Experimental aspects of top quark mass measurement

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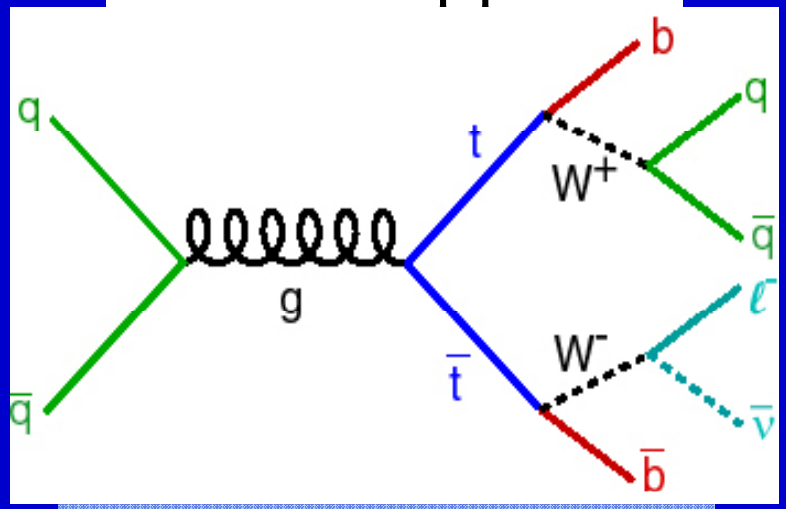
Outline

- Template method to measure top mass
- Matrix element method
  - Jet energy scale calibration on W-boson
- Controlling systematic uncertainties
- Top mass in dilepton channel
- New ideas
  - Top mass from b-meson lifetime
  - Top mass from cross section
- LHC era
- Conclusions

Challenges of M_{top} Measurement

Lepton+Jets Channel

$$t\bar{t} \rightarrow l\nu q\bar{q}'b\bar{b}$$



Observed Final state

$$l\not{E}_T + 4\text{jets}$$

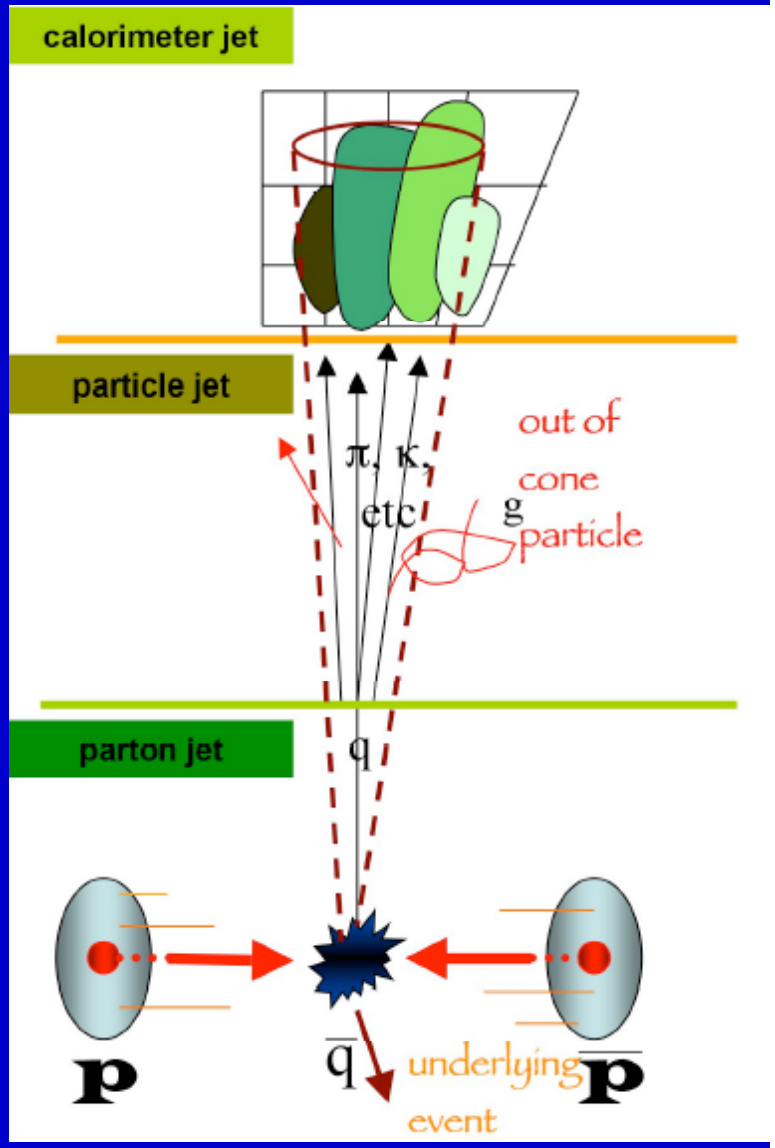
Complicated final state to reconstruct M_{top}

- **Combinatorics: leading 4 jets combinations**
  - **12 possible jet-parton assignments**
  - **6 with 1 b-tag (b-tag helps)**
  - **2 with 2 b-tags**
- **Jet energy scale and resolution**
  - **Note that two jets come from a decay of a particle with well measured mass – W-boson – built-in thermometer for jet energies**
- **Gluon radiation**
  - **Can lead to jet misassignment and**
  - **gluon radiation changes kinematics of the final state partons**
- **Backgrounds due to W+jets production**
  - **many diagrams, especially for high jet multiplicities → uncertainties in modeling, especially for heavy flavor jets**

Good b-tagging and jet energy scale and resolution and good algorithm to reconstruct M_{top}

Jets and partons

- Partons (quarks produced as a result of hard collision) realize themselves as jets seen by detectors
  - Due to strong interaction partons turn into parton jets
  - Each quark hardonizes into particles (mostly π and K's)
  - Energy of these particles is absorbed by calorimeter
  - Clustered into calorimeter jet using cone algorithm
- Jet energy is not exactly equal to parton energy
  - Particles can get out of cone
  - Some energy due to underlying event (and detector noise) can get added
  - Detector response has its resolution



Template method

A bit of history

- **Run 1 CDF's evidence PRD 50,2966(1994):**

  "Under the assumption that the excess yield over background is due to ttbar, constrained fitting on a subset of the events yields a mass of

  $174 \pm 10^{+13}_{-12}$ GeV/c^2

  for the top quark."

  7 events l+4jets (at least 1 b-tag)

  9.4% precision

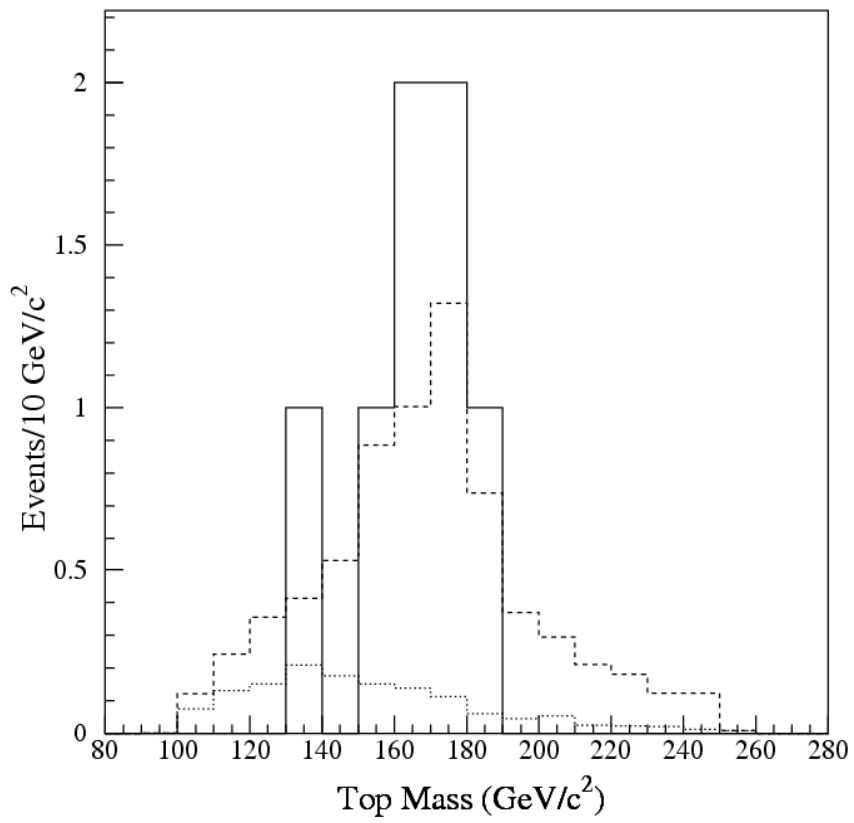


Figure 63: Top mass distribution for the data (solid histogram) and the background of 1.4 events (dots) obtained from the $W+$ multijets VECBOS events. The dashed histogram represents the sum of 5.6 $t\bar{t}$ Monte Carlo events (from the M_{top}=175 GeV/c^2 distribution) plus 1.4 background events.

Template method

$$\chi^2 = \Sigma_{i=\ell,4jets}\frac{(\hat{p}_T^i - p_T^i)^2}{\sigma_i^2} + \Sigma_{j=x,y}\frac{(\hat{p}_j^{UE} - p_j^{UE})^2}{\sigma_j^2} + \frac{(m_{jj} - m_W)^2}{\Gamma_W^2} + \frac{(m_{\ell\nu} - m_W)^2}{\Gamma_W^2} + \frac{(m_{bjj} - m_t)^2}{\Gamma_t^2} + \frac{(m_{b\ell\nu} - m_t)^2}{\Gamma_t^2}$$

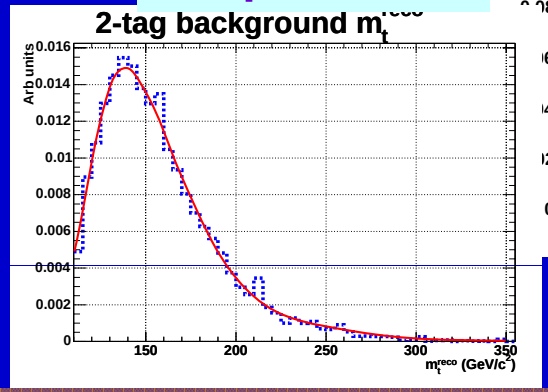
Select the reconstructed mass Mt from the choice of lowest χ^2

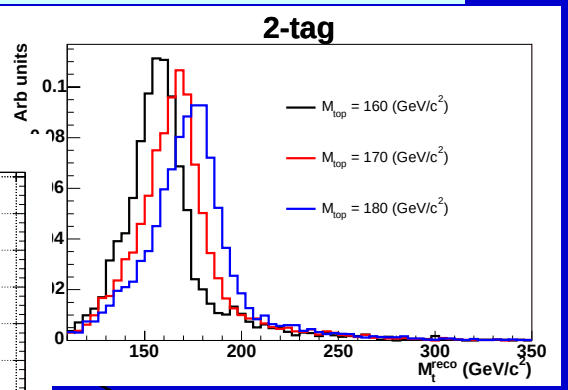
Form signal and background templates

Signals templates

background templates

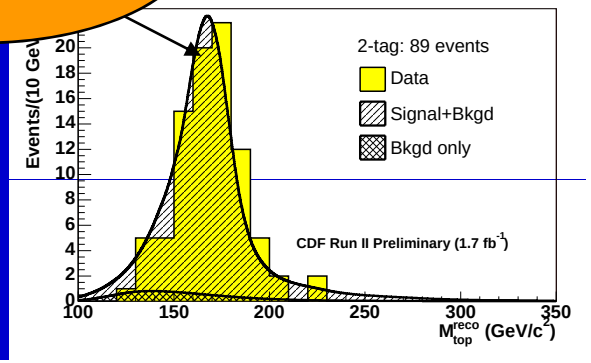
Top mass is free parameter





Likelihood fit

Result



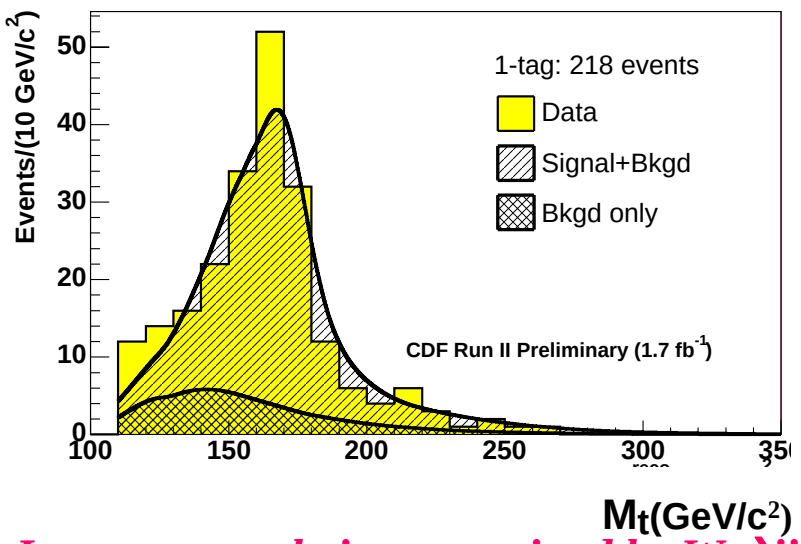
Likelihood fit:

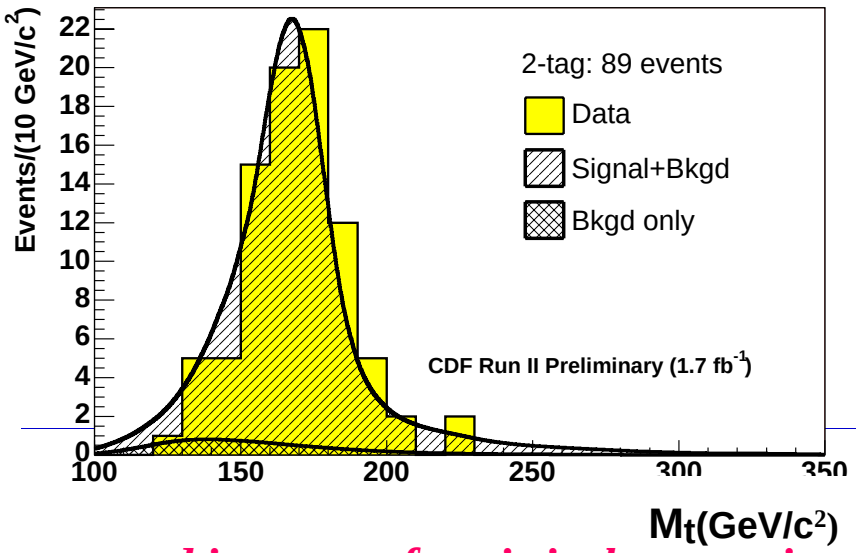
Best signal + bkgd templates to fit data with constraint on background normalization

CDF 1.7 fb^{-1}: $M_{top} = 171.6 \pm 2.1(\text{stat} + \text{JES}) \pm 1.1(syst)\text{GeV}/c^2$

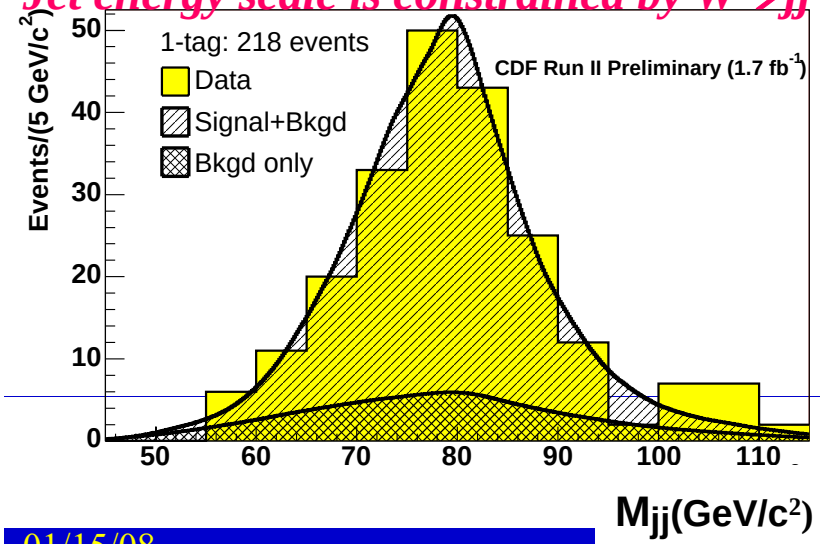
1 b-tag: 218 events(exp bg 36.6)

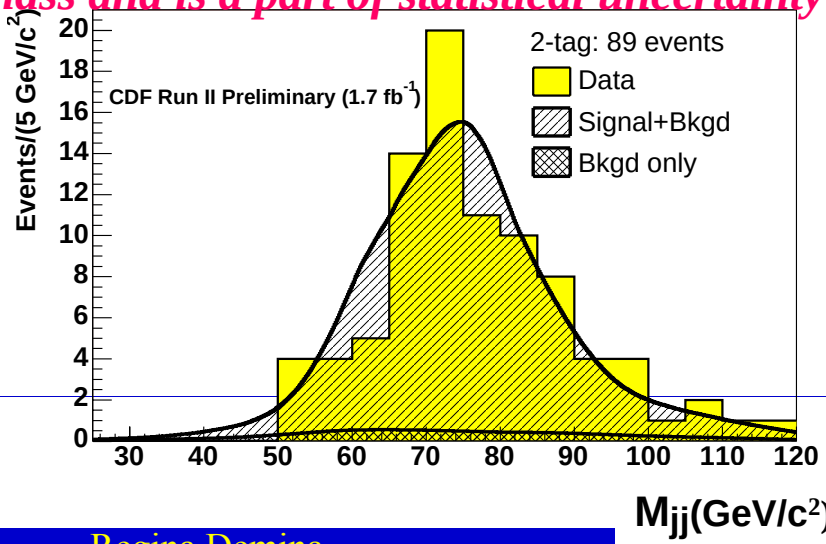
2 b-tags: 89 events(exp bg 6.4)



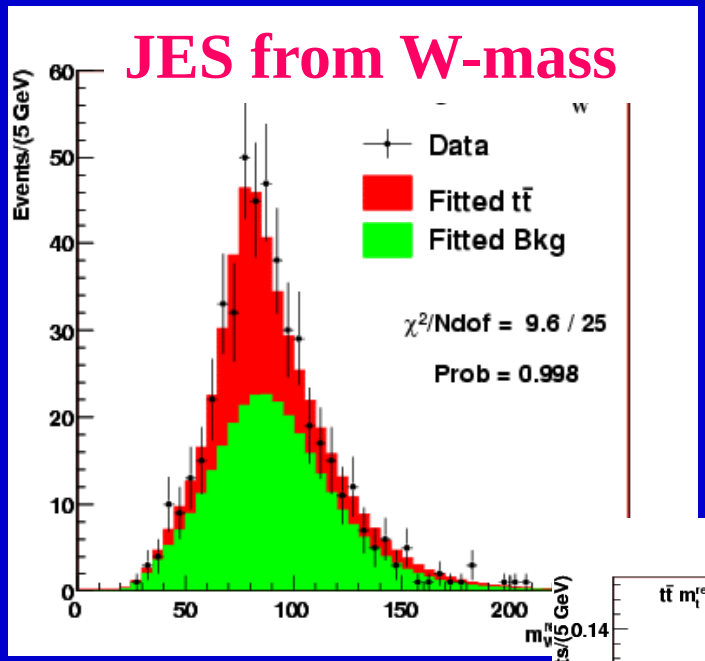


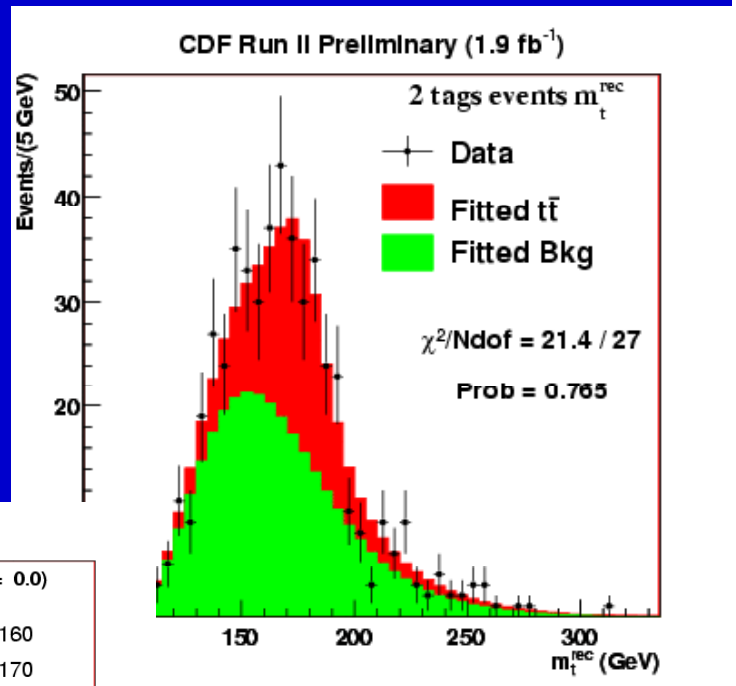
Jet energy scale is constrained by W→jj mass and is a part of statistical uncertainty

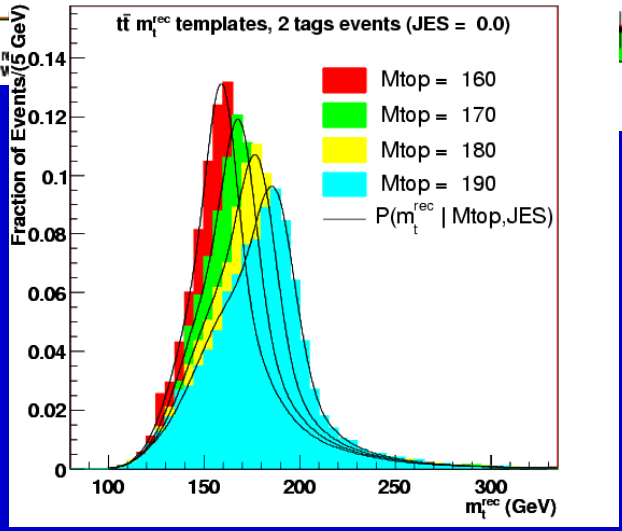




All hadronic channel, CDF 1.9/fb







- **Advantages**
  - **No neutrinos → no missing energy**
  - **Two hadronic tops, two hadronic W's (twice the calibration)**
  - **High statistics**
- **Disadvantages**
  - **High backgrounds**
  - **combinatorics**

Mt = 177.0 ± 3.8 (stat+JES) ± 1.6 (syst) GeV/c²

Matrix element method

- Method developed by DØ in Run I

Single most precise measurement of top mass in Run I

M_t =180.1±3.6(stat) ±4.0(syst) GeV/c^2=180.1±5.4 GeV/c^2

3% precision

Systematic error dominated by JES 3.3 GeV/c^2

Main strength of the method comes from accounting for resolutions on event by event basis

Matrix Element Method

probability to observe a set of kinematic variables *x* for a given top mass

d*^{n}*σ is the differential cross section
Contains **matrix element** squared

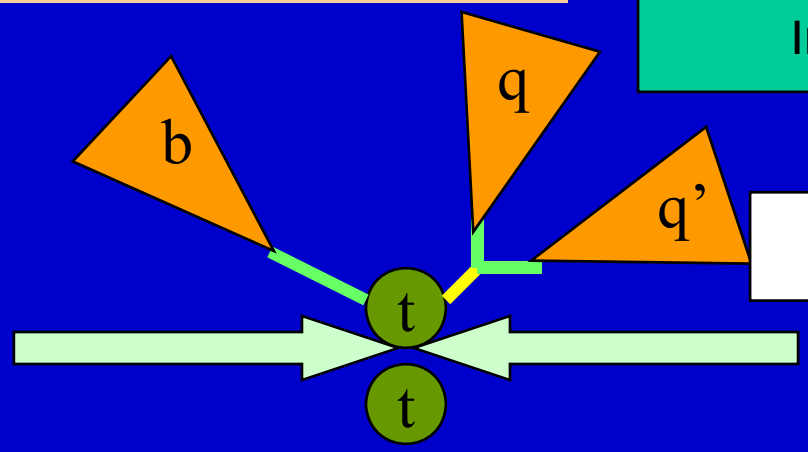
W(x,y) is the probability that a parton level set of variables ***y*** will be measured as a set of variables ***x***

$$P_{\mathrm{sgn}}(x;m_t) = \frac{1}{\sigma(m_t)} \int d^n\sigma(y;m_t)\, dq_1\, dq_2\; f(q_1)\, f(q_2)\, W(x,y)$$

f(q) is the probability distribution than a parton will have a momentum ***q***

Normalization depends on m_t
Includes acceptance effects

Integrate over unknown q_1,q_2, y

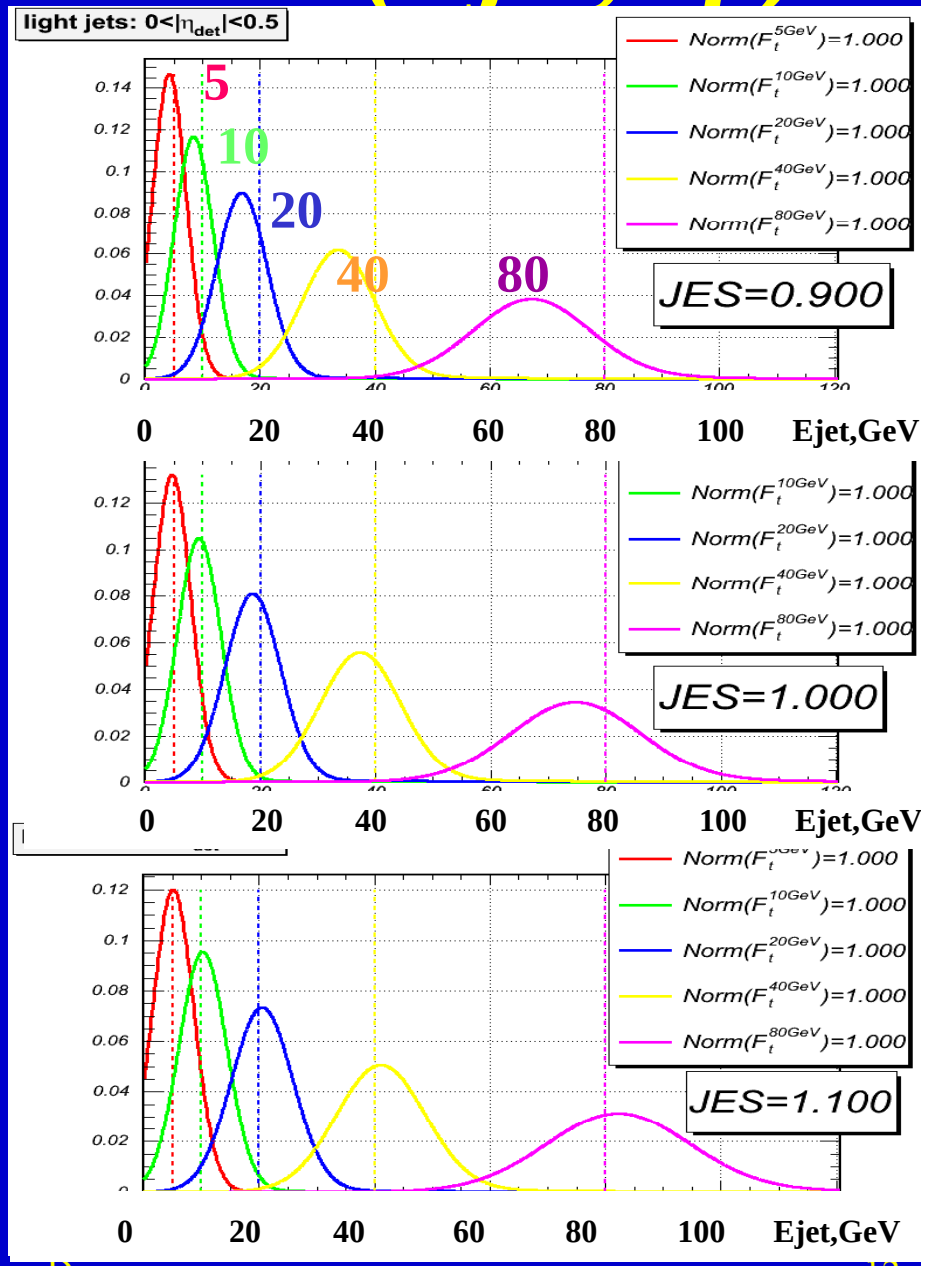


$$P_{evt}(x,m_t) = f_{top} \cdot P_{\mathrm{sgn}}(x,m_t) + (1 - f_{top}) \cdot P_{bkg}(x)$$

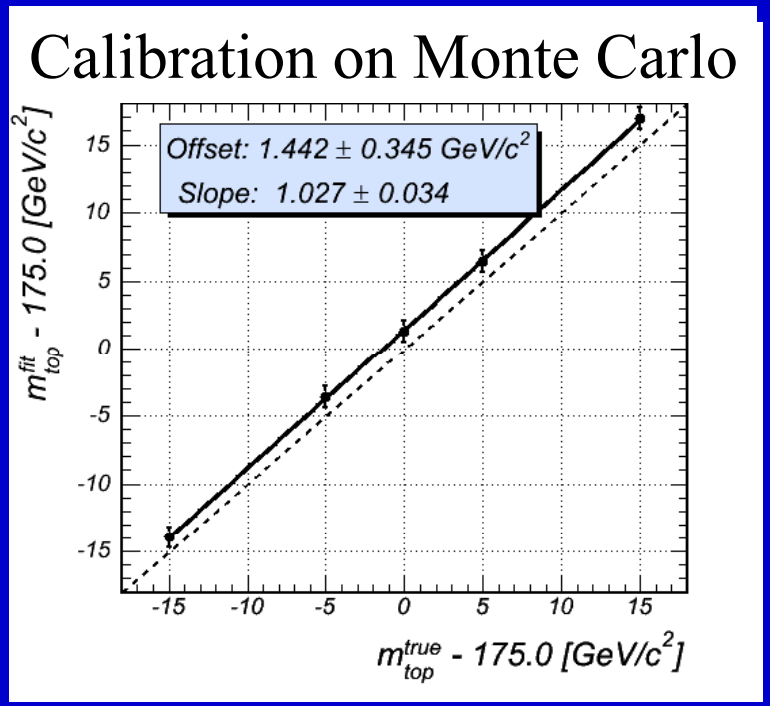
Transfer functions *W(Ejet,Ep)*

- The probability that a parton of energy Ep is measured as a jet of energy Ejet
- First all jets are corrected by standard CDF or DØ JES(p_T,, η)
- Overall JES is a free parameter in the fit – it is constrained in situ by mass of W decaying hadronically
- JES enters into transfer functions

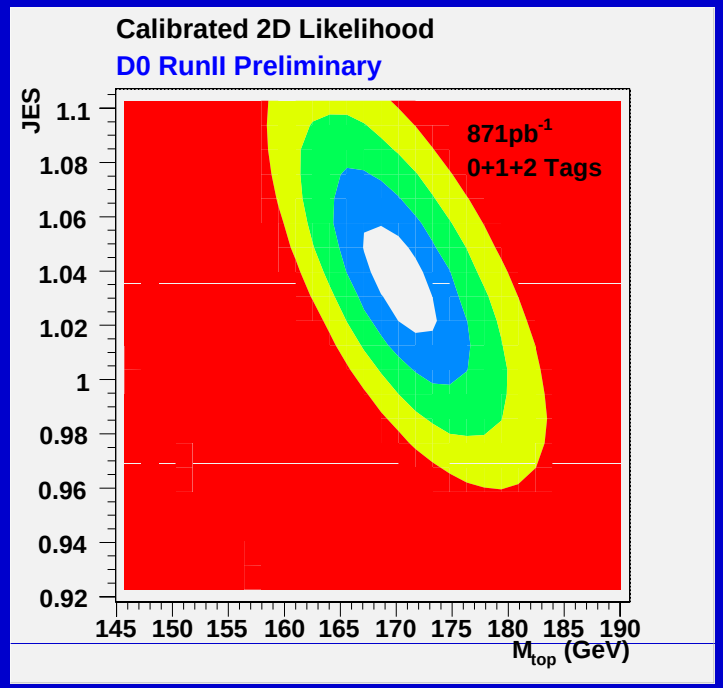
$$W(E_j, E_p, JES) = \frac{W\left(\frac{E_j}{JES}, E_p\right)}{JES}$$



M_t= 170.5±2.4(stat+JES)±1.2(sys)= 170.5±2.7 GeV/c^2



D0, 0.9/fb



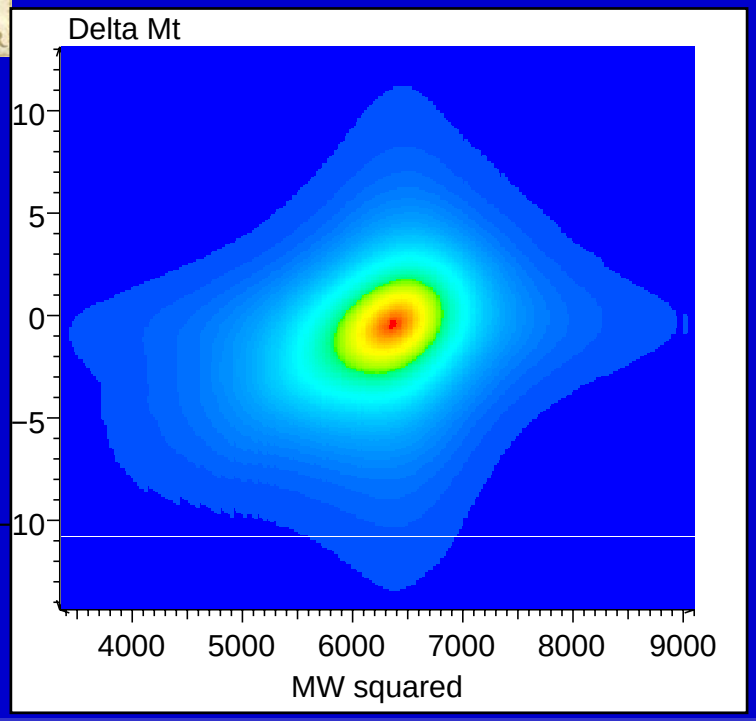
New in this analysis:

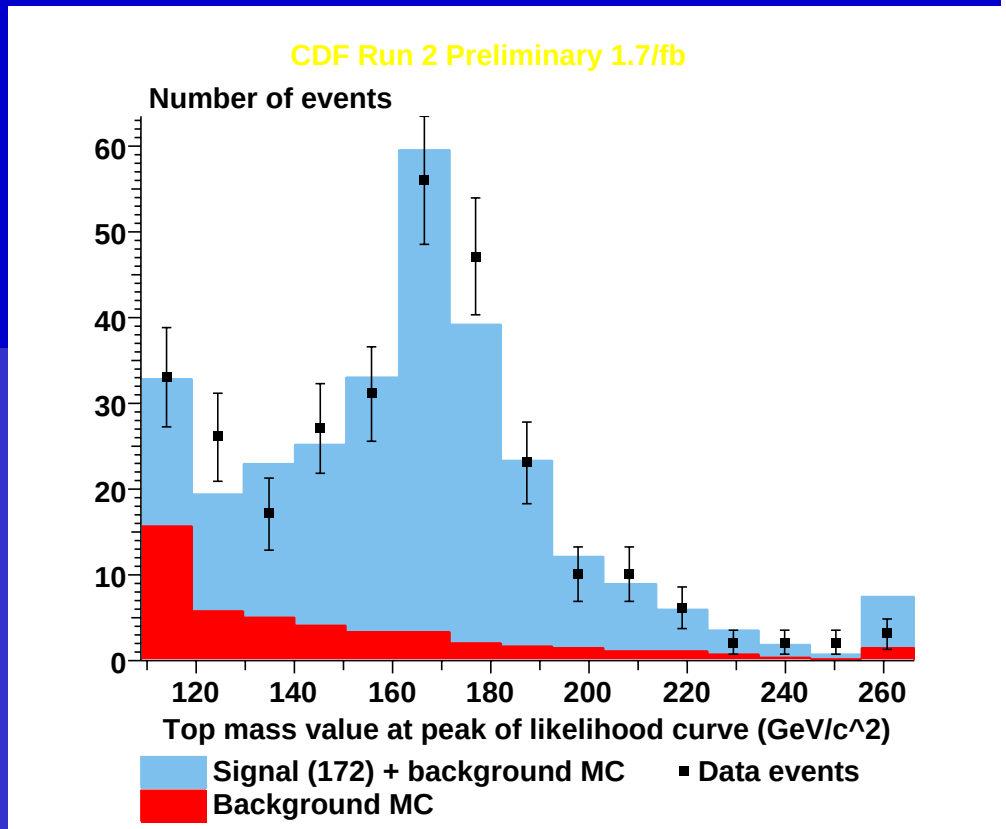
- 0,1 and 2 b-tag events are treated separately, permutations are weighted by the b-tagging probability
- Integrate over Pt of ttbar system

M_t=172.7±1.3(stat)±1.2(JES)±1.2(sys)=172.7±2.1GeV/c^2

Most precise single result 1.2%

CDF, 1.7/fb





New in this analysis:

- Employ effective propagator in ME to account for uncertainties on final state parton angles
- Background ME is not integrated instead the average background likelihood, weighted by background fraction is subtracted from likelihoods for each individual event

Systematics summary

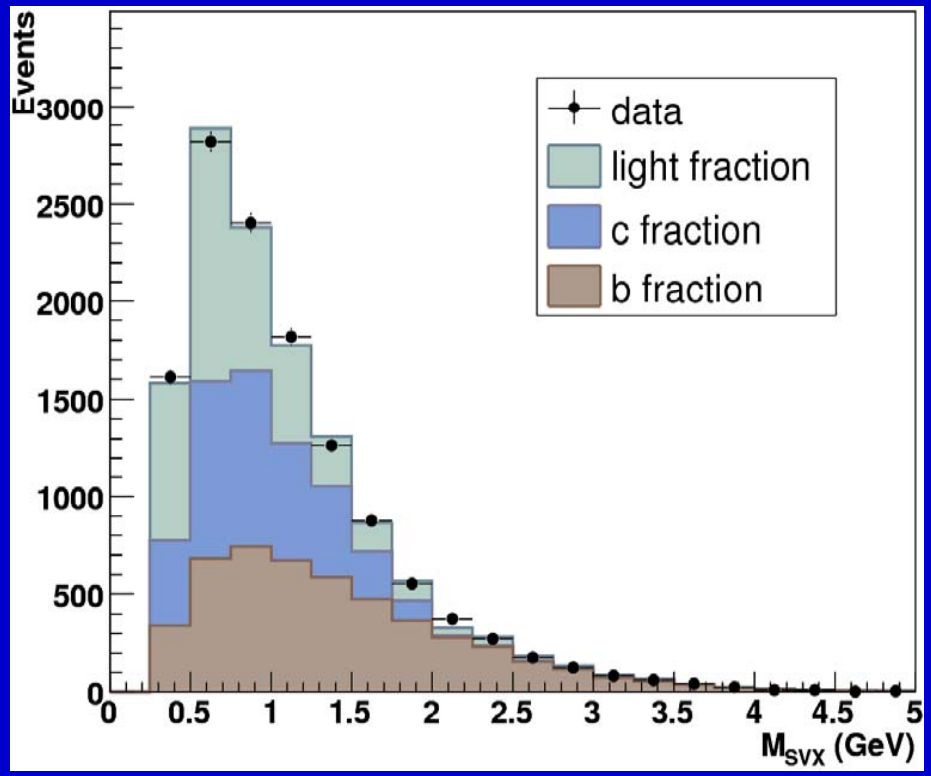
Systematic source	Systematic uncertainty (GeV/c^2)
Calibration	0.09
MC generator	0.19 ± 0.36
ISR	0.26 ± 0.37
FSR	0.13 ± 0.38
Residual JES	0.53
b-JES	0.36
Lepton P_T	0.11
Permutation weighting	0.03
Multiple interactions	0.05
PDFs	0.25
Background fraction	0.33
Background composition	0.39
Background average shape	0.31
Background Q^2	0.07 ± 0.20
Gluon fraction	0.14
b-tag E_T dependence	0.16
Total	1.16

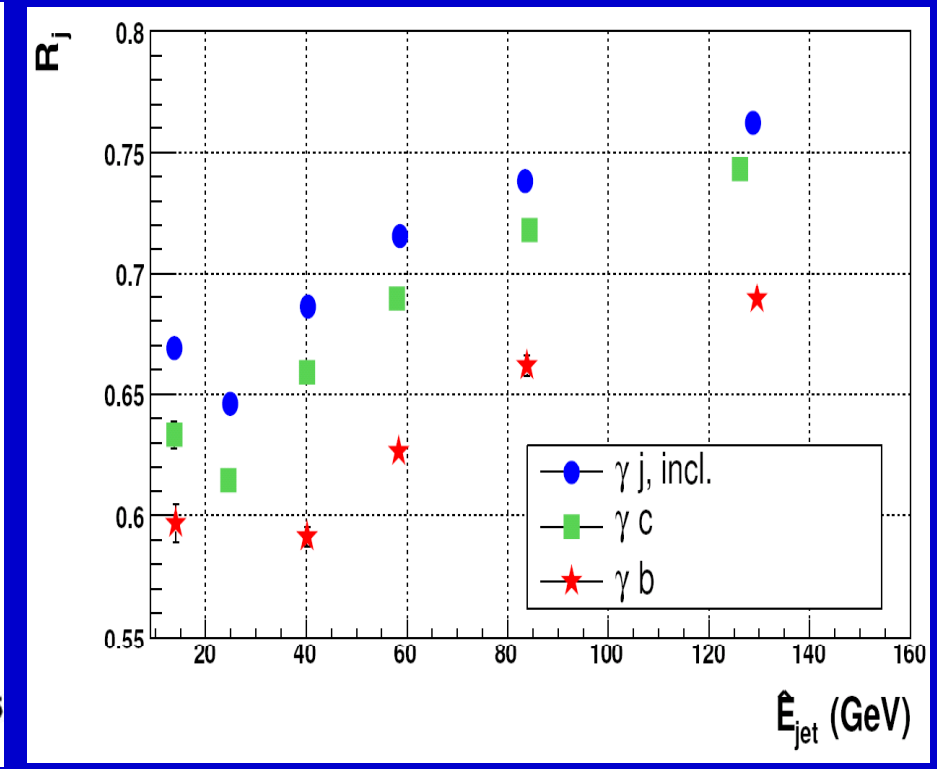
Systematic estimation

- ***Residual JES***: Accounts for potential dependence of JES on jet P_T and η. (this uncertainty will go down with more statistics in JES calibration samples)
- ***b-JES:*** Jets produced by b quarks have somewhat different response compared to light jets from W-boson decay. This difference is modeled in Monte Carlo, but there is an additional uncertainty of 0.6% in their jet energy scale due to uncertainties in the *b fragmentation* and semileptonic decay.
- ***Background composition:*** We run pseudo-experiments in which the background is entirely W+bbar, W+ccbar/c, W+light, or QCD (analyses are on the way to measure the fraction of heavy flavor in W+jets more precisely)

b-Jet Energy Scale

- DØ measures *b*-jet response in γ+b-tagged jet data → this systematic uncertainty will be reduced with more data
- Challenge: disentangle sample composition – use vertex mass

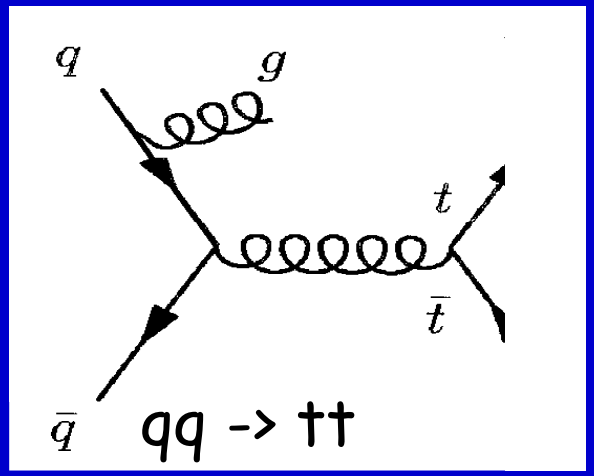


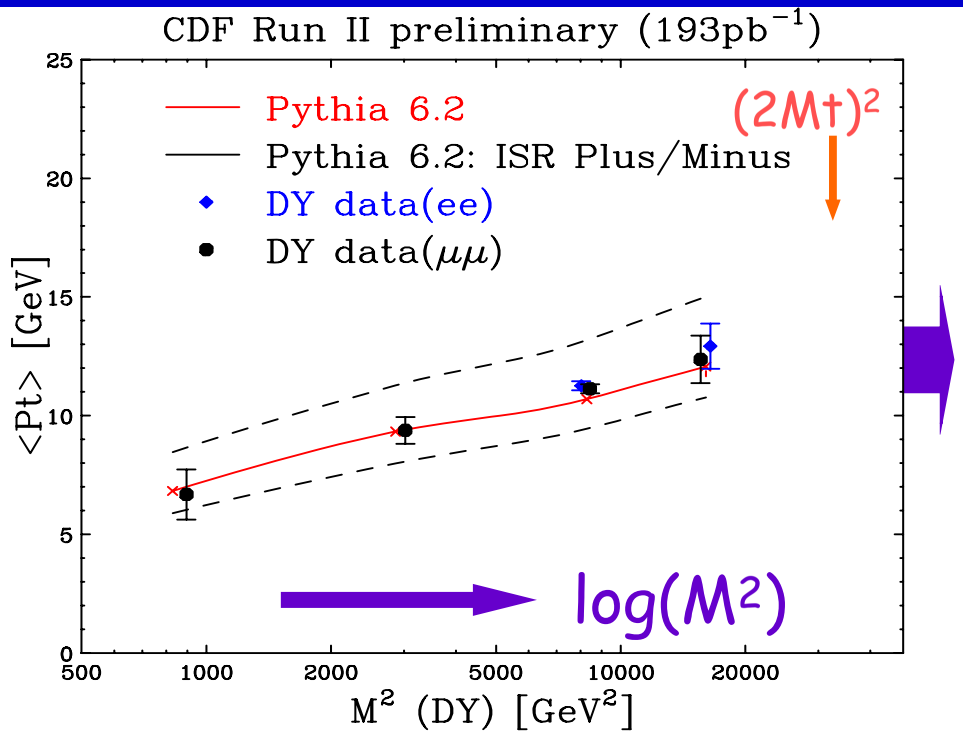


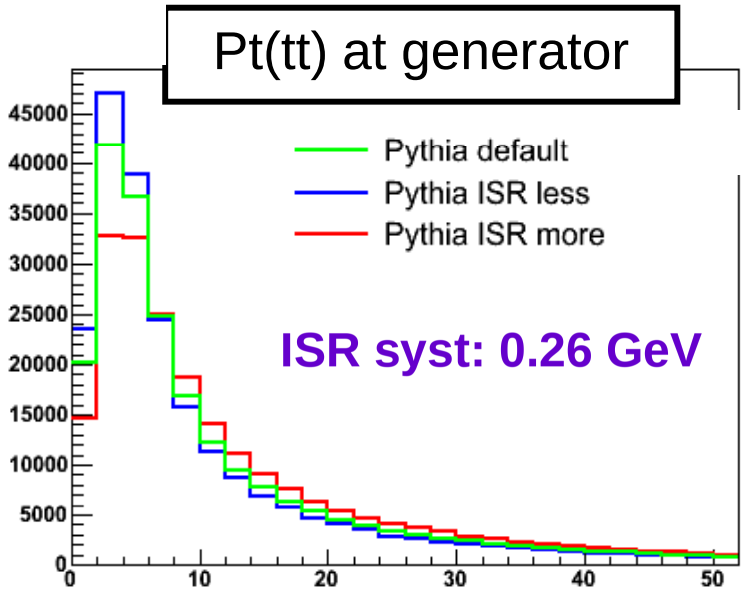
CDF:How to control ISR?

- In Run I, switch ISR on/off using PYTHIA, δMtop = 1.3GeV

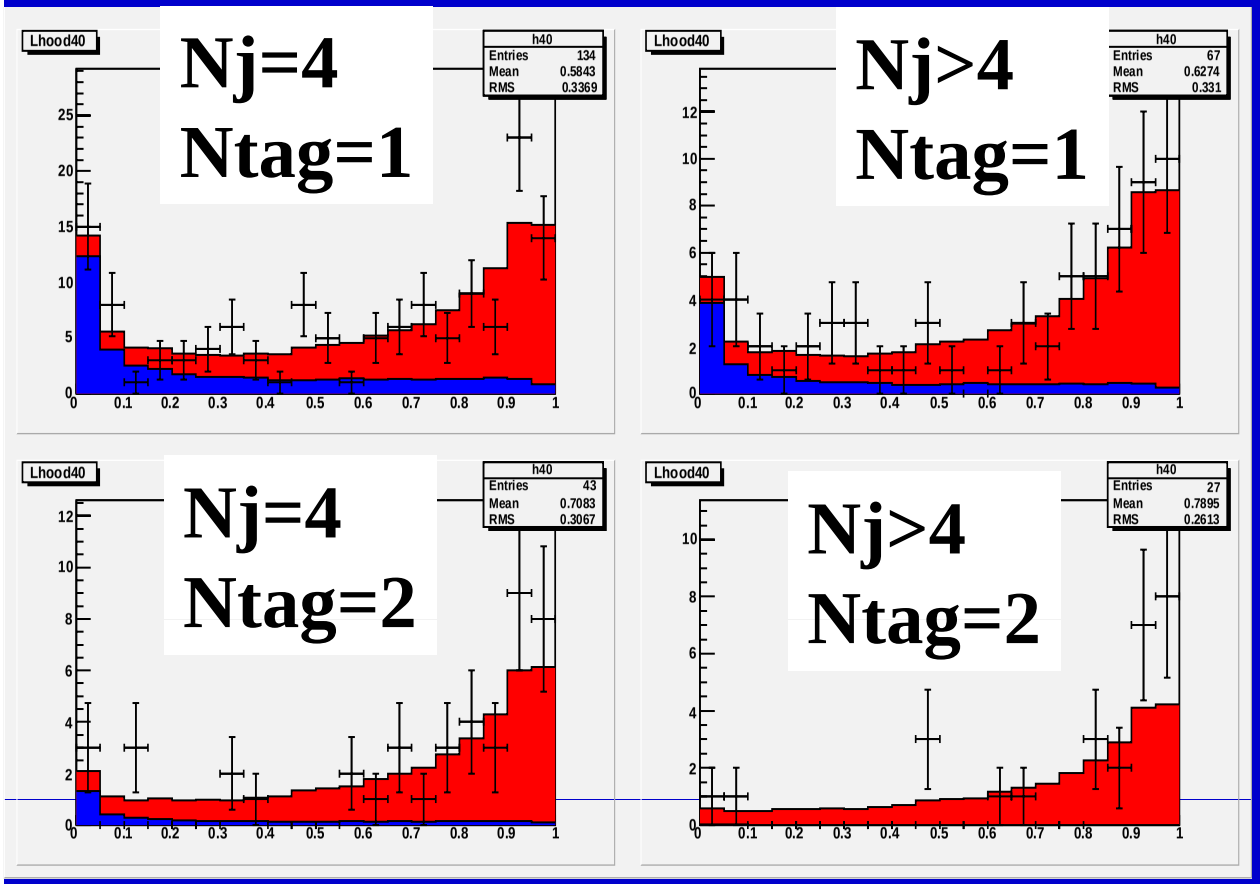
- In Run II: systematic approach
  ISR/FSR effects are governed by DGALP evolution eq.:
  <Pt> of the DY(ll) as a function of Q^2







DØ: constrain MC by measuring the rate of extra jets in ttbar events



- Extra jets are produced in ttbar events largely due to ISR/FSR
- By measuring the relative rate of such events we can determine MC parameters that control ISR/FSR
- Statistical uncertainty of our sample determines the range for MC parameters
- Then we vary these parameters within this uncertainty to study the effect on top mass

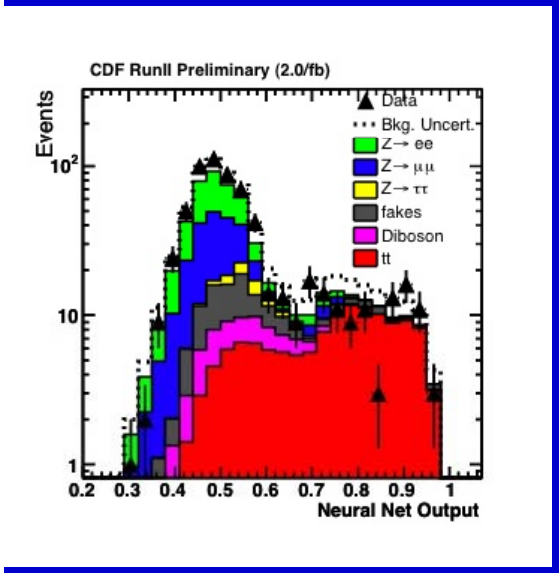
The variation range will be reduced with more statistics, thus this systematic uncertainty will go down with more data.

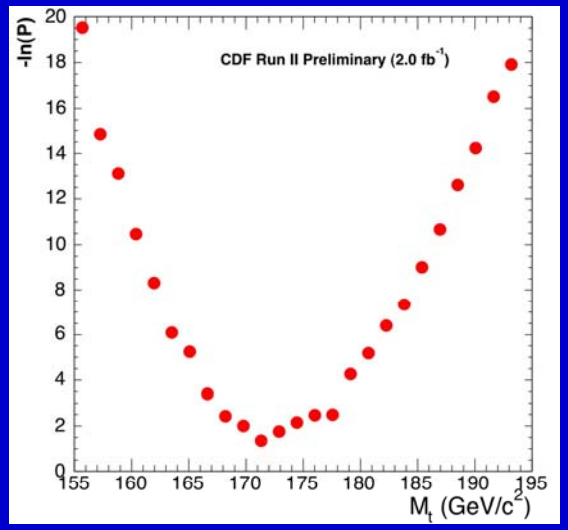
Top mass in dilepton channel

Matrix element in dileptons with neuroevolution selection

- Natural extension of ME technique approach - integrate over the unknowns. In this case – neutrino momenta.
- Starting from a very loose dilepton selection CDF uses evolutionary approach to directly search for the neural network that provides the best uncertainty on the top mass. 344 events are selected

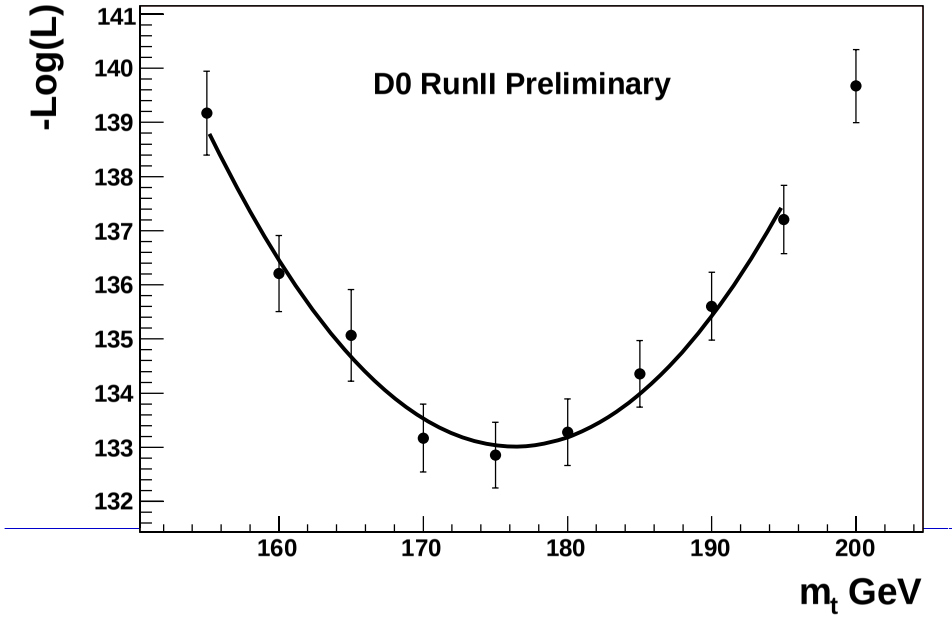
CDF(2/fb): Mt=171.2±2.7(stat)±2.9(syst) GeV/c^2

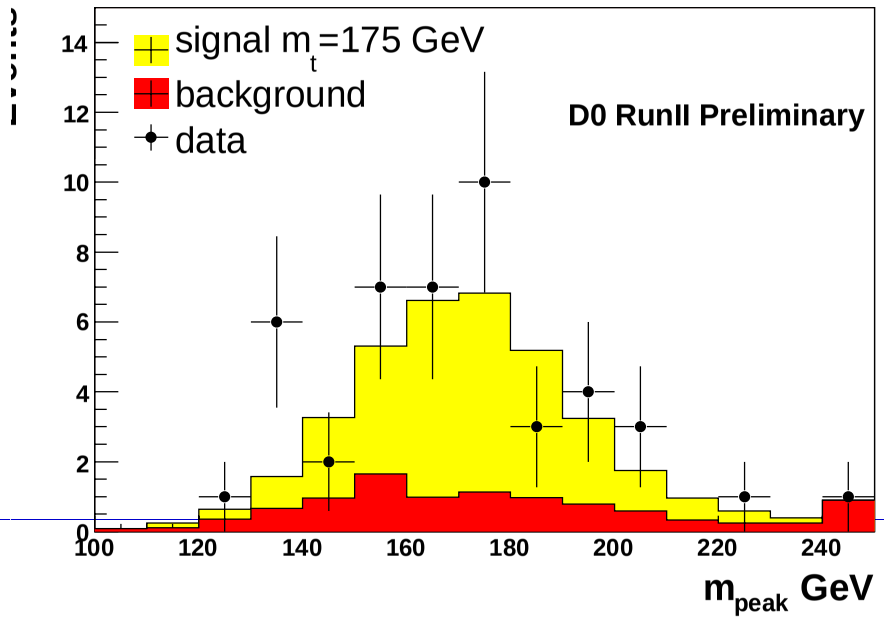




Matrix weighting method for dilepton events

- Suggested by Dalitz, Goldstein PRD 45,1531(1992)
- Each solution is assigned a weight depending on the PDF and the probability for a hypothesized Mt that each lepton has the observed energy
- DØ(1/fb): Mt=175.2±6.1(stat)±3.4(syst) GeV/c^2



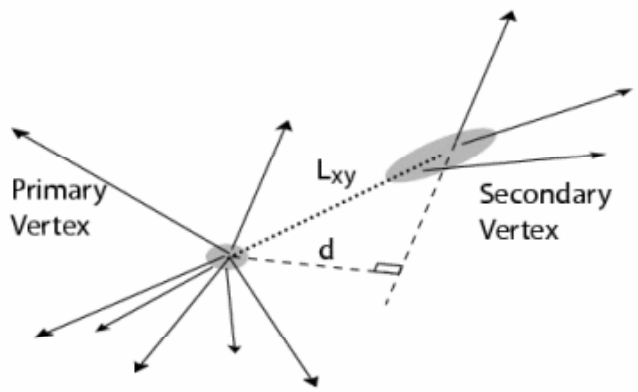


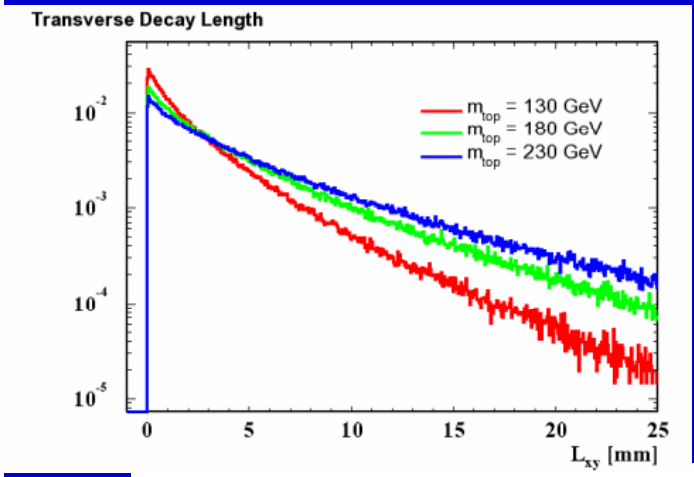
New ideas

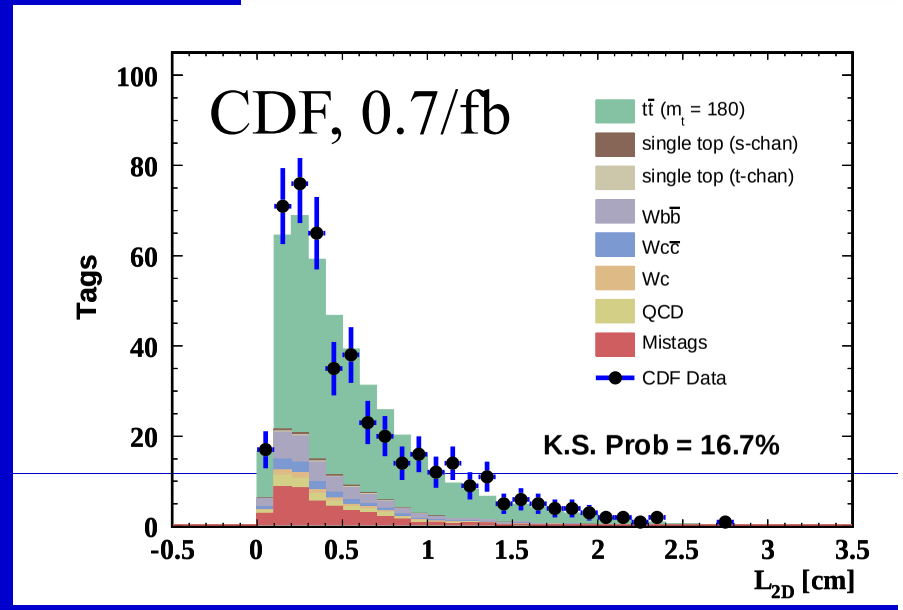
New ideas

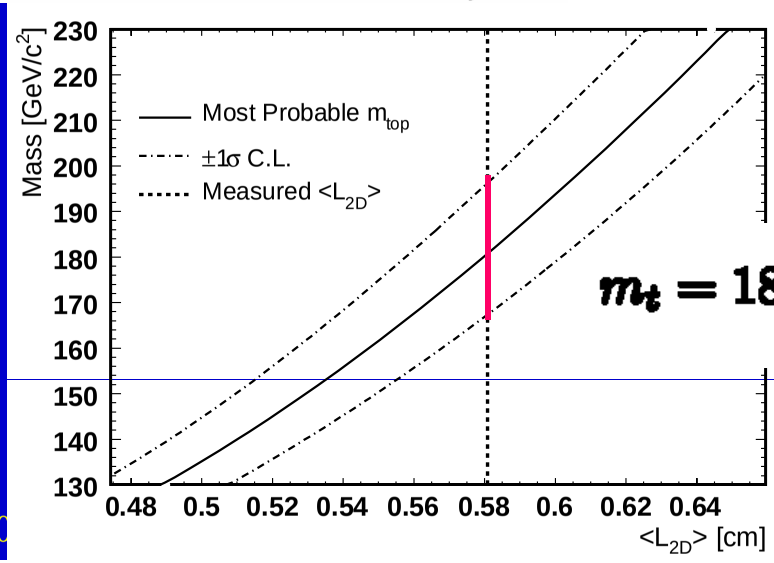
Top mass from b-meson decay length

Correlated with top mass through Lorentz boost





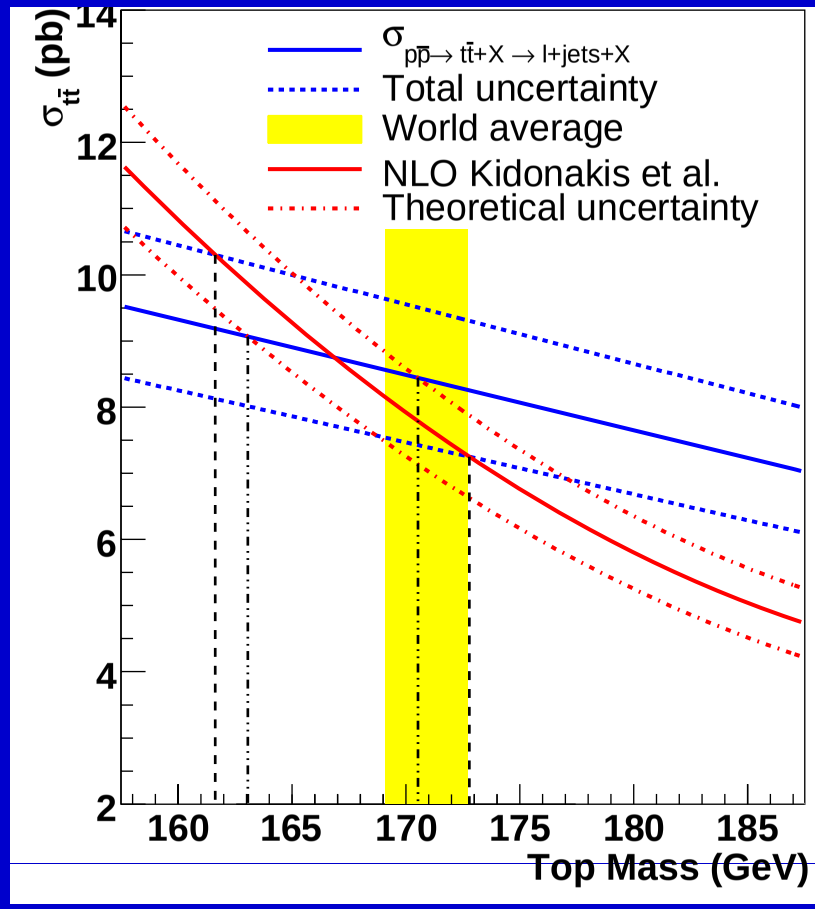




$$m_t = 180.7\ ^{+15.5}_{-13.4}\ (stat.) \pm 8.6\ (syst.)\ GeV/c^2$$

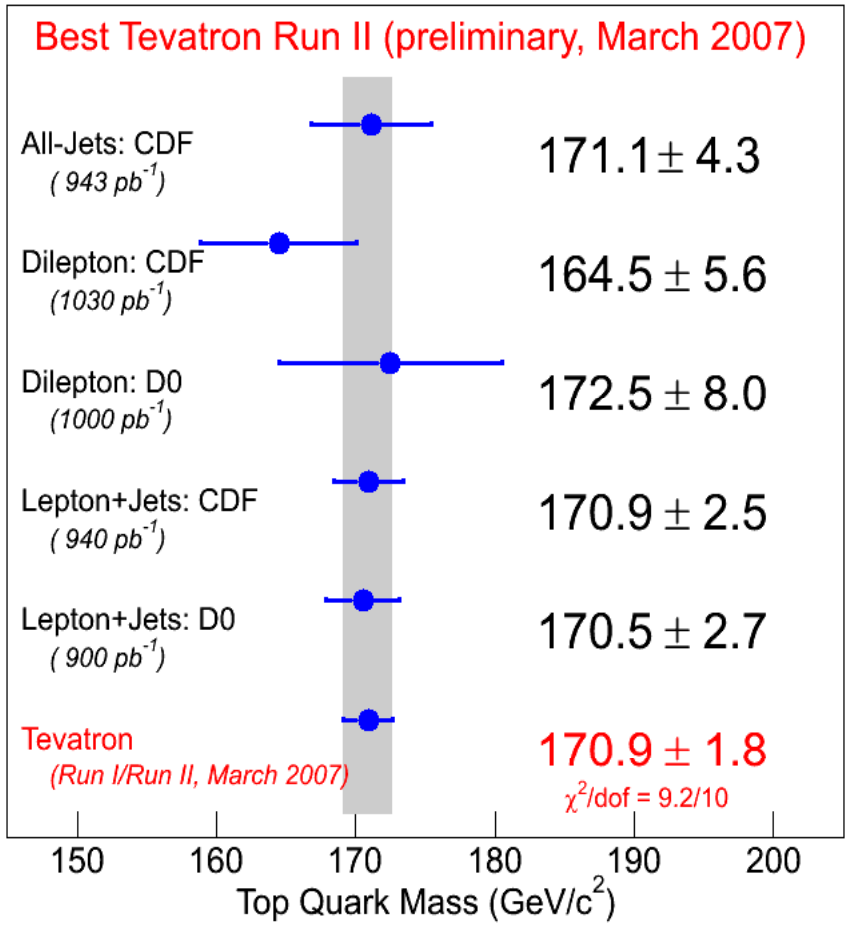
New ideas: Top mass from cross section

- DØ 1.0/fb
- Lepton+jets:
  - a) 166.9+5.9–5.2 (stat+syst)+3.7–3.8 (theory) GeV (th: Kidonakis and Vogt)
  - b) 166.1+6.1–5.3 (stat+syst)+4.9–6.7 (theory) GeV (th: Cacciari et al.)
- Dileptons:
  - c) 174.5+10.5–8.2 (stat+syst)+3.7–3.6 (theory) GeV (th:Kidonakis and Vogt)
  - d) 174.1 +9.8–8.4 (stat+syst) +4.2–6.0 (theory) GeV(th:Cacciari et al.)

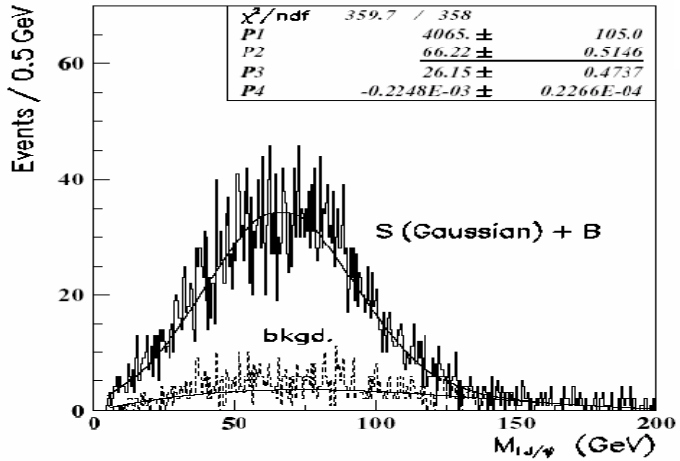


Combination

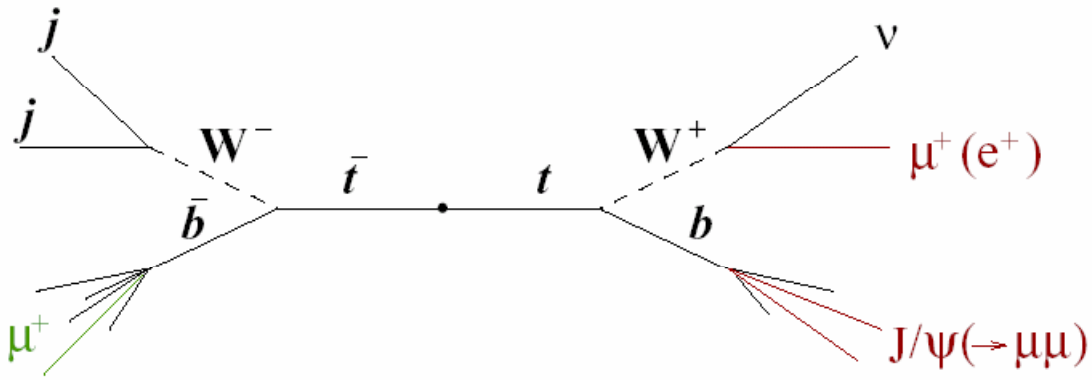
- **Does not use the latest results presented today**
- **Mt = 170.9±1.8 GeV/c^2**
- ***hep-ex/0703034*.**
- Top quark Yukawa coupling to Higgs boson
- g_t=0.982±0.010

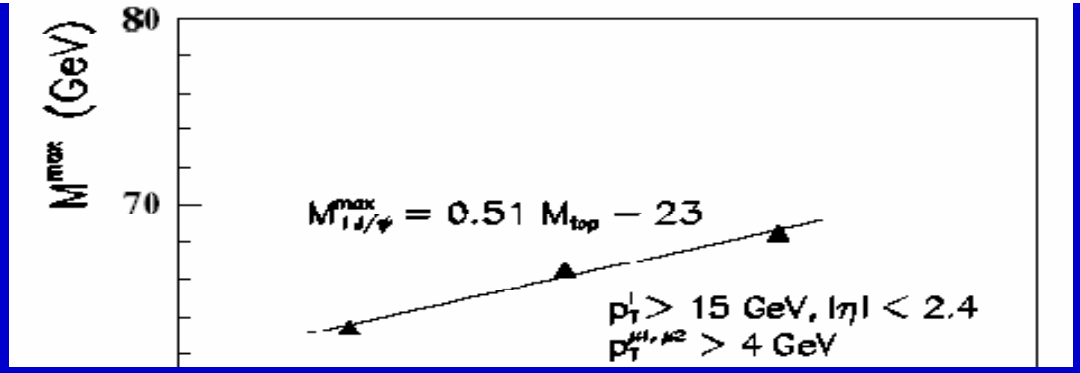


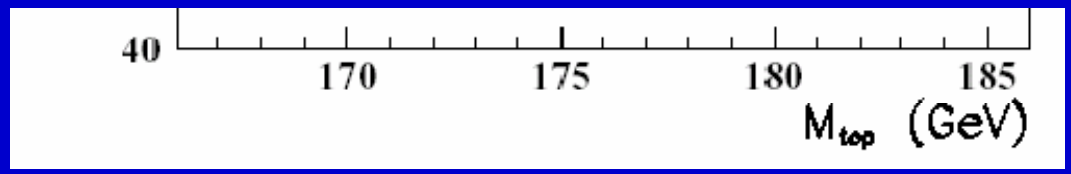
One of the ideas for high statistics (LHC) approach



In 100fb^{-1} about 1000 signal events is expected







No jes systematics !!!

Conclusions

- Tevatron's precision in measuring top mass has reached 1%
- The main factors in this success are
  - Tevatron's performance and large ttbar samples
  - Advancements in jet energy scale calibration
  - Development of event-by-event likelihood methods
- A lot of emphasis is put on careful evaluation of systematic uncertainties