Top Quark Mass Measurements at CDF

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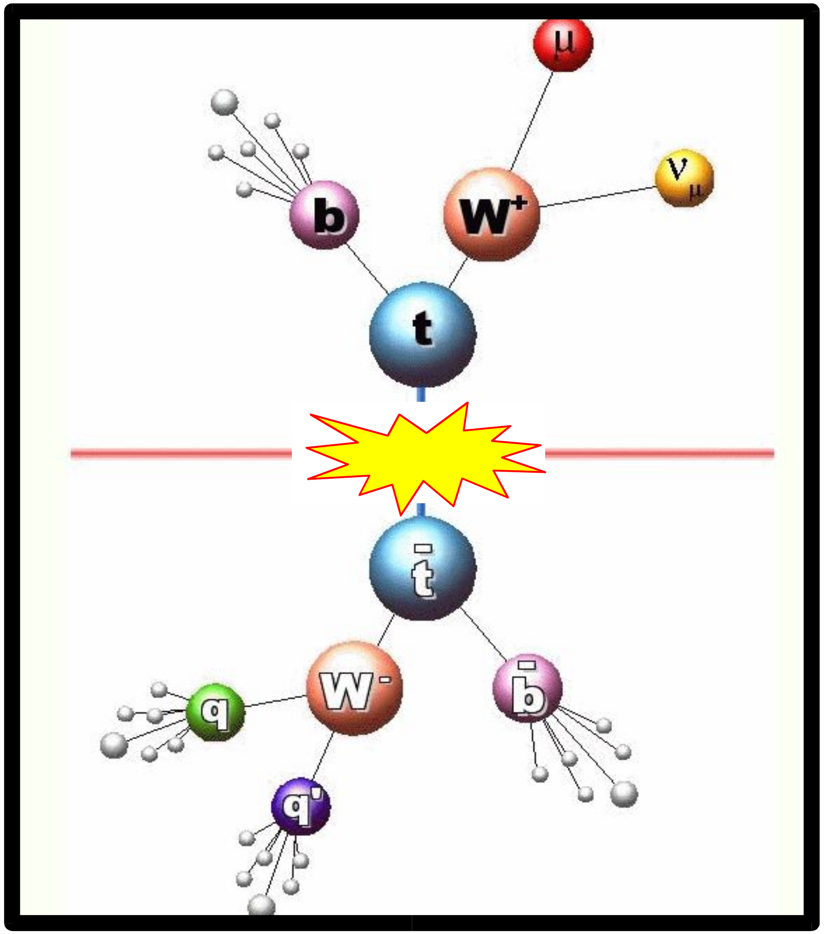
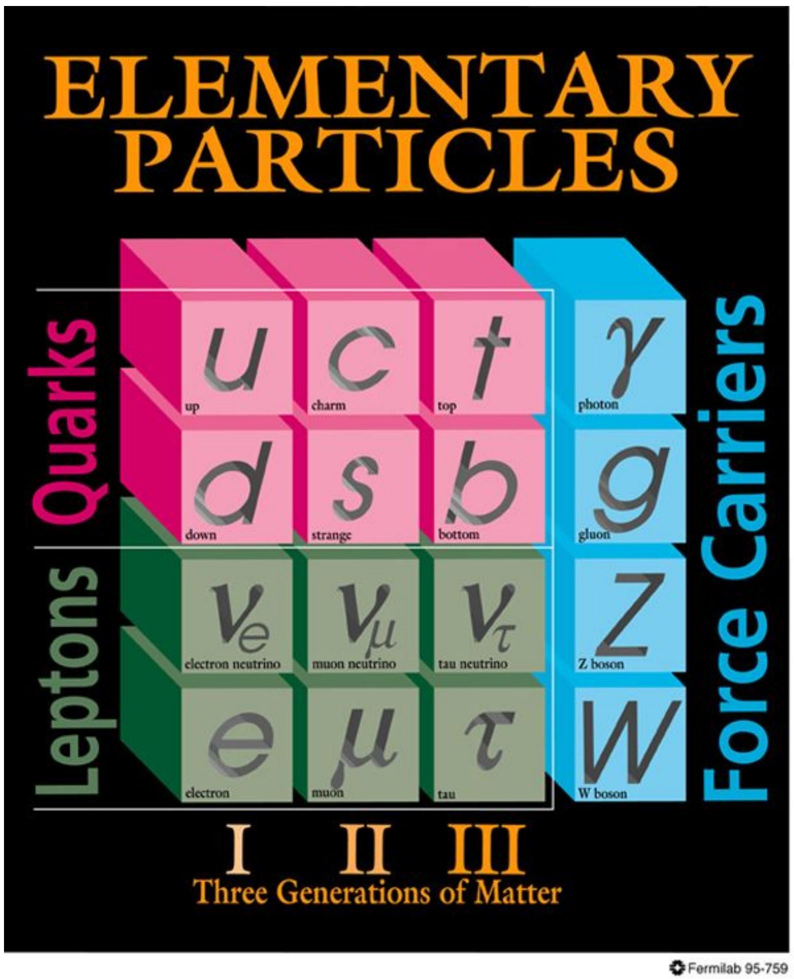
Outline

- Introduction to top quarks
- Motivation to measure top quark mass
- Overview of mass measurement techniques
- Results from **dileptonic** channel
- Results from **lepton+jets** channel
- Results from **all-hadronic** channel
- Combination
- Future prospects
- Conclusions



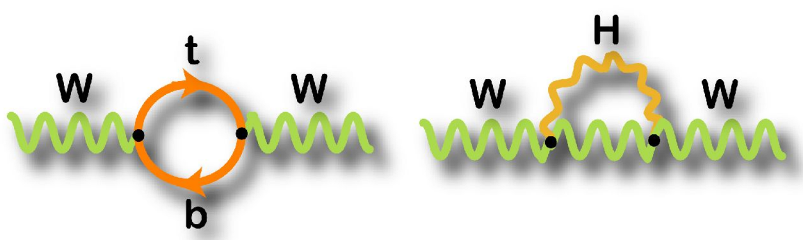
Introduction to top quarks

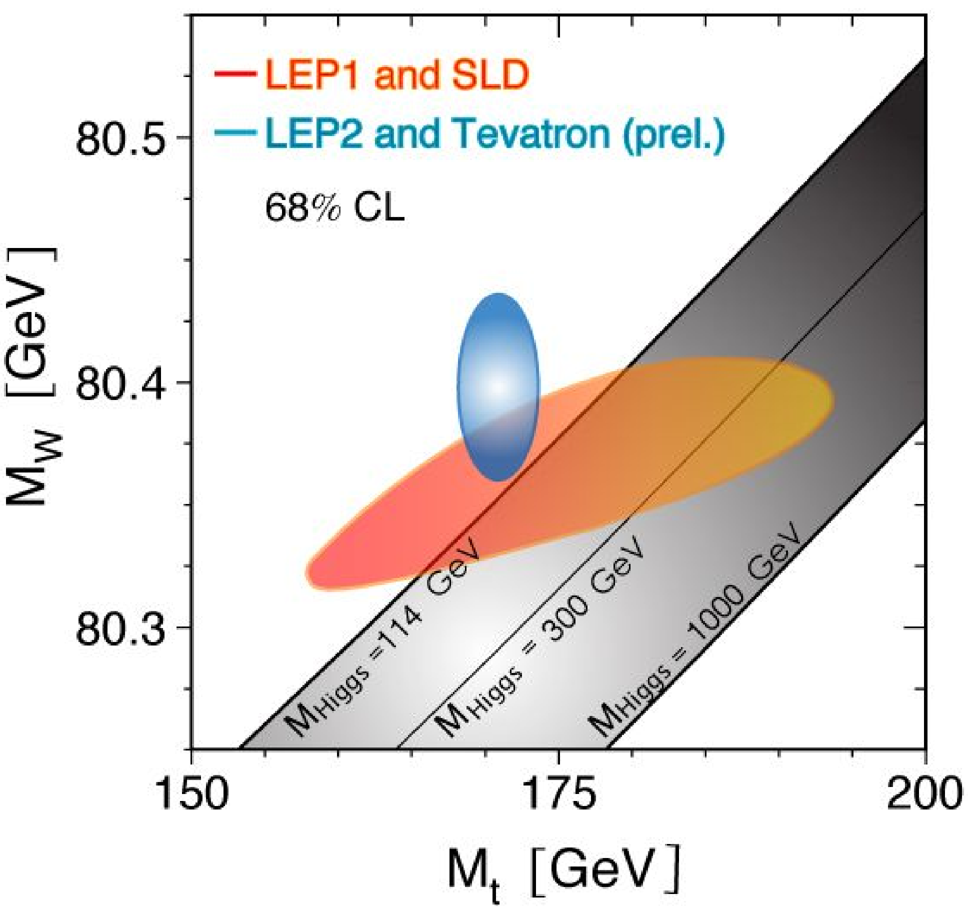


- Top quark discovered in 1995 at Fermilab
- Top quark mass suprisingly large
  - *~35x heavier than bottom quark*
  - *5 orders of magnitude between top and up quark masses*
- As top quark is so heavy, it decays before hadronization
  - *can be observed as free quark*

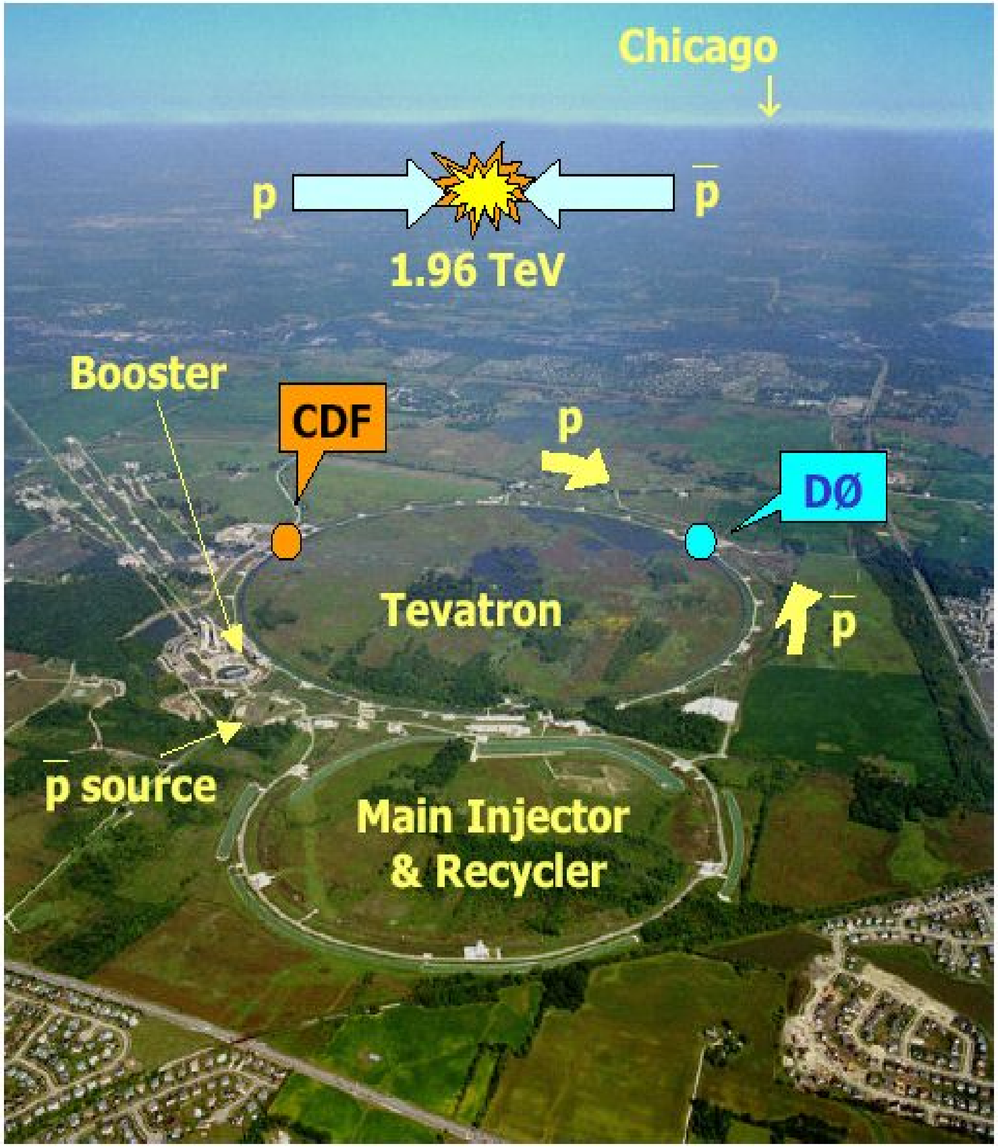
Top mass

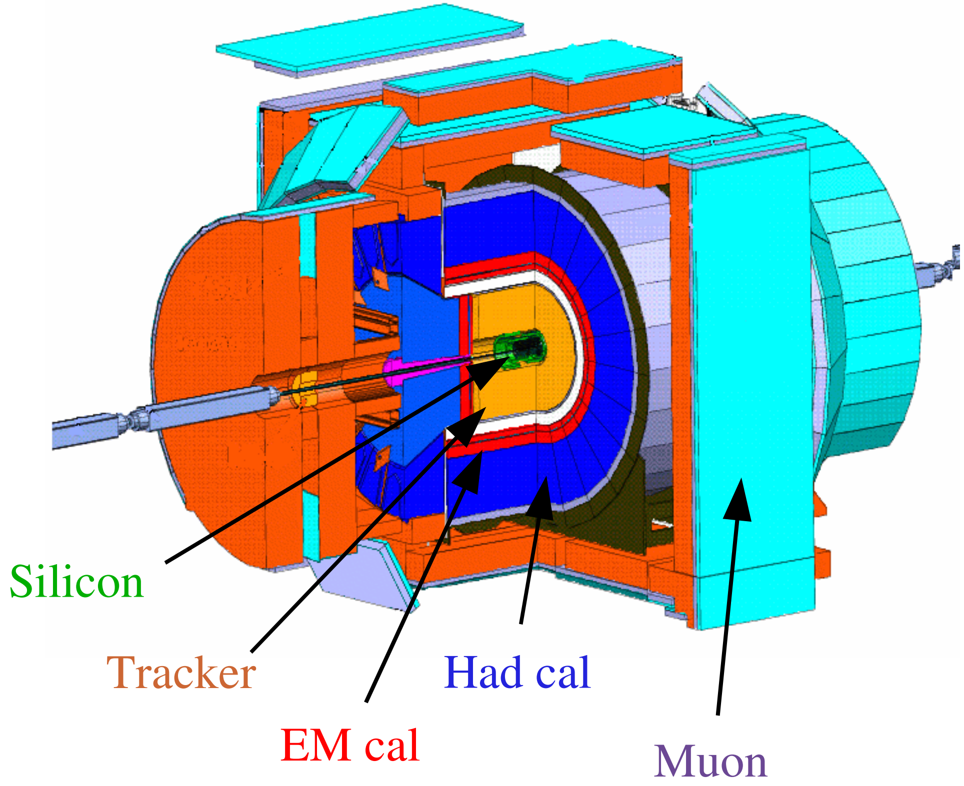
- Top mass fundamental SM parameter:
  - *tests SM predictions*
  - *important in radiative corrections*
  - *constrains SM Higgs mass*
- Top mass close to scale of electroweak symmetry breaking
- Constraints on SUSY models





Tevatron and CDF





- Tevatron record instantanous luminosity: $2.9*10^{32}$ $cm^{-2}s^{-1}$
- I will show results using ~1 fb^{-1} of data
- New results with 2 fb^{-1} coming this summer

Production of $t\bar{t}$ events

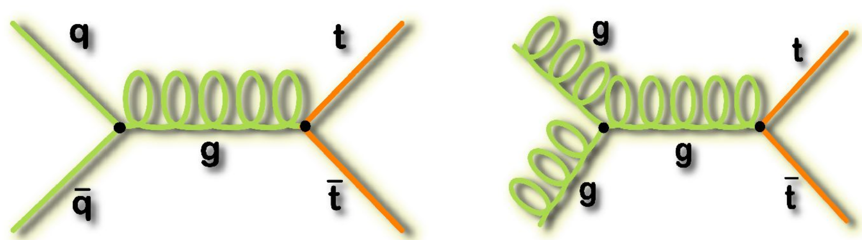
At Tevatron, **top quarks are predominantly pair produced via strong interaction**

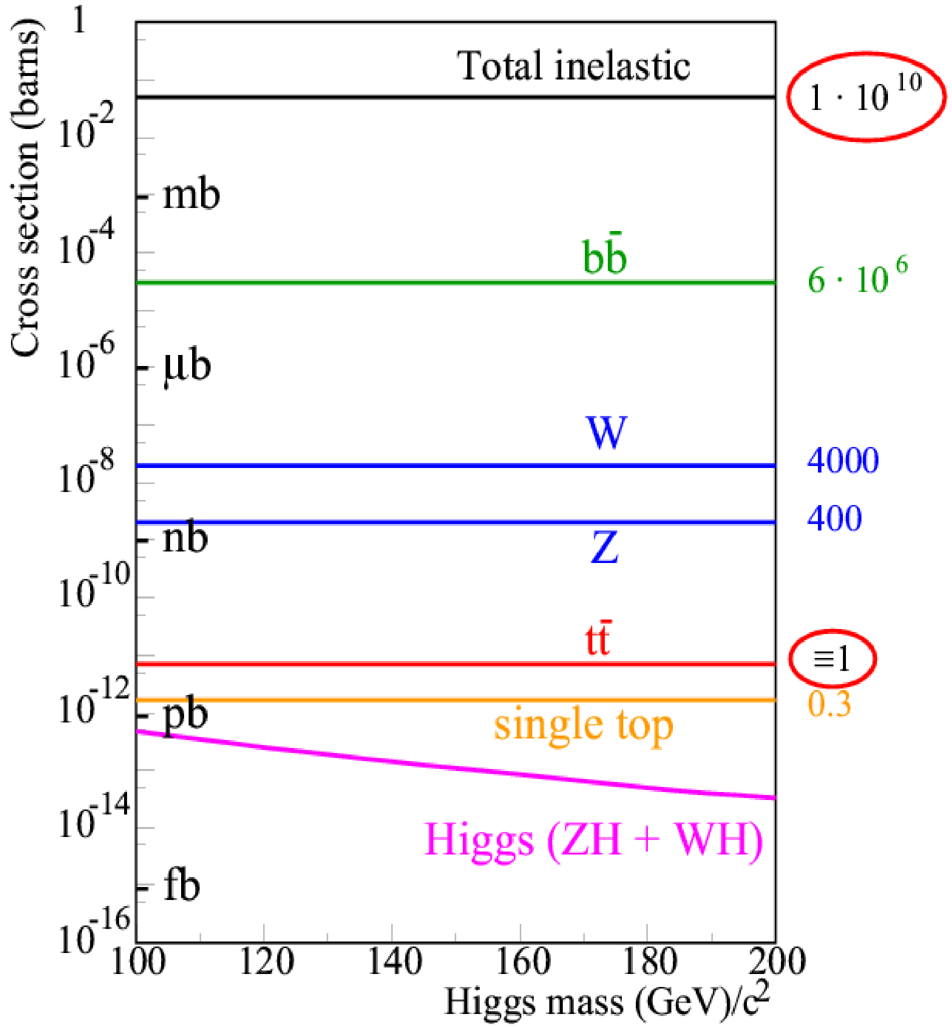
σ_{tt} = 6.7 pb for m_{top}=175 GeV/c^2

(JHEP 0404:068 (2004))

~85% from qq→tt

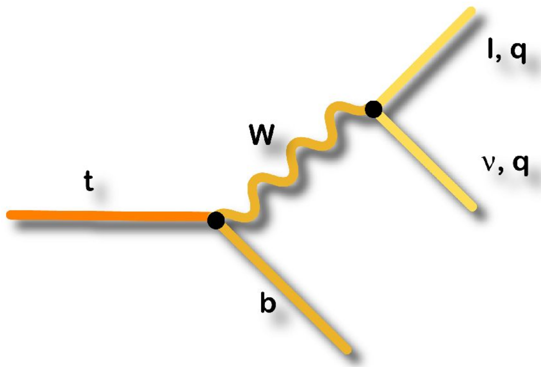
~15% from gg→tt





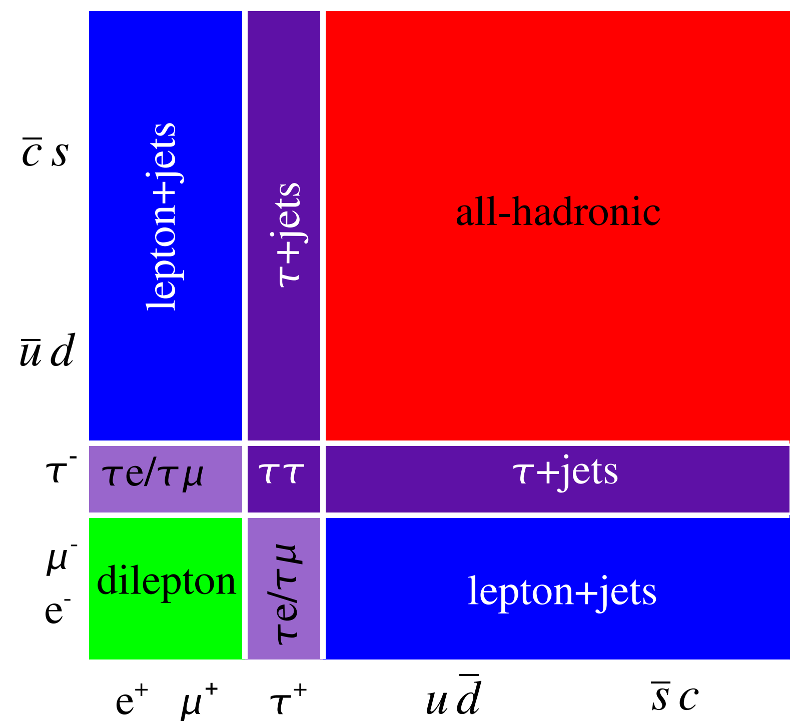
Rare at Tevatron: One top pair per 10 billion inelastic collisions

Classification of $t\bar{t}$ events



$$BR(t \to Wb) \sim 100\%$$

- *ttbar events can be classified according to W decays*



All-hadronic channel

- *6 quarks*
- *high background*

Dilepton channel

- *2 leptons (e,μ), 2 neutrinos, 2 quarks*
- *low background*

τ-leptons difficult to identify

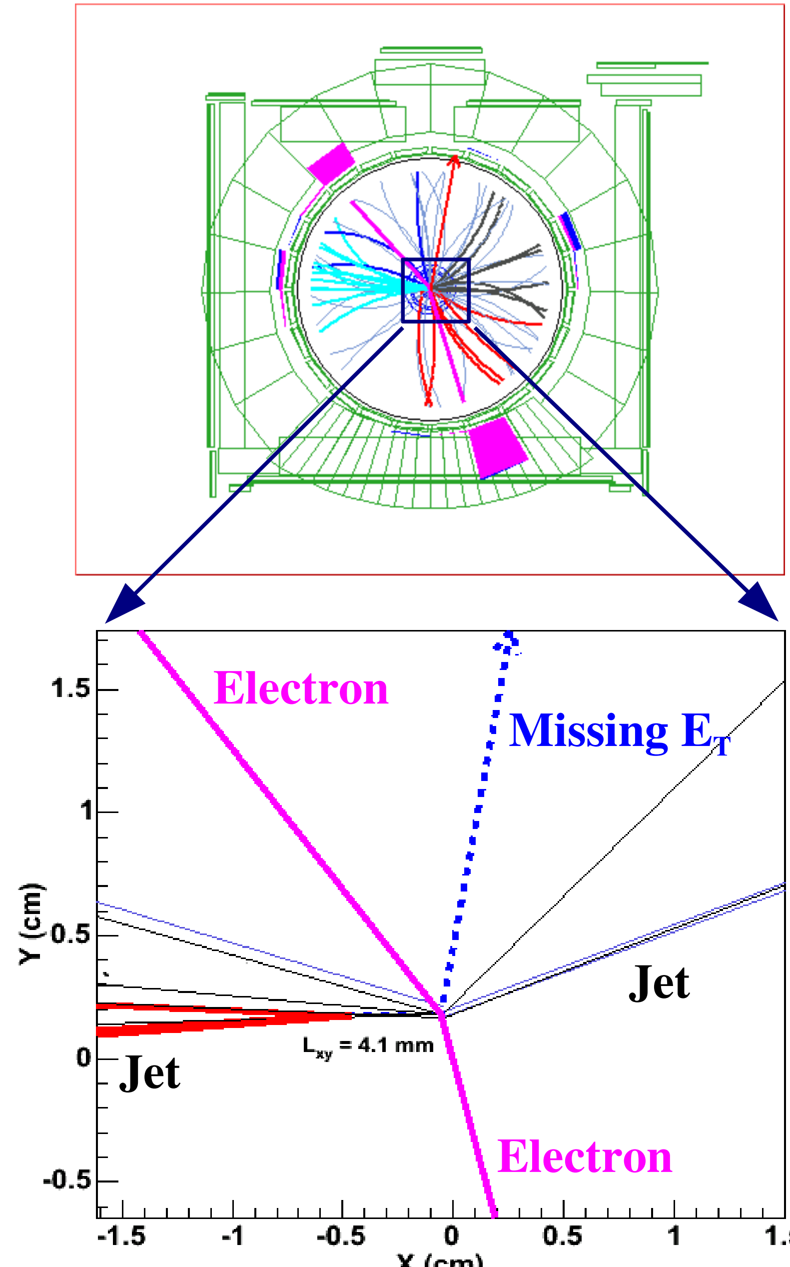
- *partially included in other categories*

Lepton+jets channel

- *1 lepton (e,μ), 1 neutrino, 4 quarks*
- *managable background*

Challenges

- Neutrinos escape detector
  - *partial information can be measured as missing E_T*
- Quarks hadronize and form jets
  - *Measured energy of jets has to be corrected back to parton level*
  - *Many ways to assign a jet to a parton*
  - *B-tagging reduces number of possible assignments, but also reduces statistics*
- Background processes mimic top events

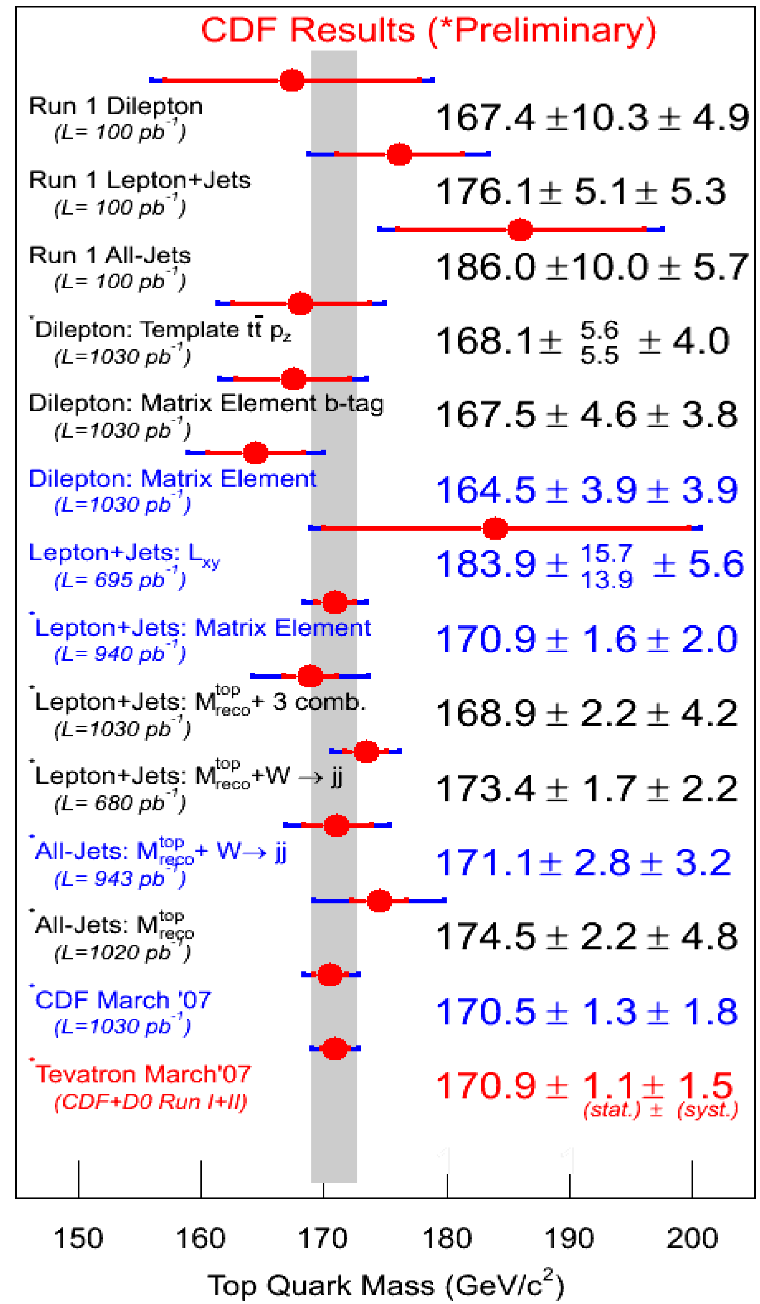


Overview of top mass measurements

Robust program of complementary measurements:

- Many measurements in all the different channels
  - *consistency*
- Different methods of extraction with different sensitivity
  - *confidence*
- Combine all channels and all methods
  - *precision*

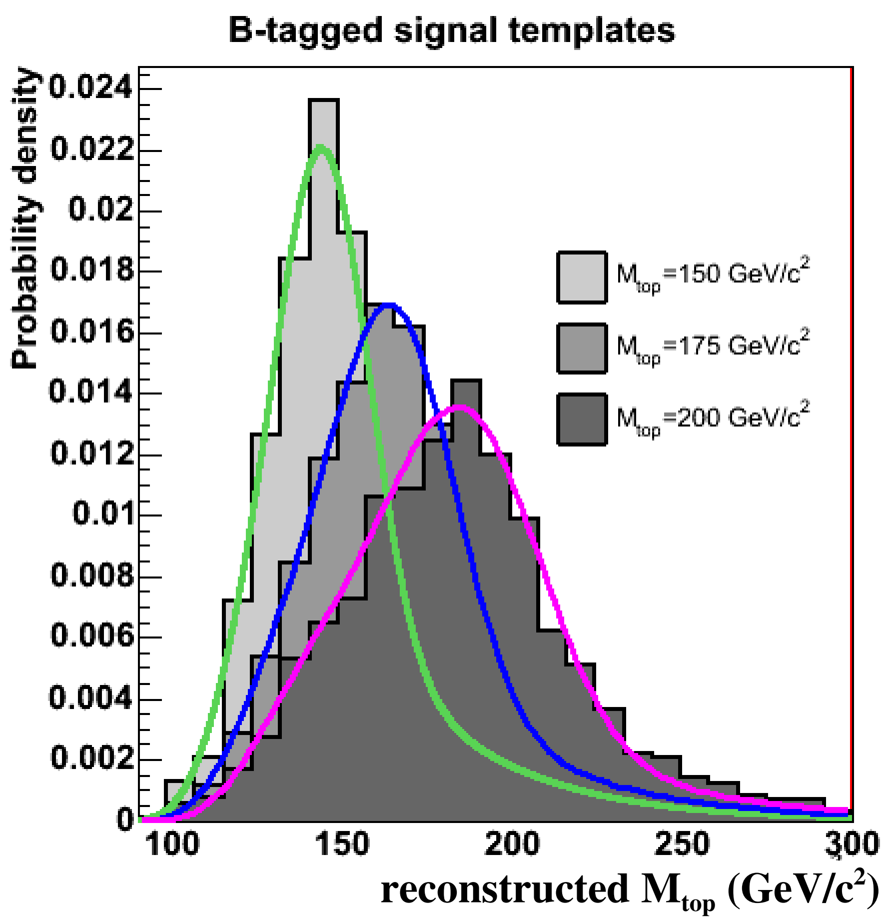
I will only talk about the most precise and representative ones



Tuula Mäki

Template method

- Calculate a per-event observable that is sensitive to M_{top}
- Make templates from signal and background events
- Use pseudo-experiments to check the method works
- Fit data to templates using maximum likelihood



Matrix element method

- Calculate probability density for each event

$$\boxed{P(\boldsymbol{x}|M_t) = \frac{1}{\sigma(M_t)} \frac{d\sigma(M_t)}{d\boldsymbol{x}}}$$

x vector of measured variables

- Use LO **Matrix Element** and **transfer functions** to calculate differential cross-section

Differential cross-section from LO matrix element

$$\boxed{P(\boldsymbol{x}|M_t) = \frac{1}{N} \int \boldsymbol{dq_1 dq_2 f_{PDF}(q_1) f_{PDF}(q_2)} |\boldsymbol{M_{t\bar{t}}(p; M_t)}|^2 \prod \boldsymbol{T(p_i, j_i)}}$$

Initial state

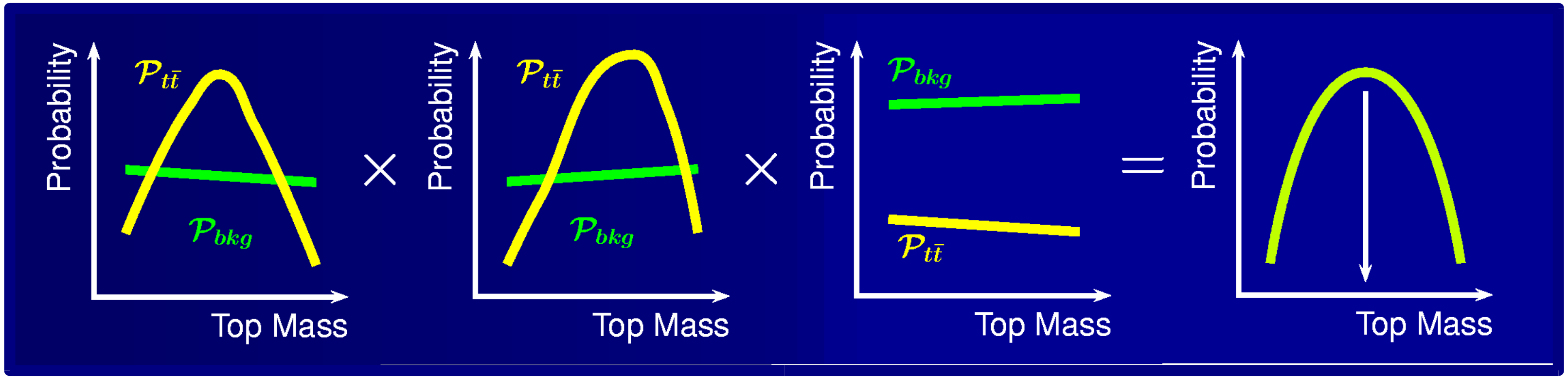
Transfer function: probability to measure j when parton-level p was produced

Matrix element method

- Evaluate differential cross-sections **for backgrounds**
- Weld together the signal and background pieces to get expression for M_t posterior distribution

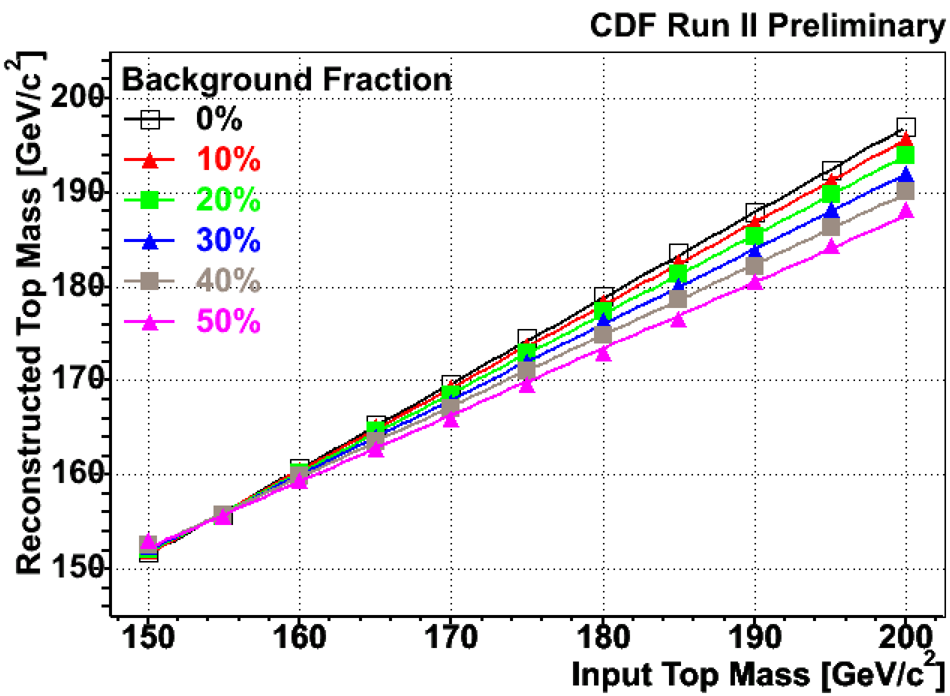
$$P(\boldsymbol{x}|M_t)=P_s(\boldsymbol{x}|M_t)\,p_s+P_{bg1}(\boldsymbol{x})\,p_{bg1}+P_{bg2}(\boldsymbol{x})\,p_{bg2}\ldots$$

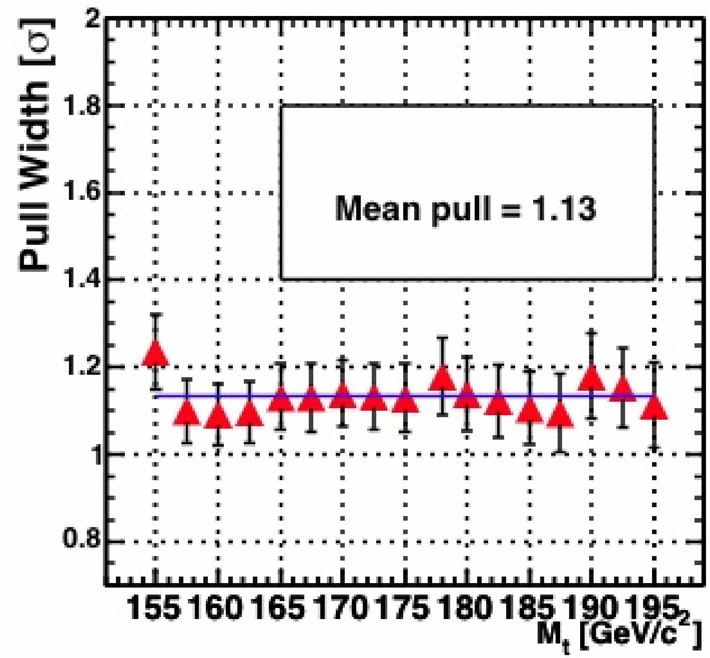
- Multiply the event probabilities to extract the most likely mass



Matrix element method

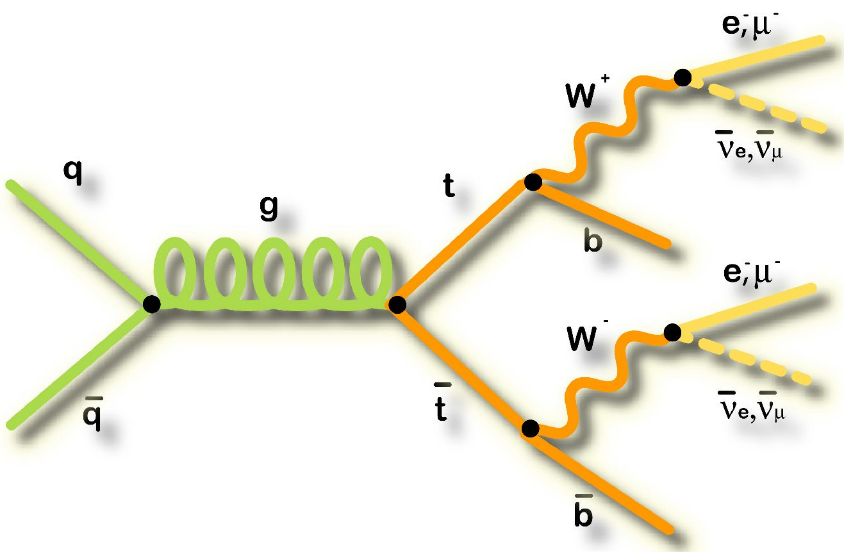
- Calibrate the method using simulation

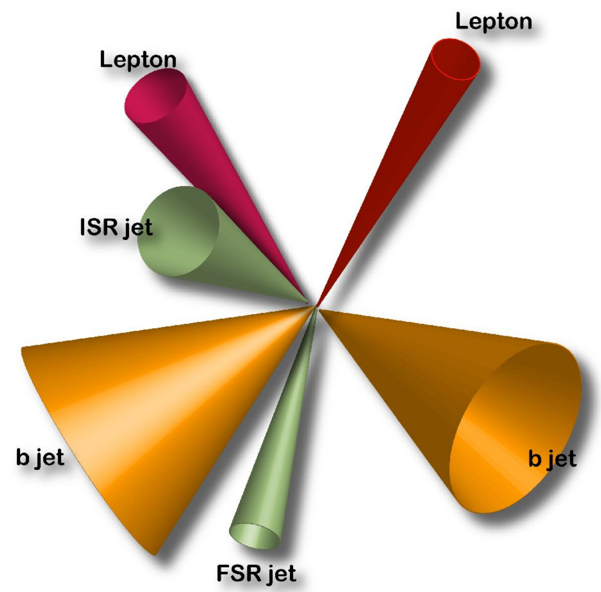




- Matrix element methods are computationally heavy

Dilepton channel



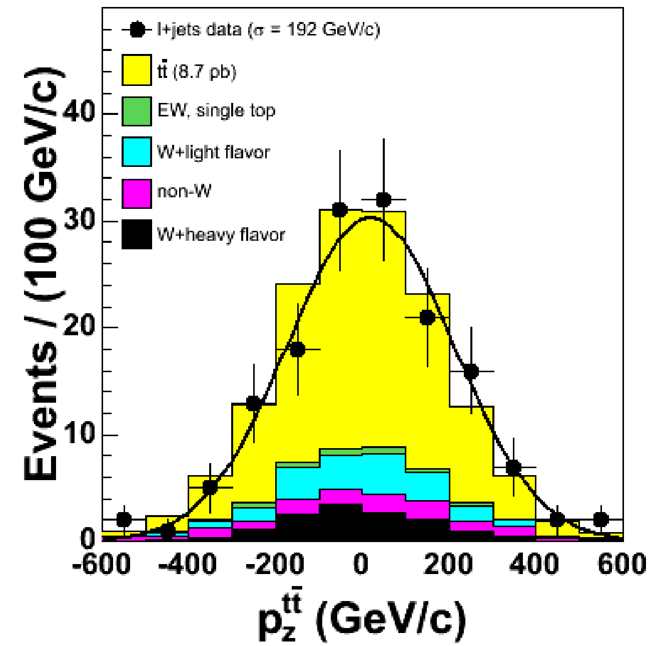


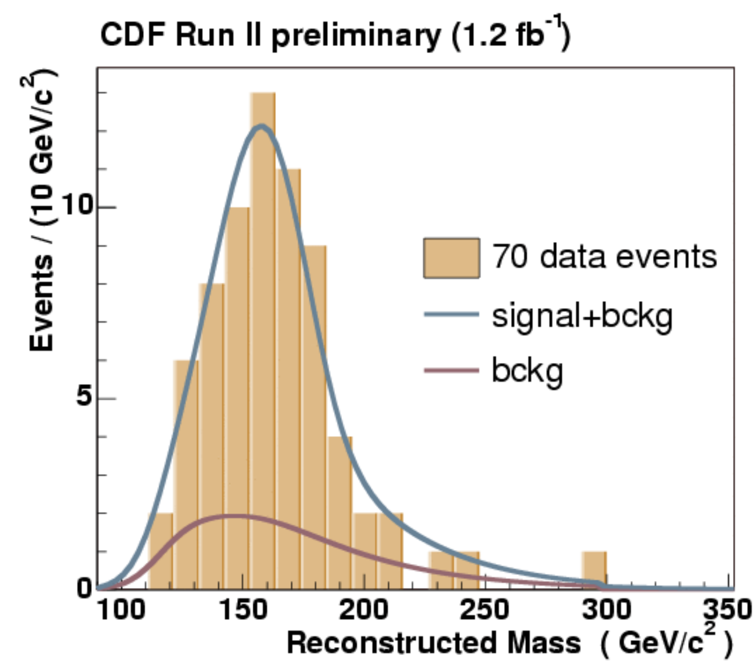
- Event signature:
  - *two high p_T leptons (e or μ)*
  - *at least two jets*
  - *large missing E_T*
- Backgrounds:
  - *Drell-Yan*
  - *W+jets where a jet fakes lepton*
  - *diboson*
- Advantage for top mass:
  - *low background*
  - *only two possible jet-parton assignments*
- Challenge for top mass:
  - *under-constrained for top mass fitting*
  - *low statistics*

Dilepton: template

- Top mass can be reconstructed assuming a top mass independent distribution
- Use $P_z^{t\bar{t}}$
- Integrate over the distribution
- Select most probable reconstructed M_{top}
- Treat b-tagged and non-tagged events separately

$$M_{top} = 169.7^{+5.2}_{-4.9}(stat.) \pm 3.1(syst.)\, GeV/c^2$$





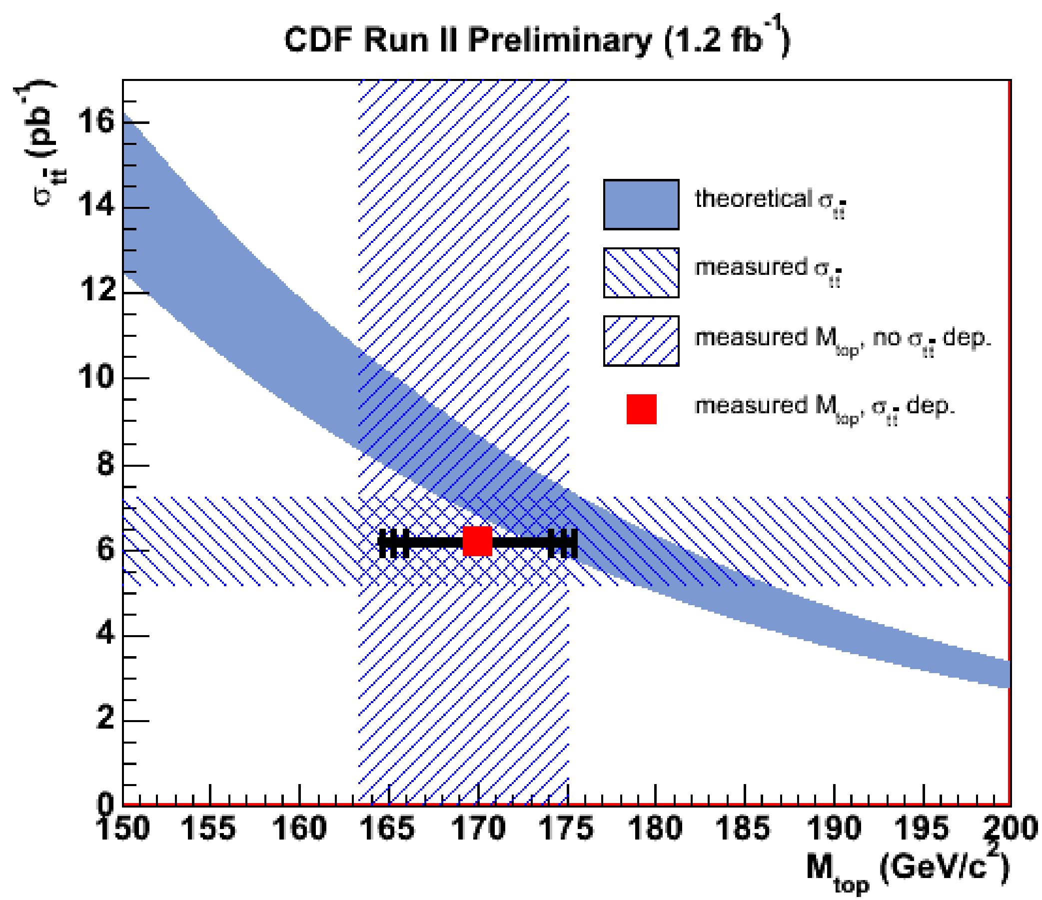
Dilepton: template

Systematic uncertainties

Source	ΔM_{top} (GeV/c^2)
Jet energy scale	± 2.9
B-jet energy scale	± 0.5
Lepton energy scale	± 0.2
Generator	± 0.3
ISR	± 0.2
FSR	± 0.4
PDF	± 0.6
Background modeling	± 0.3
Template statistics	± 0.5
Total	± 3.1

Dilepton: template with $\sigma_{t\bar{t}}$ constraint

- Theoretical $\sigma_{t\bar{t}}$ has exponential dependence on top mass
- Include theoretical $\sigma_{t\bar{t}}$ in the template method
  - *measured top mass depends on kinematics and number of events*



Dominant systematics

Jet energy scale	$\pm$1.5
Luminosity	$\pm$1.1
Number of bckg events	$\pm$0.9
B-jet energy scale	$\pm$0.9

most precise

$$M_{top} = 170.7^{+4.2}_{-3.9}(stat.) \pm 2.6(syst.) \pm 2.4(theory)\, GeV/c^2$$

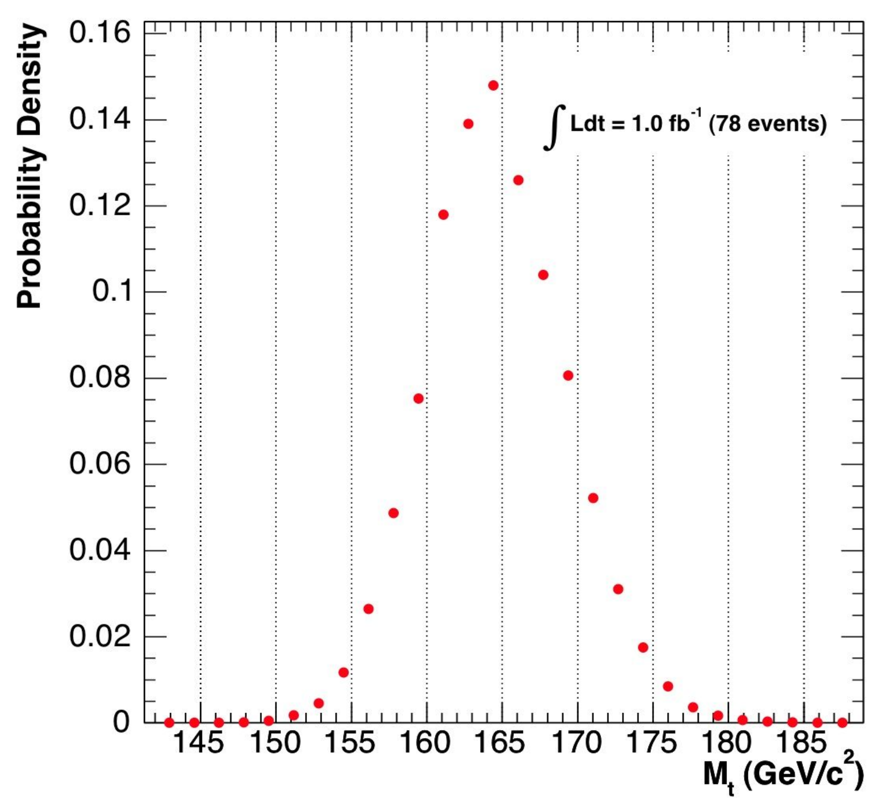
Dilepton: matrix element

- Likelihood calculated for each event using signal and background differential cross-sections
  - *leading order ttbar*
  - *Z/γ^* + jets*
  - *W + 3 jets*
  - *WW + jets*
- Integrate over all unmeasured quantities and experimental resolutions
- In 1.0 fb^{-1}, 78 events with S/B=2/1

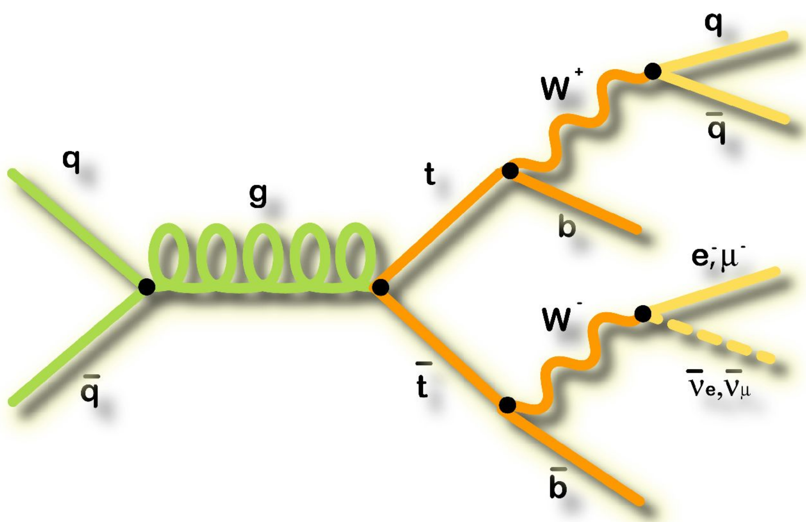
$$\boxed{M_{top} = 164.5 \pm 3.9(stat.) \pm 3.9(syst.) GeV/c^2}$$

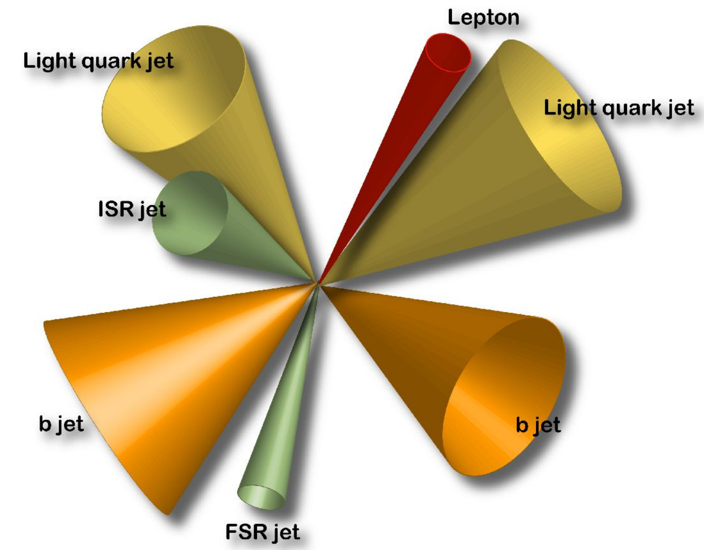
Dominant systematics

Jet energy scale	± 3.5
Generator	± 0.9
Sample composition	± 0.7
Background MC	± 0.7



Lepton+jets channel



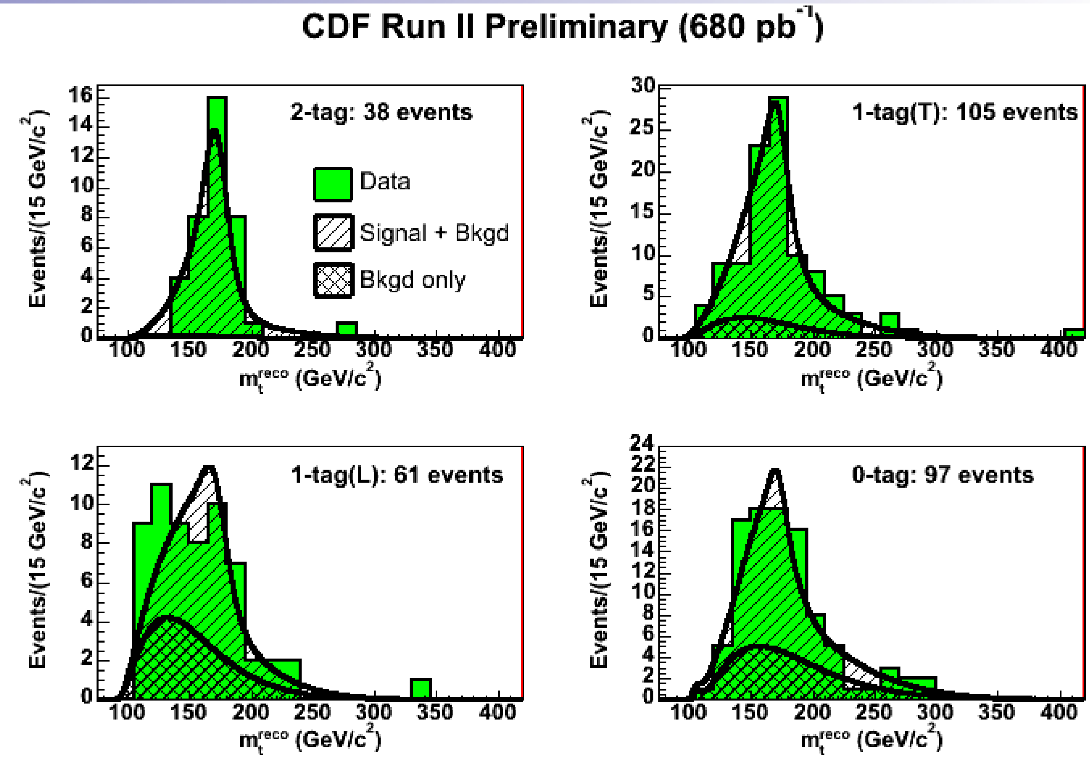


- Event signature:
  - *one high p_T leptons (e or μ)*
  - *at least four jets*
  - *large missing E_T*
- *Backgrounds:*
  - *W+jets*
  - *QCD where a jet fakes lepton*

- Golden channel for top mass measurements:
  - *reasonable statistics*
  - *reasonable background*
  - *in-situ calibration from hadronically decaying W*
  - *reasonable number of possible jet-parton assignments*
  - *top mass can be fully constrained*

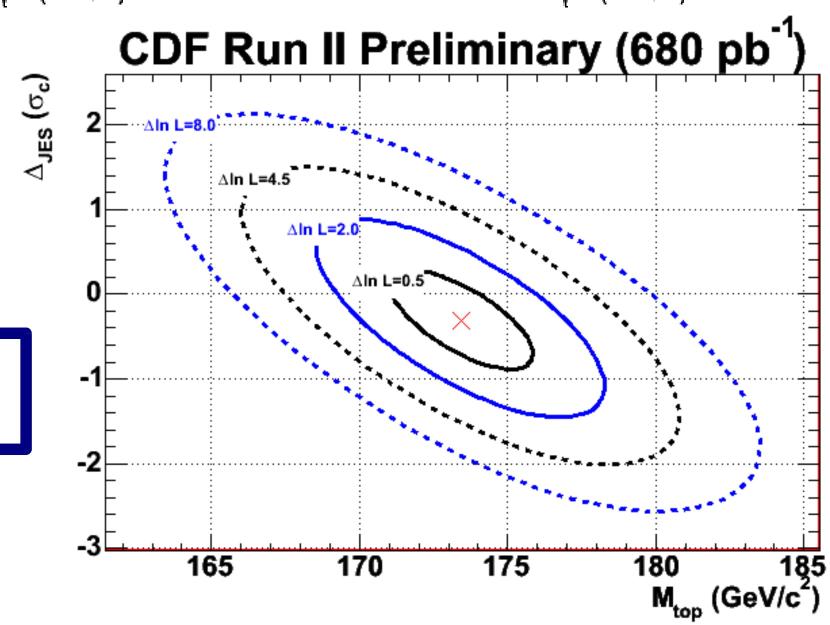
Lepton+jets: template

- Top mass reconstructed for each event
- Fitter contains W mass constraints and two top masses equal
- Jet-parton assignment with smallest χ^2 selected



Dominant systematics

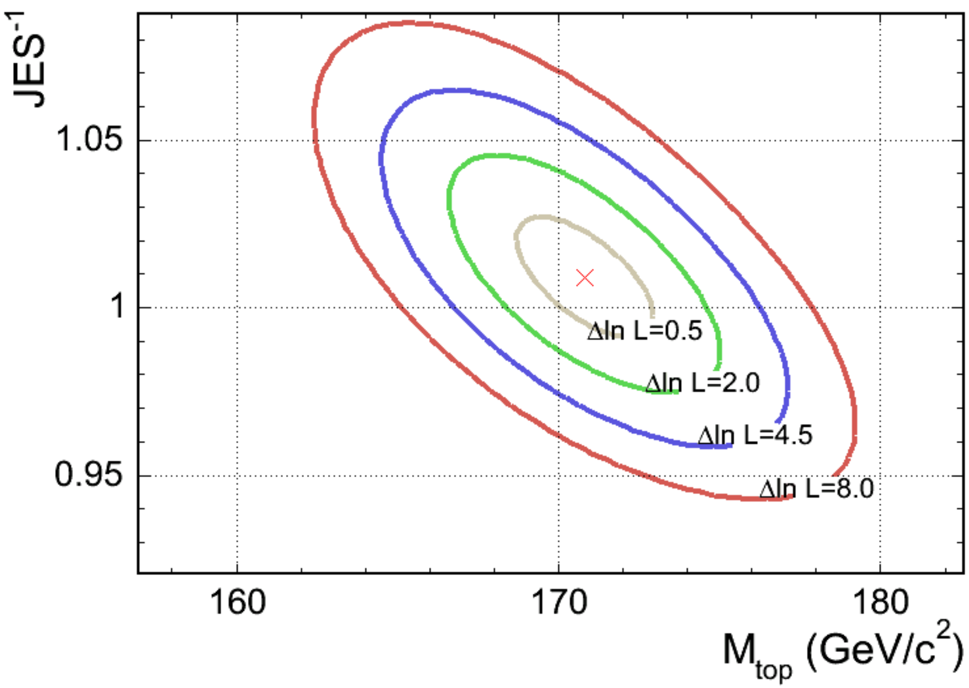
Residual JES	±0.7
b-jet energy scale	±0.6
ISR	±0.5



$$M_{top} = 173.4 \pm 2.5 (stat. + JES) \pm 1.3 (syst.) GeV/c^2$$

Lepton+jets: matrix element

- Likelihood calculated for each event using leading order ttbar and W+jets differential cross-section
- Integrate over all unmeasured quantities and experimental resolutions
- Fit simultaneously M_{top}, JES, and signal fraction



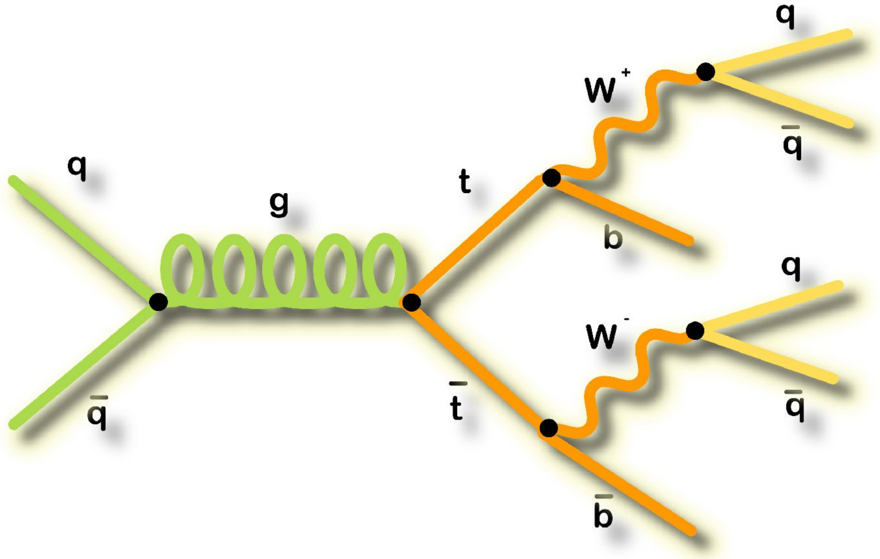
Dominant systematics

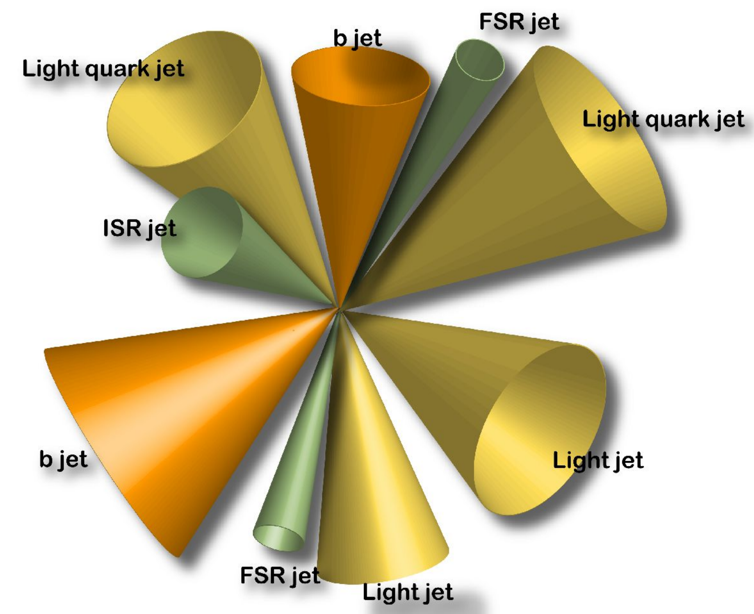
FSR	±0.8
ISR	±0.7
b-JES	±0.6

most precise

$$M_{top} = 170.8 \pm 2.2 (stat. + JES) \pm 1.4 (syst.) GeV / c^2$$

All-hadronic channel





- Event signature:
  - *at least 6 jets (≥1 b-tagged)*
- Backgrounds:
  - *QCD multijet*

- Advantage for top mass:
  - *no neutrinos in final state*
  - *large statistics*
  - *in-situ calibration from hadronically decaying W*
- Challenge for top mass:
  - *large background*
  - *90 possible ways to assign a jet to a parton*

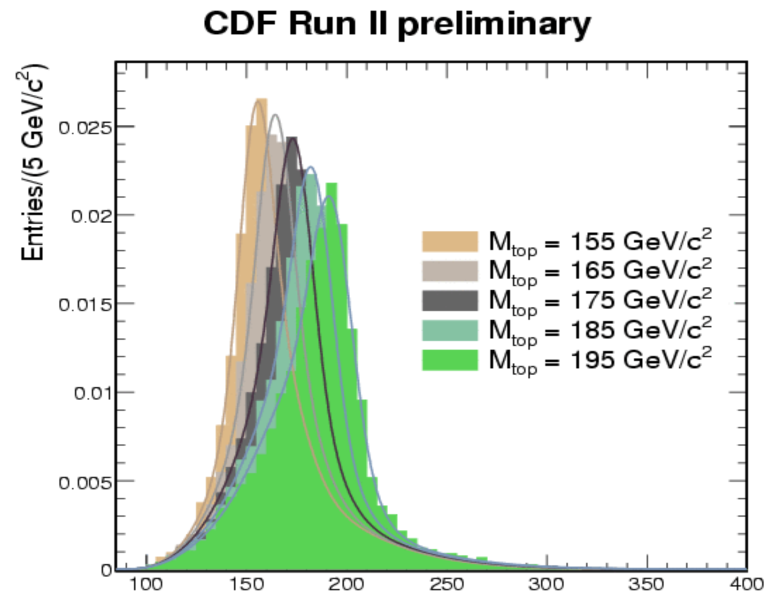
All-hadronic: template method

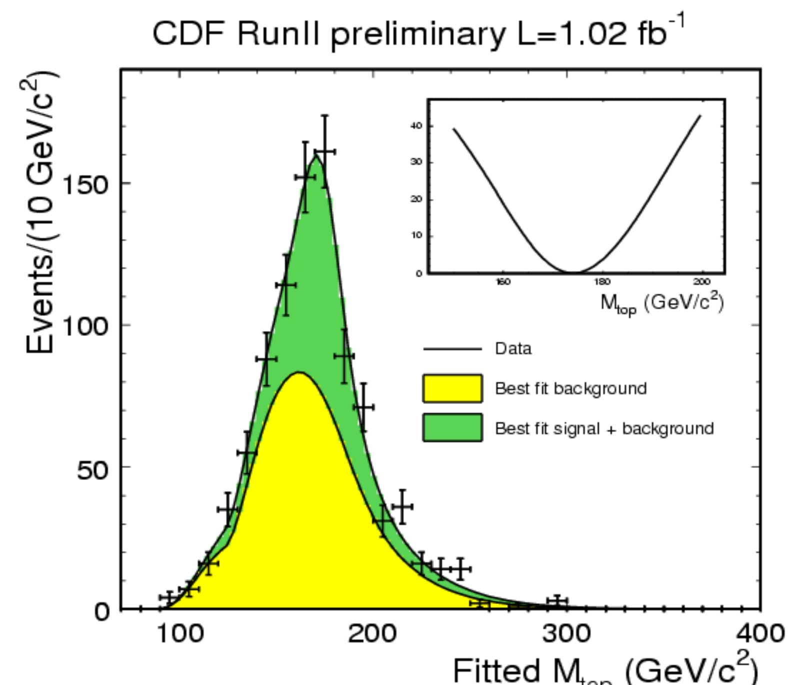
- Top mass reconstructed for each event
- Jet-parton assignments selected using kinematic fitter
- Neural network to improve S/B
- In 1.0 fb^{-1}, 772 events with S/B=1/2

$$M_{top} = 174.0 \pm 2.2 (stat.) \pm 4.8 (syst.) GeV/c^2$$

Dominant systematics

Jet energy scale	$\pm$4.5
Generator	$\pm$1.0





All-hadronic: ME assisted template

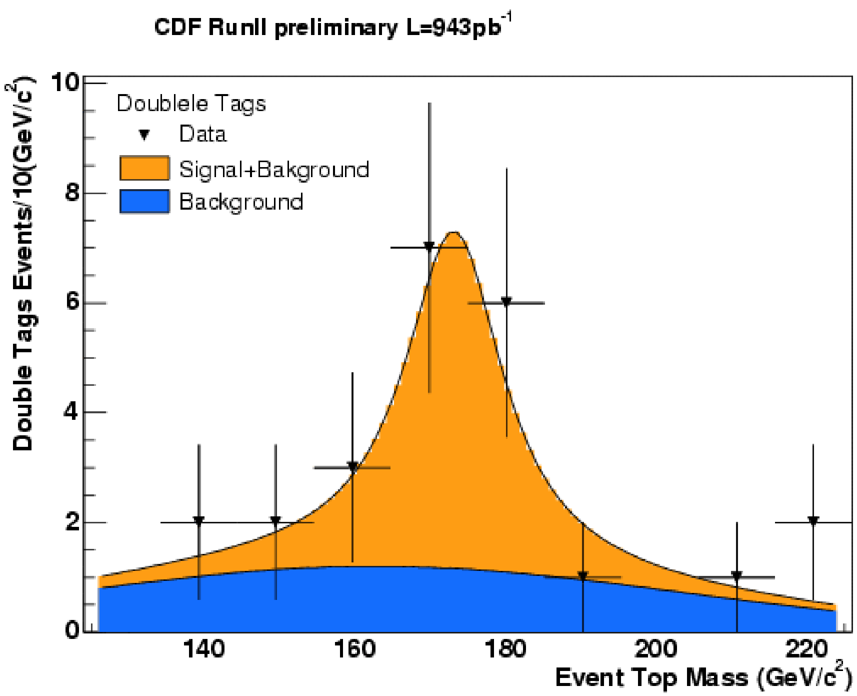
- Get per-event top mass from matrix element
- First all-hadronic result with in-situ JES
- In 0.94 fb^{-1}, 72 events with S/B≈4/1

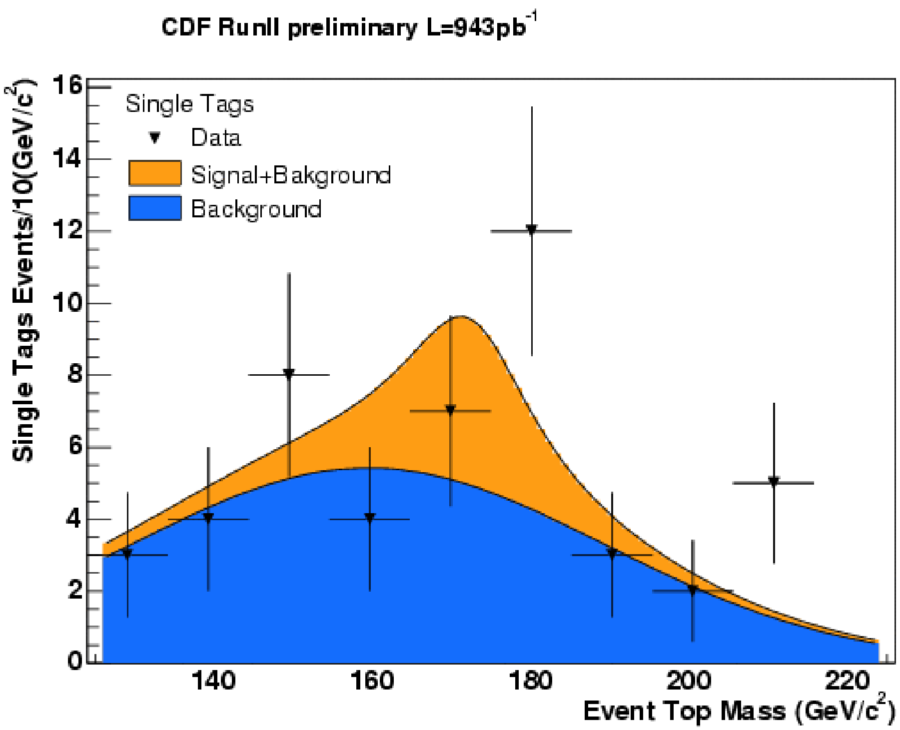
Dominant systematics

FSR	±1.2
Generator	±1.0
Background shape	±0.9
Residual JES	±0.7

most precise

$$M_{top} = 171.1 \pm 3.7(stat. + JES) \pm 2.1(syst.) GeV/c^2$$





Combination

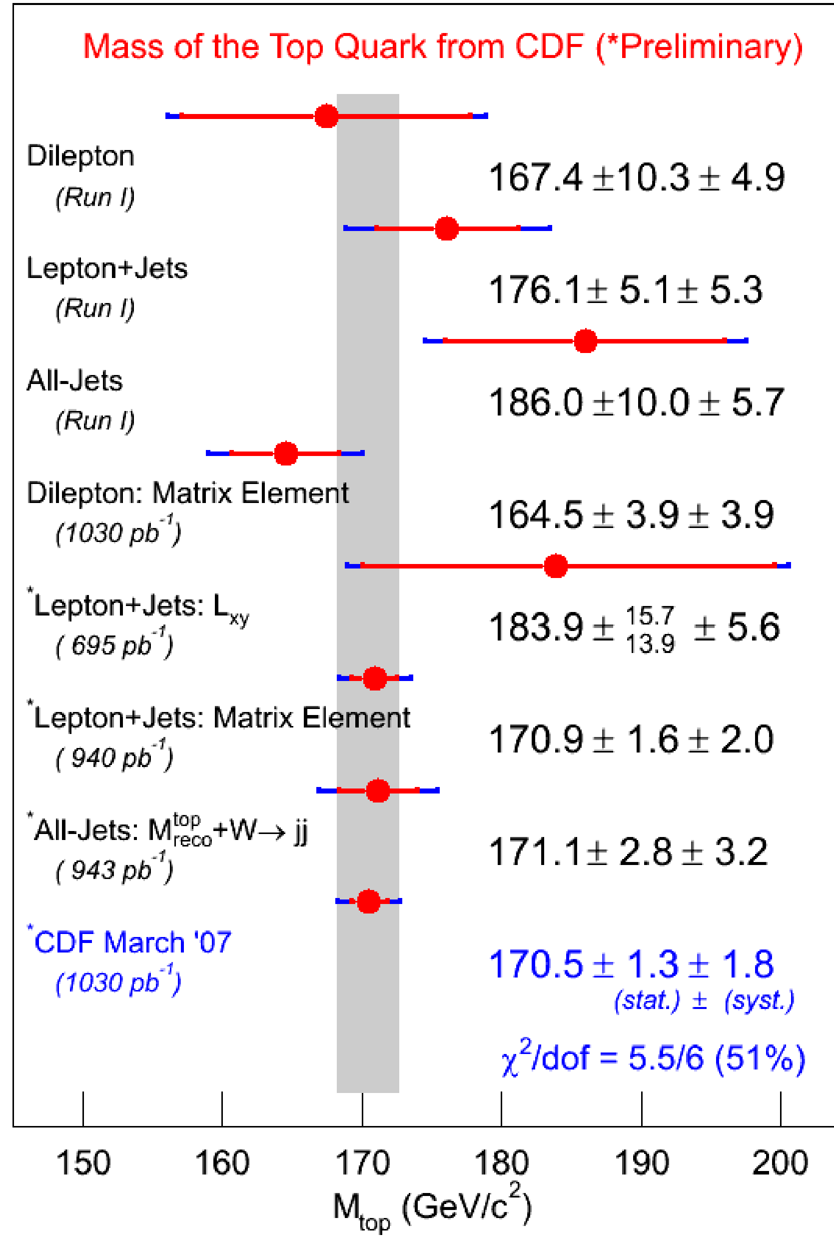
- CDF measurements combined to improve precision:
  - *Account for correlations*
  - *Use BLUE (Best Linear Unbiased Estimator), NIM **A270** 110, **A500** 391*

$$M_{top} = 170.5 \pm 1.3(stat.) \pm 1.8(syst.)\, GeV/c^2$$

- To improve further, combine with DZero measurements:

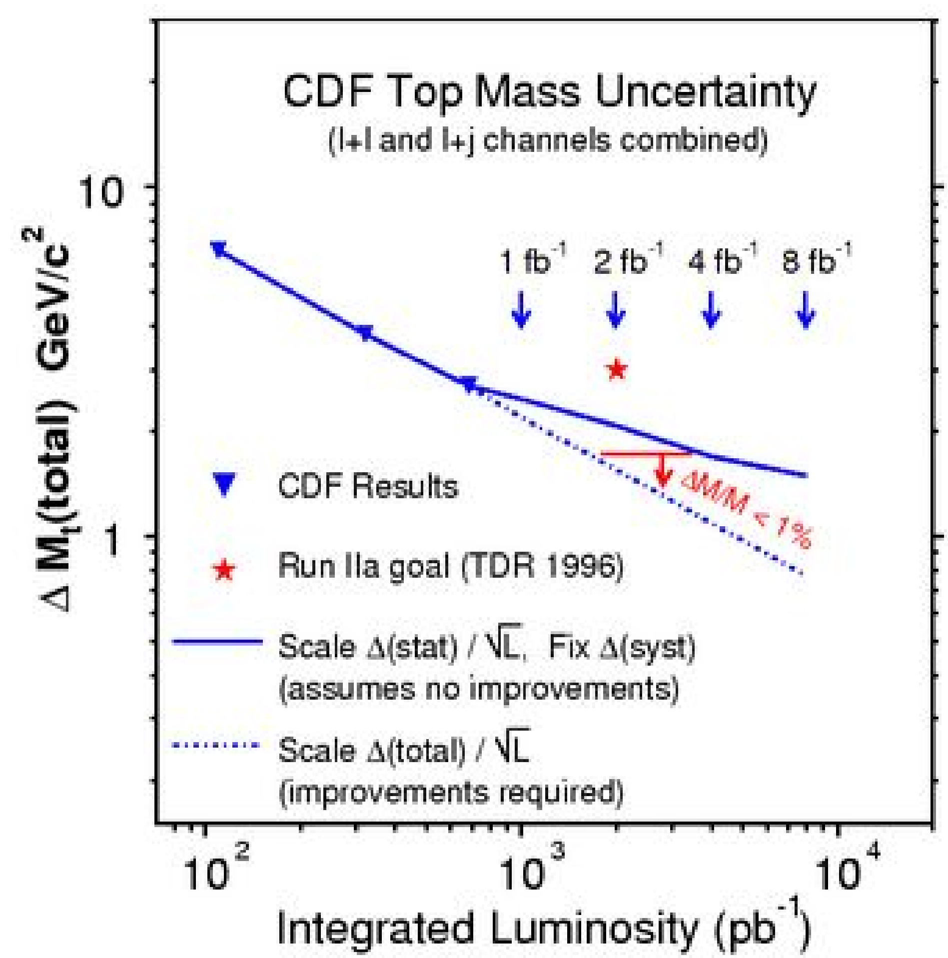
See next talk for Dzero top mass measurements!

$$M_{top} = 170.9 \pm 1.1(stat.) \pm 1.5(syst.)\, GeV/c^2$$



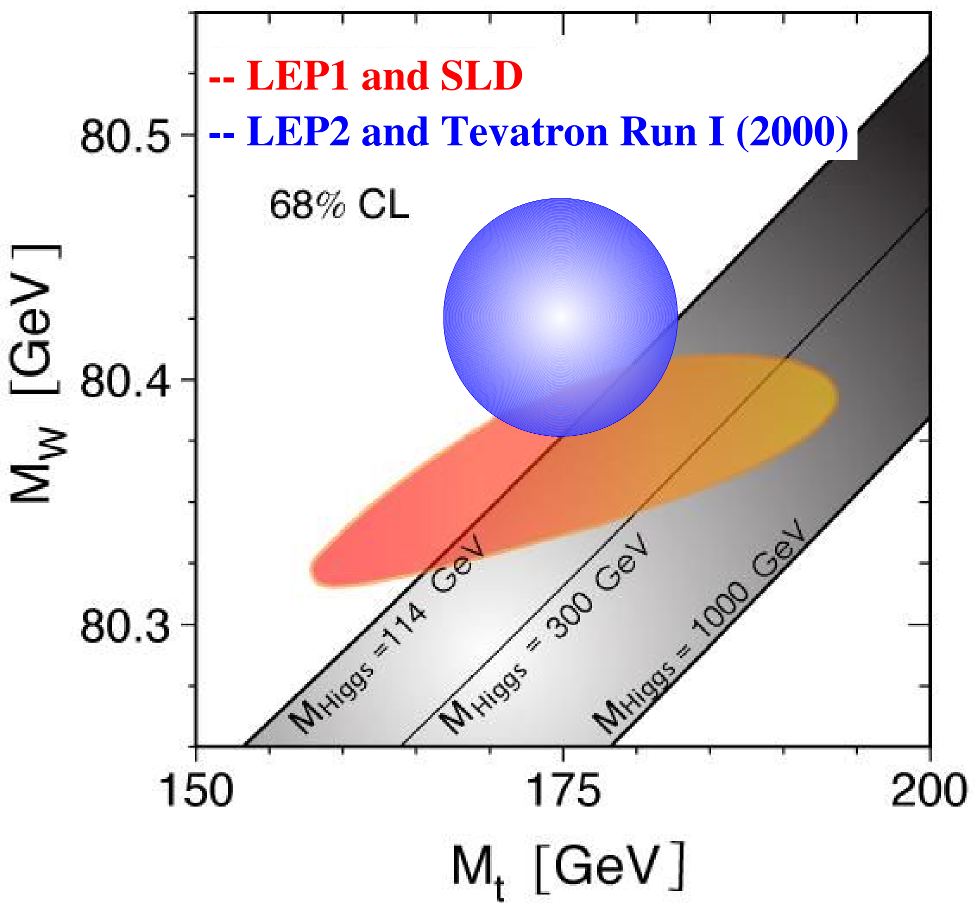
Future prospects

- CDF top mass measurement already more precise than the goal set in 1996
- All-hadronic channel not included in the prediction on right
  - *prediction will be even more precise with it*
- We are working to improve sophistication of systematic errors



Conclusions

- Top quark mass is an important parameter in Standard Model
  - *Places constraints on SM Higgs*



Conclusions

- Top quark mass is an important parameter in Standard Model
  - *Places constraints on SM Higgs*
- Excellent results from all decay channels
  - *Combined CDF top mass (~1 fb^{-1}):*

$$M_{top} = 170.5 \pm 1.3(stat.) \pm 1.8(syst.)\, GeV/c^2$$

- New top mass results using 1.7-2.0 fb^{-1} of data coming soon