Top Mass Measurements at the Tevatron

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On behalf of the CDF and DZero collaborations

PURDUE UNIVERSITY

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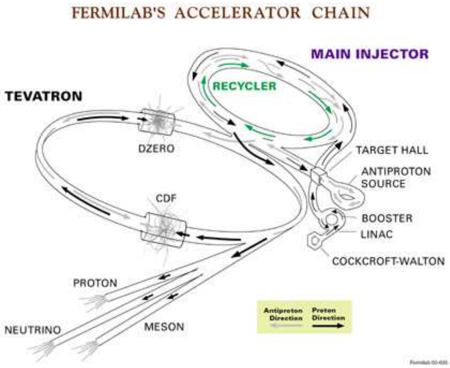
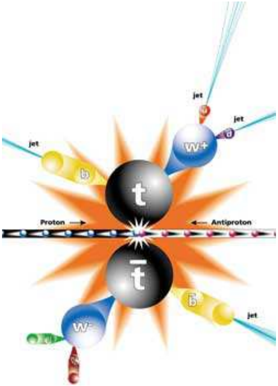
Outline

1. The Top Quark;
2. Mass Measurement Techniques;
3. Mass Measurements;
4. Top-Antitop Mass Difference
5. Combination;

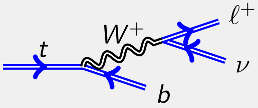


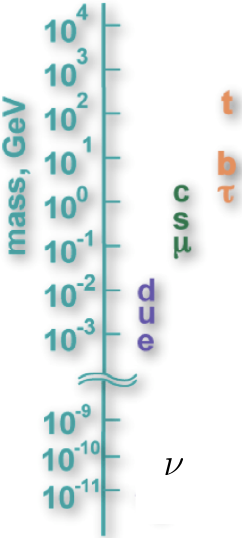


The top quark

What?

- Discovered in 1995 at Fermilab;
- Mass much larger than any other fermion;
- $L_{\text{Yukawa}} = -\lambda\bar{\psi}_L \Phi \psi_R, \ \lambda = 0.996 \pm 0.006$
  - What is its role in EWSB?
- Only quark that decays before hadronizing:





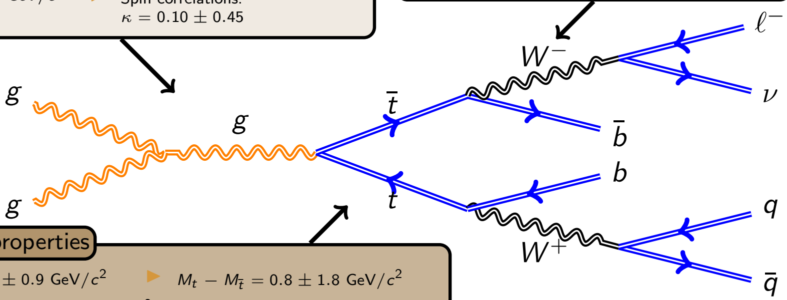
Top quark physics: intrinsic properties

Production properties

- $M_{Z'} > 900$ GeV$/c^2$ @ 95% C.L.
- $M_{W'} > 800$ GeV$/c^2$ @ 95% C.L.
- $M_{b'} > 372$ GeV$/c^2$ @ 95% C.L.
- $F_{gg} = 0.07^{+0.15}_{-0.07}$ (stat+sys)
- $A_{fb} = 15 - 40\%$ (parton level)
- Spin correlations: $\kappa = 0.10 \pm 0.45$

Decay properties

- $V_{tb} = 0.91 \pm 0.11$ (exp)± 0.07 (theory)
- No evidence for charged Higgs
- $f_0 = 0.67 \pm 0.10 \& f_+ = 0.02 \pm 0.05$



Intrinsic properties

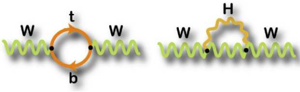
- $M_t = 173.2 \pm 0.9$ GeV$/c^2$
- $M_t - M_{\bar{t}} = -3.3 \pm 1.7$ GeV$/c^2$
- $\Gamma_t < 7.5$ GeV @ 95% C.L.
- $M_t - M_{\bar{t}} = 0.8 \pm 1.8$ GeV$/c^2$
- $\Gamma_t < 1.99^{+0.69}_{-0.55}$ GeV

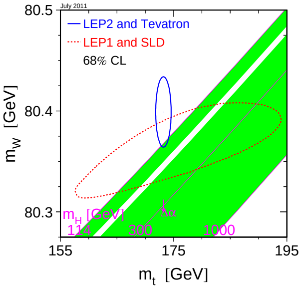
Why is the top quark (mass) so important?

- m_t is a fundamental parameter of the SM;
- Its mass (m_t) constrains the Higgs mass;

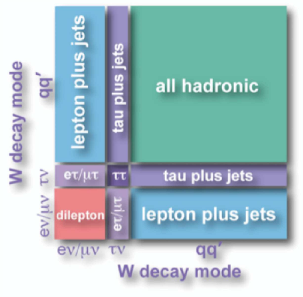
$$\left(\frac{m_W}{m_Z}\right)^2 = \left(1 - \sin^2\theta_W\right)\cdot\left(1 + \Delta\rho(m_t^2; \ln m_H)\right)$$

- Relates to many SM observables (loop diagrams)
  - Strong consistency check on SM parameters
- The top sector is expected to be sensitive to many new physics processes;





Pair production decay signatures at Tevatron



Fully-reconstructed signatures

- Lepton+Jets [$\mathcal{B} \sim 30\%$, good S/B]
  - "Golden channel" for top mass;
- All hadronic [$\mathcal{B} \sim 44\%$]
  - But very large QCD background

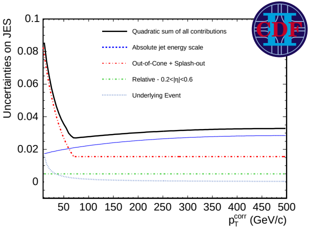
Experimentally more challenging signatures

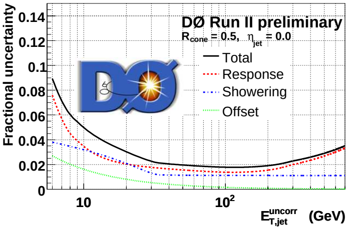
- Dilepton [$\mathcal{B} \sim 5\%$, highest S/B]
  - Challenge: the two ν's complicate the reconstruction
    - Neutrino Weighting, Matrix Weighting;
- $\not{E}_T +$ jets
  - Lepton+jets and dilepton decays where e/μ is not identified;
  - Large acceptance to τ ($\sim 40\%$ of sample); large QCD background;
  - Challenging: even less possibilities to reconstruct the m_t;

Experimental Challenges

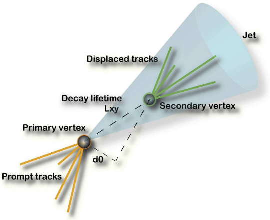
Jet Reconstruction

- Need parton information for m_t, but we measure calorimeter deposits, thus jets (using a cone algorithm);
- Jets are further corrected to the particle level;
- Jet Energy Scale (JES) is the major source of uncertainty;
- Fortunately, we can measure the JES simultaneously with m_t;
  - **In situ** calibration using $W \to jj$ to measure the W mass;
  - Transforming a systematic uncertainty into a statistical one;
  - Can be applied to the ℓ+jets and hadronic topologies.



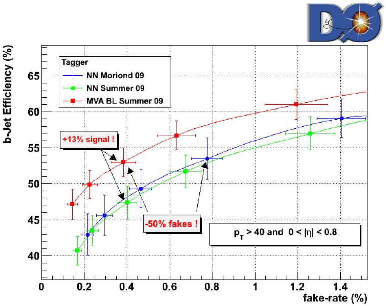


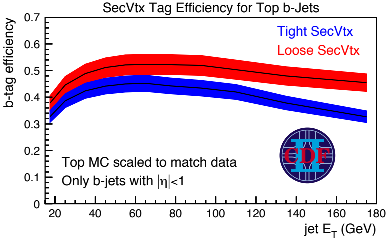
Experimental Challenges (2)



b-tagging

- Background is reduced by identifying jets from *b*-quarks;
- Either secondary vertex tagging (most efficient) or ID of semileptonic decays of *B* hardrons;





Methods used at the Tevatron (1)

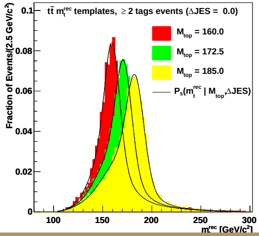
Template Method

1. Determine m_t-dependent observables (e.g. $m_t^{\text{reco.}}$ reconstructed mass);

$$\chi^2 = \underbrace{\sum \left(\frac{p_T^{\text{fit}} - p_T^{\text{meas.}}}{\sigma} \right)^2}_{\text{Kinematic constraints}} + \underbrace{\sum \left(\frac{M_{ff}^{\text{fit}} - M_{W(t)}^{(\text{reco.})}}{\Gamma_{W(t)}} \right)^2}_{\text{Mass constraints}}$$

2. Generate **template** distributions at different m_t (Monte Carlo);
3. Fit the templates to data to determine m_t.

- Does not use the full event information, nor event-by-event differences;
- Fast but statistical sensitivity worse than other methods;
- Systematic effects (e.g. JES) can be taken into account in the MC;
- Lepton p_T and b-quark decay length (L_{xy}) are also options for the observables, and do not depend on JES;



Methods used at the Tevatron (2)

Matrix Element Technique

1. Compute the **event probability density (P_E)**;

$$P_E(x; m_t, f_{t\bar{t}}) = f_{t\bar{t}} \cdot P_{t\bar{t}}(x; m_t) + (1 - f_{t\bar{t}}) \cdot P_b(x)$$

2. Obtain the sample likelihood ($L = \prod P_E$), and extract the most likely mass;

$$P_{t\bar{t}} = \frac{1}{\sigma_{t\bar{t}}(m_t)} \sum_{j-p} \int \sum_{\text{flavors}} dq_1 dq_2 \underbrace{\frac{\mathbf{d}\sigma(\mathbf{p\bar{p}} \to t\bar{t} \to \mathbf{y})}{\mathbf{dy}}}_{\text{Matrix Element}} \cdot \underbrace{f(q_1) f(q_2)}_{\text{PDFs}} \cdot \underbrace{W(x; y)}_{\text{Resolution}} \cdot dy$$

- Uses full event information, and event-by-event differences;
- Very CPU intensive (hours per event);
- Systematic effects (e.g. JES) can be taken into account when getting P_E;
- Simple version: Dynamical Likelihood, without explicit P_b.

Methods used at the Tevatron (3)

Ideogram Method

- Similar to the Matrix Element method, except in evaluating $P_{t\bar{t}}$ and P_b;

$$P_E(x; m_t, f_{t\bar{t}}) = f_{t\bar{t}} \cdot P_{t\bar{t}}(x; m_t) + (1 - f_{t\bar{t}}) \cdot P_b(x)$$

- The probability for a given process ($P_{\mathrm{proc.}}$) obtained from kinematic information to extract m_t (x_κ) and other variables (x_τ);

$$P_{\mathrm{proc.}}(x; \ldots) = P^{\kappa}_{\mathrm{proc.}}(x_\kappa; \ldots) \cdot \underbrace{P^{\tau}_{\mathrm{proc.}}(x_\tau; \ldots)}_{\text{Optional component}}$$

- Approximation of Matrix Element (ME), less accurate but faster;
- Cost and performance typically between ME and template method;
- Requires full m_t reconstruction: cannot be applied to *dilepton*;
- Again, systematics can be included in the determination of P_E.

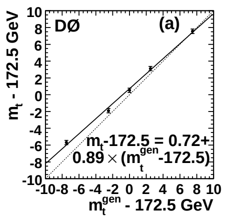
General considerations for m_t measurements

Calibration of the measurement

- Need to quantify the techniques' influence on $m_T^{\text{meas.}}$;
- Calibration with Monte Carlo pseudo-experiments (ensemble testing), correcting the average mass residual to zero and the width of the pull to unity;

$$m_t^{\text{corr}} = \alpha \times m_t^{\text{meas}} + \beta$$

- The calibration is then applied to the measurement.



What is being measured (theoretical interpretation)?

- Free particle: the physical mass usually is the **pole** of its renormalized propagator;
- Ambiguous for quarks, due to non-perturbative QCD effects, $\mathcal{O}(\Lambda_{QCD})$;
- Alternatives: $m_{\overline{MS}}$, only sensitive to short distance QCD (used for light quarks);
- Experiment: measurement (usually) through the **reconstruction of the decay products**, based on MC; is this the pole mass? [Will discuss later]
- Calibration: MC generators include model-dependent descriptions of the parton shower and the hadronization; effect of $\mathcal{O}(\Lambda_{QCD})$;

Lepton + Jets

- **Most precise m_t measurements from single channel**;
- Using **matrix elements** with **in-situ** JES to maximise sensitivity;
- $p_T(e,\mu) > 20$ GeV$/c$, $\not{E}_T > 20$ GeV, 4 jets with $p_T > 20$ GeV$/c$, $\geq 1b$-tag;
- CDF: NN to weight background contribution; Quasi-MC integration over 19 var.;
- DØ: $q\bar{q} \to t\bar{t}$ ME for signal, background ME from VECBOS;

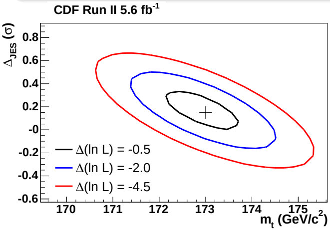
Latest results

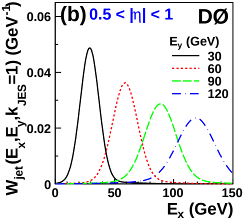
- CDF [5.6fb^{-1}]: $m_t = 173.0 \pm 1.2$ GeV$/c^2$

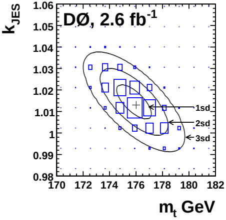
  [Phys.Rev.Lett. 105 (2010) 252001; arXiv:1010.4582 [hep-ex]]

- DØ [$1.0{+}2.6\text{fb}^{-1}$]: $m_t = 174.9 \pm 1.5$ GeV$/c^2$

  [Phys.Rev.D 84 (2011) 032004; arXiv:1105.6287 [hep-ex]]





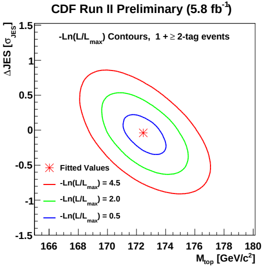


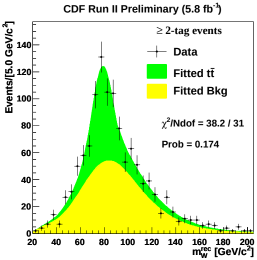
- $6 - 8$ jets with $p_T > 15$ GeV$/c$, $\geq 1b$-tags, no leptons, small $\not{E}_T$;
- NN background suppression;
- Uses jet shapes to distinguish quark jets from gluon jets;
- Template method with kinematic fitter, and in-situ JES calibration;

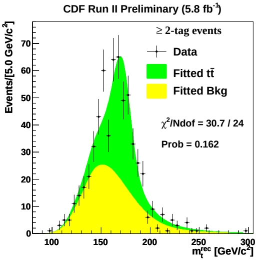
Latest results

- CDF [5.8fb^{-1}]: $m_t = 172.5 \pm 2.0$ GeV$/c^2$

[CDF/PHYS/TOP/PUBLIC/10456]





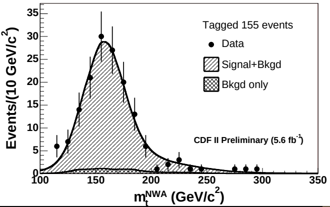


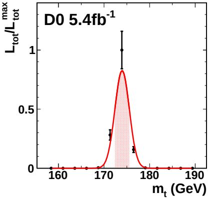
Dilepton

- No in-situ JES calibration possible (no hadronic W);
- System is underconstrained: two νs, one $\not{E}_T$;
- CDF: Templates using neutrino weighting algorithm (NWA); [also for DØRun IIa]

Latest results

- DØ [5.4fb^{-1}]: $m_t = 174.0 \pm 3.1$ GeV$/c^2$ [Matrix Element]
  [Phys. Rev. Lett. 107 (2011) 082004; arXiv:1105.0320v2 [hep-ex]]
- CDF [5.6fb^{-1}]: $m_t = 170.3 \pm 3.7$ GeV$/c^2$ [Template Method]
  [Phys.Rev.D 83 (2011) 111101; arXiv:1105.0192 [hep-ex]]
- CDF [2.0fb^{-1}]: $m_t = 172.3 \pm 4.0$ GeV$/c^2$ [Dalitz-Goldstein Method]
  [CDF/PUB/TOP/PUBLIC/10635]





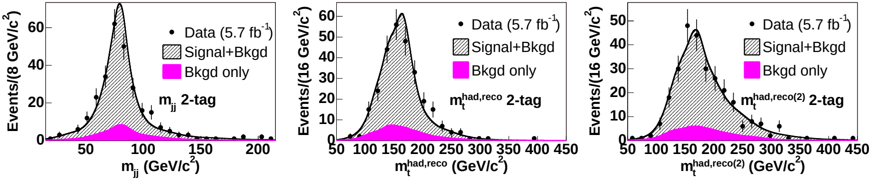
$\not{E}_T+$ jets

- Analyzes events without reconstructed e or μ; sensitive to τ's (40% of signal);
- Sensitive to new physics in the τ sector;
- $4-6$ jets ($E_T > 15$ GeV), lepton veto ($p_T > 20$ GeV$/c$), $\not{E}_T/\sqrt{\sum E_T^{\text{jets}}} > 3$ GeV$^{1/2}$
- NN event selection, data-driven background model;
- Only the hadronically decaying top is reconstructed (in two ways):
  - 3D p.d.f.s to extract m_t;

Latest results

- CDF [5.7fb^{-1}]: $m_t = 172.3 \pm 2.6$ GeV$/c^2$ [Template Method]

  [arXiv:1109.1490v1 [hep-ex]]



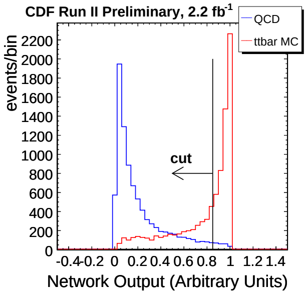
Hadronic τ + jets

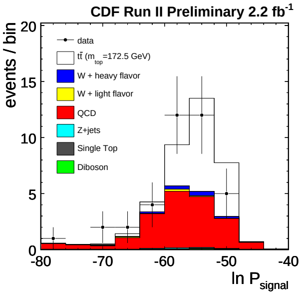
- Cross-section and first m_t measurement in τ+jets;
- Tests lepton universality; probes a channel possibly sensitive to NP;
- $p_T(\tau) > 25$ GeV/c, jets with $E_T > 20$ GeV, $\not\!\!E_T > 20$ GeV, $\geq 1b$-tag;
- JES is largest systematic (3.4 GeV/c^2);

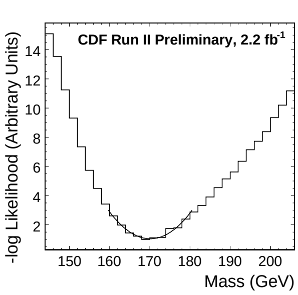
Latest results

- CDF [2.2fb^{-1}]: $m_t = 172.7 \pm 10.0$ GeV/c^2 [Matrix Element]

  [CDF/PUB/TOP/PUBLIC/10562]







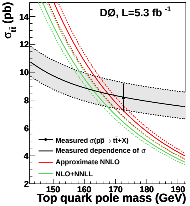
Top mass from cross-section measurement

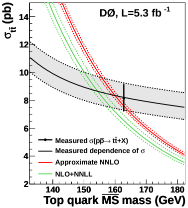
- Acceptance from MC (as a function of m_t) used to determine $\sigma_{t\bar{t}}(m_t)$;
- $\sigma_{t\bar{t}}$ compared to higher-order predictions (NLO(+(N)NLL)/Approx. NNLO);
- Most likely m_t from $L(m_t) = \int f_{\mathrm{exp}}(\sigma|m_t)\ [f_{\mathrm{scale}}(\sigma|m_t) \otimes f_{\mathrm{PDF}}(\sigma|m_t)]\ d\sigma$;
- Performed for two assumptions for $m_t^{MC} = m_t^{\mathrm{pole}}$ and $m_t^{MC} = m_t^{\overline{MS}}$.

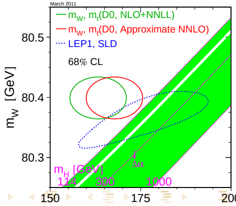
Latest results from DØ [5.3fb^{-1}]: experimental m_t closer to pole mass

- $m_t^{\mathrm{pole}} = 167.5 \pm 5.0\ \ \mathrm{GeV}/c^2$; $m_t^{\overline{MS}} = 160.0 \pm 4.6\ \ \mathrm{GeV}/c^2$ [Approx. NNLO]

  [arXiv:1104.2887v1 [hep-ex]]







Top-Antitop Mass Difference

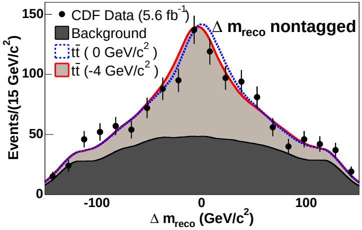
- If CPT is conserved, $\Delta \mathrm{m} = \mathrm{M}_t - \mathrm{M}_{\bar{t}} = 0$;
- This assumption is used in top mass measurements till now;
- Good agreement with SM, but still statistically limited.

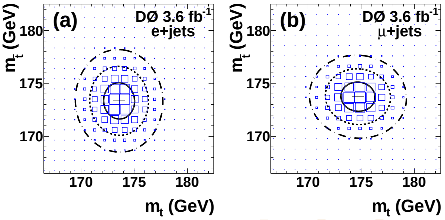
Latest results

- CDF [5.6fb^{-1}]: $\Delta \mathrm{m} = -3.3 \pm 1.7$ GeV/c^2 [Δm Templates]

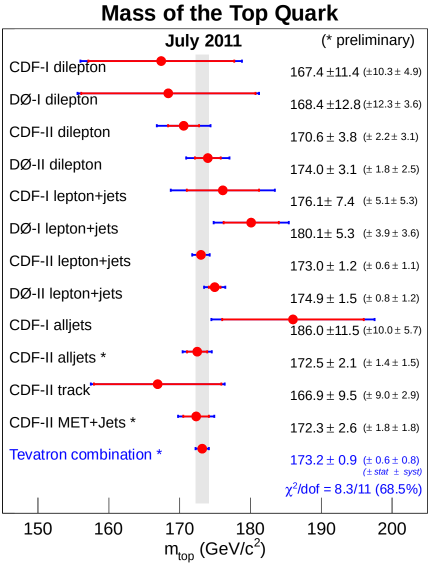
  [Phys.Rev.Lett. 106 (2011) 152001; arXiv:1103.2782 [hep-ex]]
- DØ [3.6fb^{-1}]: $\Delta \mathrm{m} = 0.8 \pm 1.9$ GeV/c^2 [Measures m_t and $m_{\bar{t}}$, ME]

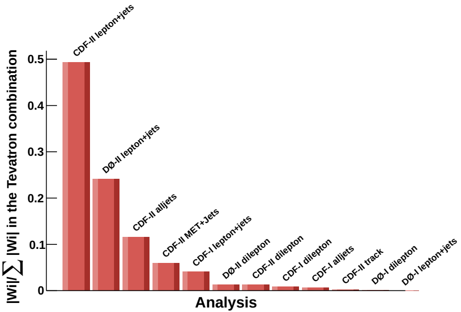
  [arXiv:1106.2063v2 [hep-ex]]





Combination





$$m_t = 173.2 \pm 0.6(\text{stat}) \pm 0.8(\text{syst})$$
$$= 173.2 \pm 0.9 \quad \text{GeV}/c^2$$

Combination of 12 measurements.

Uncertainty below 1 GeV/c^2 for the first time!

[arXiv:1107.5255v3 [hep-ex]]

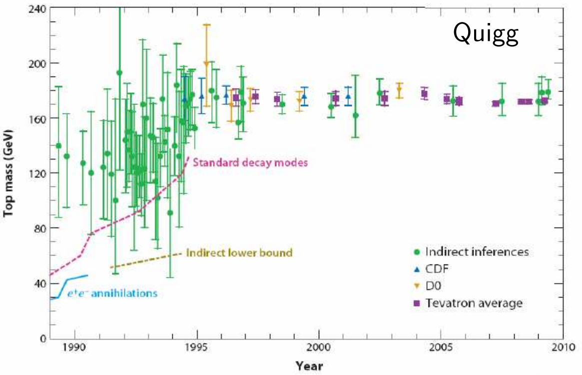
A word on systematic uncertainties

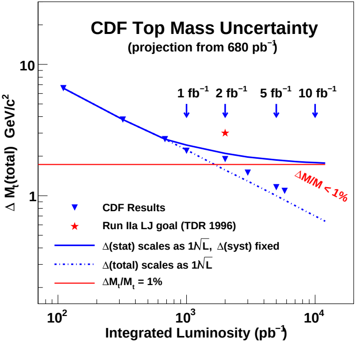
- Results are systematically limited;
- Main systematics: JES, Singal (Generator, ISR/FSR).

	Tevatron combined values (GeV/c^2)
m_t	173.18
iJES	**0.39**
aJES	0.09
bJES	0.15
cJES	0.05
dJES	**0.20**
rJES	0.12
Lepton p_T	0.10
Signal	**0.51**
Detector Modeling	0.10
UN/MI	0.00
Background from MC	0.14
Background from Data	0.11
Method	0.09
MHI	0.08
Systematics	0.75
Statistics	0.56
Total	0.94

[arXiv:1107.5255v3 [hep-ex]]

History of Top Mass Measurements





A long way to reach a precision of $< 0.5\%$ (< 1 GeV$/c^2$)

Summary

- The precise determination of the top quark mass, m_t, will be a legacy of the Tevatron;
  $m_t = 173.2 \pm 0.6(\mathrm{stat}) \pm 0.8(\mathrm{syst}) = 173.2 \pm 0.9 \ \ \mathrm{GeV}/c^2$
- Top-Antitop mass difference compatible CPT invariance;
  $\Delta\mathrm{m} = -3.3 \pm 1.7 \ \ \mathrm{GeV}/c^2$ (CDF); $\Delta\mathrm{m} = 0.8 \pm 1.9 \ \ \mathrm{GeV}/c^2$ (DØ)
- Top mass measurement dominated by systematic uncertainties;
  $\sim 0.5 \ \ \mathrm{GeV}/c^2$ Signal (Generator, ISR/FSR); $\sim 0.5 \ \ \mathrm{GeV}/c^2$ JES

Too many results to describe here

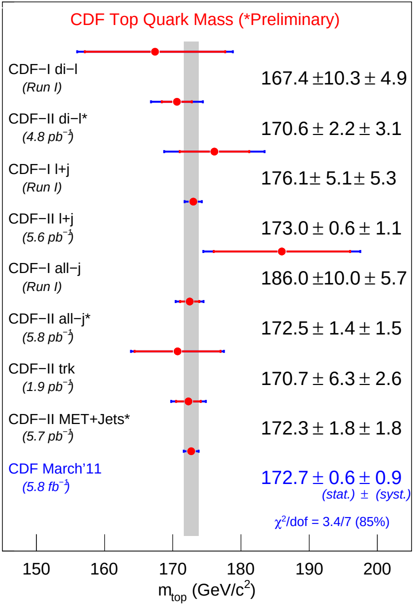
DØ `http://www-d0.fnal.gov/Run2Physics/top/`

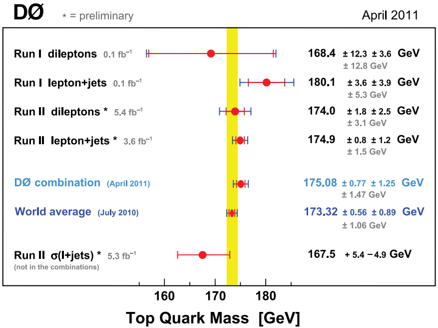
CDF `http://www-cdf.fnal.gov/physics/new/top/public_mass.html`

Thank you!

Backup Slides

Collaboration averages



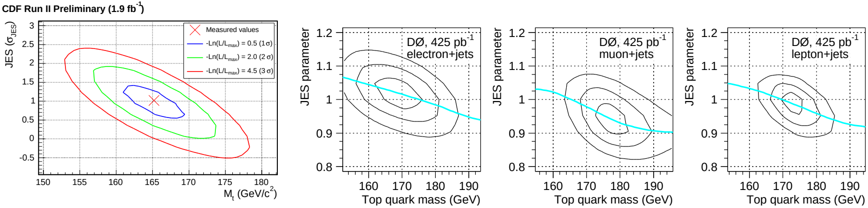


Ideogram Method

- Using in-situ JES calibration;

Latest results

- CDF [1.9fb^{-1}]: $m_t = 162.7 \pm 4.7 \quad GeV/c^2$ [All-Hadronic]
  [CDF/PHYS/TOP/PUBLIC/8233]
- DØ [0.43fb^{-1}]: $m_t = 173.7 \pm 4.8 \quad GeV/c^2$ [Lepton+Jets]
  [Phys.Rev.D 75 (2007) 092001; arXiv:0702018v1 [hep-ex]]



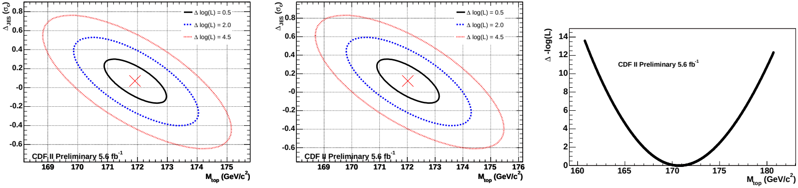
Simultaneous Fit of Lepton + Jets and Dilepton

- Main idea: bring **in-situ** JES calibration from lepton + jets to the dilepton channel;
- Dominated by lepton + jets;

Results (CDF [$5.6 fb^{-1}$])

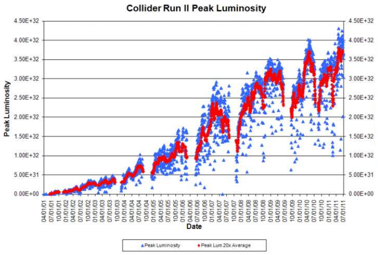
- Dilepton: 170.3 ± 3.7 GeV/c^2
- Lepton+Jets: 172.2 ± 1.5 GeV/c^2
- Combined: 172.1 ± 1.4 GeV/c^2

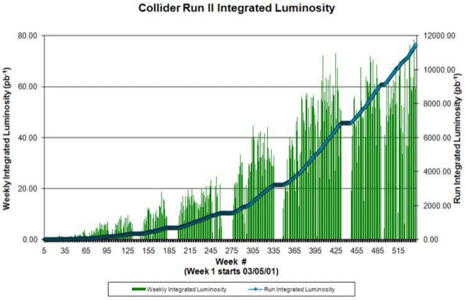
[Phys.Rev.D 83 (2011) 111101; arXiv:1105.0192 [hep-ex]]



Tevatron luminosity

- Tevatron doing great in providing collisions to experiments.
- Today's talk: up to 7.8fb^{-1}of data;





CDF and DZero, two general purpose detectors

	CDF		DØ	
Tracking	Silicon	$\|\eta\| < 2 - 2.5$	Silicon	$\|\eta\| < 3$
	Drift cell	$\|\eta\| < 1.1$	Fiber	$\|\eta\| < 1.7$
Calorimetry	Scintillators	$\|\eta\| < 3.6$	LAr/DU	$\|\eta\| < 4$
Muon chambers	Drift Scintillators	$\|\eta\| < 1.5$	Drift Scintillators	$\|\eta\| < 2.0$