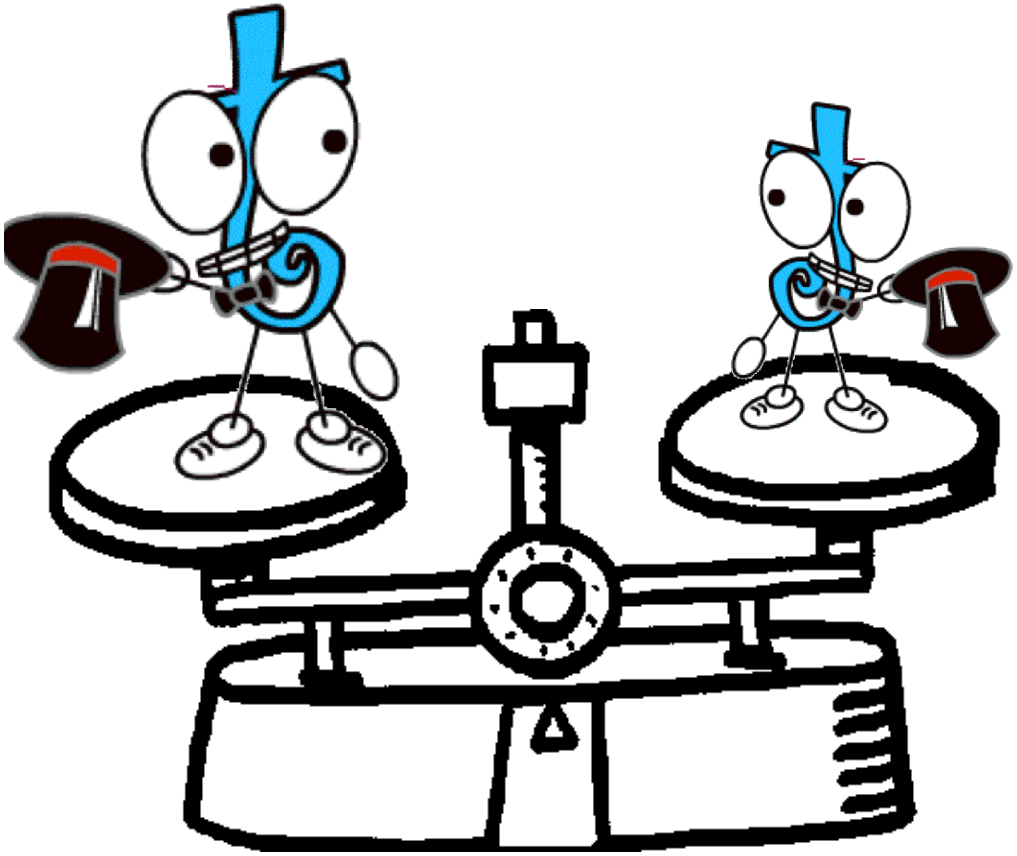
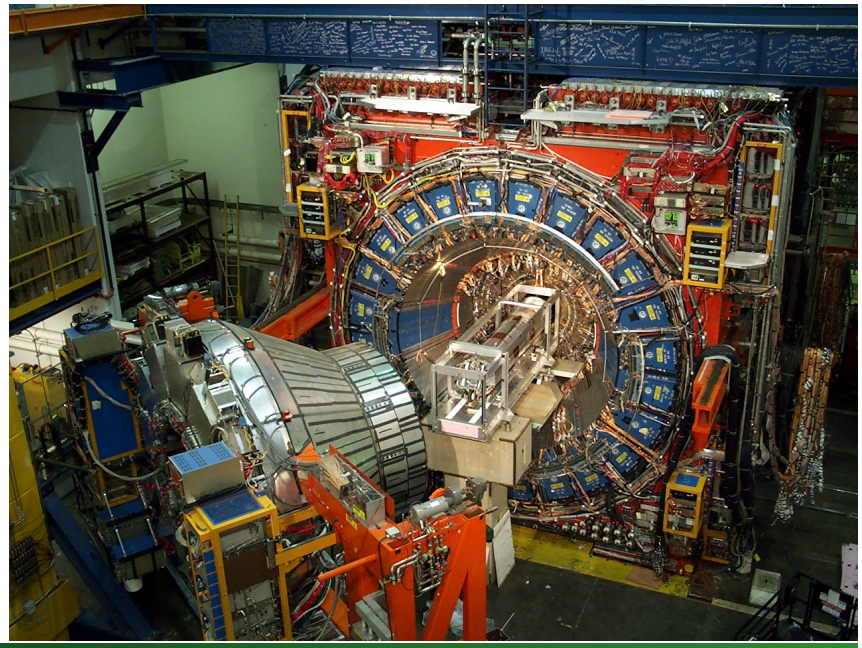
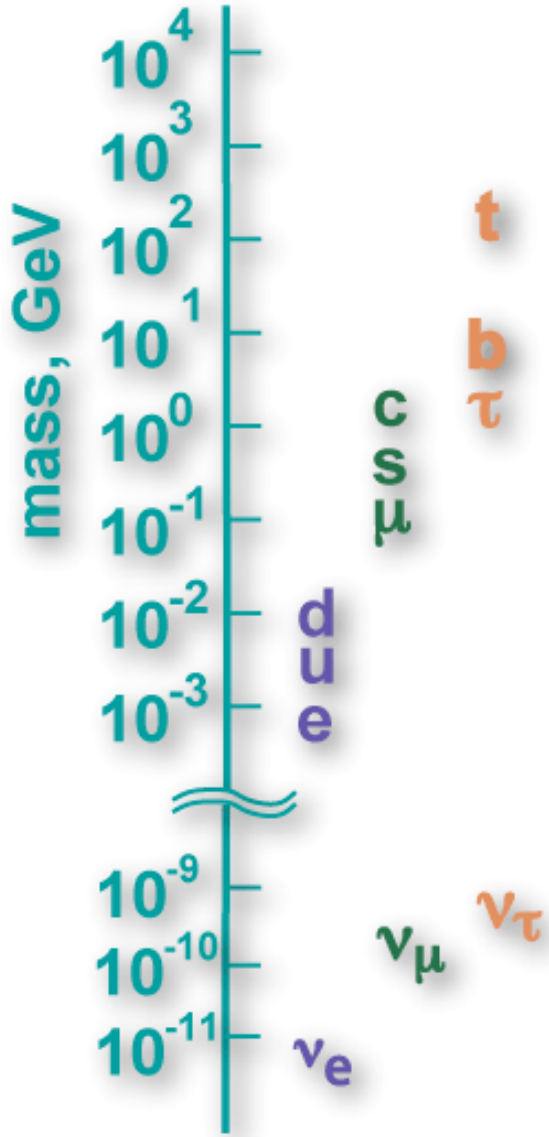
Top Quark Mass at CDF

for the CDF Collaboration





Why the top quark mass?

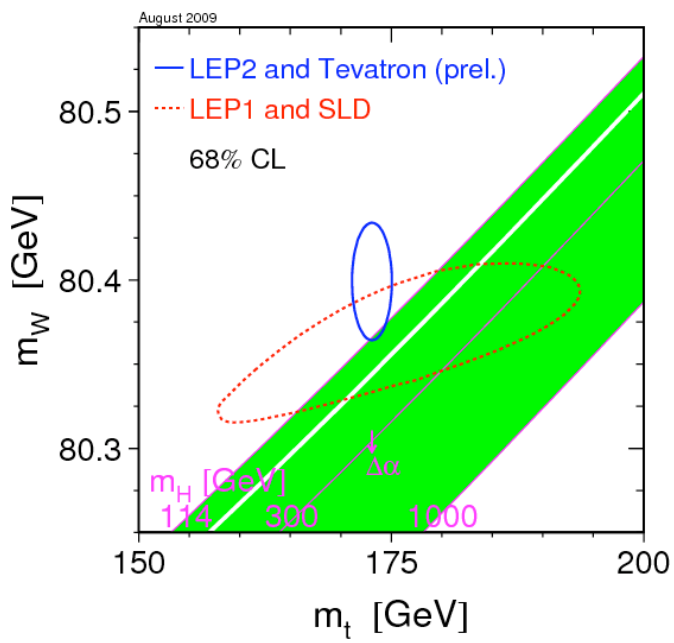


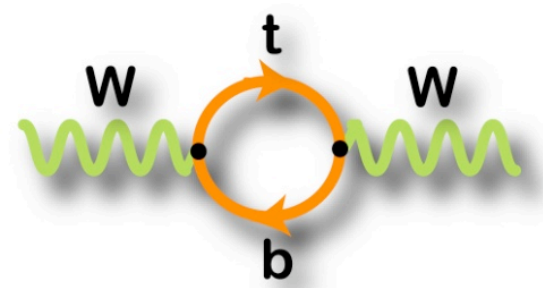
Top is by far the heaviest known particle…

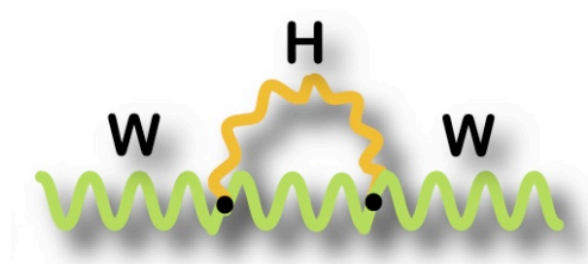
A role in electroweak-symmetry breaking?

When we find Higgs, a precision test of the SM

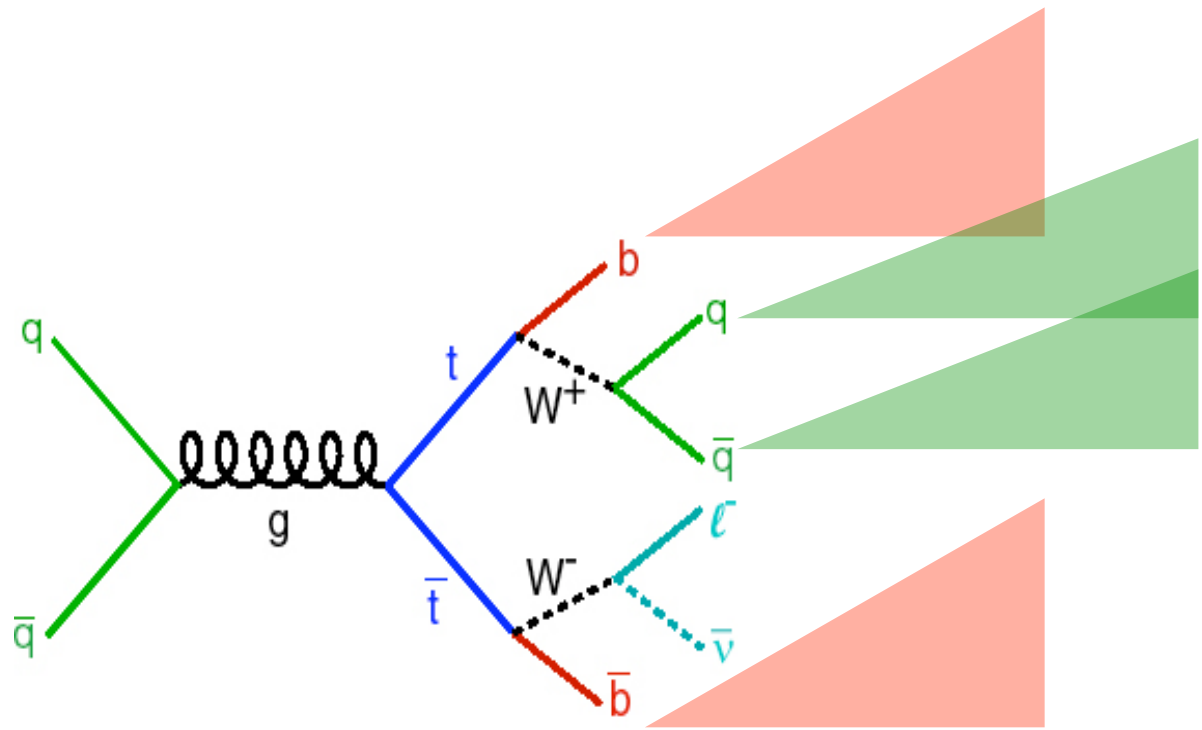
Radiative corrections for new physics







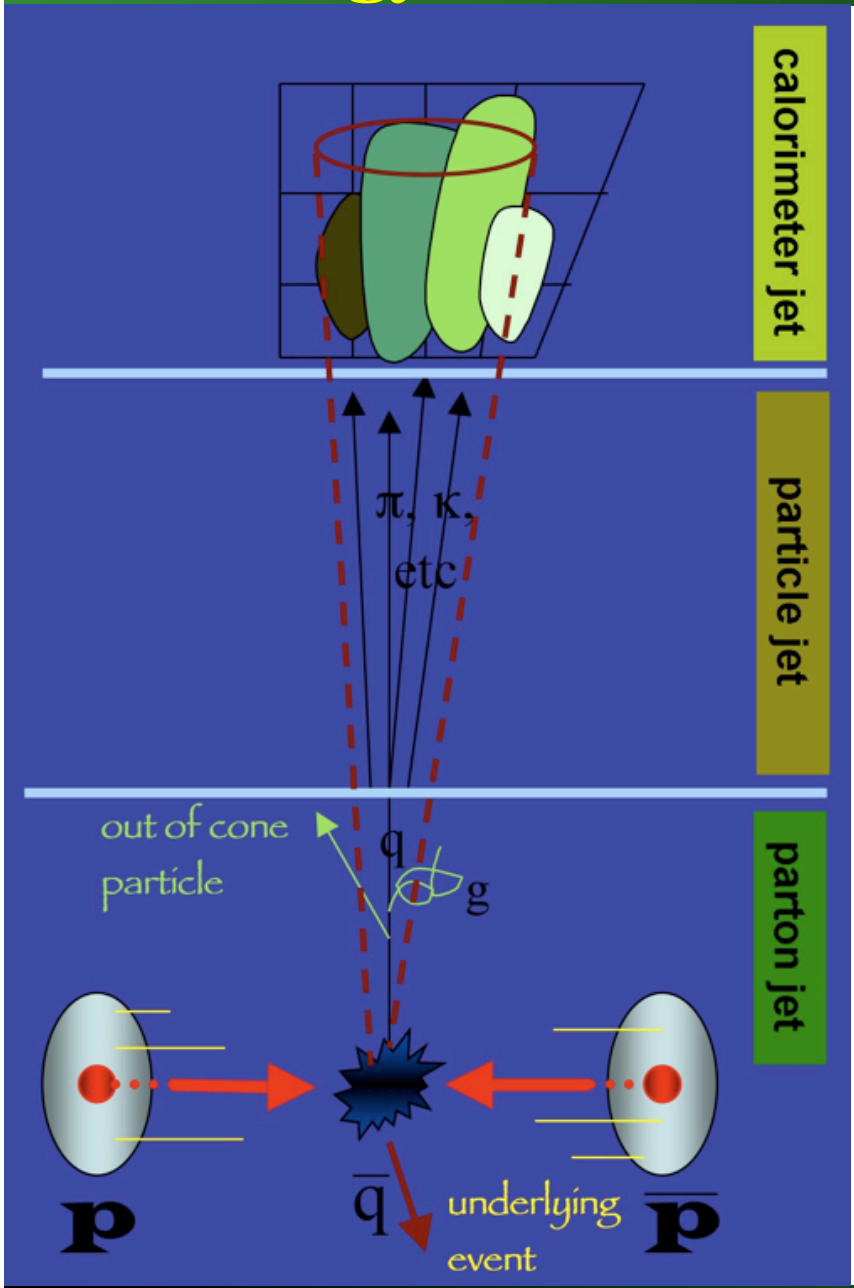
Why the top mass is difficult



Cannot simply take invariant mass of objects in the event

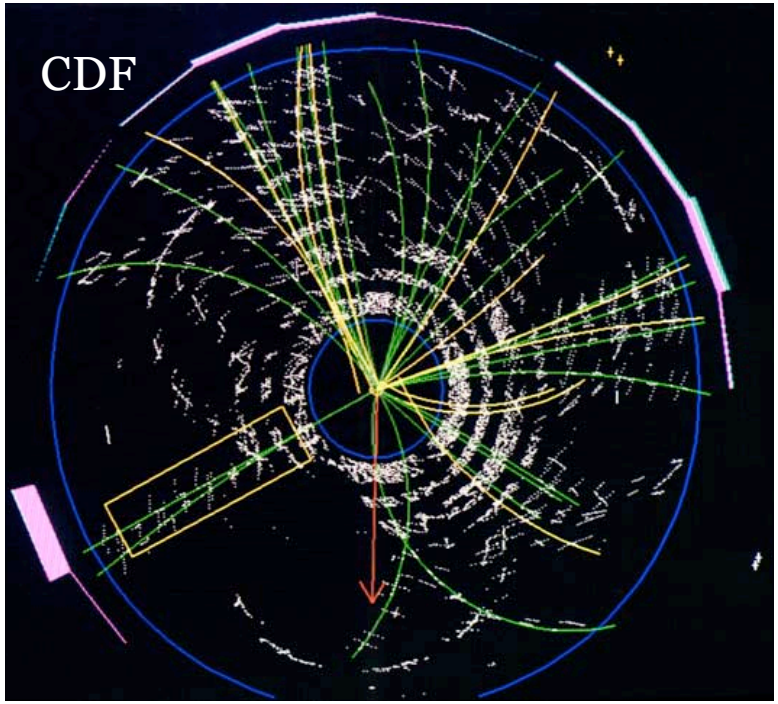
- Tops produced predominantly in pairs
- Decay ~always to Wb
- Topology depends on W decay (hadronic vs leptonic)
- Up to 6 jets (leading order) …
- Combinatorics
- Up to 2 neutrinos
- Must deal with non-negligible background

Jet Energy Scale (JES)

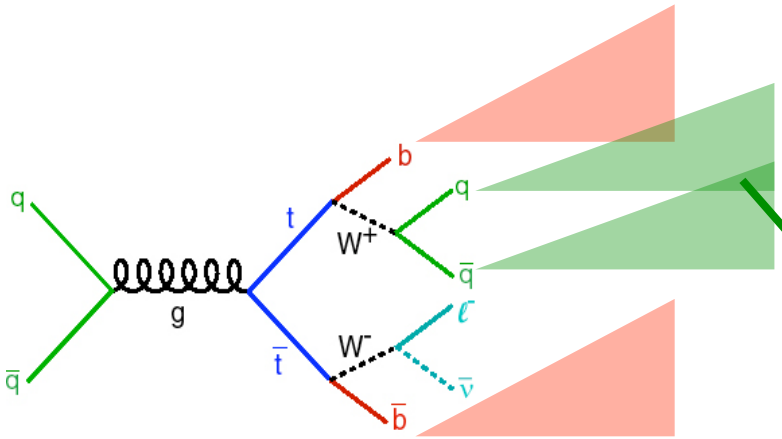


What we actually see in our detector …

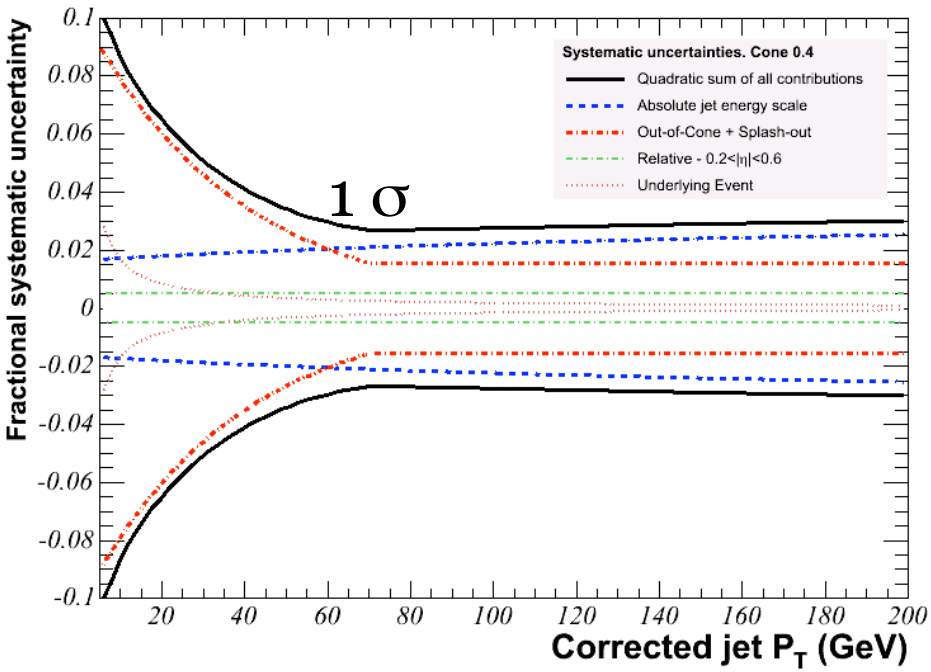
Find methods less sensitive to JES or calibrate JES *in situ*

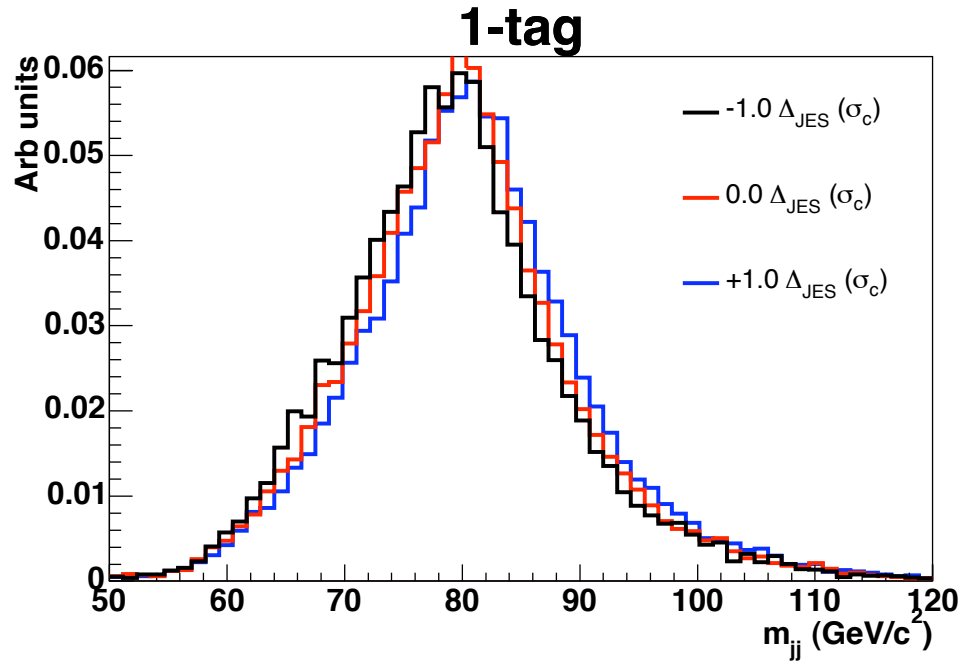


A handle on the Jet Energy Scale



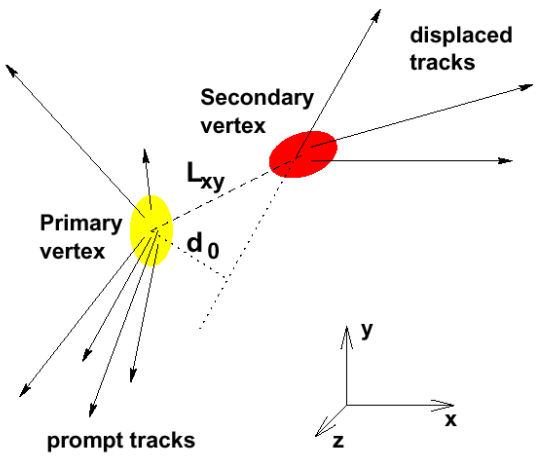
Dijet mass of hadronically decaying W provides *in situ* calibration of JES





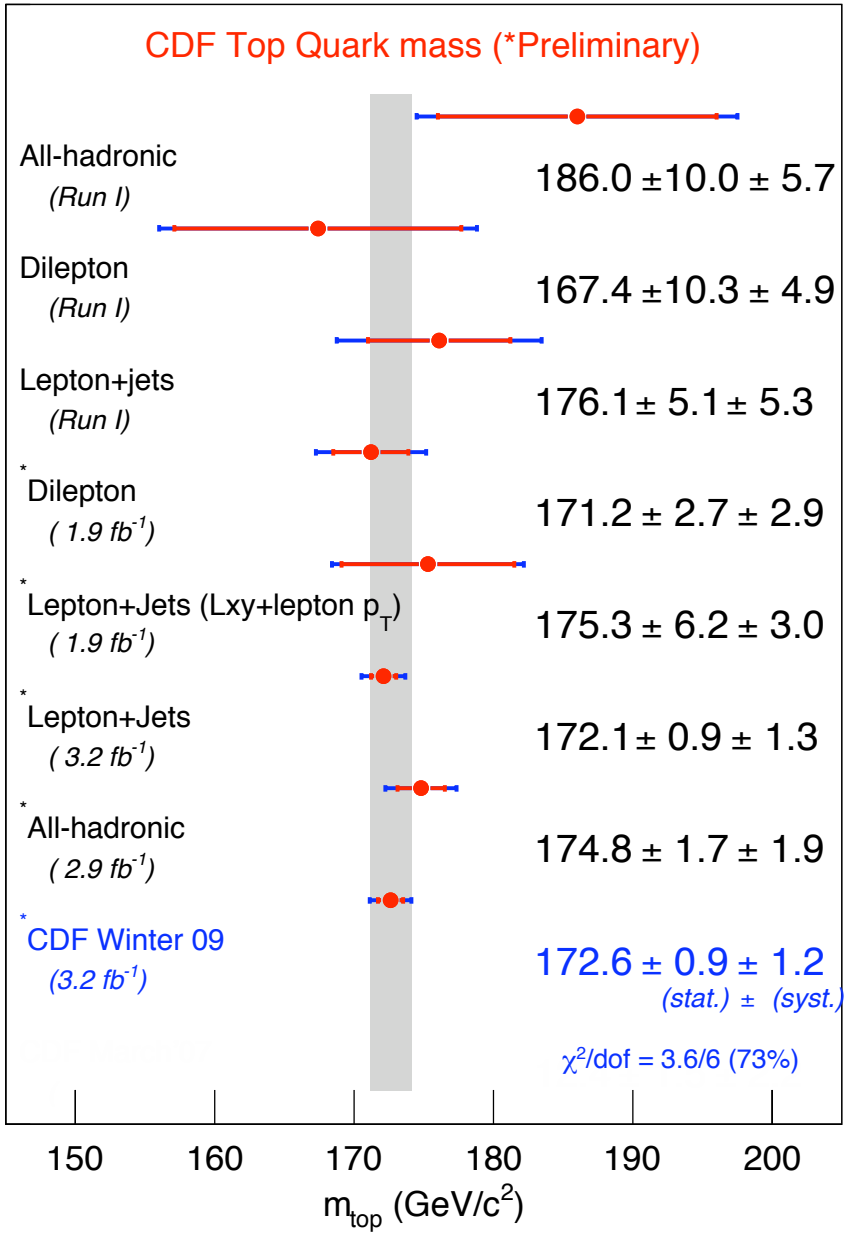
Typical S:B and event selection

	Dilepton		Lepton+Jets	
	$tt \to bbl^+l^-\nu\nu$		$tt \to bbl\nu qq$	
Jet cuts	2 jets > 20 GeV/c²		4 jets > 20 GeV/c²	
Charged leptons	2 leptons > 20 GeV/c		1 leptons > 20 GeV/c	
MET	MET > 20		MET > 20	
Tagging category	0-tag	b-tagged	1 b-tag	2 b-tag
S:B	1:1	15:1	4:1	10:1

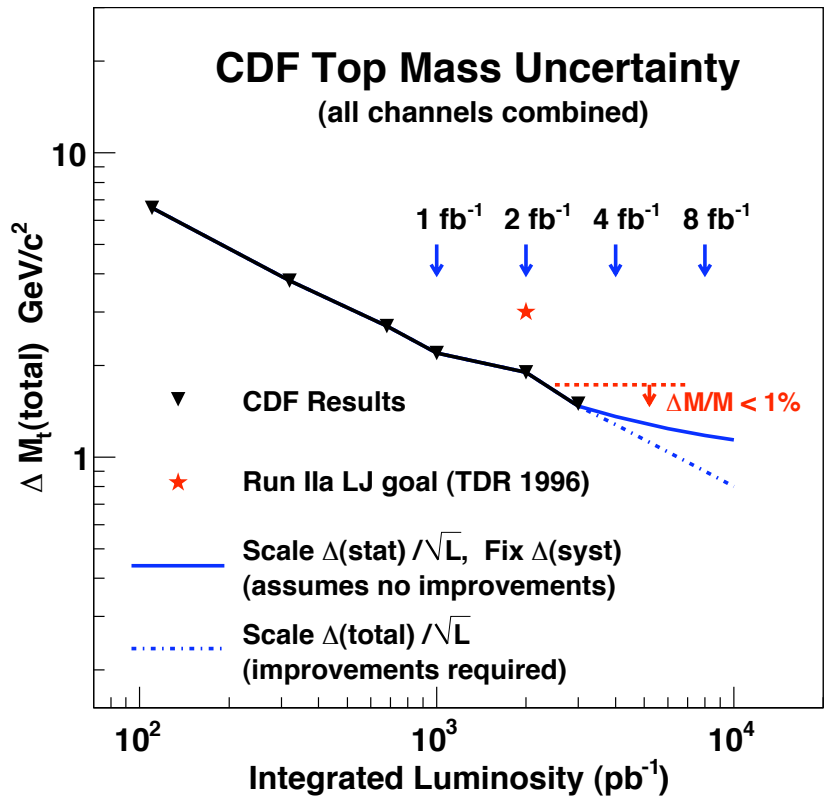


Tagging jets from b quarks reduces combinatorics, cuts away background

Status at CDF as of a year ago…



Already systematics limited at CDF alone! But we forge ahead…



Matrix Element Analysis

- Try to extract as much information as possible from every event using theoretical prediction for ttbar production and decay
- Integrate over unknown quantities (ie 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

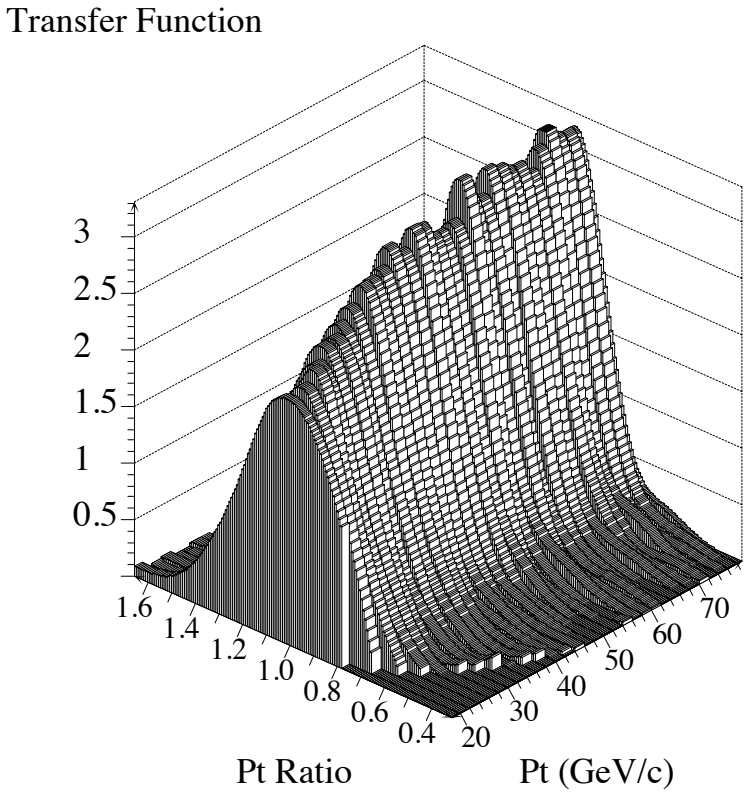
Parton-level phase space

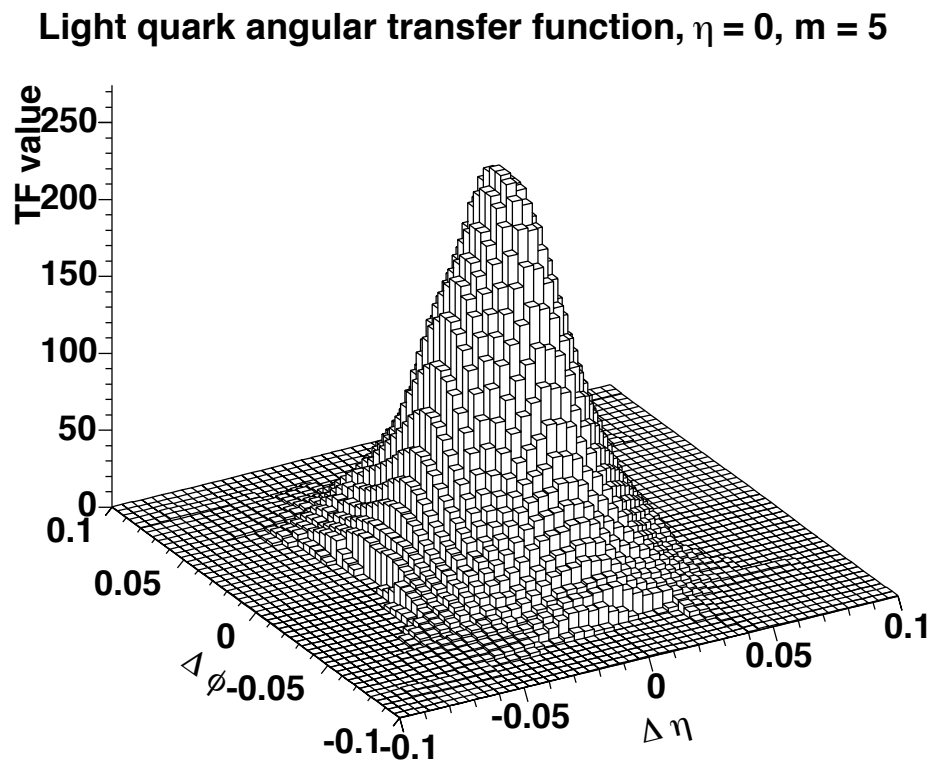
Parton Distribution Functions for incoming partons

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

Matrix Element Lepton+Jets

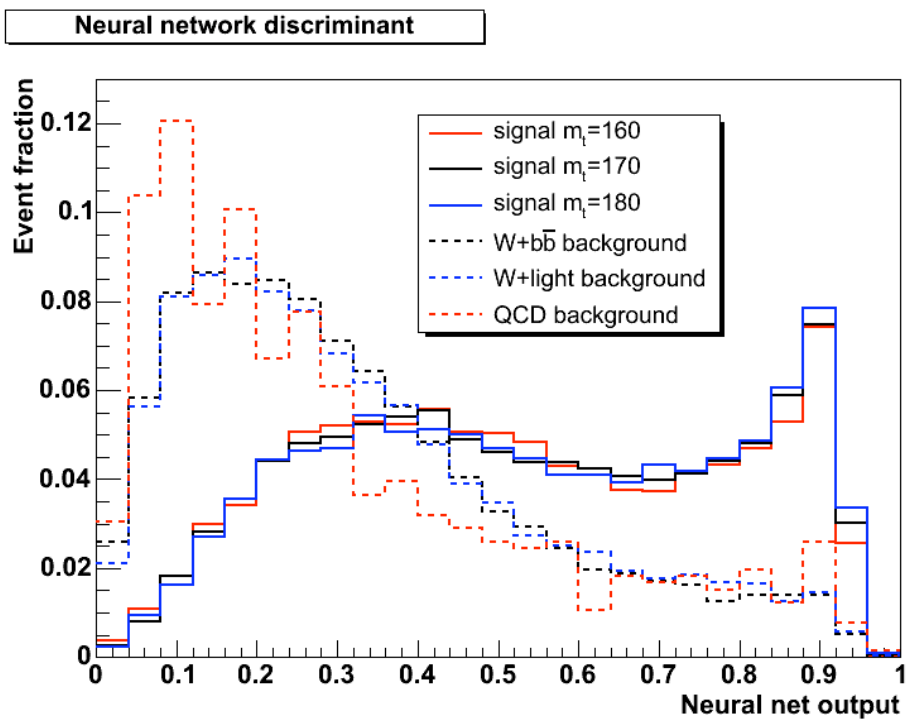
- Novel matrix element using Quasi-Monte Carlo integration to integrate in 19 dimensions
  - Many fewer assumptions made on ttbar kinematics





Matrix Element Lepton+Jets

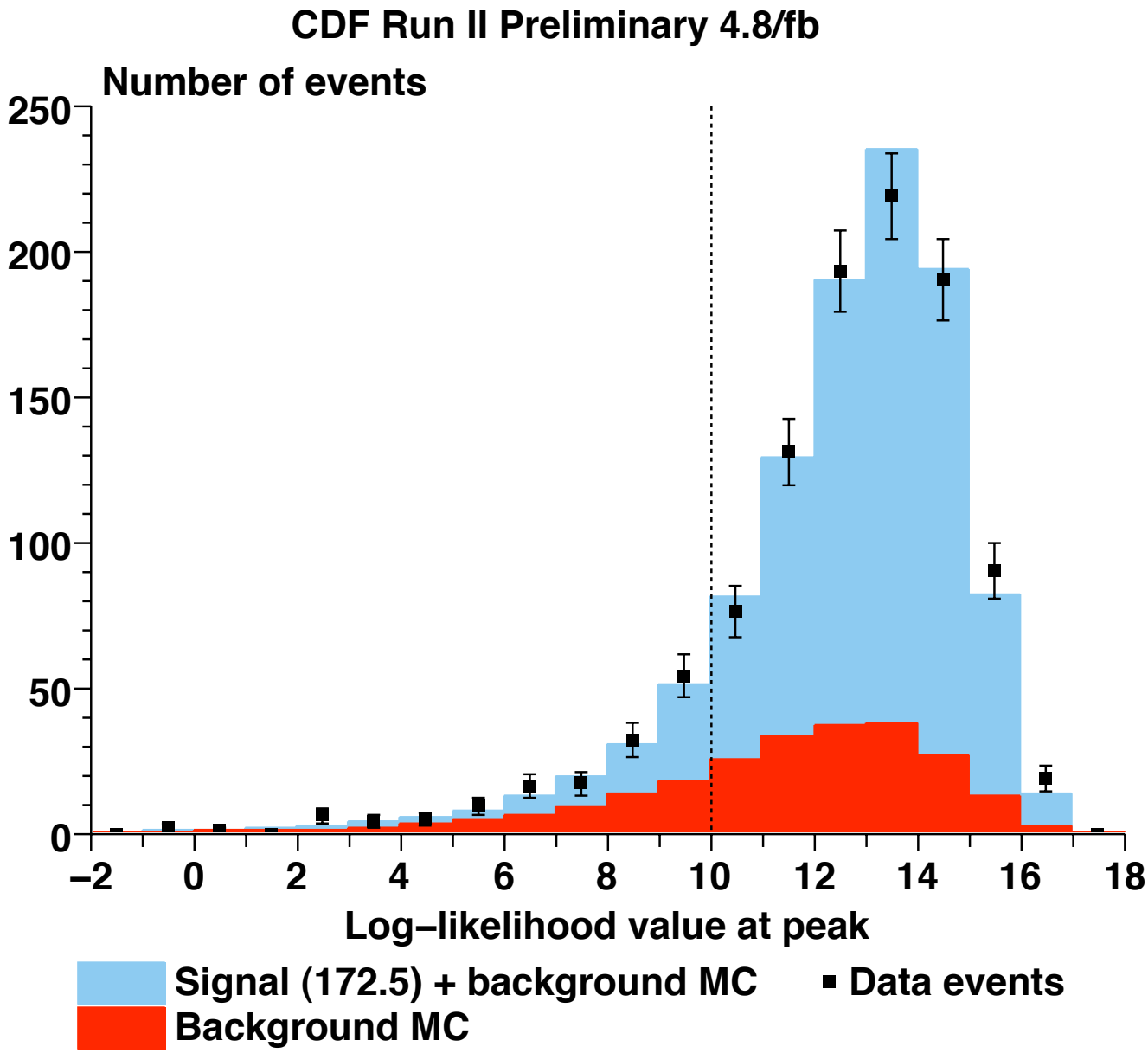
- Train a neural network to distinguish signal events from background
  - Per-event background fraction (from NN) used to subtract off average background likelihood
- Cut on peak likelihood value out of ME
  - Removes background and poorly modeled signal events

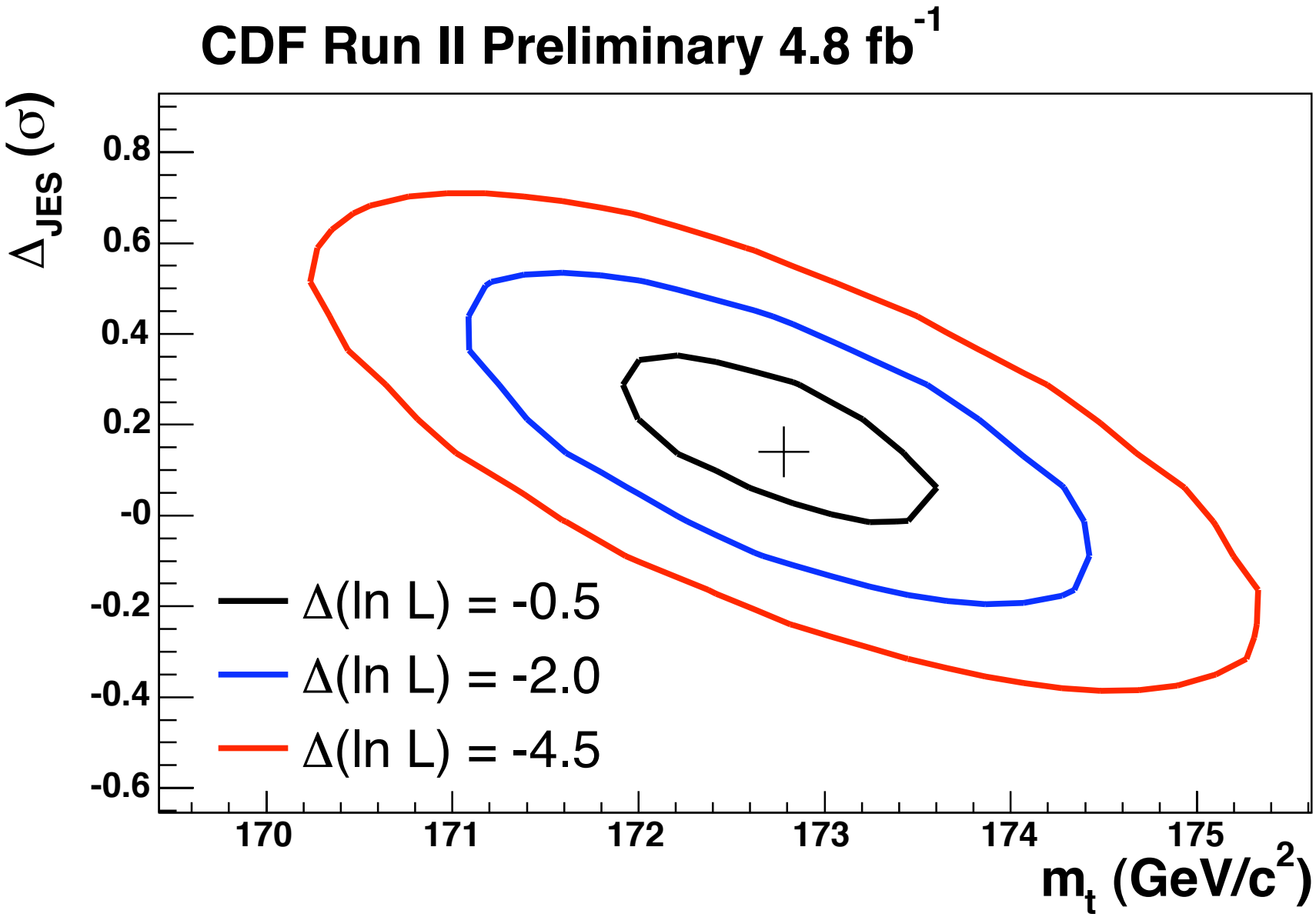


CDF Run II Preliminary, 4.8 fb^{-1}

Event type	1 tag	$\geq$ 2 tags
non-W QCD	44.5 $\pm$ 38.6	3.8 $\pm$ 4.0
W+light mistag	40.7 $\pm$ 10.1	0.8 $\pm$ 0.3
diboson (WW, WZ, ZZ)	10.6 $\pm$ 1.1	1.0 $\pm$ 0.1
$Z \to \ell\ell$ + jets	8.5 $\pm$ 1.2	0.7 $\pm$ 0.1
$W + bb$	54.6 $\pm$ 20.7	10.5 $\pm$ 3.5
$W + c\bar{c}$	33.5 $\pm$ 11.5	1.5 $\pm$ 0.5
$W + c$	16.5 $\pm$ 5.7	0.7 $\pm$ 0.3
Single top	8.7 $\pm$ 0.7	2.6 $\pm$ 0.2
Total background	217.6 $\pm$ 56.9	21.6 $\pm$ 7.8
Predicted top signal (σ = 7.4 pb)	644.2 $\pm$ 107.5	238.7 $\pm$ 36.8
Events observed	859	211

Matrix Element Lepton+Jets

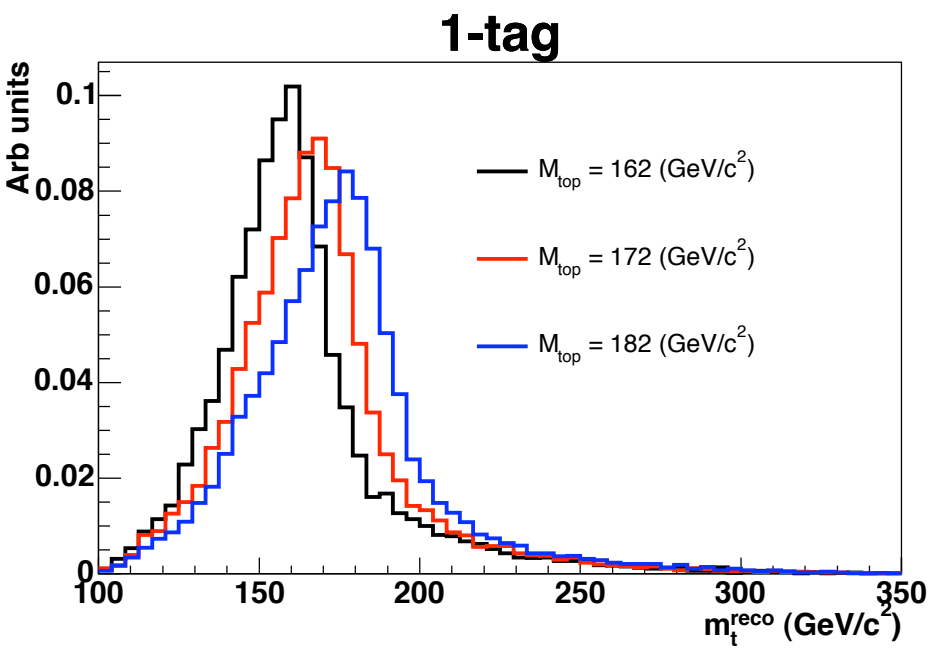


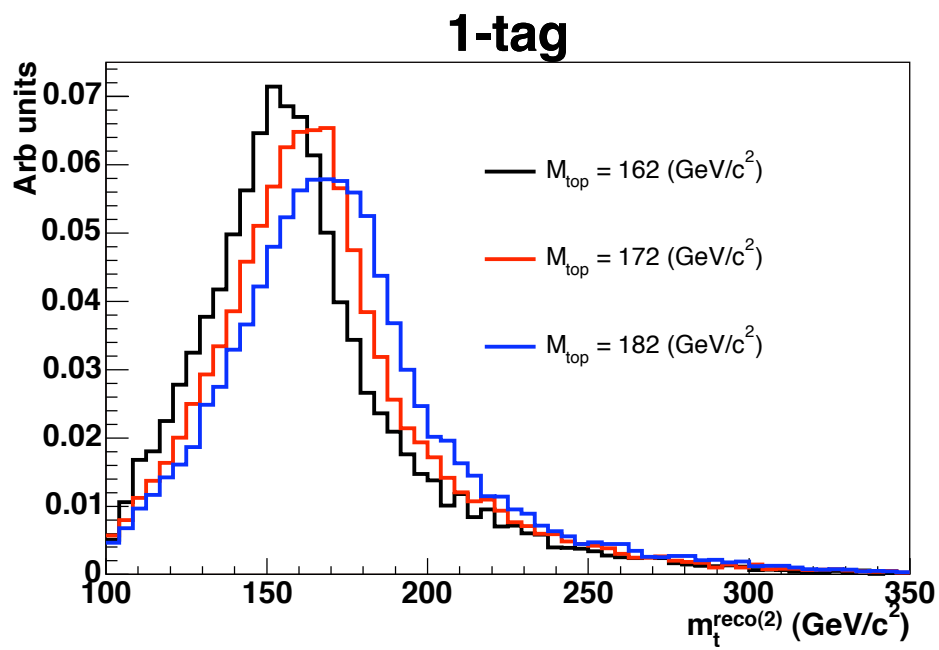


m_t = 172.8 ± 0.7 (stat) ± 0.6 (JES) ± 0.8 (syst) GeV/c²

Template measurement (Lepton+Jets)

- Find (several) variables correlated to top quark mass (and JES)
- Form multi-dimensional PDFs and fit for m_t
- For Lepton+Jets, utilize overconstrained kinematics of system in a X^2 fit
    - Pick best-fit mass from among combinatorics
    - Also use mass from second best jet-parton assignment
    - Use dijet mass to constrain JES

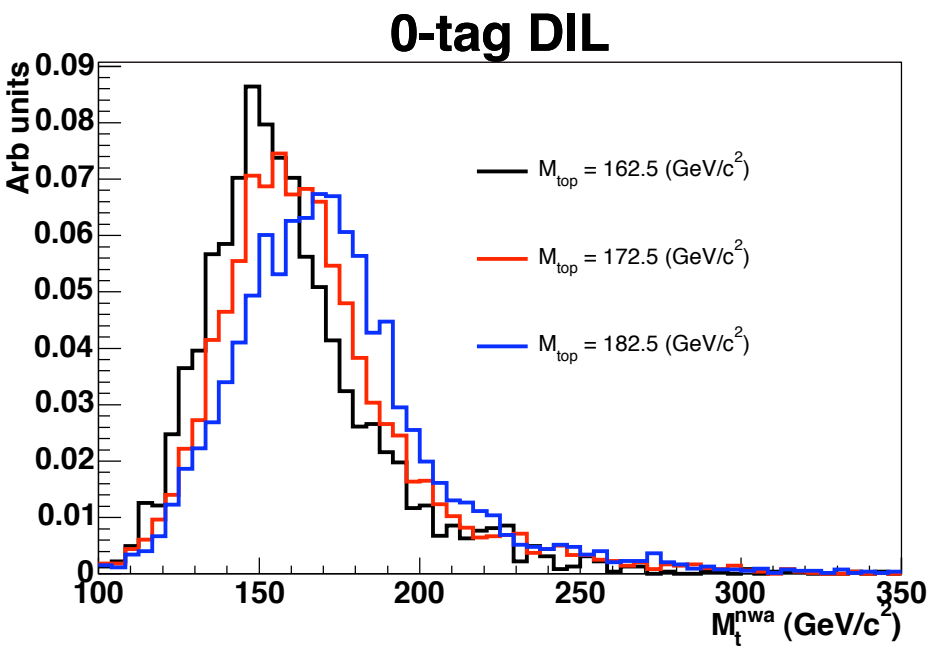


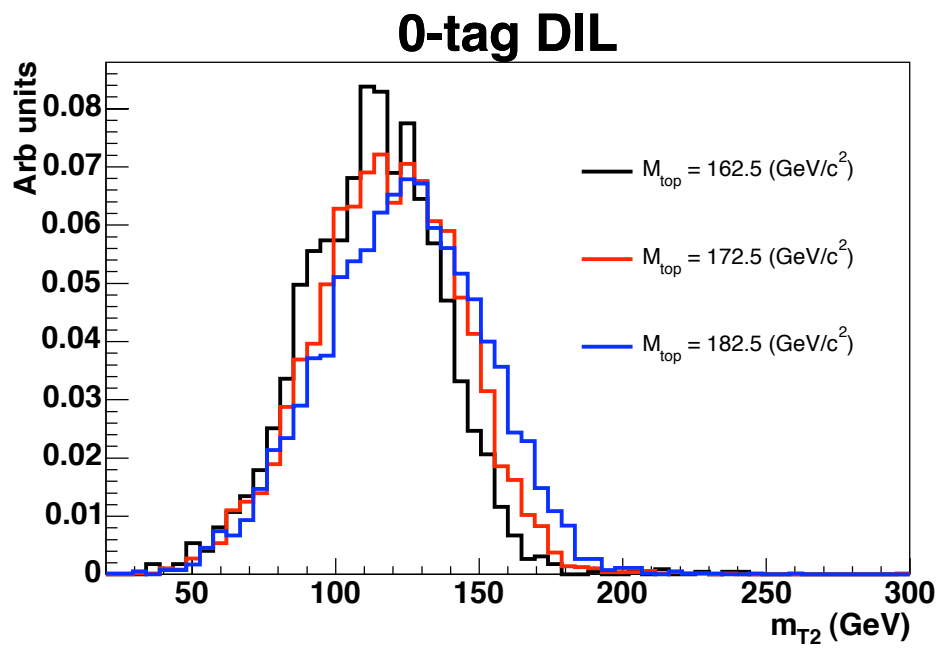


Template measurement (Dilepton)

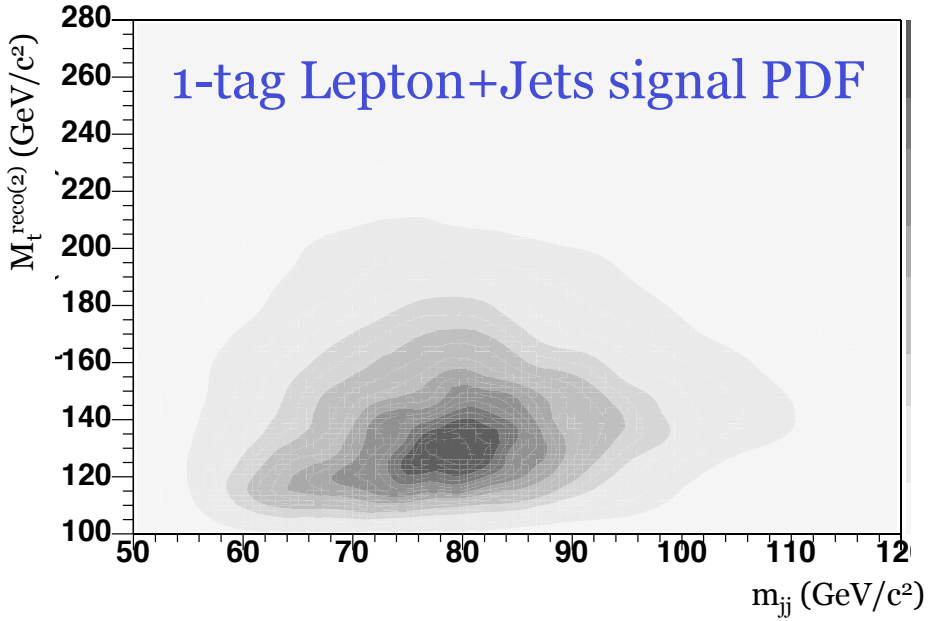
- Underconstrained kinematics (two neutrinos)
- NWA algorithm: Integrate over neutrino pseudorapidities, for a given top quark mass have some (dis)agreement with observed MET – pick top quark mass most consistent with MET
- Second variable (M_{T2}) previously introduced for SUSY searches
  - Lowest possible top mass consistent with observables (see, ex: Chris Lester and David Summers, Phys. Lett. B 463 page 99-103, 1999; Alan Barr, Christopher Lester, and Phil Stephens J. Phys. G29:2343-2363, 2003)

$$m_{T2} = min\left[max\{m_T^{(1)}, m_T^{(2)}\}\right]$$

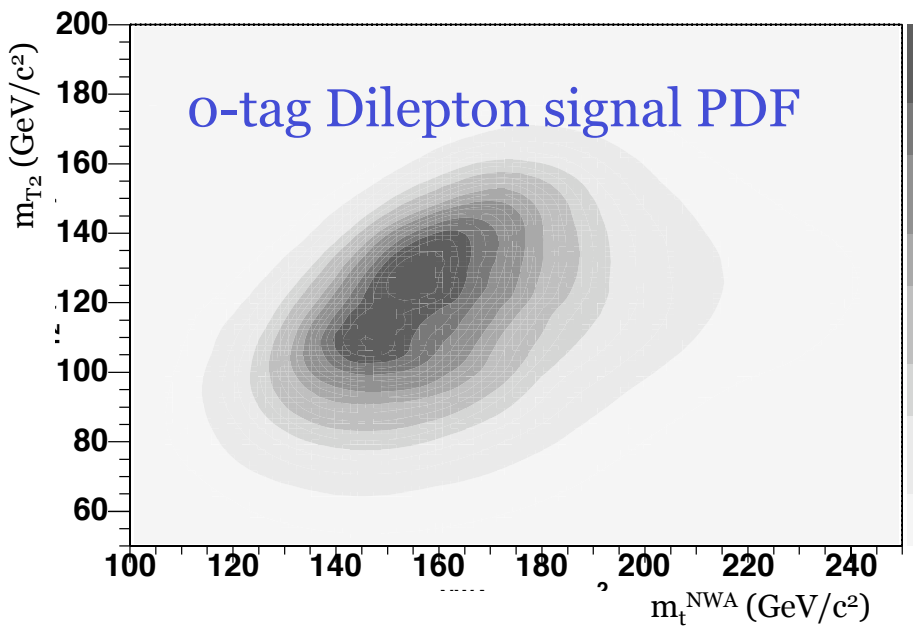




Template measurement

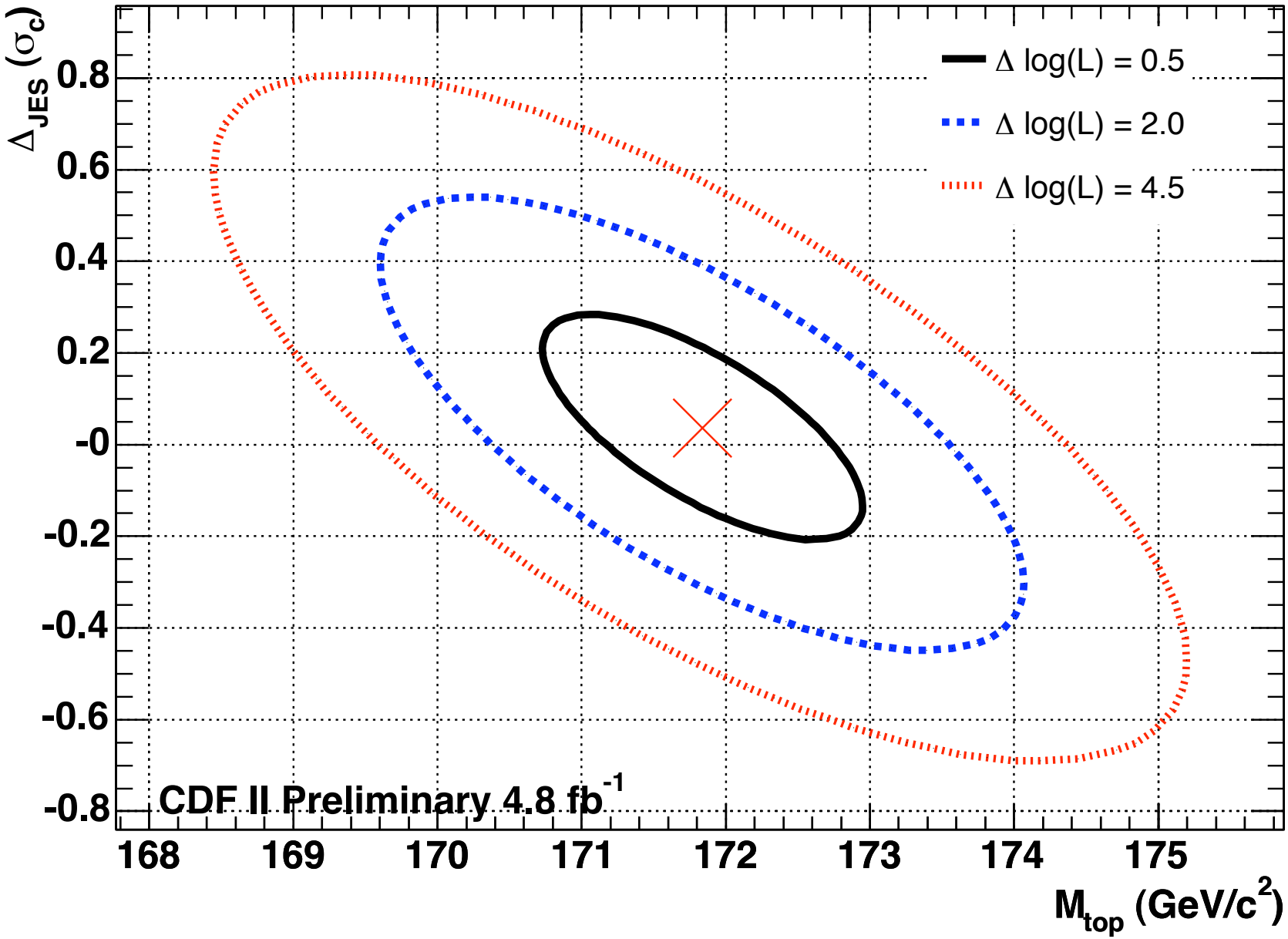


	CDF II Preliminary 4.8 fb^{-1}	
	1-tag	2-tag
Wbb	36.1 ± 11.6	8.8 ± 2.9
$Wc\bar{c}$	22.8 ± 7.6	1.4 ± 0.5
Wc	11.4 ± 3.6	0.7 ± 0.2
W+light mistag	26.8 ± 5.9	0.7 ± 0.2
Z+jets	5.7 ± 1.3	0.6 ± 0.2
single top	5.7 ± 0.5	2.2 ± 0.3
Diboson	7.7 ± 1.0	1.0 ± 0.2
QCD	30.7 ± 24.9	4.0 ± 3.5
Total	146.8 ± 56.2	19.4 ± 7.9
$t\bar{t}$ (172.5 GeV/c^2, 7.4 pb)	557.0 ± 69.5	272.0 ± 42.0



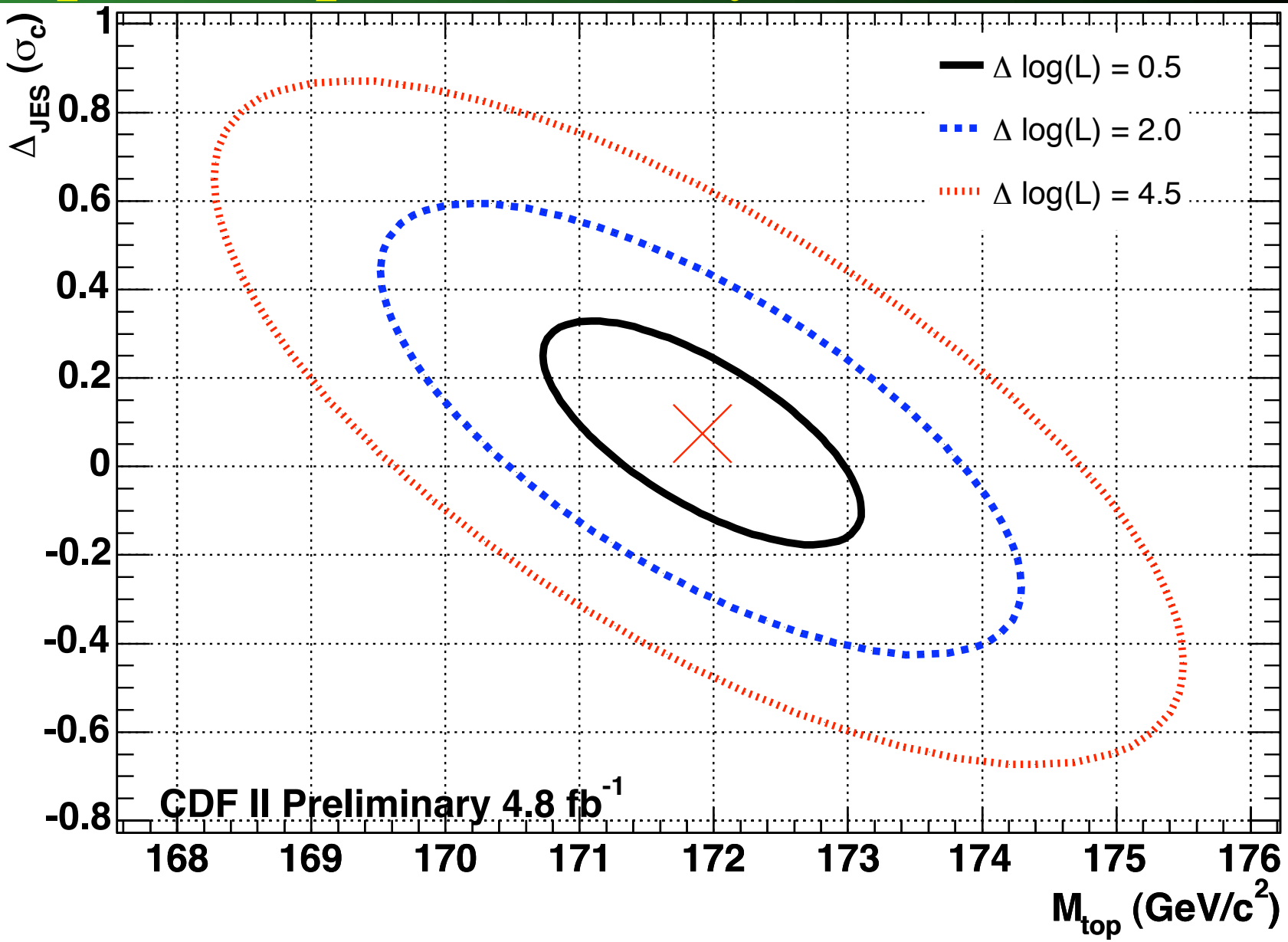
	CDF II Preliminary 4.8 fb^{-1}	
	0-tag	tagged
WW	14.6 ± 2.7	0.5 ± 0.1
WZ	3.5 ± 0.1	0.1 ± 0.0
ZZ	2.2 ± 2.0	0.2 ± 0.1
$W\gamma$	0.4 ± 0.4	0.0 ± 0.0
Drell Yan ($\tau\tau$)	11.0 ± 2.3	0.6 ± 0.1
Drell Yan (ee or $\mu\mu$)	28.7 ± 4.9	1.6 ± 0.3
Fakes	45.3 ± 14.2	6.6 ± 2.1
Total	105.6 ± 15.5	9.5 ± 2.1
$t\bar{t}$ (172.5 GeV/c^2, 7.4 pb)	108.4 ± 13.9	134.1 ± 17.4

Template (combined) measurement



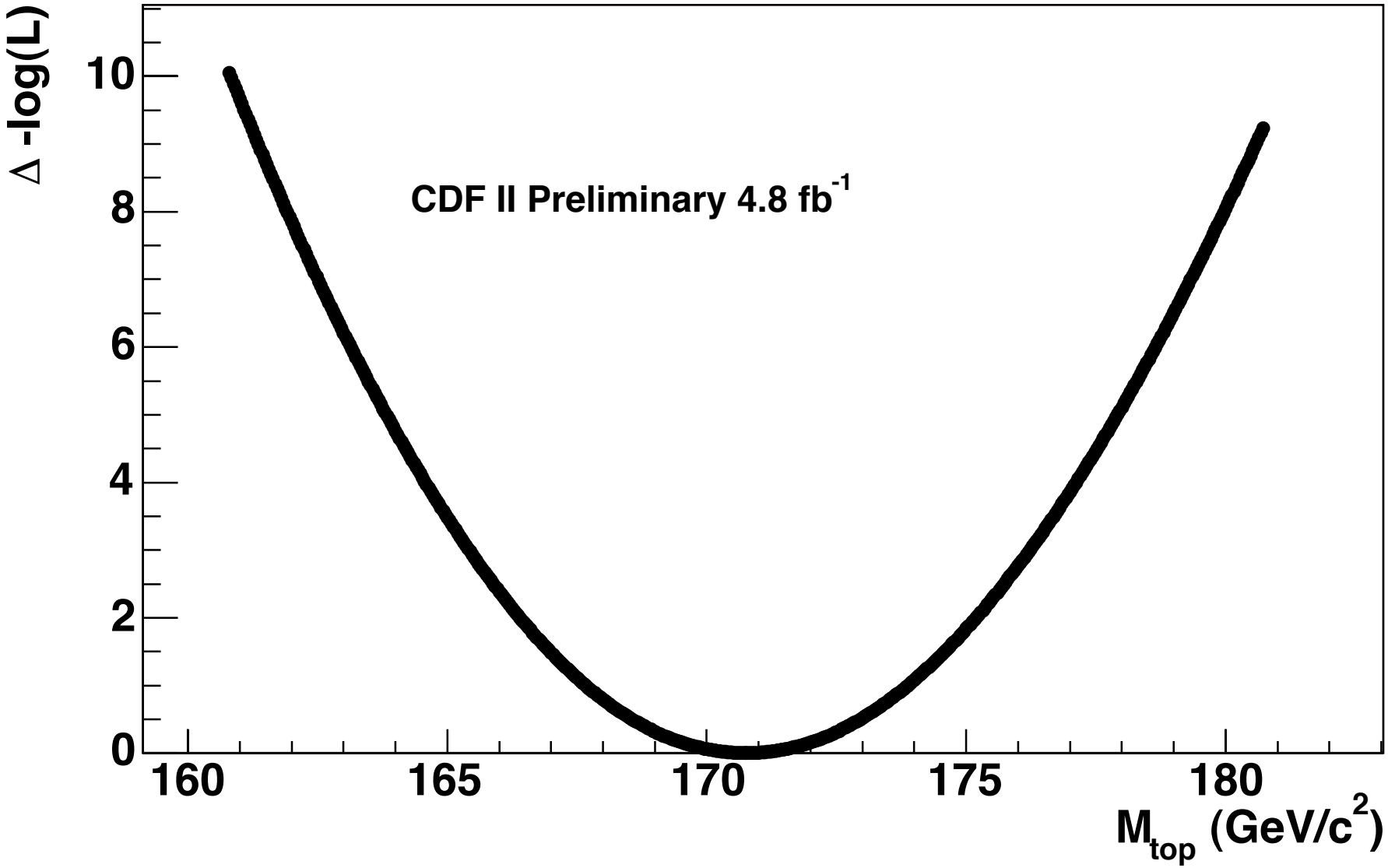
m_t = 171.9 ± 1.1 (stat+JES) ± 0.9 (syst) GeV/c²

Template (Lepton+Jets-only) measurement



m_t = 172.0 ± 1.2 (stat+JES) ± 0.9 (syst) GeV/c²

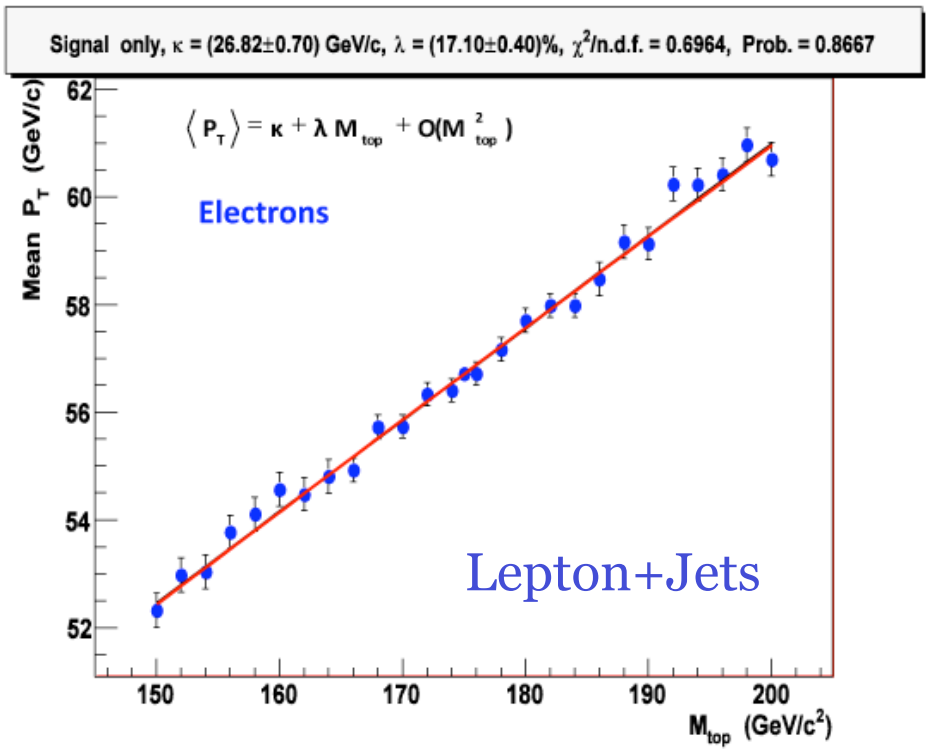
Template (Dilepton-only) measurement

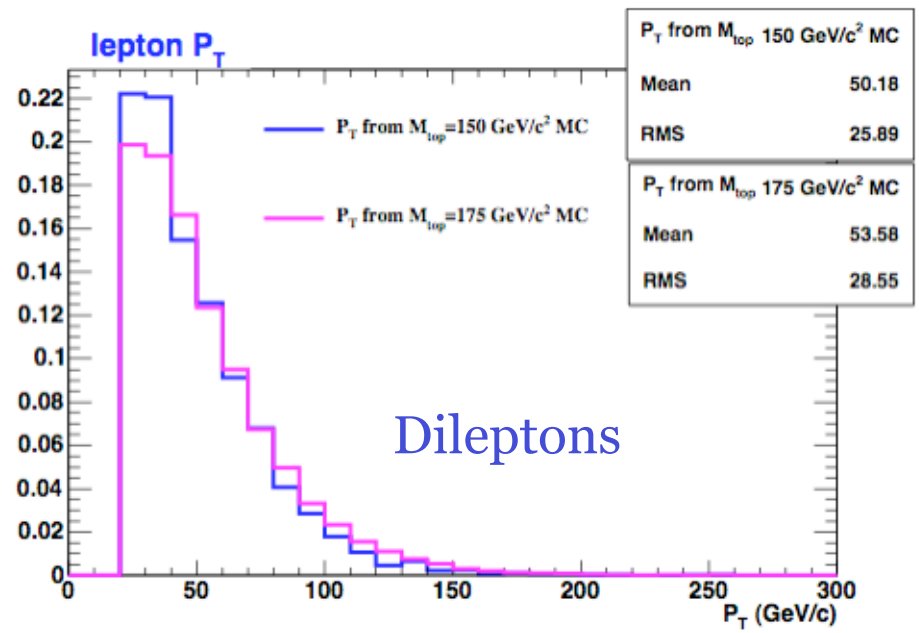


m_t = 170.6 ± 2.2 (stat) ± 3.1 (syst) GeV/c²

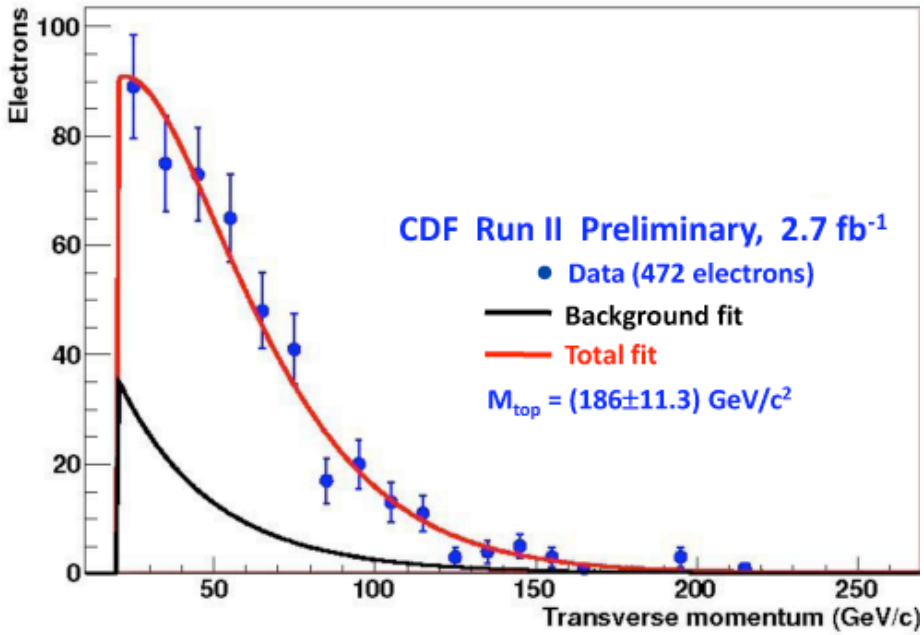
Lepton pt

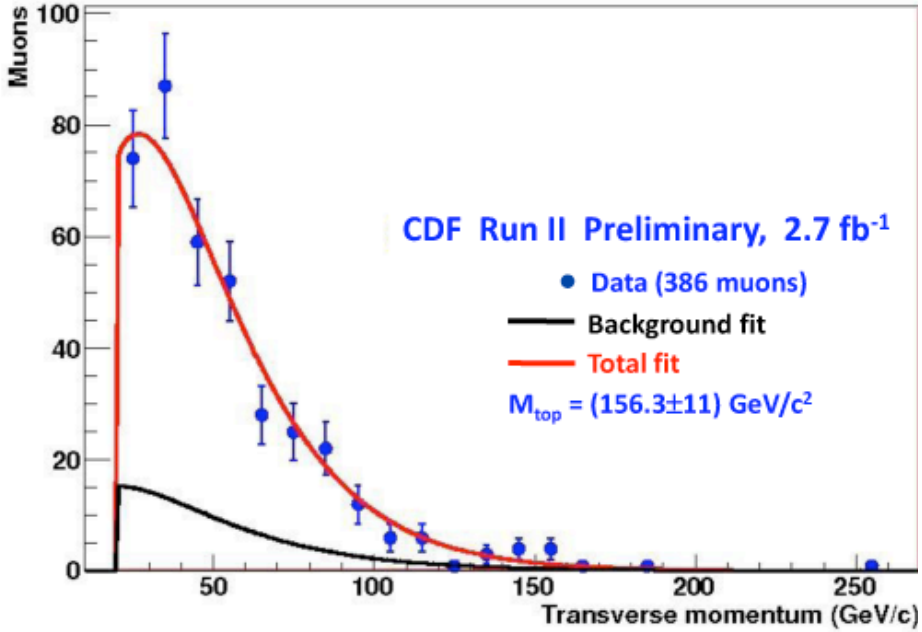
- Idea: pt of lepton from leptonic W decay is correlated to top quark mass with ~no JES dependence
    - Precise calibration from Z events
- Separate fits for electrons and muons (single leptons)/dileptons
- Require at least one b-tag in each event





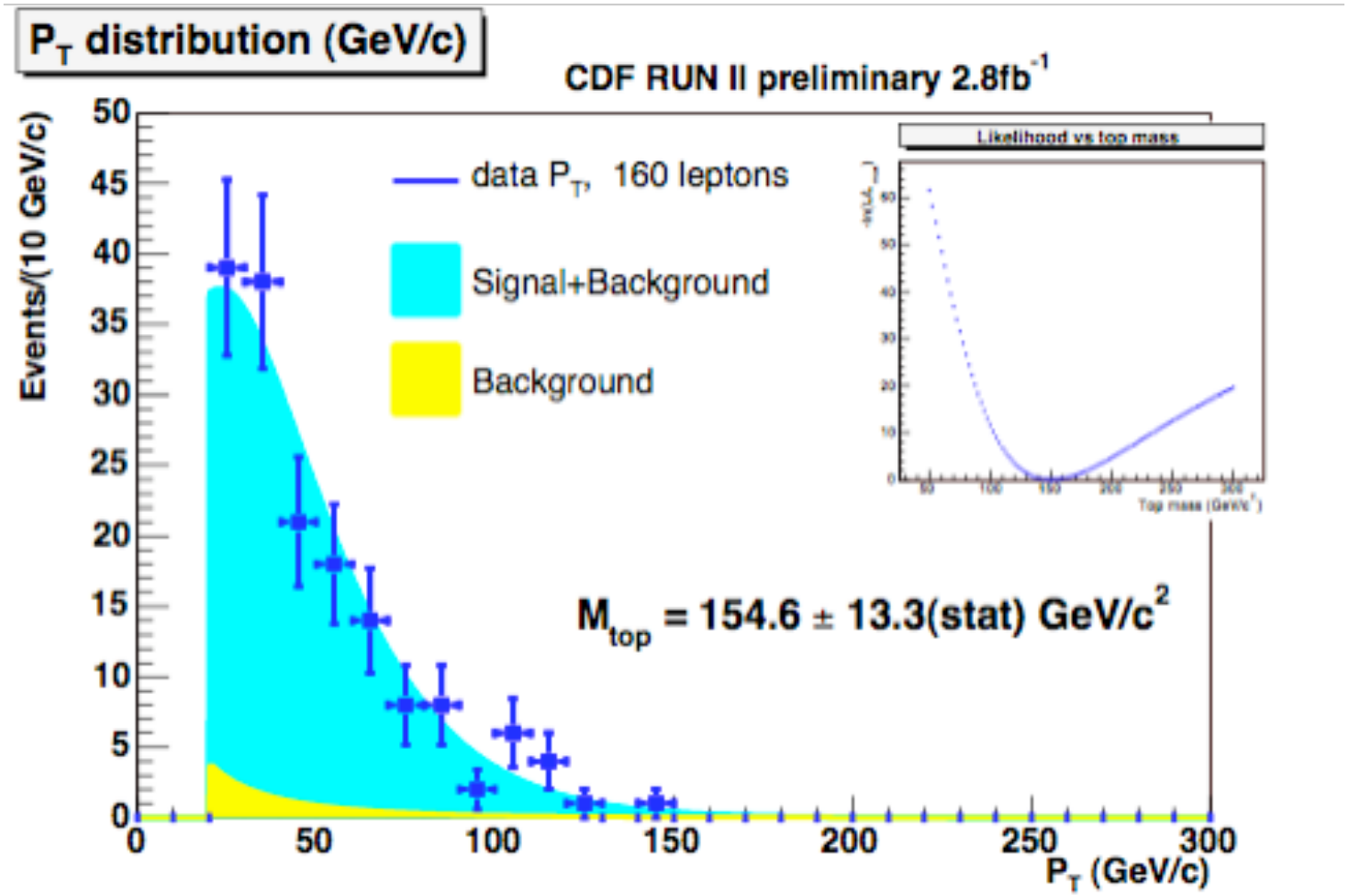
Lepton pt (Lepton+Jets)





$$m_t = 176.9 \pm 8.0\ (\text{stat}) \pm 2.7\ (\text{syst})\ \text{GeV}/c^2$$

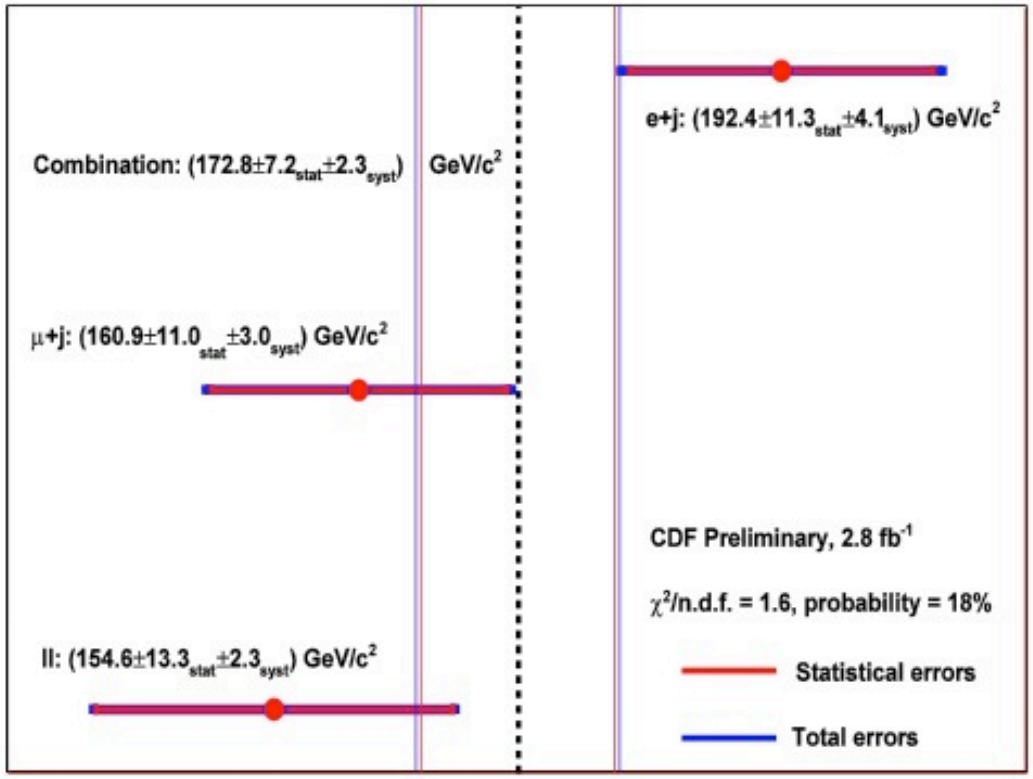
Lepton pt (Dilepton)



$m_t = 154.6 \pm 13.3\ (stat) \pm 2.3\ (syst)\ GeV/c^2$

Lepton pt (combined)

- Combine 3 lepton pt measurements using BLUE
- Account for correlations between systematics
- weight electron+jets = 0.42
- weight muon+jets = 0.40
- weight dilepton = 0.18



Top Quark Mass Measurements from the Lepton Transverse Momentum

m_t = 172.8 ± 7.2 (stat) ± 2.3 (syst) GeV/c²

Systematics

CDF Run II Preliminary, 4.8 fb^{-1}

Systematic source	Systematic uncertainty (GeV/c^2)
Calibration	0.11
MC generator	0.25
ISR and FSR	0.15
Residual JES	0.49
b-JES	0.26
Lepton P_T	0.14
Multiple hadron interactions	0.10
PDFs	0.14
Background modeling	0.33
Gluon fraction	0.03
Color reconnection	0.37
Total	0.84

Template

CDF II Preliminary 4.8 fb^{-1}

Systematic	LJ	DIL	Combination
Residual JES	0.6	2.9	0.6
Generator:	0.6	0.6	0.6
PDFs	0.1	0.3	0.1
b jet energy	0.3	0.3	0.3
Background shape	0.1	0.3	0.1
gg fraction	0.1	0.3	<0.1
Radiation	0.1	0.3	0.1
MC statistics	0.1	0.3	0.1
Lepton energy	<0.1	0.3	<0.1
MHI	0.1	0.2	0.1
Color Reconnection	0.2	0.6	0.2
Total systematic	0.9	3.1	0.9

Matrix element

Lepton pt

	δMass (GeV)				
source of systematic	e+jets	μ+jets	l+jets	DIL	combination
Global P_T scale	0.2	0.1	0.1	0.1	0.1
Local P_T scale	0.6	1.5	1.1	0.7	1.0
MC statistics	0.4	0.4	0.4	0.3	0.2
Generator	0.7	2.2	1.2	1.5	1.0
IFSR	1.5	0.7	0.8	1.3	0.7
PDF	0.6	0.6	0.6	0.7	0.6
Background shape	3.6	0.0	1.8	0.4	1.4
Background constrain	0.0	0.0	0.0	0.3	0.1
JES	0.0	0.0	0.0	0.4	0.1
Multiple Interactions	0.1	0.1	0.1	0.2	0.1
Q^2	0.7	0.8	0.5	0.0	0.4
Bias from the fit	0.0	0.0	0.0	0.3	0.1
Total	4.1	3.0	2.7	2.3	2.3

Dominated by a few uncertainties!

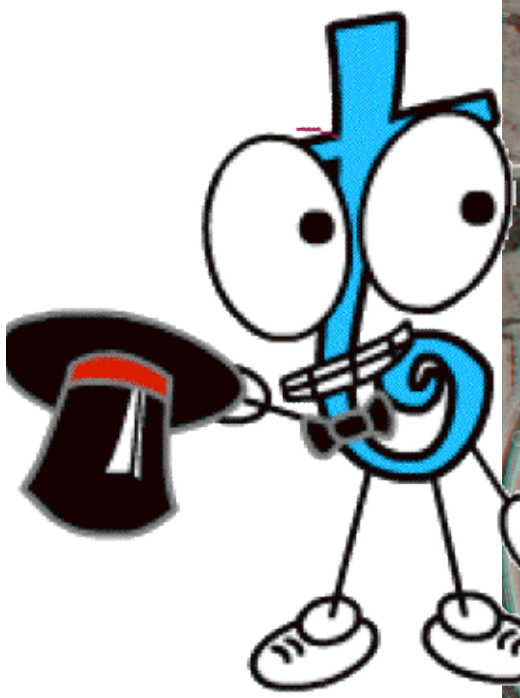
Systematics

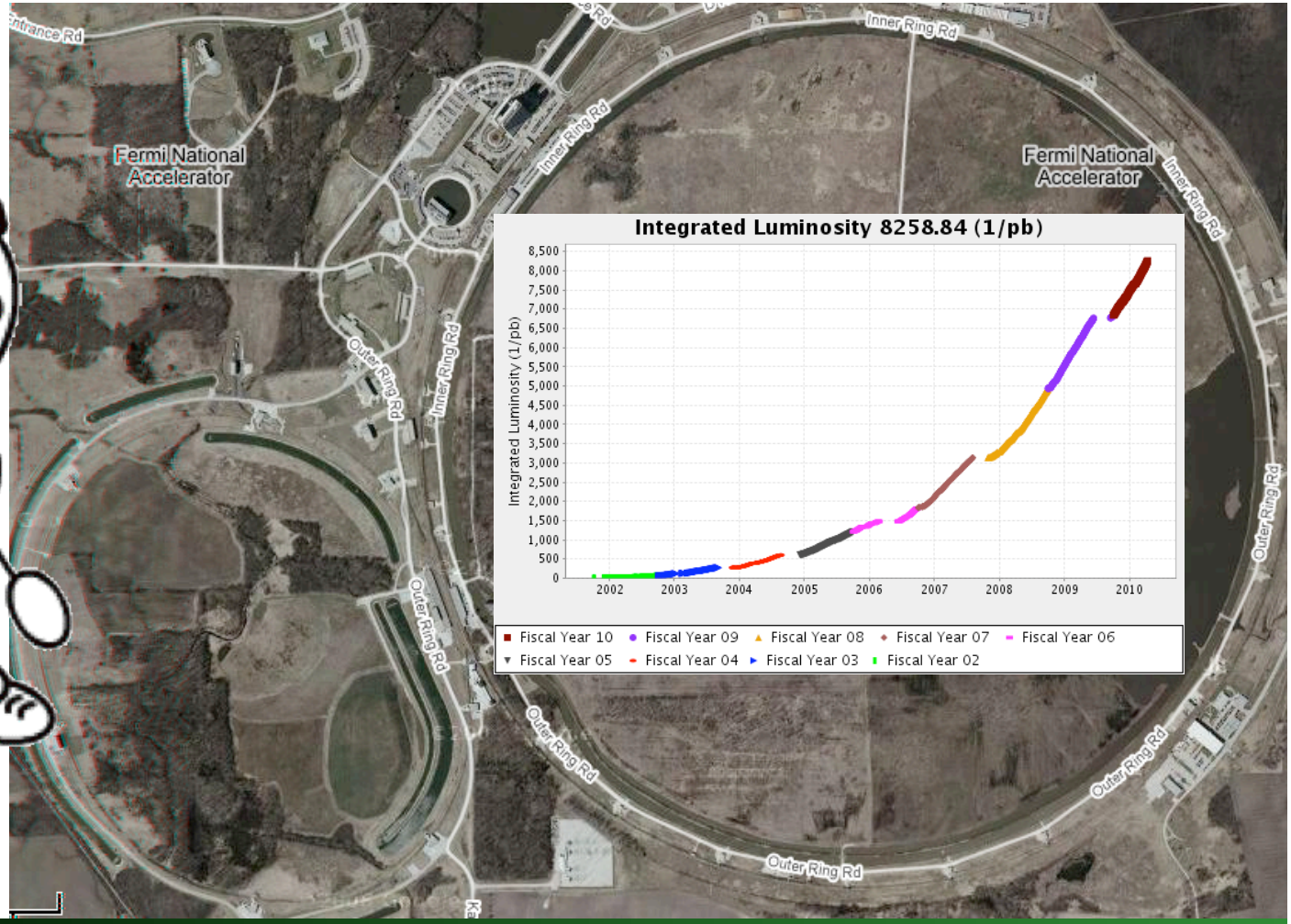
- Effort at (re-)defining common systematics for analyses
- Color reconnection: Compare Pythia 6.4 with different CR models (similar to current vs new), take difference as a systematic
- Multiple interactions: Calculate systematic due to fact that MC cannot always model luminosity profile in data
- Bkgd composition
    - Divide backgrounds into correlated categories (ex: W+HF, W +mistag, QCD, single top, diboson), shift by uncertainties
    - Composition can change with uncertain JES, too!

Analyses already systematics limited – studying and understanding them becoming even more important!

Conclusion

- CDF making precision measurements of the top quark mass
- Continue improving statistical precision, continue studying and improving systematics!





Backup

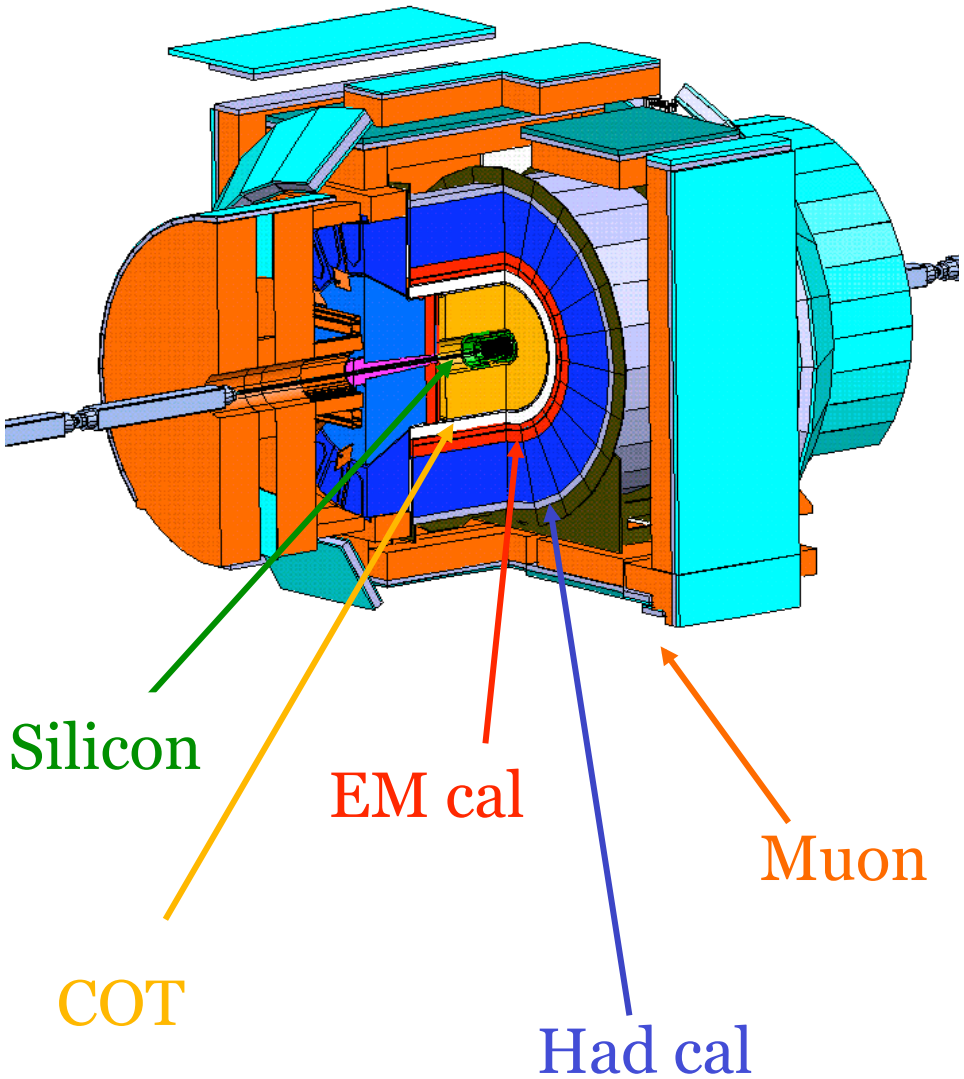
Kinematic Fitter for Lepton+Jets

- 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

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

CDF



Silicon important for good tracking, necessary for b-tagging

Drift chamber for track momentum

1.4 Tesla superconducting solenoid outside tracking system

EM Calorimeter for electrons

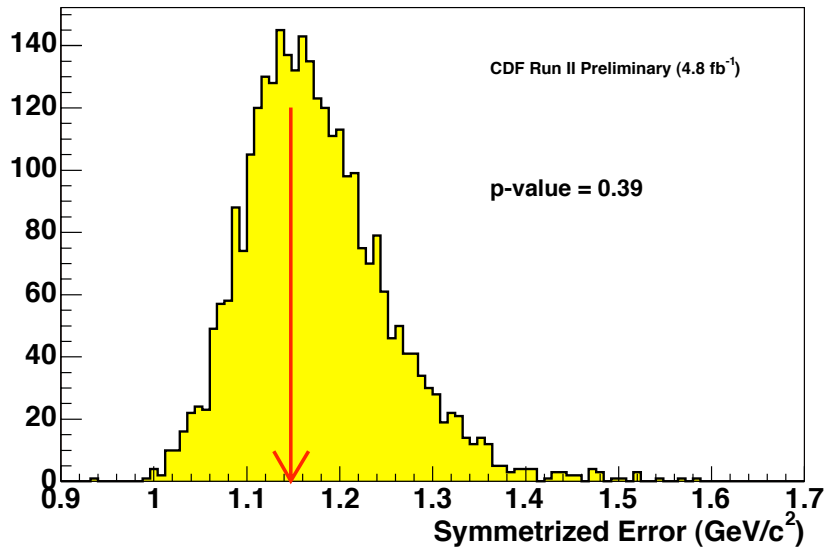
Hadronic calorimeter for jets

Muons chambers (NEW: additional muons used in latest analyses!)

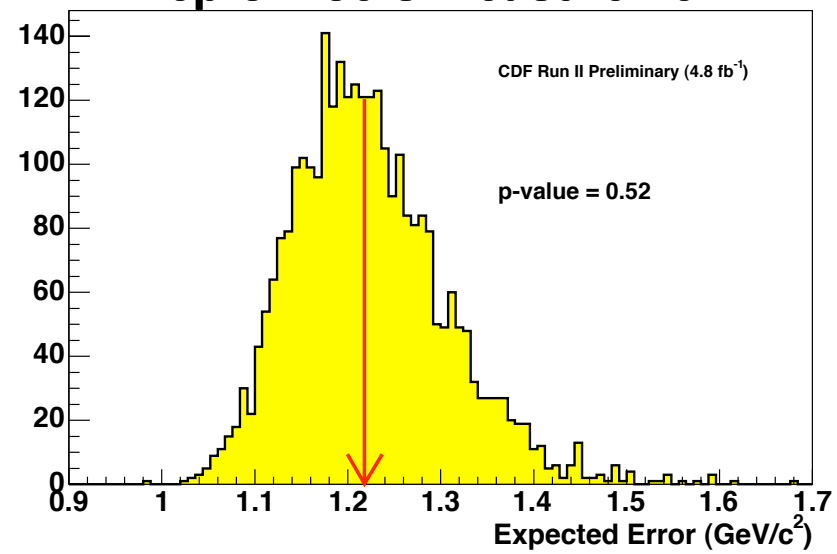
Need entire detector to get a good measurement of momentum imbalance

Did we get lucky?

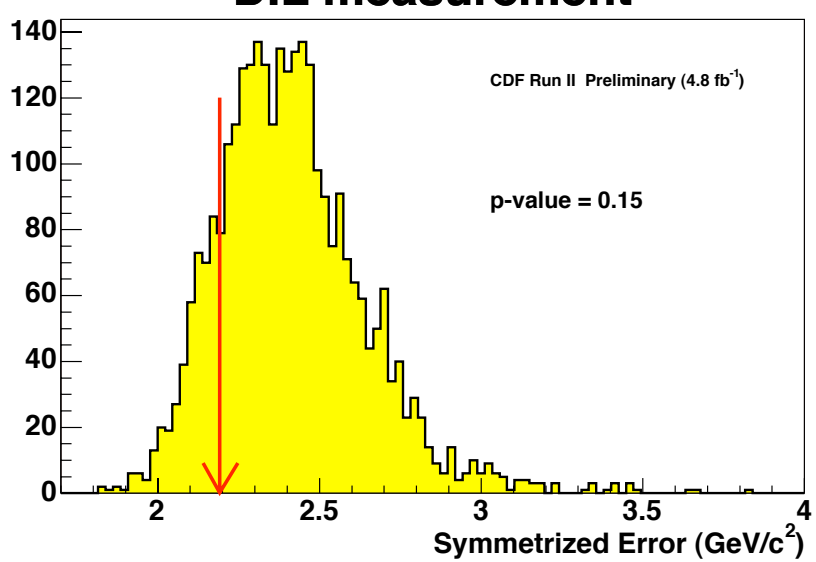
Combined measurement

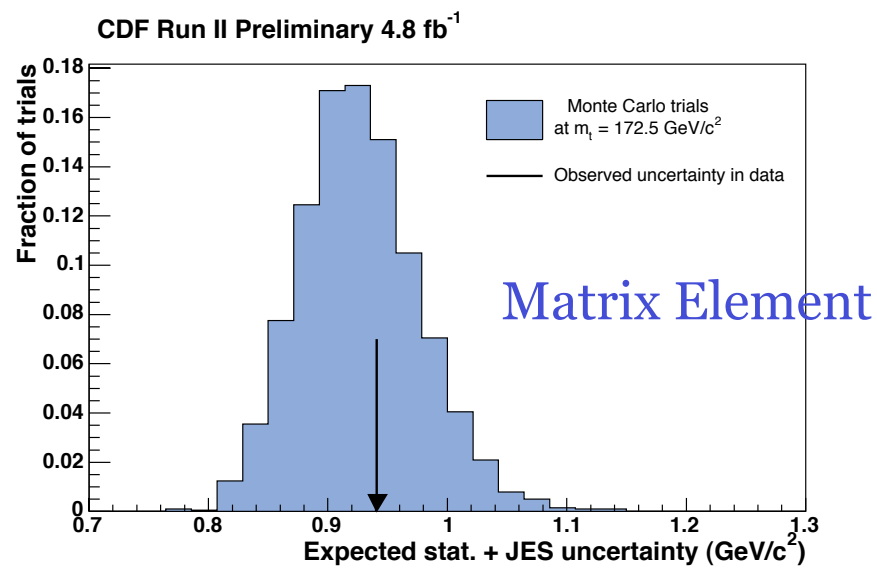


Lepton+Jets measurement

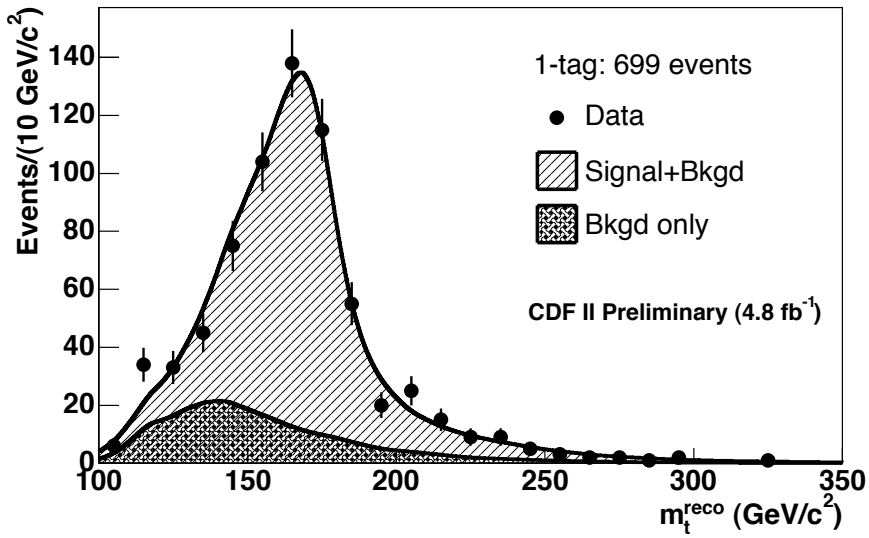


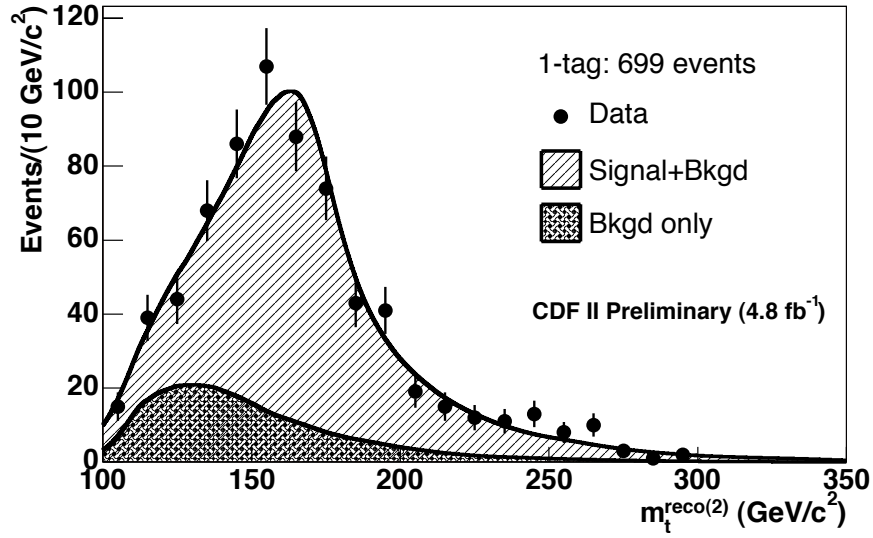
DIL measurement

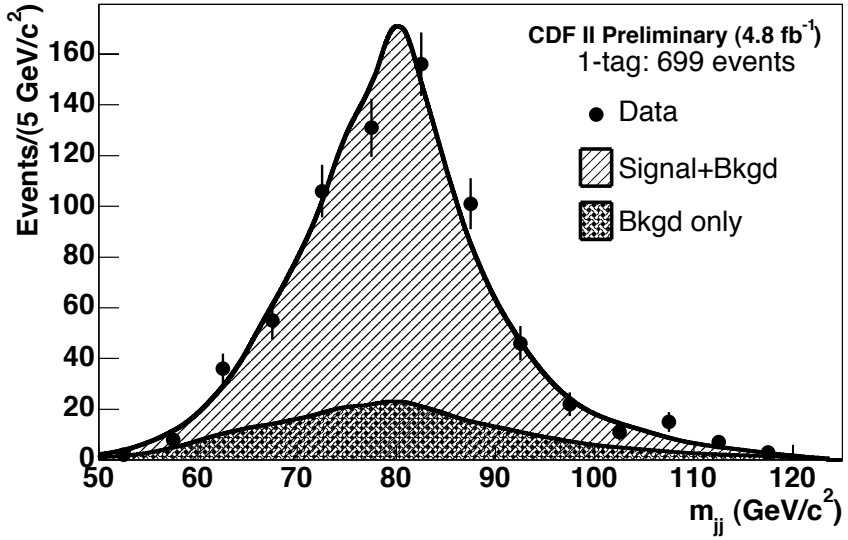


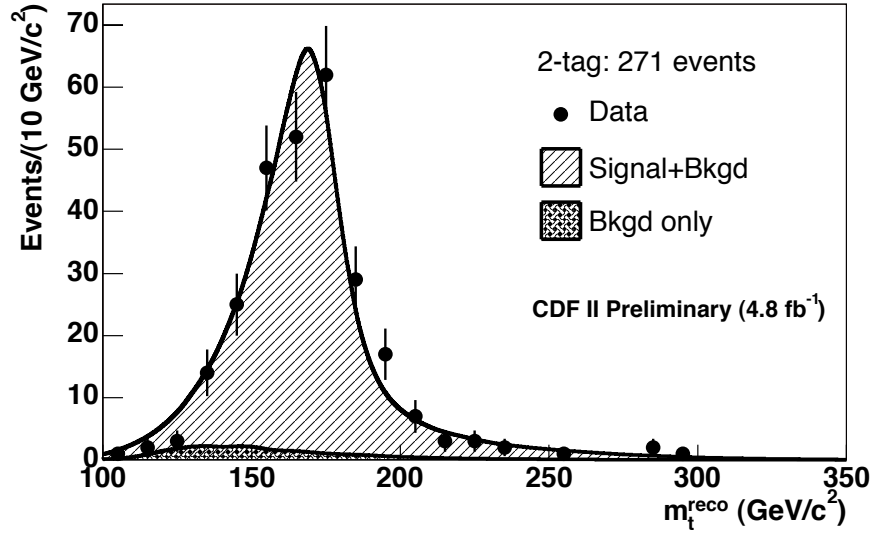


Template plots

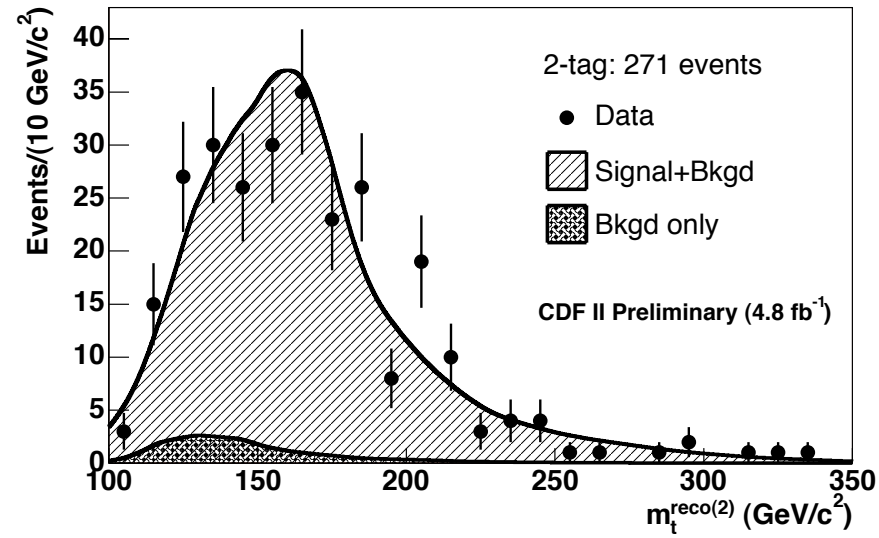


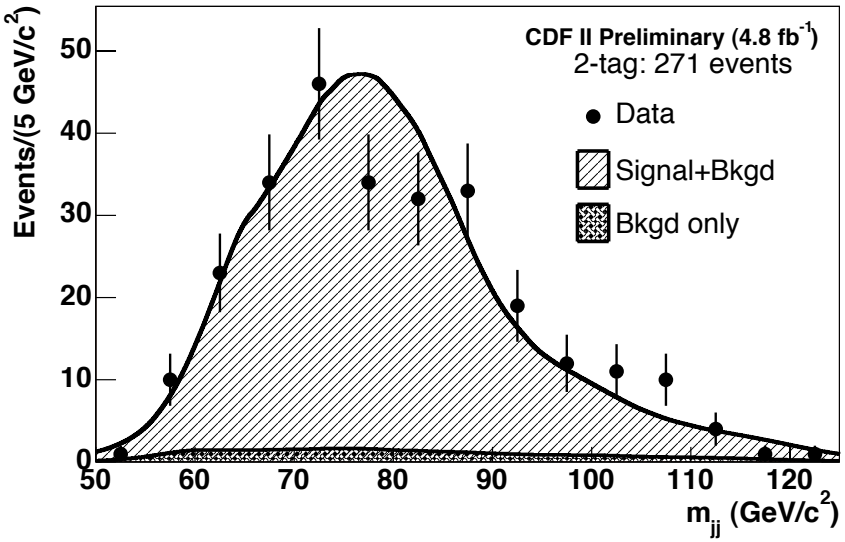


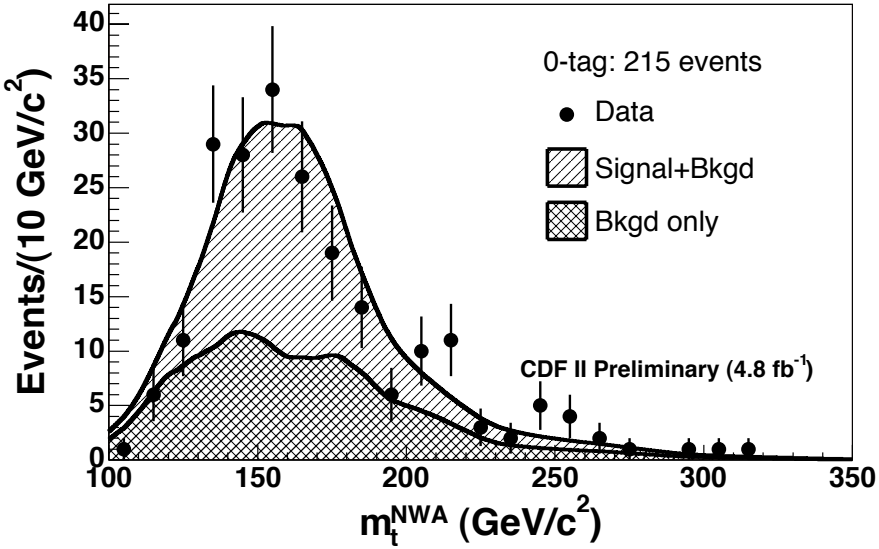


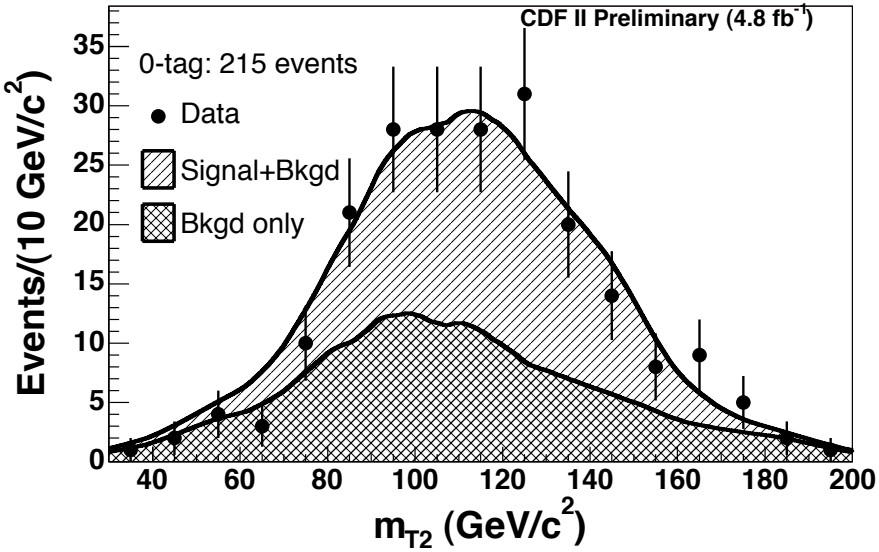


Template plots









Template plots