Top Mass at CDF: Final Results

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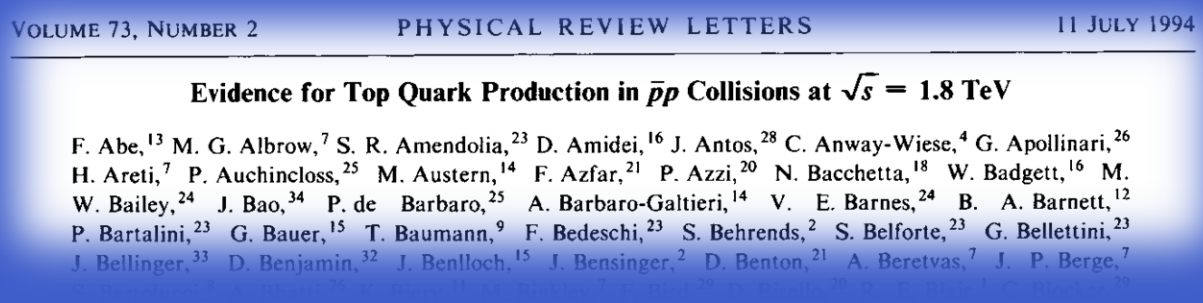
Outline

- Introduction
- Four Channels
  - Lepton+Jets
  - Missing E_T+Jets
  - All hadronic
  - Dilepton
- Combination

Introduction

- 20 years ago, CDF first assembled all the pieces needed to discover the top



VOLUME 73, NUMBER 2 PHYSICAL REVIEW LETTERS 11 JULY 1994

Evidence for Top Quark Production in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV

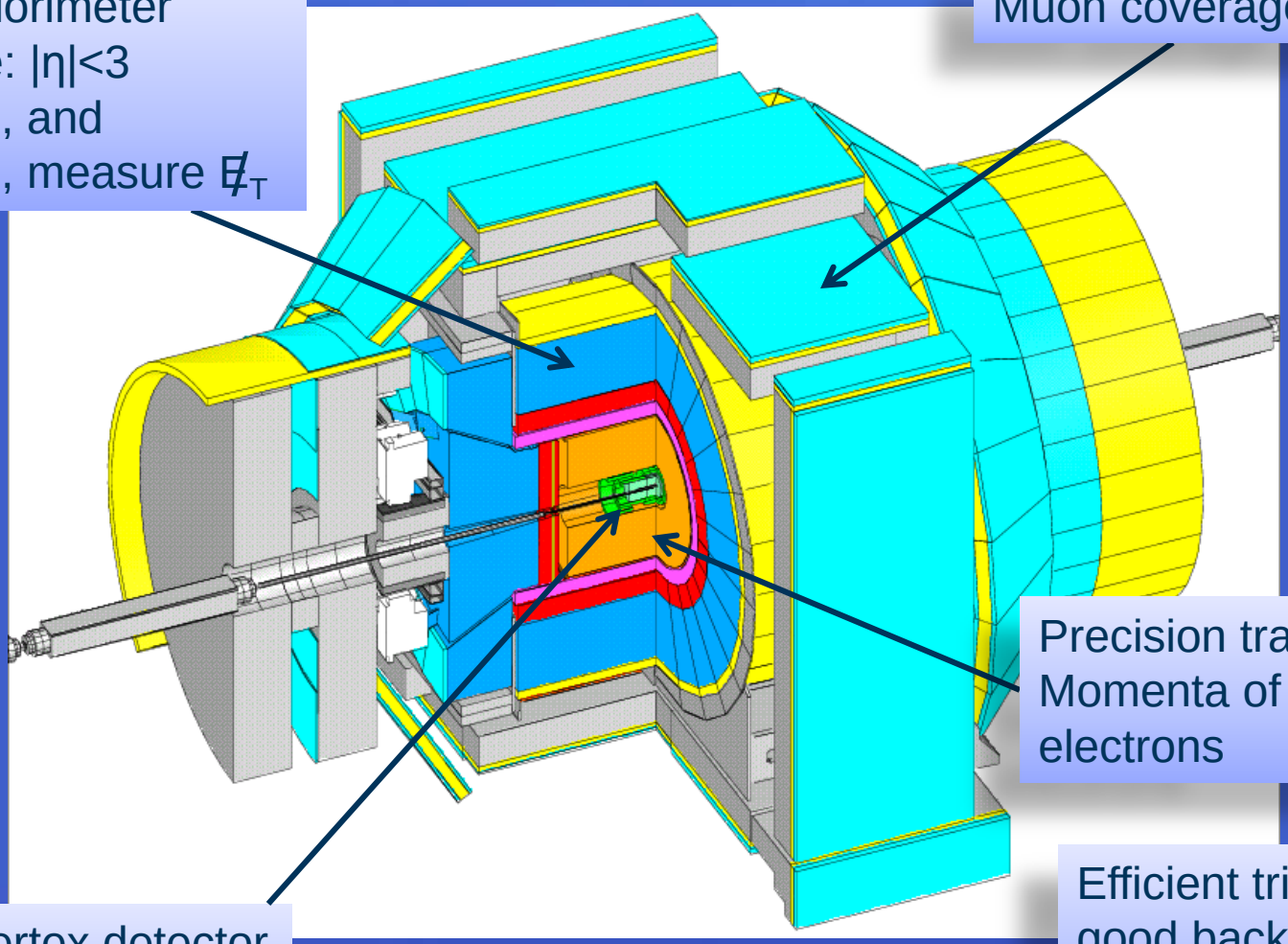
F. Abe,[13] M. G. Albrow,[7] S. R. Amendolia,[23] D. Amidei,[16] J. Antos,[28] C. Anway-Wiese,[4] G. Apollinari,[26] H. Areti,[7] P. Auchincloss,[25] M. Austern,[14] F. Azfar,[21] P. Azzi,[20] N. Bacchetta,[18] W. Badgett,[16] M. W. Bailey,[24] J. Bao,[34] P. de Barbaro,[25] A. Barbaro-Galtieri,[14] V. E. Barnes,[24] B. A. Barnett,[12] P. Bartalini,[23] G. Bauer,[15] T. Baumann,[9] F. Bedeschi,[23] S. Behrends,[2] S. Belforte,[23] G. Bellettini,[23] J. Bellinger,[33] D. Benjamin,[32] J. Benlloch,[15] J. Bensinger,[2] D. Benton,[21] A. Beretvas,[7] J. P. Berge,[7]

- The strategy to study the top quark remains the same today
- Top quark mass is a fundamental property of the standard model that must be measured precisely
- Today: CDF final results with ~9 fb^{-1}

CDF Detector

- Large calorimeter coverage: $|\eta|<3$
- Find Jets, and electrons, measure $\not{E}_T$

Muon coverage $|\eta|<1$



Precision tracking $|\eta|<1$: Momenta of muons and electrons

Efficient triggers with good background rejection

Silicon Vertex detector
- $\Delta d_0 \sim 40\mu m$
- b-jet tagging

Lepton+Jets

- Golden mode
  - $t \rightarrow W(\rightarrow \ell\nu)\ j_b$, $\bar{t} \rightarrow W(\rightarrow jj)\ j_b$
  - Event samples with 0,1, or 2 b tags
    - Loosen cuts with added tag(s)
      - Softer 4th jet, allow additional jets
- Reconstruction with kinematic fit
  - Constraints: $M(t)=M(\bar{t})$, $M(jj)=M_W$, $M(\ell\nu)=M_W$
  - b tags reduce combinatorics
  - Jet Energy scale derived from M(jj) without constraints
- 3D template fit
  - Use M_t^{reco}, M(jj) and 2nd best M_t^{reco}
  - Free parameters M_t and Δ_{JES}

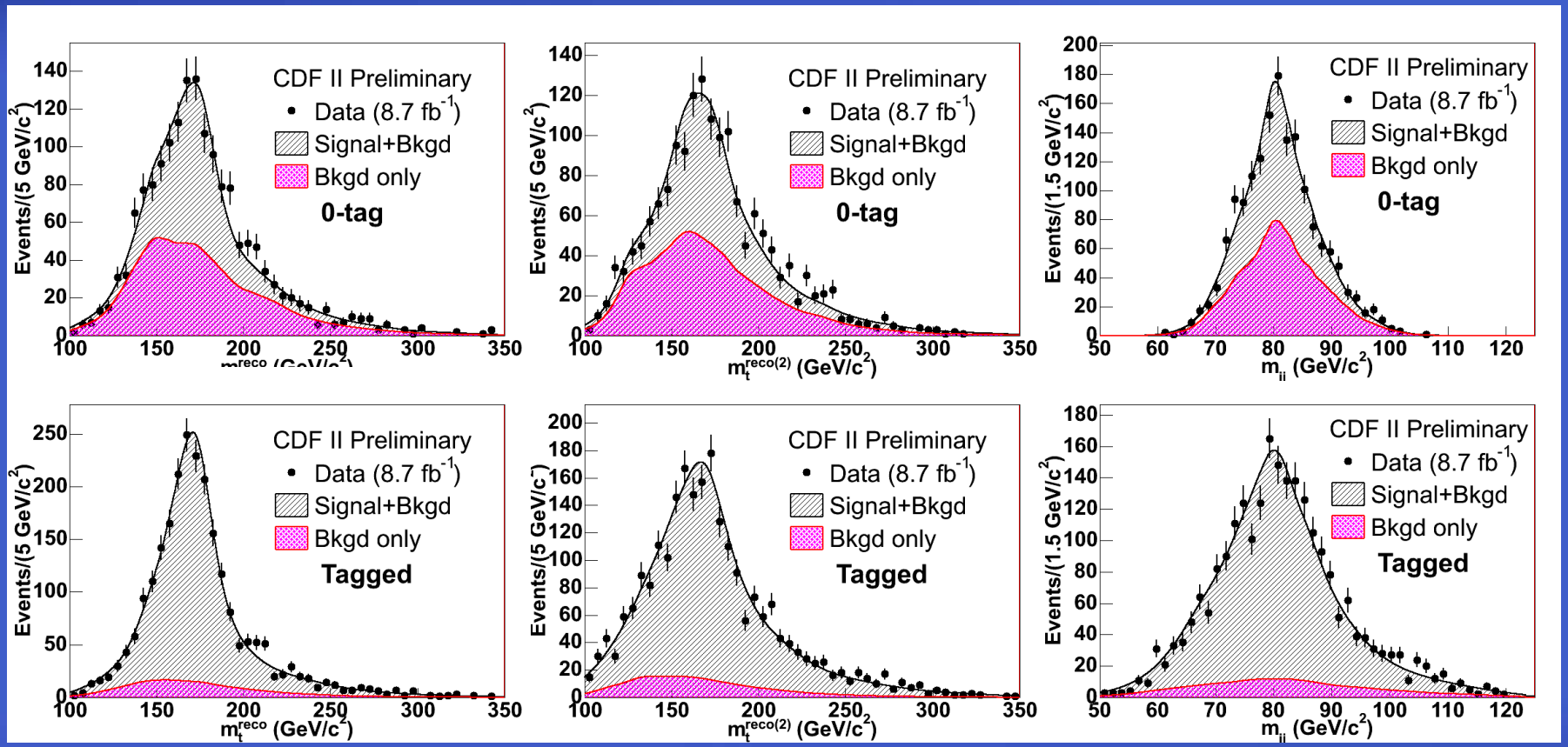
Lepton+Jets: Background

- Determined from mostly Monte Carlo
  - Data fixes normalization

CDF II Preliminary 8.7 fb^{-1}

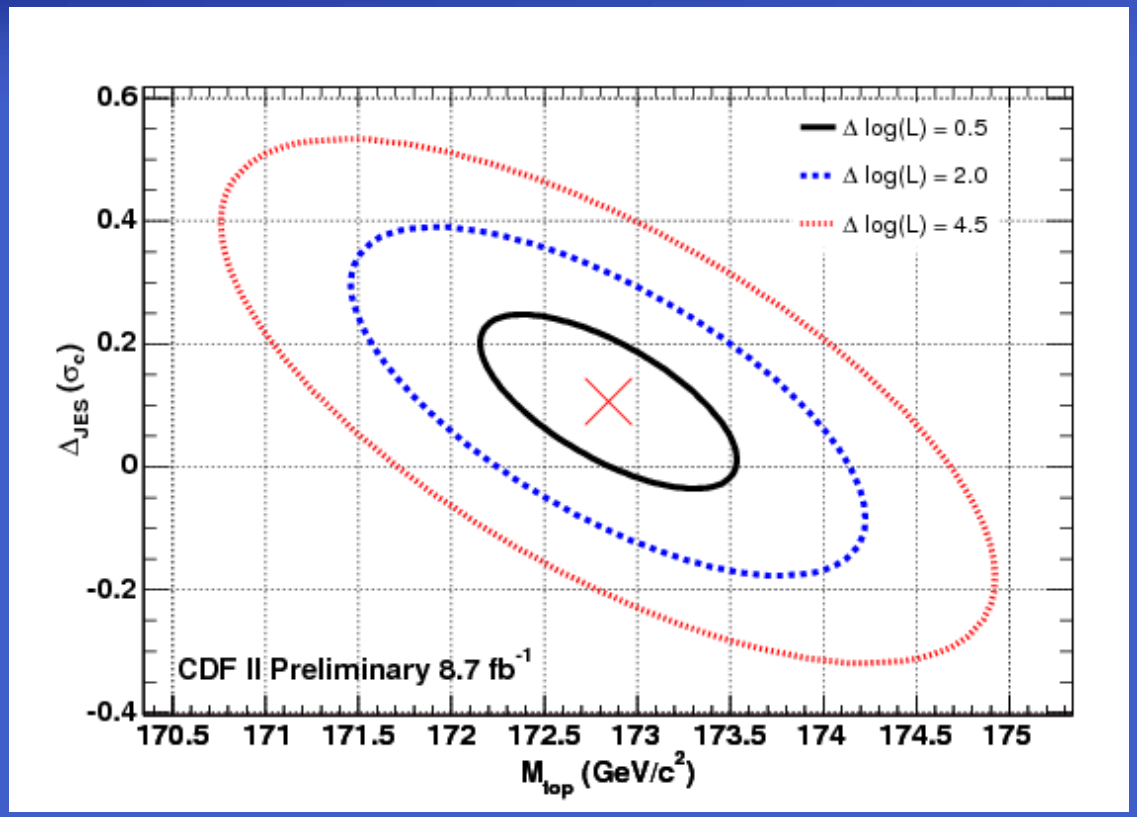
	0-tag	1-tagL	1-tagT	2-tagL	2-tagT
$Wb\bar{b}$	37.6±15.9	54.4±22.6	34.0±14.3	8.5±3.6	6.1±2.6
$Wc\bar{c}$	117.8±46.2	35.7±13.6	22.3±9.0	1.4±0.7	1.2±0.5
Wc	54.2±25.1	19.1±10.0	10.4±5.1	0.8±0.3	0.5±0.2
W+light jets	493.6±111.5	60.5±13.5	35.4±9.0	0.9±0.3	0.6±0.2
Z+jets	52.3±4.4	8.9±1.1	5.9±0.7	0.8±0.1	0.5±0.1
single top	4.9±0.5	10.5±0.9	6.8±0.6	2.2±0.3	1.7±0.2
Diboson	60.3±5.6	11.1±1.4	8.5±1.1	1.0±0.2	0.8±0.1
QCD	143.0±114.4	34.5±12.6	20.7±16.6	4.4±2.5	2.5±2.4
Total	963.5±229.3	234.7±61.1	144.0±40.9	19.9±5.5	13.8±4.2
$t\bar{t}$	644.8±86.3	695.0±86.7	867.3±107.6	192.3±29.7	303.7±46.6
Expected Events	1608.4±245.0	929.8±106.1	1011.3±115.1	212.2±30.2	317.6±46.8
Observed Events	1627	882	997	208	275

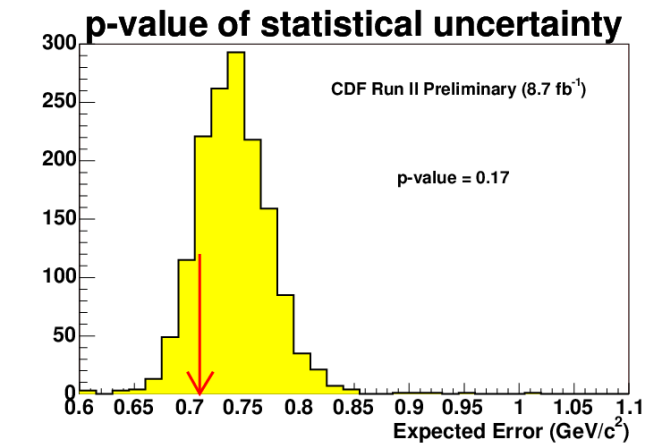
Lepton+Jets: Fit projections



Lepton+Jets: Results

- M_{top} = 172.85 ± 0.71 (stat.+JES) ± 0.84 (syst) GeV/c^2





- Systematic uncertainty dominated by Monte Carlo issues
- Result published: Phys. Rev. Lett. **109**, 152003 (2012)

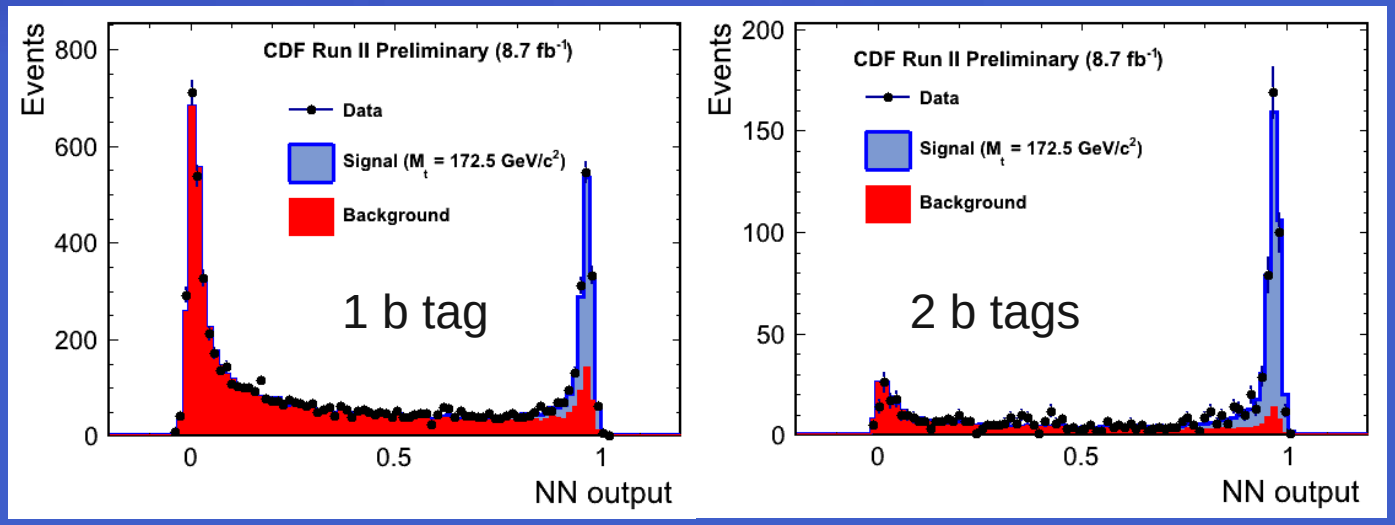
MET+Jets

- Similar Strategy as Lepton+Jets
  - Change: neither neutrino nor lepton is observed
    - Includes muons outside of acceptance, taus
    - Distinct event sample
- Multi-jet trigger sample
  - 4, 5, or 6 jets, 1 or 2 b tags
  - Require missing E_T significance >3 GeV$^{1/2}$.

$$\not{E}_T \Big/ \sqrt{\sum_{Jets} C_{JES}^2 \cos^2(\Delta\phi_{jet,\not{E}_T}) E_{T,jet}^{raw} + \cos^2(\Delta\phi_{uncl,\not{E}_T}) \sum E_{T,uncl}}$$

MET+Jets: Selection

- Neural Net Classifier
  - Data-driven background model



- Good agreement with expectations

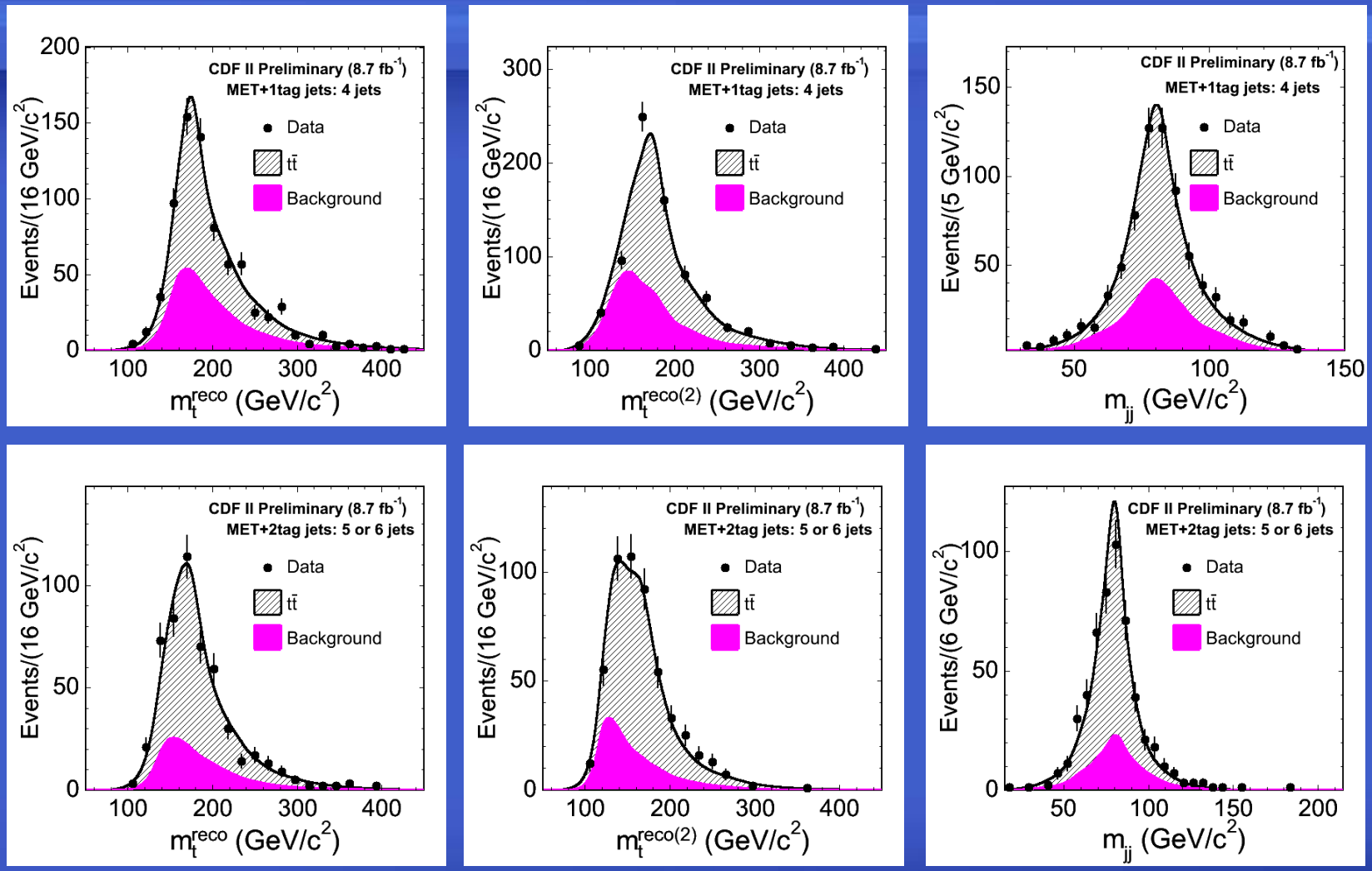
CDF II Preliminary 8.7 fb^{-1}

b-tagging	jet-multiplicity	$t\bar{t}$	Background	Total Expected	Observed
1tag	4 jets	427 ± 50	262 ± 22	690± 55	761
	5 or 6 jets	801±70	450±29	1251 ± 76	1341
2tag	4 jets	179±23	43±11	222 ±26	225
	5 or 6 jets	373 ± 37	125±23	498 ± 44	550

MET+Jets: Template results

4 jets, 1 tag

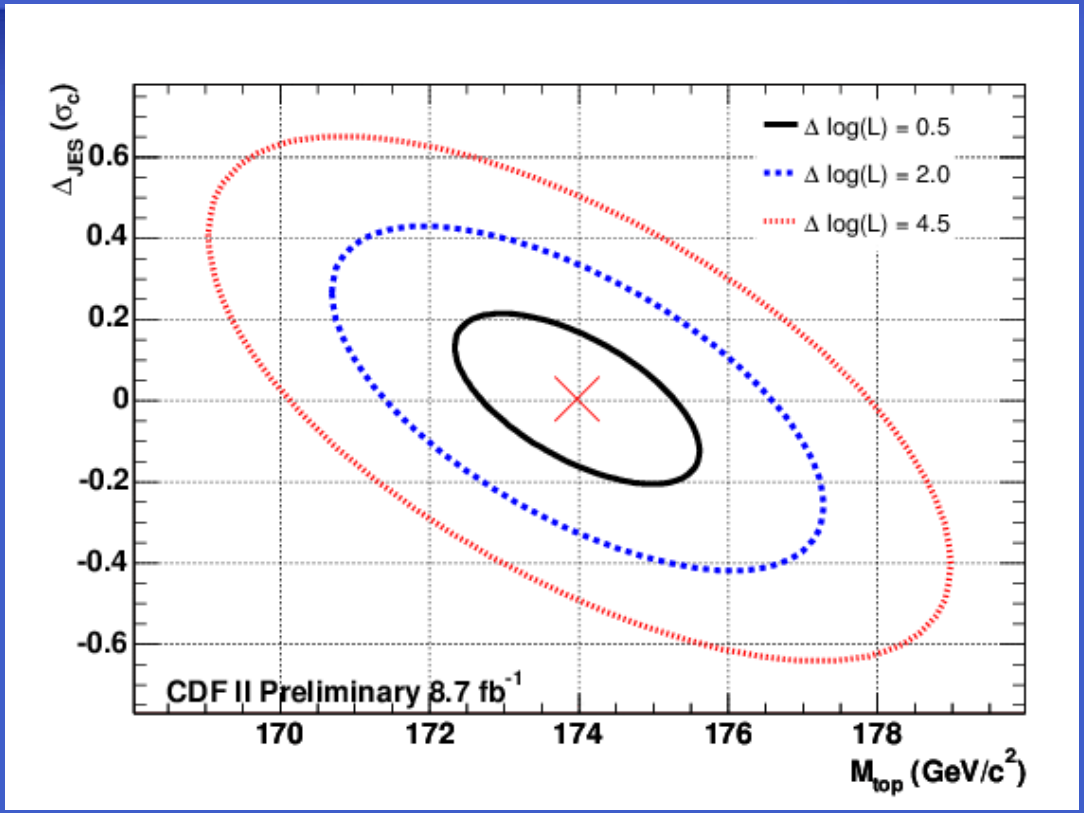
5 or 6 Jets, 2 tags



Cases not shown: 4 jets,2 tags; 5 or 6 jets,1 tag

MET+Jets: Results

- M_{top} = 173.93 ± 1.64 (stat.+JES) ± 0.87 (syst) GeV/c^2

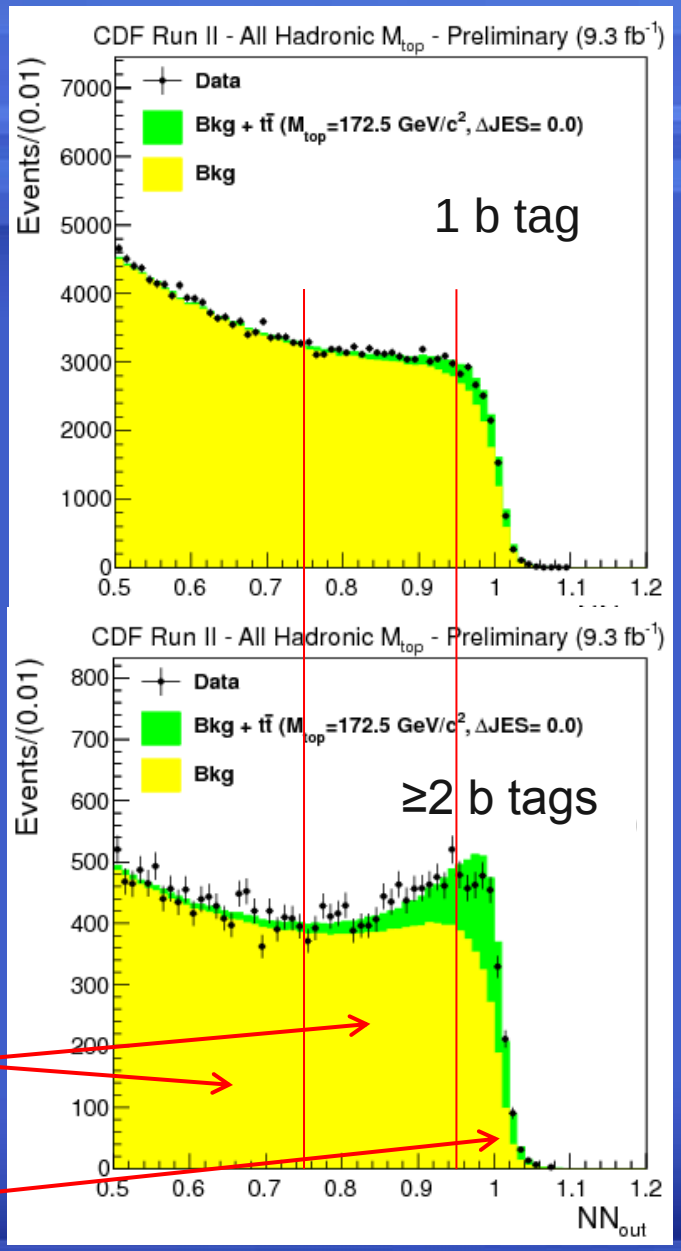


- Systematic uncertainty dominated by Monte Carlo issues
- Result published: Phys. Rev. Lett. **88**, 011101 (2013)

New!

All Hadronic

- Largest branching ratio, but also large backgrounds
- Template Method
- Sample: require at least 6 jets
  - Dedicated trigger
- Neural net classifier
  - Signal from POWHEG,
  - Background from MC with jet mistag rate from data



Control Regions

Signal Region

All Hadronic: Reconstruction

- Kinematic fit to find best candidate jet assignments

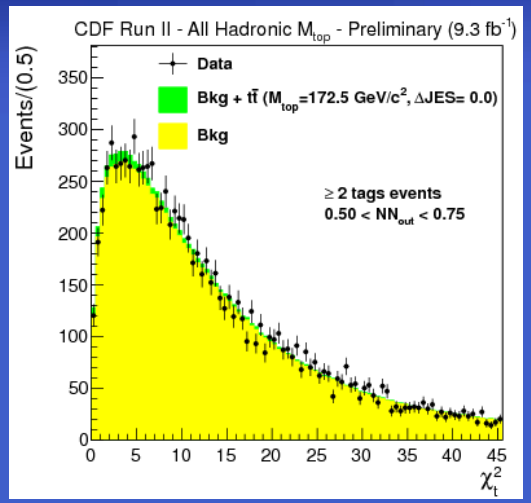
$$\chi^2 = \frac{\left(m_{jj}^{(1)} - M_W\right)^2}{\Gamma_W^2} + \frac{\left(m_{jj}^{(2)} - M_W\right)^2}{\Gamma_W^2} + \frac{\left(m_{jjb}^{(1)} - m_t^{rec}\right)^2}{\Gamma_t^2} + \frac{\left(m_{jjb}^{(2)} - m_t^{rec}\right)^2}{\Gamma_t^2} + \sum_{i=1}^{6} \frac{\left(p_{T,i}^{fit} - p_{T,i}^{meas}\right)^2}{\sigma_i^2}$$

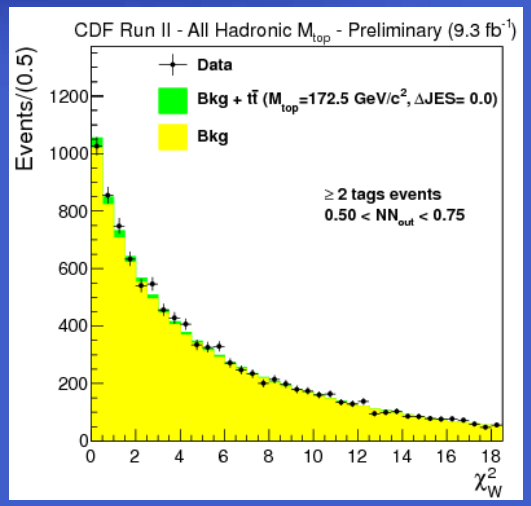
- To derive JES, modify χ^2 to have $m_{jj}^{(1)}=m_{jj}^{(2)}=m_W^{rec}$

Backgrounds

- Example: Low NN region, 2 b tags

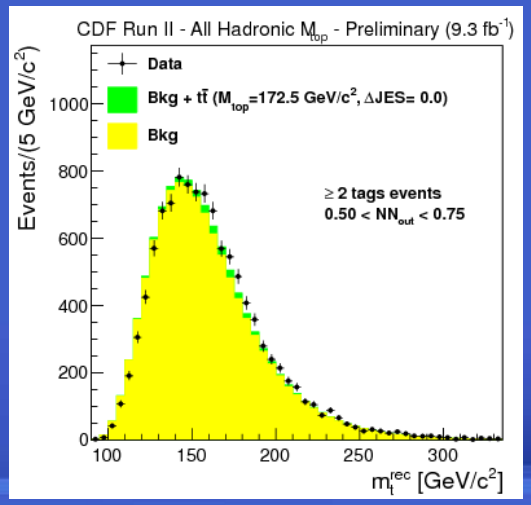
χ_t^2

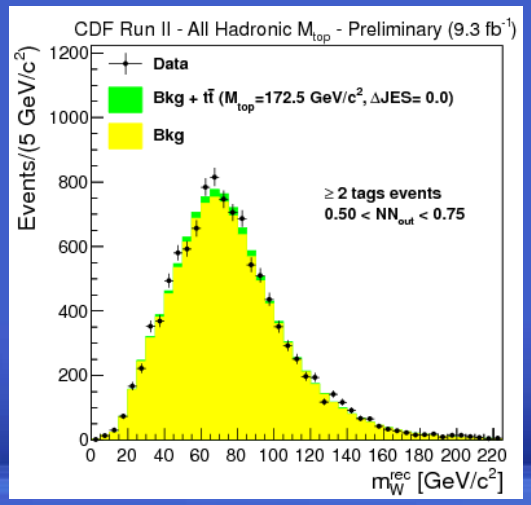




χ_W^2

m_t^{rec}

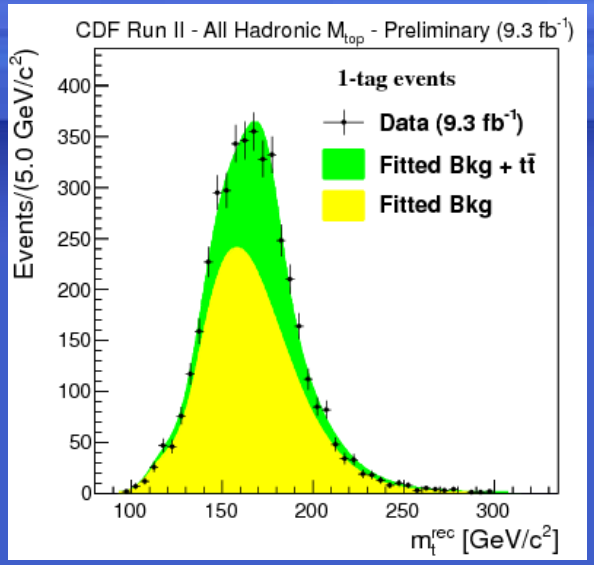


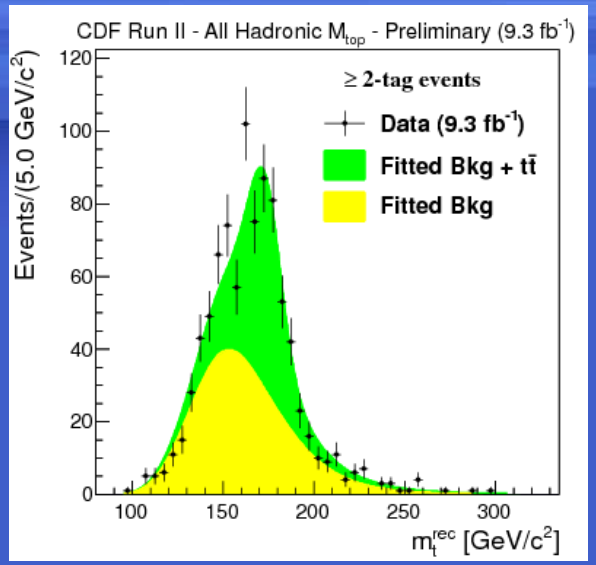


m_W^{rec}

All Hadronic: Template Fit

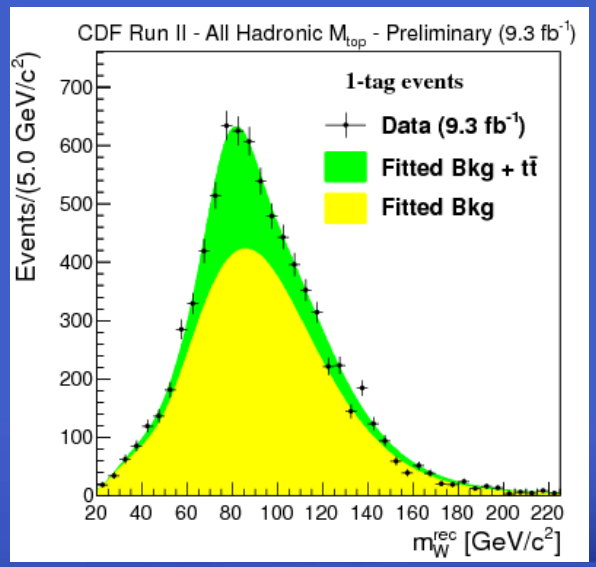
m_t^{rec} 1 tag

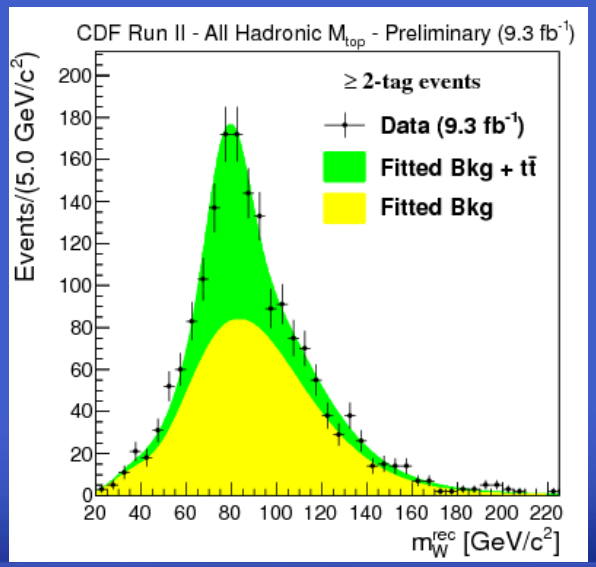




m_t^{rec} ≥2 tags

m_W^{rec} 1 tag

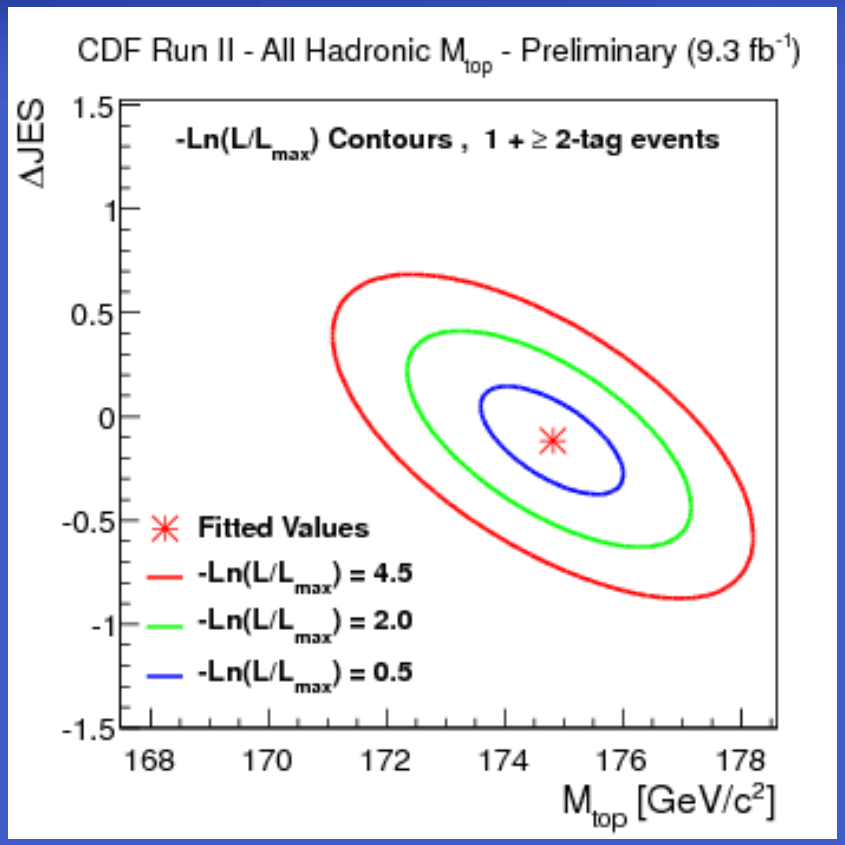


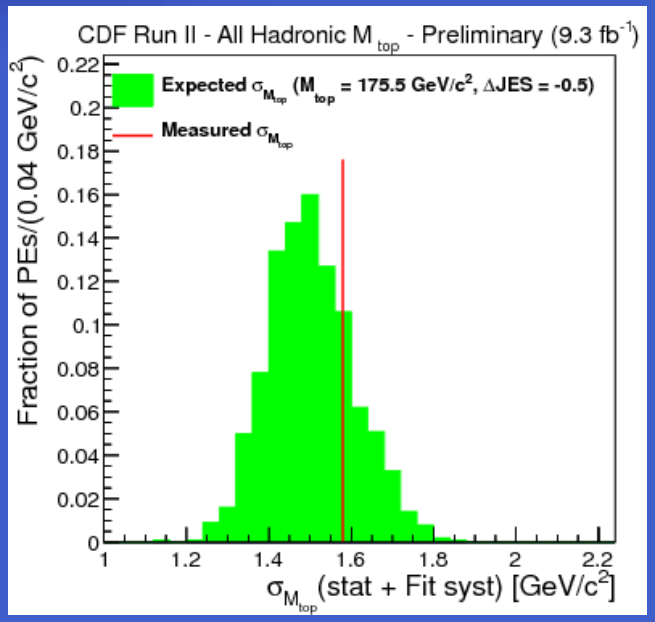


m_W^{rec} ≥2 tags

All Hadronic: Results

- m_t=175.07±1.58(stat+fit)±1.15(syst) GeV/c^2





- Details and public note:

  www-cdf.fnal.gov/physics/new/top/2014/AllHadTopMass/

Dilepton

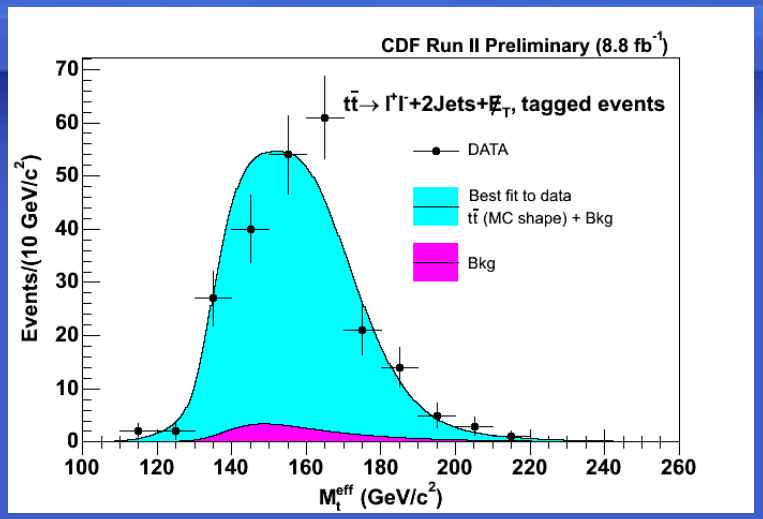
New!

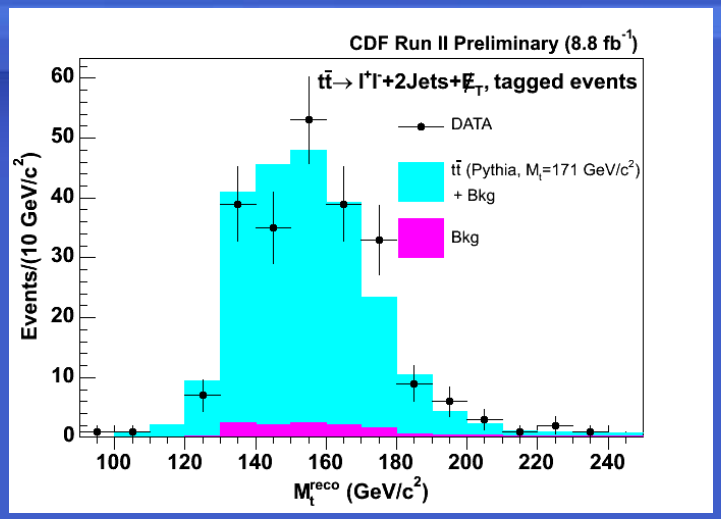
- Template method
  - Sample: two leptons and two jets
- Two variables
  - Kinematic fit for top mass
    - Account for unconstrained event kinematics with scan over the space of possibilities for the azimuthal angles of neutrinos
    - Reconstruct top quark mass by minimizing a χ^2 function in the assumption of the $t\bar{t} \rightarrow$dilepton final state
    - Assign χ^2-dependent weights to the solutions and build a single mass for each event
    - Requires external Jet Energy Scale
  - Alternate mass variable insensitive to jet energies

$$M_t^{alt} = c^2 \sqrt{\frac{(P_{l1} \cdot P_{b1})(P_{l2} \cdot P_{b2})}{E_{b1} E_{b2}}} + 120\,\mathrm{GeV}/c^2$$

Dileptons: Template Fits

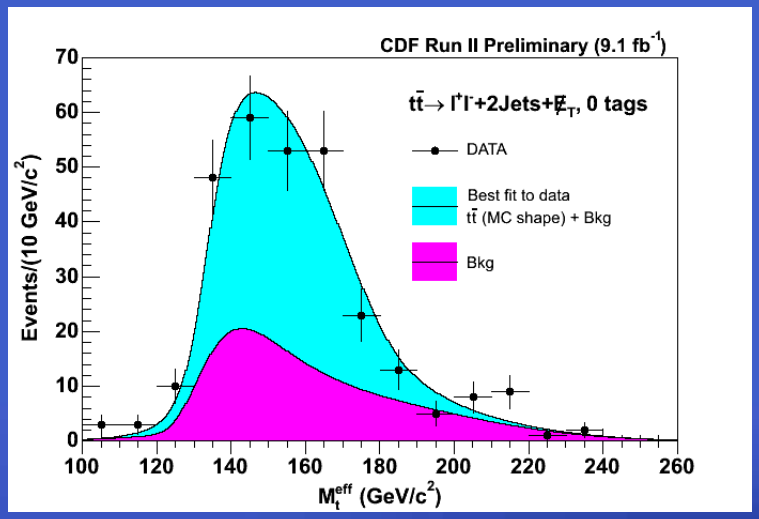
M_t^{eff} tagged

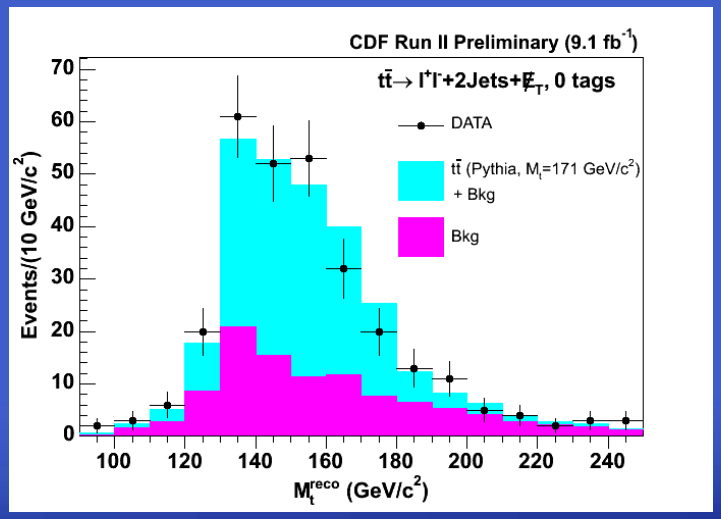




M_t^{alt} tagged

M_t^{eff} no tag

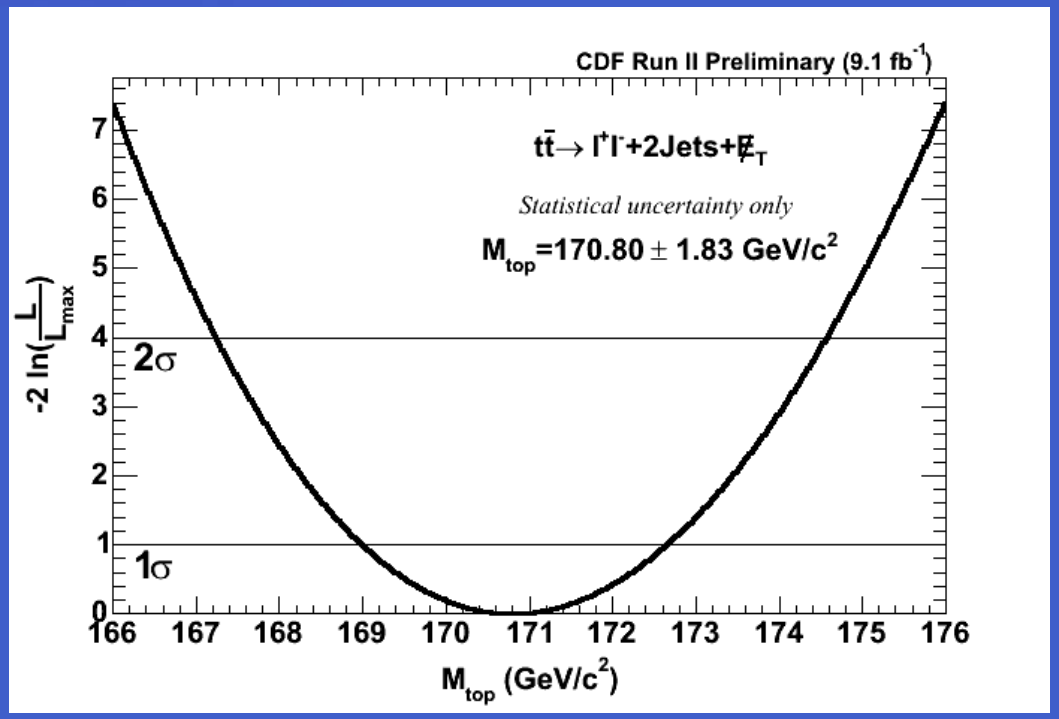


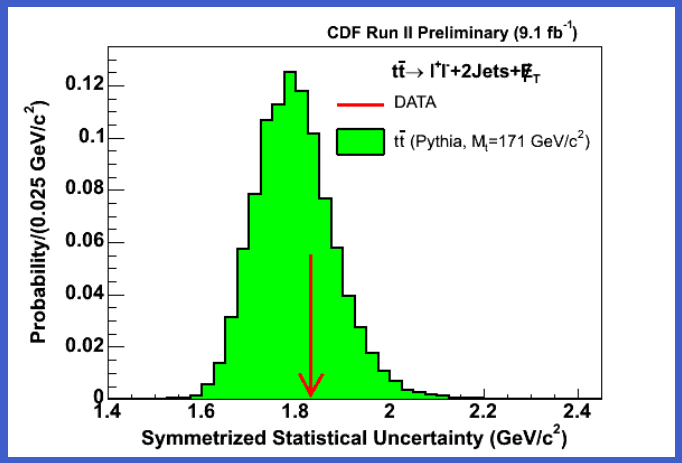


M_t^{alt} no tag

Dilepton: Results

- M_{top} = 170.80 ± 1.83(*stat.*) ± 2.69(*syst.*) GeV/c^2
  - Systematics dominated by JES

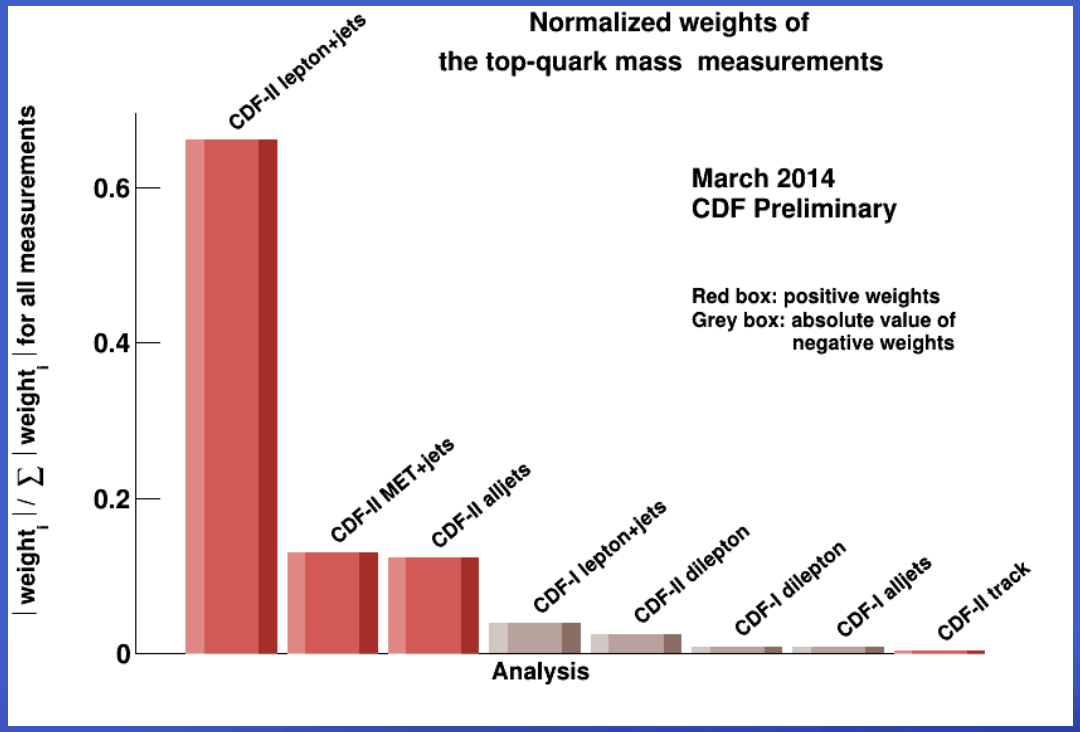




- Details and public note
  - www-cdf.fnal.gov/physics/new/top/2014/mtop_dil

Combination

- Use all CDF Run I and Run II measurements
- Combination dominated by Run II Lepton+Jets, MET+Jets, and All-hadronic measurements



Combination: Systematics

- Account for uncertainty correlations
  - Signal model and JES uncorrelated
  - Detector response from MC fully correlated
    - b tag modelling
    - Out-of-cone and underlying event corrections
    - b jet response variations
    - Multiple interactions

CDF Preliminary
(All uncertainies are in GeV/c^2)

	Run I published			Run II published			Run II preliminary	
	ℓ+jets	$\ell\ell$	alljets	ℓ+jets	Lxy	MET	$\ell\ell$	alljets
$\int \mathcal{L}\, dt$ [fb^{-1}]	0.1	0.1	0.1	8.7	1.9	8.7	9.0	9.3
Top-quark mass [GeV/c^2]	176.1	167.4	186.0	172.85	166.90	173.93	170.80	175.07
In situ light-jet calibration (iJES)	n/a	n/a	n/a	0.49	n/a	1.05	n/a	0.97
Response to $b/q/g$ jets (aJES)	n/a	n/a	n/a	0.09	n/a	0.10	0.18	0.02
Model for b jets (bJES)	0.6	0.8	0.6	0.16	n/a	0.17	0.28	0.20
Out-of-cone correction (cJES)	2.7	2.6	3.0	0.21	0.36	0.18	1.65	0.37
Light-jet response (2) (dJES)	0.7	0.6	0.3	0.07	0.06	0.04	0.46	0.09
Light-jet response (1) (rJES)	3.4	2.7	4.0	0.48	0.24	0.40	1.72	0.42
Lepton modeling (LepPt)	n/e	n/e	n/e	0.03	n/a	n/a	0.36	n/a
Signal modeling (Signal)	2.6	2.9	2.0	0.61	0.90	0.63	0.96	0.53
b-tag modeling (btag)	0.0	0.4	0.0	0.03	0.0	0.03	0.05	0.04
Background from theory (BGMC)	1.3	0.3	1.7	0.12	0.80	0.00	0.03	0.00
Background based on data (BGData)	0.0	0.0	0.0	0.16	0.20	0.15	0.35	0.15
Calibration method (Method)	0.0	0.7	0.6	0.05	2.50	0.21	0.19	0.87
Multiple interactions model (MHI)	n/e	n/e	n/e	0.07	0.00	0.18	0.30	0.22
Systematic uncertainty (Syst)	5.3	4.9	5.7	0.98	2.90	1.35	2.69	1.56
Statistical uncertainty (Stat)	5.1	10.3	10.0	0.52	9.00	1.26	1.83	1.19
Top-quark mass uncertainty	7.3	11.4	11.5	1.11	9.46	1.85	3.25	1.96

Combination: Result

- CDF final result:

$$M_{top} = 173.16 \pm 0.57\ (stat) \pm 0.74\ (syst)\ GeV/c^2$$

- Details
  - Method: Phys. Rev. D 86, 092003 (2012)
  - Current result:
    - www-cdf.fnal.gov/physics/new/top/2014/CDFTopCombo/

Conclusions

- CDF Run 2 target was 1% resolution
- Run 2 achievement is 0.5%
  - Major improvement from in situ jet energy scale
  - Also advanced other techniques
- Dominant uncertainties now from Monte Carlos
- It has been 25 years of fun
  - Good luck LHC!