Measurement of the Top Quark Mass at CDF

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What I'll Talk About

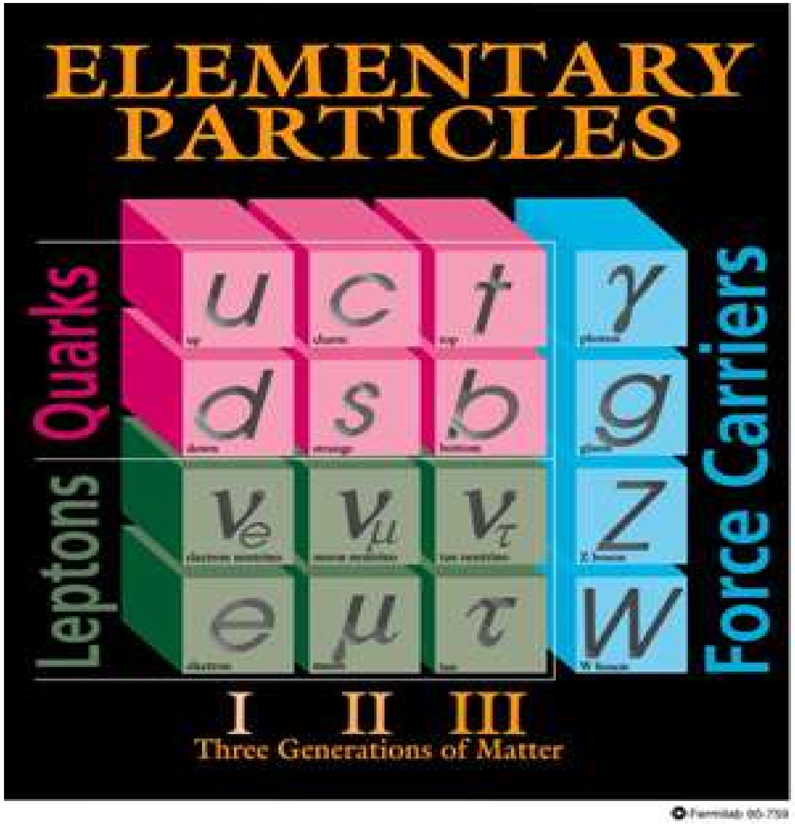
- Why the top quark mass is of interest
- CDF at the Tevatron: A guide to production and detection of top quarks
- MTM2: A novel top quark mass measurement at CDF
- Other top quark mass measurements at CDF
- The future of the top mass measurement

The Situation

- The top quark mass can be used to constrain the mass of the Higgs boson predicted by the Standard Model (SM) – or the Higgs boson NOT predicted by the SM!
- Produced and directly measured only at the Tevatron
- There are ~20 different measurements of the mass at the Tevatron, LBNL's MTM2 technique being one of them. Will focus on this particular measurement in the talk...

Overview of the SM

- The Standard Model is a quantum field theory which classifies quarks and leptons into three generations of electroweak doublets
- REMARKABLY successful – decades of experimental results have failed to disprove any of its central ideas
- Only missing particle: the Higgs (spin-0) boson, needed to provide other particles with mass



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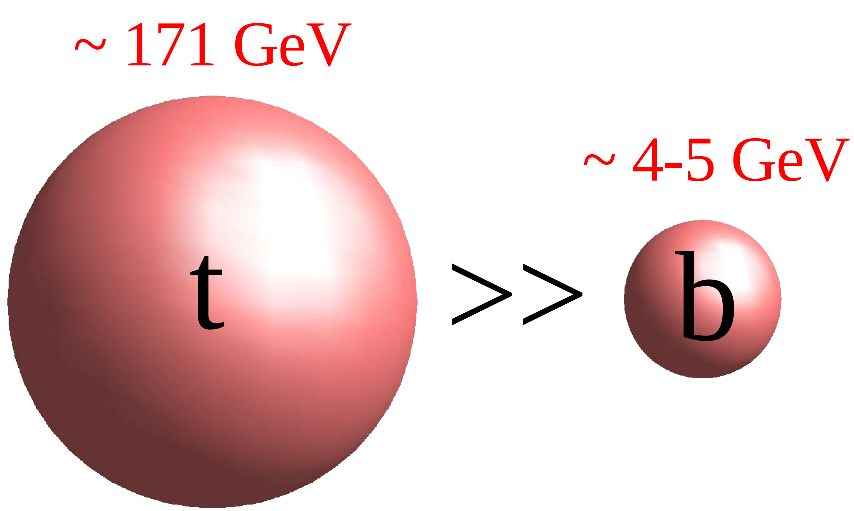
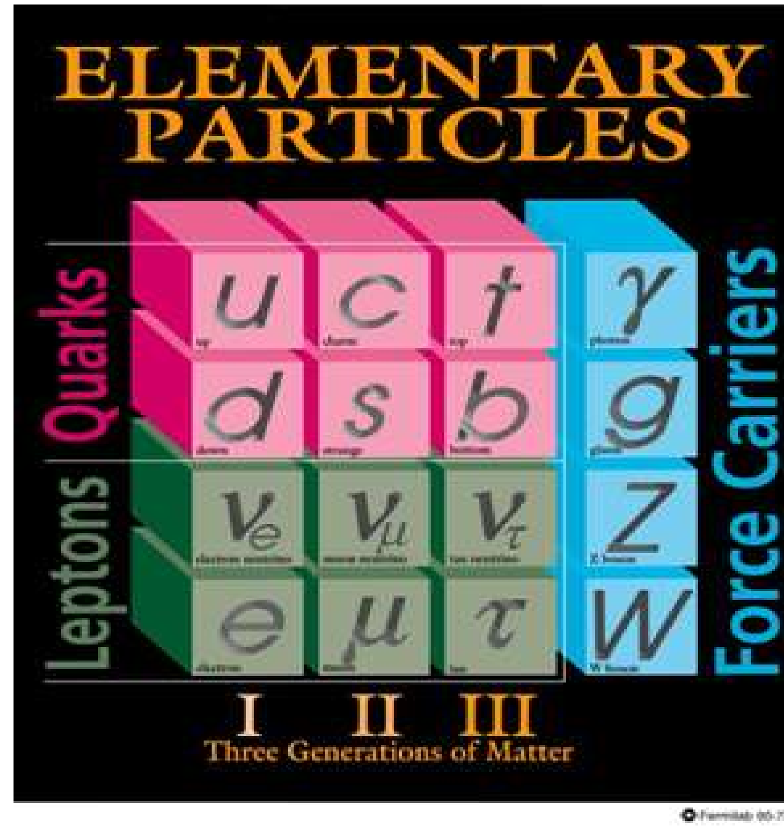
Higgs boson

Top Quark in the SM

- Discovery of bottom quark in '77 => top quark MUST exist
- Took 18 yrs to discover the top quark – it's HUGE

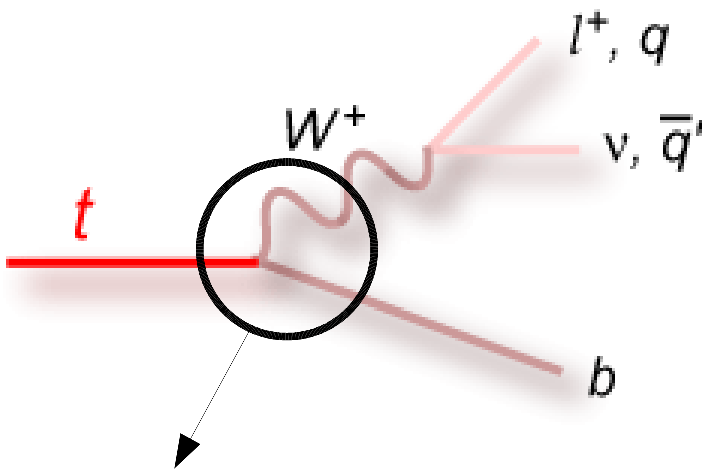




Top is ~ 35-40X larger than next largest quark, the bottom!

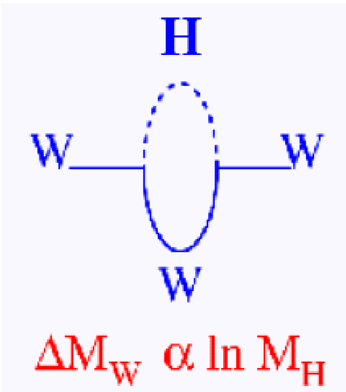
Because Top's So Big...

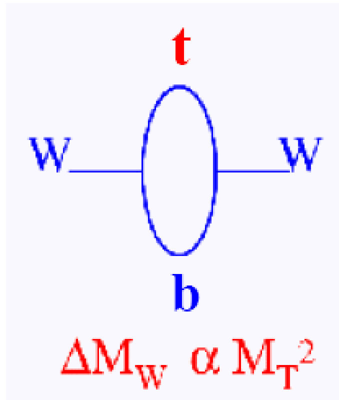
- Size of the top quark means
  - It decays before hadronizing → can measure its properties (mass, spin, charge, etc.) directly!
  - Can test the SM properties of the top quark
  - Tevatron (still) only accelerator capable of producing top quarks



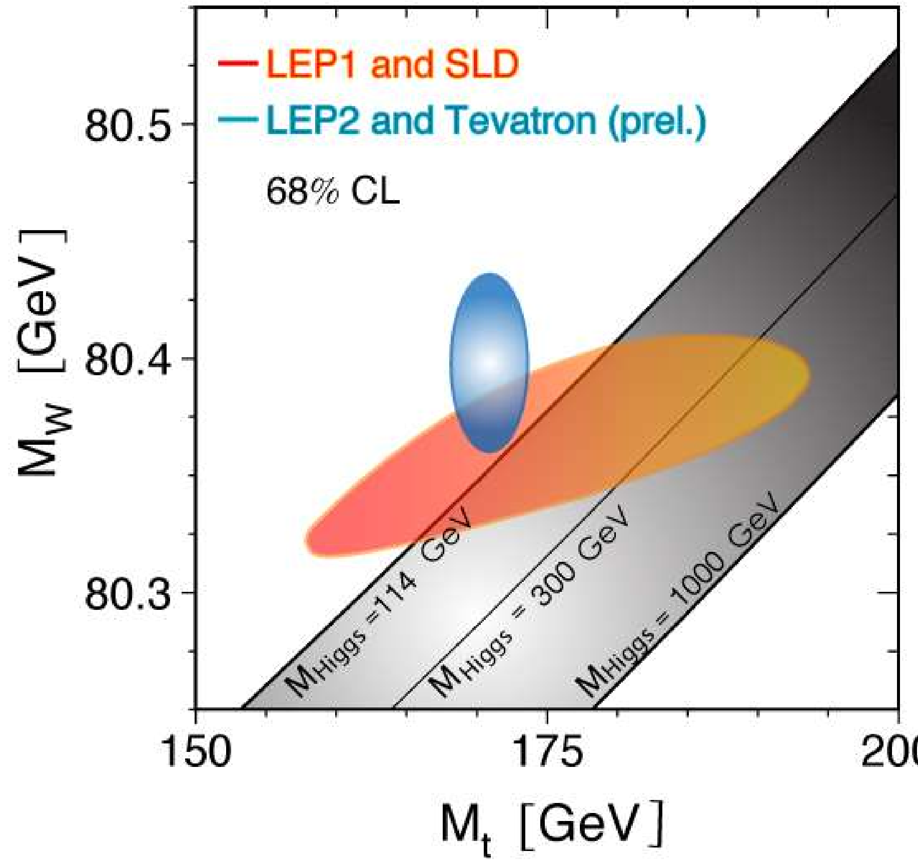
SM Br =~ 0.999
t ~ 4 x 10^-25 s << lambda_QCD

Top Quark Mass in the SM



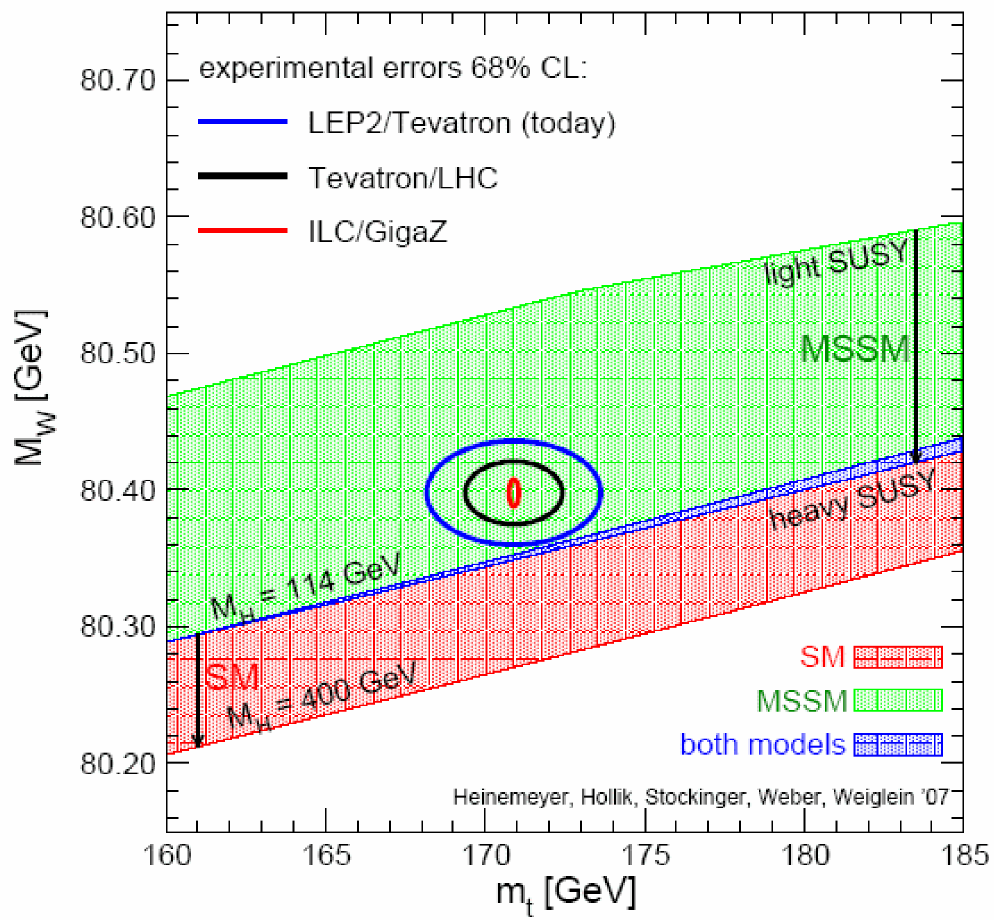


- In SM, top quark and W boson masses provide the best electroweak constraint on the Higgs mass
- Most recent world averages for the W and top have brought the mean of the Higgs mass down – deeper into non-SM territory...
- From LEP, a SM Higgs < 114 GeV has been ruled out in direct searches w/ 95% CL



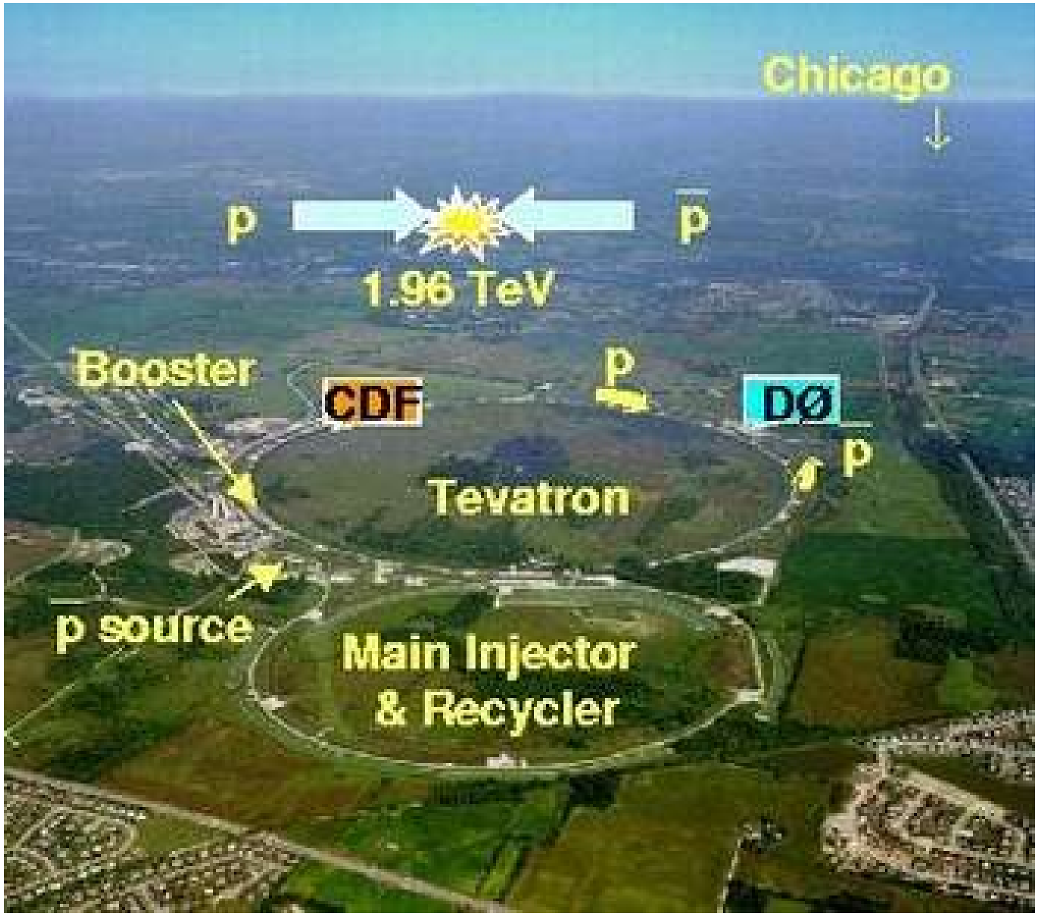
Top Quark Mass Beyond the SM

- A light Higgs, however, is permitted in the Minimal Supersymmetric Standard Model
- Over the next few years
  - Better measurements of the top and W masses will further constrain the Higgs mass
  - If it exists, the Higgs – whichever model is correct - should be discovered at Tevatron or LHC

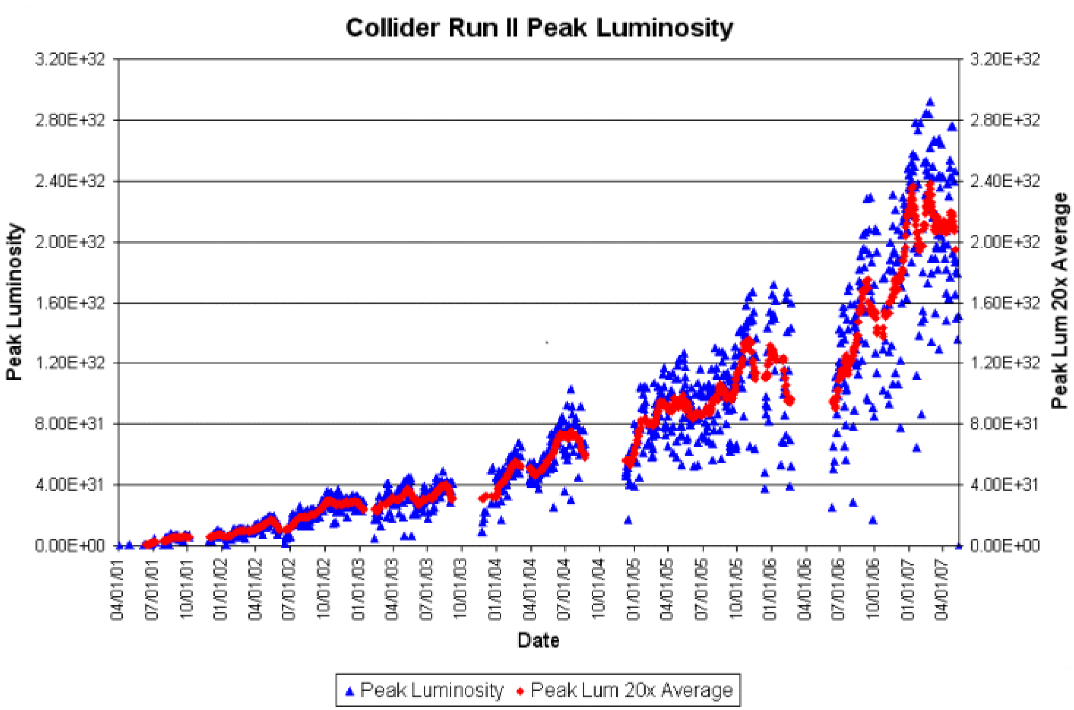


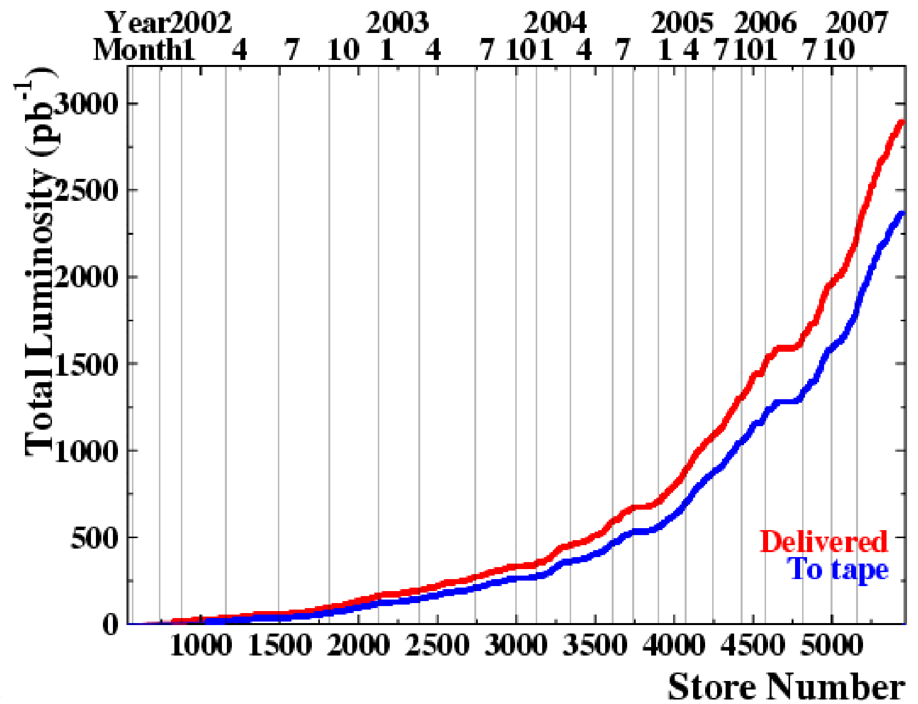
Creating top quarks (I)

- At Fermilab, a series of accelerators culminating in the Tevatron brings protons and antiprotons to 980 GeV
- Since only a fraction of this energy is carried by partons in the p's and pbars, this is only slightly above threshold for creating $t\bar{t}$ pairs
- Until LHC turns on to full energy next year the Tevatron will remain the only accelerator capable of producing tops



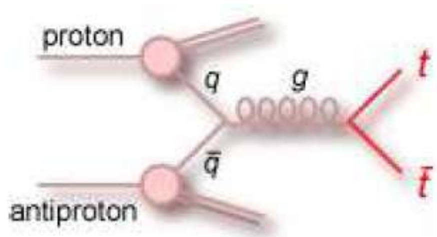
Tevatron Performance



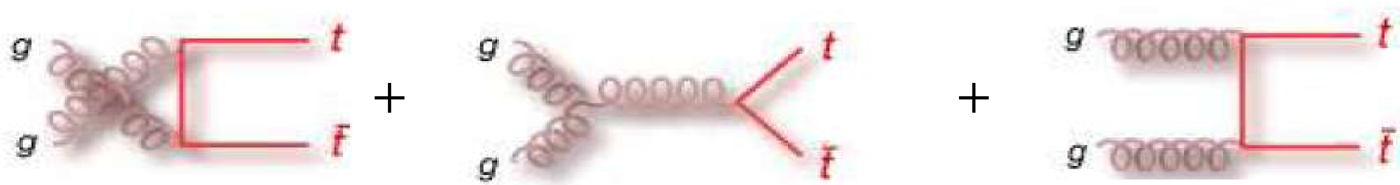


- The last year or two has seen big gains in luminosity delivered by the Tevatron
- Estimates for the total delivered luminosity over the Tevatron's lifetime range from 4-9 fb^{-1}

Creating top quarks (II)



$q\bar{q}$ annihilation ~ 85%

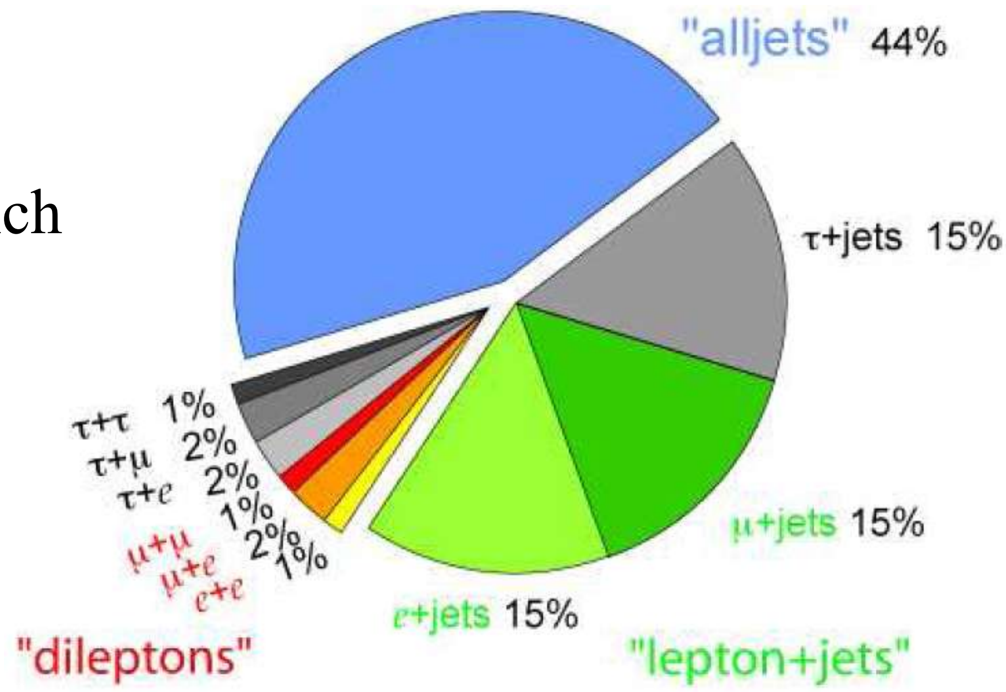


gg fusion ~ 15%

- $t\bar{t}$ production is dominated by $q\bar{q}$ annihilation at the Tevatron
  - Some uncertainty; gg fusion could be as low as 10%, as high as 20%
- The reverse will be true at the LHC

The 3 Channels

- Three primary decay channels in which top mass is measured
- Discrepancies in top mass, ttbar xsec across channels could point to new physics
- $W \to l\nu_l$ has a cleaner signal than $W \to q\bar{q}$ but less statistics
  - Dilepton events: best S/B, low stats
  - All-jets events: bad S/B, high stats
  - lepton+jets: is the ideal balance of statistics and signal-to-noise



$t \to Wb$

then

$W \to l\nu_l$

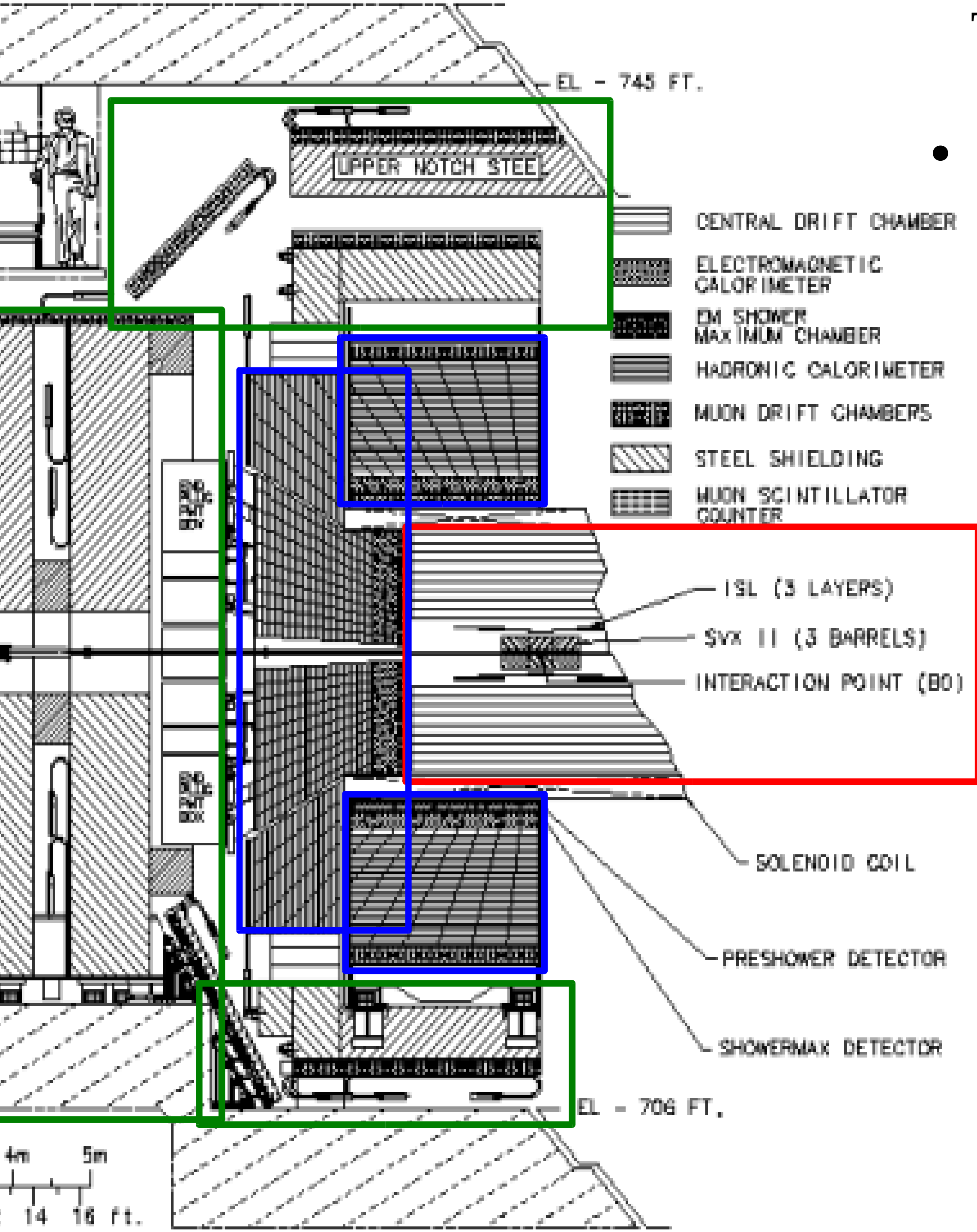
OR

$W \to q\bar{q}$ → particle jets

(3x as common)

Lingo: "lepton" here means e or mu!

THE RUN II CDF DETECTOR



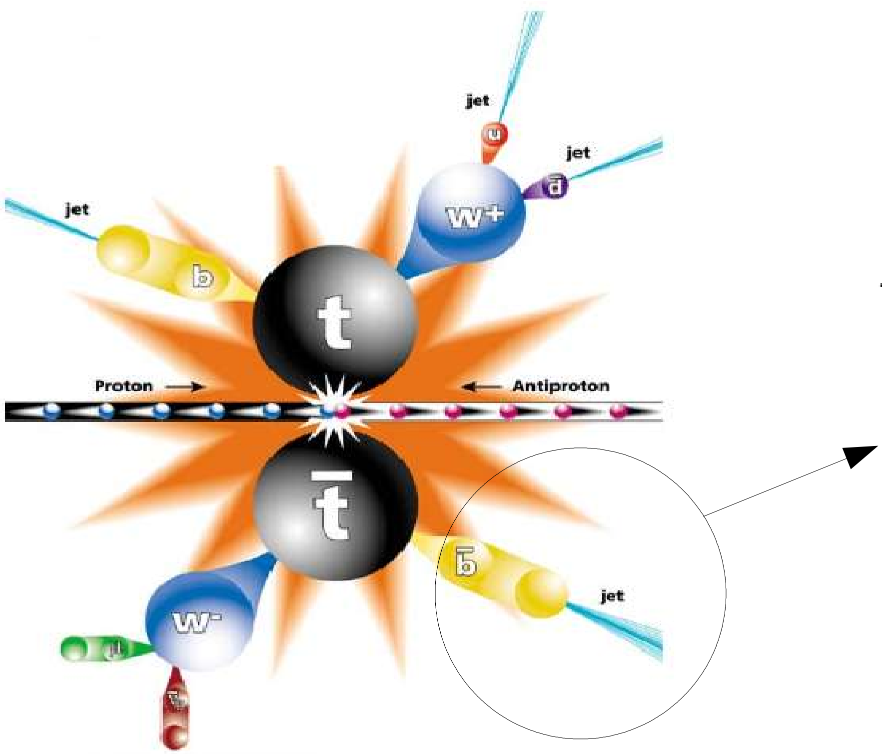
- What we use:
  - A new charged particle tracking system for Run 2
    - silicon detector (b-jet tagging)
    - Central Outer Tracker "COT" drift chamber (lepton momentum)
    - Both are immersed in a 1.4 T solenoidal field
  - A calorimetry system, (EM + hadronic), for electron/jet energy measurements
  - Muon wire chambers (much of them new for Run 2), designed for muon tracking

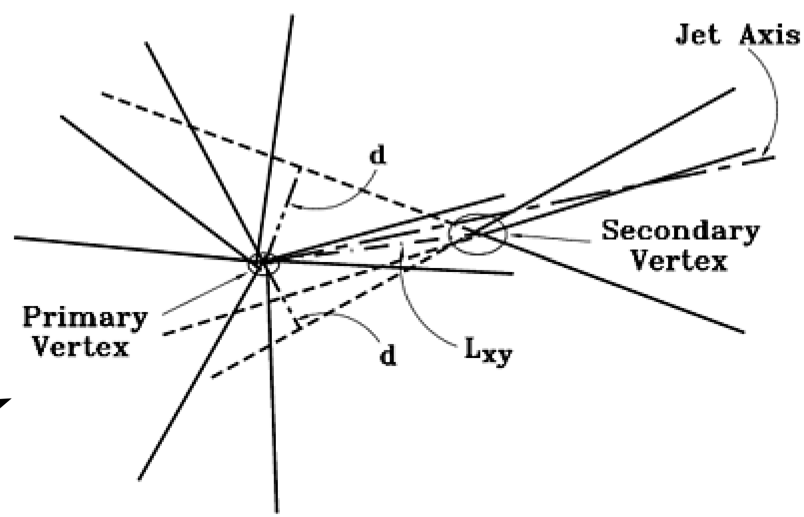
l+jets Event Selection

- High-Pt muon or high-Et electron
- Four tight jets: High Et
- >= 1 b-tagged jet
- High missing Et (for neutrino)

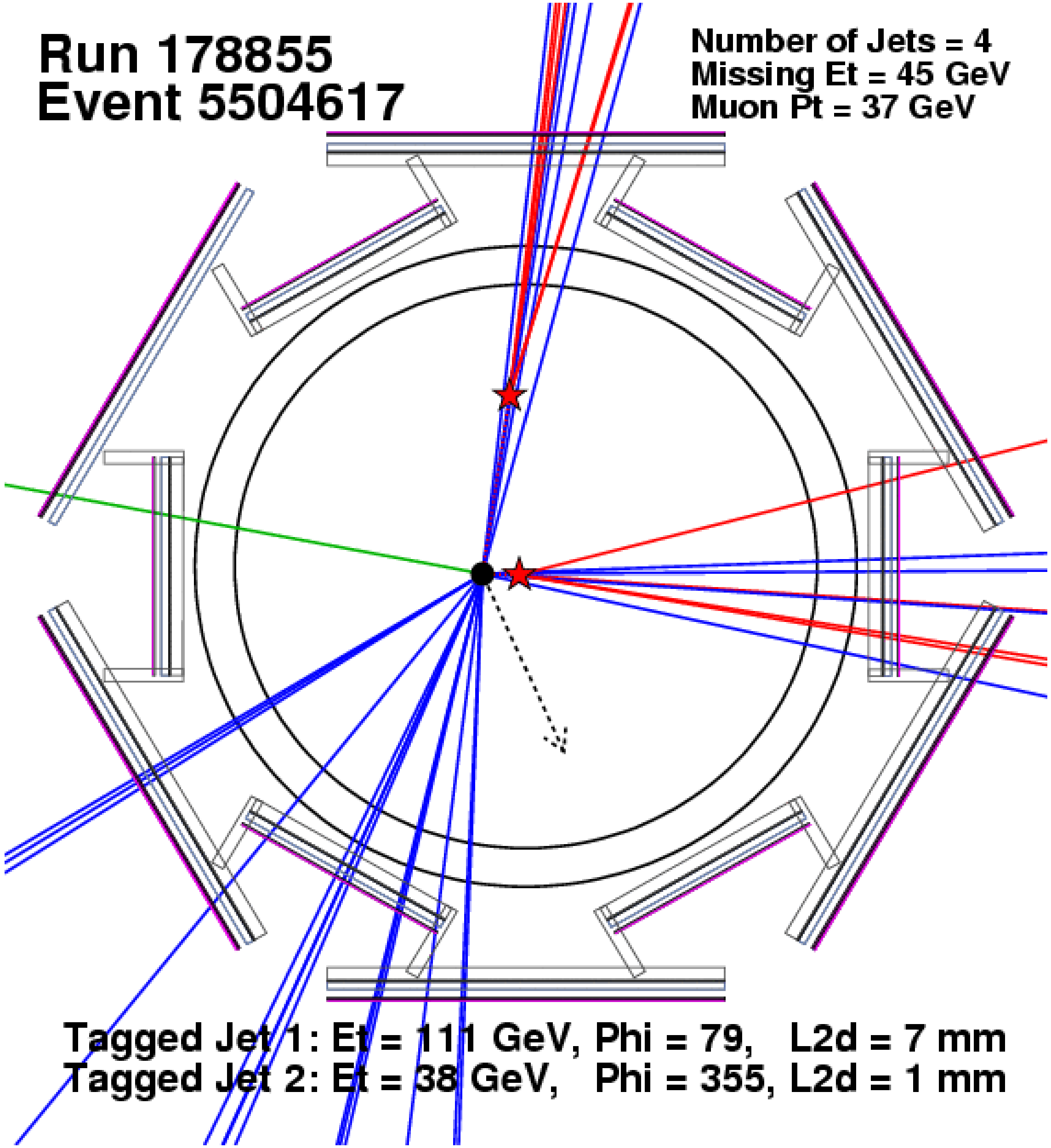
EXPECT 15% NON-TTBAR

Background	1 tag	2 tags
non-W QCD	5.5 ± 1.1	0.13 ± 0.07
W+light mistag	9.5 ± 1.6	0.65 ± 0.32
W+HF ($b\bar{b}, c\bar{c}, c$)	7.2 ± 2.6	1.03 ± 0.32
diboson (WW, WZ, ZZ)	1.4 ± 0.3	0.07 ± 0.02
single top	0.6 ± 0.1	0.00 ± 0.00
Total expected	24.1 ± 3.4	1.88 ± 0.48
Events observed	132	47



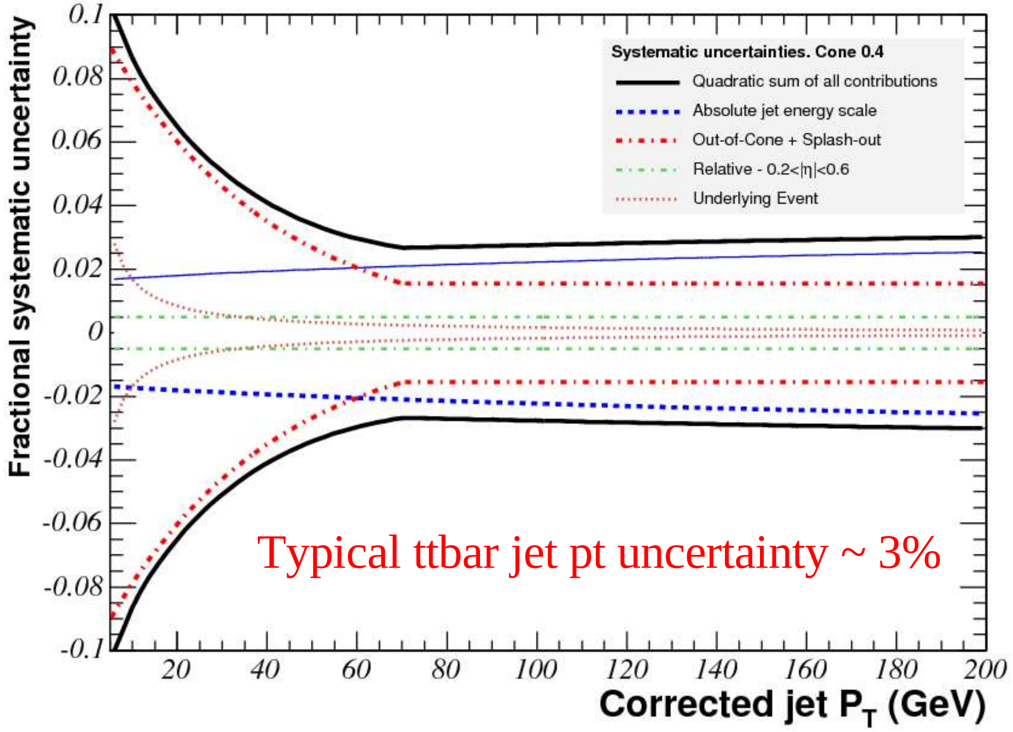


b-tag: use tracking system to determine displaced secondary vertex from B-decay

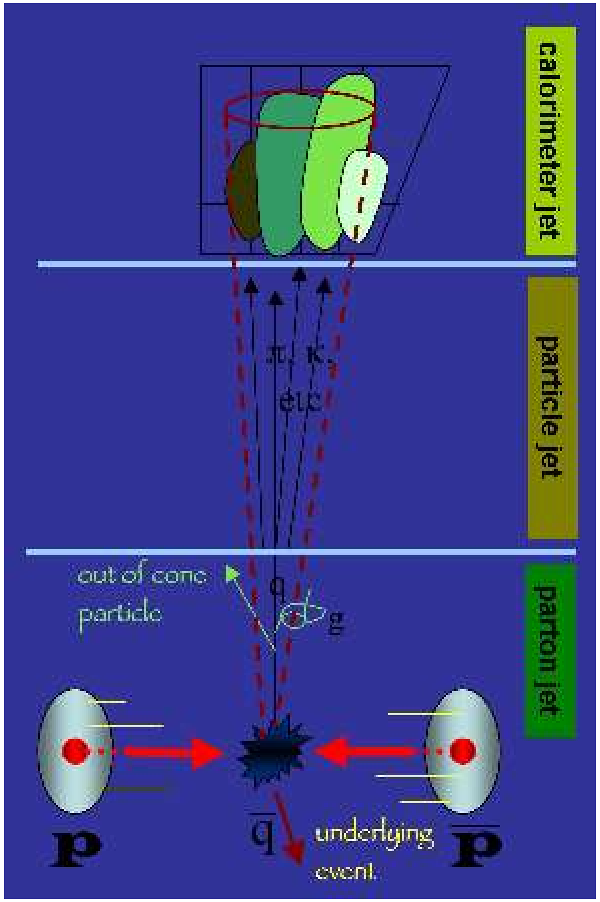


Run 178855
Event 5504617
Number of Jets = 4
Missing Et = 45 GeV
Muon Pt = 37 GeV
Tagged Jet 1: Et = 111 GeV, Phi = 79, L2d = 7 mm
Tagged Jet 2: Et = 38 GeV, Phi = 355, L2d = 1 mm

Quark Pt Measurement



$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta_{\text{evt}}^2} = 0.4$$



- Quarks hadronize into showers of particles, clustered into jets in the calorimeters
- Systematic uncertainty on the resulting Pt measurement can yield a top mass systematic ~ 3 GeV, if no attempt to address it is taken!
- The limiting error in the Tevatron's new high L_int era...

Overview of Matrix Element Methods

$$L(\vec{y}|m_t) = \int f(z_1)f(z_2)\ |M(m_t,\vec{x})|^2\ \mathrm{TF}(\vec{y}\,|\,\vec{x})\ d\vec{x}$$

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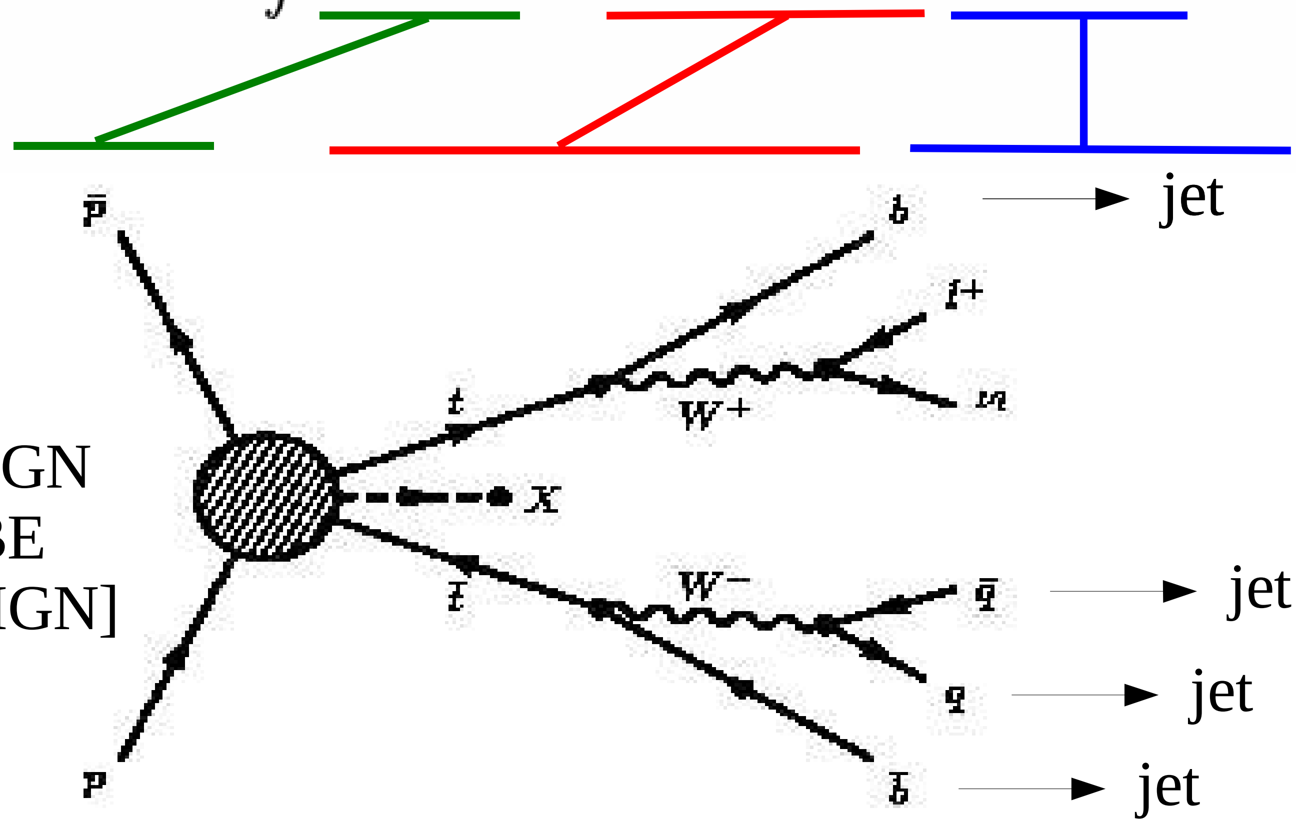


- Calculate a likelihood by integrating over a set of unique decay kinematics (x)
- For each decay kinematics, calculate a weight using distribution functions for incoming parton momenta (z), the decay amplitude (M) and a probability distribution that x would have resulted in measured quantities y (TF)

Overview of the MTM2 Method

Add JES, a scale factor
to account for jet energy systematic

Adjust matrix element
to account for integration assumptions

TF takes us from
parton Et to jet
momentum

(should be pt)

$$L(\vec{y}|m_t, JES) = \sum_{i=1}^{24} w_i \int f(z_1) f(z_2) \; |M_{\text{eff}}(m_t, \vec{x})|^2 \; \text{TF}(|p_{jet}| \cdot JES \mid E_T) \; d\vec{x}$$

Weight every jet-quark
permutation with b-tag info

x = (Mw_had^2, ...)

- Like all matrix element analyses, make integration tractable through assumptions:
  - Quark angle same as jet angle
  - P_l perfectly measured
  - Quarks have on-shell mass
  - lepton+neutrino masses are known

x + assumptions = unique kinematics

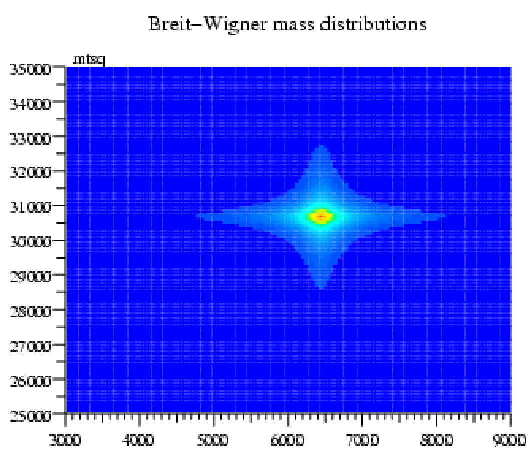
How we account for assumptions is what makes MTM2 unique...

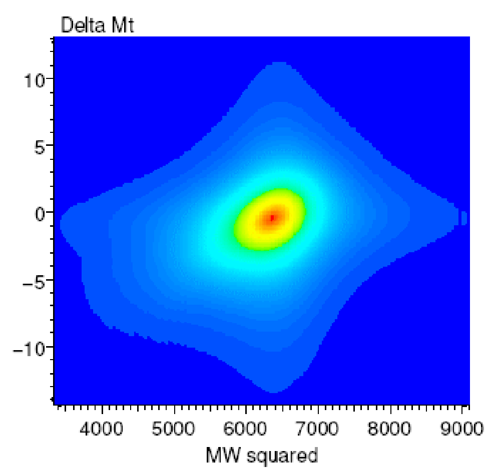
Effective Propagators

- Physically, Mw^2 and Mt^2 have Breit-Wigner distributions
- However x + assumptions => different distributions for Mw^2 and Mt^2
- Build these new distributions, and use them to replace the Breit-Wigner in the matrix element

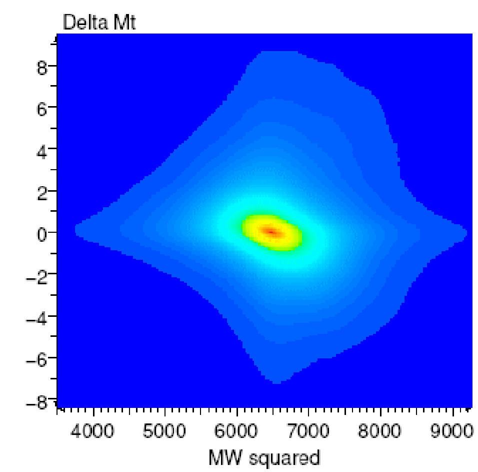
Create a Consistent Framework!

M → M_eff





Hadronic-side propagator

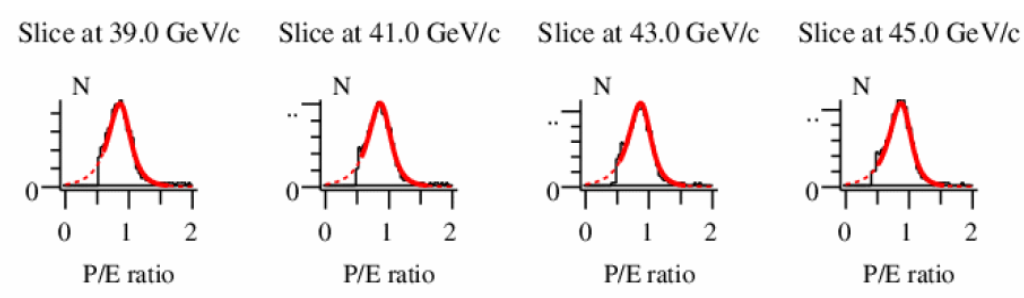


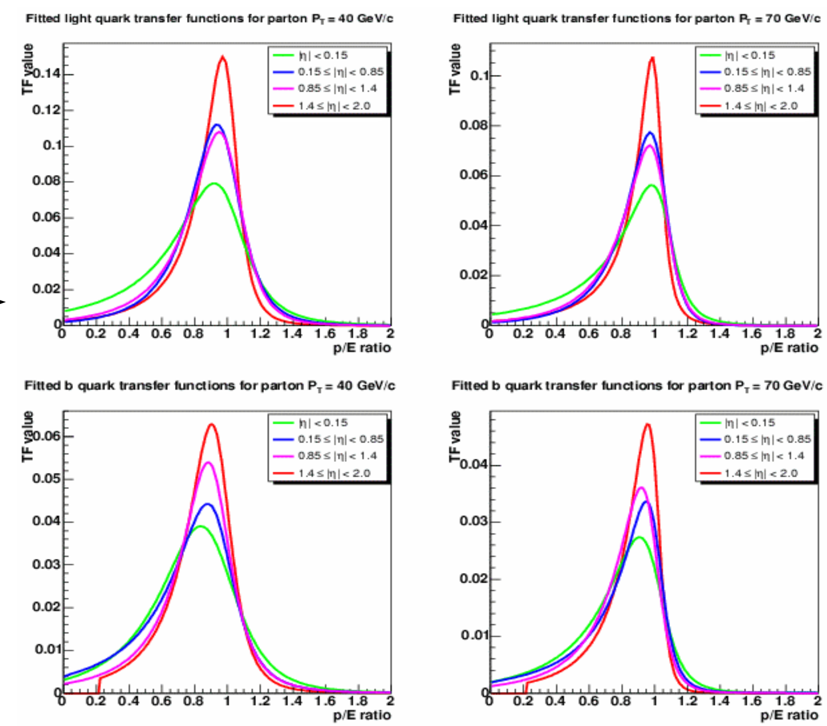
Leptonic-side propagator

Transfer Functions

- Different TF(p_jet | E_parton) for
  - Eta region of jet
  - light vs. b quark

Fit to MC distributions of jet momenta, binned by quark pt





Undesirable Events

- "Good signal": ttbar -> l+jets event, where the four jets come from the four decay quarks
- True background (non-ttbar)
- "Bad" signal: ttbar in which an assumption is violated (non-l+jets, ISR jet pickup, etc.)

→ Hurt our resolution

Can eliminate lots of undesirable events through a cut on the max value of an event's likelihood curve!

179 -> 149 events in sample

Efficiencies

Type of event	1-tag	>1-tag
Good signal	94.7%	94.1%
Bad signal	73.7%	80.2%
Background	63.1%	57.5%

Background Handling

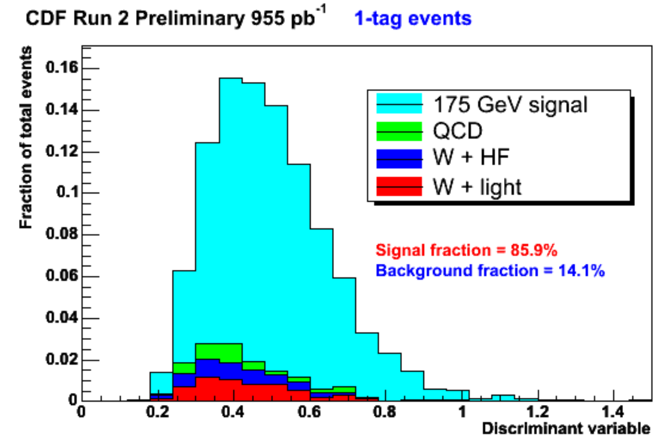
Event likelihood described previously

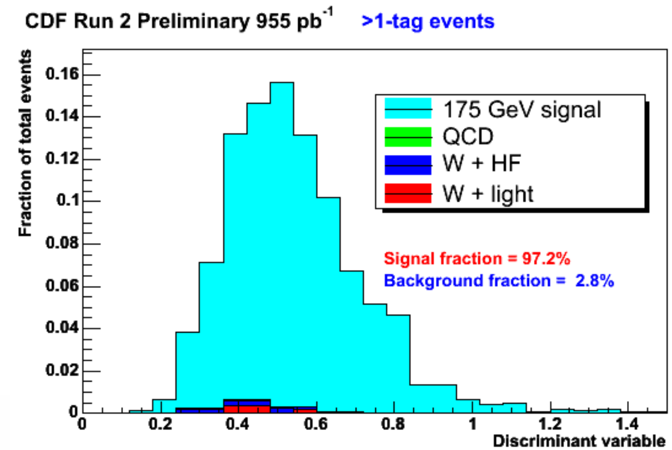
AVERAGE shape of background likelihoods

$$\log L_{\text{final}} = \log L_{\text{signal}} - f_{\text{bgnd}}\overline{\log L_{\text{bgnd}}}$$

Probability given event is background

$\overline{\log L_{\text{bgnd}}}$ al



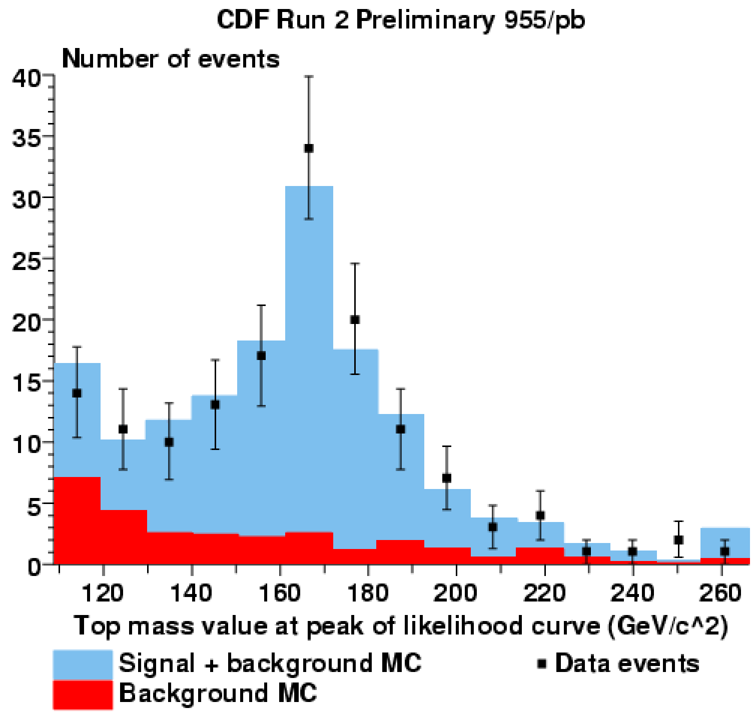


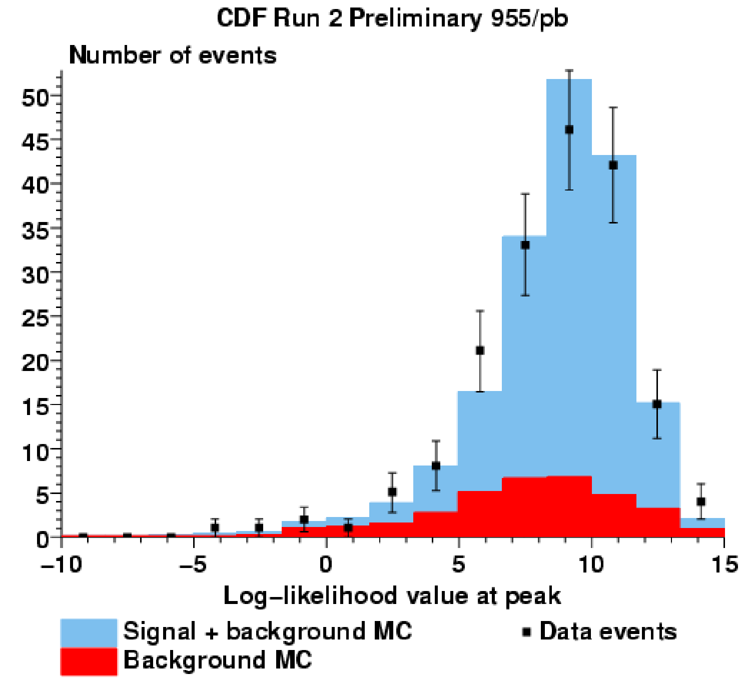
- For each event, calculate a final likelihood by subtracting off the average profile of a background log likelihood

$$f_{\text{bgnd}} = S(q) / (B(q) + S(q))$$

q an observable discriminating between signal and background

Results (I)

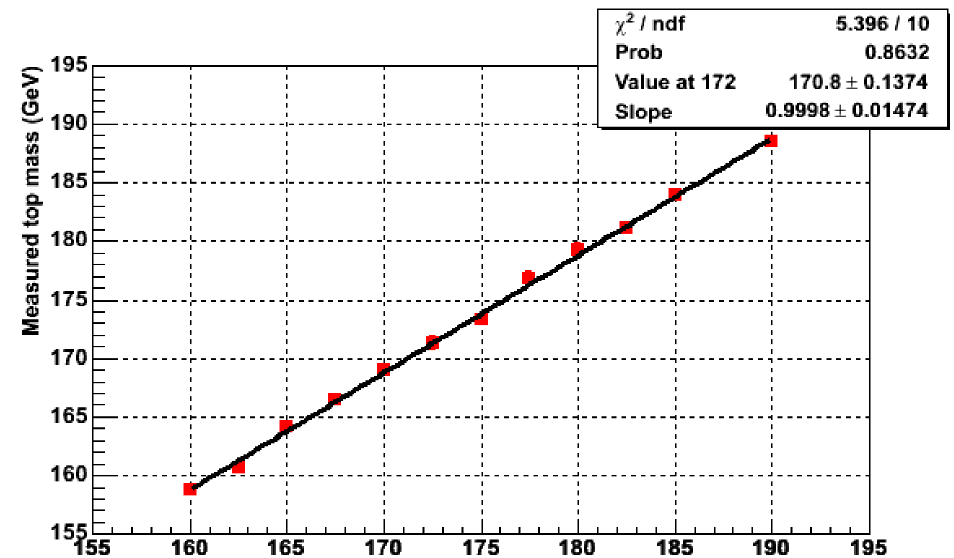


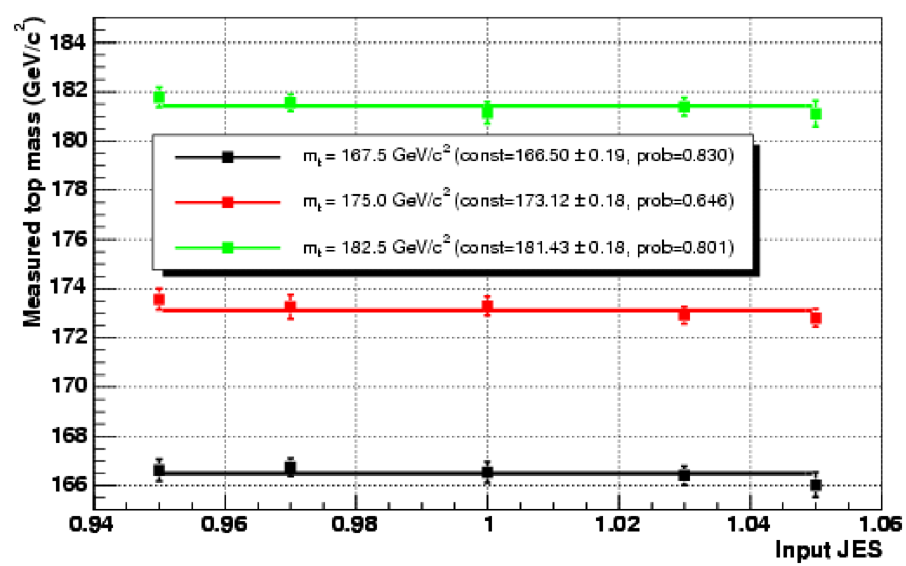


- Event-by-event, good agreement exists between data and Monte Carlo for log-likelihood and mass values at individual likelihood peaks

Results (II)

- Pseudo-experiments indicate that:
  - The technique yields a (mass-independent) bias of -1.2 GeV, used to calibrate the measurement
  - +/- 5 % shift of jet momenta affects the measurement by a few tenths of a GeV at most!





Results (III)

955 pb^-1
(149 evts) → **Mt = 169.8 +/- 2.3 (stat+JES) +/- 1.4 (syst) GeV/c^2**

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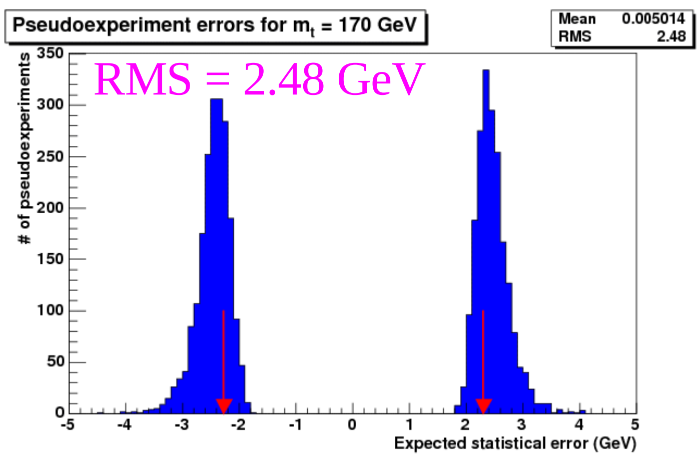
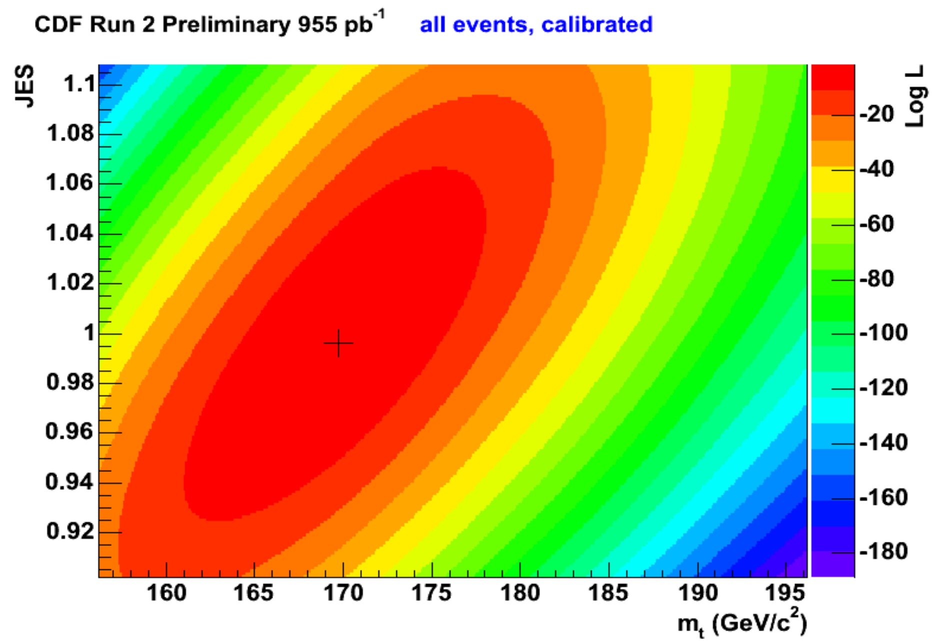


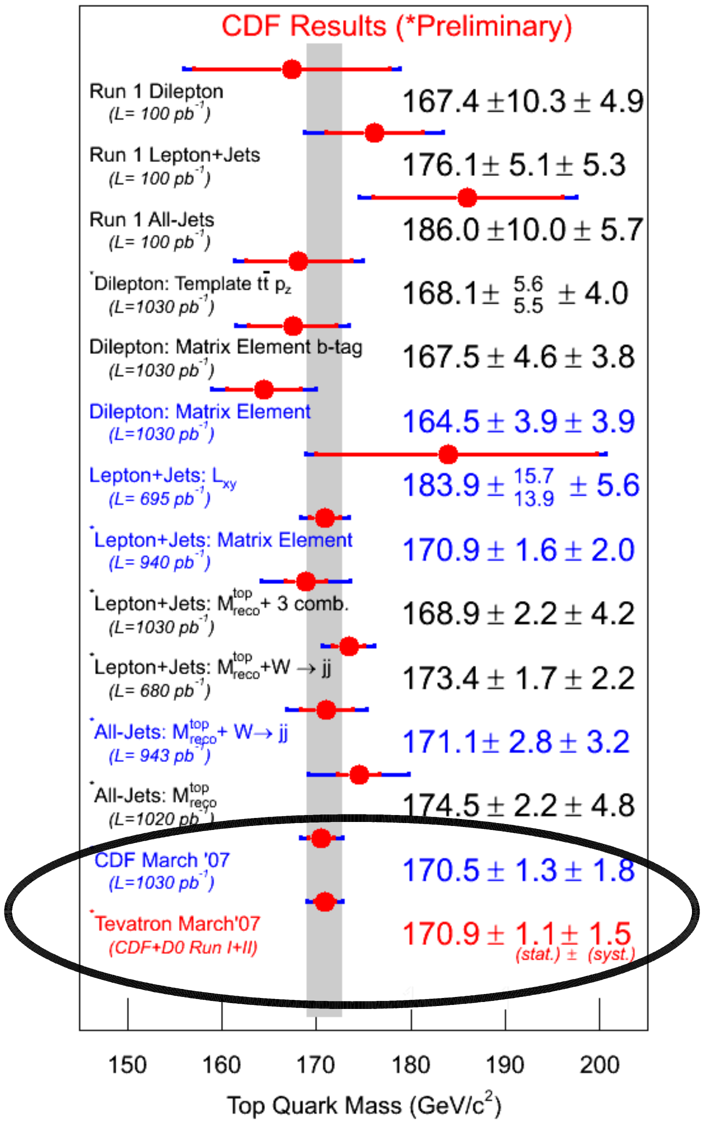


- 27% of PEs have a lower estimated stat+JES error than the measurement

Looking to the Future...

- Implementing improvements on all fronts:
  - Handle problem of integration assumptions by removing them => use a 22-D integration!
  - Deal with effect of incorrect jet selection by integrating over properties of “missed” signal jet
  - Perform more research into the background discrimination variable, “q”

In Context



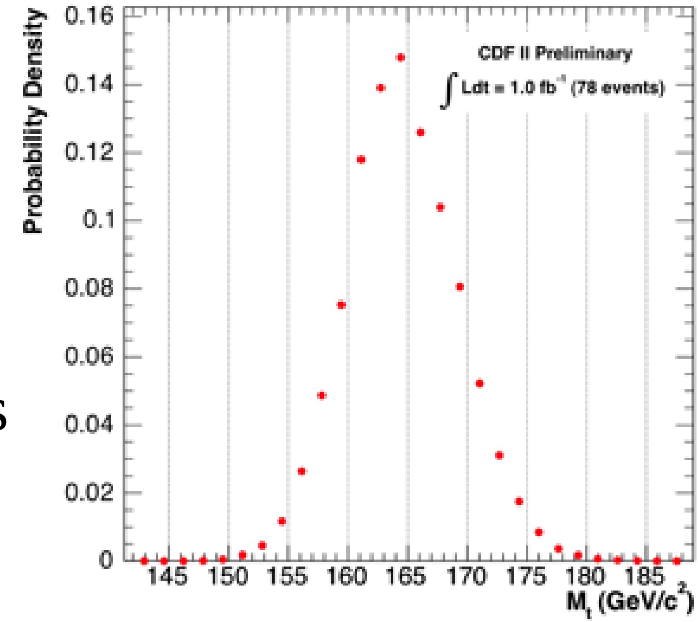
- CDF had 12 preliminary/published measurements as of Moriond EWK (ours has been added since)
- I will discuss the best measurements in each of the three decay channels

Combined top mass measurement is now systematics limited!

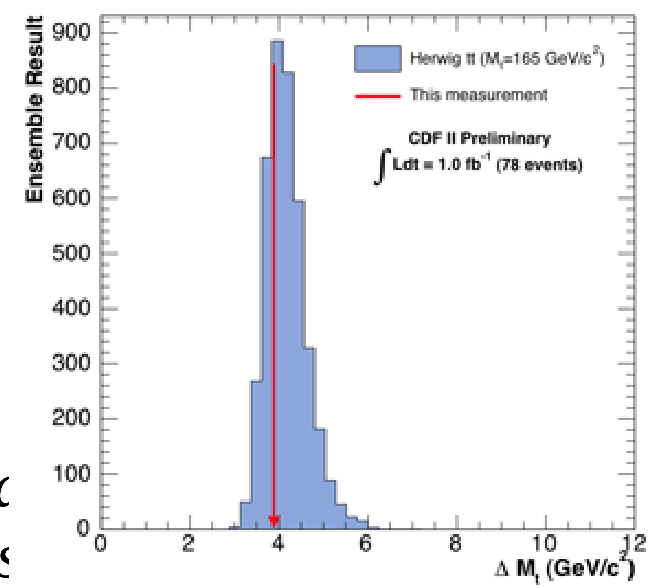
Dilepton Matrix Element Method

Using 78 evts in 1 fb^-1:

Mt = 164.5 +/- 3.9 (stat) +/- 3.9 (syst) GeV/c^2



- Dilepton channel a natural for a ME method, as two v's means kinematics are underconstrained
- JES handling not used as there's no W->qq constraint
  - -> systematic of 3.9 GeV is 3.5 JES quad everything else
  - Interesting idea: use external information from Z -> bb events

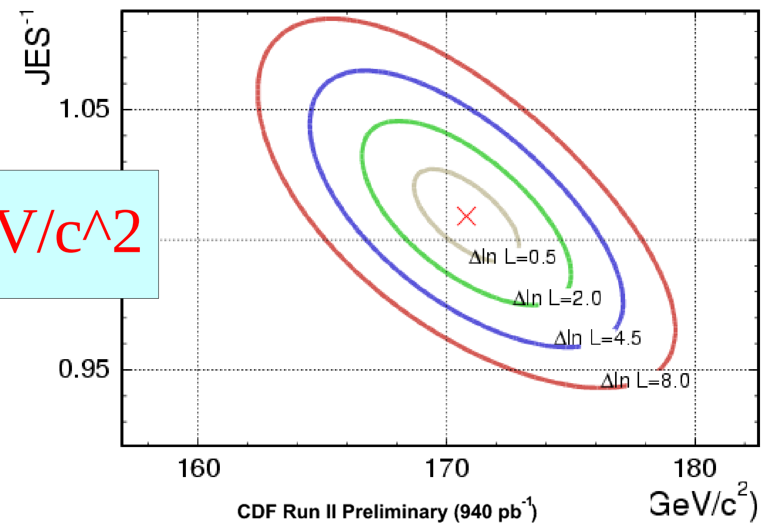


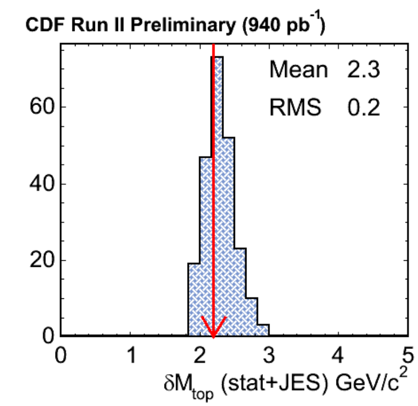
MEAT: Matrix Element Analysis Technique

Using 166 evts in 955 pb^-1:

Mt = 170.9 +/- 2.2 (stat+JES) +/- 1.4 (syst) GeV/c^2

- World's best single measurement
- For each event, calculate two likelihoods, one for signal, the other for W+4 jets
- Float background fraction to maximize likelihood

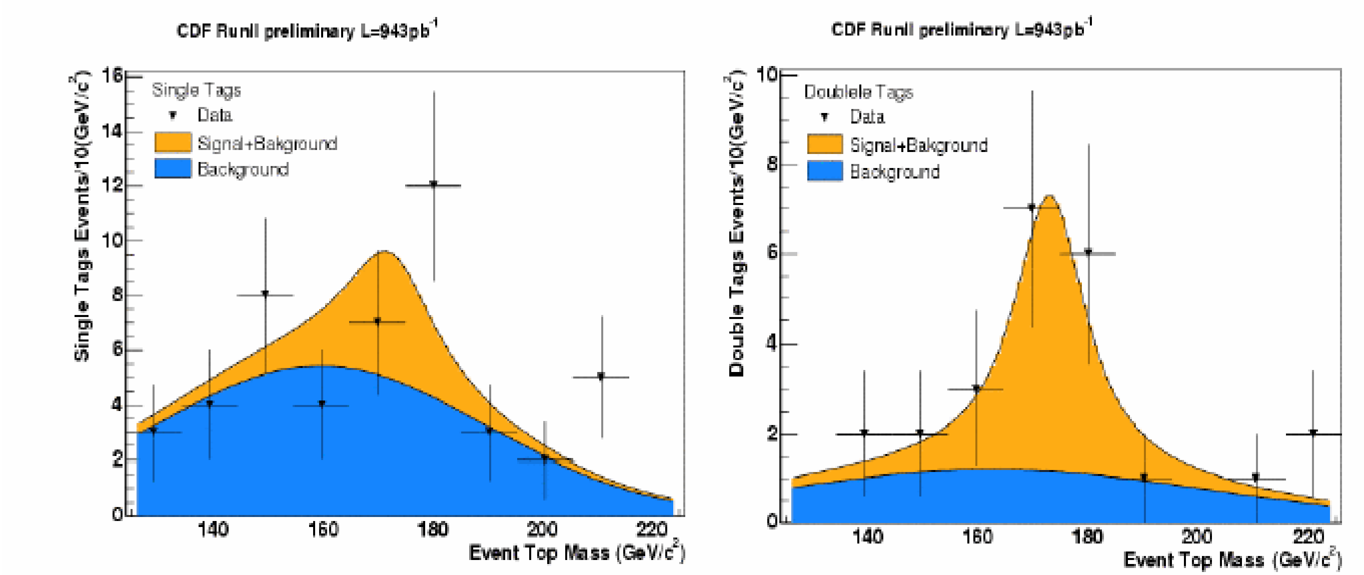




$$\mathcal{L}(M_{top}, JES, C_s; \vec{x}) \propto \prod_{i=1}^{N} [C_s P_{t\bar{t}}(\vec{x}; M_{top}, JES) + (1 - C_s) P_{W+\text{jets}}(\vec{x}; JES)]$$

FlaME

Interesting hybrid of two measurement techniques



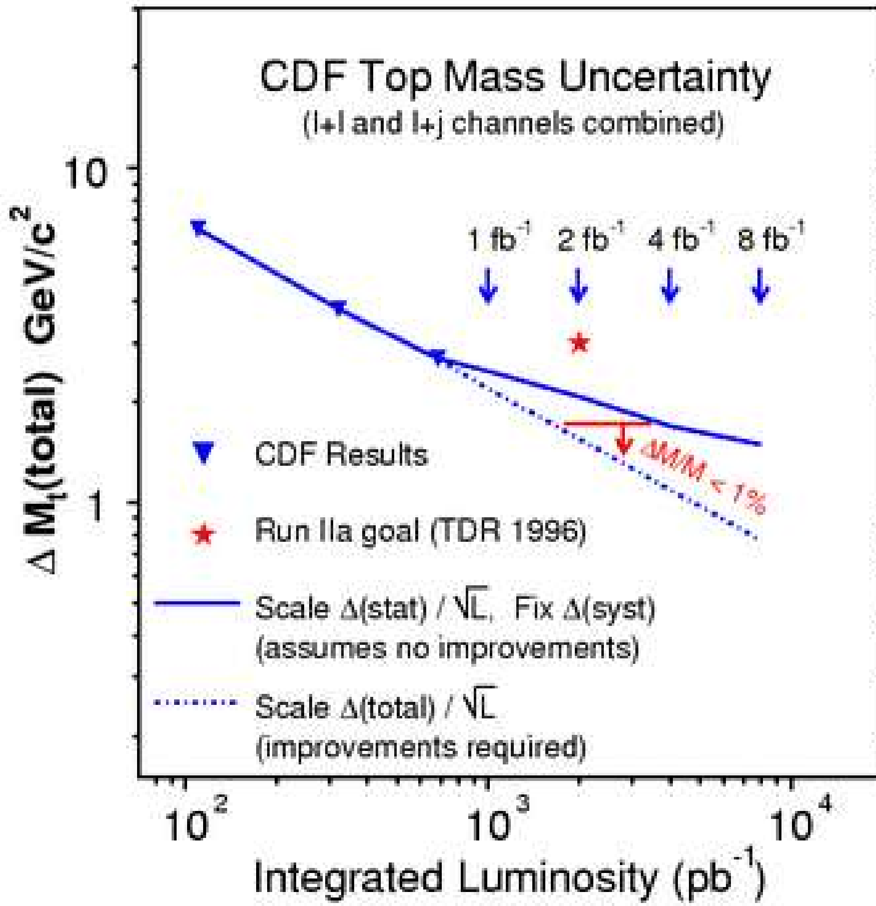
- Matrix element method
  - Use a matrix element likelihood peak to get an event-by-event top mass
- Template method
  - Fit function parameterized by mt and JES, to distributions of the event-by-event top mass as well as of invariant untagged dijet mass

Using 72 evts in 943 pb^-1:

Mt = 171.1 +/- 3.7 (stat) +/- 2.1 (syst) GeV/c^2

CDF's Top Mass Legacy

- CDF has already reached its stated goal of a +/- 3 GeV top mass measurement
- No reason to give up, however – further improvements in top mass measurement will further constrain the Higgs!
- Interesting shift in future from top quark mass as a statistical problem to a systematics problem!



Hope is for CDF to get error down to 1 GeV/c^2!

Looking to the Future

- Achieving this goal will not be simple. New issues arise:
  - Theory underlying Monte Carlo events need to be better understood
  - More rigorous study of how top mass measurements are combined will need be performed
  - Decisions will be made as to what the most powerful statistical methods are as FTEs dwindle on CDF

Conclusions

- CDF has, and will continue to have, a vibrant top mass measurement program
- LBNL has contributed to this program with innovative approaches to matrix element integration
- Hope is for LBNL to continue contributing