Experimental Particle Physics Seminar
University of Pennsylvania, October 17, 2007

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

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Yale University

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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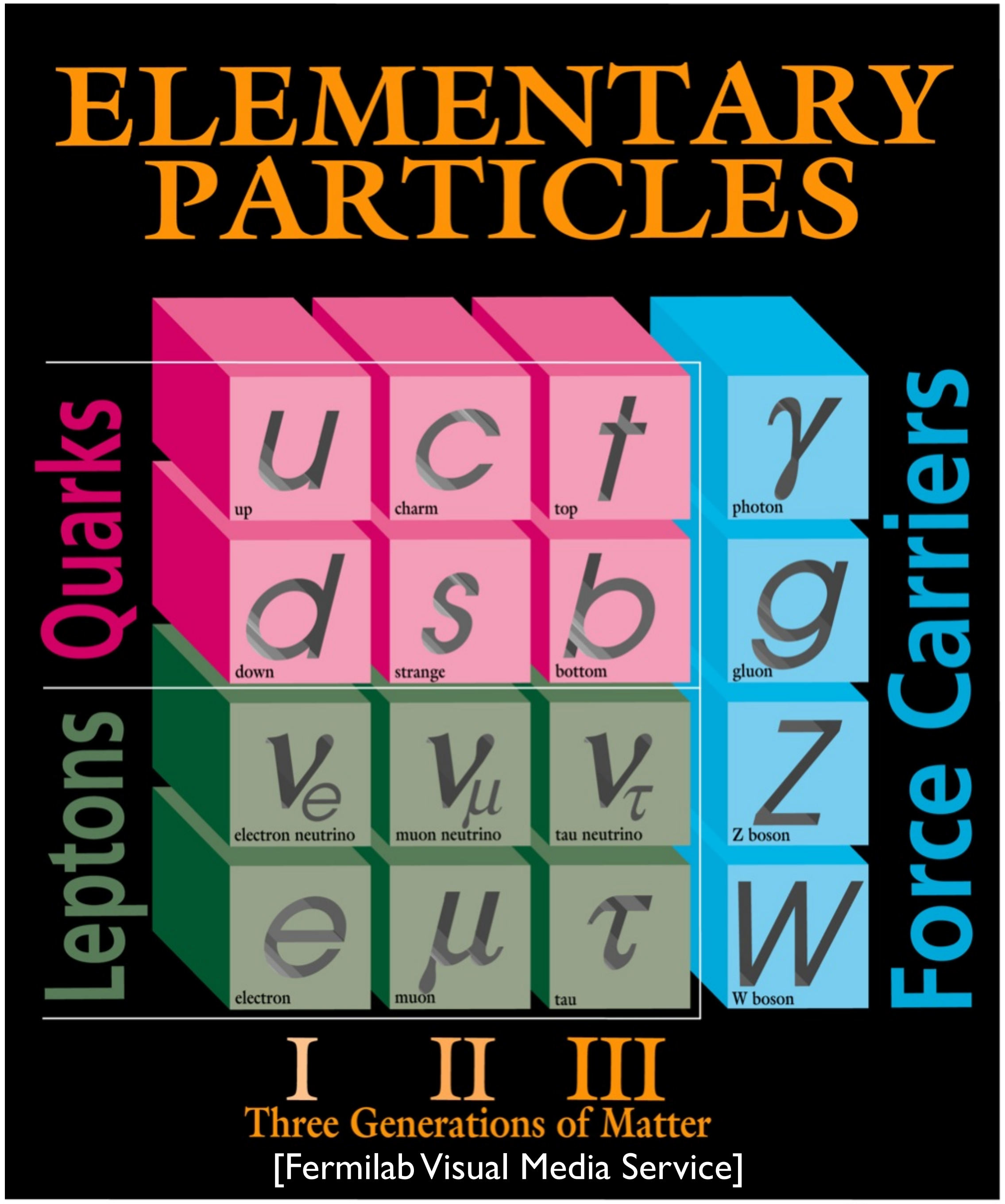
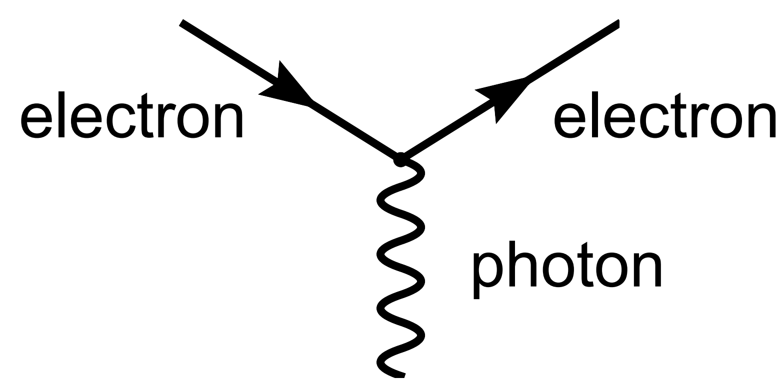
Standard Model of Particle Physics



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 can be described by "currents" coupling to gauge bosons, e.g. electromagnetic current

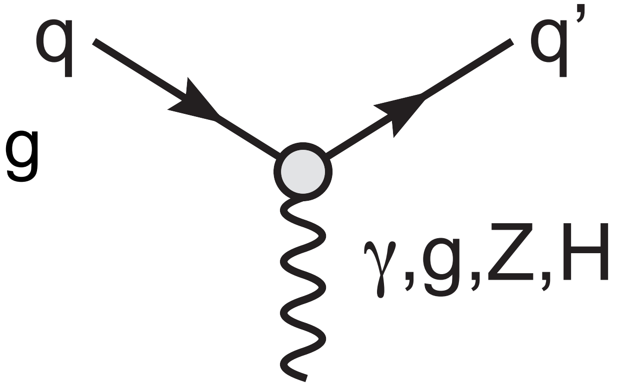


$$\mathscr{L}^{\mathrm{em}} = -q\,\bar{e}\gamma_\mu e A^\mu \equiv j_\mu^{\mathrm{em}} A^\mu$$

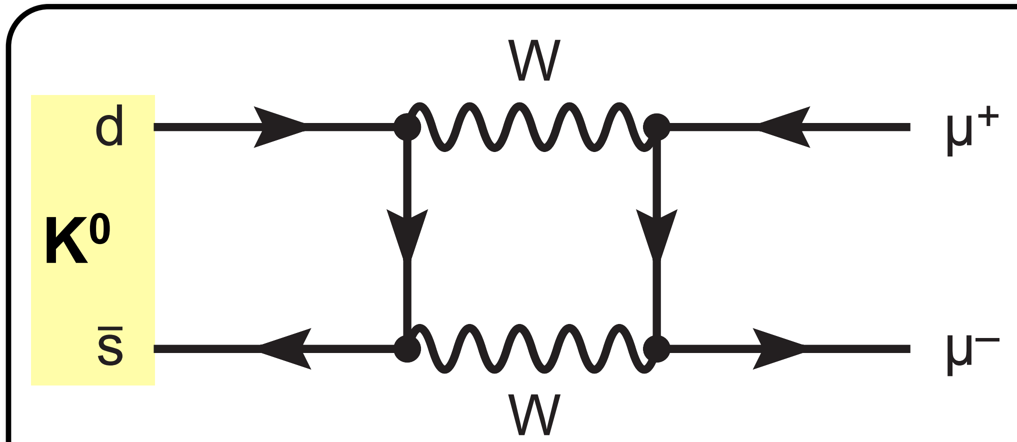
Flavor Changing Neutral Currents

- Flavor changing neutral current (FCNC) interactions:
  - Transition from a quark of flavor A and charge Q to quark of flavor B with the same charge Q
  - Examples: b → sγ, t → cH, …

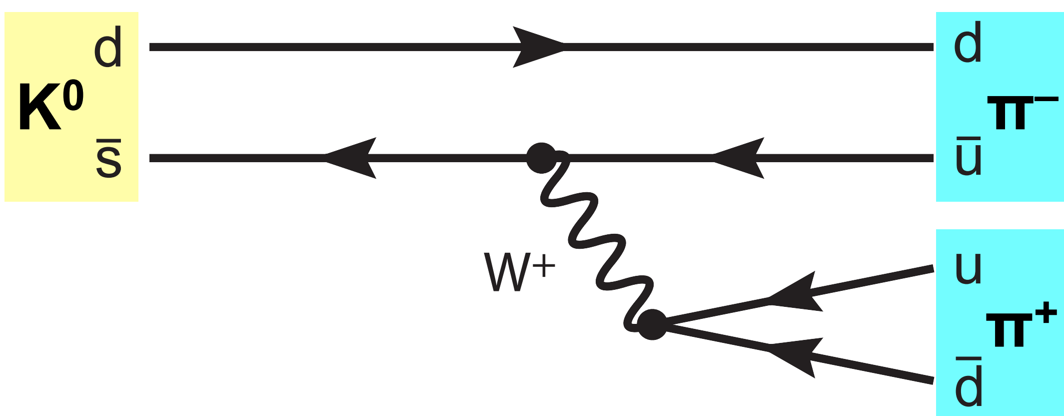
Flavor
Changing
Neutral
Current



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



10^8 times smaller than…?



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

FCNC in the Standard Model (I)

Standard model: no FCNC at Lagrangian level

- Massless theory: weak neutral current is flavor-diagonal

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

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

$$\mathscr{L}_{\mathrm{Yuk}} = \underbrace{-m_u^{\alpha\beta}\,\bar{u}_{\mathrm{L}}^{\prime\alpha} u_{\mathrm{R}}^{\prime\beta} - m_d^{\alpha\beta}\,\bar{d}_{\mathrm{L}}^{\prime\alpha} d_{\mathrm{R}}^{\prime\beta}}_{\text{Mass Terms}} \underbrace{- \frac{1}{\sqrt{2}} f_u^{\alpha\beta}\,\bar{u}_{\mathrm{L}}^{\prime\alpha} h(x)\, u_{\mathrm{R}}^{\prime\beta} - \frac{1}{\sqrt{2}} f_d^{\alpha\beta}\,\bar{d}_{\mathrm{L}}^{\prime\alpha} h(x)\, d_{\mathrm{R}}^{\prime\beta}}_{\text{Higgs Couplings}} + \mathrm{h.c.}$$

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

$$\bar{u}_{\mathrm{L}} = \bar{u}_{\mathrm{L}}'\,\mathbf{U}_{\mathrm{L}}^u \qquad u_{\mathrm{R}} = \mathbf{U}_{\mathrm{R}}^{u\dagger}\, u_{\mathrm{R}}' \qquad \mathbf{m}_u = \mathbf{U}_{\mathrm{L}}^{u\dagger}\,\mathbf{m}_u'\,\mathbf{U}_{\mathrm{R}}^u$$

$$\bar{d}_{\mathrm{L}} = \bar{d}_{\mathrm{L}}'\,\mathbf{U}_{\mathrm{L}}^d \qquad d_{\mathrm{R}} = \mathbf{U}_{\mathrm{R}}^{d\dagger}\, d_{\mathrm{R}}' \qquad \mathbf{m}_d = \mathbf{U}_{\mathrm{L}}^{d\dagger}\,\mathbf{m}_d'\,\mathbf{U}_{\mathrm{R}}^d$$

  - 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

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

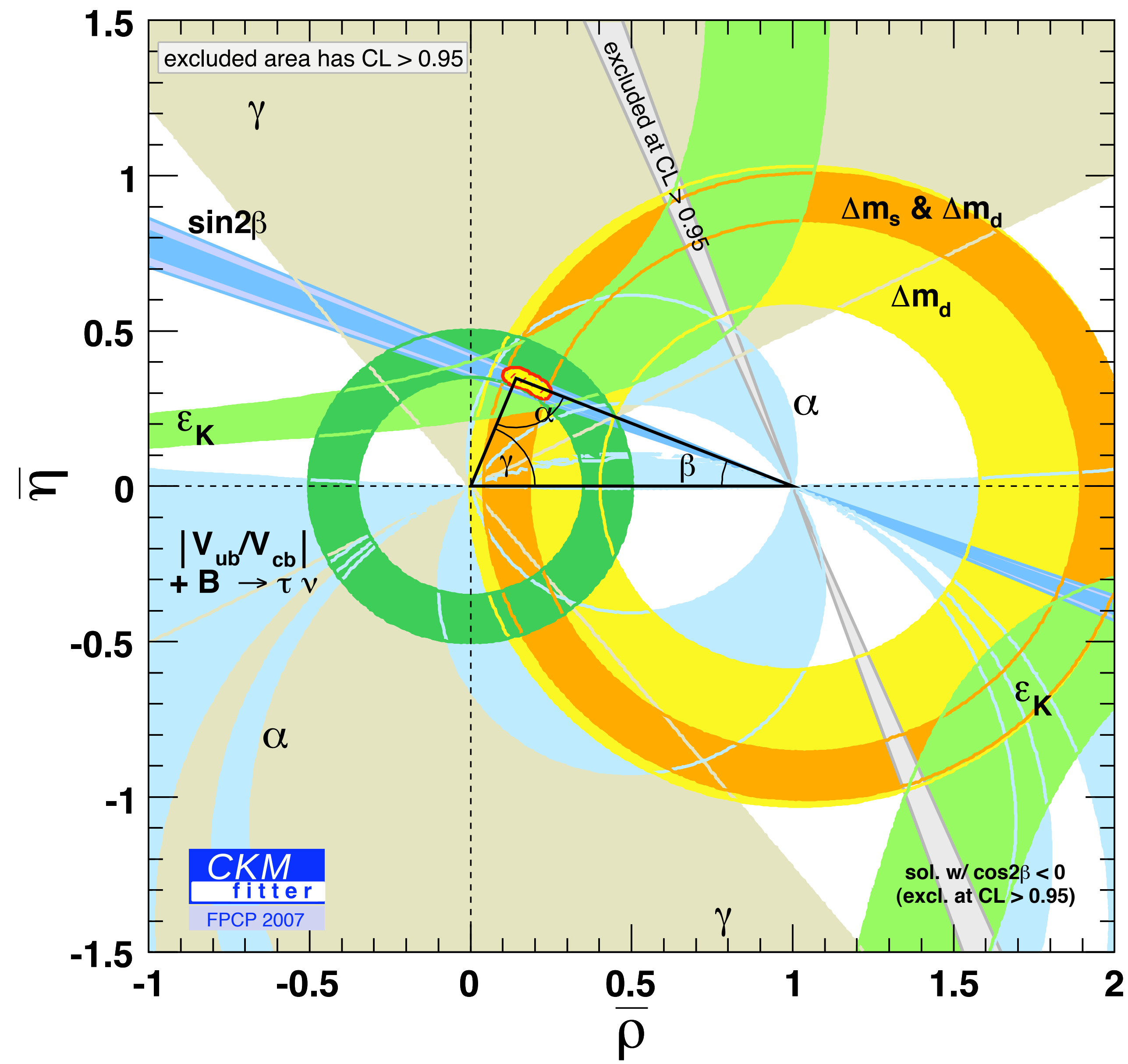
$$\mathbf{V}_{CKM} \cdot \mathbf{V}_{CKM}^\dagger = \mathbf{V}_{CKM}^\dagger \cdot \mathbf{V}_{CKM} = \mathbf{1}$$

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 $x_i = m_i^2/m_W^2$

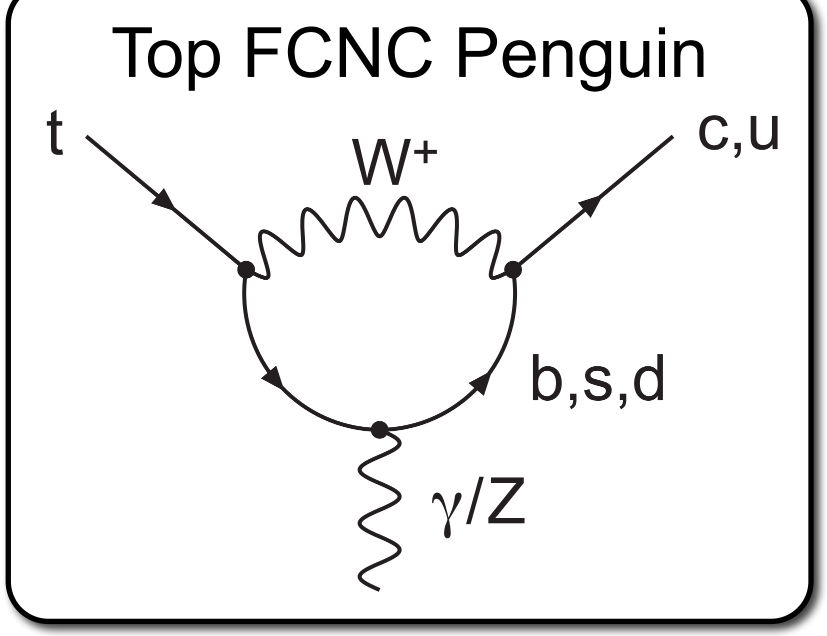
$$\mathcal{M} \propto F(x_d)\, V_{cd}^* V_{td} + F(x_s)\, V_{cs}^* V_{ts} + F(x_b)\, V_{cb}^* V_{tb},$$

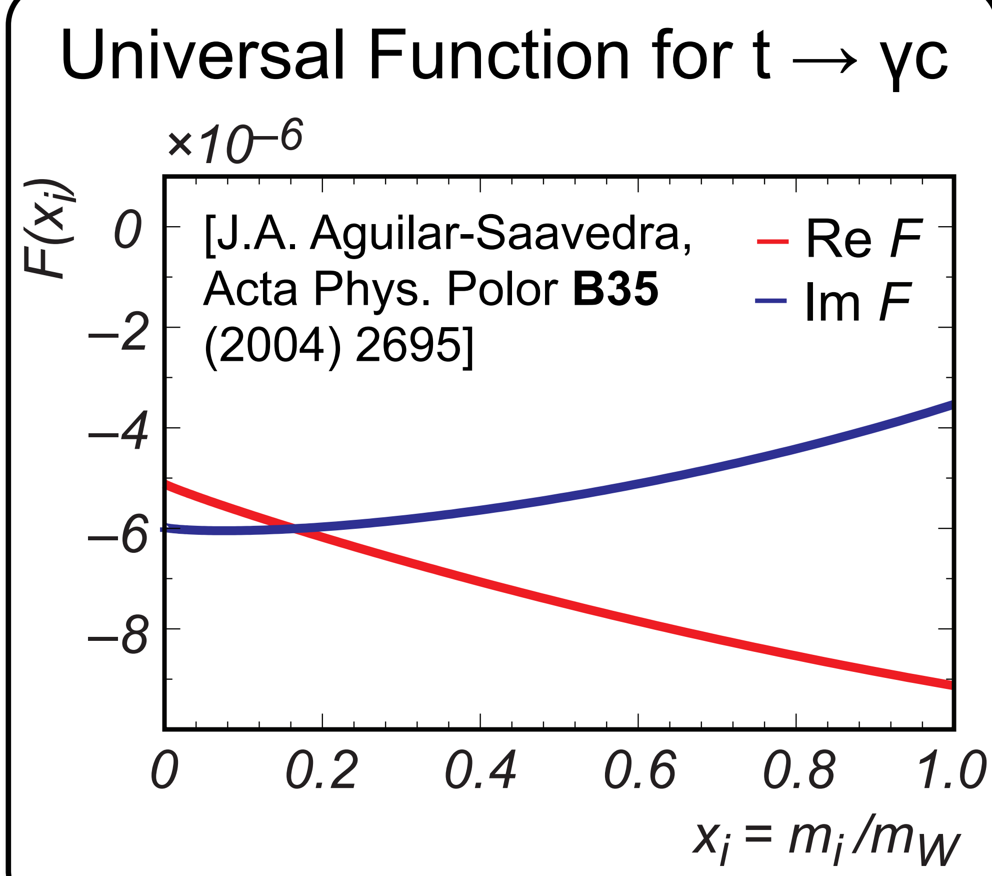
  - Compare to CKM unitarity relation:

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

    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($t \to Zq$) ≈ 10^{-14} vs. BR($b \to s\gamma$) ≈ 10^{-4}
- Suppression mechanism 2: smallness of relevant CKM matrix elements

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

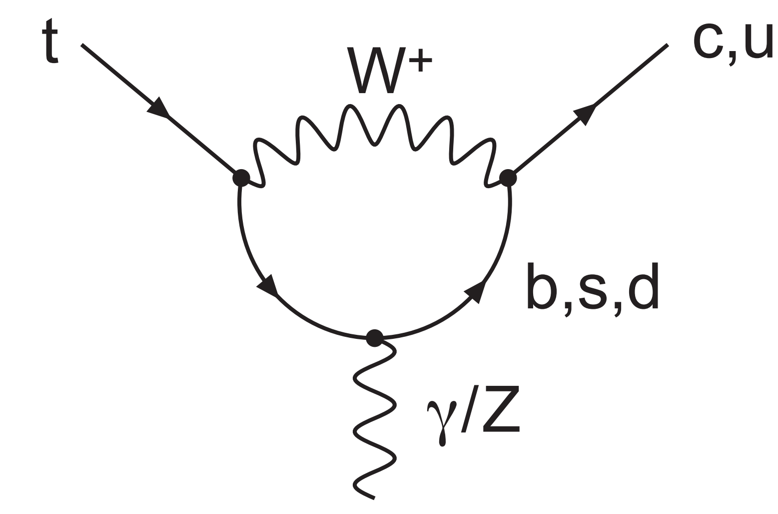




FCNC & New Physics

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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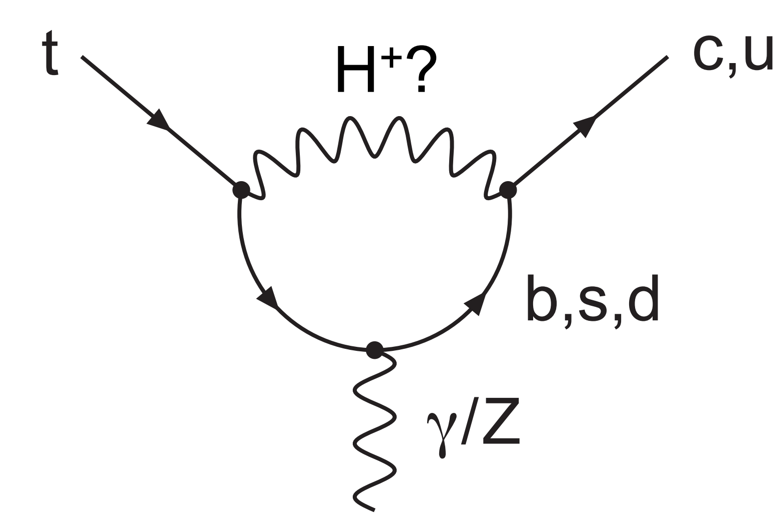

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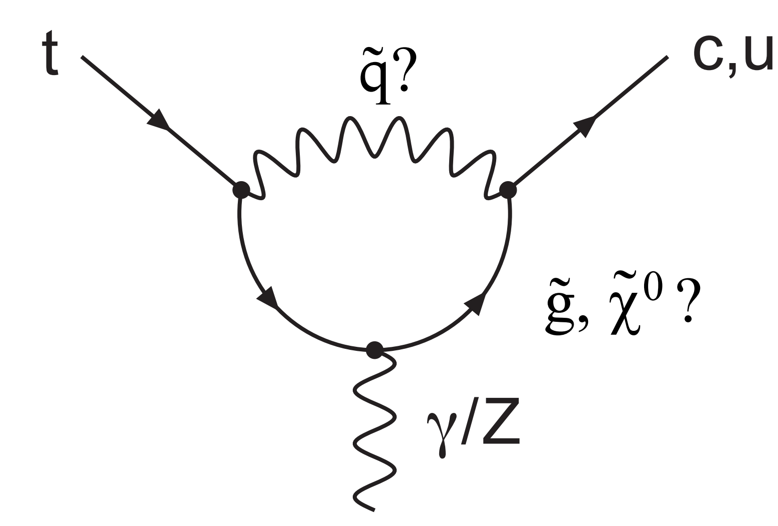

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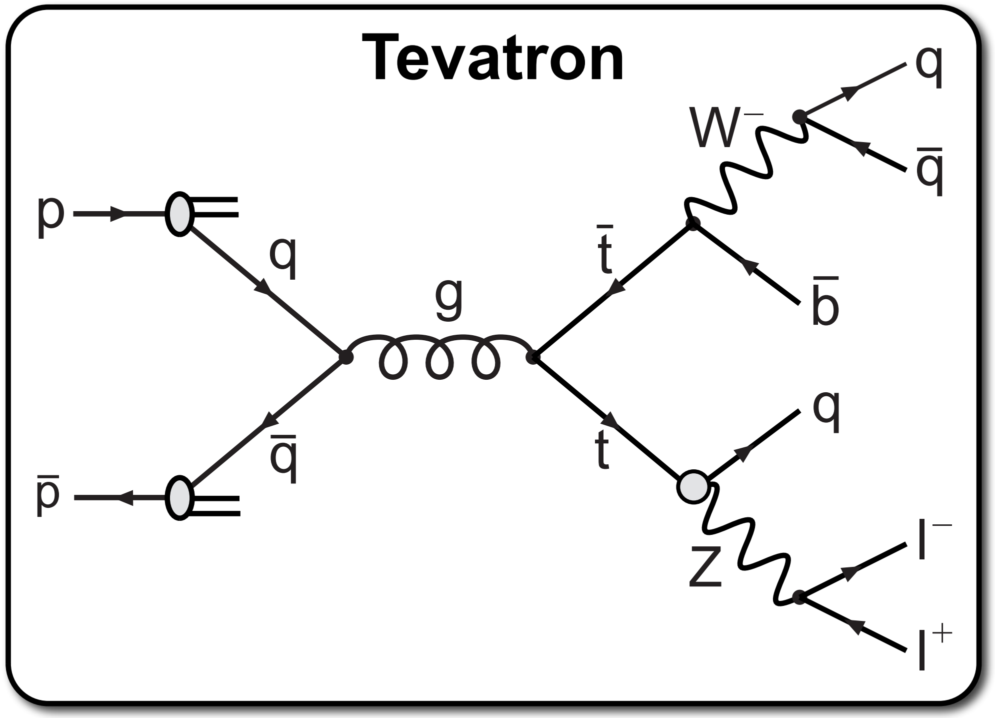
Experimental Tests of FCNC

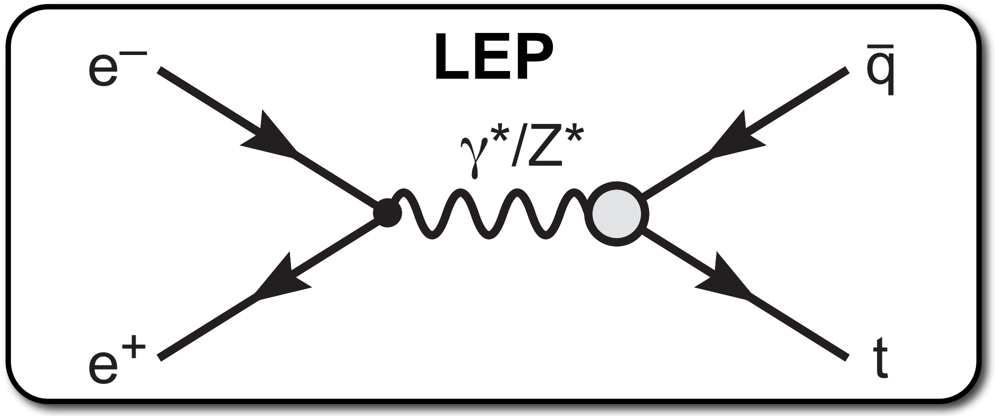
- Experimental tests of FCNC interactions: sensitive probes of new physics
  - Any signal above SM expectations would indicate new physics
  - Measurements constrain allowed phase space for new physics models
- Two types of searches for FCNC in the top sector:
  - Search for single top production (LEP, HERA, DØ)
  - Search for top quark decay via FCNC (CDF)
- Experiments usually report limits on
  - Branching fractions for specific processes, e.g. BR($t \to Zq$)
  - Coupling parameters of effective Lagrangian, e.g. for tZq coupling

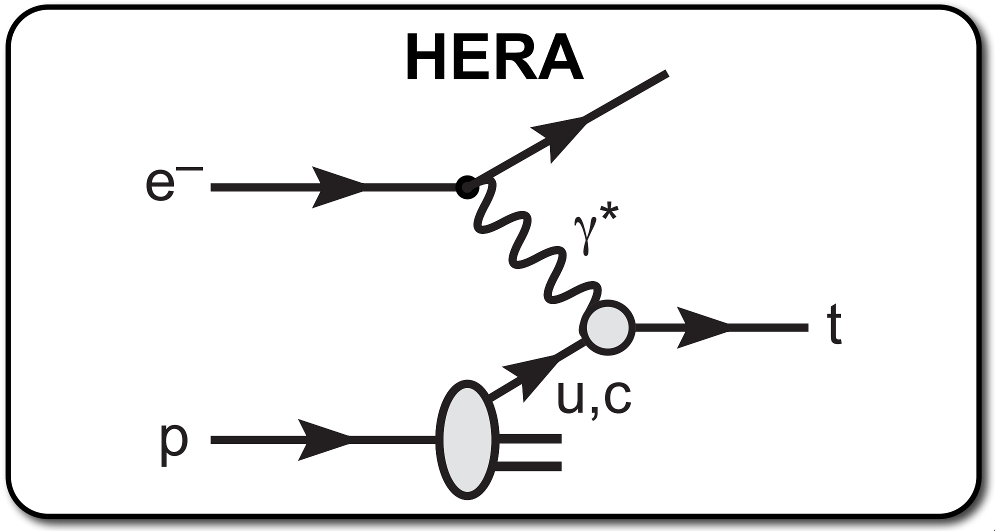
$$\mathscr{L}_{\text{eff}} = -\frac{g}{2\cos\theta_W} \cdot \kappa \cdot \left(x_{\text{L}} \cdot \bar{q}_{\text{L}} \gamma_\mu t_{\text{L}} + x_{\text{R}} \cdot \bar{q}_{\text{R}} \gamma_\mu t_{\text{R}}\right) Z^\mu + \ldots$$

Previous Searches for Top FCNC

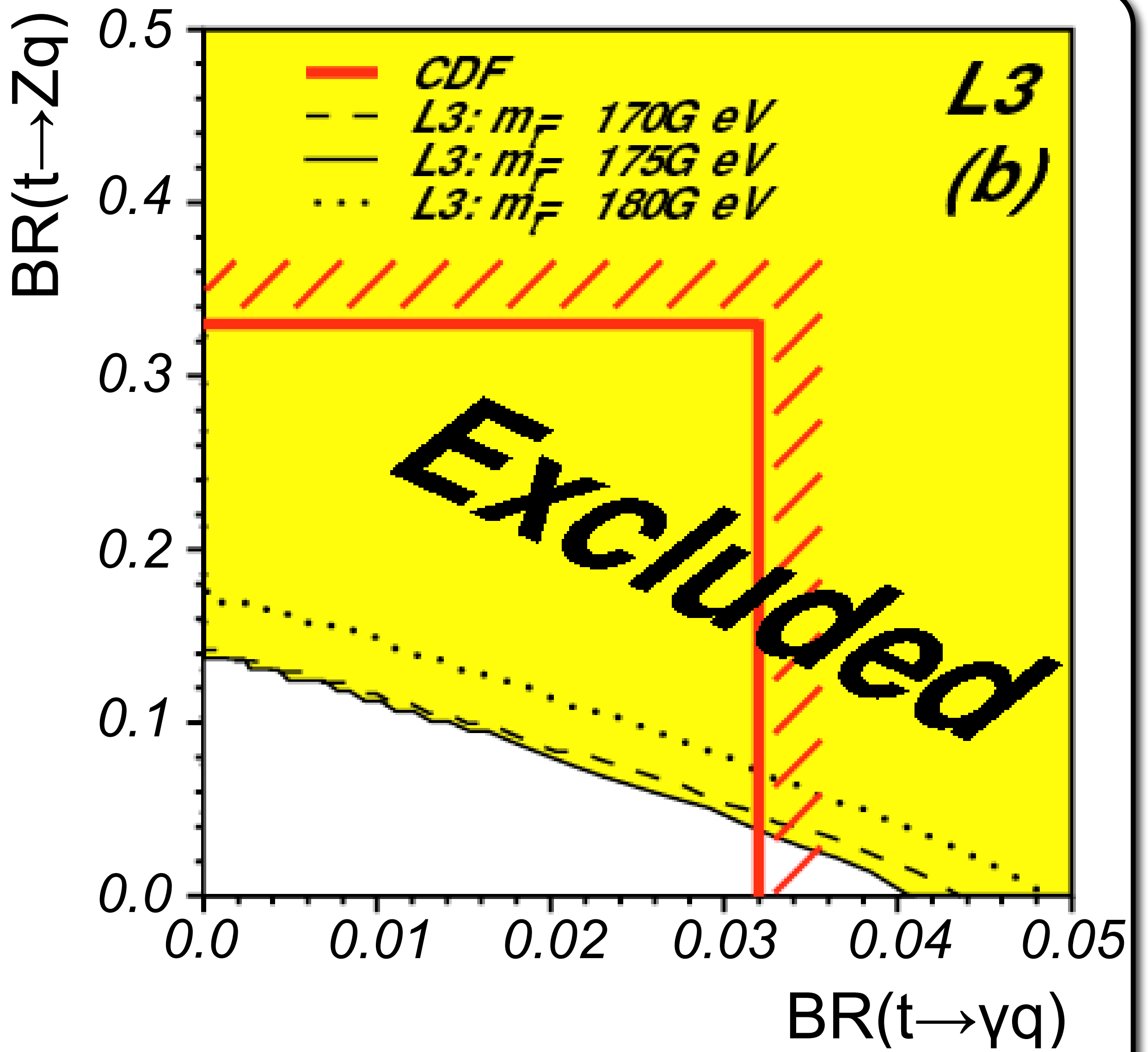
- CDF Run I search:
  F. Abe *et al.*, PRL **80** (1998) 2525.
  - Signature: $Z \rightarrow l^+ l^-$ + 4 jets (1 b-jet)
  - Limit on BR($t \rightarrow Zq$): 33%
- LEP searches:
  P. Achard *et al.* (L3), Phys. Lett. **B549** (2002) 290.
  G. Abbiendi *et al.* (Opal), Phys. Lett. **B521** (2001) 181.
  J. Abdallah *et al.* (Delphi), Phys. Lett. **B590** (2004) 21.
  A. Heister *et al.* (Aleph), Phys. Lett. **B453** (2002) 173.
  - Hadronic top decay (4 jets) or semileptonic top decay (2 jets & lepton)
  - 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.
  - Hadronic top decay (3 jets) or semileptonic top decay (lepton & jet)
  - Most sensitive to tγq vertex, preference for u over c quarks (proton sea)

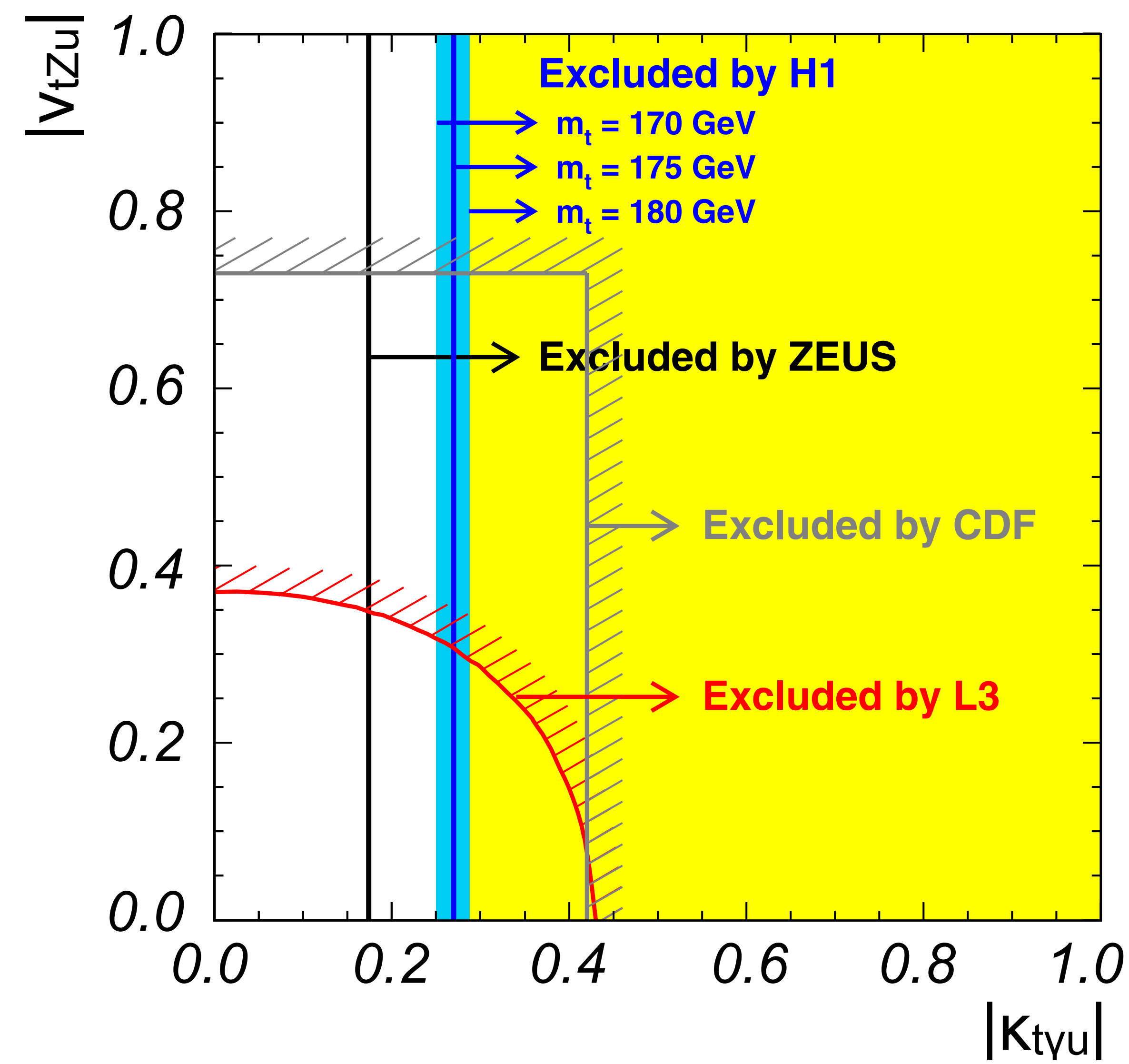






Best Limits 2006

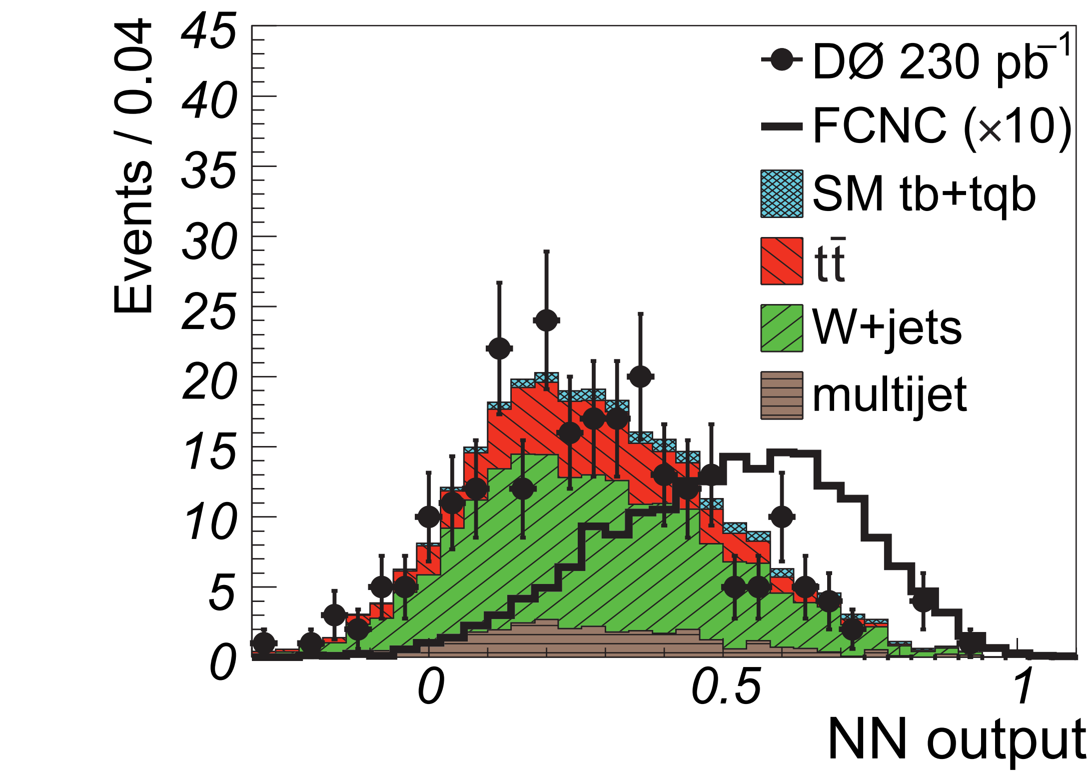


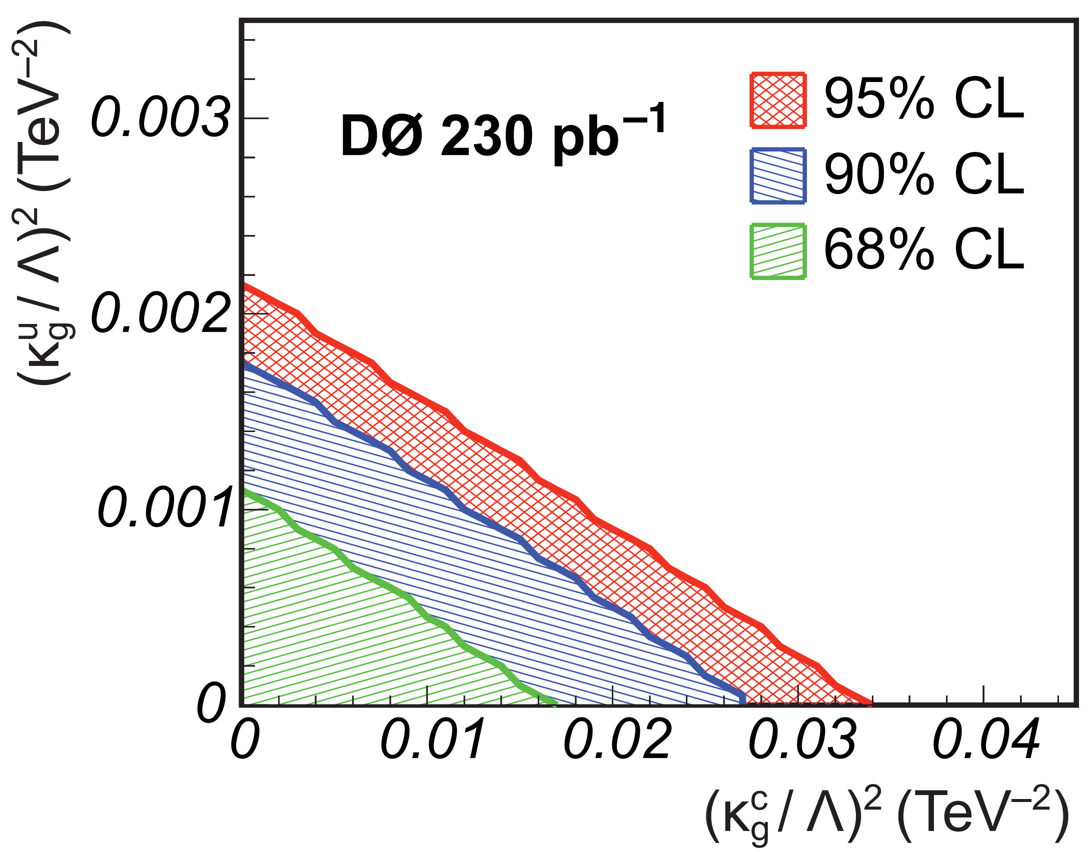


The H1 result caused some excitement:

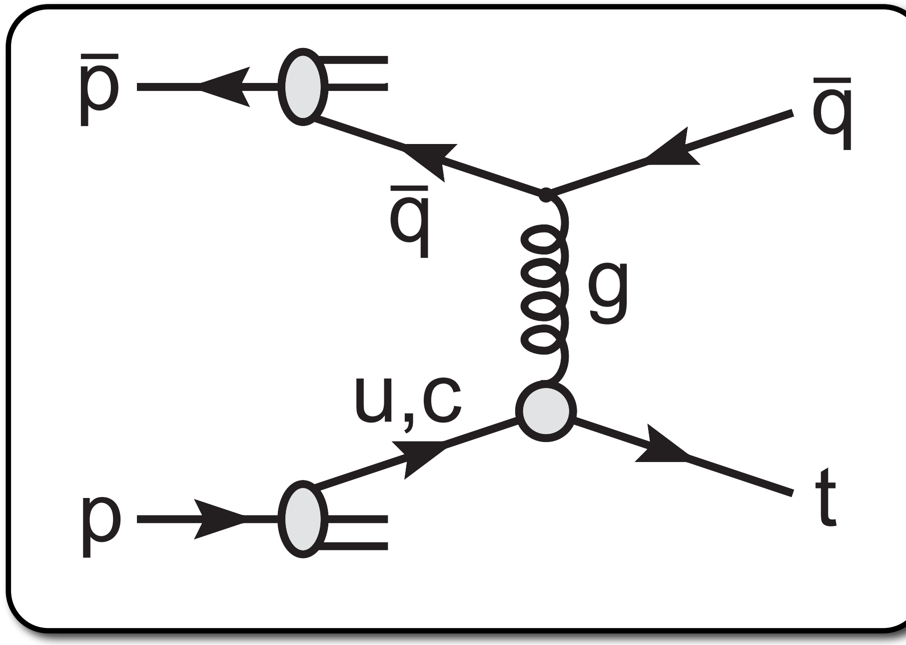
Abstract. [...] In the leptonic channel, 5 events are found while 1.31 ± 0.22 events are expected from the Standard Model background. In the hadronic channel, no excess above the expectation for Standard Model processes is found. [...]

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 t-c-g and t-u-g couplings $(\kappa/\Lambda)^2$ → 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.*, hep-ex/0702005, submitted to PRL]

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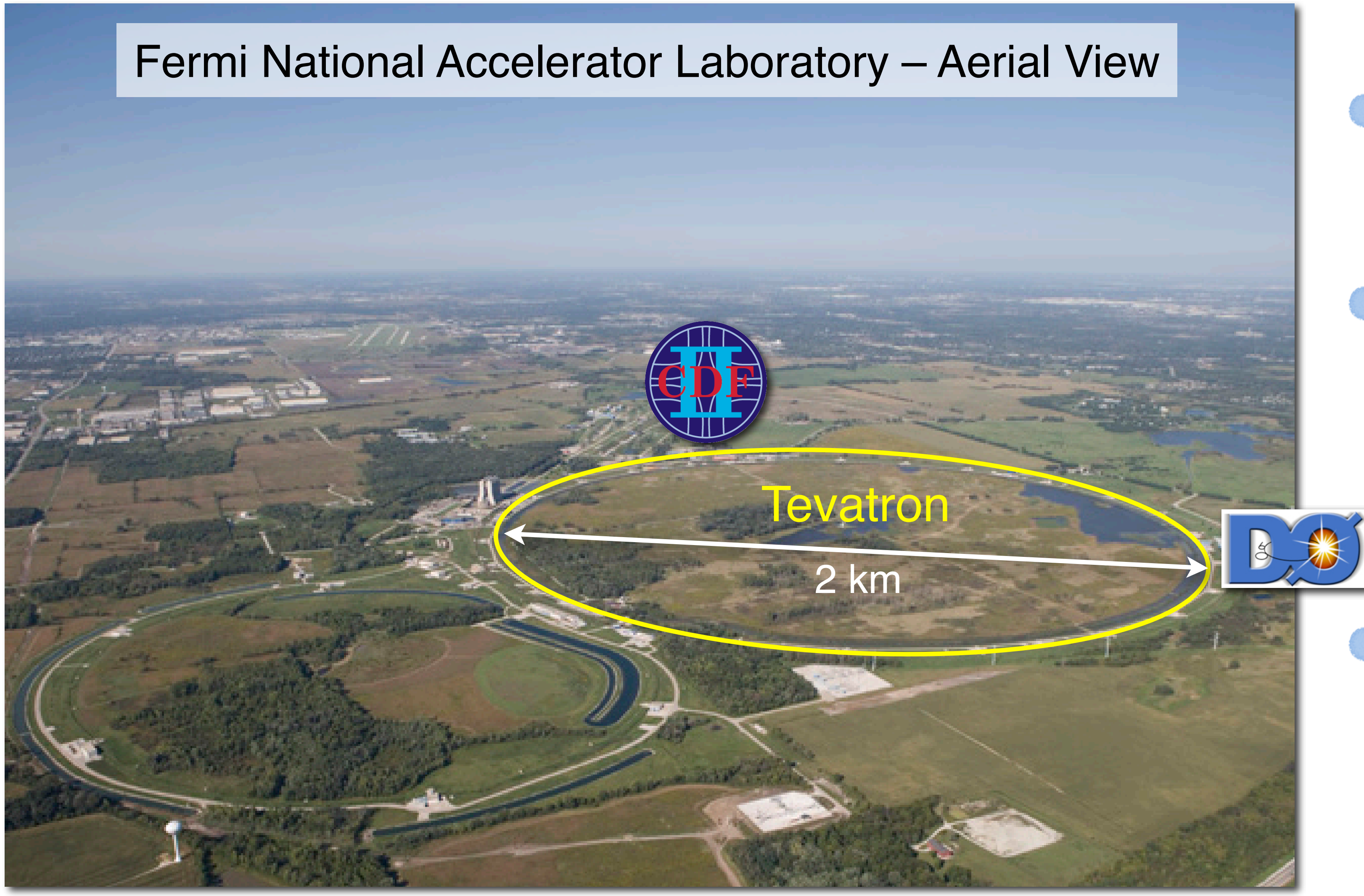
Tevatron Run II: 2001–2009 (2010?)

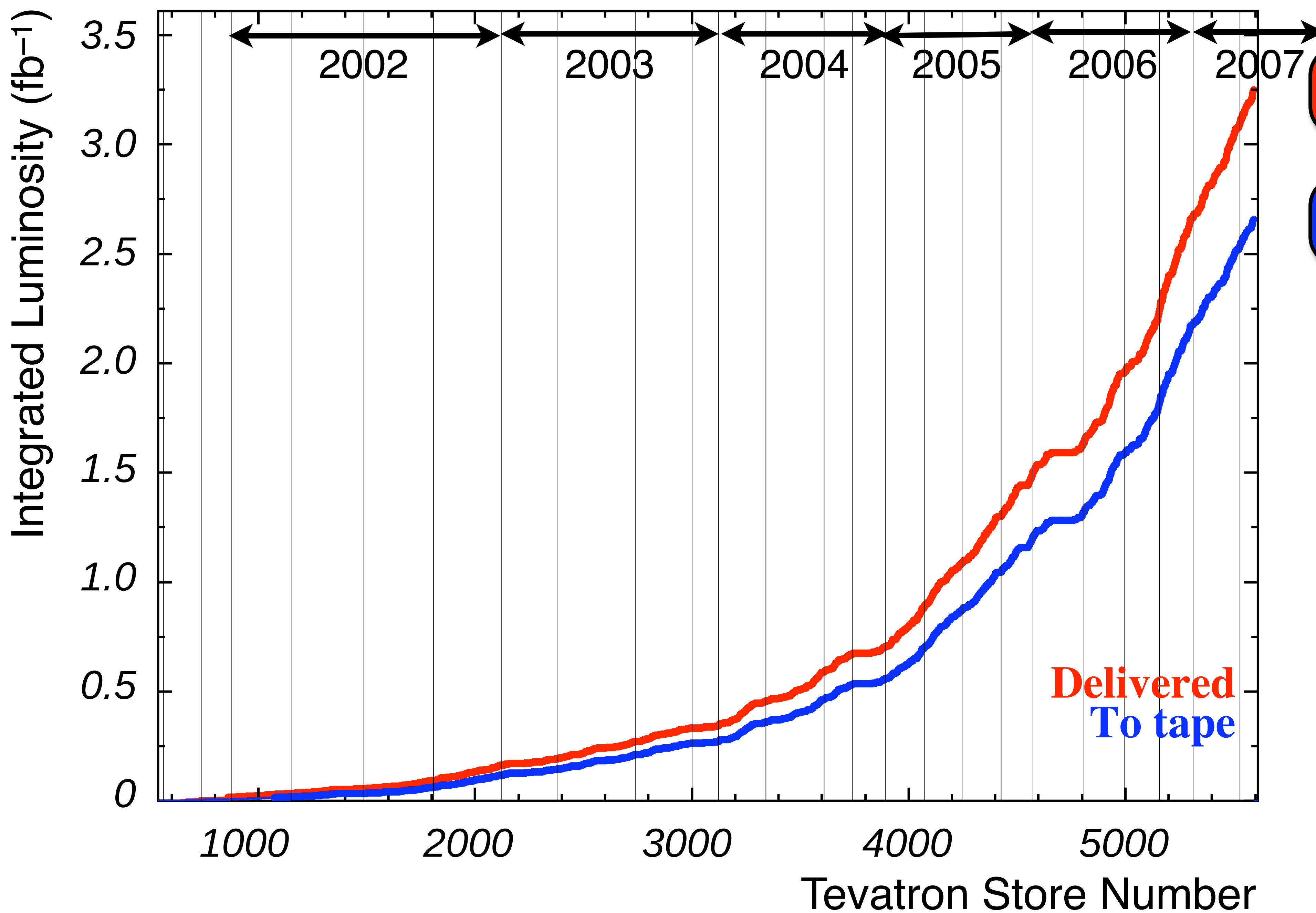


[Fermilab Visual Media Service]

- Proton-antiproton collider: $\sqrt{s}$ = 1.96 TeV
- 36×36 bunches, collisions every 396 ns
- Record instantaneous peak luminosity: 292 $\mu b^{-1} s^{-1}$ ($1\ \mu b^{-1} s^{-1} = 10^{30}\ cm^{-2} s^{-1}$)
- Luminosity goal: 5.5–6.5 fb^{-1} of integrated luminosity by 2009, running in 2010 currently under discussion
- Two multi-purpose detectors: CDF and DØ

Tevatron Performance

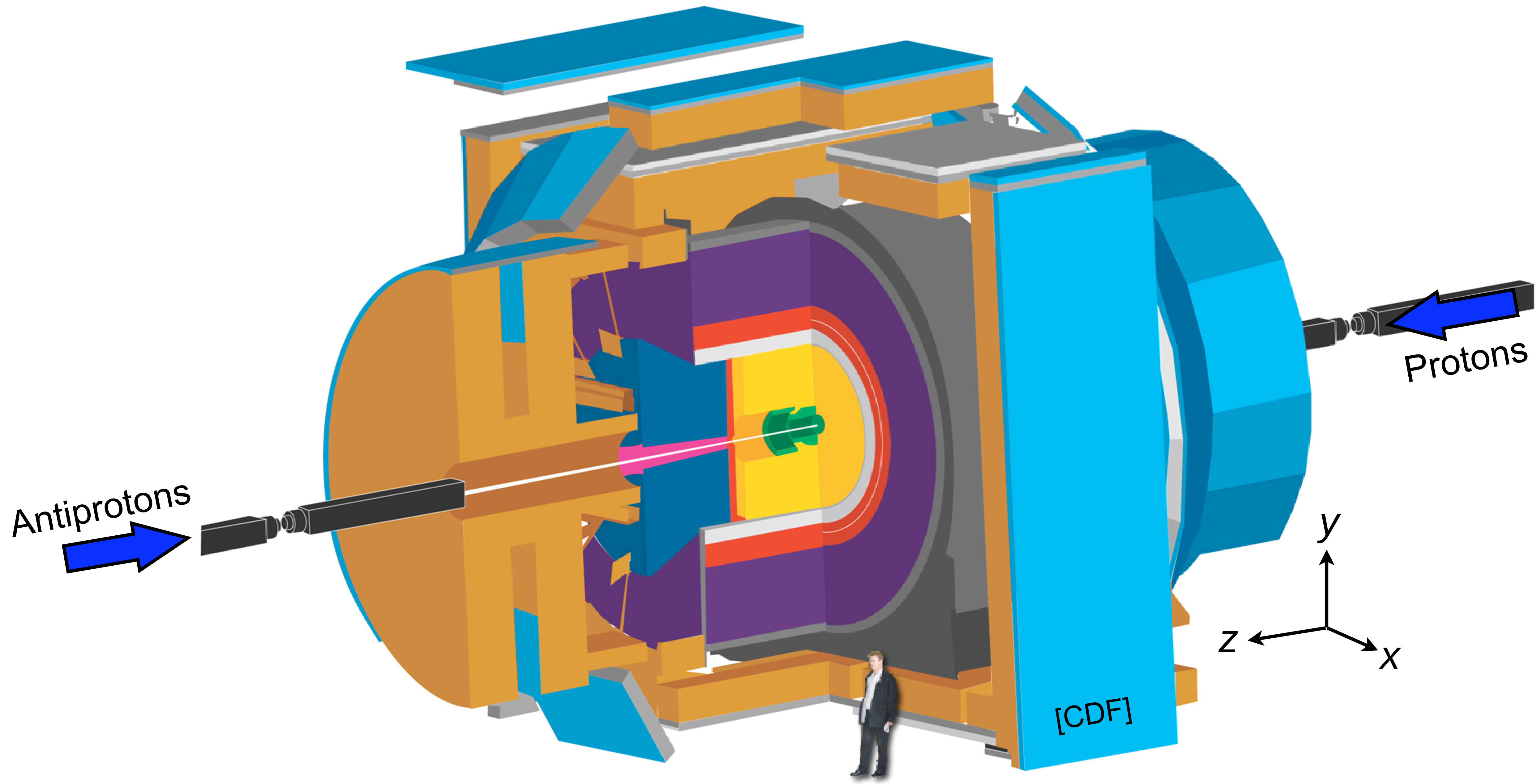
- Tevatron continues to perform very well:
  - More than 3 fb^{-1} delivered up to Summer 2007 shutdown
  - More than 2.5 fb^{-1} recorded by CDF



3.25 fb^{-1}

2.66 fb^{-1}

The CDF II Detector



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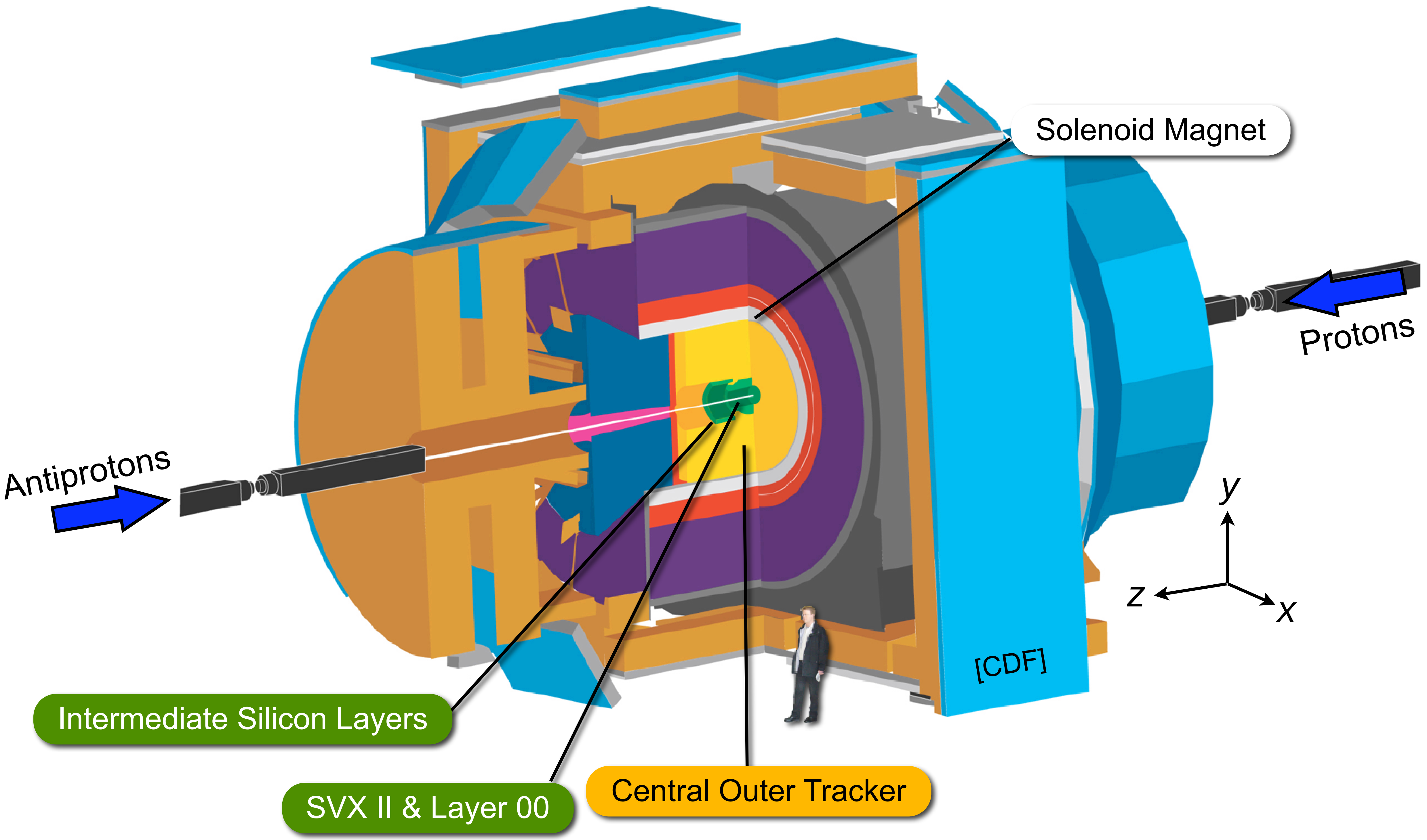

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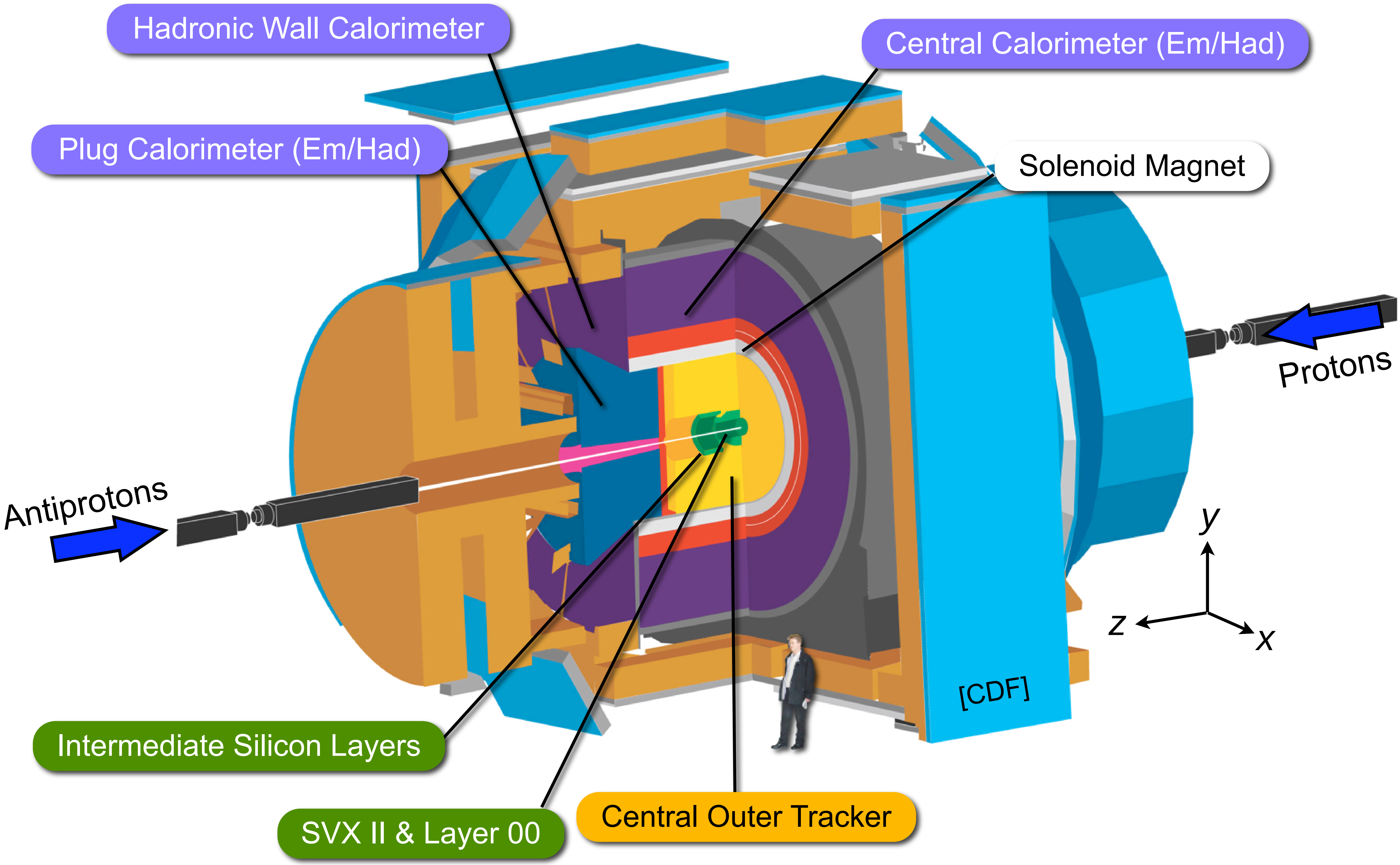

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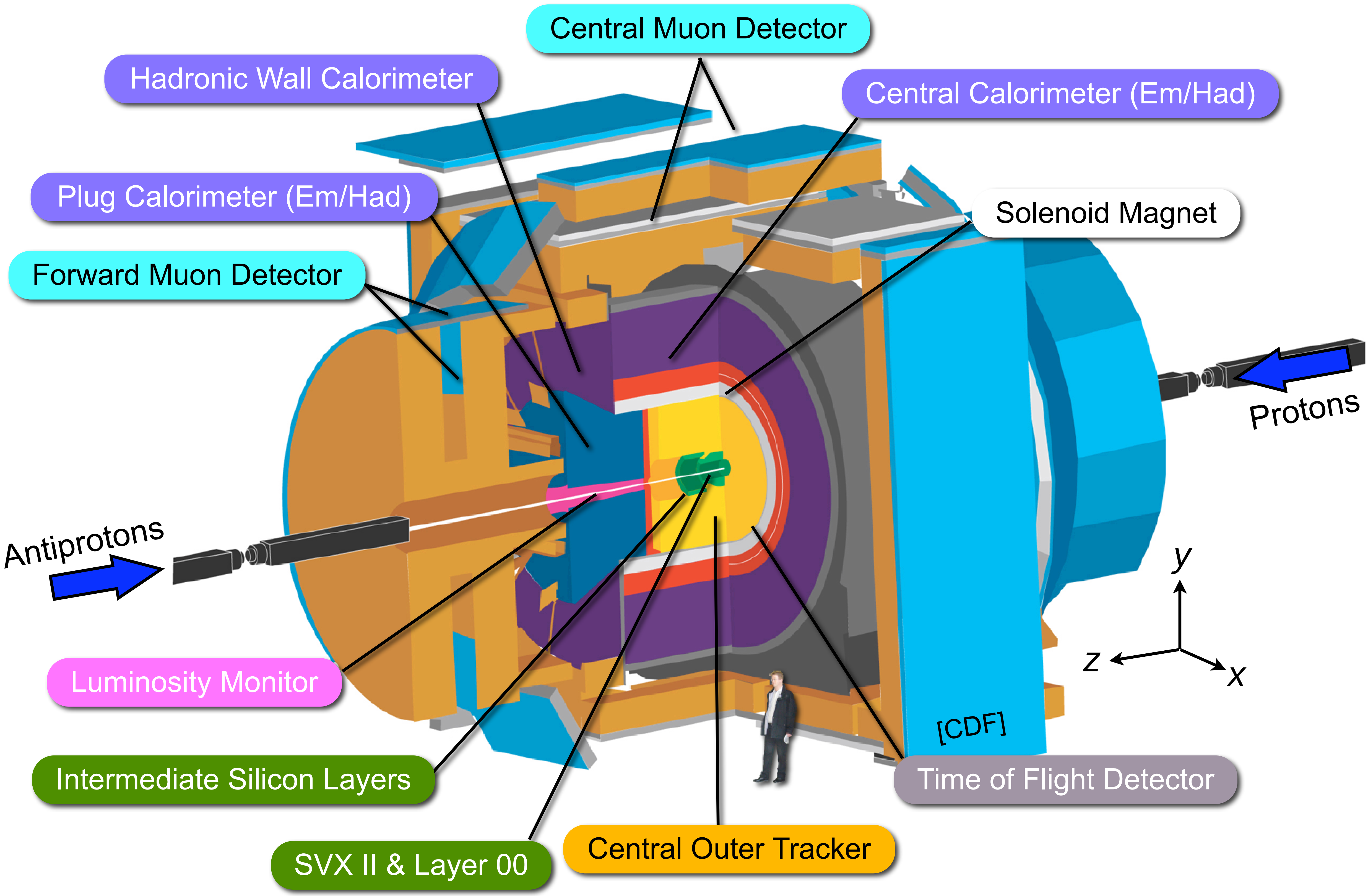
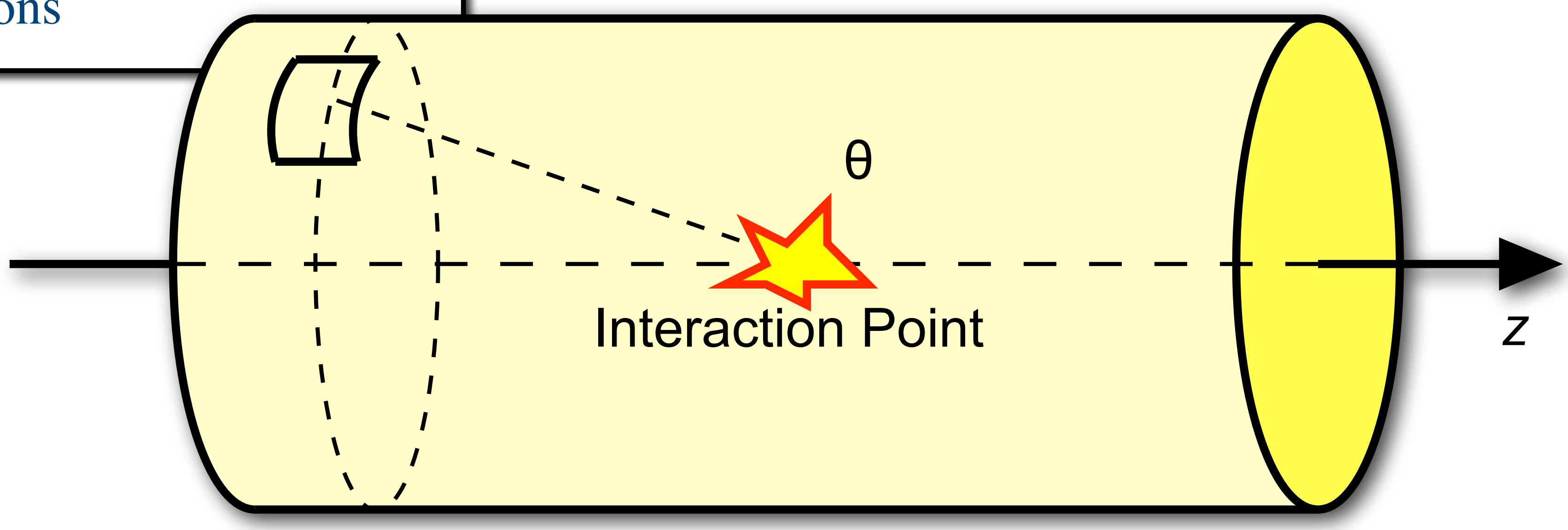


Hadron Collider Kinematics

- 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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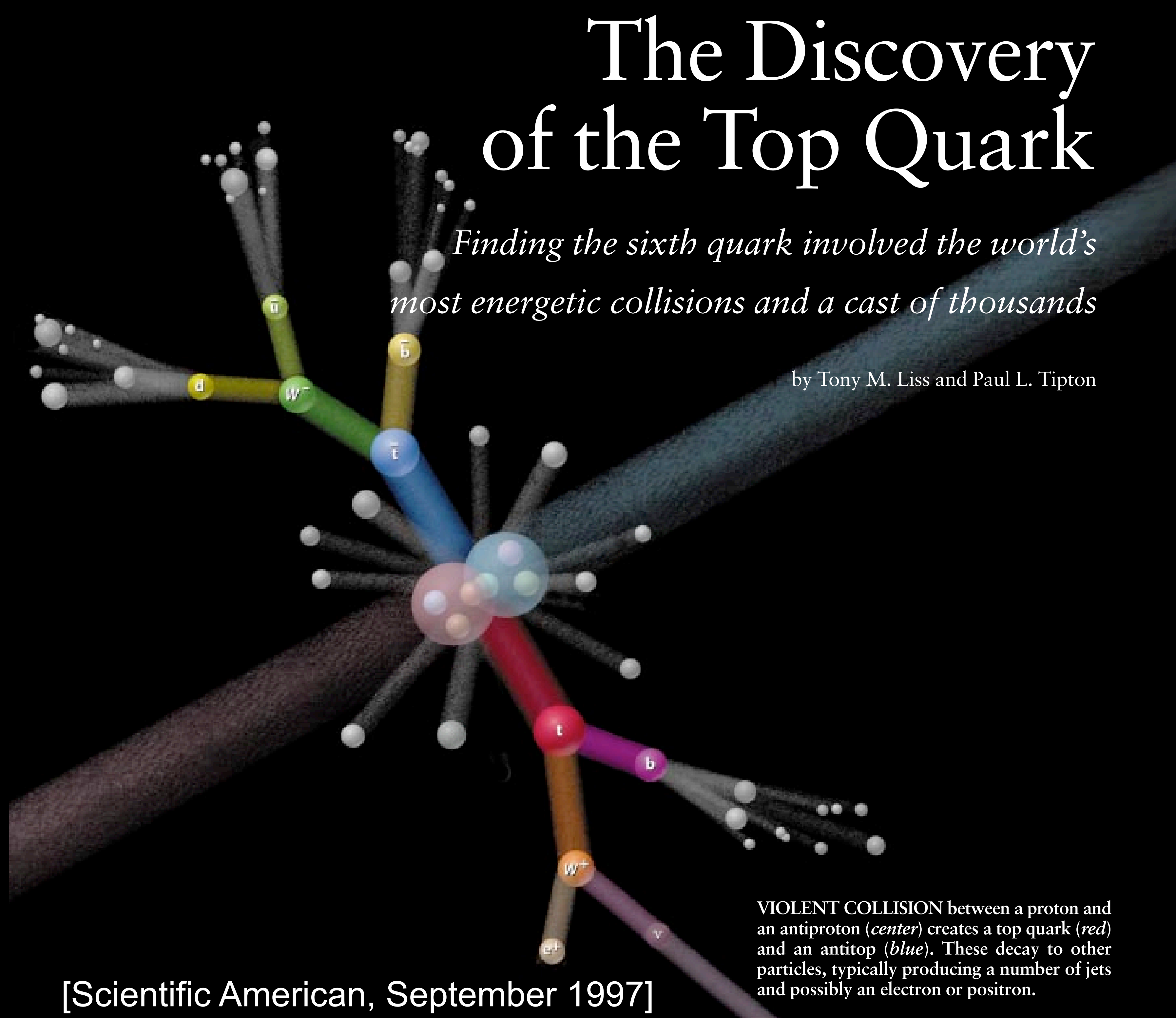
Brief history of top quark discovery:

- 1977: Υ discovery – bottom quark
- 1980s: Searches for “light” top (mass smaller than W boson mass) as 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 $f \approx 1$:

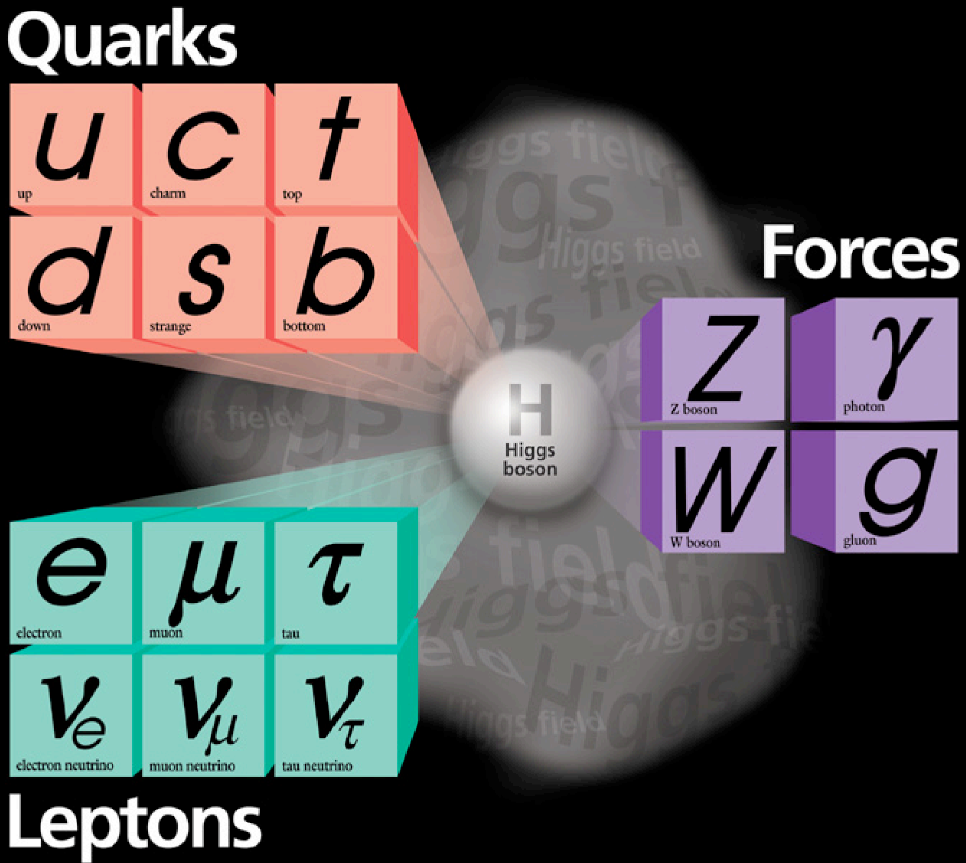
$$\mathscr{L}_{\mathrm{Yuk},t} = f \frac{v}{\sqrt{2}} \bar{t}_L t_R \equiv m_t \bar{t}_L t_R$$

(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

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

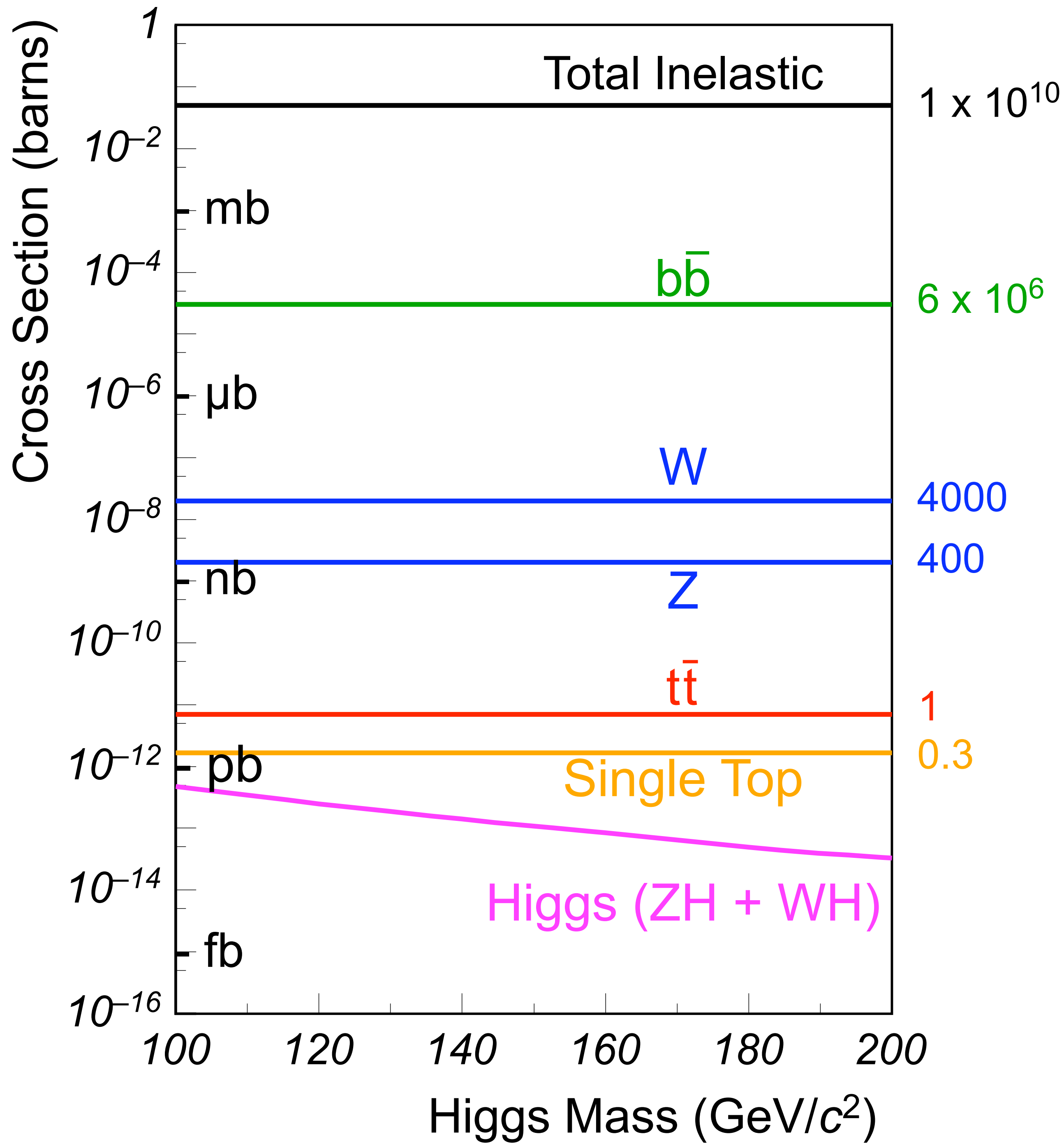
→ No spectroscopy of bound states
→ Spin transferred to decay products



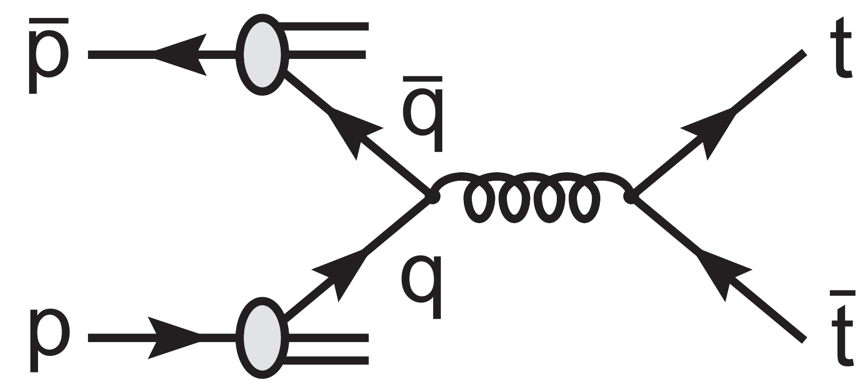
[Fermilab Visual Media Services]

Top Pair Production at the Tevatron

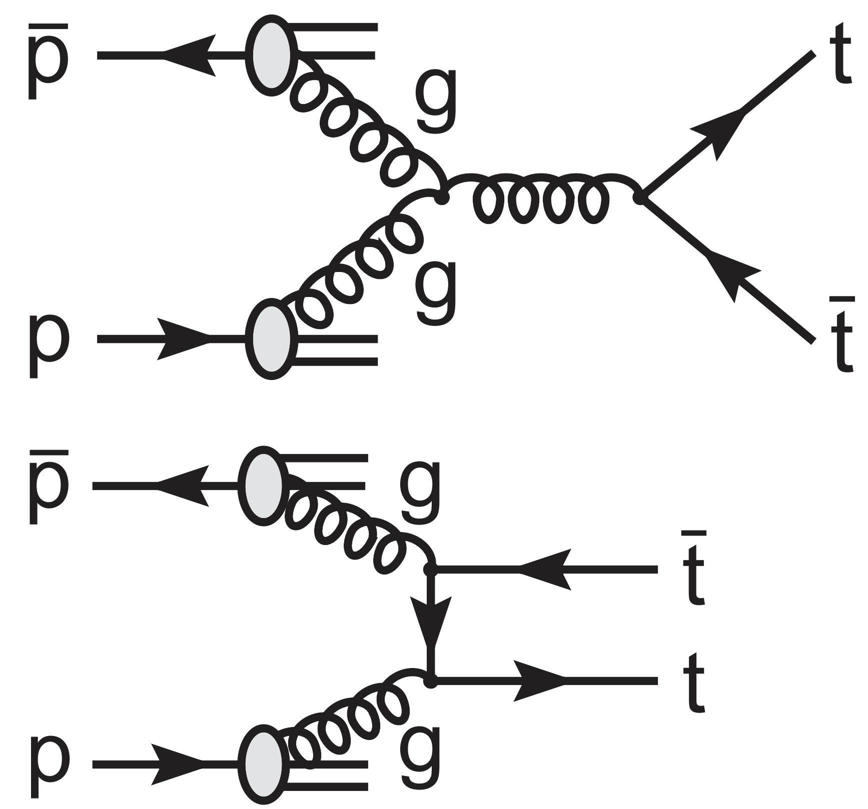
Top production is rare: one top quark pair produced every 10 billion collisions



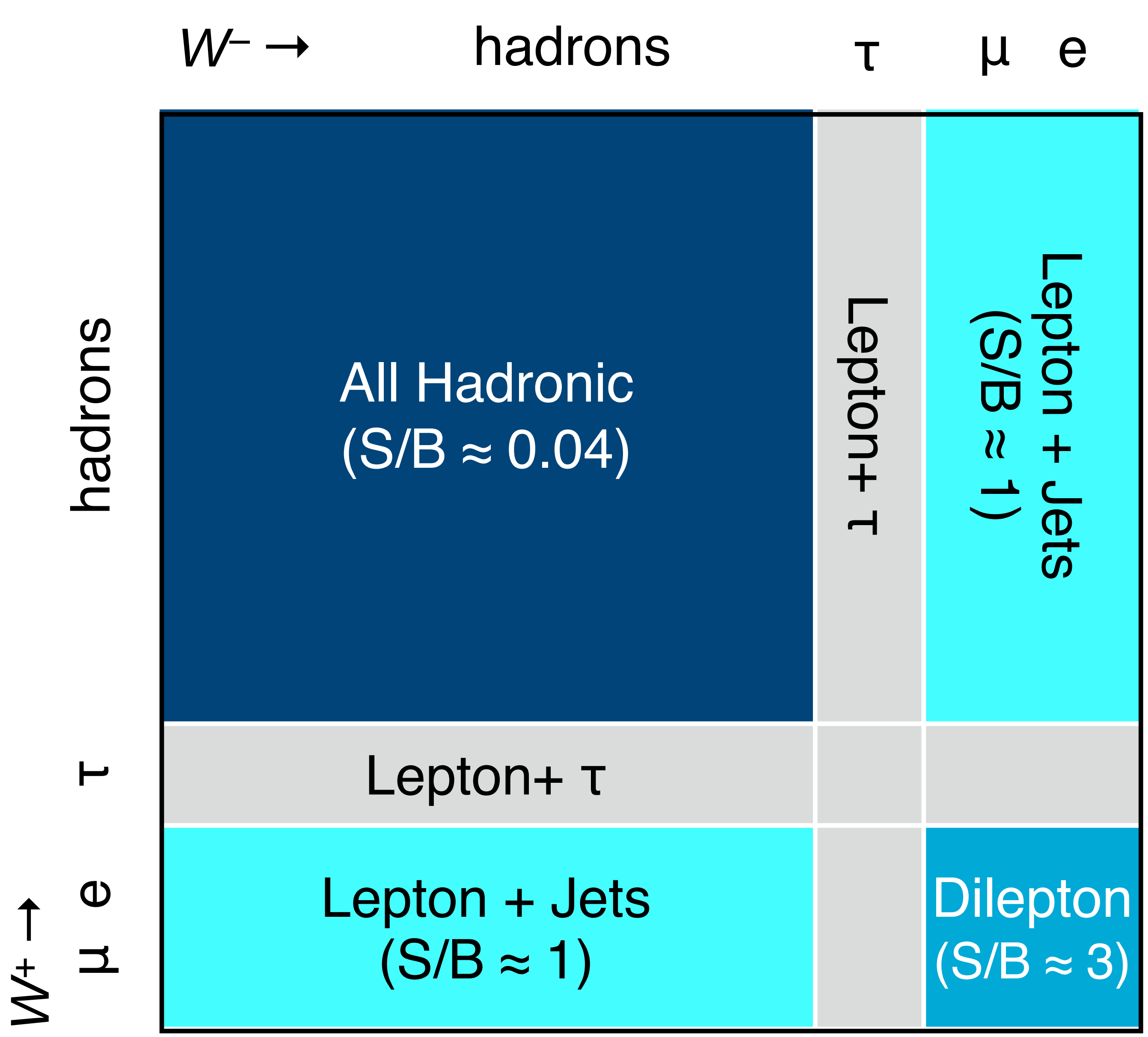
85% $q\bar{q} \rightarrow t\bar{t}$:



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



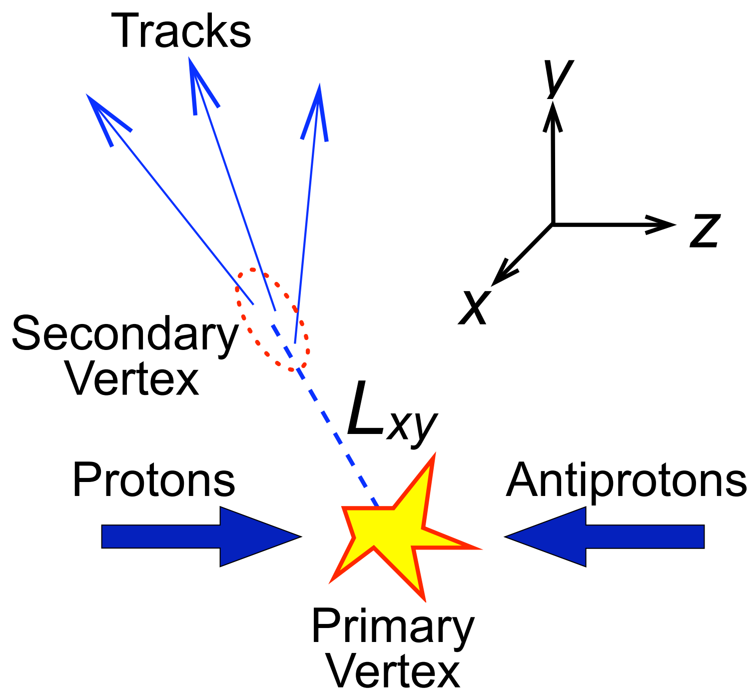
Analyzing Top Quark Events



- Top decay in the Standard Model: $t \rightarrow Wb$ (BR ≈ 100%)
- $t\bar{t}$ decay signatures characterized by W decays:
  - All-Hadronic (45% of all decays)
  - Lepton+Jets (30% of all decays)
  - Dilepton (5% of all decays)
- Main background process: production of W bosons in association with Jets
- $t\bar{t}$ events contain two b quarks: b quark identification ("b-tagging") crucial

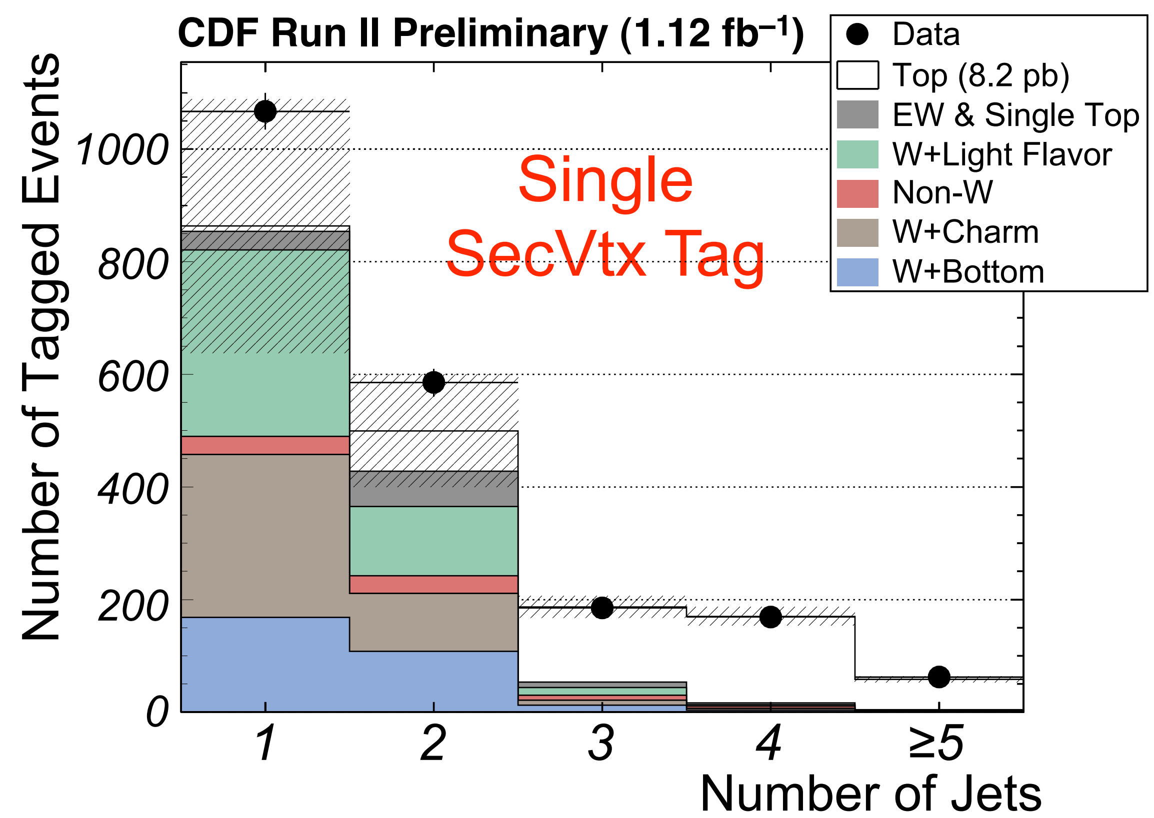
Top Pair Production Cross Section

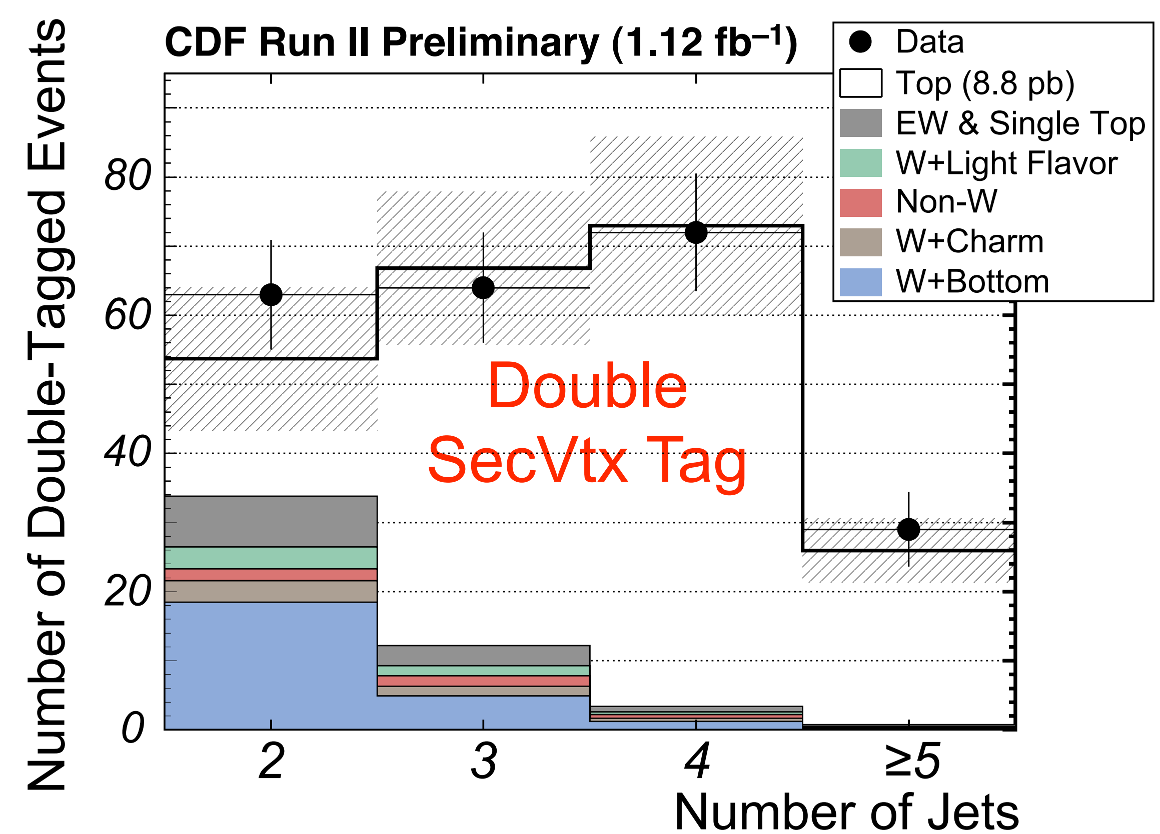
- SecVtx b-tagging algorithm: based on significance of 2D impact parameter



- CDF's single most precise top cross section measurement: Lepton + Jets channel with SecVtx b-tags
- Results (CDF Public Note 8795)

Single B-Tag	**σ_{tt} = 8.2 ± 0.5 (stat) ± 0.8 (syst) ± 0.5 (lum) pb**
Double B-Tag	**σ_{tt} = 8.8 ± 0.8 (stat) ± 1.2 (syst) ± 0.5 (lum) pb**



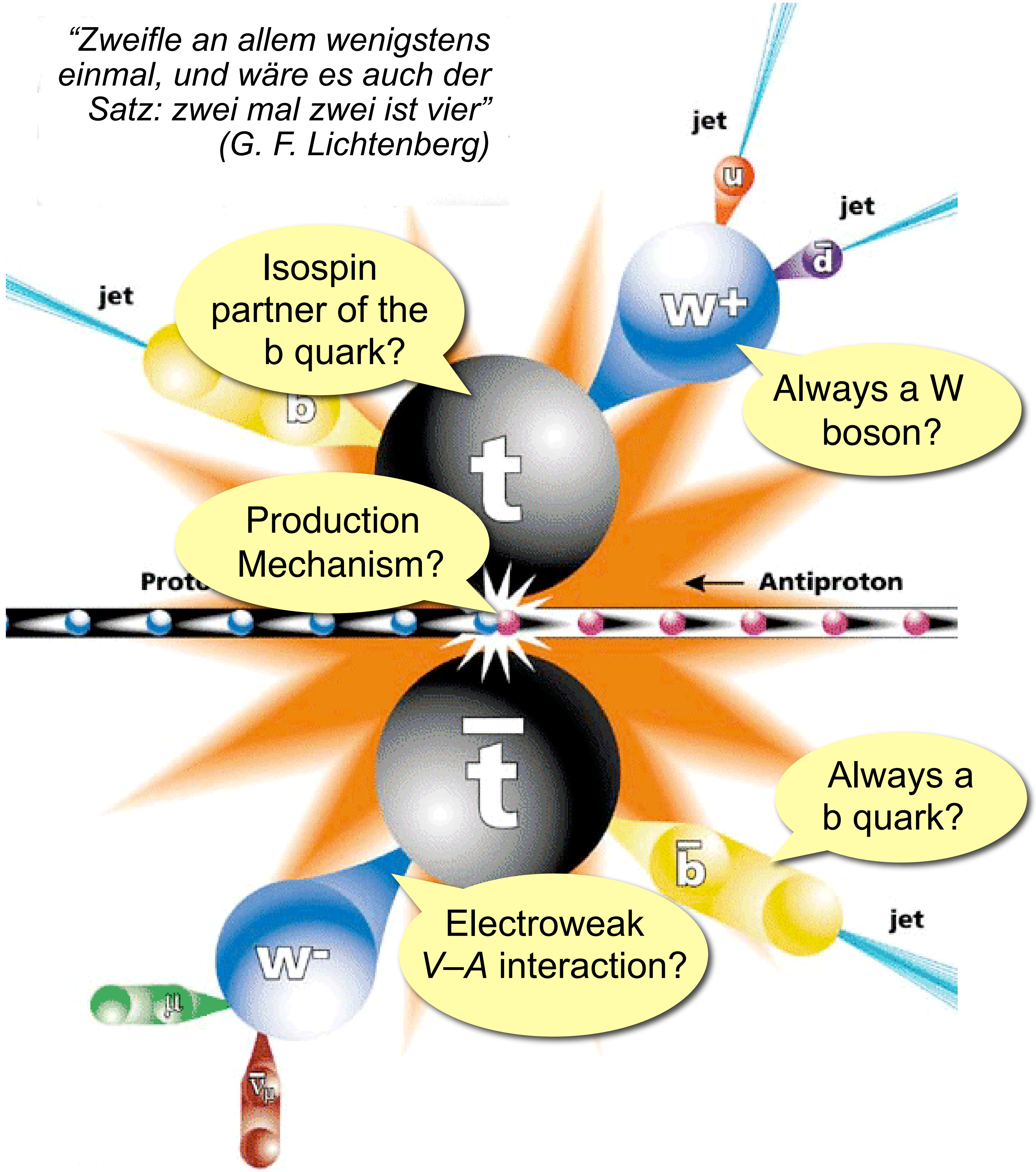


CDF's Top Properties Program

- From top discovery in 1995 to precision physics in 2007:
  - Dataset: 1000s of top events
  - Mass & cross section very precisely measured
  - Evidence for single top production
- Broad program to study properties of the top quark: production, decay, quantum numbers, …
- 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)



Outline of the Talk

What are Flavor Changing Neutral Currents?

The CDF Experiment at the Tevatron

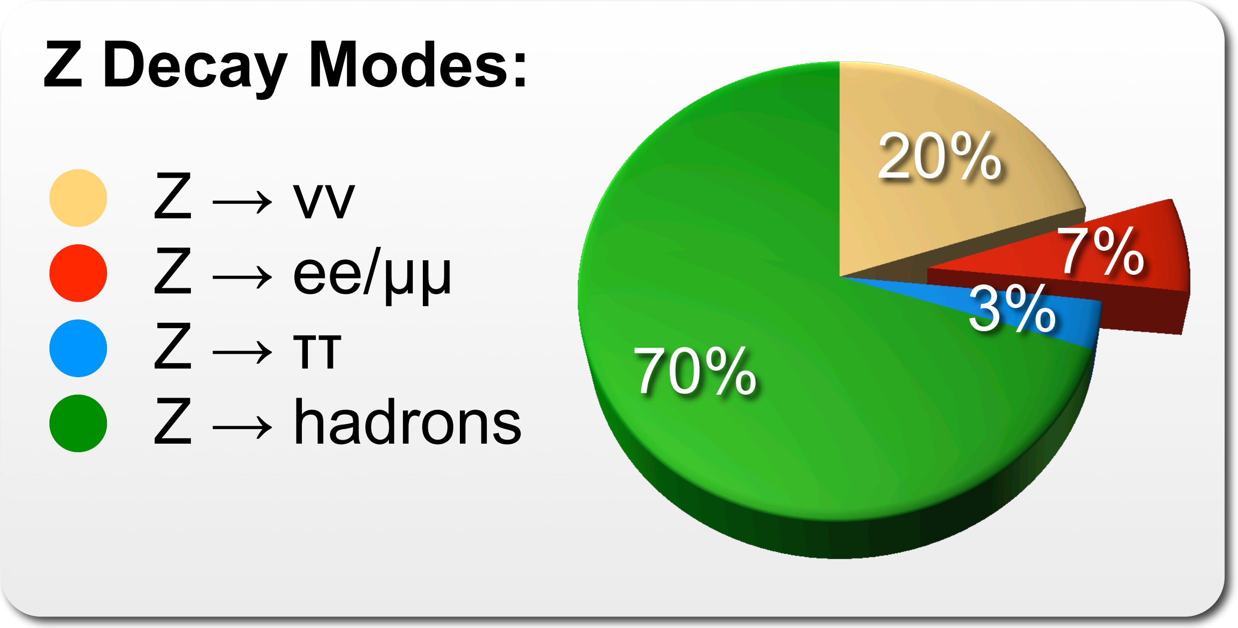
Top Quark Physics at CDF

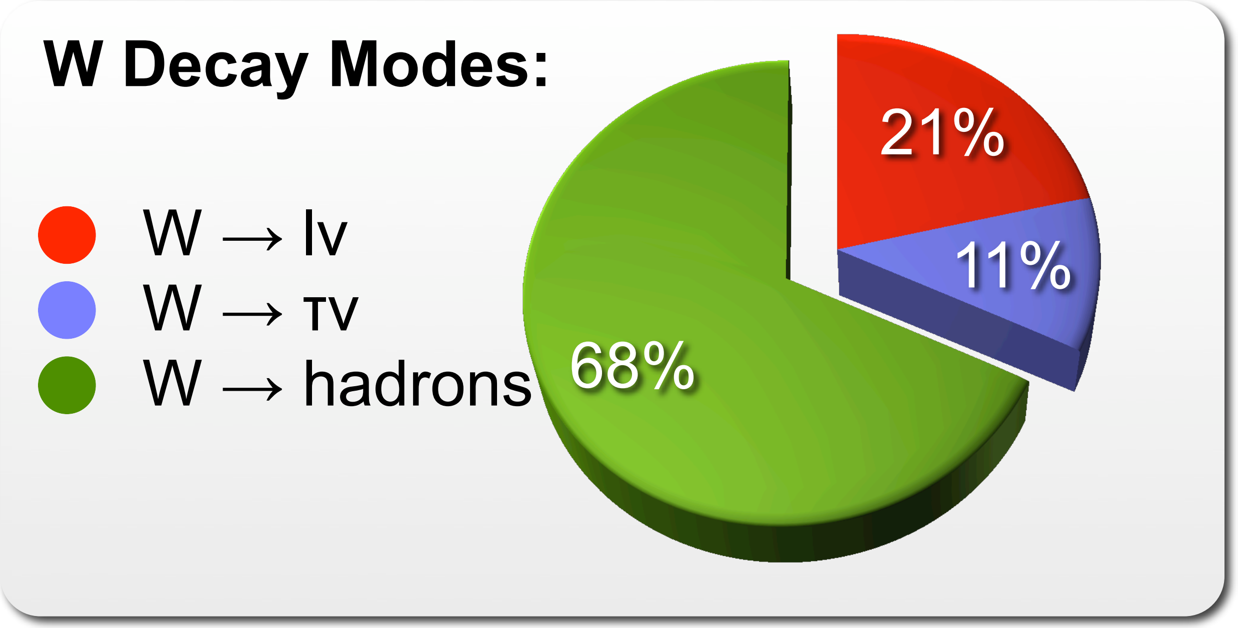
Search for FCNC in Top Quark Decays

Summary & Conclusions

Top FCNC Search: Roadmap

- Basic question: how often do top quarks decay into Zq?
  → set limit on branching fraction BR(t → Zq)
- Selection of decay channels for $t\bar{t}$ → Zq Wb:
  - Z → charged leptons: very clean signature, lepton trigger
  - W → hadrons: large branching fractions, no neutrinos
    → event can by fully reconstructed
  - Final signature: Z + ≥4 jets
- Analysis Outline:
  I. Baseline Event Selection
  II. Initial Background Estimate
  III. Optimization of Event Selection
  IV. Systematic Uncertainties
  V. Final Limit Calculation



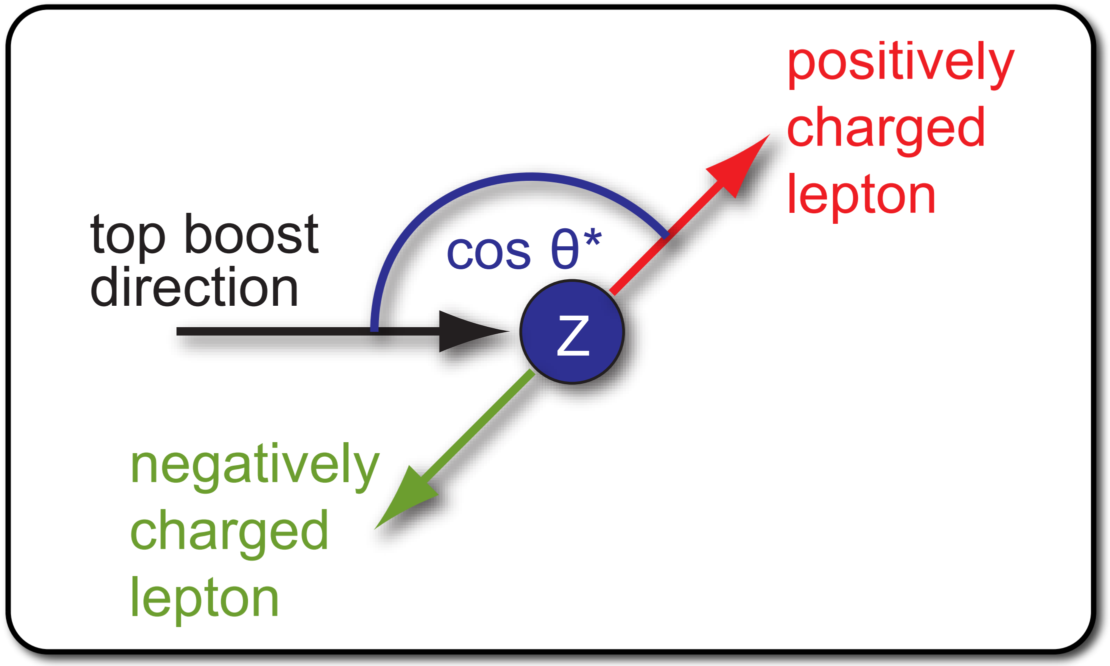


Blind Analysis

- Event signature: $Z \rightarrow l^+ l^- + 4$ jets
- Motivation for blind analysis: avoid biases by looking into the data too early
- Blinding & unblinding strategy:
  - Initial blinded region: $Z + \geq 4$ jets
  - Later: add control region in $Z + \geq 4$ jets from kinematic constraints
  - Optimization of event selection, prediction of backgrounds, and systematic uncertainties on data control regions and Monte Carlo (MC) simulation only
  - Very last step: "opening the box", i.e. look into signal region in data

Simulation of FCNC Signal

- Monte Carlo (MC) simulation of FCNC decay $t \to Zq$ with PYTHIA
  - $t \to Zq$ vertex unknown to PYTHIA
  - Decay generated flat in $\cos\theta^*$ (angle between top boost direction and lepton of same charge sign from Z decay, in Z rest frame)



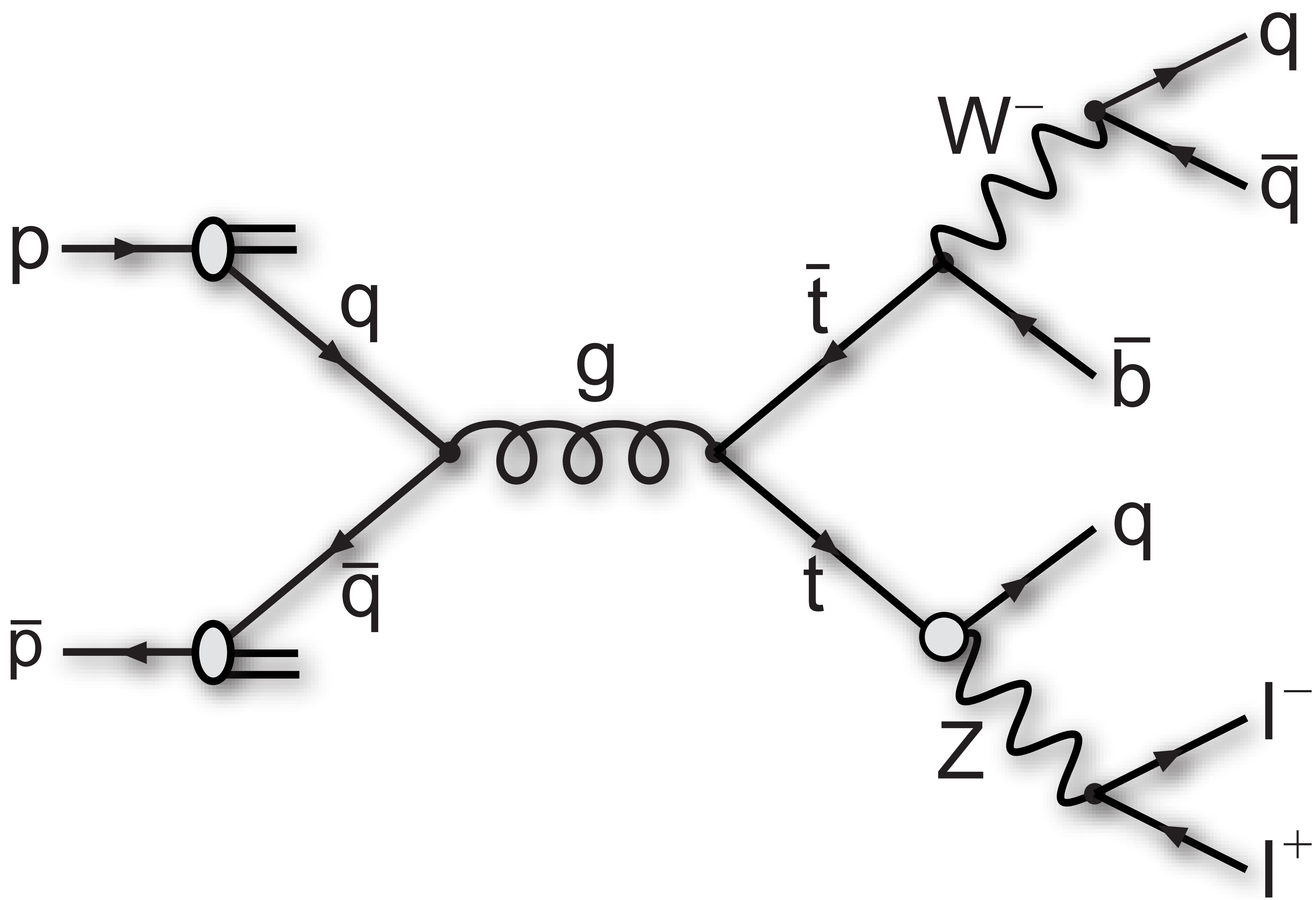
  - Solution: reweight according to expectation from standard model Higgs mechanism:

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

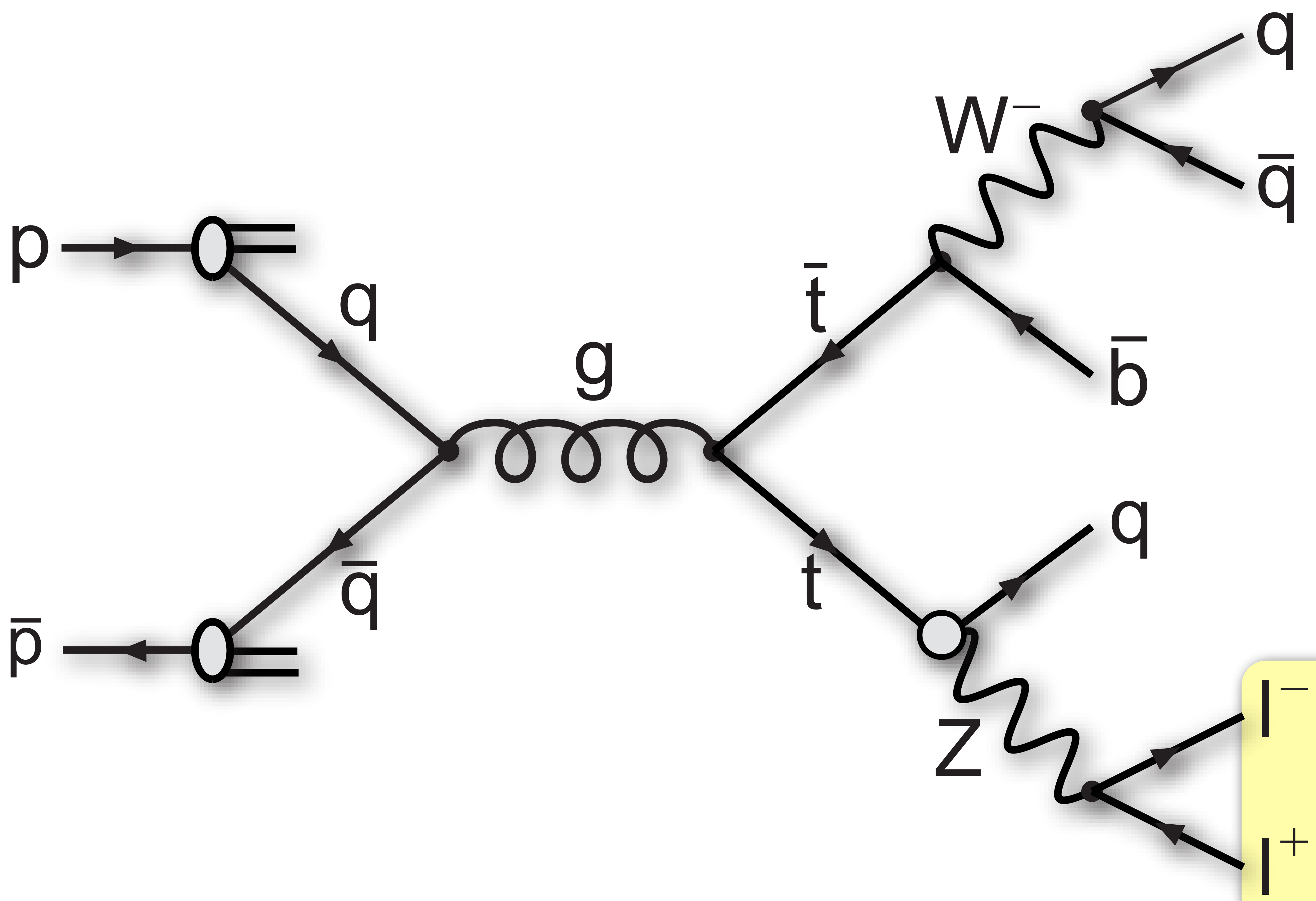
with $f^0 = 0.65$ (“longitudinal), $f^- = 0.35$(“left-handed”), $f^+ = 0$ (“right-handed”)

- Main FCNC signal sample: one top decays $t \to Zc$, other decays $t \to Wb$
  - Additional sample required for decay $t \to Zu$
  - Additional sample for “double FCNC” events, i.e. both tops decay via FCNC $t \to Zq$

Search for FCNC: Ingredients

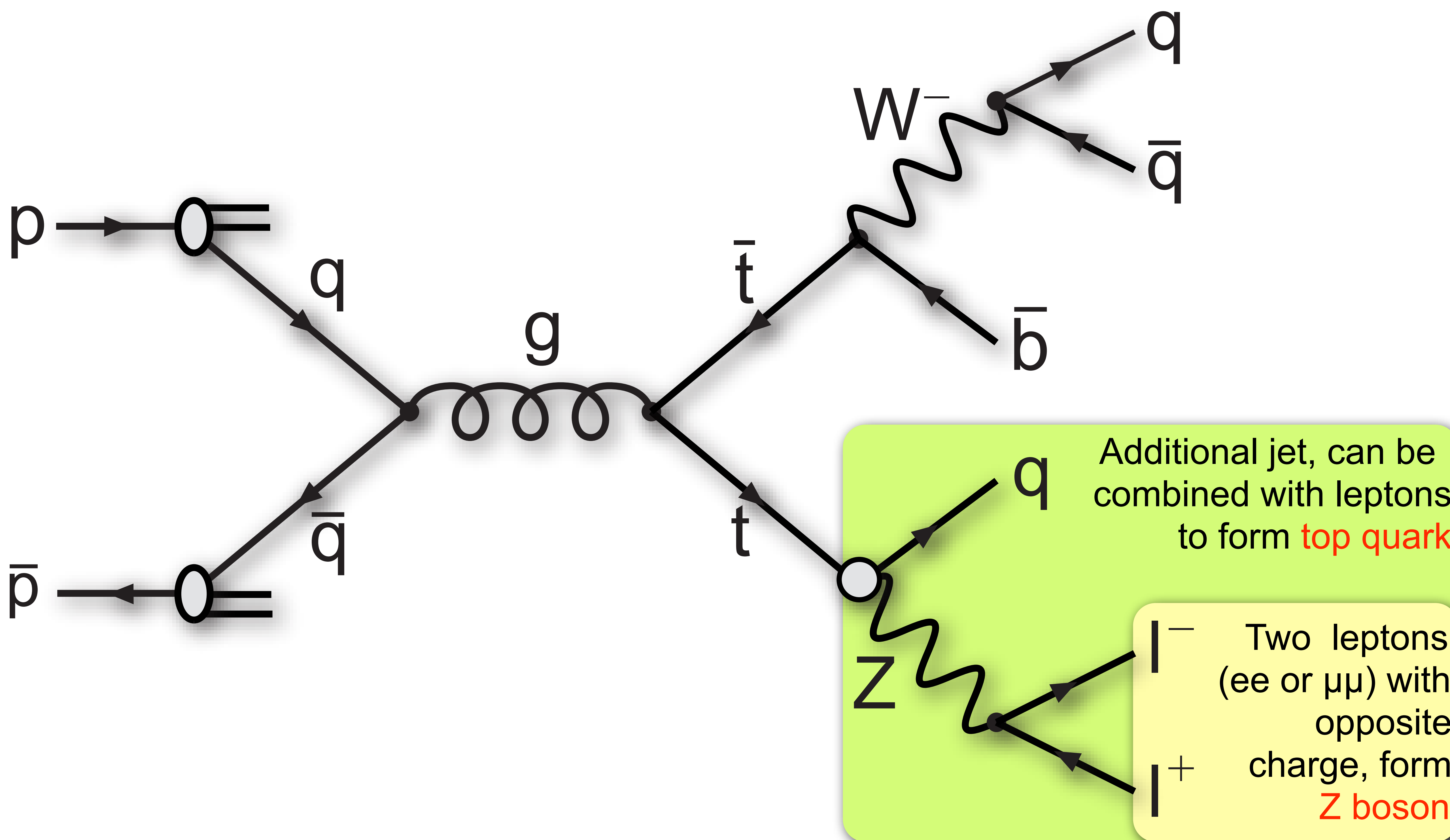


Search for FCNC: Ingredients



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

Search for FCNC: Ingredients



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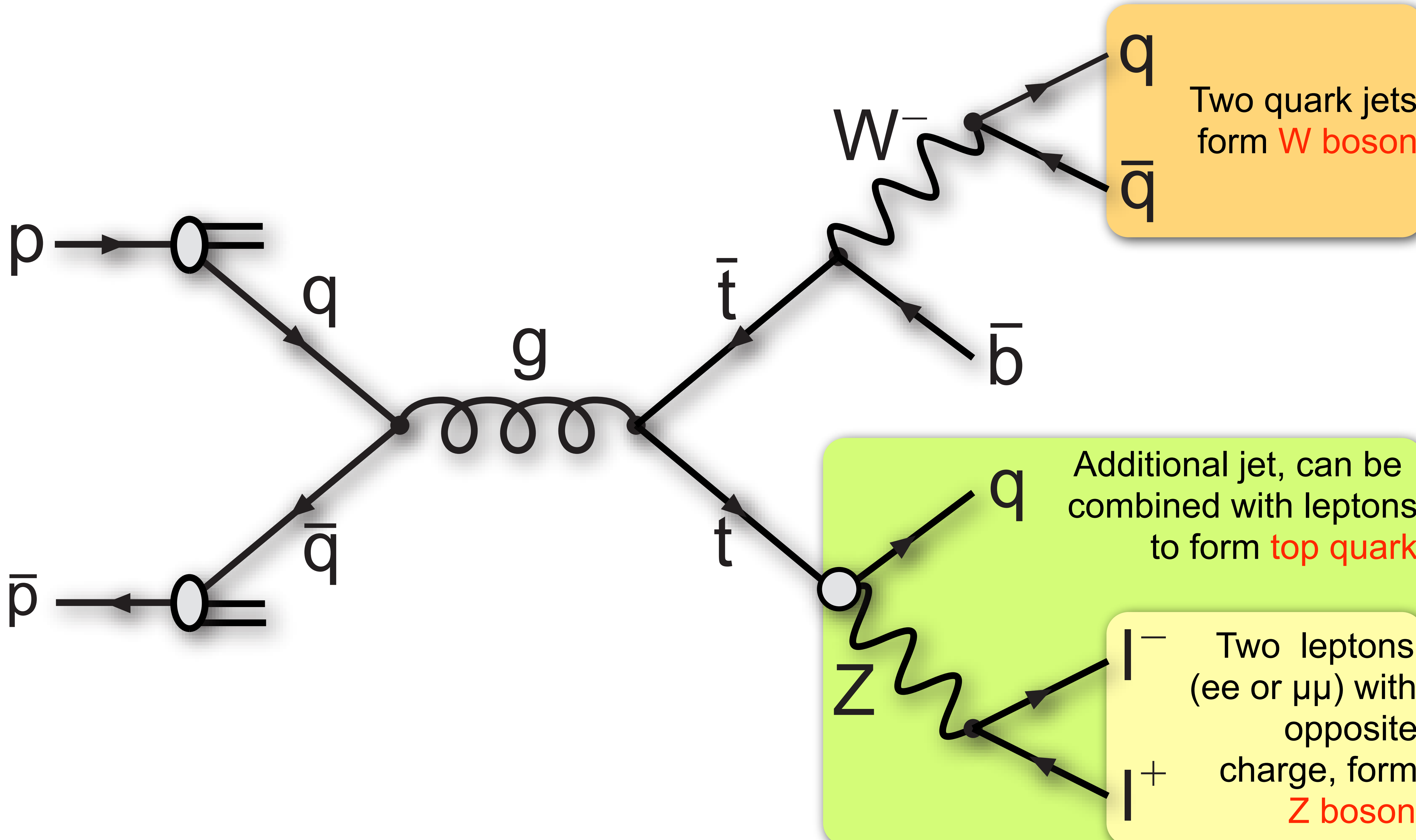

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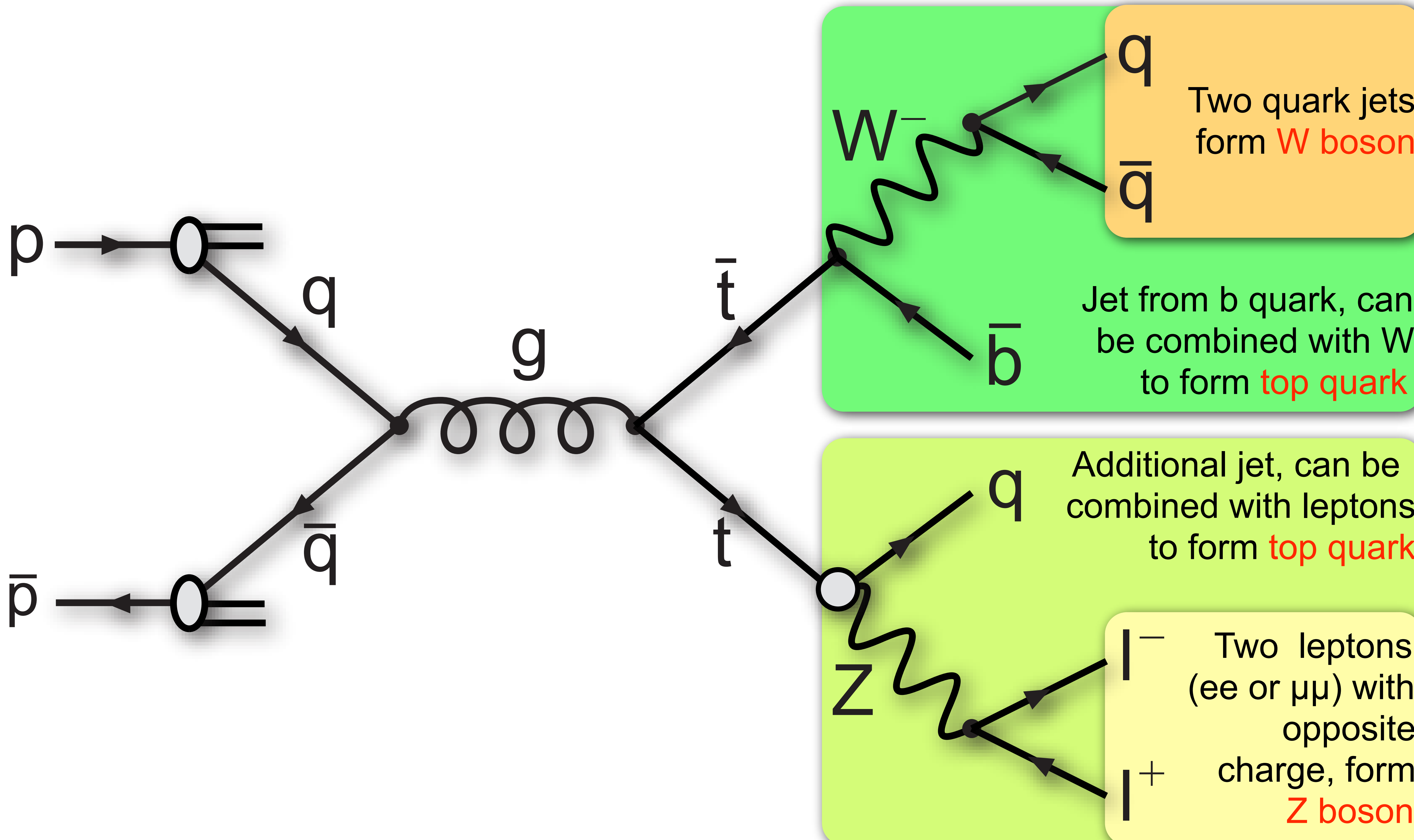
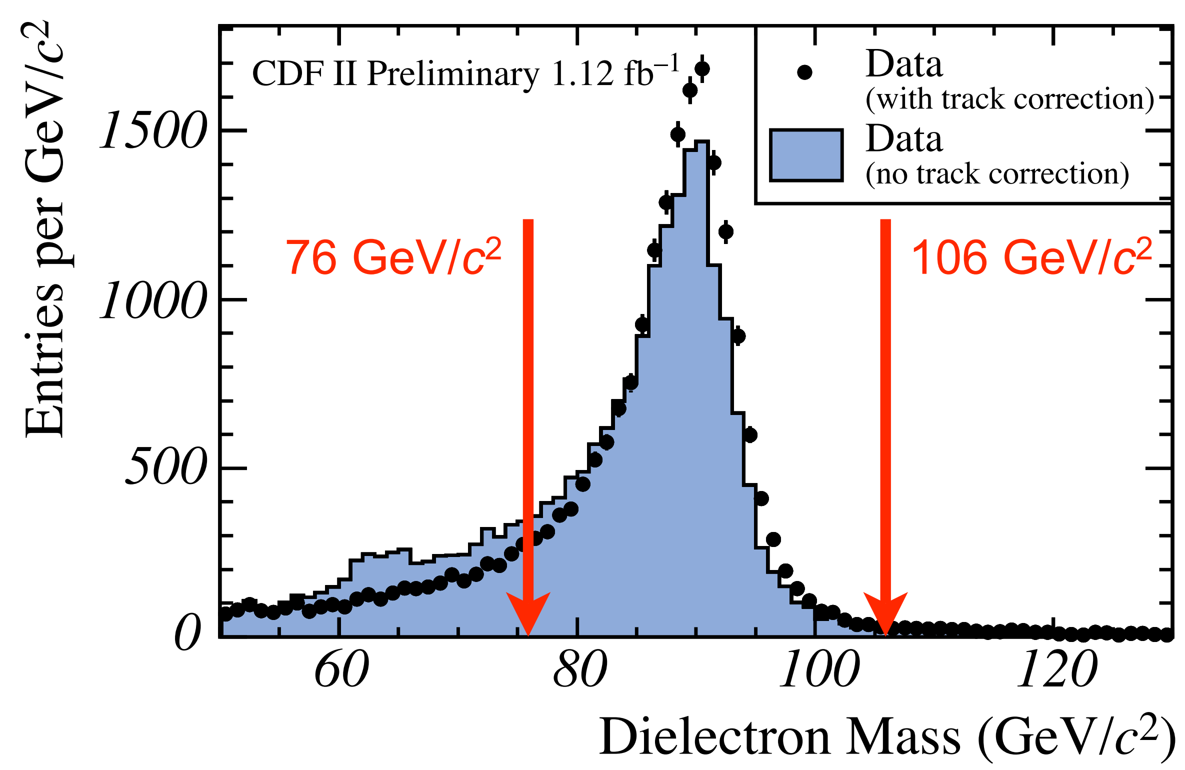


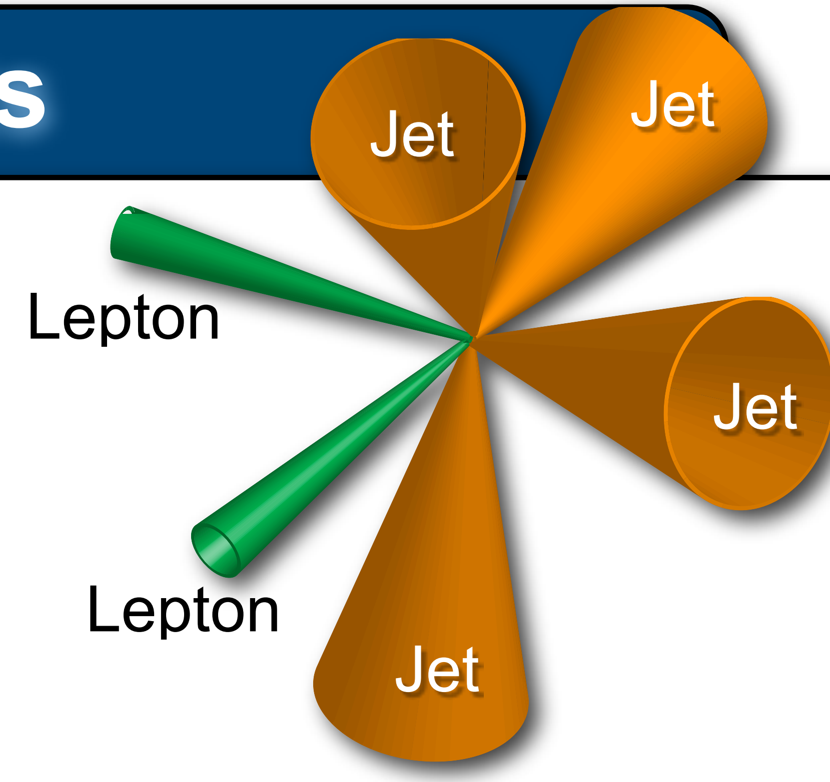
Z Boson Reconstruction

- Simple trigger: single electron or muon, transverse momentum >18 GeV/c
- Sharp Z resonance, good lepton momentum resolution
  → cut on lepton pair invariant mass: 76 GeV/c^2 < M_{ll} < 106 GeV/c^2
- Enhancing the Z acceptance:
  - Tracking systems have better coverage than calorimeter and muon detectors: allow second lepton to be isolated track
    → doubles acceptance w.r.t. standard lepton selection
  - Electron tracks lose momentum via bremsstrahlung: correct track momentum with calorimeter energy
    → 3% more dielectron pairs

Bremsstrahlung Recovery: Z → e track



Adding Jets



- FCNC: four jet assignments
  - 1 b-jet from $t \to Wb$ decay
  - 2 jets from subsequent W decay
  - 1 jet from $t \to Zq$ decay

- For all 12 possible combinations of first four jets in the event:
  1. Combine jets #1 and #2 to W, calculate invariant mass $m_{W,\mathrm{rec}}$
  2. Vary momenta of jets #1 and #2 within their resolutions to match PDG W mass ("fix W mass")
  3. Add jet #3 to fixed W, calculate invariant mass $m_{t\to Wb,\mathrm{rec}}$
  4. Vary momenta of leptons within their resolutions to match PDG Z mass ("fix Z mass")
  5. Add jet #4 to fixed Z, calculate invariant mass $m_{t\to Zq,\mathrm{rec}}$

- Pick combination with lowest

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

- Widths reflect mass resolutions as measured in MC simulation:
  $\sigma_{W,\mathrm{rec}}$ = 15 GeV/c^2,
  $\sigma_{t\to Wb,\mathrm{rec}}$ = 24 GeV/c^2
  $\sigma_{t\to Zq,\mathrm{rec}}$ = 21 GeV/c^2

Expected Backgrounds

- How do you search for a signal that is likely not there?
  Understand the background!
- Standard model processes that can mimic Z + ≥4 jets signature:
  - Z+Jets: Z boson production in association with jets
    → dominant background for top FCNC search, most difficult to estimate
  - Standard model $t\bar{t}$ production
    → small background
  - Dibosons: WZ and ZZ diboson production → small background
  - W+Jets, WW: negligible
- Top FCNC background estimate: mixture of data driven techniques and MC predictions

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  - W+Jets, WW: negligible
- Top FCNC background estimate: mixture of data driven techniques and MC predictions

Standard Model $t\bar{t}$ Production

- Small background: no real Z, need extra jets from gluon radiation and/or "fake lepton"
  - Dilepton channel ($t\bar{t}$ → Wb Wb → lνb lνb): dilepton invariant mass can fall into Z mass window
  - Lepton+Jets channel ($t\bar{t}$ → Wb Wb → lνb qq'b): misreconstruct one jet as a lepton ("fake"), invariant mass of lepton and fake lepton can fall into Z mass window
- Large fraction of heavy flavor jets: more important in b-tagged samples
- Estimated from MC simulation

Expected Backgrounds

- How do you search for a signal that is likely not there? Understand the background!
- Standard model processes that can mimic Z + ≥4 jets signature:
  - Z+Jets: Z boson production in association with jets → dominant background for top FCNC search, most difficult to estimate
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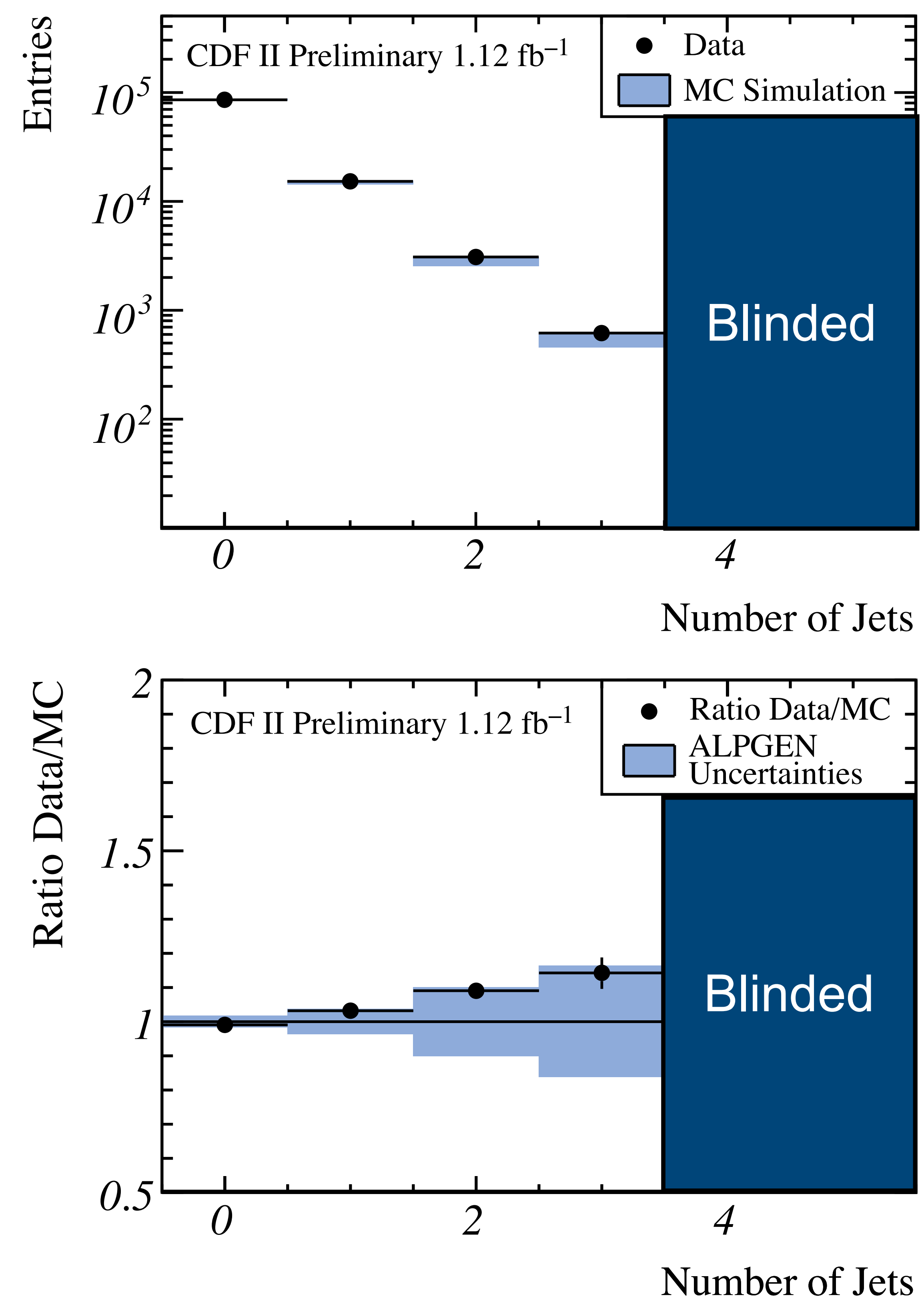
  - Dibosons: WZ and ZZ diboson production → small background
  - W+Jets, WW: negligible
- Top FCNC background estimate: mixture of data driven techniques and MC predictions

Diboson Production: WZ, ZZ

- Small background (similar in size to standard model $t\bar{t}$ production)
  - Small cross section but real Z
  - Need extra jets from gluon radiation
- ZZ: Heavy flavor contribution from $Z \to b\bar{b}$ decay
- Estimated from MC simulation

Z+Jets Production

- MC tool for Z+Jets: ALPGEN
  - Modern MC generator for multiparticle final states
  - “MLM matching” prescription to remove overlap between jets from matrix element and partons showers
- Comparing ALPGEN with data:
  - Leading order generator: no absolute prediction for cross section
  - 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



Kinematic Constraints

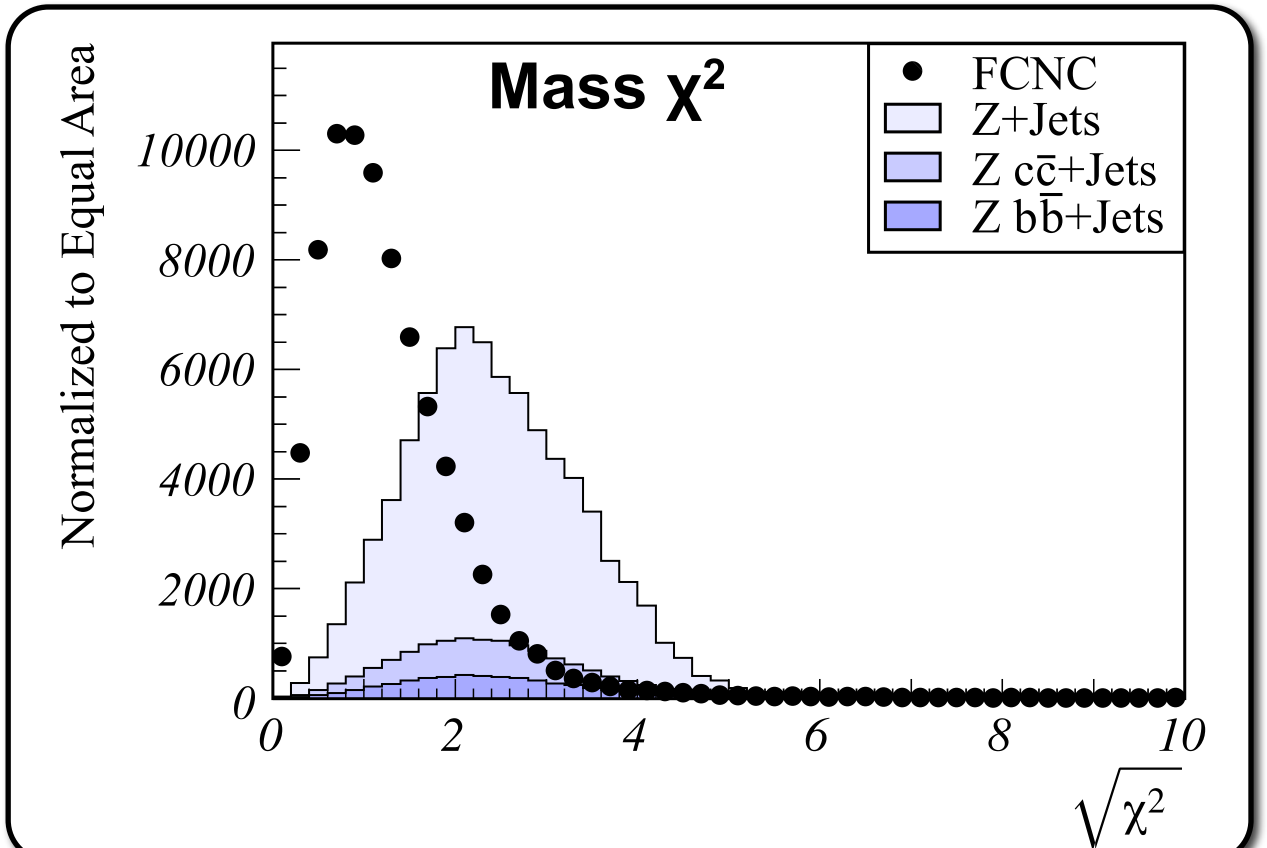
- Mass χ^2: combination of mass constraints – best discriminator

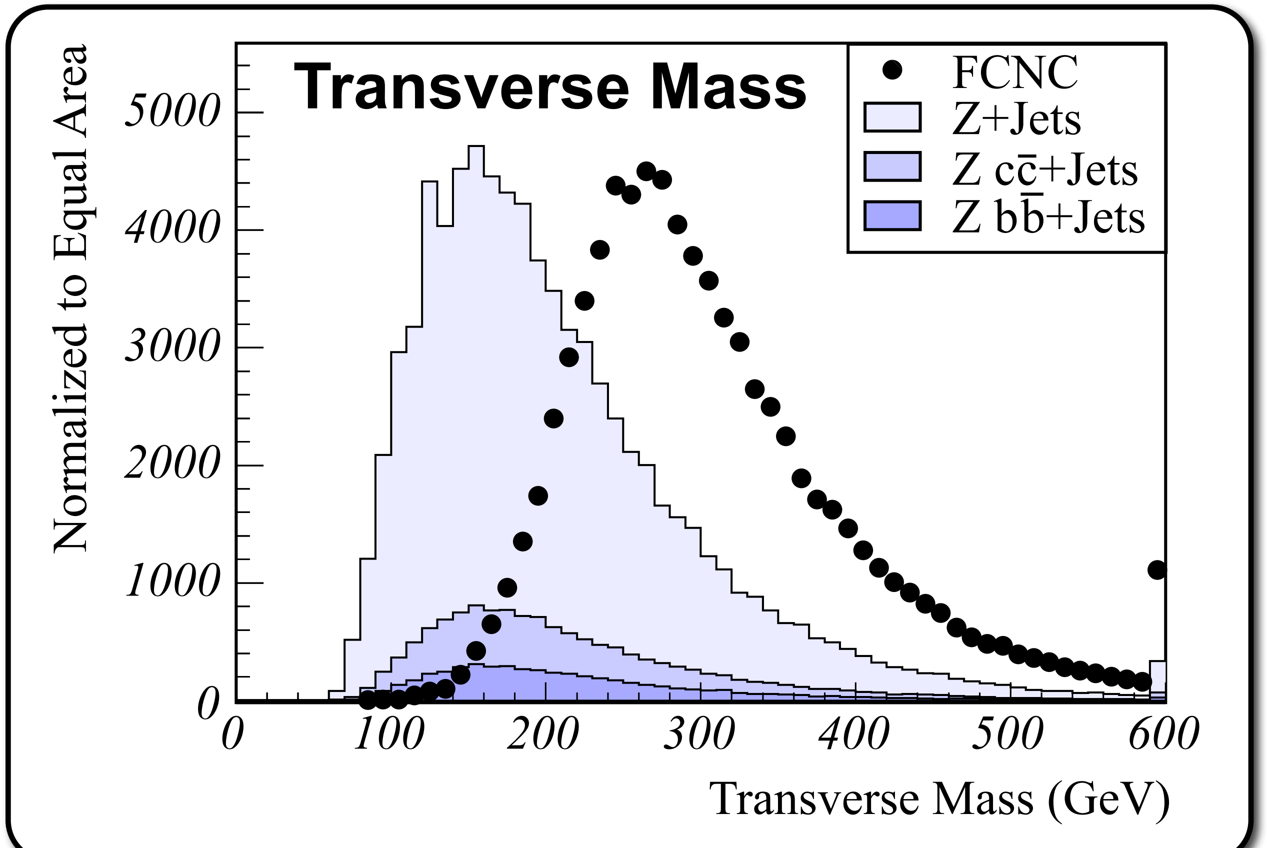
$$\chi^2 = \left(\frac{m_{W,\text{rec}} - m_{W,\text{PDG}}}{\sigma_{W,rec}}\right)^2 + \left(\frac{m_{t\to Wb,\text{rec}} - m_{t,\text{PDG}}}{\sigma_{t\to Wb}}\right)^2 + \left(\frac{m_{t\to Zq,\text{rec}} - m_{t,\text{PDG}}}{\sigma_{t\to Zq}}\right)^2$$

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

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

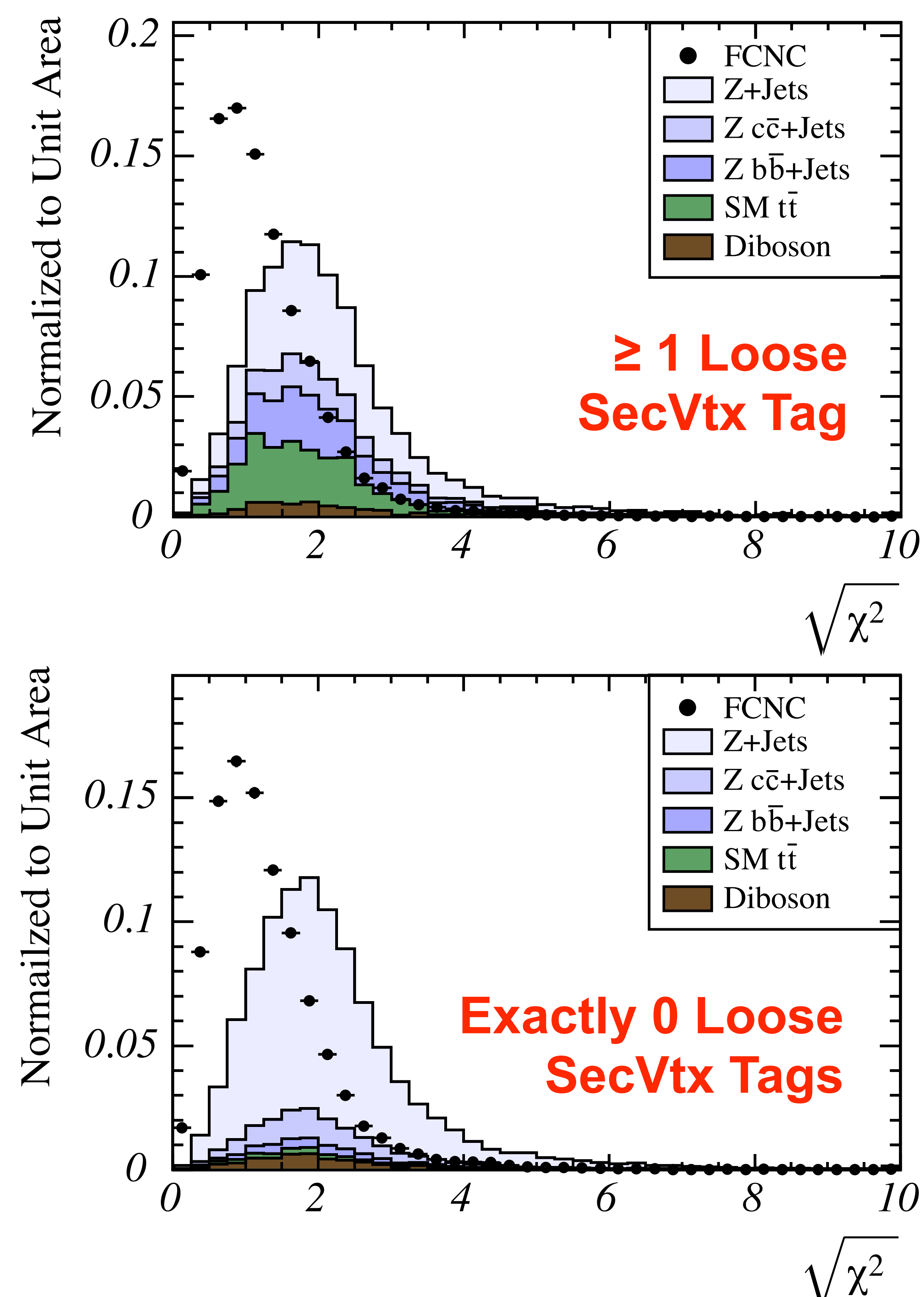
- Jet transverse energies: FCNC signal has four “hard” jets, background processes: jets have to come from gluon radiation





To B-Tag or not to B-Tag?

- Advantage of requiring b-tag:
  Better discrimination against main Z+jets background
  (heavy flavor backgrounds rather small: SM $t\bar{t}$, $Zb\bar{b}$ + jets)
- Disadvantage:
  Reduction of data sample size
- Solution: use both!
  - Split sample in tagged and anti-tagged
  - Optimize cuts individually for tagged and anti-tagged samples
  - Combine samples in limit calculation
- Main difficulty of this approach: event migration between samples
  - Systematics may be correlated or anti-correlated between samples
  - Taken into account in limit calculation



Optimization of Event Selection

- Question: best choice for cut values?
- Goal: derive limit on branching fraction of FCNC process $t \rightarrow Zq$
- No prediction for amount of signal: "signal over background" et al. do not work
- Solution: optimize cuts for best expected limit (assuming no signal)

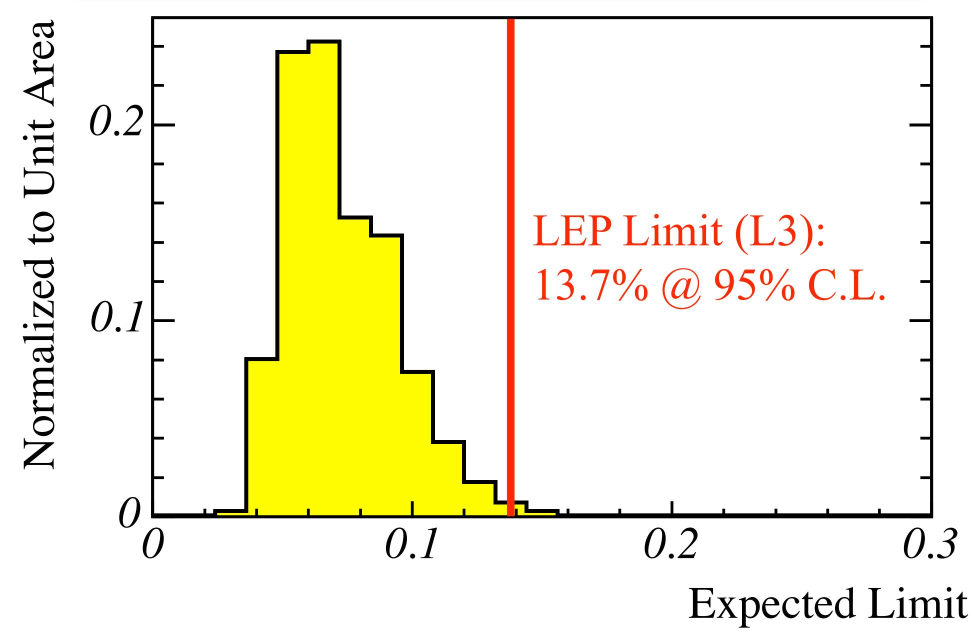
$$\sum_{n_{\text{obs}}} P(n_{\text{obs}} | n_{\text{back}}) \cdot \text{Lim}(n_{\text{obs}} | A, n_{\text{back}})$$

  - P: Poisson probability
  - L: 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

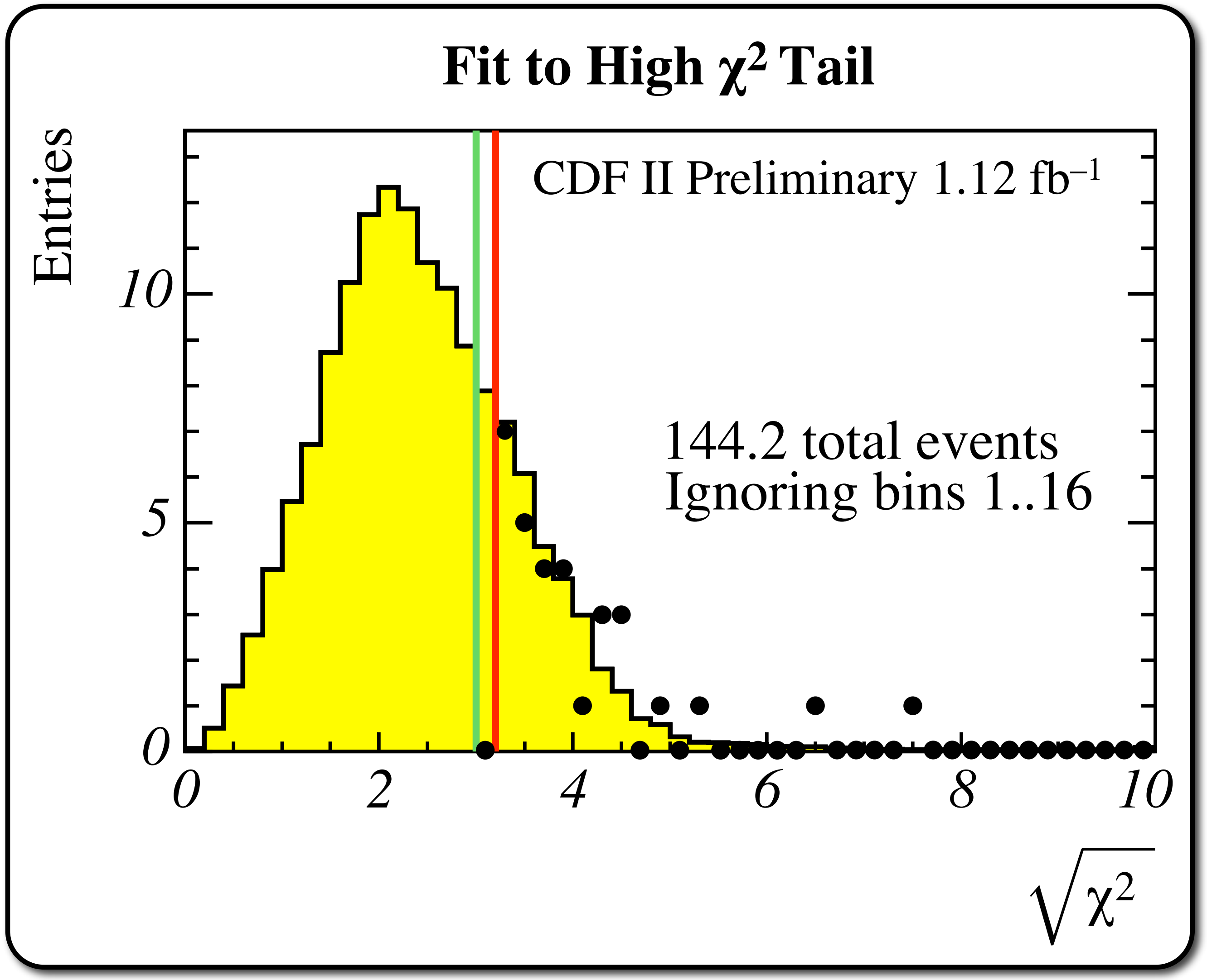
Kinematic Variable	Optimized Cut
Z Mass	$\in [76,106]\,\text{GeV}/c^2$
Leading Jet E_T	$> 40\,\text{GeV}$
Second Jet E_T	$> 30\,\text{GeV}$
Third Jet E_T	$> 20\,\text{GeV}$
Fourth Jet E_T	$> 15\,\text{GeV}$
Transverse Mass	$> 200\,\text{GeV}$
$\sqrt{\chi^2}$	< 1.6 (b-tagged)
	< 1.35 (anti-tagged)

Expected 95% C.L. Upper Limit on BR(t→Zq): 7.1% ± 3.0%



Background: Putting it all Together

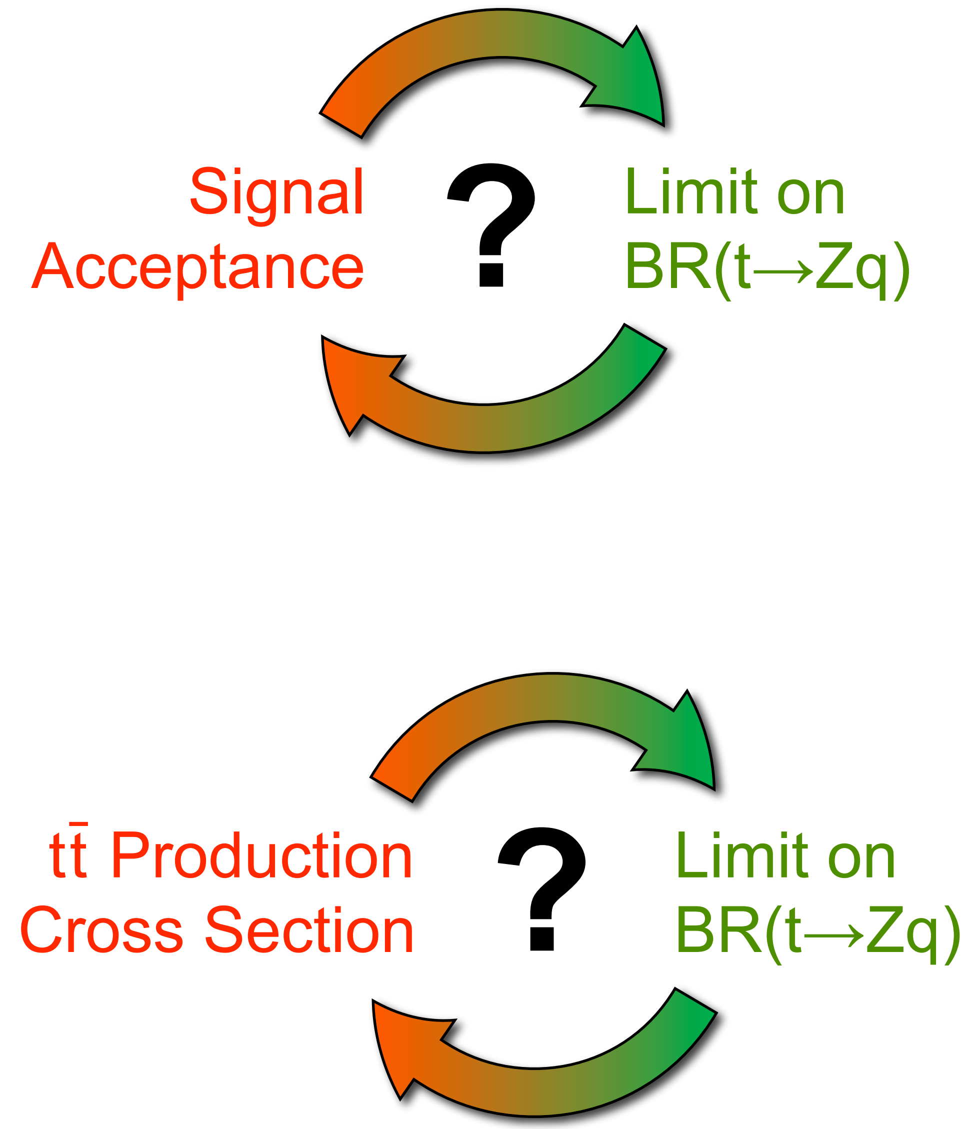
- Total background prediction from control region in data: 130 ± 28 events
  - Tail of mass χ^2 distribution
  - Average of cuts at $\sqrt{\chi^2}$ = 3.0, 3.2
- Tagging rate: 15% ± 4%
  - Tail of mass χ^2: 16% ± 7% (small sample → large uncertainties)
  - MC prediction of tagging rate: 11% (but: 30% too low for Z+≤ 3 Jets)
  - Template fit of MC tagging probabilities vs. number of jets: 14%



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

Acceptance Algebra: Catch 22?

- Question: how to get from event counts to limit on BR(t→Zq)?
  - Circular dependency #1: Limit calculation requires knowledge of 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 above dependencies implemented in limit machinery
  - Signal acceptance dynamically adjusted as a function of BR(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



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:

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

$\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

Acceptance Algebra: Details

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$$

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

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

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

Signal Systematics

- Signal 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	Base Selection (%)	Anti-Tagged (%)	Loose Tag (%)
Lepton Scale Factor	0.5	0.5	0.5
Trigger Efficiency	0.2	0.2	0.2
Jet Energy Scale	3.1	2.6	1.9
ISR/FSR	1.3	2.6	6.5
Helicity Re-Weighting	3.5	3.4	3.2
Parton Distribution Functions	0.9	0.9	0.9
Total Correlated	5.0	5.1	7.5
B-Tagging Scale Factor	10.2	16.3	5.5
Mistag $\alpha\beta$ Correction	0.6	1.0	0.4
$\mathscr{B}(t \to Zc)$ versus $\mathscr{B}(t \to Zu)$	0.0	4.0	4.0
Total Anti-Correlated	10.2	16.8	6.8

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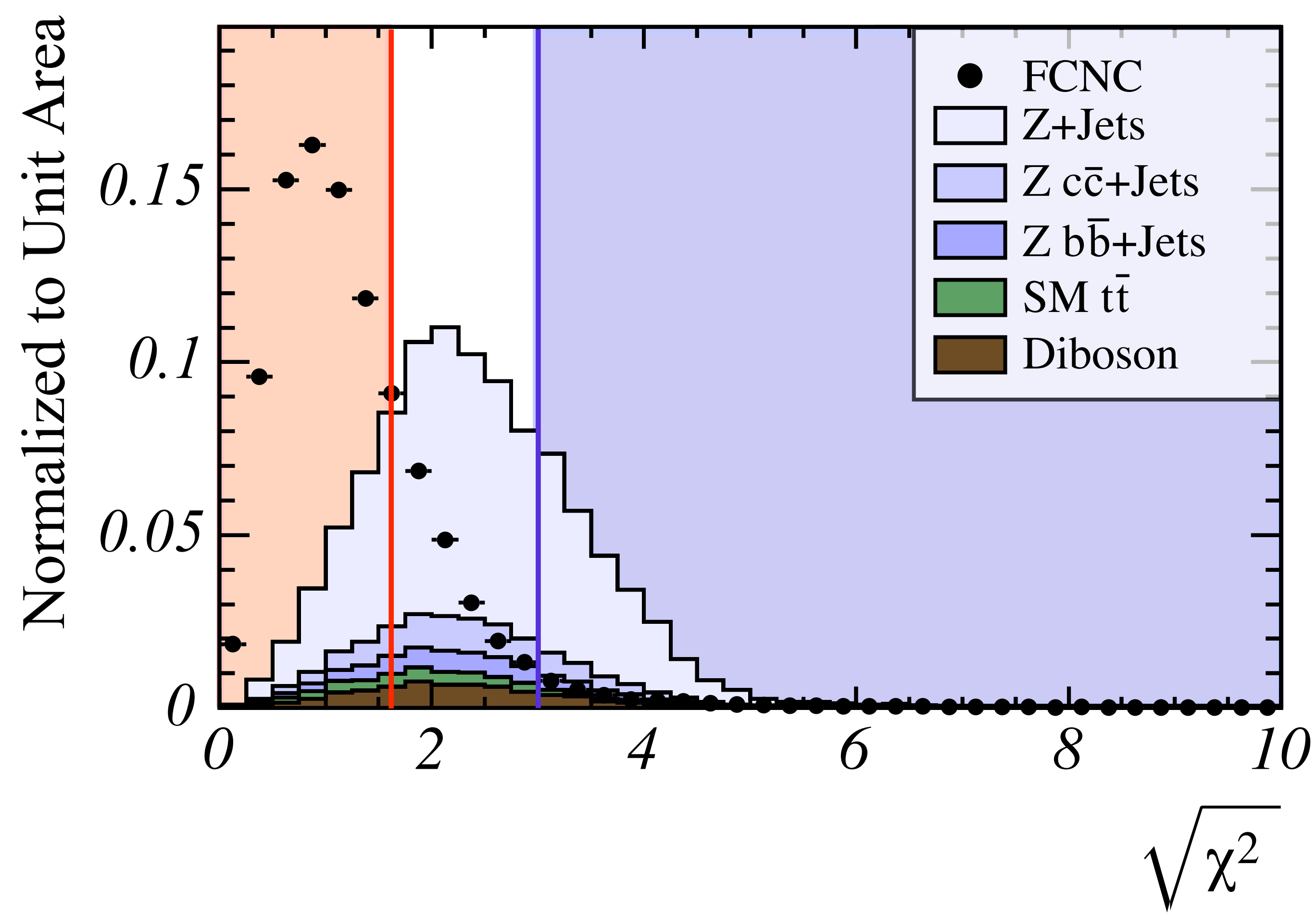
Total Anti-Correlated	10.2	16.8	6.8

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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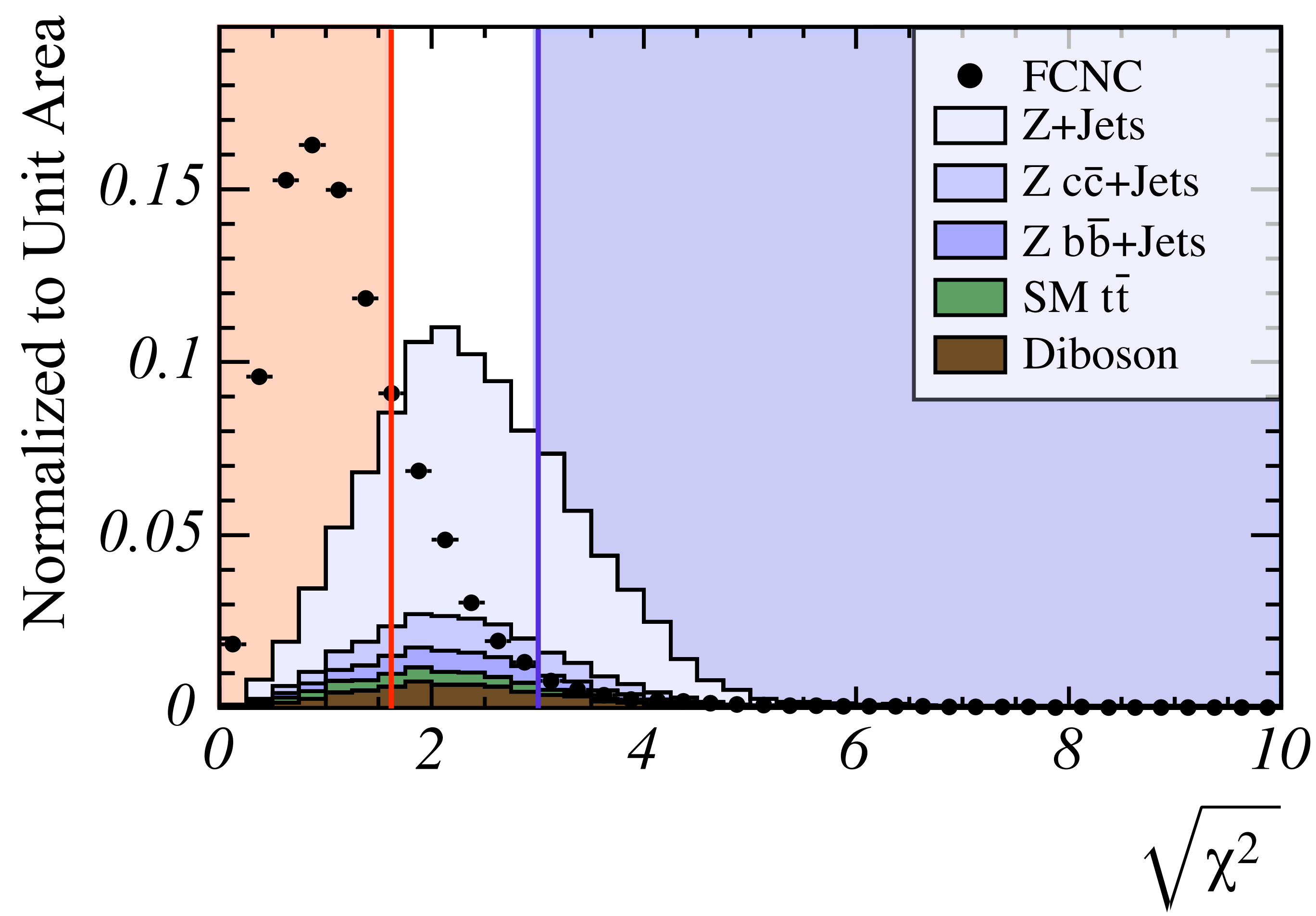
  - Ratio of events with $\sqrt{\chi^2} < 1.6$ (signal region) vs. $\sqrt{\chi^2} > 3.0$ (control region)
  - Dominated by choice of MC generator and jet energy scale



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

The World's Best Limit on BR($t \to Zq$)

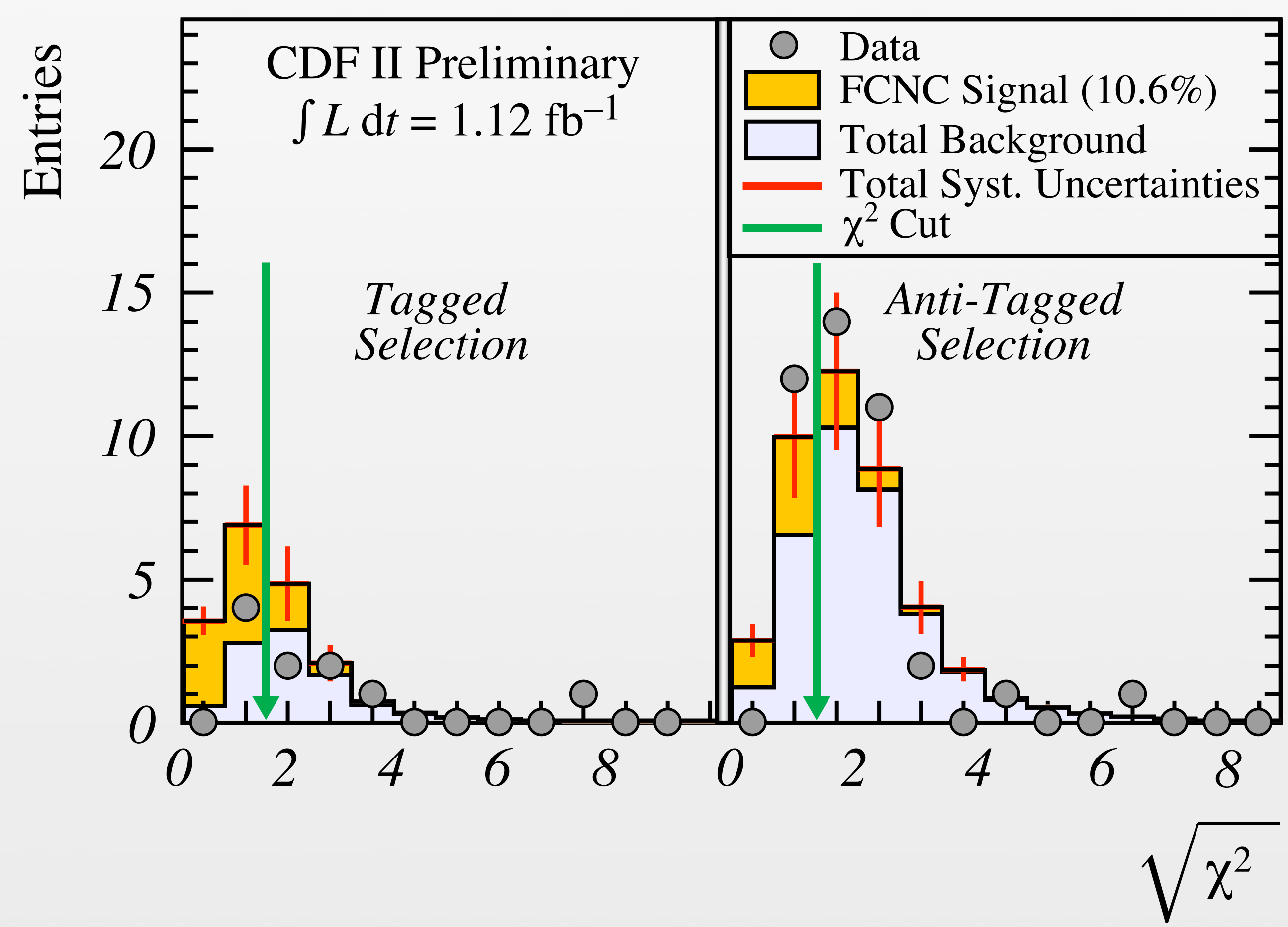
- Opening the box with 1.12 fb^{-1}
  - Event yield consistent with background only
  - Fluctuated about 1σ high: slightly unlucky
- Result: The World's Best Limit!

$$\mathscr{B}(t \to Zq) < 10.6\% \,@\, 95\% \text{ C.L.}$$

  - Expected limit: 7.1% ± 3.0%
  - 25% better than L3 (13.7%)
  - 3x better than CDF Run I (33%)
  - Above results assumes m_t = 175 GeV/c^2, limit at m_t = 170 GeV/c^2: BR($t \to Zq$) < 11.2% @ 95% C.L.
- Update with 2 fb^{-1} and improved method in the works

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

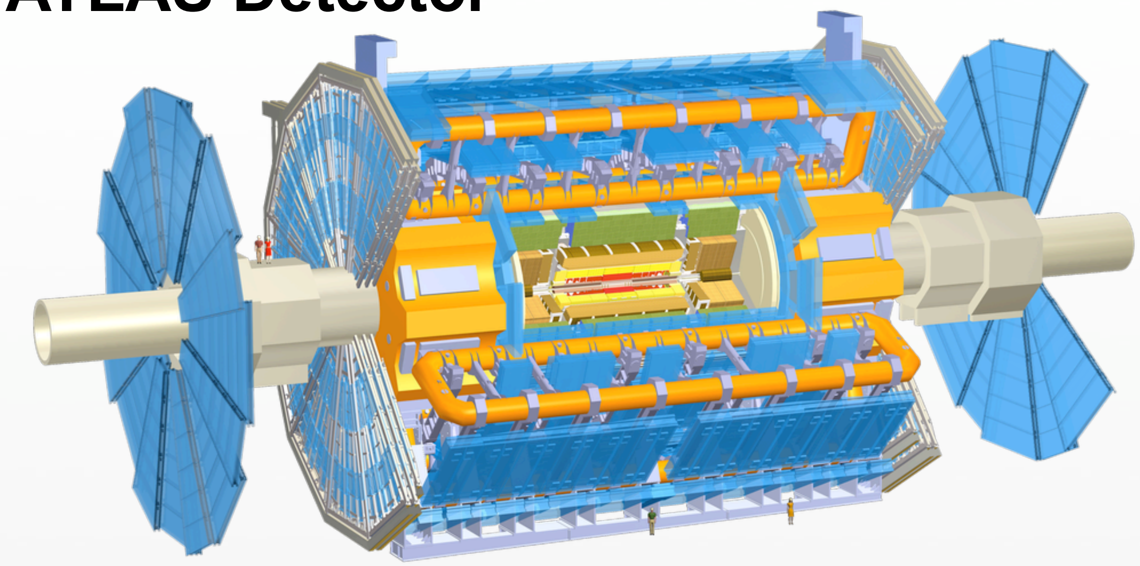
Mass χ^2 (95% C.L. Upper Limit)

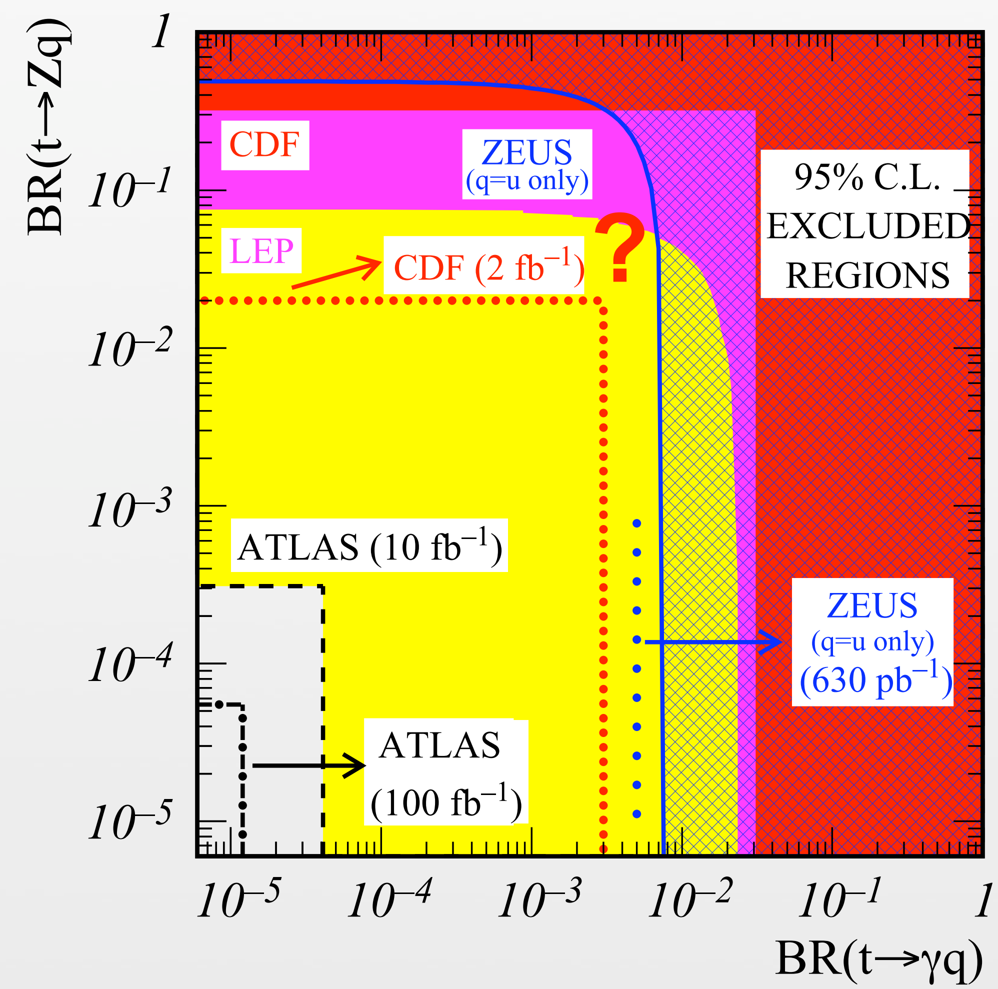


Top FCNC Searches at the LHC

- Large Hadron Collider (LHC):
  - Proton-proton collider at 14 TeV center-of-mass energy (CERN)
  - Two multi-purpuse experiments: ATLAS and CMS
  - First data expected in 2008 (2009?)
- Recent ATLAS study on sensitivity for top FCNC
  - Improvement of current limits on BR ($t \to Zq$) by 2–3 orders of magnitude
  - Entering interesting regime of 10^{-4} to 10^{-5}: exclusion of first theoretical models
- Caveat: background model
  - Existing MC tools not tuned to new energy regime
  - Tevatron experience: obtain backgrounds from data

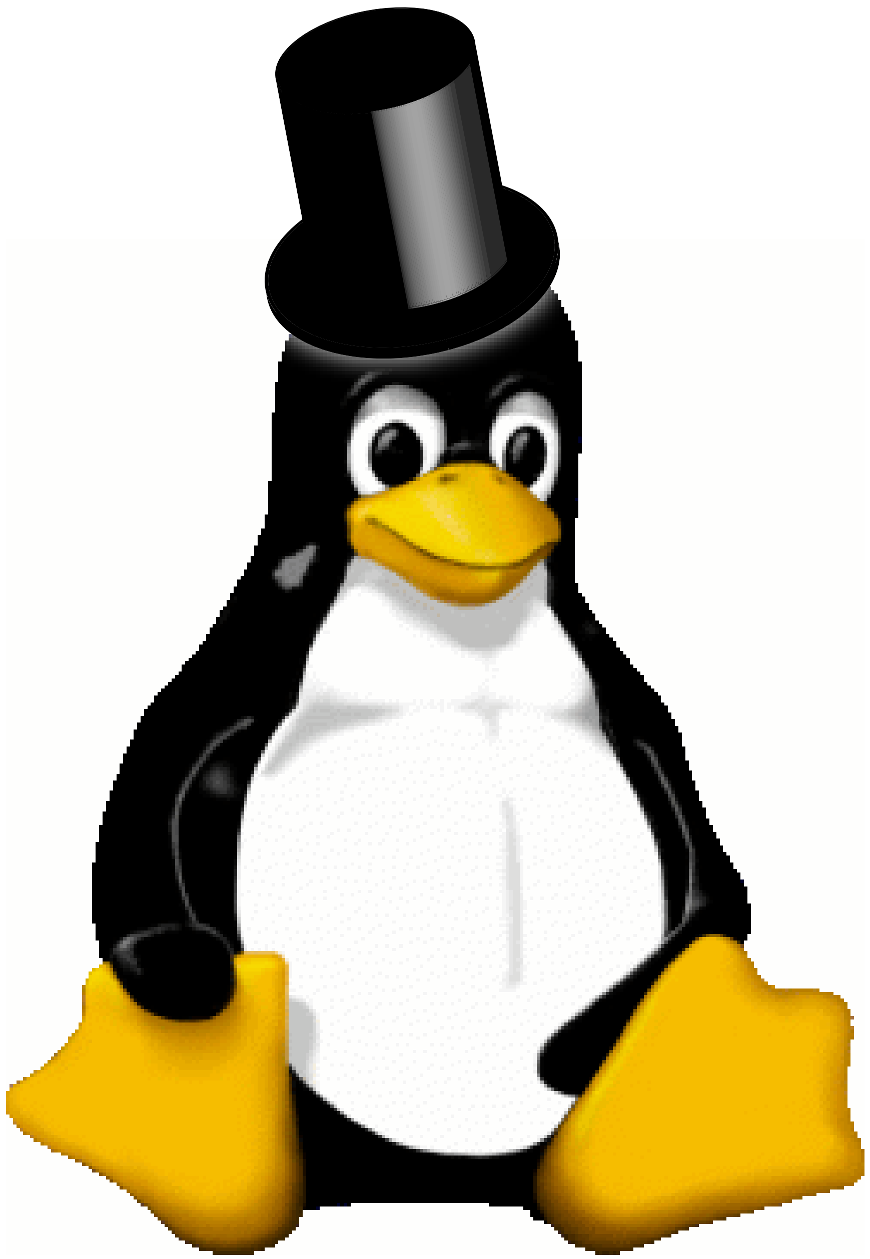
ATLAS Detector





[J. Carvalho *et al.*, SN-ATLAS-2007-059]

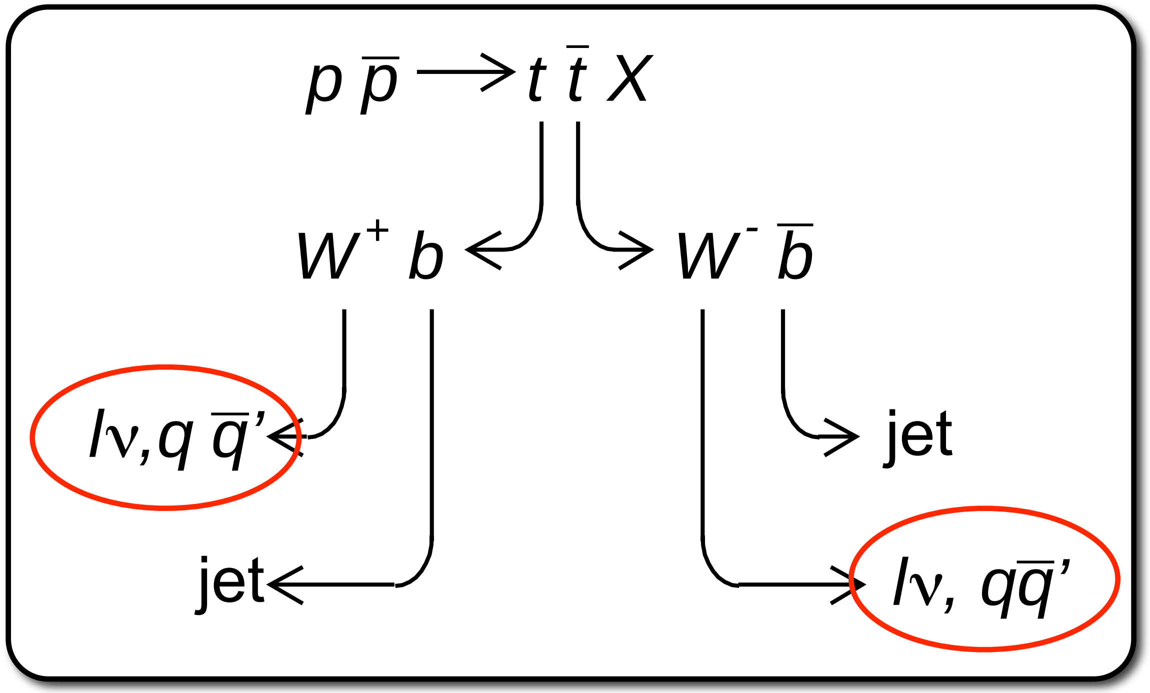
Summary and Conclusions



- Top flavor changing neutral current decays
  - Extremely rare in the standard model
  - Enhanced in theories beyond the standard model → any signal would indicate new physics
- First Tevatron Run II search for FCNC $t \rightarrow Zq$ in top quark decays
  - Event signature: $Z + \geq 4$ jets
  - Main background process: standard model Z + jets production
  - Mass χ^2 to separate signal from background
- No evidence for top FCNC found
  - World's best limit: $BR(t \rightarrow Zq) < 10.6\%$ at 95% C.L.
  - Working on improvements, stay tuned!

Backup Slides

Typical Top Selection Criteria



Cylindrical coordinate system:

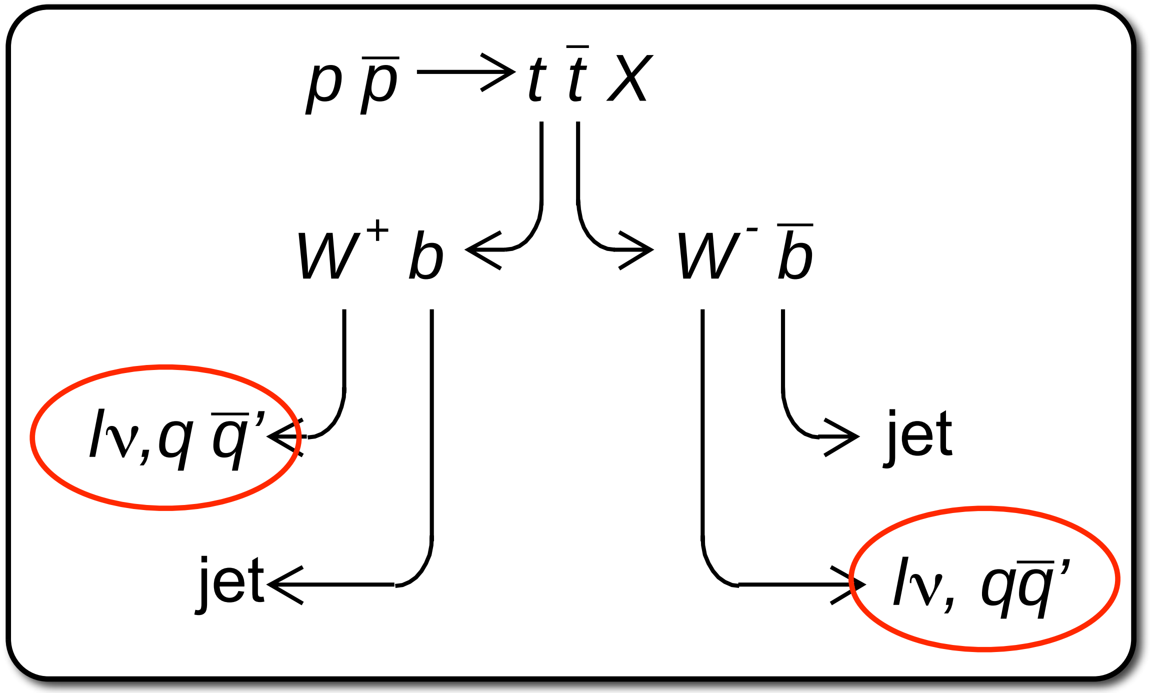
- θ: polar angle w.r.t. to proton direction
- ϕ: azimuthal angle
- Pseudorapidity: $\eta = -\ln\tan(\theta/2)$
- Transverse energy:

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

- 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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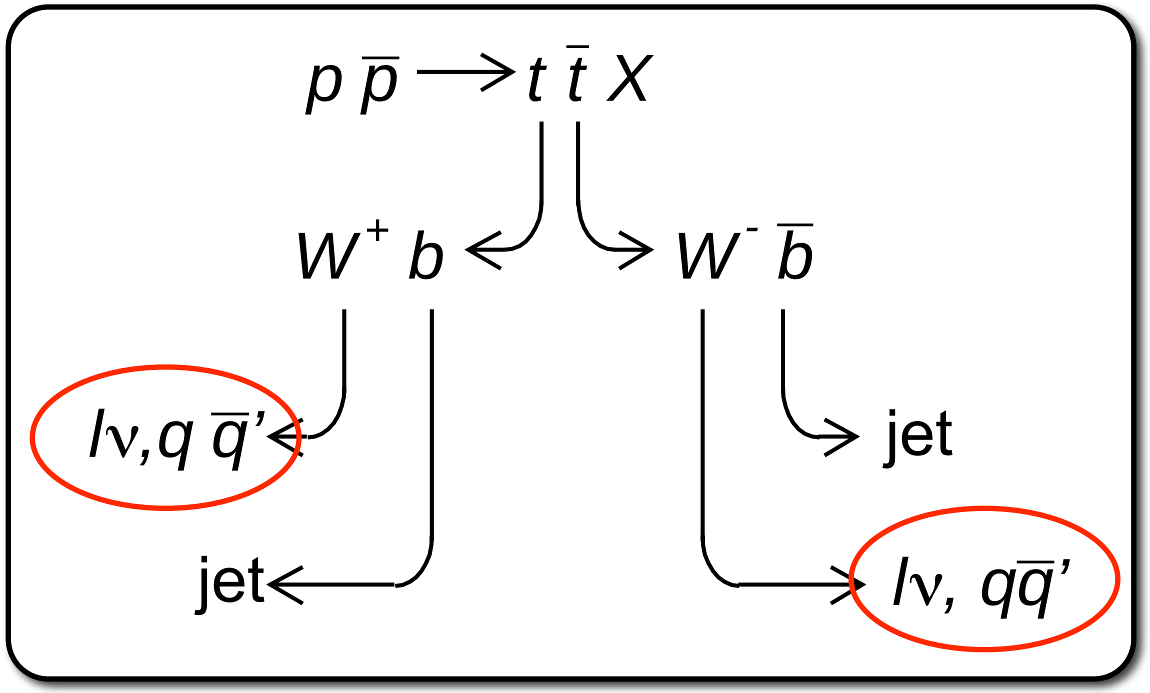
- Lepton + Jets: $t\bar{t} \rightarrow Wb\,Wb \rightarrow l\nu b\,qq'b$
  - Isolated lepton with p_T > 20 GeV/c
  - Neutrino: missing E_T ("MET") > 20 GeV
  - 3 jets within |η| < 2 with E_T > 15 GeV, 4th jet: E_T > 8 GeV
  - 0, 1, ≥ 2 identified jets from b quarks ("b-tags")

Typical Top Selection Criteria



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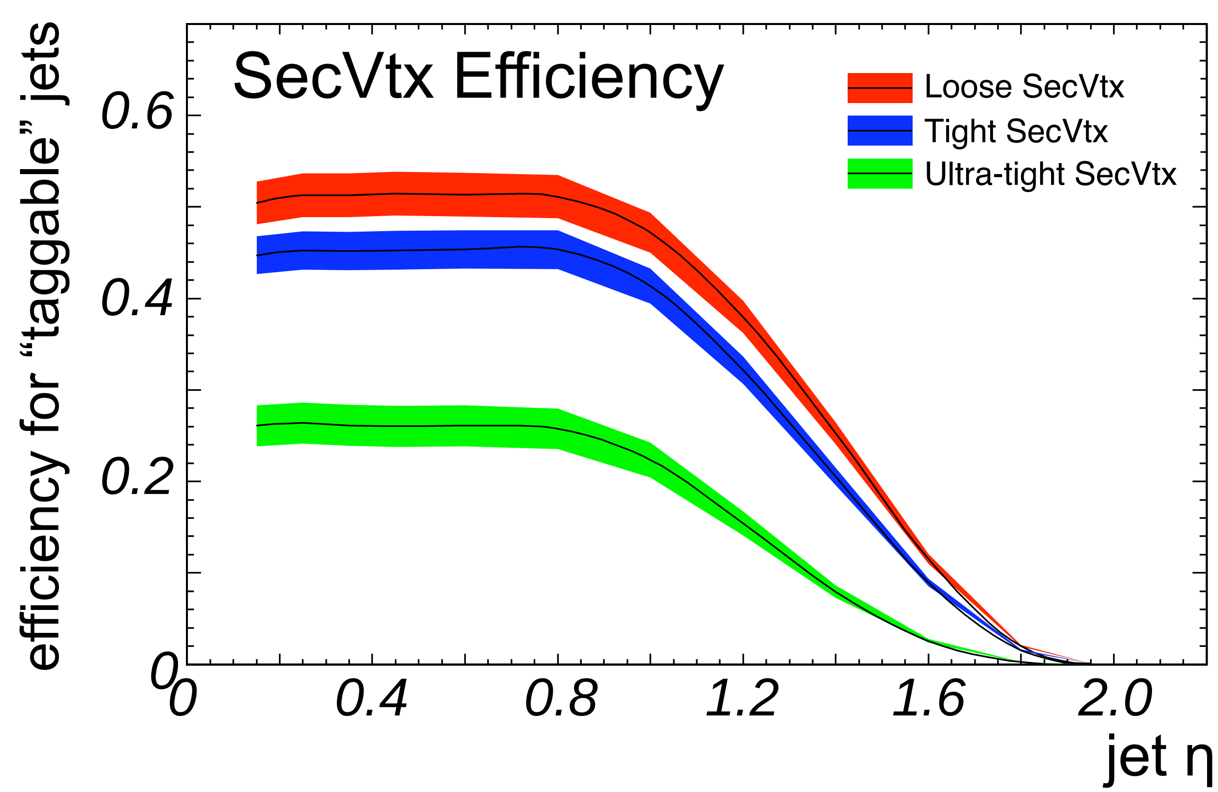
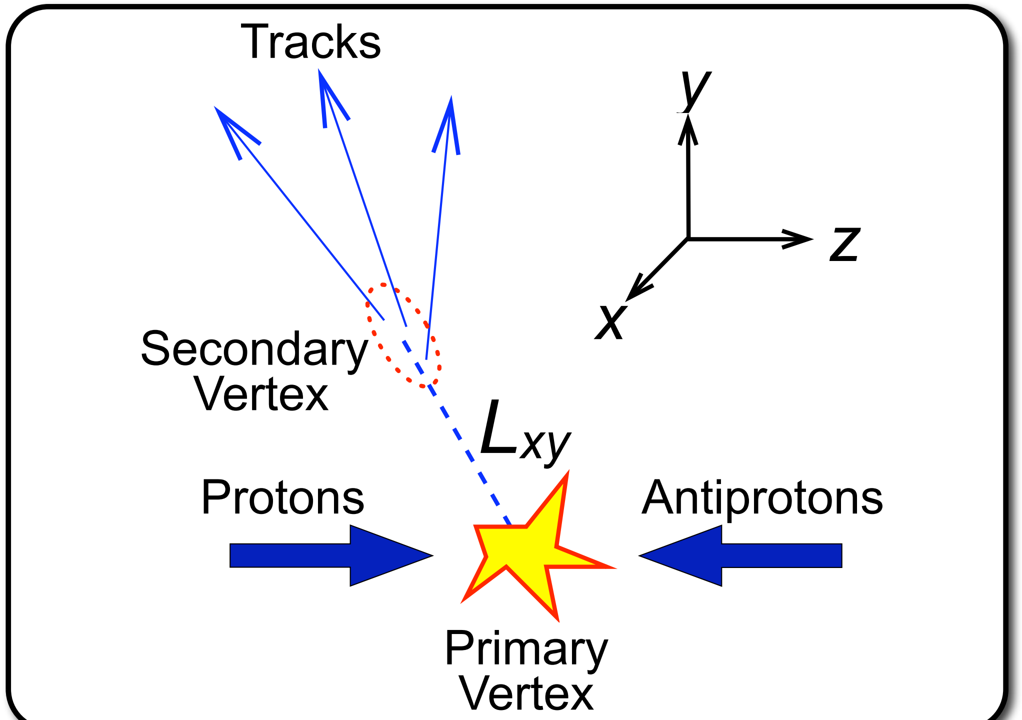
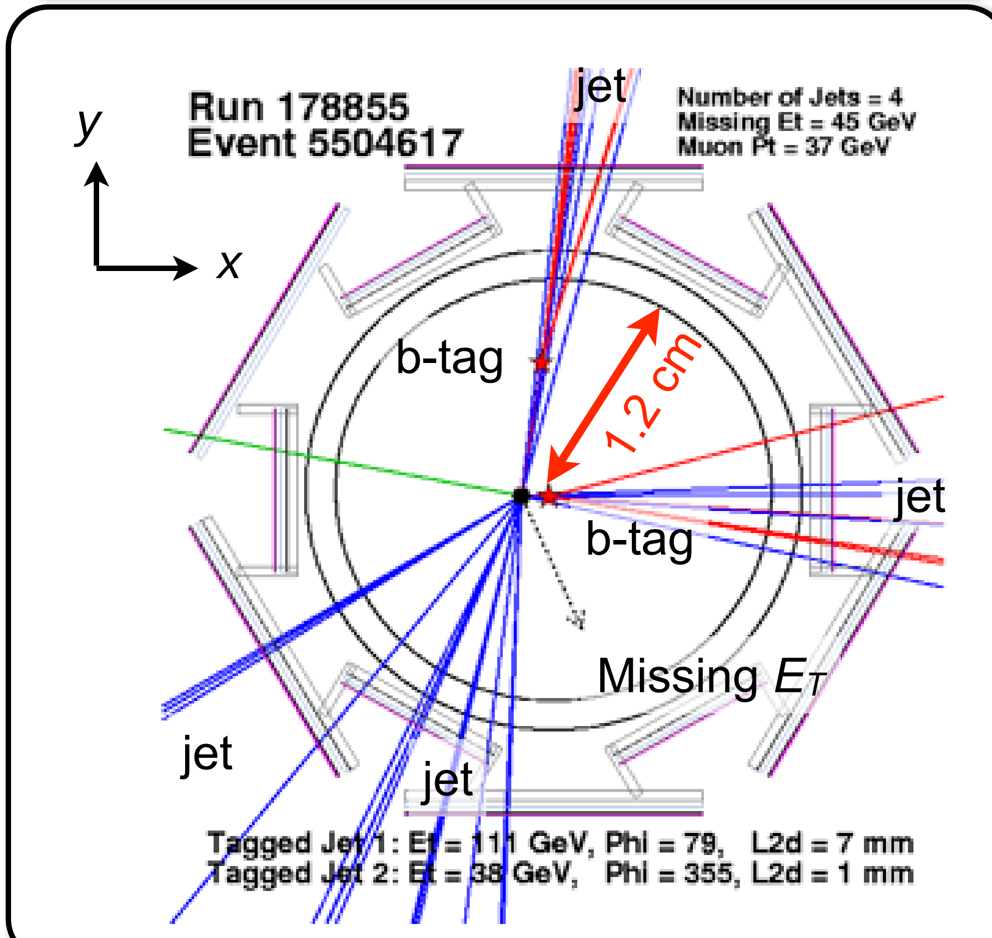
  - Isolated lepton with p_T > 20 GeV/c
  - Neutrino: missing E_T ("MET") > 20 GeV
  - 3 jets within |η| < 2 with E_T > 15 GeV, 4th jet: E_T > 8 GeV
  - 0, 1, ≥ 2 identified jets from b quarks ("b-tags")
- Dilepton: $t\bar{t} \to$ Wb Wb $\to$ lvb lvb
  - Two oppositely charged leptons with p_T > 20 GeV/c
  - 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

Secondary Vertex B-Tagging

- CDF's standard "SecVtx" algorithm:
  - Long lifetime of B mesons: detect displaced secondary vertex
  - Discriminants: Significance of displacement in *xy* plane (L_{xy}) and impact parameter
- Further taggers based on jet probability or soft leptons from semileptonic B decays

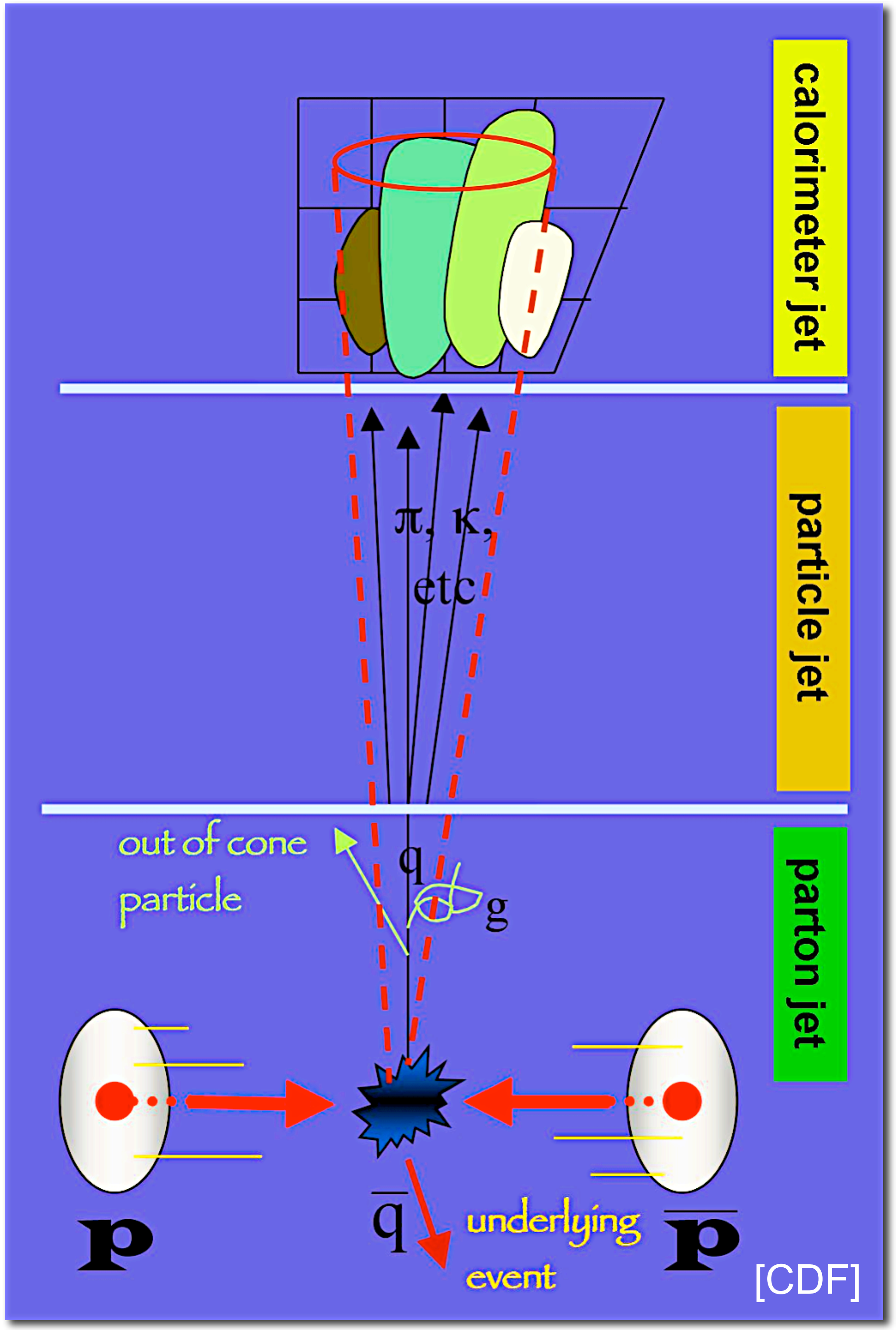






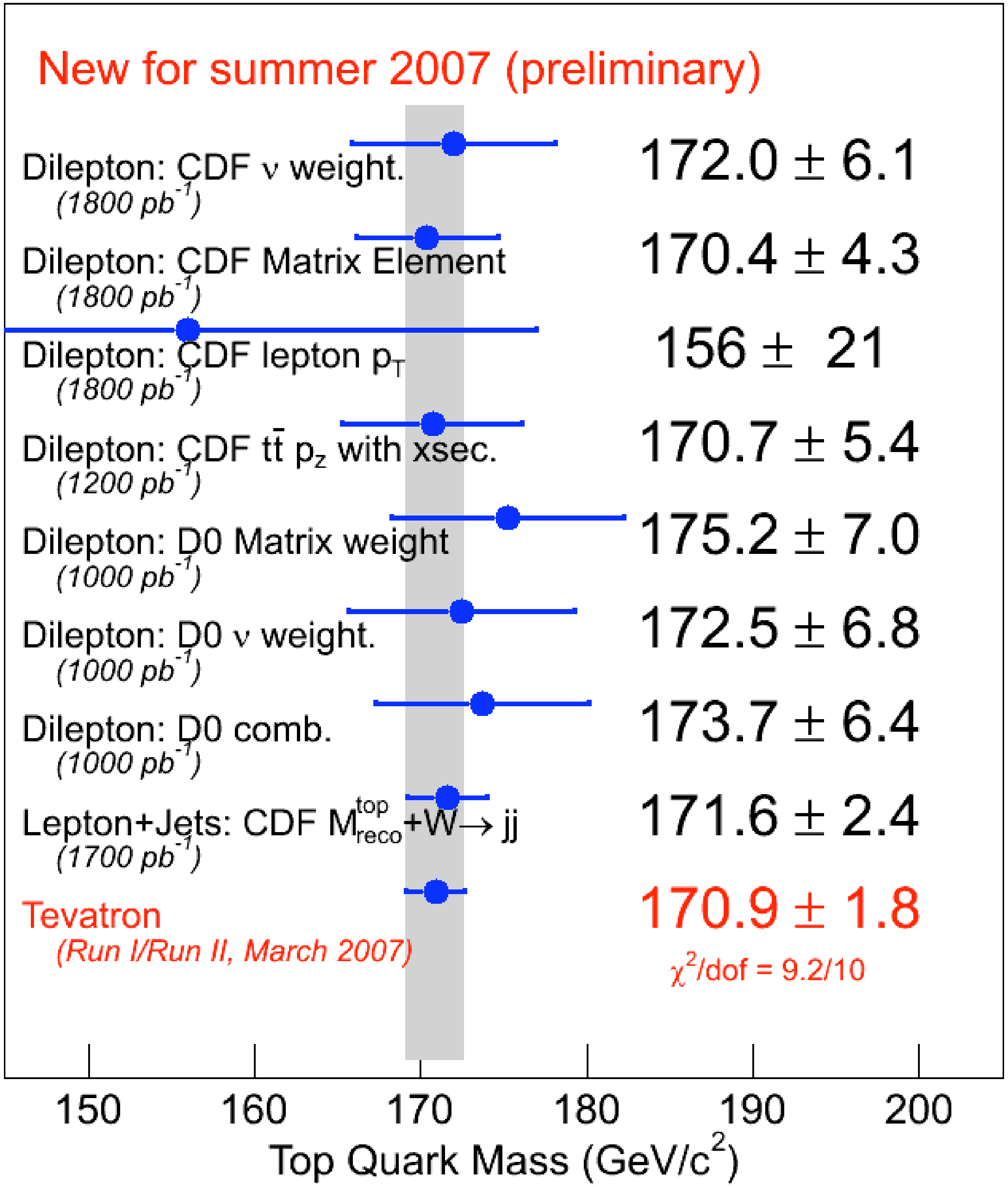
Jet Energy Corrections

- 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



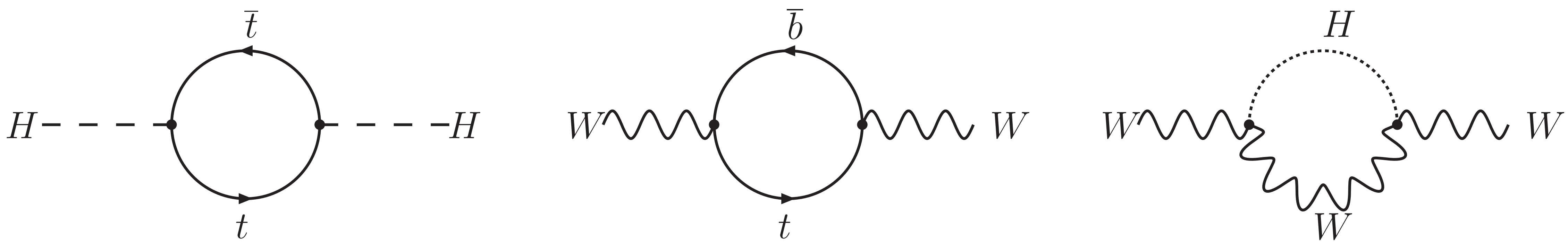
Top Quark Mass

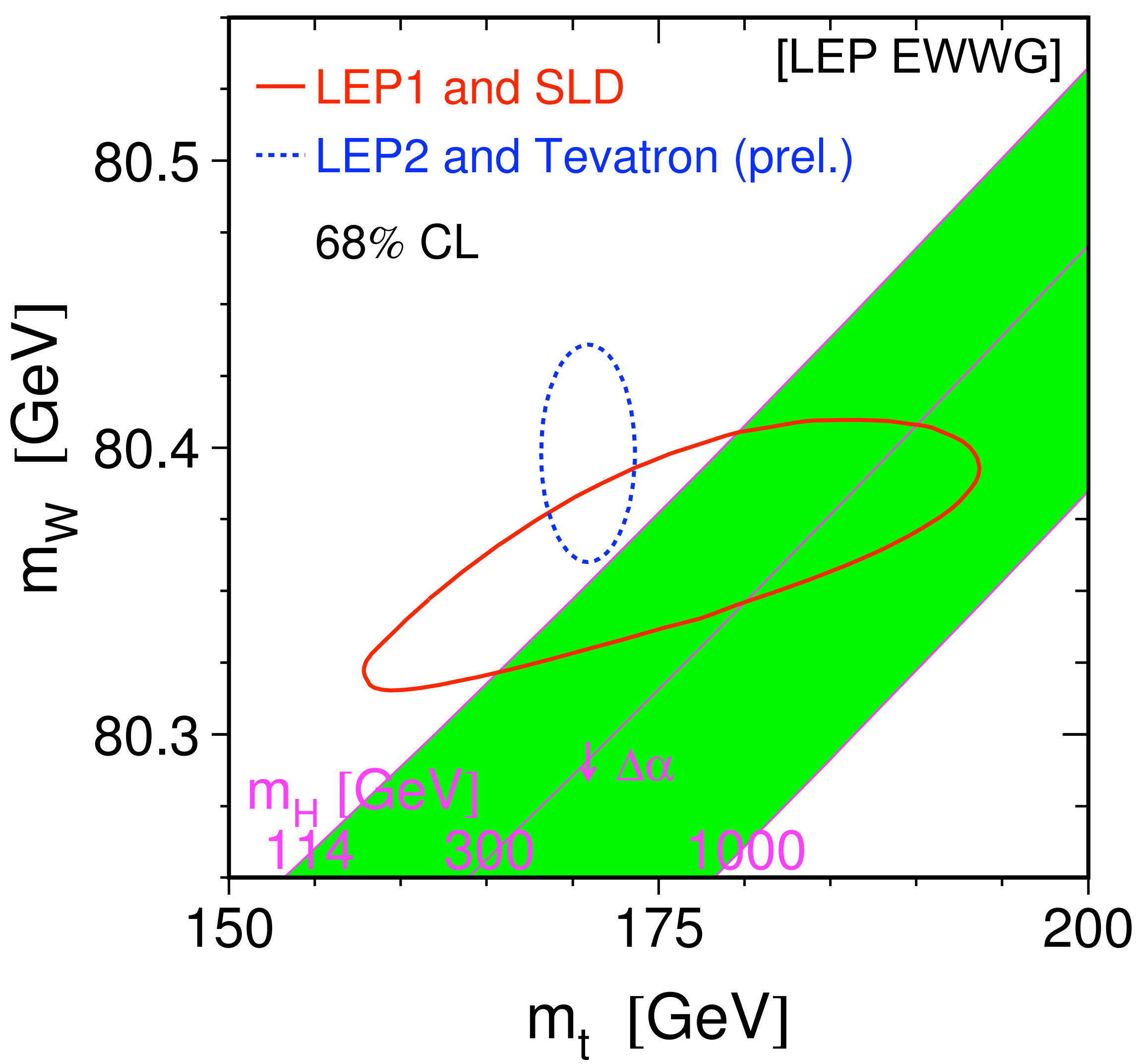
- Top mass measurements enter the era of precision physics:
  - Three independent top decay channels
  - At least a dozen different analysis techniques
  - Measurements are very consistent
  - March 2007 Tevatron combination: 1.1% uncertainty on top mass
- 8 new or updated top mass measurements from CDF & DØ presented at Lepton-Photon 2007

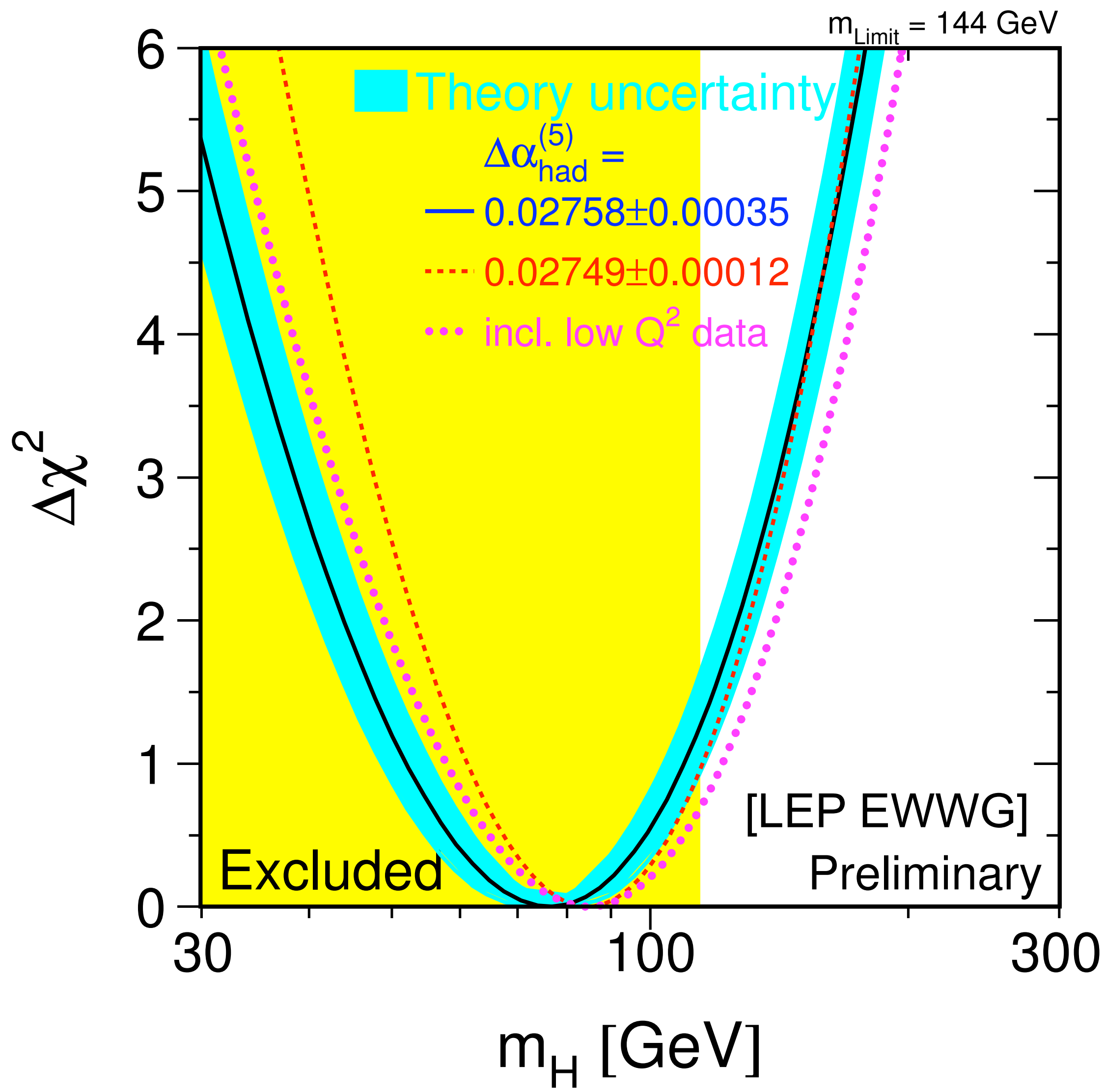


The Top, the W, and the Higgs

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







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	
$t\bar{t} \to Z(ll,q\bar{q})cZ(ll,q\bar{q})c$	116,573	Double FCNC decay: $Z \to e^+e^-, \mu^+\mu^-, q\bar{q}$	
$t\bar{t} \to Z(ll)uW(q\bar{q}')b$	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, $m_t = 170\,\mathrm{GeV}/c^2$	
$t\bar{t} \to Z(ll,q\bar{q})cZ(ll,q\bar{q})c$	116,573	As Above, $m_t = 170\,\mathrm{GeV}/c^2$	

  - 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

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

Helicity Reweighting

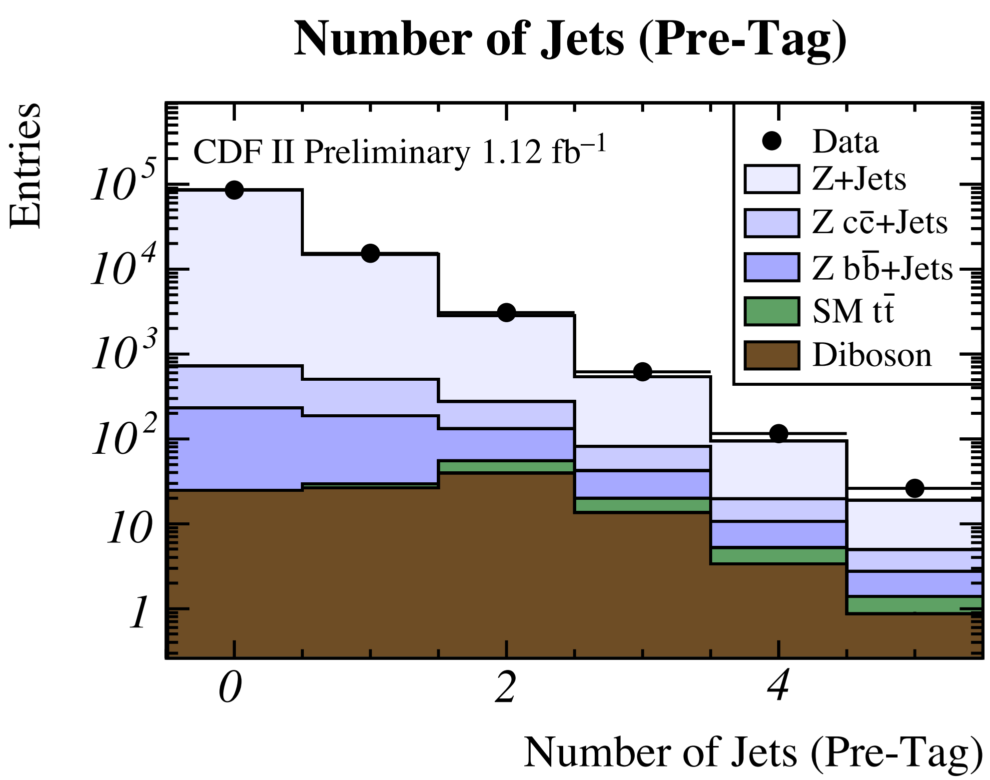
- Problem: t→Zq vertex unknown to PYTHIA
  - Decays generated flat in cos θ* (angle between top and lepton of same charge sign from Z decay, in Z rest frame)
  - Expected helicity for pure V–A decay: 65% longitudinal (f^0), 35% left-handed (f^-). According to Tim Tait: "Wacky models" may mix left-handed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

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

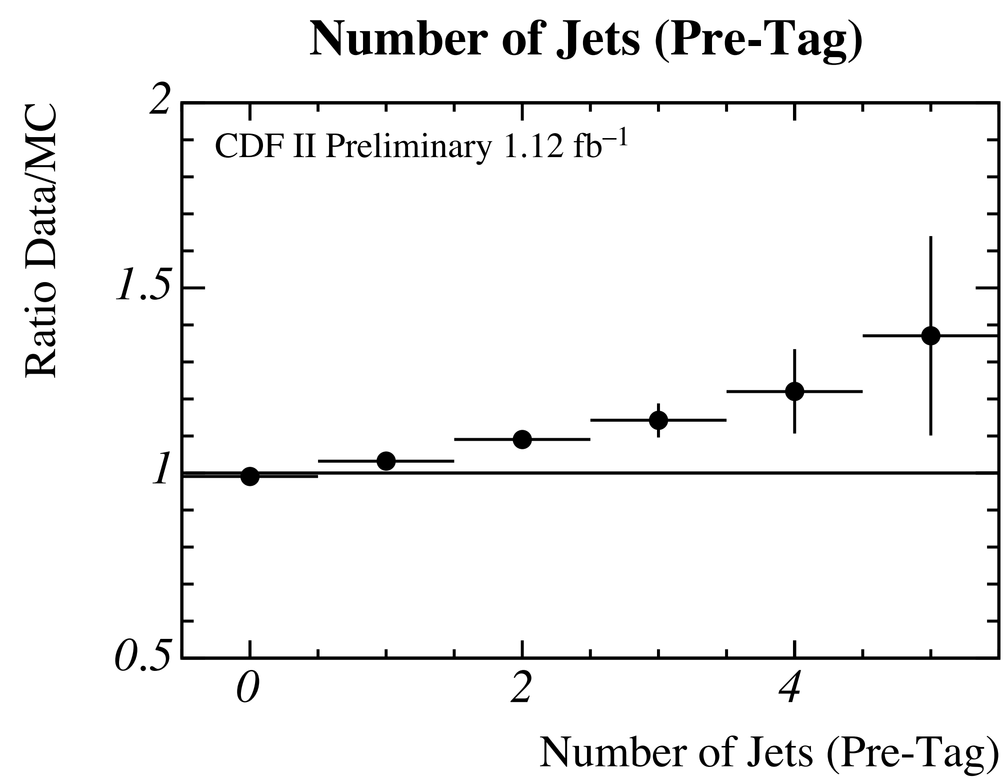
with SM prediction for f^0: $f^0 = \frac{{m_t}^2}{2m_Z^2 + {m_t}^2} \approx 0.65$

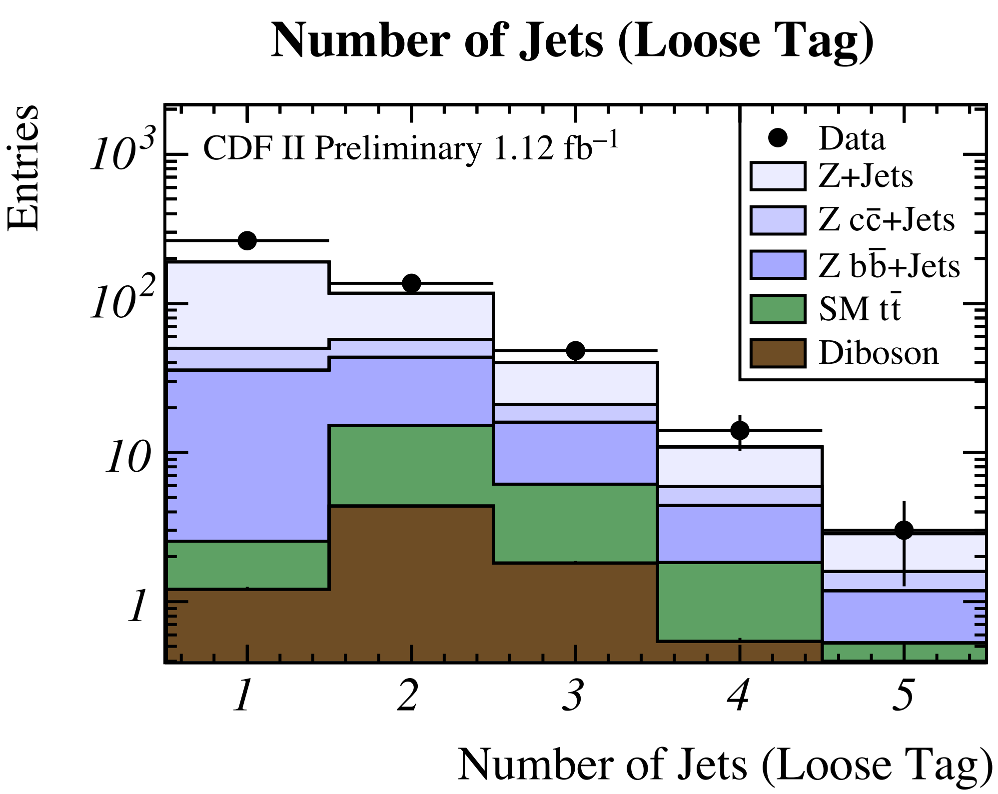
- Solution:
  - Re-weight sample for acceptance calculation: 65% longitudinal, 35% left-handed
  - Assign systematic uncertainty to unknown helicity
  - To first order: acceptance for l^+ and l^- identical → same acceptance for same fraction of left-handed/right-handed

ALPGEN & Jet Multiplicity

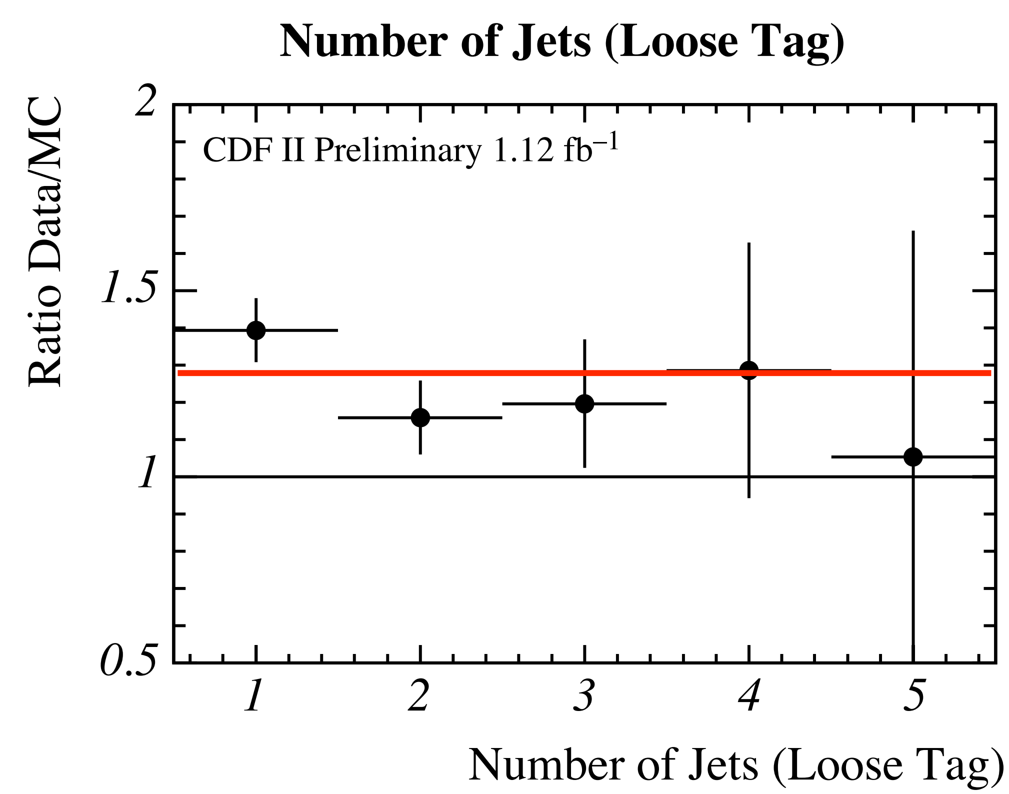


ALPGEN underestimates Jet Multiplicity



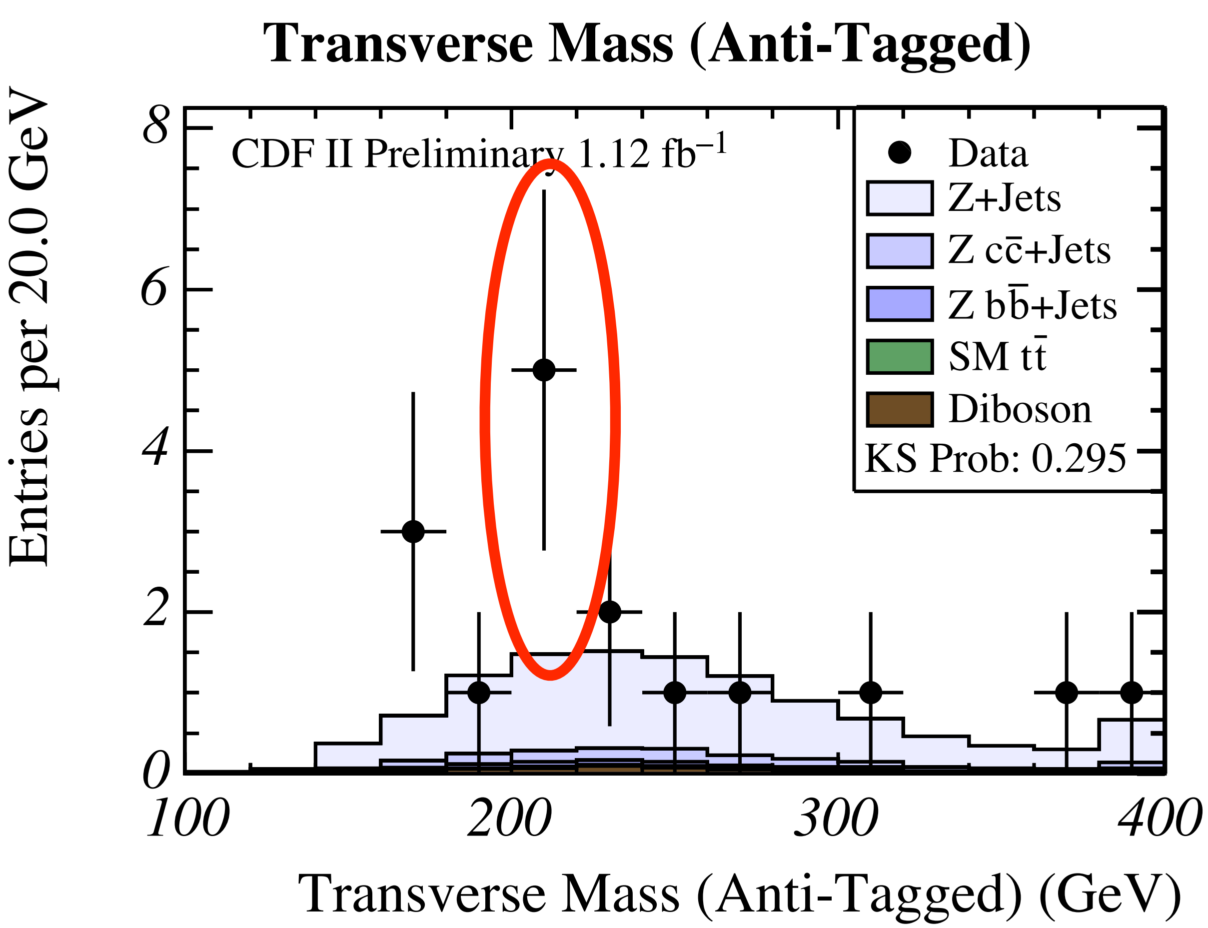


ALPGEN underestimates Tag Rate



Why is Your Background 1σ High?

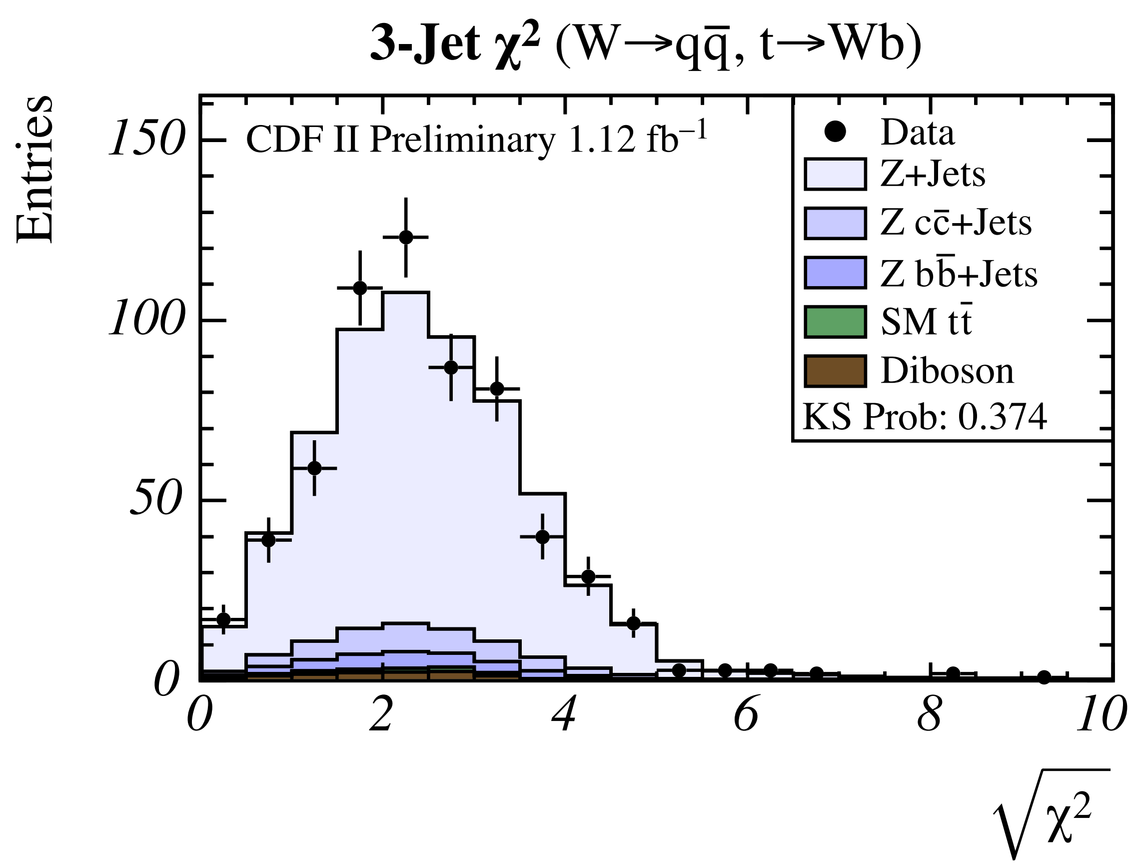
- Blind analysis: cannot change cuts after "opening the box"
- Closer look at the data: excess of events with transverse mass around 200 GeV
- Compare cuts at 200 GeV and 220 GeV: most likely explanation of higher than expected limit



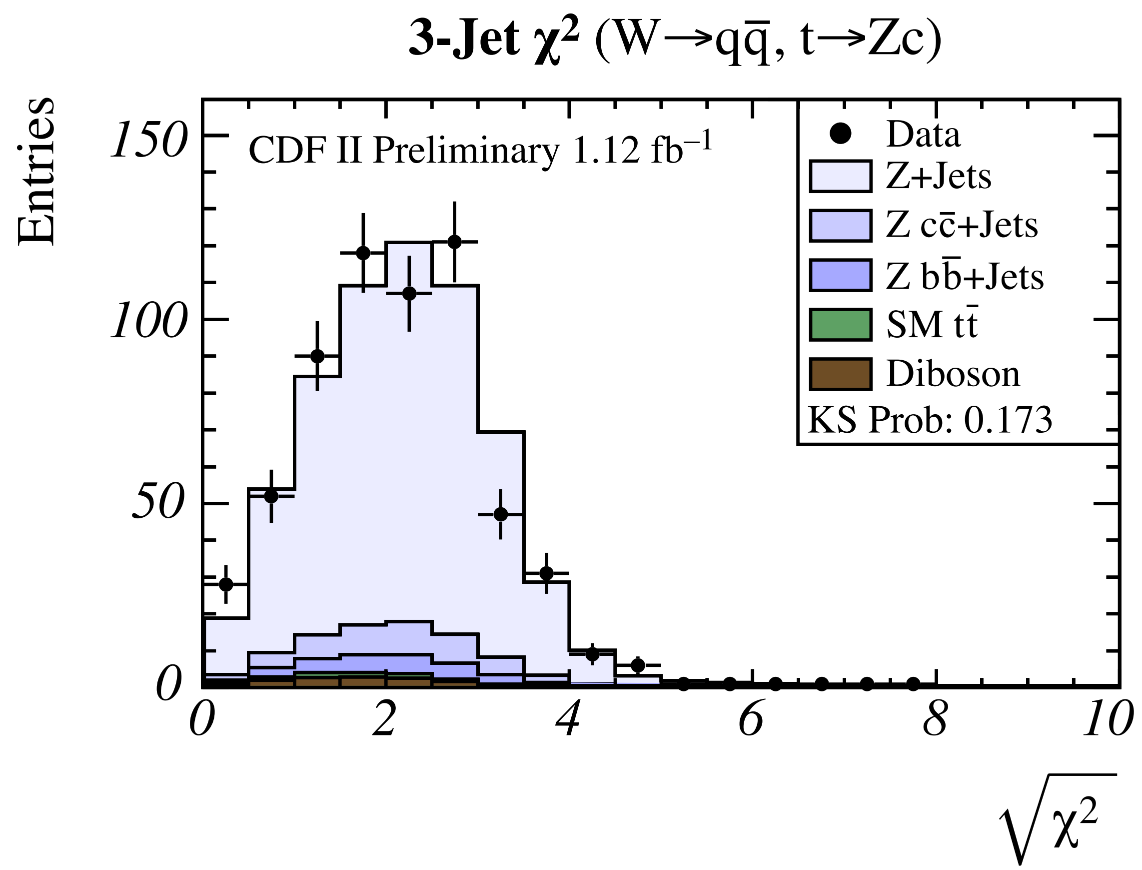
Selection	Observed (Expected) Events m_T >200 GeV	Observed (Expected) Events m_T >220 GeV
Anti-Tagged	12 (7.7)	7 (6.4)
Loose Tag	4 (3.2)	3 (2.8)
Total	16 (10.8)	10 (9.2)
Cut Efficiency (%)	11.3 (8.3)	7.1 (7.1)

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



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



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

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

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

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

Systematics: Details

Helicity	Base Selection (%)	Anti-Tagged (%)	Loose Tag (%)
35% LH, 65% Long.		default	
Flat	−4.3	−4.2	−4.5
100% Longitudinal	5.0	4.7	4.5
100% Left-Handed	−9.2	−8.8	−8.3
100% Right-Handed	−8.6	−8.6	−9.5
35% RH, 65% Long.	0.2	0.1	−0.4
Total Uncertainty (%)	3.5	3.4	3.2

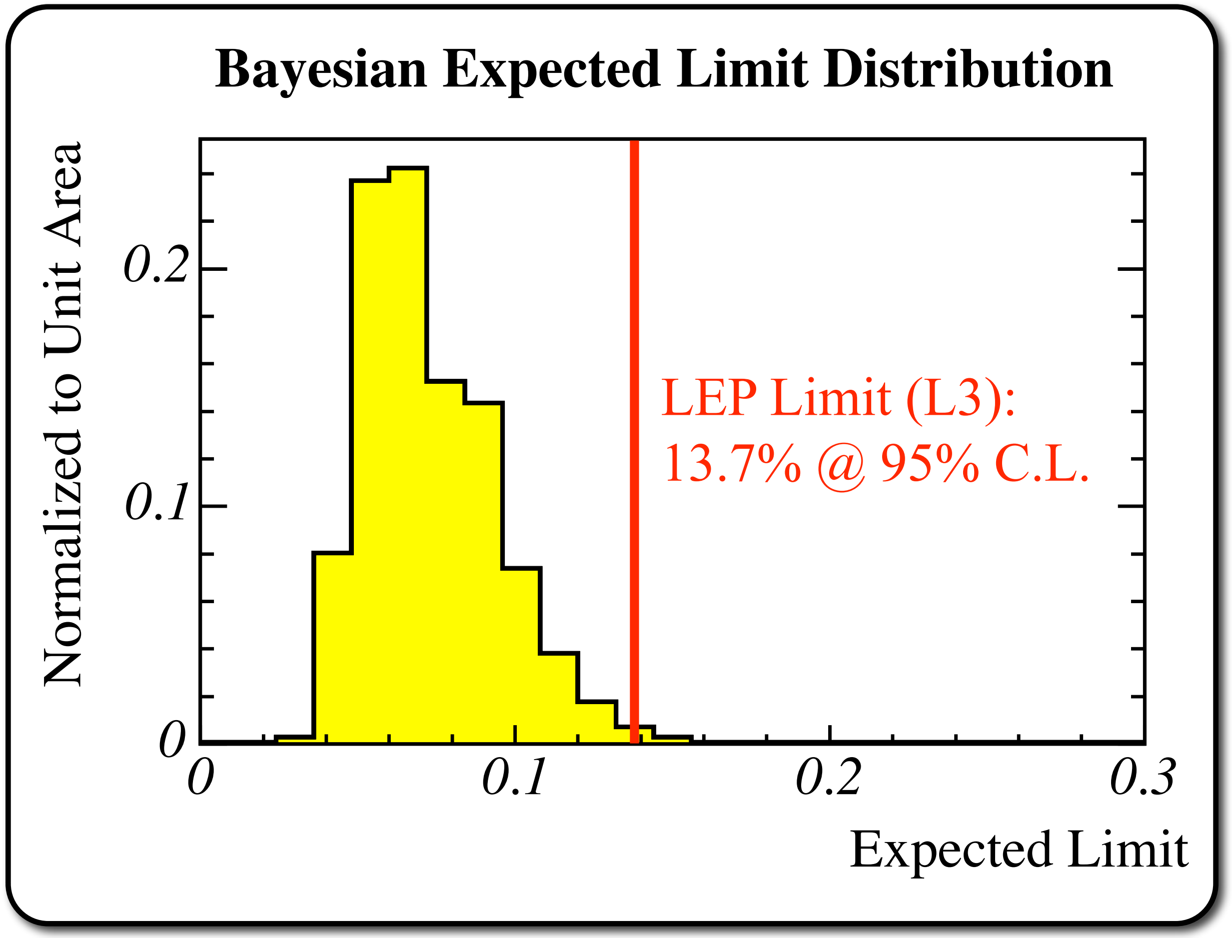
Sample	Base Selection (%)	Anti-Tagged (%)	Loose Tag (%)
More ISR	0.0	2.4	−1.6
Less FSR	0.4	−0.1	3.0
More FSR	−0.1	−0.9	2.9
Less FSR	1.3	−0.4	4.7
Total	1.3	2.6	6.5

Expected Limits and Sensitivity

- Expected limit:

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

  - *P*: Poisson probability to observe n_{obs} events with n_{back} background events
  - Lim: limit with n_{obs} events given acceptance *A* and n_{back} background events (any limit calculation machinery)
- This analysis:
  - (Faster) objective Bayesian limits for optimization
  - ("Better") Feldman-Cousins limits for final result
  - Both methods: systematic uncertainties included
  - Results track each other well



Expected 95% C.L. Upper Limit on BR(t→Zq): **7.1% ± 3.0%**

Why Feldman-Cousins?

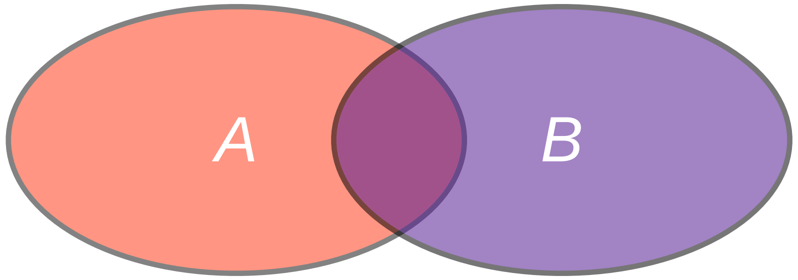
- Reporting results of particle physics experiments: confidence intervals, e.g. central value and uncertainty, upper/lower limit
- Two rivaling schools on reporting confidence intervals
  - Frequentist approach: If the experiment would be repeated infinitely many times, the true value would lie within 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: $P(x_i \mid \mu)$, 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

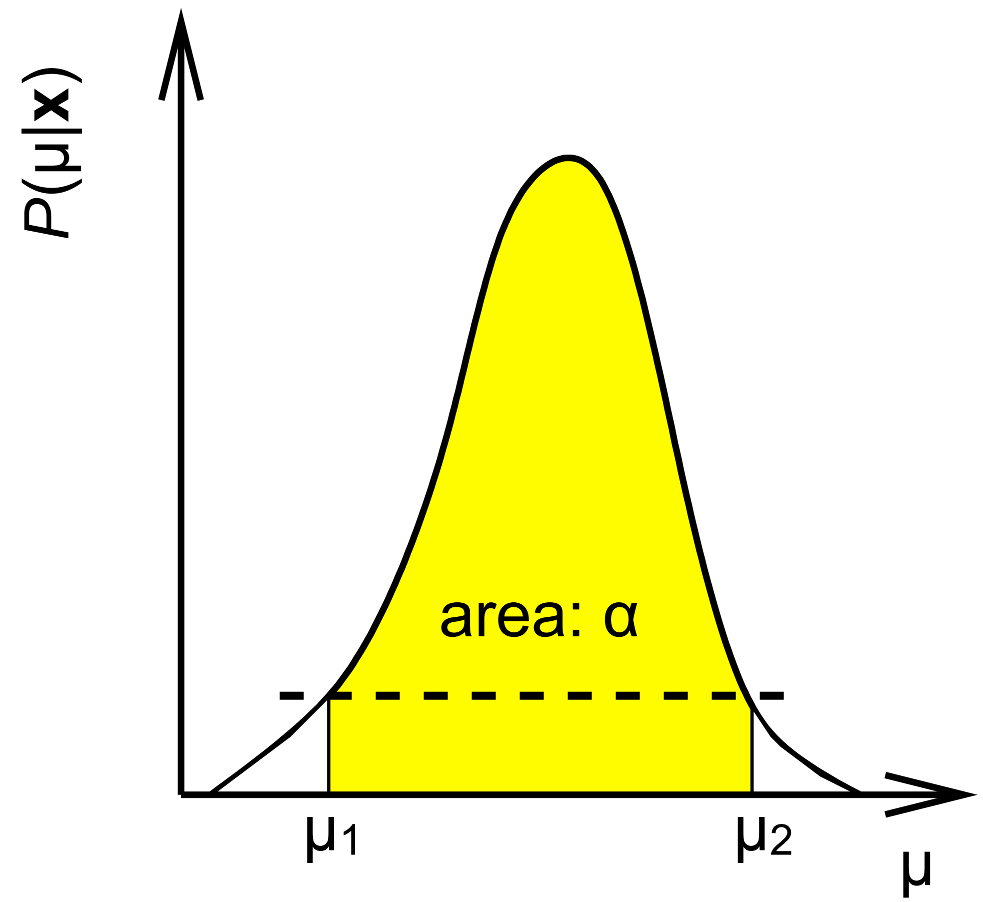
$$\int_{\mu_1}^{\mu_2} \mathrm{d}\mu' \, P(\mu'|\mathbf{x}) = \alpha$$

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)

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



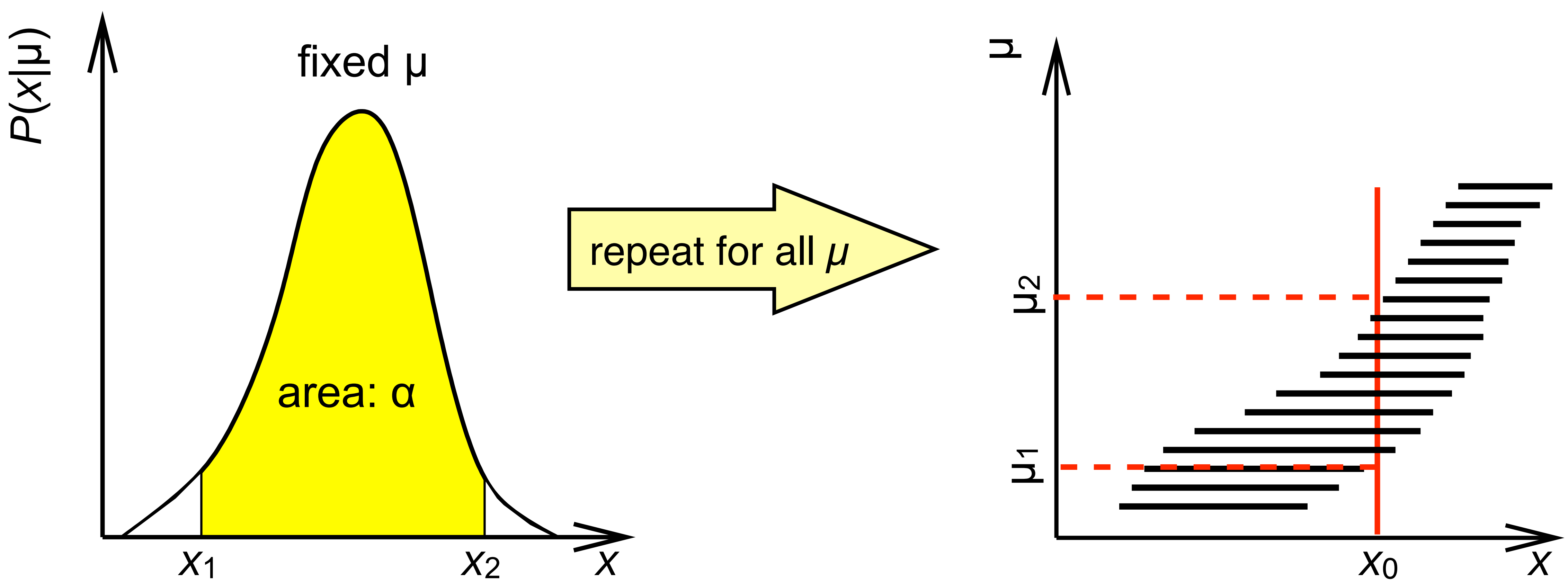
- Solution for uniquely defining μ_1: draw horizontal line at fraction α of area under posterior probability

Frequentist Intervals

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

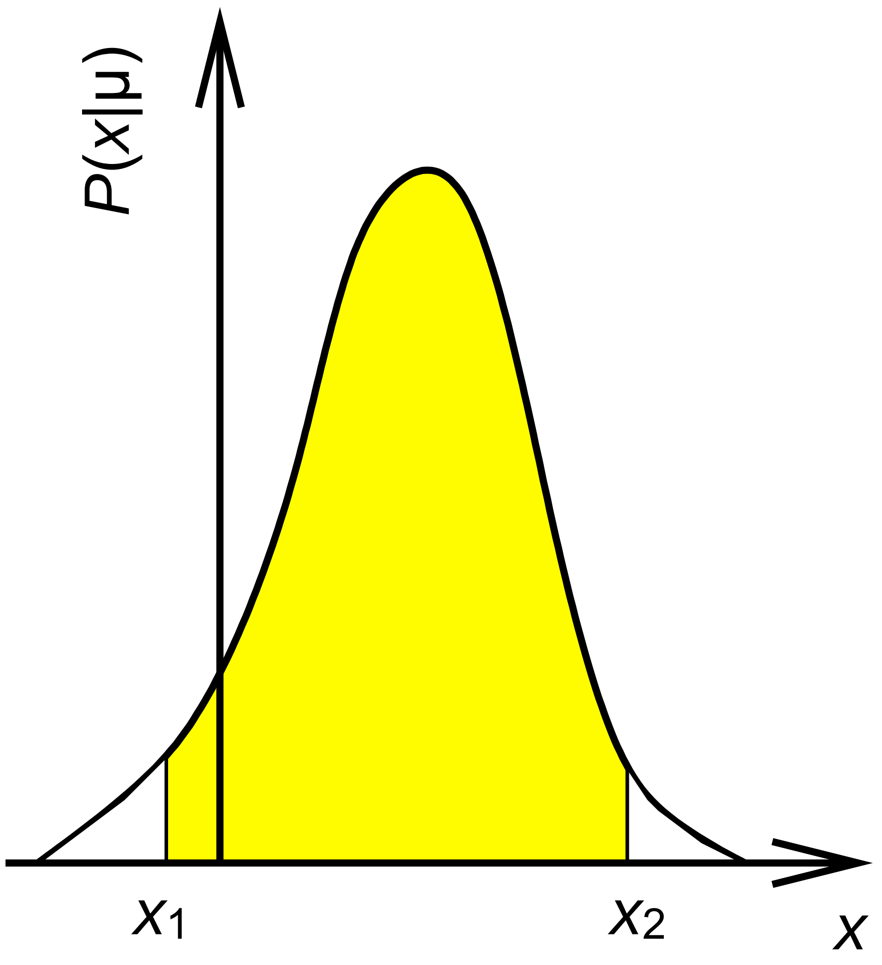
$$\frac{\partial L}{\partial \mu} = 0, \text{ with } L(\mathbf{x}|\mu) = \prod_{i=1}^{N} P(x_i|\mu)$$

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



Frequentist Interpretation

- Infinitely many repetitions of experiment: interval [$\mu_1;\mu_2$] 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"



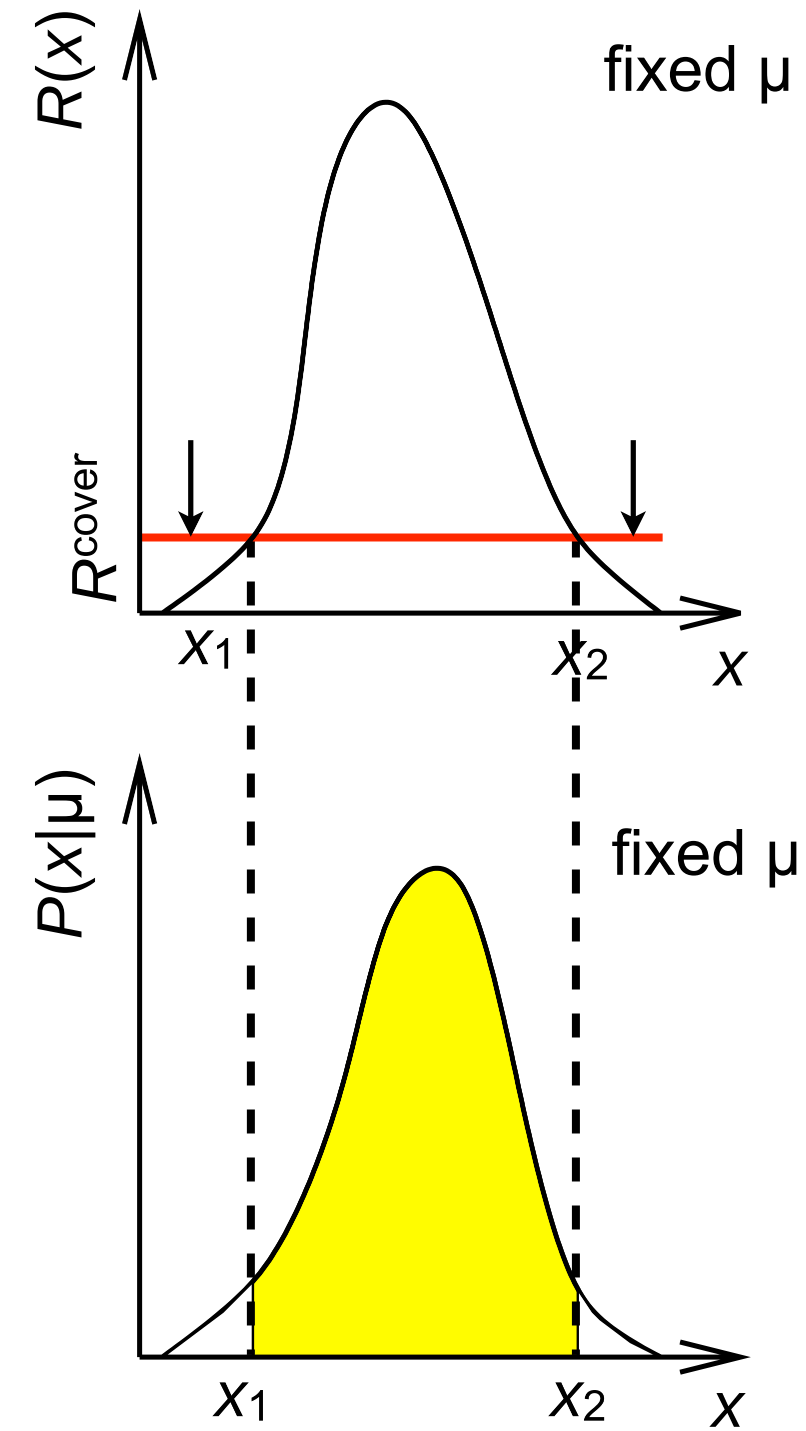
Feldman–Cousins Construction

- 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, …