Top Quark Properties at the Tevatron

Outline:

- Measurements of the Top Quark Mass
- Measurements of other Top Quark Properties
  - W Boson Helicity
  - Top Quark Charge
  - Search for $t\bar{t}$ Resonances

Philipp Schieferdecker, Munich University (LMU)

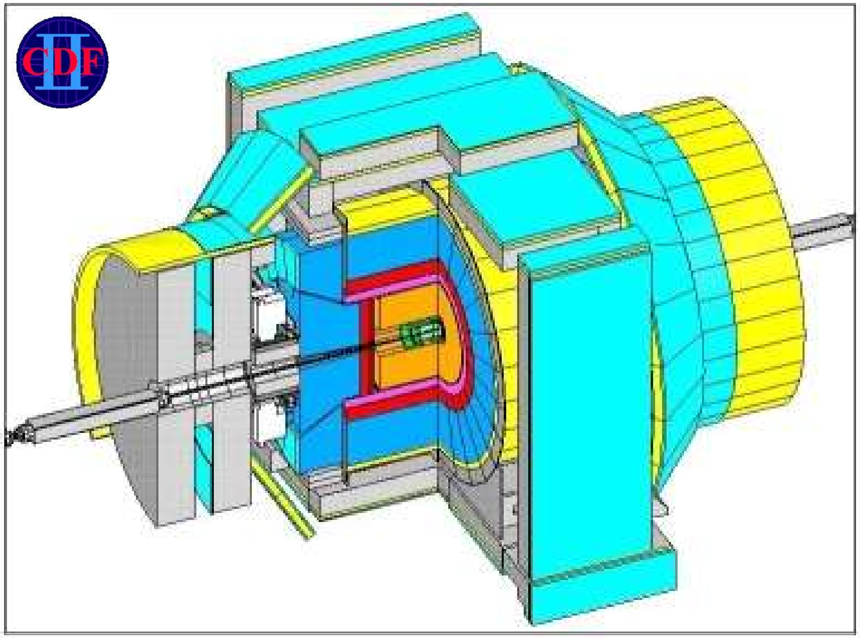
on behalf of the CDF and DØ Collaborations

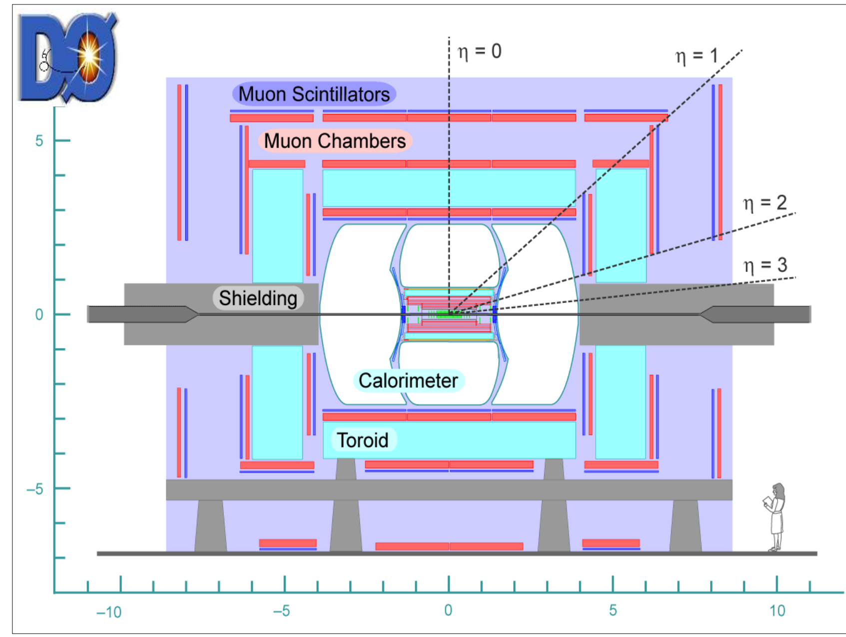
bmb+f - Förderschwerpunkt

Elementarteilchenphysik

Großgeräte der physikalischen Grundlagenforschung

CDF and DØ, the Tevatron Detectors



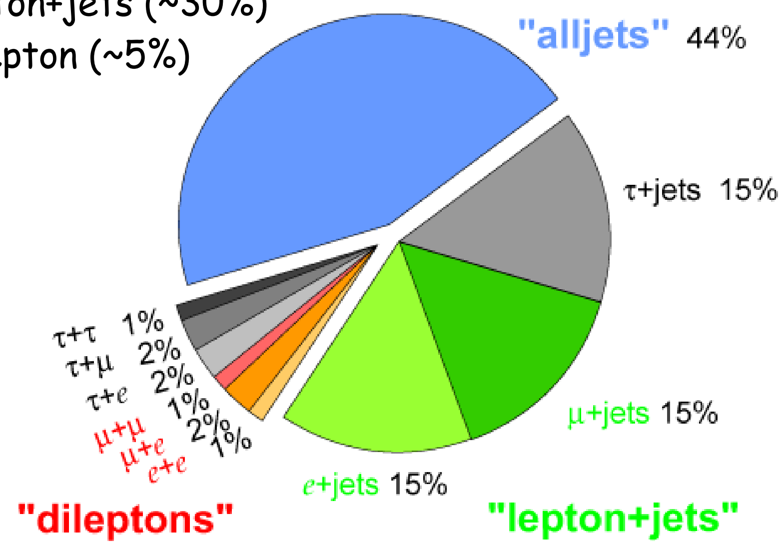


- Both CDF and DØ recording collisions at $\sqrt{s}$=1.96 TeV from the Tevatron, currently the world's only top quark factory
- Precise tracking and vertexing for b-tagging and improved lepton identification
- Data taking efficiency: >85%
- More than $1fb^{-1}$ of data recorded per experiment; Results presented here make use of up to $750pb^{-1}$

Top Production and Decay

- In ppbar collision at $\sqrt{s}$=1.96 TeV, top quarks are primarily produced in pairs
  - SM cross section: ~7 pb
  - ~85% via quark annihilation
  - ~15% via gluon fusion

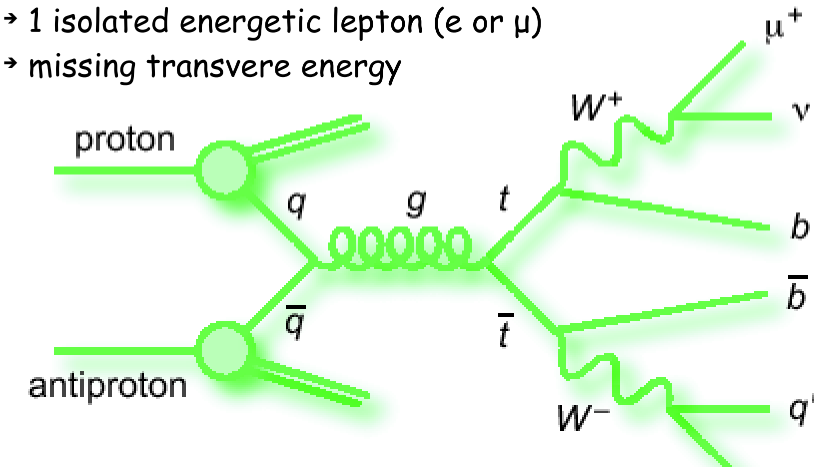
- t->Wb branching ratio ~1, different analysis channels considered according to W boson decay modes:
  - alljets (~44%)
  - lepton+jets (~30%)
  - dilepton (~5%)



- Reconstruction of τ-leptons is experimentally challenging. τ-final states are not considered in the analyses presented here, in the following "lepton" always refers to e or μ!

Lepton+Jets:

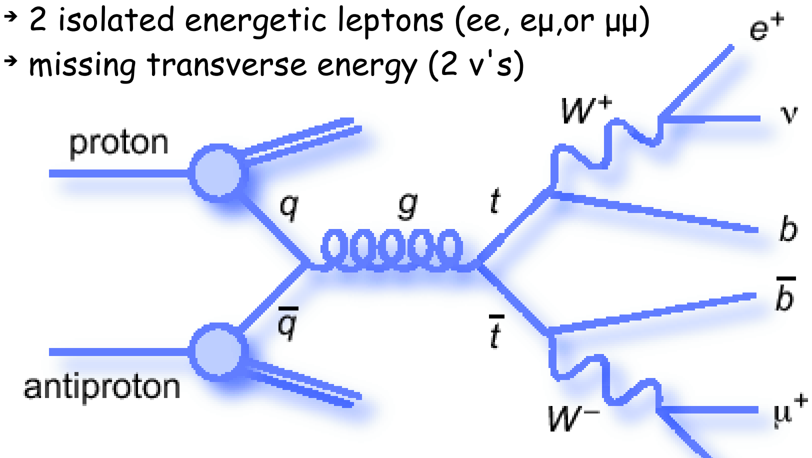
- ≥4 calorimeter jets (2 b-jets)
- 1 isolated energetic lepton (e or μ)
- missing transvere energy



Backgrounds: W+jets, fake leptons

Dilepton:

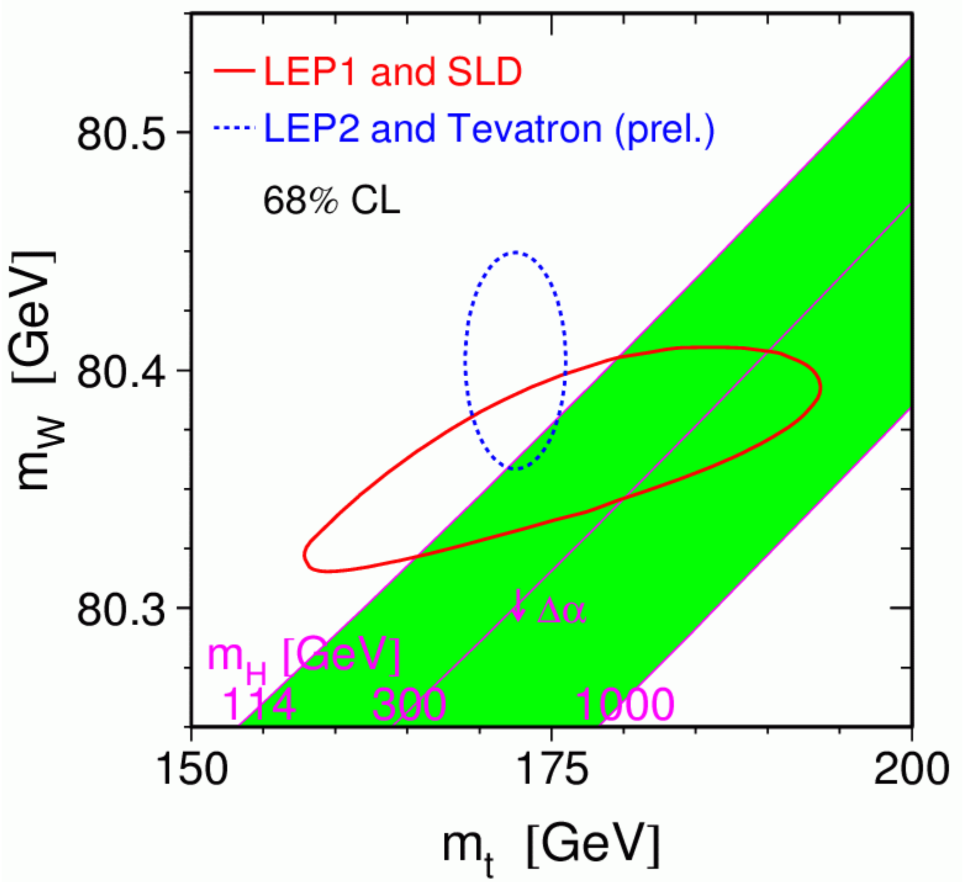
- ≥2 calorimeter jets (2 b-jets)
- 2 isolated energetic leptons (ee, eμ,or μμ)
- missing transverse energy (2 ν's)



Backgrounds: Z+jets, Diboson

Top Quark Mass

- The top quark mass is a free parameter of the Standard Model
- The top quark is by far the heaviest of the six known quarks
- Its suspiciously high mass suggests a special role of the top quark in the Standard Model yet to be revealed
- Precision measurements of the top quark and W boson masses constrain the mass of the Higgs boson via radiative corrections
- With 4-8fb^{-1} of Tevatron data: $\delta m_t \sim 1.5$ GeV (CDF and DØ combined)

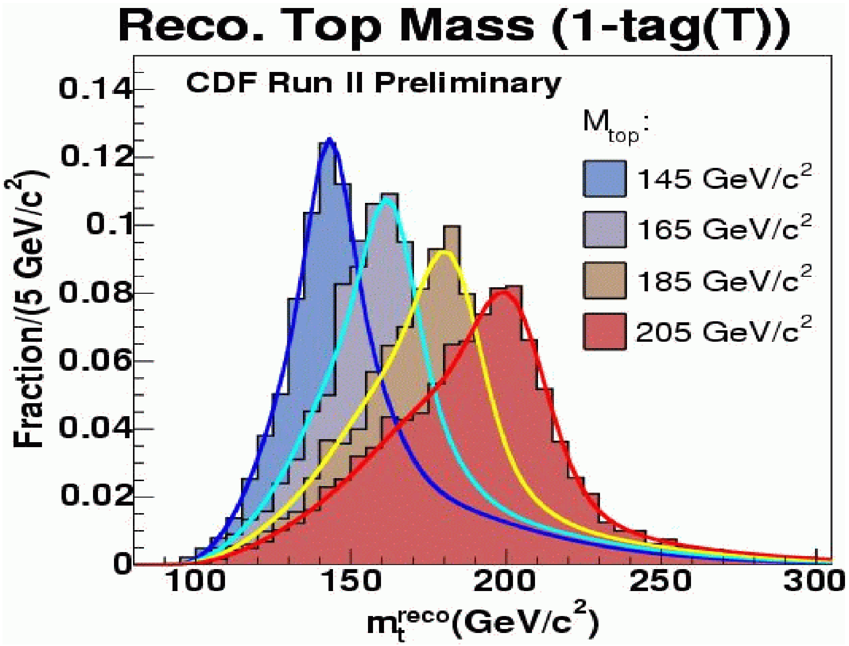


Tevatron top quark mass measurements will be relevant for many years, even after LHC turnon

CDF: Template Method (lepton+jets)

- For each event, reconstruct m_t using a kinematic fit:

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



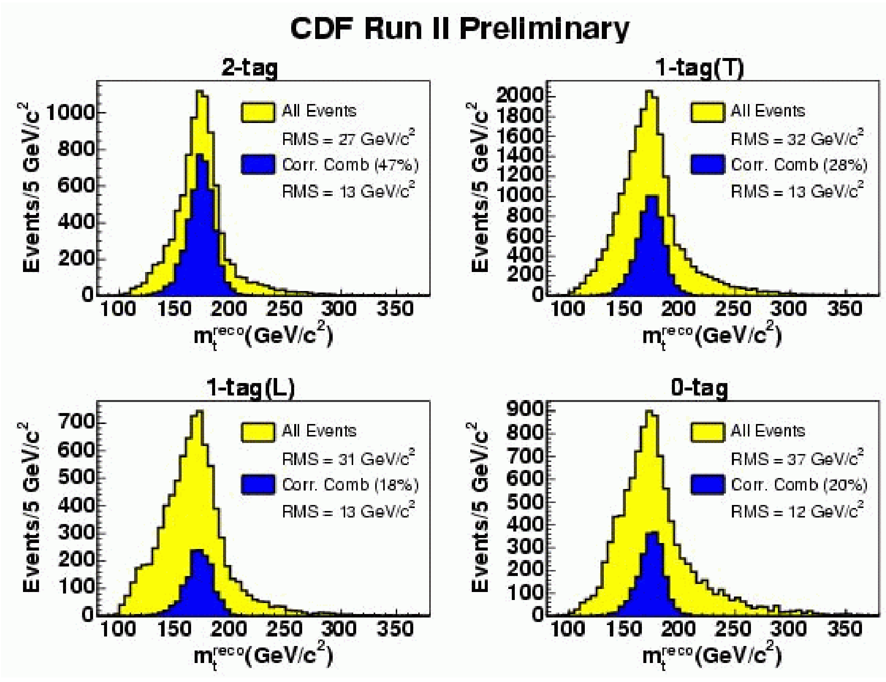
- Choose m_t from jet-parton assignment with lowest χ^2

- Build template distributions from Monte Carlo samples with different true top quark masses

- Extract result from data sample using an unbinned likelihood fit:

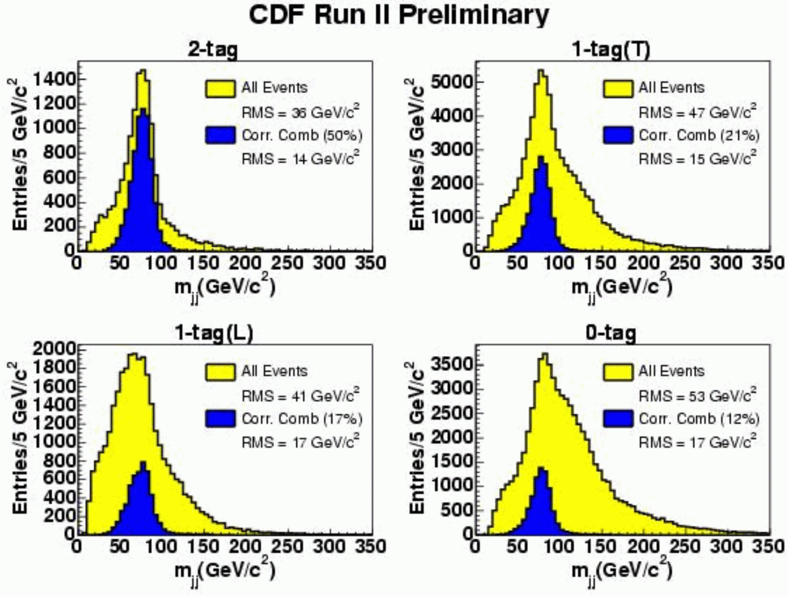
$$\mathcal{L}_{\text{sample}} = \mathcal{L}_{\text{shape}}^{m_t^{\text{reco}}} \times \mathcal{L}_{\text{shape}}^{m_{\text{jj}}} \times \mathcal{L}_{\text{nev}} \times \mathcal{L}_{\text{bg}}$$

- Divide events into 4 subsamples according to the number of identified b-jets to improve statistical sensitivity
  - events with more b-tags show better mass resolution and higher S/B
  - 1-tag(L): lower pT threshold for 4th jet than 1-tag(T)



In situ jet energy calibration:

- The mass of the hadronically decaying W boson provides a constraint on the jet energy calibration
- Expressed in units of the uncertainty $\sigma(p_T,\eta)$ of the external calibration
- Use reconstructed di-jet mass templates, various scales
- Reduce dominant systematic uncertainty due to jet energy scale!



Systematic Uncertainties:

- Dominant systematic uncertainty (JES) absorbed in likelihood fit result (~1.8 GeV)
- Residual JES error: from p_T and η dependent scale uncertainties
- Remaining uncertainties largely due to uncertainties in modeling

Source	$\Delta M_{top}(GeV/c^2)$
Residual Jet Energy Scale	0.7
ISR/FSR	0.6
B-jet modeling	0.6
Background Shape	0.5
Background JES	0.4
Parton Distributions	0.3
Generator	0.2
Simulation Statistics	0.3
B-tagging	0.1
Total	1.3

Result:

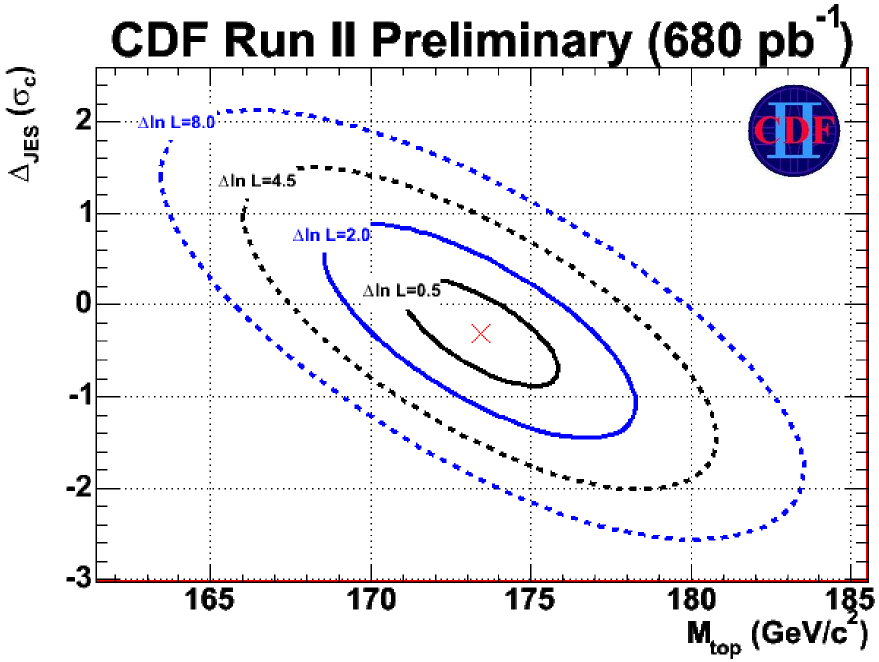
m_t=173.4 ± 2.5 (stat.+JES) ± 1.3 (syst.) GeV

or

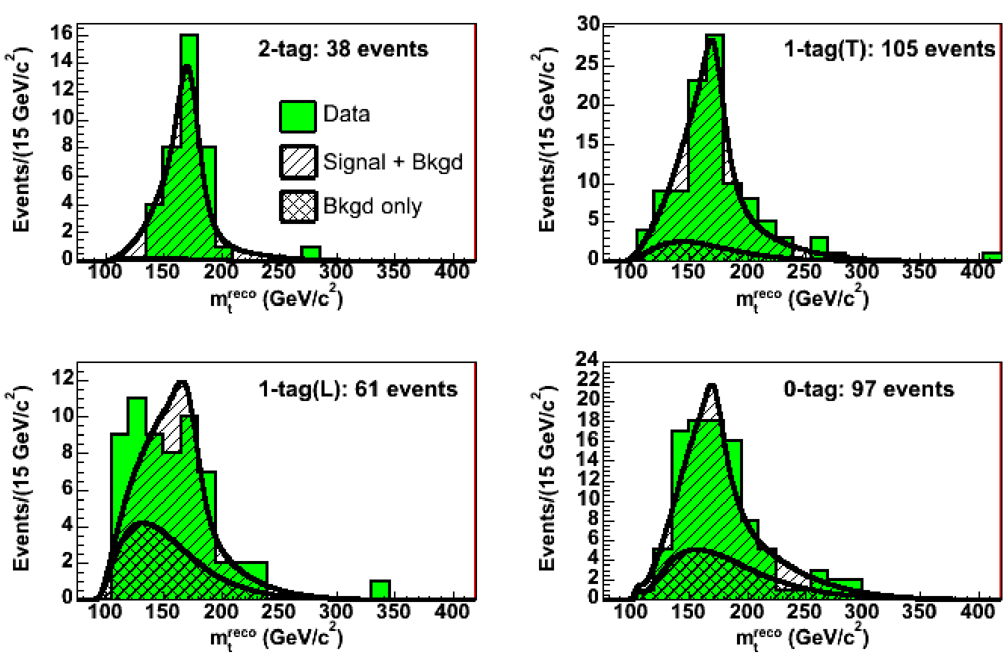
m_t=173.4 ± 2.8 GeV

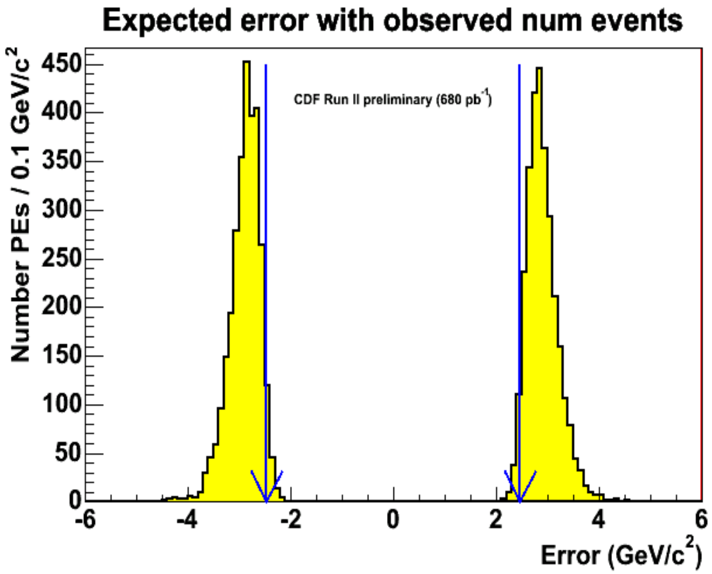
Single best measurement of m_t

ΔJES=-0.3±0.6σ



CDF Run II Preliminary (680 pb^{-1})





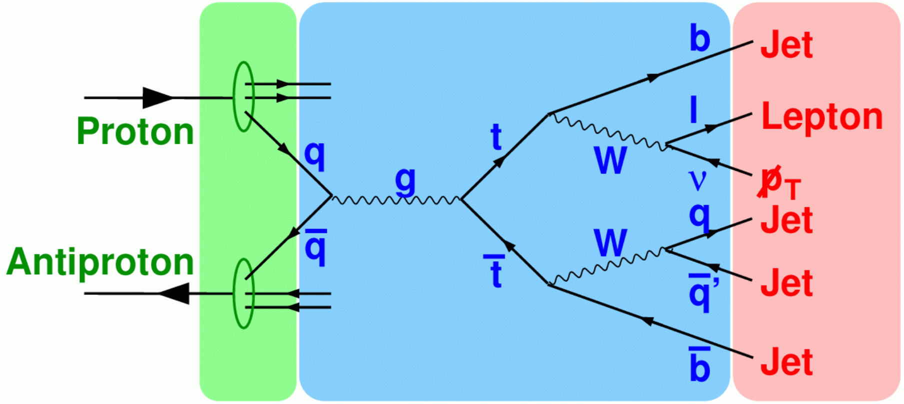
Matrix Element Method

- Use each event's full kinematic information to calculate probability to originate from $t\bar{t}$ production, as a function of assumed m_t
- Calculate the probability to be background accordingly and combine to event probability:
  - $P_{evt}(x;m_t,f_{sgn}) = f_{sgn}\ P_{sgn}(x;m_t) + (1-f_{sgn})\ P_{bkg}(x)$

  where f_{sgn} is the fraction of signal events in the sample
- Combine all events in a likelihood
  - $-\ln L(x_1,\ldots,x_n;m_t,f_{sgn}) = -\Sigma_{i=1}^{n} \ln P_{evt}(x_i;m_t,f_{sgn})$

  and maximize likelihood w.r.t. to m_t and f_{sgn}
- Well measured events contribute more than poorly measured events:
  achieve optimal use of statistical information!
- I will present applications of this method to both lepton+jets and dilepton events
- Lepton+Jets: Use invariant mass of hadronically decaying W boson to obtain JES
  - $L=L(x_1,\ldots,x_n;m_t,f_{sgn},JES)$
  - JES is global scale factor relative to external jet energy calibration
  - Reduce dominant systematic uncertainty by fitting m_t and JES simultaneously

Calculation of the signal probability:



- Integration over parton phasespace (y)
- Assume all angles to be well measured
- Assume $p_T(t\bar{t})=0$
- Parametrize detector resolution of all energies (W(x,y))
- Perform remaining (5-6) integrations using MC integration techniques:

$$\mathcal{P}_{t\bar{t}}(\vec{x}, m_t) = \underbrace{\frac{1}{\sigma_{t\bar{t}}(m_t)}}_{\text{Normalisation}} \int \underbrace{dp_q dp_{\bar{q}} f(p_q) f(p_{\bar{q}})}_{\text{PDFs}} \underbrace{d\sigma_{t\bar{t}}(\vec{y}, m_t)}_{\text{diff. xsec}} \underbrace{W(\vec{x}, \vec{y})}_{\text{det. resolutions}}$$

MATRIX ELEMENT

- Consider all possible jet-parton assignments!
- Consider all possible solutions for the z-component of the neutrino momenta

Matrix Element Method III

Parametrization of jet energy resolution: jet transfer function W(Ej,Ep)

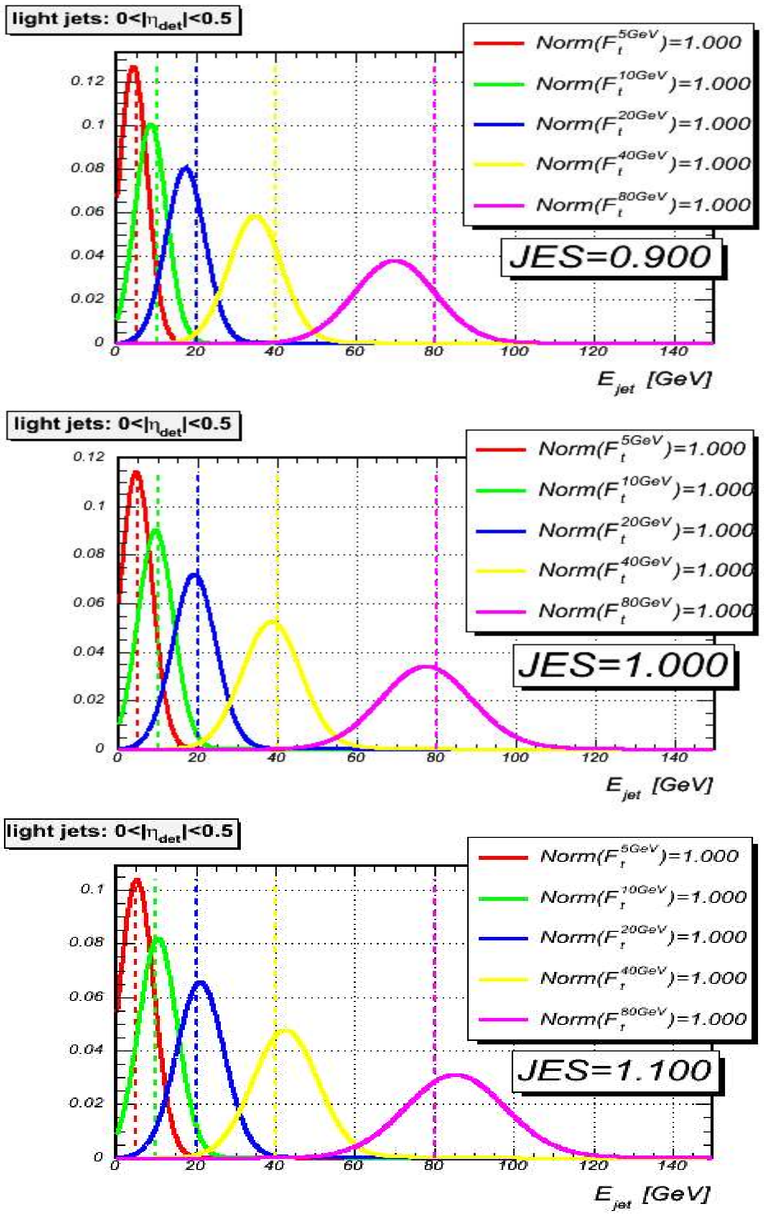
- $W(E_j,E_p)$ yields for each parton energy E_p the probability to be measured as E_j (j=jet) in the calorimeter

- Parametrized as a double Gaussian in $\delta E = E_j - E_p$ (5 parameters), where each parameter is a linear function of E_p itself
  - → jet resolution is function of E_p

- Different parameter sets for light jets, b jets, and semileptonic b-jets. Derived from Monte Carlo events.

- Lepton+Jets: The global jet energy scale parameter JES is included in the event probability via the jet transfer function:

$$W(E_j, E_p; JES) = \frac{W\left(\frac{E_j}{JES} - E_p\right)}{JES}$$

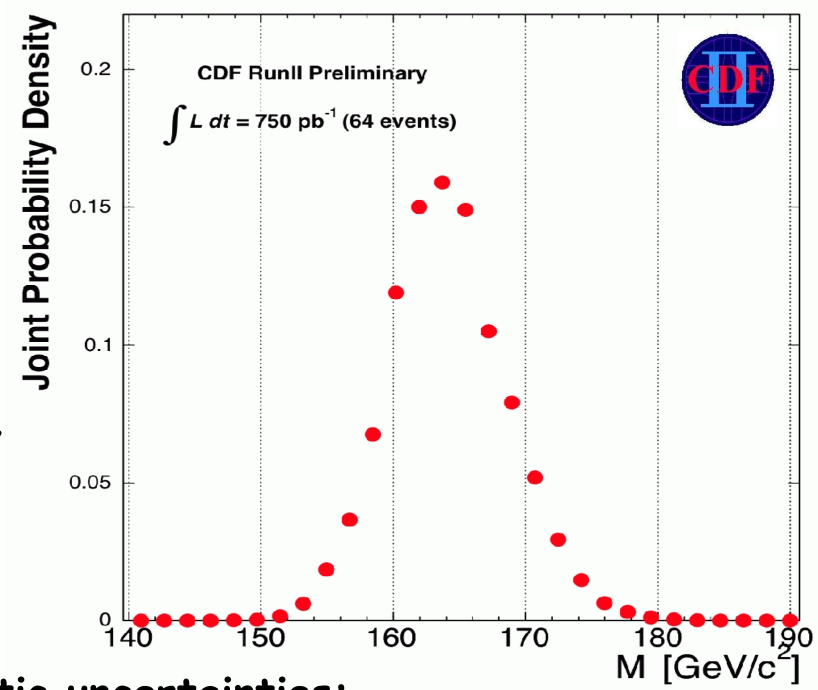


CDF: Matrix Element Method (dilepton)

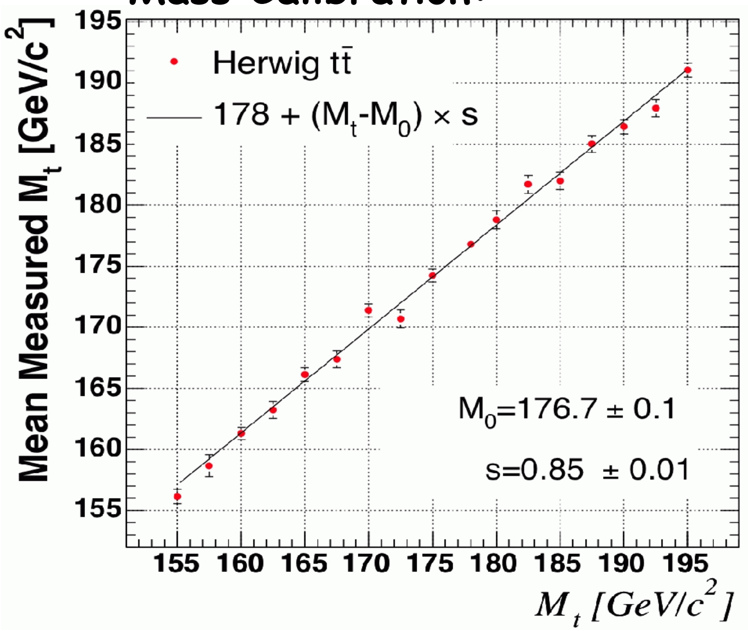
Dilepton-Result:

m_t=164.5 ± 4.5 (stat.) ± 3.1 (syst.) GeV

- Most precise dilepton-measurement to date
- No b-tagging used in result above
- Result with b-tagging: **162.7 ± 4.6_{stat} ± 3.0_{syst} GeV**
  - require at least one b-tagged jet (secondary vertex tag)



Mass Calibration:



Systematic uncertainties:

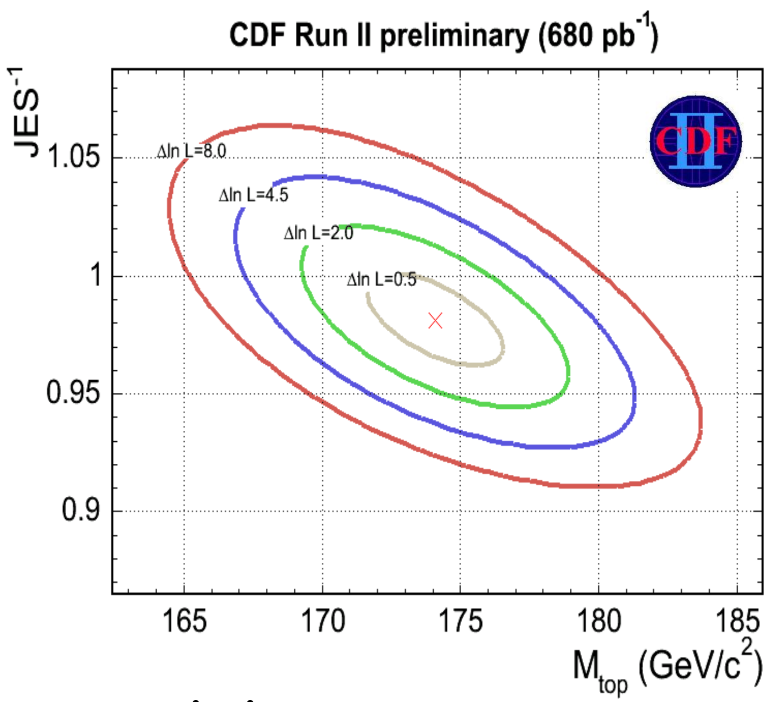
Source	ΔM_t (GeV/c^2)
Jet Energy Scale	2.6
Generator	0.5
Response uncertainty	0.3
Sample composition uncertainty	0.7
Background statistics	0.8
Background modeling	0.8
ISR modeling	0.5
FSR modeling	0.5
PDFs	0.6
Total	3.1

CDF: Matrix Element Method (lepton+jets)

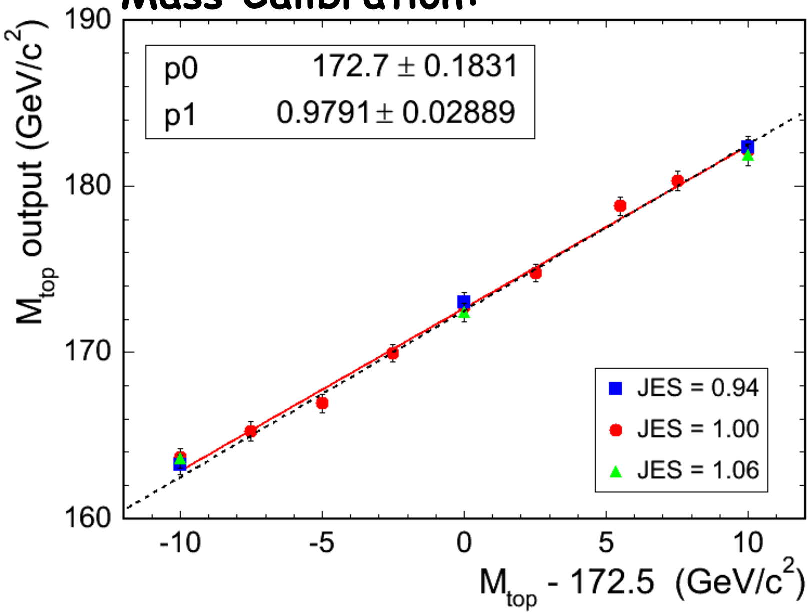
Lepton+Jets-Result:

m_t=174.1 ± 2.5 (stat.+JES) ± 1.3 (syst.) GeV

- More powerful technique than template method (p.5-7), but fewer events used (118/360)
  - exactly 4 calorimeter jets
  - at least one b-tagged jet (secondary vertex tag)



Mass Calibration:



Systematic uncertainties:

Source of systematic uncertainty	Magnitude (GeV/c^2)
Residual JES	0.42
b-JES	0.60
Generator	0.19
ISR	0.72
FSR	0.76
b-tag E_T dependence	0.31
Background composition	0.21
PDF	0.12
Monte Carlo statistics	0.04
Total	1.35

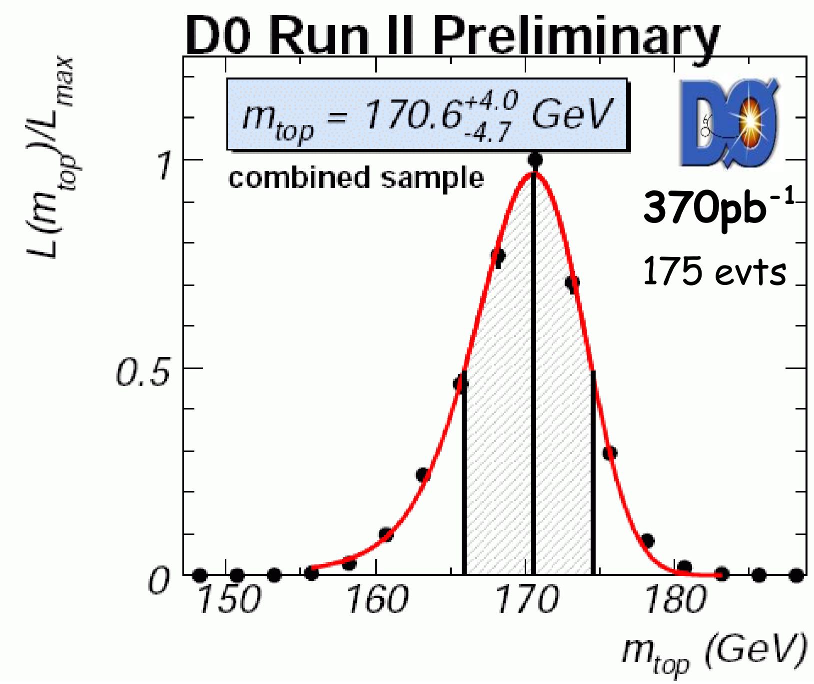
DØ: Matrix Element Method (lepton+jets)

Lepton+Jets-Result:

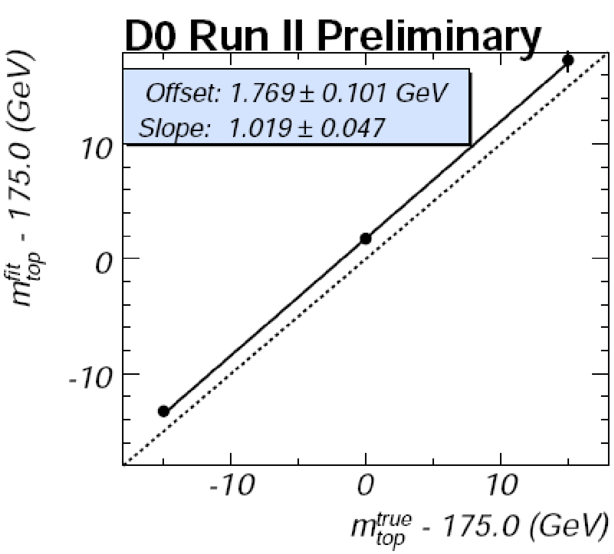
$$m_t = 170.6^{+4.0}_{-4.7}\ \text{(stat.+JES)} \pm 1.4\ \text{(syst.) GeV}$$

Single best DØ measurement

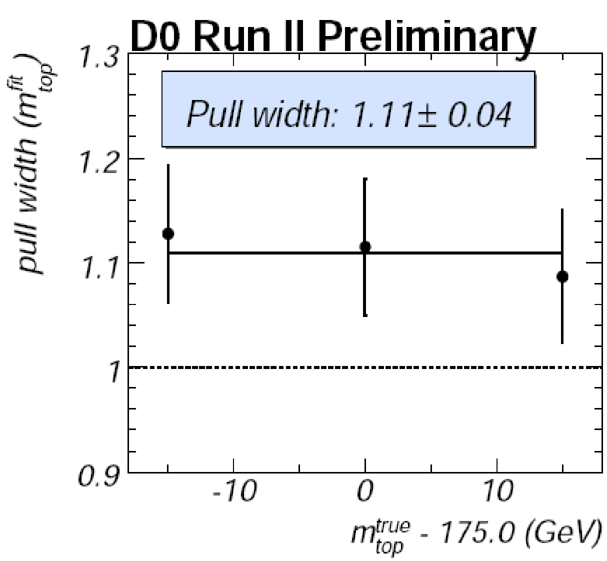
- Based on 370pb-1 dataset
- Similar to the CDF template analysis, the sample is divided in subsamples with 0,1,or 2 b-tagged jets
  - ~20% improvement w.r.t analysis w/o b-tagging
  - ~30% improvement w.r.t. selecting events with at least 1 b-tagged jet

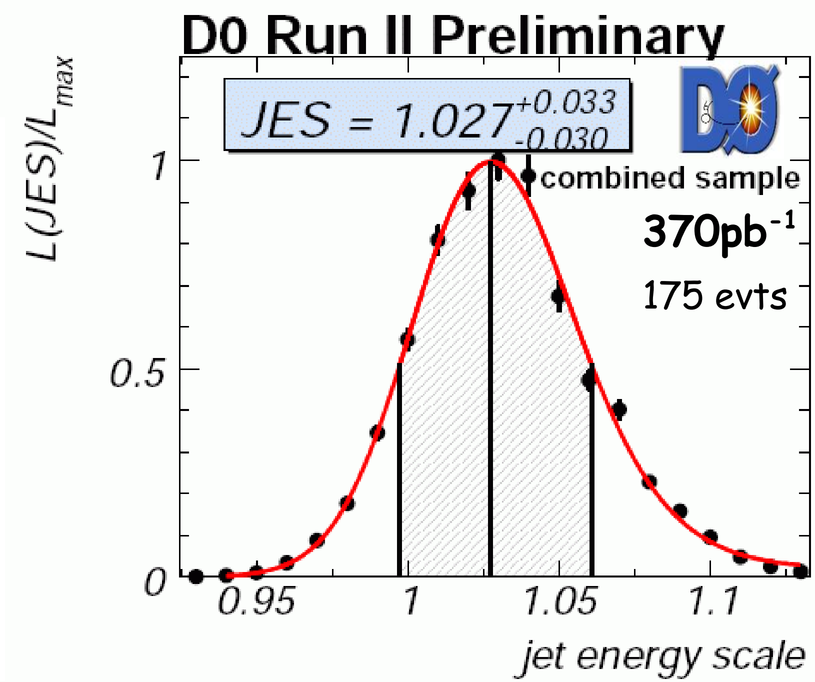


Mass Calibration:



Pull-width Calibration:





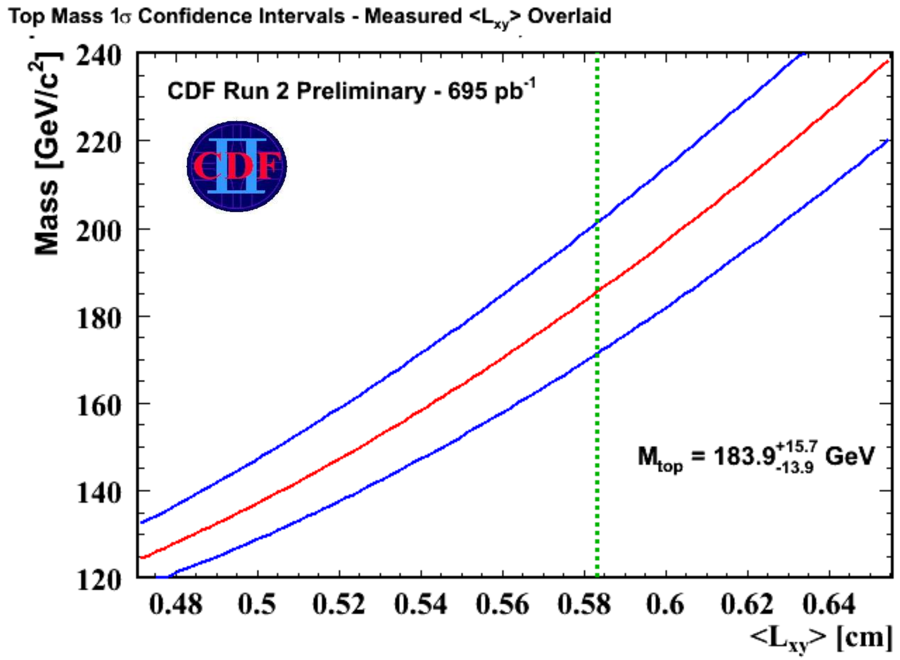
CDF: Decay Length Technique

- At the Tevatron, where top pairs are produced approximately at rest, the boost given to the b-quark is correlated to the top mass:

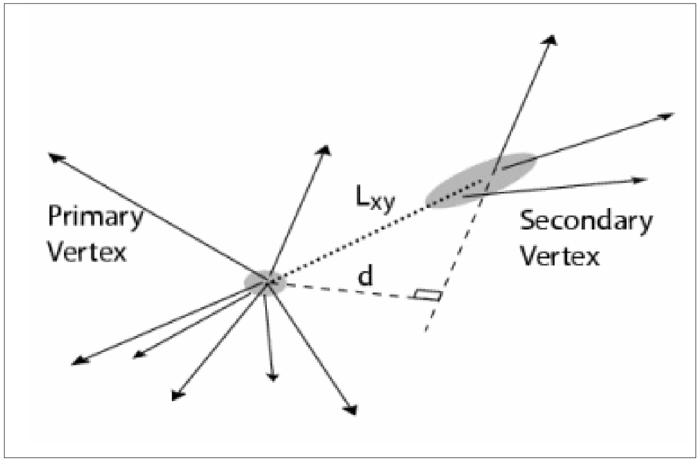
$$\gamma_b = \frac{m_t^2 + m_b^2 - m_W^2}{2 m_t m_b} \approx 0.4 \frac{m_t}{m_b}$$

- boost -> avg. lifetime -> avg. transv. decay-length
- With current statistics, this method is not competitive to other measurements yet
- no jet energy scale uncertainty, as the method relies purely on tracking
- Uncorrelated with other measurements

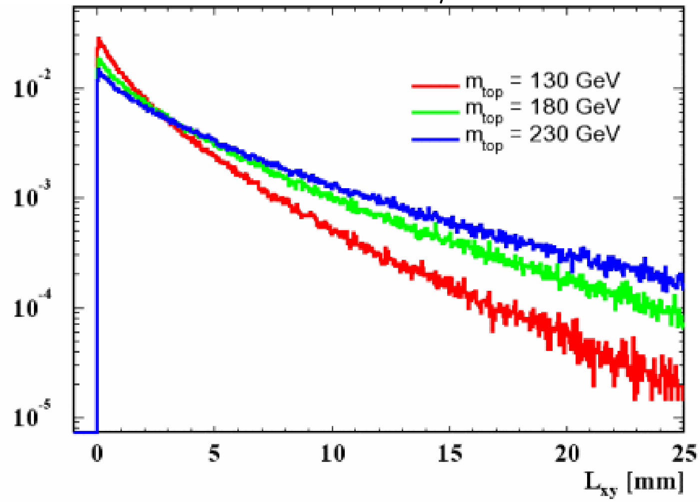
$m_t = 183.9\ ^{+15.7}_{-13.9}$ (stat.) ± 5.6 (syst.) GeV



Transverse Decay Length L_{xy}: Definition



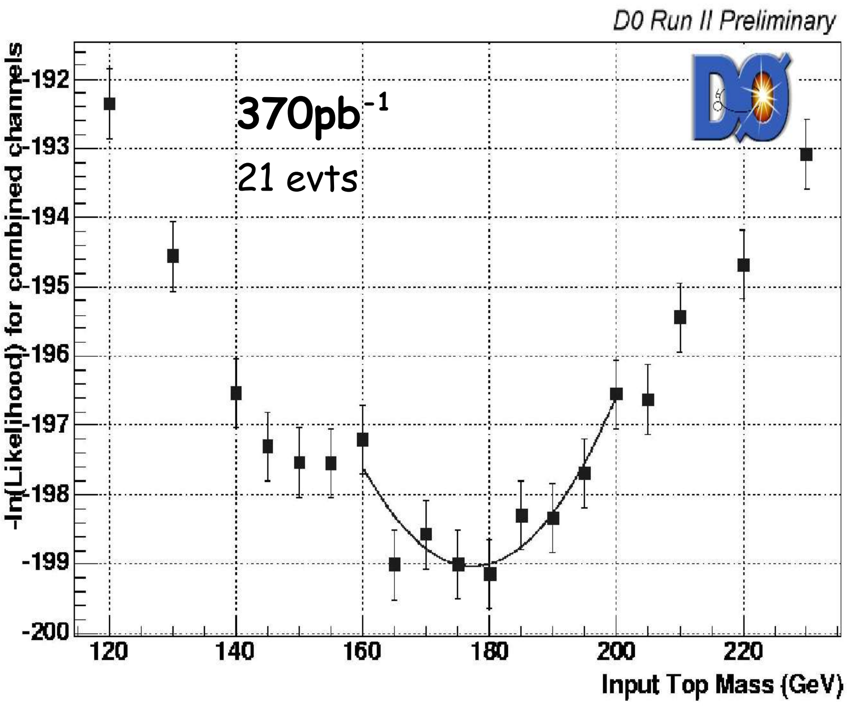
Transverse Decay Length L_{xy} in MC



Neutrino Weighting Analysis

- Underconstrained kinematic fit
- Assume η distribution of neutrinos from MC
- Compute weights for each event, m_t
- Compare weight distribution in data with MC templates

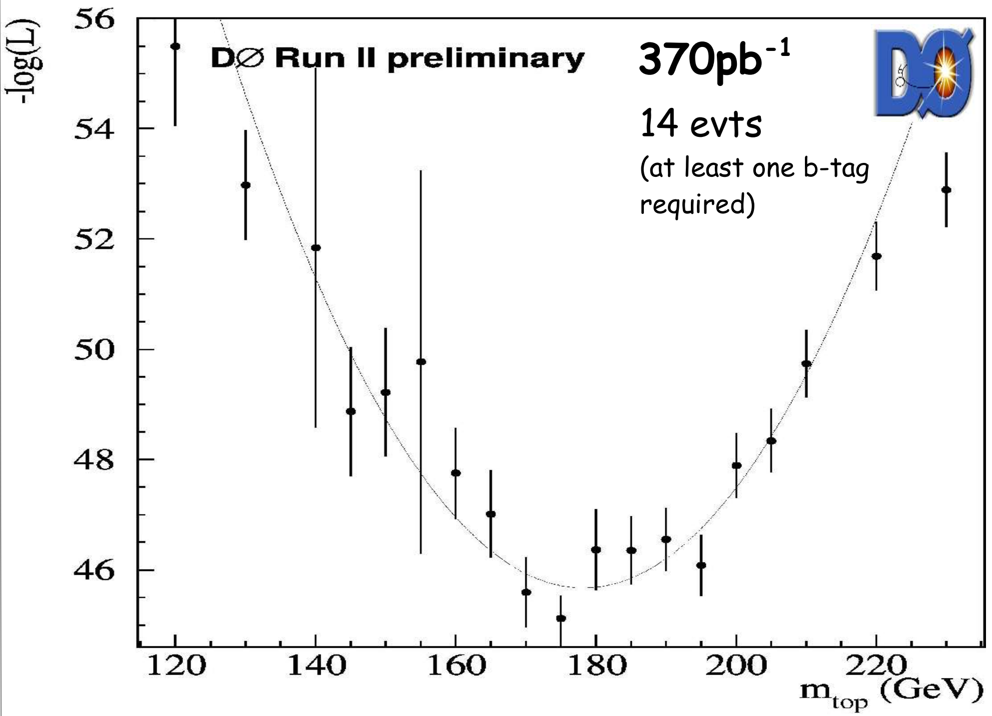
m_t=175.6 ± 10.7 (stat.) ± 6.0 (syst.) GeV



Matrix Weighting Analysis

- Use Matrix Element prediction and m_t to compute event weights
- For each event, choose m_t at the peak of the weight distribution
- Compare m_t distribution with MC templates

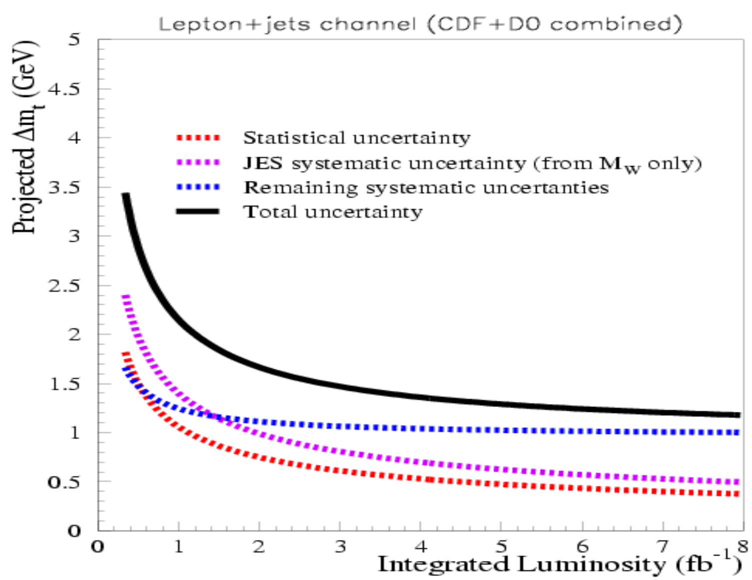
m_t=176.6 ± 11.2 (stat.) ± 3.8 (syst.) GeV

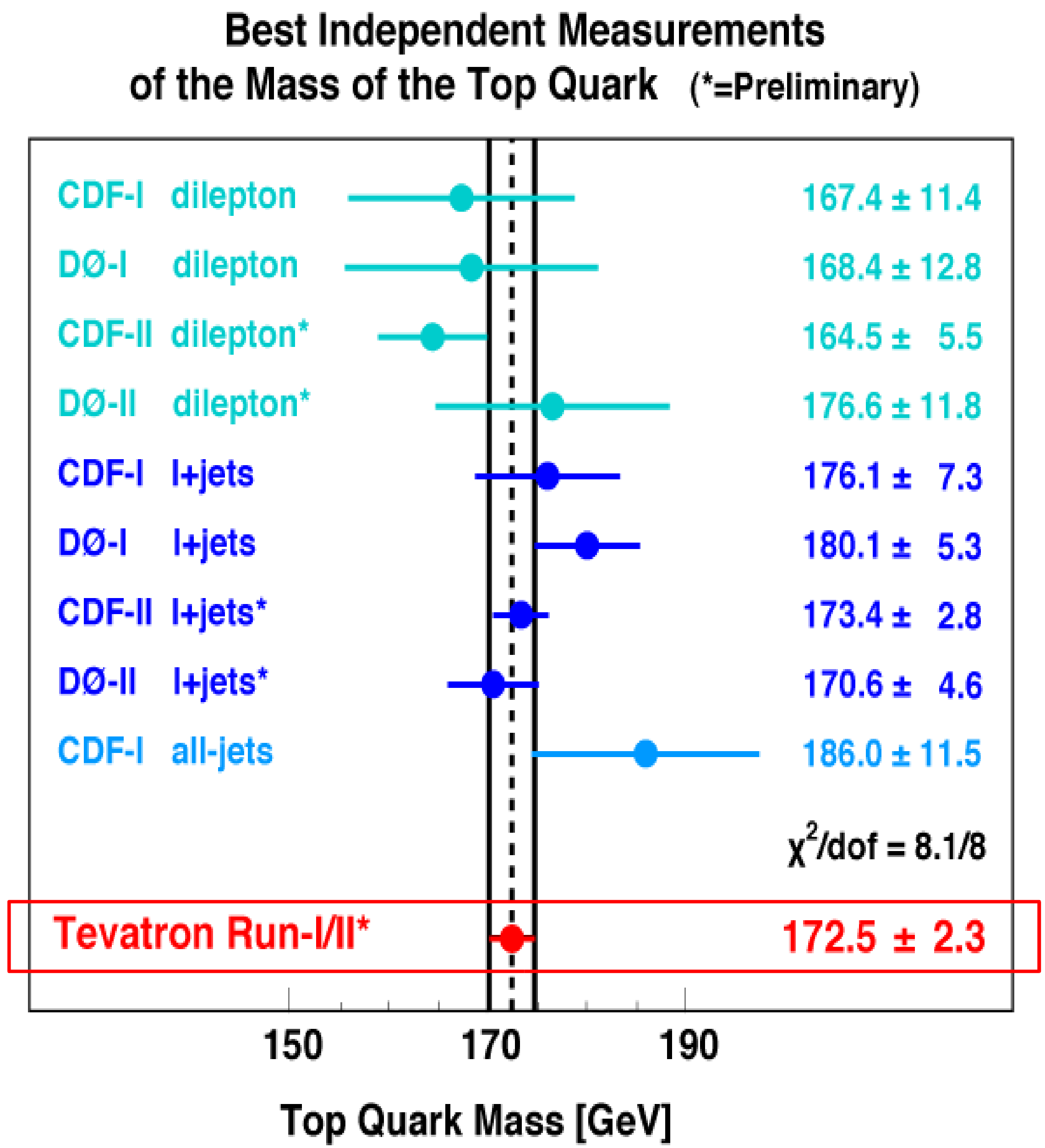


M_{top}: Combination of Tevatron Results

World Average:
m_t=172.5 ± 1.3 (stat) ± 1.9 (syst) GeV

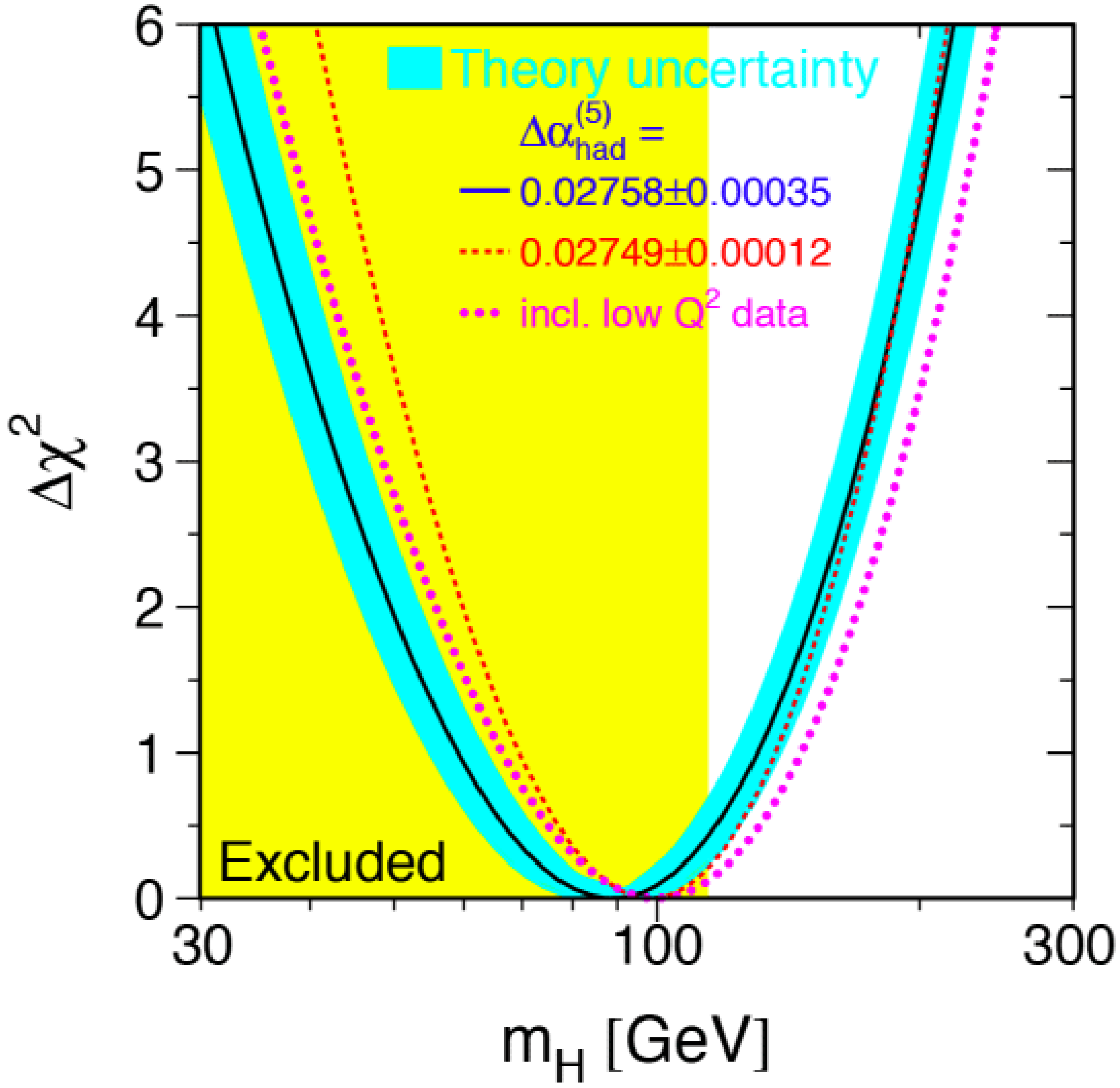
- Systematics limited!
- Precision Measurement: Δm_t~1.3%
- In the **4-8fb^{-1} future**, we expect ...
  ... ~1.5 GeV total error
  ... dilepton to become systematics limited
  ... all-hadronic measurements to contribute significantly





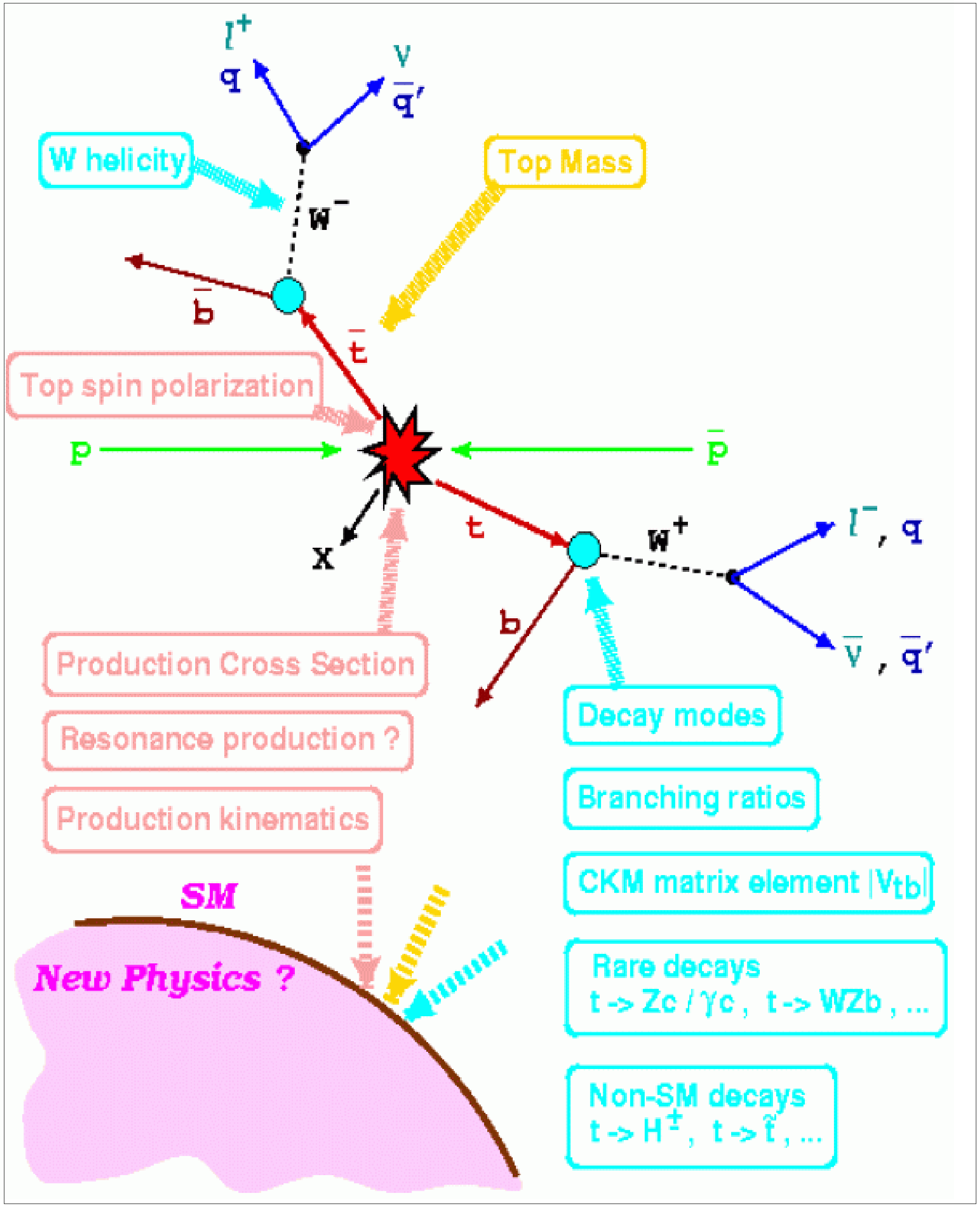
M_{Higgs}=89^{+42}_{-30} GeV

M_{Higgs}<175 GeV (95% conf.)
(207 GeV including LEP2)



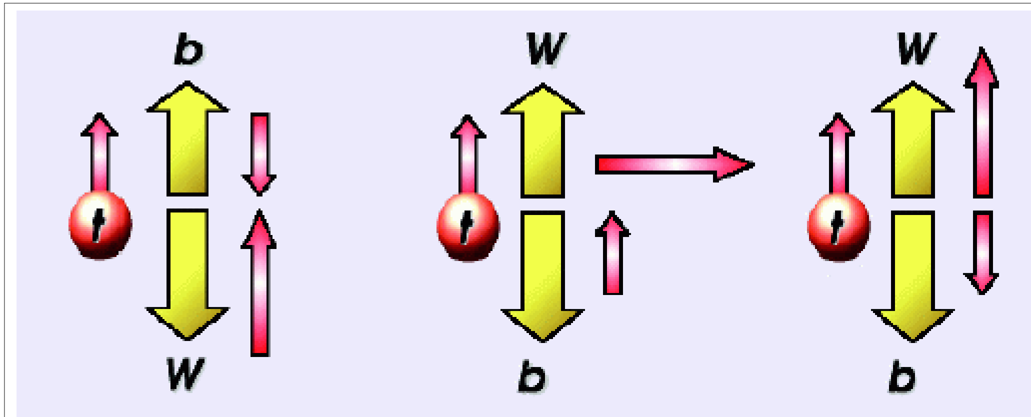
Other Top Quark Properties

- top pair decays offer countless opportunities for Standard Model tests
- Many of the top quark properties are just about to become accessible with Tevatron statistics
- Lots of room for exotic behavior
- The following slides show the latest measurements of
  - W Boson Helicity
  - Top Charge
  - Search for $t\bar{t}$ resonances

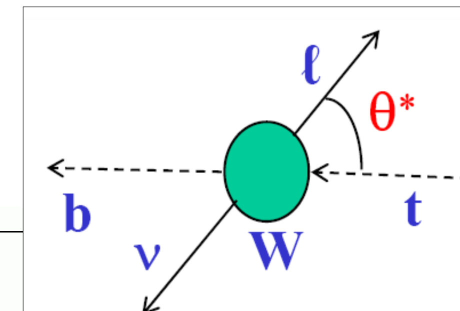


W Boson Helicity

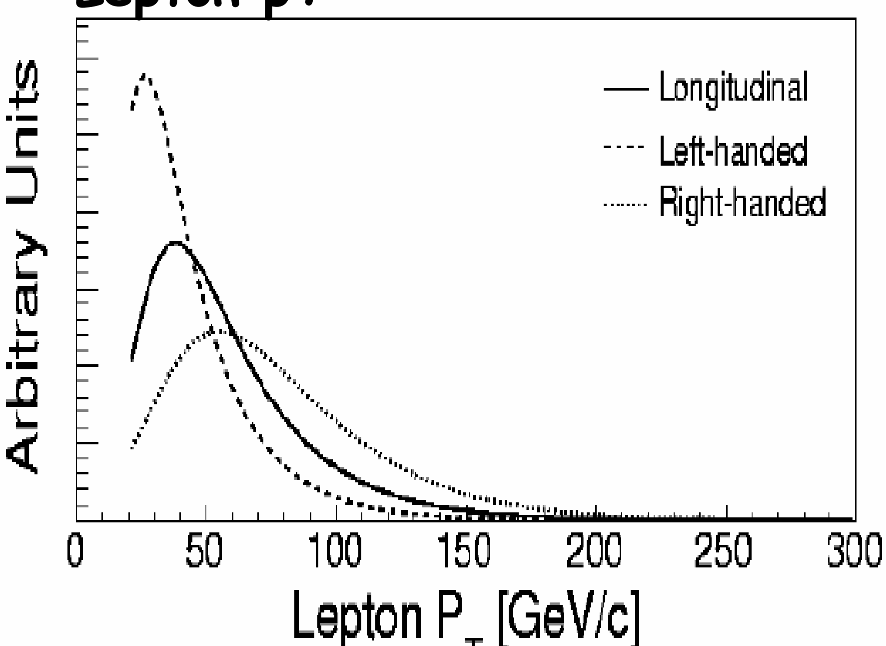
- Standard Model: right-handed W from t->Wb surpressed by V-A coupling, **f^+~0%**
- f^+>0 clear signature for non-SM physics
- Experimentally accessible via:
  - Lepton p_T: Charged lepton from a right-handed W preferentially emitted along W boson direction, therefore larger p_T
  - cos θ*: angle between charged lepton and top quark in the W boson rest frane



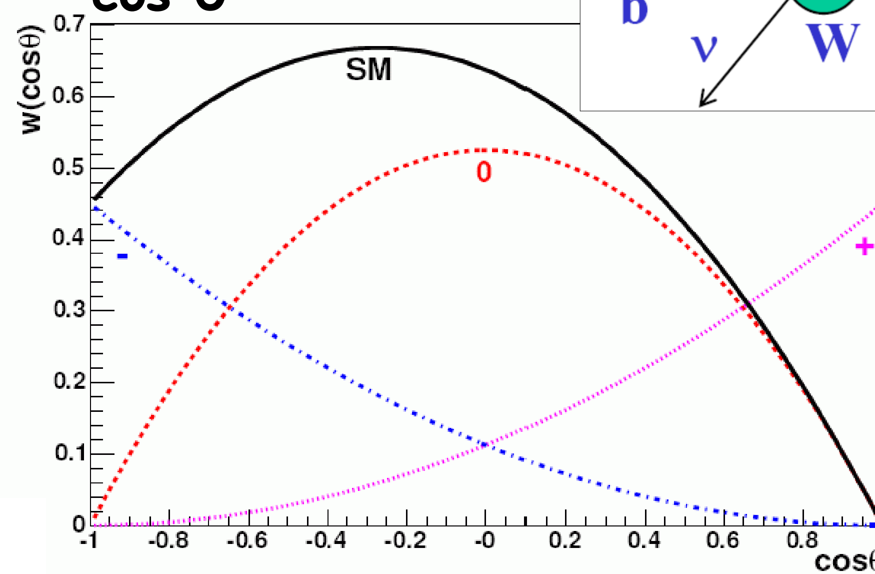
f^-~30% f^0~70% f^+~0%



Lepton pT



cos θ*



CDF: W Boson Helicity

- Lepton p_T Analysis:
  - Dilepton and lepton+jets events
  - Lepton+Jets: at least 3 jets
- cos θ* Analysis:
  - Subsample of Lepton pT lepton+jets sample, requiring at least 4 jets
- At least one b-tagged jet required in lepton+jets (secondary vertex tag)

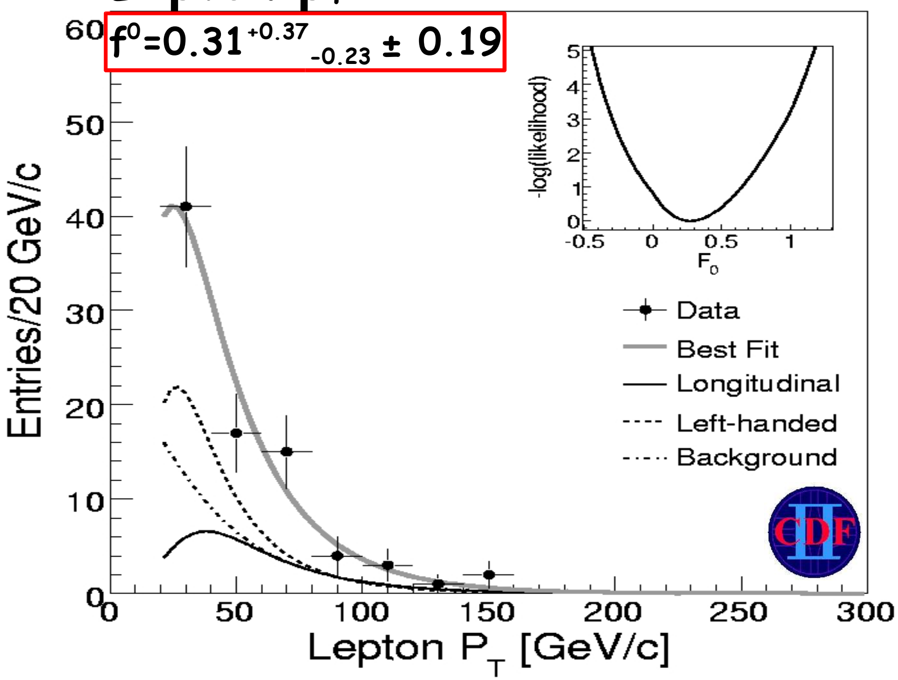
Combined Results:

$f^0=0.74^{+0.22}_{-0.34}$ $f^+=0.00^{+0.20}_{-0.19}$

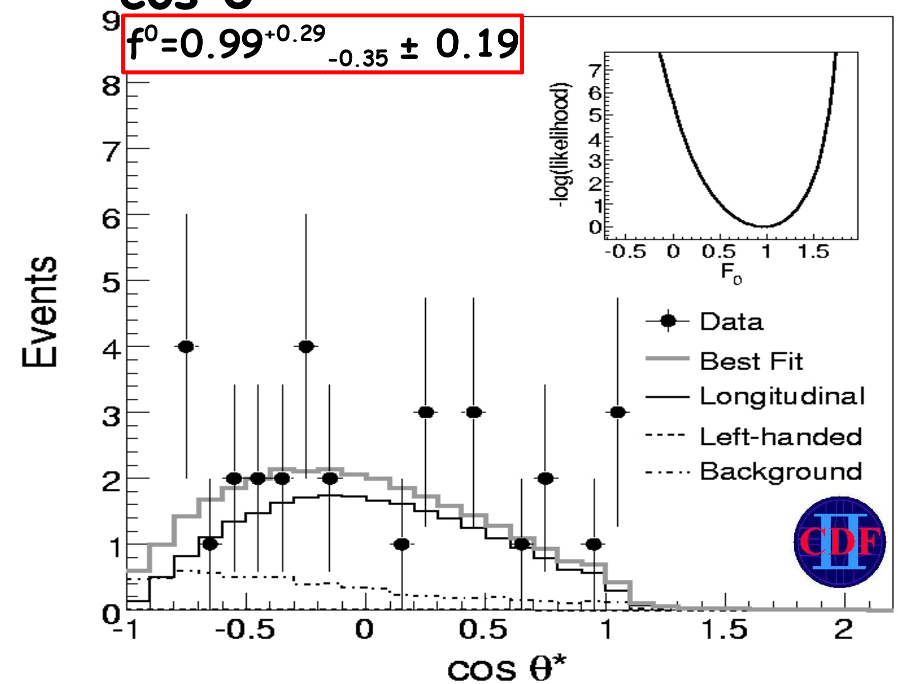
$f^+<0.27$ @95%C.L.

In agreement with SM prediction

Lepton p_T



cos θ*



DØ: W Boson Helicity

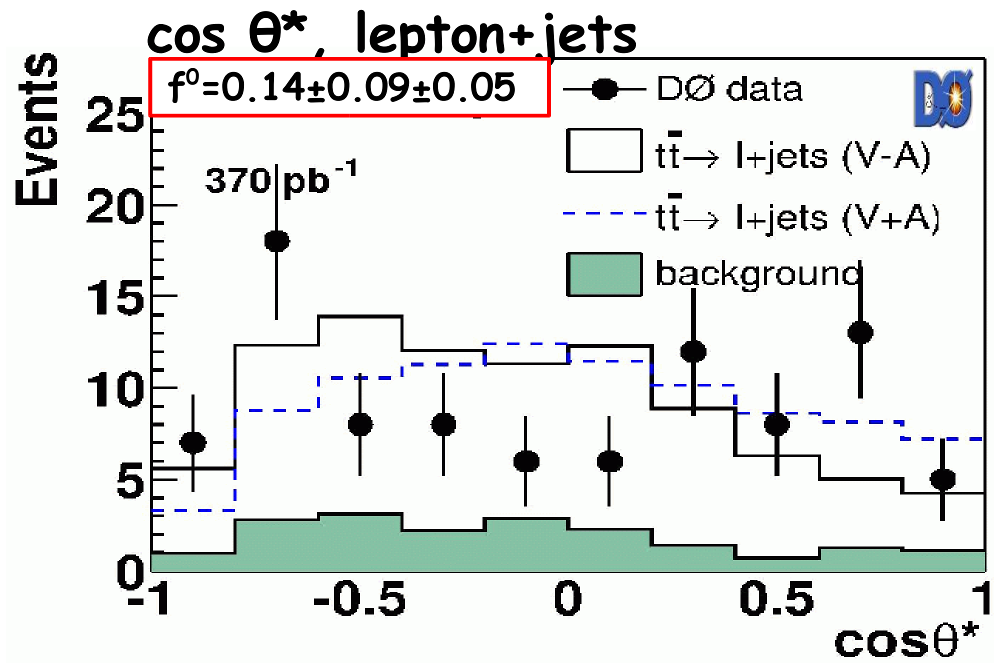
Combined Result:

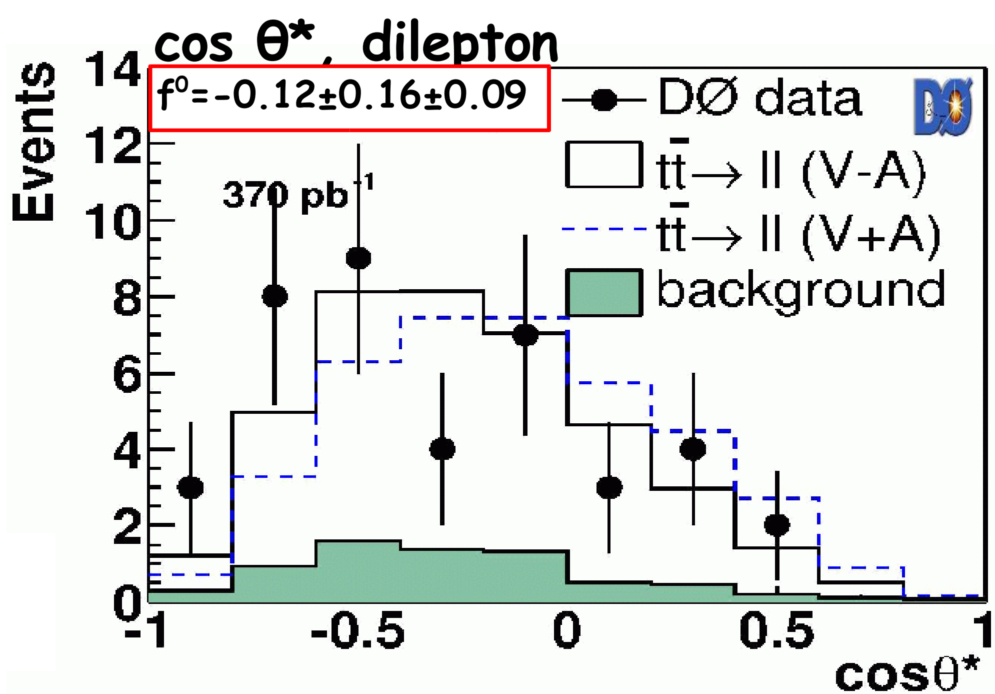
$f^{+}=0.08 \pm 0.08_{stat} \pm 0.06_{syst}$

$f^{+}<0.24$ @95%C.L.

In agreement with SM prediction

- Use topological likelihood discriminant to select top pair enriched sample
- Use kinematic fit to reconstruct top pair and W boson rest frame
- Fit cos θ* distributions with Monte Carlo templates, varying f^0 from 0.0 to 0.3
- Extract f^0 using binned likelihod technique



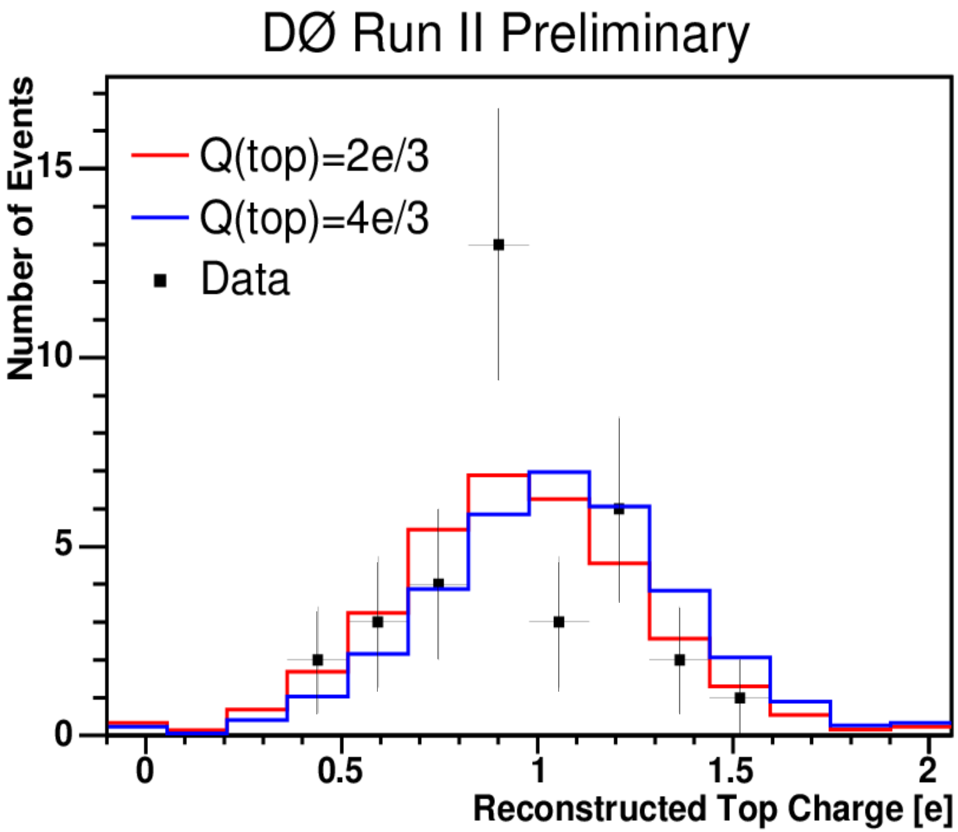


DØ: Top Charge

- Standard Model (SM): Q_t=2/3e
- Interpretation Q_t=-4/3e possible as well
- lepton+jets selection, requiring 2 b-tagged jets (secondary vertex tag). ~95% top pairs.
- Use kinematic fit to reconstruct top pairs
  - Correct t->Wb assignment: ~78%.
- Measure the jet-charge of the tagged jets to discriminate between b and $\bar{b}$, using tracks associated with each jet:

$$q_{jet} = \frac{\sum_i q_i \cdot p_{T_i}^{0.6}}{\sum_i p_{T_i}^{0.6}}$$

- Two measurements per event:
  (1) lepton charge plus associated b-jet charge
  (2) other b-jet charge minus lepton charge
- Construct Q_t=2/3e and Q_t=-4/3e templates and compare to top charge distribution derived from data



DØ: Top Charge (II)

- To test the Standard Model, a likelihood ratio Λ is computed:

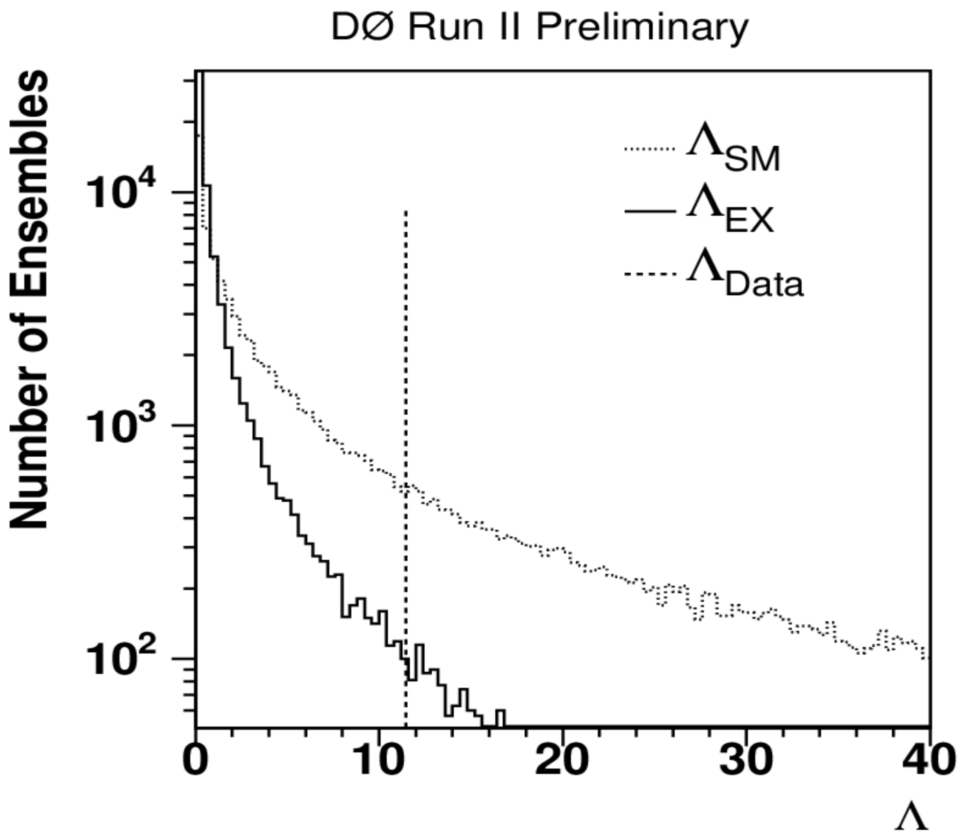
$$\Lambda = \frac{\prod_i p^{\rm sm}(q_i)}{\prod_i p^{\rm ex}(q_i)}$$

with

- $p^{sm}(q_i)$ = probability of charge q_i being observed for Q_t=2/3e (SM)
- $p^{ex}(q_i)$ = probability of charge q_i being observed for Q_t=-4/3e (EX=exotic models)

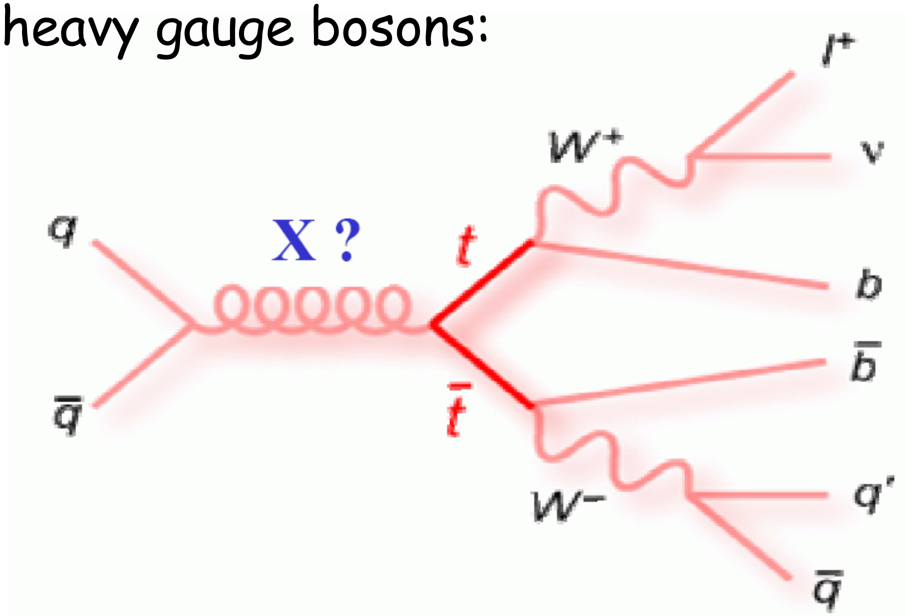
- The expected distributions of Λ are derived in Monte Carlo ensemble tests for both scenarios
- The data sample yields **Λ=11.5** (dashed line)

Q_t=-4/3e excluded @94%C.L.



Search for $t\bar{t}$ resonances

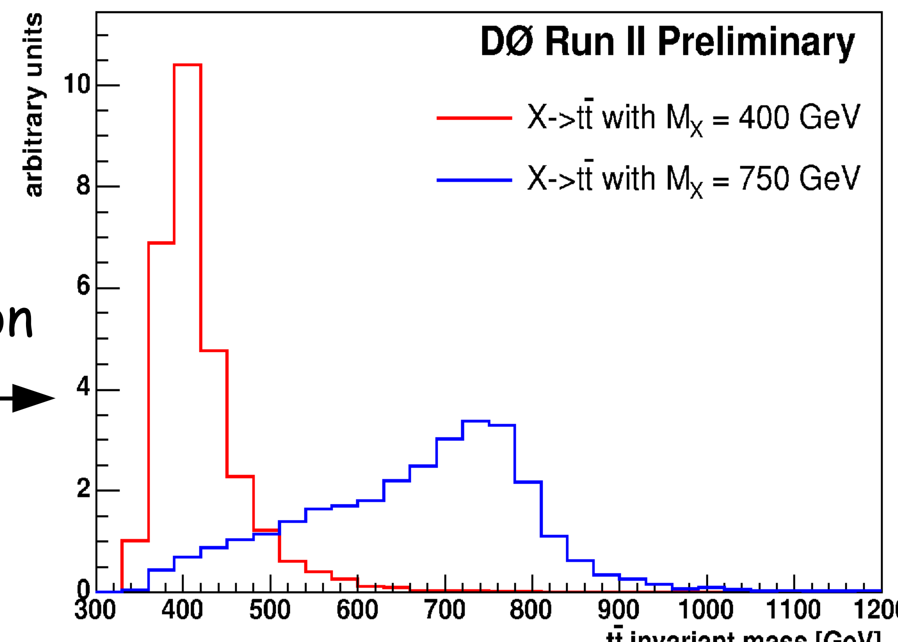
Exotic models predict top pair production through the decay of new heavy gauge bosons:



- Assume resonance mass M_X in the range [350-1000] GeV
- Assume resonance width $\Gamma_X=0.012 \cdot M_X$

Consequences:

- cross-section higher than SM expectation
- resonances in the tt invariant mass distribution →



CDF&DØ: Search for $t\bar{t}$ resonances

CDF:

- lepton+jets selection, no b-tagging requirements
- top quarks reconstructed with matrix element method

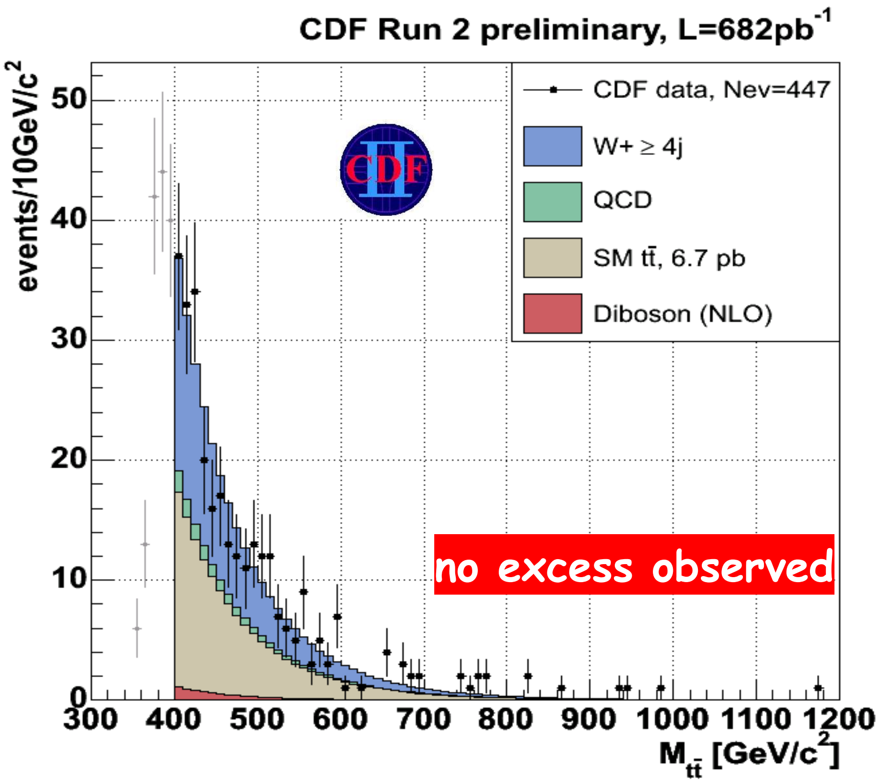
DØ:

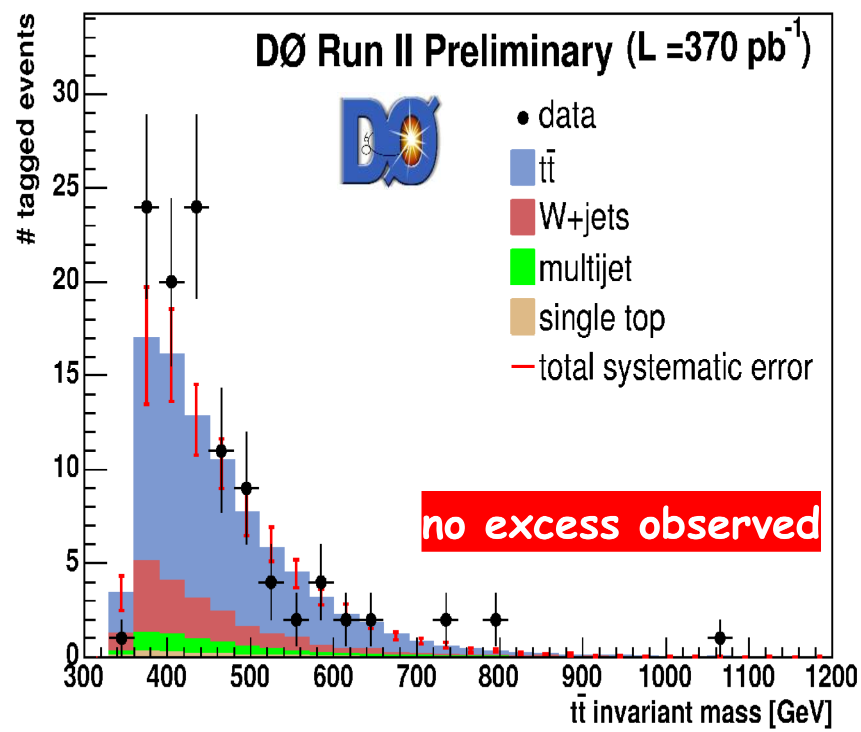
- lepton+jets selection, at least one b-tagged jet (secondary vertex tag)
- top quarks reconstructed with constrained kinematic fit

Limits on production of leptophobic Z':

M_X>725 GeV @95% C.L.

M_X>680 GeV @95% C.L.





Summary

- Top Mass Measurements at the Tevatron have entered high precision era:
  - Combination of results yields current **world average**:

$$m_t = 172.5 \pm 2.3\ \text{GeV}$$

  - Expect total error $\Delta m_t \sim 1.5$ GeV with full RunII sample (4-8fb^{-1})
  - These results will be relevant for years, even after LHC startup

- Tevatron Collaborations are zooming in on the top quark's other properties
  - Current measurements show good agreement with the Standard Model
  - Application to a larger dataset (~1fb^{-1}) forecasts interesting results for this summer with significantly improved sensitivity to potential non-SM physics