Top Quark Studies at the Tevatron

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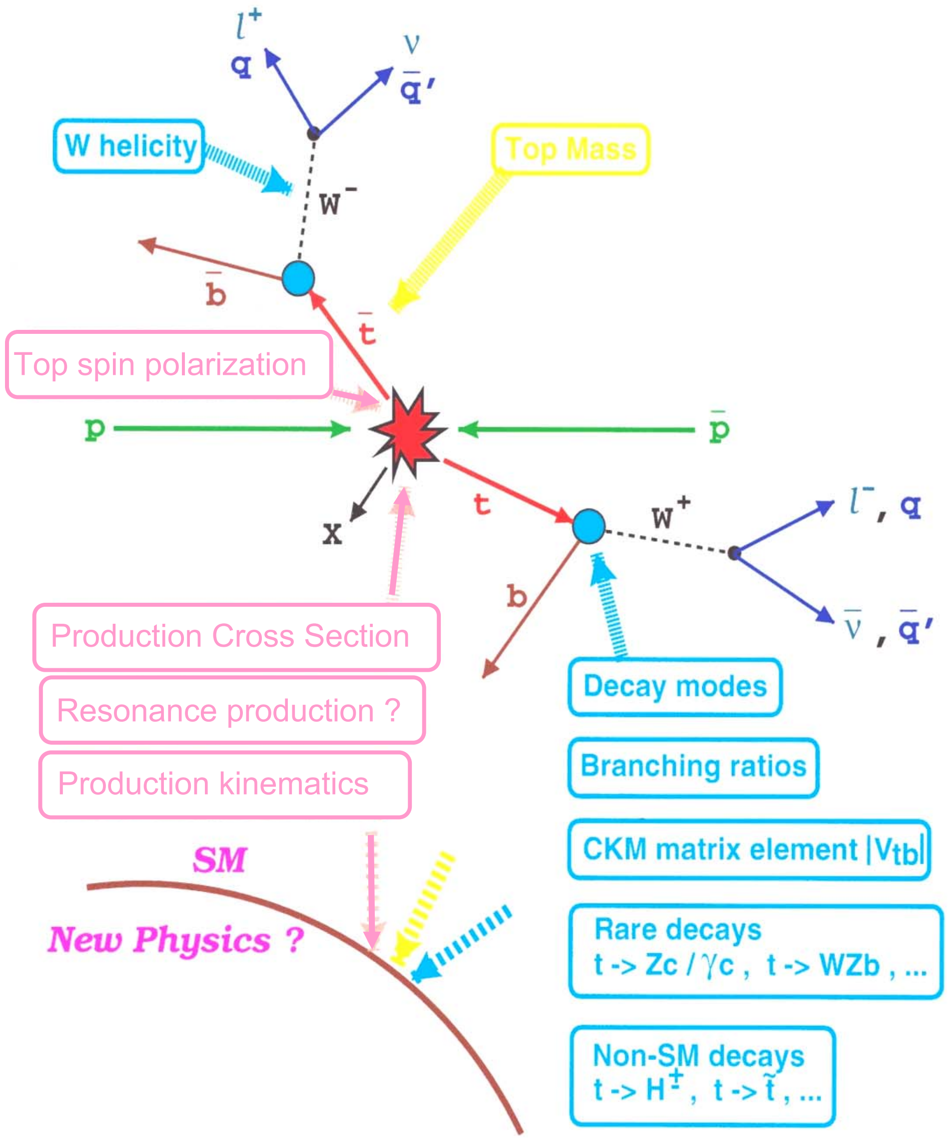
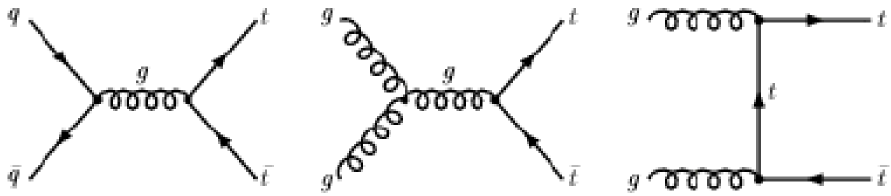
Physics of the Top Quark

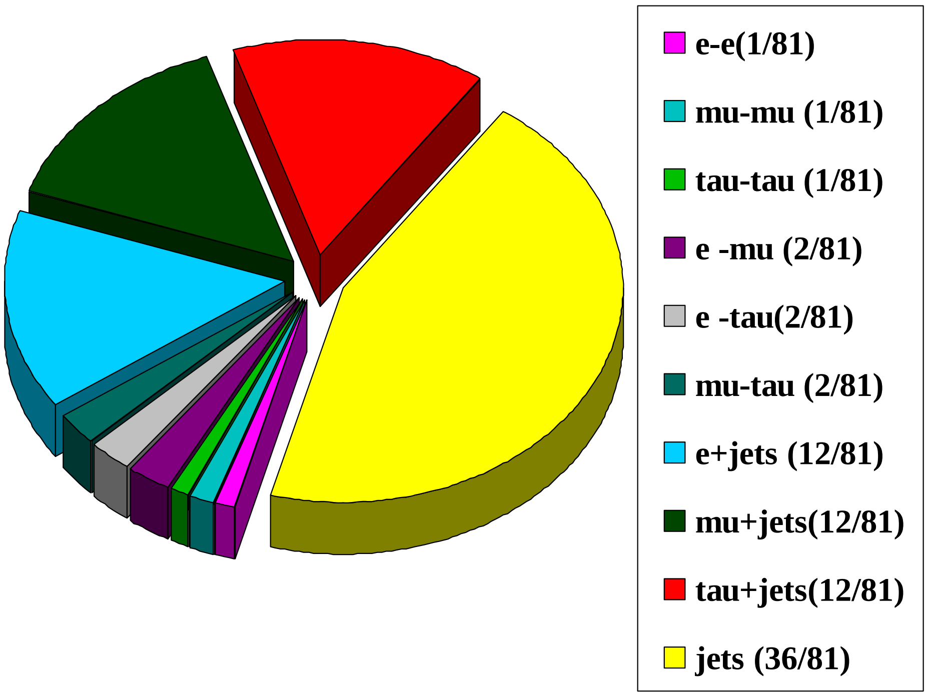
- Main question: is top quark adequately described by the Standard Model?
- Resonant production, non-SM decays?
- Background for “beyond the SM” processes: exotics, SUSY, etc.



$t\bar{t}$ Production and Decay in the SM

- At Tevatron, top quarks are produced predominantly in pairs (85% $q\bar{q}$ annihilation, 15% gluon fusion at 1.96 TeV)
- Top quark decays into Wb in ~99.9% of the cases (SM). Observed $t\bar{t}$ final states are classified according to subsequent decays of the W





$t\bar{t}$ Signatures

- Main signatures:
  - High p_T leptons and/or jets
  - Missing energy due to escaping neutrinos
  - Two b jets in the final state
  - Production near threshold – spherical topology
- Event selection:
  - High P_T lepton trigger or multijet trigger
  - Well-identified lepton with P_T > 20 GeV/c, jets with E_T > 20 GeV consistent with the final state, missing E_T > 20 GeV
  - b jet identification (by secondary vertex or soft lepton tag)
  - Additional kinematic cuts can be used to enhance the signal fraction
- Typical S/B after selection:
  - Dilepton: 3:1 (practically pure if vertex b tag is also required)
  - Lepton+jets (with b tag): 3:1
  - All hadronic (with b tag): 1:5

$t\bar{t}$ Cross Section Measurement

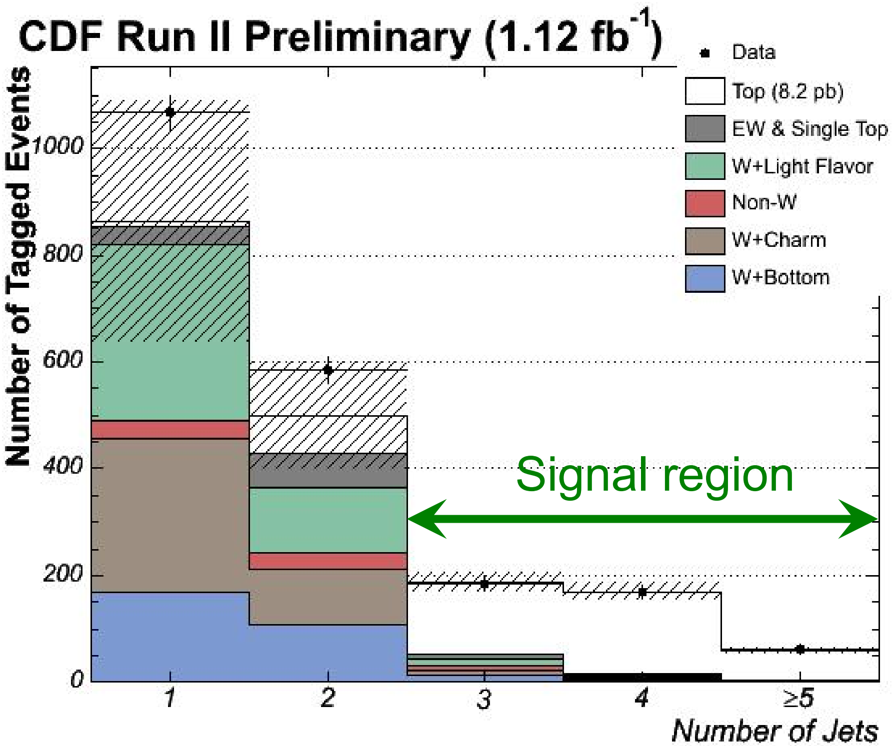
- Tests SM QCD calculations
- Sensitive to new physics (e.g., resonant $t\bar{t}$ production, production via scalar top quarks, *etc*.)
- Defines the event sample for measurement of other top properties
- Most recent theoretical calculations (using CTEQ6.5 PDFs and M_{top} = 171 GeV/c^2):
  - Approx. NNLO: Moch & Uwer, arXiv:0804.1476

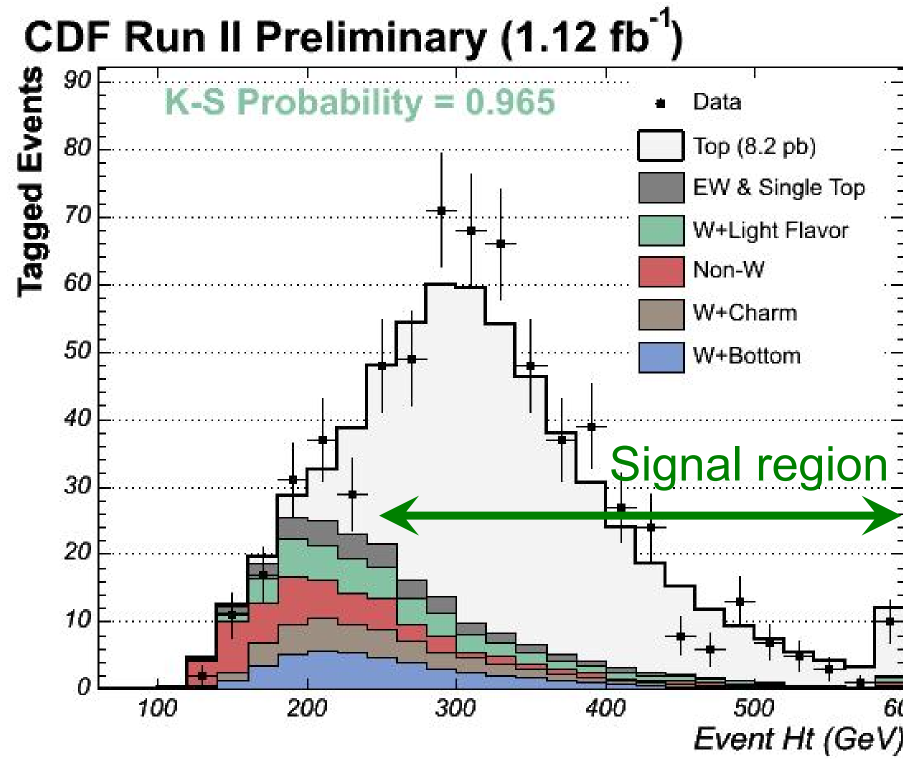
$$\sigma = 7.93\ ^{+0.06\ (1.0\%)}_{-0.28\ (3.5\%)}\ \text{(scales)}\ ^{+0.44\ (5.5\%)}_{-0.45\ (5.5\%)}\ \text{(PDFs) pb}$$

  - NLO + NLL resummed: Cacciari *et al*., arXiv:0804.2800

$$\sigma = 7.61\ ^{+0.38\ (5.1\%)}_{-0.80\ (10.9\%)}\ \text{(scales)}\ ^{+0.49\ (6.6\%)}_{-0.34\ (4.6\%)}\ \text{(PDFs) pb}$$

L+Jets $t\bar{t}$ Cross Section with b Tag: CDF





H_T>250 GeV
Missing E_T>30 GeV
≥1 tight tag

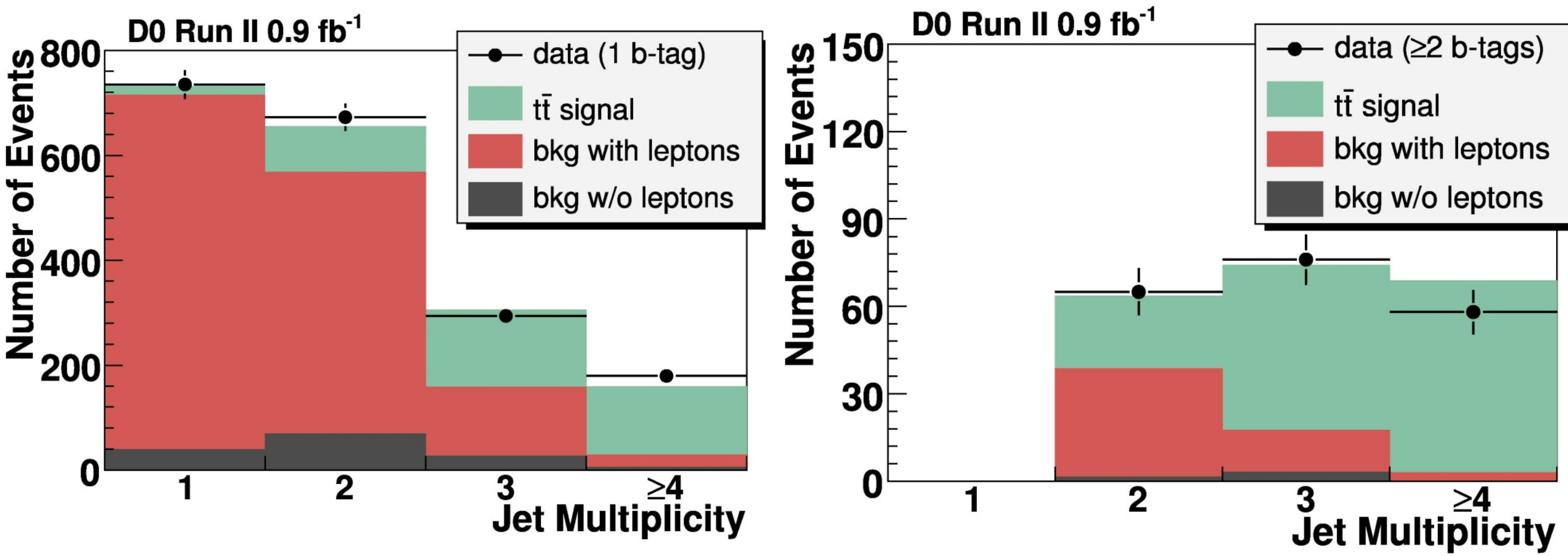
Counting experiment: $\sigma_{t\bar{t}} = \frac{N_{obs} - N_{bkg}}{(\epsilon_{tag} * SF)\left(\epsilon_{pretag} \int \mathcal{L}dt\right)}$

Signal region: 416 tags, 75±15 bg events

σ = 8.2 ± 0.5 (stat) ± 0.8 (sys) ± 0.5 (lumi) pb

L+Jets $t\bar{t}$ Cross Section: D0

- Two complementary methods: with b-tag and with "likelihood discriminant"
  - Different trade-offs between systematic and statistical uncertainties



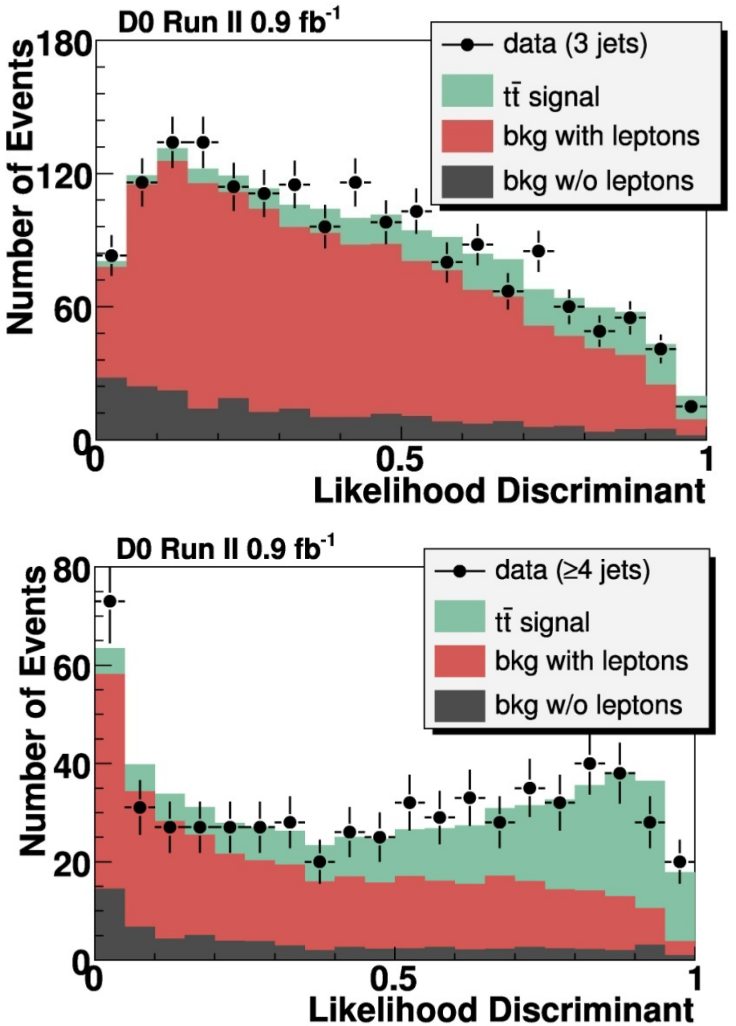
$\sigma = 8.1 \pm 0.5\ (\text{stat}) \pm 0.7\ (\text{sys}) \pm 0.5\ (\text{lumi})$ pb

L+Jets with Likelihood Discriminant: D0

- Use several kinematic variables to distinguish signal from background (sphericity, aplanarity, H_T, *etc.*)
- Construct the likelihood ratio discriminant ignoring variable correlations:

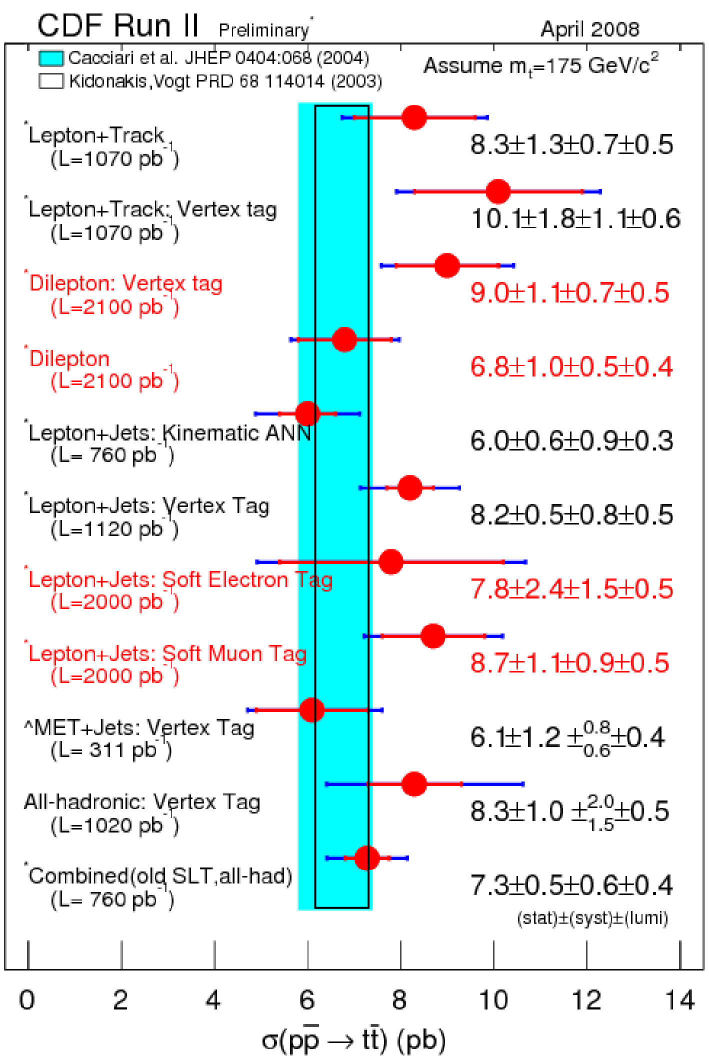
$$L = \frac{\prod_i S_i}{\prod_i S_i + \prod_i B_i}$$

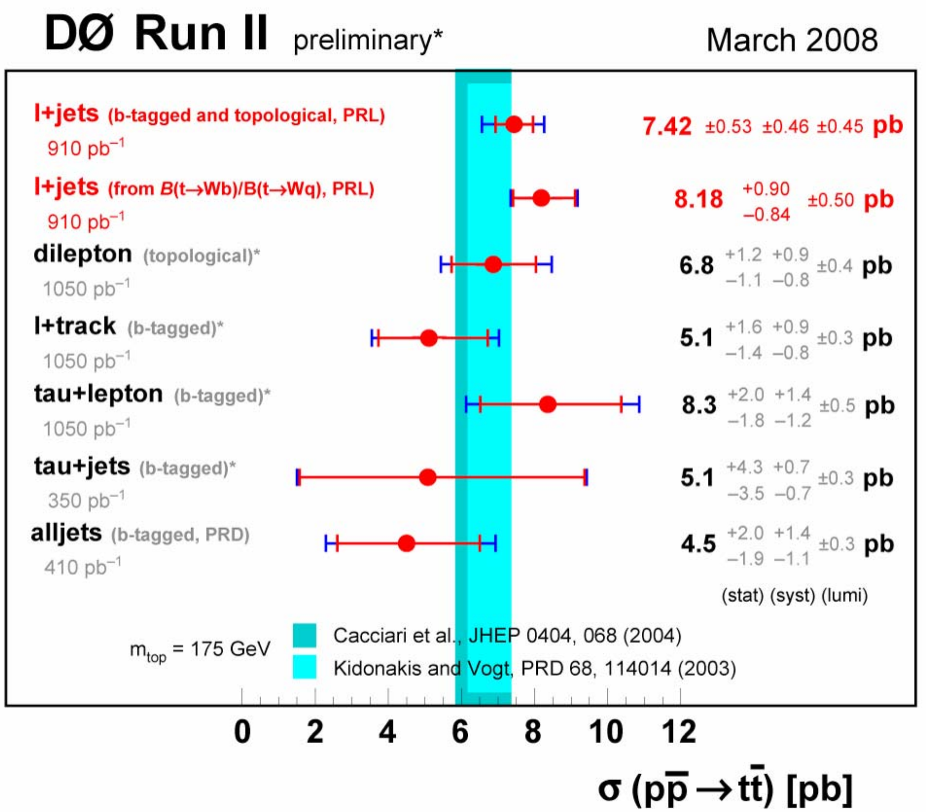
- The shape of the discriminant distribution is sensitive to $\sigma_{t\bar{t}}$



σ = 6.6 ± 0.8 (stat) ± 0.4 (sys) ± 0.4 (lumi) pb

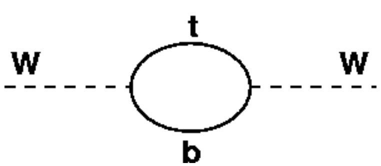
$t\bar{t}$ Cross Section Measurement Summary

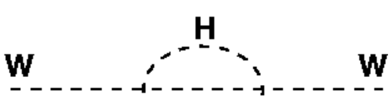




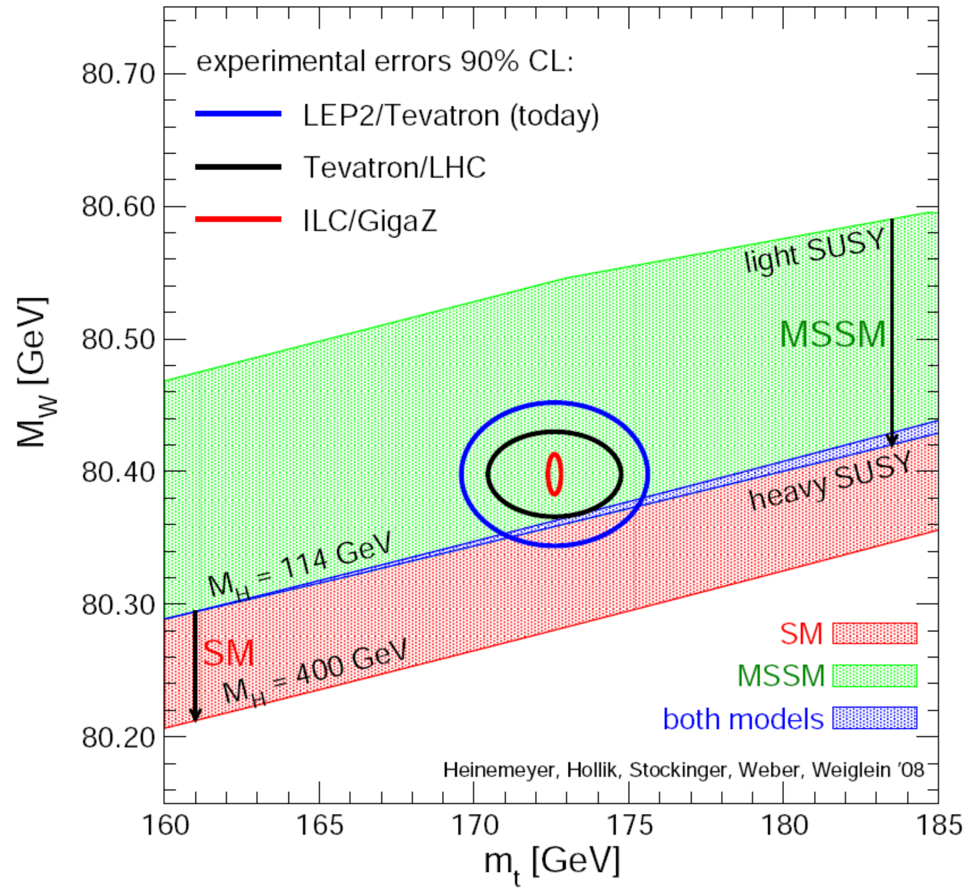
Top Quark Mass

- Fundamental parameter of the SM
- Enters into a variety of electroweak calculations at one loop level
- Example: W mass receives quantum corrections proportional to M_t^2 and $\log(M_H)$





- Highly correlated with M_H in the precision SM fit



Top Mass Measurements

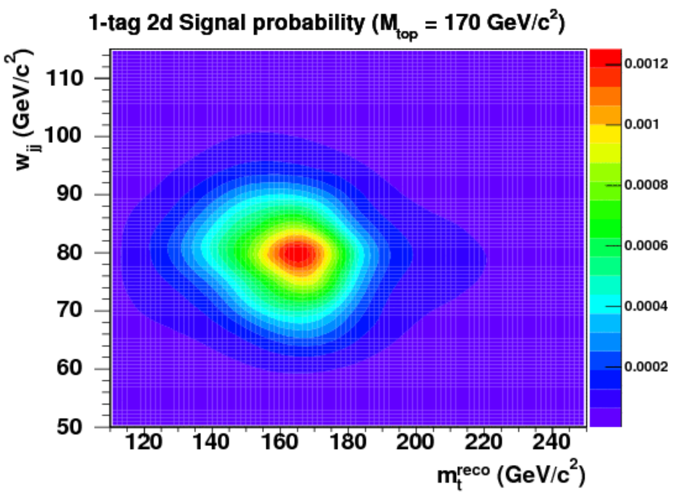
- A variety of measurement methods can be constructed: one can look at any observable sensitive to top mass
- Lepton+jets channel works best:
  - Optimal compromise between available statistics and background contamination
  - Allows for calibrating the calorimeter jet energy scale with W mass
- Precision measurement already: systematic uncertainty is larger than the statistical uncertainty
- Two most sensitive techniques: “template” method and “matrix element” method

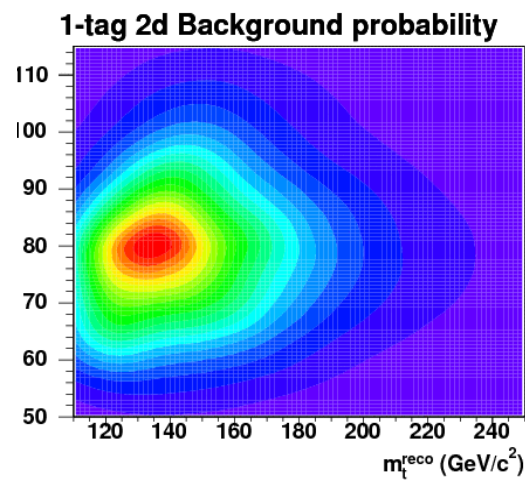
Template Top Mass Analysis: CDF

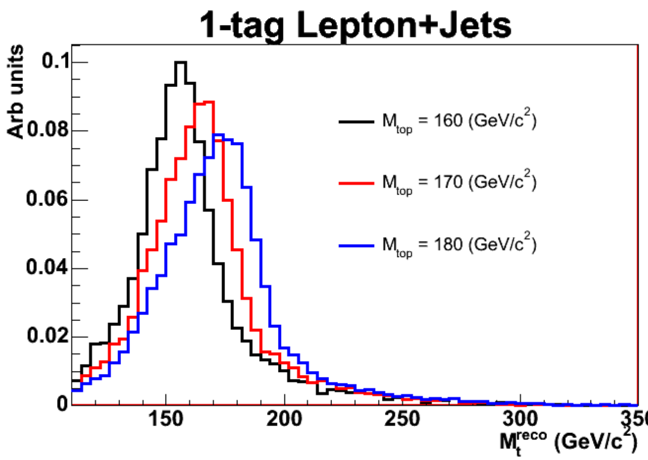
- Select best jet-to-parton assignments and m_t^{reco} by minimizing

$$\chi^2 = \Sigma_{i=\ell,4jets} \frac{(p_T^{i,fit} - p_T^{i,meas})^2}{\sigma_i^2} + \Sigma_{j=x,y} \frac{(U_j^{fit} - U_j^{meas})^2}{\sigma_j^2}$$
$$+ \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{\ell\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj} - m_t^{reco})^2}{\Gamma_t^2} + \frac{(M_{b\ell\nu} - m_t^{reco})^2}{\Gamma_t^2}$$

- Build 2-d templates of the dijet mass closest to the W mass vs. m_t^{reco} for different values of top pole mass and jet energy scale. Determine the top pole mass and the jet energy scale which maximize the overall likelihood.







M_{top} = 171.9 ± 1.7 (stat.+JES) ± 1.0 (syst) GeV/c^2 = 171.9 ± 2.0 GeV/c^2

Matrix Element Method

- Similar reasoning to Bayesian statistics: integrate over all unknown degrees of freedom. In this case, we have an extremely well justified prior – the Standard Model.
- Build the probability to see an event in the detector:

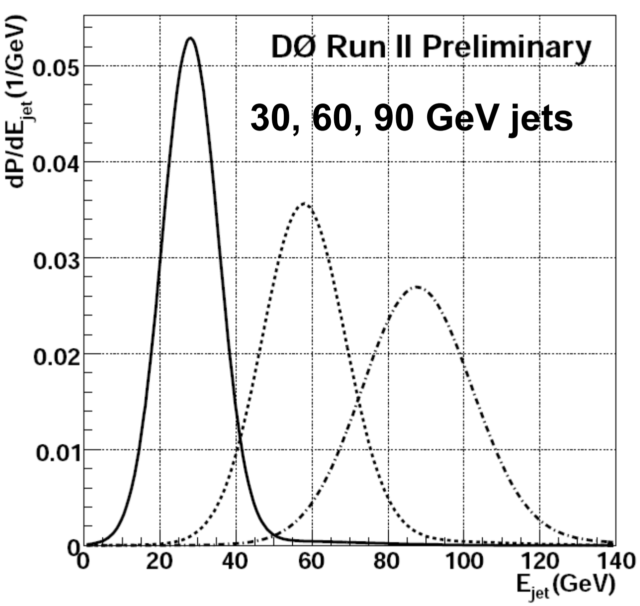
$$P_{ev}(\mathbf{y}|\mathbf{a}) = \sum_i f_i P_i(\mathbf{y}|\mathbf{a})$$

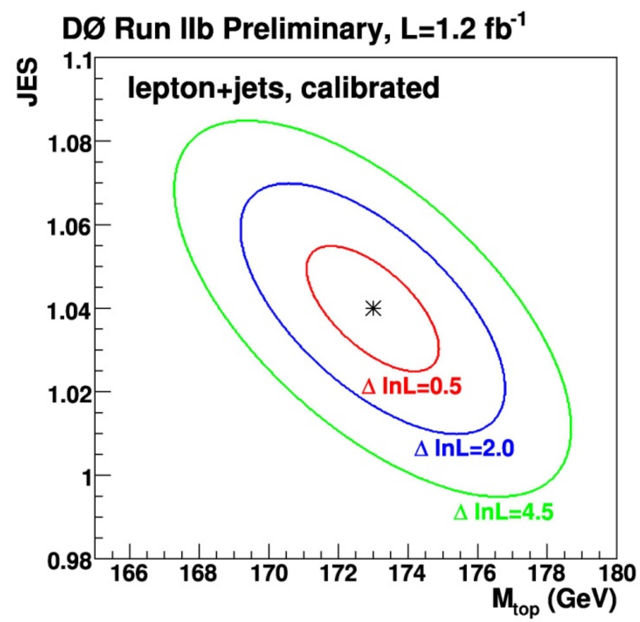
$$P_i(\mathbf{y}|\mathbf{a}) = \frac{1}{\sigma_i(\mathbf{a}) A_i(\mathbf{a})} \sum_k \int_X W_k(\mathbf{y}|\mathbf{x},\mathbf{a})\, \epsilon(\mathbf{x},\mathbf{a})\, |M_i(\mathbf{x},\mathbf{a})|^2\, T_i(\mathbf{x},\mathbf{a})\, d\mathbf{x}$$

- $\sigma_i(\mathbf{a})$: cross section
- $A_i(\mathbf{a})$: acceptance
- $\sum_k$: combinatorics
- $\int_X$: phase space
- $W_k(\mathbf{y}|\mathbf{x},\mathbf{a})$: transfer function
- $\epsilon(\mathbf{x},\mathbf{a})$: efficiency
- $|M_i(\mathbf{x},\mathbf{a})|^2$: matrix element
- $T_i(\mathbf{x},\mathbf{a})$: PDFs, flux

Matrix Element Analysis: D0

- Direct implementation of the ME scheme is difficult due to extreme CPU intensity of the method:
  - ~10^5 events, ~10^3 points in the 2-d parameter space (M_{top}, JES)
  - Highly peaked matrix element (dominated by the t, W propagator terms) requires a non-trivial phase space sampling scheme
- Simplifying assumptions: leading order ME, directions of the jets and the lepton are perfectly measured, transfer functions can be factorized
- Advanced neural net b-tagging

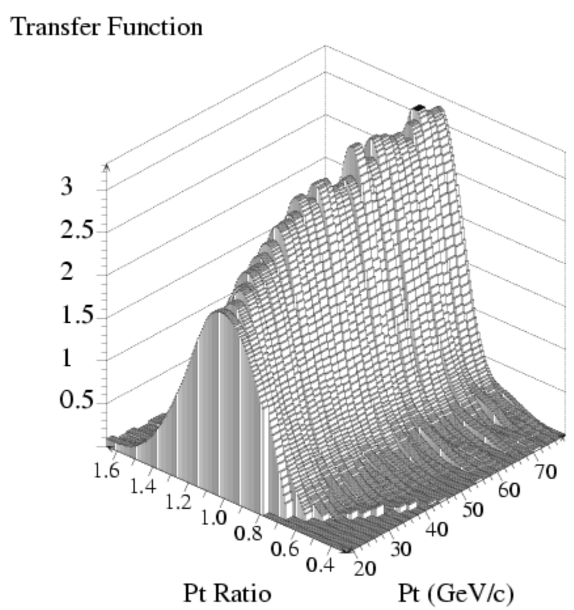


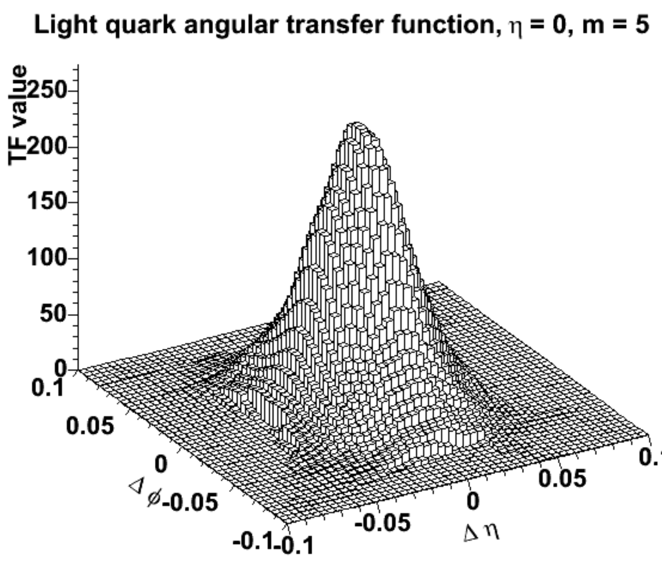


M_{top} = 172.2 ± 1.1 (stat) ± 1.6 (syst) GeV/c^2 = 172.2 ± 1.9 GeV/c^2

Matrix Element Analysis: CDF

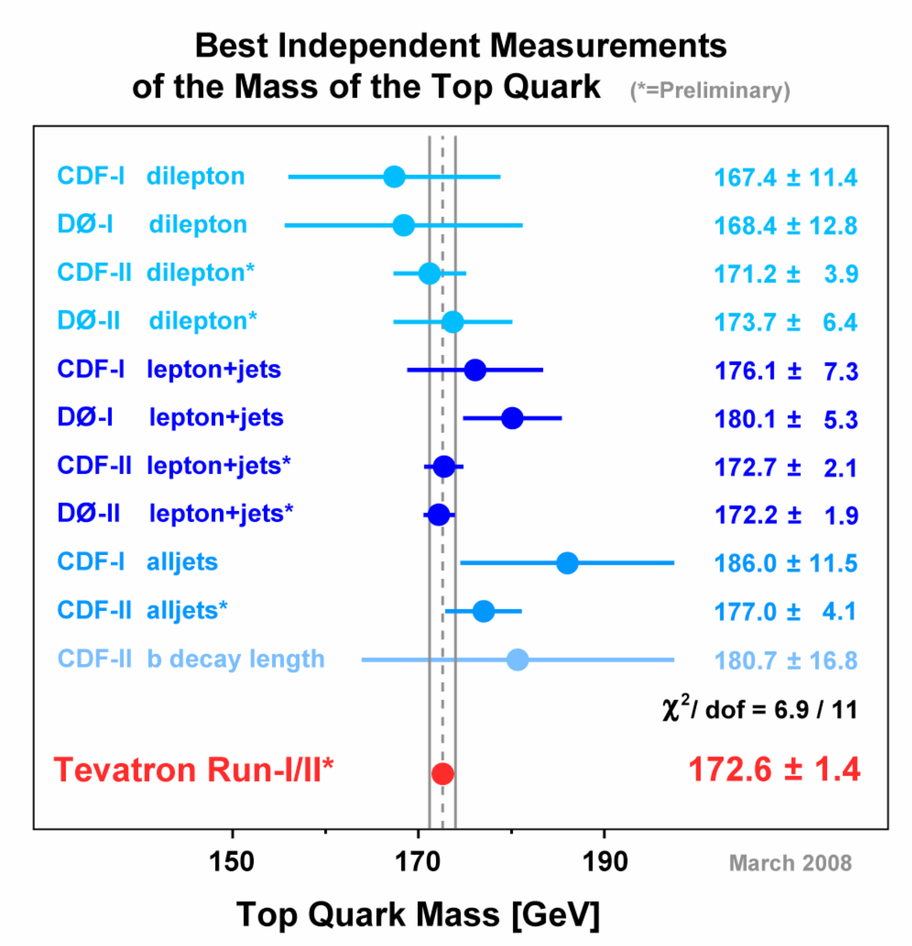
- Only a few dimensionality reduction assumptions; 19-dimensional integration is performed by Quasi-Monte Carlo
- Non-parametric models are used for transfer functions and efficiencies. Transfer functions depend on jet mass as well as on P_T
- Background probability is not used; an average expected background contribution is subtracted from the sample likelihood

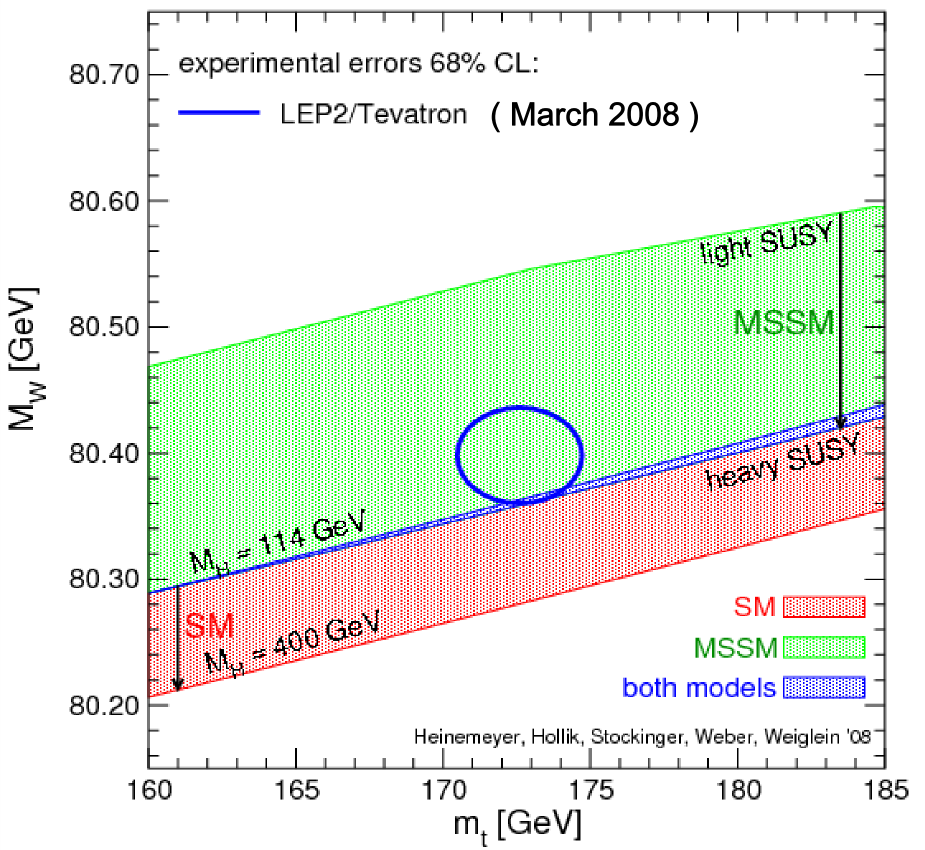




M_{top} = 171.4 ± 1.1 (stat.) ± 1.0 (JES) ± 1.0 (syst) GeV/c^2 = 171.4 ± 1.8 GeV/c^2

Summary of Top Mass Measurements

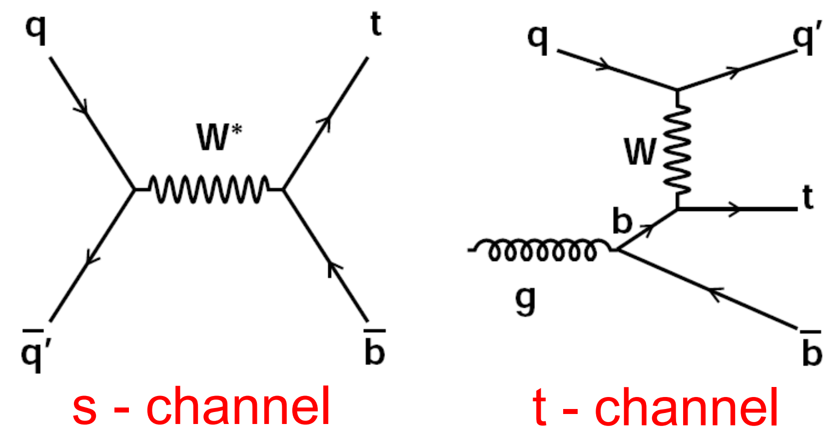


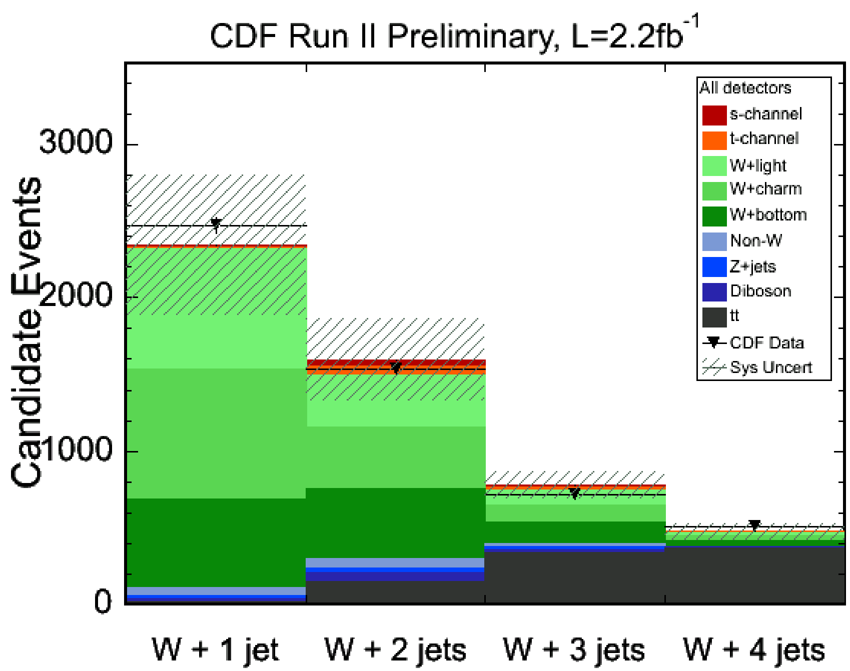


Most recent best single measurement: 171.4 ± 1.8 GeV/c^2 (CDF)

Single Top Production

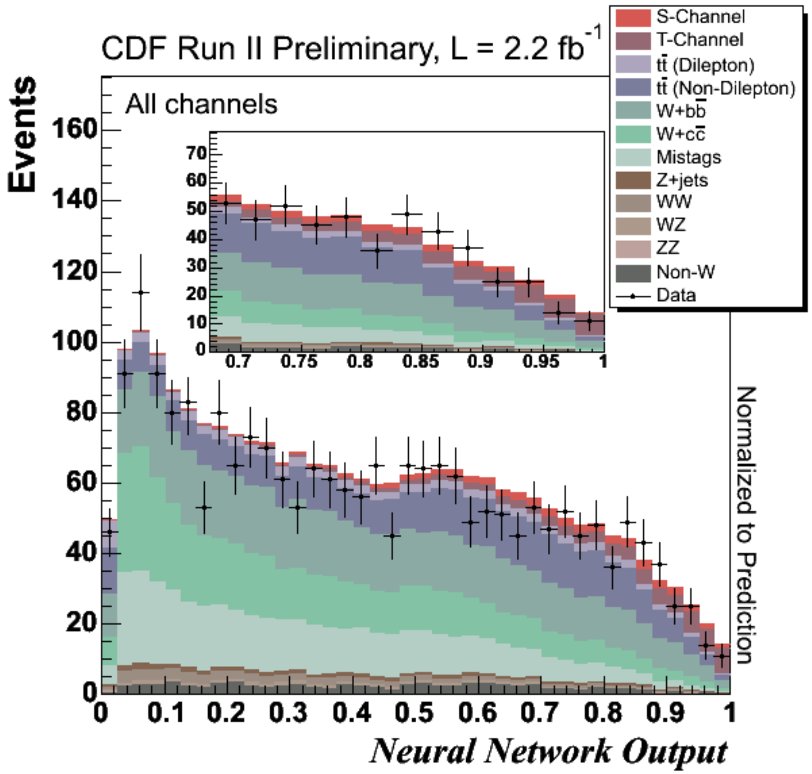
- Tests the Wtb coupling
- Measure $|V_{tb}|$: SM $\sigma \propto |V_{tb}|^2$
- Cross section sensitive to new physics
- Background for WH production
- SM prediction (NLO): $\sigma = 2.9 \pm 0.4$ pb
- Simple counting experiment in different N_{jets} bins does not work: background uncertainty is too large. Must use event kinematics to further suppress background.



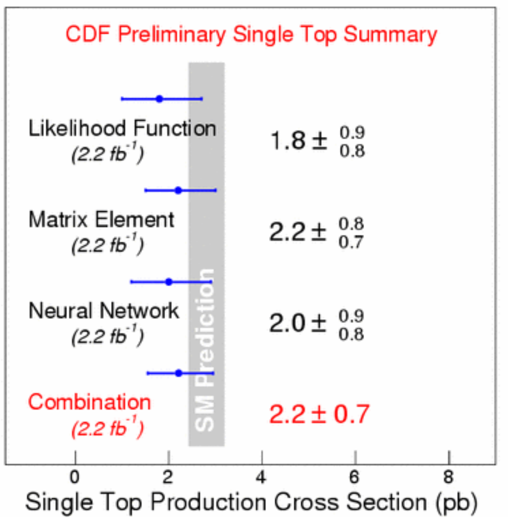


Single Top Search: CDF

- Construct a single variable (discriminant) highly sensitive to single top kinematics
- Tried to do it in four different ways: neural network, likelihood discriminant, matrix element method, boosted decision trees
- Combined result (NN, LD, and ME together) – using yet another NN

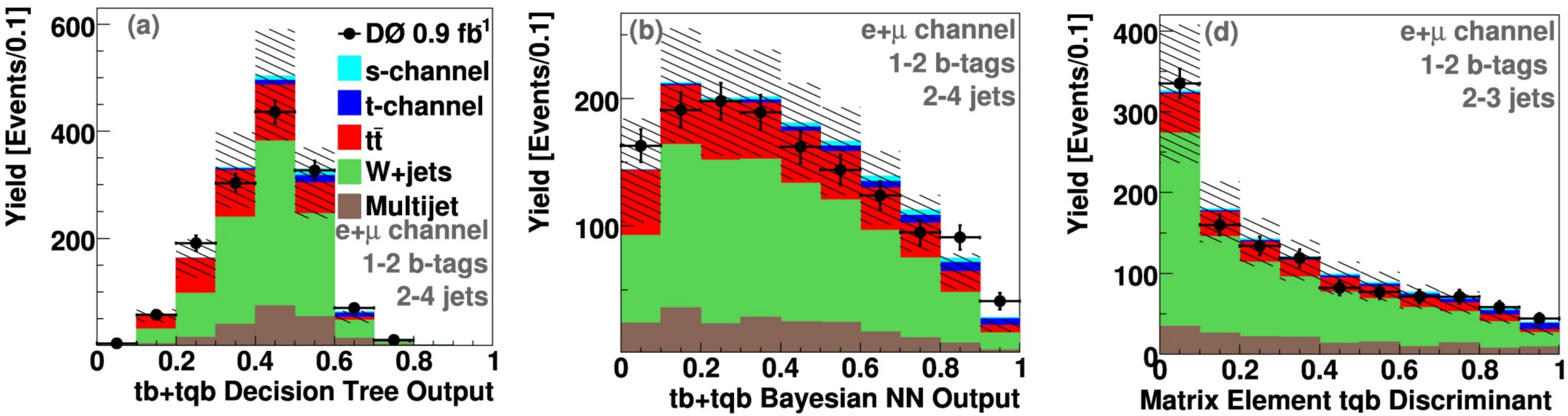


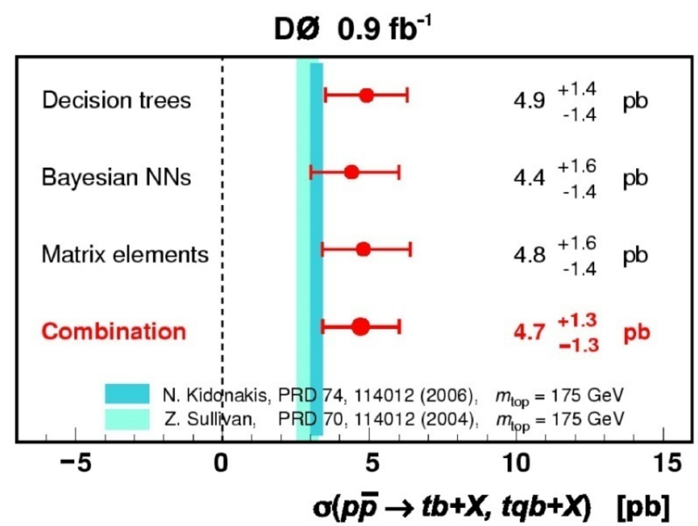
BDT result: $1.9^{+0.8}_{-0.7}$



Expected p-value = 2.0×10^{-7} (5.1 σ)
Observed p-value = 9.4×10^{-5} (3.7 σ)
$|V_{tb}| = 0.88 \pm 0.14$ (exp) ± 0.07 (theory)

Single Top Search: D0





- Three methods pursued to separate signal from background:
  - Boosted decision trees
  - Matrix element method
  - Bayesian neural network
- Combined using BLUE

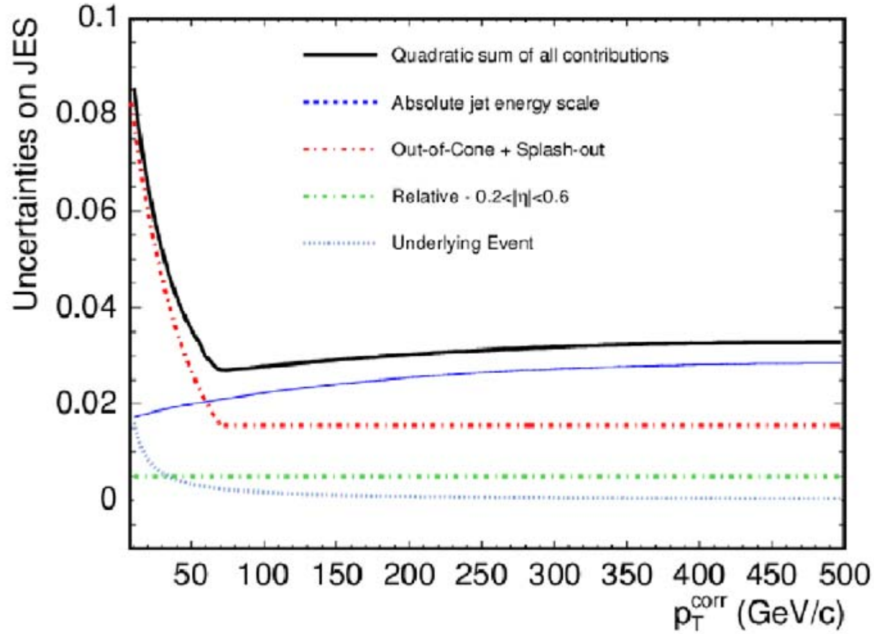
Expected p-value = 1.1×10^{-3} (2.3 σ)
Observed p-value = 1.4×10^{-4} (3.6 σ)

Top Properties and BSM Searches

- $\sigma(gg \to t\bar{t})/\sigma(p\bar{p} \to t\bar{t})$
- W helicity in top decays
- $d\sigma_{tt}/dM_{tt}$
- BR(t→Wb)/BR(t → Wq) and V_{tb}
- Forward-backward production asymmetry
- Direct BSM physics searches:
  - FCNC (CDF: t → Zq, D0: single top production)
  - Fourth generation quarks (t')
  - $t\bar{t}$ resonances (*e.g.*, Z')
  - W', H^+, stop, massive gluon
- No significant evidence for new physics found

Systematic Uncertainties

- Precision of many Tevatron top analyses is now limited by the systematic uncertainty
- Jet energy scale is the major contributor to the systematic error for many top analyses
- An effort is under way to re-evaluate systematic uncertainty calculations for precision measurements:
  - Eliminate double counting
  - Talk to phenomenologists about model misspecifications
  - Derive uncertainties event-by-event



Best M_{top}: JES uncertainty is 1.0 GeV

Systematic source	Systematic uncertainty (GeV)
Calibration	0.1
MC generator	0.4
ISR and FSR	0.5
Residual JES	0.5
b-JES	0.4
Lepton P_T	0.2
Multiple interactions	0.1
PDFs	0.2
Background	0.3
Total	1.0

Summary

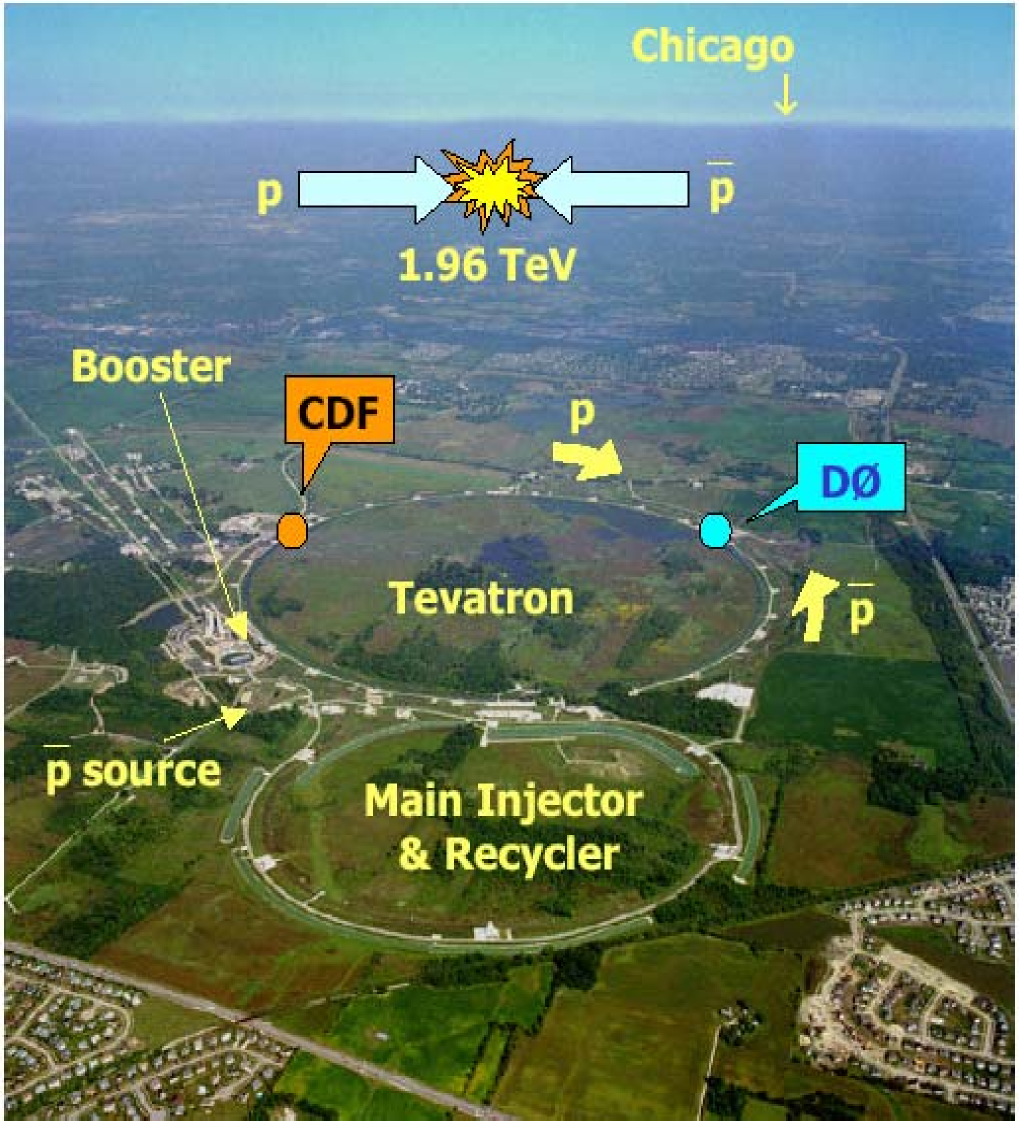
- A vigorous top physics study program is conducted by the Tevatron experiments: the SM is under continuous test
- Precision of several interesting analyses (cross section, mass) is limited by the systematic uncertainty – these results will clearly stand up well into the LHC era
- So far, no significant disagreement between the data and the SM in the top land

- Useful web pages:
  - TOP 2008 conference: http://www.pi.infn.it/top2008/
  - CDF top results: http://www-cdf.fnal.gov/physics/new/top/top.html
  - D0 top results: http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html

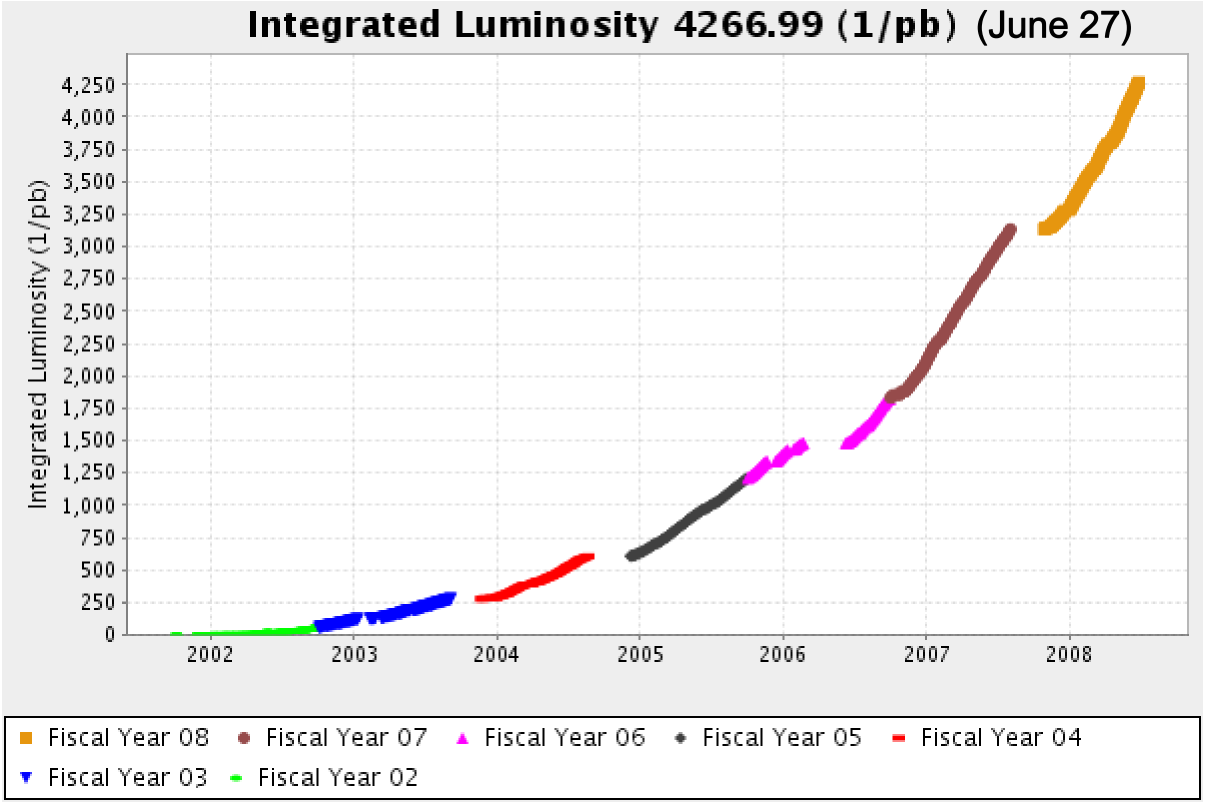
Backup Slides

Fermilab Tevatron

- The highest energy collider in operation:
  $E_{cm} = 1.96$ TeV
- Run I 1990-1995
  110 pb^{-1} per experiment
- Run II 2001-2009(?)
  6.5 to 8 fb^{-1} expected
- Top quark was discovered at Tevatron in 1995, simultaneously by CDF and D0

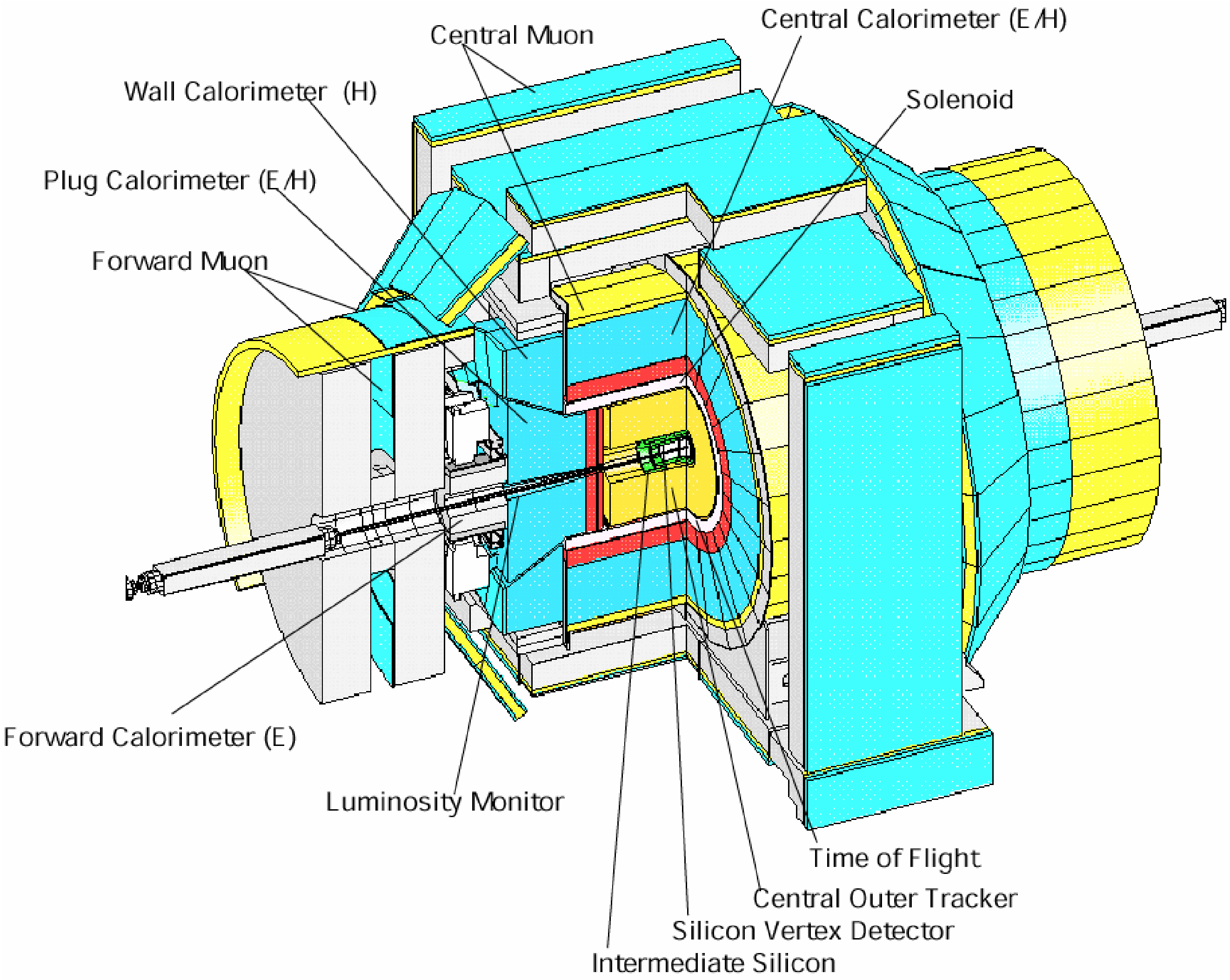


Tevatron Performance

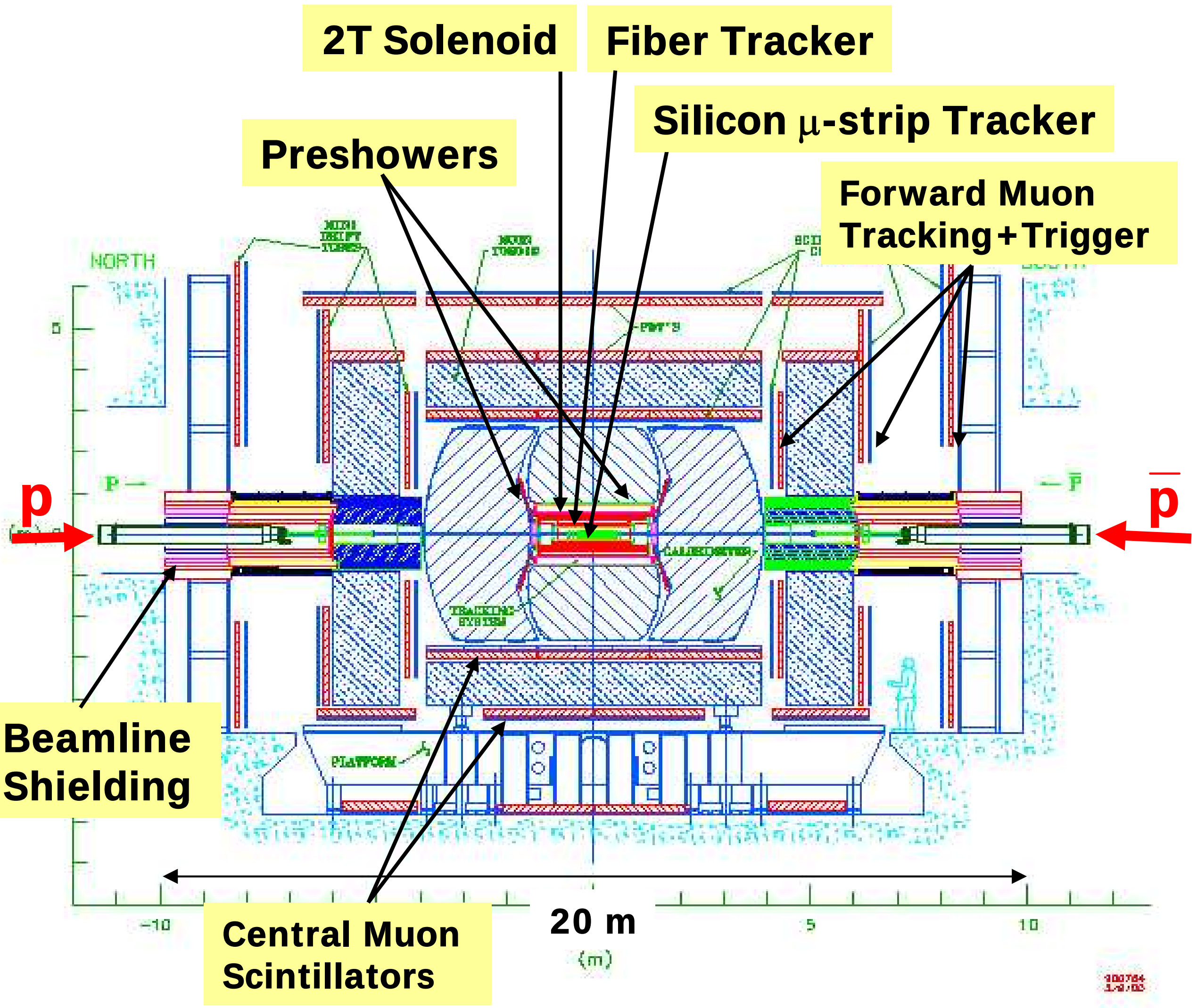


- Doubled dataset each year for four years
- 1.5-2.0 fb^{-1} per year in 2007 and beyond
- Will reach ~6.5 fb^{-1} by the end of 2009, ~8 fb^{-1} in 2010

The CDF Detector

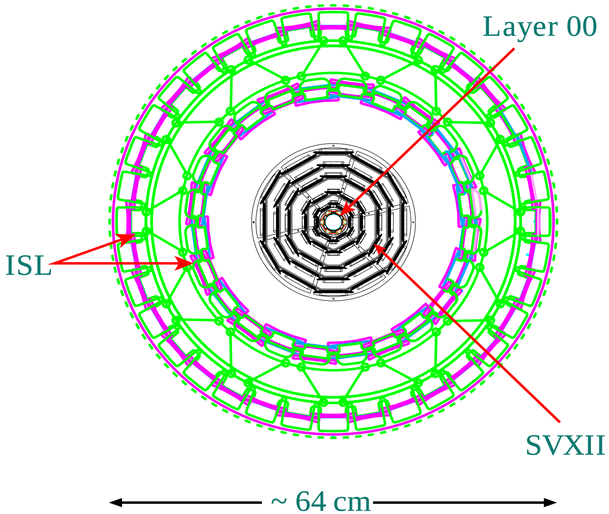


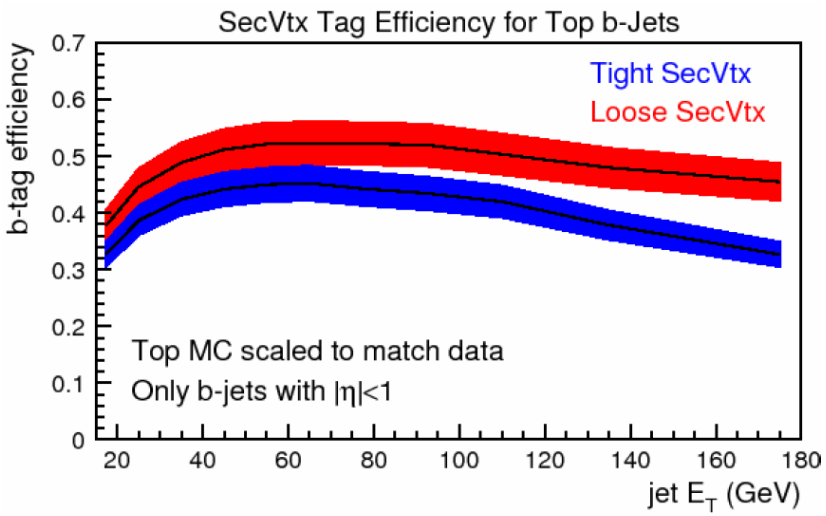
The D0 Detector

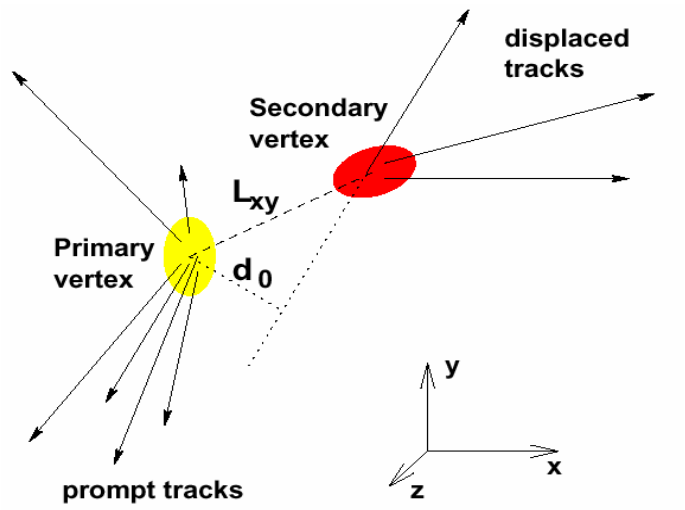


b Tagging with Silicon Vertex Detector (*e.g.*, in CDF)

- At least two well-reconstructed tracks with ≥ 3 silicon hits
- Secondary vertex L_{XY} significance at least +3σ (typical σ is ~150μm)
- Efficiency to tag a $t\bar{t}$ event is ~55%
- $t\bar{t}$ tag fake rate: ~0.5%

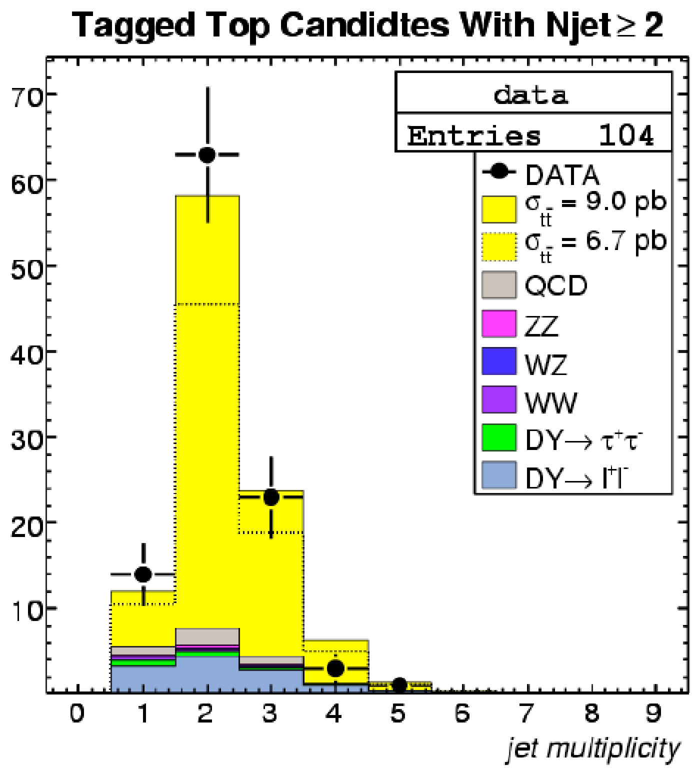


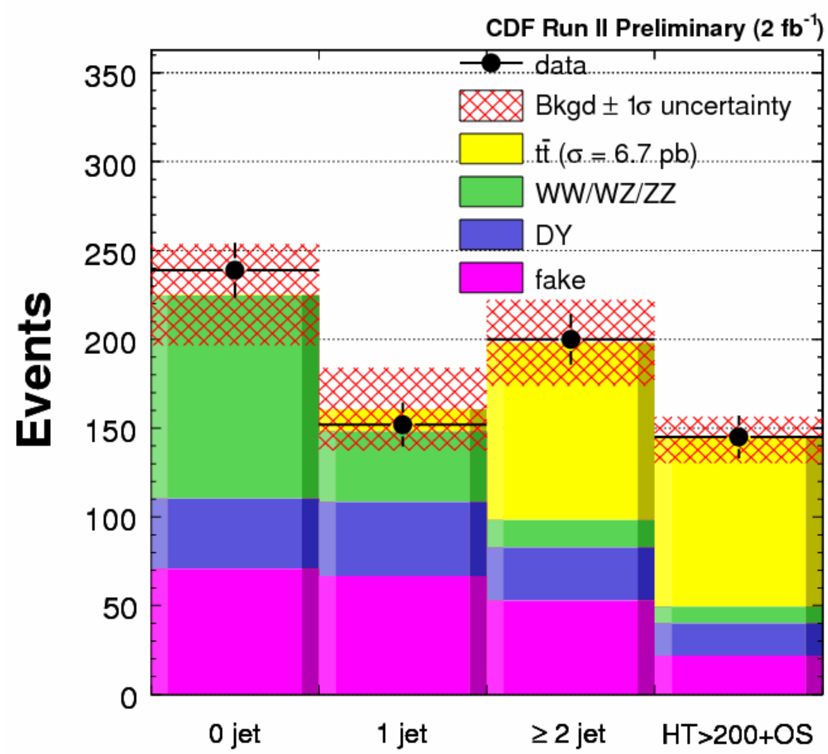




Dilepton Cross Section: CDF

- Sensitive to a different type of BSM contributions (*e.g.*, $t \rightarrow H^+b$, $H^+ \rightarrow \tau^+\nu$ in MSSM)



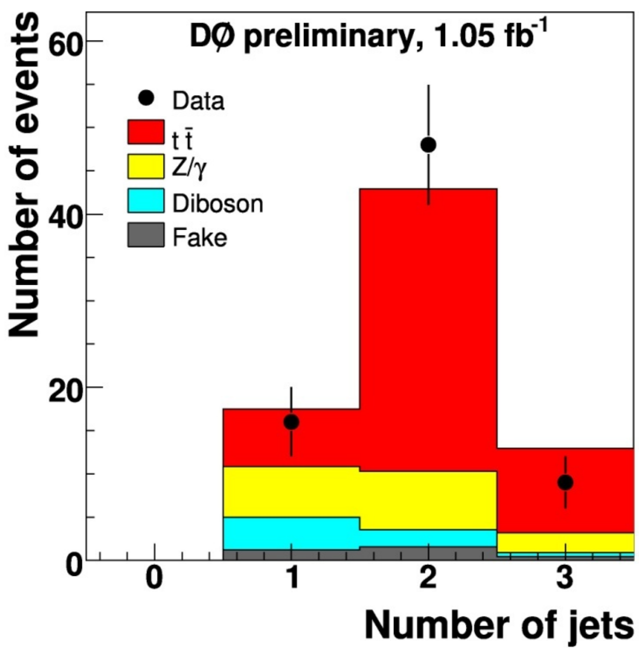


b tag required: $\sigma = 9.0 \pm 1.1$ (stat) ± 0.7 (sys) ± 0.5 (lumi) pb

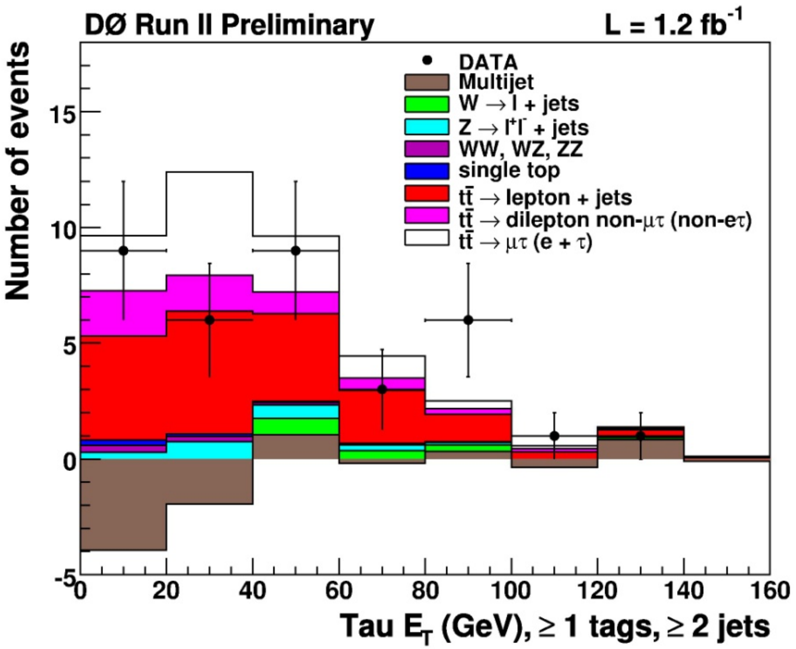
b tag not required: $\sigma = 6.78 \pm 0.96$ (stat) ± 0.42 (sys) ± 0.42 (lumi) pb

Dilepton Cross Section: D0

Topological Selection



τ + e,μ



Topological: $\sigma = 6.8 ^{+1.2}_{-1.1}$ (stat) $^{+0.9}_{-0.8}$ (sys) $\pm$ 0.4 (lumi) pb

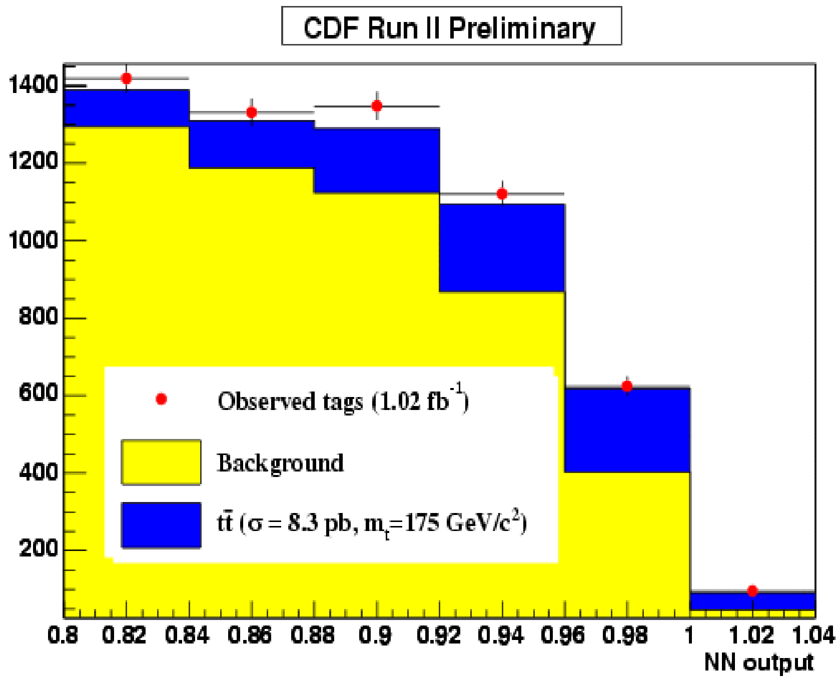
L + track + b tag: $\sigma = 5.1 ^{+1.6}_{-1.4}$ (stat) $^{+0.9}_{-0.8}$ (sys) $\pm$ 0.3 (lumi) pb

L + τ + b tag: $\sigma = 8.3 ^{+2.0}_{-1.8}$ (stat) $^{+1.4}_{-1.2}$ (sys) $\pm$ 0.5 (lumi) pb

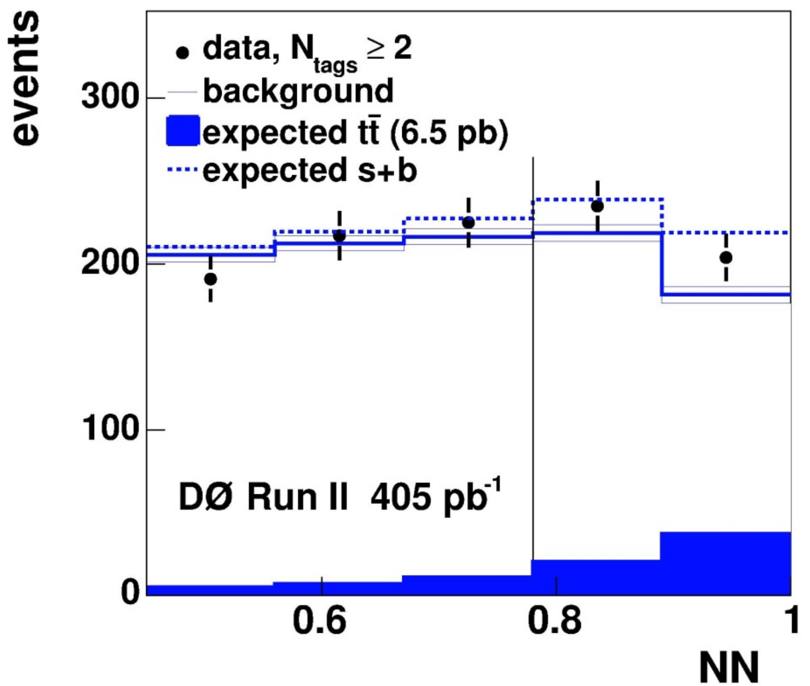
All-Hadronic Cross Section

- Both CDF and D0 use kinematic neural networks to suppress backgrounds, then count b-tags

CDF



D0

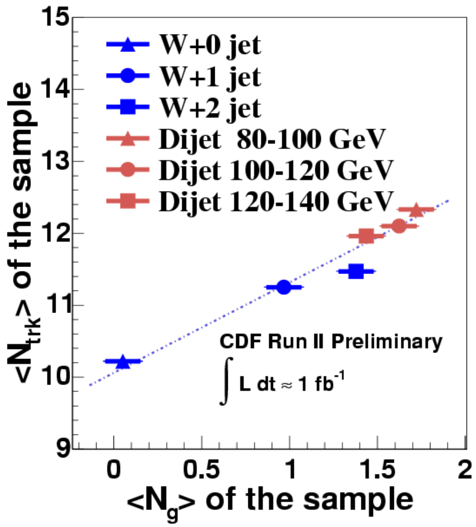


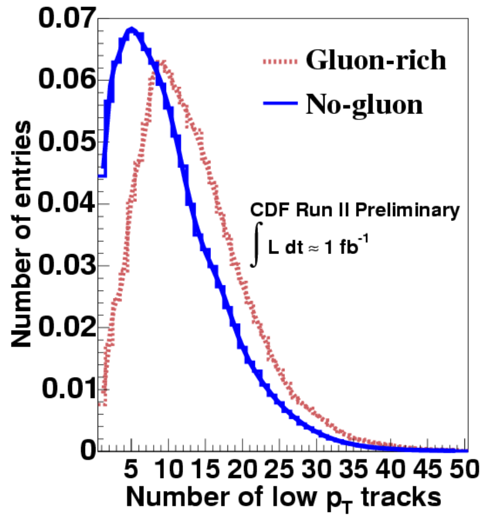
$\sigma = 8.3 \pm 1.0\ (\text{stat})\ ^{+2.0}_{-1.5}\ (\text{sys}) \pm 0.5\ (\text{lumi})\ \text{pb}$

$\sigma = 4.5\ ^{+2.0}_{-1.9}\ (\text{stat})\ ^{+1.4}_{-1.1}\ (\text{sys}) \pm 0.3\ (\text{lumi})\ \text{pb}$

Measurement of $\sigma(gg\rightarrow t\bar{t})/\sigma(pp\rightarrow t\bar{t})$: CDF

- Test of pQCD calculations
- With higher statistics could be used to improve gluon PDF uncertainty
- Sensitive to BSM production mechanisms
- The challenge: need to discriminate between identical final states
- The number of low P_T tracks (between 0.3 and 2.9 GeV/c) is correlated with the number of gluons in the sample





$\sigma(gg\rightarrow t\bar{t})/\sigma(pp\rightarrow t\bar{t})$ = 0.07 ± 0.14(stat) ± 0.07(syst)

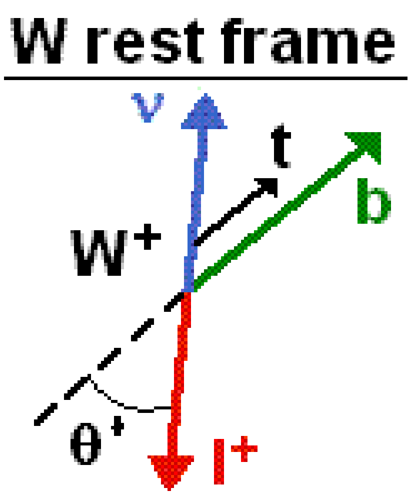
W Helicity in Top Decays

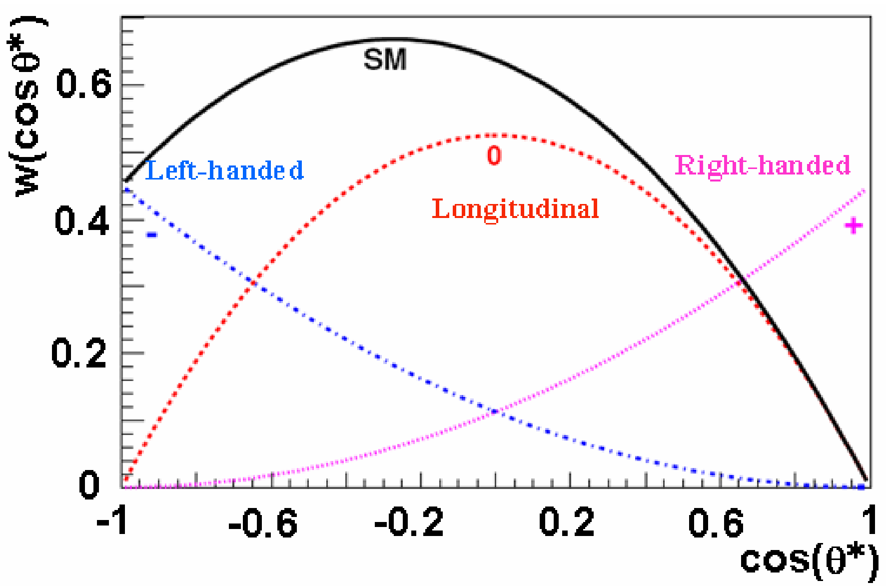
- Tests the V-A interaction in the SM
- General interaction:

$$w(\cos\theta^*) = f_- \cdot \frac{3}{8}(1-\cos\theta^*)^2 + f_0 \cdot \frac{3}{4}(1-\cos^2\theta^*) + f_+ \cdot \frac{3}{8}(1+\cos\theta^*)^2$$

$$f_- + f_0 + f_+ = 1$$

- SM values: $\boldsymbol{f_- = 0.3,\ f_0 = 0.7,\ f_+ \approx 0}$





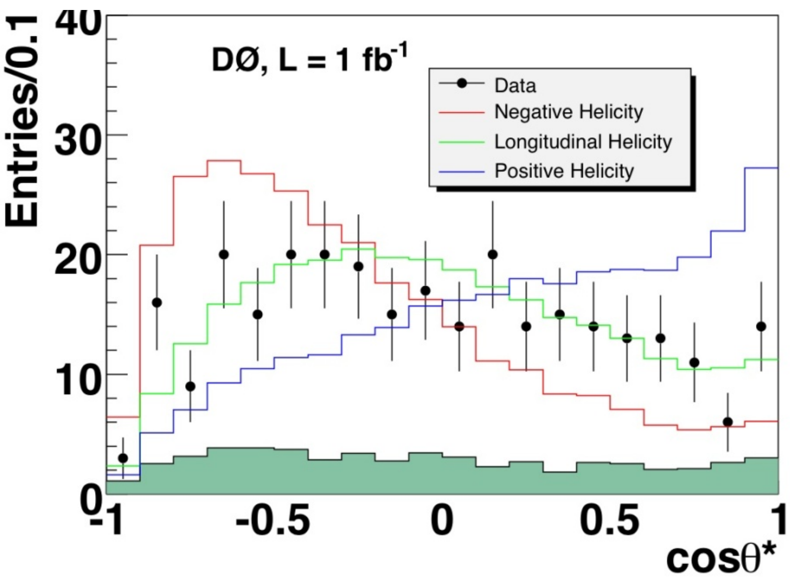
W Helicity Measurement: D0

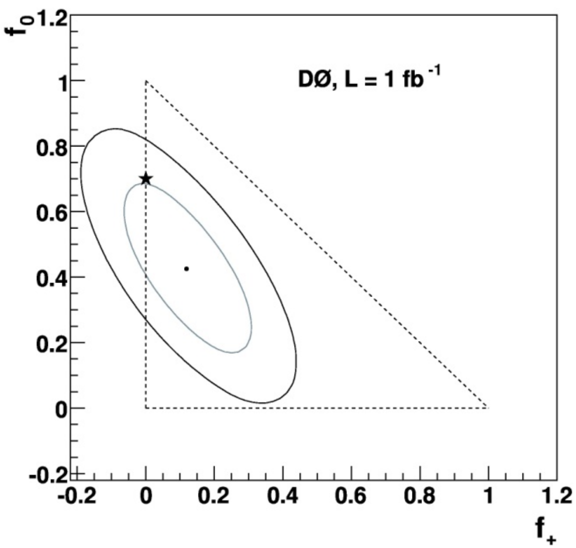
- Likelihood discriminant is used to reduce background, NN to tag b jets
- Lepton+jets and dilepton channels are combined
- Templates in cos θ* variable are built from MC and then fitted to the data sample
  - Simultaneous fit to f_0 and f_+:

$$f_0 = 0.425 \pm 0.166(\text{stat}) \pm 0.102(\text{syst})$$
$$f_+ = 0.119 \pm 0.090(\text{stat}) \pm 0.053(\text{syst})$$

  - Fit to f_0 (f_+) assuming SM f_+ (f_0):

$$f_0 = 0.619 \pm 0.090(\text{stat}) \pm 0.052(\text{syst})$$
$$f_+ = -0.002 \pm 0.047(\text{stat}) \pm 0.047(\text{syst})$$
$$(f_+ < 0.13 \text{ @ } 95\% \text{ C.L.})$$



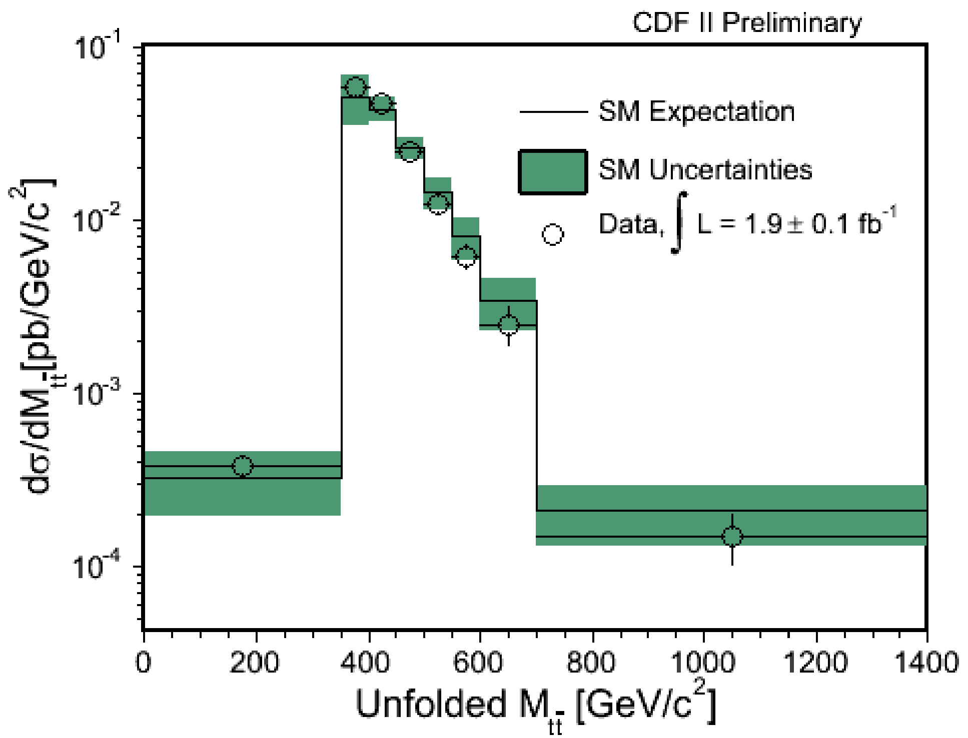


Differential Cross Section $d\sigma_{t\bar{t}}/dM_{t\bar{t}}$: CDF

- Lepton + ≥ 4 jets sample
- Measures $t\bar{t}$ production cross section in bins of $M_{t\bar{t}}$ (unfolded)

$$\frac{d\sigma^i}{dM_{t\bar{t}}} = \frac{N_i - N_i^{bkg}}{\mathscr{A}_i \int \mathscr{L} \Delta^i_{M_{t\bar{t}}}}$$

- Indirect probe for new physics (such as resonant $t\bar{t}$ production)
- Consistent with the SM (p-value = 0.45)



Measurement of BR(t→Wb)/BR(t → Wq): D0

- In the SM

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

- Measured in the l+jets sample together with the $t\bar{t}$ production cross section
- b tagging probability dependence on R is used to constrain R

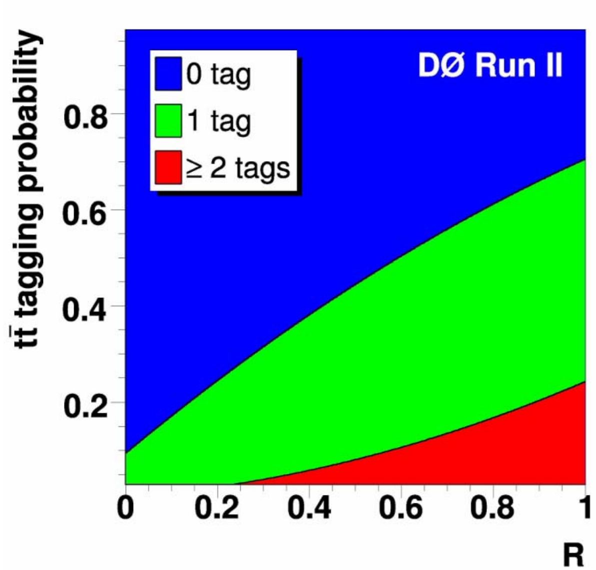
$$R = 0.97^{+0.09}_{-0.08}\ (\text{stat} + \text{syst})$$

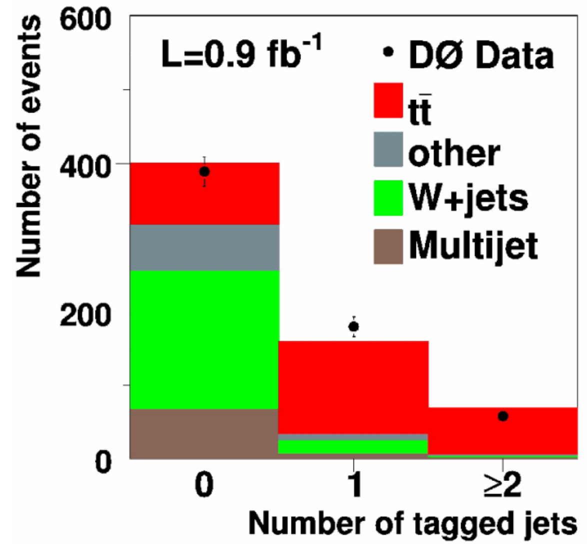
$$\sigma_{t\bar{t}} = 8.18^{+0.9}_{-0.84}(\text{stat} + \text{syst}) \pm 0.5\,(\text{lumi})\ \text{pb}$$

assume unitarity, 3 generations

$$R > 0.79 \ @\ 95\%\ \text{C.L.}$$

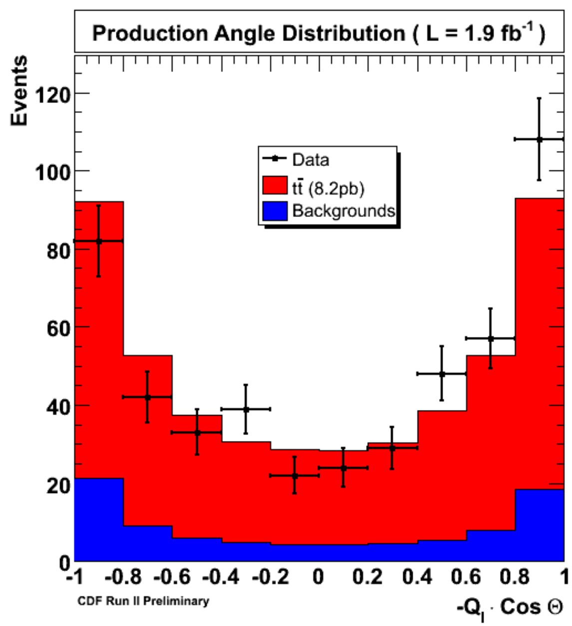
$$|V_{tb}| > 0.89 \ @\ 95\%\ \text{C.L.}$$



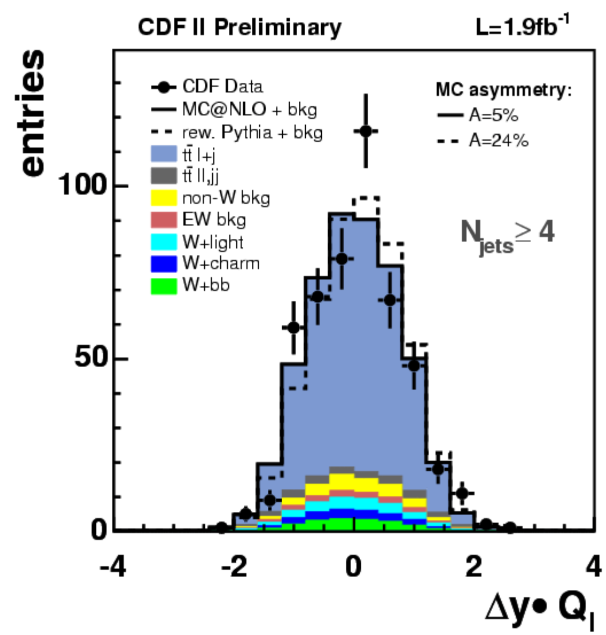


Forward-Backward Asymmetry: CDF

- $$A_{fb} = \frac{N_f - N_b}{N_f + N_b}$$
- Tests discrete symmetries in the $t\bar{t}$ production
- Sensitive to C and P violation in $t\bar{t}$ production (axigluons, Z', *etc.*)
- NLO: $A_{fb} = 0.04 \pm 0.01$ in the lab frame, about 30% larger in the $t\bar{t}$ rest frame
- Distributions sensitive to A_{fb} are corrected for background, efficiency, and smearing



Lab frame: $A_{fb} = 0.17 \pm 0.07(\text{stat}) \pm 0.04(\text{syst})$



$t\bar{t}$ rest frame: $A_{fb} = 0.24 \pm 0.13(\text{stat}) \pm 0.04(\text{syst})$