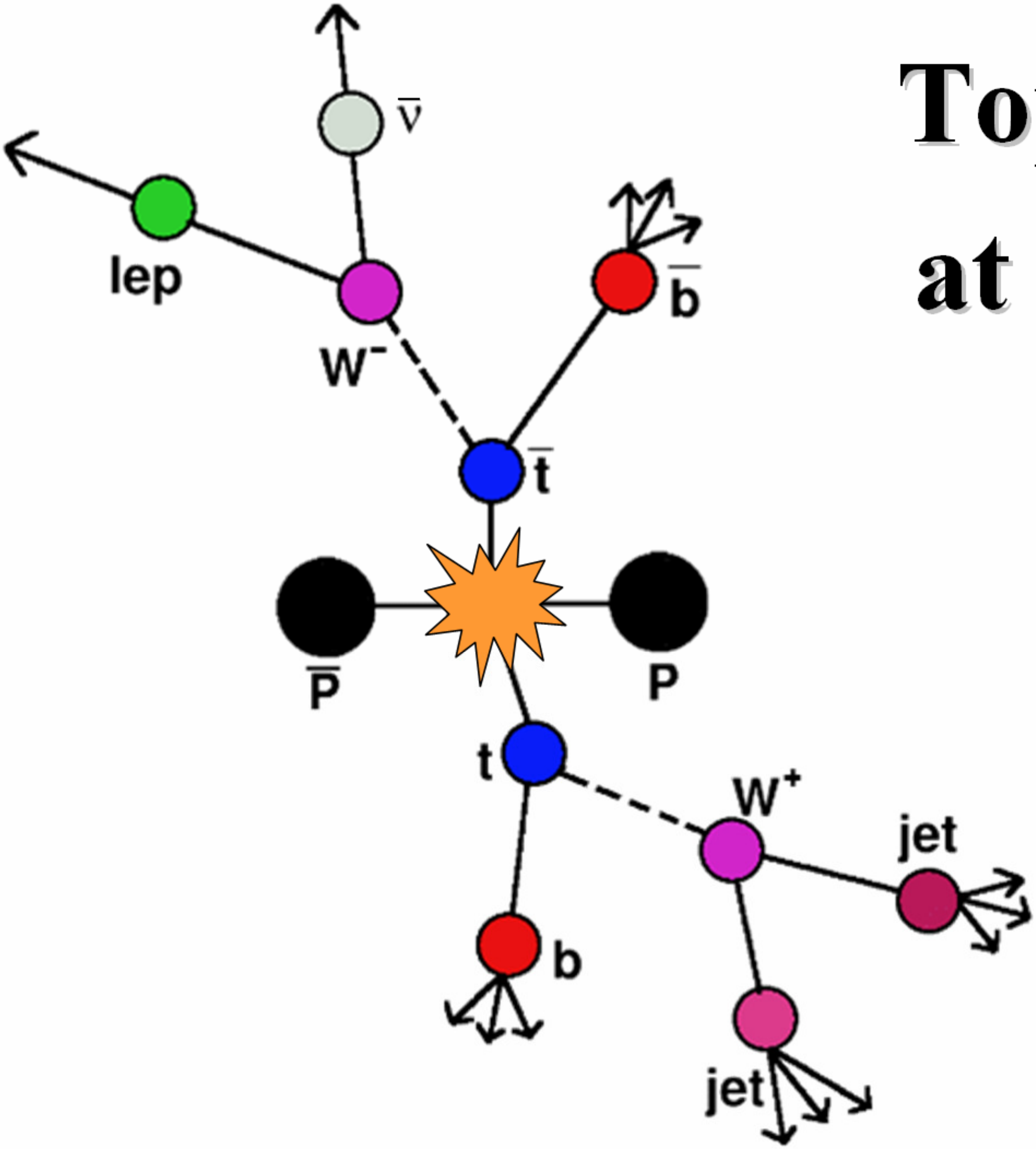


Top Properties at CDF Run II

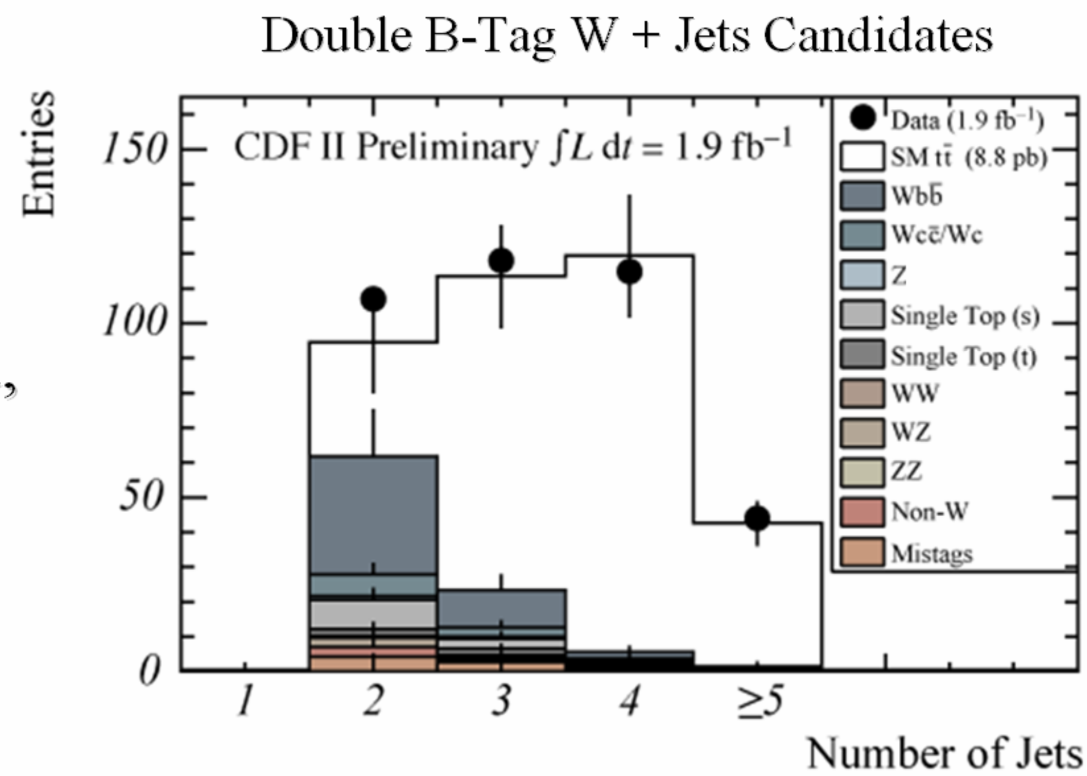
2008 Pheno Symposium

Charles Plager
UCLA

For the CDF Collaboration

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!



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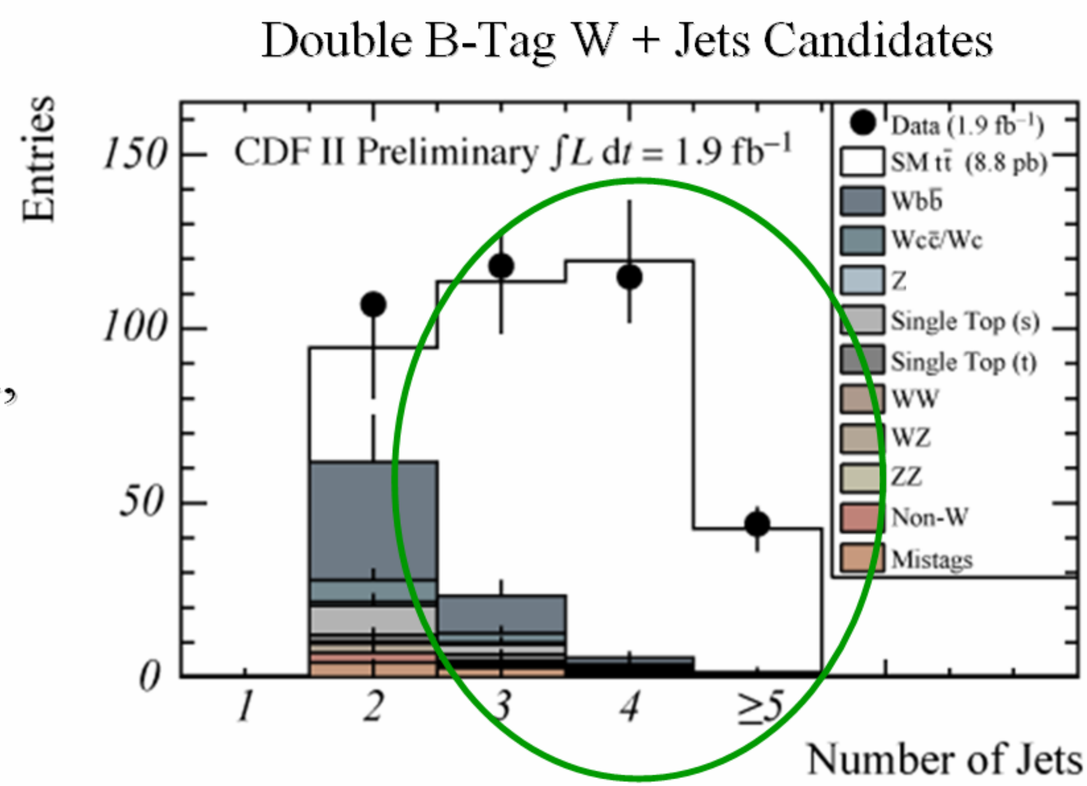
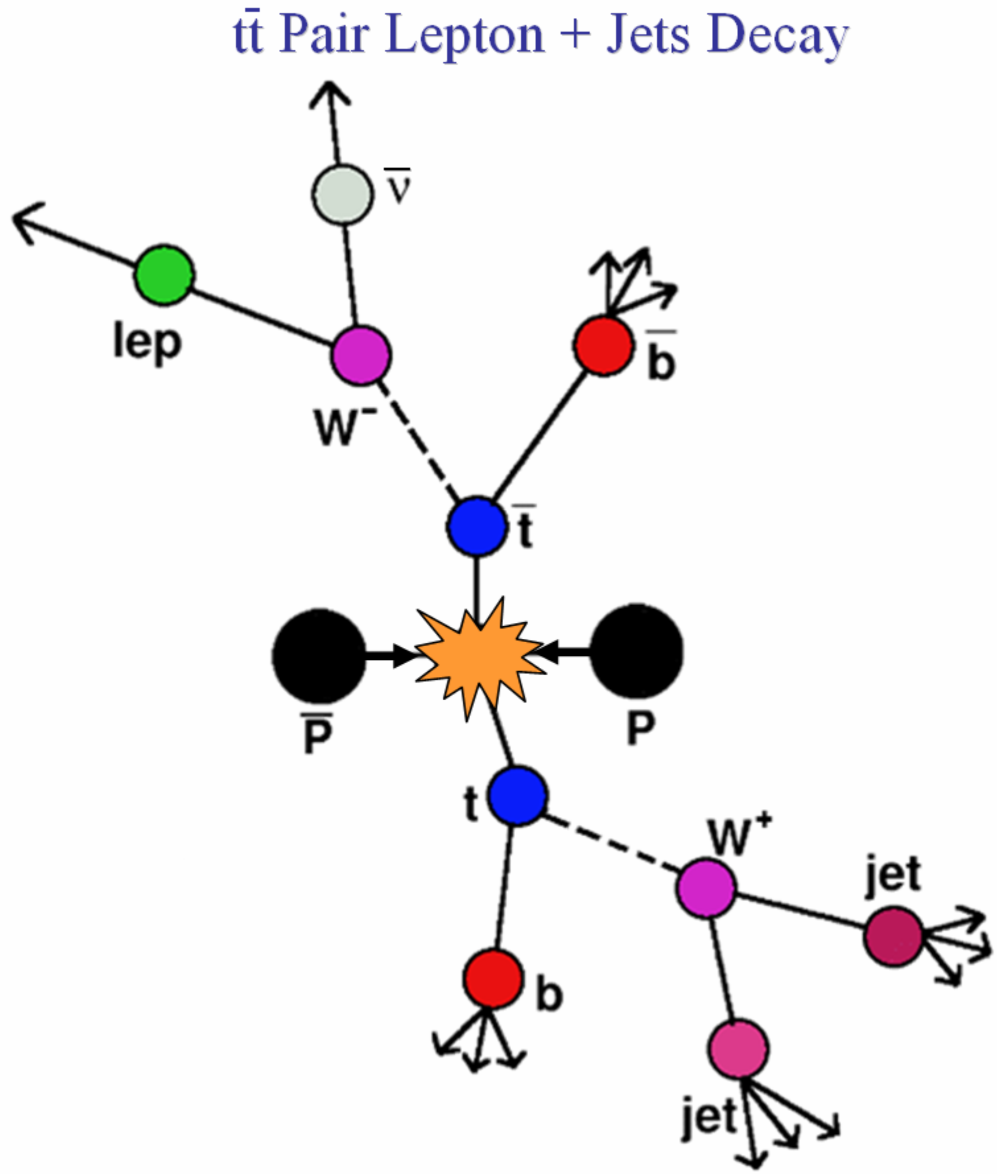


Top Quark Review

- Fundamental question:

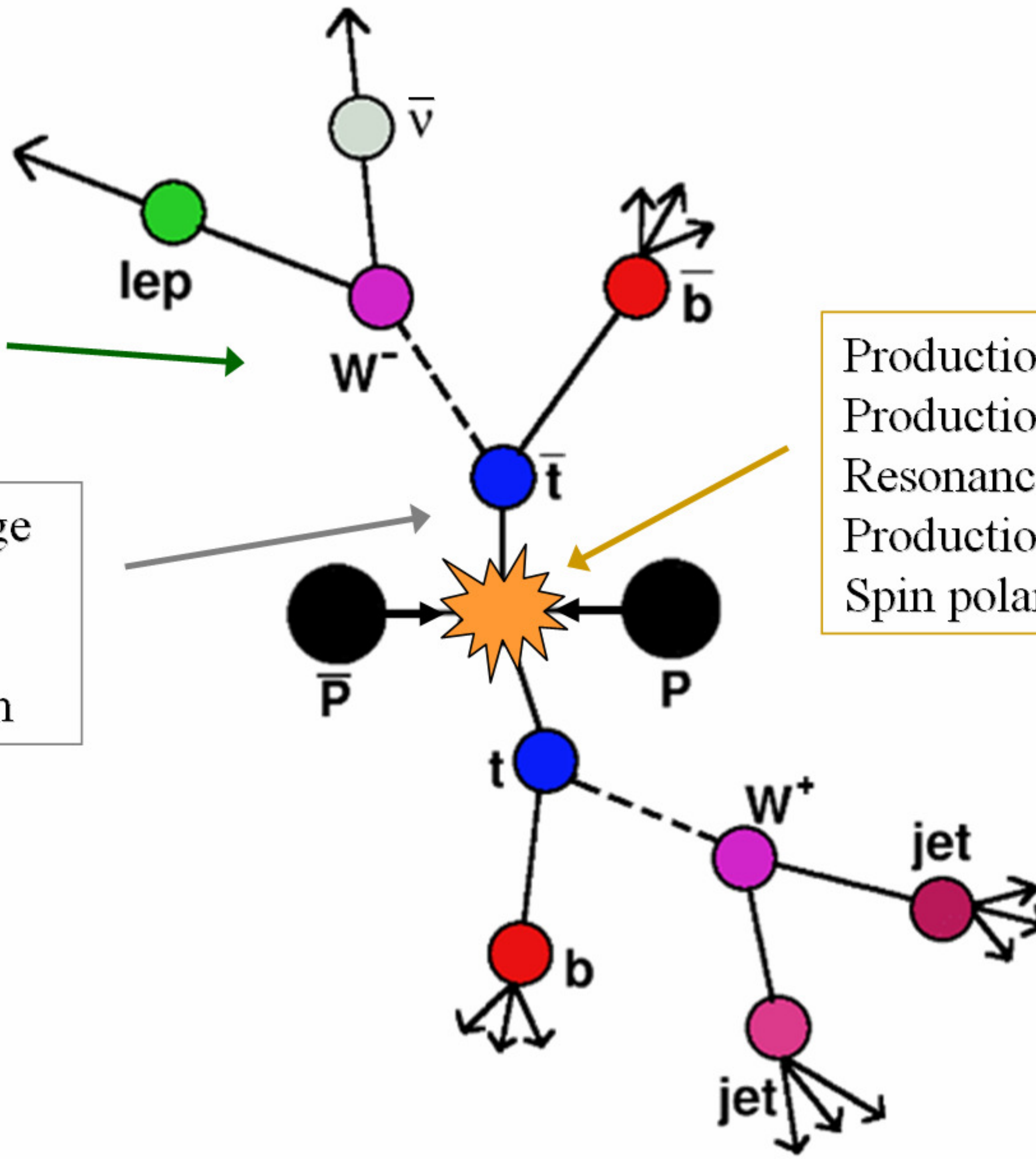
  Is it the truth, the Standard Model (SM) truth, and nothing but the truth?
  - Did we really find the top quark?
  - Is it the SM top quark?
  - Is it only the SM top quark?



- The top quark is an ideal place to look for Beyond the Standard Model Physics!

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 mass
- Top width

- Production cross section
- Production mechanism
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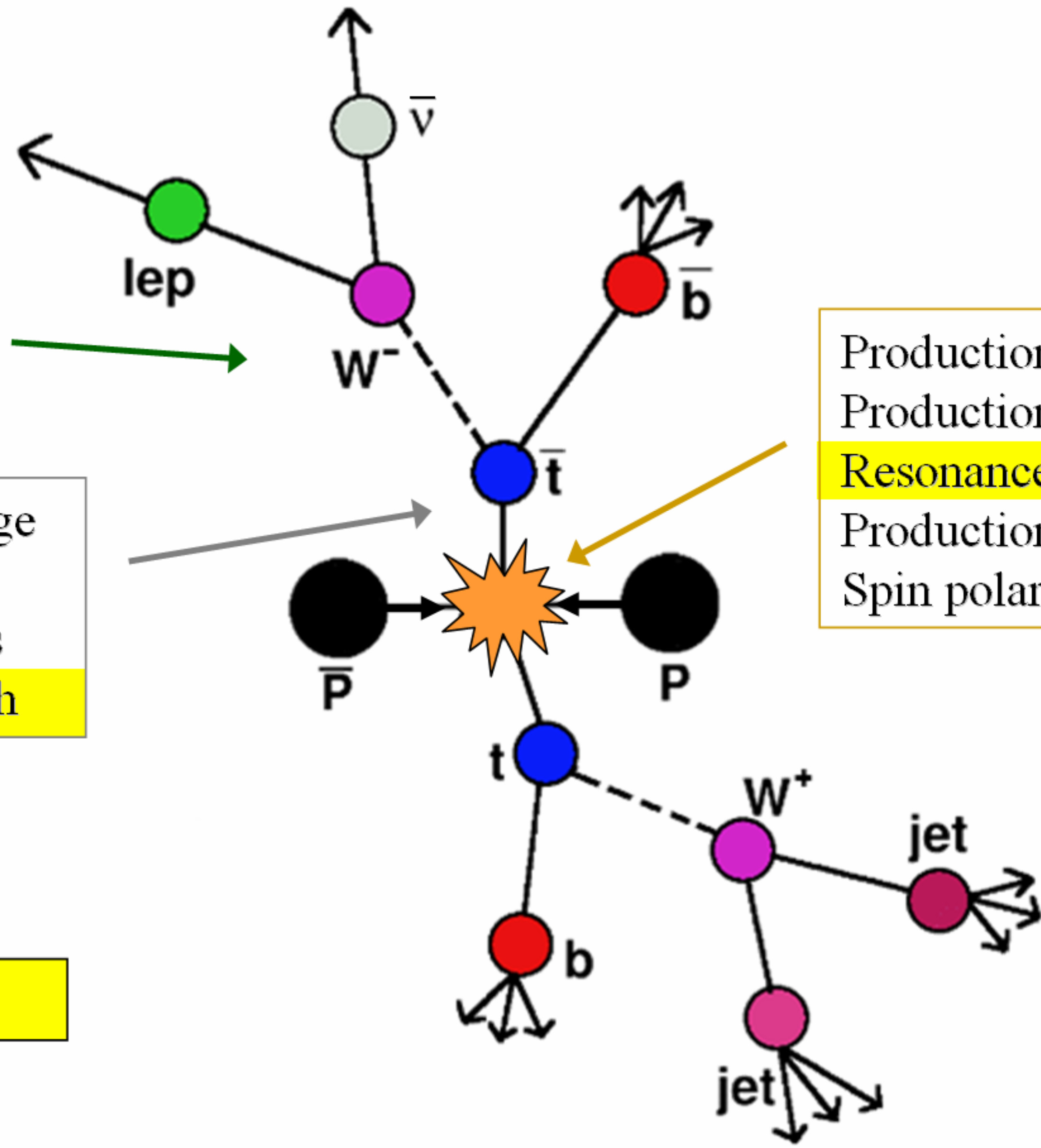

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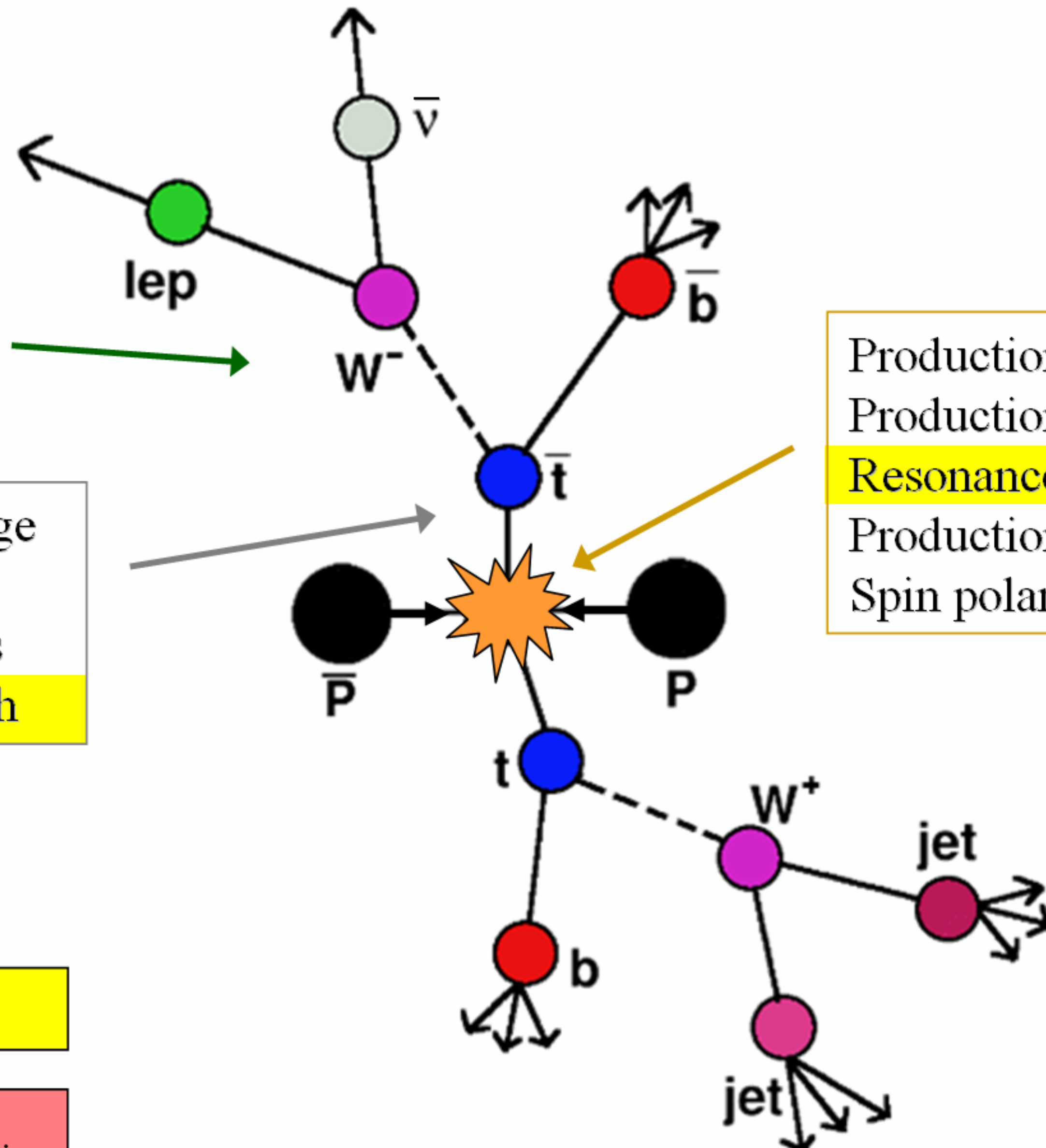

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Public CDF analyses.

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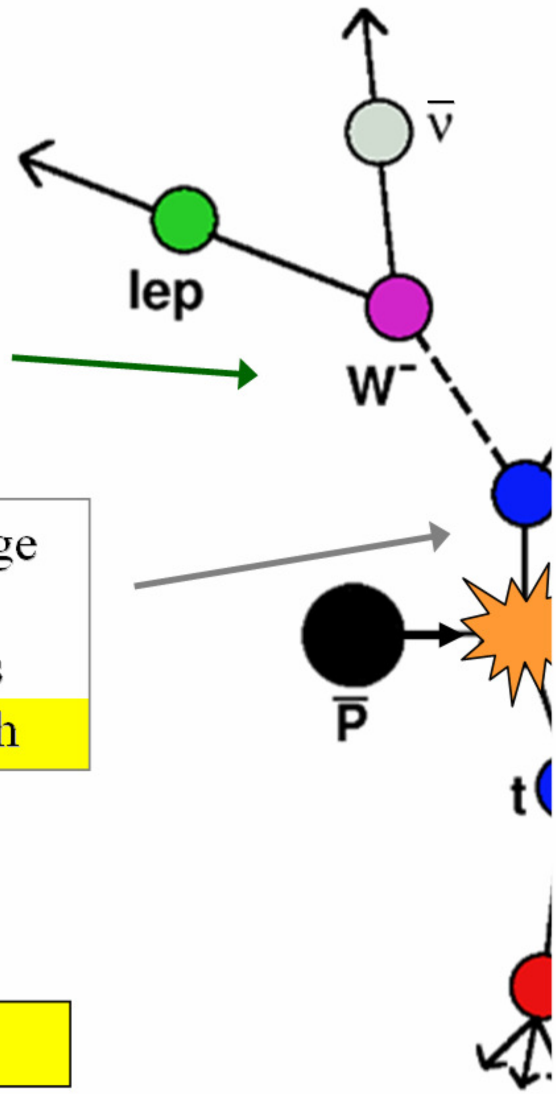

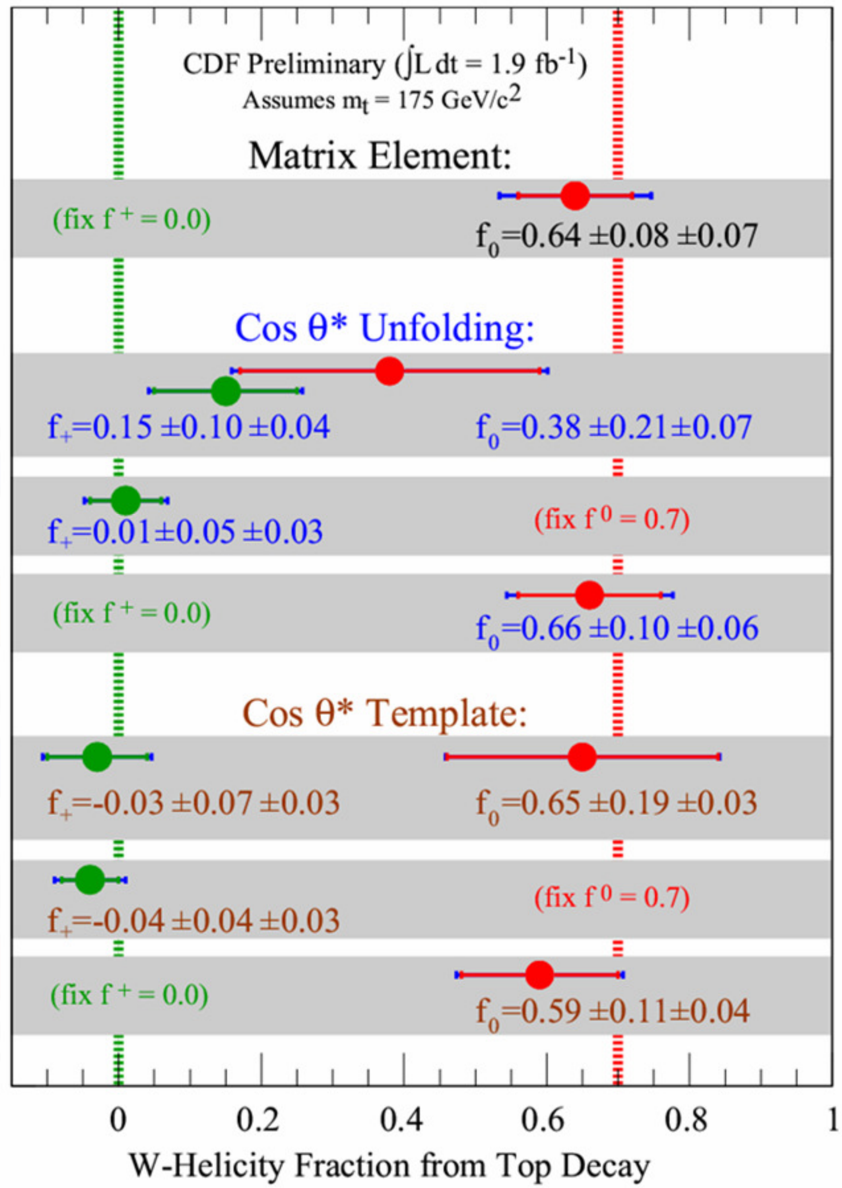

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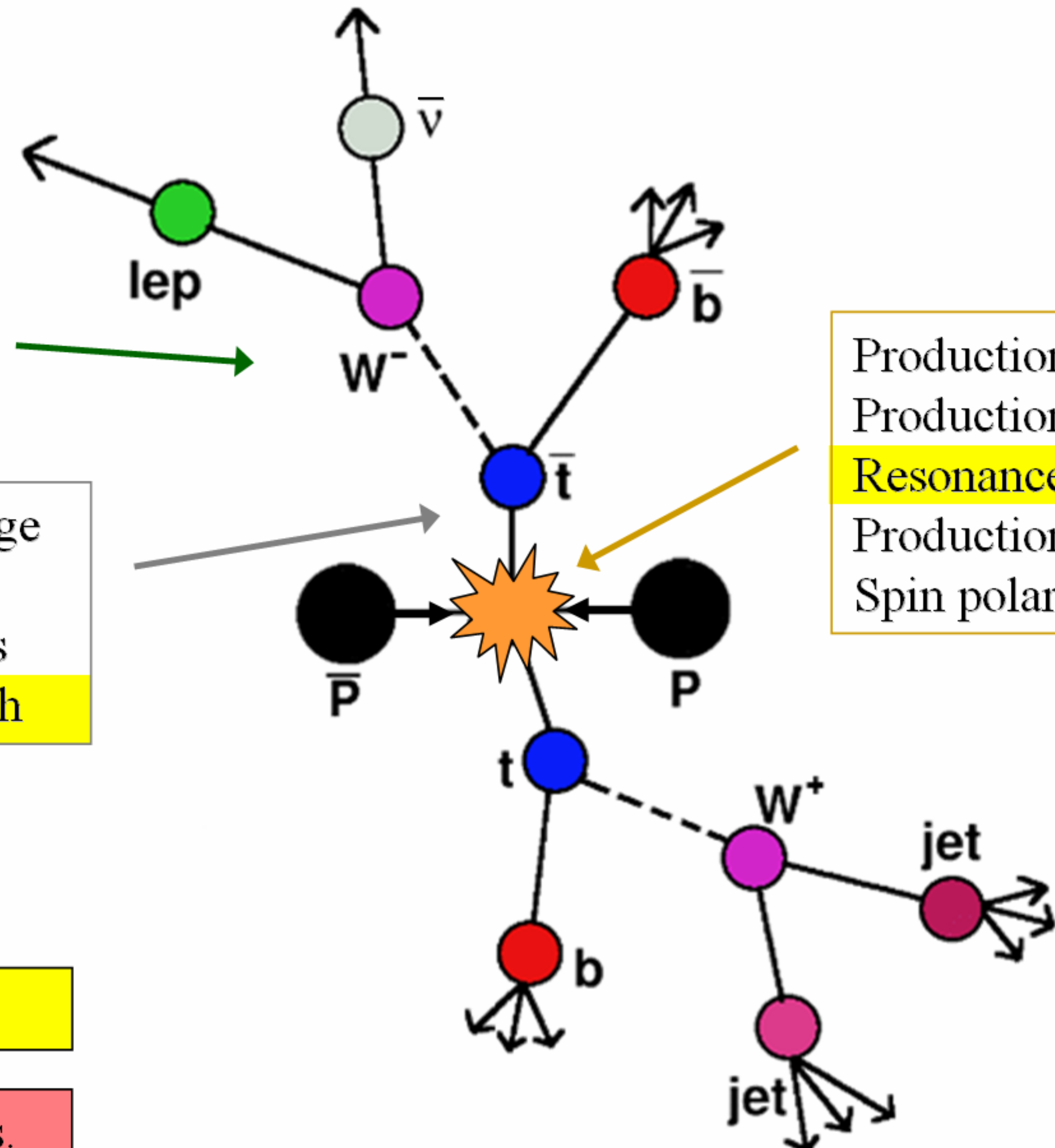

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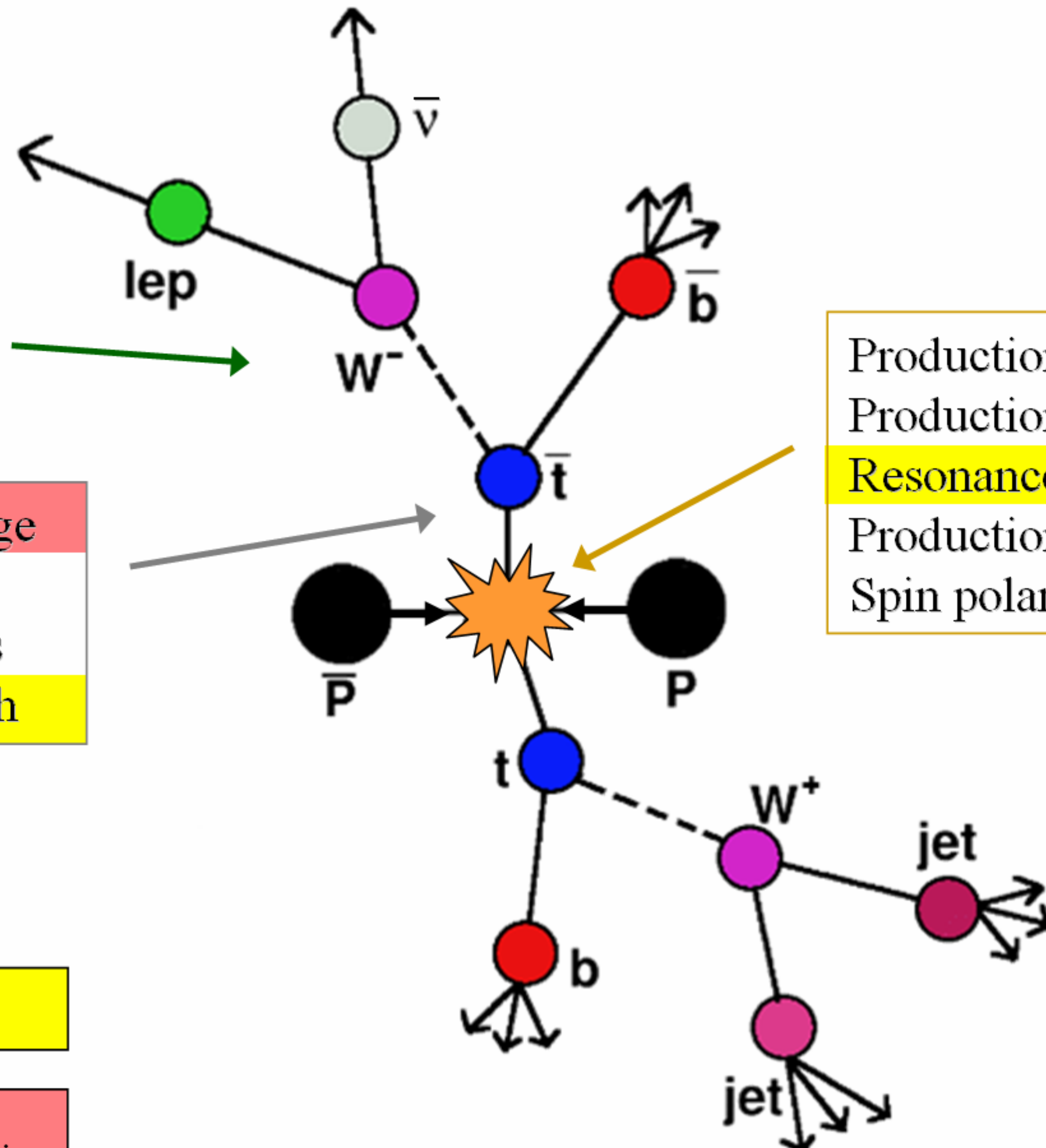

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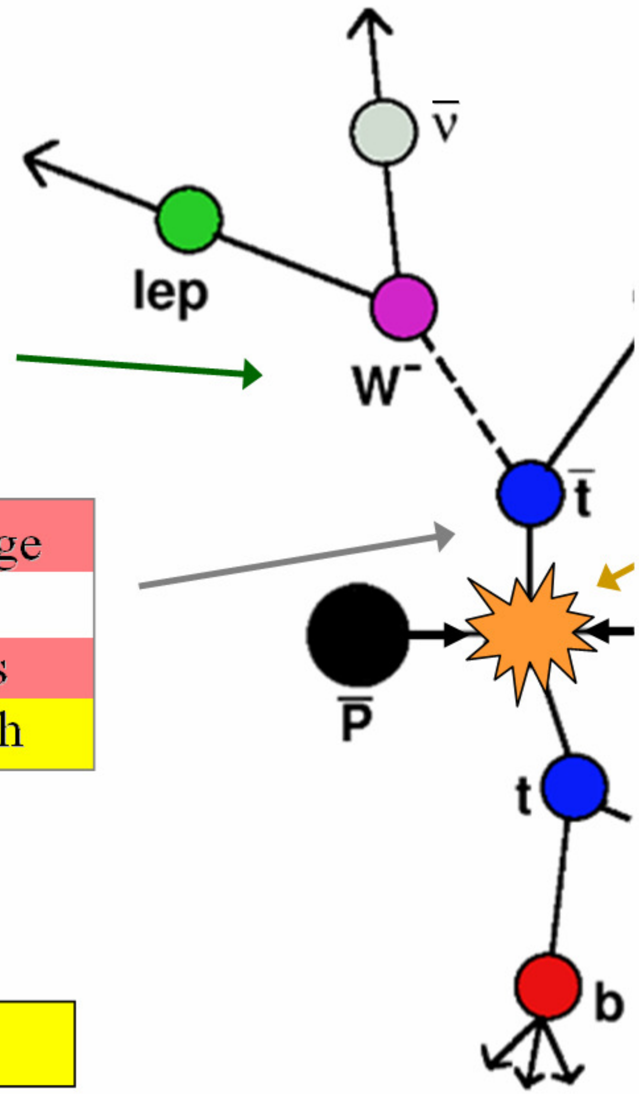

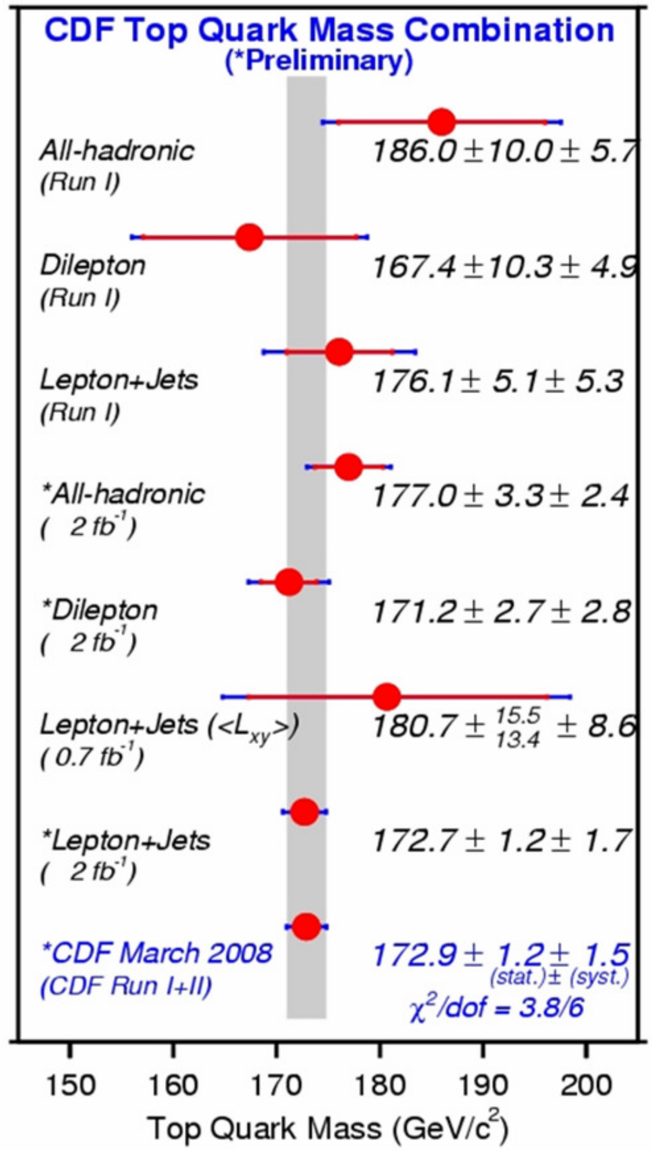

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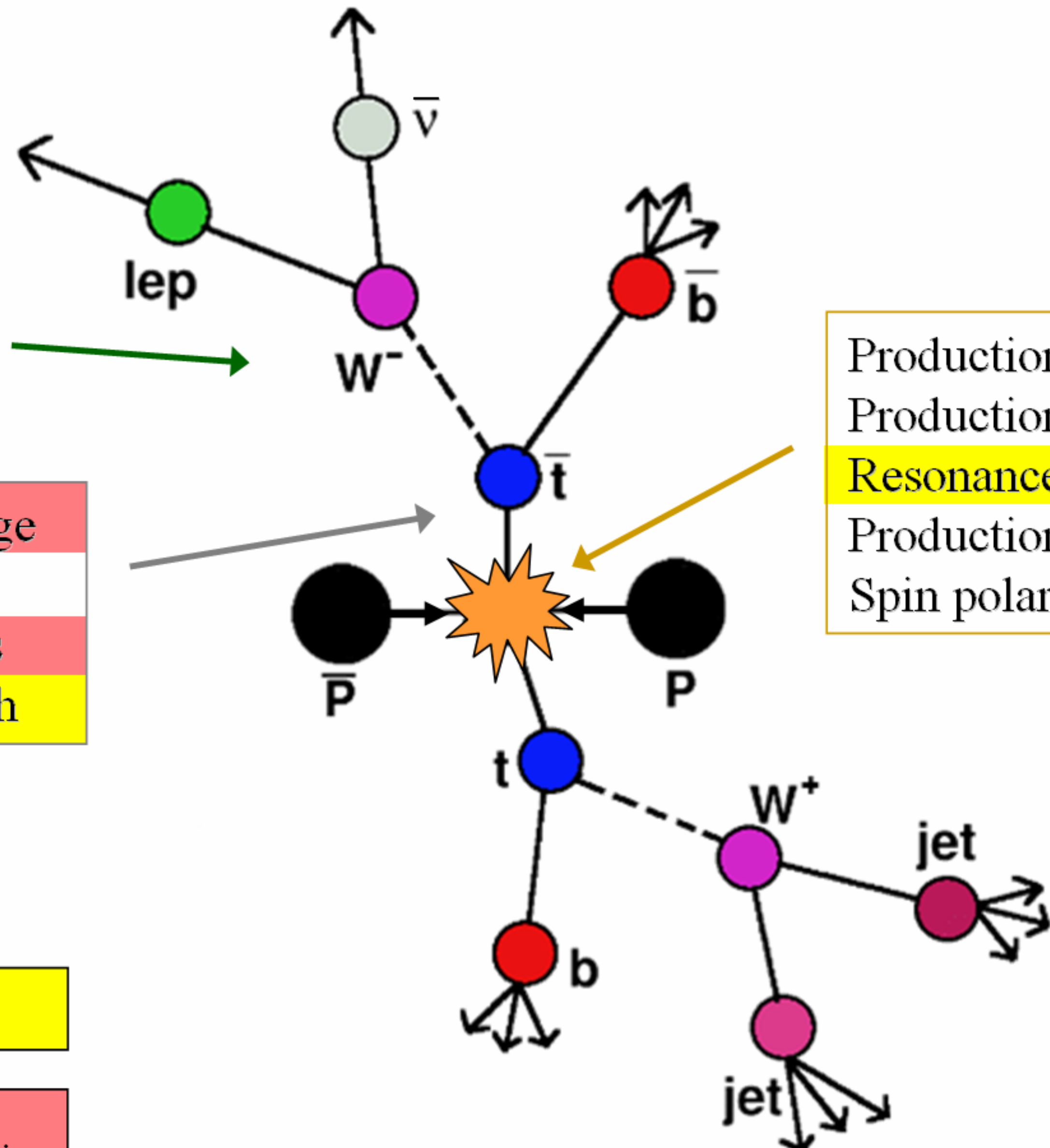

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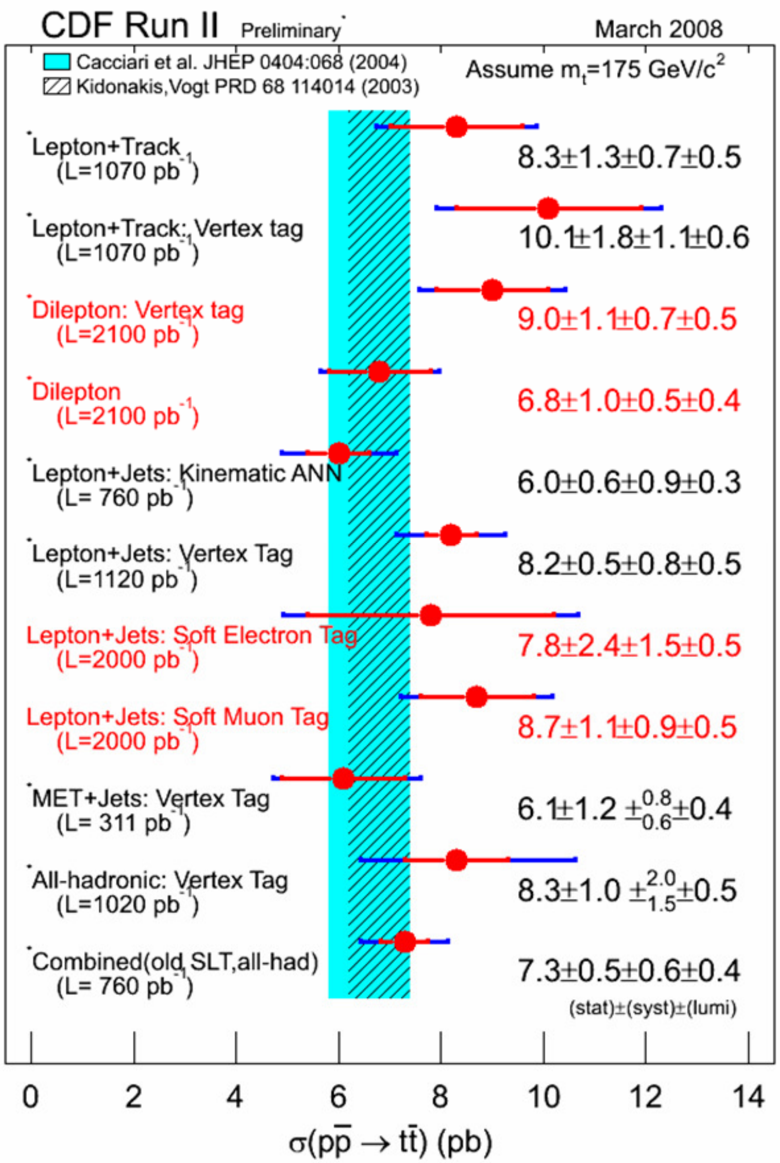
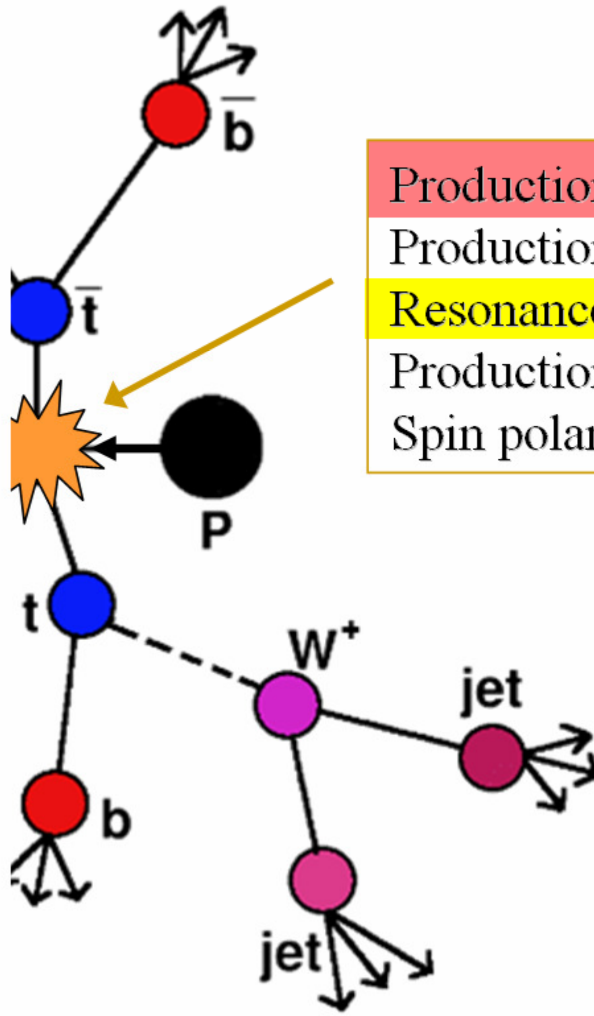


Pub... CDF analyses:



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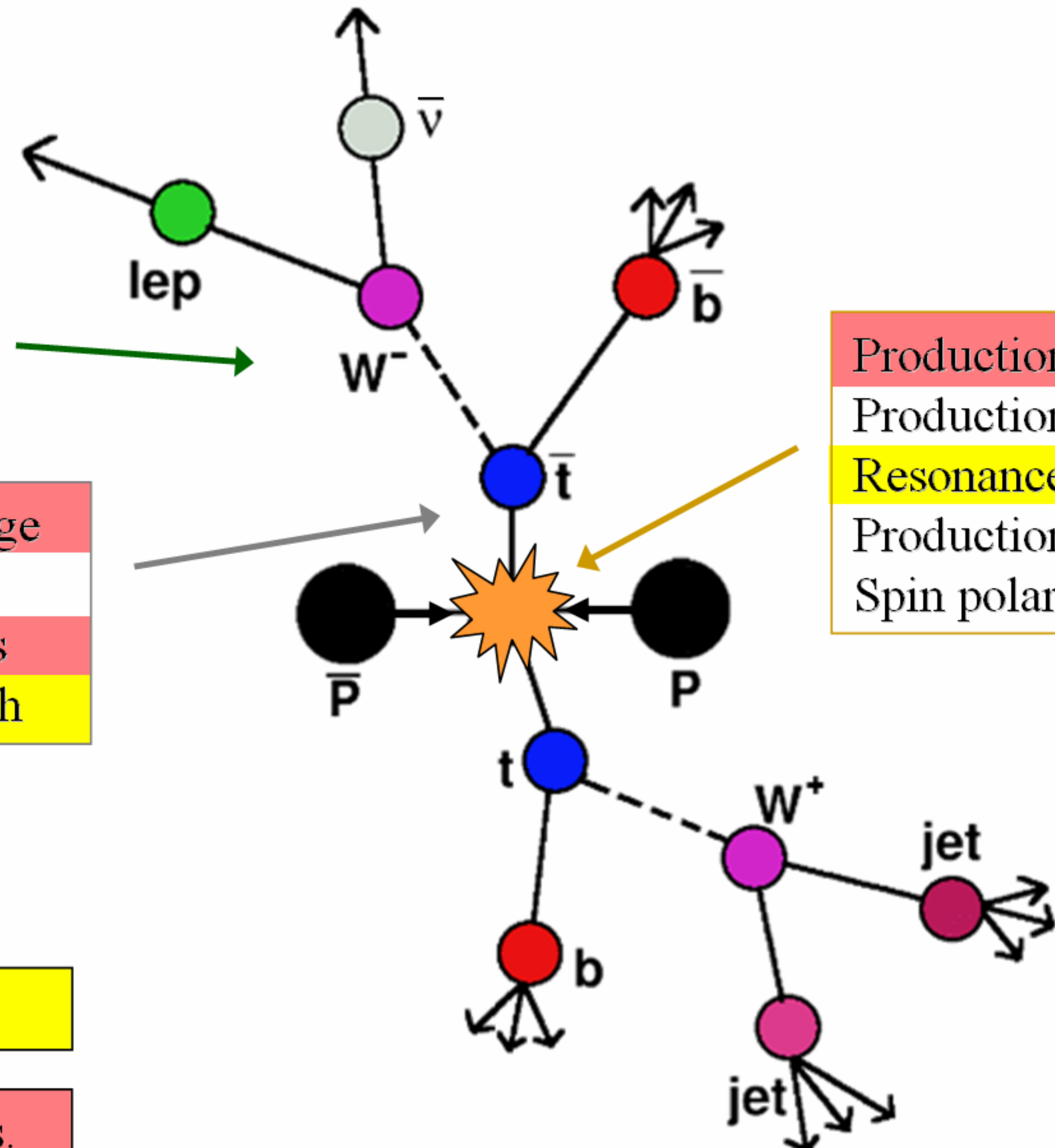

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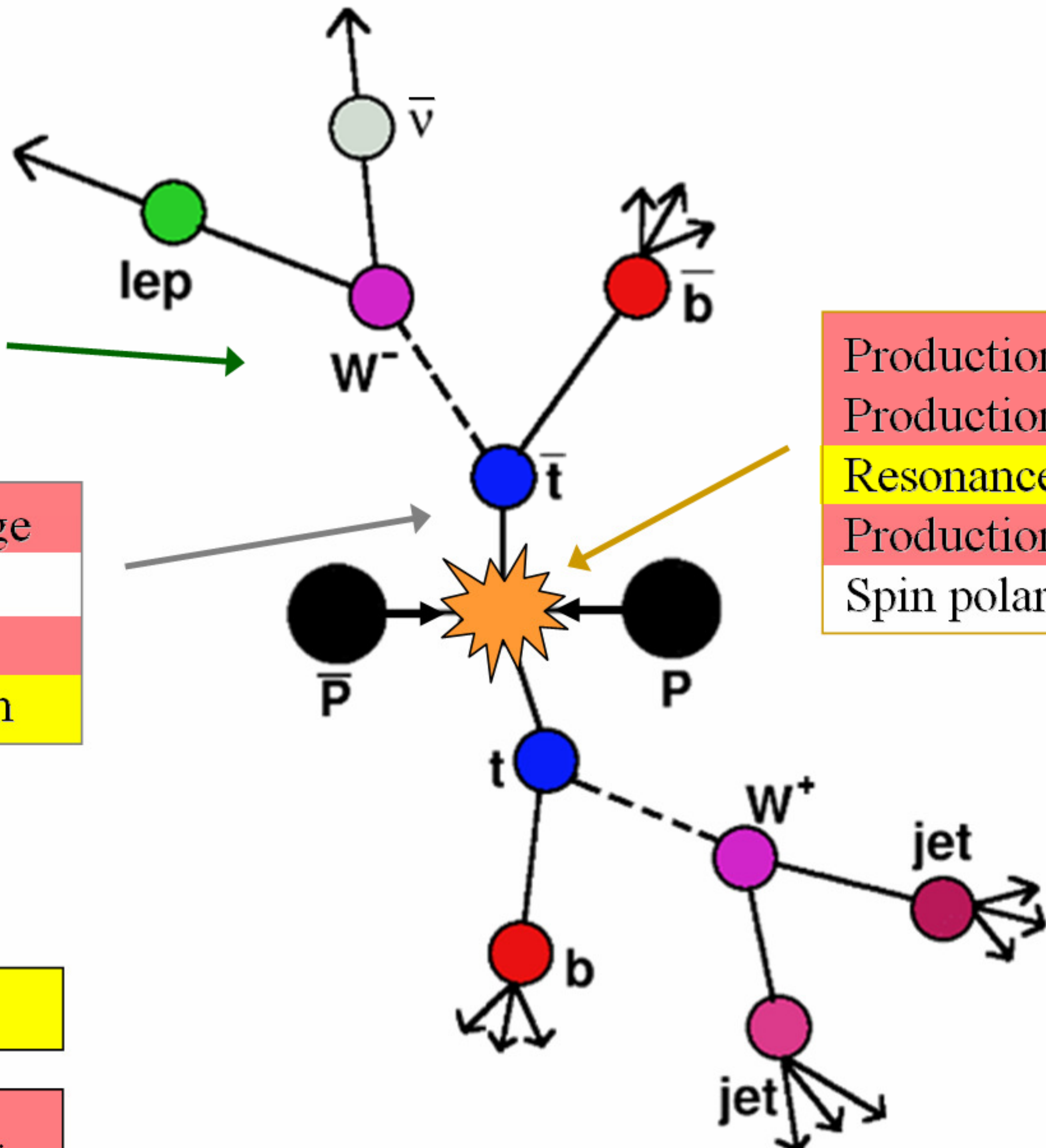

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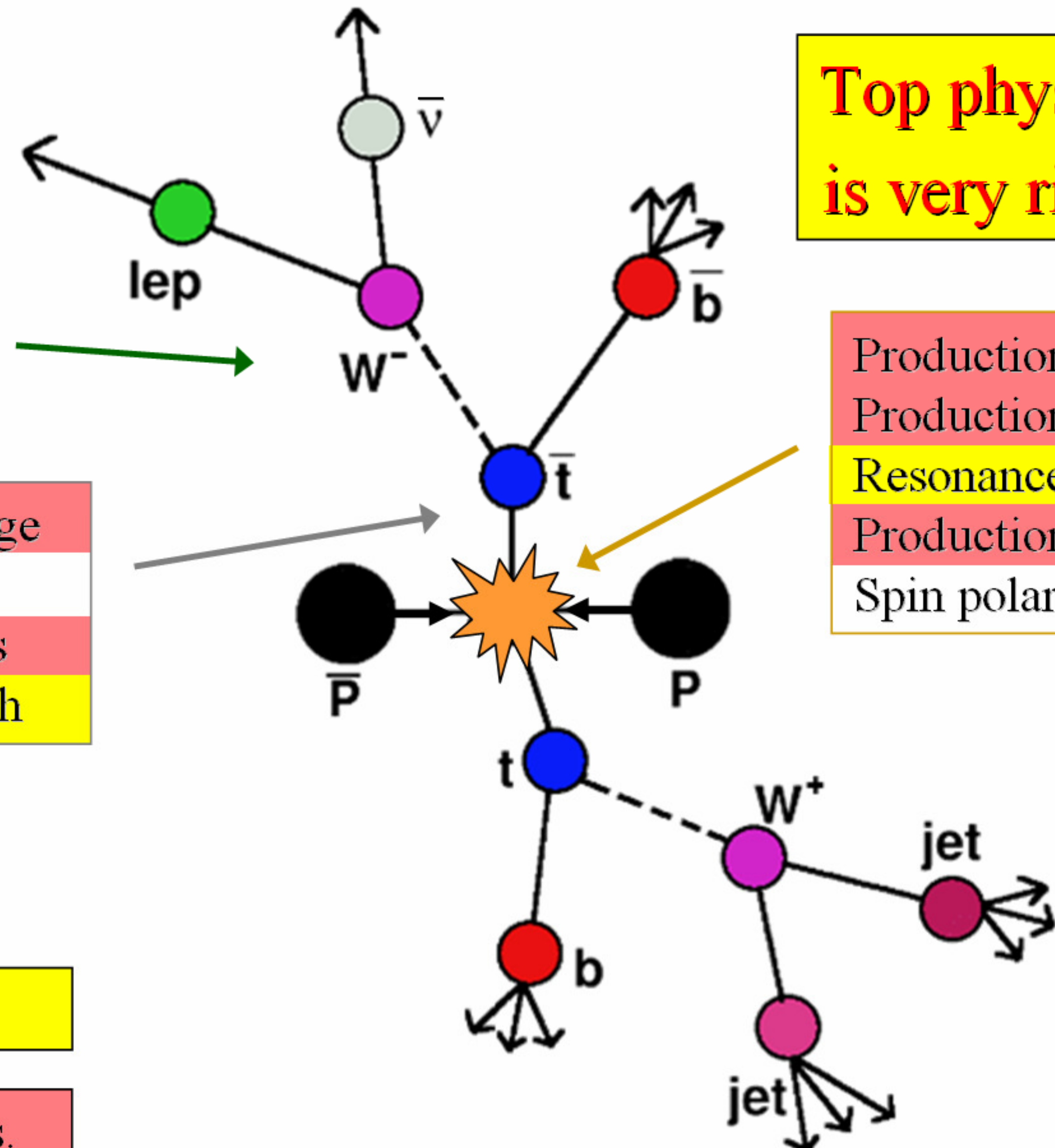


Top physics is very rich.

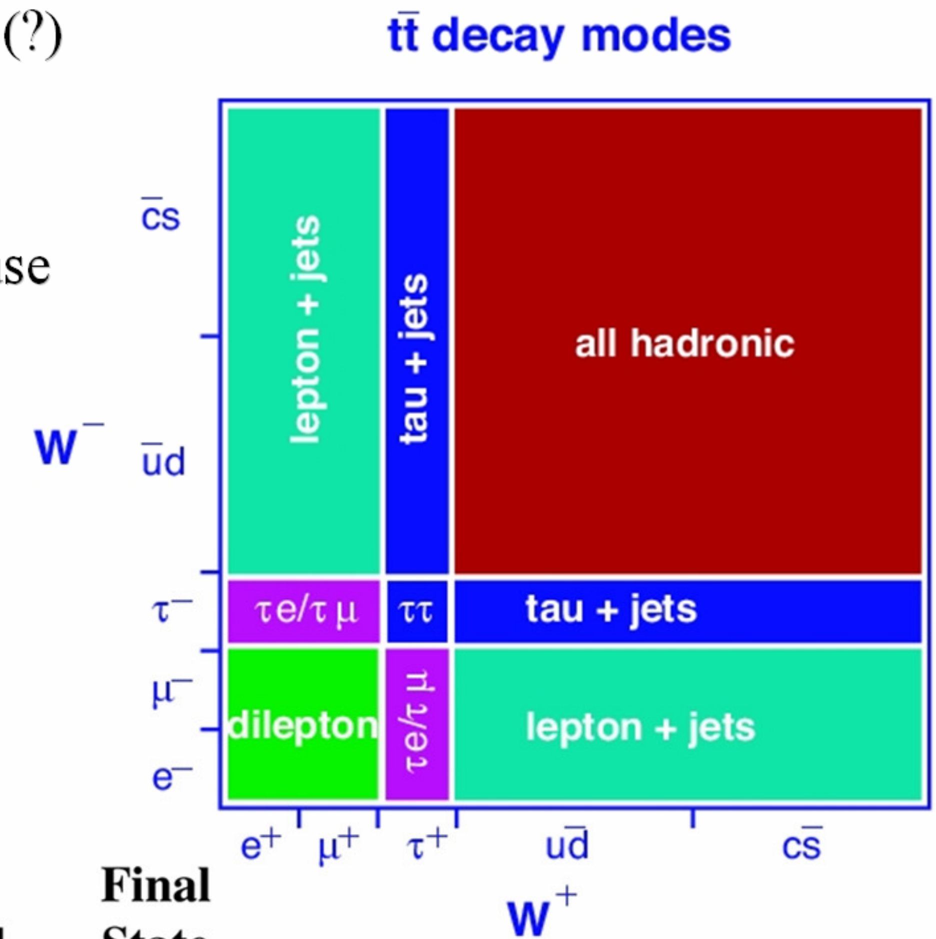
Production cross section
Production mechanism
Resonance production
Production kinematics
Spin polarization

In today's talk.

Public CDF analyses.

Top Pair Decay Modes

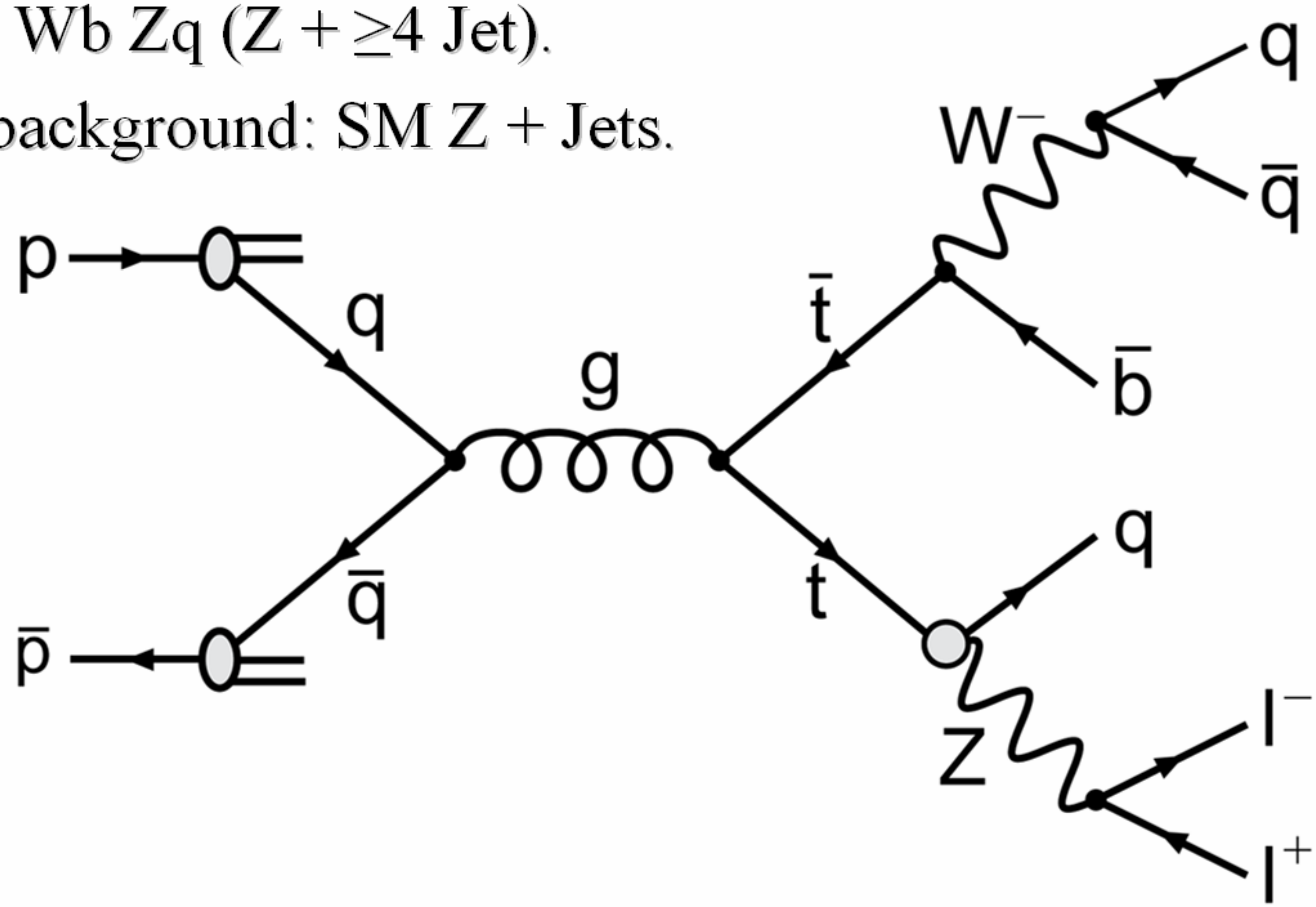
- According to the SM, top quarks almost (?) always decay to Wb.
- When classifying the decay modes, we use the W decay modes:
  - Leptonic
    - Light leptons (e or μ)
    - Tauonic (τ)
  - Hadrons



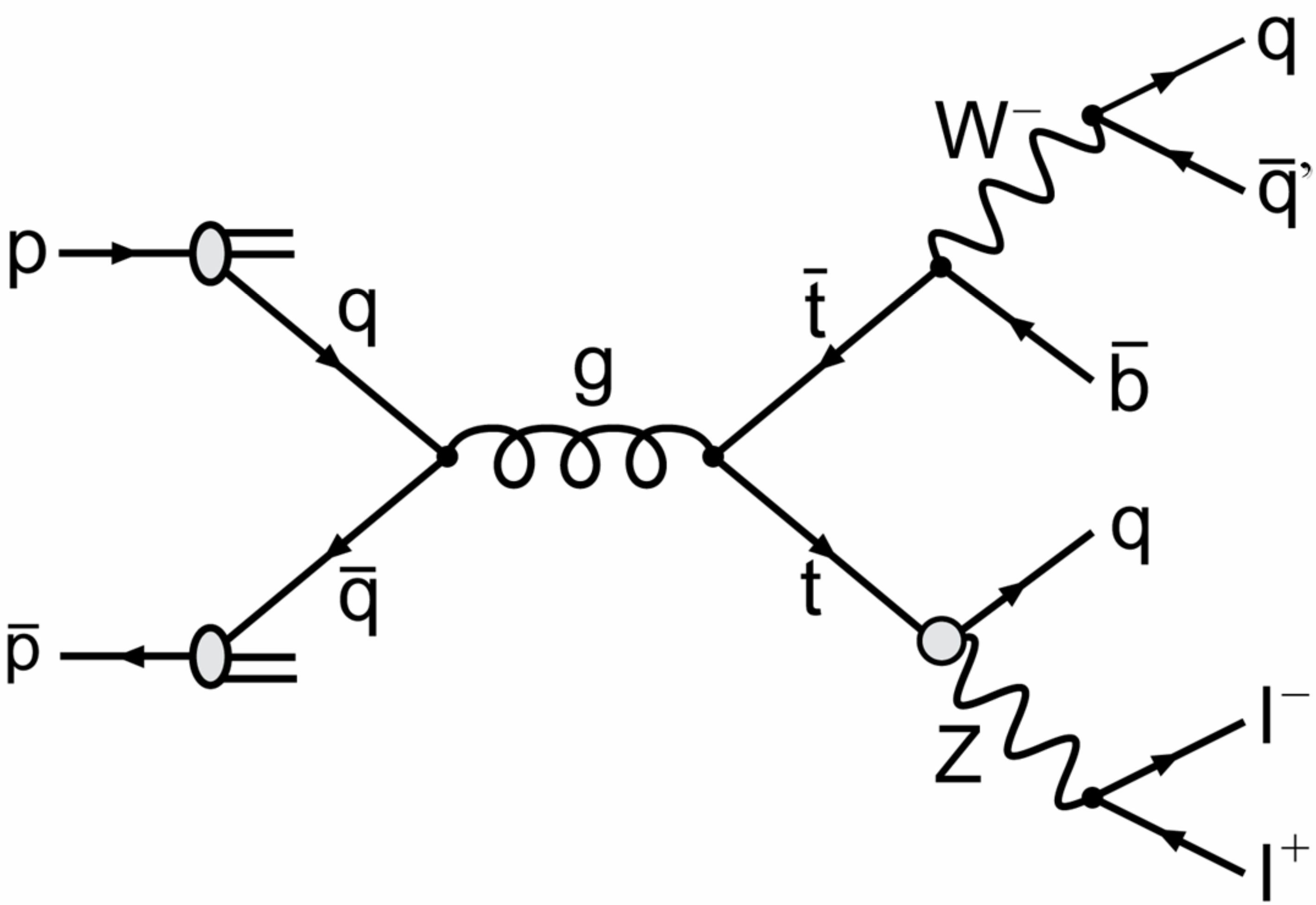
Decay Mode	Branching Fraction	Relative Background	Final State
Dilepton - no τs	~ 5%	Low	$\ell\ell\,\nu\nu$ bb
Lepton + Jets - no τs	~ 30%	Medium	$\ell\,\nu$ bb jj
All Hadronic	~ 45%	High	bb jjjj
Tauonic	~ 20%	High	

Search for the Top FCNC Decay $t \to Zq$

- Top FCNC extremely rare in the SM: $B(t \to Zq) = O(10^{-14})$
- Beyond SM: $B(t \to Zq)$ up to $O(10^{-4})$,
- Any signal at Tevatron: New Physics.
- Signature: $tt \to Wb\, Zq$ ($Z + \geq 4$ Jet).
- Dominant SM background: SM Z + Jets.

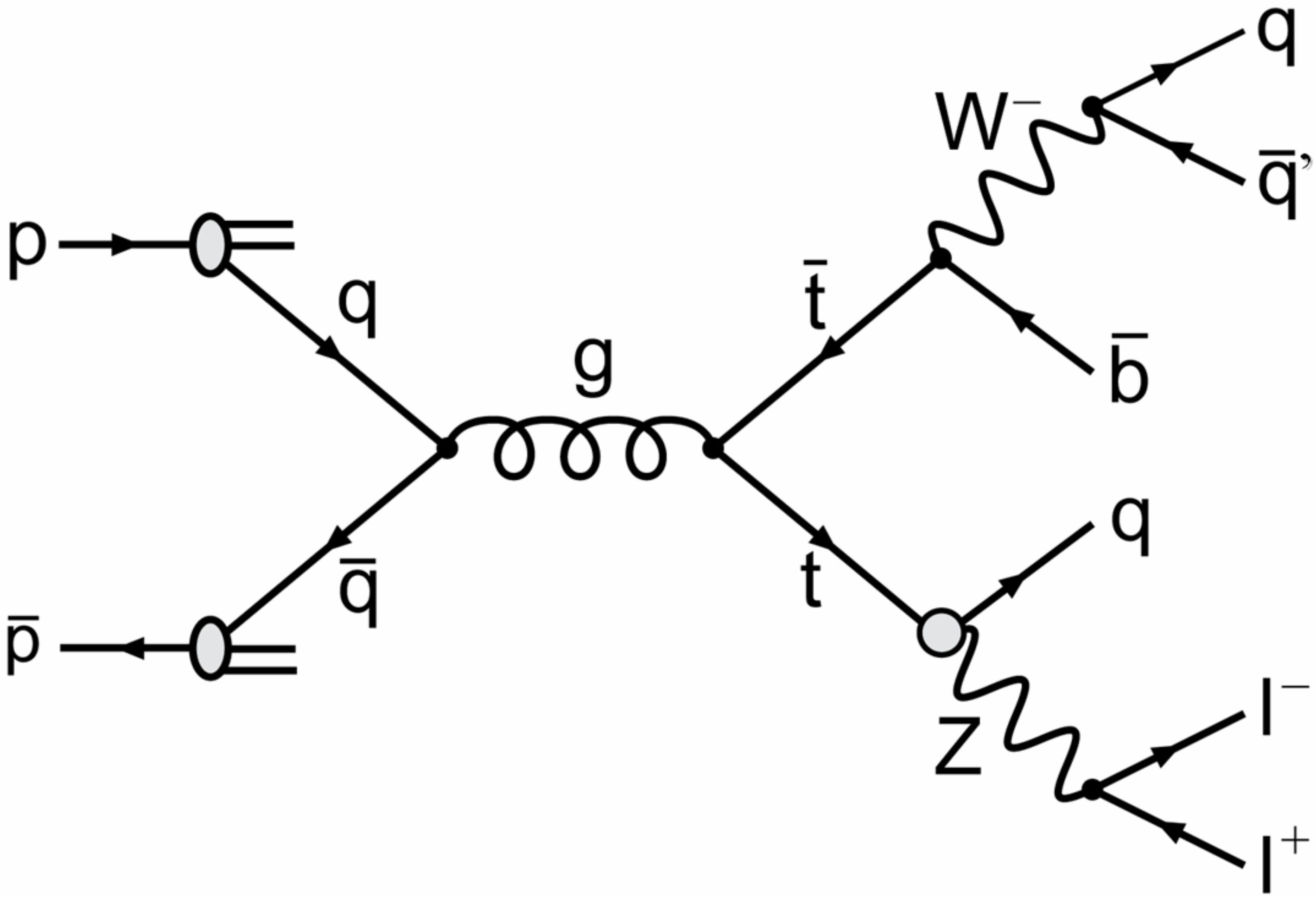


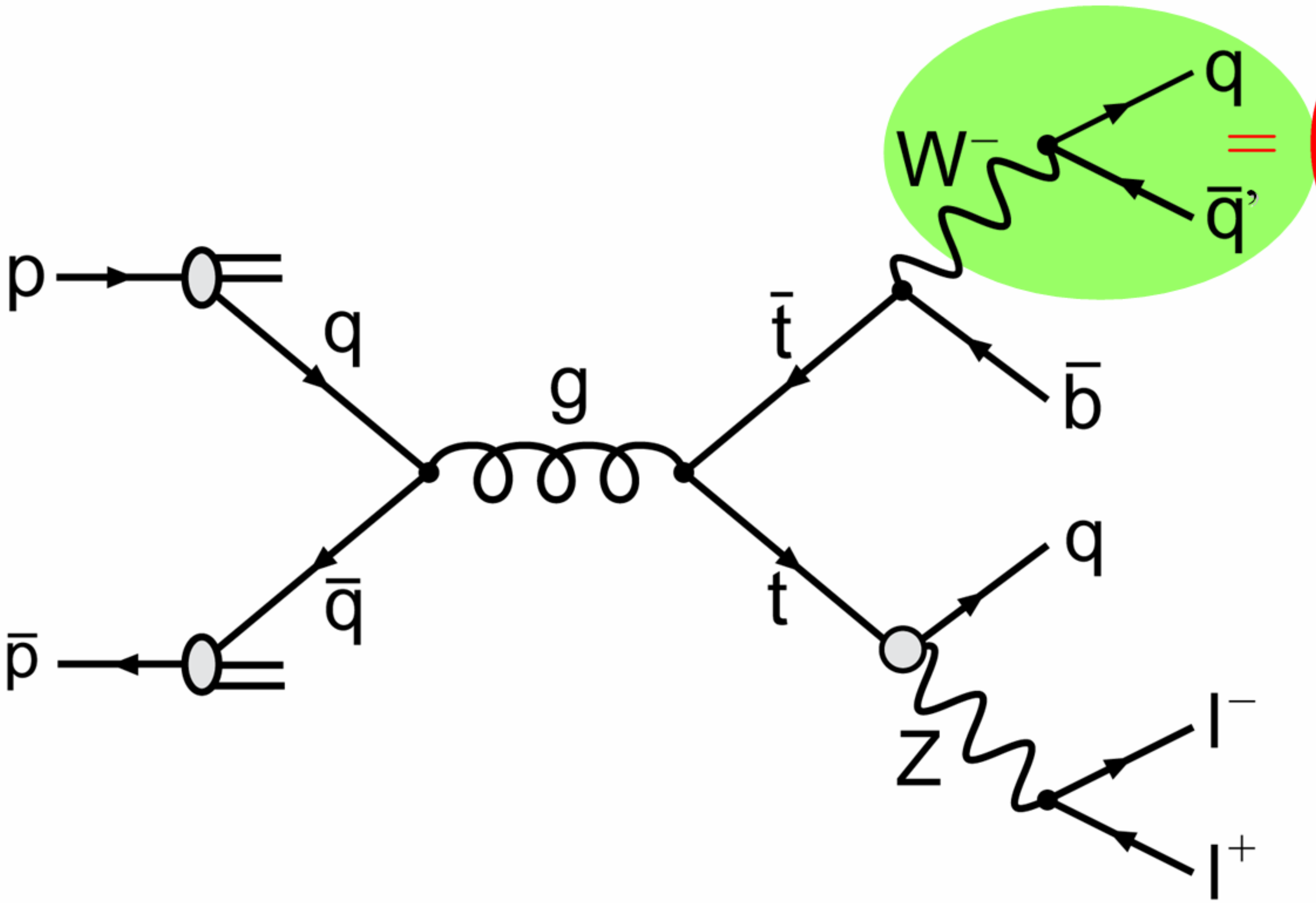
Search for $t \rightarrow Zq$: Ingredients



Search for $t \rightarrow Zq$: 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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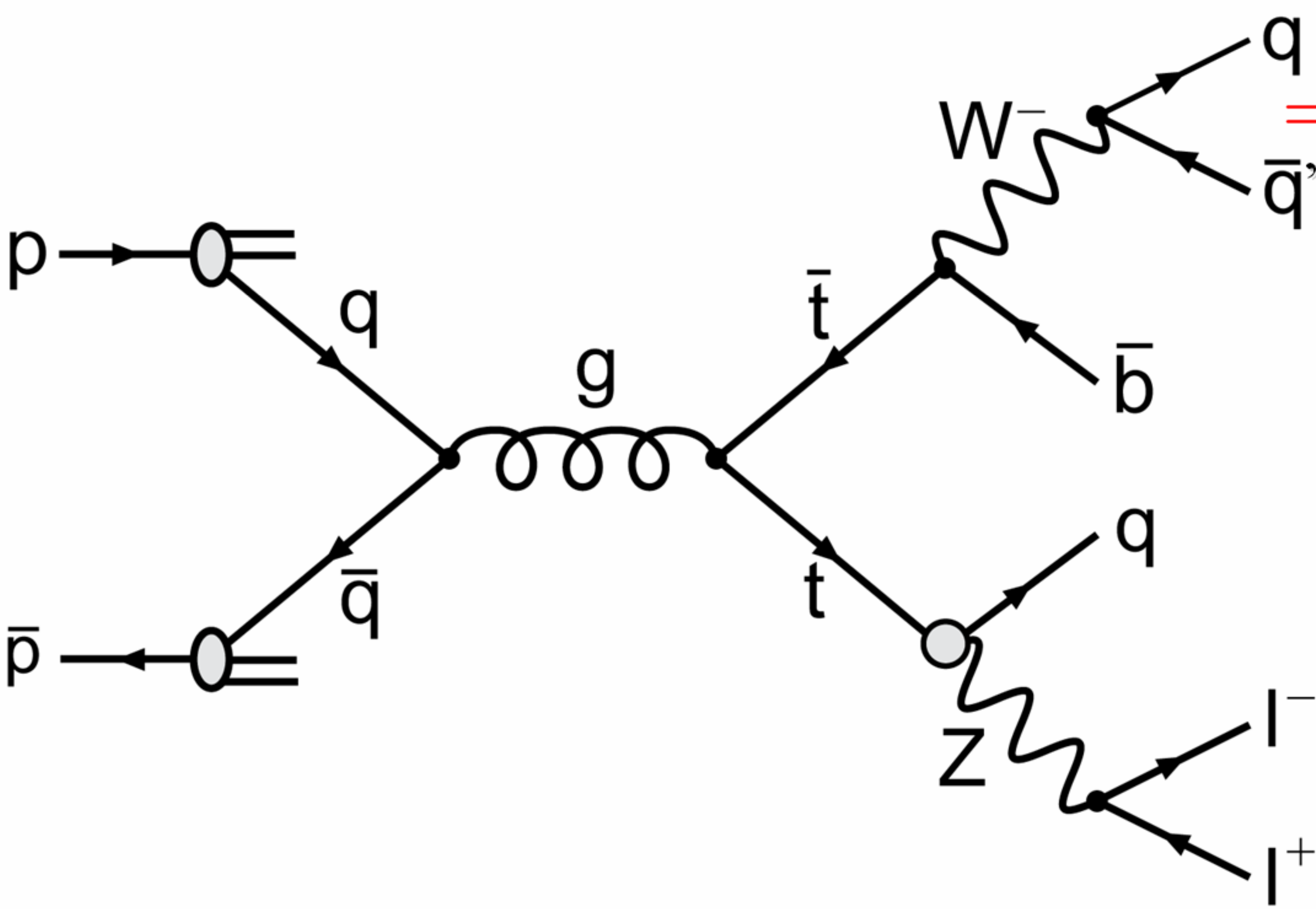

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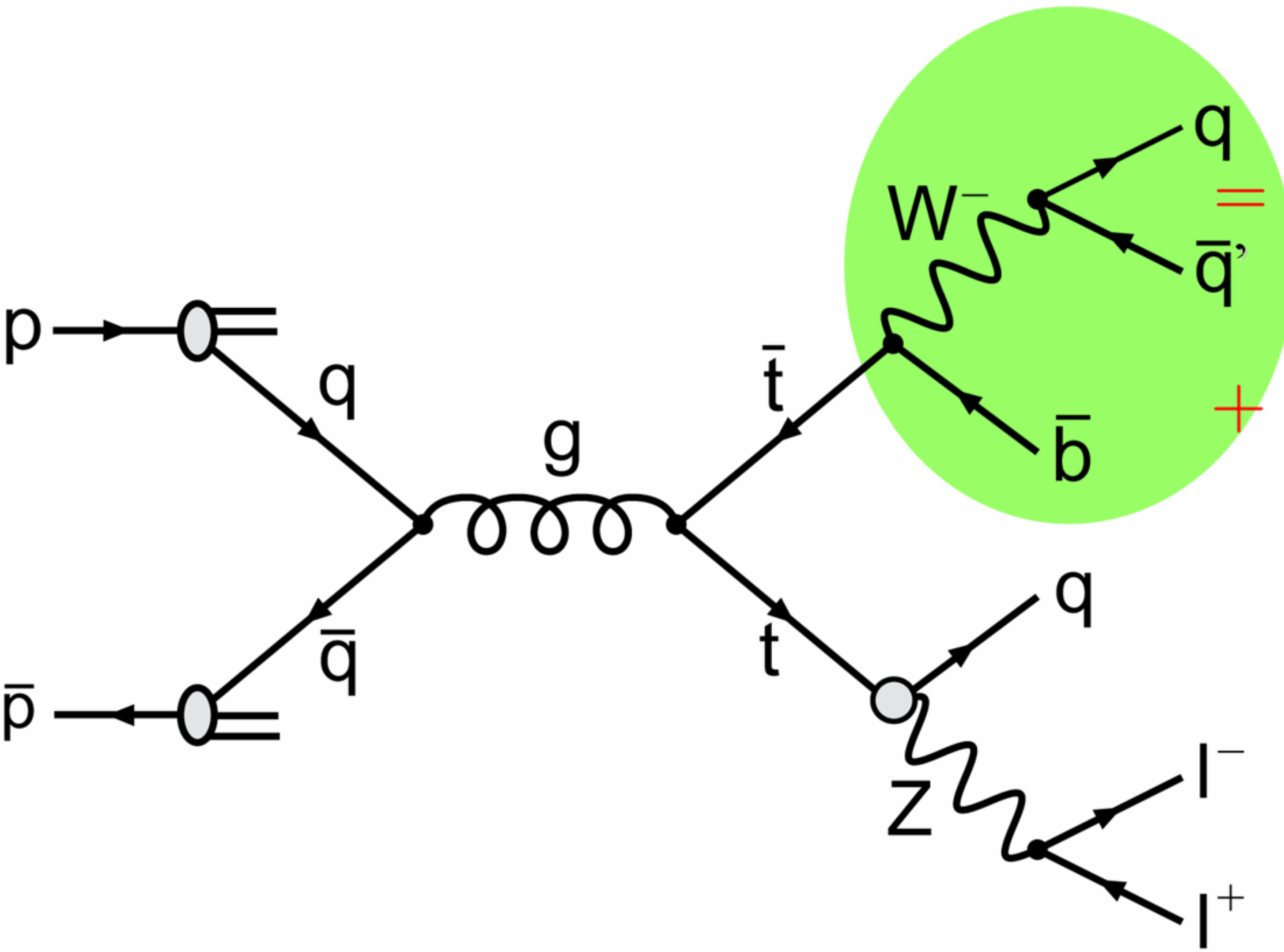

$$\chi^2_{\text{mass reconstruction}} = \left(\frac{m_{W\ \text{recon}} - m_W}{\sigma_W}\right)^2 + \left(\frac{m_{tWb\ \text{recon}} - m_t}{\sigma_{tWb}}\right)^2$$

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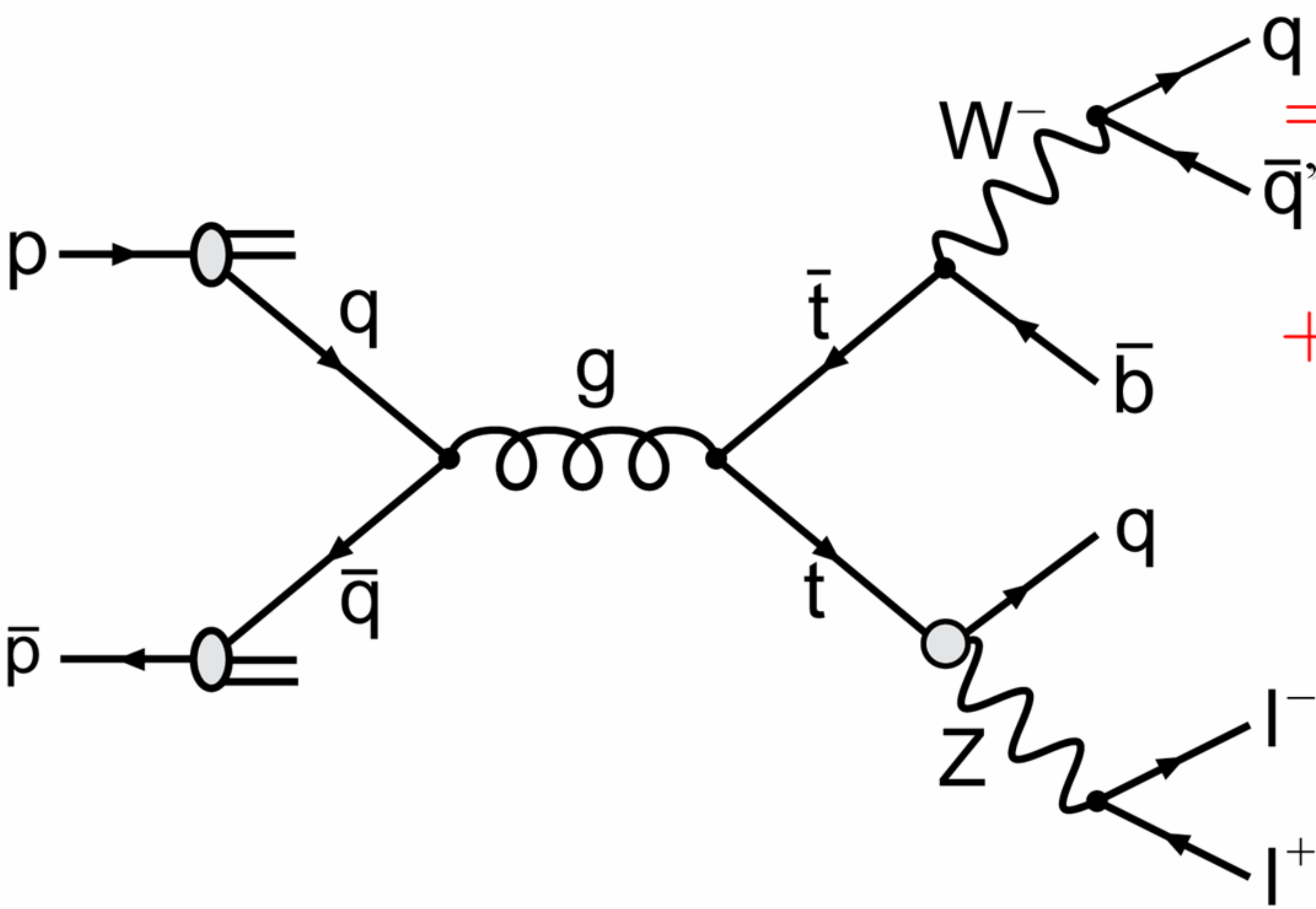

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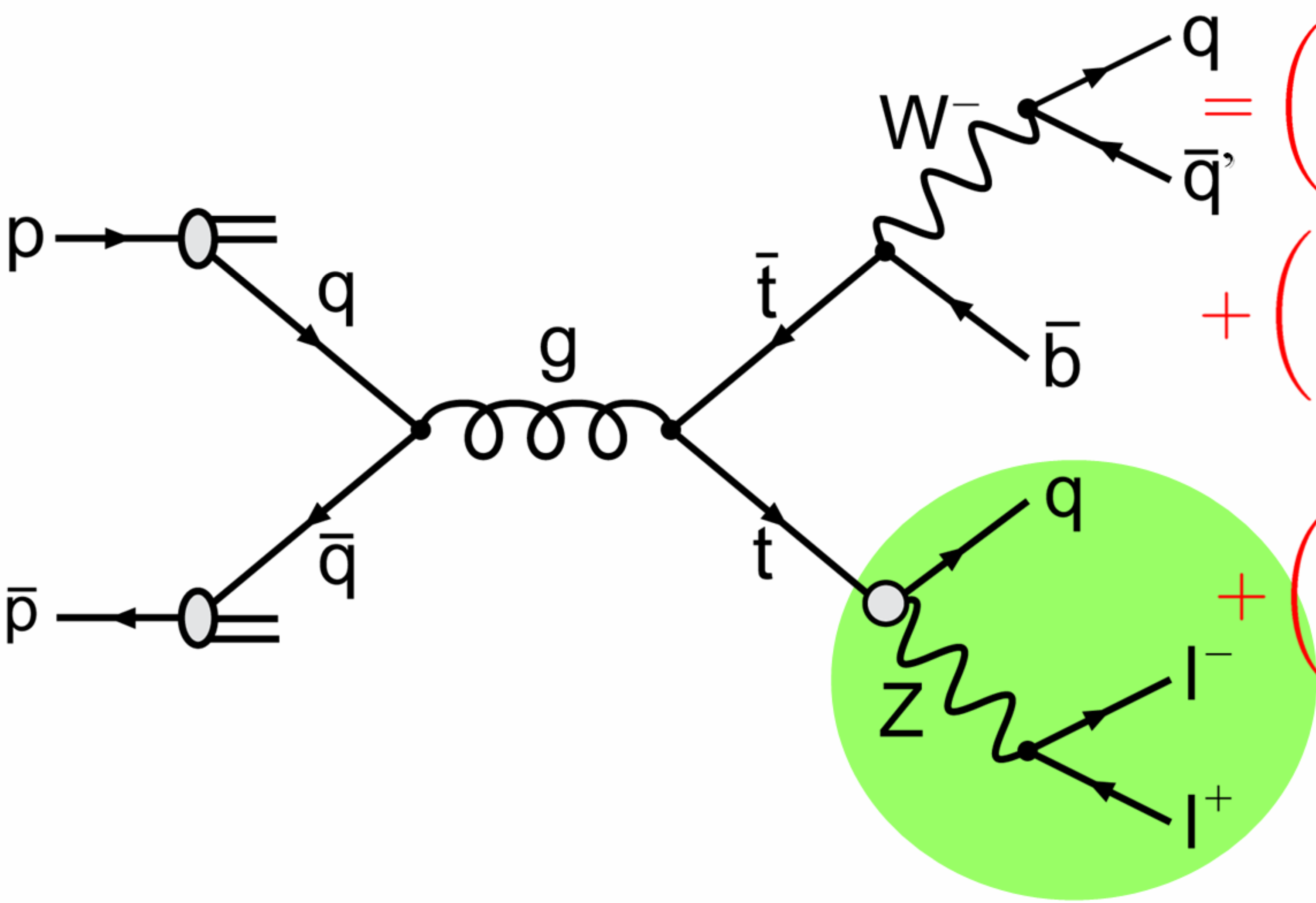

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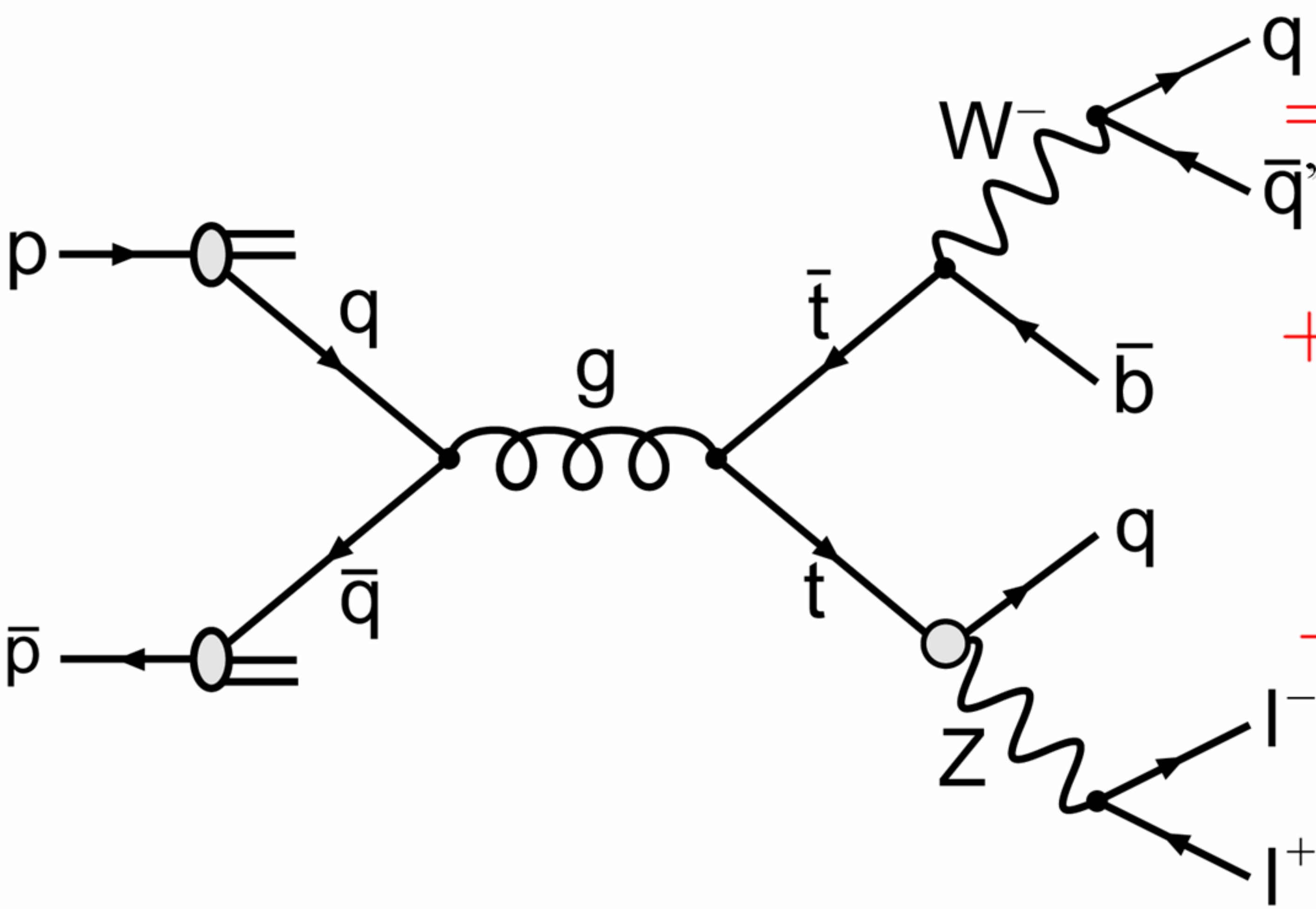

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Search for $t \rightarrow Zq$: Results

- Analysis method: Fit mass χ^2 in 3 regions:
  - Signal (B-tagged and Anti b-Tagged)
  - Control

    $\Rightarrow$ Constrain shape & normalization of Z + jets background.

- Data compatible with background only.

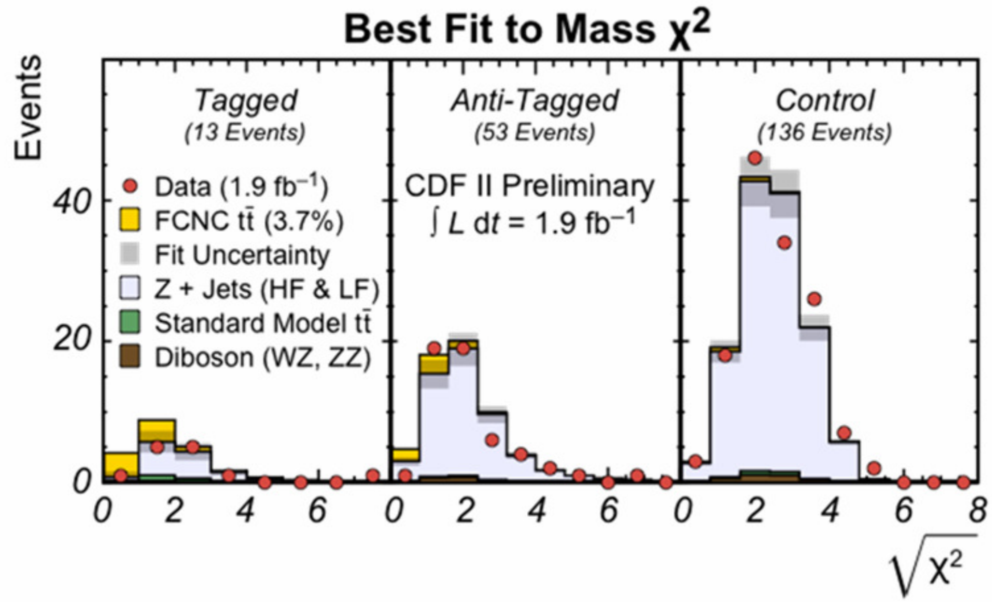
- Feldman-Cousins limit with systematic uncertainties:

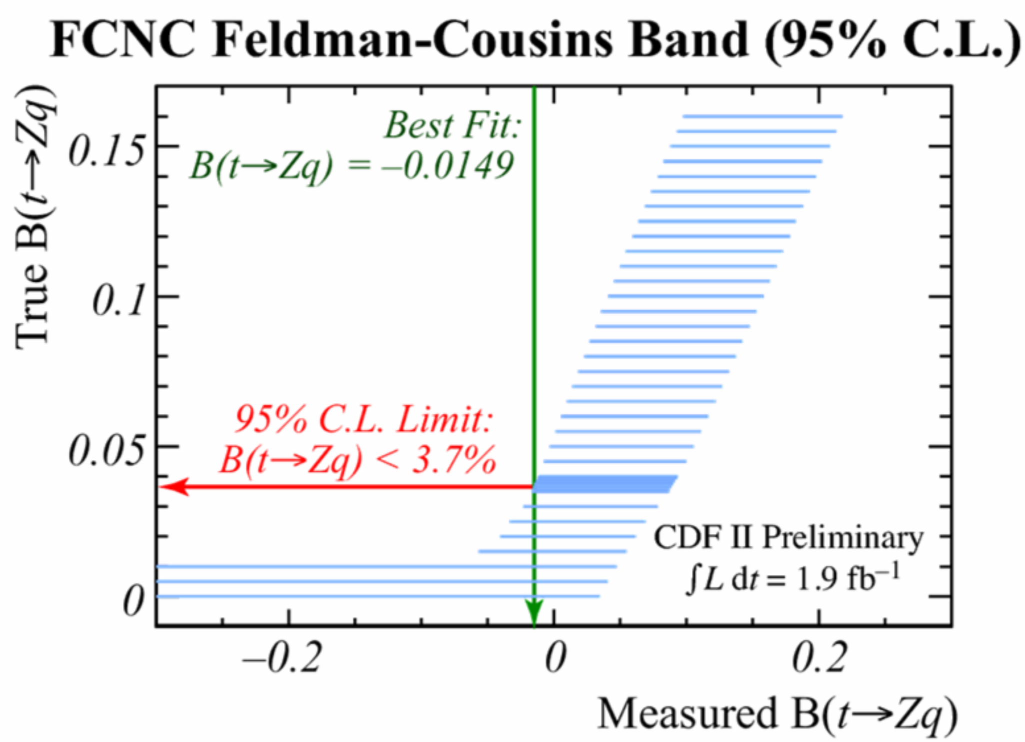
B(t→Zq) < 3.7% (95% C.L.)

- World's best limit on B(t → Zq):

- 3.5 times better than best published limit (L3)

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



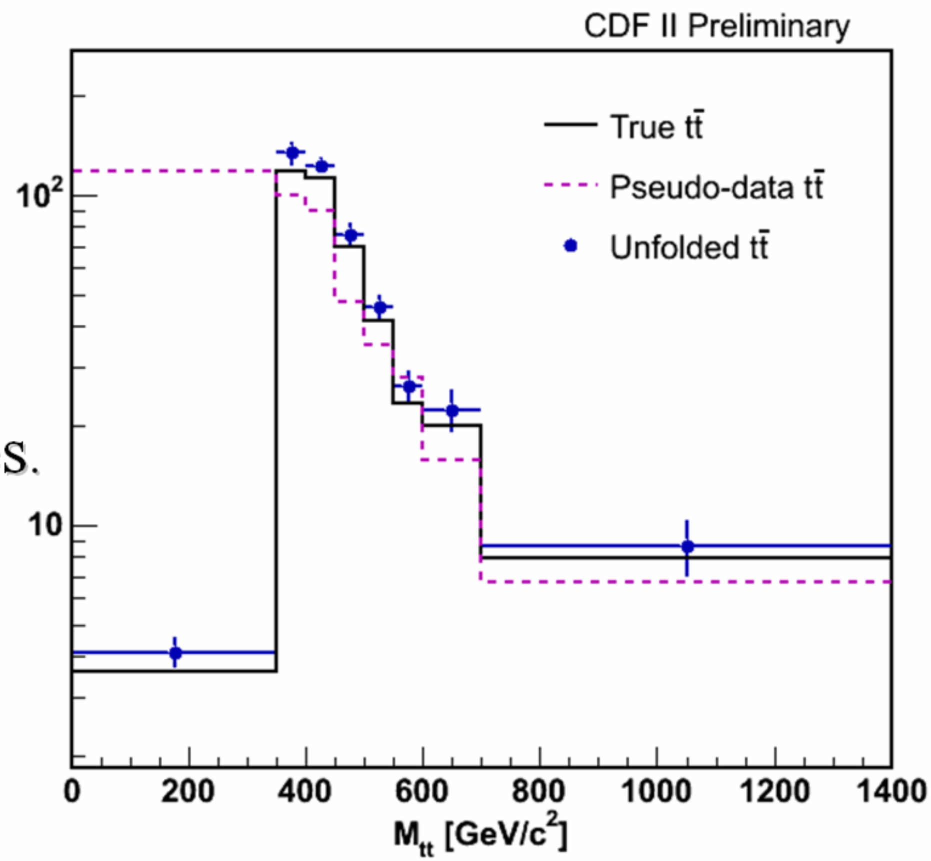


Top Pair Differential Cross Section, $d\sigma/dM_{tt}$

- SM QCD has accurate predictions of $d\sigma/dM_{tt}$.
  - Beyond SM theories predict heavy gauge particles (*e.g.*, $p\bar{p} \to Z' \to t\bar{t}$) that would interfere with SM prediction.

- $$\frac{d\sigma^i}{dM_{t\bar{t}}} = \frac{N_i - N_i^{bkg}}{\mathscr{A}_i \cdot \int \mathscr{L} dt \cdot \Delta^i_{M_{t\bar{t}}}}$$

- Analysis method:
  - Invariant mass calculated from the 4-vector sum of all observables.
  - Subtract expected backgrounds.
  - Use "*regularized unfolding*" to handle bin migration.
  - Compare with SM predictions.

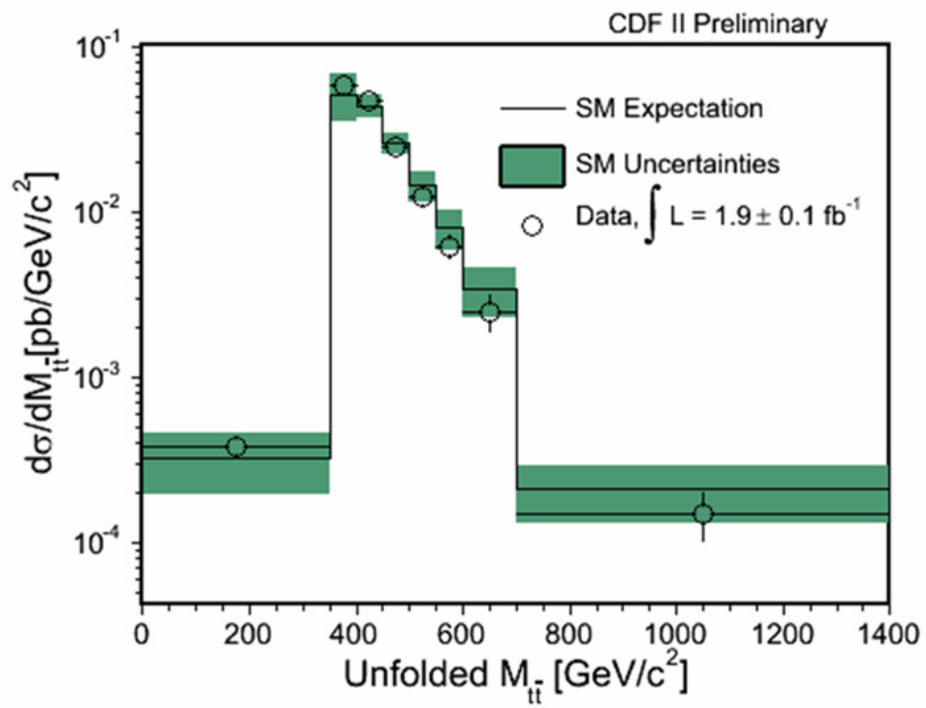


dσ/dM_{tt}, cont.

- Results consistent with SM prediction.
  - Using binned Anderson-Darling statistic, 45% of SM pseudo-experiments had a result less consistent with SM expectations.

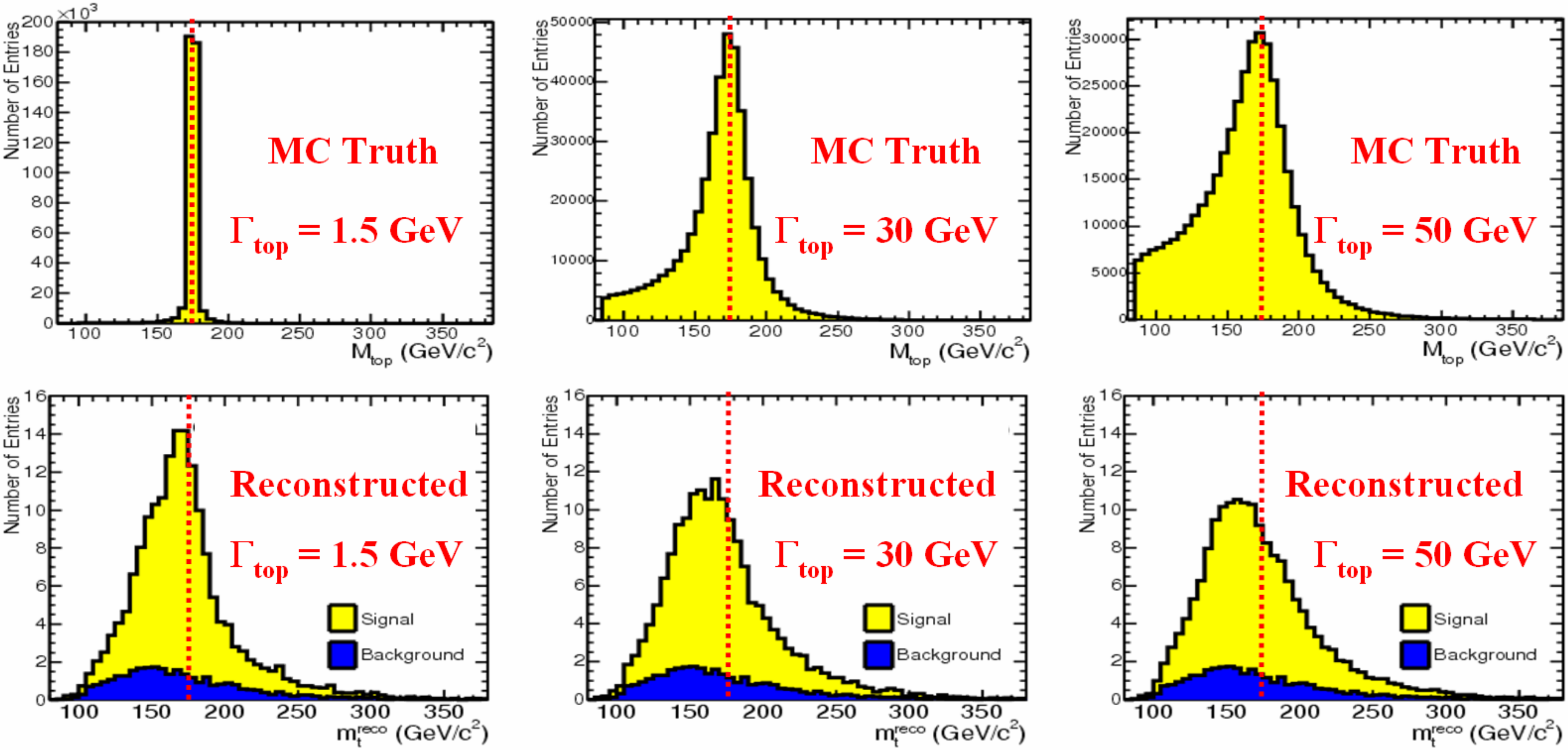
$$\int \mathcal{L} dt = 1.9 \text{ fb}^{-1}$$

$W \rightarrow \ell\nu + \geq 4$ jets data with ≥ 1 secondary vertex tag CDF II Preliminary, $\int \mathcal{L} = 1.9 \pm 0.1\ fb^{-1}$		
$M_{t\bar{t}}\ [GeV/c^2]$	$N_{t\bar{t}}^{unfolded}$	$d\sigma/dM_{t\bar{t}}\ [pb/GeV/c^2]$ (stat. uncertainties only)
≤ 350	4.21 ± 0.59	$0.00038 \pm 5.3\text{e-}05$
350-400	135.27 ± 14.69	0.059 ± 0.0064
400-450	119.63 ± 8.69	0.047 ± 0.0034
450-500	66.90 ± 6.45	0.025 ± 0.0024
500-550	35.42 ± 4.50	0.012 ± 0.0016
550-600	18.10 ± 3.03	0.0062 ± 0.001
600-700	14.61 ± 3.62	0.0025 ± 0.00062
700-1400	5.72 ± 1.79	$0.00015 \pm 4.7\text{e-}05$
Assumes $M_{top} = 175\ GeV/c^2$		

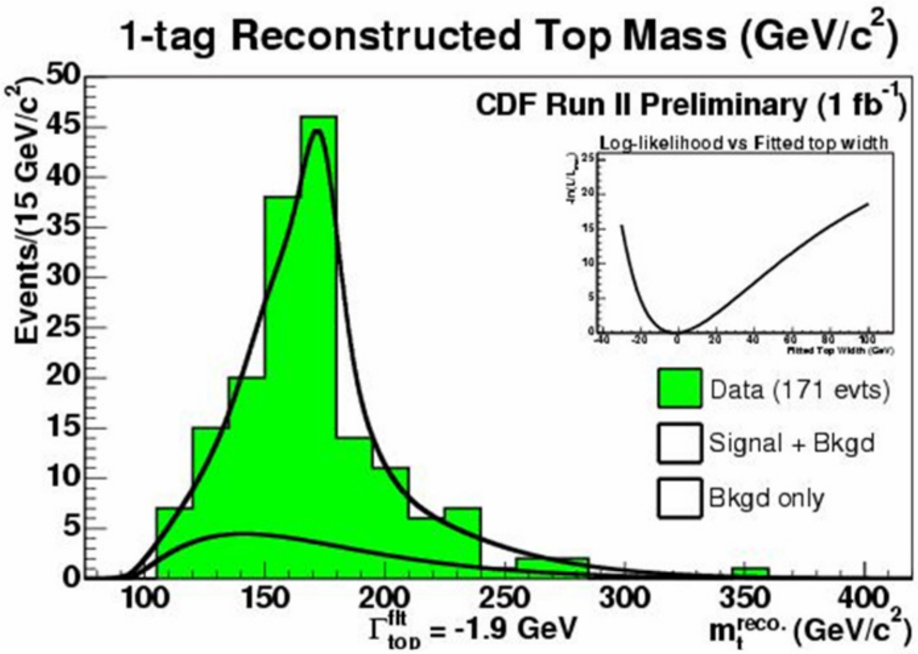


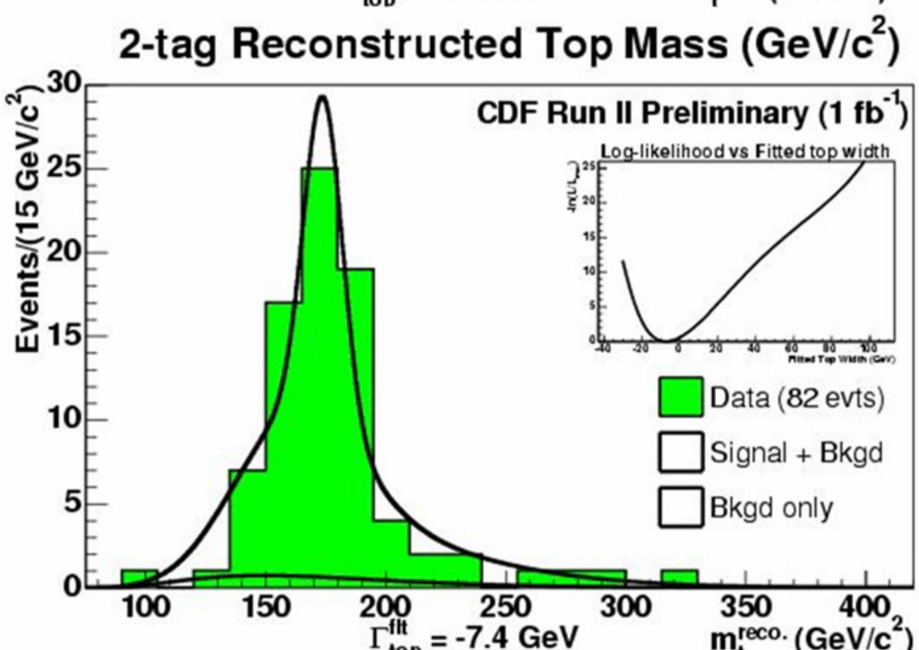
Top Width

- Top is predicted to be wide (1.5 GeV) ⇒ Very short lifetime.
- Analysis method:
  - Use top mass χ^2 (let width float).
  - Template fit to reconstructed top mass.



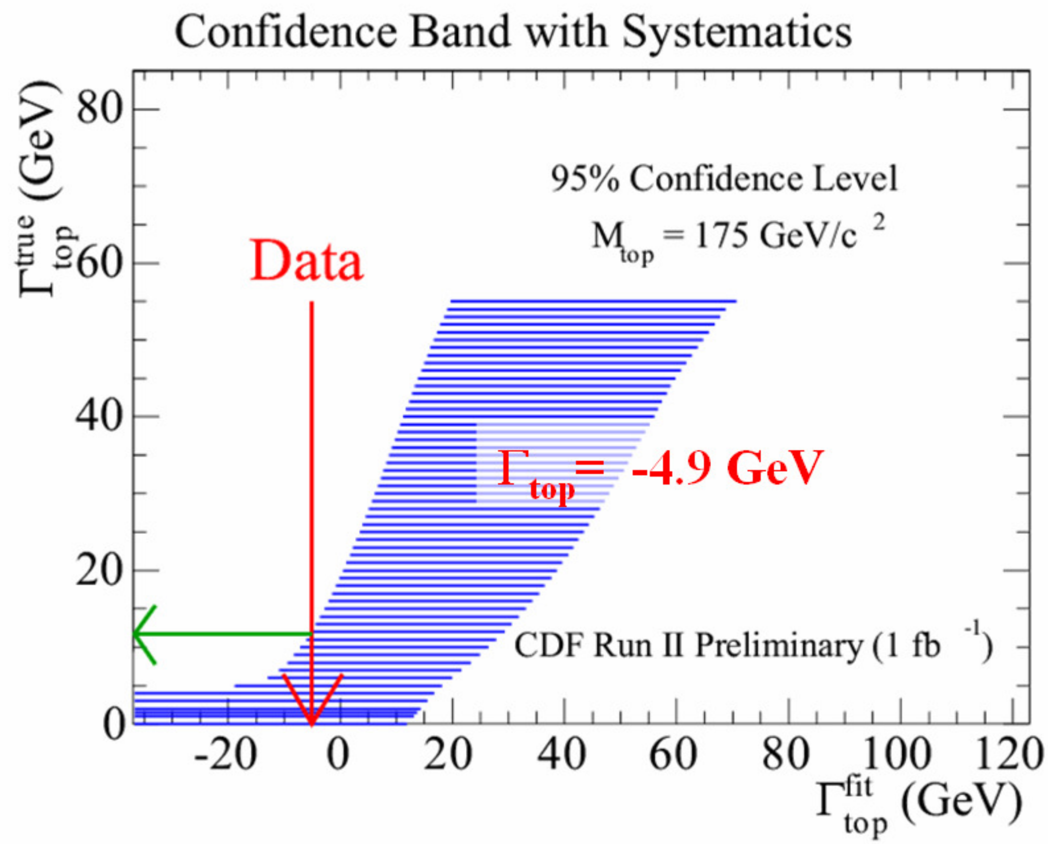
Top Width, cont.





$$\int \mathscr{L} dt = 1.0 \text{ fb}^{-1}$$

- $\Gamma_{top} < 12.7$ GeV at 95% C.L.

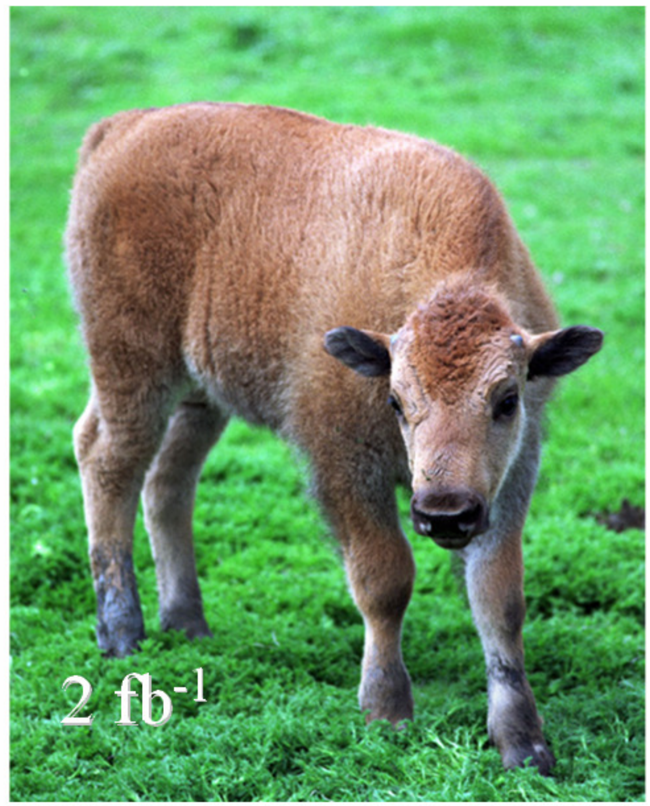


Looking Forward

- Lots of exciting top physics happening at the CDF.
  - CDF, and the Tevatron are all running **very** well.
  - A lot of room to grow.

- CDF has many of the world's best measurments:
  - http://www-cdf.fnal.gov/physics/new/top/top.html
  - Br ($t \rightarrow Zq$) < 3.7% (95% C.L.)
  - First $d\sigma/dM_{tt}$ measurement
  - Top quark width < 12.7 GeV (95% C.L.)
  - …

- Top quark physics is becoming precision field.
  - Almost all analyses (except mass) are still statistics limited.
  - So far, most (*but not all*) things are frustratingly consistent with the SM.



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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) %		–
$\tau \nu_\tau b$				–
γ 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%	–

New Era of Precision Top Physics!

2008 PDG Top Entry

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$W b$				–
$\ell \nu_\ell$ anything	[c,d]	(9.4±2.4) %		–
$\tau \nu_\tau b$				–
γ 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%	–

New Era of Precision Top Physics!

2008 PDG Top Entry

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Width Γ < 12.7 GeV

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$\frac{d\sigma}{dM_{t\bar{t}}}$

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2010 PDG Top Entry

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$W\,b$					–
$\ell \nu_\ell$ anything		[c,d]	(9.4±2.4) %		–
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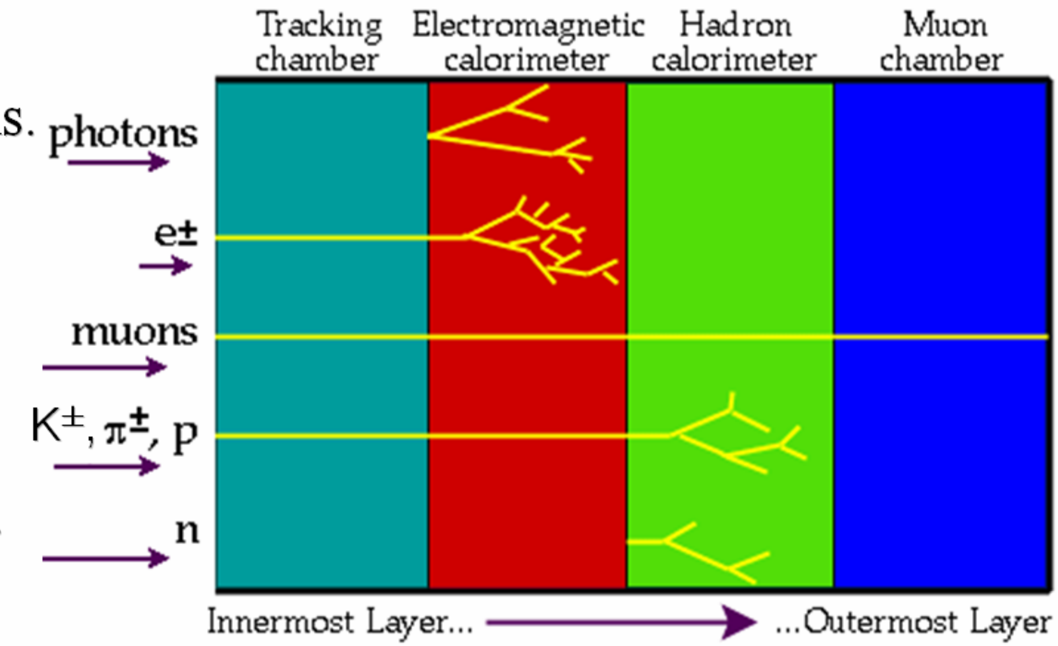
...

(Your analysis here?!)

Backup Slides

Important Tool: Lepton ID

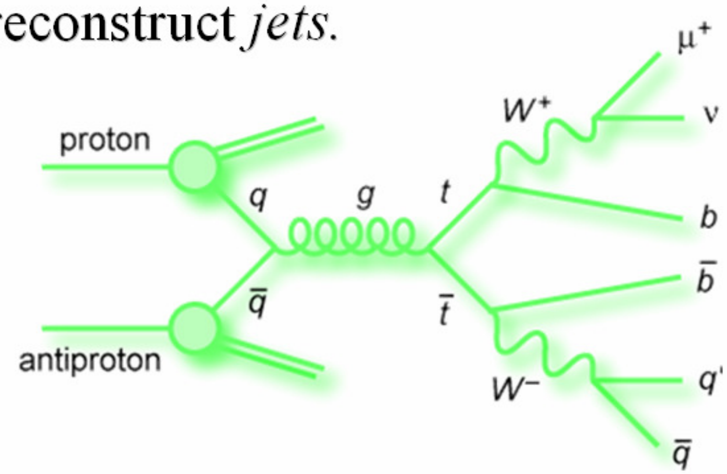
- For many analyses, we need a very pure set of high p_T electrons and muons.



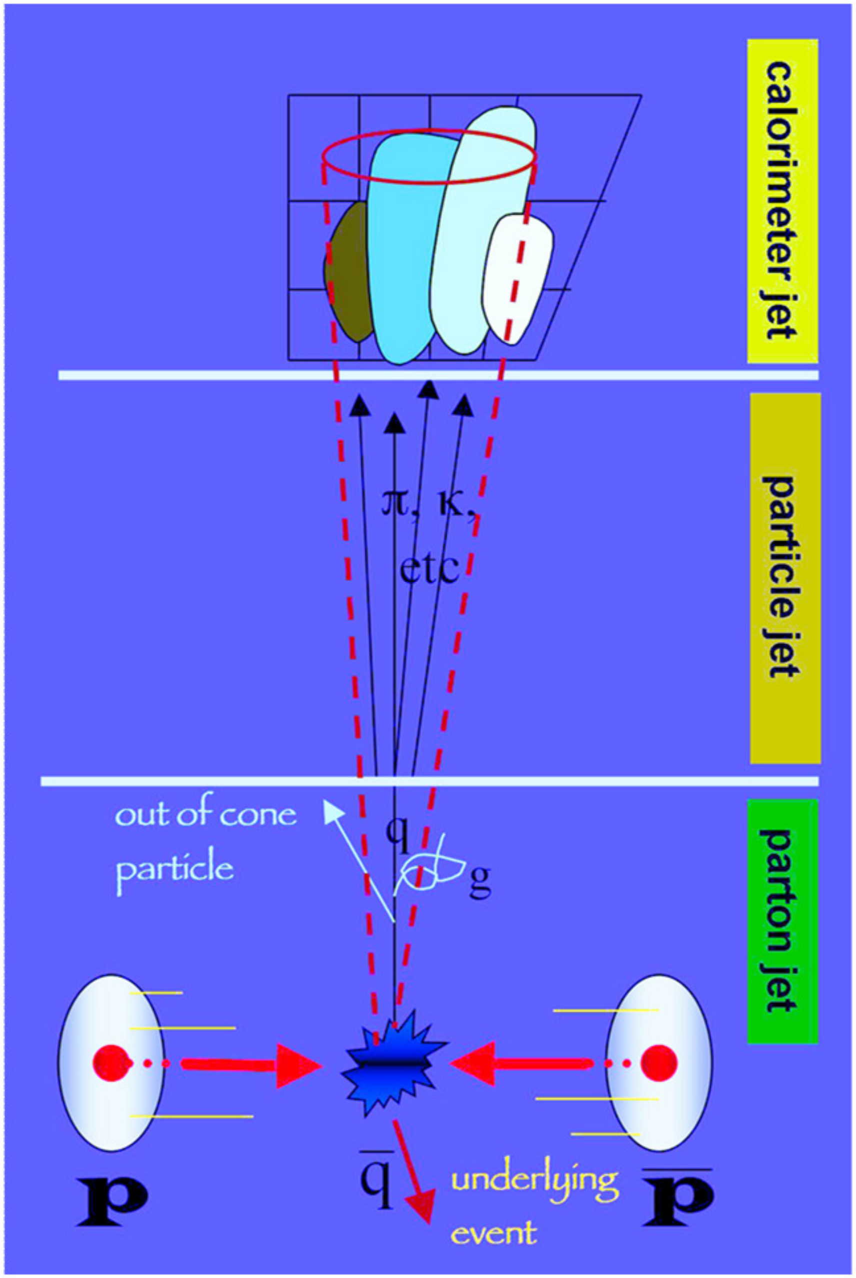
- Electrons (as we reconstruct them):
  - Have charged particle track.
  - Leave almost all of their energy in the electromagnetic calorimeter.
  - Ask for no other nearby tracks.
    - We do not want leptons from (heavy flavor) jets.
- Muons:
  - Have charged particle track.
  - ~ Minimum ionizing (leave little energy in either the electromagnetic or hadronic calorimeter)
  - Find a "stub" of a track in dedicated muon detector systems on outside of CDF.
  - Ask for no other nearby tracks.

Important Tool: Jet Reconstruction

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

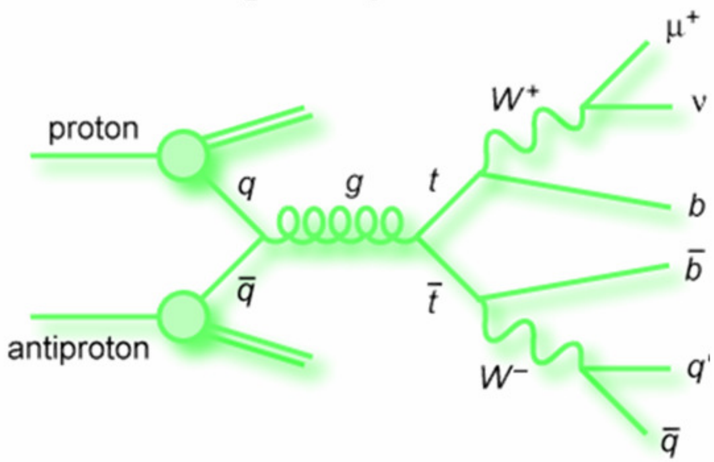


- We need to convert *"raw"* jets to *"corrected"* jets - Jet Energy Scale (JES) correction.
  - Takes into account detector effects, neutral particles in jets, particles outside of the jet cone, underlying events, multiple interactions, …



Important Tool: B Jet Tagging

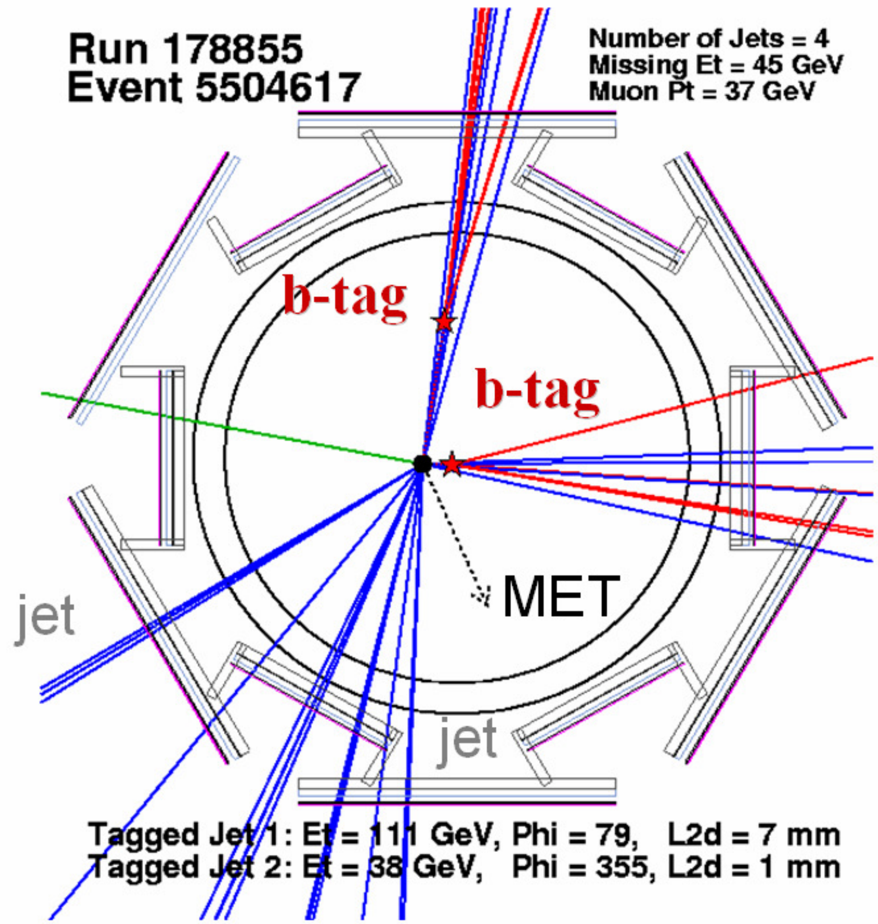
- Since we (often) expect $t \rightarrow W\, b$, b jet tagging is a very important tool.
  - Most backgrounds do not have bottom quark jets.



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

CDF Event:

Close-up View of Layer 00 Silicon Detector



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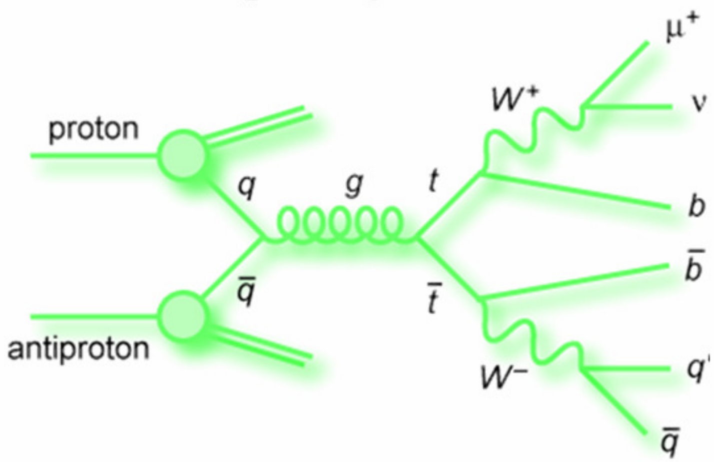

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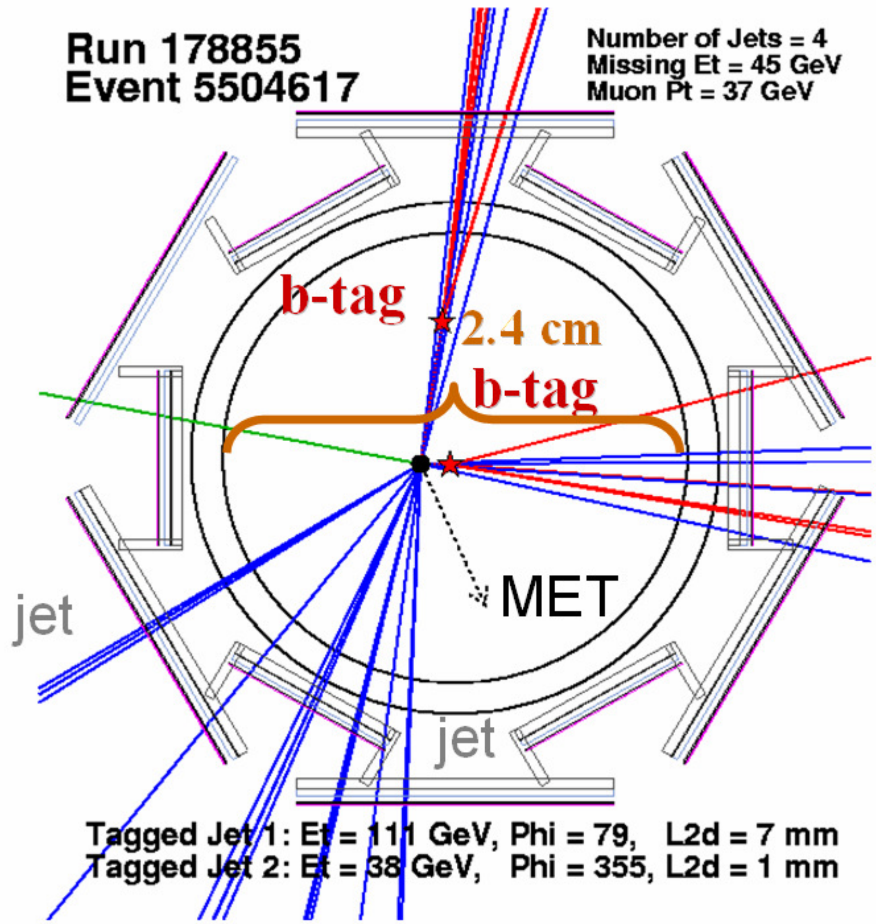

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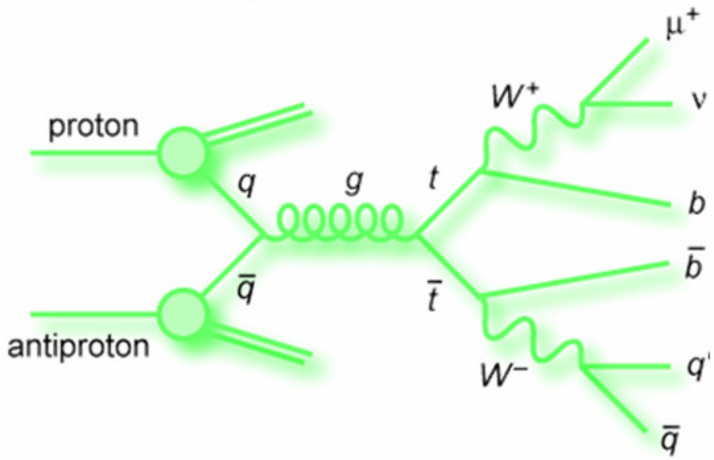

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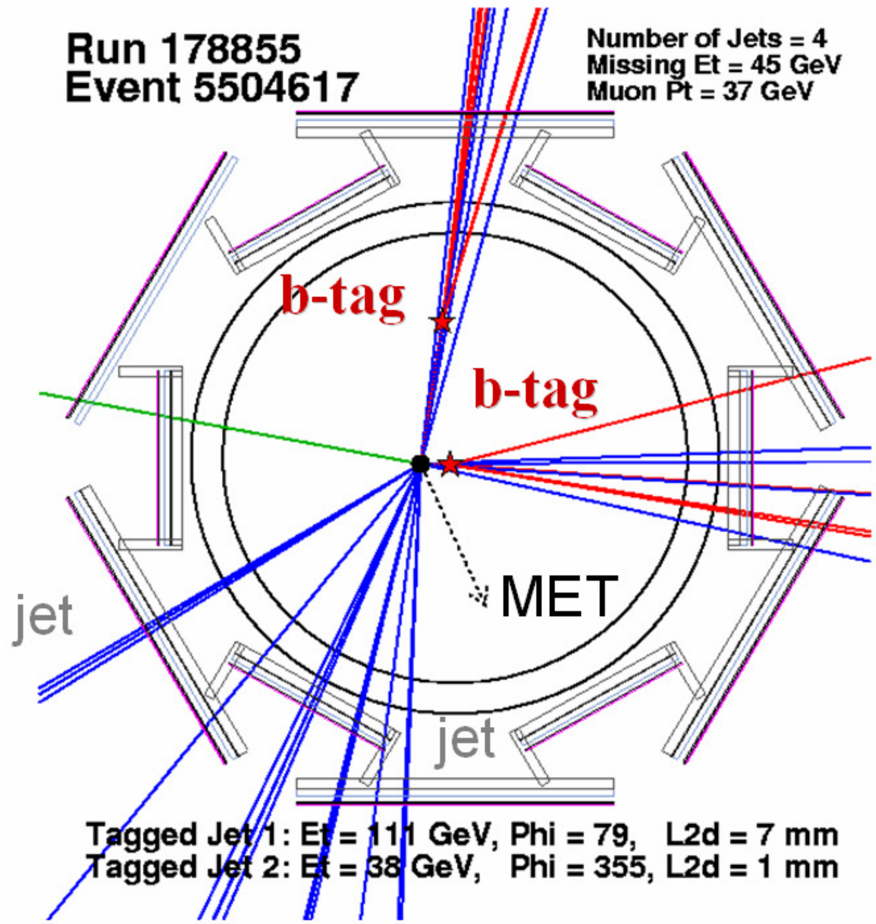

Top Physics *Finally* Makes Prime Time

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The Big Bang Theory!

Mondays at 7:00 on CBS.

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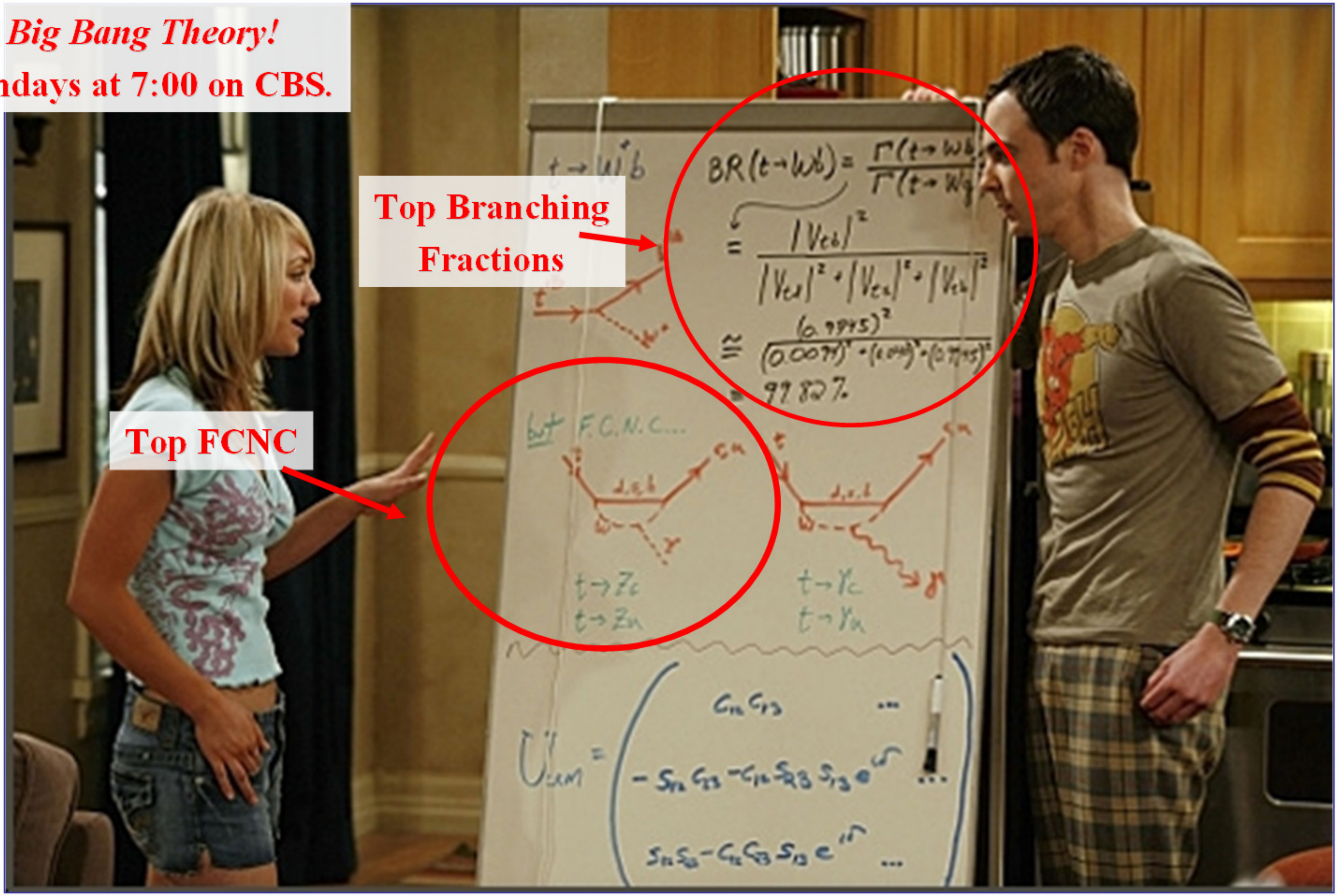
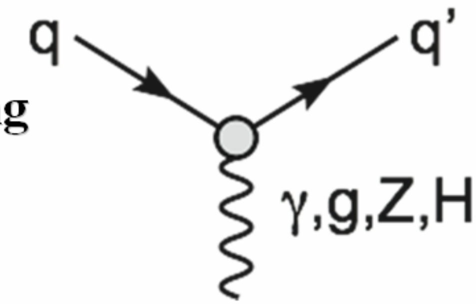


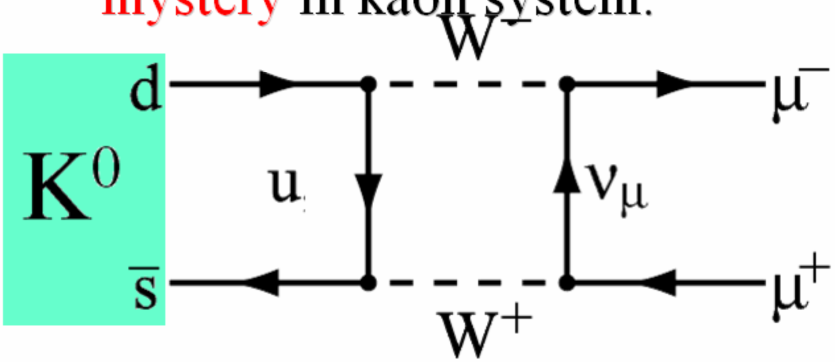
Flavor Changing Neutral Currents

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

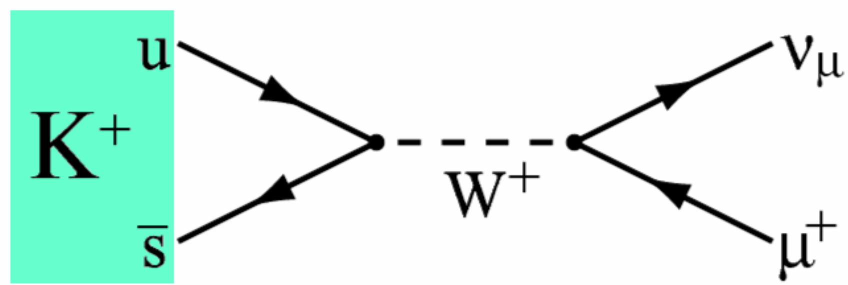
Flavor Changing Neutral Current



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



10^8 times smaller than…?



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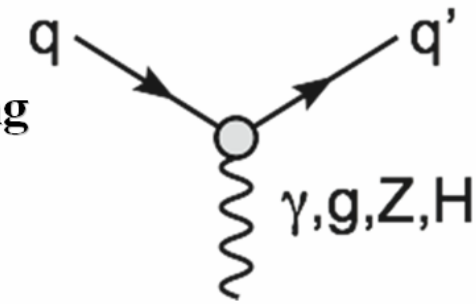

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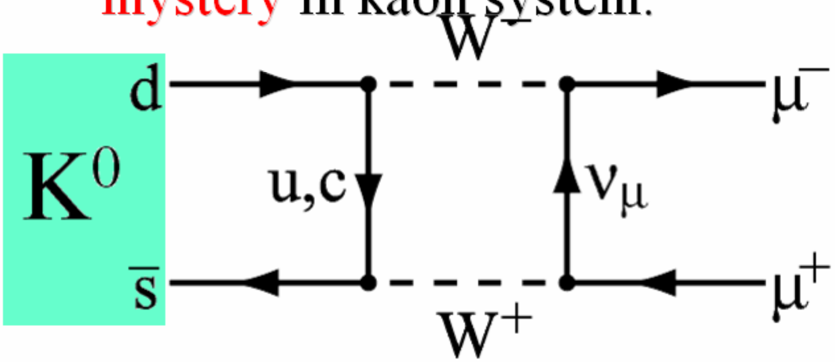

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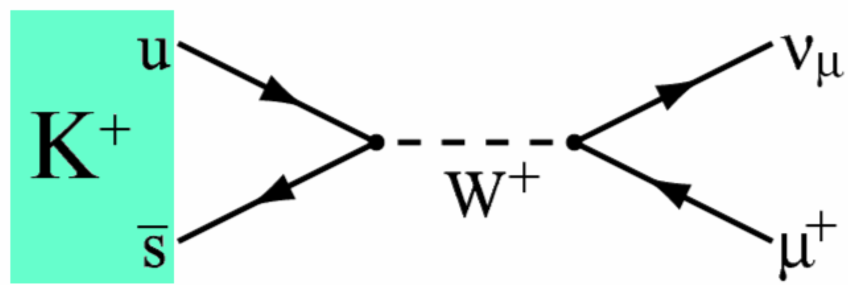

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Top Flavor Changing Neutral Currents

- SM Higgs mechanism: weak neutral currents (NC) do not change the flavor of quarks/leptons ("flavor-diagonal")
  ⇒ no FCNC at "tree level."

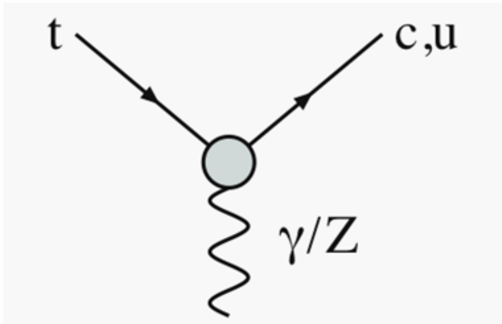
- FCNC possible e.g. via penguin diagrams.

- Suppression of this mode:
  - GIM mechanism
  - Cabibbo suppression

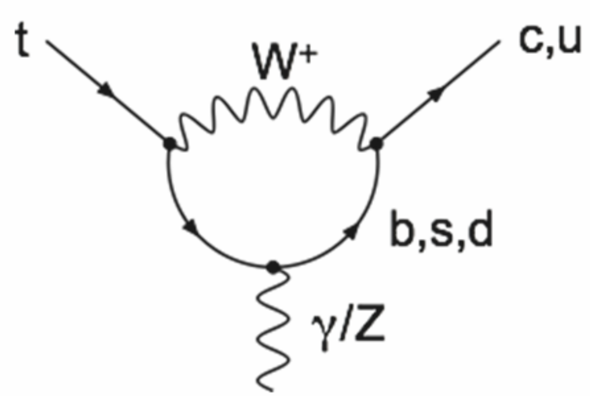
- Expected SM branching fraction (Br) for $t \to Zc$ as small as 10^{-14}.

- Any signal at the Tevatron or LHC: New Physics.

Generic FCNC

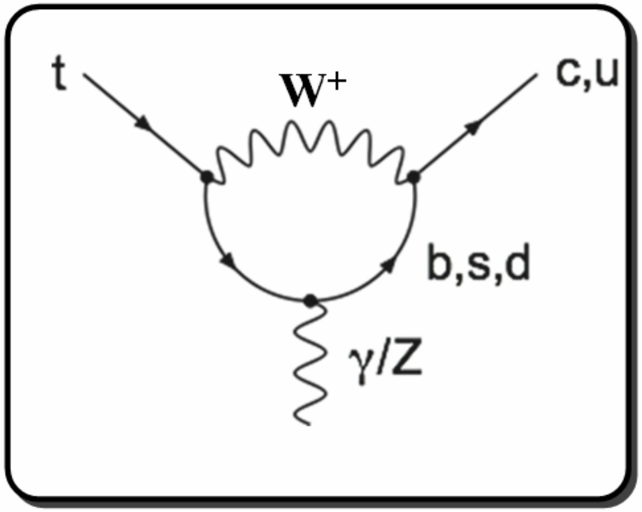


Penguin Diagram



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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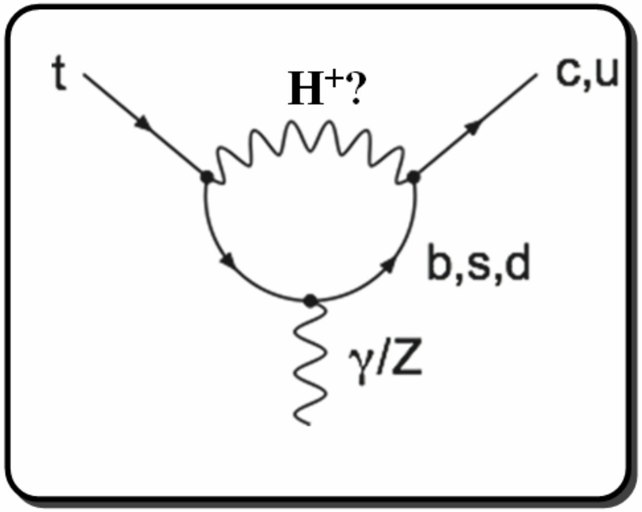

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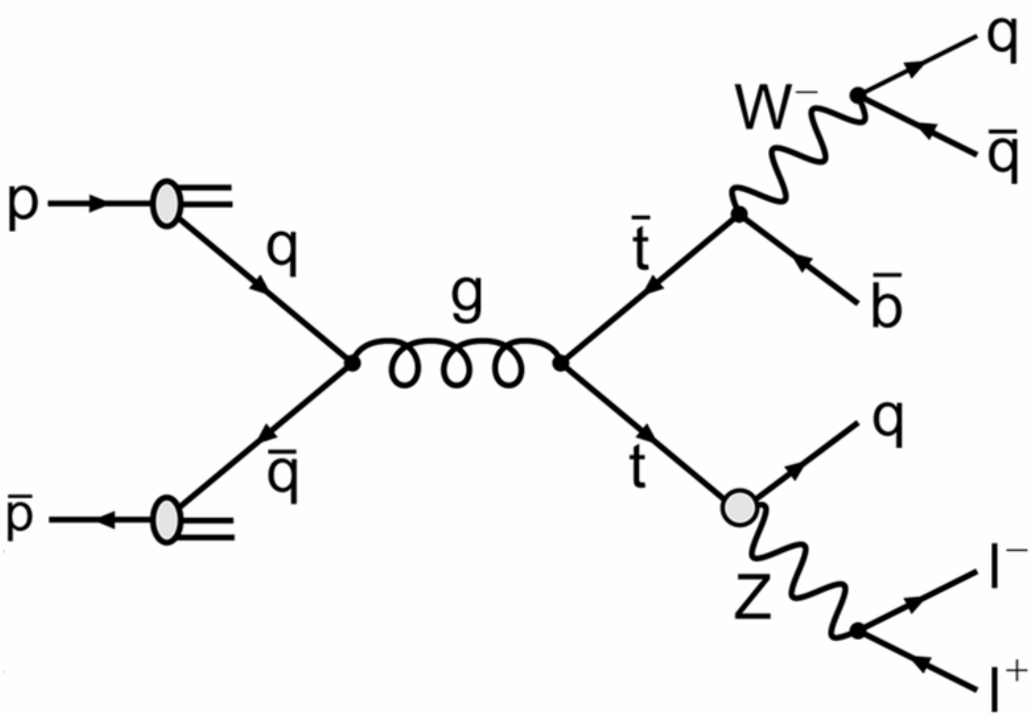
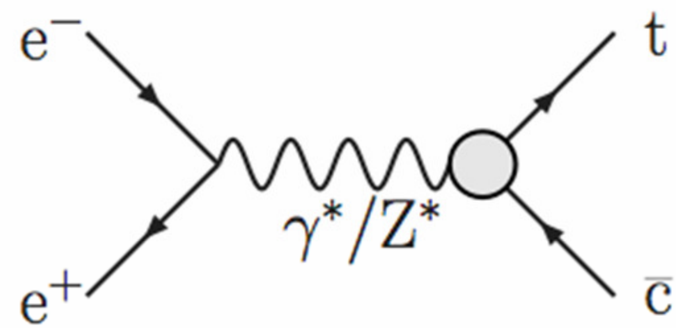
Previous Limits

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



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

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



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

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

Top Mass Reconstruction

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

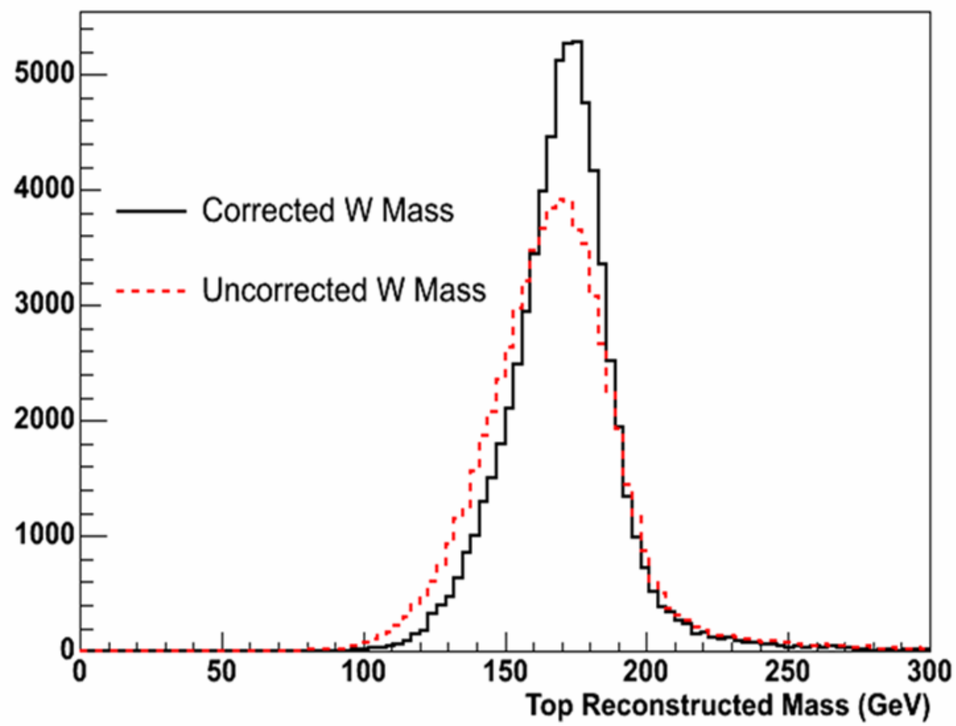
- To improve resolution, we correct the W and Z daughters so that the masses are correct.
  - Rescale the daughters within their resolutions.
  - Smaller mass resolution $\Rightarrow$ Better signal separation.

$t \to Wb$ mass

width

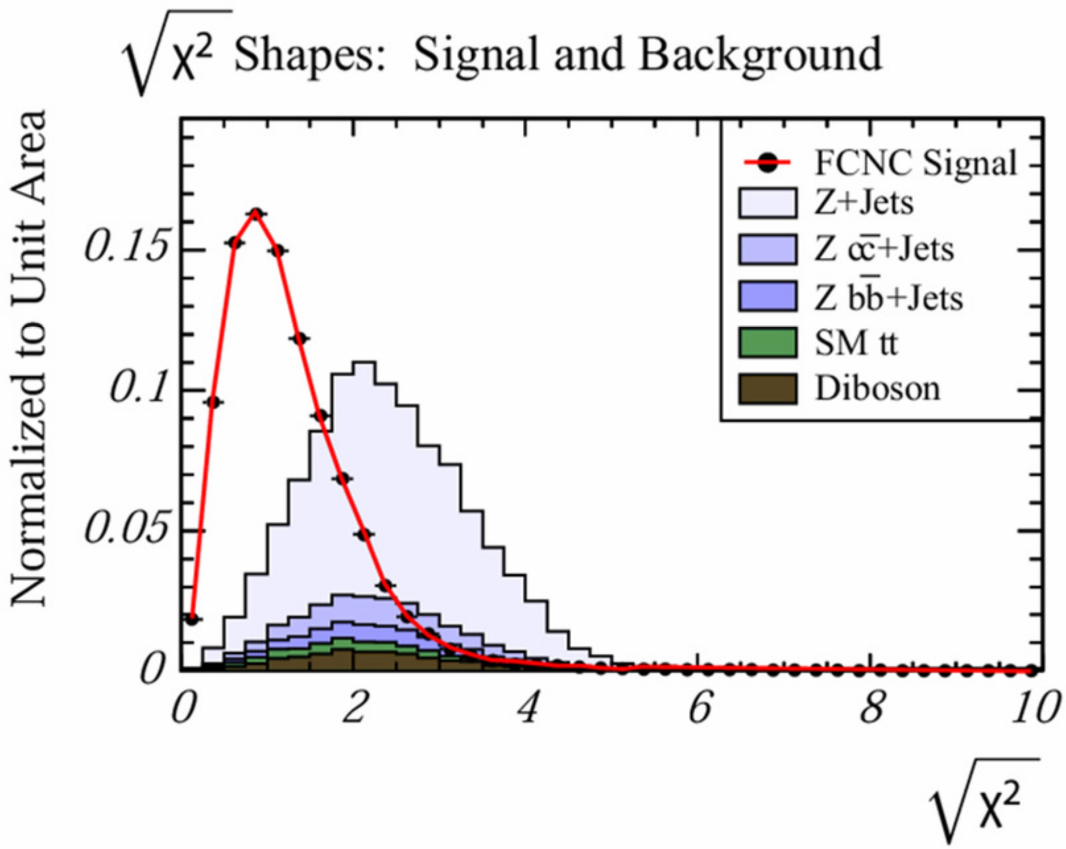
20 GeV $\Rightarrow$ 16 GeV!

Signal MC with partons correctly matched to reconstructed objects.



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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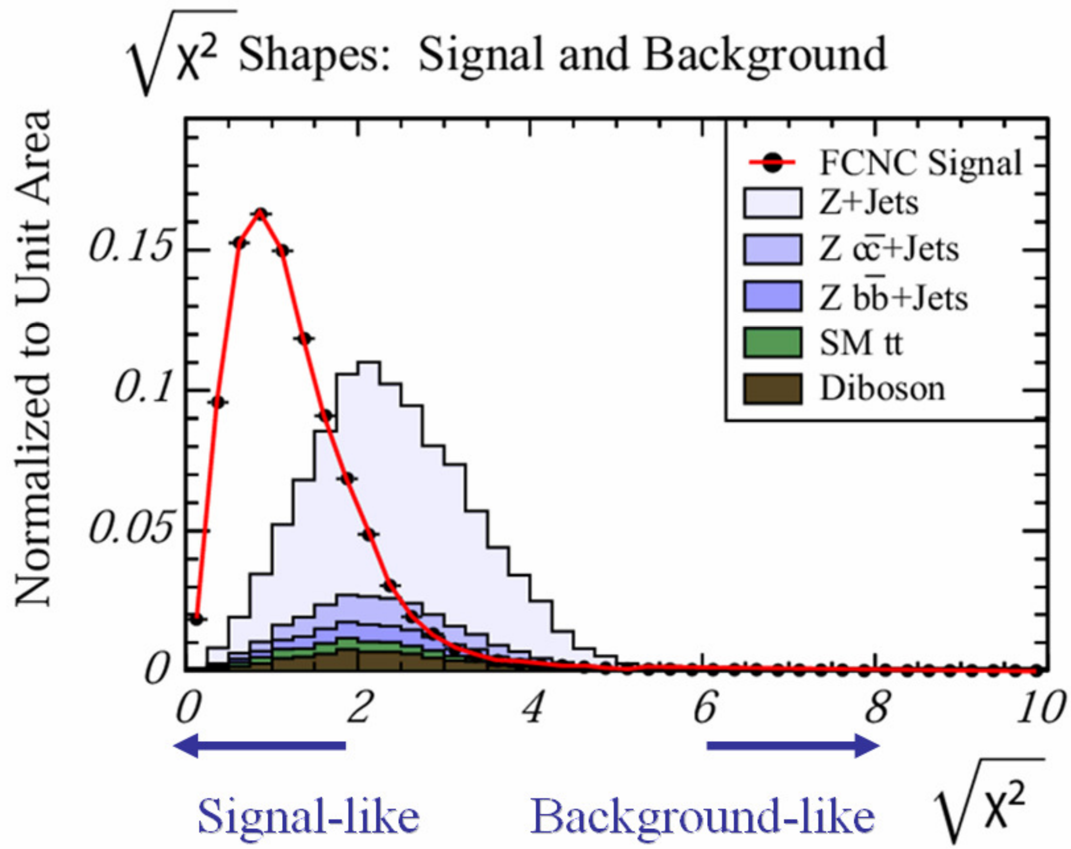

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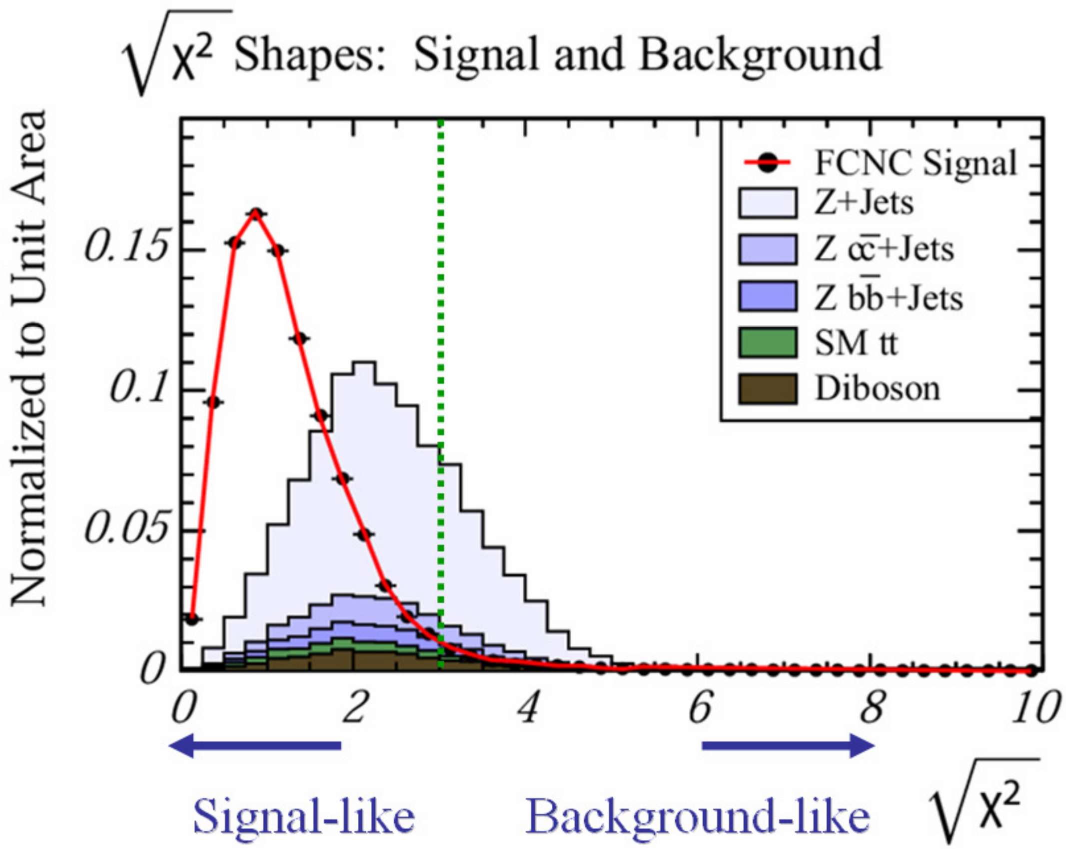

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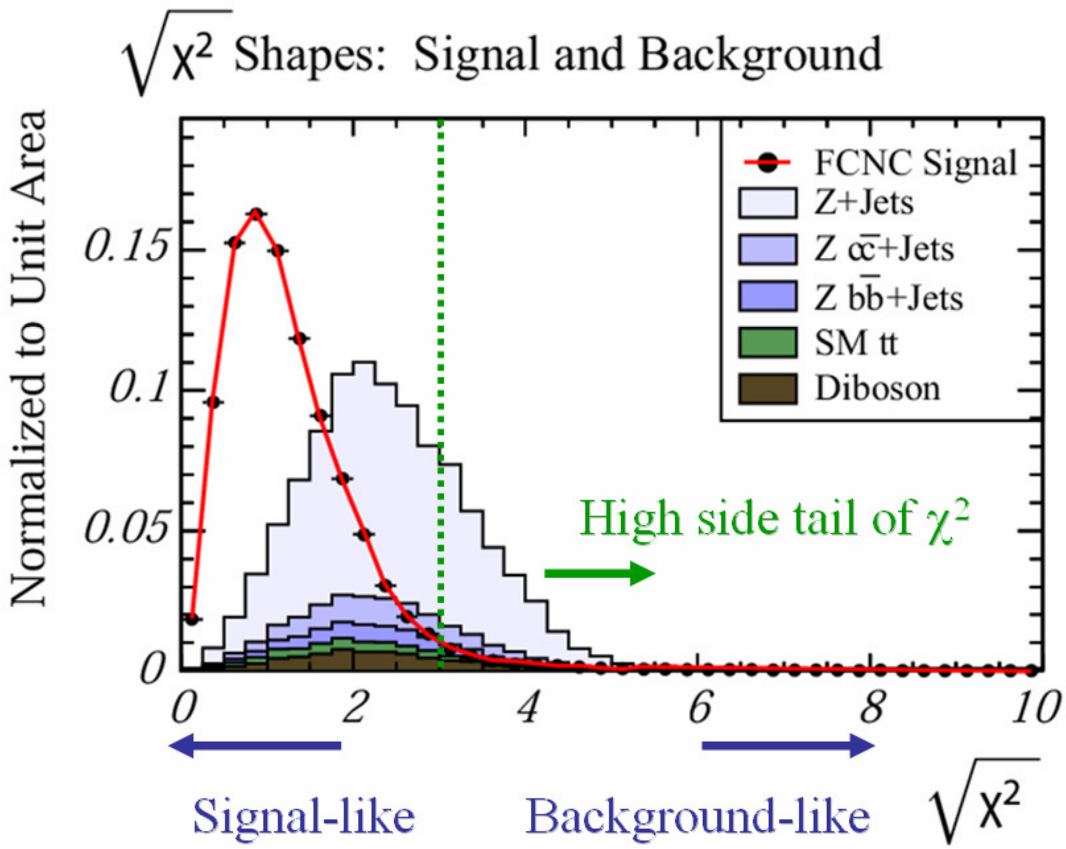
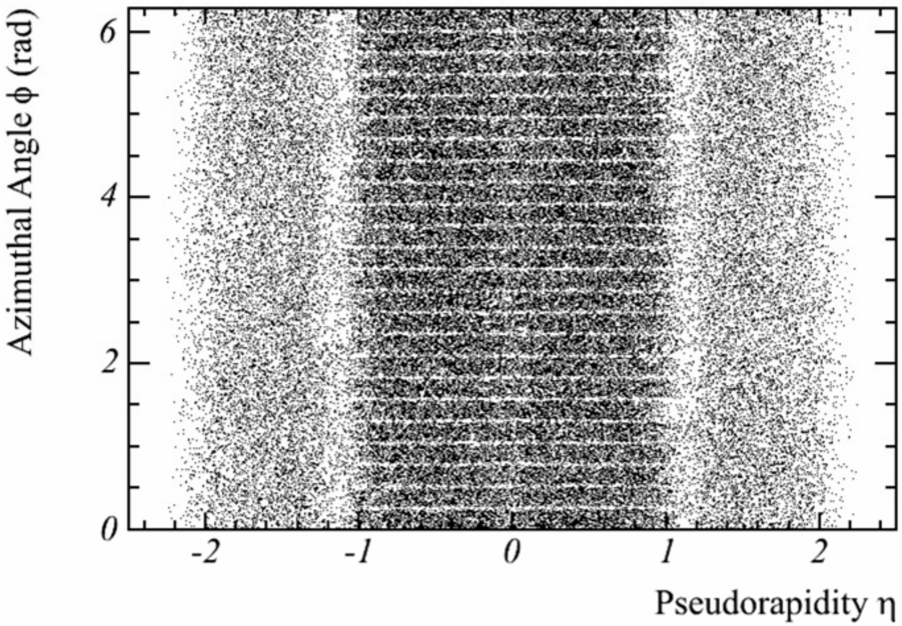
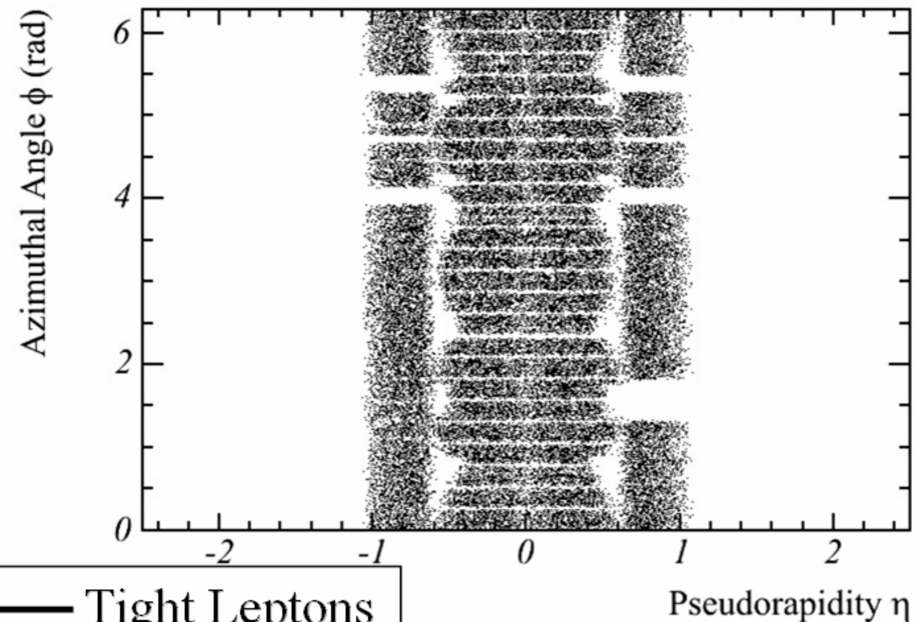


Lepton + Track Z Candidates

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).

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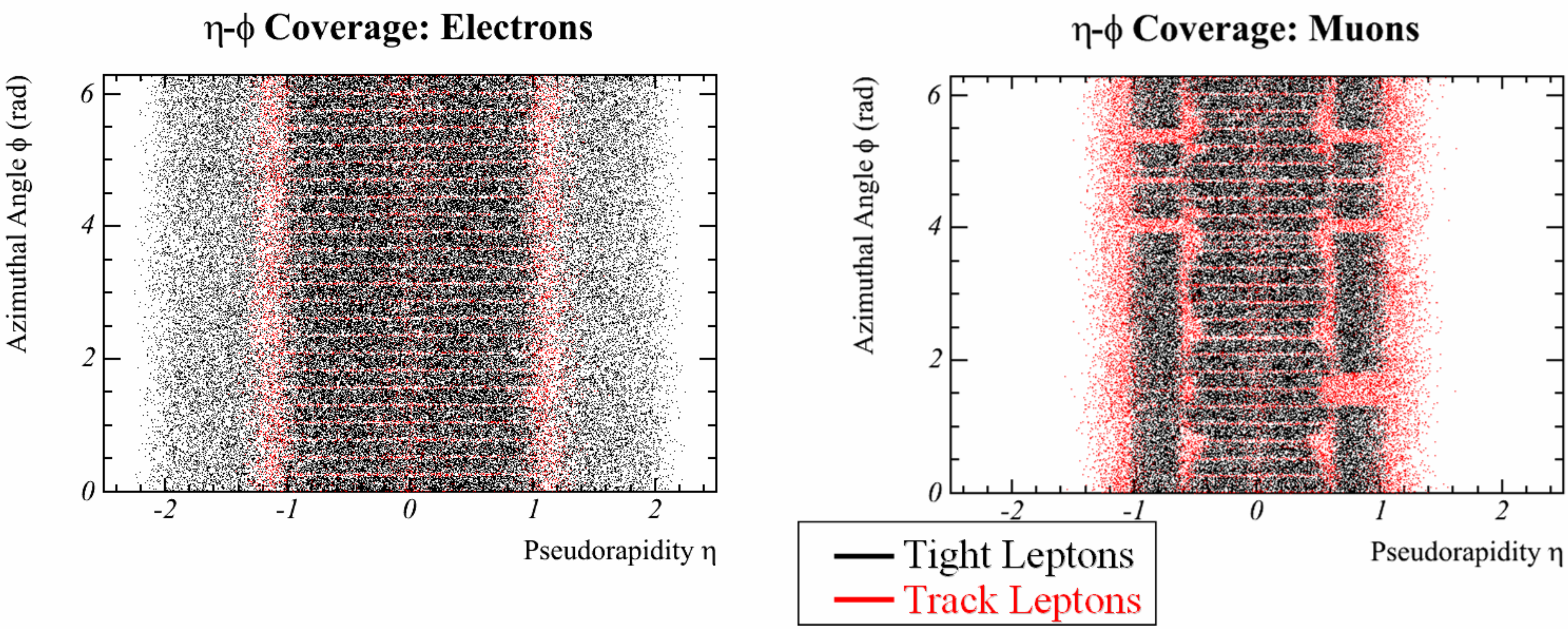

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To B-Tag or not to B-Tag?

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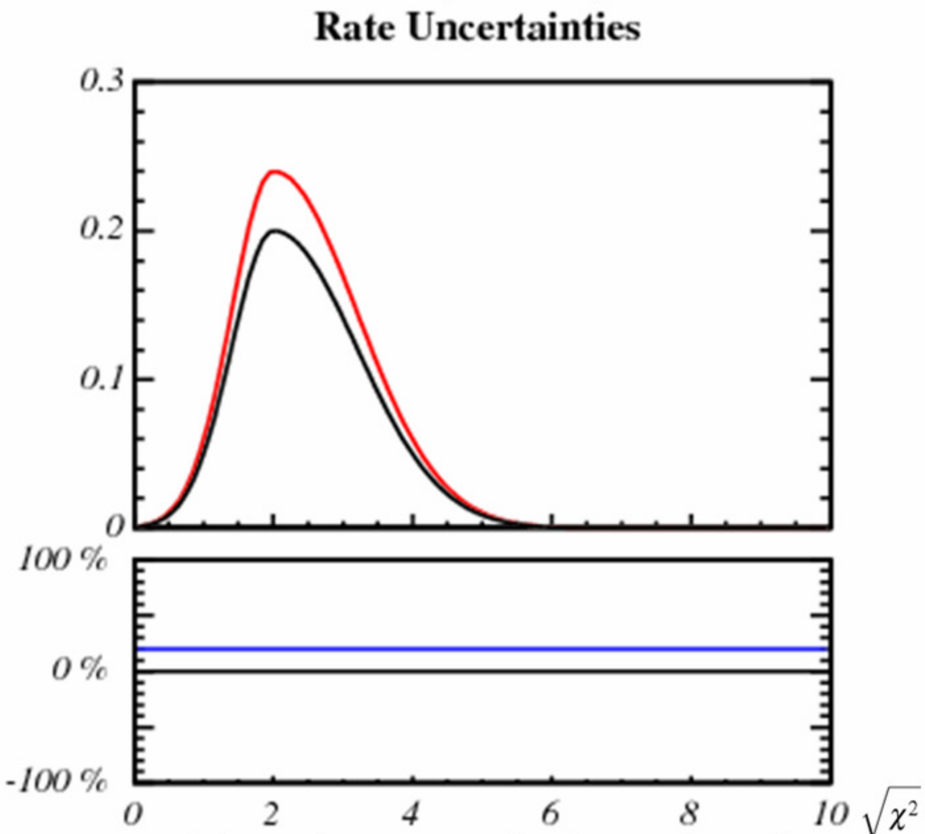
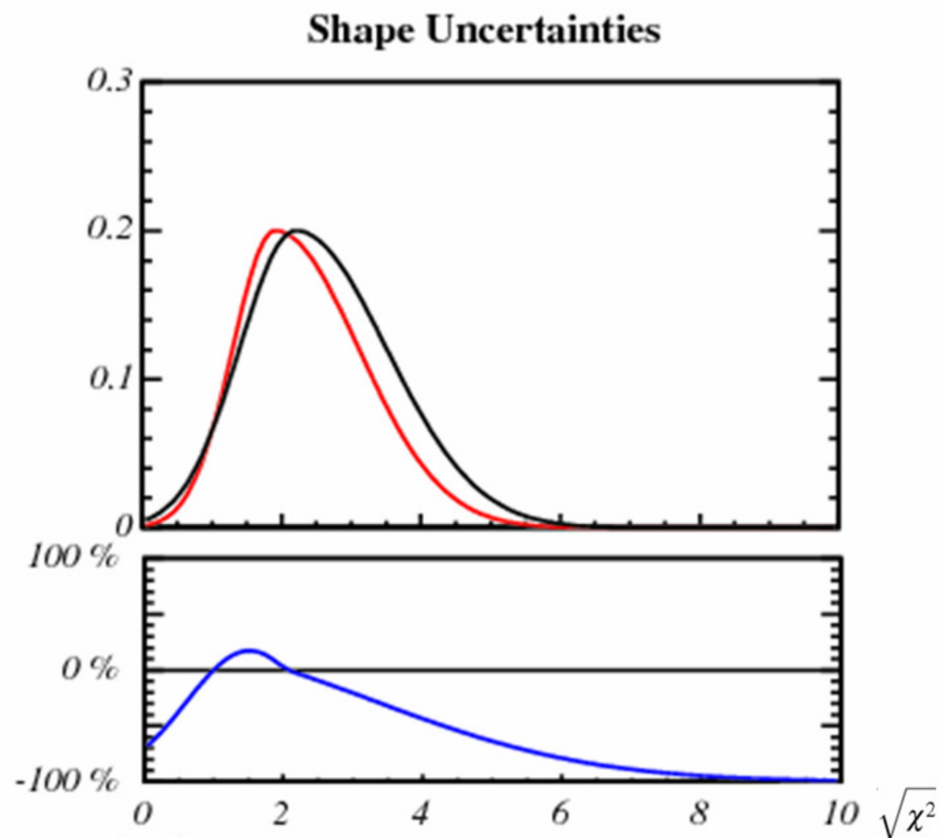
- Solution: Use both!
  - Split sample in ***tagged*** (at least one tagged jet) and ***anti-tagged*** (no tagged jets).
  - Optimize cuts individually for tagged and anti-tagged samples.
  - Combine samples in limit calculation.

Shape Uncertainties

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



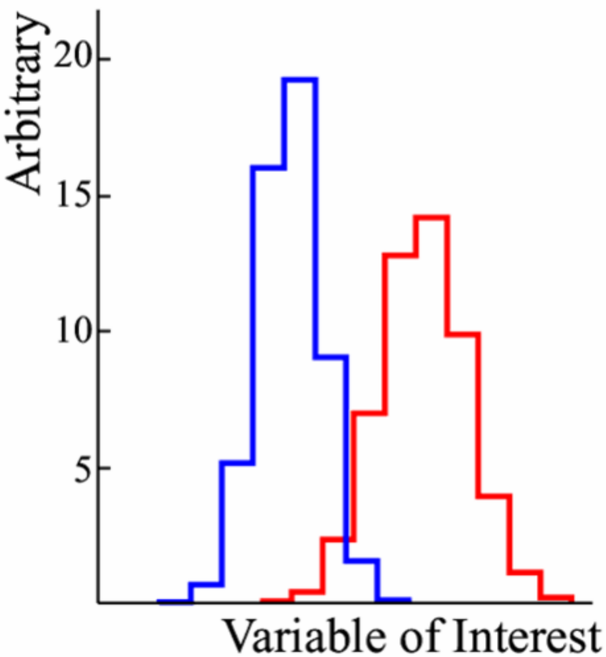


- We considered many choices for shape uncertainties.
- The two dominant effects were much larger than all others.
  - Factorization/Renormalization (Q^2) scale for Z + jets MC.
  - Jet energy scale uncertainties.

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).



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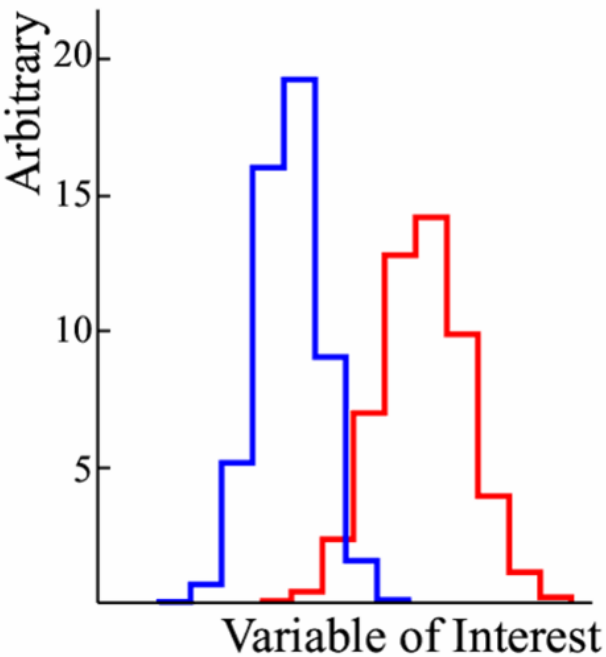

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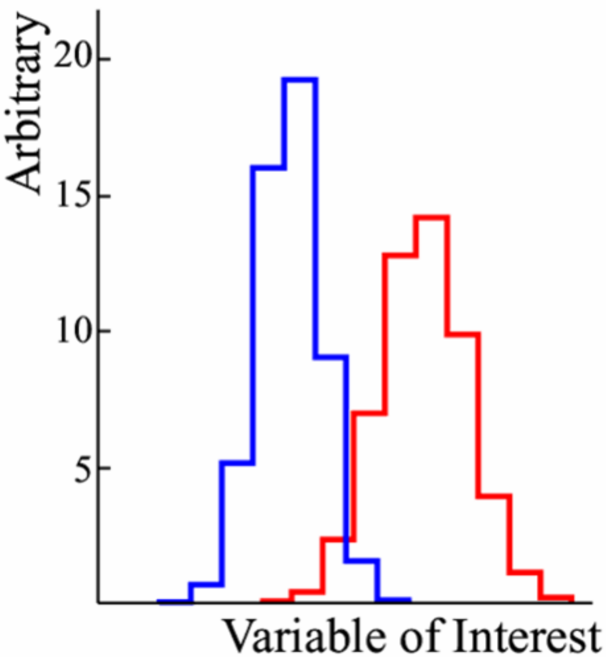

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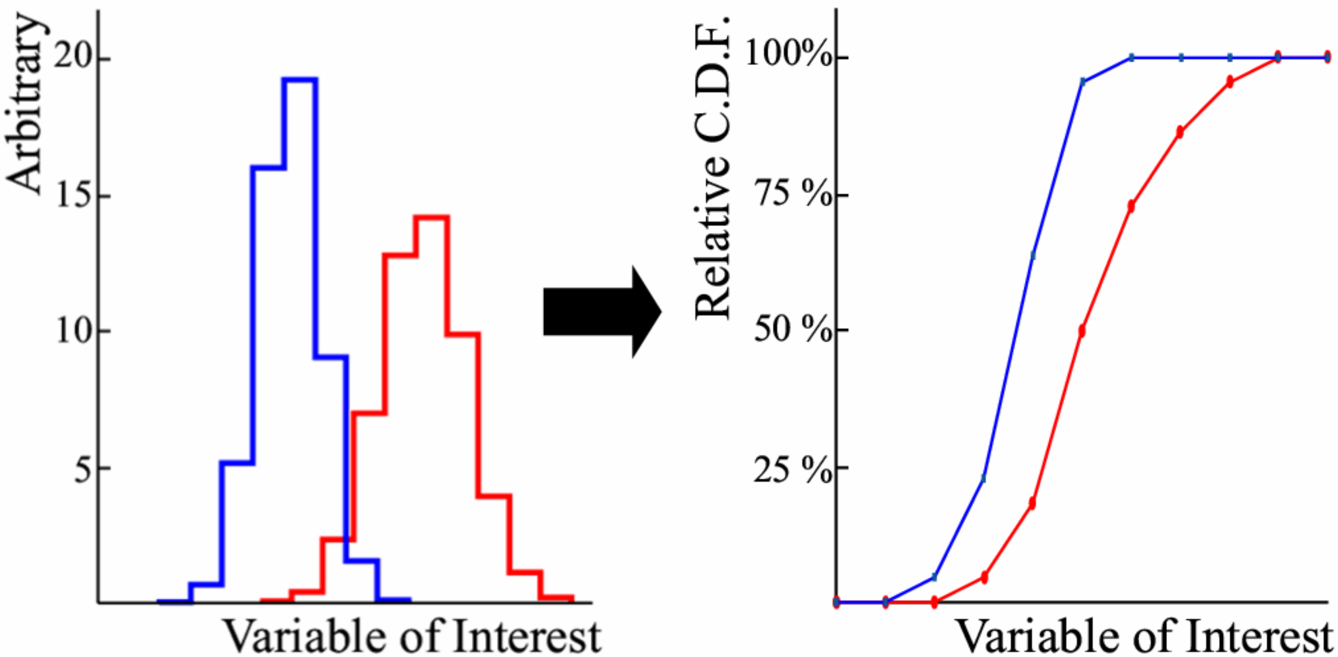

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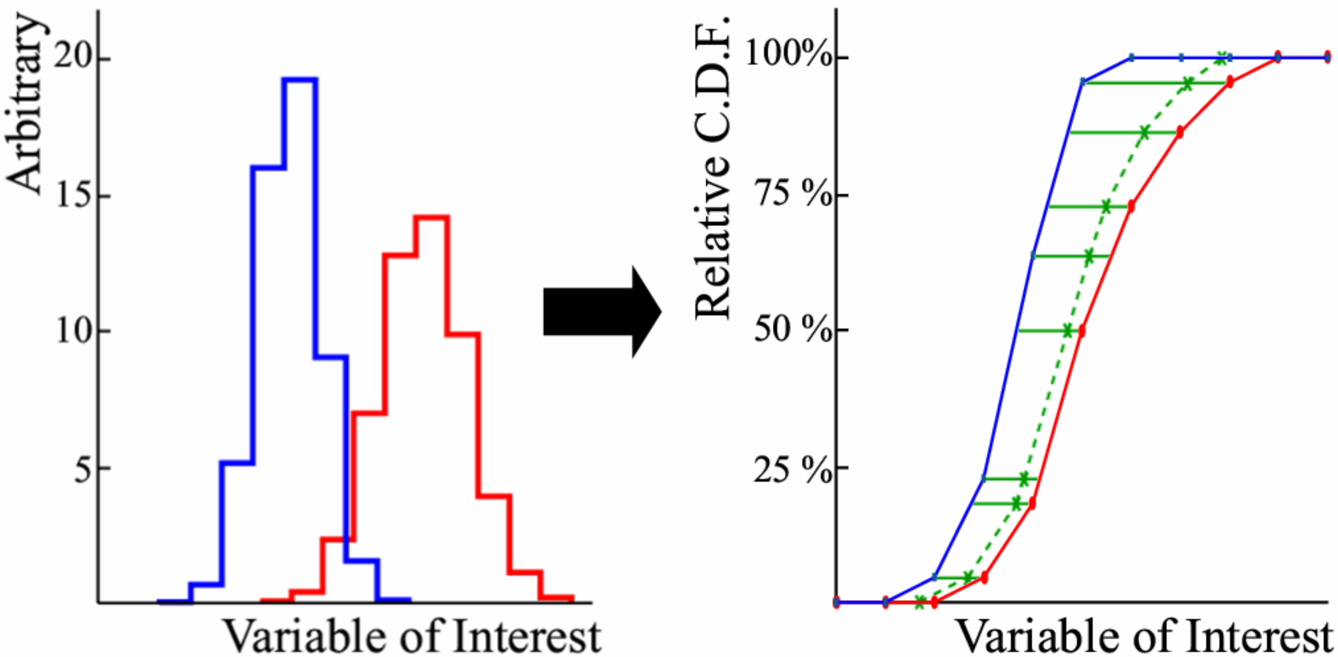

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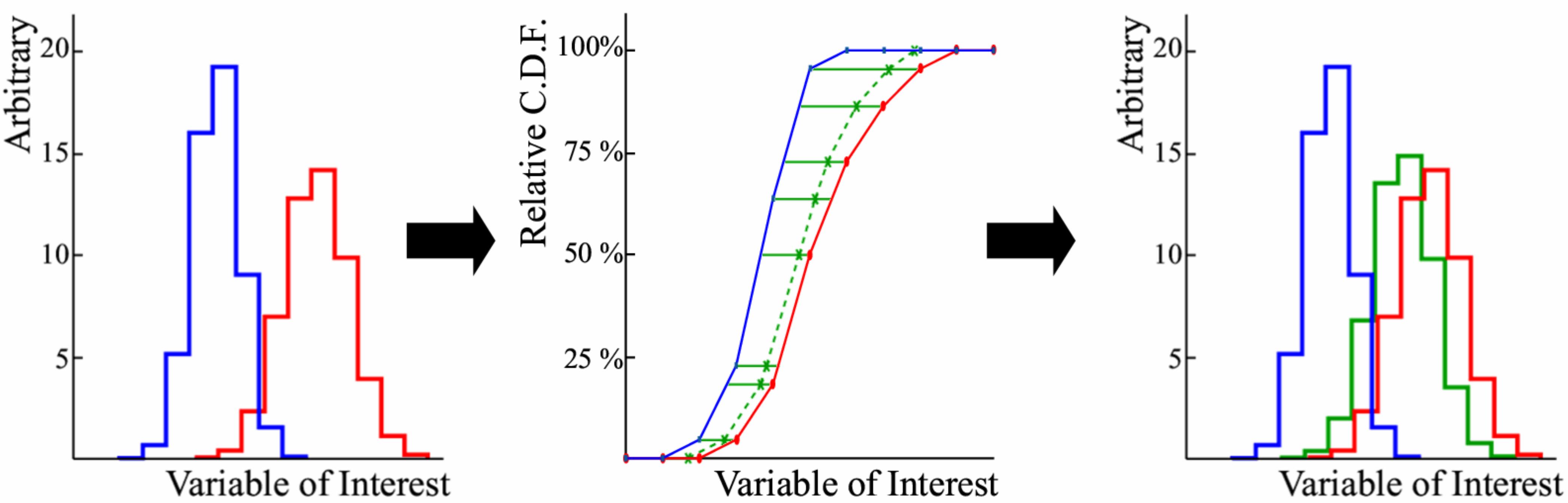
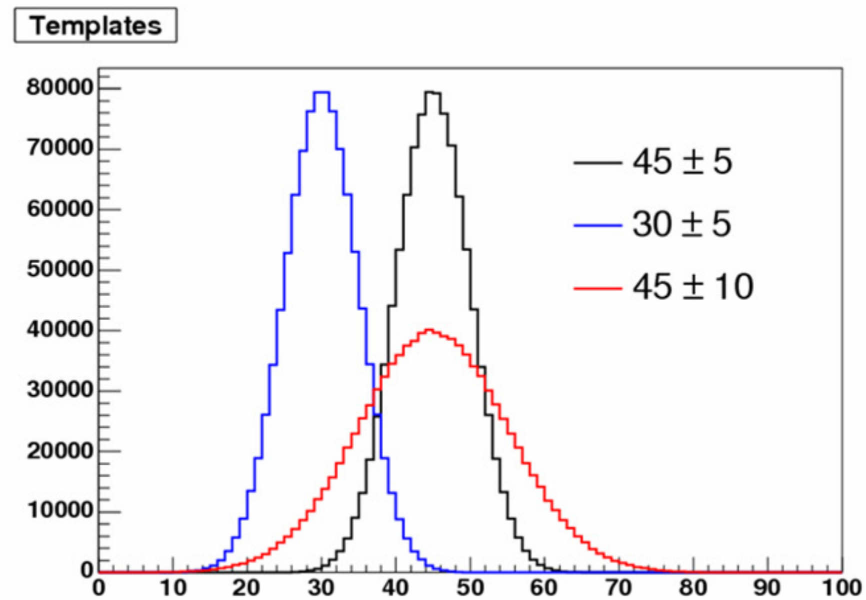
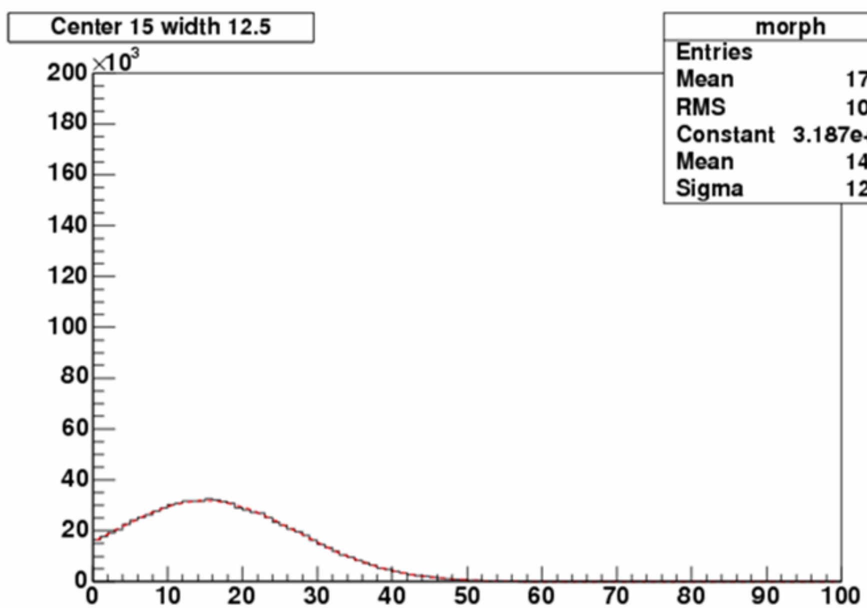


Does Morphing Work?

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





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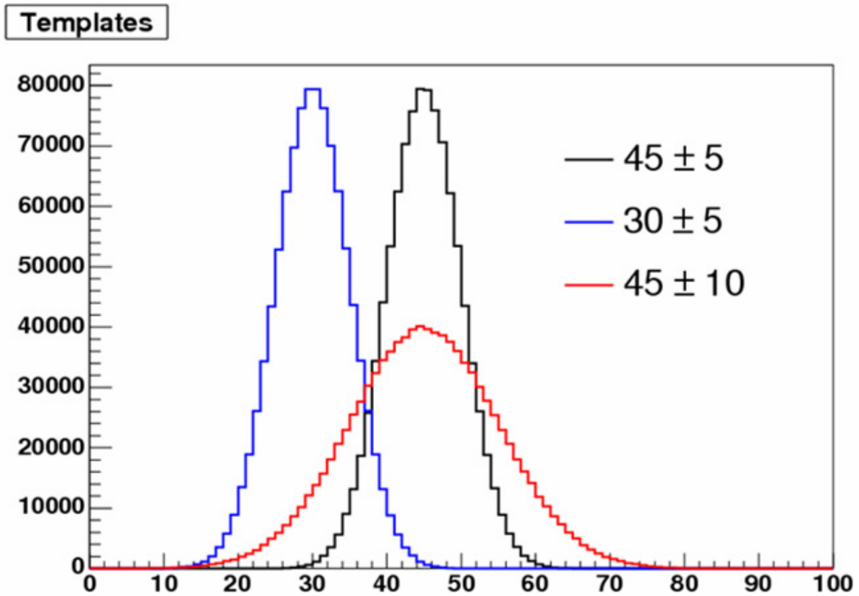
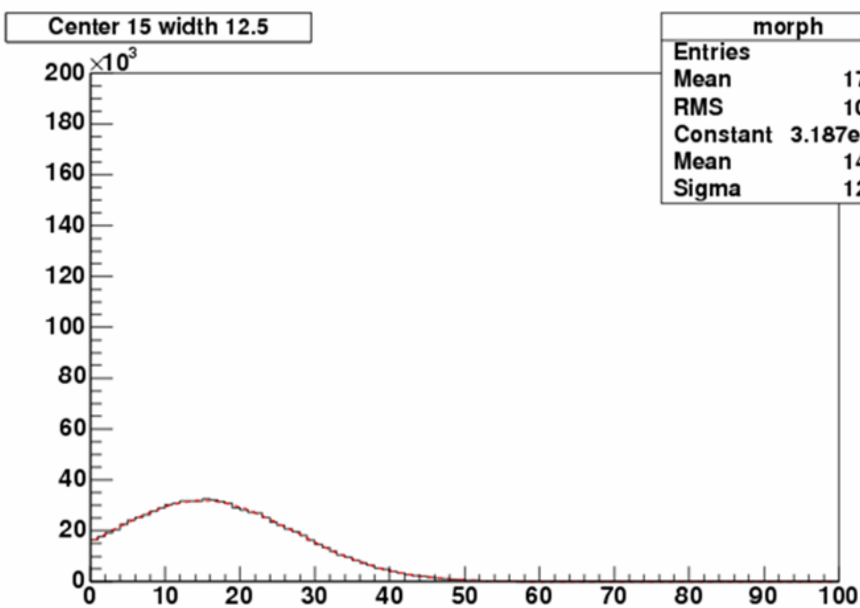
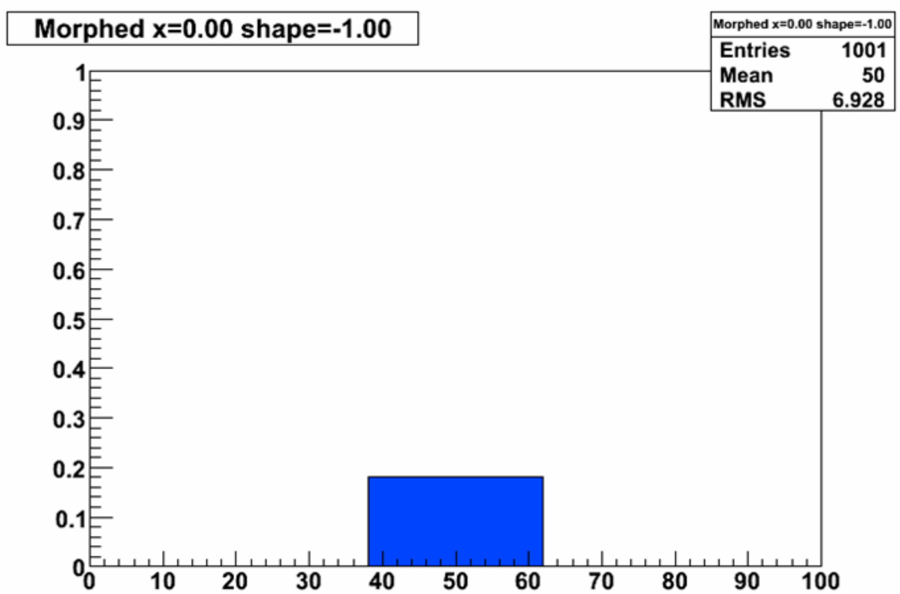


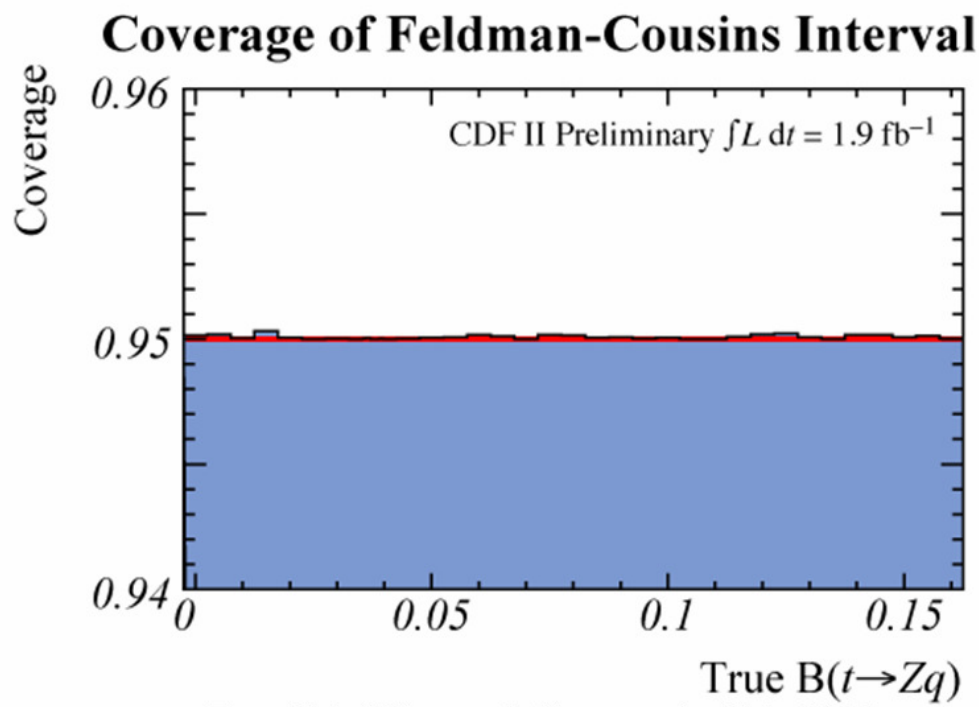




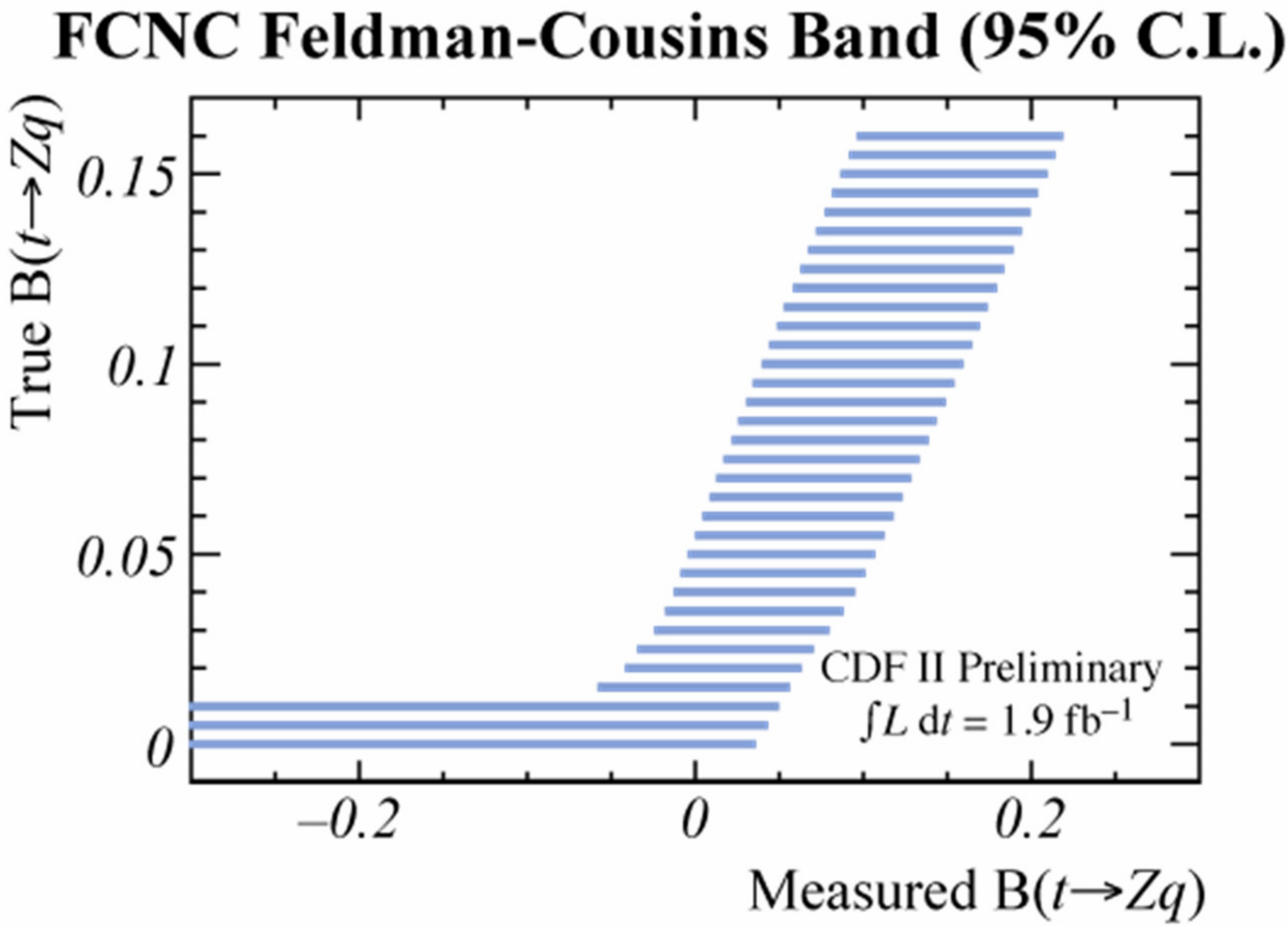
Feldman-Cousins in Five Minutes

- 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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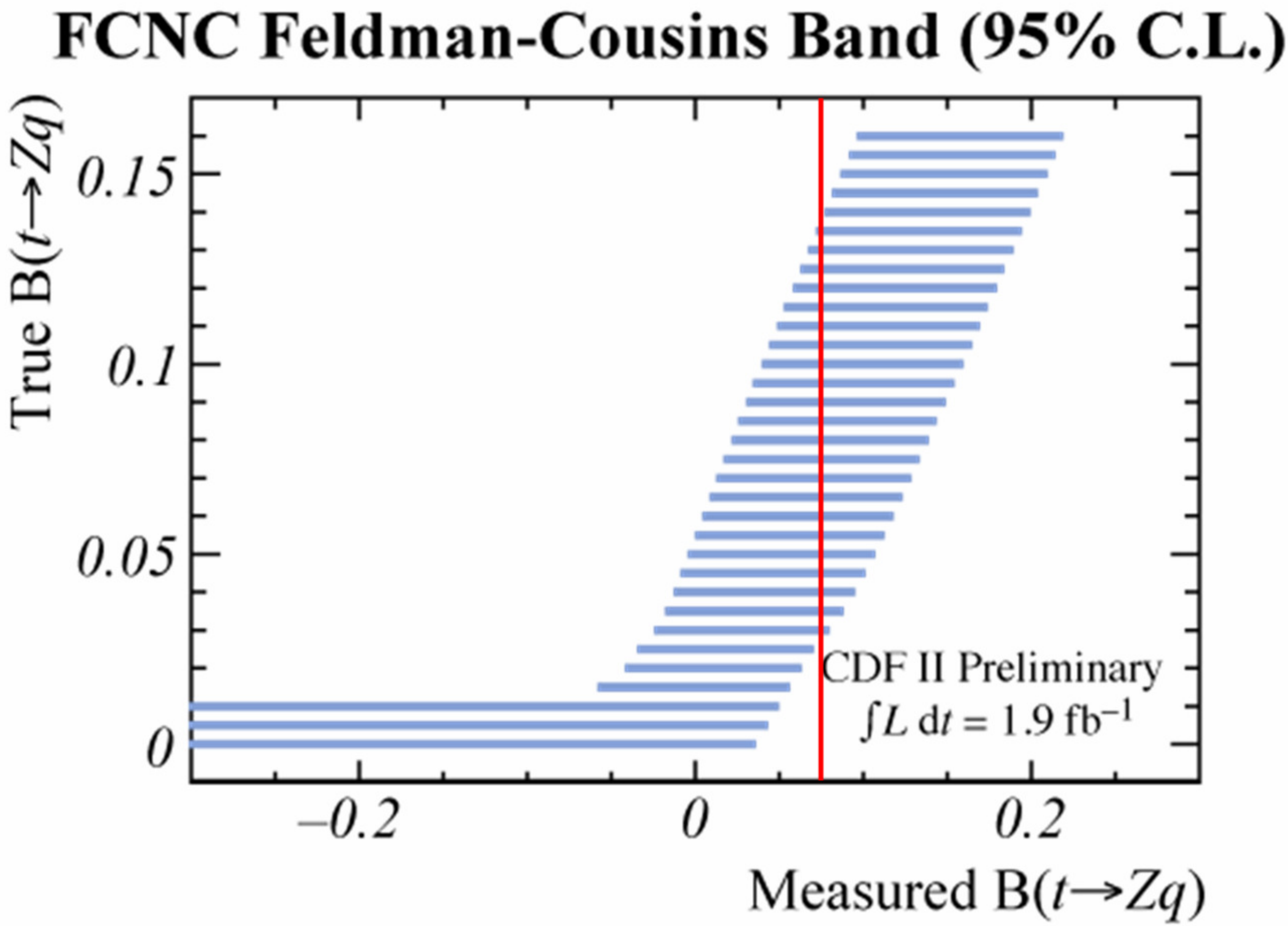

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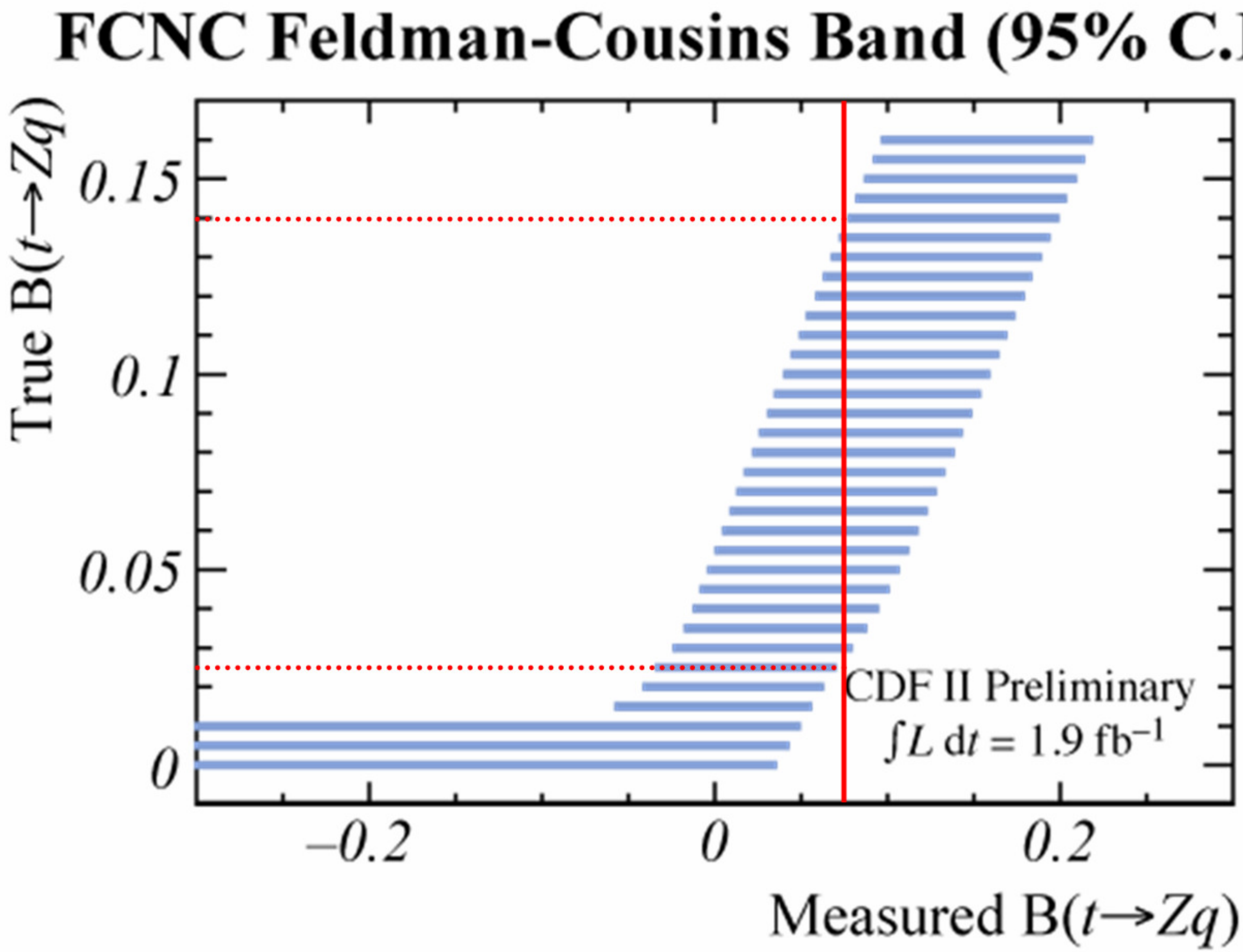

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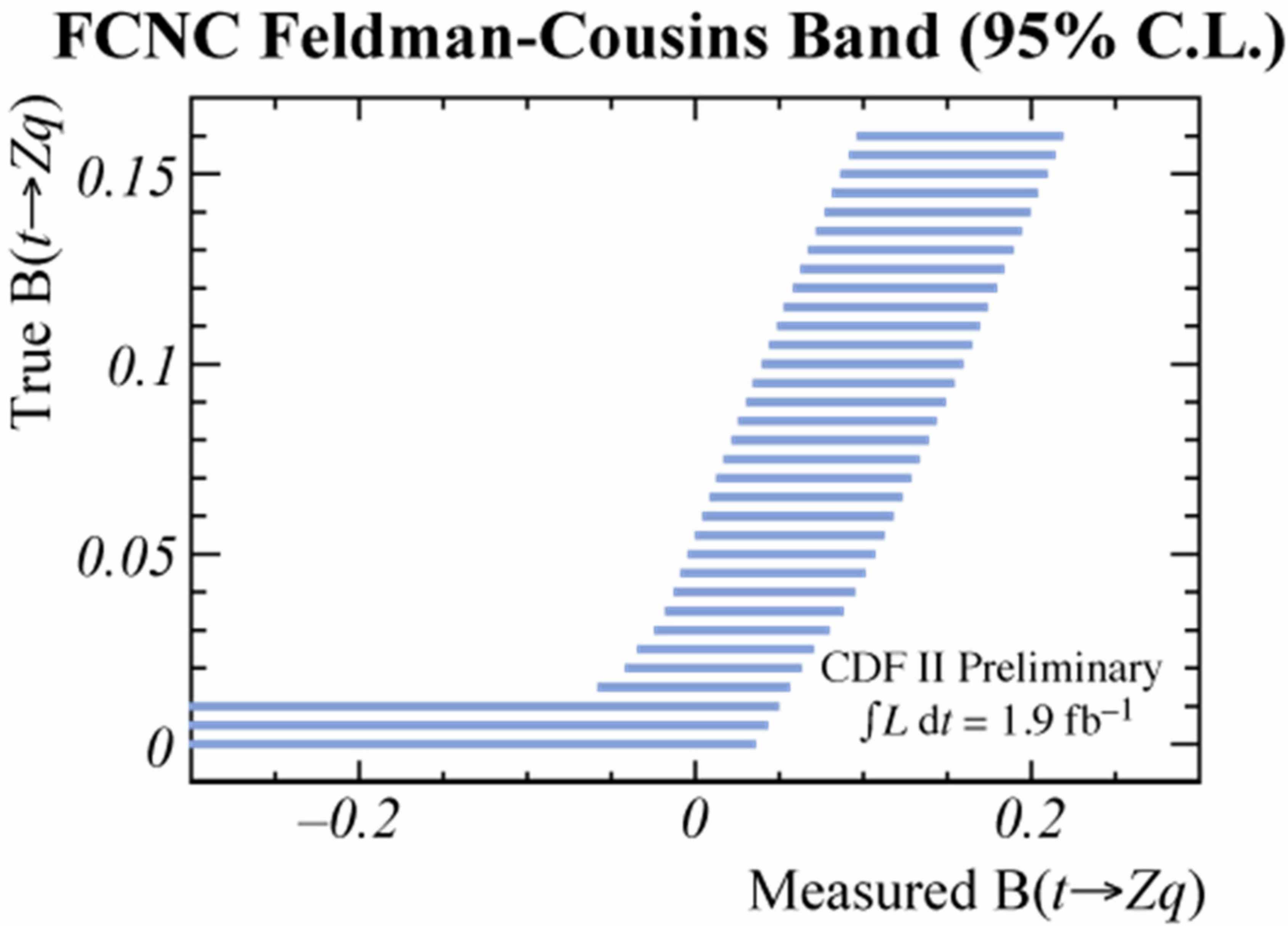

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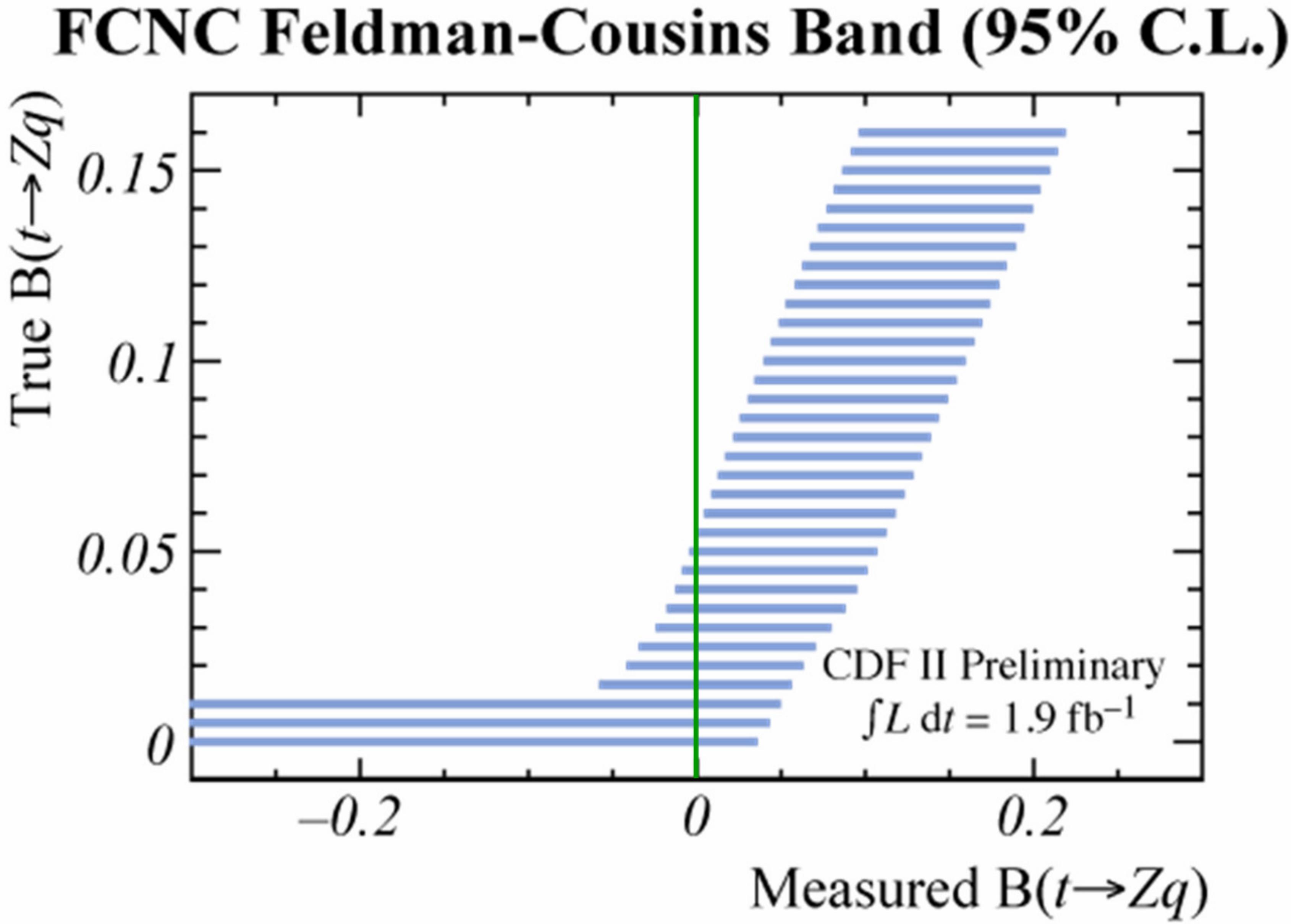

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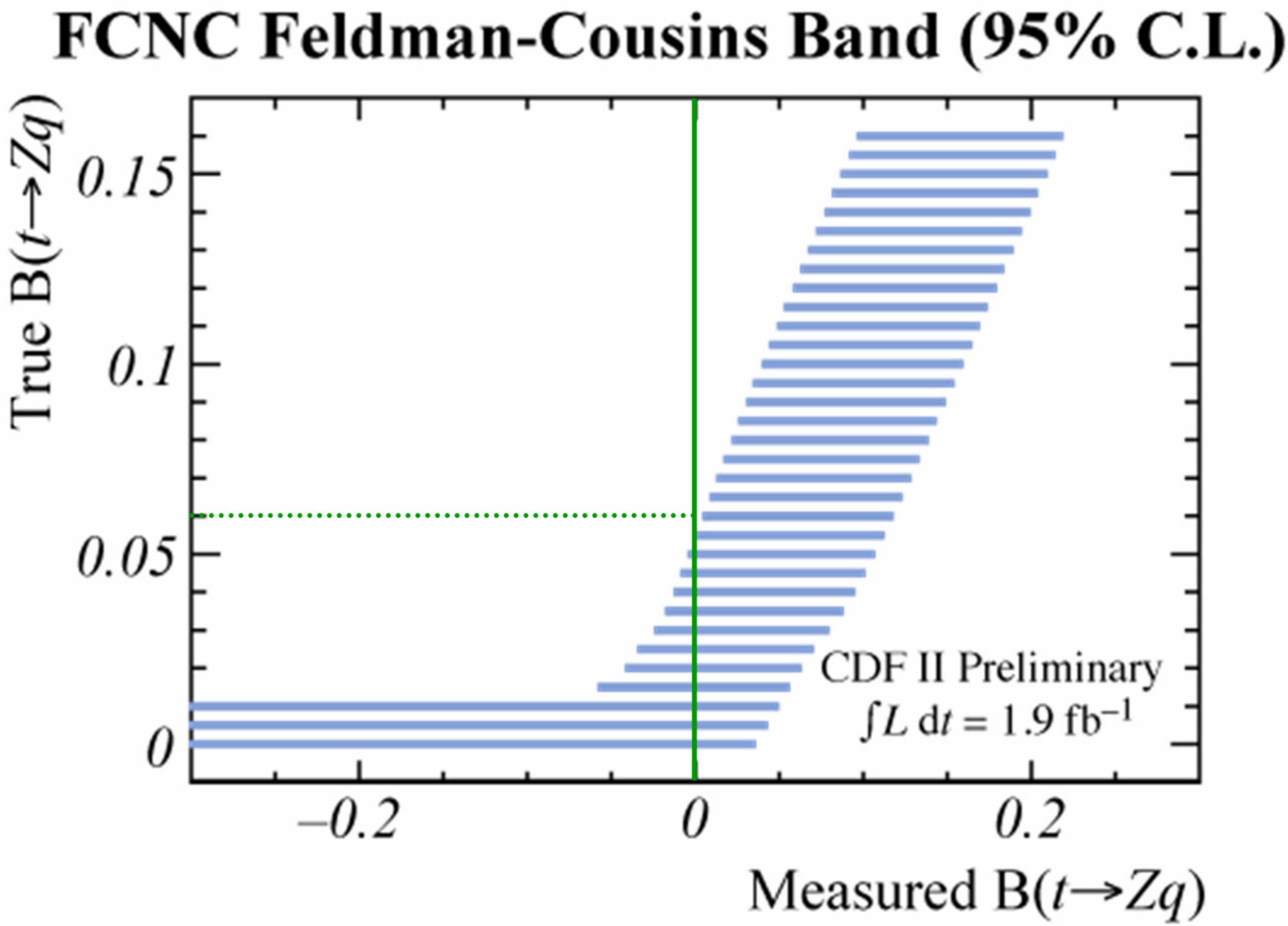
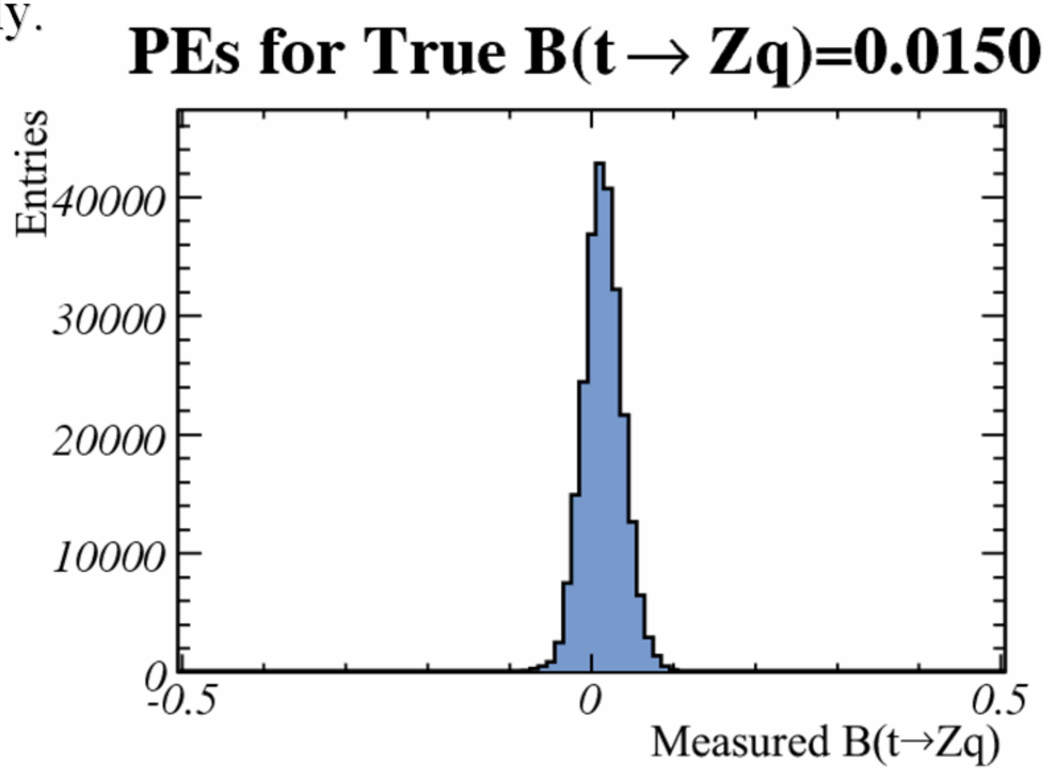


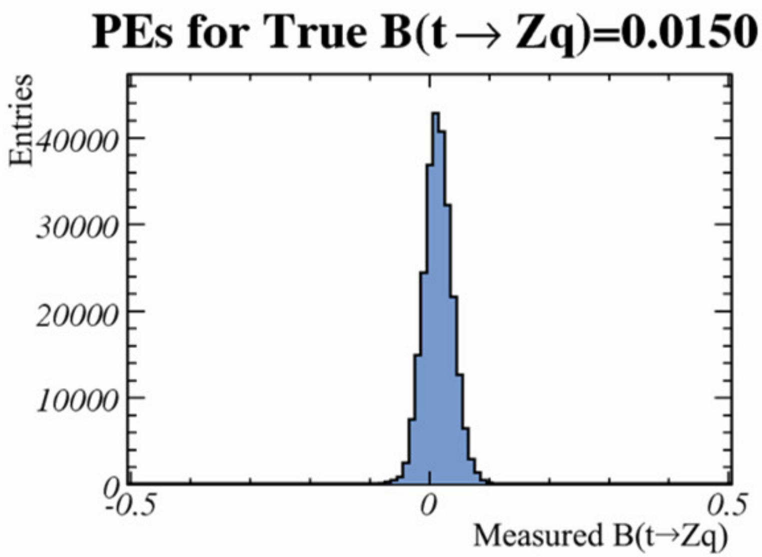
Pseudo-Experiments (PEs)

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!



FC Band Construction In A Nutshell



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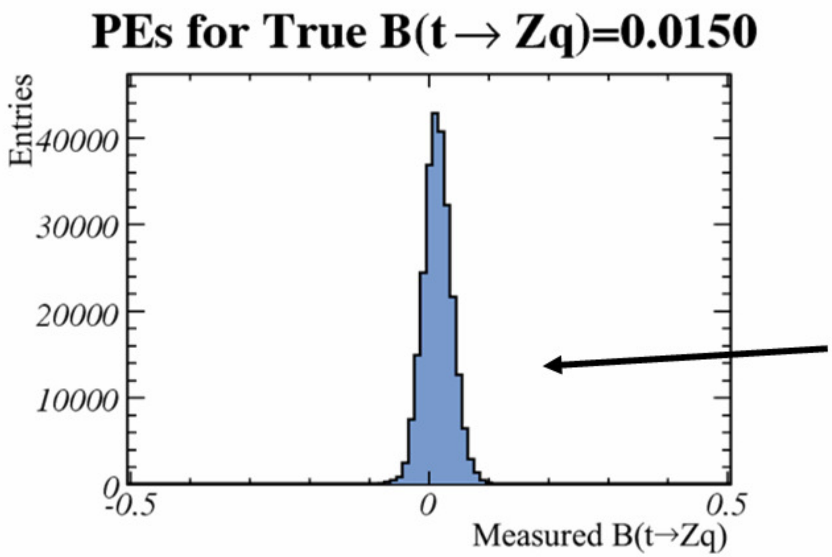

PEs generated with all statistical and systematic uncertainties.

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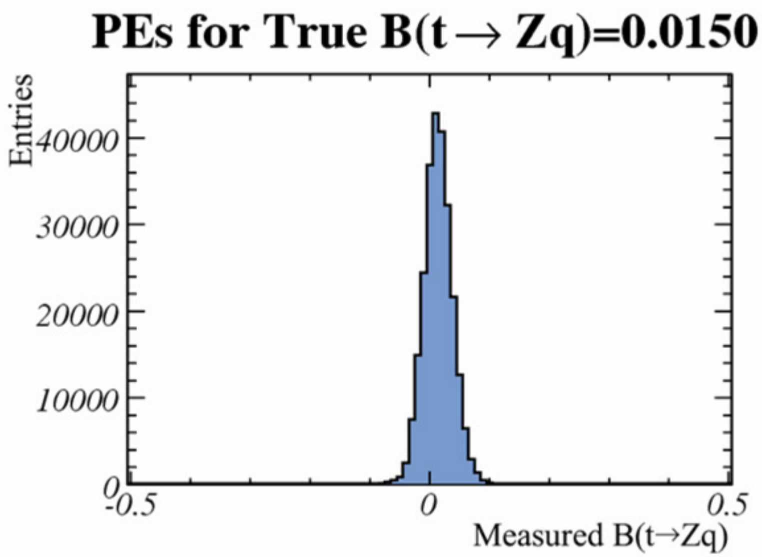

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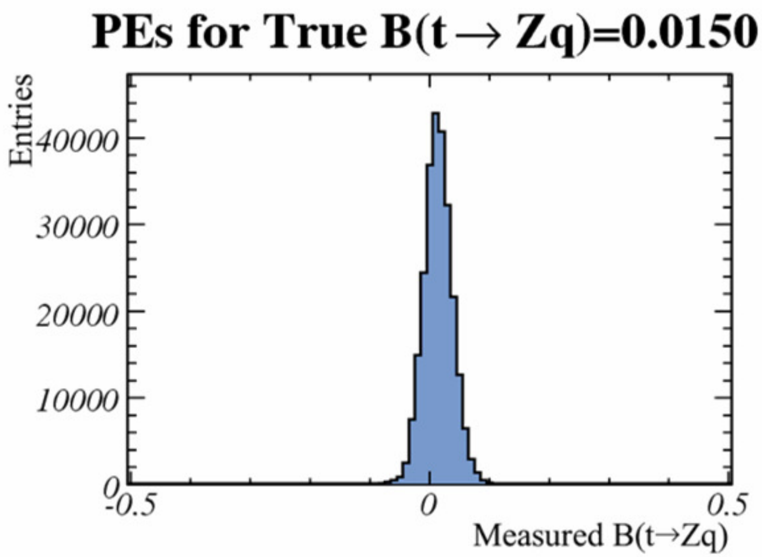
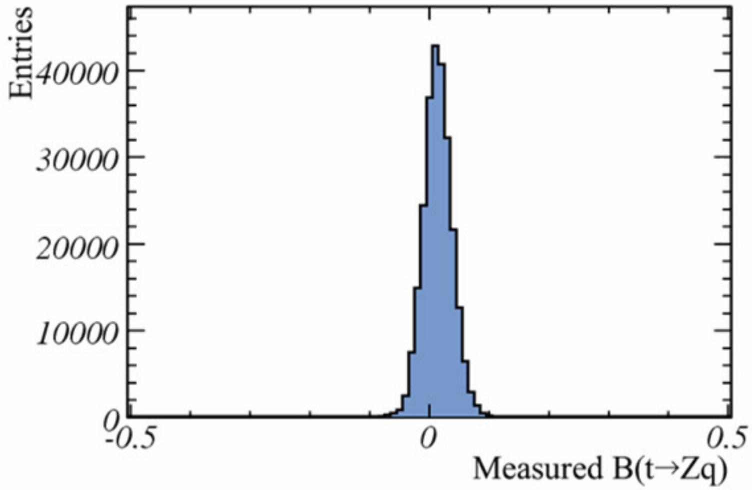


- Use *Likelihood Ratio Ordering Principle*:

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

FC Band Construction In A Nutshell

PEs for True B(t → Zq)=0.0150



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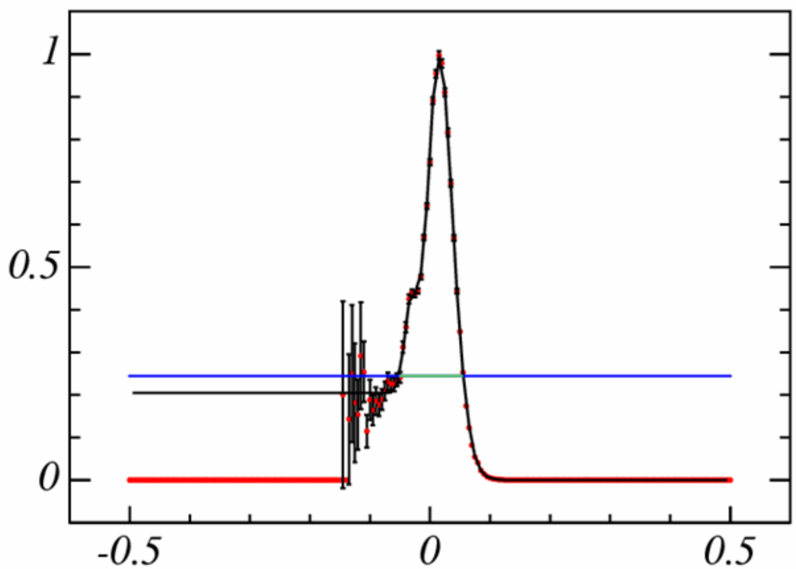
Likelihood Ratio for B(t → Zq) = 0.0150



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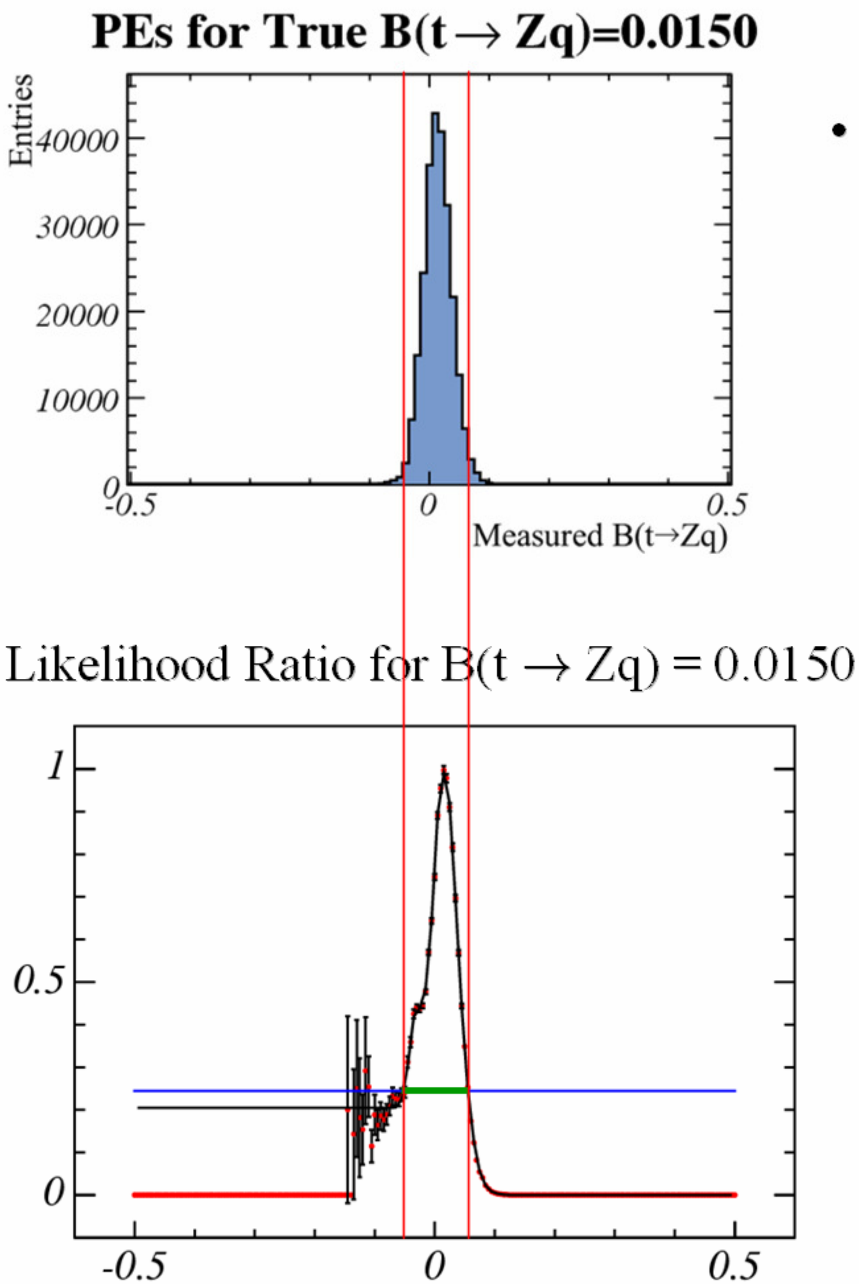

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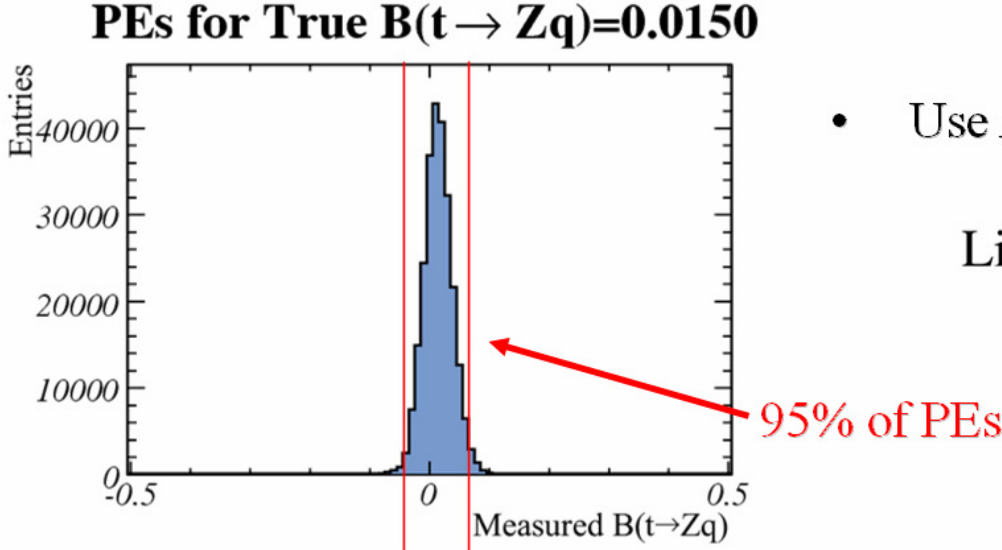

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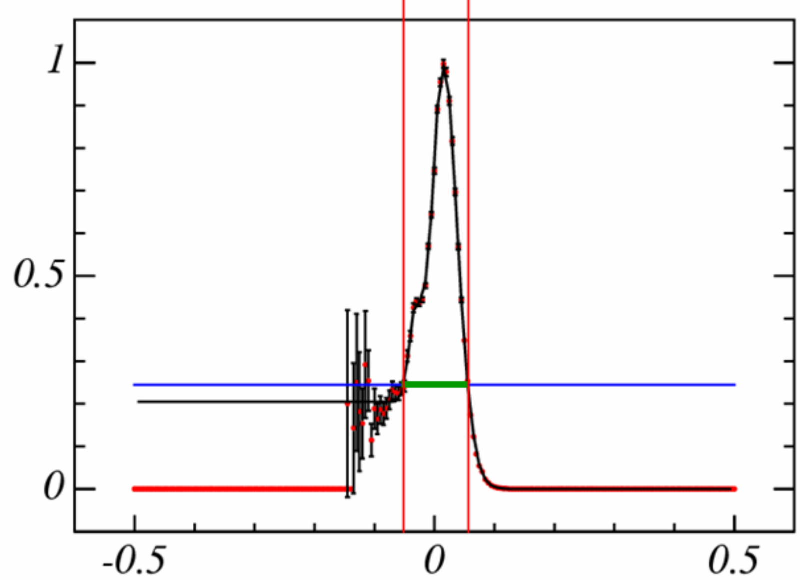

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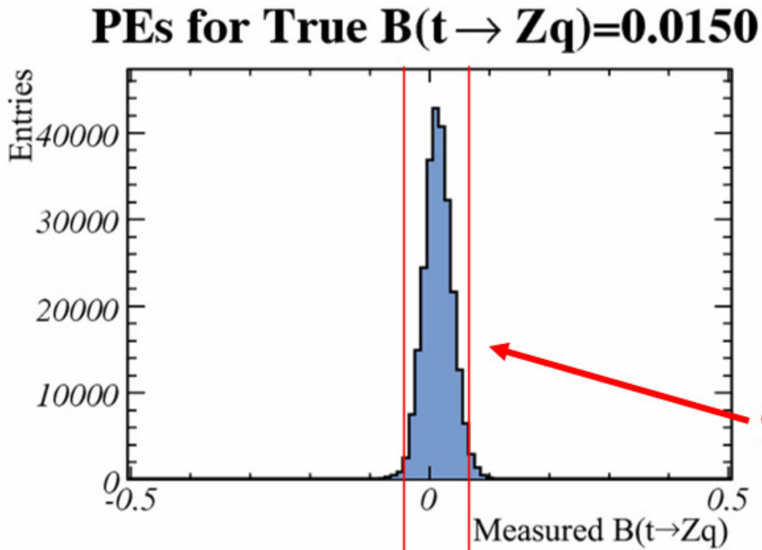

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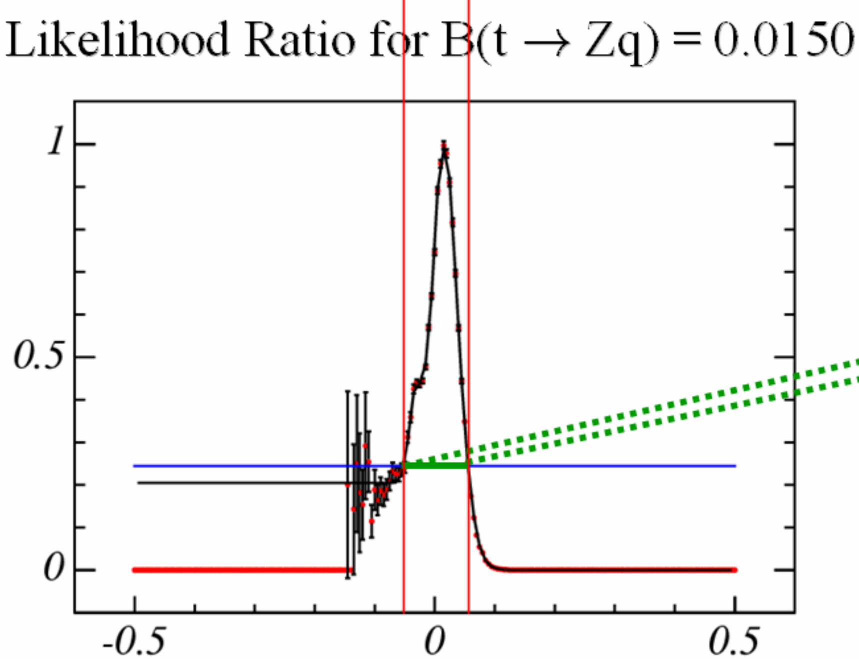
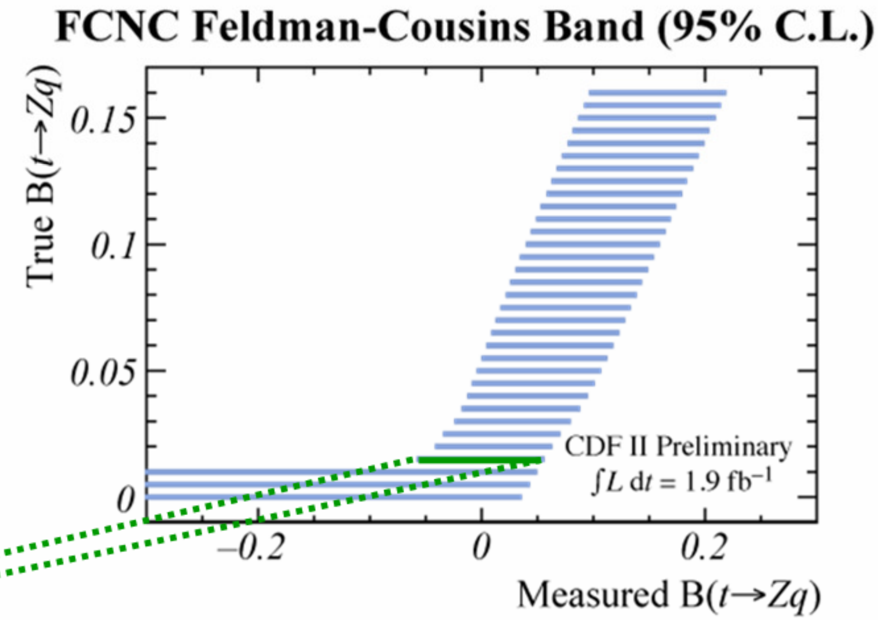
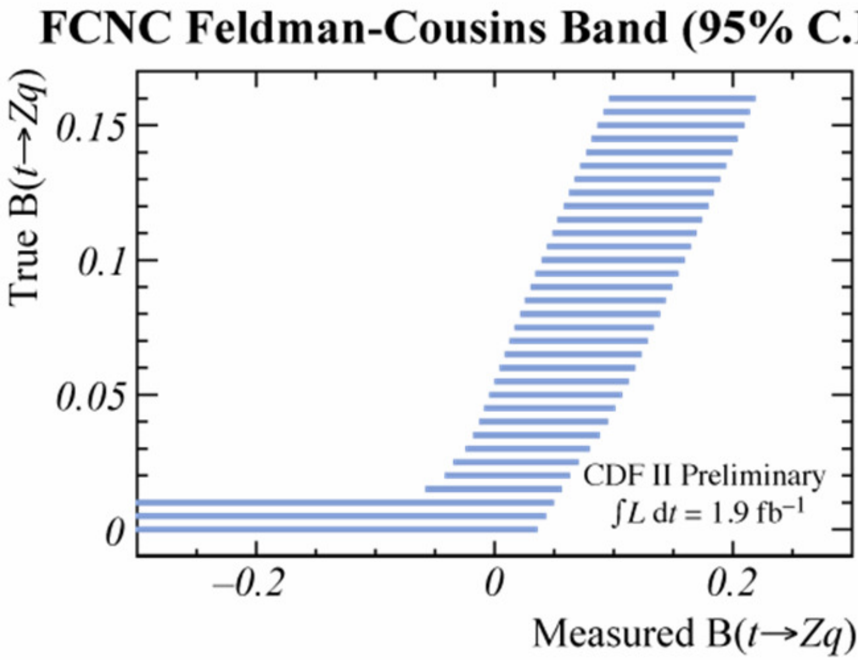




Expected Limit



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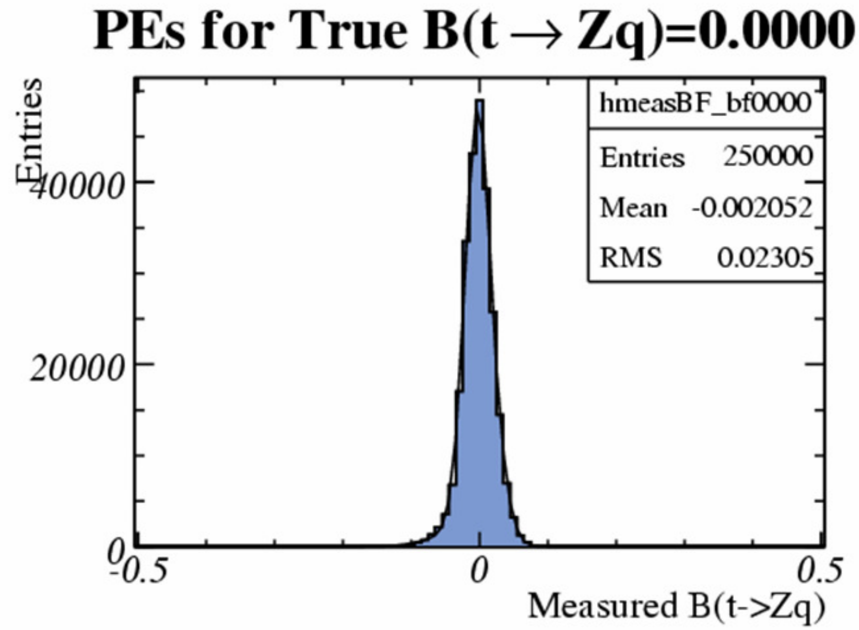

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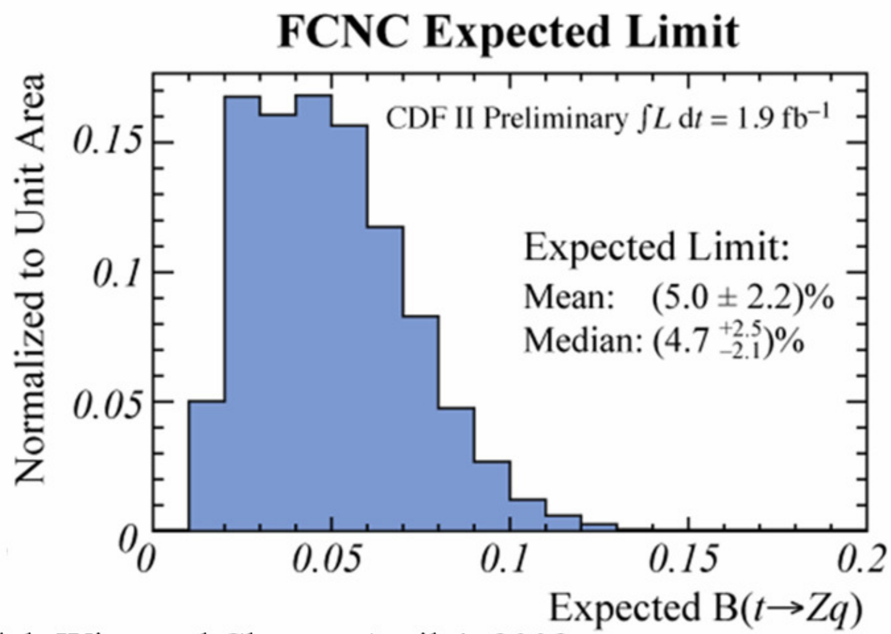
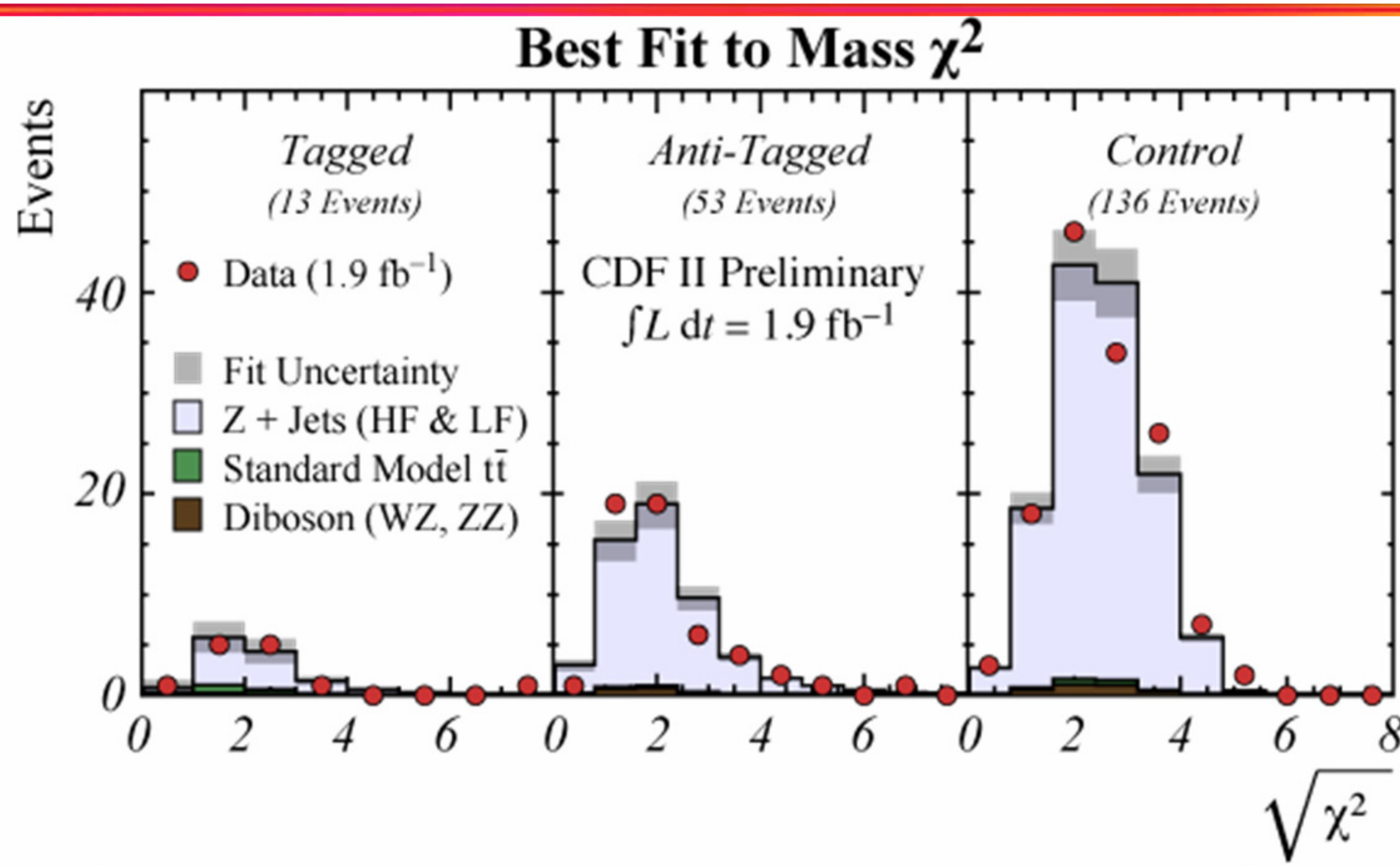


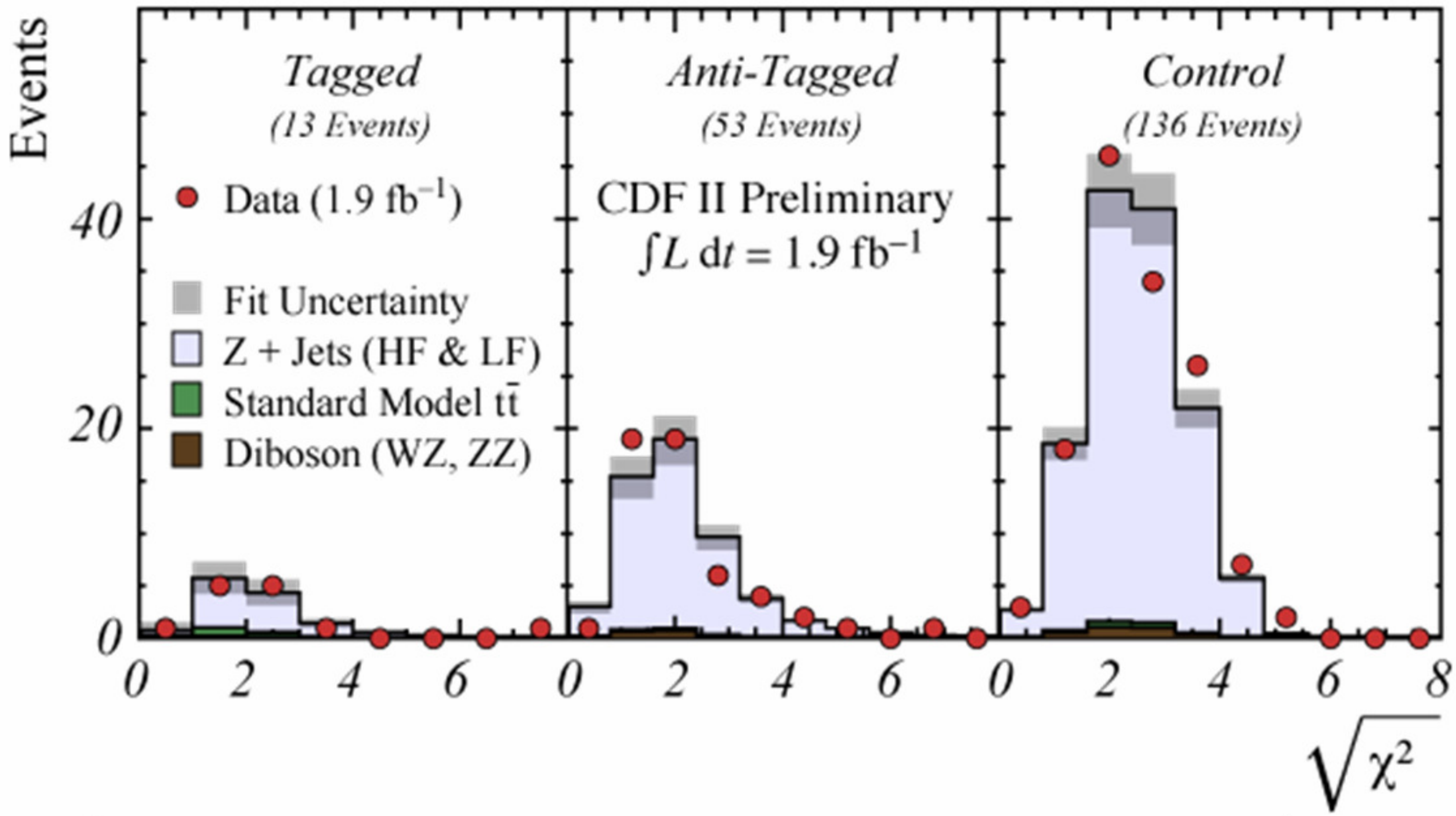
The Fit to the Data



Fit Parameter ($\int \mathscr{L}\,dt = 1.9\text{fb}^{-1}$)	**Value**		
Branching Fraction, $\mathscr{B}(t \to Zq)$ (%)	-1.49	$\pm$	1.52
Z+Jets Events in Control Region, Z_{control}	129.0	$\pm$	11.1
Ratio Signal/Control Region, $\mathscr{R}_{\text{sig}}$	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

Best Fit to Mass χ^2



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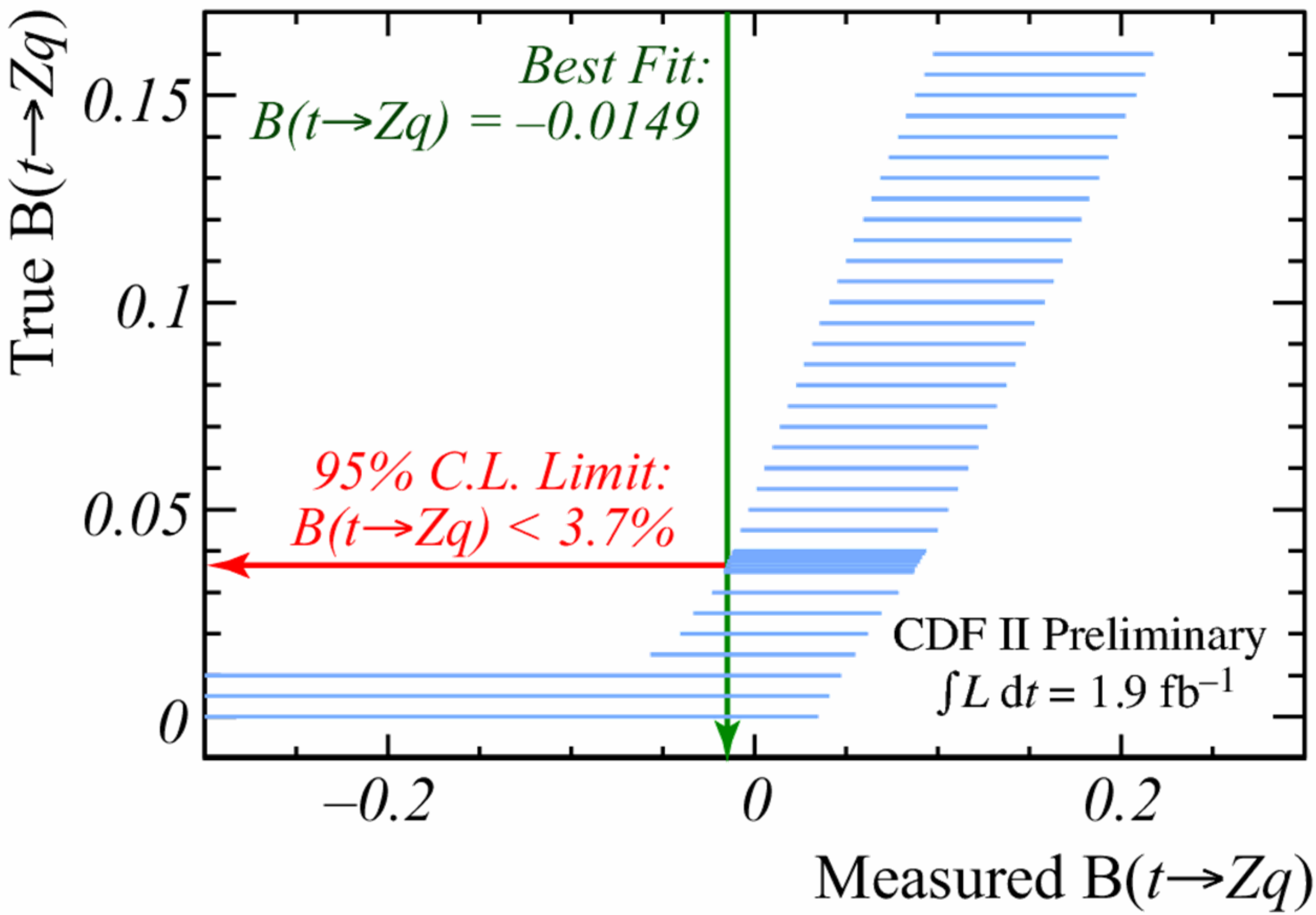
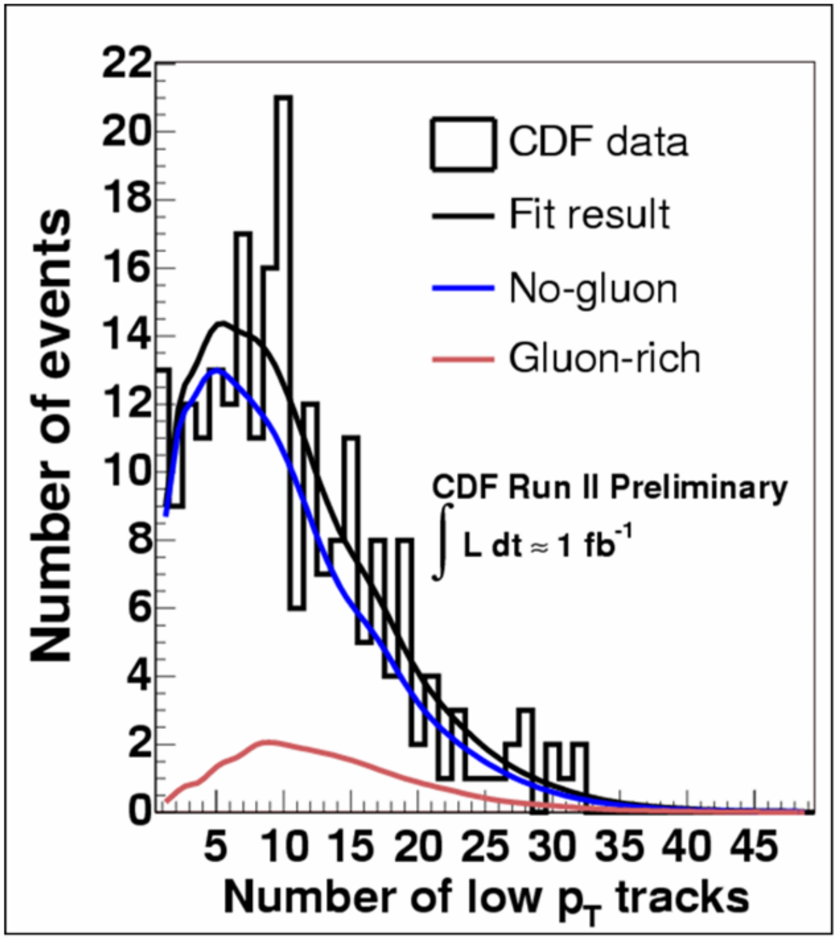
F.C. 95% C.L. Limit

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



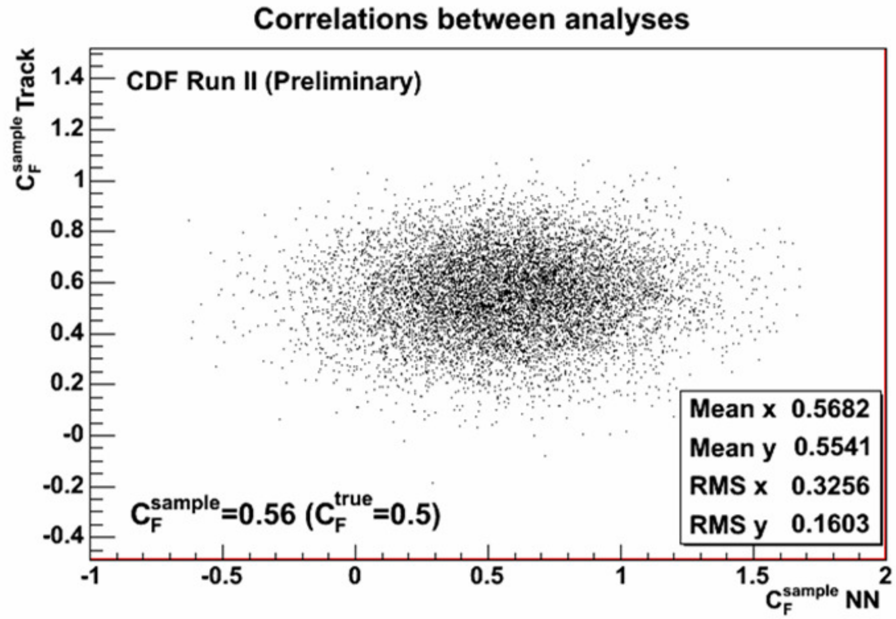
Top Pair Production Mechanism

- Theory predicts 15% glue-glue and 85% quark-antiquark production.
- Two different approaches:
  1. Use low p_T track multiplicities that are **not** from the hard scatter.
     - Uses data to describe qq versus gg
       - QCD Dijets for gg
       - W + 0 jets for qq
  2. Train Neural Net
     - Use both production and decay kinematic variables



Top Pair Production Mechanism, cont.

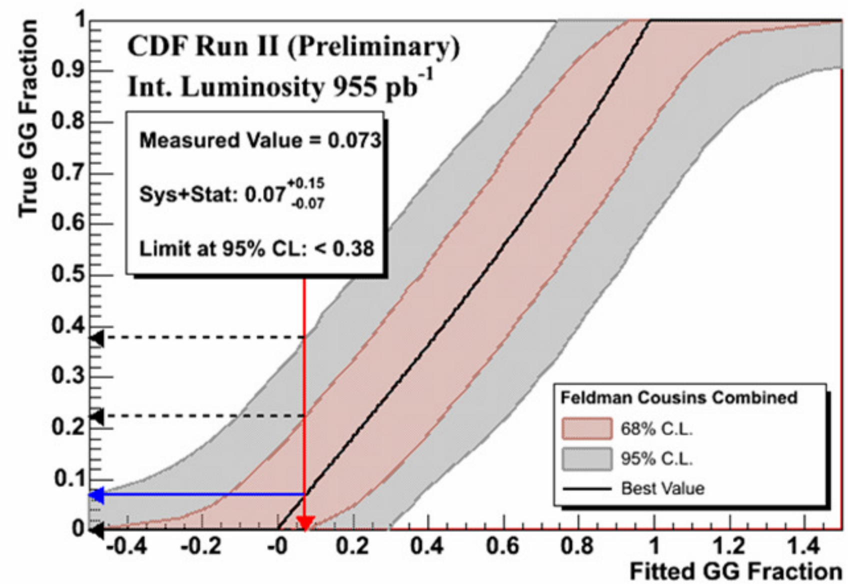
- Combine two methods.
  - Two analyses are **very** uncorrelated with each other!



- Result:

$$\frac{\sigma(gg \to t\bar{t})}{\sigma(p\bar{p} \to t\bar{t})} = 7^{+15}_{-7}\%$$

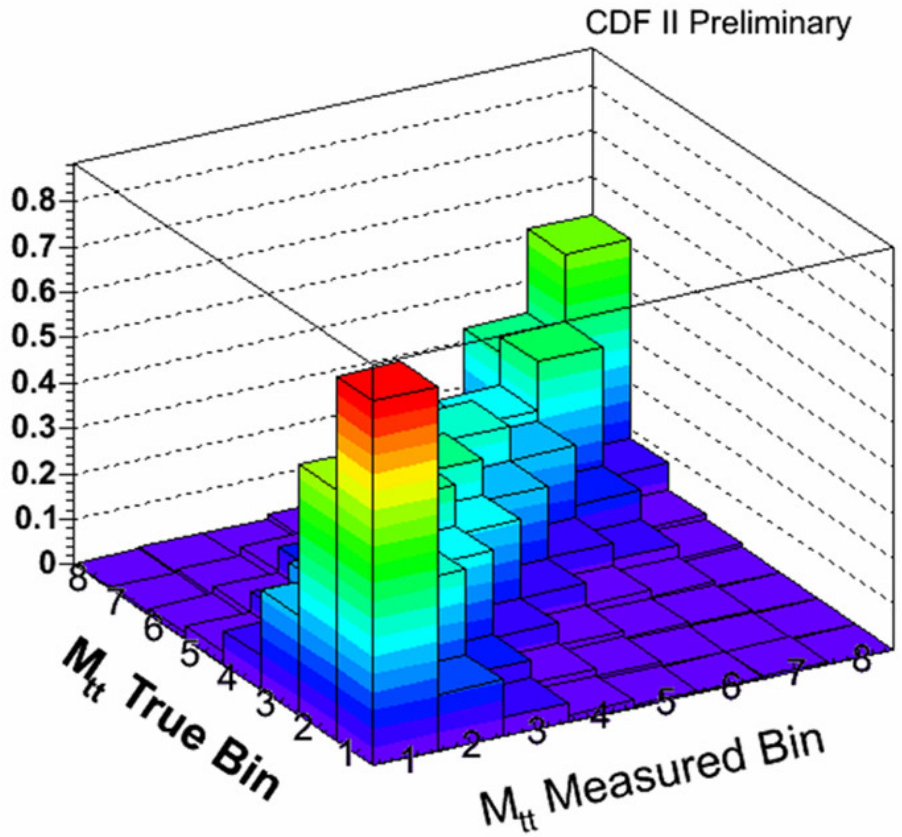
$$\frac{\sigma(gg \to t\bar{t})}{\sigma(p\bar{p} \to t\bar{t})} < 38\% \text{ at the 95\% C.L.}$$

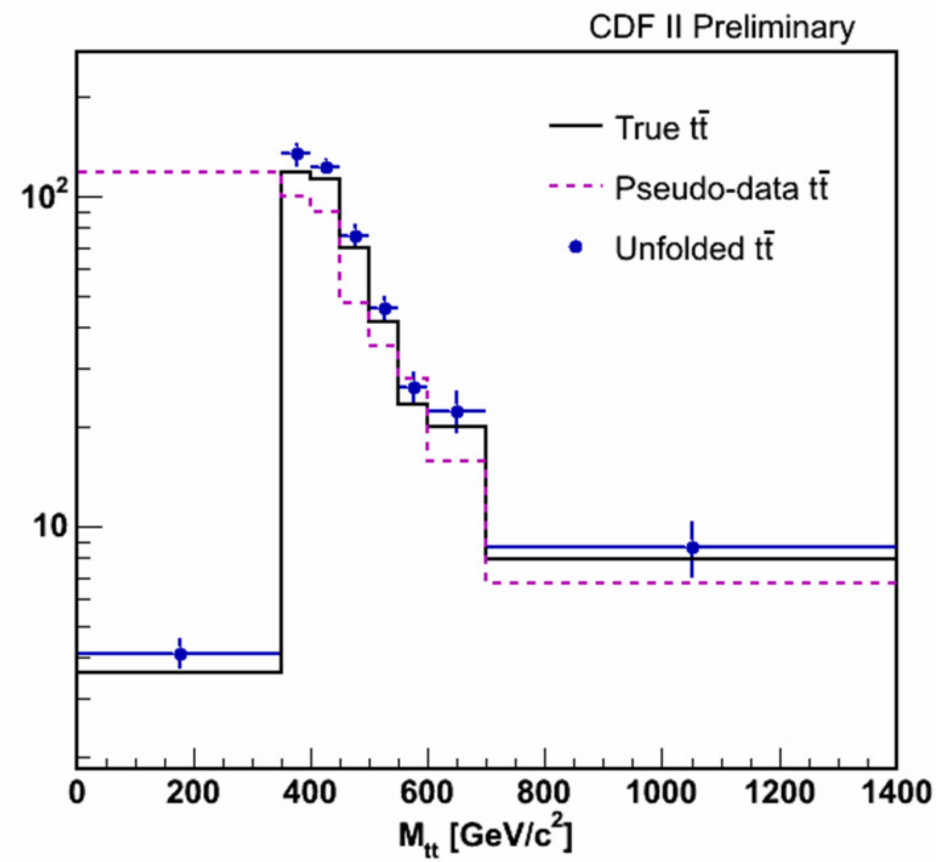


$$\text{Theory}: \frac{\sigma(gg \to t\bar{t})}{\sigma(p\bar{p} \to t\bar{t})} = 15\% \pm 10\%$$

dσ/dM$_{tt}$, cont.

- Regularized unfolding.





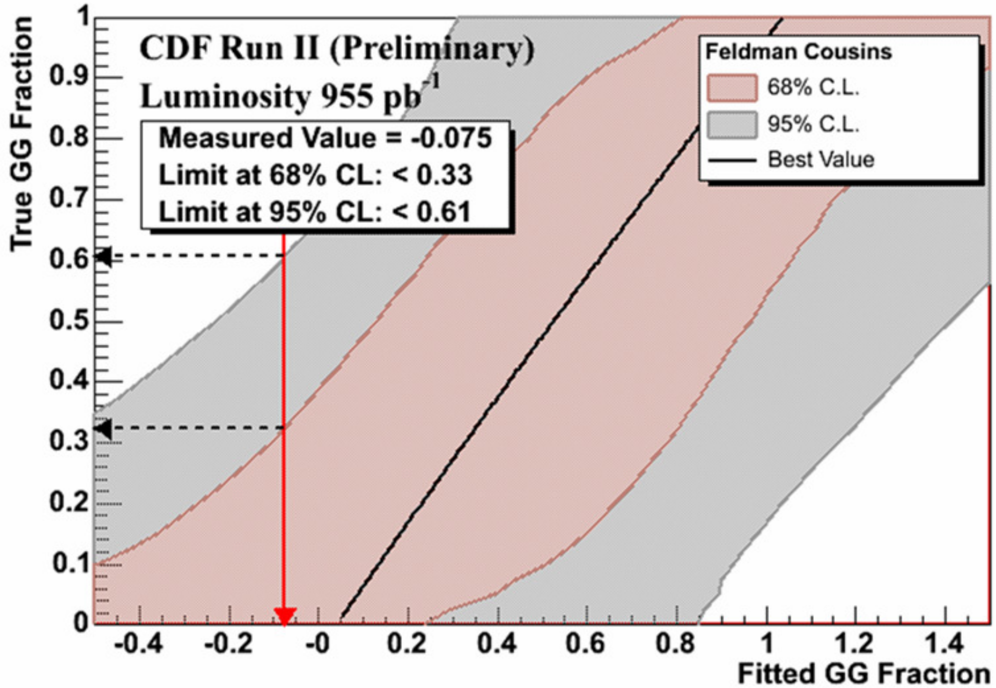
Top Pair Production Mechanism

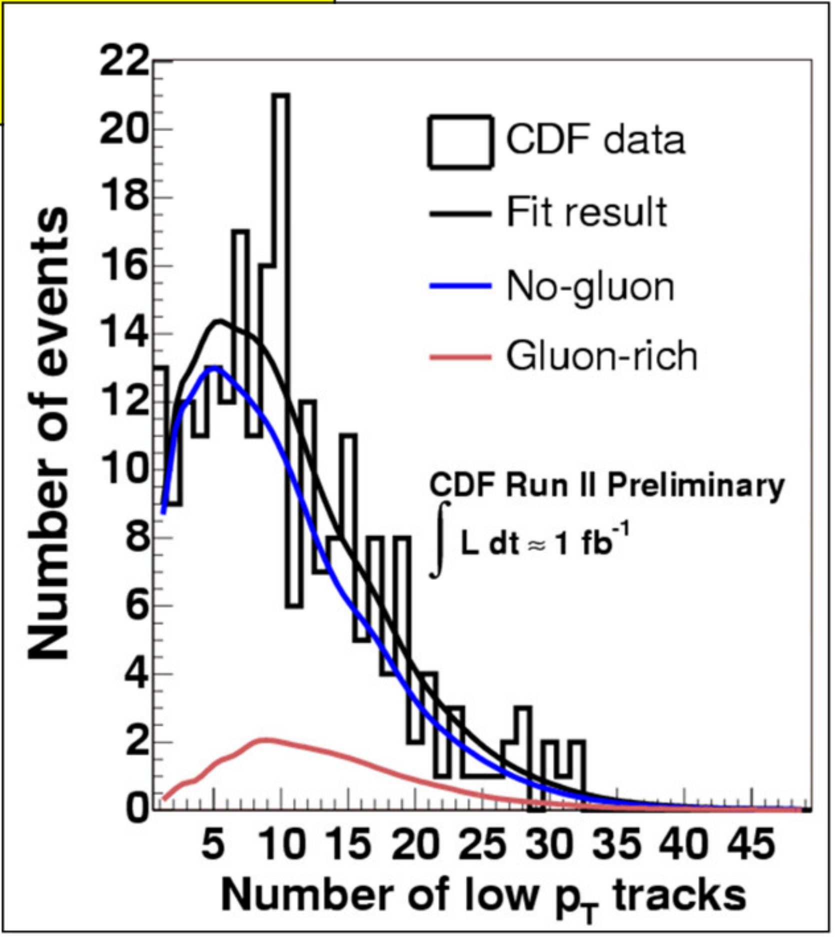
$$\frac{\sigma(gg \to t\bar{t})}{\sigma(p\bar{p} \to t\bar{t})} = 0.07 \pm 0.14\ \text{(stat)} \pm 0.07\ \text{(sys) - Track Density}$$

$$\frac{\sigma(gg \to t\bar{t})}{\sigma(p\bar{p} \to t\bar{t})} < 0.33 \text{ at } 68\% \text{ C.L. - NN}$$

$$\frac{\sigma(gg \to t\bar{t})}{\sigma(p\bar{p} \to t\bar{t})} < 0.61 \text{ at } 95\% \text{ C.L.}$$

$$\text{Theory}: \frac{\sigma(gg \to t\bar{t})}{\sigma(p\bar{p} \to t\bar{t})} = 15\% \pm 10\%$$





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^-
    - SppS (CERN): p 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

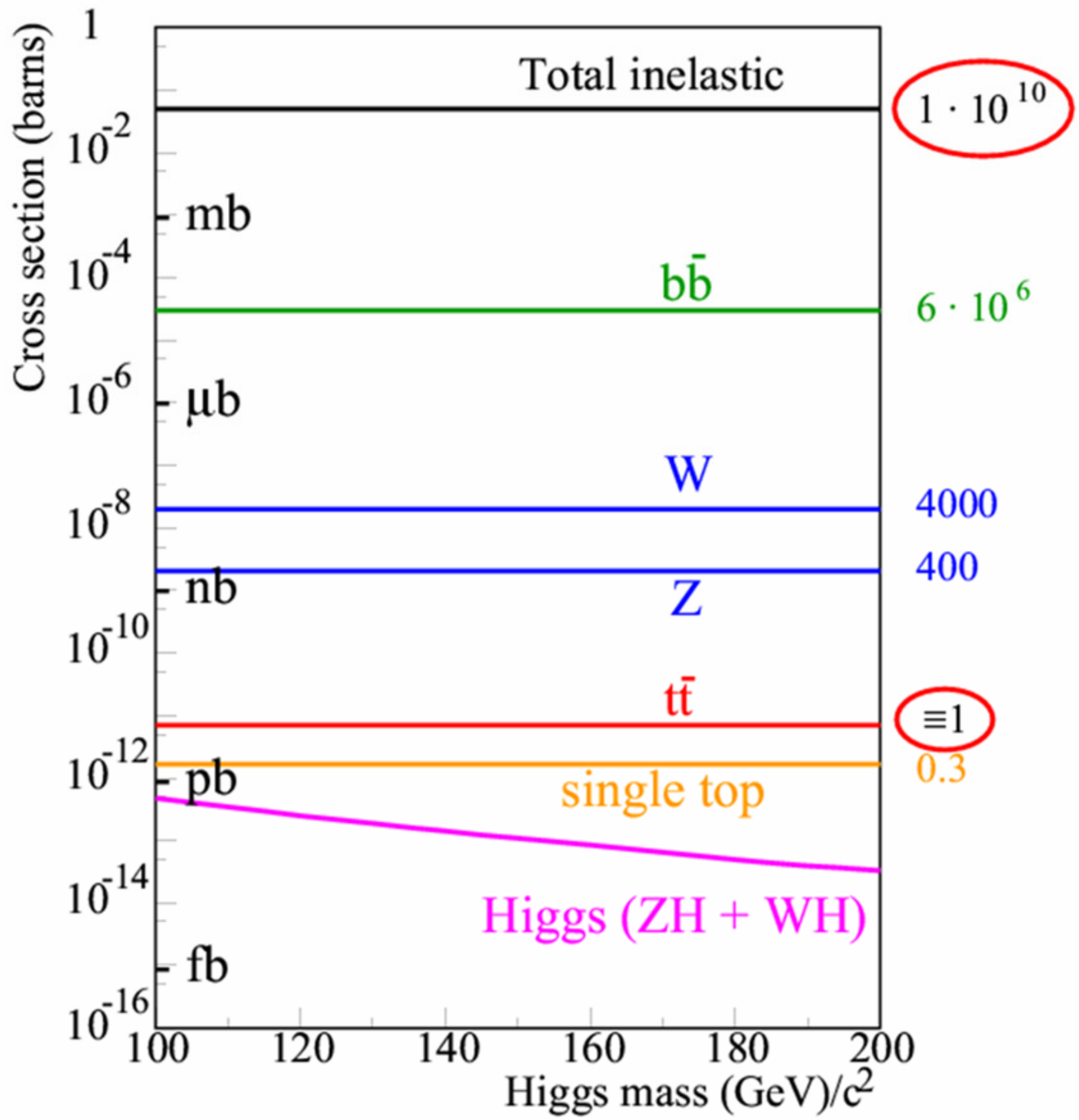
For those not intimately familiar with Tevatron high p_T Physics:

Top:

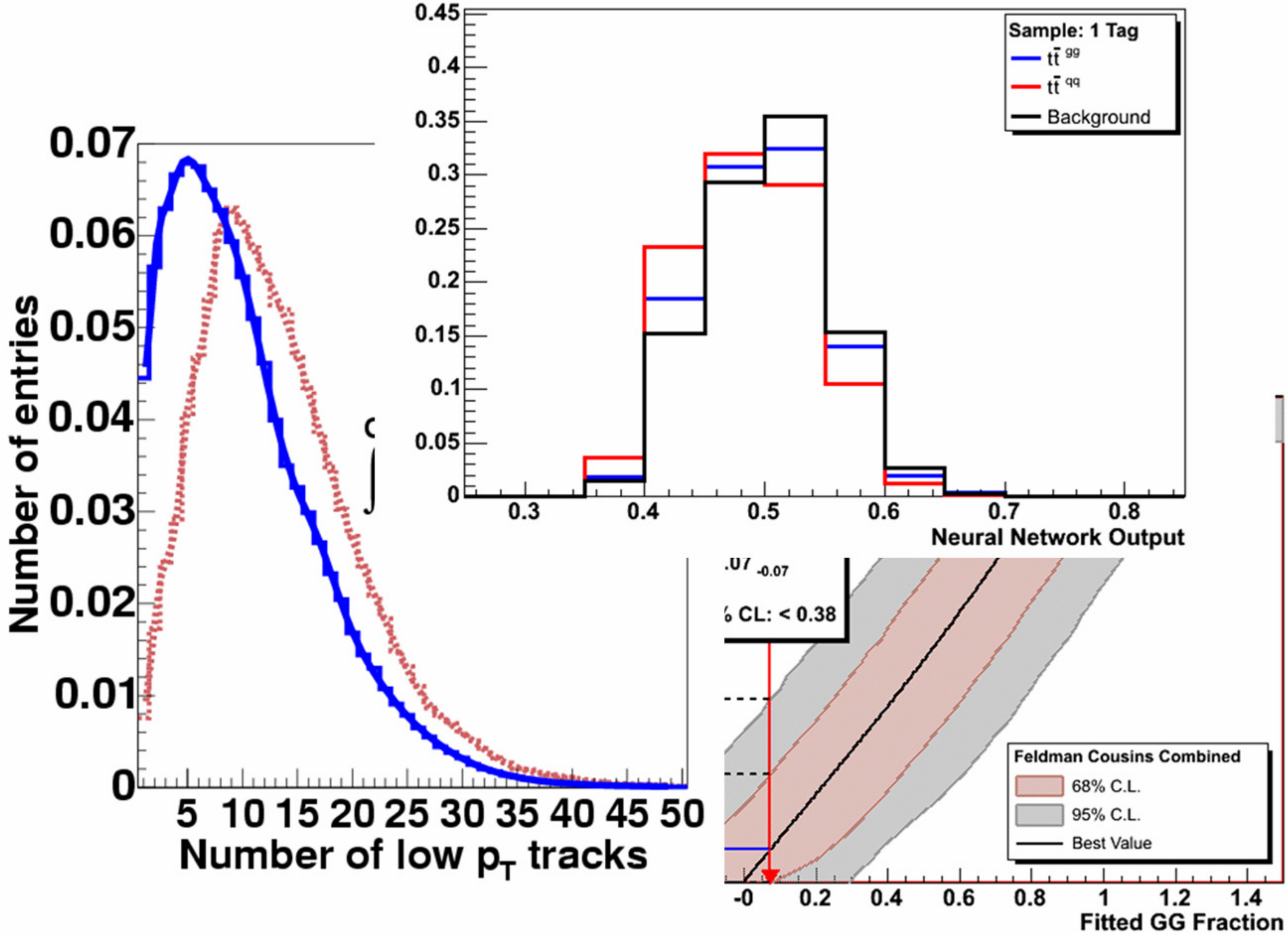
1 in 10 Billion

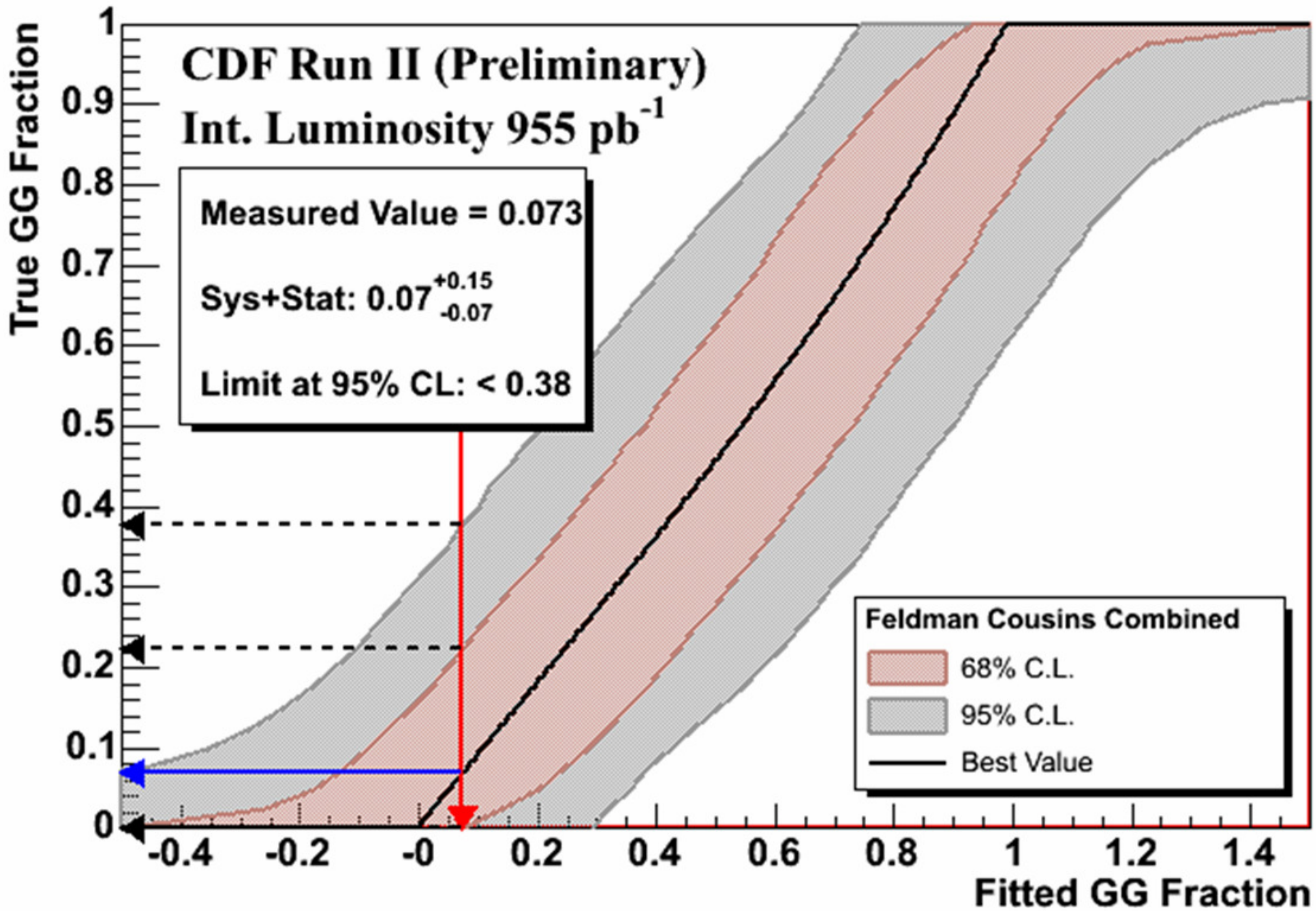
Reducing and understanding backgrounds is the key.

Cross Sections at √s = 1.96 TeV



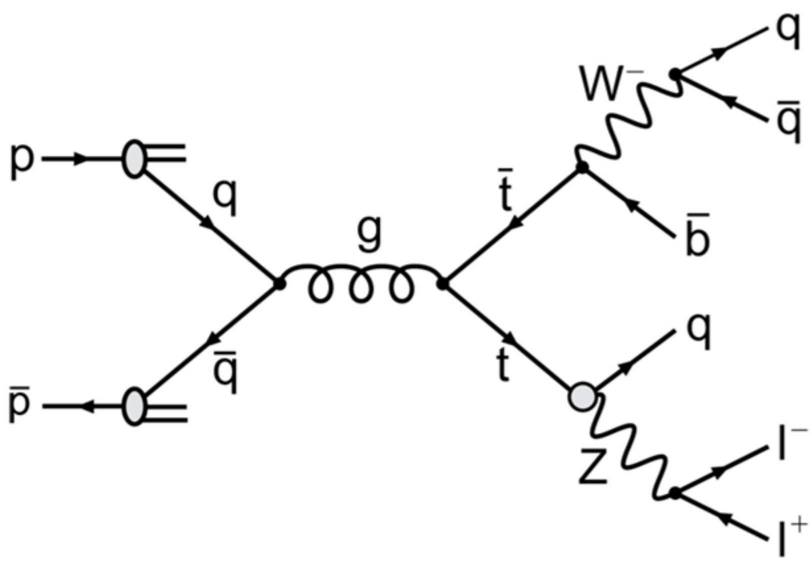
Top Production





CDF Run II (Preliminary)
Int. Luminosity 955 pb-1
Measured Value = 0.073
Sys+Stat: 0.07 +0.15 -0.07
Limit at 95% CL: < 0.38
Feldman Cousins Combined
68% C.L.
95% C.L.
Best Value
True GG Fraction
Fitted GG Fraction
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.4
-0.2
-0
0.2
0.4
0.6
0.8
1
1.2
1.4

Search for the Top FCNC Decay $t \rightarrow Zq$



$$\chi^2 = \left(\frac{m_{W,\text{rec}} - m_{W,\text{PDG}}}{\sigma_W}\right)^2 + \left(\frac{m_{t\rightarrow Wb,\text{rec}} - m_t}{\sigma_{t\rightarrow Wb}}\right)^2 + \left(\frac{m_{t\rightarrow Zq,\text{rec}} - m_t}{\sigma_{t\rightarrow Zq}}\right)^2$$