Top Quark Mass Measurement at CDF and Tevatron Combination

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On behalf of the CDF Collaboration

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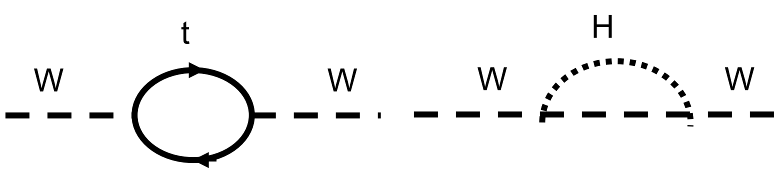
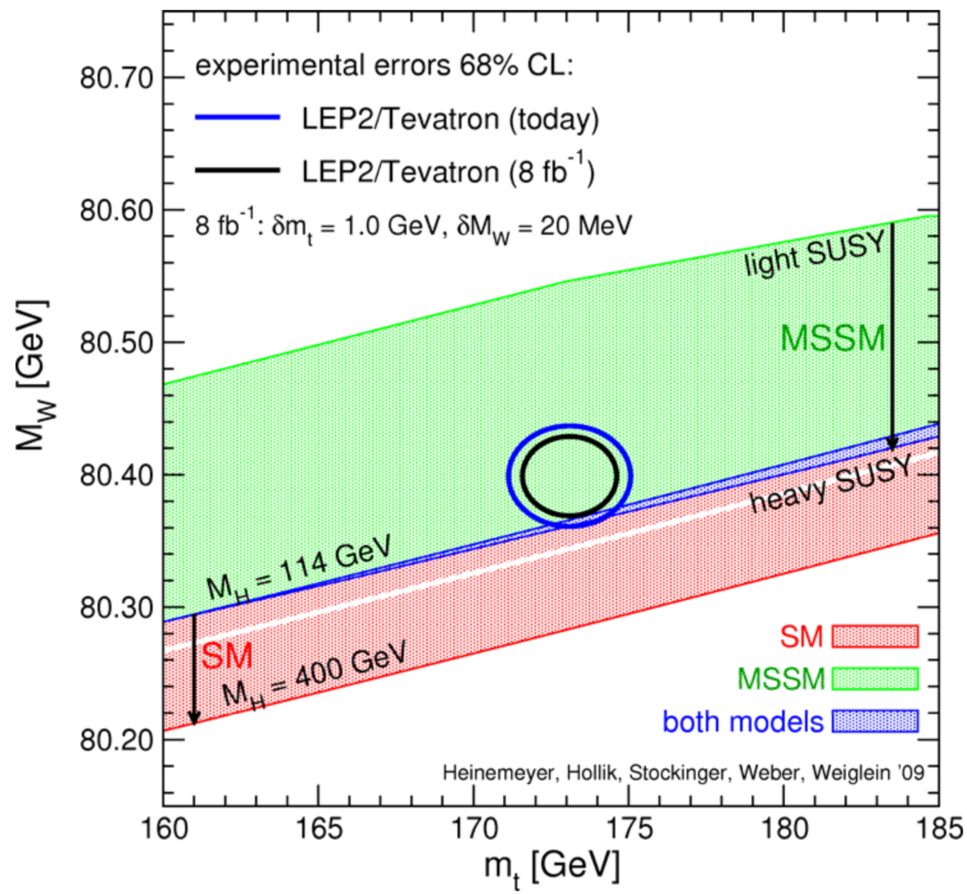
Why measure m_t?

- Top mass, m_t, is fundamental parameter of Standard Model
- Electroweak mass corrections $\propto m_t^2$ and $\ln(m_H)$



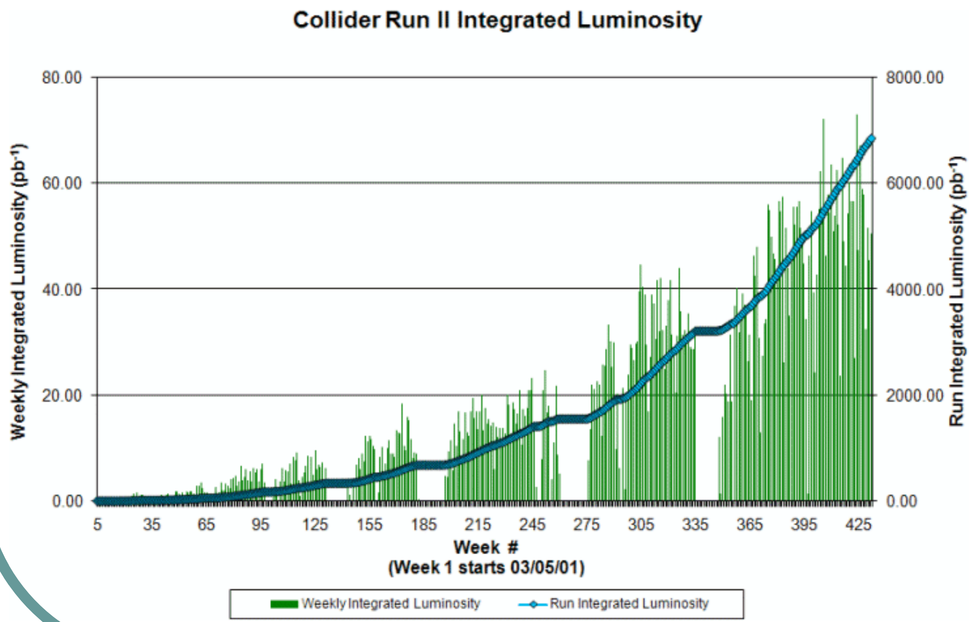
$\delta m_W \propto m_t^2$ $\delta m_W \propto \ln(m_H)$

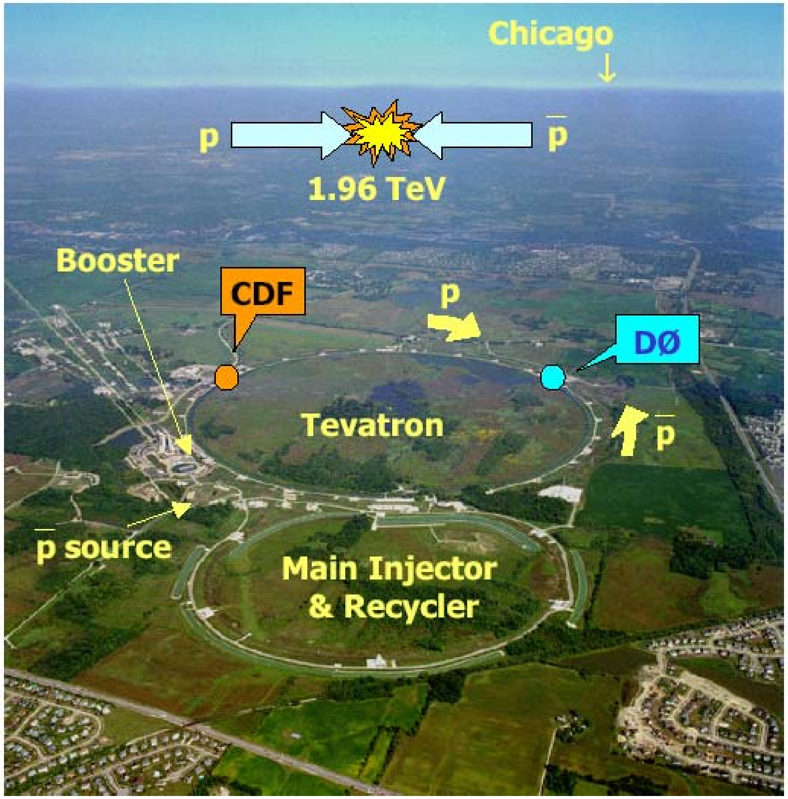
- Precision measurements of m_W and m_t give constraints on SM m_H
  - consistency test of the SM
  - new physics?



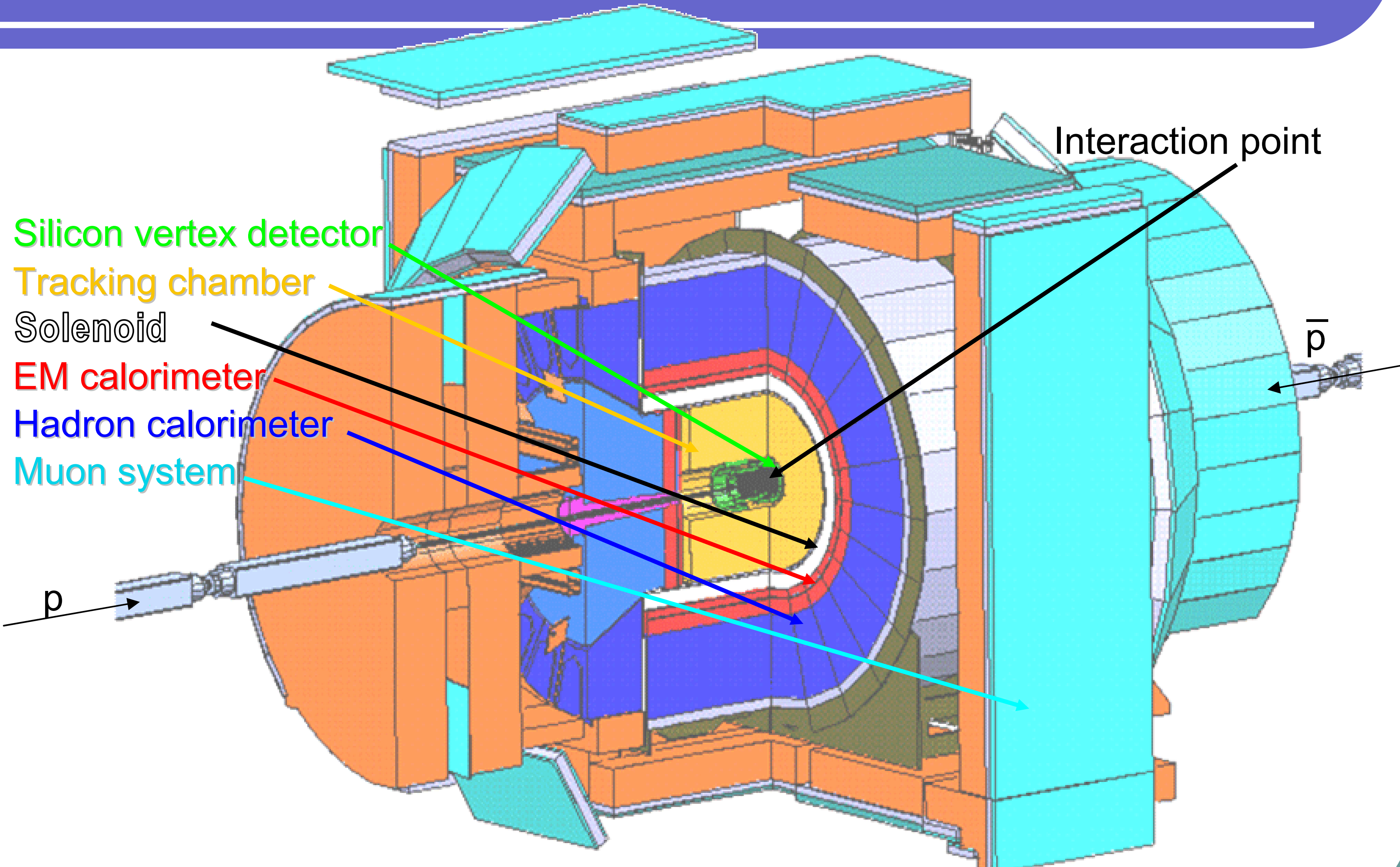
Tevatron

- Top quark produced only at Tevatron (discovered 1995)
- $p\overline{p}$ collisions at 1.96 TeV
- Peak lumi ~3.5×10^{32} cm^2 s^{-1}
- ~6 fb^{-1} delivered to tape
- Analyses here use up to 3.2 fb^{-1}



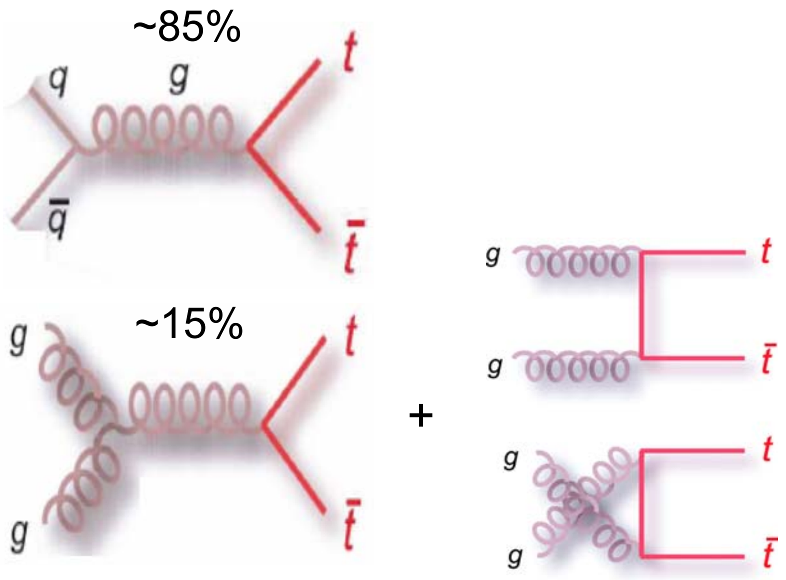


CDF detector

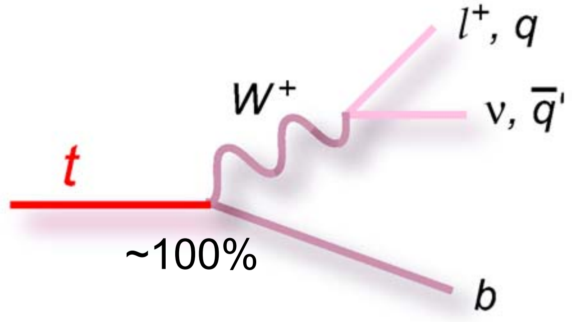


Top quark

- Dominantly produced in pairs (strong interaction)
- t decays before it can hadronize
- Mass can be directly measured from daughter particles
- Dominant decay $t \to Wb$ with $W \to qq$ or $W \to \ell\nu$
- Measurement uses pair events so three possible scenarios:

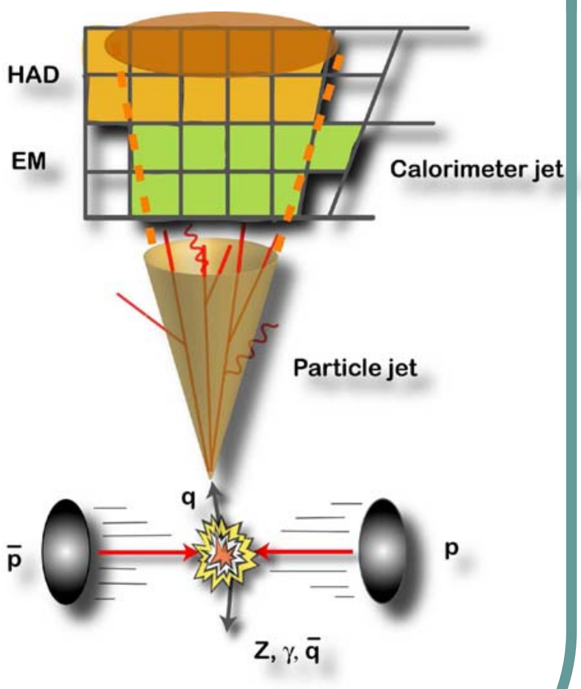


Channel	Branching Ratio
dilepton	11%
lepton+jets	44%
all hadronic	44%



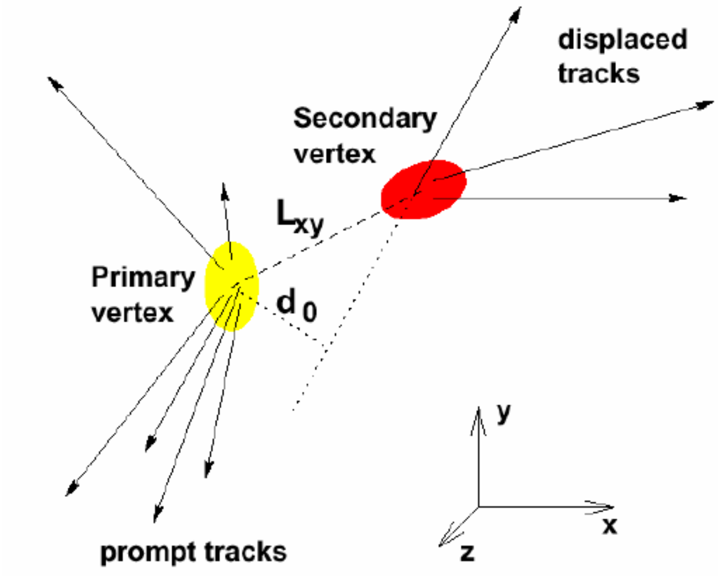
Measurement challenges

- **Top events rare**: $\sigma_{t\bar{t}} / \sigma_{p\bar{p}} \simeq 10^{-10}$, **event selection** important
- **Background processes** can mimic $t\bar{t}$, contaminate sample
- **Combinatorics**: Detector can ID e,μ, but which jets came from which parton?
- **Neutrinos not detected**: missing kinematic information
- **Jet reconstruction**
  - Measurement requires knowledge of quark momenta
  - Large jet energy scale (JES) uncertainties in jet reconstruction (right)
- Define Δ_{JES} = JES correction
  - Δ_{JES} constrained via invariant mass of jets from W boson
  - Measure Δ_{JES} simultaneously
  - Large systematic JES uncertainty replaced by smaller statistical Δ_{JES} uncertainty



Event selection

- Use Secondary Vertex b-tagging to identify b-jets
  - reduces # jet-parton assigments and reduces background fraction
- Event selection tuned to the decay signatures of the 3 channels
- Typical event selection criteria:



All hadronic

- No lepton
- Little missing E_T
- ≥ 6 jets E_T>15
- ≥ 1 b-tag

Lepton+jets

- e or μ, E_T>20
- Missing E_T
- 4 jets E_T>20
- ≥ 1 b-tag

Dilepton

- 2 leptons (e or μ)
- Missing E_T
- ≥ 2 jets E_T>15
- ≥ 1 b-tag

- Often use additional Neural Net event selection to minimise background fraction while maintaining signal efficiency

Methods: overview

Template Methods

- Choose observable(s) X sensitive to m_t
- Create 'templates', **simulated** distributions of X for different true m_t
- Simulated distributions from **M**onte **C**arlo events for predicted signal and background processes
- Measurement based on which m_t template(s) gives best fit to observed data
- Few assumptions

Matrix Element (ME) Methods

- Calculate m_t-dependent p.d.f. for each event i with observables $\vec{x}_i$

$$P_i(\vec{x}_i) = \frac{1}{N}\int \mathrm{TF}\left(\vec{x}_i \mid \vec{y}_i\right) d\sigma\left(\vec{y}_i\right)$$

- LO differential $p\bar{p} \to t\bar{t}$ x-section $d\sigma \propto |\mathcal{M}|^2$
  - $|\mathcal{M}|^2$ sensitive to m_t
- **T**ransfer **F**unction maps measured quantities $\vec{x}_i$ to parton-level quantities $\vec{y}_i$
- m_t from maximisation of the joint likelihood

$$L\left(\mathbf{x} \mid m_t\right) = \prod_{\text{events}} P_i\left(\vec{x}_i \mid m_t\right)$$

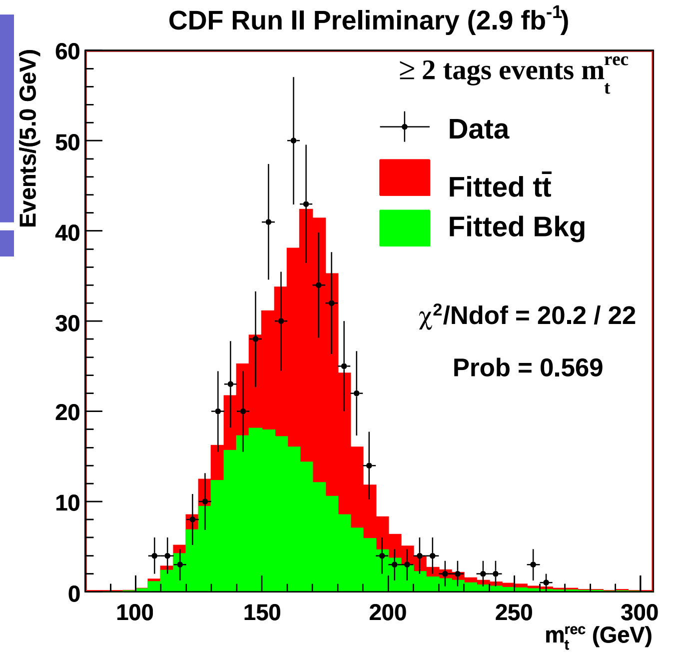
- Better statistical precision achieved by extracting more information from each event

All-hadronic, Template

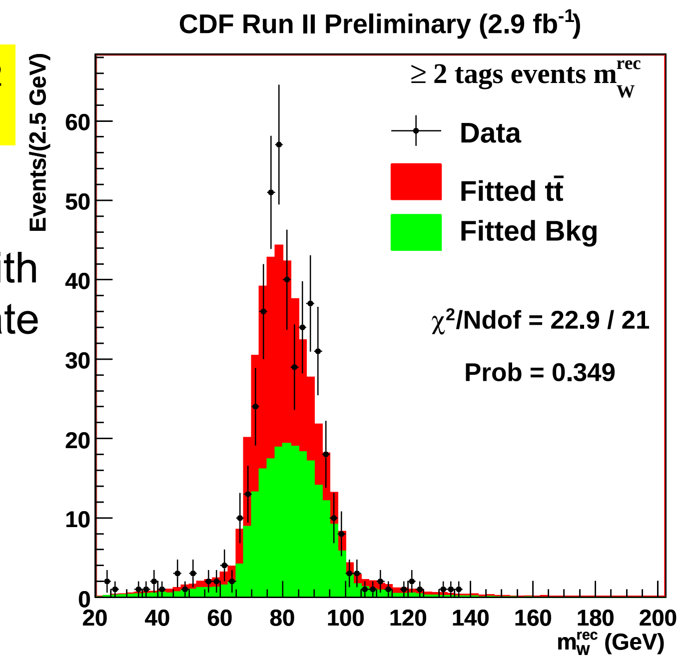
- Large QCD multi-jet background
- Jet-parton assignment from permutation with lowest χ^2 (kinematic fitter)
- Calculate invariant masses m_t^{reco}, m_W^{reco}
  - In-situ JES calibration via m_W
- Construct m_t & Δ_{JES} dependent templates from fit to MC signal and background events
- Measurement with 2.9 fb^{-1}; stat. dominated

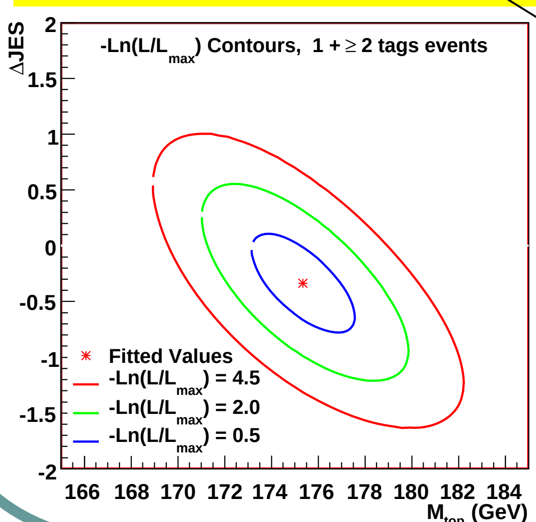
$$m_t = 174.8 \pm 2.4\ (\text{stat} + \text{JES})\ {}^{+1.2}_{-1.0}\ (\text{syst})\ \text{GeV/c}^2$$

1.7 1.6



m_t^{reco} data with fitted m_t template





m_W^{reco} data with fitted Δ_{JES} template

Log-Likelihood contours based on best fit to data

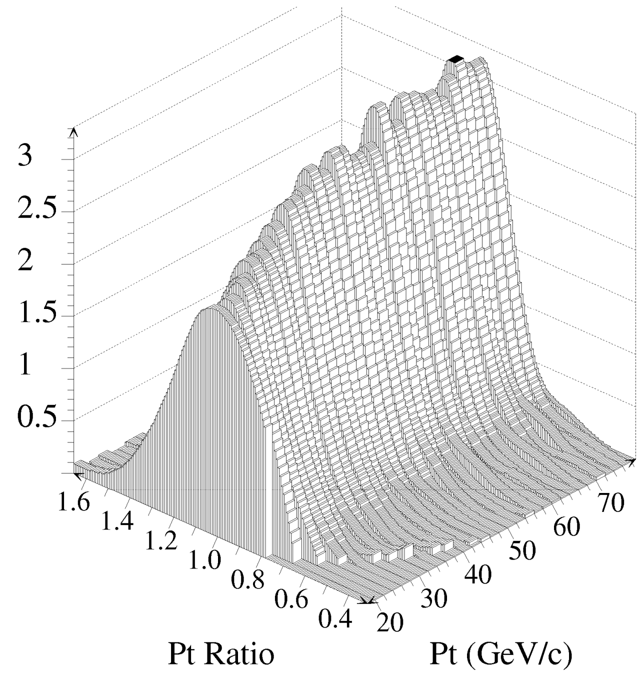
Lepton+jets, Matrix Element

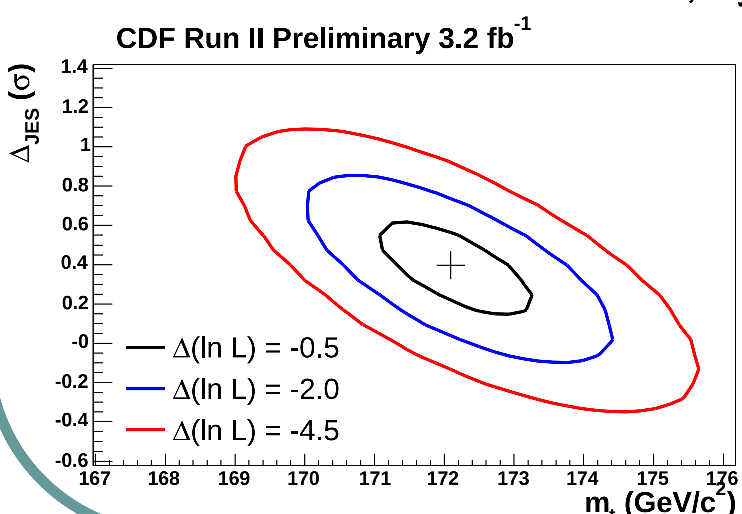
- W+4 jets, QCD multi-jet backgrounds
- Sum jet-parton permutations in each event
  - perm. weight w_j based on b-tagging info

$$P_i(\vec{x}_i \mid m_t, \Delta_{\rm JES}) = \frac{1}{N} \sum_{perm} w_j \int {\rm TF}(\vec{x}_i \mid \vec{y}_i, \Delta_{\rm JES})\, d\sigma(\vec{y}_i)$$

- neutrino p_z unconstrained: $d\sigma$ includes dp_z^{ν}
- Include $\Delta_{\rm JES}$ dependence in ${\rm TF}(\vec{x}_i \mid \vec{y}_i, \Delta_{\rm JES})$ for simultaneous measurement
- Measurement with 3.2 fb^{-1}; syst. dominated

Jet P$_T$ Transfer Function





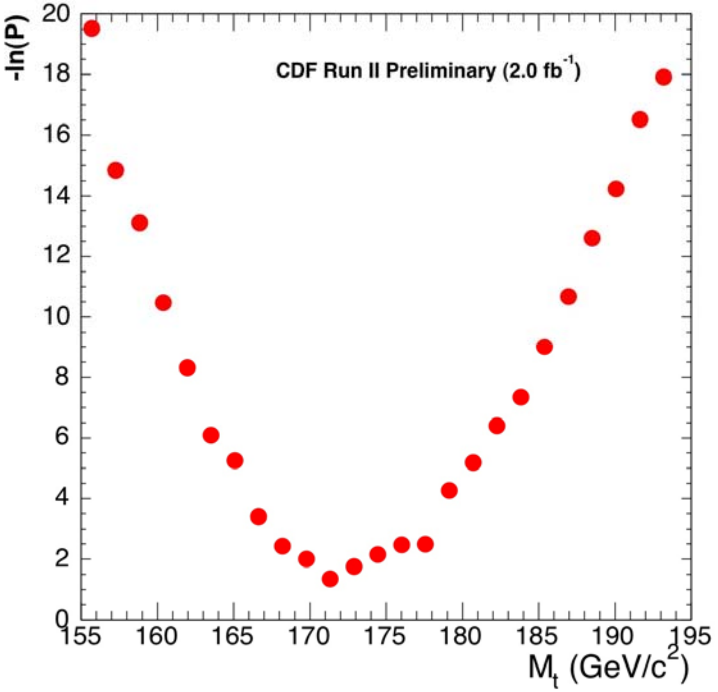
$$L(\mathbf{x} \mid m_t, \Delta_{\rm JES}) = \prod_{\rm events} P_i(\vec{x}_i \mid m_t, \Delta_{\rm JES})$$

$$m_t = 172.1 \pm 1.1({\rm stat + JES}) \pm 1.1({\rm syst})\ {\rm GeV/c^2}$$

0.9 0.7

Dilepton, Matrix Element

- Dominant background Drell-Yan: $Z \rightarrow e^+e^-$, $Z \rightarrow \mu^+\mu^-$
  Also W+jets with 'fake' lepton
- Two neutrinos: underconstrained kinematics
  - Integrate over unknowns (no additional assumptions, ME method strength)
- No in-situ JES calibration (no hadronic W decay)
- Measurement with 2.0 fb^{-1} data



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

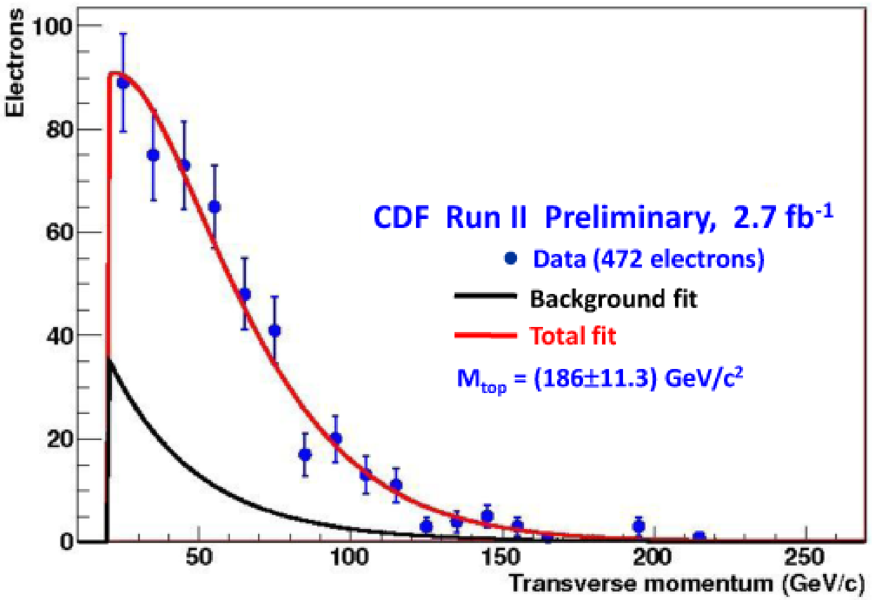
$$L(\mathbf{x} \mid m_t) = \prod_{\text{events}} P_i(\vec{x}_i \mid m_t)$$

2.5 GeV/c^2 from JES uncertainty

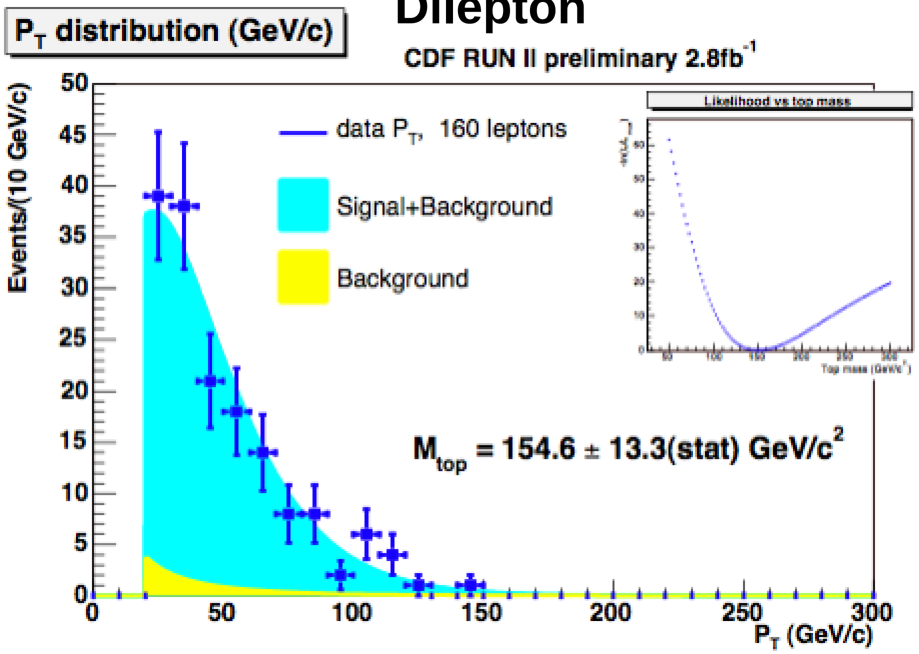
Lepton p_T, Template

- Template method using lepton transverse momentum (p_T)
  - minimal JES dependence (only affects event selection)

Lepton+jets



Dilepton



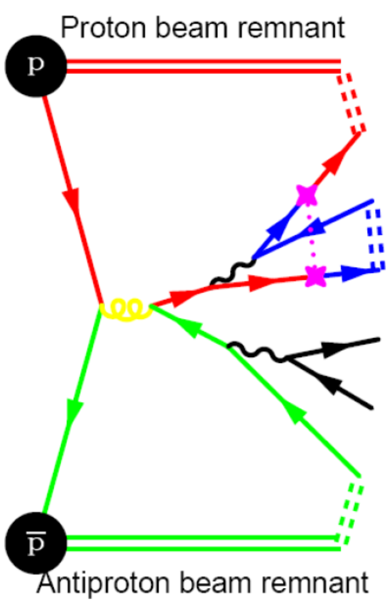
$m_t = 172.1 \pm 7.9(\text{stat}) \pm 3.0(\text{syst})\ \text{GeV/c}^2$

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

- Little correlation with conventional measurements: improve world average m_t
- Limited by statistics. Low systematics so will become competitive at LHC.

Systematic uncertainties

- Overall uncertainty on m_t dominated by systematics
- Continually working on improvements
  - May be some double counting
  - Colour reconnection recently added
  - Some effects only roughly described (eg colour reconnection)



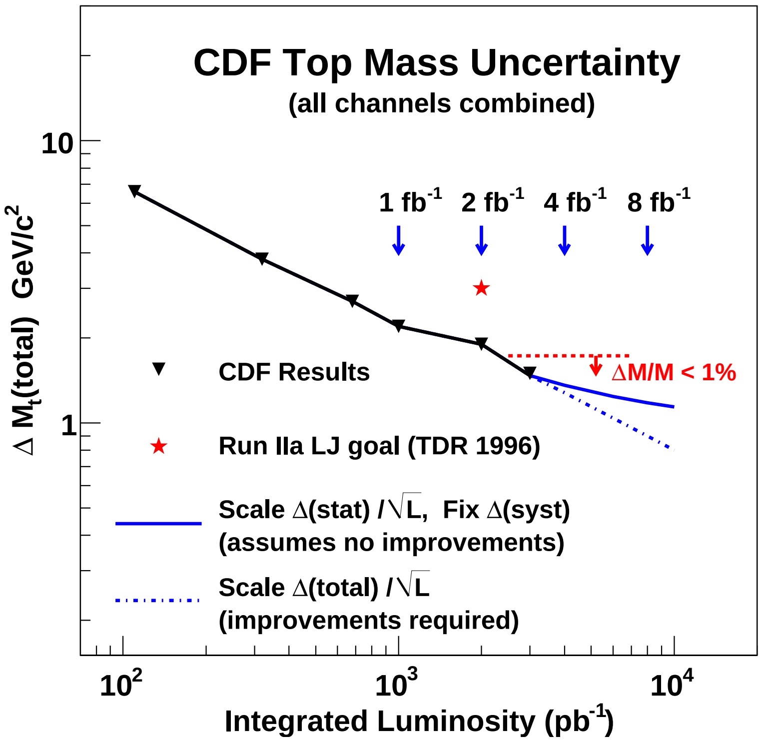
When hadronisation regions of b-jet and a W jet overlap, colour reconnection can affect measured m_W and m_t

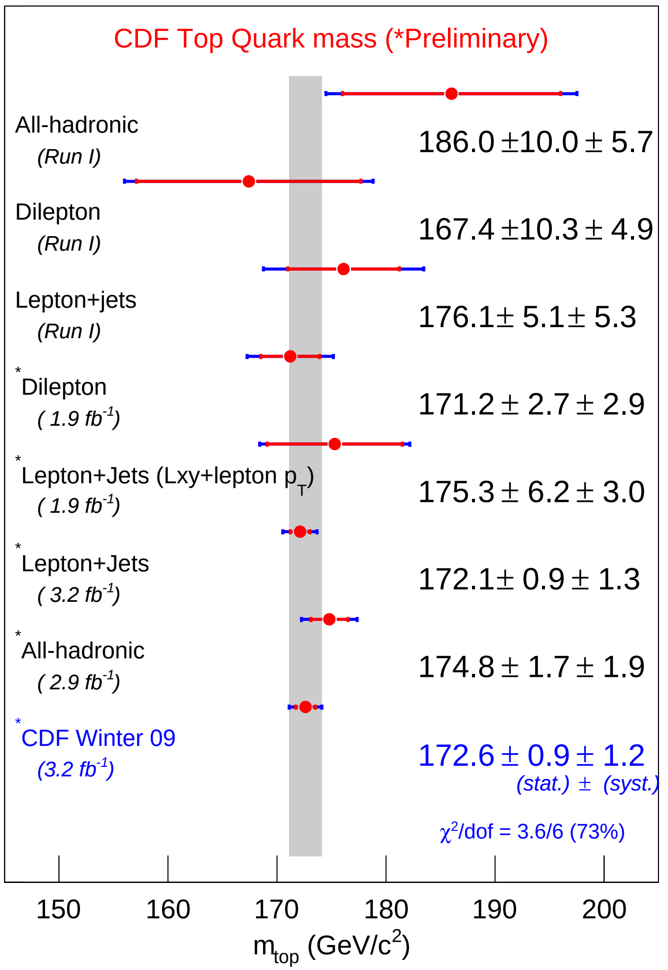
Example systematic uncertainties

Systematic source (Lepton+jets, ME)	**Systematic uncertainty (GeV/c^2)**
MC generator	0.5
Background	0.5
Residual JES	0.5
b-jet JES	0.4
Colour reconnection	0.4
ISR and FSR	0.3
Lepton P_T uncertainty	0.2
PDFs	0.2
Method calibration	0.2
Multiple hadron interactions	0.1
Total	**1.1**

CDF combination

- Combine best measurements from each channel, taking correlations into account
- Run IIa goal easily surpassed





$$m_t = 172.6 \pm 0.9\ (\text{stat}) \pm 1.2\ (\text{syst})\ \text{GeV/c}^2$$

Includes JES

Tevatron combination

- Combine CDF and DØ measurements, taking correlations into account

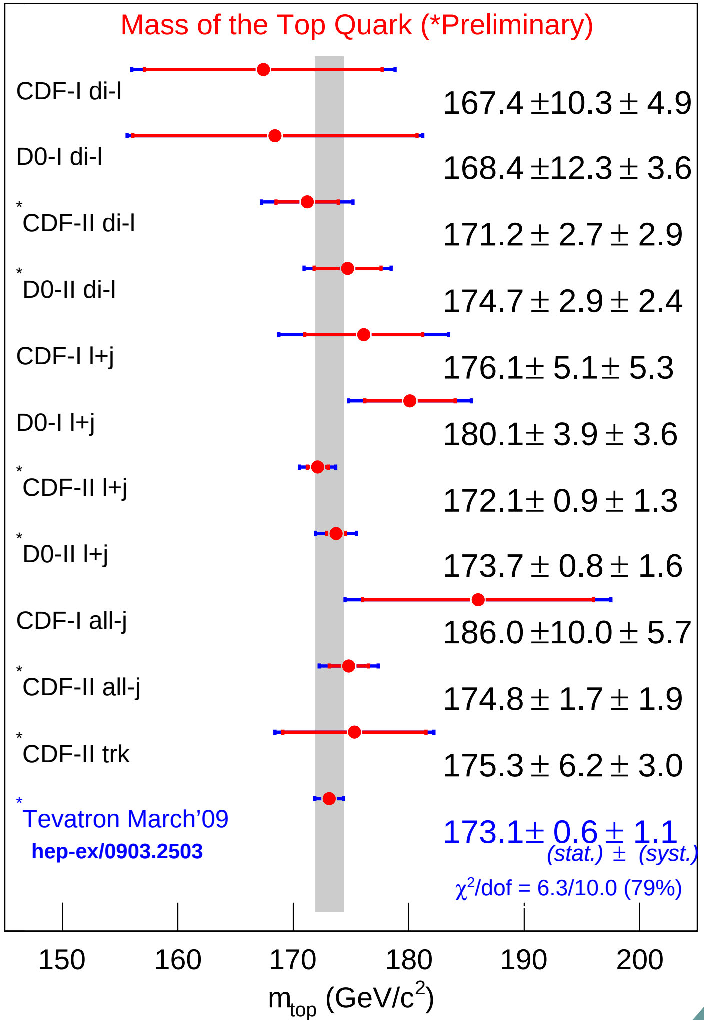
Parameter	Value (GeV/c^2)	Correlations		
$M_t^{\mathrm{all-j}}$	175.1 ± 2.6	1.00		
$M_t^{\mathrm{l+j}}$	172.7 ± 1.3	0.20	1.00	
$M_t^{\mathrm{di-l}}$	171.4 ± 2.7	0.19	0.50	1.00

- Results are all consistent (χ^2 prob 79%)

$$m_t = 173.12 \pm 0.65\ (\mathrm{stat}) \pm 1.07\ (\mathrm{syst})\ \mathrm{GeV/c^2}$$

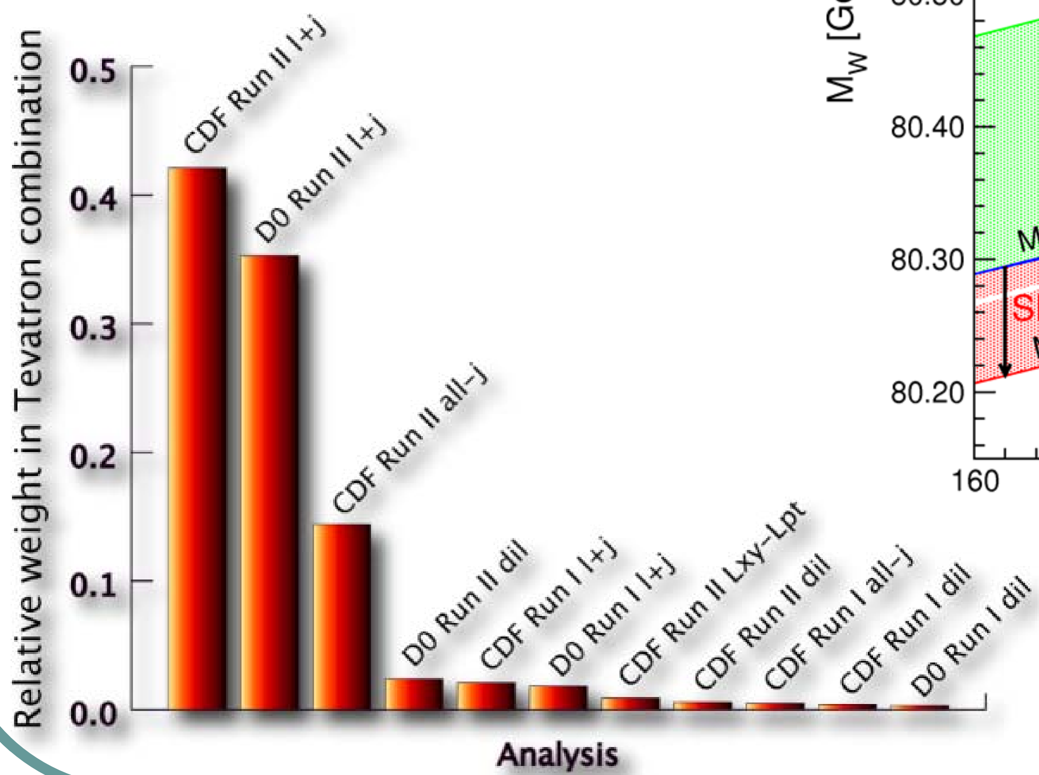
$$m_t = 173.12 \pm 1.25\ (\mathrm{total})\ \mathrm{GeV/c^2}$$

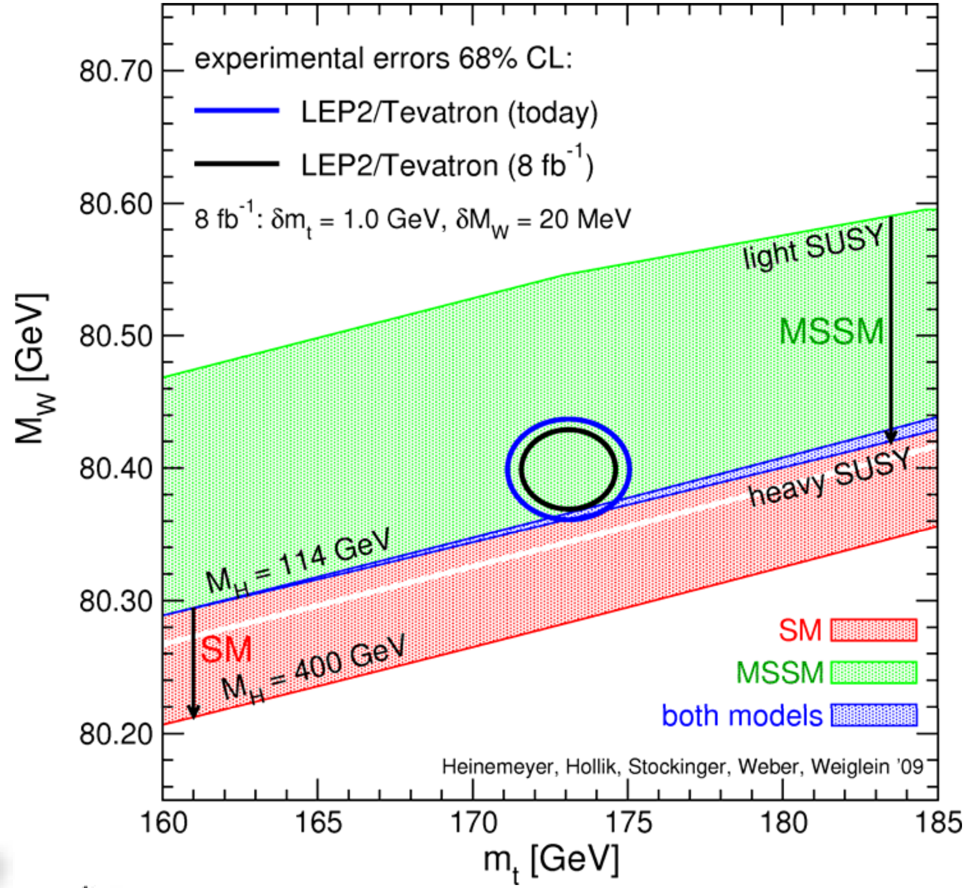
- m_t known within 0.7%
- Total uncertainty approaching 1 GeV/c^2



Tevatron combination

- Lepton+jets measurements dominate world average
- SM could be excluded @ 68% CL with 8 fb^{-1}





For more see

www-cdf.fnal.gov

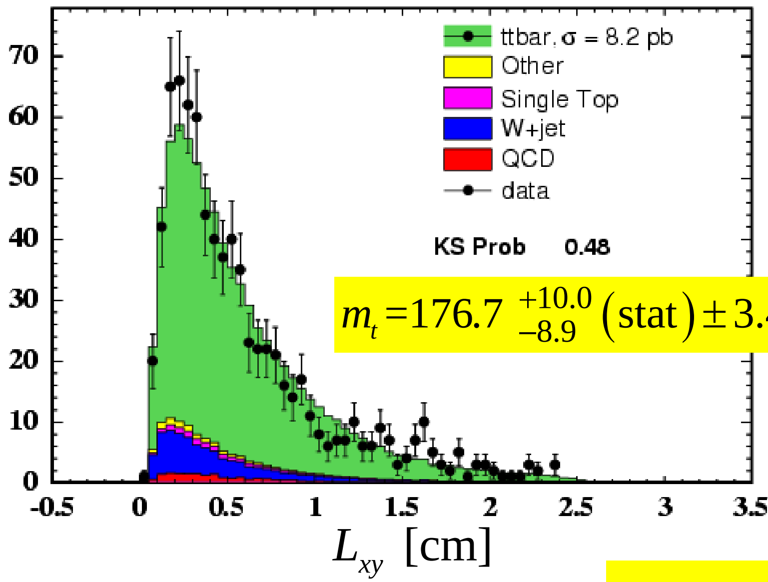
www-d0.fnal.gov

Backup

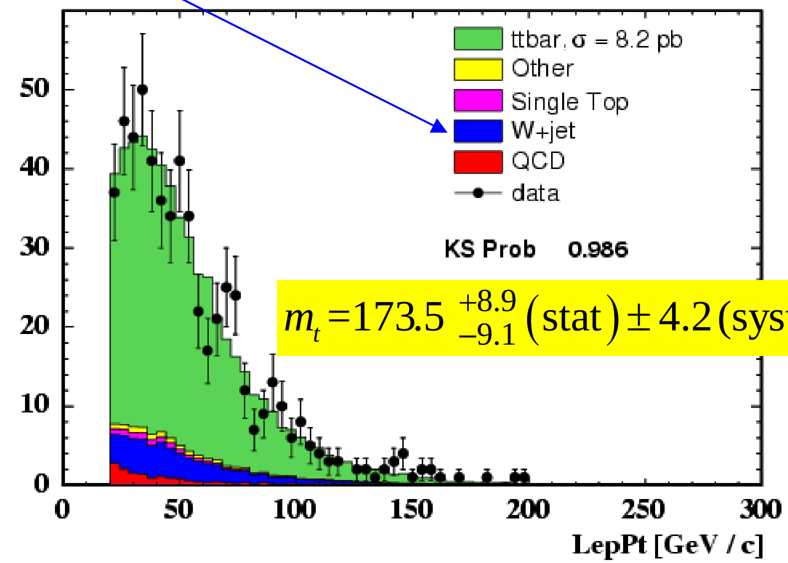
L_{xy} and Lepton p_T (lepton+jets)

- Template method using quantities with minimal JES dependence
  - **L_{xy}**: transverse decay length of b-tagged jets (SecVtx)
  - **Lepton p_T**: transverse momentum of the lepton

  approx uncorrelated: combine measurements for improved precision
- Signal:Background ~5:1 W+jets dominant background



$m_t = 176.7 \, ^{+10.0}_{-8.9}\,(\text{stat}) \pm 3.4\,(\text{syst})$



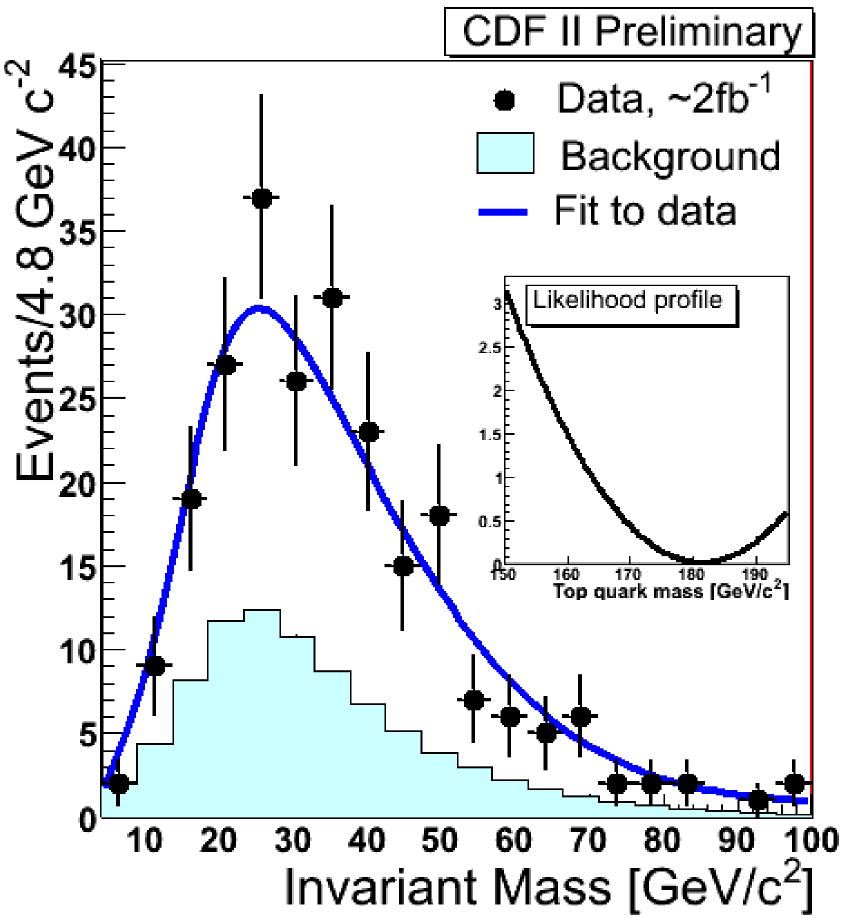
$m_t = 173.5 \, ^{+8.9}_{-9.1}\,(\text{stat}) \pm 4.2\,(\text{syst})$

Combined result: $m_t = 175.3 \pm 6.2\,(\text{stat}) \pm 3.0\,(\text{syst})\ \text{GeV}/c^2$

- Little correlation with lepton+jets ME measurement: improves world average m_t
- Limited by statistics. No longer an issue at LHC & could become competitive.

Soft muon tagger, template

- Take lepton+jets events with semi-leptonic decay of one b-quark to a muon
  - "soft muon tag"
- Template based on invariant mass between the lepton from the W decay, and the muon from the b-quark decay
- Independent of JES
- Signal:Background ~2:1
  - W+jets dominant background
- Measurement with 2.0 fb^{-1}, 240 events
  - Stat dominated, useful at LHC



$$m_t = 181.3 \pm 12.4\ (\text{stat}) \pm 3.5\ (\text{syst})\ \text{GeV/c}^2$$

systematics

MC Generator	Method is calibrated using signal MC from Pythia generator. Systematic taken as difference in result between Pythia and the Herwig generator.
Residual JES	Systematics associated with each level of the JES jet corrections, summed in quadrature
Colour Reconnection	Difference between two Pythia MC samples, tune Apro (no CR) and tune ACRpro (includes CR)
b-jet Energy	b jet energies varied by ± 1% in MC
Background	Vary background composition and fraction
ISR/FSR	Difference in result in MC with more or less I&FSR
Multiple Hadron Interaction	Systematic associated with mismodelling of luminosity profile in MC
PDFs	Difference in MC using difference PDFs
Lepton Energy	Electrons and muons shifted ± 1 sigma in MC
Method Calibration	Uncertainty associated with method calibration

transfer functions

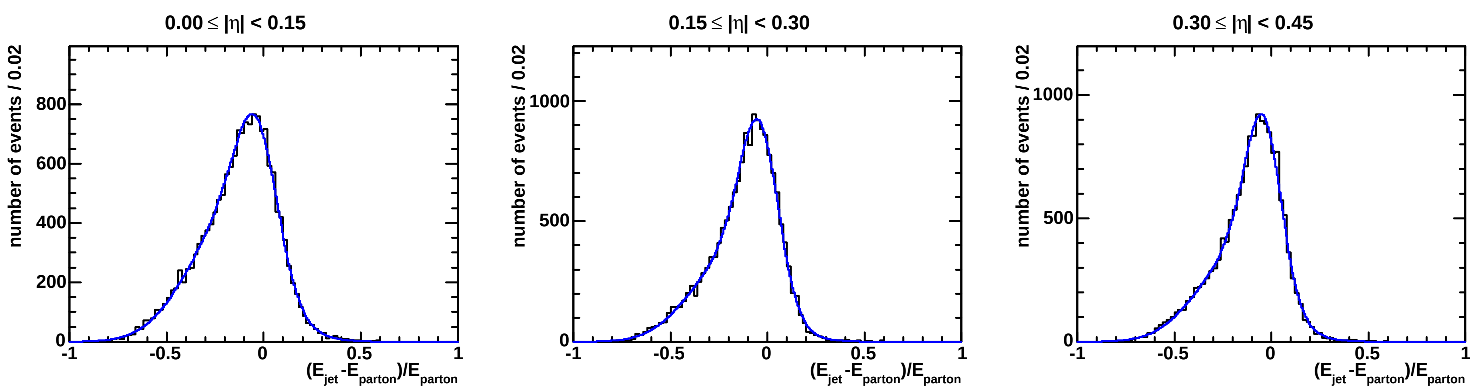
- Probability that parton quantity '*y*' resulted in measured quantity '*x*'
  - Primarily account for detector resolution
  - Taken from fit to Monte-Carlo ttbar events (known '*x*' and '*y*')
  - Allow for JES correction Δ_{JES}

$$W\left(\vec{x},\vec{y};\Delta_{\mathrm{JES}}\right)=\delta^3\left(p_l^y-p_l^x\right)\prod_{i=1}^{4}W_E\left(E_i^x,E_i^y;\Delta_{\mathrm{JES}}\right)\prod_{i=1}^{4}\frac{1}{E_i^x p_i^x}W_A\left(\Omega_i^x,\Omega_i^y\right)$$

lepton assumed well measured

jet energy TF (binned in $|\eta|$, example below)

jet angle TF (next slide)



background events

- Example for lepton+jets channel
- Numbers used to create pseudo-experiments and calibrate method
- Also used to create templates (template method)
- Expected signal fraction 76%

Sample	Expected events
Wbb	39.01 ± 12.72
Wcc	20.33 ± 6.72
Wc	10.74 ± 3.55
W+jets	22.52 ± 5.72
Non-W	25.04 ± 20.53
single top (s chan)	3.29 ± 0.32
single top (t chan)	3.33 ± 0.28
WW diboson	4.20 ± 0.54
WZ diboson	1.45 ± 0.17
ZZ diboson	0.35 ± 0.05
Z + light flavour	3.89 ± 0.48
ttbar signal	425.02 ± 58.86
Total Prediction	559.15 ± 66.99
Total Observed	578

Event sample summary

	All hadronic		Lepton+jets			Dilepton	
# b-tags	1 tag	≥2 tags	0 tags	1tag	≥2 tags	0 tags	≥1 tag
N_{acc} (~3 fb^{-1})	3452	441	N/A	459	119	246	98
Signal:Bkg	1:4	1:1	<1:1	2.5:1	10:1	1:4	4:1
# combos	30	6	12	6	2	2	2