Top Mass Measurements at the Tevatron

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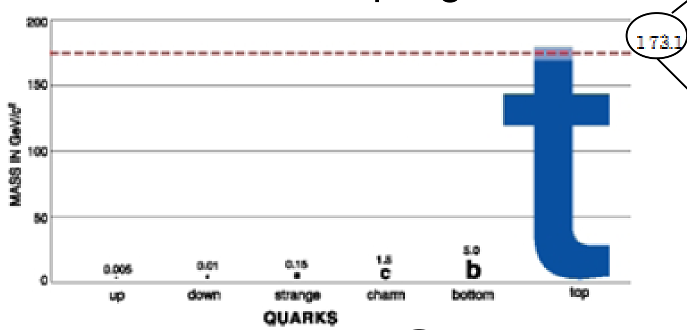
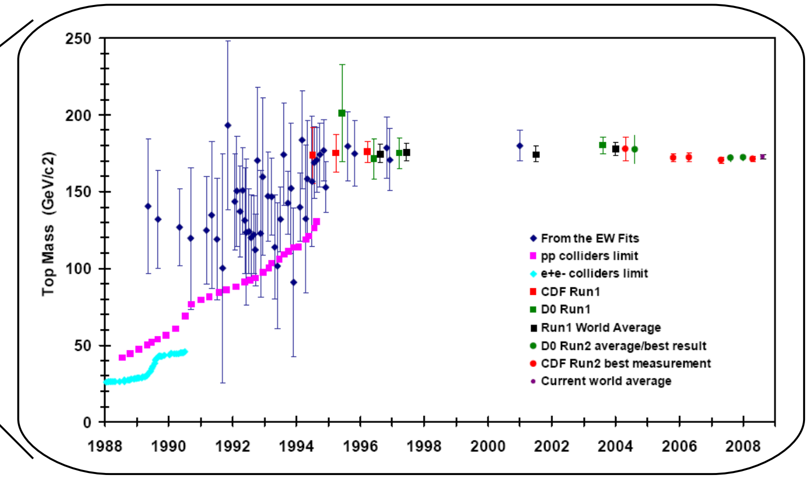
On Behalf of the

CDF and DØ Collaborations

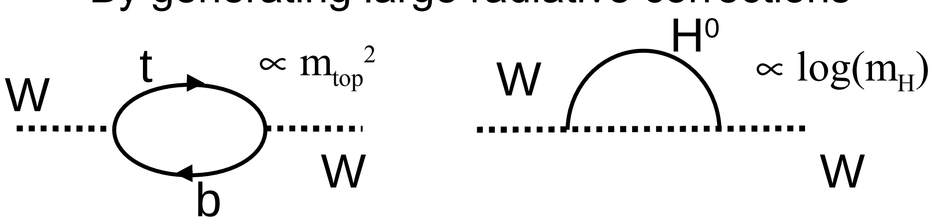
Motivation

- *Enormous mass*
  - Same scale as EWSB
  - Yukawa coupling of ~ 1

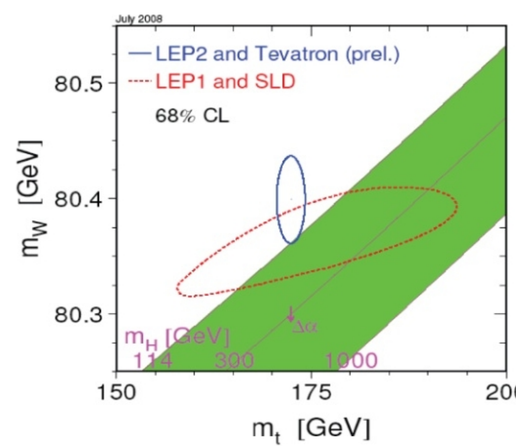




- *Within the SM*
  - By generating large radiative corrections

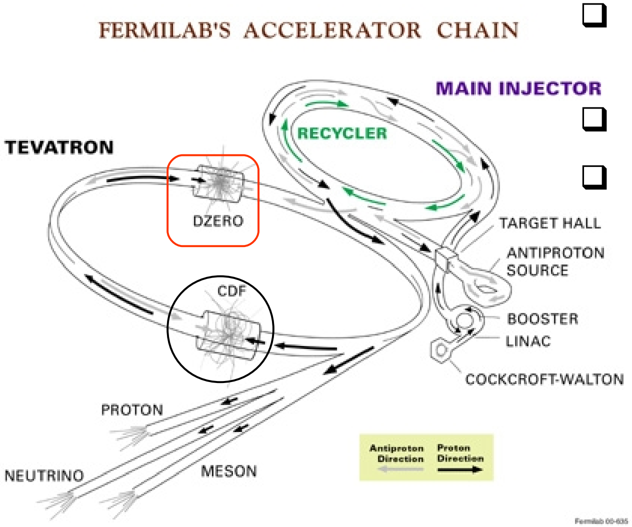


helps constraining the Higgs mass

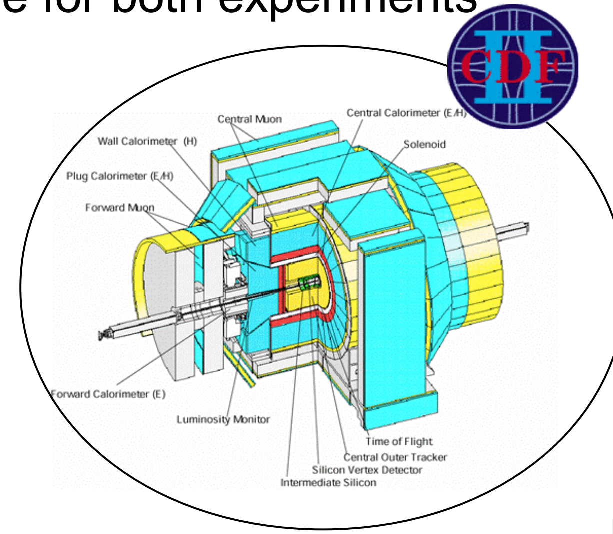


- *Beyond the SM*
  - discrepancies in the results across different decay channel could provide hints of new physics

Experimental Environment: Fermilab Tevatron

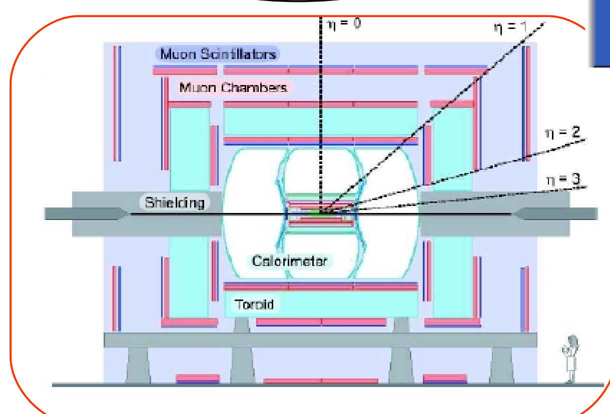


- So far the only place where top has been produced
- Ppbar collisions at 1.96 TeV (since 2001)
- About 5 fb^{-1} on tape for both experiments



- *Two multi-purpose detectors*
  - → accurate tracking system with SI
  - → Calorimeters to measure e, γ, jet energy
  - → Muon detection system

- *Peculiarities*
  - → CDF: excellent tracking system
  - → D0: excellent muon coverage

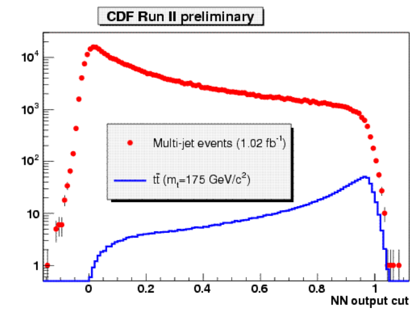


Top Mass Challenges

- A needle in the haystack: $\sigma_{tt}/\sigma_{inel} = 10^{-10}$

→ dedicated top triggers

→ sophisticated event selections

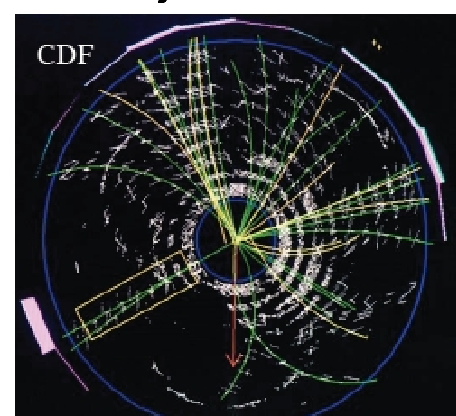


- Neutrino(s) escape the detector

→ Indirect measurement of ν energy: MET

→ hypotheses needed to constrain the kinematics (dilepton channel)

l+jets event



- Jets of particles instead of quarks are measured

→ Several jet-to-partons ("j2p") possible assignments

→ Procedure to report jet energy back to partons: "Jet energy scale" (JES)

→ Not all jets originate from top/W : gluon radiation

Jets
in top mass analyses

- JES corrections account for:

→ Detector effects (non-linearity, non-compensation, multiple ppbar interactions, ...)

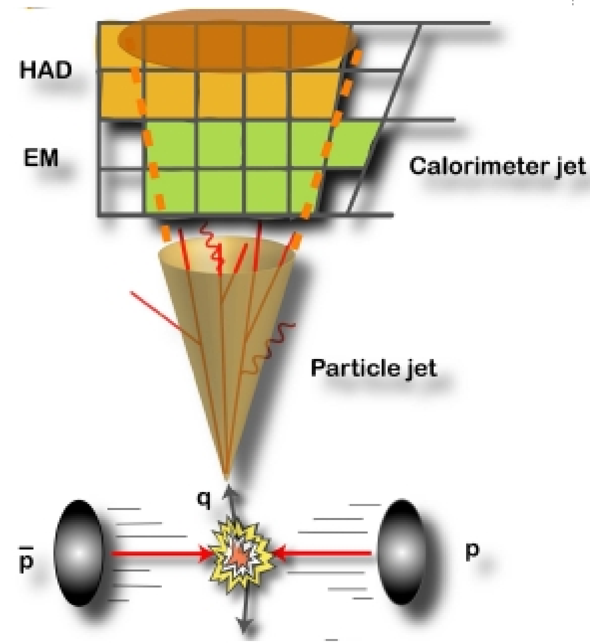
→ Physics effects (underlying event, energy out of the jet cone)

- JES calibration "in situ"(ttbar only):

→ invariant mass of dijets from W needs to match W mass

→ possible in l+jets and all-jets channels

→ Calibration returns a JES shift "Δ_{JES}"

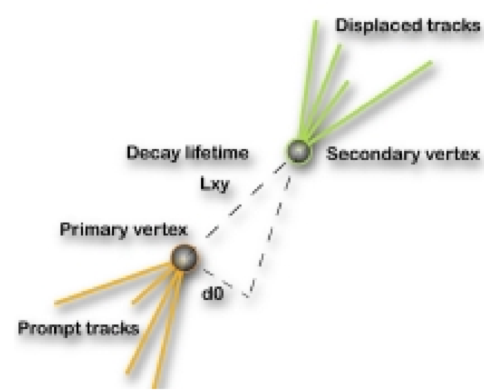


- Flavour tagging

→ vertex displacement hints to long-lifetime hadrons from b's ("b-tagging")

→ decreases j2p possible assignments

→ increases signal to bg ratio



Analysis techniques

Matrix Element (ME): exploits an event-by-event probability

$$P_{ev}(\vec{x}\,|\,m_t,\Delta_{JES}) = N\sum_{j2p}\int d\Phi_6 \frac{|M(q\bar{q}\to \ldots \to \vec{y})|^2}{FF}\, dz_1 dz_2 f_{PDF}(z_1) f_{PDF}(z_2)\, TF(\vec{x}\,|\,\vec{y},\Delta_{JES})$$

$\vec{x}$: Event observables (P_μ^{lep}, P_μ^{jet})

N : normalization factor

M : LO ME for signal or bg process

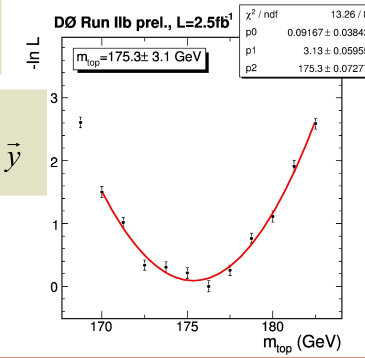
$\vec{y}$ = parton momenta

FF = flux factor

PDF for incoming partons

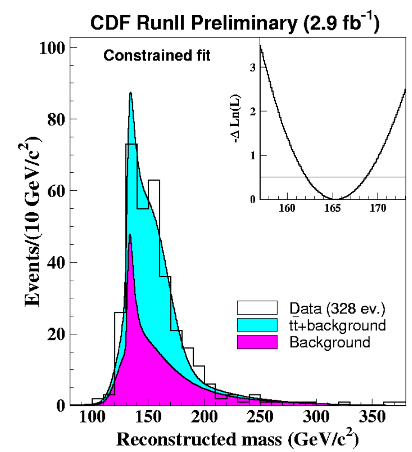
Detector response given a particle momentum $\vec{y}$

$$L = \prod_{events} P_{ev}$$



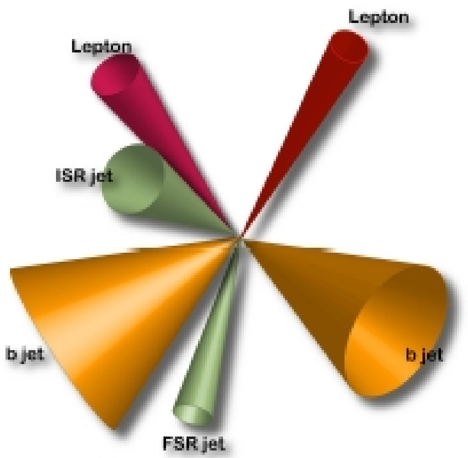
Template method (TM):

1) Choice of a m_t estimator (typically event-by-event reconstructed top mass)
2) Build distributions ("templates") on simulated events
3) Fit the data to a combination of a mass-dependent signal template and of a bg template



Dilepton channel

High S:B (3:1) ,low statistics



Event selection algorithm

- ✓ Two leptons (P_T >15 to 25 GeV)
- ✓ Large MET (>25 GeV)
- ✓ At least two jets (E_T >15 to 20 GeV)
- ✓Other topological cuts to reject bg

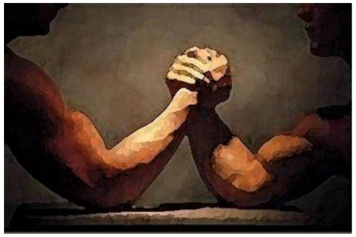
Main background

- ✓ Diboson, W+jets (fake lepton), Drell-Yan

Main Challenge

Kinematics underconstrained

(2 undetected ν's)



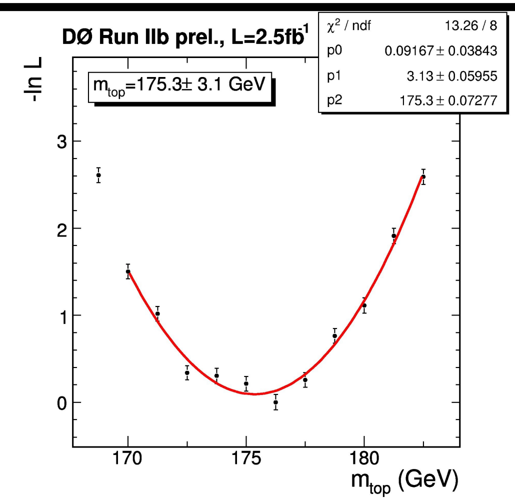
DØ: Dilepton

dilepton DØ best

ME - ∫Ldt = 3.6/fb

- eμ channel only
  - Z+jets →ττ main bg
- Combine Run IIa (∫Ldt = 1.1/fb) Run IIb (∫Ldt = 2.5/fb) to get:

$$M_{top} = 174.8 \pm 3.3\,(stat.) \pm 2.6\,(syst.)\ \mathrm{GeV}$$
$$(\delta M_{top} / M_{top} = 2.4\%)$$



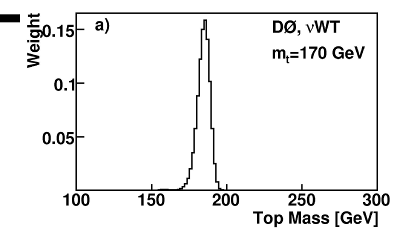
Neutrino Weighting (TM) - ∫Ldt = 1/fb

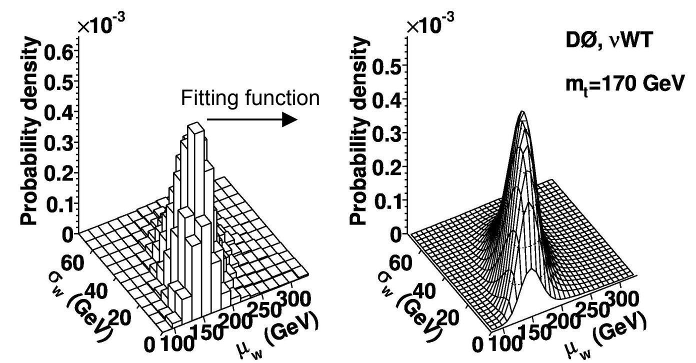
- Integrate over neutrino η's to constrain kinematics
- define a event-by-event weight *w* distribution

→ *w* depends on MET_{obs}-MET_{calc}

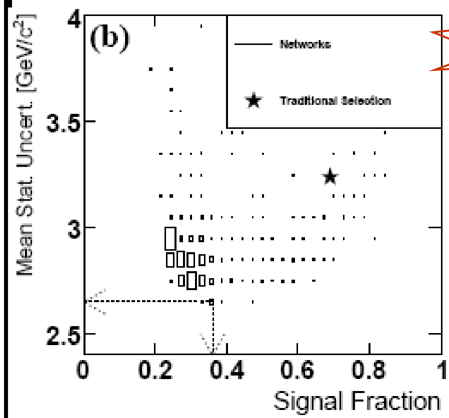
- Templates for ($mean_w$,$width_w$)
- Combination with ME measurement gives:

$$M_{top} = 174.7 \pm 2.9\,(stat.) \pm 2.4\,(syst.)\ \mathrm{GeV}$$
$$(\delta M_{top} / M_{top} = 2.2\%)$$





: Dilepton

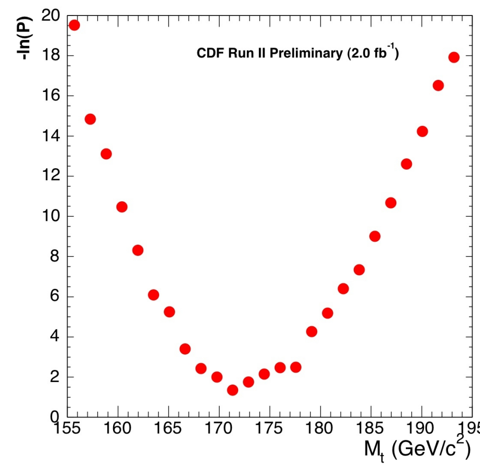


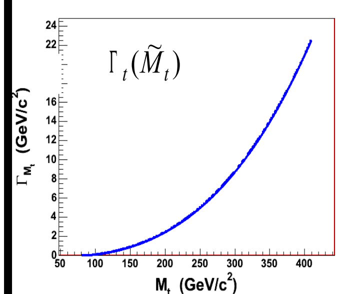
dilepton CDF best

ME - ∫Ldt = 2.0/fb

- Evolutionary NN for event selection
  - Optimized on mass resolution
  - 20% improvement despite of lower S:B

$$M_{top} = 171.2 \pm 2.7\,(stat.) \pm 2.9\,(syst.)\ \text{GeV}$$
$$(\delta M_{top} / M_{top} = 2.3\%)$$





Neutrino φ Weighting (TM) - ∫Ldt = 2.9/fb

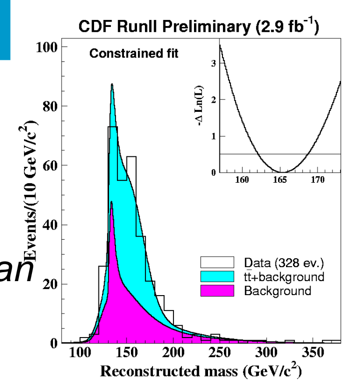
- 328 selected events (about 163 ttbar)
- Integrate over neutrino φ's to constrain kinematics
- Reconstruct an event-by-event m_t via χ^2 minimization

→ *use of a) Breit-Wigner distribution functions instead of Gaussian*

b) and $\Gamma_t = \Gamma_t(m_t)$ as in the SM

leads to 20% improvement

- Build templates and fit to data



$$M_{top} = 165.5 \pm^{3.4}_{3.3}\,(stat.) \pm 3.1\,(syst.)\ \text{GeV}$$
$$(\delta M_{top} / M_{top} = 2.8\%)$$

Lepton+jets channel

Reasonable S:B (1:2), high statistics: the golden channel!

Top-quark discovery in 1995

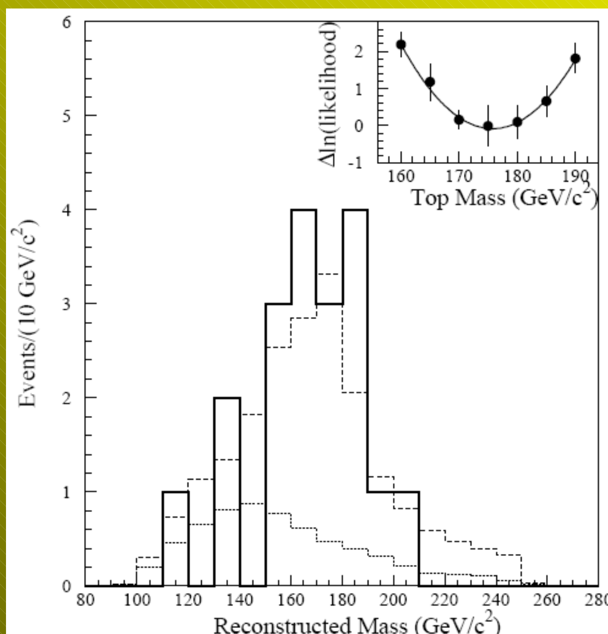


Figure 3: Reconstructed mass distribution for the b-tagged W + ≥ 4-jet events (solid). Also shown are the background shape (dotted) and the sum of background plus $t\bar{t}$ Monte Carlo for M_{top} = 175 GeV/c^2 (dashed), with the background constrained to the calculated value, $6.9^{+2.5}_{-1.9}$ events. The inset shows the likelihood fit used to determine the top mass.

Event selection algorithm

- ✓ 1 lepton (P_T > 20 GeV)
- ✓ Large MET (> 20 to 25 GeV)
- ✓ At least 4 jets (>20 GeV)
- ✓ 1 b-tag → S:B = 3:1

Main background

- ✓ QCD multi-jets (fake lepton), W+HF (HF=b,c), W+jets (fake b-tag)

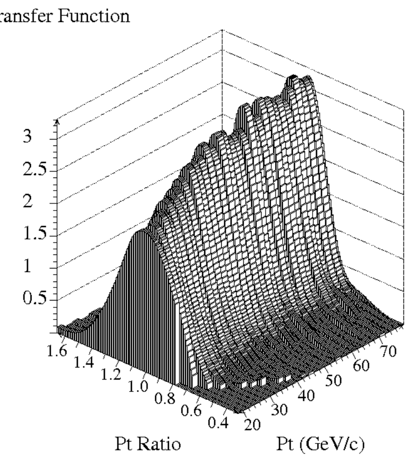
Problems

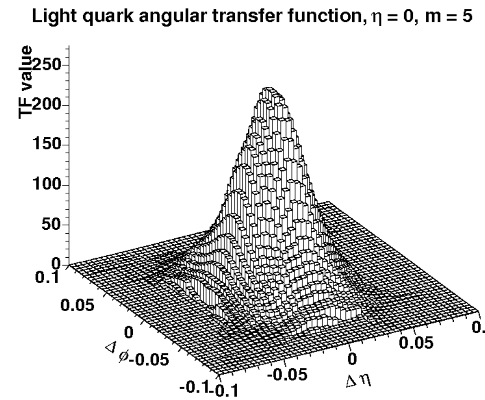
- ✓ J2p possible assignments: 12 (1 b-tag), 4 (2 b-tags)

CDF: lepton+jets

CDF best

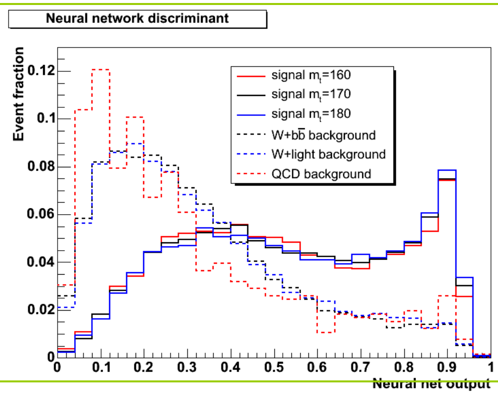
ME, $\int L dt = 3.2/fb$





- 578 selected events (about 425 ttbar)

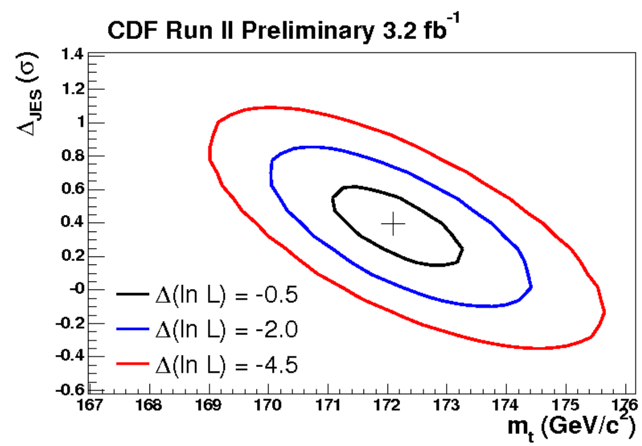
- Parametrizations of angular and energetic detector response



- NN for a better signal from bg separation

→ returns the per-event expected bg fraction f_{bg}

→ different f_{bg} evaluated for "bad signal" (ttbar with gluon jets, dilepton, etc.) and non-ttbar bg



- Weight j2p assignments with b-tag probability
- JES calibrated in situ
- M_{top} estimated from likelihood profile along Δ_{JES} axis

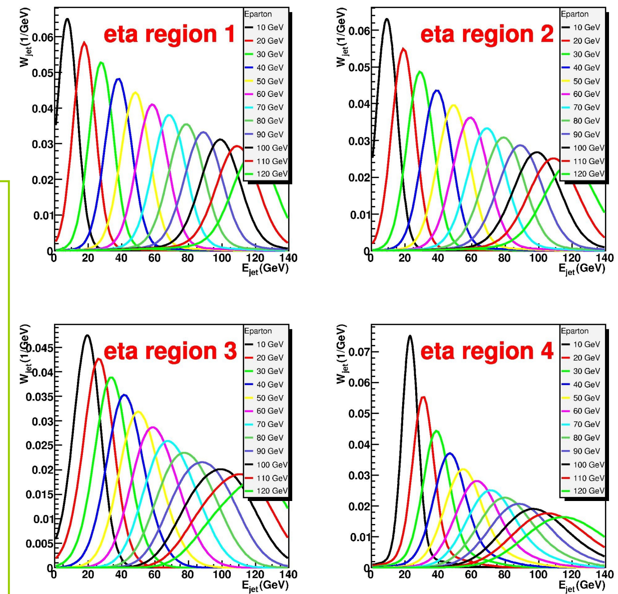
$$M_{top} = 172.1 \pm 1.2(stat.+JES) \pm 1.1(syst.)\ \text{GeV}$$
$$(\delta M_{top} / M_{top} = 0.9\%)$$

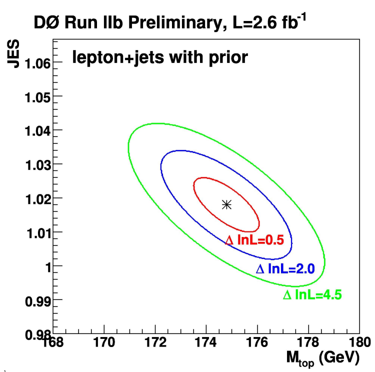
: lepton+jets

D0 best

ME, ∫Ldt =3.6/fb

- Events with at least 1b-tag are selected
→ optimized NN is used for b-tagging
- Energetic detector response parameterized for different quark flavours, jet P_T and η
- e+jet and μ+jets samples studied separately
→ signal fraction for likelihood calibrated in each sample

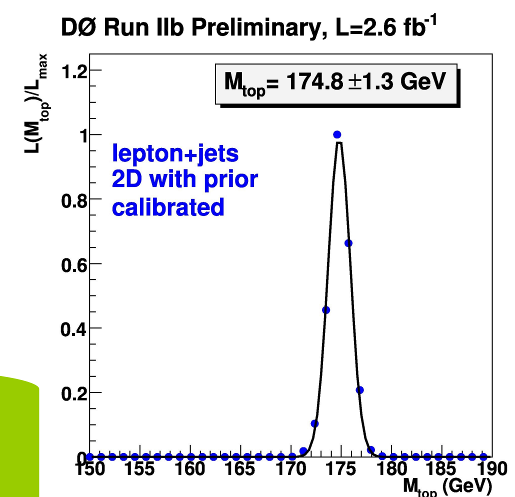




- Combination of Run IIa (∫Ldt = 1.0/fb) and Run IIb (∫Ldt = 2.6/fb)) returns:

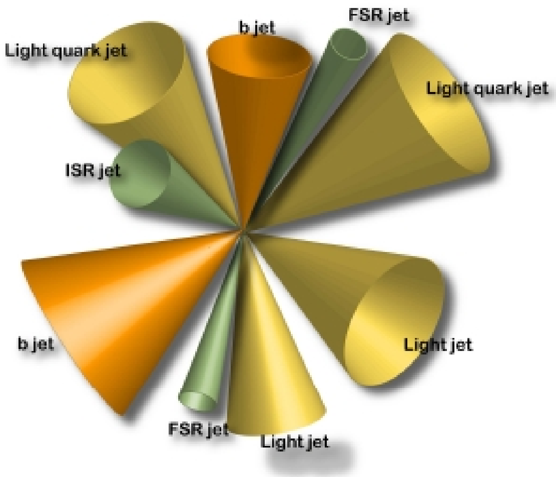
$$M_{top} = 173.7 \pm 0.8(stat.) \pm 1.6\,(syst. + JES)\ \text{GeV}$$

$$(\delta M_{top} / M_{top} = 1.0\%)$$



All-jets channel

Very tiny S:B (1:400) ,high statistics



Event selection algorithm

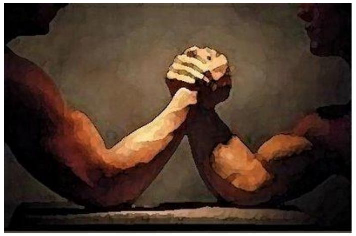
- ✓ 6 to 8 central jets (P_T >15 GeV)
- ✓ At least 1 b-tag

Main background

- ✓ QCD multi-jets

Main Challenge

- ✓ Huge background
- ✓ Many j2p assignments



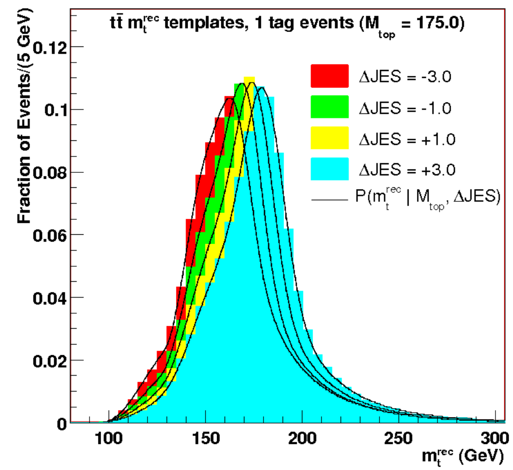
: all-jets

All-jets best

TM, ∫Ldt =2.9/fb

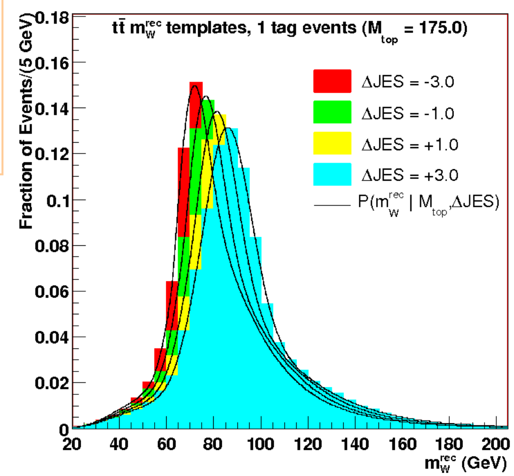
- NN exploited to select events

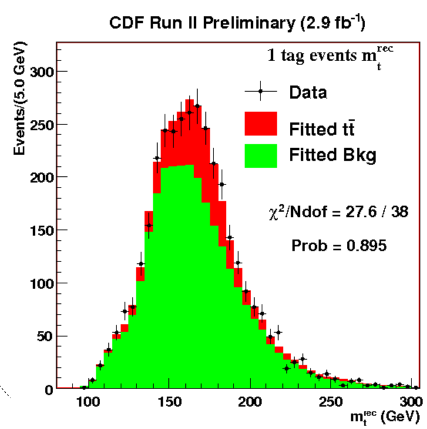
→ jet-shape variables recently added to distinguish between gluon jets (bg) and light-quark jets (signal)
→ increases S:B up to 1:4 (1:1 if 2-tags)
→ NN different threshold for 1-tag and 2-tag sample
→ 3893 selected events (about 907 ttbar)



- Event-by-event we reconstruct (via χ2 minimization)

→ top mass (mt)
→ W mass → allows a mt-independent JES calibration





- Fit templates to data:

$$M_{top} = 174.8 \pm 2.4(stat. + JES) \pm ^{1.2}_{1.0} (syst.)\ \text{GeV}$$

$$(\delta M_{top} / M_{top} = 1.5\%)$$

Orthogonal measurements

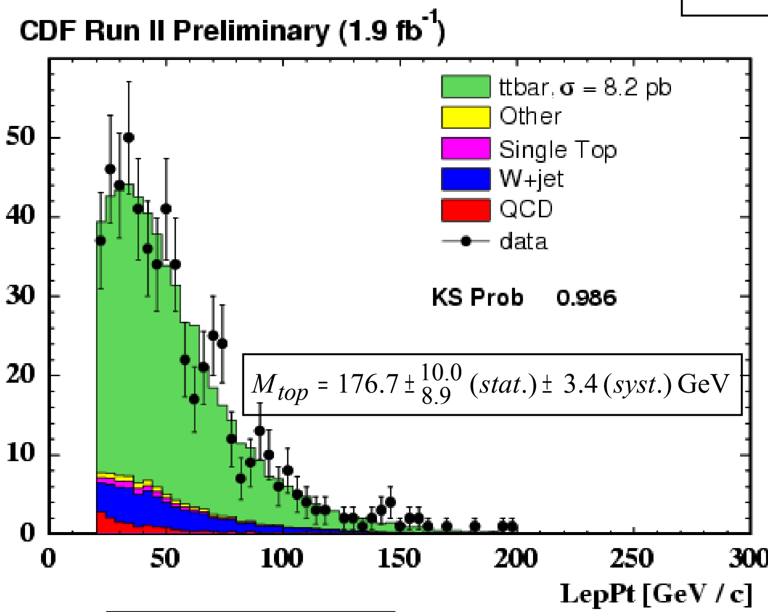
CDF II: Orthogonal measurement

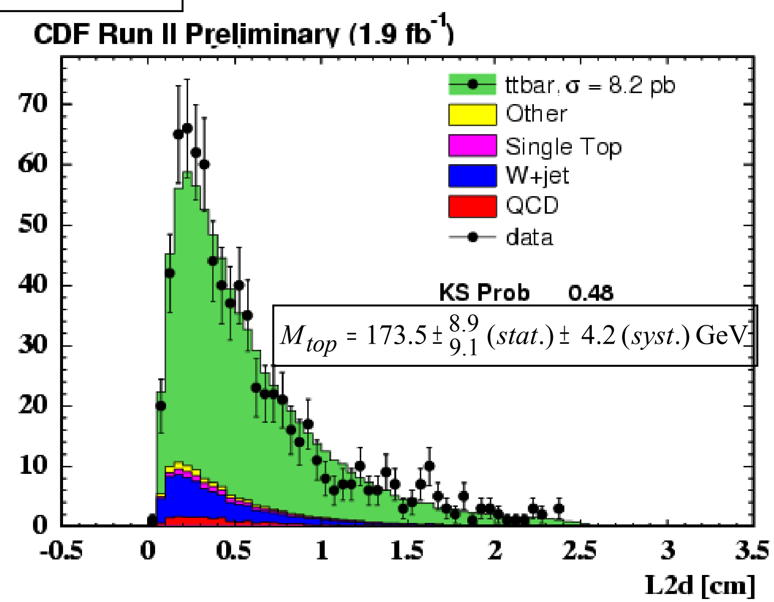
TM, $\int Ldt$ = 1.9/fb

- L+jets sample

→ 3 jets (1 b-tag), ≥4 jets (2 b-tag)

Two m_t estimators





Combination

$$M_{top} = 175.3 \pm 6.2 (stat.) \pm 3.0 (syst.) \text{ GeV}$$
$$(\delta M_{top} / M_{top} = 3.9\%)$$

- ✓ Minimal correlation to JES
- ✓ But poor statistical resolution

→ promising for LHC!

DØ: Orthogonal measurement

Based on m_t-dependence of σ_{tt}

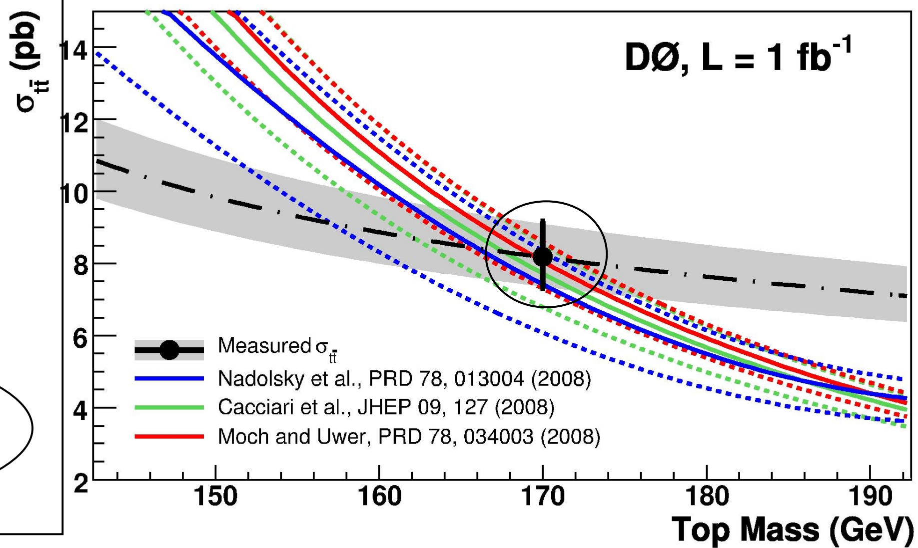
- l+jets, dilepton samples

→ τ included

→ ≥3 jets (l+jets), ≥2 jets (dilepton)

→ 1 b-tag

$$\sigma_{t\bar{t}}^{measured}(M_{top} = 170\,\mathrm{GeV}) = 8.18 \pm^{0.98}_{0.87}\,(stat. + syst.)\,\mathrm{pb}$$



Depending on the input from theory we obtain

$$M_{top} = 165.5 \pm^{6.1}_{5.9}\,\mathrm{GeV\ (NLO\ QCD)}$$

$$M_{top} = 167.5 \pm^{5.8}_{5.6}\,\mathrm{GeV\ (NLO + NLL\ QCD)}$$

$$M_{top} = 169.1 \pm^{5.9}_{5.4}\,\mathrm{GeV\ (approximate\ NNLO\ QCD)}$$

✓ Less accurate than direct easurements

✓ Does not heavily rely on (LO) simulated ttbar

→ less sensitive to difference between MC and pole masses

Systematic uncertainty on top mass

Example of δM_{top}^{syst} @CDF

Systematic source	L+jets (GeV/c^2)	Dilepton
Calibration	0.2	-
MC generator	0.5	0.2
ISR and FSR	0.3	0.2
Residual JES	0.5	2.9
b-JES	0.4	0.4
Lepton P_T	0.2	0.3
Multiple hadron interactions	0.1	0.2
PDFs	0.2	0.3
Background	0.5	0.7
NEW Color reconnection	0.4	To be done
Total	1.1	3.1

✓ JES uncertainty dominates (also after in situ calibration)

With the available high stats, M_{top} measurements are limited by δM_{top}^{syst}

CDF and DØ are discussing intensively to:

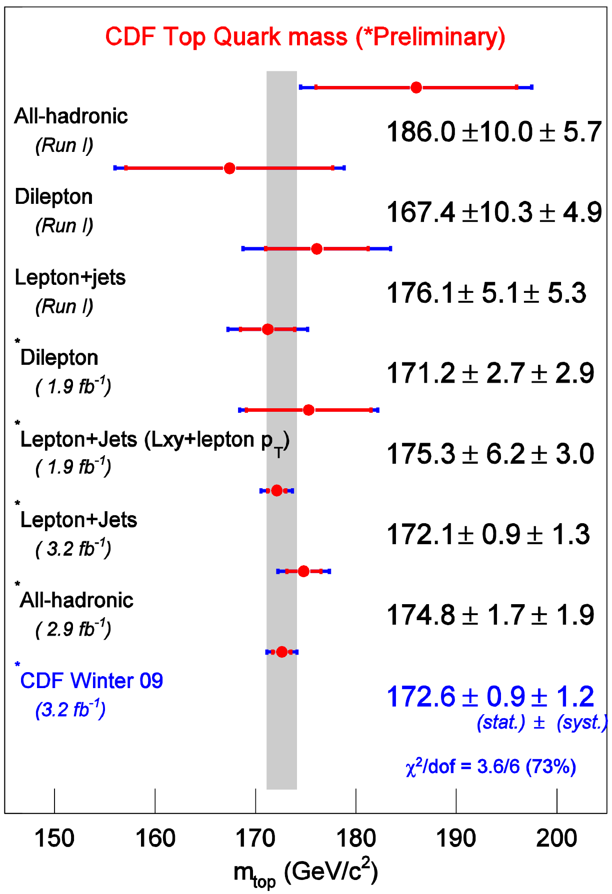
→ make sure to consider all relevant uncertainties

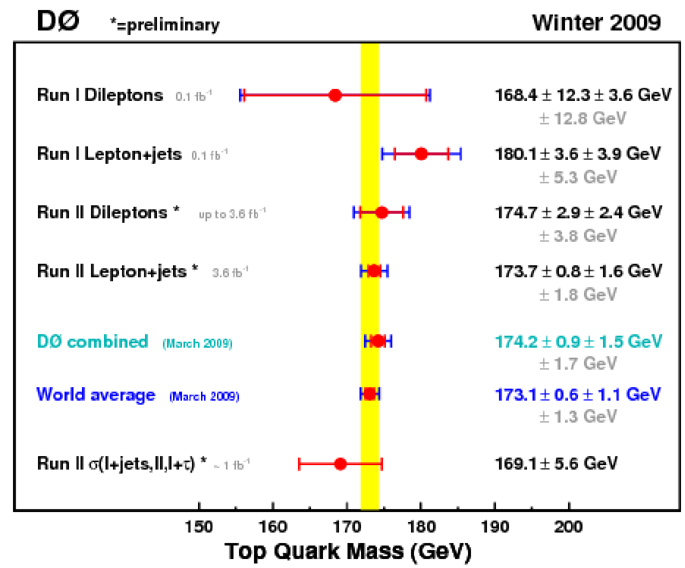
→ avoid double-counting of the same effect

→ achieve a uniform treatment of systematic uncertainties where possible

Combination

- Combination of most accurate analyses leads to





arXiv:0903.2503

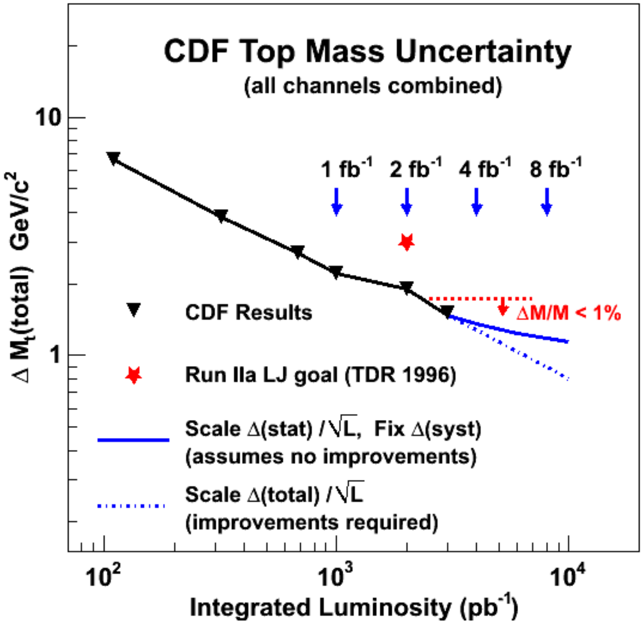
Tevatron world average (March '09)

$$M_{top} = 173.1 \pm 0.6\,(stat.) \pm 1.1\,(syst.)\, GeV$$

$$(\delta M_{top} / M_{top} = 0.75\%)$$

Conclusions & plans for the future

Both CDF and DØ reached <1% precision in their combined measurements



- Already beyond Run II goal (δMtop ~3 GeV)
  → but still more data coming

- Precison now dominated by systematic uncertainties

→ In order to push it down we are planning to:

i. Understand better physics models
   - ISR/FSR with the increased Drell_Yan samples
   - Improved color reconnection models

i. Disentagle correlations among different uncertainties (i.e. residual JES Vs MC generator)

More info available at

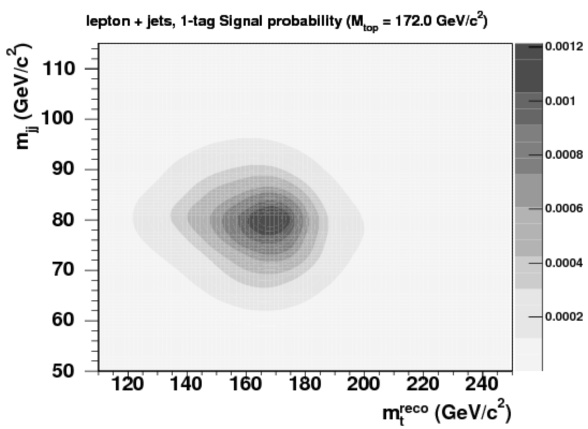
- http://www-cdf.fnal.gov/physics/new/top/public_mass.html
- http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html

Backup

Lepton+jets & dilepton

TM, $\int Ldt = 3.2/fb$

- Simultaneous measurement in the lepton+jets and dilepton channel
  → lepton+jets events with at least 1 b-tag



- Two event-by-event m_t estimators are chosen

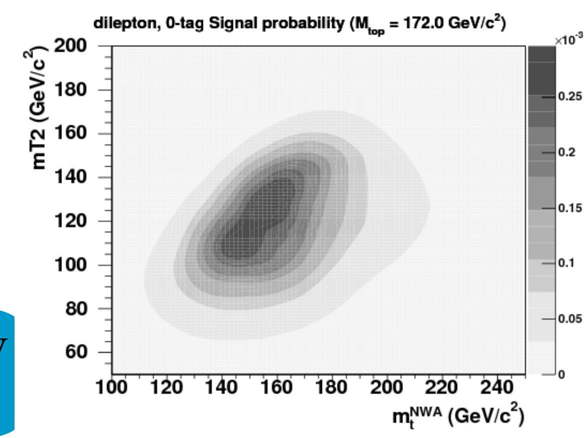
Lepton+jets: reconstructed top and W masses
→ allow for in situ JES calibration
Dilepton: reconstructed top and transverse top masses
→ assumptions on neutrino η's (Neutrino Weighting Algorithm) to constrain kinematics

- Fit the data with 2D templates:

$$\text{Lepton+ jets}: M_{top} = 172.8 \pm^{1.5}_{1.6} (stat. + JES) \pm 1.1 (syst.)\ \text{GeV}$$

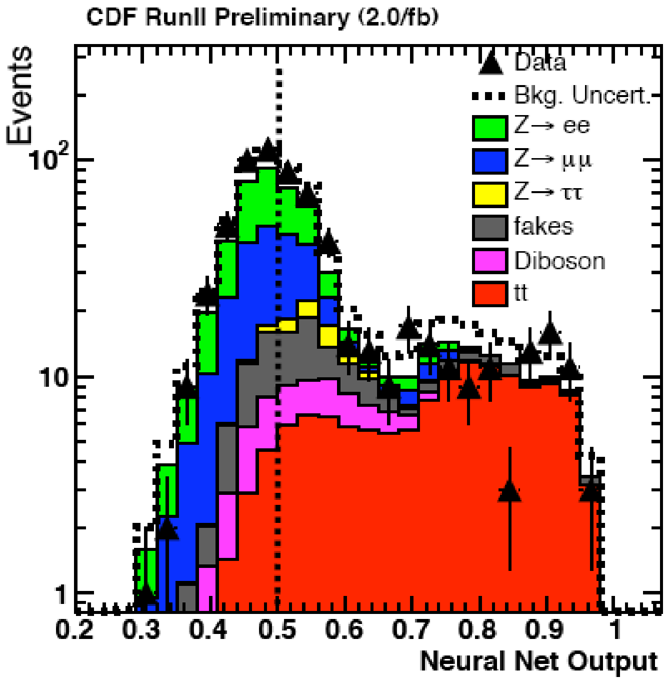
$$\text{Dilepton}: M_{top} = 169.3 \pm 2.7 (stat.) \pm 3.2 (syst.)\ \text{GeV}$$

$$\text{Combined}: M_{top} = 171.7 \pm^{1.5}_{1.4} (stat. + JES) \pm 1.1 (syst.)\ \text{GeV}$$
$$(\delta M_{top} / M_{top} = 1.1\%)$$



: Dilepton

ME - ∫Ldt = 2.0/fb

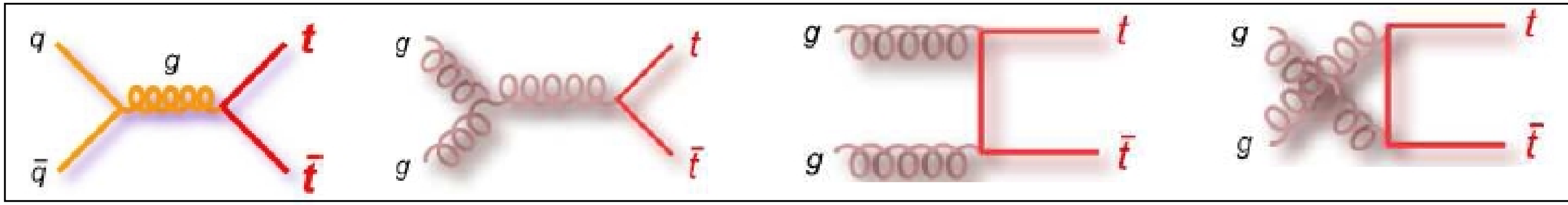


Sample composition dependending on NN cut

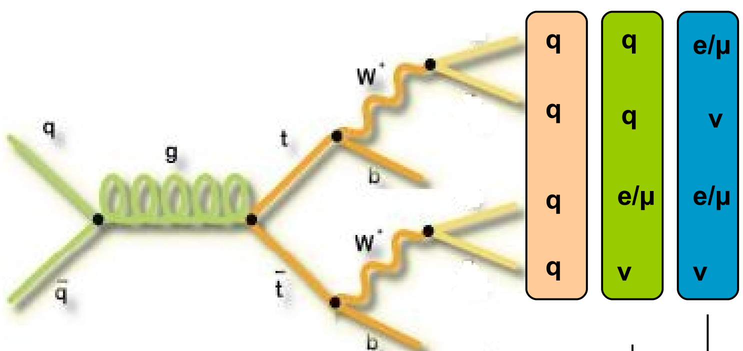
→ Drell-Yan reduced

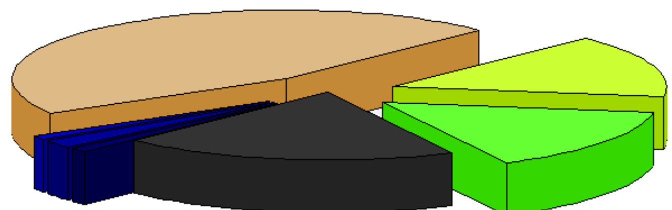
Top Production and Signature

Produced in pairs mainly via strong interactions → ~ 6.7 pb (Mtop =175 GeV)



Decaying in Wb ~ 100 % of the times → 3 possible signatures depending on W's products

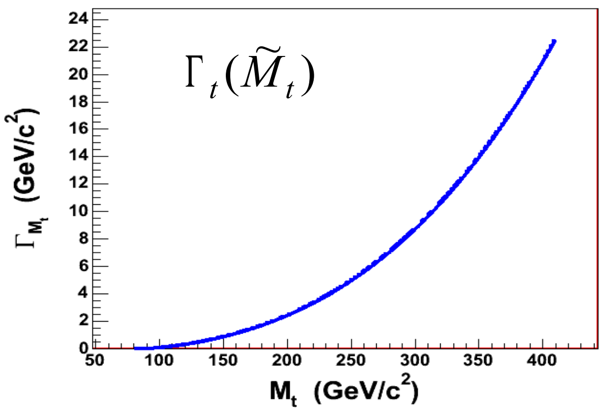




all jets 44%
→ 2 b-jets
→ 4 q-jets

dilepton 5%
→ 2 b-jets
→ 2 high PT e/ μ
→ large missing transverse energy (MET)

l+jets 30%
→ 2 b-jets, 2 q-jets
→ high PT e/ μ
→ large MET



$$\Gamma(m_t) = \frac{G_F}{8\sqrt{2}\pi} m_t^3 \left(1 - \frac{M_W^2}{m_t^2}\right)^2 \left(1 + 2\frac{M_W^2}{m_t^2}\right)$$

Acceptances

Dilepton (Neutrino φ Method)

Process	Expected number
Signal ($t\bar{t}$)	162.6 ± 5.1
WW	10.5 ± 1.0
WZ	3.8 ± 0.3
ZZ	0.9 ± 0.1
$Z/\gamma^* \to e^+e^-$	20.8 ± 6.0
$Z/\gamma^* \to \mu^+\mu^-$	9.1 ± 3.1
$Z/\gamma^* \to \tau^+\tau^-$	19.6 ± 2.4
Fakes	80.2 ± 15.7
Total background	145.0 ± 17.3

Lepton+jets

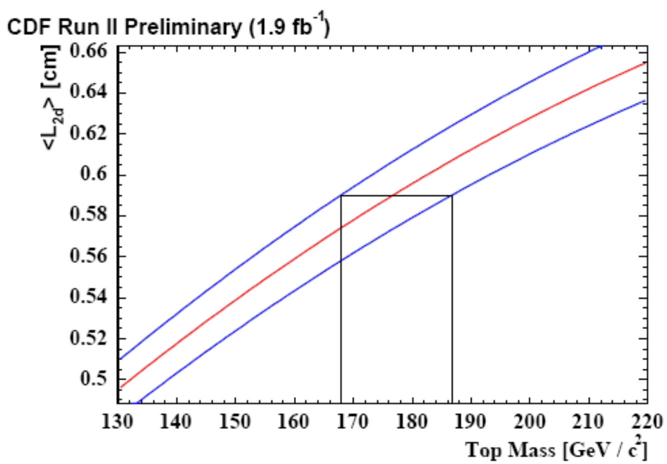
Background	1 tag	$\geq$ 2 tags
non-W QCD	23.4 ± 20.4	1.6 ± 2.3
W+light mistag	22.1 ± 5.7	0.4 ± 0.2
diboson (WW, WZ, ZZ)	5.5 ± 0.6	0.5 ± 0.1
$Z \to ee, \mu\mu, \tau\tau$	3.6 ± 0.5	0.3 ± 0.1
Sum of above 3	31.2 ± 5.8	1.2 ± 0.2
$W + bb$	32.4 ± 12.5	6.6 ± 2.2
$W + c\bar{c}$	19.4 ± 6.7	0.9 ± 0.3
$W + c$	10.3 ± 3.6	0.5 ± 0.2
Single top s-chan	2.4 ± 0.3	0.9 ± 0.1
Single top t-chan	2.7 ± 0.3	0.7 ± 0.1
Sum of above 5	67.2 ± 21.8	9.5 ± 2.6
Total background	121.8 ± 31.7	12.3 ± 4.4
Predicted top signal	307.8 ± 55.7	117.2 ± 19.0
Events observed	459	119

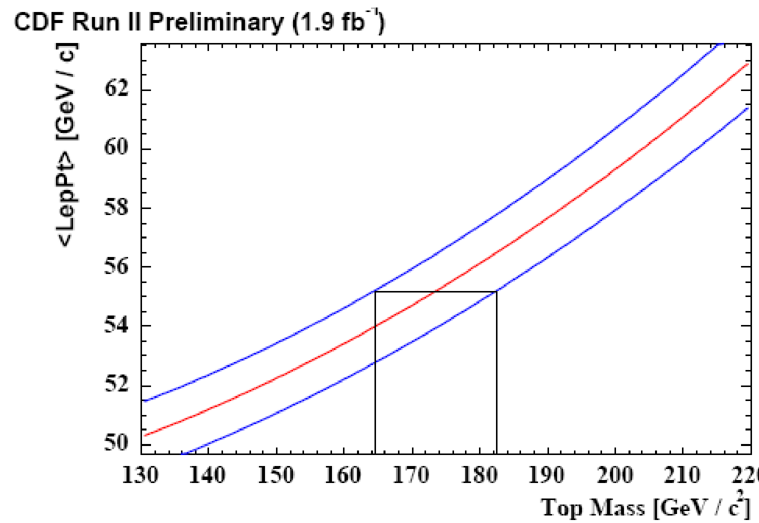
CDF: lepton+jets

$$M_{top} = 172.1 \pm 0.9(stat.) \pm 0.7\,(JES) \pm 1.1\,(syst.)\ \mathrm{GeV}$$

$$\Delta_{\mathrm{JES}} = (0.40 \pm 0.26)\sigma$$

: Orthogonal measurement





: Orthogonal measurement

Systematic	L2d	LepPt	Combination
Level 1, Eta Dependent	0	0	0
Level 4, Multiple Interactions	0.1	0	0
Level 5, Absolute	0.2	0.1	0.1
Level 6, Underlying Event	0	0	0
Level 7, Out of Cone	1.0	0.2	0.6
Level 8, Splash out	0.1	0.1	0.1
Simultaneous	1.0	0.3	0.6

TABLE IV: Systematic Results

Systematic	L2d	LepPt	Combination
QCD Radiation	0.9	2.3	1.5
PDFs	0.3	0.6	0.5
Generator	0.7	1.2	0.6
L2d Scale Factor	2.9	0	1.4
LepPt scale	0	2.3	1.1
Bkg Shape	1.0	2.3	1.6
Out of Cone JES	1.0	0.3	0.6
Total	3.4	4.2	3.0

: Orthogonal measurement

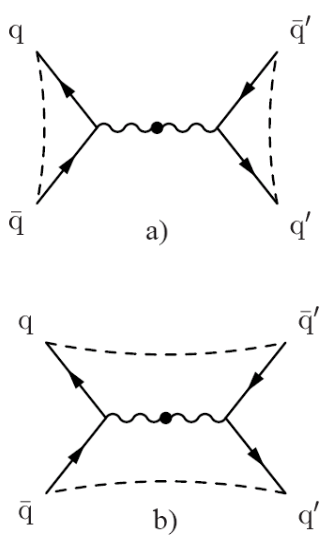
$$\sigma_{t\bar{t}}(m_t) = \frac{1}{m_t^4}[a+b(m_t-m_0)+c(m_t-m_0)^2+d(m_t-m_0)^3]$$

Color Reconnection Systematic

Strong color correlations between the hard process and the underlying event are required by tune A and similar tunes. These effects are interpreted as sign for color reconnection.

The issue has been studied at LEP for the W mass measurement

LEP



CR effects on the M_W measurement at LEP contribute to systematics

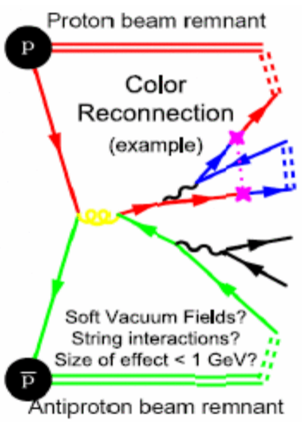
CR(sys) = 8 MeV

out of 22 MeV (total sys)

(LEPEWWG hep-ex/061203)

Tevatron

Preliminary MC studies have indicated possible contributions



to the top mass systematics of order

CR(sys)≈ 0.5 GeV

D. Wicke and P. Skands arXiv:0807.3248V1