Top Quark Physics Results at the Tevatron

Lucio Cerrito
Queen Mary, University of London

(on behalf of the CDF and DØ Collaborations)

Heavy Quarks and Leptons
Munich, October 2006

Introduction

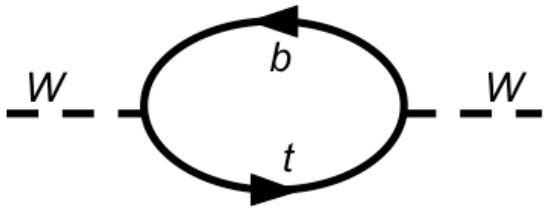
Particle type: the weak isospin partner of the bottom-quark

Mass: x35 the mass of the *b*, similar to a gold nucleus. Measured as: 171.4±2.1 GeV/c² it is intriguingly close to the scale of EW symmetry breaking

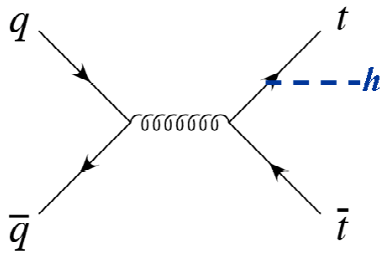
Width: 1.42 GeV

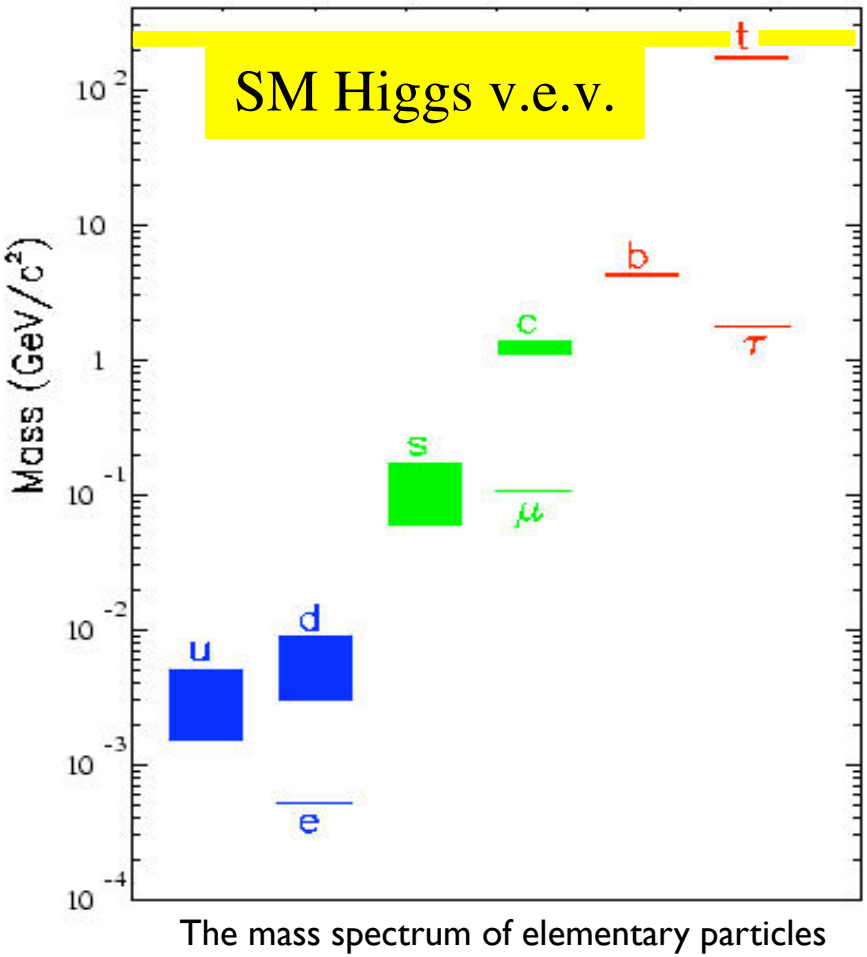
Charge: 2/3 *e*

Decay: almost exclusively $t \rightarrow W + b$

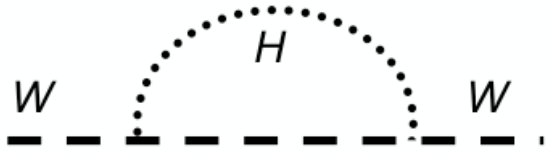


$$\Delta M_W \propto M_t^2$$





The mass spectrum of elementary particles



$$\Delta M_W \propto \ln(M_H)$$

The top Yukawa coupling is "natural": $y = \sqrt{2}\frac{M_t}{v} \sim 1$

Why top physics

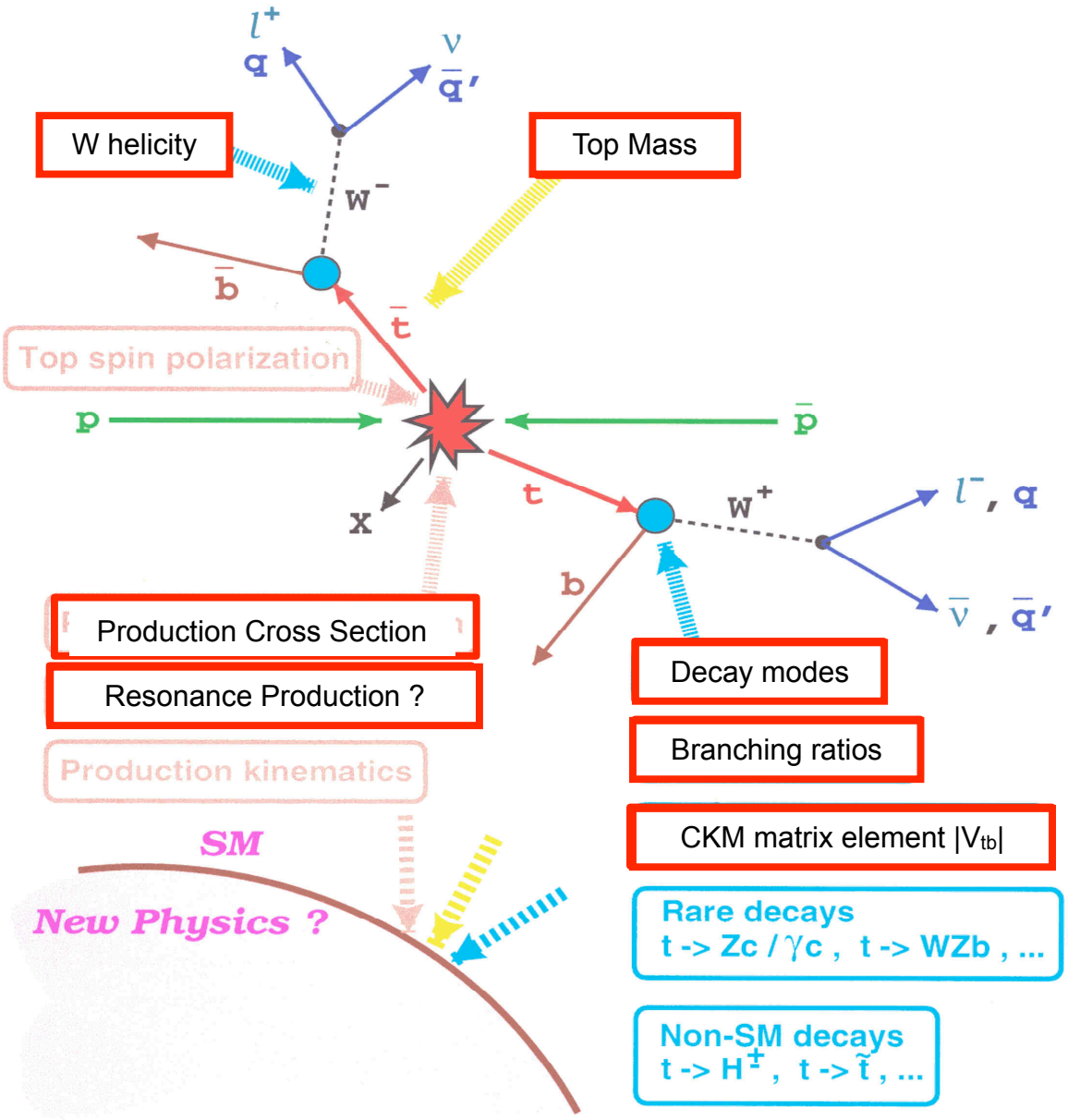
➢Test of SM (production, decay, coupling....etc)

➢ Does not hadronize: momentum and spin transferred to decay products

➢ Search for processes with similar signature (t', Z', V+A..)

➢ Measure the t mass, to predict the SM Higgs mass

The Tevatron is performing the first precision exploration of the top-quark energy regime



Experimental Overview

The Tevatron top physics program seen from the perspective of precision:

Measurement already/towards limited by:

Luminosity Uncertainty

Pair production cross section

Systematics

Top quark mass

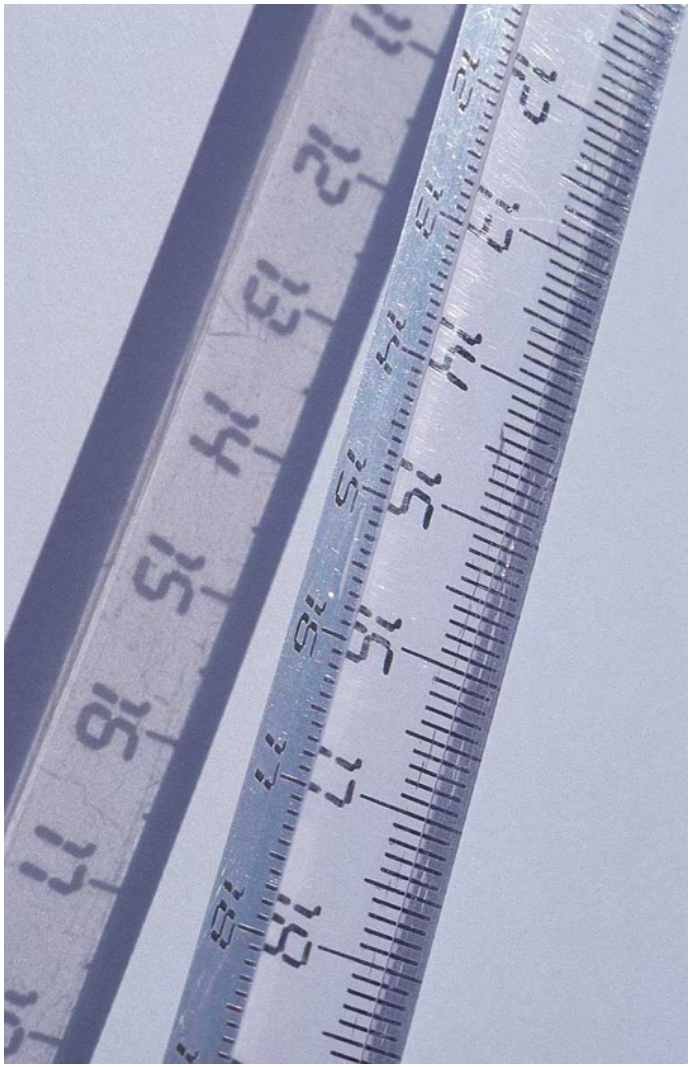
Statistics

Polarizations

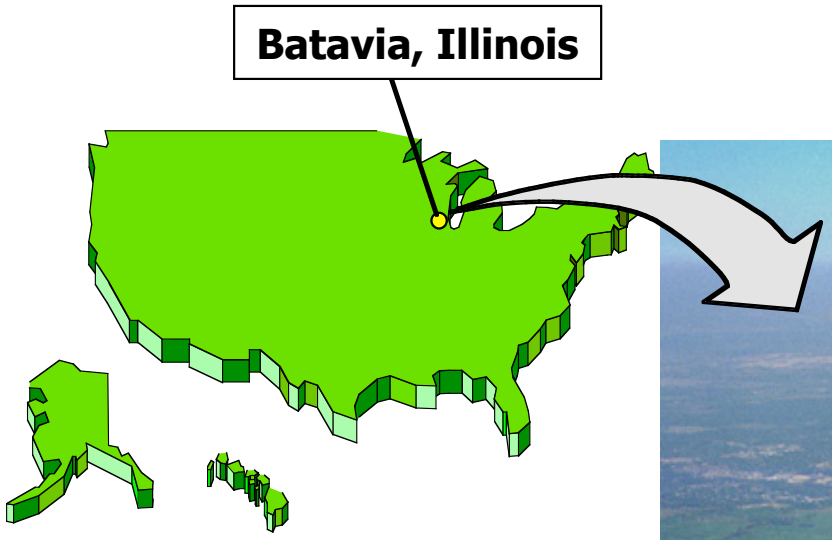
Single top production

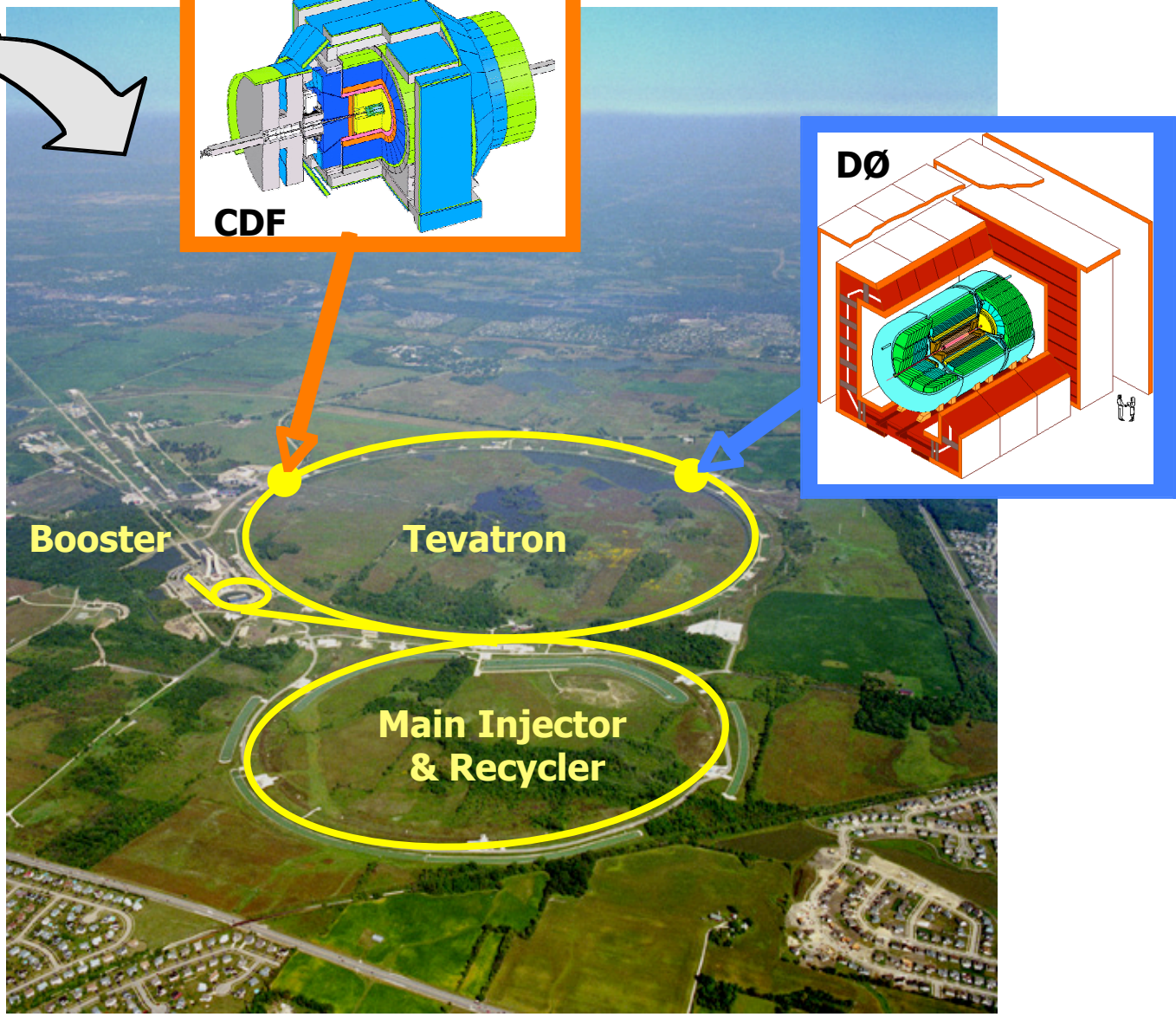
$|V_{tb}|$, top charge, resonances

Summary and Outlook



The Tevatron at Fermilab





- Proton-antiproton collisions at 1.96 TeV
- 396 ns bunch spacing
- Run I operating 1992-1996
- Run II operating since 2001

The only accelerator capable today of producing top quarks.

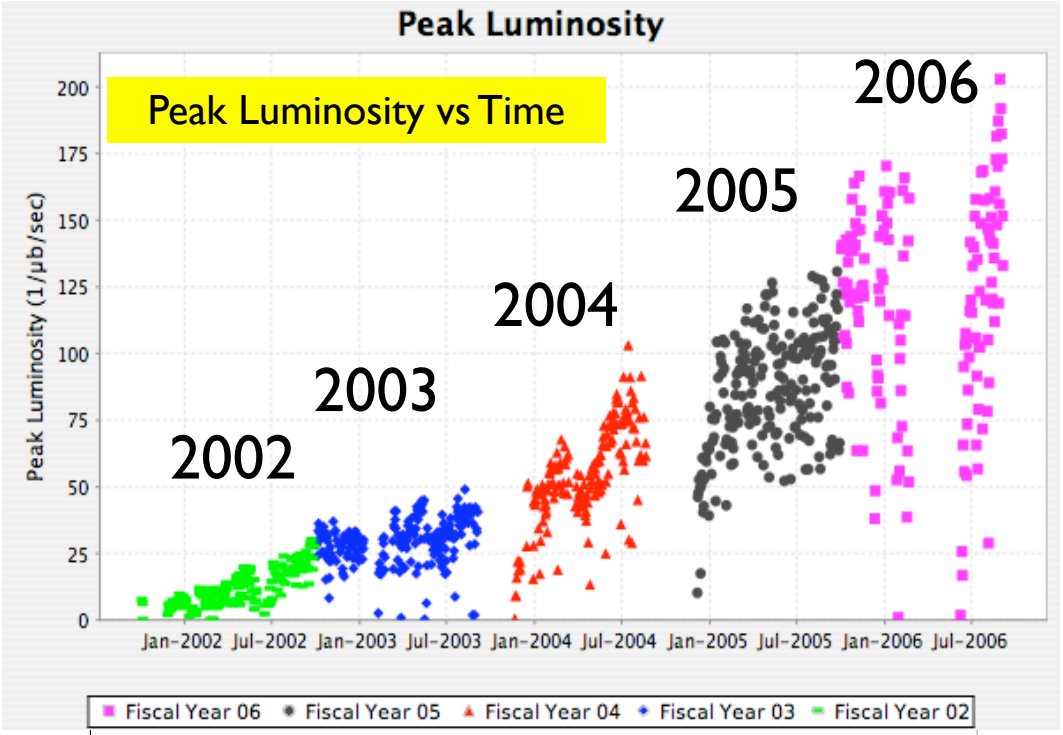
Tevatron performance

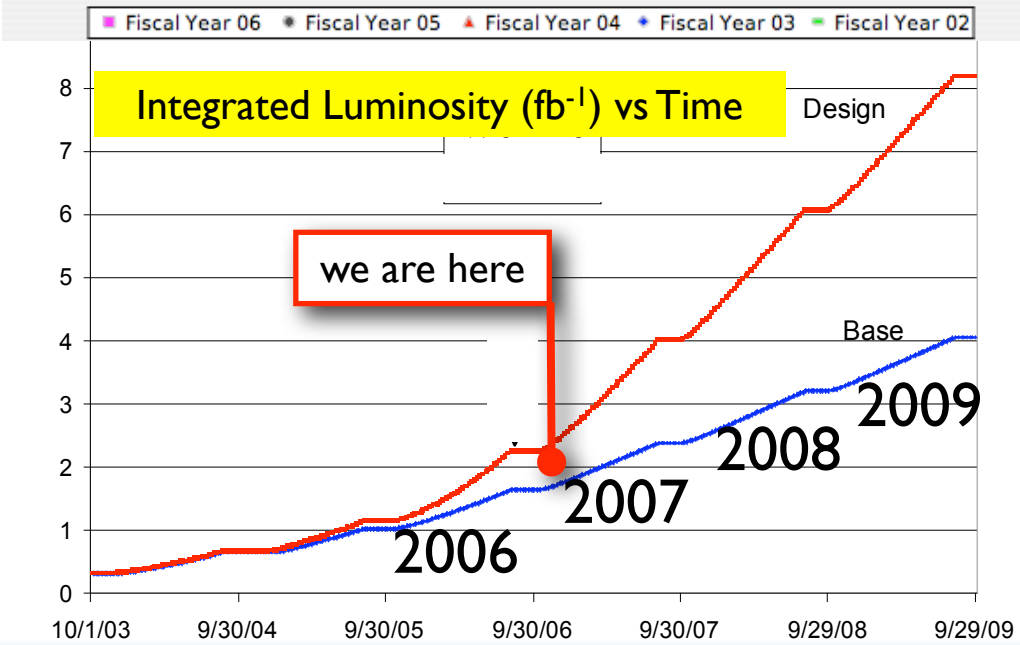
Top quarks are still relatively rare at 1.96 TeV, therefore luminosity is key.

➢The peak luminosity is approaching the machine design (3.3×10^{32} $cm^{-2}s^{-1}$)

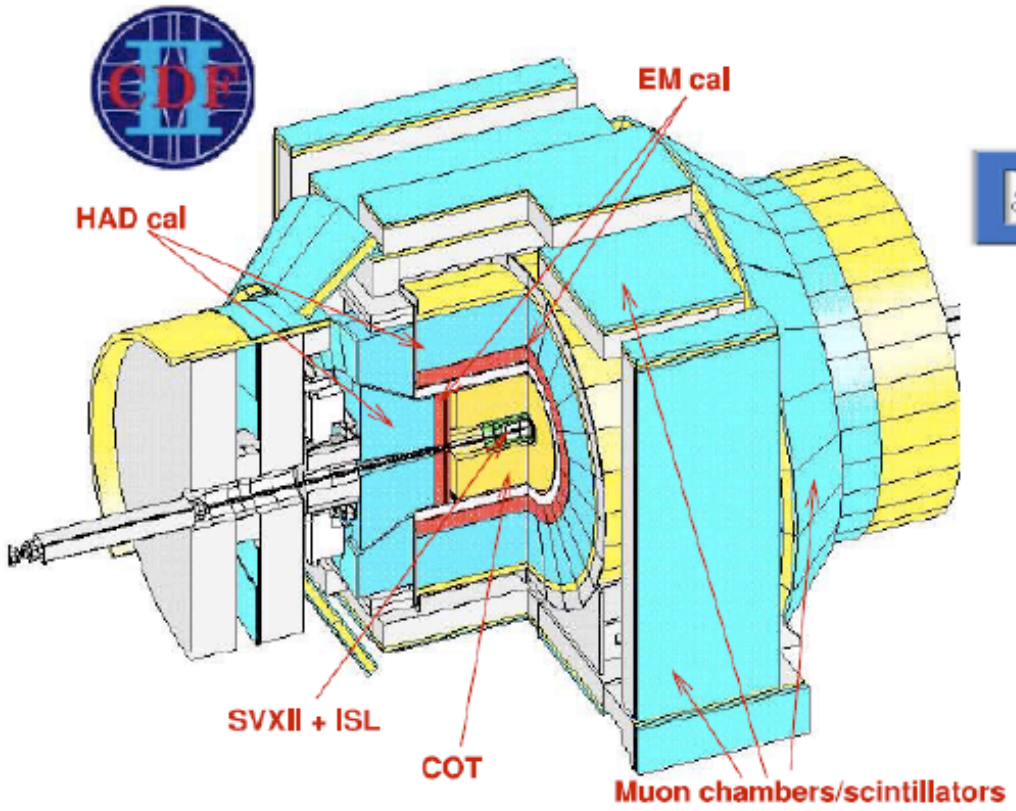
➢The weekly luminosity is following suit

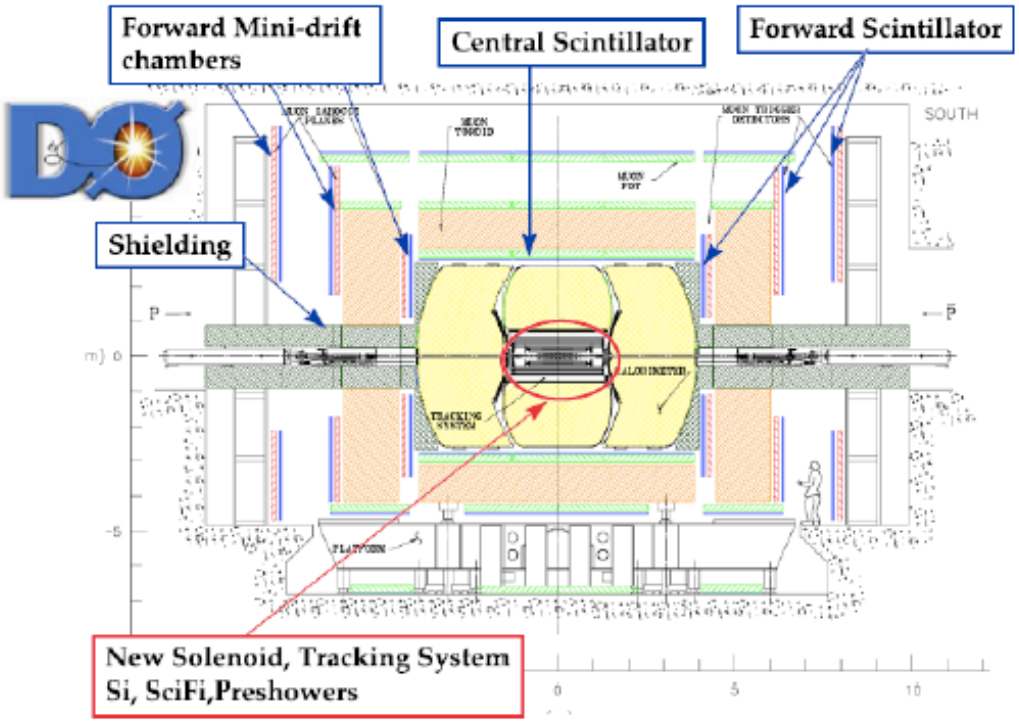
➢The FY06 integrated luminosity was slightly behind





The Experiments

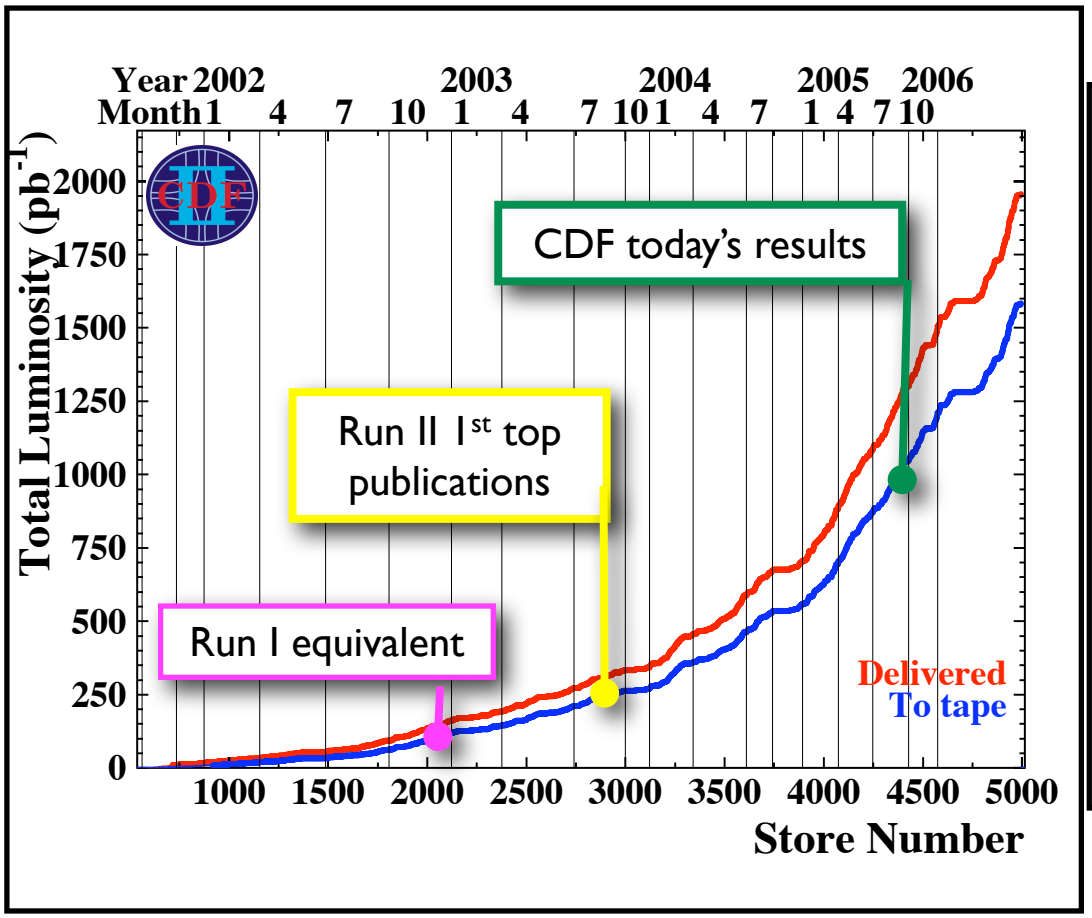


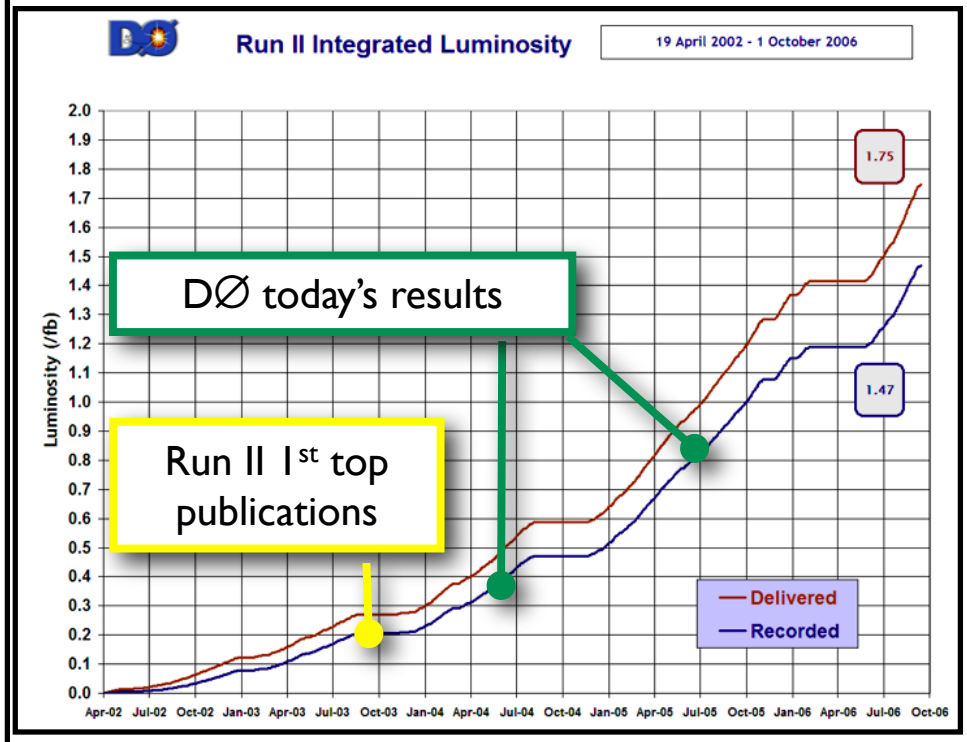


Top quark measurements rely on all detectors for electrons, muons, jets, MET and *b*-tagging.

Datasets and analyses

Collision data delivered and recorded vs. time



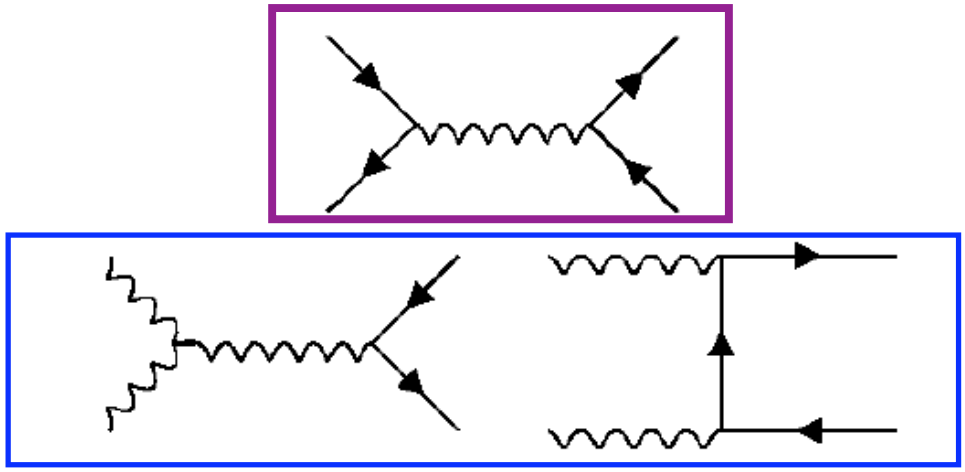


➢ Nearly 2 fb^{-1} of collisions delivered (Run IIa goal), ~85% on tape

Top quark, production at 1.96 TeV

Pair:

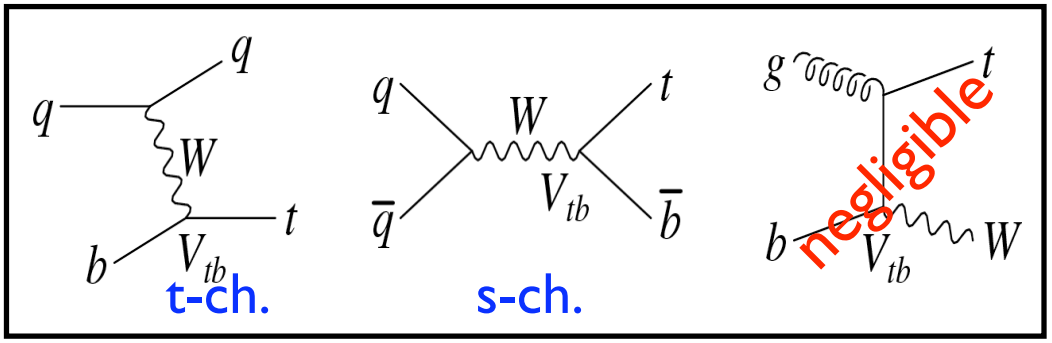
- *qq* annihilation via strong interaction (~85% at the Tevatron)
- *gg* fusion (dominant at LHC)



NOTE: Production through virtual Z and γ are much smaller

Single:

Not observed yet, due to larger backgrounds



Harris, Laenen, Phaf, Sullivan, Weinzierl, PRD 66 (02) 054024.
Campbell, Ellis, Tramontano, PRD 70 (04) 094012.

Theoretical Predictions

t-tbar NLO QCD (m_t=175 GeV/c^2)

- 6.8±0.8 pb (Kidonakis, Vogt)
- $6.8^{+0.7}_{-0.9}$ pb (Cacciari et al.)

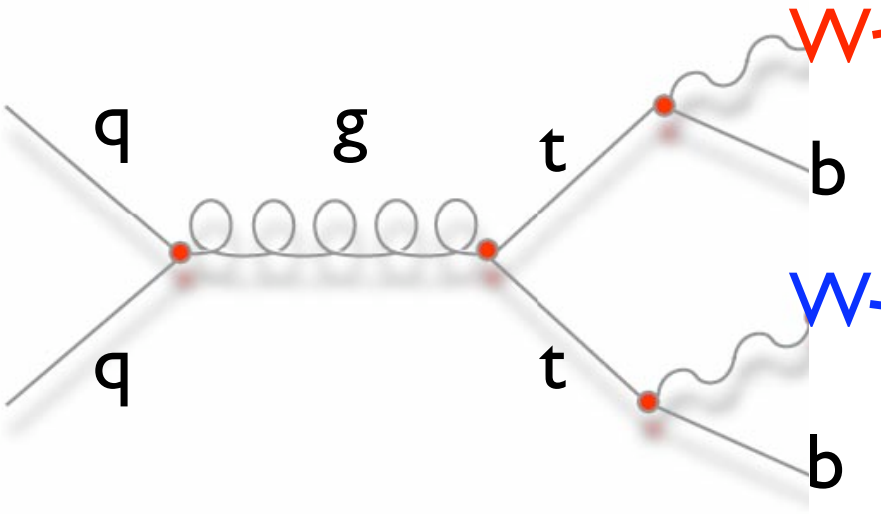
Single top NLO QCD (m_t=175 GeV/c^2)

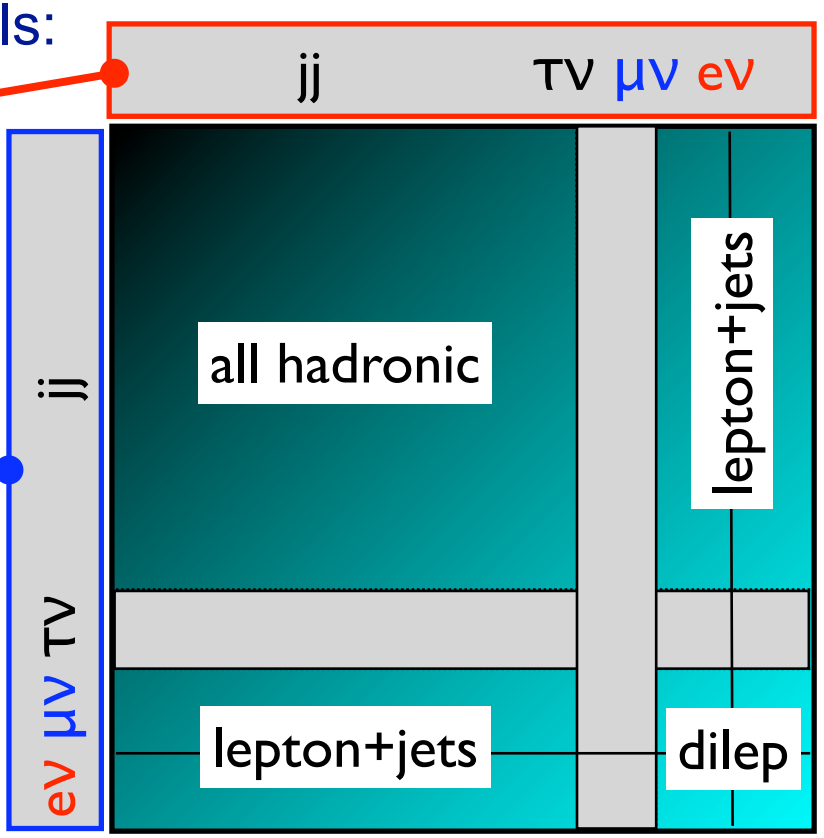
- 1.98±0.25 pb (t-channel)
- 0.88±0.11 pb (s-channel)

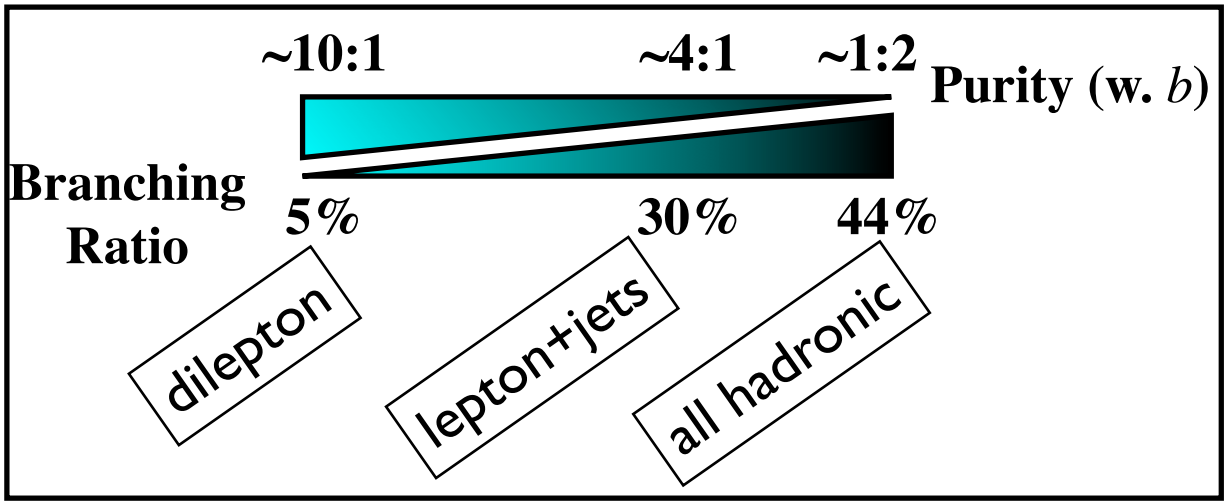
Top decay and event classification

V_{tb}~1, and $M_t > M_W + M_b$ ⇒ $t \to Wb$ almost exclusively.

Event classification follows the W decay channels:







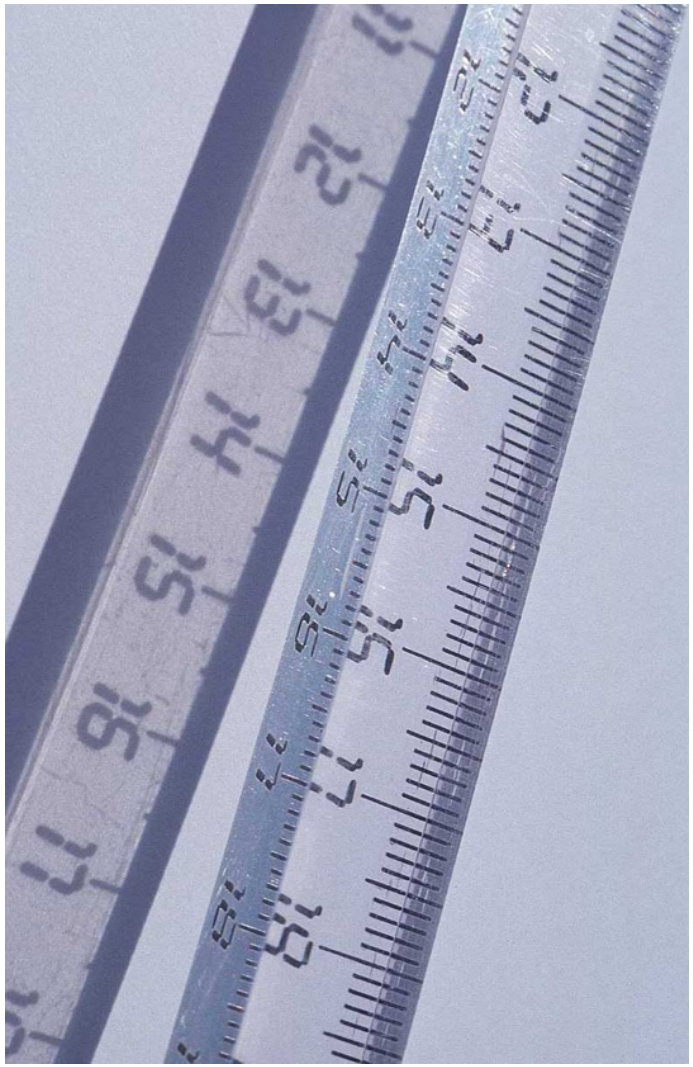
Experimental Overview

The Tevatron top physics program seen from the perspective of precision:

Measurement already/towards limited by:

- Luminosity Uncertainty
  - Pair production cross section
- Systematics
  - Top quark mass
- Statistics
  - Polarizations
  - Single top production
  - $|V_{tb}|$, top charge, resonances

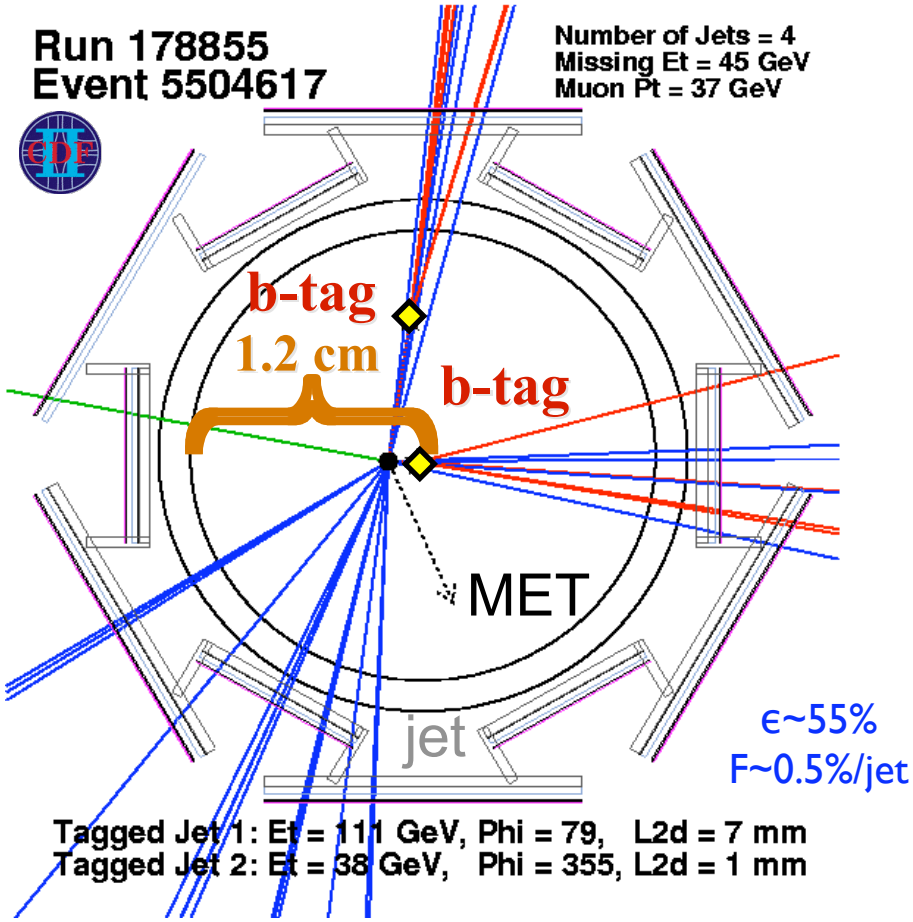
Summary and Outlook



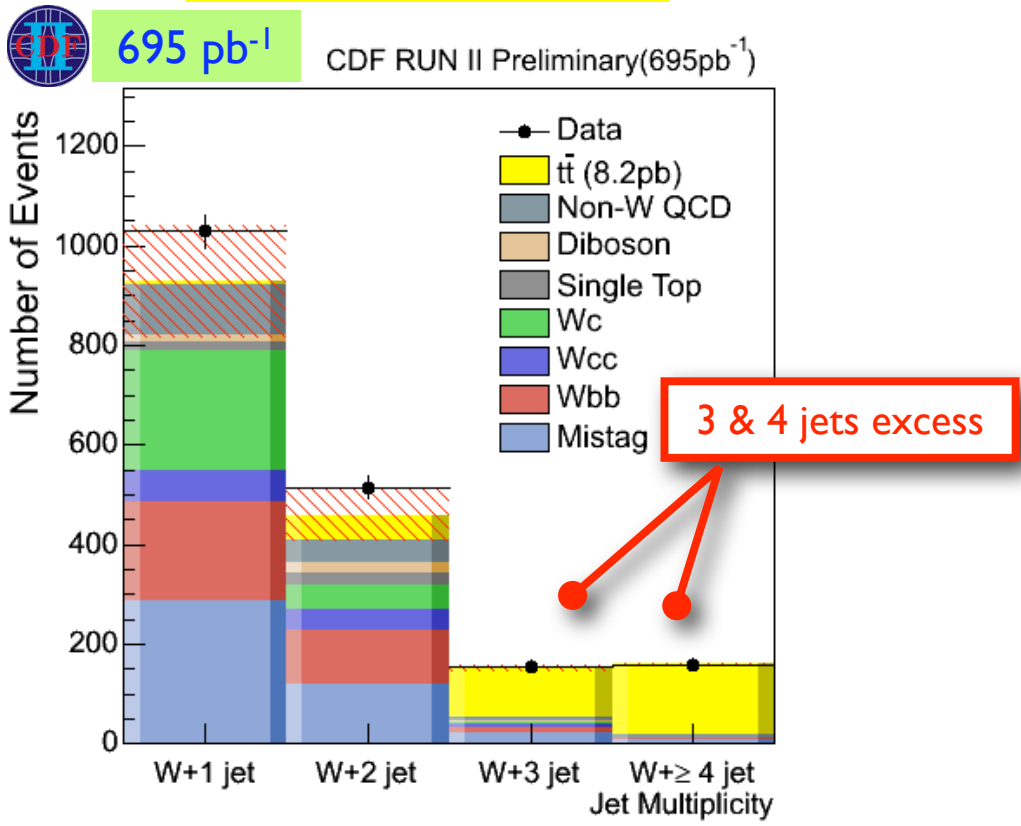
Pair production

- Comparison in different channels works as a non-SM search
- Precise average is important as pair-production test & against non-SM
- Basis for other measurements

CDF Event:
Close-up View of Layer 00 Silicon Detector



W+n jets spectrum

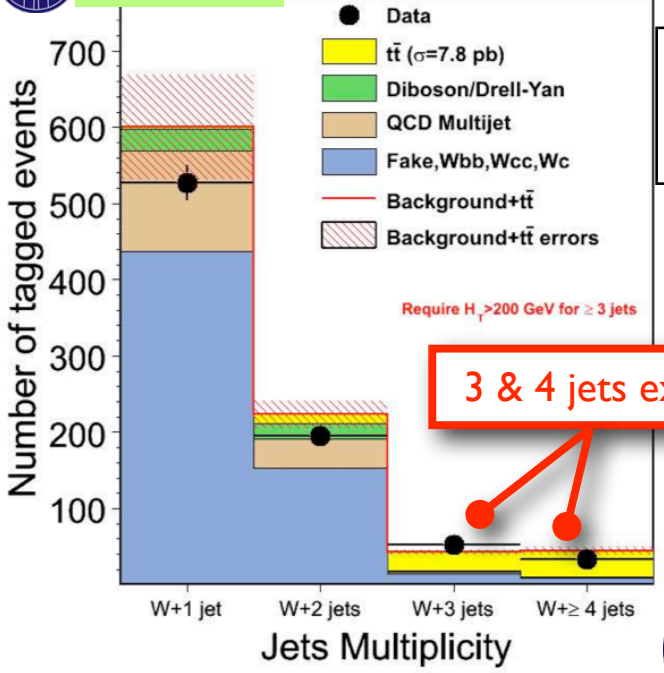


lepton+jets (displaced vertex)

Pair production

760 pb^{-1} CDF II Preliminary **new**

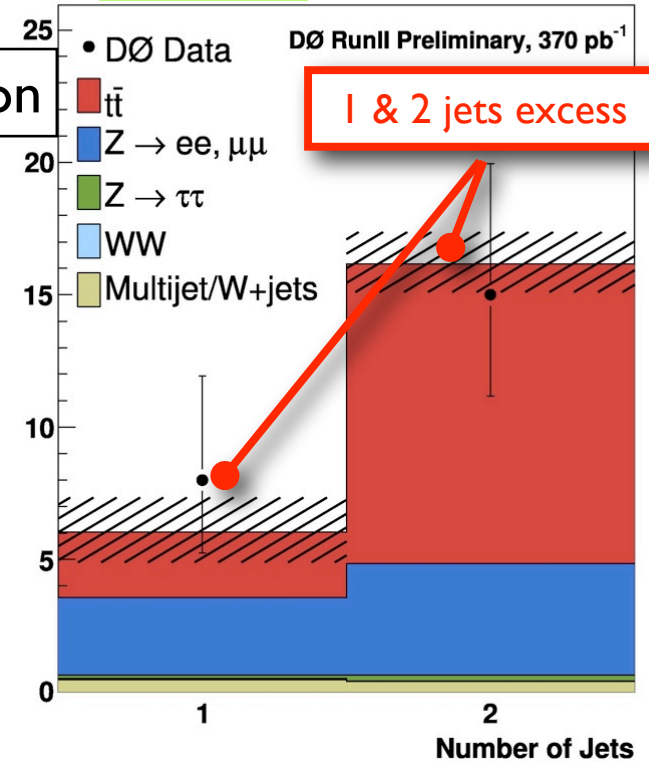
lepton+jets (semileptonic *b*)



3 & 4 jets excess

370 pb^{-1}

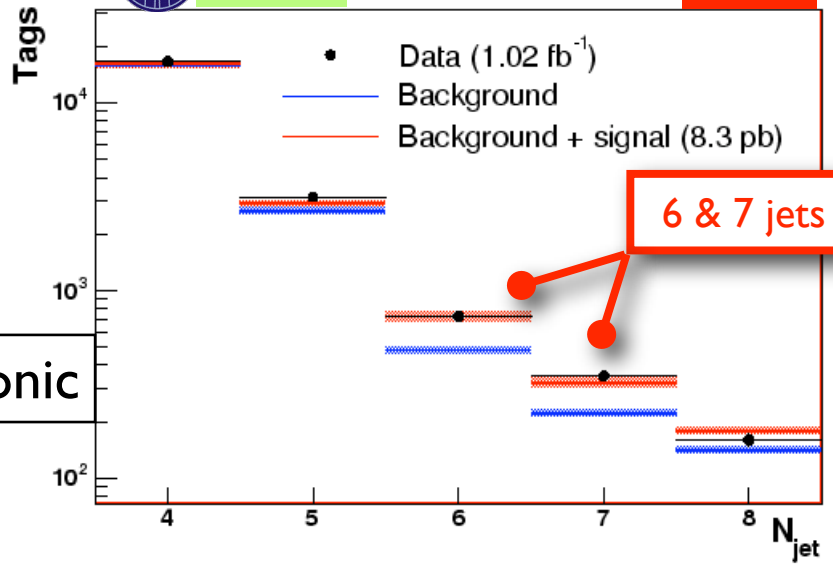
dilepton



1 & 2 jets excess

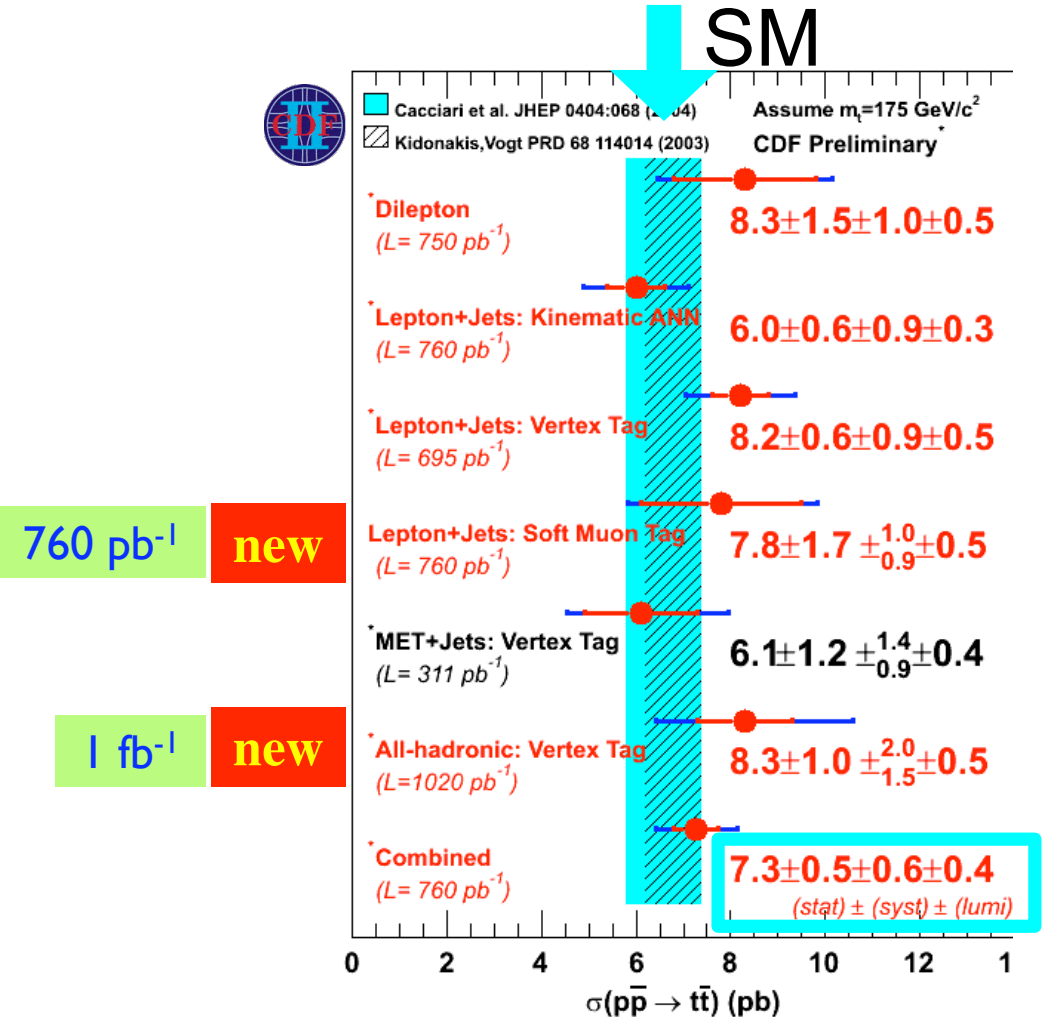
1 fb^{-1} Run II preliminary **new**

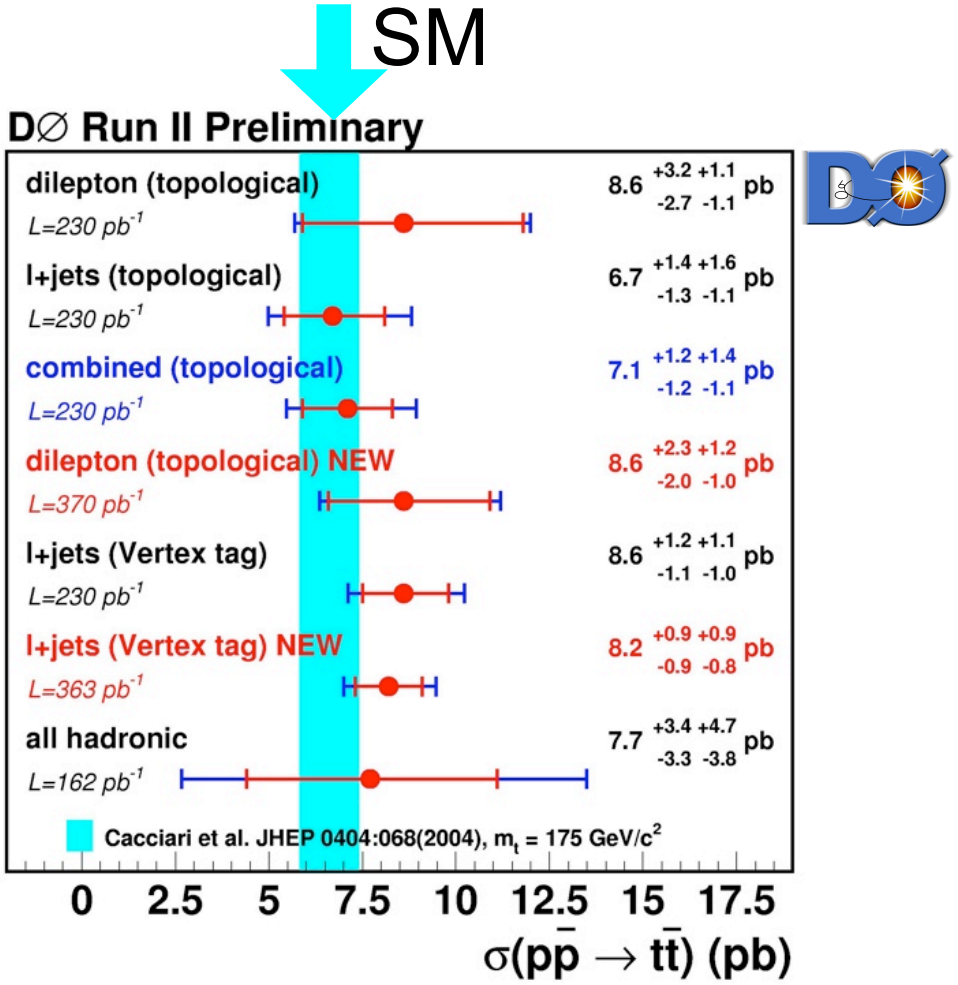
all hadronic



6 & 7 jets excess

Channel-by-channel cross section





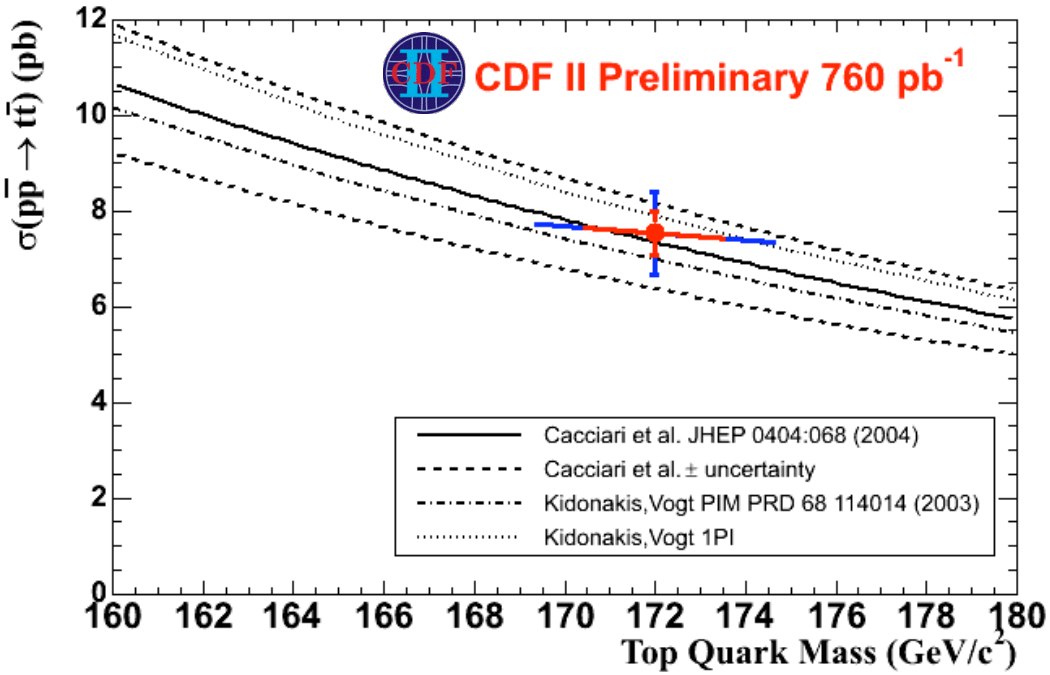
➢Individual measurements are accurate to within ~15-30% (excl. lumi.)

➢The CDF combination includes 6 measurements, accounting for all decay channels.

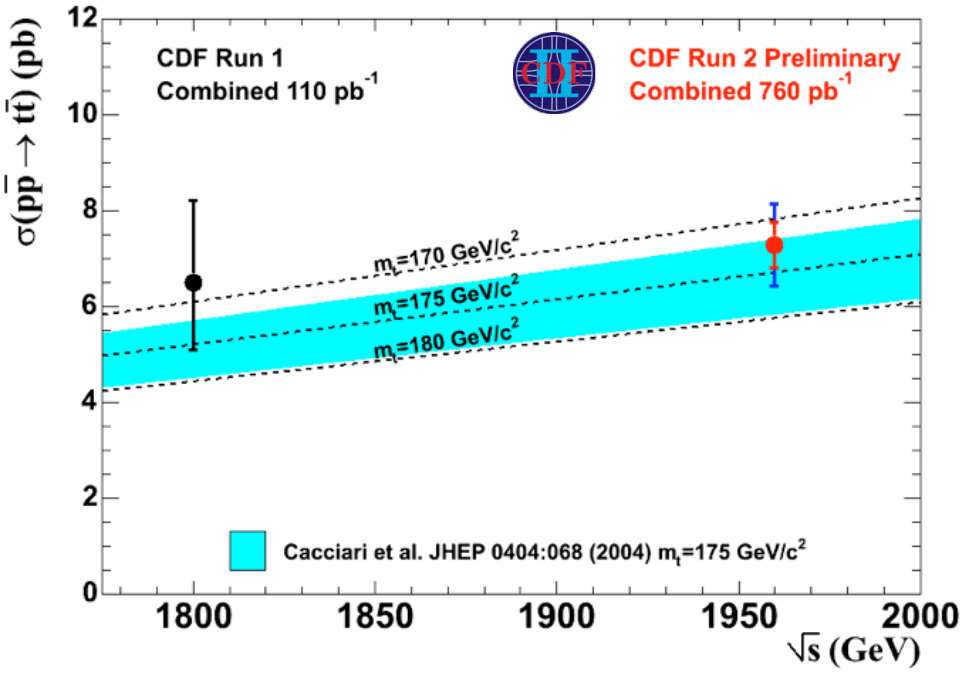
➢The combined accuracy is similar (~12%) to the the theory uncertainty

CDF II average cross section

cross section vs measured mass



cross section vs $\sqrt{s}$



➢ Due to ~±12% (theory) ⇒ $\delta M_t > 4 GeV/c^2$ for top mass measurements from the cross section

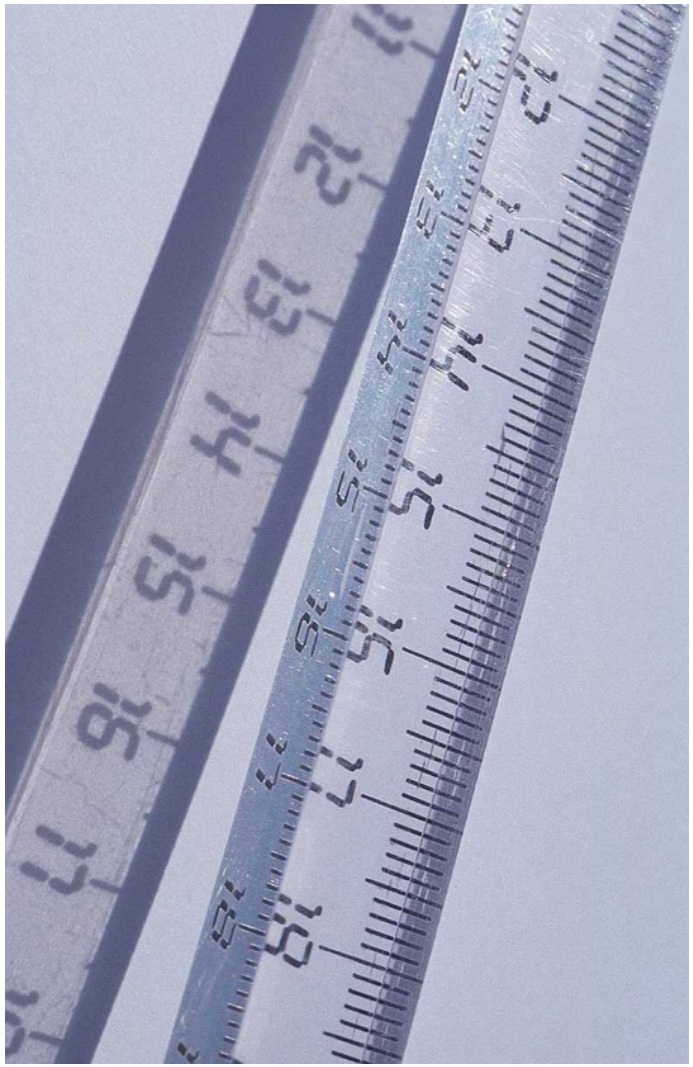
Experimental Overview

The Tevatron top physics program seen from the perspective of precision:

Measurement already/towards limited by:

- Luminosity Uncertainty
  - Pair production cross section
- Systematics
  - Top quark mass
- Statistics
  - Polarizations
  - Single top production
  - $|V_{tb}|$, top charge, resonances

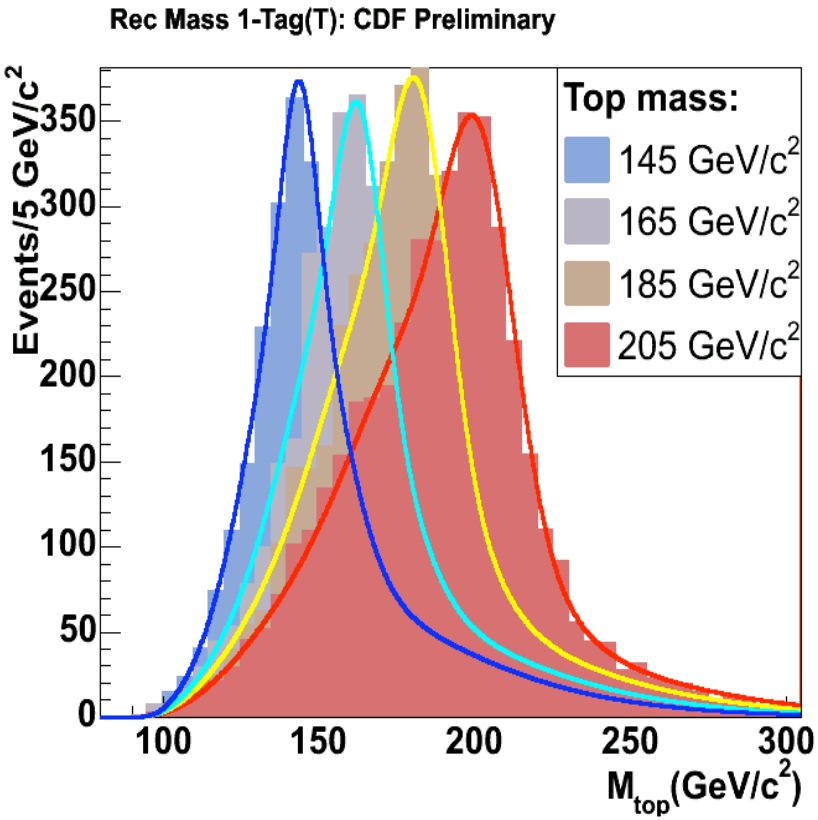
Summary and Outlook



Determining the top mass

Template Method

Compare to MC templates an observable that is strong function of the top mass



Matrix Element Method

Maximize the combined likelihood of the observed events

Calculate a probability per each event:

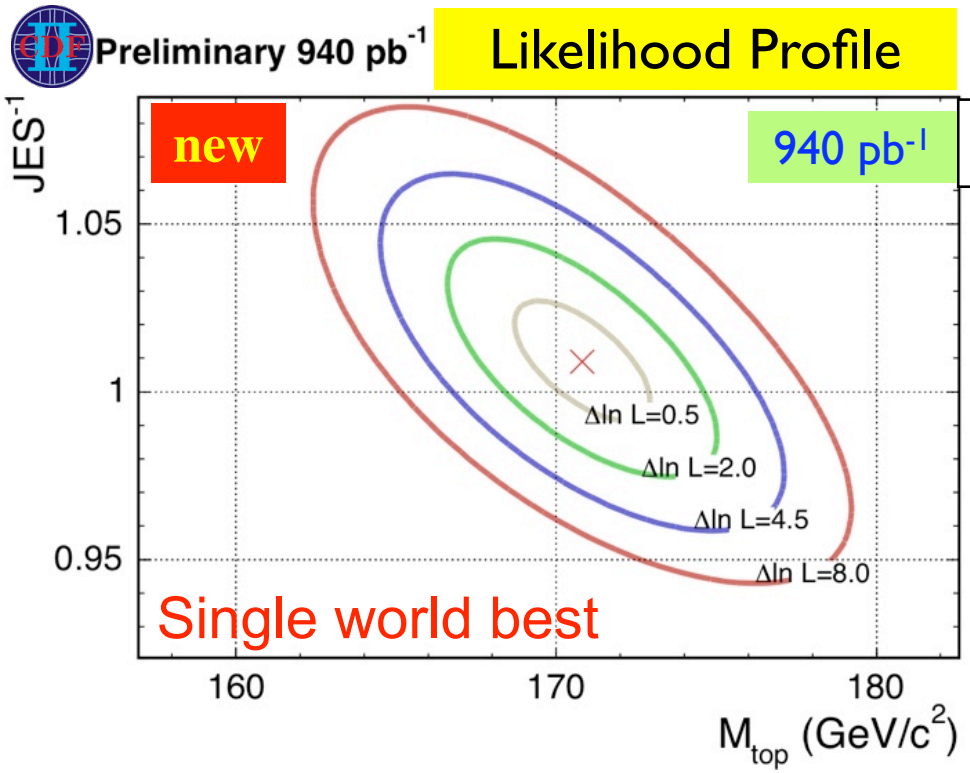
Use the differential cross section: LO Matrix element

Determine the probability that a parton level set of variables ***y*** will be measured as a set of variables ***x***

Maximize $\Pi_i P^i(M_{top})$

In *l*+jets, both methods simultaneously fit for the JES

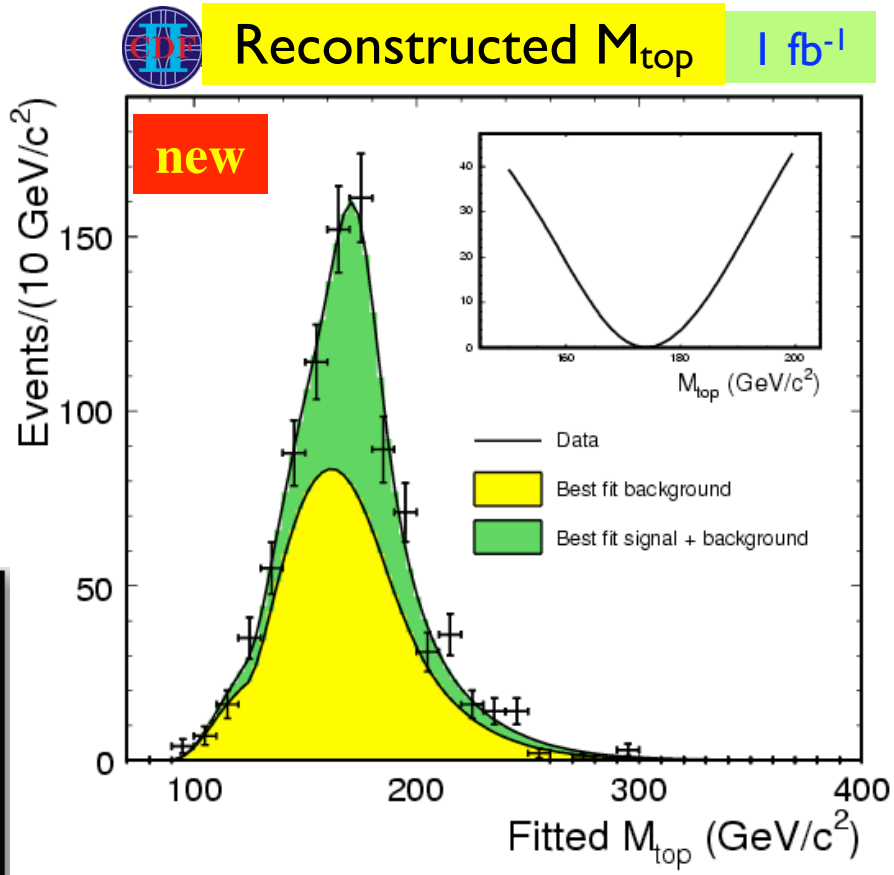
Top mass measurements



$m_t = 170.9 \pm 1.6(stat) \pm 1.4(JES) \pm 1.4(syst)$ GeV/c²

Source of uncertainty	CDF Magnitude (GeV/c²)
b-JES	0.6
Signal (Initial and final state radiation, parton distribution functions)	1.1
Background (composition and shape)	0.2
Fit (Method, Monte Carlo statistics)	0.4
Monte Carlo (Modeling of ttbar)	0.2
Total	**1.4**

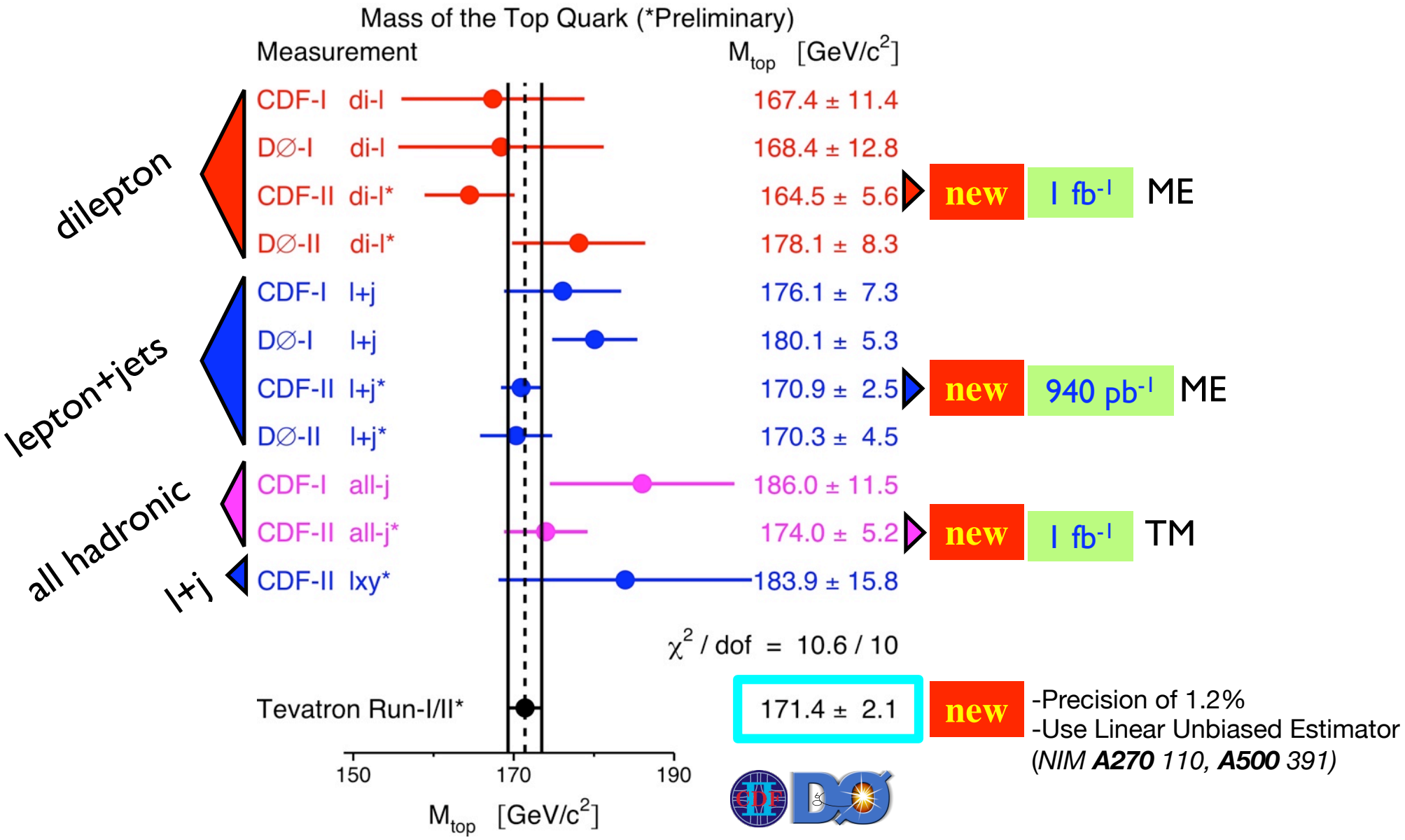
all hadronic, TM



$m_t = 174.0 \pm 2.2(stat) \pm 4.8(syst)$ GeV/c²

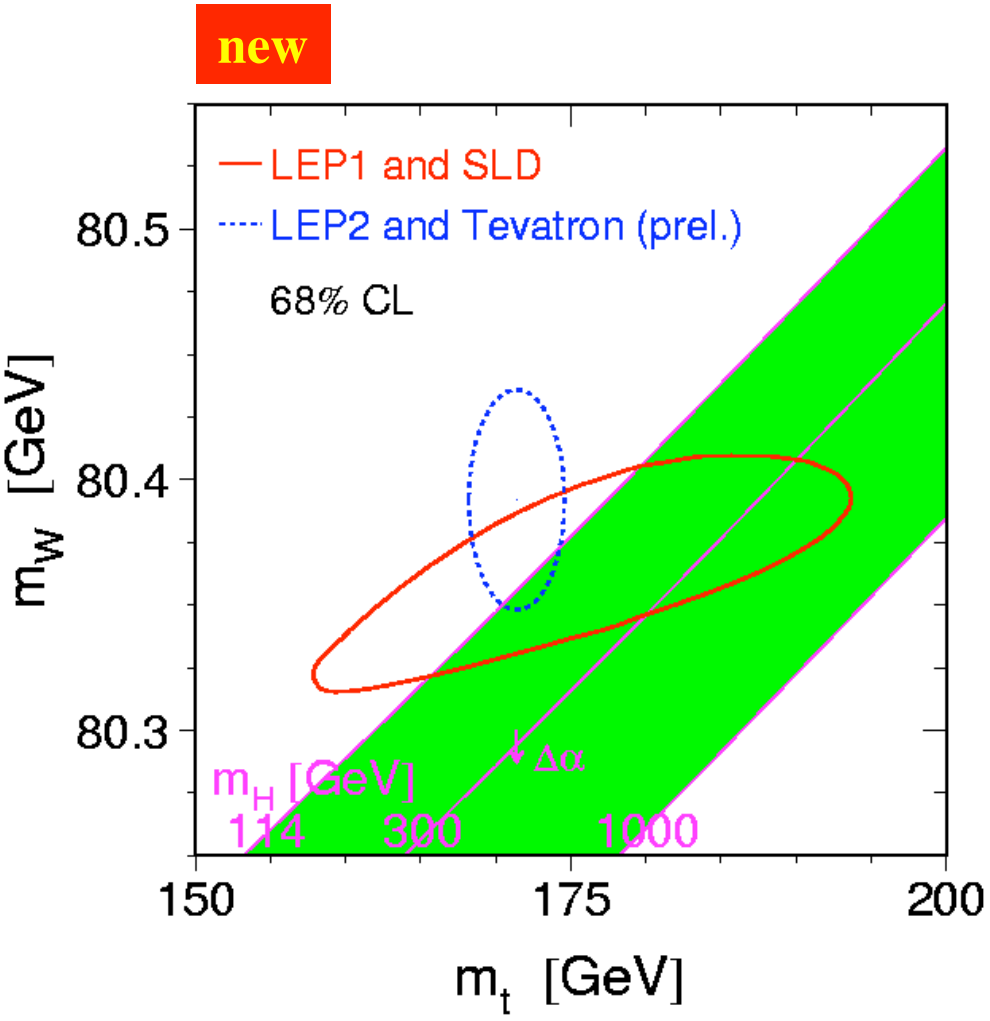
Note: NN+*b* tag, no JES fit

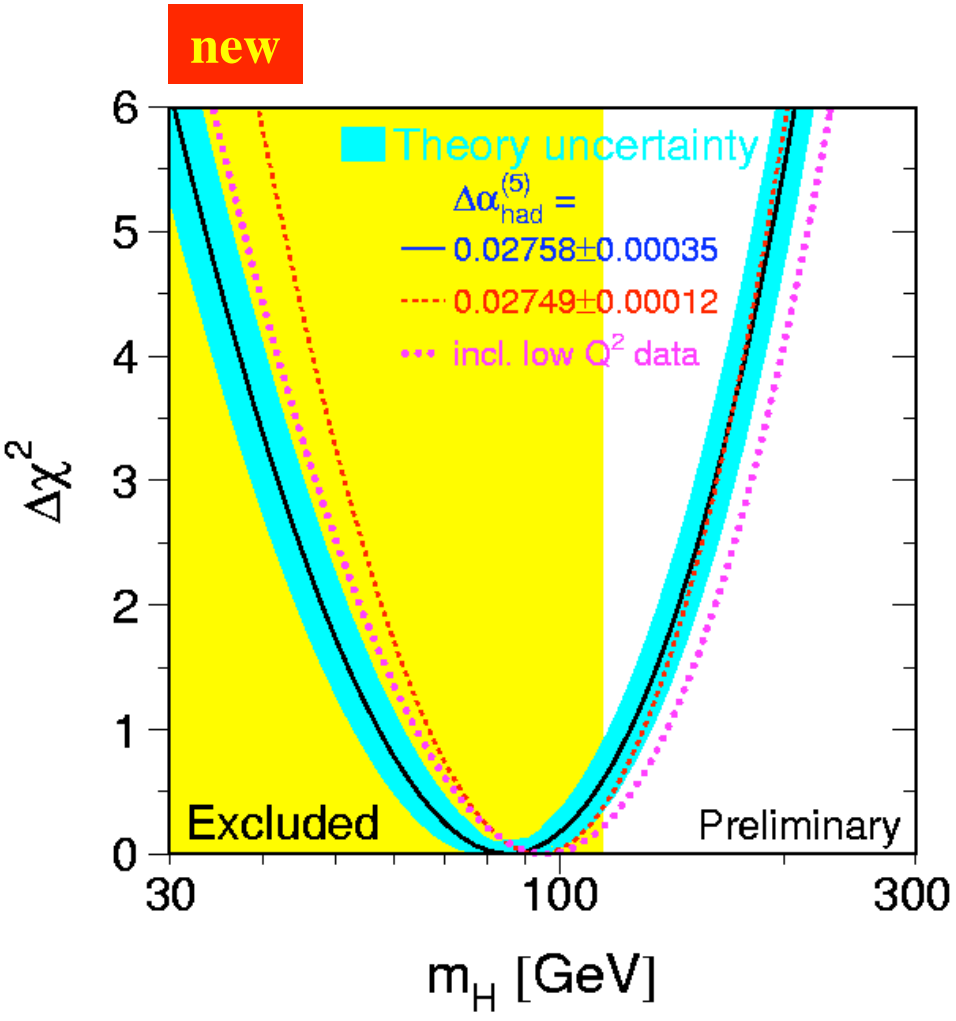
2006 Tevatron M_{top} average



Note: historically there is a trend between all-jets and dilepton

The consequences of M_{top}





Minimum at: $M_H = 85^{+39}_{-28}\,GeV/c^2$

or: M_H<199 GeV/c² @ 95% C.L.

Note: ΔM_t=3 GeV corresponds to ~±20% uncertainty of the predicted M_H

Top mass outlook

CDF-only precision expectation

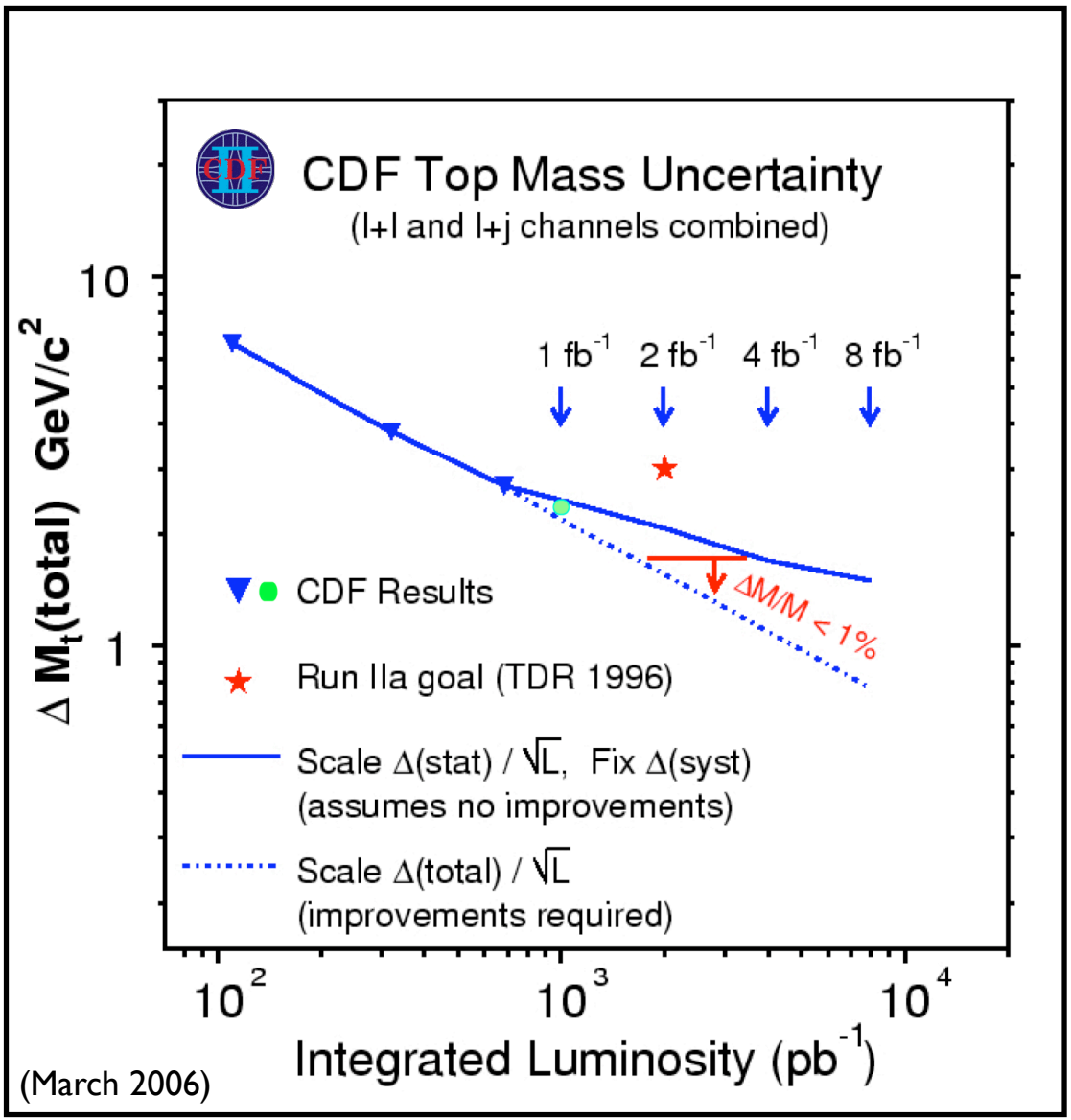
➢ New results are better than our predictions in March

➢ Will add to the prediction the all-jets channel

➢ Add JES to all-jets could also make sensitivity comparable to lepton+jets

➢ DØ has similar sensitivity (new results with 1fb^{-1} coming soon)

➢ Expect to achieve an uncertainty of ~1-1.5 GeV/c^2 in the next years



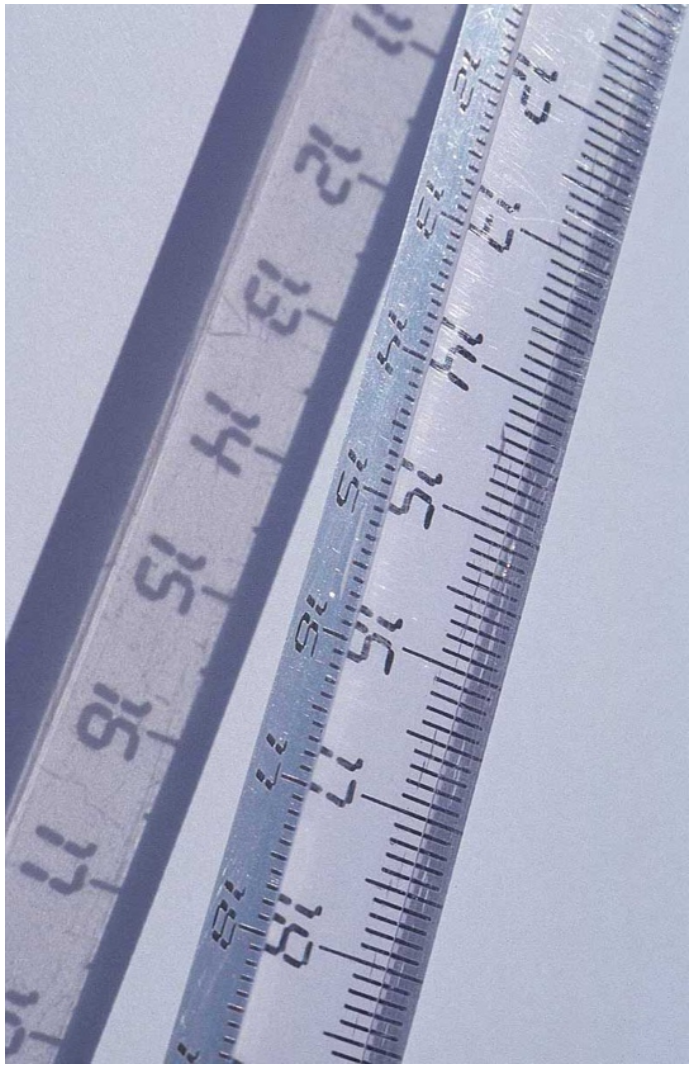
Experimental Overview

The Tevatron top physics program seen from the perspective of precision:

Measurement already/towards limited by:

- Luminosity Uncertainty
  - Pair production cross section
- Systematics
  - Top quark mass
- Statistics
  - Polarizations
  - Single top production
  - $|V_{tb}|$, top charge, resonances

Summary and Outlook

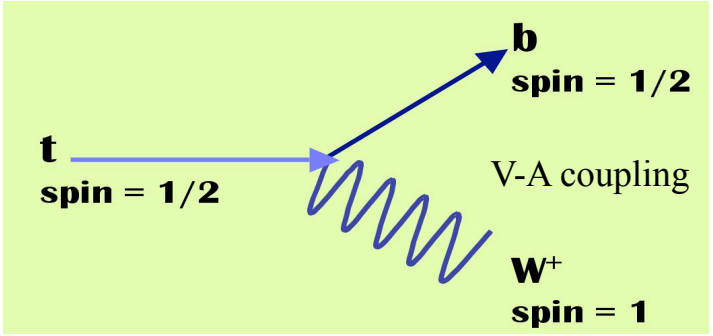


Helicity of W bosons in top decays

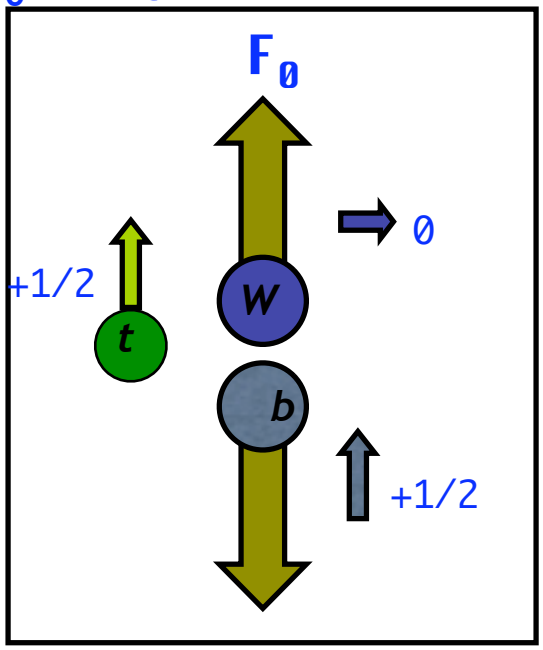
Are there new interactions in top quark decay ?

- Positive helicity F_+ suppressed by chiral factors $\sim M_b^2 / M_W^2$
- Relative fraction of F_0 is:

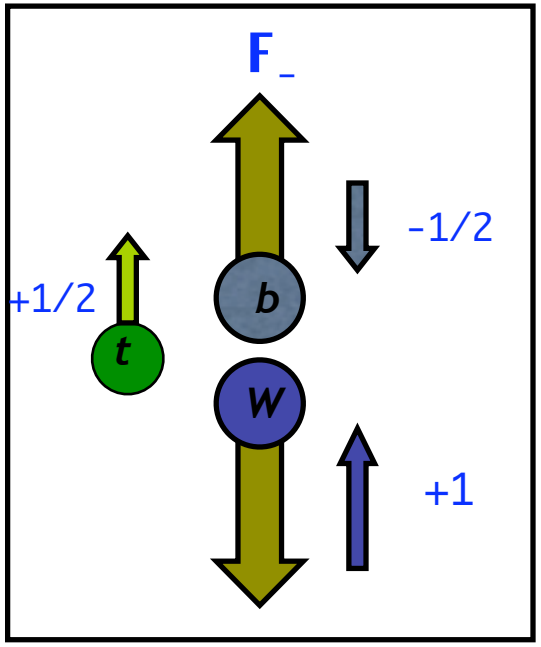
$$F_0 = \frac{M_t^2 / 2M_W^2}{1 + M_t^2 / 2M_W^2} \cong 0.7$$



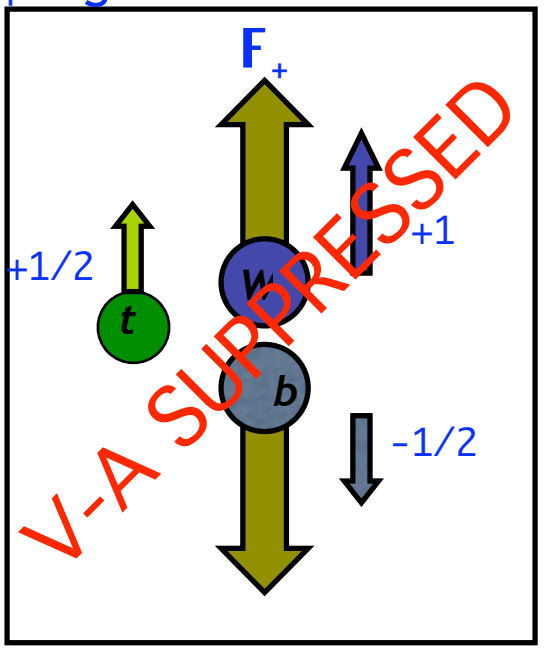
F_0 Longitudinal fraction



F_- Left-Handed fraction



F_+ Right-Handed fraction



F_0 and F_+ fractions

- Template based Likelihood analysis of cos θ*, fit for F_+ and F_0
- Lepton+jets sample: ~200 events

Combined *l*+jets and dilepton samples
- Single and double *b*-tag separately
- Compares rec. M^2_{lb} to $V\pm A$ templates

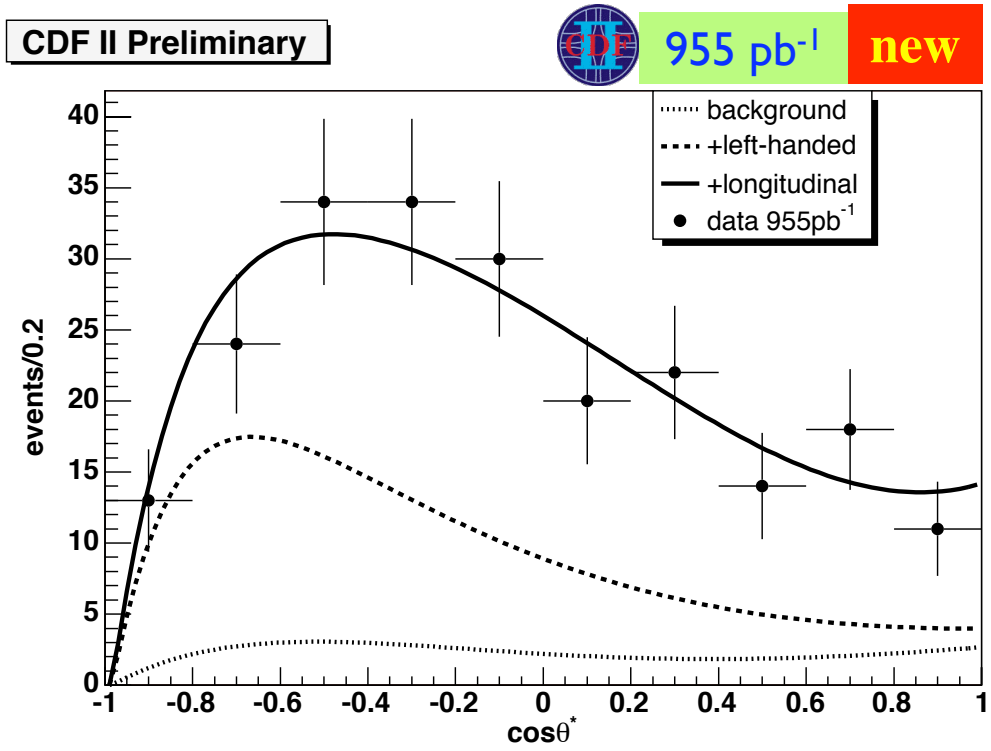
Best value, fixing F_+=0:

$$F_0 = 0.61 \pm 0.12(stat) \pm 0.04(syst)$$

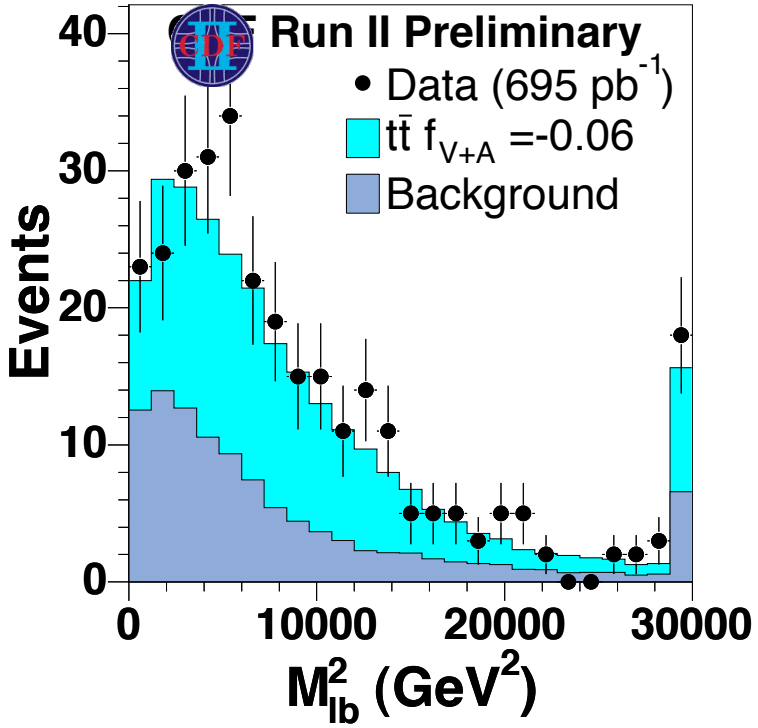
$F_+ = -0.02 \pm 0.07$

$F_+ < 0.09$ 95%CL

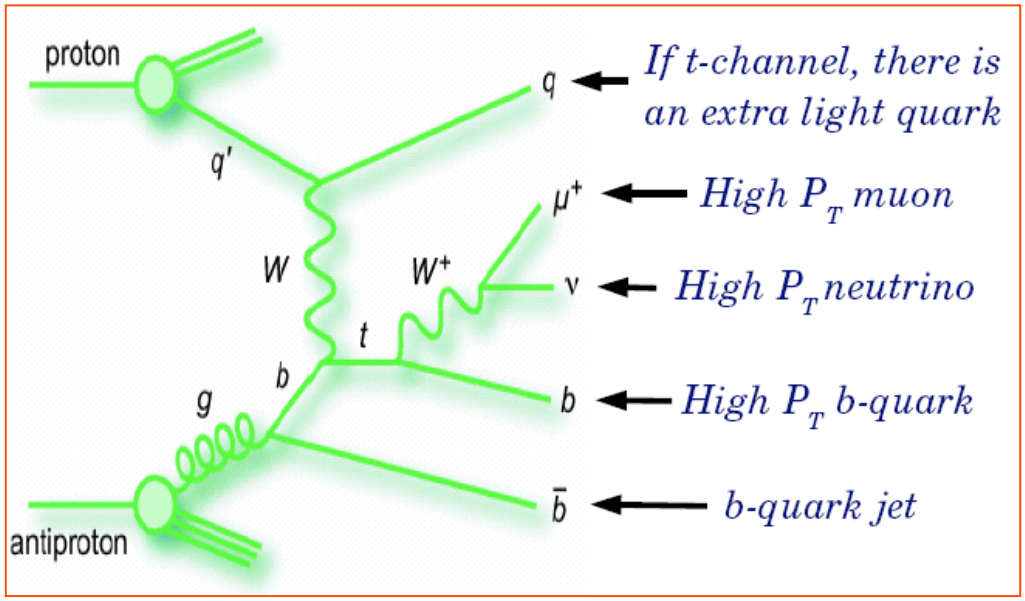
Spectrum of lepton cosθ* in W rest frame



lepton-*b* invariant mass 695 pb^{-1}



Search for single top production



Motivation

- Is it there ?
- Cross section $\propto |V_{tb}|^2$
- same final state as WH (H→bb)
- Allows for several other measurements (polarization..) and searches (W'...)

Signature

- Lepton+Missing E_T+ Jets
- *t*-channel extra jet tends to be forward
- similar to top pair production, but with less jets

Backgrounds

Anything with a lepton+jets+MET signature (W+jets, bb, tt, Z+jets)

Strategies

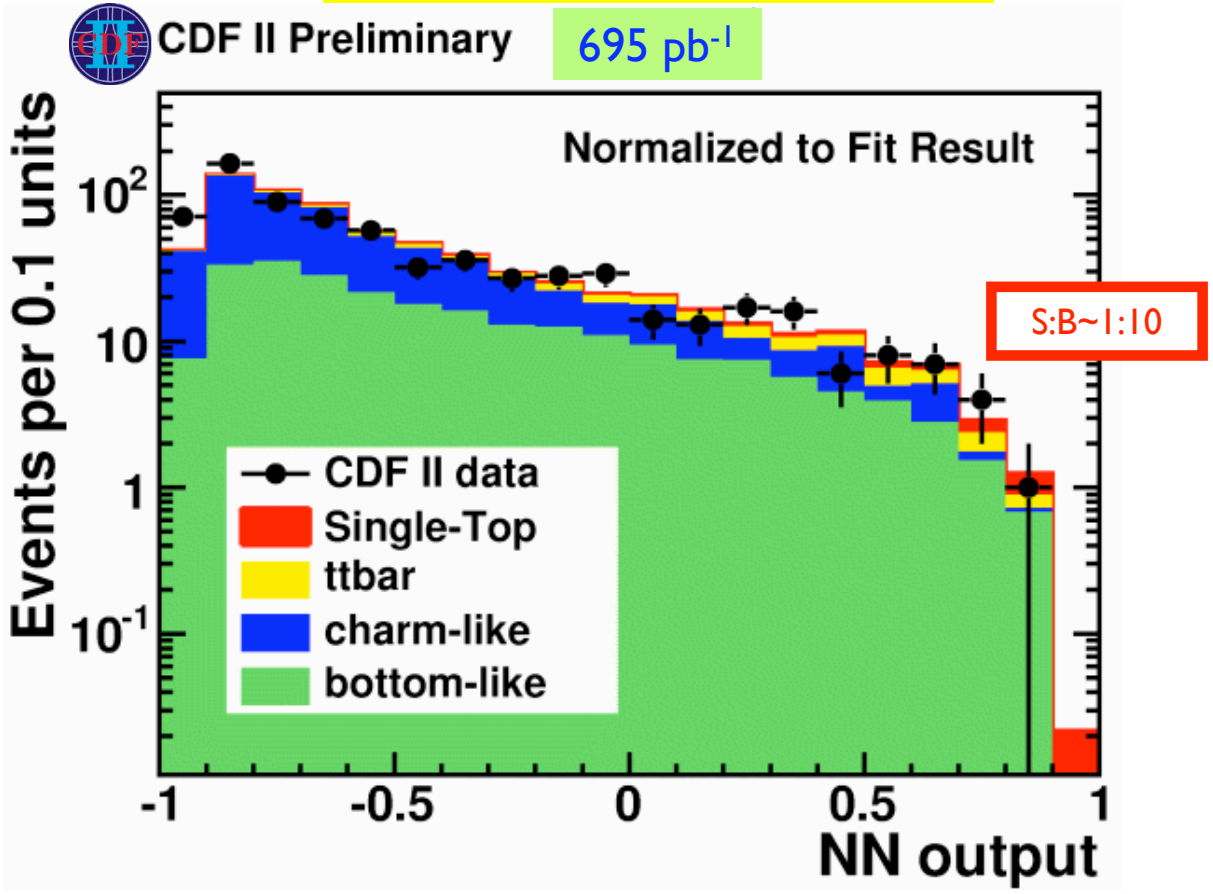
- Combined search (for discovery)
- Separate search (for non-SM searches)

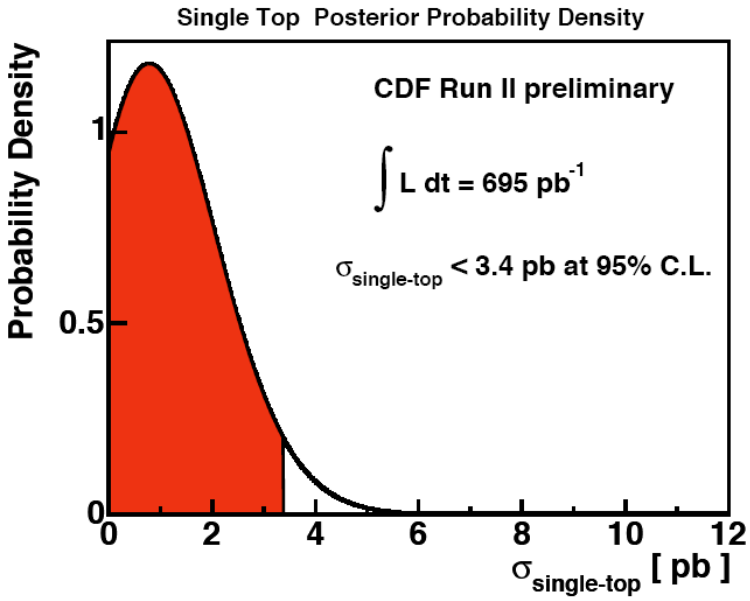
Methods

- Likelihood discriminant
- Neural Network

Combined limit

W+2-jets NN s+t output





CDF observes a deficit in the signal region

Expected cross section: 2.9±0.4 pb (M_t=175 GeV/c^2)

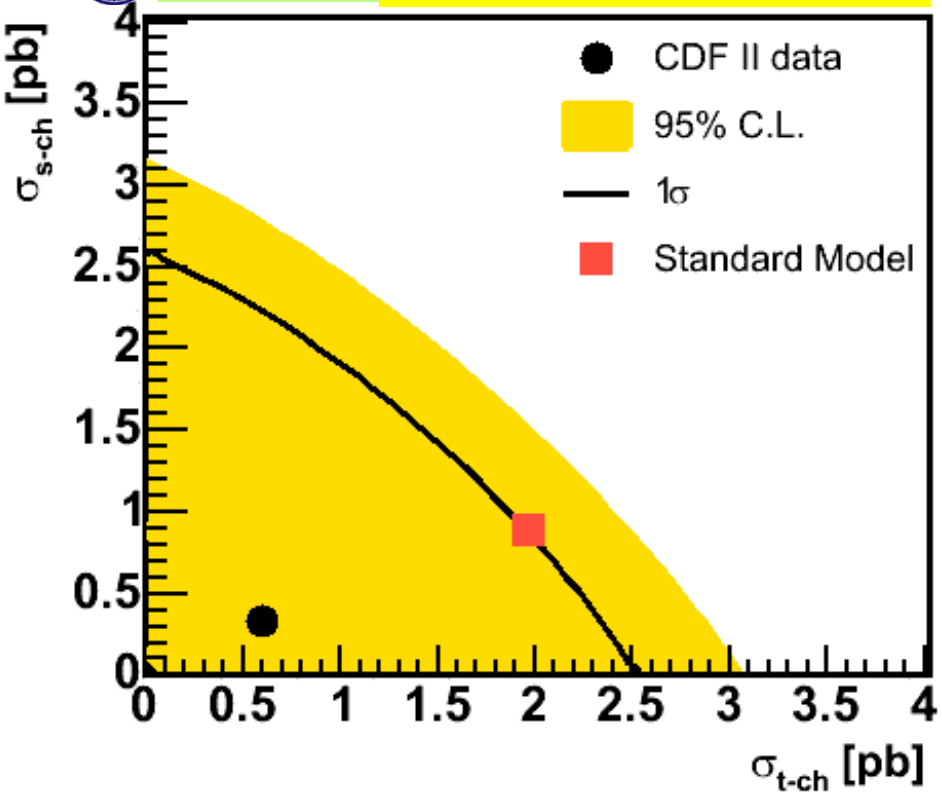
NN Limit: < 3.4 pb @ 95% C.L.

NN Best Fit: $0.8^{+1.3}_{-0.8}(\text{stat})^{+0.2}_{-0.3}(\text{syst})$ pb

~2.5σ sensitivity !

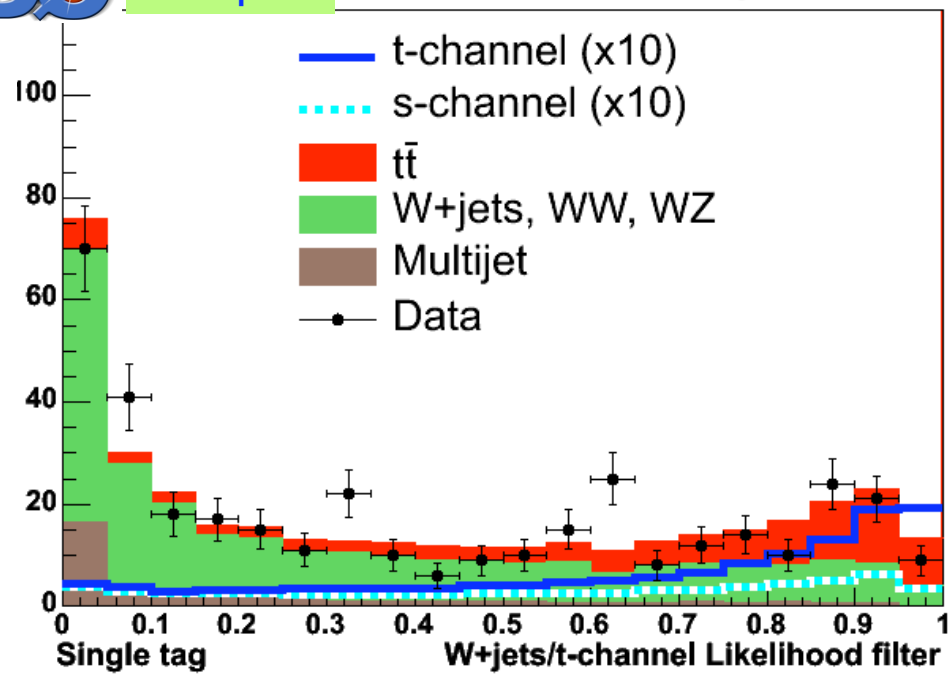
Separate limits

695 pb^{-1} σ_s vs σ_t, NN limits



Wj vs top Likelihood discriminant

370 pb^{-1} DØ Run II Preliminary, 370 pb^{-1}



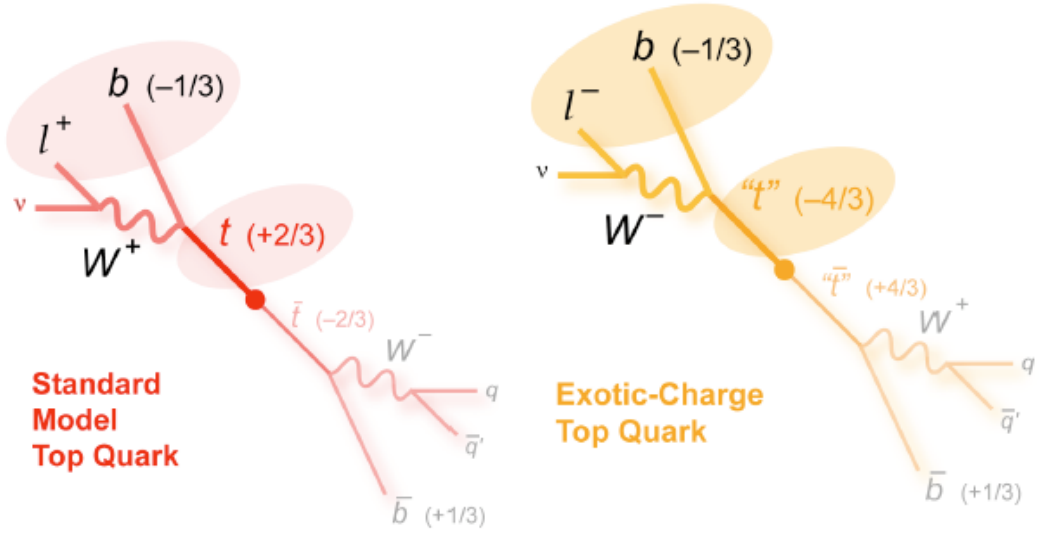
Expected cross section: σ_t=1.98±0.25 pb | σ_s=0.88±0.11 pb

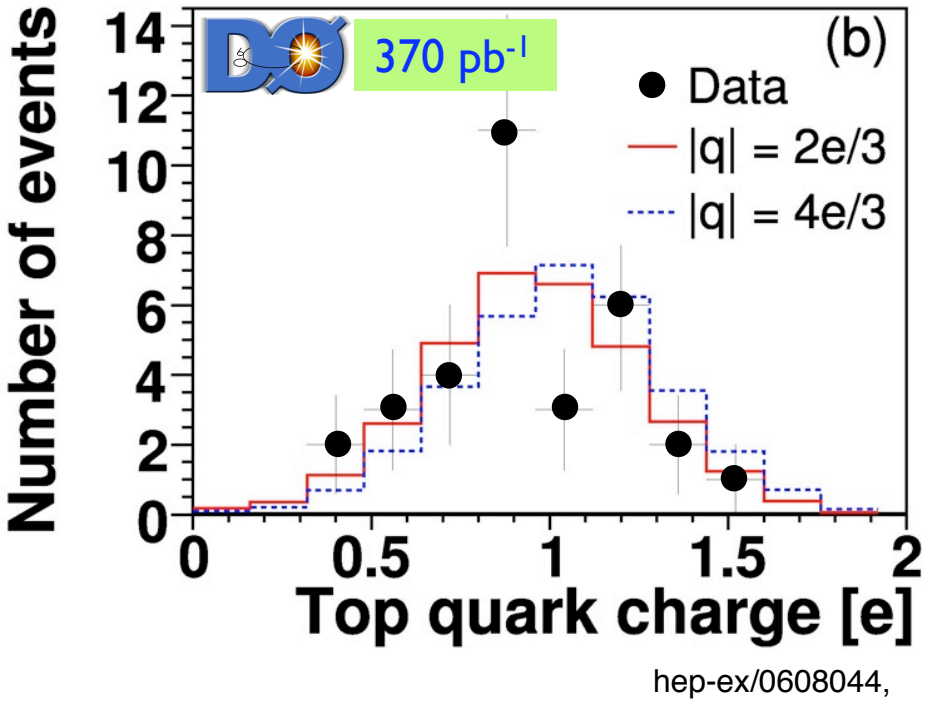
NN Limit: $\sigma_t < 3.1$ pb ; $\sigma_s < 3.2$ pb @ 95% C.L.

LD Limit: $\sigma_t < 4.4$ pb ; $\sigma_s < 5.0$ pb @ 95% C.L.

➢Updates with 1fb^{-1} are underway

Top quark charge





hep-ex/0608044,

Requires *b*-quark charge from jet charge

- Sum of charge of tracks in *b*-jet
- Calibrated using *bb* dijets, with 1 soft μ

$$L(\rho, q) = \prod_{i=1}^{N_{\text{data}}} (1-\rho) P_{\text{SM}}(q_i) + \rho P_{\text{ex}}(q_i)$$

exotic quark

ρ = -0.13±0.66(stat)±0.11(syst)

ρ < 0.8 @ 90% C.L.

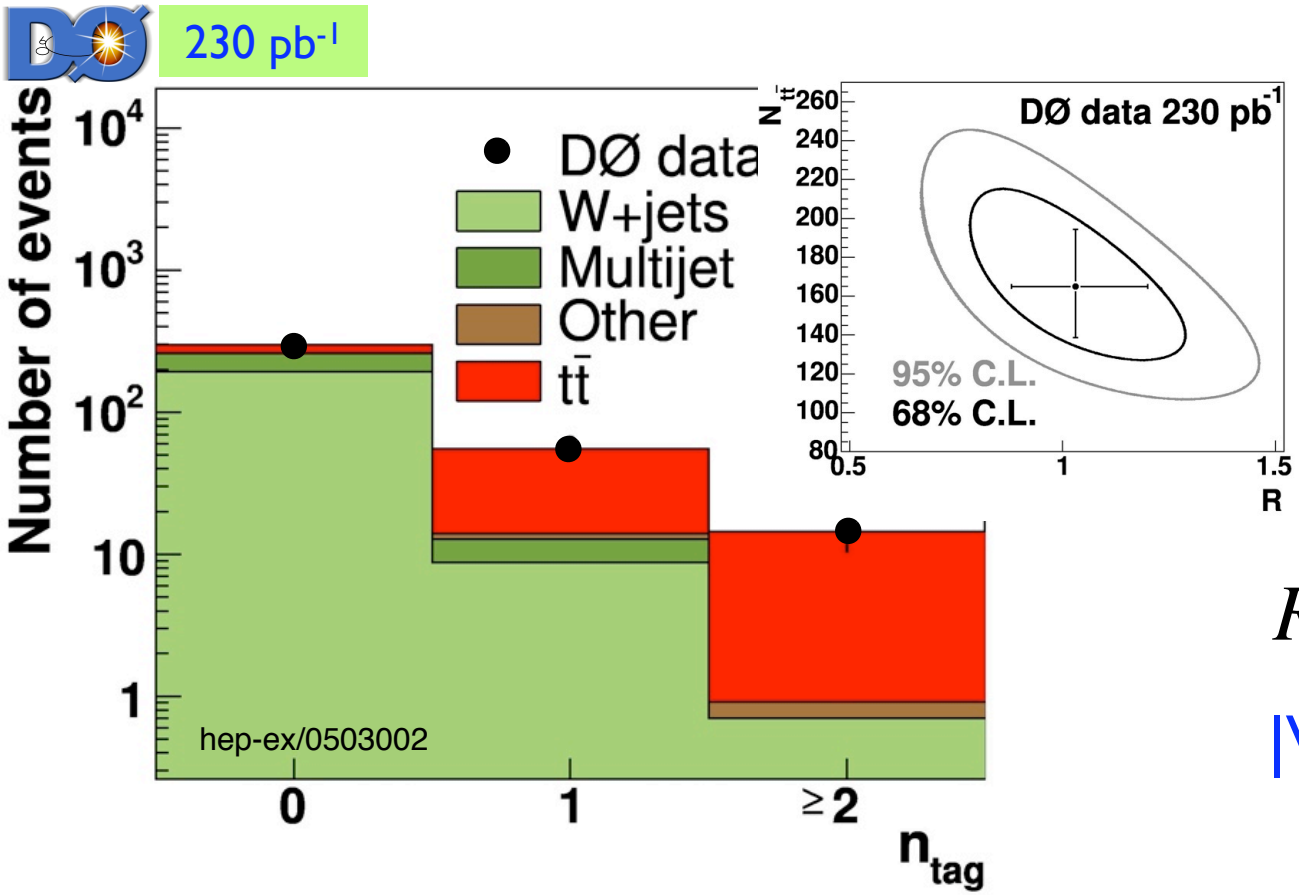
|q|=4*e*/3 excluded at 92% C.L.

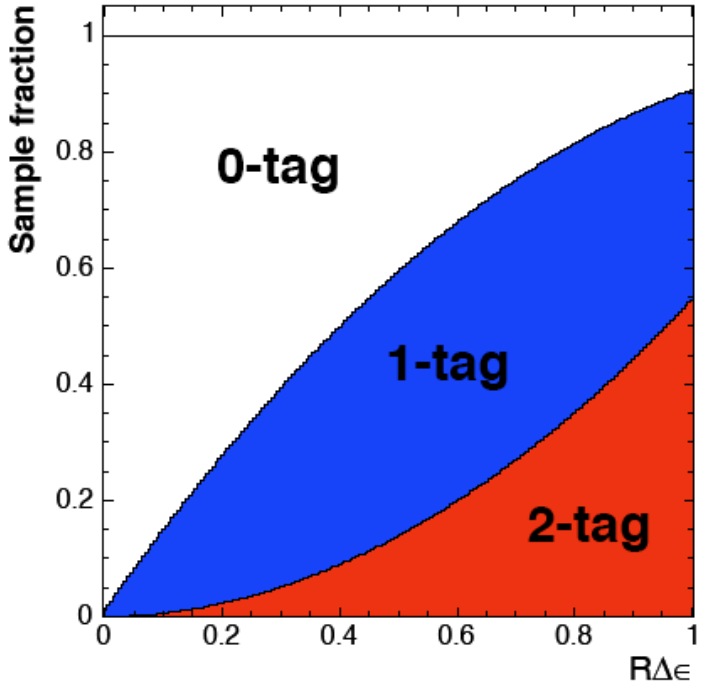
Measurement of $|V_{tb}|$

Under the assumption of unitarity and three generations of quarks:
$0.9980 < |V_{tb}| < 0.9984$ at 90% C.L.

$$R = Br(t \to Wb)/Br(t \to Wq) \approx 1$$

Can measure the branching ratio by counting the rate of *b*-tags in ttbar events





$$R = 1.03^{+0.19}_{-0.17}$$

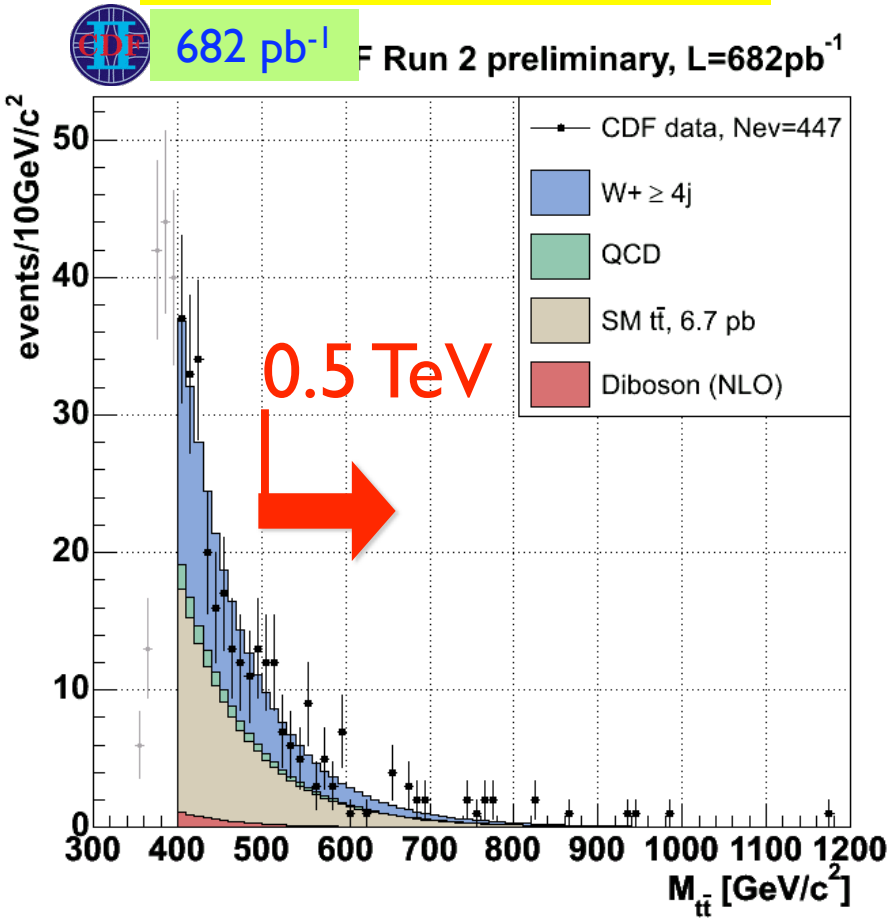
$|V_{tb}| > 0.80$ @ 95% C.L.

Search for $t\bar{t}$ resonances

Models with a dynamically broken EW symmetry (technicolor) predict a top-quark condensate, X, that decays to a *t-tbar pair.*

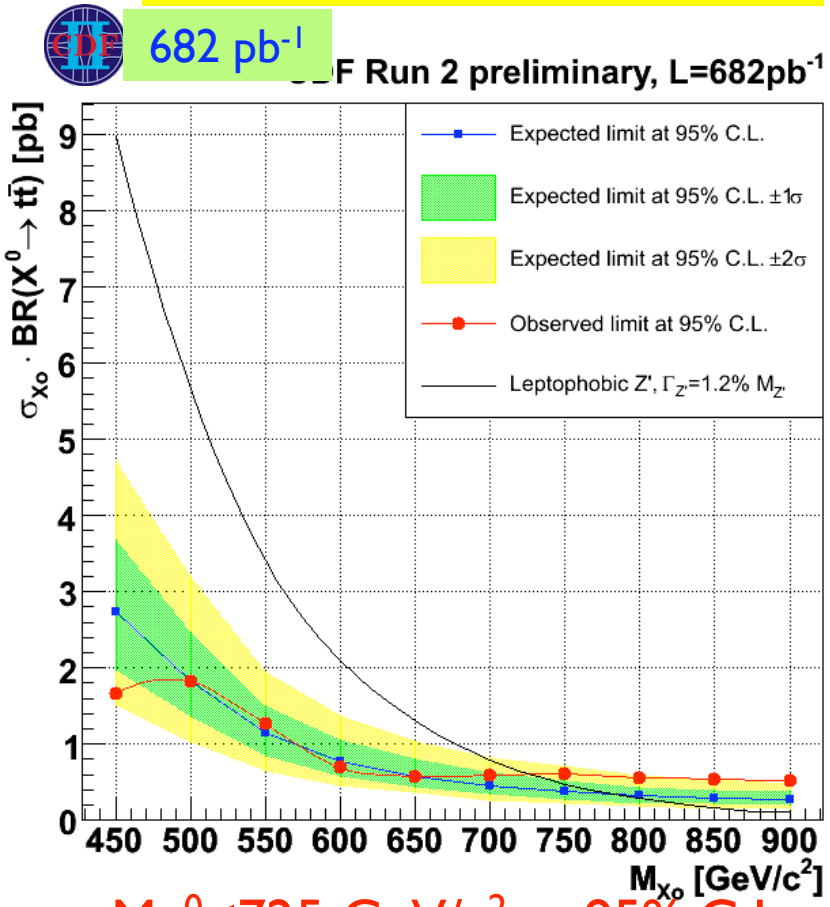
Search for tt resonances, the limit is generally model-independent, look at the t-tbar invariant mass:

ttbar system invariant mass



Bump search: no signal

Limits vs Resonance X_0 Mass



$M_X{}^0$<725 GeV/c^2 at 95% C.L.

(Leptofobic X^0 with $\Gamma_X{}^{0=}$1.2%$M_X{}^0$)

Summary and Outlook

The Tevatron top physics program seen from the perspective of precision:

Measurement already/towards limited by:

Luminosity Uncertainty

Pair production cross section..... **±12%**

Systematics

Top quark mass..... **±1.2%**

Statistics

Polarizations..... **±10−15%**

Single top production..... **~2.5σ**

Properties.....charge..... **not 4*e*/3, 92% C.L.**

....V_{tb}..... **~±20%**

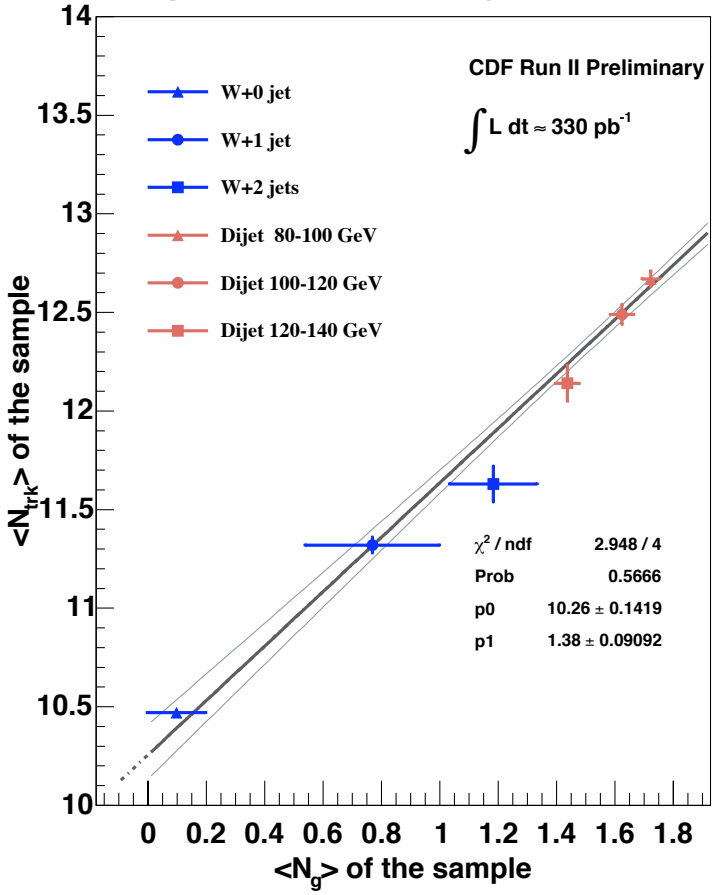
.... resonance..... **see slides**

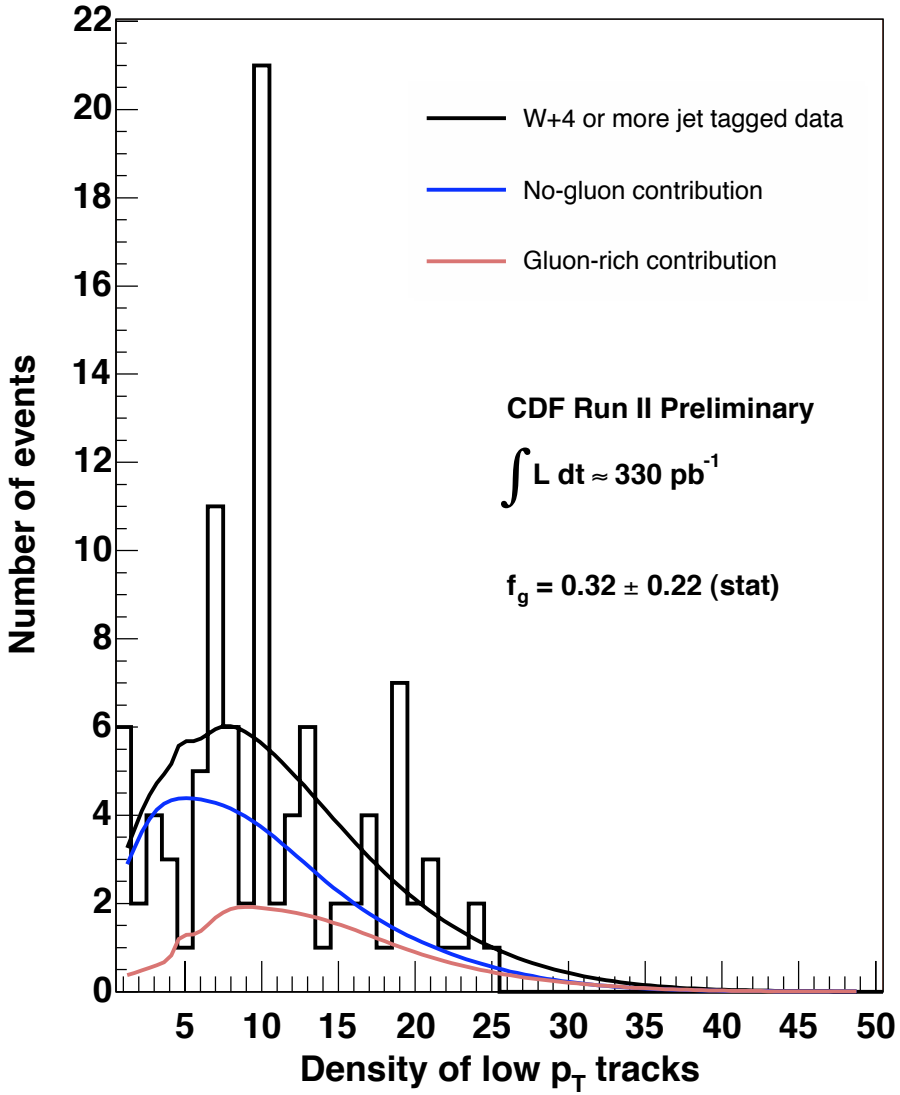
Additional Information

gg vs qq production

Test of the ttbar production mechanism (qq, vs gg)

Uses low-pT track multiplicity (scales with the gluon content)





0.25±0.24(stat)±0.10(syst)
for (gg → t t)/ (p p→ t t).

F_0 fraction

- Unfold w/ migration matrix, compare to theory *lep*+4 or more jets using all assignments; weighed. fit for F_+ and F_0
- Lepton+jets sample: ~200 events

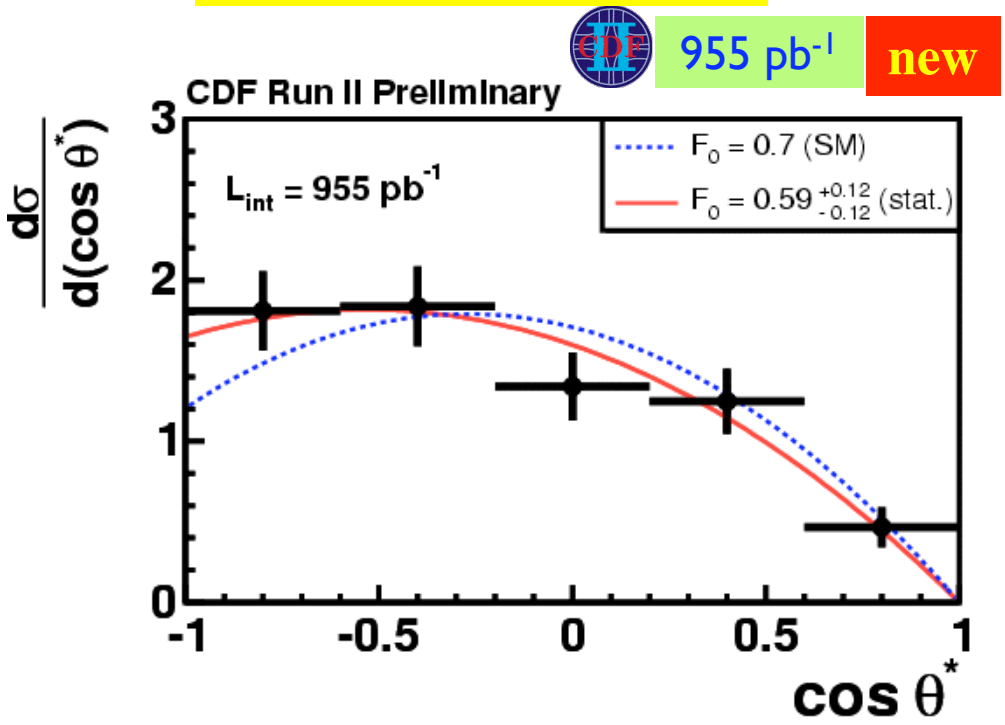
$$F_0 = 0.59 \pm 0.12(stat) \pm 0.06(syst)$$

- Template based Likelihood analysis of cos θ^*, fit for F_+ and F_0
- Lepton+jets sample: ~200 events

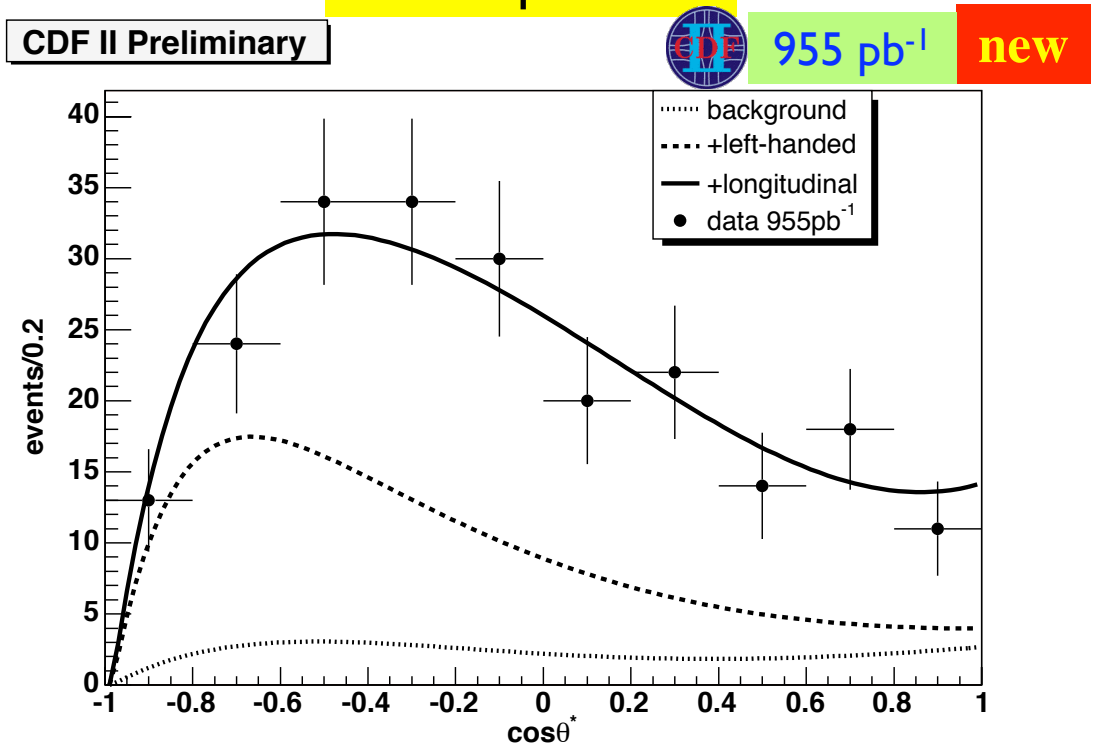
Best value, fixing F_+=0:

$$F_0 = 0.61 \pm 0.12(stat) \pm 0.04(syst)$$

cosθ^* differential xsec

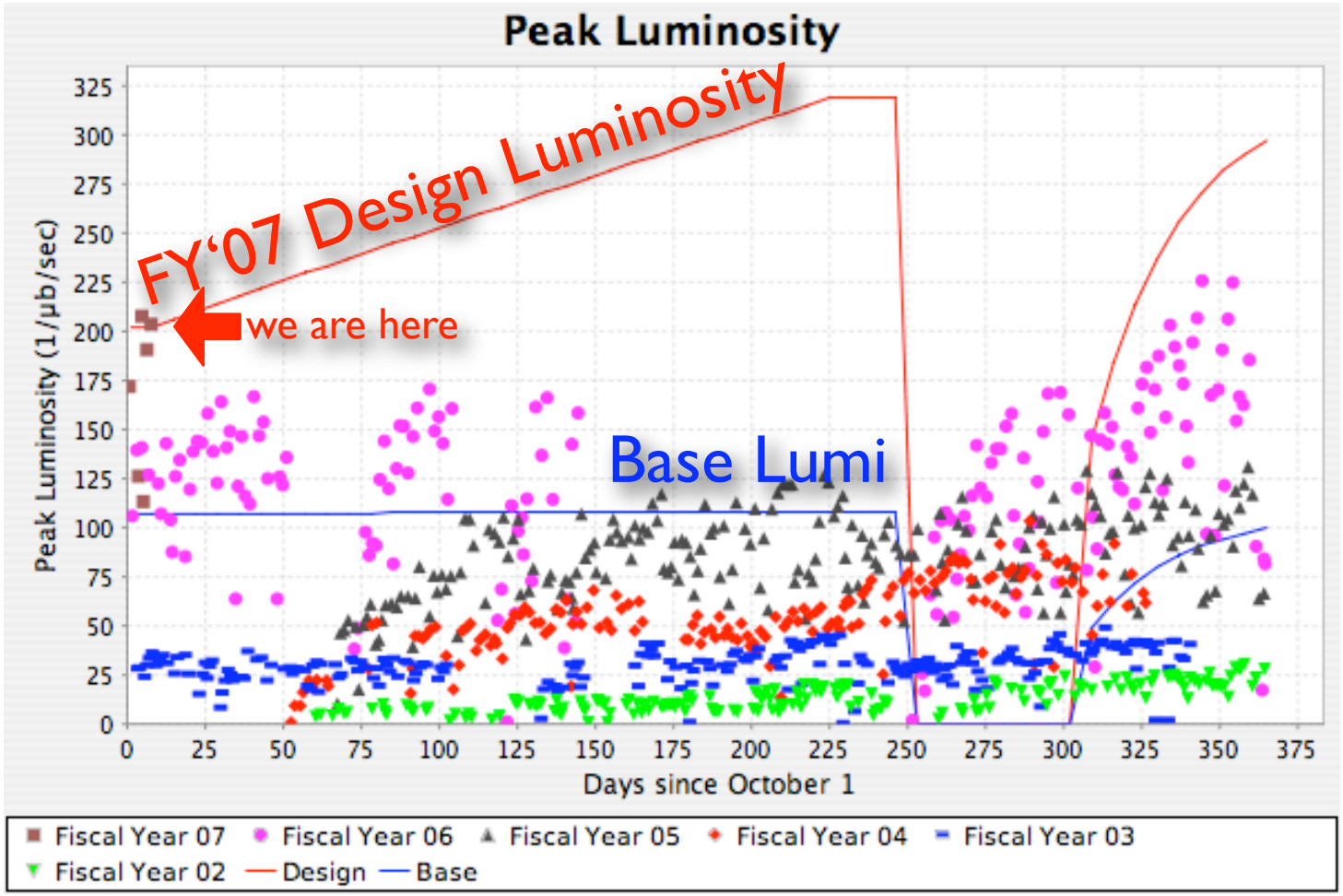


cosθ^* spectrum



Tevatron Performance

Peak Luminosity vs Time, per year

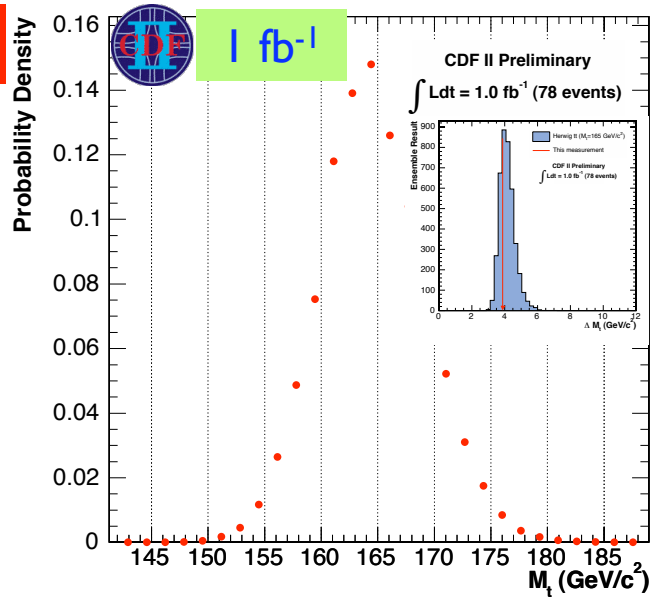


(Fiscal Year starts on Oct 1st)

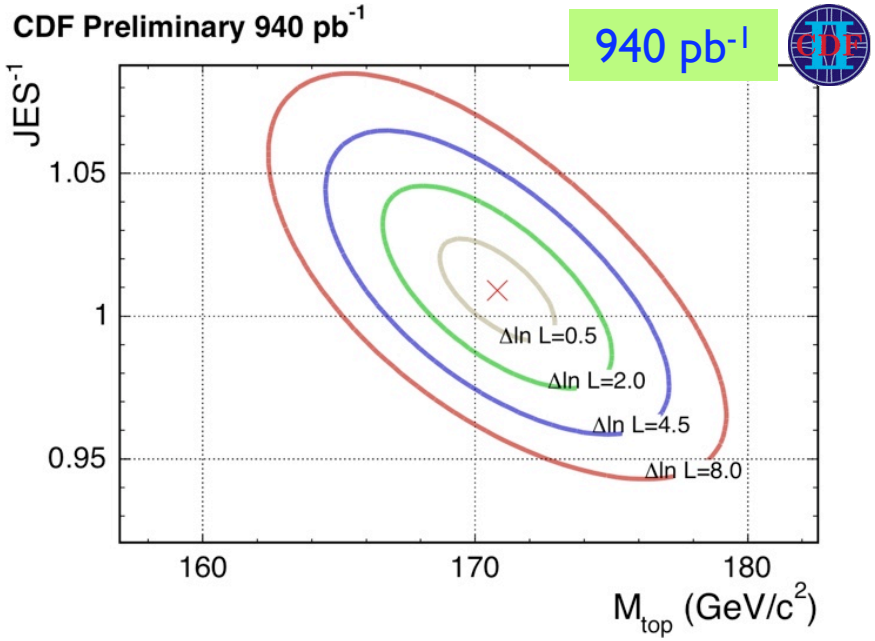
Top Mass Measurements

new

dilepton



1 fb^{-1}



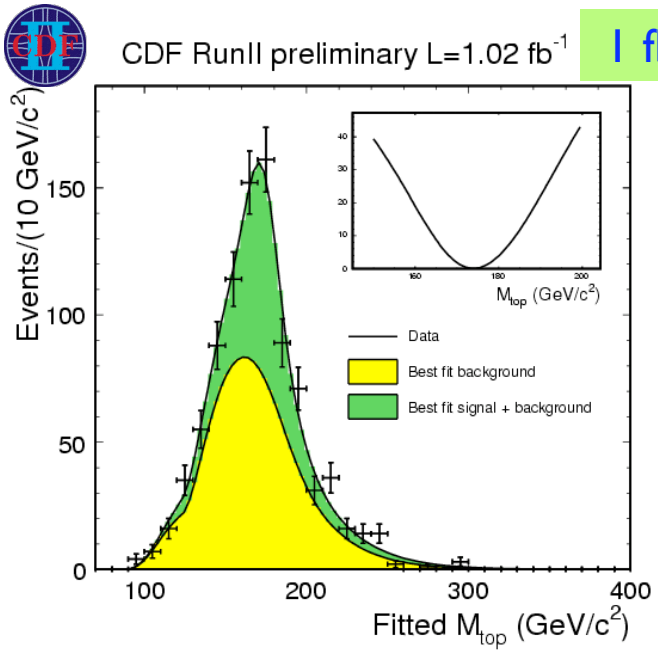
940 pb^{-1}

new

lepton +jets

new

all hadronic



1 fb^{-1}

Single world best:

m_t=170.9±1.6(stat)±1.4(JES)±1.4(syst) GeV/c^2

Source of uncertainty	CDF Magnitude (GeV/c^2)
b-JES	0.6
Signal (Initial and final state radiation, parton distribution functions)	1.1
Background (composition and shape)	0.2
Fit (Method, Monte Carlo statistics)	0.4
Monte Carlo (Modeling of ttbar)	0.2
Total	**1.4**