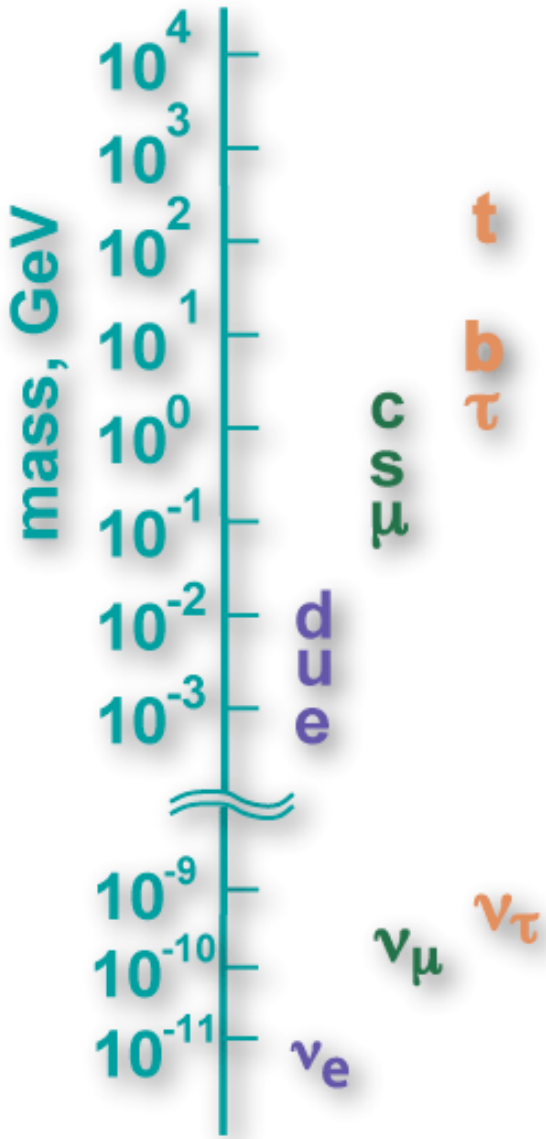
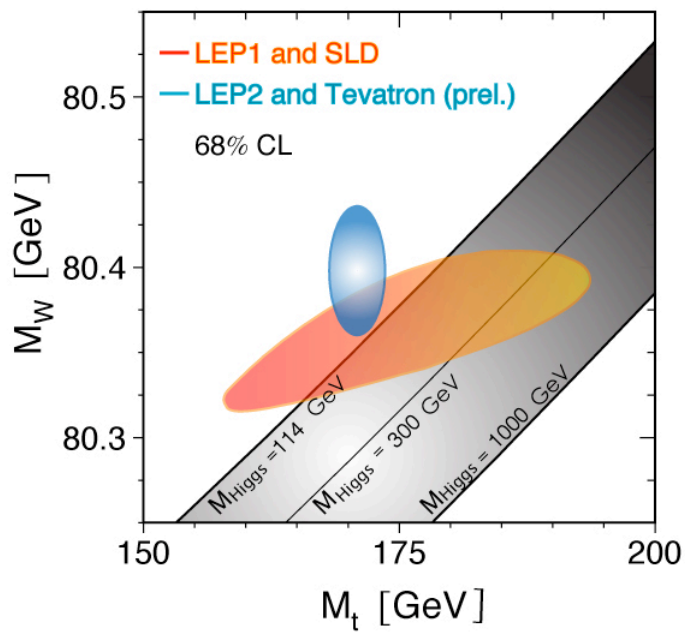
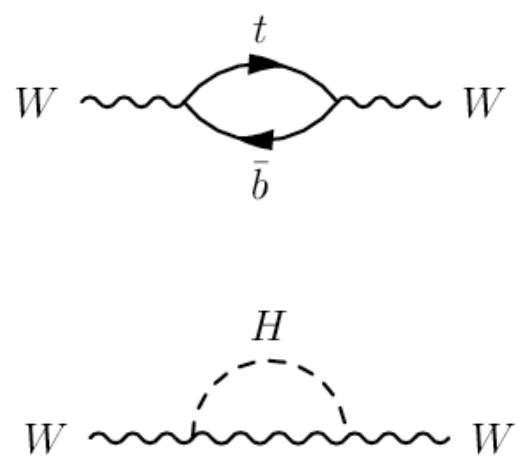
Top Mass at the Tevatron

The top quark

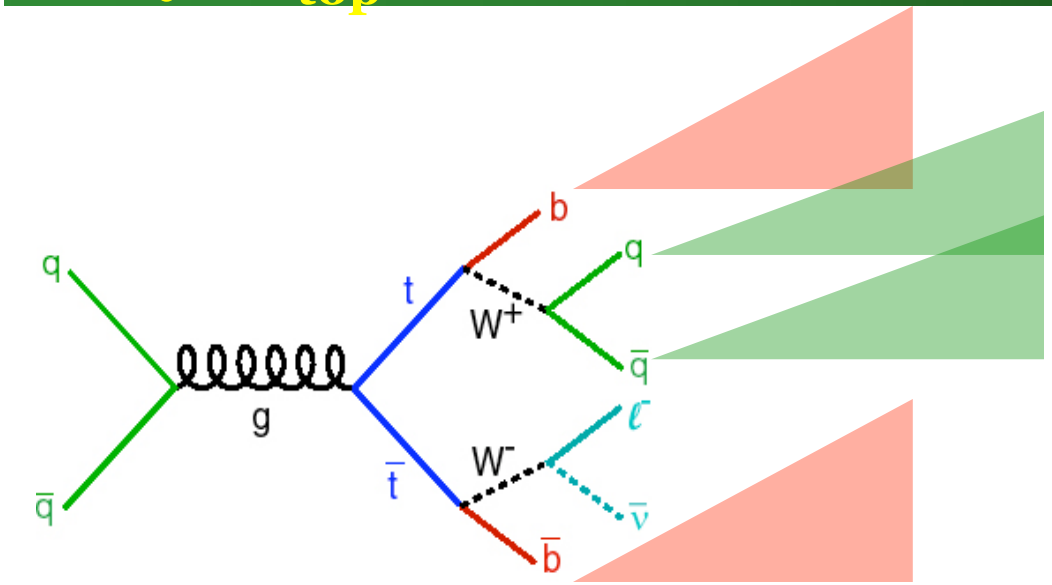


- Top is by far the heaviest known particle
- A role in electroweak-symmetry breaking?
- When we find Higgs, a precision test of the SM

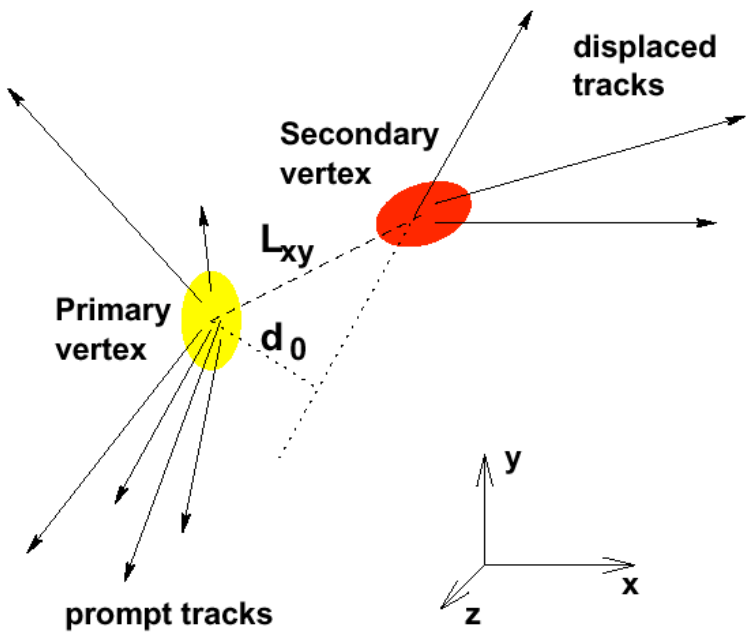




Why M_{top} is difficult

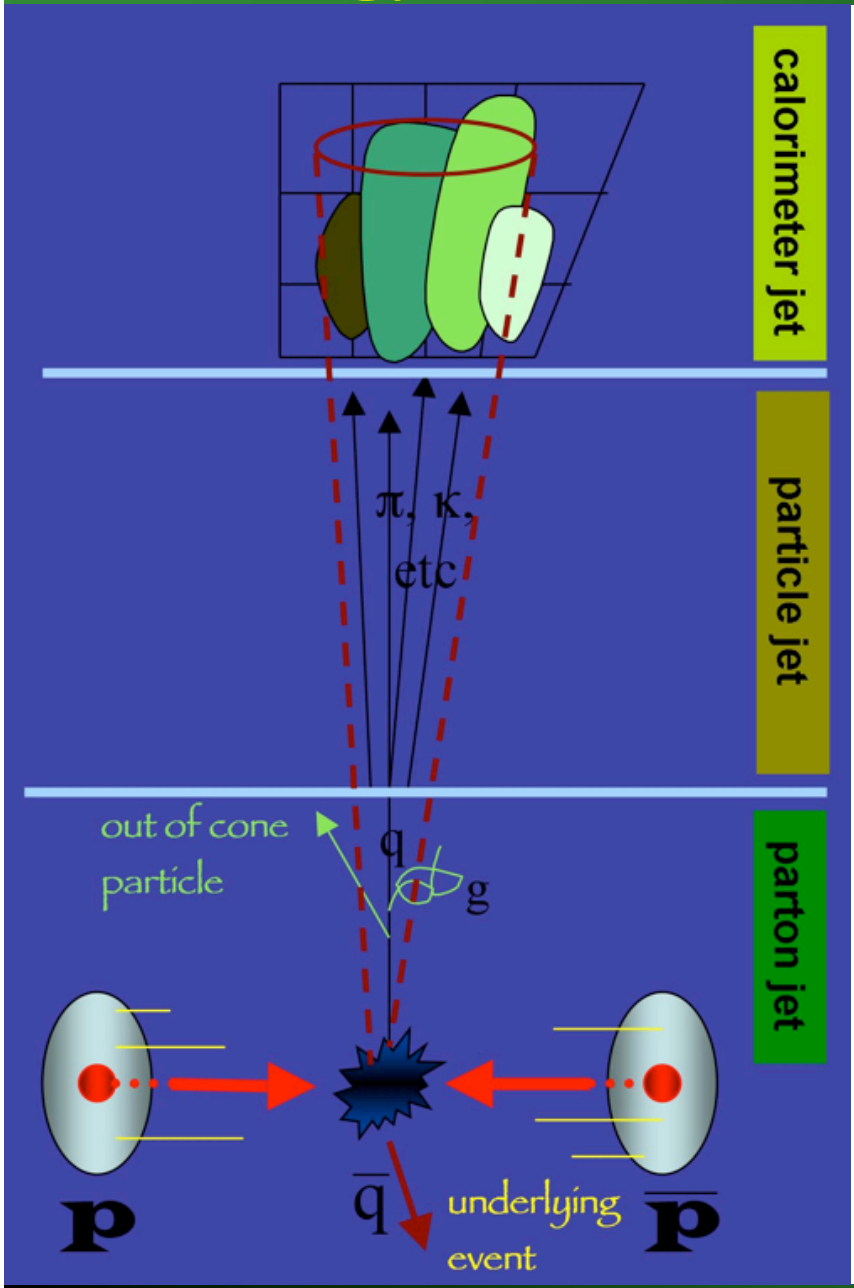


- Tops produced predominantly in pairs
- Decay ~always to W+b
- Topology depends on W decay (hadronic vs leptonic)
- Combinatorics …
- Up to 6 jets …
- Up to 2 neutrinos …

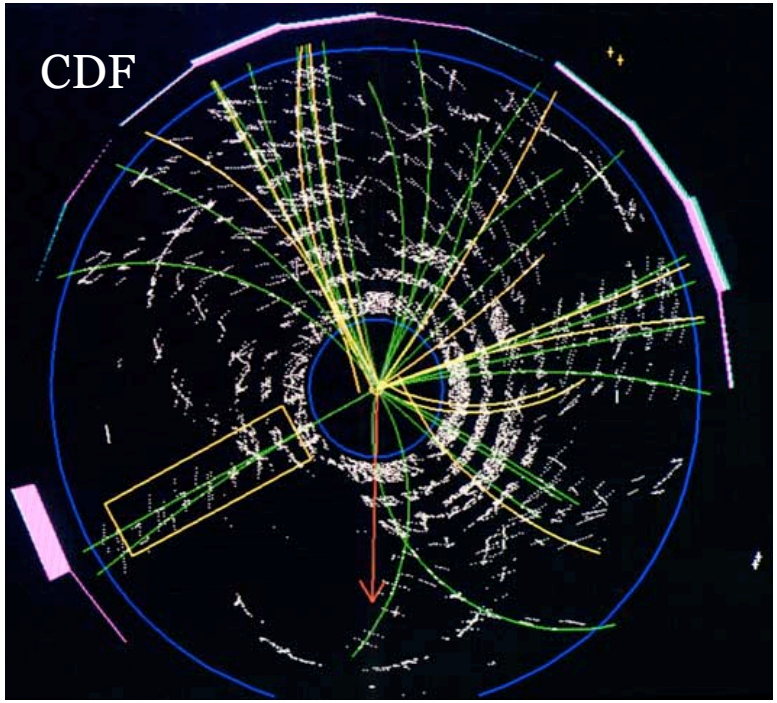


Tagging jets from b quarks reduces combinatorics, cuts away background

Jet Energy Scale (JES)



What we actually see in our detector ...

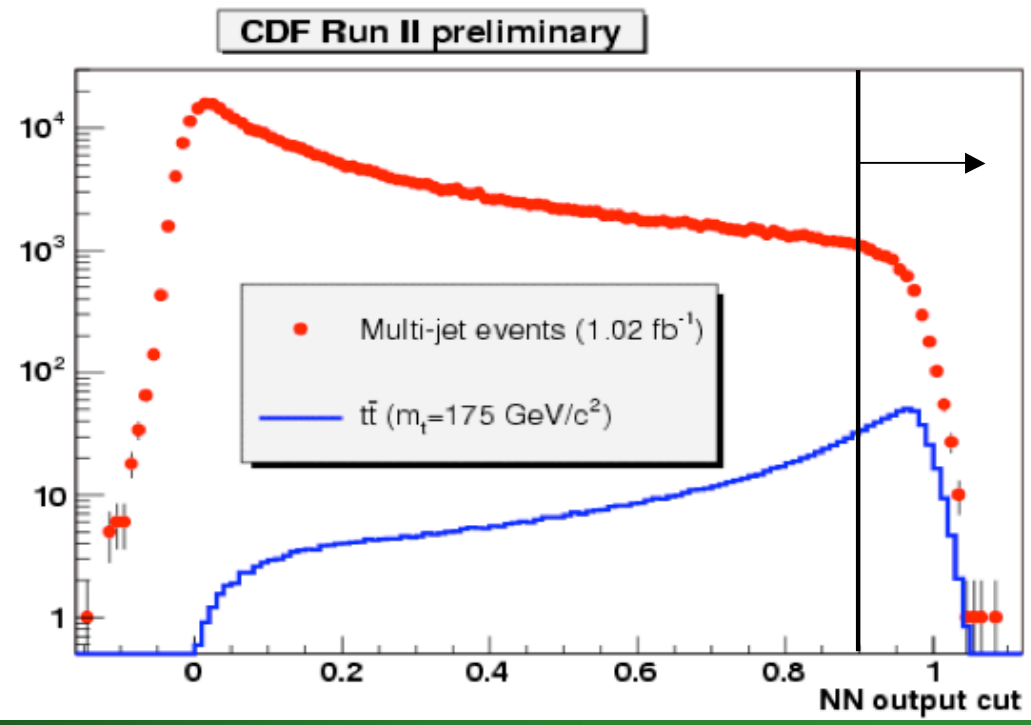


Typical S:B

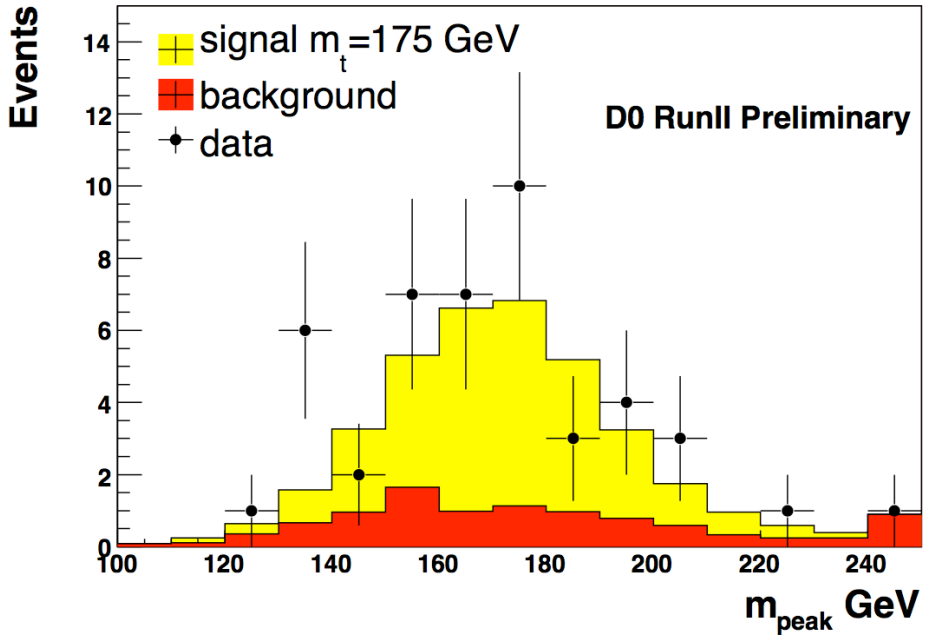
Typical S:B values for different channels

Dilepton		Lepton+Jets		All-Hadronic	
$tt \to bbl^+l^-\nu\nu$		$tt \to bbl\nu qq$		$tt \to bbqqqq$	
0-tag	b-tagged	1 b-tag	2 b-tag	1 b-tag	2 b-tag
1:1	20:1	4:1	20:1	1:5	1:2

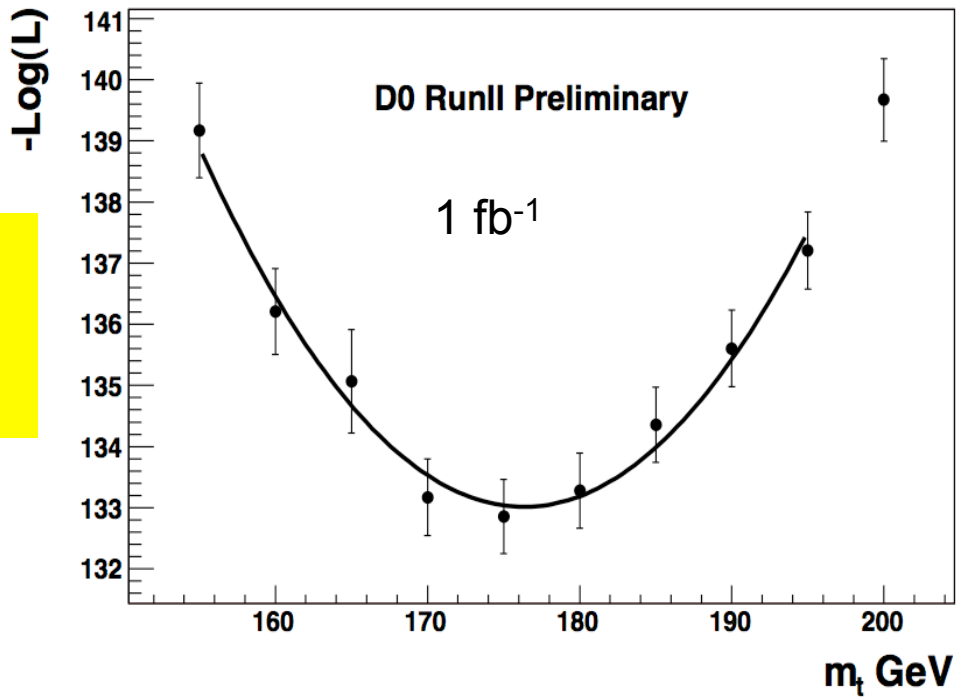
All-hadronic Neural Network used in selection to improve S:B



DZero dilepton Matrix Weighting New!



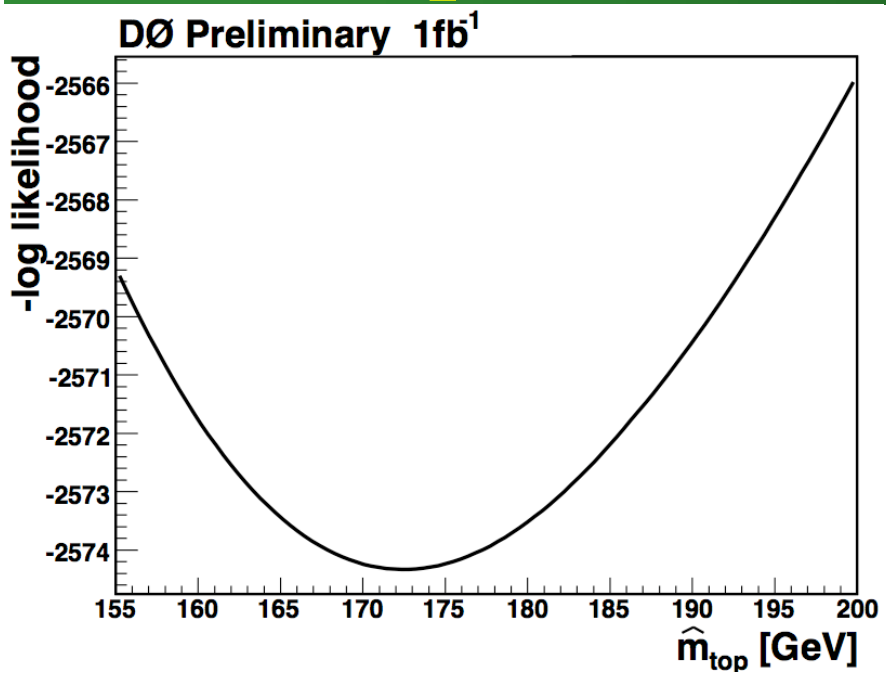
- Each lepton-jet pairing given weight of expectation to find lepton with measured energy, PDFs for initial quark energy, integrate over unknown t and tbar pt
- Jet Energy Scale once again dominates the systematics



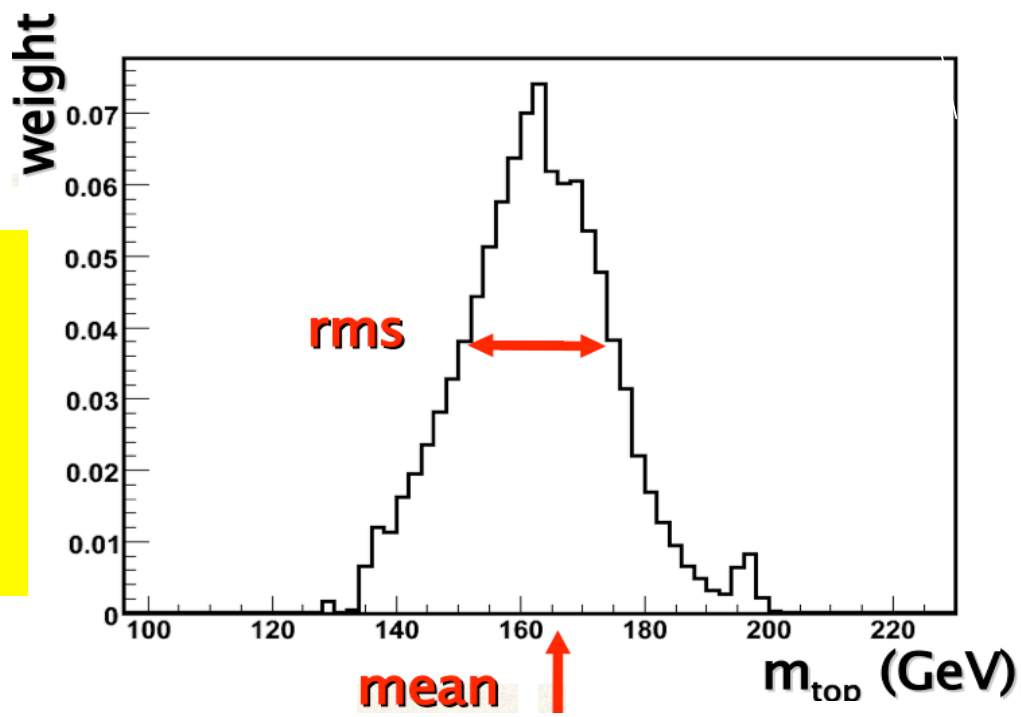
M_{top} = 175.2 ± 6.1 (stat) ± 3.4 (syst) GeV/c²

1 fb^{-1}

DZero dilepton NWA measurement New!



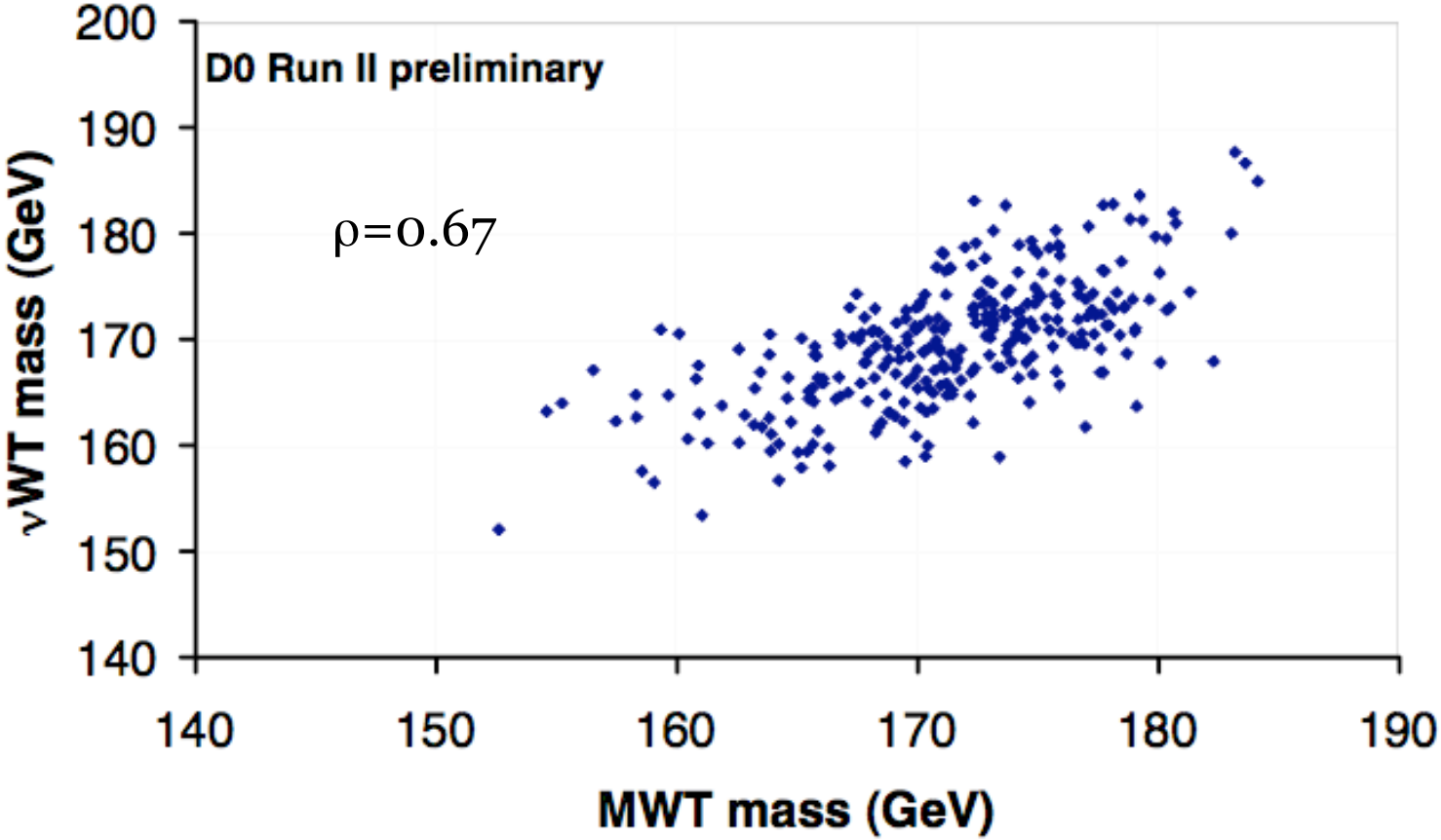
- Neutrino Weighting Algorithm integrates over unknown pseudorapidities of the two neutrinos, weights solutions by agreement with missing ET (MET)
- Use mean and RMS of weight distributions from MC as estimators, fit to 3d templates
- Systematics dominated by JES



$M_{top} = 172.5 \pm 5.8$ (stat) $\pm$ 3.5 (syst) GeV/c²

1 fb-1

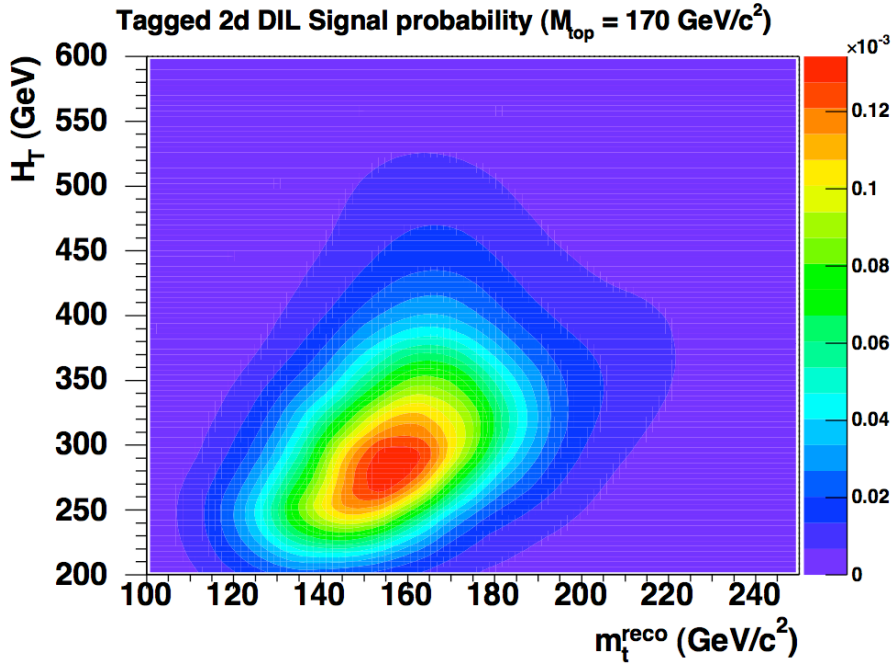
DZero dilepton combination New!



$M_{top} = 173.7 \pm 5.4\ (stat) \pm 3.4\ (syst)\ GeV/c^2$

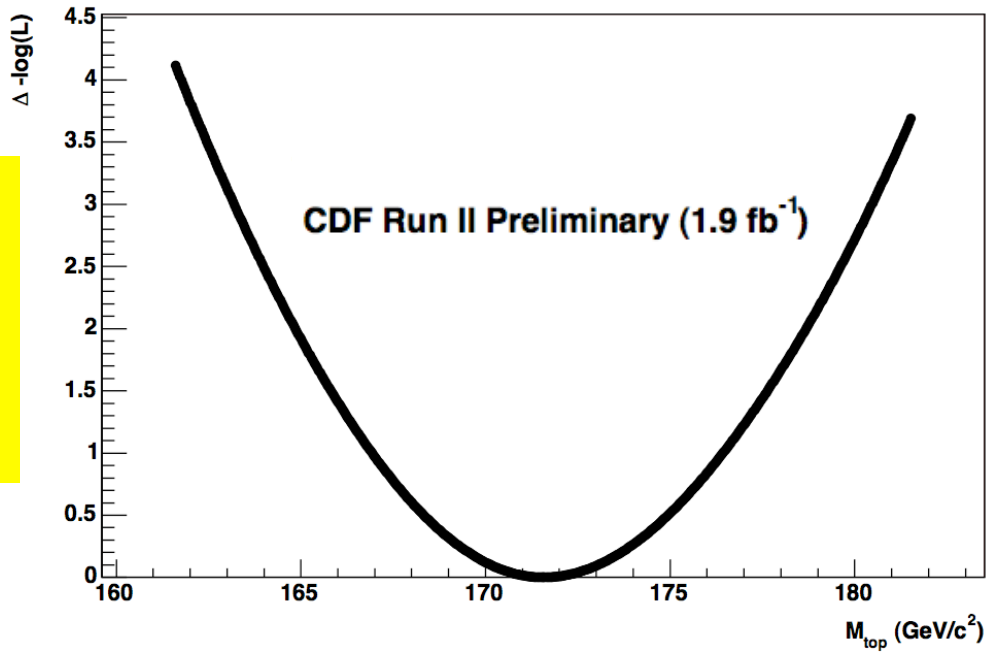
1 fb^{-1}

CDF dilepton template measurement New!



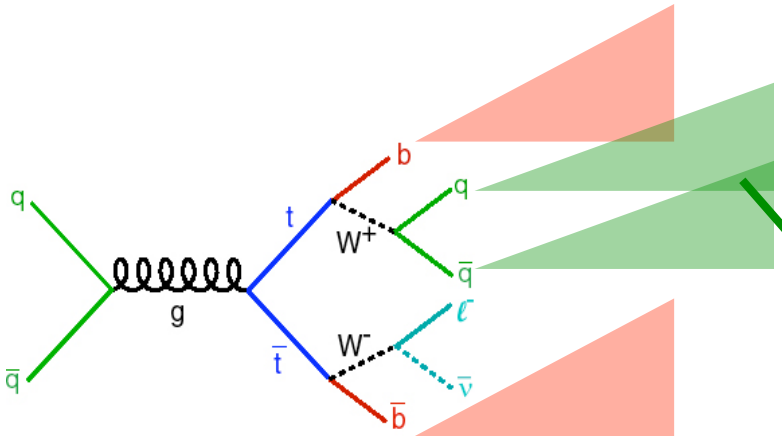
- Also uses Neutrino Weighting Algorithm, selects peak (most probable value) of weight distribution as first observable
- Second observable is the H_T (scalar sum MET, lepton P_T, jet P_T) in the event
- Again limited by JES systematic

M_{top} = 171.6 +3.4/-3.2 (stat) ± 3.8 (syst) GeV/c²

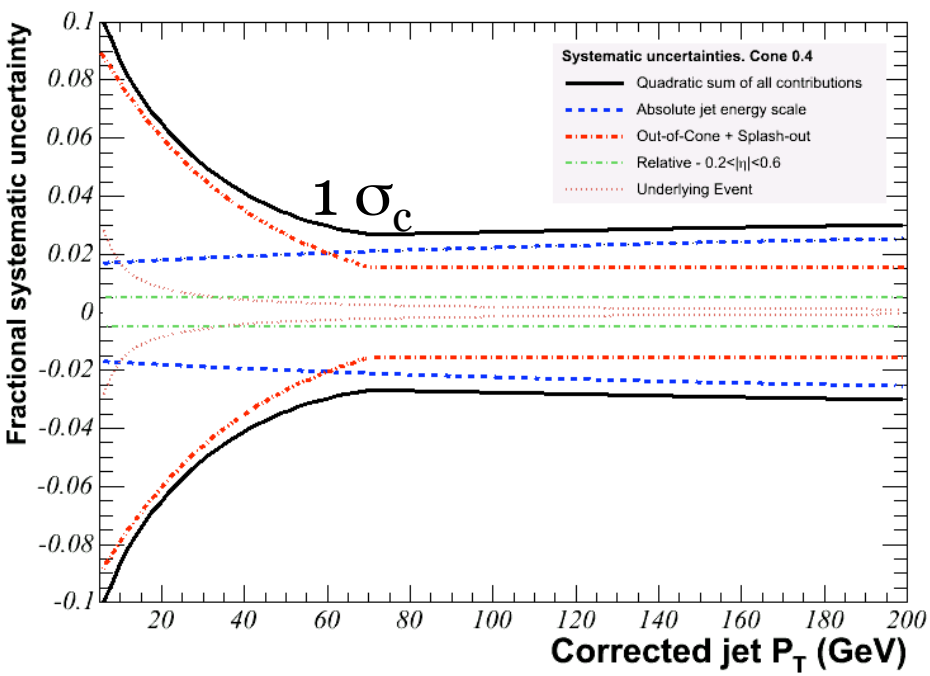


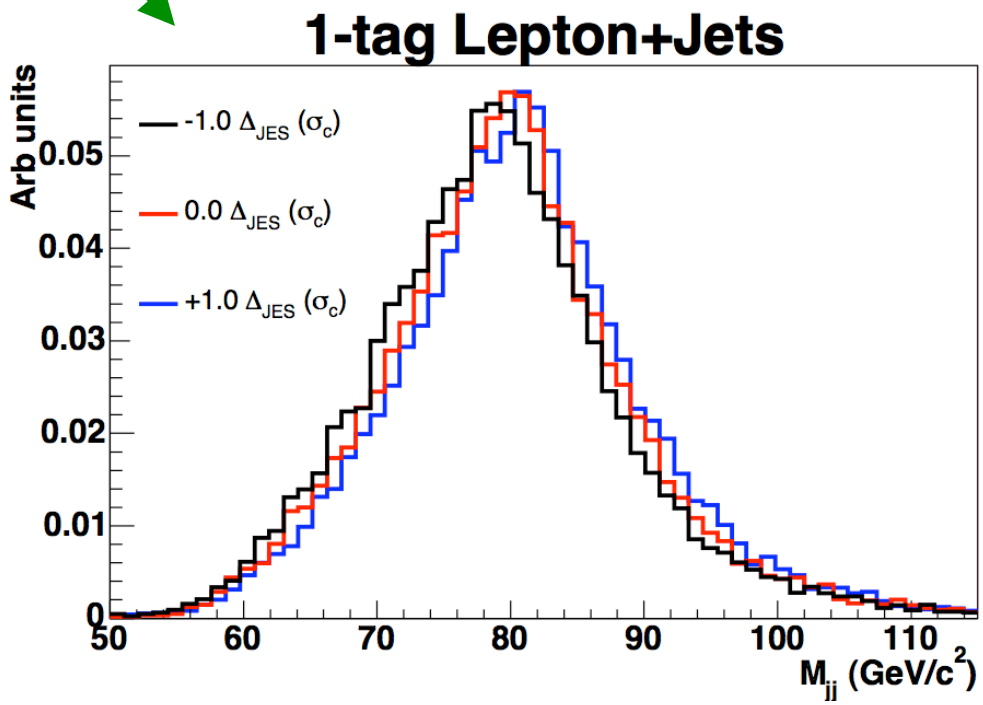
1.9 fb^{-1}

A handle on the Jet Energy Scale

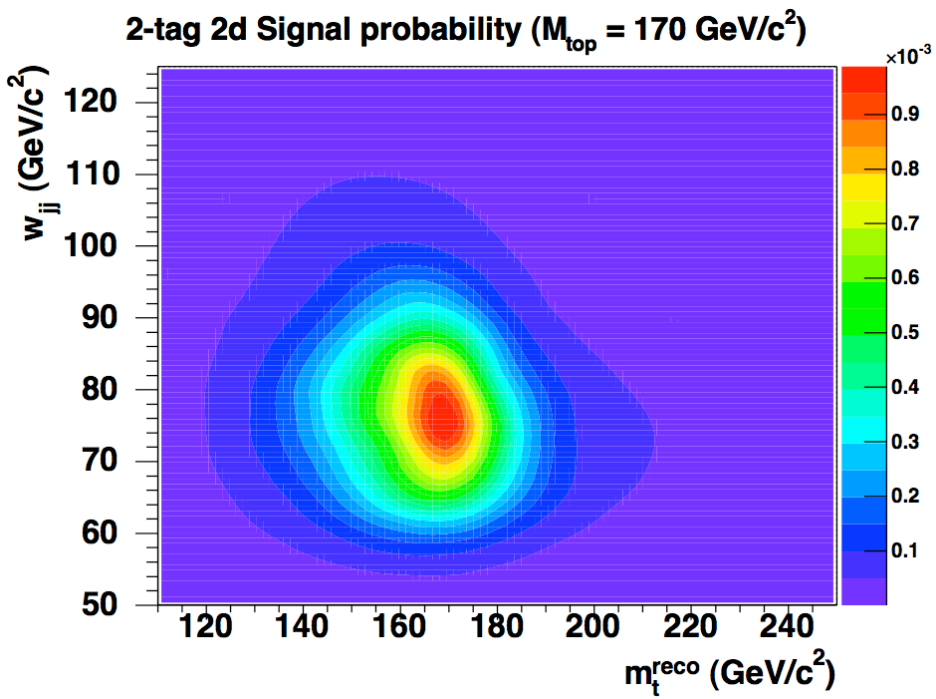


Dijet mass of hadronically decaying W provides *in situ* calibration of JES



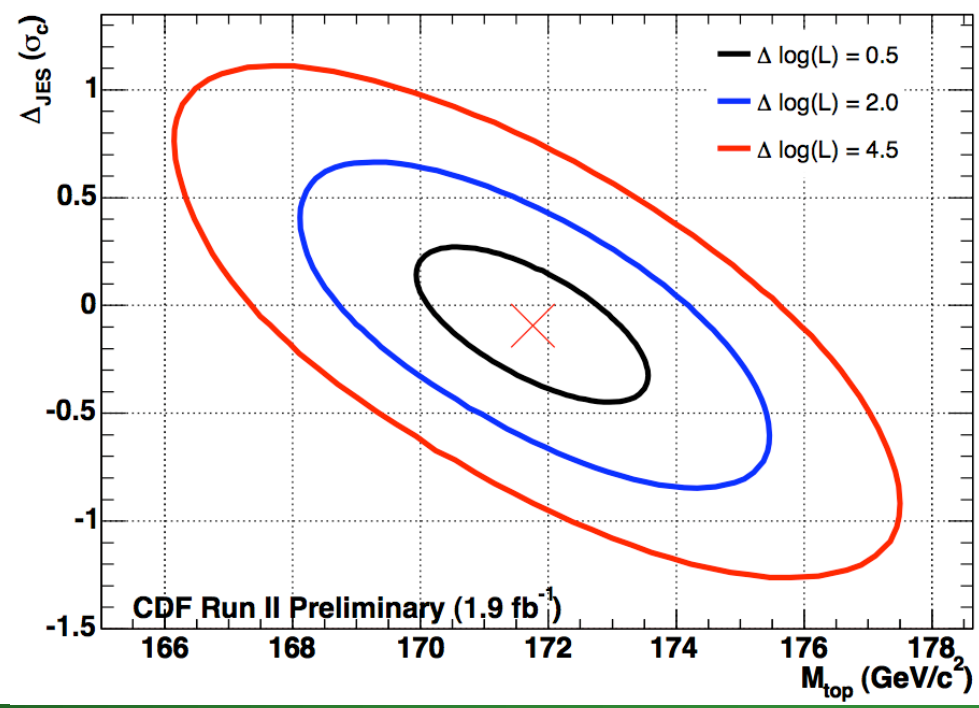


CDF Lepton+Jets template measurement New!



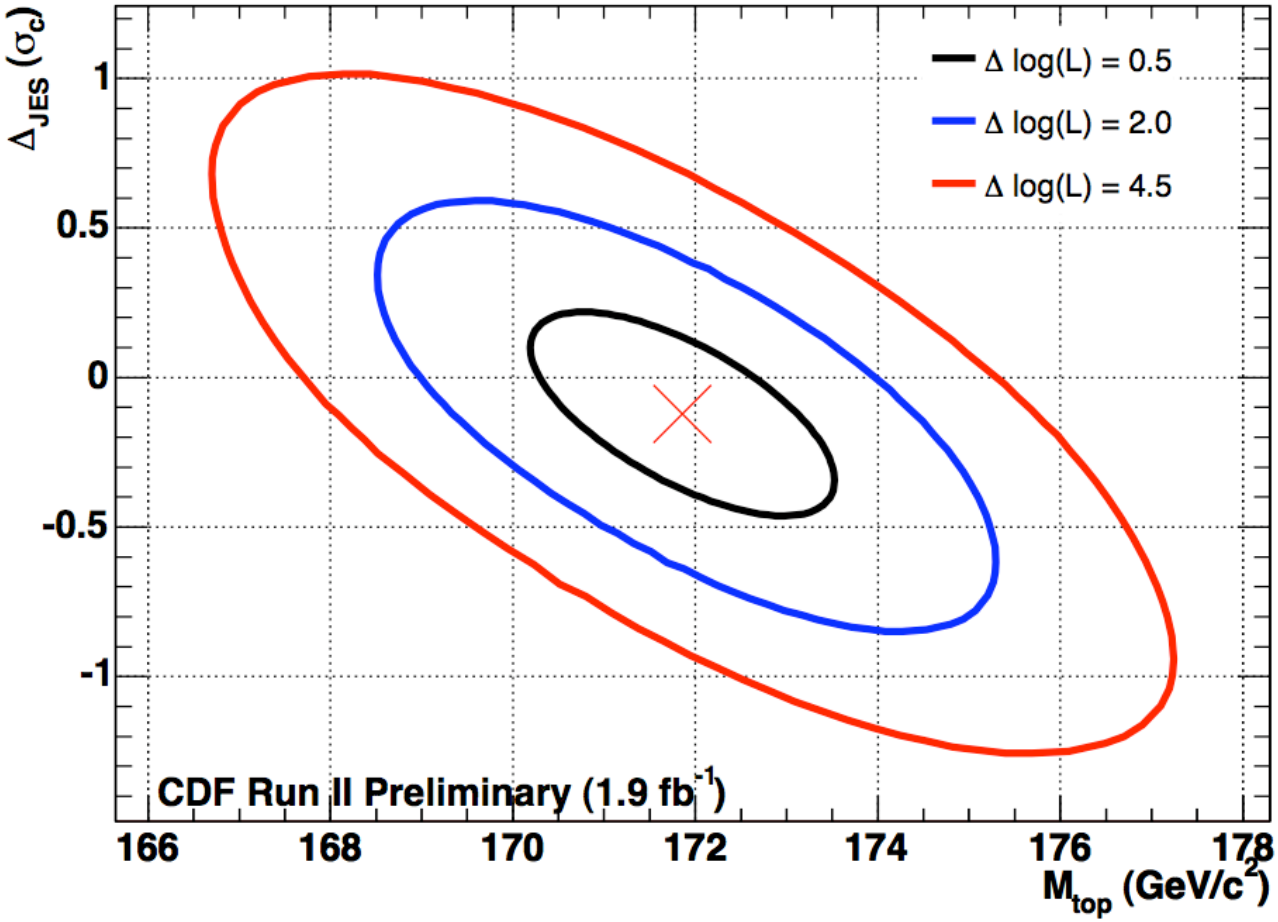
- Form an estimator for the top quark mass using knowledge of overconstrained kinematics (one number per event)
- Use dijet mass of hadronically decaying W as second observable, to constrain JES

M_{top} = 171.8 ± 1.9 (stat+JES) ± 1.0 (syst) GeV/c²



1.9 fb^{-1}

CDF combined template measurement New!

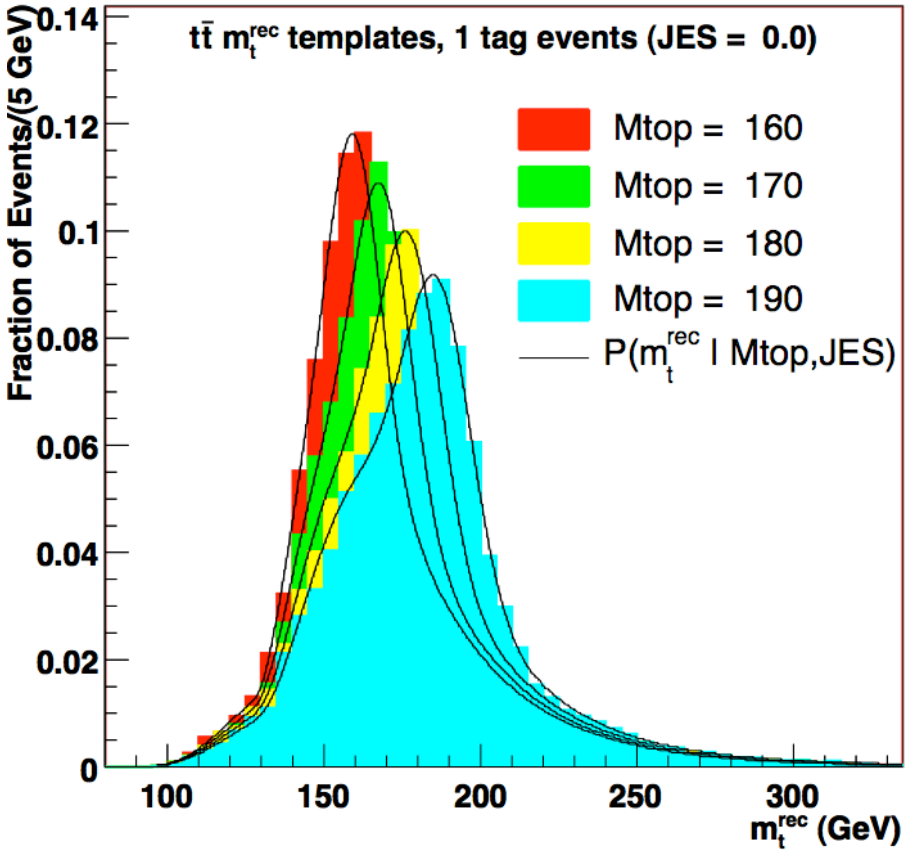


- Combine Lepton+Jets and Dilepton template measurements in the same likelihood
- Robust combination
- No assumptions about correlations for systematics
- Dileptons make use of the Lepton+Jets *in situ* JES calibration

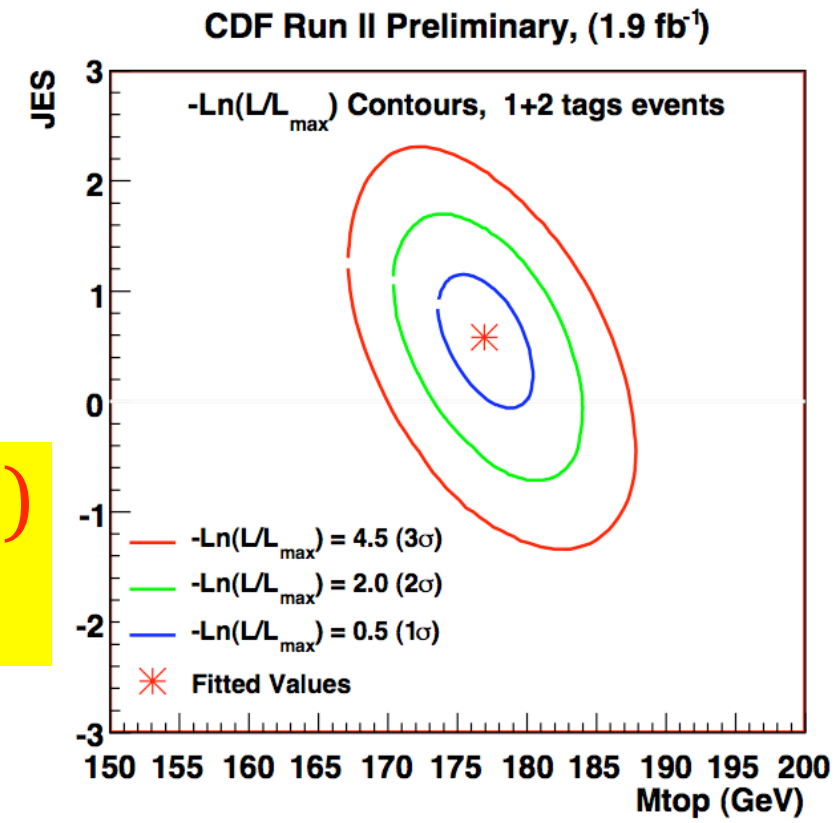
M_{top} = 171.9 ± 1.7 (stat+JES) ± 1.0 (syst) GeV/c²

1.9 fb^{-1}

CDF All-hadronic template measurement New!



- All-hadronic selection with neural network to increase S:B
- Kinematic fitter using knowledge of overconstrained kinematics: one estimator for top quark mass
- Use fitted mass of hadronically decaying Ws to get a handle on JES



M_{top} = 177.0 ± 3.7 (stat+JES) ± 1.6 (syst) GeV/c²

CDF II 1.9 fb^{-1}

Matrix Element Analyses

- Try to extract as much information as possible from every event using theoretical prediction for ttbar production and decay
- Integrate over unknown parton energies given a measured jet energy

ME for ttbar production and decay

Transfer function: probability to observe jet j given parton p

$$P(\vec{x}|M_t) = \frac{1}{N}\int d\Phi \left|M_{t\bar{t}}(p;M_t)\right|^2 \prod_{objects} W(p,j) f_{PDF}(q_1) f_{PDF}(q_2)$$

Normalization

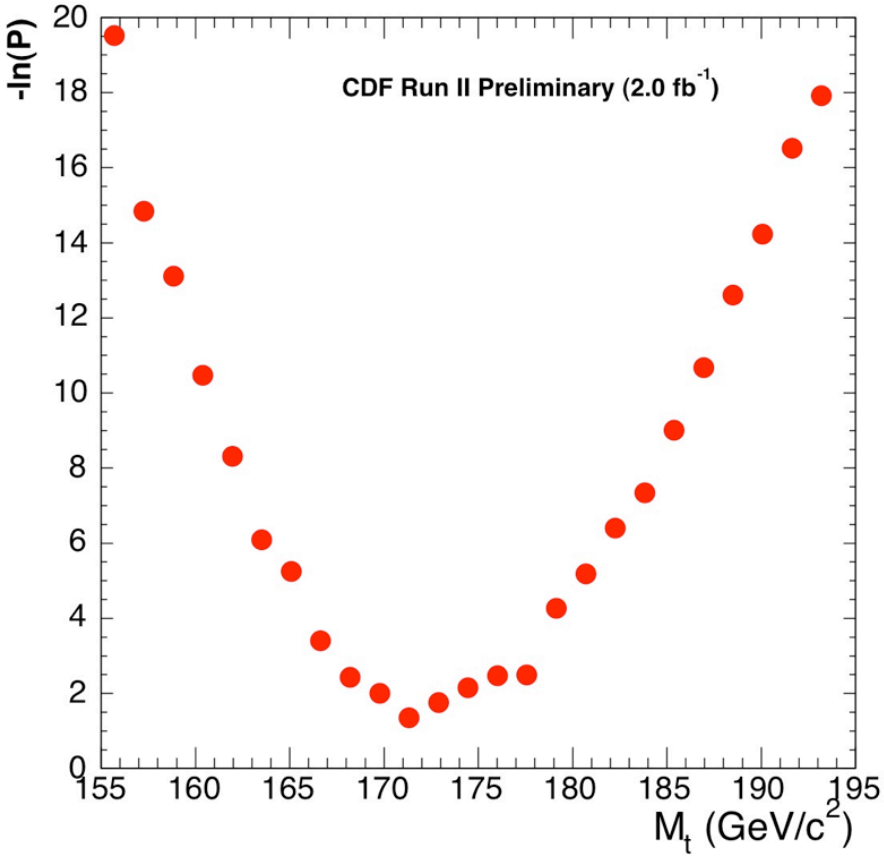
Parton-level phase space

Parton Distribution Functions for incoming partons

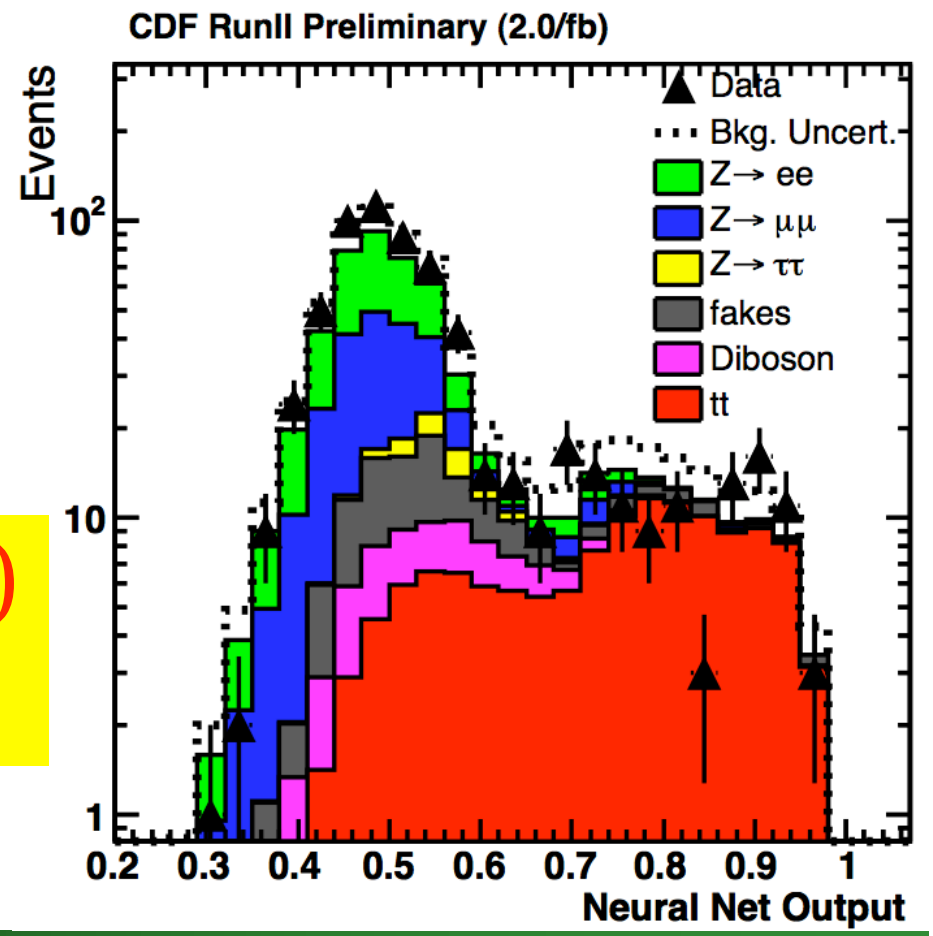
Probability to observe x in detector, given a top quark mass

CDF dilepton ME measurement

New!



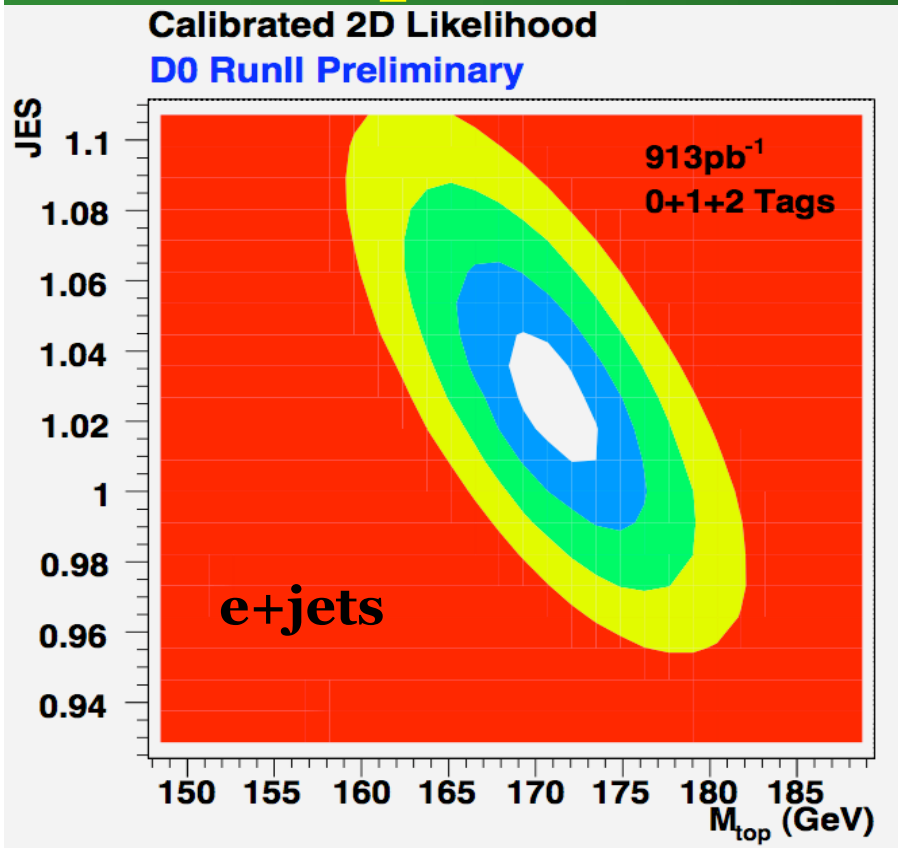
- Revisit event selection via evolutionary neural networks (20% improvement in *a priori* statistical uncertainty on top mass)
- JES dominates systematics



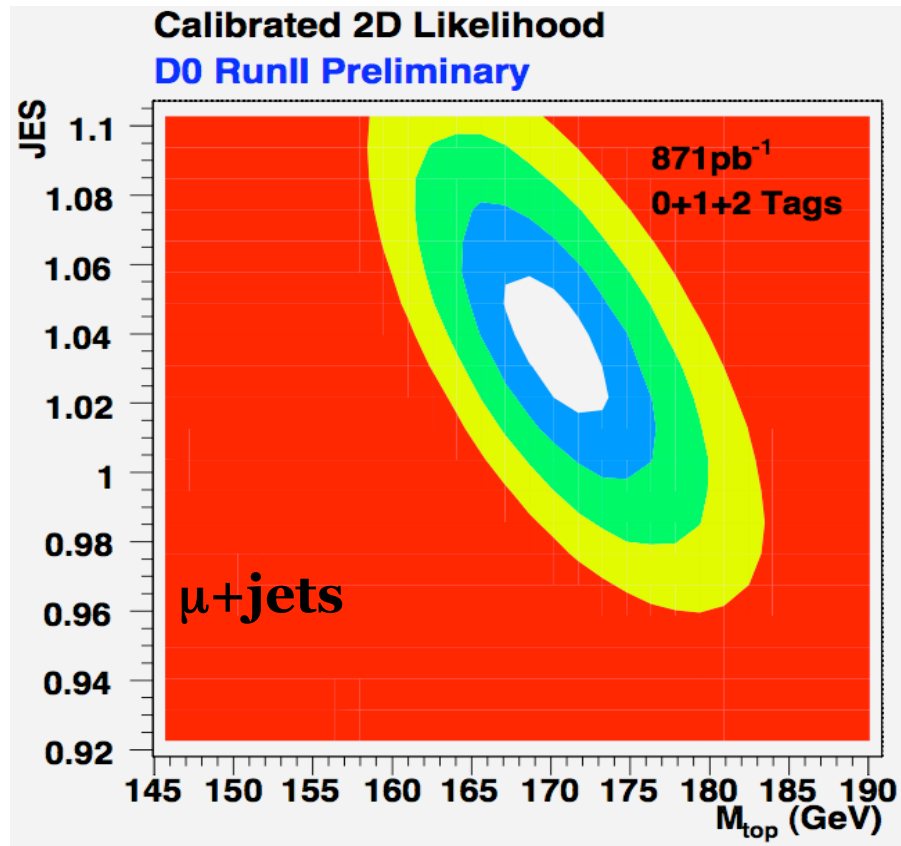
$$M_{top} = 171.2 \pm 2.7\ (stat) \pm 2.9\ (syst)\ GeV/c^2$$

CDF II 2.0 fb^{-1}

DZero Lepton+Jets ME measurement



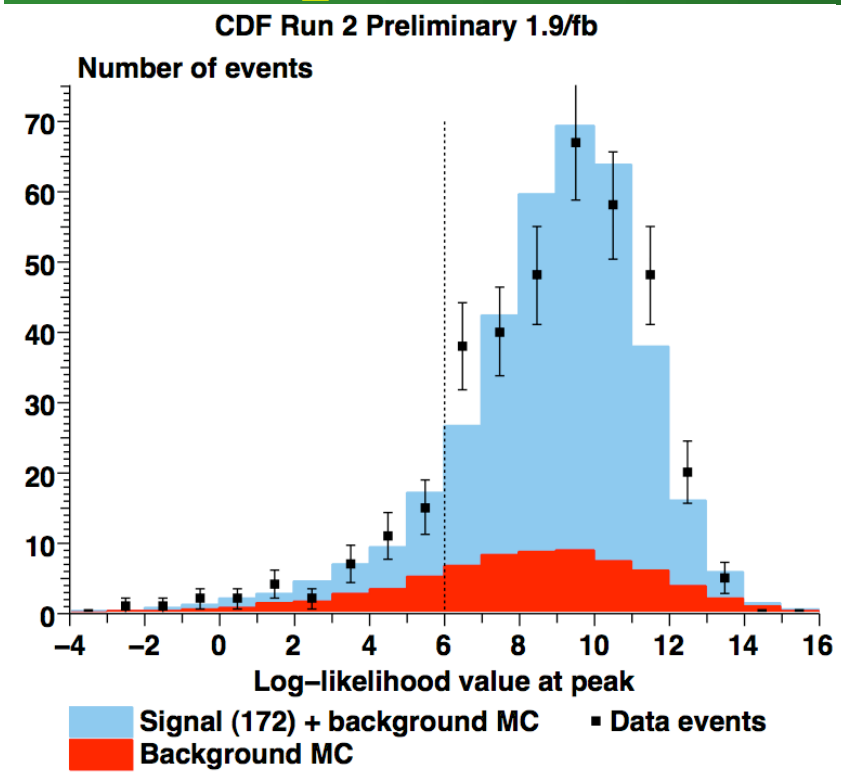
- Weight permutations by b-tagging probability, including 0-tag events
- Integrate over P_T of ttbar system



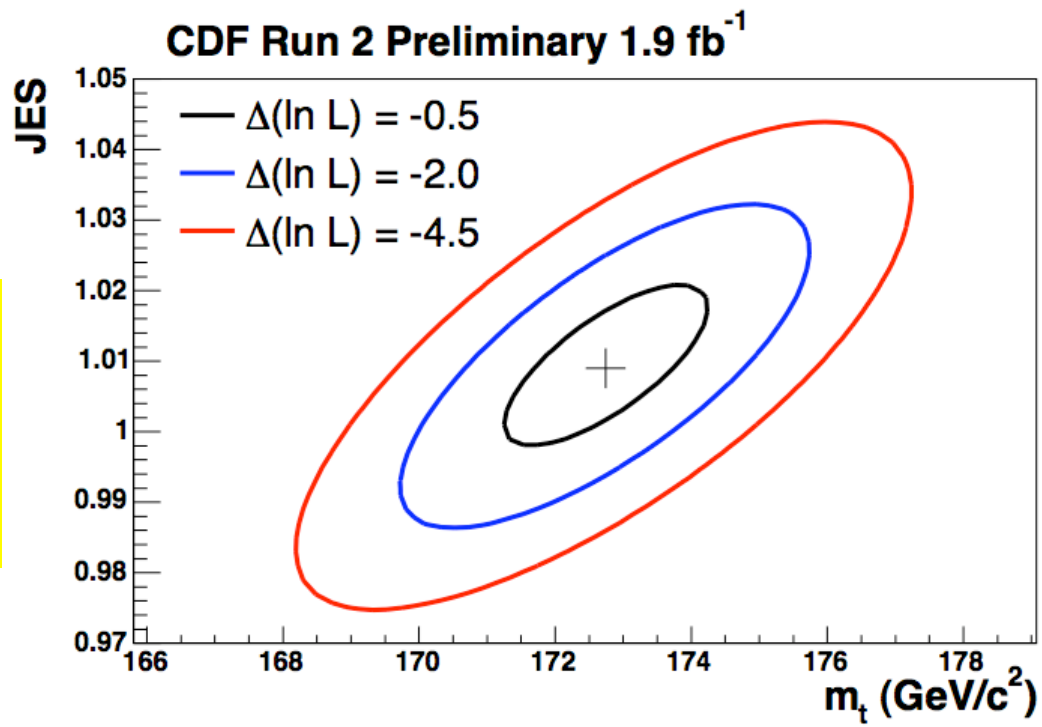
M_{top} = 170.5 ± 2.4 (stat+JES) ± 1.2 (syst) GeV/c²

0.9 fb^{-1}

CDF Lepton+Jets ME measurement New!



- Weight permutations by b-tagging probability, use only tagged events
- Make peak likelihood cut to remove poorly modeled events (signal+background)
- Modify propagators in matrix element to account for incorrect assumptions in integration



M_{top} = 172.7 ± 1.8 (stat+JES) ± 1.2 (syst) GeV/c²

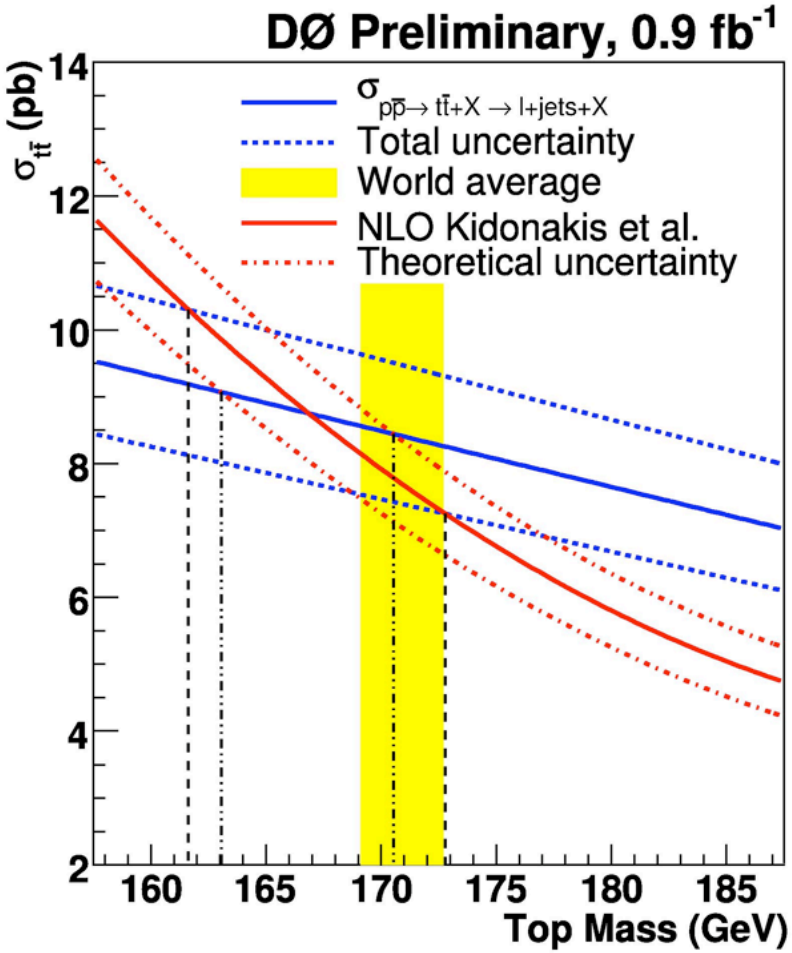
1.9 fb^{-1}

Example of systematics

Systematic	Lepton+Jets	Dilepton
b-JES	0.6	0.5
Residual JES	0.5	3.5
ISR	0.3	0.4
FSR	0.2	0.5
PDFs	0.3	0.5
Generator	0.2	0.8
LJ bkgd shape	0.2	0.0
DIL bkgd shape	0.0	0.4
MC statistics	0.1	0.2
lepton energy scale	0.1	0.4
pileup	0.1	0.1
gg fraction	0.0	0.2
Combined	1.0	3.8

- Systematics (in GeV/c²) from CDF Lepton+Jets and Dilepton template measurements
- In the process of revisiting all of these numbers
- Trying to understand similarities, differences between CDF and DZero procedures

DZero Mtop from Lepton+Jets Xsec New!



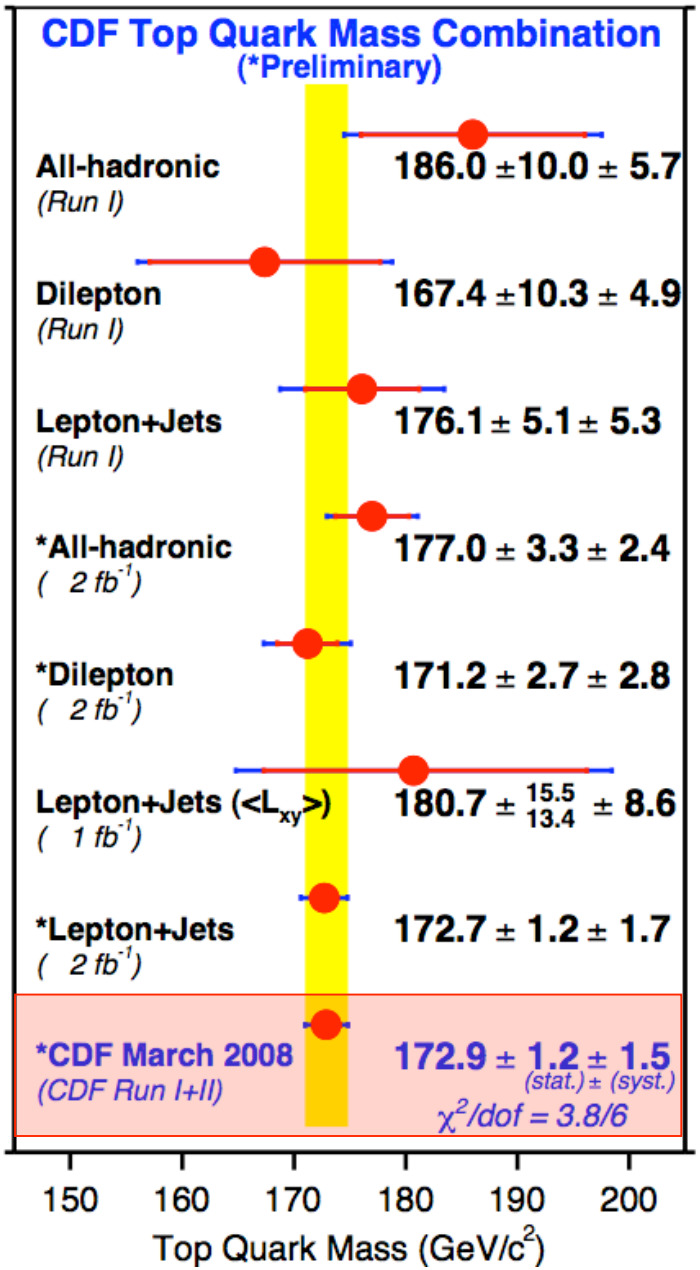
- Pair production cross section depends on top mass
- Measurement of mass using xsection makes very different assumptions than other analyses
- Require b-tag, at least 3 jets
- Needs input from theory!

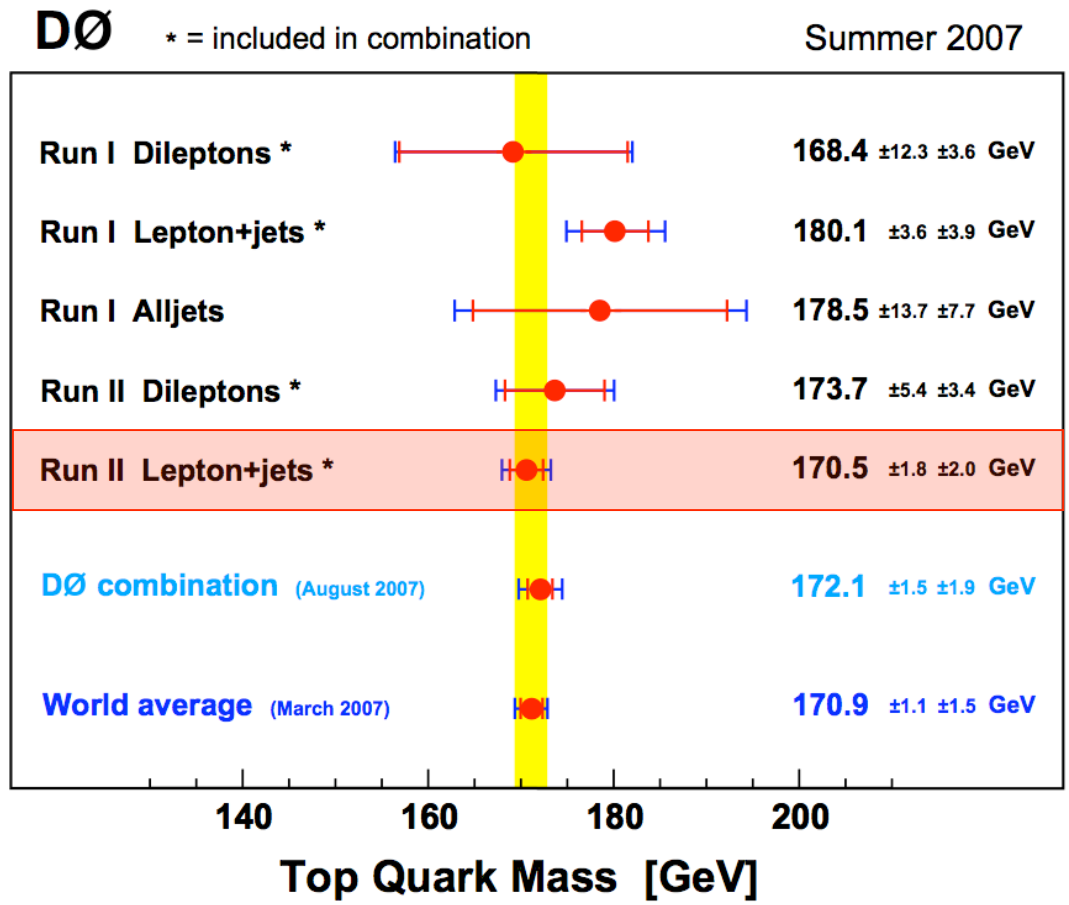
M_{top} = 166.9 +5.9/-5.2 (stat+syst) +3.7/-3.8 (theory) GeV/c² theory: Kidonakis and Vogt

M_{top} = 166.1 +6.1/-5.3 (stat+syst) +4.9/-6.7 (theory) GeV/c² theory: Cacciari et al.

0.9 fb^{-1}

Combinations

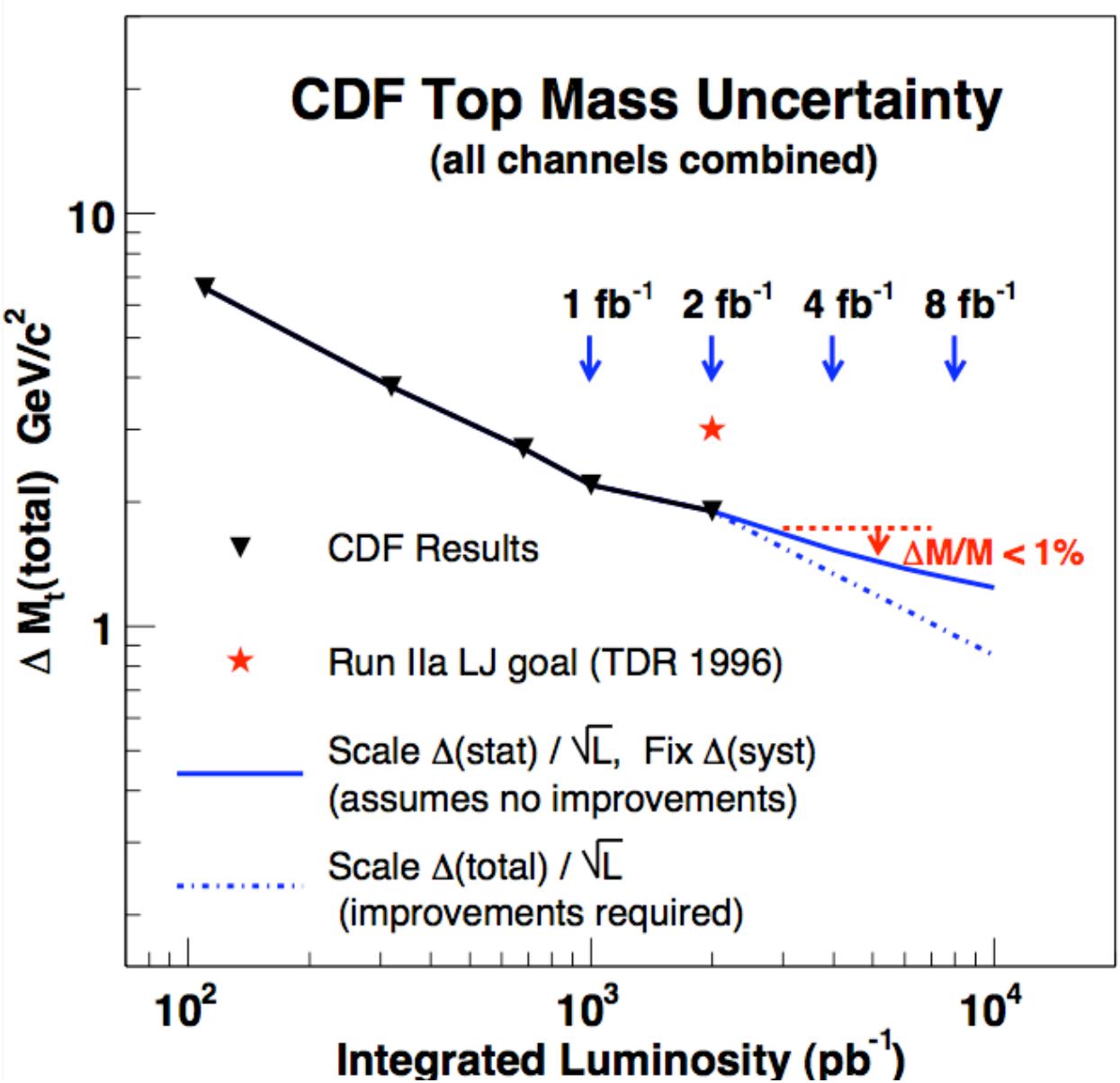




Tevatron world average March 07:

$$M_{top} = 170.9 \pm 1.1\ (stat) \pm 1.5\ (syst)\ GeV/c^2$$

Future prospects (view from one experiment)



- Analyses becoming systematics limited, but no reason to think we can't make improvements with more data and new ideas
- Approaching a 1% top mass measurement!

Backup

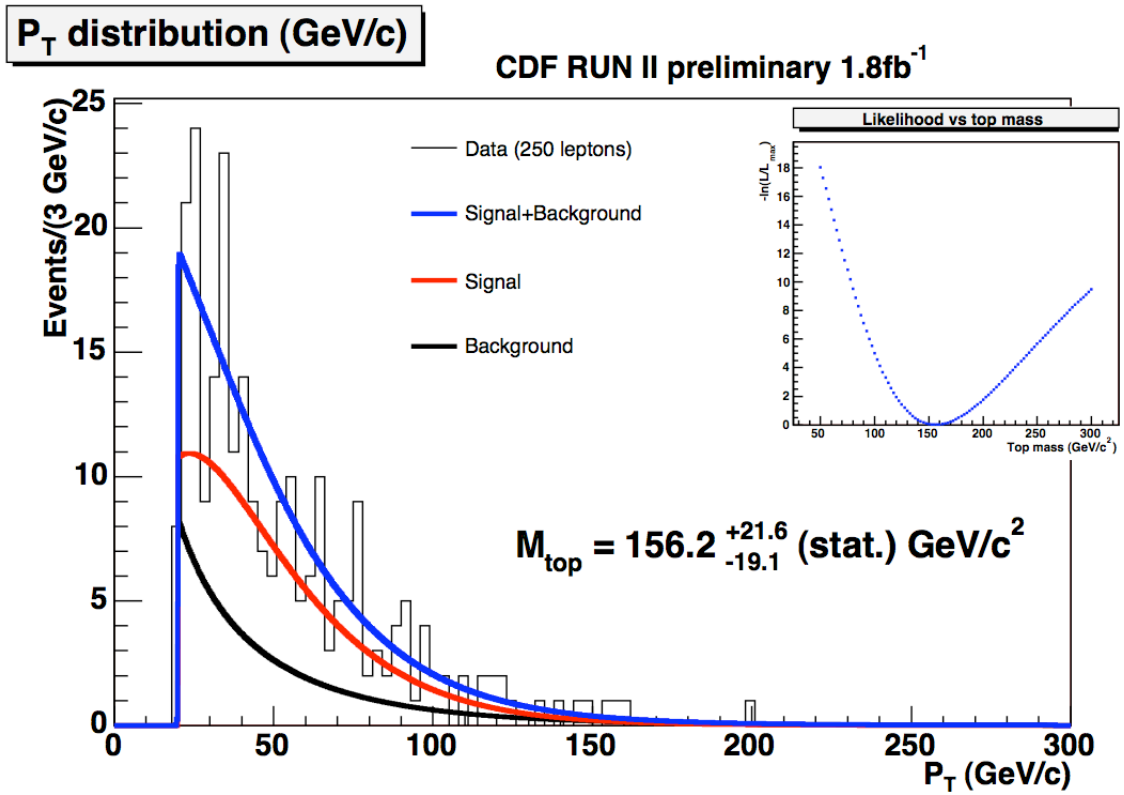
Example of backgrounds

	0-tag	tagged
WW	6.3 ±1.0	0.2 ±0.04
WZ	1.5 ±0.2	0.03 ±0.00
ZZ	1.1 ±0.8	0.1 ±0.1
DY$\tau\tau$	4.3 ±1.3	0.2 ±0.1
DY$ee, \mu\mu$	11.7 ±1.9	0.6 ±0.1
fakes	5.6 ±0.4	1.2 ±0.2
Total Background	30.4 ±4.1	2.4 ±0.4
$t\bar{t}$ (6.7 pb)	40.1 ±3.1	55.8 ±4.2

	1-tag	2-tag
Wbb	9.1	2.1
W$c\bar{c}$	5.0	0.4
Wc	3.3	0.1
W(mistags)	10.4	0.2
single top	2.0	0.7
diboson	2.4	0.2
QCD	10.4	0.3
Total Background	42.7±12.5	4.2±1.9
$t\bar{t}$ (6.7 pb)	156.7	76.6

- Background estimates for CDF template dilepton (top) and Lepton+Jets (bottom) analyses (1.9 fb^{-1})
- Most background shapes/kinematics are MC-based, except for fakes/QCD
- Rates are typically a combination of data and MC
- Requiring a b-tag significantly cuts away background

CDF Dilepton Pt



- Lepton from W decays get larger boost with increasing top mass
- Measurement very statistical limited, but good practice for LHC
- Systematics largely uncorrelated to JES

$M_{top} = 156 \pm 20$ (stat) ± 4.6 (syst) GeV/c^2

Kinematic Fitter for Lepton+Jets

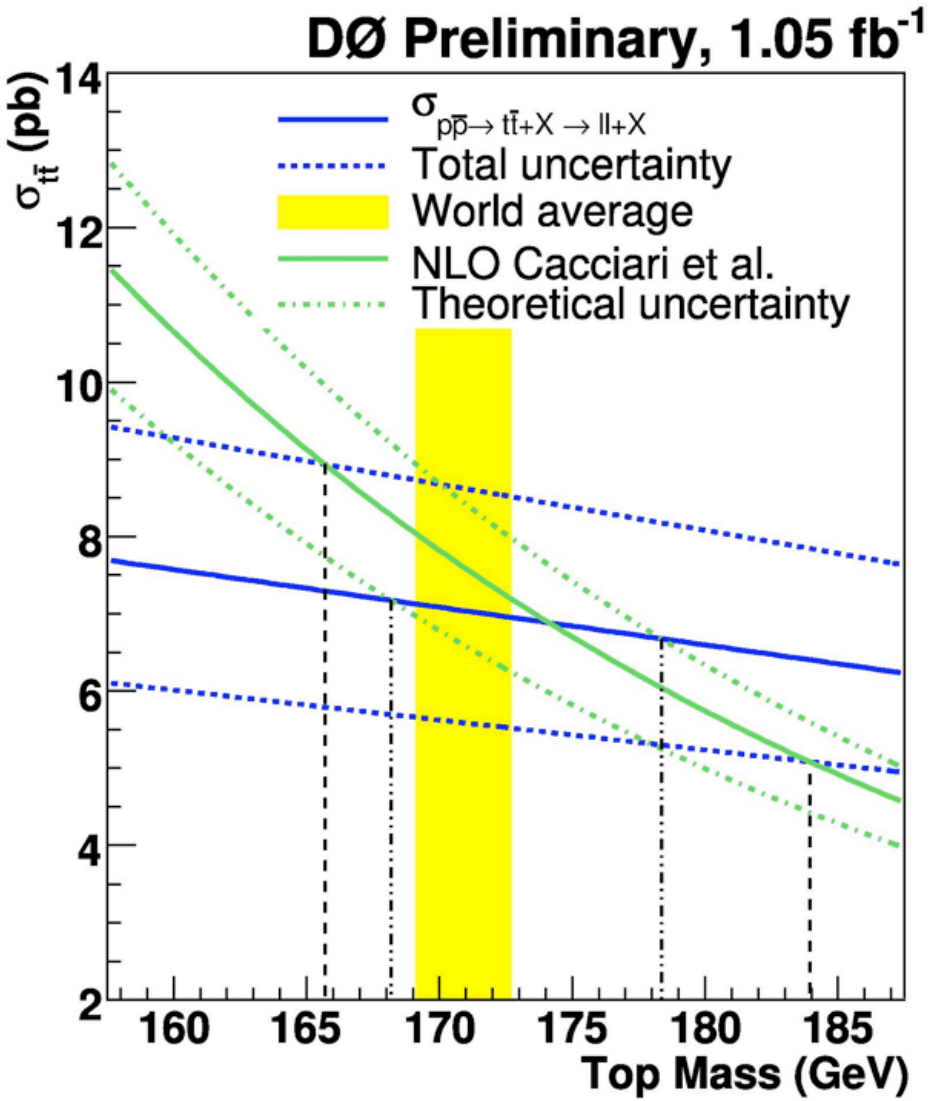
- Instead of taking the invariant mass of the system, we will have to make a measurement by comparing data to Monte Carlo simulation
  - Find the parent top mass distribution most consistent with our data
  - We want to measure a variable that's correlated to the top mass
- System is over-constrained (helps choose from 12 possible jet-parton assignments)

What we know	What we don't know
6 final-state particles *4 vectors = 24 needed	24 unknowns
4 jets and charged lepton 4-vectors = 4*5 = 20	4 unknowns
We know the mass of the neutrino = 1	3 unknowns
We know the W mass quite well (both of them) = 2	1 unknown
Require $m_{top} = m_{anti\text{-}top} = 1$	0 unknowns
Transverse components of p_ν from momentum conservation = 2	2 constraints

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

DZero Mtop from Dilepton XSec

New!



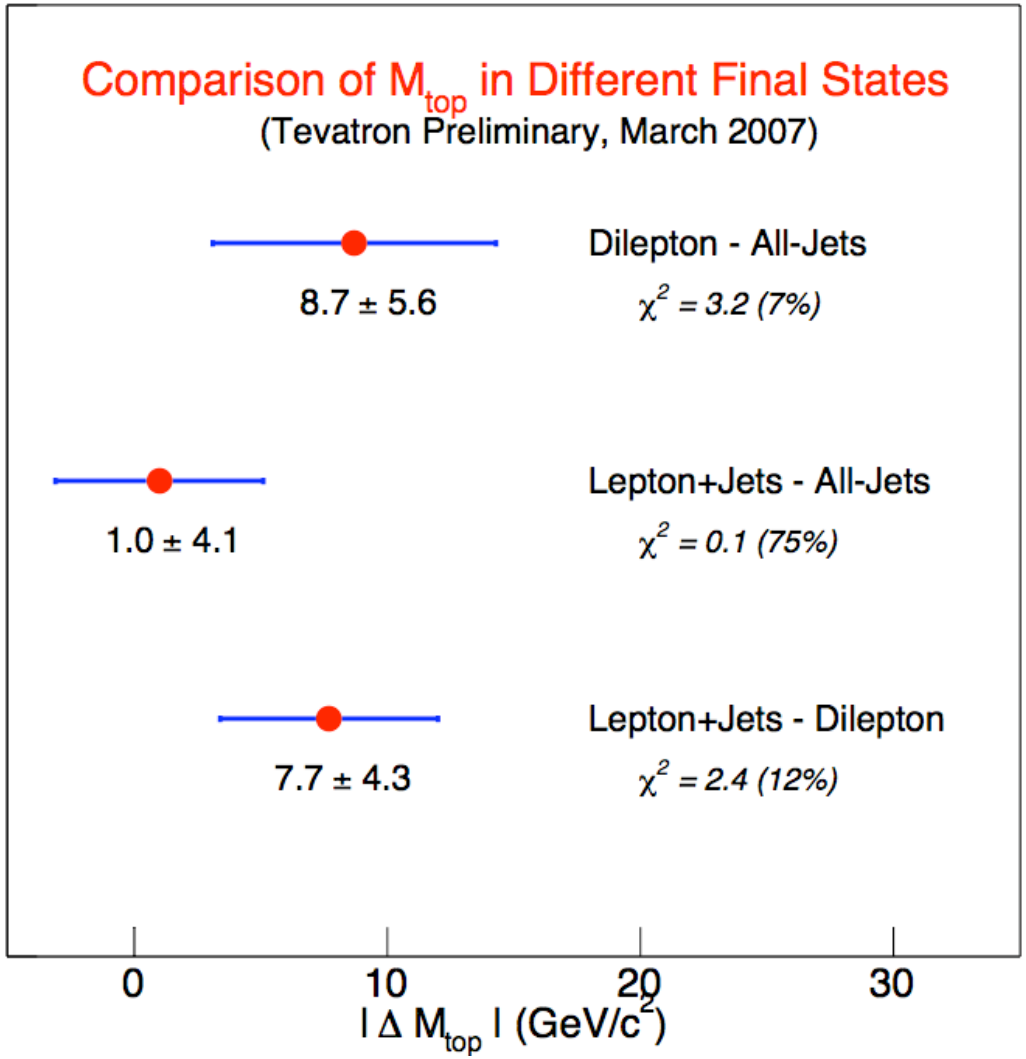
- Dilepton branching fraction smaller -> larger uncertainty on top mass

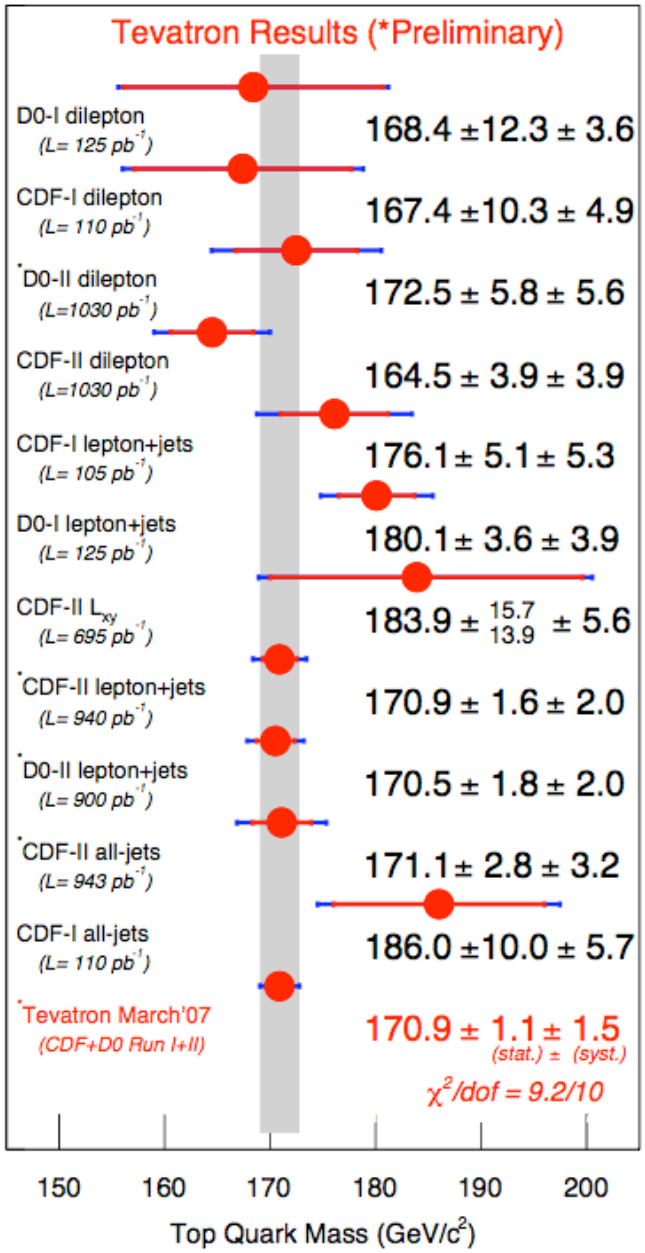
M_{top} = 174.5 +10.5/-8.2 (stat+syst) +3.7/-3.7 (theory) GeV/c² theory: Kidonakis and Vogt

M_{top} = 174.1 +9.8/-8.4 (stat+syst) +4.2/-6.0 (theory) GeV/c² theory: Cacciari et al.

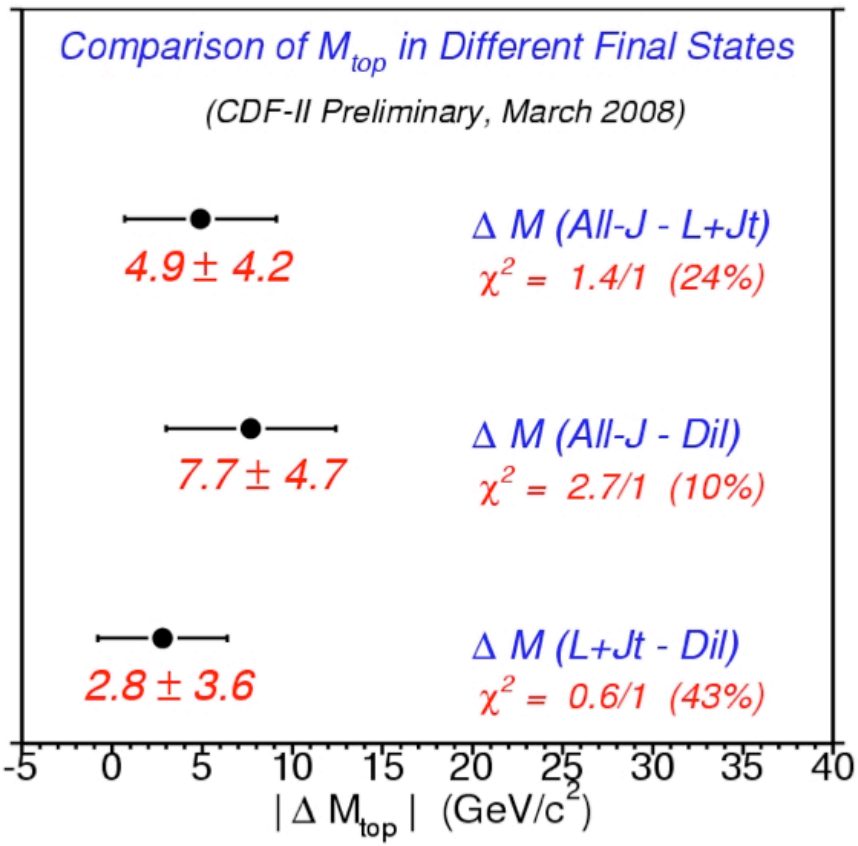
1.1 fb^{-1}

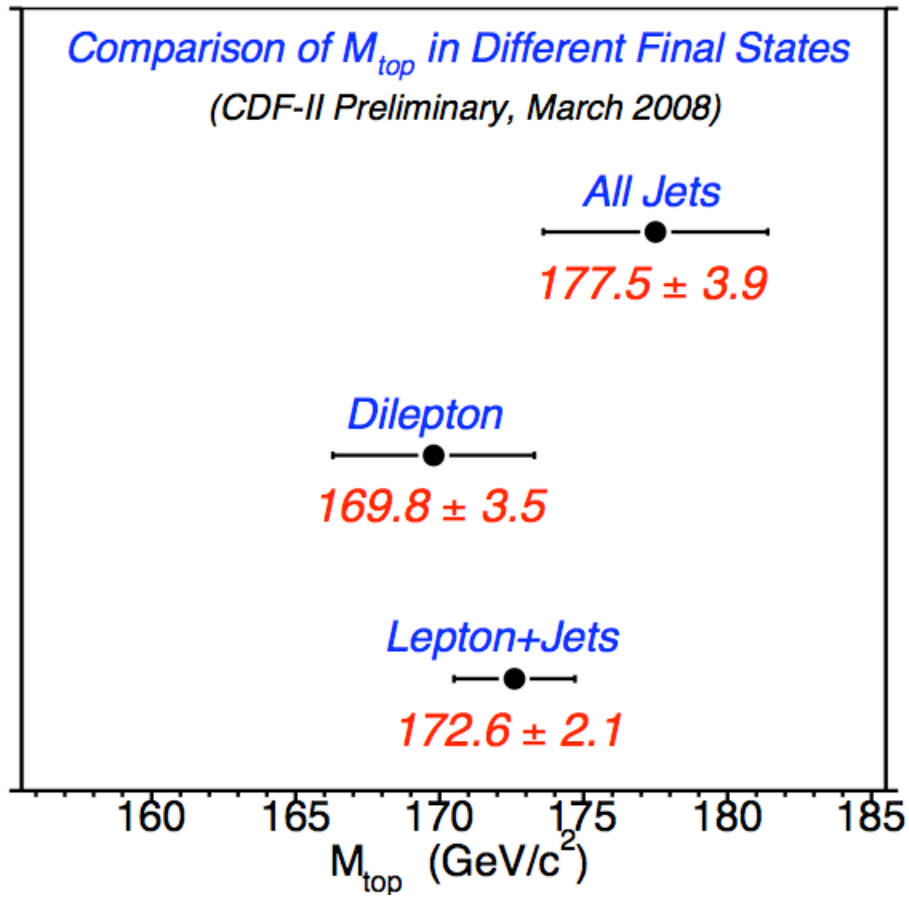
More TeV mass combination



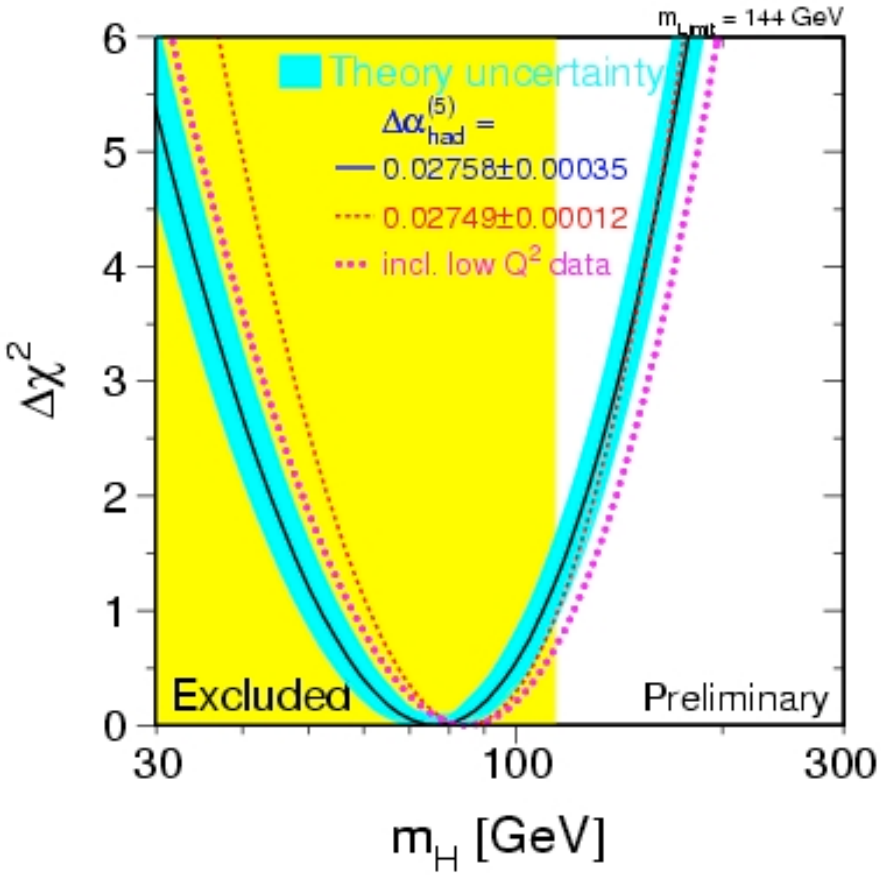


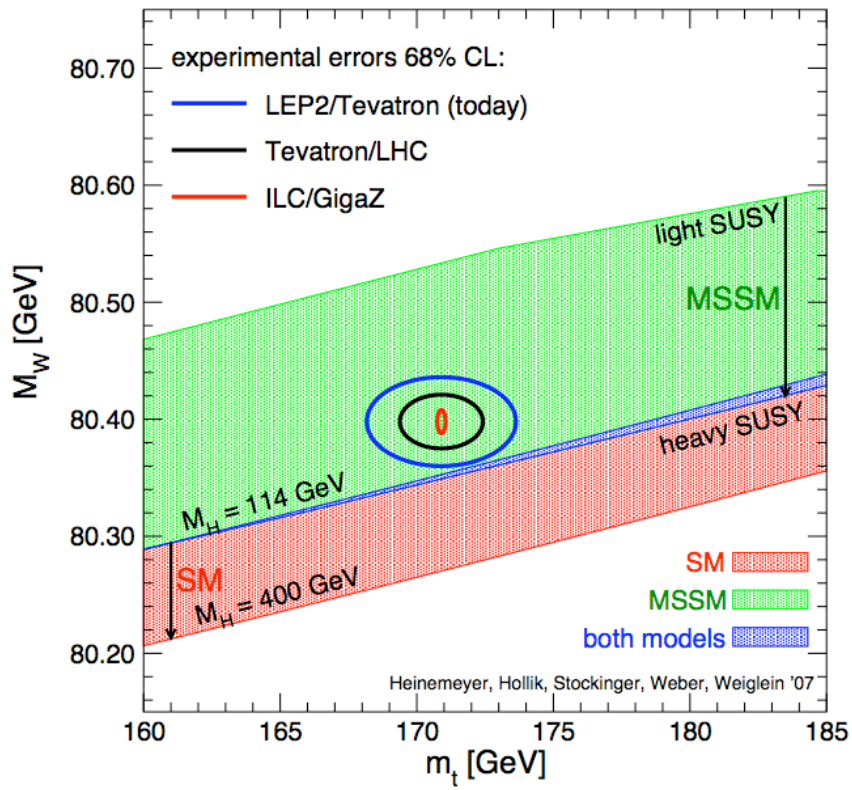
More CDF mass combination





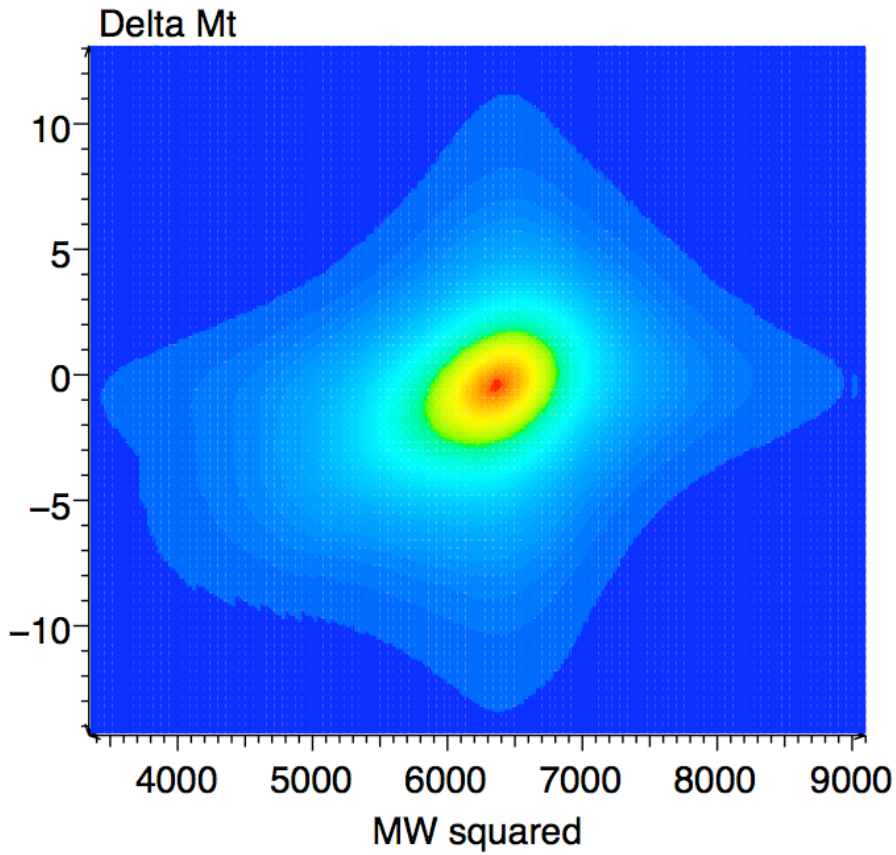
Implications of the top mass …



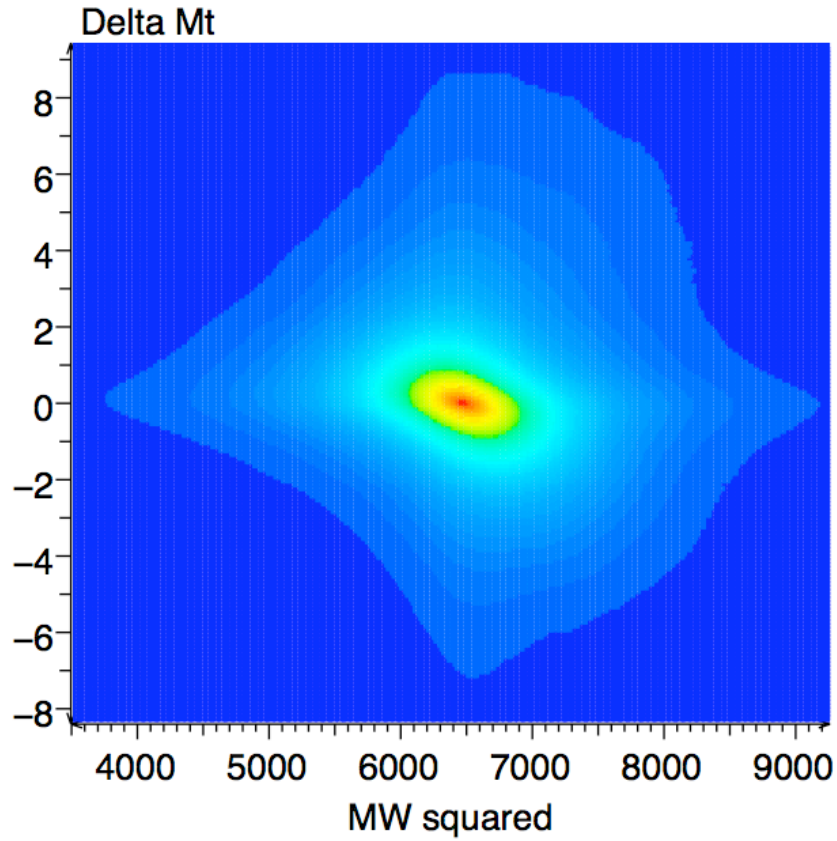


Effective propagators

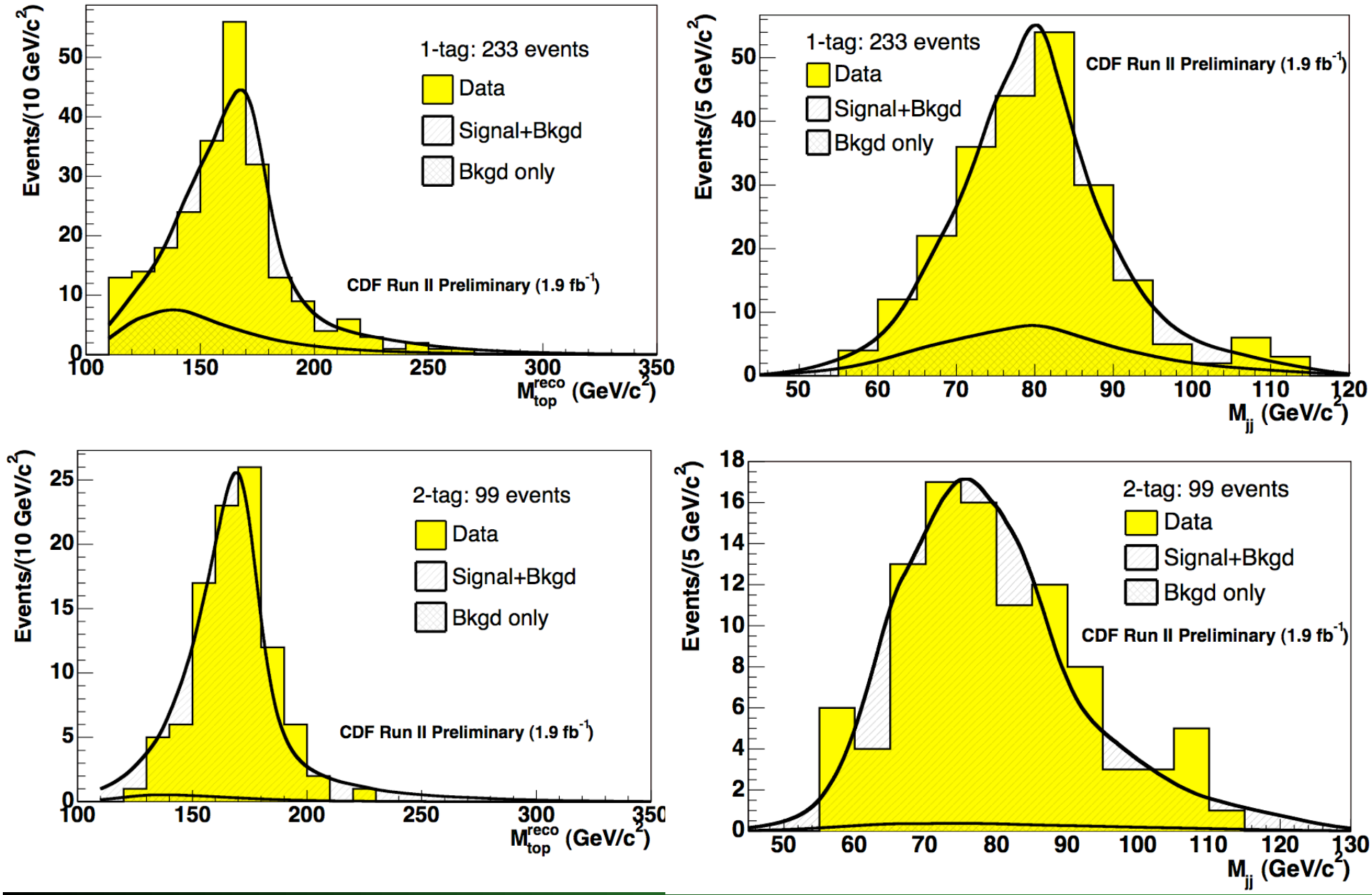
Hadronic effective propagator



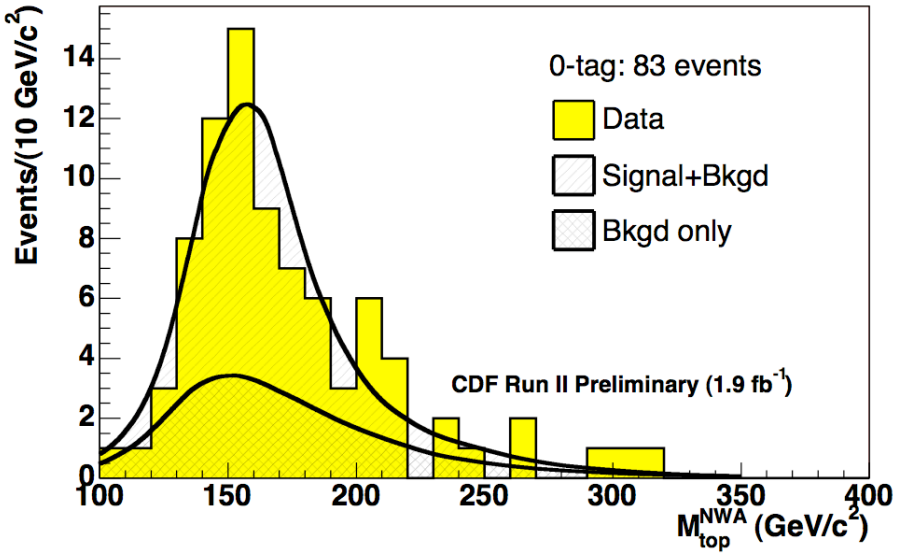
Leptonic effective propagator

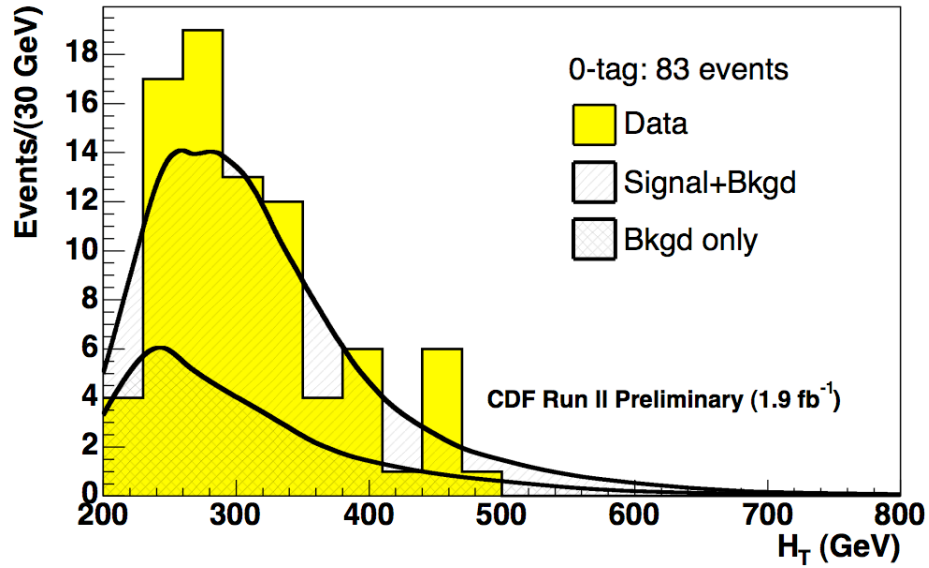


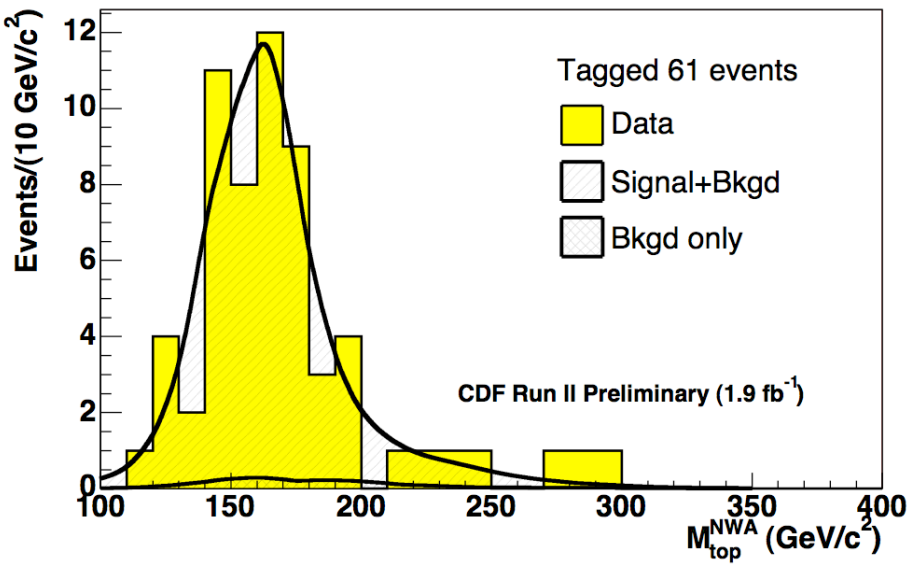
CDF Lepton+Jets template 1d projections

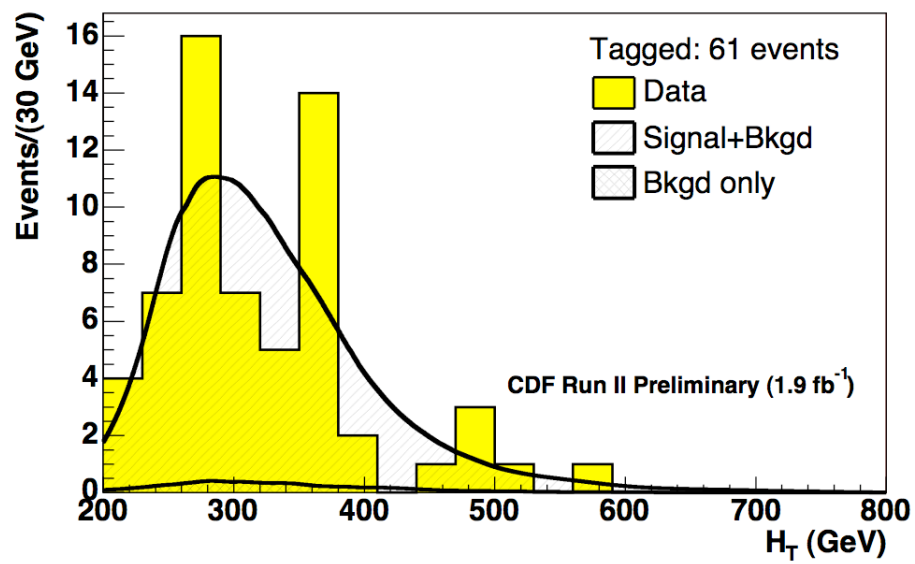


CDF Dilepton template 1d projections

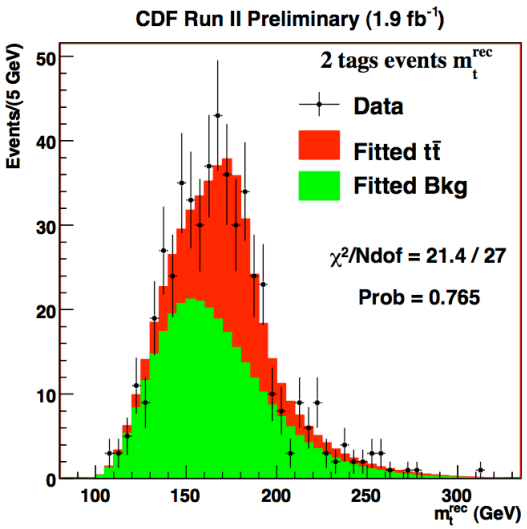


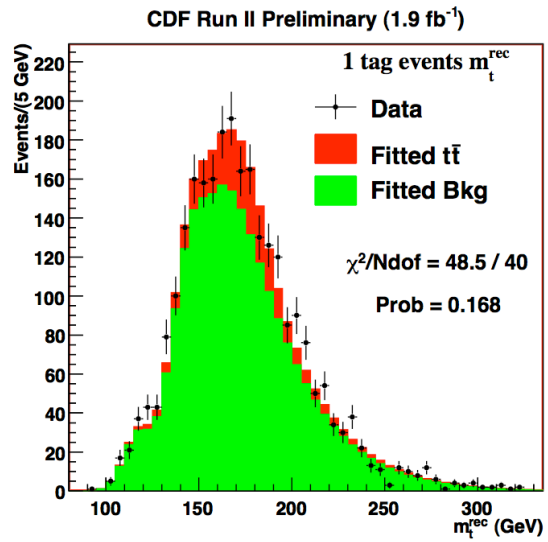


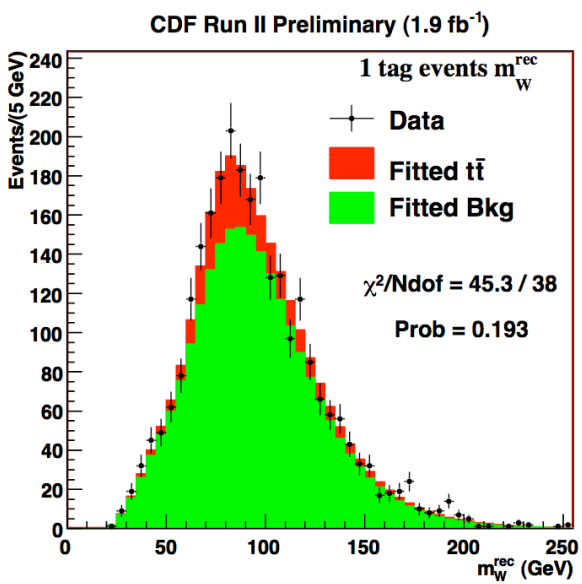


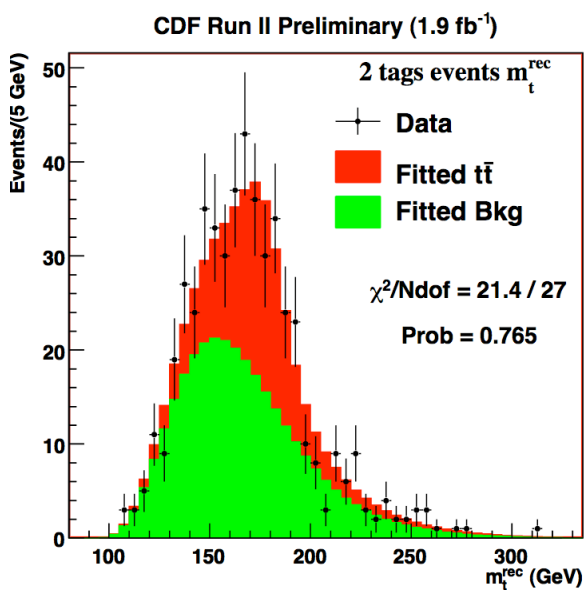


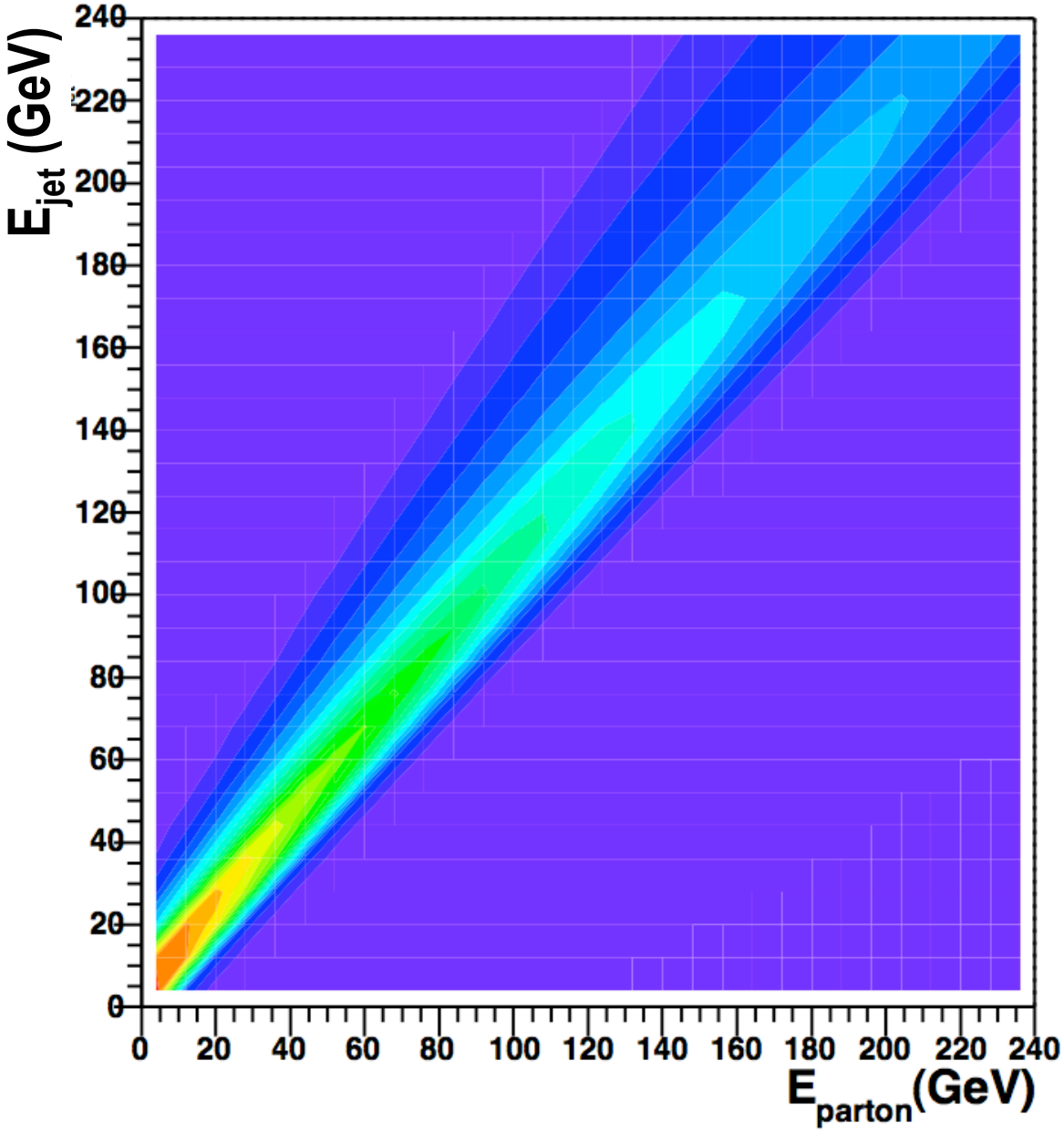
CDF All-Hadronic









Source	δM_{top}^{syst} (GeV/c^2)
Residual bias	0.31
2D calibration	0.04
Generator	0.34
ISR	0.34
FSR	0.33
Background templates	1.03
Signal templates	0.26
b-jets energy scale	0.11
SF E_T dependence	0.35
Residual JES	0.80
PDF	0.41
m_t^{rec}/m_W^{rec} correlations	0.21
Total	1.60

An example transfer function