Top Quark Properties at the Tevatron

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on behalf of the CDF and DØ collaborations

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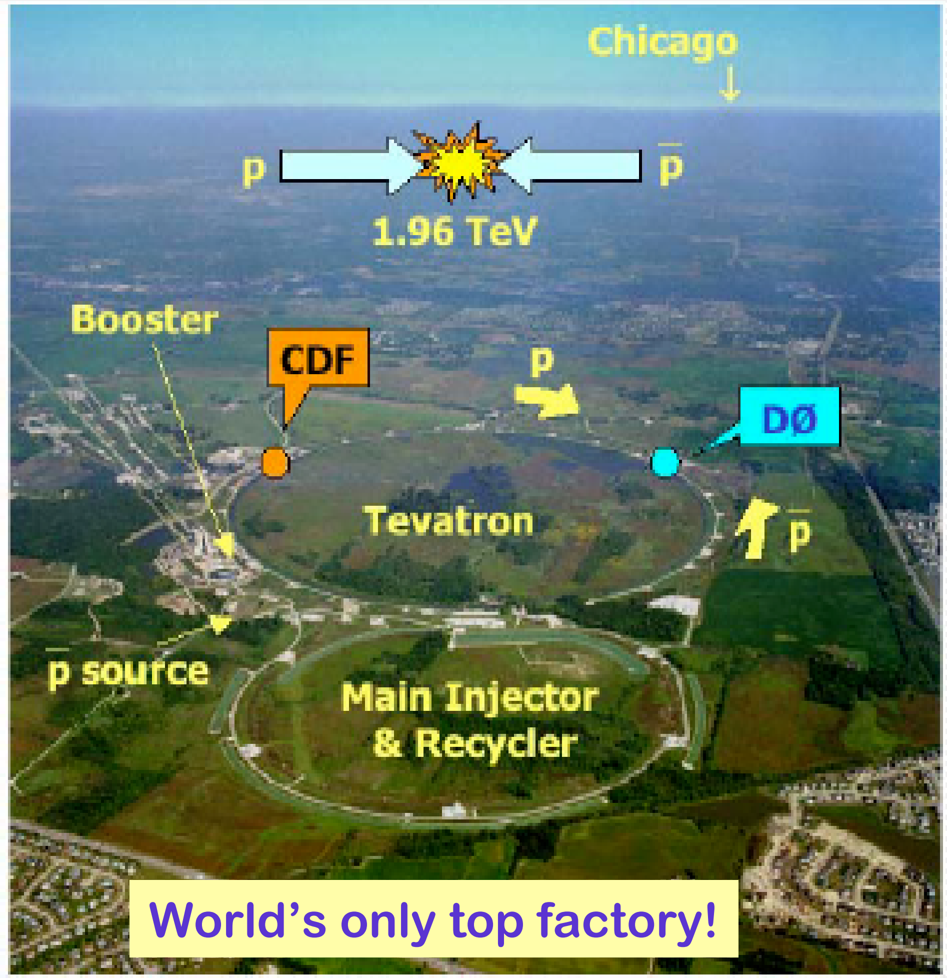
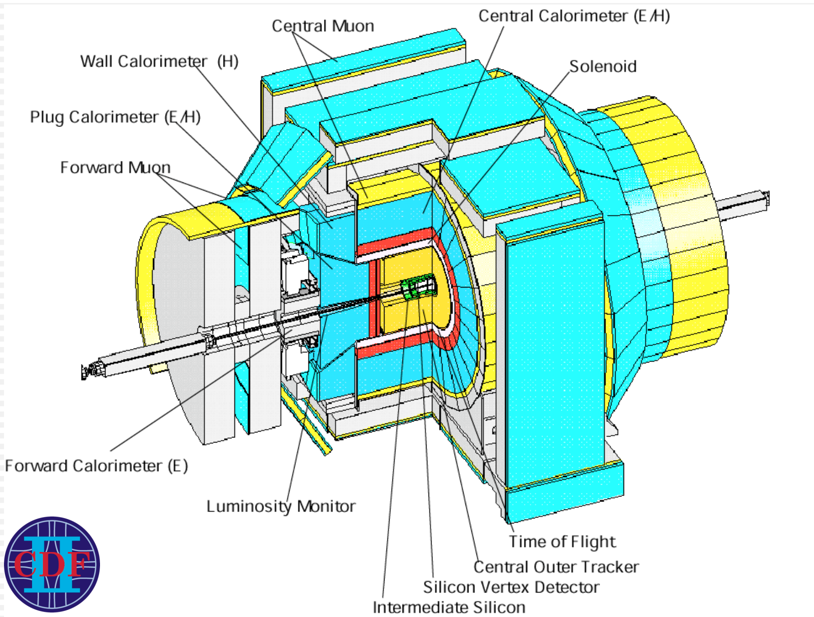
Top Quark at the Tevatron

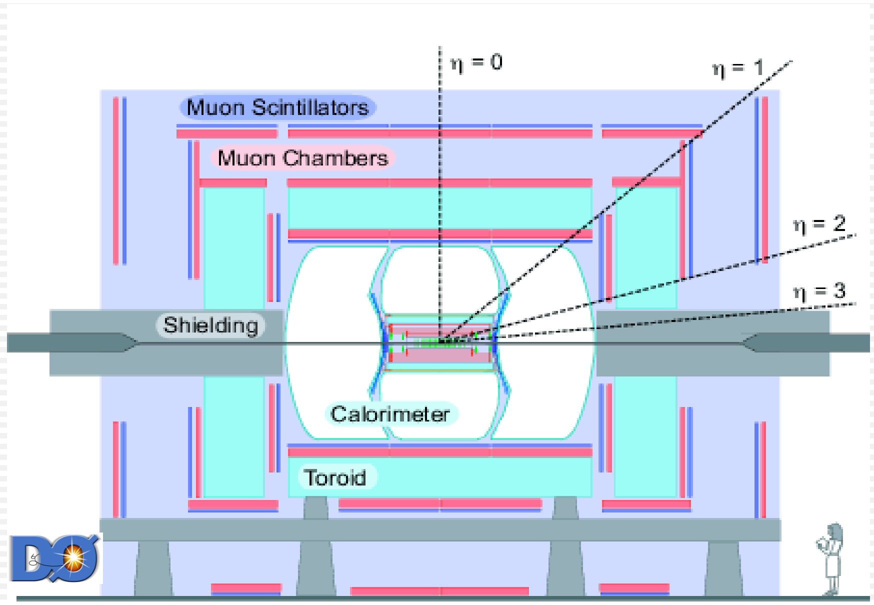
- Fermilab Tevatron:
  - World's highest particle energy collisions
  - ~4 miles circumference protons-antiprotons
- Run I (1992-1996)
  - $\sqrt{s}$ = 1.8 TeV
  - Discover top quark in 1994!
  - Integrated luminosity 120 pb^{-1}
- Run II (2001-present)
  - $\sqrt{s}$ = 1.96 TeV
  - Integrated luminosity by April, 05:
    - In tape ~600pb^{-1}
    - Analyzed up to ~350 pb^{-1}
- 2 multi-purpose detectors
  - D∅ and CDF



Run II Detectors

- Inner Silicon Tracking
- Tracking Chambers
- Solenoid
- EM and Hadronic Calorimeters
- Muon Detectors





Top Quark Physics

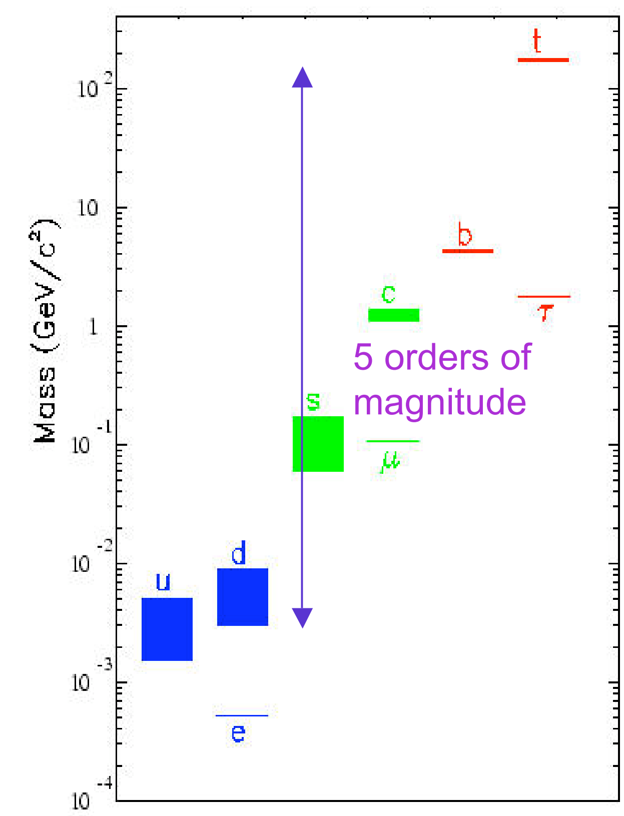
- **Top is very massive => It probes physics at much higher energy scale than the other fermions.**

  M_{top} (Run I world average)= 178 ± 4.3 GeV

- **Top decays before hadronizing => momentum and spin information is passed to its decay products. No hadron spectroscopy.**

  $\tau_{top} \sim 10^{-24}$ sec

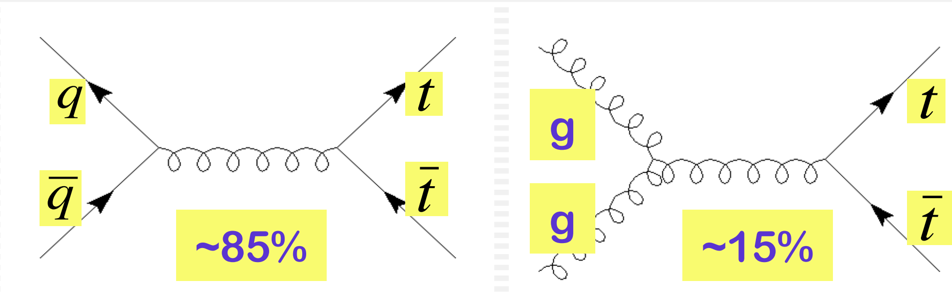
- **Top mass constrains the Higgs mass => M_{top}, enters as a parameter in the calculation of radiative corrections to other Standard Model observables it is also related, along with the mass of the W boson, to the that of the Higgs boson.**



12 orders of magnitude for the fundamental SM fermions!!!!

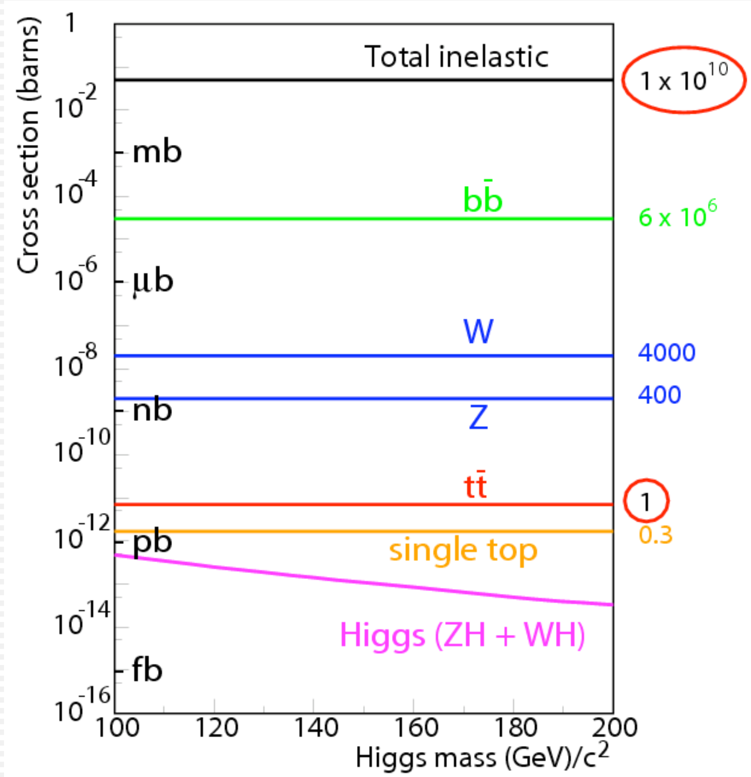
Top Quark Production

- In proton-antiproton collisions at TeVatron energies, top quarks are primarily **produced in pairs** via the strong interactions.



$$\sigma(\bar{p}p \rightarrow t\bar{t} \,@\, M_{top} = 178 GeV) \approx 6.1\,\text{pb}$$

~ one top event every 10 BILLION inelastic collisions



Top Quark Decay

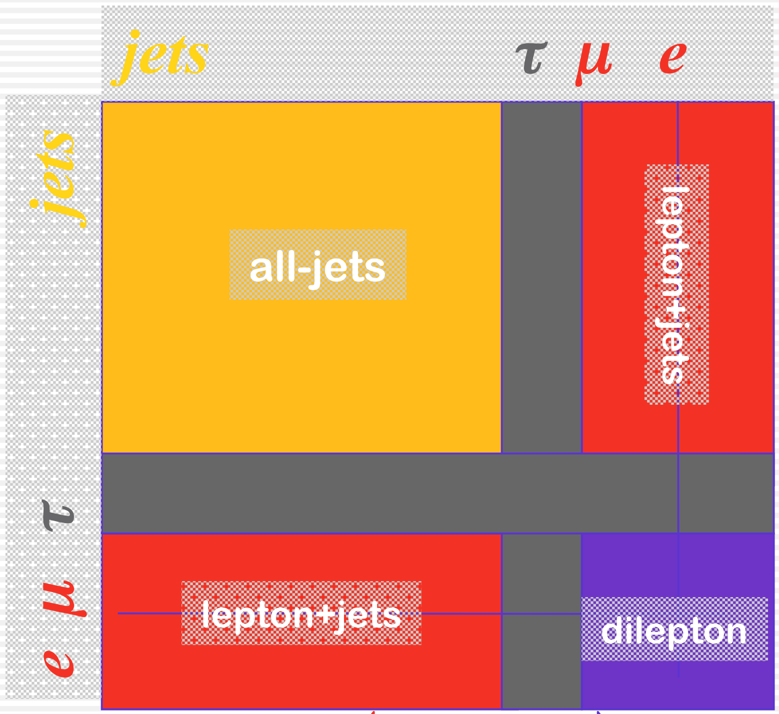
- $M_{top} > M_W$ decays to real Ws

Br(t → Wb) ~ 100%

- Final state is given by W^+ and W^- decays

Br(W → leptons) = 1/3
Br(W → quarks) = 2/3

- Excellent branching ratio
- Large Signal/Background

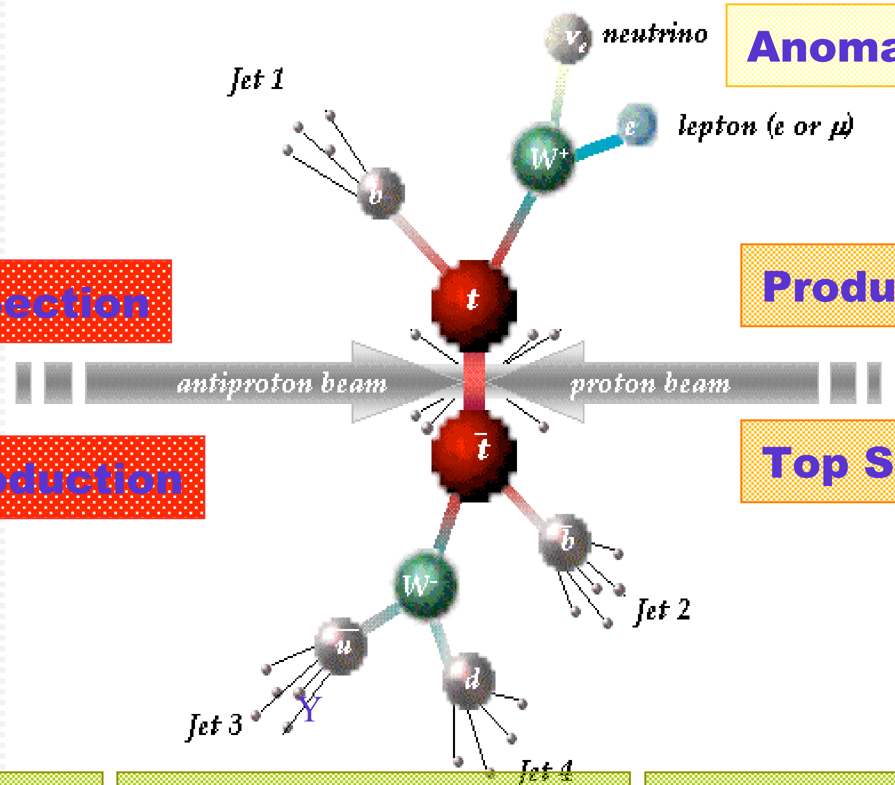


- Larger branching ratio
- Reasonable Signal/Background
- Over-constrained kinematics

- Less statistics
- Excellent S/B
- Under constrained kinematics

The Top Properties Tour

- Top Width
- Top Charge
- W helicity
- Top Spin
- Top Mass
- CP Violation
- Anomalous Couplings
- Production X-Section
- Production Kinematics
- Resonance Production
- Top Spin Polarization

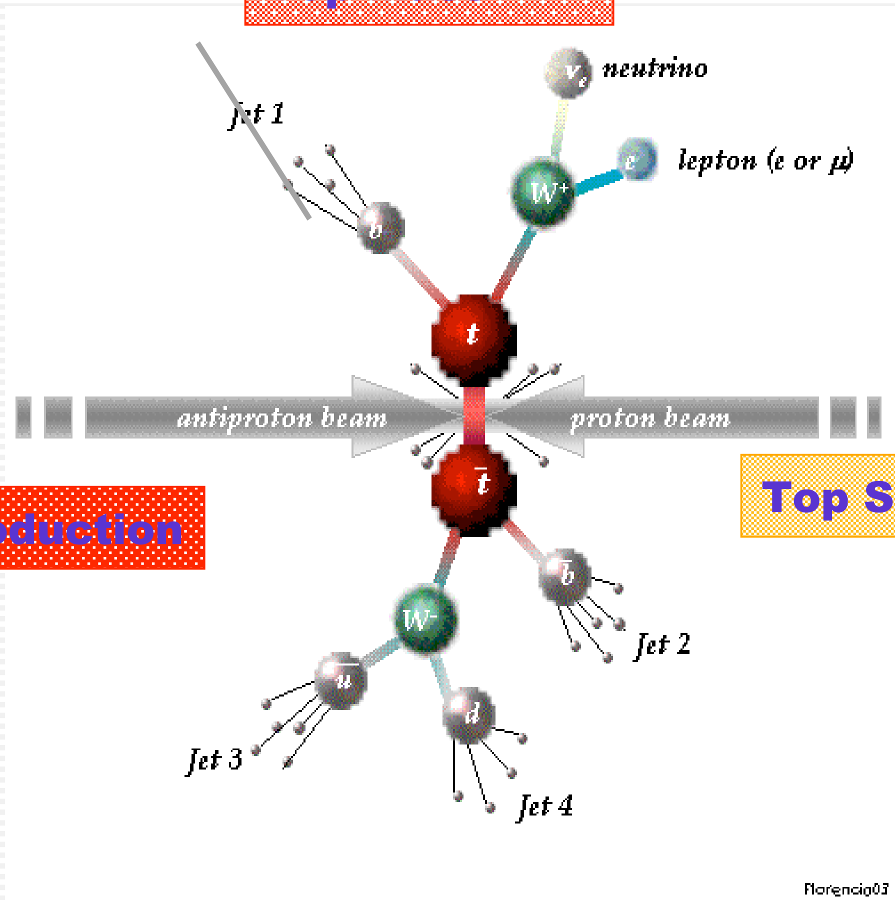


- |Vtb|
- Rare/non SM decays
- Branching Fractions

In this Talk

W helicity

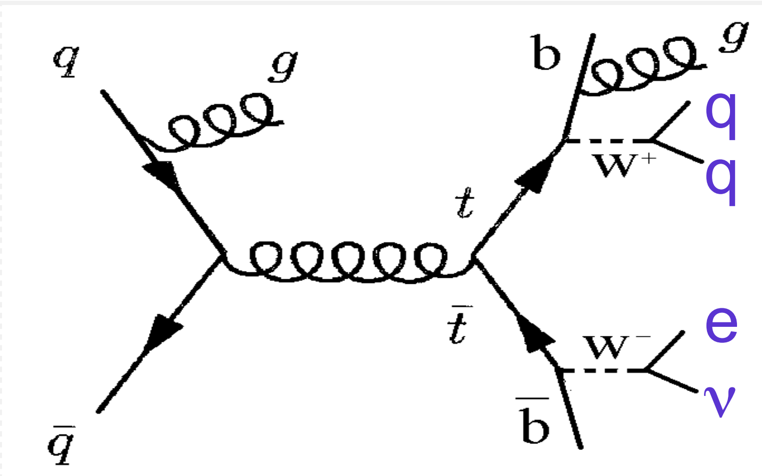
Top Mass



Resonance Production

Top Spin Polarization

Event Topology



- Energetic, central, and spherical
- Missing transverse energy ($\not{E}_T$) from neutrino in lepton+jets and dilepton modes
- High transverse energy, E_T, jets
- Two b-jets
- Possible additional jets from gluon radiation (ISR, FSR)
- Events are busy:
  - need to reconstruct parton level to measure top properties
  - different ways to assign jets to partons

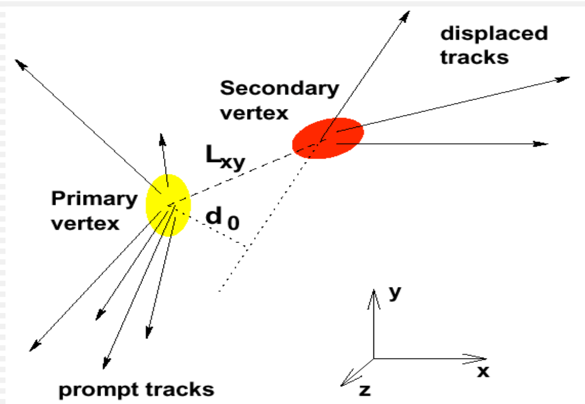
- General characteristics of the background:
  - No neutrinos, less $\not{E}_T$
  - No b-jets
  - Leptons could be fakes (less isolated)
  - Less central

Tagging b-jets

- Use different properties of the B hadrons to identify (tag) them
  - Reduce backgrounds from light-quark/gluon jets
  - Reduce combinatorics effects

B hadrons are long-lived

Vertex of displaced tracks



60%	Top Event Tagging Efficiency
0.5%	False Tag Rate (QCD jets)

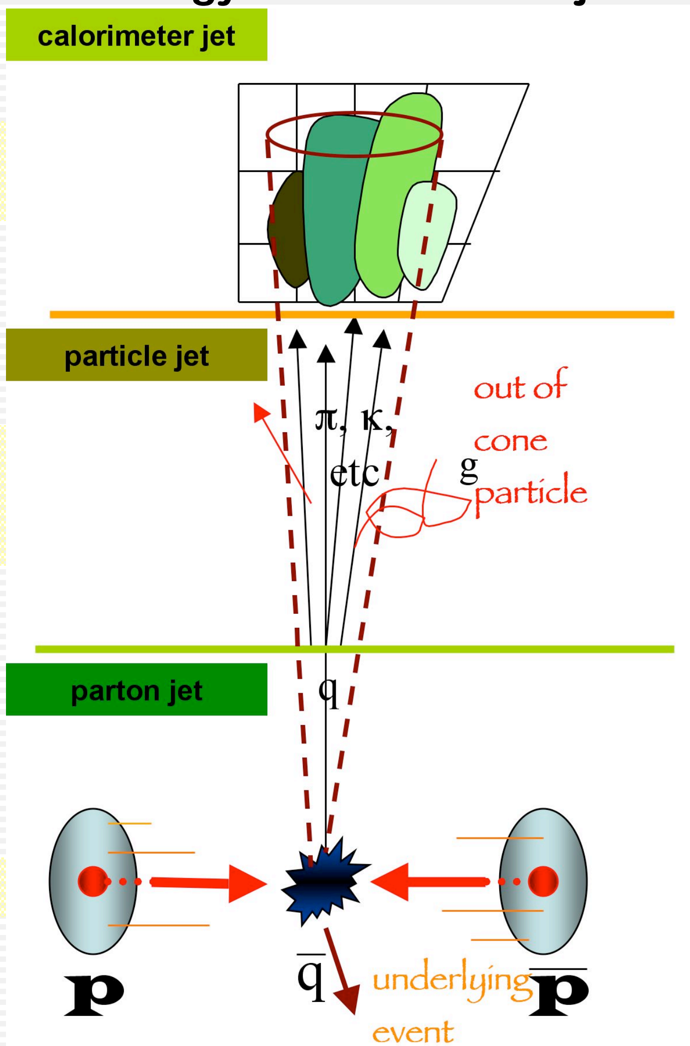
Jet Energy Scale (JES)

- Determine the true parton energy from measured jet energy in a cone

Complex detector properties

Algorithms with complex behavior such as cone, cone-midpoint, KT

Complex underlying physics

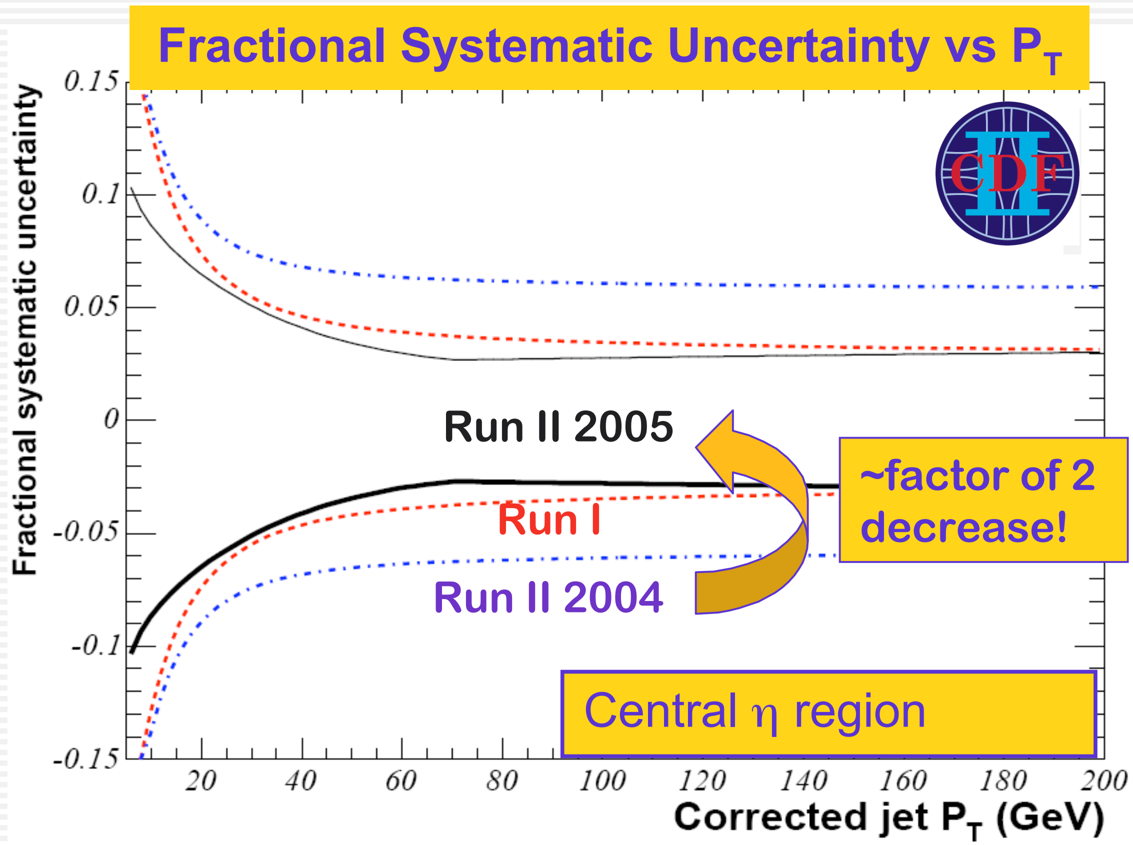


Need to correct for detector, algorithm and physics effects to obtain the true energy of the jets:
Jet Energy Scale (JES)

Jet Energy Scale Systematic Uncertainty

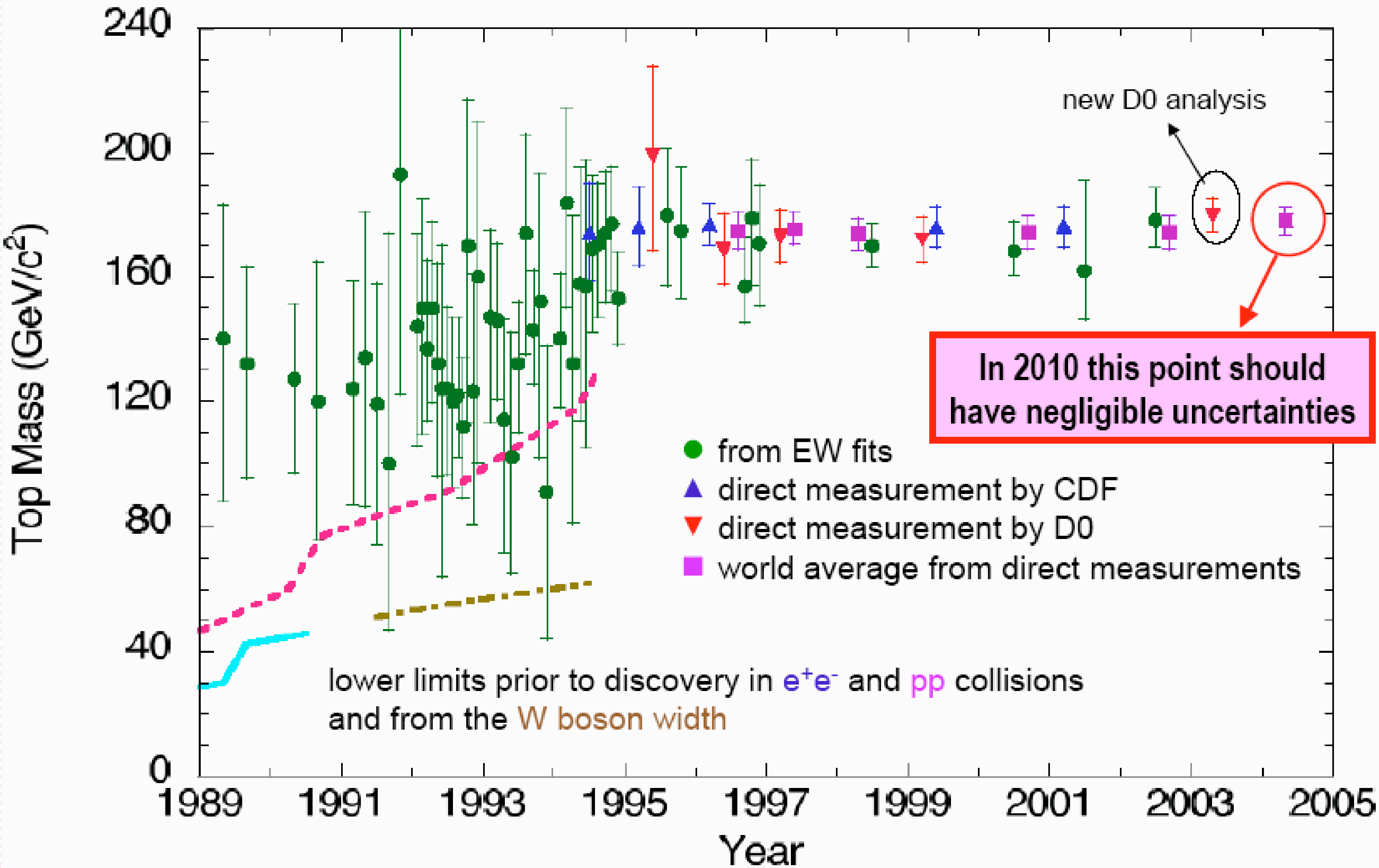
- How well do we know the energy of the jets (or quarks)?
- Events with lots of jets => dominant uncertainty for some top analyses, i.e, top mass in lepton+jets channel.
- Also expect significant improvements from D∅ very soon.

~3% jet P_T uncertainty in top events

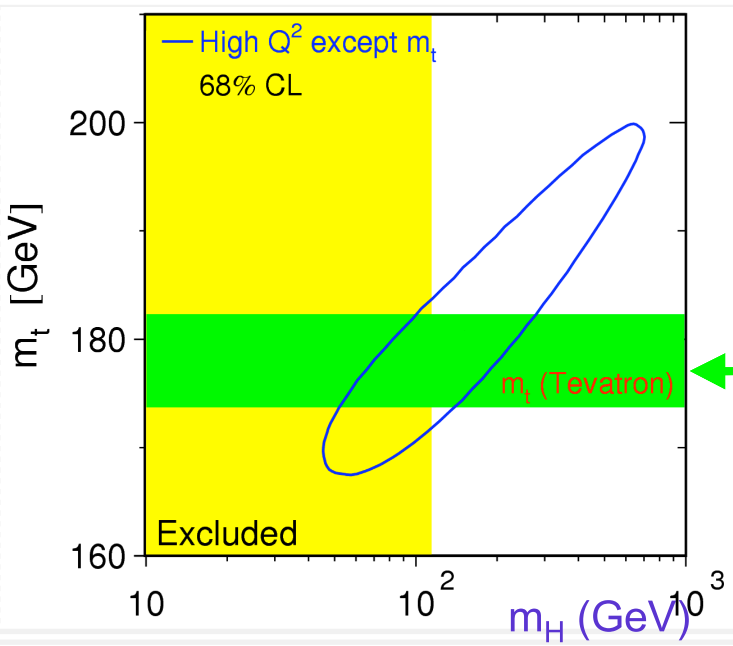


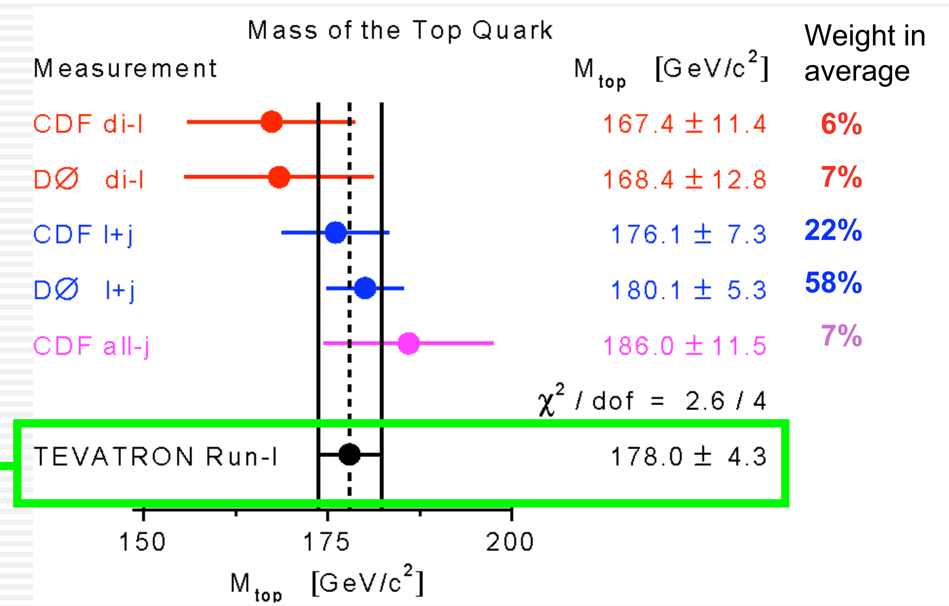
Top Quark Mass Measurements

Publishing Top Quark Masses for 15 years



Top Quark Mass



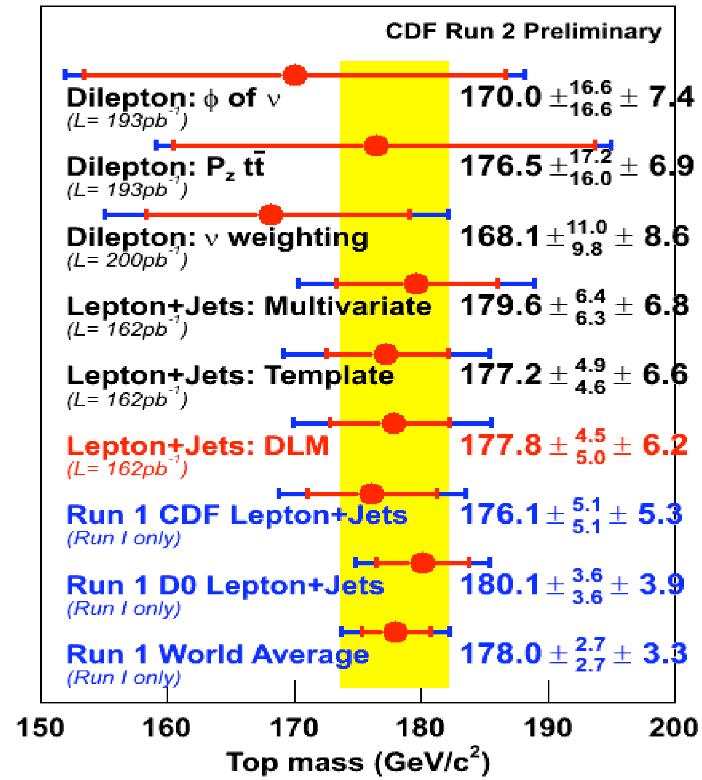


M_{top} all-jets DØ result is not included in TeVatron average: M_{top} = 178.0±15.7 GeV/c^2

Measuring the Top Quark Mass

- Run II began in March 2001:
  - take data, commissioning detectors,
  - calibrate detectors,
  - tune Monte Carlo and detector simulation,
  - prepare analysis
- By the end of 2004 after 3 years of Run II running the top mass measurement did not reach to Run I precision (~5.1 GeV)
- Better precision comes from l+jets (golden channel), but are we looking at the same top among channels?
- By the end of Run I, the JES uncertainty was as large as the statistical uncertainty ~3.5 GeV
- Different methods: try to optimize the statistical and systematic performance

Results by the end of 2004



Two different techniques: Template and Matrix Element based

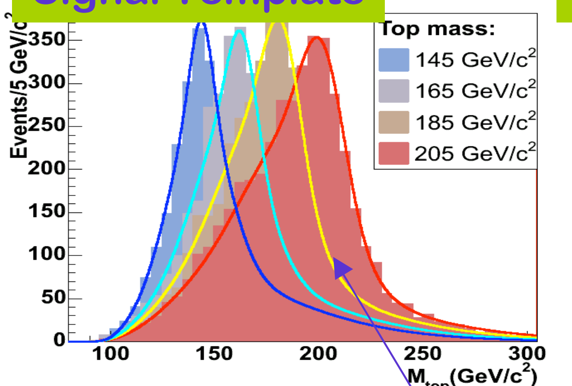
Template Technique

- Determine mass of the top quark using a quantity strongly dependent on the top quark mass M_{top} (usually *Reconstructed* M_{top})

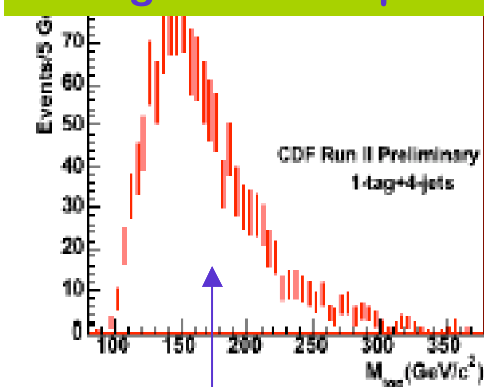
- **Determine the *Reconstructed* M_{top} per event**: Minimize a χ^2 expression for the resolutions and kinematic relationships in the ttbar system. Choose jet to parton assignment and P^{ν}_z based on best fit quality. Build signal and background templates

- **Obtain the measurement from the data**: Compare *Reconstructed* M_{top} from data with same from randomly generated and simulated signal at various input top mass (M_{top}) and backgrounds using an unbinned likelihood fit

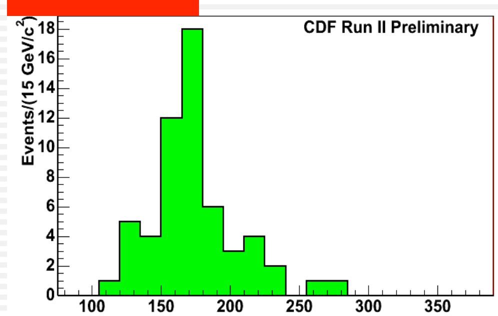
Signal Template



Background Template



Data



$$L = L_{shape} \times L_{background}$$

Best signal + background templates to fit the data

Template Analysis at CDF

- Improve statistical power of the method dividing the sample in 4 subsamples that have different background contamination and different sensitivity to the top mass

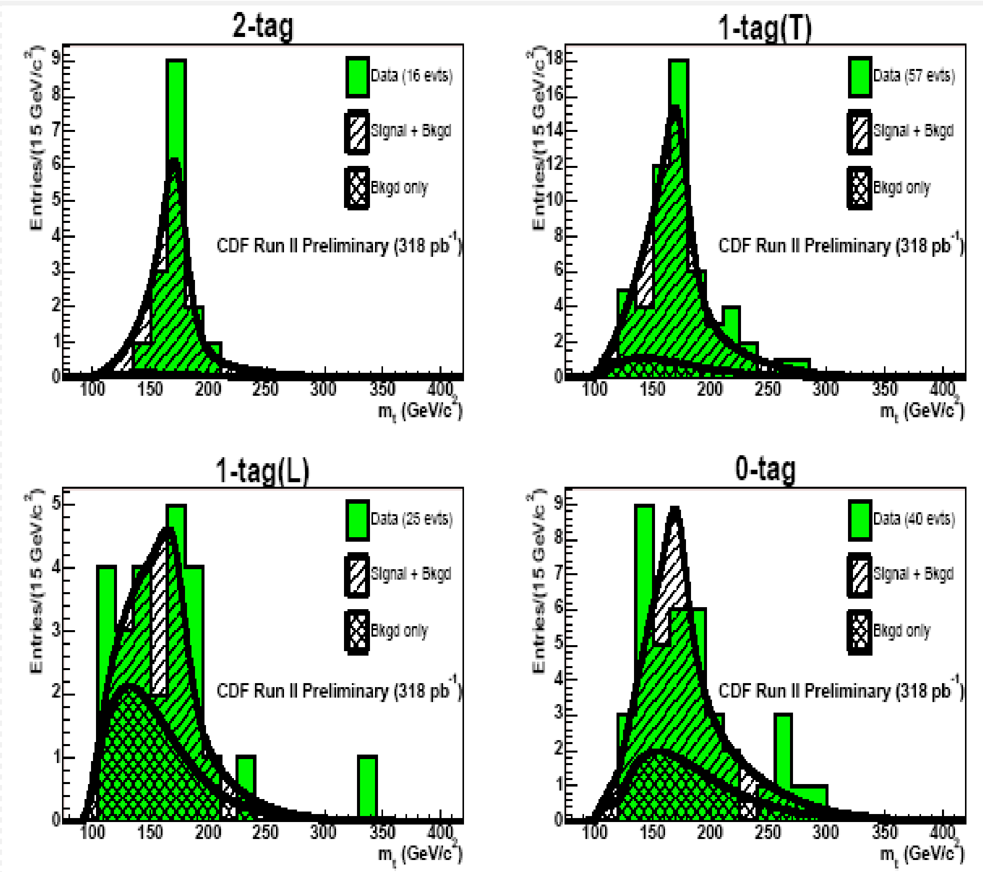
Sample	# b-tags	Jet E_T cut [GeV]
2-tag	2	3 jets w/ E_T>15 4th jet w/ E_T> 8
1-tag(L)	1	3 jets E_T> 15 4th jet 8 < E_T <15
1-tag(T)	1	4 jets E_T > 15
0-tag	0	4 jets E_T > 21

- Extend 1-D template (only on *Reconstructed M_{top}*) to maximize sensitivity to JES:
  - M_{top} and JES are simultaneously determined in likelihood fit using shape comparisons of *Reconstructed M_{top}* and, *Reconstructed M_{jj}* distributions, taking correlations between them
  - Use a priori CDF information on JES (page 8): JES Gaussian constraint (mean=0, width=1 σ)

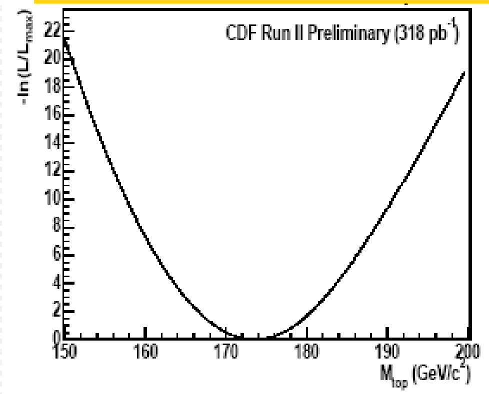
$$-\ln L_{JES} = \frac{(JES - JES_{STD})^2}{2\sigma^2_{JES}} = \frac{(JES - 0)^2}{2 \cdot 1^2}$$

$$L_{total} = L_{2tag} \times L_{1tagT} \times L_{1tagL} \times L_{0tag} \times L_{JES}$$

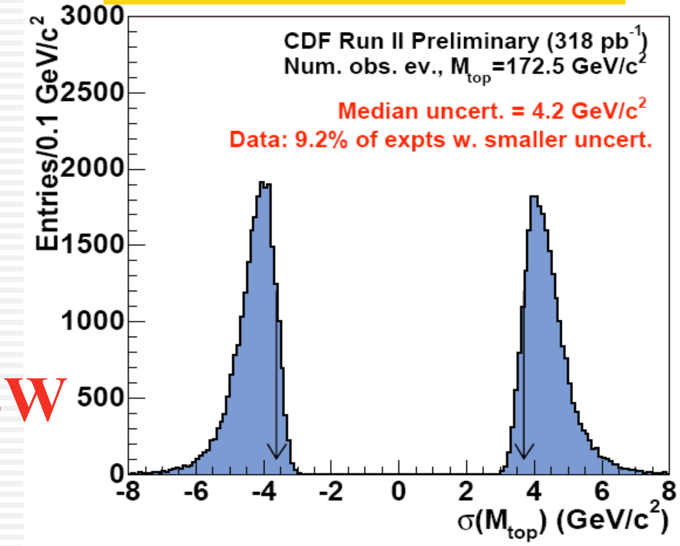
Template Results from CDF



Combined –Log(L)



Expected error



$$M_{top} = 173.5^{+3.7}_{-3.6} (\text{stat} + \text{JES})\ \text{GeV/c}^2$$

NEW

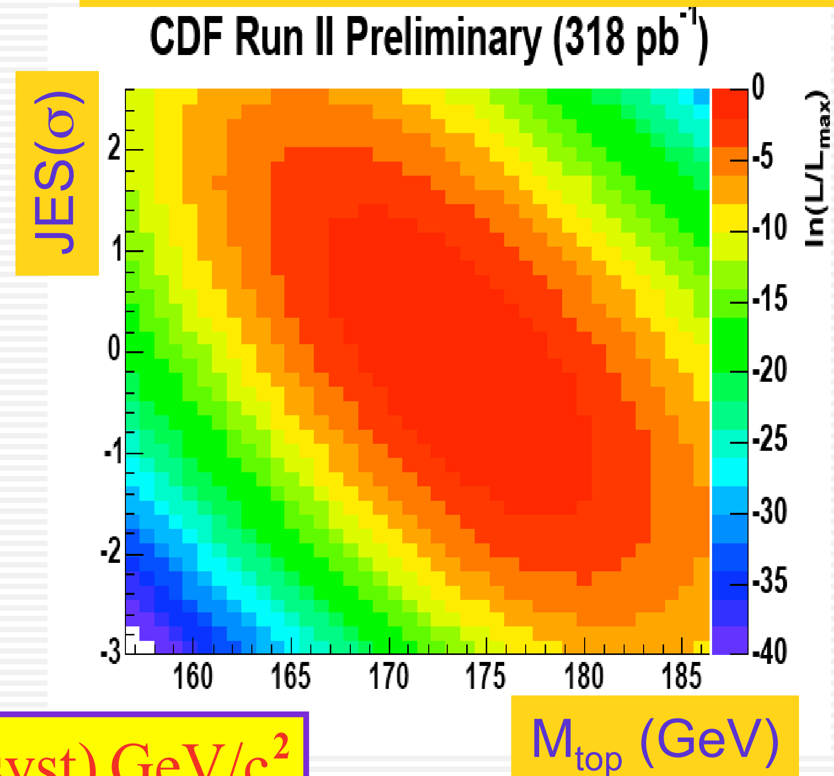
Template Results from CDF

Systematic uncertainties

Source	$\delta M_{top}(GeV/c^2)$
B-jets modeling	0.6
Method	0.5
ISR	0.4
FSR	0.6
Background shape	1.1
PDF	0.3
Other MC modeling	0.4
Total	1.7

Most of these can be reduced with more data

–Log Likelihood vs M_{top}, JES



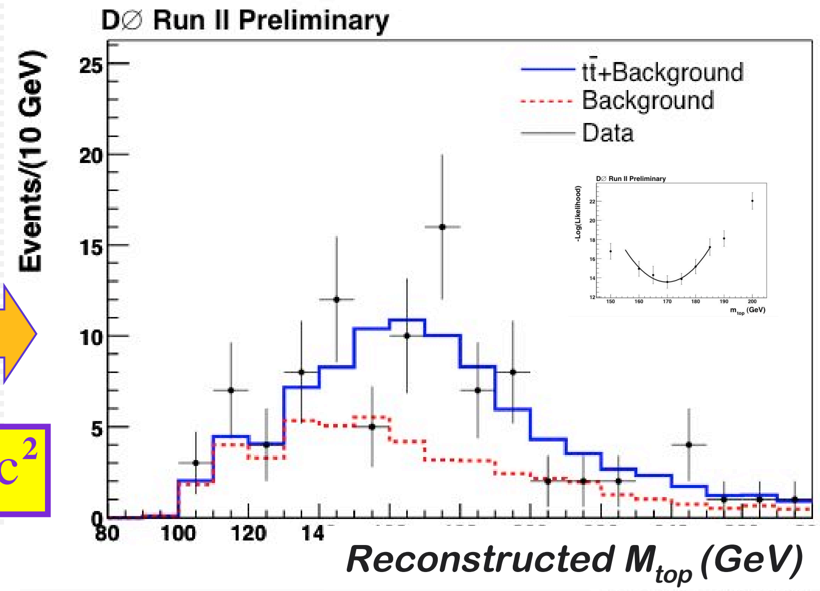
$$M_{top} = 173.5^{+3.7}_{-3.6}(stat + JES) \pm 1.7(syst)\ GeV/c^2$$
$$= 173.5^{+4.1}_{-4.0}\ GeV/c^2$$

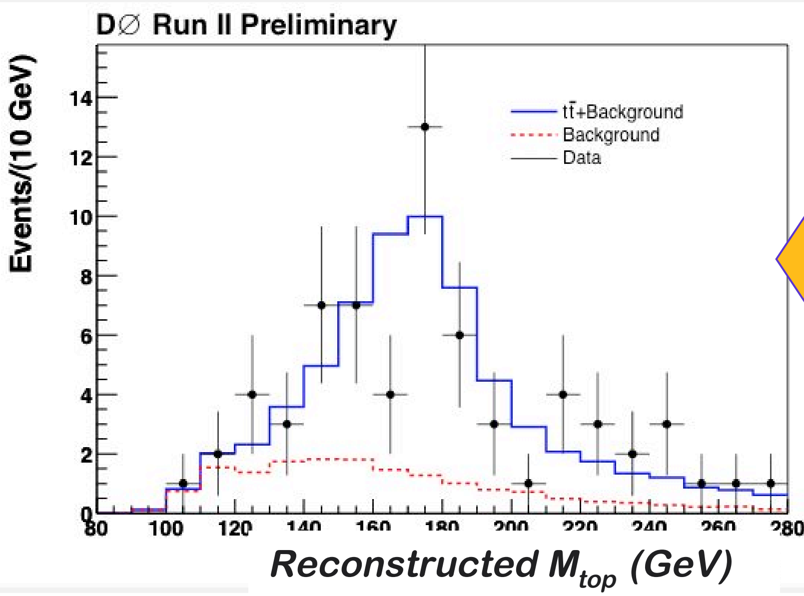
Measurement is more precise than the current world average!

Template Results from DØ

- Topological
  - No b-tagging requirement
- Construct a discriminant using topological variables (D_{LB}) to improve S/B

$$M_{top} = 173.5 \pm 5.8(\text{stat})^{+7.8}_{-7.1}(\text{syst})\ \text{GeV/c}^2$$





- At least one b-tagged jet:
  - no requirement on discriminant D_{LB}
- First top mass at DØ top mass measurement with b-tagging

ttbar candidates 94
S/B~1/1

$$M_{top} = 170.6 \pm 4.2(\text{stat}) \pm 6.0(\text{syst})\ \text{GeV/c}^2$$

Matrix Element Technique

- **Determine mass of the top quark evaluating a probability using all the variables in the event, integrate over all unknowns**

W(y,x) is the probability that a parton level set of variables ***y*** will be measured as a set of variables ***x***

$d^n\sigma$ is the differential cross section: LO Matrix element

$$P(x;M_{top}) = \frac{1}{\sigma}\int d^n\sigma(y;M_{top})\, dq_1\, dq_2\, f(q_1)\, f(q_2)\, W(x,y)$$

f(q) is the probability distribution than a parton will have a momentum ***q***

- **Sum over all permutations of jets and neutrino solutions**

- **Background process probabilities are or not be explicitly included in the likelihood**

- **Top mass: maximize** $\Pi_i P^i(x;M_{top})$
  - **Each event has its own probability**
  - **Correct permutation is always considered (along with the other eleven)**
  - **All features of individual events are included, thereby well measured events contribute more information than poorly measured events**

Matrix Element at DØ

- Last result from Run I: June, 2004

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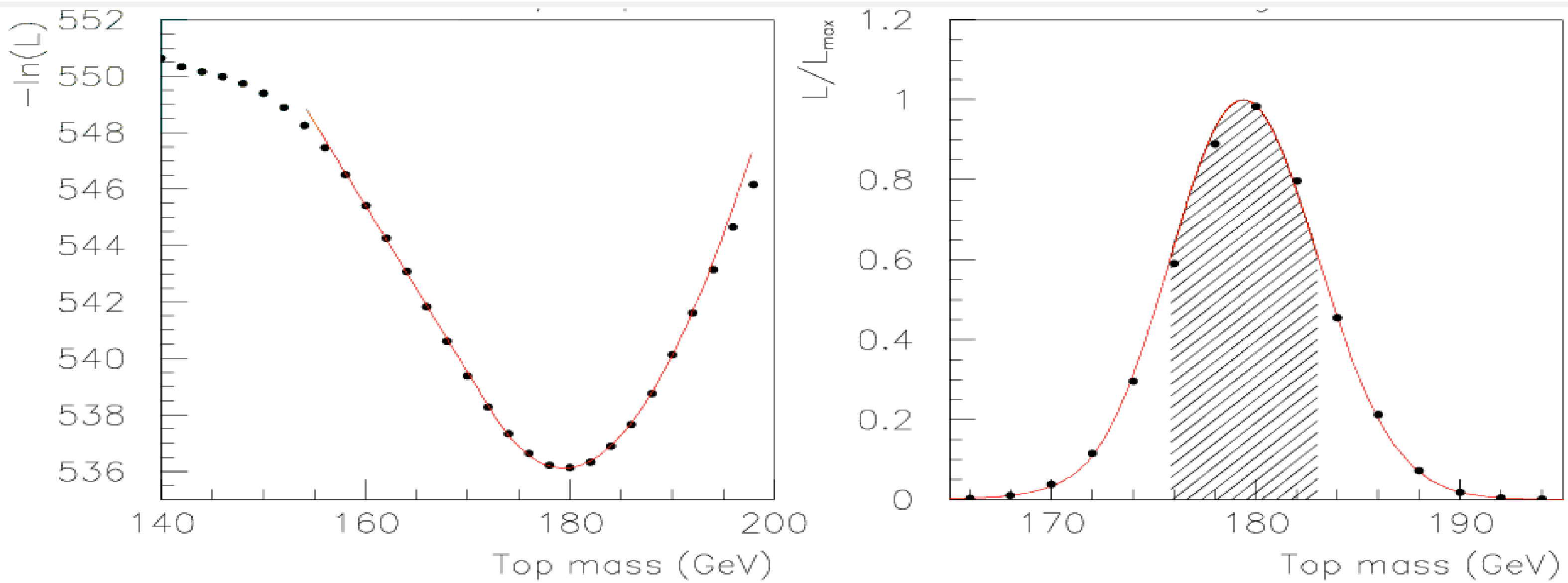
- Reduced the statistical uncertainty from 5.6 to 3.6 (expected error from 7.4 to 4.4) => 2.4 times more data

- Total uncertainty from 7.3 (lepton+jets CDF) to 5.3 (D0)

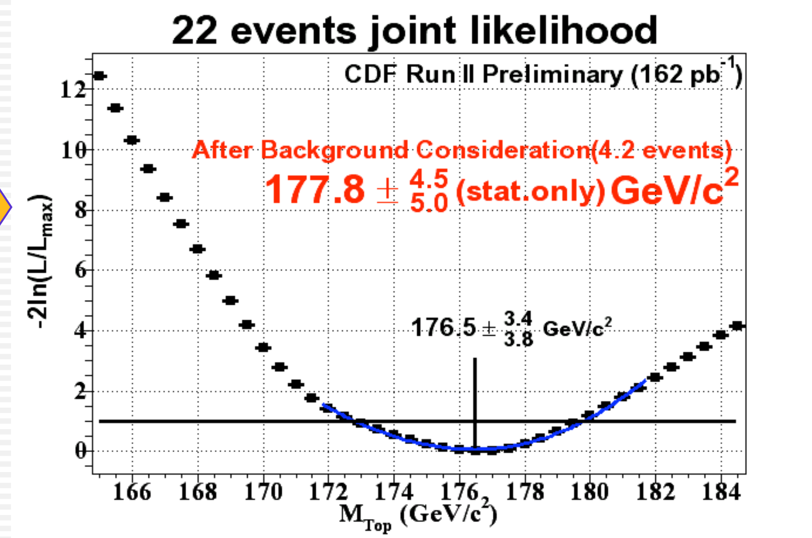


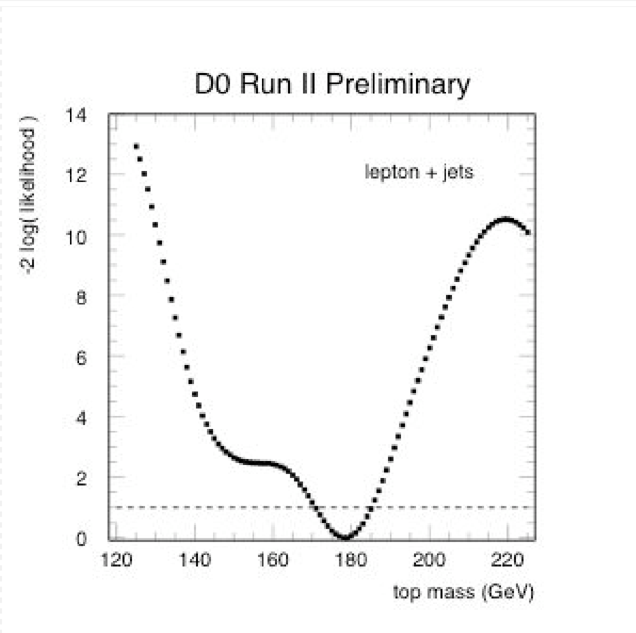
- Run II results from DØ and CDF coming soon!

Other Matrix Element based M_{top}

- **DLM**: only a signal probability, requires b-tagging
- New results with decrease JES and more data coming soon!

$M_{top} = 177.8 \pm^{4.5}_{5.0}$ (stat) $\pm$ 6.2(syst) GeV/c^2



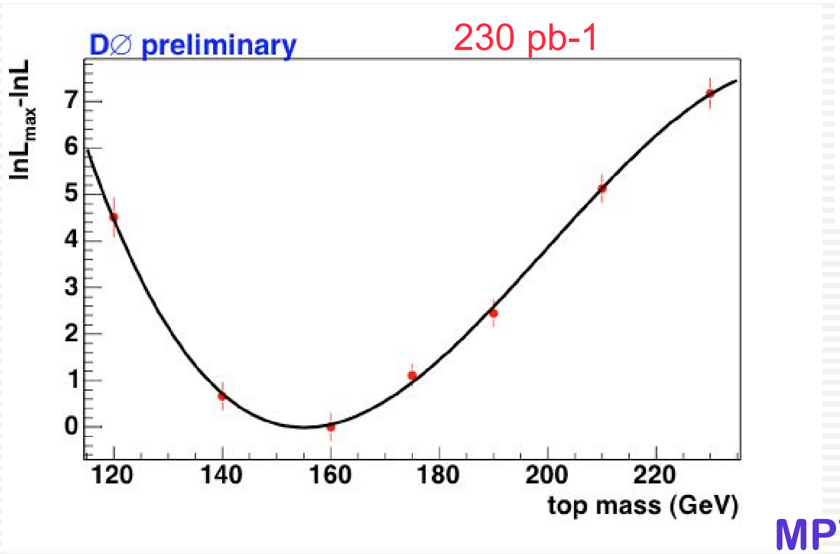


- **Ideogram**: Uses same kinematic fit as DØ template method, and includes D_{LB} discriminant in likelihood fit
- Uses background probability

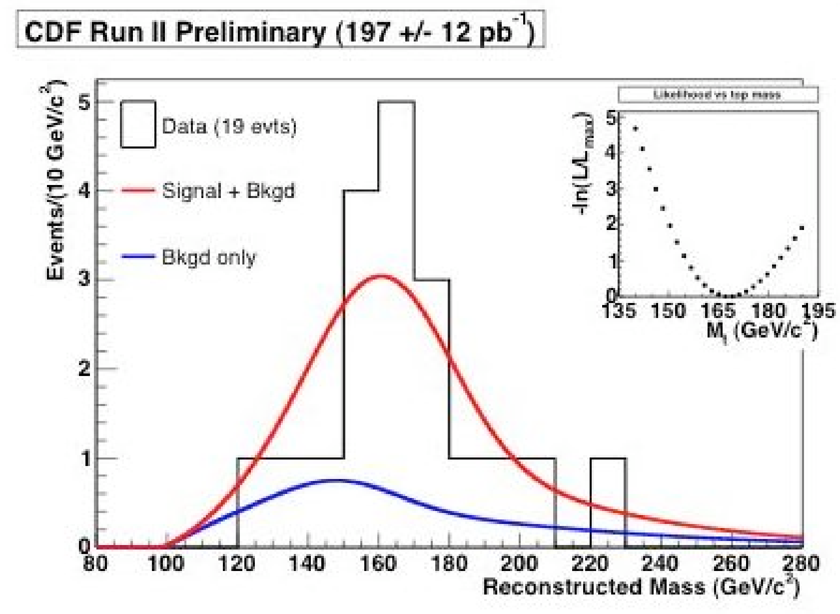
$M_{top} = 177.5 \pm 5.8$(stat) $\pm$ 7.1(syst) GeV/c^2

Current Best Results in Dilepton Channel

- How the analyses solve the problem of under-constrained kinematics?
  - Integrate over 2 variables
  - Weight neutrino solutions
  - Follow template procedure



$$M_{top} = 155 \pm^{14.0}_{13.0} \text{ (stat)} \pm 7.0\text{(syst) GeV/c}^2$$

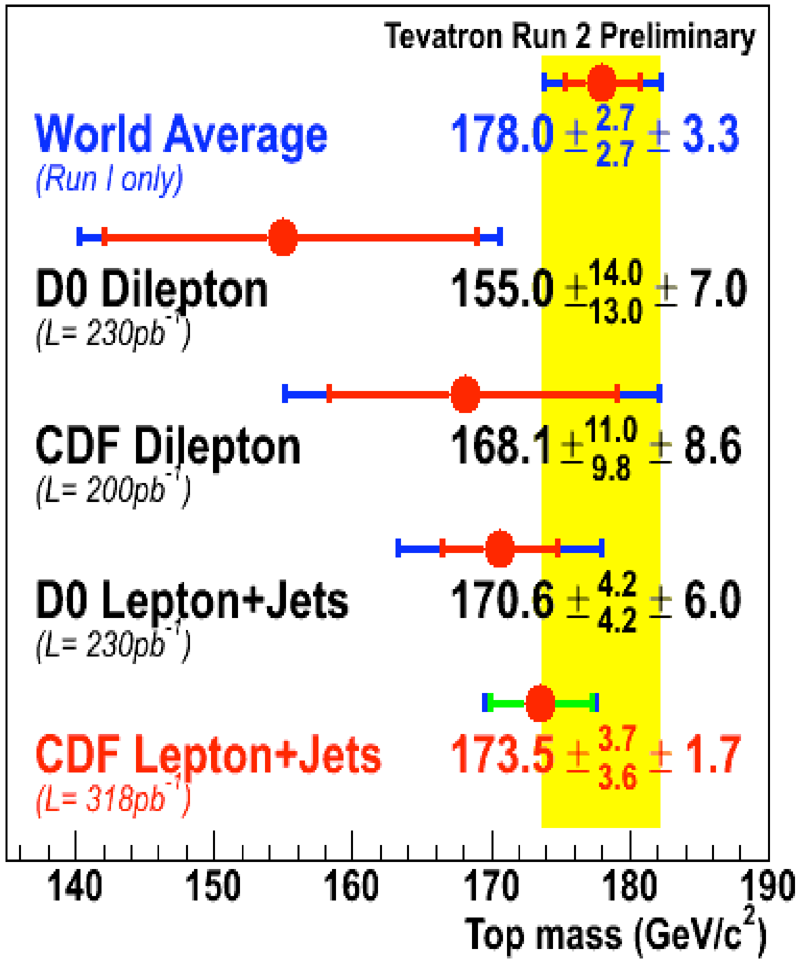


$$M_{top} = 168.1 \pm^{11.0}_{9.8} \text{ (stat)} \pm 8.6\text{(syst) GeV/c}^2$$

S/B ~ 3/1

MPV expectation with $320 pb^{-1}$ δM_{top} ~ 9 GeV !

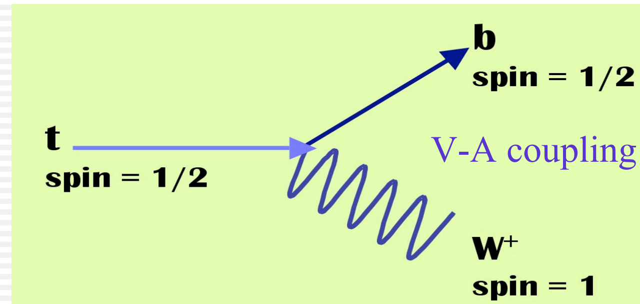
Summary of Top Mass Results

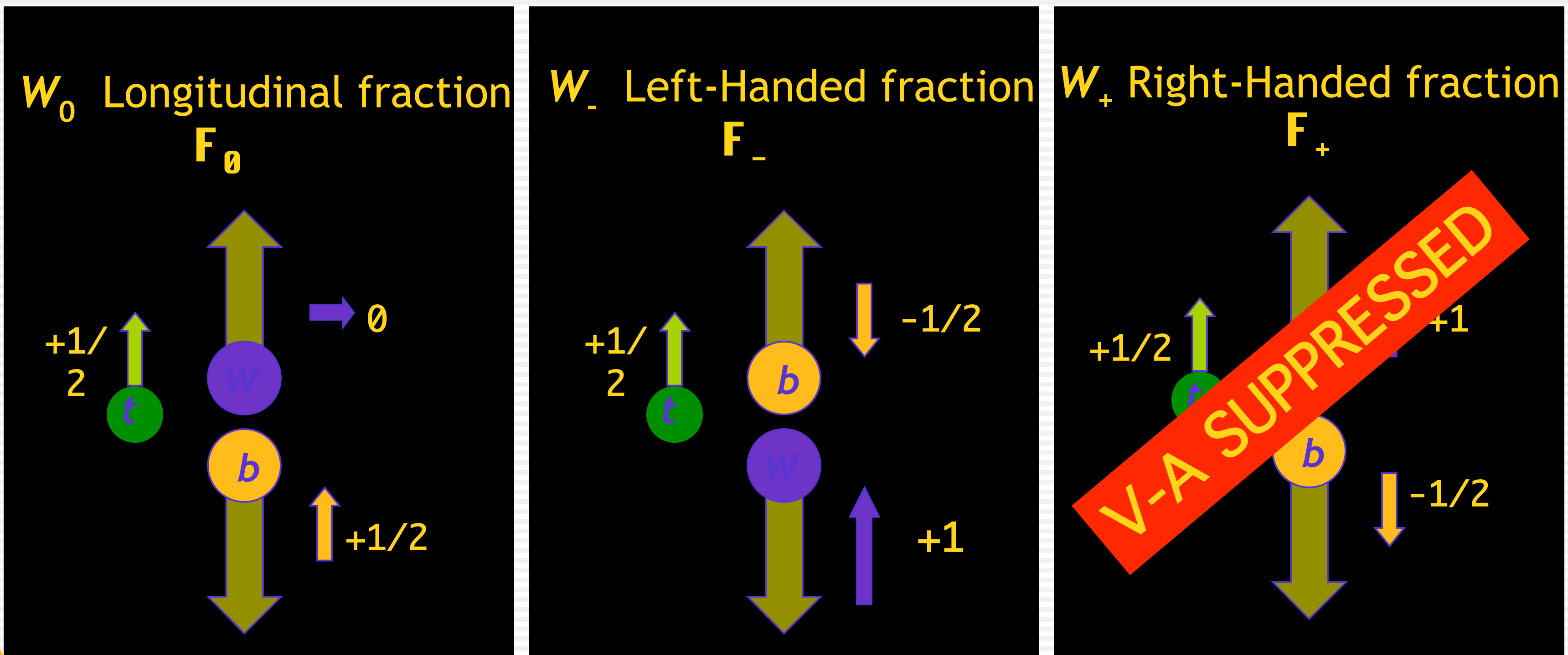


W helicity

W helicity

- Are there **new interactions** at this high energy scale?
- Measuring the helicity of the *W* boson examines the nature of the *tbW vertex*, and provides a stringent test of Standard Model

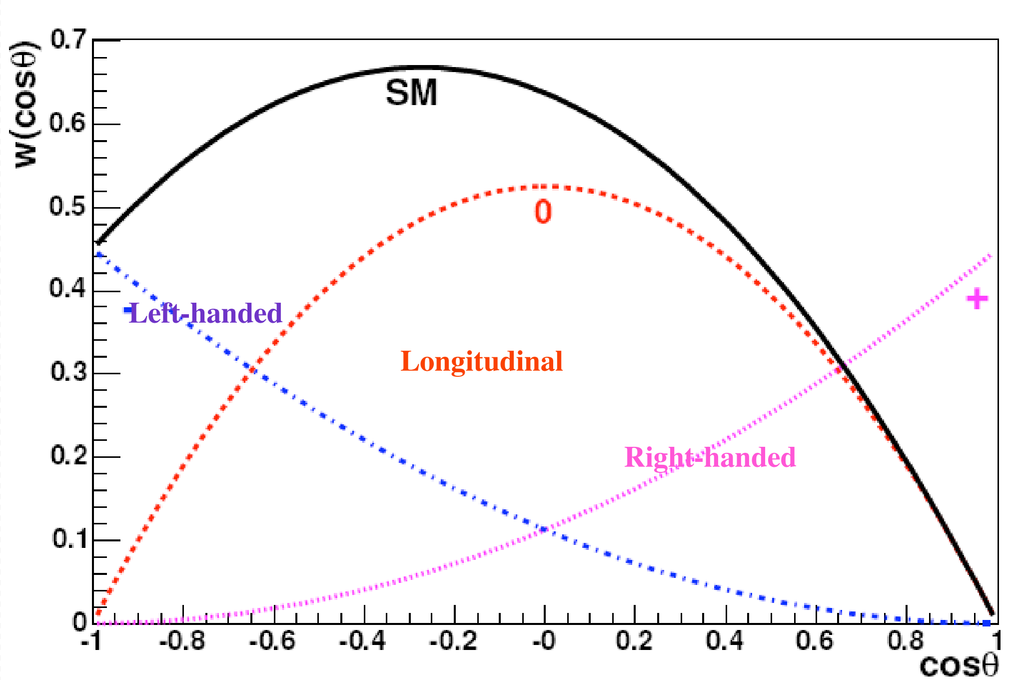


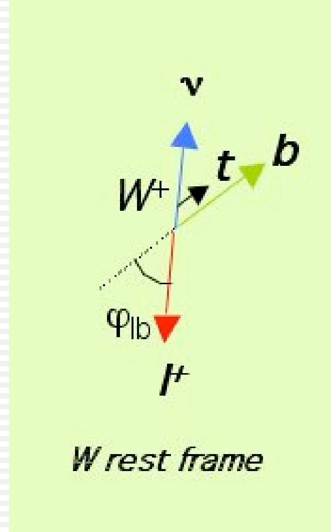


W helicity

- In the Standard Model (with m_b=0):

$$w(\cos\varphi_{l\bar{b}}) = F_- \cdot \frac{3}{8}(1-\cos\varphi_{l\bar{b}})^2 + F_0 \cdot \frac{3}{8}(1-\cos^2\varphi_{l\bar{b}}) + F_+ \cdot \frac{3}{8}(1+\cos\varphi_{l\bar{b}})^2$$



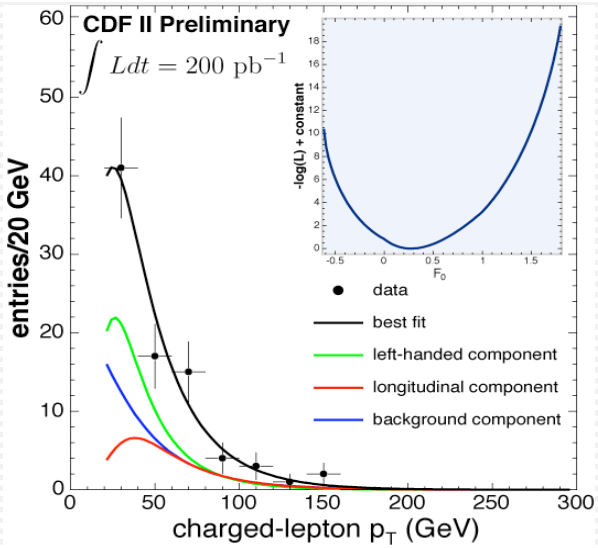


$F_- = 0.3$ $F_0 = 0.7$ $F_+ = 0$

- The P_T of the lepton has information about the helicity of the W boson:
  - longitudinal: leptons are emitted perpendicular to the W (harder lepton P_T)
  - left-handed: leptons are emitted opposite to W boson (softer lepton P_T)

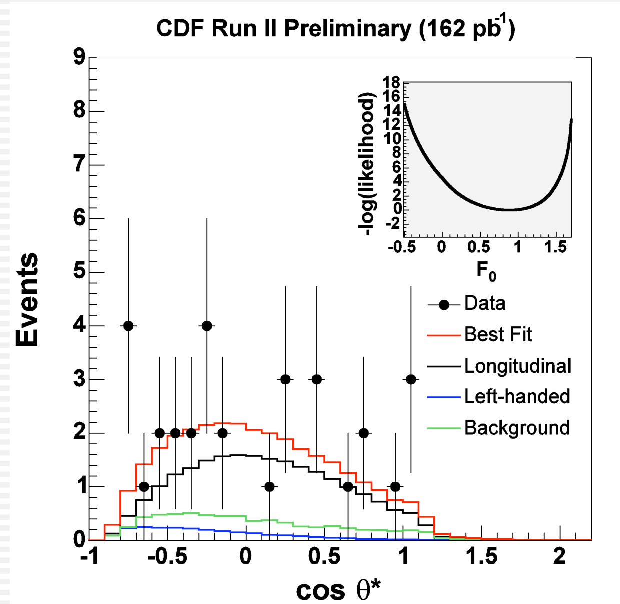
Longitudinal Fraction, F_0

- Likelihood analysis of P_T spectrum
- Combined lepton+jet and dilepton samples: 70 events



$$F_0 = 0.27 \pm^{0.35}_{0.21}\ (stat + syst)$$
$$F_0 < 0.88 @ 95\%CL$$

- Likelihood analysis of cos θ*
- Combined lepton+jet and dilepton samples: 31 events

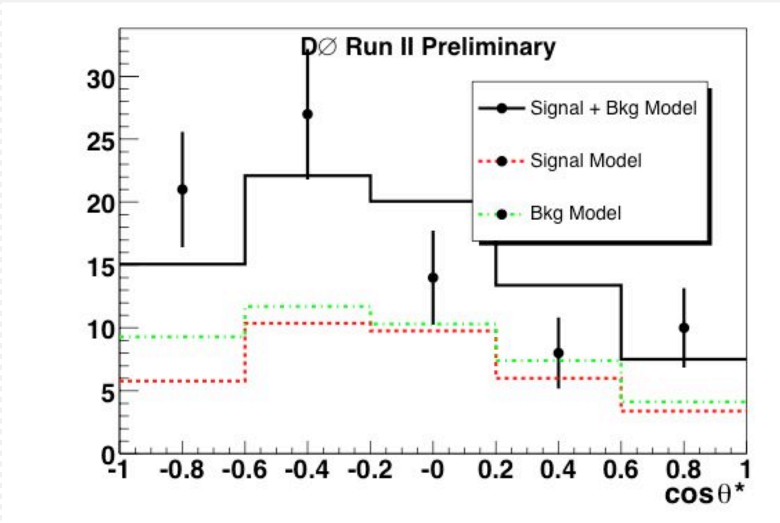


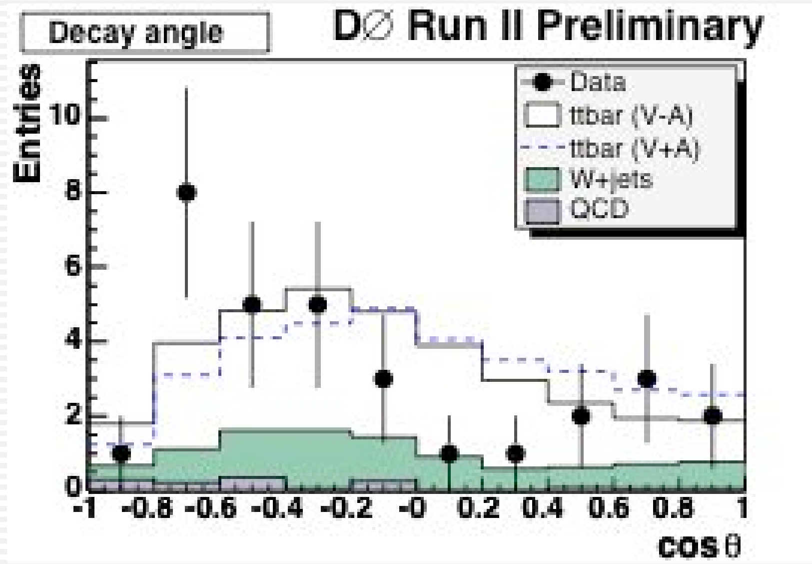
$$F_0 = 0.89 \pm^{0.30}_{0.34}\ (stat) \pm 0.17 (syst)$$
$$F_0 > 0.25 @ 95\%CL$$

- Assuming F_+=0
- Dominated by statistical uncertainties
- Run I best result (DØ) 125pb^{-1}: 0.56 +- 0.31 using ME Technique

Right Handed Fraction, F_+

- Likelihood on cosθ*
- Topological selection: 80 events
- b-tagged selection: 31 events





$$F_+ = -0.11 \pm 0.19(stat)$$
$$F_+ < 0.24 @ 90\% CL(stat + syst)$$

$$F_+ = -0.13 \pm 0.23(stat)$$
$$F_+ < 0.24 @ 90\% CL(stat + syst)$$

- Assuming F_0=0.70
- Dominated by statistical uncertainties
- Run I best result (CDF) $109pb^{-1}$: F_+<0.18 @95% CL using cosθ*

ttbar Spin Correlations

ttbar Spin Correlations

- Agreement between σ_{ttbar} experimental and theoretical expectations => assume top has spin 1/2.

- Since Γ_t~1.4 GeV
  - spin transferred to final state (decay products correlated to top quark spin).
  - use polarization properties of the top quark as additional observables for testing the SM and to search for New Physics.

- Can be observed in single-top since it is produced 100% correlated.

- Some net polarization of top quark in pair production: $N(t_\uparrow)=N(t_\downarrow)$ but in the proper spin quantization axes a large asymmetry between like- and unlike-spin configurations can be observed

⇐ k = 0.88 SM, correlation coefficient between top- antitop spin polarizations.

- DØ Run I: k>-0.25 @ 68% CL.

- CDF Run II preliminary sensitivity study 340pb-1 σ =1.6, 2fb-1 σ=0.62.

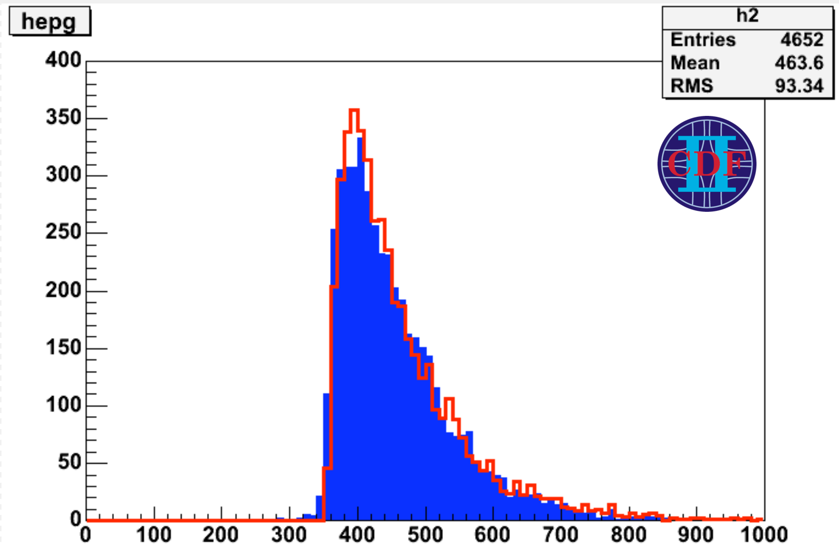
Search for ttbar Resonances

ppbar->X->ttbar

- Test ttbar production from new sources such as narrow resonances

$$p\bar{p} \longrightarrow X^0 \longrightarrow t\bar{t}$$

- Many models of New Physics predict new particles coupled to the 3rd generation, in particular the top quark.
- Better analyses techniques, from templates to ME based searches.
- Use the differential cross section to reconstruct the M_{ttbar} at parton level.
- Follow template procedure for establishing limits.



SM ttbar (Pythia)
Red : parton level Mttbar
Blue: reconstructed Mttbar

Run I search of Z' with G=1.2%M:
CDF(D0): $M_{Z'}$>480(560) GeV @ 95% CL

Conclusions

- Top quark physics program at the Tevatron Run II is extremely rich: from *QCD* tests to search for *New Physics*.
- Challenging final states:
  - requires to fully use detector capabilities
- Method of extraction of observables are getting far more sophisticated:
  - making maximal use of the statistics
  - smarter ways to account for systematic uncertainties
- We are moving from discovery to precision measurements of top quark properties.

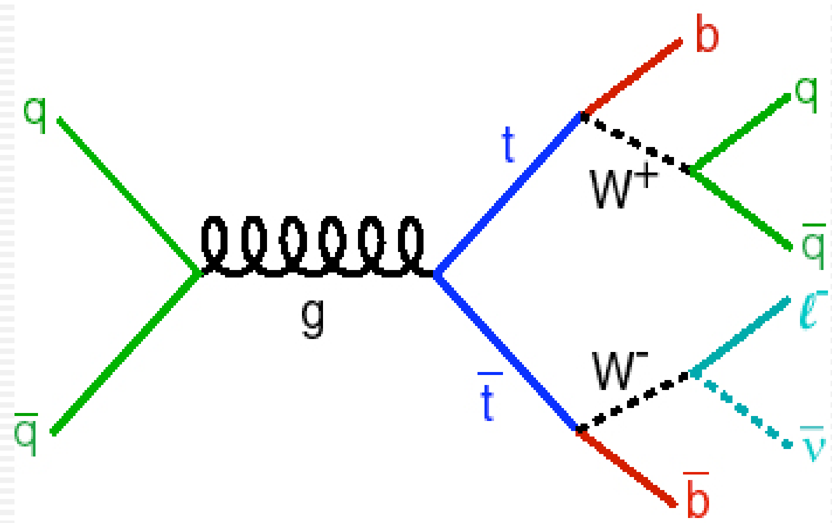
$$M_{top} = 173.5^{+4.1}_{-4.0} \, GeV/c^2$$

Top Quark at APS

- Top Mass in all-jets channel CDF, Georghe Lungu, Top Quark Session I, yesterday: using ME
- Top Mass in dilepton channel CDF, Tuula Maki, Top Quark Session I, yesterday: using Pz ttbar
- Top Mass in dilepton channel CDF: Simon Sabik, Top Quark Session I, yesterday: using neutrino weighting
- Top Mass in lepton+jets channel CDF: Jean-Francois Arguin, Top Quark Session I, yesterday: using 2-D template
- Top Mass in lepton+jets CDF/LHC: James Lamb, Top Quark Session I, yesterday: using decay length
- Top Mass in lepton+jets D0: Philipp Schienferdecker, Top Quark Session II, today: using D0 matrix element in Run II
- Top Mass in lepton+jets D0: Robert Harrington, Top Quark Session II, today: using D0 matrix element in Run II + b-tagging
- Top Mass in dilepton D0: Petr Homola, Top Quark Session II, today: neutrino weighting
- Top Mass in lepton+jets D0: Martjin Mulders, Top Quark Session II, today: matrix element Ideogram
- Top Mass in dilepton D0: Jeff Temple, Top Quark Session II, today: neutrino weighting
- X->ttbar at CDF: Top Quark Session III, Brandon Parks, Valentin Necula, NN and ME technique
- W-helicity: Top Quark Session III, Bryan Gmyrek, cos(theta*)

M_{top} Measurement in lepton+jets Channel

- Larger branching ratio
- Reasonable Signal/Background
- Over-constrained kinematics



- Signature
  - Two b quarks
  - Two light quarks
  - High p_T lepton
  - Neutrino (undetected)
    - P_x and P_y from E_T conservation
    - P_z constrained by kinematics

Leading 4 jets combinatorics
- 12 possible jet-parton assignments
- 6 with 1 b-tag
- 2 with 2 b-tags

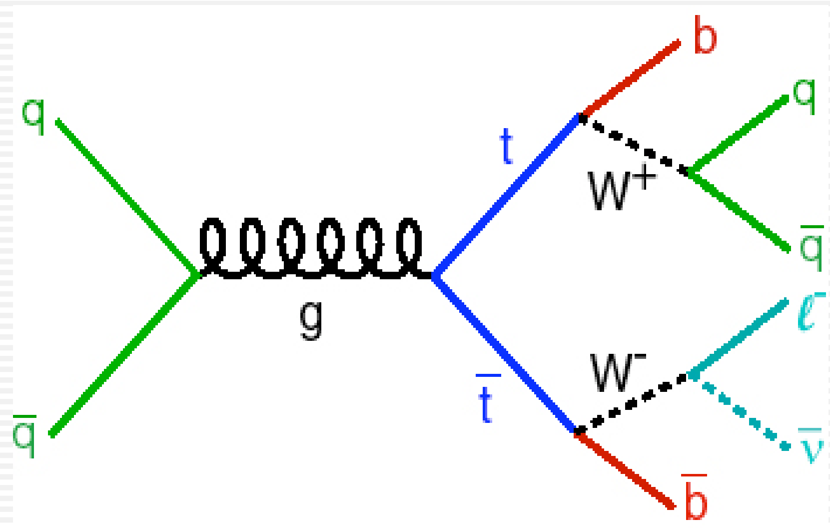
ISR + FSR: Extra jets from initial/final state gluons

- Typical event selection:
  - One high P_T lepton (20 GeV)
  - 4 or more jets (>15 GeV)
  - $\not{E}_T$ (>20 GeV)
  - b-tagging (optional)

Two different techniques: Template and Matrix Element based

M_{top} Measurement in Dilepton Channel

- Less statistics
- Excellent S/B
- Underconstrained kinematics: need to assume knowledge of some quantity
- Less combinatorics: 2 jets
- Smaller jet systematics



- Signature:
  - Two b quarks
  - Two high P_T leptons
  - Two neutrinos

- Typical event selection:
  - One high P_T lepton (>15 GeV)
  - Oppositely charged high P_T lepton or isolated track (>15 GeV)
  - Two or more high P_T jets (>20 GeV)
  - $\not{E}_T$ (>25 GeV)

- Backgrounds:
  - Diboson, Drell-Yan, Z->tautau, W+jets (fake lepton)