Forschungsseminar Physik
Universität Dortmund
July 8, 2008

Search for Flavor Changing Neutral Currents in Top Quark Decays at CDF

Ulrich Husemann
Deutsches Elektronen-Synchrotron

Outline of the Talk

What are Flavor Changing Neutral Currents?

The CDF Experiment at the Tevatron

Top Quark Physics at CDF

Search for FCNC in Top Quark Decays

Summary & Conclusions

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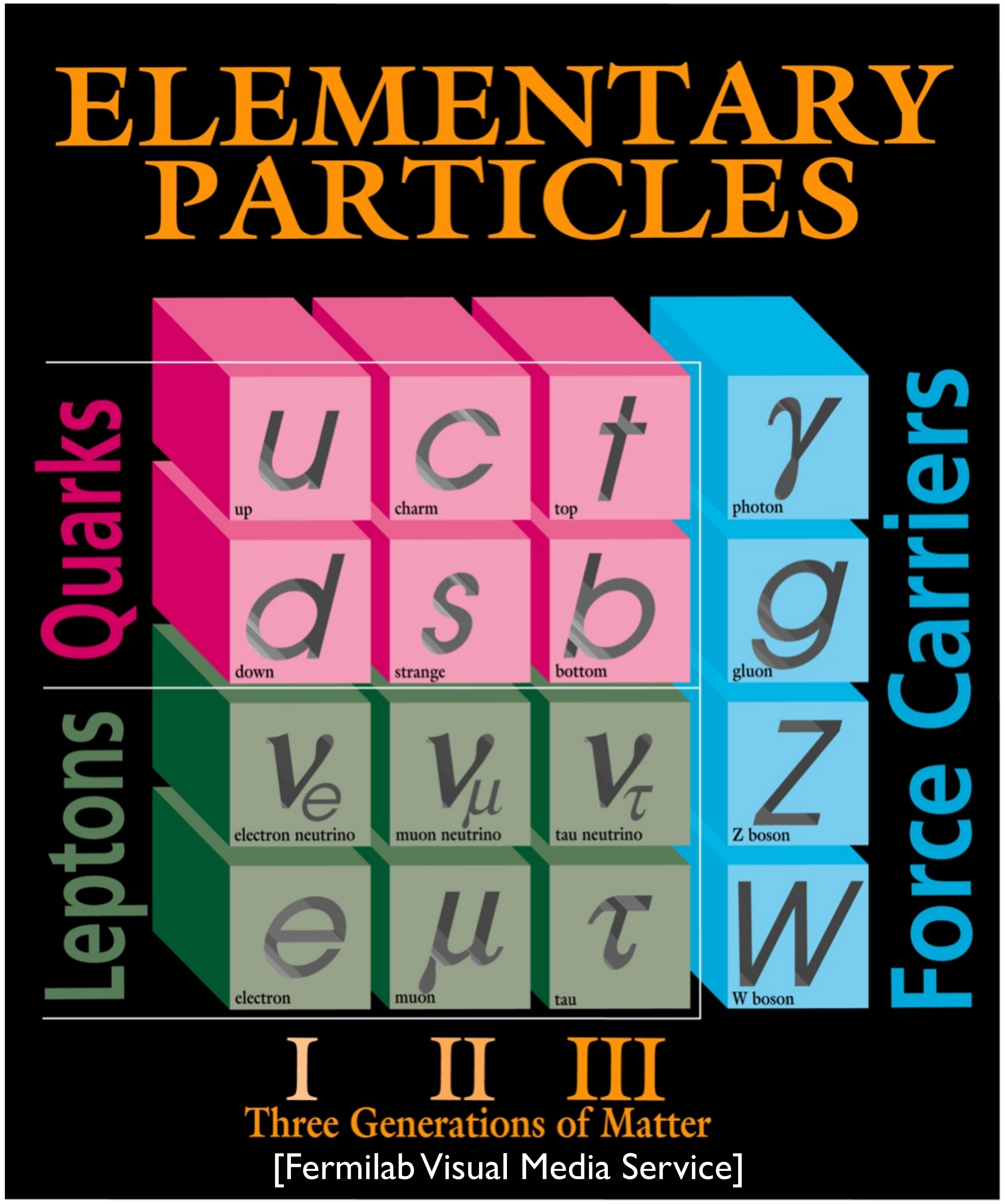
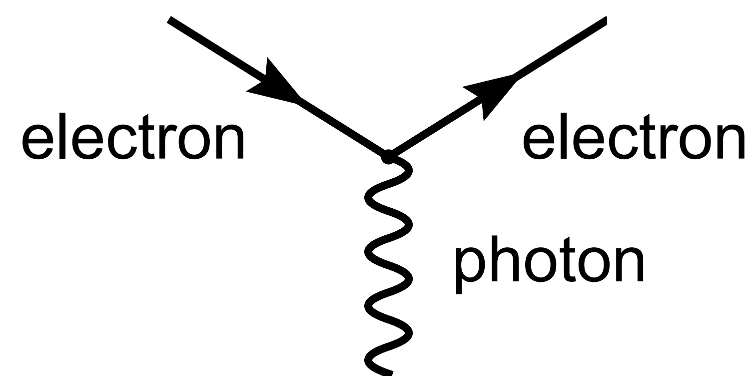
Standard Model of Particle Physics



Fermilab 95-759

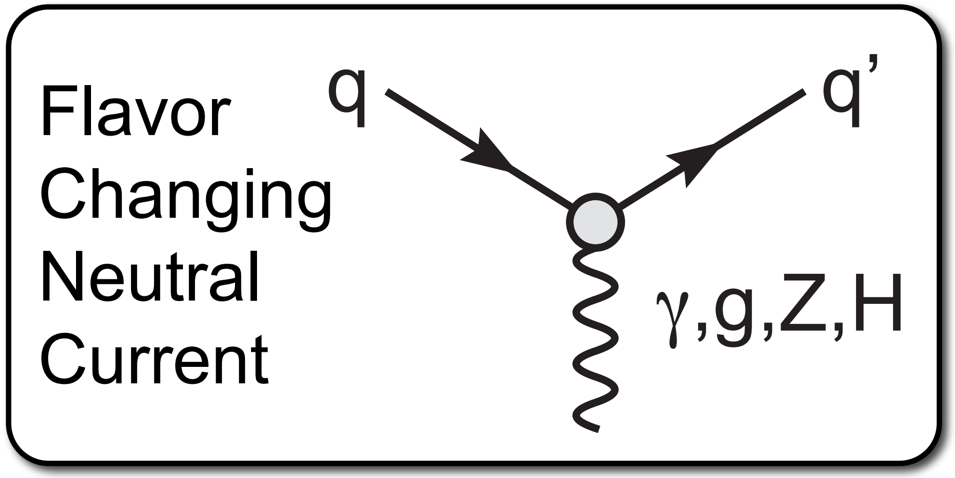
- Matter in the standard model: 12 fermions in three generations
  - Six quarks and their anti-particles
  - Six leptons and their anti-particles
- Forces in the standard model:
  - Strong force (carrier: gluon)
  - Electroweak force (carriers: photon, $W^{\pm}$ bosons, Z boson)
- Interactions = "currents" coupling to gauge bosons, e.g. electromagnetic current



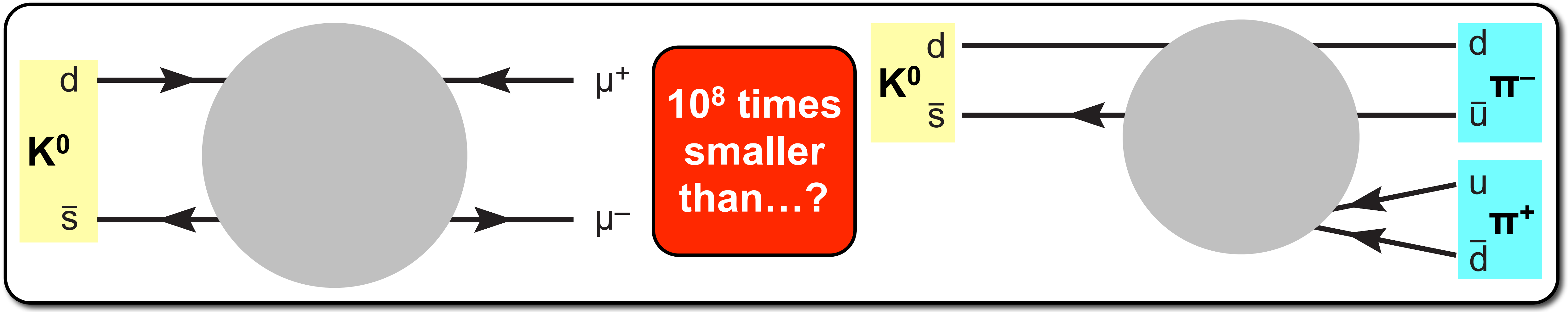
$$\mathscr{L}^{\mathrm{em}} = -q\,\bar{e}\gamma_\mu e\,A^\mu \equiv j_\mu^{\mathrm{em}} A^\mu$$

Flavor Changing Neutral Currents

- Flavor changing neutral current (FCNC):
  - Transition: from a quark q of flavor A and charge Q to quark q' of flavor B with the same charge Q
  - Examples: $b \to s\gamma$, $t \to cH$, …



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



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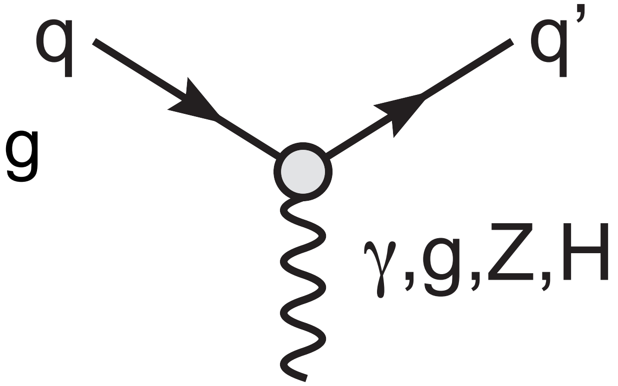
Flavor Changing Neutral Current



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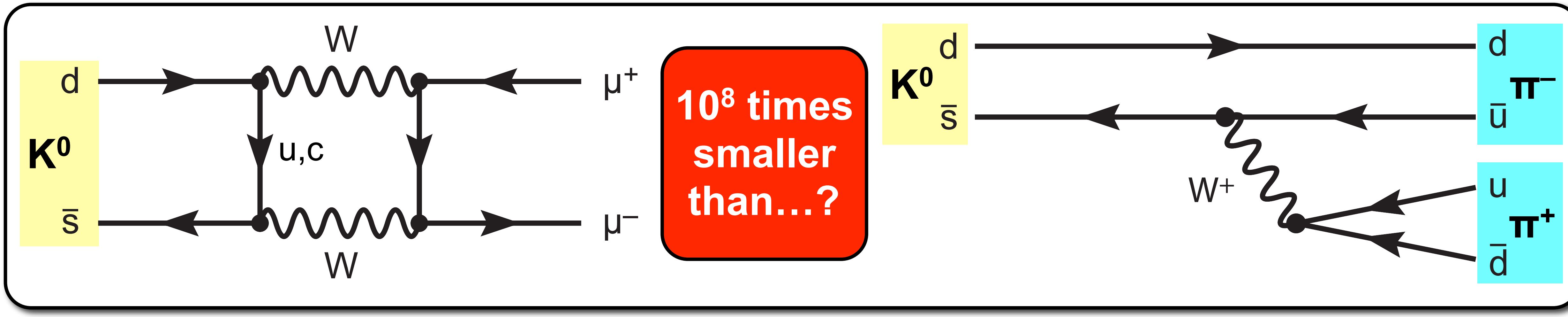
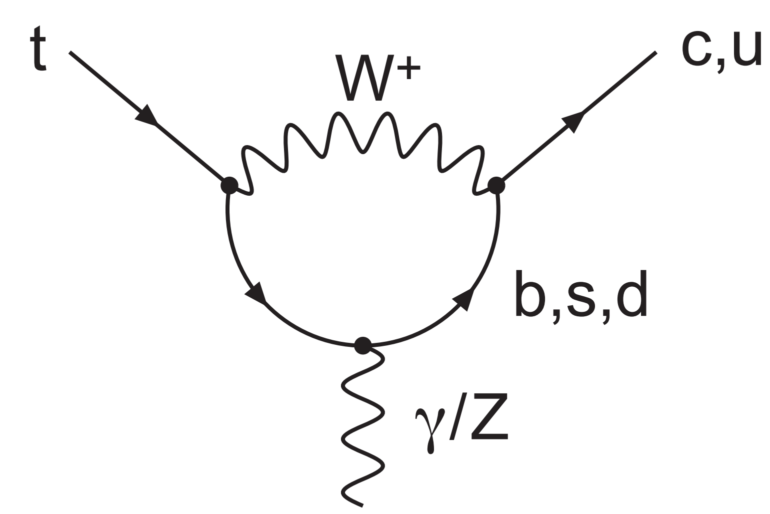


- Solution: "GIM Mechanism" (Glashow, Iliopoulos, Maiani, 1970)
  - Fourth quark needed for cancellation in box diagram: prediction of charm quark
  - Cancellation exact if all quarks had the same mass: estimate of charm quark mass

Top FCNC & New Physics

- Top FCNC not at tree level, only in higher orders → very rare in SM: $B(t \to Zq) \approx 10^{-14}$ (q=u,c)
- Top FCNC enhanced in many models of physics beyond the SM → signal at CDF = new physics
- 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
  - Supersymmetry: gluino/neutralino and squark in loop corrections

Penguin Diagram



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. Polon. **B35** (2004) 2695]

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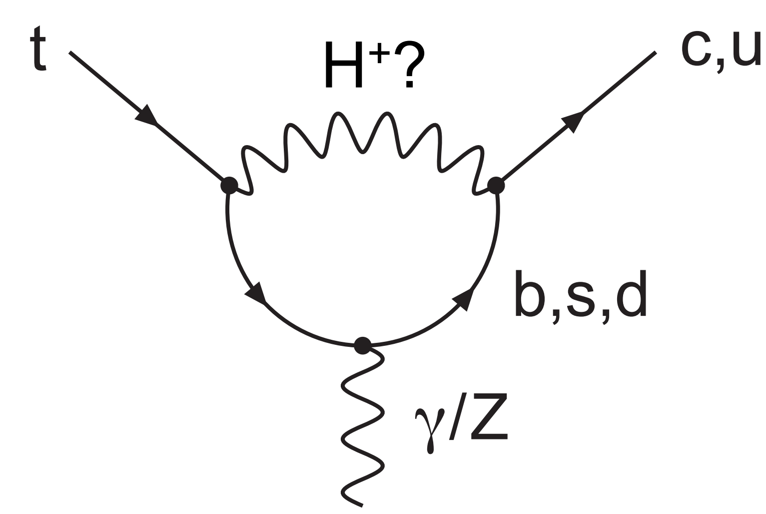

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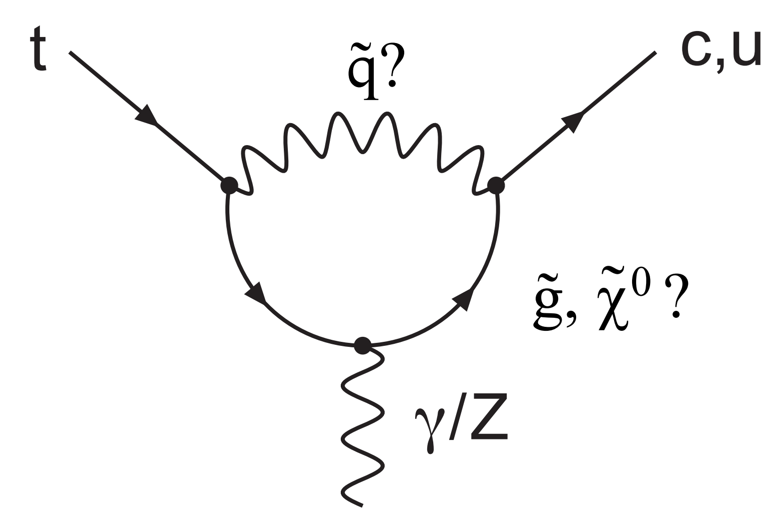

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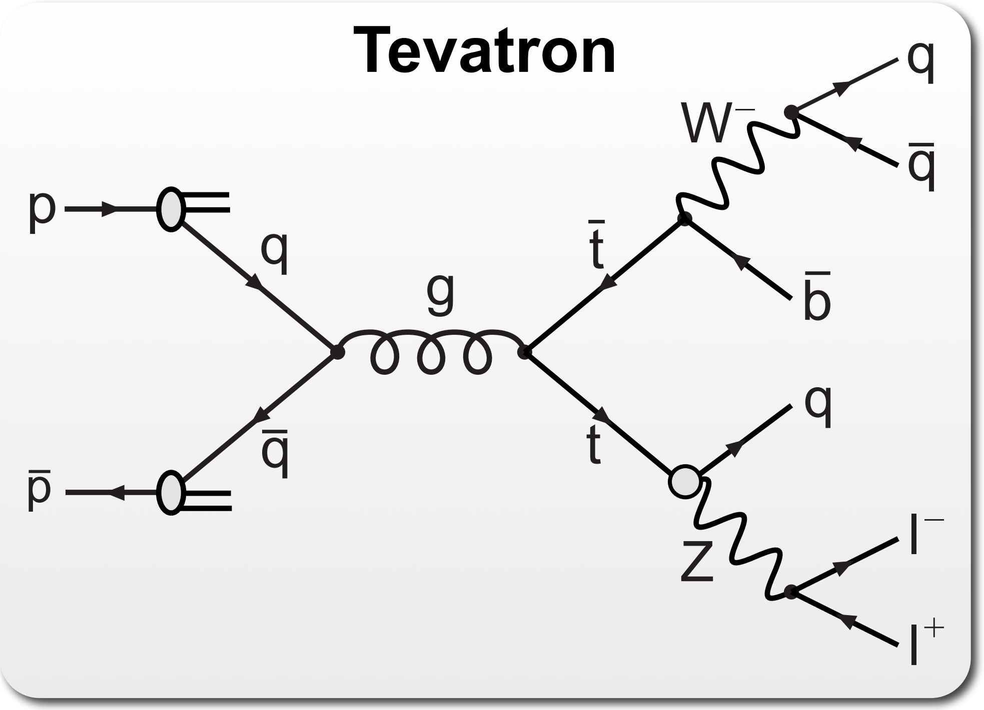
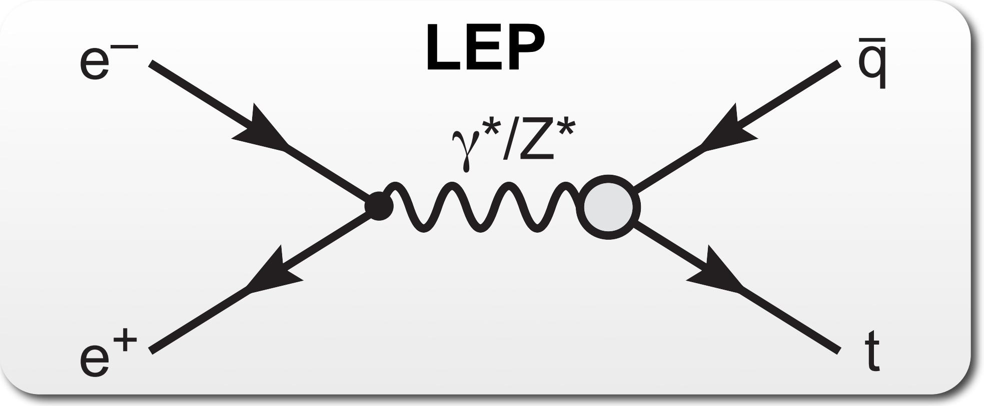
Previous Searches for Top FCNC

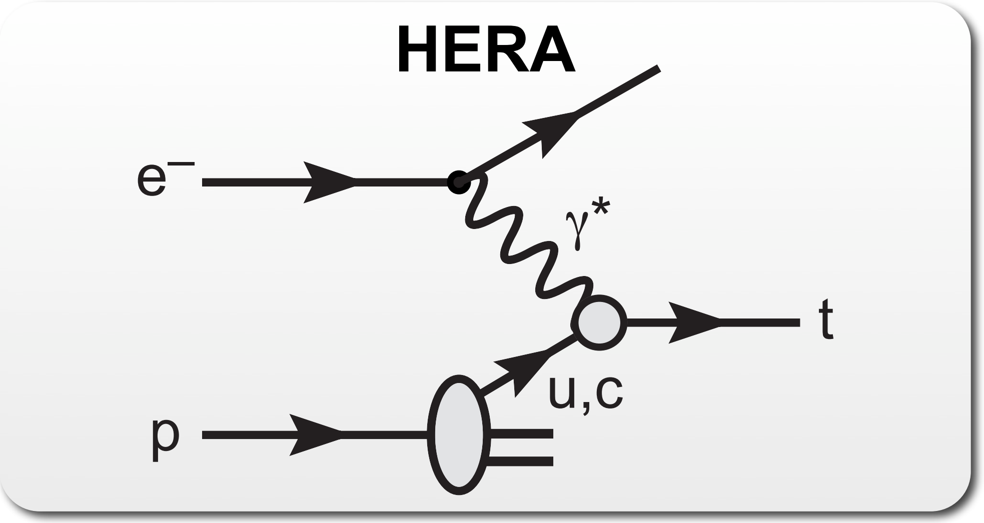
- CDF Run I search:
  F. Abe *et al.*, PRL **80** (1998) 2525.
  - Signature: $Z \rightarrow l^+ l^-$ + 4 jets (1 b-jet)
  - Limit on BR($t \rightarrow Zq$): 33%

- LEP searches:
  P. Achard *et al.* (L3), Phys. Lett. **B549** (2002) 290.
  G. Abbiendi *et al.* (Opal), Phys. Lett. **B521** (2001) 181.
  J. Abdallah *et al.* (Delphi), Phys. Lett. **B590** (2004) 21.
  A. Heister *et al.* (Aleph), Phys. Lett. **B453** (2002) 173.
  - Anomalous single top production in e^+e^-
  - Very similar results among all LEP experiments, best limit on BR($t \rightarrow Zq$): 13.7% (L3)

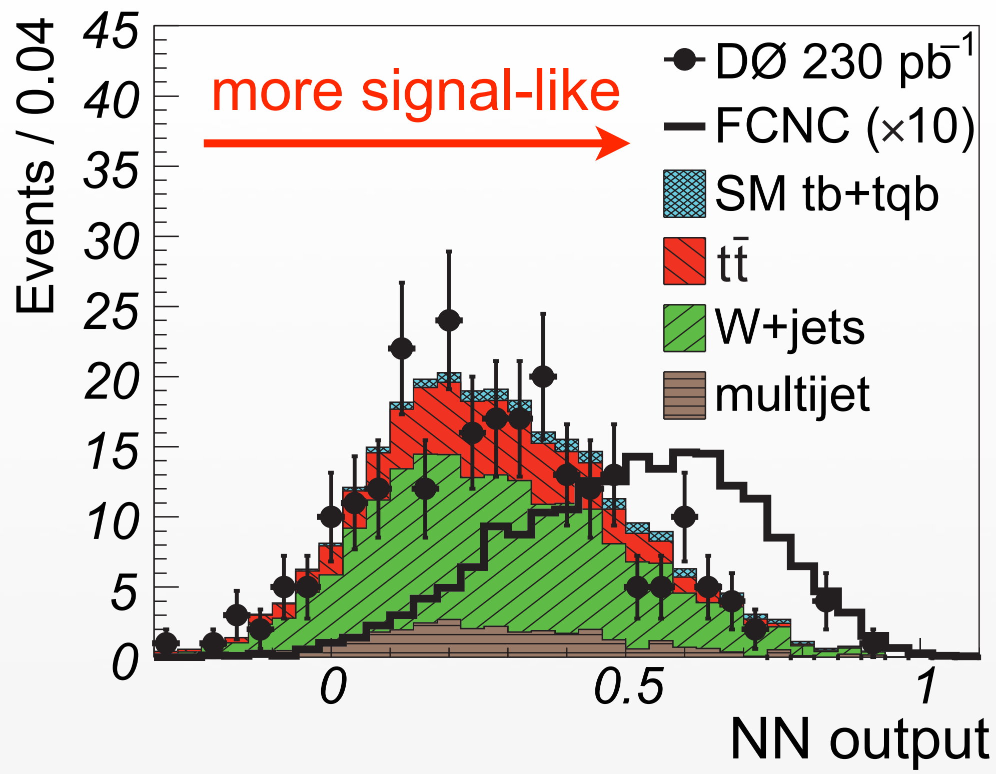
- HERA searches:
  A. Aktas *et al.* (H1), Eur. Phys. J. **C33** (2004) 9.
  S. Chekanov *et al.* (ZEUS), Phys. Lett. **B559** (2003) 153.
  - Anomalous single top production in ep
  - Most sensitive to tγq vertex, preference for u over c quarks (proton sea)

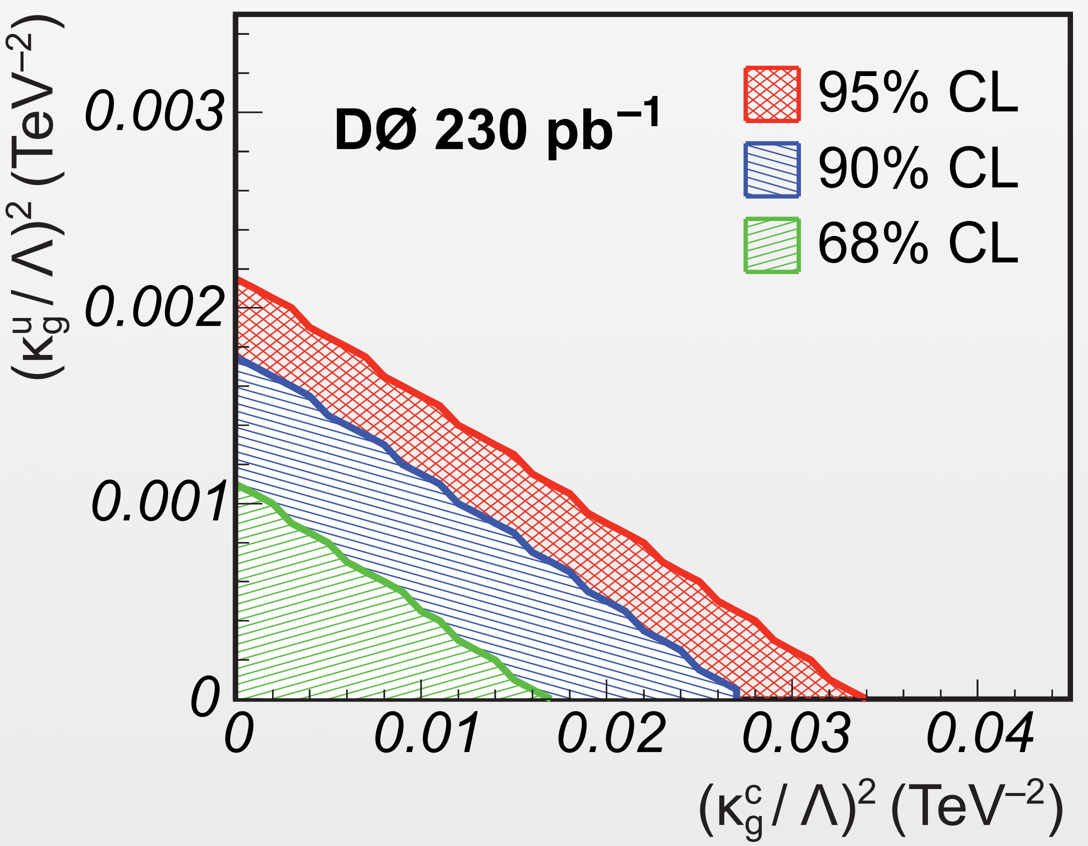




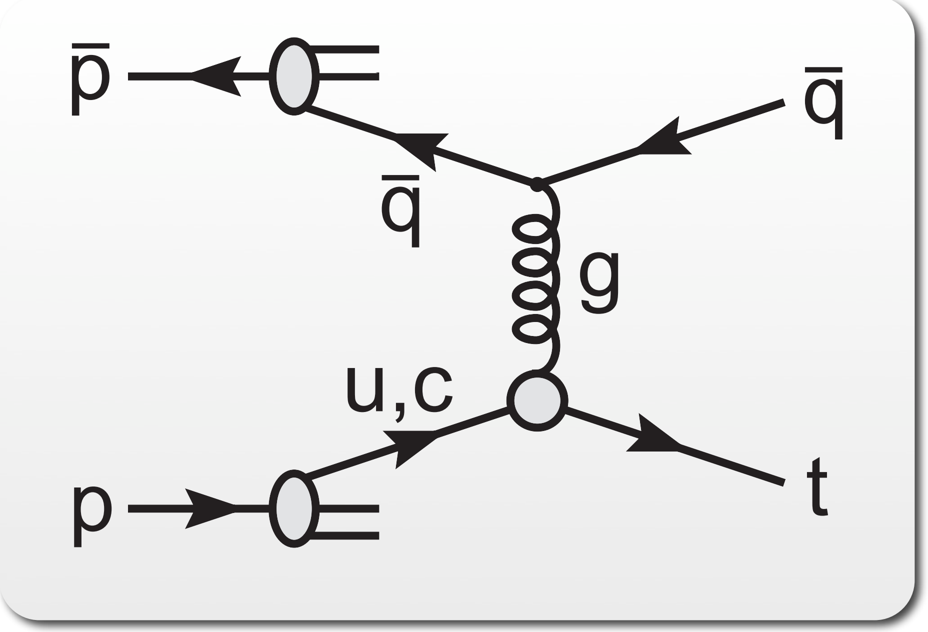


DØ 2007: Single Top via FCNC





- Study single Top production via FCNC:



- Artificial neural network to discriminate signal from background
- World's best limit on tcg and tug couplings $(\kappa/\Lambda)^2 \rightarrow$ previous limits improved by order of magnitude

$$\left(\kappa_g^c/\Lambda\right)^2 < 0.023\,\mathrm{TeV}^{-2} \quad (95\%\ \mathrm{C.L.})$$
$$\left(\kappa_g^u/\Lambda\right)^2 < 0.0014\,\mathrm{TeV}^{-2} \quad (95\%\ \mathrm{C.L.})$$

[V. M. Abazov *et al.*, Phys. Rev. Lett. **99** (2007) 191802]

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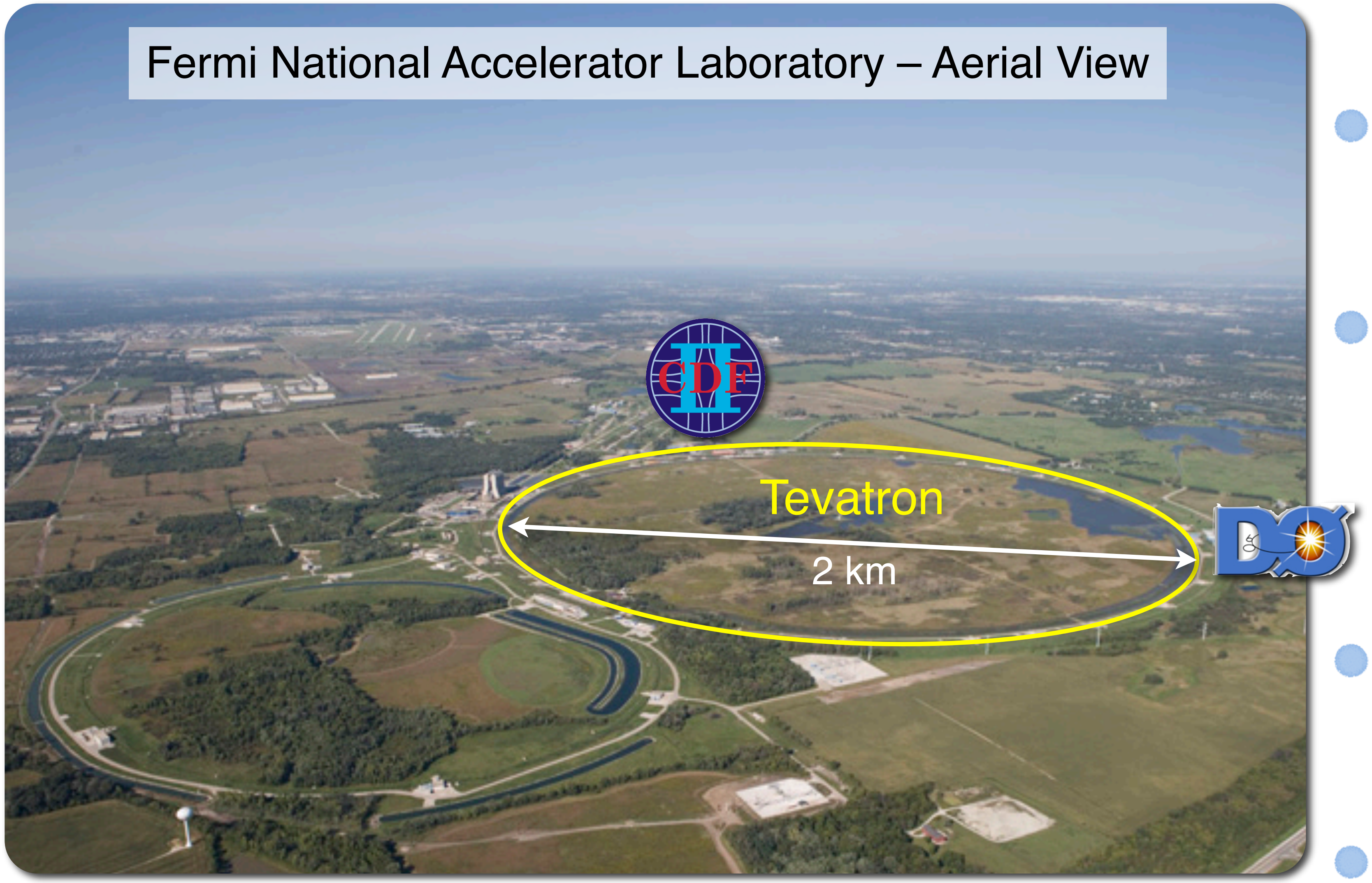
Tevatron Run II: 2001–2009 (2010?)

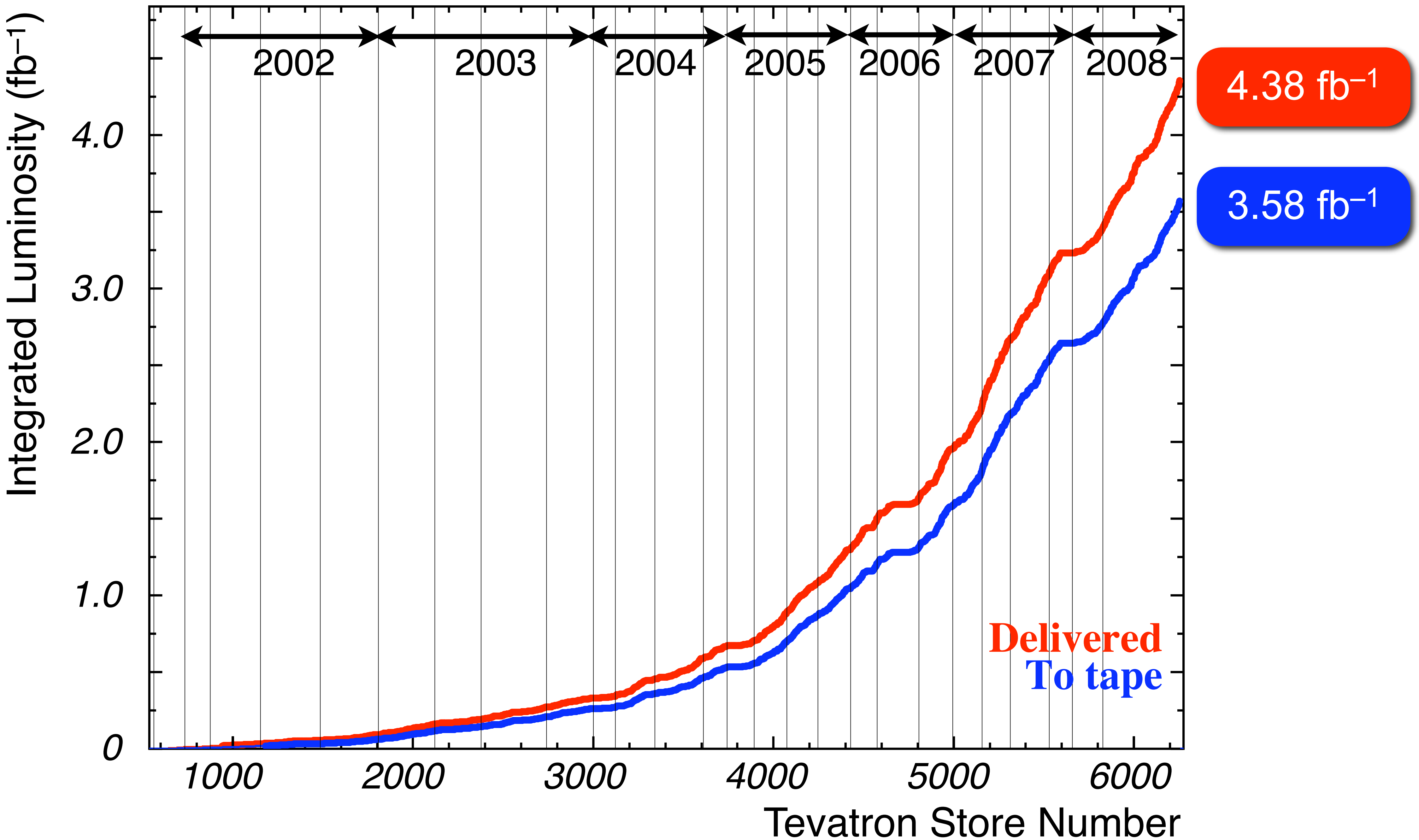


[Fermilab Visual Media Service]

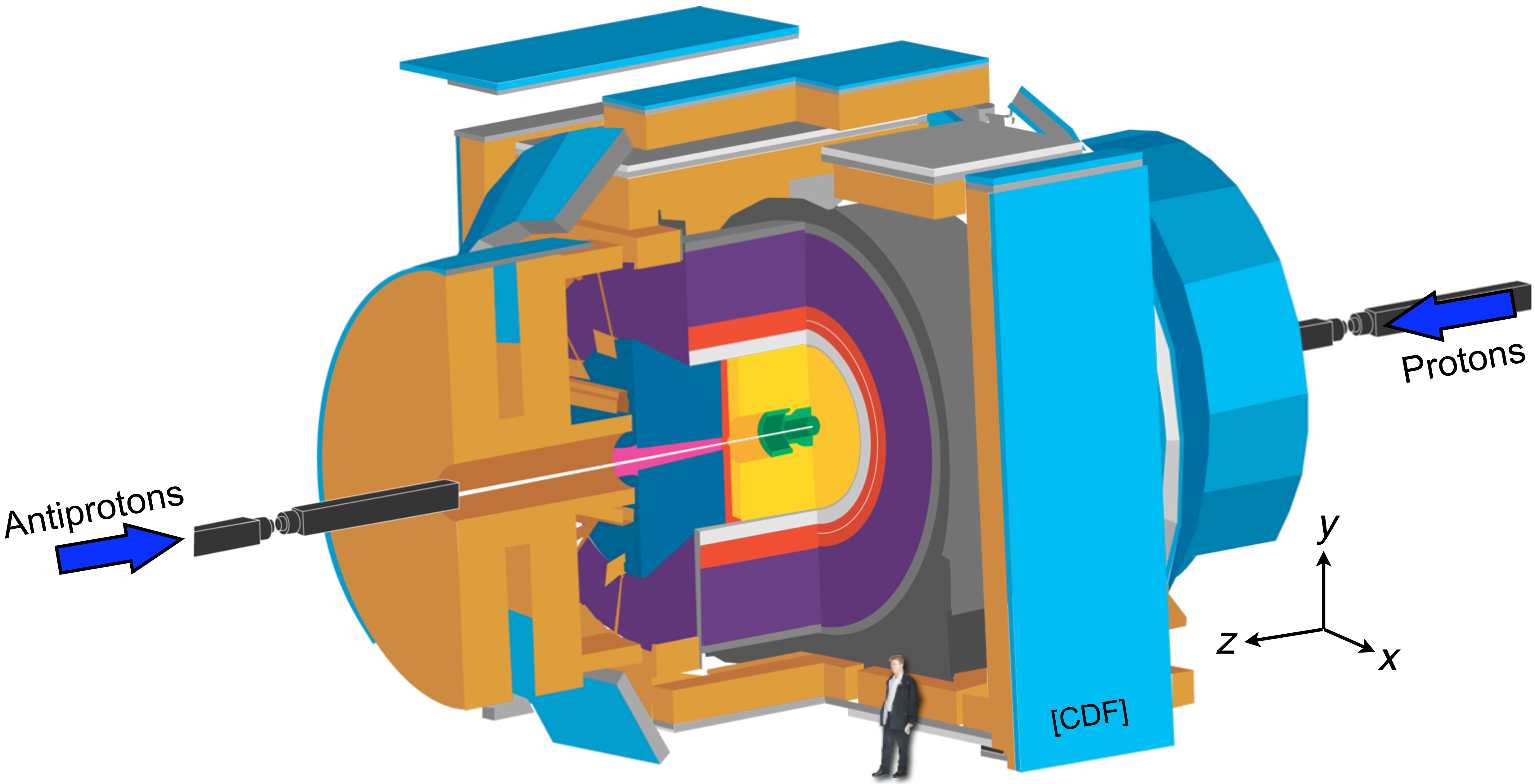
- Proton-antiproton collider: $\sqrt{s}$ = 1.96 TeV
- 36×36 bunches, collisions every 396 ns
- Record instantaneous peak luminosity: 316 $\mu b^{-1}\,s^{-1}$ (1 $\mu b^{-1}\,s^{-1} = 10^{30}\,cm^{-2}\,s^{-1}$)
- Integrated luminosity goal: 5.5–6.5 fb^{-1} by 2009
- Running in 2010 currently under discussion
- Two multi-purpose detectors: CDF and DØ

Tevatron Performance

- Tevatron continues to perform very well:
  - Almost 4.5 fb^{-1} delivered by Tevatron as of 1 July 2008
  - More than 3.5 fb^{-1} recorded by CDF



The CDF II Detector



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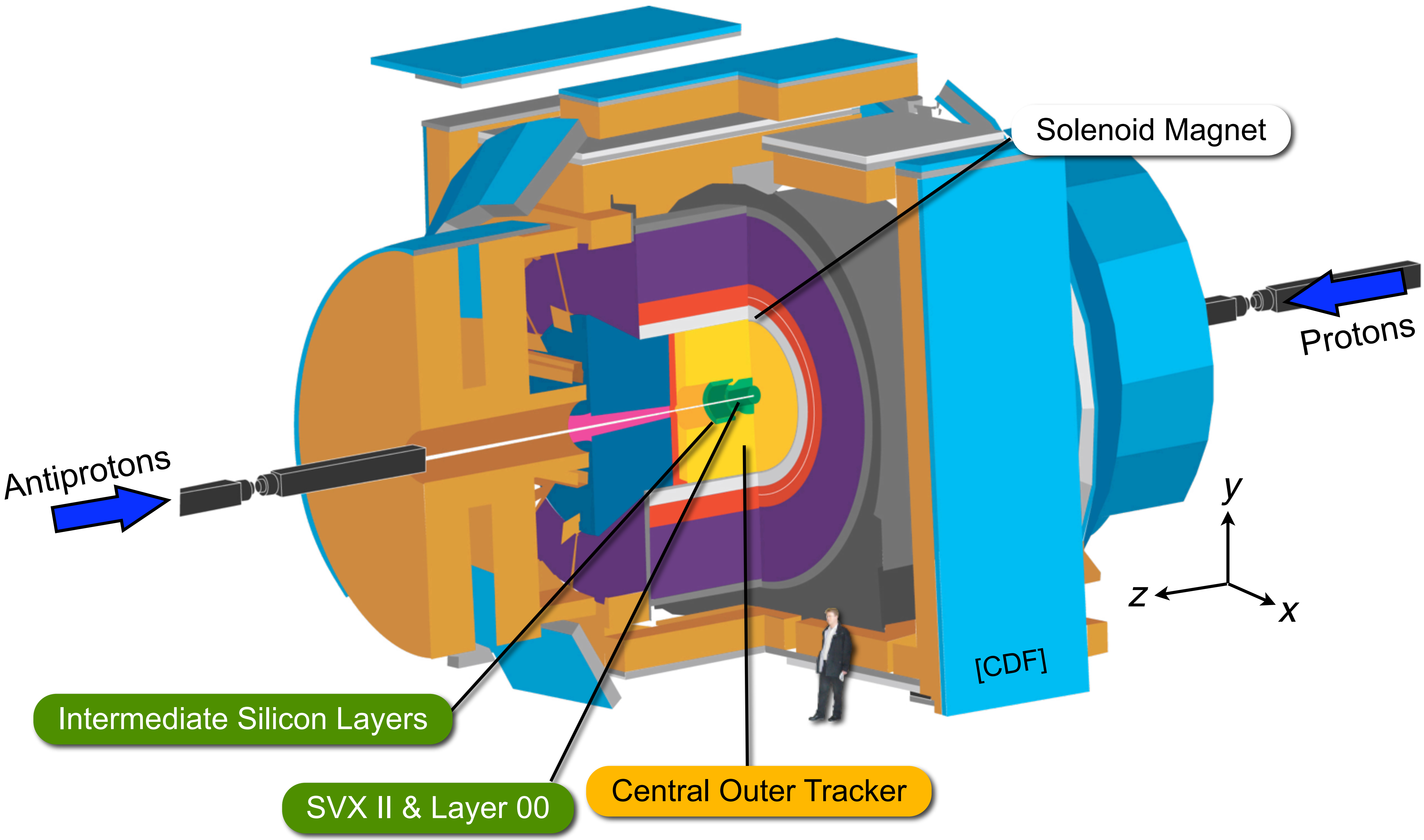

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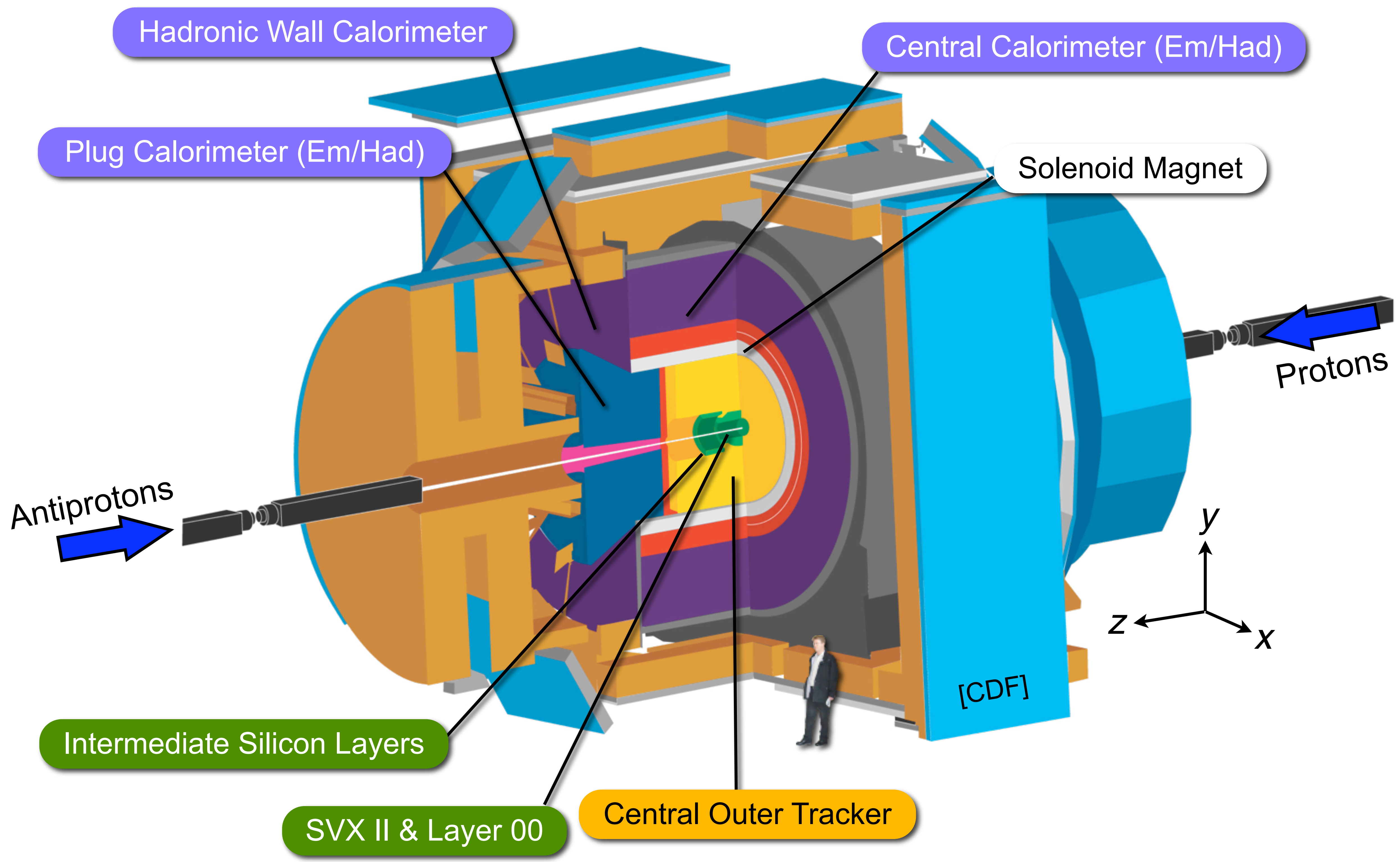

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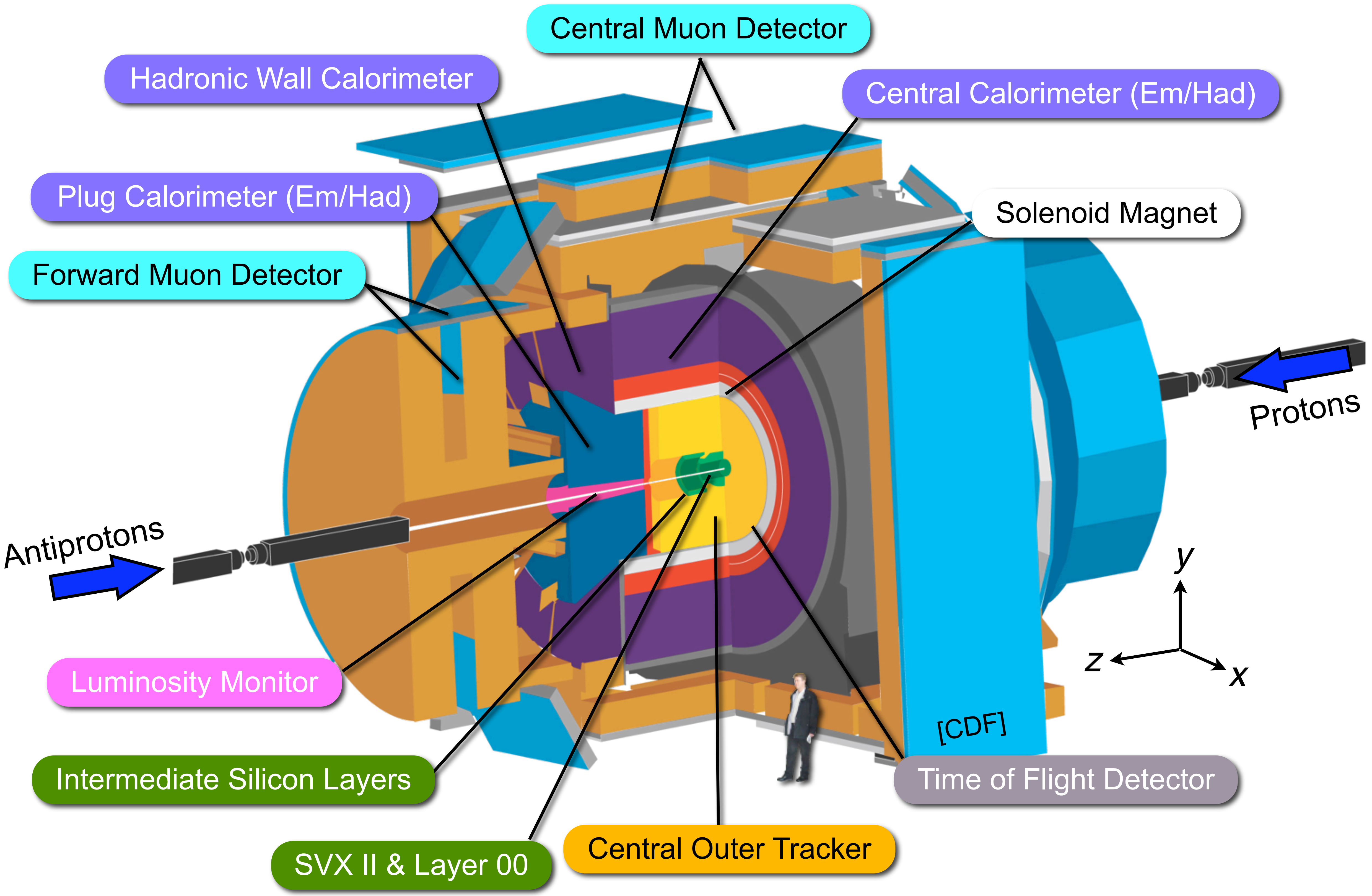
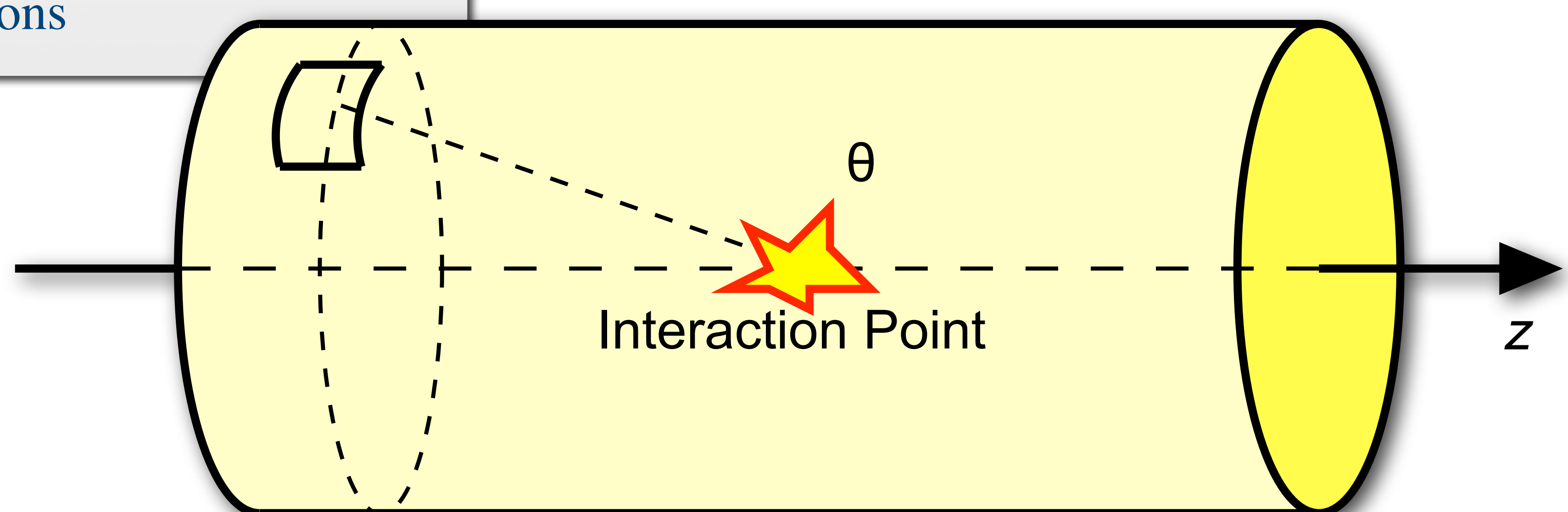


Hadron Collider Kinematics

- Cylindrical coordinate system:
  - θ: polar angle w.r.t. to proton direction
  - ϕ: azimuthal angle
  - Pseudorapidity:
    $\eta = -\ln\tan(\theta/2)$
  - Transverse energy:
    $$\vec{E}_T = \sum_{\text{cal towers}} E_i(\sin\theta_i, \phi_i)$$
  - Missing transverse energy (“MET”):
    $$\vec{\not{E}}_T = -\sum_{\text{jets}} \vec{E}_T - \sum_{\text{leptons}} \vec{p}_T$$



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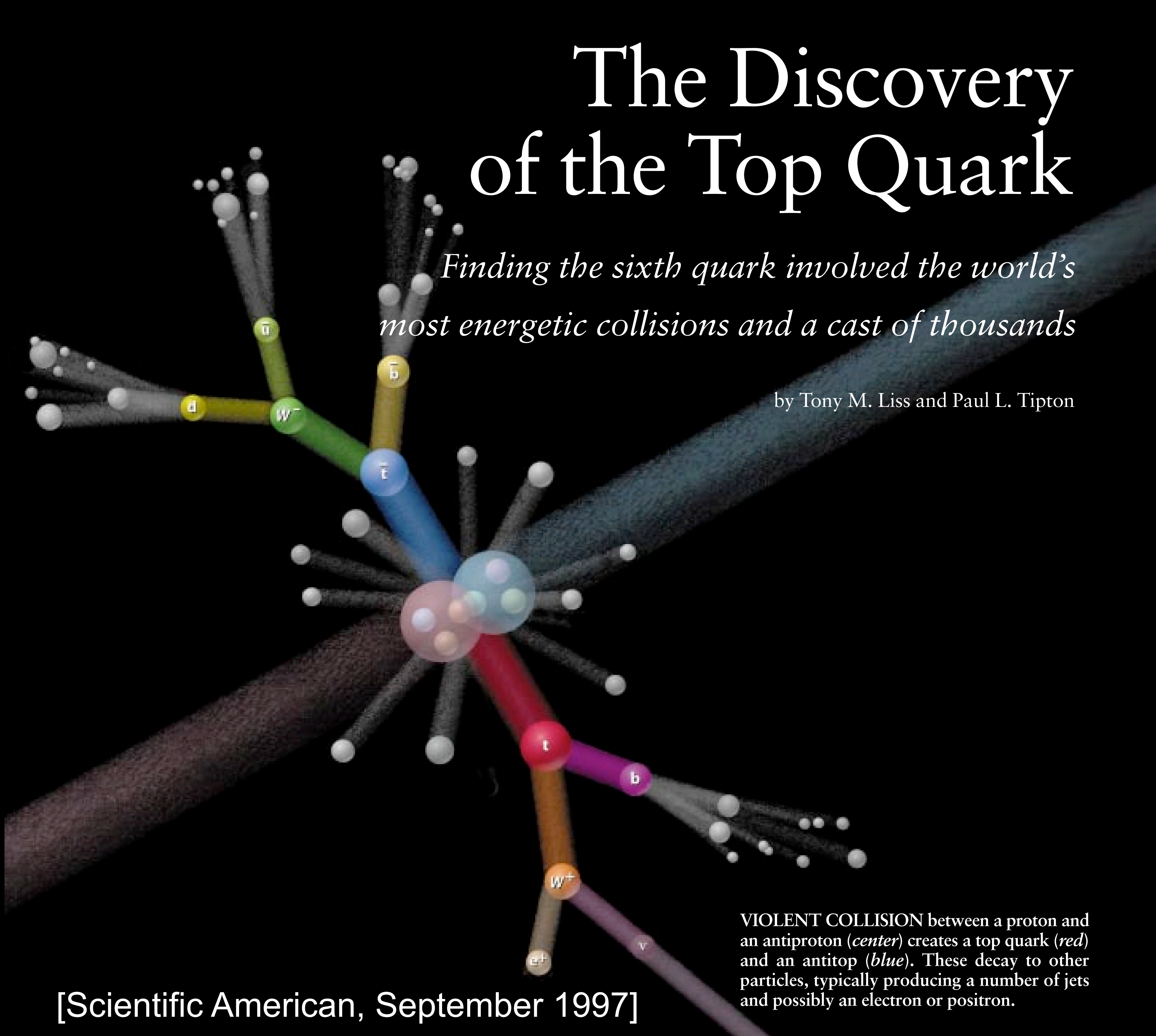
Brief history of top quark discovery:

- 1977: Υ discovery – bottom quark
- 1980s: Searches for “light” top ($m_t < m_W$): isospin partner of bottom at PETRA, Sp$\bar{p}$S, LEP, CDF Run 0
- 1992/3: Tevatron Run I starts, first indications for top quark production
- March 2, 1995: CDF and DØ announce top quark discovery



[Scientific American, September 1997]

The Top Quark in the Standard Model

- The top is heavy: $m_t \approx 170$ GeV/c^2 (40×m_b, approx. mass of gold atom)
- Mass close to scale of electroweak symmetry breaking (EWSB), top Yukawa coupling $f \approx 1$:

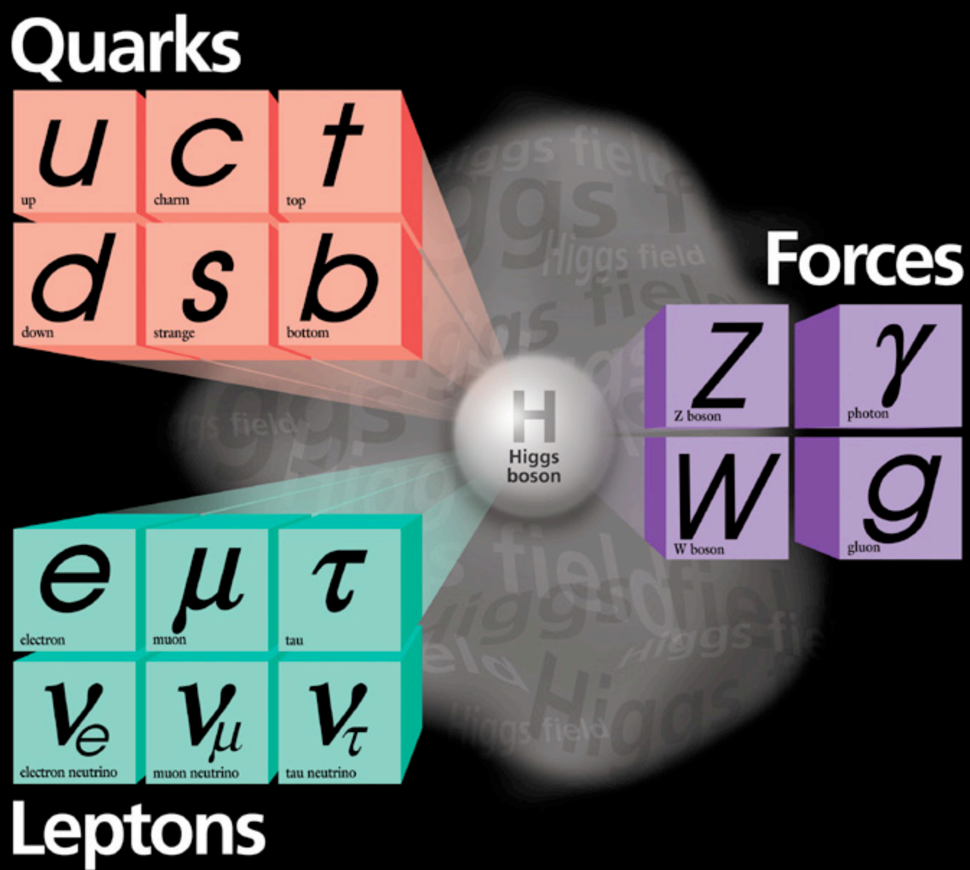
$$\mathscr{L}_{\mathrm{Yuk},t} = f \frac{v}{\sqrt{2}} \bar{t}_L t_R \equiv m_t \bar{t}_L t_R$$

(vacuum expectation value of Higgs field: $v/\sqrt{2} \approx 178$ GeV)
→ Important role in EWSB models

- Top is the only “free” quark: lifetime shorter than hadronization time

$$\tau = \frac{1}{\Gamma} \approx \frac{1}{1.5\,\mathrm{GeV}} < \frac{1}{\Lambda_{\mathrm{QCD}}} \approx \frac{1}{0.2\,\mathrm{GeV}}$$

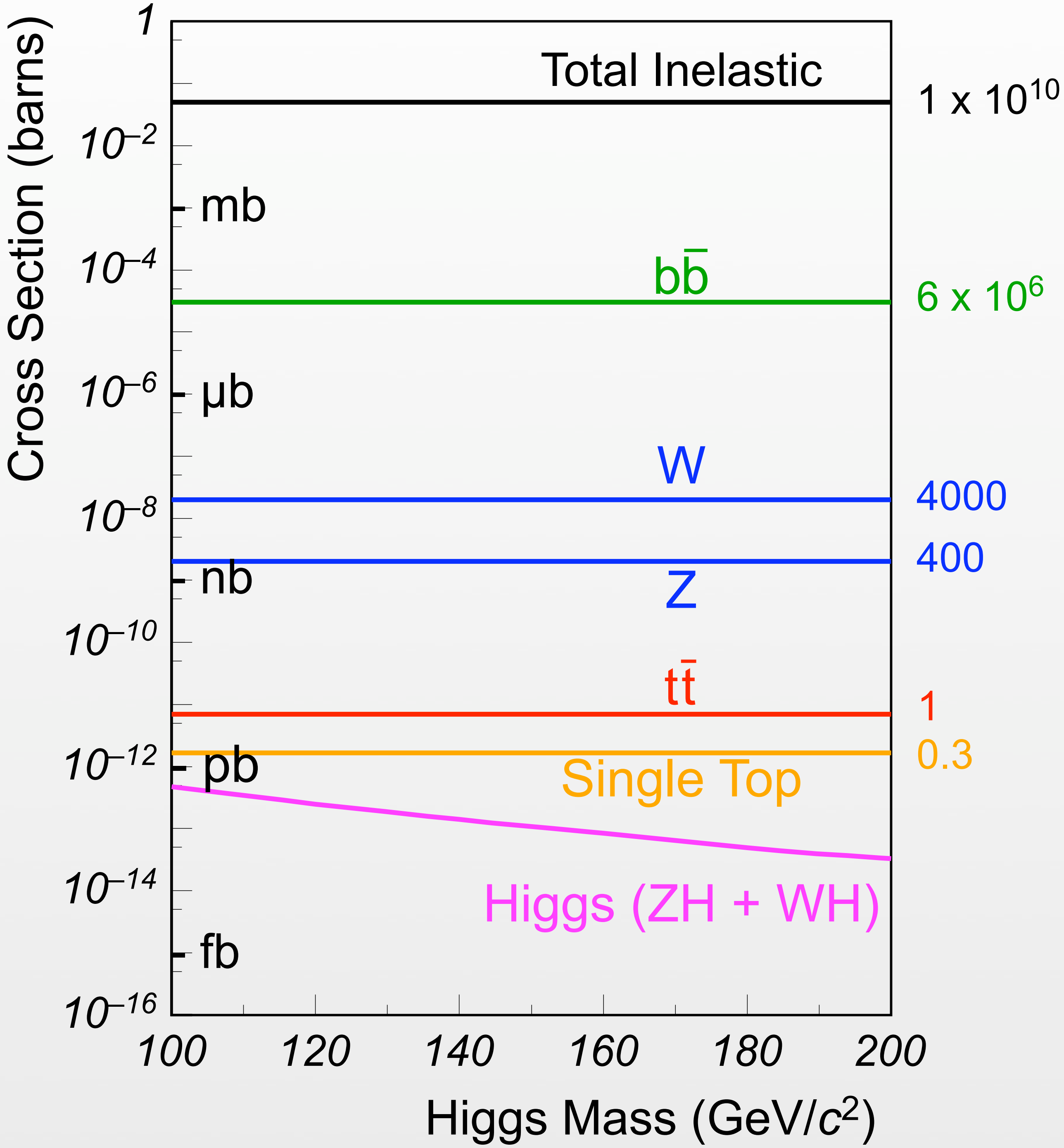
→ No spectroscopy of bound states
→ Spin transferred to decay products



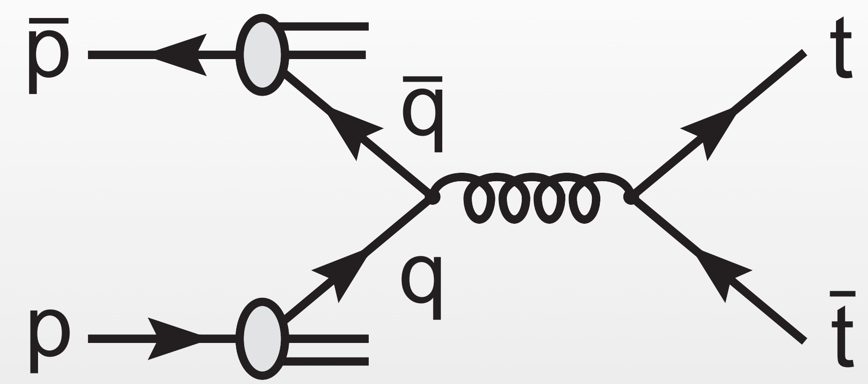
[Fermilab Visual Media Services]

Top Pair Production at the Tevatron

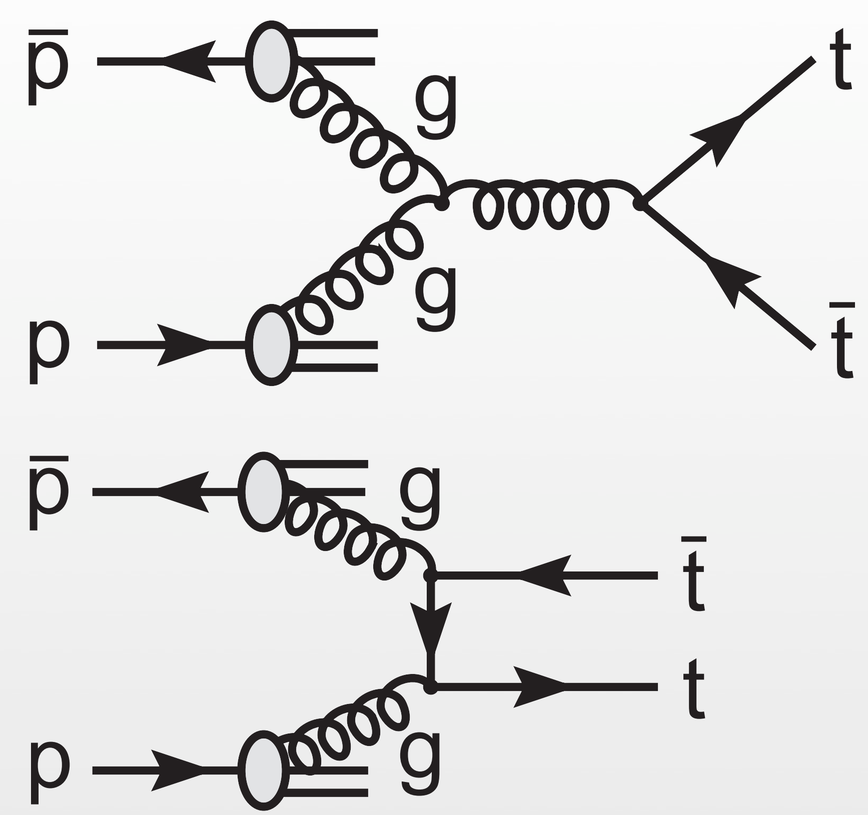
Top production is rare: one top quark pair produced every 10 billion collisions



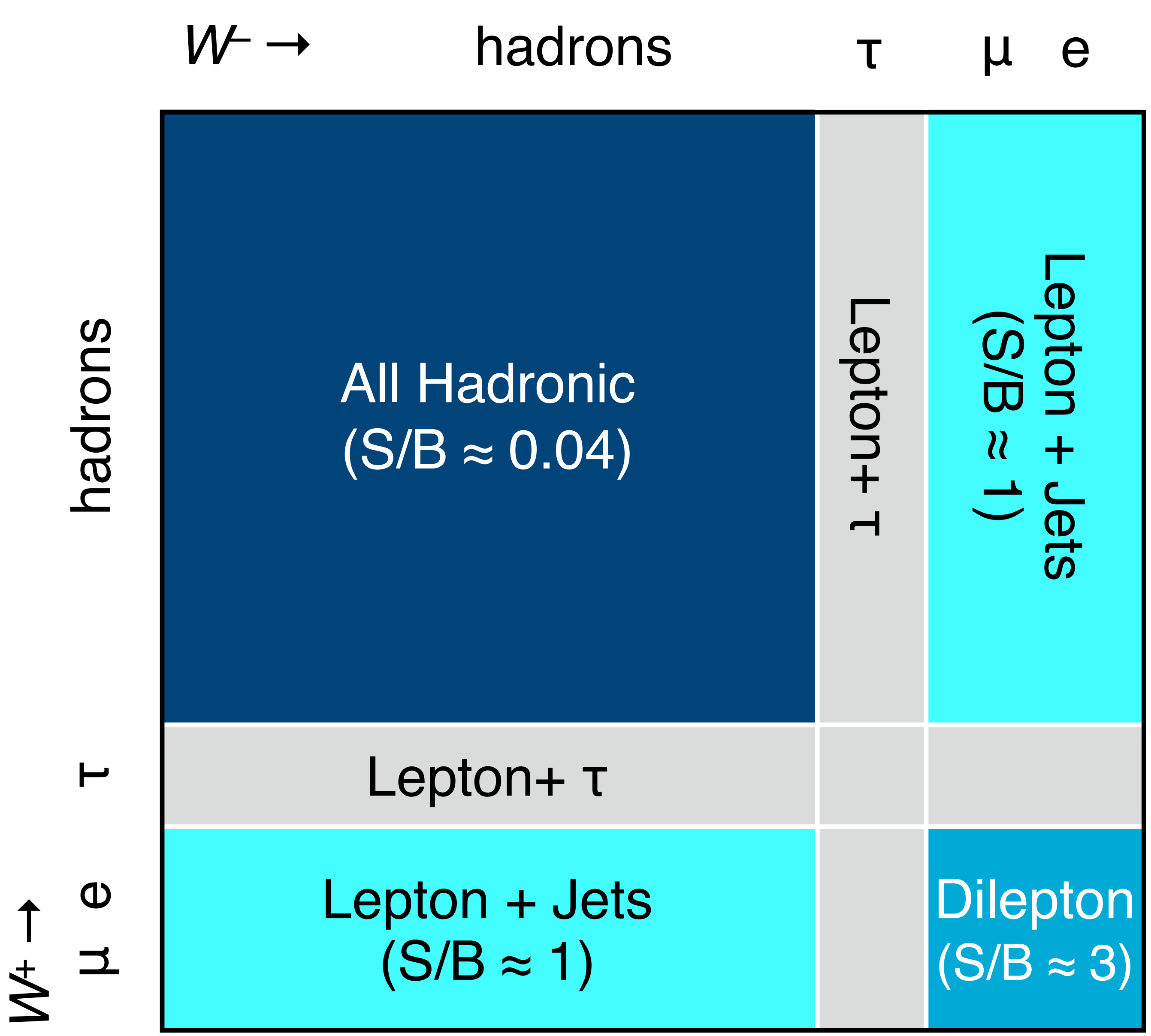
85% $q\bar{q} \to t\bar{t}$:



15% $gg \to t\bar{t}$:



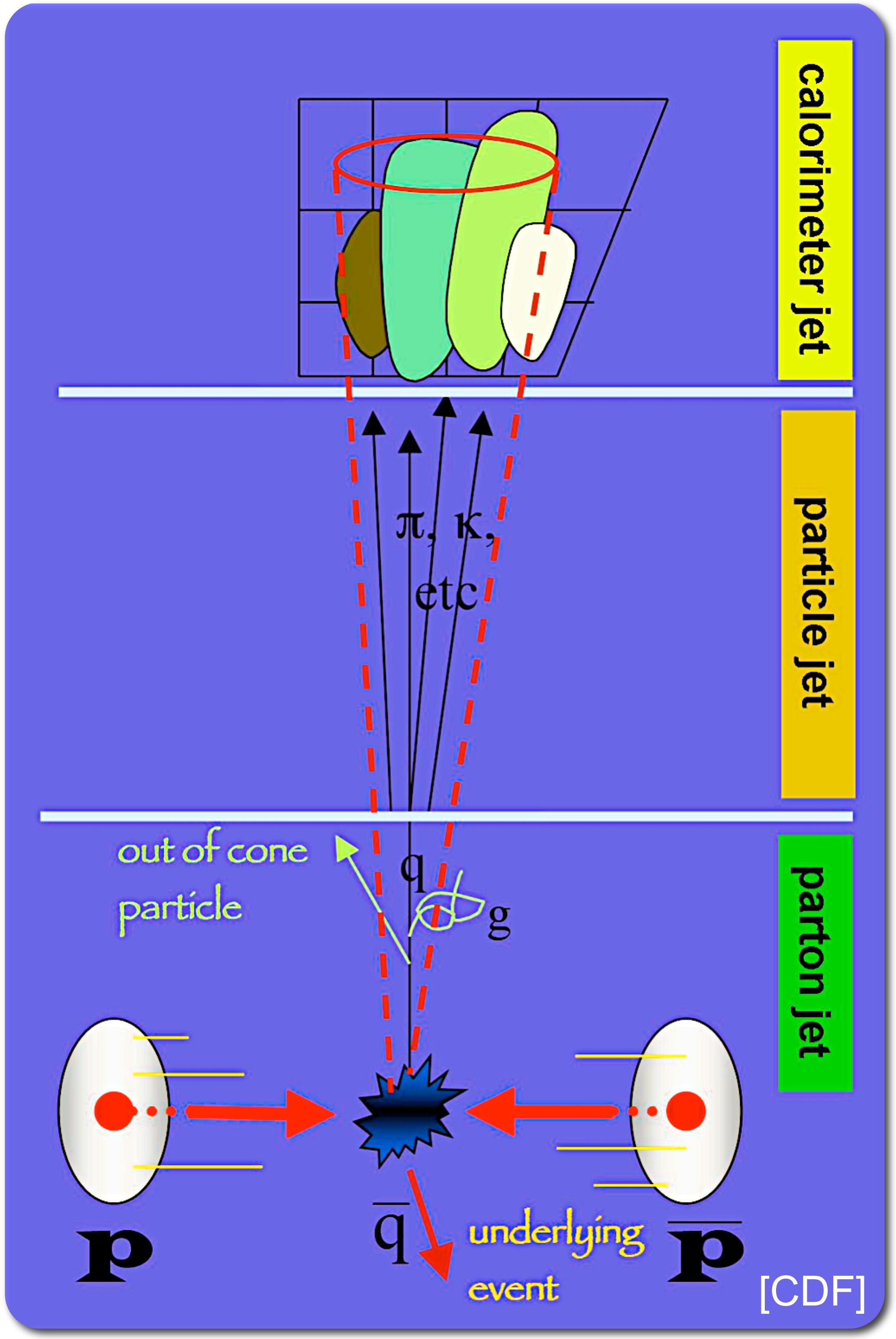
Analyzing Top Quark Events



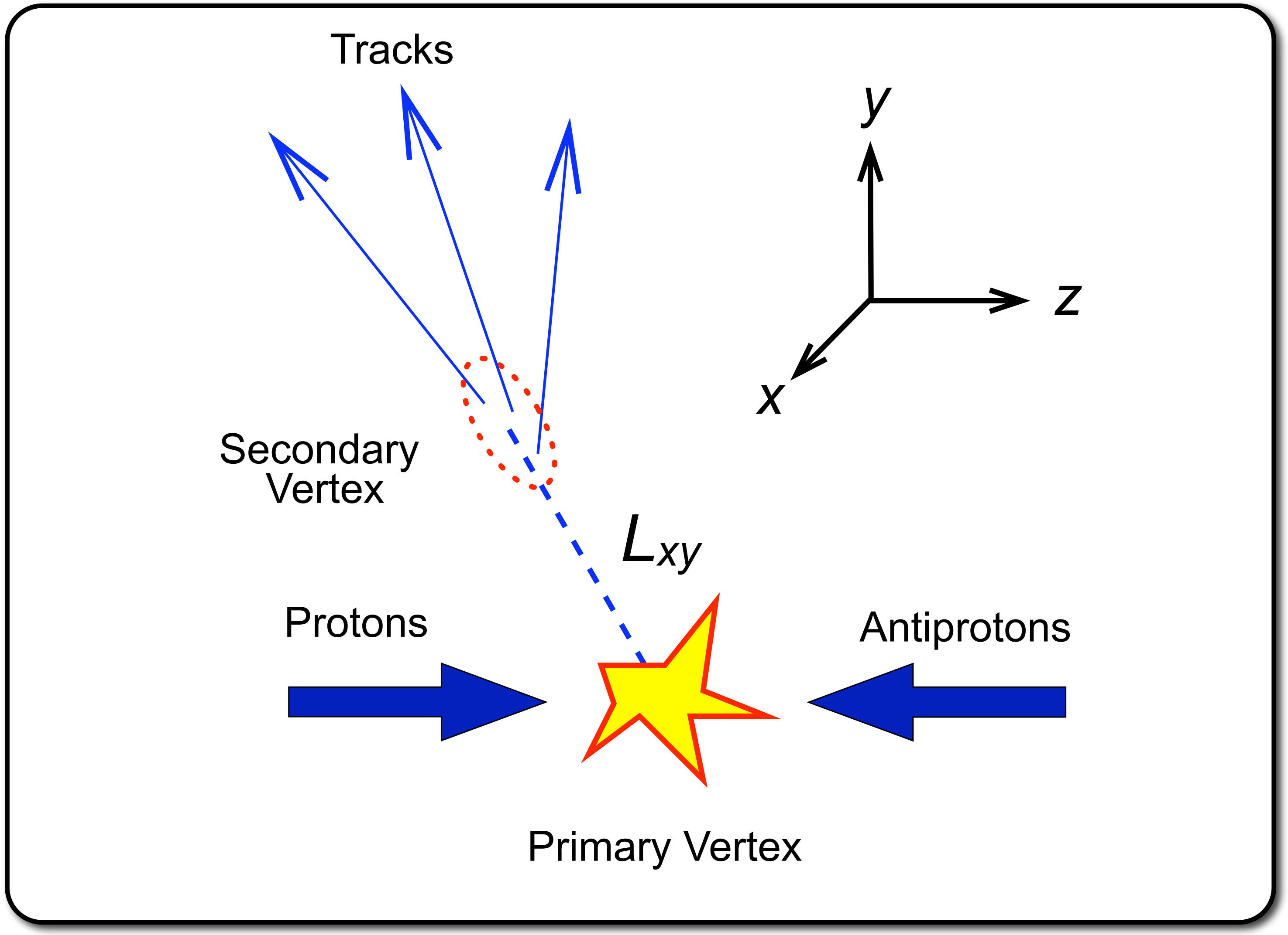
- Top decay in the standard model: t → Wb (BR ≈ 100%)
- $t\bar{t}$ decay signatures characterized by W decays:
  - All-Hadronic: 45% of all decays, large QCD background
  - Lepton+Jets: 30% of all decays, the "gold-plated" channel
  - Dilepton: 5% of all decays, very clean, but small branching fraction
- Main background process: "W+Jets" (production of W bosons in association with jets)
- $t\bar{t}$ events contain two b quarks: "b-tagging" (identification of jets from b quarks) crucial

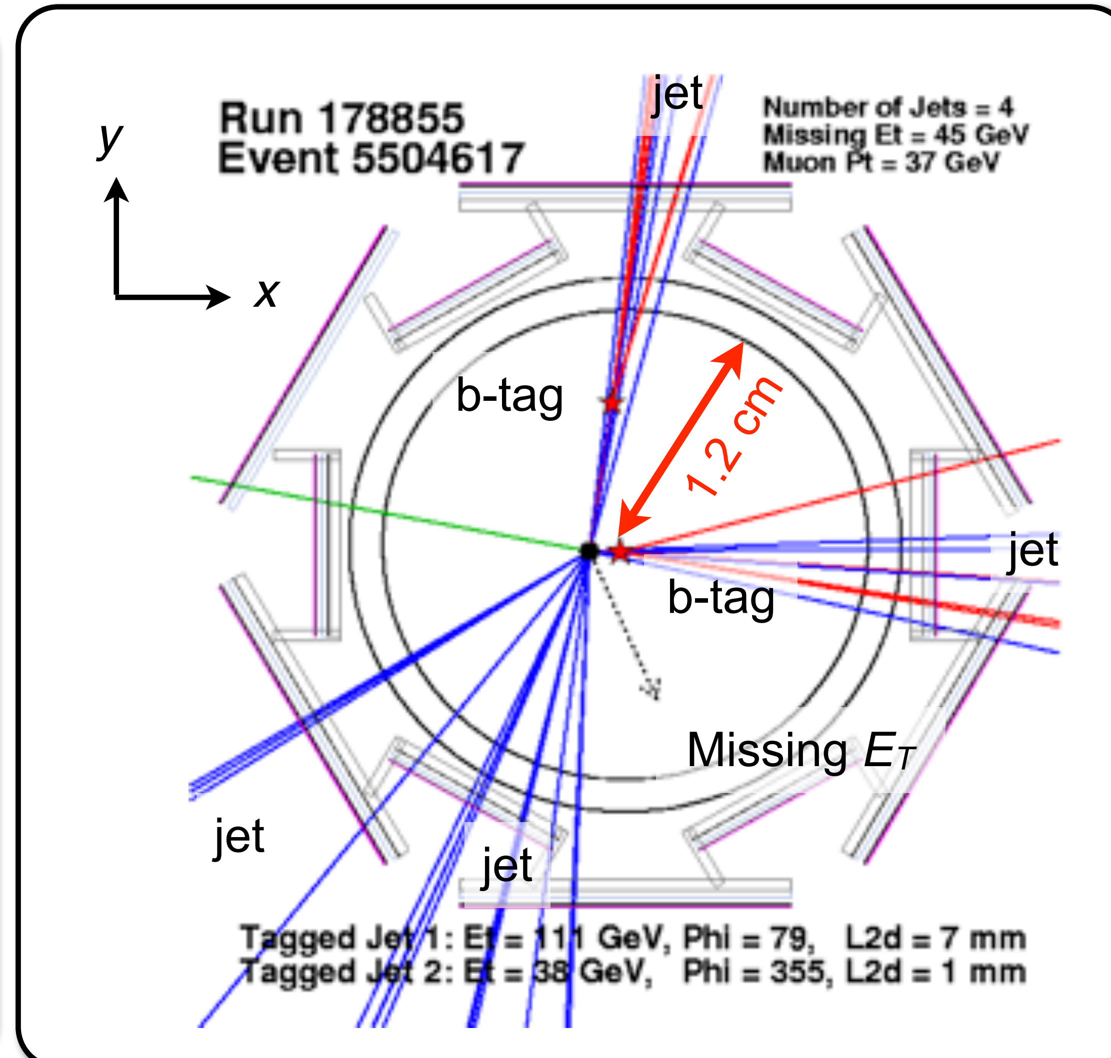
Lepton and Parton Identification

- High p_T electron identification:
  - Isolated charged particle track (no nearby tracks)
  - Almost all energy deposited in electromagnetic calorimeter
- High p_T muon identification:
  - Isolated charged particle track (no nearby tracks)
  - Little energy in calorimeters
  - “Stub” in dedicated muon detector
- Parton identification:
  - Reconstruct energies of jets, not partons
  - Jet energy scale (JES) correction: estimate parton energies from “raw” jet energies



Secondary Vertex B-Tagging

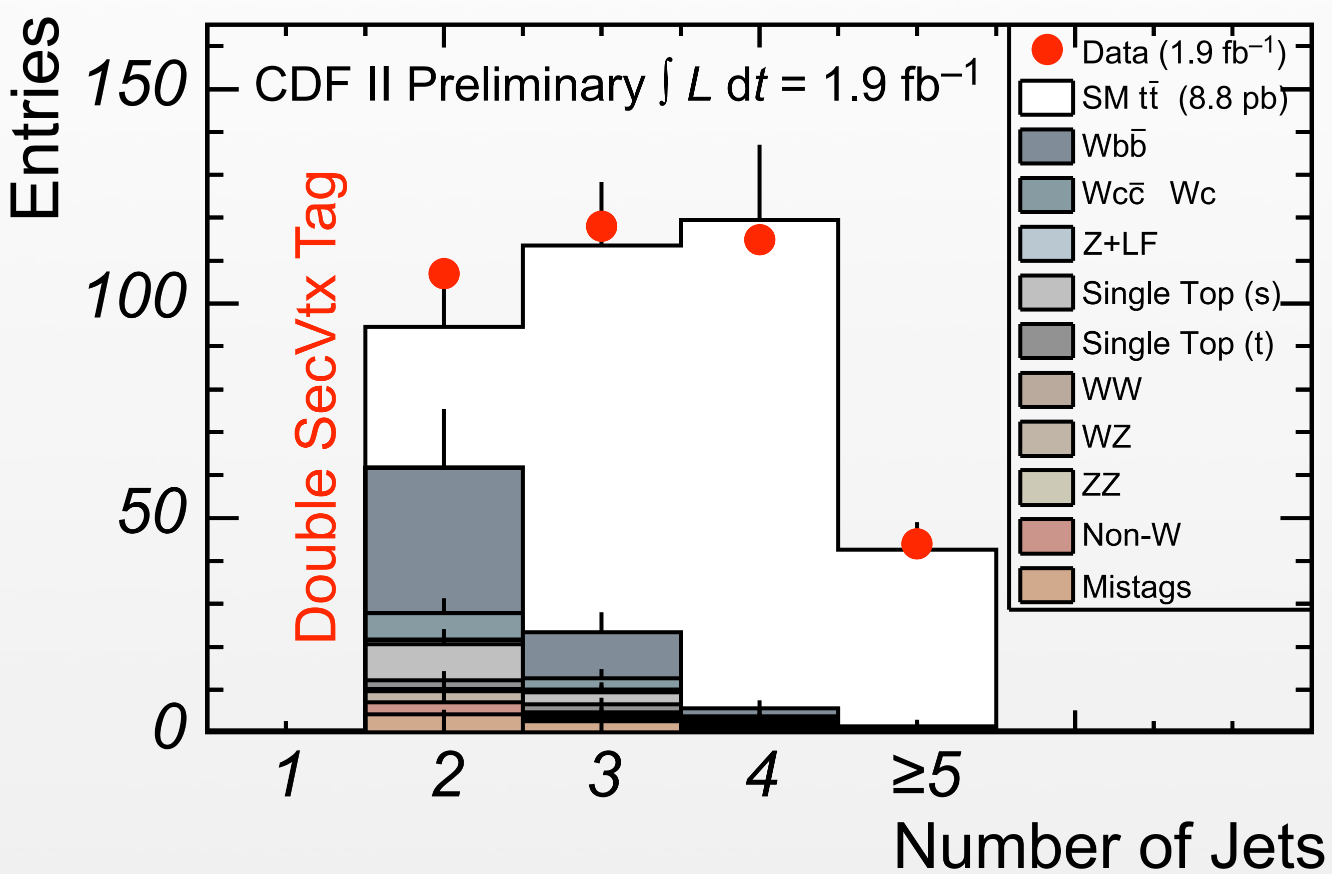




- CDF's standard "SecVtx" algorithm:
  - Long lifetime of B mesons: detect displaced secondary vertex
  - Main discriminant: significance of displacement in *xy* plane (L_{xy})

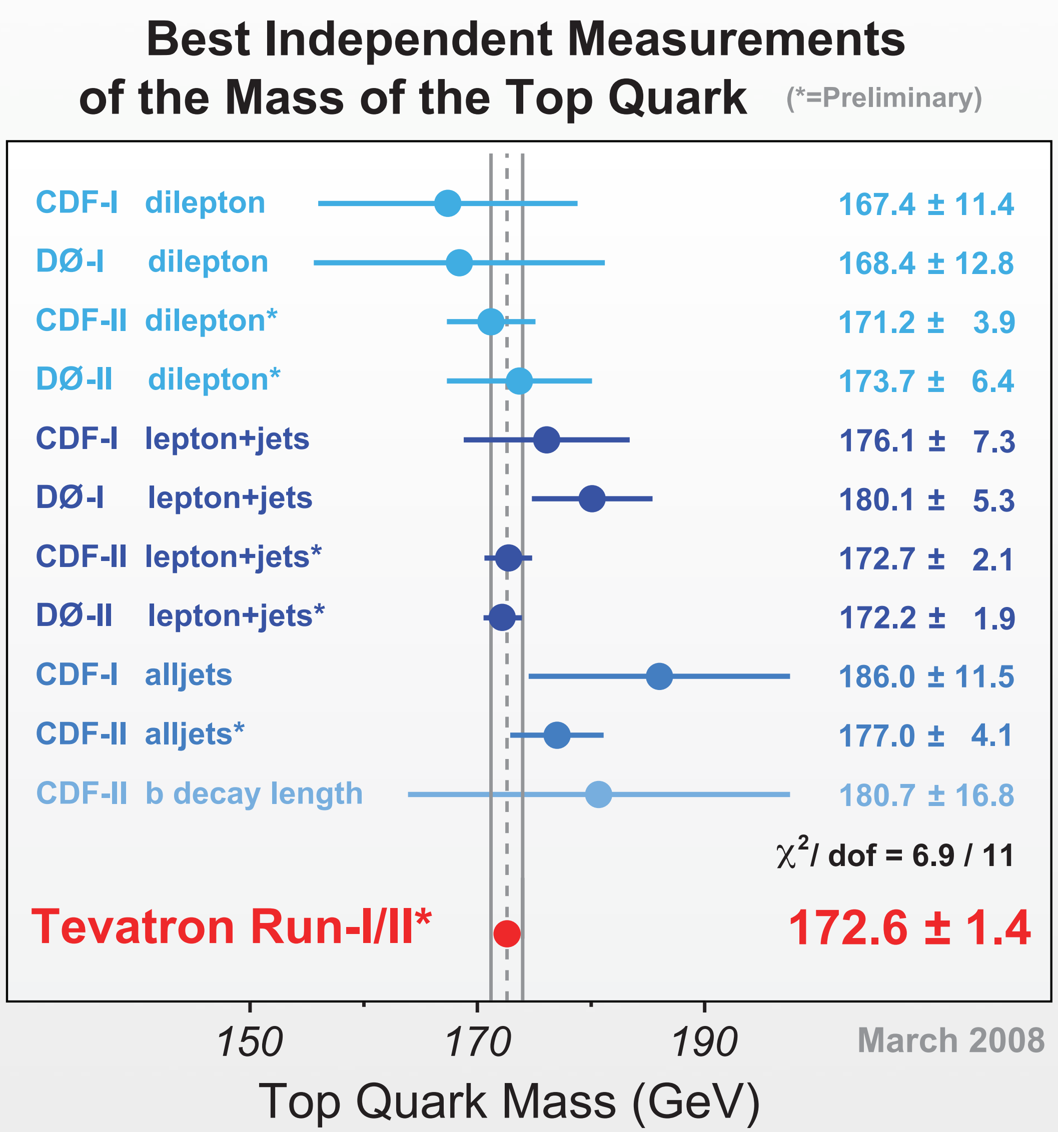
Top Basics: Mass and Cross Section

Top Cross Section (Lepton+Jets): Very Pure Top Sample



- Double SecVtx tag: $\sigma_{t\bar{t}}$ = 8.8 pb
- Background cocktail used in many top analyses
- Normalization mode for FCNC analysis

Top Mass Combination 2008: 0.8% Uncertainty



arXiv:0803.1683 [hep-ex]

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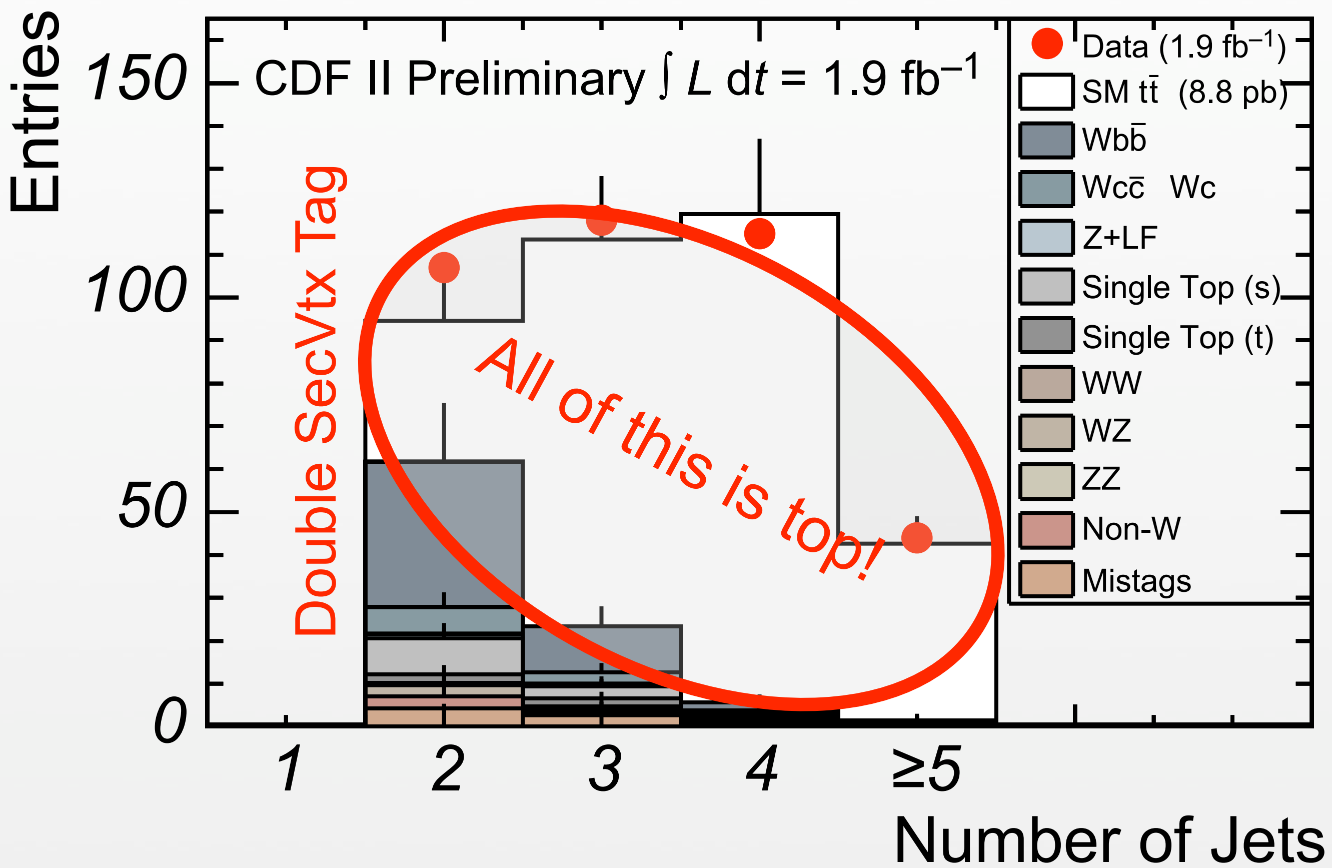

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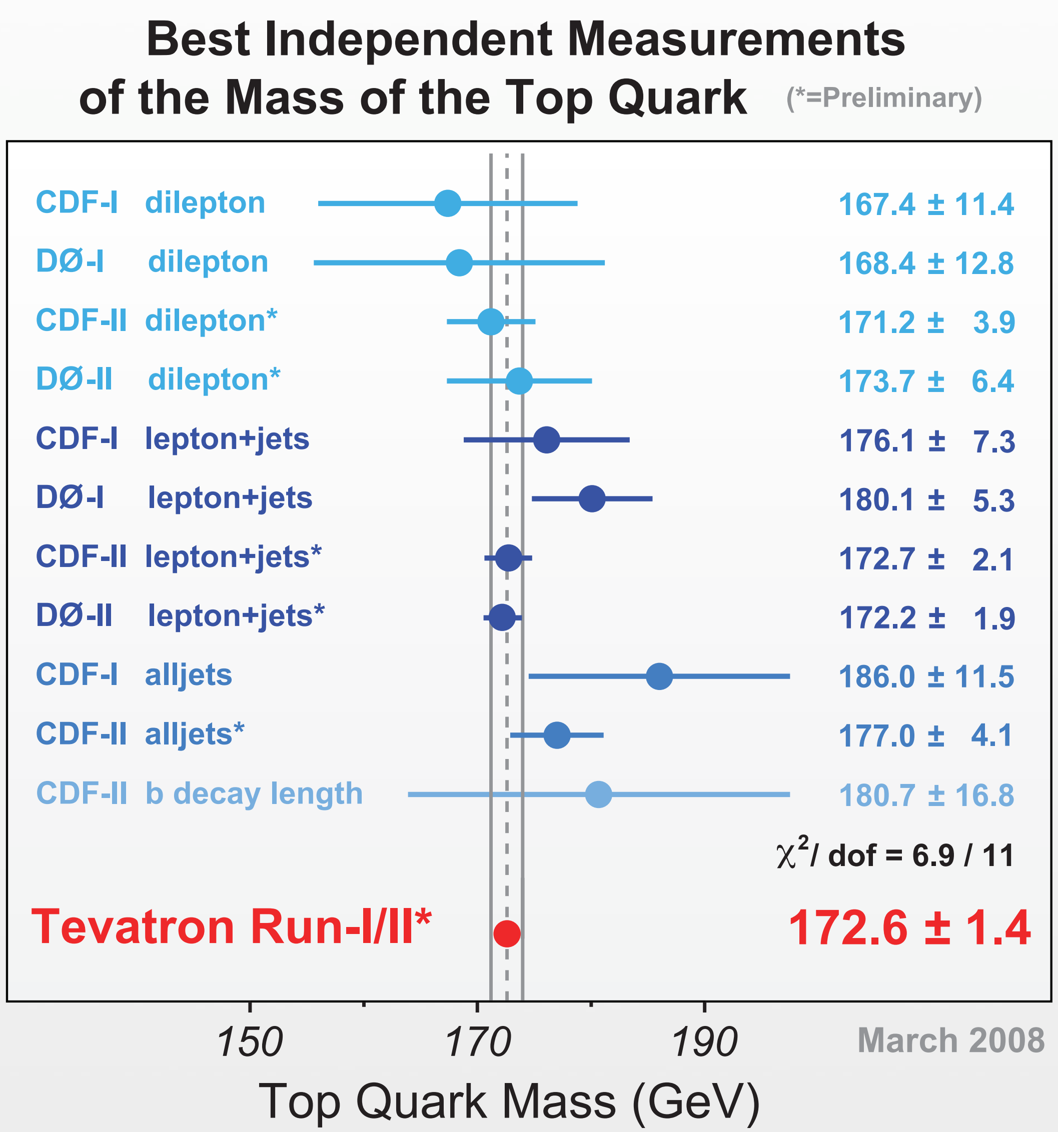


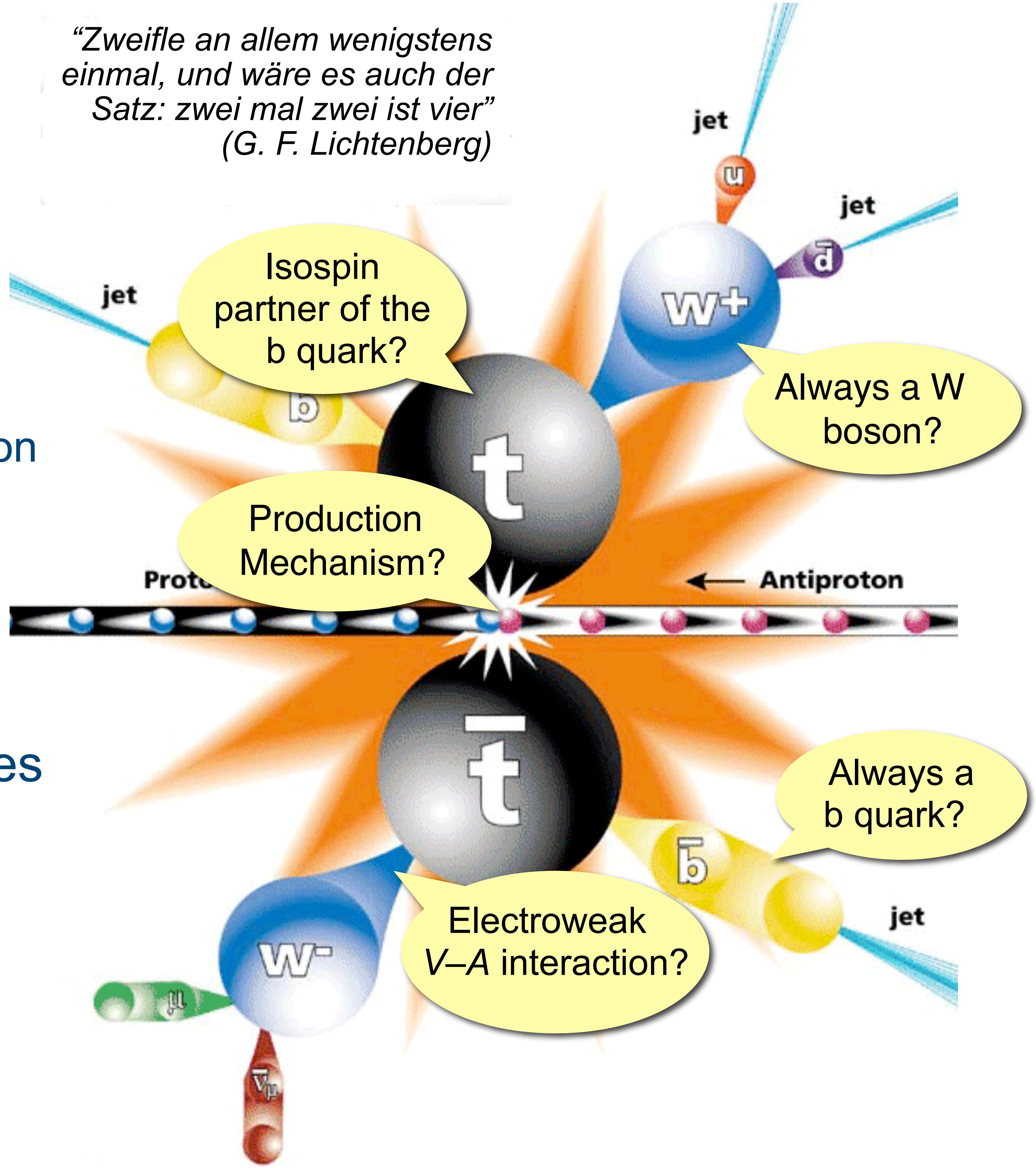
arXiv:0803.1683 [hep-ex]

CDF's Top Properties Program

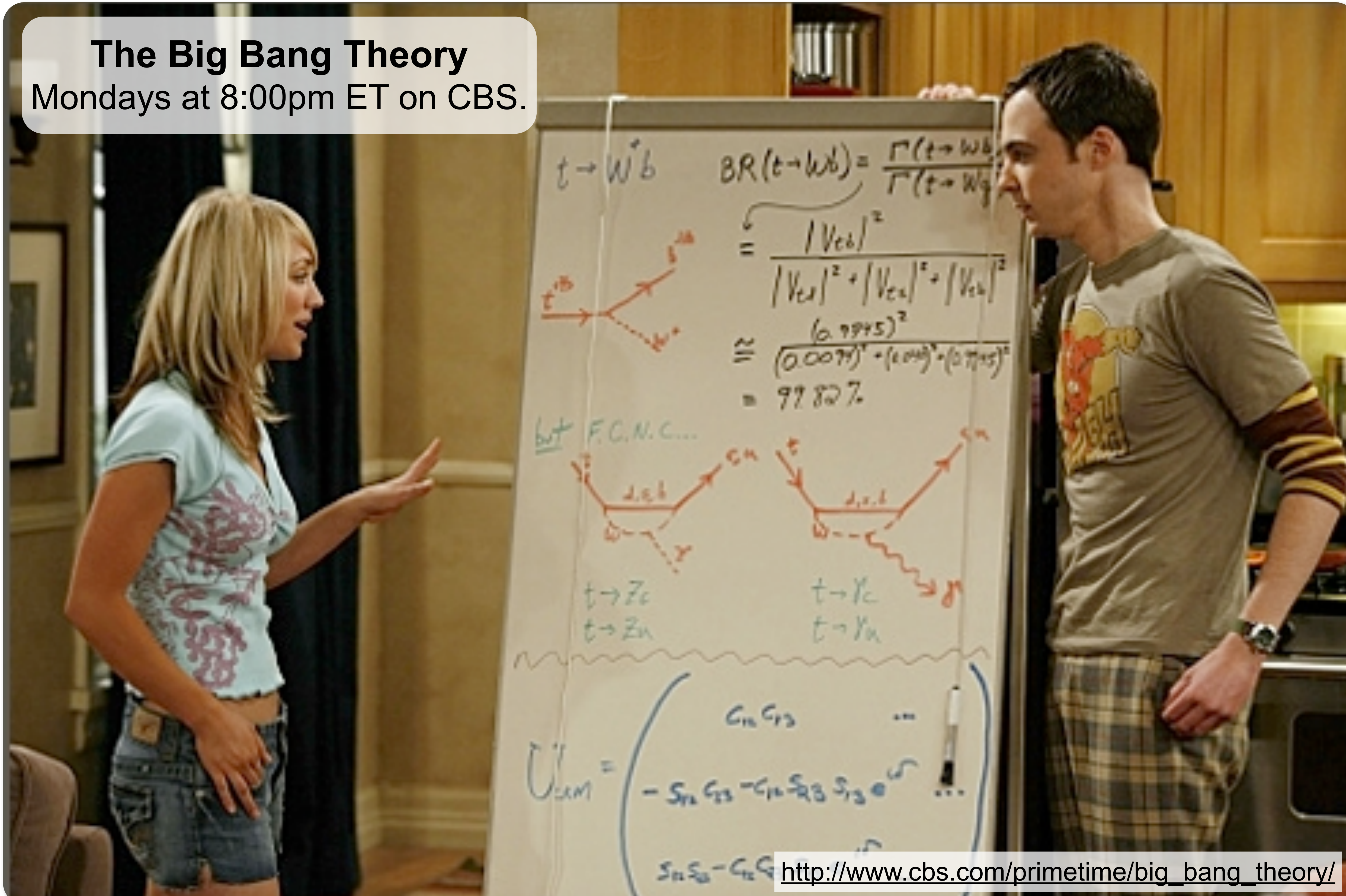
- From top discovery in 1995 to precision physics in 2008:
  - Large top samples
  - Precision mass measurements
  - Evidence for single top production
- Broad top properties program (≈ 50 CDF results for winter conferences, half from top!)
- Measurements of top properties try to answer:

Is the top really the standard model top?

“Zweifle an allem wenigstens einmal, und wäre es auch der Satz: zwei mal zwei ist vier” (G. F. Lichtenberg)



Top Physics Makes Prime Time!



The Big Bang Theory
Mondays at 8:00pm ET on CBS.

http://www.cbs.com/primetime/big_bang_theory/

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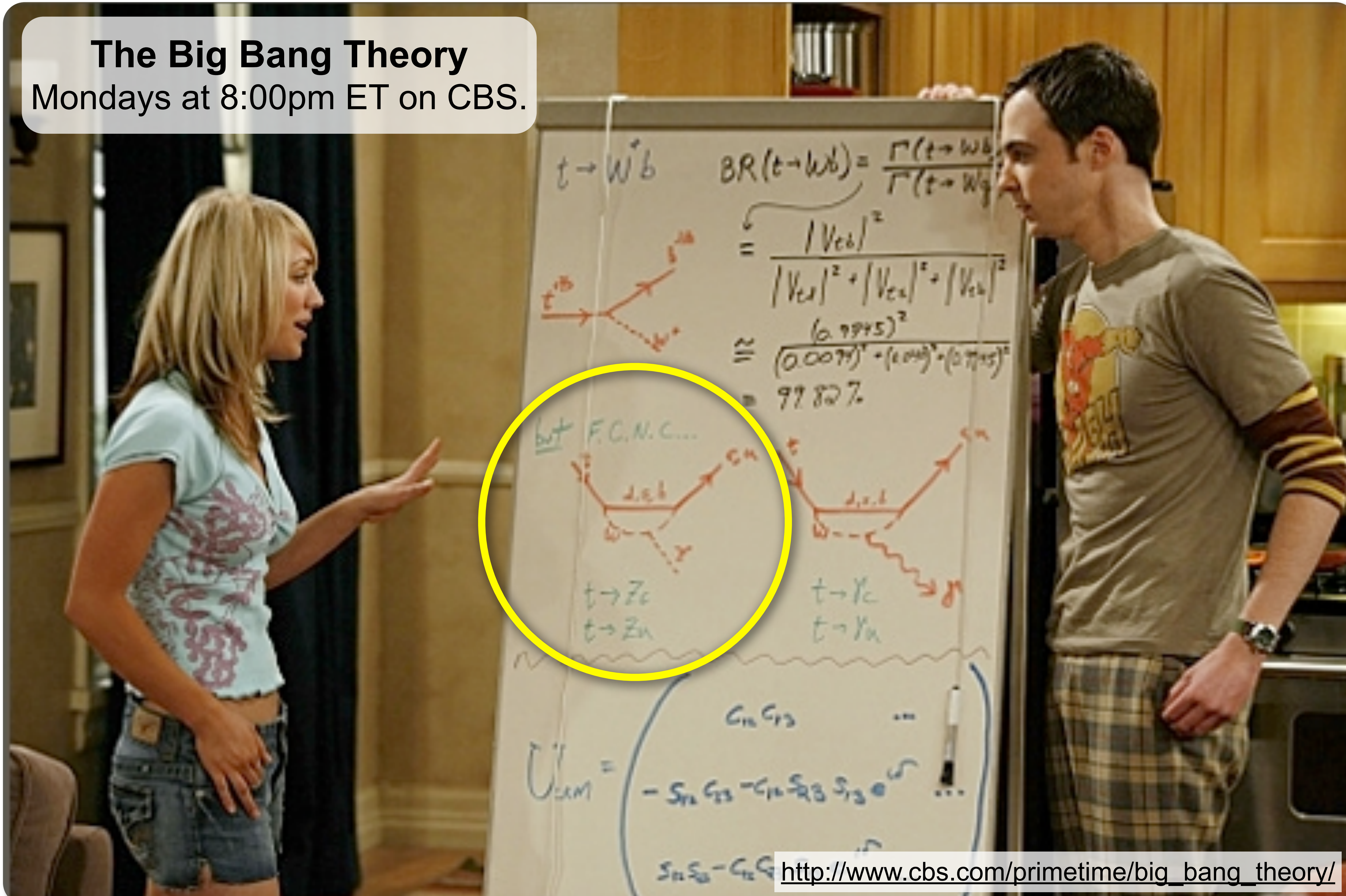

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Basic Ingredients:
Signal and Background

Round I:
Counting Experiment

Round II:
Template Fit

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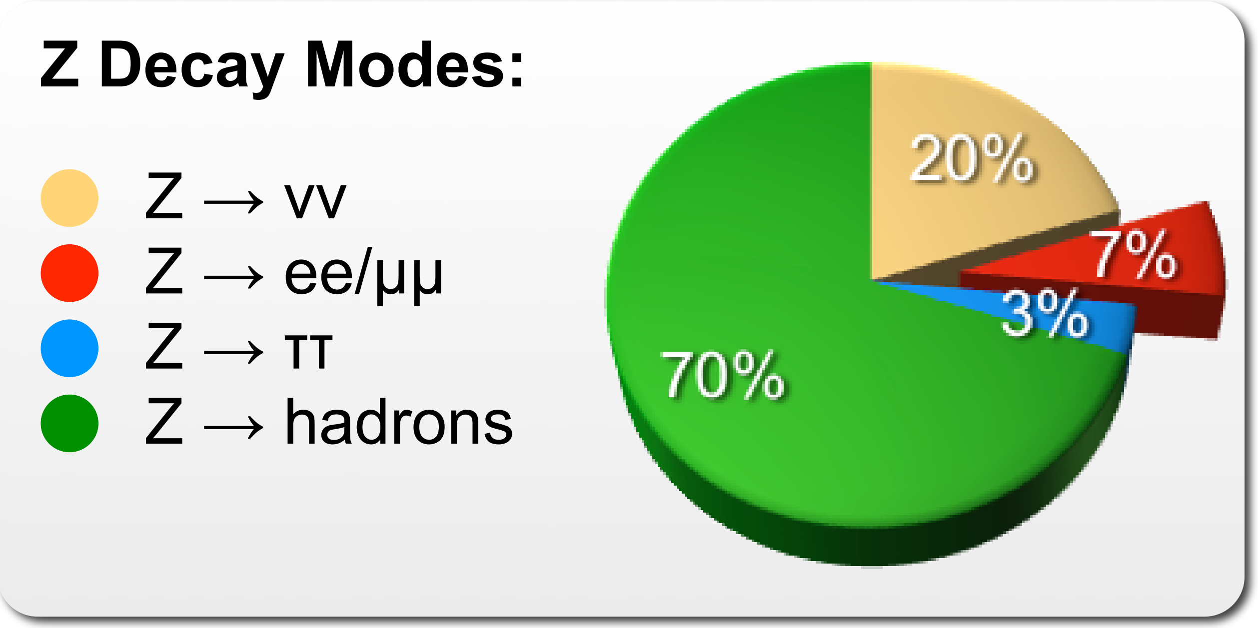
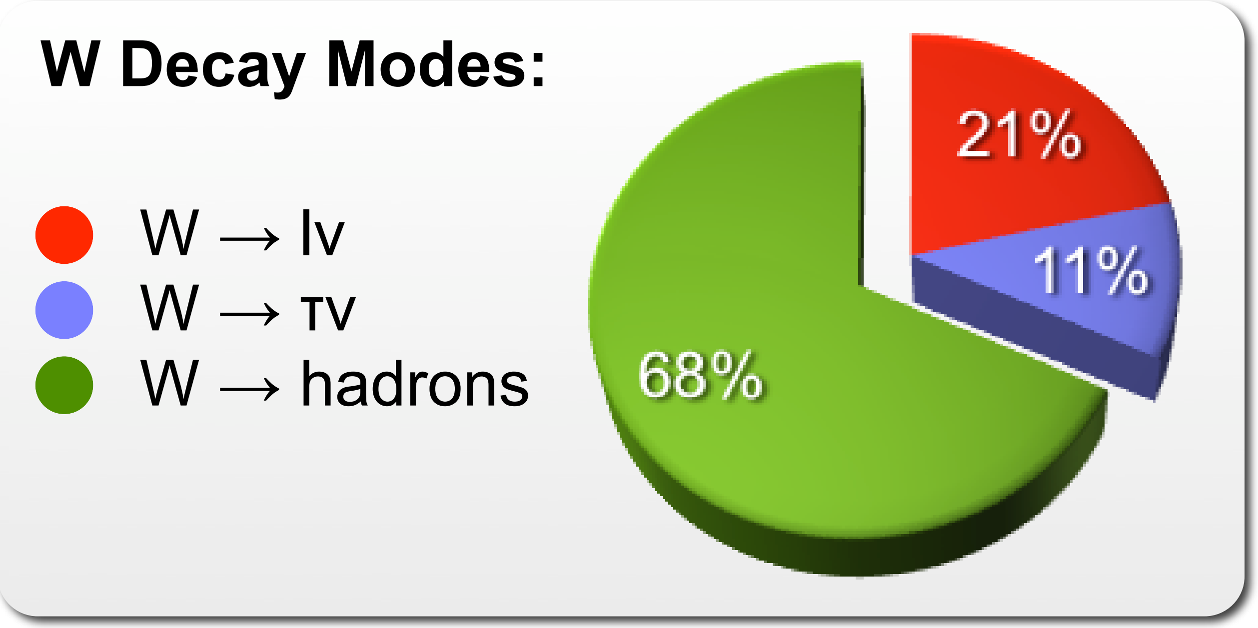
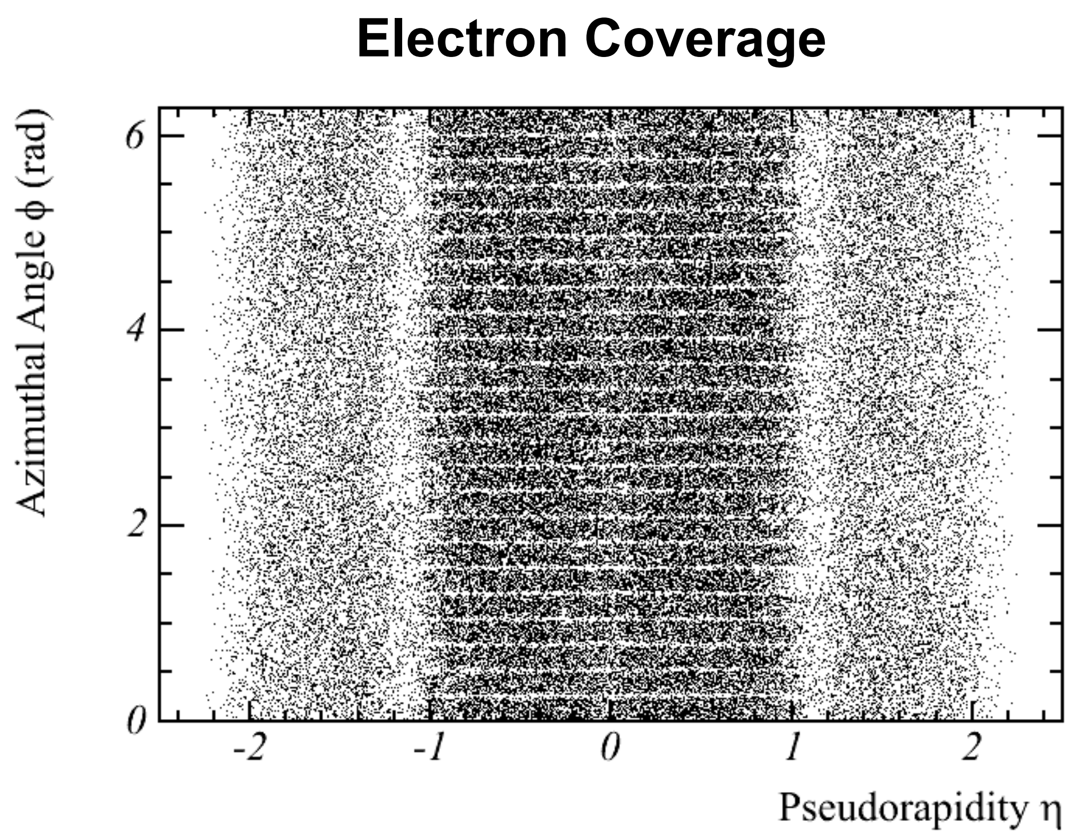
Top FCNC Event Signature

- Basic question: how often do top quarks decay into Zq?
- Result: discovery of top FCNC or limit on branching fraction $B(t \to Zq)$, where q=u,c
- Selected decay channels for $t\bar{t} \to Zq\,Wb$:
  - $Z \to$ charged leptons: very clean signature, lepton trigger
  - $W \to$ hadrons: large branching fractions, no neutrinos ($\to$ event can be fully reconstructed)
- Final signature: $Z + \geq 4$ jets

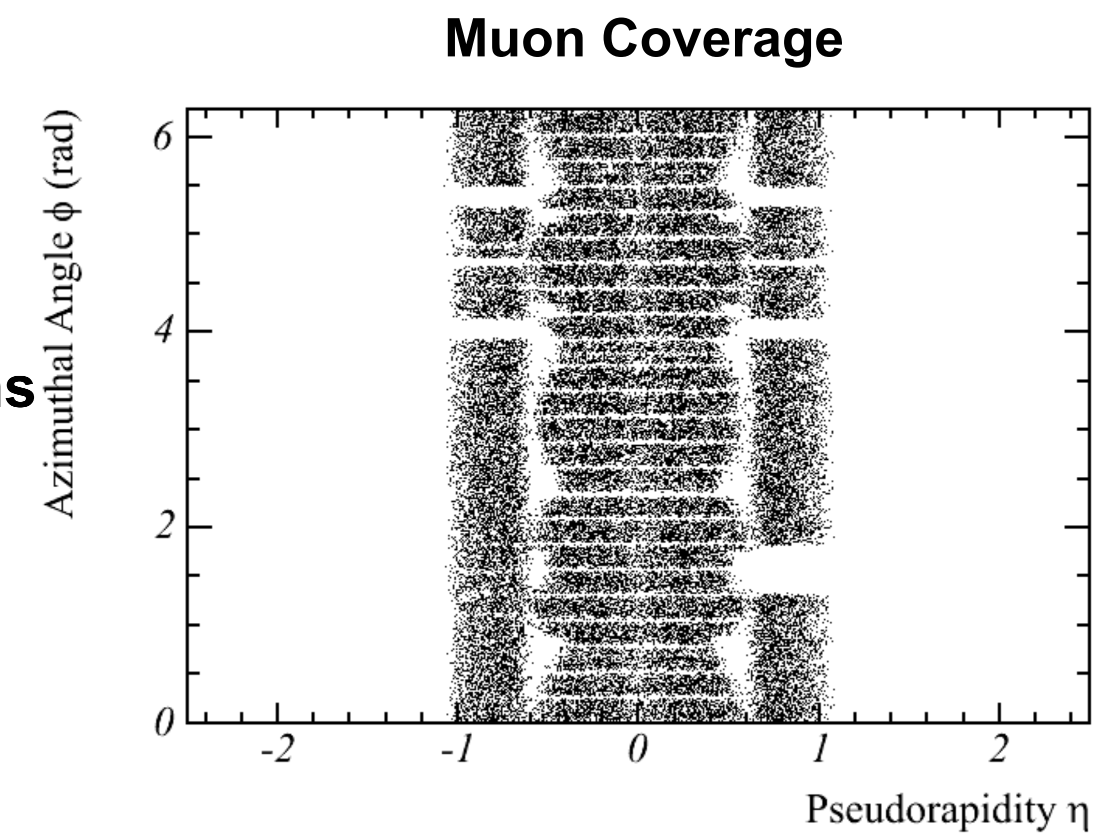




Z Boson Reconstruction



Tight Leptons



- Simple trigger: single e/μ with p_T >18 GeV/c
- Sharp Z resonance, good lepton p_T resolution
  → mass window: 76 GeV/c^2 < M_{ll} < 106 GeV/c^2
- Enhancing the Z acceptance for this analysis:
  - Allow second lepton to be isolated track
    → doubles Z acceptance w.r.t. standard lepton selection
  - Correct track momentum with calorimeter energy → 3% more dielectron pairs

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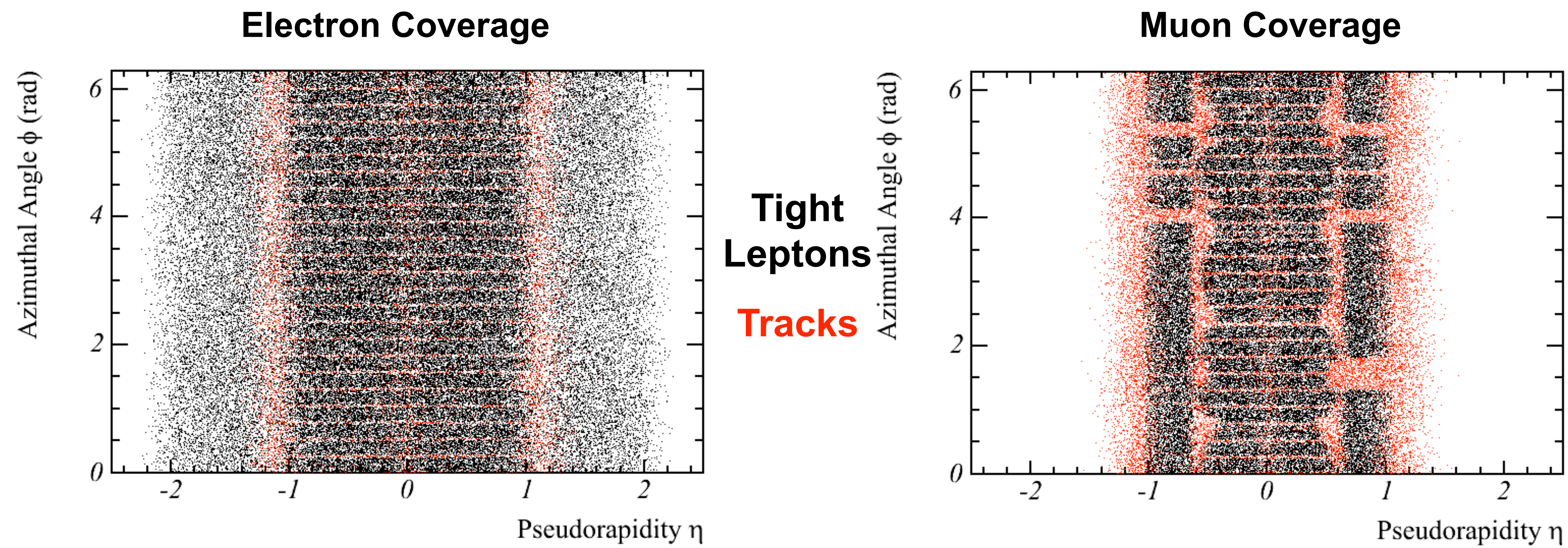

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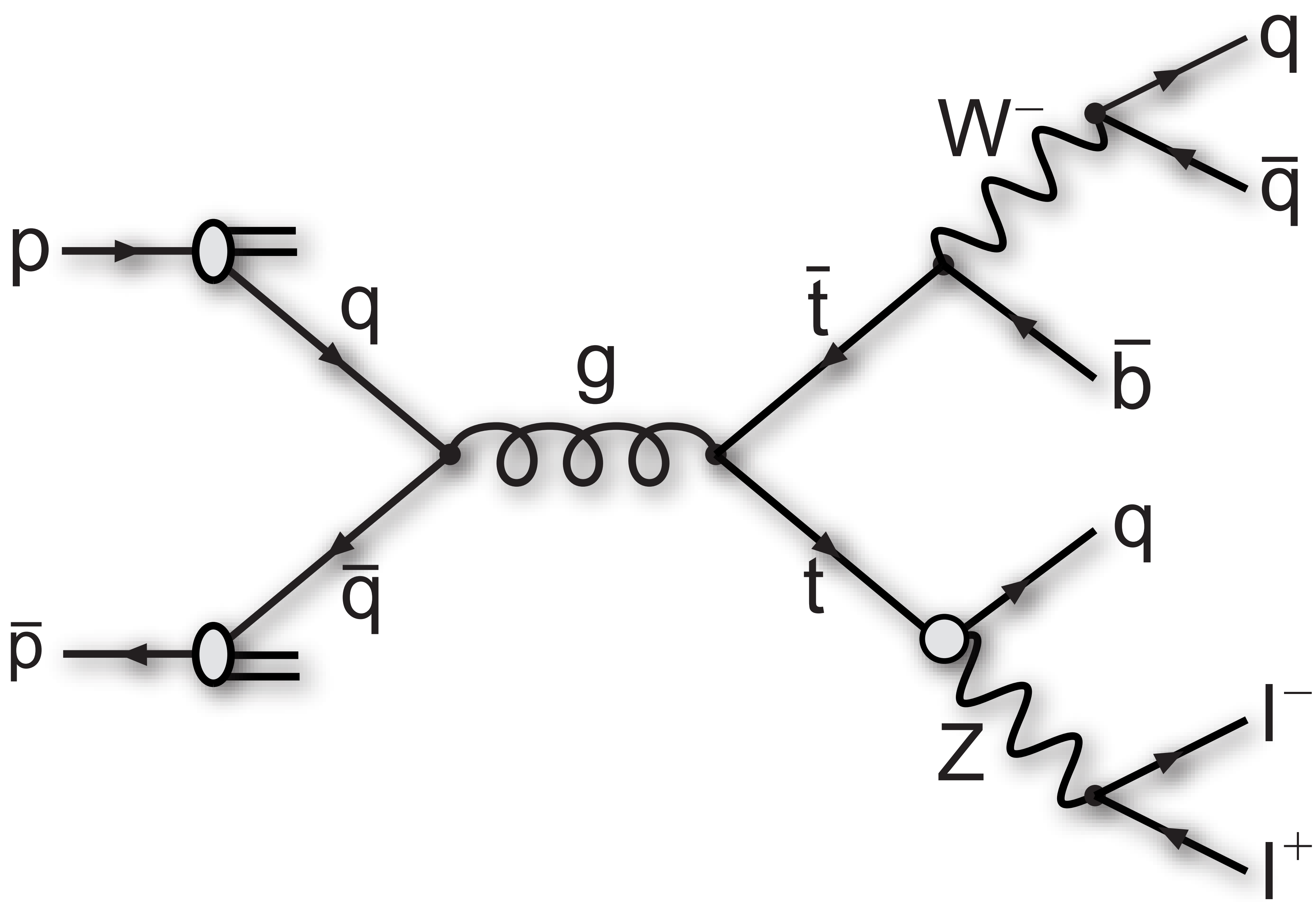
Kinematic Constraints



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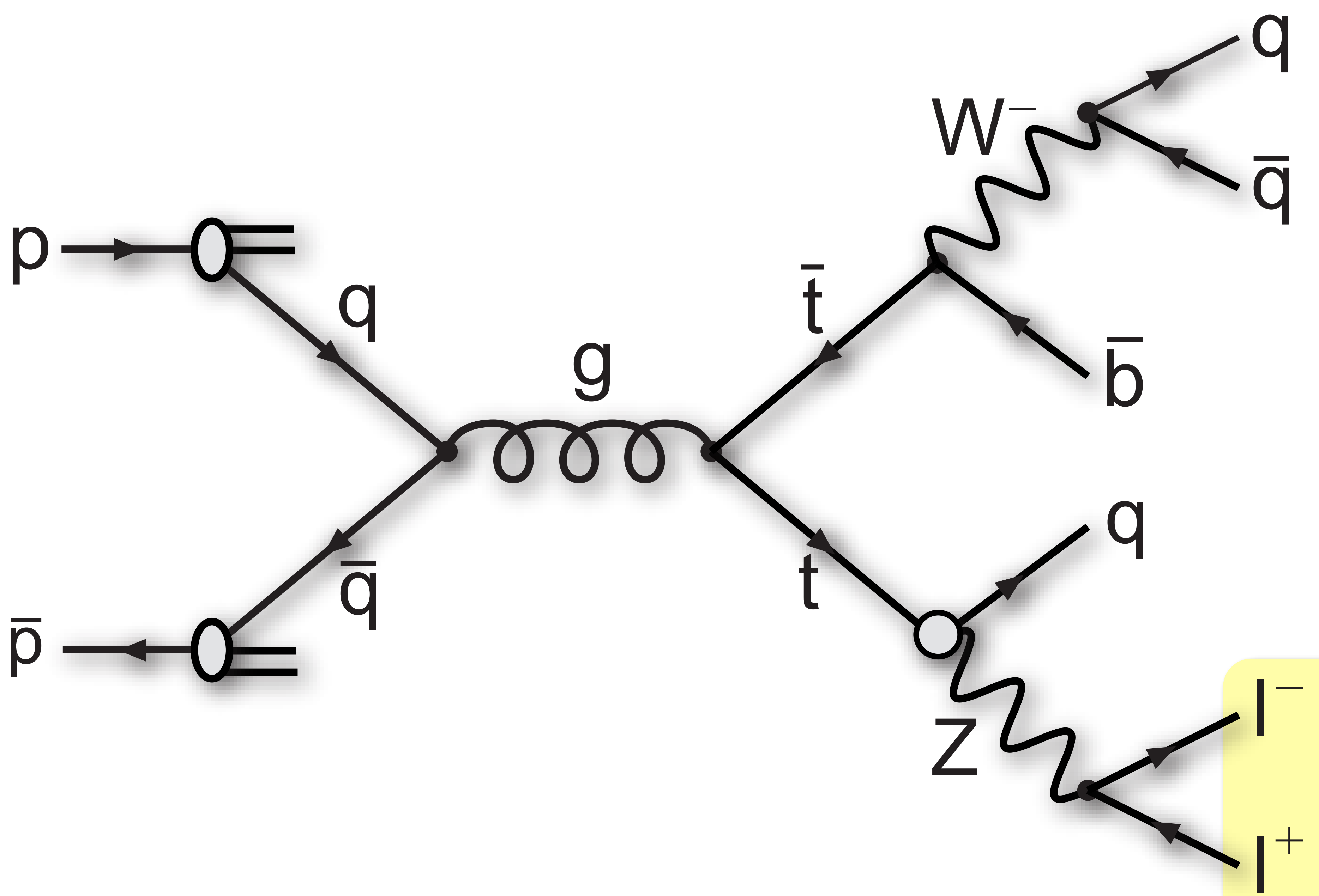
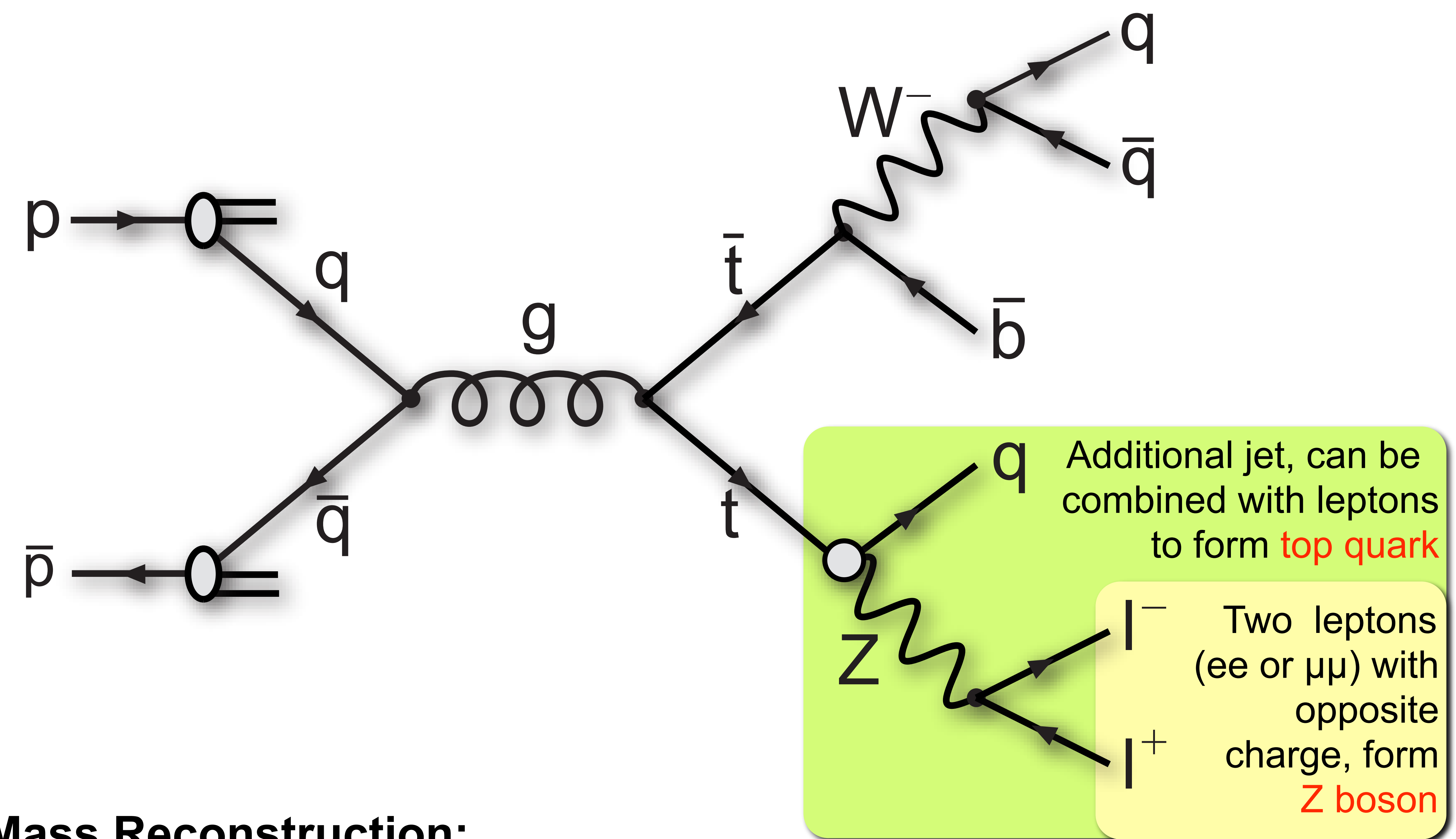


Two leptons (ee or μμ) with opposite charge, form Z boson

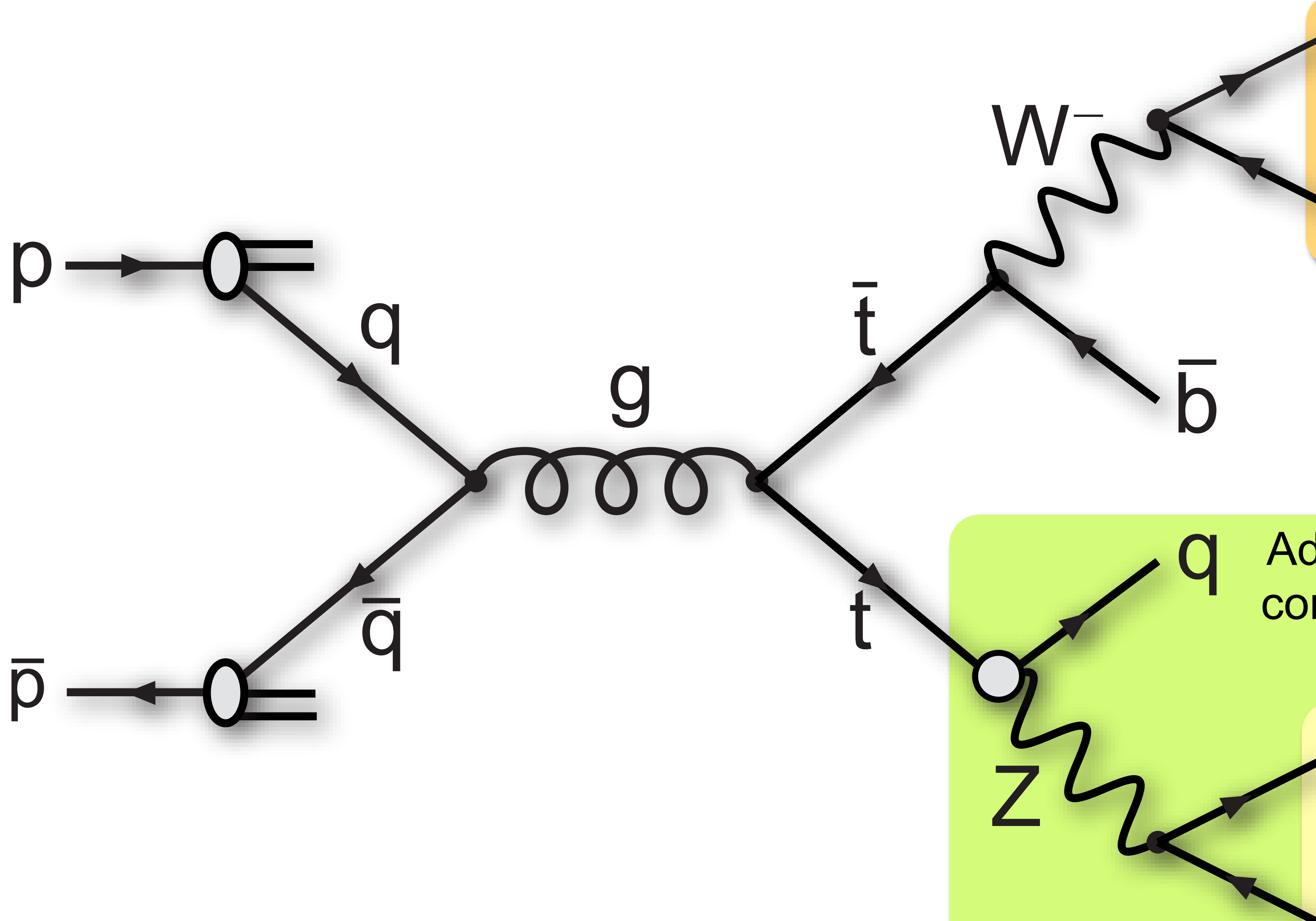
Kinematic Constraints



Mass Reconstruction:

$$\chi^2 = \left(\frac{m_{t\rightarrow Zq,\mathrm{rec}} - m_t}{\sigma_{t\rightarrow Zq}} \right)^2$$

Kinematic Constraints



Two quark jets form W boson

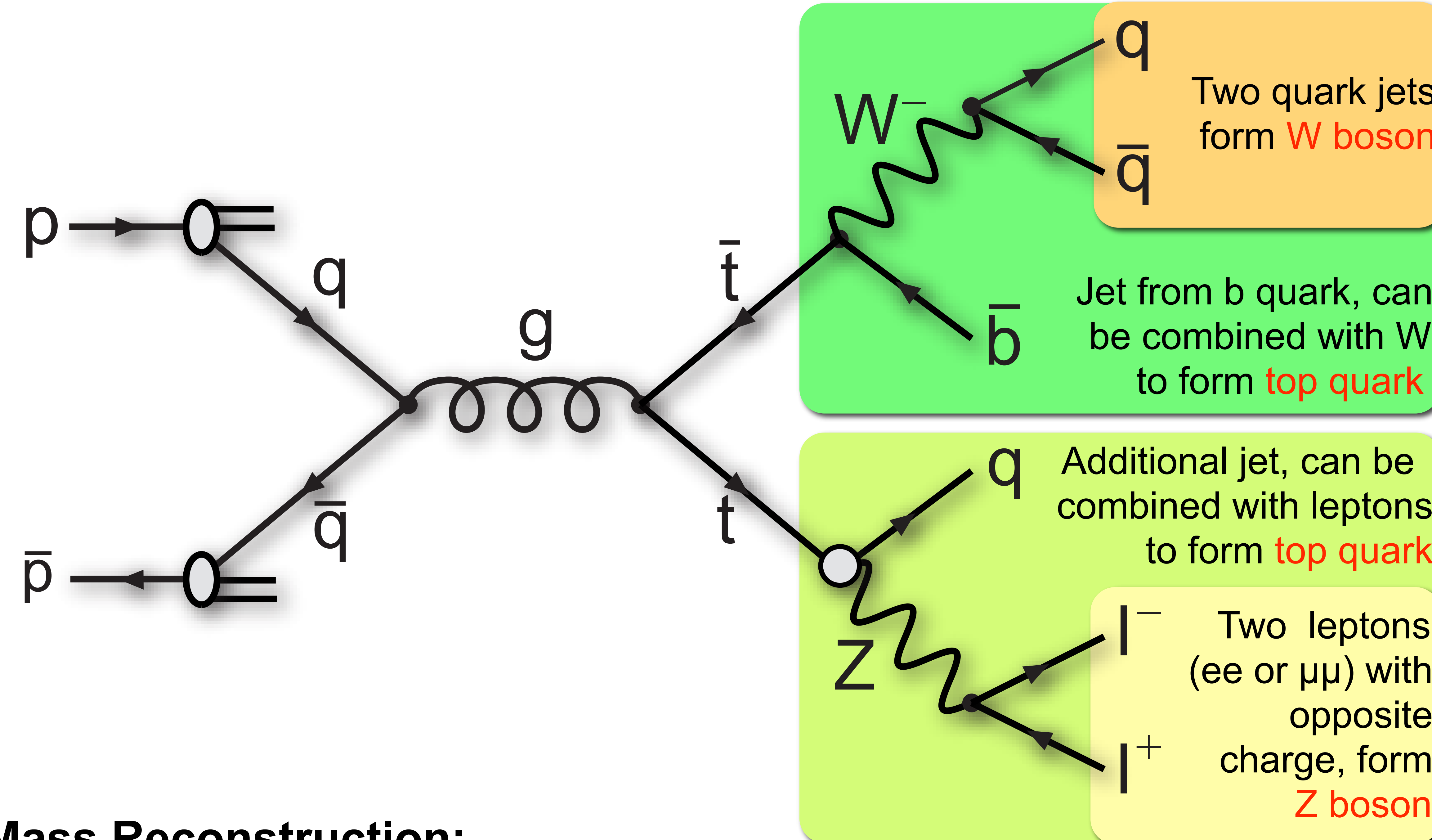
Additional jet, can be combined with leptons to form top quark

Two leptons (ee or μμ) with opposite charge, form Z boson

Mass Reconstruction:

$$\chi^2 = \left(\frac{m_{t\to Zq,\mathrm{rec}} - m_t}{\sigma_{t\to Zq}}\right)^2 + \left(\frac{m_{W,\mathrm{rec}} - m_W}{\sigma_W}\right)^2$$

Kinematic Constraints



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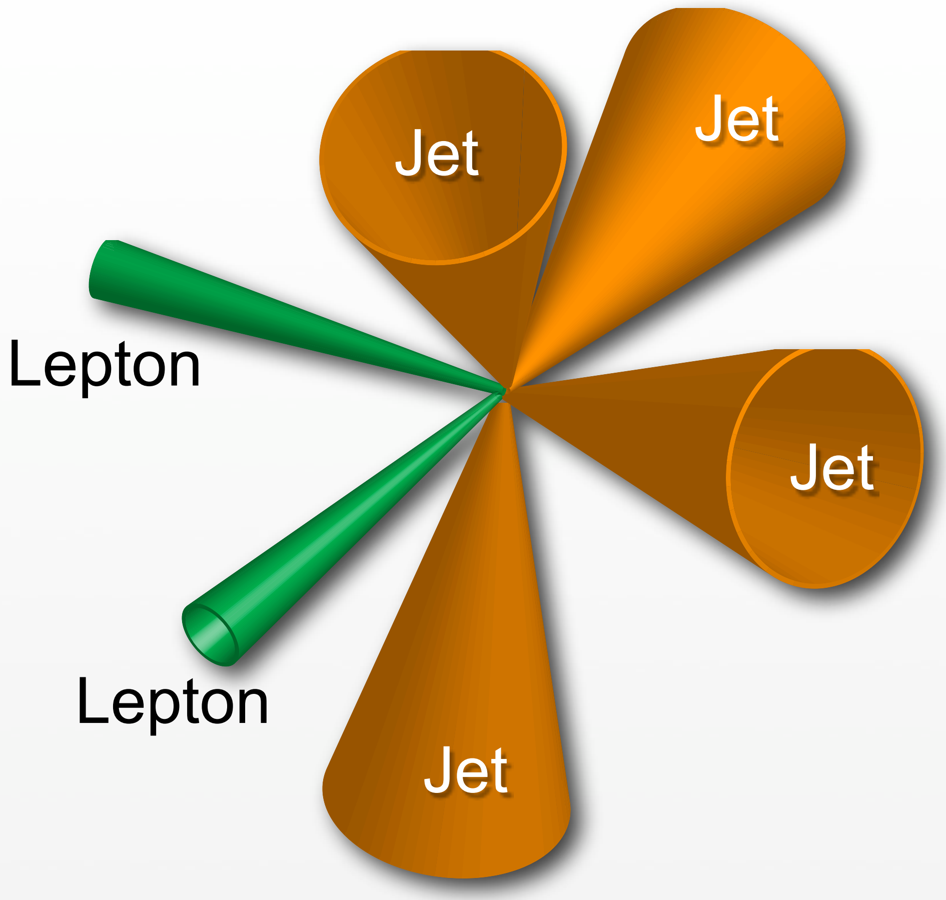
Mass χ^2 Details



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

- Jet-parton assignment unknown:
  - Check all 12 possible combinations of four highest E_T jets
  - Pick combination with lowest mass χ^2
- "Fix" reconstructed W/Z masses
  - Vary momenta of W/Z daughters within resolution to to adjust masses
  - Improves mass resolution → better sensitivity
- Widths reflect mass resolutions as measured in MC simulation:
  - $\sigma_{W,\text{rec}}$ = 15 GeV/c^2
  - $\sigma_{t\to Wb,\text{rec}}$ = 24 GeV/c^2
  - $\sigma_{t\to Zq,\text{rec}}$ = 21 GeV/c^2

Expected Backgrounds

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

Standard Model Background	Signature	Importance	Estimated from
Z+Jets Production	Real Z boson, very similar to FCNC signal	Dominant, most difficult to estimate	Data (normalizations) & MC (shapes)

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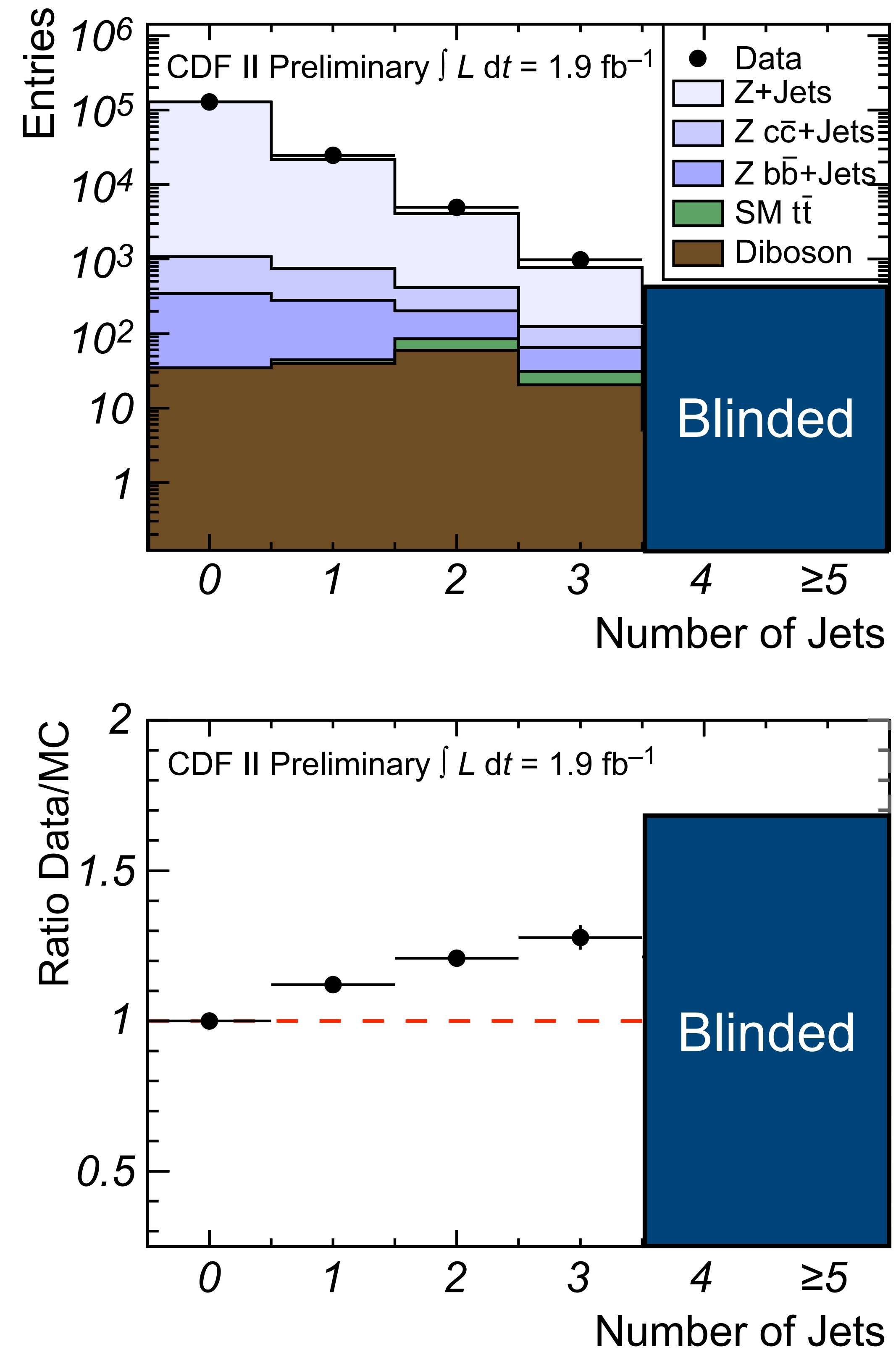
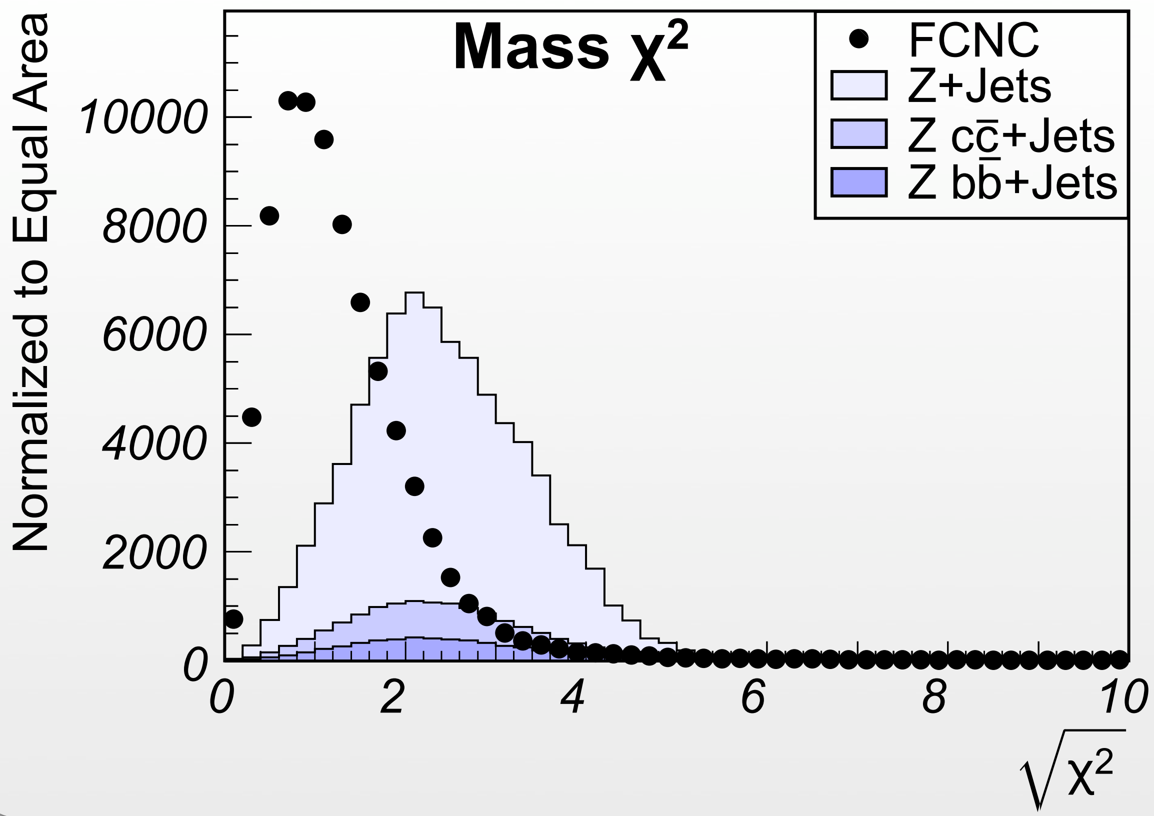
Diboson Production: WZ, ZZ	Real Z boson	Small, more important if b-tag required ($Z \rightarrow b\bar{b}$)	Monte Carlo
Others: W+Jets, WW Production	No real Z boson	Negligible	Monte Carlo & Data

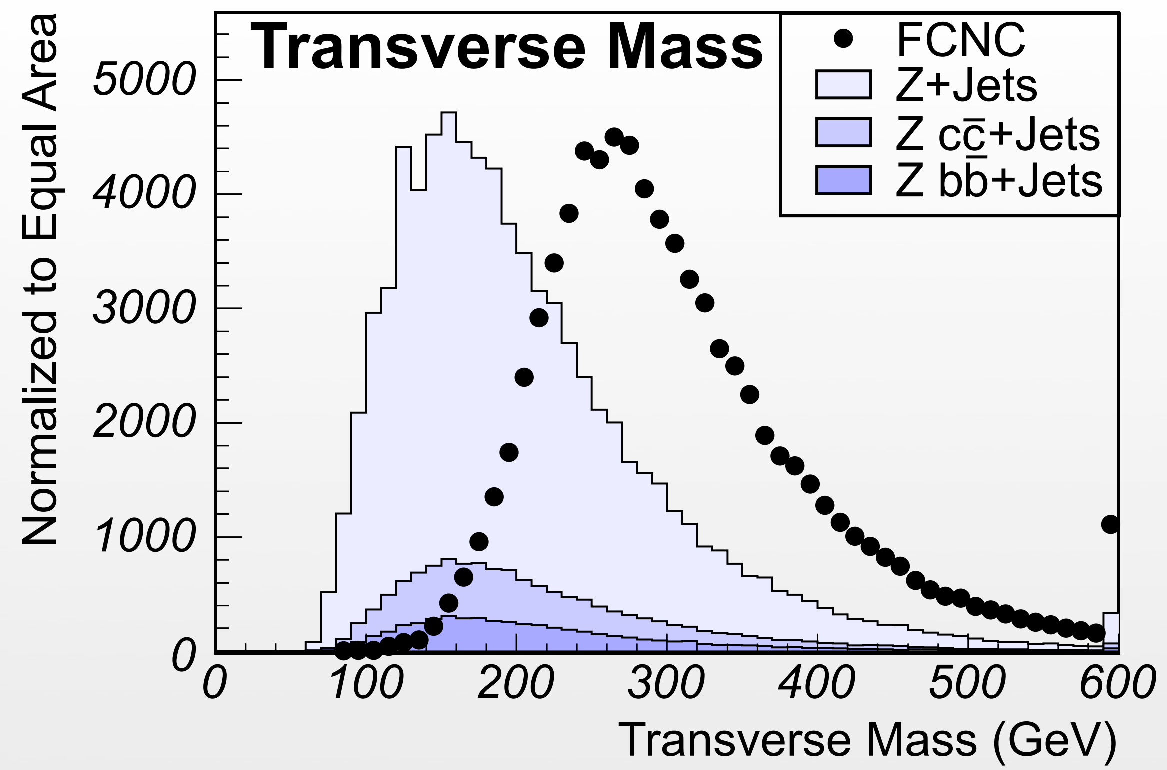
Z+Jets Production

- MC tool for Z+Jets: ALPGEN
  - Modern MC generator for multiparticle final states (exact 2→n matrix elements), PYTHIA for parton showers
  - "MLM matching": remove overlap between jets from matrix element and partons showers
- Comparing ALPGEN with data:
  - Leading order generator: no absolute prediction for cross section
  - Underestimate of number of events with large jet multiplicities, large uncertainties
- Our strategy: only shapes of kinematic distributions from MC, normalization from control samples in data



Separating Signal from Background





- Mass χ^2: combination of mass constraints – best discriminator

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

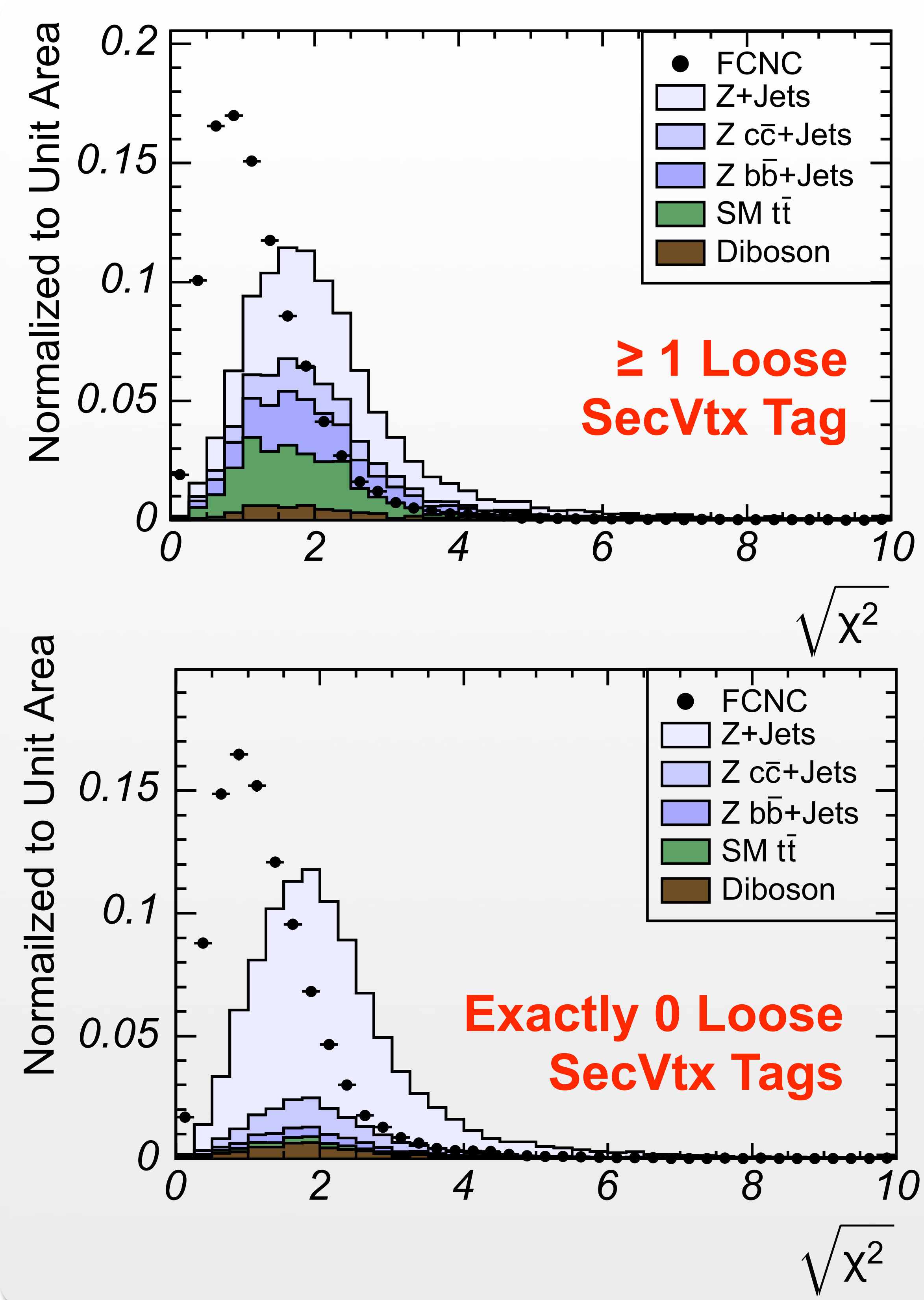
- Transverse mass: top decays (including FCNC) are more central than Z+jets

$$M_T = \sqrt{\left(\sum E_T\right)^2 - \left(\sum \vec{p}_T\right)^2}$$

- Jet transverse energies: FCNC signal has four “hard” jets, background processes: jets have to come from gluon radiation

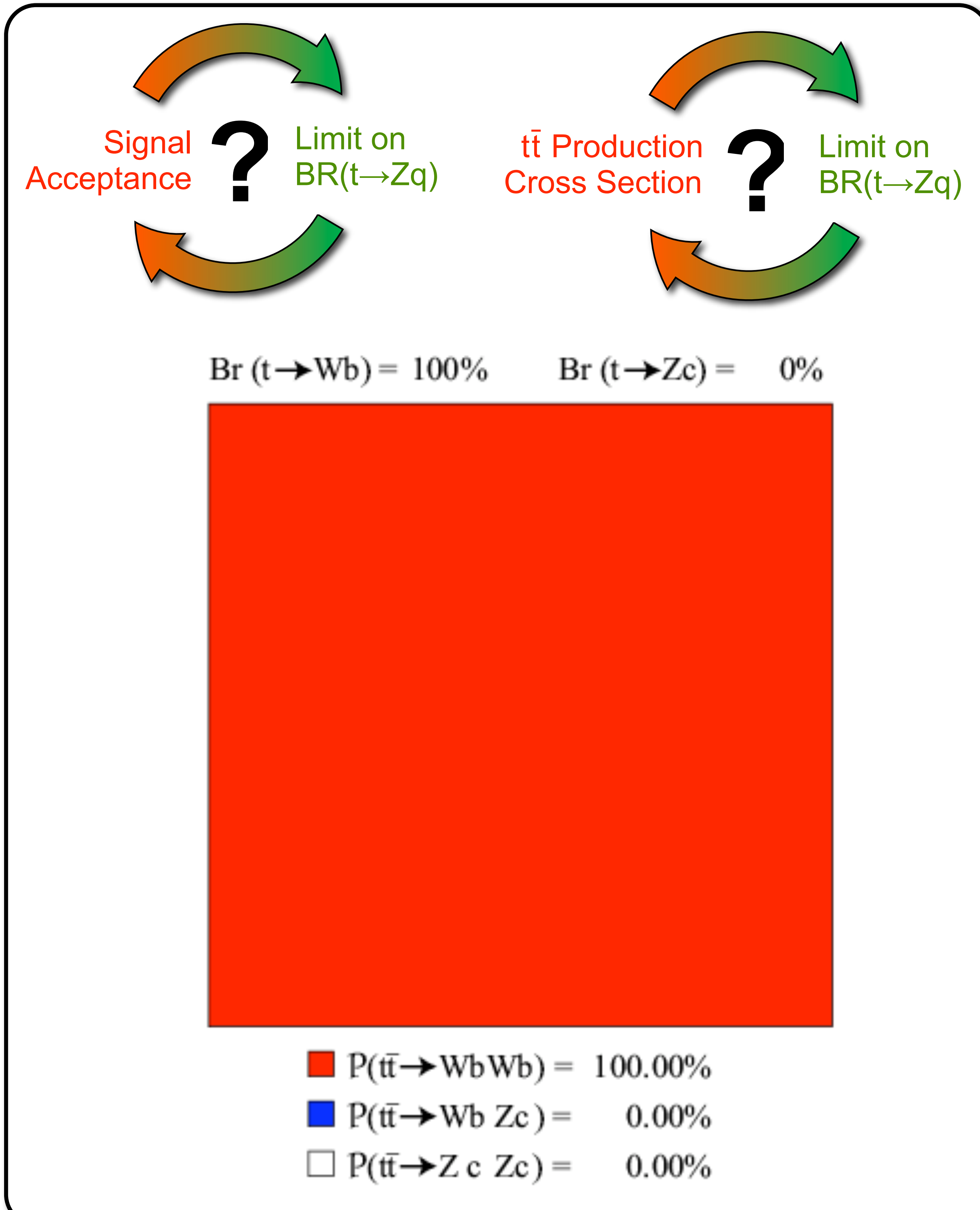
To B-Tag or not to B-Tag?

- Requiring a SecVtx b-tag?
  - Advantage:
    Better discrimination against Z+jets
  - Disadvantage:
    Reduction of data sample size
- Solution: use both!
  - Split sample in tagged and anti-tagged
  - Combine samples in limit calculation
- Need to take into account event migration between samples
  - Correlated systematic uncertainties: affect samples in same direction
  - Anti-correlated uncertainties: move events between samples (e.g. b-tagging efficiency)



Acceptance Algebra: Catch 22?

- Question: how do we convert event counts into limit on $B(t\to Zq)$?
  - Circular dependency #1: Limit calculation requires signal acceptance, but signal acceptance depends on limit
  - Circular dependency #2: Measure limit on fraction of $t\bar{t}$ production cross section, but cross section changes with changing FCNC contribution



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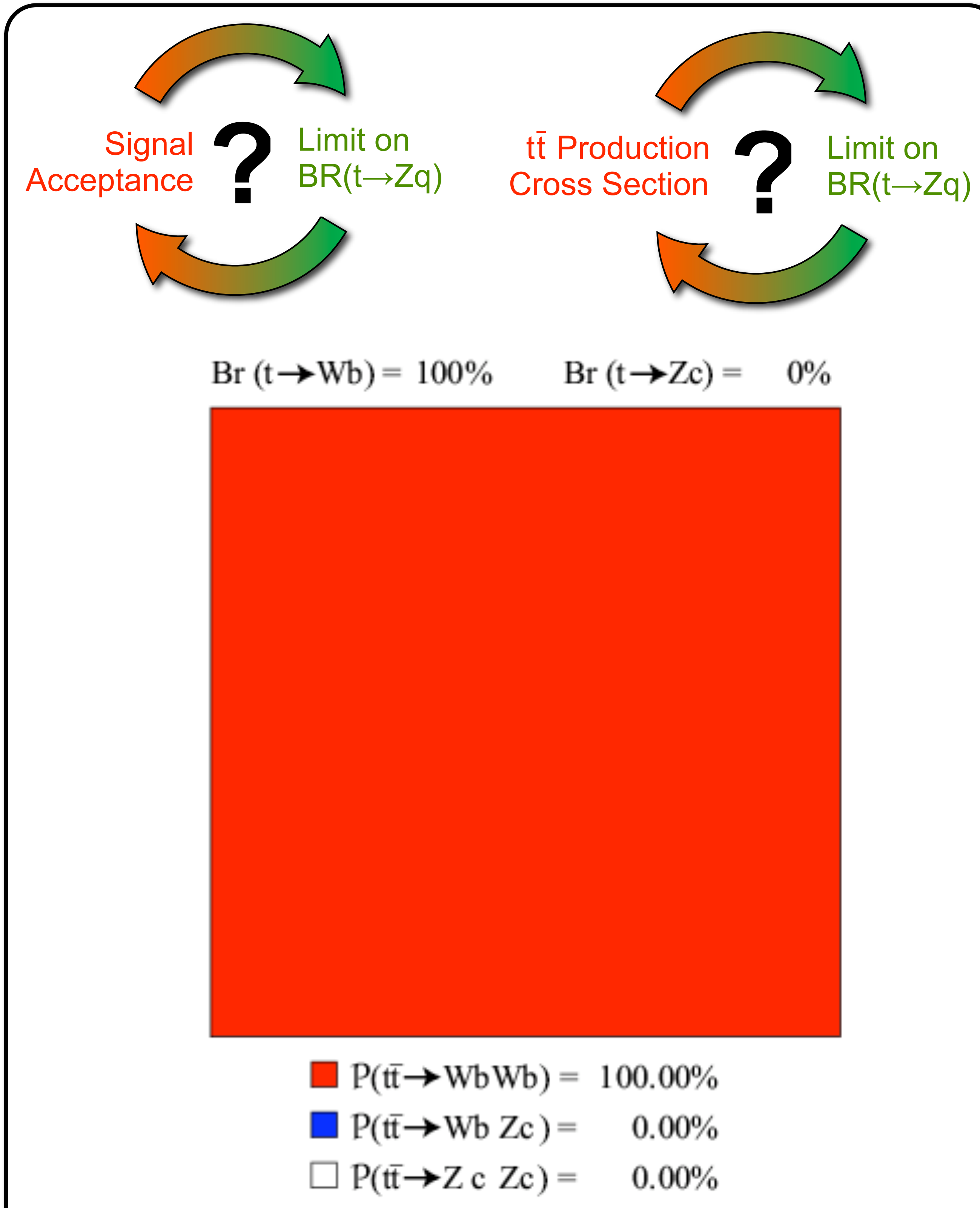
  - Circular dependency #1: Limit calculation requires signal acceptance, but signal acceptance depends on limit
  - Circular dependency #2: Measure limit on fraction of $t\bar{t}$ production cross section, but cross section changes with changing FCNC contribution
- Solution: "running acceptance" – functional form of dependencies implemented in limit machinery
  - Signal acceptance dynamically adjusted as a function of B(t→Zq)
  - Signal normalized to measured $t\bar{t}$ production cross section measurement
  - $t\bar{t}$ cross section re-interpreted as a function of BR(t→Zq) to allow for FCNC contribution



Outline of the Talk

Search for FCNC in Top Quark Decays

Basic Ingredients:
Signal and Background

↓

**Round I:
Counting Experiment**

↓

Round II:
Template Fit

Blind Counting Experiment: Outline

- Blind analysis: avoid biases by looking into the data too early
- Analysis strategy :
  - Blind signal region: Z + ≥ 4 jets (minus control region in Z + ≥ 4 jets)
  - Optimization on data control regions and Monte Carlo (MC) simulation only (event selection, prediction of backgrounds, systematic uncertainties)
  - Very last step: “opening the box”, i.e. look into signal regions in data (tagged and anti-tagged)

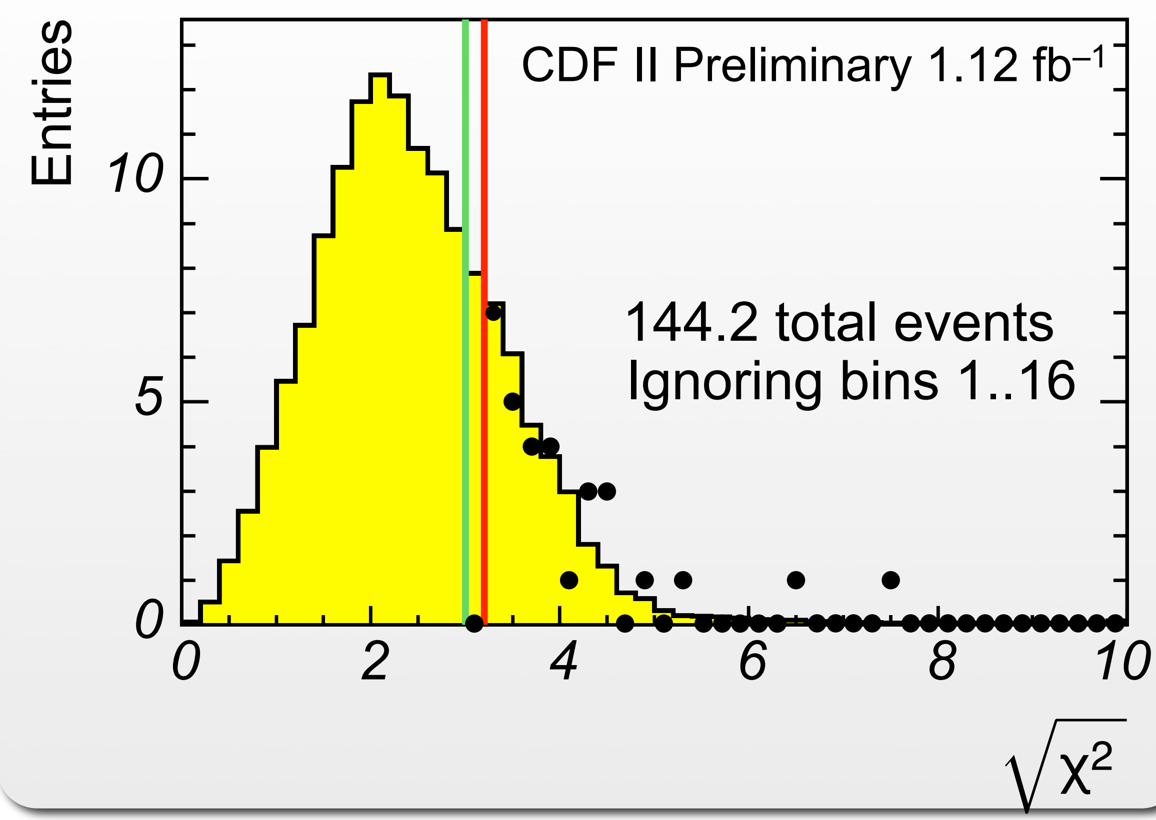
Optimization and Backgrounds

- Selection cuts optimized for best expected limit (in the absence of an FCNC signal)
  - Separately for tagged and anti-tagged sample
  - Expected 95% C.L. upper limit on B(t→Zq): 6.8% ± 3.0% (L3 limit: 13.7%)
- Background estimate: from data
  - Fit to tail of mass χ^2 distribution (little FCNC signal)
  - Use mass χ^2 shape from MC to estimate total background
  - Tagging rate: similar technique

Final Event Selection

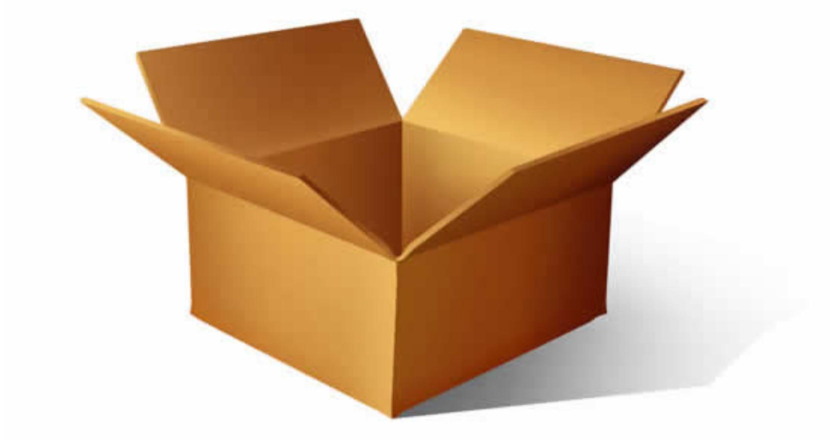
Kinematic Variable	Optimized Cut
Z Mass	$\in [76,106]\,\mathrm{GeV}/c^2$
Leading Jet E_T	$> 40\,\mathrm{GeV}$
Second Jet E_T	$> 30\,\mathrm{GeV}$
Third Jet E_T	$> 20\,\mathrm{GeV}$
Fourth Jet E_T	$> 15\,\mathrm{GeV}$
Transverse Mass	$> 200\,\mathrm{GeV}$
$\sqrt{\chi^2}$	< 1.6 (b-tagged)
	< 1.35 (anti-tagged)

Background Estimate



The World's Best Limit on B(t → Zq)

- Opening the box with 1.12 fb^{-1}



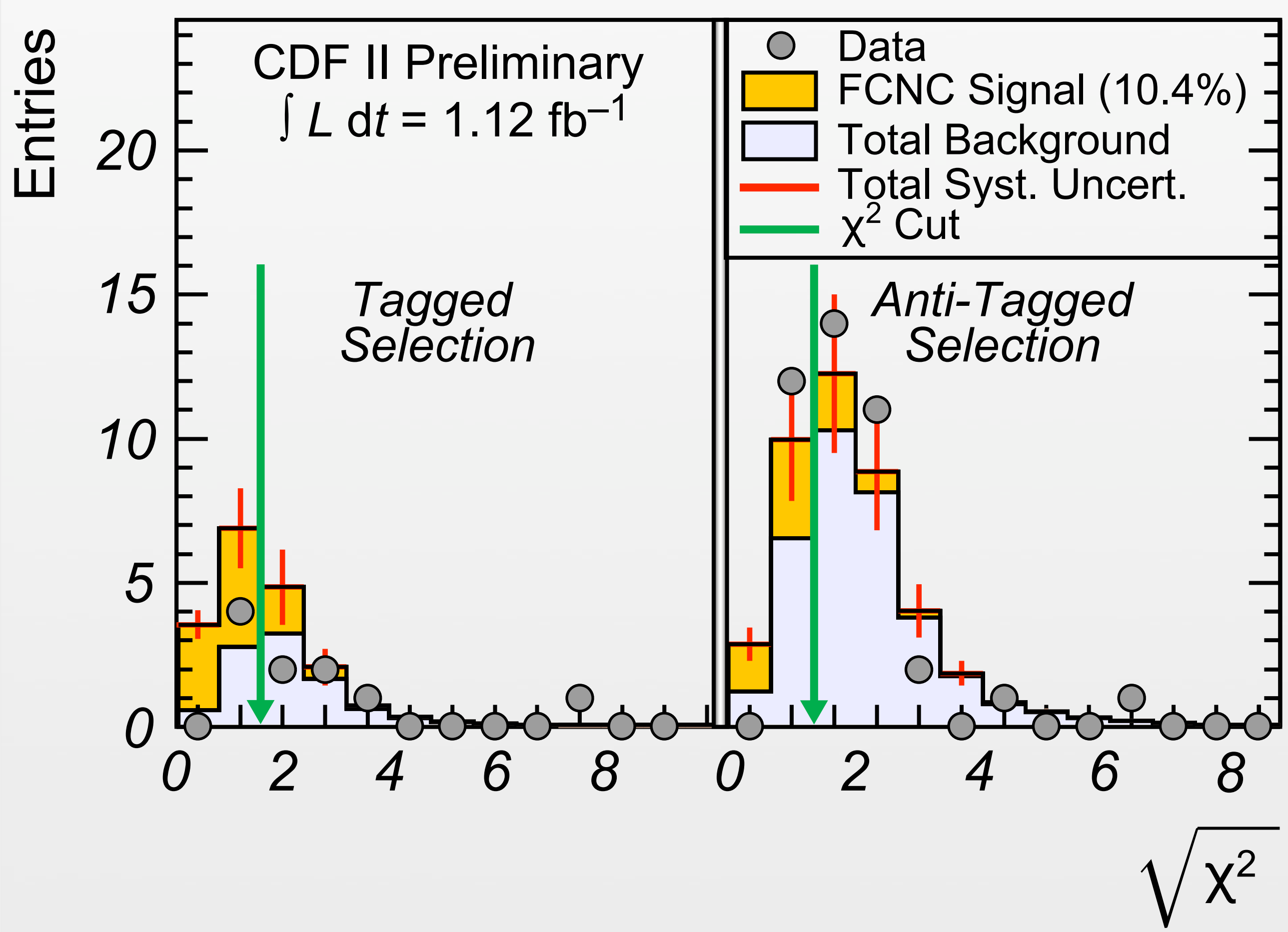
  - Event yield consistent with background only
  - Fluctuated about 1σ high: slightly unlucky
- Result: The World's Best Limit!

B(t→Zq) < 10.4% @ 95% C.L.

  - Expected limit: 6.8% ± 3.0%
  - 25% better than L3 (13.7%)
  - 3x better than CDF Run I (33%)

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

Mass χ^2 (95% C.L. Upper Limit)




The World's Is Not Enough
Best
Limit

Outline of the Talk

Search for FCNC in Top Quark Decays

Basic Ingredients:
Signal and Background

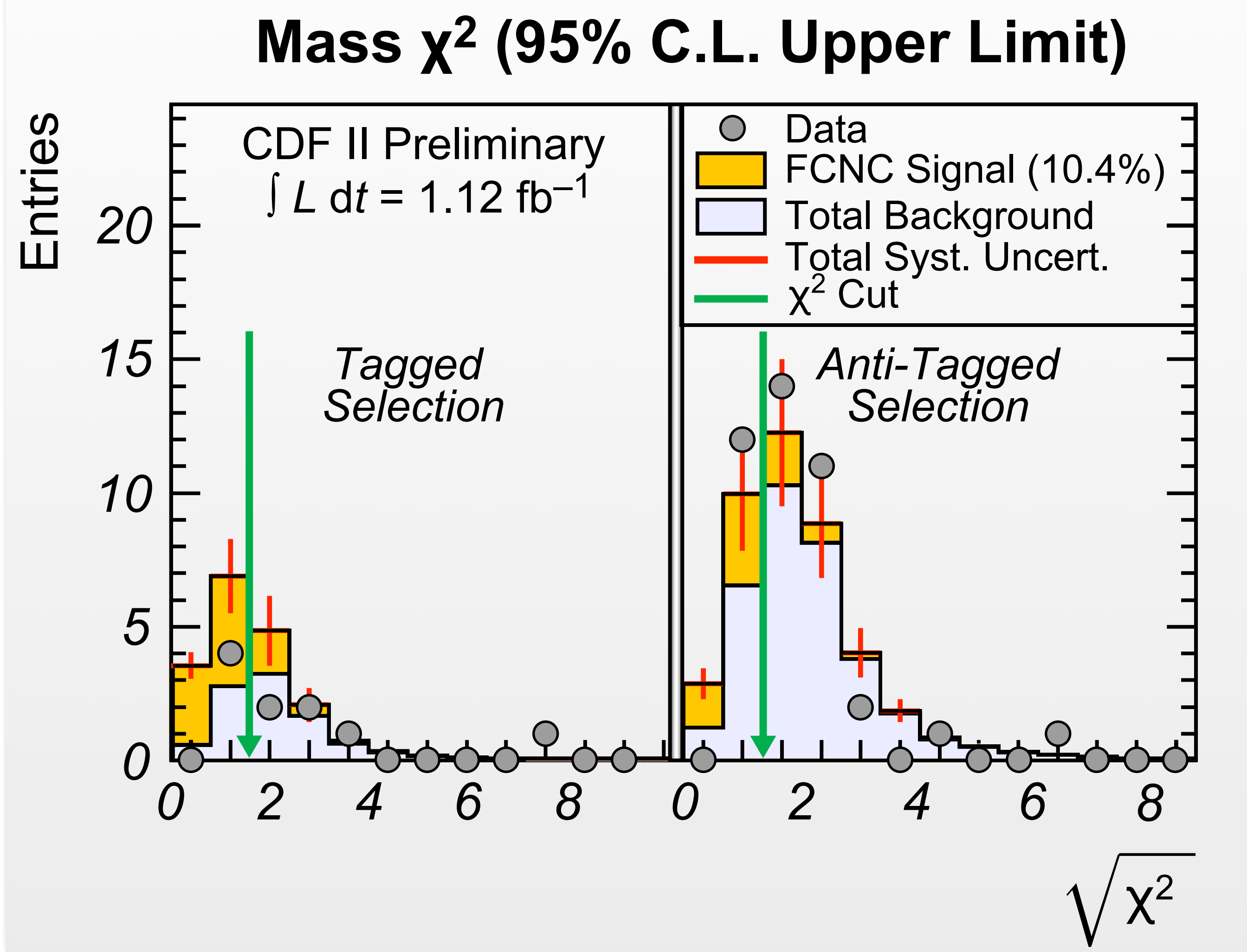
Round I:
Counting Experiment

Round II:
Template Fit

How can we do better?

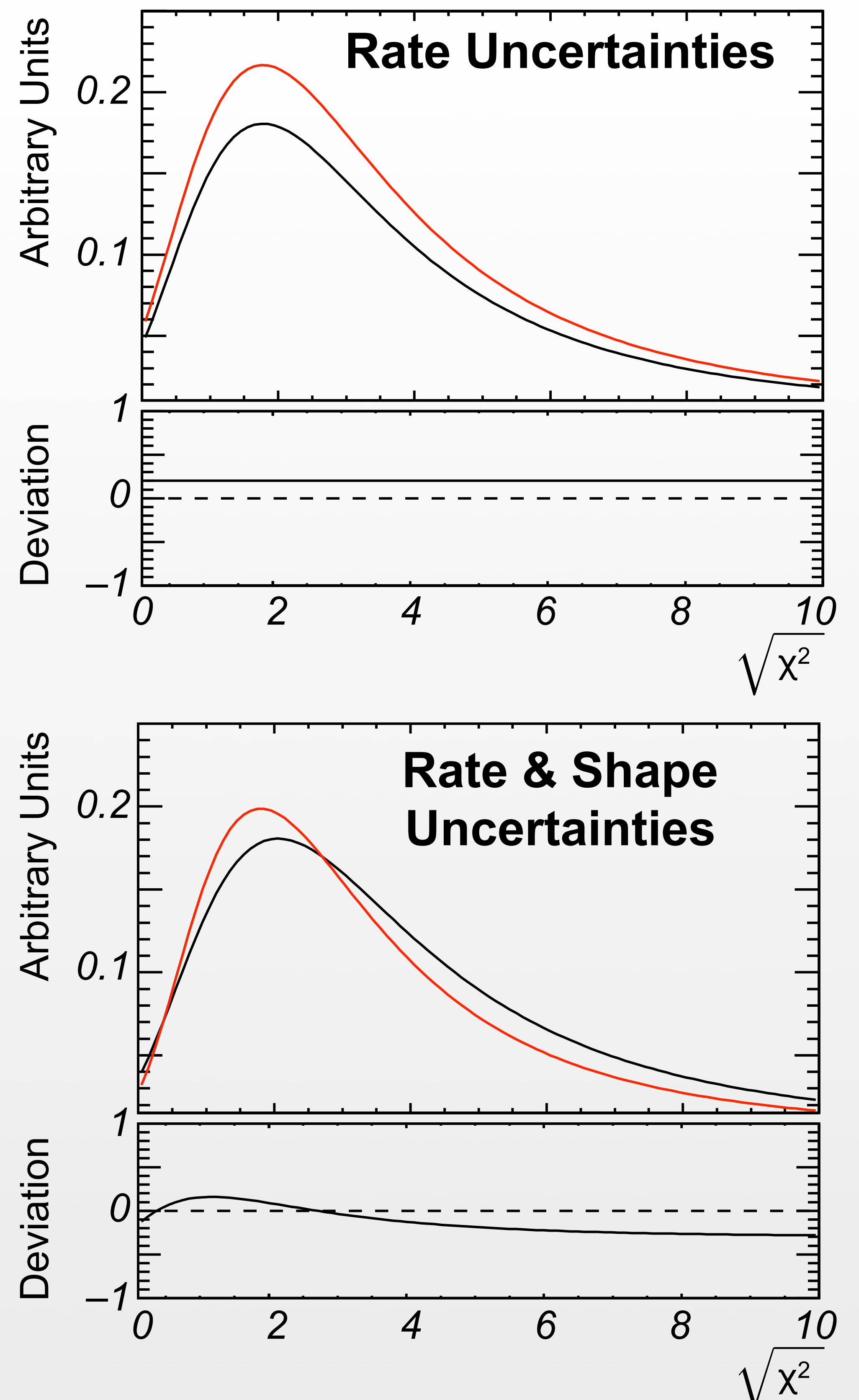
- 70% more data:
  Update with 1.9 fb^{-1}
- More sensitivity:
  Template fit to $\sqrt{\chi^2}$ shape
  - Exploit full shape information
  - Reduce sensitivity to background normalization
- Build on previous experience:
  - Same event selection
  - Same acceptance algebra
  - Same method of calculating (most) systematic uncertainties

Counting Experiment → Template Fit

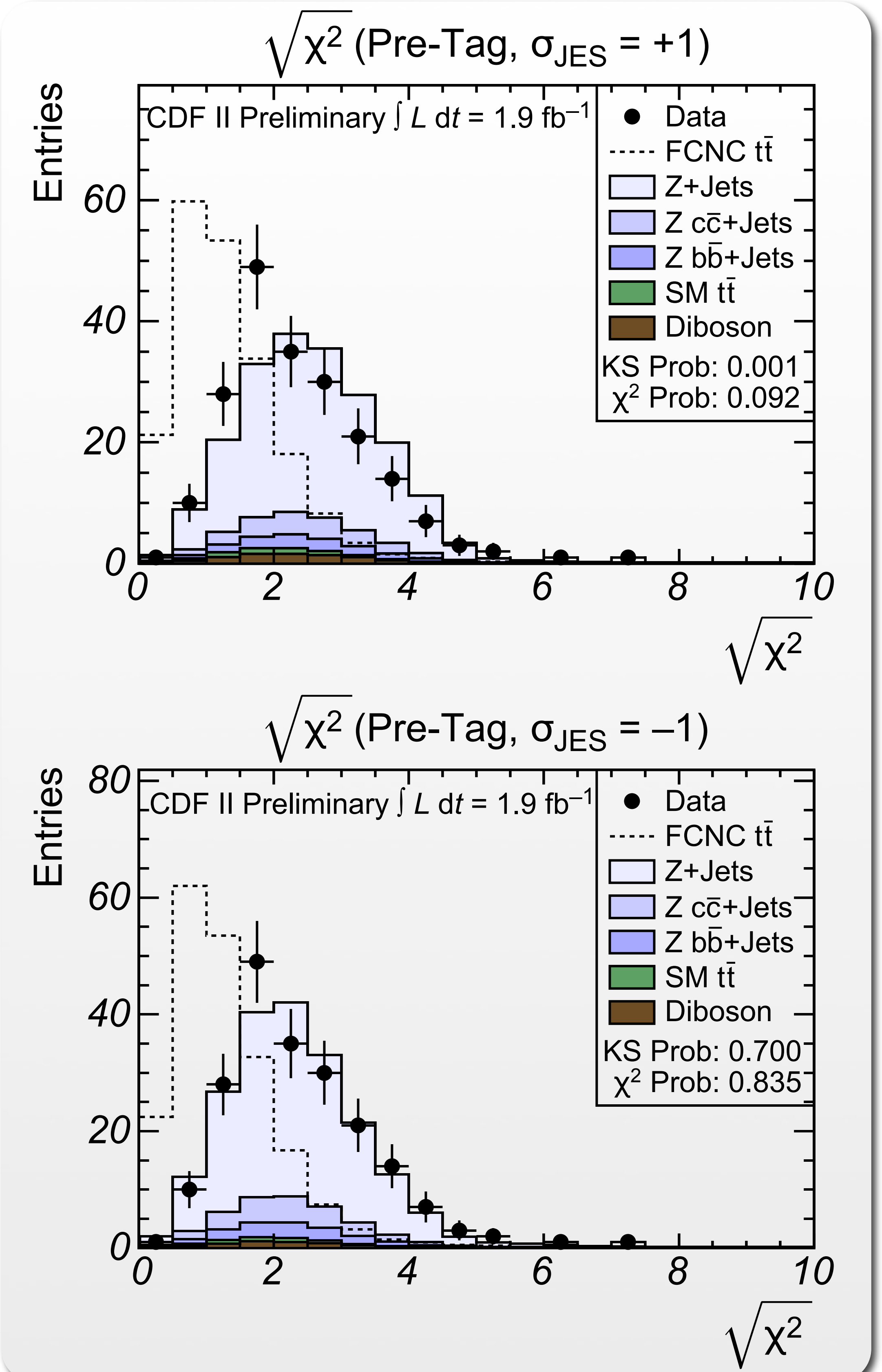


Mass χ^2 Template Fitting

- Strategy: fit signal and background templates to mass χ^2 distribution → extract B(t→Zq)
- Advantage: reduced uncertainty
  - Dominant uncertainty in counting experiment: absolute prediction of Z +Jets background
  - Fit total background and tagging rate → uncertainty reduced
- Challenge: shape systematics
  - Need to account for systematic uncertainties of template shape (in addition to rate uncertainties)
  - Investigated many sources, dominant effect: jet energy scale



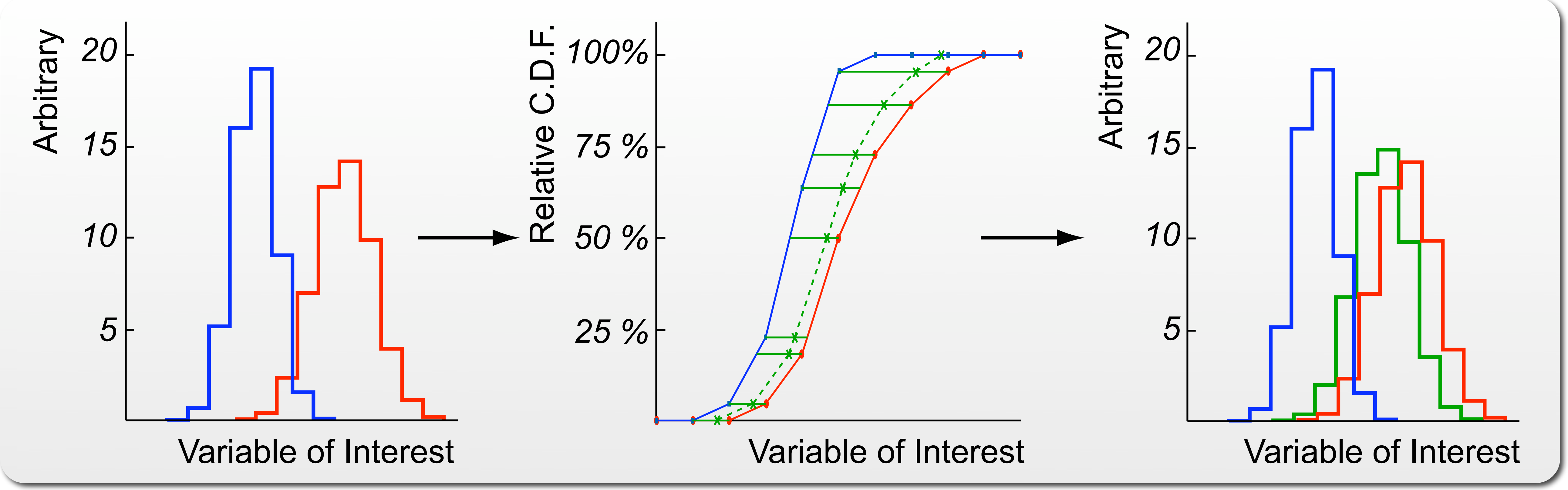
Shape Uncertainties



- Dominant uncertainty: jet energy scale (JES)
  - Translation: "raw" jet energy → partons energy
  - Many corrections: detector effects, neutral particles, underlying event, out-of-cone partons …
    → JES uncertainty $\pm\sigma_{JES}$
- Much smaller uncertainty: ALPGEN Z+jets MC simulation
  - Tunable parameters: factorization/ renormalization scale, vertex Q^2 scale
  - Big effect on jet multiplicity, small effect on mass χ^2 shape

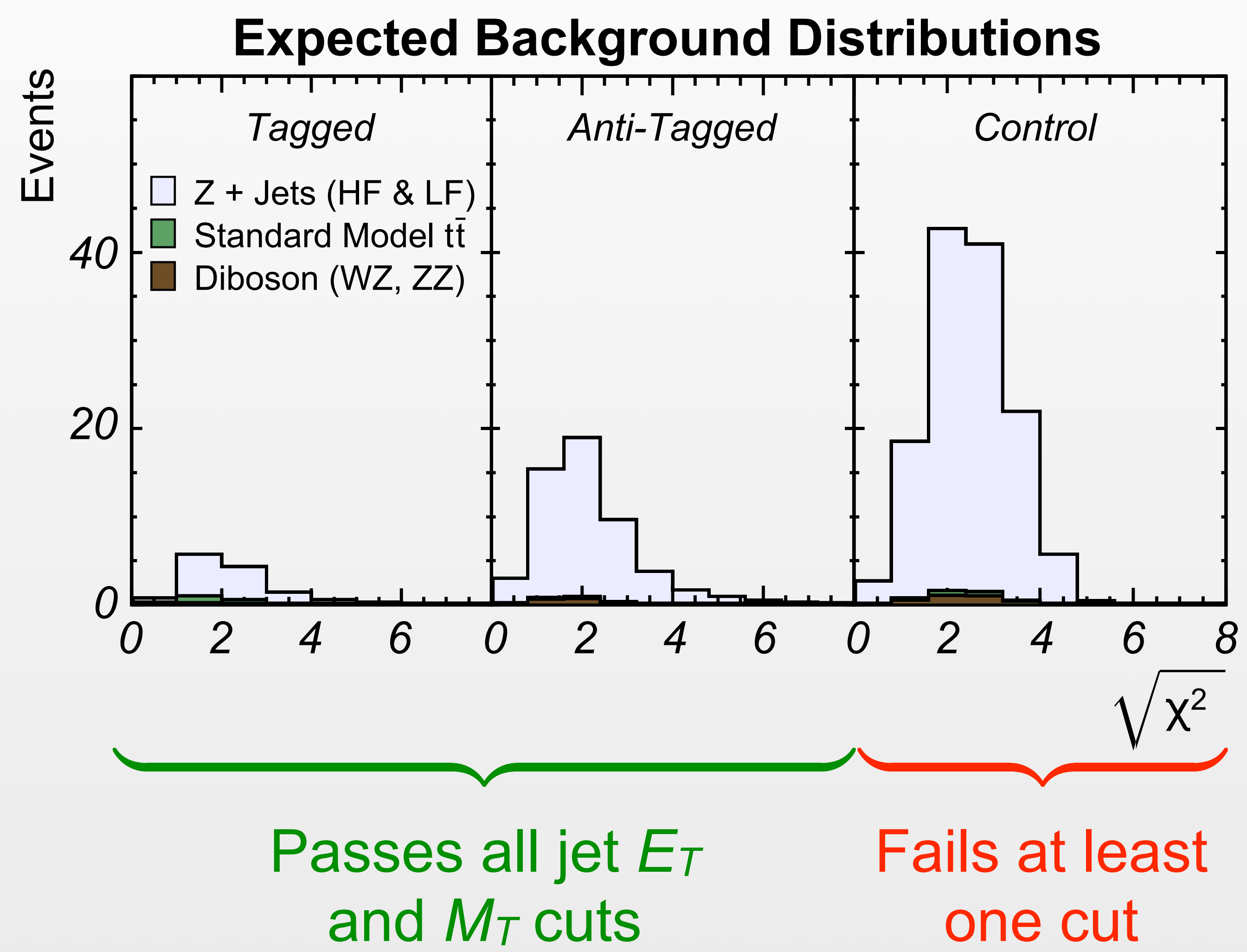
Template Morphing

- Treatment of shape uncertainties:
  - Assume that all shape uncertainties are due to JES
  - All others: much small effect → treated as systematic uncertainty
- Template fit: allow JES to float
  - Fitter knows how to “morph” templates → linear interpolation between normalized cumulative distribution functions (C.D.F.)
  - JES shift = free parameter in the fit



Adding a Control Region

- Challenge: control shape uncertainties but don't "morph away" a possible small signal
- Solution: add a control region
  - Definition: event fails at least one optimized cut (jet E_T, M_T)
  - Only 12% FCNC signal, but 67% Z+jets



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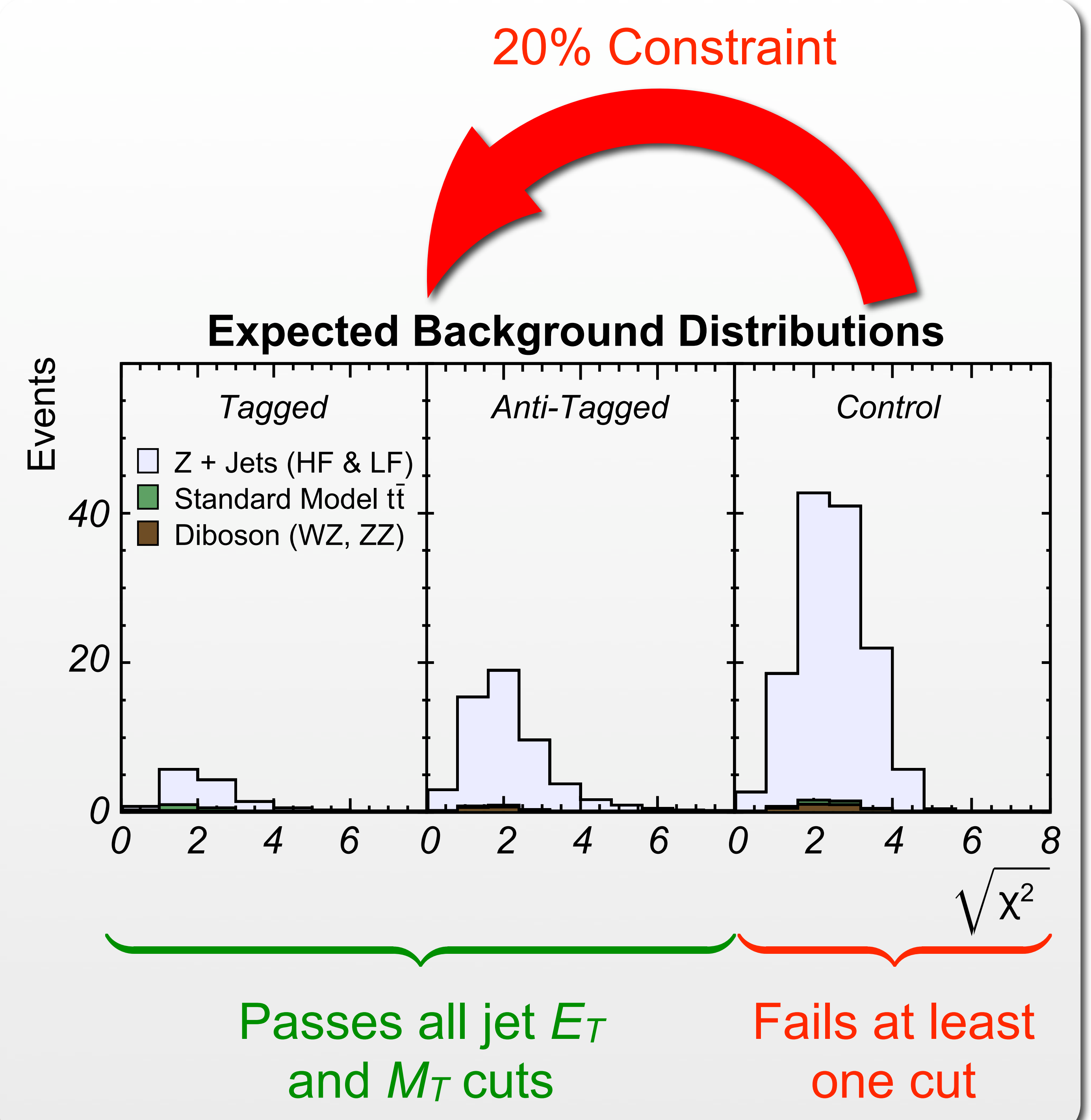
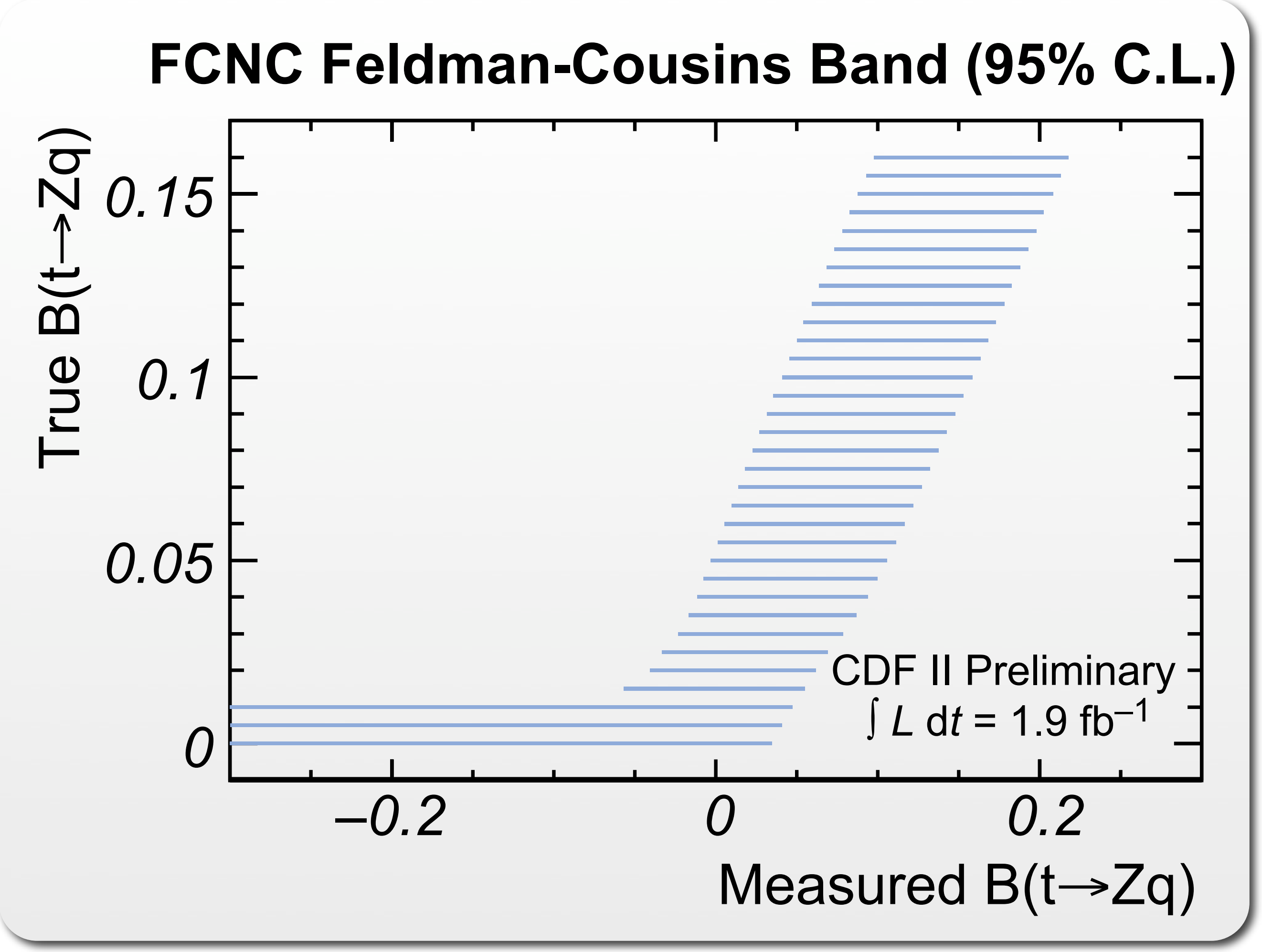
  - Definition: event fails at least one optimized cut (jet E_T, M_T)
  - Only 12% FCNC signal, but 67% Z+jets
- Additional benefit: constrain Z+jets background
  - Trust MC within a jet bin, but not across jet bins
  - Use amount of Z+jets found in control region to constrain signal regions to within 20%



Feldman-Cousins Limit

- Interpretation of fitted B(t→Zq): Feldman-Cousins (FC) method [G.J. Feldman, R.D. Cousins, Phys. Rev. **D57** (1998) 3873]
- FC answers the question: "What range of true values are likely to lead to the fitted value?"
- FC features:
  - Measurement or limit → data decide
  - Coverage of confidence intervals guaranteed
- Our implementation:
  - Includes systematic uncertainties
  - Based on "pseudo-experiments"



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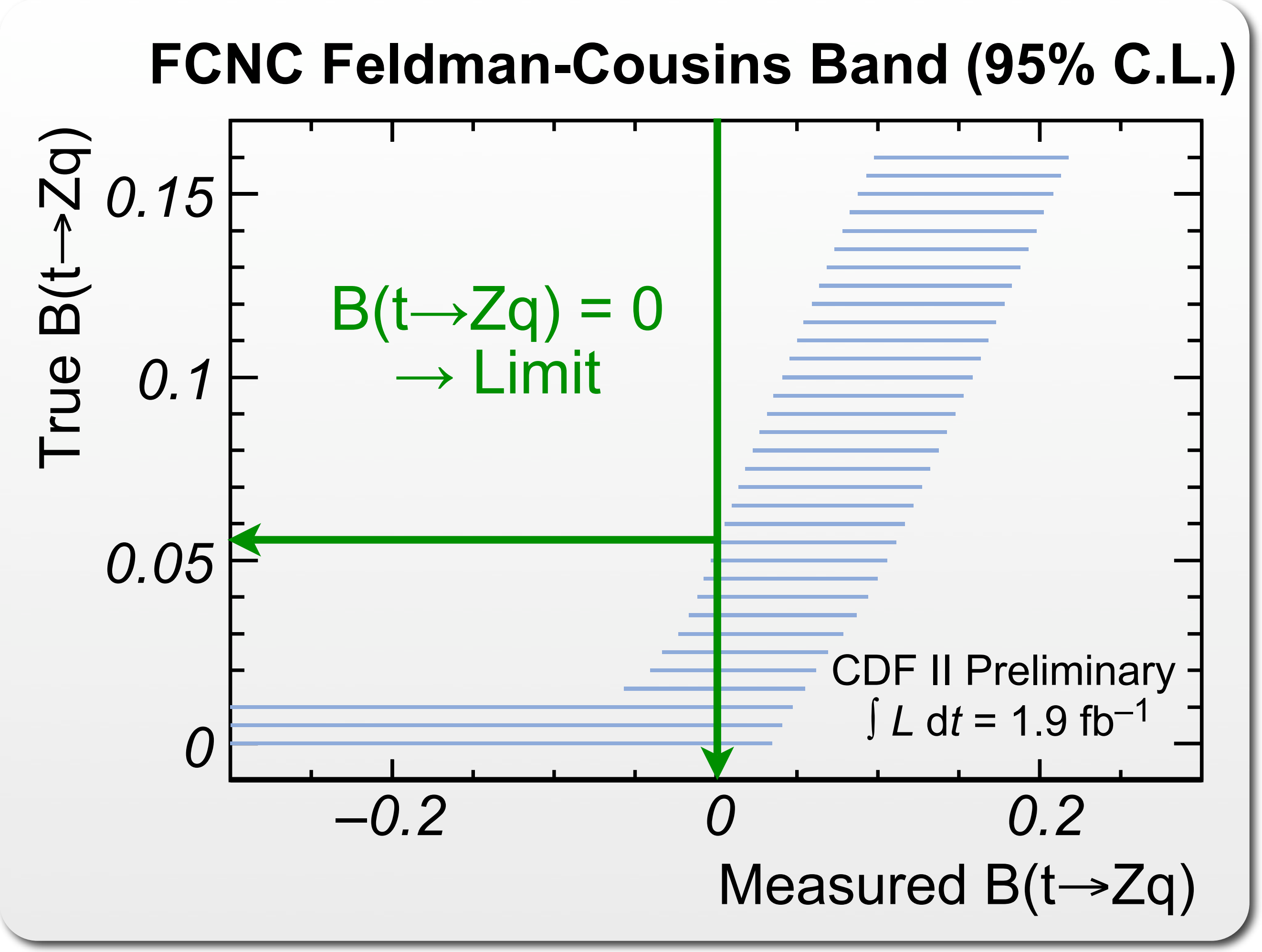

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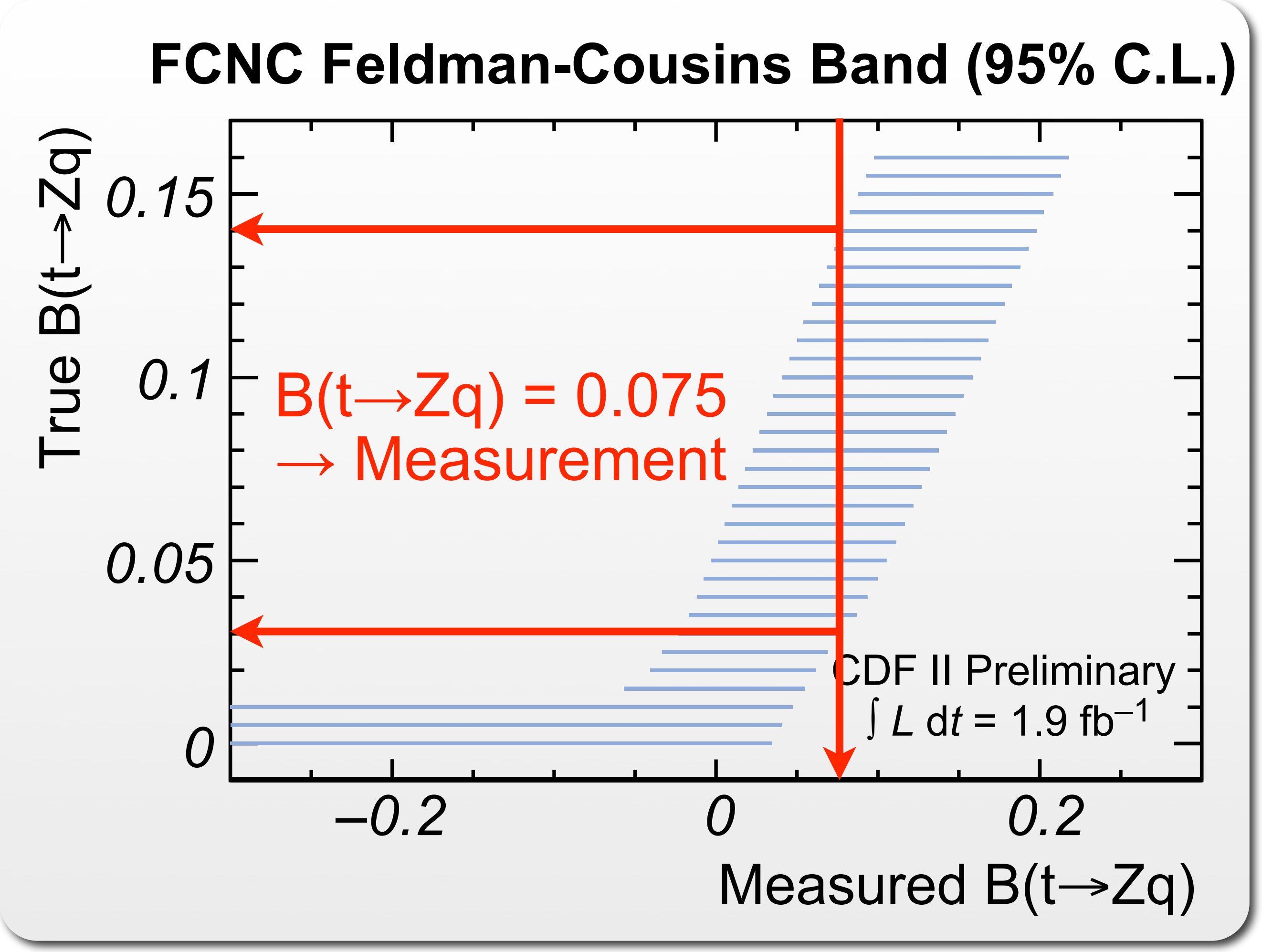

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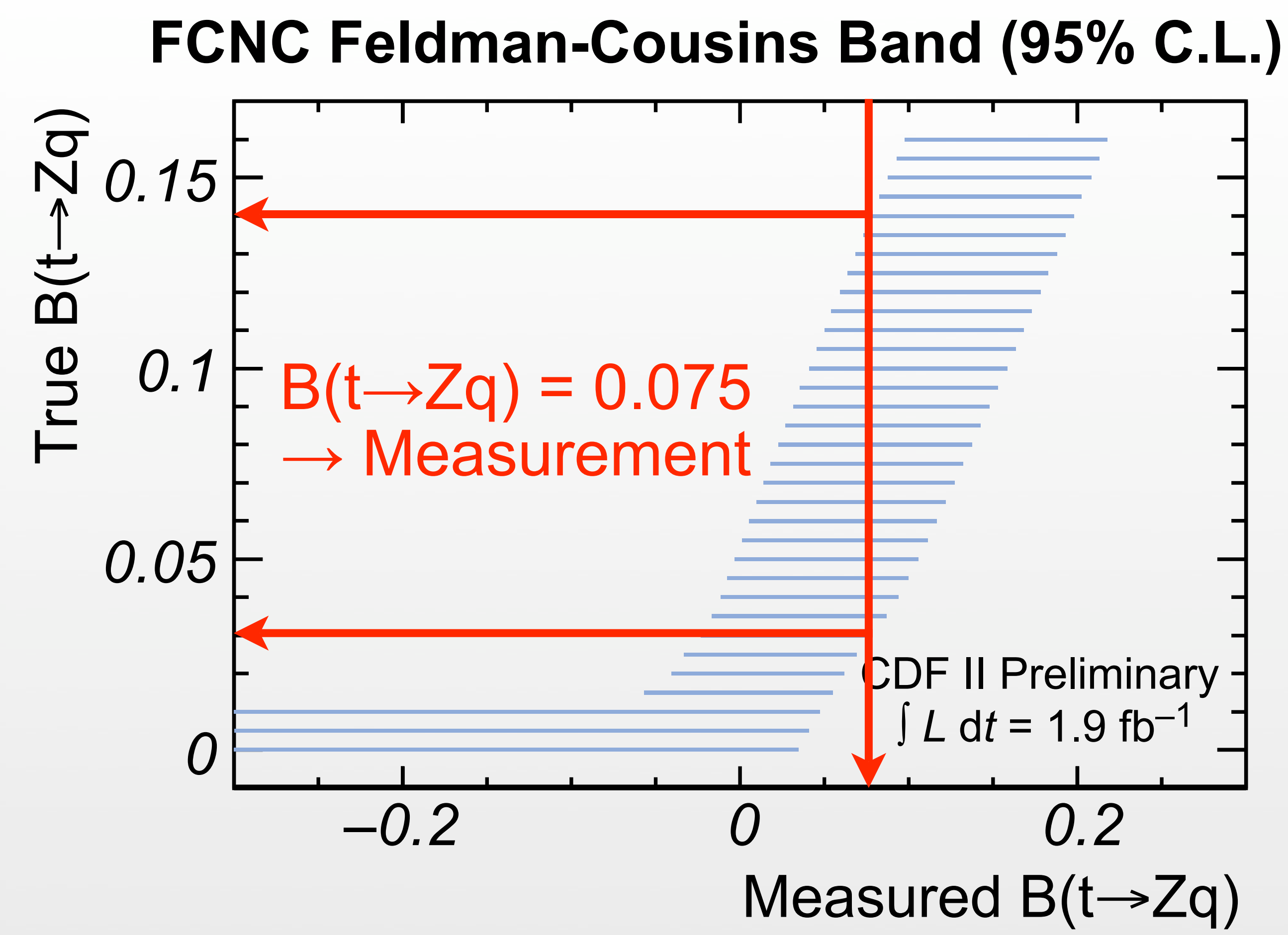
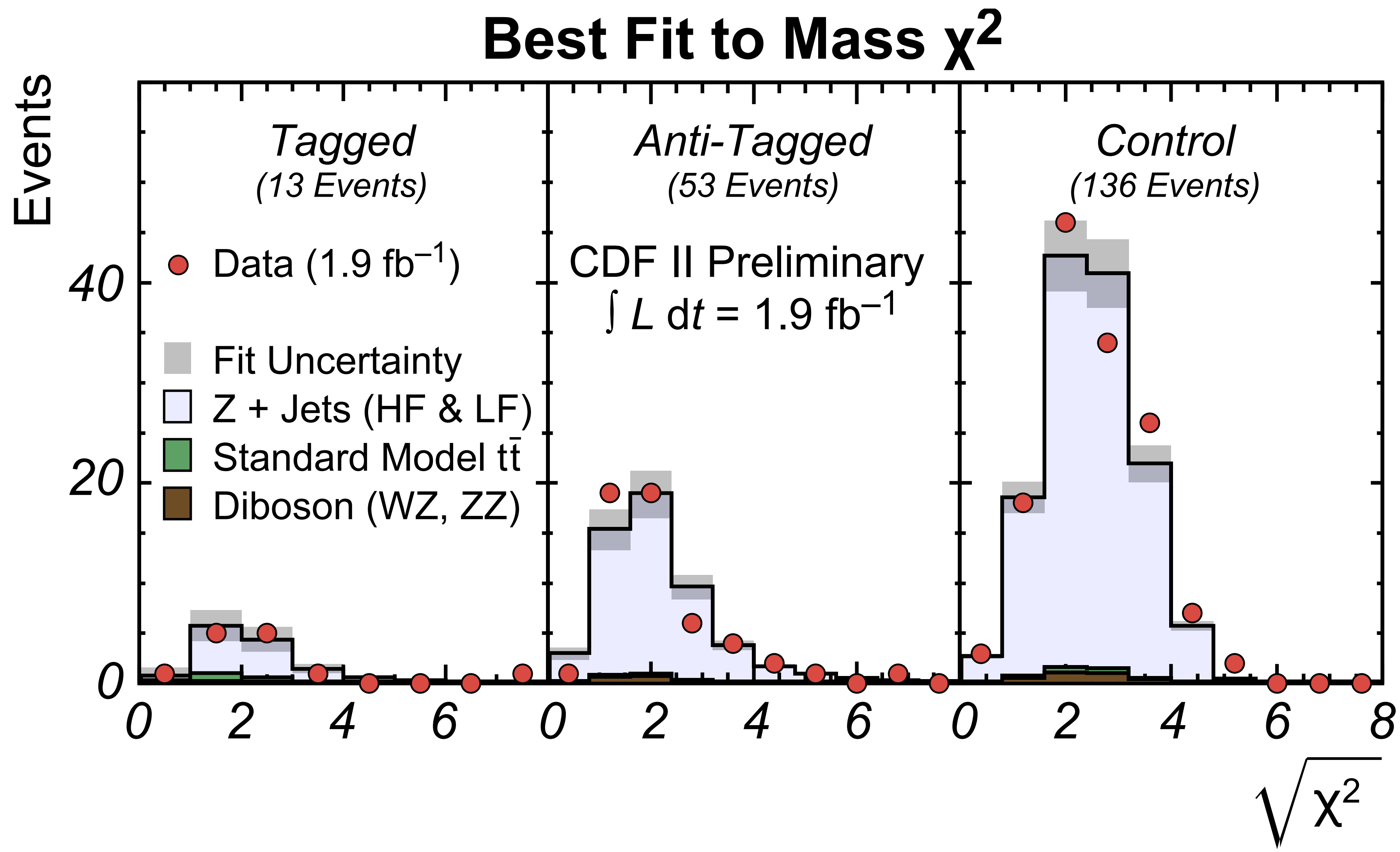


What are Pseudo-Experiments?

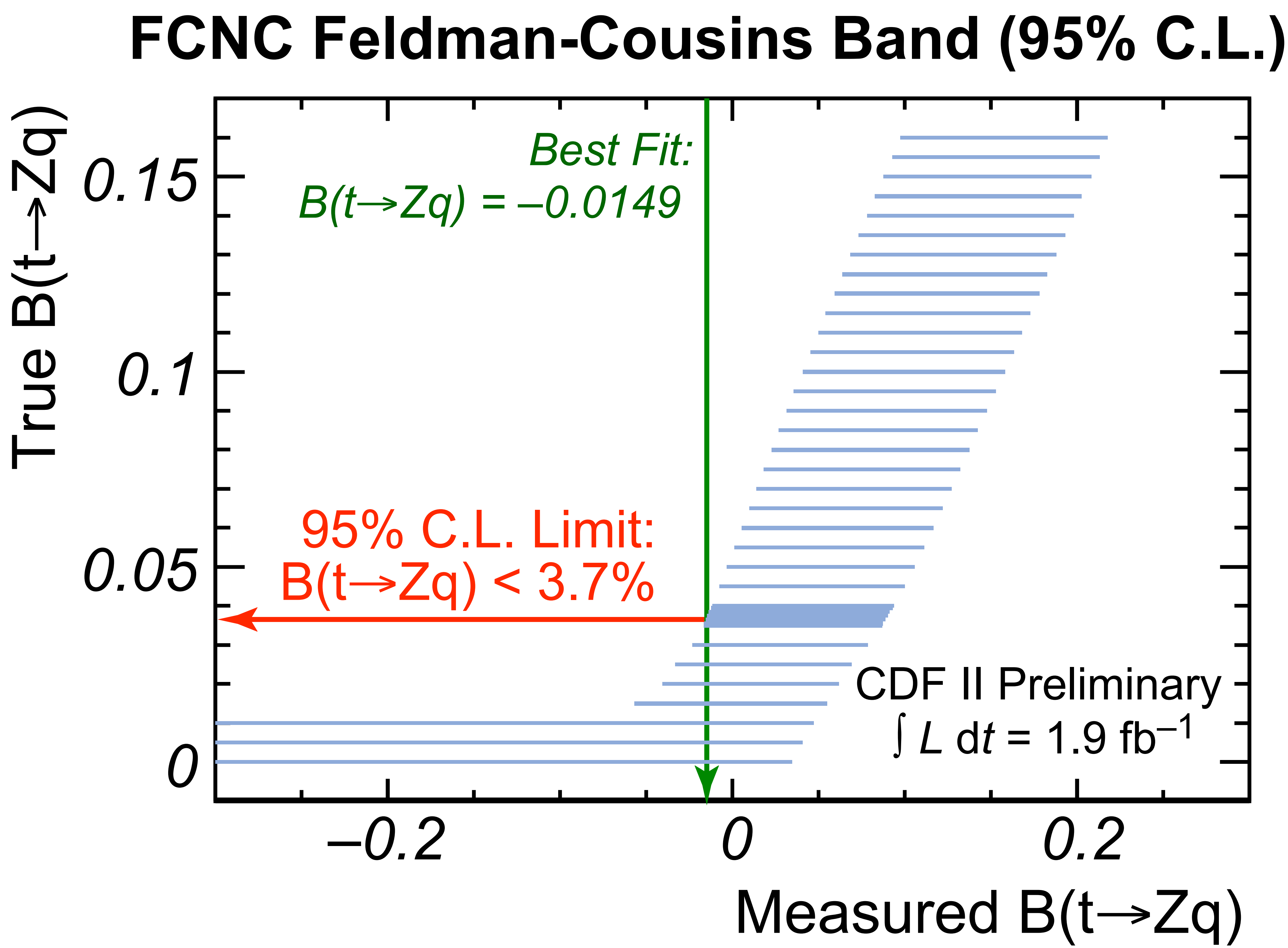
* Simulated experiments from MC
* Smear MC templates according to all known correlations and systematic uncertainties
* Draw Poisson random numbers from smeared MC templates → mass χ^2 distribution
* Fit as in data → "measured" B(t→Zq)
* Repeat

Fit to the Data



Fit Parameter	Value		
Branching Fraction $B(t \to Zq)$ (%)	-1.49	$\pm$	1.52
Z+Jets Events in Control Region	129	$\pm$	11
Ratio Signal/Control Region (%)	52	$\pm$	7
Tagging Fraction (%)	20	$\pm$	6
Jet Energy Scale Shift (σ)	-0.74	$\pm$	0.43

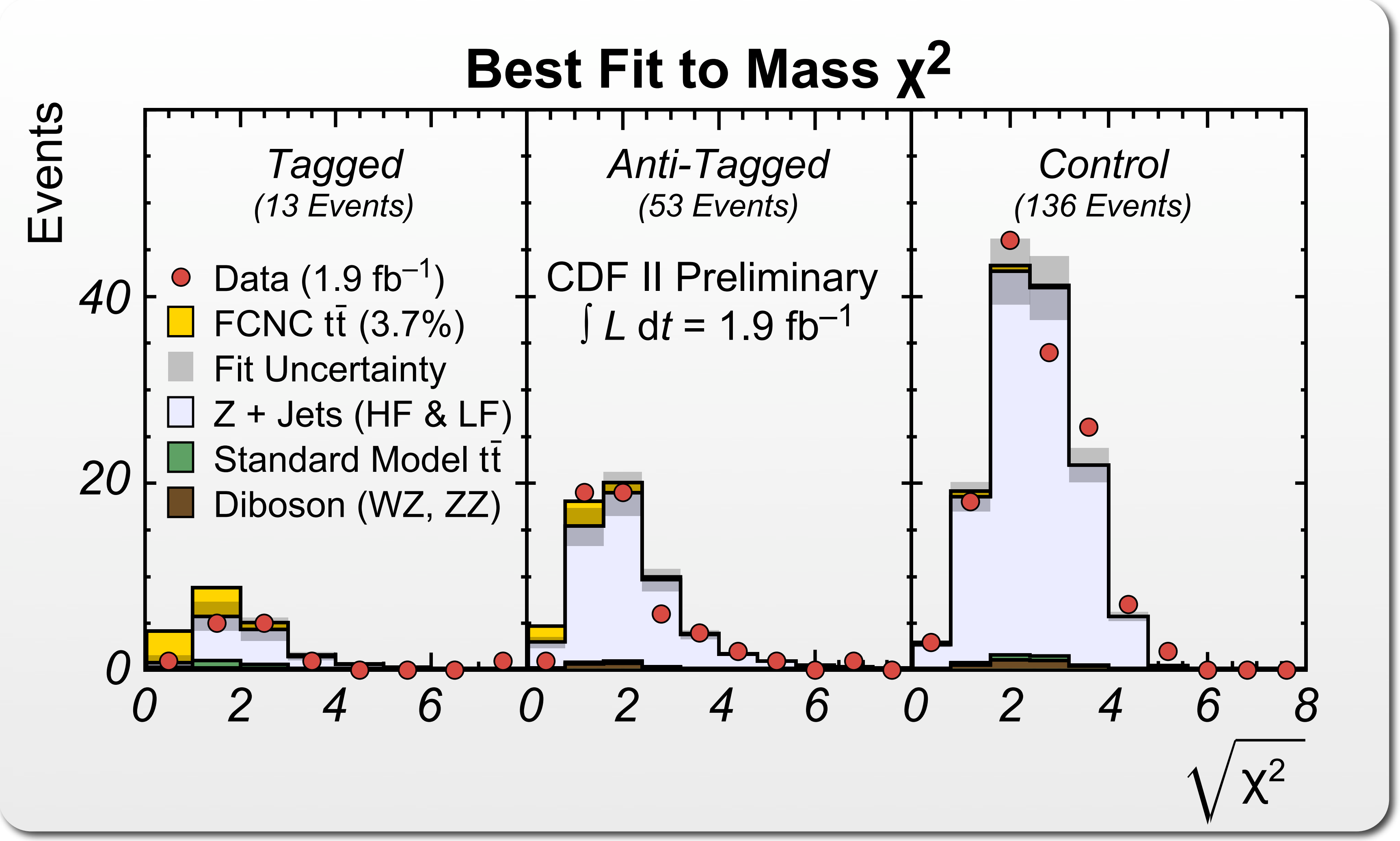
The World's New Best Limit



Summary

B(t→Zq) < 3.7% @ 95% C.L.

- Expected limit: 5.0% ± 2.2%
- Order of magnitude improvement over CDF Run I (33%)
- Almost 4× better than LEP (13.7%)



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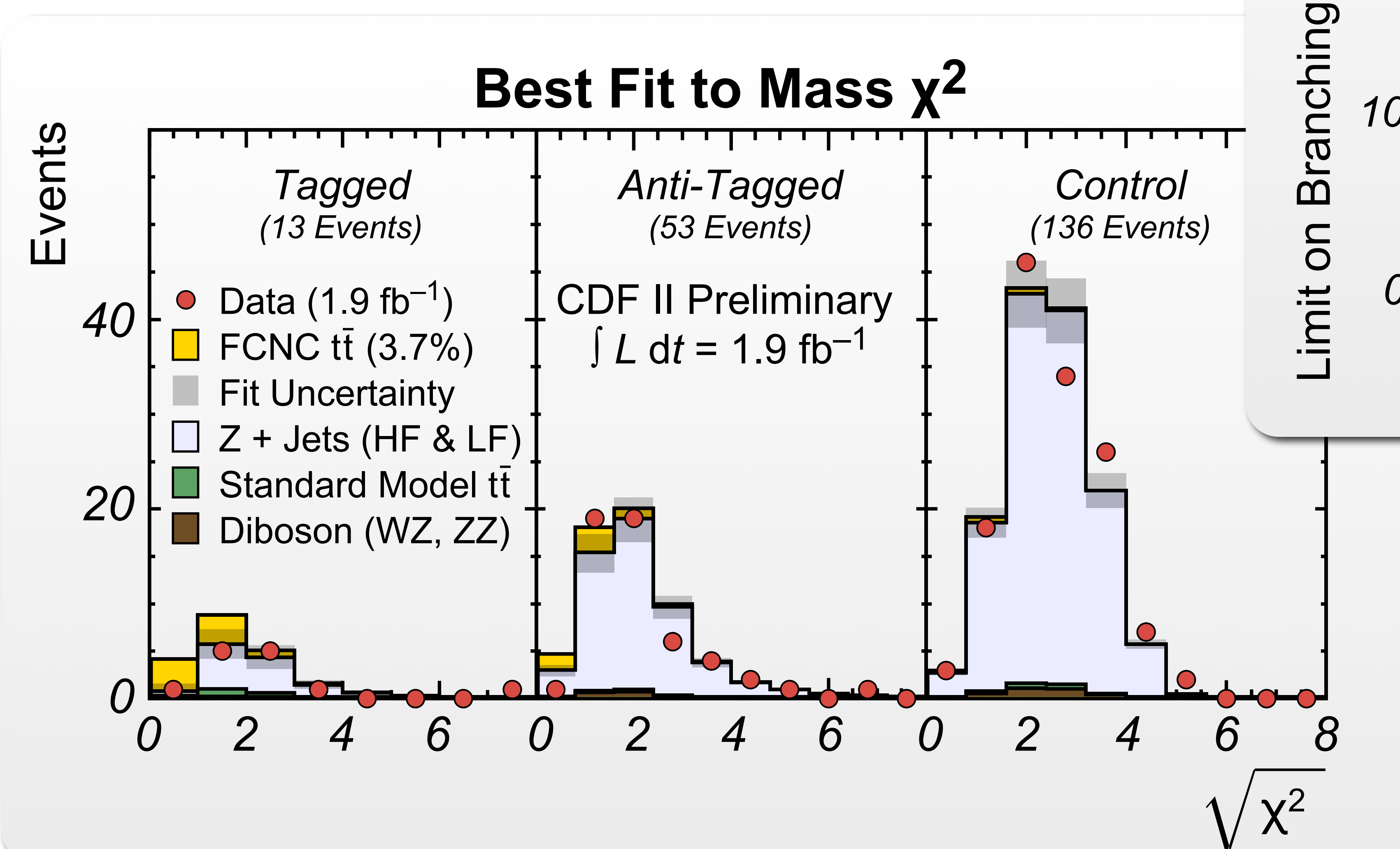
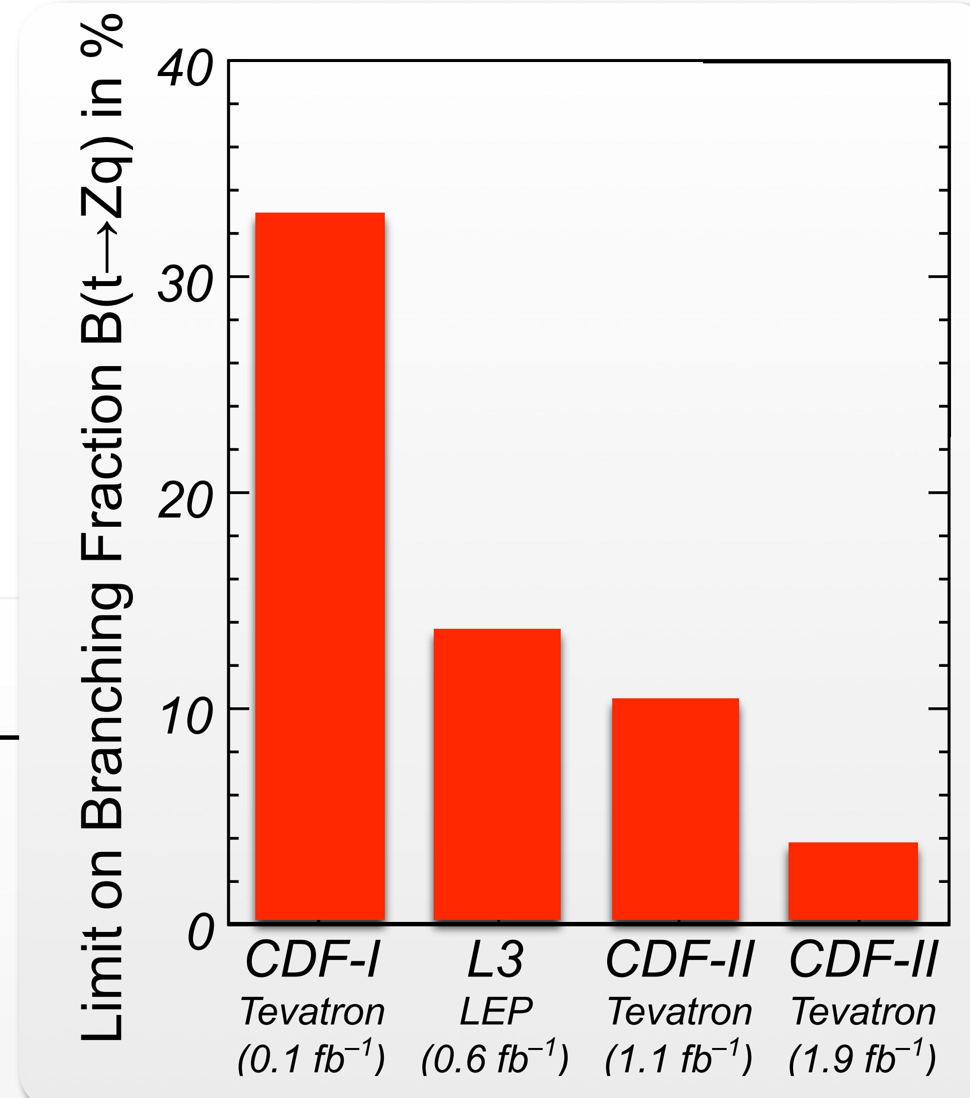
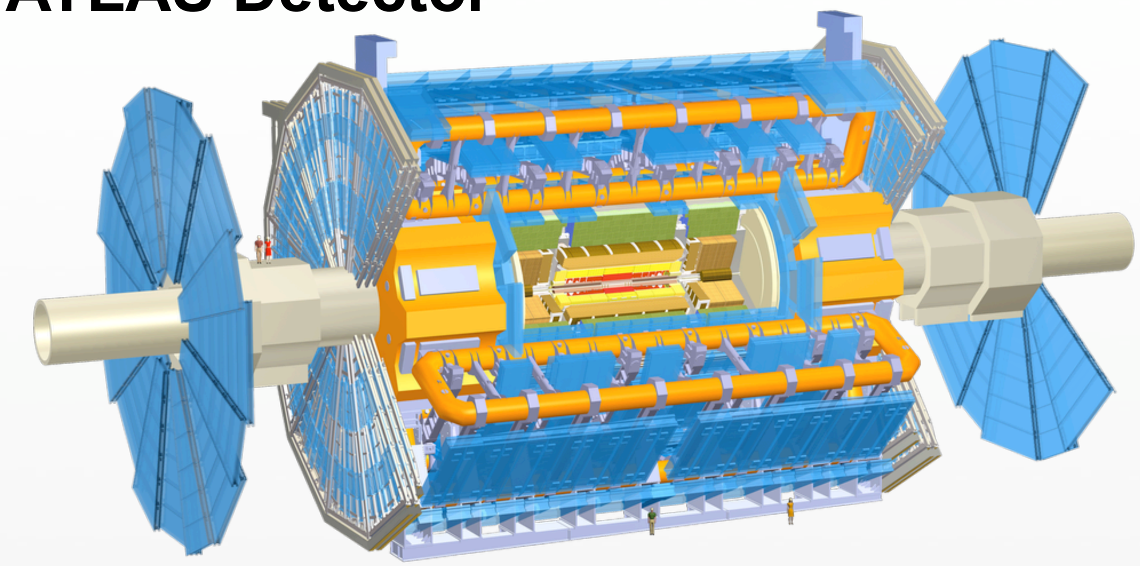


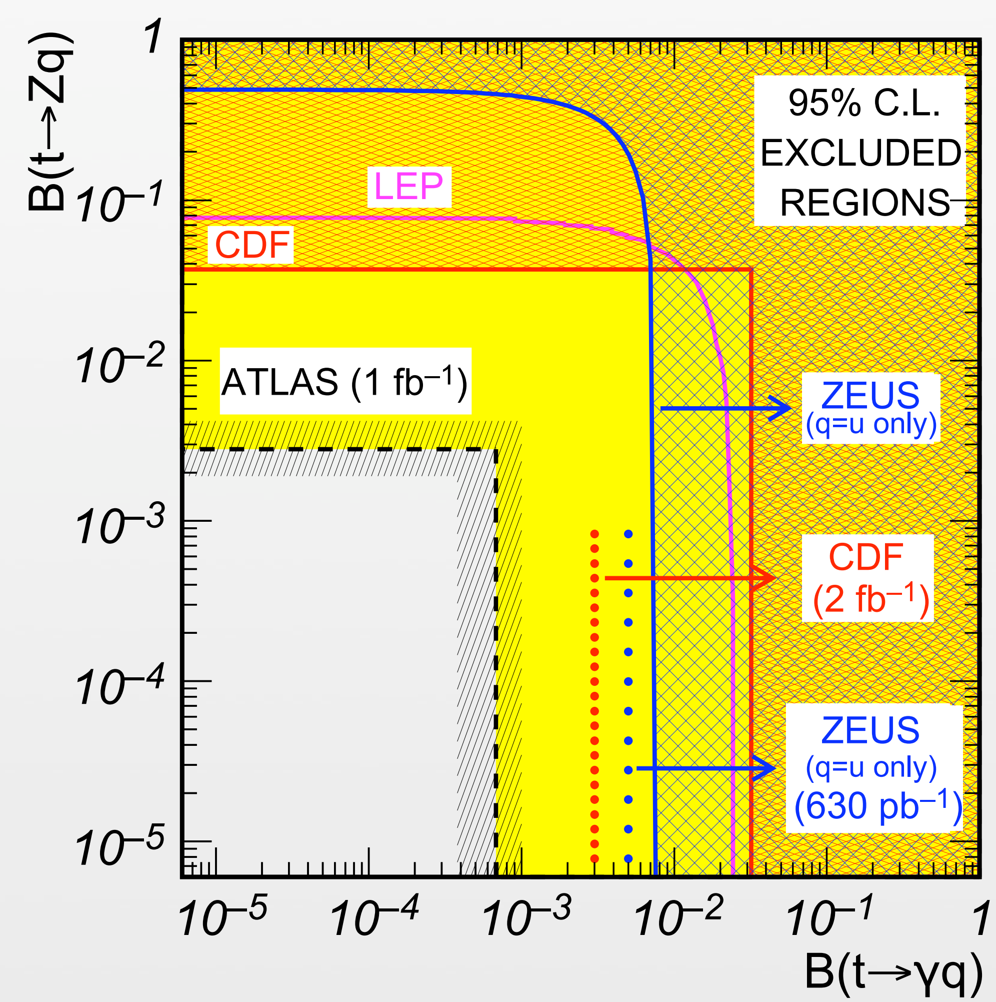


Outlook: Top FCNC at the LHC

- Large Hadron Collider (LHC):
  - Proton-proton collider at 14 TeV center-of-mass energy (CERN)
  - Two multi-purpuse experiments: ATLAS and CMS
  - First collisions (late) this summer!
- Recent ATLAS study on sensitivity for top FCNC (1 fb^{-1} ≈ first few months of data-taking)
  - Improvement of current limits on BR(t→Zq) by 1–2 orders of magnitude
  - Entering interesting regime of 10^{-3} to 10^{-4} → exclusion of first theoretical models?
  - Caveat: MC model not tuned to LHC energies

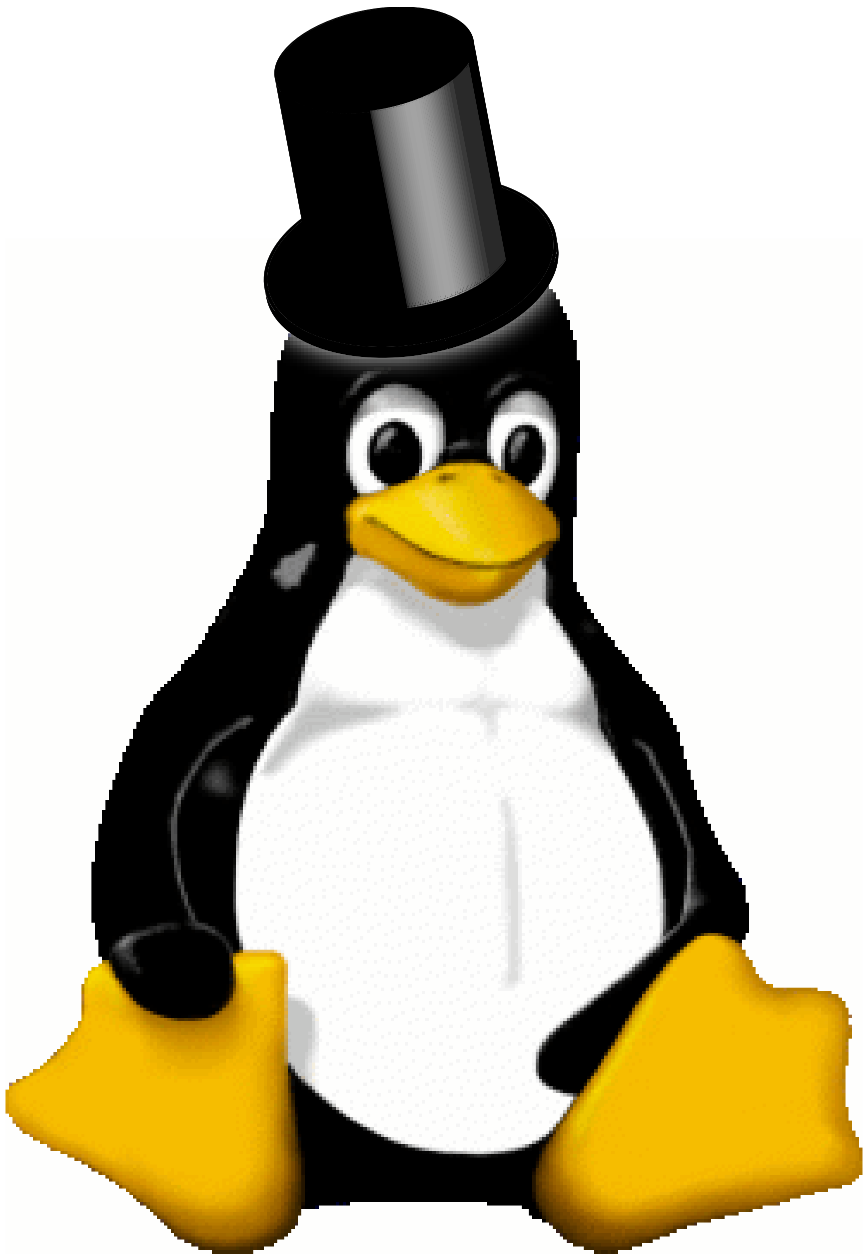
ATLAS Detector





[F. Veloso, Proc. TOP2008]

Conclusions



- Top flavor changing neutral current (FCNC) decays
  - Extremely rare in the standard model
  - Enhanced in theories beyond the standard model → any signal: new physics
- First Tevatron Run II search for FCNC $t \to Zq$ in top quark decays
  - Event signature: Z + ≥ 4 jets
  - Mass χ^2 to separate signal from background
- No evidence for top FCNC found
  - World's best limit: BR($t \to Zq$) < 3.7% at 95% C.L.
  - Paper submitted to PRL, arXiv:0805.2109 [hep-ex]

Backup Slides

FCNC in the Standard Model (I)

Standard model: no FCNC at Lagrangian level

- Massless theory: weak neutral current is flavor-diagonal

$$J_\mu^{NC} = J_\mu^3 - 2\sin^2\theta_W j_\mu^{em} = \bar{u}\left[\frac{1}{2}\gamma_\mu(1-\gamma_5) - \frac{4}{3}\sin^2\theta_W\gamma_\mu\right]u - \bar{d}\left[\frac{1}{2}\gamma_\mu(1-\gamma_5) - \frac{2}{3}\sin^2\theta_W\gamma_\mu\right]d$$

- Quark masses via Higgs mechanism:
  - Eigenstates of electroweak interactions are not mass eigenstates

$$\mathcal{L}_{Yuk} = \underbrace{-m_u^{\alpha\beta}\,\bar{u}_L'^{\alpha}u_R'^{\beta} - m_d^{\alpha\beta}\,\bar{d}_L'^{\alpha}d_R'^{\beta}}_{\text{Mass Terms}}\underbrace{-\frac{1}{\sqrt{2}}f_u^{\alpha\beta}\,\bar{u}_L'^{\alpha}h(x)\,u_R'^{\beta} - \frac{1}{\sqrt{2}}f_d^{\alpha\beta}\,\bar{d}_L'^{\alpha}h(x)\,d_R'^{\beta}}_{\text{Higgs Couplings}} + \text{h.c.}$$

  - Unitary transformation of Lagrangian to mass basis, i.e. for physical particles:

$$\bar{u}_L = \bar{u}_L'\,\mathbf{U}_L^u \qquad u_R = \mathbf{U}_R^{u\dagger}\,u_R' \qquad \mathbf{m}_u = \mathbf{U}_L^{u\dagger}\,\mathbf{m}_u'\,\mathbf{U}_R^u$$

$$\bar{d}_L = \bar{d}_L'\,\mathbf{U}_L^d \qquad d_R = \mathbf{U}_R^{d\dagger}\,d_R' \qquad \mathbf{m}_d = \mathbf{U}_L^{d\dagger}\,\mathbf{m}_d'\,\mathbf{U}_R^d$$

  - Kinetic terms: unchanged
  - Higgs couplings proportional to mass terms: no flavor changing Higgs couplings
  - Neutral currents have same structure as kinetic terms: unchanged → no FCNC

FCNC in the Standard Model (II)

- Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix (obtained from transformation of charged current to mass basis):

$$J_\mu^{CC} = \bar{u}' \left(\frac{1}{2}\gamma_\mu (1-\gamma_5)\right) d' = \bar{u}'_L \gamma_\mu d'_L = \bar{u}_L \mathbf{U}_L^{u\dagger} \gamma_\mu \mathbf{U}_L^d d_L = \bar{u}_L \gamma_\mu \mathbf{V}_{CKM} d_L,$$

- CKM matrix: unitary 3×3 matrix

$$\mathbf{V}_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \quad \text{with}$$

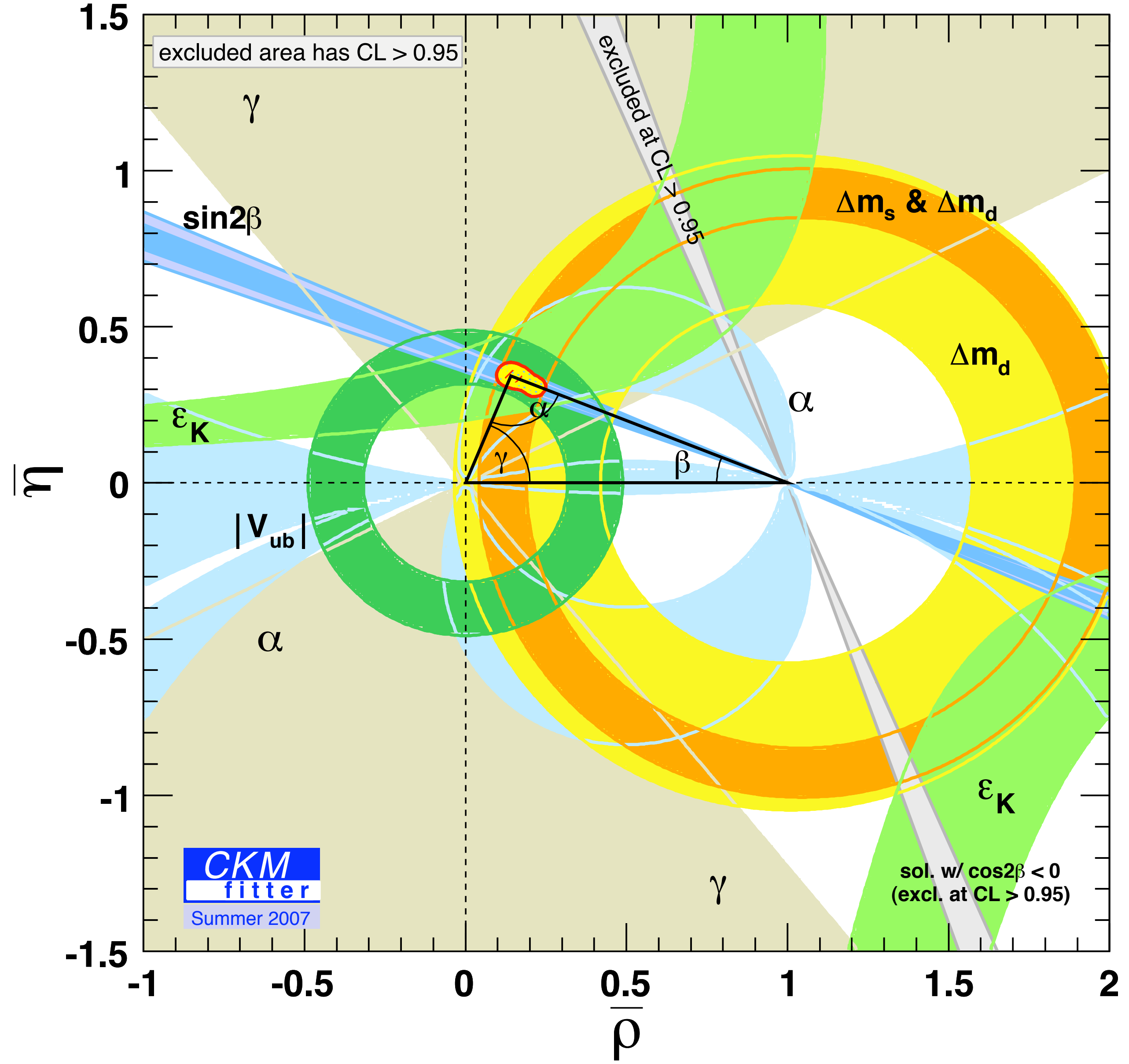
$$\mathbf{V}_{CKM} \cdot \mathbf{V}^\dagger_{CKM} = \mathbf{V}^\dagger_{CKM} \cdot \mathbf{V}_{CKM} = \mathbf{1}$$

yields unitarity relations, e.g. the unitary triangle of flavor physics (1st vs. 3rd column)

$$V_{ud}^* V_{ub} + V_{cd}^* V_{cb} + V_{td}^* V_{tb} = 0$$

or (used in top FCNC):

$$V_{cd}^* V_{td} + V_{cs}^* V_{ts} + V_{cb}^* V_{tb} = 0$$



FCNC in the Standard Model (III)

FCNC are allowed via higher order mechanisms such as penguin diagrams, but heavily suppressed

- Suppression mechanism 1: GIM
  - Penguin matrix element depends on universal functions of single parameter $x_i = m_i^2/m_W^2$

$$\mathcal{M} \propto F(x_d)\, V_{cd}^* V_{td} + F(x_s)\, V_{cs}^* V_{ts} + F(x_b)\, V_{cb}^* V_{tb},$$

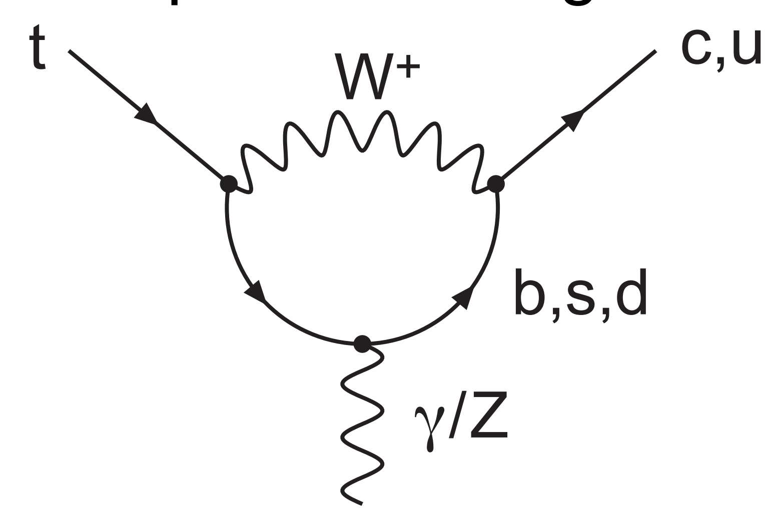
  - Compare to CKM unitarity relation:

$$V_{cd}^* V_{td} + V_{cs}^* V_{ts} + V_{cb}^* V_{tb} = 0$$

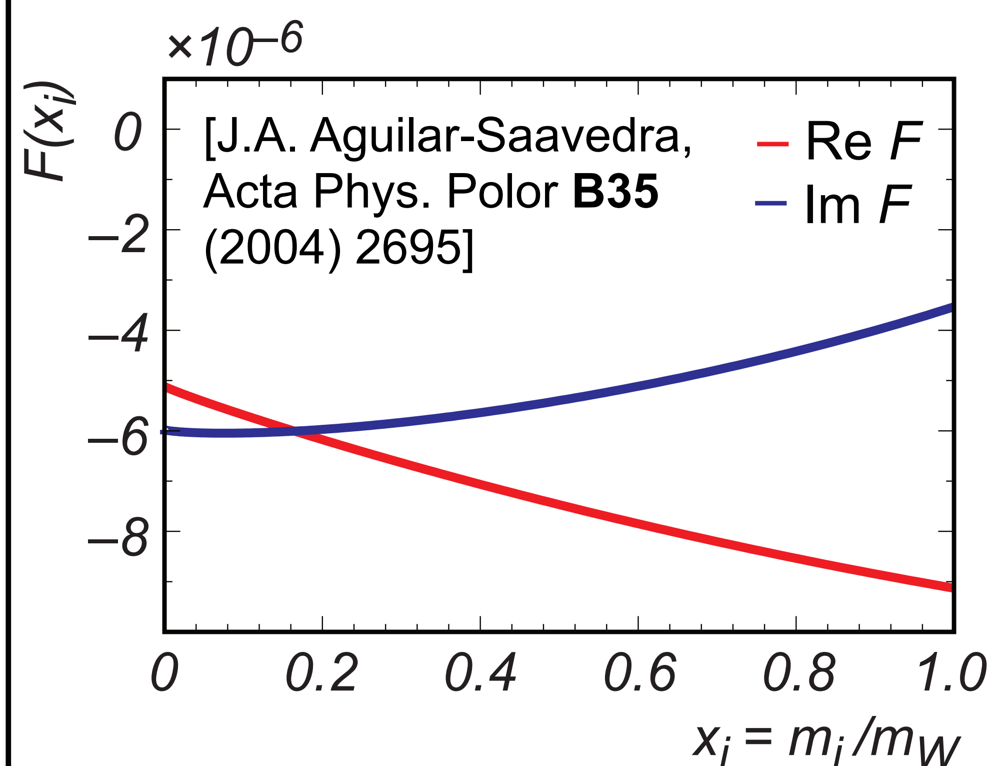
    Exact cancellation if masses of b, s, and d quarks were the same
  - Quark masses more similar for down-type than for up-type: top FCNC more strongly suppressed than bottom FCNC, e.g. BR(t → Zq) ≈ 10^{-14} vs. BR(b→ sγ) ≈ 10^{-4}
- Suppression mechanism 2: smallness of relevant CKM matrix elements

$$|V_{cd}^* V_{td}| \approx 0.002,\ |V_{cs}^* V_{ts}| \approx 0.04,\ |V_{cb}^* V_{tb}| \approx 0.04$$

Top FCNC Penguin



Universal Function for t → γc



Experimental Tests of FCNC

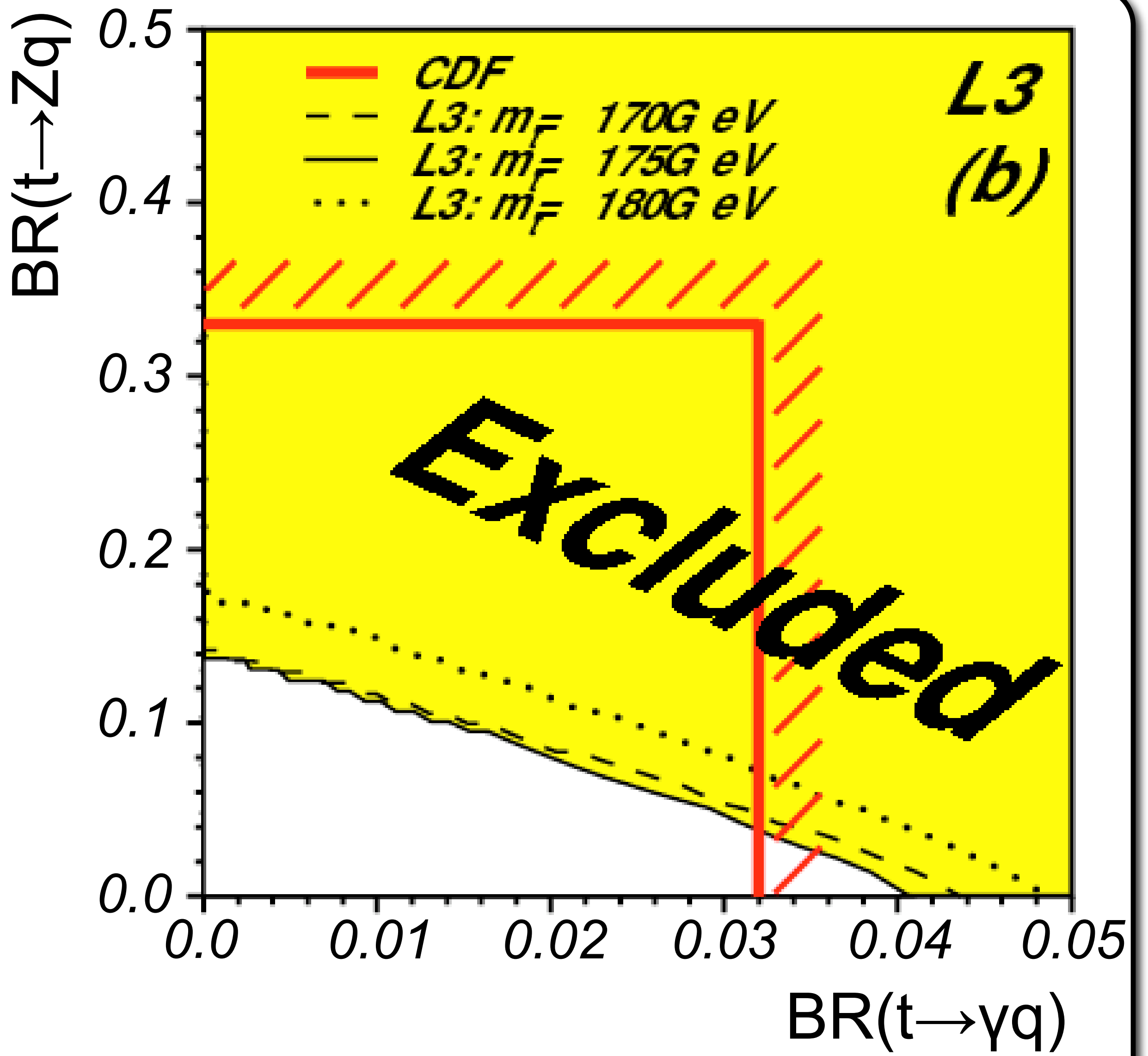
- Experimental tests of FCNC interactions: sensitive probes of new physics
  - Any signal above SM expectations: new physics
  - Measurements constrain allowed phase space for new physics models

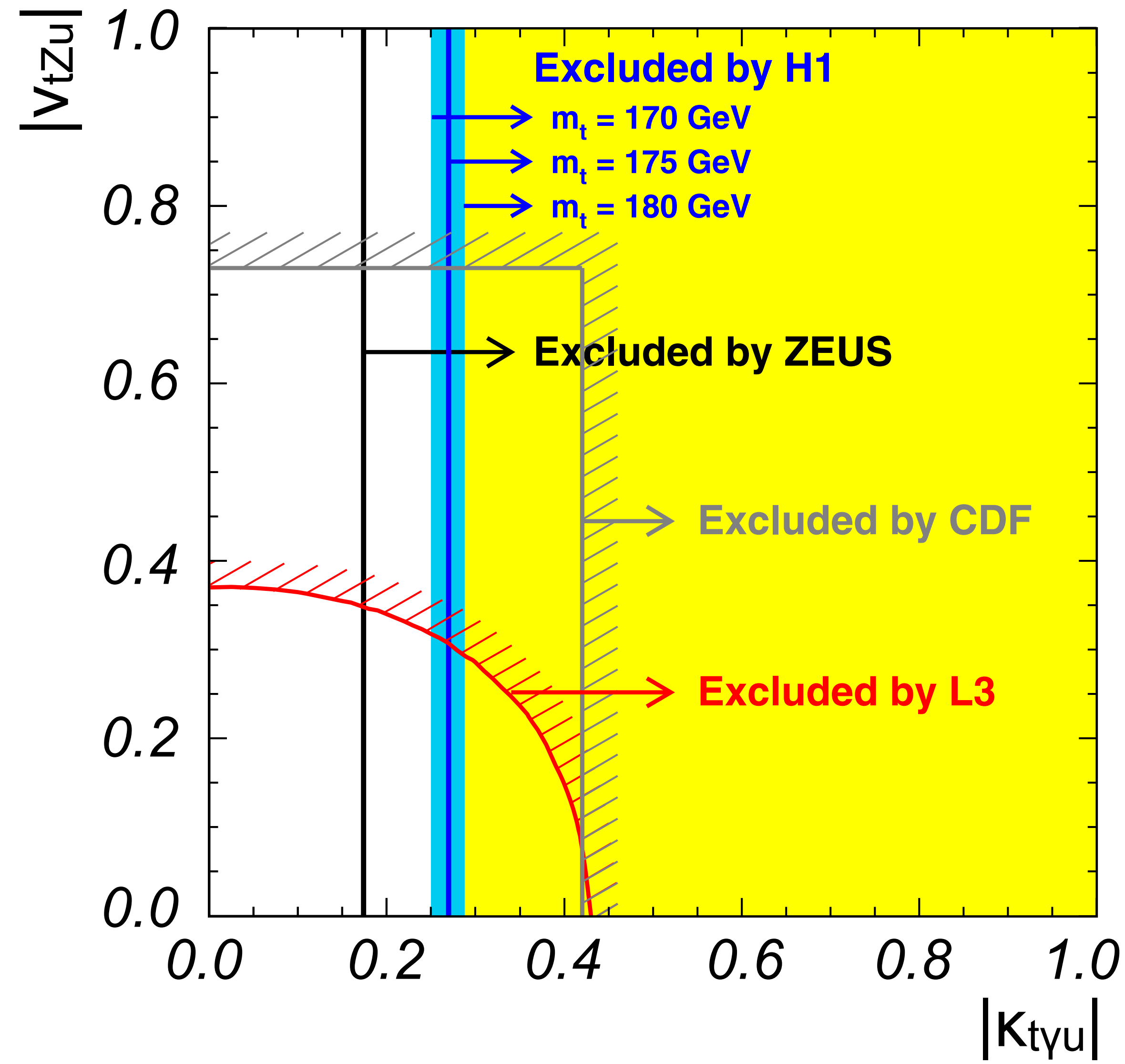
- Two types of searches for FCNC in the top sector:
  - Search for single top production (LEP, HERA, DØ)
  - Search for top quark decay via FCNC (CDF)

- Experiments usually report limits on
  - Branching fractions for specific processes, e.g. B(t → Zq)
  - Coupling parameters of effective Lagrangian, e.g. for tZq coupling

$$\mathscr{L}_{\text{eff}} = -\frac{g}{2\cos\theta_W} \cdot \kappa \cdot \left(x_{\text{L}} \cdot \bar{q}_{\text{L}} \gamma_\mu t_{\text{L}} + x_{\text{R}} \cdot \bar{q}_{\text{R}} \gamma_\mu t_{\text{R}}\right) Z^\mu + \ldots$$

Best Limits 2006





The H1 result caused some excitement:

Abstract. [...] In the leptonic channel, 5 events are found while 1.31 ± 0.22 events are expected from the Standard Model background. In the hadronic channel, no excess above the expectation for Standard Model processes is found. [...]

Simulation of FCNC Signals

- FCNC signal MC generated with Pythia (Gen6):

Sample	Sample Size	Description	
$t\bar{t} \to Z(ll)cW(q\bar{q}')b$	539,445	$Z \to e^+e^-, \mu^+\mu^-$ and $W \to q\bar{q}'$	Main Sample
$t\bar{t} \to Z(ll)cW(l\nu)b$	111,181	$Z \to e^+e^-, \mu^+\mu^-$ and $W \to e\nu$, $\mu\nu$, $\tau\nu$	Additional Acceptance
$t\bar{t} \to Z(incl.)cW(incl.)b$	116,573	Inclusive Z and W decays	Additional Acceptance
$t\bar{t} \to Z(ll,q\bar{q})cZ(ll,q\bar{q})c$	116,573	Double FCNC decay: $Z \to e^+e^-$, $\mu^+\mu^-$, $q\bar{q}$	Additional Acceptance
$t\bar{t} \to Z(ll)uW(q\bar{q}')b$	116,573	$Z \to e^+e^-, \mu^+\mu^-$ and $W \to q\bar{q}'$	t→Zu vs. t→Zc
$t\bar{t} \to Z(ll)cW(q\bar{q}')b$	116,573	As Above, $m_t = 170\,\mathrm{GeV}/c^2$	Top Mass 170 GeV/c^2
$t\bar{t} \to Z(ll)cW(l\nu)b$	106,465	As Above, $m_t = 170\,\mathrm{GeV}/c^2$	Top Mass 170 GeV/c^2
$t\bar{t} \to Z(ll,q\bar{q})cZ(ll,q\bar{q})c$	116,573	As Above, $m_t = 170\,\mathrm{GeV}/c^2$	Top Mass 170 GeV/c^2

  - Full 1.12 fb^{-1} run range, underlying event
  - Reweight samples to get SM expected helicity of Zs from top decay: 65% longitudinal, 35% left-handed
- Signal acceptance:
  - Defined after helicity reweighting
  - Corrected for trigger efficiencies and lepton ID and reconstruction scale factors on object-by-object basis

$$\text{acceptance} = \frac{\sum_{i=0}^{N_{\mathrm{rec}}} w_i^{\mathrm{hel}} \varepsilon_i}{\sum_{i=0}^{N_{\mathrm{gen}}} w_i^{\mathrm{hel}}}$$

Luminosity Reweighting & Acceptance

- Run dependent MC only for periods 0–8
  - Need proper reweighting to represent periods 0–12
- Our choice: periods 1–8 represent periods 1–12
  - Motivated by difference in CMX performance in period 0
  - Assign luminosity weight w^{lumi} on event-by-event basis
  - Apply average Joint Physics scale factors for periods 1–12 to MC from periods 1–8
- Our definition of signal acceptance:
  - Denominator: sum of helicity weights for generated events within Z mass window
  - Numerator: geometrical acceptance and per-event trigger efficiencies, lepton scale factors, …

$$\mathscr{A} = \frac{\mathscr{L}^{0-8}}{\mathscr{L}^{0-12}} \cdot \frac{\sum_i^{0-8} \mathscr{S}_i \cdot \mathscr{E}_i \cdot w_i^{\text{hel}} \cdot w_i^{\text{lumi}}}{\sum_i^{0-8} w_i^{\text{hel}}}$$

$$\begin{aligned} \text{with } w_i^{\text{lumi}} &= 1 \text{ for period } 0 \\ w_i^{\text{lumi}} &= \mathscr{L}^{1-12}/\mathscr{L}^{1-8} \approx 2 \text{ for periods } 1\text{–}8 \end{aligned}$$

Acceptance for Weighted Events

Acceptance for period *j*
$$\mathscr{A}^j = \frac{\sum_i^j \mathscr{S}_i \cdot \mathscr{E}_i \cdot w_i^{\text{hel}}}{\sum_i^j w_i^{\text{hel}}}$$

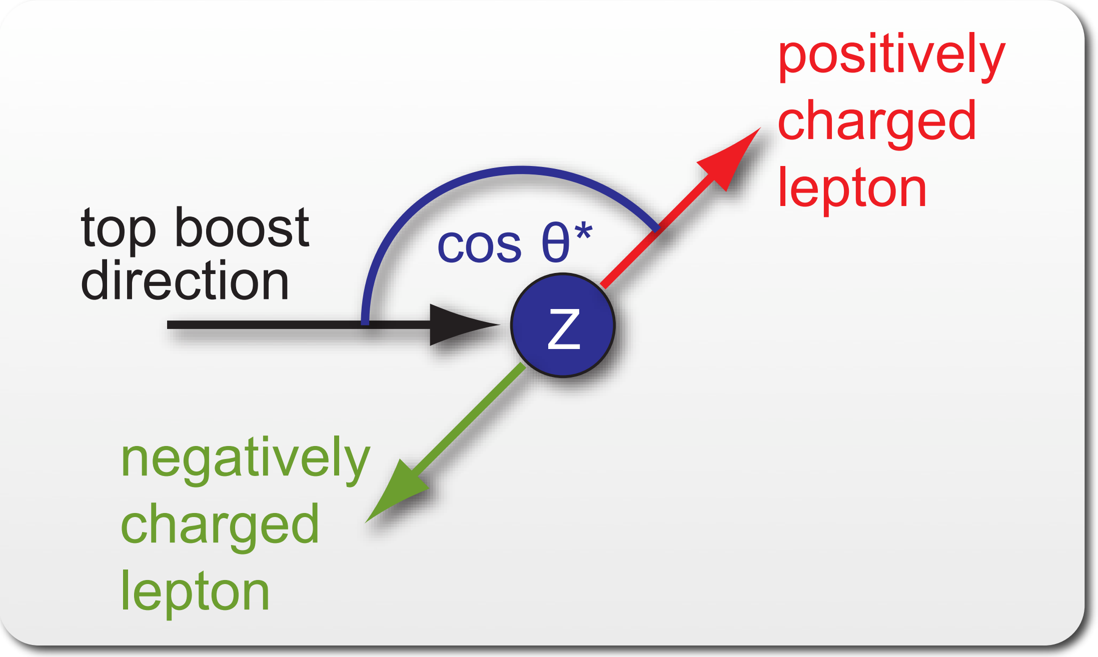
Total acceptance
$$\mathscr{A} = \frac{\mathscr{L}^0}{\mathscr{L}^{0-12}} \cdot \mathscr{A}^0 + \frac{\mathscr{L}^{1-12}}{\mathscr{L}^{0-12}} \cdot \mathscr{A}^{1-8}$$
$$= \frac{\mathscr{L}^0}{\mathscr{L}^{0-12}} \cdot \frac{\sum_i^0 \mathscr{S}_i \cdot \mathscr{E}_i \cdot w_i^{\text{hel}}}{\sum_i^0 w_i^{\text{hel}}} + \frac{\mathscr{L}^{1-12}}{\mathscr{L}^{0-12}} \cdot \frac{\sum_i^{1-8} \mathscr{S}_i \cdot \mathscr{E}_i \cdot w_i^{\text{hel}}}{\sum_i^{1-8} w_i^{\text{hel}}}$$

Helicity weights are not run dependent:
$$\sum_i^j w_i^{\text{hel}} = \frac{\mathscr{L}^j}{\mathscr{L}^{0-8}} \sum_i^{0-8} w_i^{\text{hel}}$$

$$\mathscr{A} = \frac{\mathscr{L}^{0-8}}{\mathscr{L}^{0-12}} \left(\frac{\sum_i^0 \mathscr{S}_i \cdot \mathscr{E}_i \cdot w_i^{\text{hel}}}{\sum_i^{0-8} w_i^{\text{hel}}} + \frac{\mathscr{L}^{1-12}}{\mathscr{L}^{1-8}} \cdot \frac{\sum_i^{1-8} \mathscr{S}_i \cdot \mathscr{E}_i \cdot w_i^{\text{hel}}}{\sum_i^{0-8} w_i^{\text{hel}}} \right)$$
$$= \frac{\mathscr{L}^{0-8}}{\mathscr{L}^{0-12}} \cdot \frac{\sum_i^{0-8} \mathscr{S}_i \cdot \mathscr{E}_i \cdot w_i^{\text{hel}} \cdot w_i^{\text{lumi}}}{\sum_i^{0-8} w_i^{\text{hel}}}$$

Simulation of FCNC Signal

- Monte Carlo (MC) simulation of FCNC decay $t \rightarrow Zq$ with PYTHIA
  - $t \rightarrow Zq$ vertex unknown to PYTHIA
  - Decay generated flat in cos θ*
  - Solution: reweight according to expectation from standard model Higgs mechanism:



$$\frac{d\sigma}{d\cos(\theta^*)} = f^0 \cdot \frac{3}{4}\left(1-\cos(\theta^*)^2\right) + f^- \cdot \frac{3}{8}\left(1-\cos(\theta^*)\right)^2 + f^+ \cdot \frac{3}{8}\left(1+\cos(\theta^*)\right)^2$$

with $f^0 = 0.65$ ("longitudinal"), $f^- = 0.35$ ("left-handed"), $f^+ = 0$ ("right-handed")

- Main FCNC signal sample: one top decays $t \rightarrow Zc$, other decays $t \rightarrow Wb$
  - Additional sample: $t \rightarrow Zu$ (lower heavy flavor tagging rate)
  - Additional sample: "double FCNC" events (both tops decay via $t \rightarrow Zq$)

Helicity Reweighting

- Problem: t→Zq vertex unknown to PYTHIA
  - Decays generated flat in cos θ* (angle between top and lepton of same charge sign from Z decay, in Z rest frame)
  - Expected helicity for pure V–A decay: 65% longitudinal (f^0), 35% left-handed (f^-). According to Tim Tait: "Wacky models" may mix left-handed and right handed fractions, but not longitudinal and handed:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos(\theta^*)} = f^0 \cdot \frac{3}{4}(1-\cos(\theta^*)) + f^- \cdot \frac{3}{8}(1-\cos(\theta^*))^2 + f^+ \cdot \frac{3}{8}(1+\cos(\theta^*))^2$$

with SM prediction for f^0: $f^0 = \frac{m_t^{\,2}}{2m_Z^2 + m_t^{\,2}} \approx 0.65$

- Solution:
  - Re-weight sample for acceptance calculation: 65% longitudinal, 35% left-handed
  - Assign systematic uncertainty to unknown helicity
  - To first order: acceptance for l^+ and l^- identical → same acceptance for same fraction of left-handed/right-handed

Acceptance Algebra: Details

- Signal count: probability for one or both tops to decay via FCNC

  $\mathscr{P}(t\bar{t} \to ZcWb, ZcZc, \ldots)$

- Normalization to double-tagged $t\bar{t}$ cross section measurement:
  - Double-tagged: smallest overlap between acceptances
  - Luminosity uncertainties cancel, other uncertainties reduced

$$\begin{aligned}
\mathscr{B}_Z &\equiv \mathscr{B}(t \to Zc) = 1 - \mathscr{B}(t \to Wb) \\
\mathscr{A}_{WZ} &\equiv \text{FCNC Acceptance} \\
\mathscr{A}_{ZZ} &\equiv \text{Double FCNC Acceptance} \\
\mathscr{A}_{LJ_{WW}} &\equiv \text{L+J Acceptance for SM } t\bar{t} \\
\mathscr{A}_{LJ_{WZ}} &\equiv \text{L+J Acceptance for FCNC} \\
\mathscr{A}_{LJ_{ZZ}} &\equiv \text{L+J Acceptance for Double FCNC} \\
K_{ZZ/WZ} &\equiv \mathscr{A}_{ZZ}/\mathscr{A}_{WZ} \\
\mathscr{R}_{WZ/WW} &\equiv \mathscr{A}_{LJ_{WZ}}/\mathscr{A}_{LJ_{WW}} \\
\mathscr{R}_{ZZ/WW} &\equiv \mathscr{A}_{LJ_{ZZ}}/\mathscr{A}_{LJ_{WW}}
\end{aligned}$$

Acceptance Master Formula:

$$N_{\text{signal}} = [(\mathscr{P}(t\bar{t} \to WbZc) \cdot \mathscr{A}_{WZ}) + (\mathscr{P}(t\bar{t} \to ZcZc) \cdot \mathscr{A}_{ZZ})] \cdot \sigma_{t\bar{t}} \cdot \int \mathscr{L}\,\mathrm{d}t$$

…1/2 page of algebra…

$$= \mathscr{B}_Z \cdot (N_{LJ} - B_{LJ}) \cdot \frac{\mathscr{A}_{WZ}}{\mathscr{A}_{LJ_{WW}}} \cdot \frac{(2 \cdot (1 - \mathscr{B}_Z) + K_{ZZ/WZ} \cdot \mathscr{B}_Z)}{(1 - \mathscr{B}_Z)^2 + 2\mathscr{B}_Z \cdot (1 - \mathscr{B}_Z) \cdot \mathscr{R}_{WZ/WW} + \mathscr{B}_Z^2 \cdot \mathscr{R}_{ZZ/WW}}$$

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

Acceptance Algebra: Details

- Signal count: probability for one or both tops to decay via FCNC

  $\mathscr{P}(t\bar{t} \to ZcWb, ZcZc, \ldots)$

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$$
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\mathscr{A}_{WZ} &\equiv \text{FCNC Acceptance} \\
\mathscr{A}_{ZZ} &\equiv \text{Double FCNC Acceptance} \\
\mathscr{A}_{LJ_{WW}} &\equiv \text{L+J Acceptance for SM } t\bar{t} \\
\mathscr{A}_{LJ_{WZ}} &\equiv \text{L+J Acceptance for FCNC} \\
\mathscr{A}_{LJ_{ZZ}} &\equiv \text{L+J Acceptance for Double FCNC} \\
K_{ZZ/WZ} &\equiv \mathscr{A}_{ZZ}/\mathscr{A}_{WZ} \\
\mathscr{R}_{WZ/WW} &\equiv \mathscr{A}_{LJ_{WZ}}/\mathscr{A}_{LJ_{WW}} \\
\mathscr{R}_{ZZ/WW} &\equiv \mathscr{A}_{LJ_{ZZ}}/\mathscr{A}_{LJ_{WW}}
\end{aligned}
$$

Acceptance Master Formula:

$$N_{\text{signal}} = [(\mathscr{P}(t\bar{t} \to WbZc) \cdot \mathscr{A}_{WZ}) + (\mathscr{P}(t\bar{t} \to ZcZc) \cdot \mathscr{A}_{ZZ})] \cdot \sigma_{t\bar{t}} \cdot \int \mathscr{L}\,\mathrm{d}t$$

$\ldots$1/2 page of algebra$\ldots$

$$= \mathscr{B}_Z \cdot (N_{LJ} - B_{LJ}) \cdot \frac{\mathscr{A}_{WZ}}{\mathscr{A}_{LJ_{WW}}} \cdot \frac{(2 \cdot (1 - \mathscr{B}_Z) + K_{ZZ/WZ} \cdot \mathscr{B}_Z)}{(1 - \mathscr{B}_Z)^2 + 2\mathscr{B}_Z \cdot (1 - \mathscr{B}_Z) \cdot \mathscr{R}_{WZ/WW} + \mathscr{B}_Z^2 \cdot \mathscr{R}_{ZZ/WW}}$$

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

Optimization of Event Selection

- Question: best choice for cut values?
- No prediction for amount of signal: "signal over background" et al. do not work
- Solution: optimize cuts for best expected limit (assuming no signal)

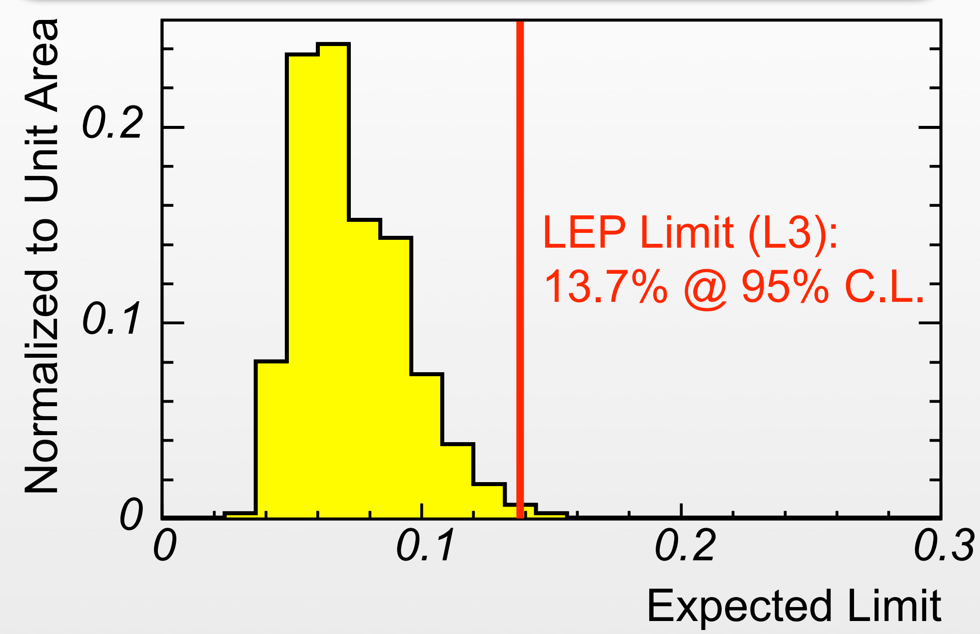
$$\sum_{n_{\text{obs}}} P(n_{\text{obs}}|n_{\text{back}}) \cdot \text{Lim}(n_{\text{obs}}|A, n_{\text{back}})$$

  - P: Poisson probability
  - Lim: any limit calculation method
  - Our analysis: faster objective Bayesian limits for optimization, "better" Feldman-Cousins limits for final result (both including systematic uncertainties)
- Correlations among variables: multi-dimensional optimization

Final Event Selection

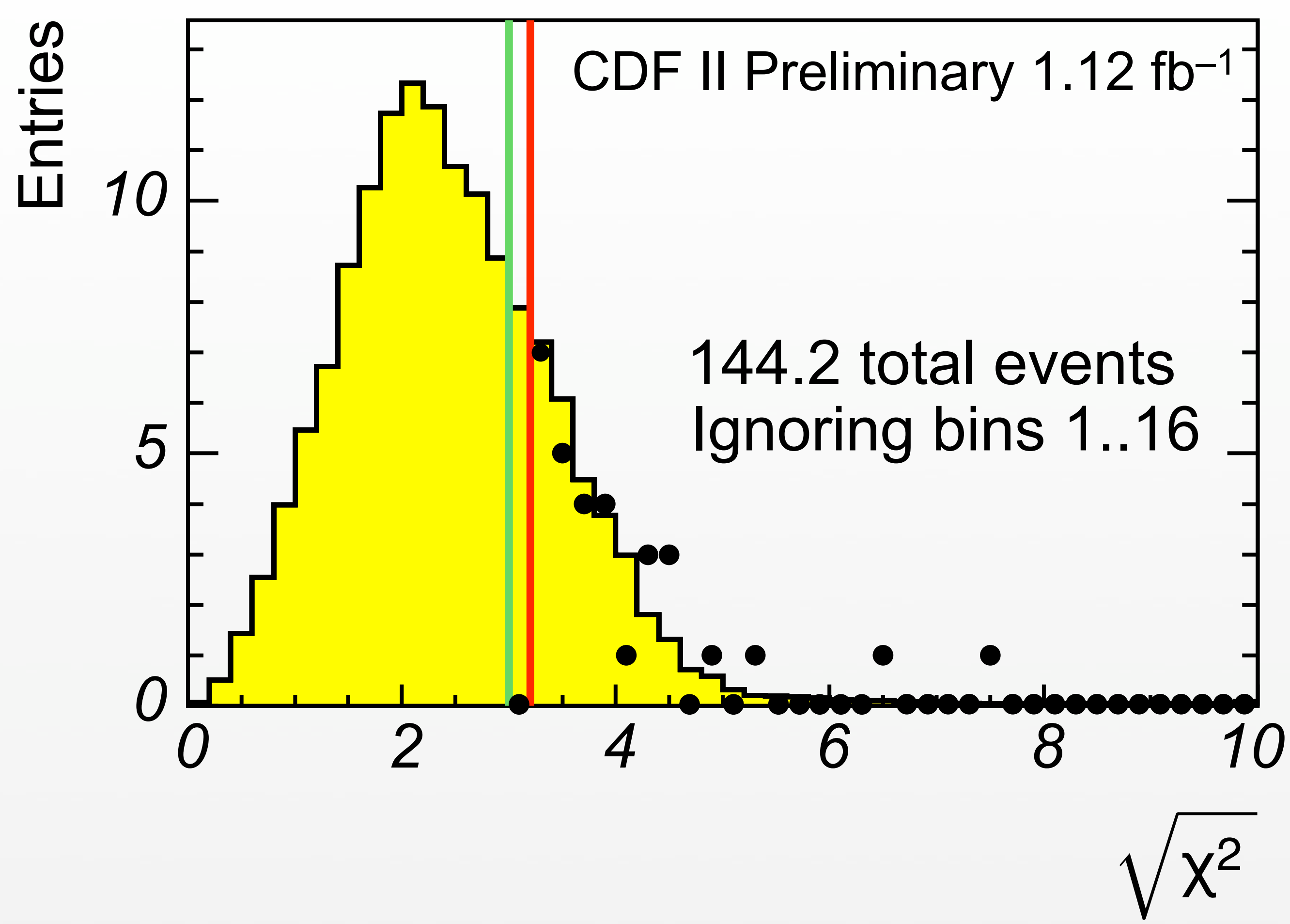
Kinematic Variable	Optimized Cut
Z Mass	$\in [76,106]\,\text{GeV}/c^2$
Leading Jet E_T	$> 40\,\text{GeV}$
Second Jet E_T	$> 30\,\text{GeV}$
Third Jet E_T	$> 20\,\text{GeV}$
Fourth Jet E_T	$> 15\,\text{GeV}$
Transverse Mass	$> 200\,\text{GeV}$
$\sqrt{\chi^2}$	< 1.6 (b-tagged)
	< 1.35 (anti-tagged)

Expected 95% C.L. Upper Limit on BR(t→Zq): 6.8% ± 3.0%



Background Estimate

- Total background → fits to control region in data: tail of mass χ^2 distribution
  - Result: 130 ± 28 events
- Tagging rate → mixture of techniques
  - Tail of mass χ^2: 16% ± 7% (small sample → too large uncertainties)
  - MC prediction of tagging rate: 11% (but: 30% too low for Z+≤ 3 Jets) → lower bound
  - Template fit of MC tagging probabilities vs. number of jets: 14%
  - Result: 15% ± 4%

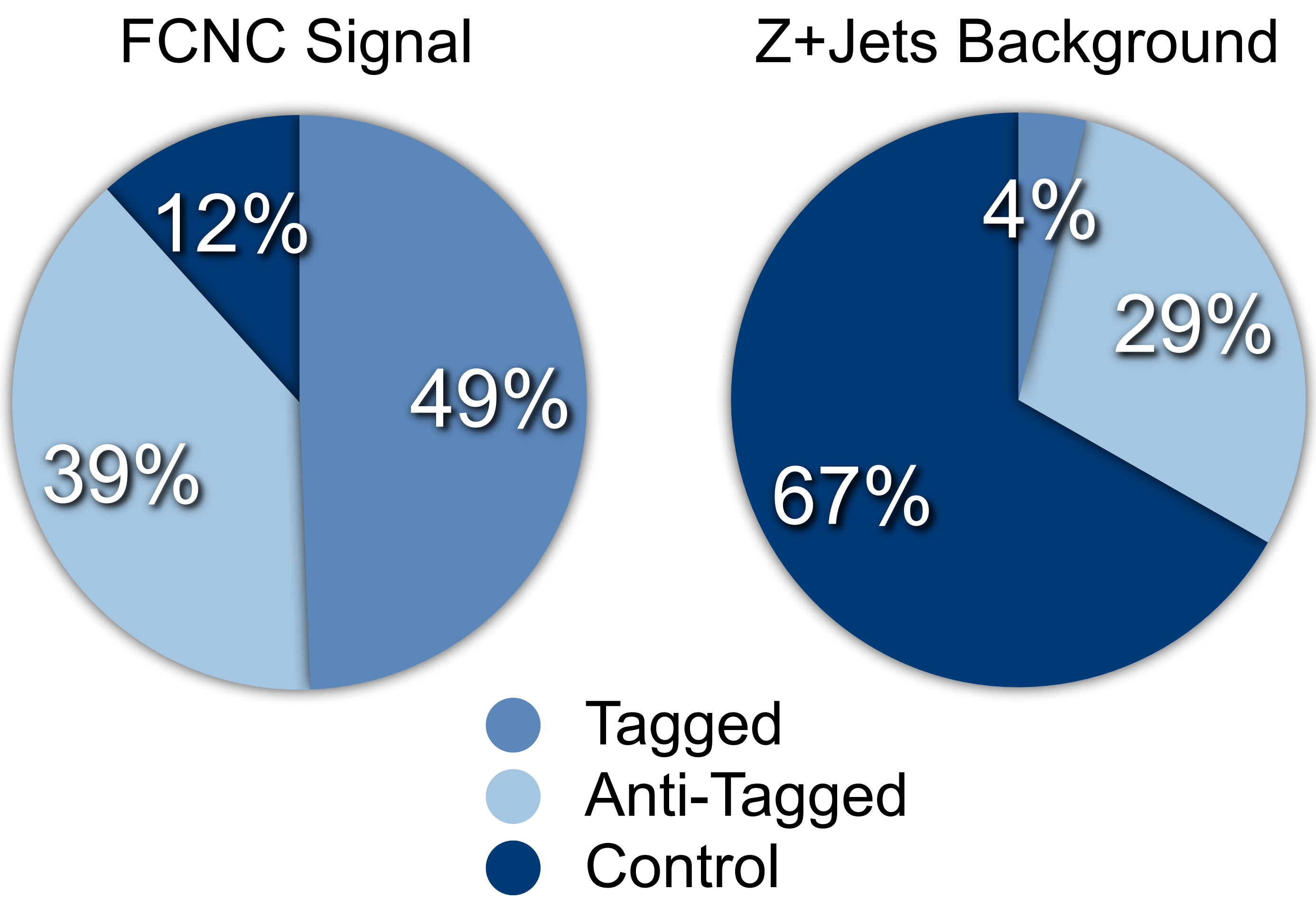


Source	Without b-tag	Loose SECVTX b-tag
Z+Jets	123.3±28	17.6±6
Standard Model $t\bar{t}$	2.4±0.3	1.7±0.2
Diboson (WZ, ZZ)	4.3±0.2	0.7±0.1
WW, W+Jets	< 0.1	negligible
Total Backgrounds:	130±28	20±6

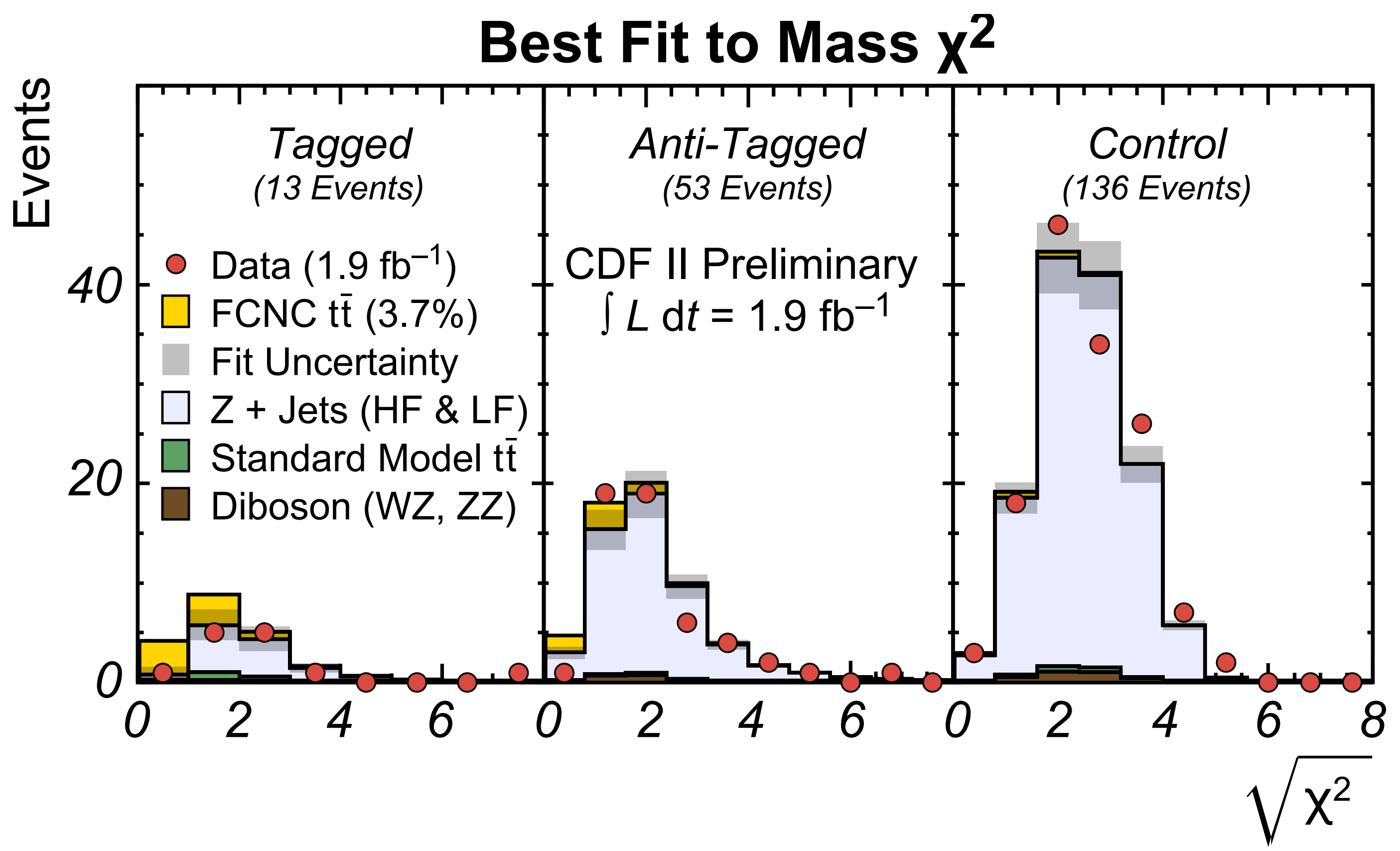
Signal and Control Regions

- Godfather Nielsen asks: "But how do you avoid morphing away a 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, no b-tagging information used

Kinematic Variable	Optimized Cut
Z Mass	$\in [76\,\mathrm{GeV}/c^2, 106\,\mathrm{GeV}/c^2]$
Leading Jet	$\geq 40\,\mathrm{GeV}$
Second Jet	$\geq 30\,\mathrm{GeV}$
Third Jet	$\geq 20\,\mathrm{GeV}$
Fourth Jet	$\geq 15\,\mathrm{GeV}$
Transverse Mass	$\geq 200\,\mathrm{GeV}$

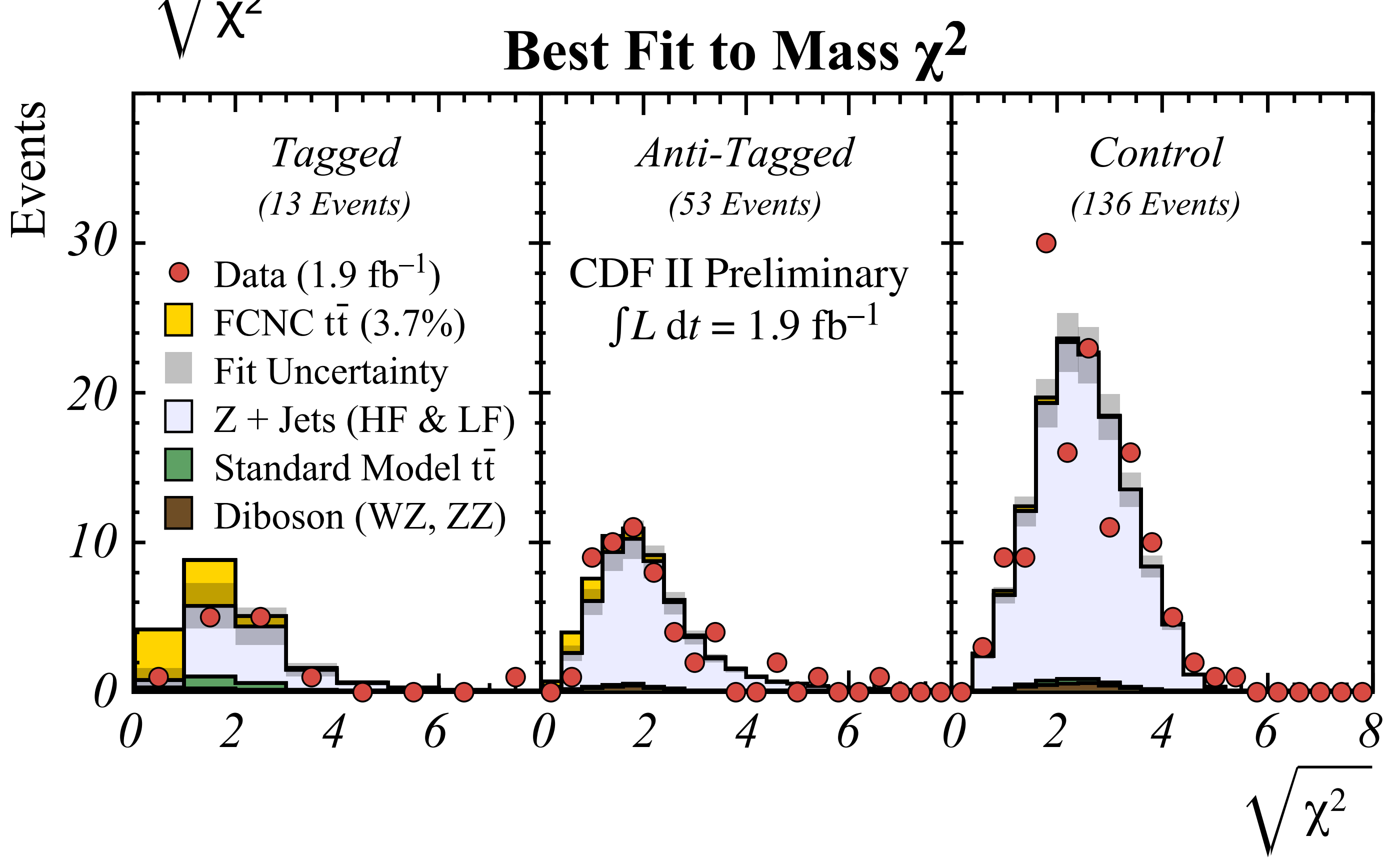


Expected Signal at Limit



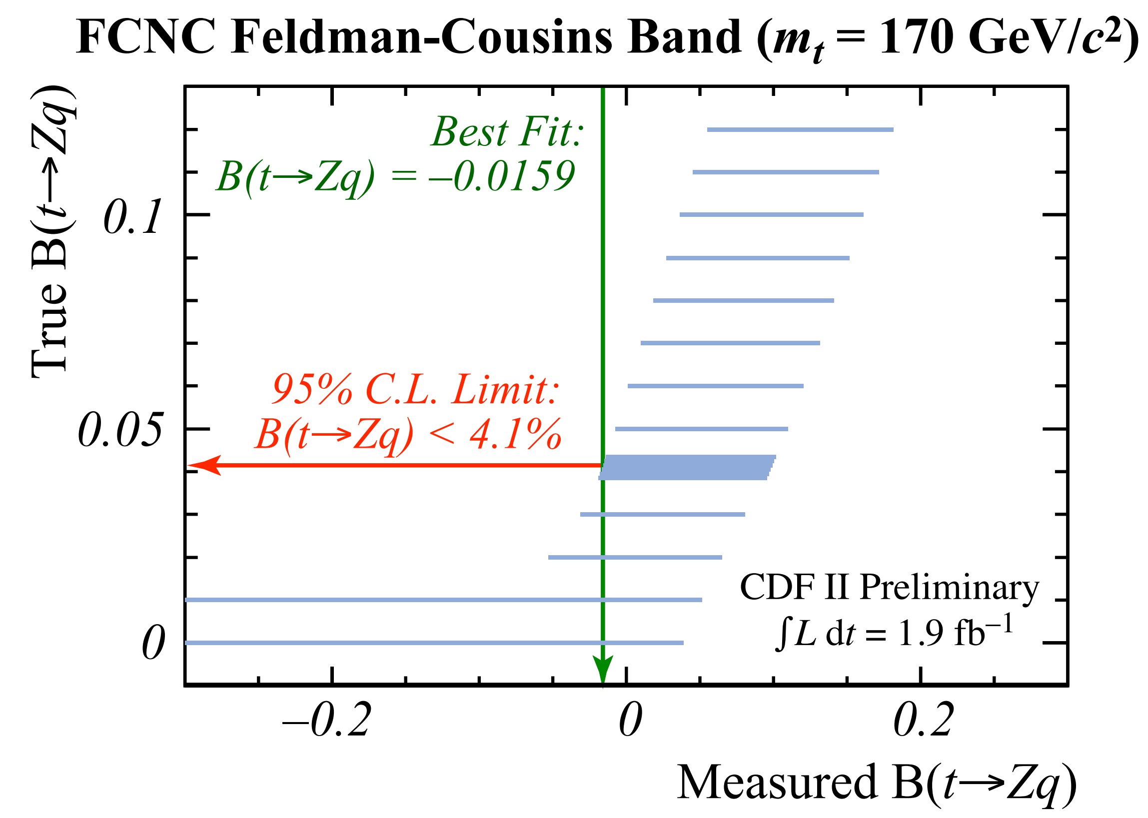
Coarse Binning

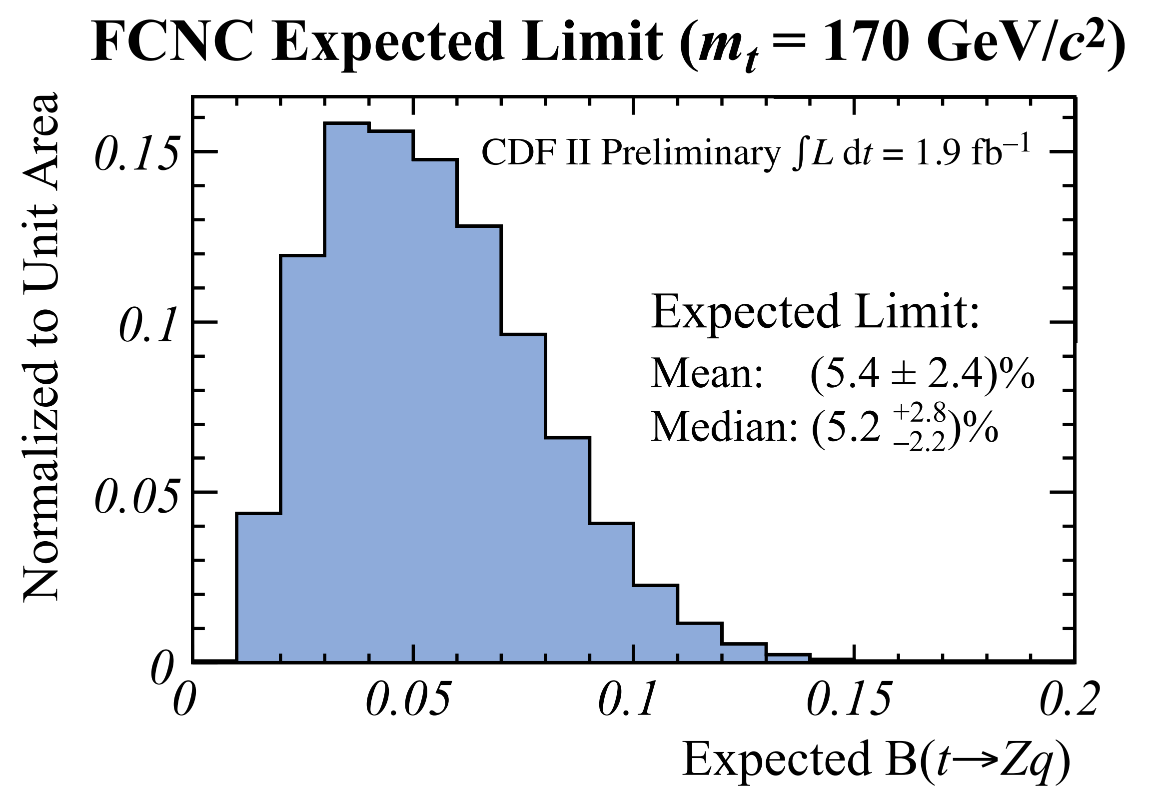
Fine Binning



Limit on B(t→Zq) at m_t = 170 GeV/c^2

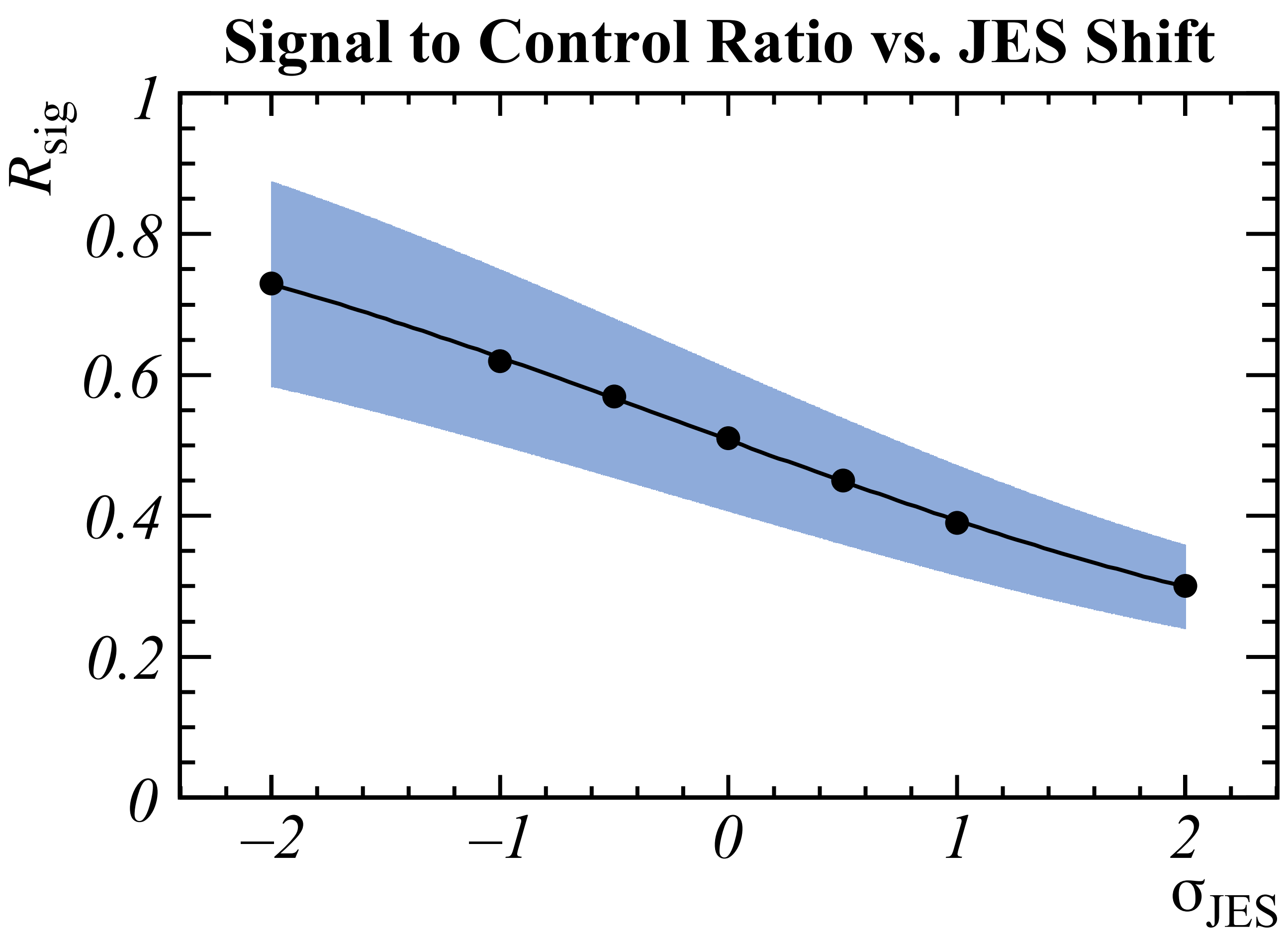
- Following top group's policy to re-do analysis at m_t = 170 GeV/c^2
- Changed:
  - FCNC signal and standard model top MC samples with m_t = 170 GeV/c^2
  - All ingredients of "running acceptance": acceptances for FCNC selection and Lepton+Jets selection (normalization channel)
- Not changed:
  - Event selection, including definition of mass χ^2 (was optimized with 175 GeV/c^2)
  - Non-top backgrounds
  - Systematic uncertainties
- Results:
  - B(t→Zq) < 4.1% @ 95% C.L.
  - Expected limit: 5.4% ± 2.4%





The 20% Constraint

- Constraint on ratio R_{sig} of Z +jets events in signal region vs. control region (not on total prediction)
- Constraint: function of JES shift → measured in MC
- Uncertainty of R_{sig}: 20% → derived from ALPGEN MC with different energy scales



Systematics Overview

- Signal systematics:
  - Jet energy scale ^{R,S,C}
  - Helicity reweighting ^{R,C}
  - B-tagging & mistags ^{R,A}
  - Lepton scale factors ^{R,C}
  - Trigger efficiency ^{R,C}
  - $t \to Zu$ vs. $t \to Zc$ ^{R,A}
  - ISR/FSR ^{R,C}
  - PDFs ^{R,C}

- Background systematics:
  - Jet energy scale ^{R,S,C}
  - MC generator ^{R,S,C}
  - Lepton scale factors ^{R,C}
  - B-tagging & mistags ^{R,A}
  - Luminosity *

- Other systematics:
  - Normalization to Lepton +Jets cross section

^{R} Rate Systematic
^{S} Shape Systematic
^{C} Correlated
^{A} Anti-Correlated
* Only Diboson and $t\bar{t}$

Only difference in treatment of systematic uncertainties w.r.t. v1.0: shape uncertainties

A Word on Systematic Uncertainties

- Both rate and shape uncertainties
- Uncertainties can be correlated or anti-correlated between tagged and anti-tagged signal regions
- Signal acceptance:
  - Relative to acceptance for $t\bar{t}$ normalization mode → many uncertainties cancel
  - Dominant effect: B-tagging efficiency (16%)
- Background: fit for dominant rate and shape uncertainties
  - Z+jets normalization and tagging rate
  - JES shift
- Dominant remaining uncertainties:
  - Z+jets: ALPGEN energy scale choice (6%)
  - Small backgrounds ($t\bar{t}$, dibosons): luminosity (6%)

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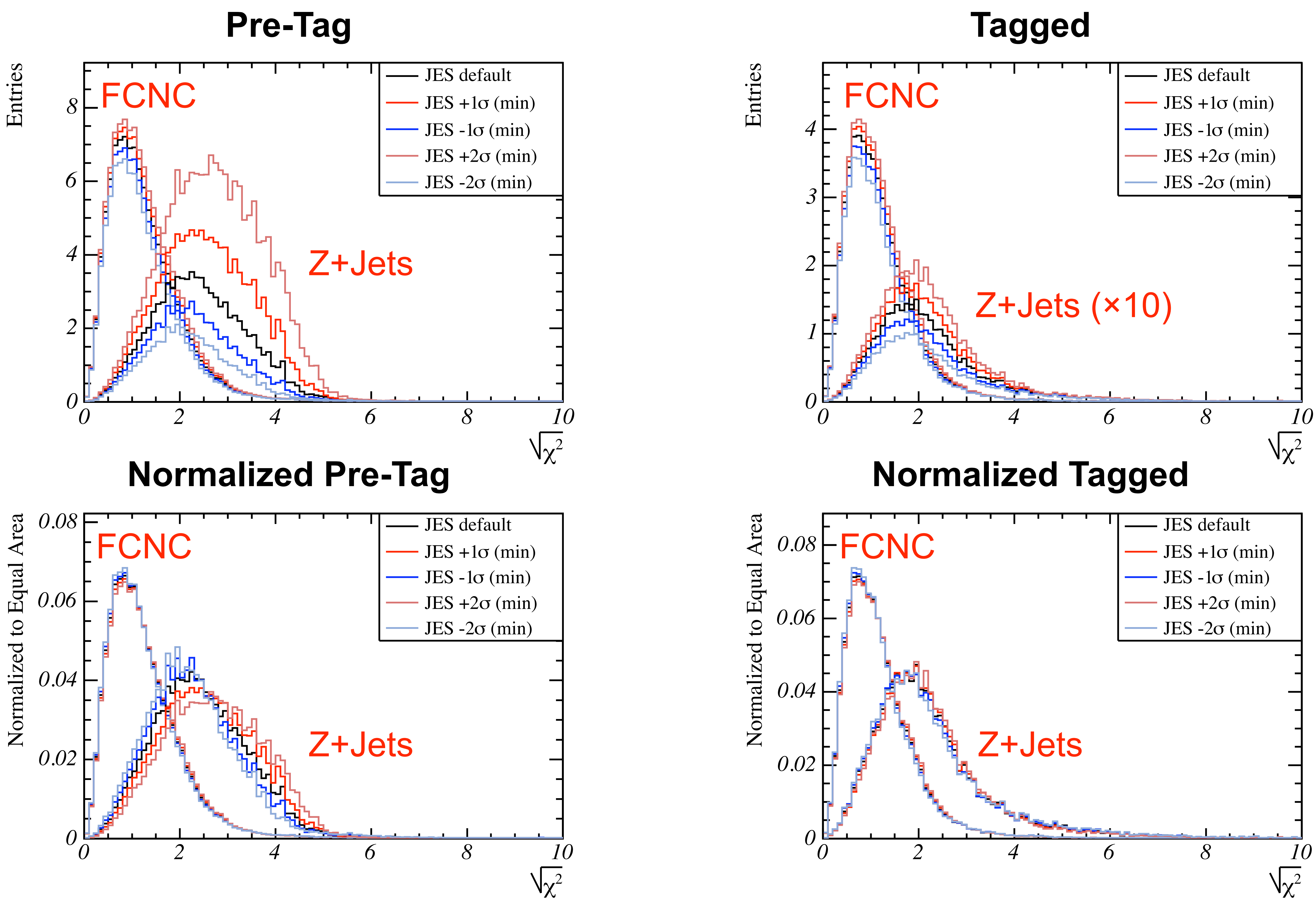
- PDF uncertainty: taken from top cross section measurement: 0.9%

Signal Rate Systematics

- Signal rate systematic evaluated for acceptance ratio A_{WZ}/A_{LJ}
- Distinguish uncertainties: correlated or anti-correlated between selections
  - Correlated: shift anti-tagged & tagged selection into same direction (e.g. lepton SF)
  - Anti-correlated: shift anti-tagged & tagged into opposite directions (e.g. b-tagging)

Systematic Uncertainty: Signal Acceptance Ratio	**Base Sel. (%)**	**Tagged Region (%)**	**Anti-Tagged Region (%)**	**Control Region (%)**
Lepton Scale Factor	0.5	0.5	0.5	0.6
Trigger Efficiency	0.2	0.2	0.2	0.2
ISR/FSR	1.8	4.8	5.5	4.0
Helicity Re-Weighting	3.5	3.4	3.6	4.0
Parton Distribution Functions	0.9	0.9	0.9	0.9
Jet Energy Scale	— *Fit Parameter* —			
Total Correlated	3.9	6.2	6.1	5.9
B-Tagging Scale Factor	10.2	5.6	16.1	10.2
Mistag Parameterization	0.6	0.4	1.0	0.6
$\mathscr{B}(t \to Zc)$ versus $\mathscr{B}(t \to Zu)$	0.0	4.5	4.5	0.0
Total Anti-Correlated	10.2	7.2	16.7	10.2

JES Systematics



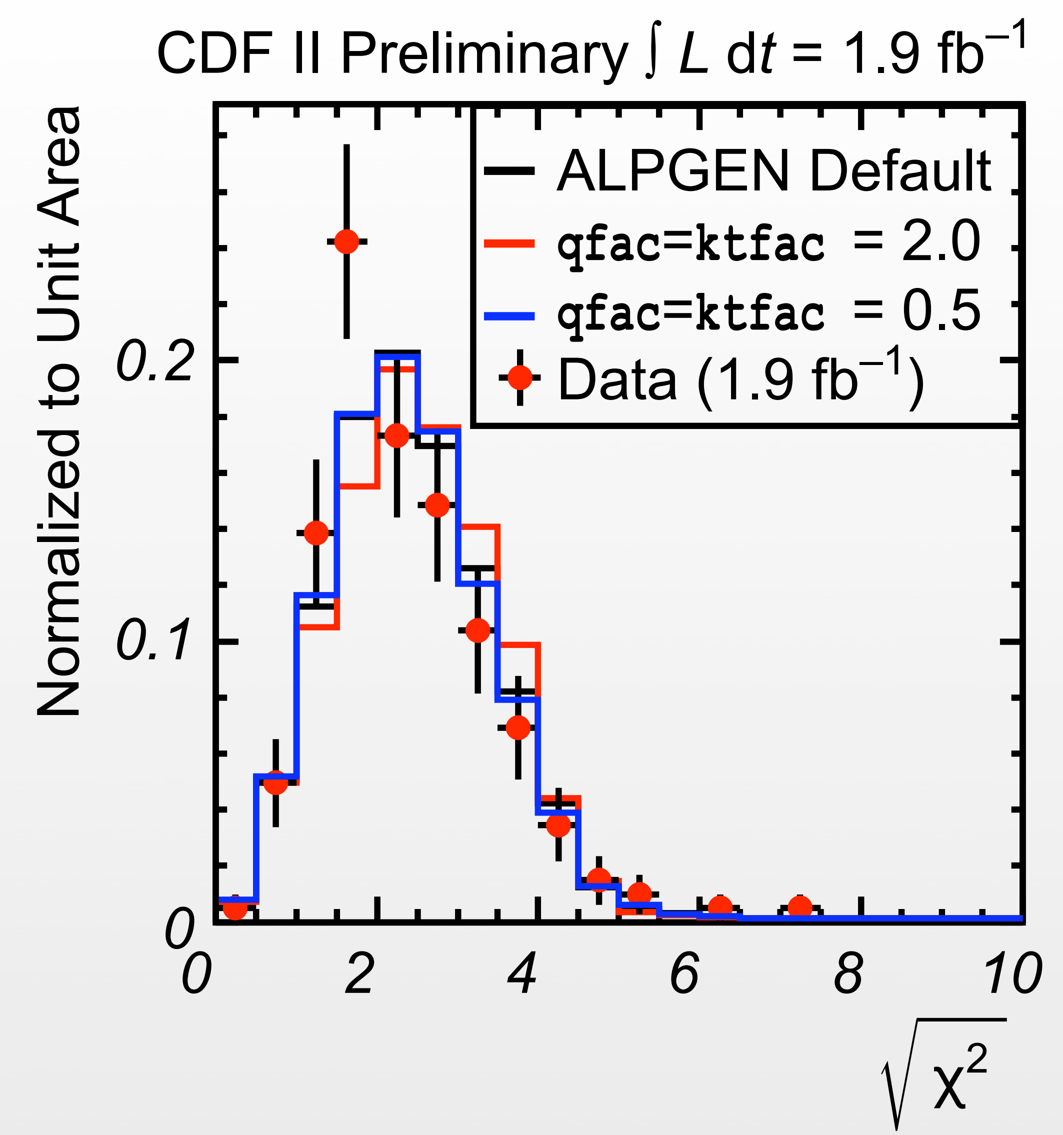
Signal Systematics: Details

Z Helicity	Base Sel. (%)	Loose Tag (%)	Anti-Tagged (%)	Control (%)
35% LH, 65% Long.		*— Default —*		
Flat	−4.3	−4.3	−4.0	−5.1
100% Longitudinal	+5.0	+4.7	+5.1	+5.7
100% Left-Handed	−9.3	−8.8	−9.5	−10.6
100% Right-Handed	−8.6	−8.9	−7.8	−10.4
35% RH, 65% Long.	+0.2	±0.0	+0.6	+0.1
Total Uncertainty (%)	3.6	3.4	3.7	4.1

Sample	Base Selection (%)	Loose Tag (%)	Anti-Tagged (%)	Control (%)
More ISR	−0.2	0.3	0.1	−3.6
Less ISR	0.2	2.7	−2.8	1.1
More FSR	−0.3	2.1	−3.2	0.4
Less FSR	1.1	3.7	−2.1	1.7
Total	1.1	5.1	4.8	4.2

ALPGEN Q^2 Scale Systematics

- 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)
    $$Q = \text{ktfac} \times p_T$$
- Top group generated ALPGEN test samples (Z+0–4p):
  - qfac = ktfac = 2.0
  - qfac = ktfac = 0.5
- Study of Z+Jets vs. data
  - Caveat: neglecting smaller backgrounds from Z+HF, $t\bar{t}$, diboson
  - Effect on χ^2 templates small
  - Sizable effect on jet multiplicity



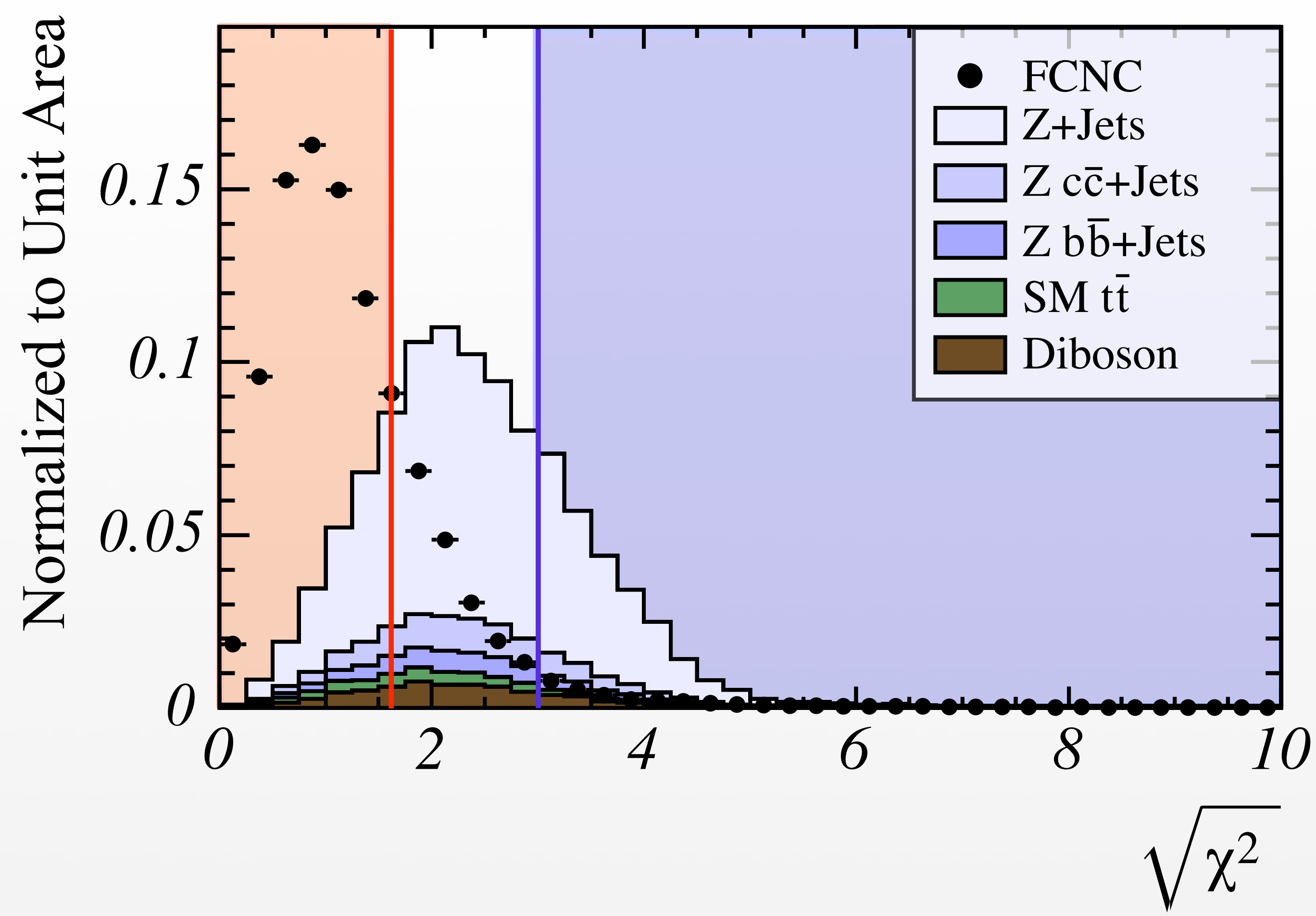
Small Backgrounds: Events and Systematics

Small Backgrounds $\left(\int \mathscr{L} dt = 1.9\,\text{fb}^{-1}\right)$				
Sample	**Cross Section (pb)**	**Events Tagged**	**Events Anti-Tagged**	**Events Control**
SM $t\bar{t}$	8.8±1.1	1.7±0.2	0.7±0.1	1.8±0.2
WZ	3.96±0.06	0.2±0.1	1.4±0.1	2.1±0.1
ZZ	3.40±0.25	0.3±0.1	1.1±0.1	1.8±0.1

Systematic Uncertainty: Small Backgrounds	Base Sel. (%)	Tagged Region (%)	Anti-Tagged Region (%)	Control Region (%)
Luminosity	6.0	6.0	6.0	6.0
Lepton Scale Factor	1.3	1.4	1.4	1.3
Trigger Efficiency	0.4	0.4	0.4	0.4
Jet Energy Scale	— *Fit Parameter* —			
Total Correlated	6.2	6.2	6.2	6.2
B-Tagging Scale Factor	0.0	3.1	2.4	0.0
Mistag Parameterization	0.0	0.8	0.7	0.0
Total Anti-Correlated	0.0	3.2	2.5	0.0

Round 1: Background Systematics

- Background systematics dominated by yield uncertainties
  - Total background yield: 130 ± 28 (21.5% relative uncertainty)
  - Tagging rate: 15% ± 4% (relative uncertainty: 26.7% tagged, 4.7% anti-tagged)
- Remaining uncertainties: efficiency of χ^2 cut
  - Ratio of events with $\sqrt{\chi^2} < 1.6$ (signal region) vs. $\sqrt{\chi^2} > 3.0$ (control region)
  - Dominated by choice of MC generator and jet energy scale



Systematic Uncertainty	Anti-Tagged (%)	Loose Tag (%)
Lepton Scale Factor	< 0.1	< 0.1
Trigger Efficiency	< 0.1	< 0.1
Jet Energy Scale	5.1	2.1
B-Tagging Scale Factor	< 0.1	0.3
Mistag $\alpha\beta$ Correction	0.2	0.4
ALPGEN MC Generator	10.0	5.9
Total Uncertainty	11.2	6.3

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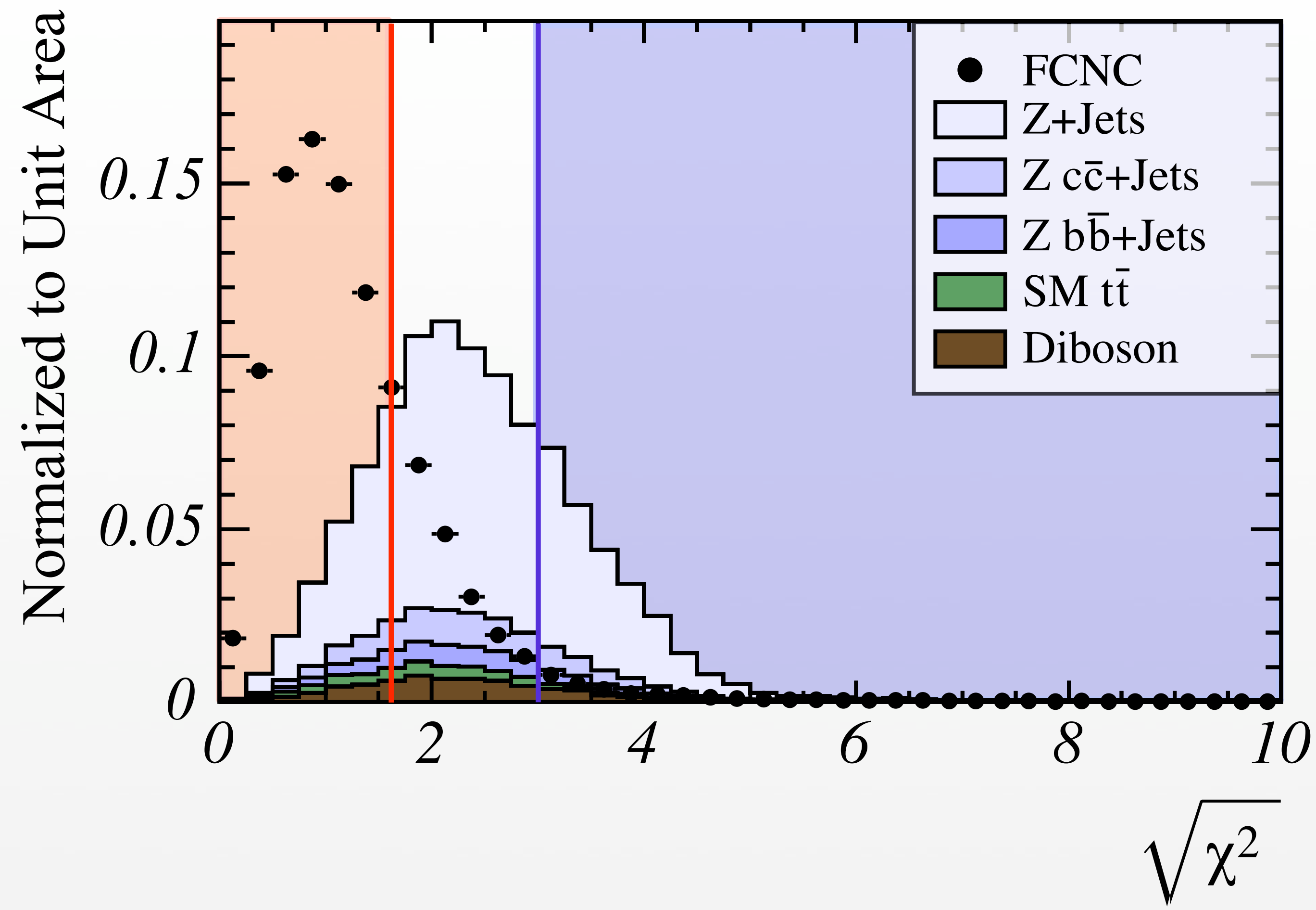

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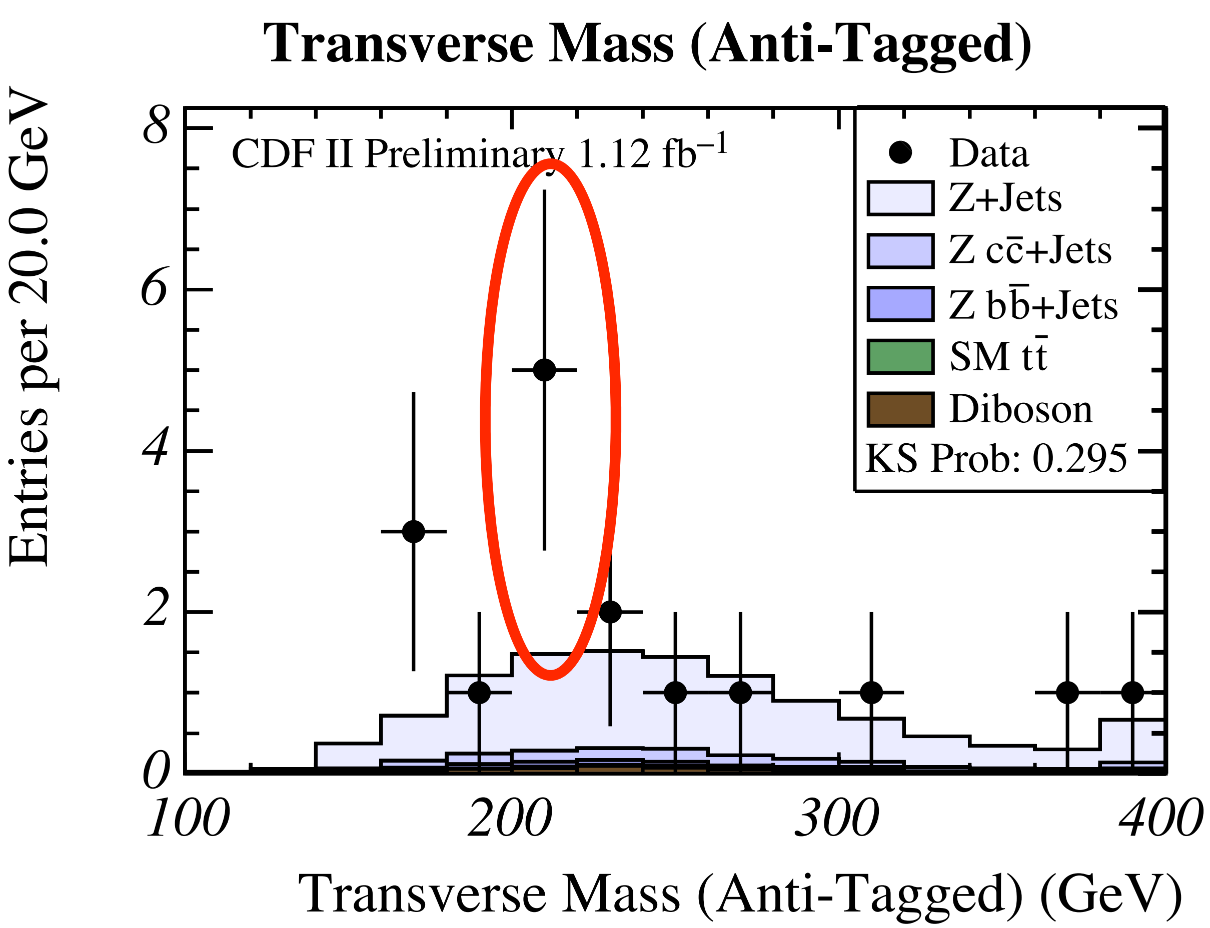
Why is Your Background 1σ High?

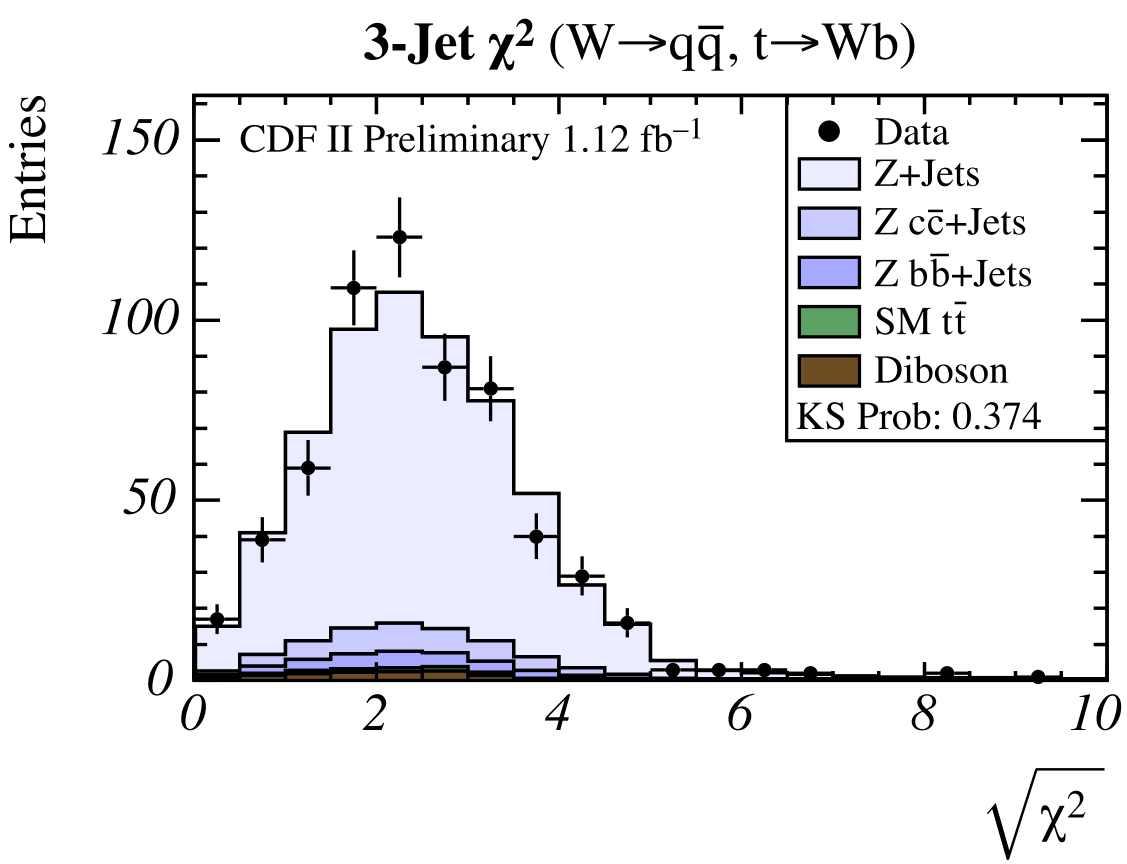
- Blind analysis: cannot change cuts after "opening the box"
- Closer look at the data: excess of events with transverse mass around 200 GeV
- Compare cuts at 200 GeV and 220 GeV: most likely explanation of higher than expected limit



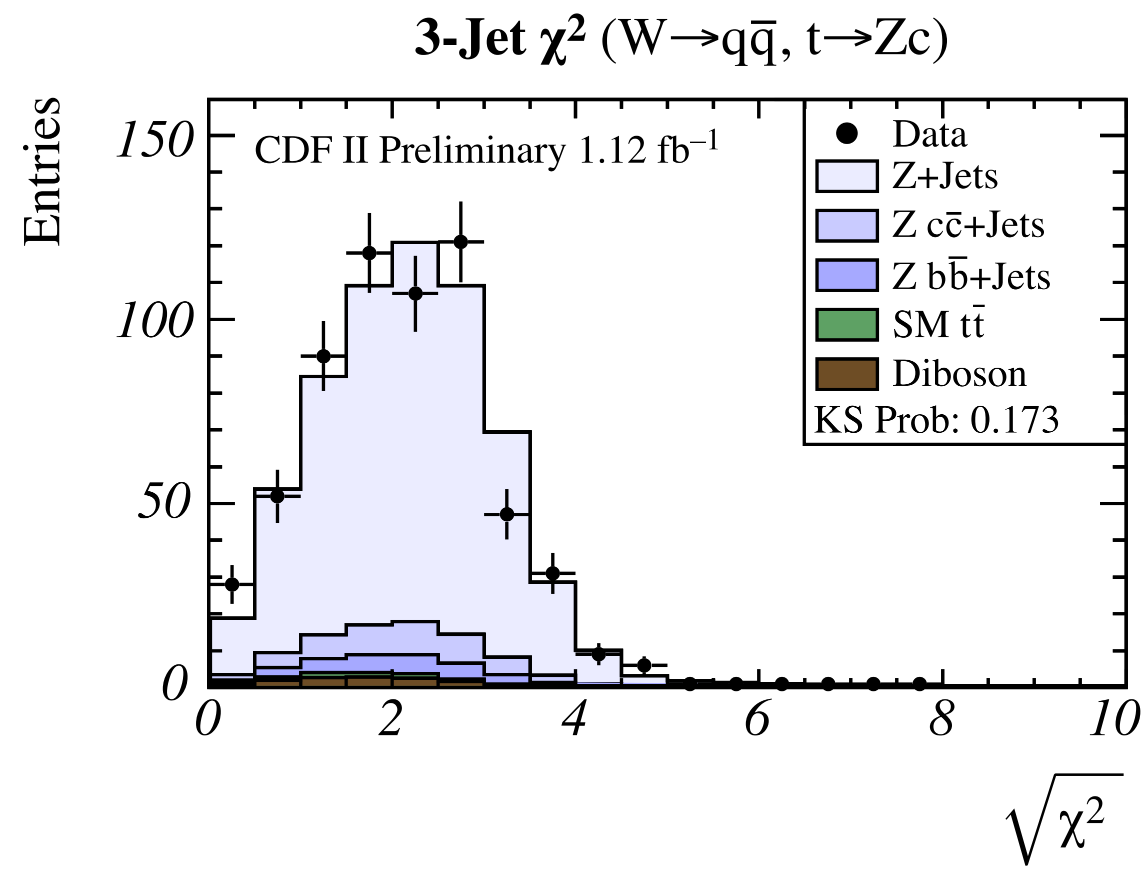
Selection	Observed (Expected) Events m_T >200 GeV	m_T >220 GeV
Anti-Tagged	12 (7.7)	7 (6.4)
Loose Tag	4 (3.2)	3 (2.8)
Total	16 (10.8)	10 (9.2)
Cut Efficiency (%)	11.3 (8.3)	7.1 (7.1)

Validation in 3-Jet Bin

- Original mass χ^2 only defined with four or more jets (mostly blind)
- Validate two out of three pieces in 3-jet bin: good agreement

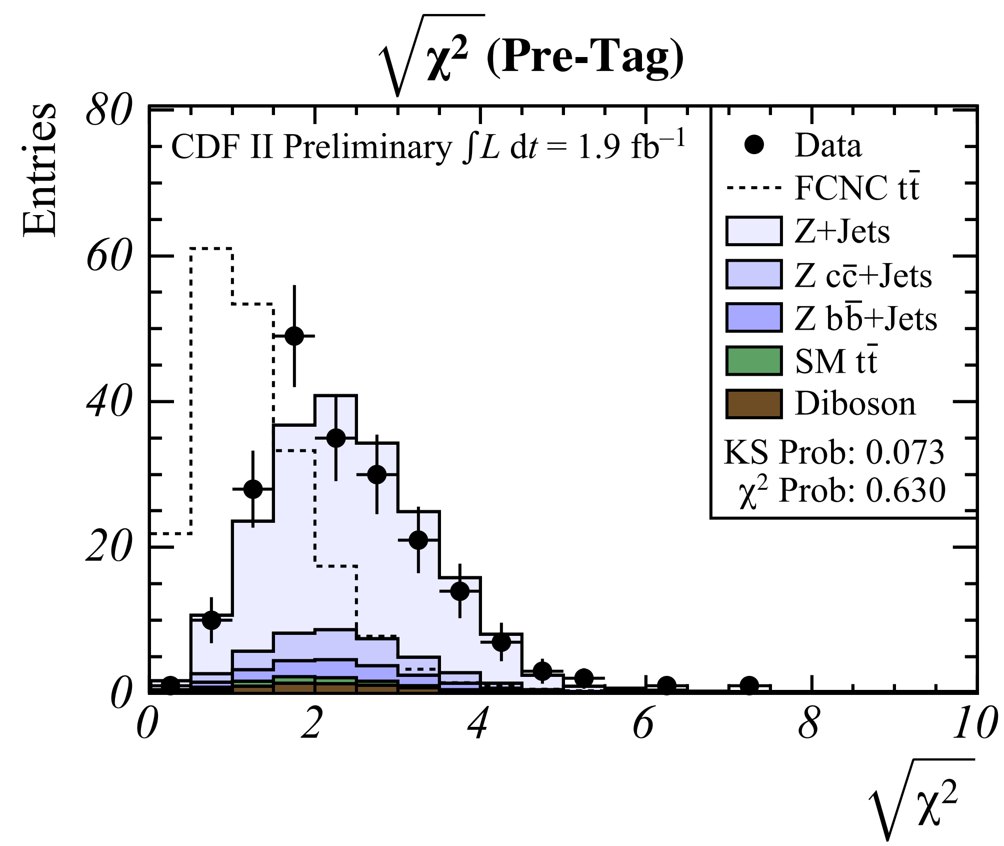


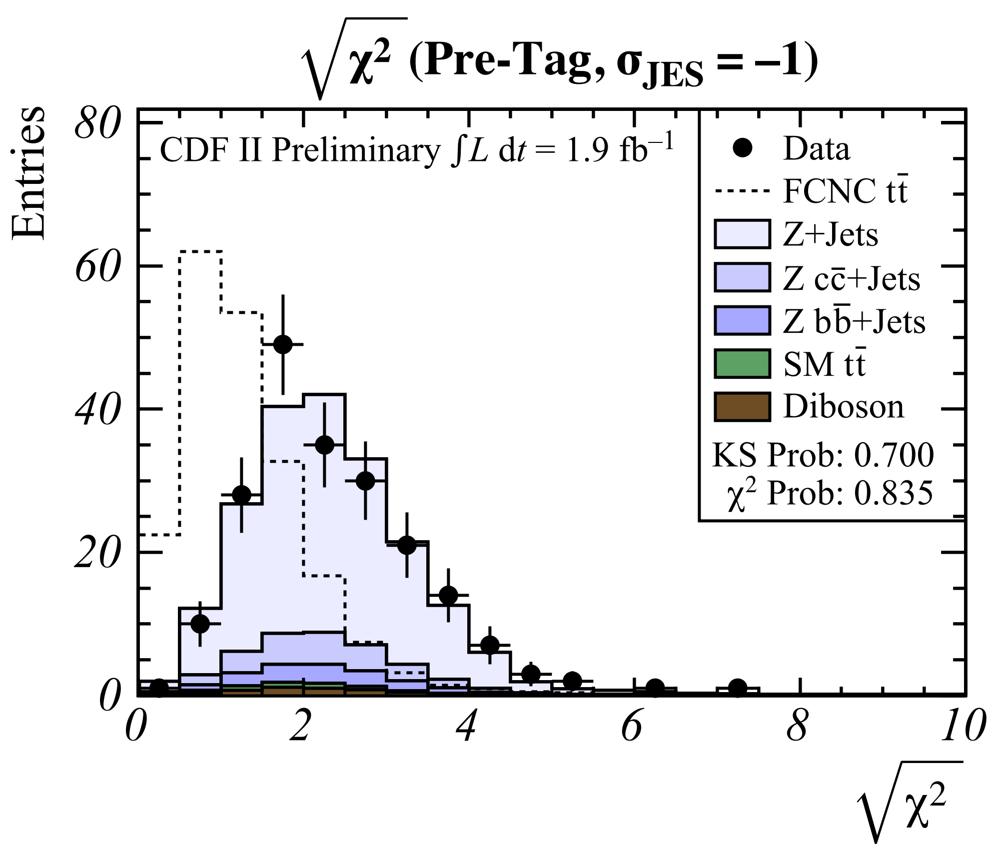
$$\chi_1{}^2 = \left(\frac{m_{W,\mathrm{rec}} - m_{W,\mathrm{PDG}}}{\sigma_{W,rec}}\right)^2 + \left(\frac{m_{t\to Wb,\mathrm{rec}} - m_{t,\mathrm{PDG}}}{\sigma_{t\to Wb}}\right)^2$$

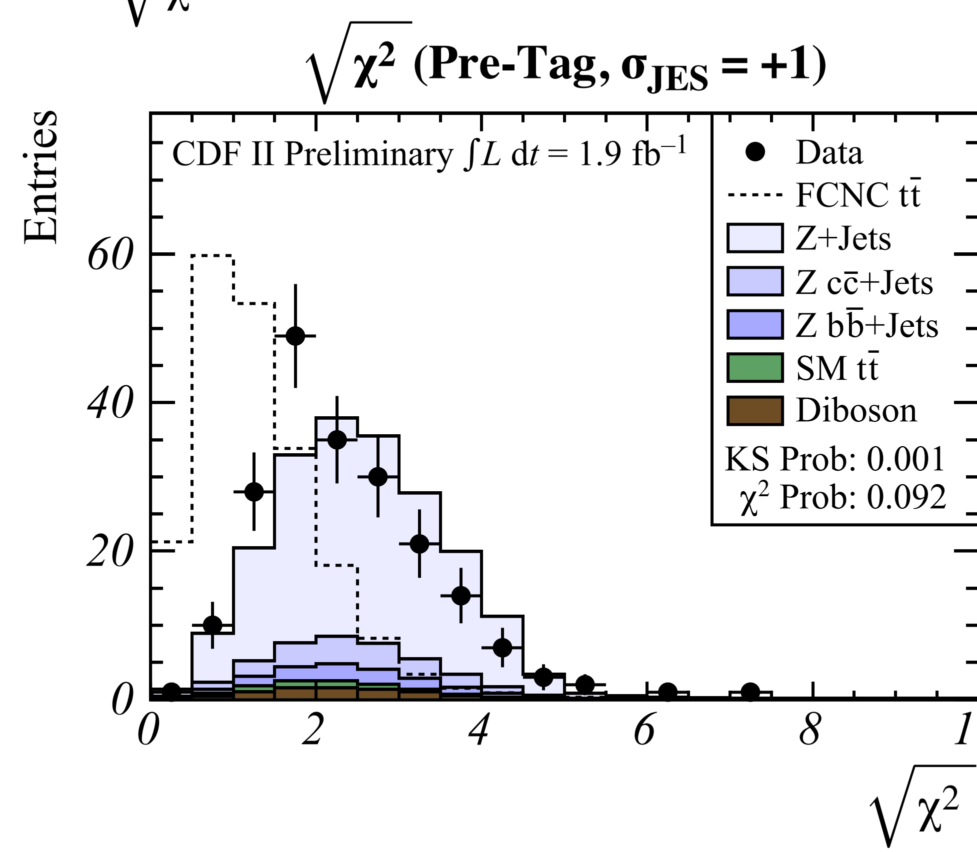


$$\chi_2{}^2 = \left(\frac{m_{W,\mathrm{rec}} - m_{W,\mathrm{PDG}}}{\sigma_{W,rec}}\right)^2 + \left(\frac{m_{t\to Zq,\mathrm{rec}} - m_{t,\mathrm{PDG}}}{\sigma_{t\to Zq}}\right)^2$$

Mass χ^2 and JES Shifts

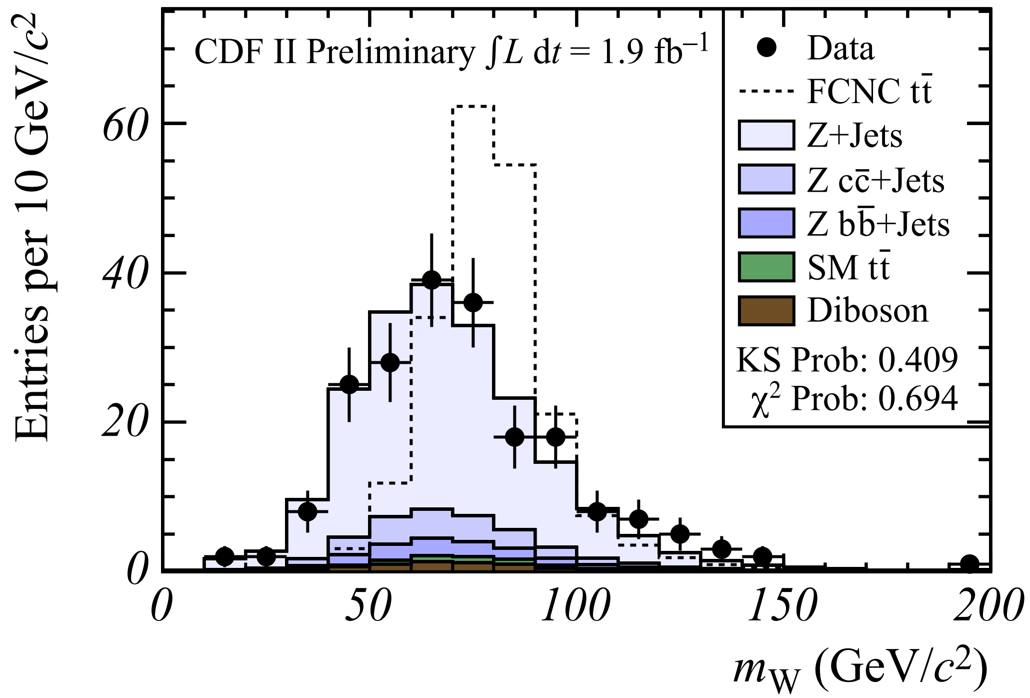




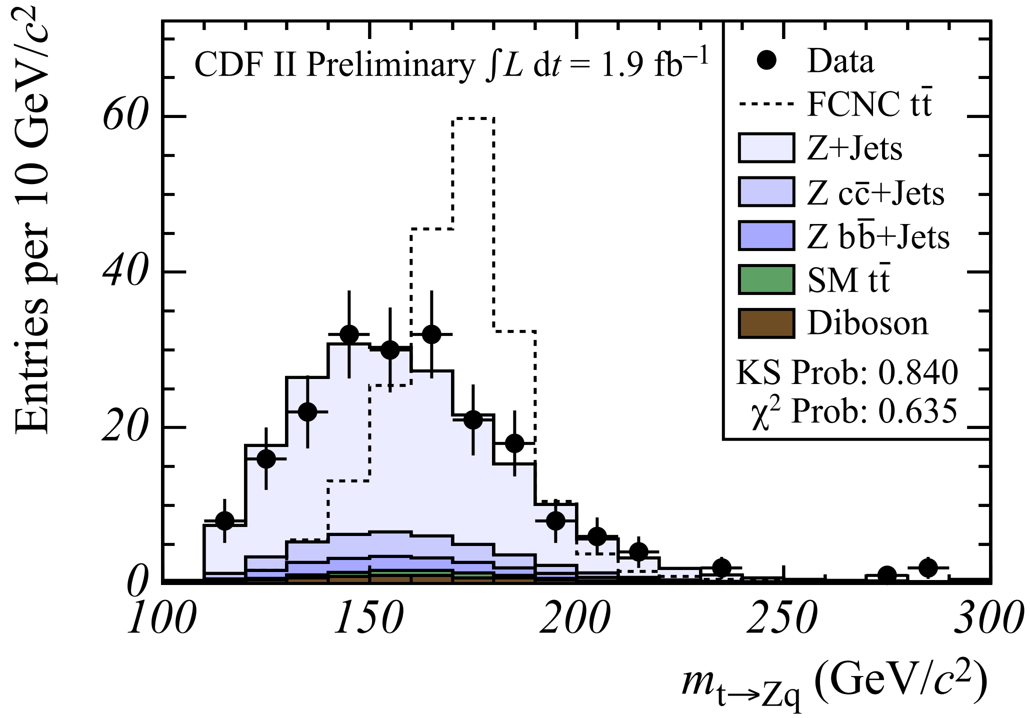


χ^2 Ingredients: Nominal JES

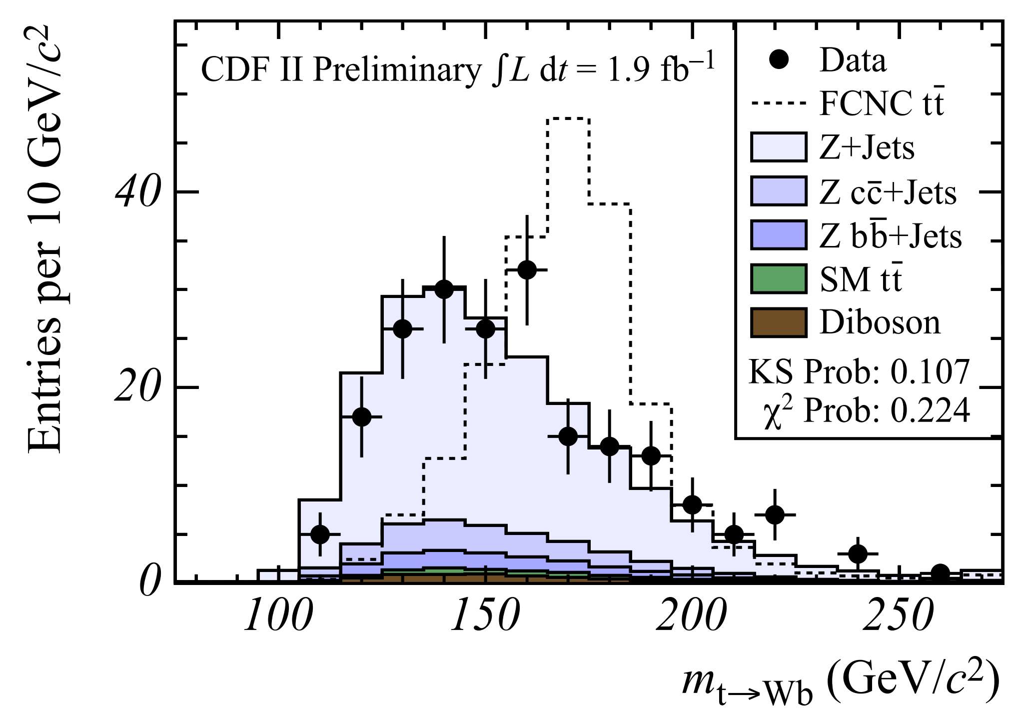
Jet Combination with Best χ^2: W Mass



Jet Combination with Best χ^2: FCNC Top Mass

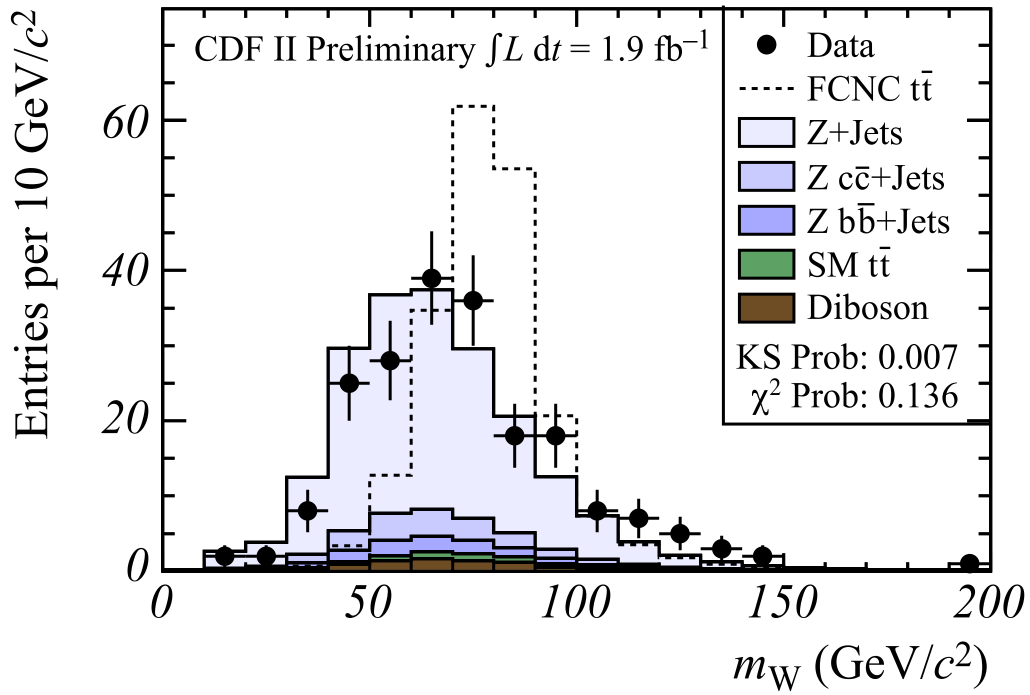


Jet Combination with Best χ^2: Standard Model Top Mass



χ^2 Ingredients: σ_{JES} = +1

Jet Combination with Best χ^2:
W Mass (σ_{JES} = +1)



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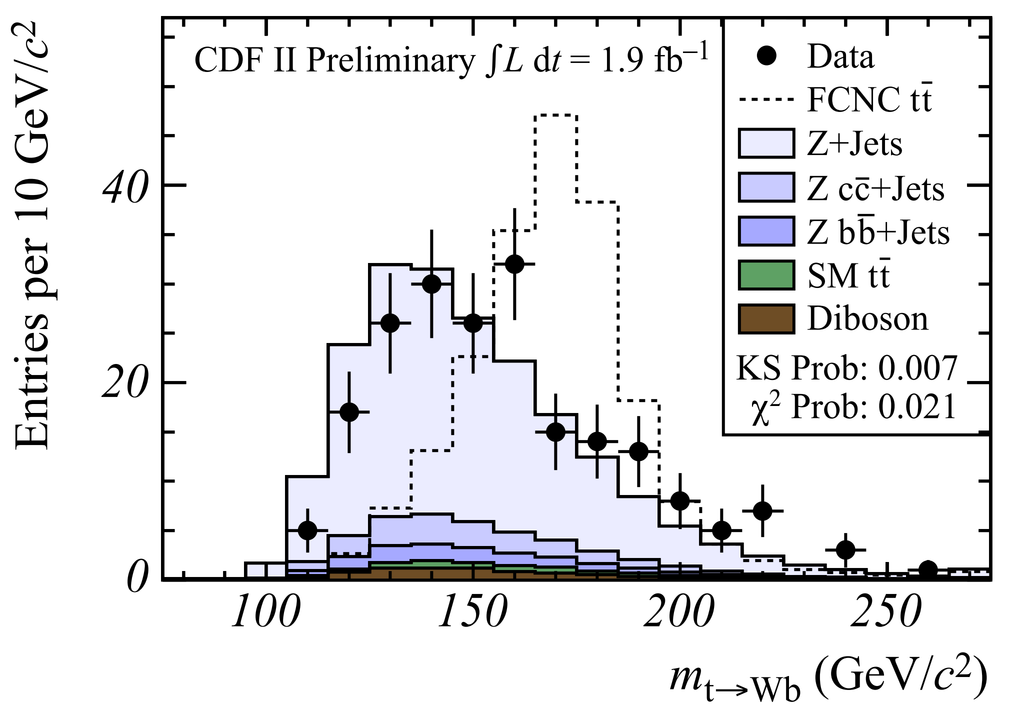

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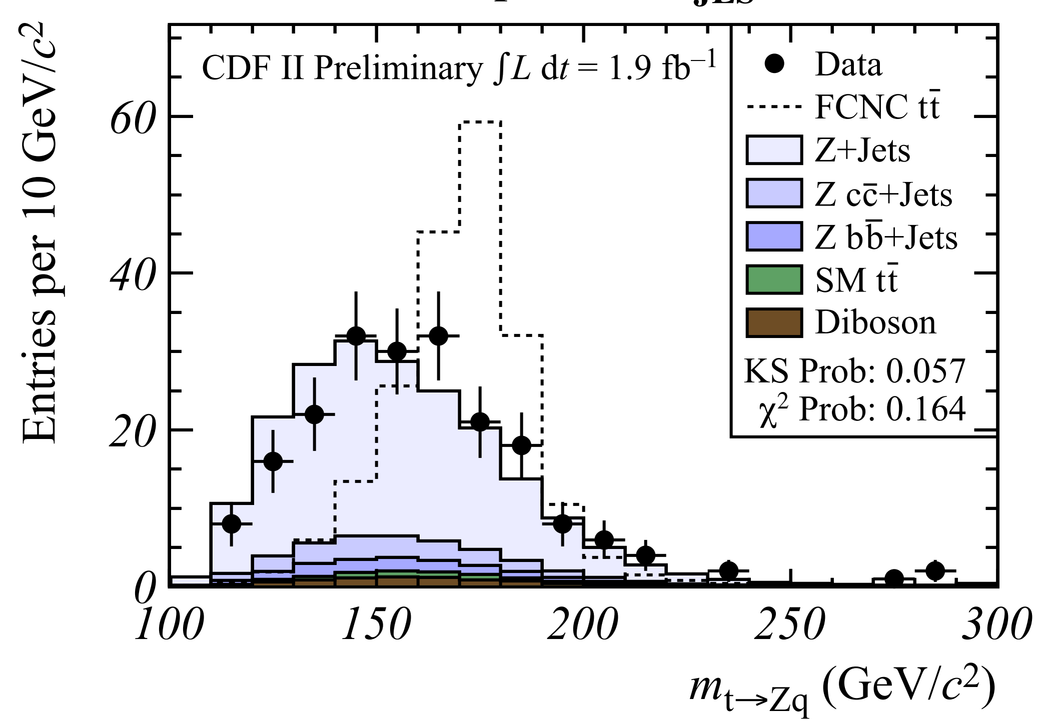
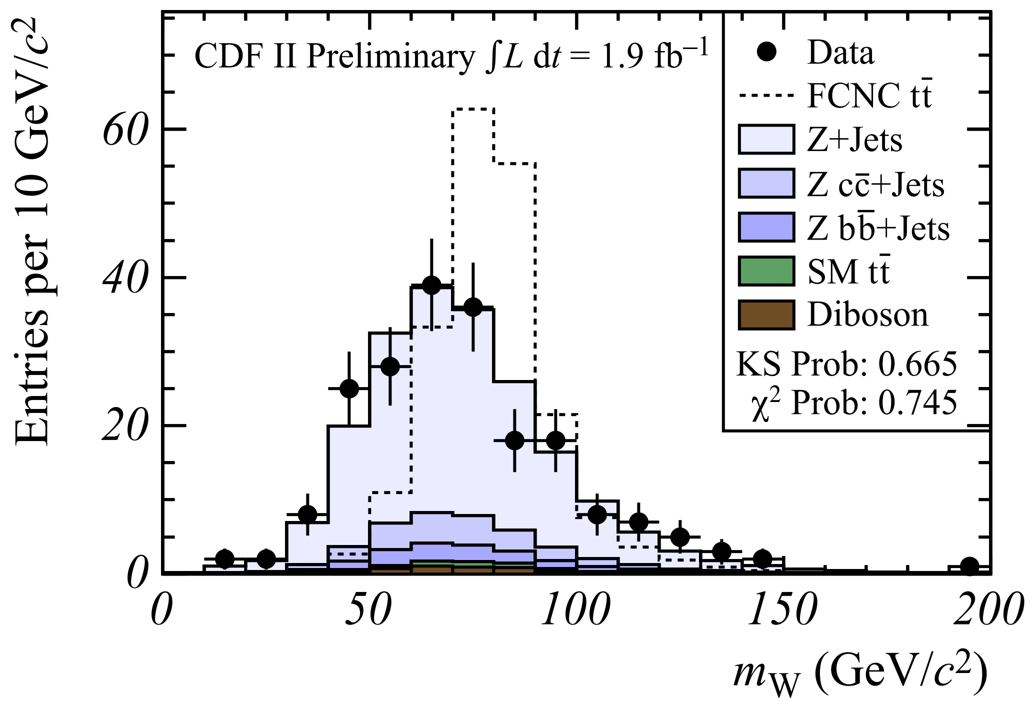


χ^2 Ingredients: $\sigma_{JES} = -1$

Jet Combination with Best χ^2: W Mass ($\sigma_{JES} = -1$)



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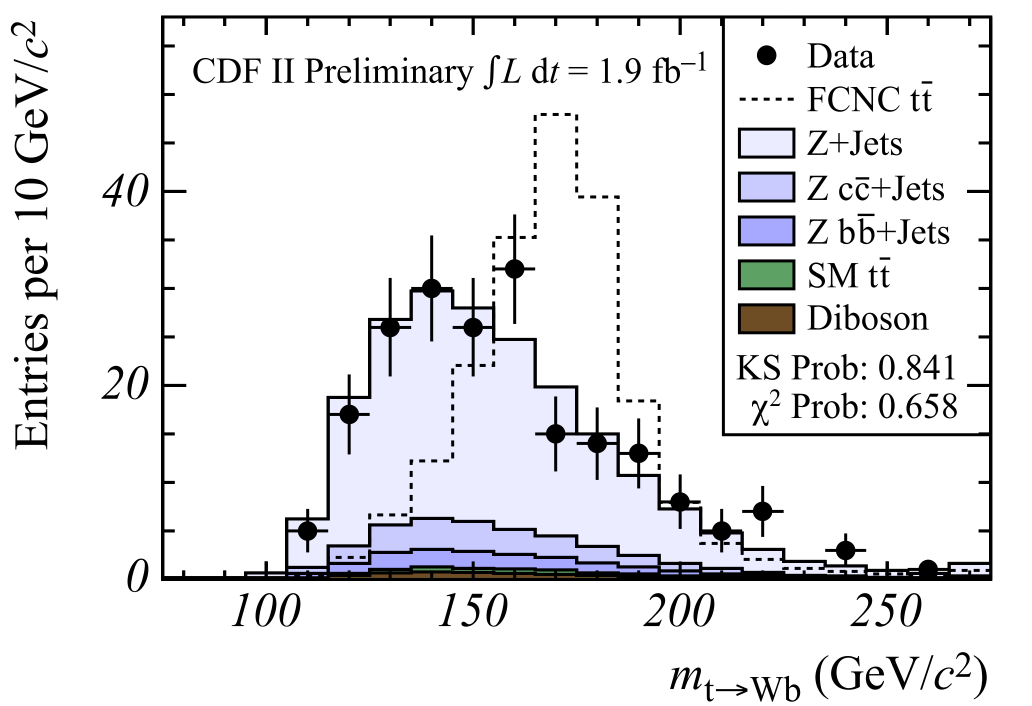

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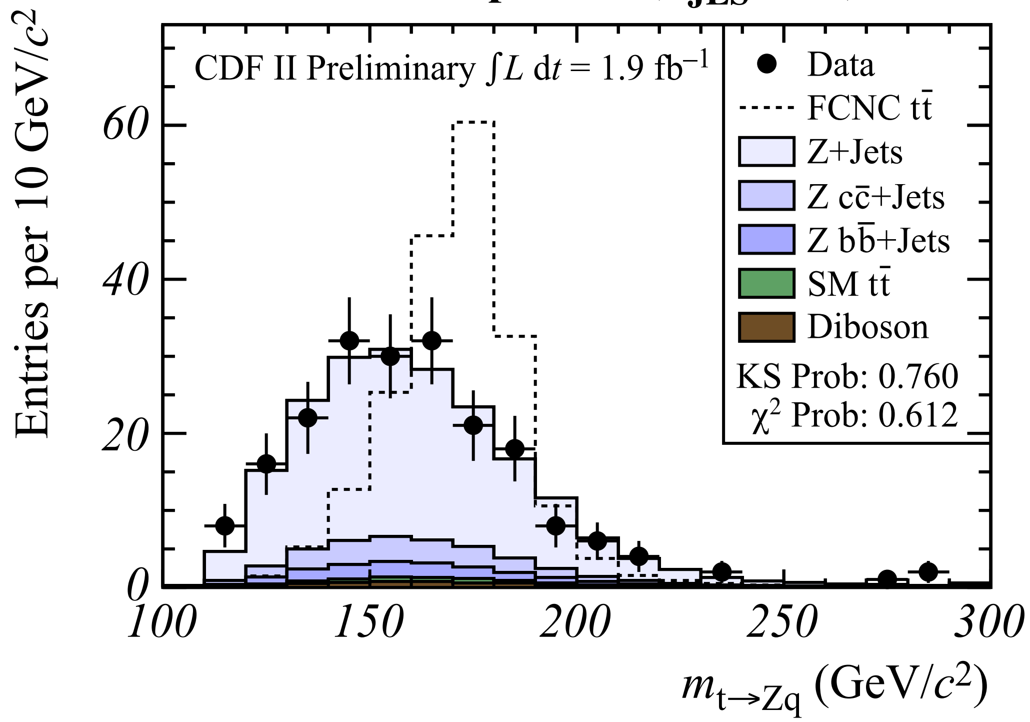
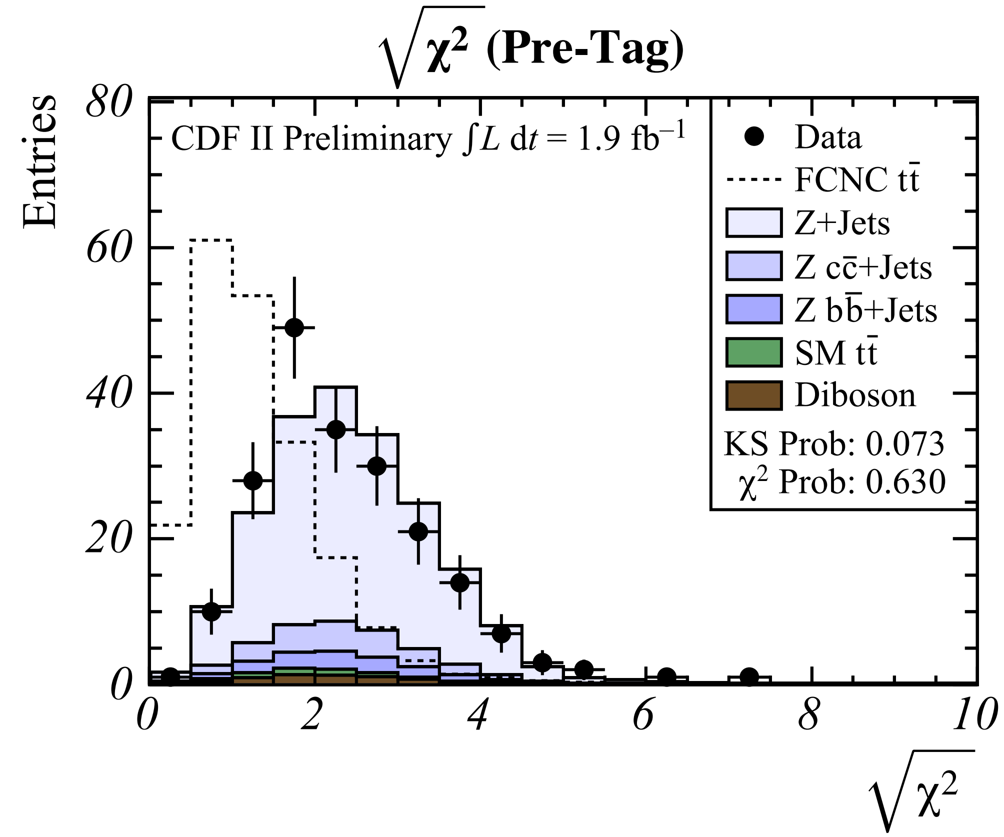
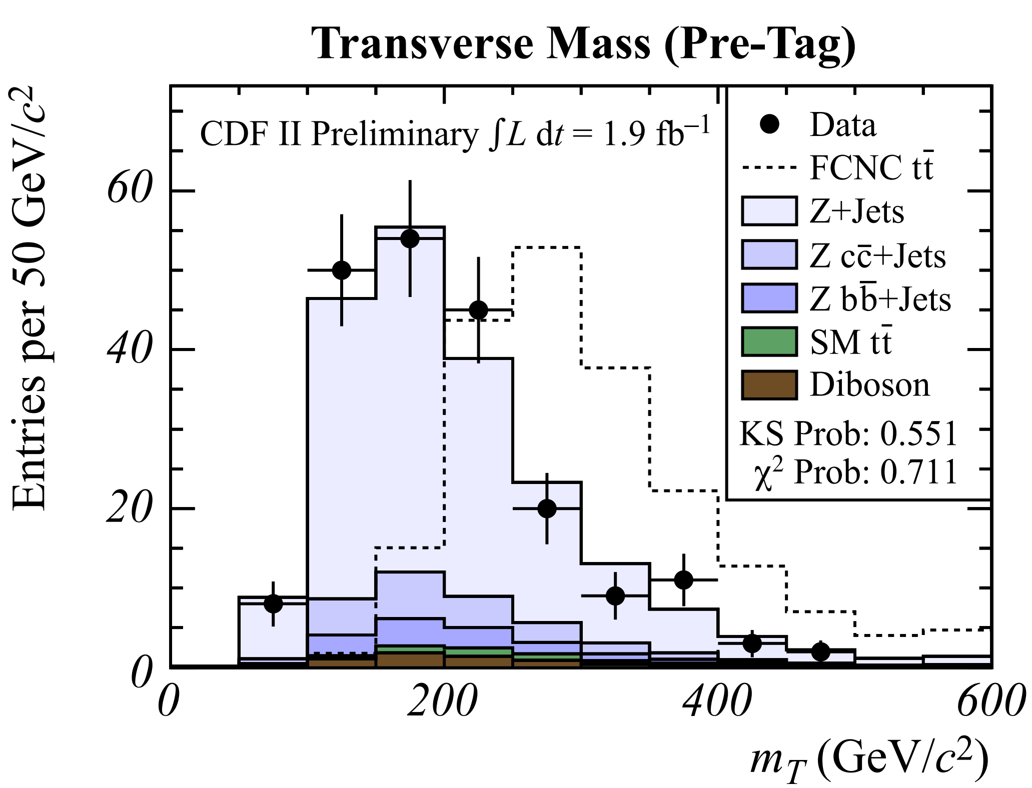
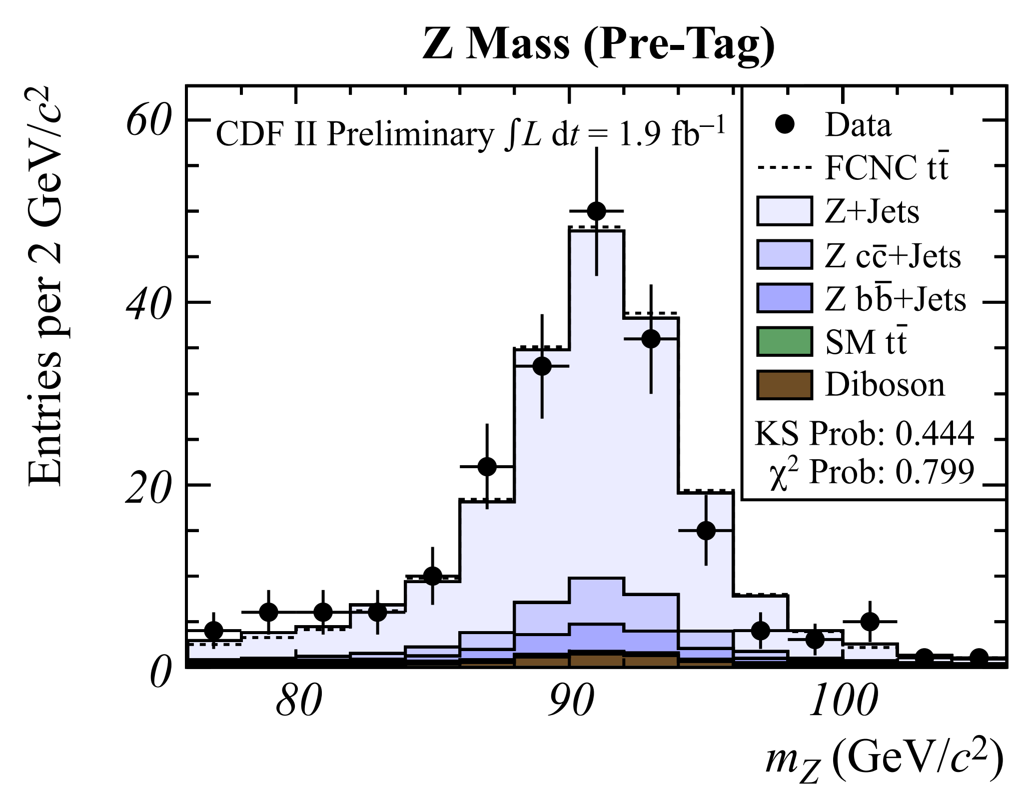


Kinematics: Pretag

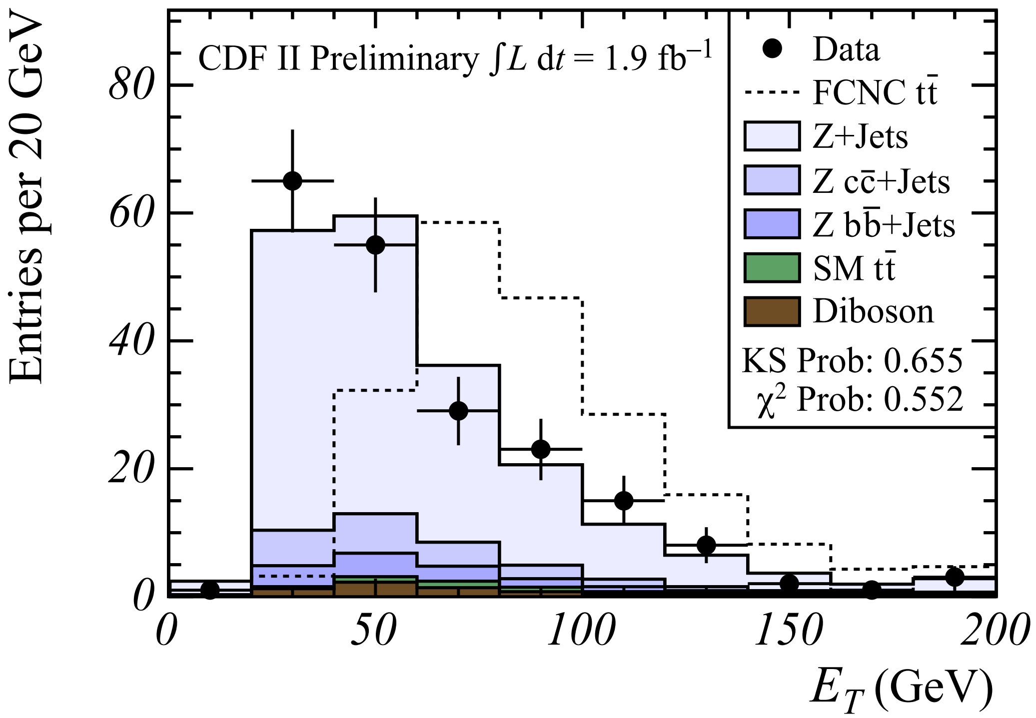




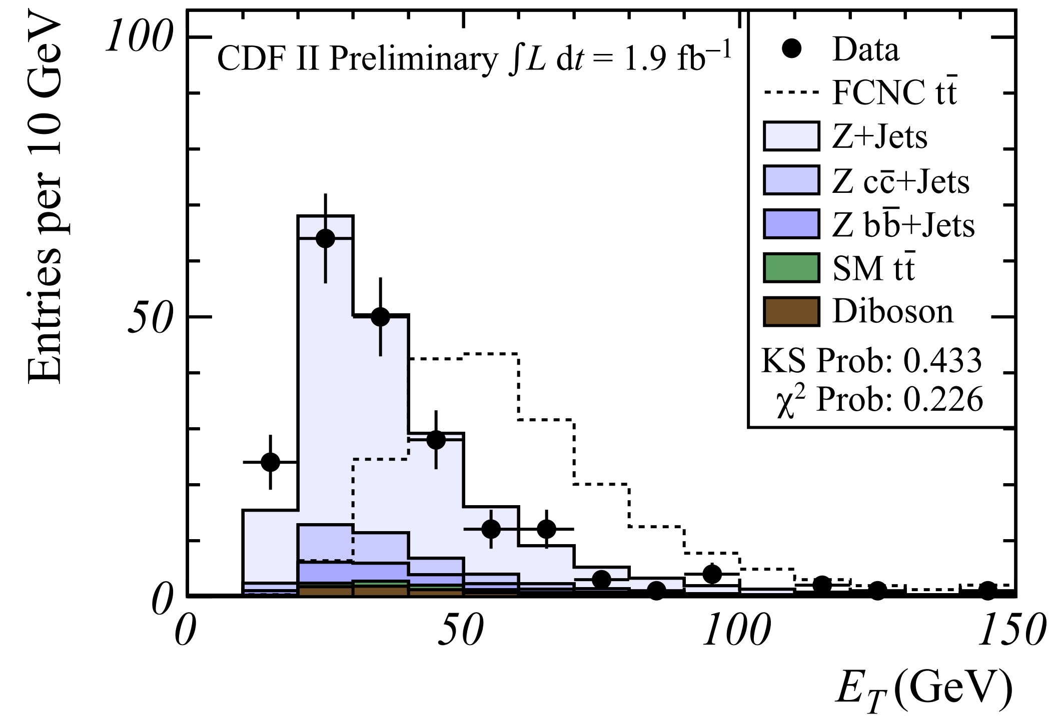


Jet Transverse Energies: Pretag

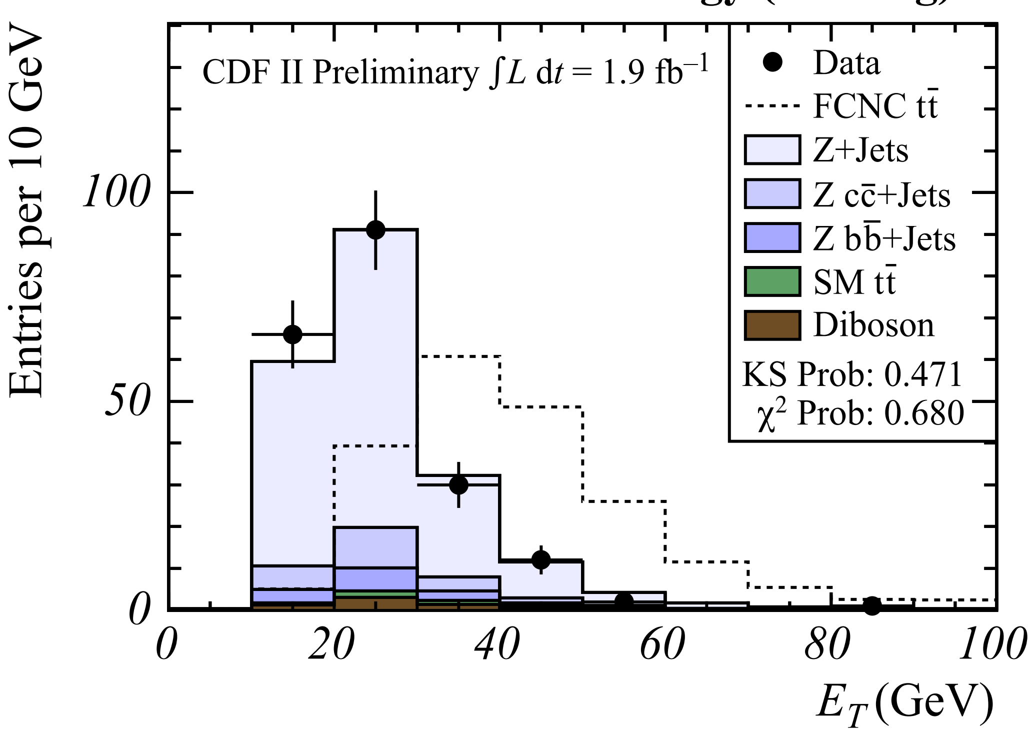
Leading Jet Transverse Energy (Pre-Tag)



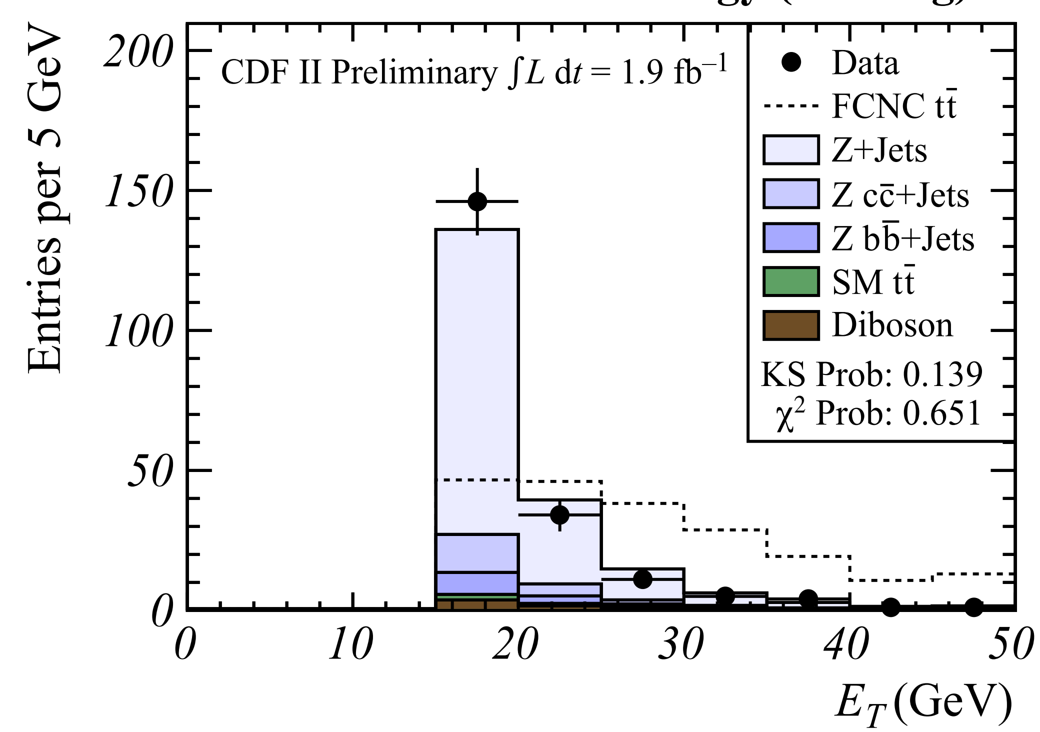
2nd Jet Transverse Energy (Pre-Tag)



3rd Jet Transverse Energy (Pre-Tag)

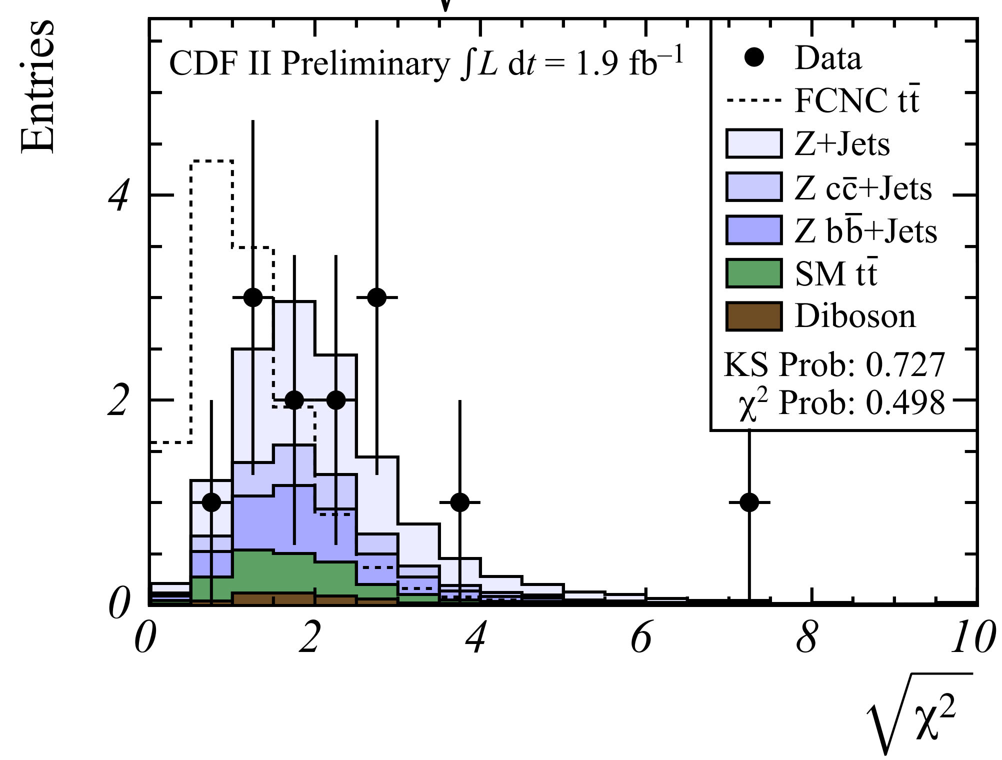


4th Jet Transverse Energy (Pre-Tag)

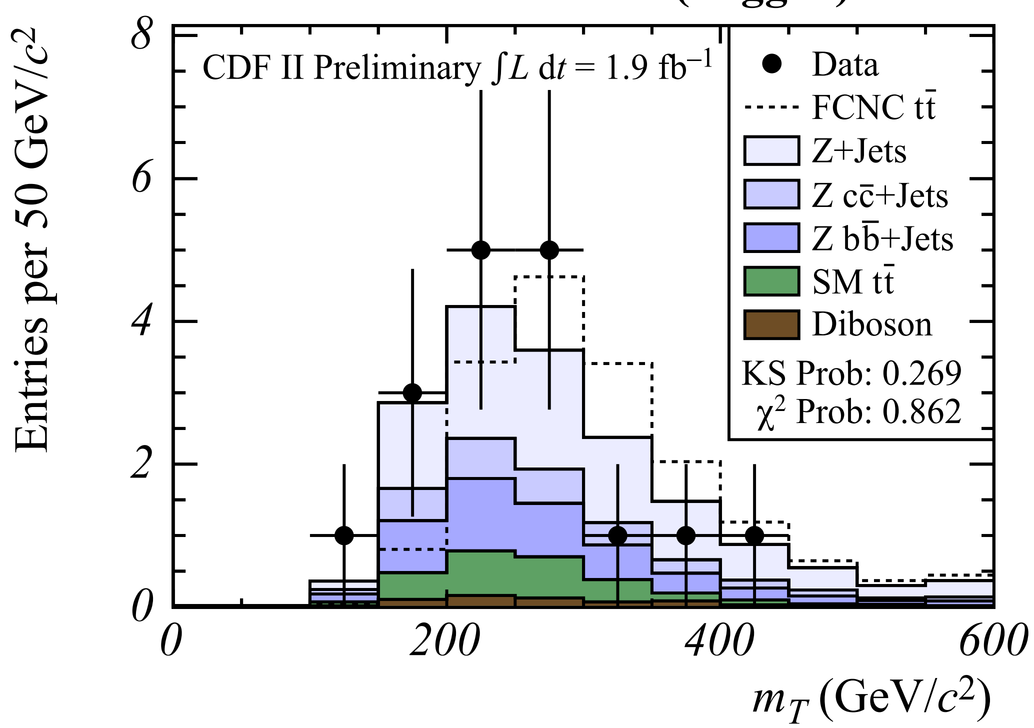


Kinematics: Tagged

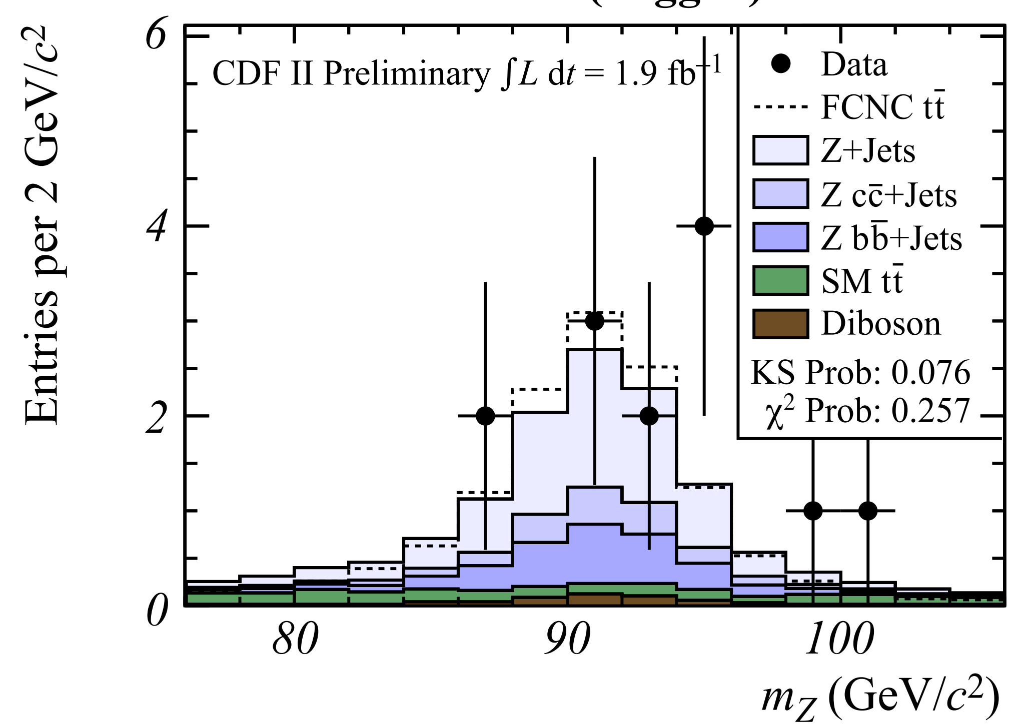
$\sqrt{\chi^2}$ (Tagged)



Transverse Mass (Tagged)

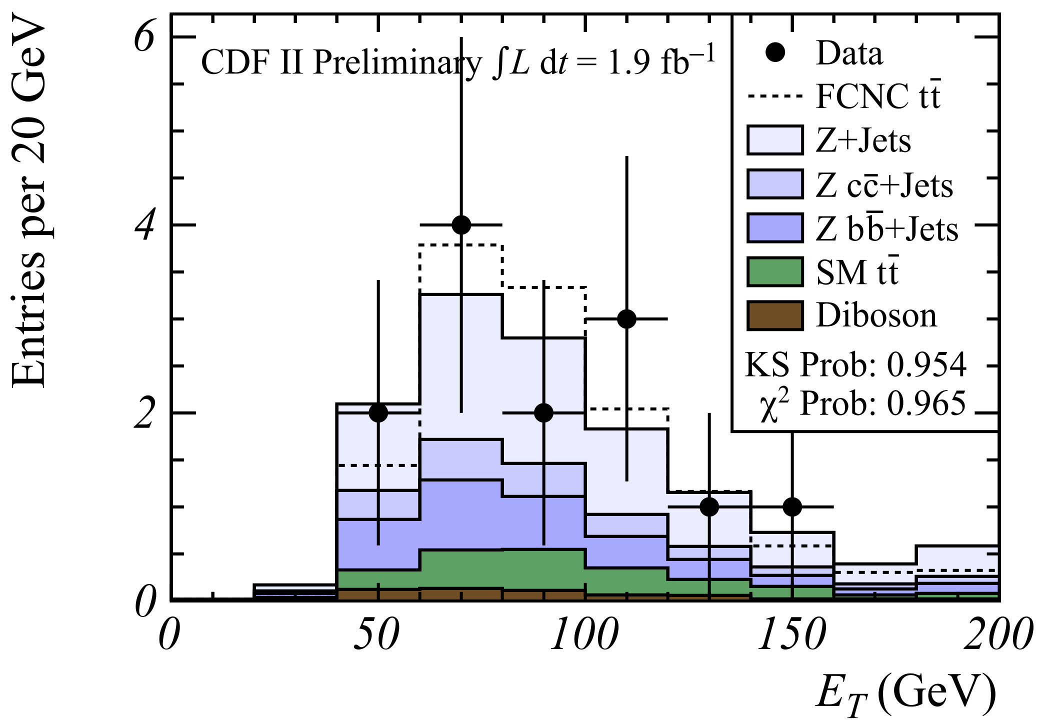


Z Mass (Tagged)

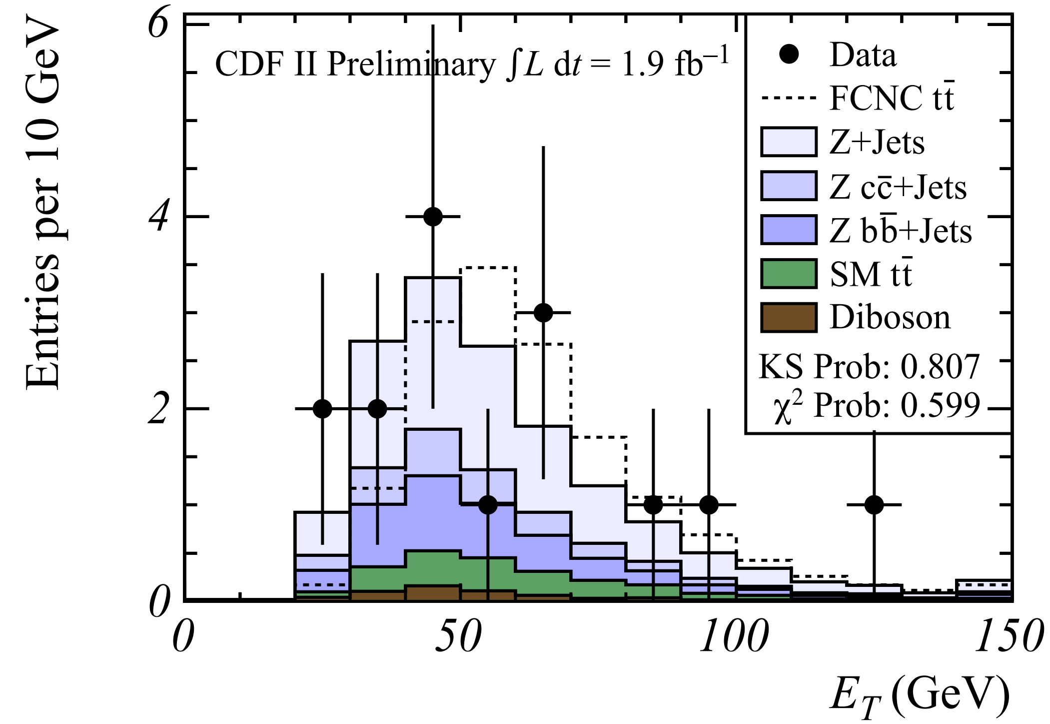


Jet Transverse Energies: Tagged

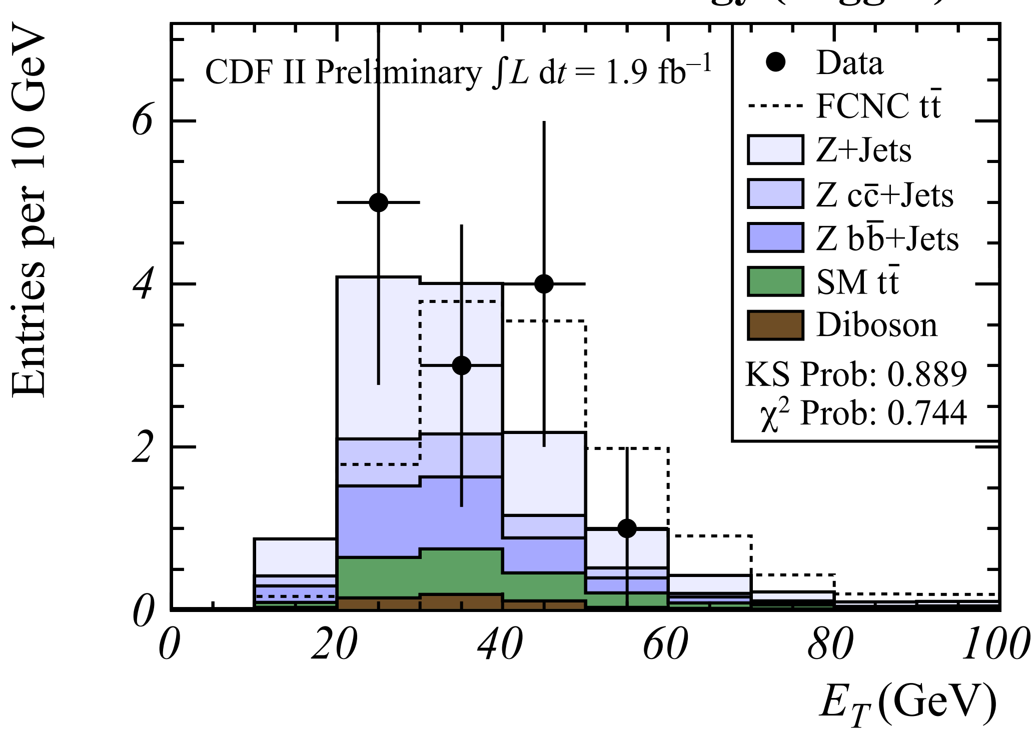
Leading Jet Transverse Energy (Tagged)



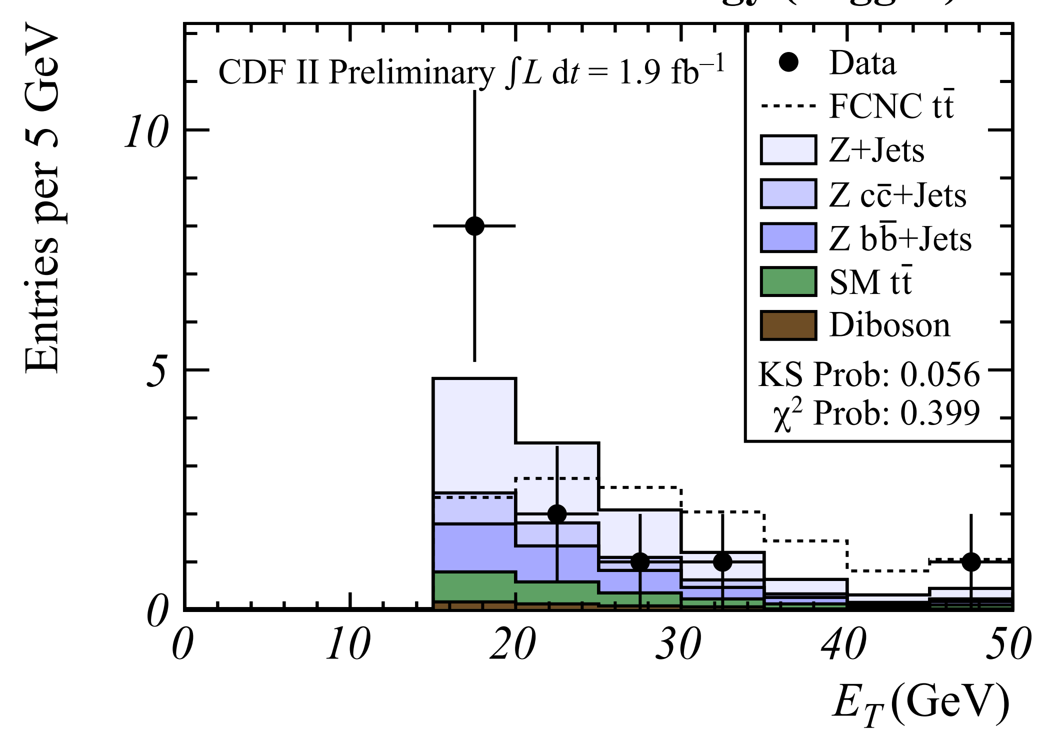
2nd Jet Transverse Energy (Tagged)



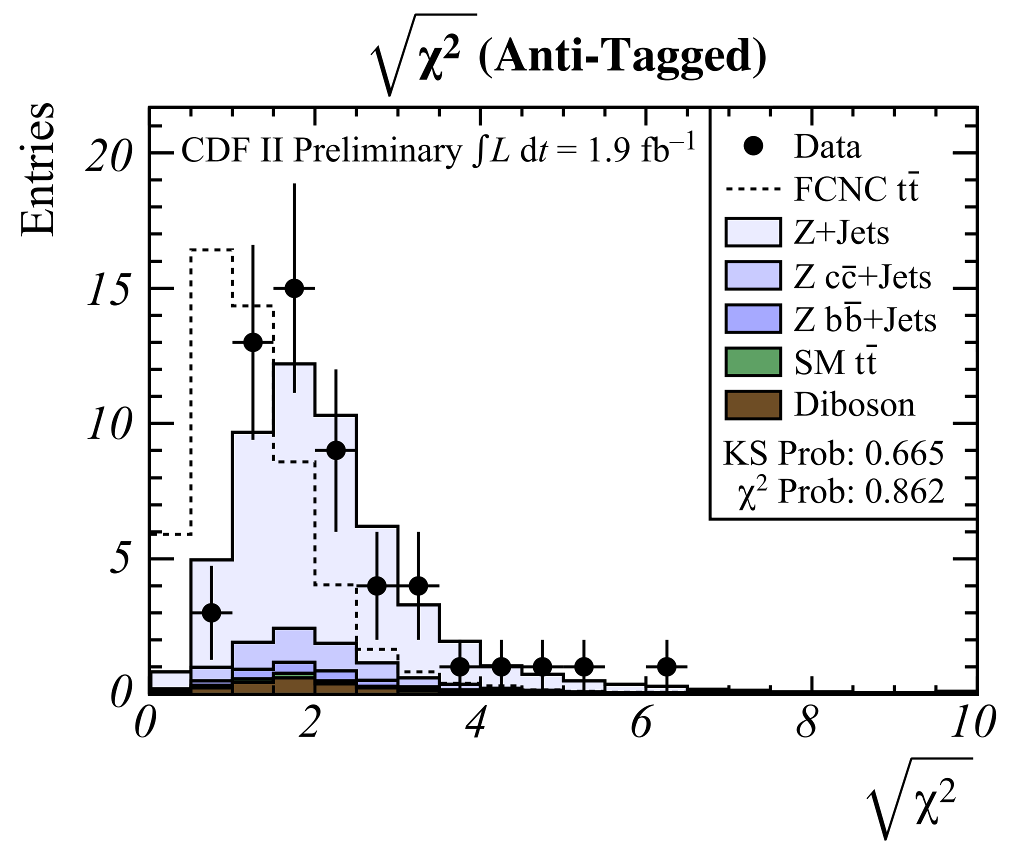
3rd Jet Transverse Energy (Tagged)

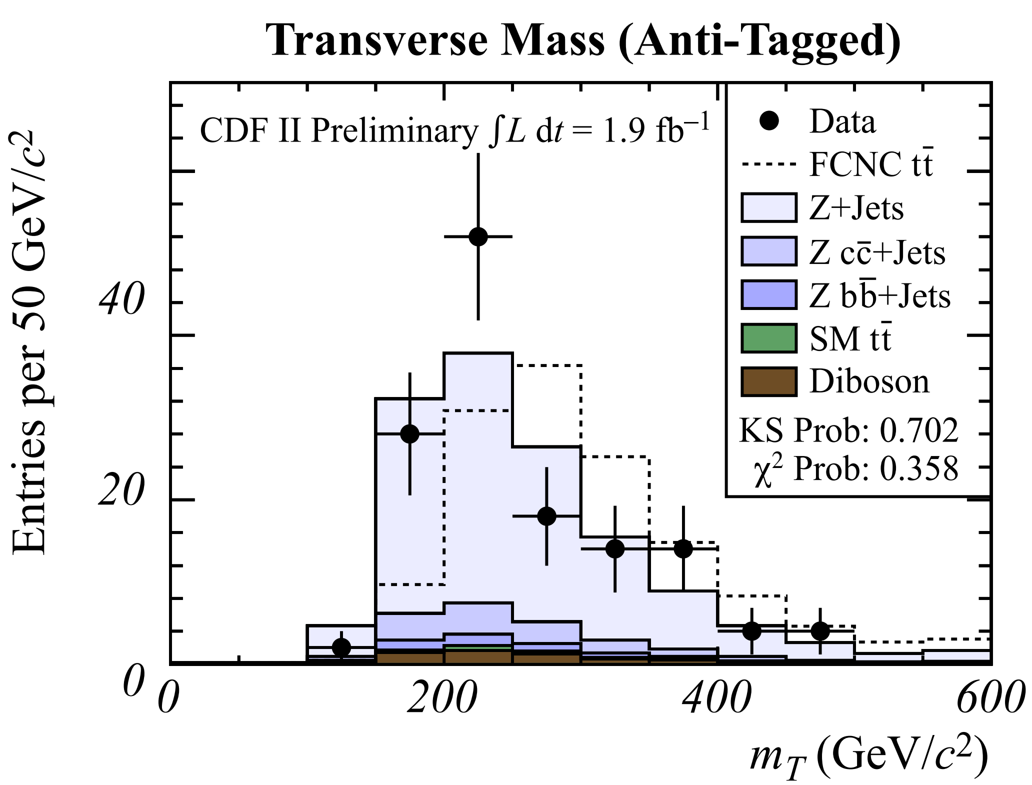


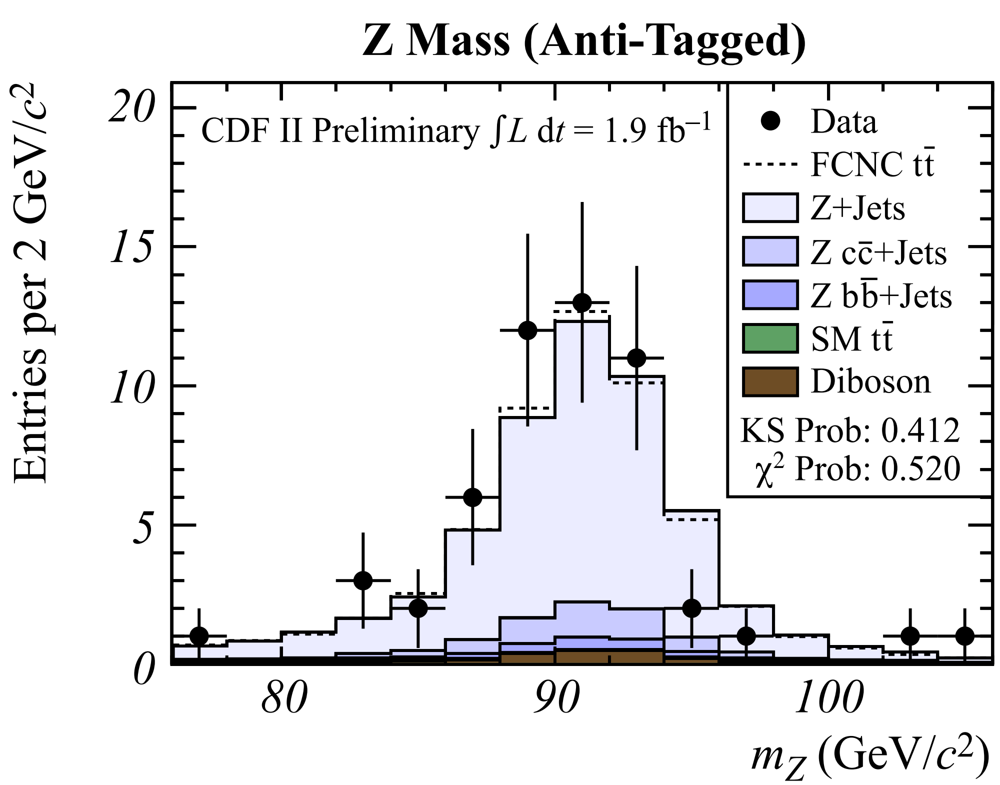
4th Jet Transverse Energy (Tagged)



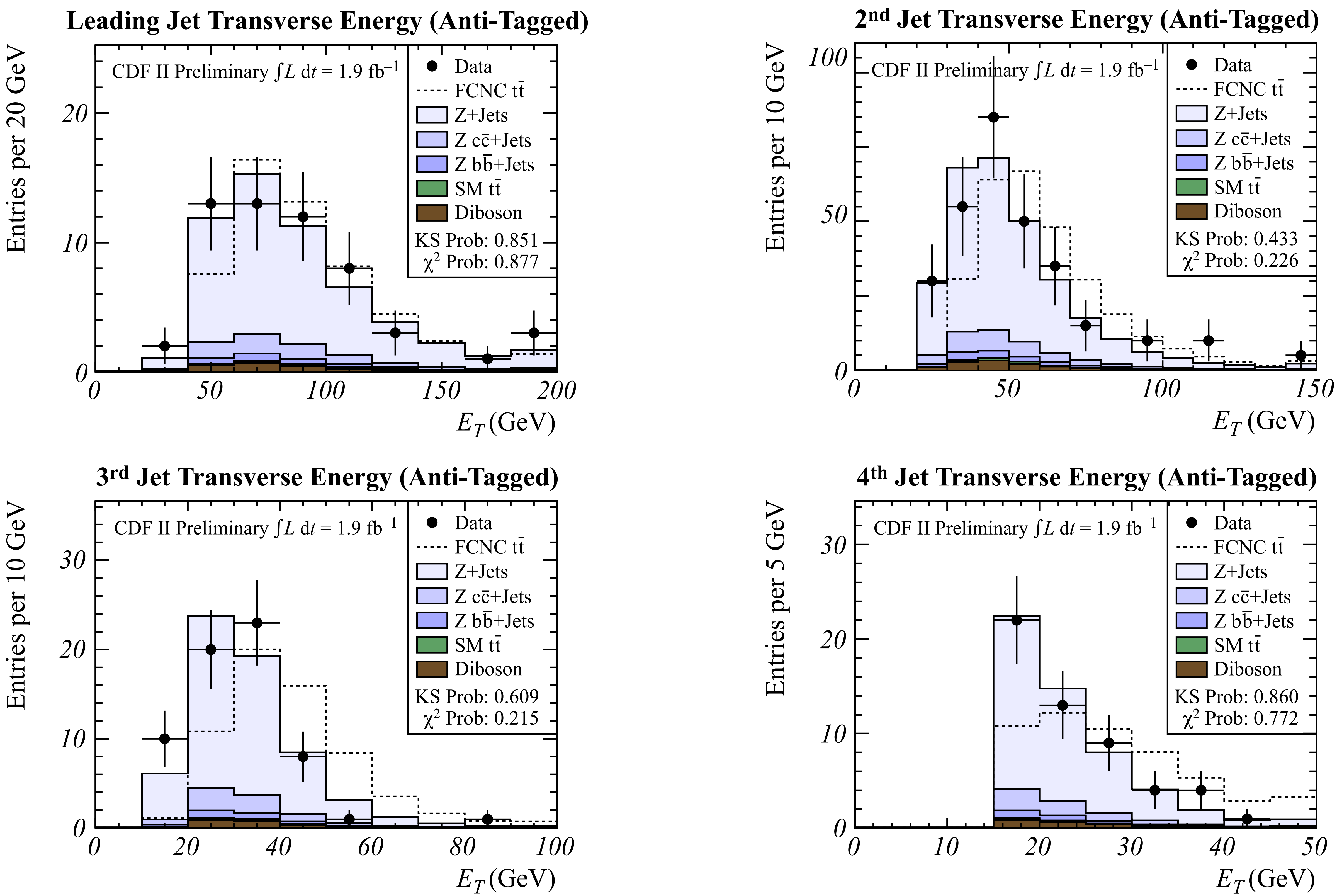
Kinematics: Anti-Tagged



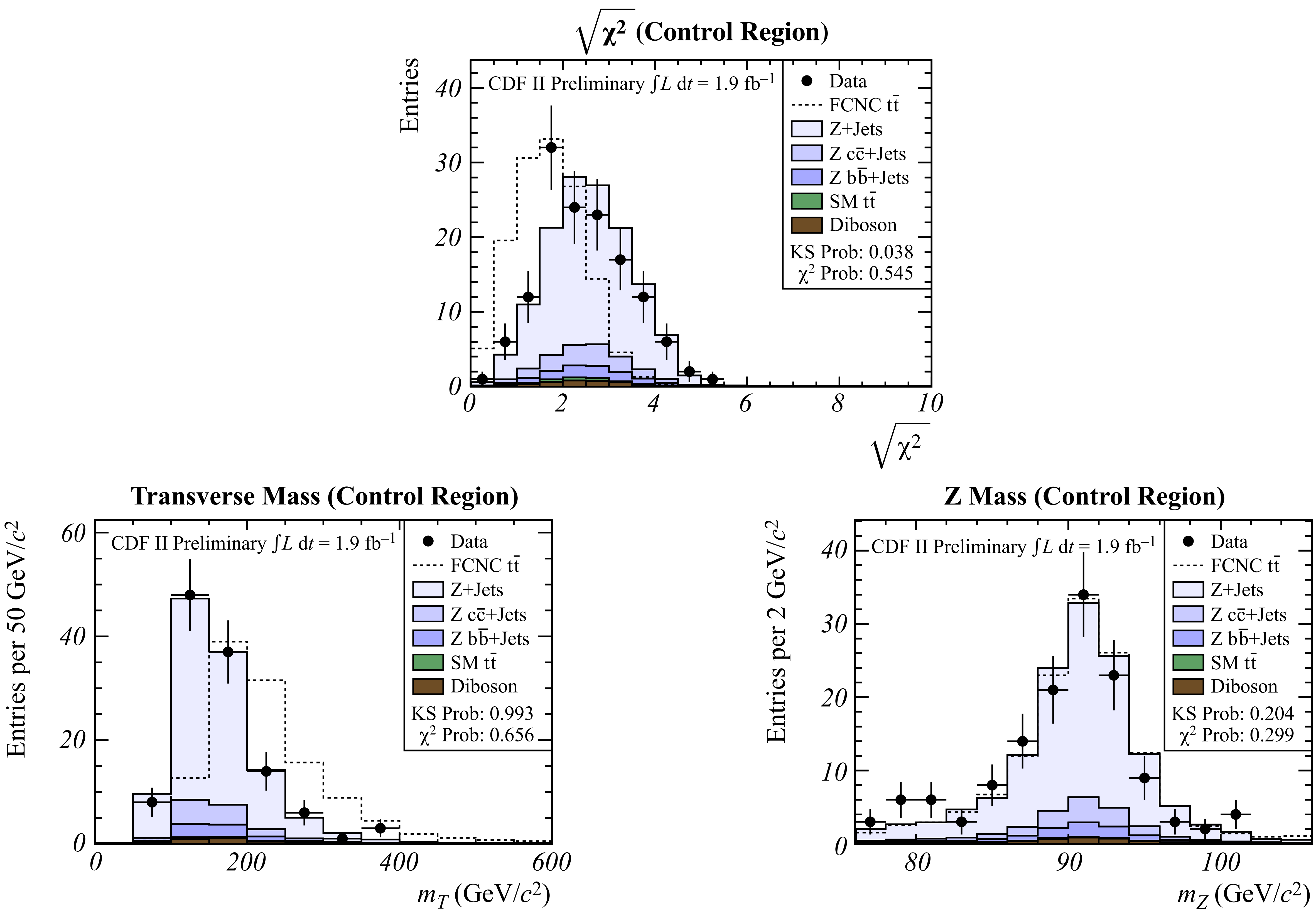




Jet Transverse Energies: Anti-Tagged

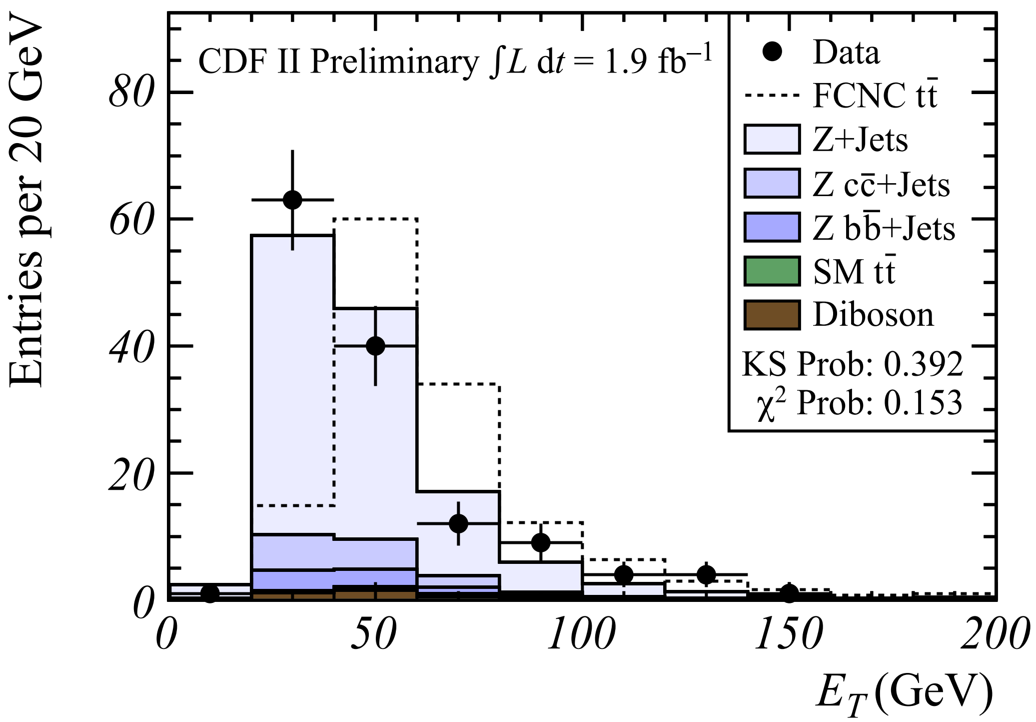


Kinematics: Control Region

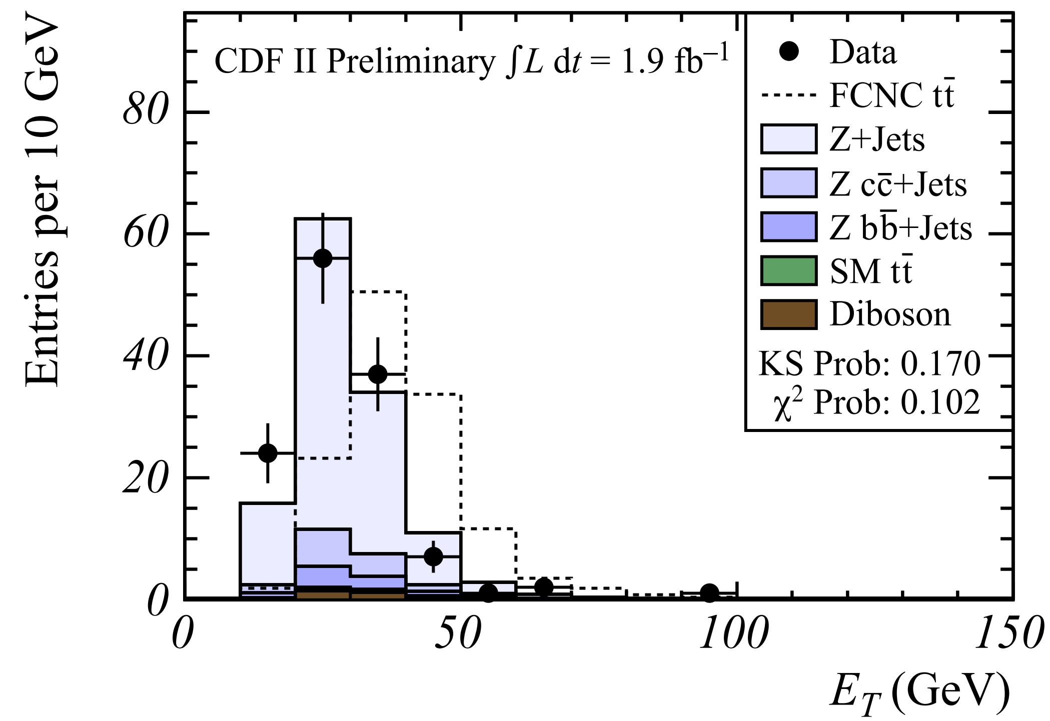


Jet Transverse Energies: Control

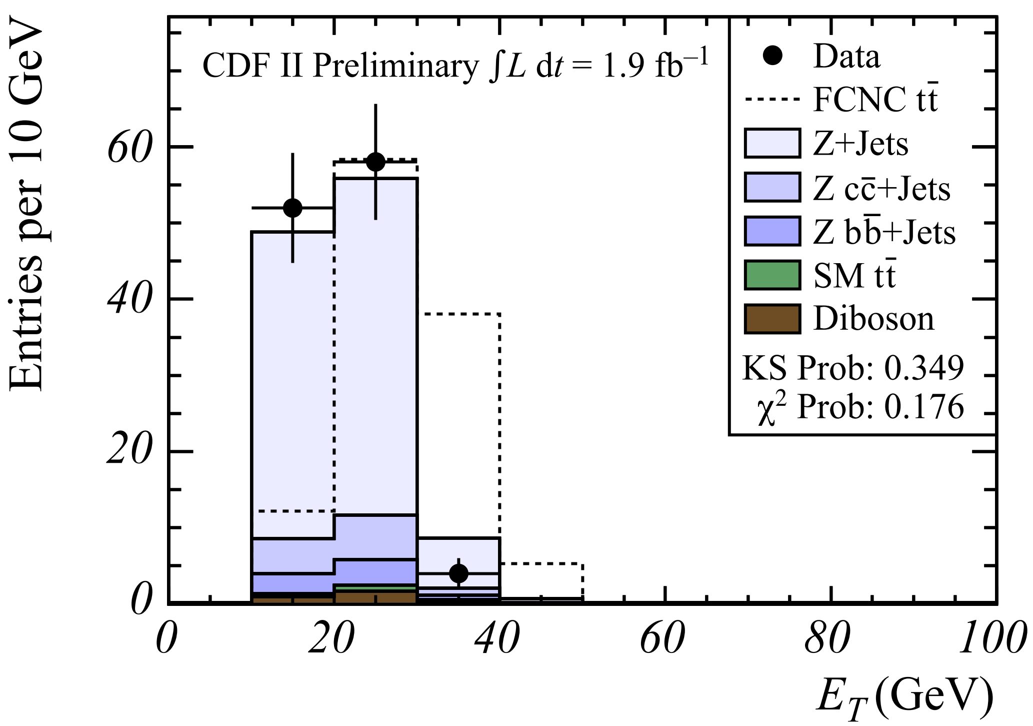
Leading Jet Transverse Energy (Control Region)



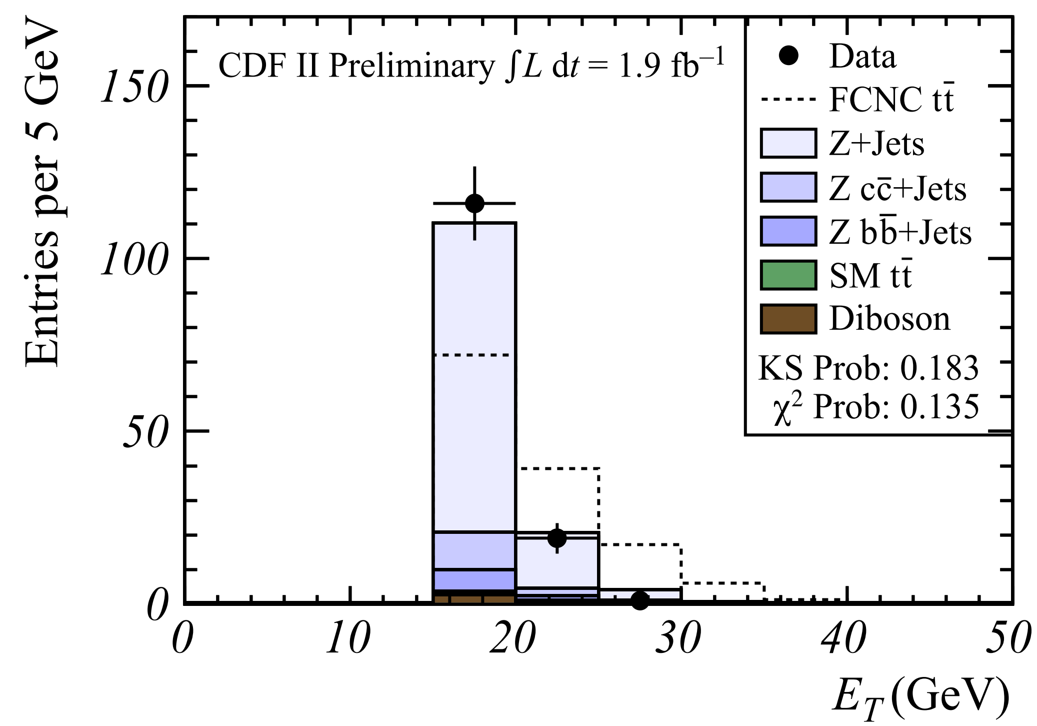
2nd Jet Transverse Energy (Control Region)



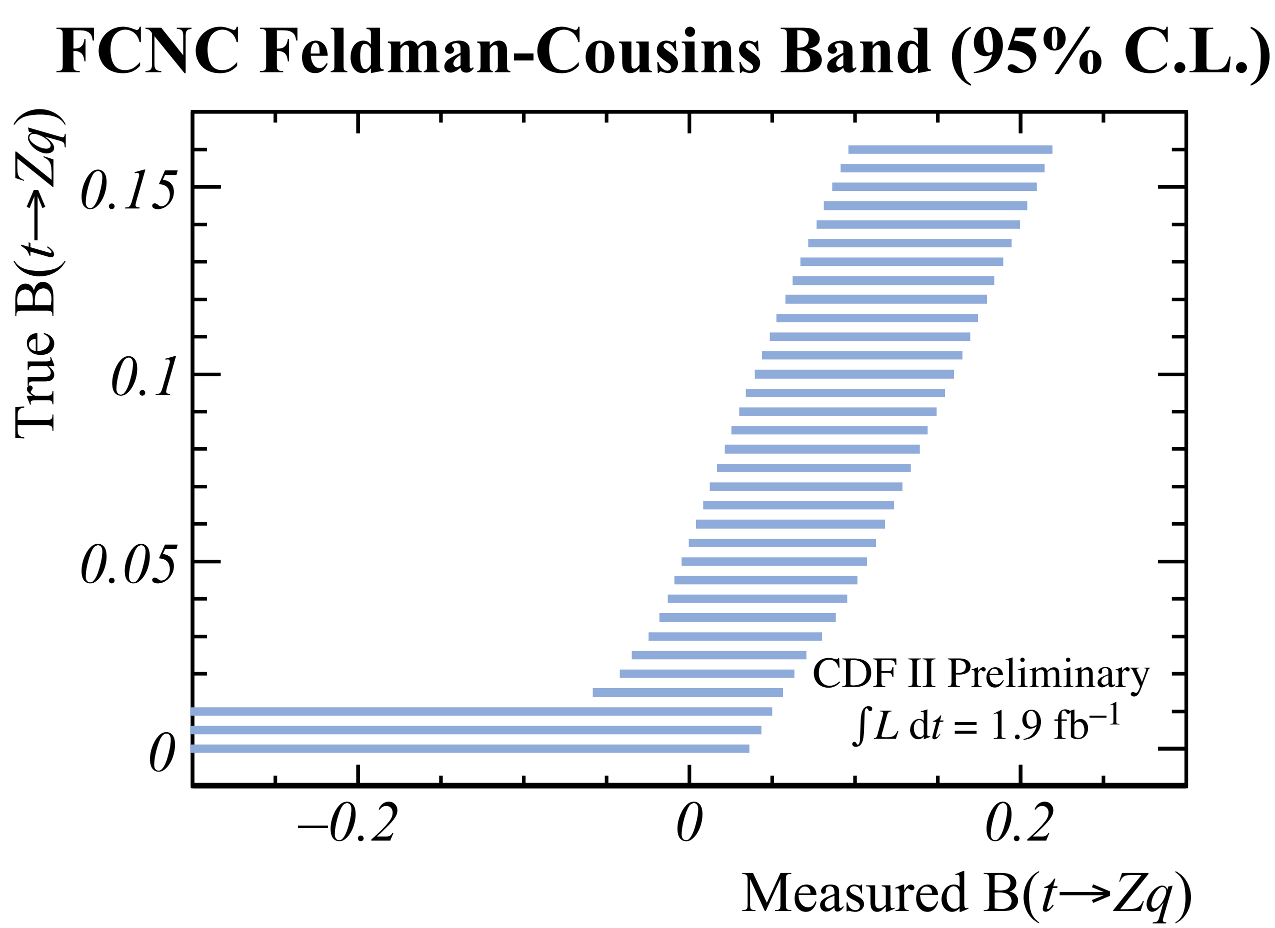
3rd Jet Transverse Energy (Control Region)

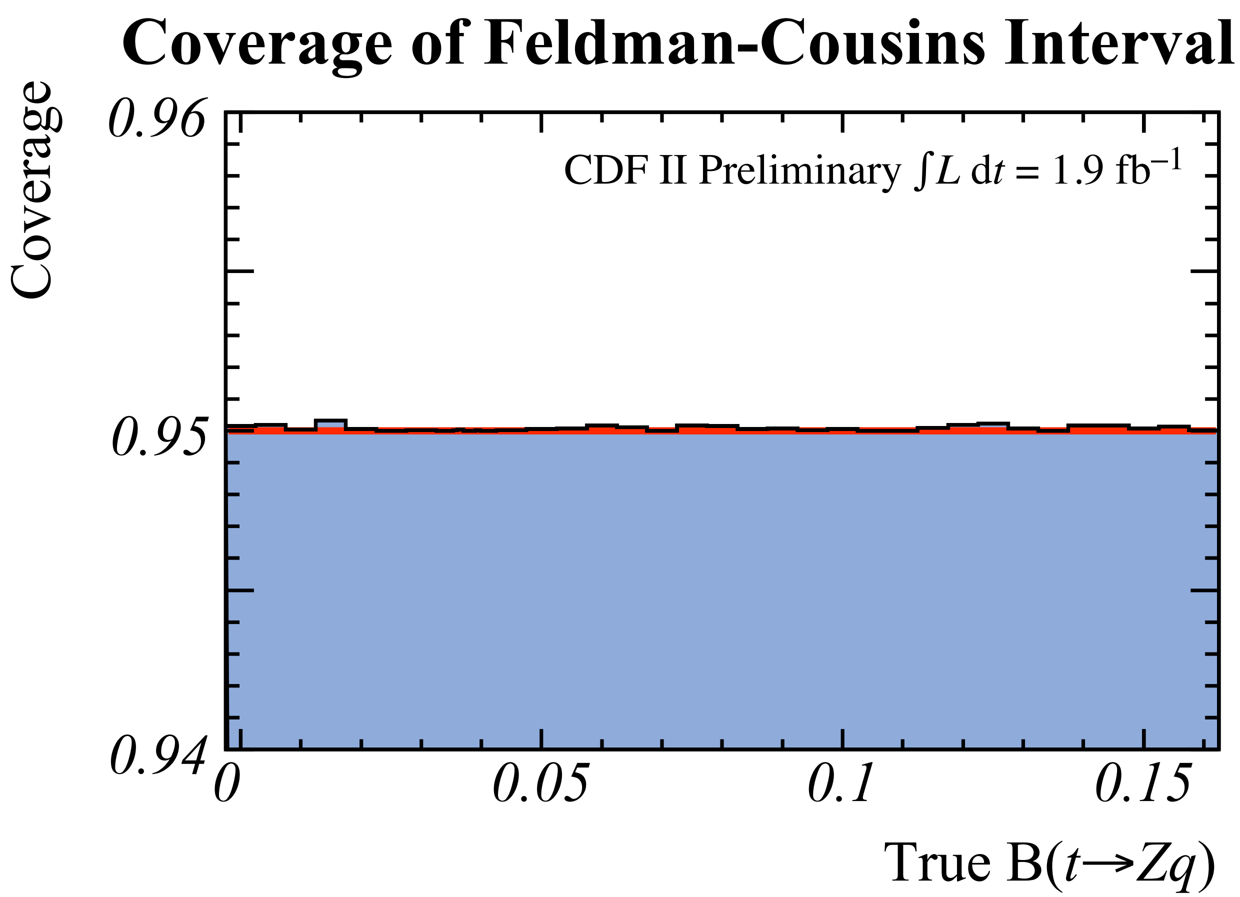


4th Jet Transverse Energy (Control Region)

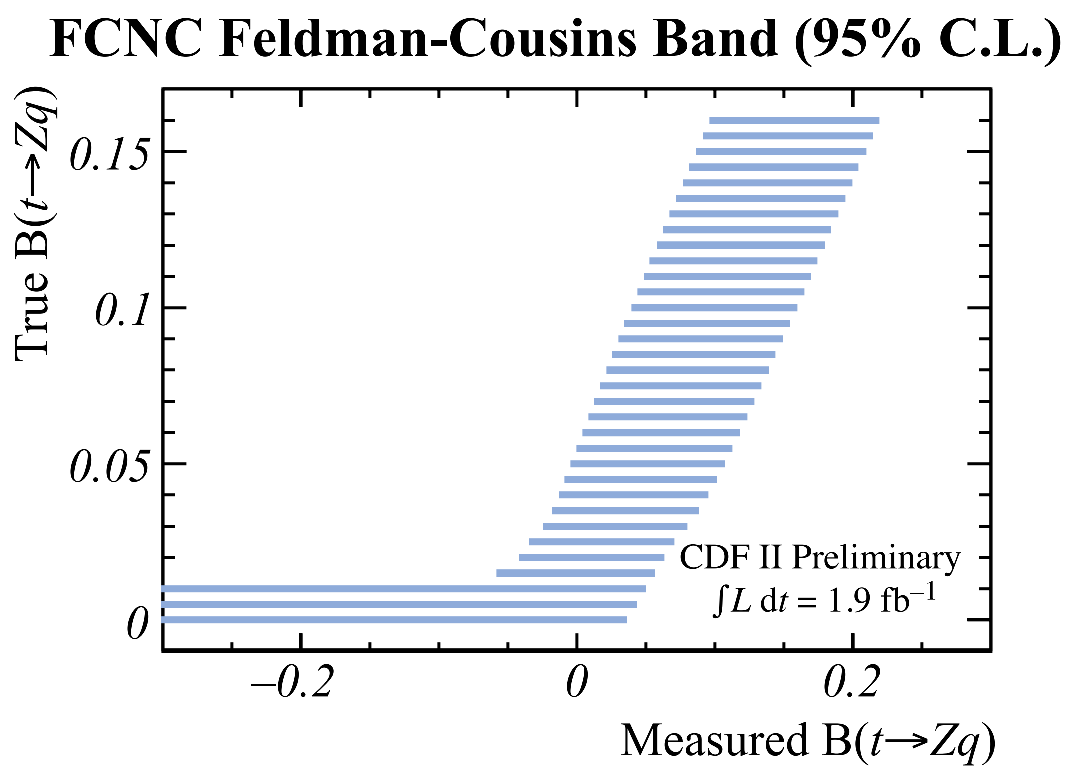


Feldman-Cousins Details





Expected Limits



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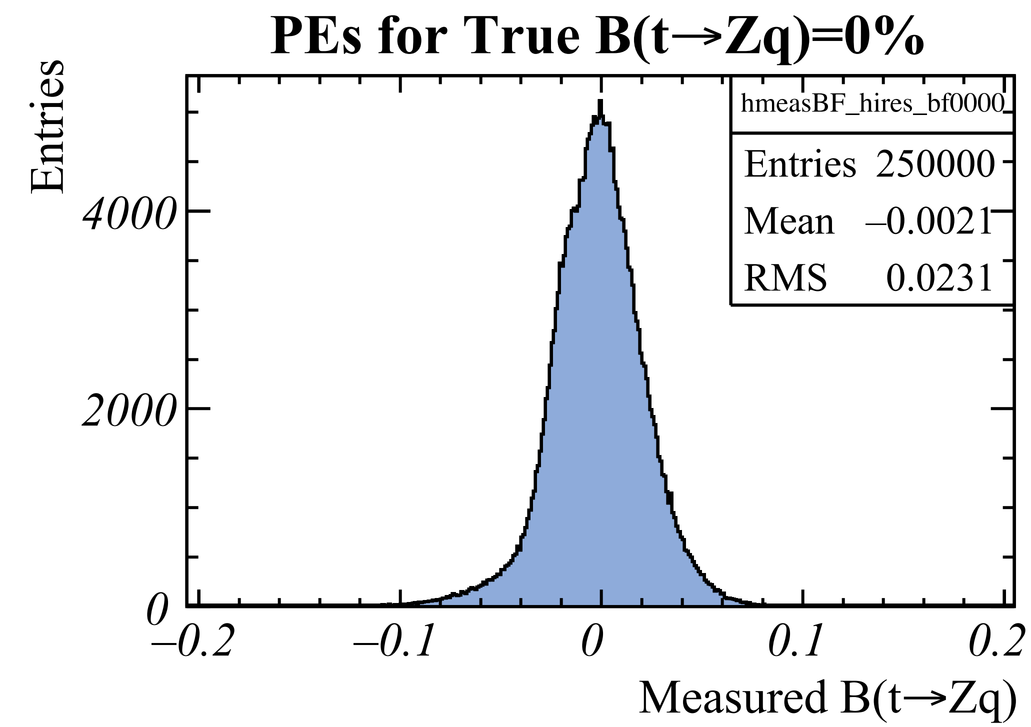

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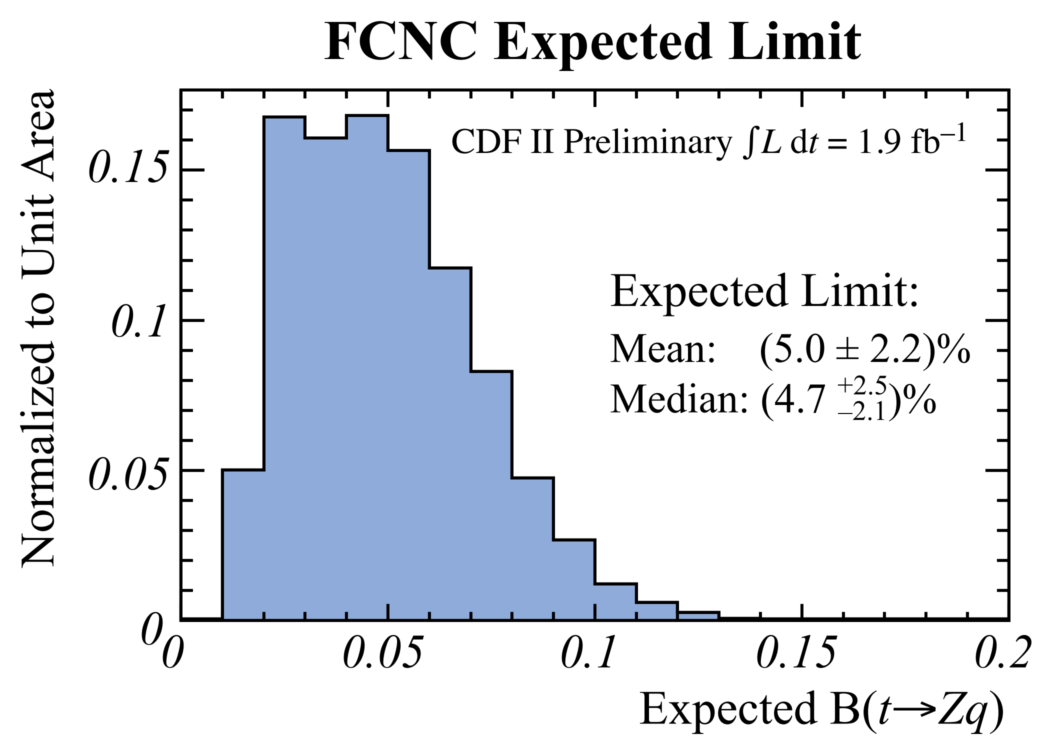
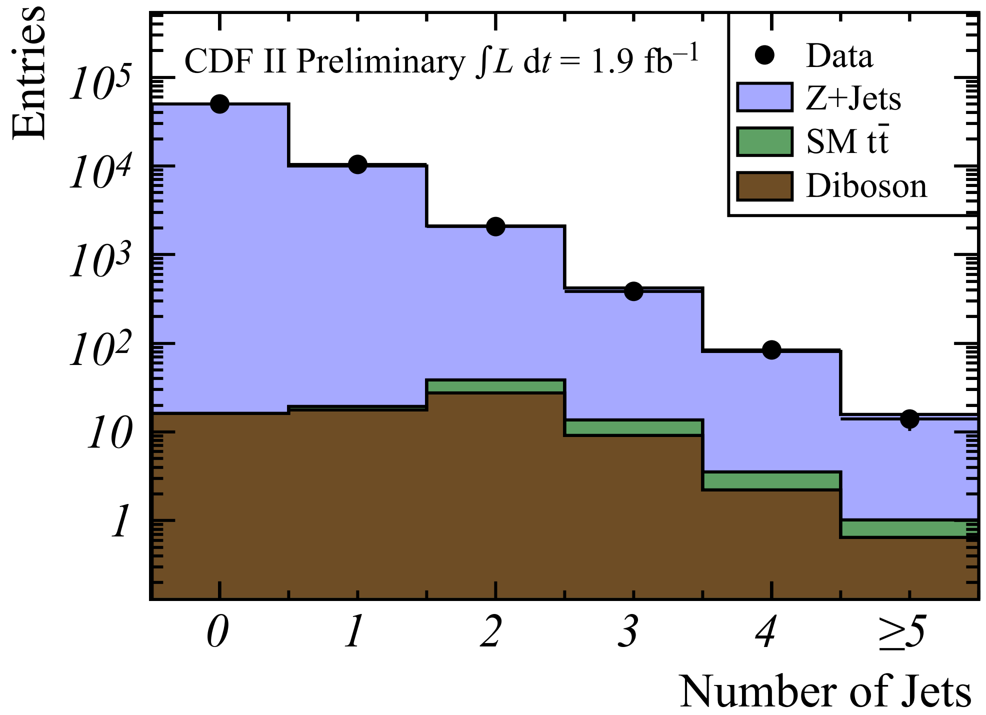
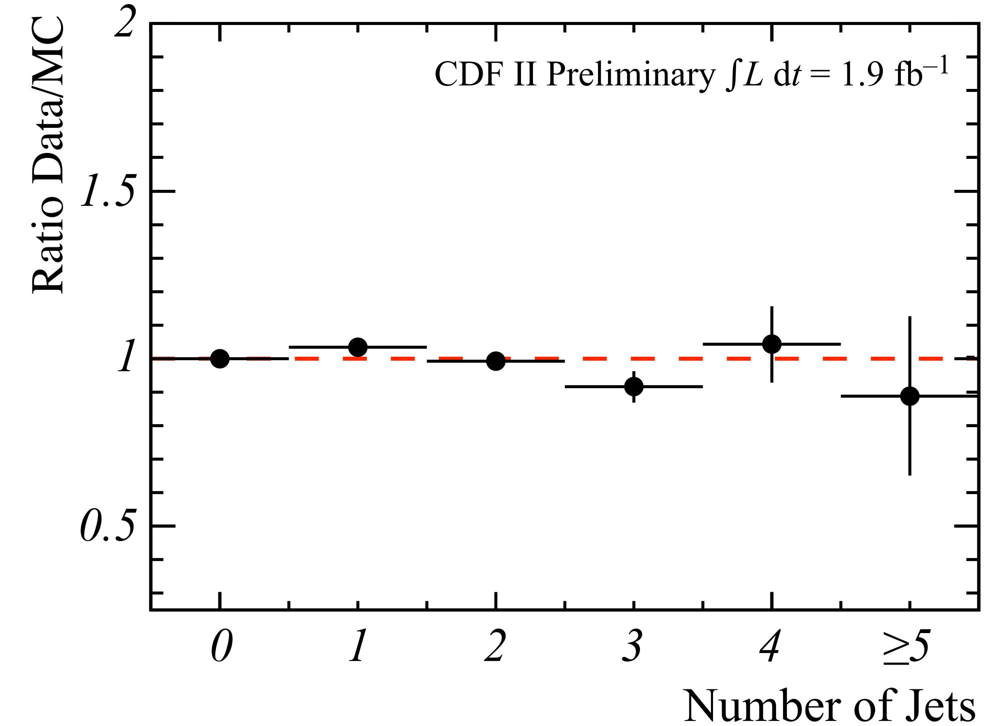


ALPGEN Energy Scales

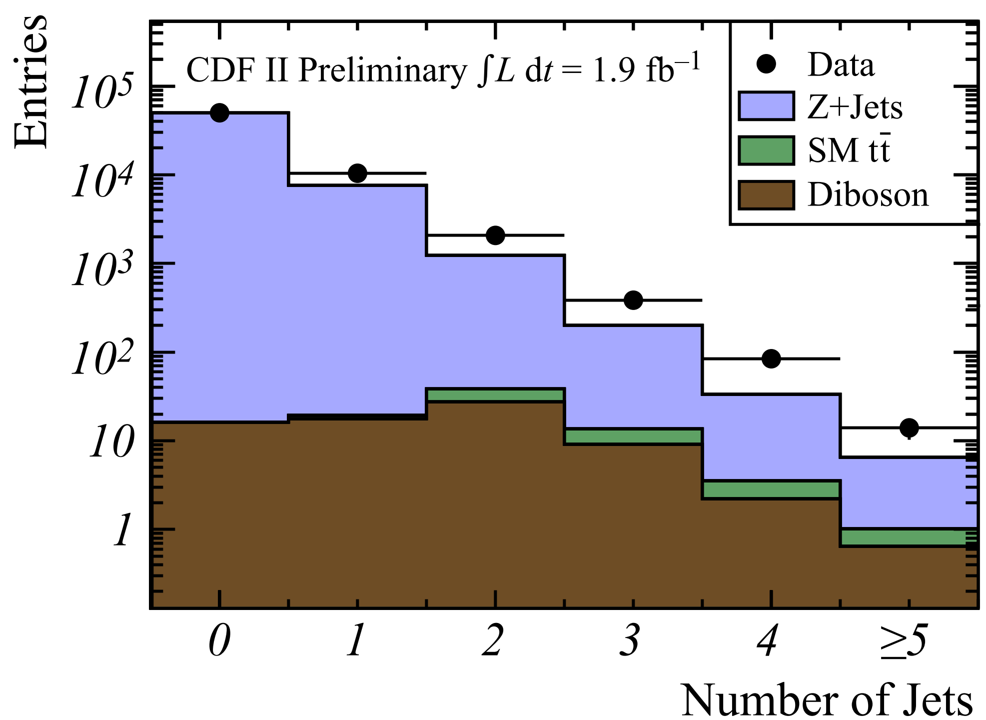
$Z \to \mu^+\mu^-$: Number of Jets (ALPGEN `qfac=ktfac=0.5`)



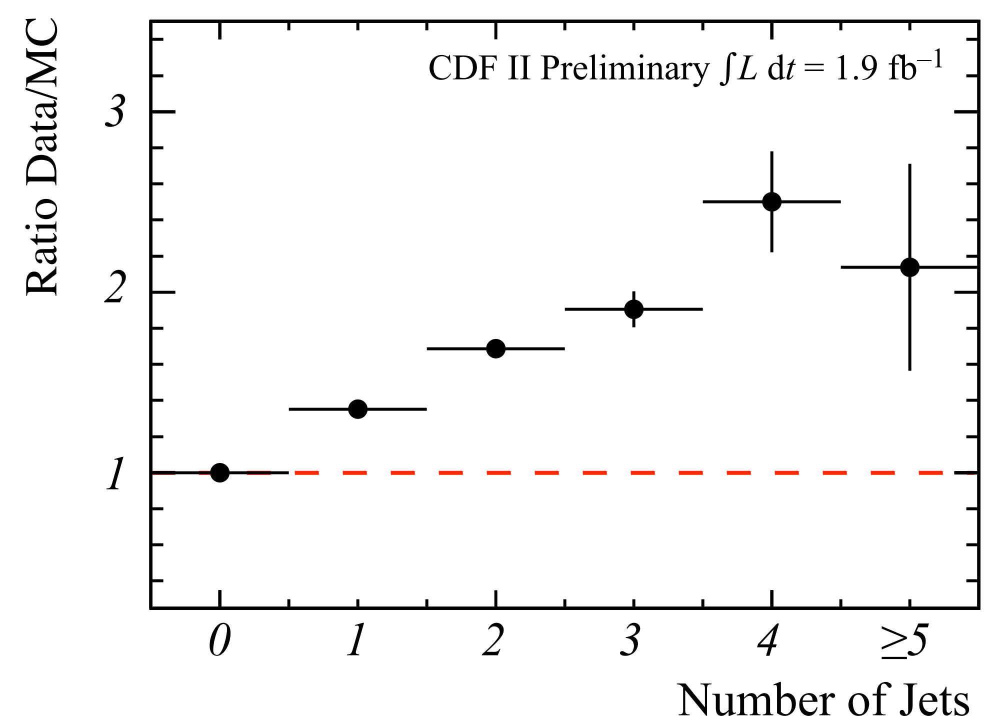
$Z \to \mu^+\mu^-$: Number of Jets (ALPGEN `qfac=ktfac=0.5`)



$Z \to \mu^+\mu^-$: Number of Jets (ALPGEN `qfac=ktfac=2.0`)



$Z \to \mu^+\mu^-$: Number of Jets (ALPGEN `qfac=ktfac=2.0`)



Tight Central Electron Selection

Electron Variable	Base Cut
Fiducial to CES	Yes
From photon conversion	No
E_T	$\geq 20\,\mathrm{GeV}$
Fractional isolation	≤ 0.10
E/p	≤ 2 (unless $p_T > 50\,\mathrm{GeV}/c$)
E_{Had} / E_{Em}	$\leq 0.055 + 0.00045E\,(\mathrm{GeV})$
Track $\lvert z_0 \rvert$	$\leq 60\,\mathrm{cm}$
Track p_T	$\geq 10\,\mathrm{GeV}/c$
Track L_{shr}	≤ 0.2
COT axial superlayer hits	2
COT stereo superlayer hits	3
Hits per COT superlayer	5
CES Δz	$(-3\,\mathrm{cm}; 3\,\mathrm{cm})$
CES Δx times charge	$(-3\,\mathrm{cm}; 1.5\,\mathrm{cm})$
CES strip χ^2	≤ 10

Tight Phoenix Electron Selection

Electron Variable	Base Cut
Matched to a Phoenix track	Yes
E_T	$\geq 20\,\mathrm{GeV}$
PES two-dimensional η	$1.2 < \lvert\eta\rvert < 2.8$
E_{Had} / E_{Em}	≤ 0.05
PEM χ^2	≤ 10
PES 5×9 U and V	≥ 0.65
Fractional isolation	≤ 0.10
ΔR between the PES and PEM centroids	$\leq 3.0\,\mathrm{cm}$
Silicon hits	≥ 3
Track $\lvert z_0\rvert$	$\leq 60\,\mathrm{cm}$

Tight Muon (CMUP, CMX) Selection

Muon Variable	Base Cut
p_T	$\geq 20\,\mathrm{GeV}/c$
E_T	$< 2\,\mathrm{GeV}$
Sliding addition for E_{Em}	$0.115 \cdot (p - 100(\mathrm{GeV}/c))$ for muons with $p > 100\,\mathrm{GeV}/c$
E_{Had}	$< 6\,\mathrm{GeV}$
Sliding addition for E_{Had}	$0.028 \cdot (p - 100(\mathrm{GeV}/c))$ for muons with $p > 100\,\mathrm{GeV}/c$
Fractional isolation	≤ 0.10
COT axial superlayer hits	2
COT stereo superlayer hits	3
Hits per COT superlayer	5
Track $\lvert z_0 \rvert$	≤ 60 cm
Impact parameter d_0	$< 0.02\,\mathrm{cm}$ (with silicon) or $< 0.2\,\mathrm{cm}$ (without silicon)
CMU $\lvert \Delta x \rvert$	$< 7\,\mathrm{cm}$, for CMUP
CMP $\lvert \Delta x \rvert$	$< 5\,\mathrm{cm}$, for CMUP
CMX $\lvert \Delta x \rvert$	$< 6\,\mathrm{cm}$, for CMX
Fiducial x_{CMP}	$< 0\,\mathrm{cm}$
Fiducial z_{CMP}	$< 0\,\mathrm{cm}$
Fiducial $x_{\mathrm{CMU,CMUP,CMX}}$	$< 0\,\mathrm{cm}$
Fiducial $z_{\mathrm{CMU,CMUP,CMX}}$	$< -3\,\mathrm{cm}$

Tight Track Selection

Track Variable	Base Cut
p_T	$\geq 20\,\mathrm{GeV}/c$
Track Isolation	> 0.9
COT axial superlayer hits	≥ 24
COT stereo superlayer hits	≥ 20
Silicon hits	≥ 3, unless < 3 expected
Impact parameter d_0	$< 0.025\,\mathrm{cm}$ (< 3 silicon hits)
Impact parameter d_0	$< 0.25\,\mathrm{cm}$ (> 3 silicon hits)
Track χ^2	Not used.

- For tracks used as electrons:
  - Replace p_T with E_T if $E_T > p_T$
  - E_T: transverse energy of central calorimeter cluster matched to track

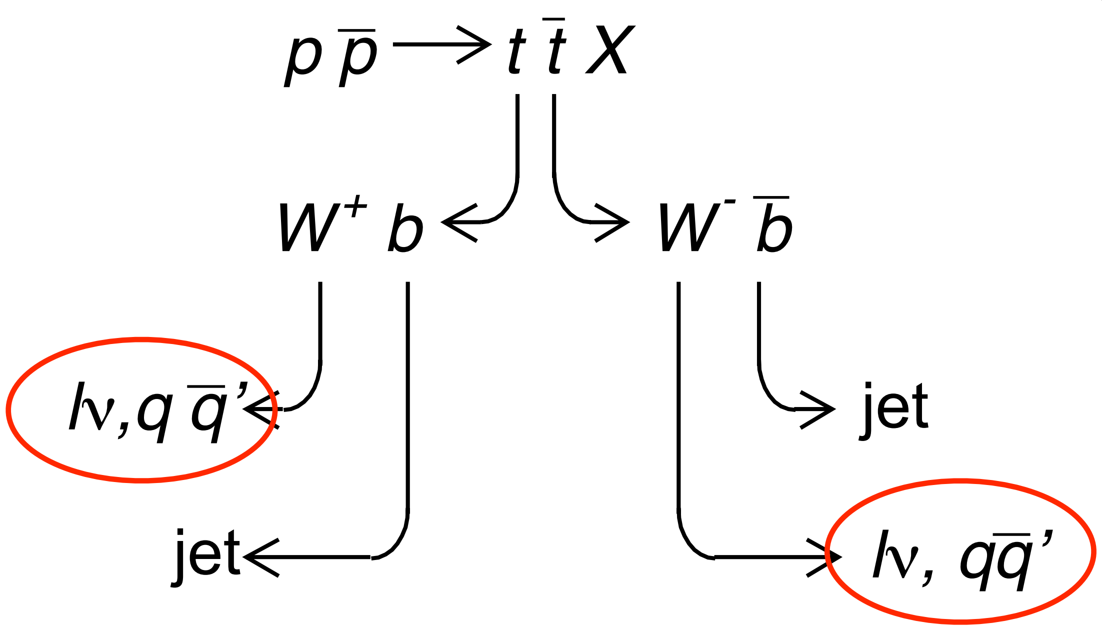
Lepton + Jets Selection Criteria

Selection Criteria	Base Cut
Lepton type	Tight central leptons: TCE, CMUP, CMX
Number of tight leptons	exactly 1
Number of jets	≥ 3
Jet , JCL 5	$\geq 20\,\text{GeV}$
Missing	$\geq 30\,\text{GeV}$
Z veto	Yes
Dilepton Veto	Yes
$\lvert z \rvert$ jet vertex	$\leq 60\,\text{cm}$
Δz lepton-jet vertex	$\leq 5\,\text{cm}$
H_T	$\geq 200\,\text{GeV}$
Number of loose SECVTX tags	≥ 2

Average Joint Physics Scale Factors

	Period 0	Periods 1–12
Tight CEM		
Trigger Efficiency	0.962 ± 0.007	0.967 ± 0.004
ID/Reconstruction Scale Factor	0.991 ± 0.004	0.976 ± 0.005
Tight Phoenix		
ID/Reconstruction Scale Factor	0.929 ± 0.006	0.935 ± 0.008
CMUP		
Trigger Efficiency	0.902 ± 0.004	0.920 ± 0.006
ID/Reconstruction Scale Factor	0.936 ± 0.006	0.923 ± 0.007
CMX (Arches)		
Trigger Efficiency	0.967 ± 0.004	0.955 ± 0.007
ID/Reconstruction Scale Factor	1.010 ± 0.006	0.989 ± 0.008
CMX (Miniskirts/Keystone)		
Trigger Efficiency	—	0.866 ± 0.012
ID/Reconstruction Scale Factor	—	0.888 ± 0.020
Track Leptons		
Reconstruction Scale Factor	0.954 ± 0.011	

Typical Top Selection Criteria



Cylindrical coordinate system:

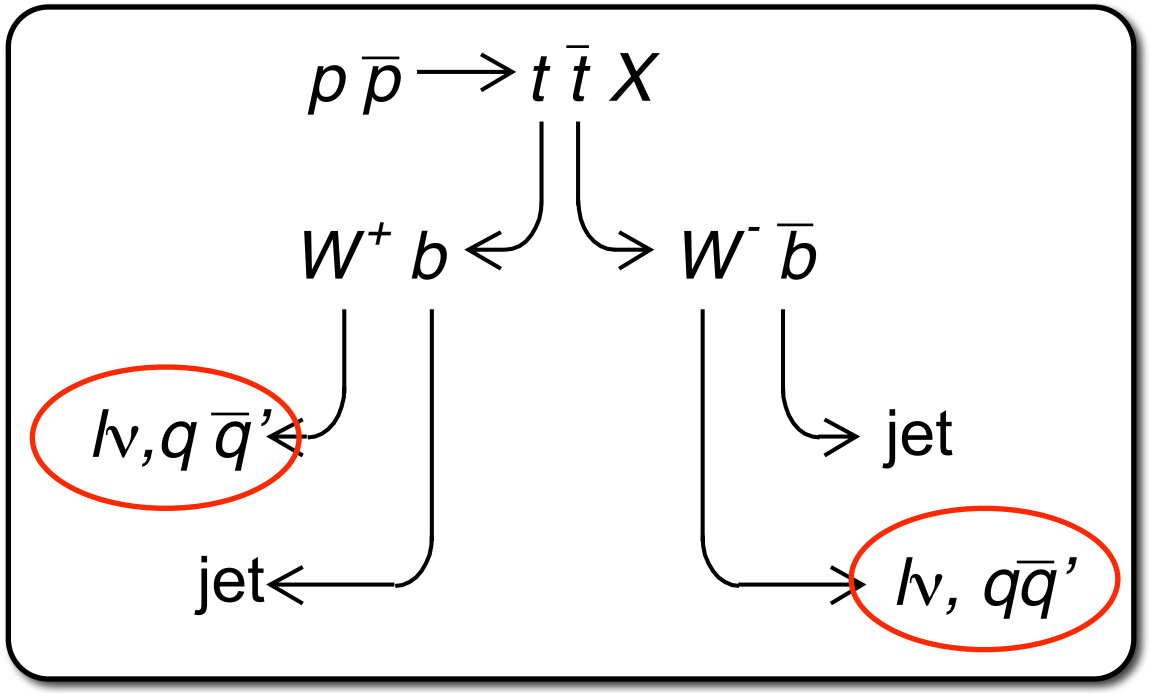
- θ: polar angle w.r.t. to proton direction
- ϕ: azimuthal angle
- Pseudorapidity: $\eta = -\ln \tan(\theta/2)$
- Transverse energy:

$$\vec{E}_T = \sum_{\text{cal towers}} E_i(\sin\theta_i, \phi_i)$$

- Missing transverse energy ("MET"):

$$\vec{\not{E}}_T = -\sum_{\text{jets}} \vec{E}_T - \sum_{\text{leptons}} \vec{p}_T$$

Typical Top Selection Criteria



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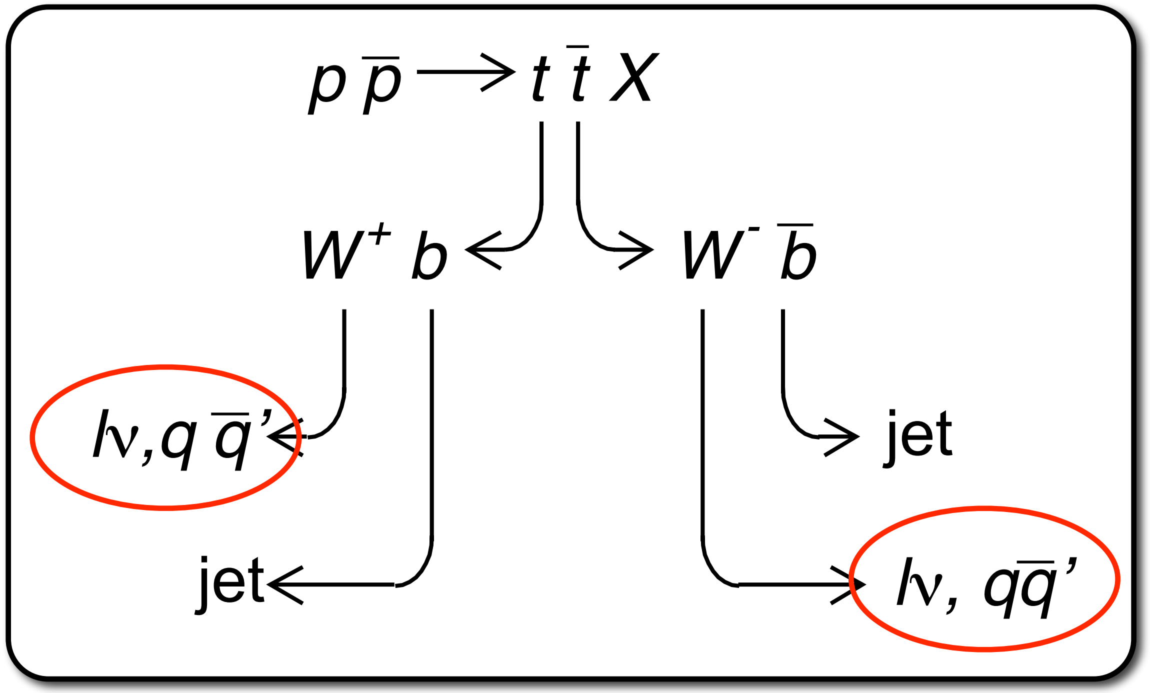
$$\vec{\not{E}}_T = -\sum_{\text{jets}} \vec{E}_T - \sum_{\text{leptons}} \vec{p}_T$$

- Lepton + Jets: tt → Wb Wb → lνb qq'b
  - Isolated lepton with p_T > 20 GeV/c
  - Neutrino: missing E_T ("MET") > 20 GeV
  - 3 jets within |η| < 2 with E_T > 15 GeV, 4th jet: E_T > 8 GeV
  - 0, 1, ≥ 2 identified jets from b quarks ("b-tags")

Typical Top Selection Criteria



Cylindrical coordinate system:

- θ: polar angle w.r.t. to proton direction
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- Transverse energy:

$$\vec{E}_T = \sum_{\text{cal towers}} E_i(\sin\theta_i, \phi_i)$$

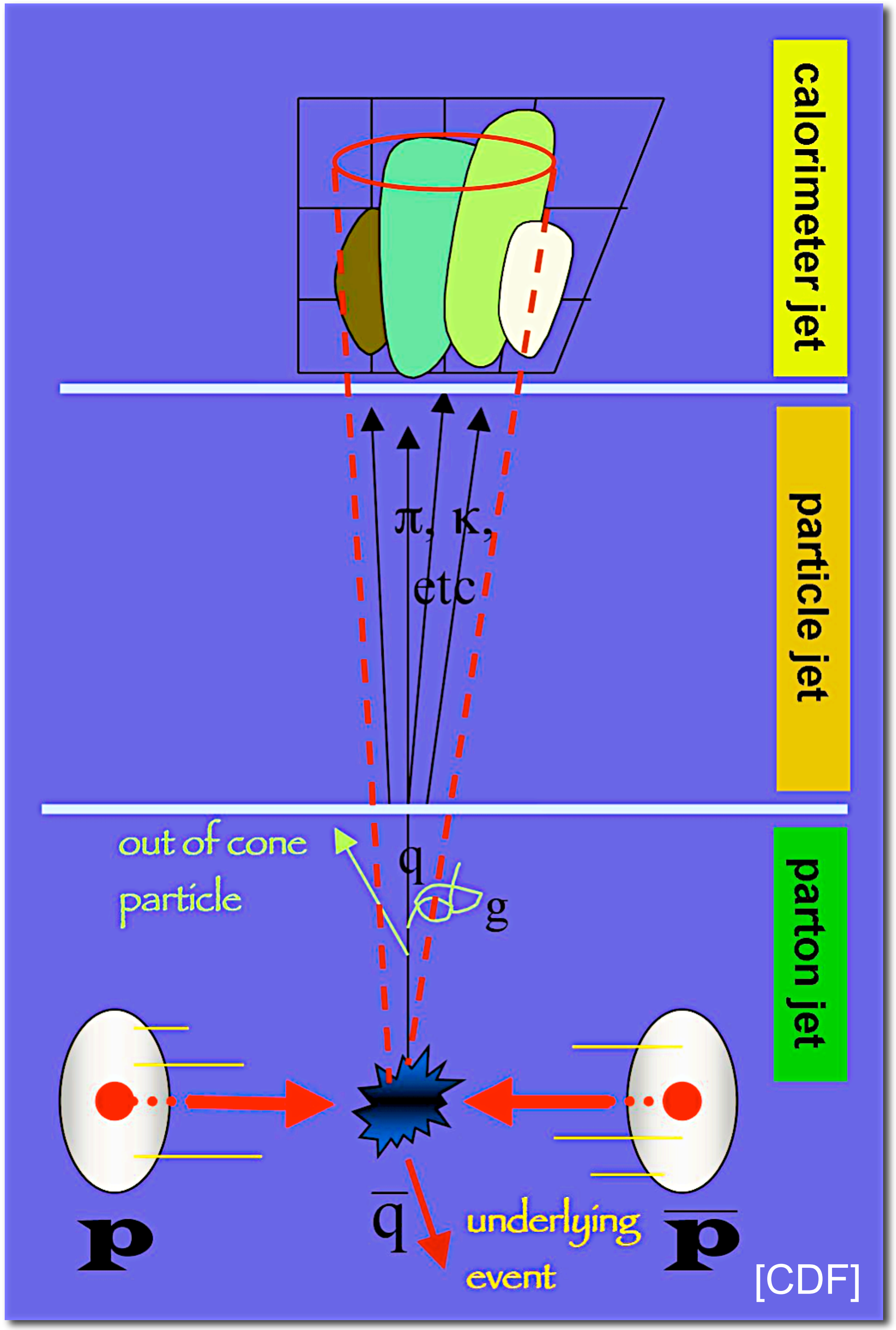
- Missing transverse energy ("MET"):

$$\vec{\not{E}}_T = -\sum_{\text{jets}} \vec{E}_T - \sum_{\text{leptons}} \vec{p}_T$$

- **Lepton + Jets**: tt → Wb Wb → lνb qq'b
  - Isolated lepton with p_T > 20 GeV/c
  - Neutrino: missing E_T ("MET") > 20 GeV
  - 3 jets within |η| < 2 with E_T > 15 GeV, 4th jet: E_T > 8 GeV
  - 0, 1, ≥ 2 identified jets from b quarks ("b-tags")
- **Dilepton**: tt → Wb Wb → lνb lνb
  - Two oppositely charged leptons with p_T > 20 GeV/c
  - Two neutrinos: MET > 25 GeV
  - ≥ 2 jets within |η| < 2.5 with E_T > 15 GeV
  - Scalar sum of lepton p_T's, jet E_T's and MET: H_T > 200 GeV
  - 0, 1, ≥ 2 b-tags

Jet Energy Corrections

- Problem: infer parton energy (hard scattering process) from measured jet energy
- Jet reconstruction by clustering algorithm with fixed cone size
- Jet energy corrected for:
  - Non-uniform detector response
  - Different response to different particles
  - Multiple $p\bar{p}$ interactions
  - Un-instrumented areas
  - Underlying event (spectators)
  - “Out-of-cone” energy
- Correction leads to large systematic uncertainties, partly compensated by in-situ calibration in data



Event Tagging Rates

- Goal: assign probability to each MC event that at least one jet is b-tagged
- MC: can match reconstructed jet to true B hadron
- Difficulty: MC simulation does not reproduce data perfectly
  - Introduce “scale factor” for b-tagging efficiency (= ratio of data to MC efficiency)
  - Derive “mistag probability” from data (= probability to assign b-tag to light flavor jet)
- Per-event tag rate: combine probabilities for all jets

$$P_{\text{event,tag}} = 1 - \prod_i \text{probability that jet } i \text{ is not tagged}$$

$$= 1 - \underbrace{\prod_j \left(1 - P_{\text{mistag},j}\right)}_{\text{LF or non-matched HF}} \cdot \underbrace{\prod_k \left(1 - \text{SF}_k\right)}_{\text{Tagged \& matched HF}} \cdot \underbrace{\prod_l 1}_{\text{Non-tagged \& matched HF}}$$

Why Feldman-Cousins?

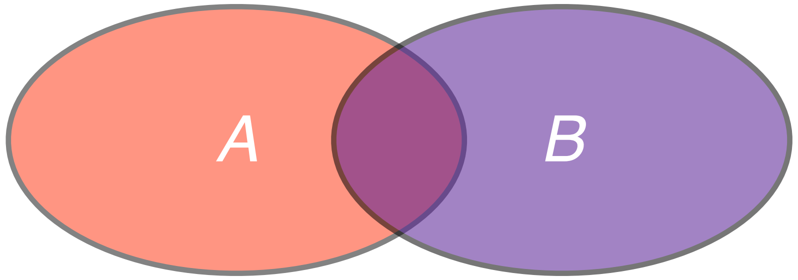
- Reporting results of particle physics experiments: confidence intervals, e.g. central value and uncertainty, upper/lower limit
- Two rivaling schools on reporting confidence intervals
  - Frequentist approach: If the experiment would be repeated infinitely many times, the true value would lie within the interval in a fraction α of the experiments
  - Bayesian approach: degree of belief that the true value lies within the interval is α
- Both approaches have their advantages and disadvantages
  - New (frequentist) approach by Gary J. Feldman (Harvard) and Robert D. Cousins (UCLA)
  - Published in Phys. Rev. **D57** (1998) 3873 (quite readable)

Gary Feldman

Bob Cousins

Bayes' Theorem

- Classical probability theory:
  - Probability that an element belongs to two sets *A* and *B*



$$P(A \cap B) = P(A) \cdot P(B|A)$$
$$P(A \cap B) = P(B) \cdot P(A|B)$$

  - In words: the probability of an element to belong to the union of two sets *A* and *B* is the probability of the element to belong to set *A* times the probability to belong to *B* *given* it belongs to *A* (and vice versa: probability to belong to *B* times probability to belong to *A* given it belongs to *B*)
- Result: Bayes' theorem $P(A) \cdot P(B|A) = P(B) \cdot P(A|B)$

Bayesian Confidence Interval

Goal: measure parameter μ, i.e. construct Bayesian confidence interval for μ from a set of measurements $\mathbf{x} = (x_1, x_2, \ldots, x_N)$

1. Know probability to observe experimental value x_i for a given value of μ: $P(x_i | \mu)$, e.g. Poisson distribution
2. Construct joint probability for **x** ("likelihood function"):

$$L(\mathbf{x}|\mu) = \prod_{i=1}^{N} P(x_i|\mu)$$

3. Apply Bayes' theorem to obtain posterior probability

$$P(\mu|\mathbf{x}) = \frac{L(\mathbf{x}|\mu)P(\mu)}{\int \mathrm{d}\mu' P(\mathbf{x}|\mu')P(\mu')}$$

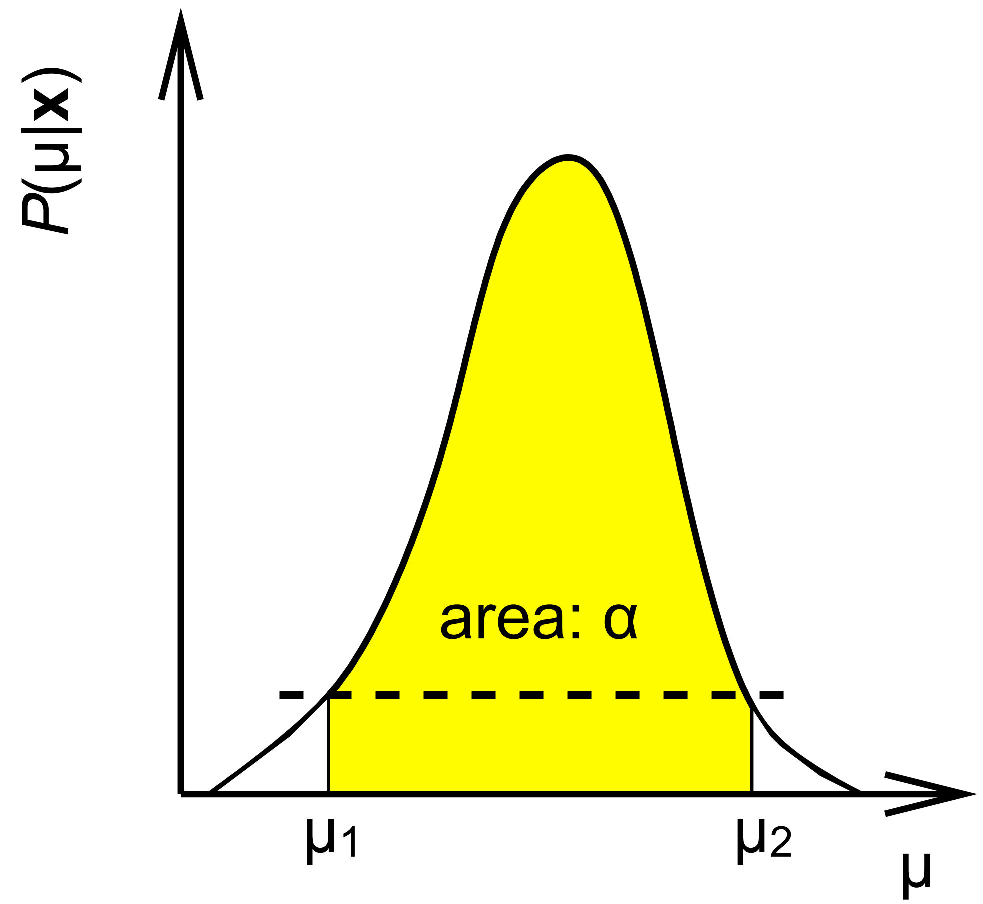
4. Find confidence interval $[\mu_1;\mu_2]$ such that

$$\int_{\mu_1}^{\mu_2} \mathrm{d}\mu' \, P(\mu'|\mathbf{x}) = \alpha$$

Bayesian Interpretation

- α is degree of belief that μ is in $[\mu_1;\mu_2]$
- Problem: Bayes' theorem requires prior probability density $P(\mu)$, i.e. prior knowledge about the the parameter to be measured (intrinsically subjective)

$$P(\mu|\mathbf{x}) = \frac{L(\mathbf{x}|\mu)P(\mu)}{\int \mathrm{d}\mu' P(\mathbf{x}|\mu')P(\mu')}$$



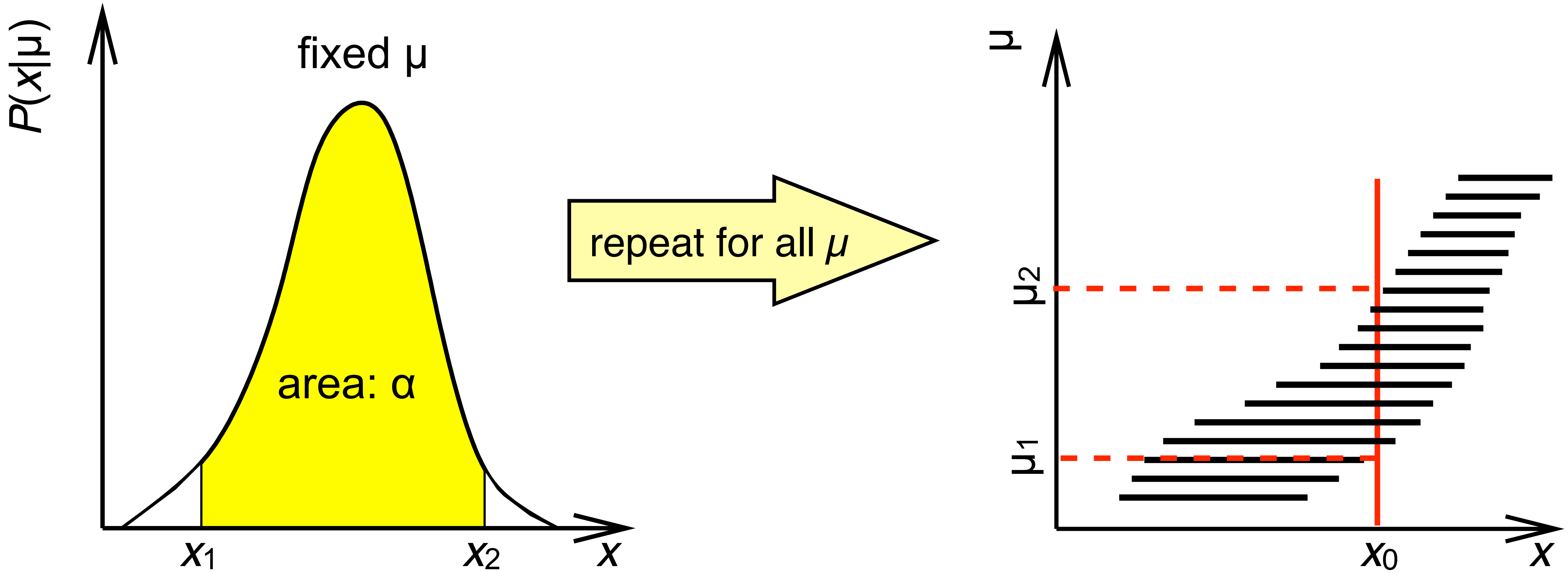
- Solution for uniquely defining μ_1: draw horizontal line at fraction α of area under posterior probability

Frequentist Intervals

- Likelihood function is only source of information: estimator for μ from maximum likelihood, i.e.

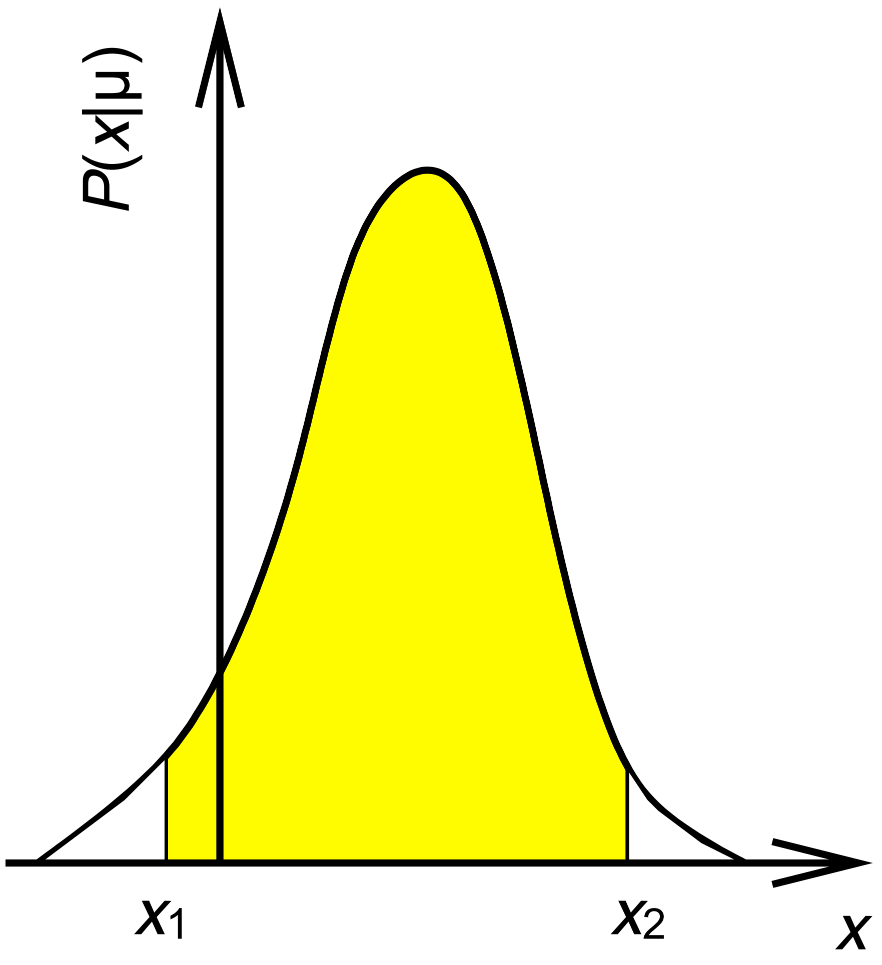
$$\frac{\partial L}{\partial \mu} = 0, \text{ with } L(\mathbf{x}|\mu) = \prod_{i=1}^{N} P(x_i|\mu)$$

- Confidence interval $[\mu_1;\mu_2]$ from Neyman construction ("confidence belt")



Frequentist Interpretation

- Infinitely many repetitions of experiment: interval [μ_1;μ_2] includes true value of μ in a fraction α of the experiments
- Problem 1: freedom of choice for x_1
  - Flip-flopping (as for Bayesian limit)
- Problem 2: "Under-coverage"
  - If $P(x|\mu)$ leaks into unphysical values (e.g. $x_1 < 0$), interval [0;x_2] does not cover a fraction α
  - Over-coverage is unavoidable for discrete x
  - Generally: over-coverage tolerable, but just too "conservative"



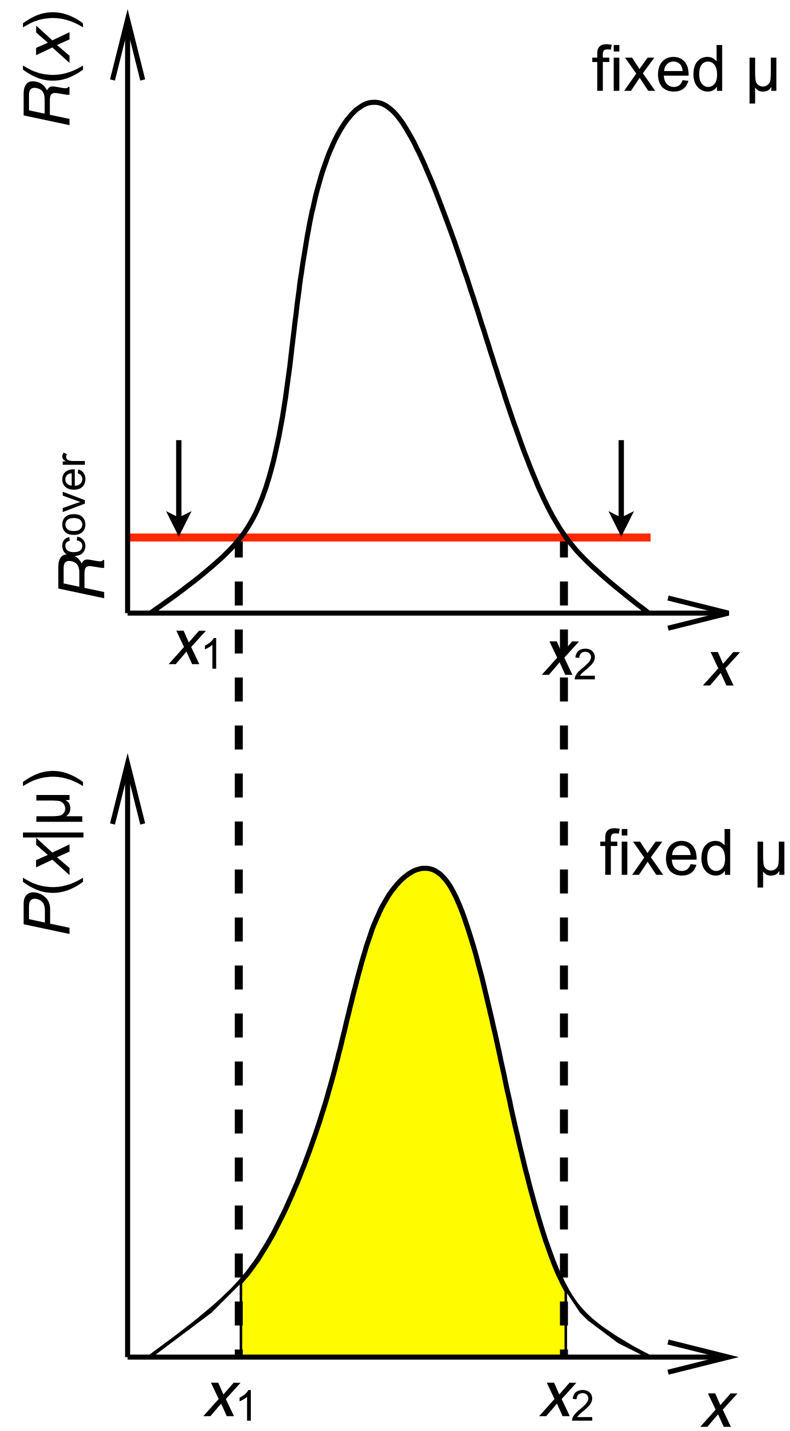
Feldman–Cousins Construction

- Use freedom in Neyman construction, i.e. choice of x_1, to achieve
  - Smooth transition between upper/lower and central intervals (“unified” limits)
  - Correct treatment of unphysical regions
- Introduce (i.e. re-discover for high-energy physics) ordering principle based on likelihood ratio

$$R(x) = \frac{P(x|\mu)}{P(x|\mu^{\text{best}})}$$

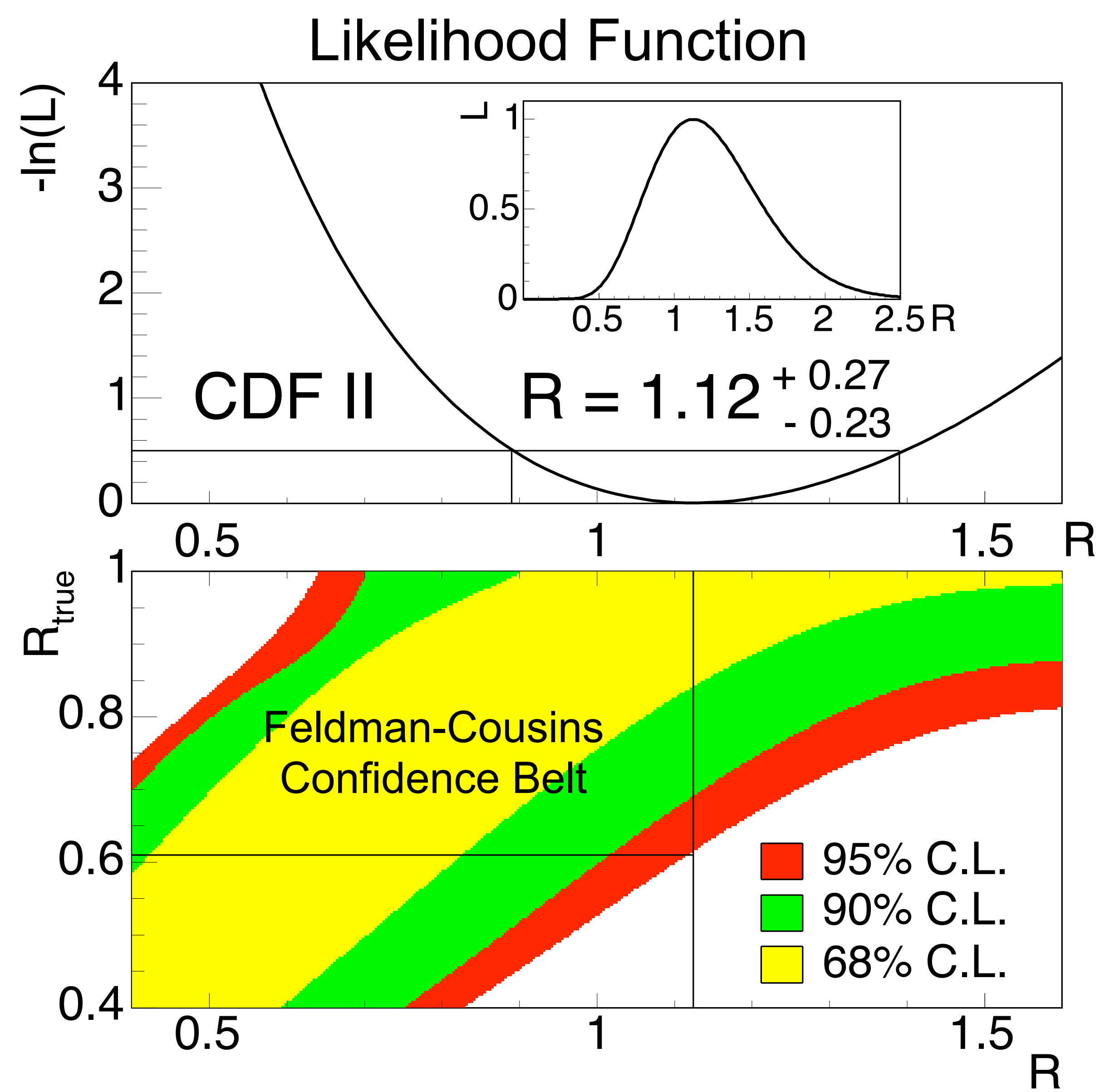
(μ^{best}: physically allowed value of μ for which $P(x|\mu)$ is maximum)

- Construct frequentist confidence belt



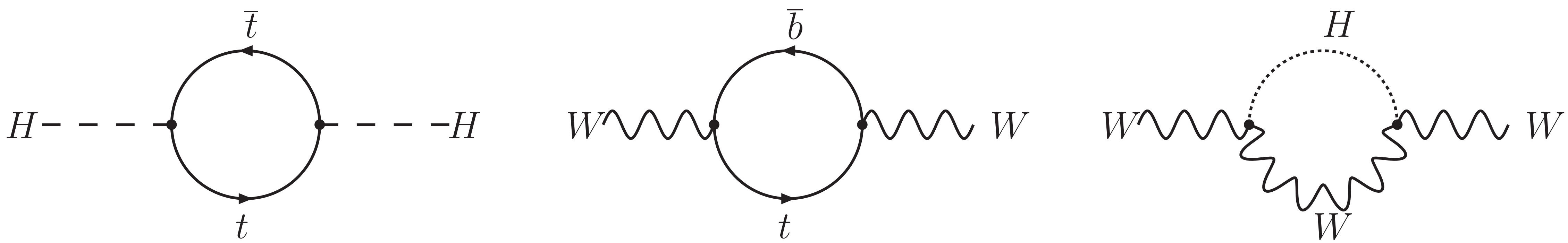
Feldman-Cousins: Conclusions

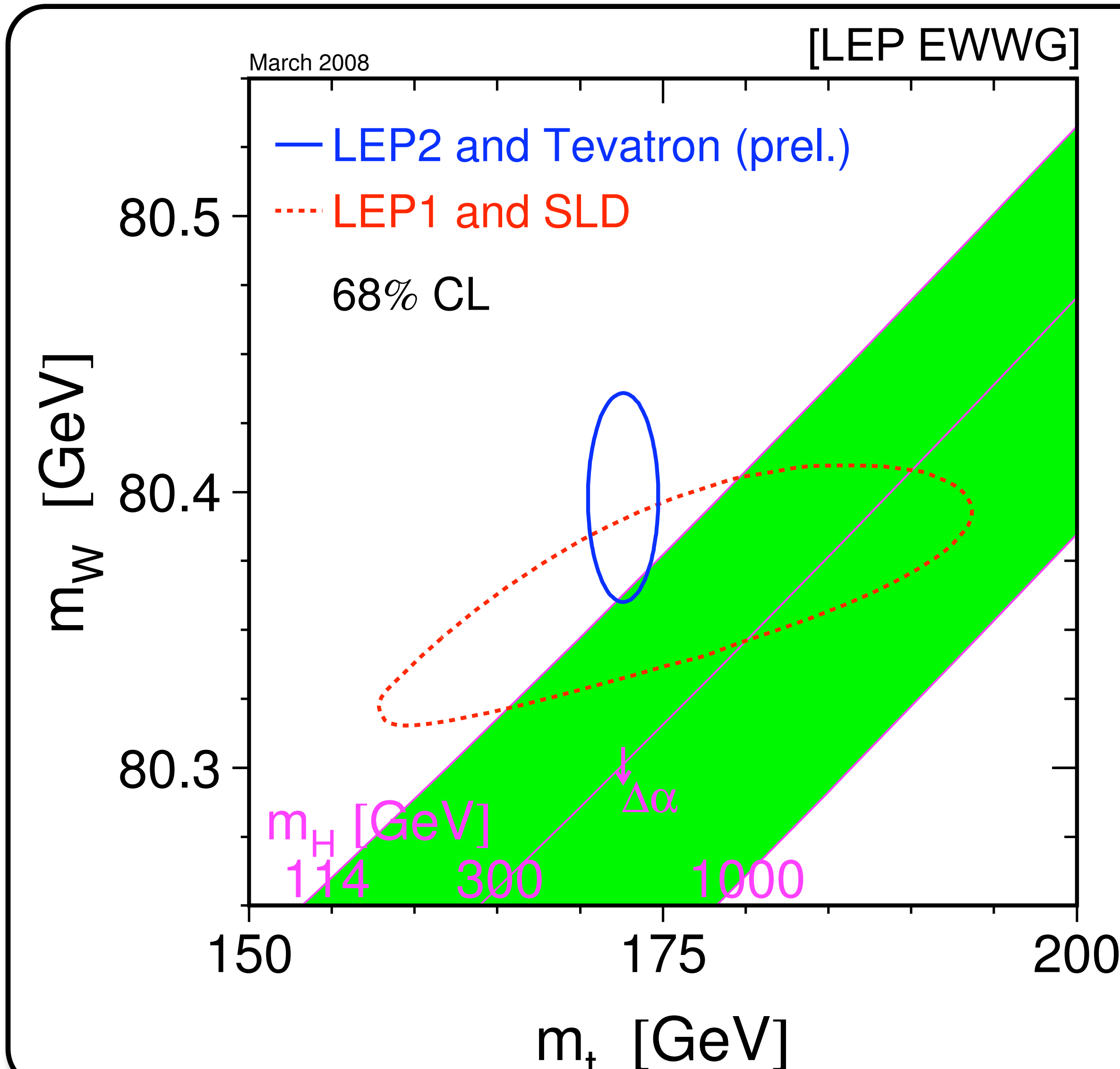
- Feldman–Cousins approach:
  - Solves problems present in construction of Bayesian and frequentist confidence intervals
  - Widely accepted in scientific community
  - Applications: check out original paper (quite readable)
- Further developments: incorporation of systematic uncertainties (impossible in frequentist approach)
- Many examples for application in CDF: measurement of $|V_{tb}|$, fraction of $t\bar{t}$ production from gluon fusion, FCNC search, …

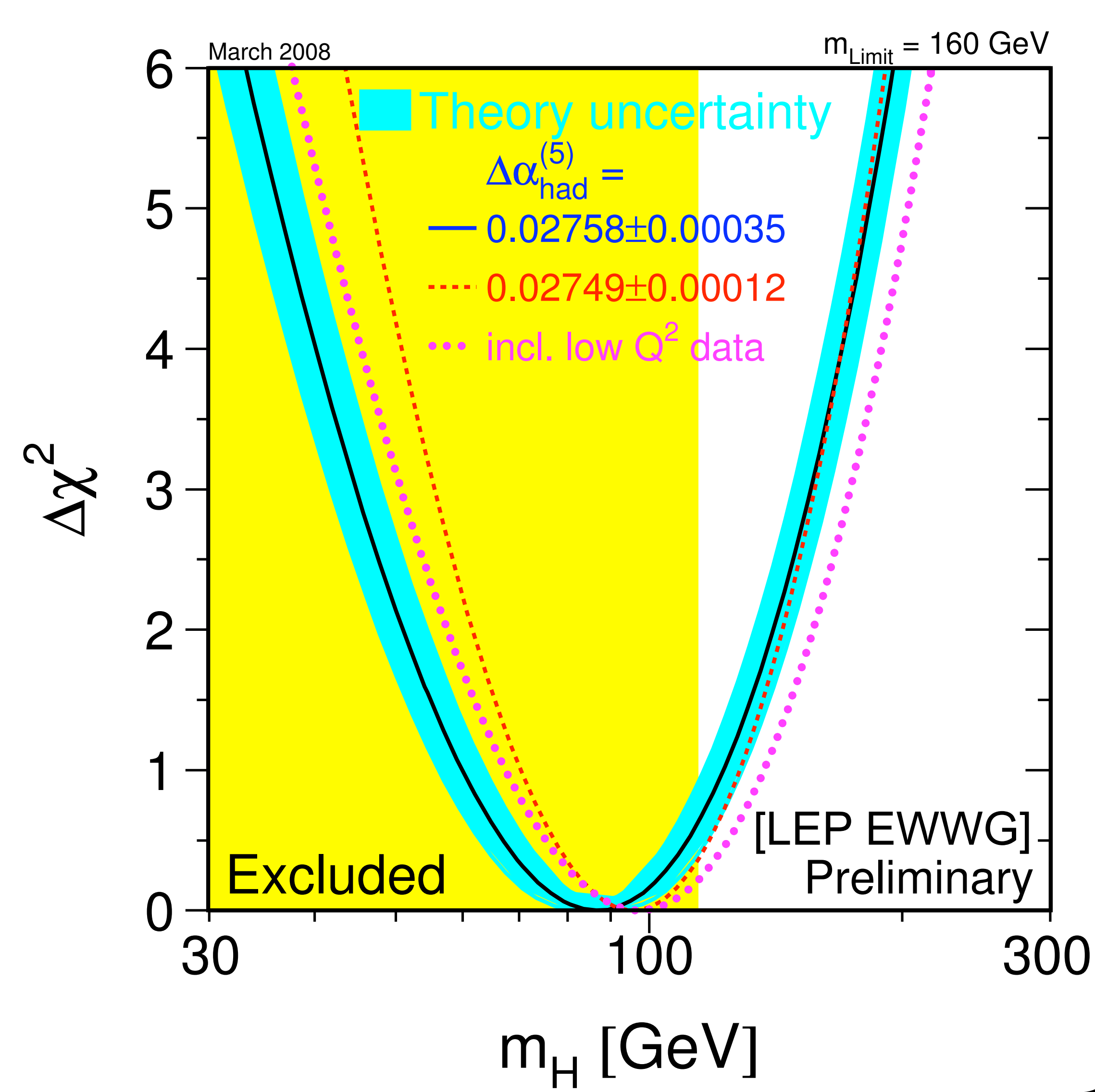


The Top, the W, and the Higgs

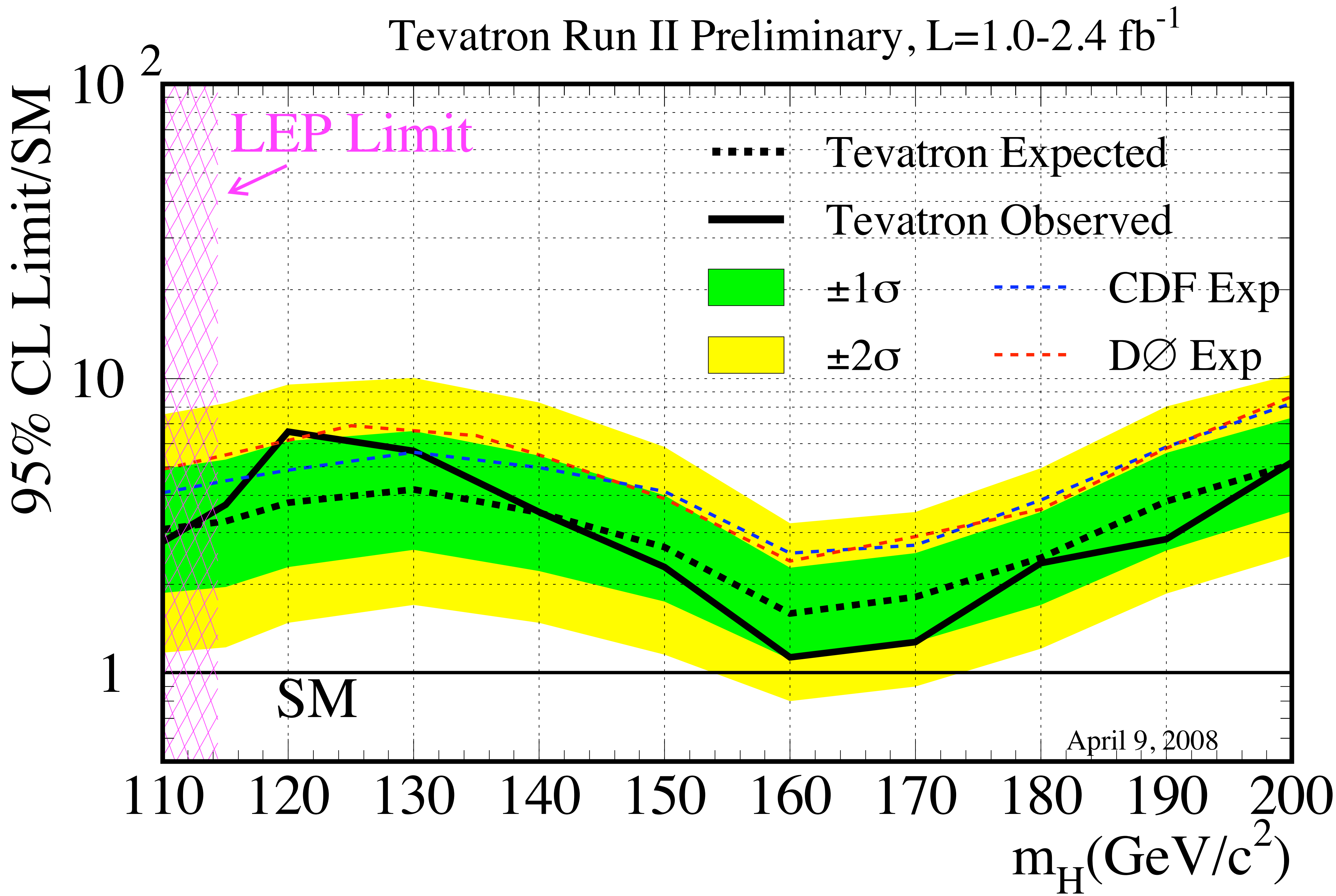
Top, W, and Higgs masses closely related by loop corrections:







Tevatron SM Higgs Limits 2008



[arXiv:0804.3423v1 [hep-ex]]