Highlights from High P_T Physics at CDF

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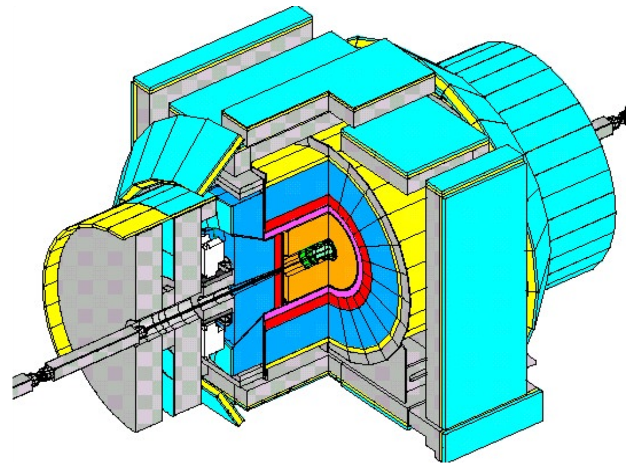
Fermilab Users' Meeting, June 8, 2005

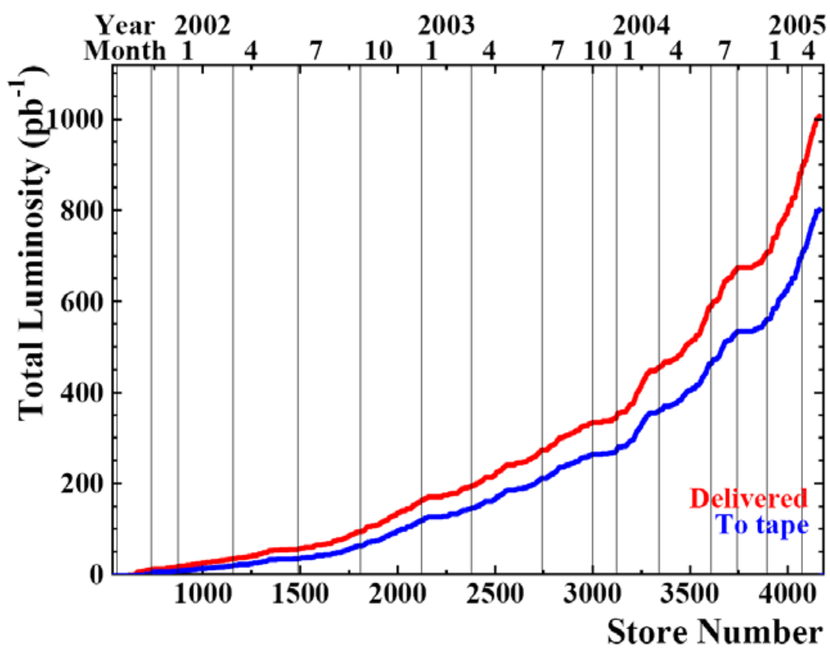
Topics from electroweak, top, and exotic physics

CDF at the Tevatron

Records falling like dominos!



- Tevatron and CDF performance:
  - Last month was very exciting:
    - Init. luminosity > **1.3×10^{32} cm^{-2}s^{-1}**
    - Single store: > **5 pb^{-1}**
    - Delivered integrated luminosity: **1fb^{-1}**
    - CDF recorded ~**0.8 fb^{-1}**
  - High-luminosity upgrades on schedule
- Current analyses use 0.3-0.4 fb^{-1}



Electroweak Physics

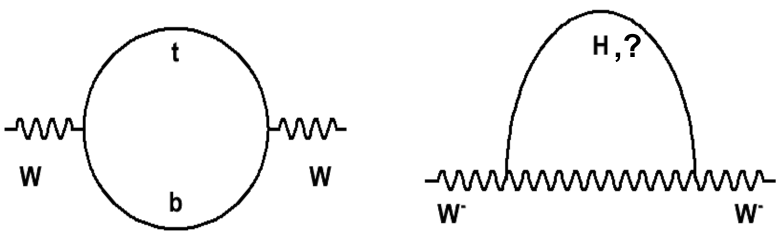
- W and Z leptonic decays
  - Yardstick for all high-P_T lepton analyses
  - Backgrounds for many new physics processes
  - Used for calibration of energy/momentum scales

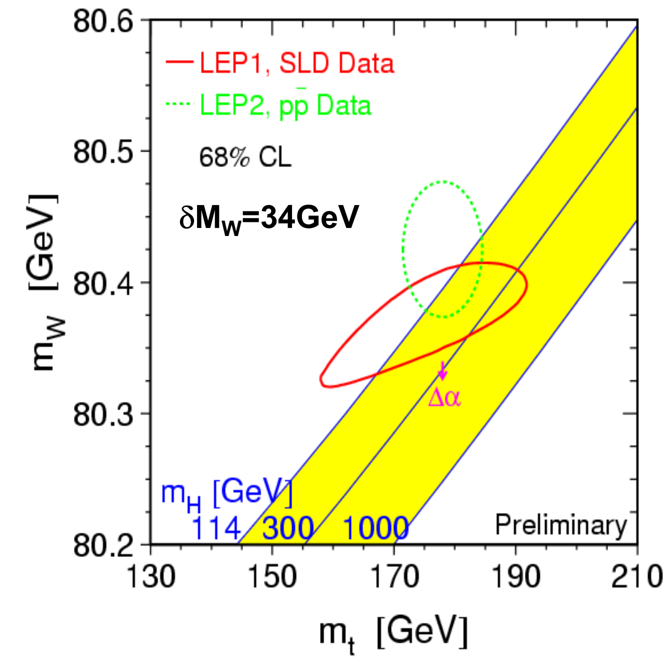
- Large datasets → better and broader physics reach:
  - √ W/Z cross-sections: Phys.Rev.Lett.94:091803,2005
  - √ Z boson asymmetry:Phys.Rev.D71:051104,2005
  - √ W charge asymmetry: Phys.Rev.D71:051104,2005
  - √ $W\gamma$, $Z\gamma$ production: Phys.Rev.Lett.94:041803,2005
  - √ ZZ, ZW production: Phys.Rev.D71:091105,2005
  - √ WW production: hep-ex/0501050

- Highlights:
  - W boson mass measurement
  - Diboson measurements

Introduction to m_W

- $W^{\pm}$ mass fundamental parameter of SM
  - Radiative corrections: depend on m_t and m_H



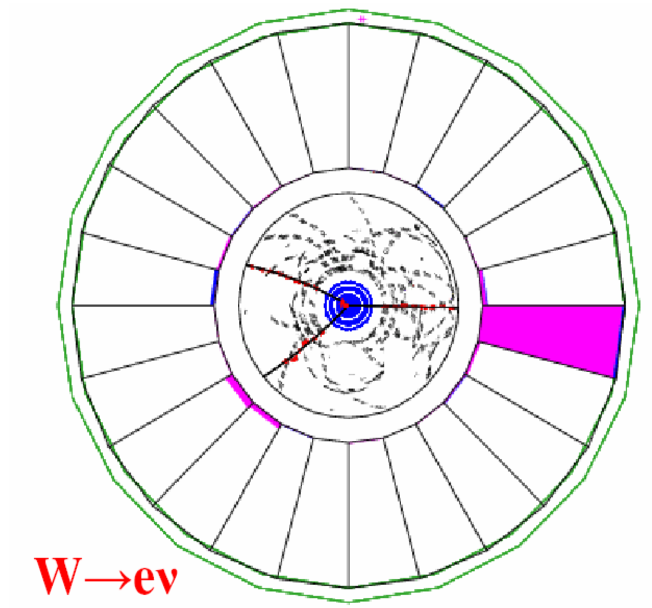


- Measure m_W, m_t precisely → constrain m_H!
- Currently, m_W known to a precision of 34 MeV:
  - LEP: 80,447 ±42 MeV
  - Tevatron: 80,454 ±59 MeV (Run I)
    - Uncertainty: 79 MeV (CDF), 84 MeV (D0), with $L \approx 120\ pb^{-1}$
- Run II Goal: uncertainty < 40 MeV per experiment

W Mass

- How do we measure W mass:
  - Clean signals: $W \rightarrow e\nu$, $W \rightarrow \mu\nu$
  - Most information comes from $P_T(\ell)$, $\ell = e, \mu$
  - Neutrino $P_T(\nu)$ inferred via hadronic recoil
  - Calculate transverse mass:

$$m^2_{W,T} = 2P^l_T P^\nu_T (1 - \cos\Delta\Phi^{l\nu})$$



$W \rightarrow e\nu$

- Backgrounds (contribute δm_W~20 MeV)

$W \rightarrow \mu\nu$

Background	%
Hadronic Jets	0.9 ± 0.5
Kaons	1.0 ± 1.0
Cosmic Rays	0.3 ± 0.1
$Z \rightarrow \mu\mu$	4.4 ± 0.2
$W \rightarrow \tau\nu$	1.9 ± 0.1

$W \rightarrow e\nu$

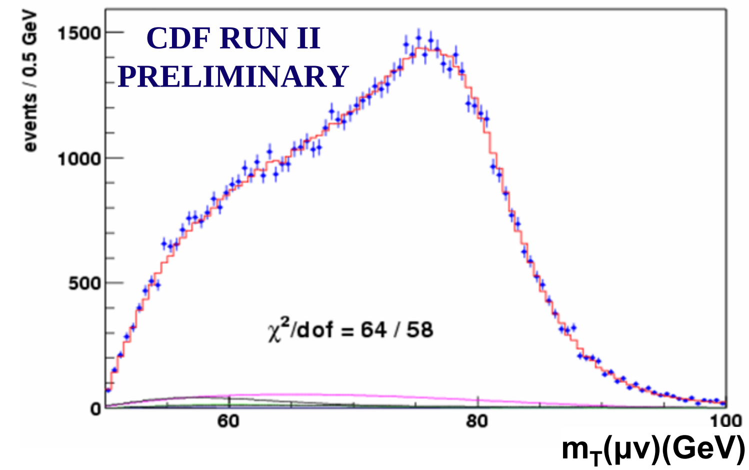
Background	%
Hadronic Jets	1.1 ± 0.4
$Z \rightarrow ee$	0.27 ± 0.03
$W \rightarrow \tau\nu$	1.9 ± 0.1

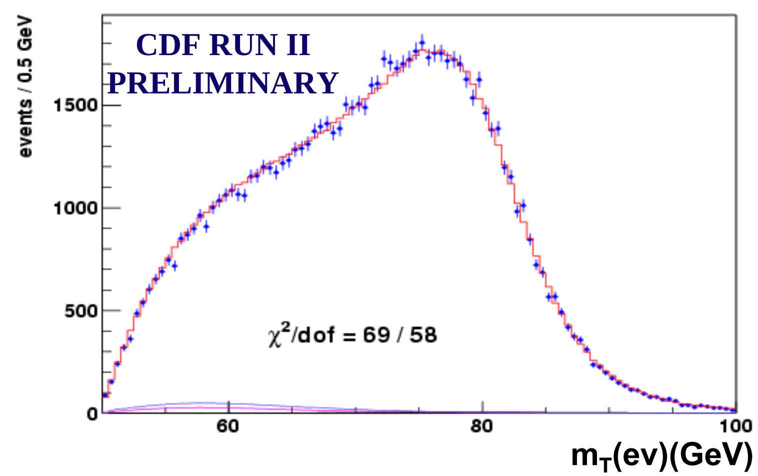
W Mass Status

Source	e: Run2 (IB)	μ: Run2 (IB)
Lepton Energy Scale and Resolution	70 (80)	30 (87)
Recoil Scale and Resolution	50 (37)	50 (35)
Backgrounds	20 (5)	20 (25)
Production and Decay Models	30 (30)	30 (30)
Statistics	45 (65)	50 (100)
Total	105 (110)	85 (140)

- First pass at W mass with 200 pb^{-1}:
  - Uncertainty δm_W=76 MeV lower than CDF Run I
  - Work in progress to reduce δm_W :
    - **Adjust tracker aligment**
    - **Recoil resolution and $P_T(W)$**
    - **Passive material and radiation**
  - First m_W results to be finalized soon

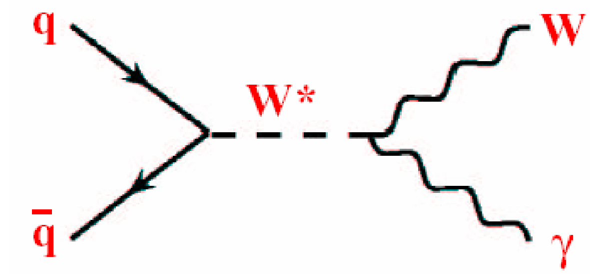
W transverse mass m_T fit:





Dibosons: Wγ, Zγ, WZ, ZZ

- Test of WWγ couplings
- Constrain ZZγ and Z γ γ vertices (absent in SM)
- Background of gauge-mediated SUSY Breaking models



Phys.Rev.Lett.94:041803,2005

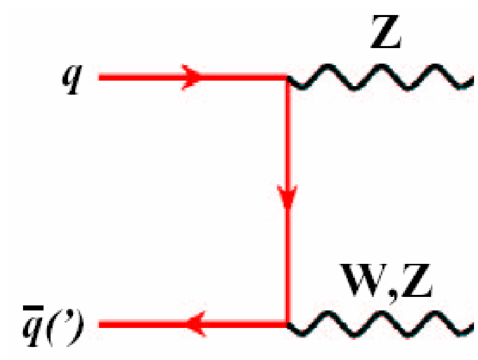
$$\sigma(p\bar{p} \to W\gamma) = 18.1 \pm 3.1\,\text{pb}$$

SM expect: σ(Wγ) = 19.3 ± 1.4 pb

$$\sigma(Z\gamma) = 4.6 \pm 0.6\,\text{pb}$$

SM expect: σ(Z γ) = 4.5 ± 0.3 (pb)

- WZ, ZZ important step towards Higgs searches
- $W^{\pm}Z$ unavailable at e^+e^- colliders => unique meas. of WWZ



σ(pp→ZZ/ZW+X) <15.2 pb at 95% C.L.

$\sigma(pp\to ZZ/ZW+X)^{THEORY}_{NLO} = 5.0 \pm 0.4$ pb

Phys.Rev.D71:091105,2005

Dibosons: WW

- History:
  - large statistics at LEP2 (but lower en. scales)
  - Tevatron Run I low significance: 5 events over 1.3±0.3 bkgrd.
- First Run 2 result:

  hep-ex/0501050

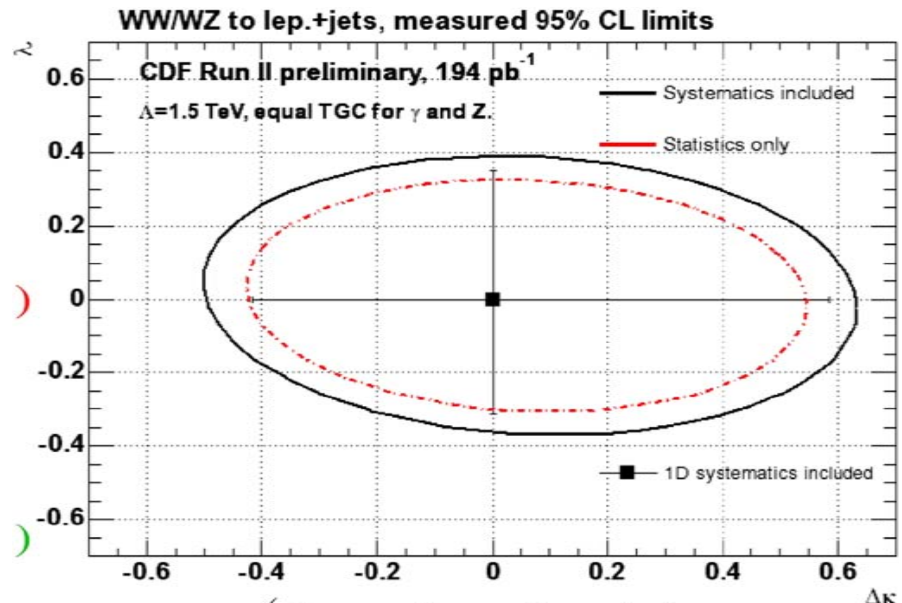
  $\sigma(pp\to WW)^{THEORY}_{NLO} = 12.4 \pm 0.8$ pb

  $$\sigma(WW) = 14.6^{+5.8}_{-5.1}(stat.)^{+1.8}_{-3.0}(sys.) \pm 0.9(lum)\ \mathrm{pb}$$

- Can also search for lepton+jets signature (lνjj):
  - Higher BR than dilepton final state
  - Larger uncertainties
  - Smaller S/B ratio

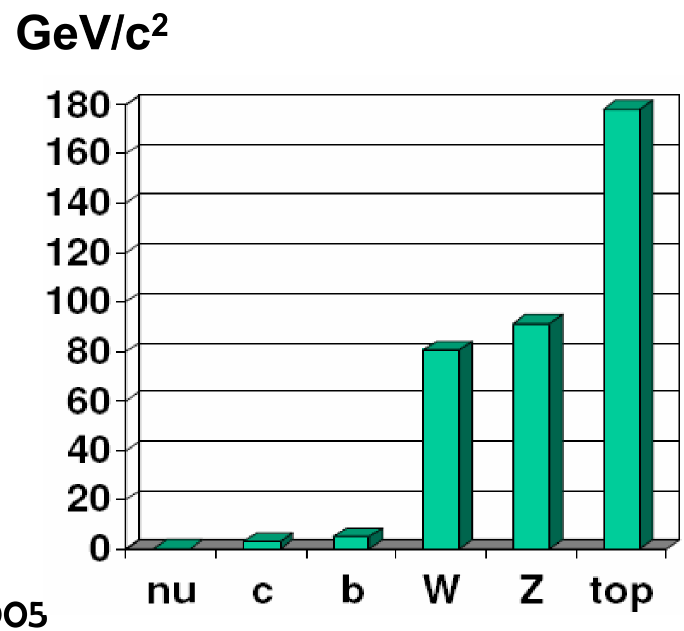
  $$\sigma(WW/WZ) < 40\mathrm{pb}\ (\mathrm{at}\ 95\%\ \mathrm{C.L.})$$

  - Constrain anomalous triple gauge couplings



$(\Delta\kappa_\gamma = \Delta\kappa_Z,\ \lambda_\gamma = \lambda_Z)$

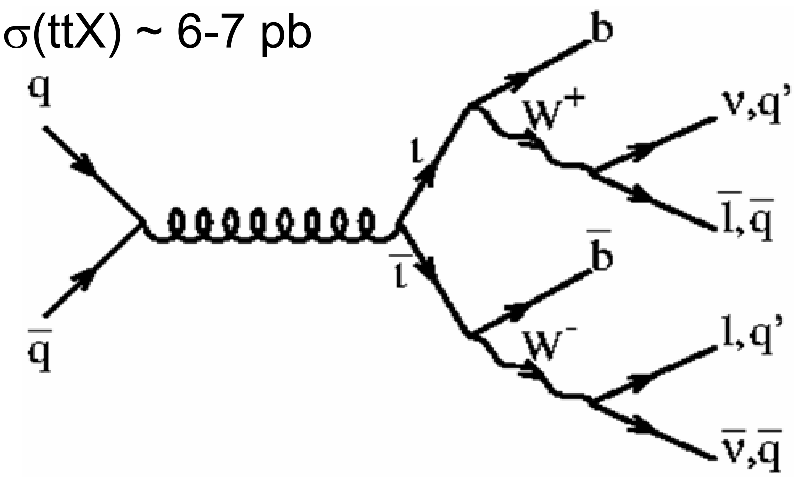
Top Physics at CDF

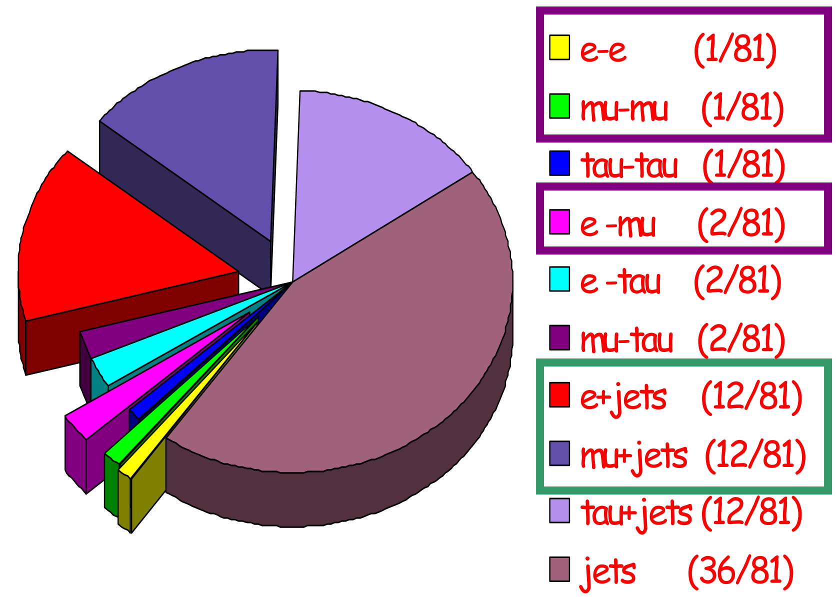


- Top is the most intriguing particle we know:
  - Why so heavy?
  - m_t, m_W, m_H are related via loop diagrams
  - Top decays before hadronizing ($4 \cdot 10^{-25}$ s)
  - SM Yukawa coupling ~1 (coincidence?)
- CDF top group very dynamic:
  - √ Single-top-quark search: **Phys.Rev.D71:012005,2005**
  - √ W polarization in top decays: **Phys.Rev.D.71:031101,2005**
  - √ Top pair cross section b-tag: **Phys.Rev.D71:052003,2005**
  - √ Top pair cross section kinematic+b-tag: **Phys.Rev.D71:072005,2005**
  - √ Top pair cross section kinematic (NN): **hep-ex/0504053,2005**
  - √ Top pair cross section with Soft Muon Tagging: **hep-ex/0506001,2005**
  - √ Anomalous kinematics in tt dilepton events: **FERMILAB-PUB-04-396-E**
  - √ $Br(t \to Wb)/B(t \to Wq)$: **FERMILAB-PUB-05-219-E**
- Highlights:
  - Top mass measurement
  - Top cross-section measurement

Top Phenomenology

- Only at the Tevatron! (so far)
- Strong (pair) production – main channel
  - $\sigma(ttX) \sim 6\text{-}7$ pb





- Top decay:
  - SM: $t \rightarrow Wb$ almost 100% of the time
  - CDF: $V_{tb} >> V_{ts}$, V_{td}
  - Classified according to W decays
    - **Lepton+jets, dilepton, all hadronic**

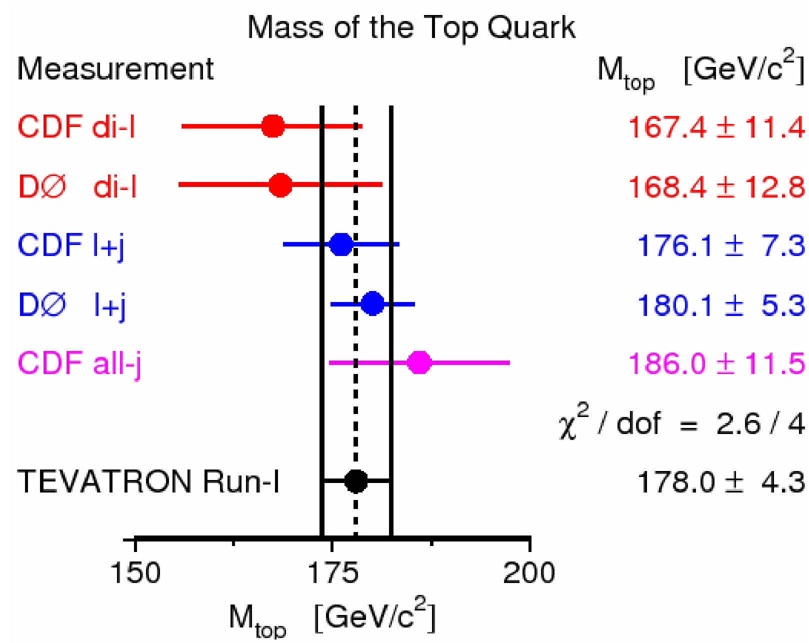
- 5% Dilepton (ee, μμ, eμ)
- 30% Lepton+jets (e+j, μ+j)
- 45% All hadronic

Top Quark Mass

- Run I average:

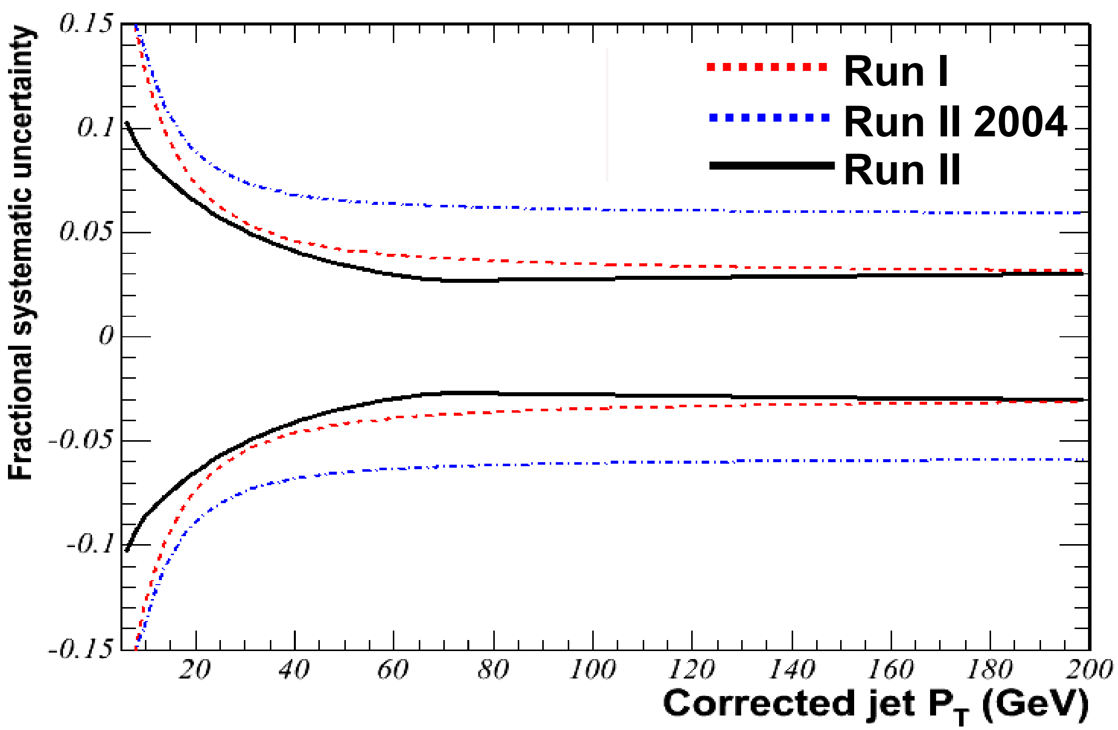
$$m_t = 178.0 \pm 4.3 \text{GeV}/c^2$$

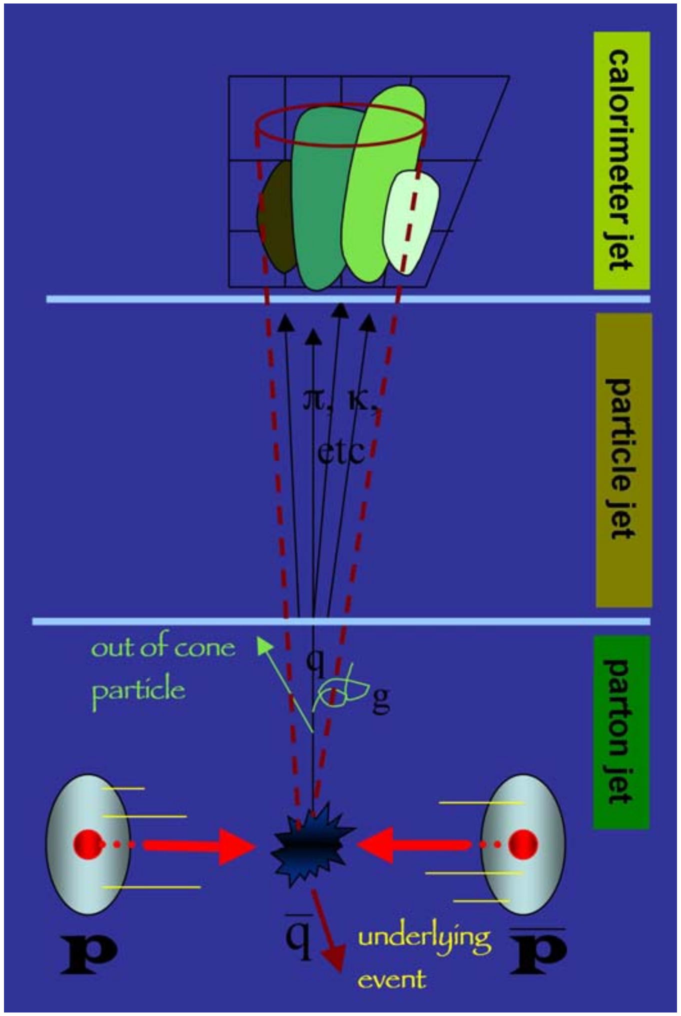
  - Using 106-120 pb^{-1} per exp.
  - Lowest uncertainty: D0 l+jets result
- Run 2 goal:
  - <2.5 GeV uncertainty per experiment
- Already analyzed >300 pb^{-1}
  - We should do better than Run I
- Difficult measurement:
  - Jet energies not precisely measured
  - Final state difficult to reconstruct
    - Many possible configurations
    - ISR and FSR further complicate the picture
  - Small statistics (esp. dileptons)…



Jet Energy Scale Uncertainty

- Jet energies imprecisely measured.
  - Poor resolution → statistical error.
    - 50 GeV quark measured as 30 GeV jet
  - Uncertain scale → systematic error.
    - Jets are hard to calibrate (3-5%)
    - (no nice resonance to use)

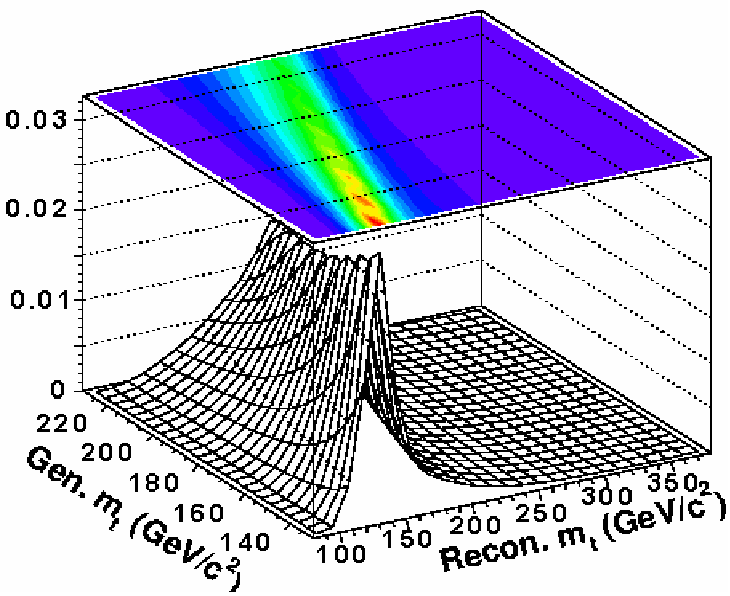




Top Mass in l+jets events

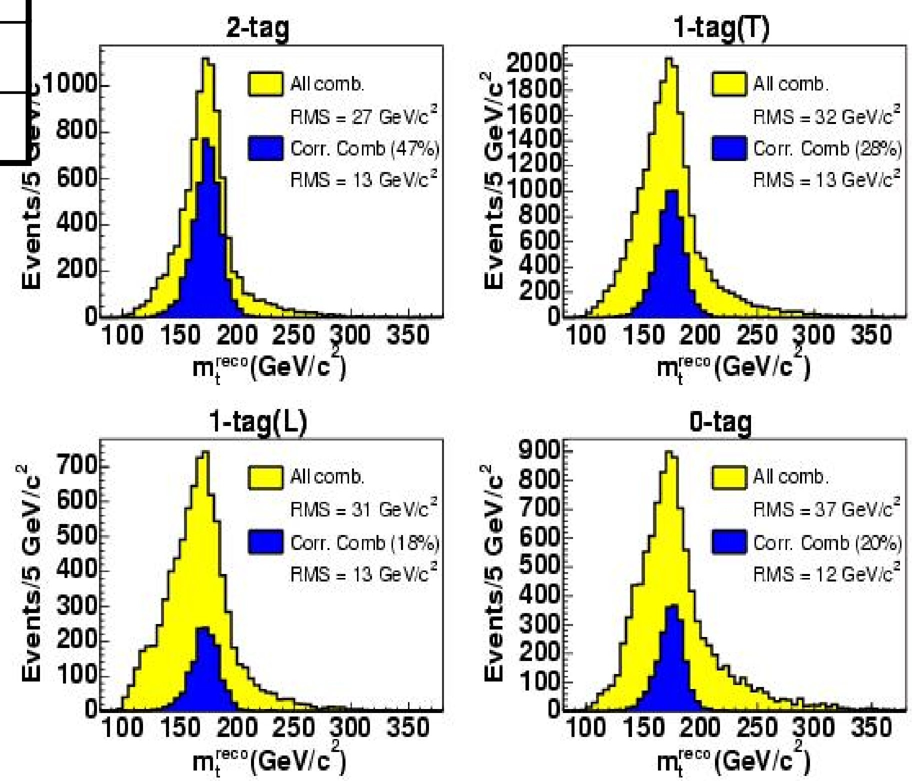
- Lepton+jets channel:
  - ttbar b-tag event efficiency ≅60%

Category	2-tag	1-tag(T)	1-tag(L)	0-tag
j1-j3 j4	E_T>15 E_T>8	E_T>15 E_T>15	E_T>15 15>E_T>8	E_T>21 E_T>21
S:B	18:1	4.2:1	1.2:1	0.9:1
Observe	16	57	25	40



- Reconstruct mass:
  - χ^2 mass fitter – one number per event
  - Best m_t and combination assignment

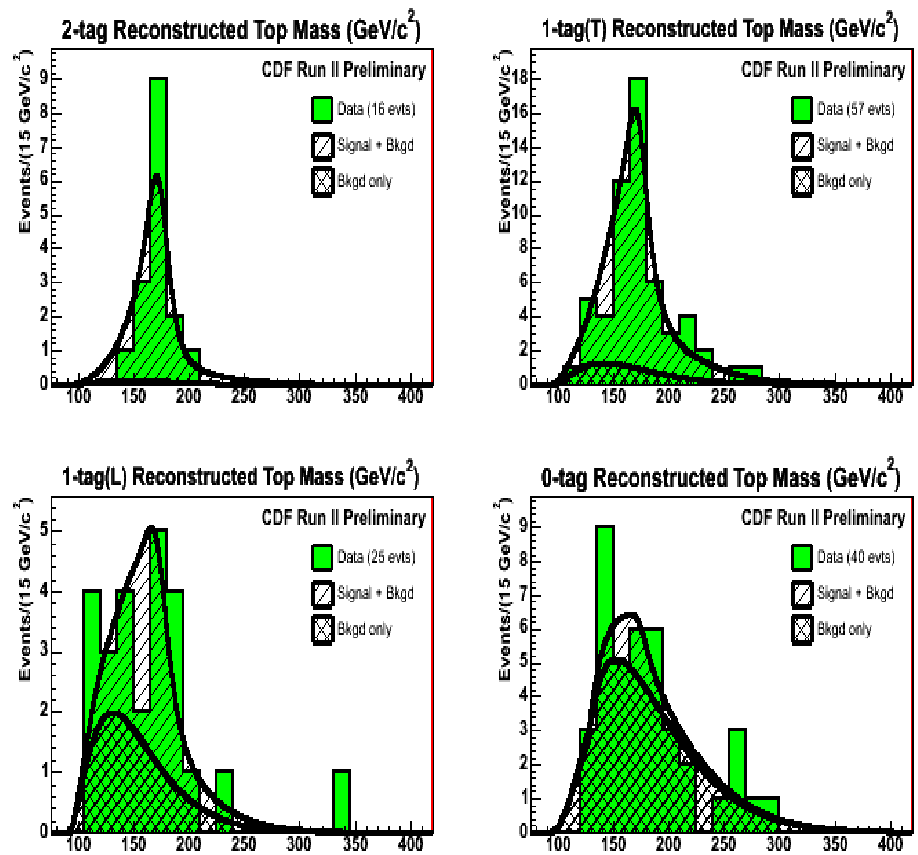
ttbar Monte Carlo



Fit to Data

- Simultaneous fit in the 4 channels
  - **Luminosity: 318 pb^{-1}**
- Systematic uncert. dominated by JES:

Jet Energy Systematic Source	Uncert. (GeV/c^2)
Relative to Central Region	0.6
Corrections to Hadrons (Absolute Scale)	2.2
Corrections to Partons (Out-of-Cone)	2.1
Total	3.1

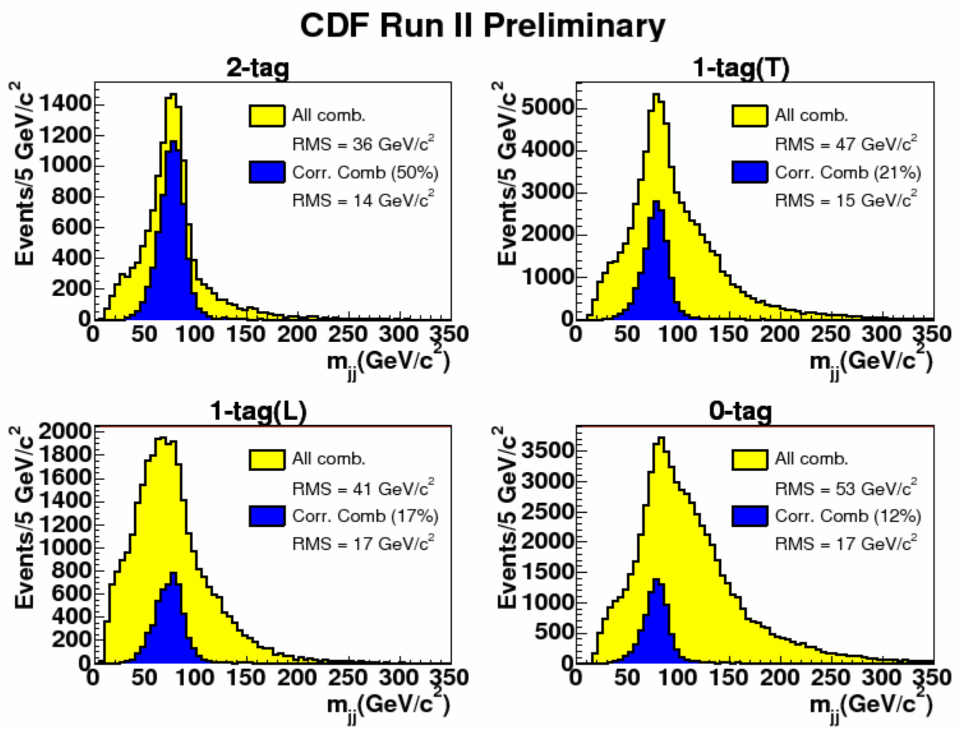


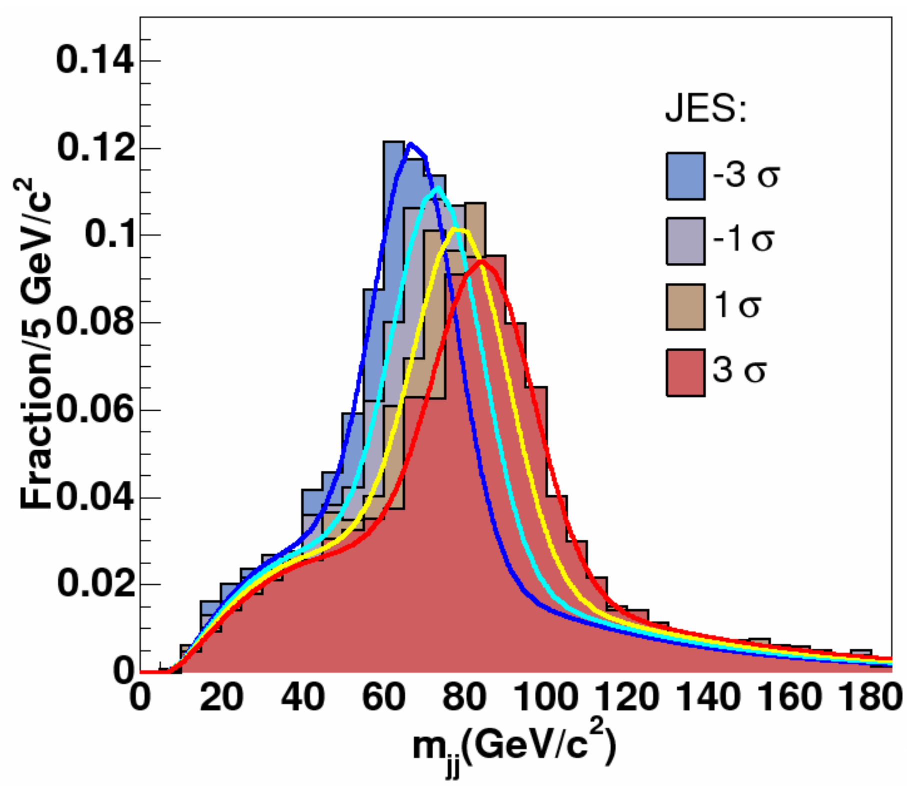
….The answer is:

$$m_t = 173.2 + 2.9/-2.8\ (stat) +/- 3.4\ (syst)\ GeV/c^2$$
$$= 173.2 +4.5/-4.4\ GeV/c^2$$

Using M_W to constrain JES

- Build templates using invariant mass m_{jj} of all non-tagged jet pairs
- $1\sigma \equiv 3.1$ GeV uncertainty

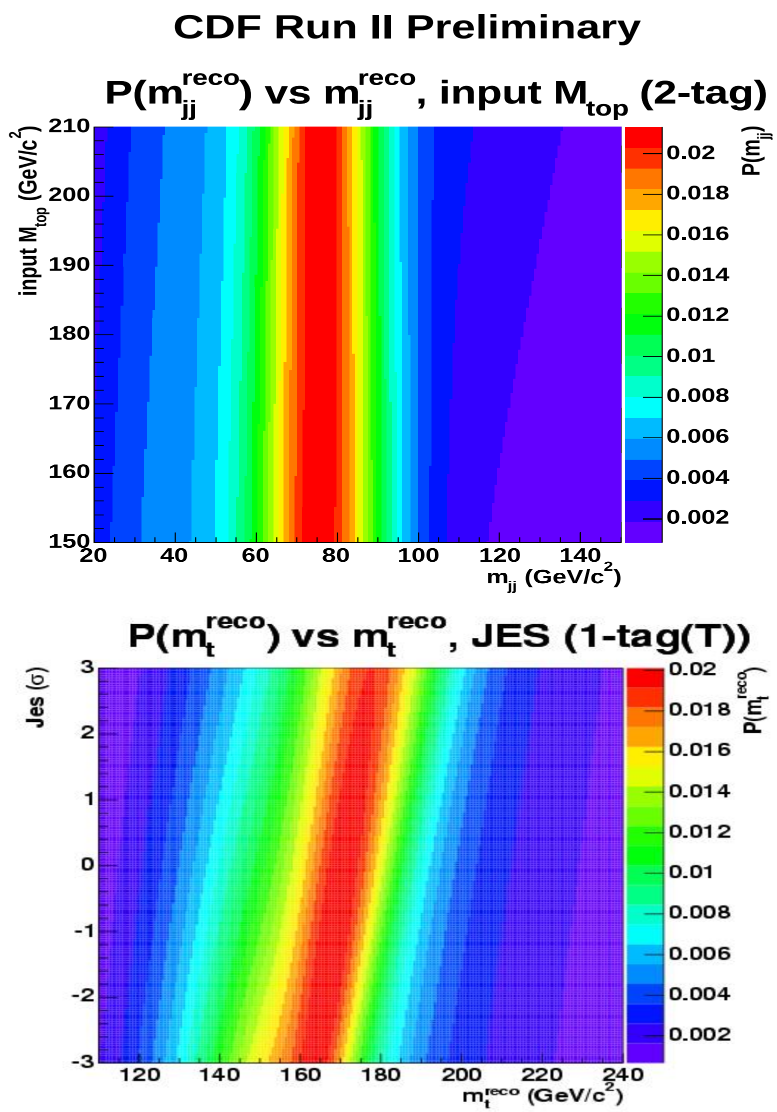




- Rather than assuming JES and measuring M_W...
- Assume M_W and measure JES
- Parameterize $P(m_{jj};JES)$ same as $P(m_t^{reco};M_{top})$

2D Templates

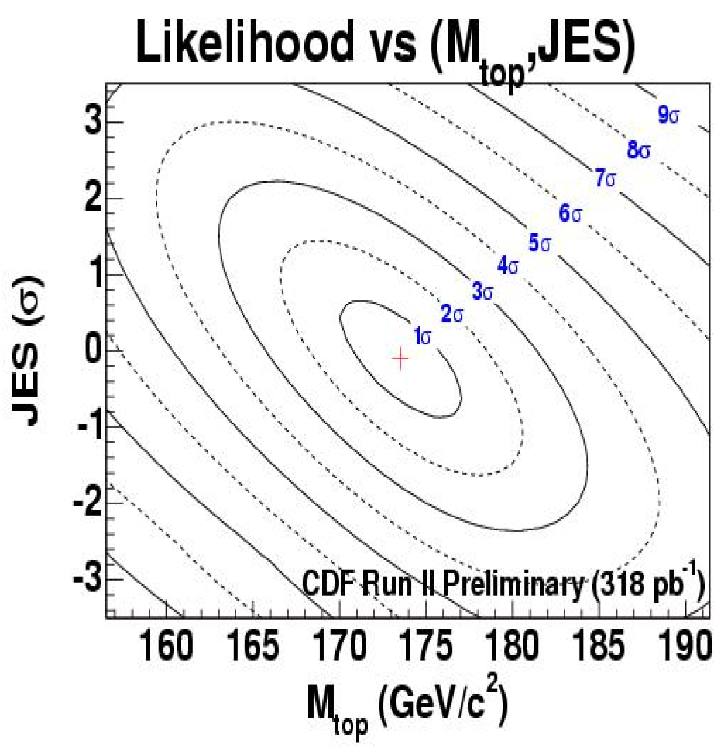
- Account for correlations:
  - $P(m_{reco}|M_t,JES)$ and $P(m_{jj}|M_t, JES)$ templates for every point (M_t, JES)
  - More complex, but tractable
- (2D) Fit data simultaneously for M_t, JES
- This reduces JES uncertainty:
  - In turn, top mass uncertainty is reduced
- Bonus:
  - Using this method, JES scales down directly with luminosity!



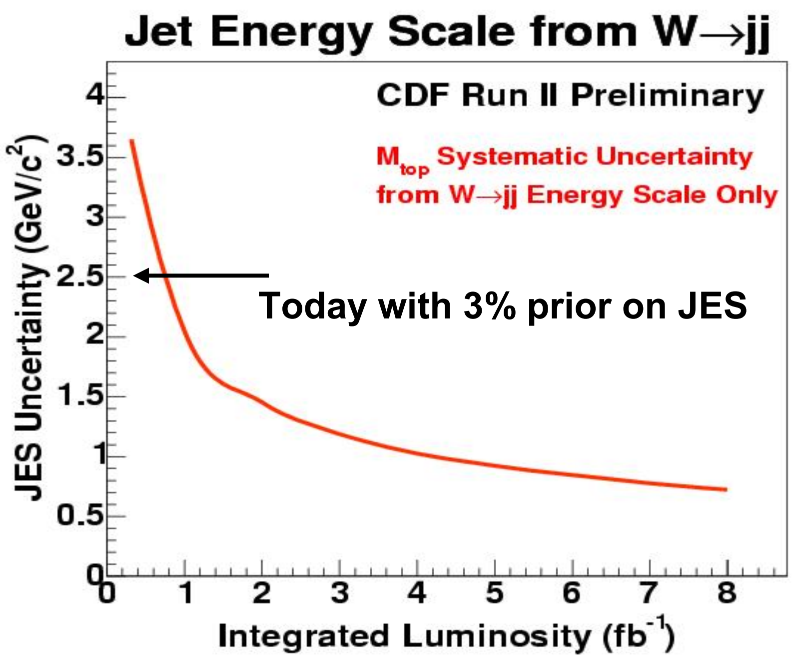
Fit to Data (318 pb^{-1})

$$m_t = 173.5^{+2.7}_{-2.6}(stat.) \pm 2.5(JES) \pm 1.7(syst.)\text{GeV} / c^2$$
$$= 173.5 + 4.1/-4.0 \ \text{GeV} / c^2$$

$$JES = -0.10^{+0.78}_{-0.80}\,\sigma$$

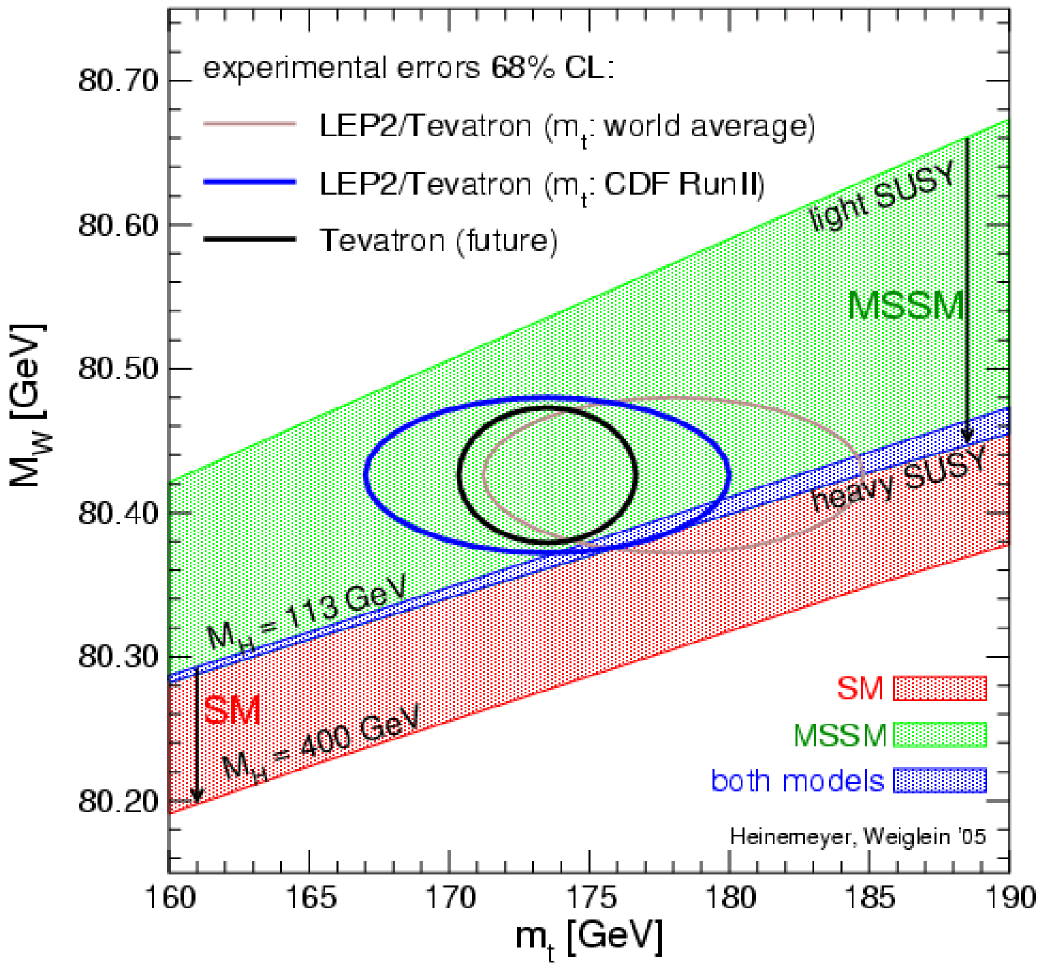


Future is bright ahead!



Implications

- New result is world best measurement of M_{top}!



Thanks to:

S. Heinemeyer

G. Weiglein

M. Grunewald

$$M_{Higgs} = 94^{+54}_{-35}\ GeV/c^2$$

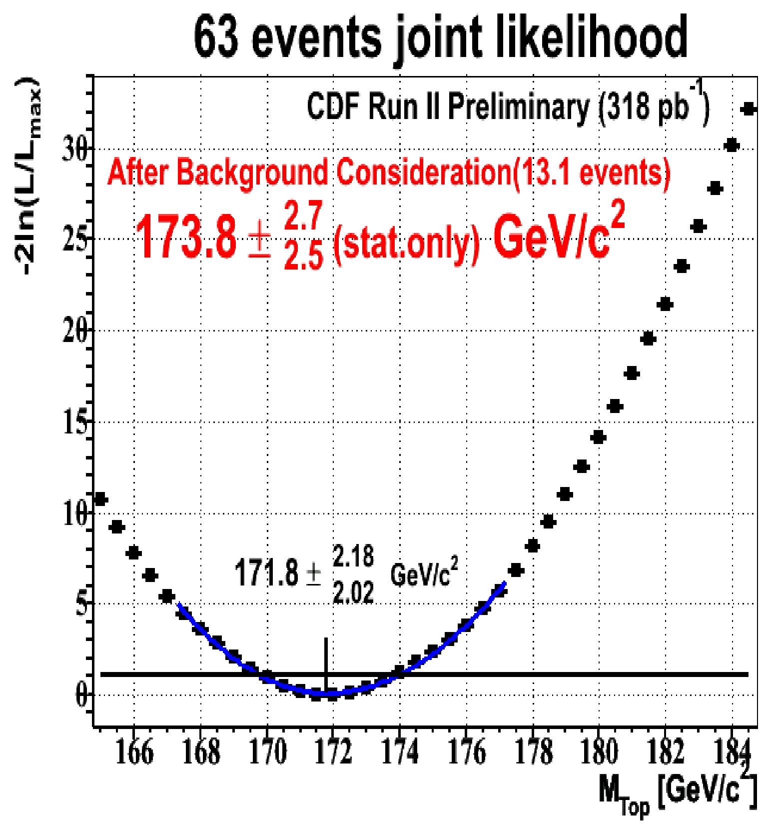
$$M_{Higgs} < 208\ GeV/c^2\ (95\%C.L.)$$

Other Techniques and Results

- Dynamical Likelihood Method
  - Similar to Run I best measurement (DØ): (Nature 429, 638 (2004))
  - Calculates probability for each event to be signal with a given top mass
  - Calculation based on full Standard Model matrix-element
  - **Very statistically powerful!**

$$m_t = 173.8 \pm^{2.7}_{2.5} \text{ (stat) } \pm 3.3 \text{ (syst.) GeV}/c^2$$

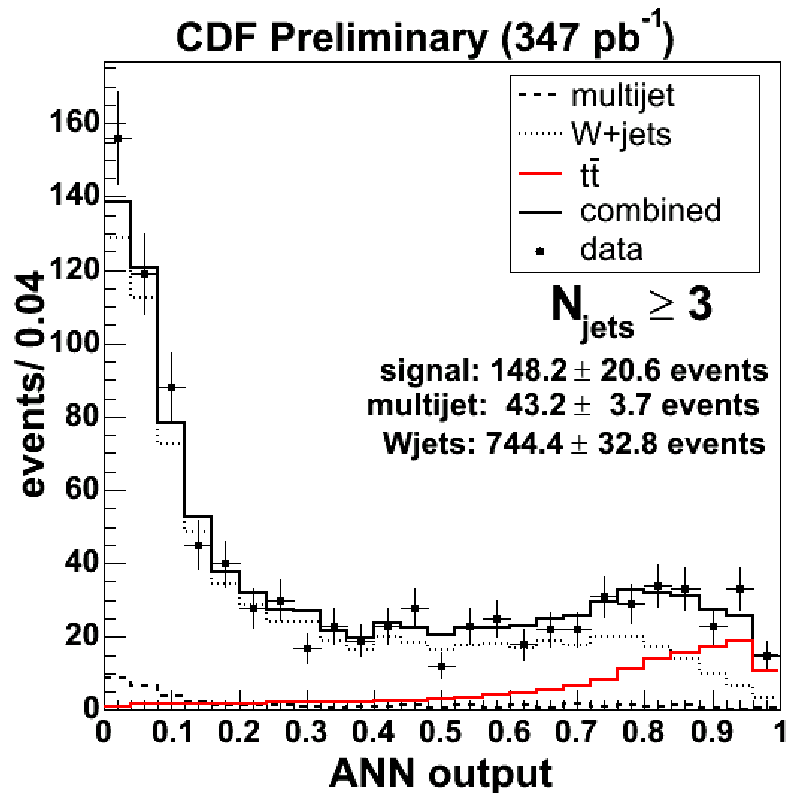
= **173.8 + 4.3 – 4.1 GeV**



- Stay tuned for results from dilepton and all-hadronic analyses
- Publications out by end of summer

Top Pair Cross-Section

- Top pair cross-section:
  - Depends on top mass m_t
  - We need to measure both m_t and $\sigma(tt)$
- Use e+jets, μ+jets events
- Traditionally, require ≥ b-tag
- Alternately, relax b-tag condition:
  - Increase statistics
  - But decrease S/B
- Use 7-input Neural-Network:
  - Energy and angular information



CDF Preliminary (347 pb^{-1})

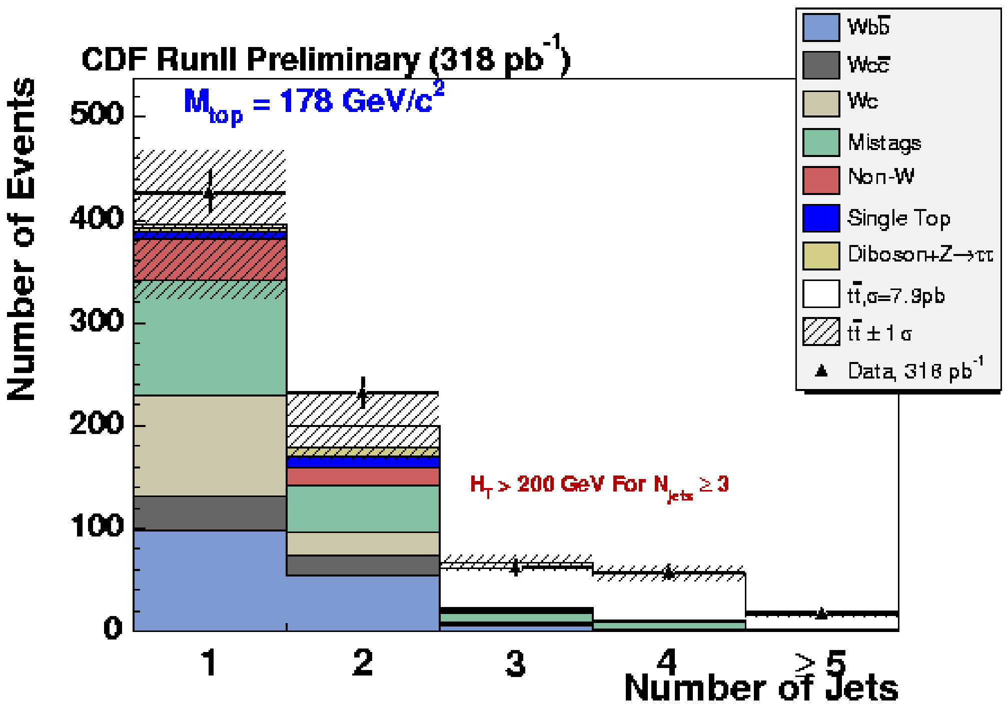
Sample	Events	Fitted $t\bar{t}$	$\sigma(t\bar{t})$
$W+\geq 3$ jets	936	148.2 ± 20.6	$6.0 \pm 0.8 \pm 1.0$ pb
$W+\geq 4$-Jet	210	80.9 ± 15.0	$6.1 \pm 1.1 \pm 1.4$ pb

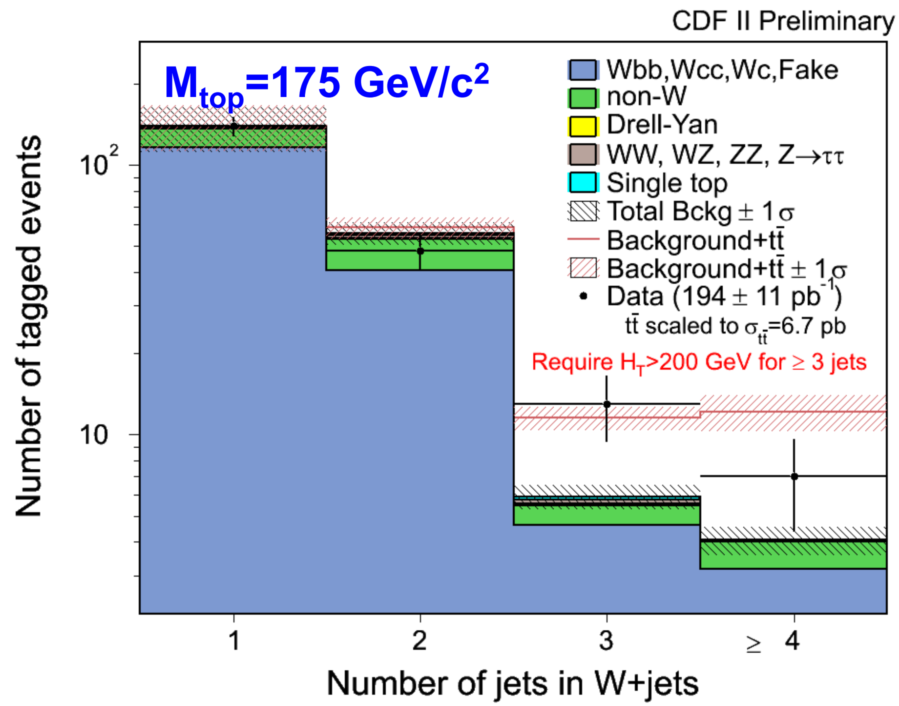
M_{top}=178 GeV/c^2

tt Cross-Section: b-tagging

Displaced vertices (silicon vertex detector)

Soft lepton (muon) tagging



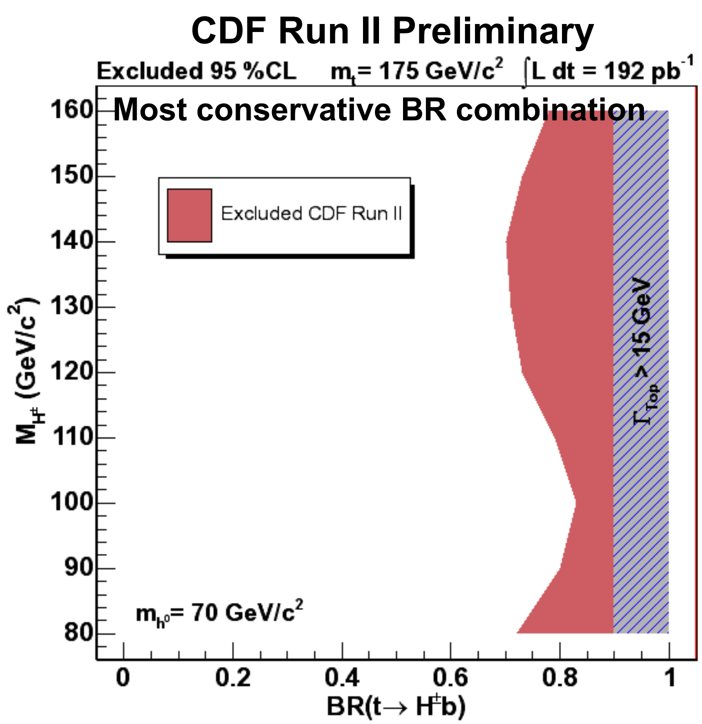


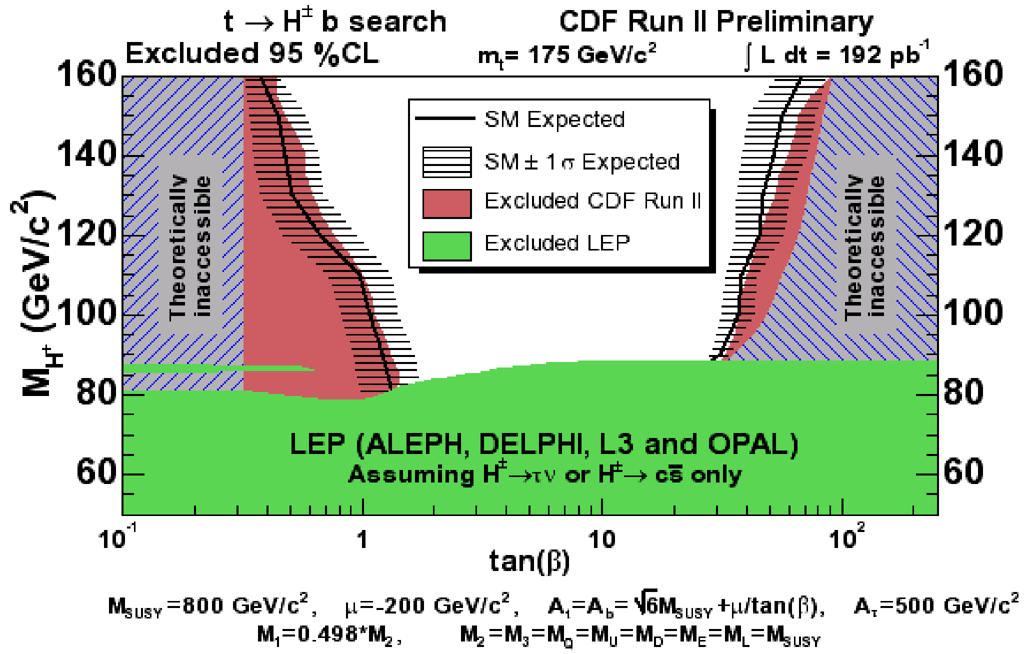
$\sigma(tt) = 7.9 \pm 0.9 \text{ (stat)} \pm 0.9 \text{ (syst) pb}$

$\sigma(tt) = 5.3 \,^{+3.3}_{-3.3} \text{ (stat)} \,^{+1.3}_{-1.0} \text{ (syst) pb}$

Exotic Top Decays?

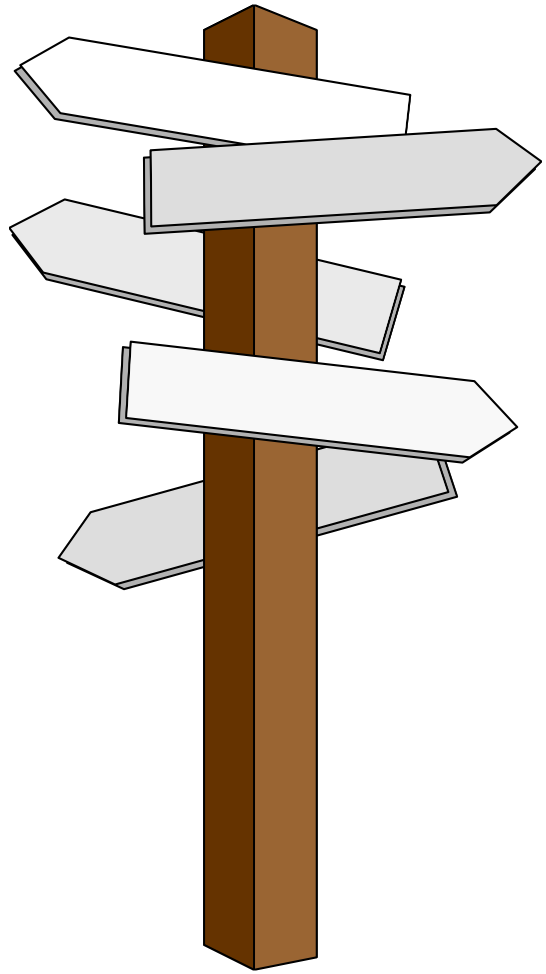
- Standard Model decay: $t \to Wb$
- Two Higgs doublet extension of SM: $H^{\pm}$, A(CP-odd), H,h (CP-even)
  - $t \to H^{+}b$ with $H^{+} \to \tau\nu$, $H^{+} \to cs$, $H^{+} \to Wbb$
- Search in 4 channels:
  - Dileptons, lepton+jets (1, or ≥2 b-tags), lepton+τ (decaying hadronically)





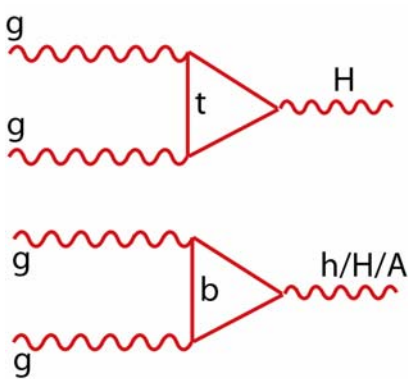
New Physics at CDF

- Where to look?
  - Everywhere we can!
- Events with leptons (even τ's) provide clean signals
- Higgs searches:
  - MSSM Higgs
    - **$A \rightarrow \tau^+\tau^-$ (310 pb^{-1})**
- Search for massive resonances:
  - Spin 0: **Scalar neutrino production and decay (344 pb^{-1})**
  - Spin 1: **Z'-bosons search (448 pb^{-1})**
  - Spin 2: Randall-Sundrum gravitons

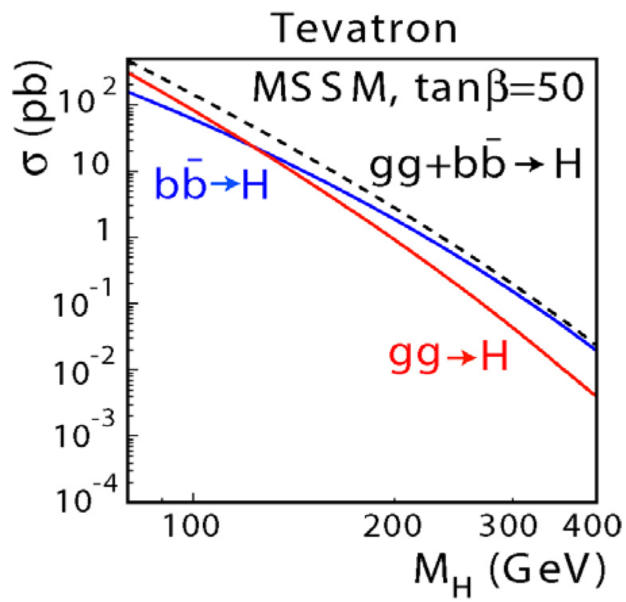


MSSM Higgs: A→ττ

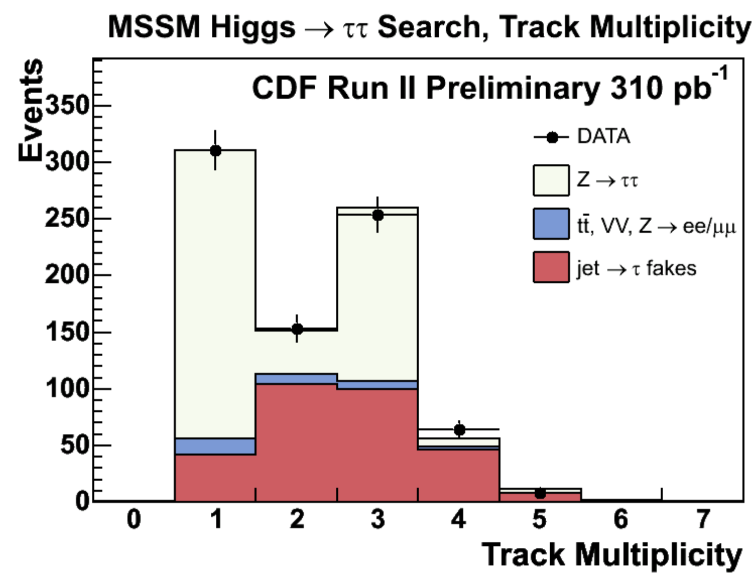
- Enhanced production of A at hadron colliders



$\sigma(pp \to H/A/h) \propto \tan^2\beta$

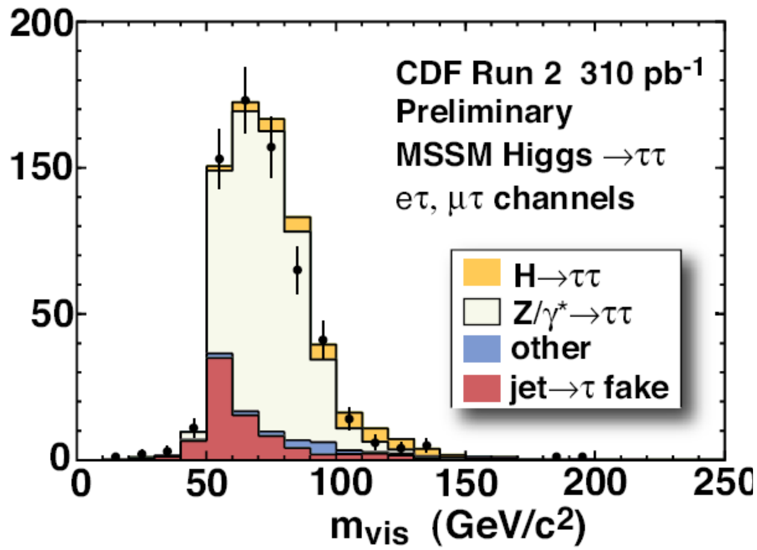


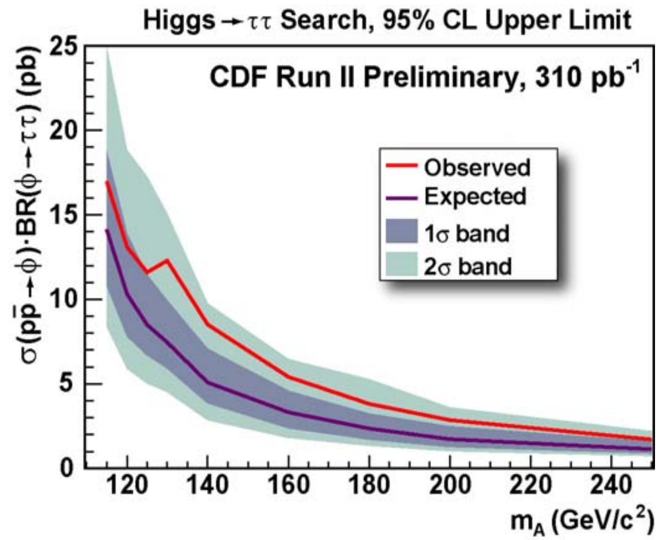
- A decays: bb (~90%) , ττ (~8-9%)
  - bb: larger BR, but need production in association of b-quarks to control bgrds
  - ττ : allows searches in all production channels
- One tau decays leptonically, the other one hadronically
- Backgrounds:
  - **Z→ττ**
  - **Events with jet →τ fakes**



A→ττ Results

Limits set using a likelihood fit of m_{vis} (mass-like variable)

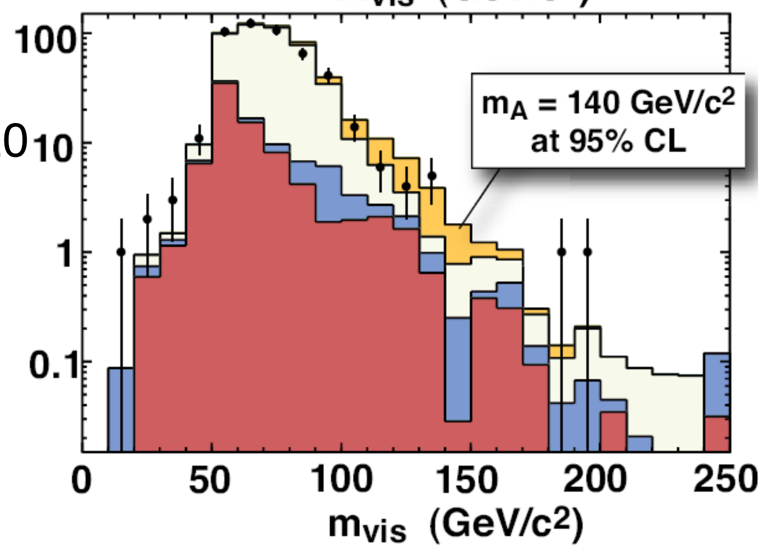


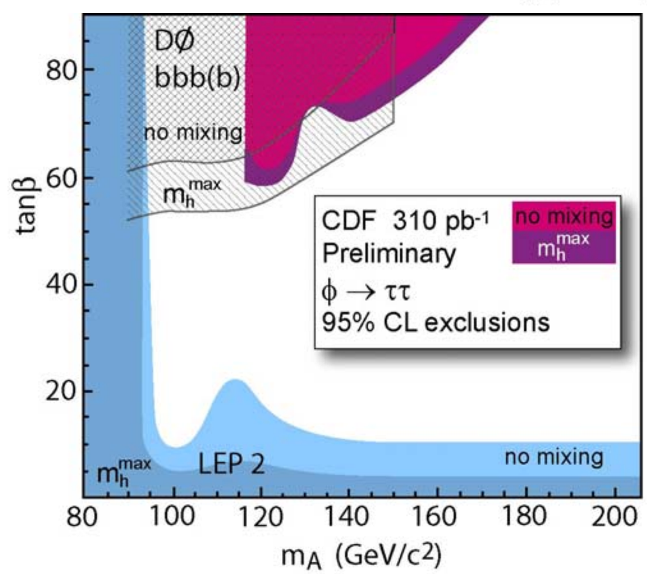


Signal region: M>120

Expect: 8.4 events

Observe: 11 events

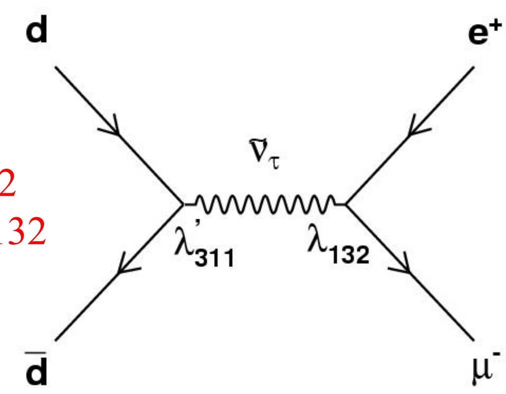


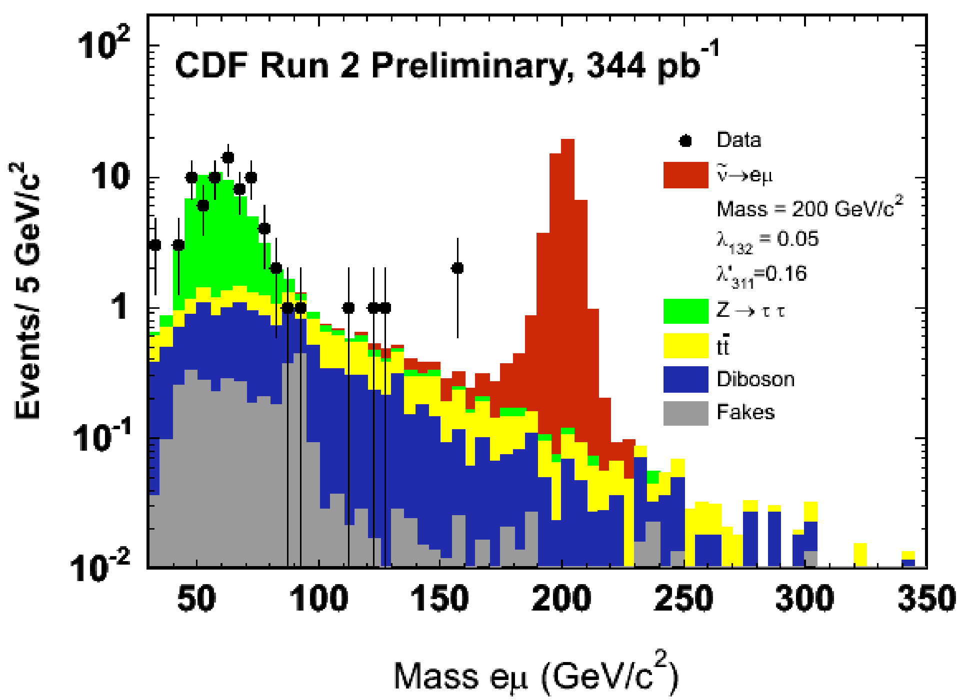


Scalar Neutrino Search

- R-parity violation
  - Lepton-number violating terms: λ_{ijk}, λ'_{ijk}
- Resonance-like production
- Start with e+μ channel
  - Very clean signature
  - Sensitive to both λ and λ'
- High acceptance in the region of interest
- Dominant background is $Z \to \tau\tau$
- Expect 71.3 events. Observe 74
  - Set limits

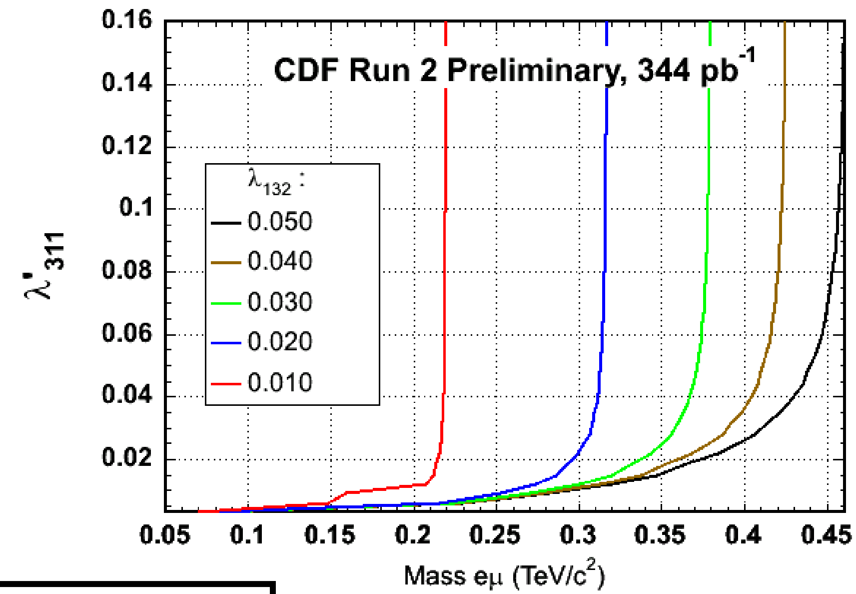
$$\sigma \propto \lambda'^{2}_{311}\ \lambda^{2}_{132}$$





Scalar Neutrino Search

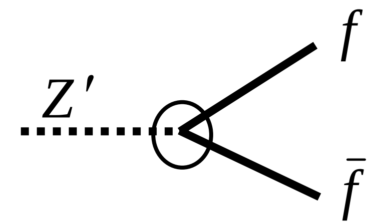
- Interpret x-section limit:
  - For λ^{132}=0.05 λ'^{311}=0. 16
    - M>450 GeV
  - Can set a limit in 2D λ'^{311} vs M(ν)
  - Assume λ^2 Br($\nu \to \mu e$)=0.01



Coupling	Channel	Limit (GeV)
λ_{131}	**ee**	**M>680**
λ_{132}	**eμ**	**M>460**
λ_{133}	**eτ**	**-**
λ_{232}	$\mu\mu$	**M>665**
λ_{233}	$\mu\tau$	**-**
λ_{333}	$\tau\tau$	**M>375**

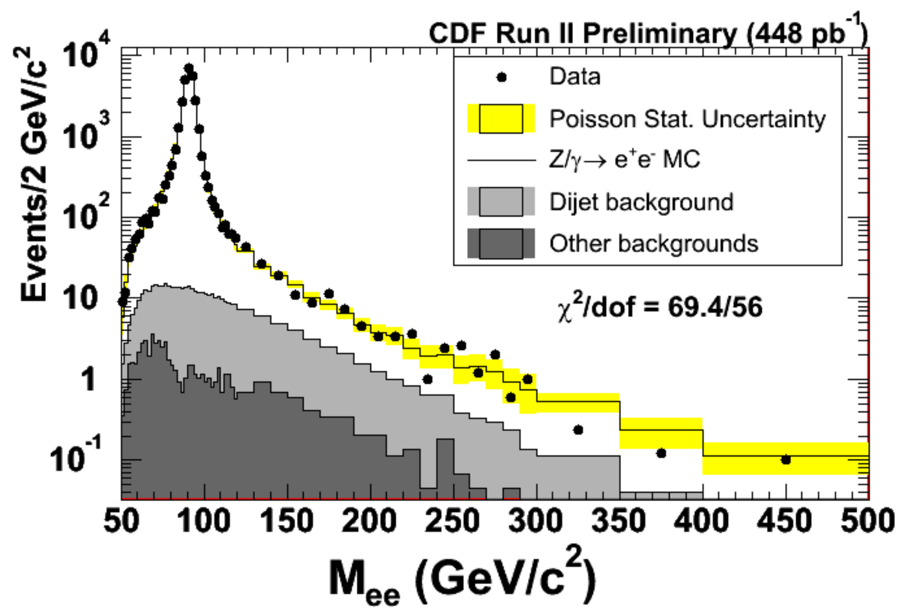
Z' Searches

- Most extensions to SM predict new gauge interactions
  - Most give neutral or singly charged bosons
  - Tight constraints on Z^0-Z' mixing from LEP



- Search for decays: $Z' \to e^+e^-$
  - Use dielectron mass M_{ee} and $\cos\theta^*$
  - Dataset: 448 pb^{-1}
- No evidence of signal:
  - Set 95% C.L. limits:

Z' Model	M_Z Limit (GeV)
Seq. Z'	845 √
E6 Z_χ	720 √
E6 Z_ψ	690 √
E6 Z_η	715
E6 Z_I	625 √



√ = world best

√ = world best excluding LEP

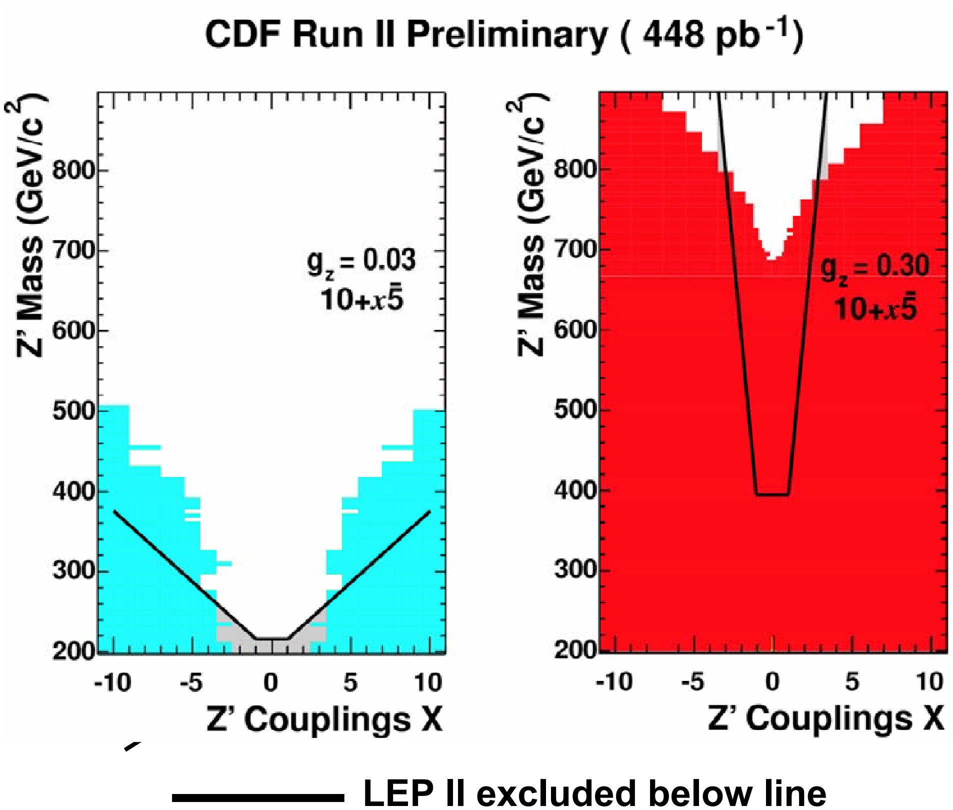
Z' Searches

- Adding angular information helps:
  - At 448 pb^{-1}: use $\cos\theta^* \equiv$ +25% data (seq. Z')

- 2004 paper by *Carena et al* defines 4 general model classes (***PRD70:093009,2004***):
  - B-xL, q+xu, 10+x5, d-xu
  - Within each class, Z' defined by:

    mass $M_{Z'}$, strength g_z, parameter x

- Comparisons to LEP 2 possible:
  - **q+xu, 10+x5, d-xu more exclusion than LEP II**
  - **As well as LEP II for B-xL**
  - More sensitive than LEP to low g_z couplings



Conclusions

- The high-P_T physics program at CDF is broad:
  - 10 Run 2 high-P_T papers published in 2005
  - Top program entering new territory
    - World's best top mass measurement
    - Unprecedented top-quark datasets
  - Electroweak:
    - W mass result being finalized
    - New precision on Diboson results
  - Exotics:
    - New MSSM Higgs and heavy boson searches
    - Many searches for New Phenomena ongoing
- CDF has 800 pb^{-1} on tape
  - More precise measurements and increased sensitivity for New Physics searches

W Mass Uncertainty

- Production and Decay Model Uncertainties:
  - PDFs, QED corrections, $P_T(W)$ and $\Gamma(W)$ model: δm_W~30 MeV
- Tracker Calibration:
  - Use $J/\psi \rightarrow \mu\mu$ and $\Upsilon(1S) \rightarrow \mu\mu$: δm_W~25 MeV
- Electron Energy Calibration:
  - Energy scale set using using E/p peak from W electrons δm_W~35 MeV
  - Non-linear calorimeter response: δm_W~25 MeV
  - E/p tail used for tuning passive material upstream (silicon) δm_W~55 MeV
- Hadronic Recoil Measurement (impacts neutrino measurement):
  - Recoil u measured by summing over all calorimeter towers
    - Lepton energy is removed: δm_W~10 MeV
  - Hadronic Recoil Model:
    - Parametrize R = $\boldsymbol{u}_{meas}/\boldsymbol{u}_{true}$ Just $\boldsymbol{u}_{true}$ contributes δm_W~20 MeV
    - Underlying event: δm_W~40 MeV
    - Jet energy resolution: δm_W~20 MeV