CDF Top Quark Mass Measurements

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on behalf of the CDF Collaboration

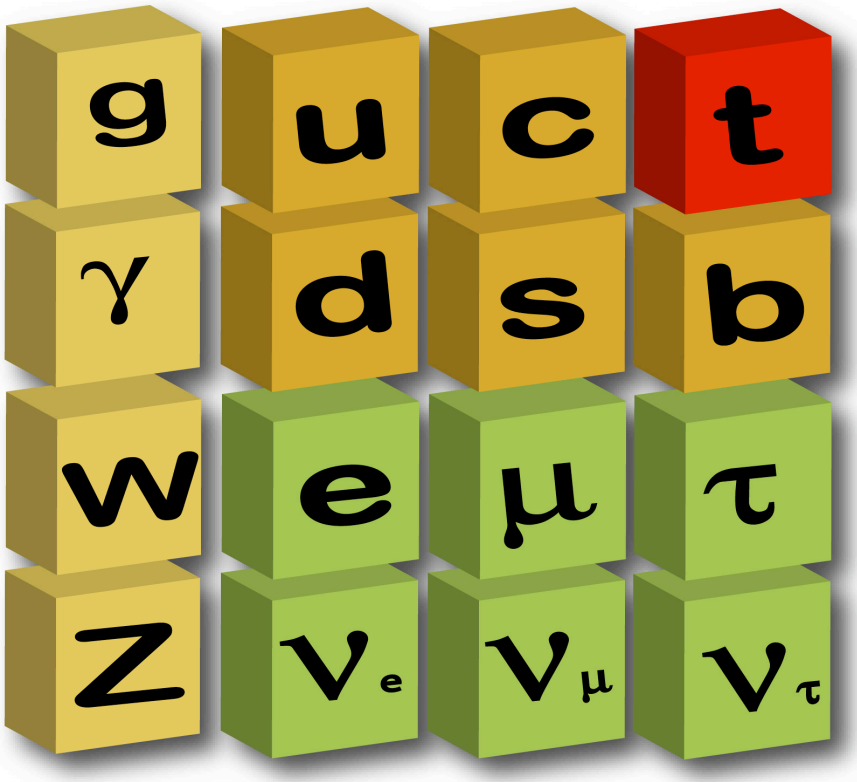
Outline

- State of the Art in CDF M_{top} measurements
- CDF M_{top} program
- New measurements
- New CDF combination
- Future

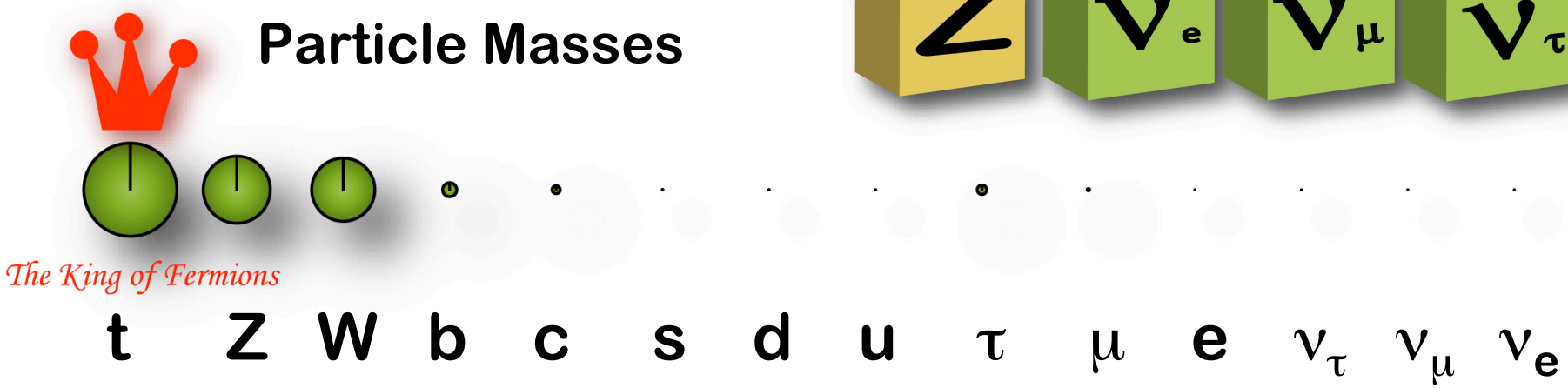
The Top Quark

- The top quark was discovered only 10 years ago
- Existence is required by the SM, but striking characteristics:
  - Its mass was surprisingly large
  - Short-lived, it doesn't hadronize
- Studied only at the Tevatron

The Standard Model

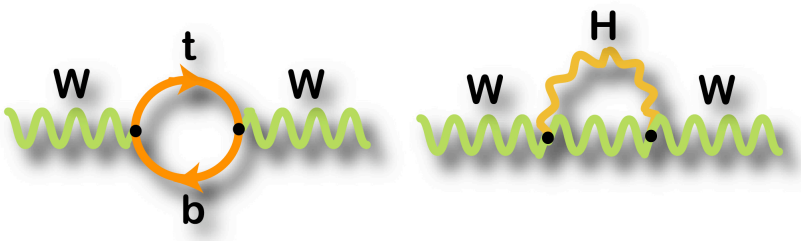


Particle Masses

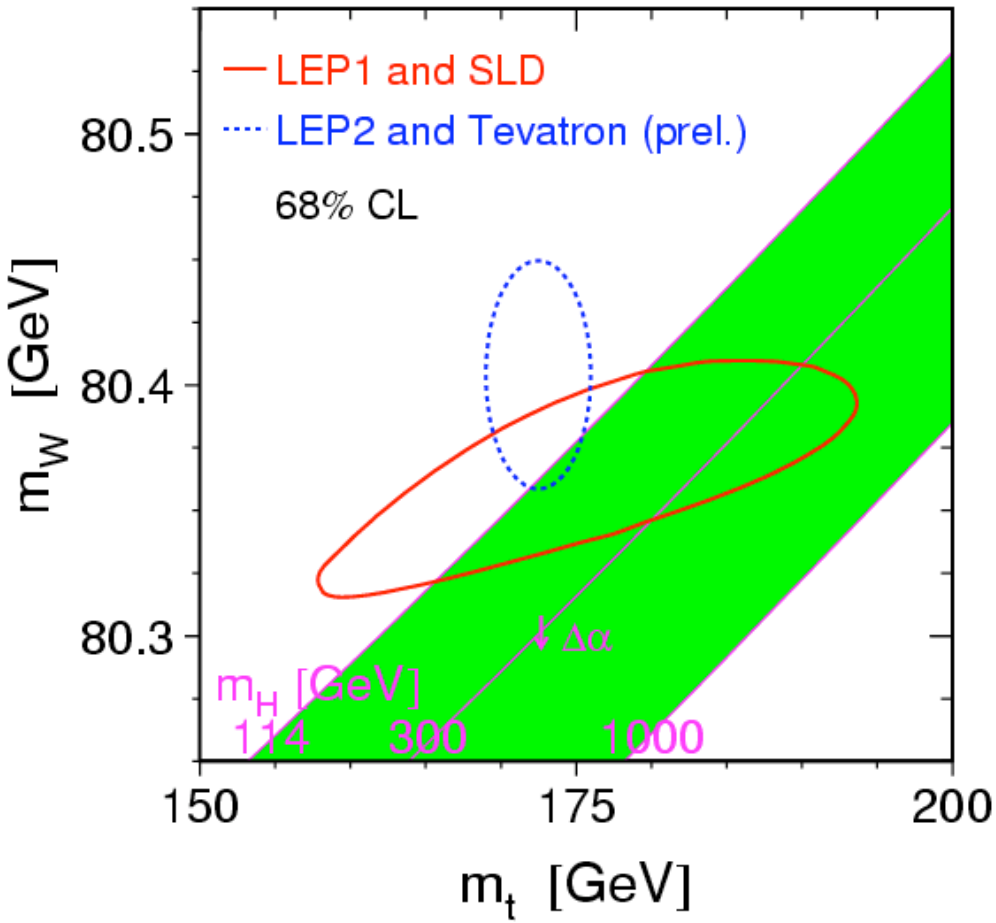


Why measure the Top Quark Mass?

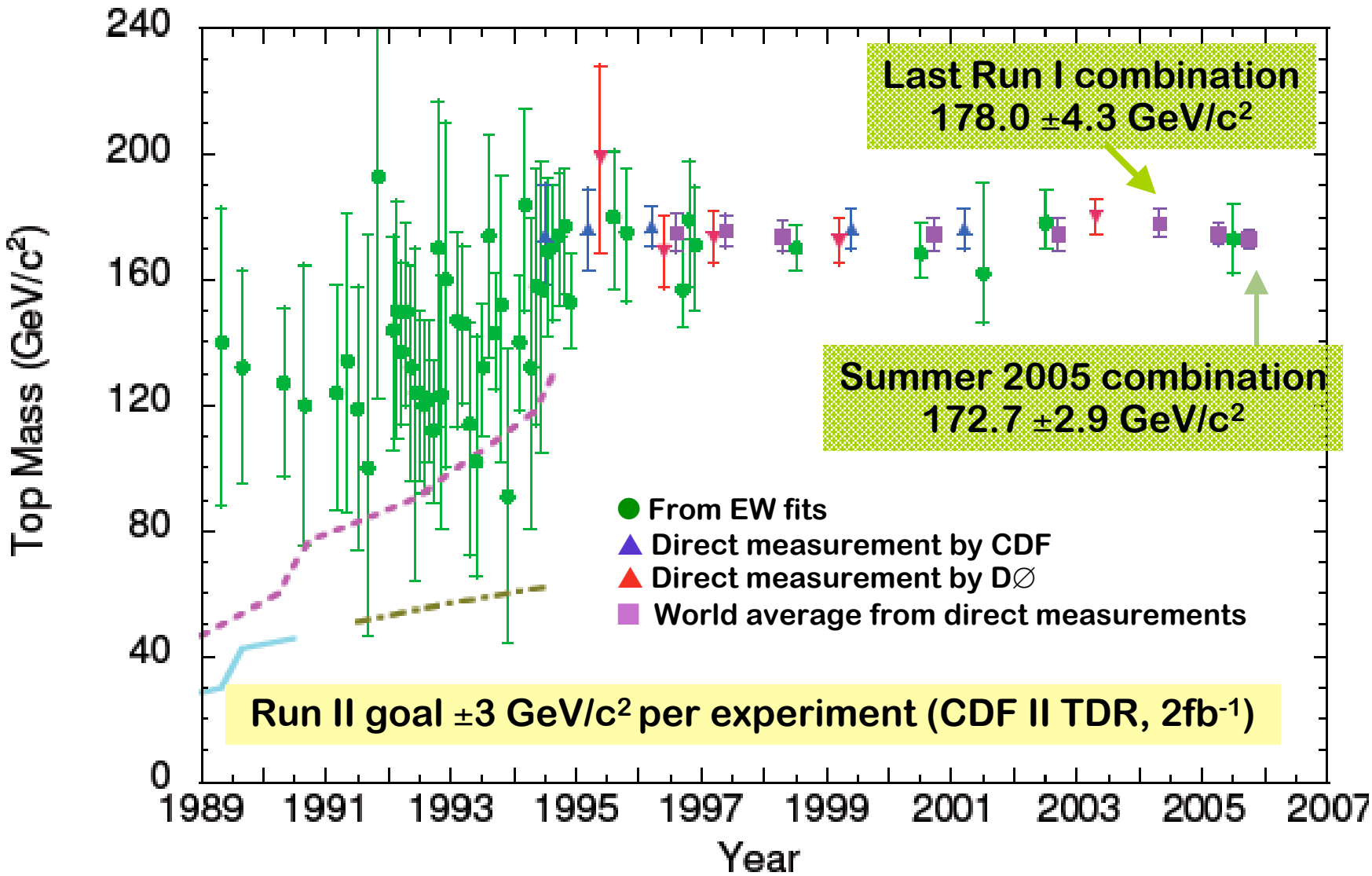
- Related to standard model observables and parameters through **loop diagrams**



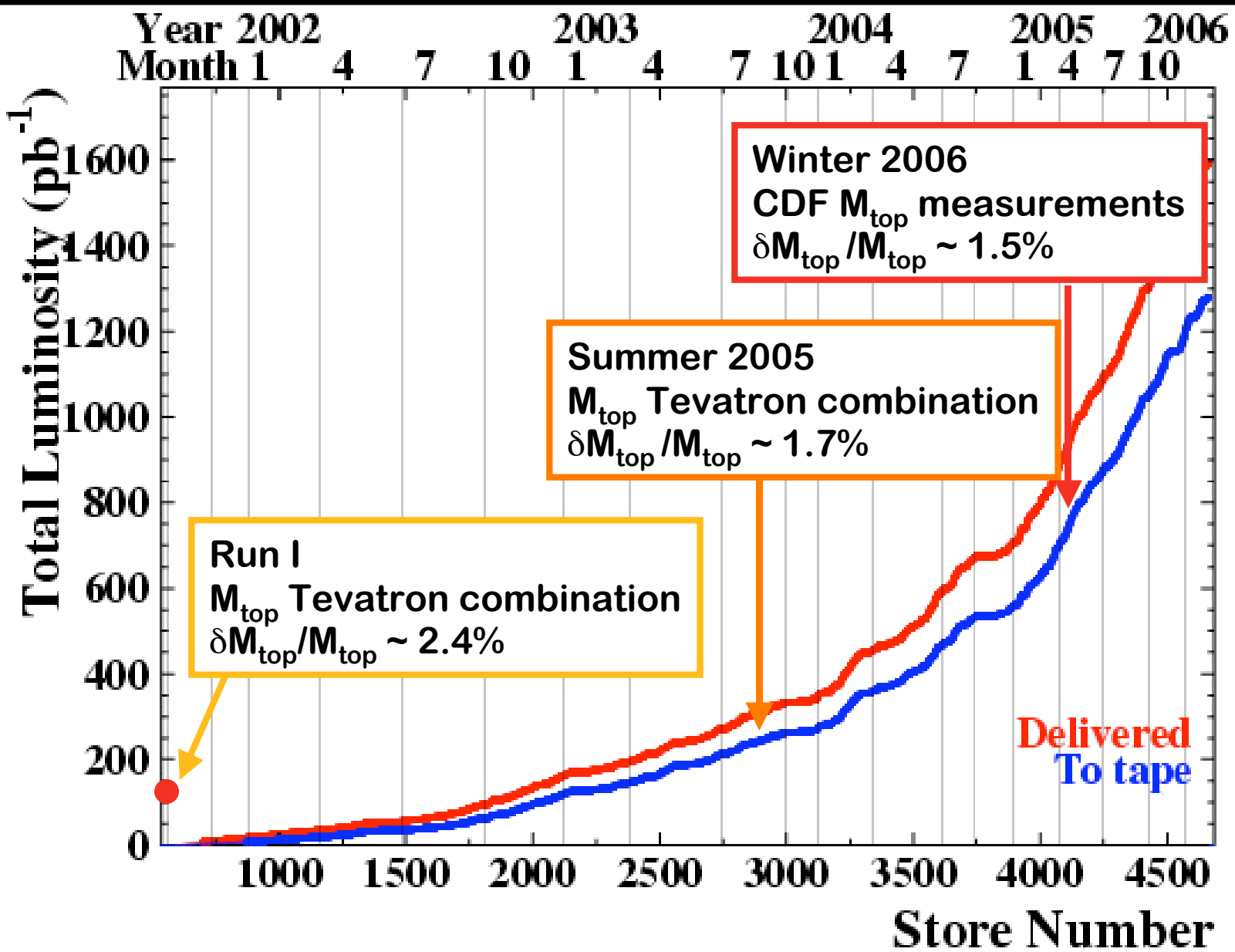
- Consistency checks of SM parameters
- Precision measurements of the M_{top} (and M_W) allow prediction of the M_{Higgs}
- Overconstraint of Higgs mass can point to physics beyond the standard model



Top Quark Mass History

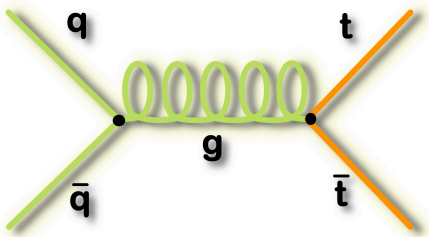


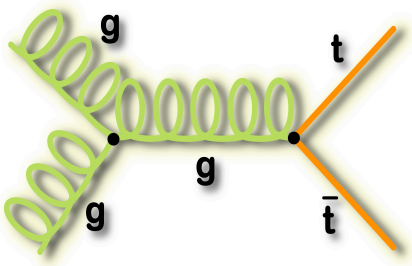
Tevatron Performance in $\delta M_{top}/M_{top}$



Production and Decay

- Mainly produced in pairs via the strong interaction





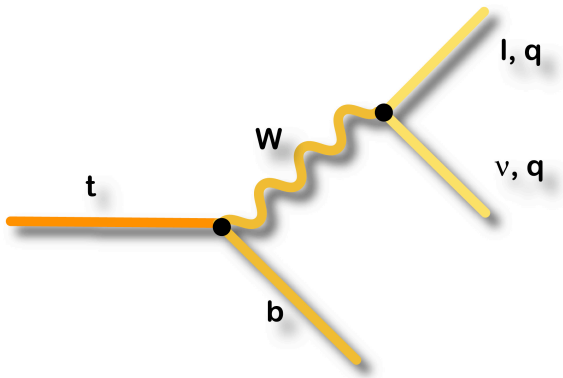
At $\sqrt{s}$ = 1.96 TeV 85% 15%

- Decay via the electroweak interactions Br(t →Wb) ~ 100%
  Final state is characterized by the decay of the W boson

Dilepton

Lepton+Jets

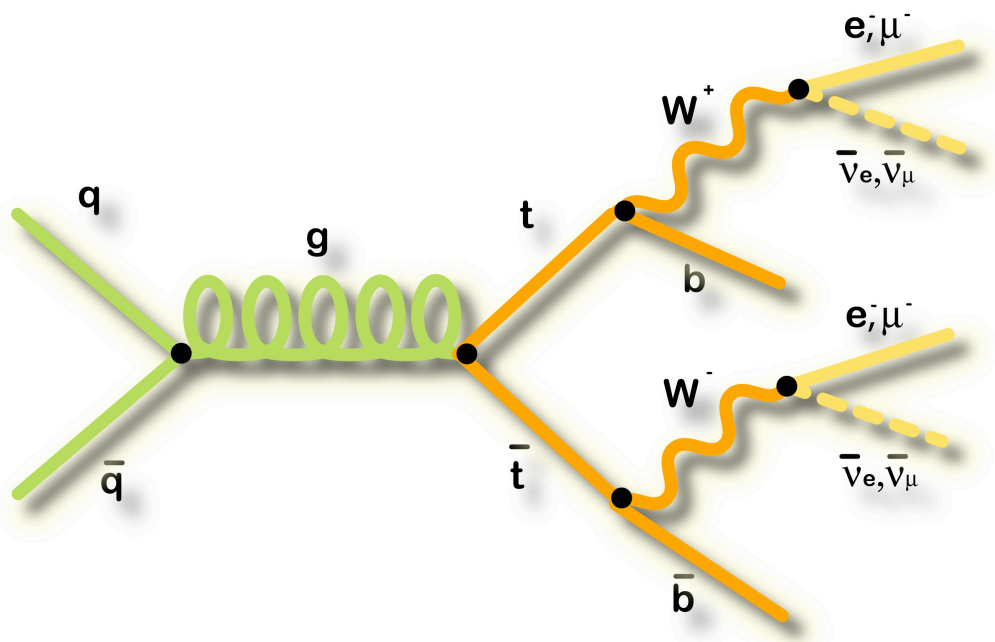
All-Jets



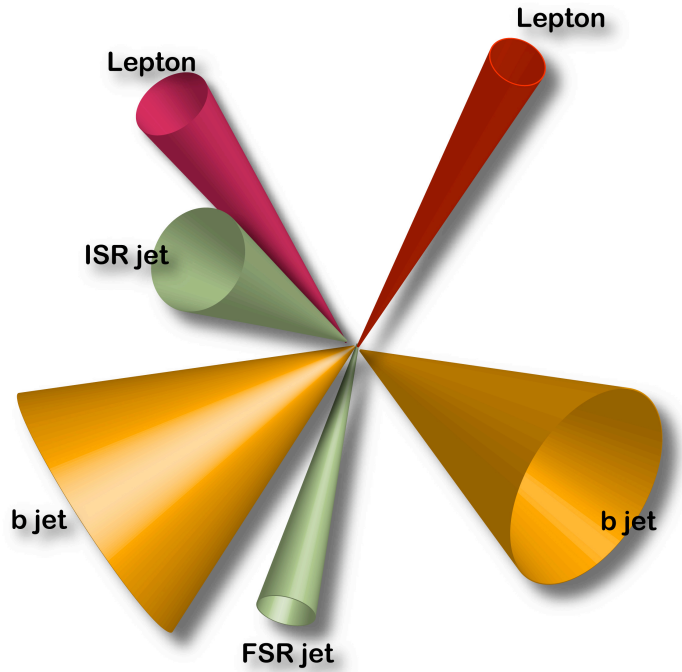
Different sensitivity and challenges in each channel

Dilepton Channel

Final State from Leading Order Diagram



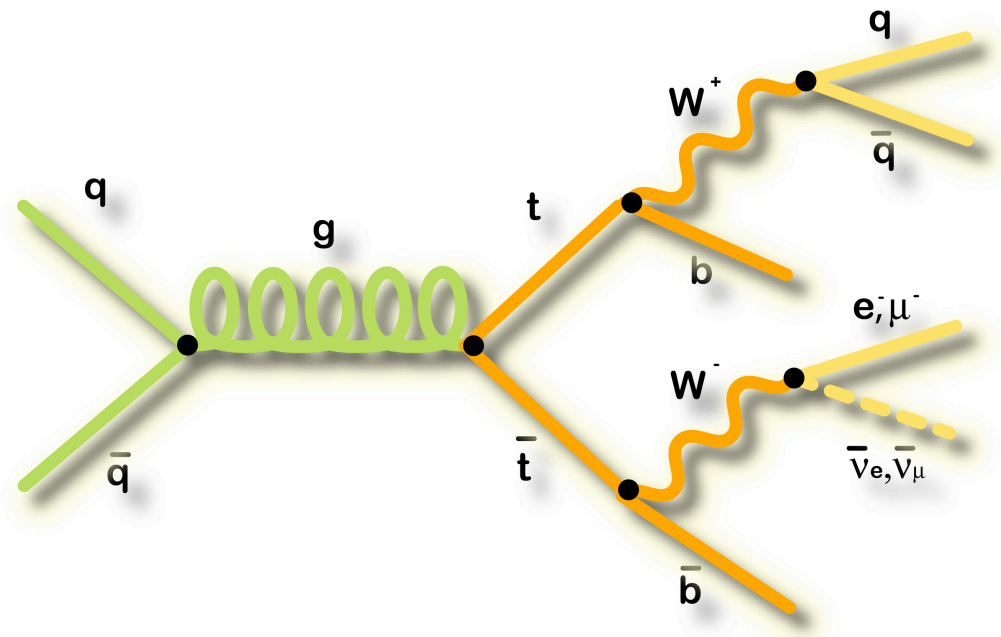
What we measure



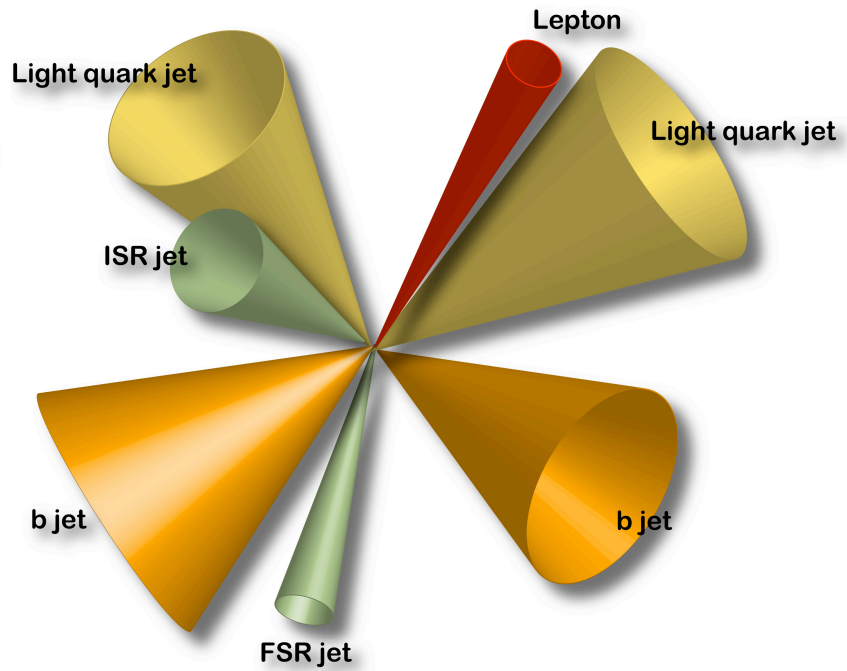
- Branching fractions = 7% (lepton = e or μ)
- Final state: 2 leptons, 2 b quarks, 2 neutrinos
- S:B = 2:1 and 20:1 requiring 1>= b-tagging
- Combinatorial background: 2 combinations
- Backgrounds: mainly instrumental
- 2 neutrinos: kinematically more complicated to solve M_{top}

Lepton+Jets Channel

Final State from Leading Order Diagram



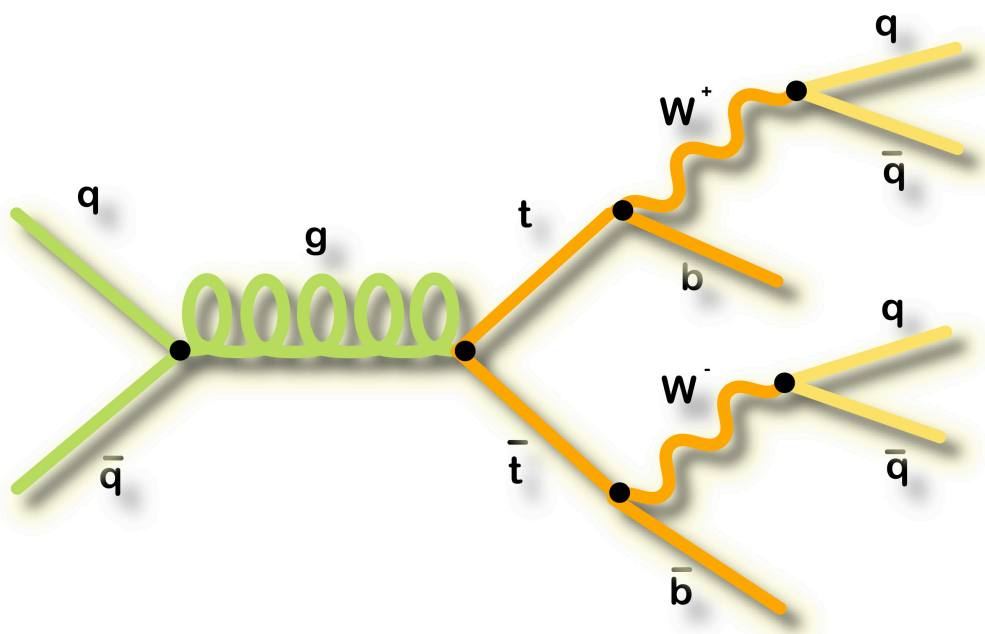
What we measure



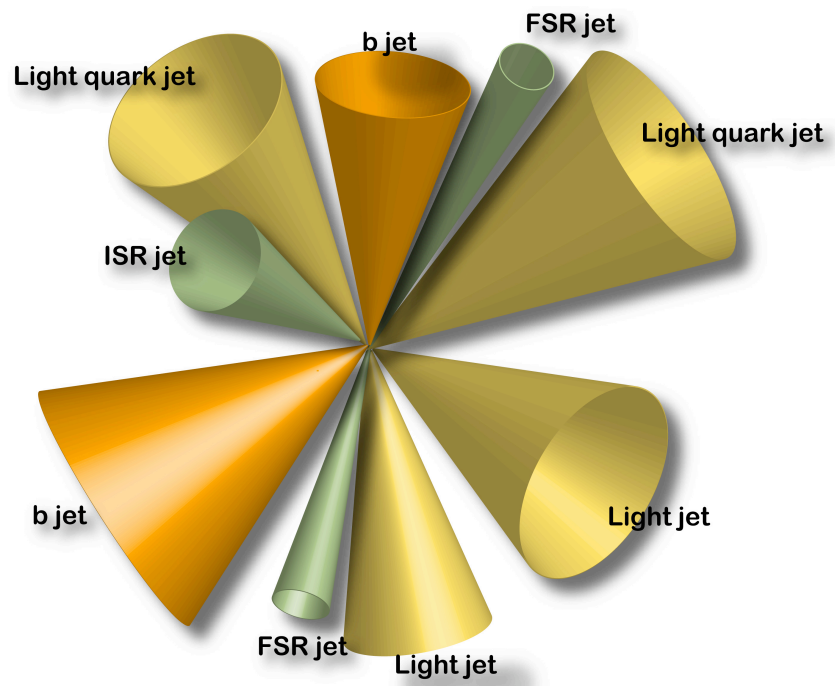
- Branching fraction: 30% (lepton = e or μ)
- S:B = 1:4 to 11:1 depending on the b-tagging requirement
- Combinatorial background: 12 (0 b tag), 6 (1btag), and 2 (2 btags)
- Most precise M_{top} measurements

All Jets Channel

Final State from Leading Order Diagram



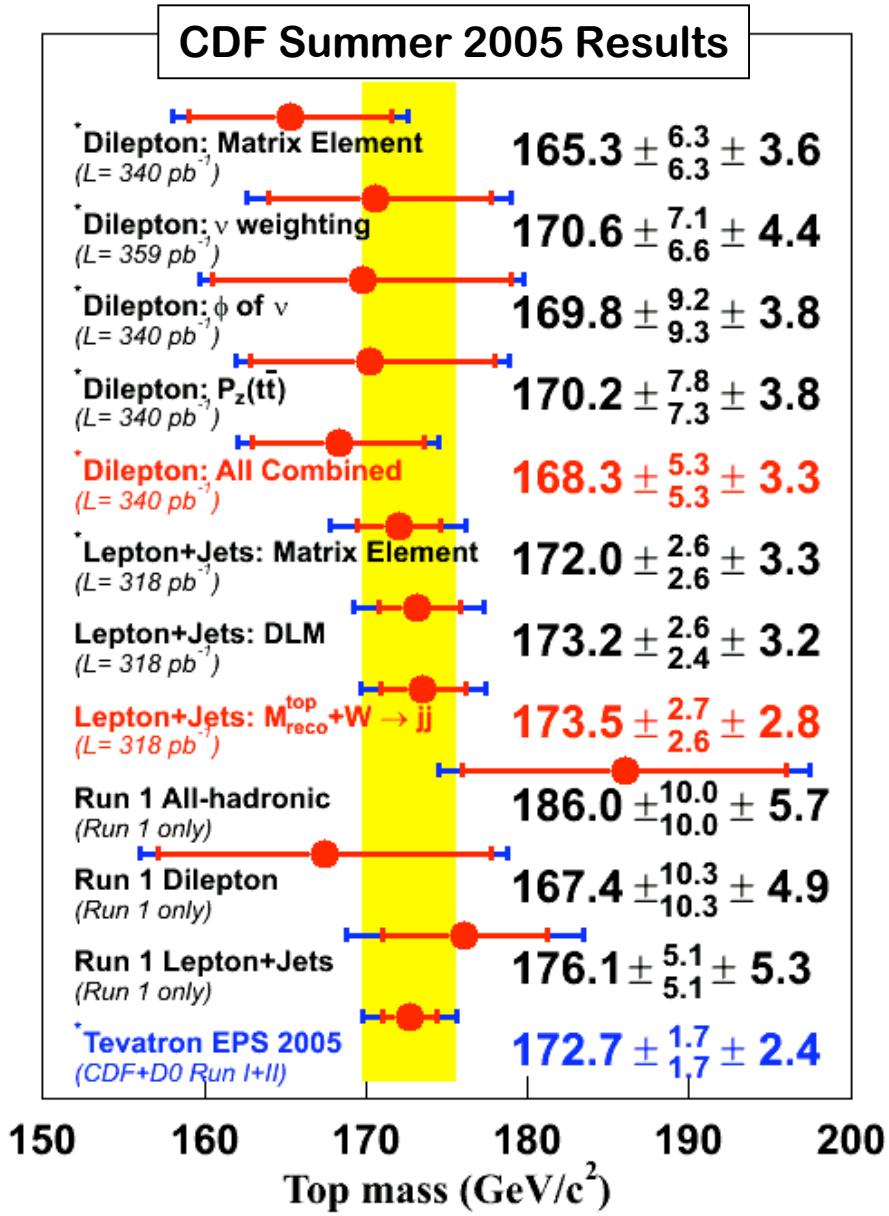
What we measure



- Branching fraction: 44%
- Huge amount of background S:B = 1:8
- Combinatorial background: 90 combinations
- Backgrounds mainly from multi-jet

Top Quark Mass at CDF

- Robust program of top quark mass measurements
- Many measurements in all the different channels -> consistency
- Different methods of extraction with different sensitivity -> confidence
- Combine all channels and all methods



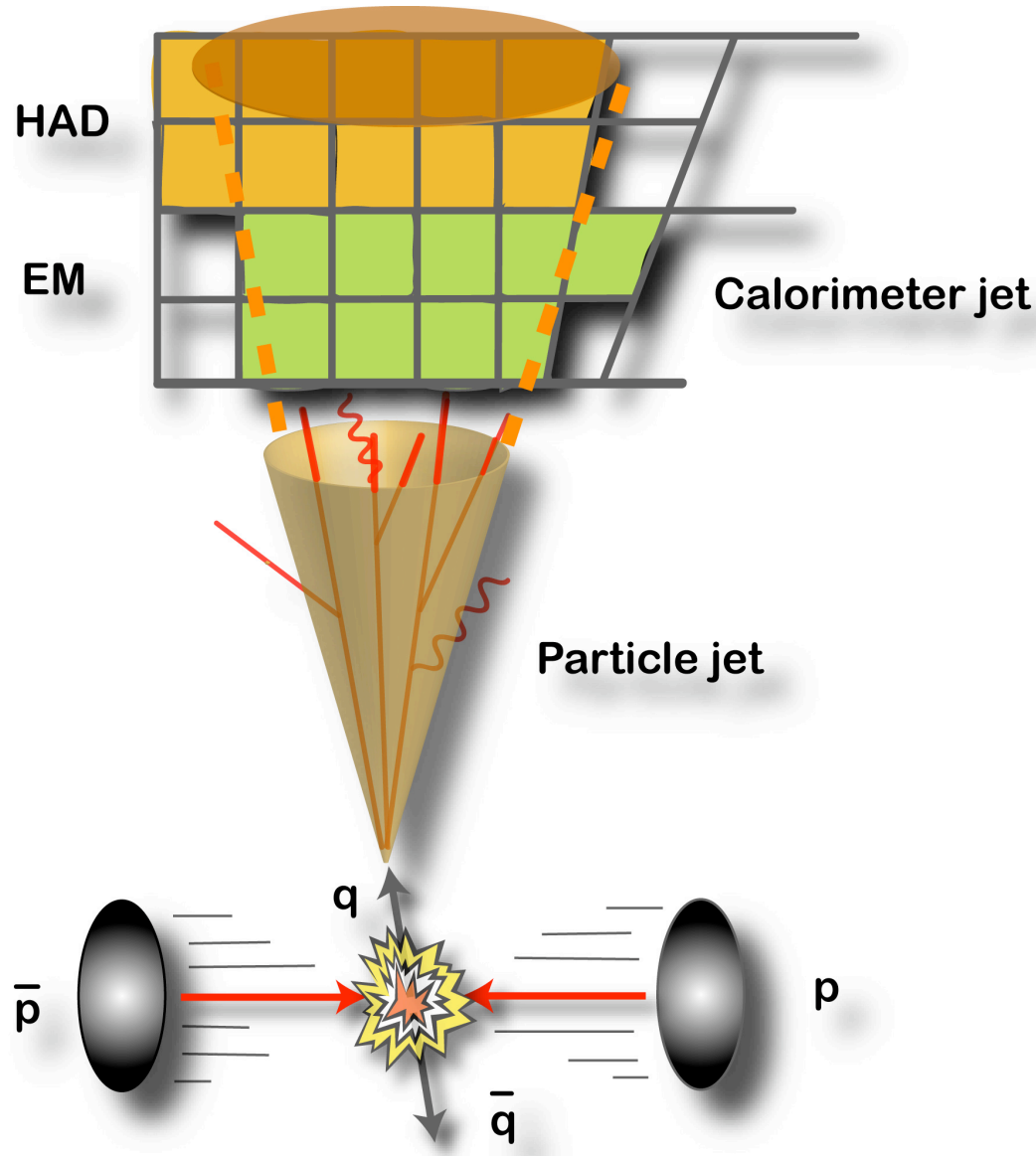
Anatomy of δM_{top}

CDF Measurement (~350pb^{-1})	Statistical (GeV/c^2)	JES (GeV/c^2)	Other syst (GeV/c^2)
Dilepton	6.3	2.6	2.2
Lepton+Jets	2.7	2.5	1.3
All Jets	4.7	4.3	1.9

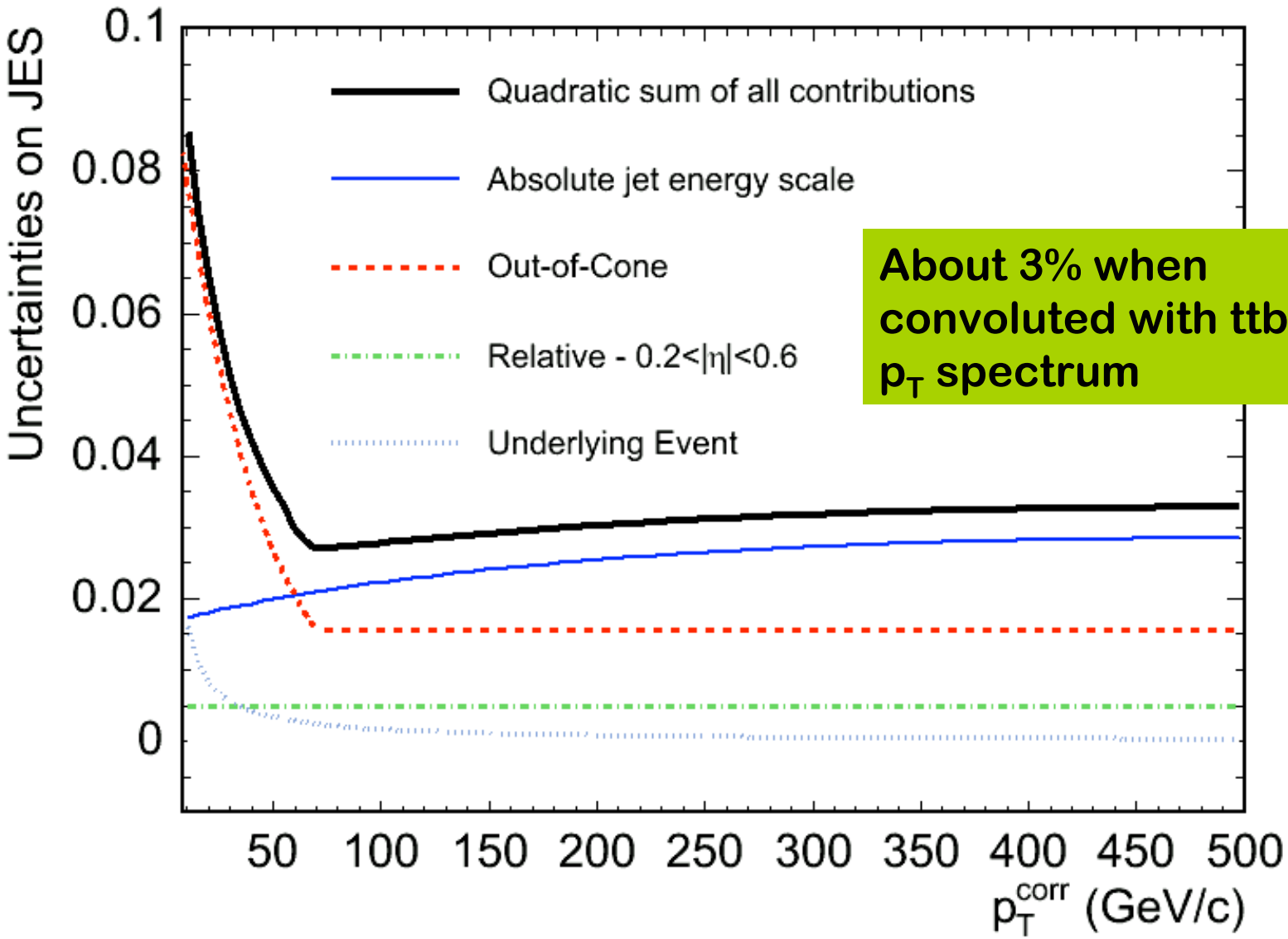
- Different difficulties in each channel
- Systematics dominated by the uncertainty on parton energies (Jet Energy Scale, JES)
- Other sources arise from the assumptions employed to infer M_{top}:
  - Initial state and final state radiation
  - Parton distribution functions
  - b-jet energy scale
  - Generators
  - Background modeling and composition
  - b-tagging efficiency
  - MC statistics

Jet Energy Scale

- Jet energy scale
  - Determine the energy of the quarks produced in the hard scattered
  - We use the Monte Carlo and data to derive the jet energy scale
- Jet energy scale uncertainties
  - Differences between data and Monte Carlo from all these effects



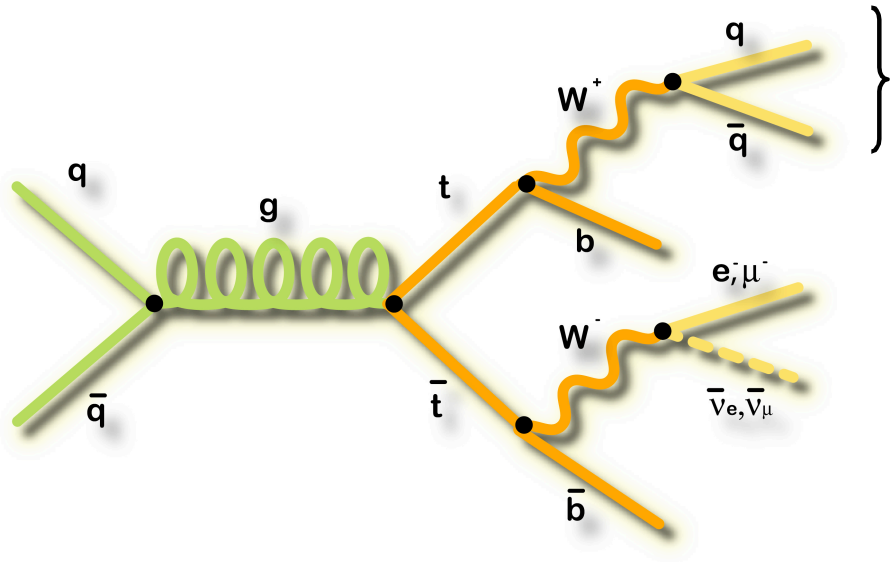
Jet Energy Scale Uncertainties



About 3% when convoluted with ttbar p_T spectrum

In-situ Measurement of JES

- We use W→jj mass resonance (M_{jj}) to measure the jet energy scale (JES) uncertainty

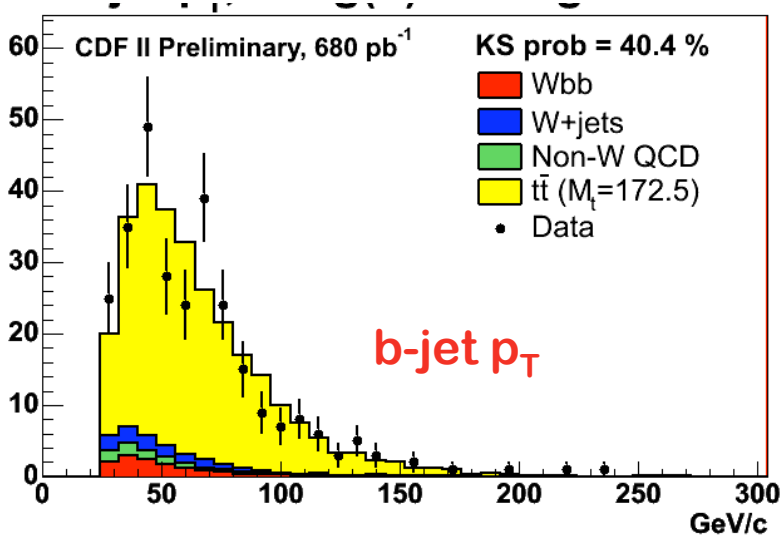


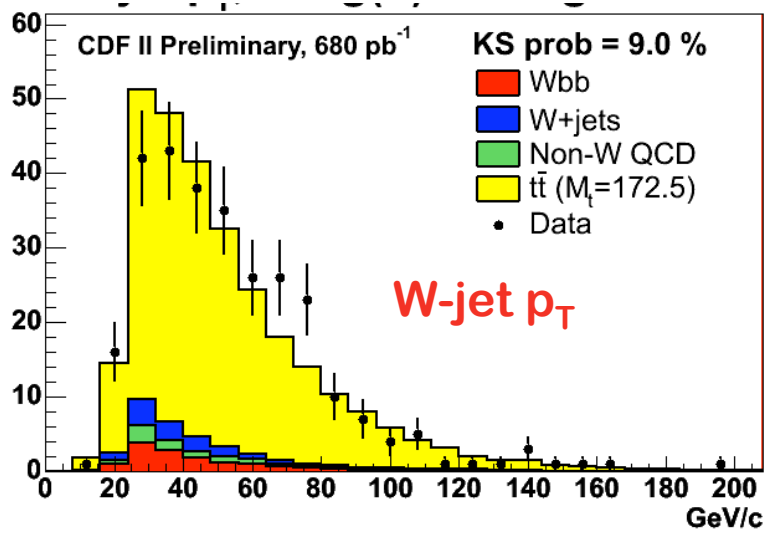
M_{jj}

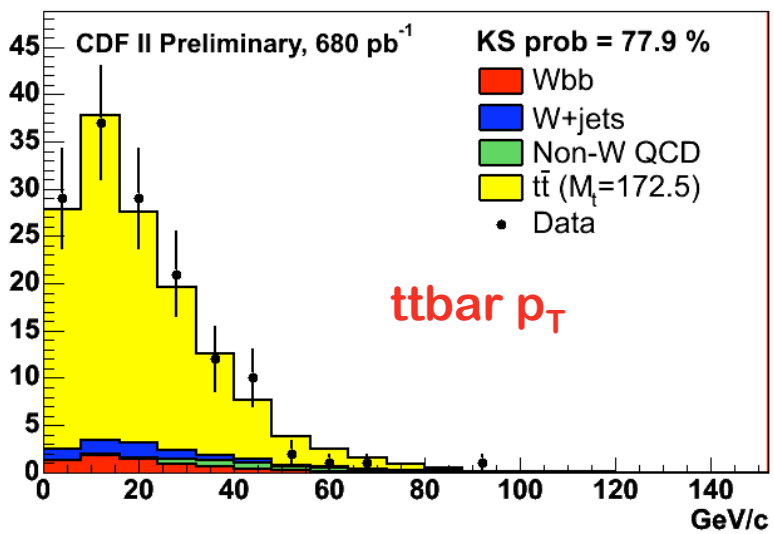
Constrain the invariant mass of the non-b-tagged jets to be 80.4 GeV/c^2

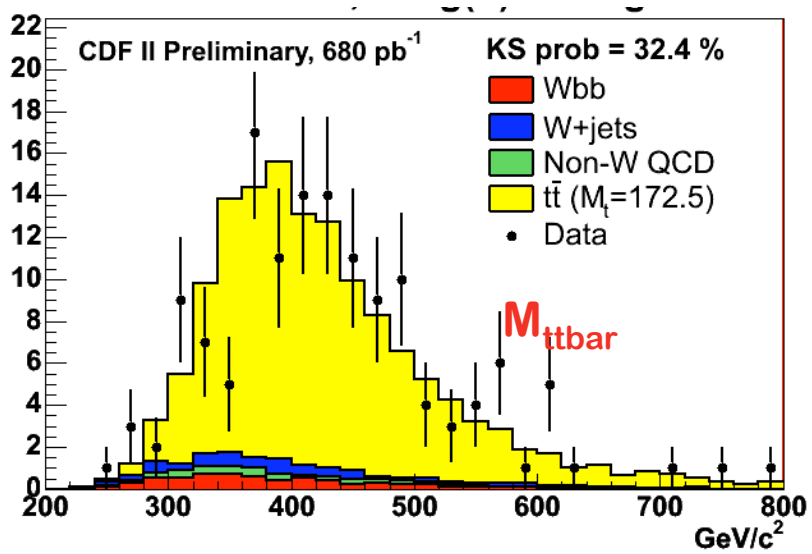
- Measurement of JES systematic uncertainty scales directly with statistics!
  - Used in lepton+jets channel
  - Could be used in all-hadronic channel

Data and Monte Carlo









In this Talk

- Results in dilepton, lepton+jets and all-hadronic channel
- New results with 680-750 pb^{-1}
- First Tevatron M_{top} in all hadronic channel (320 pb^{-1})
- Published before 2 of these results with 320 pb^{-1}
- Will talk more about the new ones
  - Lepton + jets: Template analysis
  - Lepton + jets: Matrix Element
  - Lepton + jets: Decay Length
  - Dilepton: Matrix Element
  - All Hadronic: Ideogram

Template Analysis

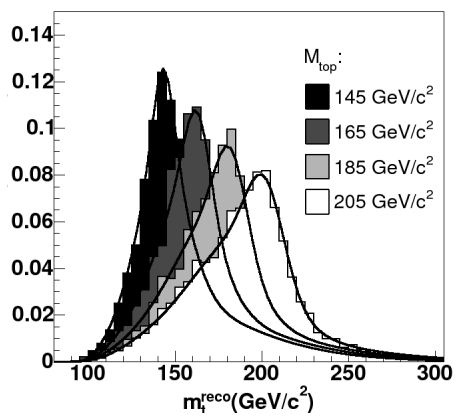
- Measurement using this method with 318 pb^{-1}: PRL 96, 022004; PRD 72, 032003, Wine and Cheese xxx
- Four samples to increase sensitivity

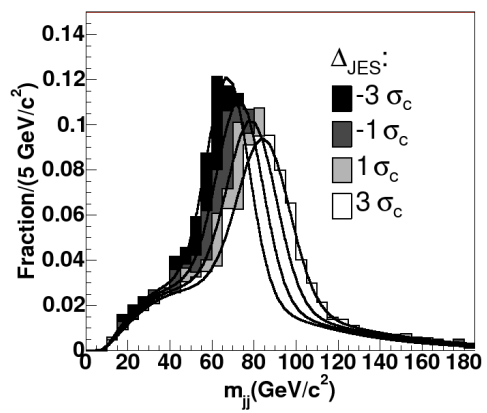
	2 b tags	1 b tag (T)	1 b tag L	0 b tag
Expected S:B	10.6:1	3.7:1	1.1:1	no a priori estimate
Expected Number of Events	46.8	104.4	64.2	no a priori estimate
Data (680 pb^{-1})	57	120	75	108

- Reconstructed m_{top} and m_{jj} from data are compared to templates of various true M_{top} and ΔJES (jet energy uncertainty shift) using an unbinned likelihood

M_{top}

m_t^{reco}

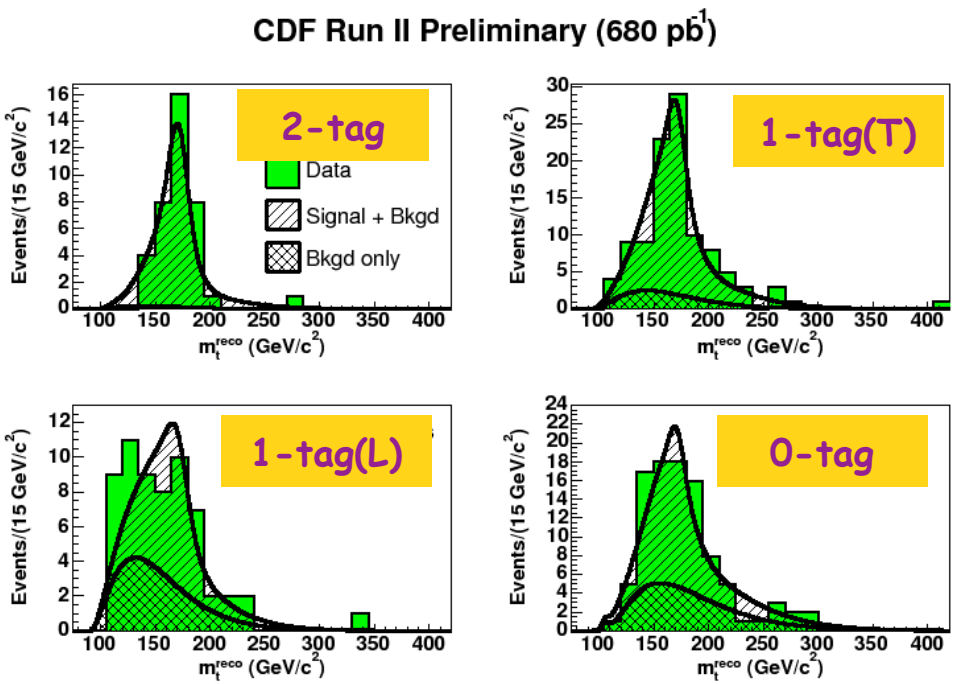




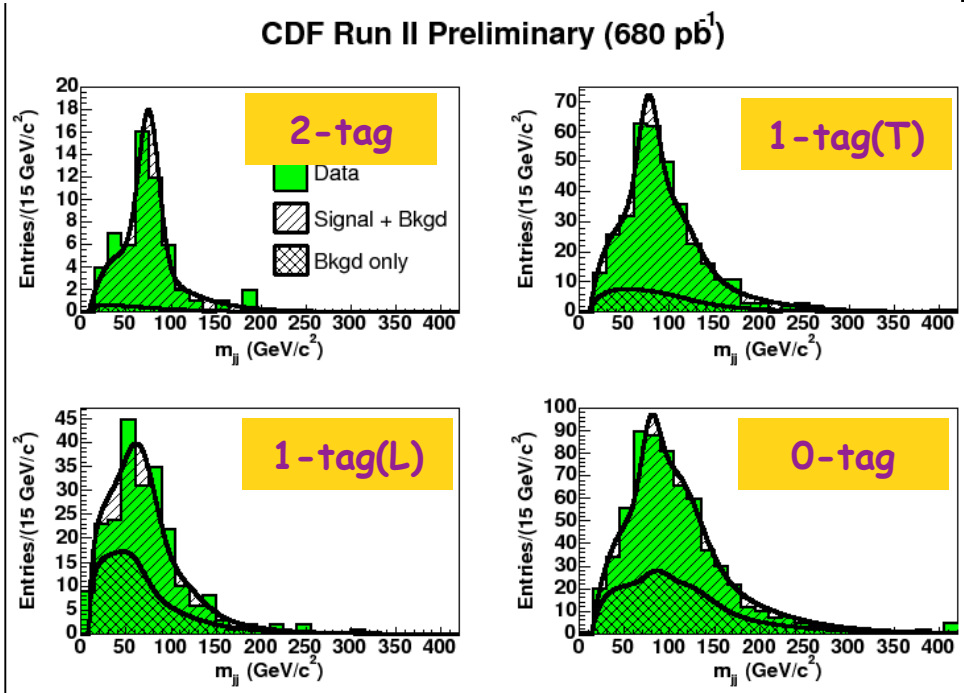
Δ_{JES}

m_{jj}

Template Analysis Results



m_t^{reco} in data w/ fit overlaid



m_{jj} in data w/ fit overlaid

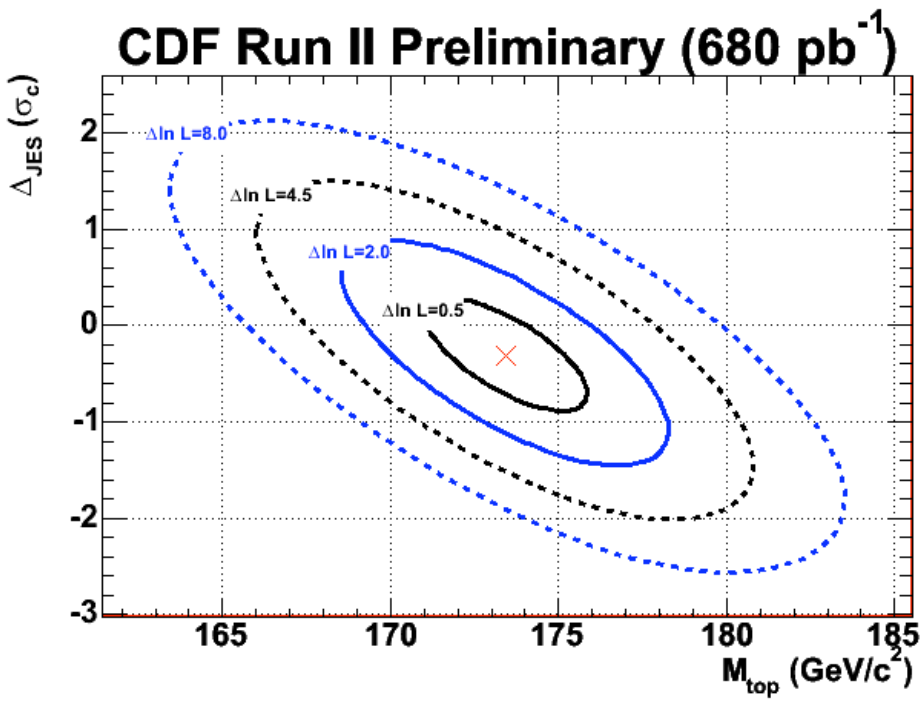
$$\Delta_{JES} = -0.3 \pm 0.6\ (\text{stat.} + M_{top})\ \sigma_c$$

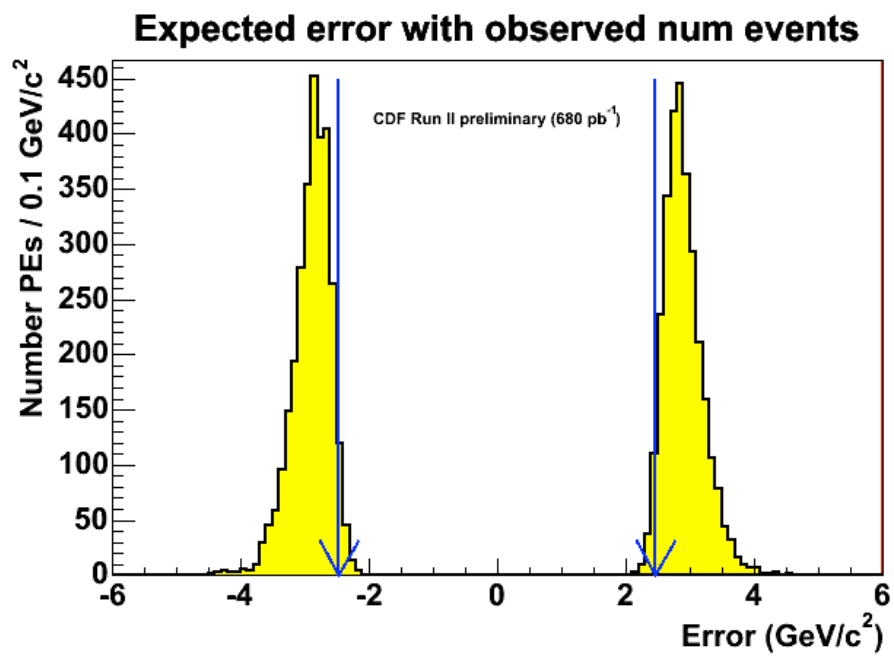
40% improvement on the external JES systematic!

Template Analysis Results

- Using 360 candidate events in 680 pb^{-1} we measure

$$M_{top} = 173.4 \pm 1.7\,(stat) + 1.8\,(JES) \pm 1.3\,(syst)\ GeV/c^2$$
$$= 173.4 \pm 2.8\ GeV/c^2$$





Matrix Element Analysis Technique

- CDF adaptation of method used by D0 published in Run I: Nature xxx. Similar to DLM PRL xxx, PRD xxx, Wine and Cheese

- Build a probability for a signal and background hypothesis

$$\bar{P}(x;C_s, M_{top}, JES) = C_s P_{signal}(x;M_{top}, JES) + (1 - C_s) P_{background}(x;JES)$$

- Likelihood simultaneously determines M_{top}, Jet Energy Scale, and signal fraction:

$$L(M_{top}, JES) \propto \prod_{i=1}^{N} \bar{P}(x_i;M_{top}, JES)$$

Matrix Element Analysis Technique

- Uses kinematic and dynamic information to construct a probability

$d^n\sigma$ is the differential cross section: LO Matrix element

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

$$\bar{P}(x; M_{top}, JES) = \frac{1}{\sigma} \int d^n\sigma(y; M_{top})\, dq_1\, dq_2\, f(q_1)\, f(q_2)\, W(JES\, x, y)$$

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

where *x* is a set of measured variables

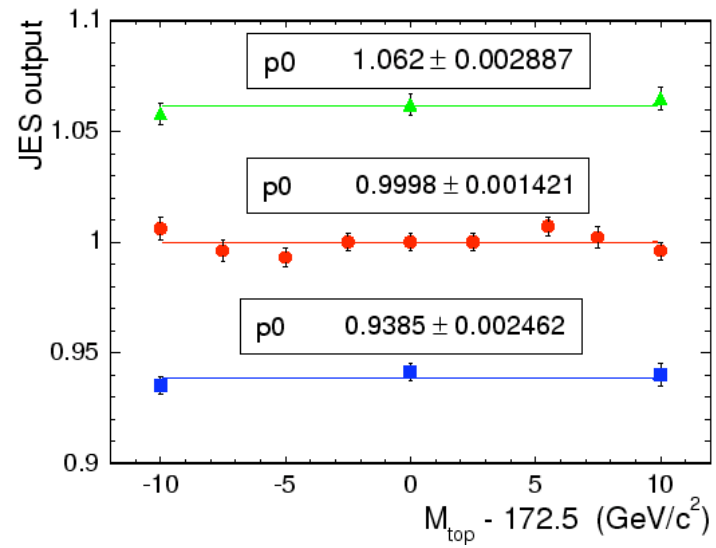
- JES sensitivity comes from W resonance
- All permutations and neutrino solutions are taken into account
- Lepton momenta and all angles are considered well measured

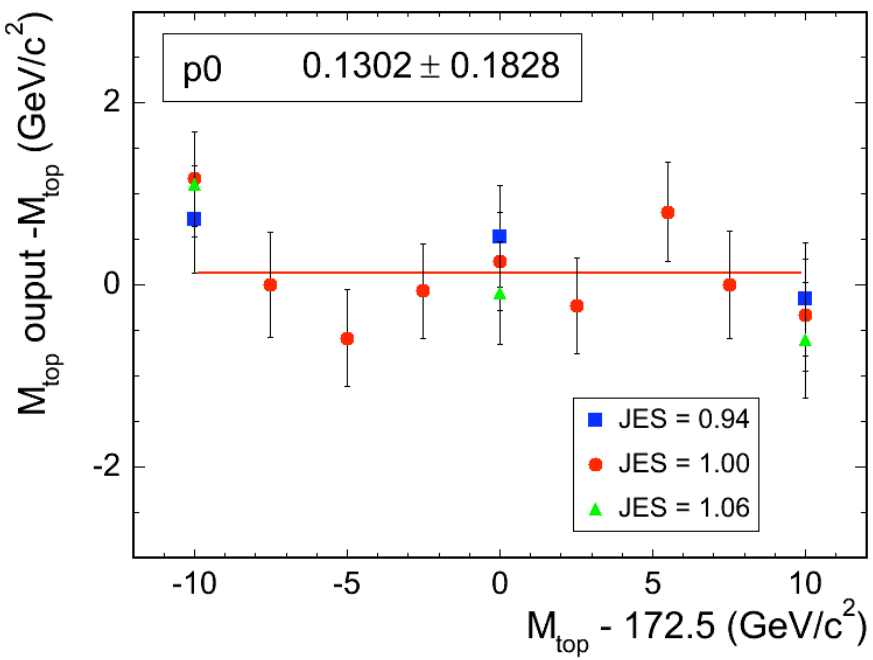
$$W(JES\, x, y) = \delta^3(p^y_{lepton} - p^x_{lepton}) \prod_{j=1}^{4} W_{jet}(JES\, E^x_j, E^y_j) \prod_{i=1}^{4} \delta^2(\Omega^y_i - \Omega^x_i)$$

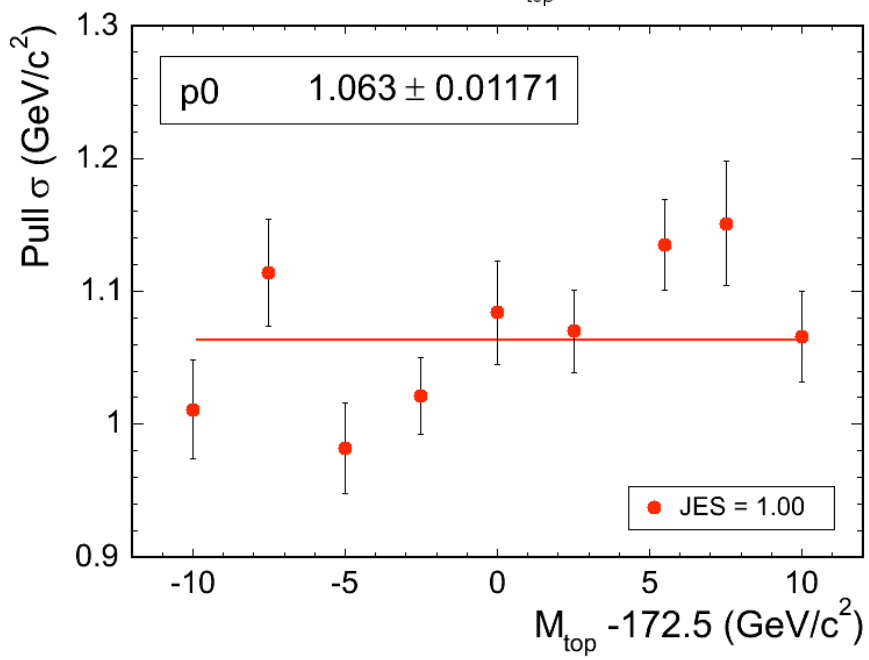
- Background probability is similar, no dependence on M_{top}

Matrix Element Analysis Results

- Calibrate method against MC samples:
  - Shows unbiased measurement
  - Errors rescaled to account for observed pull width







Matrix Element Analysis Results

- Event Selection
  - Exactly 4 jets
    - 1-b tag T: 4 jets E_T>15 GeV (S:B=5:1)
    - 2-b tags: 4 jets E_T>15 GeV (S:B=13:1)

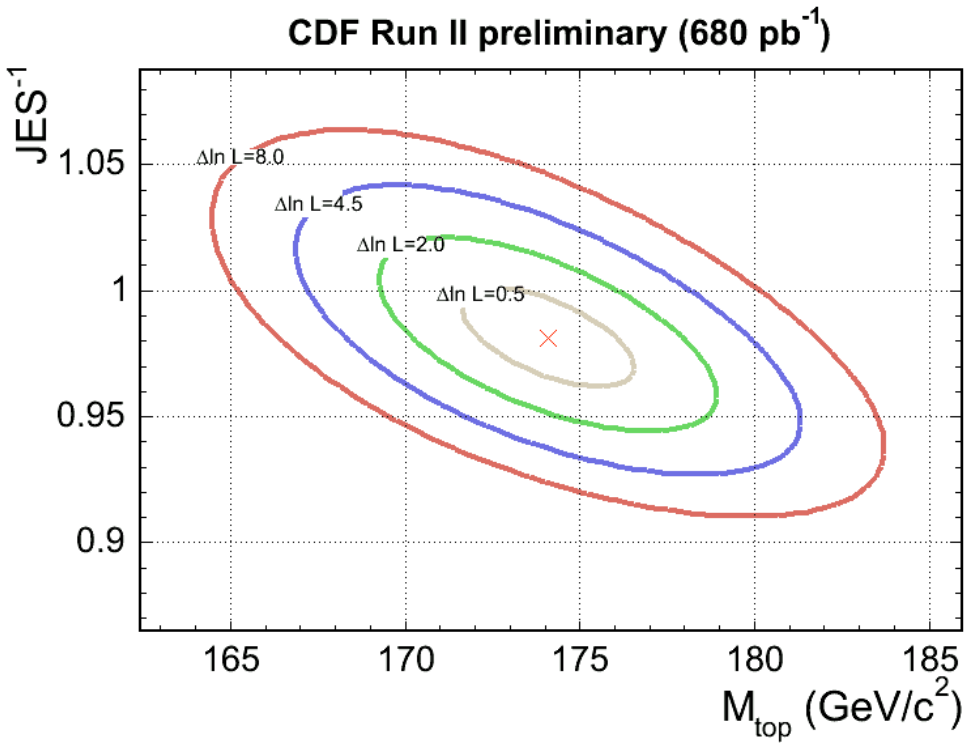
	Expected Events (681 pb^{-1})
W+4 jets (Mistags)	4.39 ± 0.91
Non-W (QCD)	3.75 ± 1.86
Wbb	3.35 ± 1.54
Wcc	1.60 ± 0.76
Wc	1.00 ± 0.45
Single top	0.81 ± 0.19
EW (WZ,WZ,ZZ)	0.77 ± 0.17
Total background	15.67 ± 2.54
tt (6.1 pb)	78.89 ± 2.74
Data	118

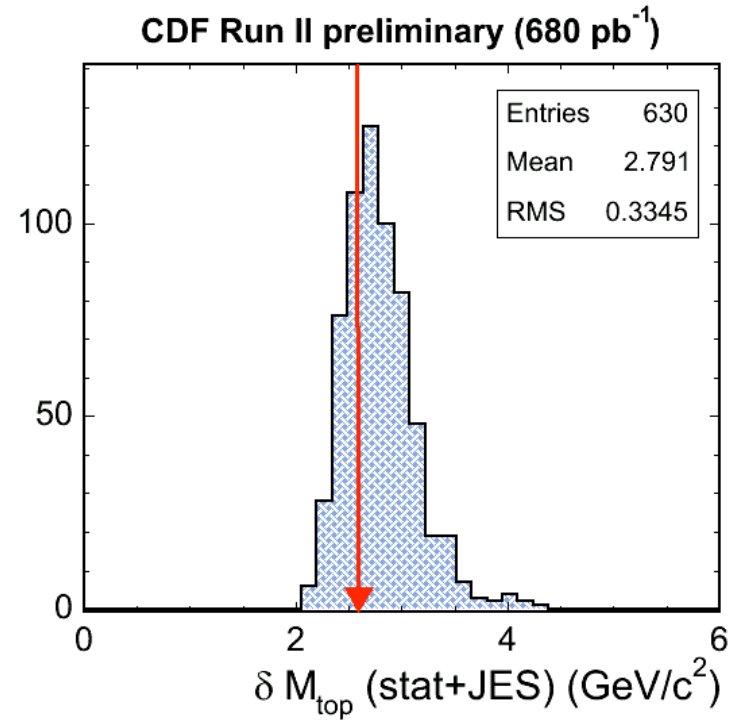
Matrix Element Analysis Results

- Using the 118 candidates in 680 pb^{-1} our top quark mass measurement is:

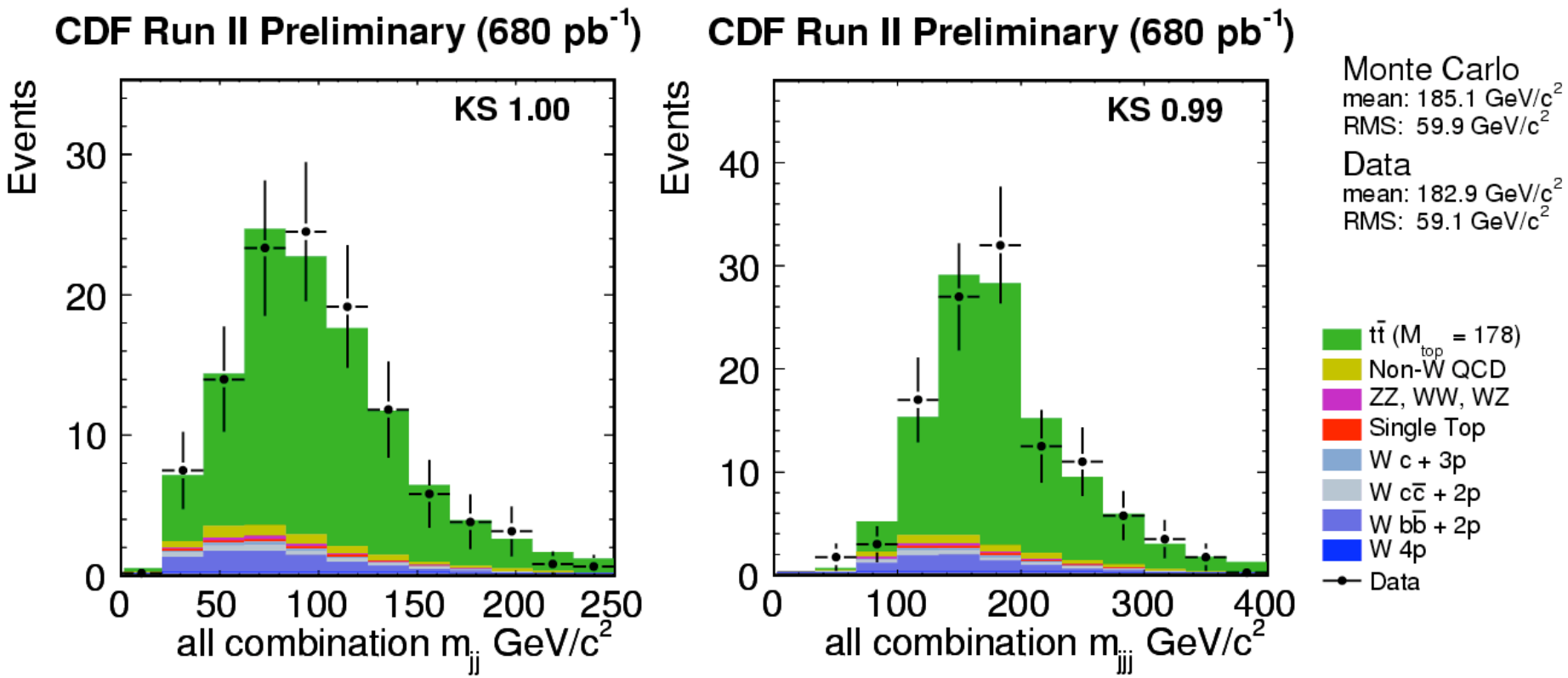
$$M_{top} = 174.0 \pm 2.0\,(stat) \pm 1.8\,(JES) \pm 1.3\,(syst)\ GeV/c^2$$

with JES = 1.019 ± 0.022 (stat) and signal fraction = 0.83 ± 0.08 (stat)
consistent with cross-section

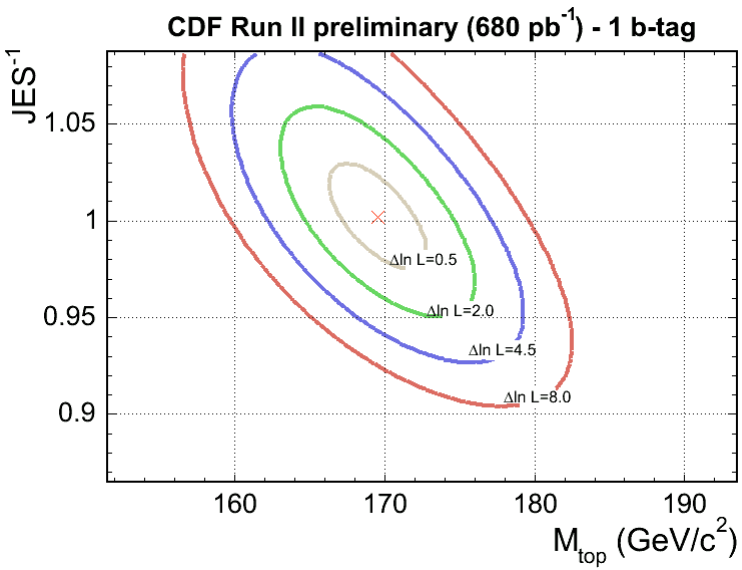


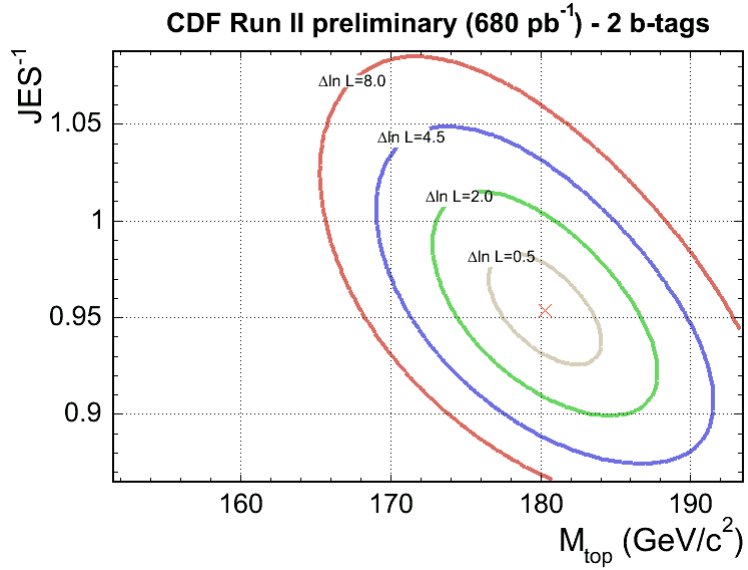


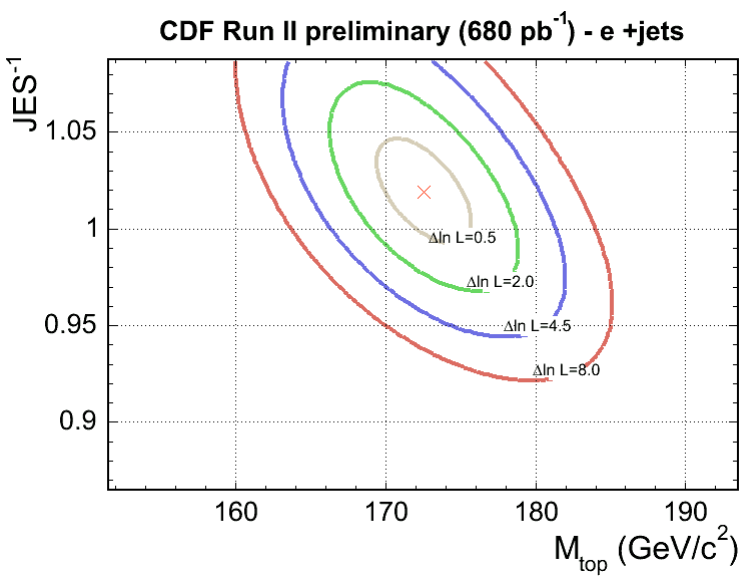
Matrix Element Analysis Results

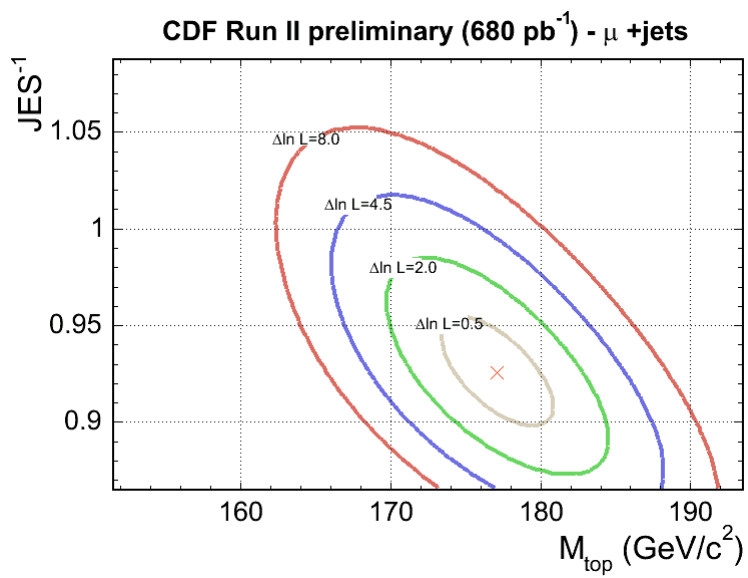


Matrix Element Analysis Results



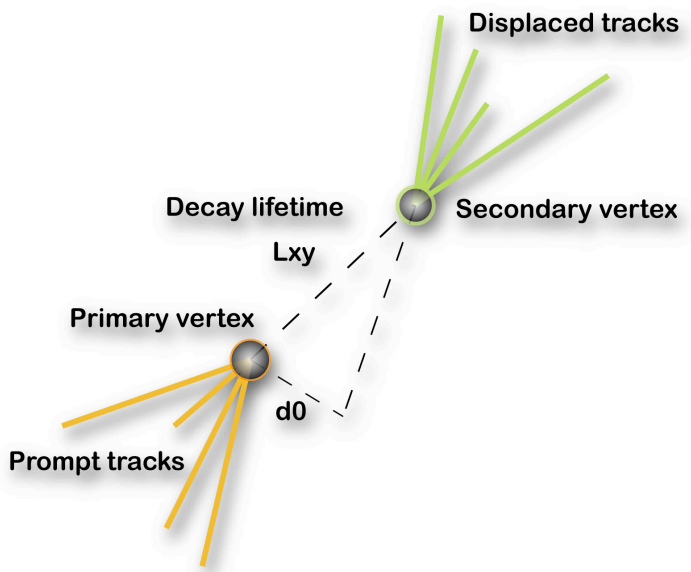


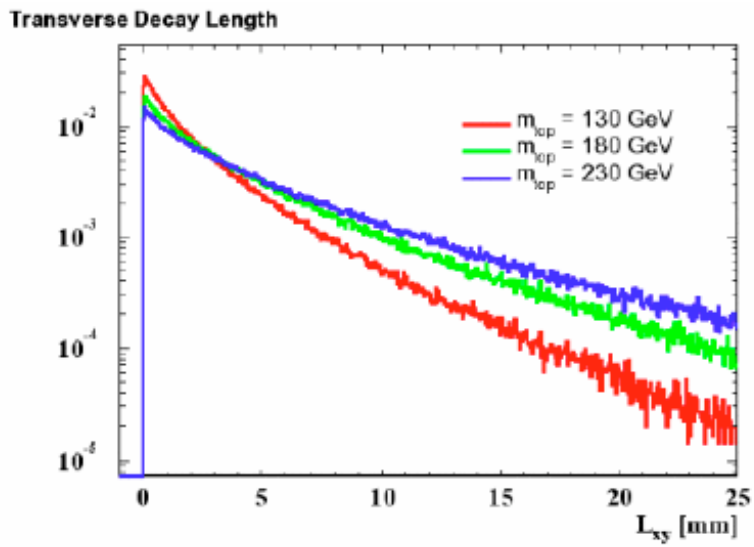




Decay Length

- The method has been published in PRD 71, 054029
- B hadron decay length ∝ b-jet boost ∝ M_{top}





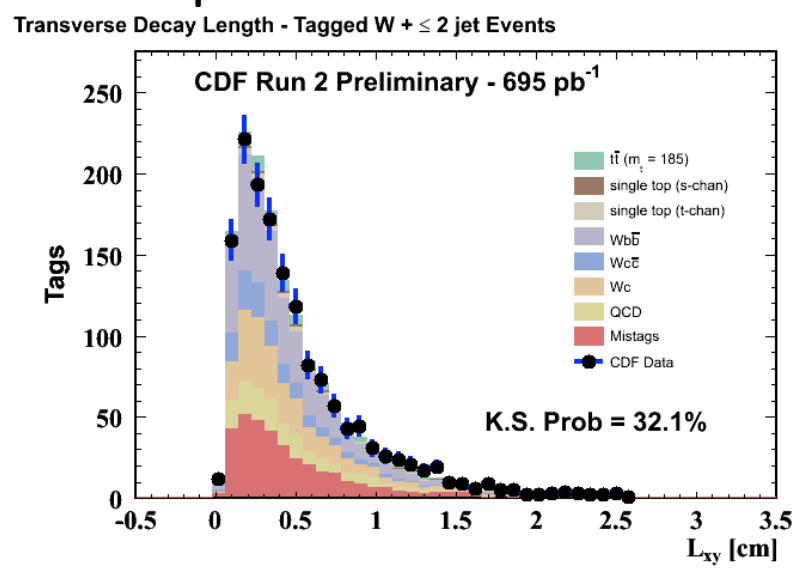
- Uses the average transverse decay length of the b-hadrons <Lxy>
- Relies on tracking, does not use calorimeter information
  - Uncorrelated with other M_{top} measurements

Decay Length

- Event selection used to maximize the amount of signal in the sample:
  - 3 or more jets
  - 1>= b tag jet
  - 375 events S:B = 3:1

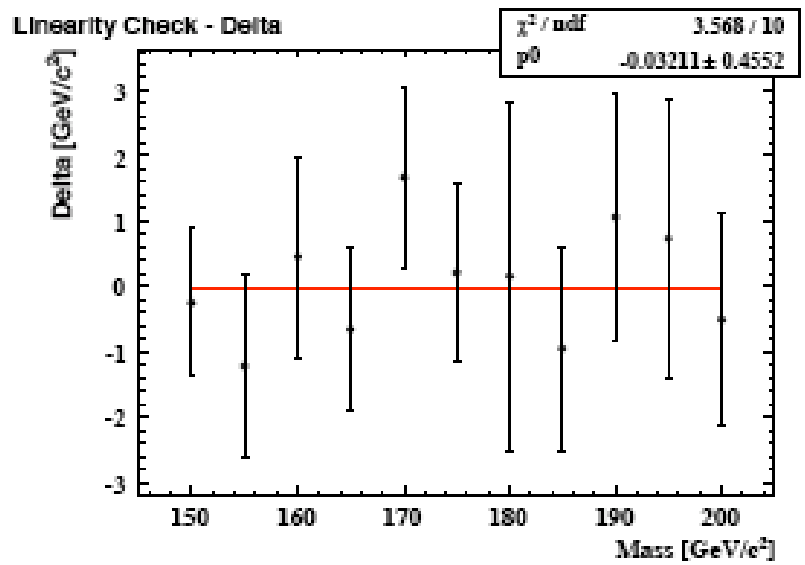
	Expected Events (695 pb^{-1})
Total background	x ± 2.54
tt (6.1 pb)	x ± 2.74
Data	375

- Requires accurate simulation of Lxy
  - Enriched heavy-flavor samples
    - SF = 0.992 ± 0.012 cm
    - Major systematic uncertainty
  - Data and Monte Carlo comparison in control sample



Decay Length

- The method is unbiased



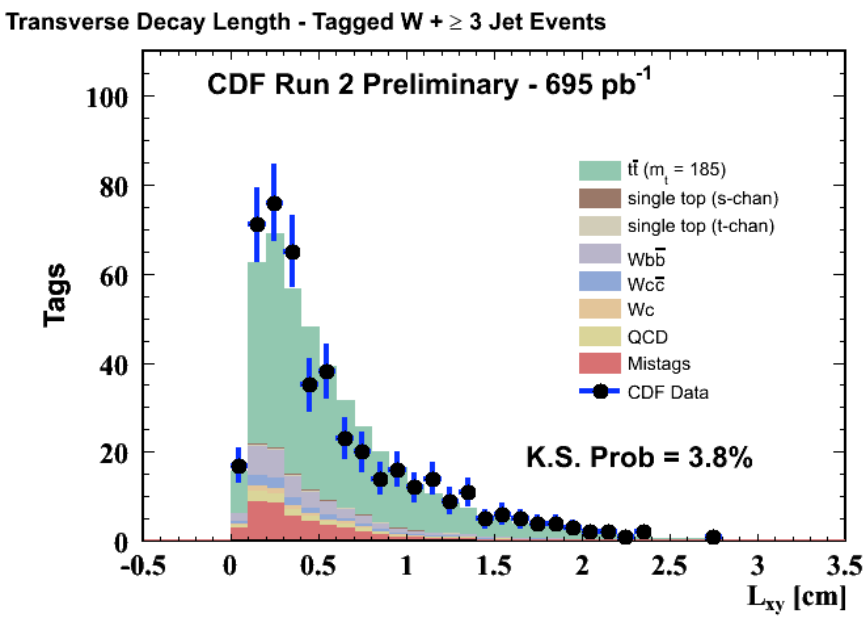
Source of Systematic Error	Uncertainty (GeV)
Generator/Fragmentation	0.7
ISR	1.0
FSR	0.9
PDF	0.5
Jet Energy Scale	0.3
Background Shape	2.3
Background Normalization	2.3
Multiple Interactions	0.2
Data/MC $\langle L_{xy} \rangle$ SF	4.2
Total	5.6

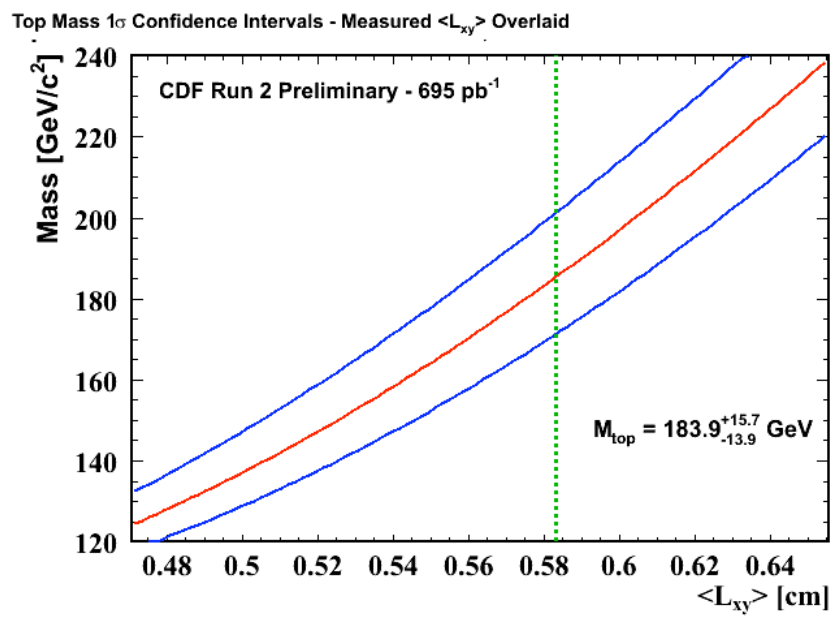
Decay Length

- Using 695pb^{-1} we have 375 candidates
  - <Lxy> = 0.5808 ±0.0227 cm

$$M_{top} = 183.9^{+15.7}_{-13.9}\ (stat) \pm 5.6\ (syst)\ GeV/c^2$$

- Statistics limited now
  - Can make significant contribution at LHC
  - Lepton+jets: planning to add dilepton and all hadronic channel





Dileptons: Matrix Element Overview

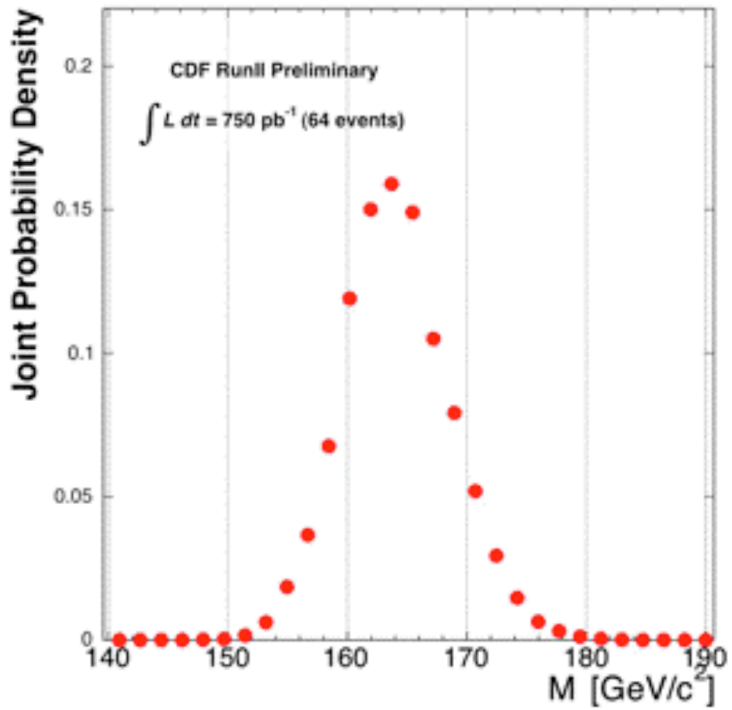
- Measurement with this method using 340 pb^{-1} published: hep-ex/0512070, PRL xxx, PRD xxx, Wine and Cheese
- Likelihood is similar to lepton+jets
  - No W resonance ->no fit for JES
  - Add Matrix Element for dominant backgrounds: Drell-Yan, WW+jets, fakes
- Approximations have a significant effect
  - Monte Carlo calibration essential
  - Correct fitted mass for calibration slope of 0.85
  - Correct for pull width of 1.49 (constant in M_{top})
- Updated measurement using 750 pb^{-1}

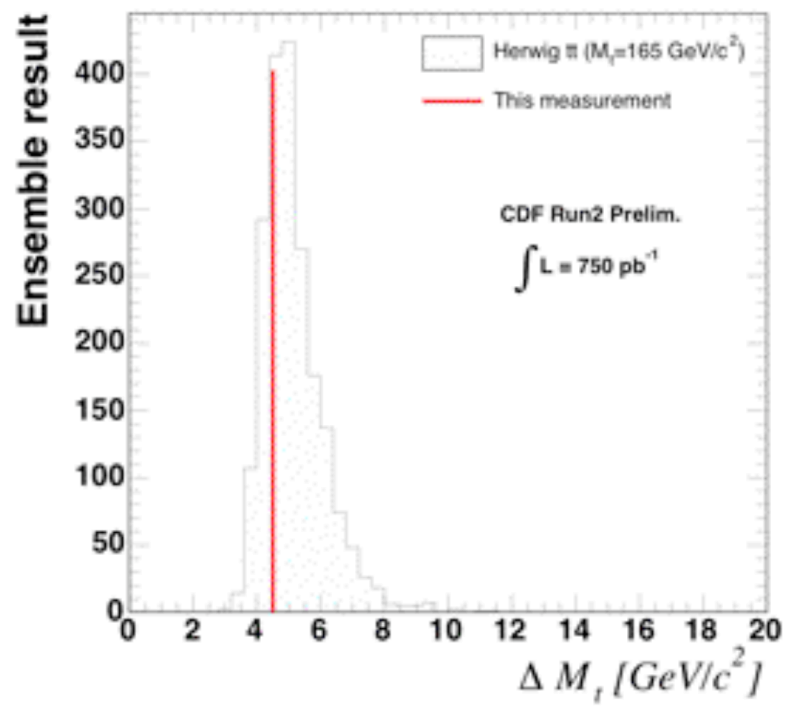
	Expected Events (750 pb^{-1})
Z->tt	1.60 ± 0.83
Drell-Yan	7.83 ± 3.15
Fakes	6.29 ± 3.15
EW (WZ,WZ,ZZ)	3.63 ± 0.72
Total background	19.4 ± 3.4
tt (6.1 pb)	36.1 ± 1.2
Data	64

Dileptons: Matrix Element Results

- Using 750pb^{-1} and 64 candidates events we measure

$$M_{top} = 164.5 \pm 4.5\ (stat) \pm 2.6\,(JES) \pm 1.7\ (syst)\ \ GeV/c^2$$





Restrict sample to b-tagged events: $M_{top} = 162.7 \pm 4.6 \pm 3.0$ GeV/c^2

Ideogram Overview

- Ideogram method from the Delphi experiment for the W mass measurement, used in D0 for top mass measurement in lepton+jets channel

- Event-by-Event likelihood based in M_{top} with simultaneous determination of signal cross-section

- Main challenges in all-hadronic channel:
  - Small signal fraction S:B = 1:8
  - Large combinatorial background: 90 combinations

Ideogram Overview

- Define a 2D event likelihood as

$$L_{event}(M_{top}, C_s) = \sum_{i=1}^{90} w_i \left[C_s S(m_i^1, m_i^2, \sigma_i^1, \sigma_i^2, M_{top}) + (1 - C_s) B(m_i^1, m_i^2) \right]$$

- The sample purity C_s is left free and determined simultaneously with M_{top}
- Extract from kinematical fit m_{top} and $m_{anti\text{-}top} \propto m^1, m^2$, s1,s2, chi2

$$S(m_i^1, m_i^2, \sigma_i^1, \sigma_i^2, M_{top}) = P_m \cdot S_m + (1 - P_m) \cdot S_{non-m}(M_{top}, m_i^1, m_i^2)$$

  - S, Signal term

$$S_m(m_i^1, m_i^2, \sigma_i^1, \sigma_i^2, M_{top}) = \int d\,m_1 d\,m_2\, G(m_1, m_i^1, \sigma_i^1)\, BW(m_1, M_{top}, \Gamma_{top}) \cdot G(m_2, m_i^2, \sigma_i^2)\, BW(m_2, M_{top}, \Gamma_{top})$$

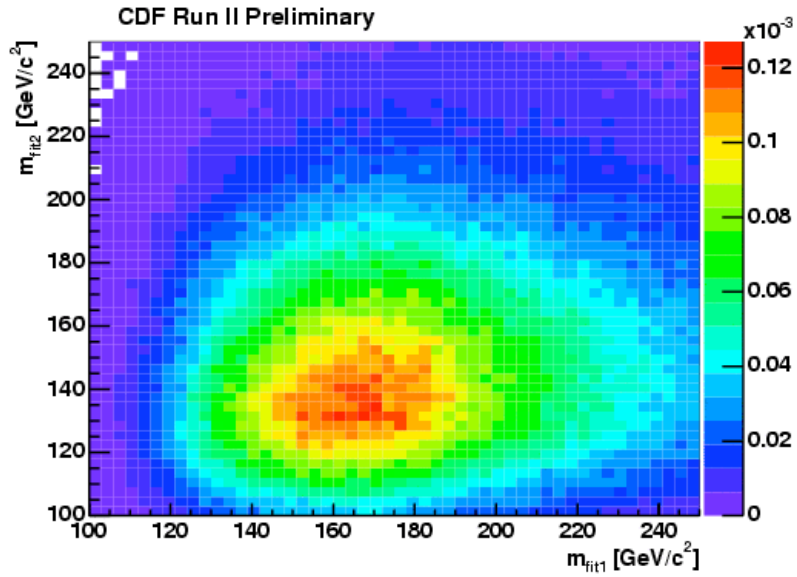
$S_{non\text{-}m}$ from Monte Carlo

  - B, Background term from Monte Carlo

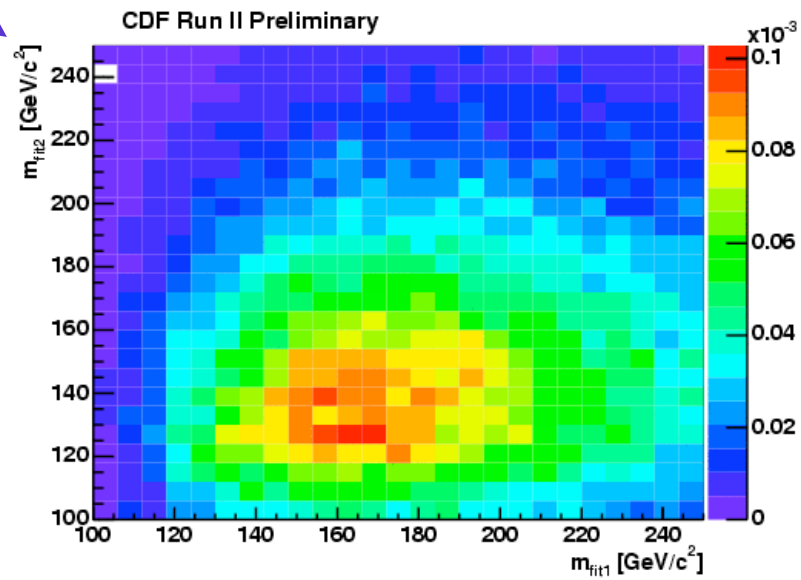
- Weight each combination with kinematical and b-tagging information: wi

Ideogram Overview

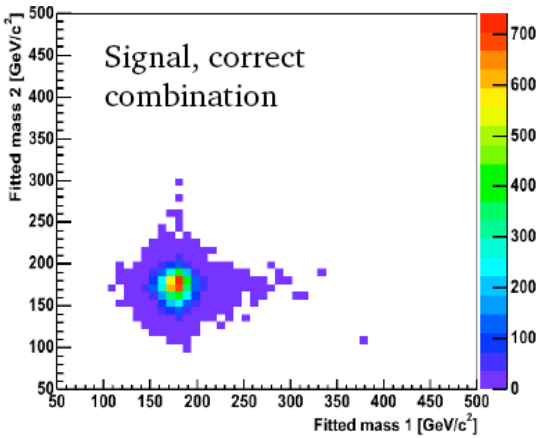
- $S_{non\text{-}m}$, Template for non-matched hypothesis



- B, Template for background hypothesis



Signal, correct combination

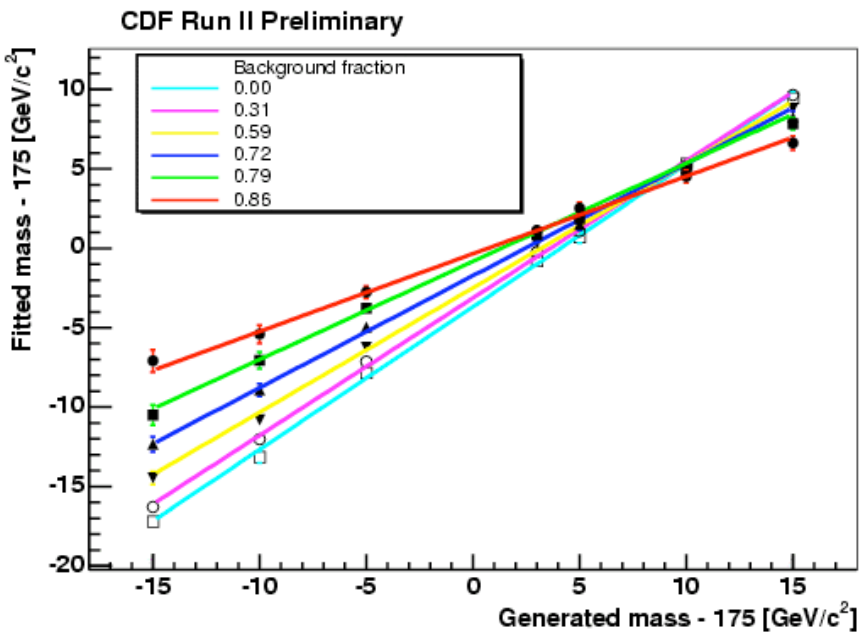


Ideogram Results

- Background validation

Ideogram Results

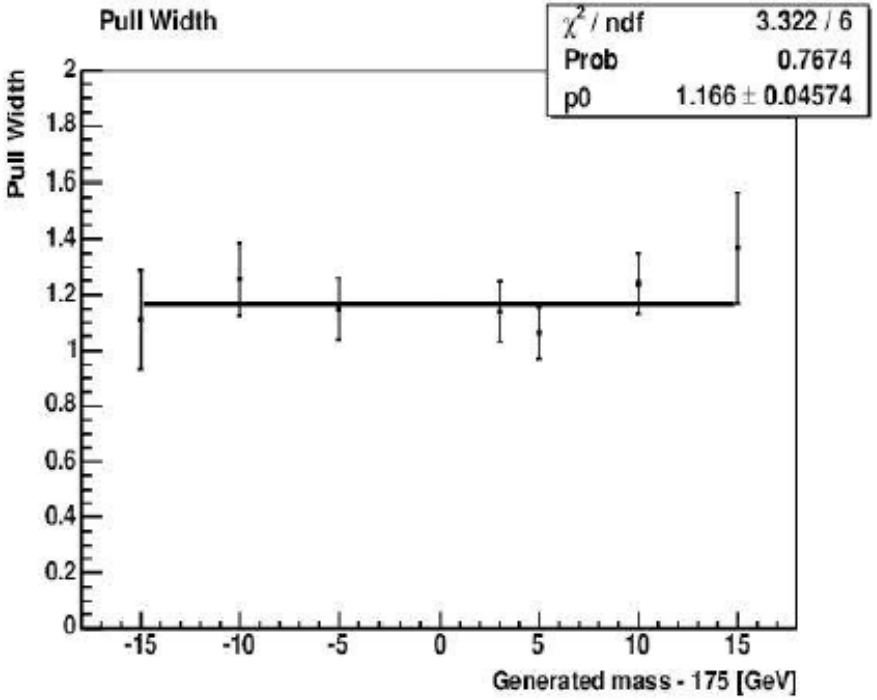
- From 290 observed events we estimate S/B by measuring the sample purity in data
  - From data we fit a signal fraction C_s=0.55 ± 0.09
  - After calibration C_s = 0.21 ± 0.07
  - Resulting in 61 ± 20 signal events
  - Compatible with all hadronic cross sections measurements with 320 pb^{-1}

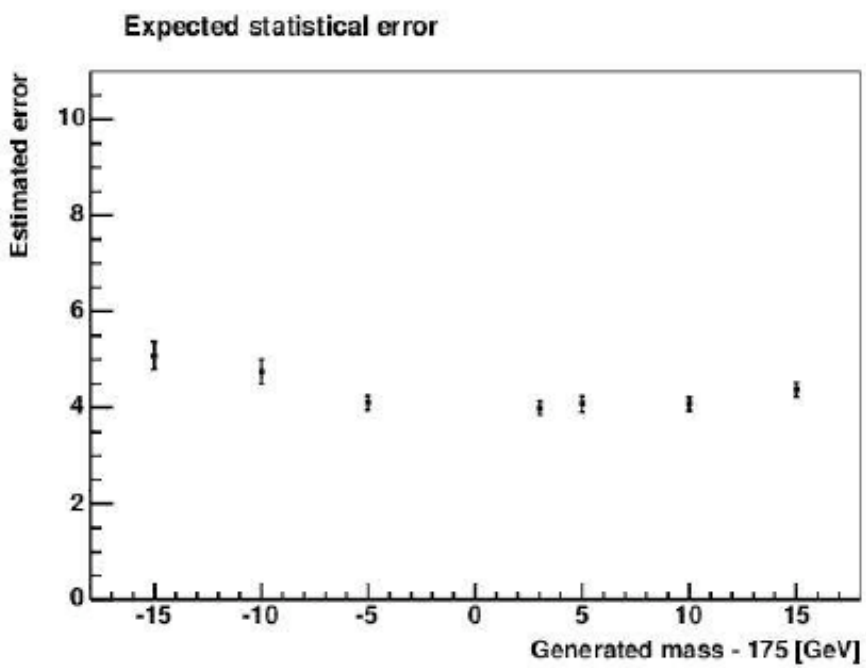


- We obtain a slope = 0.62 ± 0.02 and a bias at 175 GeV = -0.83 0.17
- The Monte Carlo fitted purity is consistent with the purity obtained from data and independent of M_{top}

Ideogram Results

- Pull width = 1.17 ± 0.05
- Expected statistical errors after correcting for pull width = 4-5 GeV



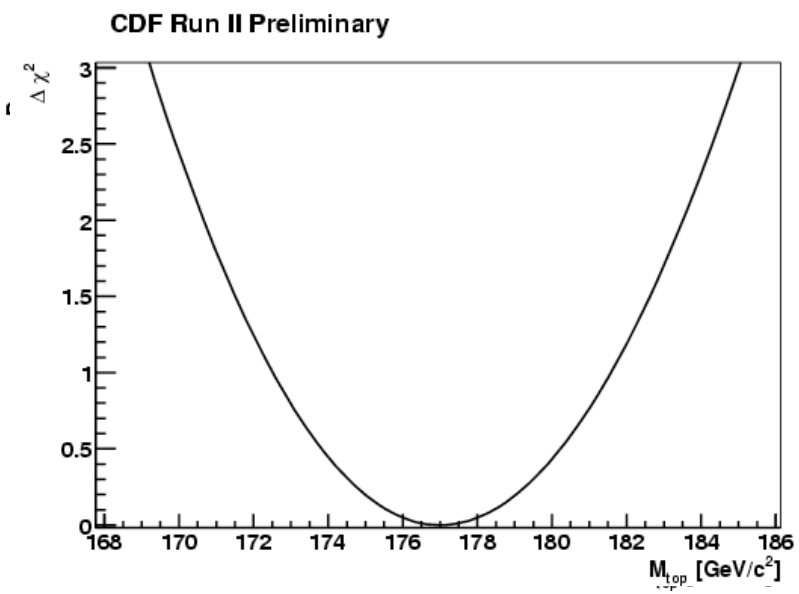


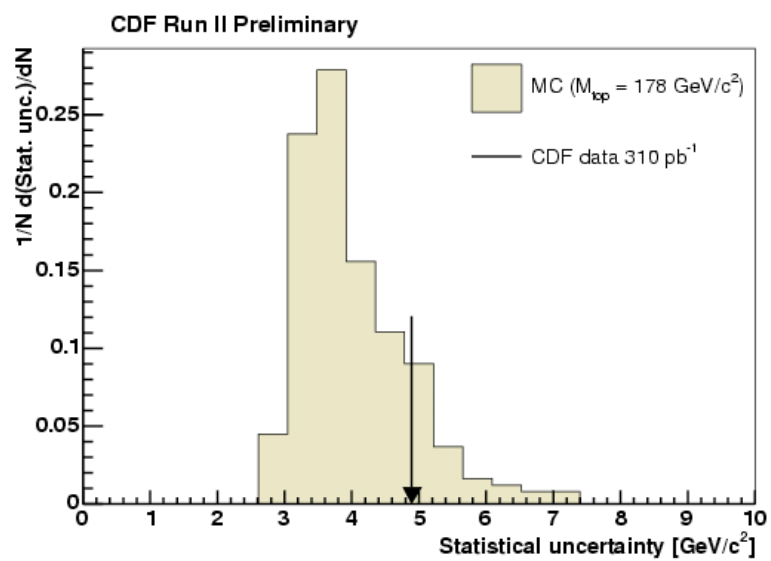
Ideogram Results

- Using 315pb^{-1} and 290 candidates we measure

$$M_{top} = 177.1 \pm 4.9\,(stat) \pm 4.3\,(JES) \pm 1.9\,(syst)\ GeV/c^2$$

- JES 4.3 GeV/c^2
- Great potential!



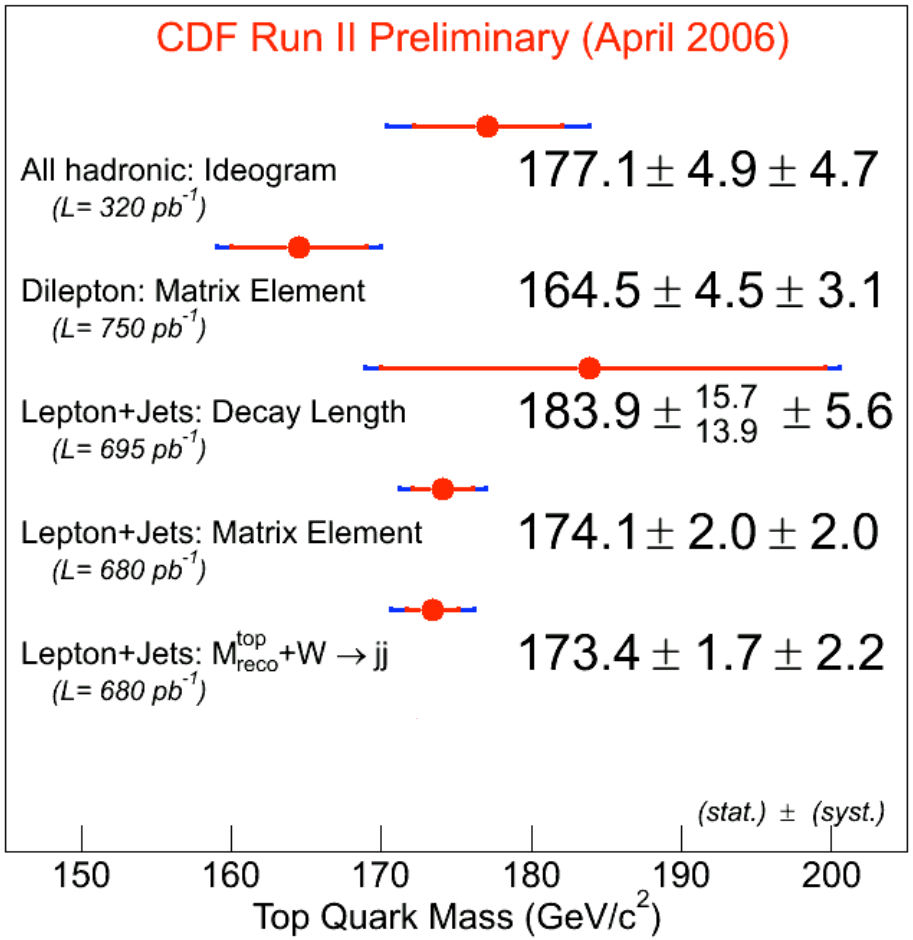


Summary of M_{top} Results

CDF Measurement	Extracted value (GeV/c^2)	Statistical (GeV/c^2)	JES (GeV/c^2)	Other syst (GeV/c^2)
Lepton+Jets: Template ($680pb^{-1}$)	173.5	1.7	1.8	1.3
Lepton+Jets: ME($680pb^{-1}$)	174.1	2.0	1.5	1.3
Lepton+Jets: Decay Length ($750pb^{-1}$)	175.0	+15.7 -13.9	0.3	5.6
Dilepton: Matrix Element ($750pb^{-1}$)	164.0	4.5	2.6	1.7
All Jets: Ideogram ($320pb^{-1}$)	177.5	4.7	4.3	1.9

Combining M_{top}

- Excellent results in each channel
- Use BLUE (Best Linear Unbiased Estimator) technique.
  - *NIM A270 110, A500 391.*
- Accounts for correlations in systematics
- So far only combine measurements on independent datasets (including all Run I results)



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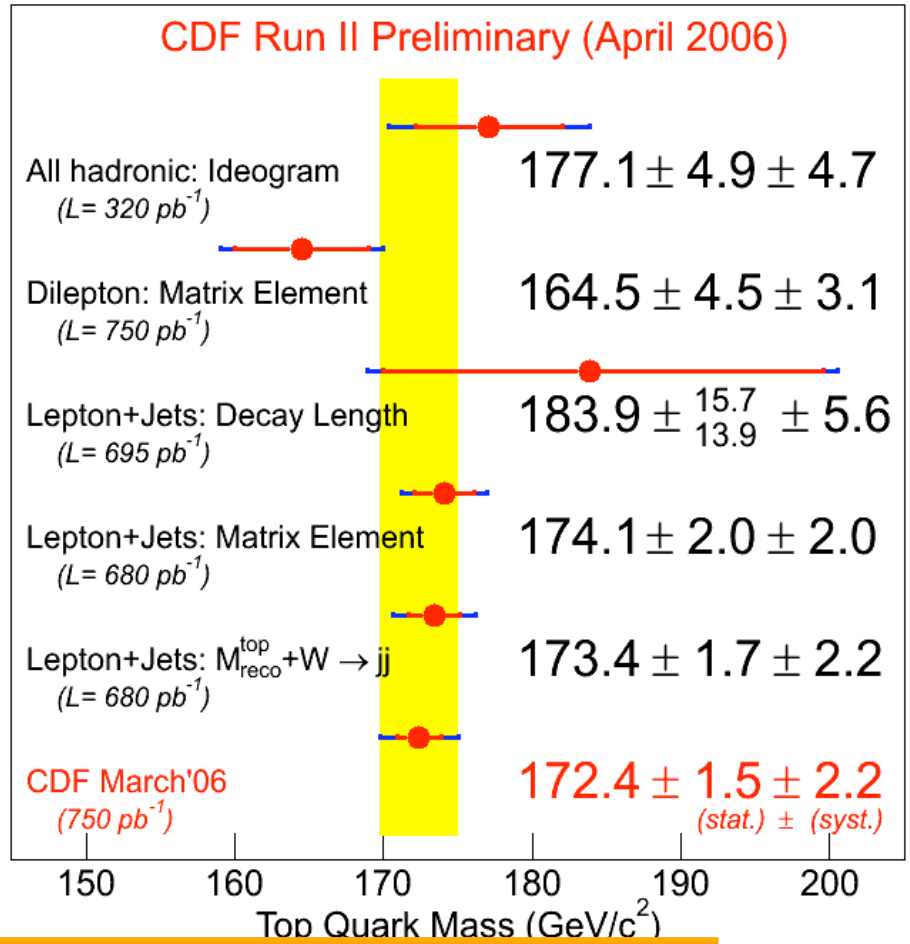


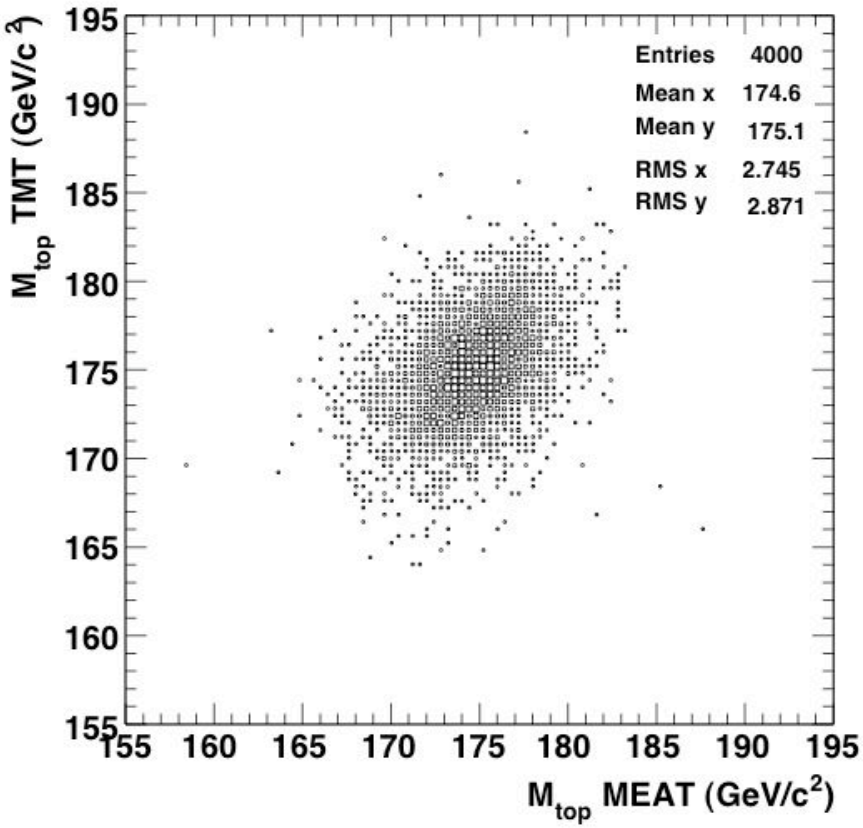
$$M_{top}(CDF) = 172.4 \pm 1.5(stat) \pm 2.2(syst)\ GeV/c^2$$
$$= 172.4 \pm 2.6\ GeV/c^2$$
$$\chi^2/dof = 6.2/6$$

Combining M_{top}

- Comparing different channels
- See some discrepancy between dilepton channel and lepton+jets and all-hadronic M_{top} measurements
- Statistically consistent so far
- Something to keep an eye on

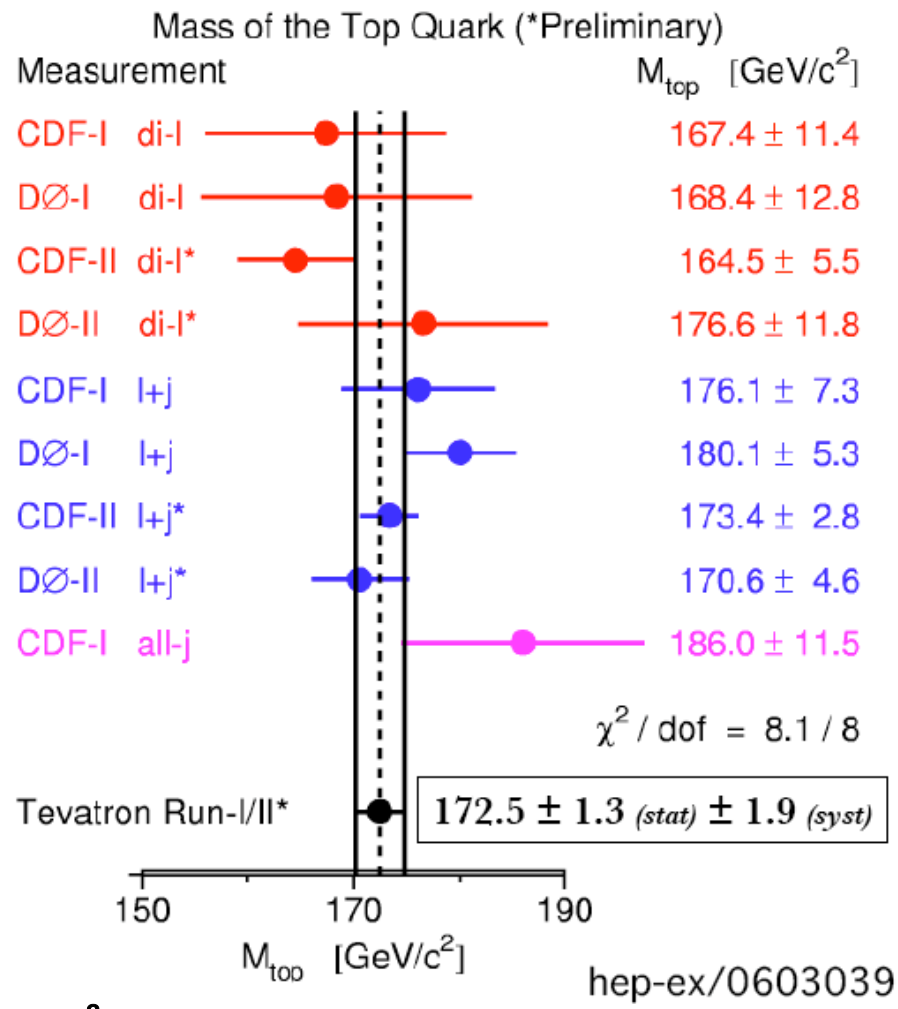
Combining M_{top}

- What about combining the two best results from
- Looks promising
- Will be ready to show it by summer



Combining M_{top}

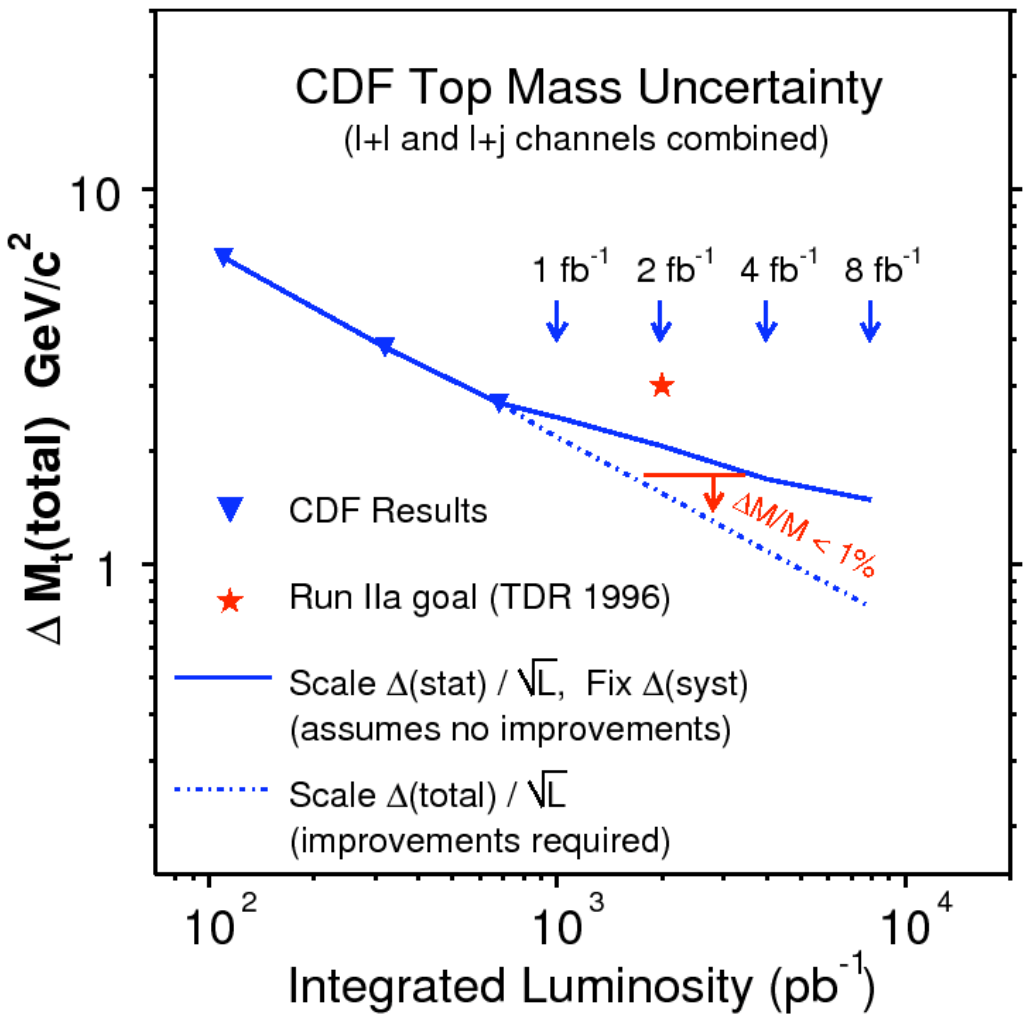
- Combining with D0 (winter 2006)
- From CDF only dilepton and one lepton+jet result
- The combination is already systematically limited
- Will update it in Summer 2006



$$M_{top}(CDF) = 172.5 \pm 1.3(stat) \pm 1.9(syst)\ GeV/c^2$$
$$= 172.5 \pm 2.3\ GeV/c^2$$

Future

- We surpassed the goal of Run II per experiment (3 GeV/c^2 with 2 fb^{-1})
- Only one template and dilepton result
- A new realistic goal for Run II is 1.5 GeV/c^2 per experiment



Conclusions

$$M_{top}(CDF) = 172.4 \pm 2.6 \ \ GeV/c^2$$

- Includes a measurement in each channel and first Tevatron M_{top} in the all hadronic channel
- With *in situ* JES calibration, dominant "systematic" now scales as 1/sqrt(N)
- 1% uncertainty on M_{top} is in sight as we concentrate on reducing remaining systematics
- All these results and more will be combined with D0 in the summer

$$M_{top}(Tevatron) = 172.5 \pm 2.3 \ \ GeV/c^2$$

Template Analysis

- Use as much stat as possible
- Divide in 4 samples to maximize stat error

Category	2 b tags	1 b tag (T)	1 b tag L	0 b tag
Expected S:B	10.6:1	3.7:1	1.1:1	no a priori estimate
Expected Number of Events	46.8	104.4	64.2	no a priori estimate
Data (680pb-1)	57	120	75	108

$$\mathcal{L}_{subsample} = \mathcal{L}^{mtop}_{shape} \times \mathcal{L}^{mjj}_{shape} \times \mathcal{L}_{nev} \times \mathcal{L}_{bg}$$

Combined likelihood $\mathcal{L}_{total} = \mathcal{L}_{2btag} \times \mathcal{L}_{1btag(T)} \times \mathcal{L}_{1btag(L)} \times \mathcal{L}_{0\ btag} \times \mathcal{L}_{JES}$

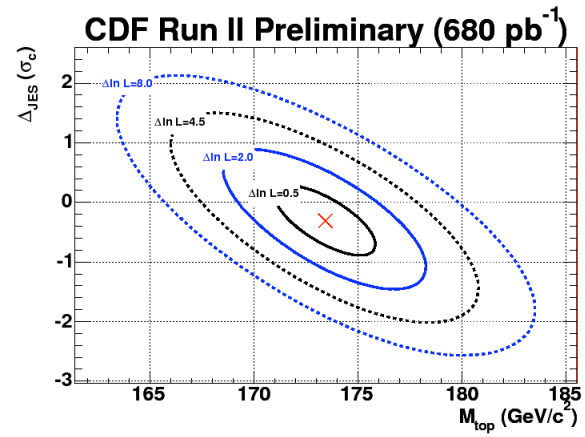
Gaussian constrain on ΔJES
External ΔJES ~ 3 GeV

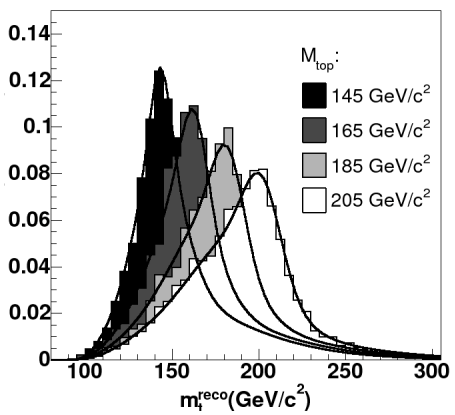
Template Analysis

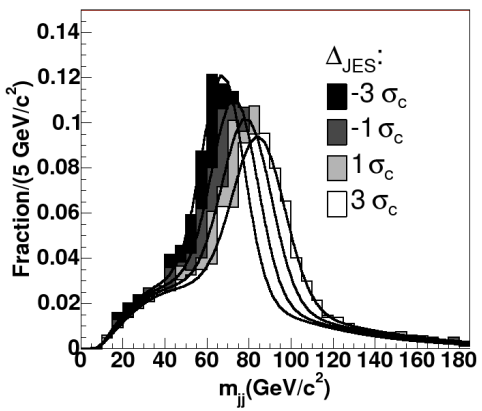
- Reconstructed M_{top} and M_{jj} from data are compared to templates of various true Mtop and Delta JES (jet energy uncertainty shift) using an unbinned likelihood

Parameter M_{top} Δ_{JES}

Observable m_t^{reco} m_{jj}







Δ_{JES}: deviation from nominal in units of external calibration

Constrain $\Delta_{JES} = 0 \pm 1\ \sigma_c$

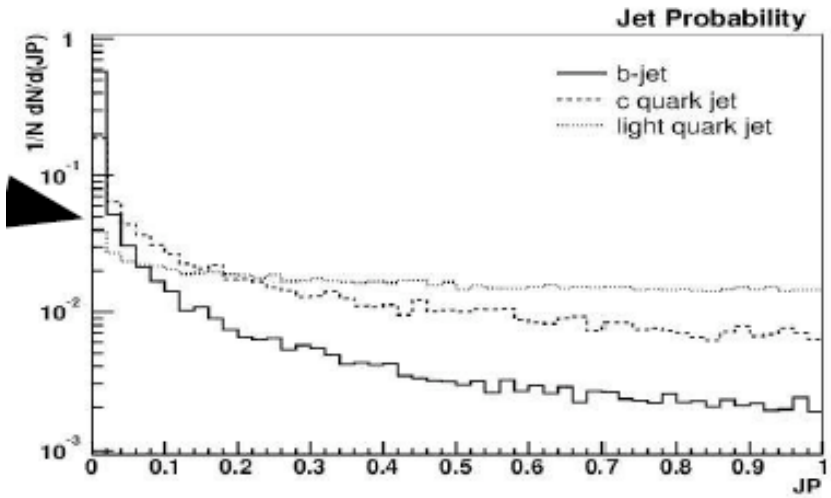
Kinematic fit to reconstruct top quark mass in each event

Invariant mass of possible W decay jets

This method, 318 pb^{-1}:
PRL 96, 022004; PRD 72, 032003

Ideogram Overview

- Info
- Jet prob



$$L_i^b = \frac{P(b|JP_i)}{P(b|JP_i) + P(b|JP_i)} \qquad L_i^q = \frac{P(q|JP_i)}{P(b|JP_i) + P(b|JP_i)}$$

$$w_{JP}^k = \prod_{i=1}^{2} L_i^b \prod_{j=3}^{6} L_j^q$$

$$w_i = e^{\left(-\frac{\chi_i^2}{2}\right)} \cdot w_{JP}$$

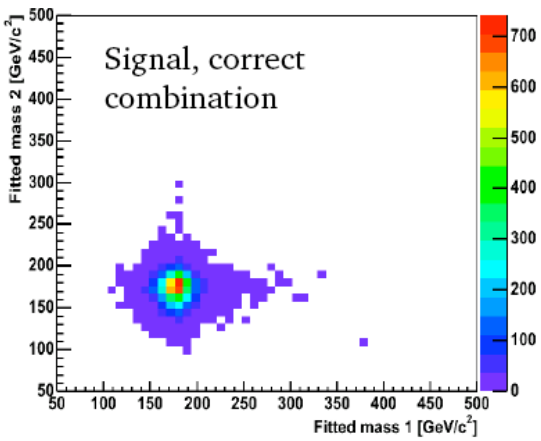
Ideogram Overview

- Kinematical fit

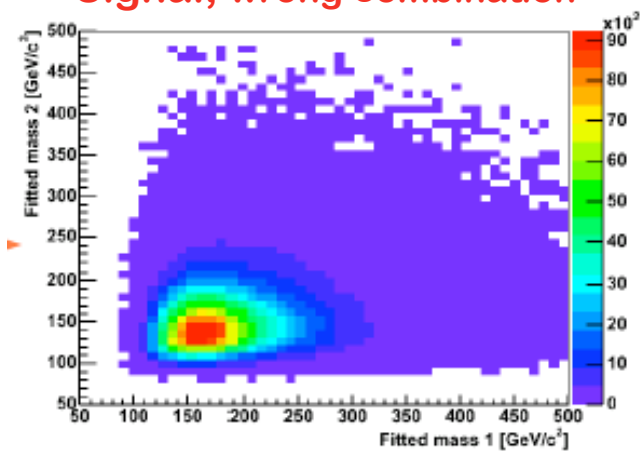
$$\chi_i^2(m_i^1, m_i^2) = \frac{(m_{top}^{fit,1} - m_i^1)^2}{\Gamma_{top}^2} + \frac{(m_{top}^{fit,2} - m_i^2)^2}{\Gamma_{top}^2} + \frac{(M_W - M_W^{fit,1})^2}{\Gamma_W^2} + \frac{(M_W - M_W^{fit,2})^2}{\Gamma_W^2} + \sum_{j=1}^{6} \frac{(p_{T,j}^{meas} - p_{T,j}^{fit})^2}{\sigma_i^2}$$

  - From fit for each combination we obtain:
    - 2 top masses: m_i^1, m_i^2
    - their errors: σ_i^1, σ_i^2
    - χ^2 of the fit

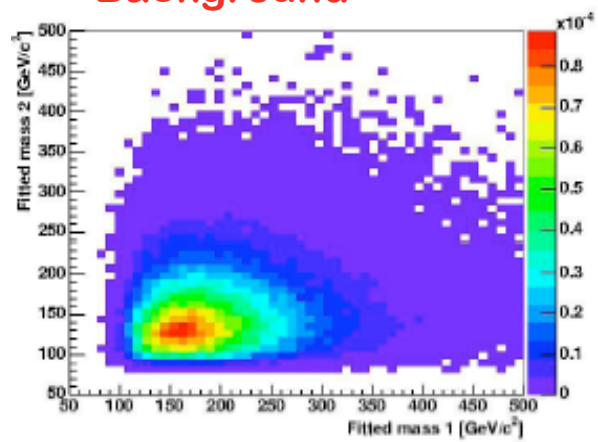
Signal, correct combination



Signal, wrong combination



Background

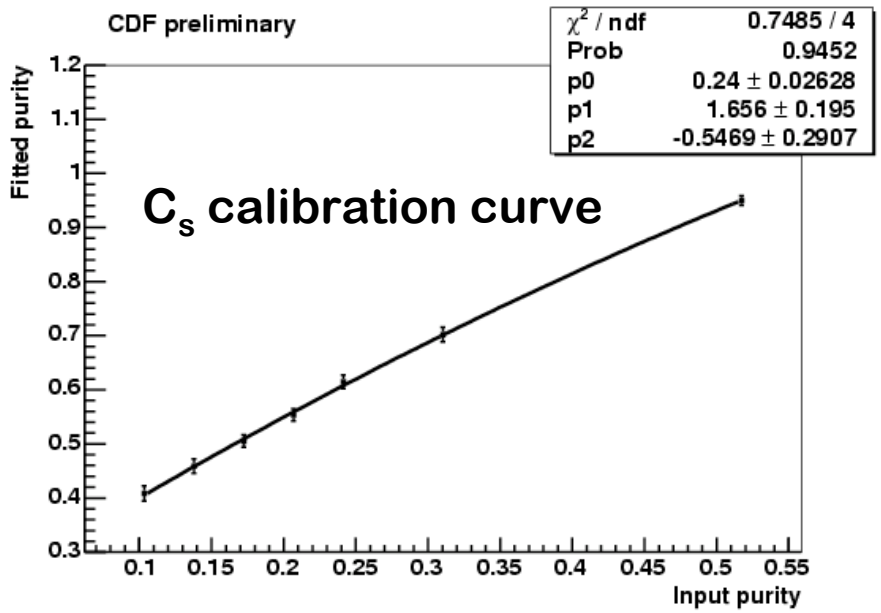


- Weight each jet with a probability of being a b-jet w_{JP}

$$w_i = e^{\left(-\frac{\chi_i^2}{2}\right)} \cdot w_{JP}$$

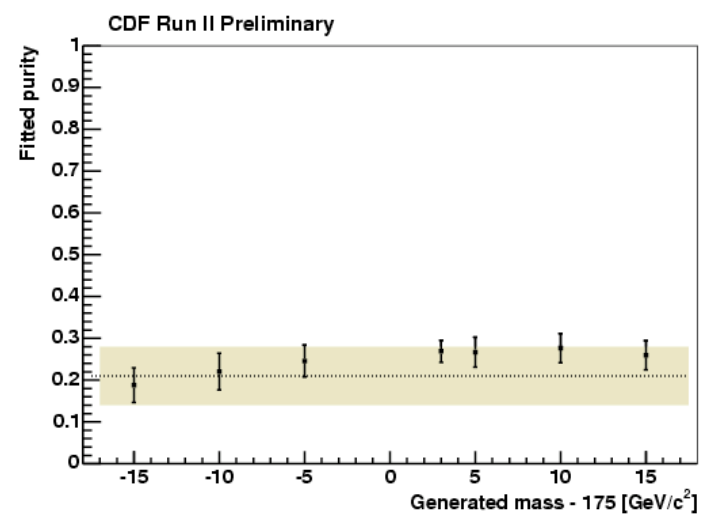
Ideogram Results

- We estimate S/B by measuring the sample purity in data



From data we fitted C_s=0.55 ± 0.09

After calibration C_s = 0.21 ± 0.07

Resulting in 61 ± 20 signal events

Compatible with all hadronic cross sections measurements with 320 pb^{-1}