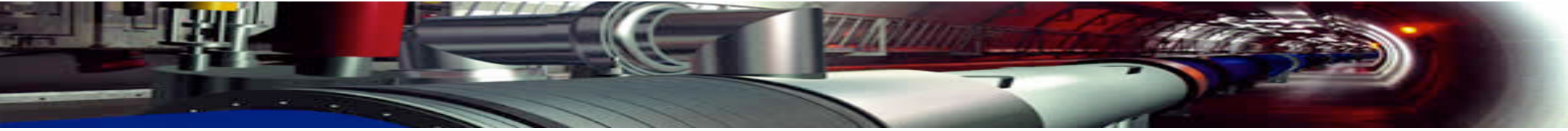


Top Workshop IN2P3: From D0 to Atlas Grenoble, October 9-10 2006

Top Mass Measurements: Review of the main methods & performance

Outline:
- Top Quark Mass at the Tevatron Run II
- Top Pair Production and Decay
- Methods employed by CDF and D0, recent results
- Top Mass Error Projection
- Conclusion

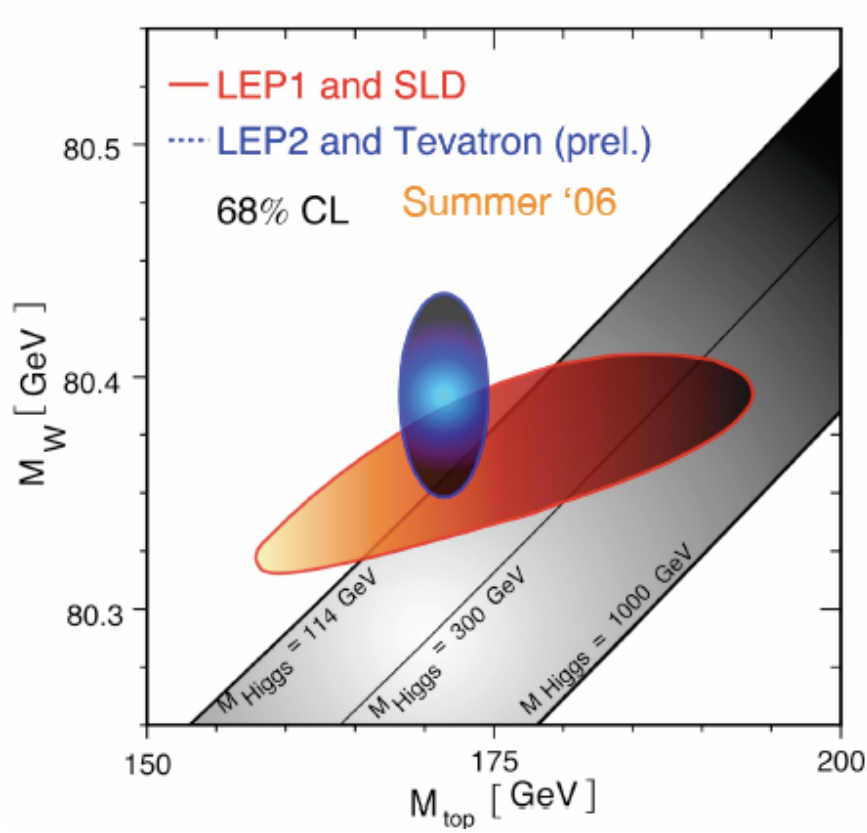
Philipp Schieferdecker
CERN

Top Quark Mass at TeVatron II

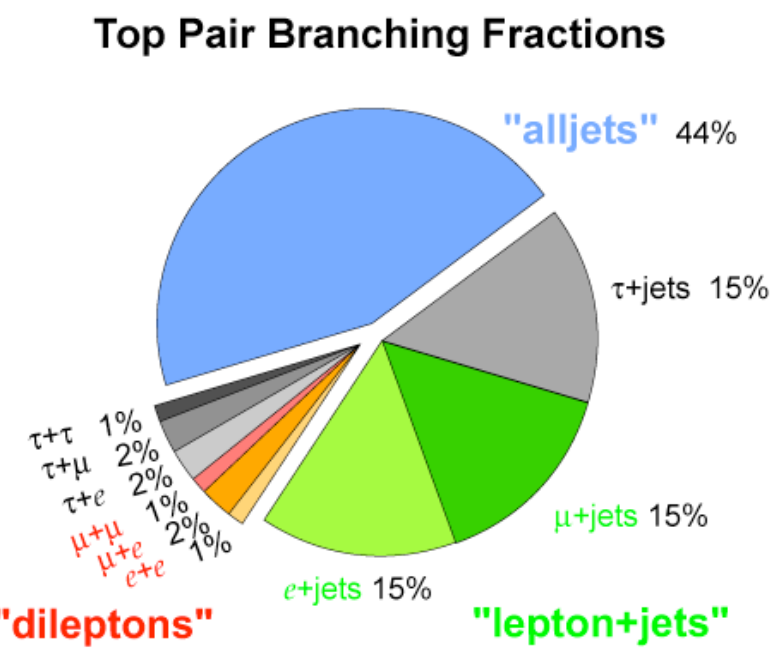
- CDF and D0 produced and combined several precision measurements in RunII
  - ★Large top pair sample, improved methods
  - ★In-Situ JES calibration!
- Current world average (July 2006):

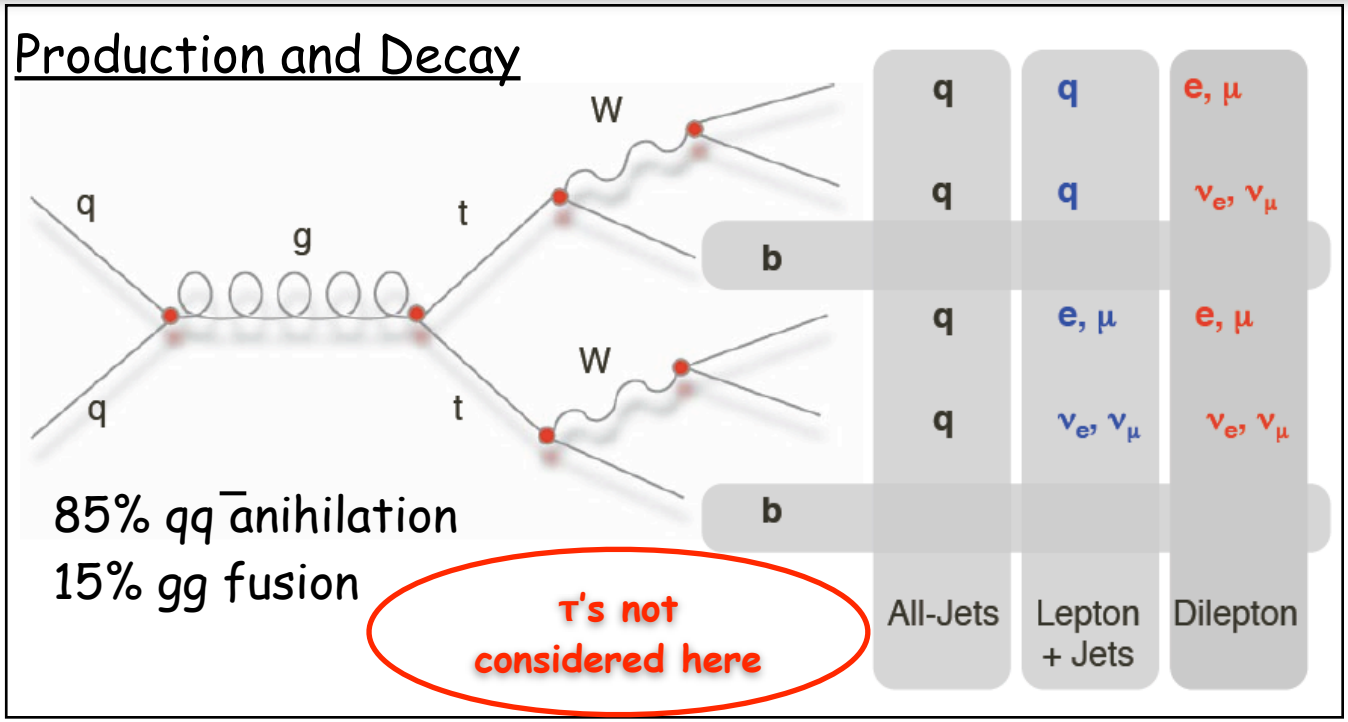
m_{top}= 171.4 ± 1.2 (stat) ± 1.7 (syst) GeV

  - ★Remarkable precision, ~1.2%
  - ★Systematically limited!
  - ★Will improve with raising statistics until LHC startup (<1%)
  - ★It will be a major challenge to improve this precision with the LHC sample



Top Pair Production and Decay





	All-Jets	Lepton+Jets	Dilepton
BR	~44%	~30%	~5%
S/B	1:1000 to 1:4	1:4 to 11:1 varies w/ #b-tags	~2:1
Backgrounds	Jet Production	W+jets fake leptons	Z+jets WW,WZ

Template Method (1)

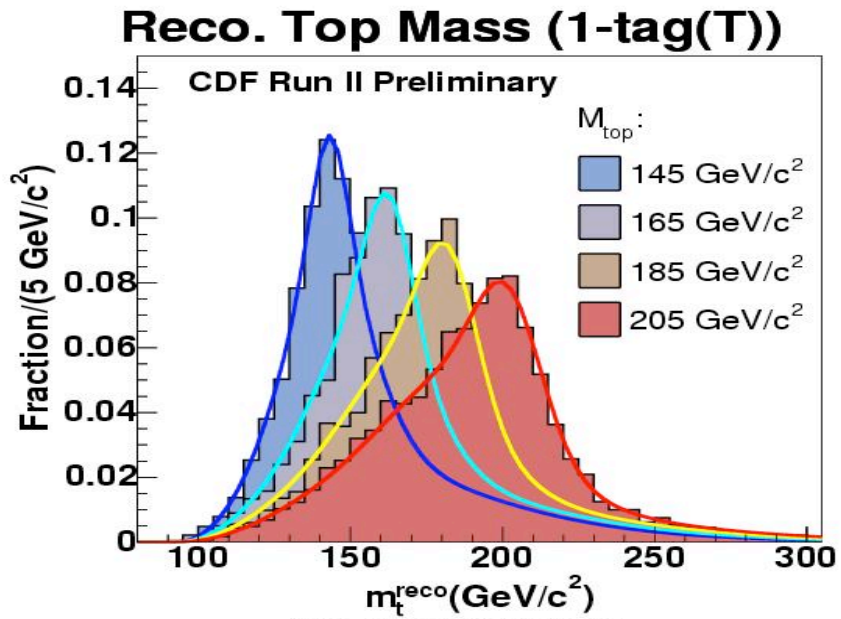
- For each event, reconstruct m_t using a kinematic fit:

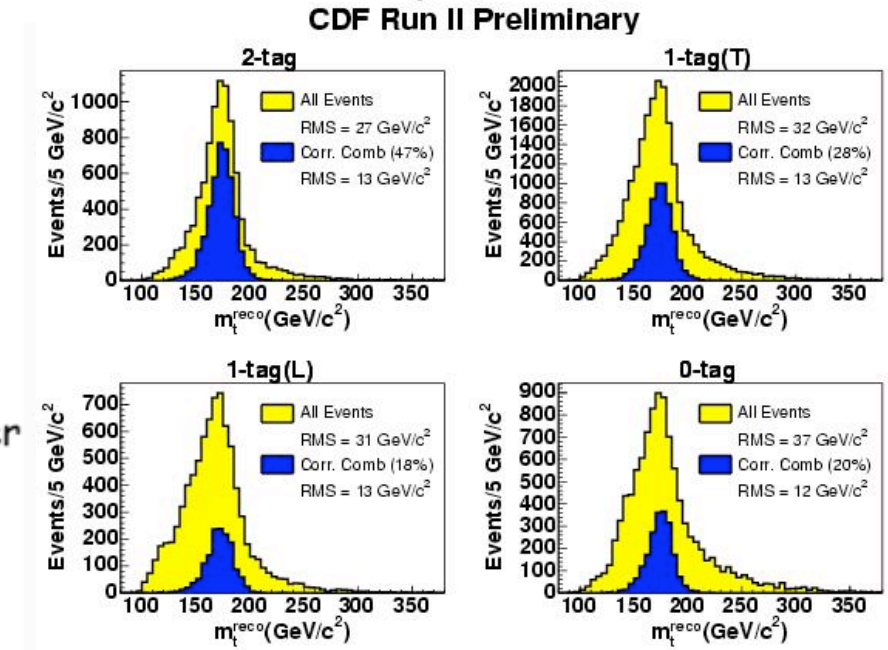
$$\chi^2 = \sum_{i=\ell,4jets} \frac{(p_T^{i,fit} - p_T^{i,meas})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,fit} - p_j^{UE,meas})^2}{\sigma_j^2} + \frac{(M_{\ell\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{b\ell\nu} - m_t^{reco})^2}{\Gamma_t^2} + \frac{(M_{bjj} - m_t^{reco})^2}{\Gamma_t^2}$$

- Choose m_t from jet-parton assignment with lowest χ^2
- Build template distributions from Monte Carlo samples with different true top quark masses
- Extract result from data sample using an unbinned likelihood fit:

$$\mathcal{L}_{\text{sample}} = \mathcal{L}_{\text{shape}}^{m_t^{\text{reco}}} \times \mathcal{L}_{\text{shape}}^{m_{\text{jj}}} \times \mathcal{L}_{\text{nev}} \times \mathcal{L}_{\text{bg}}$$

- Divide events into 4 subsamples according to the number of identified b-jets to improve statistical sensitivity
  - events with more b-tags show better mass resolution and higher S/B
  - 1-tag(L): lower pT threshold for 4th jet than 1-tag(T)

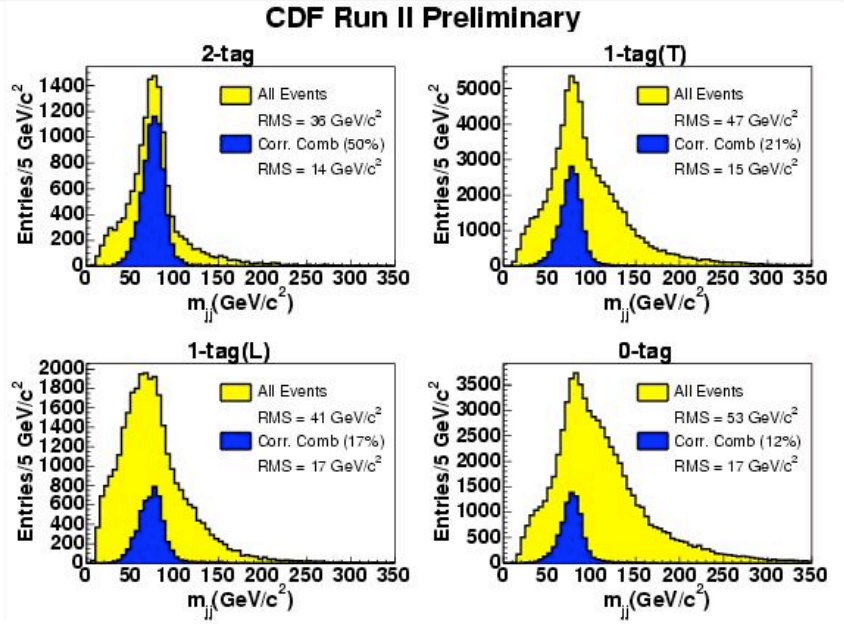


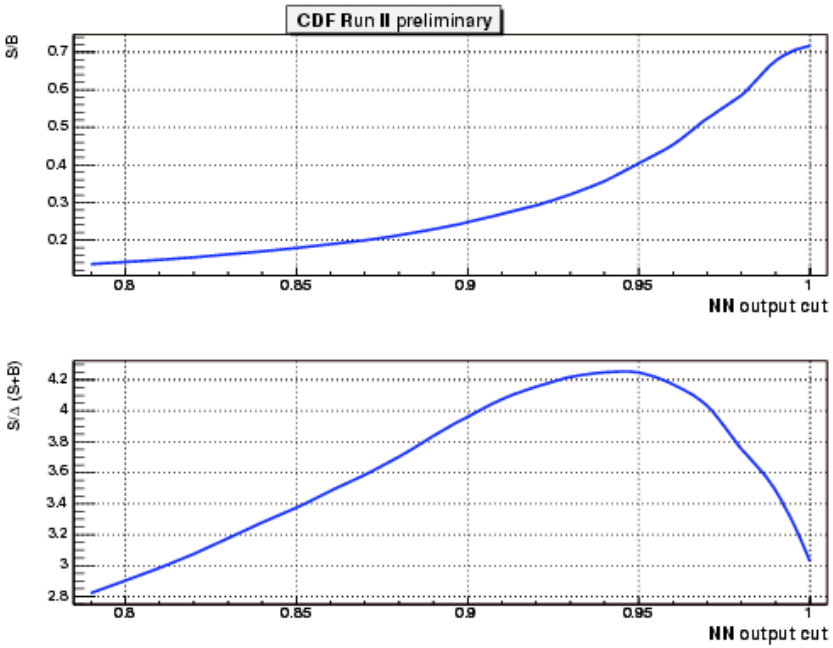


Template Method (2)

In situ jet energy calibration:

- The mass of the hadronically decaying W boson provides a constraint on the jet energy calibration
- Expressed in units of the uncertainty $\sigma(p_T,\eta)$ of the external calibration
- Use reconstructed di-jet mass templates, various scales
- Reduce dominant systematic uncertainty due to jet energy scale!





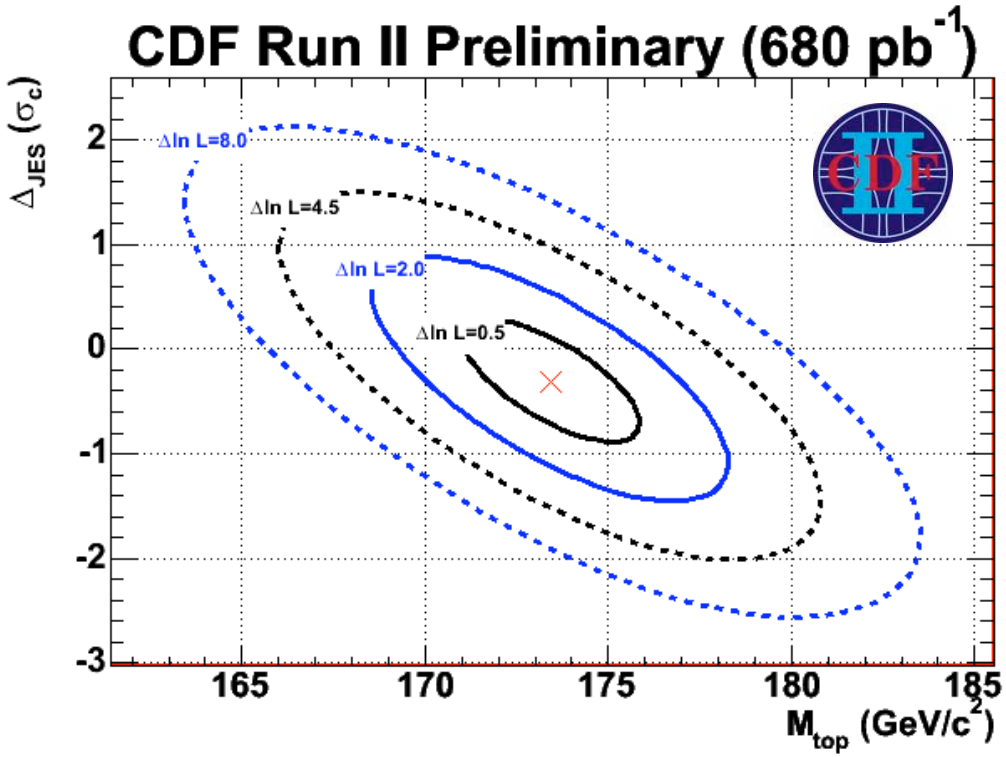
Application to All-Jets sample:

- Neural Network Selection with 11 input variables
- 6-8 reconstructed calorimeter jets, at least 1 btag
- Expected S/B: ~0.25
- Data-Driven Background description
- No In-Situ Jet Energy Scale Calibration

Template Method: Results

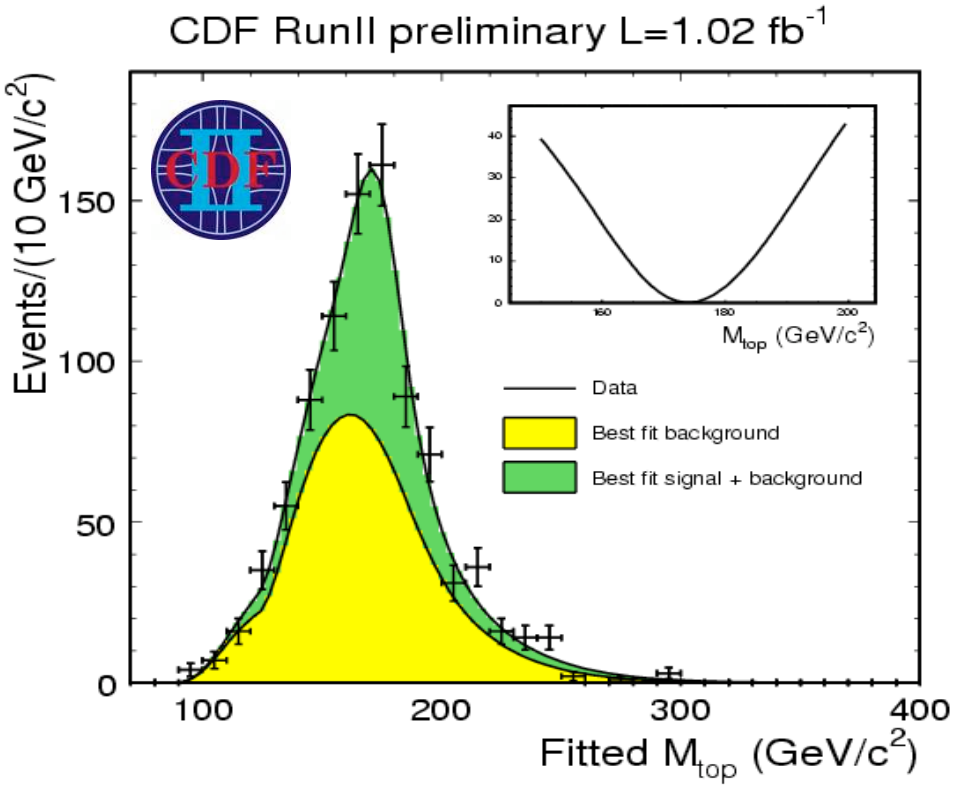
CDF, Lepton+Jets, 680 pb-1

m_t=173.4 ± 1.7 (stat) ± 2.2 (syst) GeV



CDF, All-Jets, 1020 pb-1

m_t=174.0 ± 2.2 (stat) ± 4.8 (syst) GeV



Ideogram Method (1)

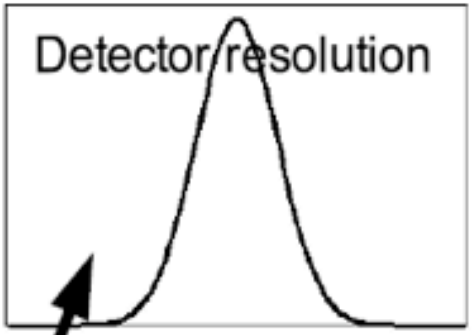
- Based on event-by-event likelihood
  - better use of statistical information, as well measured events contribute more than poorly measured events
- Use kinematic fit to reconstruct top mass for each possible jet-parton assignment
  - take resolution of leptons and jets into account
  - weight solutions by $\chi 2$ of the kinematic fit
- Use Topological Likelihood Discriminant to determine the probability of each event to arise from signal/background
- Applied to D0 Lepton+Jets dataset, w/ In-Situ JES calibration
- Applied to CDF All-Jets dataset, w/o In-Situ JES calibration

Ideogram Method (2)

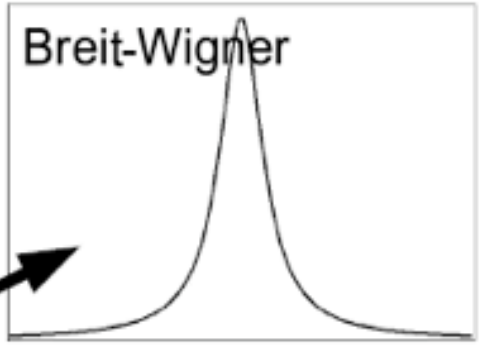
Chi2 weighted combinatorics

$$w_i = e^{-1/2 \cdot \chi_i^2}$$

Detector resolution

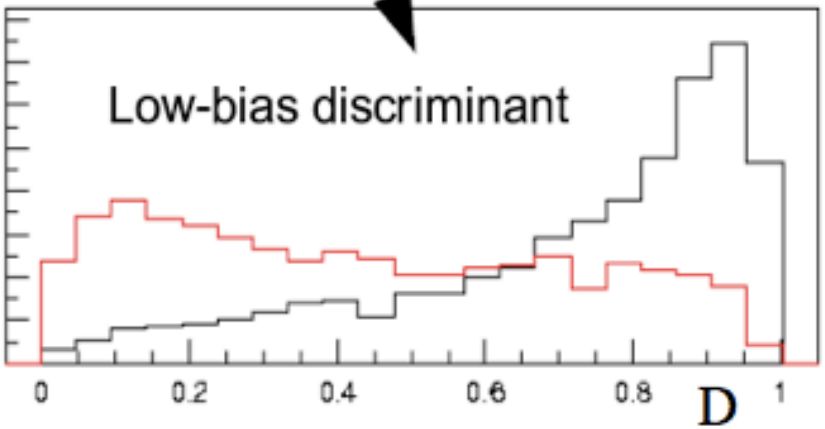


Breit-Wigner

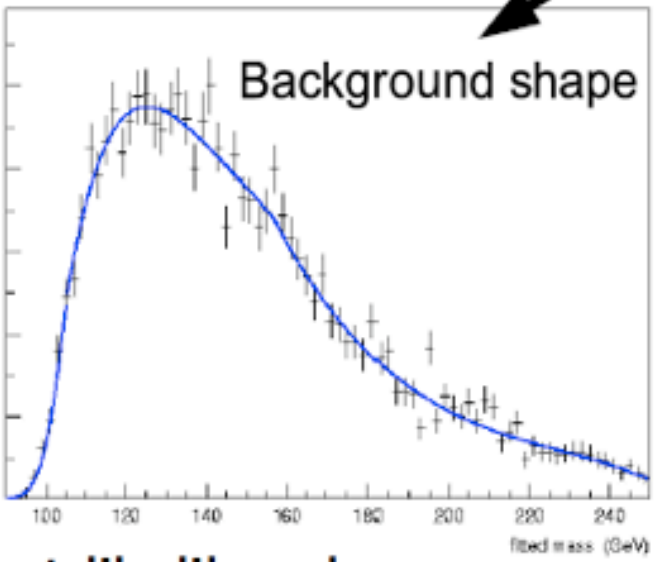


$$L(m_{top}, P_{samp}) = P_{evt} \cdot \left[\int \sum w_i \cdot G(m_i, m') \cdot BW(m', m_{top}) \, dm' \right] + (1 - P_{evt}) \cdot \sum w_i \cdot BG(m_i)$$

Low-bias discriminant



Background shape

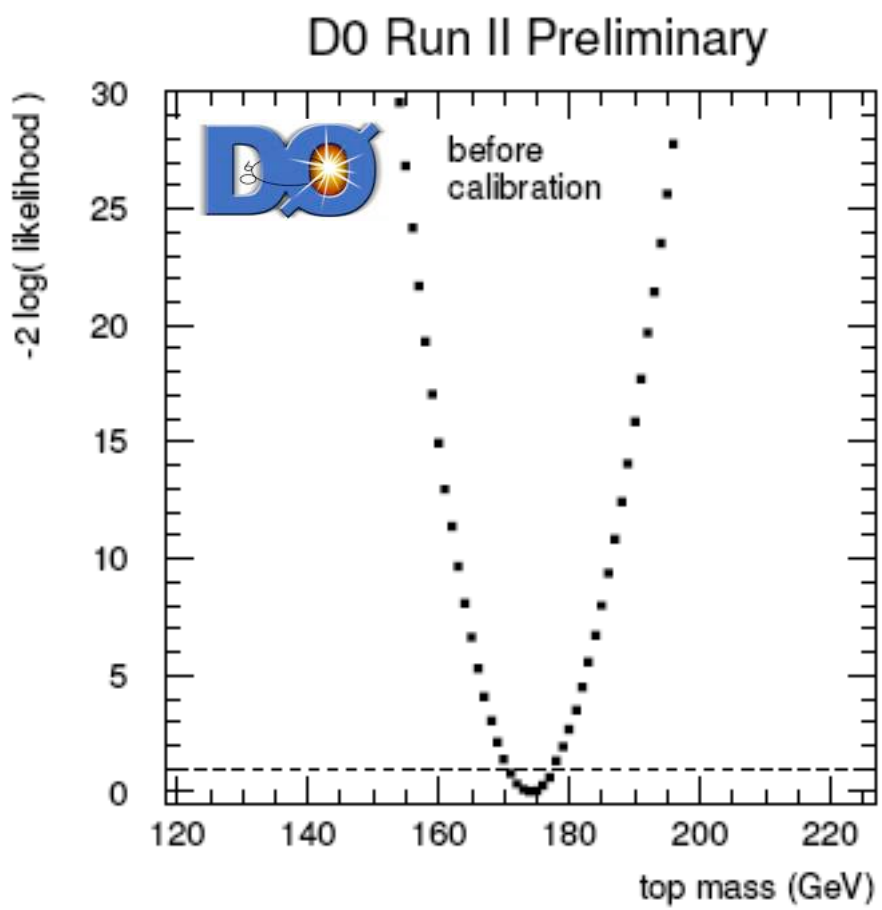


- Overall combined likelihood is product of event likelihoods

Ideogram Method: Results

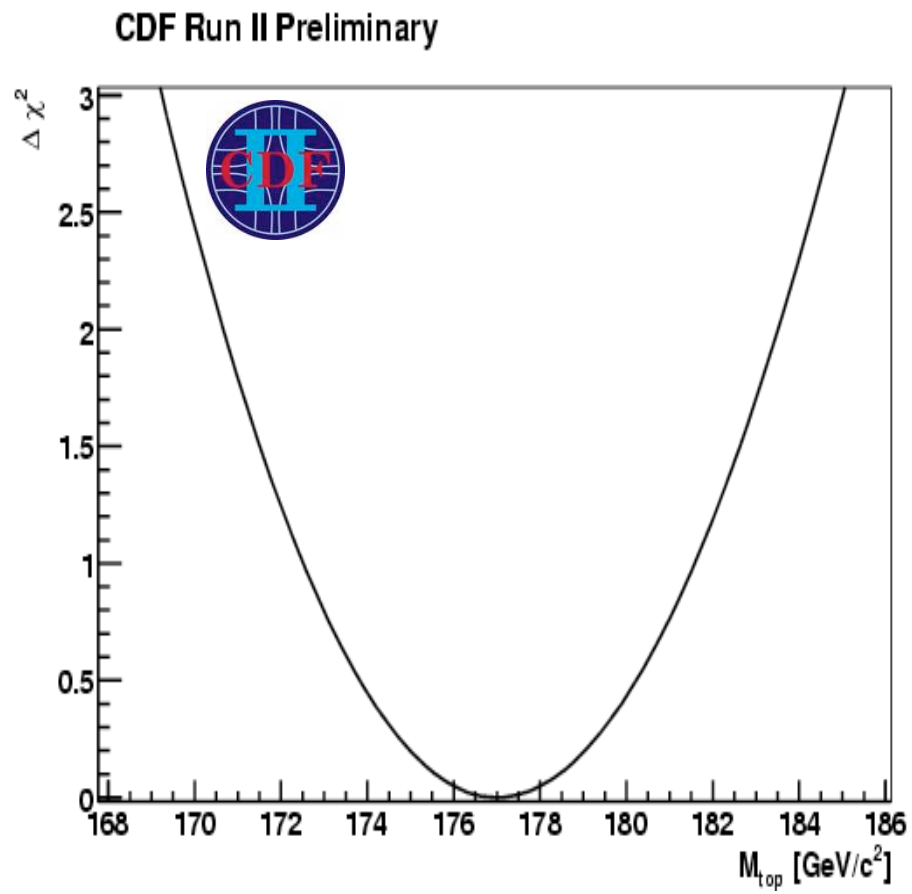
D0, Lepton+Jets, 370 pb-1

m_t=173.9 ± 3.6 (stat) ± 2.1 (syst) GeV



CDF, All-Jets, 310 pb-1

m_t=177.1 ± 4.9 (stat) ± 4.7 (syst) GeV



Matrix Element Method (1)

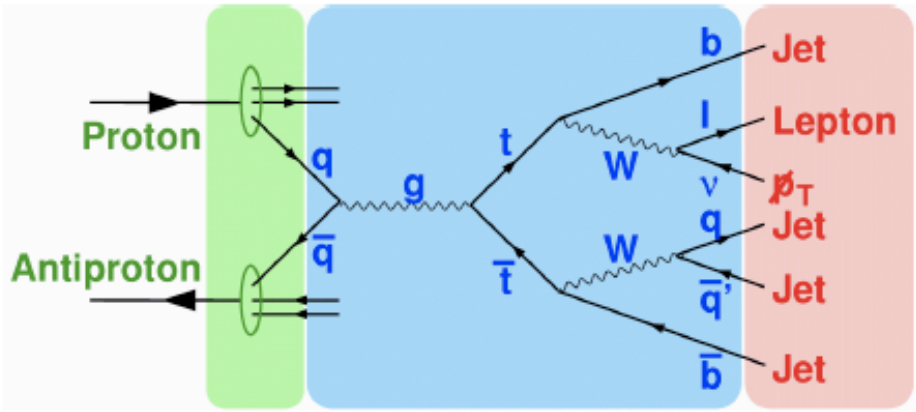
- Use each event's full kinematic information to calculate probability to originate from $t\bar{t}$ production, as a function of assumed m_t
- Calculate the probability to be background accordingly and combine to event probability:
  - $P_{evt}(x;m_t,f_{sgn}) = f_{sgn}\, P_{sgn}(x;m_t) + (1-f_{sgn})\, P_{bkg}(x)$

  where f_{sgn} is the fraction of signal events in the sample
- Combine all events in a likelihood
  - $-\ln L(x_1,\ldots,x_n;m_t,f_{sgn}) = -\Sigma_{i=1}^{n} \ln P_{evt}(x_i;m_t,f_{sgn})$

  and maximize likelihood w.r.t. to m_t and f_{sgn}
- Well measured events contribute more than poorly measured events:
  achieve optimal use of statistical information!
- I will present applications of this method to both lepton+jets and dilepton events
- Lepton+Jets: Use invariant mass of hadronically decaying W boson to obtain JES
  - $L=L(x_1,\ldots,x_n;m_t,f_{sgn},JES)$
  - JES is global scale factor relative to external jet energy calibration
  - Reduce dominant systematic uncertainty by fitting m_t and JES simultaneously

Matrix Element Method (2)

Calculation of the signal probability:



- Integration over parton phasespace (y)
- Assume all angles to be well measured
- Assume $p_T(t\bar{t})=0$
- Parametrize detector resolution of all energies (W(x,y))
- Perform remaining (5-6) integrations using MC integration techniques:

$$\mathcal{P}_{t\bar{t}}(\vec{x}, m_t) = \underbrace{\frac{1}{\sigma_{t\bar{t}}(m_t)}}_{\text{Normalisation}} \int \underbrace{dp_q dp_{\bar{q}} f(p_q) f(p_{\bar{q}})}_{\text{PDFs}} \underbrace{d\sigma_{t\bar{t}}(\vec{y}, m_t)}_{\text{diff. xsec}} \underbrace{W(\vec{x}, \vec{y})}_{\text{det. resolutions}}$$

MATRIX ELEMENT

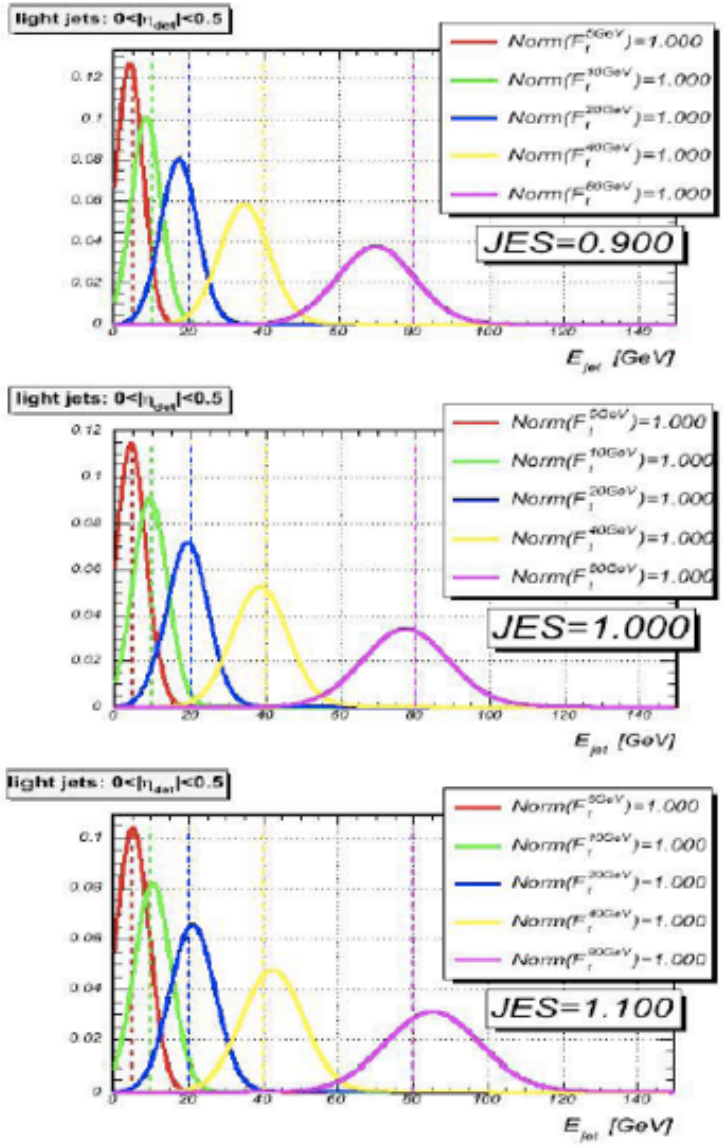
- Consider all possible jet-parton assignments!
- Consider all possible solutions for the z-component of the neutrino momenta

Matrix Element Method (3)

Parametrization of jet energy resolution: jet transfer function W(Ej,Ep)

- $W(E_j,E_p)$ yields for each parton energy E_p the probability to be measured as E_j (j=jet) in the calorimeter
- Parametrized as a double Gaussian in $\delta E=E_j-E_p$ (5 parameters), where each parameter is a linear function of E_p itself
  - jet resolution is function of E_p
- Different parameter sets for light jets, b jets, and semileptonic b-jets. Derived from Monte Carlo events.
- Lepton+Jets: The global jet energy scale parameter JES is included in the event probability via the jet transfer function:

$$W(E_j, E_p; JES) = \frac{W\left(\frac{E_j}{JES} - E_p\right)}{JES}$$

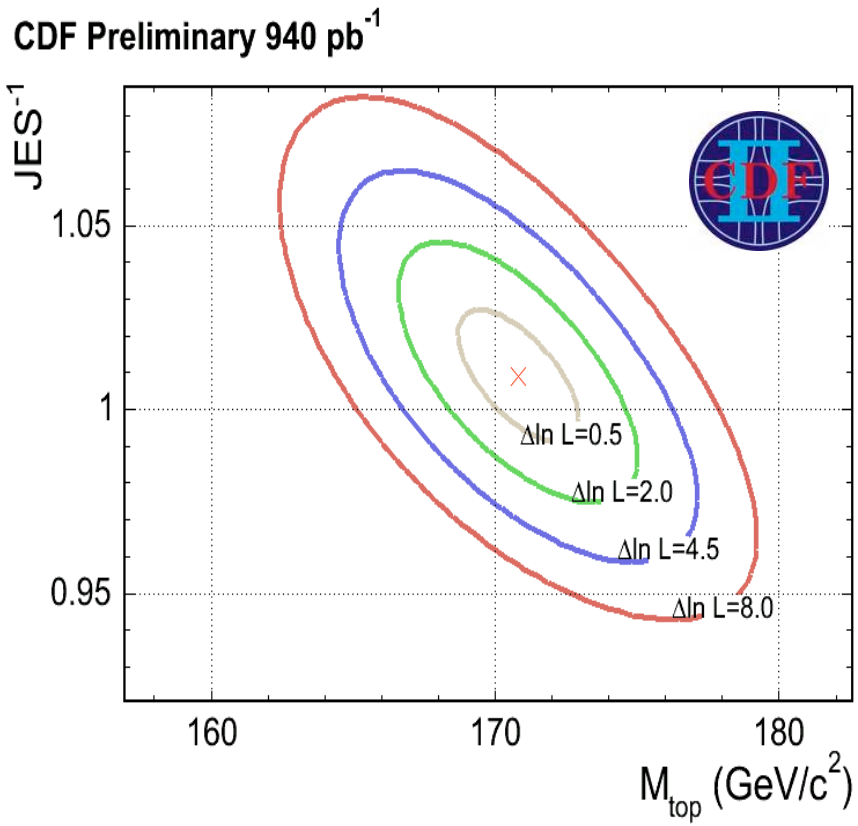


Matrix Element Method: Results

CDF, Lepton+Jets, 940 pb-1

m_t=170.9±2.2(stat+JES)±1.4(syst) GeV

Single best world measurement

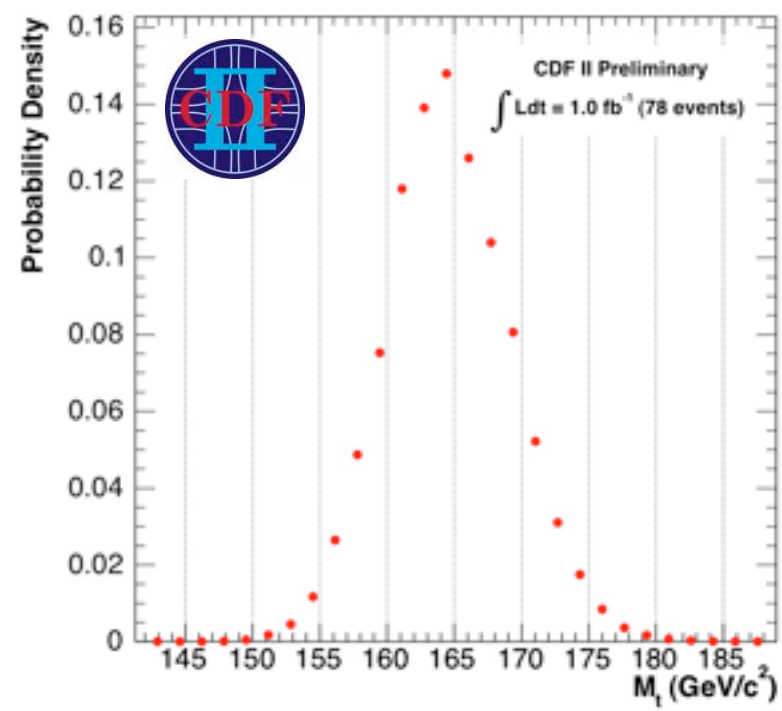


CDF, Dilepton, 1030 pb-1

m_t =164.5 ± 3.9 (stat) ± 3.9 (syst) GeV

w/o b-tagging

Single best world dilepton measurement



Matrix Element Method: Results

D0, Lepton+Jets, 370 pb-1

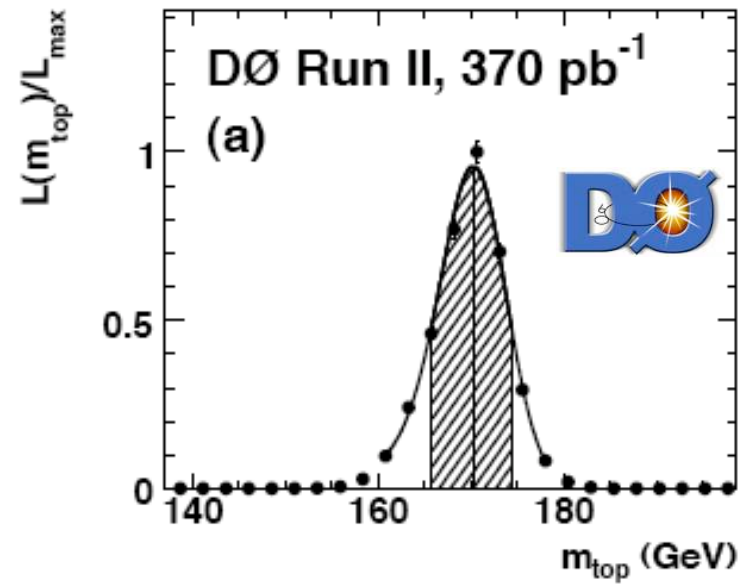
m_t=169.2 ± 4.3 (stat+JES) ± 1.4 (syst) GeV

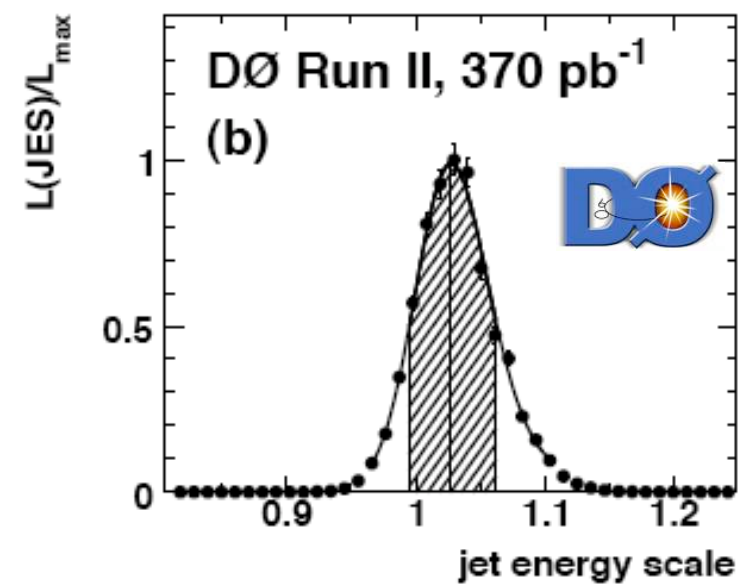
Single best D0 measurement

- As in the CDF template analysis, the data sample is subdivided in events with 0, 1, and 2 b-tags

★ ~20% improvement w.r.t. analysis w/o b-tagging

★ ~30% improvement w.r.t. requiring at least one b-tagged jet

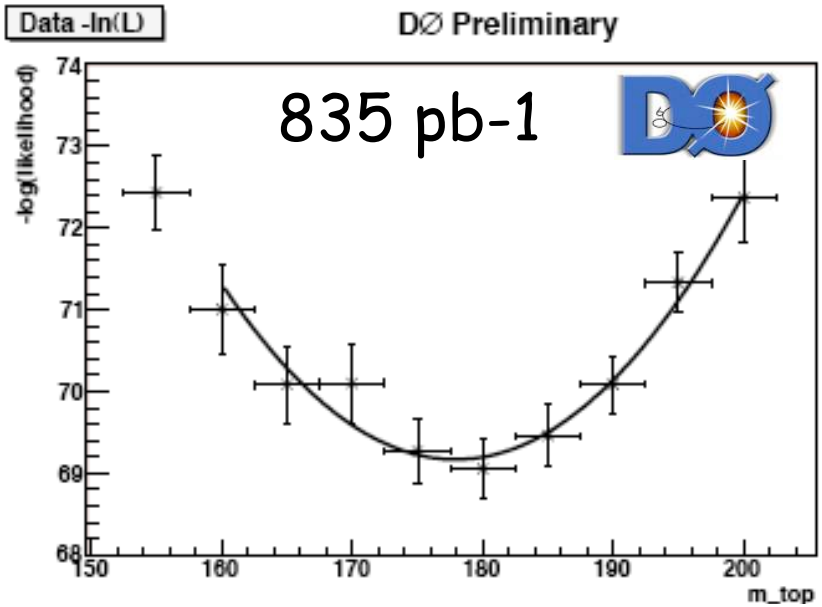


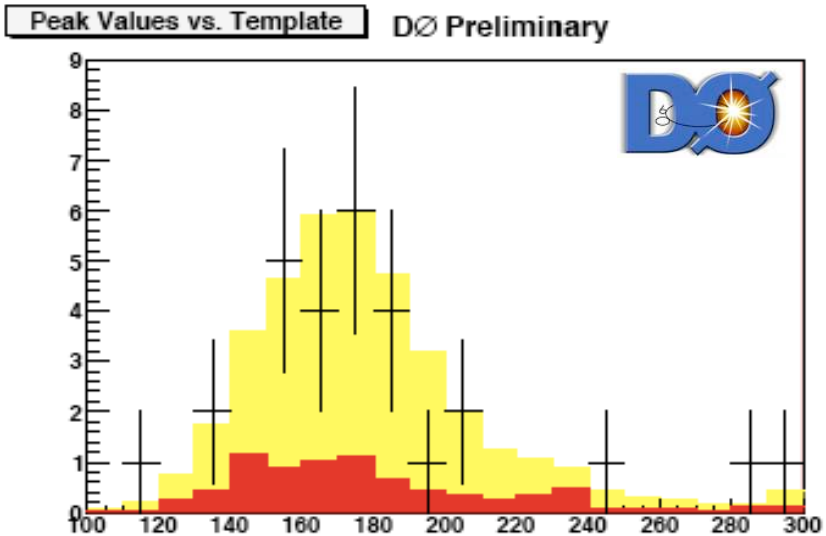


Matrix Weighting Method

- Template Method to be applied to Dilepton events
- Instead of a kinematic fit, solve the kinematic system of each event numerically
  - ★ up to four solutions for each assumed mass and each jet assignment
  - ★ calculate weight w(mtop) for each solution, based on PDFs and the probability for the lepton energies to arise from the top decay
  - ★ Resolution sampling: repeat procedure with the inputs smeared according to lepton and jet resolutions
  - ★ For each mtop, Sum up all the derived weights; the mtop with the highest weight is the estimated top mass for the event (~result of kinematic fit for lepton +jets)
  - ★ Alternative Analysis in preparation, where the kinematic solutions are calculated analytically, according to an algorithm developed by L. Sonnenschein: **Phys.Rev. D73 054015 (2006)**

m_t =177.7 ± 8.8 (stat) ± 4.3 (syst) GeV





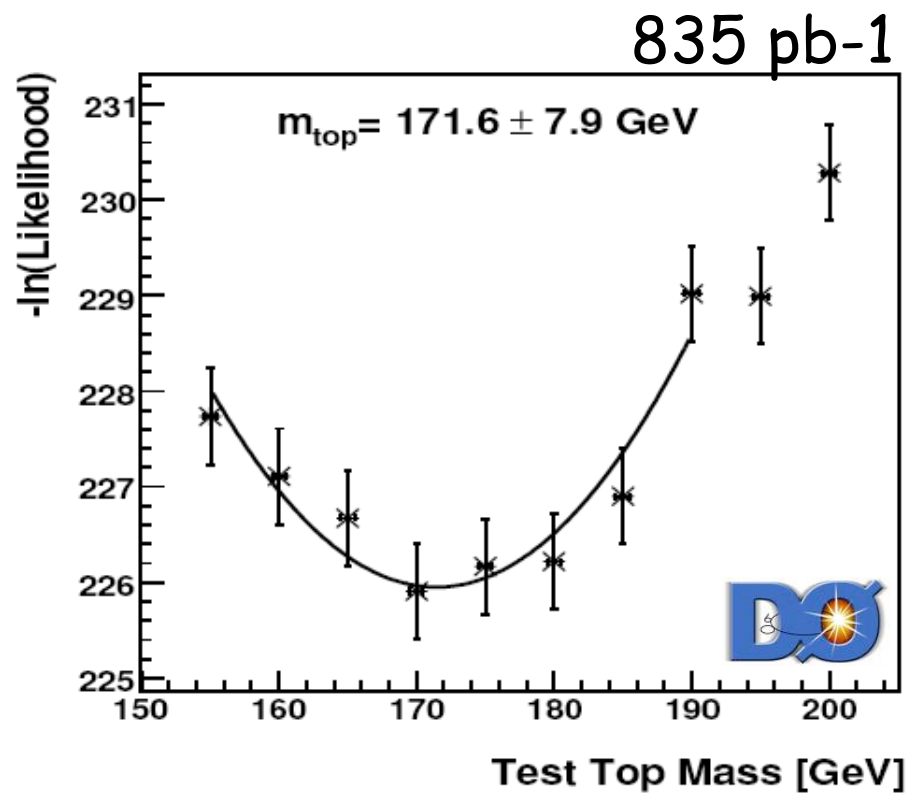
Neutrino Weighting Method

- Another Template Method to be applied to Dilepton events
- Instead of a kinematic fit, solve the kinematic system of each event assuming a top mass value and (several) pseudorapidities η of both neutrinos
  - ★ compute weight w(mtop) comparing the missing transverse energy inferred by the solution with the calorimeter measurement:

$$\omega = \frac{1}{N_{\text{iter}}} \sum_{i=1}^{N_{\text{iter}}} \exp\left(\frac{-(\not{E}_{x,i}^{\text{calc}} - \not{E}_x^{\text{obs}})^2}{2\sigma_{\not{E}_x}^2}\right) \exp\left(\frac{-(\not{E}_{y,i}^{\text{calc}} - \not{E}_y^{\text{obs}})^2}{2\sigma_{\not{E}_y}^2}\right)$$

  - ★ Resolution sampling: repeat procedure several times with inputs smeared according to detector resolutions
  - ★ For each event, a weight distribution as a function of the top mass is generated from the weighted neutrino solutions. Mean and RMS of that distribution are considered in the template analysis

m_t =171.6 ± 7.9 (stat) ± 4.6 (syst) GeV



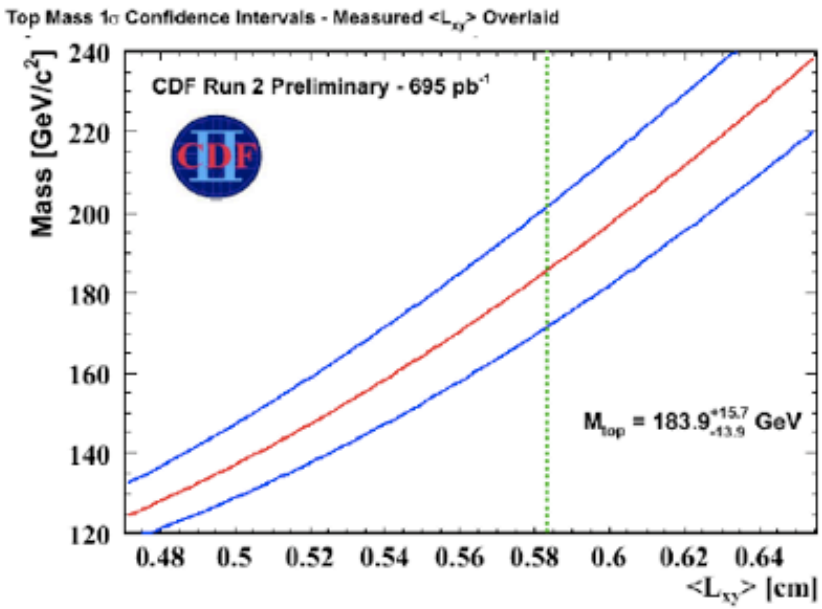
Decay-Length Technique

- At the Tevatron, where top pairs are produced approximately at rest, the boost given to the b-quark is correlated to the top mass:

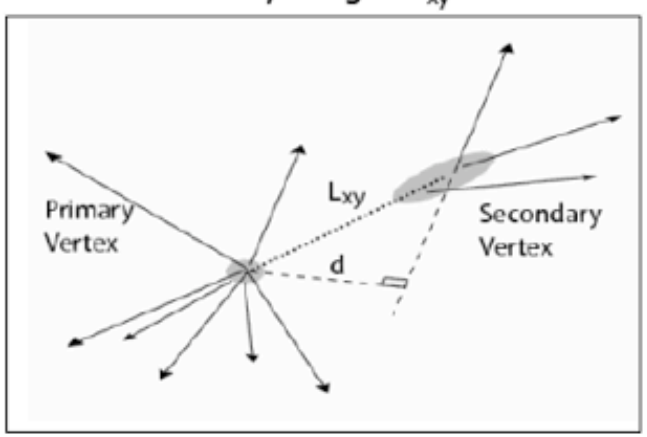
$$\gamma_b = \frac{m_t^2 + m_b^2 - m_W^2}{2 m_t m_b} \approx 0.4 \frac{m_t}{m_b}$$

- boost -> avg. lifetime -> avg. transv. decay-length
- With current statistics, this method is not competitive to other measurements yet
- no jet energy scale uncertainty, as the method relies purely on tracking
- Uncorrelated with other measurements

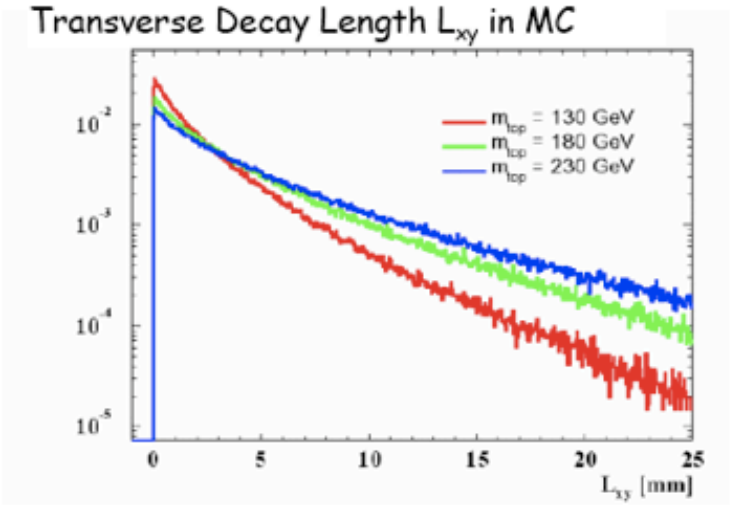
$m_t = 183.9\ ^{+15.7}_{-13.9}$ (stat.) ± 5.6 (syst.) GeV



Transverse Decay Length L_{xy}: Definition

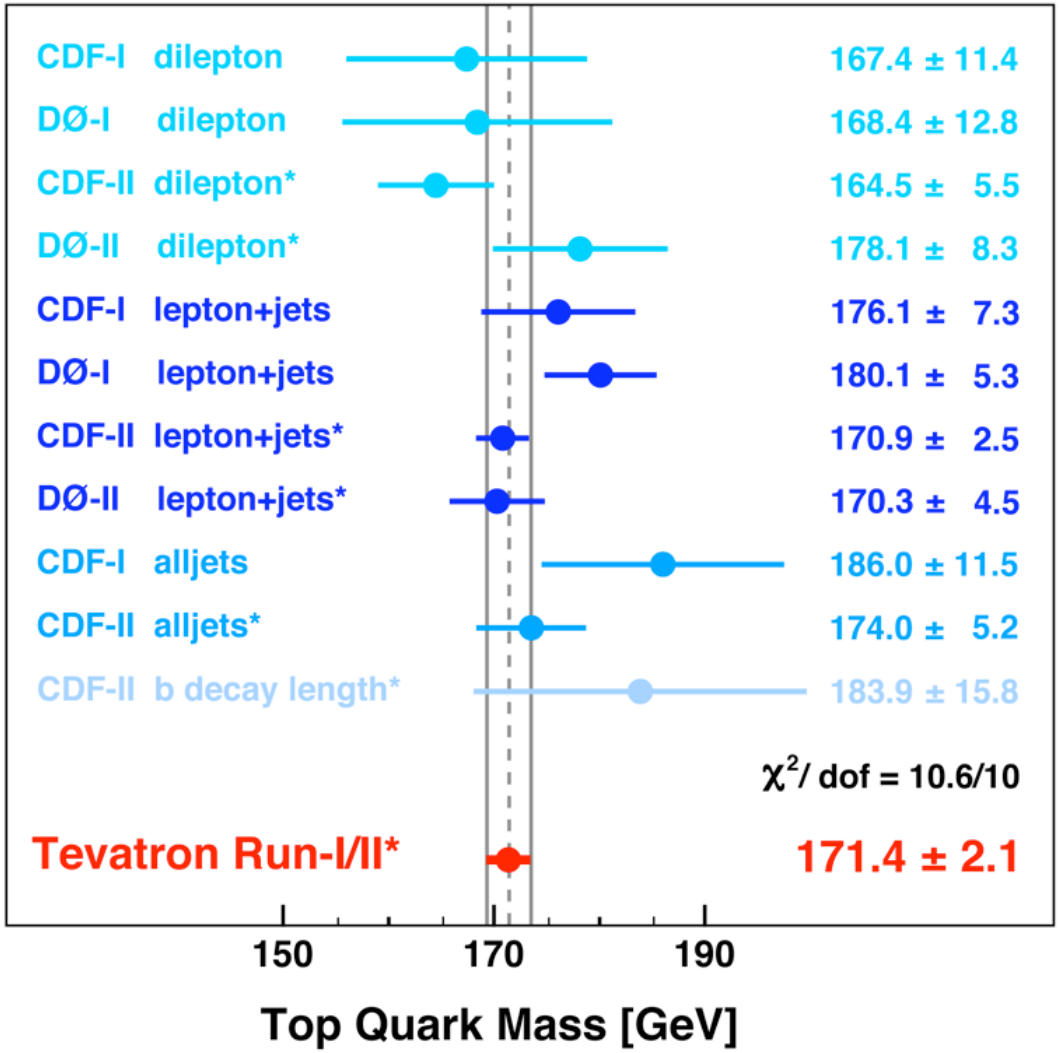


Transverse Decay Length L_{xy} in MC

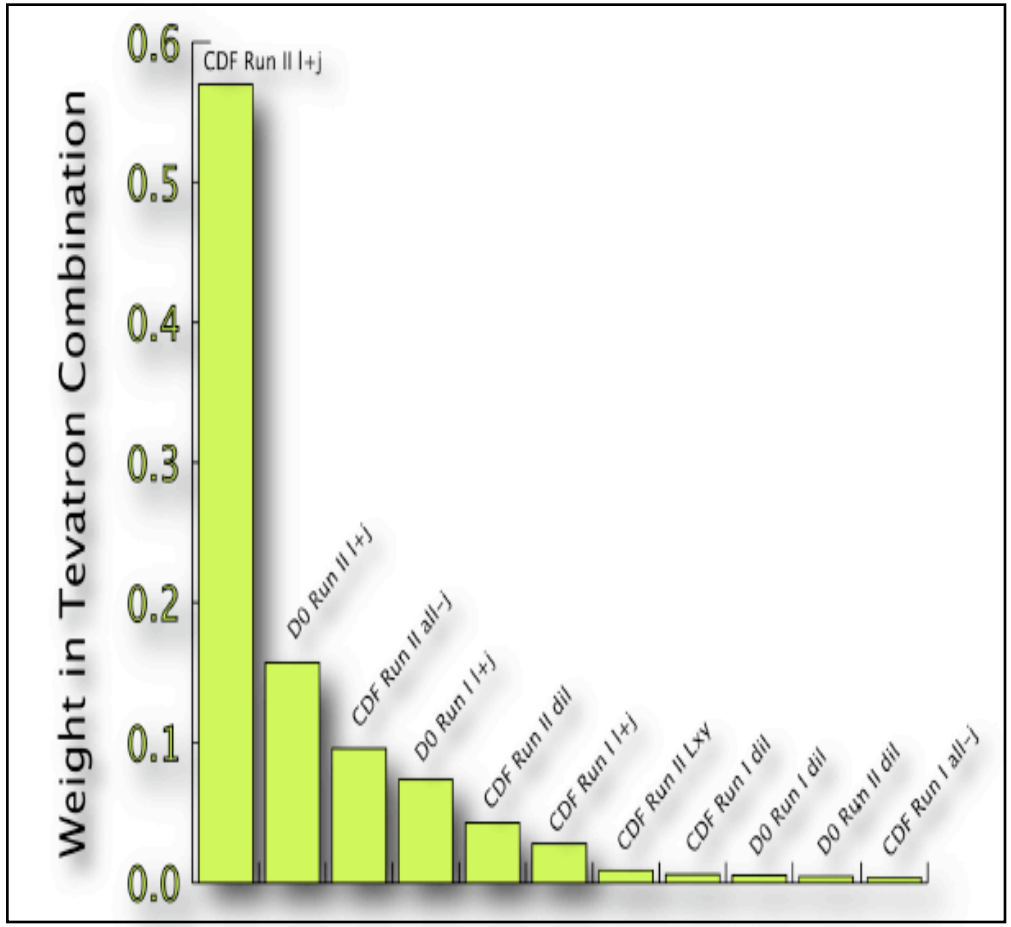


Current World Average:Overview

Best Independent Measurements of the Mass of the Top Quark (*=Preliminary)

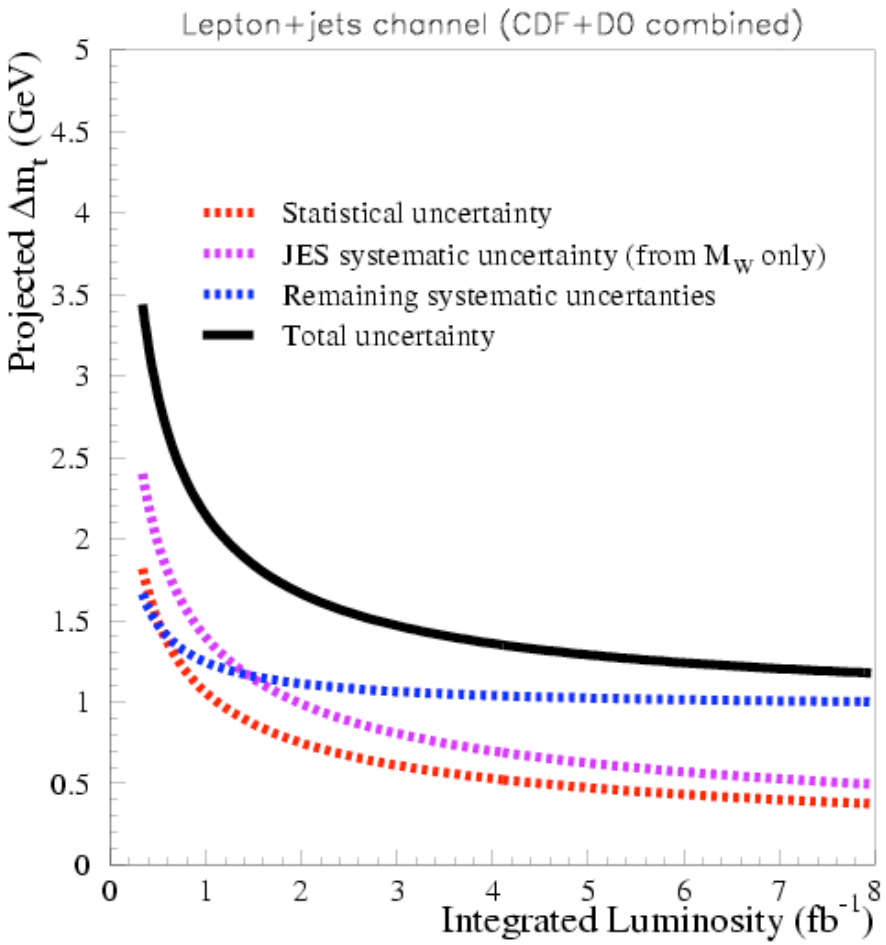


Individual Weights in World Average



Top Mass Error Projection

- The figure projects the future development of the Tevatron top mass precision in the lepton+jets channel
- With increasing statistics, both statistical and systematic JES precision (In-Situ Jet Energy Scale measurement!) keep improving
- The remaining systematic uncertainties hit a plateau though
- Fresh ideas and concepts needed to further improve the systematic precision, both at the Tevatron and LHC



Conclusion

- The Tevatron experiments CDF and D0 have measured the mass of the top quark with remarkable precision (1.2%)
- The precision is expected to improve further before LHC startup (<1%)
- The precision of the current world average is already limited by systematic uncertainties
  - ★Many "sophisticated" methods employed, designed to squeeze out the last bit of statistical information of only a few signal events
  - ★Future improvements to the precision of the top quark mass both at the Tevatron and the LHC require new ideas to reduce systematic uncertainties