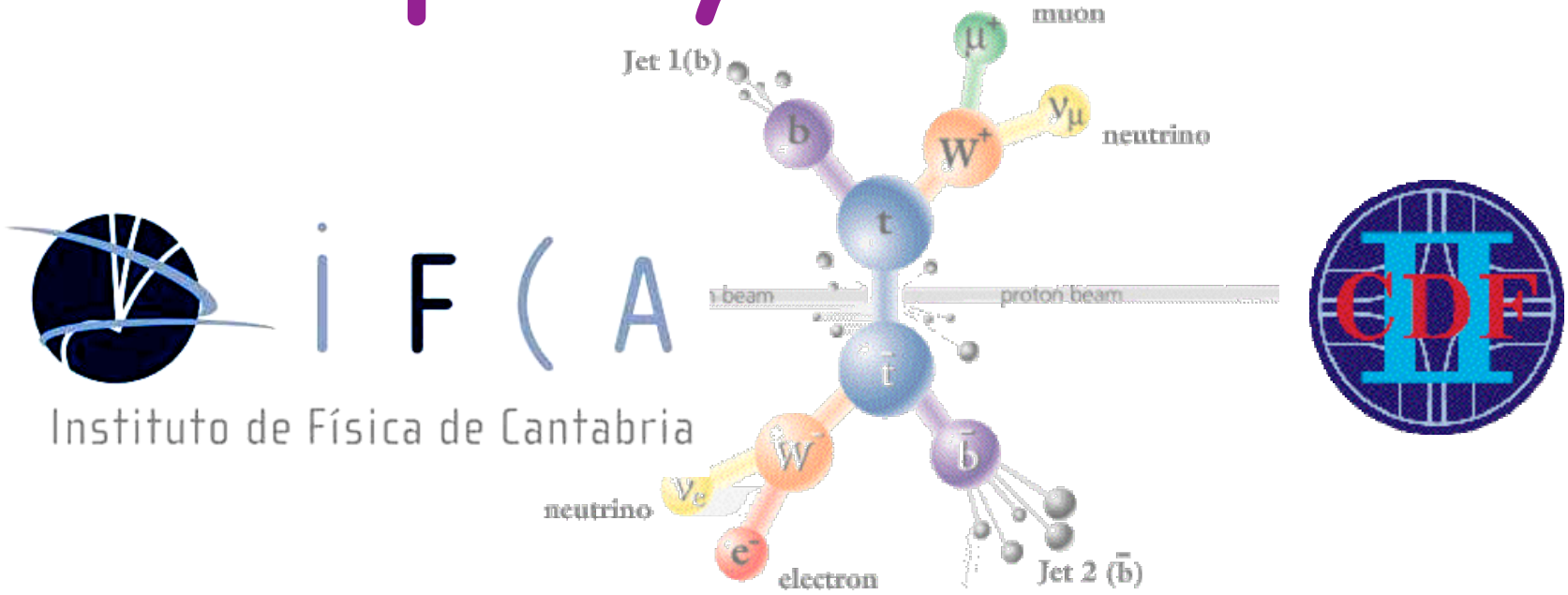
# Top Physics at CDF





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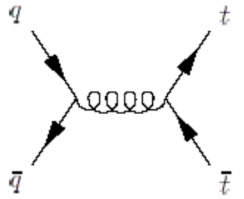
For the CDF Collaboration


**Rencontres de Moriond EWK 2005**

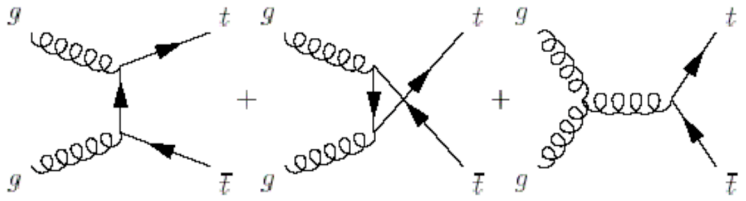
# Top Production at Tevatron

**Tevatron:** $p\bar{p}\,@\,\sqrt{s} = 1.96$ TeV

**top-antitop pairs:**



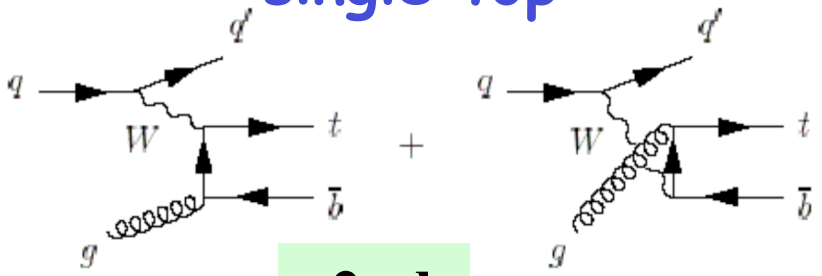

85%



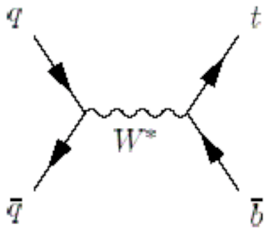

15%

$$\sigma(\bar{p}p \to t\bar{t}) \approx 6.1 \text{ pb}$$

**single top:**




**~2 pb**




**~1 pb**

$$\sigma_{inel}(p\bar{p} \to X) \approx 60\,\text{mb} \approx 10^{10} \times \sigma(p\bar{p} \to t\bar{t}) \approx 6\,\text{pb}$$

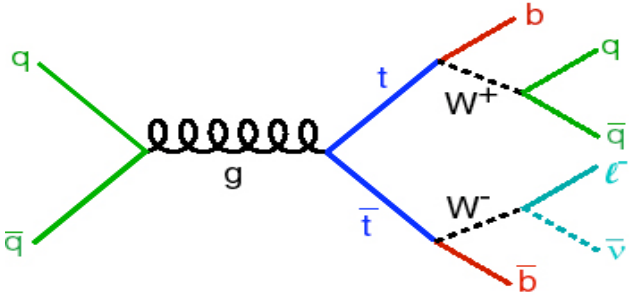
**~ one top event every 10 BILLION inelastic collisions**

# Top Decay

$\Lambda_{QCD}^{-1} \approx (100\ \mathrm{MeV})^{-1} \approx 10^{-23}\ \mathrm{s}$ ← Hadronization time

$M_t > 120\ \mathrm{GeV} \rightarrow \Gamma_t > 1\ \mathrm{GeV} \Rightarrow \tau_t < 10^{-23}\ \mathrm{s}$

NO top hadrons



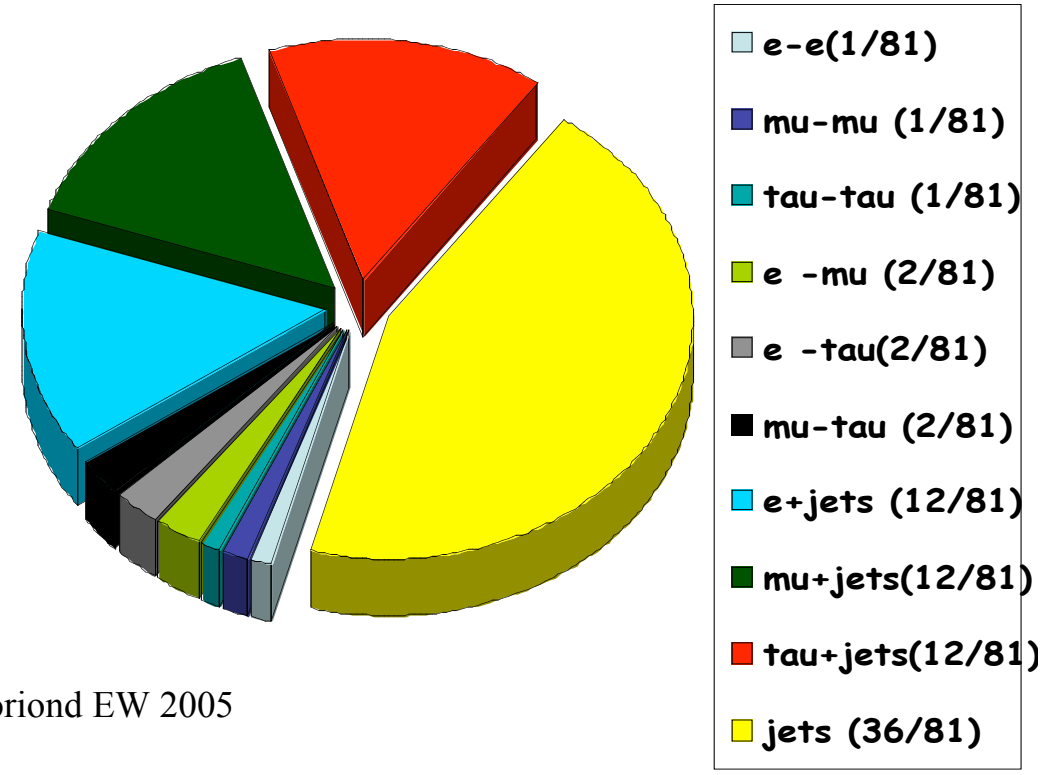

$$Br(t \rightarrow Wb) \approx 100\%$$

final state given by $W^+$ $W^-$ decays

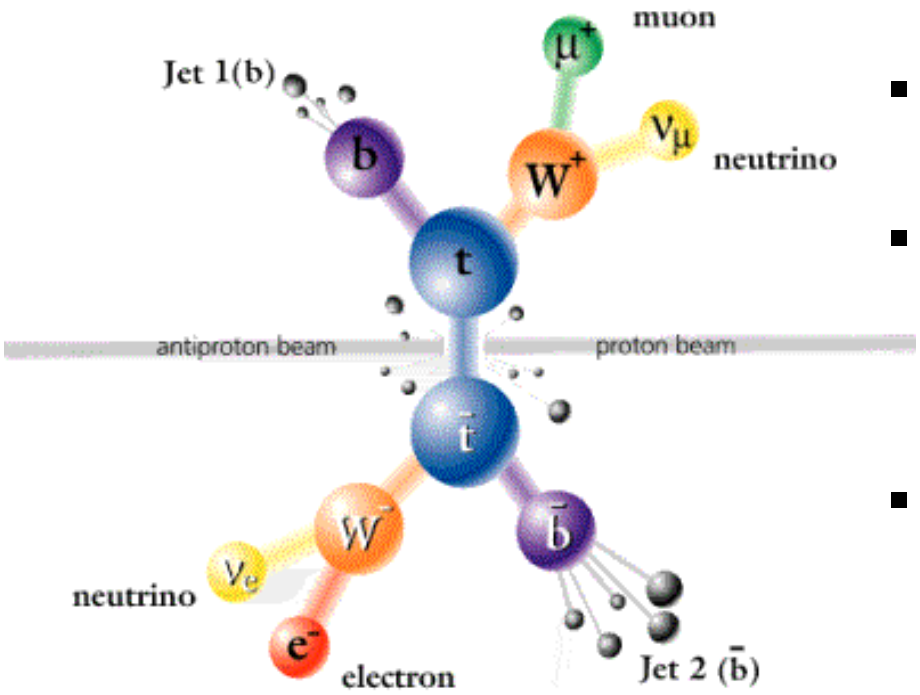
## Event Classification

| | | |
|---|---|---|
| tt→lνlνbb | dilepton | 5% |
| tt→lνqqbb | lepton+jets | 30% |
| tt→qqqqbb | hadronic | 45% |

here lepton = e or μ



# Top Detection



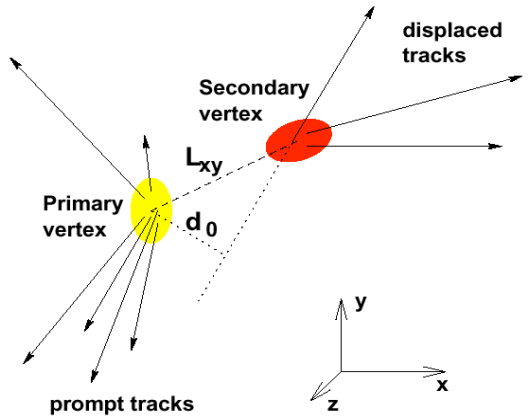

- Events are energetic
  - Large total transverse energy: Ht
- Events are central and spherical
  - $|\eta|< 2.0$, aplanarity
- High energy jets and isolated leptons
  - missing Et from neutrino in leptonic modes
  - High Et jets
- Two high $E_T$ b-jets
  - Displaced secondary vertex
  - Soft lepton inside jet
- Possible additional jets from gluon radiation (isr,fsr)

# Tagging B-jets

- Top events contain B hadrons
- Only 1-2% of dominant W+jets background contains heavy flavor
- Great S/B improvement

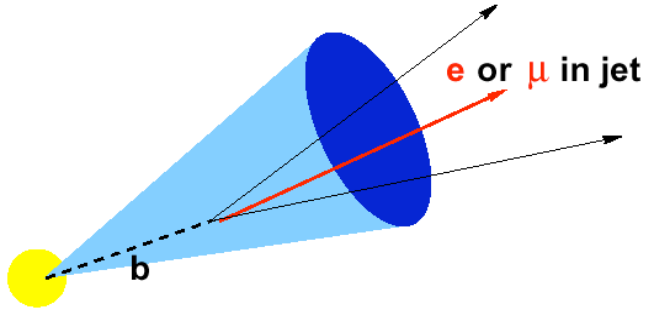
## B hadrons are long-lived

### Vertex displaced tracks




## semileptonic B hadron decay

### Soft Lepton Tagging




- $b \to \ell\nu c$ (BR $\sim$ 20%)
- $b \to c \to \ell\nu s$ (BR $\sim$ 20%)

| | | |
|---|---|---|
| 55% | Top Event Tagging Efficiency | 15% |
| 0.5% | False Tag Rate (QCD jets) | 3.6% |

# Top Pair Cross Section

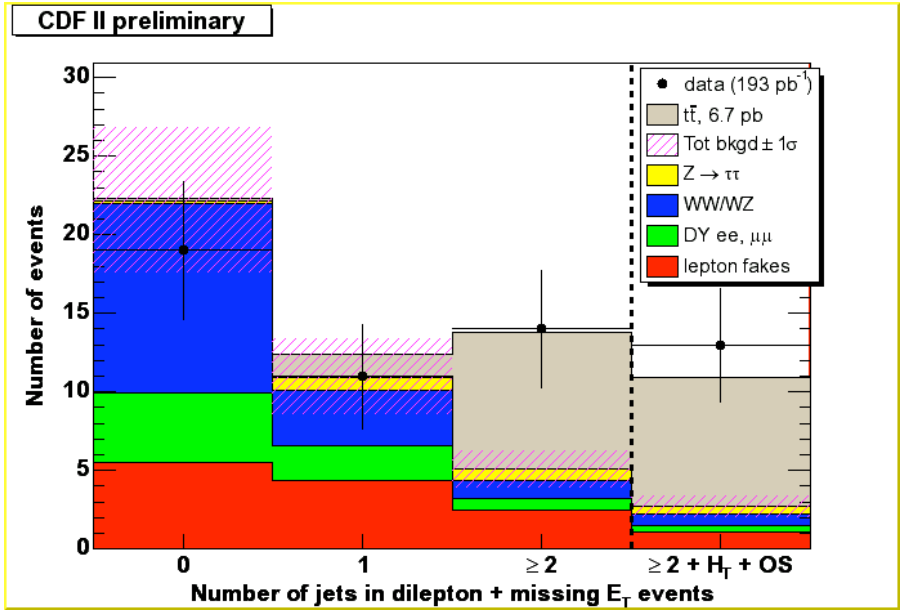
- Measure in different samples
  - Understand top kinematics
  - Understand heavy flavor content
  - Cross check results
  - Validate top samples for other top measurements
- Test of SM predictions
- Sensitivity to physics beyond SM
  - Background to Higgs and SUSY searches

# Cross Section: dileptons

- Selection: 2 leptons (e, μ), 2 jets, high MET
  - Second lepton can be "loose" -- even an isolated track
- Main backgrounds: DY, dibosons, & "fakes" j→lepton

$$\sigma = \frac{N_{obs} - Bkg}{\varepsilon \int Ldt}$$

includes kinematical and geometric acceptance and branching fraction

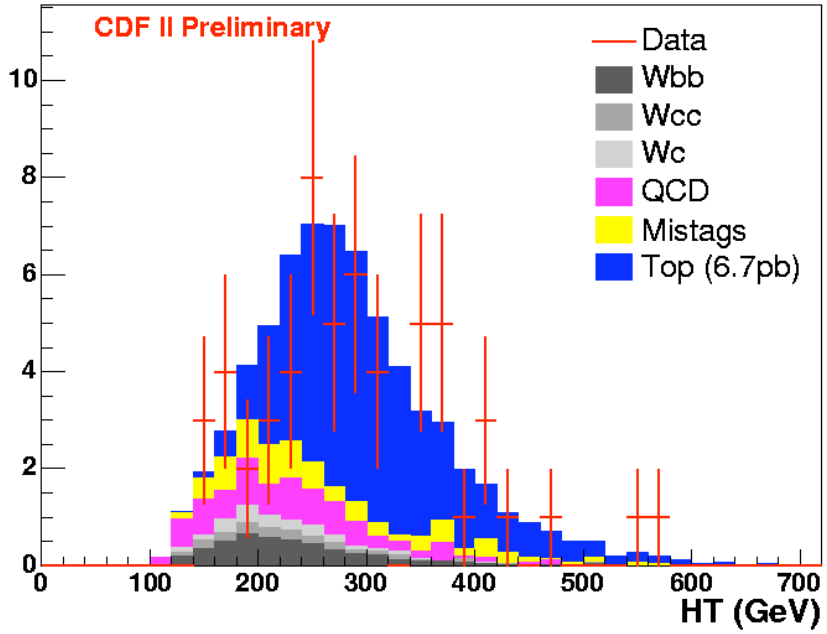


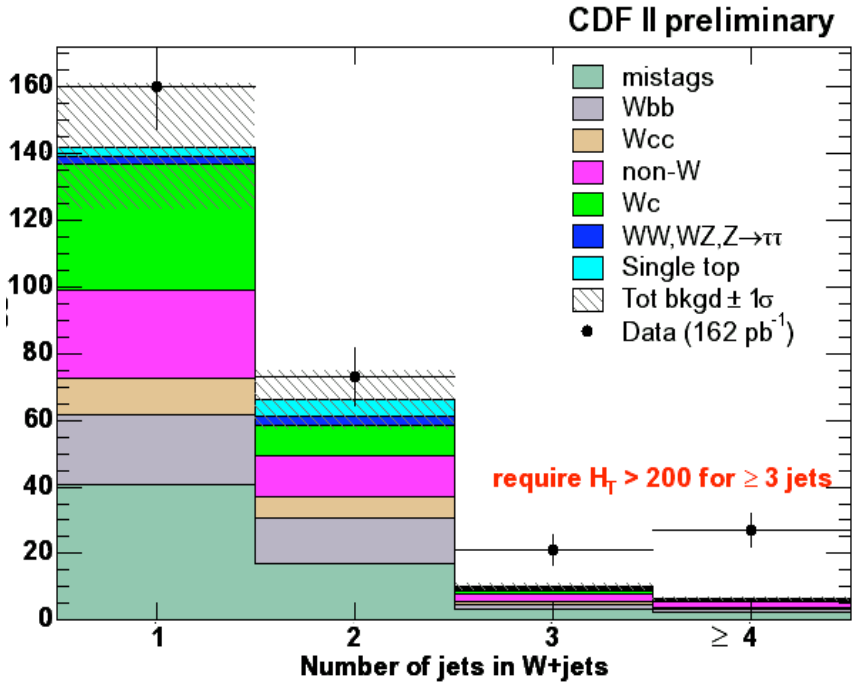

control signal

**CDF most precise:** $\sigma = 7.0^{+2.4}_{-2.1}(\text{stat})^{+1.7}_{-1.2}(\text{sys})$ pb $\int Ldt = 197\ \text{pb}^{-1}$

# Cross Section: l+jets+Btag

- Selection: 1 lepton (e, μ), >=3 jets, high MET
- Btag
- Main backgrounds: W+HF, QCD, W+jets (mistags)



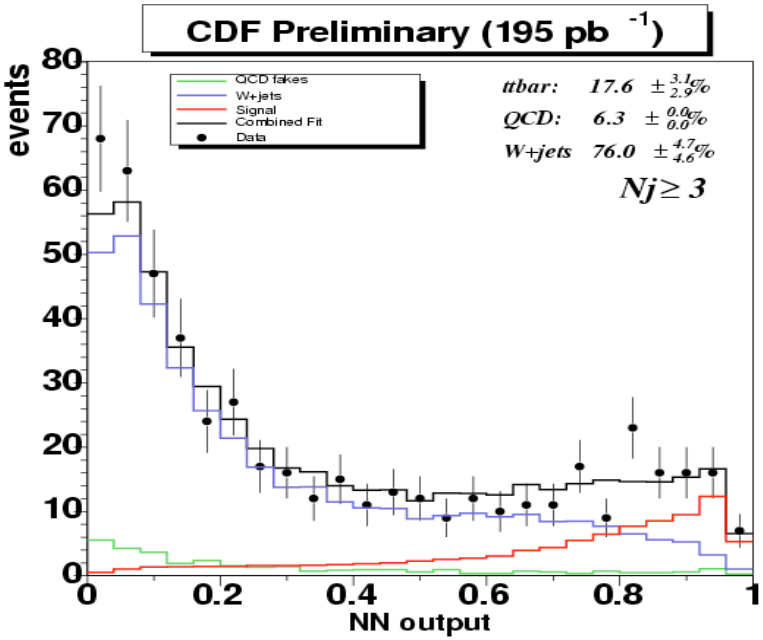



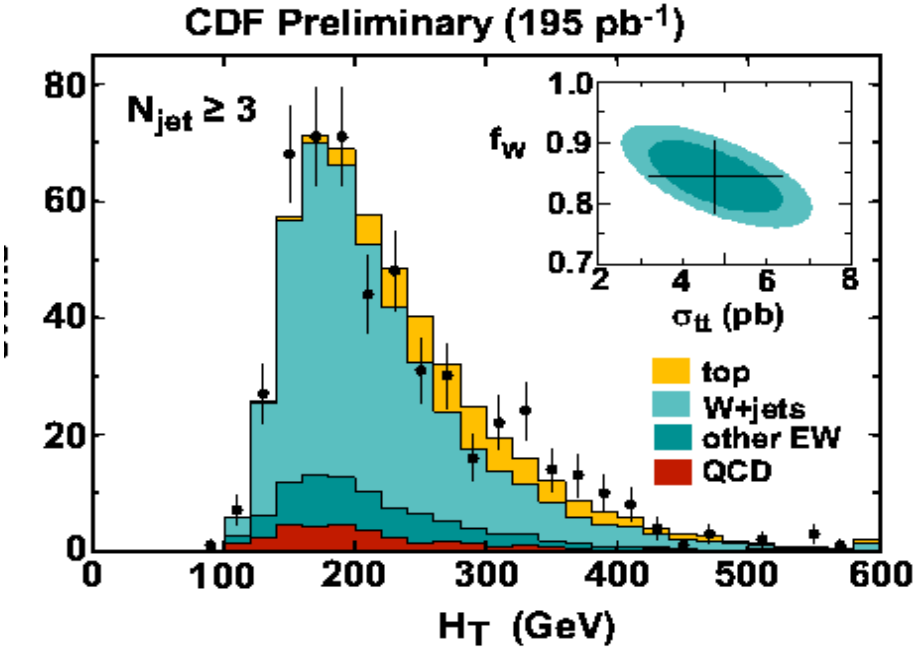

**CDF most precise:** $\sigma = 5.6^{+1.2}_{-1.1}(\text{stat})^{+0.9}_{-0.6}(\text{sys})\ \text{pb}$ $\int Ldt = 162\,\text{pb}^{-1}$

# x-sec: l+jets+kinematics

- Selection: 1 lepton (e, μ), >=3 jets, high MET
- NO Btag: higher statistics, worse S/B
- Main backgrounds: W+jets, QCD, EW

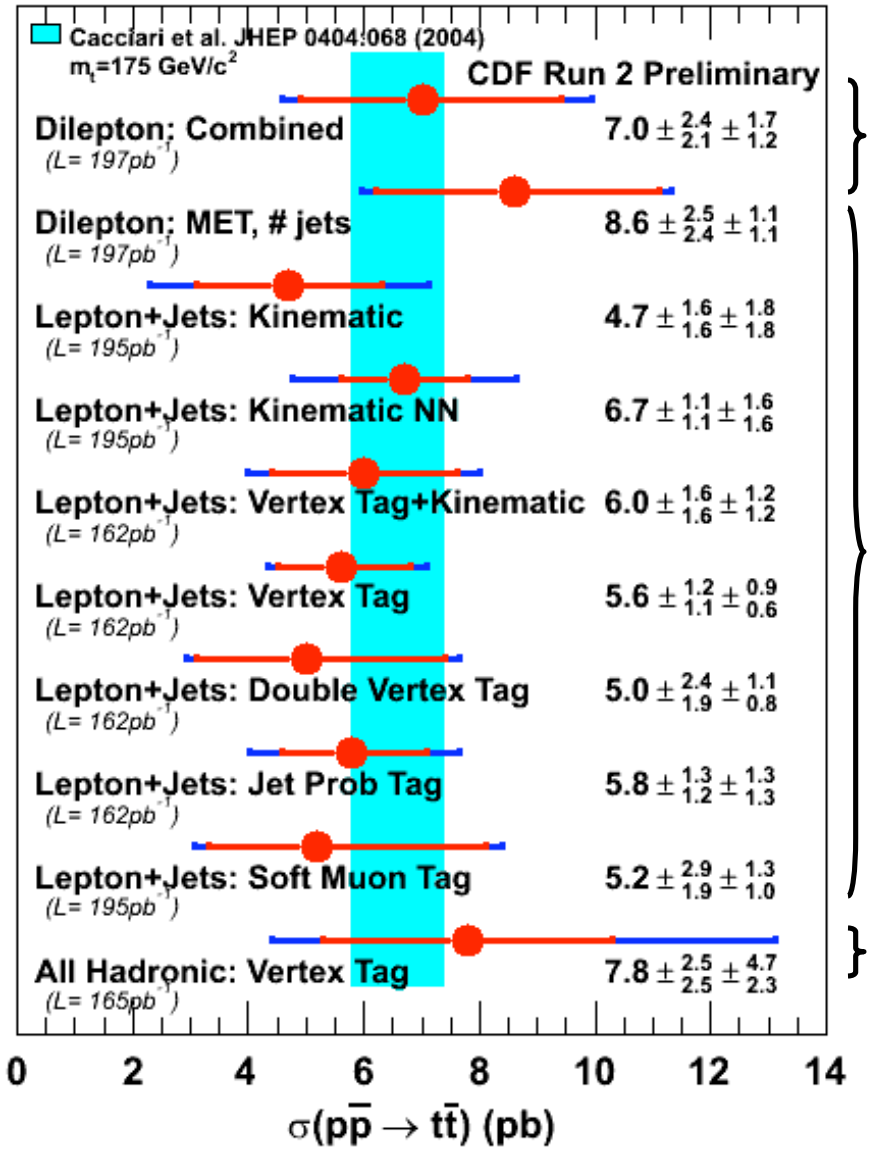
**kinematic distributions: likelihood or NN**



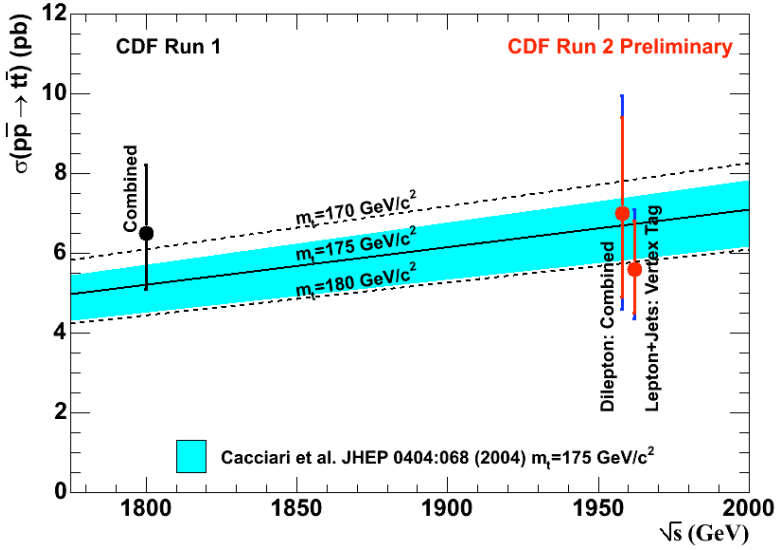




**CDF most precise:** $\sigma = 6.7^{+1.1}_{-1.1}(\text{stat})^{+1.6}_{-1.6}(\text{sys})\ \text{pb}$ $\int Ldt = 195\ \text{pb}^{-1}$

# Cross Section Measurements




**Measurements consistent with each other…..**



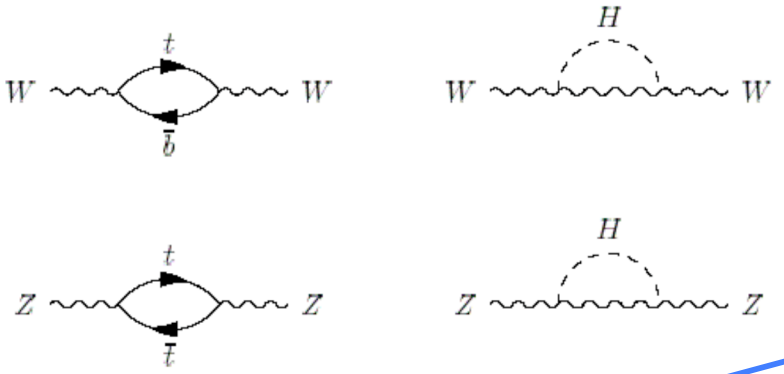

**… and with theory**

**error bars: red=stat, blue=total**

# Top Mass

Mt ≅ 175 GeV → Yukawa coupling ≅ 1 Special role in EWSB?

**Dominant parameter in radiative corrections:**




$$\rho = \frac{M_W^2}{M_Z^2(1-\sin^2\theta_W)} \equiv 1 + \Delta r$$

$$\Delta r = \frac{3G_F}{8\pi^2\sqrt{2}} m_t^2 + \frac{\sqrt{2}G_F}{16\pi^2} M_W^2 \left[\frac{11}{3}\ln\left(\frac{M_H^2}{M_W^2}\right) + \ldots\right] + \ldots$$

**quadratic in $m_t$ , logarithmic in $m_H$**

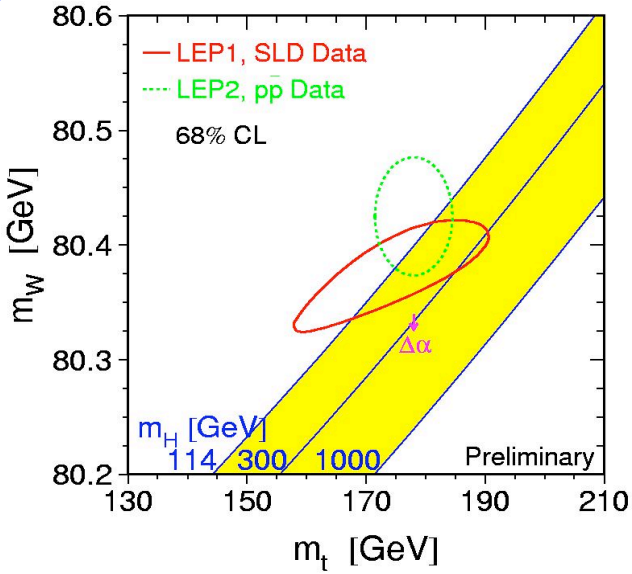
**Mt from precision EW measurements**

$$M_Z, \Gamma_Z, \sin^2\theta, A_{FB}(Z), M_W \Rightarrow$$

$$M_{top} \approx 181 \pm 6 \pm 16 \text{ GeV}$$

$$M_{Higgs} = 70 \rightarrow 1000 \text{ GeV}$$

$$M_{top} + EW \Rightarrow M_{Higgs}$$

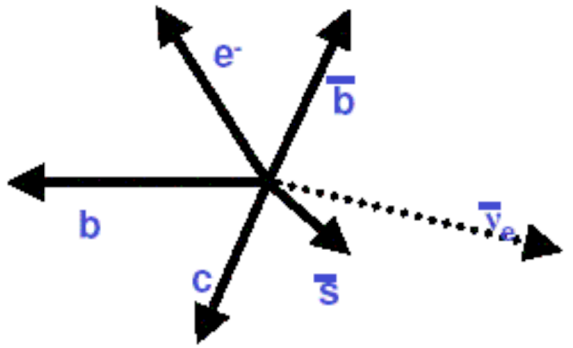


# Measuring Mtop

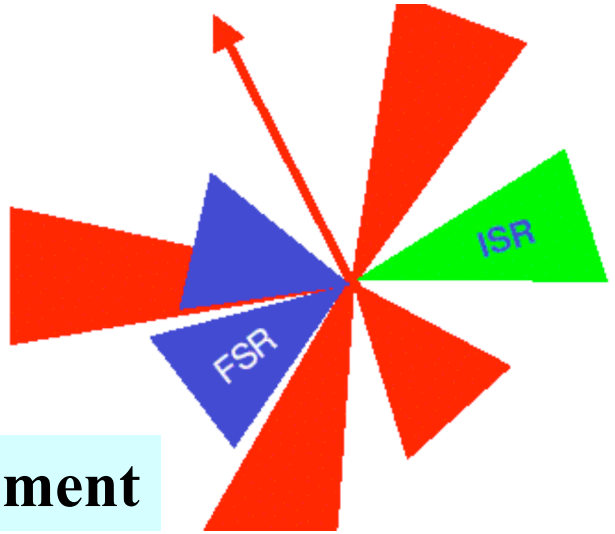
**Challenging**:

- **Lepton+jets**
  - **Undetected neutrino**
    - **$P_x$ and $P_y$ from Et conservation**
    - **2 solutions for $P_z$ from $M_W=M_{lv}$**
  - **Leading 4 jets combinatorics**
    - **12 possible jet-parton assignments**
    - **6 with 1 b-tag**
    - **2 with 2 b-tags**
  - **ISR + FSR**
- **Dileptons**
  - **Less statistics**
  - **2 undetected neutrinos**
  - **Less combinatorics: 2 jets**

LO ME final state:




CDF sees:

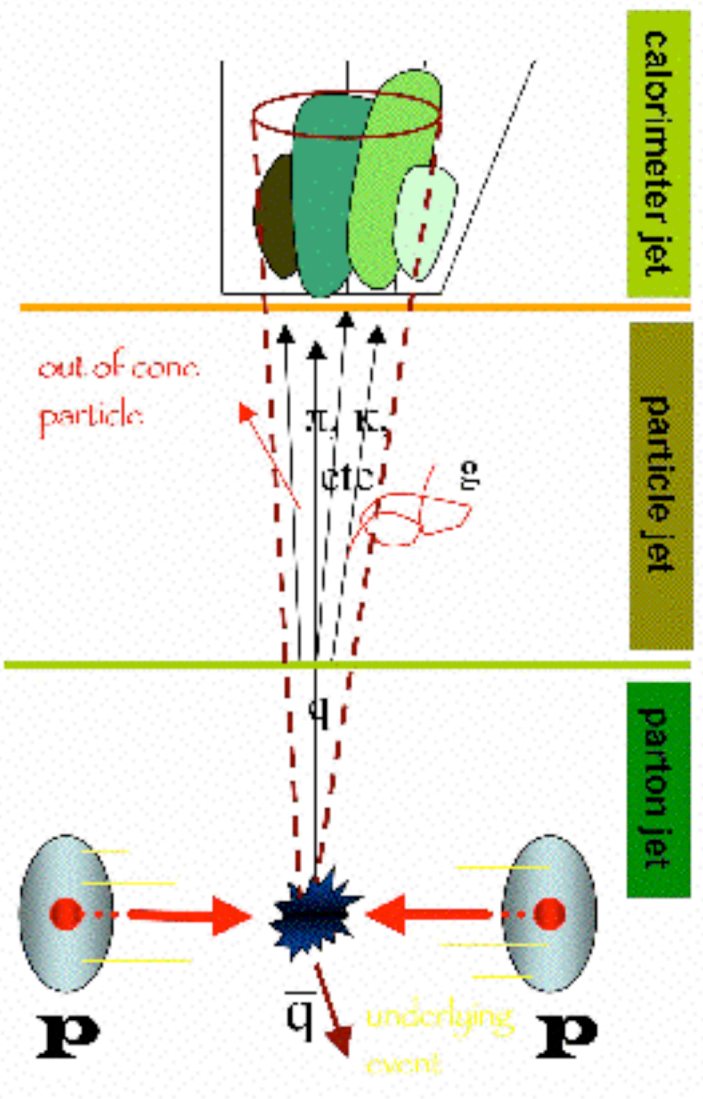



**Largest uncertainty: Jet Energy Measurement**

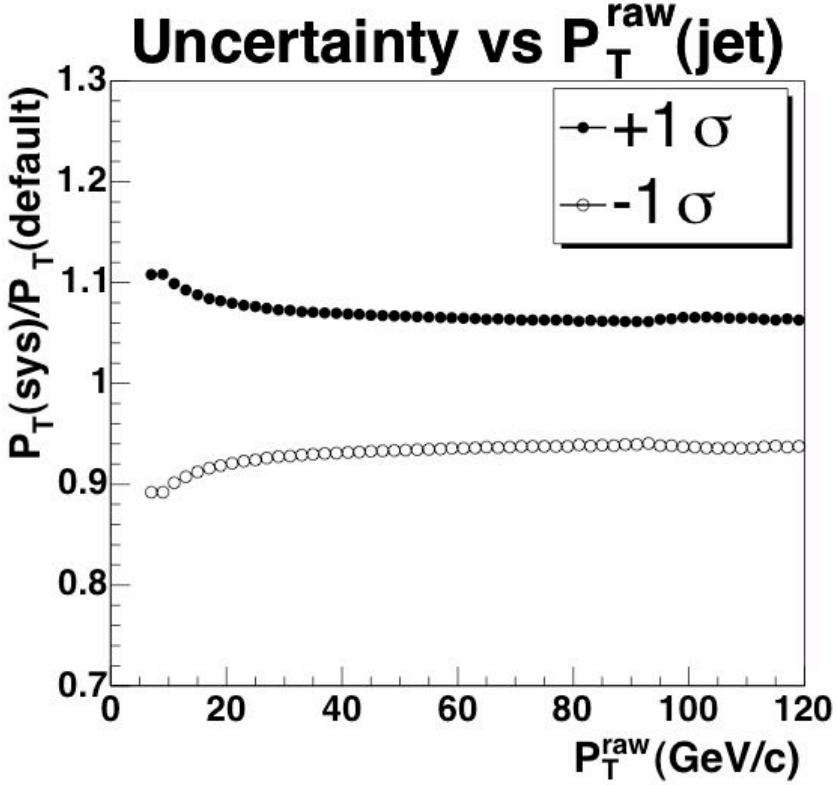
# Jet Energy Corrections

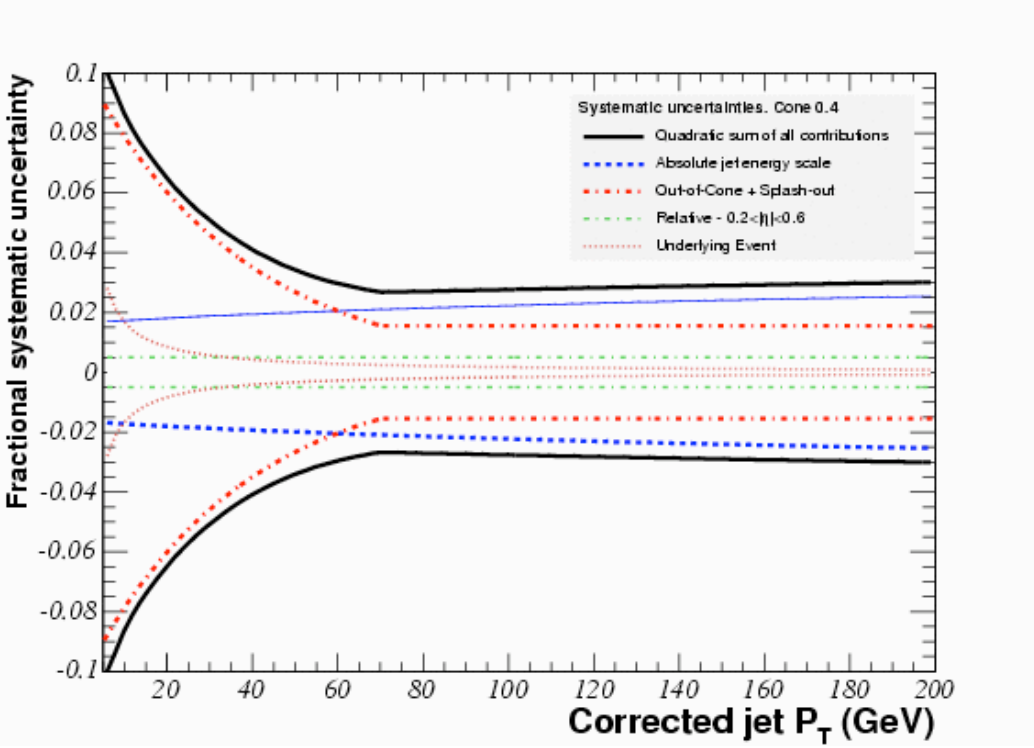
**Determine true "particle", "parton" jet E from measured jet E**

- Non-linear response
- Uninstrumented regions
- Response to different particles
- Out of cone E loss
- Spectator interactions
- Underlying event



# Jet Energy Uncertainty



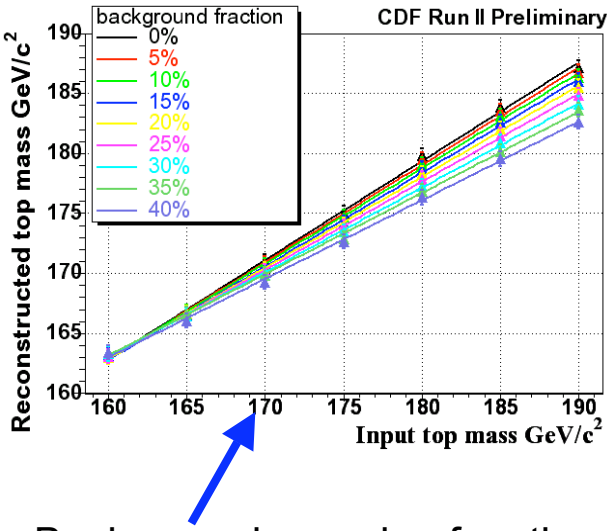



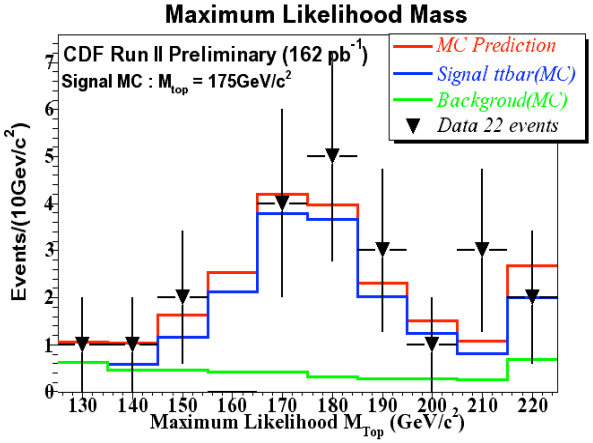

- **Old systematic uncertainty**
- **Used for all mass results shown here**
- **Dominant systematic uncertainty**

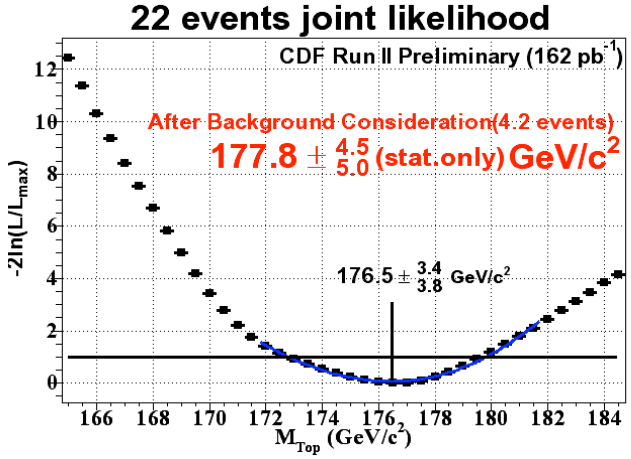
- **New Systematic Uncertainty**
- **Significant Improvement**
- **Redoing mass analyses**
- **Improved results soon**

# Mtop: DLM

- "Dynamical Likelihood Method"
- Likelihood vs. $m_t$ per event from LO ME for $tt \rightarrow l+4j$ and "transfer functions" for quark $E_T \rightarrow$ jet $E_T$
  - Minimize -ln L (combined likelihood from all events)



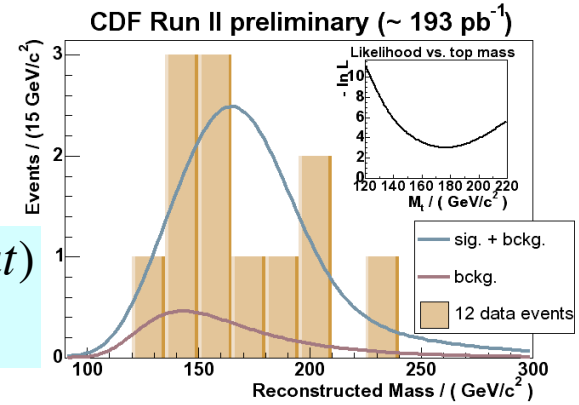

Background mapping function: measured to true mass for a given bkg fraction (19% for l+4j with b-tag)

$$m_t = 177.8^{+4.5}_{-5.0}(stat) \pm 6.2(syst)\ \text{GeV}$$

# Mtop: templates

- Mass templete method
  - Reconstruct one top mass for each event
  - Compare Mtop distribution to simulated top templates at various masses
  - Minimize -ln L vs Mtop to extract mass

loop over j-p assignments
loop over $P_Z$ for ν
impose kinematic constrains
choose m that best fits event

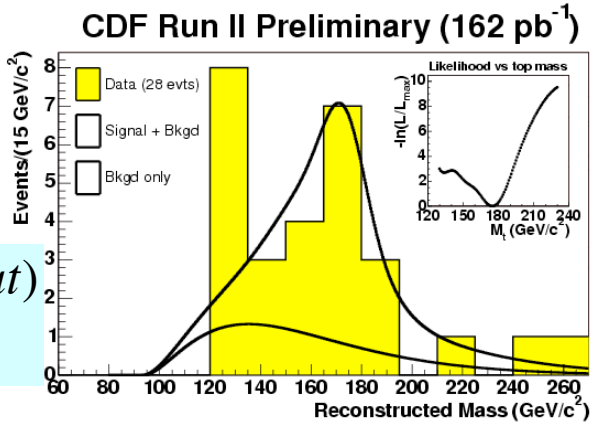



Dileptons:

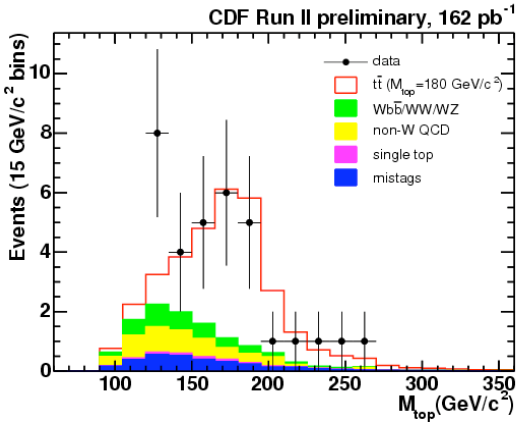
$$m_t = 176.5^{+17.2}_{-16.0}(stat)$$
$$\pm 6.9\,(syst)\ \text{GeV}$$

b-tagged l+jets:

$$m_t = 174.8^{+7.1}_{-7.7}(stat)$$
$$\pm 6.5(syst)\ \text{GeV}$$

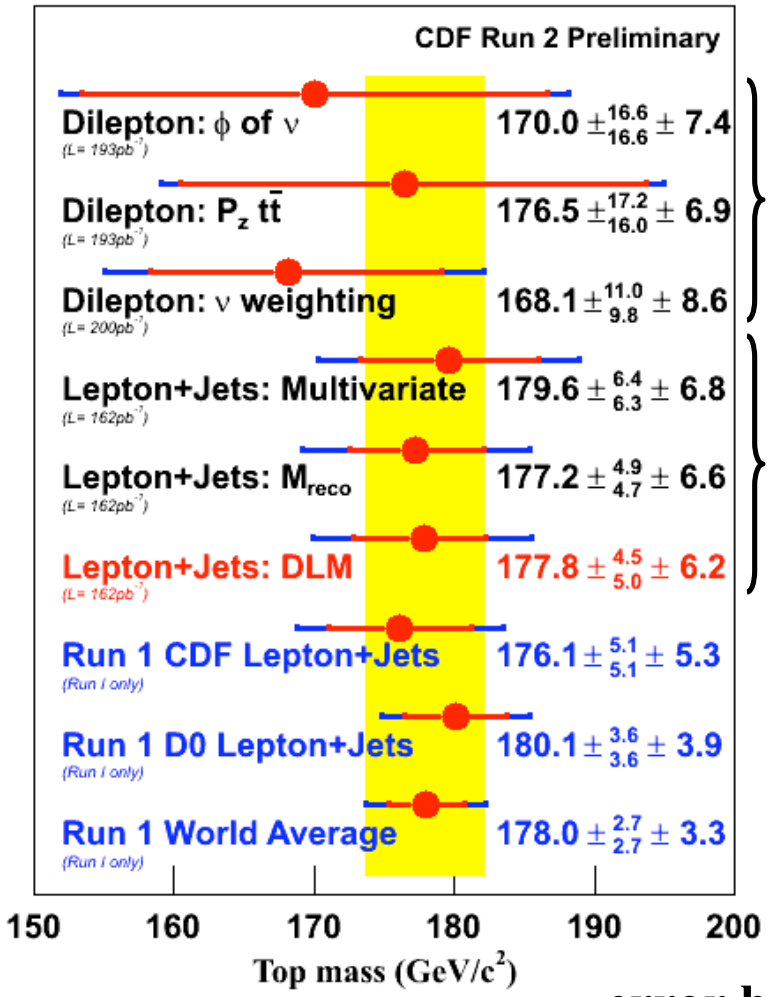



- b-tagged l+jets w/ multivar templates:
  - Probability for Mt from likelihood based on MC multidimensional templates




$$m_t = 179.6^{+6.4}_{-6.3}(stat)$$
$$\pm 6.8(syst)\ \text{GeV}$$

# Mtop Measurements

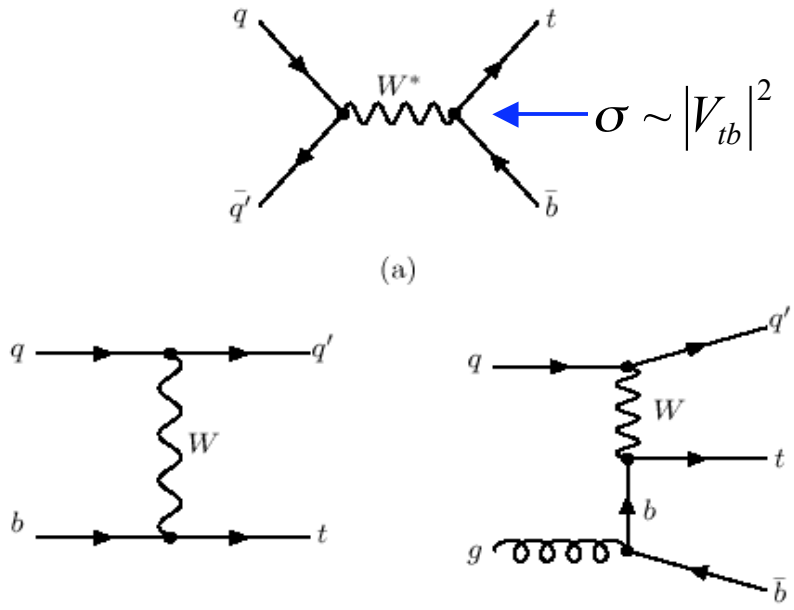



- **Combined RunI mass:**
  - $m_t = 178.0 \pm 4.3$ GeV/$c^2$
    - was: $174.3 \pm 5.1$ GeV/$c^2$
  - Higgs mass
    - Best-fit $M_H \approx 113$ GeV/$c^2$
    - 95% C.L. : $M_H < 237$ GeV/$c^2$
- **Run II measurements**
  - Systematic uncertainty largely dominated by jet energy correction: will be reduced
  - RunII goal is $\delta m \sim 2\text{-}3$ GeV/$c^2$

**error bars: red=stat, blue=total**

# Single Top Search

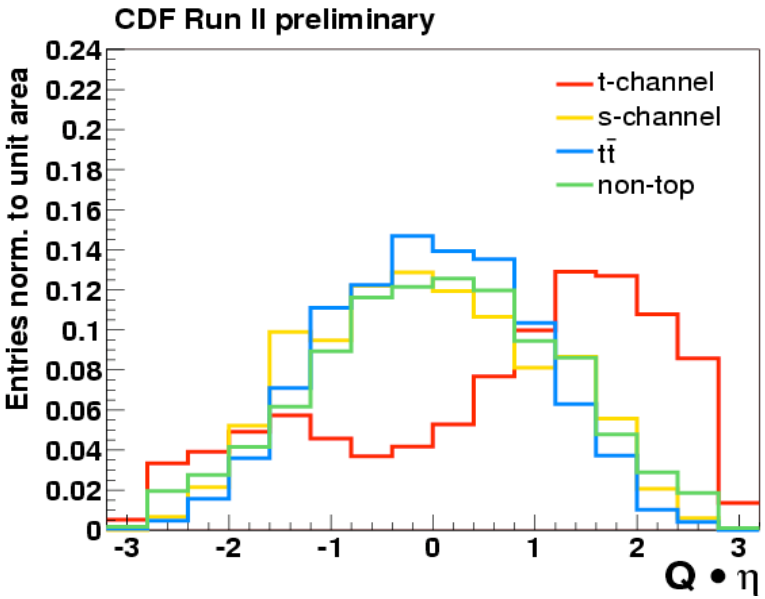
$$\sigma_t^{NLO} = 0.88 \pm 0.07 \text{ pb}$$



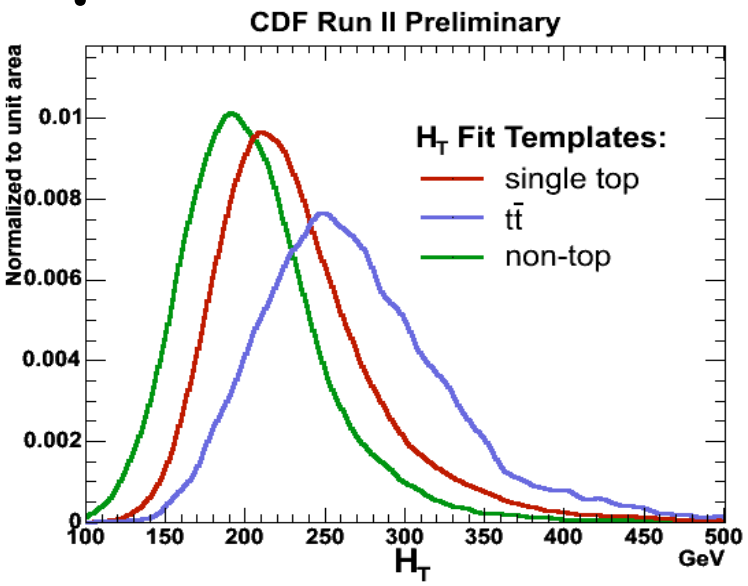

$$\sigma_t^{NLO} = 1.98 \pm 0.21 \text{ pb}$$

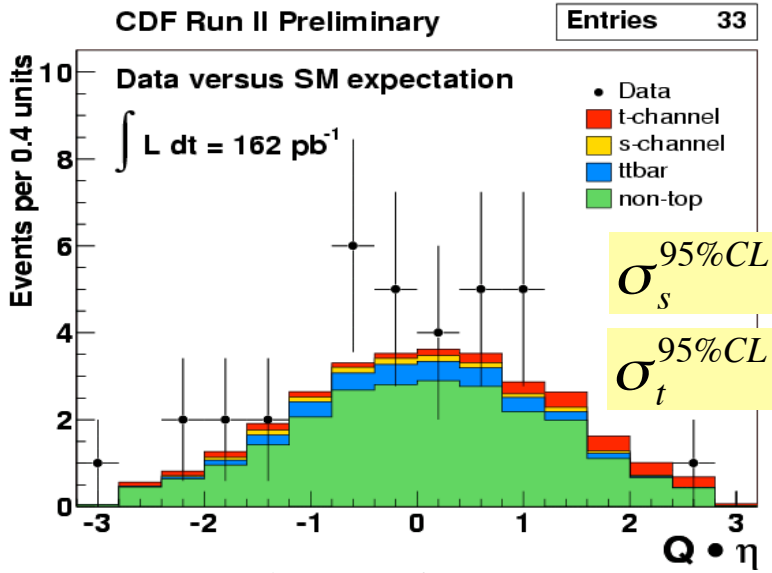
- Direct measurement of $|V_{tb}|^2$
- Sensitive to new physics
  - W', anomalous couplings, FCNC
- Final state: lepton, MET, 2 jets & at least 1 b-jet
- Challenging
  - Small cross section
  - tt now background
  - Large additional backgrounds

# Single top



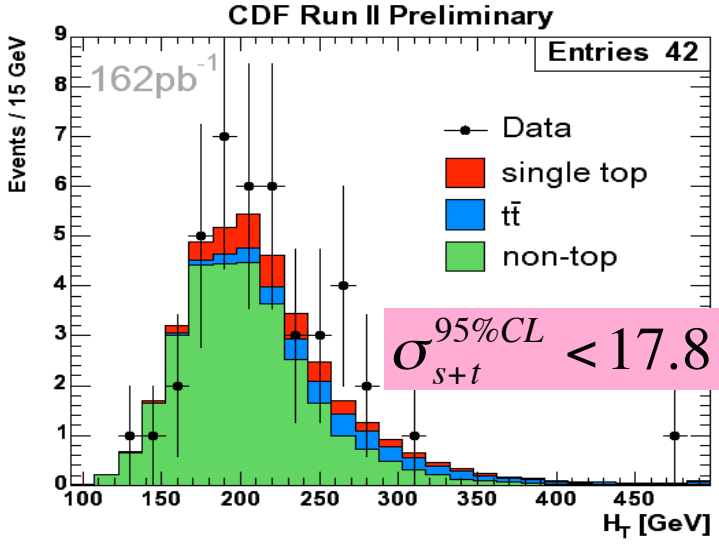

MC Templates




$\sigma_s^{95\%CL} < 13.6$ pb

$\sigma_t^{95\%CL} < 10.1$ pb




$\sigma_{s+t}^{95\%CL} < 17.8$ pb

# W Helicity

**SM (V-A) prediction:**

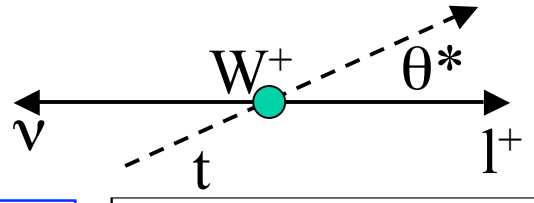
$t \to W_T$ : left handed W (30%)

$t \to W_0$ : longitudinal W (70%)

$$F_0 = \frac{\Gamma(t \to W_0 b)}{\Gamma(t \to W_0 b) + \Gamma(t \to W_T b)} = \frac{1}{1 + 2(m_W / m_t)^2} = 0.70$$

**test of V-A tWb vertex**

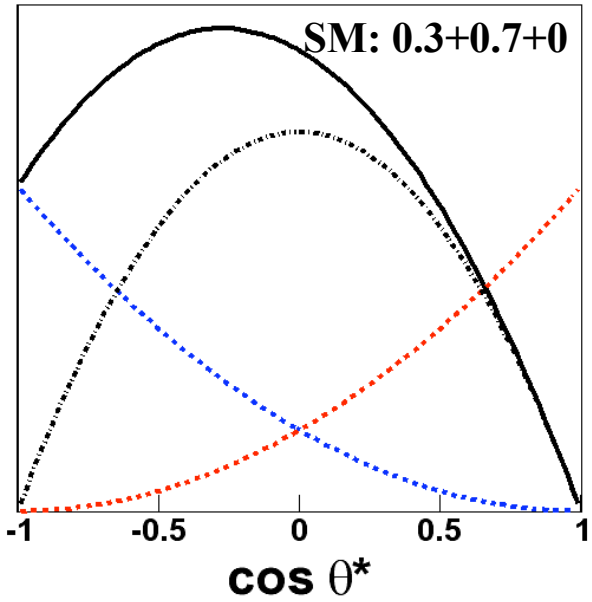
Kinematic distributions for the different helicity states are different



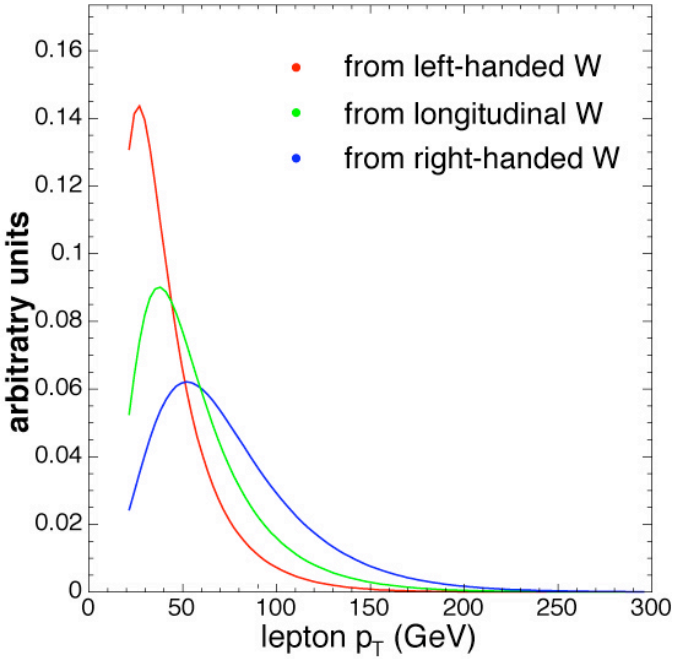

left – handed $\frac{1}{4}(1-\cos\theta^*)^2$

longitudinal $\frac{1}{2}(1-\cos^2\theta^*)$

right – handed $\frac{1}{4}(1+\cos\theta^*)^2$

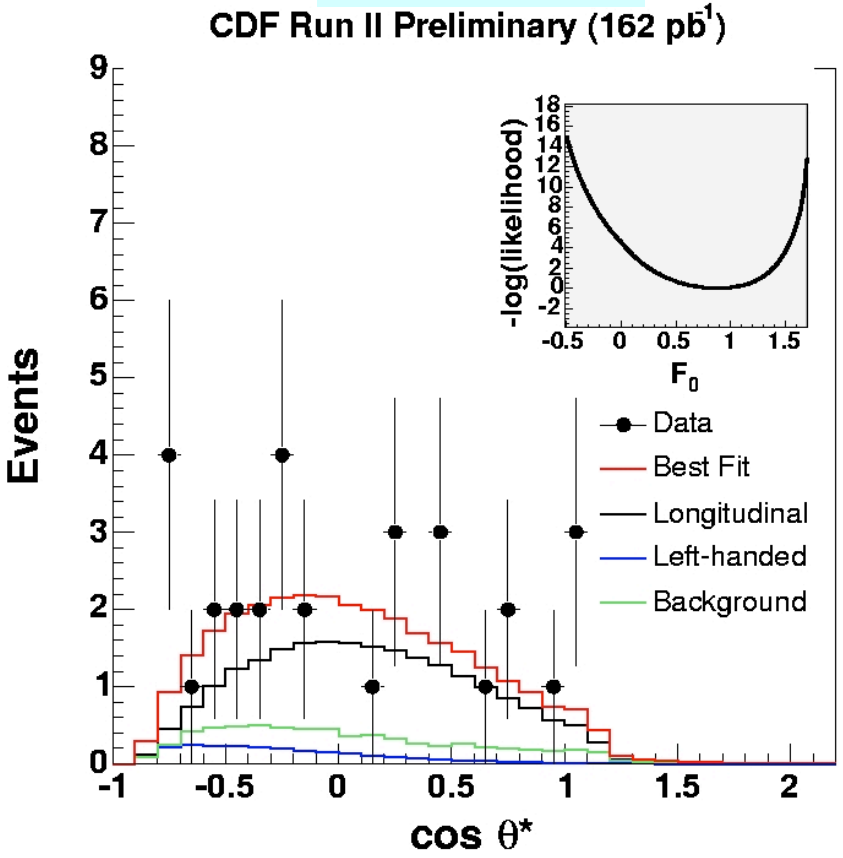



Lepton Pt



# W Helicity

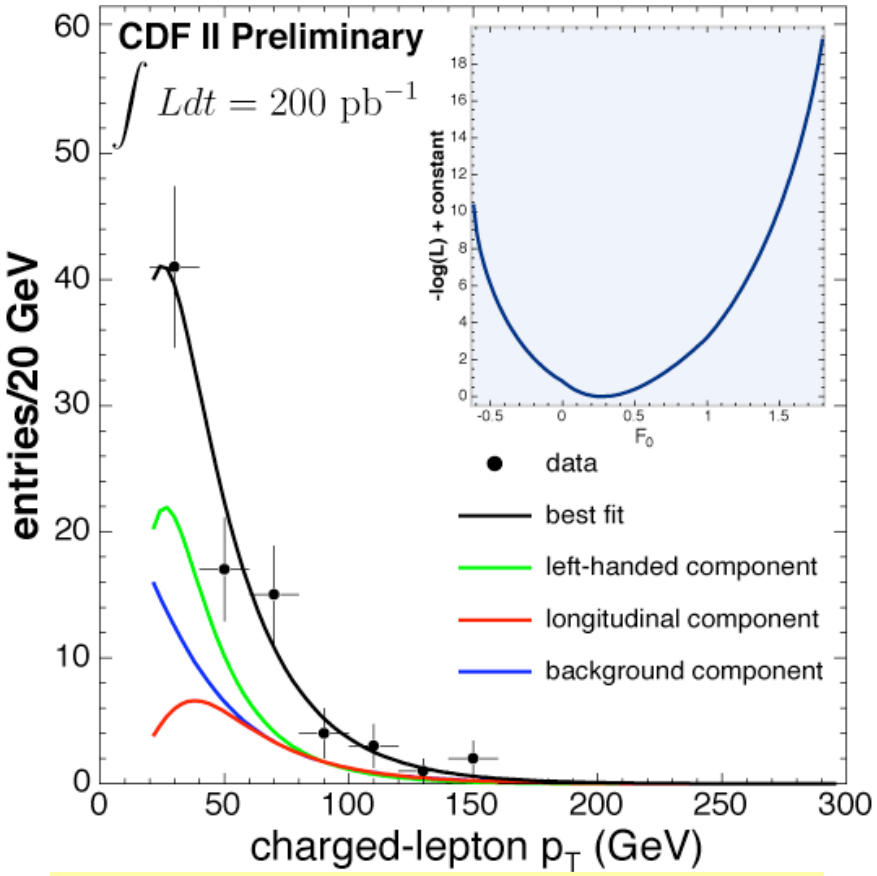
## lepton+jets




$$F_0 = 0.89^{+0.30}_{-0.34}(stat) \pm 0.17(sys)$$

$$F_0 > 0.25 \text{ @ } 95\% \text{ CL}$$

## dilepton and lepton+jets

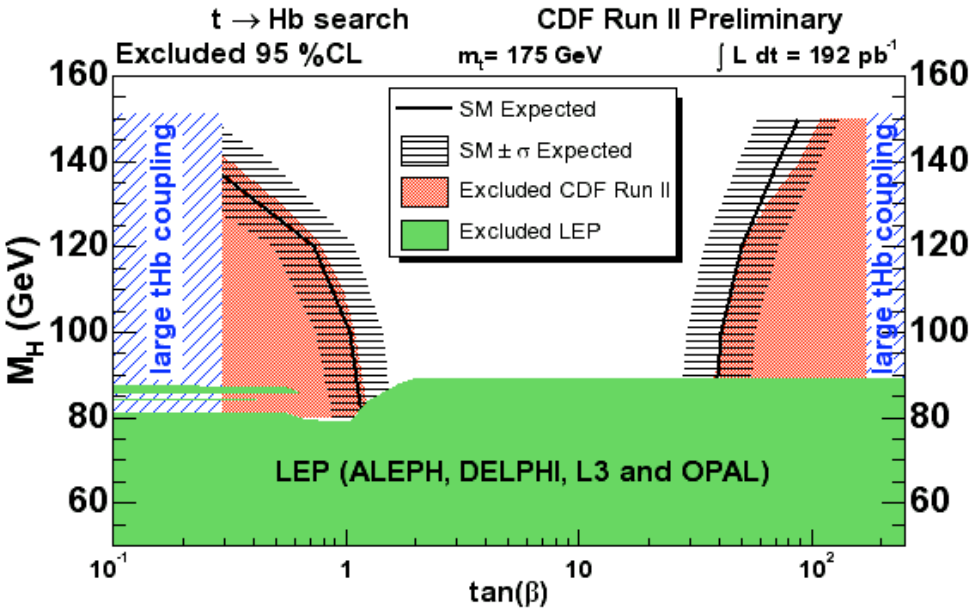


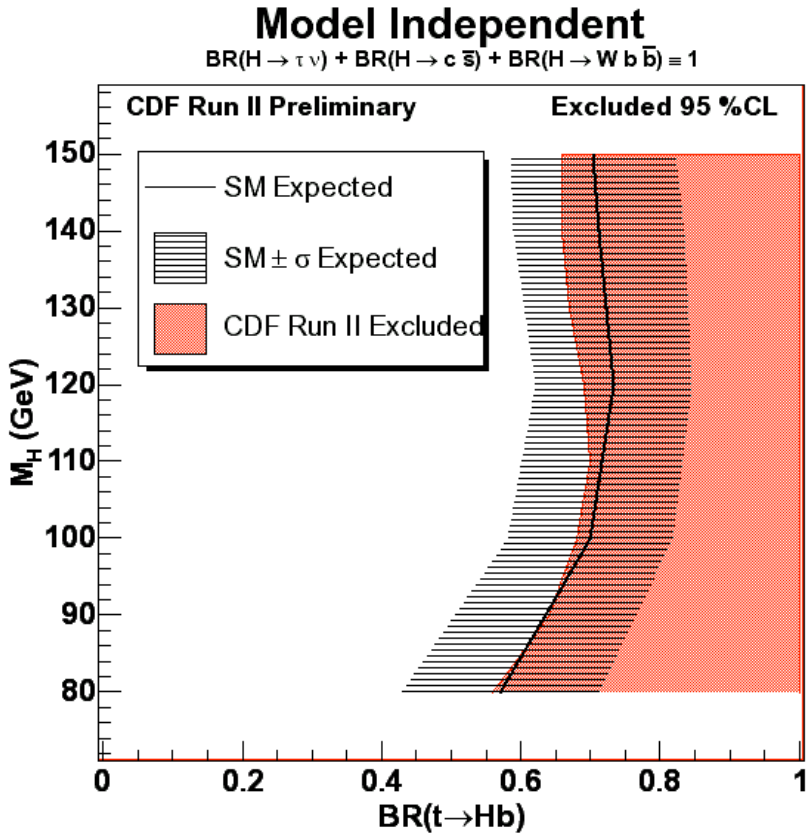

$$F_0 = 0.27^{+0.35}_{-0.24}(stat) \pm 0.17(sys)$$

$$F_0 < 0.88 \text{ @ } 95\% \text{ CL}$$

# Search for $H^+$

$$\left.\begin{array}{l} \sigma_{tt}^{SM}(th) \\ \varepsilon(t \to Wb + t \to Hb) \\ N^{\text{expected}} \; vs \; N^{obs} \\ L(m, BR(t \to Hb), BR(H \to c\bar{s}, Wb\bar{b})) \end{array}\right\} \Rightarrow$$



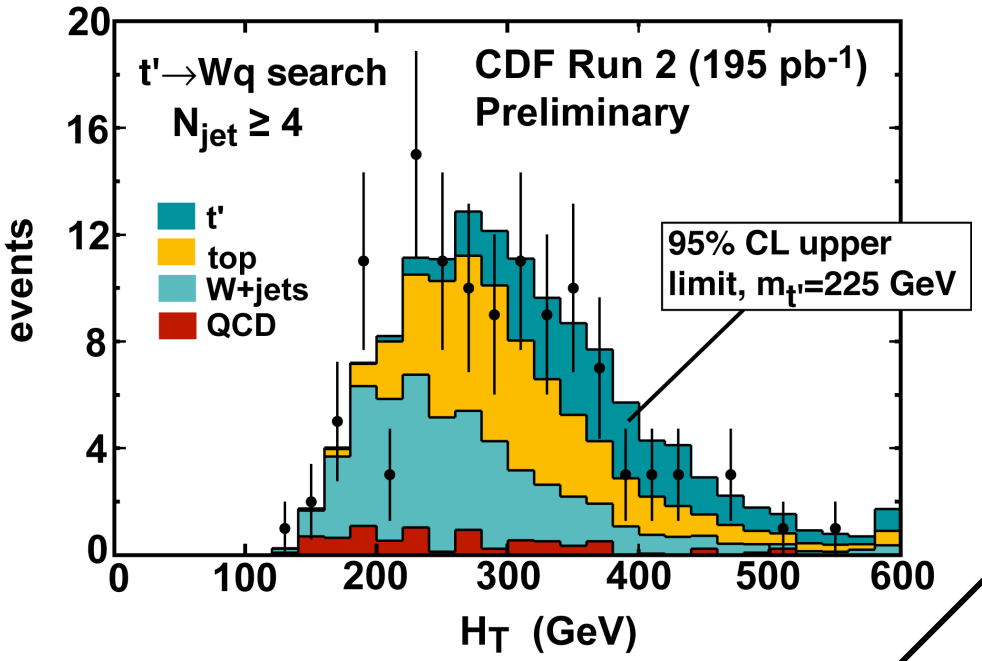




$BR(t \to Hb) < 0.7$ @ 95% CL

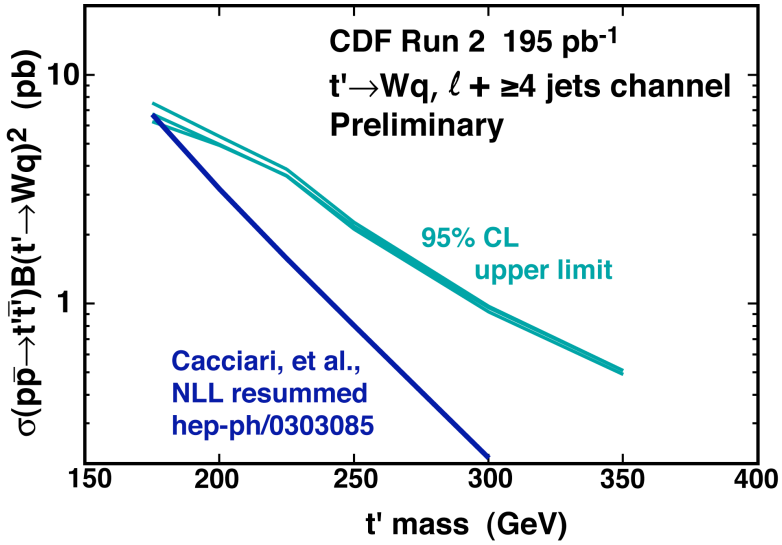
(for $80 < M_H < 150$ GeV)

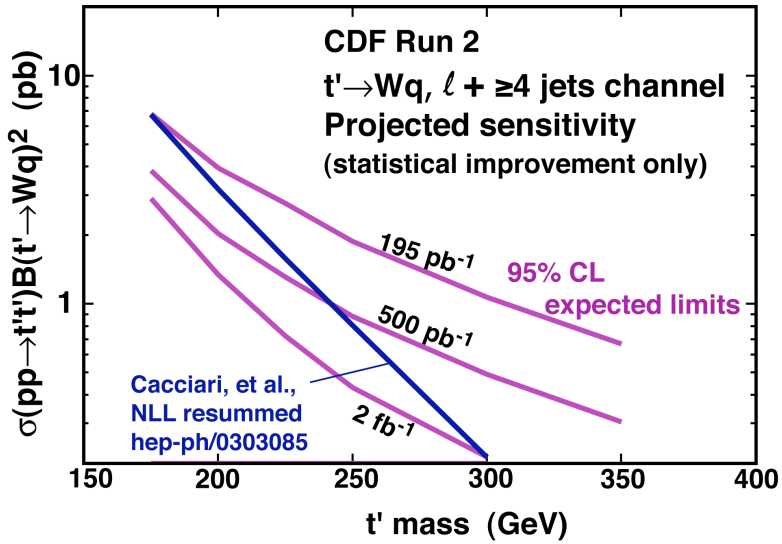
# Search for 4th generation t'

- Same selection as kinematic top xs
- Fit Ht to t',t,W+jets and QCD
- Likelihood for different Mt'




(one such plot for each point)



# Other Top Measurements

| Measurement | Result | $\int Ldt$ ($\text{pb}^{-1}$) |
|---|---|---|
| $BR(t \to Wb)/BR(t \to Wq)$ | $> 0.62$ @ 95% CL | **162** |
| $\sigma_{\text{dilepton}}/\sigma_{1+\text{jets}}$ | $1.45^{+0.83}_{-0.55}$ | **126** |
| $BR(t \to \tau\nu b)/BR_{\text{SM}}(t \to \tau\nu b)$ | $< 5.0$ @ 95% CL | **193** |
| Search for Anomalous Kinematics | dilepton low Pt excess<br>consistency with SM 1 - 4 % | **193** |
| $V + A$ in $tWb$ | $\left.\begin{array}{l} f_{V+A} < 0.61 \\ f_{+} < 0.18 \end{array}\right\}$ @ 95% CL | **109 (runI)** |
| Search for $t\bar{t}$ resonances | in progress | **~300** |

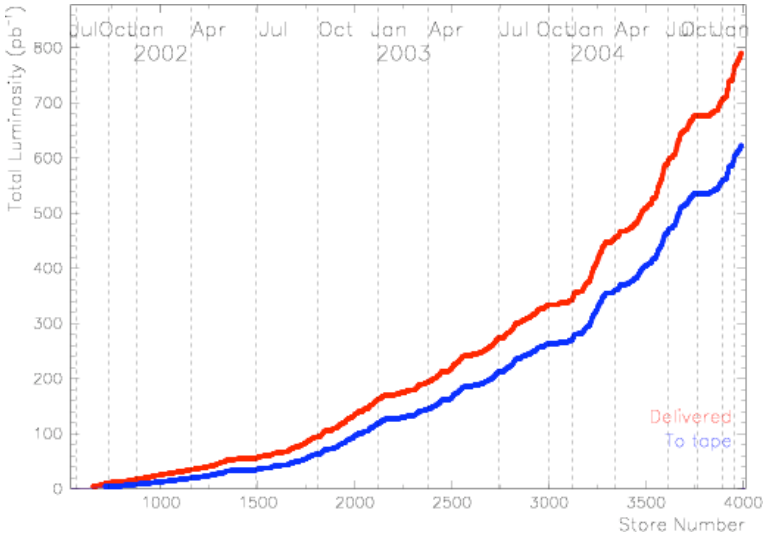
# Summary & Outlook

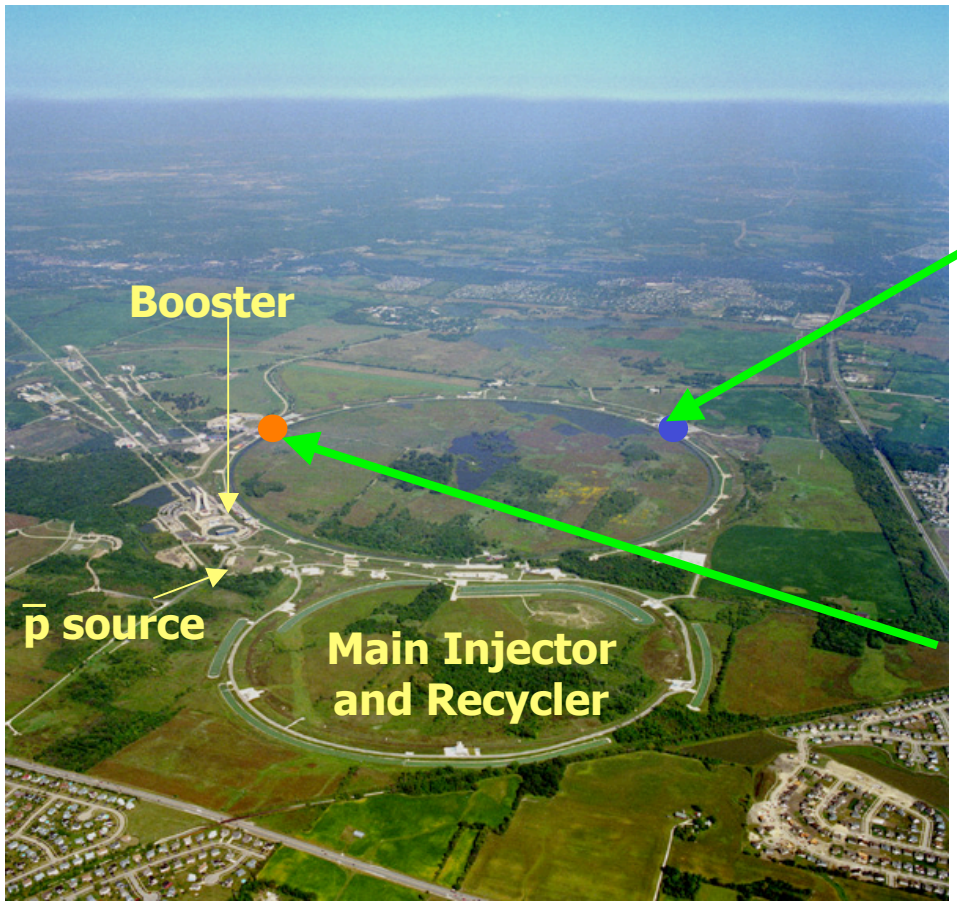
- All measurements consistent with SM
  - Recently published or submitted:
    - "Measurement of the t anti-t Production Cross Section in p anti-p Collisions at S**(1/2)=1.96 TeV Using Dilepton Events", Phys. Rev. Lett 93, 142001 (2004)
    - "Search for Electroweak Single Top Quark Production in p anti-p Collisions at S**(1/2)=1.96 TeV", Phys. Rev. D 71, 012005 (2005)
    - "Measurement of the W Boson Polarization in Top Decay at CDF at S**(1/2)=1.8 TeV", Phys. Rev. D71, 031101(R) (2005)
    - "Measurement of the t anti-t Production Cross Section in p anti-p Collisions at S**(1/2)=1.96 TeV Using Kinematic Fitting of B-Tagged Lepton+Jet Events", hep-ex/0409029
    - "Measurement of the t anti-t Production Cross Section in p anti-p Collisions at S**(1/2)=1.96 TeV Using Lepton+Jet Events with Secondary Vertex B-Tagging", hep-ex/0410041
    - "Search for Anomalous Kinematics in t anti-t Dilepton Events at CDF II", hep-ex/0412042
  - Reduced Jet Energy Scale uncertainty to be applied soon
- Hope for 2 $fb^{-1}$ or more by end of 2007
  - $\delta\sigma$ ~ 10% (now ~30%)
  - $\delta m$ ~2-3 GeV (now 4.3 GeV from RunI)
  - Single Top: possible observation
  - $\delta F_0$ reduced uncertainty (now 50-100%)
  - Mass limit on t'

# Backup Slides

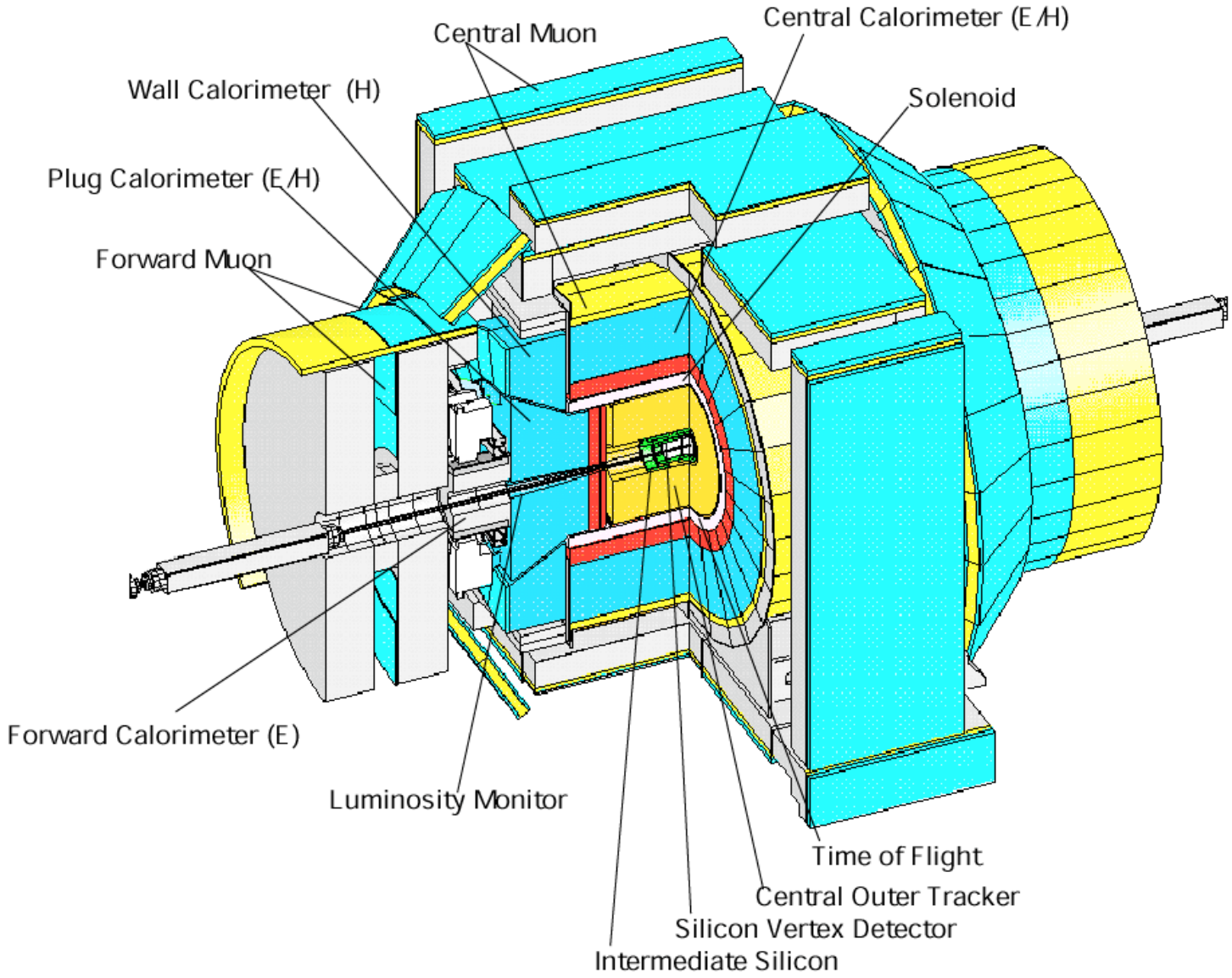
# Tevatron

- P-Pbar
- Collisions every 396 ns
- Beam energy 980 GeV
- $\sqrt{s}$ = 1.96 TeV
- Inst. Lum. ~$5 \times 10^{32}$ $cm^{-2}s^{-1}$

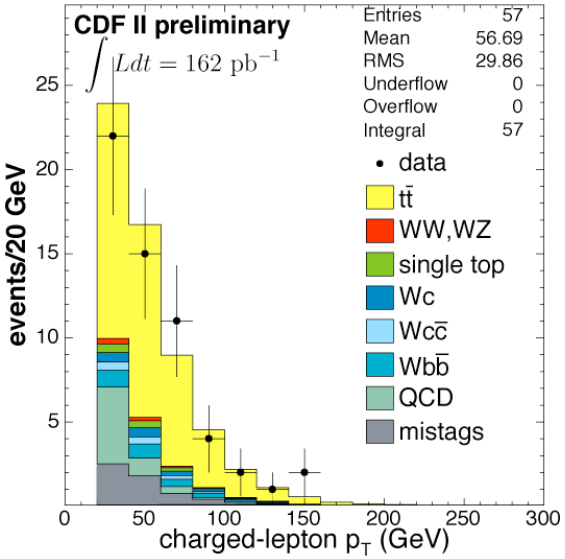


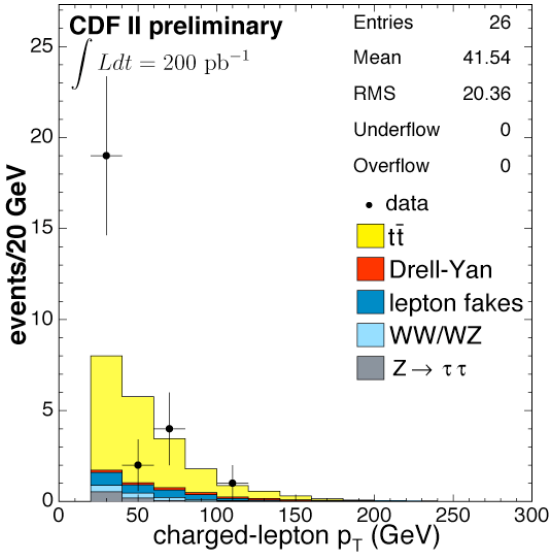



# CDF Detector



# W Helicity from lepton Pt



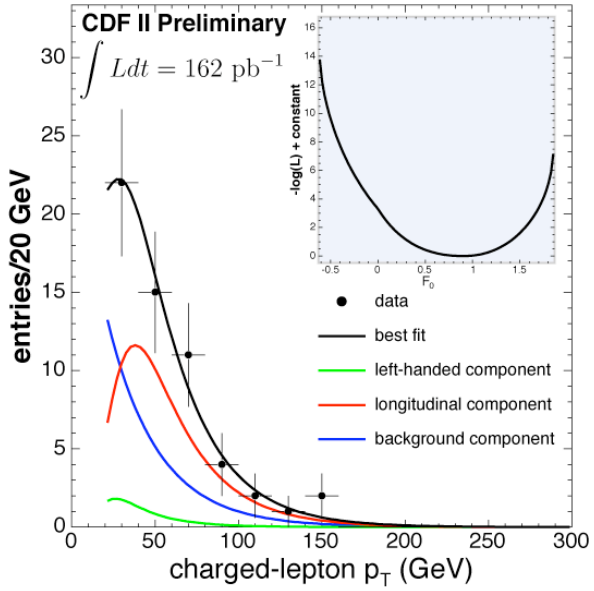

## l + jets

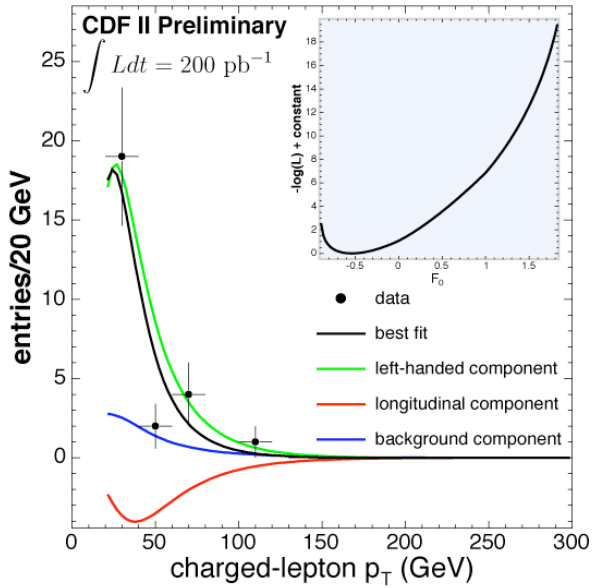
$$F_0 = 0.88^{+0.12}_{-0.47}(total)$$

$$F_0 > 0.24 \text{ @ } 95\% \text{ CL}$$

## dilepton

$$F_0 < 0.52 \text{ @ } 95\% \text{ CL}$$



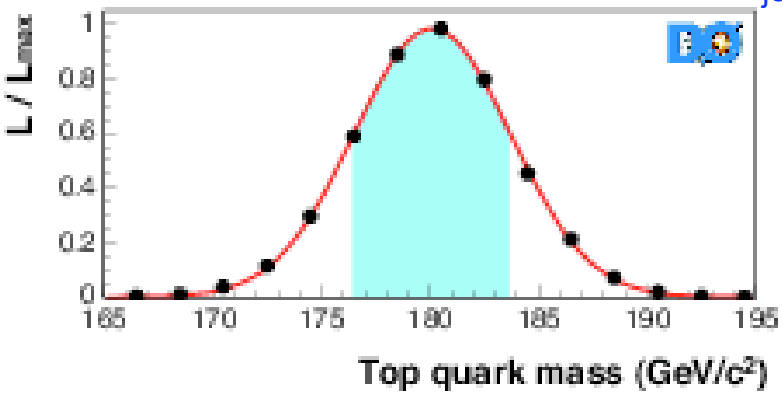



# Mass: DO RunI

- Statistical uncertainty reduced: 5.6 to 3.6 GeV/$c^2$
  - Equivalent to Lx2.4 !
- Likelihood vs. $m_t$ for each event:

$$P(x,m_t) = \frac{1}{\sigma(m_t)} \int \underbrace{d\sigma(x,m_t)}_{\text{Phase space x LO ME for top or BG (W+4j)}} dq_1 dq_2 \underbrace{f(q_1) f(q_2)}_{\text{PDFs}} \underbrace{W(x,y)}_{\text{Probability for observable x given parton y (Ex: quark } E_T \rightarrow \text{jet } E_T)}$$

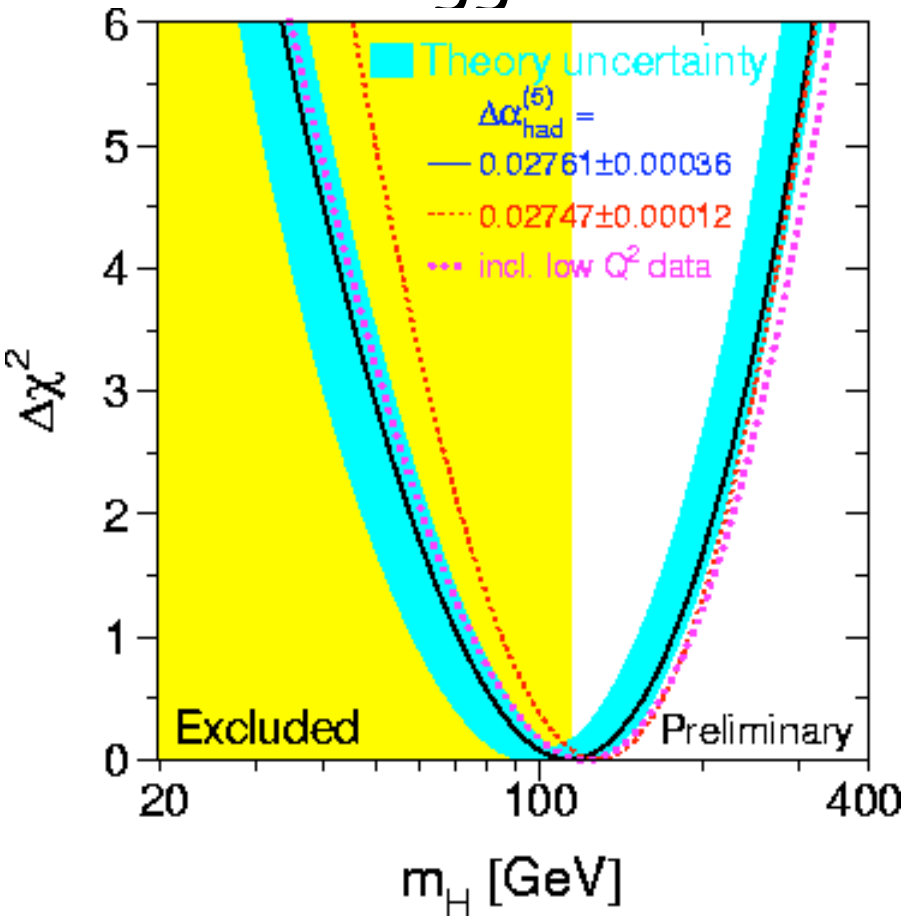
- Likelihood gives effective weigh to each event
- Maximize combined likelihood to extract $m_t$




$m_t$ = 180.1 ± 3.6(stat) ± 3.9(syst) GeV/$c^2$

# Implications for $M_{Higgs}$

- New combined D0 mass:
  - $M_t = 179.0 \pm 5.1$ GeV/$c^2$
- New World Average:
  - $M_t = 178.0 \pm 4.3$ GeV/$c^2$
- Global EW fit using new average
  - LEPEWWG method (hep-ex 0312023)
  - Best-fit $M_H \approx 113$ GeV/$c^2$
  - Upper limit @ 95% C.L. : 237 GeV/$c^2$




Yellow region excluded (direct search):
$M_H < 114.4$ GeV/$c^2$ @95% CL