Top Properties and Rare Decays from the Tevatron

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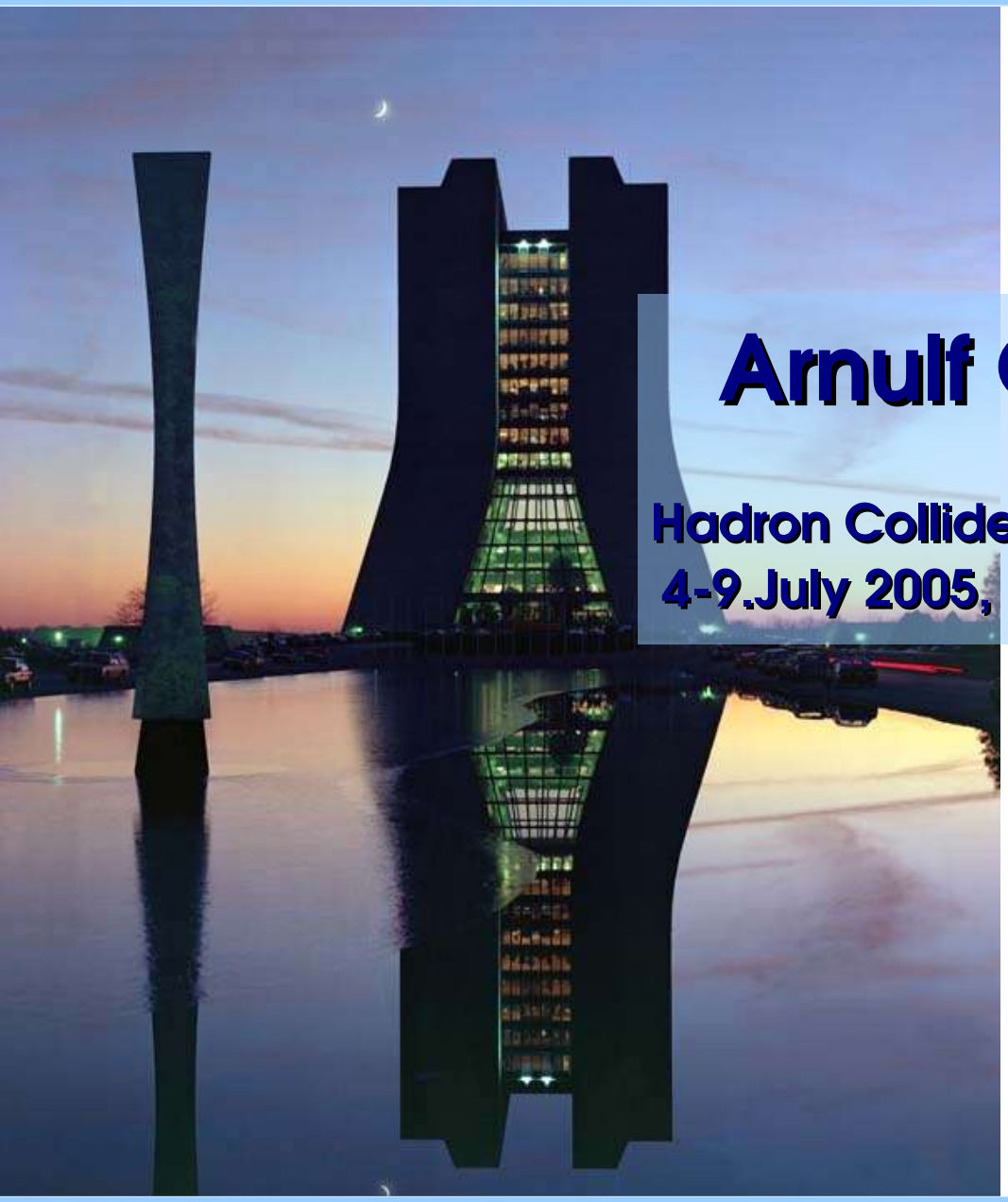
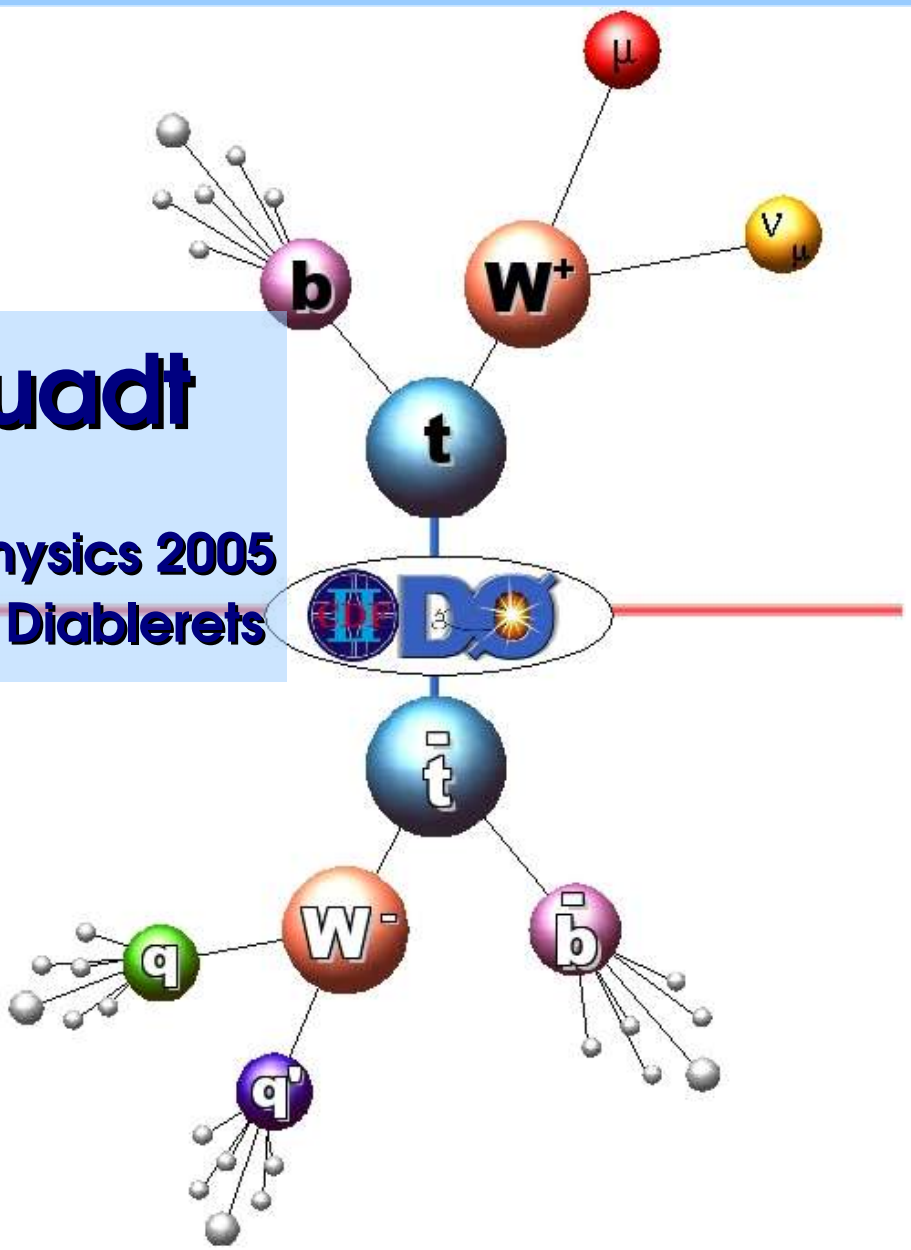
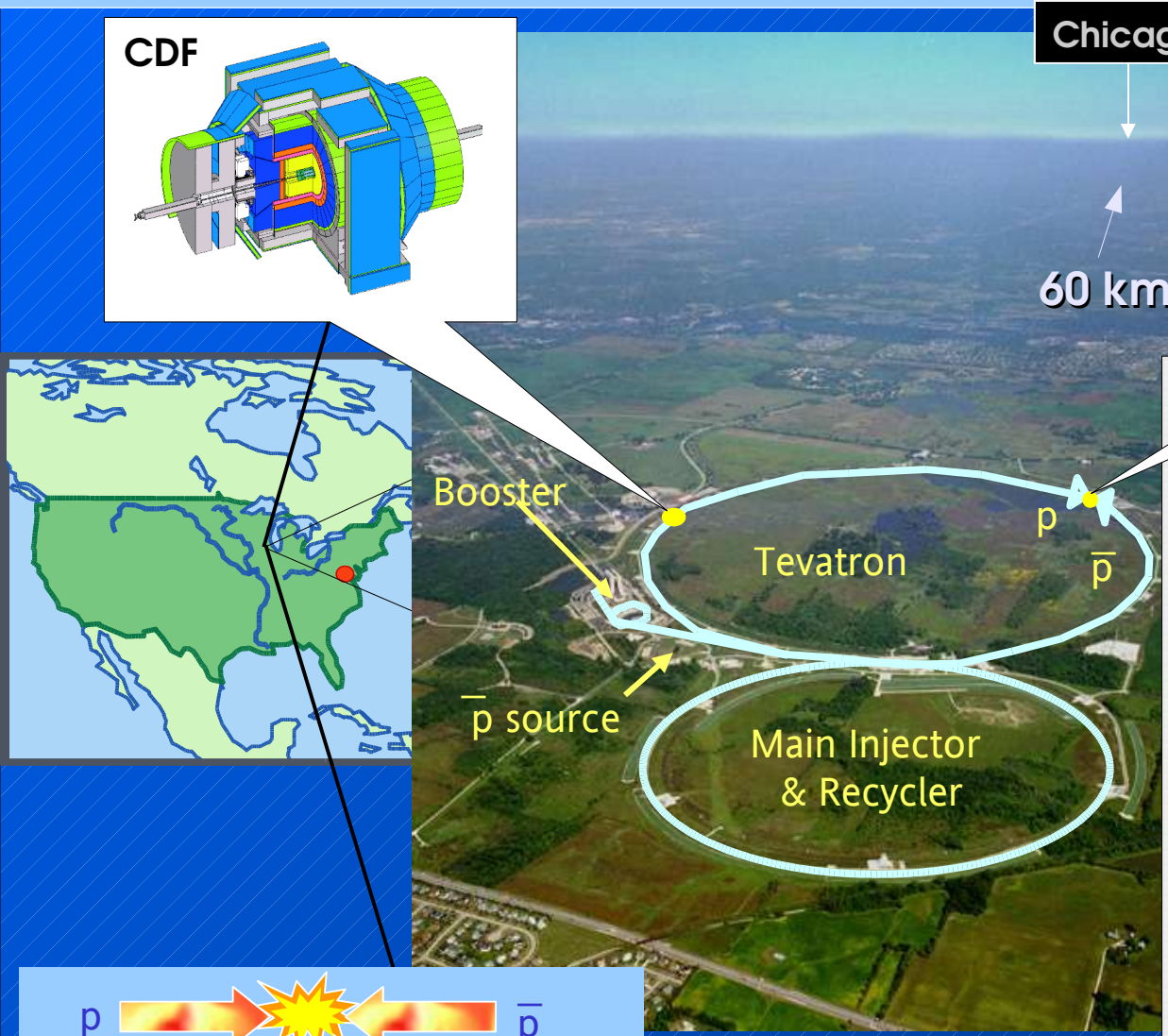


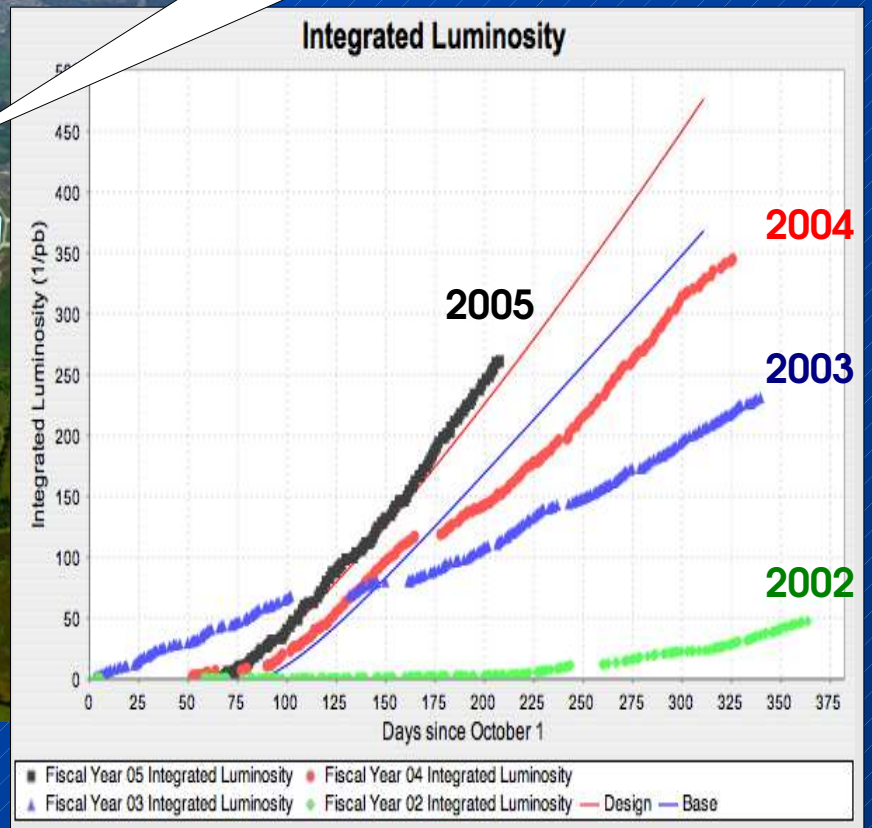


Outline

- Introduction
- σ_{ll}/σ_{lj}
- search for anomalous kinematics
- search for heavy 4th generation t'
- Br(t → Wb)/Br(t → Wq)
- Br(t → $\tau\nu$)
- charged Higgs search in top decays
- W-helicity in top quark decays
- outlook

The TEVATRON at Fermilab





p $\overline{p}$

$\sqrt{s}$ =1.8 - 1.96 TeV, Δt = 396 ns

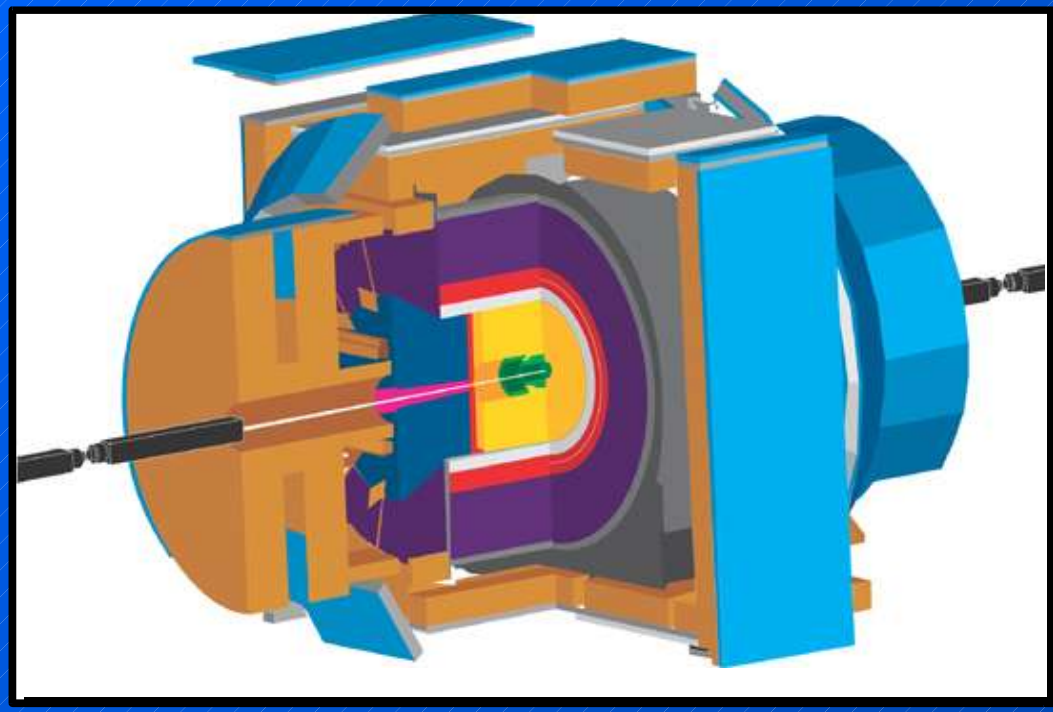
Run I 1987 (92)-95 L_{int} ~ 125 pb^{-1}

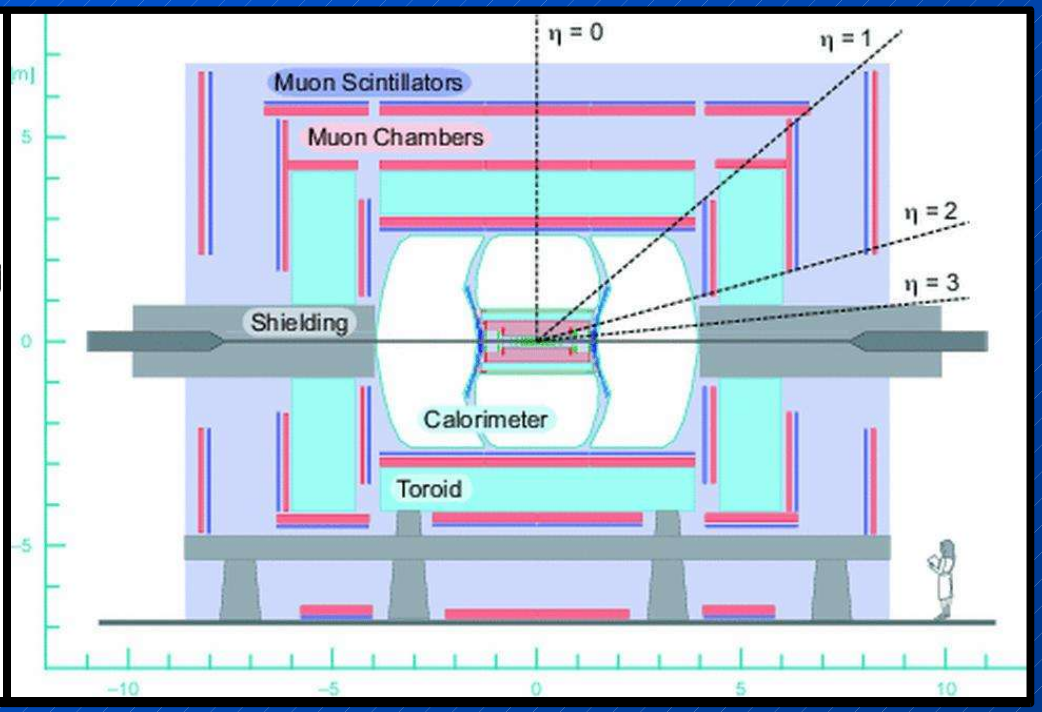
Run II 2001-09(?) 4-9 fb^{-1}

In spring 2002 passed Run-I lumi record

CDF and DØ ~780 pb^{-1} recorded each (ε ~90%)

The CDF and DØ Experiment





- Precise tracking and vertexing
  new bigger silicon/fiber tracker, new drift chamber, TOF
- Upgraded calorimeter and muon system
- Upgraded DAQ/trigger
- ~670 - 750 physicists

resolutions:

EM: σ_E/E = 13.5 - 15% / sqrt(E)

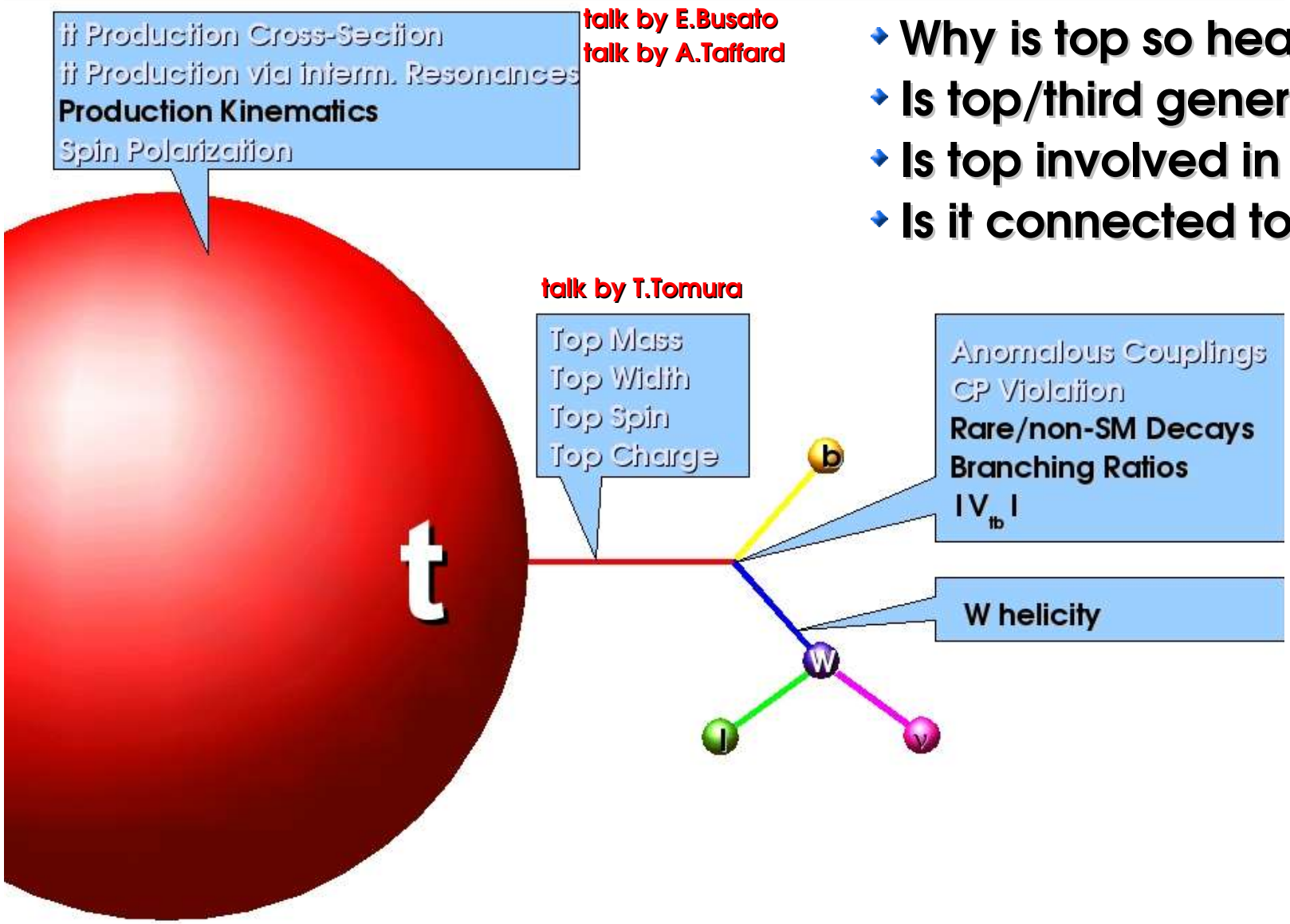
HAD: σ_E/E = 50 – 80 % / sqrt(E)

Top Quark Physics

Tevatron Run I : top quark discovery

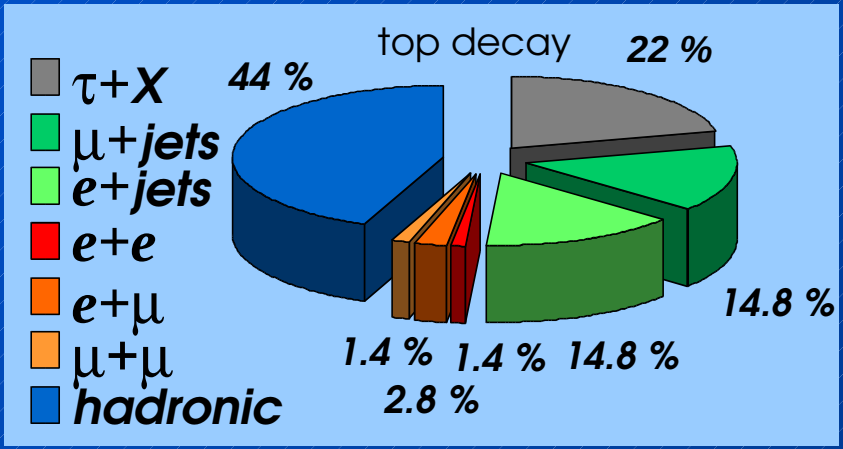
Run II : with high precision answer ...

- Why is top so heavy ?
- Is top/third generation special ?
- Is top involved in EWSB ?
- Is it connected to new physics ?



Decay Topology in $t\bar{t}$

Top quarks decay predominantly (~100%) to a W-Boson and a b-quark



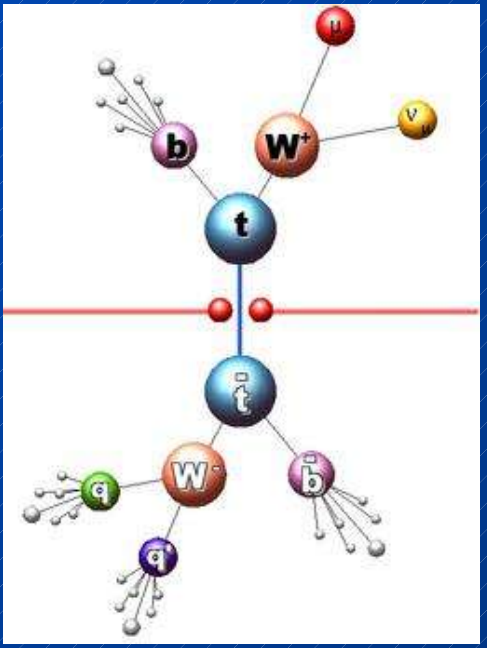
Top-Antitop Signatures:

`dilepton channel'
5% : 2 jets, 2 charged leptons, 2 ν

'lepton+jets channel'
30%: 4 jets, 1 charged lepton, 1 ν

'all-jets channel'
40%: 6 jets

always 2 jets are b-jets

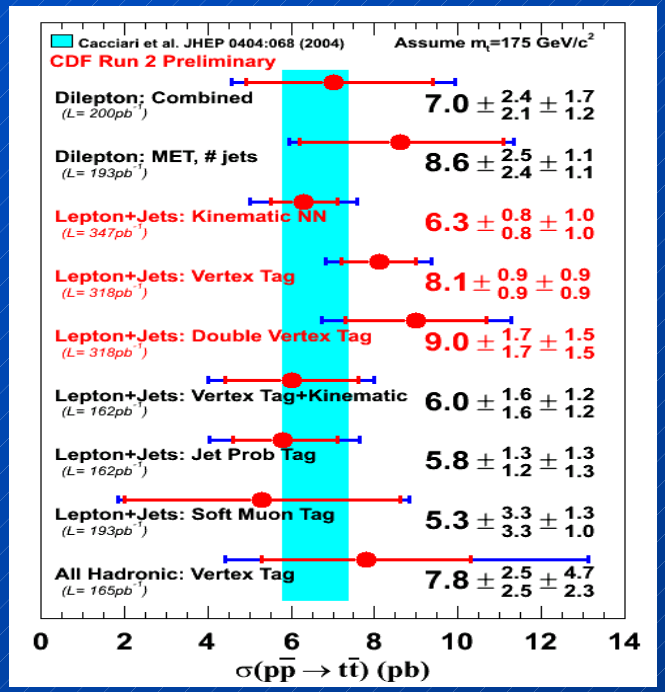


Anomalous $t\bar{t}$ Production (I)

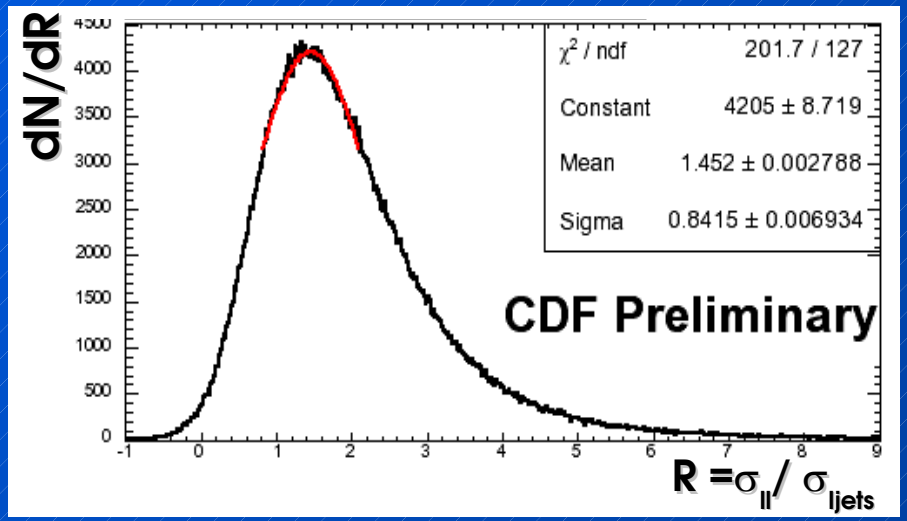
Test if top → dilepton the same as top → lepton+jets

Does top decay into something else than Wb ?
(for example $H^{\pm} \to cs, \tau\nu$)

like Xb, where X → qq (100%)
or Yb, where Y → $l\nu$ (100%) ?



estimate using ratio of top cross section $R = \sigma_{ll} / \sigma_{ljets}$



CDF, 125 pb^{-1}

$R = 1.45^{+0.83}_{-0.55}$

$R > 0.46$ (< 4.45) at 95%CL

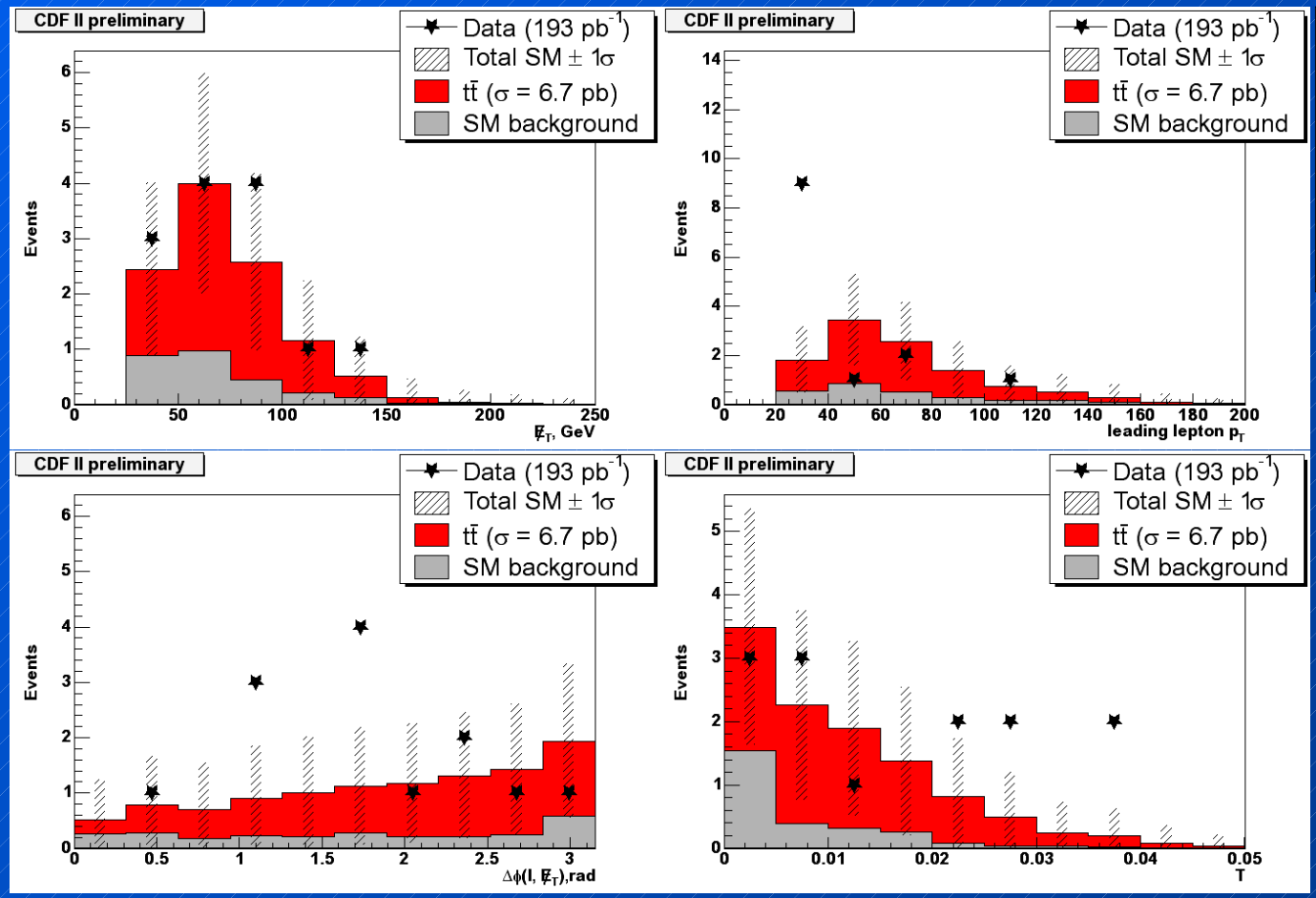
$BR(t \to Xb) < 0.46$ at 95% CL
$BR(t \to Yq) < 0.47$ at 95% CL

Anomalous $t\bar{t}$ Production (II)

In Run-I several CDF dilepton events at very high MET and P_T^{lepton}

⇨ suggested to originate from heavy squark decay

here: study four kinematic distributions of dilepton events (a priori choice)



$$MET$$

$$p_T^{lepton}$$

$$\Delta\phi(l, \overrightarrow{MET})$$

$$T = \int \exp\left\{\frac{-\left|\overrightarrow{MET}^{pred} - \overrightarrow{MET}^{obs}\right|^2}{2\sigma_{MET}^2}\right\} d\,\overrightarrow{MET}^{pred}$$

CDF, 193 pb^{-1}

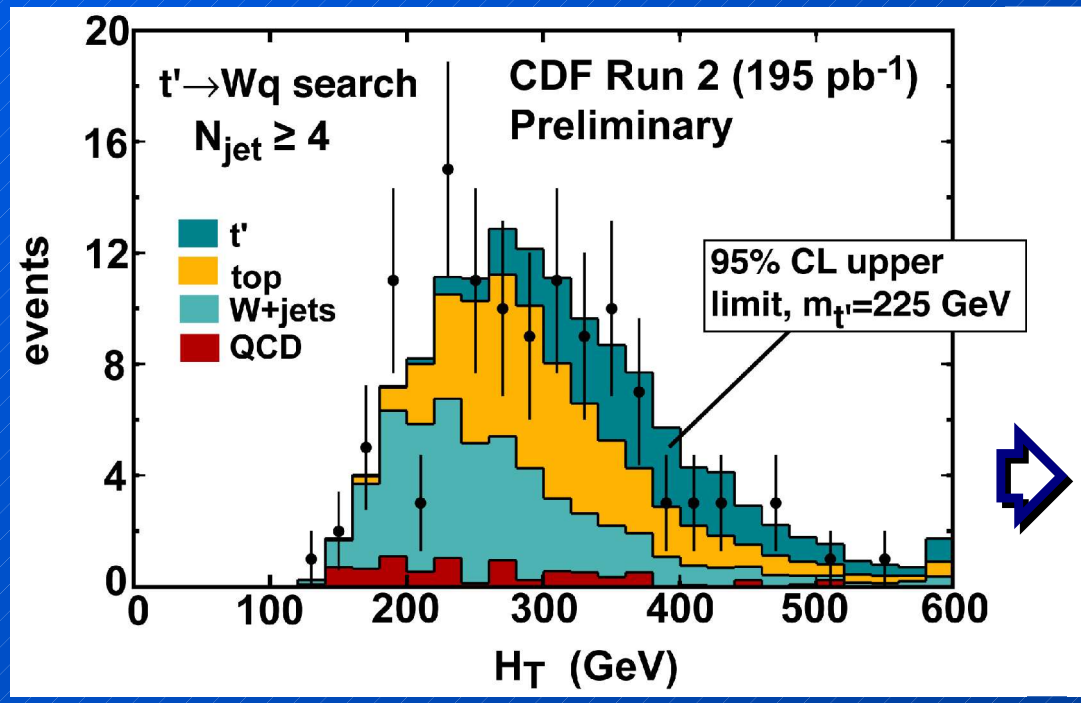
Probability of 1.0-4.5% to be less consistent with SM than observation

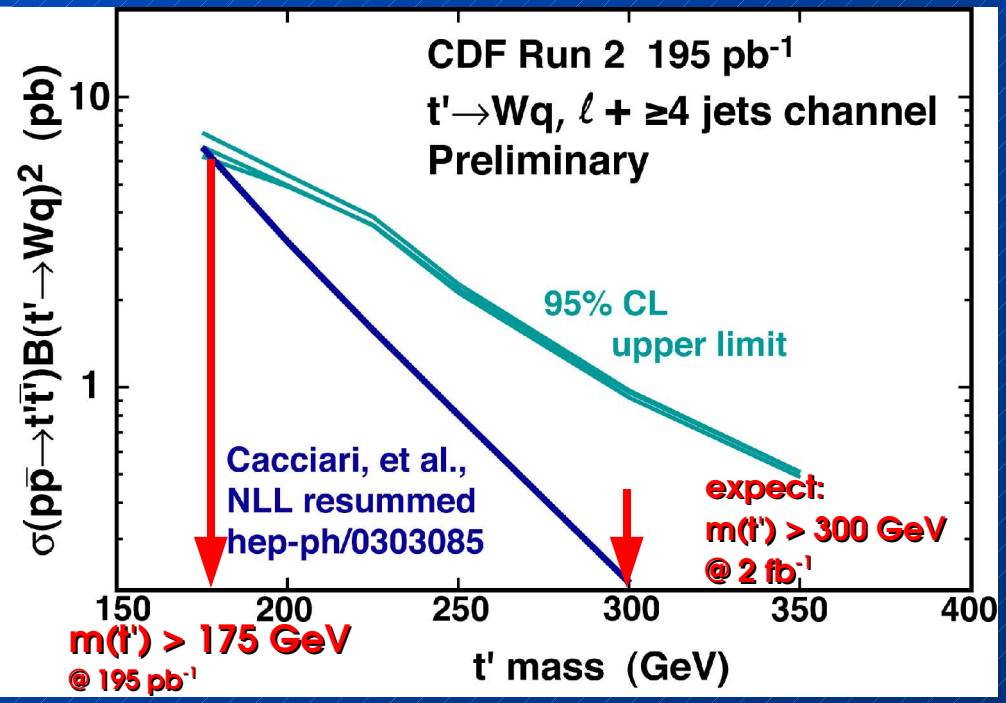
Anomalous $t\bar{t}$ Production (III)

Heavy quarks (4th generation) t' → Wq exist in various extensions of SM:

- **2-Higgs Doublet Model, N=2 SUSY** ⇨ **4th generation fermions**
- **"beautiful mirrors model",accommodate A_{FB}^{b} (LEP):** ⇨ **$\chi^{\text{up-type}}$ → Wb**
- **Little Higgs Models (hierarchy problem)** ⇨ **heavy t'**
  (non-minimal models ⇨ m(t') < 1 TeV)

⇨ search for t' → Wq in lepton+jets+MET events (CDF, 195 pb^{-1})
fit H_T distribution for possible contributions





Top Quark Decays (I)

Assuming 3 quark generations & CKM unitarity: 0.9990 < $|V_{tb}|$ < 0.9992 (90% CL)

$$R = \frac{BR(t \to Wb)}{BR(t \to Wq)} = 0.9980 - 0.9984$$

- **If non-SM top decay**
- **or non-SM background to ttbar**
- **or a fourth quark generation** ⇨ **R and $|V_{tb}|$ significantly less than unity**

Compare expected and observed rate of 0, 1 and 2 b-tag ttbar events in l+j and di-lepton (CDF, 162 pb^{-1}) or l+jets events (DØ, 230 pb^{-1})

- counting experiment in ≥ 1 tag
- ANN / likelihood in 0-tag

event tagging efficiency depends on flavour composition

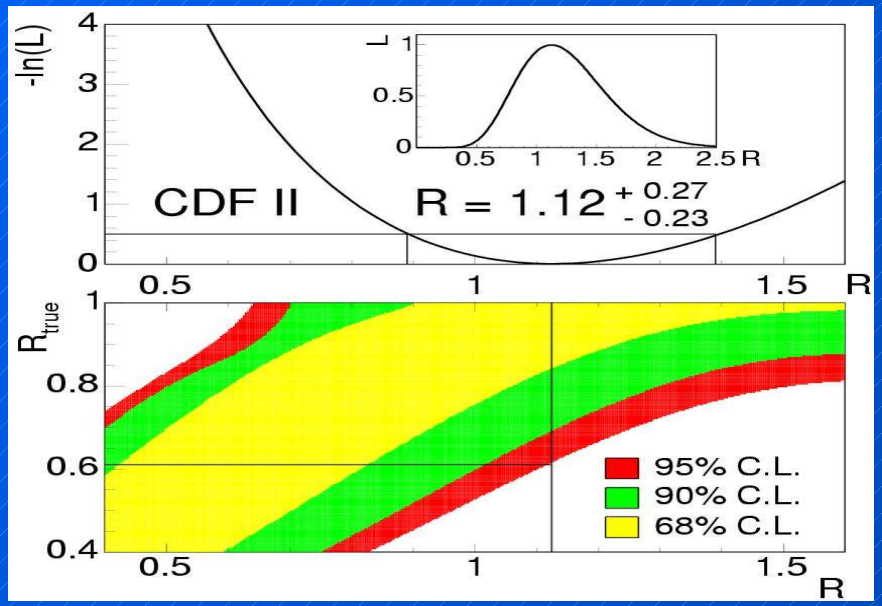
$$N_i^{\exp} = N^{t\bar{t}} \cdot \epsilon_i(R) + N_i^{bkg}$$ **in *i*-tag sample**

$$N^{t\bar{t}} = \sum_i (N_i^{obs} - N_i^{bkg})$$ **inclusive (CDF)**

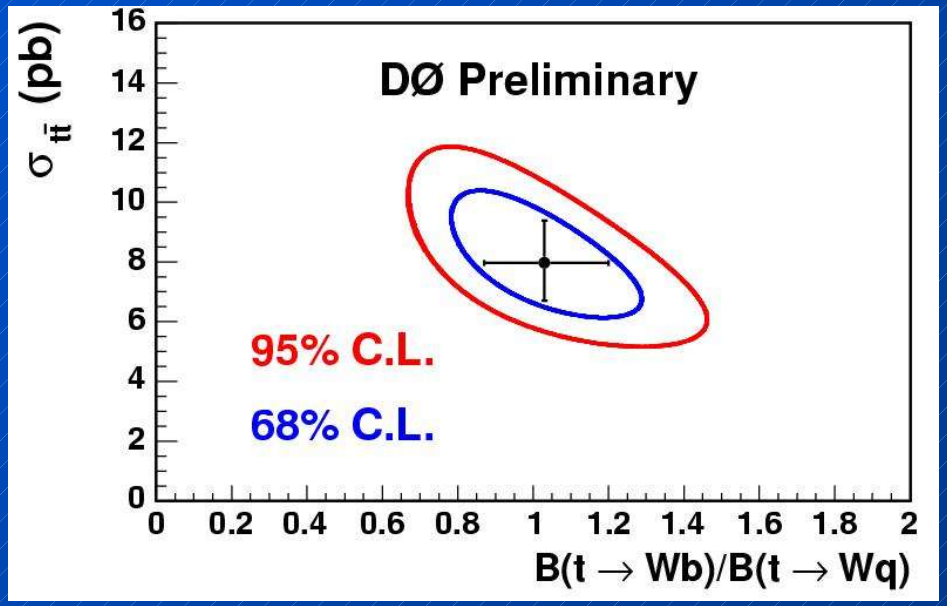
$$N^{t\bar{t}} = \sigma_{t\bar{t}} \cdot \epsilon_{selection} \cdot accept. \cdot BR(t \to \ldots)$$ **per channel (D0)**

Top Quark Decays (II)

CDF: fit for R



DØ: simultaneous fit for R and σ_{tt}



$R = 1.12^{+0.27}_{-0.23}$ (stat+syst)

$R > 0.61$ @ 95% C.L.

$|V_{tb}| > 0.78$ @ 95% C.L.

$R = 1.03^{+0.19}_{-0.17}$ (stat+syst)

$R > 0.64$ @ 95% C.L.

$|V_{tb}| > 0.80$ @ 95% C.L.

$\sigma_{tt} = 7.9^{+1.7}_{-1.5}$ (stat+syst) ± 0.5 (lumi) pb

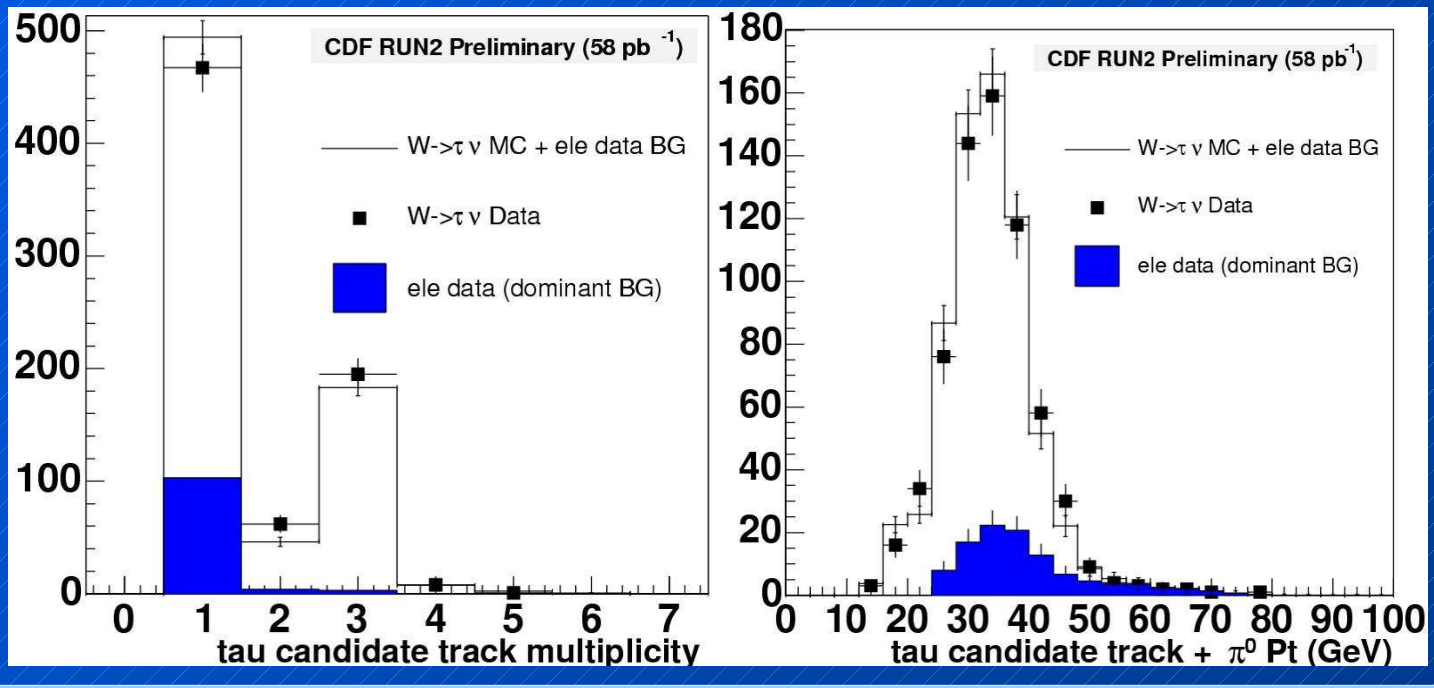
Top quark decay to W and b quark is indeed dominant ... !

$t \rightarrow \tau\nu$ Decays

- Standard Model's third generation is intriguing
- Study third generation to shed light on origin of particle masses
- Extensions of Standard Model predict similar topologies e.g. charged Higgs

Compare rate of lepton + τ + jets + MET events in CDF data with hadronically decaying τ to SM expectation :

⇨ expect 2.3 events, observe 2 events



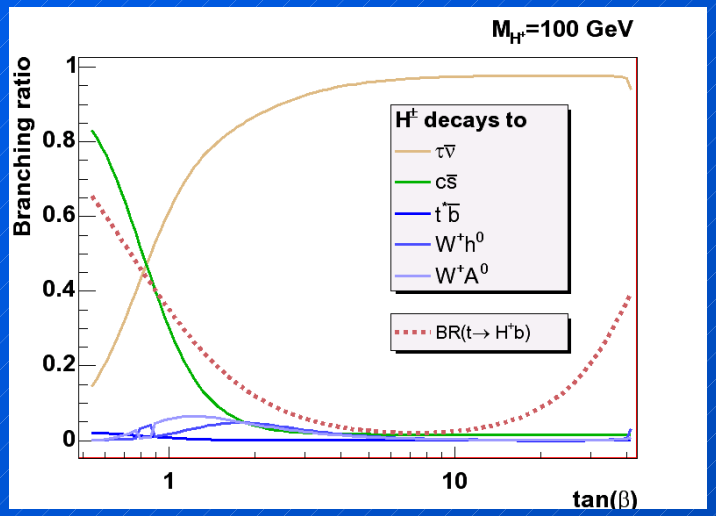
CDF, 193 pb^{-1}

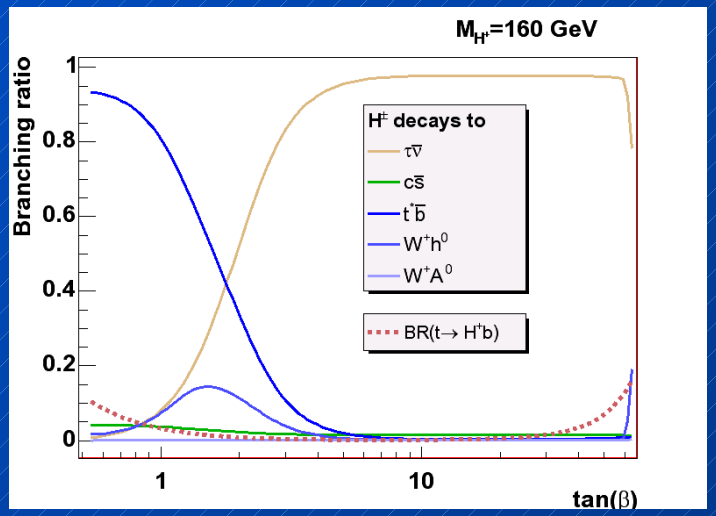
$$r_\tau \equiv \frac{BR(t \rightarrow \tau\nu)}{BR_{SM}(t \rightarrow \tau\nu)}$$

r_τ < 5.0 at 95% C.L.

Search for Charged Higgs (I)

- In 2-Higgs Doublet Models (e.g. MSSM) $H^{\pm}$ exist
- If $m_{H^{\pm}} < m_t$ $t \to H^{\pm} b$ can compete with $t \to Wb$
- Changes in event topology according to $H^{\pm}$ decay (scalar, channels) :



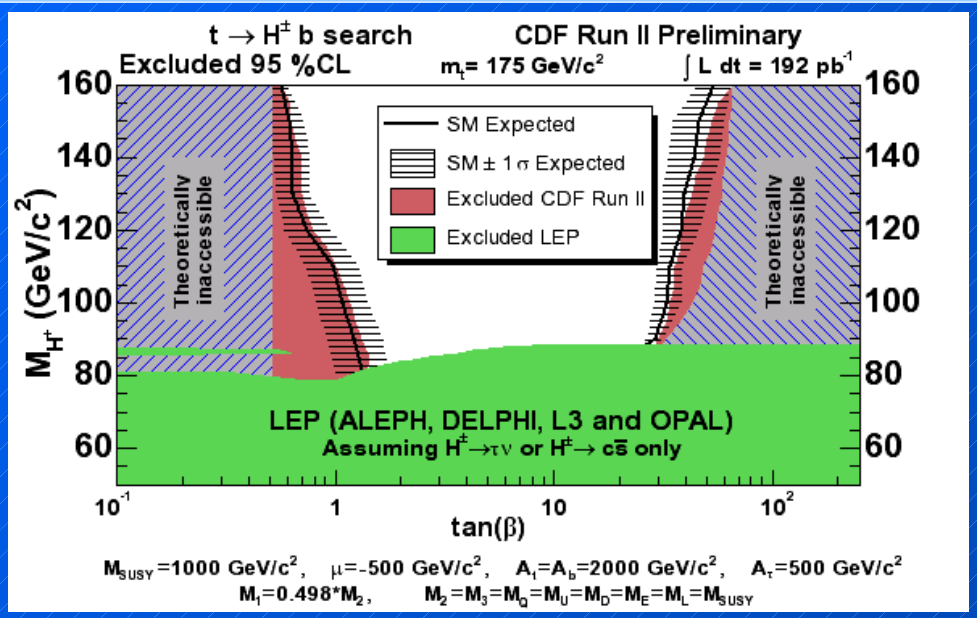


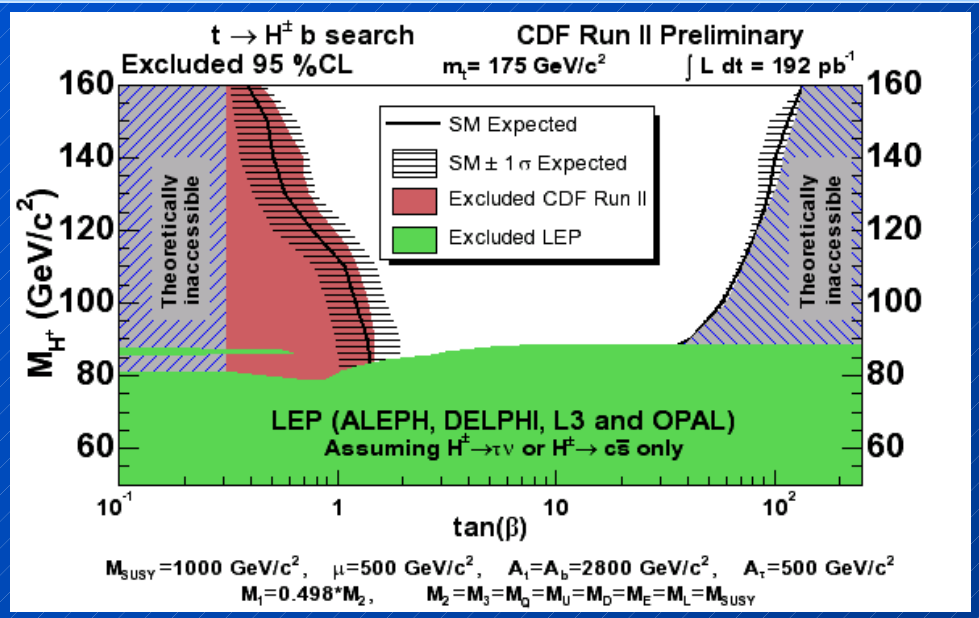
large tan β $\quad H^{\pm} \to \tau\nu$ — excess of τ decays in ttbar events

small tan β: $\begin{cases} H^{\pm} \to c\bar{s} \\ H^{\pm} \to W h \to W b\bar{b} \end{cases}$ — excess of fully hadronic ttbar events; 2 extra b-jets in ttbar events

- Combine CDF data (192 pb^{-1}) in dilepton, lepton+jets (1 b-tag), lepton+jets (≥ 2 b-tags), lepton+hadronically decaying τ
- taking $t \to H^{\pm}b$ and $H^{\pm}$ decay branching ratios into account

Search for Charged Higgs (II)

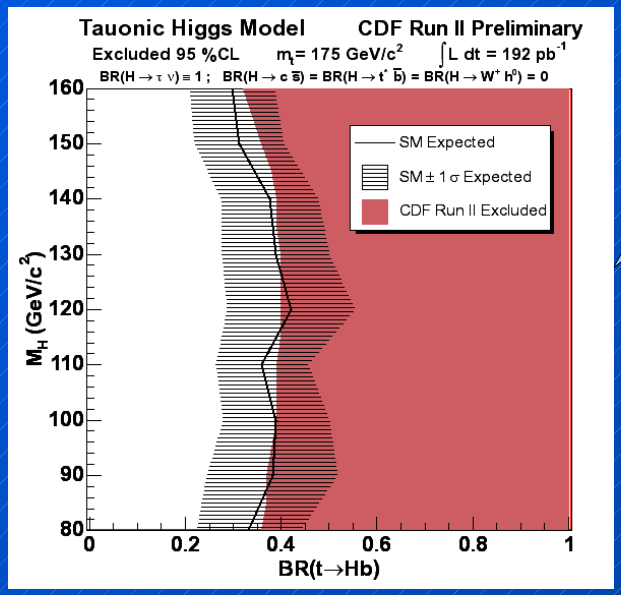




tan β >30: Br(t→H±b) enhanced by low μ

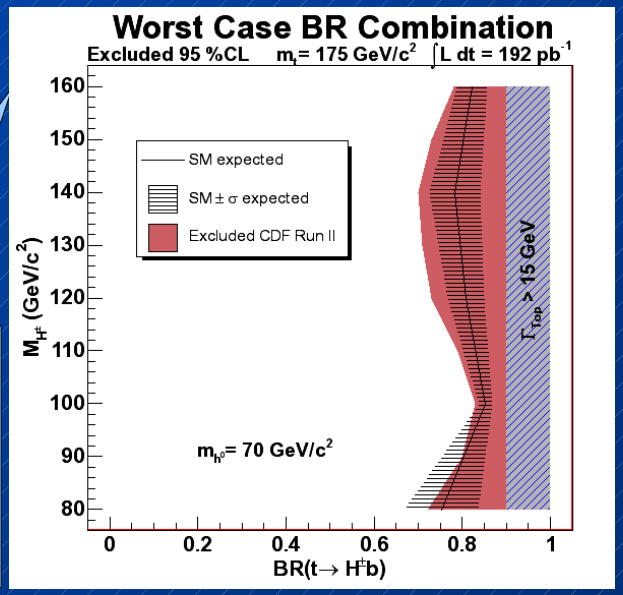
tan β >30: Br(t→H±b) suppressed by large μ

tan β ~ 1: H±→Wh0 occurs



If Br(H±→τν) = 100%
⇨ limit on Br(t→H±b)

Scan over all Br(H±→..)
⇨ quote weakest limit on Br(t→H±b)
(model independent)



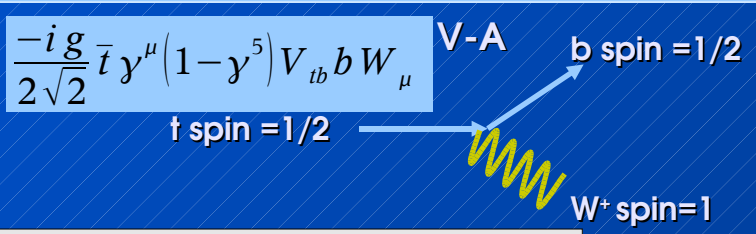
Weak Top Decay - Helicity of the W

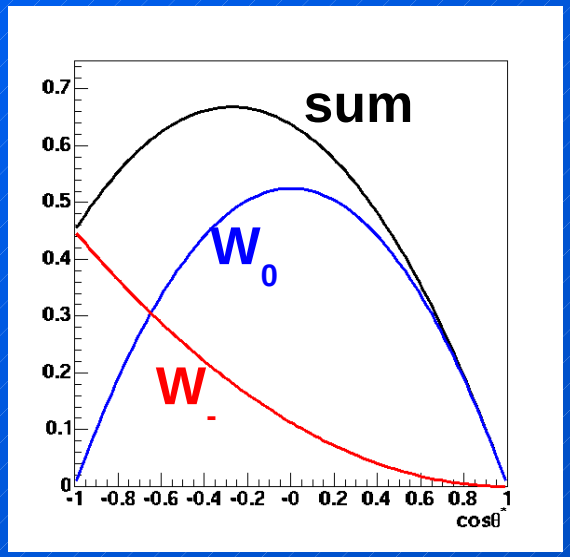
Top Standard Model weak decay →

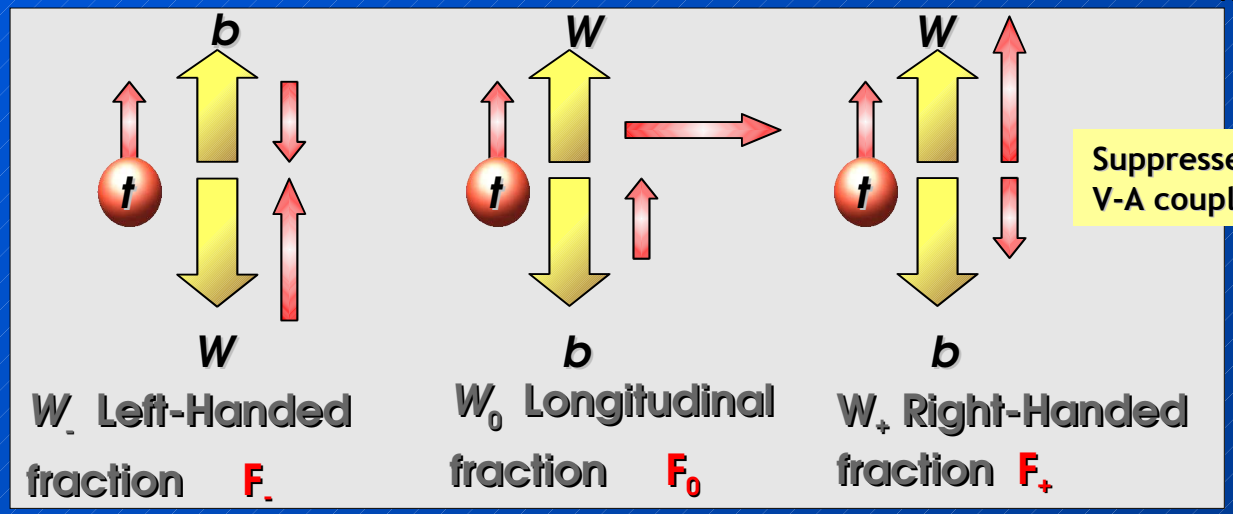
V-A coupling as it is for all the other fermions

$$\frac{-ig}{2\sqrt{2}}\bar{t}\gamma^{\mu}(1-\gamma^{5})V_{tb}bW_{\mu}$$

V-A







$$w(\cos\phi_{l\bar{b}}) = F_{-}\cdot\frac{3}{8}(1-\cos\phi_{l\bar{b}})^{2} + F_{0}\cdot\frac{3}{4}(1-\cos^{2}\phi_{l\bar{b}}) + F_{+}\cdot\frac{3}{8}(1+\cos\phi_{l\bar{b}})$$

In SM

$$F_{-} = \frac{2\frac{m_W^2}{M_{top}^2}}{1+2\frac{m_W^2}{M_{top}^2}} \approx 0.30$$

$$F_{0} = \frac{1}{1+2\frac{m_W^2}{M_{top}^2}} \approx 0.70$$

... for any V, A combinations ...

$$F_{+} \propto (m_b/m_t)^2 \approx 0$$

Helicity of W manifests itself in decay product kinematics

Helicity of the W in ttbar Events (I)

Charged leptons from ...

... left-handed W opposite to W ⇨ soft p_T

... longitudinal W transverse to W ⇨ harder p_T

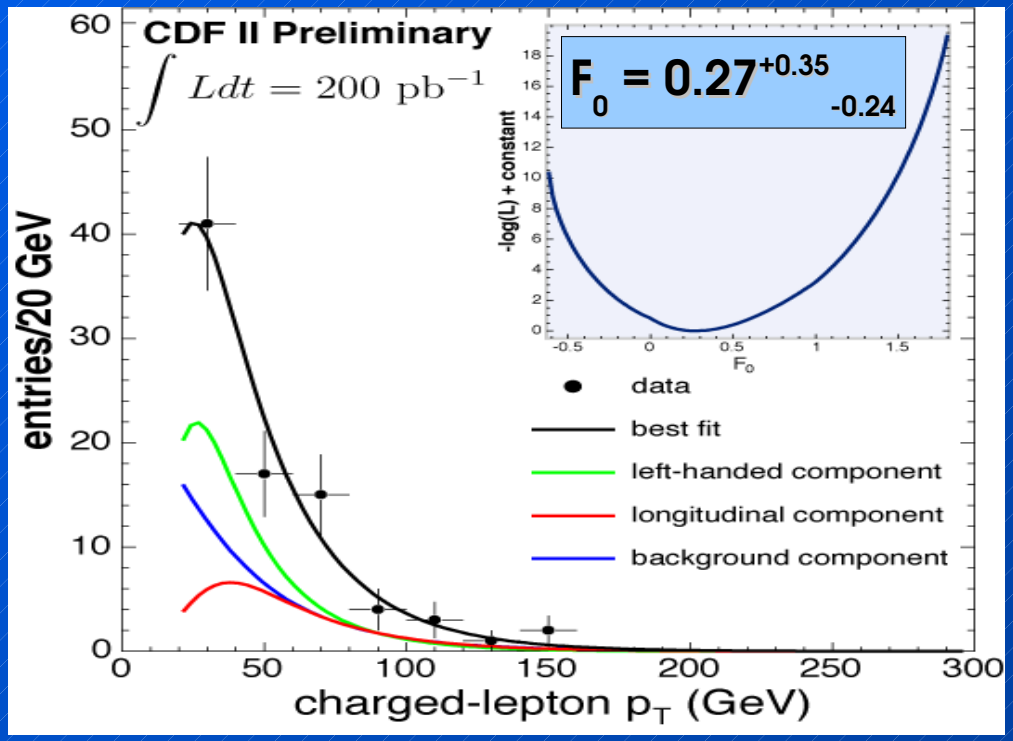
CDF, 162 – 200 pb^{-1}:

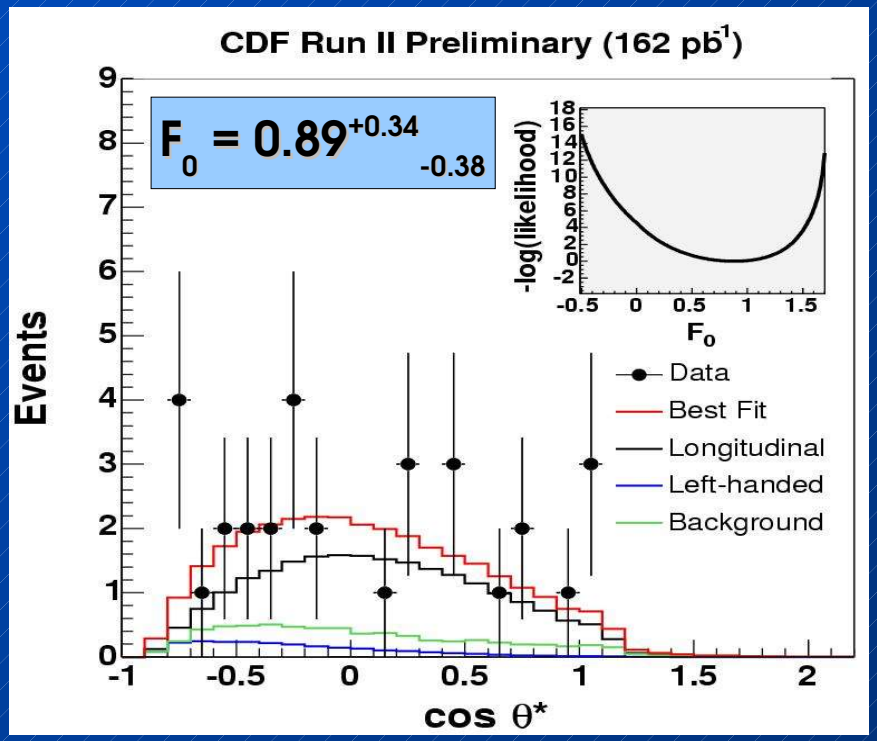
l+jets with 1, ≥2 b-tag and di-lepton

Explicit reconstr. of decay angle

$$\cos\theta^* = \frac{2\, m_{lb}^2}{m_t^2 - m_W^2} - 1$$

CDF, 162 pb^{-1}, l+jets with≥ 1 b-tag





Run-I analysis (CDF, l+j, di-lepton): $F_+ < 0.18$ @ 95% C.L.

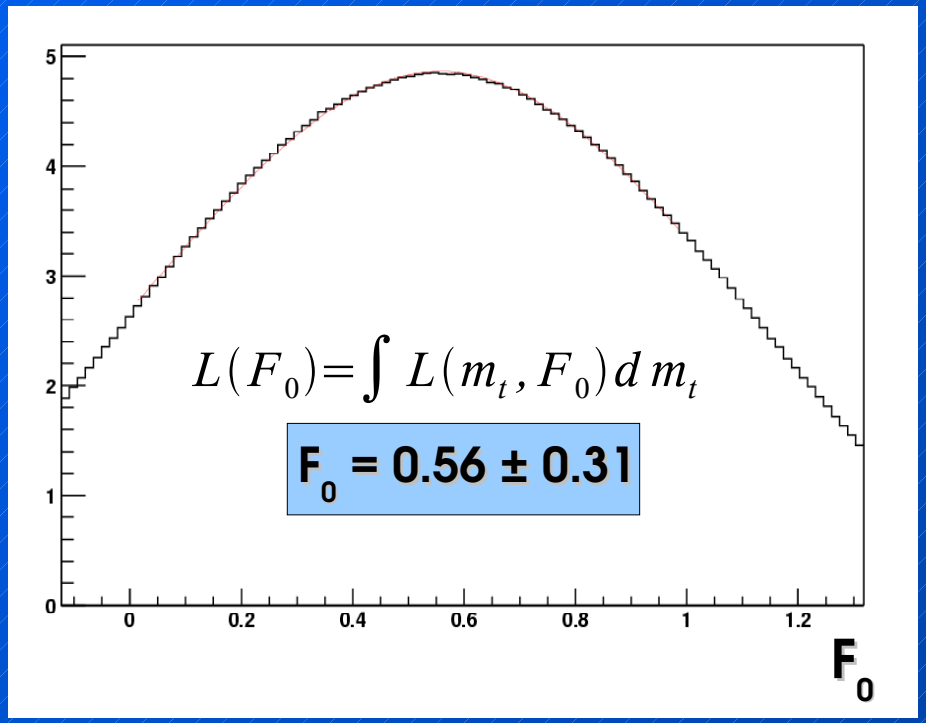
Helicity of the W in ttbar Events (II)

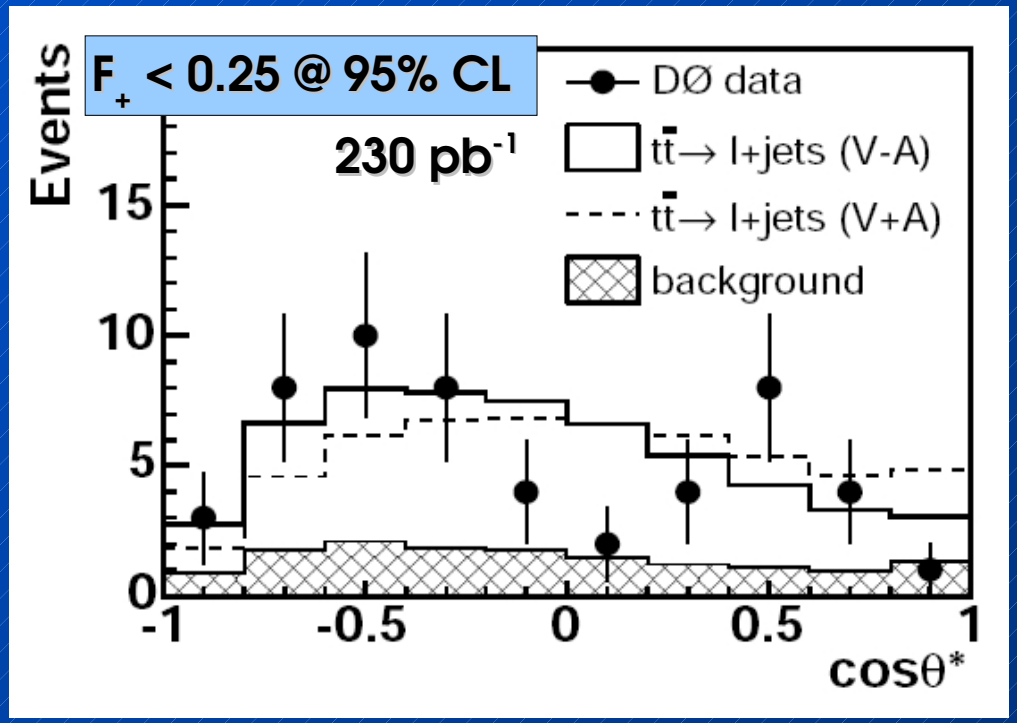
DØ Run I:

- extended `Matrix Element' technique (á la Run-I m_t measurement)

DØ Run II:

- kinematic fit + decay angle reconstr.
- topological + b-tag sample in l+jets
- Now also dilepton p_T analysis (new)

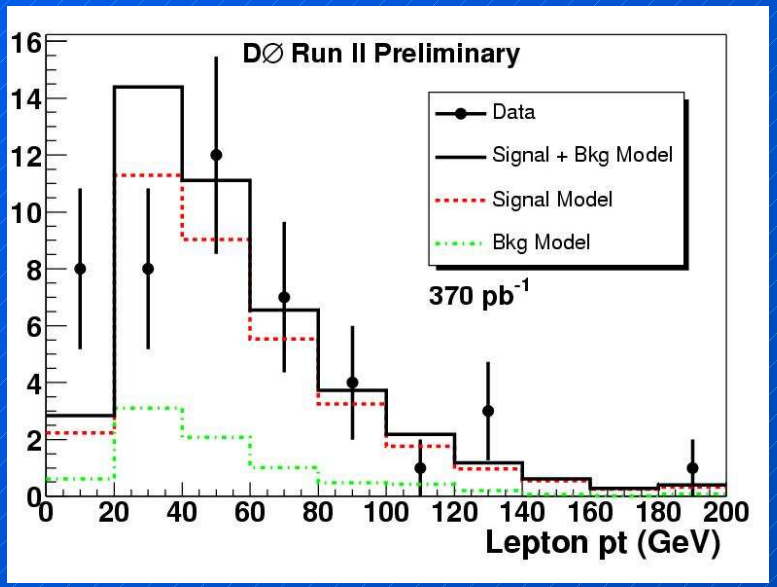


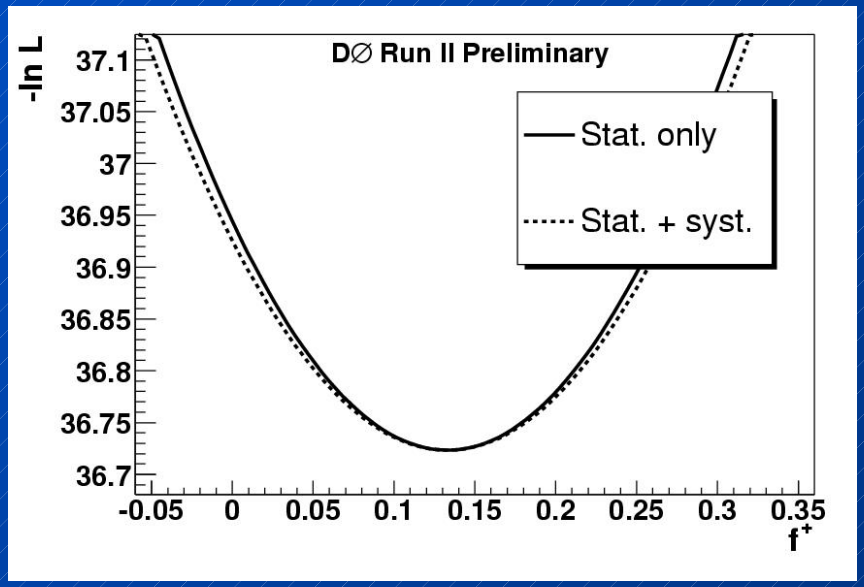


... no deviations from SM predictions
eventually simultaneous fit for F_0 and F_+ ...

Helicity of the W in ttbar Events (III)

- DØ search for right-handed W in dilepton channel (370 pb^{-1})
- $e\mu$ (15), ee (5), $\mu\mu$ (2) events
- compare dilepton p_T spectrum with template distribution for V+A contribution





$$F_+ = 0.13 \pm 0.20(stat) \pm 0.06(syst) \quad (dilepton)$$
$$F_+ = 0.00 \pm 0.13(stat) \pm 0.07(syst) \quad (l + jets)$$
$$F_+ = 0.04 \pm 0.11(stat) \pm 0.06(syst) \quad (combined)$$

$F_+ = 0.0 - 0.25$ **@ 95% CL**

Summary

- The top quark is unique among the six quarks

  - mass
  - charge
  - spin
  - ...
  - production (strong & weak)
  - decay
  - couplings (gauge or new)
  - ...

- Will study the top quark and its role in Nature with unprecedented precision ...

<u>Outlook:</u>

in addition to analyses presented further studies ongoing

* tt production via intermediate resonances
* top quark charge
* top spin correlation
* anomalous top quark production via FCNC coupling