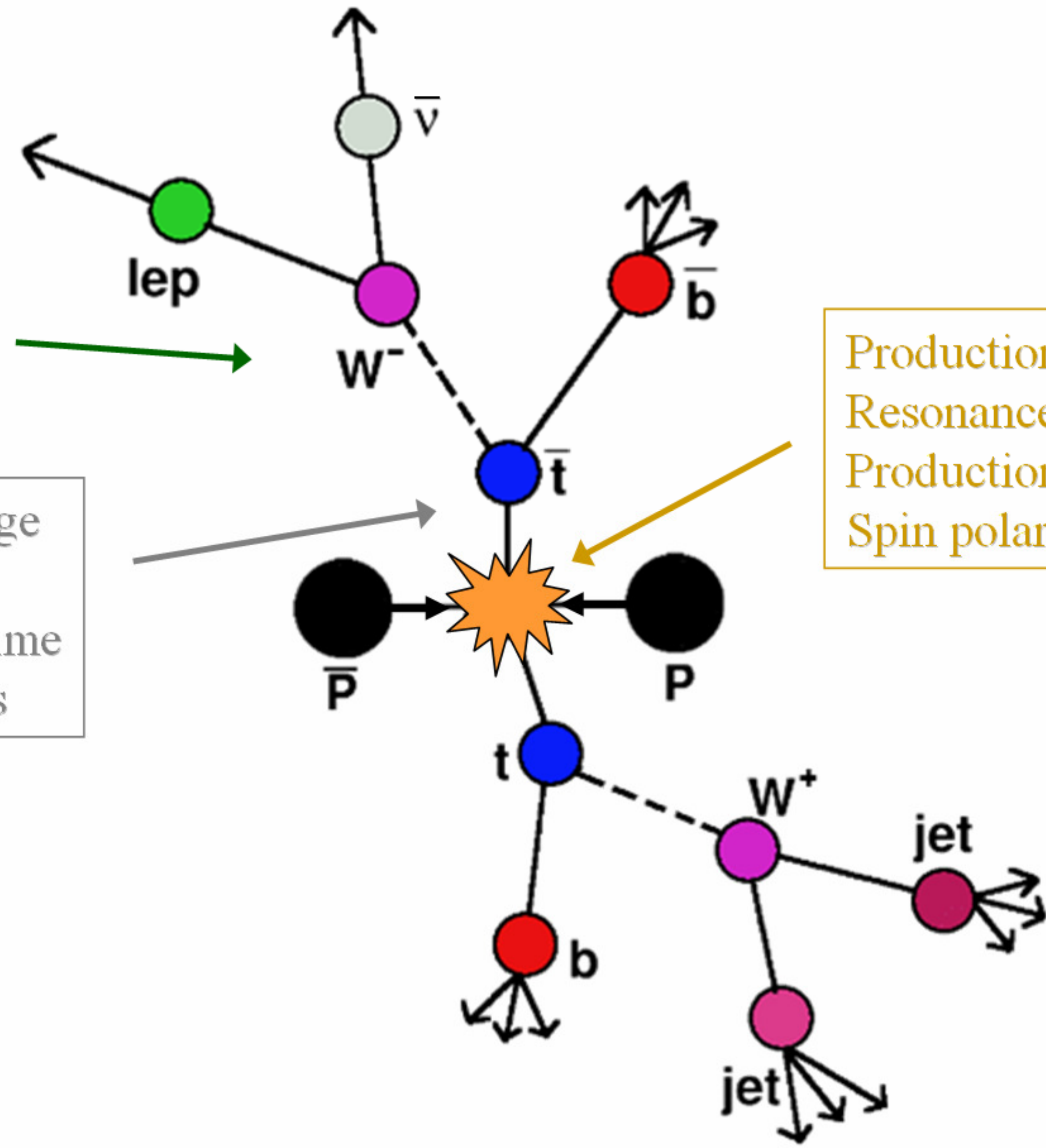

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Top physics is very rich.

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Spin polarization

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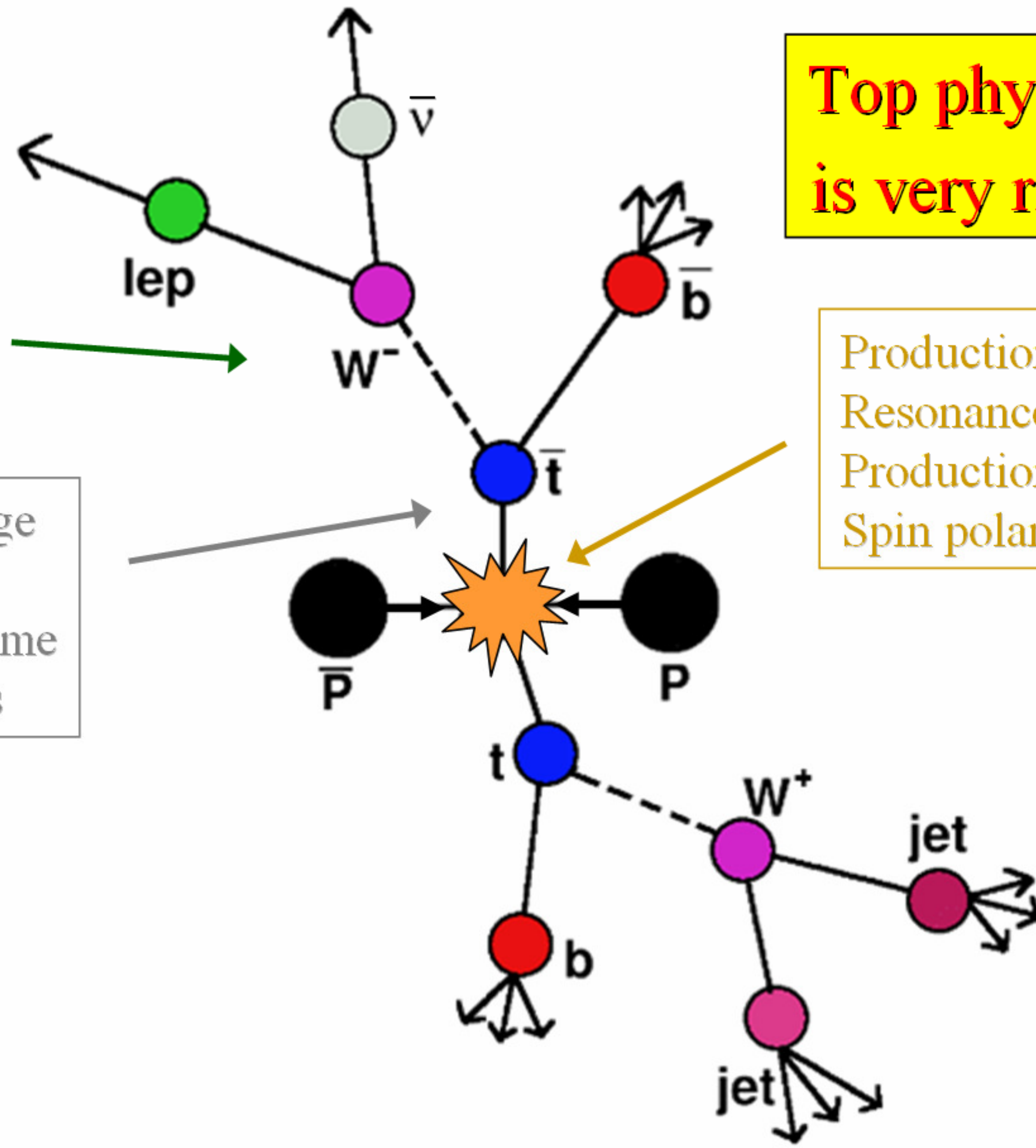
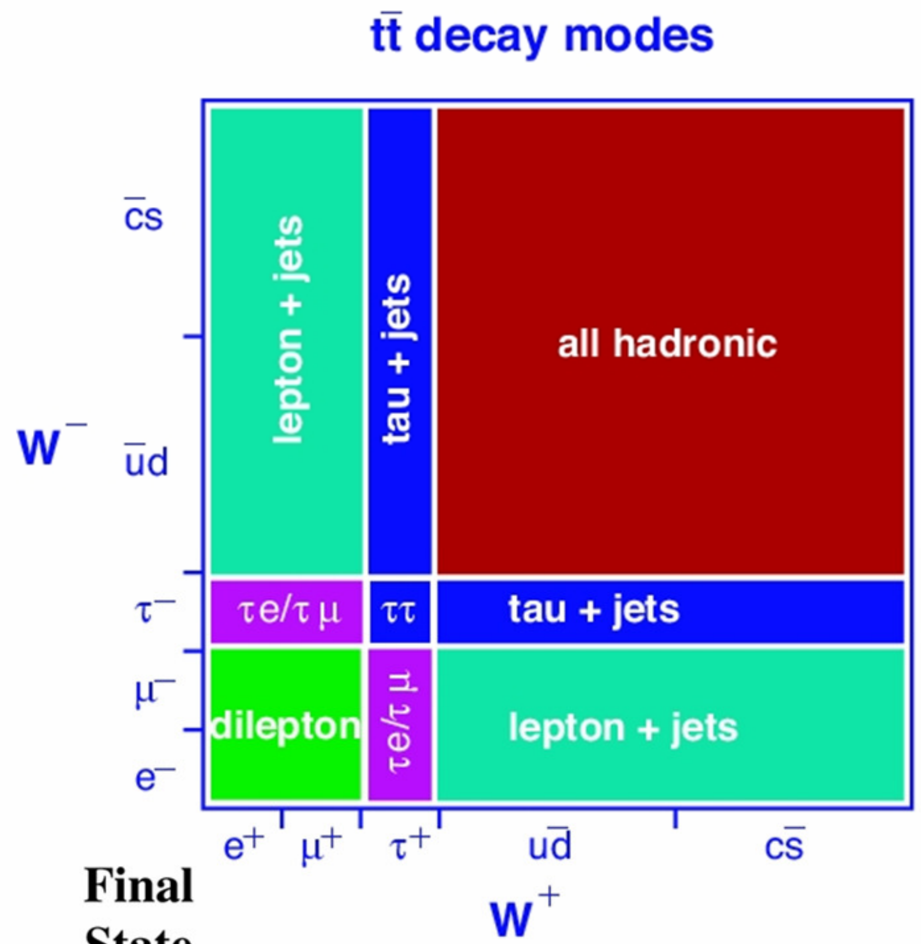
Top spin
Top lifetime
Top mass



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	

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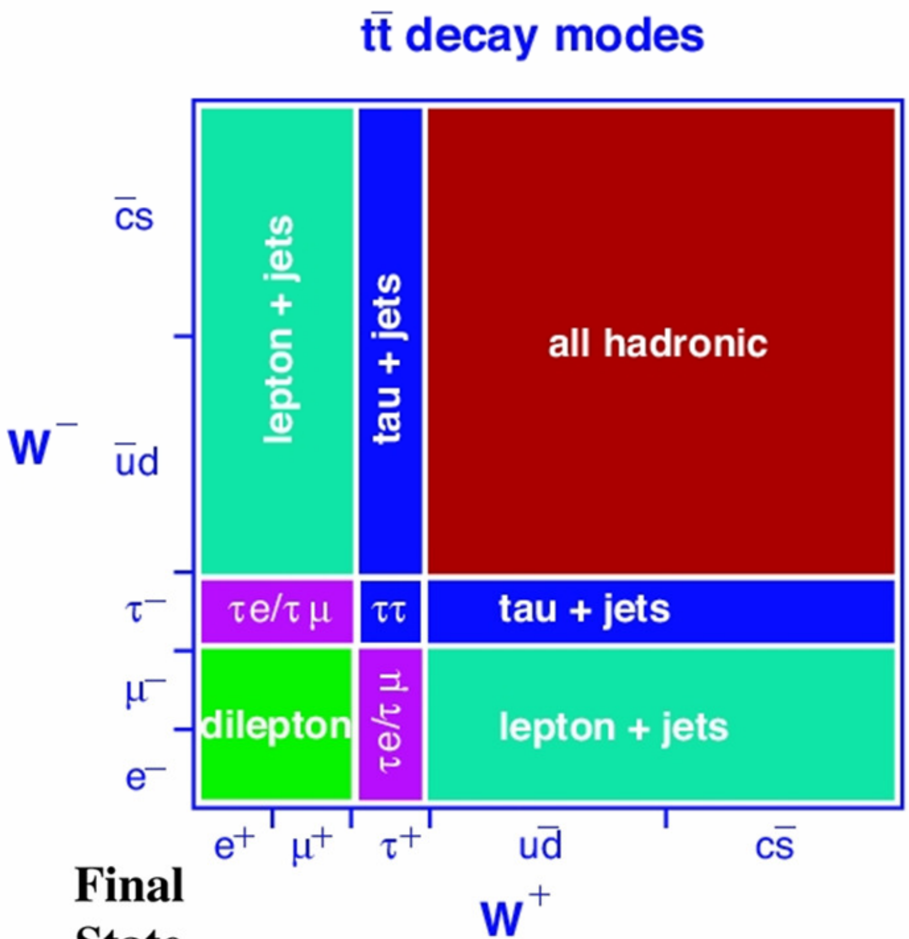

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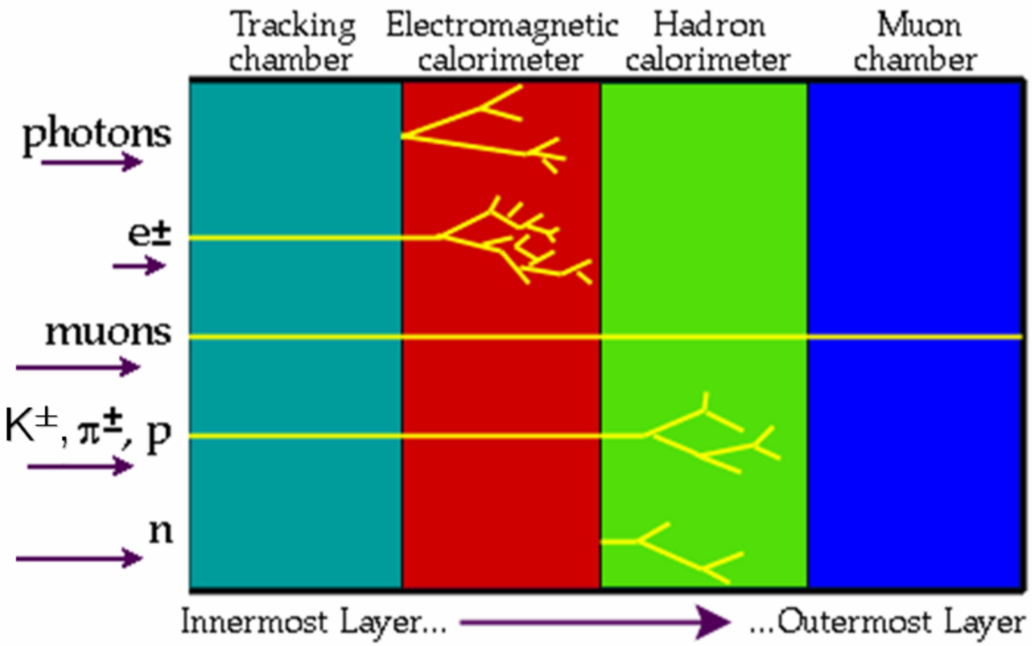
Lepton + Jets - no τs	~ 30%	Medium	ℓ ν bb jj
All Hadronic	~ 45%	High	bb jjjj
Tauonic	~ 20%	High	

Important Tool: Lepton ID

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

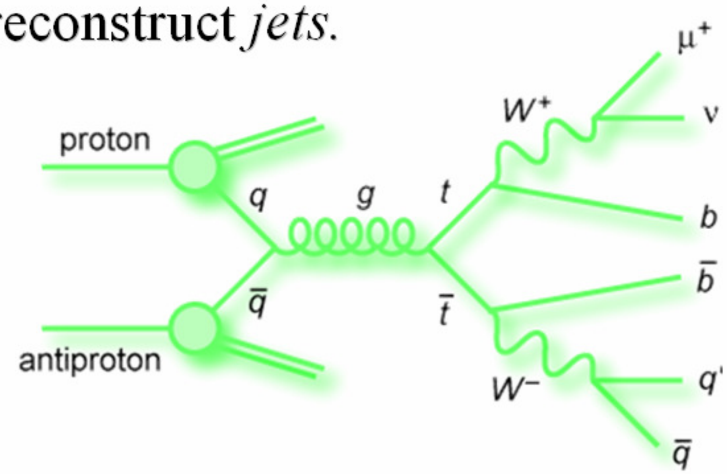


- Electrons (as we reconstruct them):
  - Have charged particle track.
  - Leave almost all of their energy in the electromagnetic calorimeter.
  - Ask for no other nearby tracks.
    - We do not want leptons from (heavy flavor) jets.

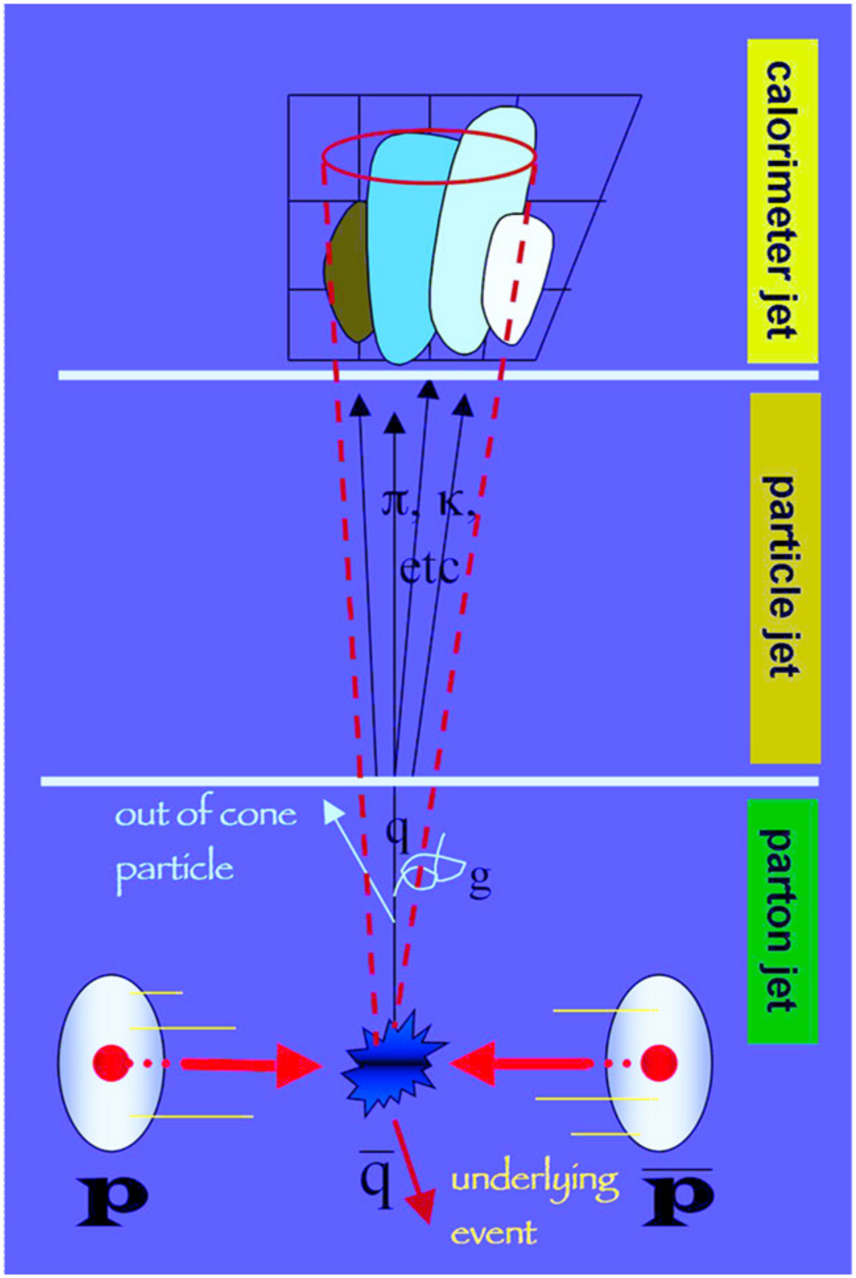
- Muons:
  - Have charged particle track.
  - ~ Minimum ionizing (leave little energy in either the electromagnetic or hadronic calorimeter)
  - Find a "stub" of a track in dedicated muon detector systems on outside of CDF.
  - Ask for no other nearby tracks.

Important Tool: Jet Reconstruction

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

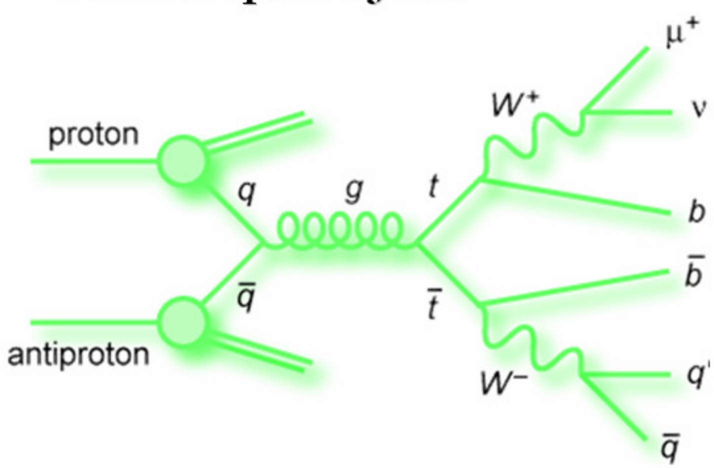


- We need to convert "*raw*" jets to "*corrected*" jets - Jet Energy Scale (JES) correction.
  - Takes into account detector effects, neutral particles in jets, particles outside of the jet cone, underlying events, multiple interactions, …



Important Tool: B Jet Tagging

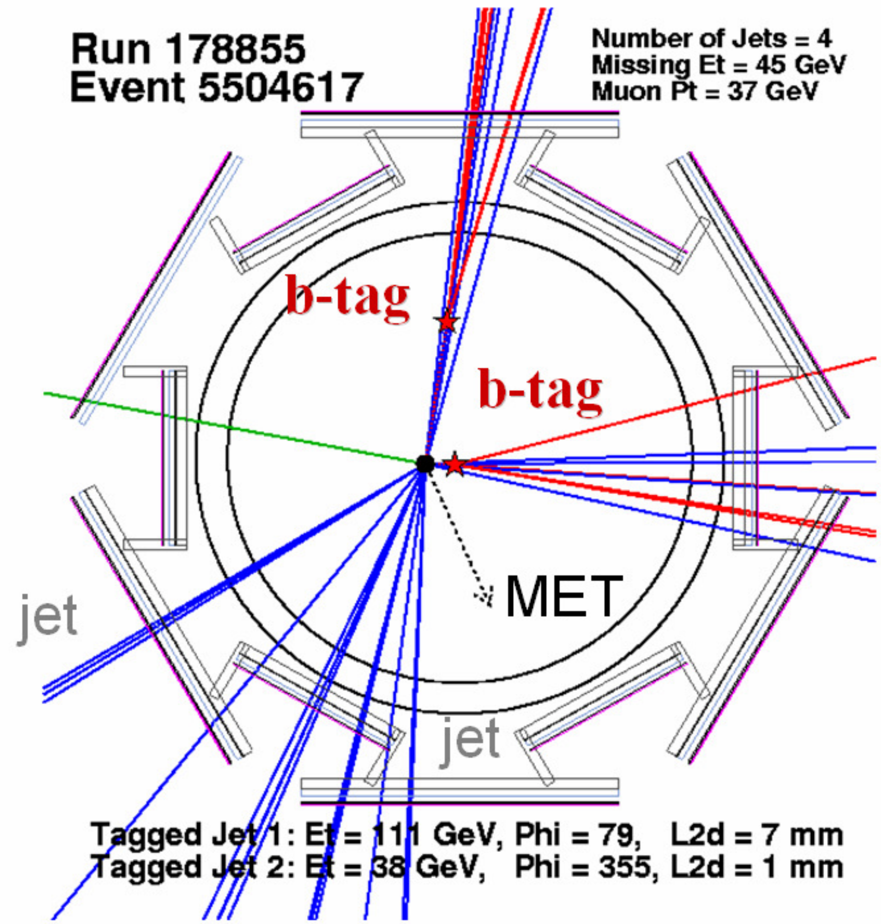
- Since we (often) expect t → W b, b jet tagging is a very important tool.
  - Most backgrounds do not have bottom quark jets.



- 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



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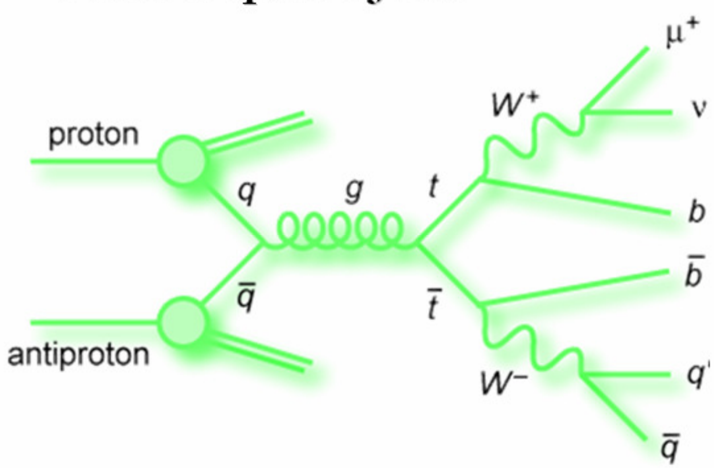

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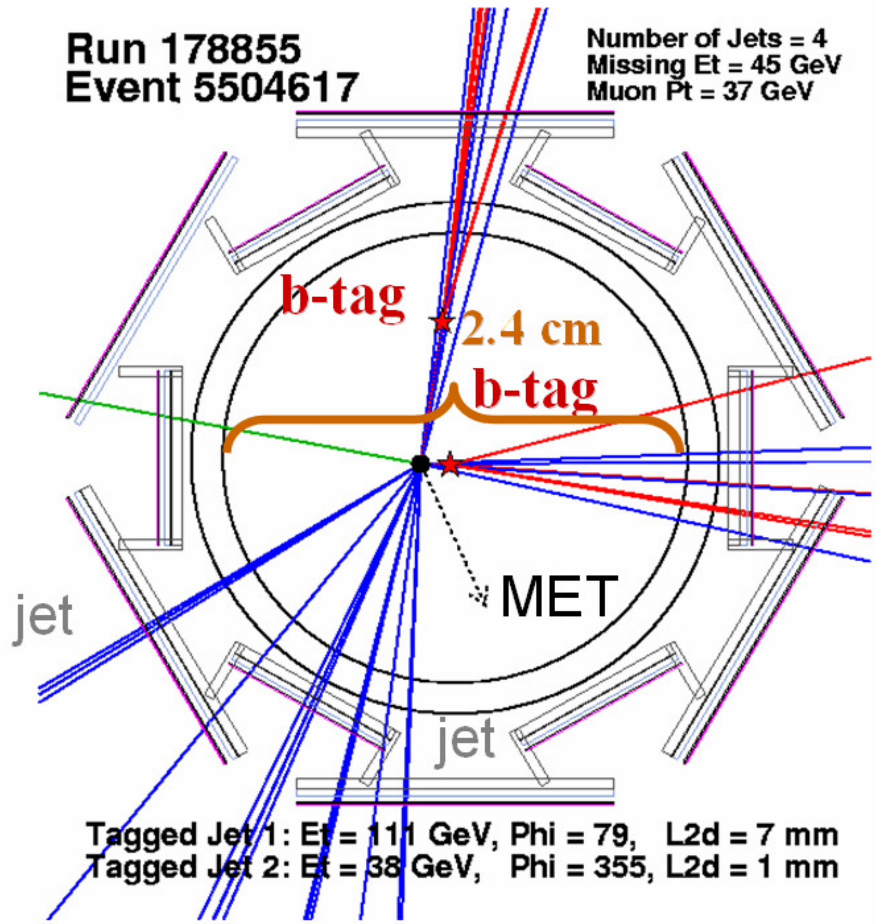

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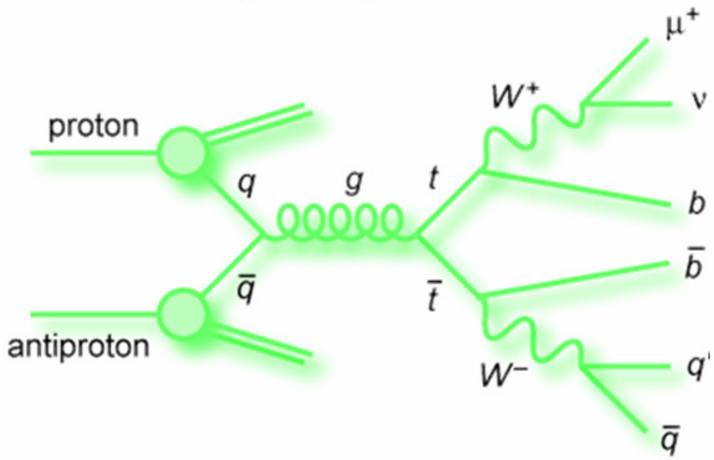

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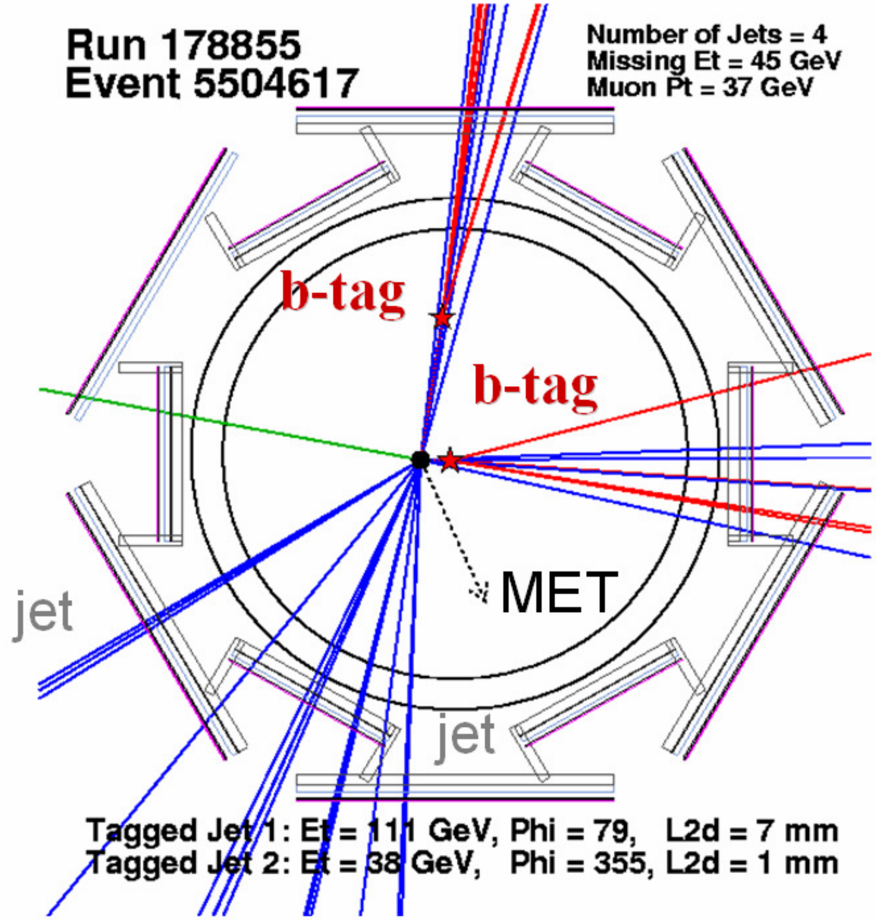

Top Physics *Finally* Makes Prime Time

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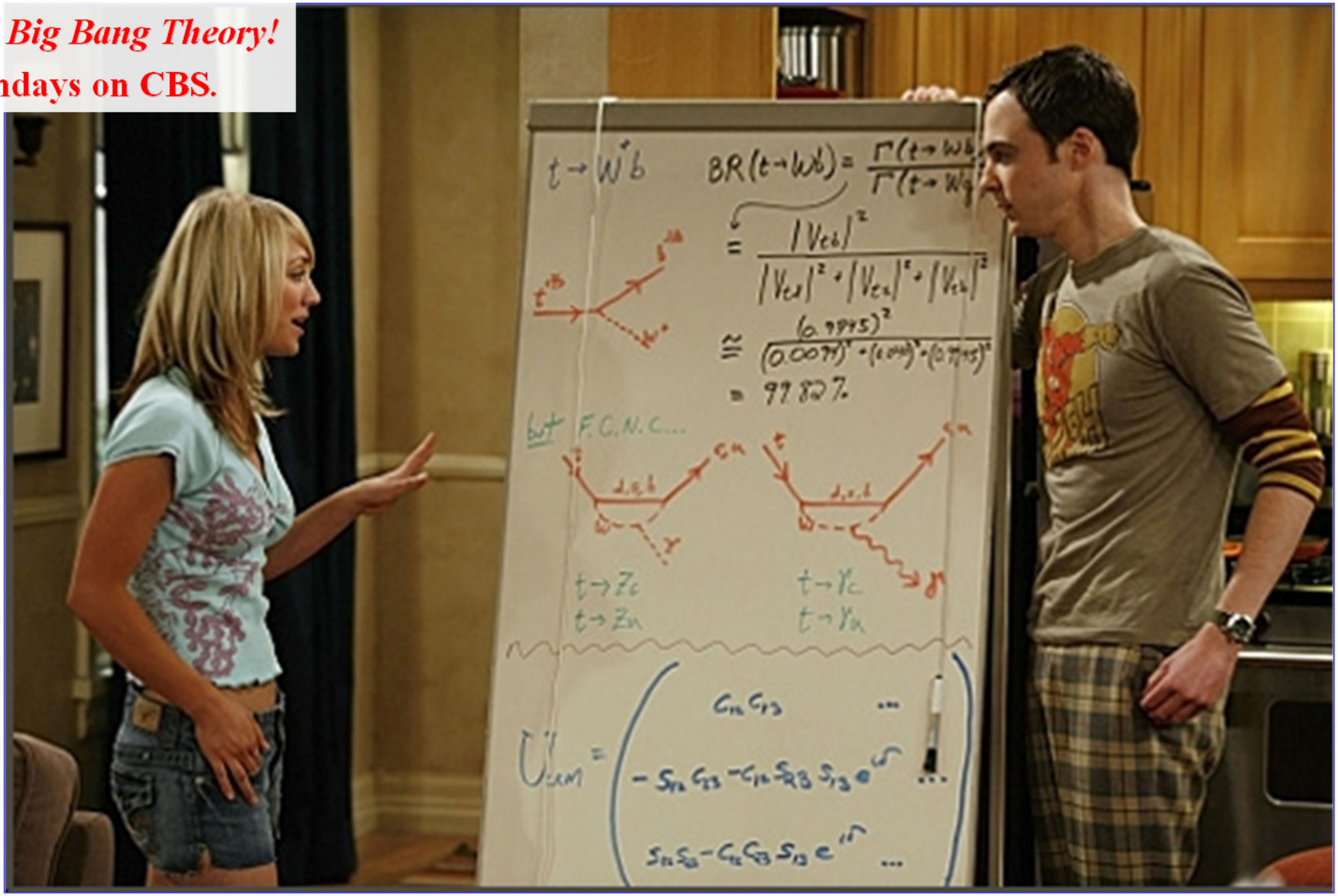
The Big Bang Theory!

Mondays on CBS.



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Top Branching Fractions

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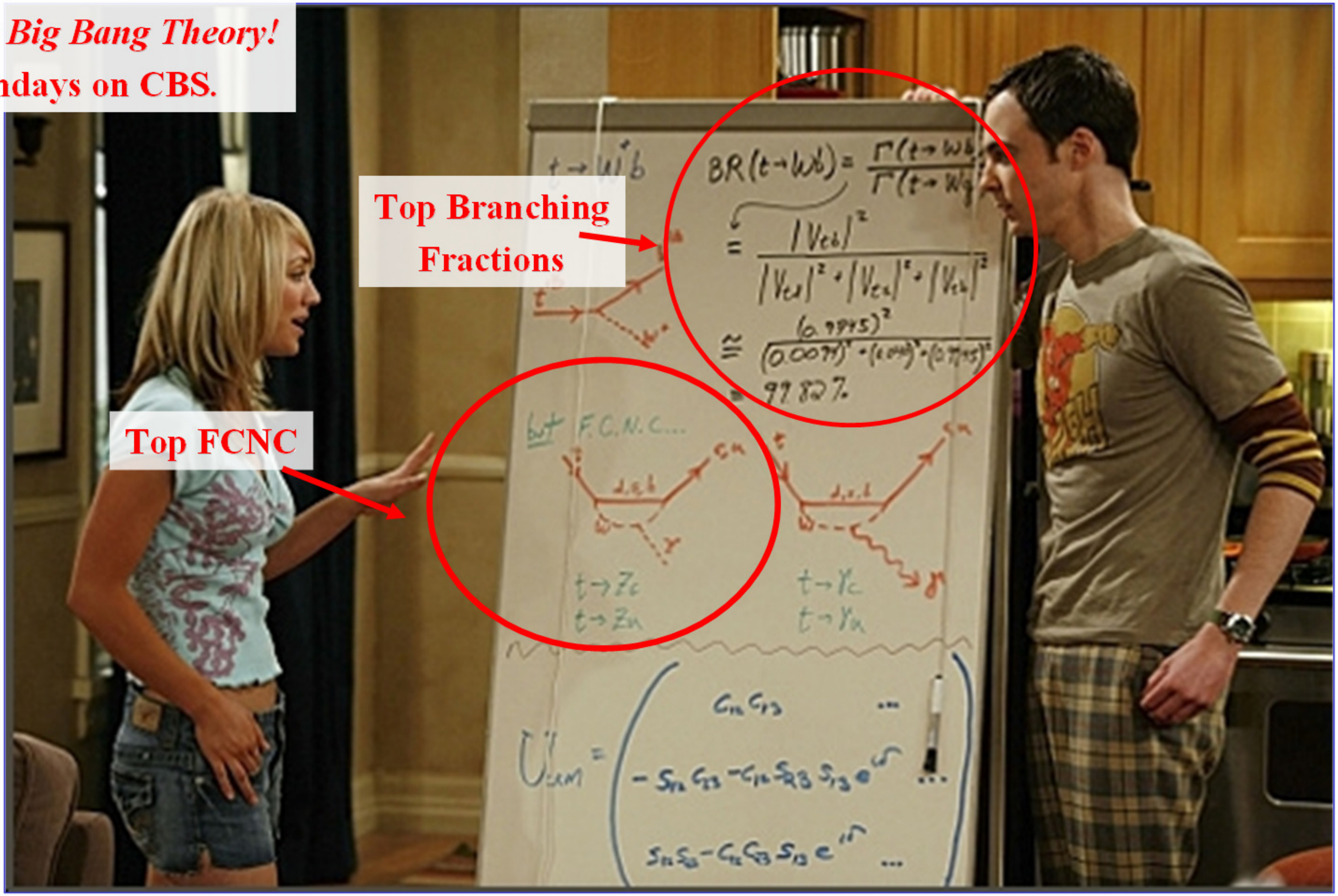

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- Introduction
- Search For Invisible Top Decays
- Direct FCNC Search
- Acceptances
- Backgrounds
- Unblinding
- Fitting For Everything

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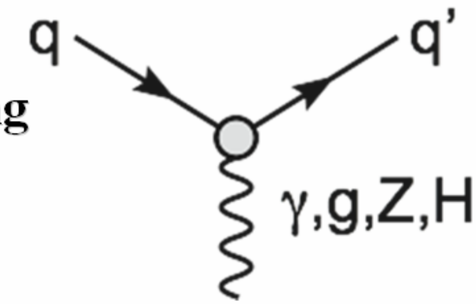
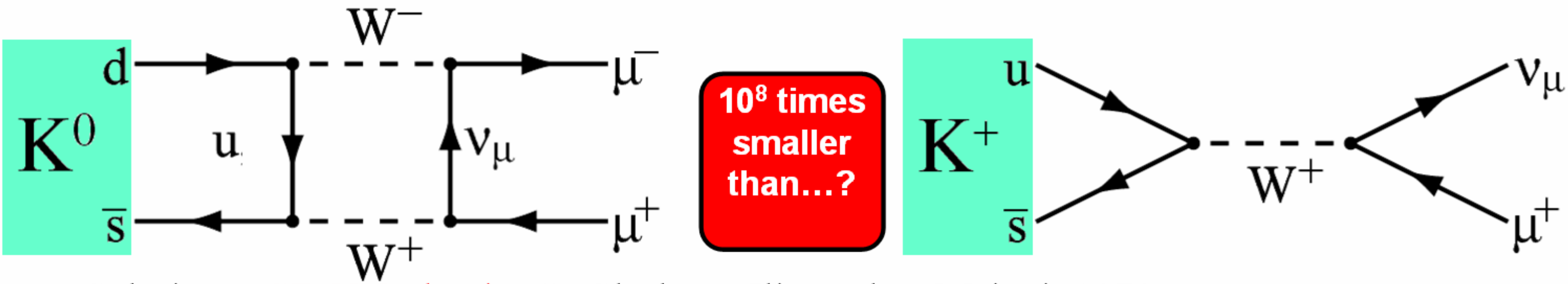
Flavor Changing Neutral Currents

- 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:



- Solution: "GIM Mechanism" (Glashow, Iliopoulos, Maiani, 1970)
  - Fourth quark needed for cancellation in box diagram: prediction of charm quark.
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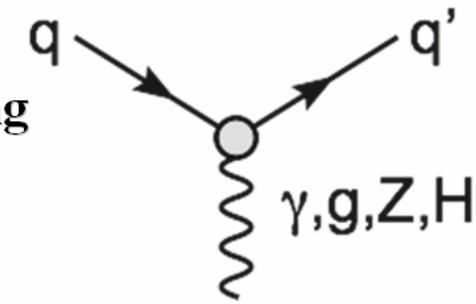

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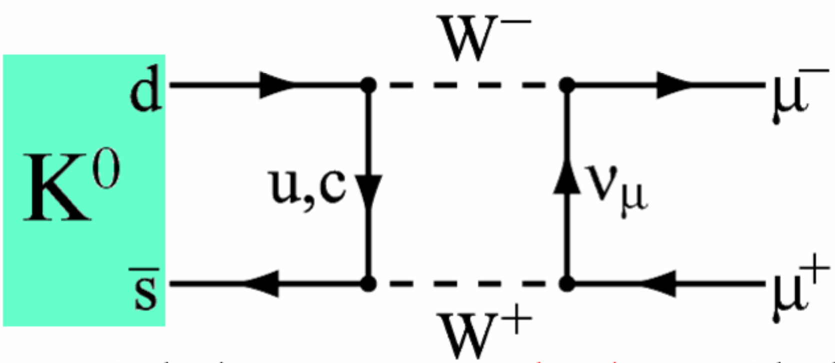
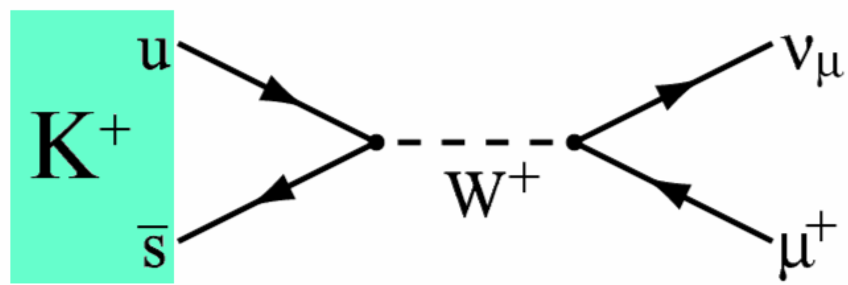


10^8 times smaller than…?



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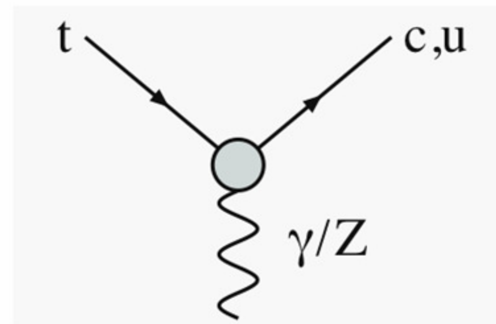
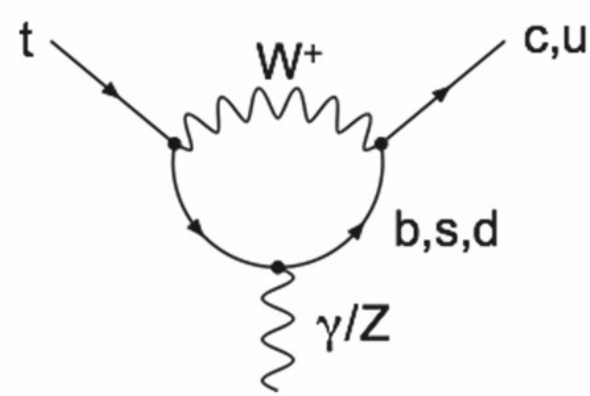
Top Flavor Changing Neutral Currents

- 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

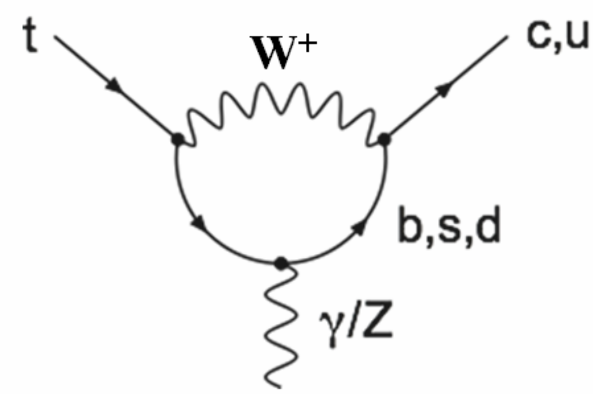


Penguin Diagram



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]

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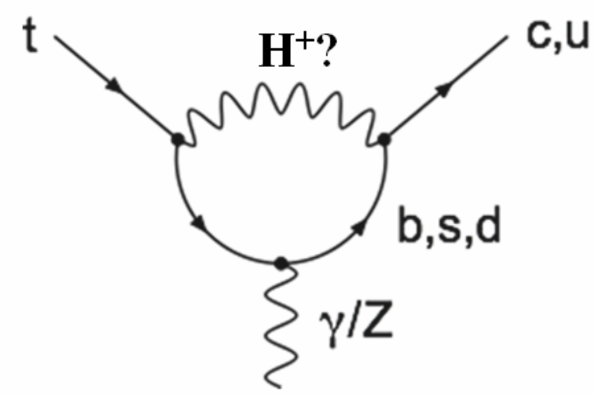

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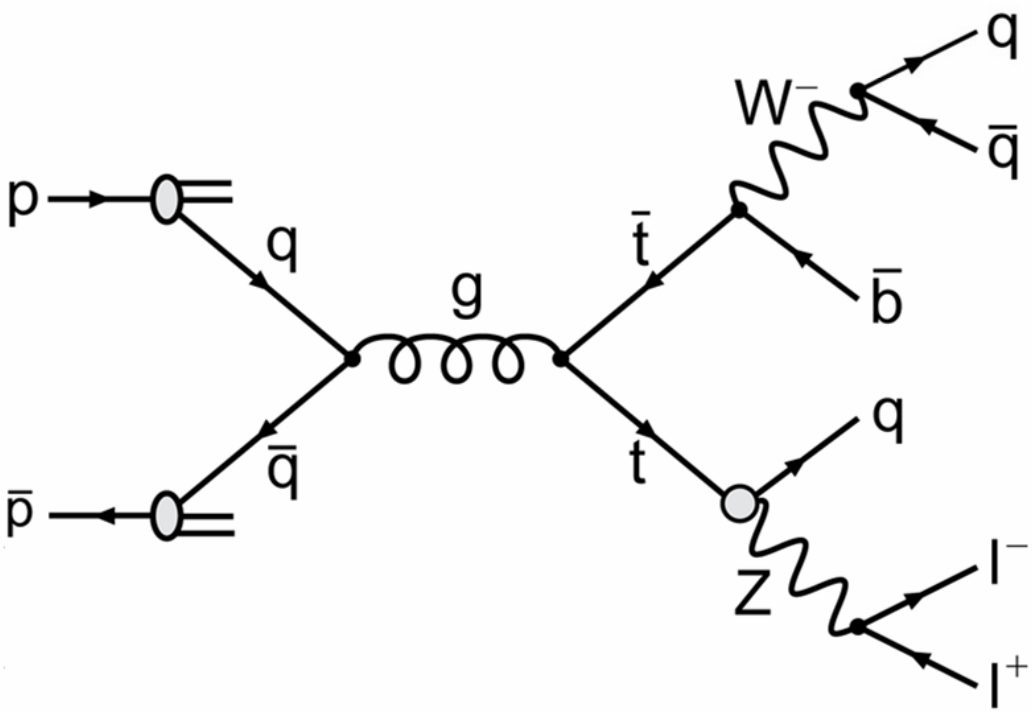
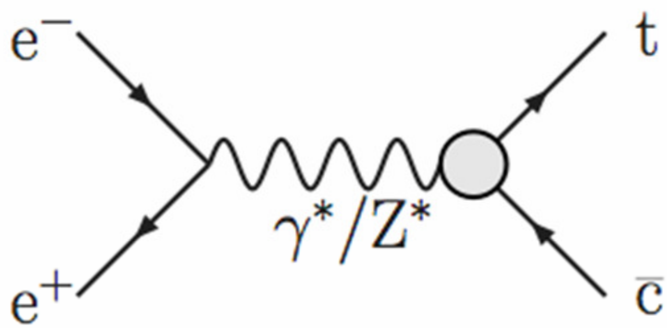
Previous Limits

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



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

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



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

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

Top FCNC Outline

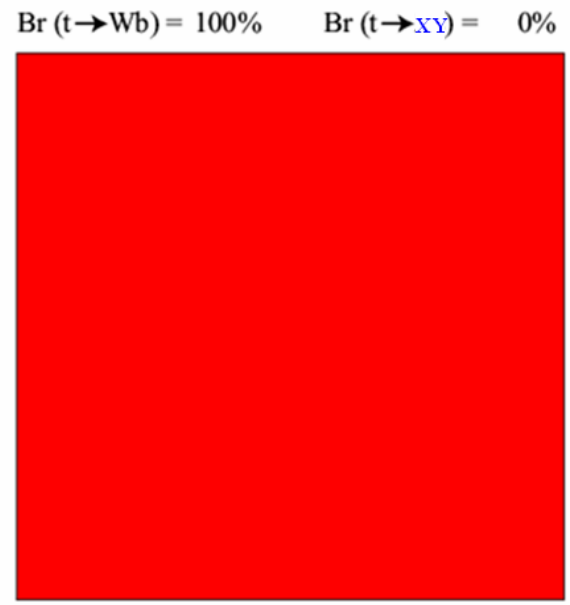
The Search for Top FCNC Decay

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

Search for Invisible Top Decays

- What do we mean by *"invisible?"*
  - Not (well) reconstructed as double b-tag lepton + jets.
- What would happen if there were a large branching fraction to an *invisible* decay? For example,
  Br ($t \to$ *Invisible*) = 10%?
  - Br ($t \to Wb$) = 90%
  - P ($tt \to Wb\ Wb$) = 81%

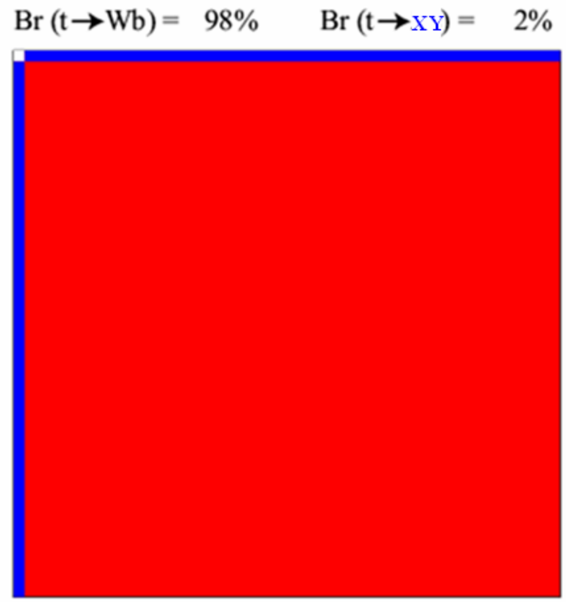
  $\Rightarrow$ For a purely invisible decay, we should have an 19% deficit when we look at the L + J event yield for a given theoretical cross section.



Search for Invisible Top Decays

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

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



- 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.

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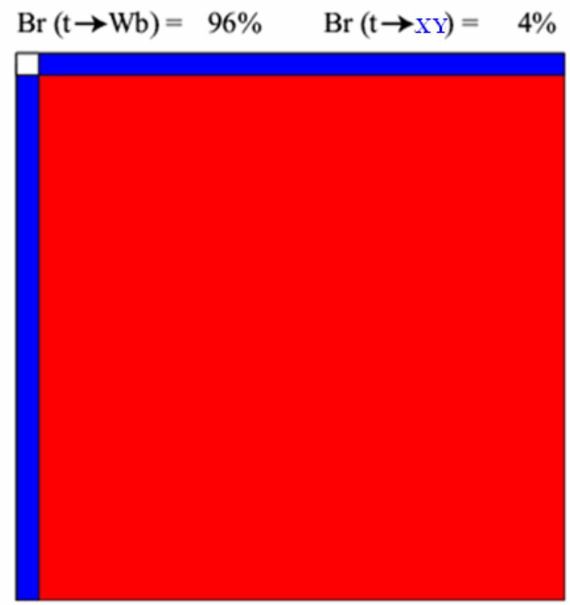

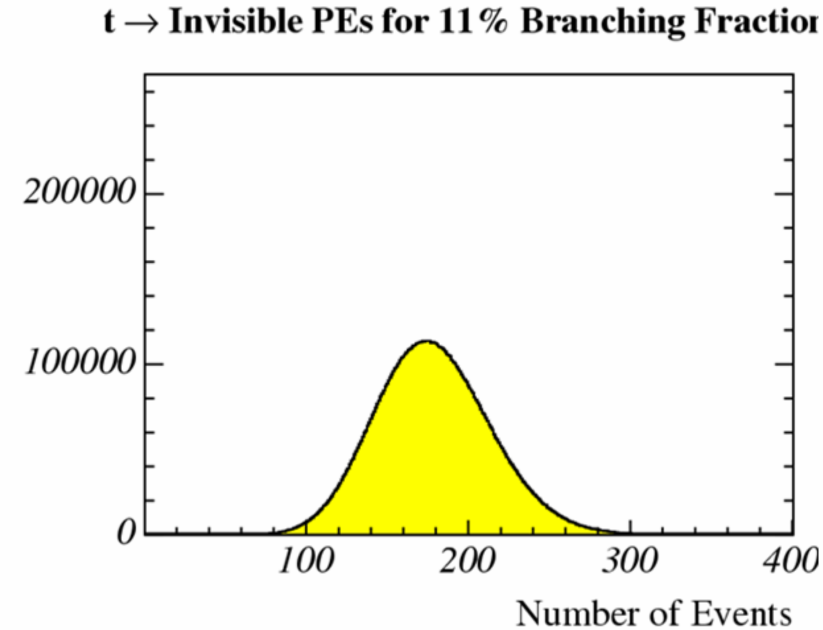

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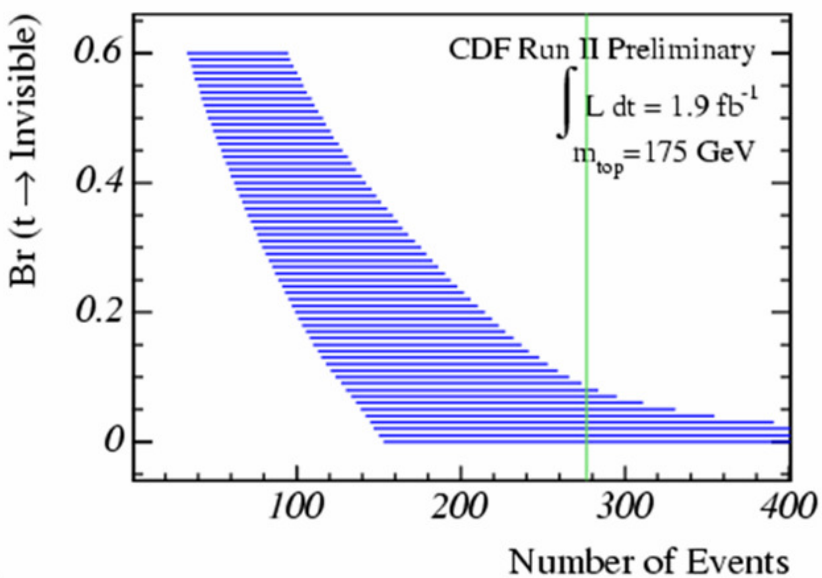
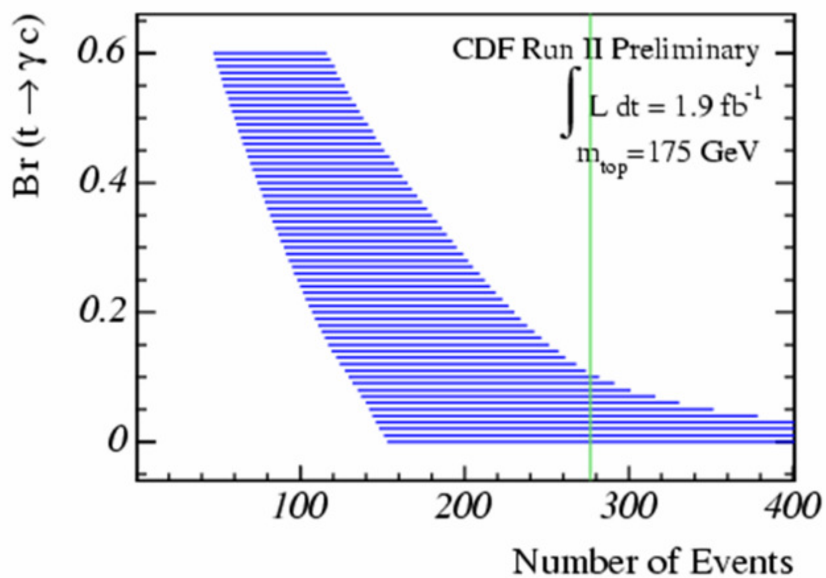
Feldman-Cousins Acceptance Bands

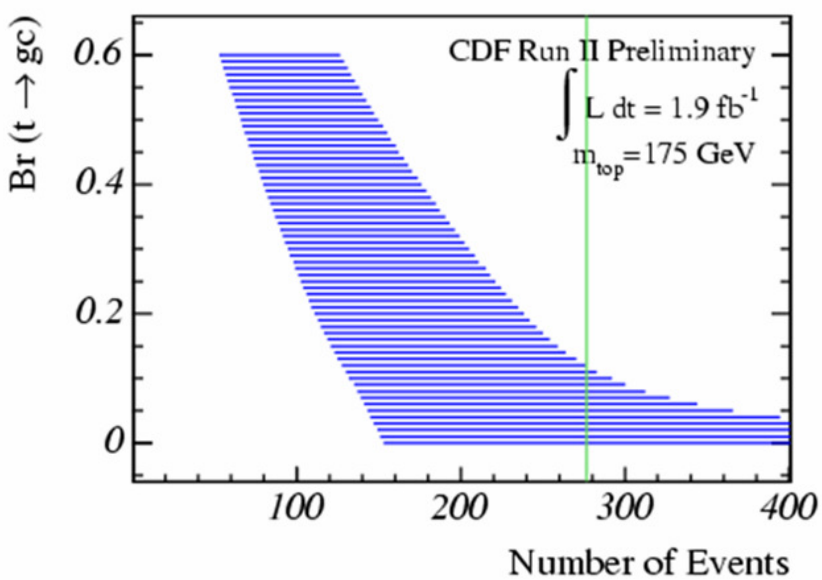
FC Bands for t → Invisible



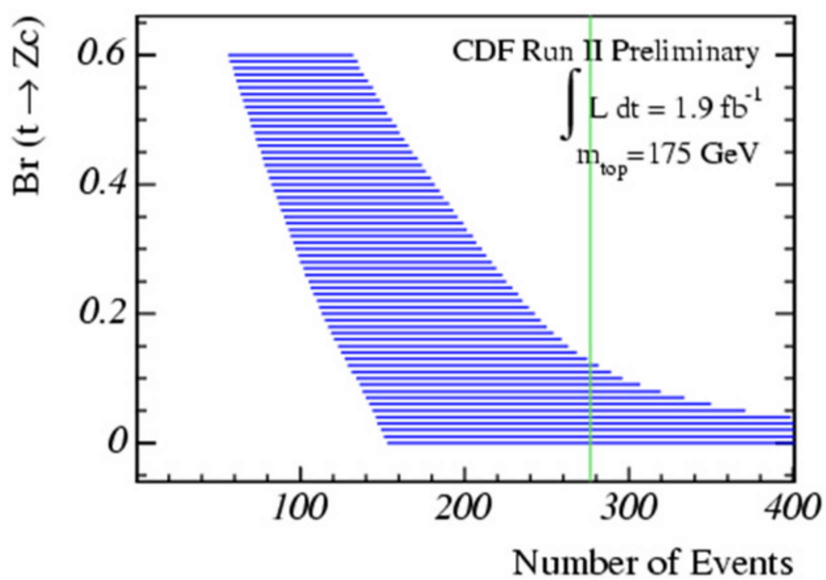
FC Bands for t → γ c



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}
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$t \to$ invisible	0	20^{+10}_{-8}

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

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Better Than L3's Published Limit!

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World's First Measurement!

Top FCNC Outline

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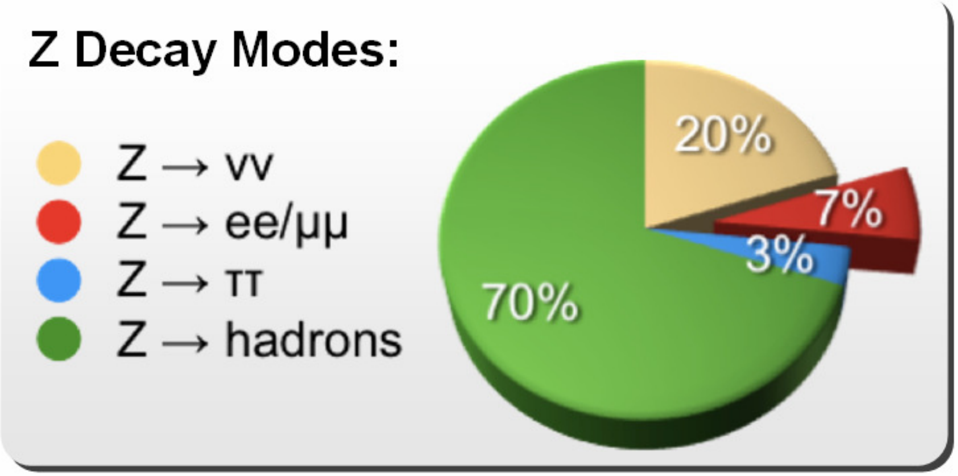
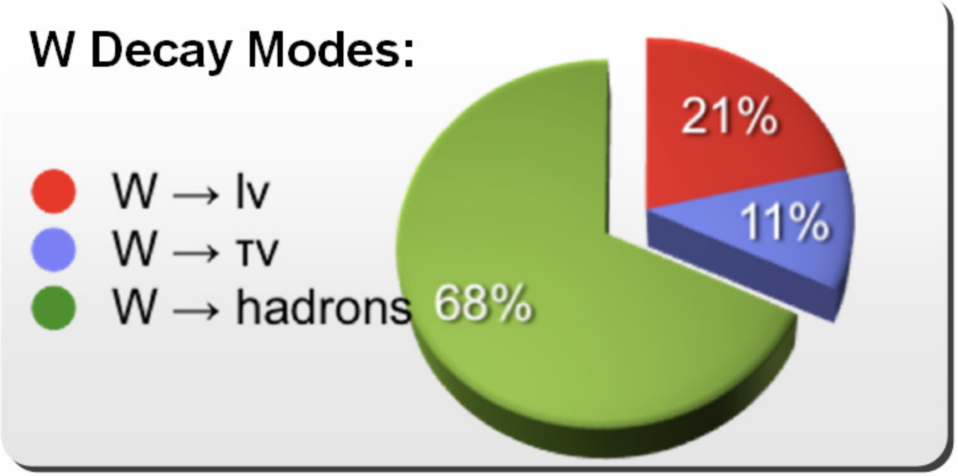
Top FCNC Direct Search: Roadmap

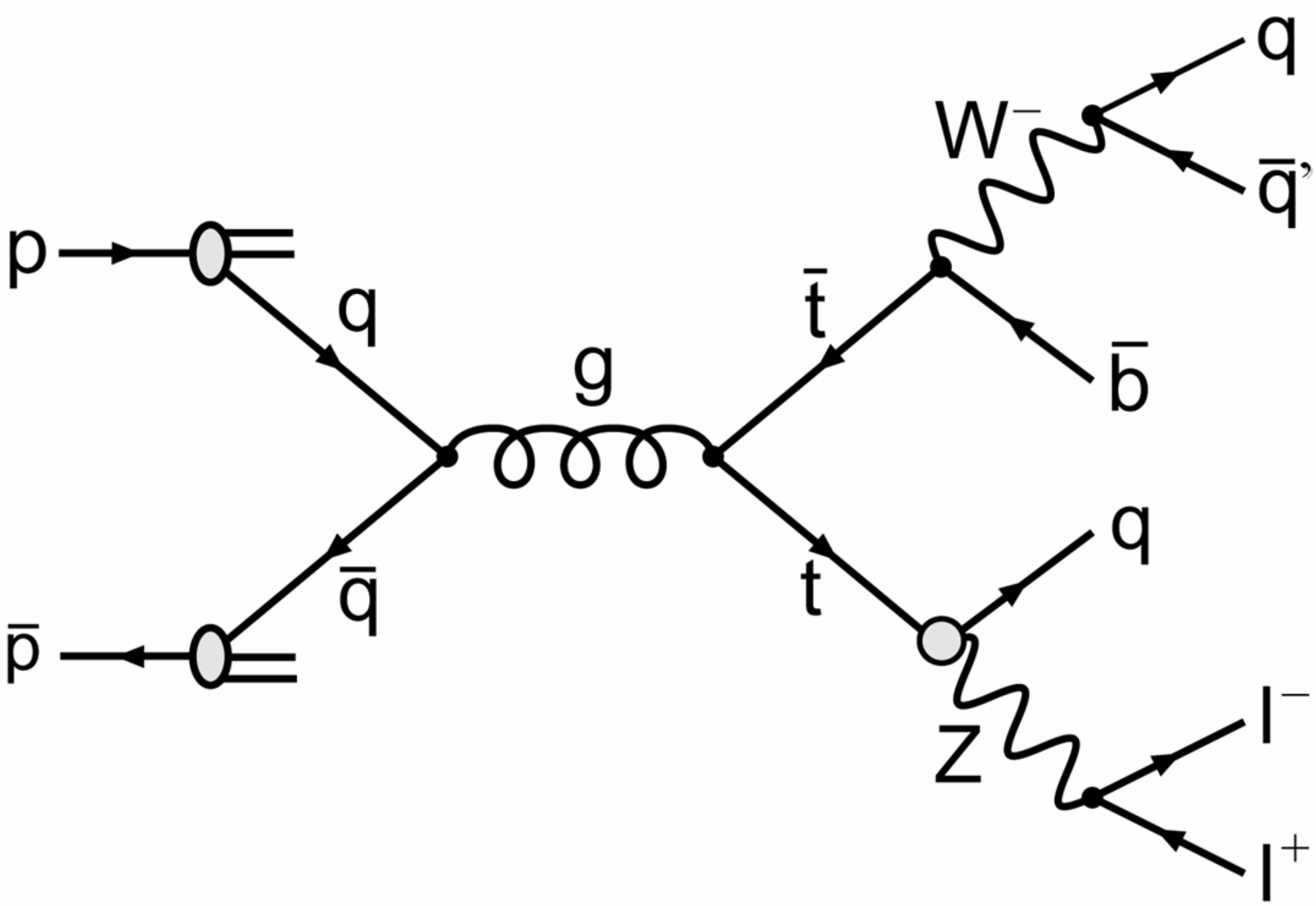
- Basic question: how often do top quarks decay into Zc?
  - Measure (or set limit) on branching fraction, Br ($t \rightarrow Zc$).
  - Normalize to lepton + jets top pair decays.



- 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.

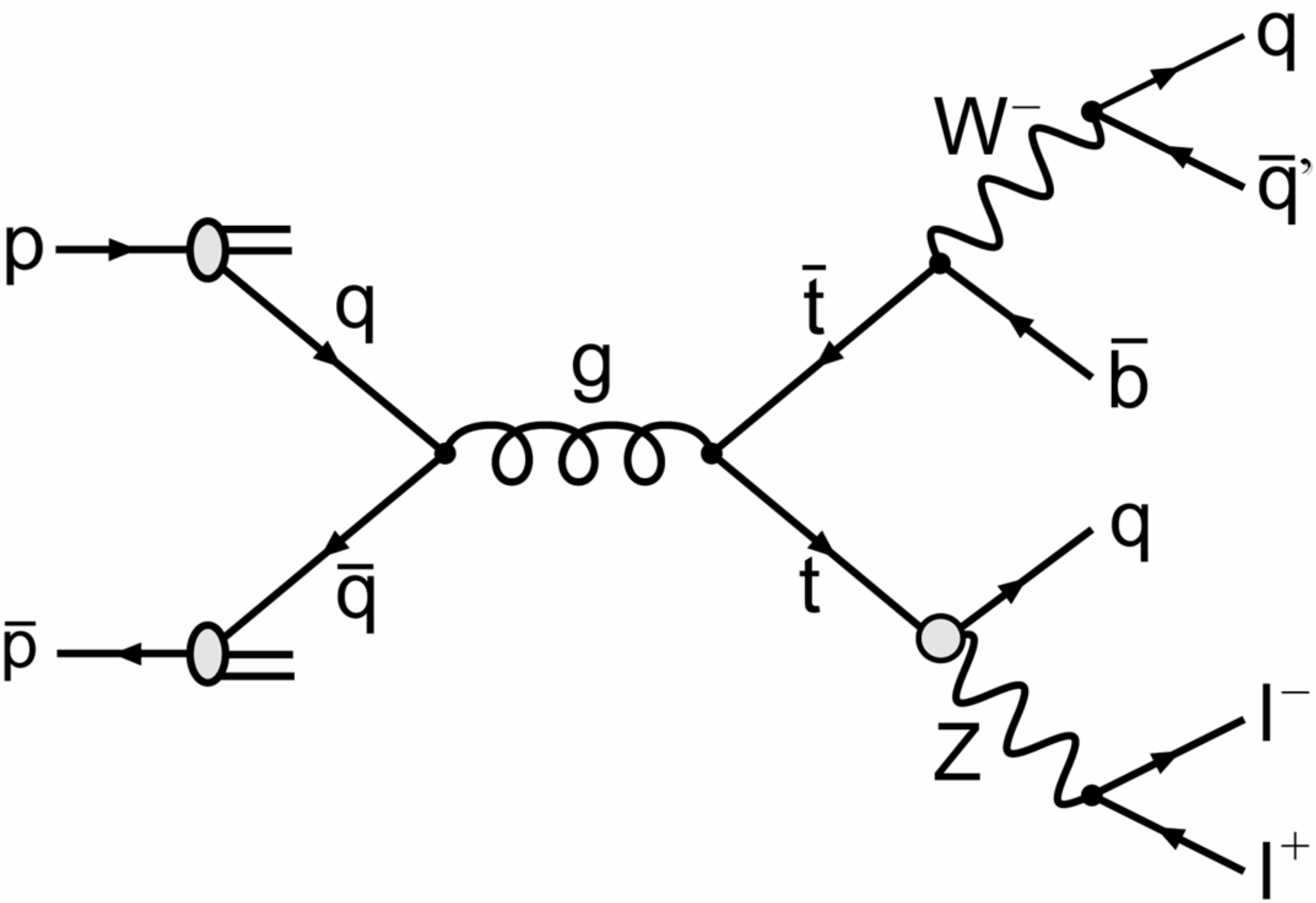


Search for FCNC: Ingredients



Search for FCNC: Ingredients

$\chi^2_{\text{mass reconstruction}}$



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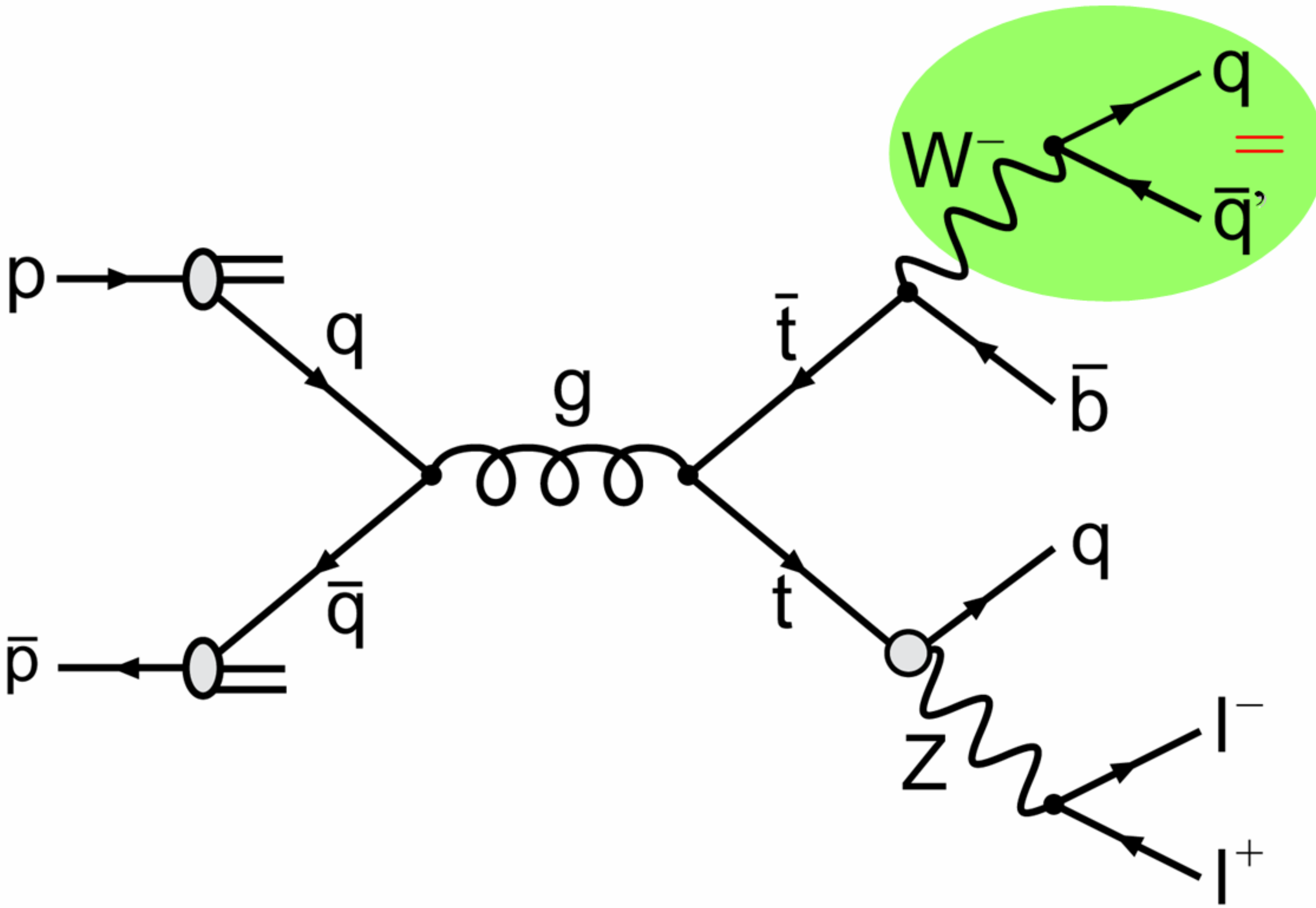

$$\chi^2_{\text{mass reconstruction}} = \left(\frac{m_{W\ \text{recon}} - m_W}{\sigma_W} \right)^2$$

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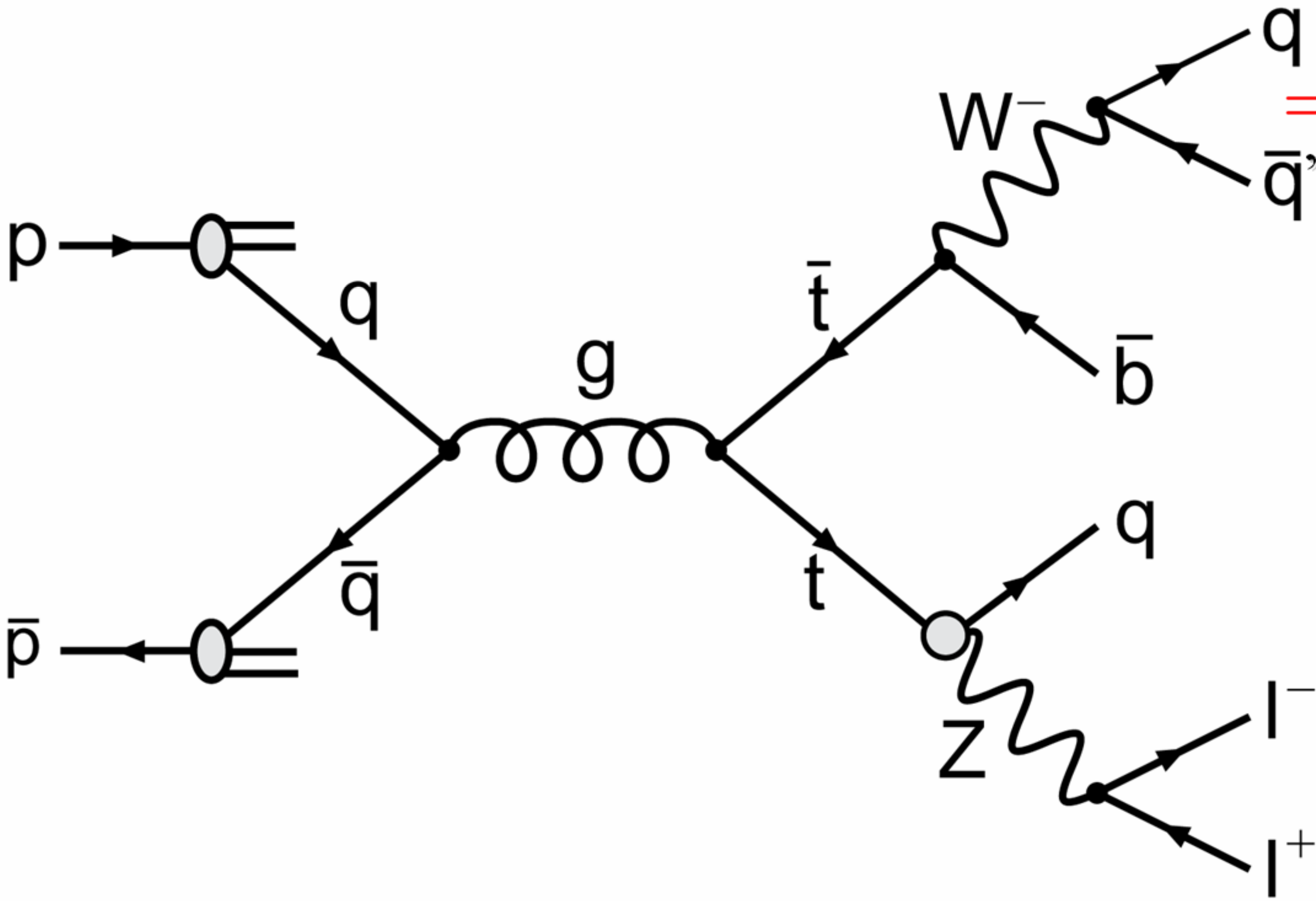

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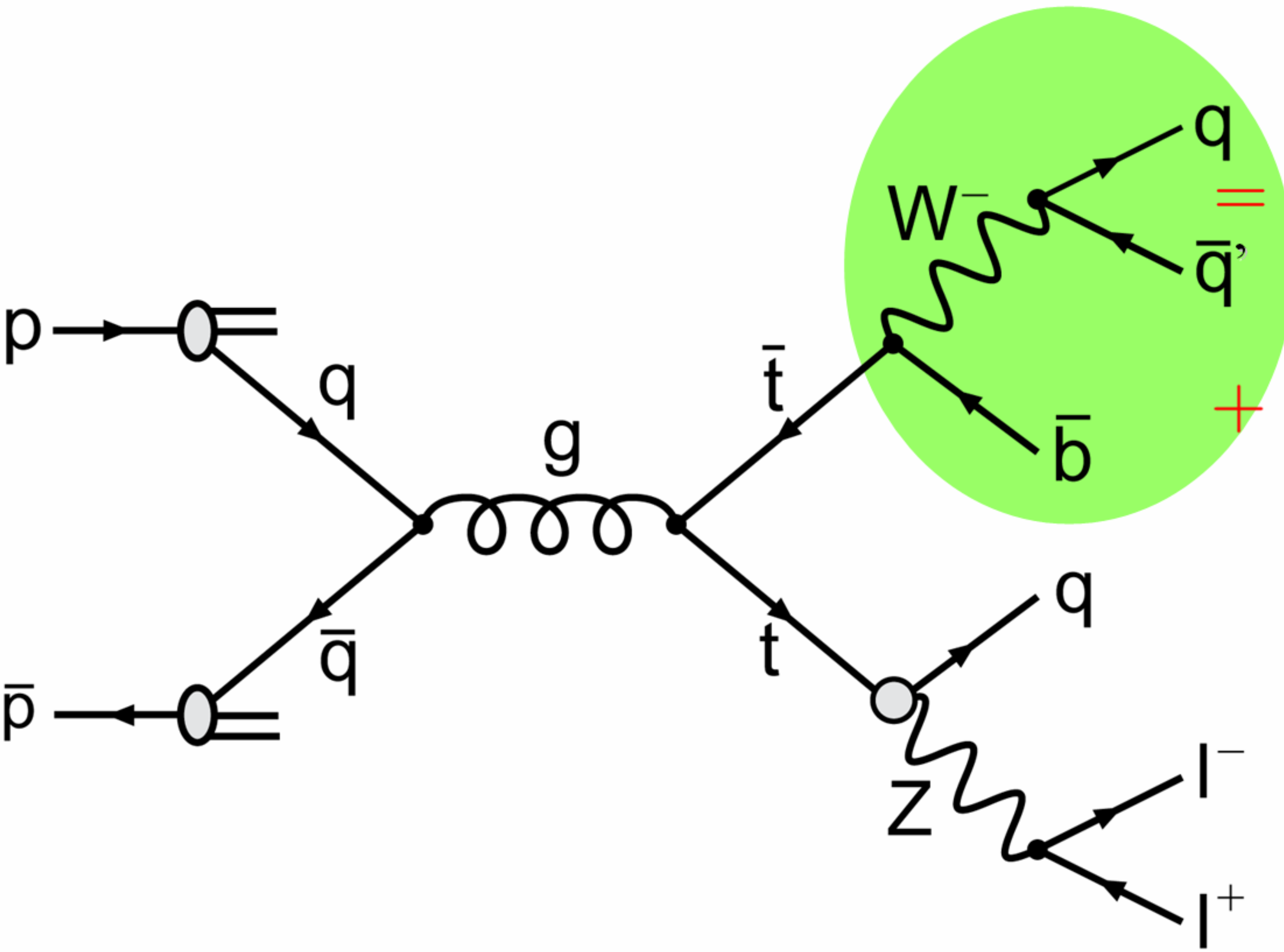

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Search for FCNC: Ingredients

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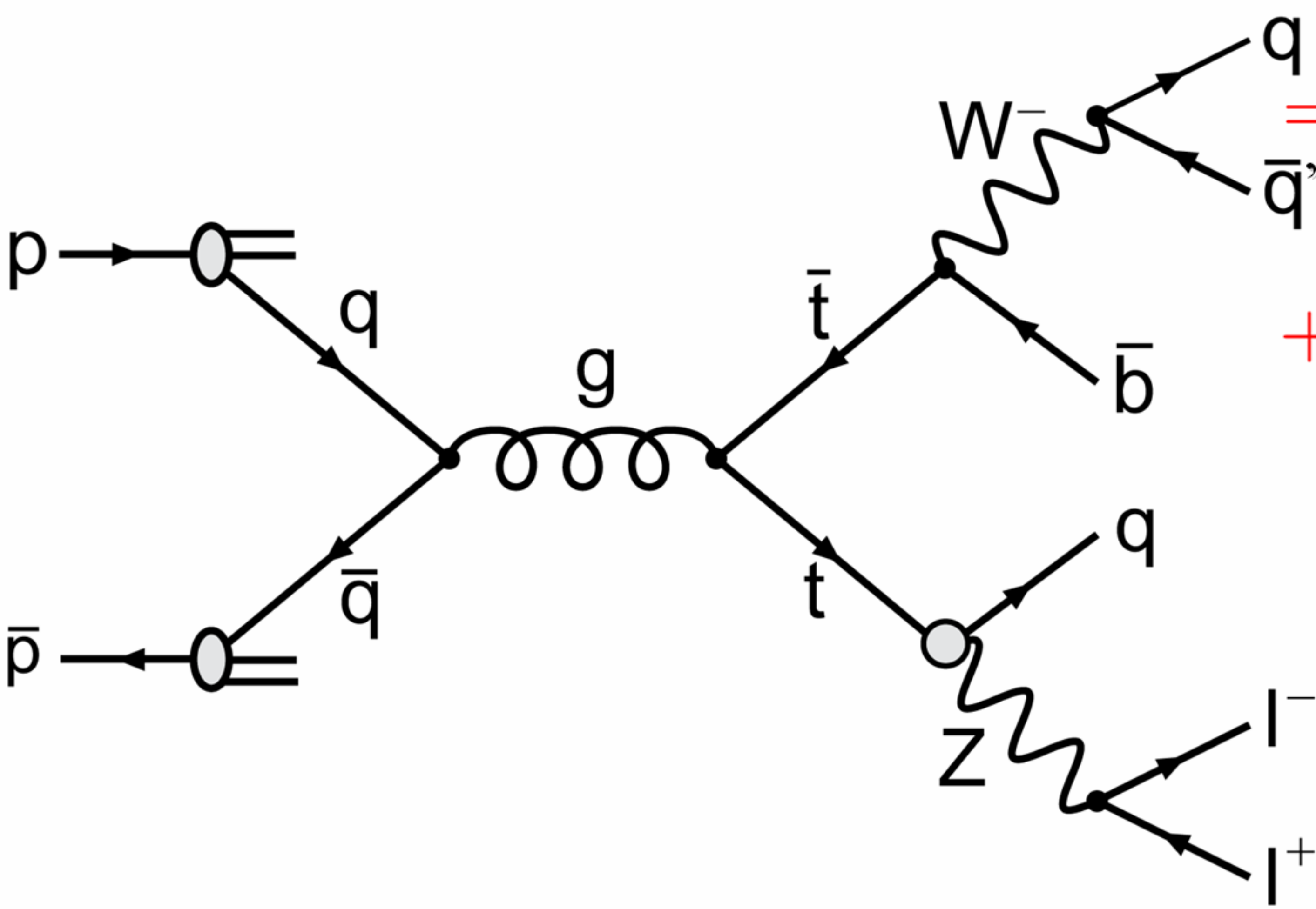

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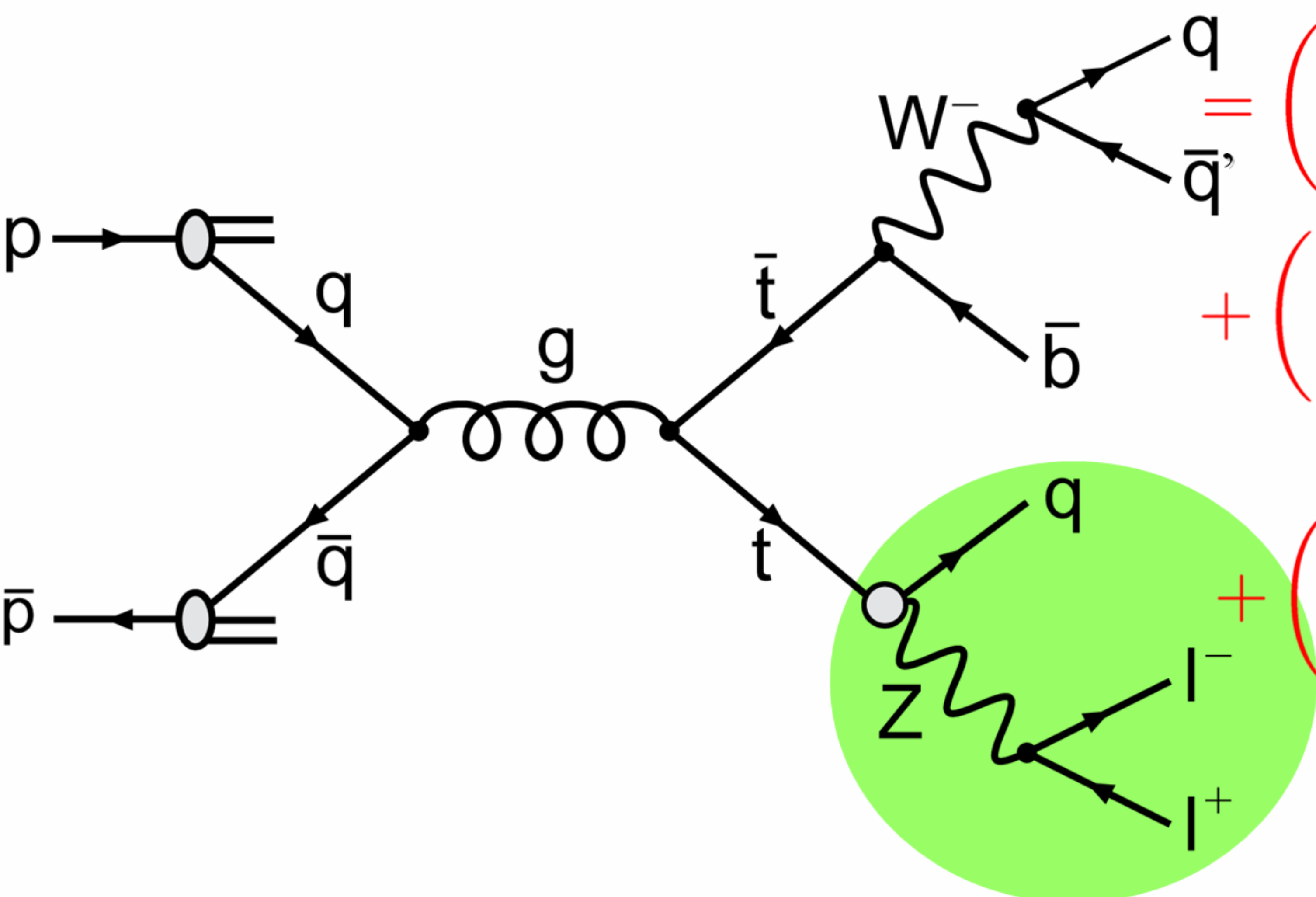

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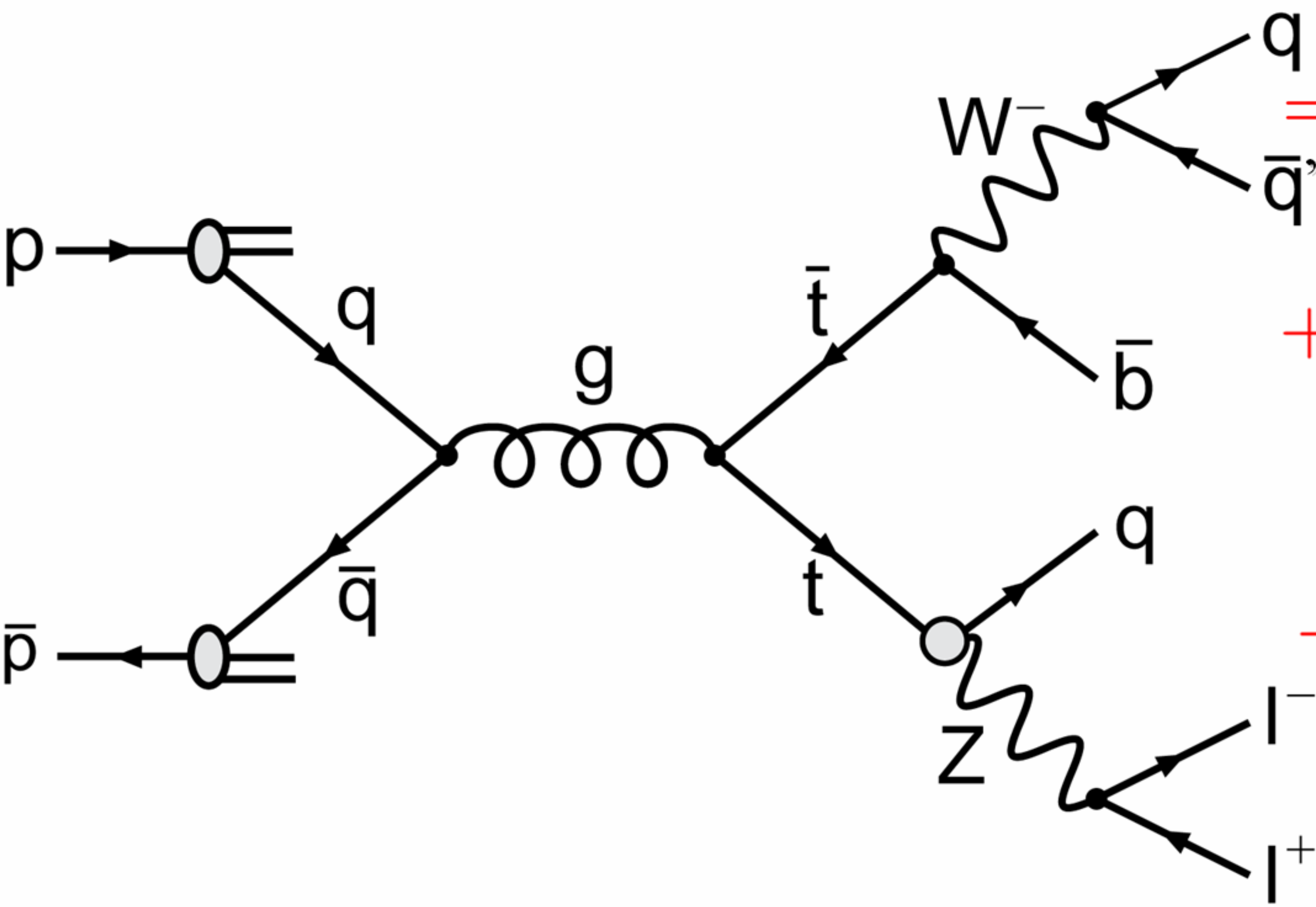

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Top Mass Reconstruction

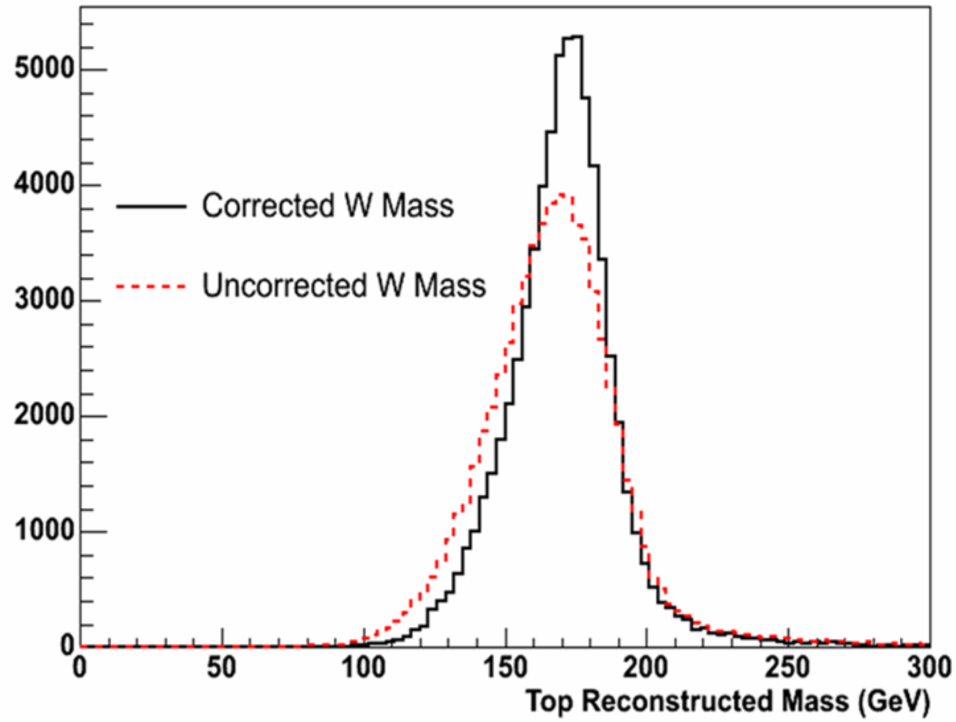
- For our signal, we have three hadronic masses to reconstruct:
  - W mass
  - $t \rightarrow Wb$ mass
  - $t \rightarrow Z\,c$ mass

$t \rightarrow Wb$ mass resolution:

20 GeV ⇒ 16 GeV!

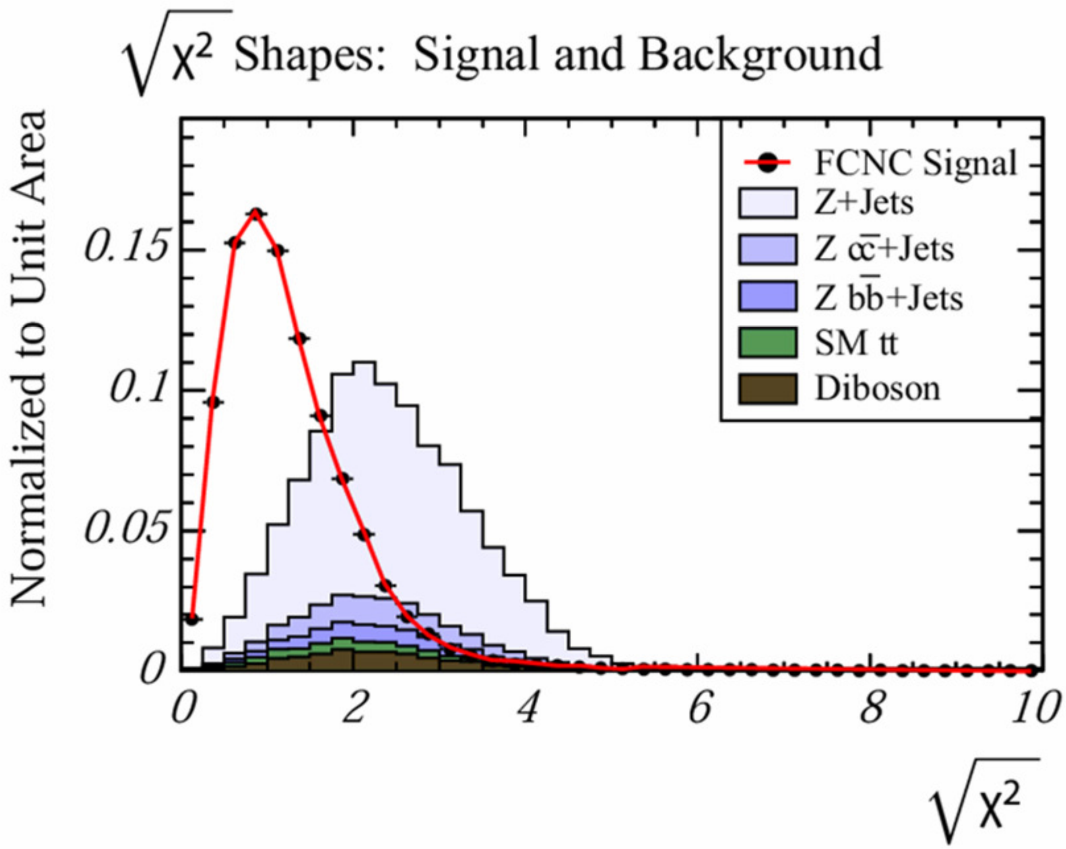
Signal MC with partons correctly matched to reconstructed objects.

- 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.



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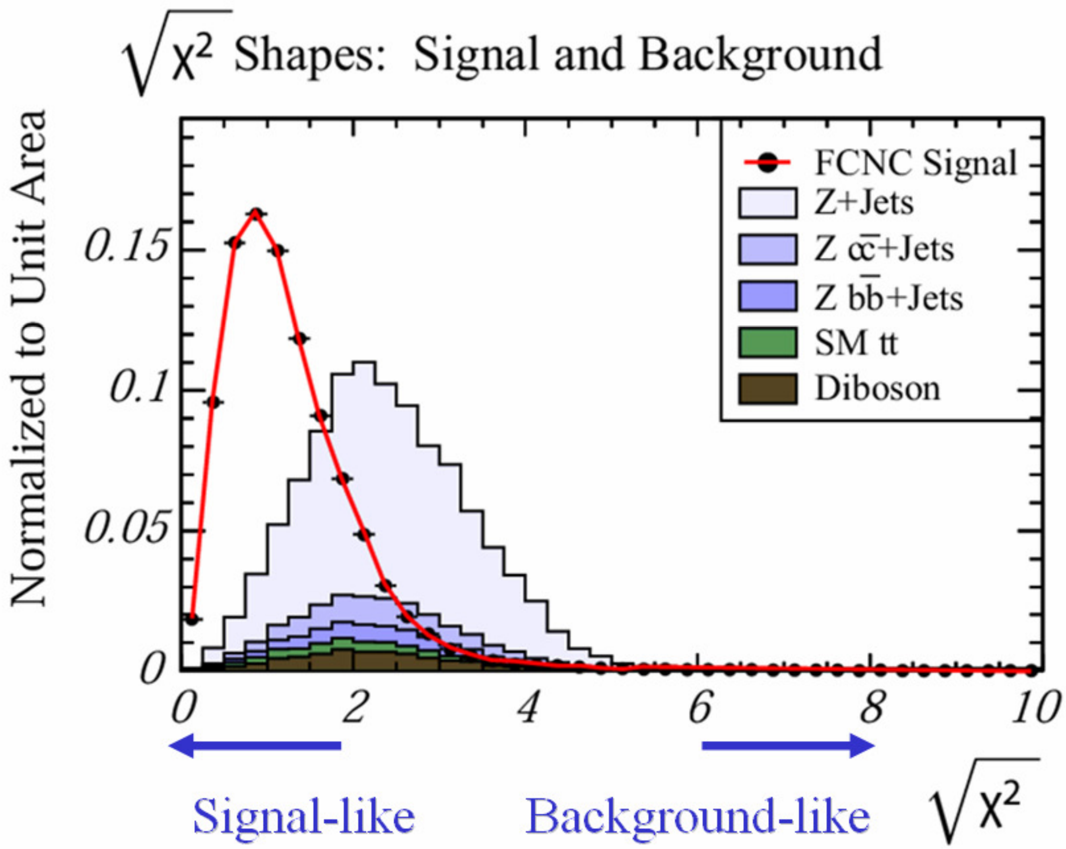

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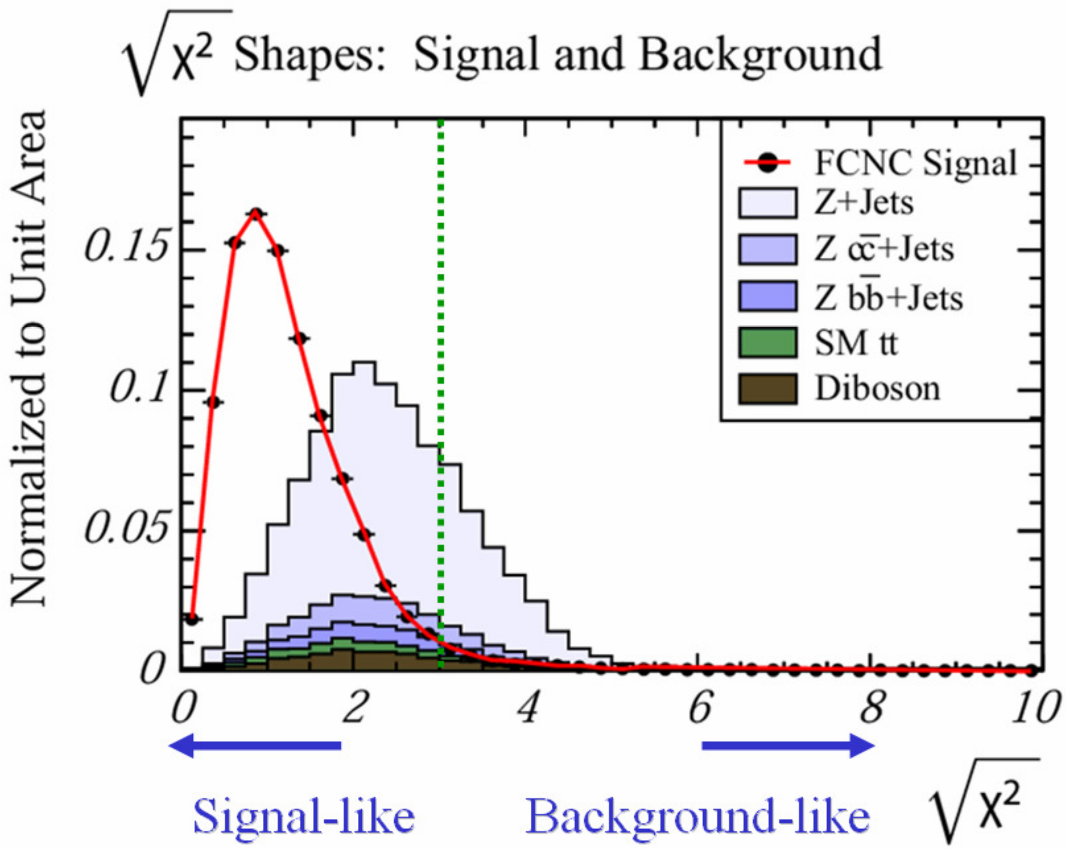

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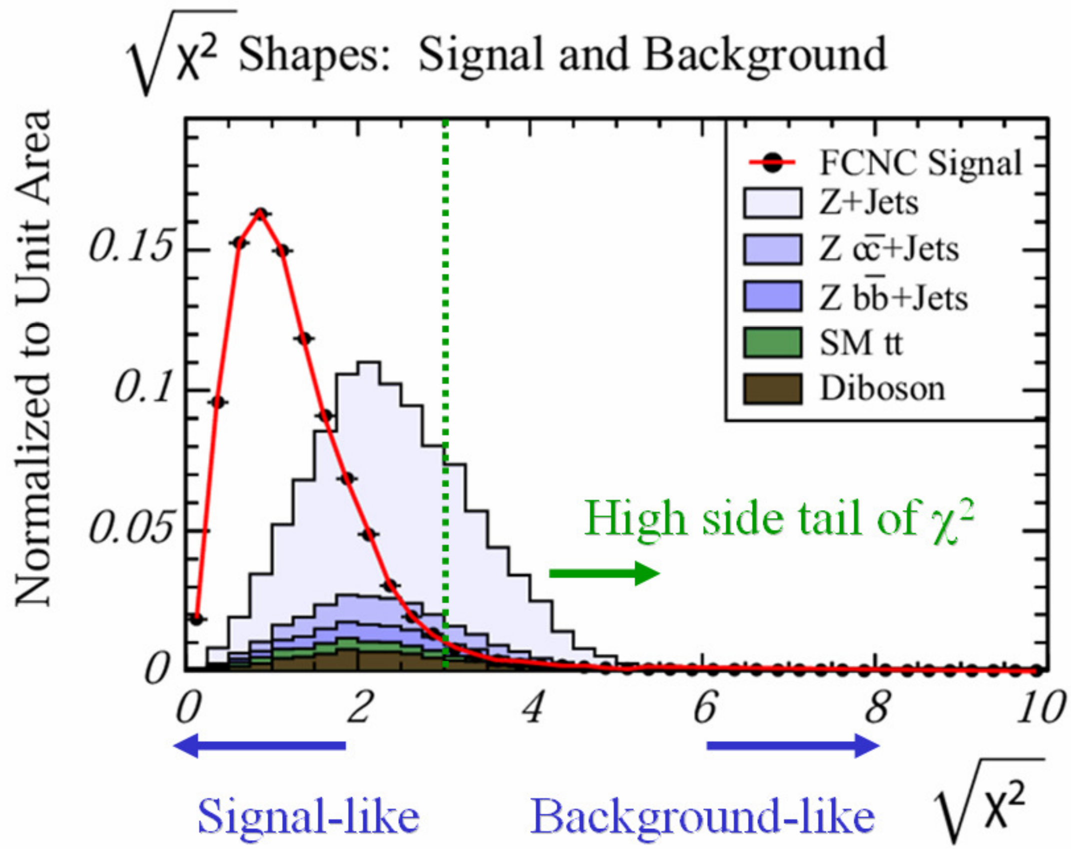

Round 1: Blind Analysis

- 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:
    $\Rightarrow$ Compared expected background to observed events.

Top FCNC Outline

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Unblinding

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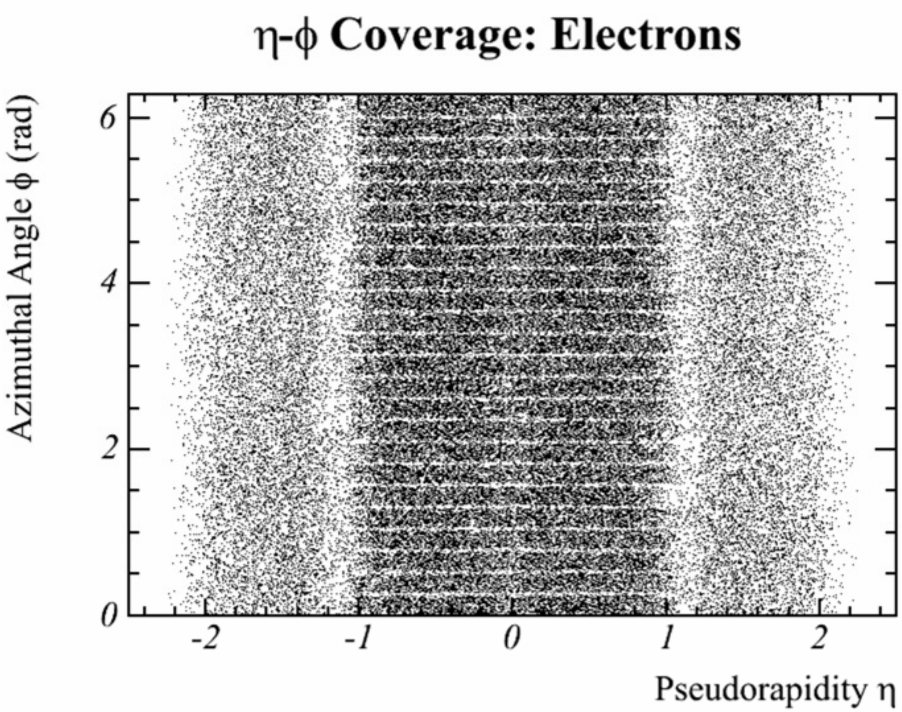
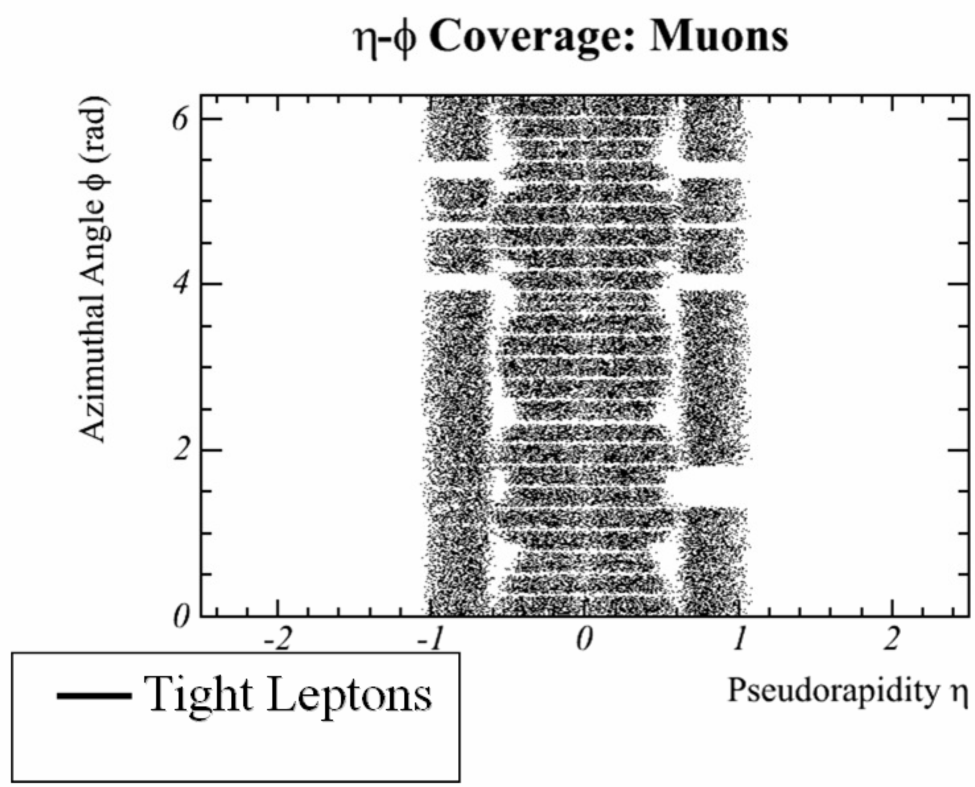
Lepton + Track Z Candidates



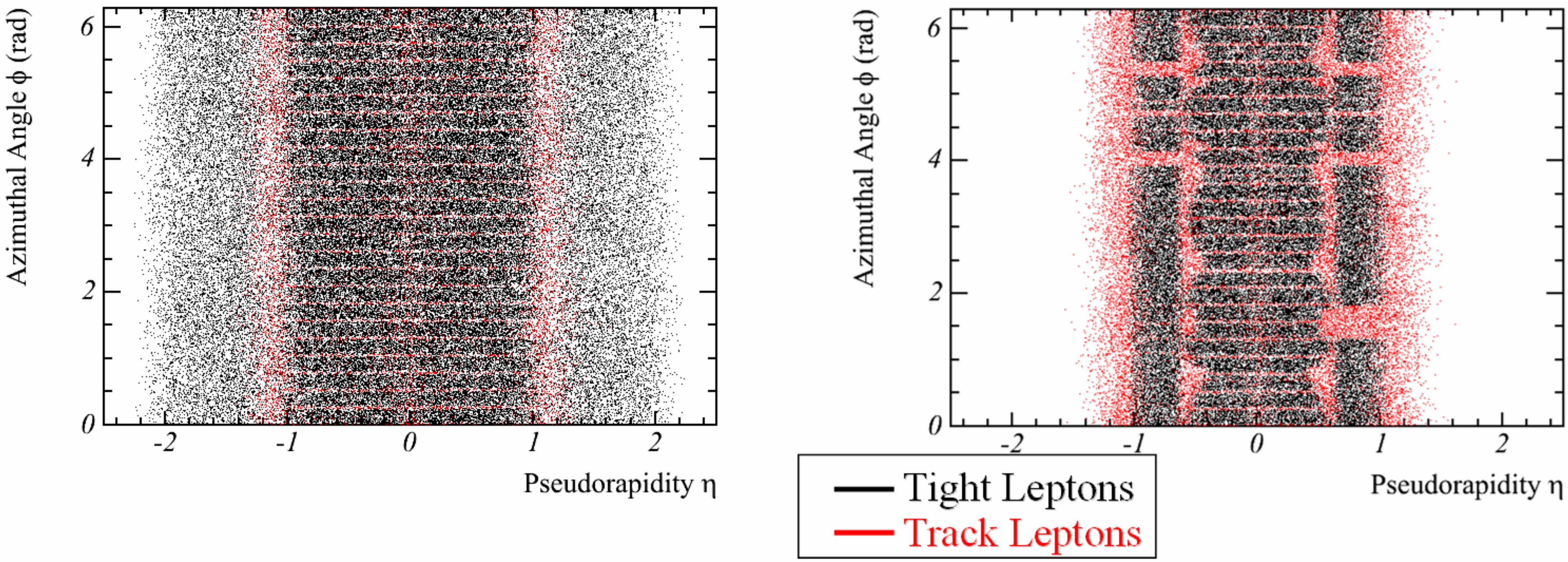


- Use isolated track (instead of tight lepton) for second lepton.
  - Doubles acceptance.
  - Almost all backgrounds have real leptons.

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

Lepton + Track Z Candidates

η-ϕ Coverage: Electrons **η-ϕ Coverage: Muons**



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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%

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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?

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

Acceptance Calculation: Catch 22?

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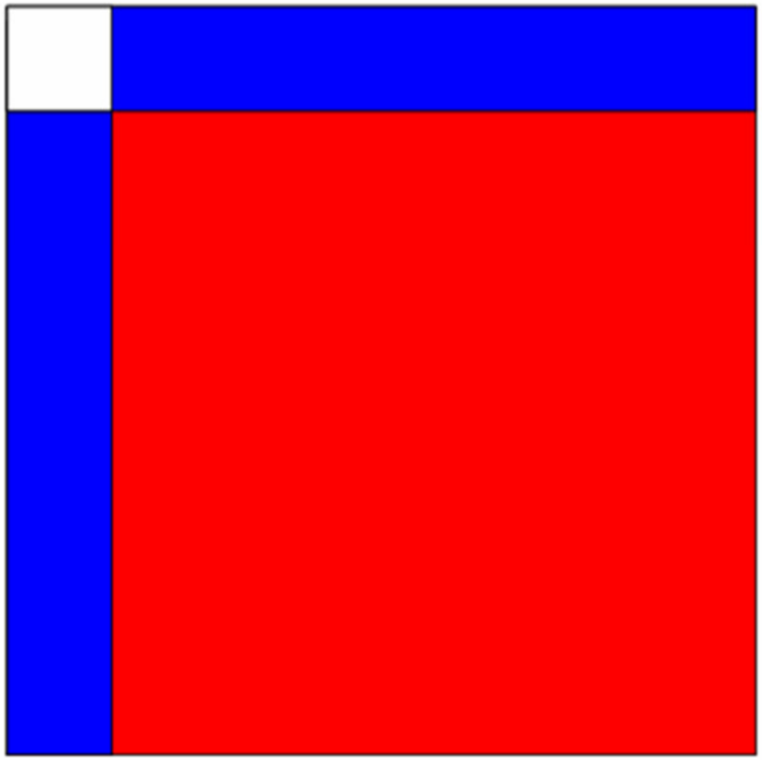
Br (t→Wb) = 86% Br (t→Zc) = 14%



- P(tt̄→WbWb) = 73.96%
- P(tt̄→Wb Zc) = 24.08%
- P(tt̄→Z c Zc) = 1.96%

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 ...

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

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 ($\mathcal{R}_{\text{wz/ww}}$) 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
$\mathcal{A}_{LJ\,\text{ww}}$	$\equiv$	L+J acceptance for SM $t\bar{t}$
$\mathcal{A}_{LJ\,\text{wz}}$	$\equiv$	L+J acceptance for FCNC
$\mathcal{A}_{LJ\,\text{zz}}$	$\equiv$	L+J acceptance for FCNC
$K_{ZZ/WZ}$	$\equiv$	$\mathcal{A}_{ZZ} / \mathcal{A}_{WZ}$
$\mathcal{R}_{\text{wz/ww}}$	$\equiv$	$\mathcal{A}_{LJ\,\text{wz}} / \mathcal{A}_{LJ\,\text{ww}}$
$\mathcal{R}_{\text{zz/ww}}$	$\equiv$	$\mathcal{A}_{LJ\,\text{zz}} / \mathcal{A}_{LJ\,\text{ww}}$

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 $\mathcal{B}_Z$
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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

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Standard Model Top Pair Production

- Small background: no real Z, need extra jets from gluon radiation and/or "fake lepton."

- Dilepton channel
($t\bar{t} \to$ Wb Wb $\to$ lνb lνb):
dilepton invariant mass can fall into Z mass window.

- Lepton + Jets channel
($t\bar{t} \to$ Wb Wb $\to$ lνb qq'b):
misreconstruct one jet as a lepton ("fake"), invariant mass of lepton and fake lepton can fall into Z mass window.

- Large fraction of heavy flavor jets: more important in b-tagged samples.

- Estimated from MC simulation.

Expected Backgrounds

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

- Standard model processes that can mimic $Z + \geq 4$ jets signature:
  - Z+Jets: Z boson production in association with jets $\rightarrow$ dominant background for top FCNC search, most difficult to estimate
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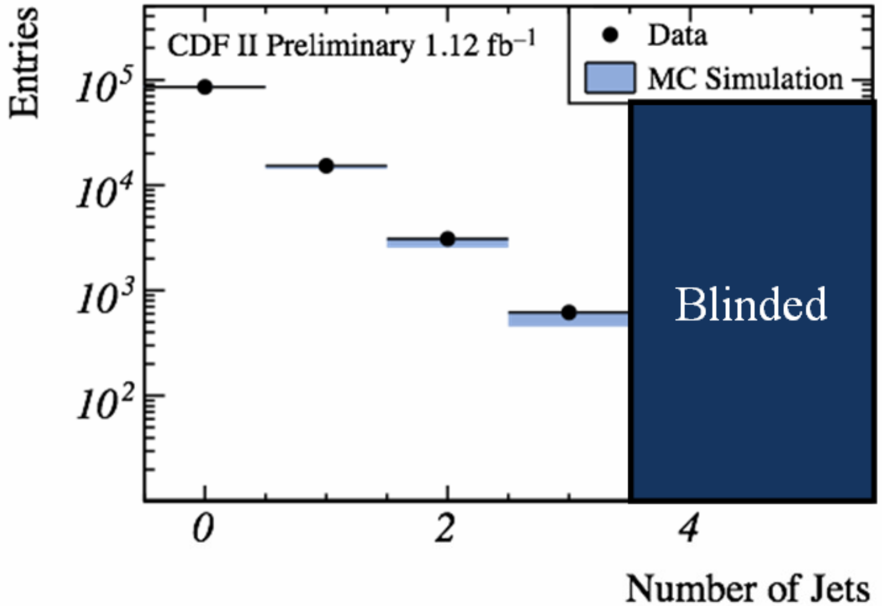
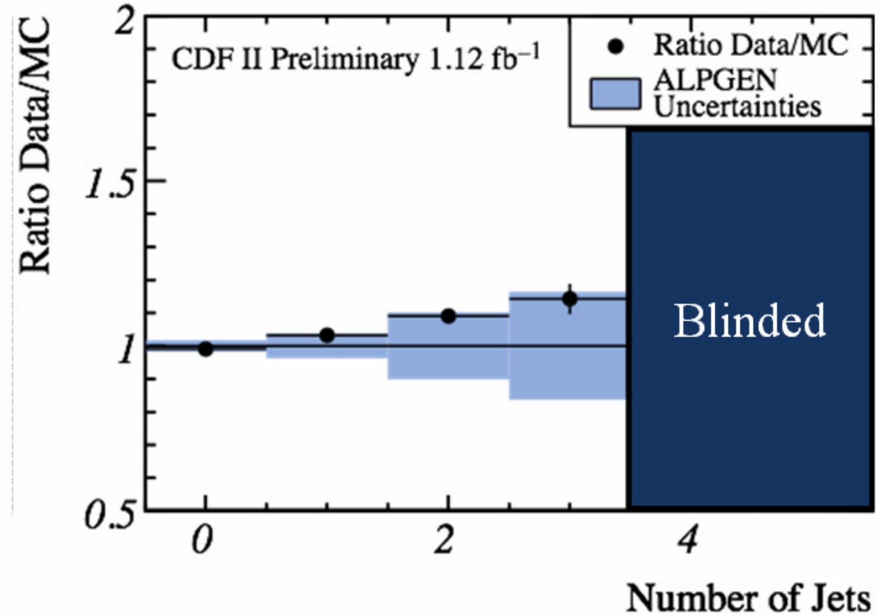
Diboson Production: WZ, ZZ

- Small background (similar in size to standard model tt production).
- Small cross section but real Z.
- Need extra jets from gluon radiation.
- ZZ: Heavy flavor contribution from $Z \rightarrow bb$ decay.
- Estimated from MC simulation.

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.

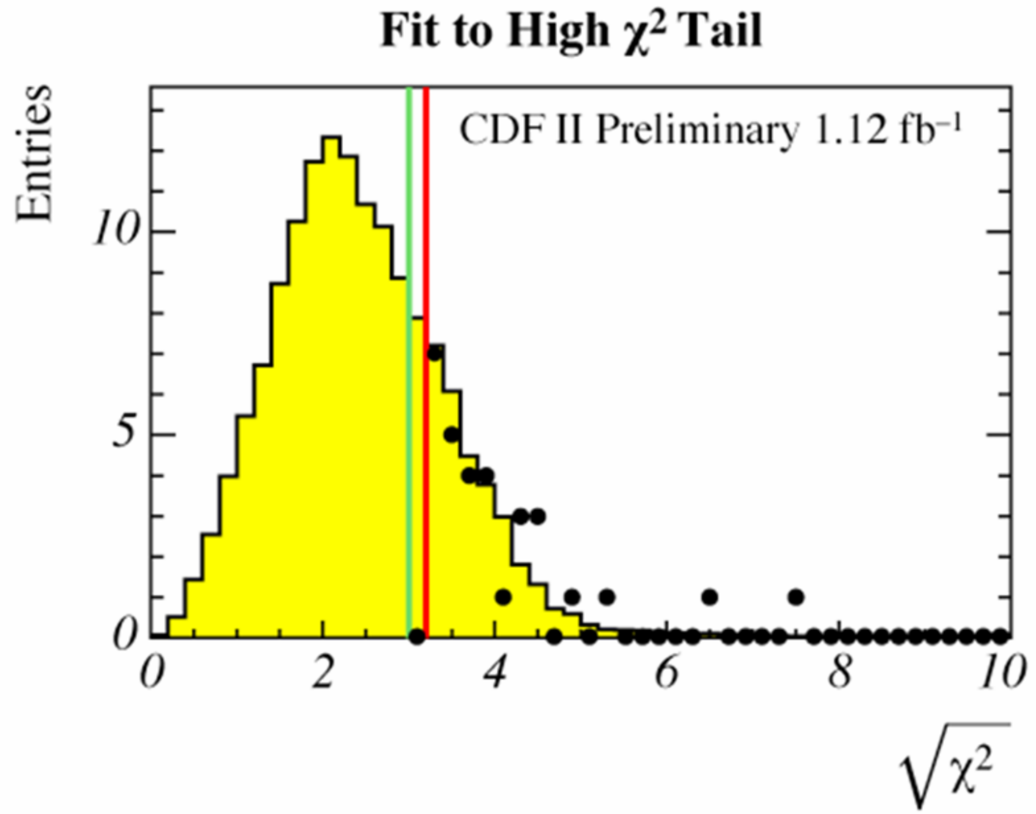




Base Selection Background Estimate

- 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.



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	$\in [76,106]\,\mathrm{GeV}/c^2$
Leading Jet E_T	$\geq 40\,\mathrm{GeV}$
Second Jet E_T	$\geq 30\,\mathrm{GeV}$
Third Jet E_T	$\geq 20\,\mathrm{GeV}$
Fourth Jet E_T	$\geq 15\,\mathrm{GeV}$
Transverse Mass	$\geq 200\,\mathrm{GeV}$
$\sqrt{\chi^2}$	< 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:
$6.8\% \pm 2.9\%$

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

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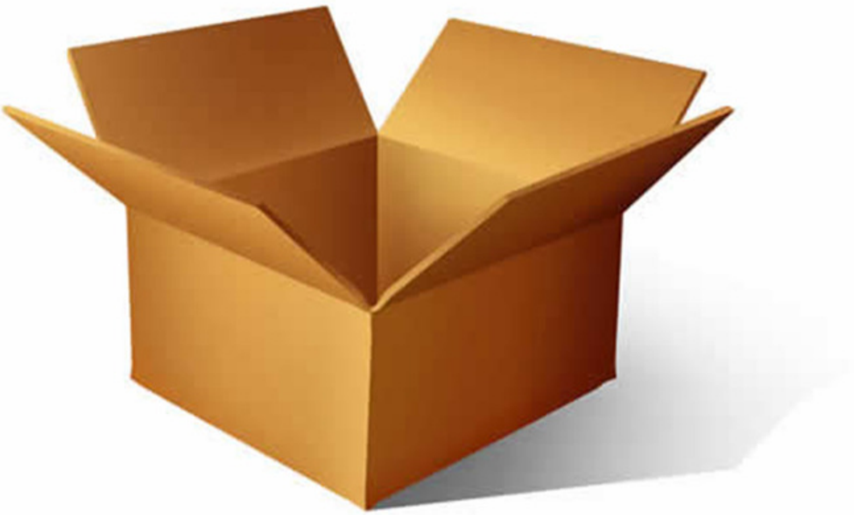
- So far, so good… Let's open the box!



Open the Signal Box

- Opening the box with 1.1 fb^{-1}
  - Event yield consistent with background only.
  - Fluctuated about 1σ high: slightly *"unlucky."*

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

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

  - Expected limit: 6.8% ± 2.9%.

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

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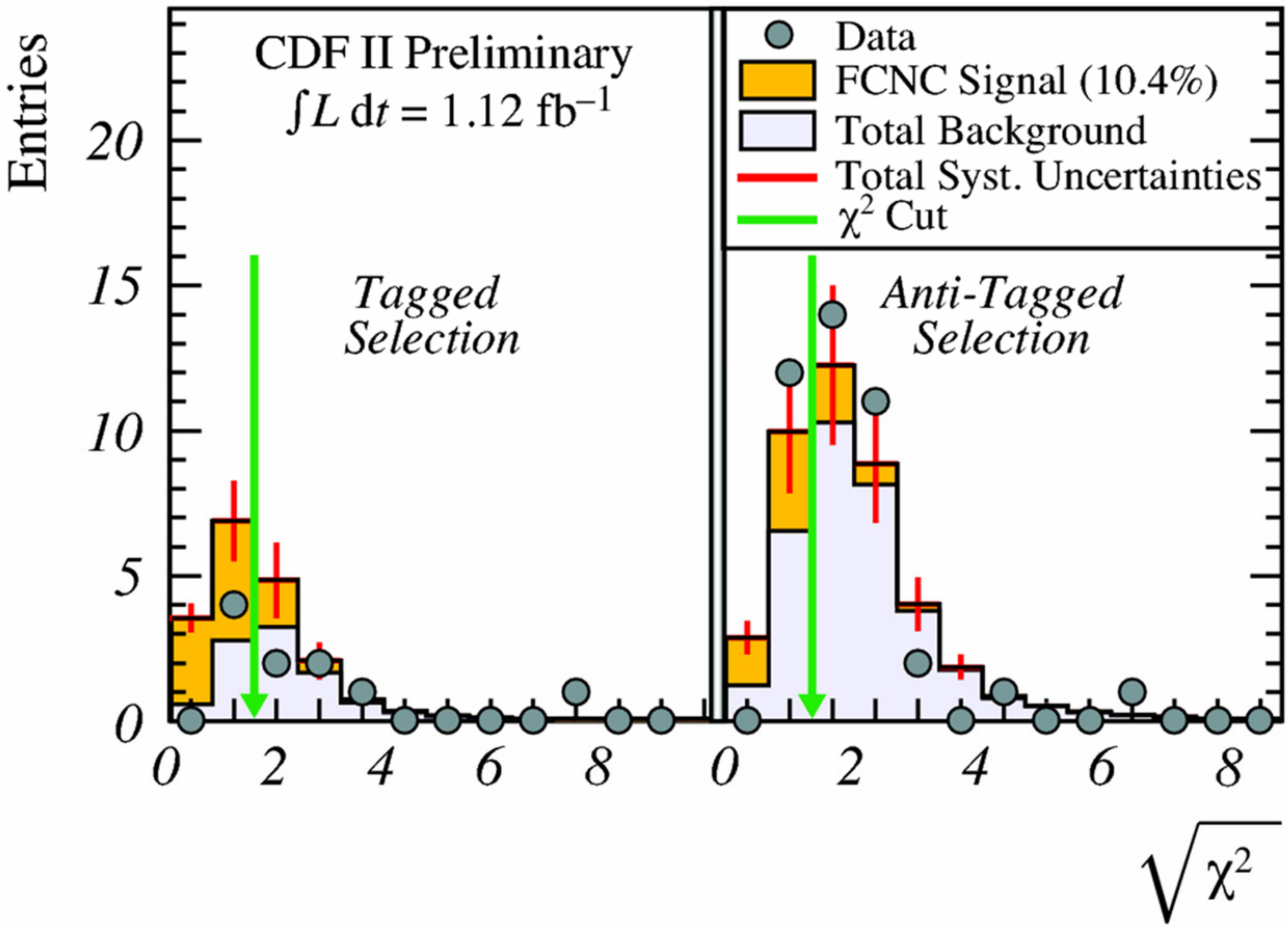
Mass χ^2 (95% C.L. Upper Limit)



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Round 2: Is That The Best We Can Do?

- More $\int \mathcal{L}dt$:
  - 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

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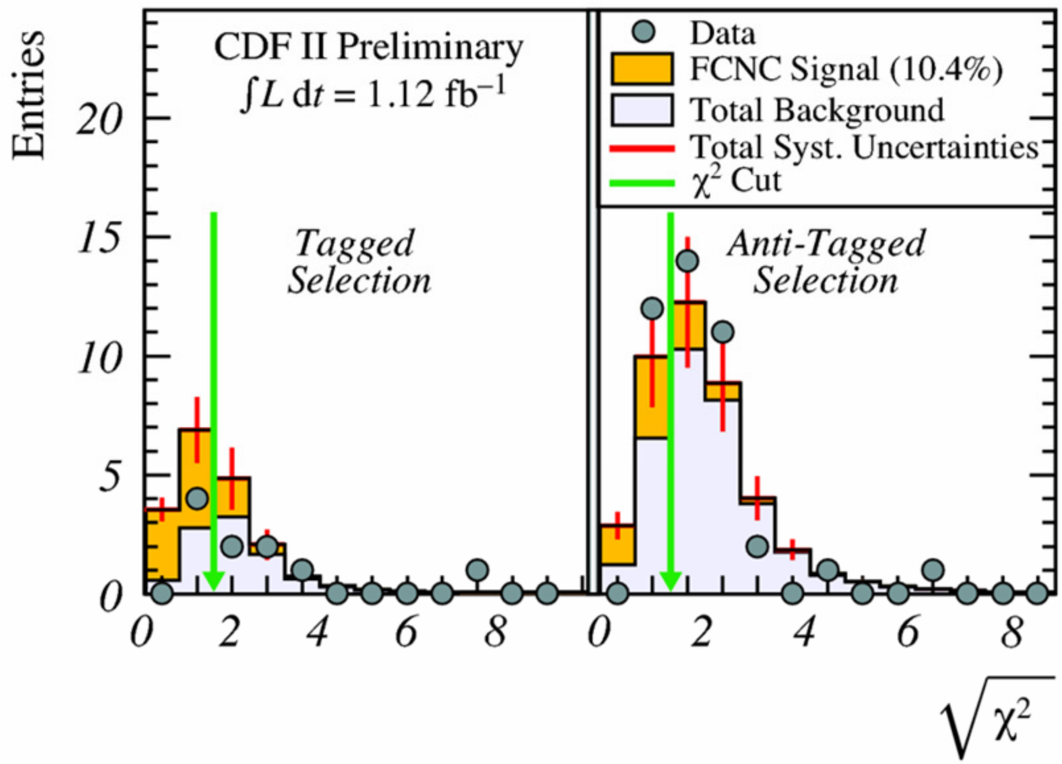


Differences From Counting Experiment

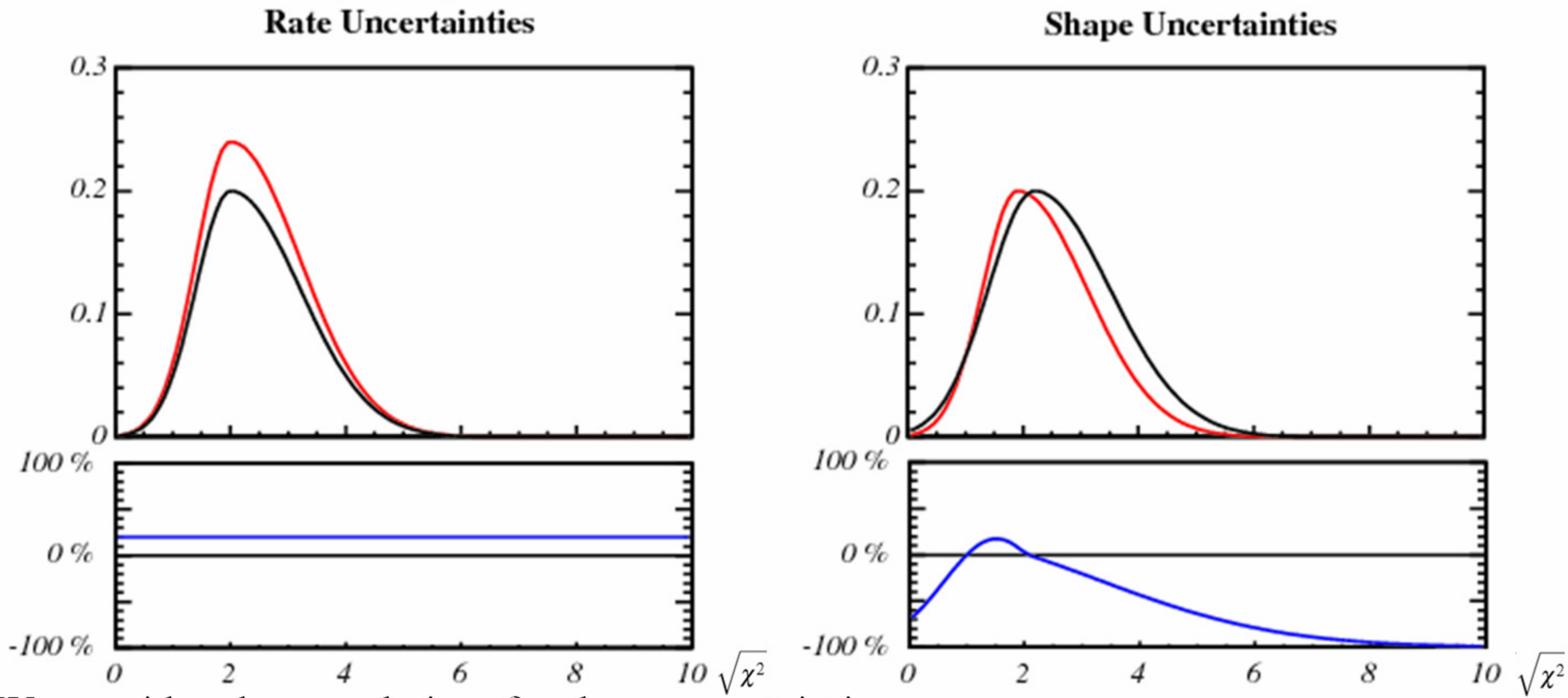
- Advantages:
  - Absolute estimation of Z + jets background is difficult. This drove the counting experiment.
  - Since we are fitting:
    - No absolute Z + jets background estimation needed.
    - No estimate of Z + jets tagging fraction needed.

  ⇒ 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

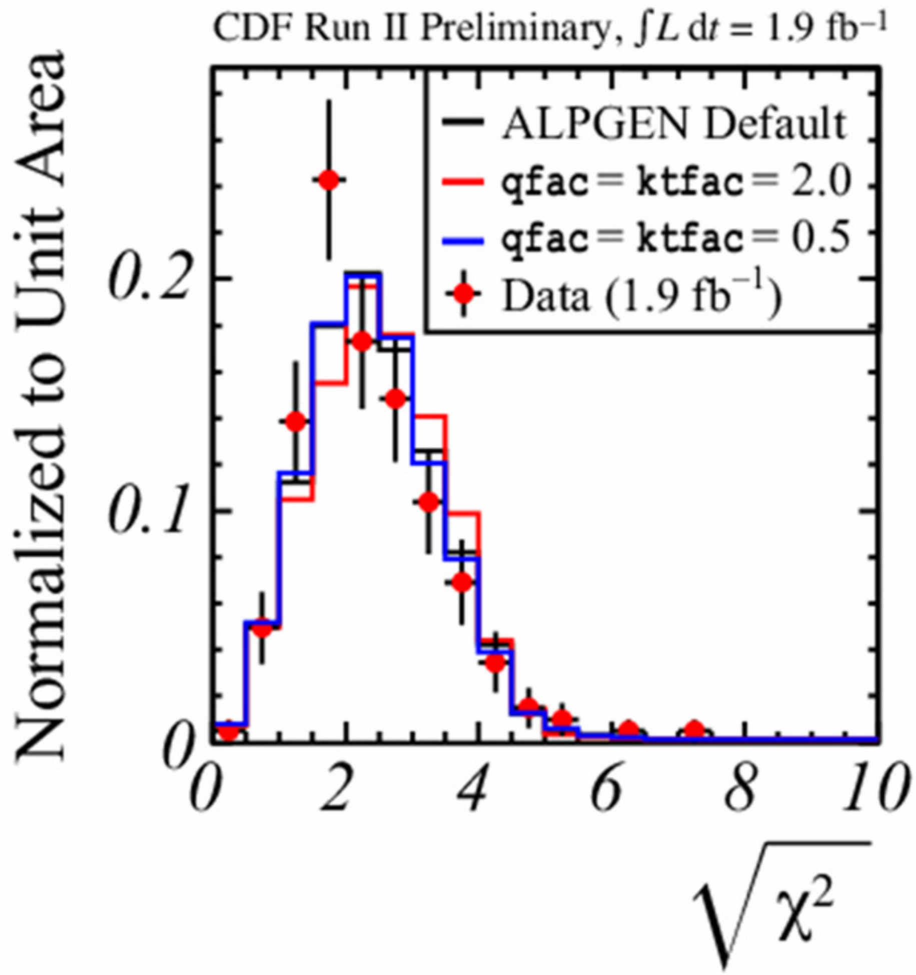
- ALPGEN: two Q^2 "knobs" to turn.
  - Factorization/renormalization scale:

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

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

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

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

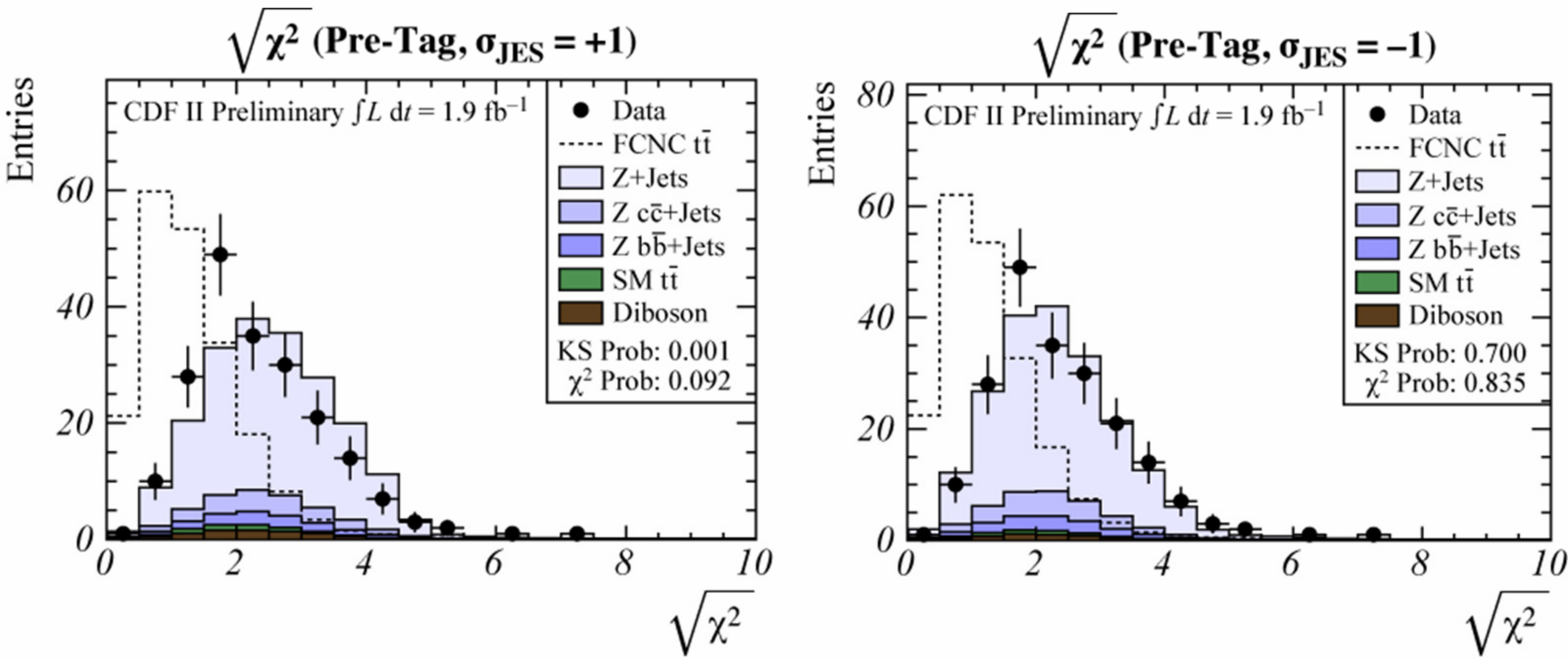


Shape Uncertainties: JES

- 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, …



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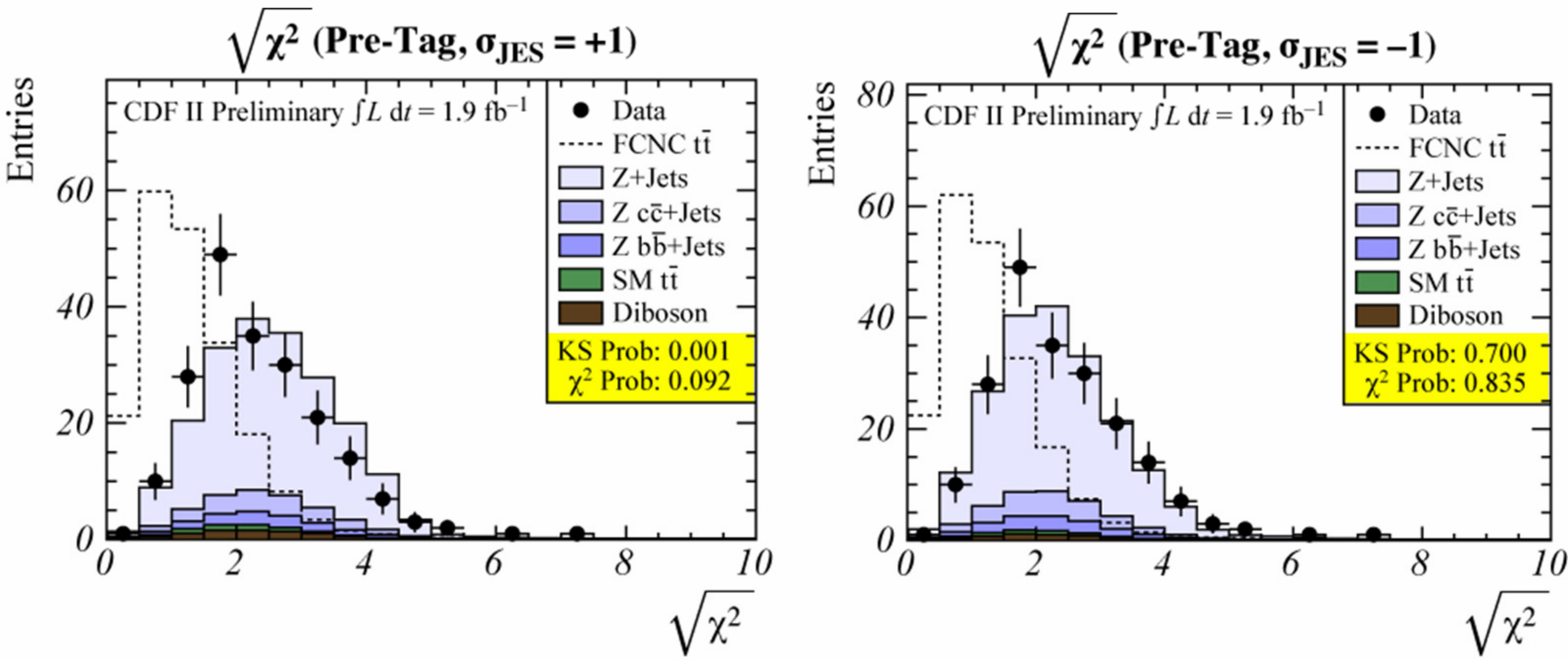
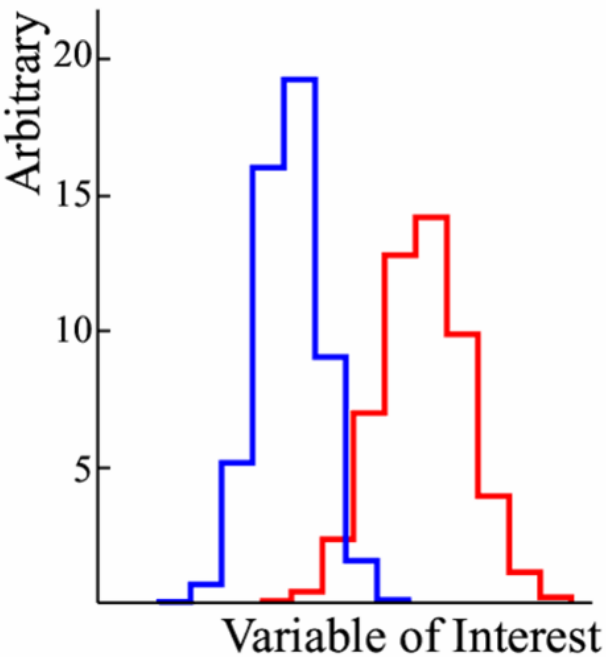


Template Morphing

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

- Horizontal morphing is simply interpolating between two normalized cumulative distribution functions (*i.e.*, the normalized integral of the histogram).



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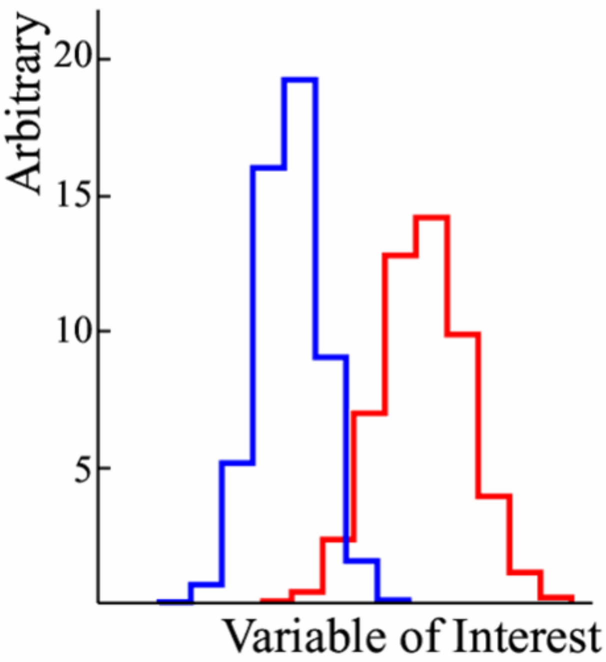

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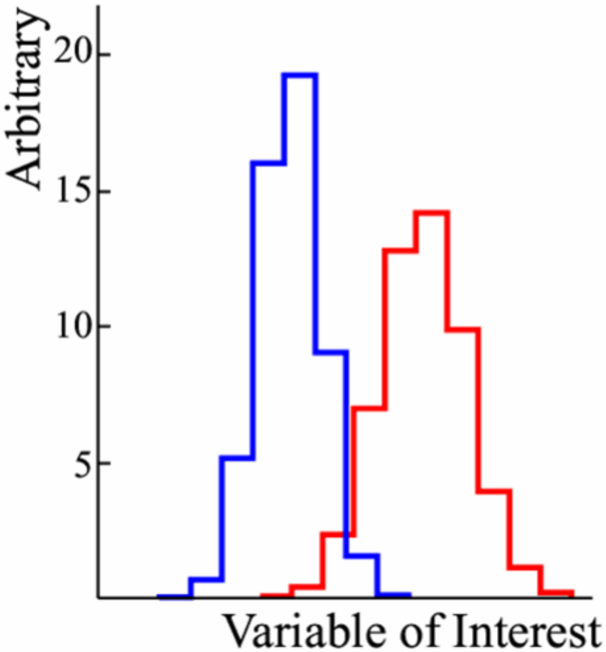

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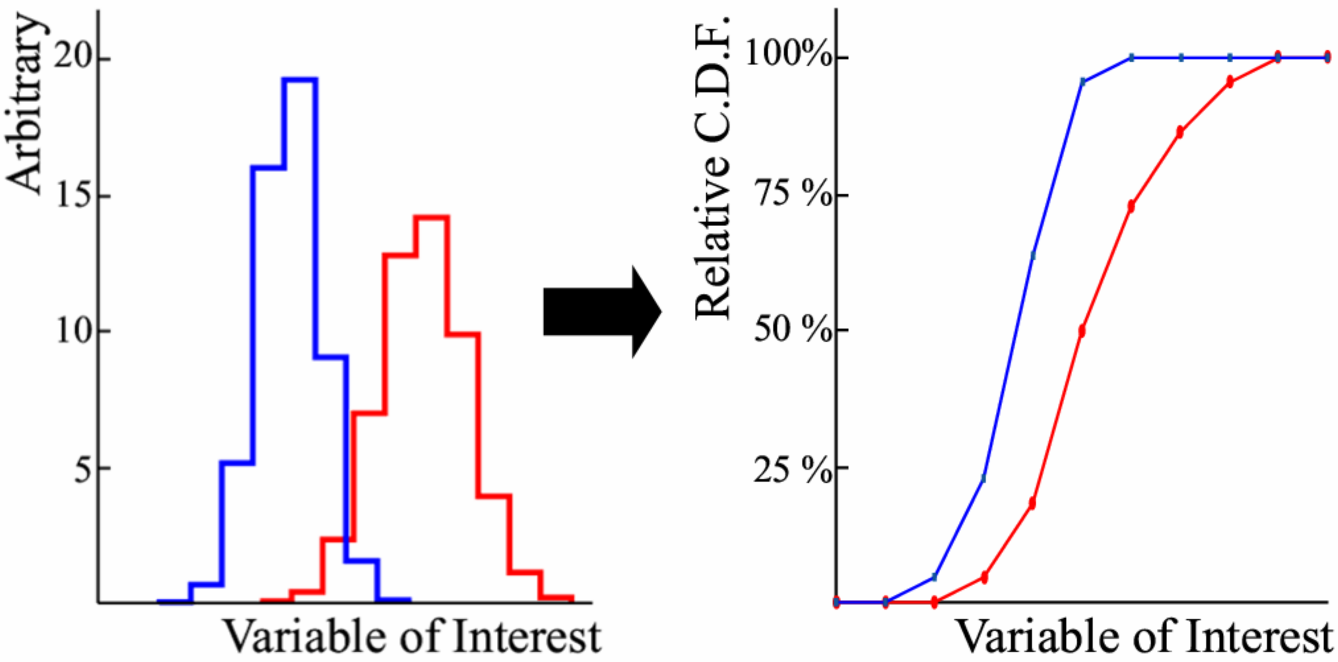

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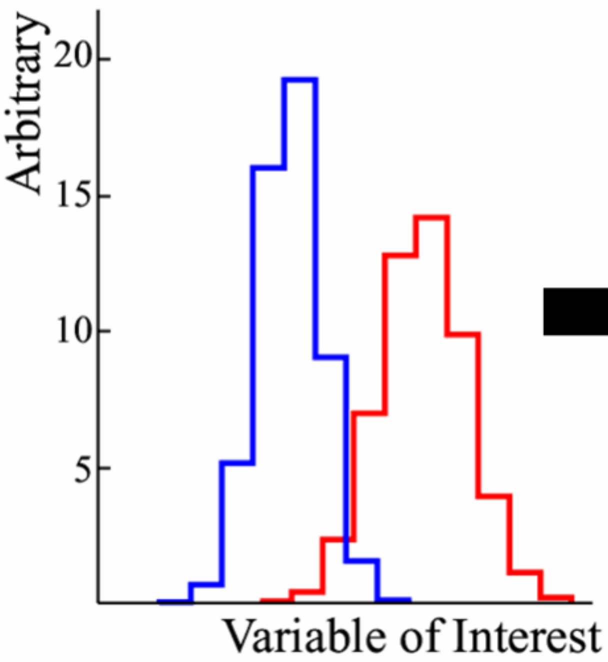

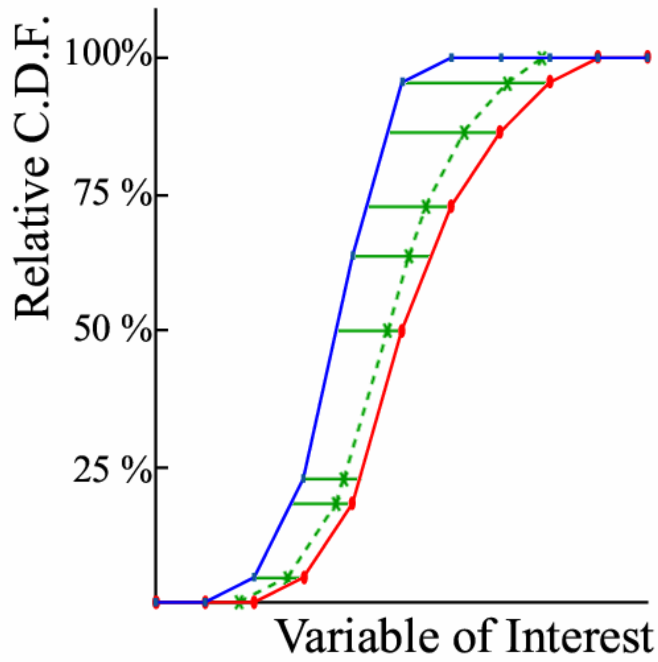

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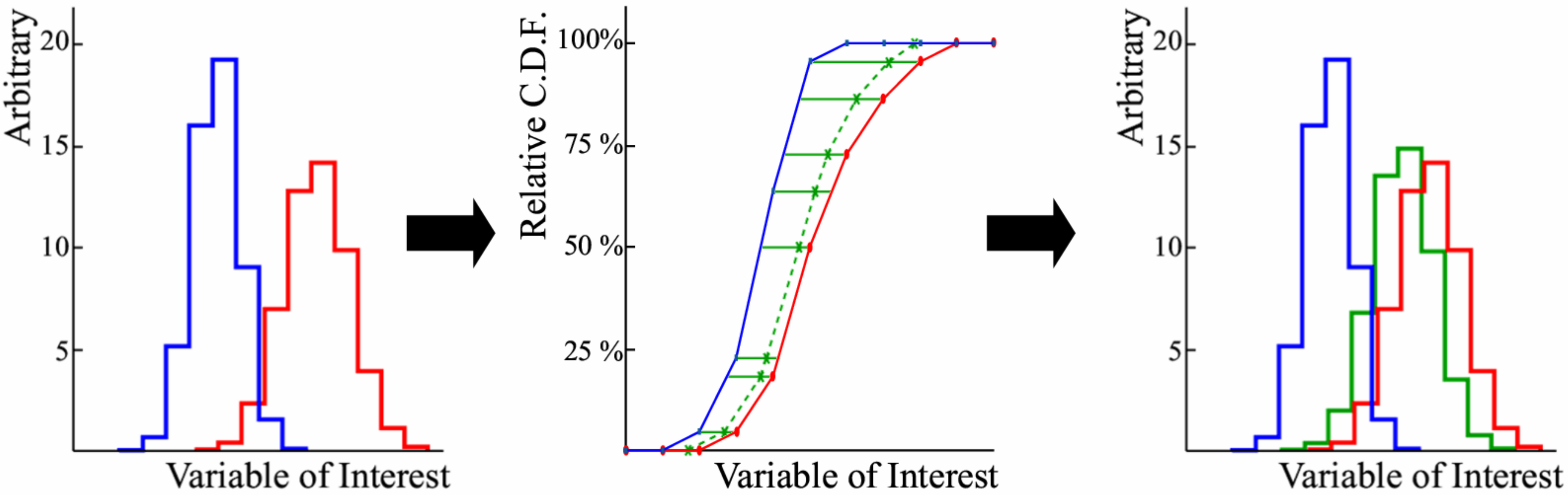
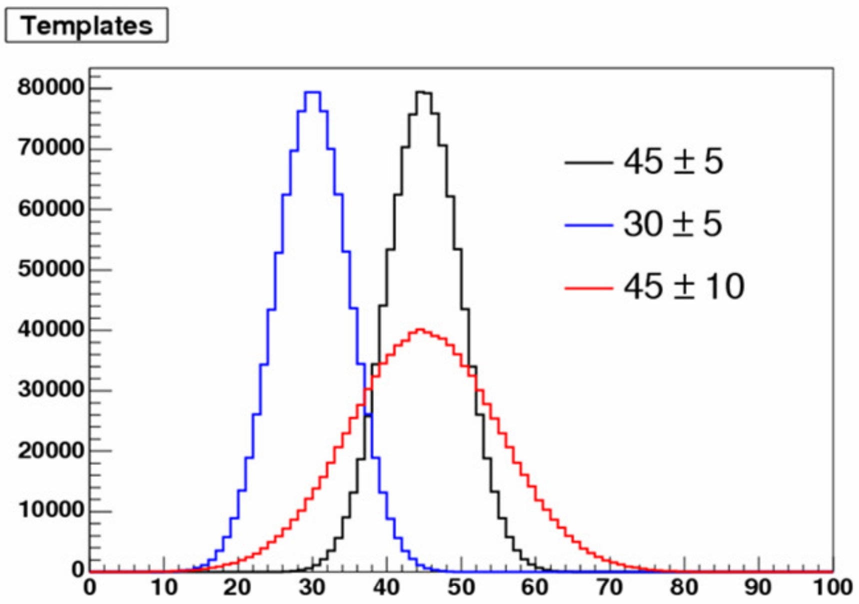
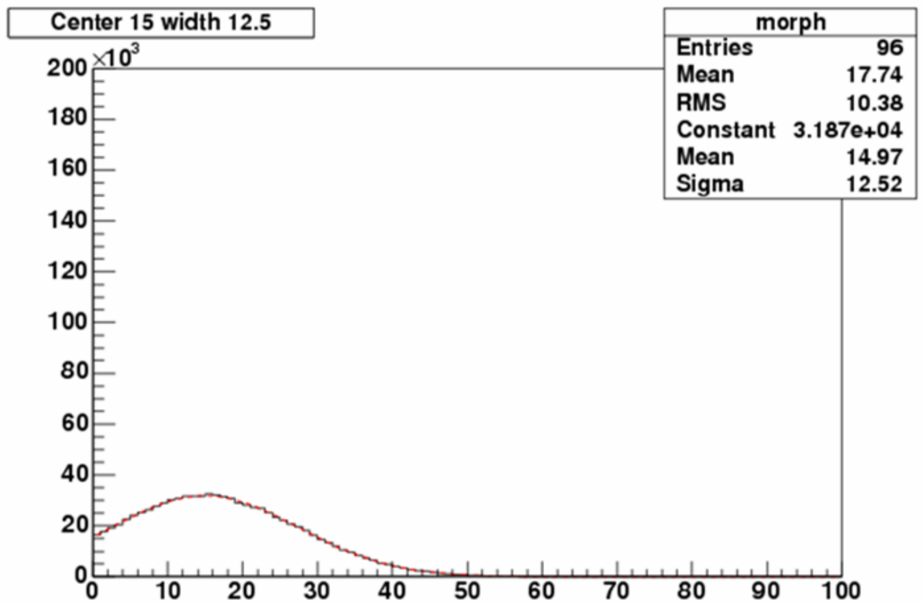


Does Morphing Work?

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





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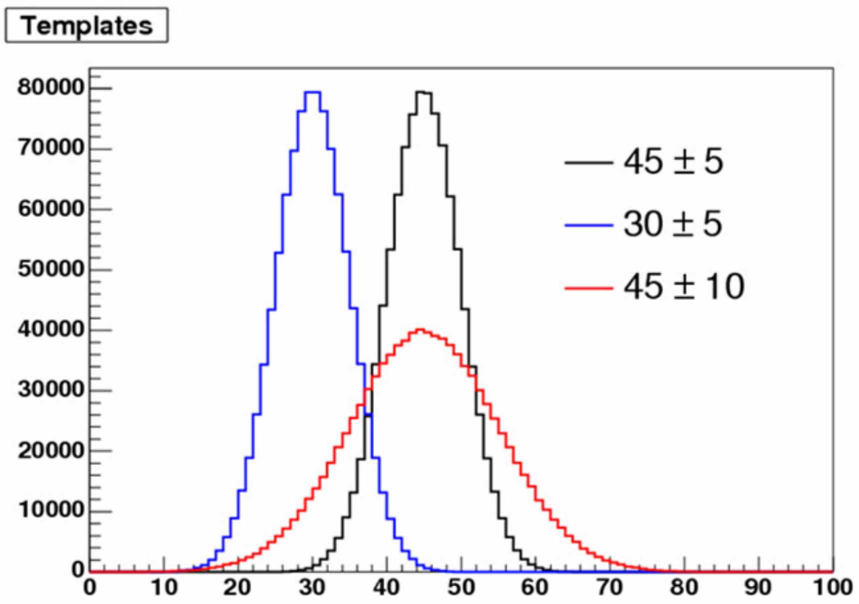
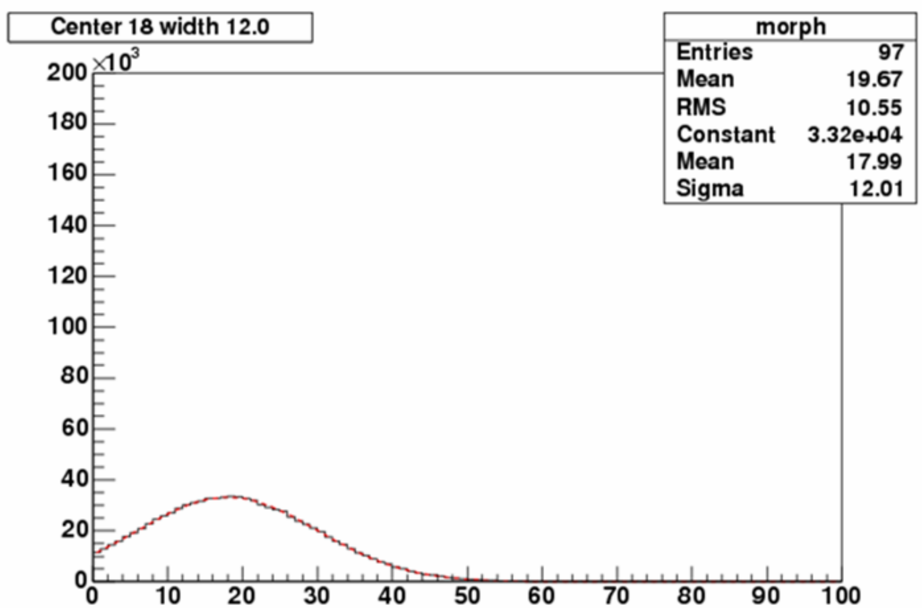
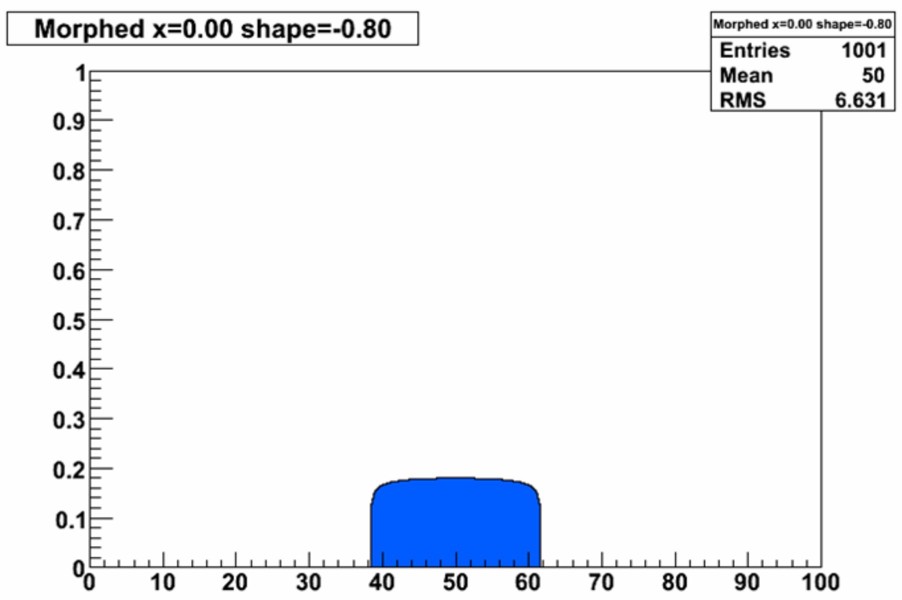


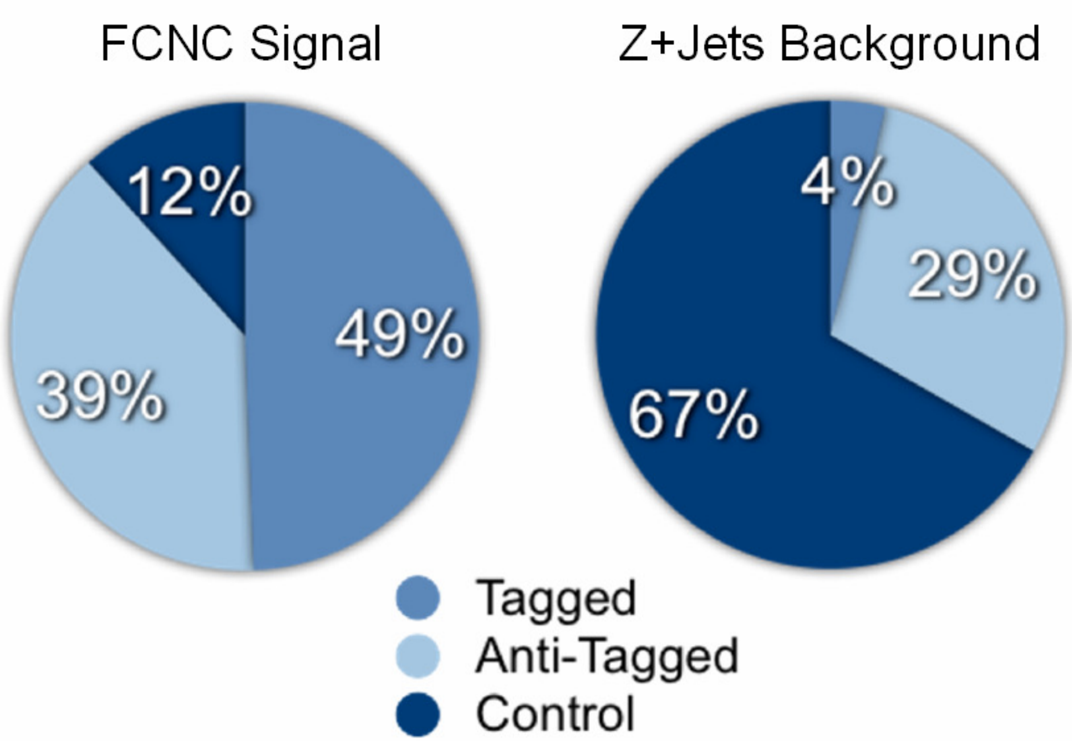




Signal and Control Regions

- *"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	≥ 200 GeV
Leading Jet	≥ 40 GeV
Second Jet	≥ 30 GeV
Third Jet	≥ 20 GeV
Fourth Jet	≥ 15 GeV



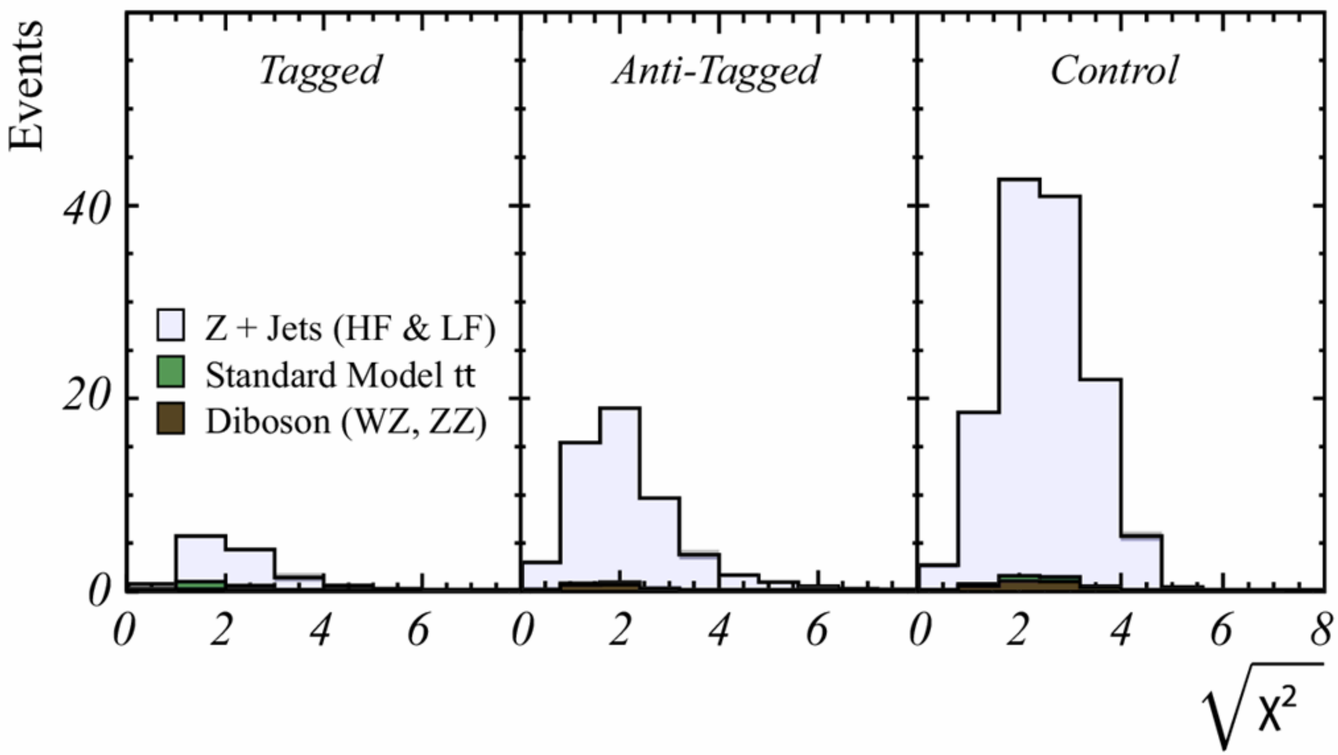
Constraining Z + Jets Background

- 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



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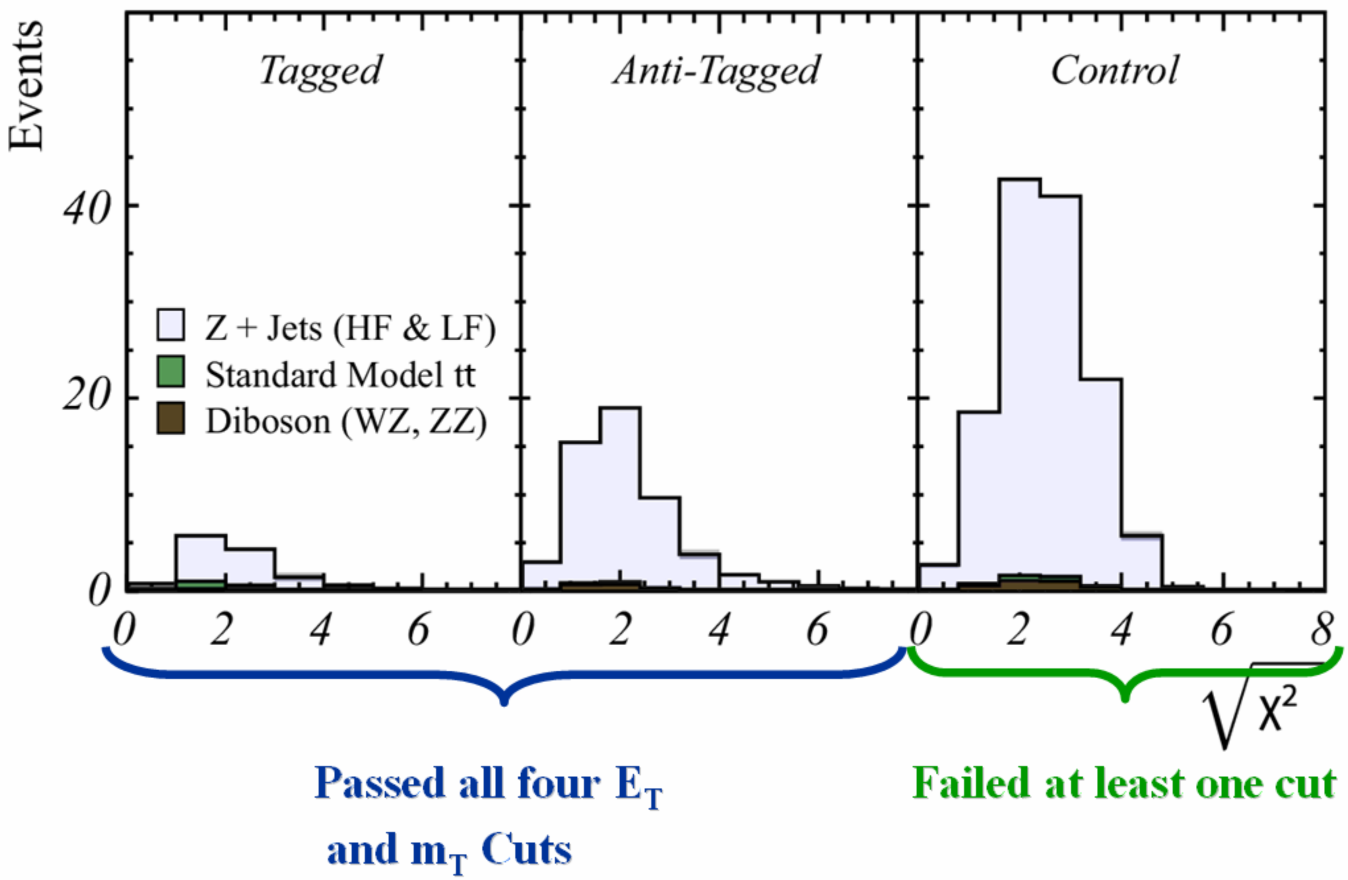

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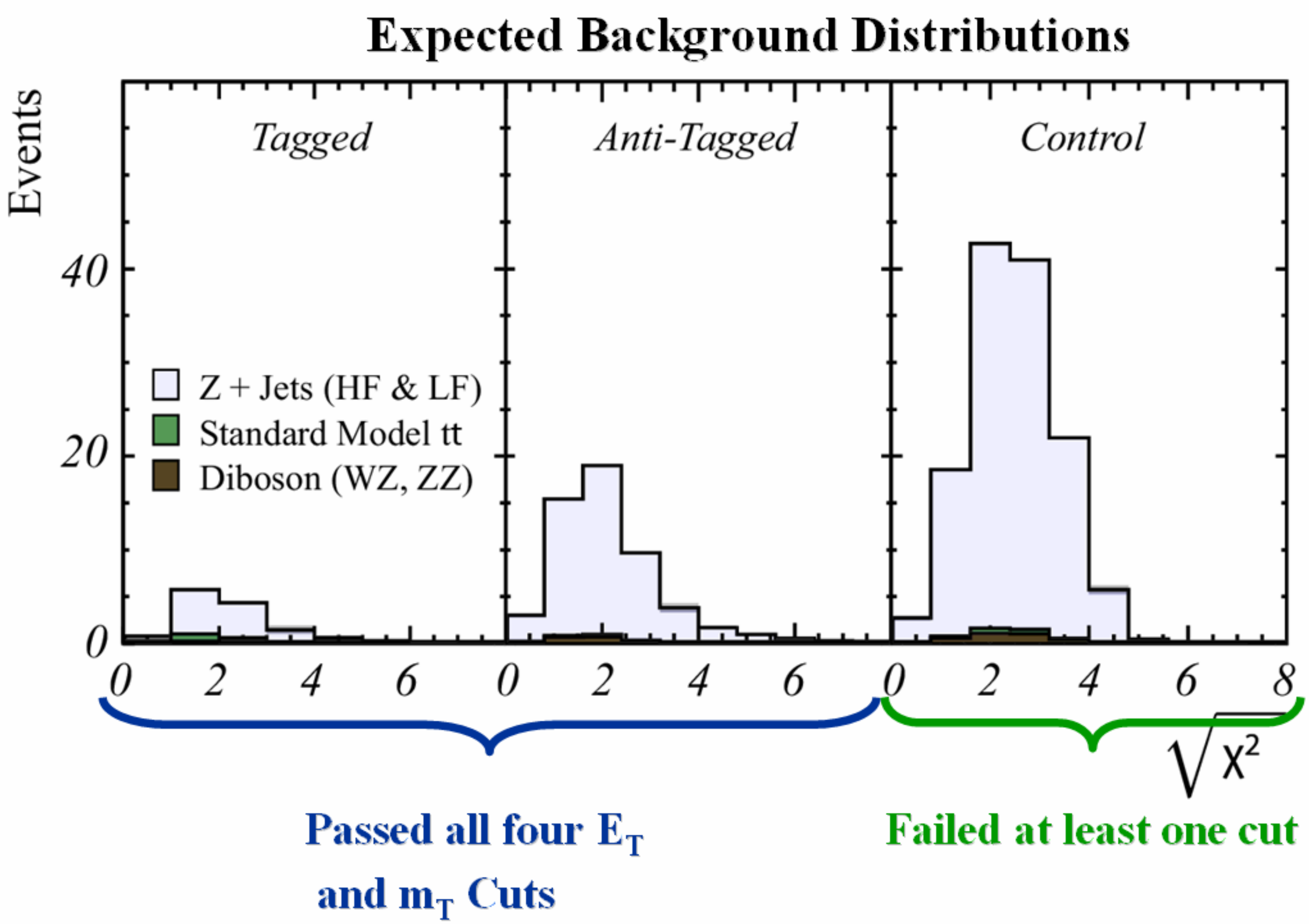

$\mathscr{R}_{sig} \equiv$ Ratio of Z + jets in the signal regions to the control region.

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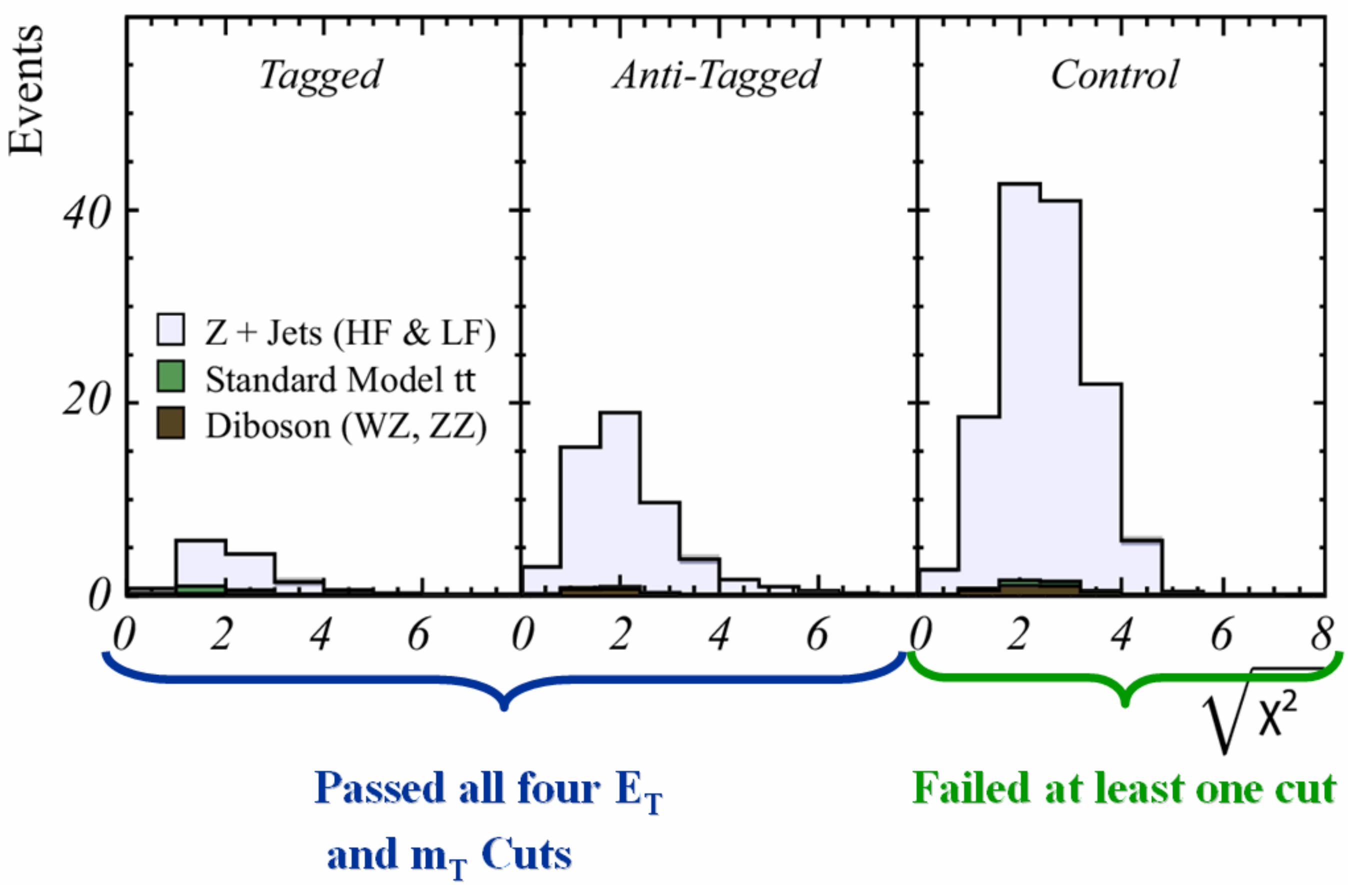

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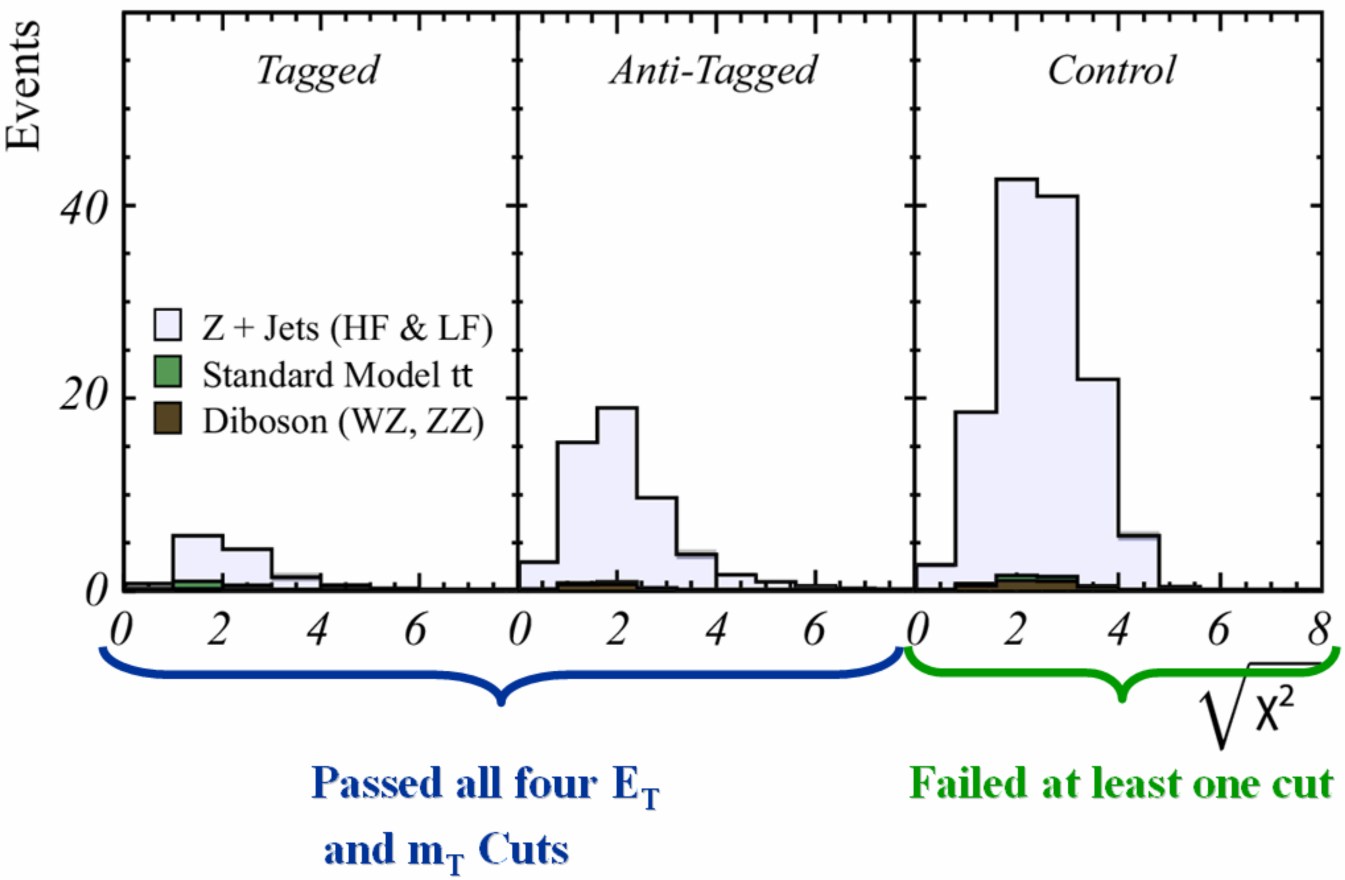

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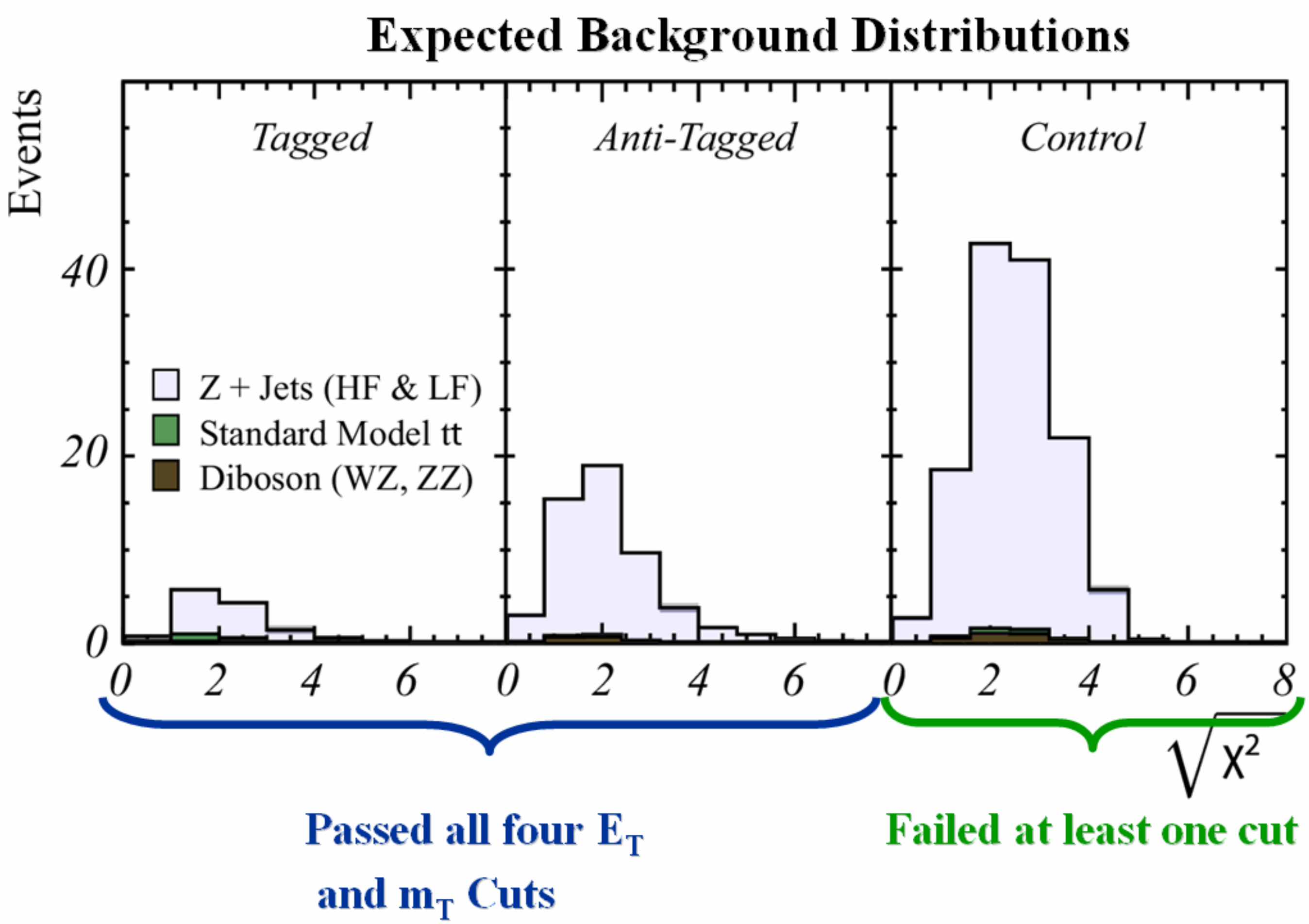

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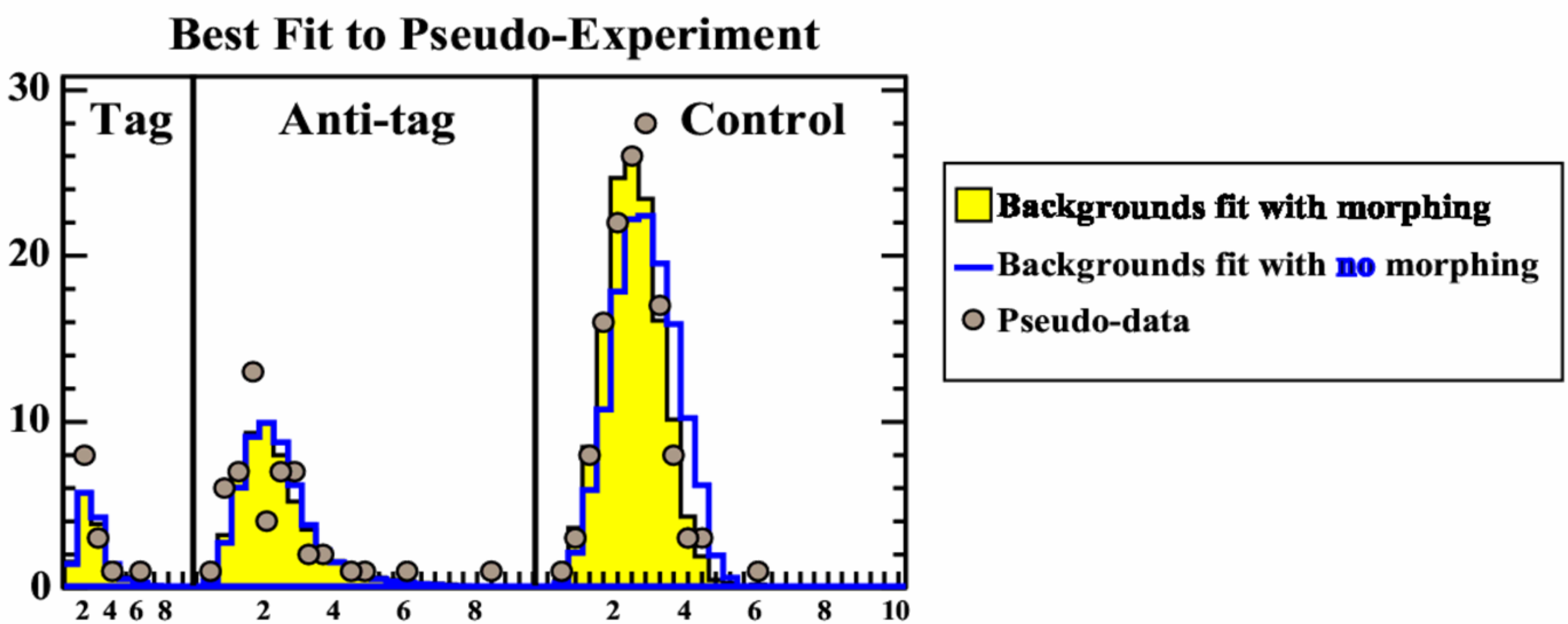
⇒ No constraint!

Fitting χ^2 Roundup

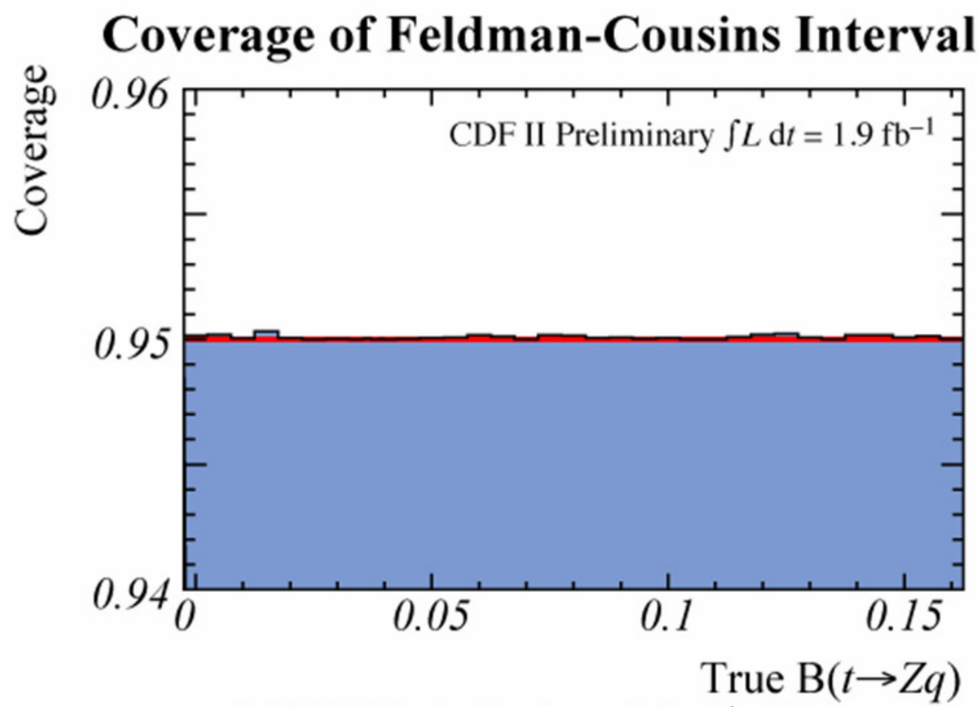
- No absolute Z + jet background estimate needed.
- For the template fit, we need to deal with shape uncertainties.
  - Find dominant sources ⇒ JES
  - Morphing of JES templates in fitter.
- Do not want to *"morph away"* a real signal ⇒ Control region.
  - Use control region also for Z + jet constraints.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



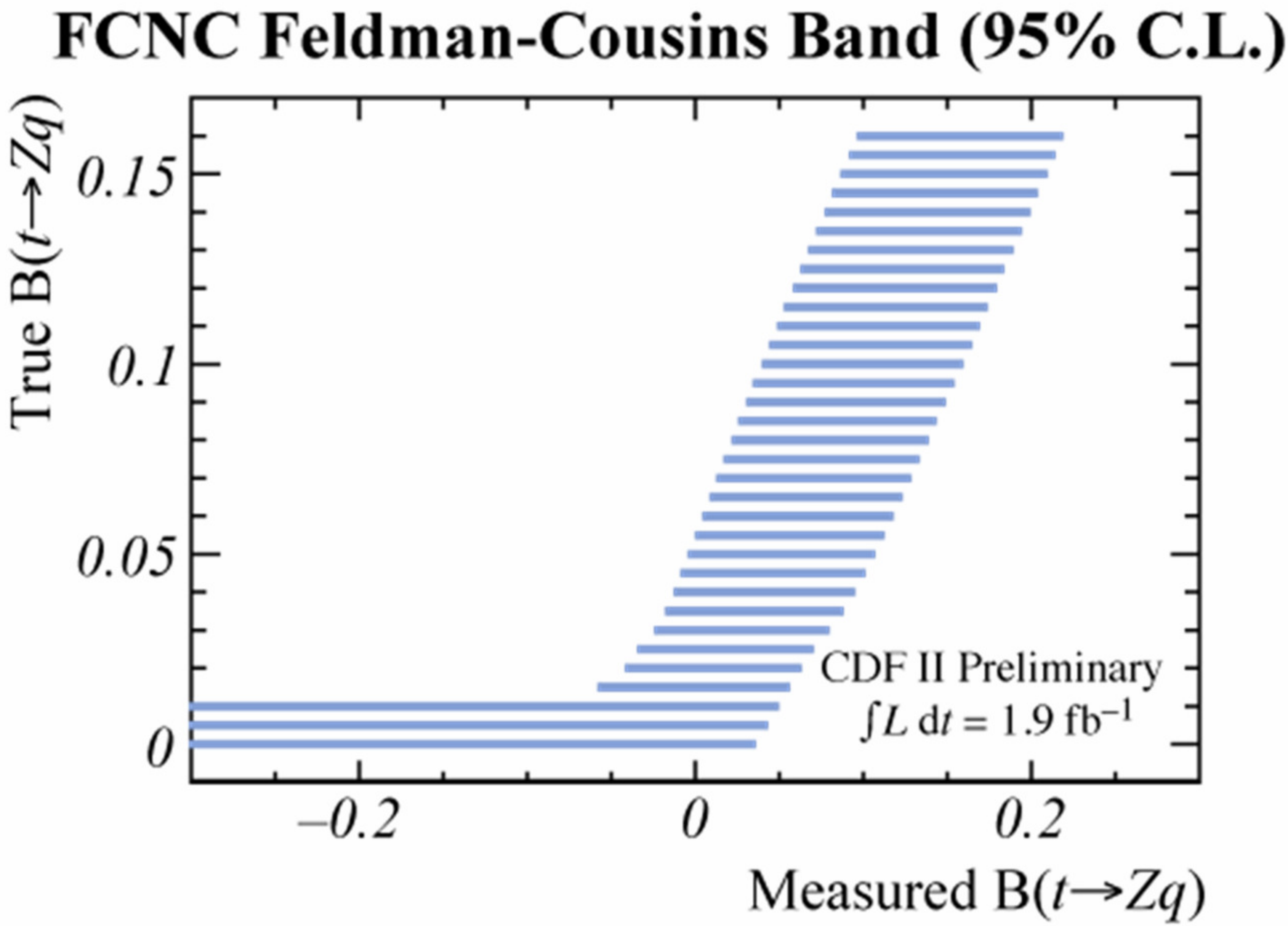
Feldman-Cousins in Five Minutes

- 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



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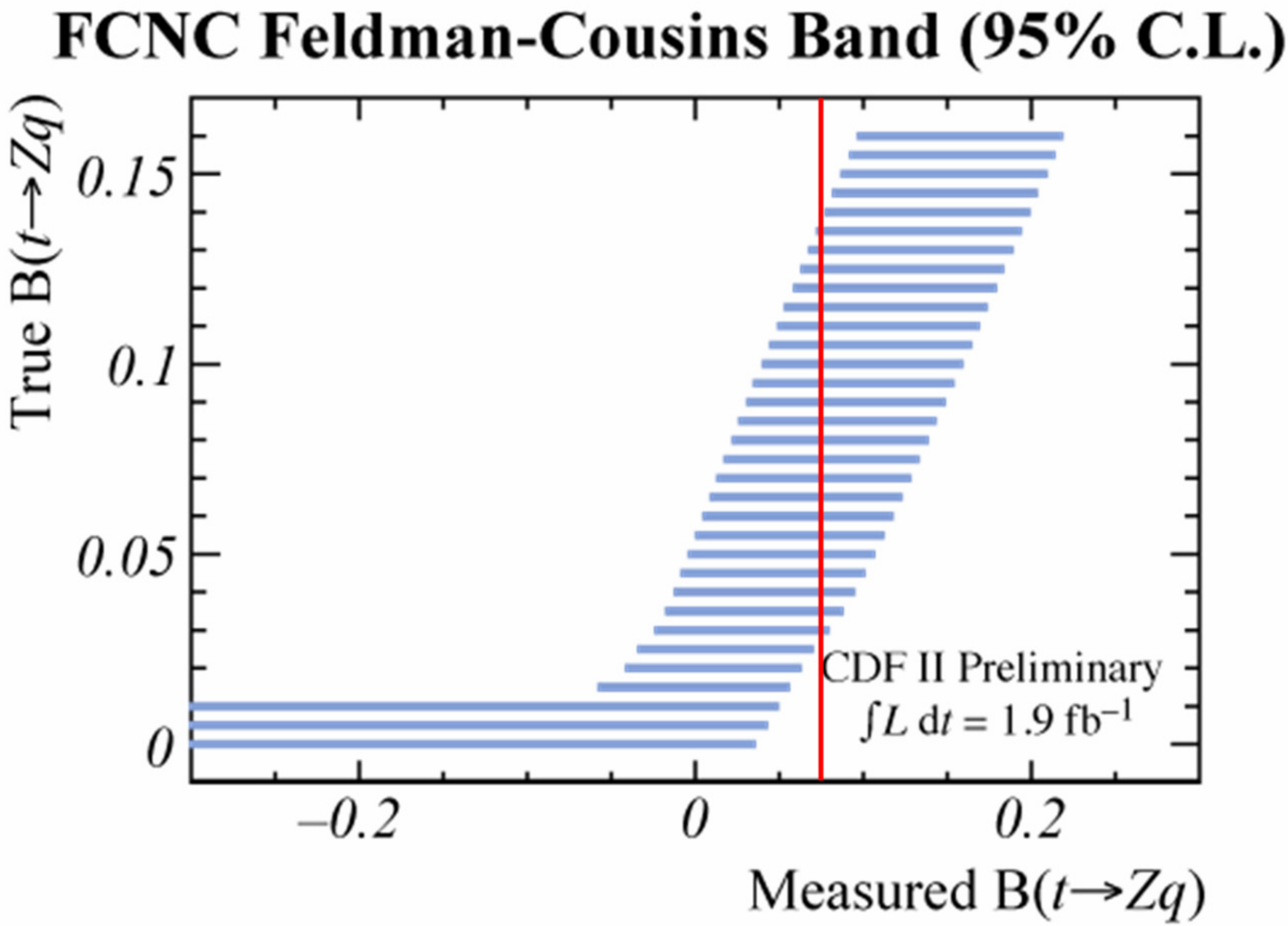

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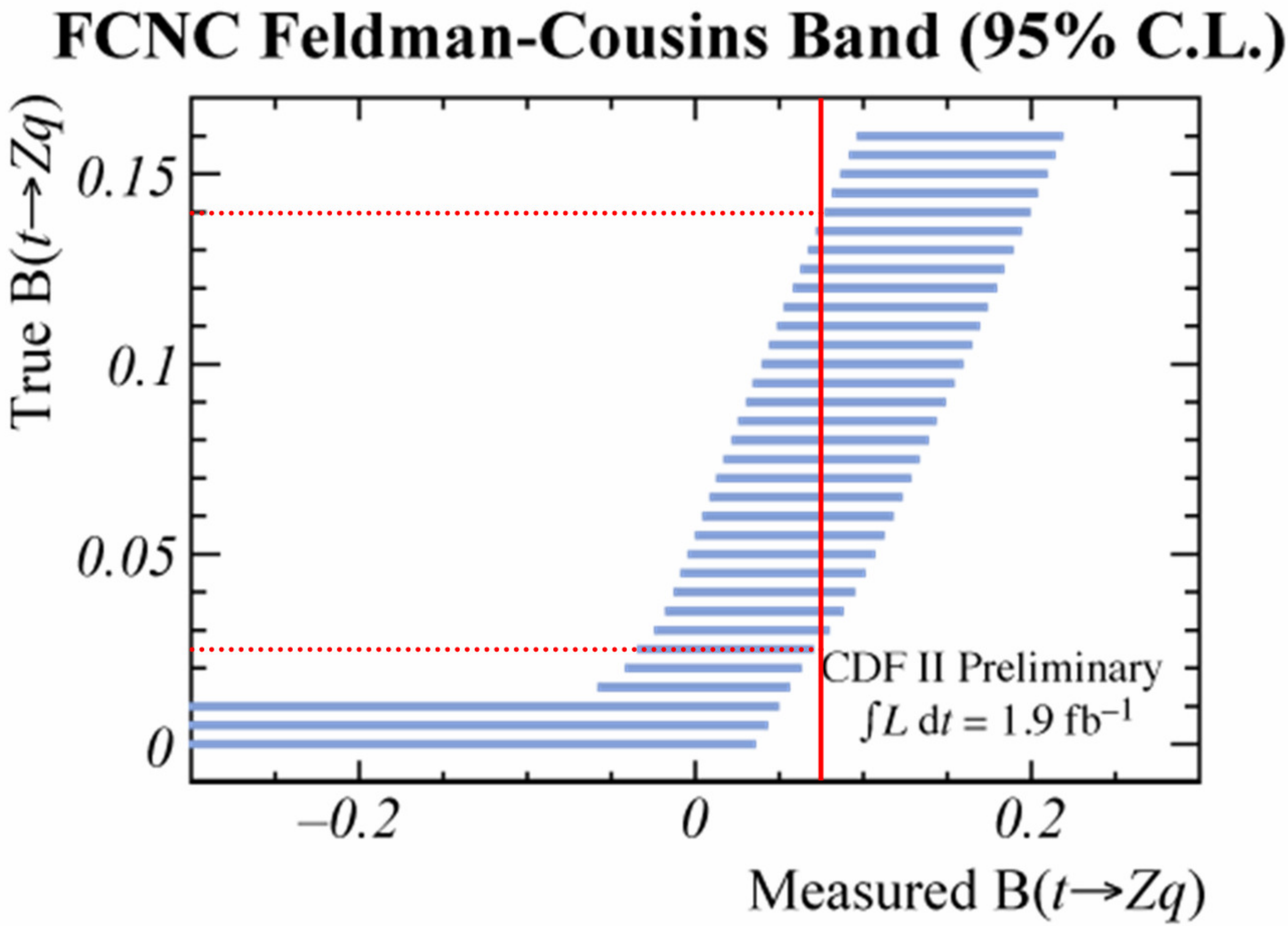

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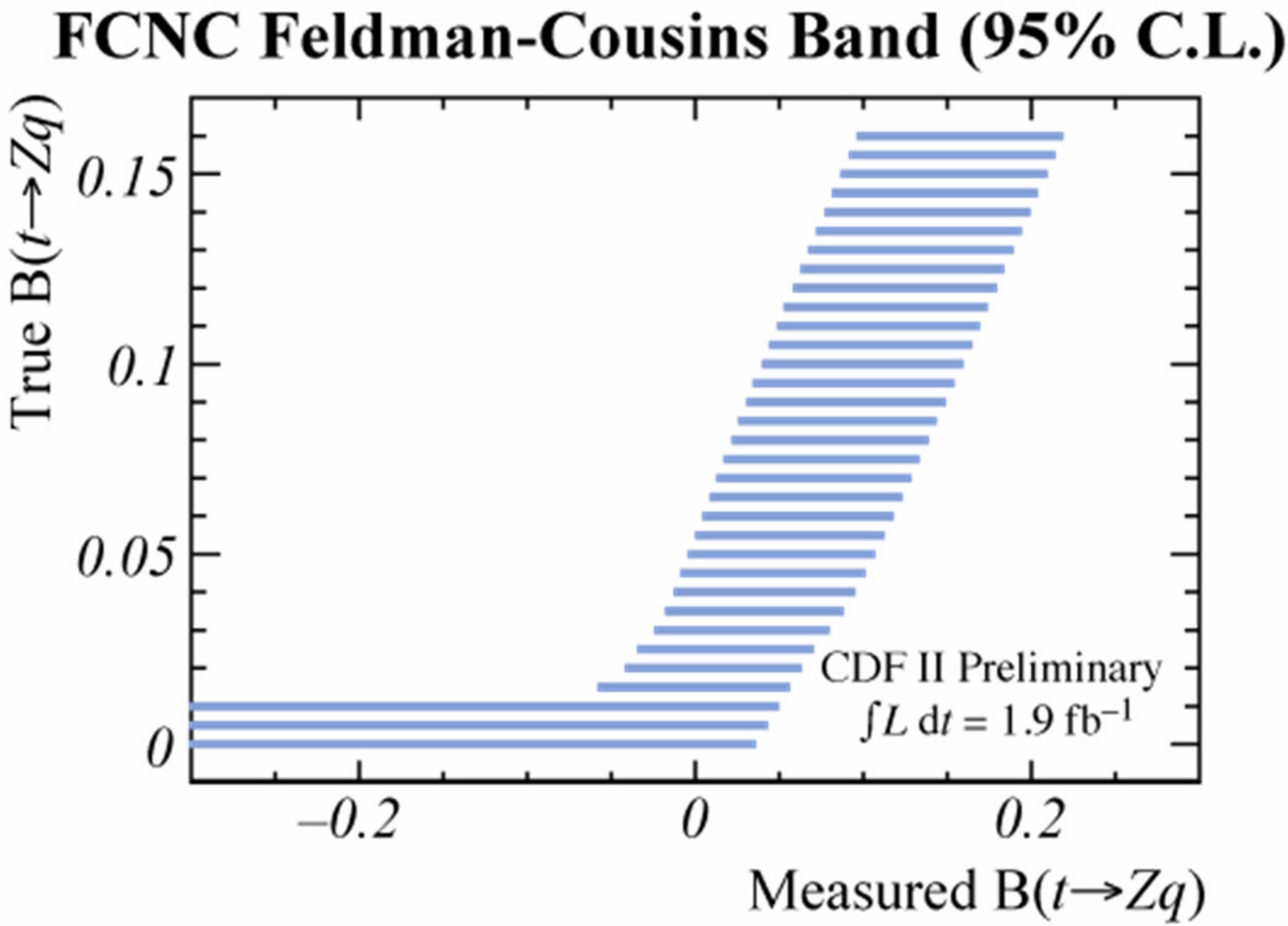

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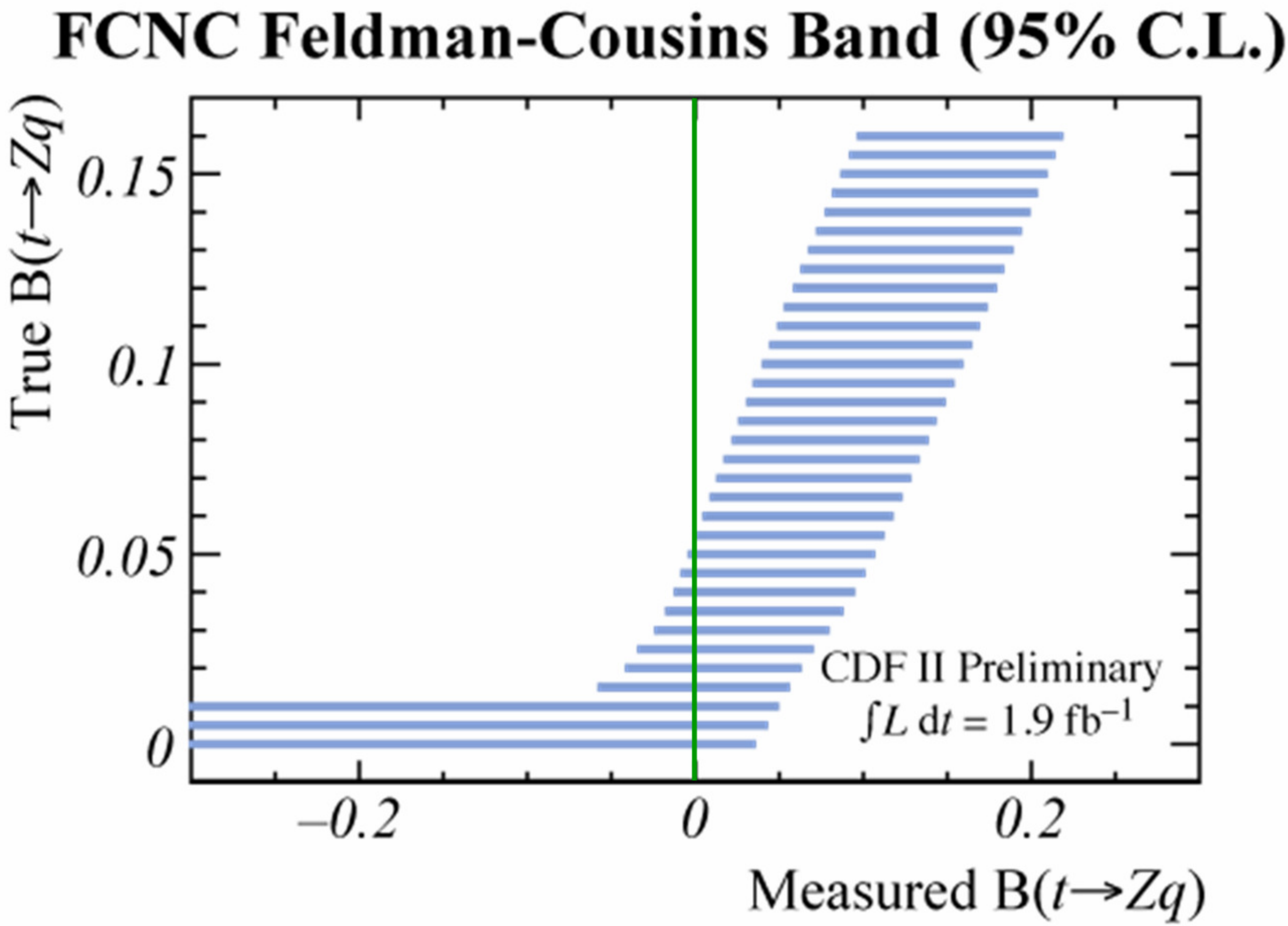
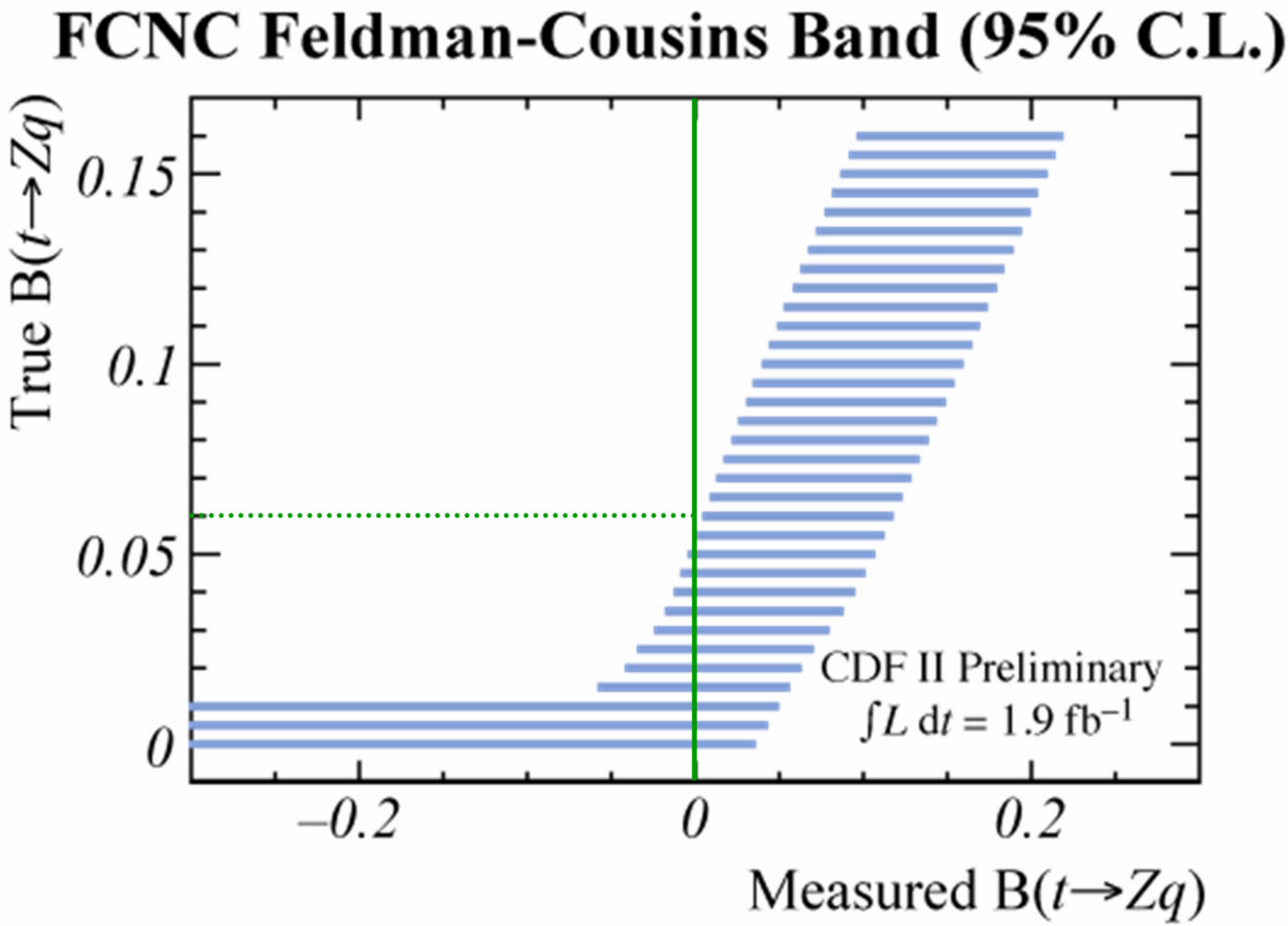


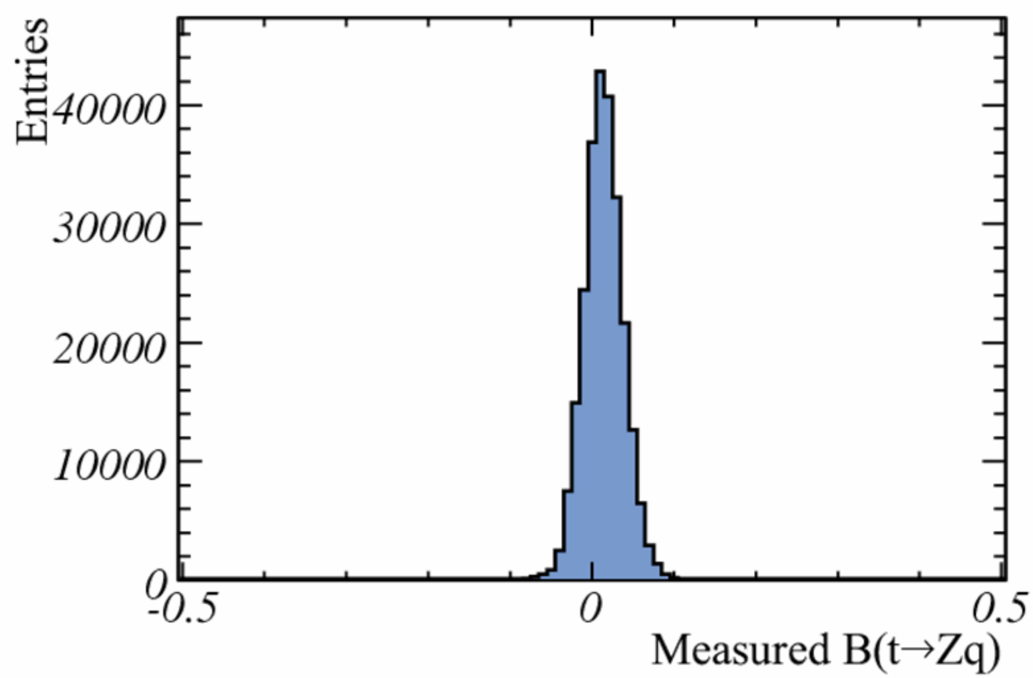

FCNC Feldman-Cousins Band (95% C.L.)
True B(t→Zq)
0.15
0.1
0.05
0
−0.2
0
0.2
Measured B(t→Zq)
CDF II Preliminary
∫L dt = 1.9 fb⁻¹

Pseudo-Experiments (PEs)

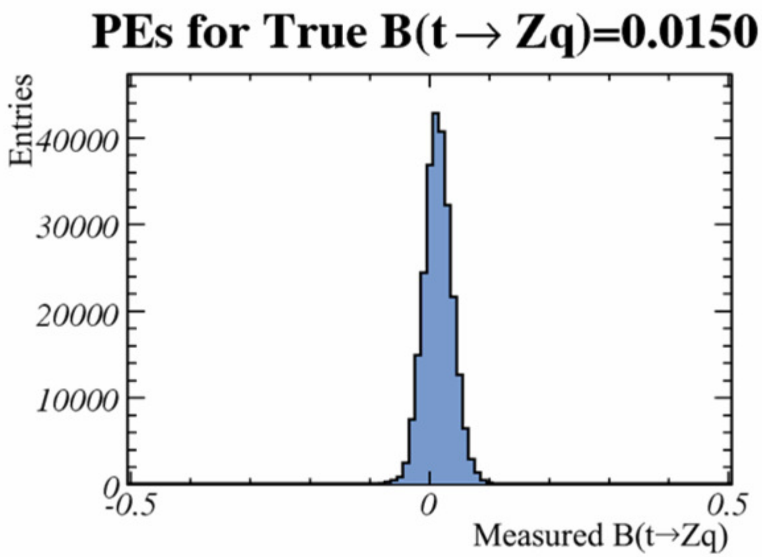
Pseudo-experiment: Generate all necessary numbers/templates to emulate data from an experiment.

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!

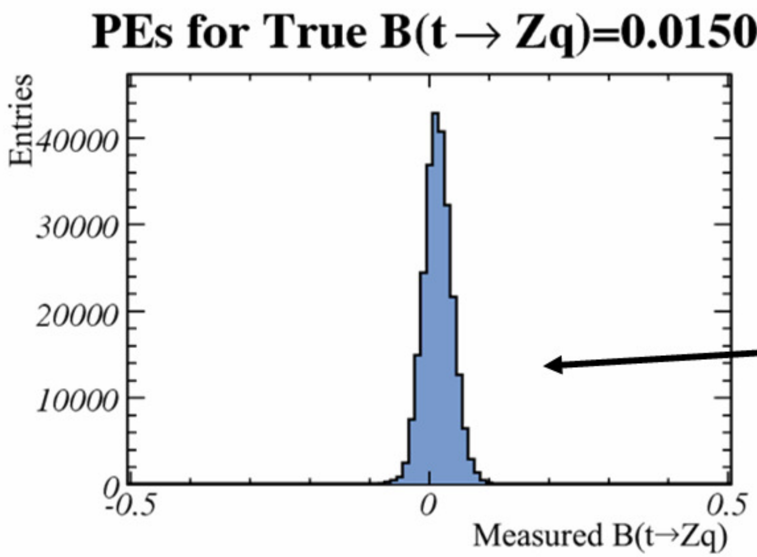
PEs for True B(t → Zq)=0.0150



FC Band Construction In A Nutshell

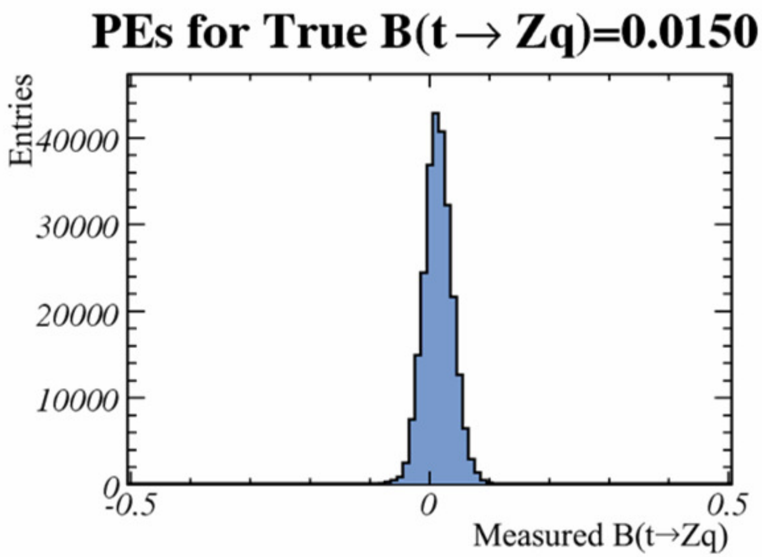


FC Band Construction In A Nutshell



PEs generated with all statistical and systematic uncertainties.

FC Band Construction In A Nutshell



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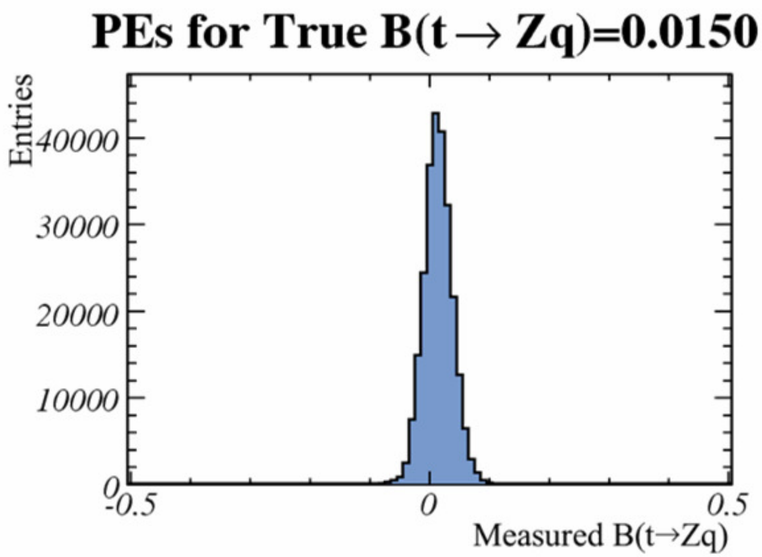

- Use *Likelihood Ratio Ordering Principle*:

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

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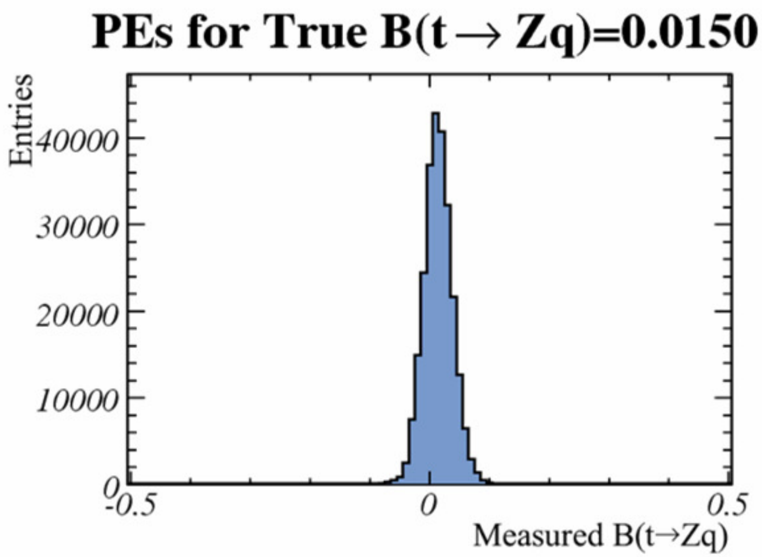

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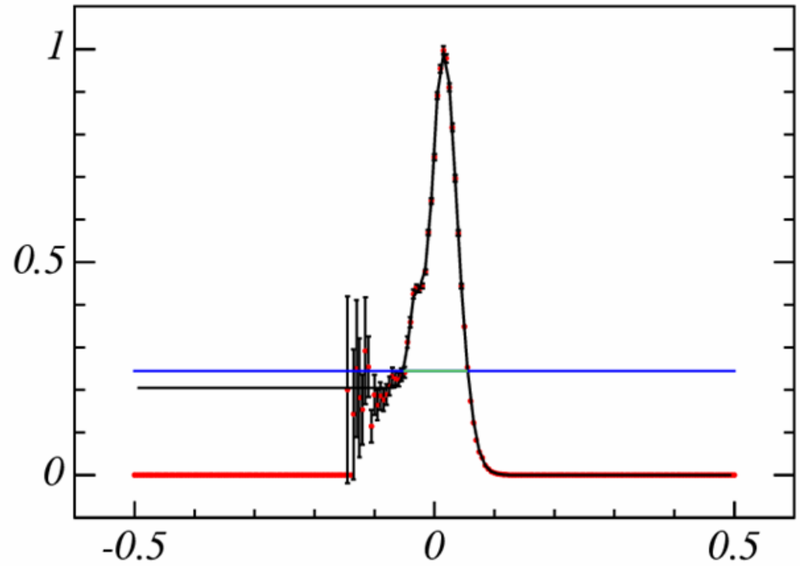

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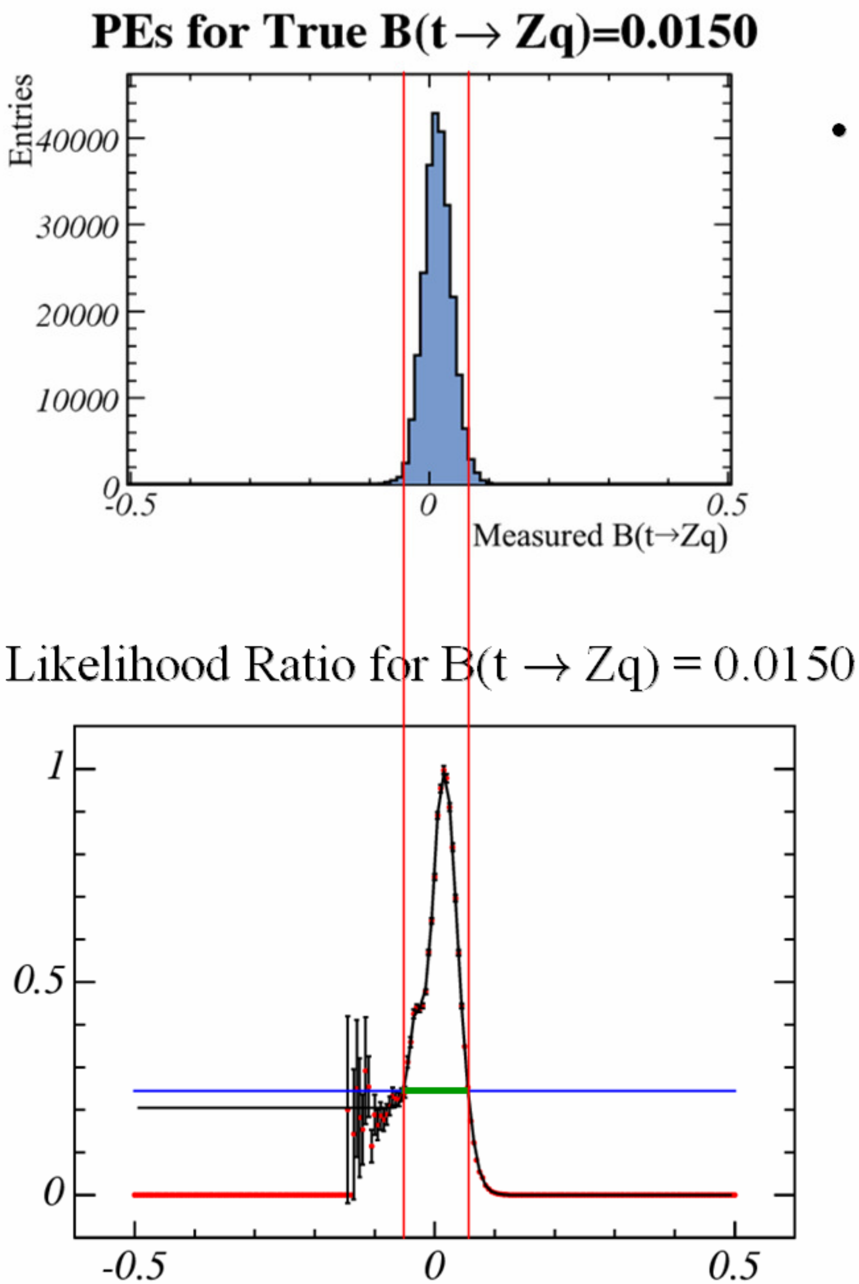

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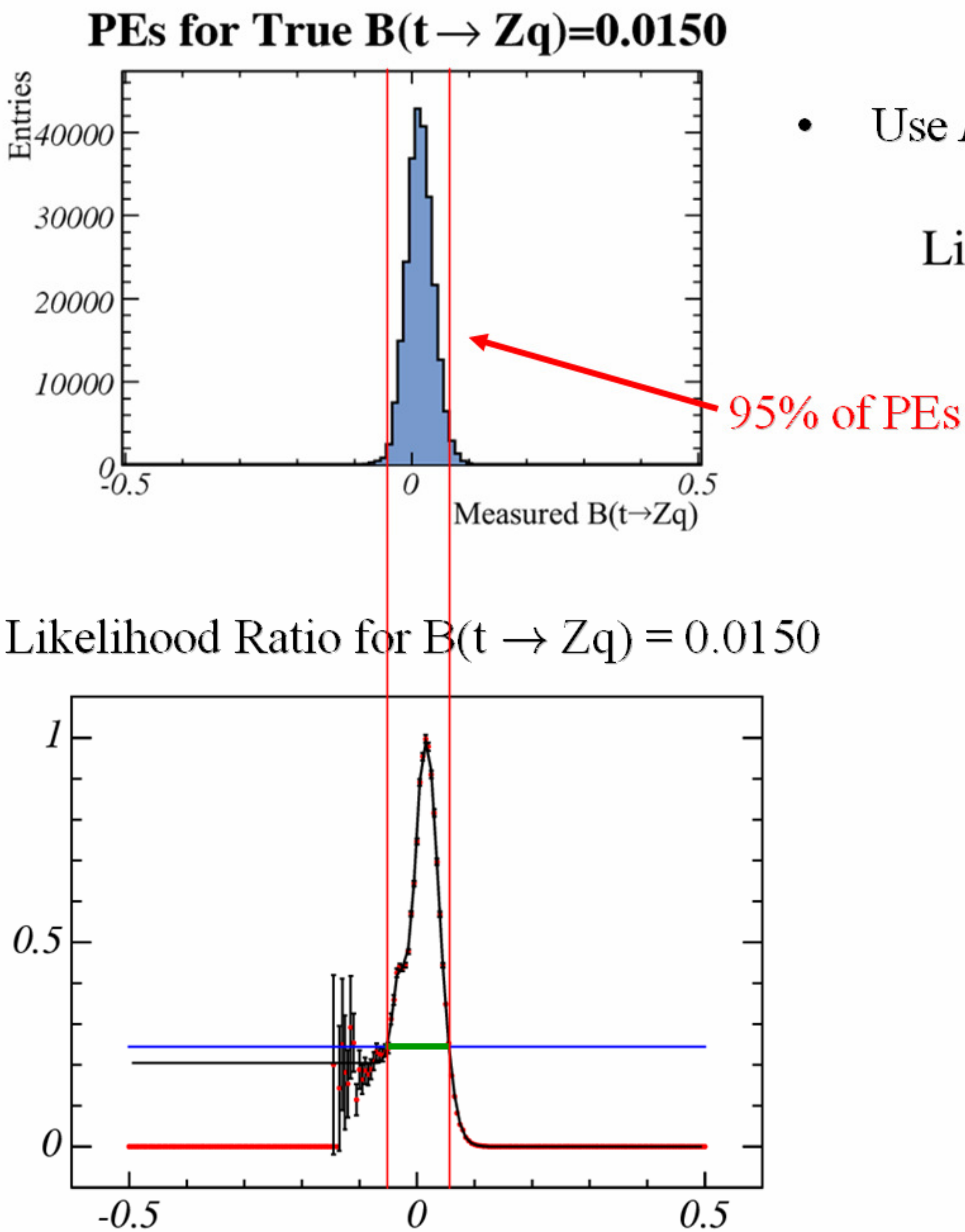

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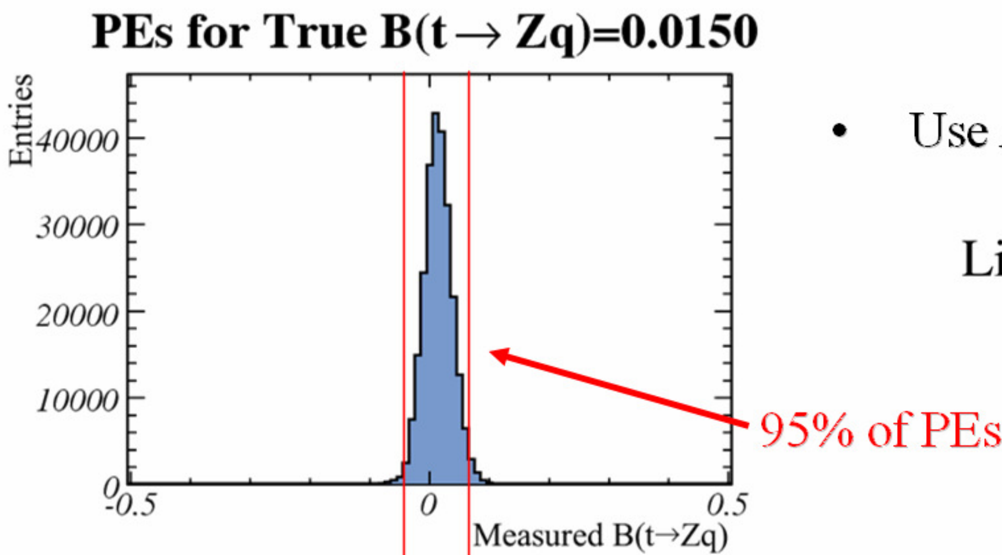

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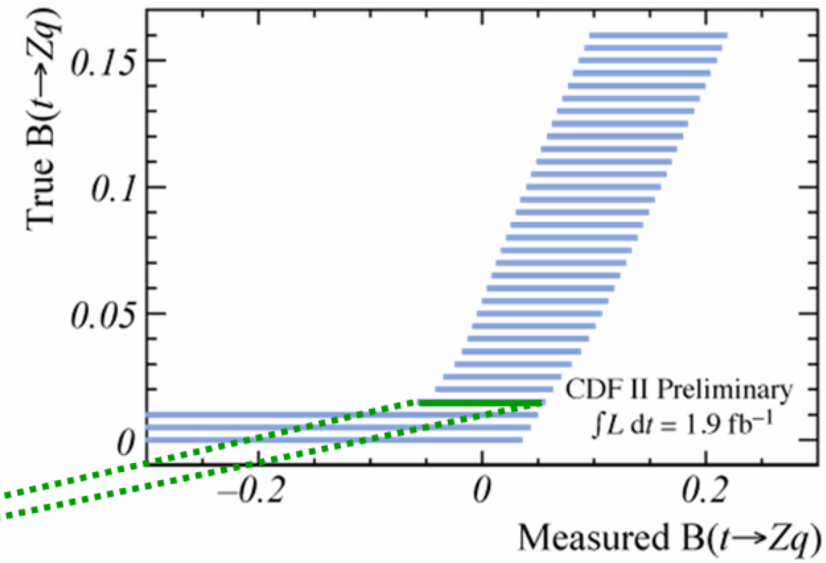
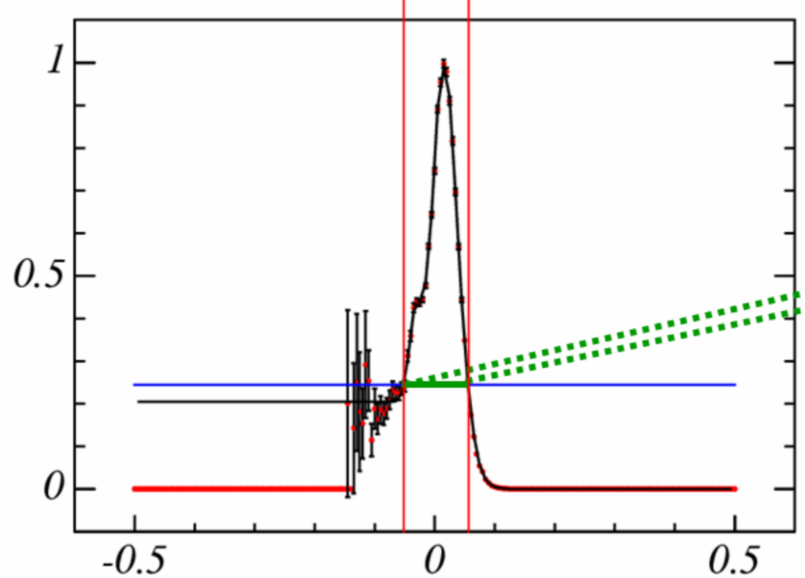
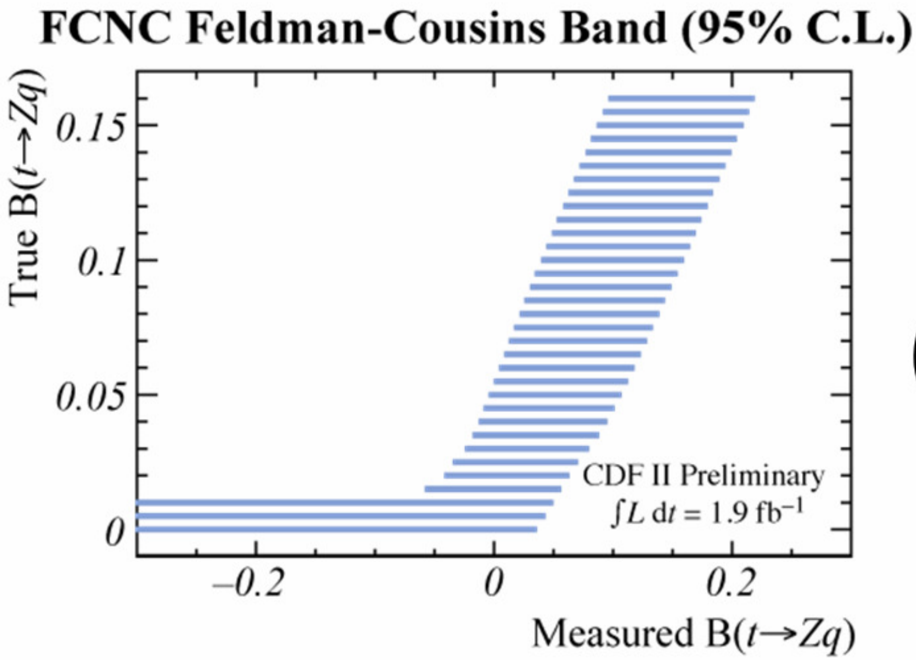
FCNC Feldman-Cousins Band (95% C.L.)

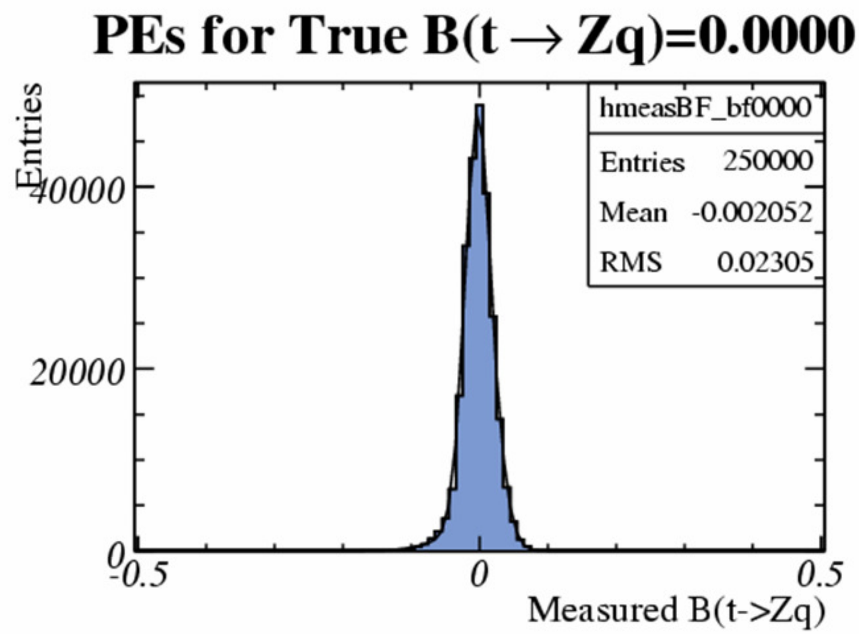


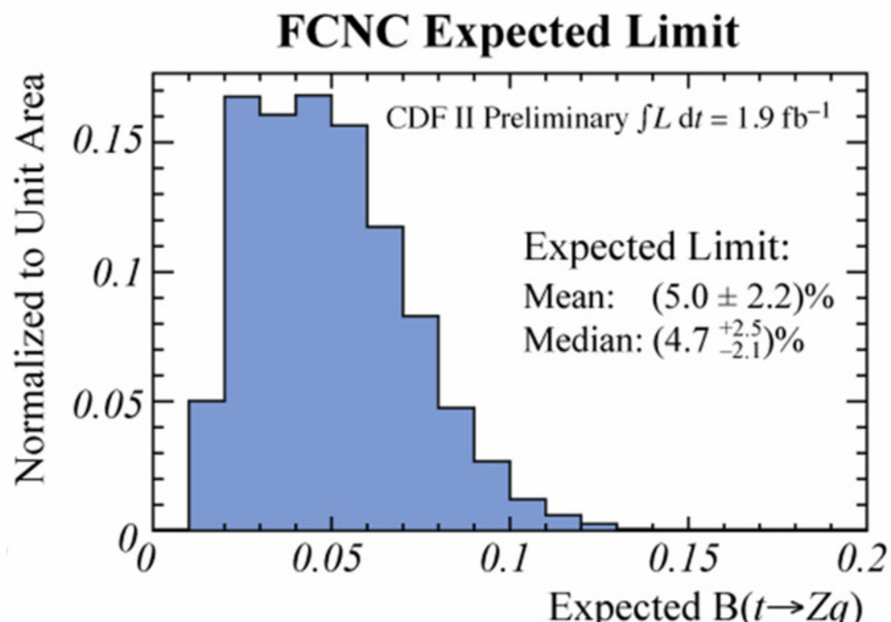
Likelihood Ratio for B(t → Zq) = 0.0150



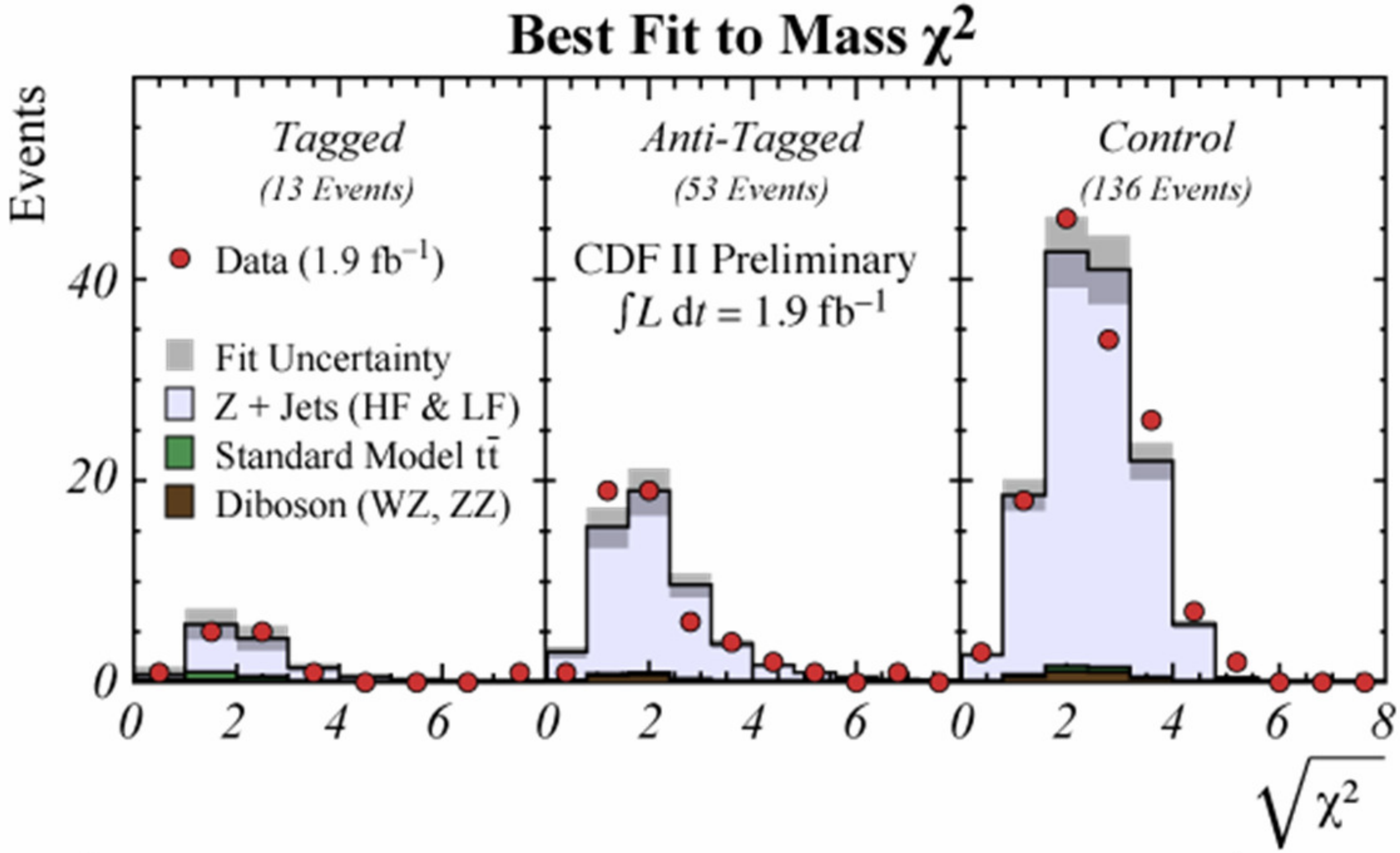
Expected Limit







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

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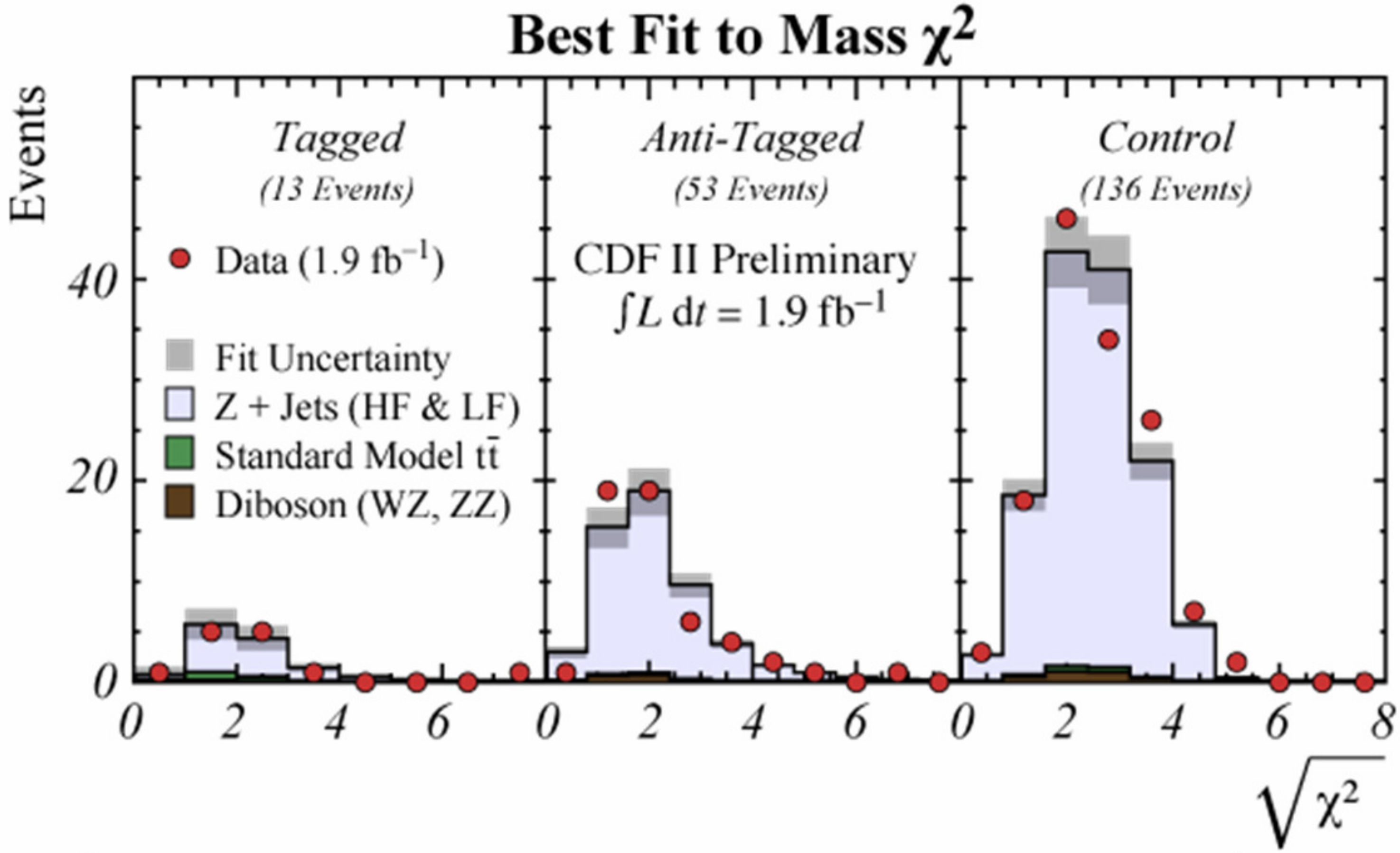

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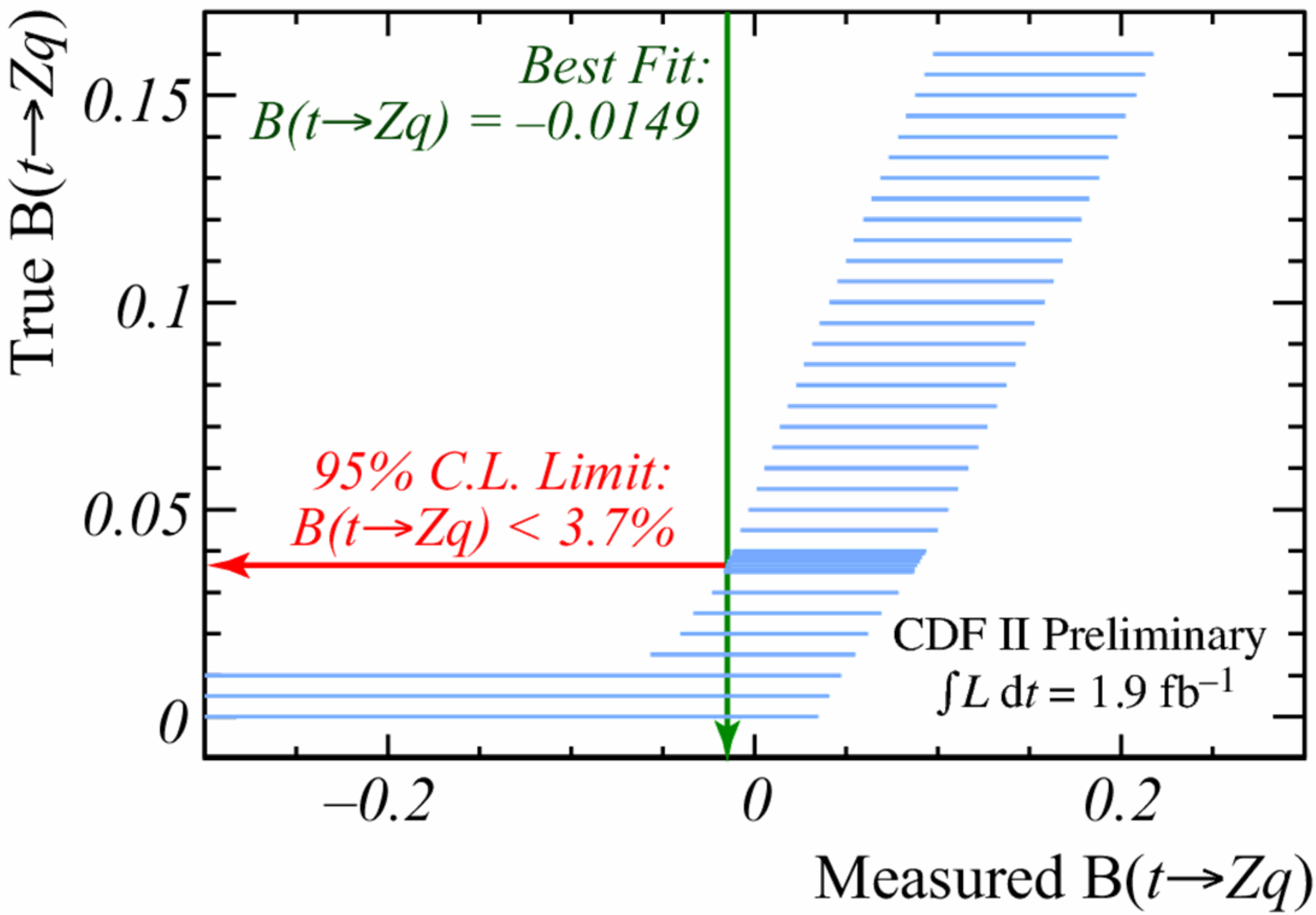
F.C. 95% C.L. Limit

FCNC Feldman-Cousins Band (95% C.L.)



Outline

The Tevatron and the CDF Experiment

Top Quark Physics

The Search for Top FCNC Decay

Summary

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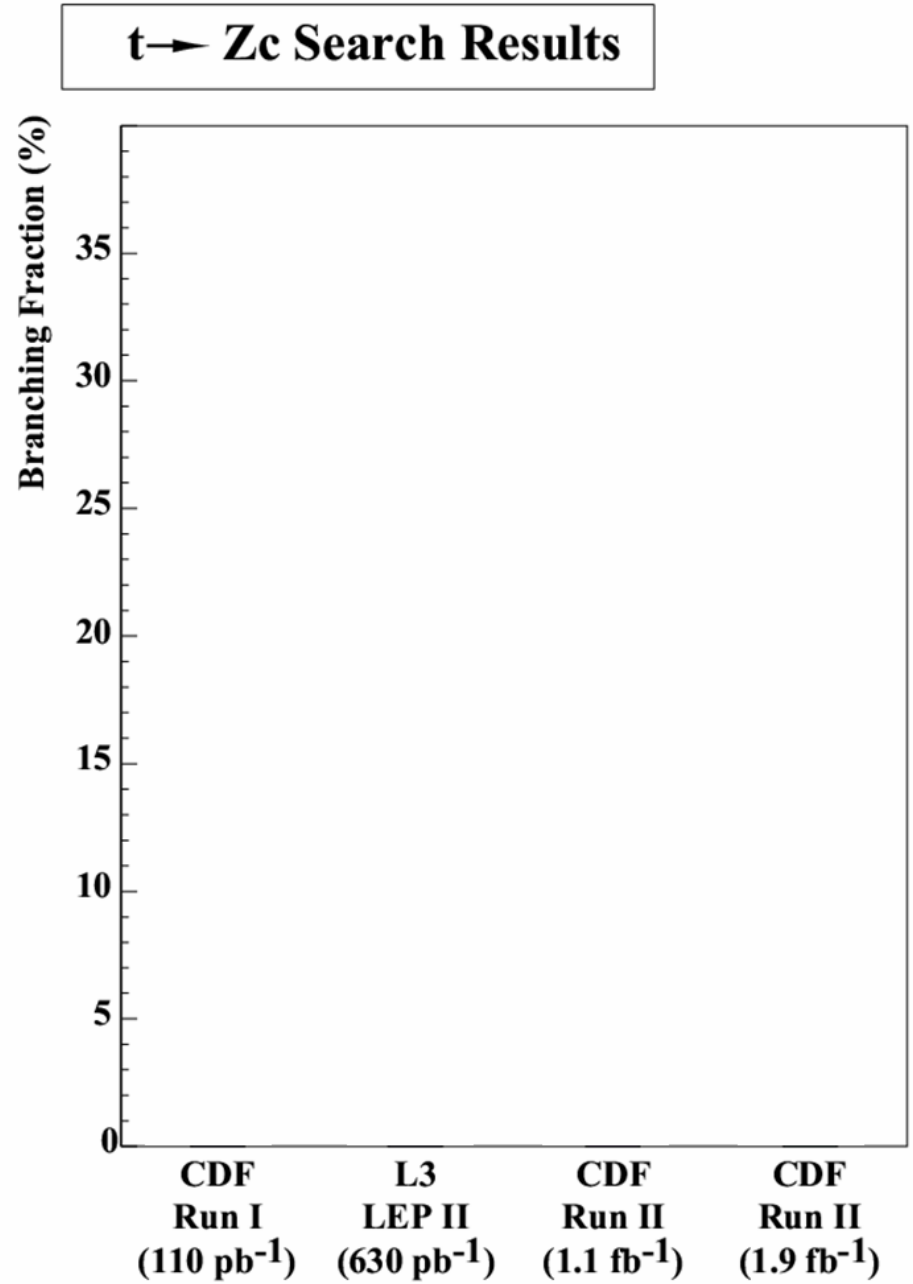
- CDF and the Tevatron are running very well.
  - Thanks Tevatron!
- We just finished Run II's first search for Top FCNC $t \rightarrow Z c$.
  - Using **1.9 fb^{-1}**,

    we have the world's best limit:

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



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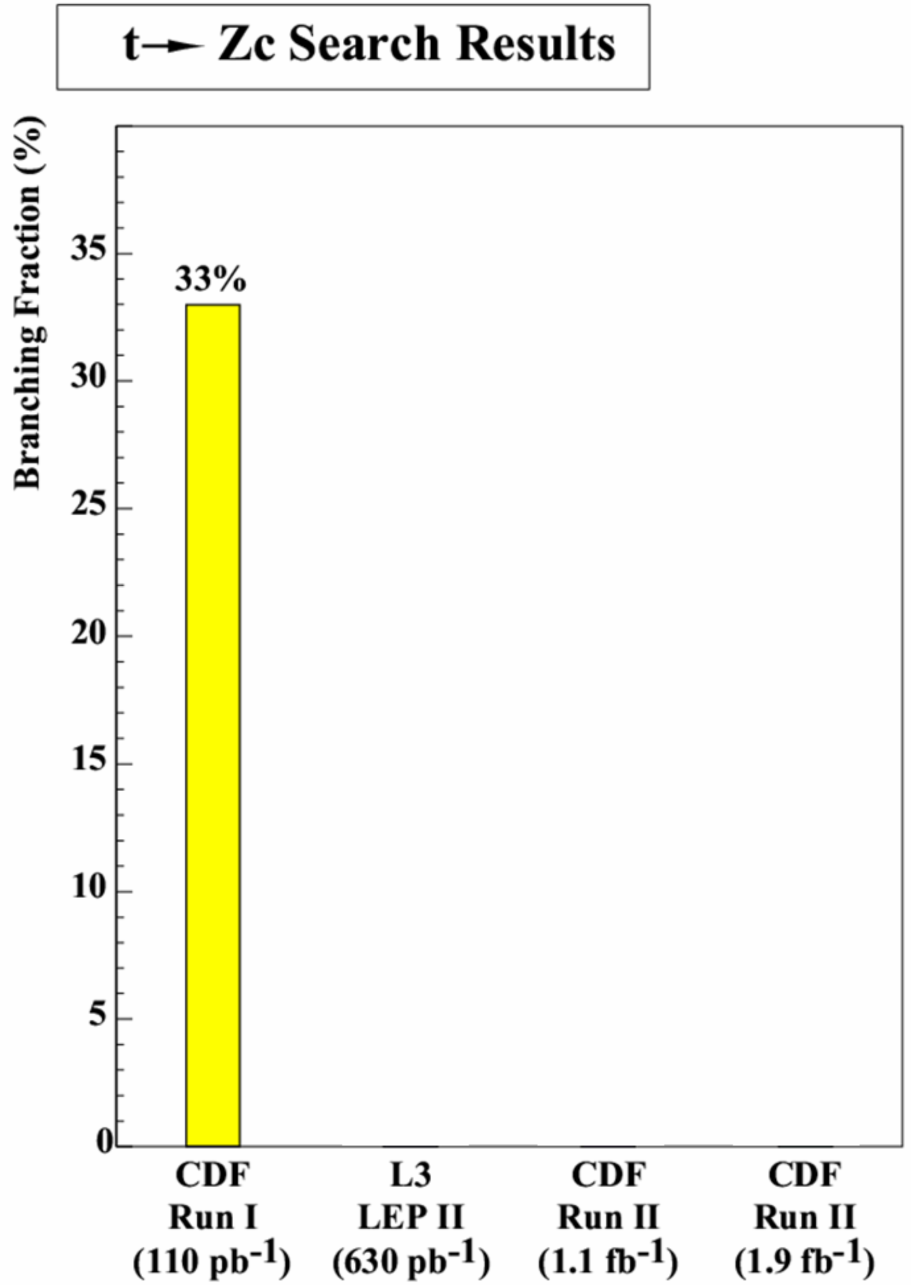

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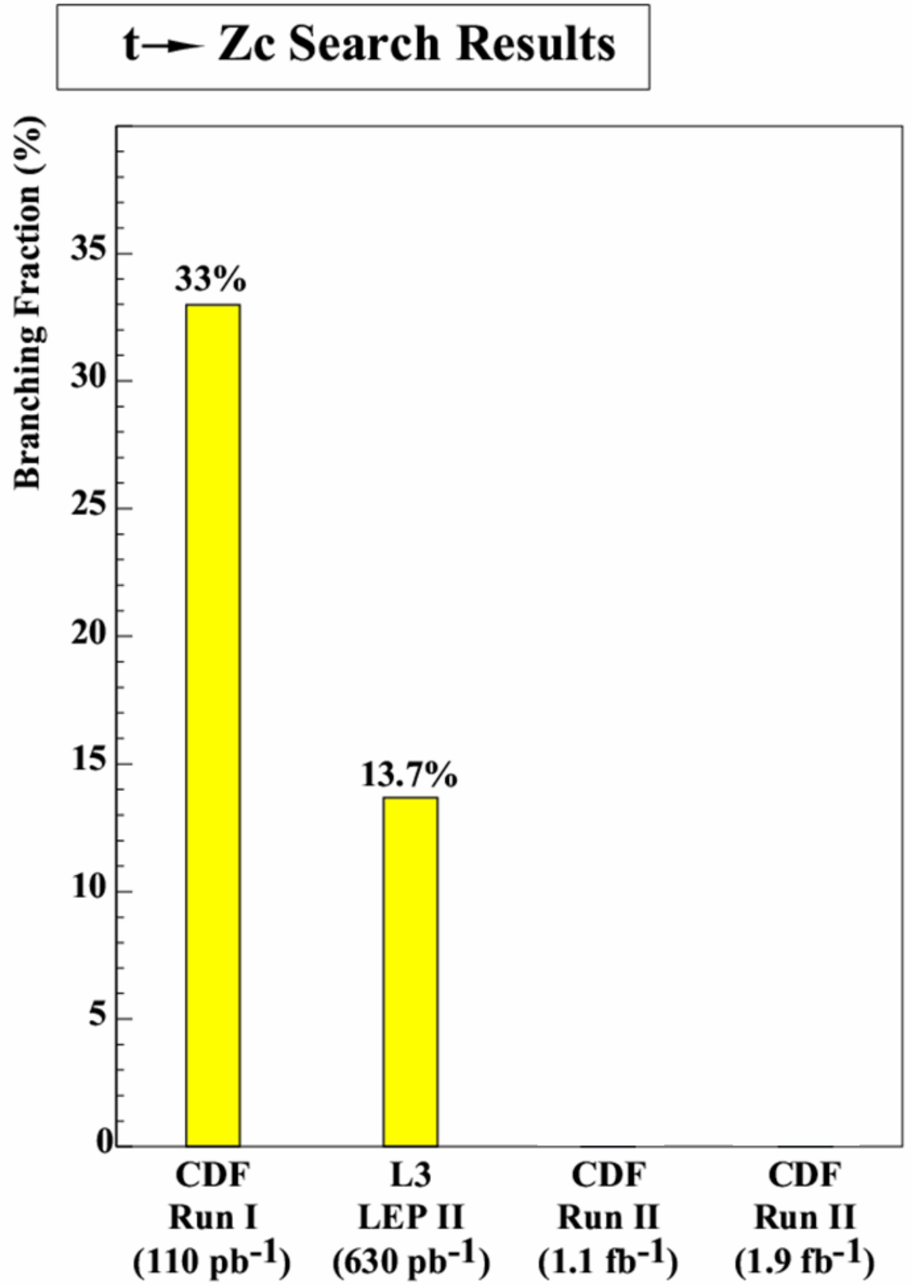

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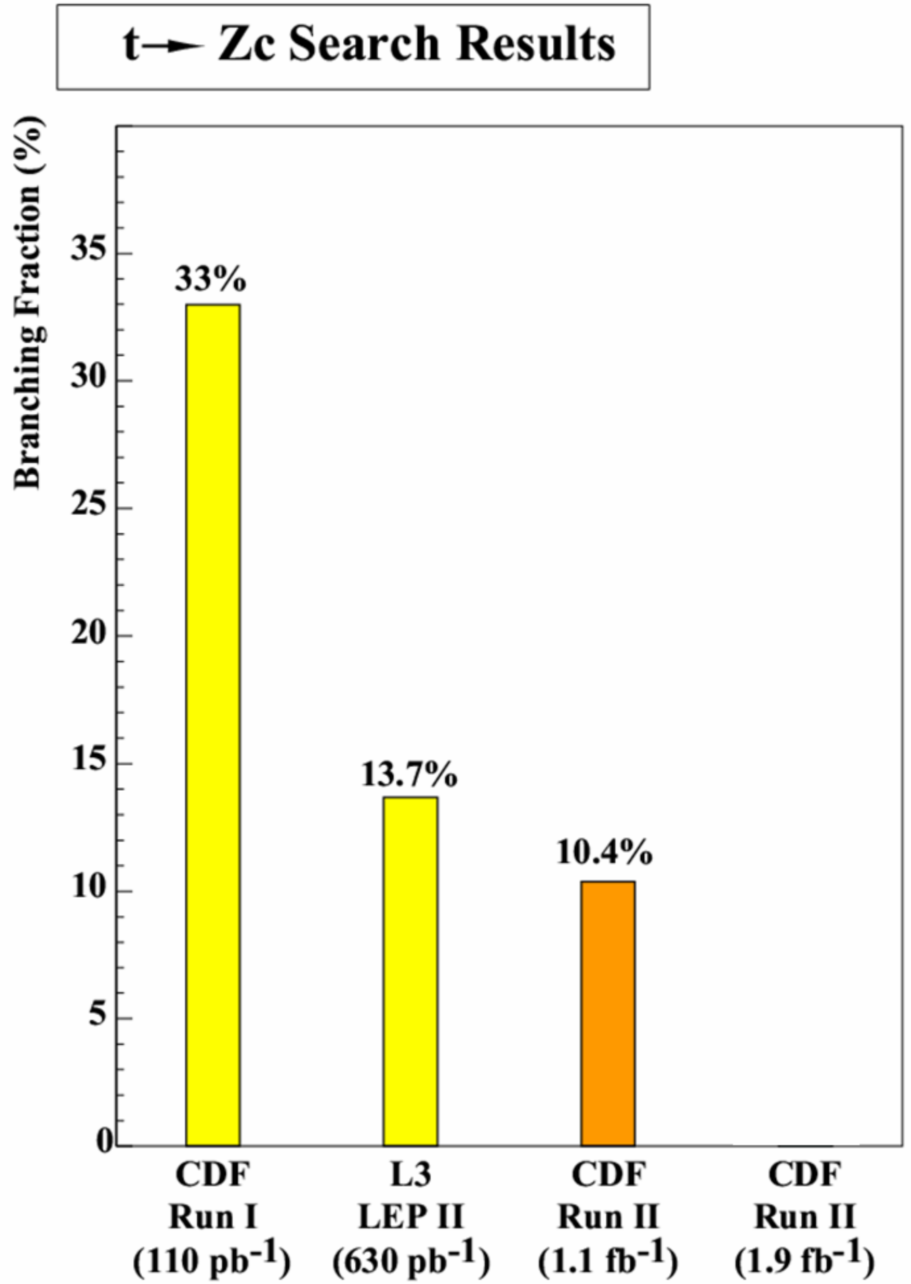

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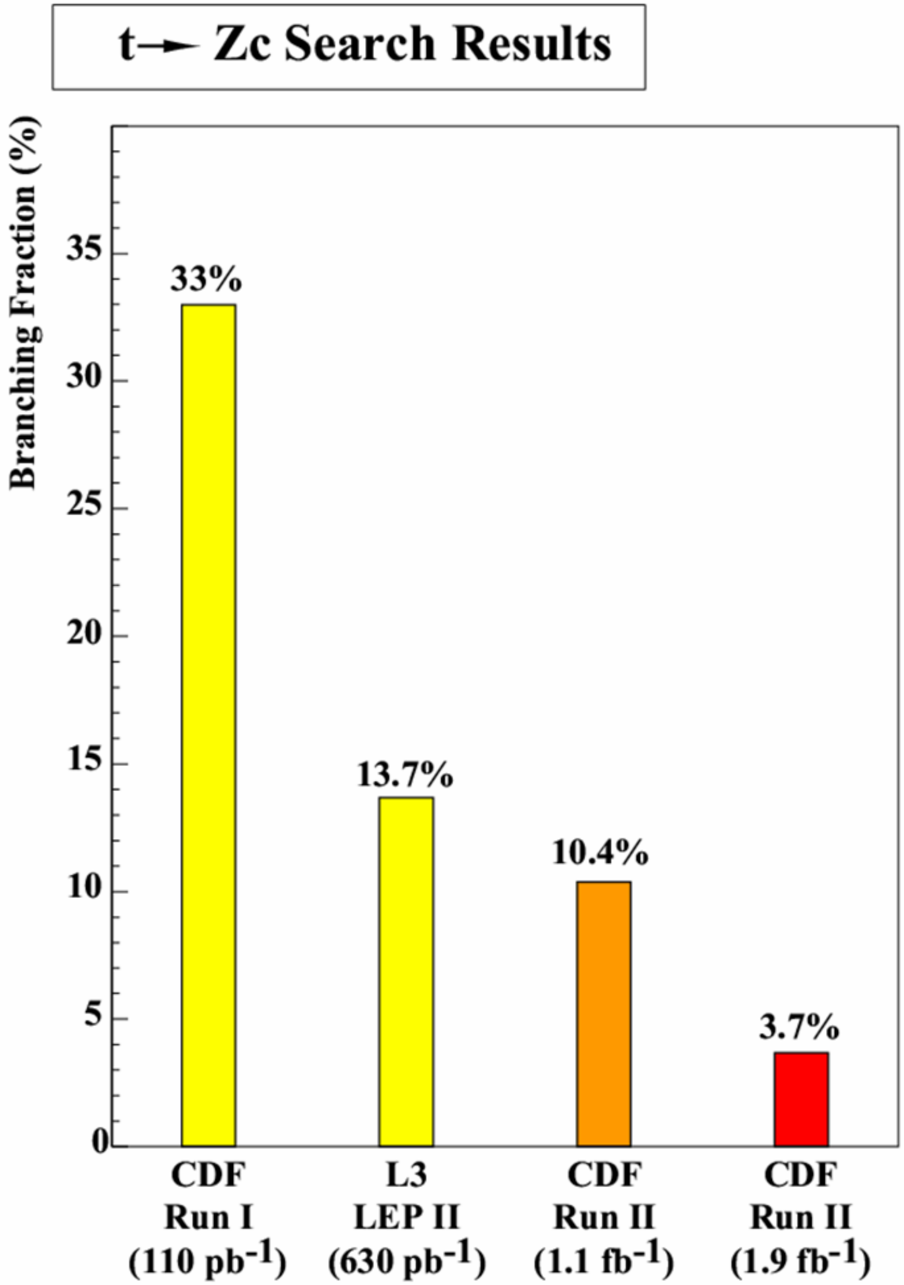
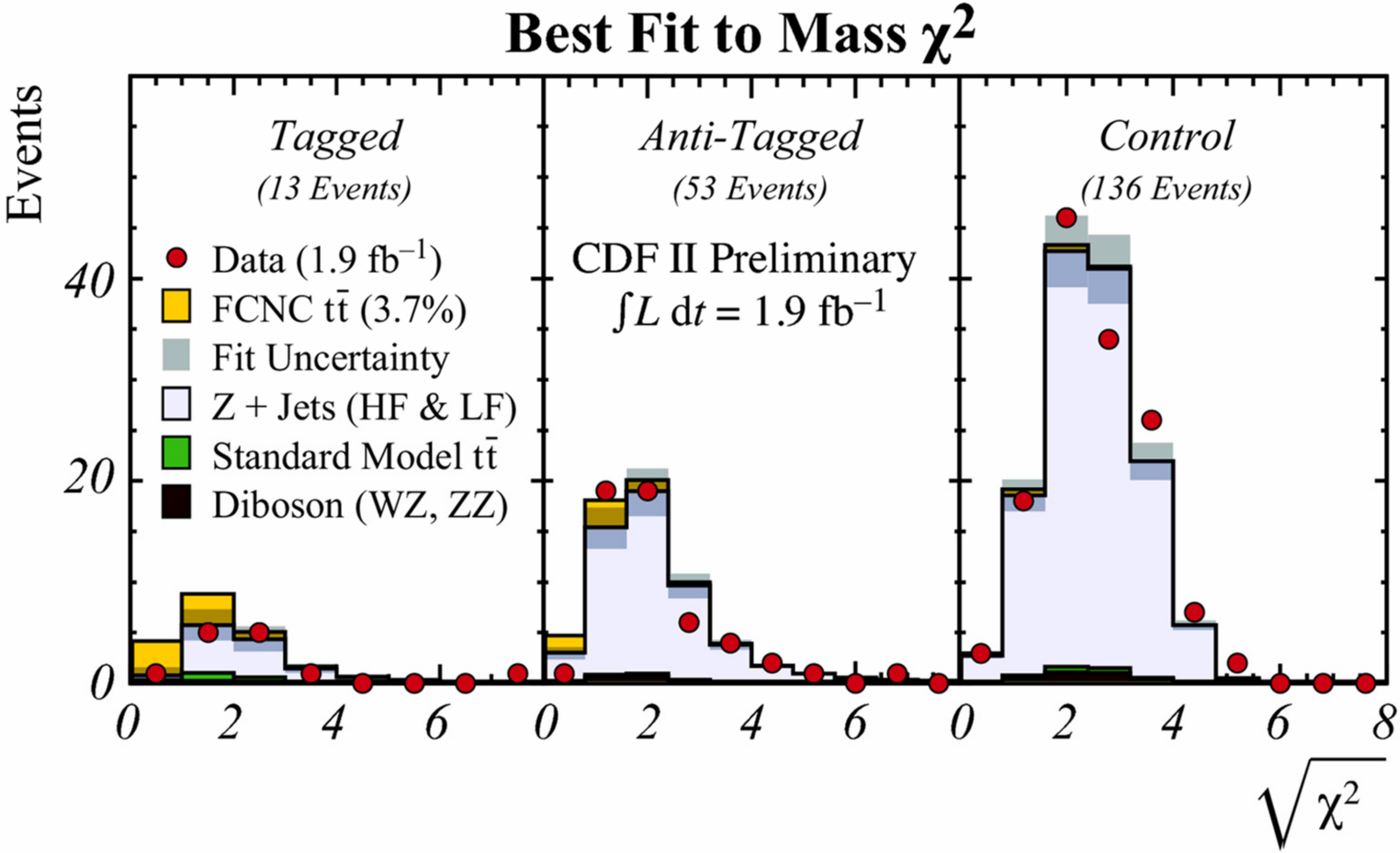


Money Plot



Best Fit to Mass χ^2
Events
Tagged
(13 Events)
Anti-Tagged
(53 Events)
Control
(136 Events)
Data (1.9 fb^{-1})
FCNC $t\bar{t}$ (3.7%)
Fit Uncertainty
Z + Jets (HF & LF)
Standard Model $t\bar{t}$
Diboson (WZ, ZZ)
CDF II Preliminary
$\int L\,dt = 1.9$ fb^{-1}
0
20
40
0
2
4
6
8
$\sqrt{\chi^2}$

New Era of Precision Top Physics!

2006 PDG Top Entry

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

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

Mass $m = 174.2 \pm 3.3$ 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] < 13.7 %	95%	–

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New Era of Precision Top Physics!

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γ q (q = u,c)
g q (q = u,c)
5 σ Evidence for single top production

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$W\,b$				–
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$\tau\,\nu_\tau\,b$				–
$\gamma\,q\,(q{=}u,c)$	[e]	$< 5.9 \times 10^{-3}$	95%	–
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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 $\times 10^{-3}$	95%	–
$\Delta T = 1$ weak neutral current ($T1$) modes				
$Z q (q=u,c)$	$T1$	[f] < 3.7 %	95%	–

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

Thank You!

Best Fit to Mass χ^2