

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

Fermilab Joint Theoretical and Experimental

Physics Seminar

April 4, 2008



Outline

The Tevatron and the CDF Experiment

Top Quark Physics

The Search for Top FCNC Decay

Summary



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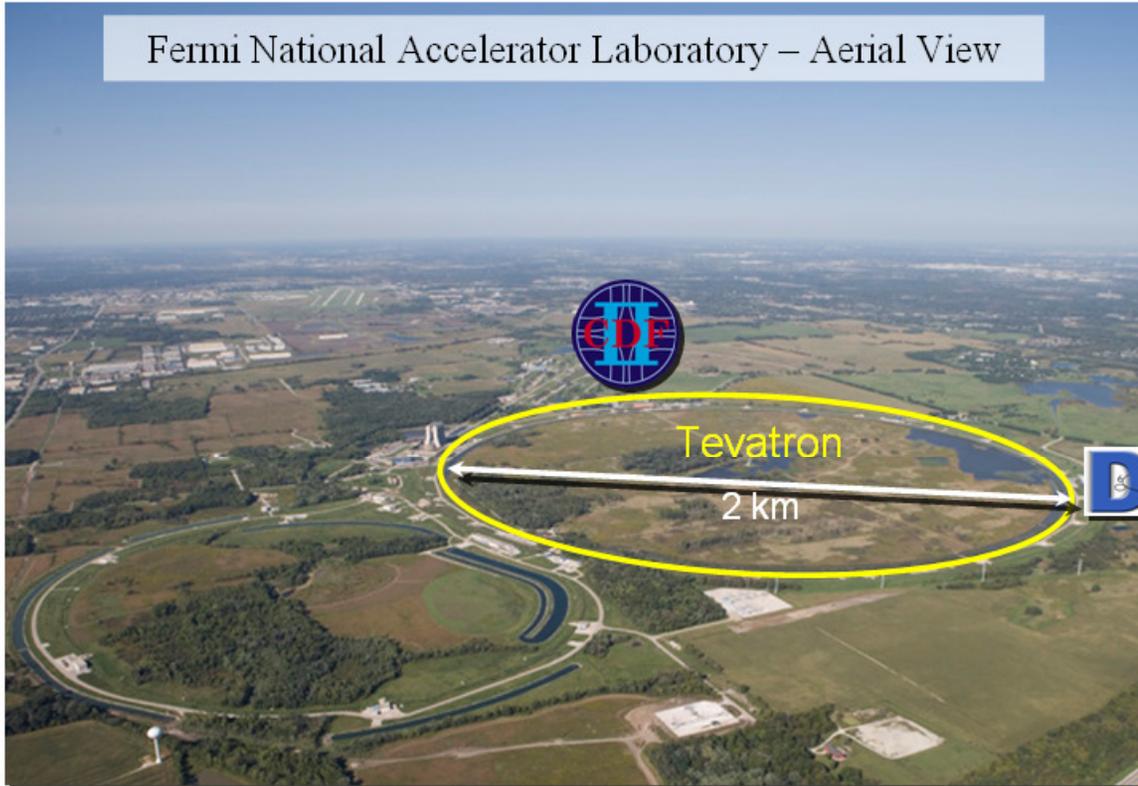
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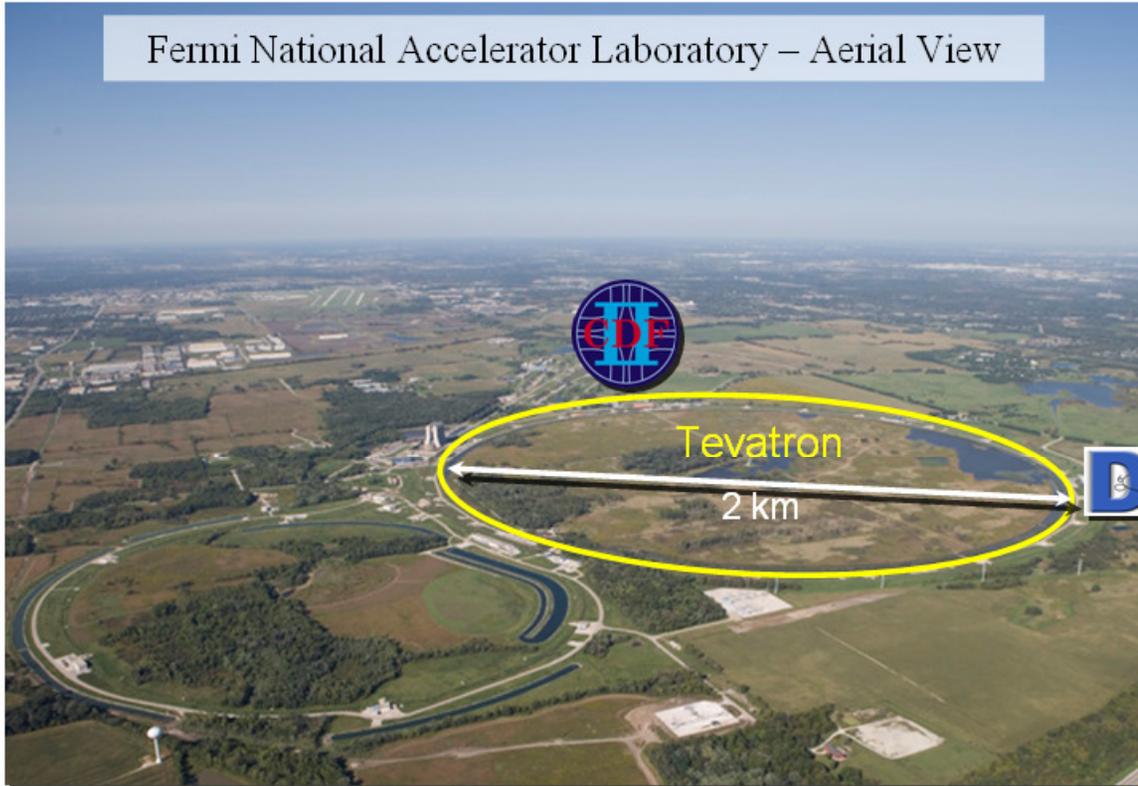
Tevatron Run II: 2001–2009 (2010?)



- Proton-antiproton collider:
 $\sqrt{s} = 1.96 \text{ TeV}$.
- 36×36 bunches, collisions every 396 ns.
- Record instantaneous peak luminosity:
 $290 \cdot 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$.
- Luminosity goal:
 $5.5 - 6.5 \text{ fb}^{-1}$ of integrated luminosity by 2009, running in 2010 currently under discussion.
- Two multi-purpose detectors: CDF and DØ.



Tevatron Run II: 2001–2009 (2010?)



Fermi National Accelerator Laboratory – Aerial View

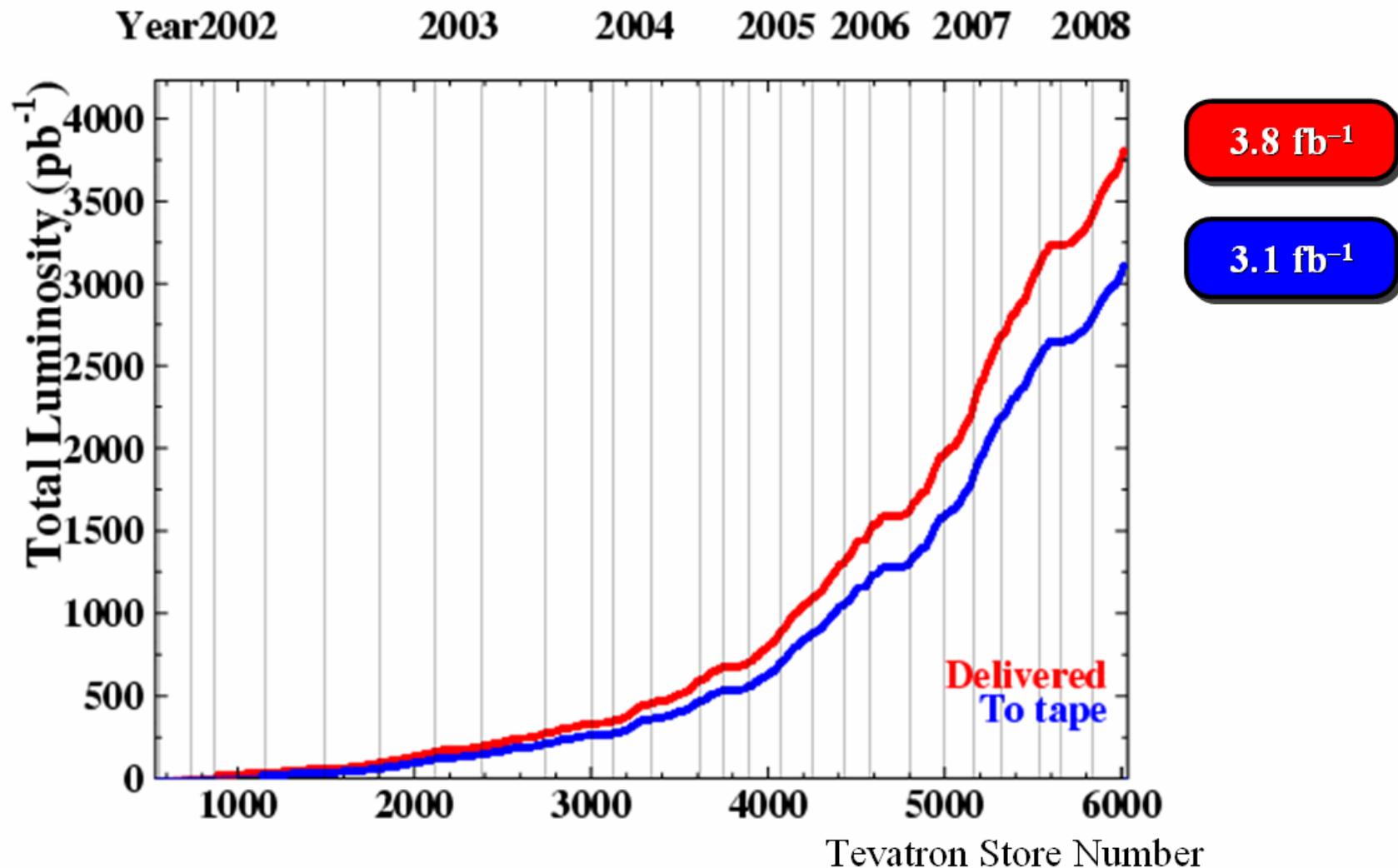
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Tevatron Performance



- Tevatron continues to perform **very** well:
 - More than 3.8 fb^{-1} delivered.
 - More than 3.1 fb^{-1} recorded by CDF.



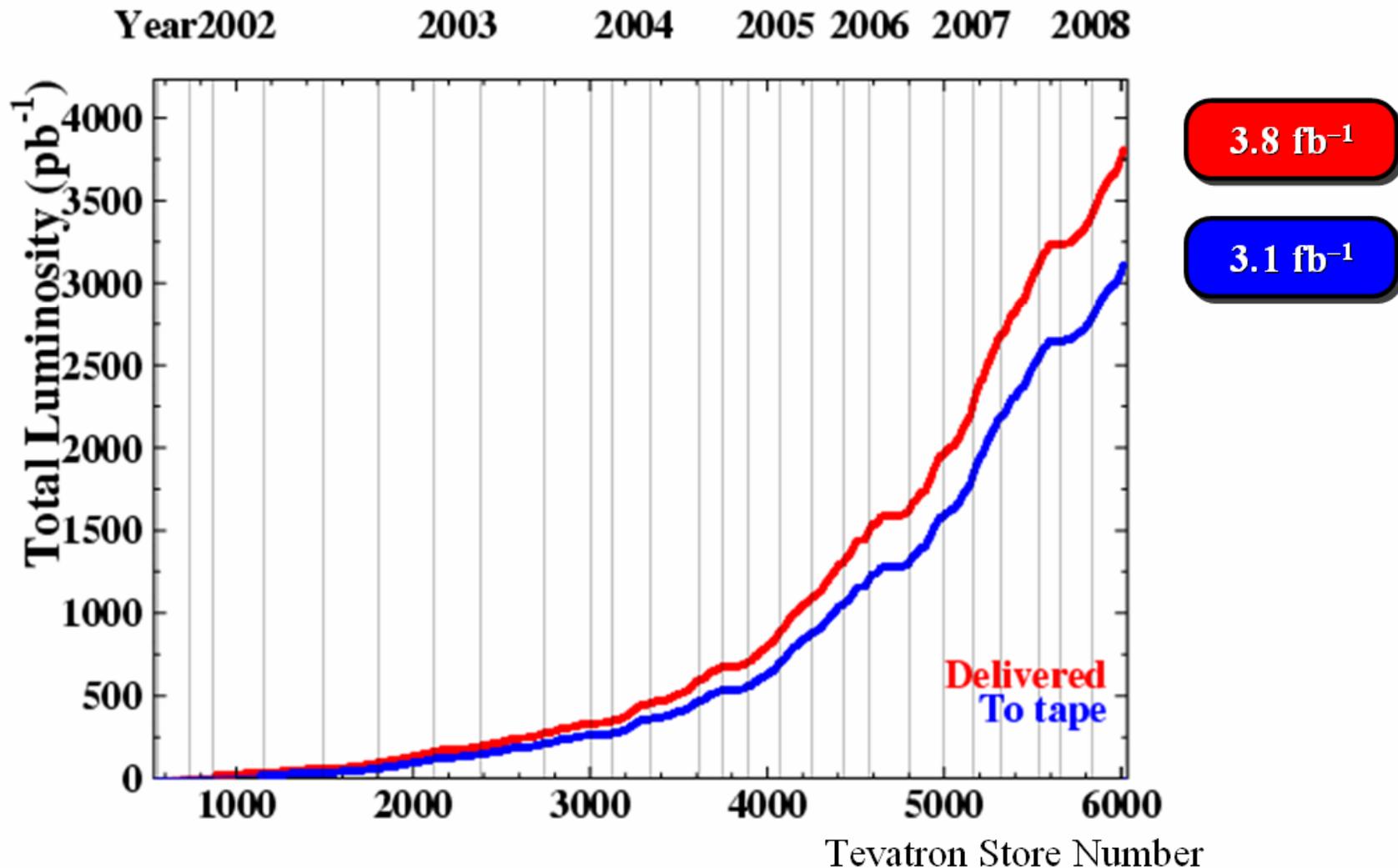


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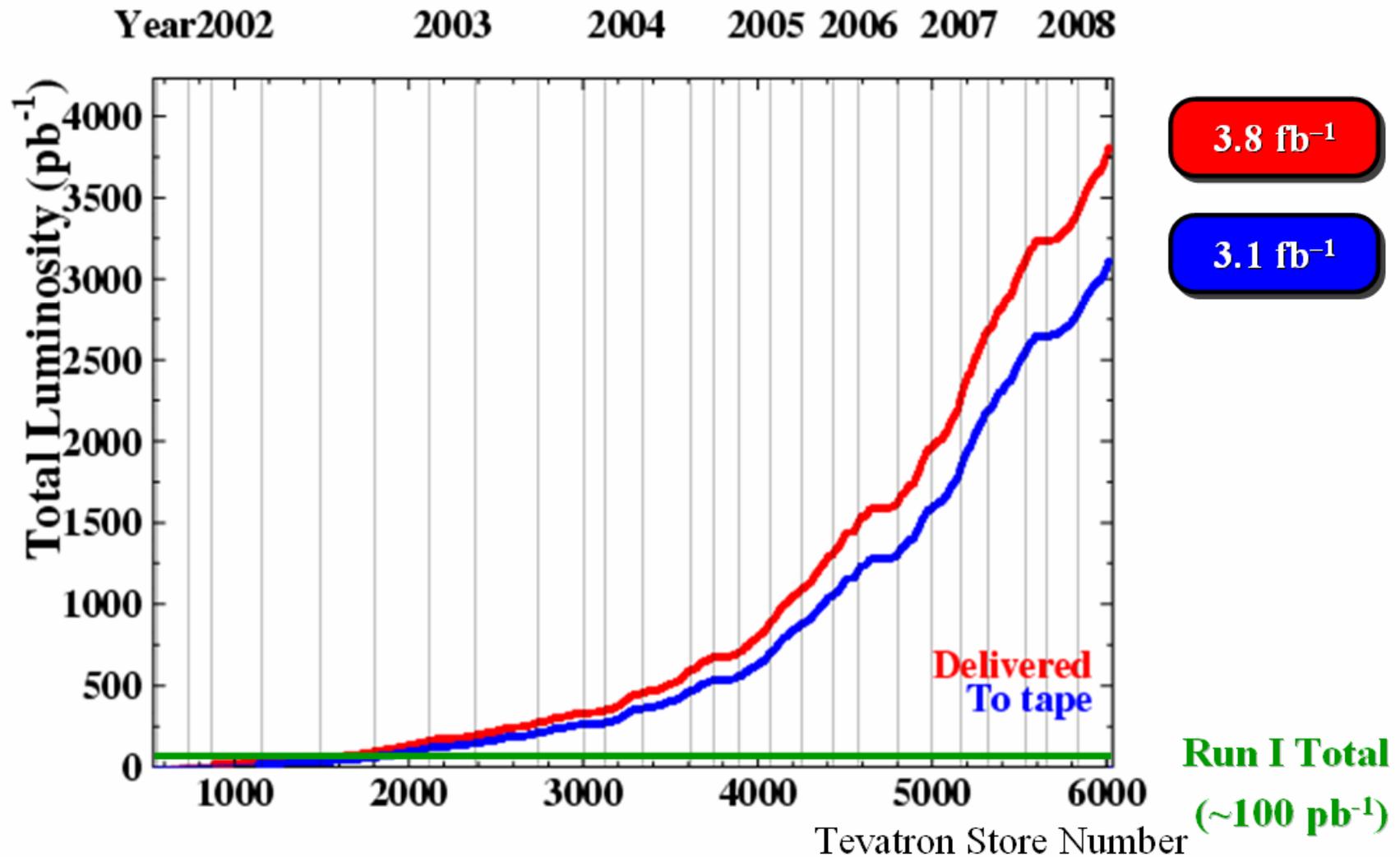


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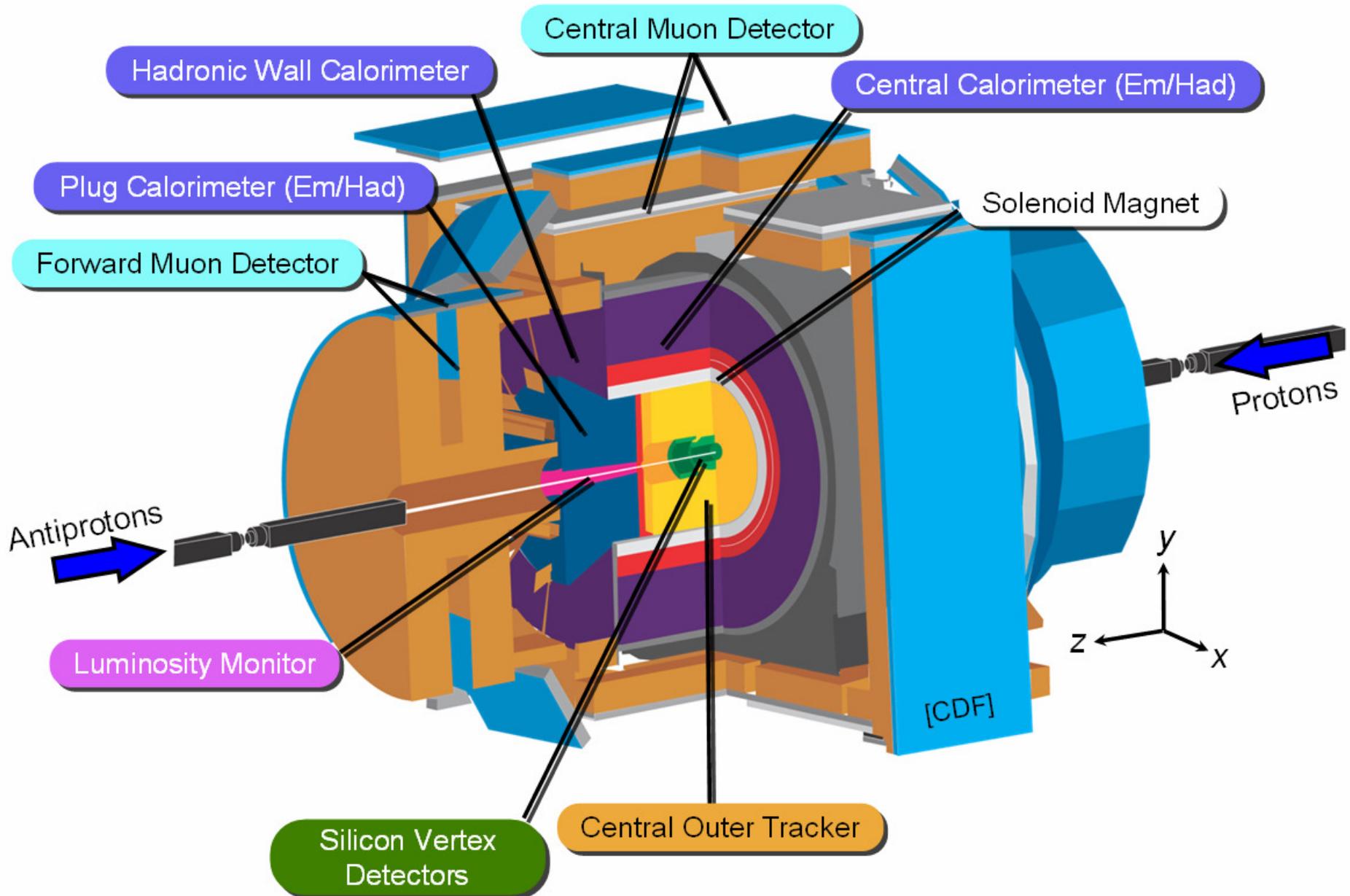


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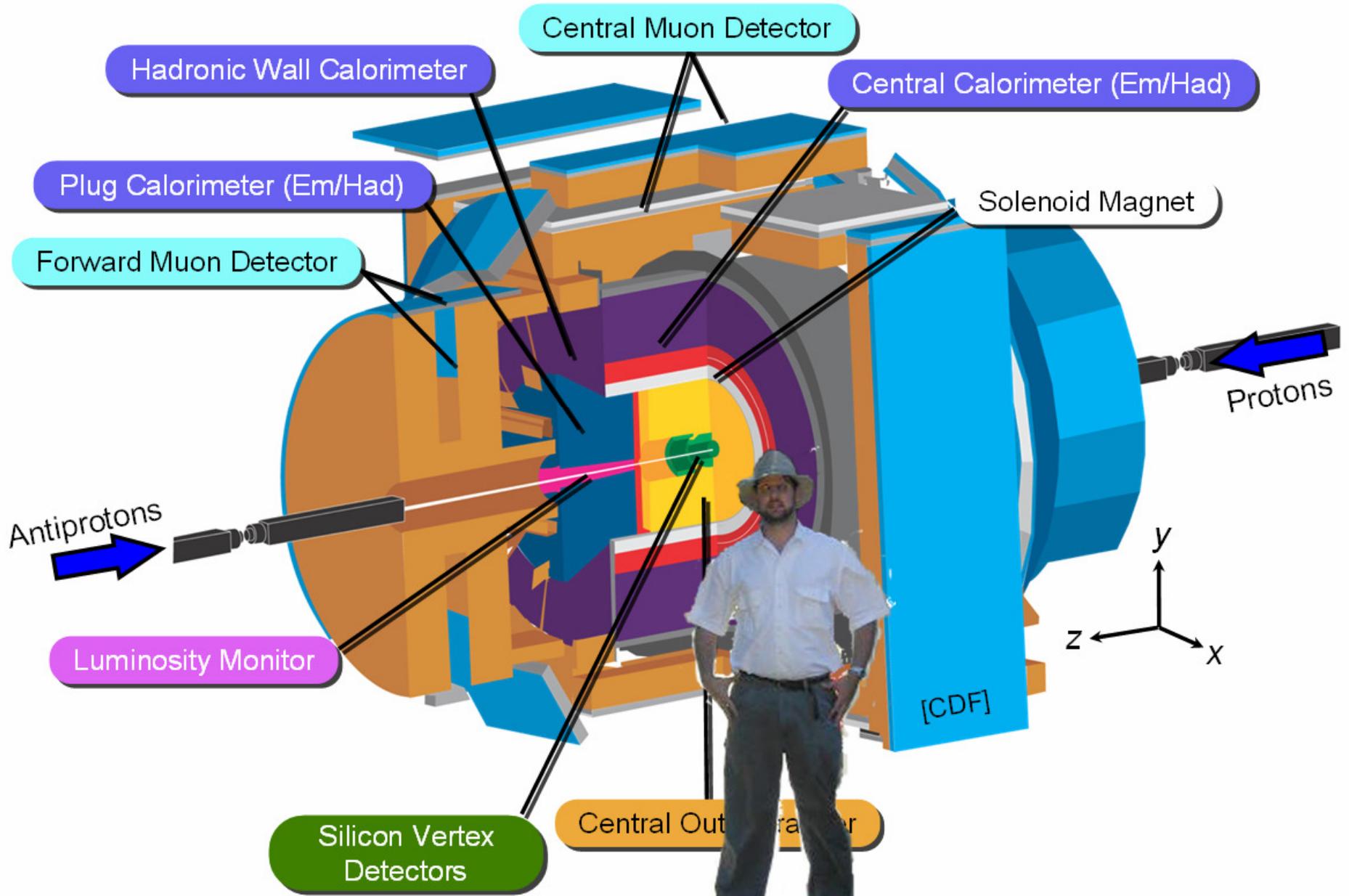
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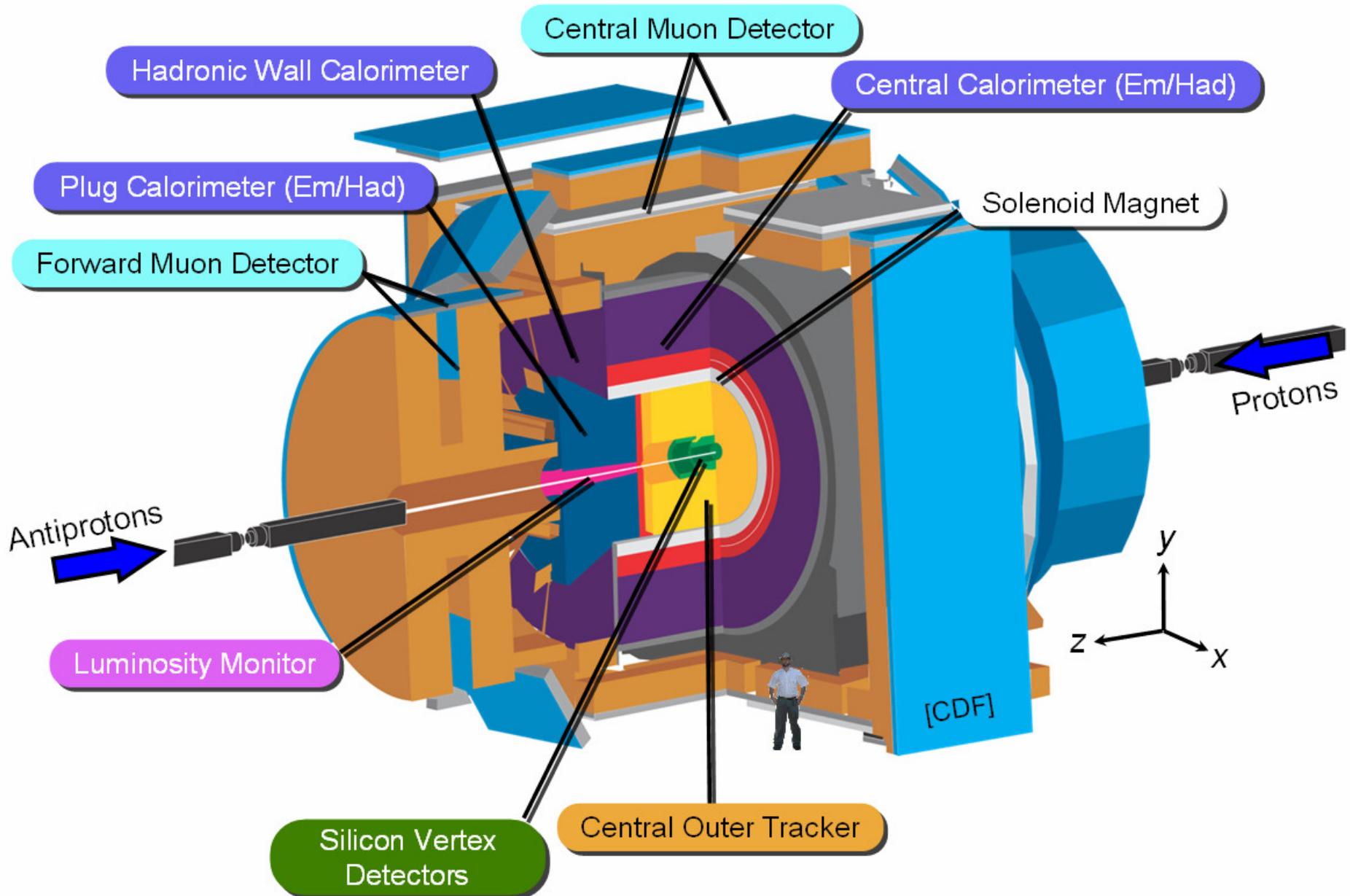
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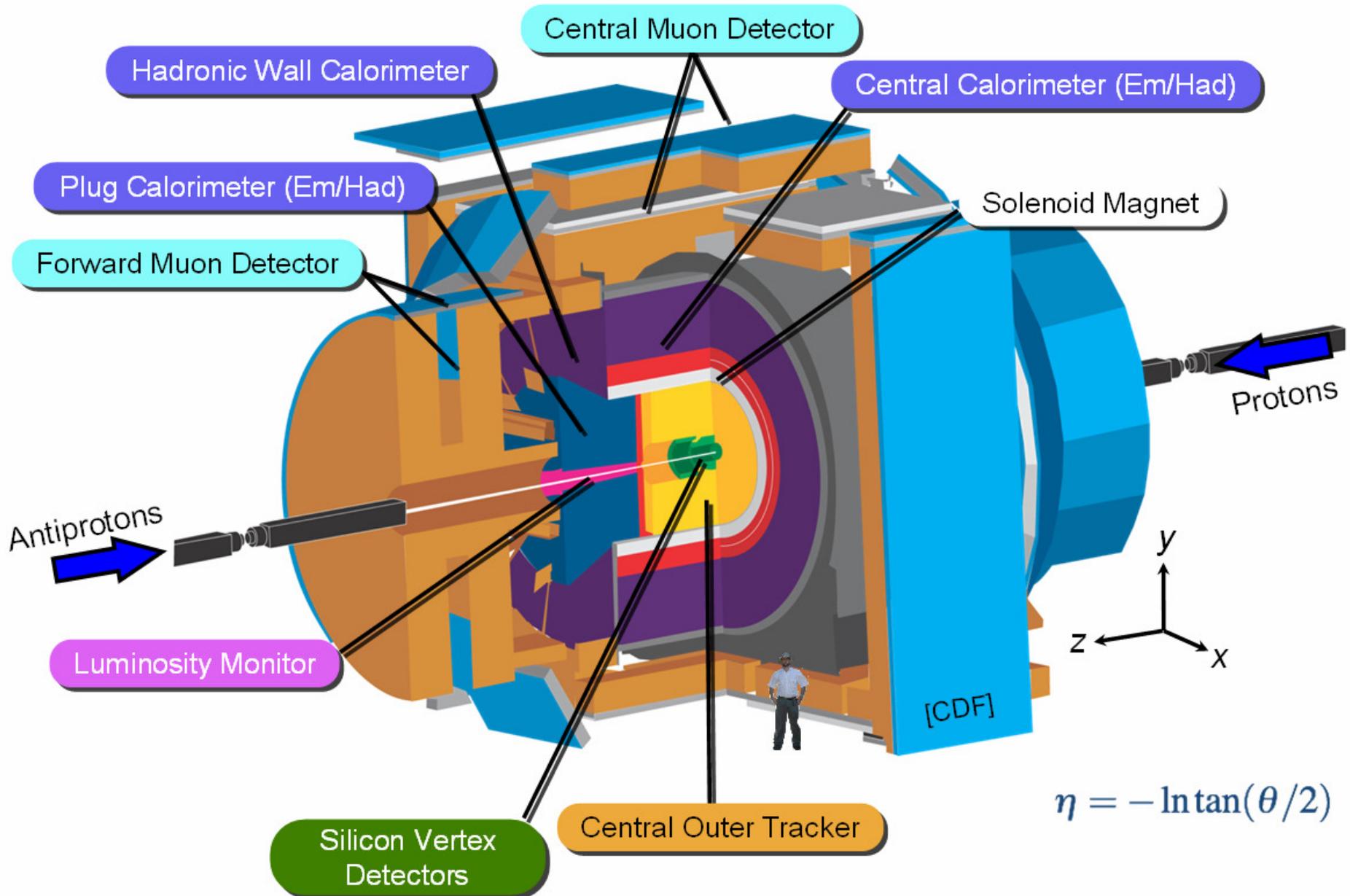
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The CDF II Detector





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- 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).



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A Quick Note About Scale

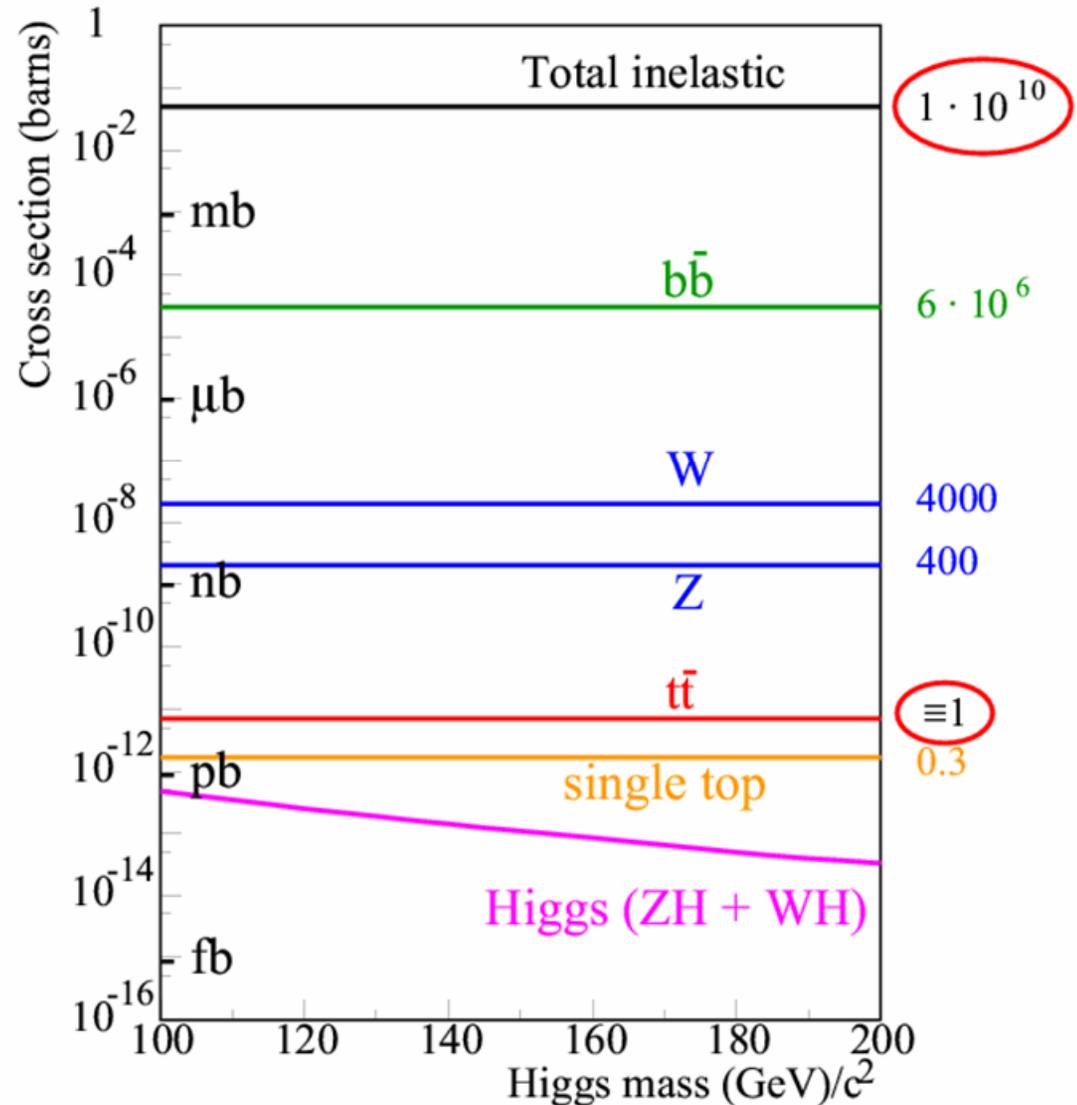


For those not intimately familiar with Tevatron high p_T Physics:

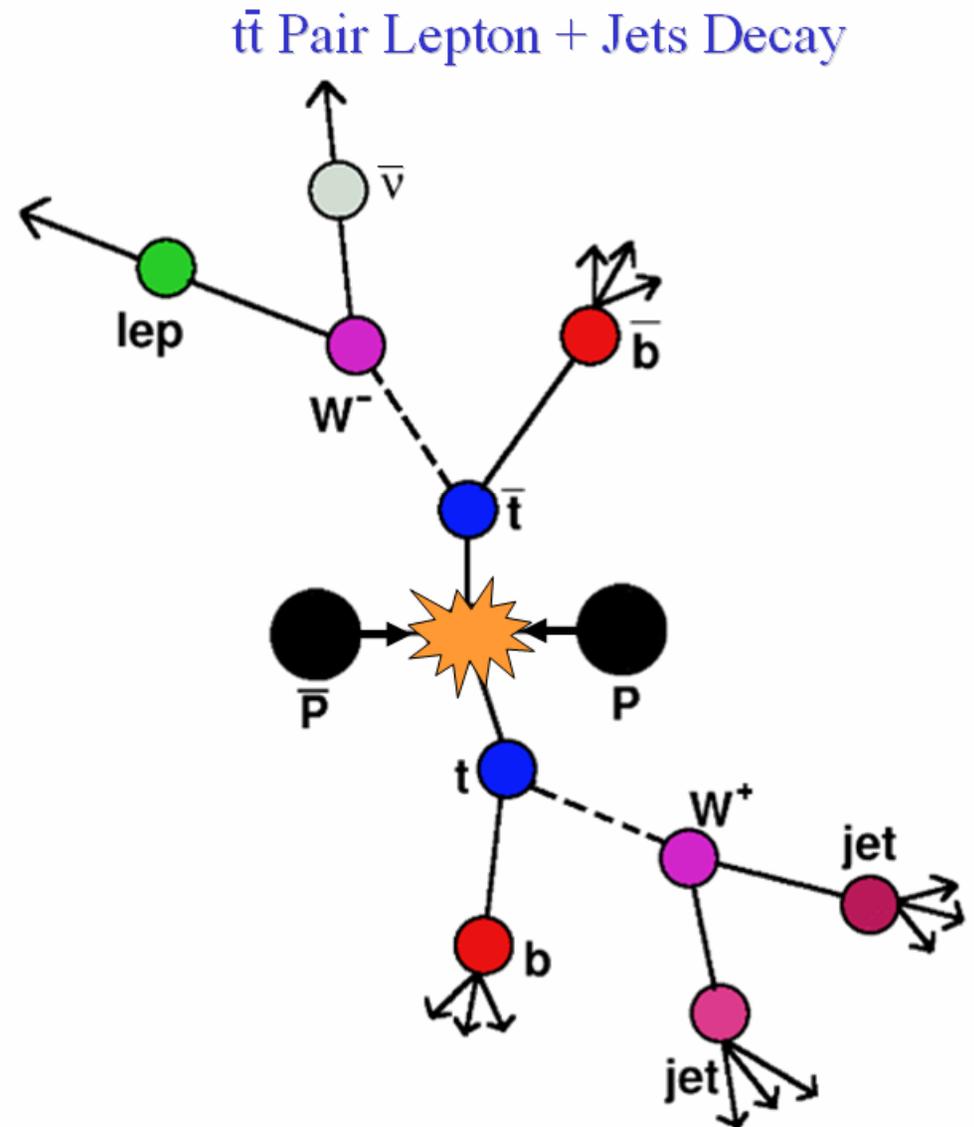
**Top:
1 in 10 Billion**

Reducing and understanding backgrounds is the key.

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



- Top: the **Golden** quark ($\sim 175 \text{ GeV}/c^2$)
 - Only fermion with mass near EW scale.
 - 40 times heavier than the bottom quark.
- Very wide ($1.5 \text{ GeV}/c^2$)
 - 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!



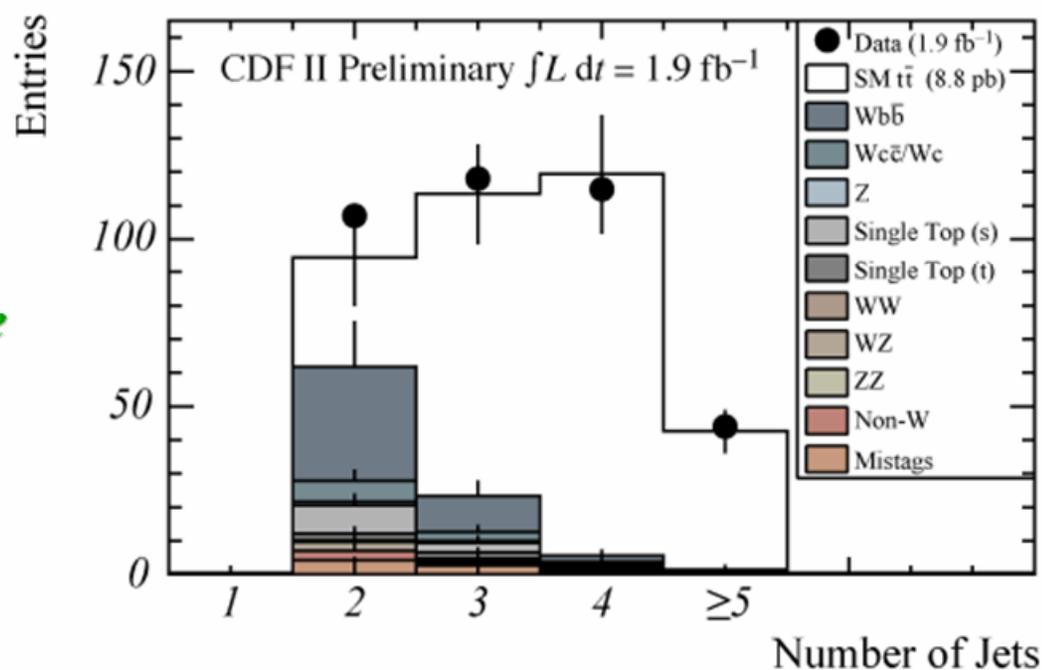


New Era of Top Precision Physics!



- 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



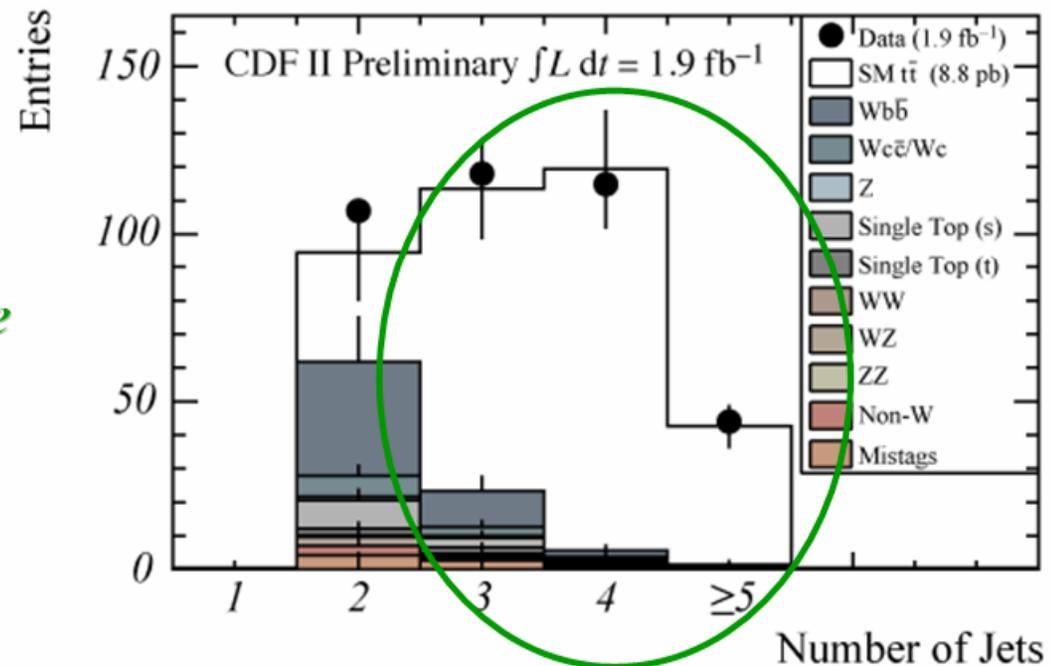


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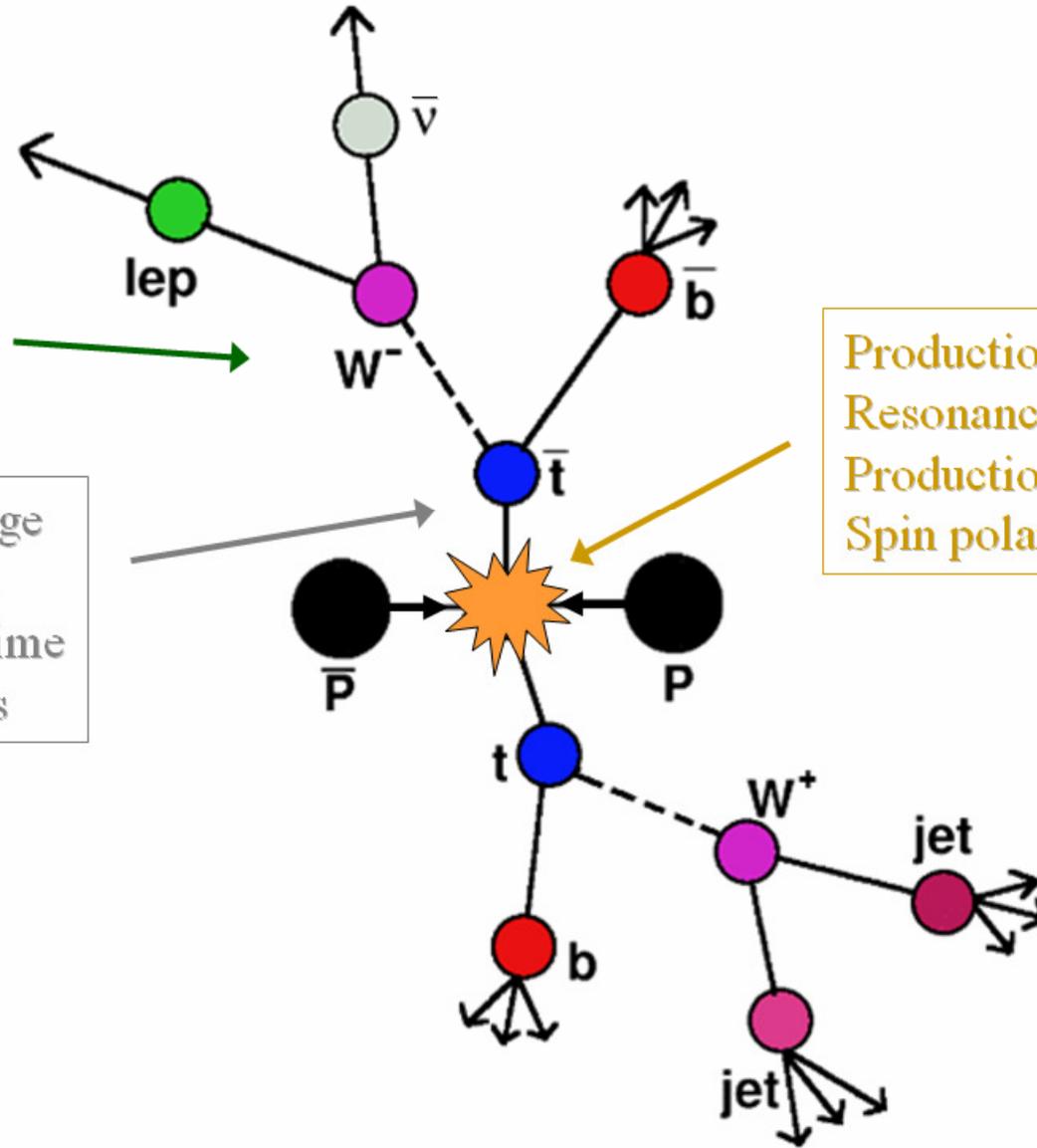
Double B-Tag W + Jets Candidates



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

Top charge
 Top spin
 Top lifetime
 Top mass

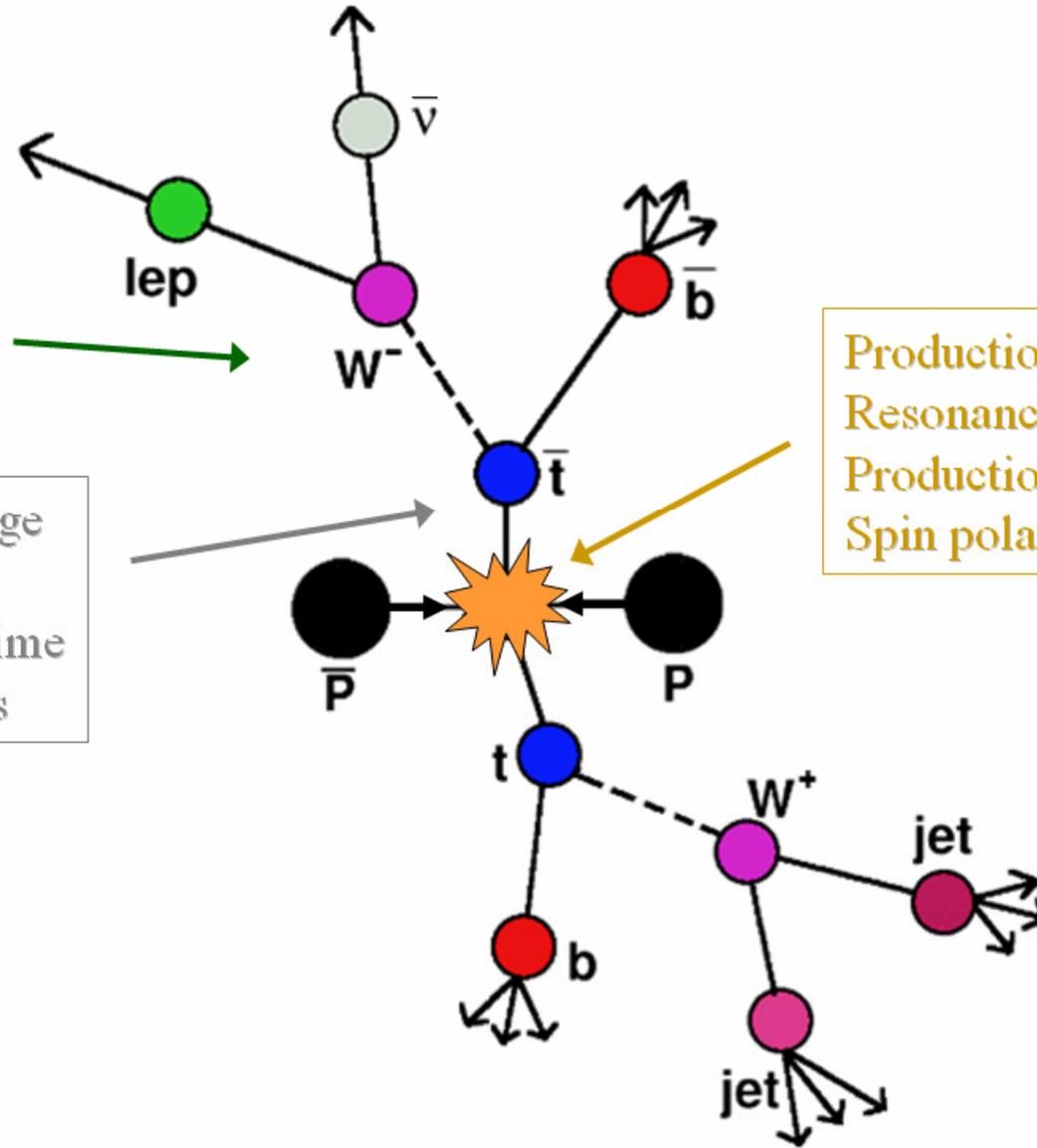
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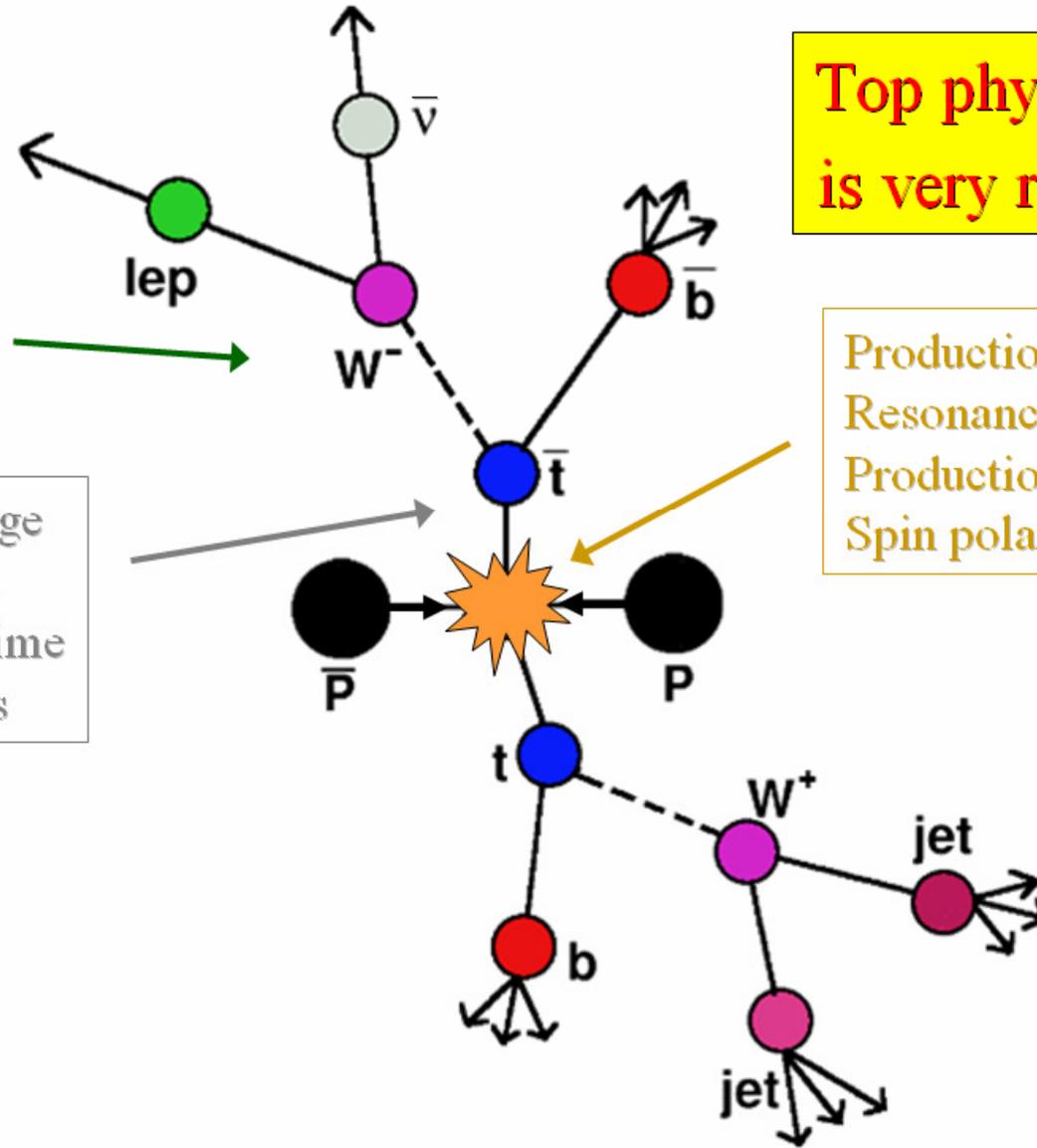


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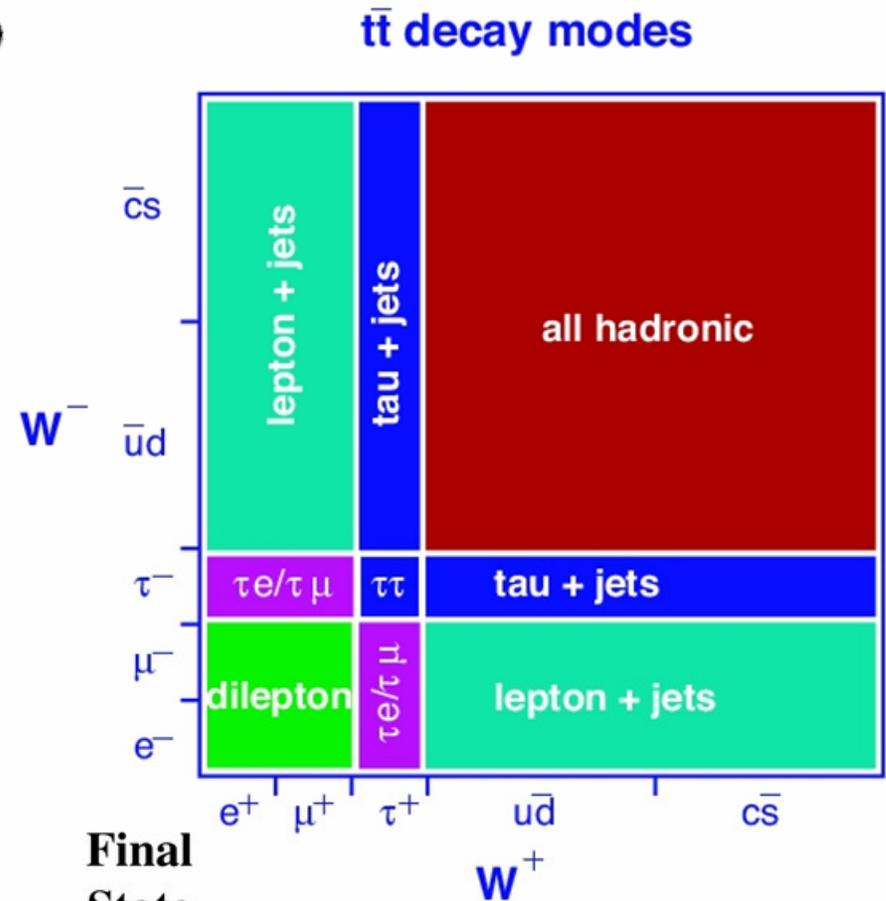
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**Top physics
 is very rich.**

Production cross section
 Resonance production
 Production kinematics
 Spin polarization

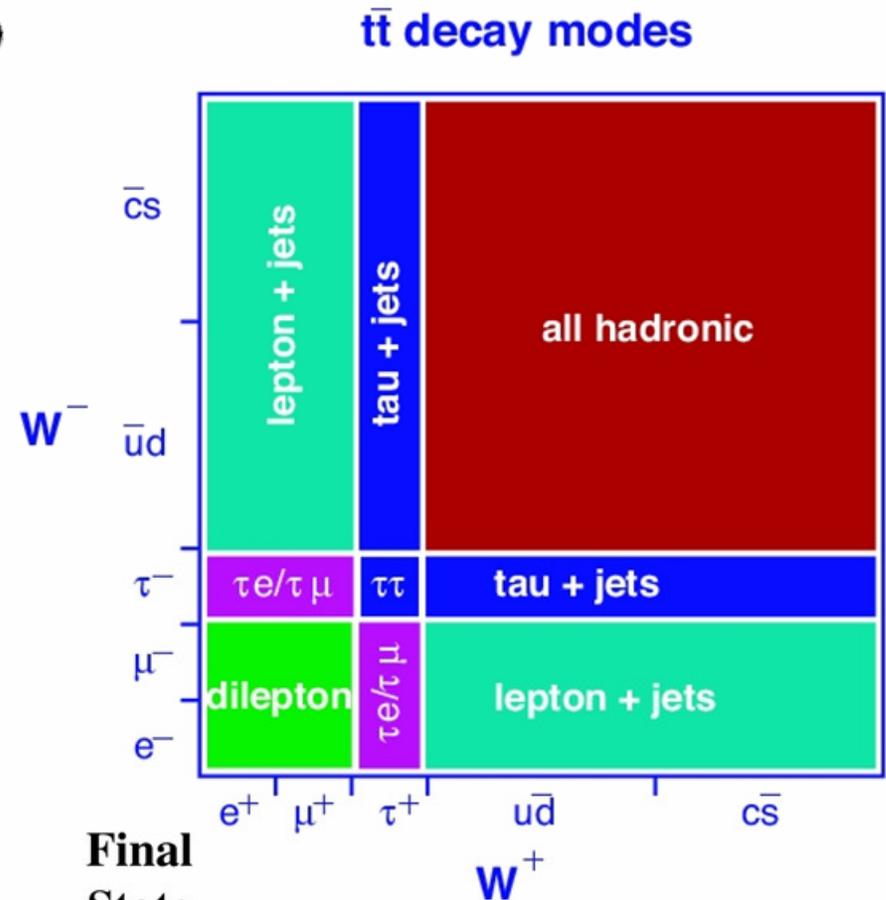


- According to the SM, top quarks almost (?) always decay to Wb .
- When classifying the decay modes, we use the W decay modes:
 - Leptonic
 - Light leptons (e or μ)
 - Tauonic (τ)
 - Hadrons



Decay Mode	Branching Fraction	Relative Background	Final State
Dilepton - no τ s	$\sim 5\%$	Low	$ll \nu\nu bb$
Lepton + Jets - no τ s	$\sim 30\%$	Medium	$l \nu bb jj$
All Hadronic	$\sim 45\%$	High	$bb jjjj$
Tauonic	$\sim 20\%$	High	

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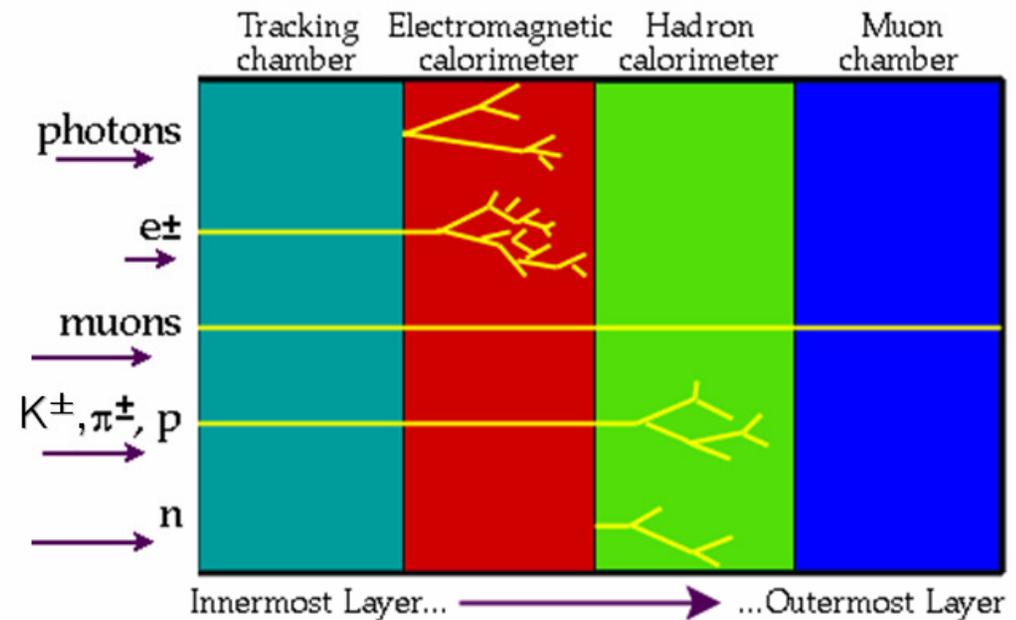
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Important Tool: Lepton ID

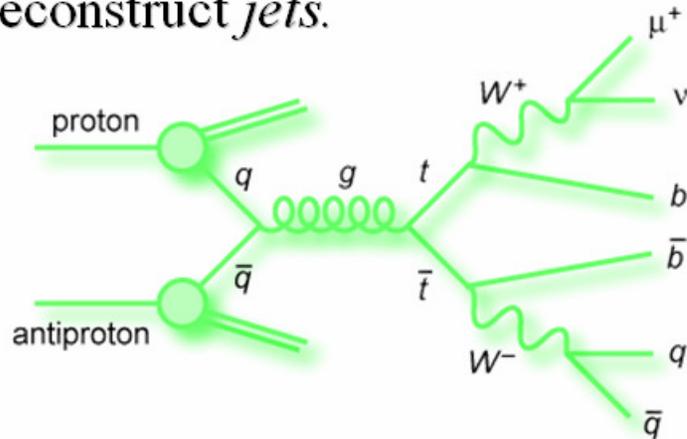


- For many analyses, we need a very pure set of high p_T electrons and muons.
- Electrons (as we reconstruct them):
 - Have charged particle track.
 - Leave almost all of their energy in the electromagnetic calorimeter.
 - Ask for no other nearby tracks.
 - We do not want leptons from (heavy flavor) jets.

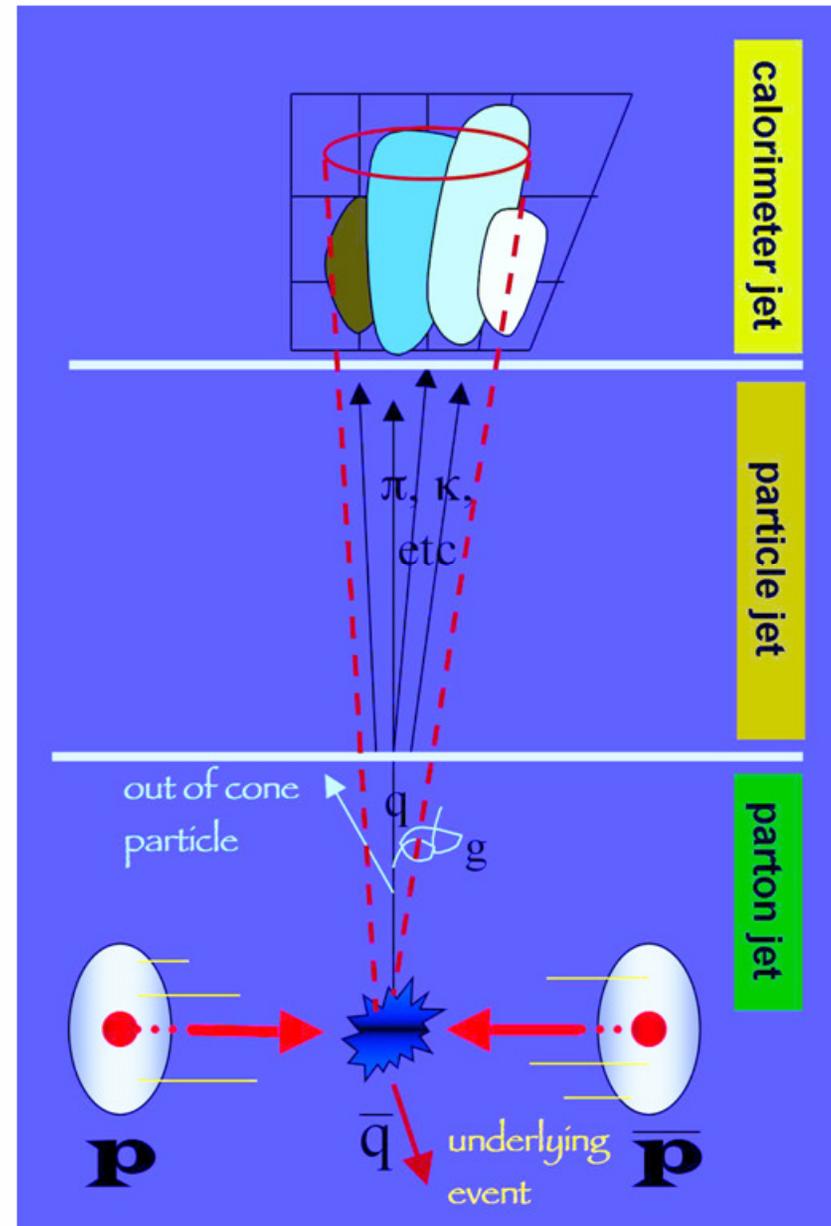


- Muons:
 - Have charged particle track.
 - \sim Minimum ionizing (leave little energy in either the electromagnetic or hadronic calorimeter)
 - Find a “stub” of a track in dedicated muon detector systems on outside of CDF.
 - Ask for no other nearby tracks.

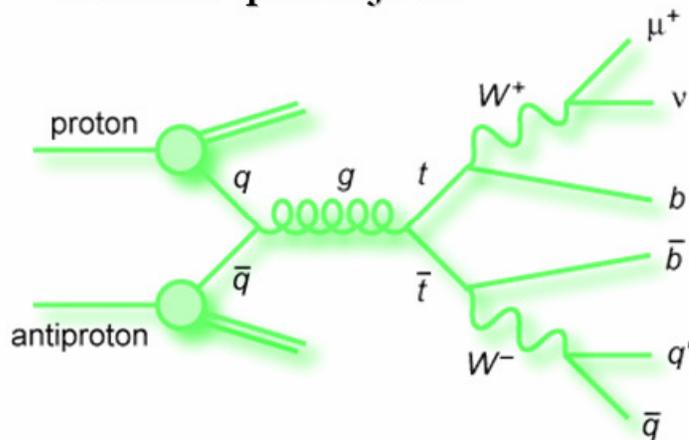
- We think of *partons*, but we reconstruct *jets*.



- 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, ...



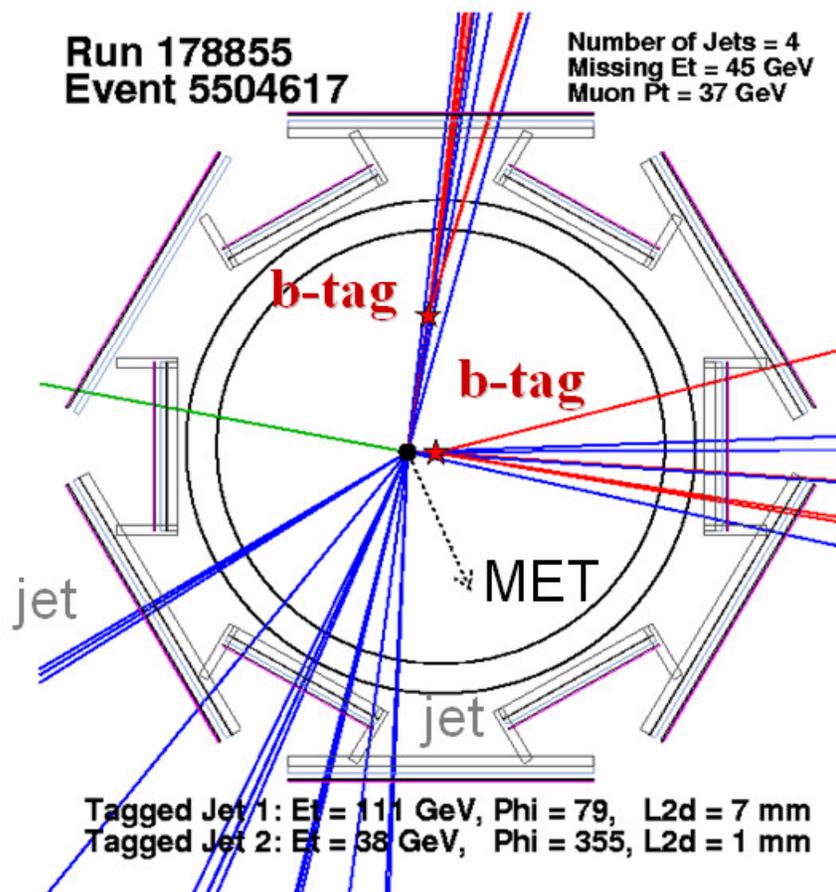
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 - Most backgrounds do not have bottom quark jets.



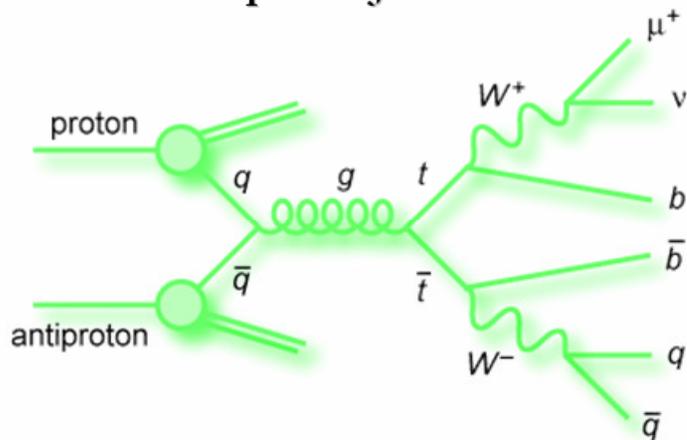
- We rely on the long b quark lifetime.
 - B hadrons can travel several millimeters before decaying.
 - Use displaced vertices or many displaced tracks (impact parameter).

CDF Event:

Close-up View of Layer 00 Silicon Detector



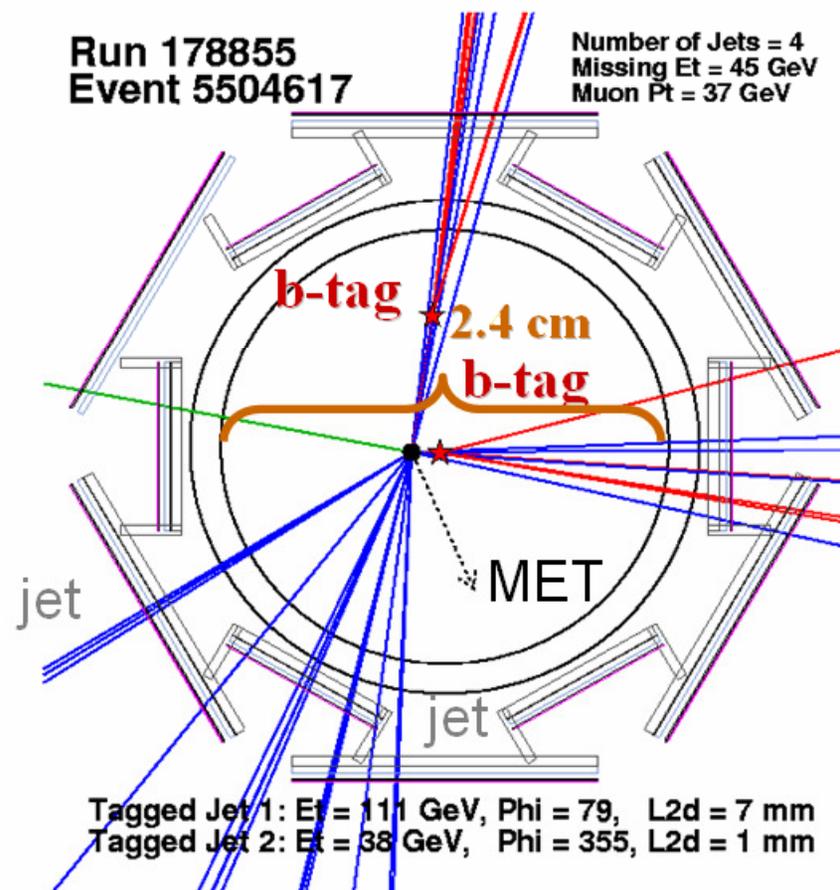
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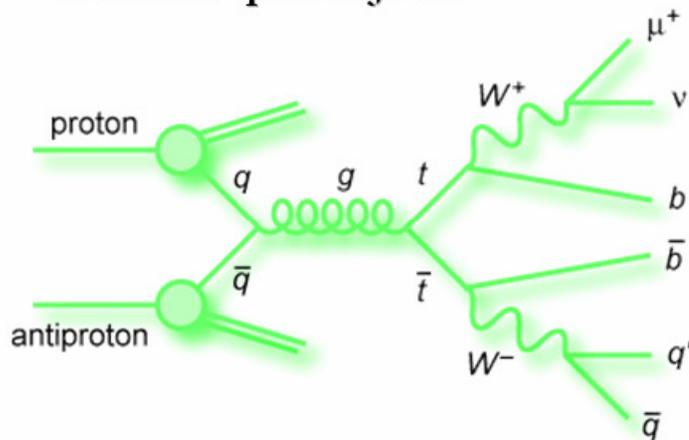
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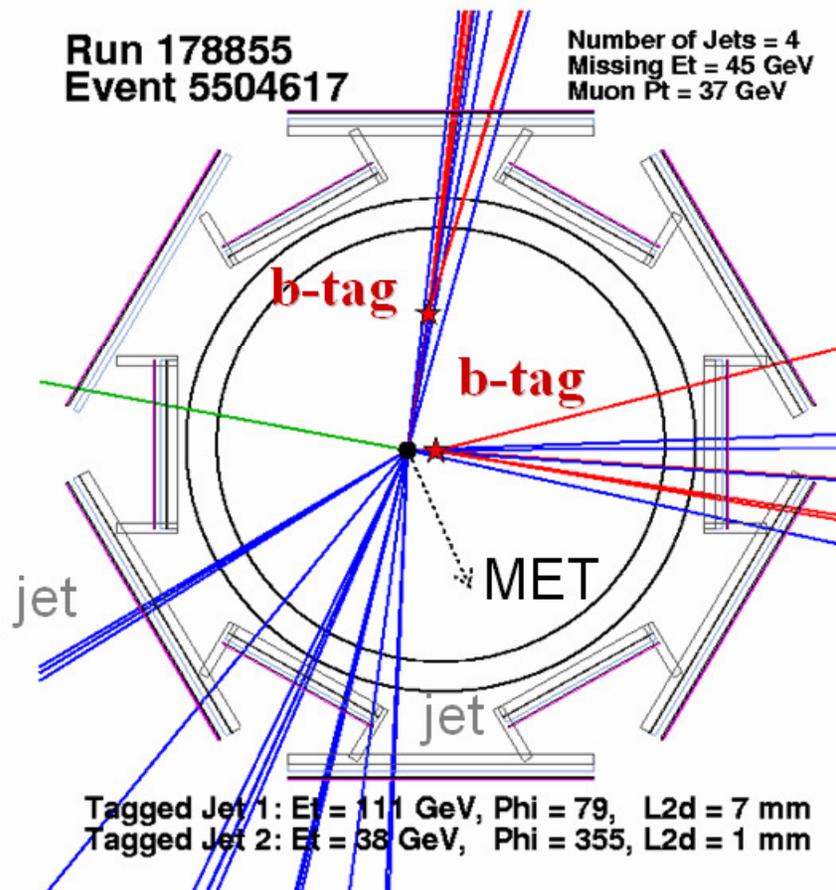
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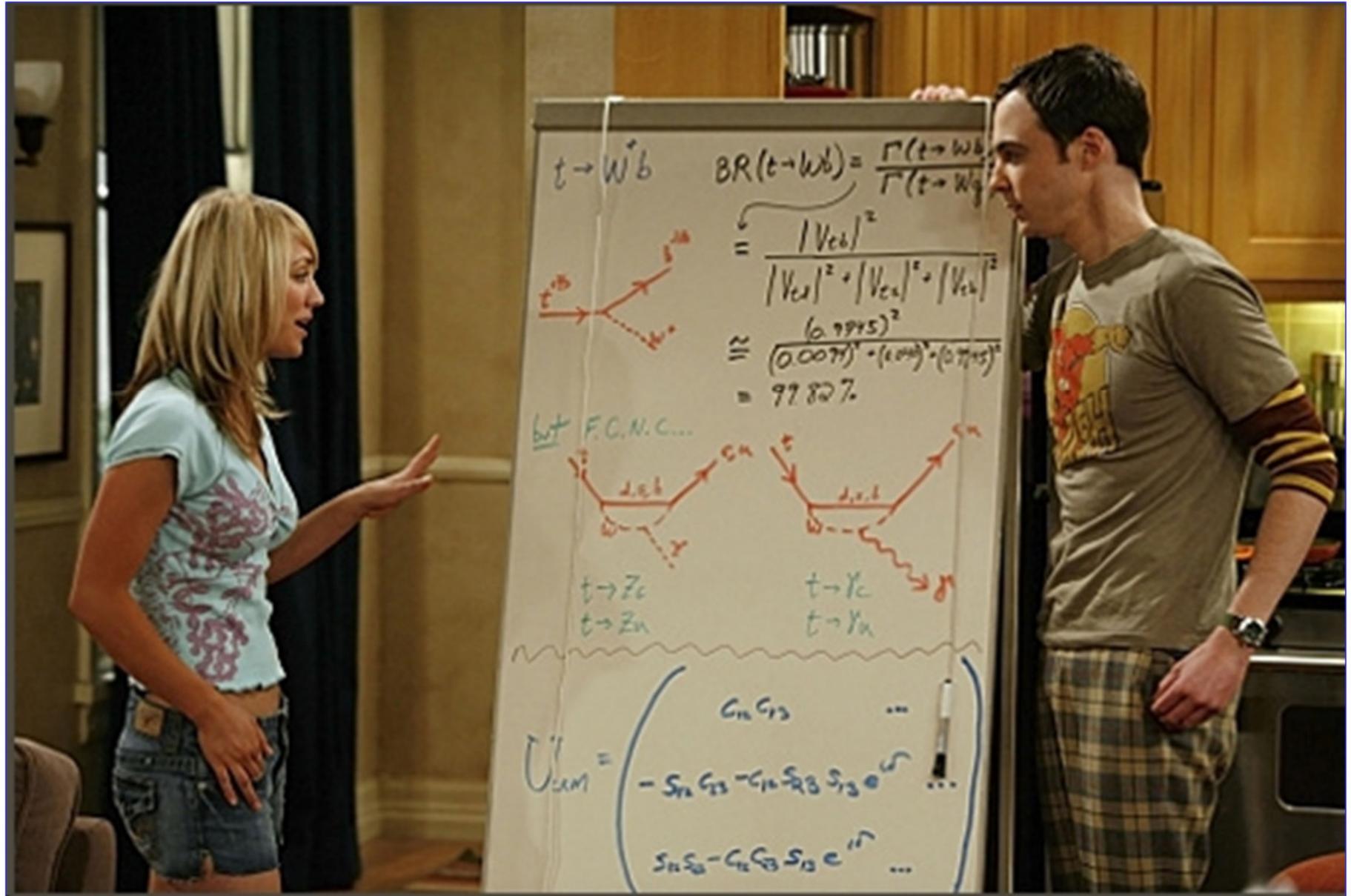


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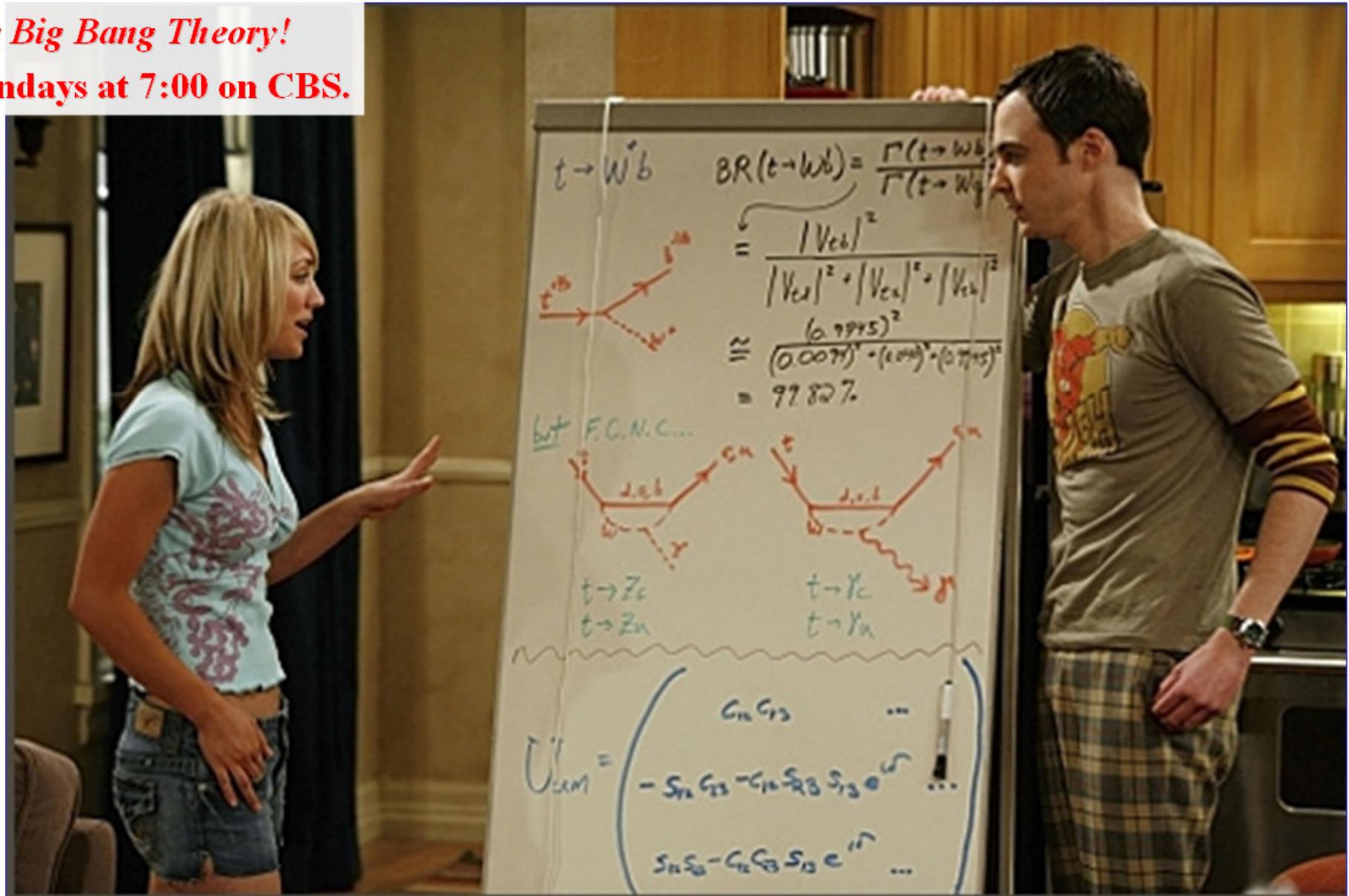
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The Big Bang Theory!
Mondays at 7:00 on CBS.



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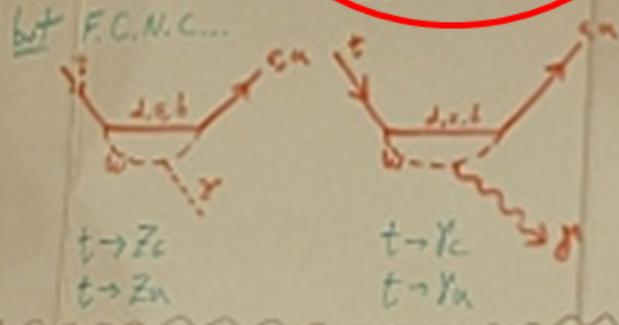
Top Branching Fractions

$$BR(t \rightarrow Wb) = \frac{\Gamma(t \rightarrow Wb)}{\Gamma(t \rightarrow Wq)}$$

$$= \frac{|V_{cb}|^2}{|V_{cb}|^2 + |V_{cb}|^2 + |V_{cb}|^2}$$

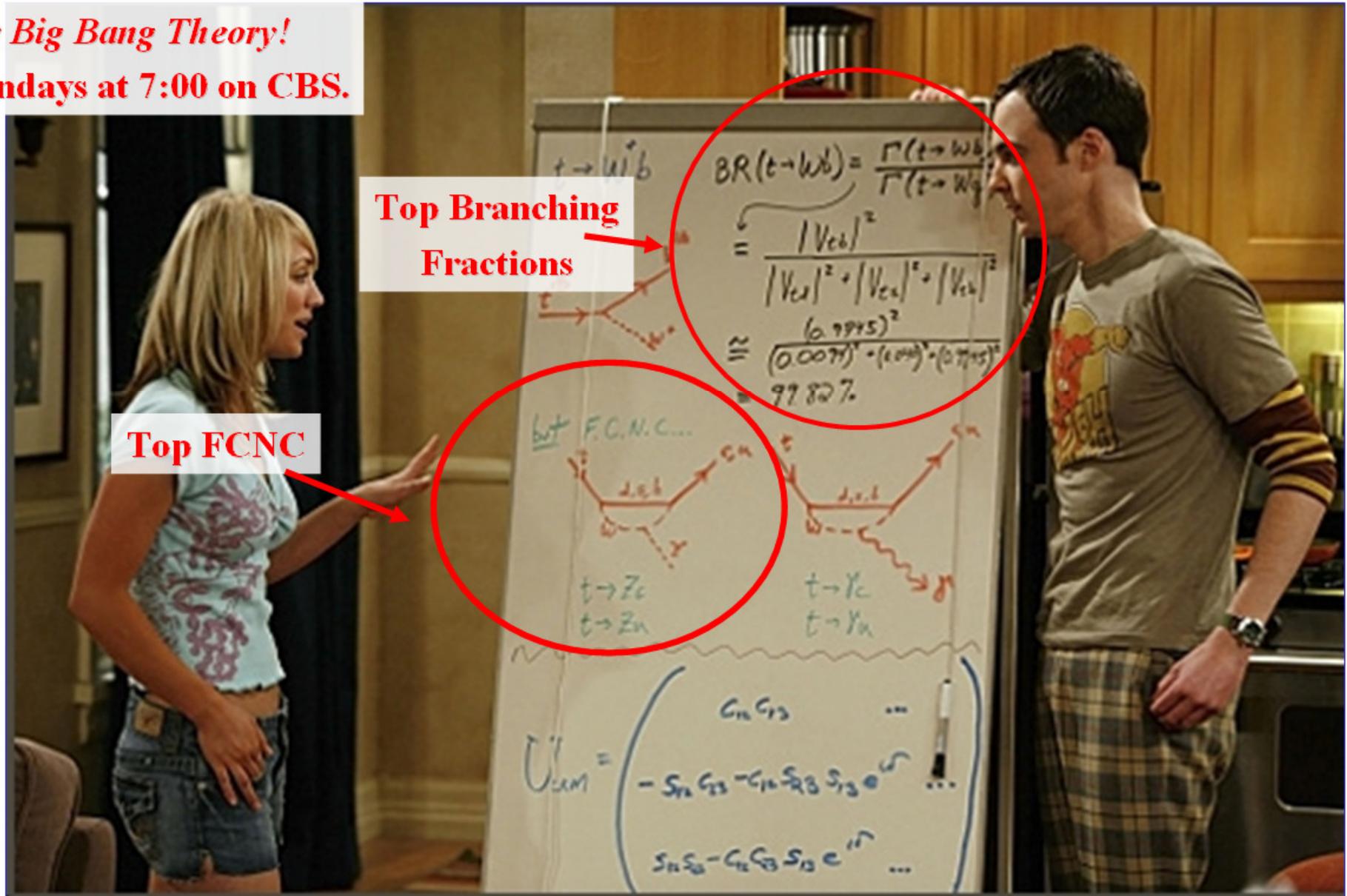
$$\approx \frac{(0.9945)^2}{(0.007)^2 + (0.04)^2 + (0.9945)^2}$$

$$= 99.827\%$$



$$U_{CKM} = \begin{pmatrix} c_{12}c_{13} & & \dots \\ -s_{12}c_{13} - c_{12}s_{23}s_{13}e^{i\delta} & & \dots \\ s_{12}s_{13} - c_{12}c_{23}s_{13}e^{i\delta} & & \dots \end{pmatrix}$$

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Top Branching Fractions

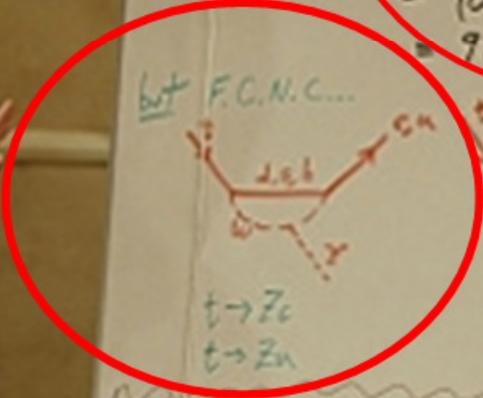
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Top FCNC



$$U_{cbm} = \begin{pmatrix} c_{12}c_{13} & & \dots \\ -s_{12}c_{13} - c_{12}s_{23}s_{13}e^{i\delta} & & \dots \\ s_{12}s_{13} - c_{12}c_{23}s_{13}e^{i\delta} & & \dots \end{pmatrix}$$



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Acceptances

Backgrounds

Unblinding

Round 2



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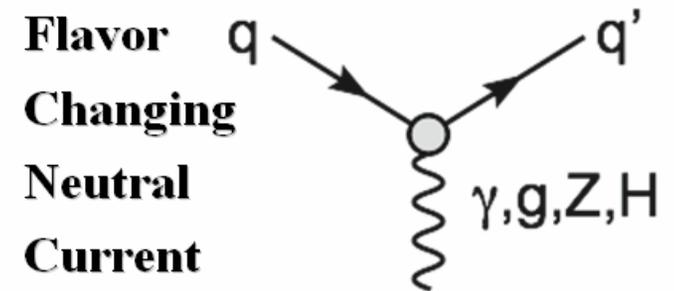
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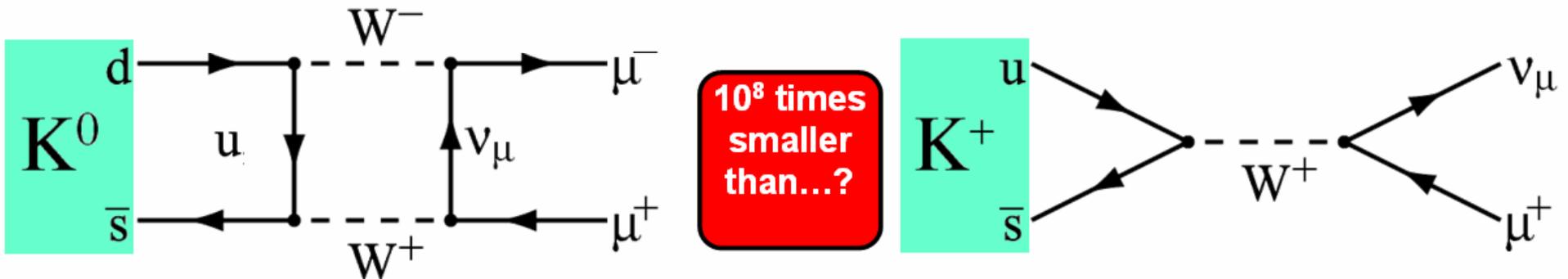
Unblinding

Round 2

- 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: $b \rightarrow s\gamma$, $t \rightarrow Hc$, ...

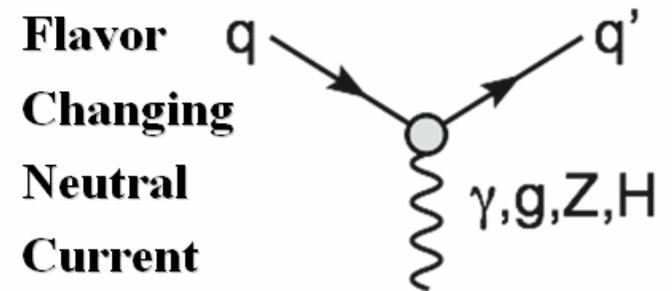


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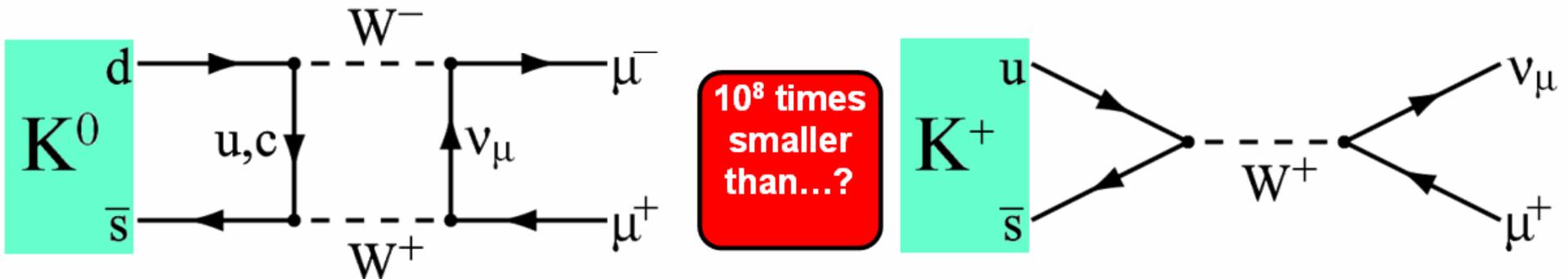


- Solution: “**GIM Mechanism**” (Glashow, Iliopoulos, Maiani, 1970)
 - Fourth quark** needed for cancellation in box diagram: prediction of charm quark.
 - Cancellation would be **exact** if all quarks had the **same mass**: estimate of charm quark mass.

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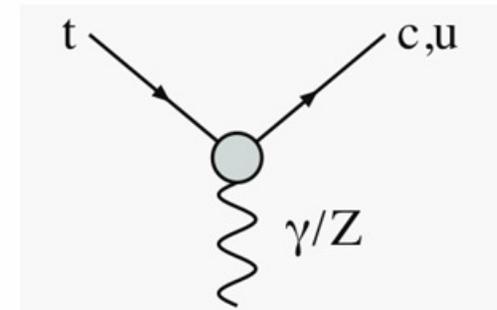
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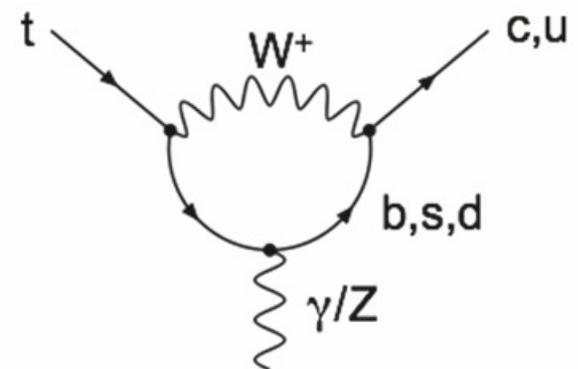
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- SM Higgs mechanism: weak neutral currents (NC) do not change the flavor of quarks/leptons (“flavor-diagonal”)
 - ⇒ no FCNC at “tree level.”
- FCNC possible e.g. via **penguin diagrams**.
- Suppression of this mode:
 - **GIM mechanism**
 - **Cabibbo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

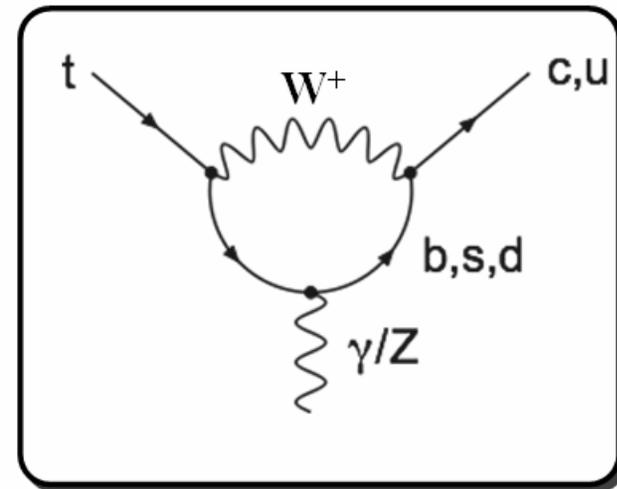
Generic FCNC



Penguin Diagram



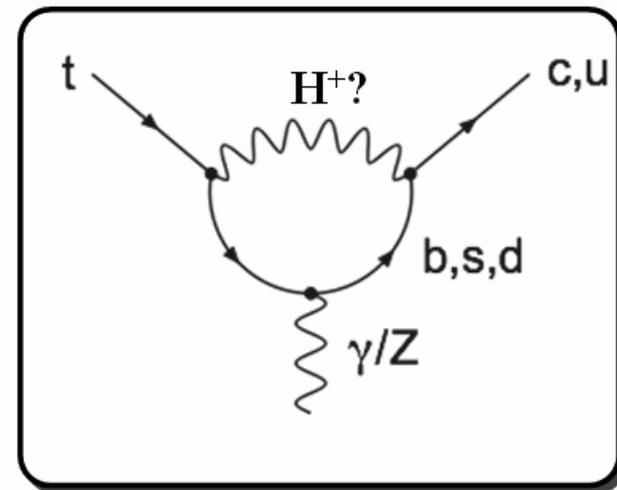
- FCNC are **enhanced** in many models of physics beyond the SM.
- Enhancement mechanisms:
 - FCNC interactions at **tree level**.
 - Weaker GIM cancellation by **new particles in loop corrections**.
- Examples:
 - **New quark singlets**: Z couplings not flavor-diagonal → tree level FCNC.
 - **Two Higgs 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($t \rightarrow Zq$)
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. Polon **B35** (2004) 2695]

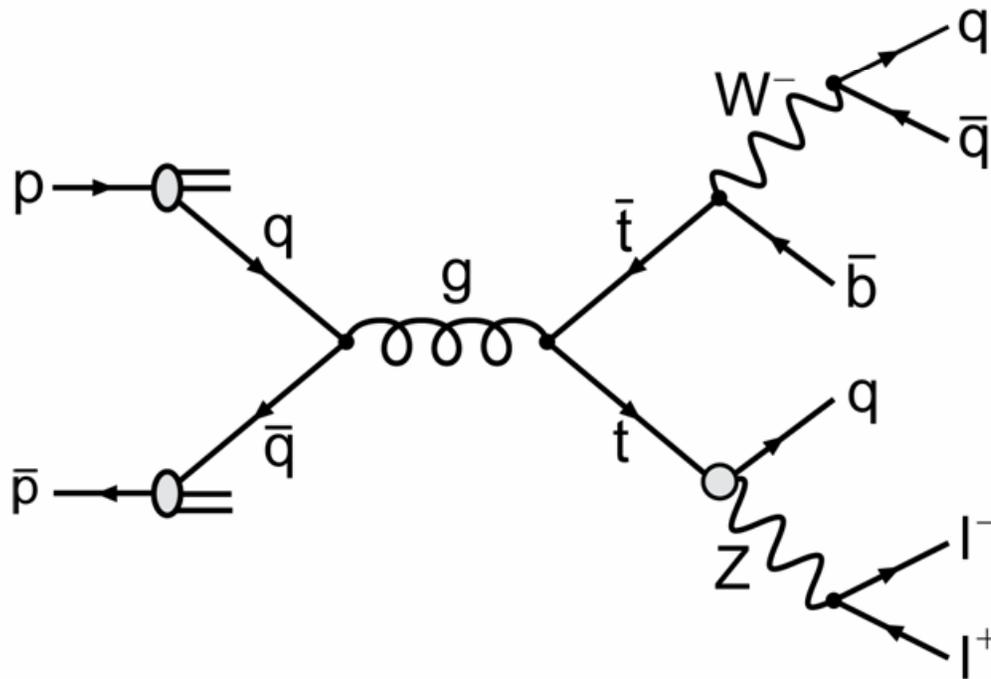
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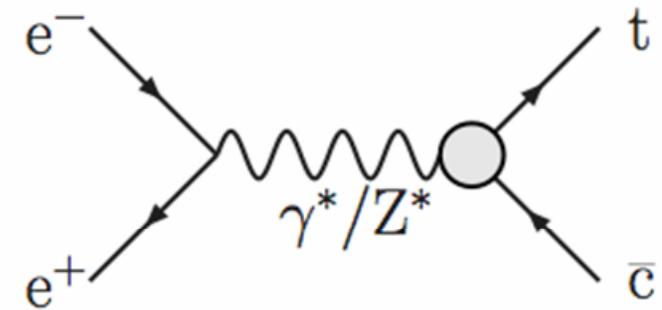
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- Run I Search:
 - 110 pb⁻¹ of data
 - $t\bar{t} \rightarrow Zc Wb \rightarrow Z+\geq 4j$
 - Limit: **Br (t → Zc) < 33%** at 95% C.L.



- Limit from LEP II
 - search for single top production:
 $e^+ e^- \rightarrow t \bar{c}$

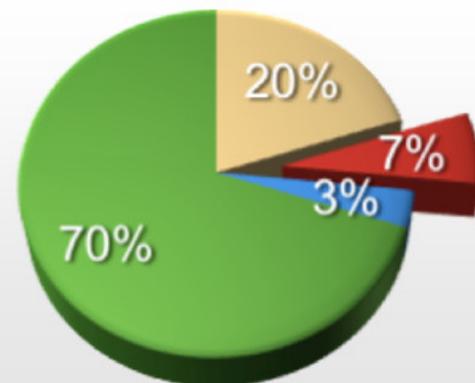


- 634 pb⁻¹
- Limit: **Br (t → Zc) < 13.7%** at 95% C.L.
- ⇒ **Best limit so far with Z bosons.**

- 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 $t\bar{t} \rightarrow Zc Wb$:
 - $Z \rightarrow$ **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**.

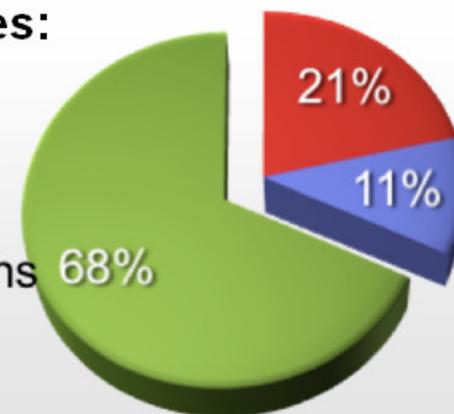
Z Decay Modes:

- $Z \rightarrow \nu\nu$
- $Z \rightarrow ee/\mu\mu$
- $Z \rightarrow \tau\tau$
- $Z \rightarrow$ hadrons



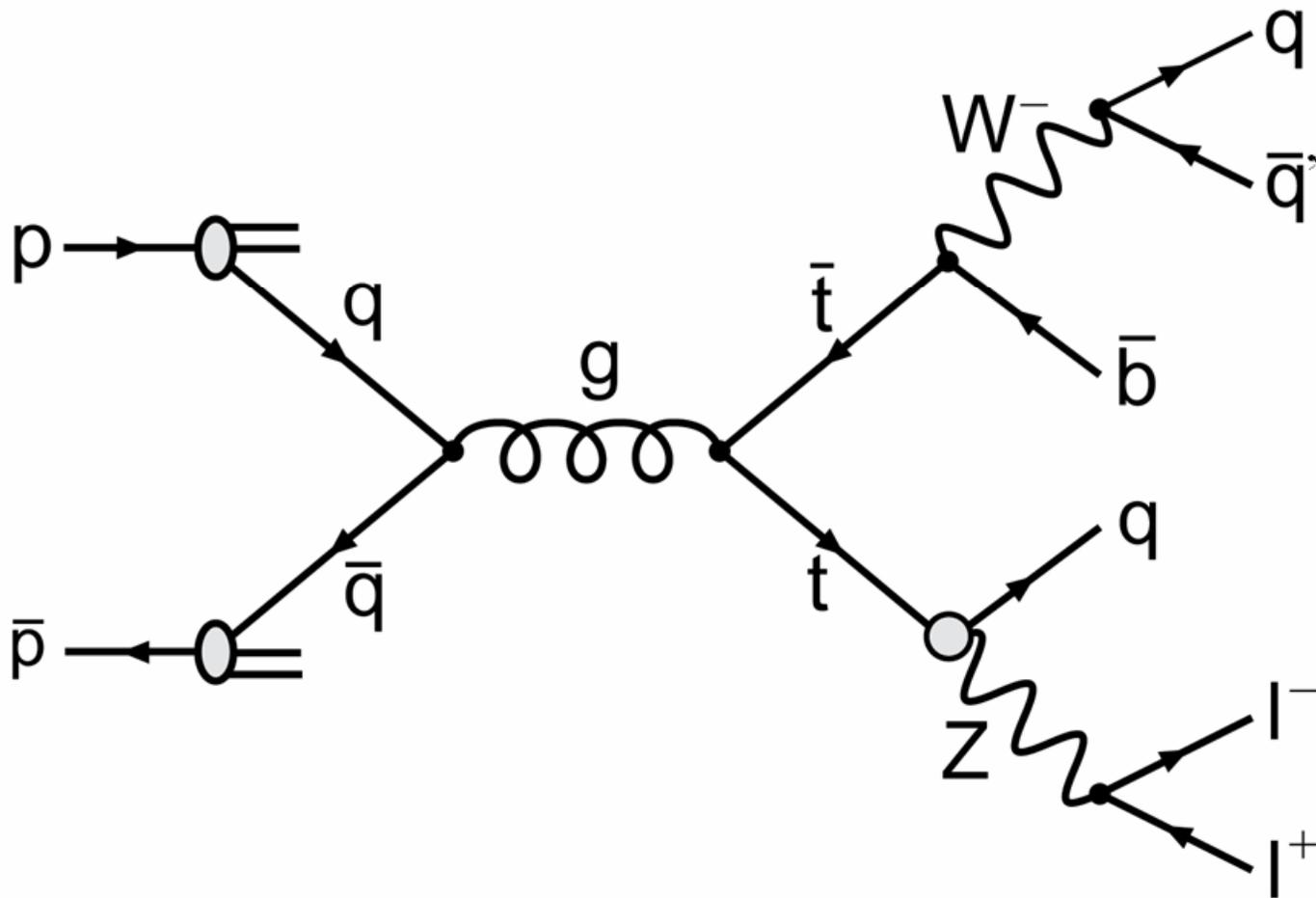
W Decay Modes:

- $W \rightarrow l\nu$
- $W \rightarrow \tau\nu$
- $W \rightarrow$ hadrons



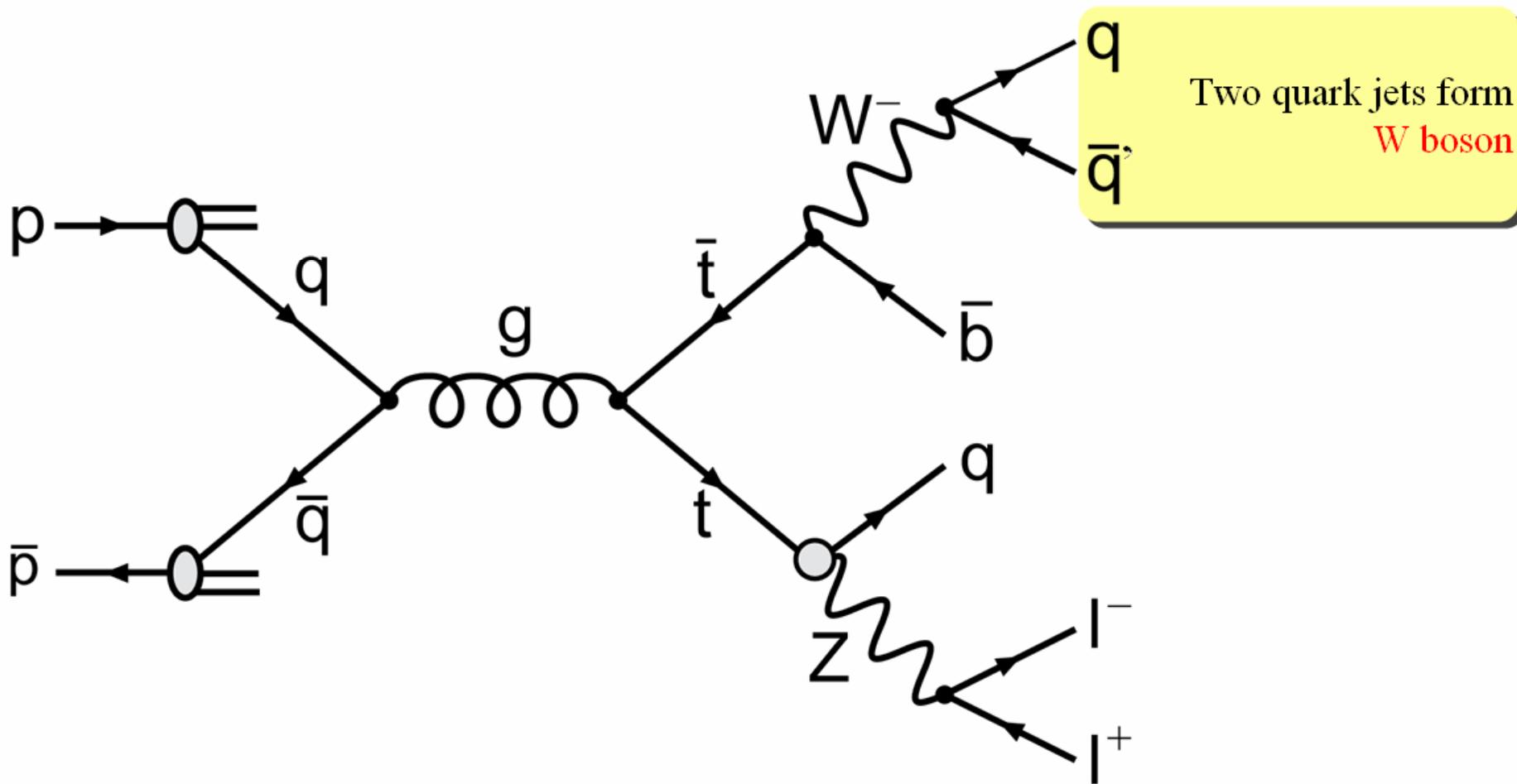


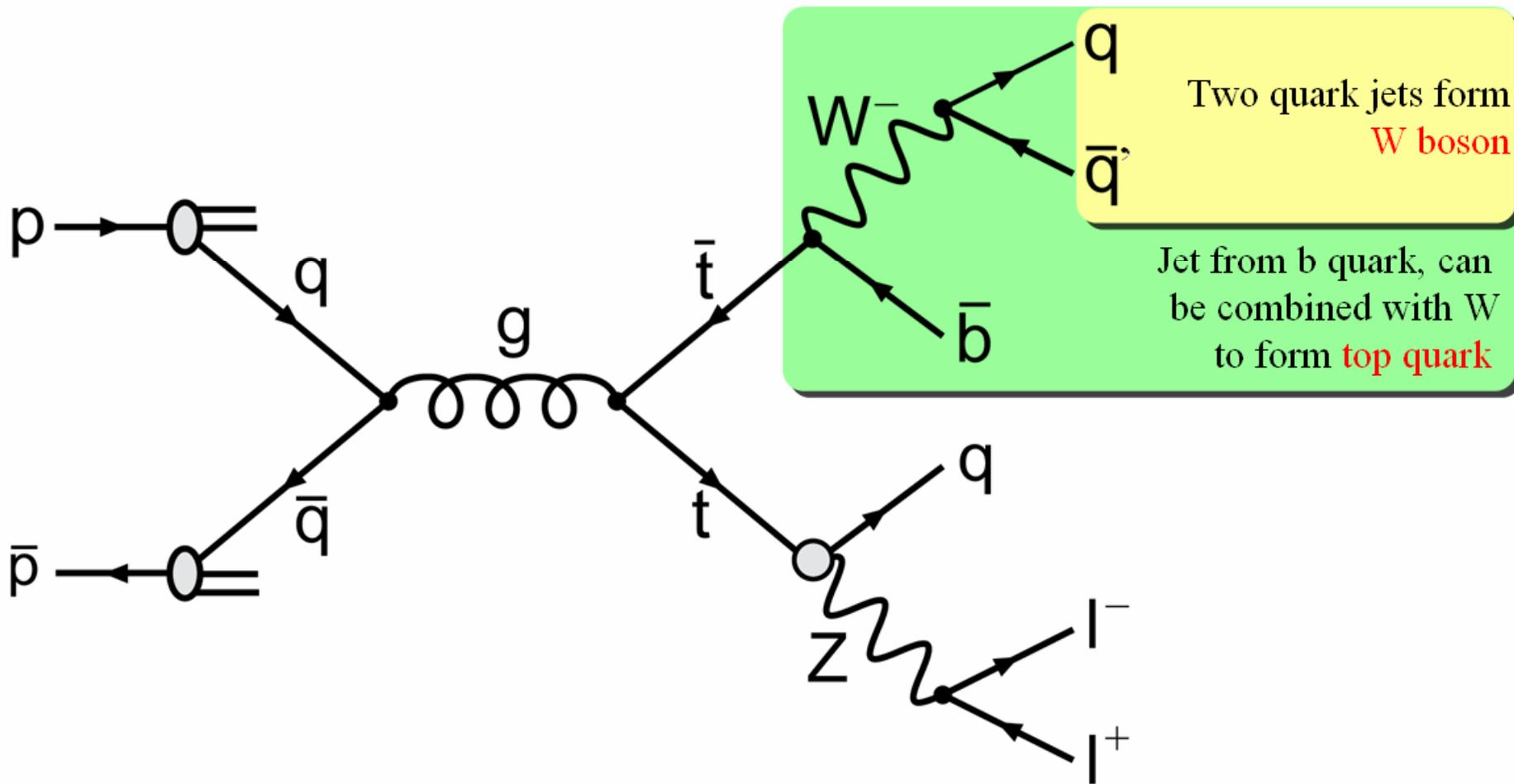
Search for FCNC: Ingredients

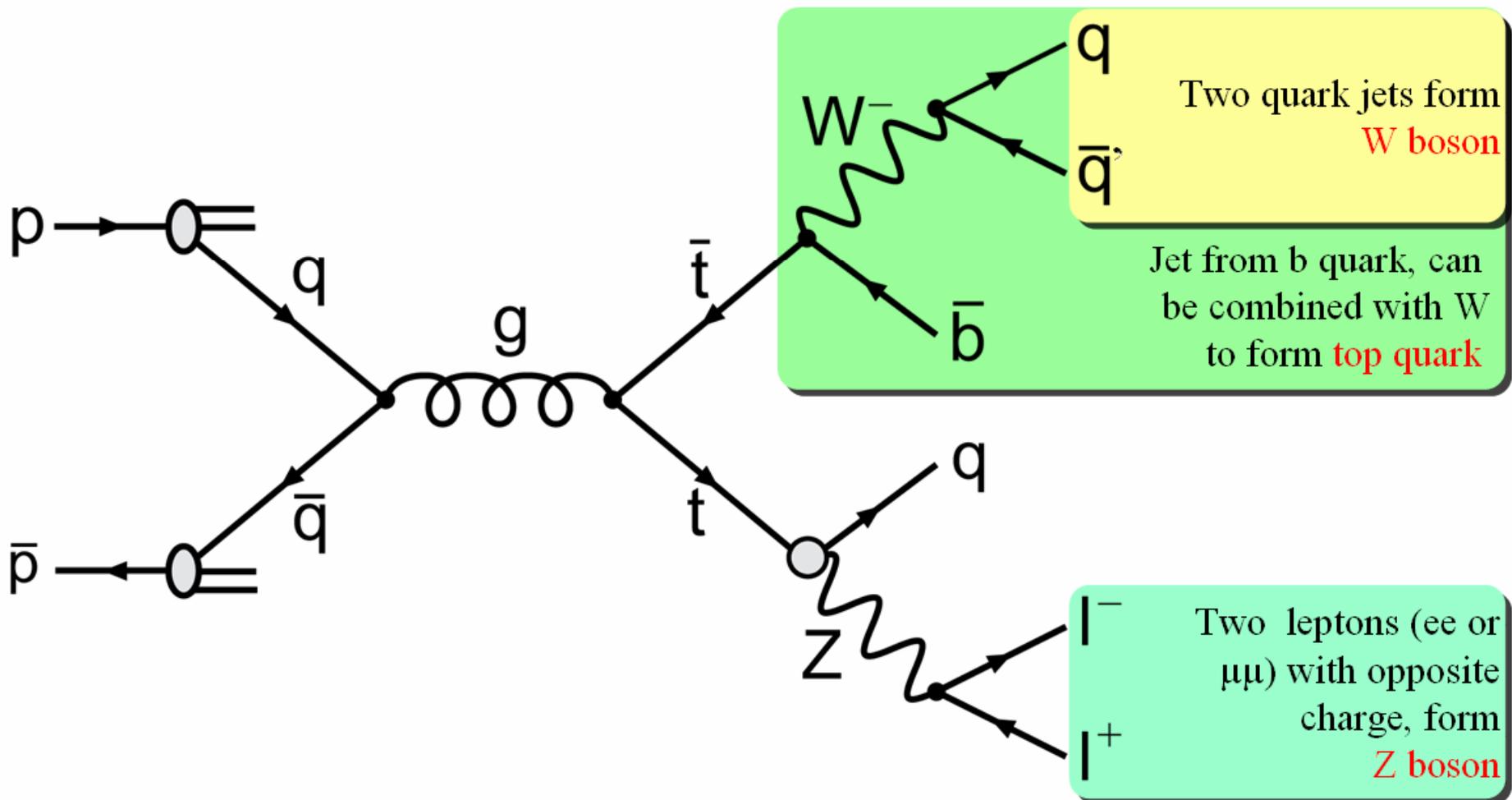


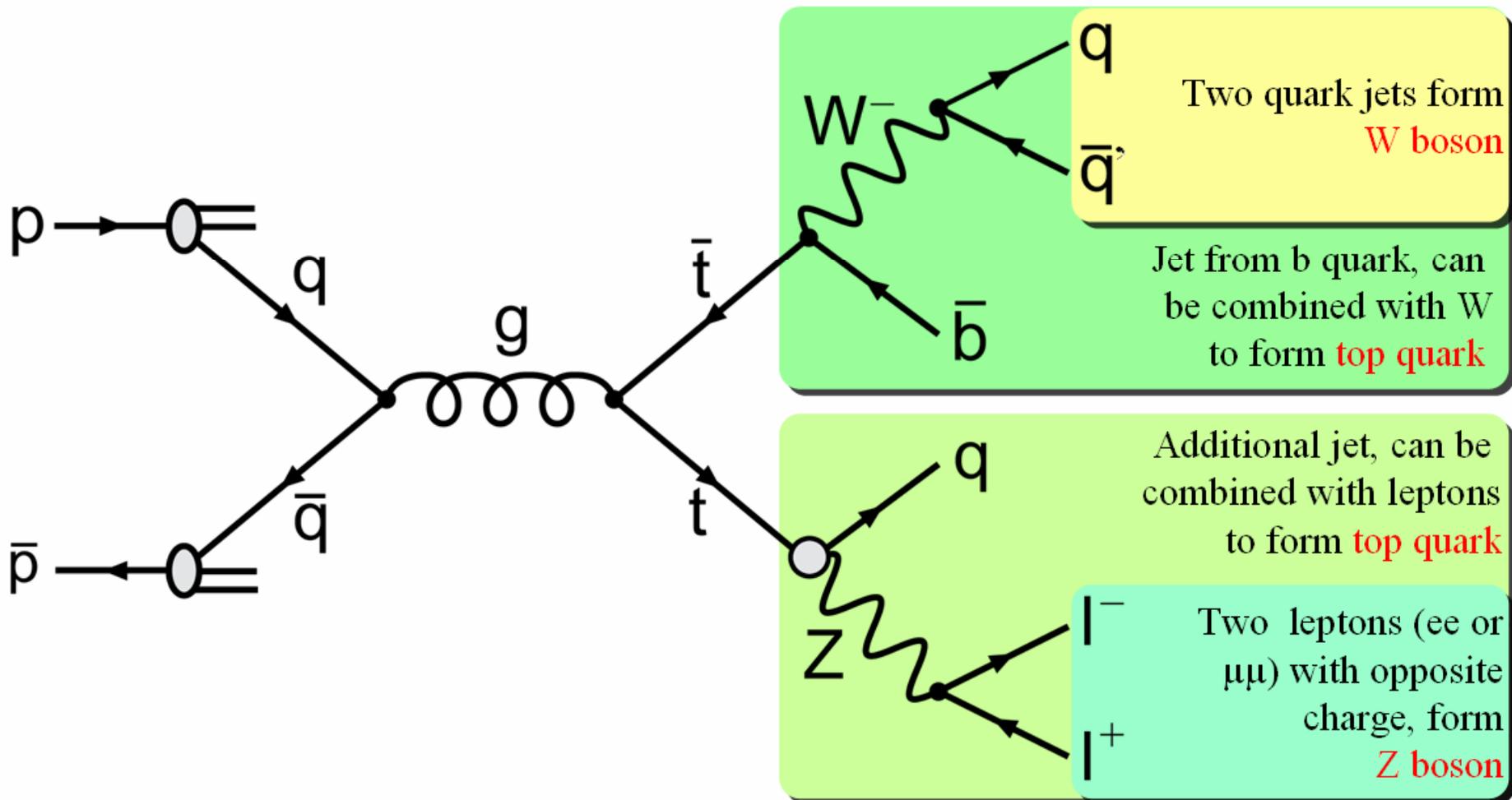


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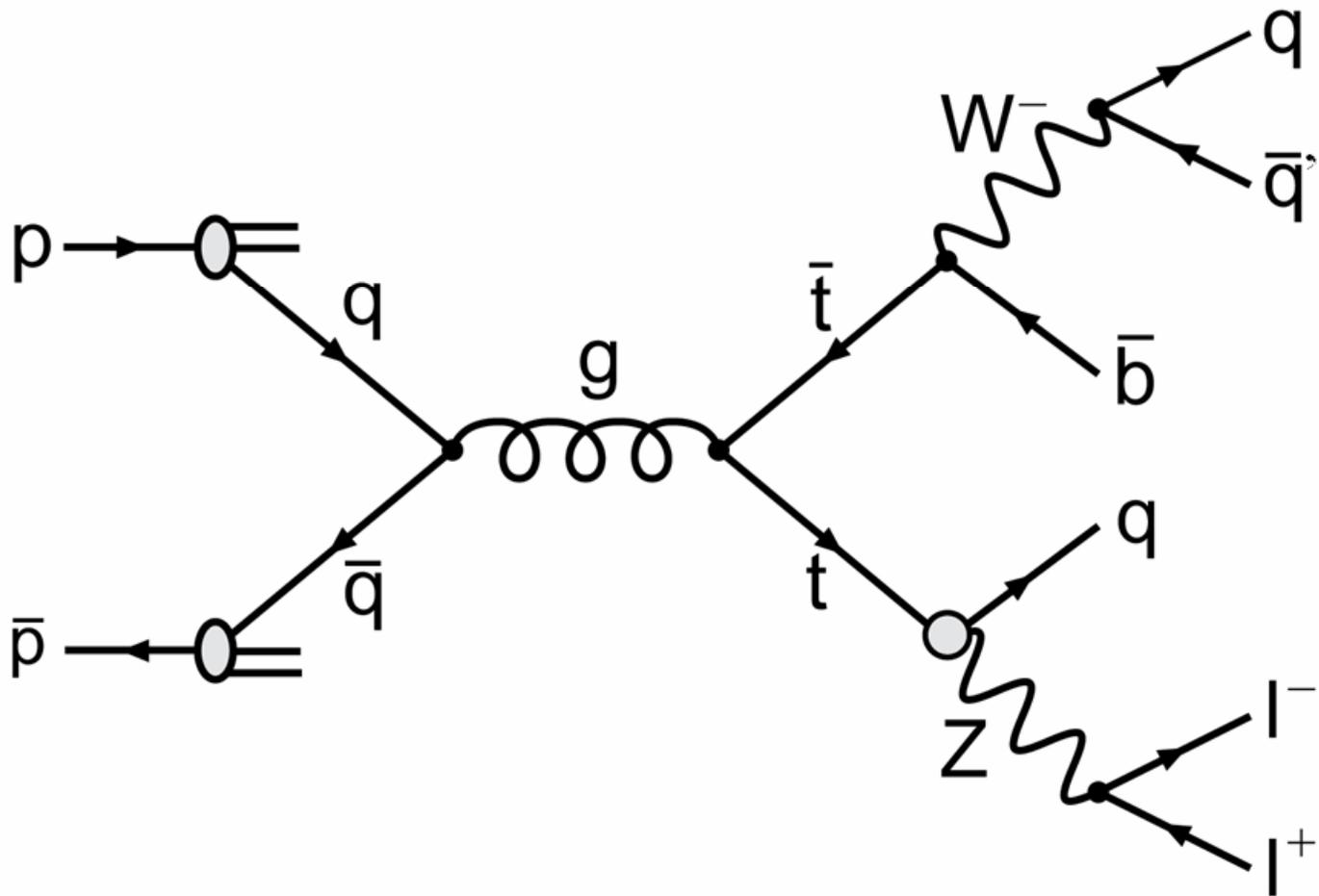








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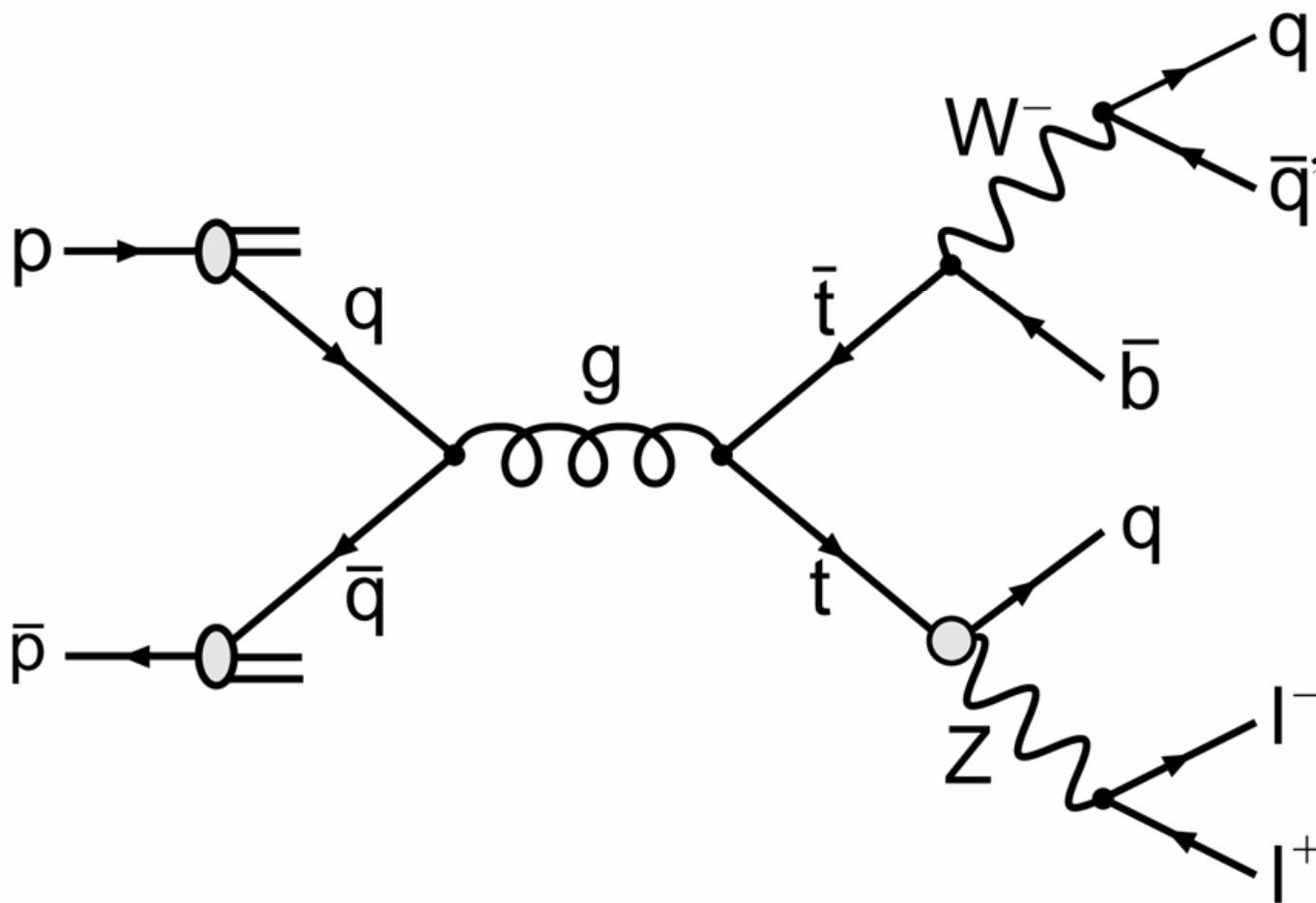




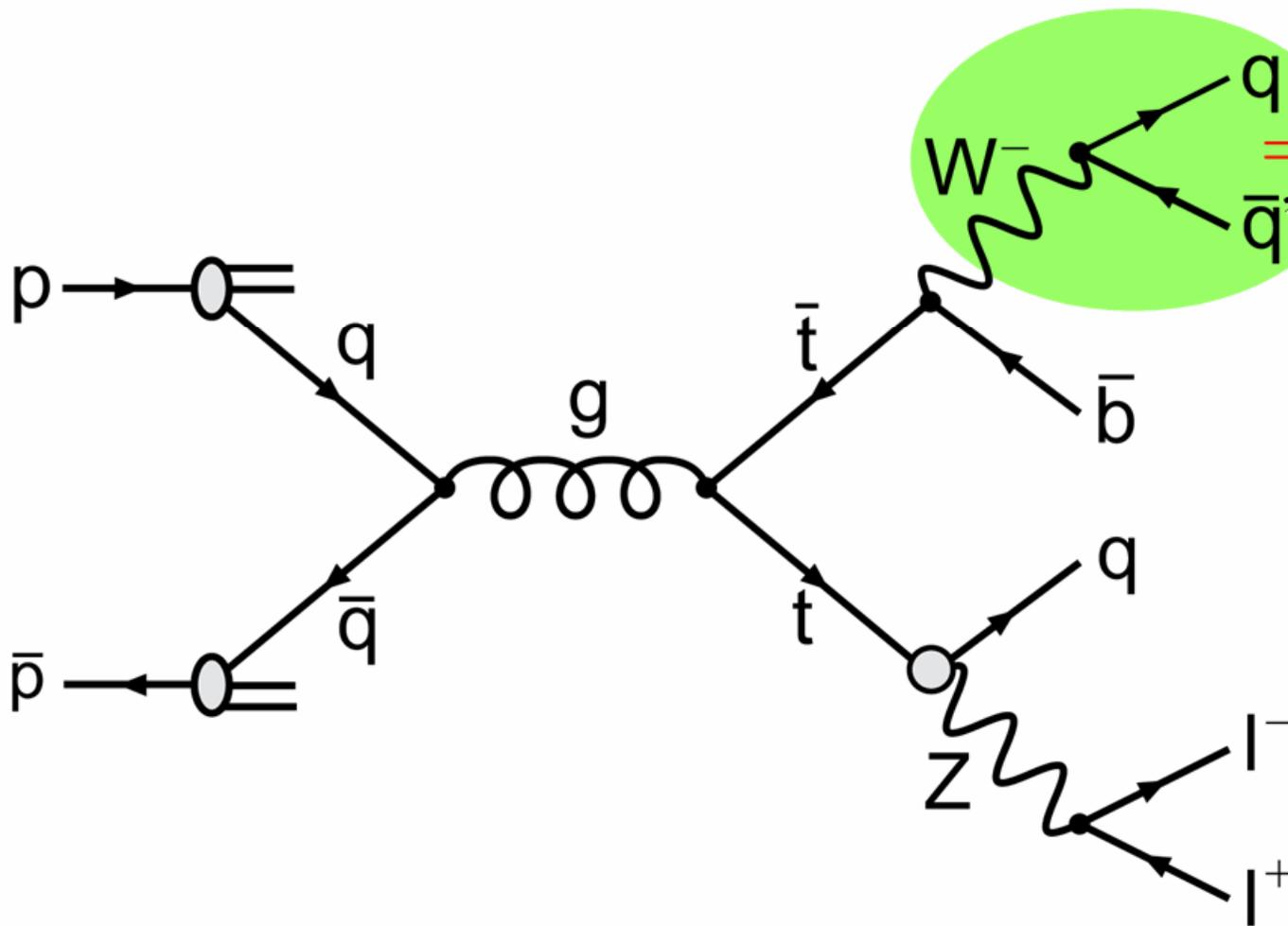
Search for FCNC: Ingredients



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



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



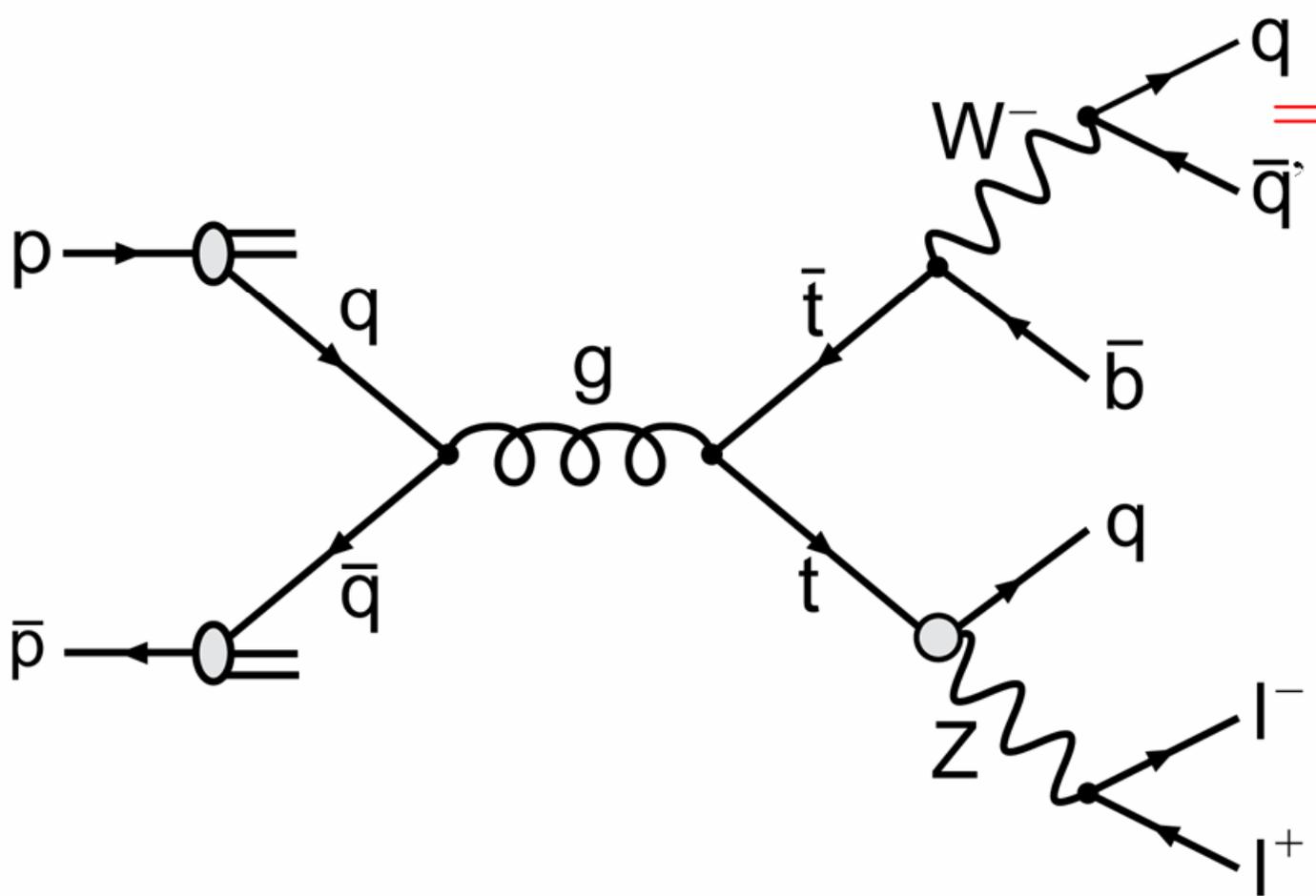
$$\left(\frac{m_W \text{ recon} - m_W}{\sigma_W} \right)^2$$



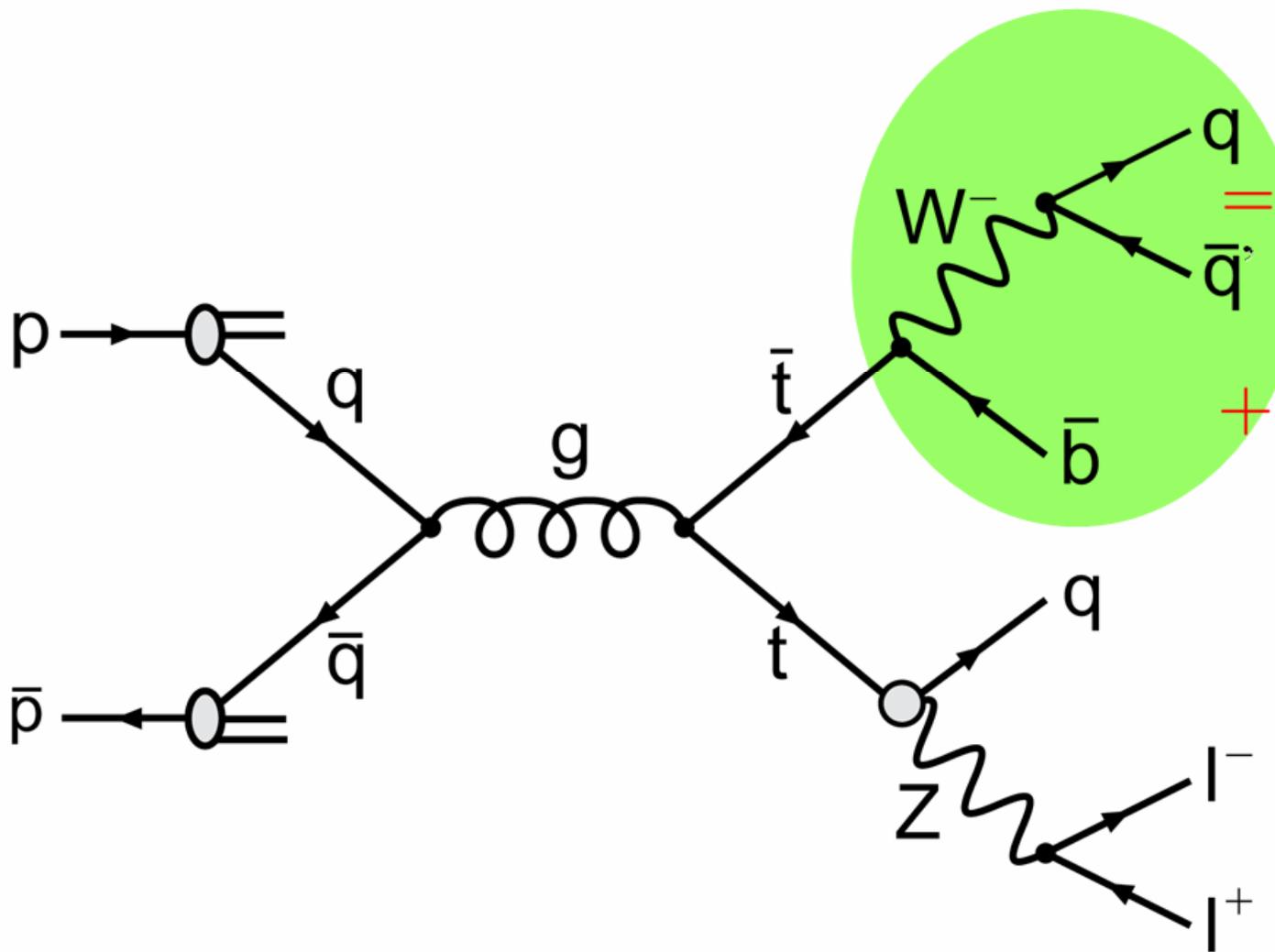
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$\chi^2_{\text{mass reconstruction}}$



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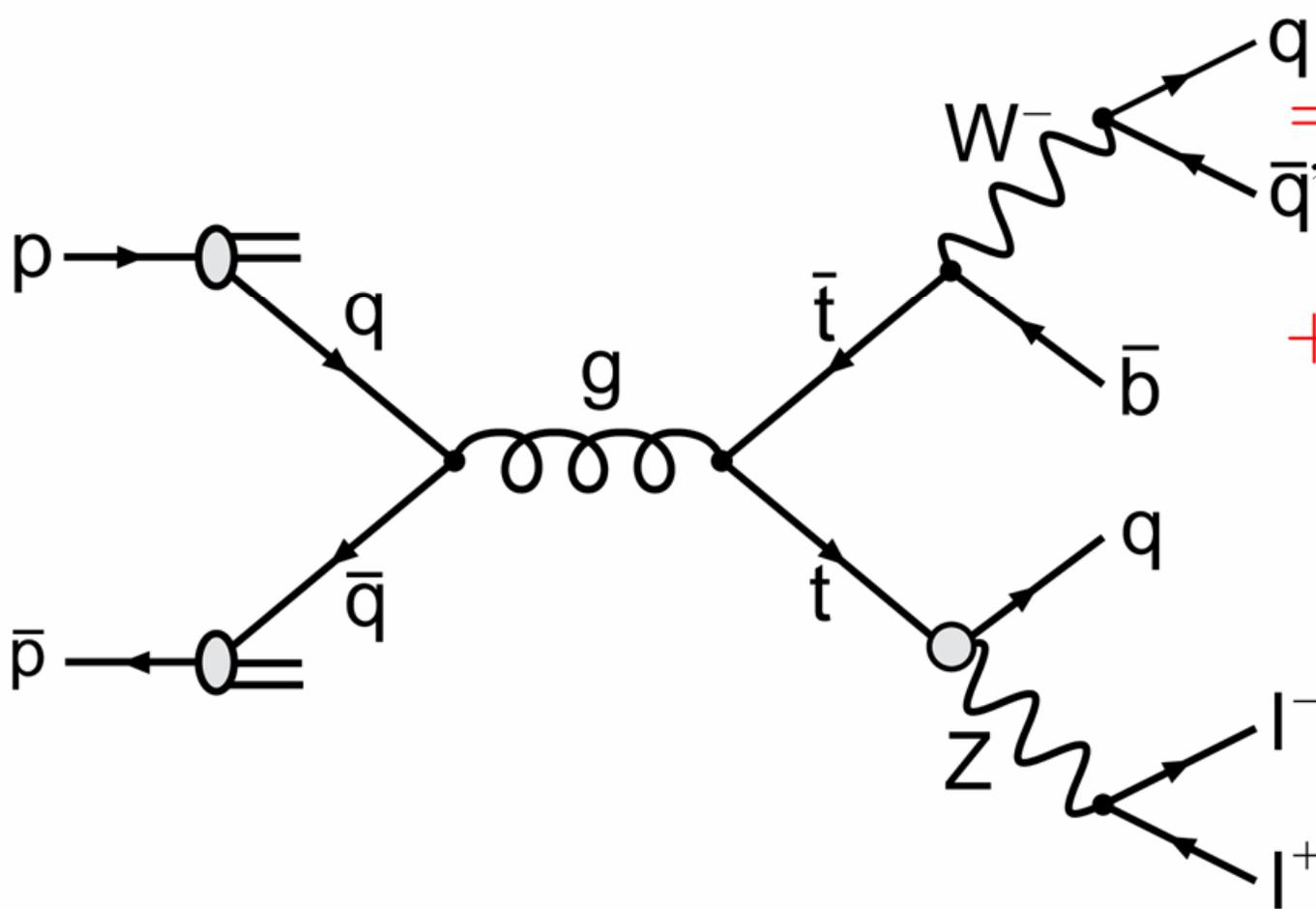
$$\left(\frac{m_{W \text{ recon}} - m_W}{\sigma_W} \right)^2 + \left(\frac{m_{tWb \text{ recon}} - m_t}{\sigma_{tWb}} \right)^2$$



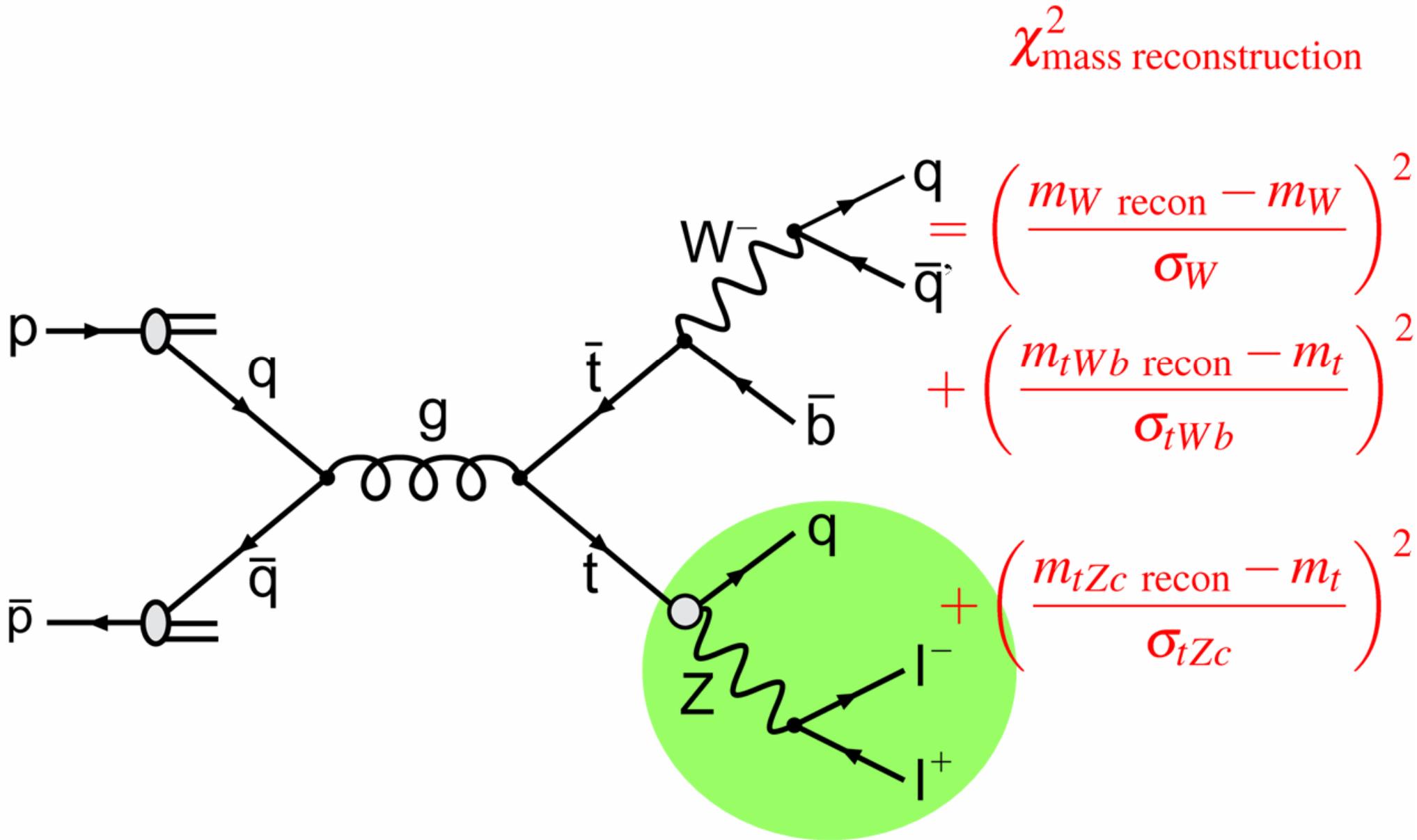
Search for FCNC: Ingredients



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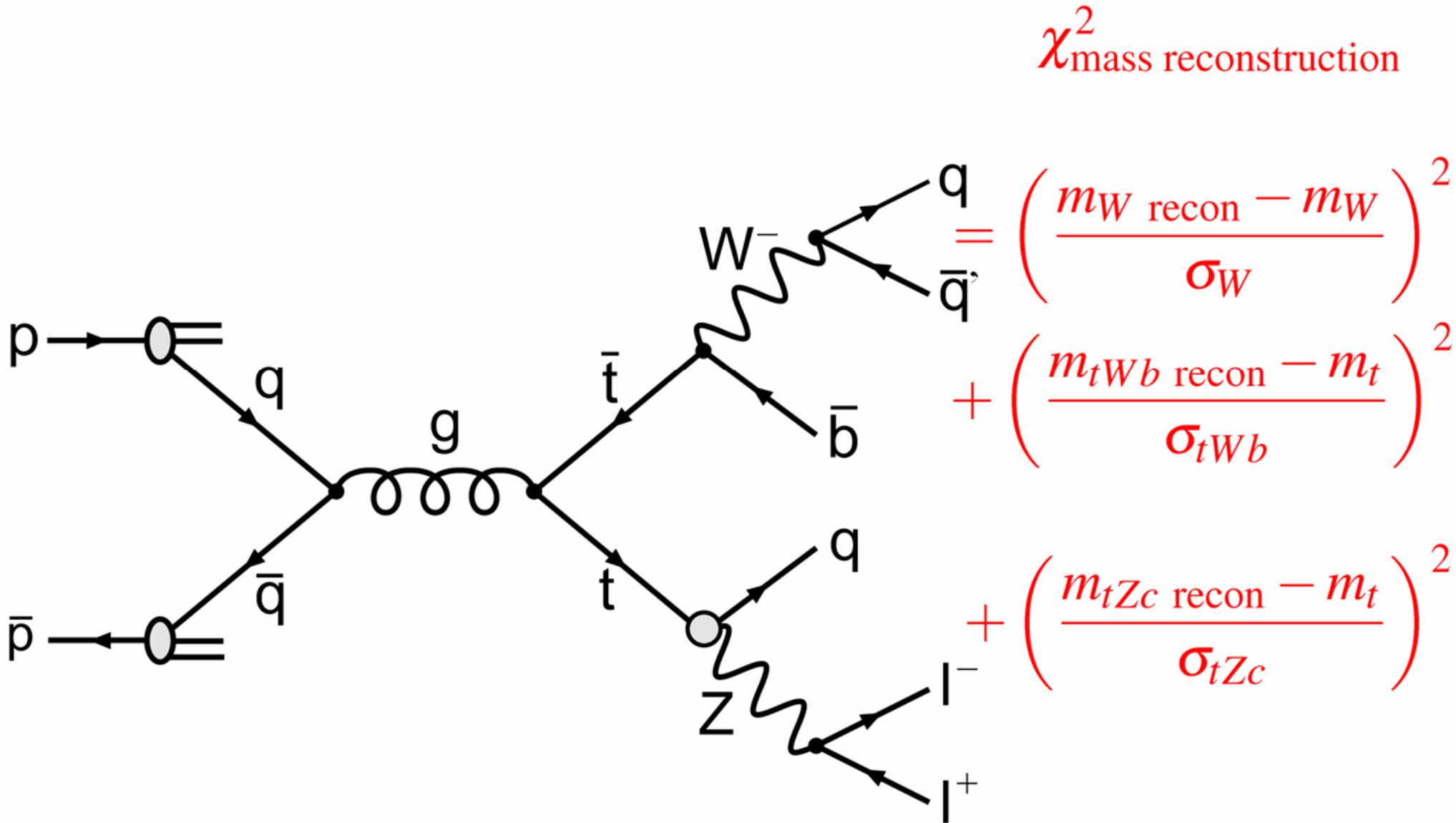


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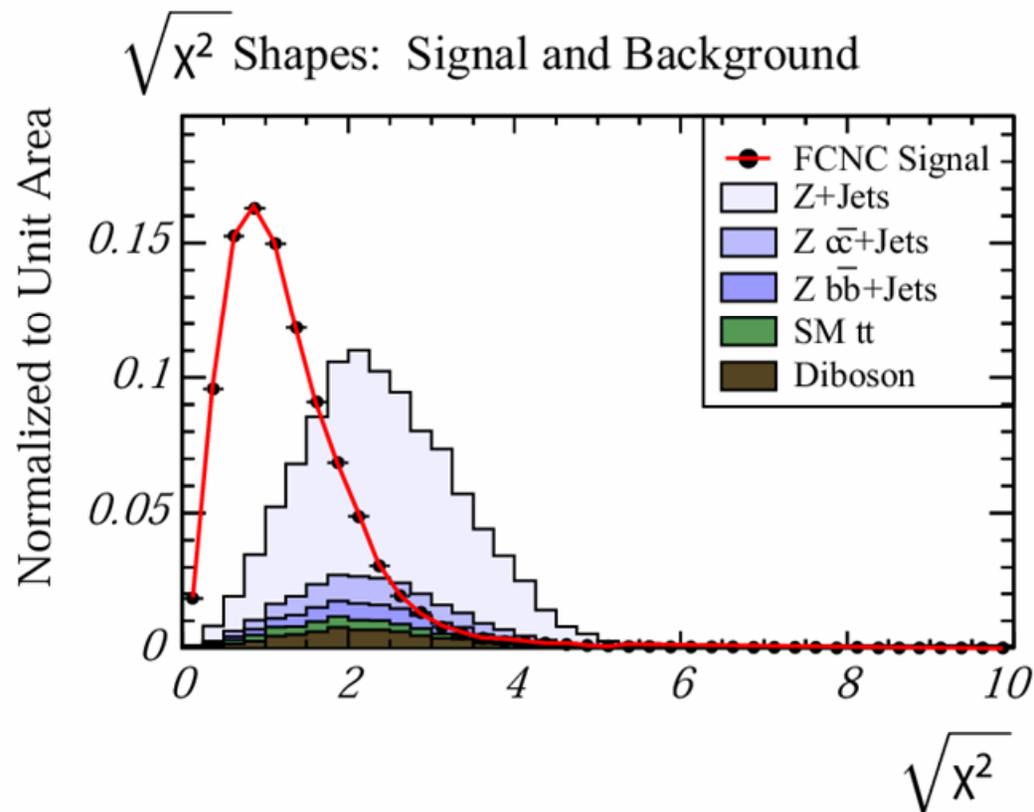




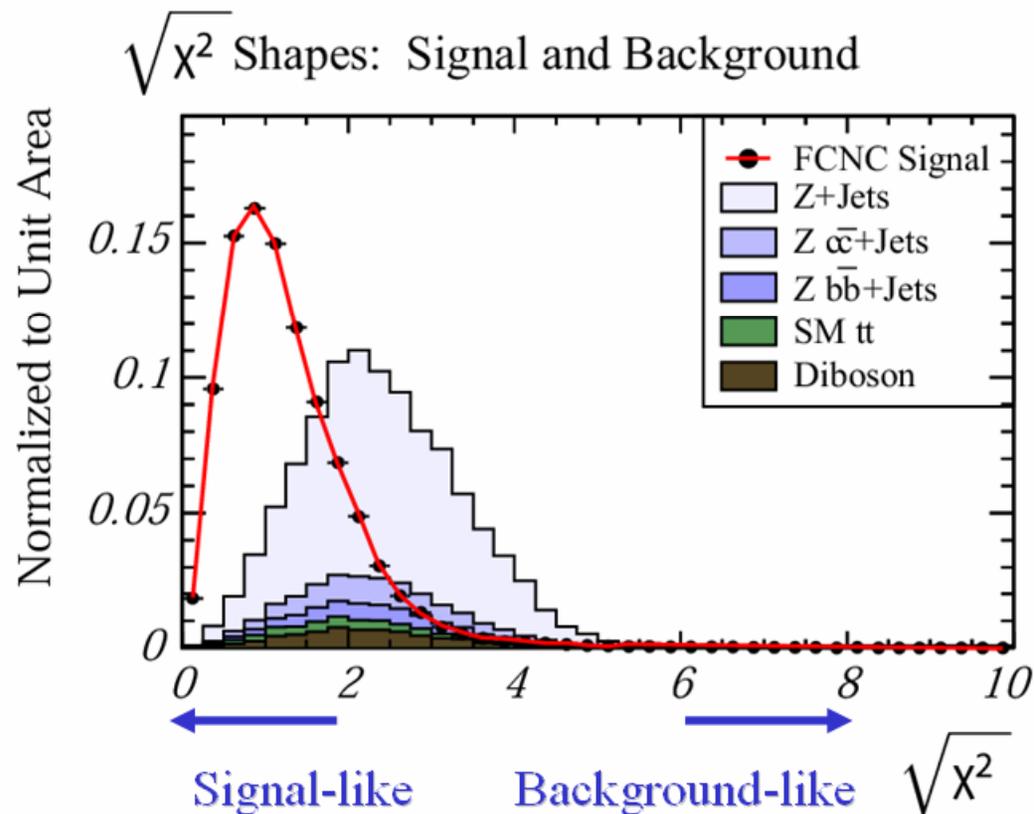
Search for FCNC: Ingredients



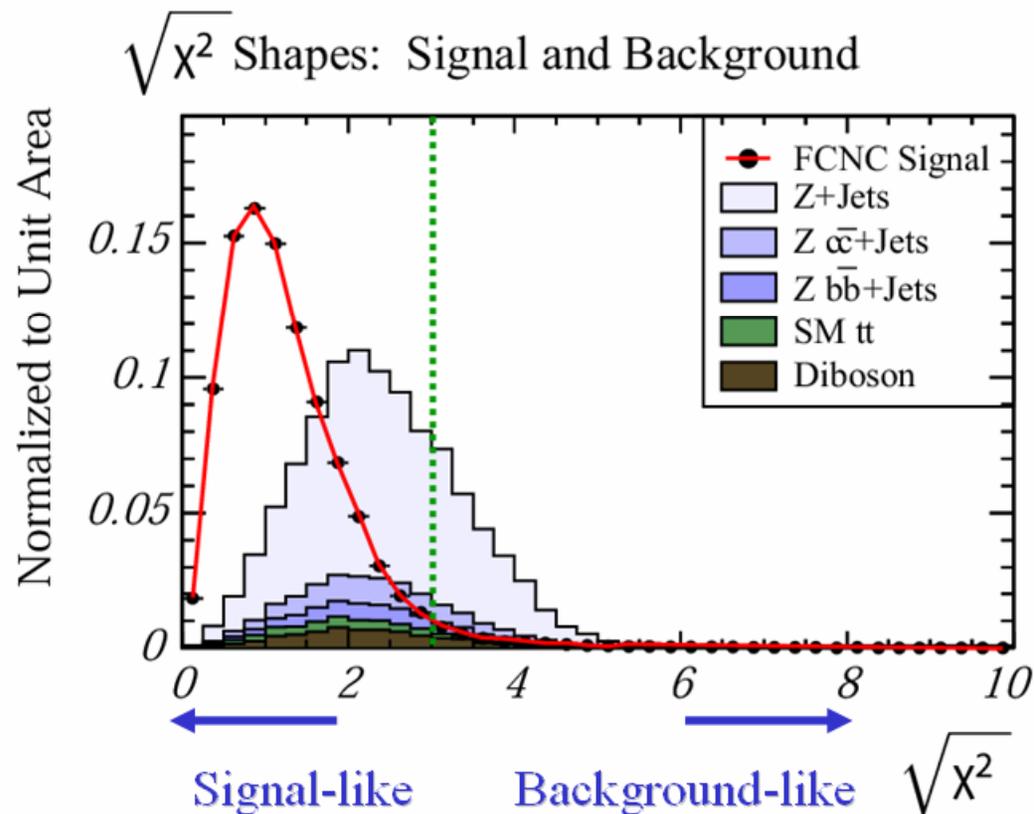
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⇒ Loop over all 12 permutations and take lowest χ^2 value.



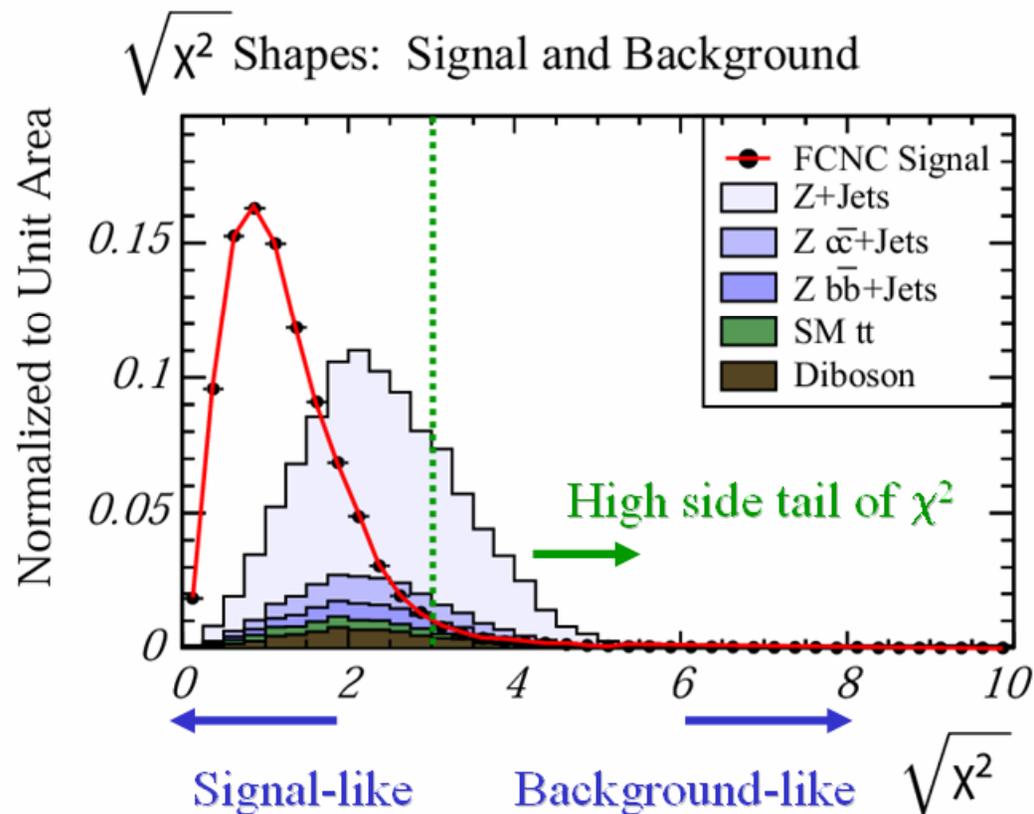
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Top Mass Reconstruction



- For our signal, we have three hadronic masses to reconstruct:

- W mass
- $t \rightarrow Wb$ mass
- $t \rightarrow Zc$ mass

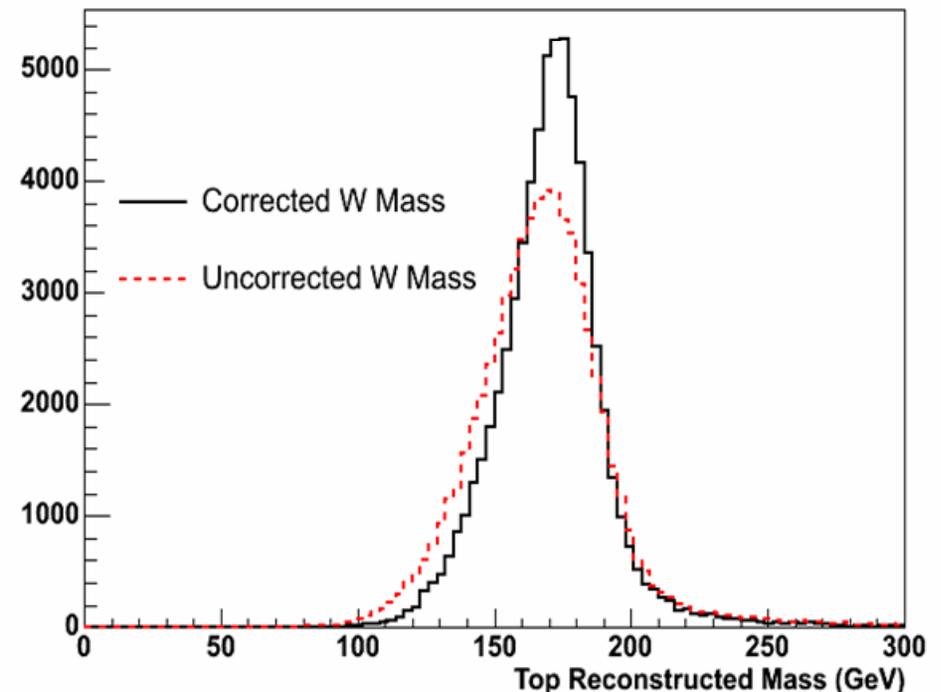
$t \rightarrow Wb$ mass
width

20 GeV \Rightarrow 16 GeV!

- 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**
 \Rightarrow **Better signal separation.**

Signal MC with partons correctly matched to reconstructed objects.





- Event signature: $Z \rightarrow l^+ l^- + 4 \text{ jets}$.
- Motivation for blind analysis: **Avoid biases** by looking into the data too early.
- Blinding & unblinding strategy:
 - Initial blinded region: $Z + \geq 4 \text{ jets}$.
 - Later: add **control region** in $Z + \geq 4 \text{ jets}$ 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.



Top FCNC Outline



The Search for Top FCNC Decay

Introduction

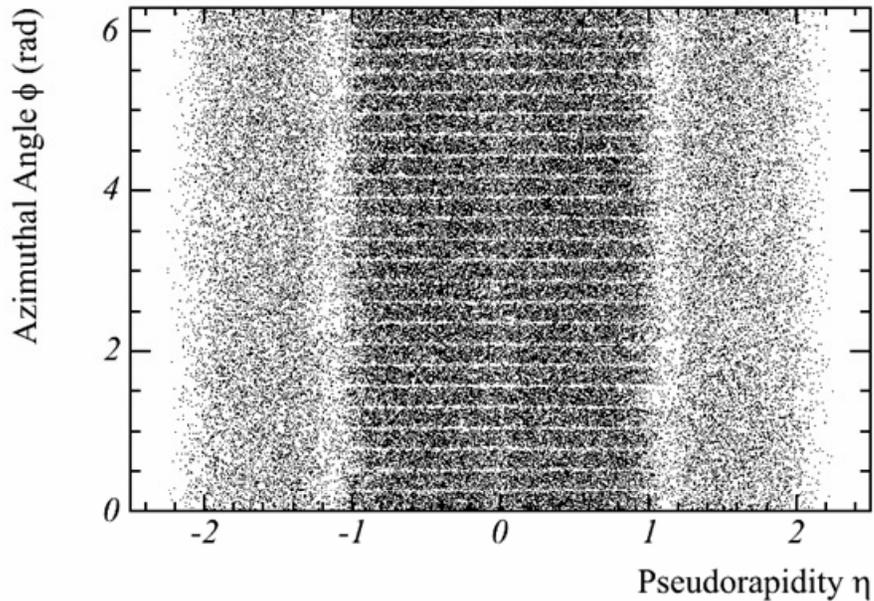
Acceptances

Backgrounds

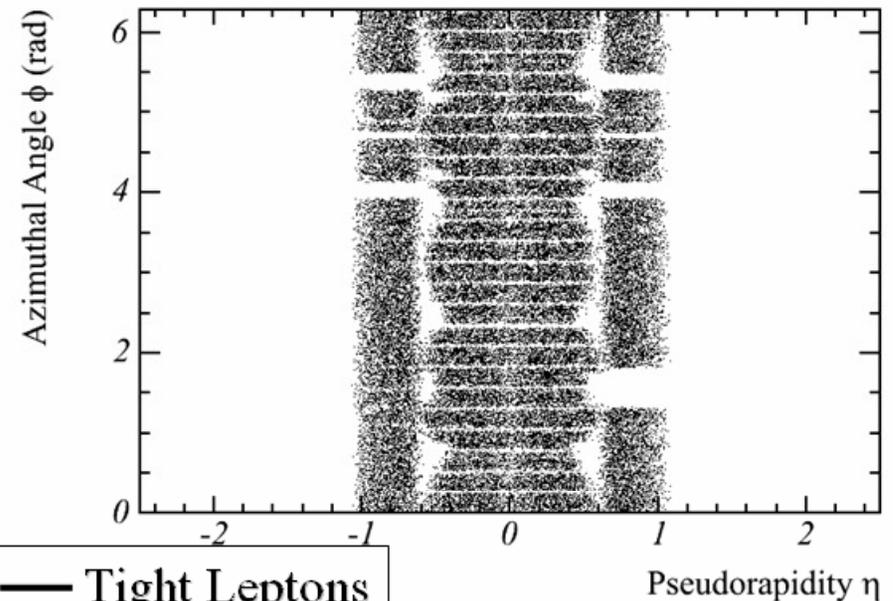
Unblinding

Round 2

η - ϕ Coverage: Electrons



η - ϕ Coverage: Muons

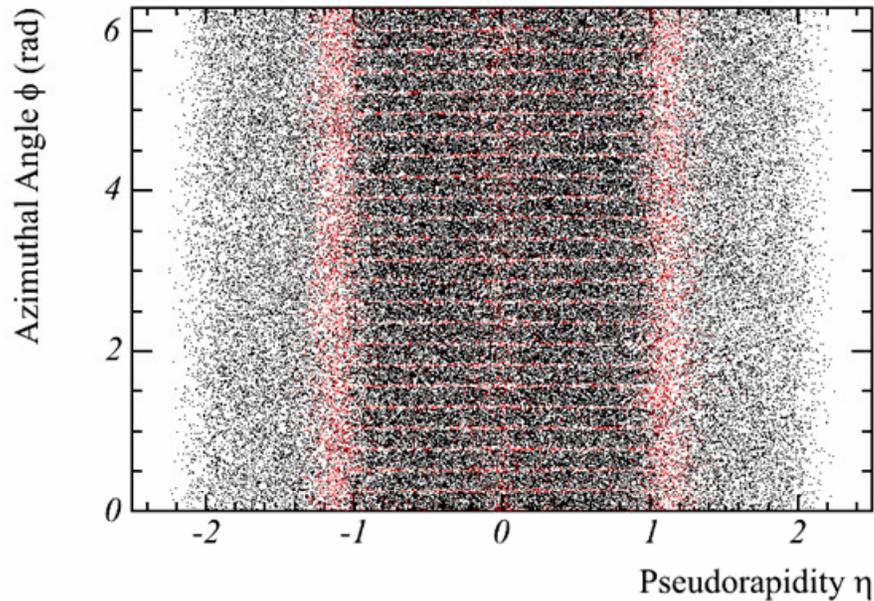


— Tight Leptons

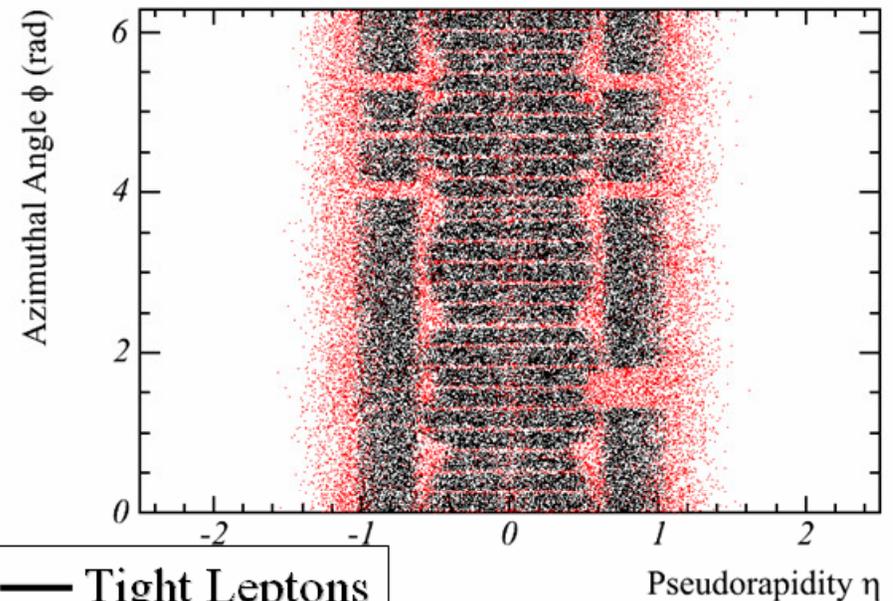
- Use isolated track (instead of tight lepton) for second lepton.
 - **Doubles** acceptance.
 - Almost all backgrounds have real leptons.

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

η - ϕ Coverage: Electrons



η - ϕ Coverage: Muons



— Tight Leptons
— Track Leptons

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To B-Tag or not to B-Tag?



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

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



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.
- 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.

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



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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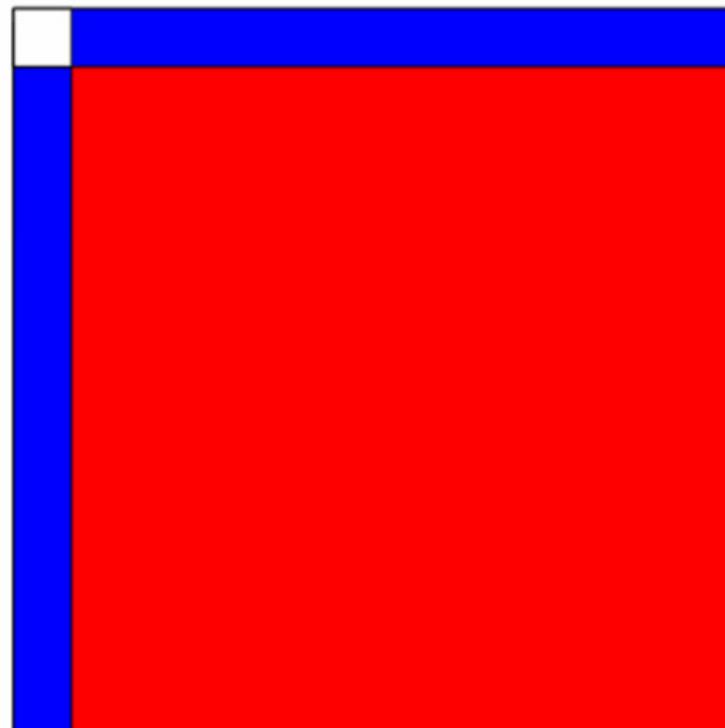


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Br (t → Wb) = 92% Br (t → Zc) = 8%



- P(t \bar{t} → WbWb) = 84.64%
- P(t \bar{t} → Wb Zc) = 13.12%
- P(t \bar{t} → Zc Zc) = 0.64%



Solution: Running Acceptance



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

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

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

L+J yield
Acc. Ratio
“Running” Acceptance Correction

- Acceptance and $\sigma_{t\bar{t}}$ 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** ($\mathcal{R}_{wz/ww}$) between acceptances.

\mathcal{B}_Z	\equiv	$Br(t \rightarrow Zc) = 1 - Br(t \rightarrow Wb)$
\mathcal{A}_{WZ}	\equiv	FCNC acceptance
\mathcal{A}_{ZZ}	\equiv	Double FCNC acceptance
\mathcal{A}_{LJww}	\equiv	L+J acceptance for SM $t\bar{t}$
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\mathcal{A}_{LJzz}	\equiv	L+J acceptance for FCNC
$K_{ZZ/WZ}$	\equiv	$\mathcal{A}_{ZZ}/\mathcal{A}_{WZ}$
$\mathcal{R}_{wz/ww}$	\equiv	$\mathcal{A}_{LJwz}/\mathcal{A}_{LJww}$
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Top FCNC Outline



The Search for Top FCNC Decay

Introduction

Acceptances

Backgrounds

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Round 2

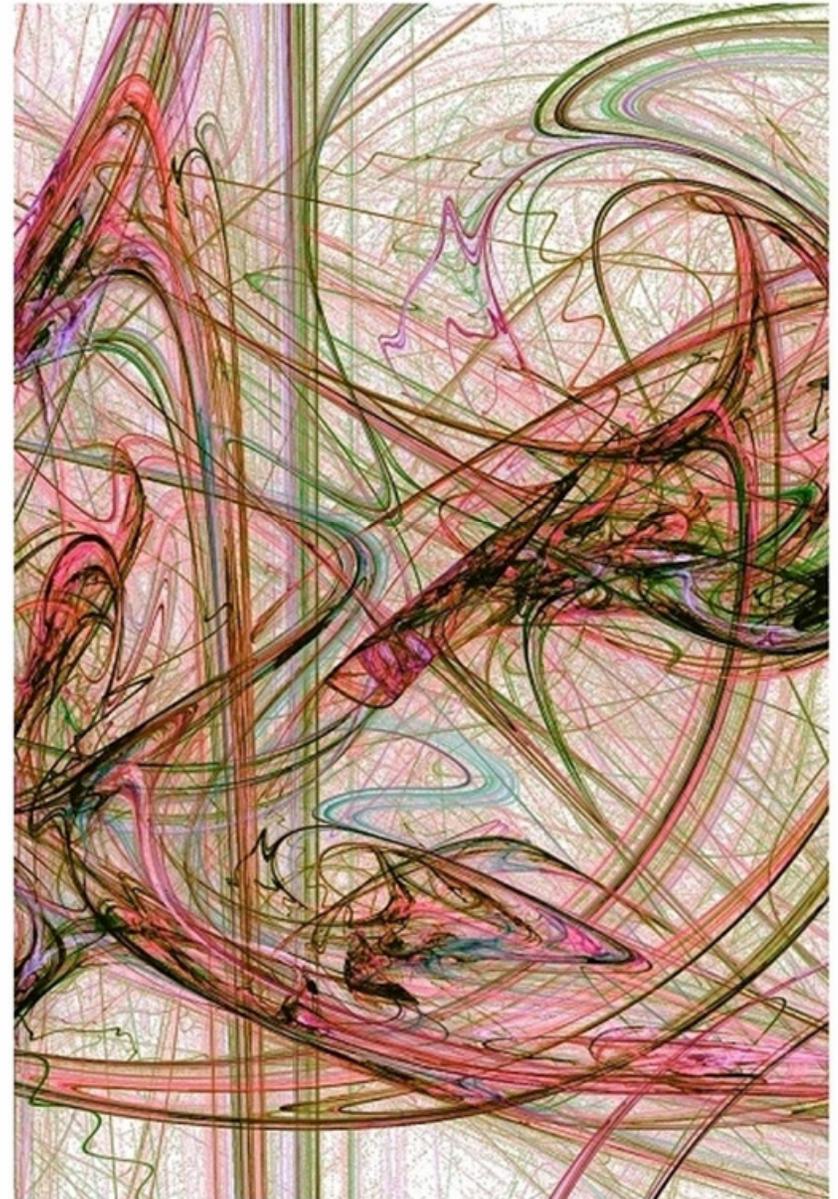


Expected Backgrounds



- 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
→ **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**
($t\bar{t} \rightarrow Wb Wb \rightarrow l\nu b l\nu b$):
dilepton invariant mass can fall into Z mass window.
- **Lepton + Jets channel**
($t\bar{t} \rightarrow Wb Wb \rightarrow l\nu b qq'b$):
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



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Diboson Production: WZ, ZZ

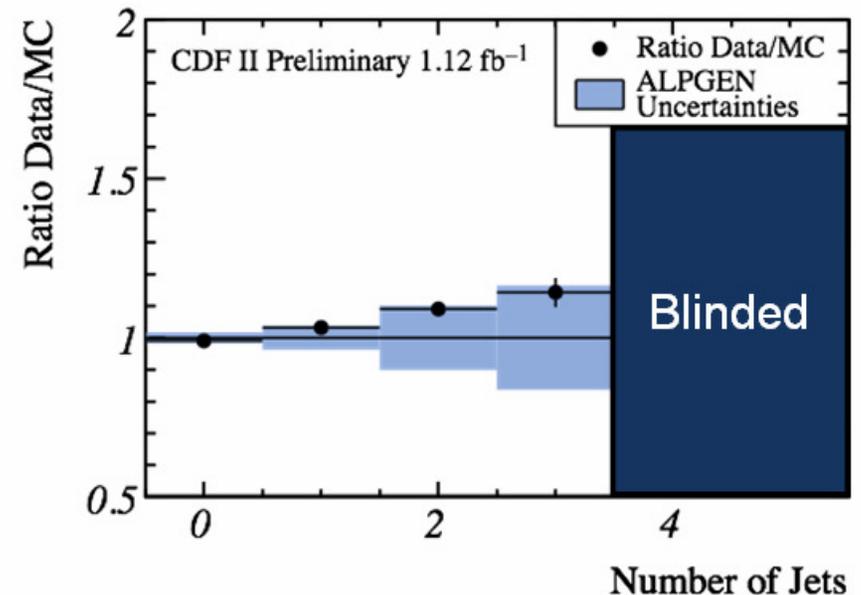
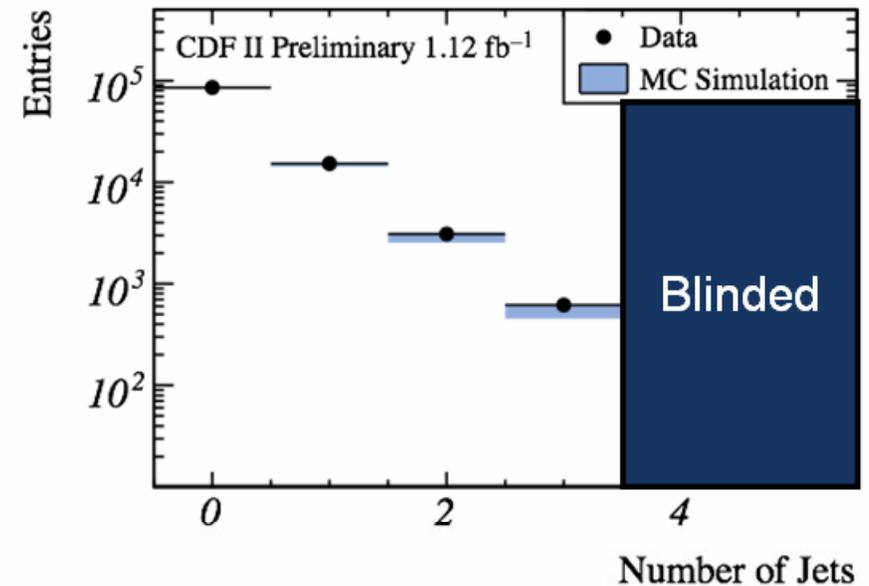
- Small background (similar in size to standard model tt production).
- Small cross section but **real Z**.
- Need extra jets from gluon radiation.
- **ZZ**: **Heavy flavor contribution** from $Z \rightarrow bb$ decay.
- Estimated from MC simulation.



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.

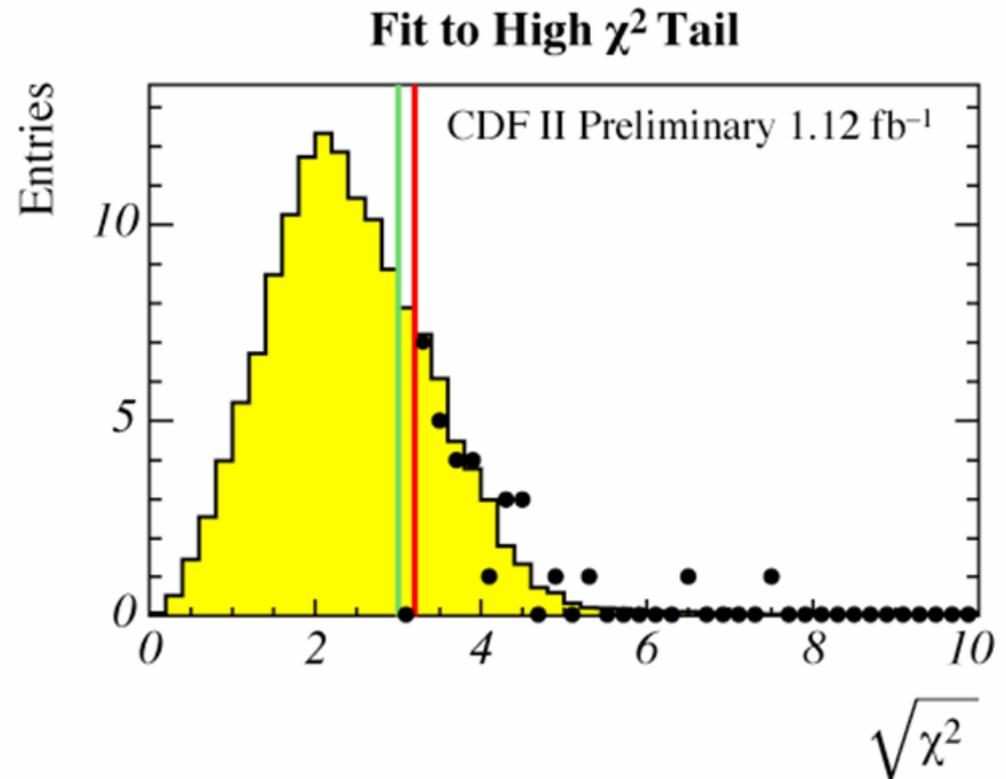




Base Selection Background Estimate



- 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. **$\Rightarrow 15\% \pm 4\%$ 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	$\in [76,106] \text{ GeV}/c^2$
Leading Jet E_T	$\geq 40 \text{ GeV}$
Second Jet E_T	$\geq 30 \text{ GeV}$
Third Jet E_T	$\geq 20 \text{ GeV}$
Fourth Jet E_T	$\geq 15 \text{ GeV}$
Transverse Mass	$\geq 200 \text{ GeV}$
$\sqrt{\chi^2}$	< 1.6 (<i>b</i> -tagged)
	< 1.35 (anti-tagged)

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

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

Expected Limit:
 $6.8\% \pm 2.9\%$



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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



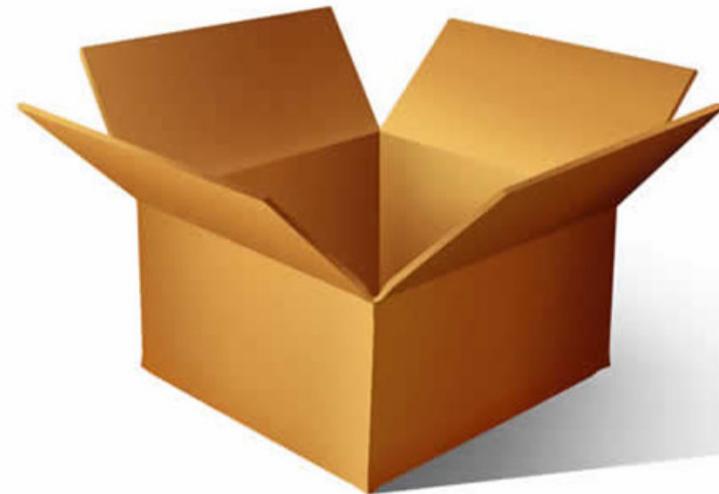
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- So far, so good... Let's open the box!





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
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: $6.8\% \pm 2.9\%$.



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 - *Or is it the first hint of a signal?!*

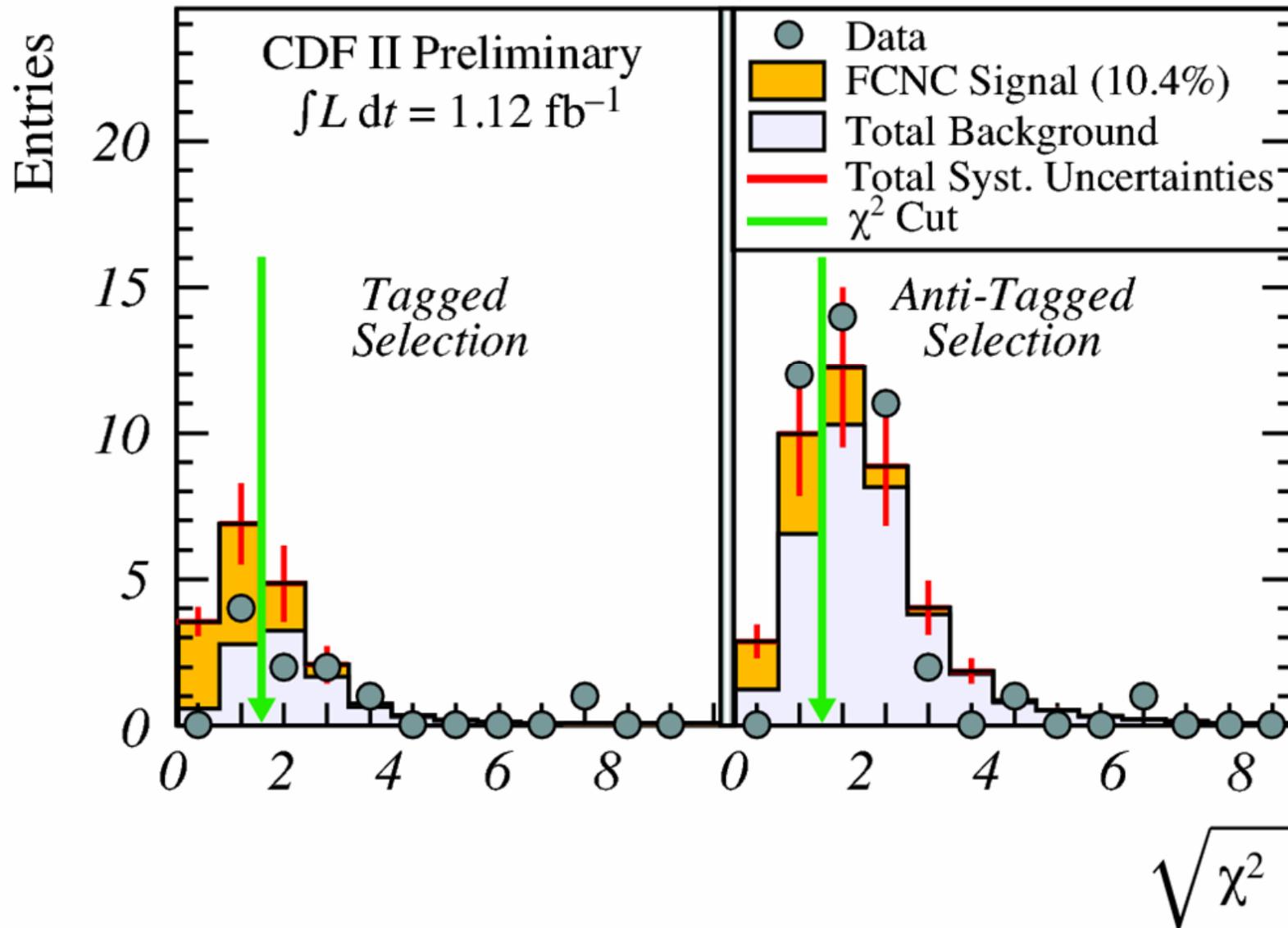
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- Expected limit: $6.8\% \pm 2.9\%$.

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

Acceptances

Backgrounds

Unblinding

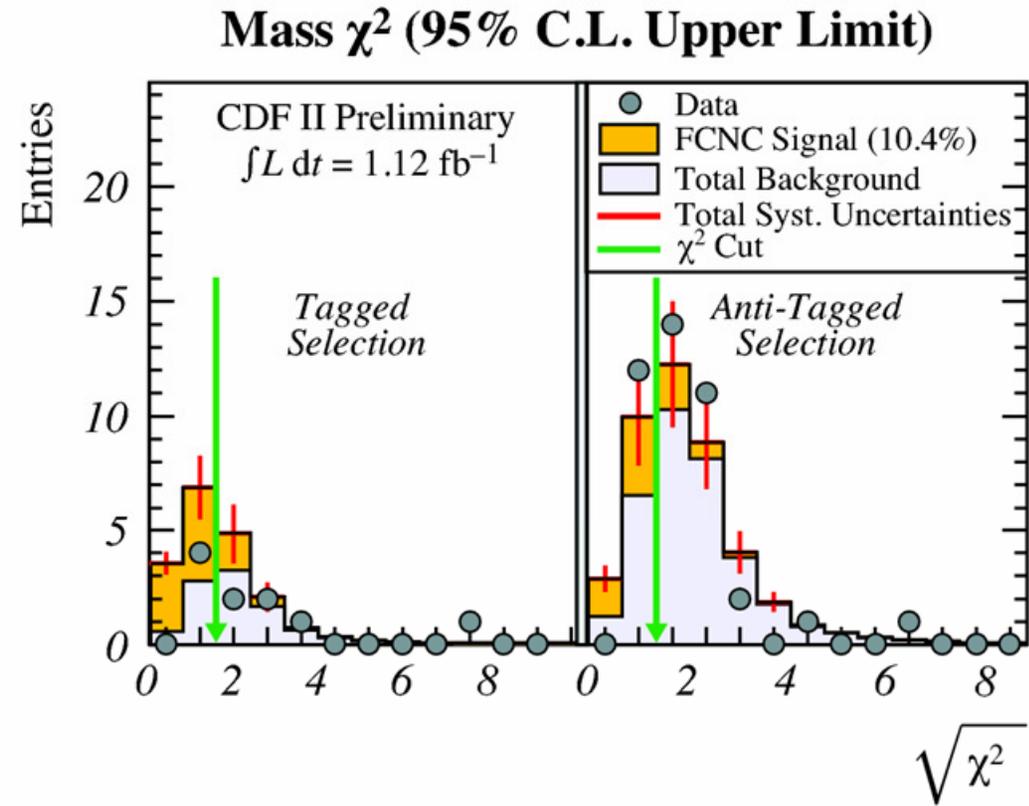
Round 2



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





Differences From Counting Experiment



- **Advantages:**

- Absolute estimation of $Z + \text{jets}$ background is difficult. This drove the counting experiment.
- Since we are fitting:
 - No absolute $Z + \text{jets}$ background estimation needed.
 - No estimate of $Z + \text{jets}$ tagging fraction needed.
- ⇒ Let these both float in the fit.
 - Smaller backgrounds are fixed to SM expectations.

- **Disadvantages:**

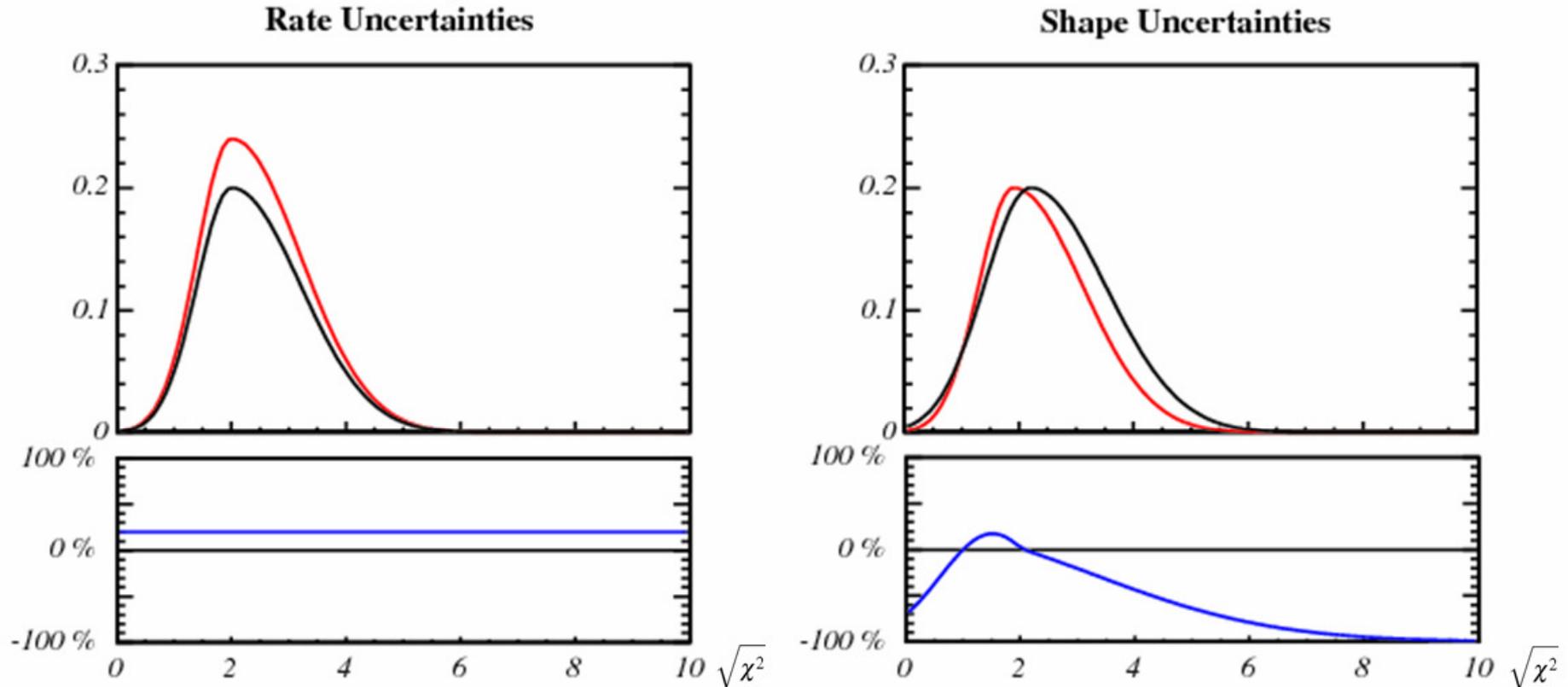
- Counting experiment does not have shape systematic uncertainties.
 - **Counting experiment:** Only worry about ratios of acceptances.
 - **Fit χ^2 :** We need to understand and account for this.



Shape Uncertainties



- What do we mean by “*shape uncertainties*”?



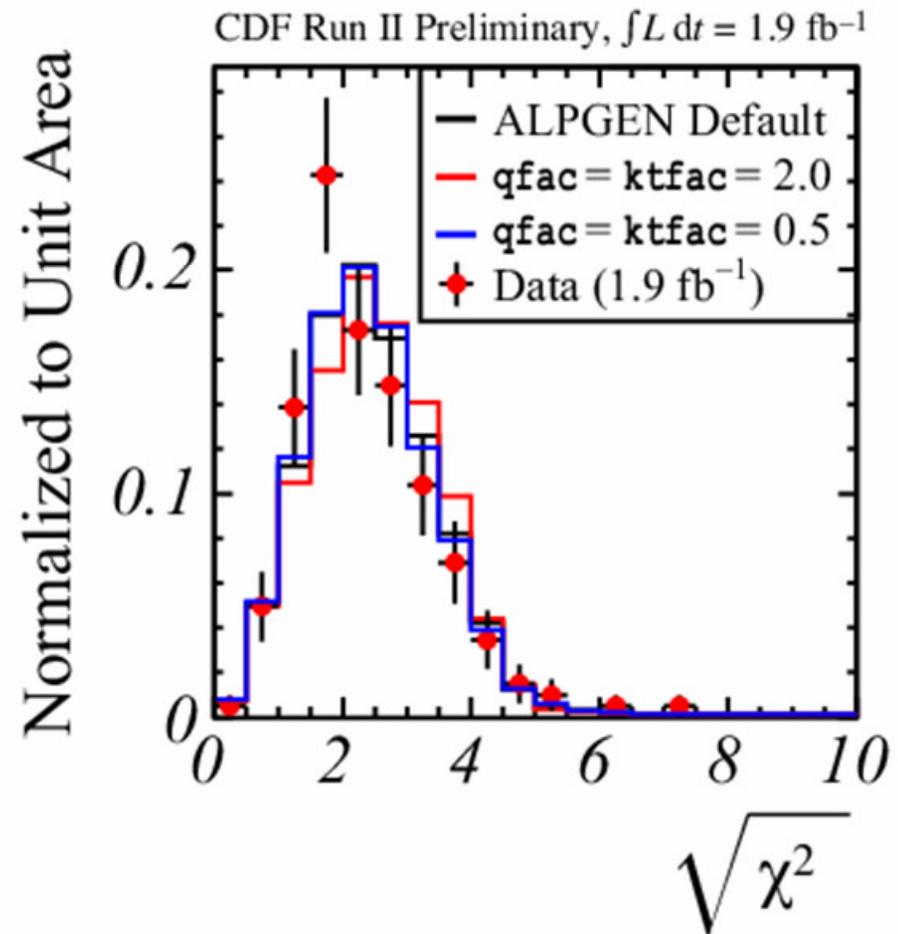
- We considered many choices for shape uncertainties.
- The two dominant effects were much larger than all others.
 - Factorization/Renormalization (Q^2) scale for Z + jets MC.
 - Jet energy scale uncertainties.



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.



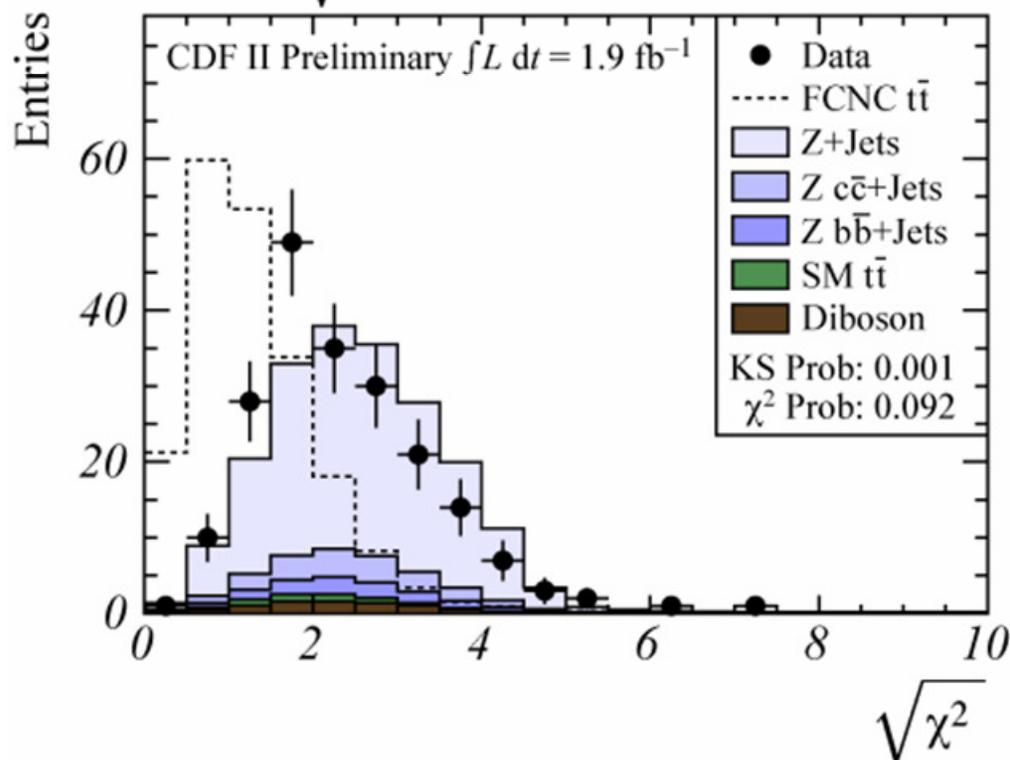


Shape Uncertainties: JES

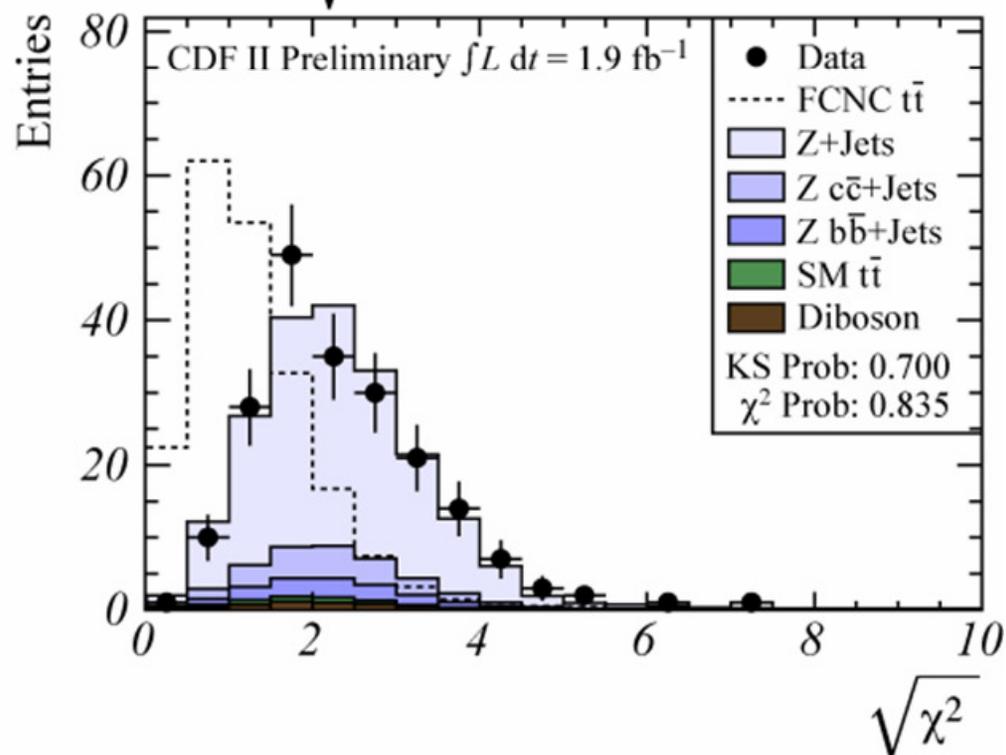


- We need to convert “*raw*” jets to “*corrected*” jets
⇒ **Jet Energy Scale correction (JES)**
 - Takes into account detector effects, neutral particles in jets, particles outside of the jet cone, underlying events, multiple interactions, ...

$\sqrt{\chi^2}$ (Pre-Tag, $\sigma_{\text{JES}} = +1$)



$\sqrt{\chi^2}$ (Pre-Tag, $\sigma_{\text{JES}} = -1$)



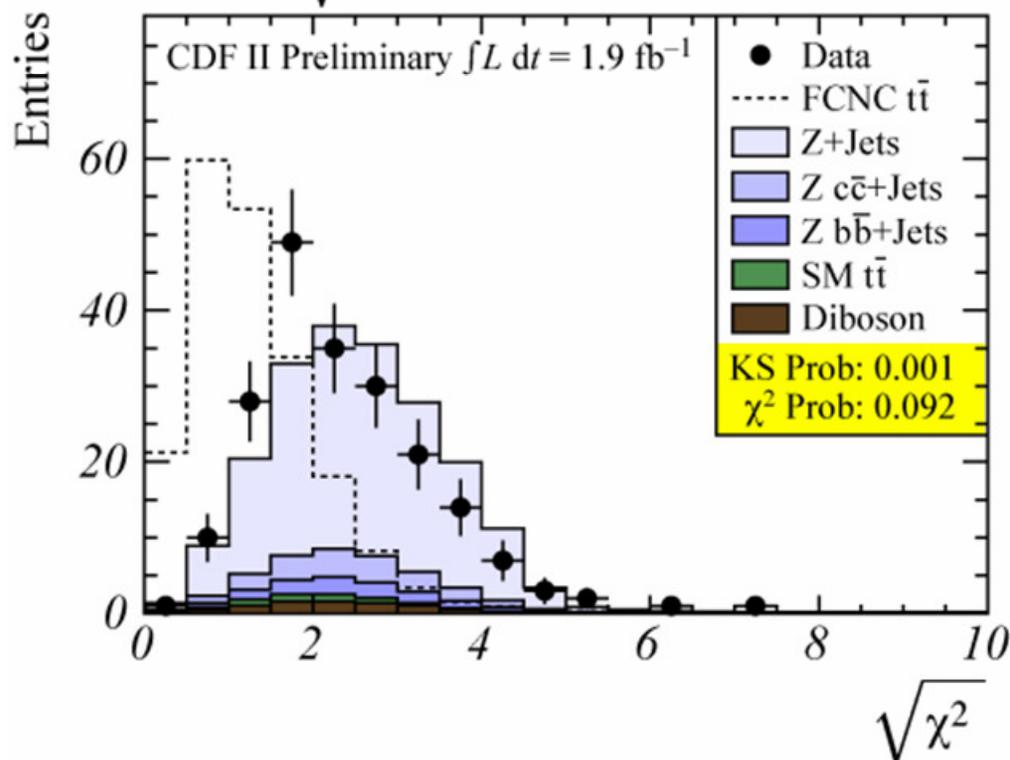


Shape Uncertainties: JES

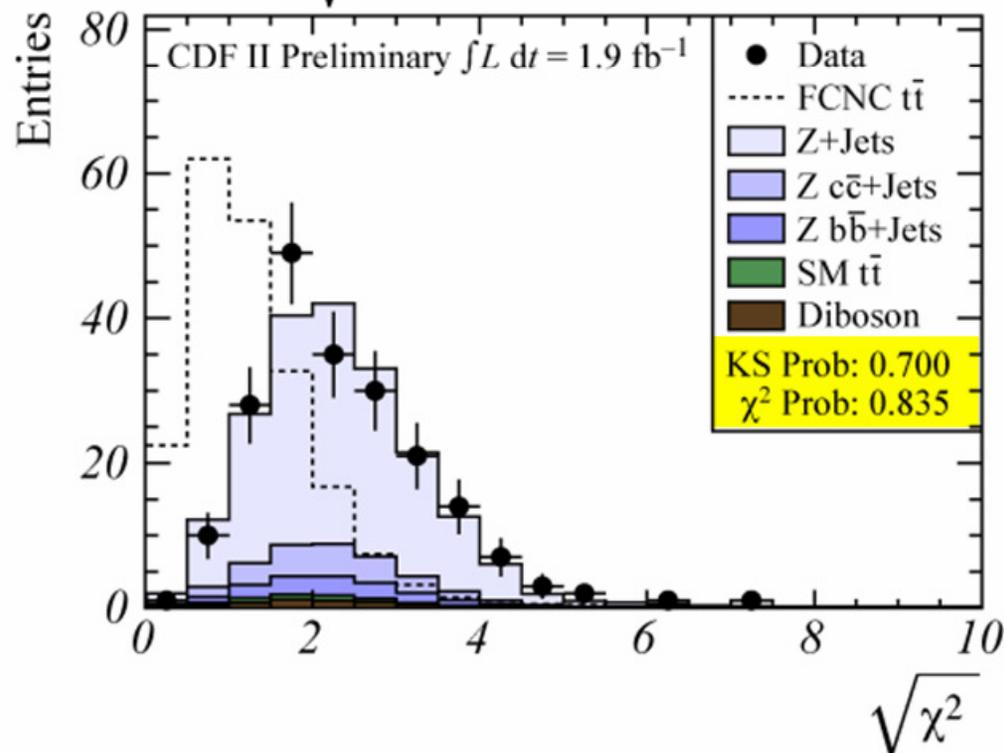


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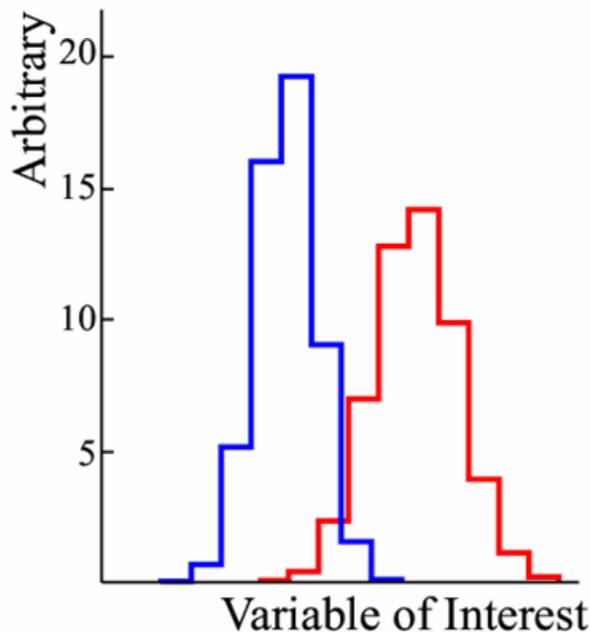




Template Morphing



- 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).

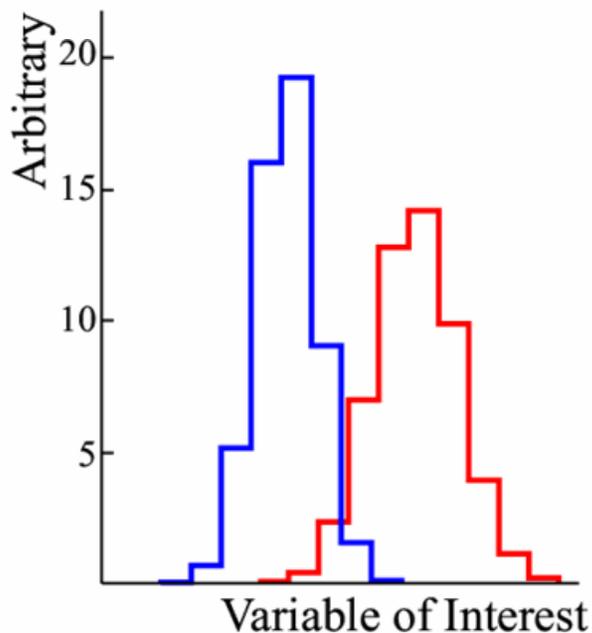




“Everything You Always Wanted To Know About Template Morphing But Were Afraid To Ask.”



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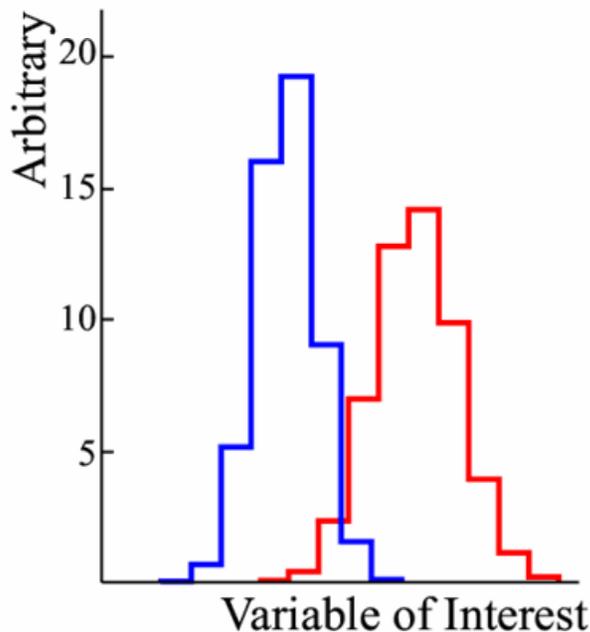




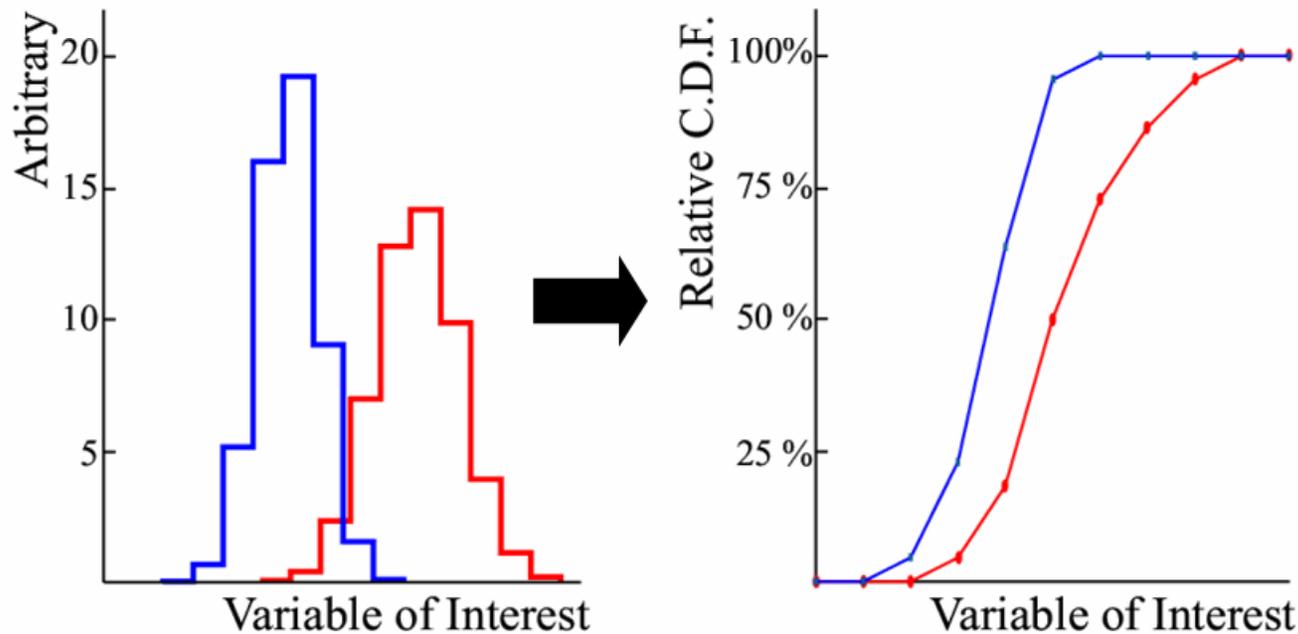
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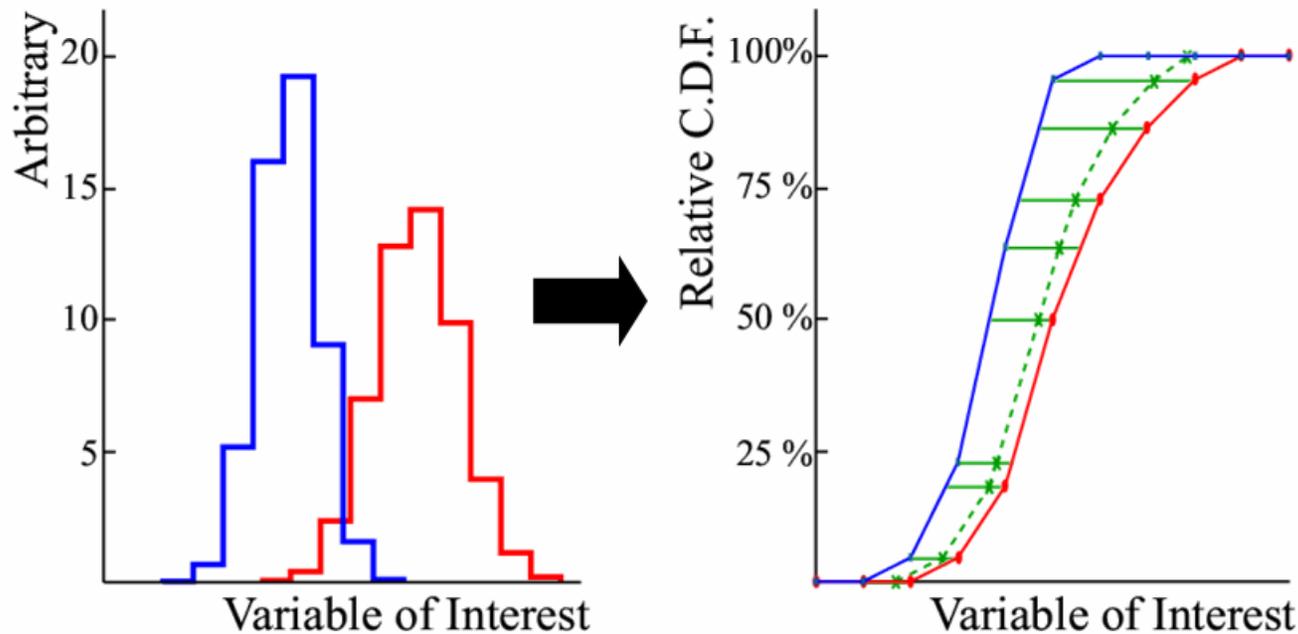
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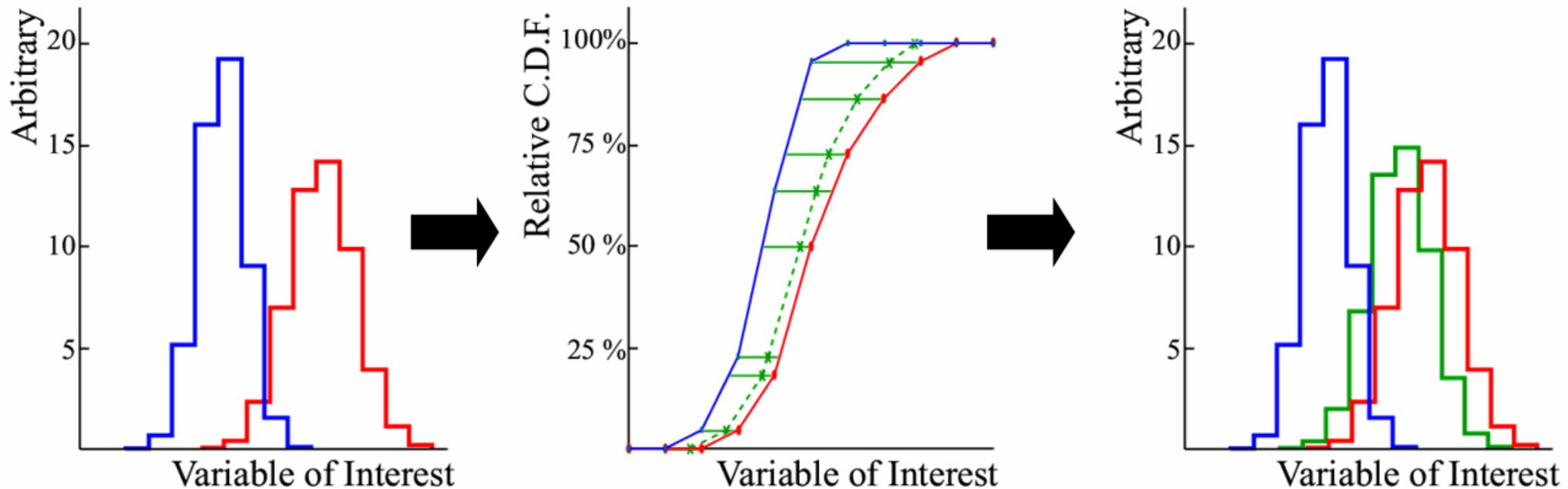
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 - The **green** C.D.F. curve is the 75% interpolation between the **blue** and **red** C.D.F. curves.



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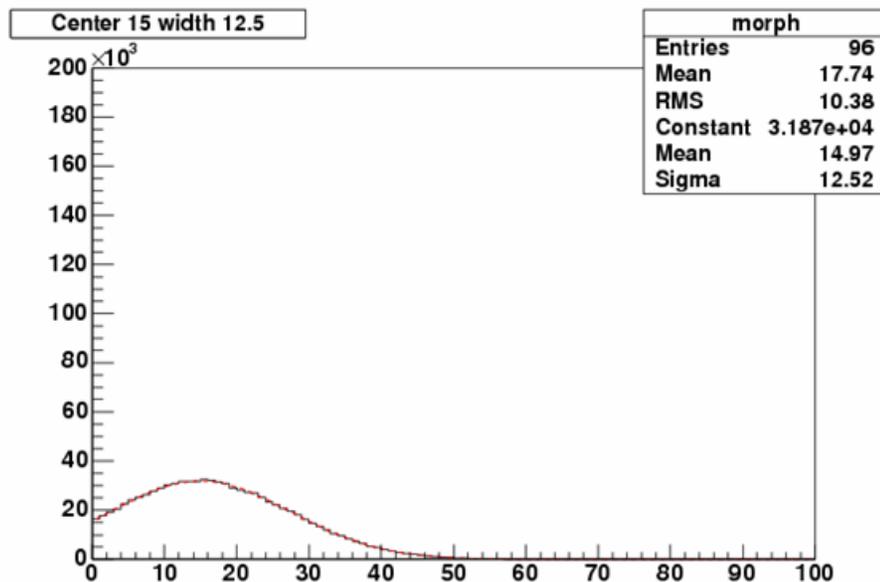
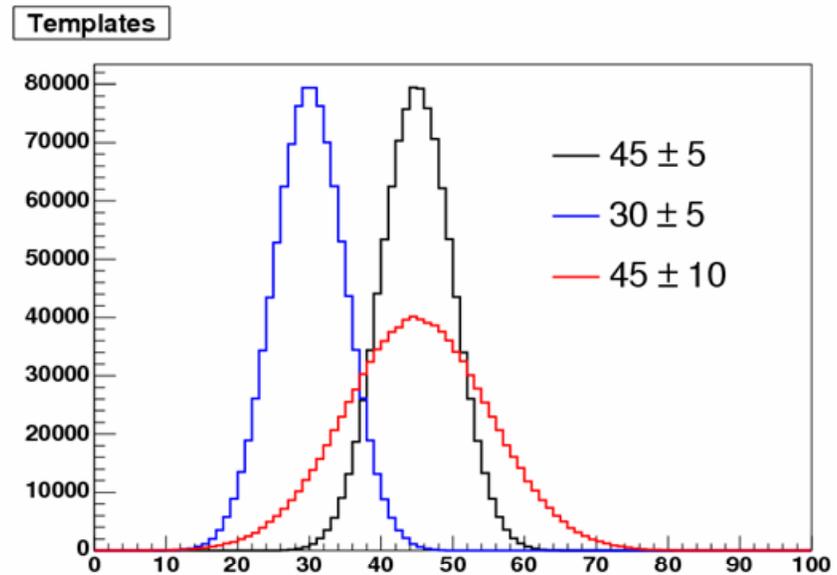




Does Morphing Work?



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

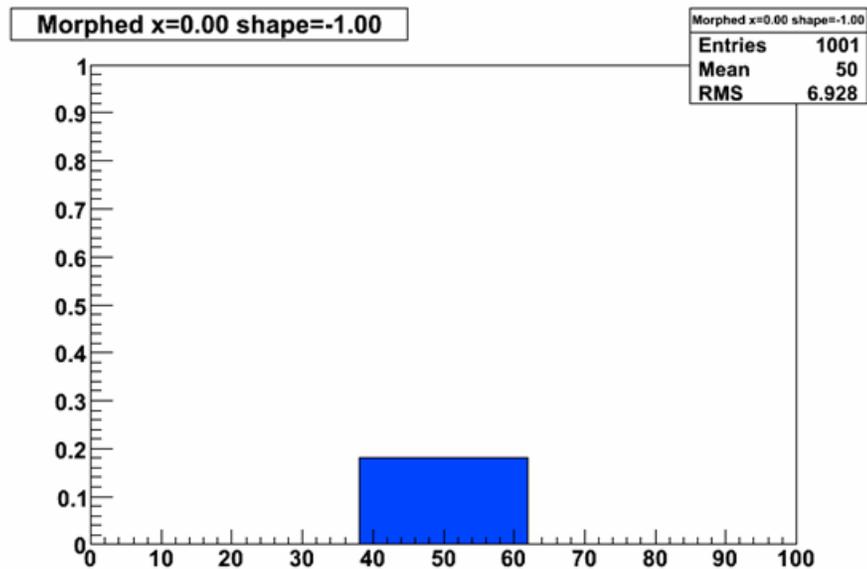
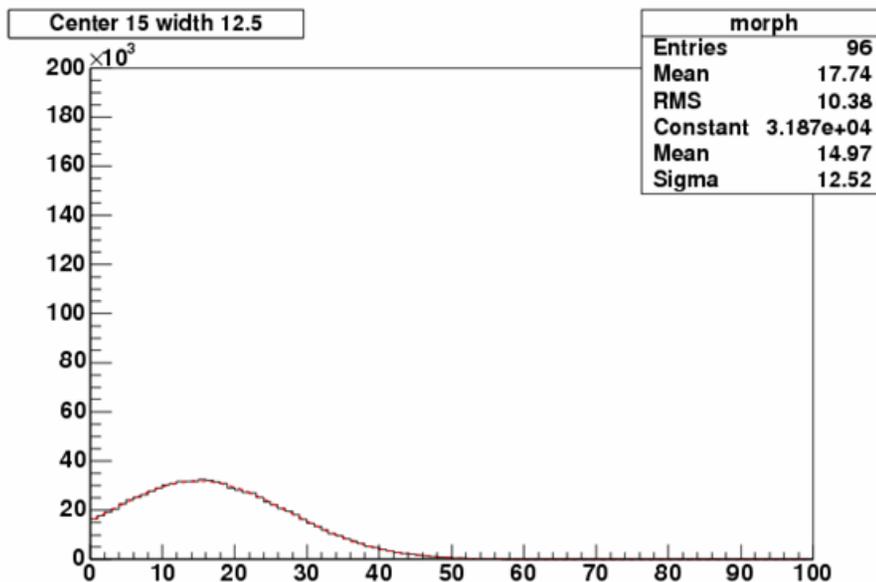
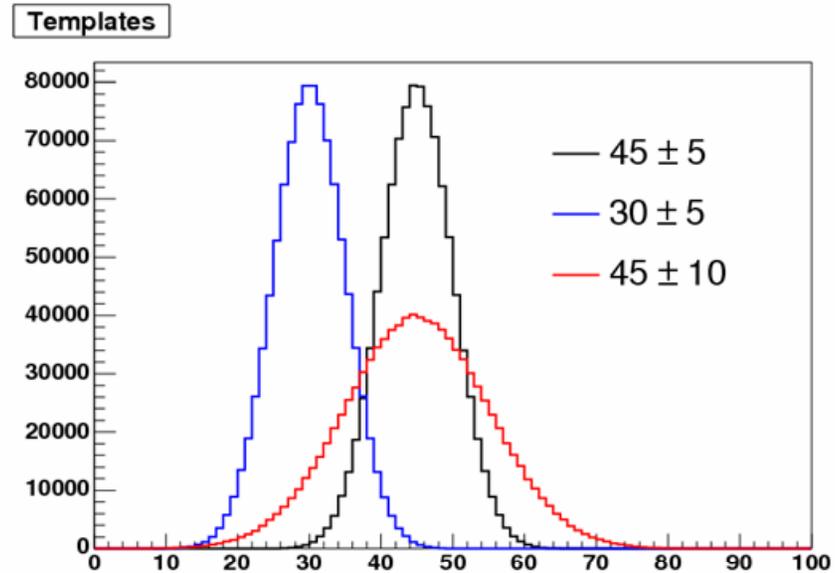




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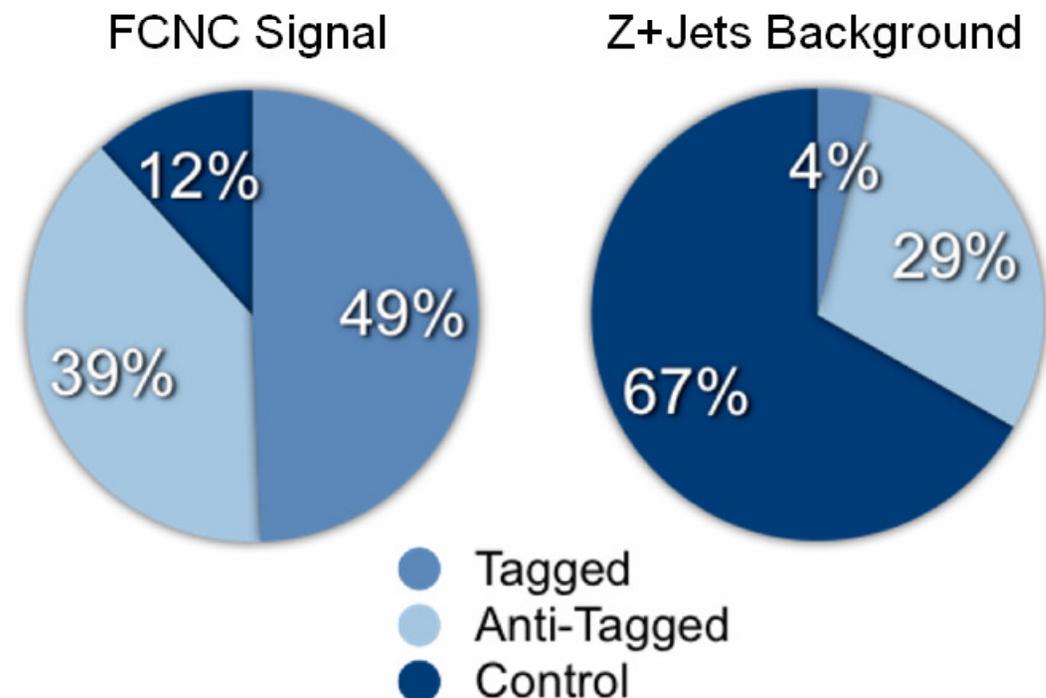


Signal and Control Regions



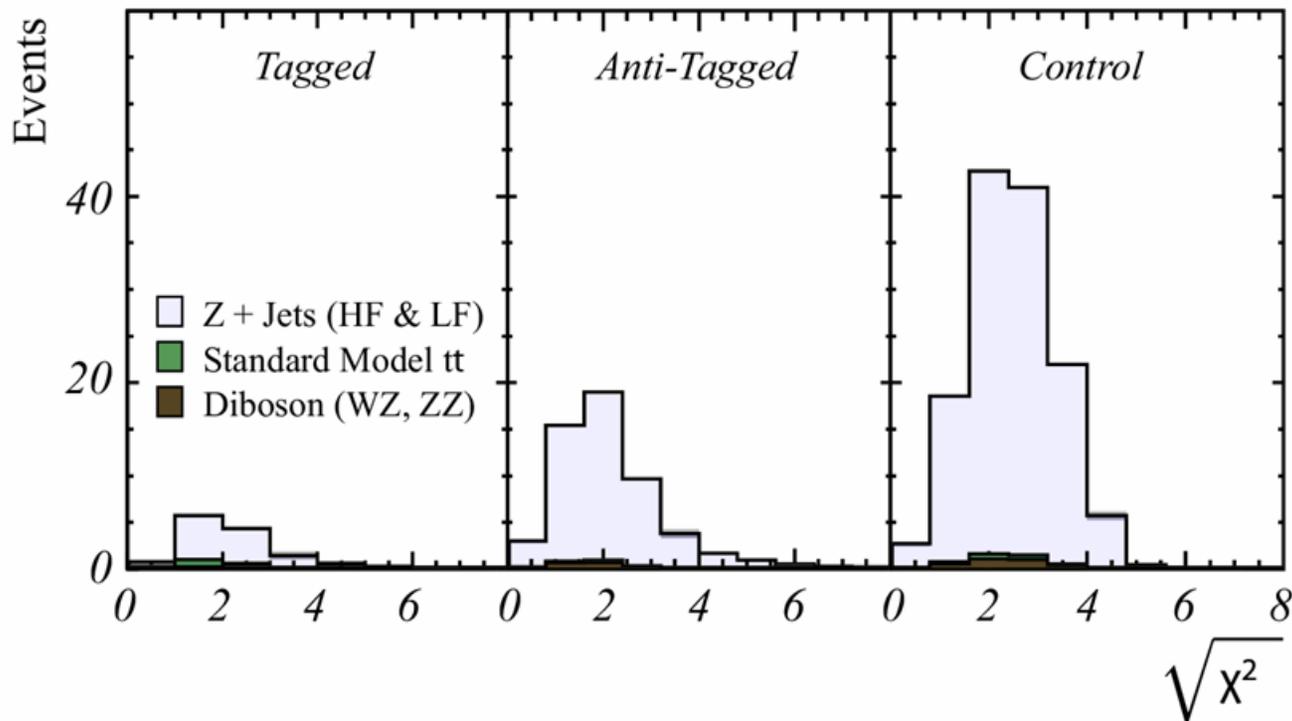
- “How do we control shape uncertainties without hiding a small signal?”
- Solution: add control region with little signal acceptance:
 - Constrain shape uncertainties without “morphing away” signal.
 - Definition: At least one optimized E_T or m_T cut failed (do not look at any b-tagging information).

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



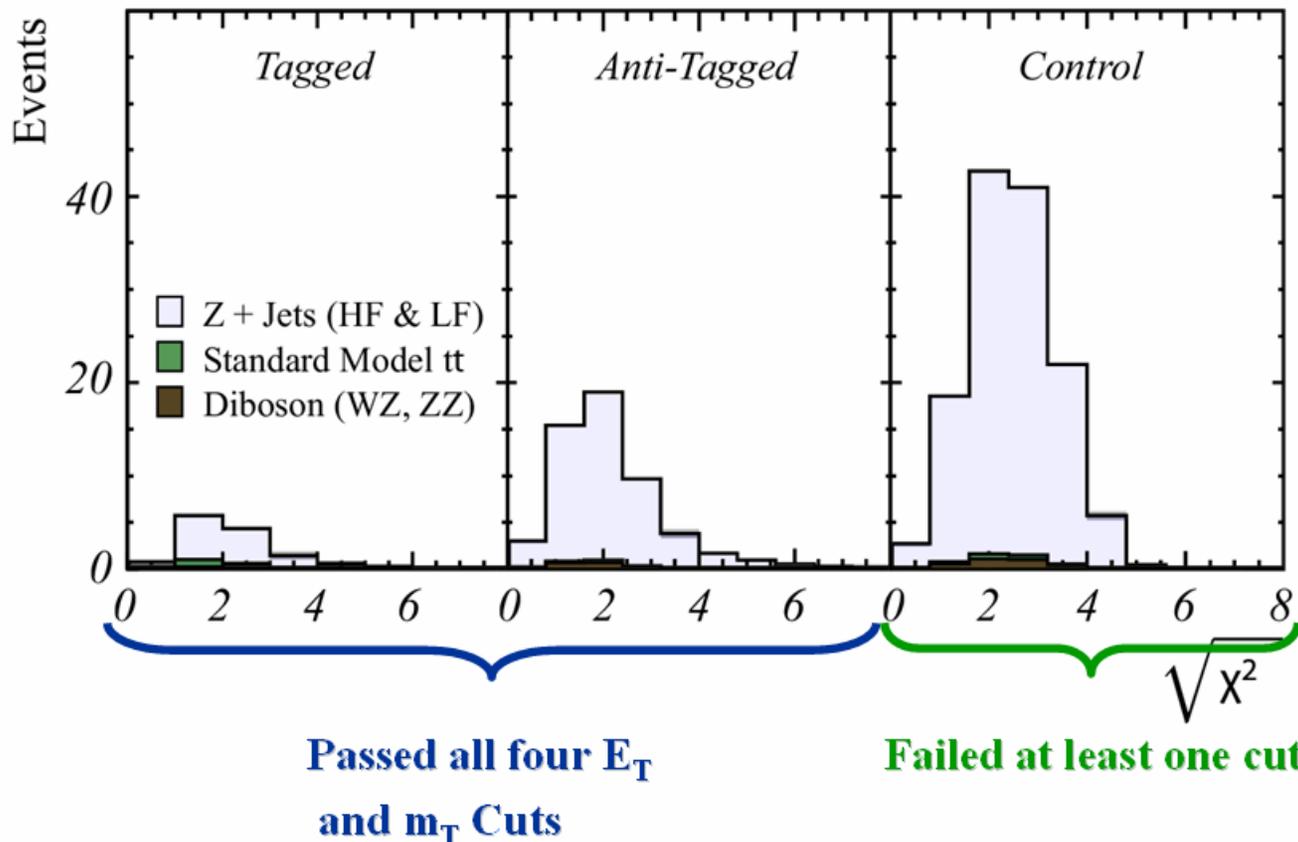
- We have validated that the MC works fairly well in a jet bin, but we do not trust it across jet bins.
 \Rightarrow **No absolute Z + jet constraints.**
- Use MC to predict the ratio of Z + jets acceptance in the two signal regions to the control region.

Expected Background Distributions



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Expected Background Distributions



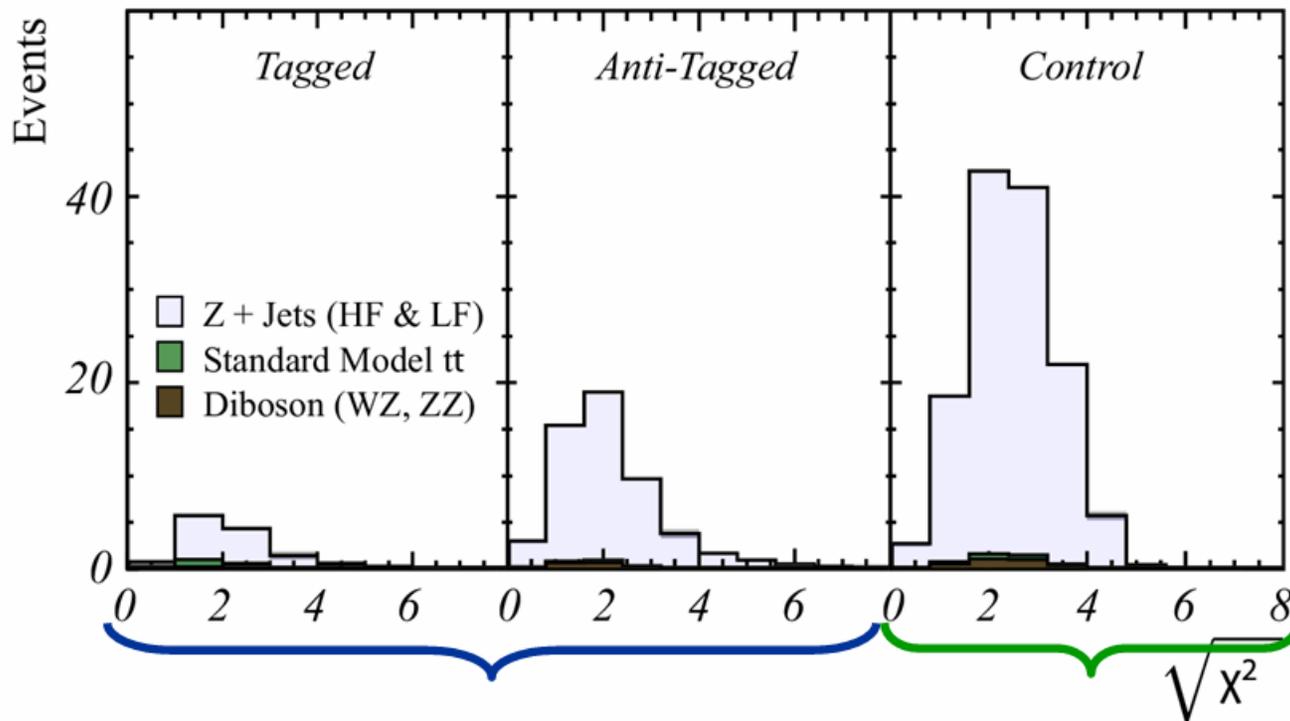


Constraining Z + Jets Background



- 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.**
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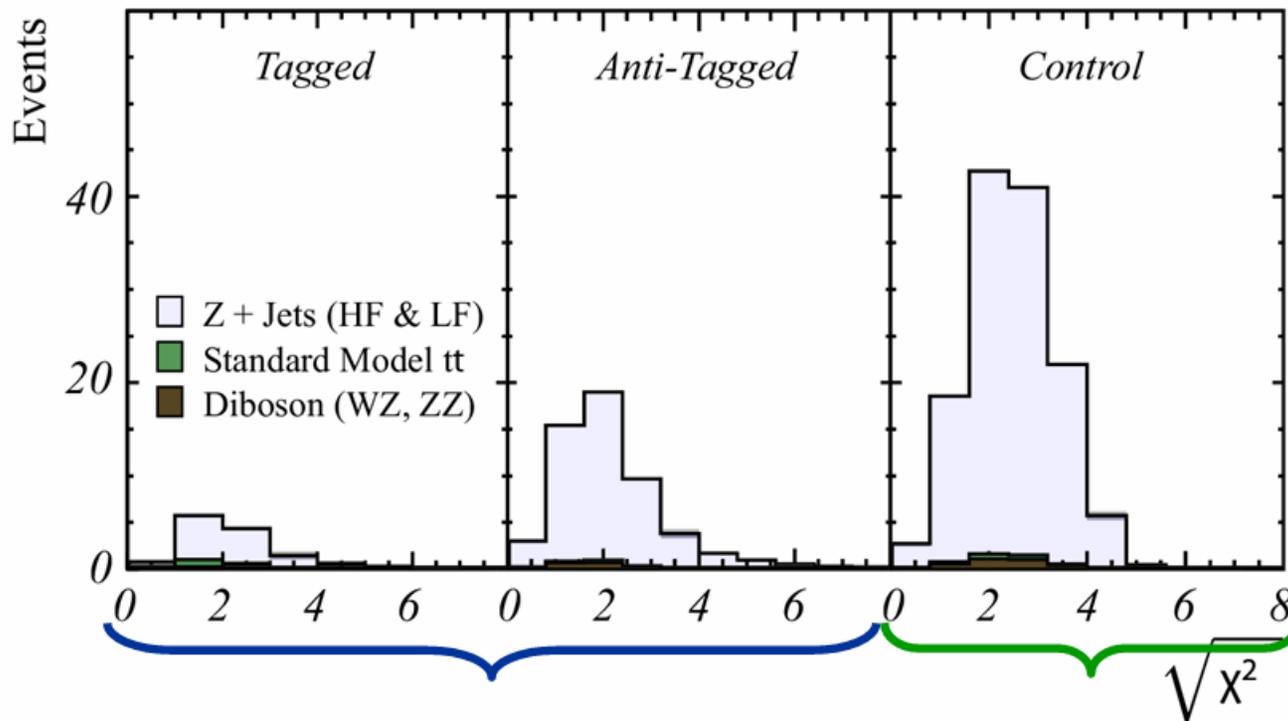
Expected Background Distributions



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

- We have validated that the MC works fairly well in a jet bin, but we do not trust it across jet bins.
 \Rightarrow **No absolute Z + jet constraints.**
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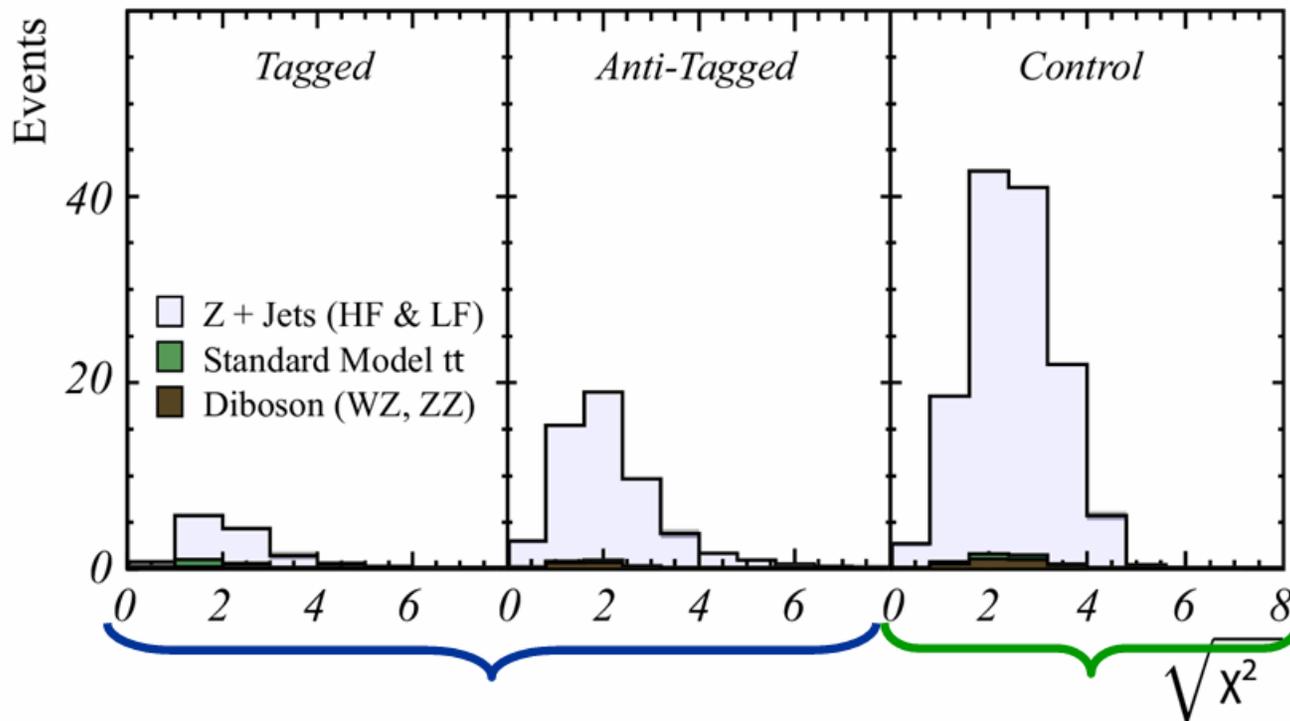
Expected Background Distributions



$\mathcal{R}_{sig} \equiv$ Ratio of Z + jets
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to the control region.
 \Rightarrow 20% constraint

- 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

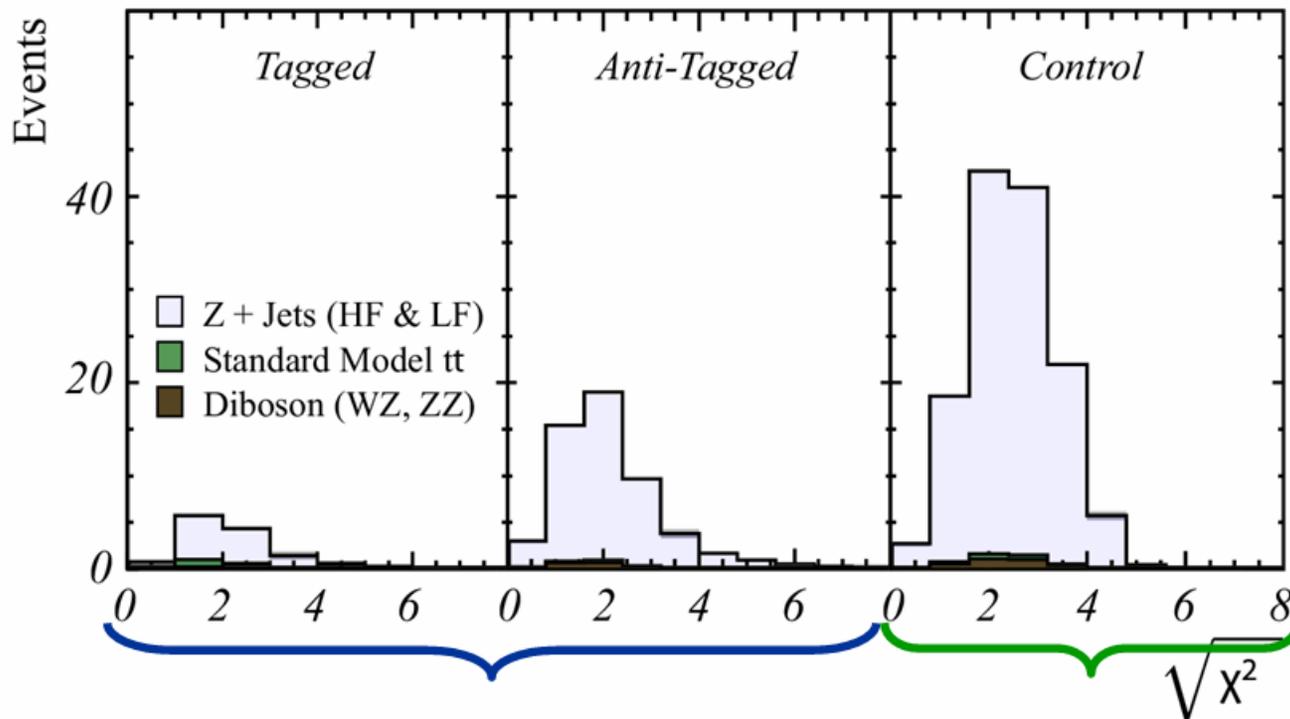


$\mathcal{R}_{sig} \equiv$ Ratio of Z + jets in the signal regions to the control region.
⇒ 20% constraint

$f_{tag} \equiv$ Fraction of signal region Z + jet events that contain at least on b-tag.

- 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



**Passed all four E_T
and m_T Cuts**

Failed at least one cut

$\mathcal{R}_{sig} \equiv$ Ratio of Z + jets
in the signal regions
to the control region.
⇒ 20% constraint

$f_{tag} \equiv$ Fraction of signal
region Z + jet events
that contain at least
on b-tag.
⇒ No constraint!

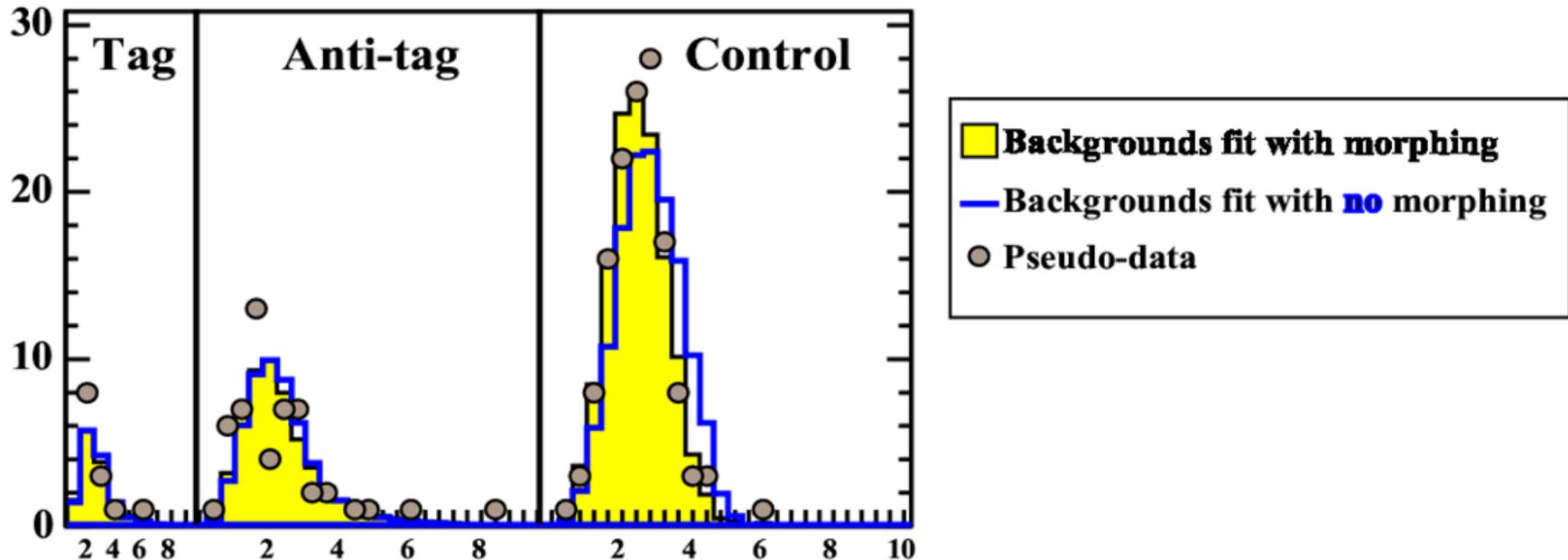


Fitting χ^2 Roundup



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

Best Fit to Pseudo-Experiment

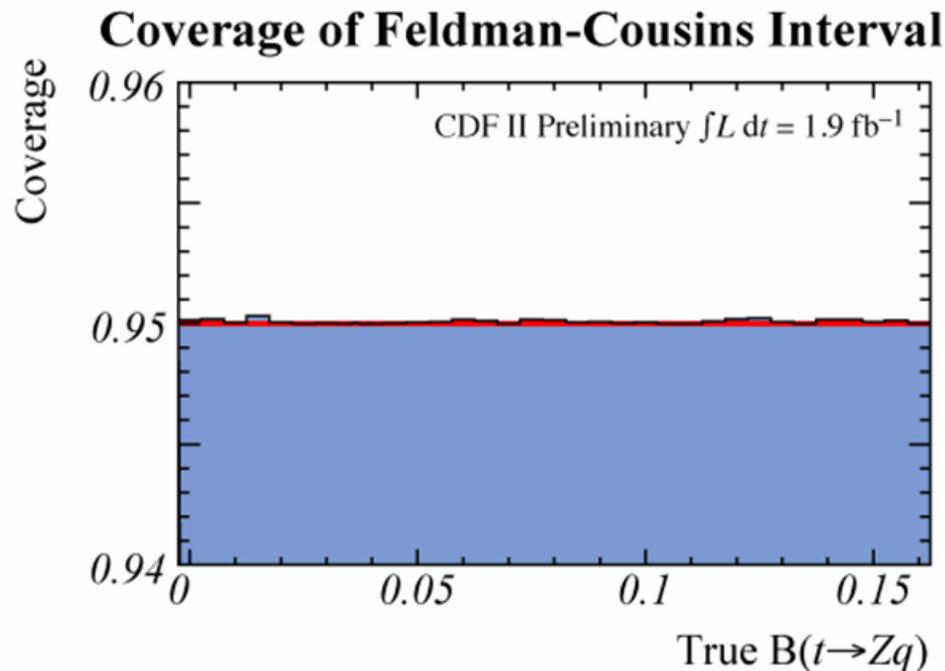




Feldman-Cousins in Five Minutes



- 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.

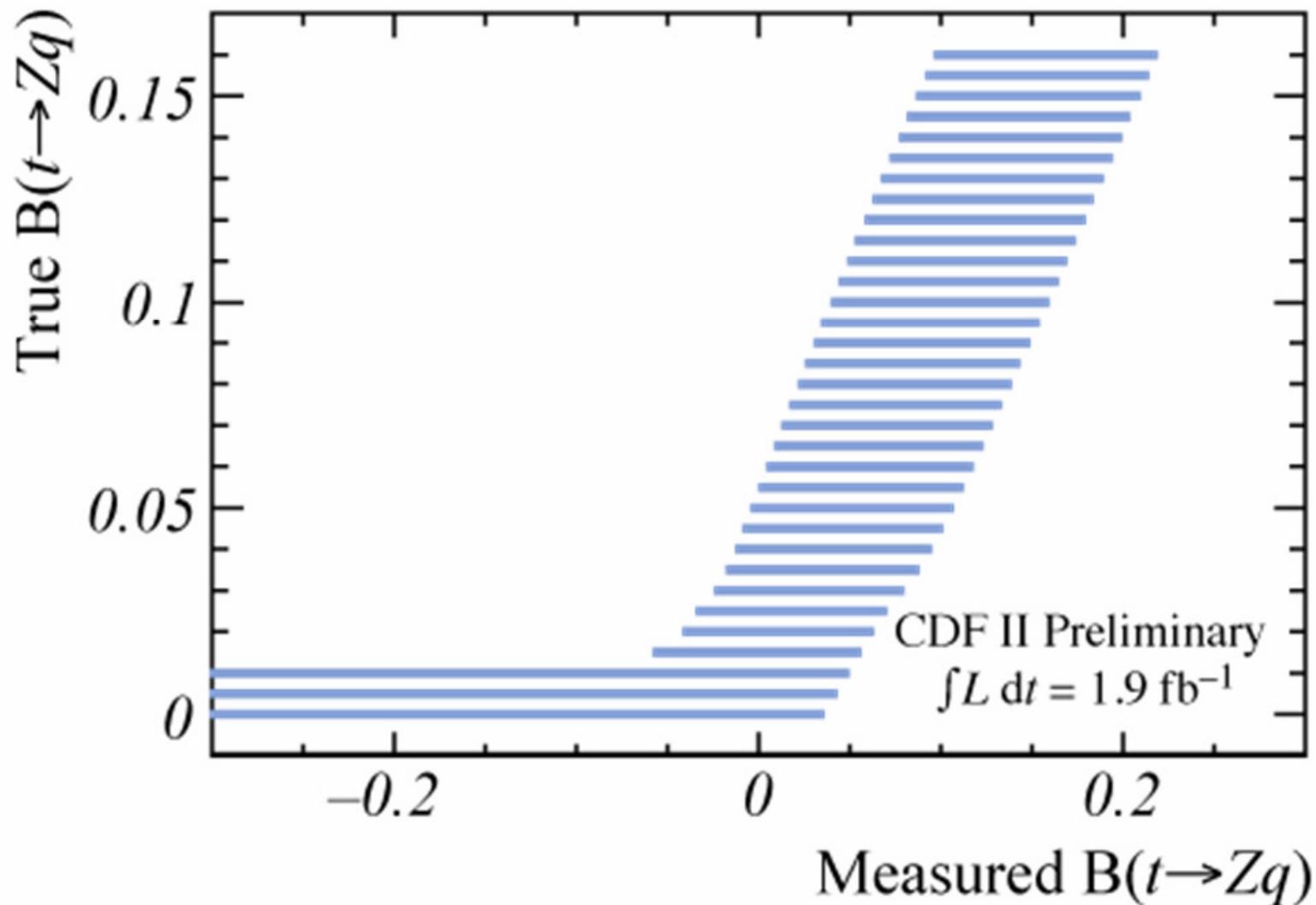




Top FCNC Feldman-Cousins Bands



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

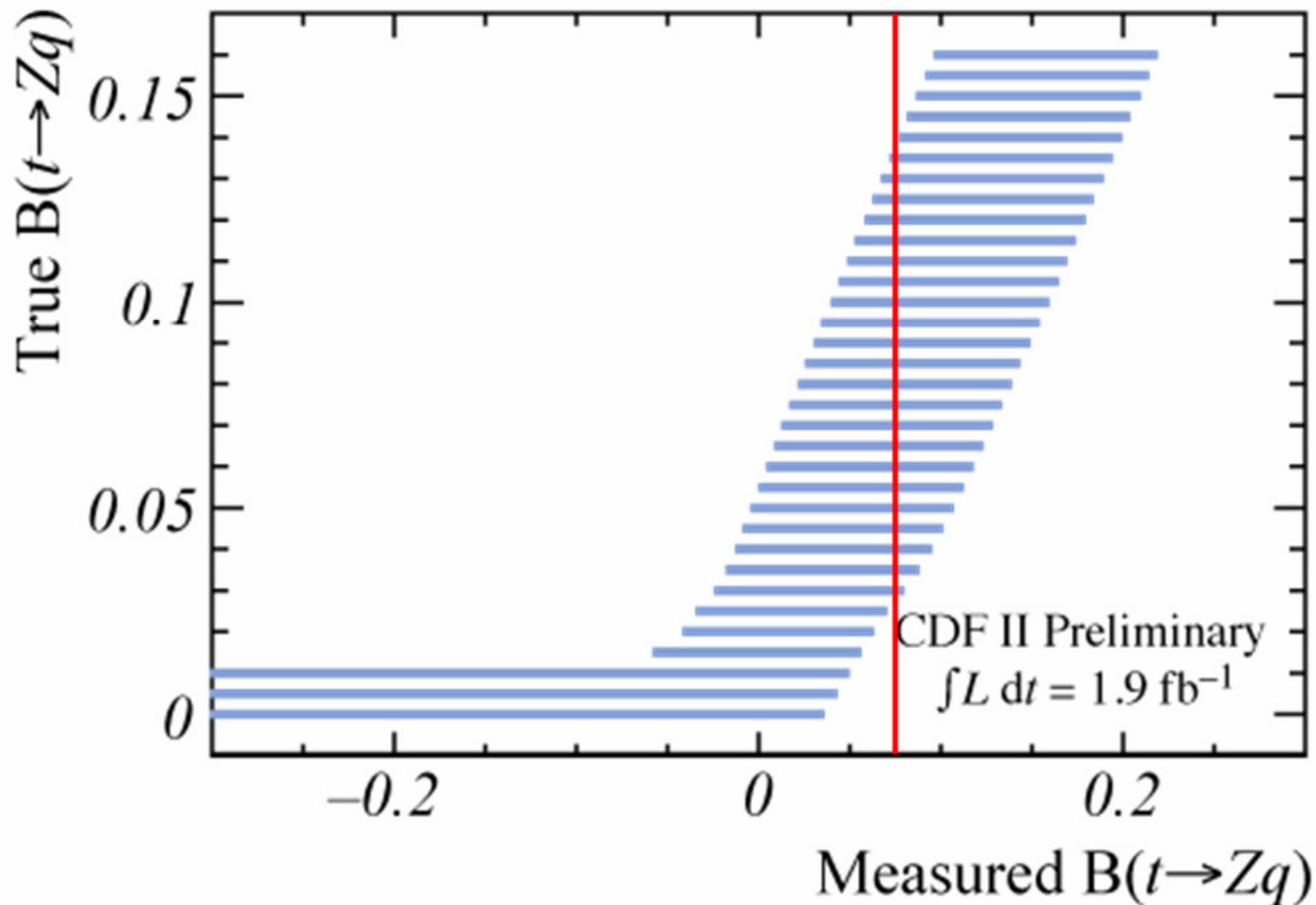




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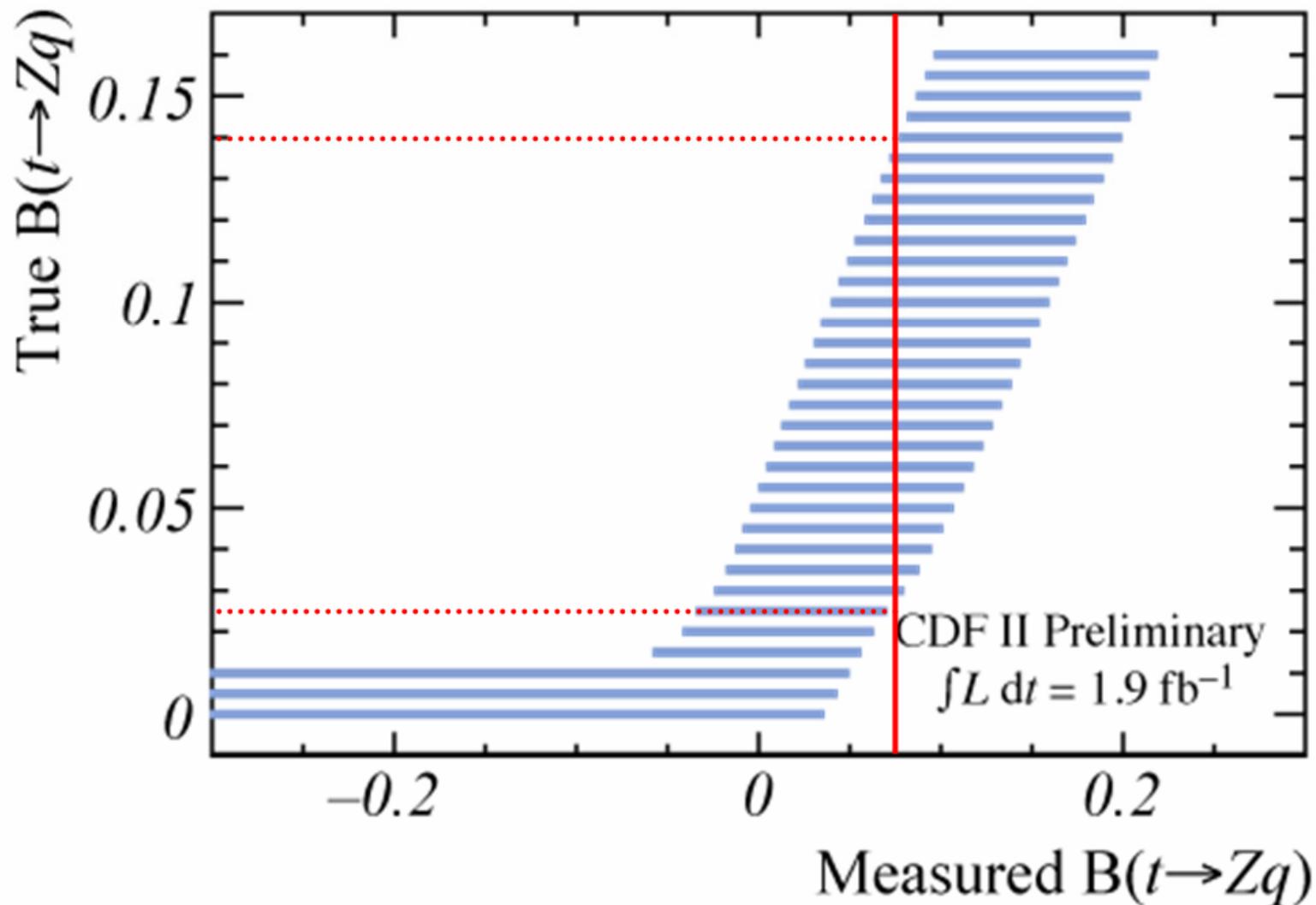




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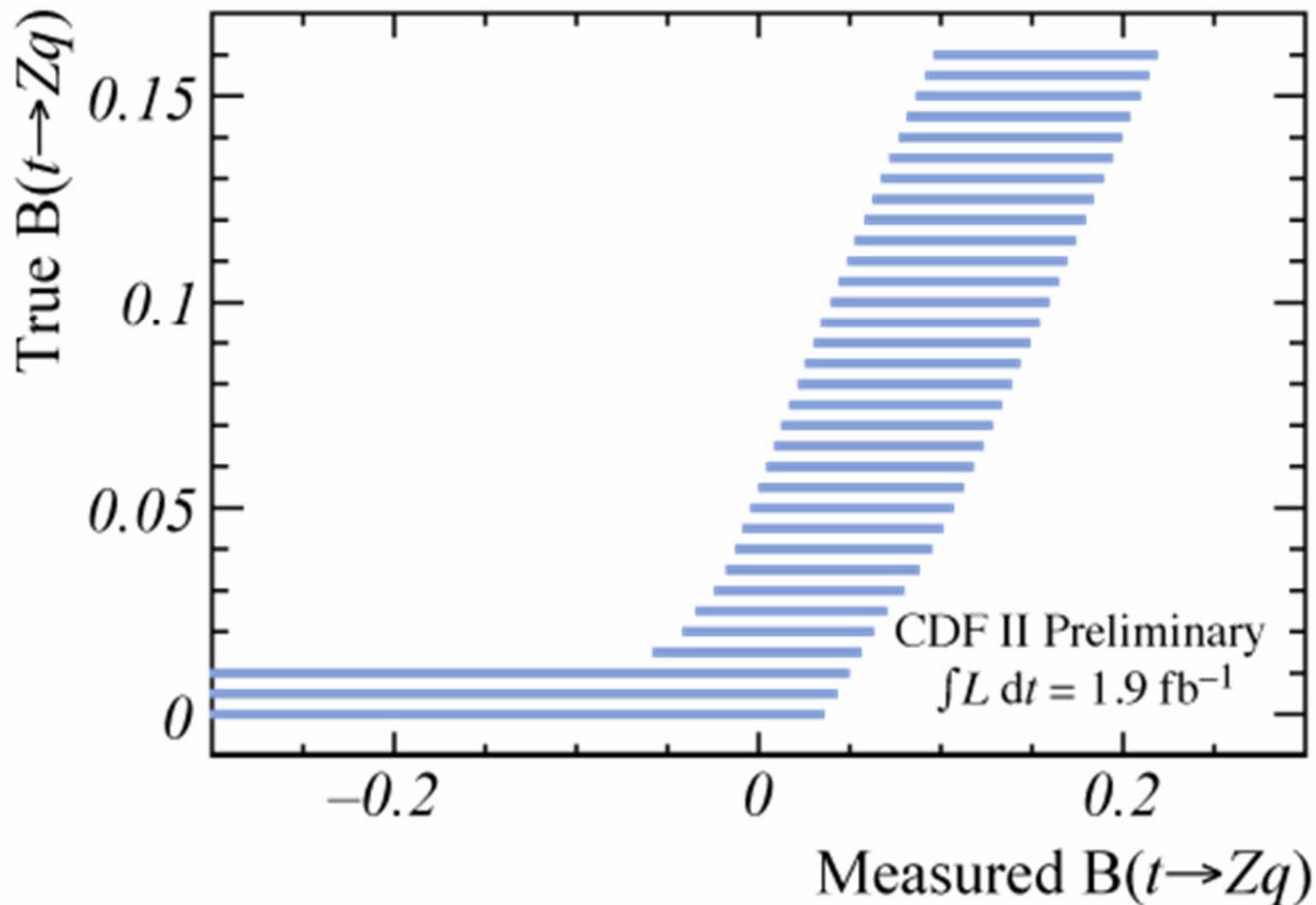




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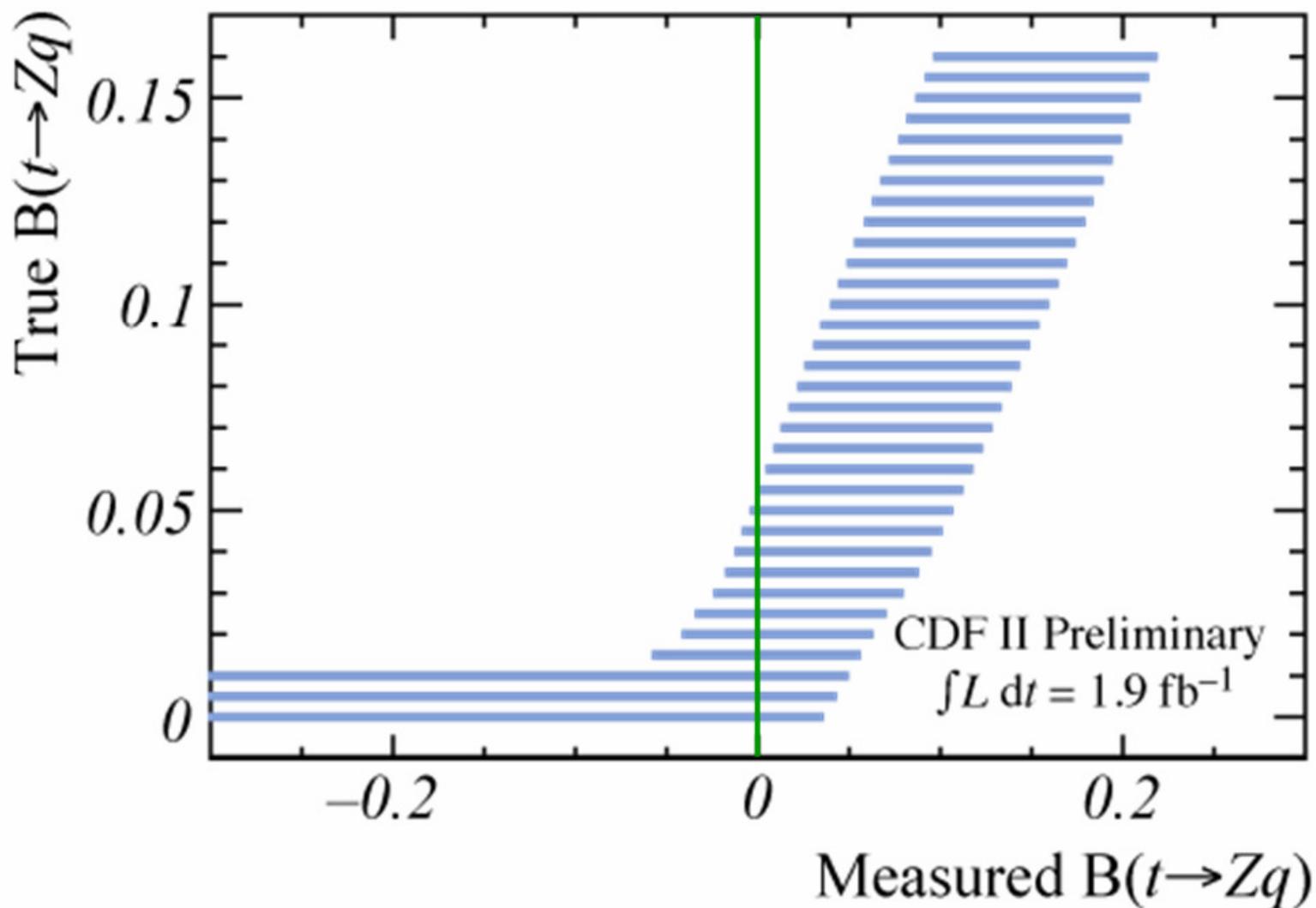




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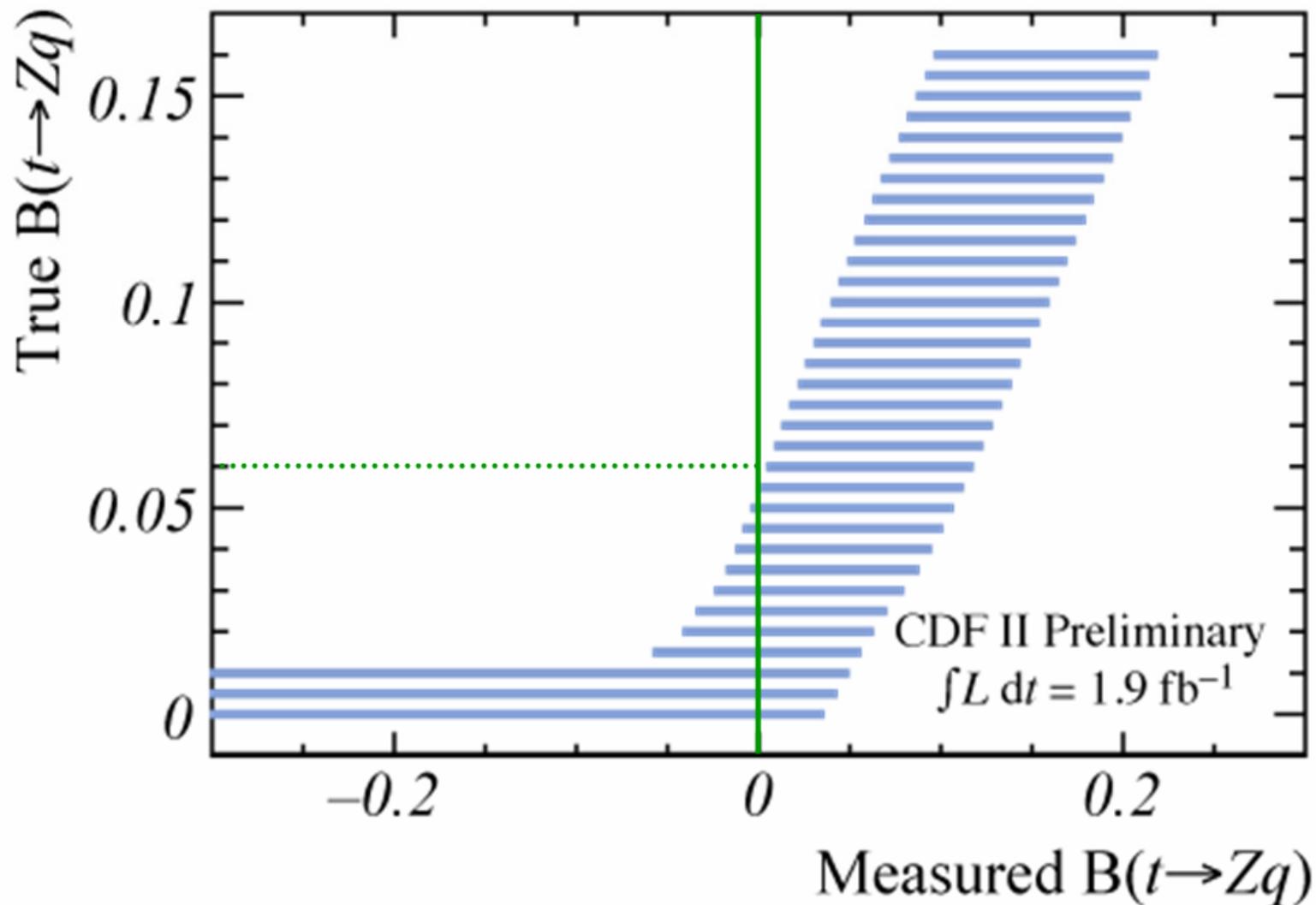




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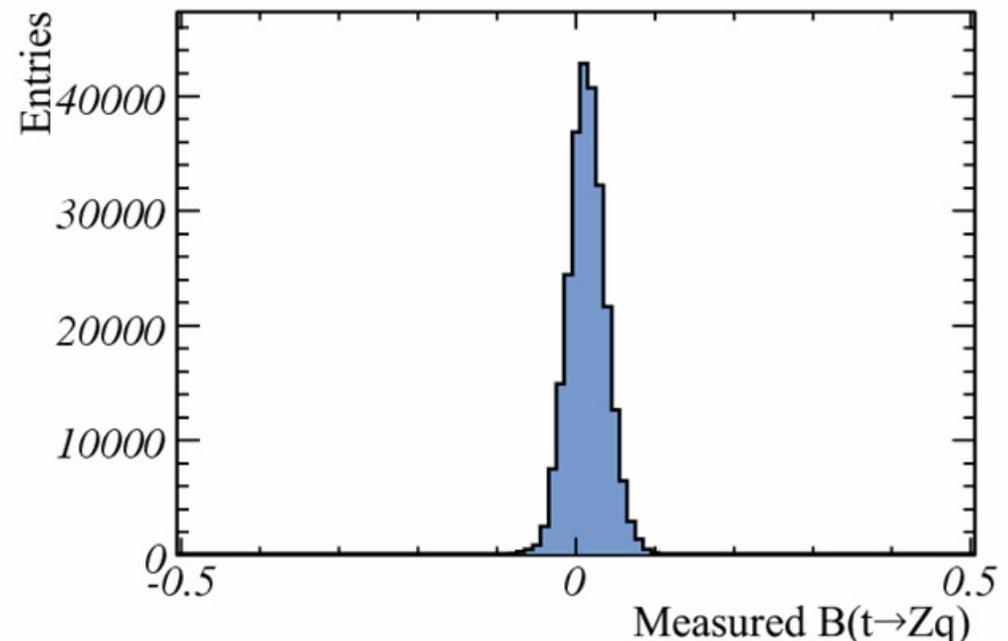
Pseudo-Experiments (PEs)



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 $B(t \rightarrow Zq) = 0.0150$

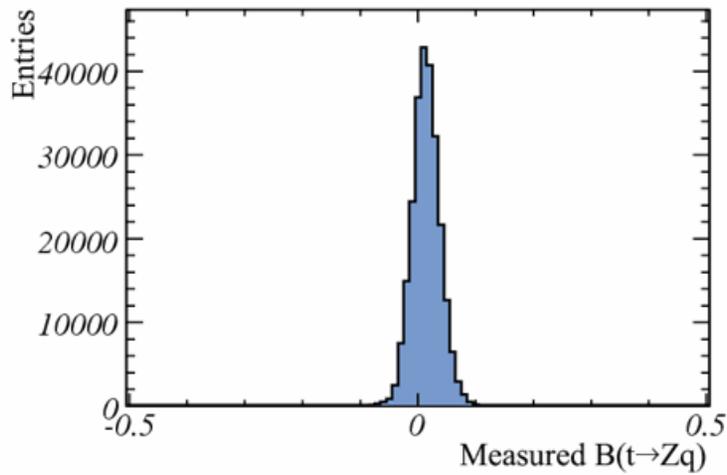




FC Band Construction In A Nutshell



PEs for True $B(t \rightarrow Zq)=0.0150$

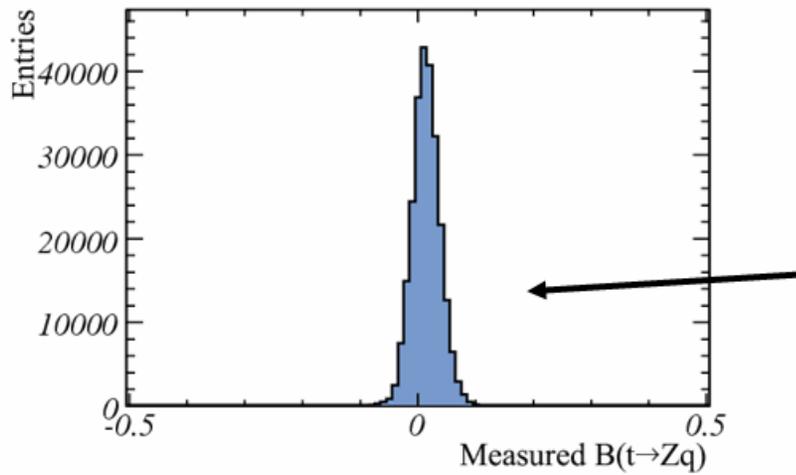




FC Band Construction In A Nutshell



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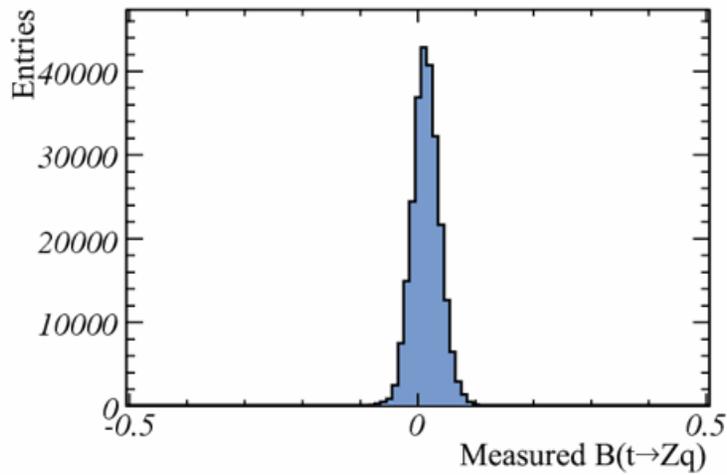
PEs generated with all statistical
and systematic uncertainties.



FC Band Construction In A Nutshell



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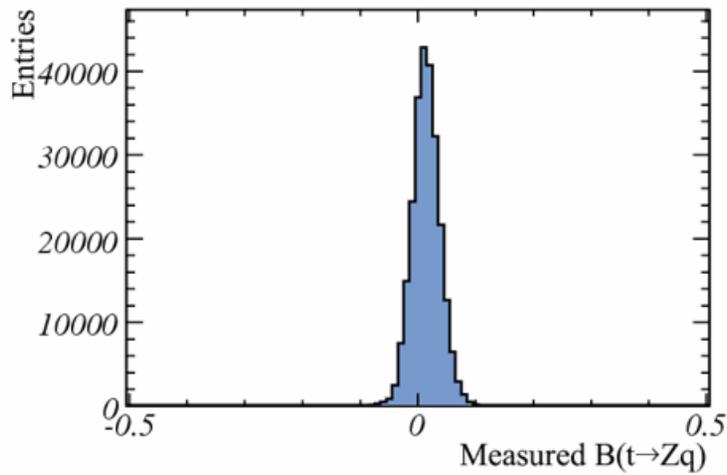




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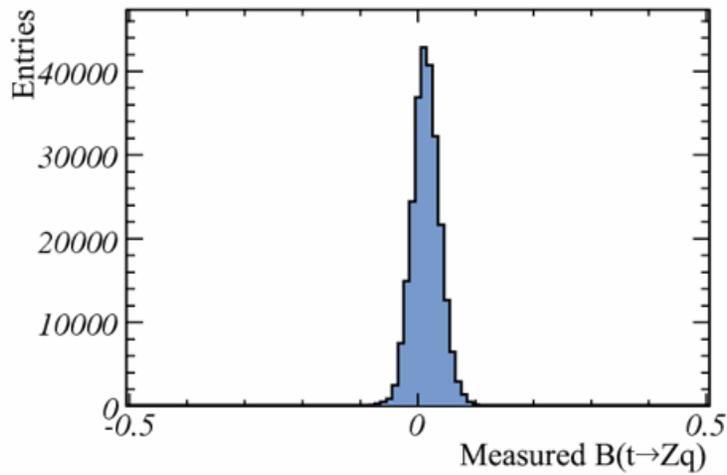
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- Use *Likelihood Ratio Ordering Principle*:

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

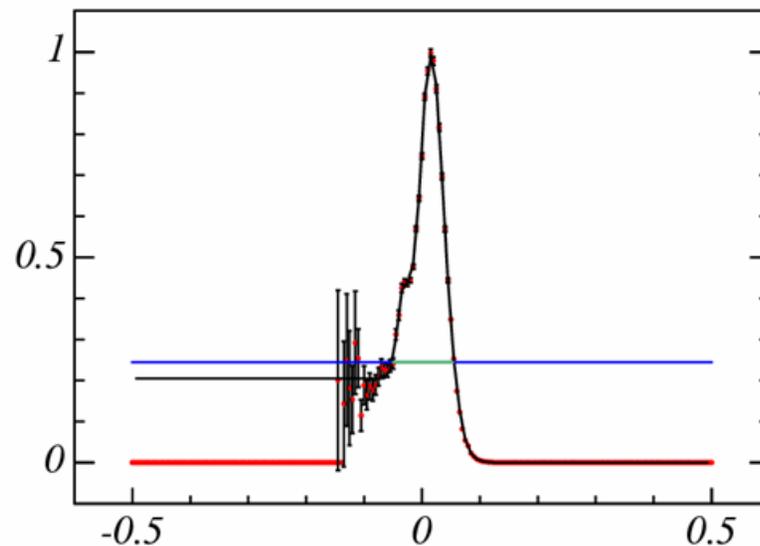
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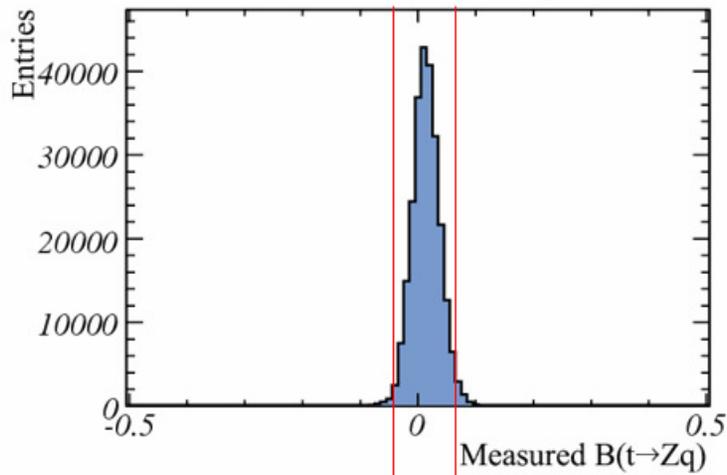
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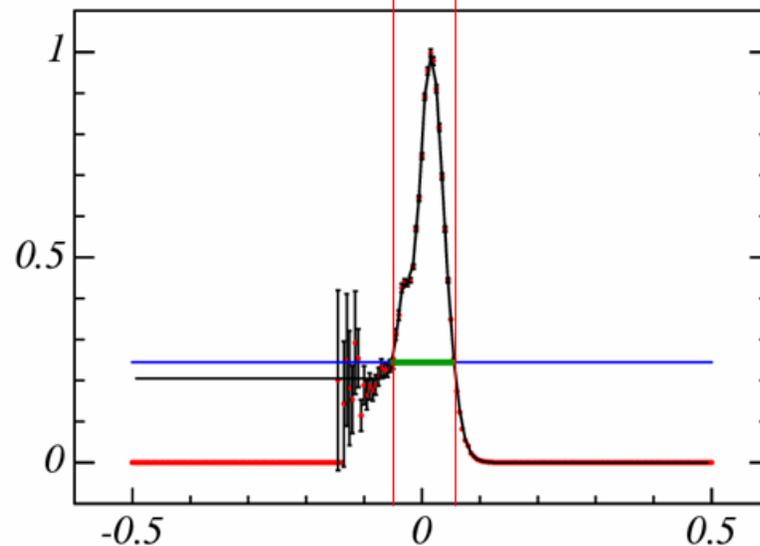
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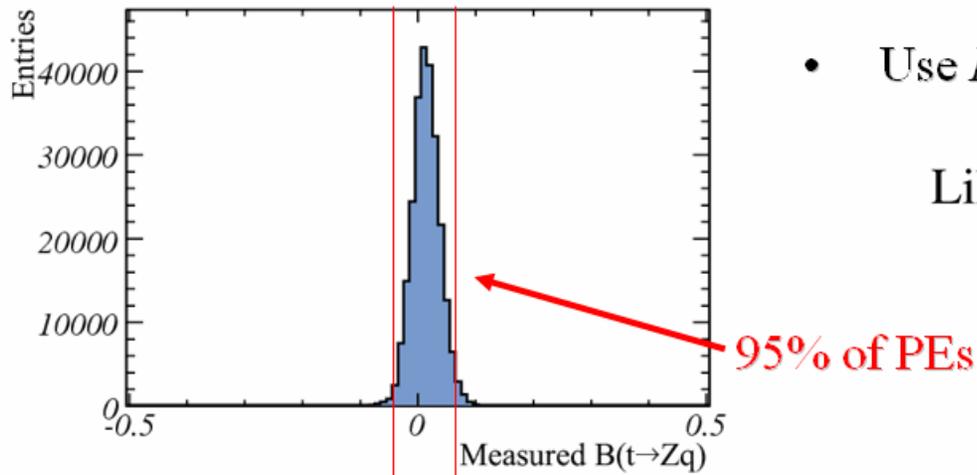
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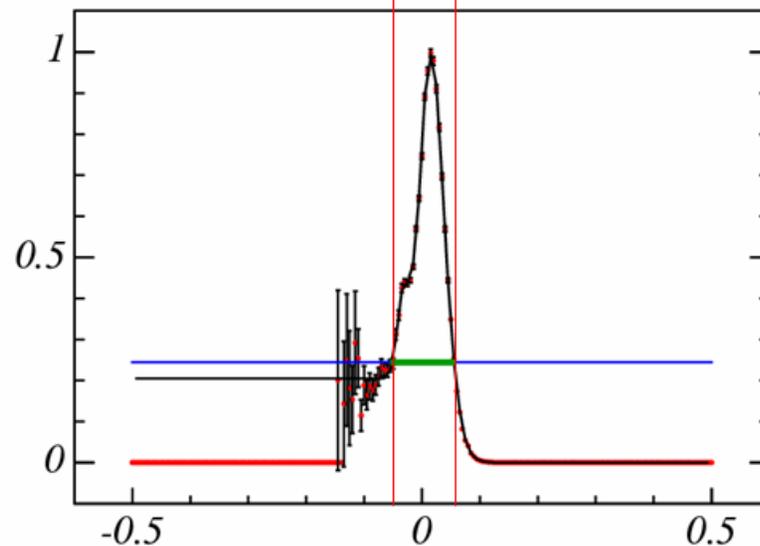
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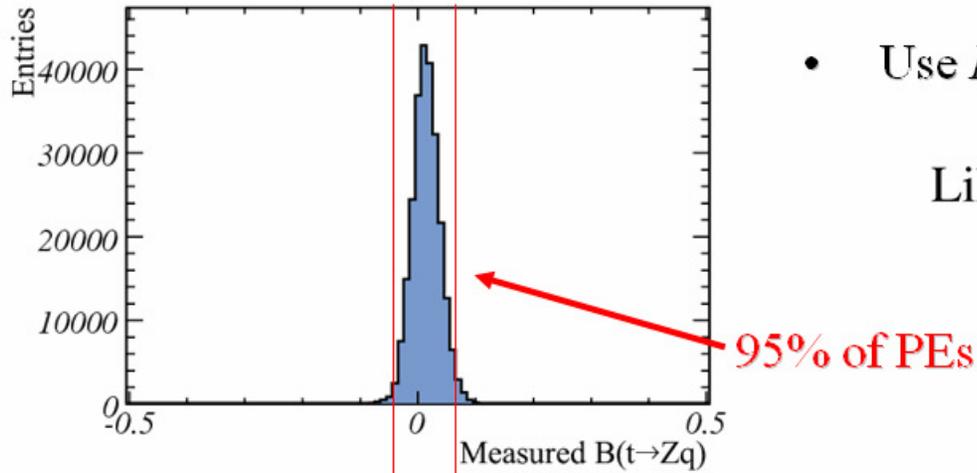
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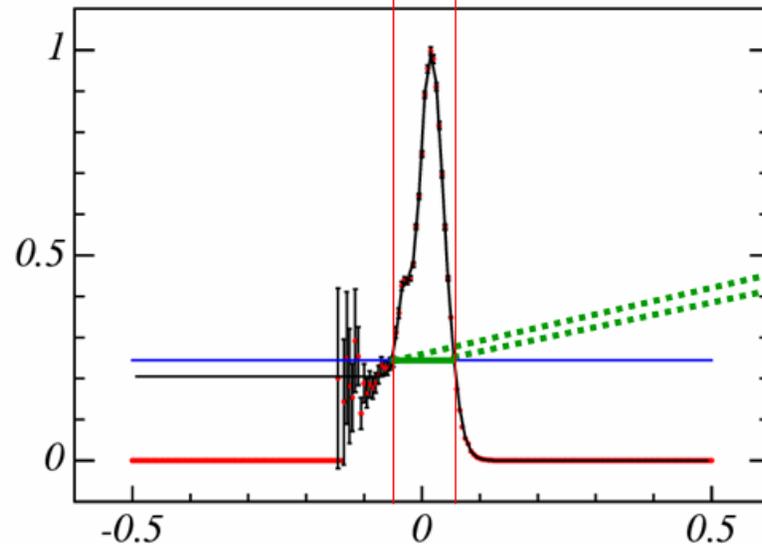
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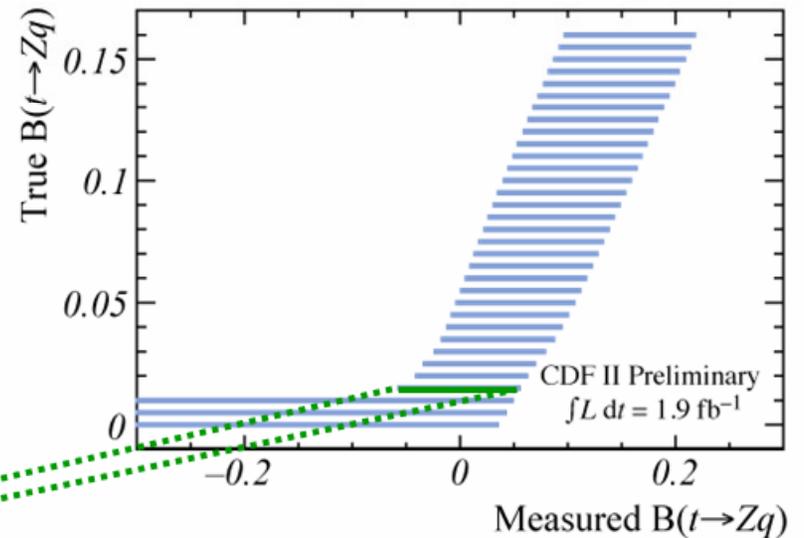
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FCNC Feldman-Cousins Band (95% C.L.)

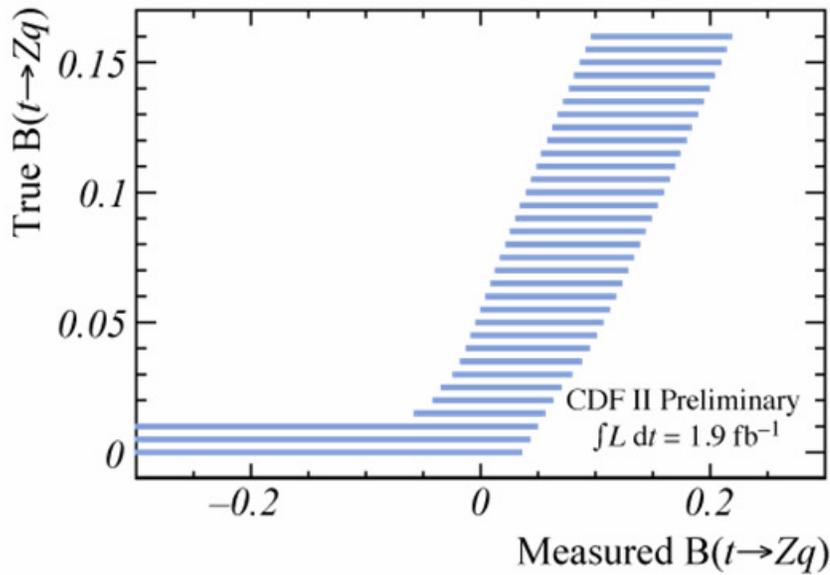




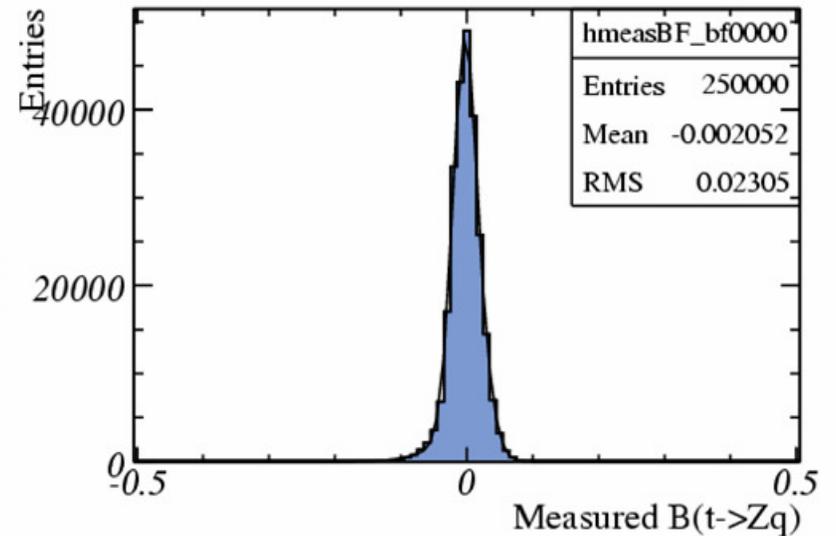
Expected Limit



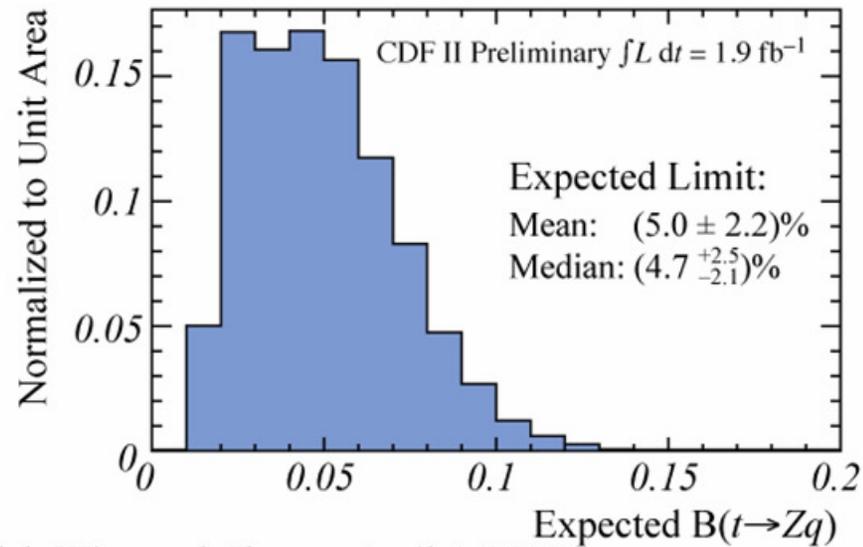
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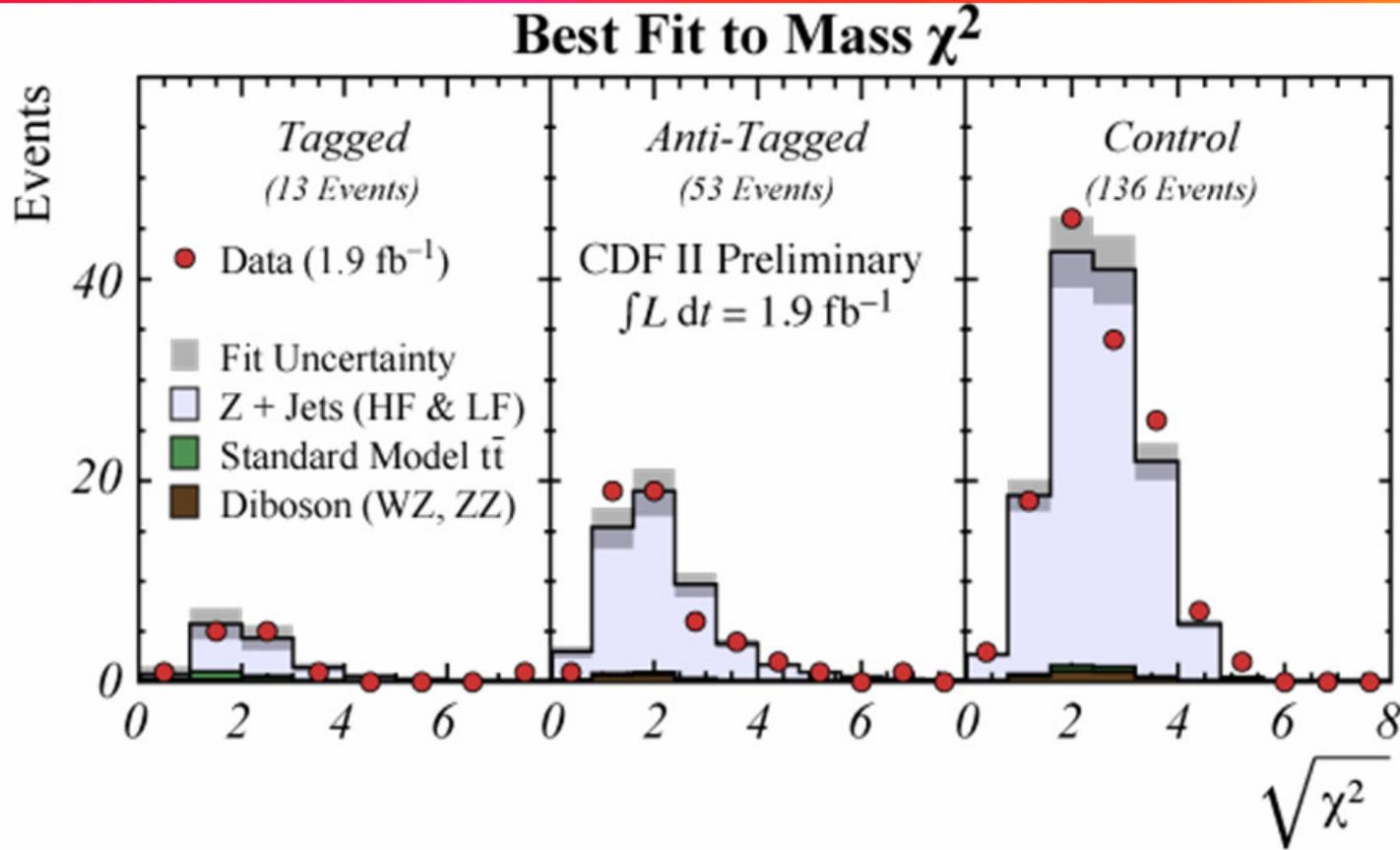
PEs for True $B(t \rightarrow Zq) = 0.0000$



FCNC Expected Limit

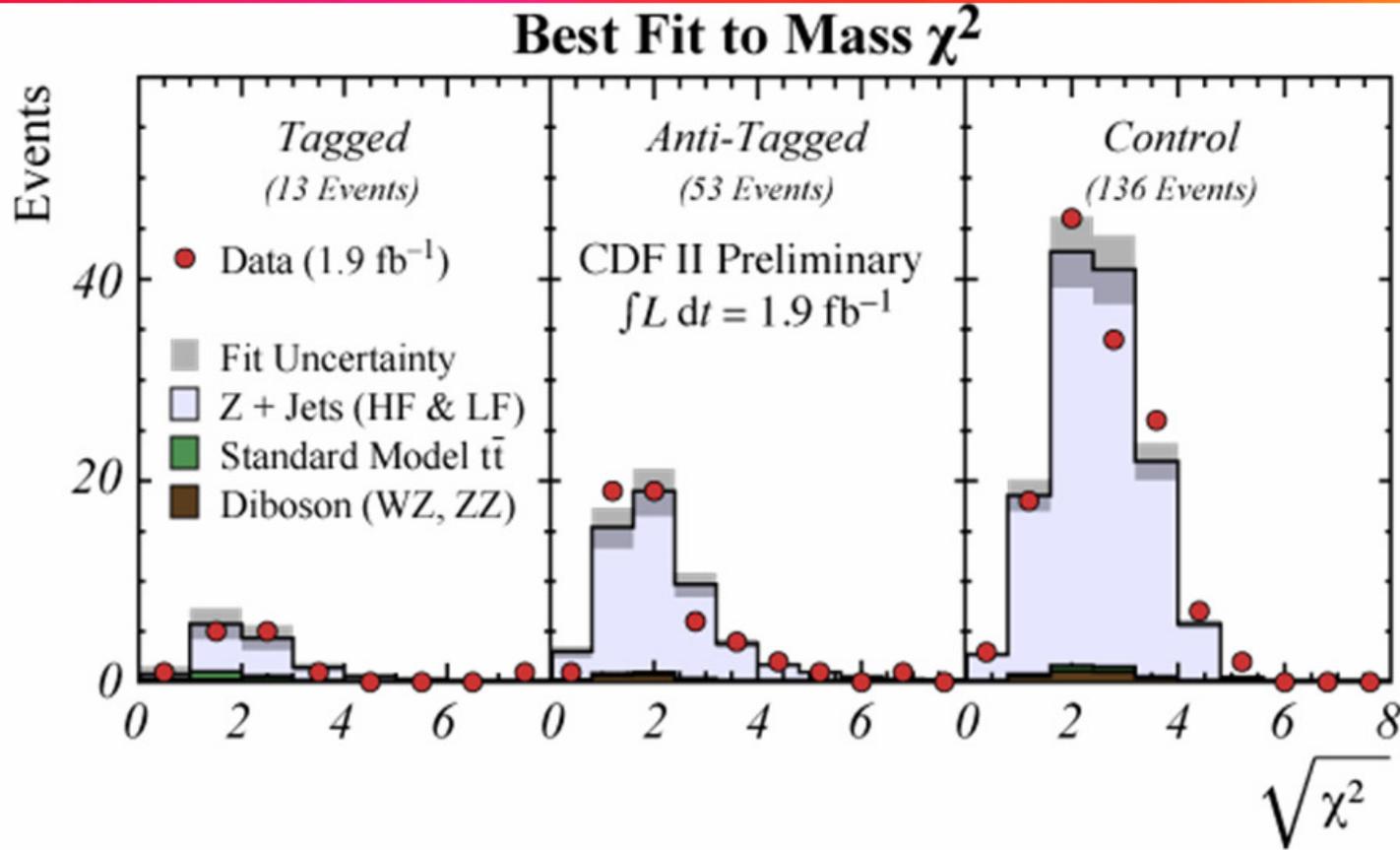


The Fit to the Data



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

The Fit to the Data



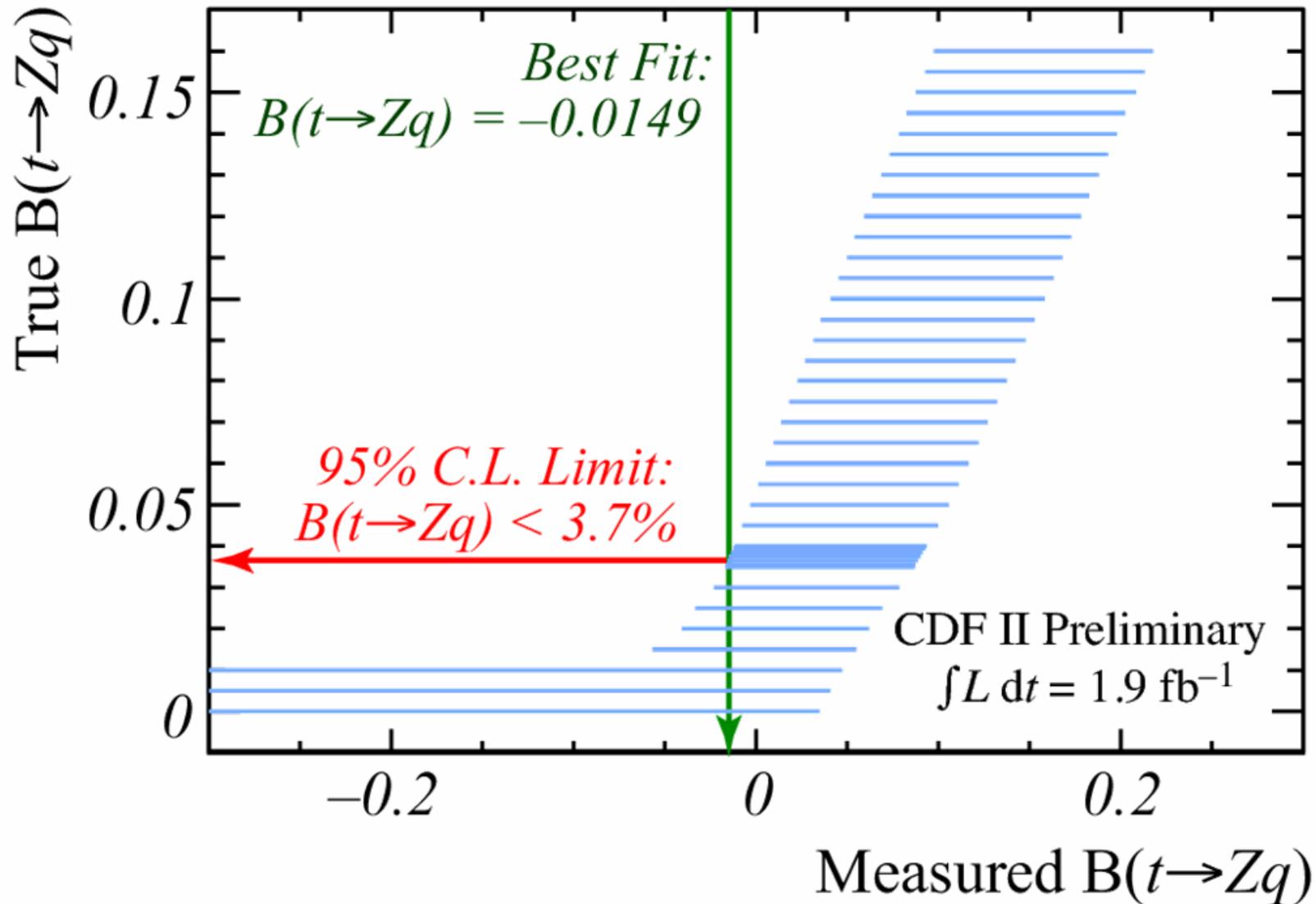
Fit Parameter ($\int \mathcal{L} dt = 1.9\text{fb}^{-1}$)	Value		
Branching Fraction, $\mathcal{B}(t \rightarrow Zq)$ (%)	-1.49	\pm	1.52
Z+Jets Events in Control Region, Z_{control}	129.0	\pm	11.1
Ratio Signal/Control Region, \mathcal{R}_{sig}	0.52	\pm	0.07
Tagging Fraction, f_{tag} (%)	20.0	\pm	5.9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



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

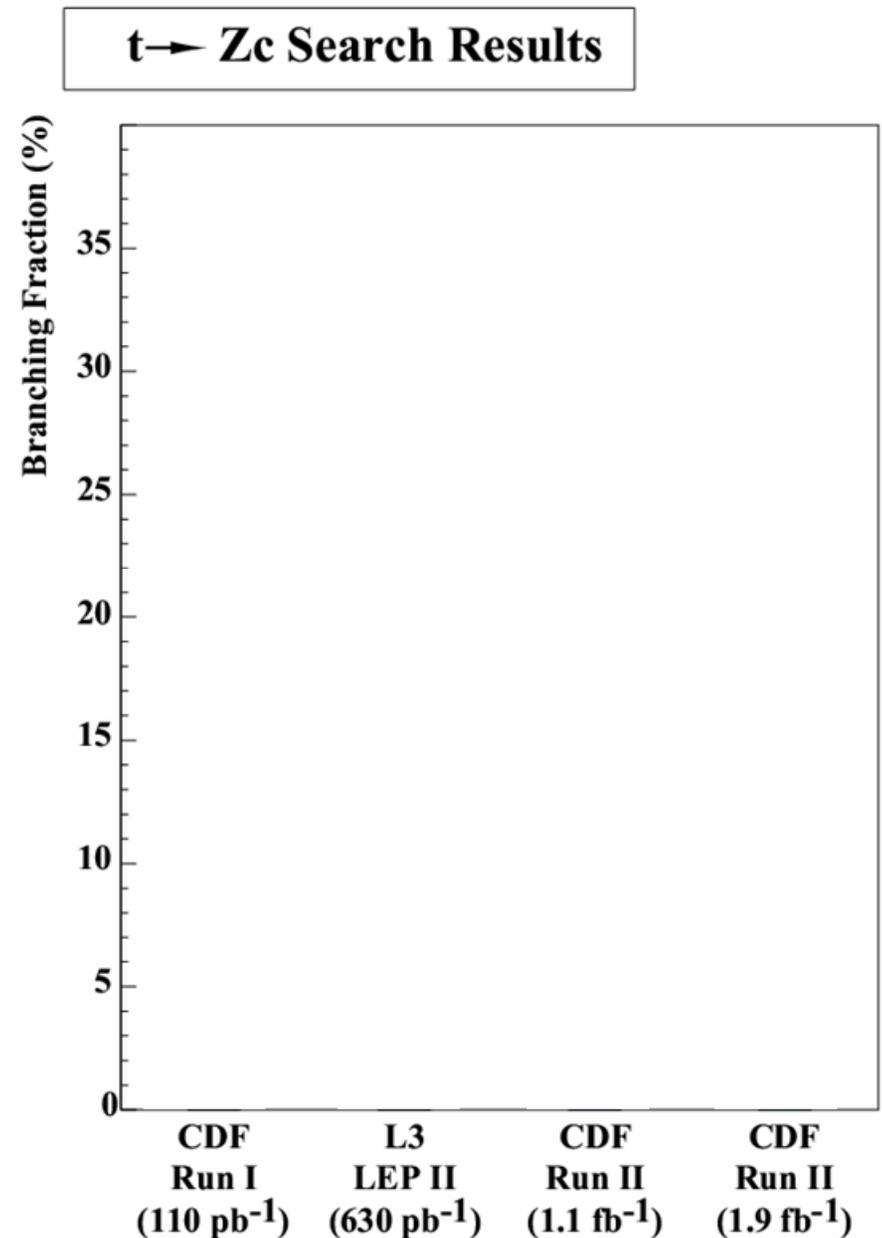
Summary



Summary



- CDF and the Tevatron are running very well.
 - Thanks A.D.!
- 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:
 $\text{Br}(t \rightarrow Z c) < 3.7\%$ at 95% C.L.
- Using data-based background techniques will be very important for the LHC.

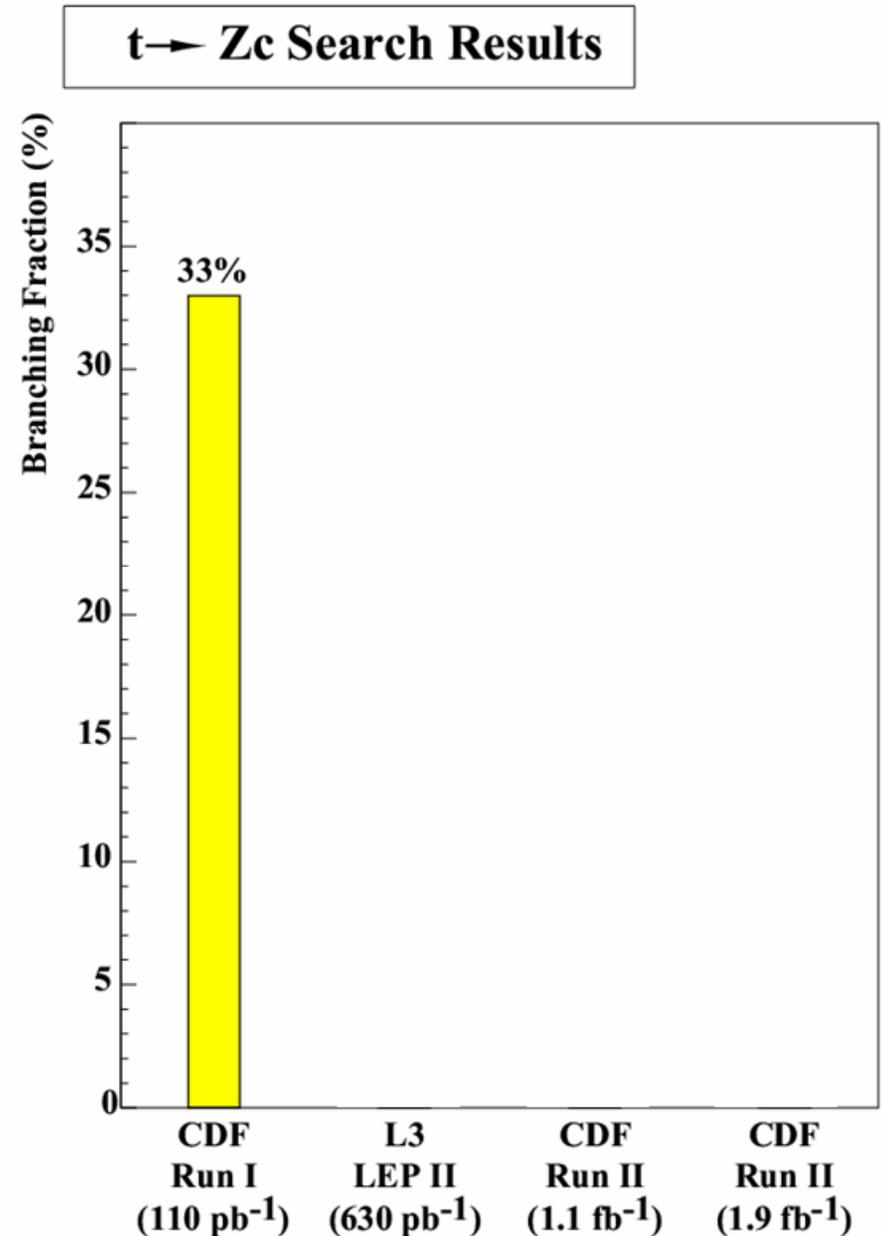




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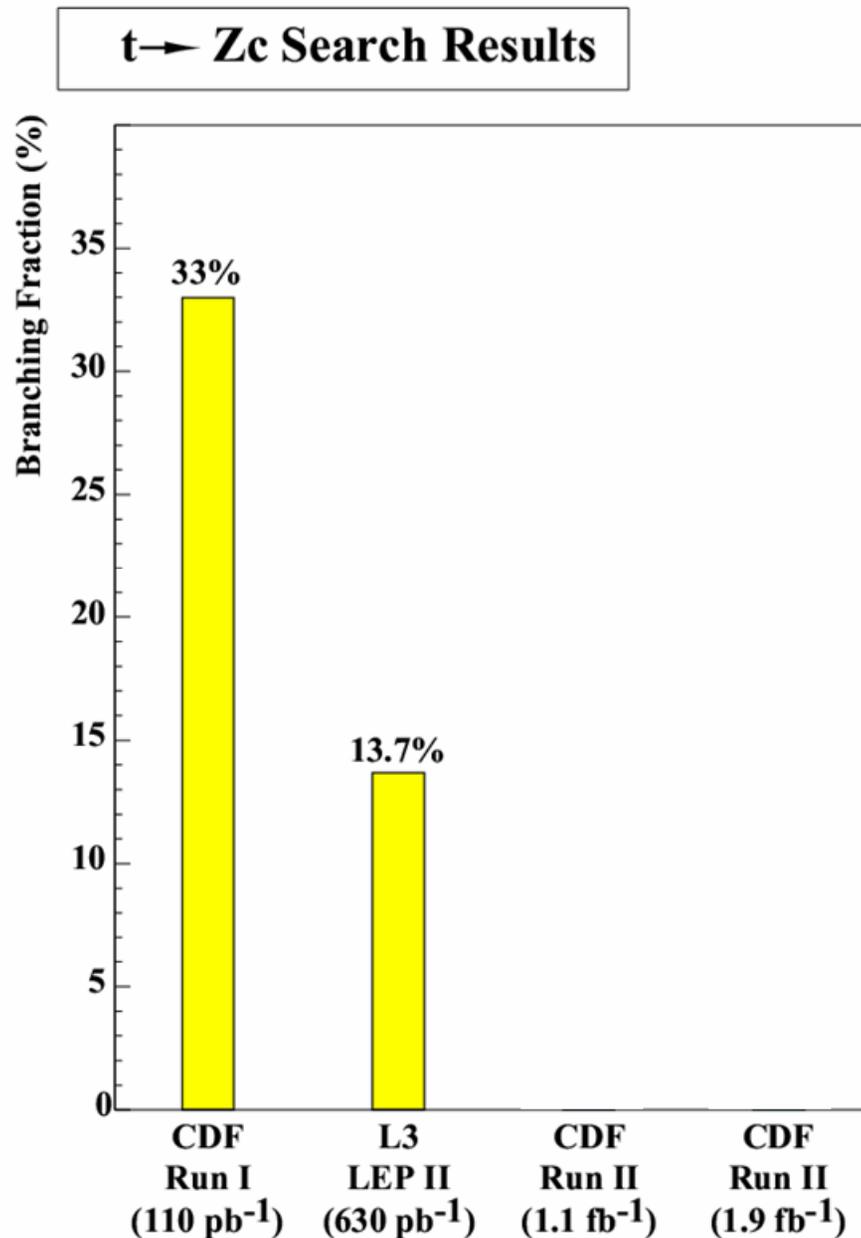




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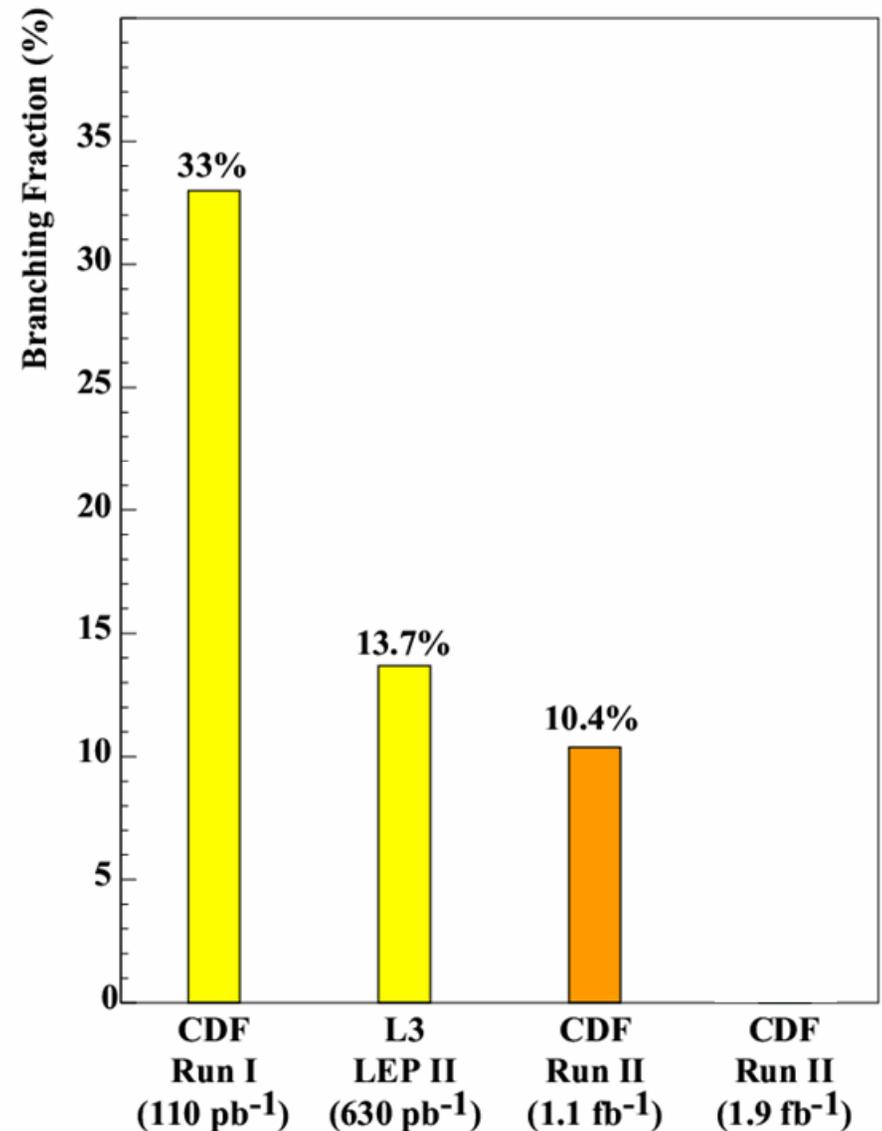


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$t \rightarrow Z c$ Search Results



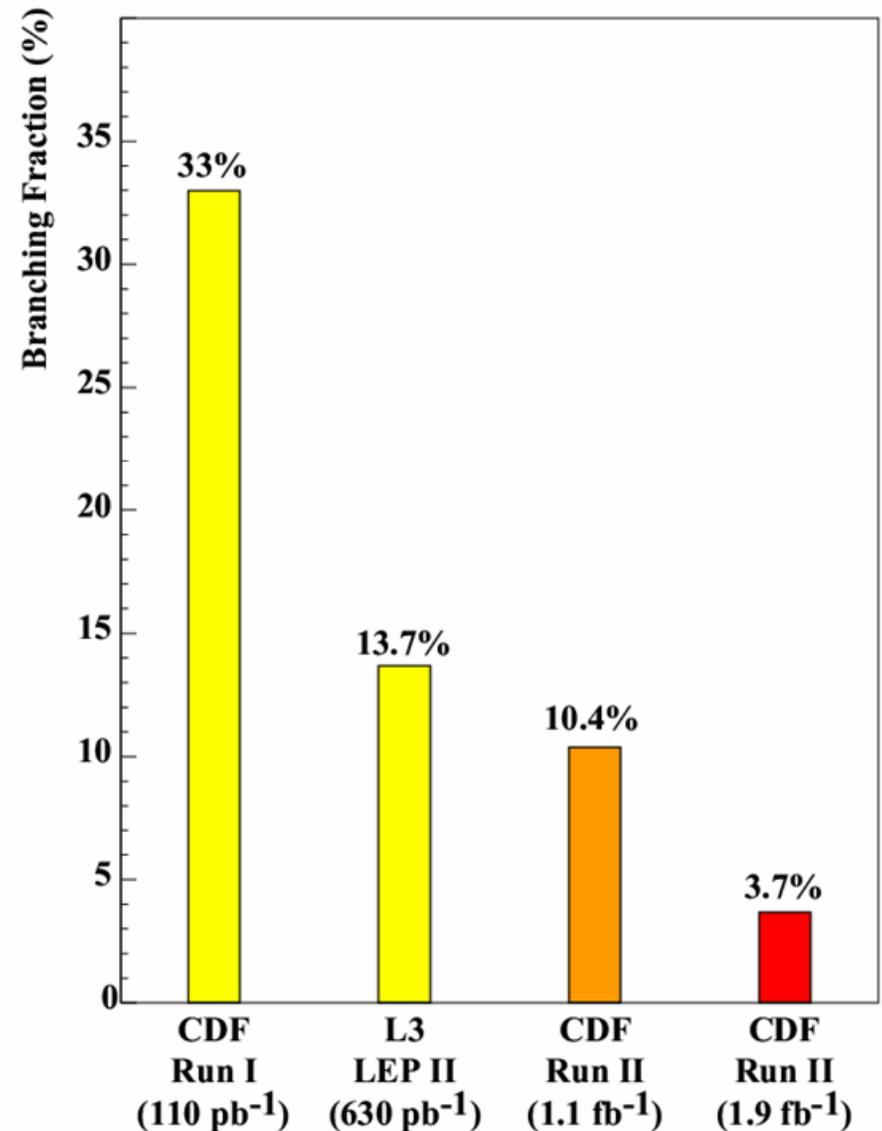


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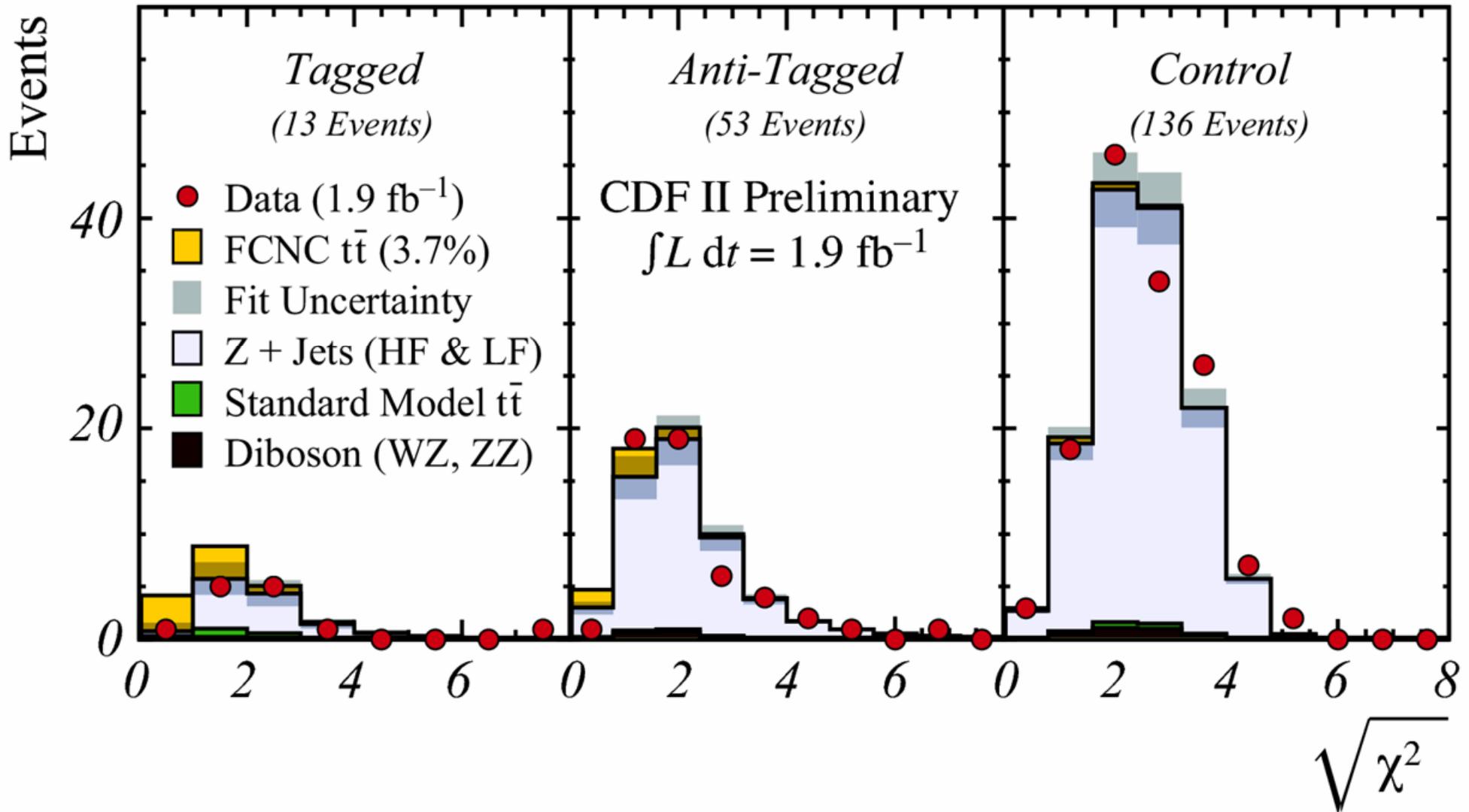




Money Plot



Best Fit to Mass χ^2





New Era of Precision Top Physics!



2006 PDG Top Entry

t

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

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

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	$\frac{p}{\text{MeV/c}}$
$W q (q = b, s, d)$			—
$W b$			—
$\ell \nu_\ell \text{ anything}$	[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] < 13.7	%	95%



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5σ Evidence for single top production



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(Your analysis here?!)



Thank You!

Best Fit to Mass χ^2

