TOP 2006 - International Workshop on Top Quark Physics
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Top Quark
Current Experimental Status

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OUTLINE

- Introduction
- Top quark pair production cross section
- Top quark mass and charge
- Top quark interactions
- New particles in top production and decay
- Conclusions

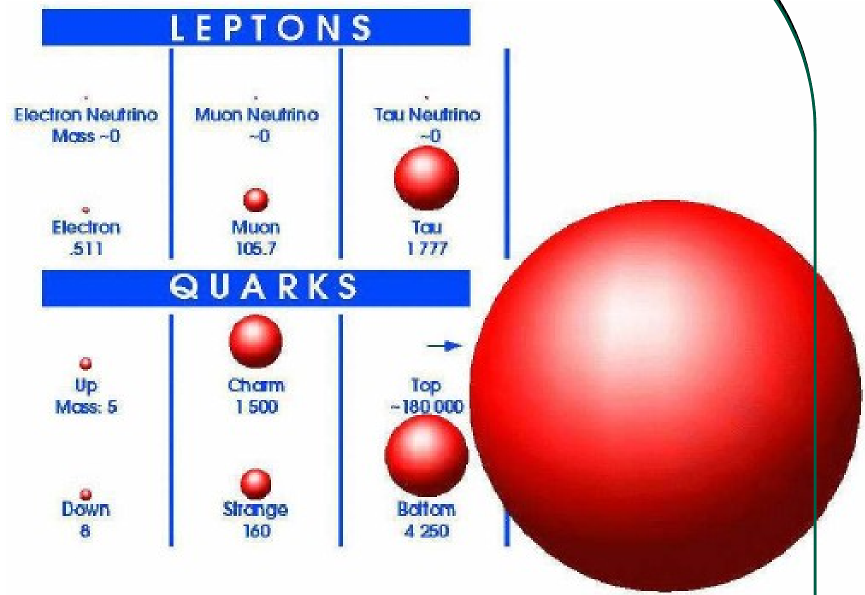
Why is Top Quark Physics Important?

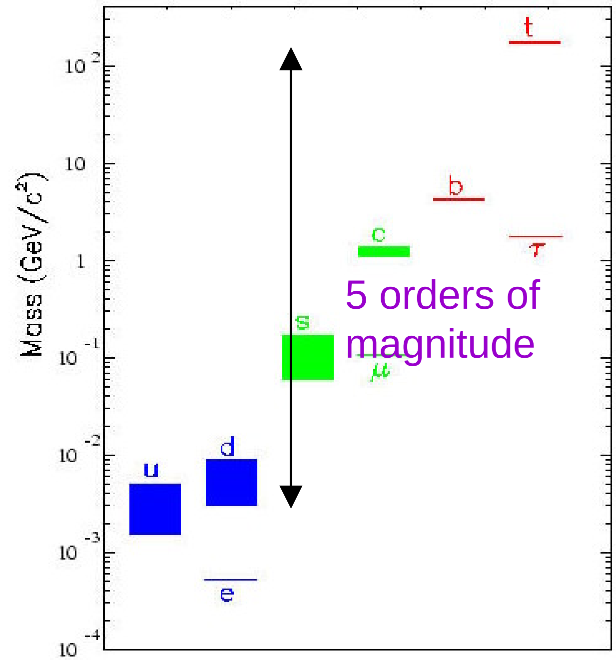
- The top quark was discovered in 1995 by CDF and DØ. Not a surprise: required by self-consistency of the Standard Model (SM).

- m_t ~ 175 GeV vs m_b~ 5 GeV
  Top-Higgs Yukawa coupling $\lambda_t = \sqrt{2}\, m_t/v \approx 1$
  $\Rightarrow$ the top quark may help resolve one of the most urgent problems in HEP: identifying the mechanism of ElectroWeak Symmetry Breaking (EWSB) and mass generation!
  The top quark may either play a key role in EWSB, or serve as a window to New Physics related to EWSB which might be preferentially coupled to the top quark.

- We still know little about the top quark: existing indirect constraints on top quark properties from low energy data or the statistics-limited direct measurements at Tevatron Run I leave plenty of room for New Physics.

- Even if the top quark is just a normal quark:
  - most of the experimental measurements have no analogue for the lighter quarks,
  - will allow to make stringent tests of the SM.





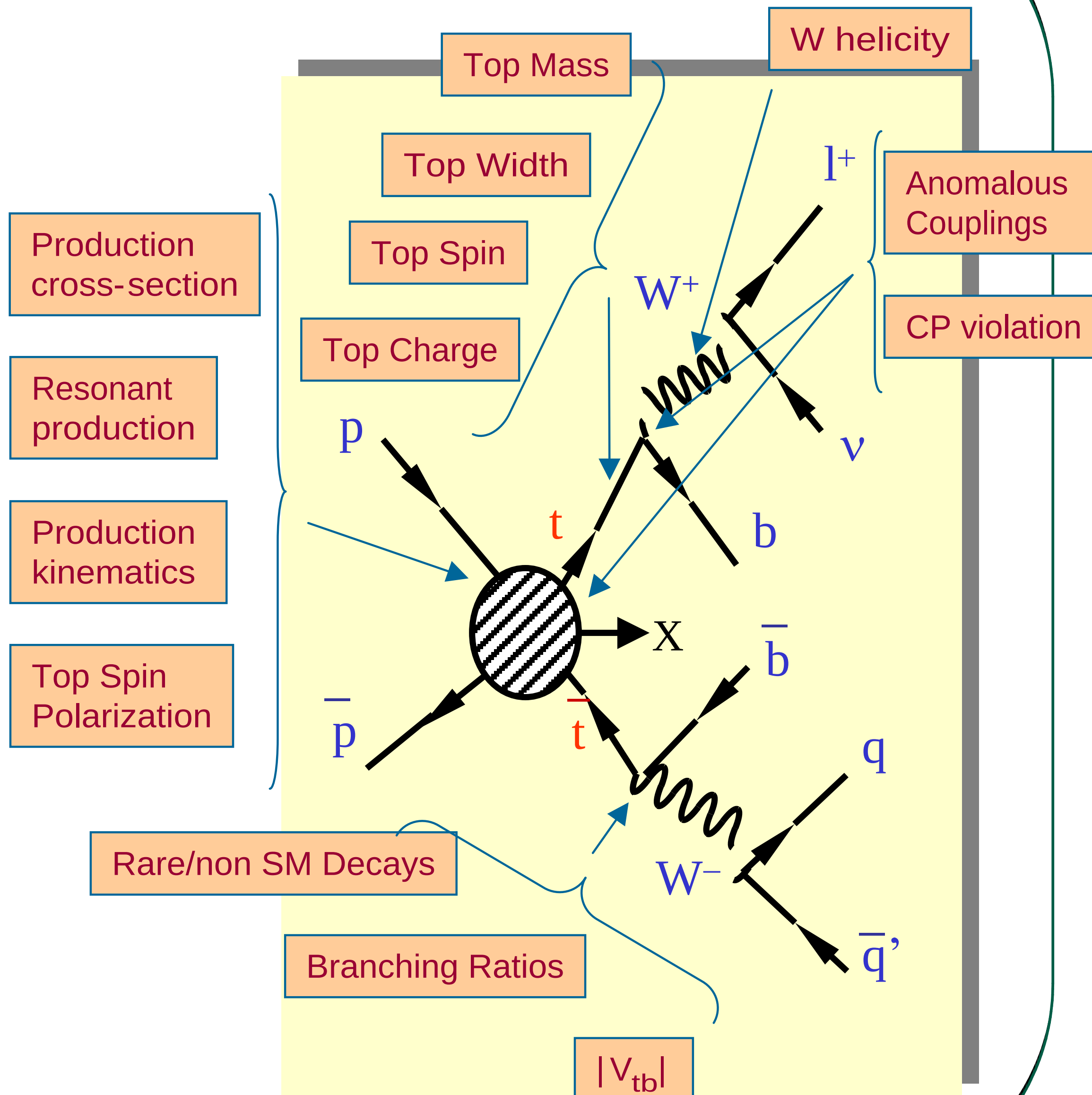
Outlining the Top Quark Profile

- Precision measurements of top quark properties crucial in order to unveil its true nature.

- So far experimental information from:
  - Indirect constraints from precision measurements ($b \rightarrow s\gamma$, electroweak precision observables);
  - Direct searches for non-SM production mechanisms (LEP, HERA);
  - Direct measurements at Tevatron

- Tevatron: currently world's only source of top quarks. Large top samples in Run II allow to make the transition from the discovery phase to a phase of precision measurements of top quark properties.

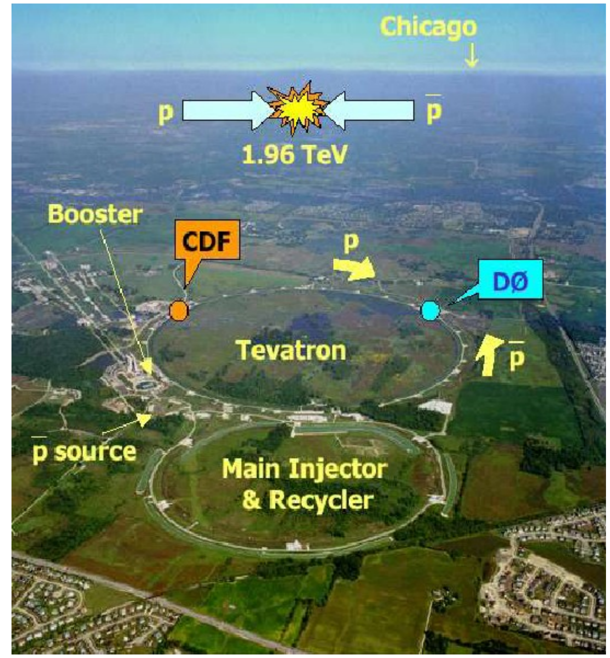
- Future accelerators (LHC,ILC) will allow a scrutiny of the top quark far beyond anything previously achieved.

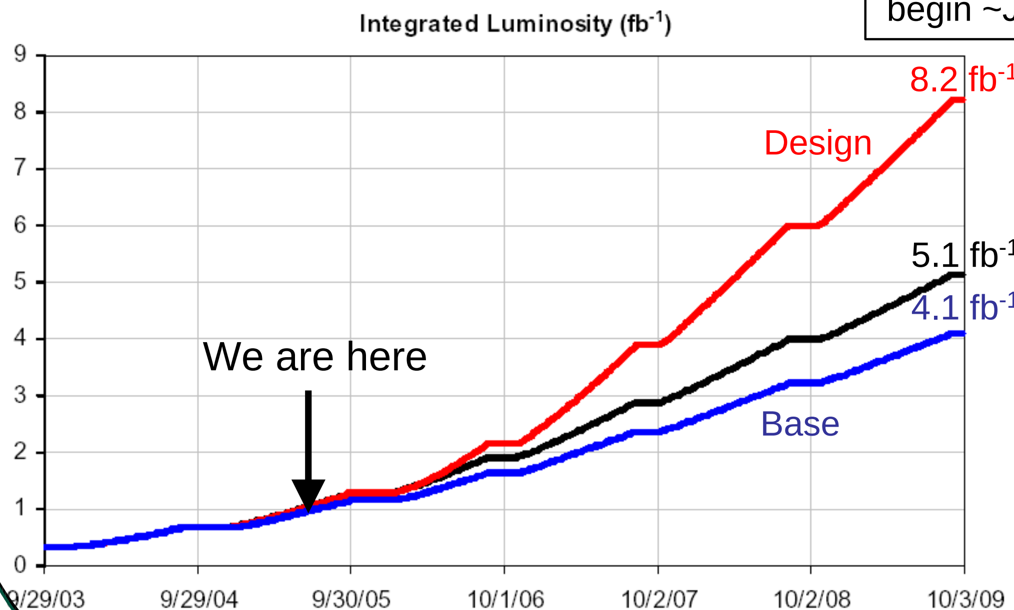


Tevatron Accelerator

	Run I	Run IIa	**Run IIb**
Bunches in Turn	6 × 6	36 × 36	**36 ×36**
√s (TeV)	1.8	1.96	**1.96**
Typical L ($cm^{-2}s^{-1}$)	1.6 $\times 10^{30}$	9 $\times 10^{31}$	**3 $\times 10^{32}$**
∫Ldt (pb^{-1}/week)	3	17	**50**
Bunch crossing (ns)	3500	396	**396**
Interactions/ crossing	2.5	2.3	**8**

Provisional schedule: begin ~June 2006





Current performance

- Instantaneous luminosity: ≥1.5×10^{32} $cm^{-2}s^{-1}$
- Delivered integrated luminosity: ~1.3 fb^{-1}
- Meeting "Design" performance in 2004 and 2005.

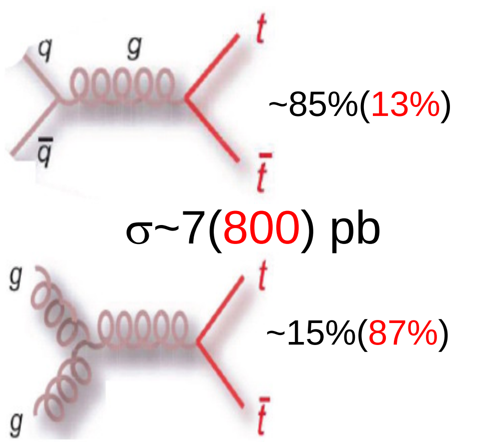
Long term luminosity plan

- Instantaneous luminosity: 3×10^{32} $cm^{-2}s^{-1}$ by 2007
- Delivered integrated luminosity: 4.1 fb^{-1} (Base) - 8.2 fb^{-1} (Design) ⇒ ~ x40-80 Run I data set!!

Top Quark Production in p-$\overset{(-)}{p}$ Collisions

Tevatron (LHC)

Strong Interaction

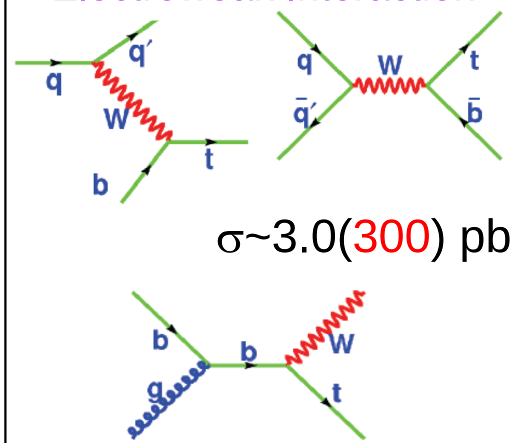


~85%(13%)

σ~7(800) pb

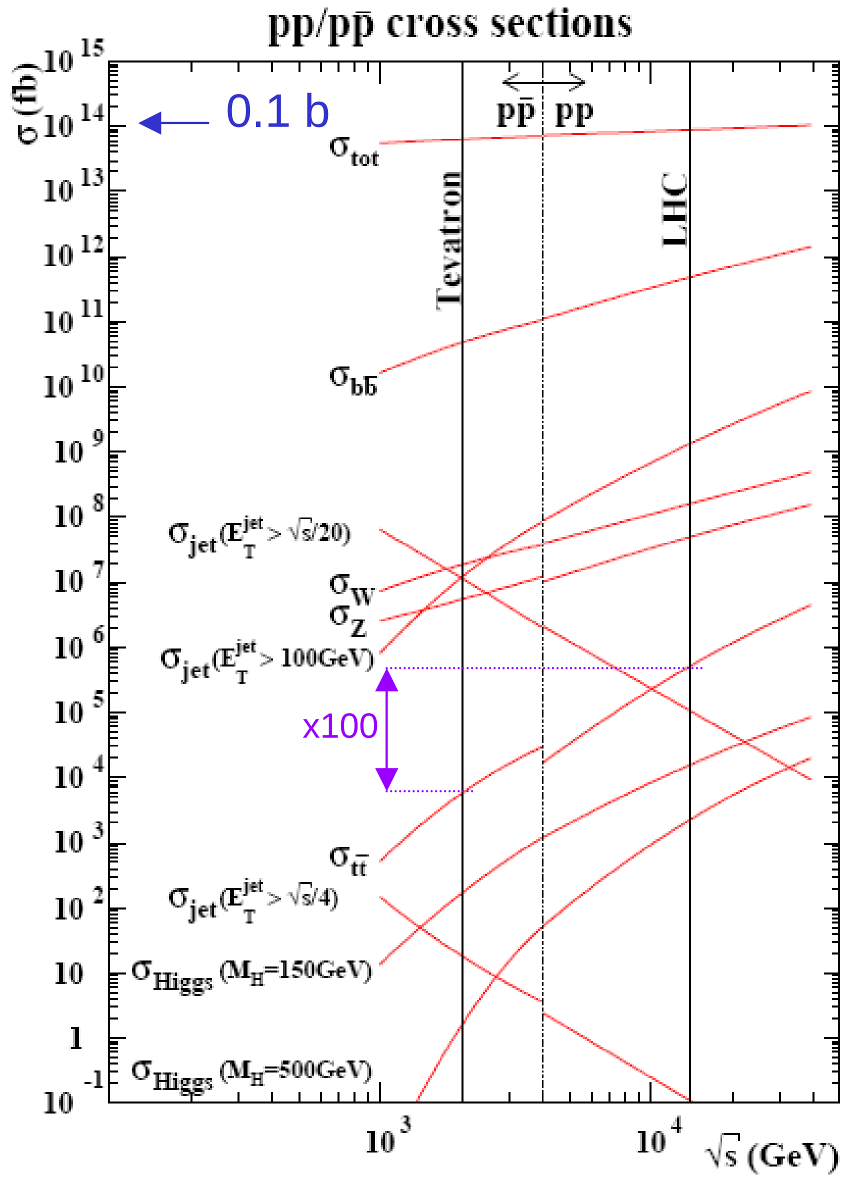
~15%(87%)

Electroweak Interaction



σ~3.0(300) pb

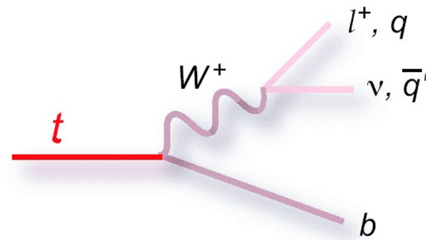
- Dominant production mechanism is in pairs, mediated by the strong interaction.
  Electroweak production of single top quarks not discovered yet.
- Tevatron (@ 10^{32} cm^{-2}s^{-1}): 7k(3k) events/year
  LHC (@ 10^{33} cm^{-2}s^{-1}): 8M(3M) events/year
- Experimental conditions (e.g. at Tevatron):
  …like drinking from a fire hose:
  σ_{inel} ~ 70 mb $\Rightarrow$ 7 M events/s @ 10^{32} cm^{-2}s^{-1}
  …like panning for gold: $\sigma_{inel}/\sigma_{t\bar{t}}$ ~ 10^{10}
  $\Rightarrow$ ~ 1 $t\bar{t}$ event/24 min @ 10^{32} cm^{-2}s^{-1}
  $\Rightarrow$ high luminosity and highly efficient and selective triggers crucial



Top Quark Decay

Within the SM:

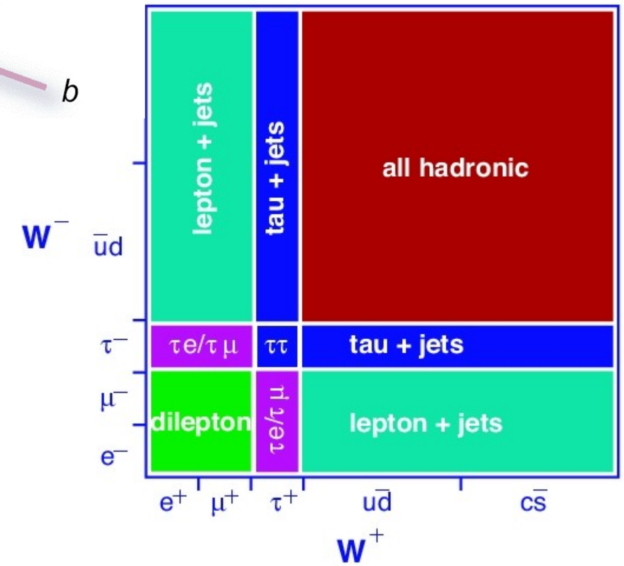
- $m_t > m_W + m_b \Rightarrow$ dominant 2-body decay $t \to Wb$
  ($t \to Ws$, Wd CKM suppressed)
  Assuming unitarity of 3-generation CKM matrix:
  $|V_{tb}| = 0.9990\text{-}0.9992$ @ 90% CL $\Rightarrow$ B($t \to Wb$) ~ 100%



B(W → qq) ~ 67%

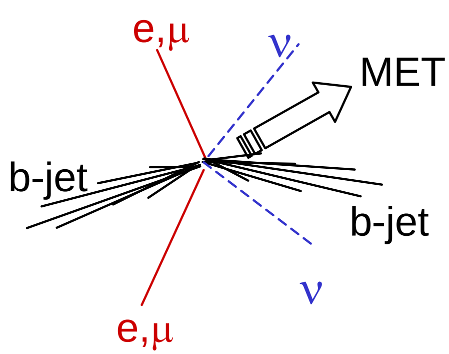
B(W → lν) ~ 11%, l=e,μ,τ

$t\bar{t}$ decay modes

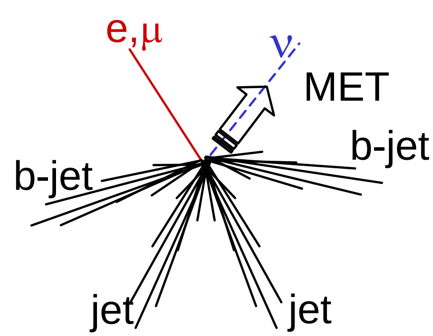


- $\Gamma_t^{SM} \approx 1.4$ GeV at $m_t = 175$ GeV $\quad \Gamma_t >> \Lambda_{QCD}$
  Top decays before top-flavored hadrons or tt-quarkonium bound states can form.
  Top quark spin efficiently transferred to the final state.

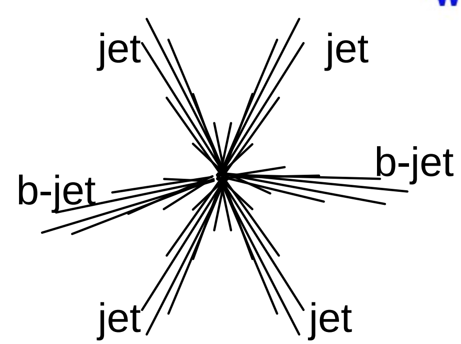
Typical final state signatures in top quark pair production:



Dilepton
(BR~5%, low bckg)



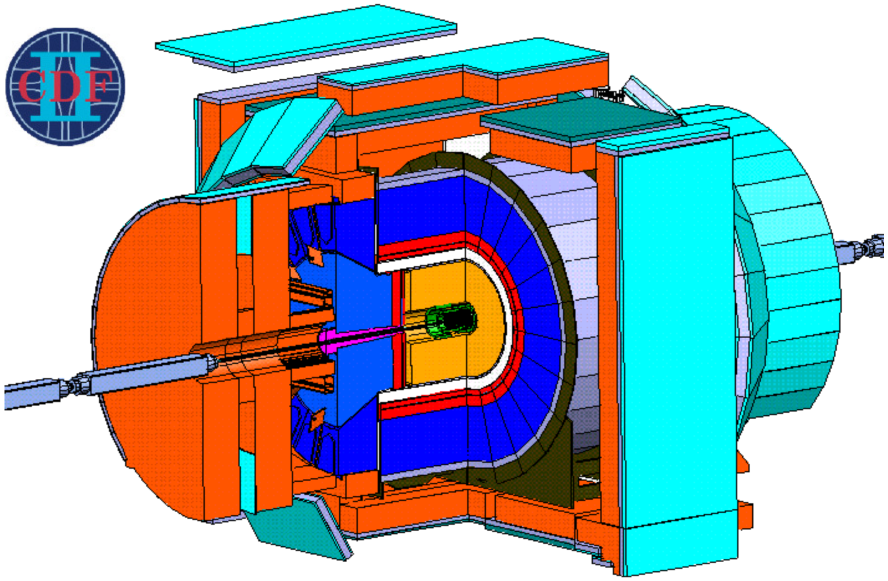
Lepton+jets
(BR~30%, moderate bckg)

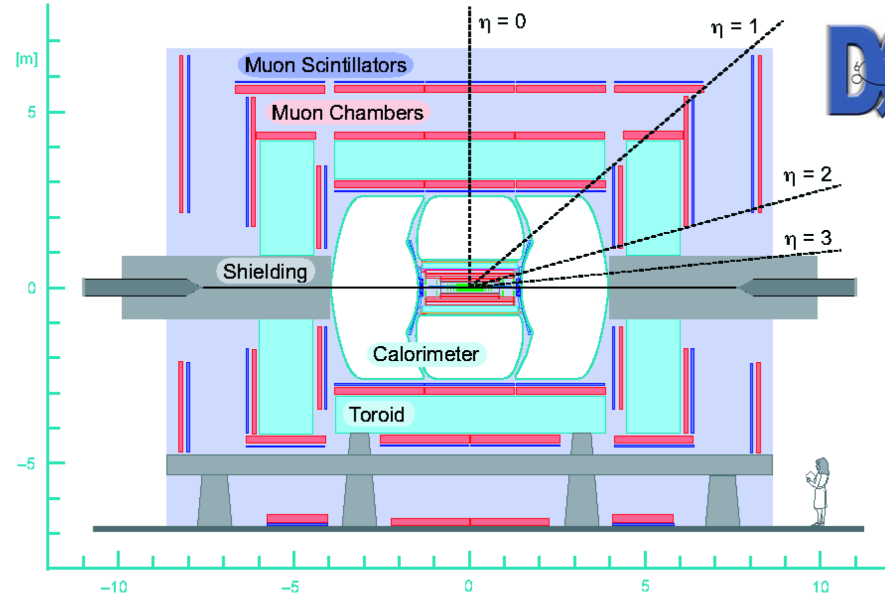


All-hadronic
(BR~46%, huge bckg)

$\Rightarrow$ require multipurpose detectors

CDF and DØ Detectors





62 institutions (12 countries)
767 physicists

83 institutions (19 countries)
664 physicists

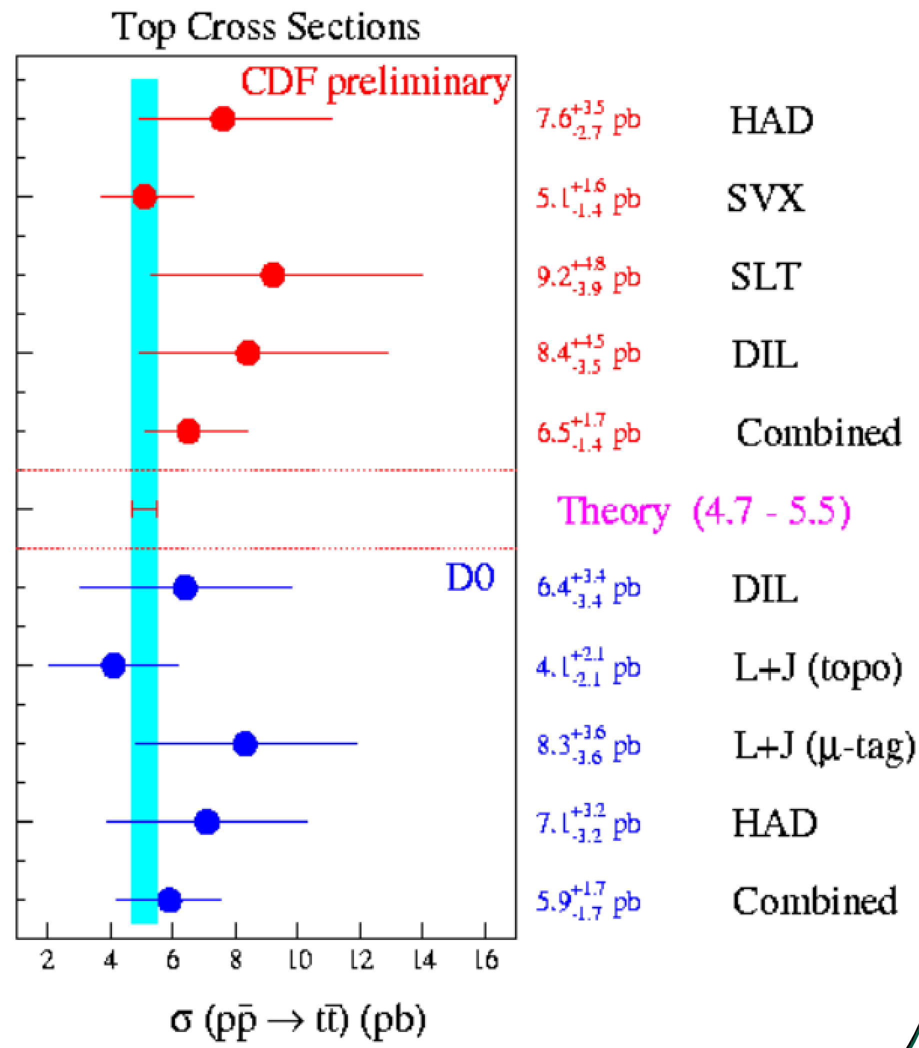
- Two truly international collaborations
- Two multipurpose detectors:
  - Central tracking system embedded in a solenoidal field
    - Silicon vertex detector
    - Tracking chamber(CDF)/fiber tracker(DØ)
  - Preshowers
  - Electromagnetic and hadronic calorimeters
  - Muon system
- Data taking efficiency: ≥85%
- Run II results presented here: 160-370 pb^{-1}

Top Quark Pair Production Cross Section

- The precise measurement of the top quark production cross section is a key element of the Top Physics program:
  - test of perturbative QCD and sensitive to New Physics (very important to compare measurements in as many channels as possible);
  - cross section analyses are the basis of any other top properties measurements;
  - crucial input for searches for which top events are a dominant background.
- Run I measurements consistent with the SM but precision ($\Delta\sigma_{tt}/\sigma_{tt}$~25%) limited by statistics.
- In Run II, most measurements will be systematics-limited: jet energy scale, signal/background modeling, luminosity determination (currently ~6%),…

  Large data samples should allow to control many of these uncertainties.

Run I Summary



σ_{tt} : Dilepton Final States

- Two high p_T leptons (e,μ,τ or isolated track)
- High missing E_T (all but inclusive analysis)
- ≥2 high p_T central jets (all but inclusive analysis)

Backgrounds:

- Physics: $Z/\gamma^* \rightarrow \tau\tau$, diboson (WW,WZ,ZZ)
- Instrumental: fake leptons, fake missing E_T

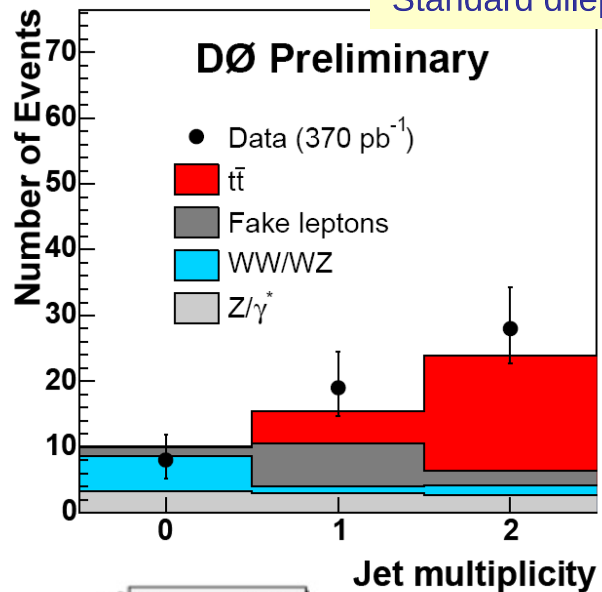
Different techniques to exploit the potential of the sample:

- standard dilepton analysis
- lepton+track analysis
- inclusive analysis

\+ Purity -

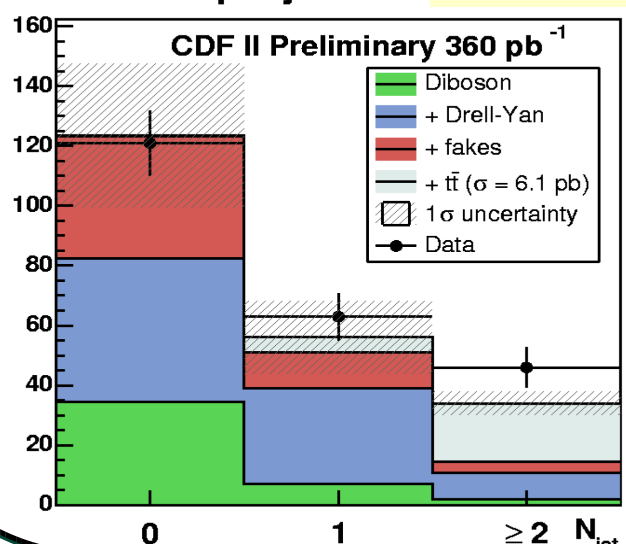
\- Signal +

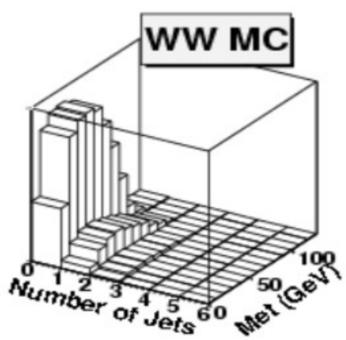
Standard dilepton

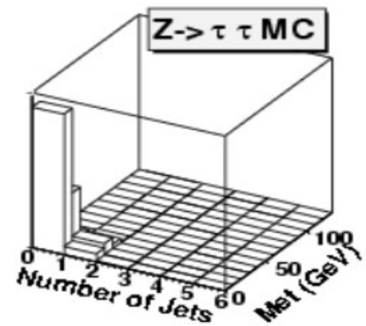


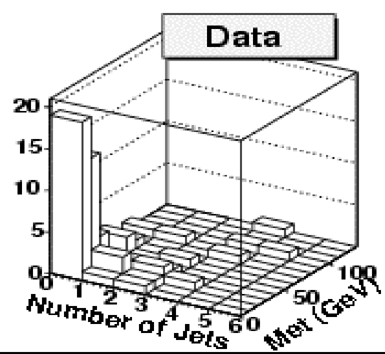
Event count per jet bin

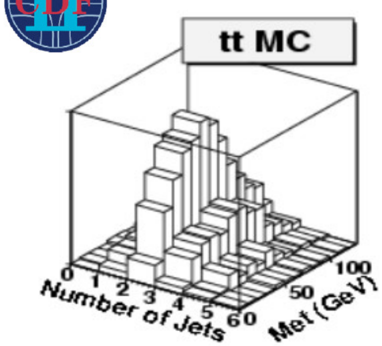
Lepton+track











Inclusive

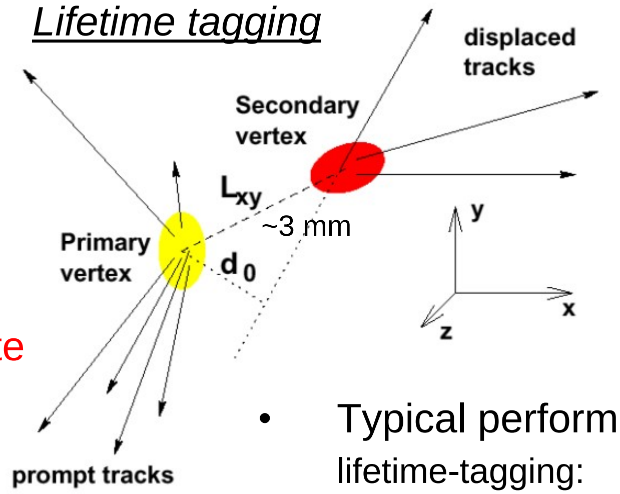
σ_{tt} : Lepton+Jets Final States (B-Tagging)

- One high p_T lepton (e or μ)
- High missing E_T
- $\geq$3 high p_T central jets,
  $\geq$1 b-tagged jets

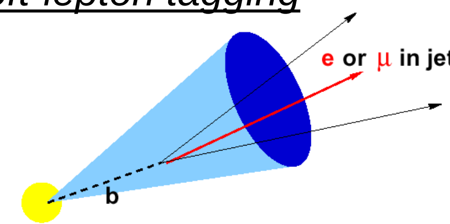
Backgrounds: W+jets, multijets

Use b-quark content to discriminate between signal and background.

Lifetime tagging



Soft-lepton tagging

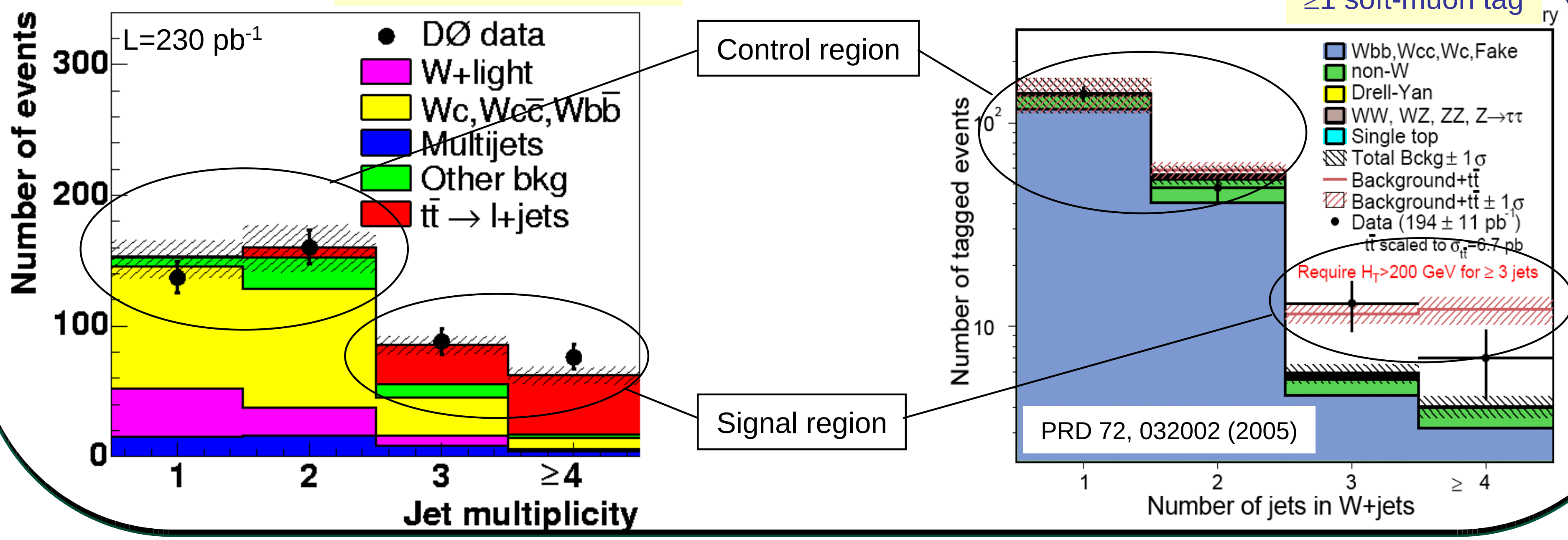


- $b \to \ell\nu c$ (BR ~ 20%)
- $b \to c \to \ell\nu s$ (BR ~ 20%)

- Typical performance (events with $\geq$4 jets)
  lifetime-tagging: $P_{\geq 1\text{-tag}}(tt)$ ~ 60%,
  soft-muon tagging: $P_{\geq 1\text{-tag}}(tt)$ ~ 16%,
  } $P_{\geq 1\text{-tag}}$(W+jets) ~ 4%

PLB 626, 35 (2005) — $\geq$1 secondary vertex tag

$\geq$1 soft-muon tag



σ_{tt} : Lepton+Jets Final States (Kinematic)

- One high p_T lepton (e or μ)
- High missing E_T
- $\geq$3 high p_T central jets

Backgrounds: W+jets, multijets

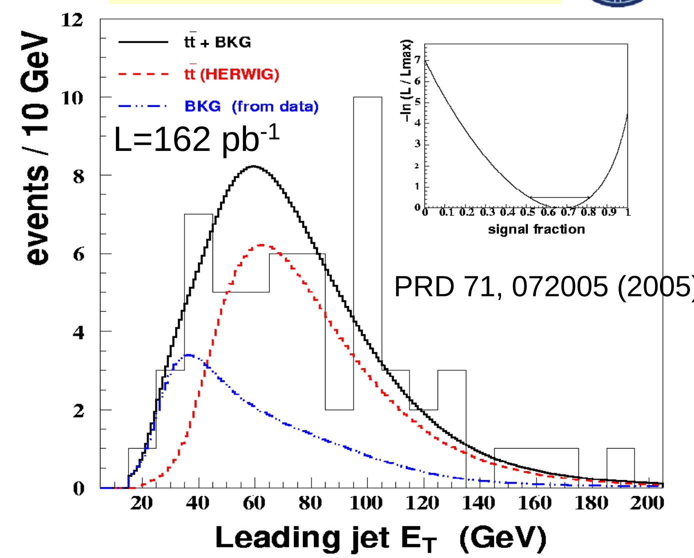
Exploit kinematic and topological characteristics of signal events to discriminate against backgrounds:

- Lepton and jets are more energetic and central
- More spherical topology

Strategies:

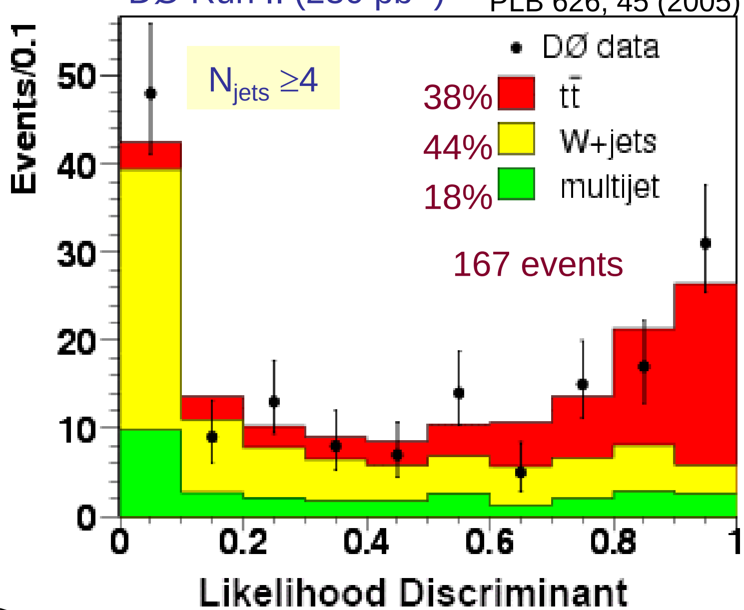
- Multivariate techniques to maximize statistical sensitivity
- More inclusive analyses to minimize systematics
- Combine kinematic and b-tagging information

N_{jets} $\geq$3 (b-tag+kinematics)

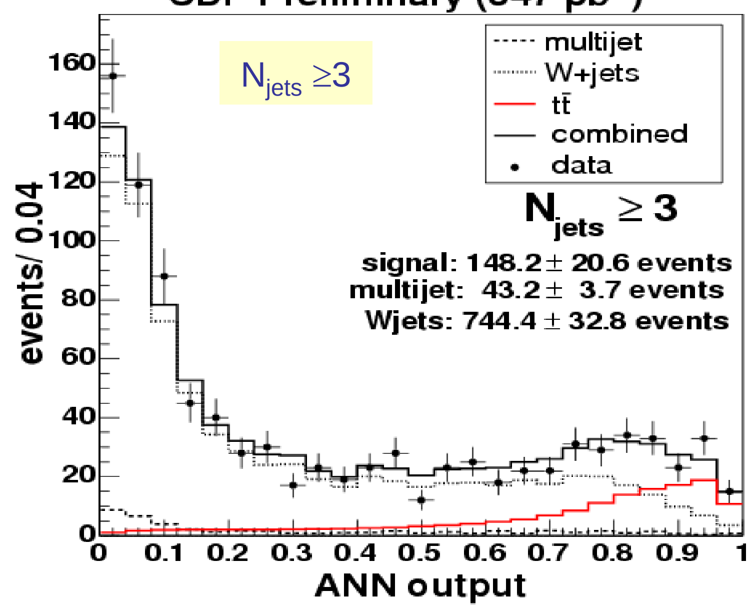


DØ Run II (230 pb^{-1})

PLB 626, 45 (2005)



CDF Preliminary (347 pb^{-1})

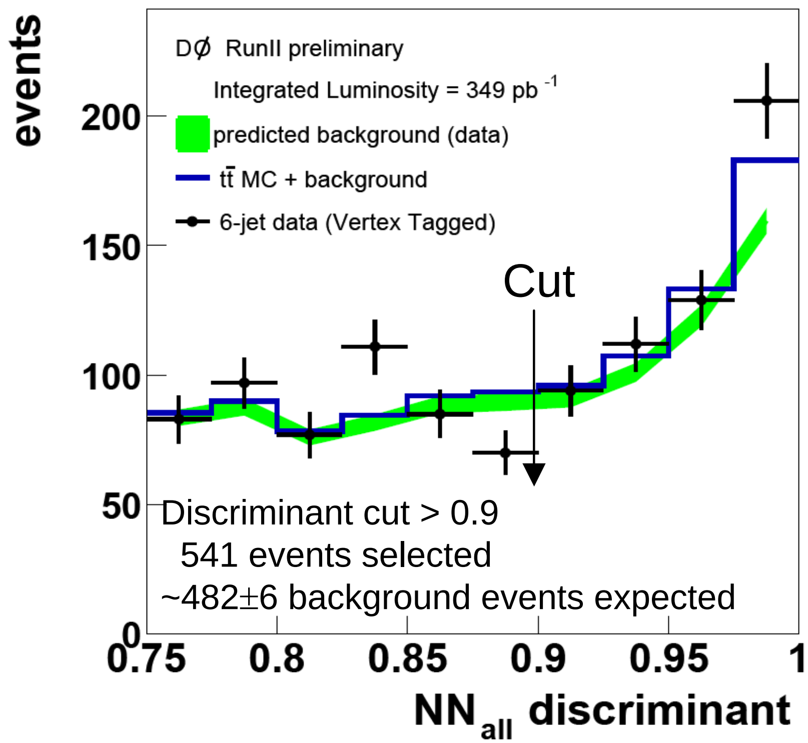


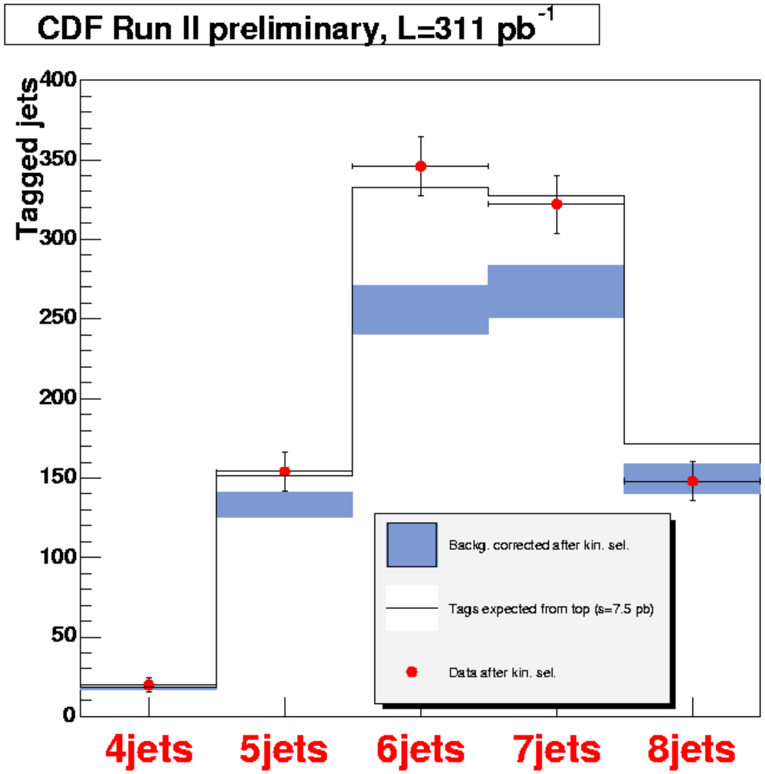
σ_{tt} : All-Hadronic Final State

- $\geq$ 6 high p_T central jets
- Overwhelming QCD multijets background (S/B~1/2500 after $\geq$ 6 jets requirement)
- Very challenging: currently considered very difficult at the LHC.
- Jet energy scale dominant systematic uncertainty.

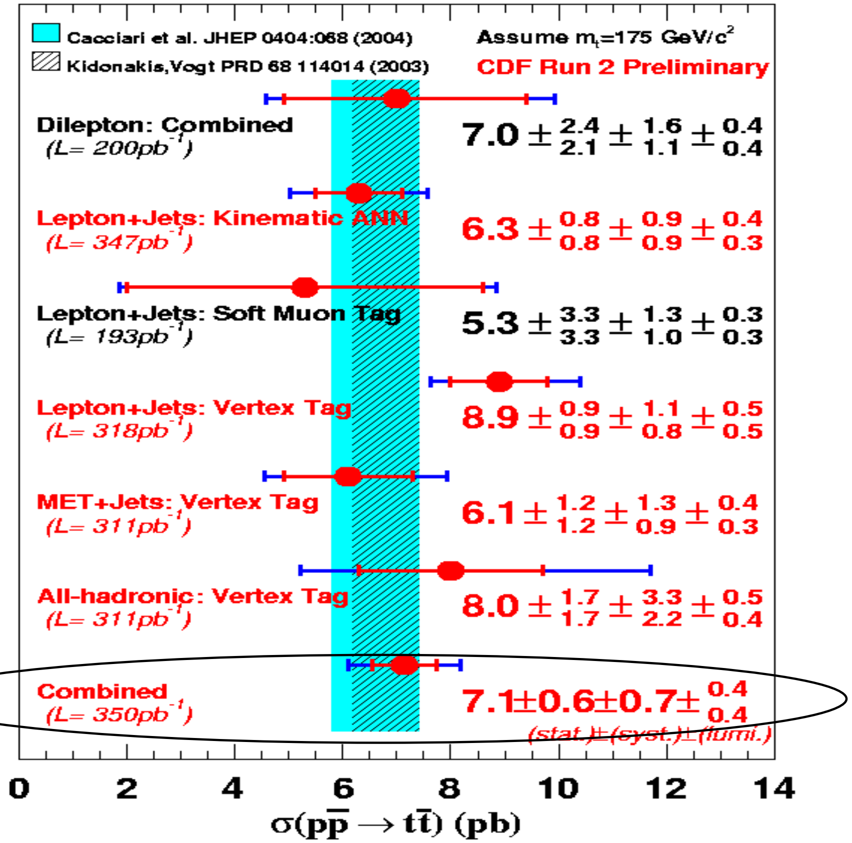
Strategy:

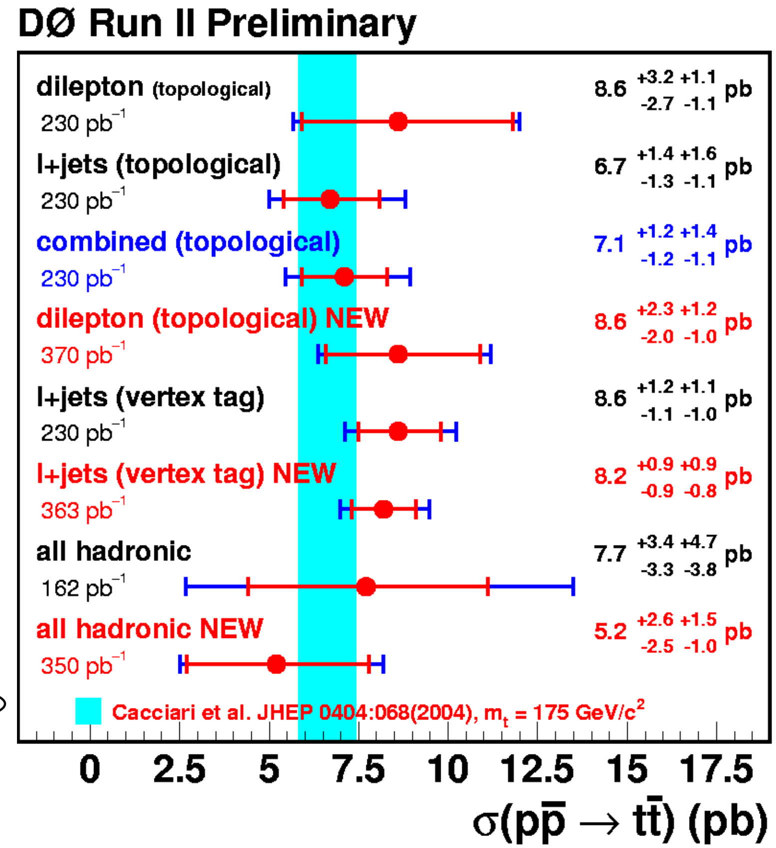
- Use kinematic and topological variables to further increase S/B: cuts (CDF) or multivariate discriminant (DØ)
- Require b-tagging
- Background predicted from data





Top Pair Production Cross Section: Summary

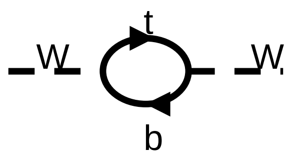




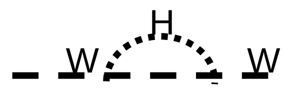
- Measurements in many different channels are self-consistent and so far in agreement with the SM prediction. As precision continues to increase, comparison among channels will become sensitive to New Physics effects.
- Most precise single measurement: $\Delta\sigma_{tt}/\sigma_{tt}$~16%, already being limited by systematic uncertainties. Much work underway to control systematics.
- Ongoing effort to combine measurements within and among experiments.
- Expectation (2 fb^{-1}): $\Delta\sigma_{tt}/\sigma_{tt} \leq 10\%$/experiment.

Top Quark Mass: Motivation

- Fundamental parameter of the Standard Model.
- Important ingredient for EW precision analyses at the quantum level:



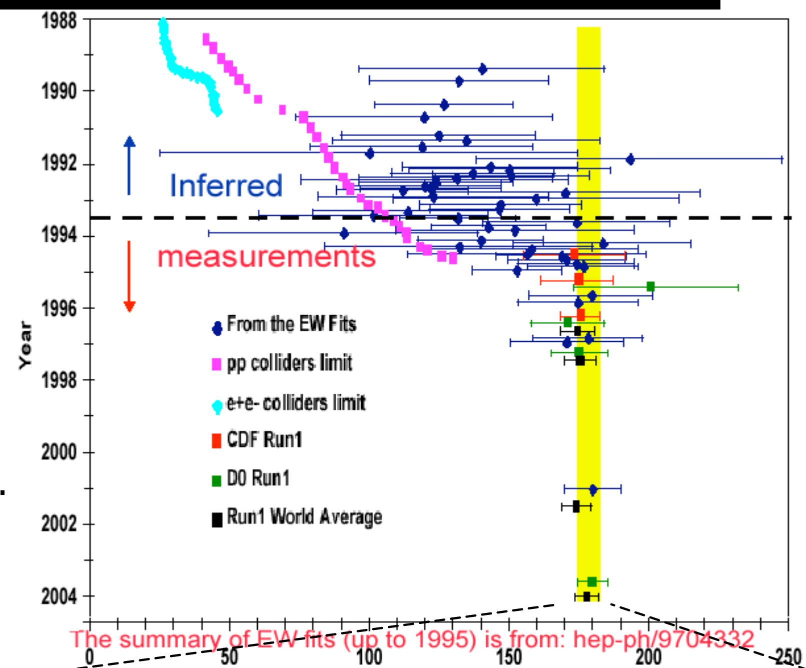
$\delta M_W \propto m_t^2$



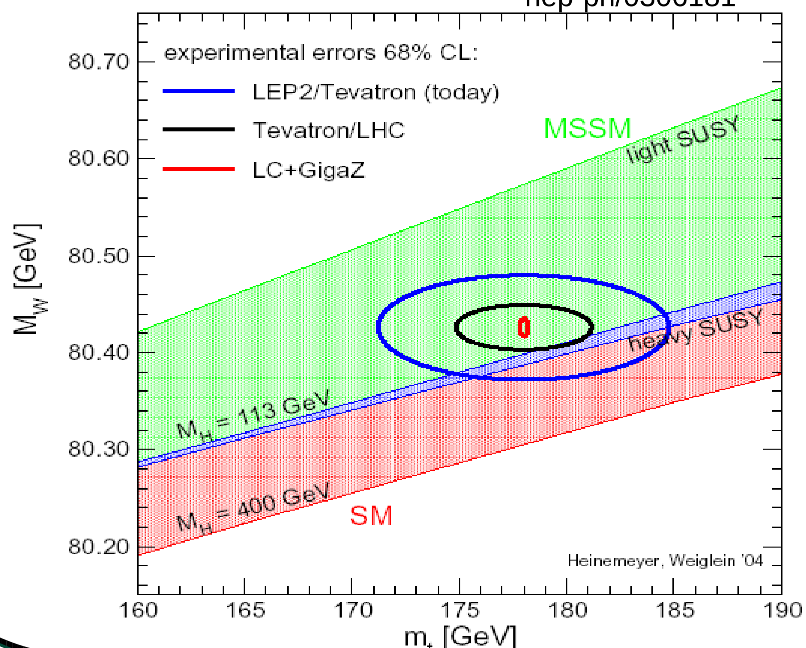
$\delta M_W \propto \ln(M_H)$

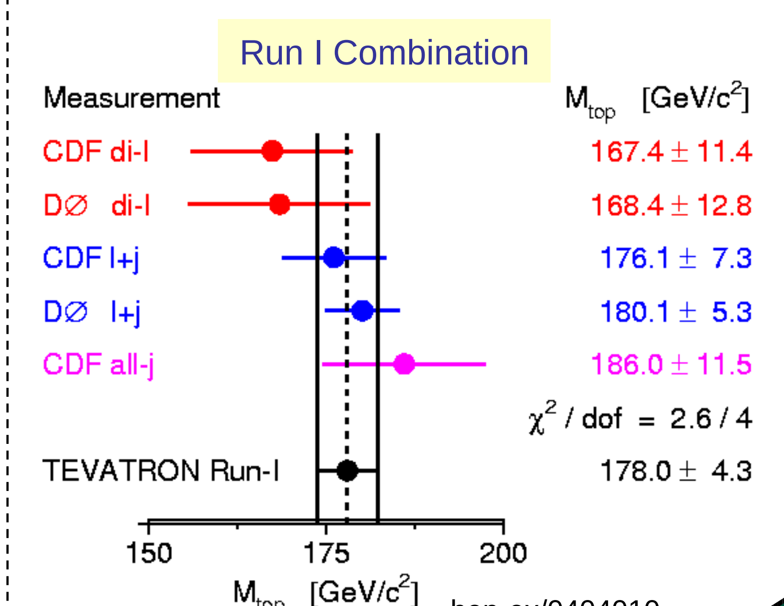
which were initially used to indirectly determine m_t.

After the top quark discovery, use precision measurements of M_W and m_t to constrain M_H.



hep-ph/0306181





hep-ex/0404010

Handles for a Precision Measurement

Jet Energy Scale (JES)

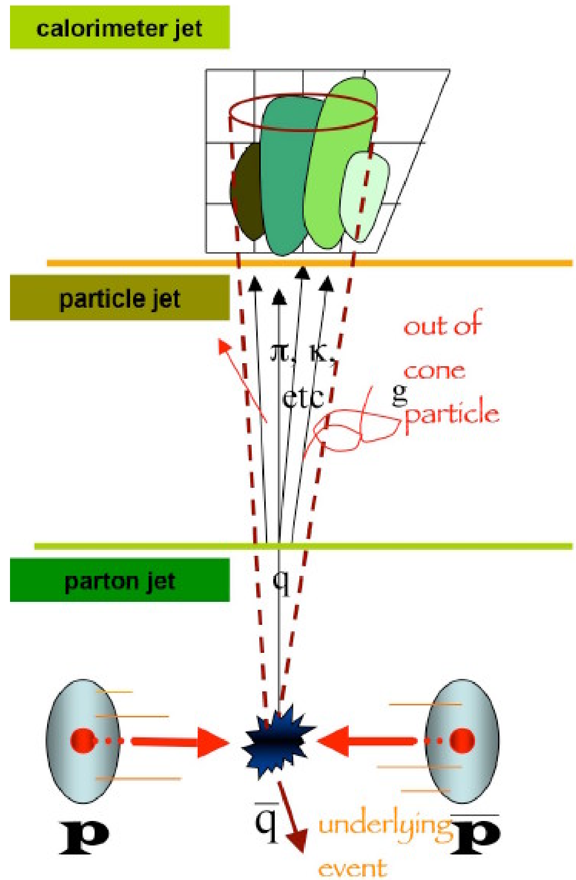
- Dominant systematic uncertainty in Run I measurements.
- Top mass measurement requires precise mapping between reconstructed jets and original partons:

  $\Rightarrow$ correct for detector, jet algorithm and physics effects.
- Handles:
  - dijets, photon+jets, Z+jets
  - W mass from $W \to jj$ in top quark decays (in-situ calibration)
  - $Z \to bb$ (verification of b-jet energy scale)

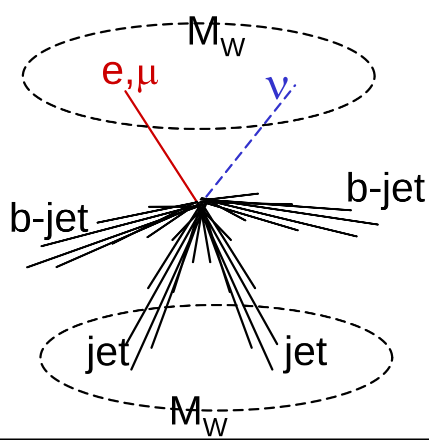
B-tagging: reduction of physics as well as combinatorial background

Sophisticated mass extraction techniques: maximize statistical sensitivity; minimize some systematic uncertainties (e.g. JES)

Simulation: accurate detector modeling and state-of-the-art theoretical knowledge (gluon radiation, PDFs, etc) required



Golden channel: lepton+jets



- Over-constrained kinematics
- Combinatorial background:
  - 2 ν solutions (M_W constraint)
  - 12 possible jet-parton assignments. Can be reduced using b-tagging: 6 (1-btag), 2 (2 b-tags)

Top Quark Mass: Template Methods

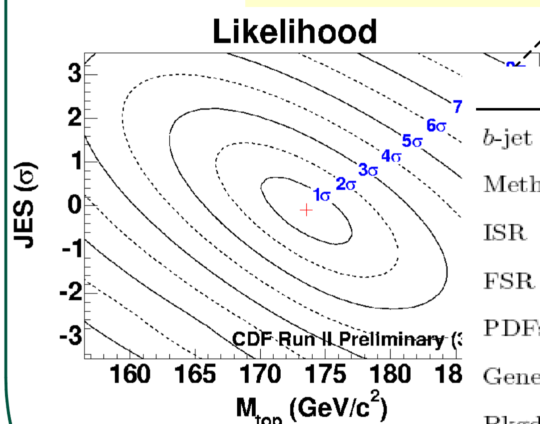
- Principle: perform kinematic fit and reconstruct top mass event by event. Build templates from MC for signal and background and compare to data.

- Recent developments in this approach have lead to the most precise to date top mass measurement:

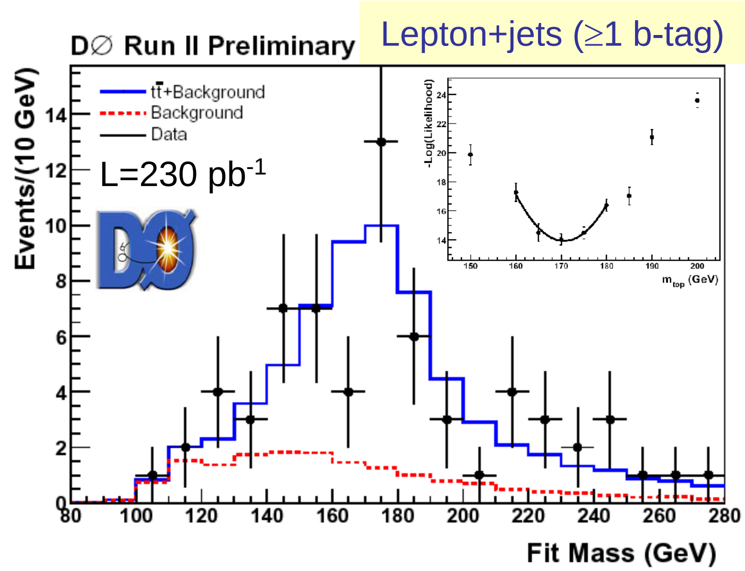
hep-ex/0510048

$$m_t = 173.5^{+3.7}_{-3.6}(stat + JES) \pm 1.3 \text{ GeV}$$
$$= 173.5^{+3.9}_{-3.8} \text{ GeV}$$

More precise than Run I world average!
(m_t = 178.0 ± 4.3 GeV)



	ΔM_{top} (GeV/c^2)
b-jet Energy	0.6
Method	0.5
ISR	0.4
FSR	0.6
PDFs	0.3
Generators	0.2
Bkgd Shape	0.5
b tagging	0.1
MC stats	0.3
Total	1.3



- Improve statistical power by defining four subsamples (based on number of tags) with different background content and sensitivity to m_t.
- Reduce JES systematic by using in-situ hadronic W mass in tt events: simultaneous determination of m_t and JES from reconstructed m_t and M_W templates. Implement constraint on JES from external measurement (~3%).
- Many systematics are expected to decrease with larger data samples.

Top Quark Mass: Dynamic Methods

- <u>Principle</u>: compute event-by-event probability as a function of m_t making use of all reconstructed objects in the events (integrate over unknowns). Maximize sensitivity by:
  - summing over all permutations of jets and neutrino solutions
  - allowing better measured events to contribute more.

Transfer function: mapping from parton level variables (y) to reconstructed level variables (x)

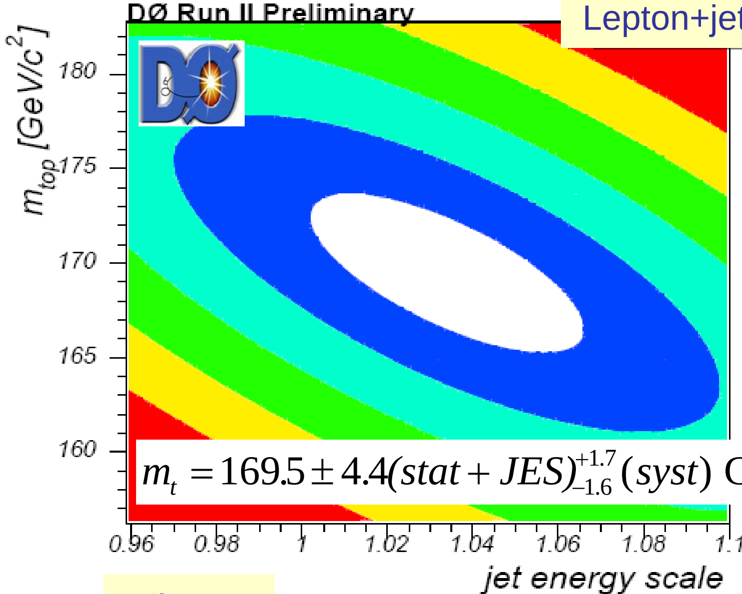
$$P(x;m_t) = \frac{1}{\sigma}\int d^n\sigma(y;m_t)dq_1dq_2 f(q_1)f(q_2)W(x|y)$$

differential cross section (LO matrix element)

parton distribution functions

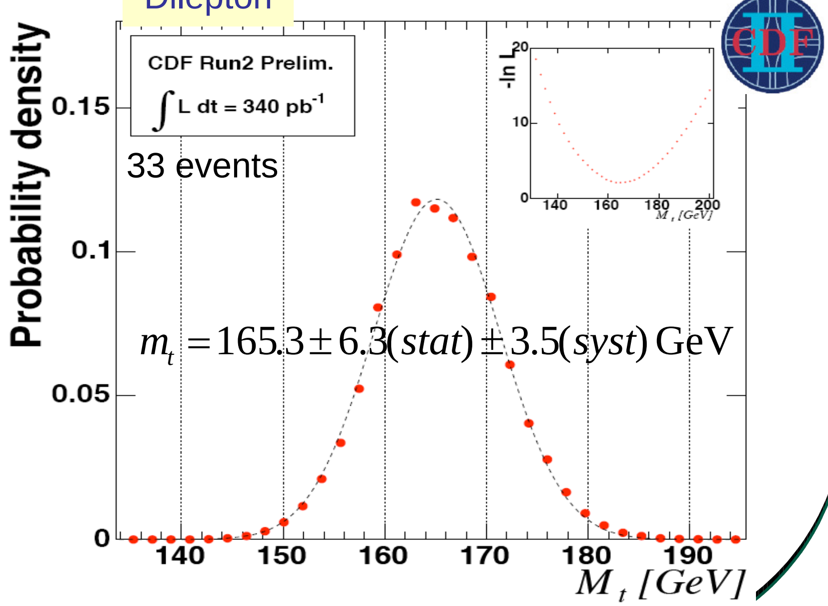
- Pioneered by DØ (Run I re-analysis in lepton+jets channel): statistical improvement was equivalent to x2.4 more data.
- Being extensively used in Run II:
  - lepton+jets w/ (CDF) and w/o b-tagging (DØ): results competitive with Template Method
  - dilepton sample (CDF): statistical uncertainty reduced by ~x2 with respect to any previous measurement in this channel.

Lepton+jets



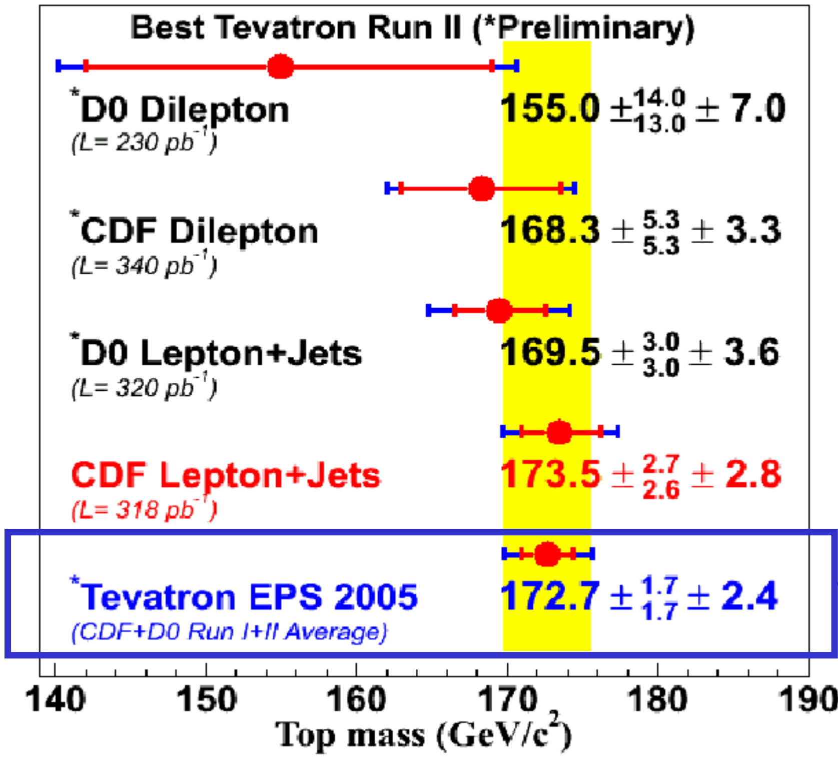
$m_t = 169.5 \pm 4.4(stat+JES)^{+1.7}_{-1.6}(syst)$ GeV

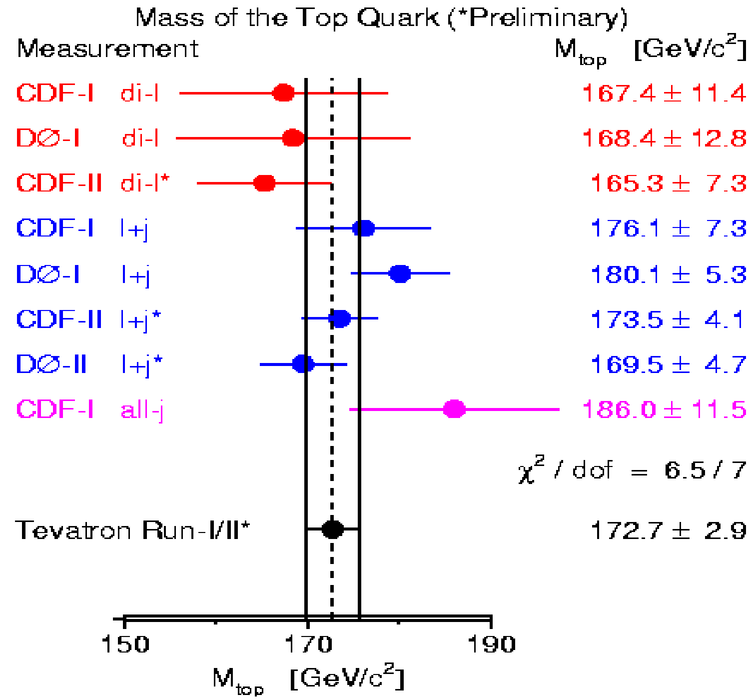
Dilepton



$m_t = 165.3 \pm 6.3(stat) \pm 3.5(syst)$ GeV

Top Quark Mass: Summary





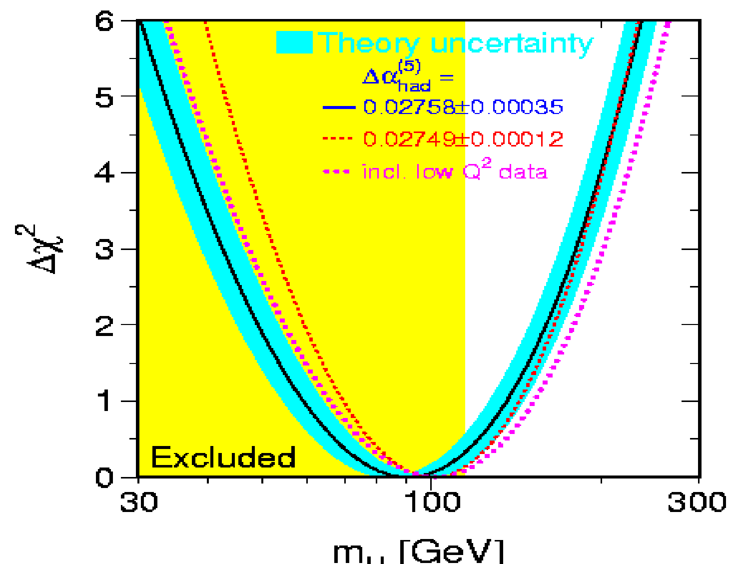
- New Run II single measurements achieving uncertainties comparable to/better than Run I world average.
- New Run I+ Run II world average:

$$m_t = 172.7 \pm 2.9\,\mathrm{GeV};\ \chi^2/dof = 6.5/7$$

Impact on SM Higgs boson:

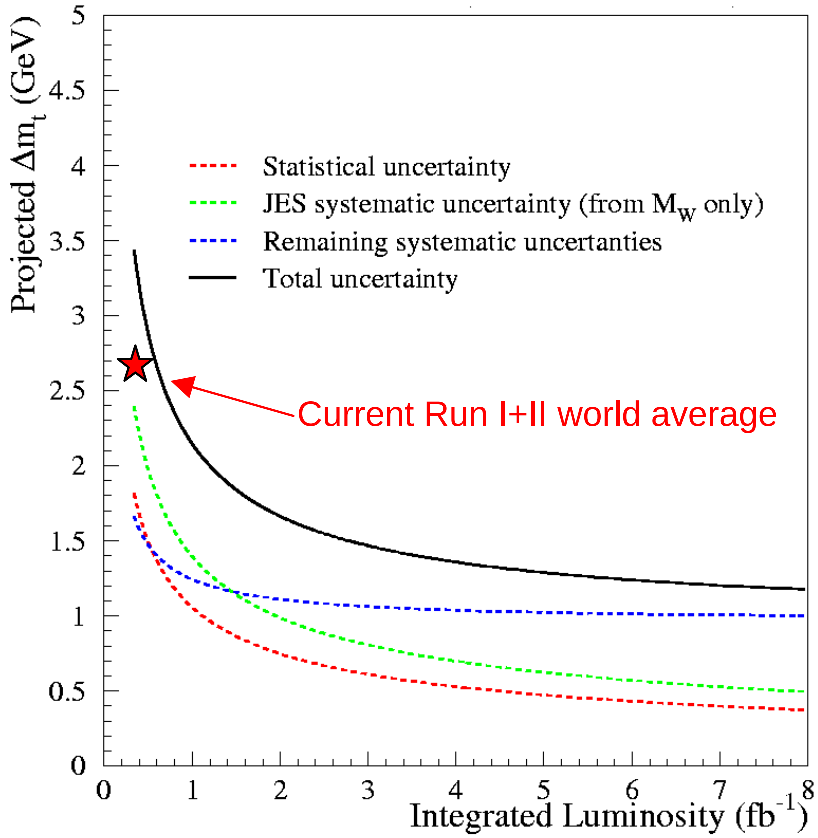
$$M_H = 91^{+45}_{-32}\,\mathrm{GeV};\ M_H < 186\,\mathrm{GeV} @ 95\%\mathrm{CL}$$

⇒uncertainty now dominated by ΔM_W



Top Quark Mass: Projected Uncertainty

Projected Uncertainty (CDF+DØ Run II; lepton+jets ONLY)



- Current understanding of systematic uncertainties in lepton+jets:

hep-ex/0510048

	ΔM_{top} (GeV/c^2)
b-jet Energy	0.6
Method	0.5
ISR	0.4
FSR	0.6
PDFs	0.3
Generators	0.2
Bkgd Shape	0.5
b tagging	0.1
MC stats	0.3
Total	1.3

(b-jet Energy, ISR, FSR, PDFs, Generators, Bkgd Shape) $\oplus$ = ~1.1 GeV

- Large data samples could be used to constrain theory-related systematics (gluon radiation, b-fragmentation, PDF's, etc)

- Projected CDF+DØ top mass uncertainty (2 fb^{-1}): ~1.5 GeV ⇒ $\Delta M_H/M_H \sim 30\%$

- An ultimate top mass uncertainty of ~1 GeV appears feasible!!

Top Quark Charge

- The top quark charge, one of the most fundamental quantities characterizing a particle, has not been directly measured yet.
- A priori there is no guarantee that we are observing pair production of resonances with Q=±2/3e.

$$p\bar{p} \to t\bar{t} \to (W^+b)\ (W^-\bar{b})$$

A possible scenario (D. Chang et al, Phys Rev D59, 09153 (1999)):

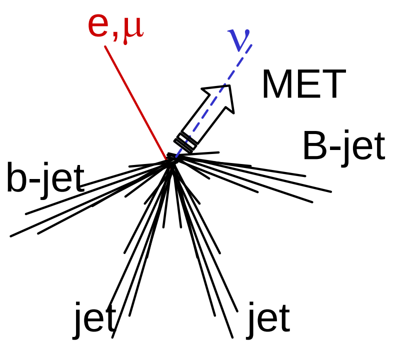
  - Introduce exotic 4th family of quarks and leptons + heavy Higgs triplet. In particular:

$$(Q_1,Q_4),\ q_{Q1} = -1/3,\ q_{Q4} = -4/3 \text{ and } m_{Q4} = 175 \text{ GeV}.$$

  - The actual "discovered top-quark" is really Q_4: $p\bar{p} \to Q_4\bar{Q}_4 \to (W^-b)\ (W^+\bar{b})$

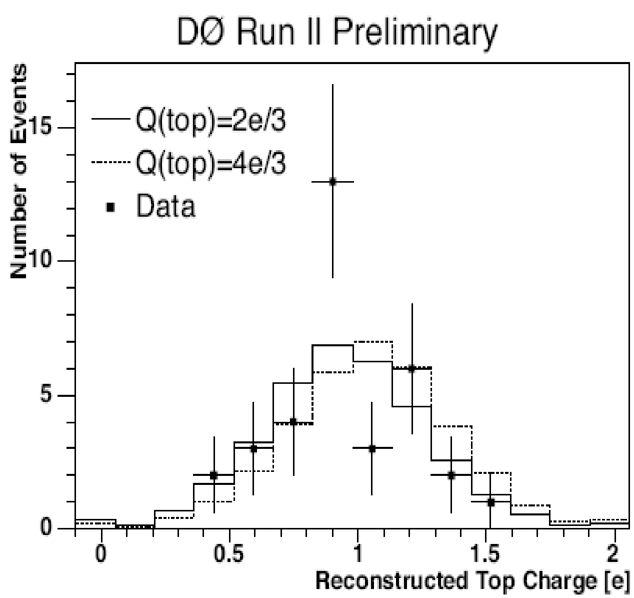
    The SM top quark is heavier (m_t~270 GeV) and has not been observed yet.
  - This model accounts for all data, in particular R_b and A_{FB}^b

- DØ Run II (365 pb^{-1})
  - 17 double-tagged (secondary vertex tagger) lepton+≥4jets candidate events
  - constrained kinematic fit to assign b-jet to lepton
  - jet-charge algorithm to reconstruct charge of b-jets
  - two measurements of $|Q_t|$ per event. Build $|Q_t|$ template for SM and exotic hypotheses and perform likelihood ratio test of hypothesis



$$|Q_{t1}| = |q_\ell + q_b|$$

$$|Q_{t2}| = |-q_\ell + q_B|$$



Q_t=-4/3e excluded @ 94% CL

Anomalous Top Interactions: Phenomenology

- Anomalous top couplings can manifest themselves affecting many observables:
  - total cross-sections,
  - tt invariant mass distribution,
  - angular distributions of decay products (both tt and single top),
  - spin correlations in tt,
  - rare decays (e.g. flavor-changing neutral current processes),
  - CP-sensitive observables,
  - ...
- Many operators can contribute to a given observable. Very important to try to disentangle effects (use of polarization observables crucial) and cross-checks using different processes.
- Very important to have accurate theoretical predictions: full spin transmission, at least NLO QCD in differential distributions, etc

GOALS

- constrain (discover) new physics by careful examination of top quark observables
- identify operators responsible and disentangle effects from one another
- rule out (figure out) specific models of New Physics

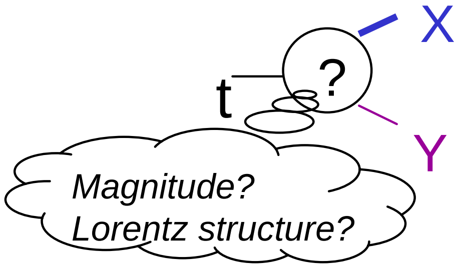
$\Rightarrow$ Analyses should be as model-independent as possible

Top Couplings to Gauge Bosons: W

- Large m_t ⟺ New Physics (EWSB-related)??

⇒ interactions between the top quark and weak gauge bosons extremely interesting!!

⇒ at Tevatron only the *tbW* vertex can sensitively be probed



In the SM: X=W 100% of the time, Y=b ~100% of the time ($|V_{tb}|$~1)

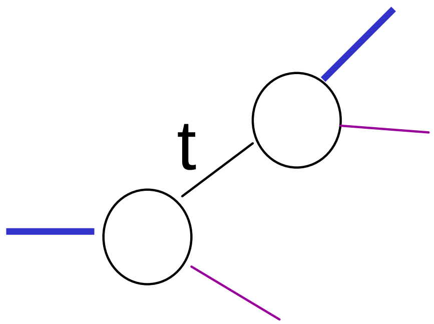
$$\Gamma^{\mu}_{tbW} = -\frac{g}{\sqrt{2}} V_{tb} \left\{ \gamma^{\mu} \left[f_1^L P_L + f_1^R P_R \right] - \frac{i\,\sigma^{\mu\nu}}{M_W} (p_t - p_b)_{\nu} \left[f_2^L P_L + f_2^R P_R \right] \right\}$$

$f_1^L = \bar{f}_1^L = 1$ with the rest equal to 0 (pure V-A interaction)

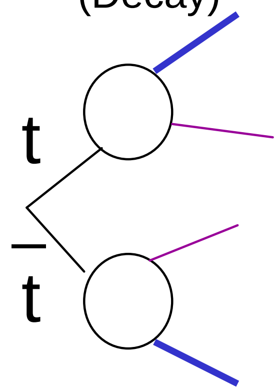
If $f_1^{L,R} - \bar{f}_1^{L,R} \neq 0$ *or* $f_2^{L,R} - \bar{f}_2^{R,L} \neq 0 \Rightarrow$ CP-violation

- Charged current interactions <u>define most of the top quark phenomenology</u>:

Single Top
(Production and Decay)



Top Pair
(Decay)

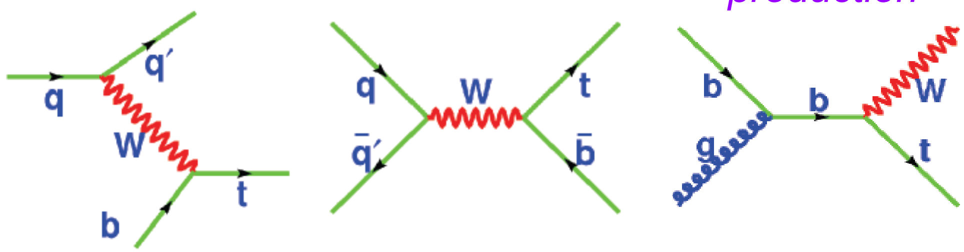


Top quark width
Single top quark production rate
B(t→Wb)
W helicity in top quark decays
Top quark polarization
Anomalous couplings
Spin correlations
Rare decays
…

Single Top Quark Production

- Main production mechanisms for (SM-like) single top production:

t-channel *s-channel* *associated production*



	t-channel	s-channel	associated production
Tevatron:	~1.98 pb	~0.88 pb	~0.09 pb
LHC :	~245 pb	~10 pb	~60 pb

- Experimental signature: similar to tt→lepton+jets but lower jet multiplicity.
- Dominant backgrounds: W+jets, tt

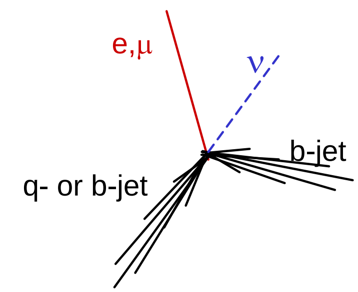
- <u>Motivation</u>:
  - Direct measurement of $|V_{tb}|$ ($\sigma \propto |V_{tb}|^2$)
  - Anomalous couplings in *tbW* vertex
  - s- and t-channels sensitive to different New Physics
  - Top spin physics (~100% polarized top quark)

Not discovered yet

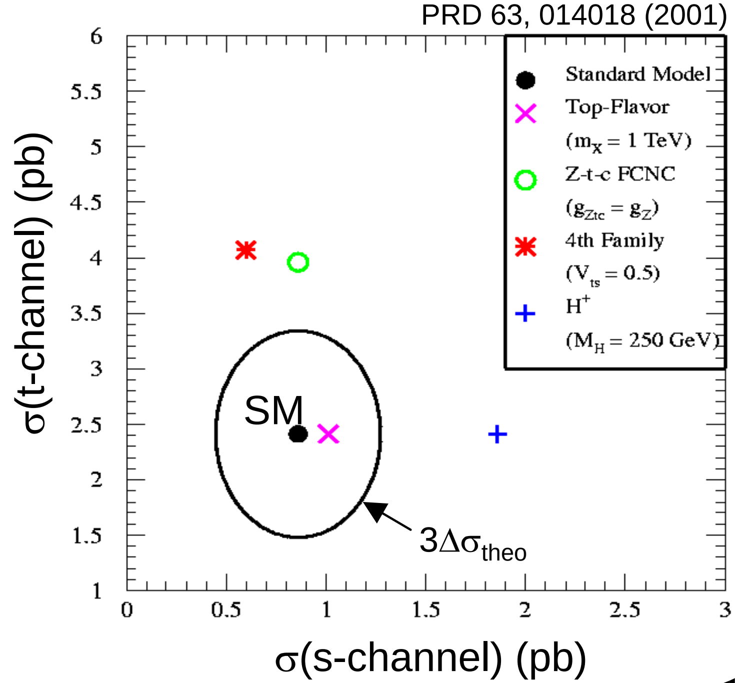
Run I upper limits (@ 95% CL):

CDF: $\sigma_s < 18$ pb, $\sigma_t < 13$ pb, $\sigma_{s+t} < 14$ pb

DØ: $\sigma_s < 17$ pb, $\sigma_t < 22$ pb



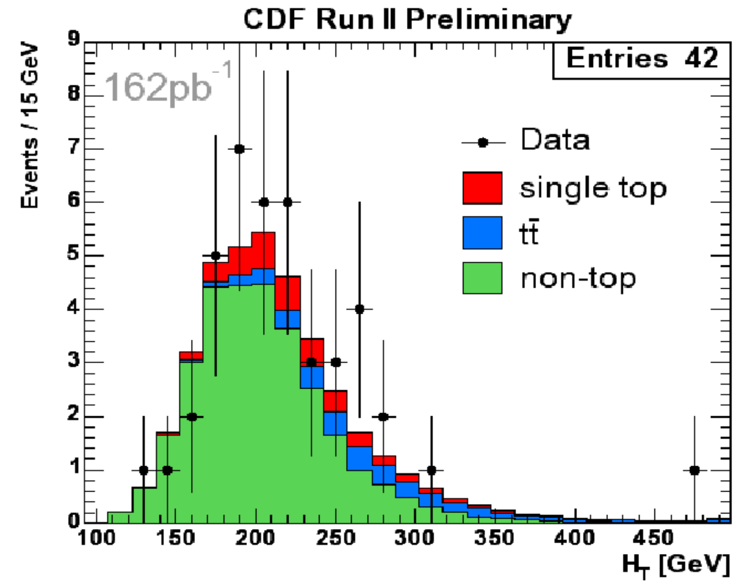
PRD 63, 014018 (2001)

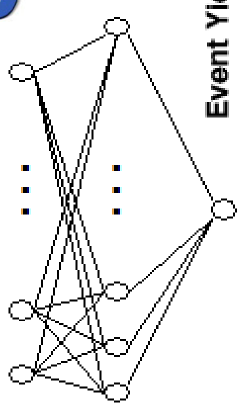


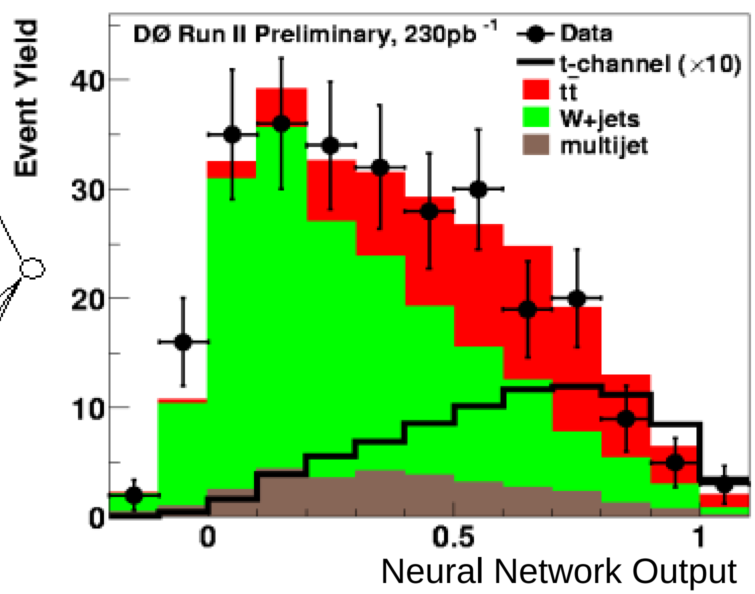
Single Top Quark Production

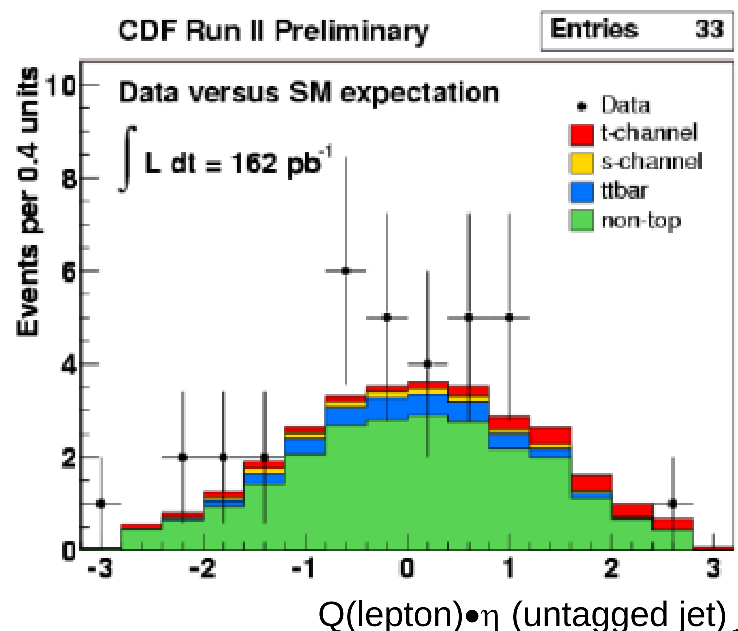
Strategy:

- Select b-tagged lepton+≥2jets candidate events
- Consider discriminant variables between single top and backgrounds:
  - Total event transverse energy (H_T)
  - Q(lepton)•η(untagged jet)
  - Top spin-related angular variables
  - ….
  - ⇒ Best discrimination achieved using multivariate techniques (e.g. Neural Networks, Likelihoods)
- Exploit shape information from discriminant variables to estimate upper limit on σ (Bayesian approach).









Single Top Quark Production: Summary

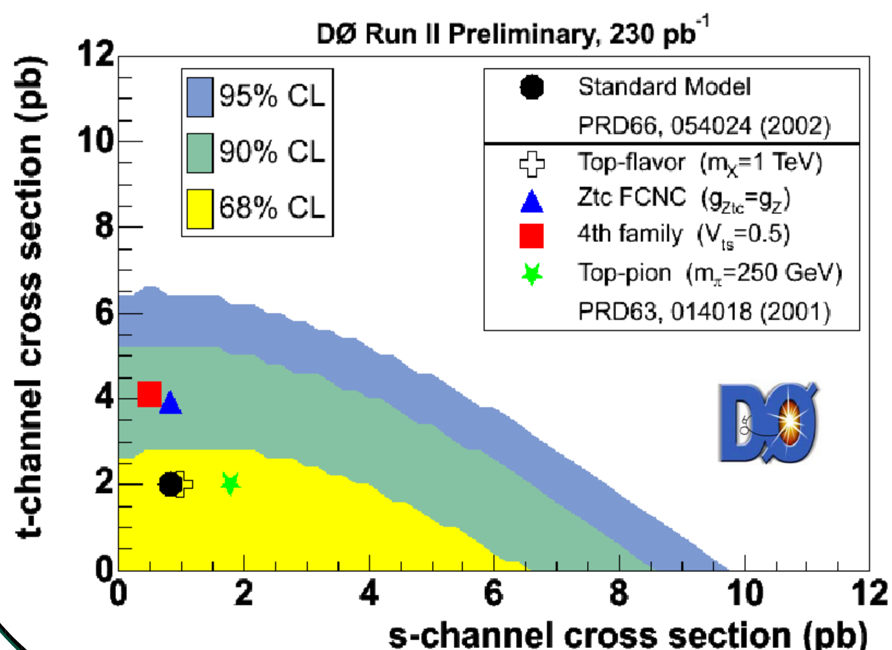
- Increasingly more sophisticated analyses have resulted in major improvements in the single top cross section limits. Analyses continue to be optimized.
- Possibility of a surprise around the corner (e.g. note excess in s-channel for both CDF and DØ).

Current analyses becoming sensitive to New Physics effects!

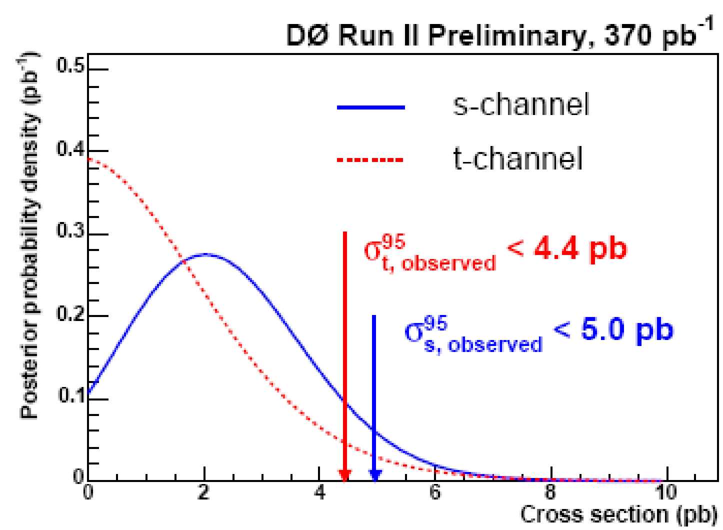
		σ_s (pb)	σ_t (pb)	σ_{s+t} (pb)
SM (NLO prediction)		0.88 ± 0.07	1.98 ± 0.21	~2.86
160 pb^{-1} CDF	95% CL upper limits Observed(expected)	13.6(12.1)	10.1(11.2)	17.8(13.6)
	MPV ± 68% CL	4.6 ± 3.8	$0.0^{+4.7}_{-0.0}$	$7.7^{+5.1}_{-4.9}$
230 pb^{-1} DØ	95% CL upper limits Observed(expected)	6.4(5.8)	5.0(4.5)	
	MPV ± 68% CL	$1.9^{+1.9}_{-1.6}$	$0.0^{+2.4}_{-0.0}$	
370 pb^{-1}	95% CL upper limits Observed(expected)	5.0(3.3)	4.4(4.3)	

World's best limits

muon channel data only



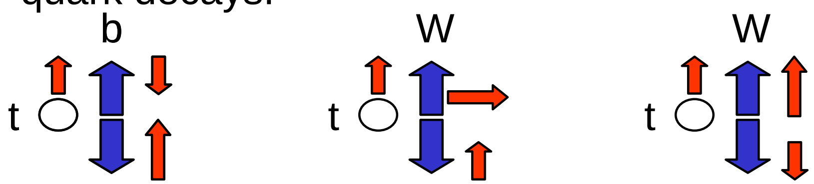
electron channel data only



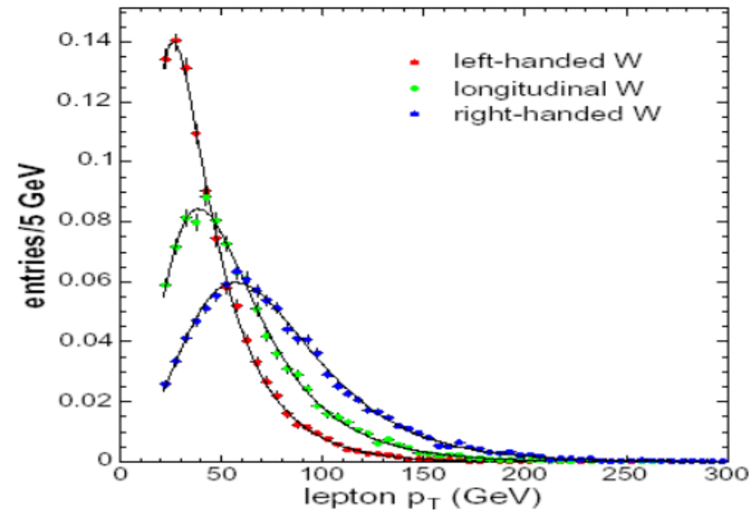
Tevatron projection for 4 fb^{-1} x 2 experiments: $S/\sqrt{B} \sim 5\sigma(3\sigma)$ in t-(s-)channel; $(\Delta|V_{tb}|/|V_{tb}|)_{stat}$~9%

W Helicity in Top Quark Decays

- Use tt events to study the Lorentz structure of the *tbW* interaction. Possible W helicity configurations in top quark decays:



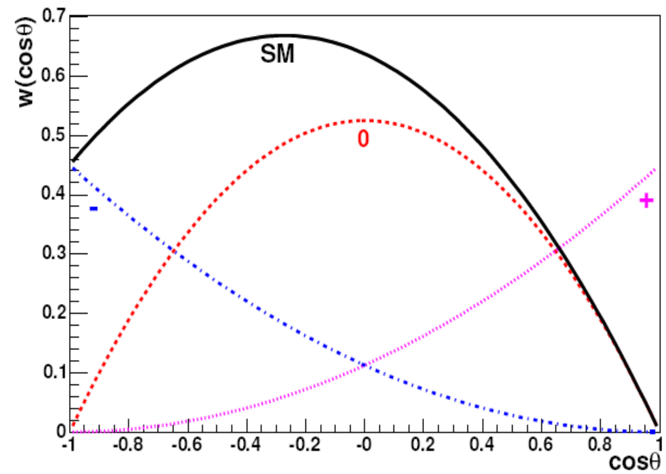
Left-handed W (λ_W=-1)   Longitudinal W (λ_W=0)   Right-handed W (λ_W=+1)



$$F_0 = \frac{\frac{1}{2}\left|\frac{m_t}{M_W} f_{1L} + f_{2R}\right|^2 + \frac{1}{2}\left|\frac{m_t}{M_W} f_{1R} + f_{2L}\right|^2}{\frac{1}{2}\left|\frac{m_t}{M_W} f_{1L} + f_{2R}\right|^2 + \frac{1}{2}\left|\frac{m_t}{M_W} f_{1R} + f_{2L}\right|^2 + \left|f_{1L} + \frac{m_t}{M_W} f_{2R}\right|^2 + \left|f_{1R} + \frac{m_t}{M_W} f_{2L}\right|^2}$$

Within the SM (V-A coupling), only two W helicity configurations are allowed:

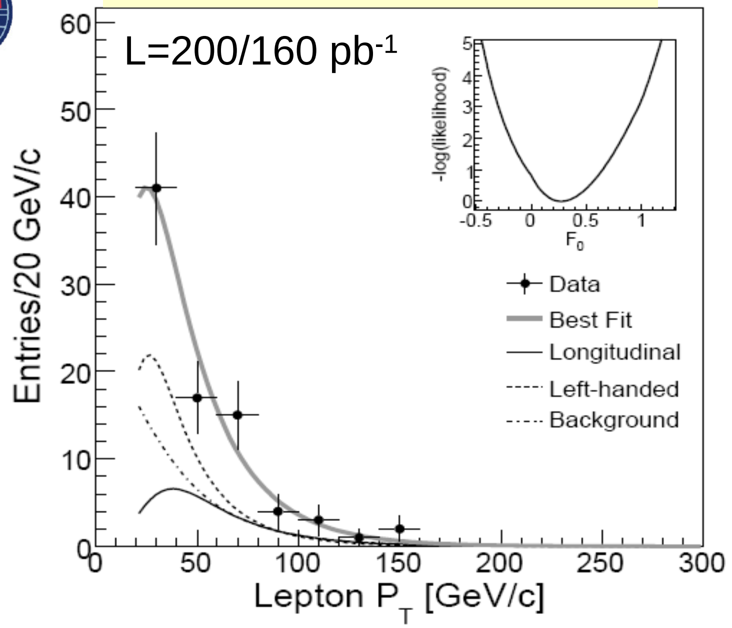
$$F_- \approx \frac{2M_W^2}{m_t^2 + 2M_W^2} = 0.30 \qquad F_0 \approx \frac{m_t^2}{m_t^2 + 2M_W^2} = 0.70 \qquad F_+ = 0$$



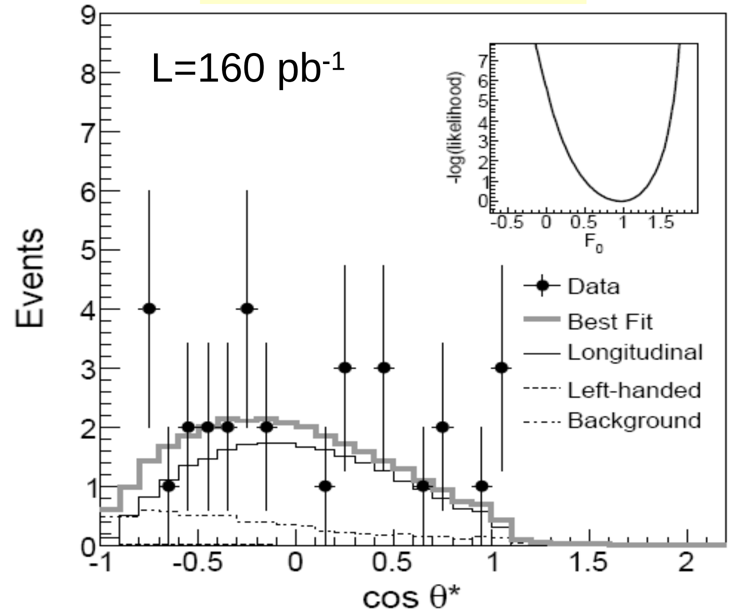
- Lepton kinematical distributions rather sensitive to W boson helicity:
  - Lepton p_T distribution in LAB frame
    ⇒ final states: lepton+jets, dileptons.
  - θ(lepton,W direction) distribution in W rest frame (explicit top reconstruction needed)
    ⇒ final states: lepton+jets only.

W Helicity in Top Quark Decays

Dilepton + Lepton+≥3 jets (b-tag)



Lepton+≥4 jets (b-tag)



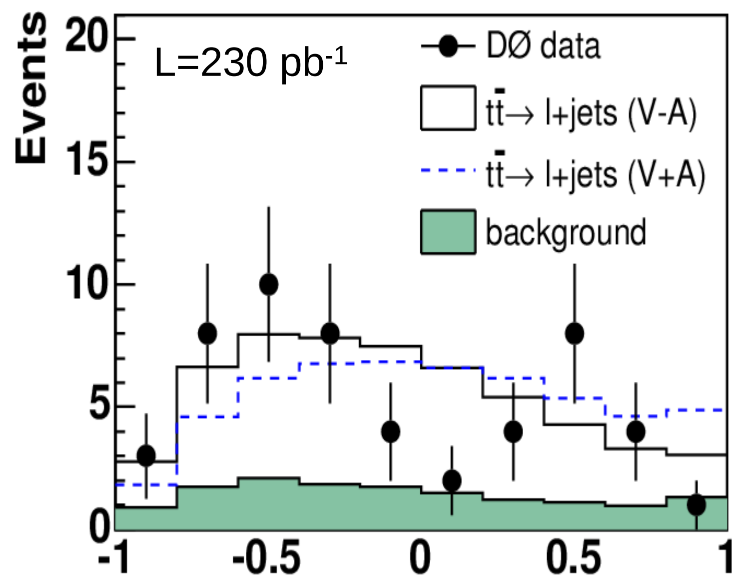
CDF/DØ Run II: combination of lepton p_T and $\cos\theta^*$ methods.

	Best Run I	Run II	
F_0	0.56 ± 0.31(D0)	$0.74^{+0.22}_{-0.34}$(CDF)	
F_+(95%CL)	< 0.18(CDF)	< 0.27(CDF)	< 0.25(D0)

Results consistent with the SM prediction: F_0=0.7, F_+=0

Projected per-experiment uncertainties:

Tevatron (4 fb⁻¹): ΔF_0~0.06, ΔF_+~0.03



PRD 72, 011104 (2005)

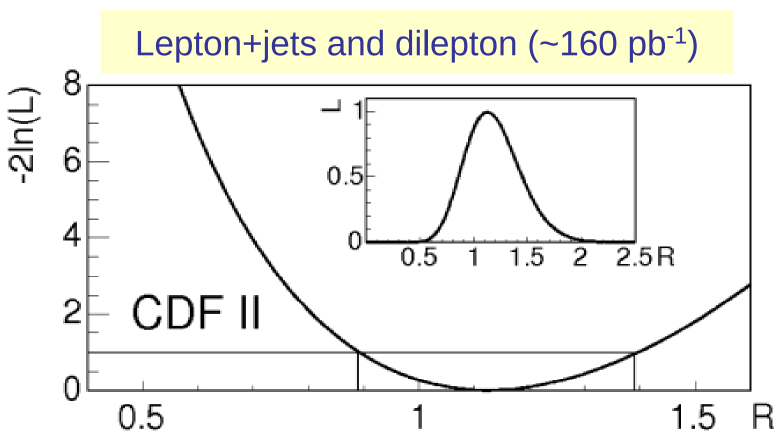
Measurement of B(t→Wb)/B(t→Wq)

- Within the SM, assuming unitarity of the CKM matrix, B(t→Wb)~1.
  An observation of a B(t→Wb) significantly different than unity would be a clear indication of new physics: non-SM top decay, non-SM background to top decay, fourth fermion generation,..
- B(t→Wb) can be accessed directly in single top production.
  Top decays give access to B(t→Wb)/B(t→Wq):

In the SM

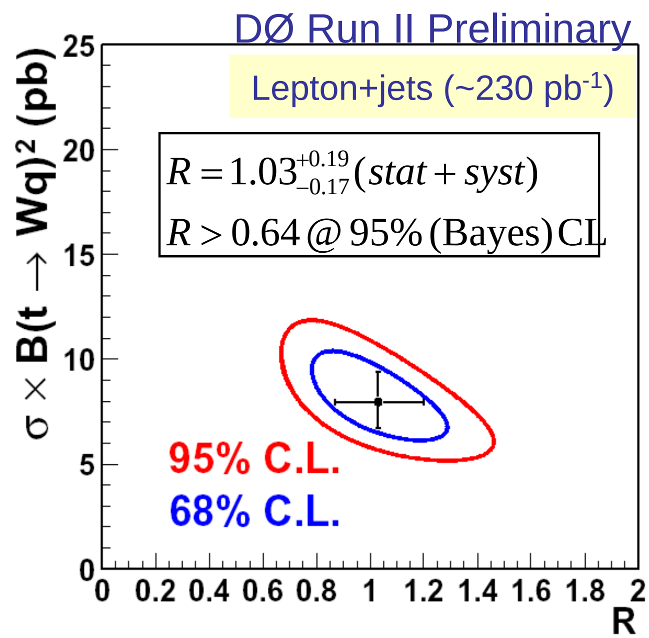
$$R = \frac{B(t \to Wb)}{B(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{ts}|^2 + |V_{td}|^2 + |V_{tb}|^2} = |V_{tb}|^2 \sim 0.998$$

- R can be measured by comparing the number of ttbar candidates with 0, 1 and 2 jets tagged.
  In the 0-tag bin, a discriminant variable exploiting the differences in event kinematics between ttbar and background is used.



$$R = 1.12^{+0.27}_{-0.23}(stat+syst)$$
$$R > 0.61 @ 95\% \, (F\&C) \, CL$$

PRL 95, 102002 (2005)



Results consistent with the SM prediction

Top Couplings to Gauge Bosons: FCNC

- Within the SM, neutral current interactions are flavor-diagonal at tree level.

  FCNC loop-induced and tiny: $B(t\to cg) \approx 10^{-10}$, $B(t\to c\gamma) \approx 10^{-12}$
  $B(t\to cZ) \approx 10^{-12}$, $B(t\to cH) \approx 10^{-7}$

  Can be significantly enhanced in models beyond the SM (~10^3-10^4).

  Observation would be a clear signal of New Physics!

- Search strategies:

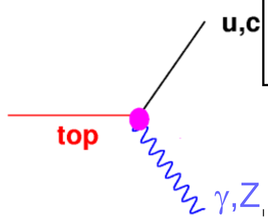
$p\bar{p}$ collisions

CDF Run I (@ 95% CL):
$B(t\to c\gamma)+B(t\to u\gamma)<3.2\%$
$B(t\to cZ)+B(t\to uZ)<33\%$

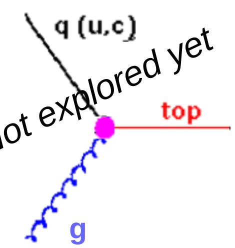
Projection:

2 fb^{-1} (@ 95% CL):
$B(t\to q\gamma)<0.3\%$
$B(t\to qZ)<2\%$

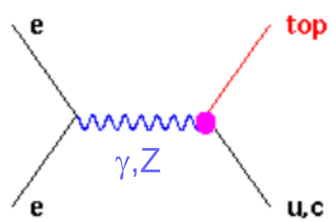
Anomalous top decays in tt events



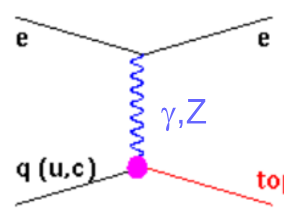
Anomalous single top production

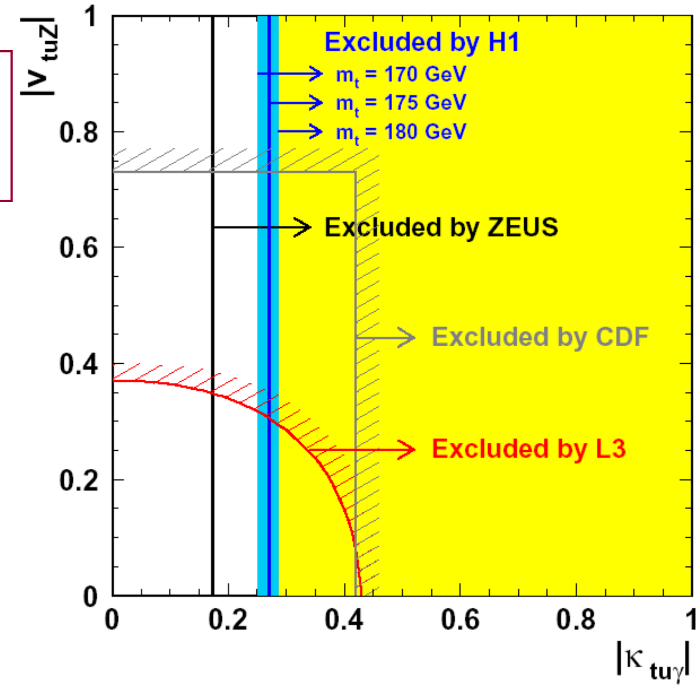


e^+e^- collisions



$e^{\pm}p$ collisions





- H1: ~2.2σ excess consistent with FCNC single top production in the leptonic channels: 5 events observed; 1.31 ± 0.22 expected

  No excess observed in the hadronic channel.

  Combination of all channels (L= 118.3 pb^{-1}):

$$\sigma = 0.29^{+0.15}_{-0.14}\,pb \text{ at } \sqrt{s} = 319\text{ GeV}$$

$$|\kappa_{tu\gamma}| = 0.20^{+0.05}_{-0.06}$$

Eur. Phys. J. C 33, 9 (2004)

HERA-II and Tevatron will confirm or exclude

New Particles in Top Production

Many models of New Physics predict new particles preferentially coupled to the the top quark:

- Vector gauge bosons: e.g $qq \rightarrow Z' \rightarrow tt$ (Topcolor)
- Charged scalars: e.g. $t \rightarrow H^+b$ (generic 2HDMs)
- Neutral scalars: e.g $gg \rightarrow \eta_T \rightarrow tt$ (Technicolor)
- Exotic Quarks: e.g $qq \rightarrow W^* \rightarrow tb'$ (E_6 GUT)

Very important to perform model-independent searches:

- Deviations in kinematic properties
- Comparison of cross section measurements in different channels,
- …

Top p_T spectrum measurement

- Many exotic models predict sizeable enhancements in $d\sigma_{tt}/dp_{T,t}$ for $p_{T,t}$>200 GeV.
- CDF Run I:
  - lepton+≥4jets channel and 3-constraint kinematic fit; measured $p_{T,t}$ extracted from hadronic top branch.
  - $(1/\sigma_{tt})(d\sigma_{tt}/dp_{T,t})$ in four bins of true $p_{T,t}$ within the [0,300] GeV range, obtained by an unfolding procedure and corrected by acceptance effects.

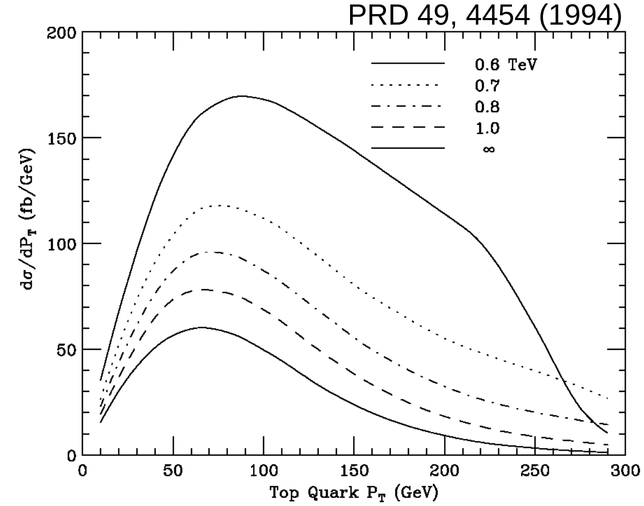
    ⇒ measurement consistent with the SM but statistically limited;

    ⇒ model-independent measurement which can be compared to different models with the higher Run II statistics.

PRL 87, 102001 (2001)

Gauge color-octet vector resonance model

PRD 49, 4454 (1994)

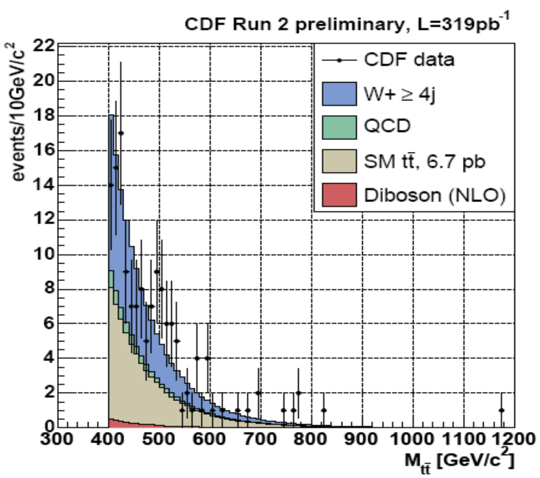


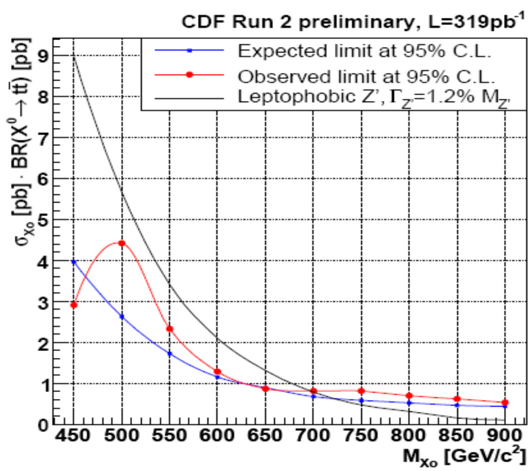
p_T Bin	Parameter	Measurement	Standard Model Expectation
$0 \leq p_T < 75$ GeV/c	R_1	$0.21^{+0.22}_{-0.21}(\text{stat})^{+0.10}_{-0.08}(\text{syst})$	0.41
$75 \leq p_T < 150$ GeV/c	R_2	$0.45^{+0.23}_{-0.23}(\text{stat})^{+0.04}_{-0.07}(\text{syst})$	0.43
$150 \leq p_T < 225$ GeV/c	R_3	$0.34^{+0.14}_{-0.12}(\text{stat})^{+0.07}_{-0.05}(\text{syst})$	0.13
$225 \leq p_T < 300$ GeV/c	R_4	$0.000^{+0.031}_{-0.000}(\text{stat})^{+0.024}_{-0.000}(\text{syst})$	0.025
$0 \leq p_T < 150$ GeV/c	$R_1 + R_2$	$0.66^{+0.17}_{-0.17}(\text{stat})^{+0.07}_{-0.07}(\text{syst})$	0.84

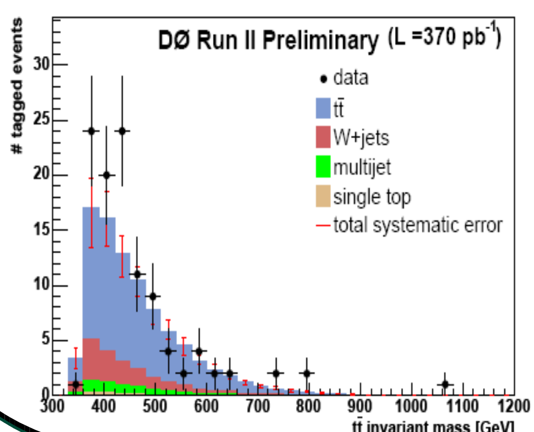
New Particles in Top Production

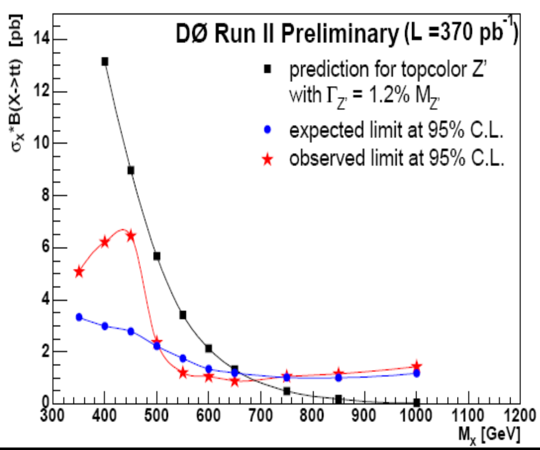
Search for a narrow resonance $X \to tt$

- Selection of lepton+≥4jets candidate events (DØ: require ≥1 b-tag)
- Reconstruction of tt invariant mass under the tt production hypothesis (DØ: constrained kinematic fitting, CDF: usage of LO matrix element for tt)
- In the absence of a clear signal, derive (model-indep) limits on $\sigma_X B(X \to tt)$
- Derive limits on M_X within a particular model









- Tantalizing, although not statistically significant, excesses corresponding to M_X~500 GeV (CDF) and ~450 GeV (DØ) are currently observed.
- Significant improvement in limits on $M_{Z'}$ for a leptophobic Z' with $\Gamma_{Z'} = 1.2\% M_{Z'}$ in topcolor-assisted technicolor:

	Run I	Run II
DØ:	$M_{Z'}$>560 GeV	>680 GeV @ 95% CL
CDF:	$M_{Z'}$>480 GeV	>700 GeV @ 95% CL

- Both collaborations are eagerly analyzing more data. Results with 1 fb^{-1} expected by Summer'06.

New Particles in Top Decay

- Many extensions of the SM include two Higgs doublets. EWSB produces five Higgs bosons: h^0, H^0, A^0 and $H^\pm$.
- If $M_{H\pm}<m_t-m_b$ then $t\rightarrow H^+b$ competes with $t\rightarrow W^+b$ and results in $B(t\rightarrow Wb)<1$.

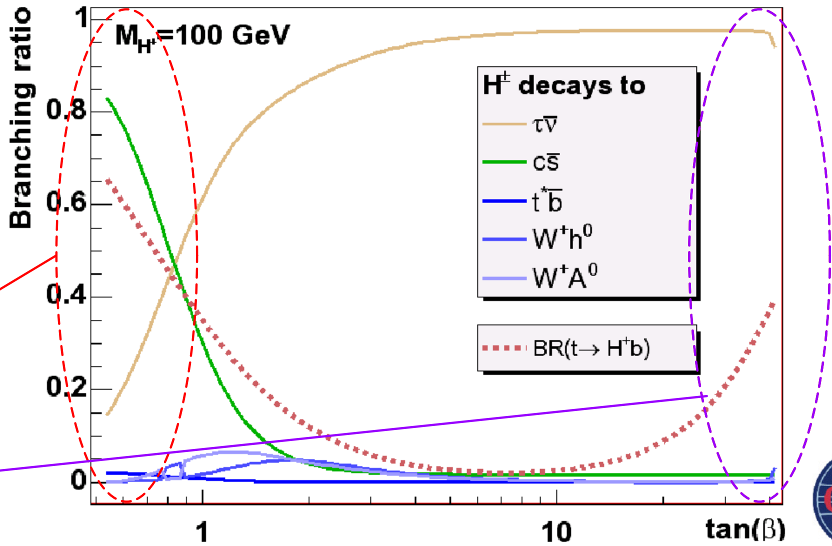
  Sizeable $B(t\rightarrow H^+b)$ expected at

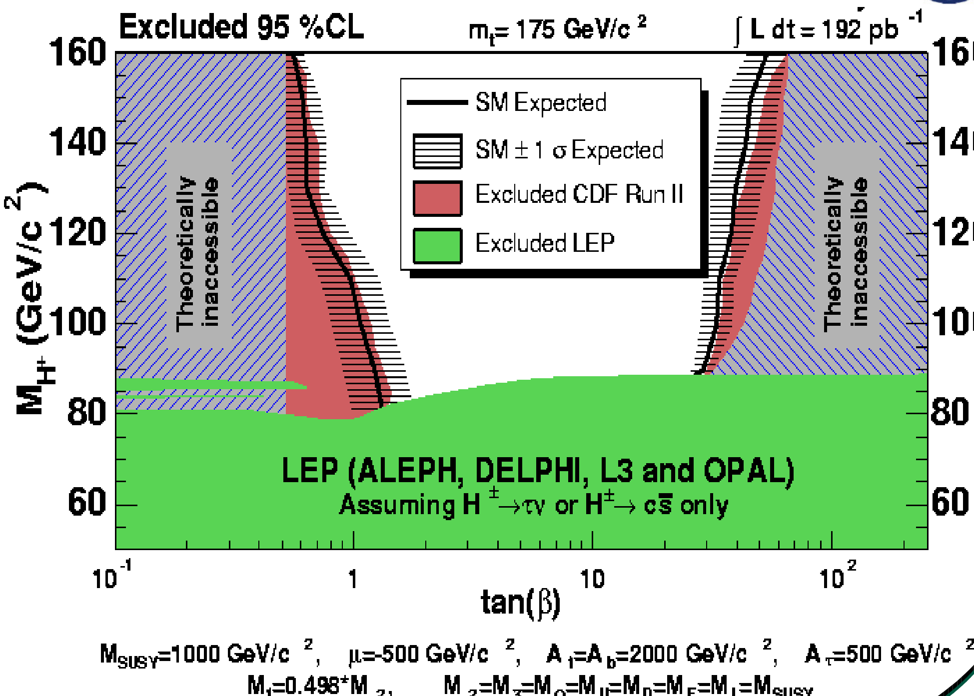
  low $\tan\beta$: $H^\pm\rightarrow cs$, Wbb dominates

  high $\tan\beta$: $H^\pm\rightarrow\tau\nu$ dominates

  $\Rightarrow$ affect differently σ_{tt} measurements in various channels.
- Consider σ_{tt} measurements in dileptons, lepton+jets and lepton+tau channels.

  Assume SM σ_{tt} and allow for a contamination from $t\rightarrow H^+b$ decays. Perform simultaneous fit to the observation in all channels and determine exclusion region in ($\tan\beta$, $M_{H\pm}$) within the MSSM framework.
- Exclusion region in high $\tan\beta$ region dependent on assumed model parameters.





hep-ex/0510065

New Physics Contamination in Top Samples

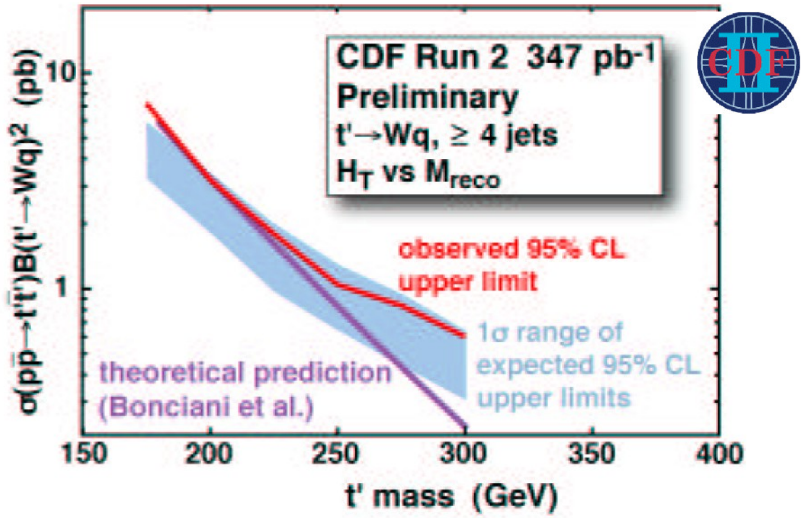
- Top events are a major background to New Physics processes with similar signature
  ⇒ top samples could contain an admixture of exotic processes.
- Important to perform model-independent searches

- *Run I dilepton anomaly (CDF)*
  - kinematic anomaly: excess of events with high MET and lepton p_T.
    Consistent e.g. with $\tilde{q}\bar{\tilde{q}}$ pair production with
    $\tilde{q} \to q\tilde{\chi}, \tilde{\chi} \to \nu\tilde{\ell}, \tilde{\ell} \to \ell\tilde{\chi}_1^0$
    R.M. Barnett and L.J. Hall, PRL 77, 3506 (1996)
  - flavor anomaly: excess of events in eμ channel
- CDF Run II: model-independent search for subsamples with non-SM kinematics yields overall agreement ~1.0-4.5% level. PRL 95, 022001 (2005)
- Flavor anomaly persists, but not statistically significant.

(*) Assuming σ_{tt}=6.7 pb		ee+μμ	eμ
CDF Run II (~200 pb^{-1})	Expected (*)	3.9±0.7	4.3±0.8
	Observed	4	9
DØ Run II (~370 pb^{-1})	Expected (*)	8.0±0.6	15.3±2.6
	Observed	7	21
CDF+DØ Run II	Expected (*)	11.9±0.9	19.6±2.7
	Observed	11	30

More data being analyzed!

- *Search for t't' production (t' →Wq)*
  - Search for a new quark which is pair-produced strongly, has $m_{t'}>m_t$ and dominant t'→Wq.
  - Consider lepton+≥4jets channel and obtain reconstructed t' mass (M_{reco}) from a 3-constraint kinematic fit.
  - Perform binned likelihood fit in (H_T,M_{reco}) plane and set limits on $\sigma_{t't'}$ using a Bayesian method.



  - Expected limit: $m_{t'}$<250 GeV excluded at 95% CL.
  - Observed limit: 196 GeV<$m_{t'}$<207 GeV excluded at 95% CL if m_t=175 GeV.

Conclusions

- Till the beginning of the LHC, the Tevatron will remain the world's only top quark factory.

- A comprehensive program on top quark measurements is underway at the Tevatron Run II. The excellent performance of the accelerator and CDF and DØ detectors opens a new era of precision measurements in top physics, required to unravel the true nature of the top quark and possibly shed light on the EWSB mechanism.

- This is a largely unexplored territory, and thus it has the potential to reveal signs of New Physics preferentially coupled to the top quark. A number of tantalizing (yet not statistically significant) "anomalies" have been presented in this talk, which should be clarified in the very near future.

- Results reported here correspond to a maximum of 370 pb^{-1} of data per experiment. Expect first preliminary results with ~1 fb^{-1} by Winter'06 Conferences and 4-8 fb^{-1} by the end of 2009.

$\Rightarrow$ The Tevatron will continue to deliver highly competitive top physics results till the end of the decade.

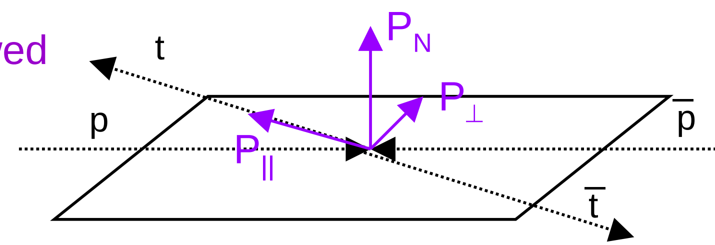
Techniques developed at the Tevatron to control systematic uncertainties to the percent level will be an invaluable experience for the LHC.

Backup

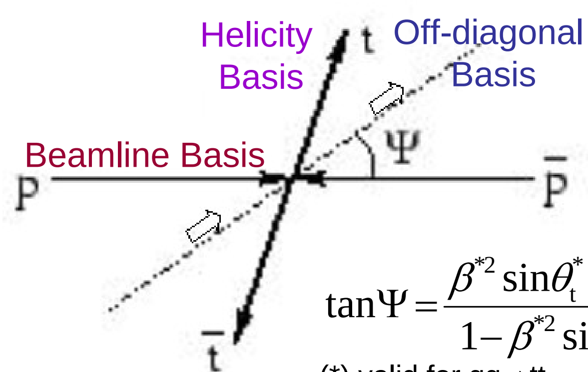
Spin Issues in Top Production

Strong interaction: Top Pair Production

- C and P conserving ➔ only transverse polarization allowed
  $P_{\parallel} = P_{\perp} = 0$
  P_N ~ few % in SM from QCD effects at the loop level



Net polarization of top quarks very small: $N(t_{\uparrow}) = N(t_{\downarrow})$...
BUT large asymmetry, $C = \frac{N_{\parallel} - N_X}{N_{\parallel} + N_X}$, if proper spin quantization axes chosen:



$$\tan\Psi = \frac{\beta^{*2}\sin\theta_t^*\cos\theta_t^*}{1-\beta^{*2}\sin^2\theta_t^*}$$

(*) valid for $q\bar{q} \to t\bar{t}$

	Tevatron	LHC	ILC (500 GeV)
P_X	90% / 70% / 90%	34%	95% / 79% / 99%
C	-0.80 / -0.39 / -0.81	0.32	-0.91 / -0.58 / -0.98

- β=0 (at threshold) ➔ Ψ= 0 (Beamline Basis)
- β=1 (ultra-relativistic) ➔ $\Psi=\theta_t^*$ (Helicity Basis)
- any β (at Tevatron <β>~0.6) (Off-diagonal Basis)

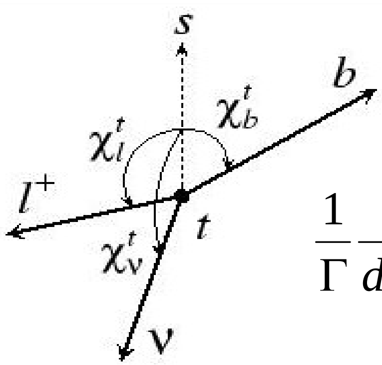
Electroweak interaction:

- Single Top Production: V-A weak interaction ➔ $P_{\parallel}\uparrow\uparrow$
- Top Pair Production in e^+e^-: the EW interaction leads to sizeable $P_{\parallel}$ and $P_{\perp}$ at tree level.
  Also, can use beam polarization to produce samples of highly polarized top quarks.

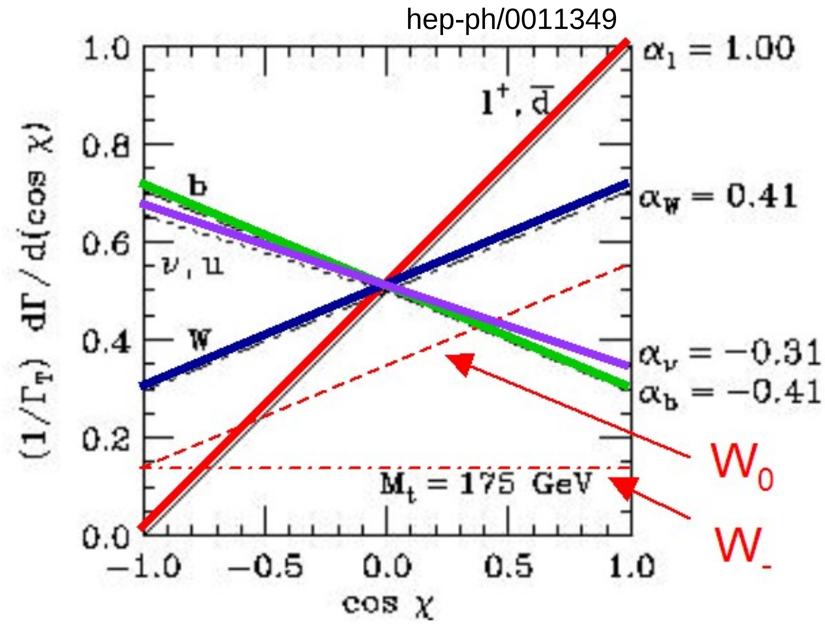
Spin Issues in Top Decay

- Decays like a "free quark"

  ➔ spin efficiently transmitted to the final state



$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\chi_i^t} = \frac{1}{2}\left(1+\alpha_i\cos\chi_i^t\right)$$



- The production mechanism of t t correlates the spin

  The t($\bar{t}$) decay products are strongly correlated with the t($\bar{t}$) spin

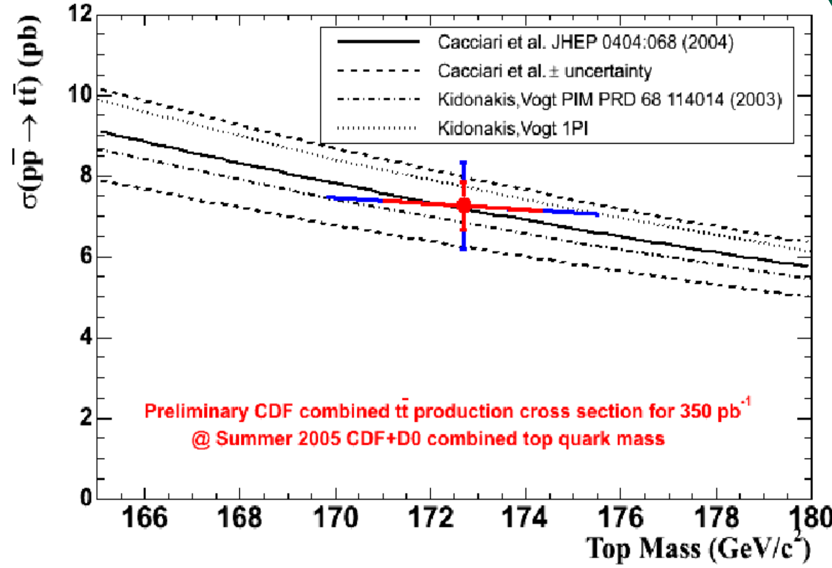
  ➔ Angular correlations between t and t decay products

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\chi_i^t\, d\cos\chi_j^{\bar{t}}} = \frac{1}{4}\left[1+\frac{N_\parallel - N_X}{N_\parallel + N_X}\alpha_i\alpha_j\cos\chi_i^t\cos\chi_j^{\bar{t}}\right]$$

Use polarization properties of the top quark as additional observables for testing the SM and to probe for New Physics

Top Couplings to Gauge Bosons: g

- The g-t-t vertex can be affected by strong dipole moments related to New Physics (in particular in some strongly-coupled EWSB scenarios).
- tt production is a direct test of the top coupling to gluons. Must test, not only the effective coupling strength (total rate), but also the presence of a more complicated Lorentz structure.
- In order to disentangle the effects of the different operators, observables sensitive to different combinations need to be used: cross-section, spin correlations, tt invariant mass, etc



- Net polarization of top quark in pair production very small: $N(t_\uparrow)=N(t_\downarrow)$ but large asymmetry between like- and unlike-spin configurations if proper spin quantization axes are chosen:

$$\frac{N_{\parallel} - N_X}{N_{\parallel} + N_X} \sim -0.8 \quad \text{(off-diagonal basis @ NLO)}$$

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_i^t \, d\cos\theta_j^{\bar{t}}} = \frac{1}{4}\left[1 + \underbrace{\frac{N_{\parallel} - N_X}{N_{\parallel} + N_X}\alpha_i\alpha_j}_{\kappa\sim+0.8\ \text{(dilepton channel)}} \cos\theta_i^t \cos\theta_j^{\bar{t}}\right]$$

$\Rightarrow$ angular correlation between top and anti-top decay products

DØ Run II dileptons:
$\kappa=2.3\pm2.5$, $\kappa>-0.25$ @ 68% CL

CDF Run II sensitivity study (dileptons):
340 pb^{-1}: $N^{exp}=19.2$, $\Delta\kappa = 1.6$
2 fb^{-1}: $N^{exp}=113.0$, $\Delta\kappa = 0.6$