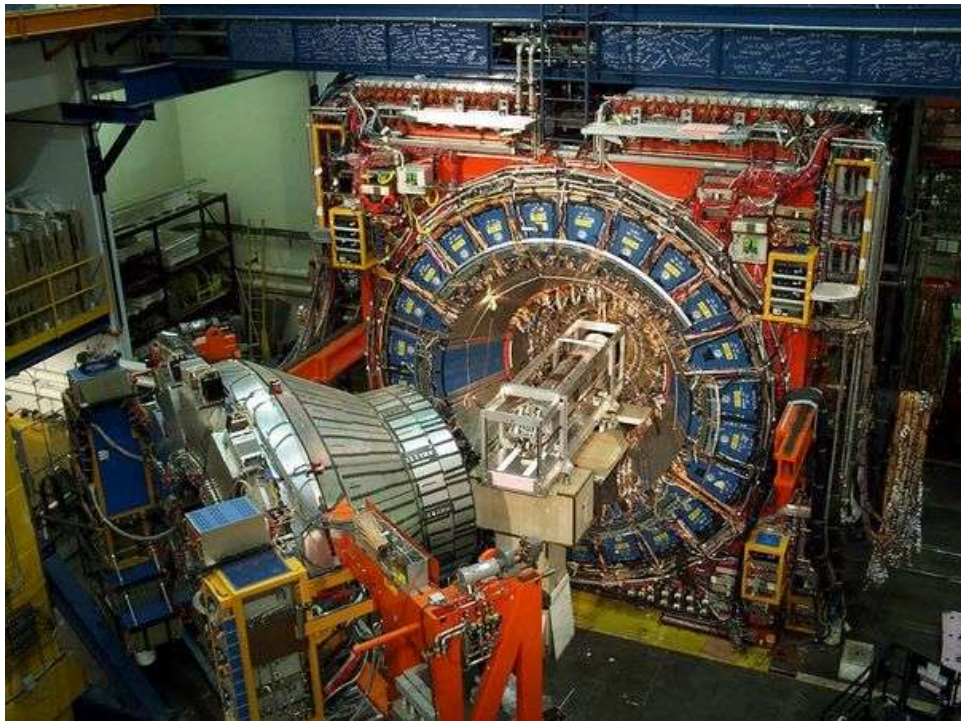
A Top Quark Mass Measurement at CDF Using a Novel Matrix Element Method



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LBNL/UC Berkeley

What I'll Talk About

- ***Why the top quark mass is of interest***
- ***CDF at the Tevatron: production and detection of top quarks***
- ***Multivariate Template Method 2 (MTM2): A novel top quark mass measurement at CDF***
- ***The CDF and world (Tevatron) average, present and future***

MTM2 Members: John Freeman, Lina Galtieri, Paul Lujan, Jeremy Lys, Pedro Movilla Fernandez, Jason Nielsen, Igor Volobouev

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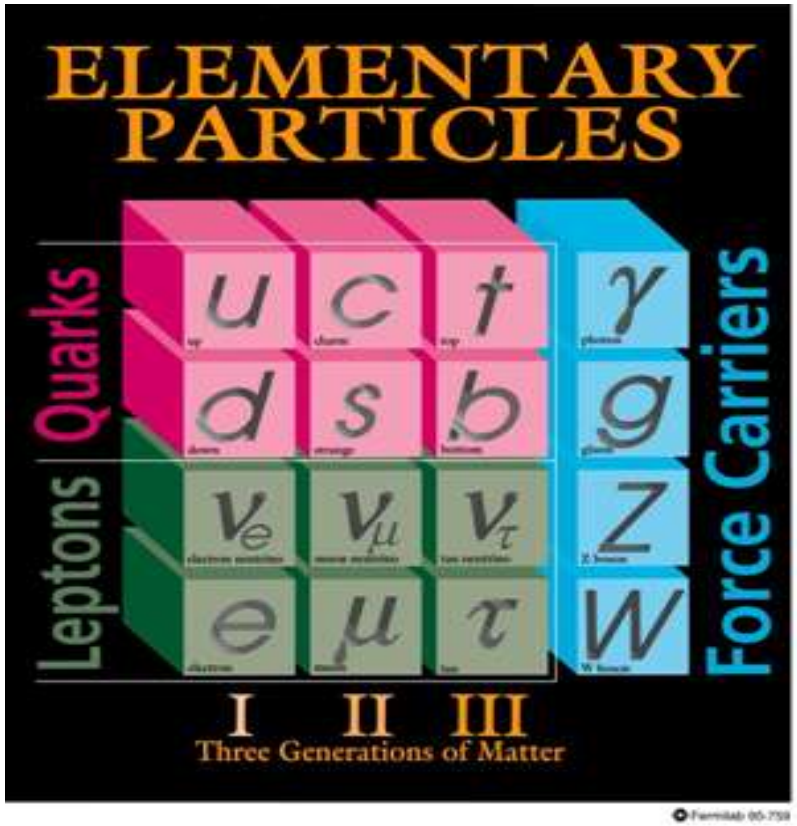
Overview of the SM

- The Standard Model is currently the most successful model of particle interactions
  - Agrees with all collider results
  - Doesn't accommodate dark matter/energy from cosmological observations
  - Only missing particle: the Higgs boson, needed to provide other particles with mass



+

Higgs boson

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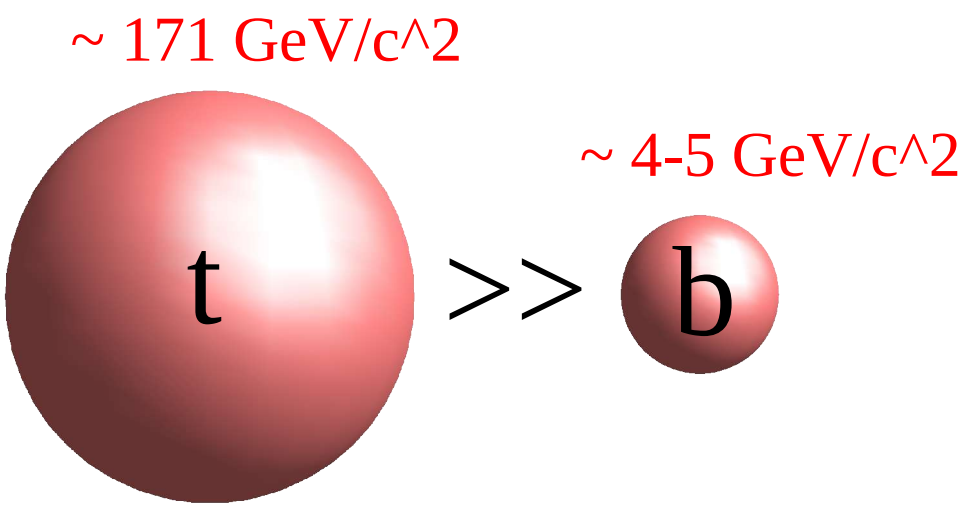
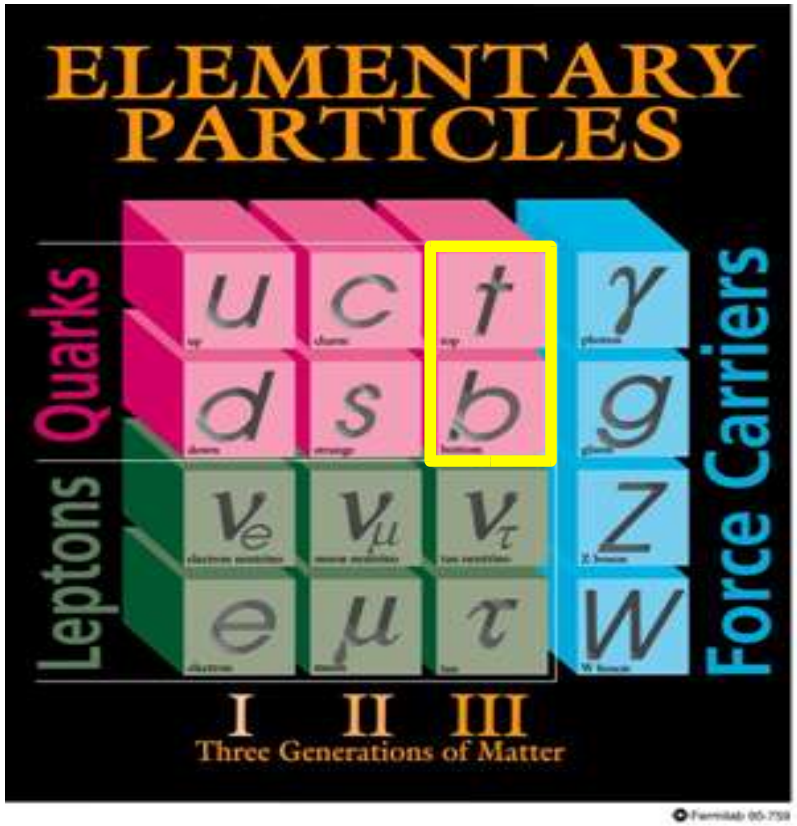
Discovering the Top Quark

- Discovery of bottom quark in 1977
  → top quark MUST exist in SM
  as SU(2) electroweak partner
- Took 18 yrs to discover the top quark – it's very heavy!





Top is ~ 35-40X more massive than next heaviest quark, the bottom!

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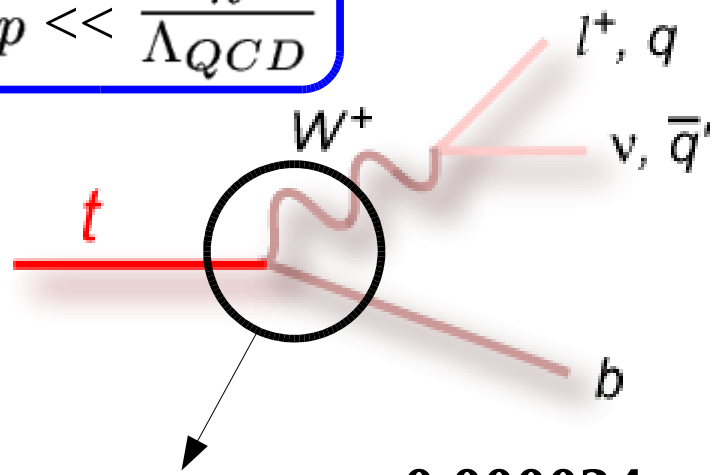
Because Top's So Massive...

$$\tau_{top} << \frac{\hbar}{\Lambda_{QCD}}$$

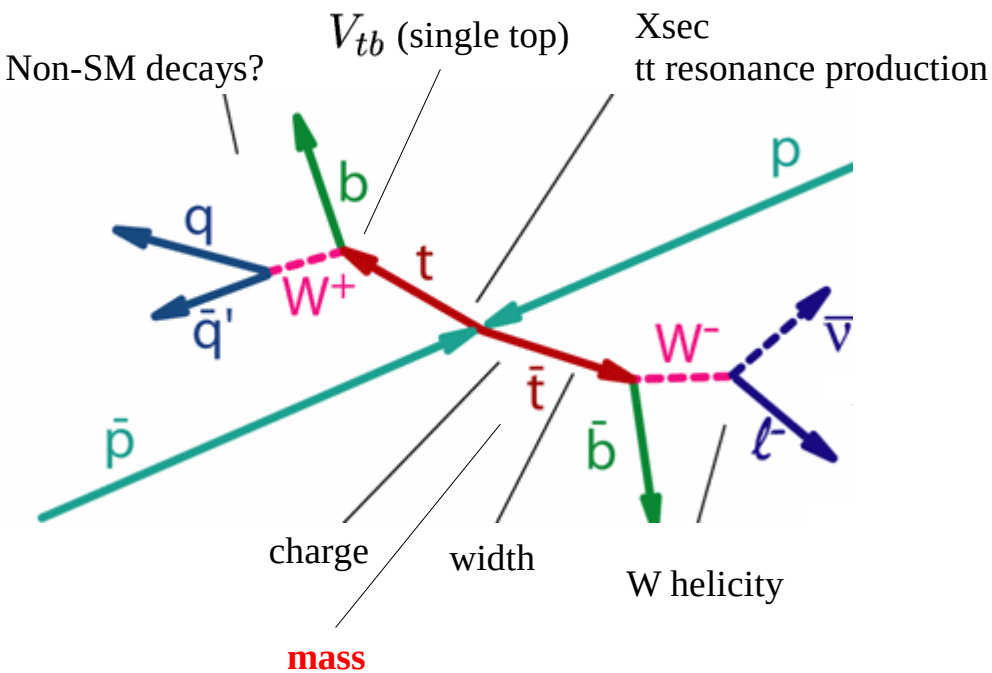


SM $|V_{tb}|$ **= 0.9991** $^{+0.000034}_{-0.000004}$

- Top decays before hadronizing ⟶ can measure its properties (mass, spin, charge, etc.) directly!
- Electroweak scale of top mass gives it unique role among quarks in extensions to SM

Do we have a SM top?

... many ongoing CDF measurements of top properties are investigating this!



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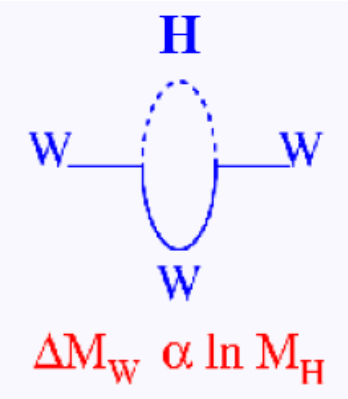
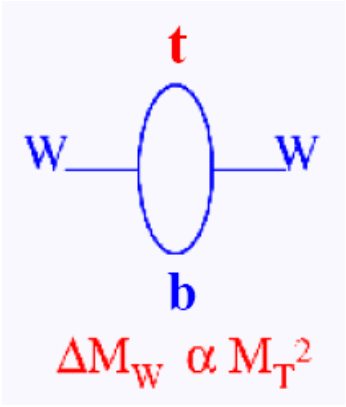
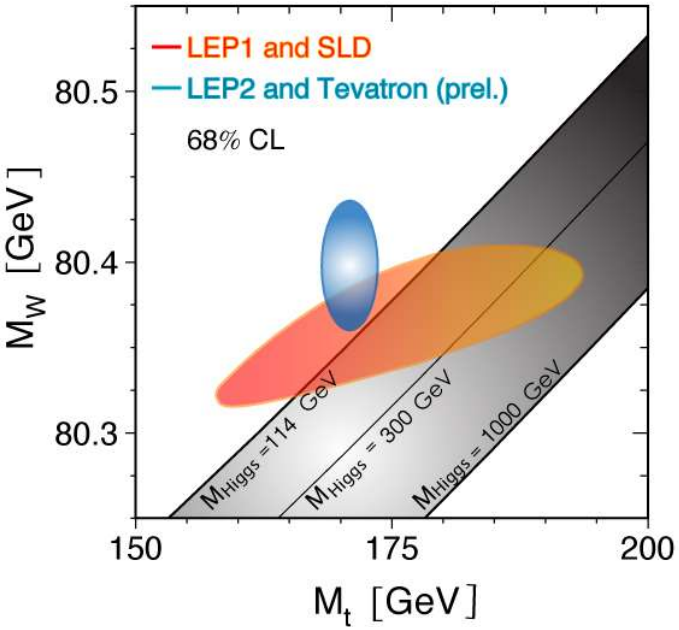
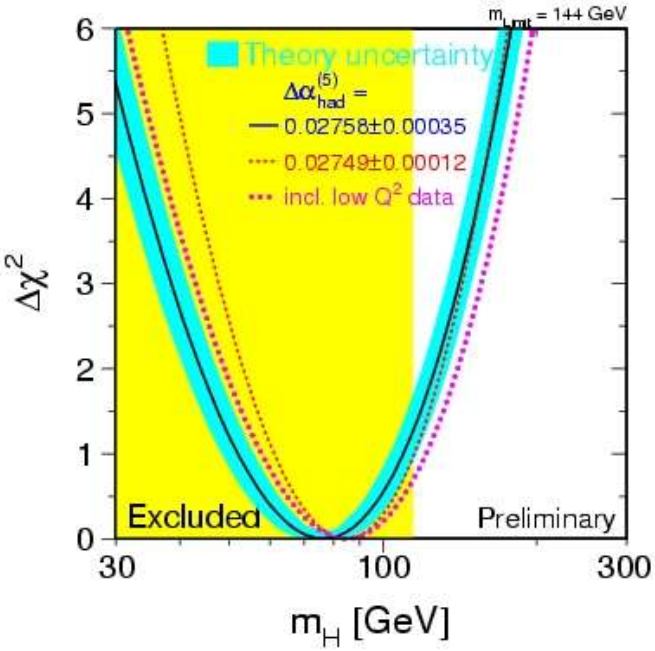
Top Quark Mass in the SM





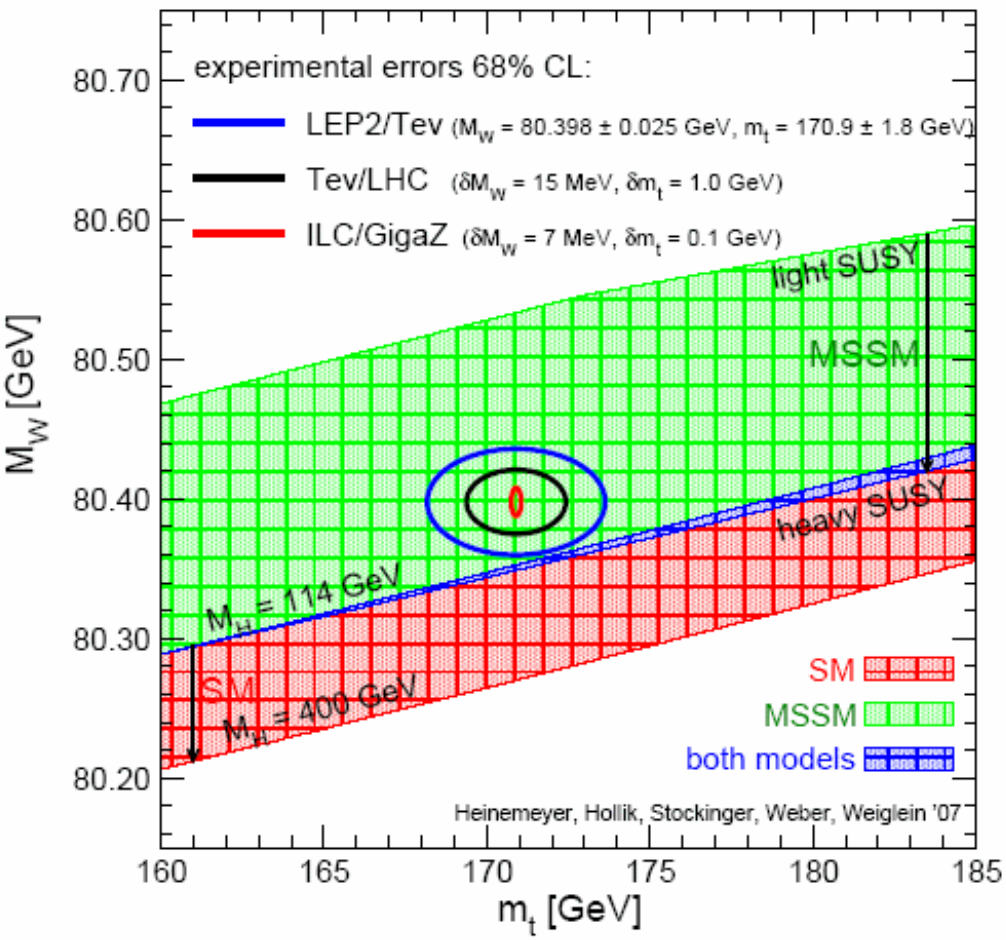


- In SM, top quark and W boson masses provide the best electroweak constraint on the Higgs mass
- From LEP, a SM Higgs < 114 GeV has been ruled out in direct searches w/ 95% CL
- But most recent world averages for top and W predicts a light Higgs: M_H = **76 +33 -24 GeV/c^2**



Top Quark Mass Beyond the SM

- A Higgs < 114 GeV *isn't* ruled out in the Minimal Supersymmetric Standard Model (MSSM)
- Over the next few years:
  - Better measurements of the top and W masses will further constrain the Higgs mass
  - If it exists, might get evidence of Higgs @ Tevatron; should discover at LHC



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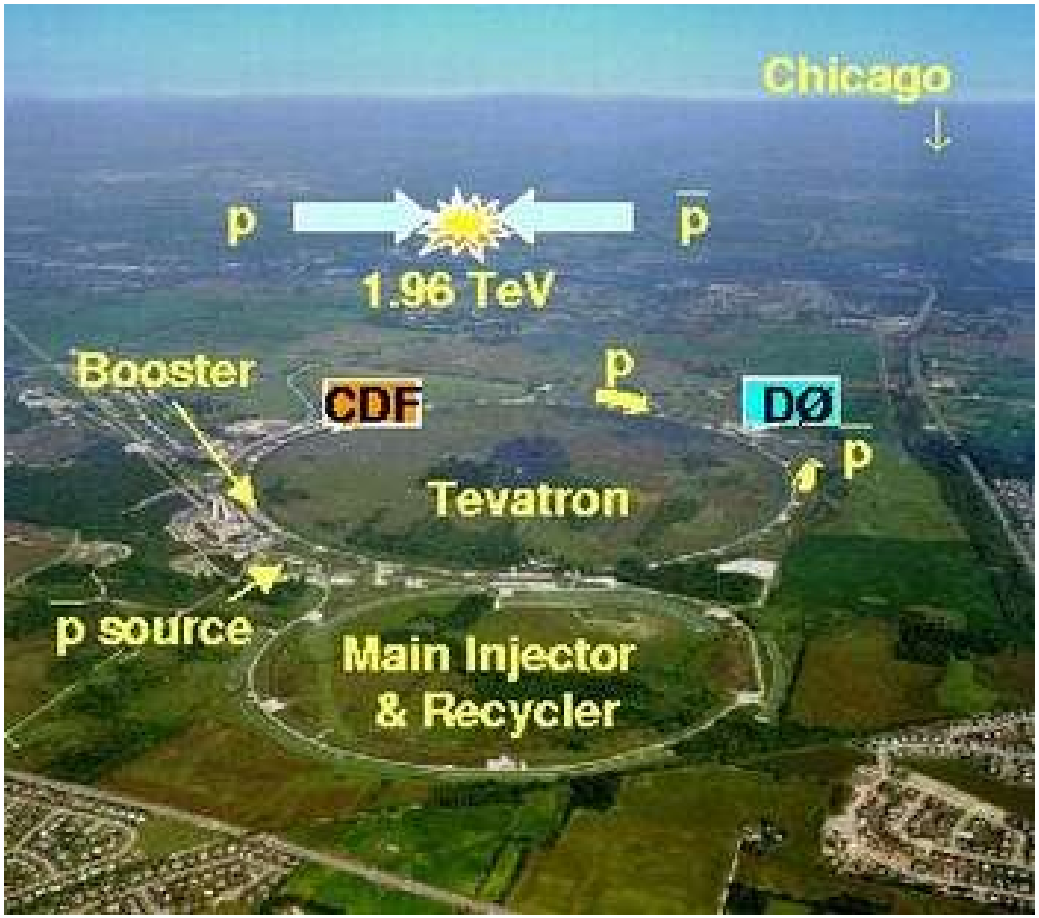
Creating top quarks (I)

- At Fermilab, a series of accelerators culminating in the Tevatron brings protons and antiprotons to 980 GeV
- Until LHC turns on to full energy next year the Tevatron will remain the only accelerator capable of producing tops
- Since only a fraction of this energy is carried by partons in the protons and antiprotons, the cross section for creating $t\bar{t}$ pairs is low: for top mass of 175 GeV/c^2, SM prediction is 6.7 pb



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Tevatron Performance

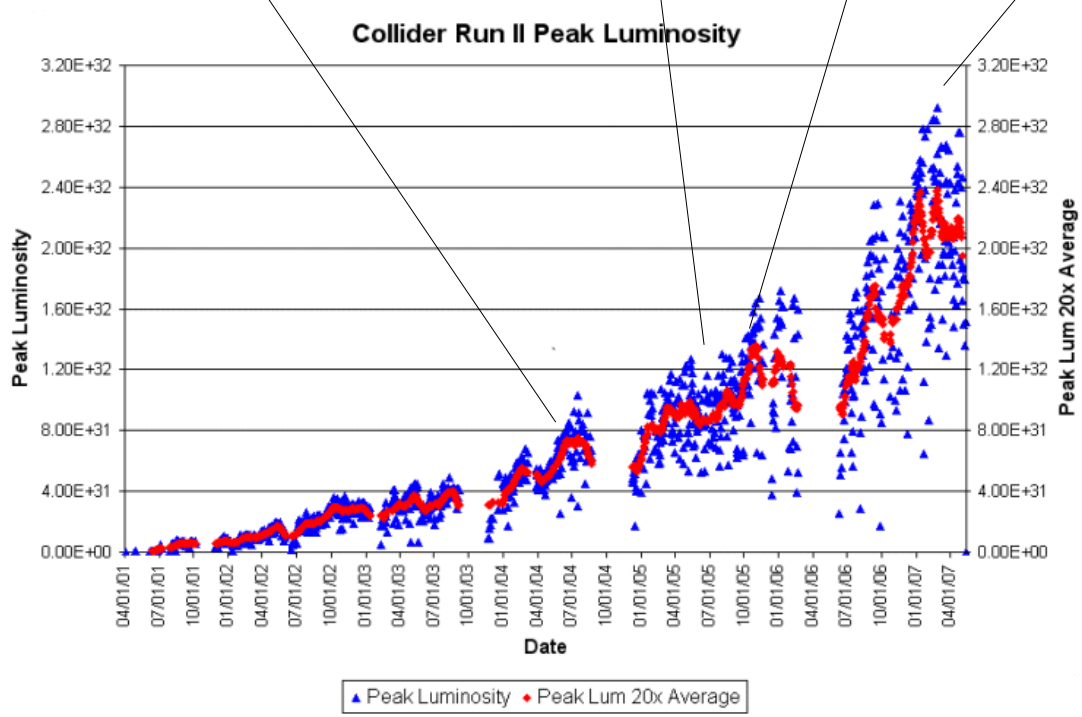
- Technological improvements have produced big gains in luminosity delivered by the Tevatron in last couple of years
- Current estimates for the total delivered luminosity through FY09 range from 6-8 fb^{-1}

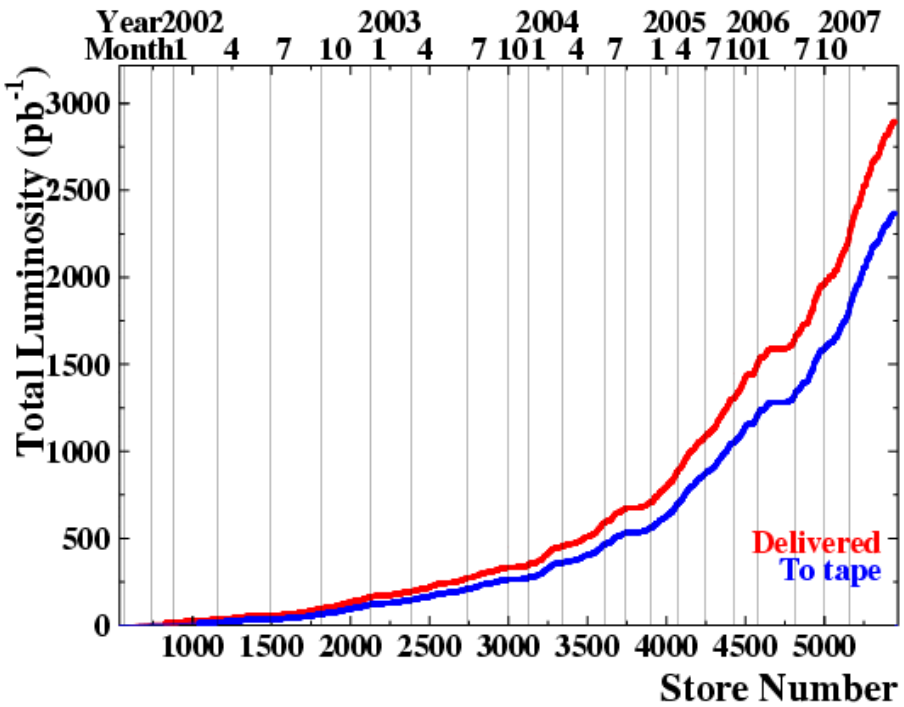
Jun '04: Recyler+accumulator first used together for pbar injection into Tevatron

Jul '05: electron cooling first used

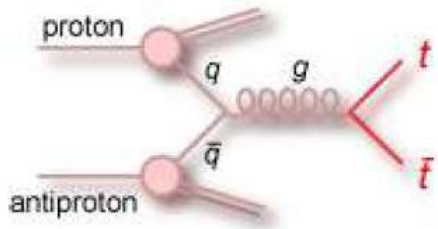
Oct '05: previous hadronic lum record (ISR '83) beaten (140e30 cm^-2 s^-1)

Current record: 291e30 cm ^-2 s^-1

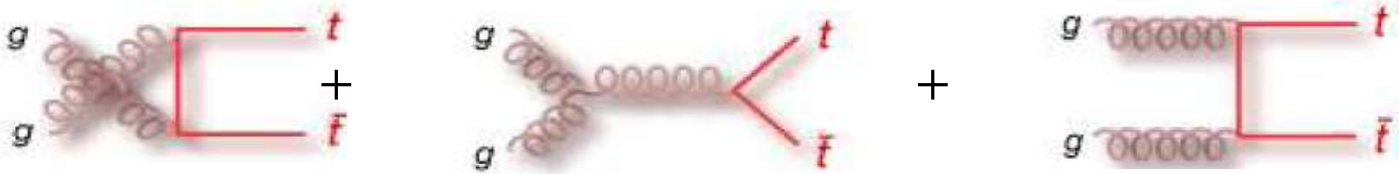




Creating top quarks (II)



$q\bar{q}$ annihilation (85% of $\sigma_{t\bar{t}}$)



gg fusion (15% of $\sigma_{t\bar{t}}$)

- $t\bar{t}$ creation 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

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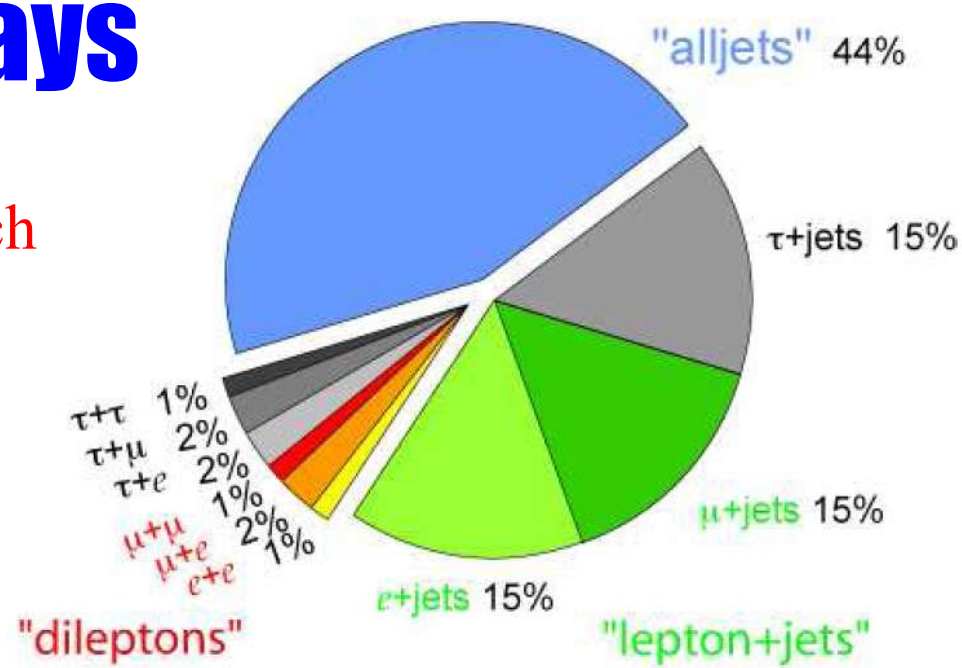
Top Decays



- Three primary decay channels in which top mass is measured
- Discrepancies in top mass, $\sigma_{t\bar{t}}$ 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: low stats
  - All-jets events: bad S/B
  - lepton+jets: provides ideal balance of statistics and signal-to-noise

In this talk, "lepton" means e or μ !

$$t \to Wb$$

THEN

$$W \to l\nu_l$$

OR

$$W \to q\bar{q}$$ → particle jets

(~3x as common)

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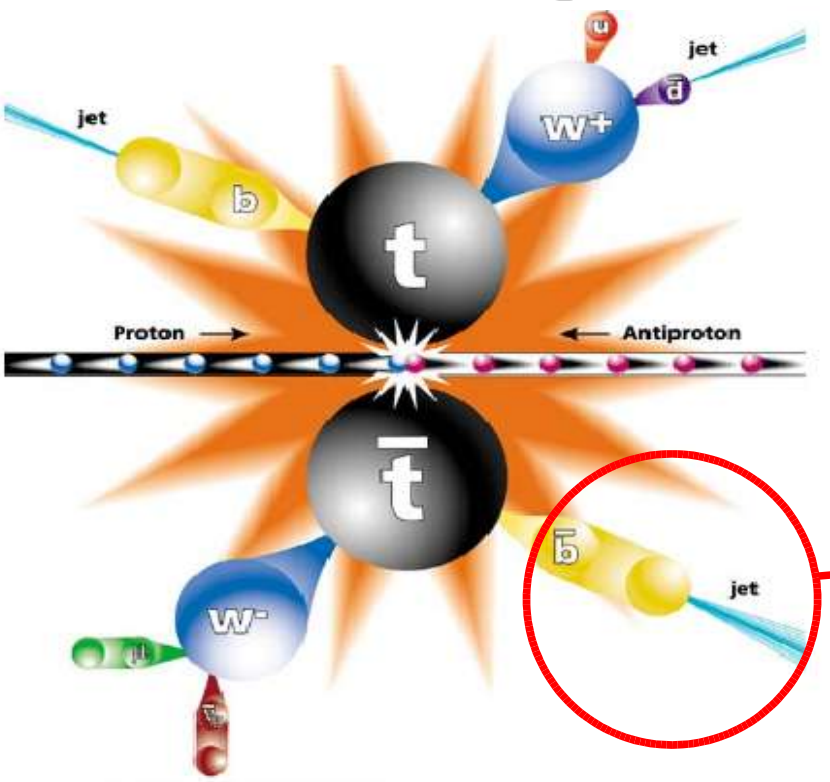
Lepton+Jets Event Selection

- High p_T muon or high E_T electron
- Four particle jets with high E_T
- High missing E_T (for neutrino)
- >= 1 b-tagged jet

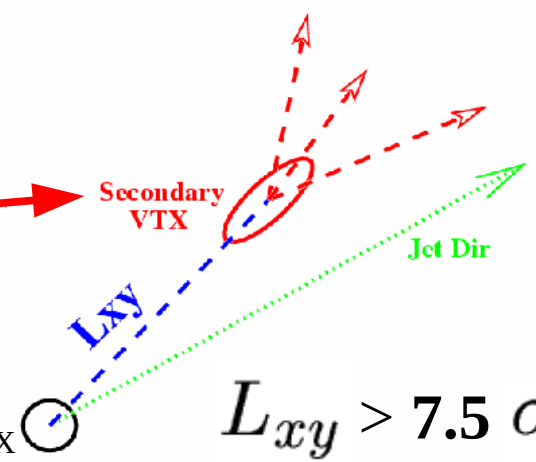
→ ***179 events in 955*** pb^{-1}

EXPECT 15% NON- $t\bar{t}$

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



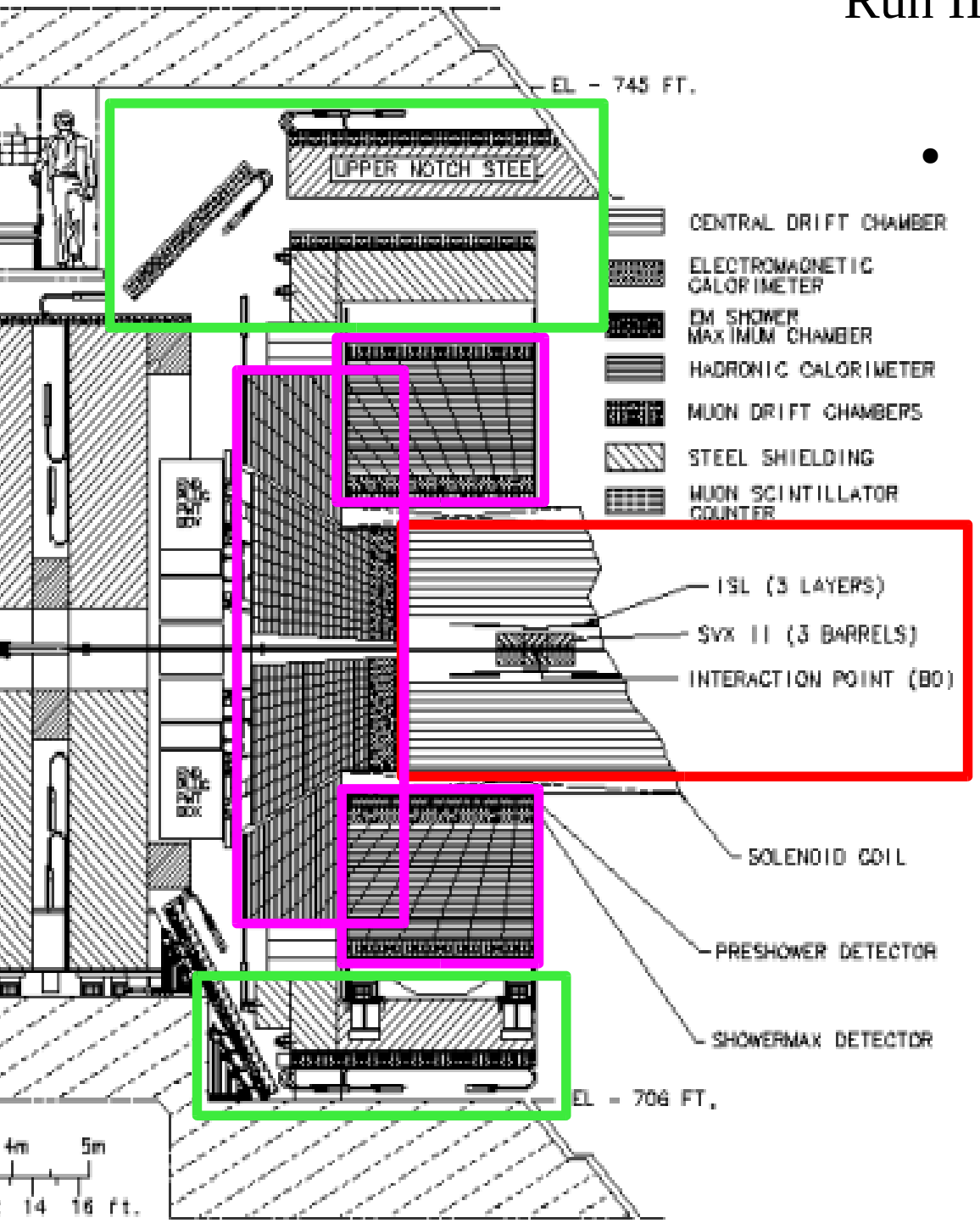
b-tag: use tracking system to determine displaced secondary vertex from B hadron decay



$L_{xy} > 7.5\ \sigma_{L_{xy}}$

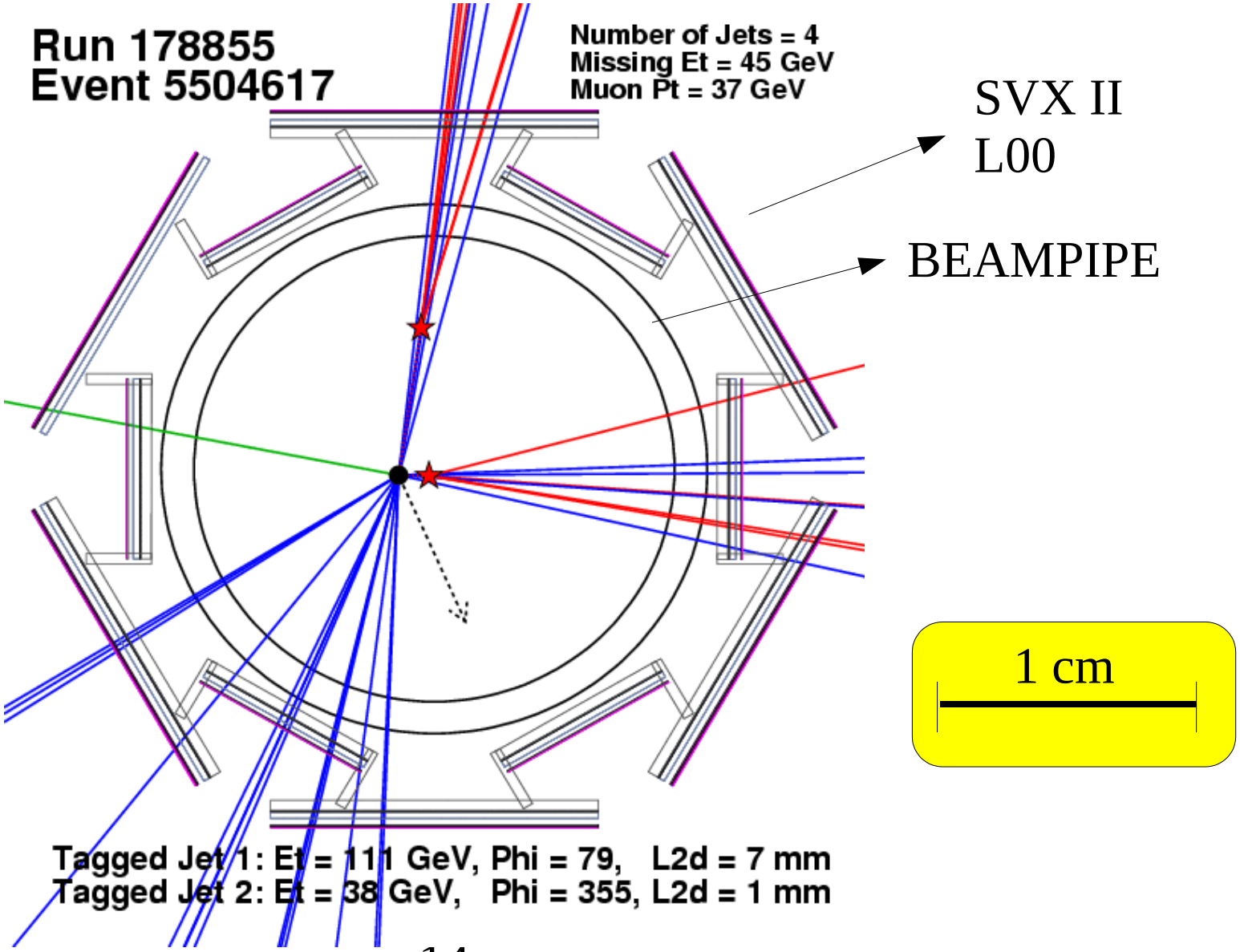
Joh
LB

Run II CDF Detector



- **What we use**:
  - A charged particle tracking system built for Run 2
    - Silicon detector (b-jet tagging)
    - Central Outer Tracker "COT" drift chamber (lepton momentum + b-jet tagging)
    - Both are immersed in a 1.4 T solenoidal field
  - EM + hadronic calorimeters for electron/jet energy measurements (plug new for Run 2)
  - Wire chambers / scintillators (some of them new for Run 2), designed for muon tracking

A Sample Lepton + Jets Event



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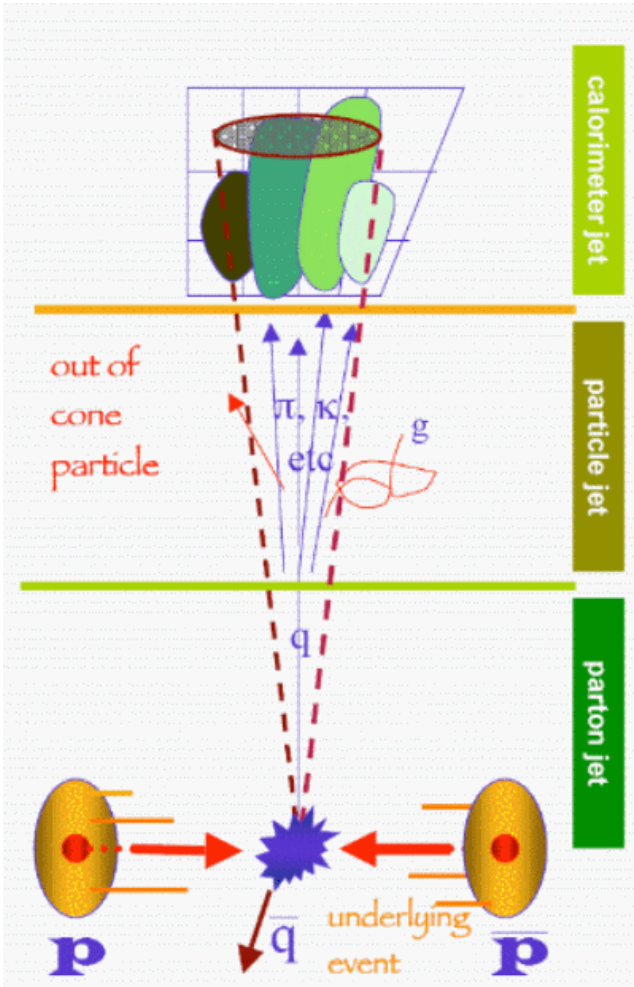
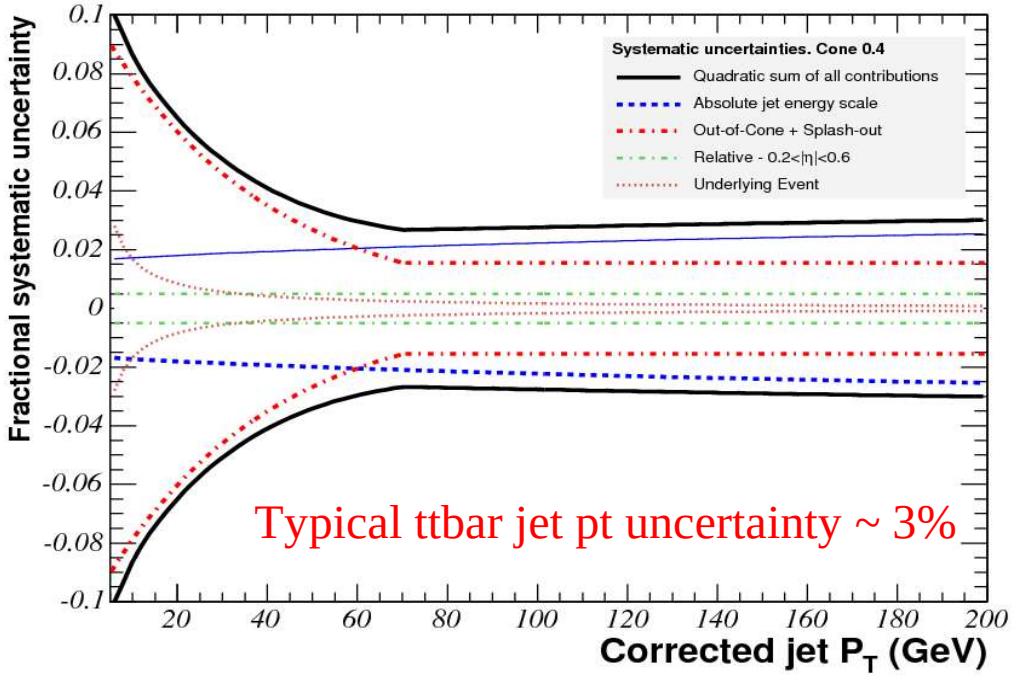
Jet Pt Measurement

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





- Quarks hadronize into particles, clustered into jets in the calorimeter towers
- Systematic uncertainty on the resulting p_T measurement can yield a top mass systematic ~ 3 GeV/c^2 if no attempt to address it is taken!
- The limiting error in the Tevatron's new high L_{int} era...

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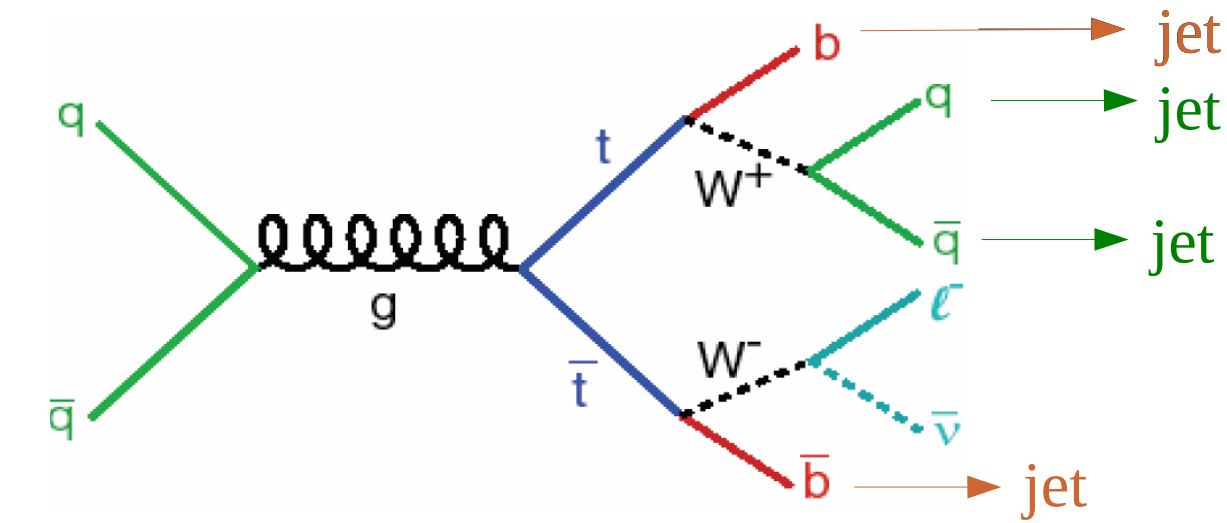
Overview of Matrix Element Methods

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



- Calculate a per-event likelihood in top mass by integrating over a set of unique parton-level $t\bar{t}$ decay kinematics ($\vec{x}$)
- Given $\vec{x}$, calculate a weight using distribution functions for incoming parton momenta, $f(z)$, the SM amplitude, $|M(m_t, \vec{x})|$, and a probability distribution that $\vec{x}$ would have resulted in measured quantities $\vec{y}$, $\mathrm{TF}(\vec{y} \mid \vec{x})$

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Matrix Element Methods for Lepton+Jets Channel

Add jet energy scale into the likelihood

TF used only for each of the four parton-jet pairs

$$L(\vec{y} \mid m_t, JES) \propto \sum_{i=1}^{24} \int f(z_1) f(z_2) \; |M(m_t, \vec{x})|^2 \; \prod_{j=1}^{4} \mathrm{TF}(y_j, JES \mid x_j) \; d\vec{x}$$

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Sum over every jet-quark permutation

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Sum over every jet-quark permutation

$\vec{x}$ a subspace of potential 22-dimensional space

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Sum over every jet-quark permutation

$\vec{x}$ a subspace of potential 22-dimensional space

- Make integration tractable through assumptions:
  - Quark angle same as jet angle
  - Lepton momentum perfectly measured
  - Quarks have on-shell mass
  - lepton+neutrino masses are known

$\vec{x}$ + *assumptions = unique kinematics*

Some assumptions are more accurate than others...

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Overview of the MTM2 Method

Adjust matrix element
to account for
integration assumptions

$$L(\vec{y} \mid m_t, JES) \propto \sum_{i=1}^{24} w_i \int f(z_1) f(z_2) \; |M_{\text{eff}}(m_t, \vec{x})|^2 \; \prod_{j=1}^{4} \text{TF}(p_{jet} \cdot JES \mid p_{Tparton}) \; d\vec{x}$$

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Weight every jet-quark
permutation with b-tag info

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Overview of the MTM2 Method

Adjust matrix element to account for integration assumptions

TF takes us from parton p_T to jet momentum

Treat JES as constant scale factor for all jets

$$L(\vec{y} \mid m_t, JES) \propto \sum_{i=1}^{24} w_i \int f(z_1) f(z_2) \; |M_{\text{eff}}(m_t, \vec{x})|^2 \; \prod_{j=1}^{4} \text{TF}(p_{jet} \cdot JES \mid p_{Tparton}) \; d\vec{x}$$

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Weight every jet-quark permutation with b-tag info

$\vec{x}$ = hadronic, leptonic side M_W^2 and M_t^2

transverse $\vec{p_{t\bar{t}}}$

$\log(p_1/p_2)$

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transverse $\vec{p_{t\bar{t}}}$
$\log(p_1/p_2)$

Unique features of MTM2 I'll describe:

-How we handle background events

-How we compensate for the integration assumptions

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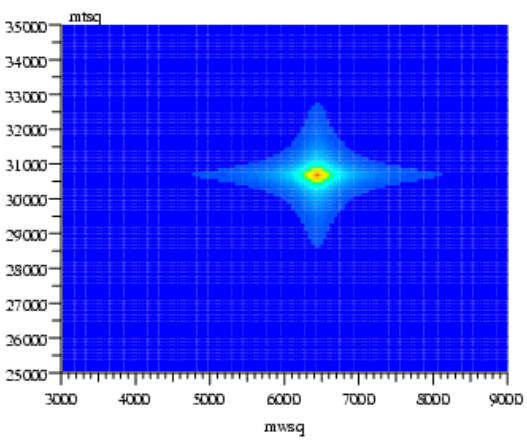
"Effective Propagators"

- In nature, M_t^2 and M_W^2 have Breit-Wigner distributions
- However $\vec{x}$ + (imperfect) assumptions ⟶ different distributions for M_t^2 and M_W^2
- Build these new distributions, and use them to replace the Breit-Wigner propagators in the matrix element

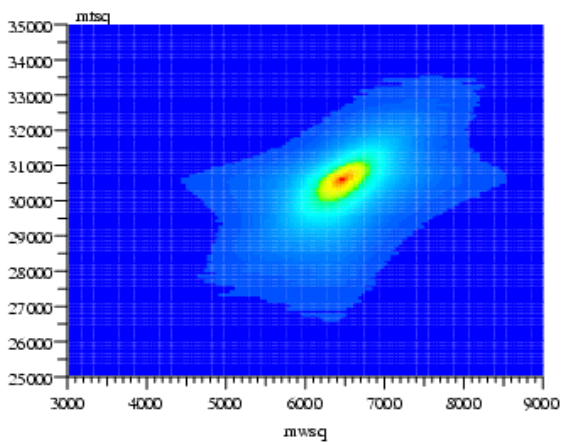
Create a Consistent Calculation!

$|M(m_t, \vec{x})|$ ⟶ $|M_{\text{eff}}(m_t, \vec{x})|$

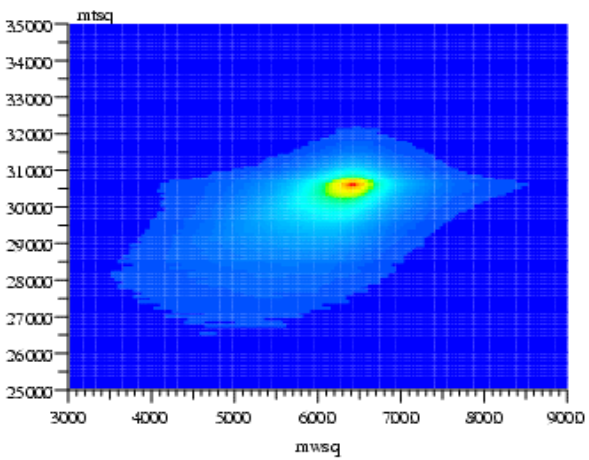
Breit–Wigner mass distributions



Breit-Wigner propagator



Hadronic-side eff. propagator



Leptonic-side eff. propagator

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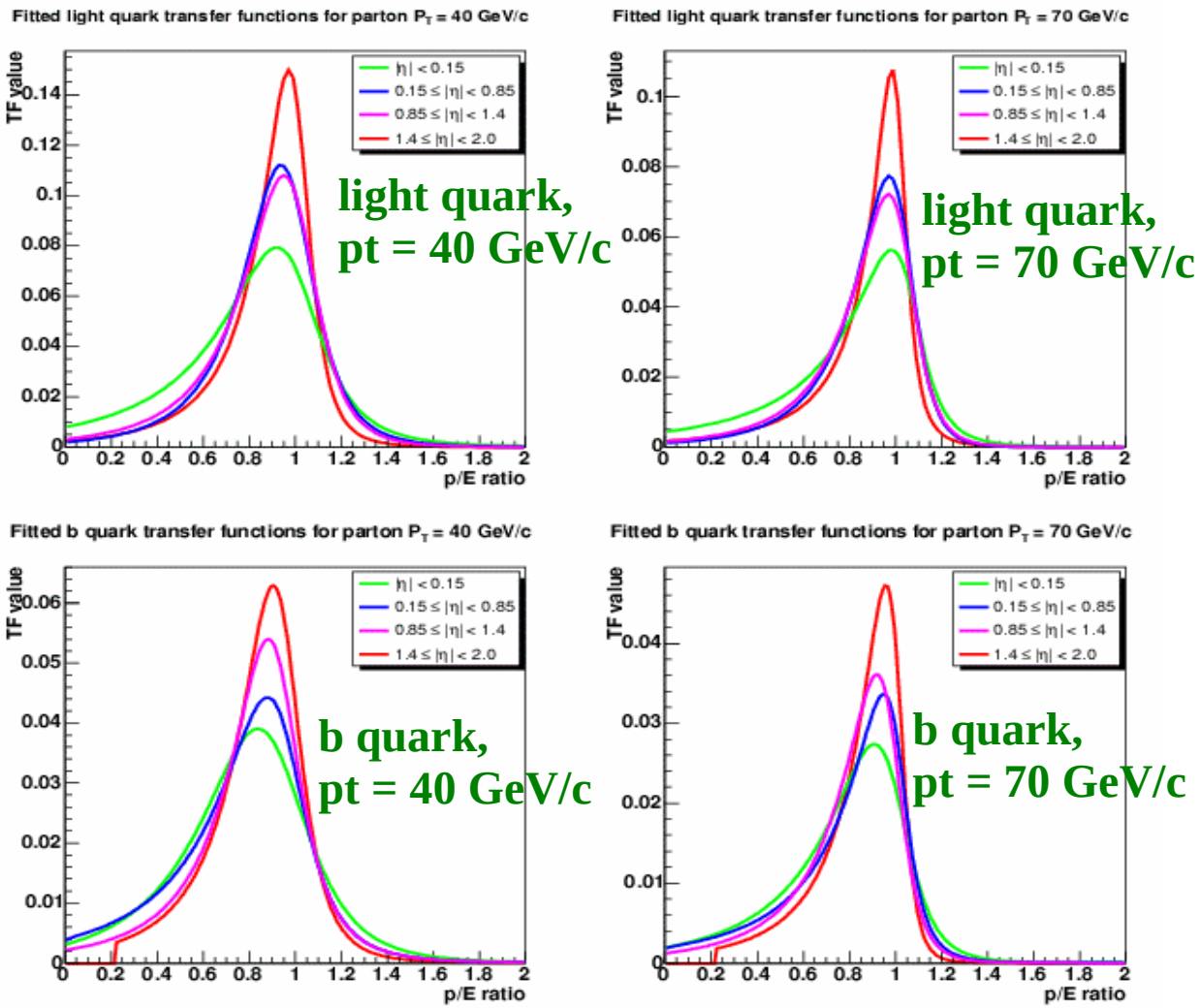
Transfer Functions

- Different $TF(p_{jet} \mid p_{Tparton})$ for:
  - Detector eta region of jet
  - light vs. b quark



Dip: 0 < |eta| < 0.15
Central: 0.15 < |eta| < 0.85
Crack: 0.85 < |eta| < 1.4
Plug: 1.4 < |eta| < 2

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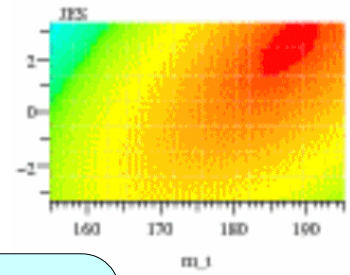
Obtaining A Measurement

- How do we turn the individual likelihoods for a set of events into a measurement, m_{meas} +/- σ_{meas} ?

#1 Multiply likelihoods

$L(\vec{y}_1 \mid m_t, JES)$ $L(\vec{y}_2 \mid m_t, JES)$ $L(\vec{y}_3 \mid m_t, JES)$

$L_{total}(m_t, JES)$ =



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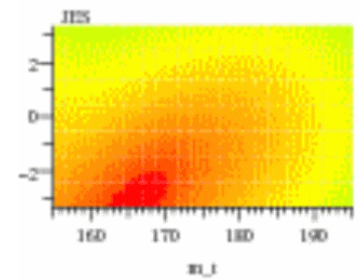

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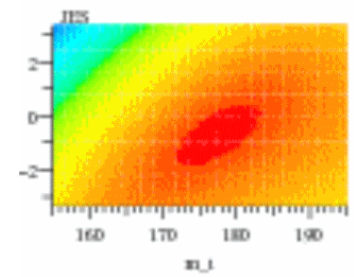

X . . .

#2 Take mass profile of likelihood

$$L_{total}(m_t) = \max_{j \in JES} L_{total}(m_t, j)$$

#3 Treat likelihood as a gaussian

m_{meas} is mass at which $L_{total}(m_{meas})$ has max value

$\sigma_{meas} = \frac{1}{2}(\sigma_+ + \sigma_-)$, where

$$L_{total}(m_{meas} - \sigma_-) = L_{total}(m_{meas} + \sigma_+) = e^{-\frac{1}{2}} L_{total}(m_{meas})$$

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Testing the Method

- To test the method, Monte Carlo (MC) events with various input top mass and JES values were used
  - Herwig for signal*
  - Alpgen + Herwig for background
- For a given configuration, 2000 "pseudoexperiments" (PEs) were run
- Quantities of interest are:
  - Bias: E[$m_{meas} - m_{true}$]
  - Resolution: RMS[m_{meas}]
  - Pull width: RMS[$\frac{m_{meas} - m_{true}}{\sigma_{meas}}$]

* Pythia was used for some systematics studies

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Not All Signal Is Created Equal

- "Good signal": $t\bar{t}$ → l+jets event, where the four selected jets have a good angular match with the four partons in the MC → Help our resolution
- "Bad signal": all other $t\bar{t}$ events in MC (e.g., non-l+jets / large initial or final state radiation) → Hurt our resolution

From 179-event pseudoexperiments:

	Bias (GeV/c^2)	*Resolution (GeV/c^2)*	*Pull Width*
GOOD SIGNAL	-0.3	1.7	1.05
GOOD AND BAD SIGNAL	-3.1	2.5	1.30

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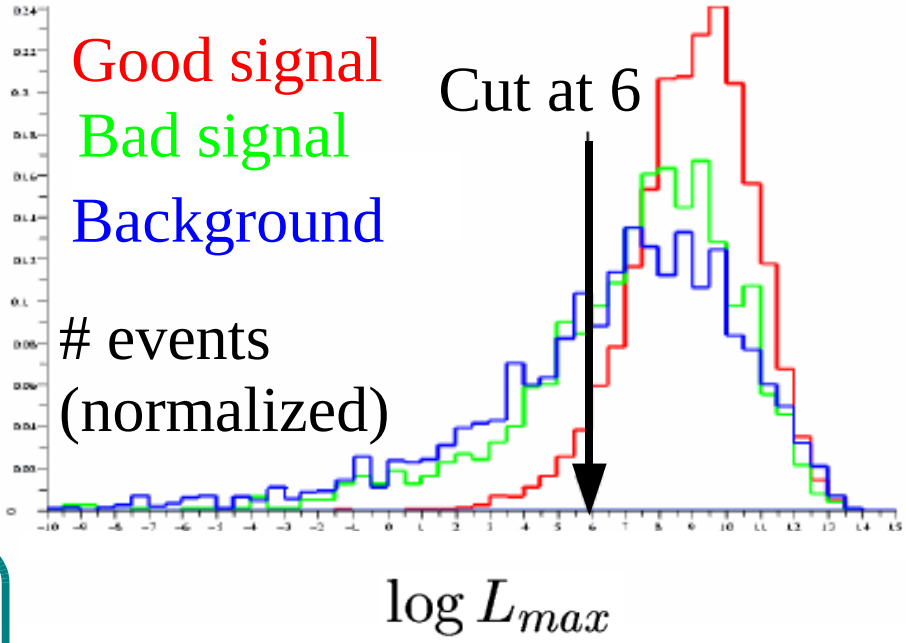
The Likelihood Cut

- Adding a cut on the maximum log likelihood value of a given event eliminates lots of bad signal (and even more background!)



Final efficiencies after likelihood cut

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

179 ⟶ 149 events in data

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Background Handling

Given event's likelihood

AVERAGE shape of background log likelihoods

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

Probability given event is background

Modify each event's likelihood

- After likelihood cut, still expect 11% background
- But all events are integrated using a matrix element which assumes signal!
- Modify each event's log likelihood curve: subtract off the characteristic log likelihood for background events weighted by f_{bgnd}
- Get characteristic log likelihood by averaging the log likelihoods calculated for our background MC events!

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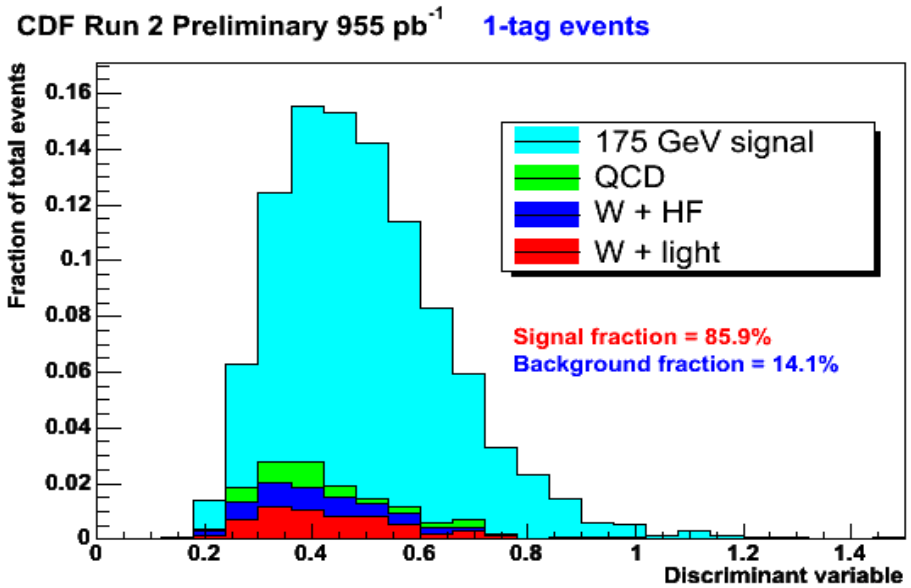
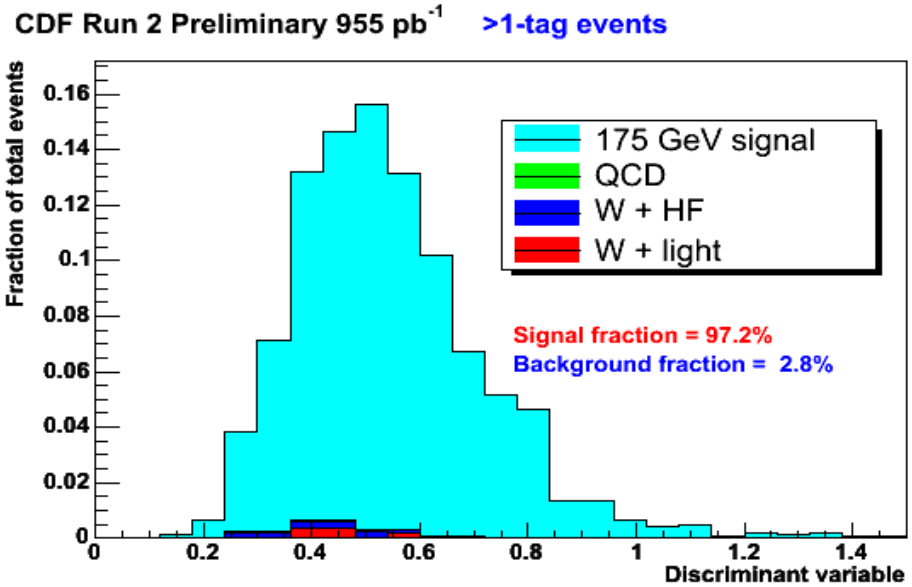
Background Handling

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

- q is a linear combination of geometric event properties
  - Aplanarity
  - $H_{\mathrm{TZ}} = \sum_{i=2}^{4} |p_T^i| / (\sum_{i=1}^{4} |p_z^i| + |p_z^\ell| + |p_z^\nu|)$
  - $D_{\mathrm{R}} = \Delta R_{ij}^{(\min)} \times \min(p_T^{(i,j)}) / p_{\mathrm{T}}(l^{\pm})$
- q has different distributions for signal vs. background MC
- Normalize signal/background MC distributions to expected fractions to calculate f_{bgnd}





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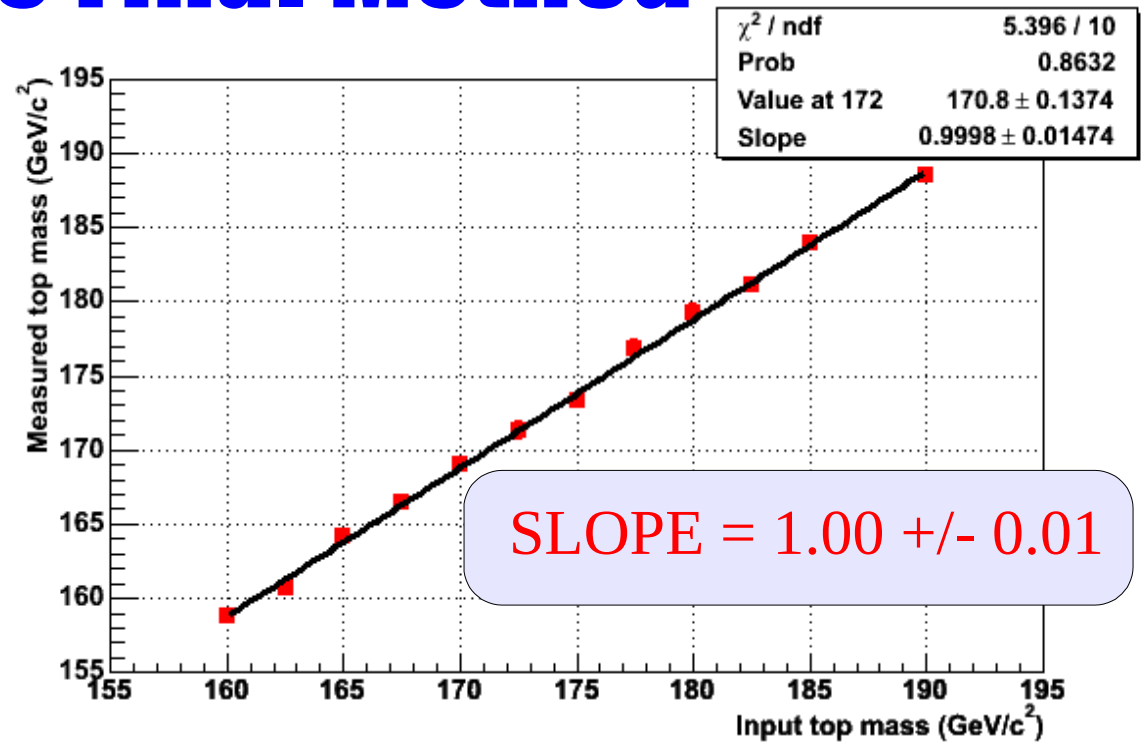
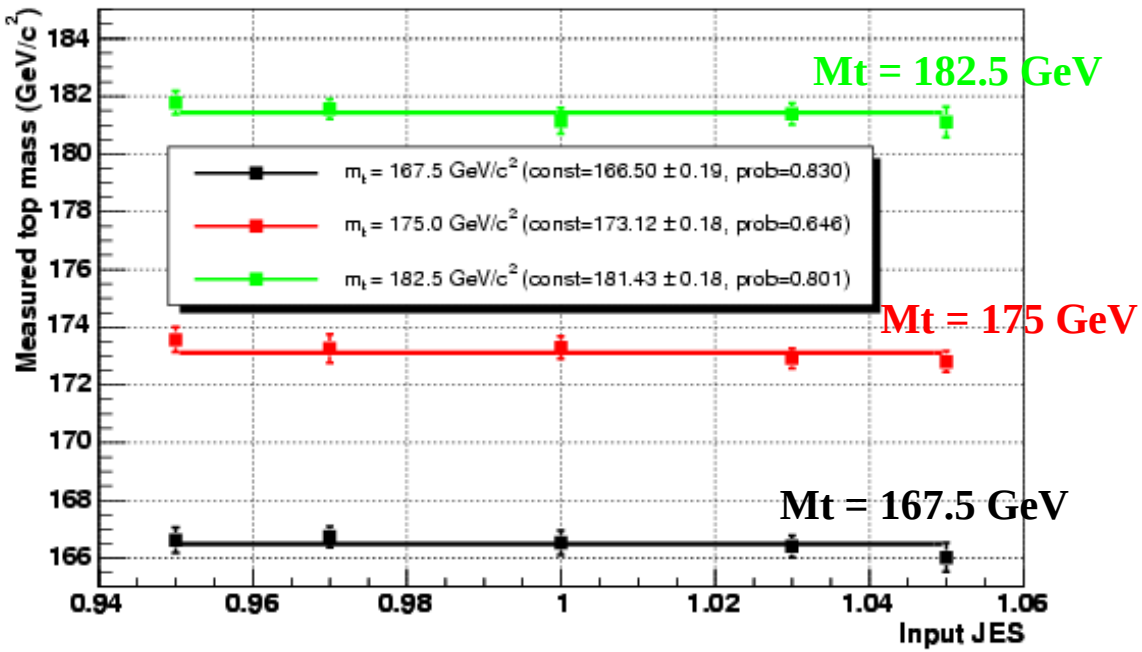
Tests of the Final Method

Run the final method on signal+background MC (use 2000 PEs, 149 evts/PE)

Reconstructed vs. input top mass indicates mass-independent bias of -1.2 GeV/c^2 → used for calibration of measurement



Reconstructed mass vs. input JES demonstrates a 5% shift in input jet momenta affects measurement at most by a few tenths of a GeV!



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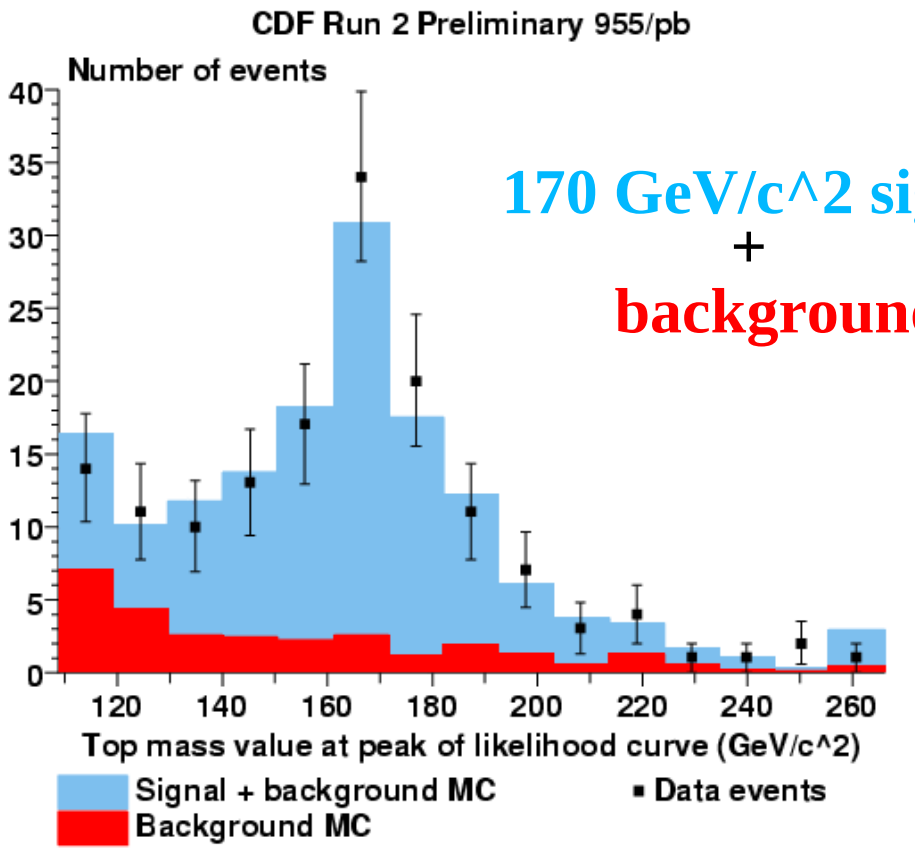
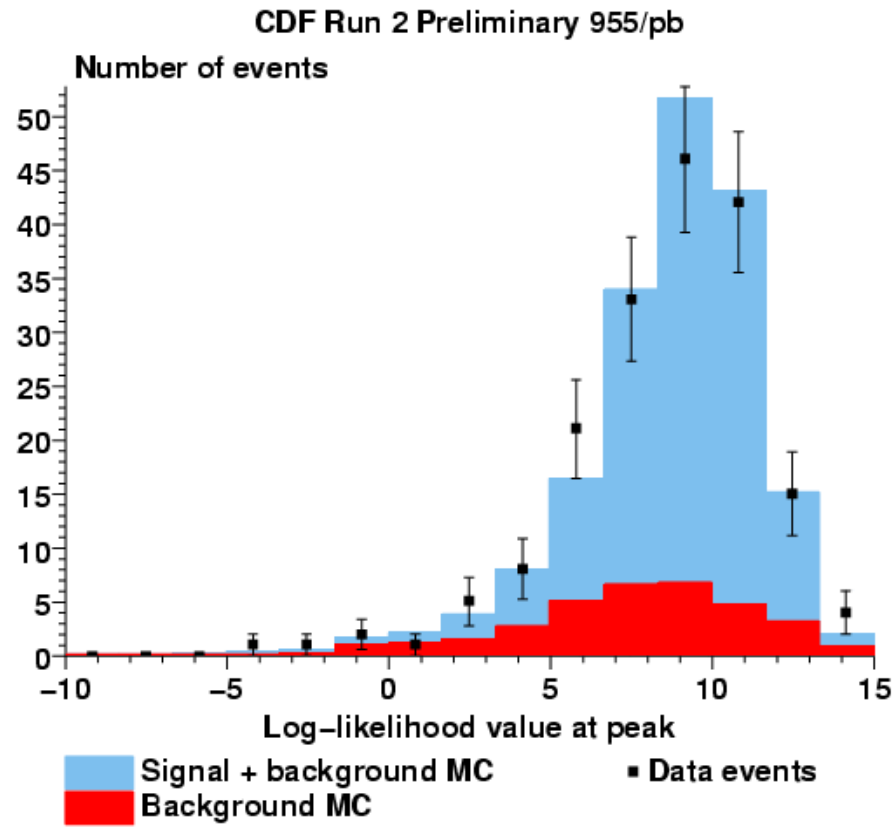
Data Vs. MC Crosscheck



170 GeV/c^2 signal
+
background



- Good agreement exists between the per-event likelihood peaks of data and MC

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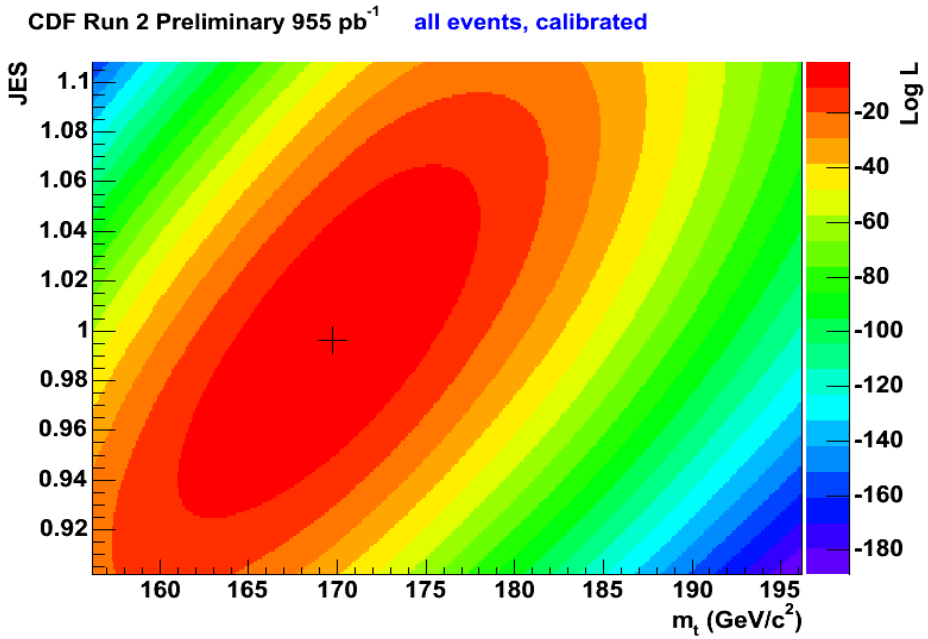
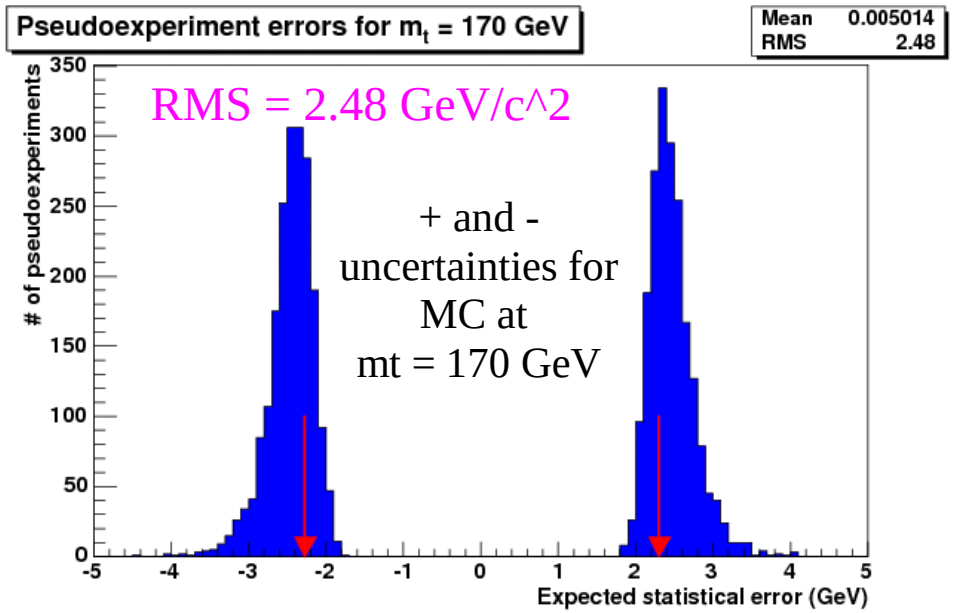
The Result

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





- 27% of PEs have a lower estimated statistical uncertainty than the data measurement
- Statistical uncertainty calibrated by expected pull width of 1.22

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Systematics

- Total systematic is 1.4 GeV/c^2
- Our largest systematic uncertainty came from the amount of initial/final state radiation assumed in the MC (1.0 GeV/c^2)
- Systematic of eta/pt dependent jet energy corrections is only 0.3 GeV/c^2!

Systematic source	2-D systematic (GeV)
ISR	0.75
FSR	0.67
MC generator	0.44
Gluon fraction	0.05
PDF re-weighting	0.46
Background fraction	0.39
Background composition	0.20
Background shape	0.29
Calibration	0.14
JES residual	0.28
Multiple interactions	0.05
b-JES	0.23
b-tag E_T dependence	0.02
Charm tag ratio	0.06
Lepton P_T	0.05
Background Q^2	0.30
Total	1.39

Breakdown of statistical resolution in measurement is
2.3 = 1.6 (non-JES) ⊕ 1.7 (JES) GeV/c^2

JES effect on total error has been reduced!

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Looking to the Future...

- Implementing improvements on all fronts - "MTM3":
  - Handle problem of integration assumptions by removing them ➞ use a 19-D integration!
  - Deal with effect of bad signal events by integrating over properties of poorly measured 4th jet
  - Perform more research into the background discrimination variable, "q"

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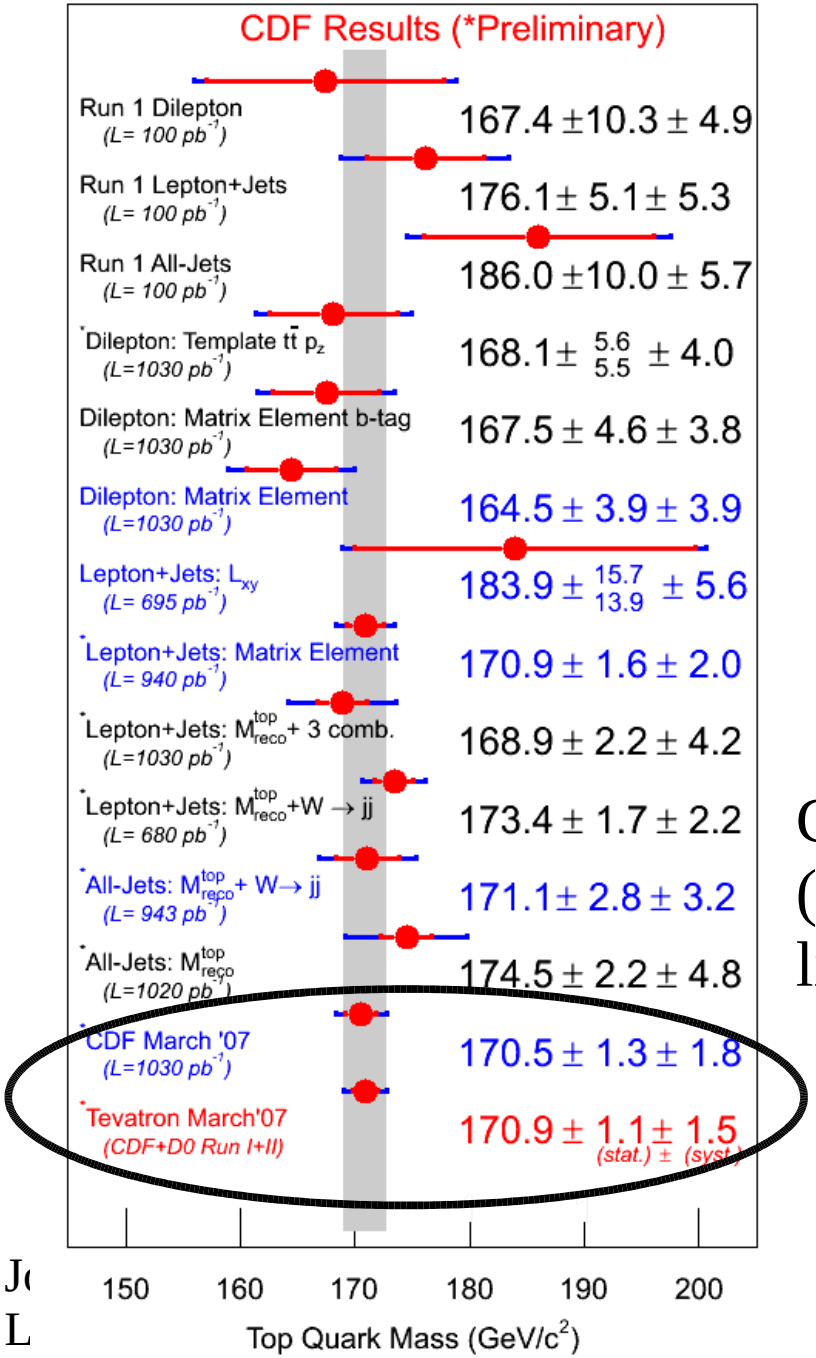
In Context



- There have many measurements tof the top quark mass at CDF!
- Here is a partial list of preliminary or published measurements as of Moriond EWK (ours has been added since)

Combined top mass measurement for CDF (not to mention for CDF+D0) is now systematics limited)

Uncertainty on world avg. is 1.8 GeV/c^2, or 1.1%

Best CDF Measurements By Channel

	Measurement	*Total Err. (GeV/c^2)*	*Stat. Err. (GeV/c^2)*	*Sys. Err. (GeV/c^2)*
DILEPTON	164.5	5.5	3.9	3.9
L+JETS	170.9	2.6	2.2	1.4
ALL-JETS	171.1	4.3	3.7	2.1

- **All use ~1 fb^{-1} of data**
- **All use matrix element method techniques**

→ CDF Avg: 170.5 +/- 2.2 GeV/c^2 (stat+syst)

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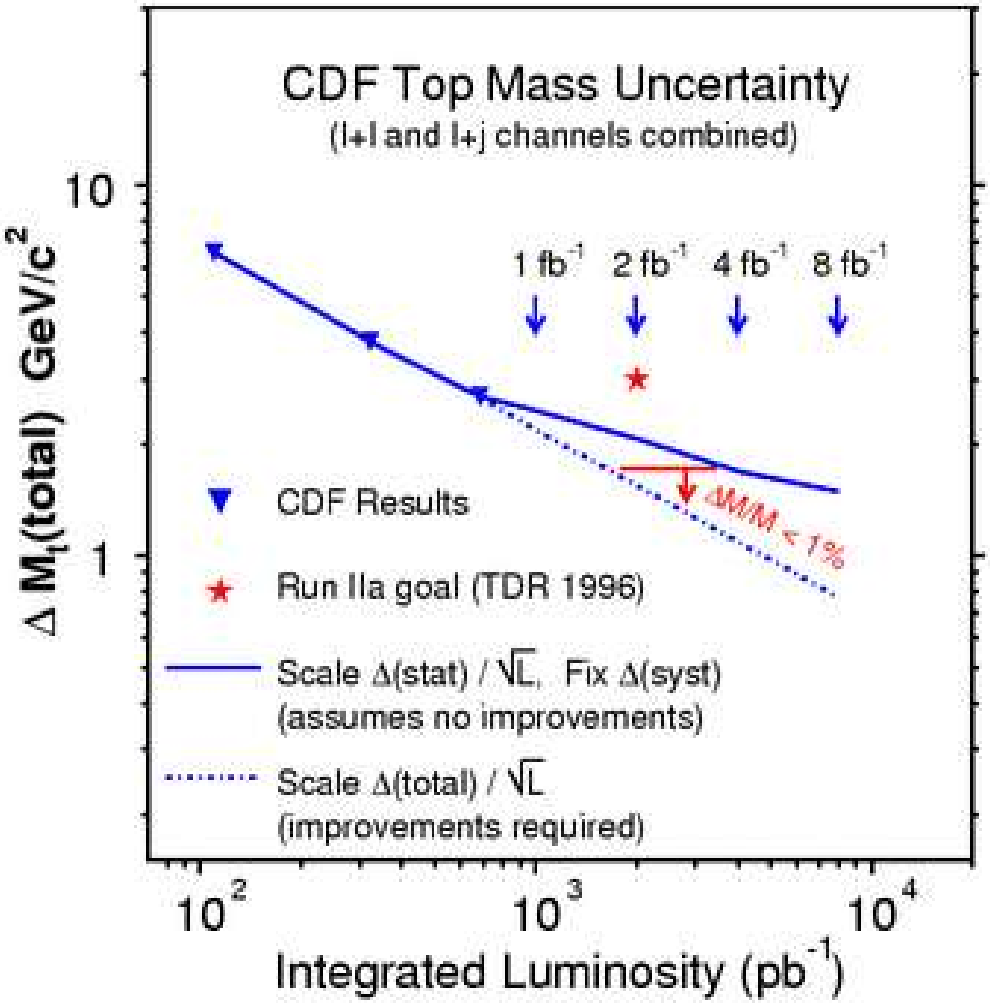
The Top Mass Legacy

- CDF has already reached its Run II goal of a +/- 3 GeV/c^2 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



Plan is for CDF+D0 to get uncertainty down to 1 GeV/c^2!

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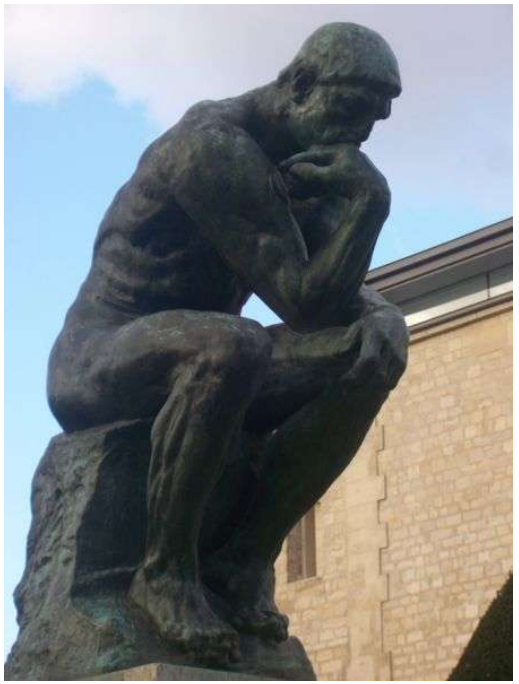
Improving the World Average

- To achieve a 1 GeV/c^2 uncertainty, will need a better understanding of:
  - The MC we use (modeling of background, initial/final state radiation, QCD issues, etc.)
  - The Jet Energy Scale (differences between b- and light-jets, etc.)
  - How to combine CDF+D0 systematics

Also: how can we combine correlated measurements within a channel?



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Conclusions

- The top quark mass measurement will be one of CDF (and the Tevatron's) greatest legacies
- Lots of work has gone into a great world average; lots more work will be needed to make it even better
- LBNL looks forward to continuing to contribute to this program!

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BACKUP SLIDES

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PEs In Different Situations

Input used	Bias	slope	σ at 172 GeV	pull
Good signal	-0.26 ± 0.12	0.99 ± 0.01	1.67 ± 0.06	1.05 ± 0.02
All signal, no cut	-3.09 ± 0.14	0.96 ± 0.02	2.50 ± 0.06	1.30 ± 0.02
All signal, cut at 6	-1.15 ± 0.13	0.99 ± 0.02	2.06 ± 0.06	1.16 ± 0.02
Sig+bkgnd, no cut	-2.14 ± 0.16	0.97 ± 0.02	2.83 ± 0.06	1.33 ± 0.02
Sig+bkgnd, cut at 6	-1.20 ± 0.14	1.00 ± 0.01	2.53 ± 0.06	1.22 ± 0.02
Sig+bkgnd, no cut or handling	-4.73 ± 0.17	0.95 ± 0.02	3.01 ± 0.06	1.42 ± 0.02
Sig+bkgnd+cut, no handling	-1.98 ± 0.14	0.98 ± 0.02	2.53 ± 0.06	1.21 ± 0.02

- Signal only PEs: 179 evts/PE
- Signal+background PEs: 149 evts/PE

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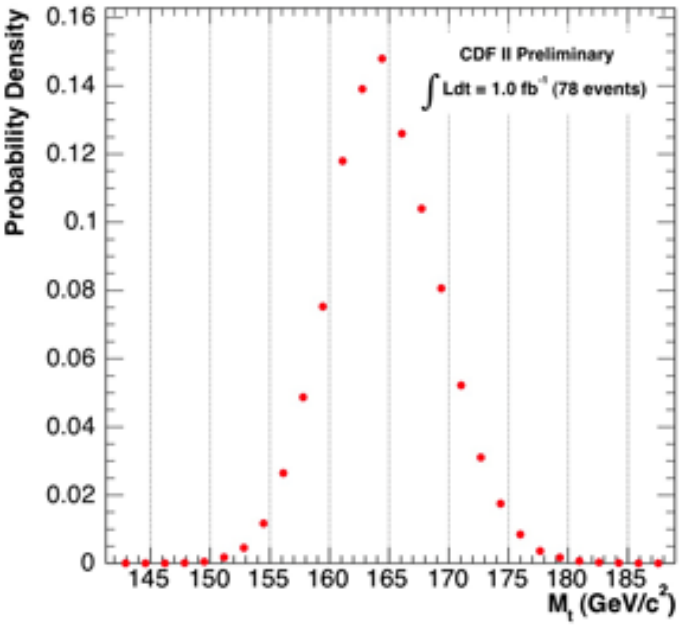
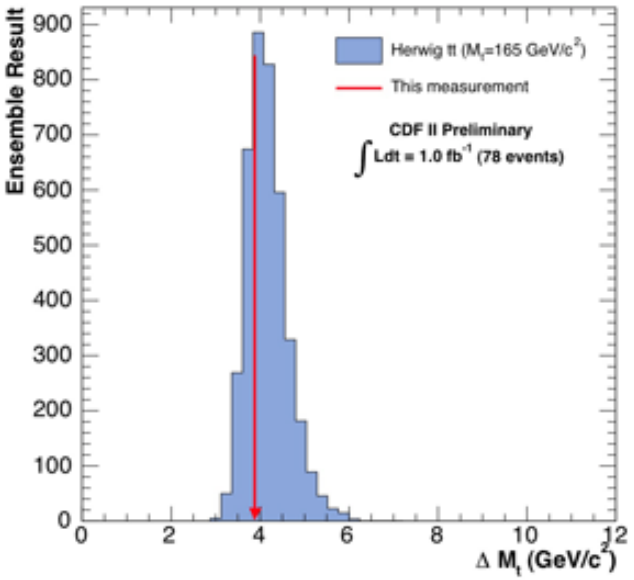
Dilepton Matrix Element Method

Using 78 dilepton evts in 1030 pb^-1:

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



- Dilepton channel a natural for a ME method, as two ν's means kinematics are underconstrained
- JES handling not used (no W->qq constraint)
  - 3.9 GeV (syst) = 3.5 GeV (JES) + 1.7 GeV (other)
  - To handle JES in future: use external information from Z -> bb events!



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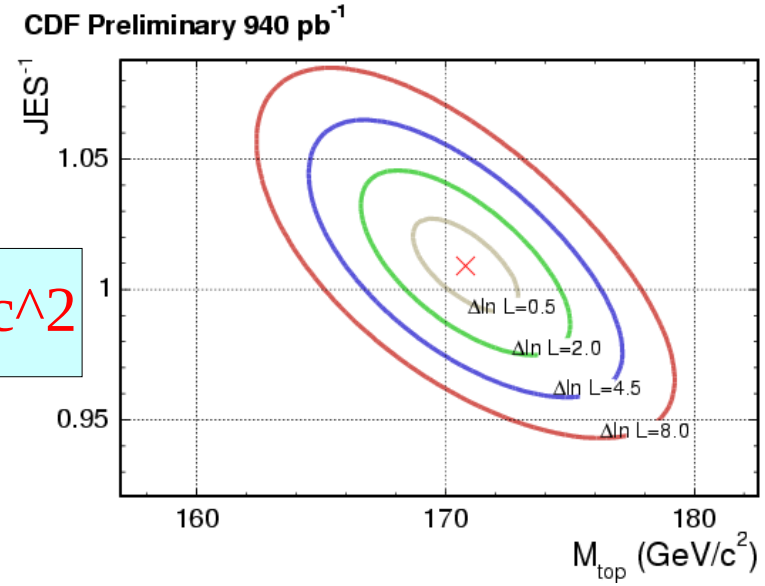
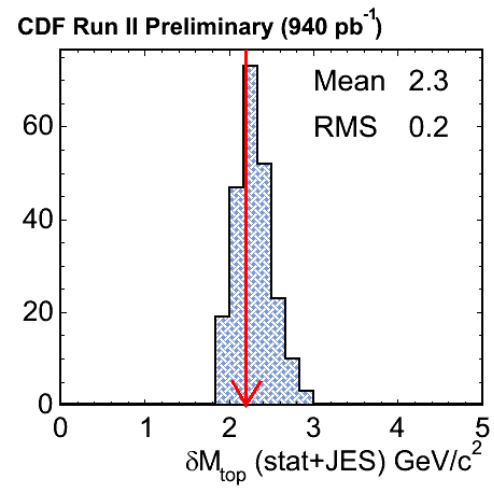
MEAT: Matrix Element Analysis Technique

Using 166 l+jets evts in 940 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





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

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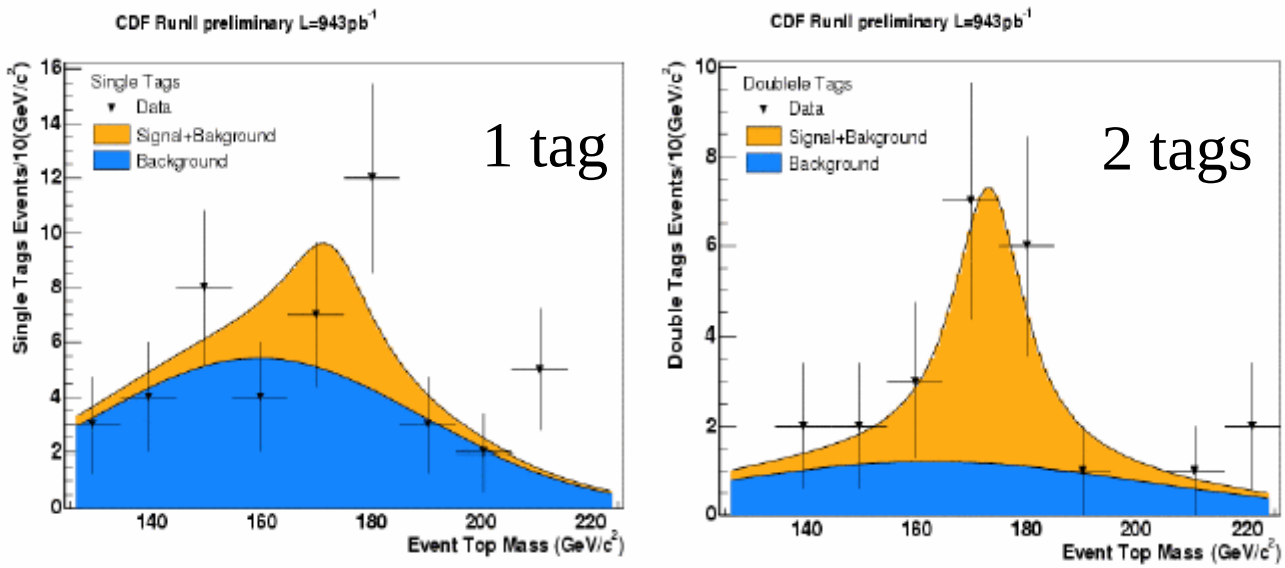
FAST (FlaME Assisted Template Method)

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 all-jets evts in 943 pb^-1:

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

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Signal Likelihood Components

$$\mathrm{L}_{t\bar{t}}(\vec{y} \mid m_t, S) = \frac{1}{N(m_t)} \frac{1}{A(m_t,S)} \int \frac{f(z_1)f(z_2)}{FF} \, TF(S * \vec{y} \mid \vec{x}) \, |M(m_t, \vec{x})|^2 \, d\Phi(\vec{x})$$

- $N(m_t)$ is the normalization of the likelihood
- $A(m_t, S)$ is the acceptance (corrects for event selection effect on normalization)
- $f(z_1)f(z_2)$ are the incoming parton PDF's – CTEQ5L
- $TF(S * \vec{y} \mid \vec{x})$ are the transfer functions
- $|M(m_t, \vec{x})|^2$ are the Kleiss-Stirling ttbar matrix elements
- $d\Phi(\vec{x})$ is the phase space factor
- FF is the flux factor of the incoming partons

Full Likelihood Formula

$$L_{mod}(m_t, \mathrm{JES}) = \sum_{\text{events}} [\log\{L(m_t, \mathrm{JES}\,|\mathrm{signal})(1 - f_{bg}(q)\kappa(m)) + f_{bg}(q)\kappa(m)U\}$$

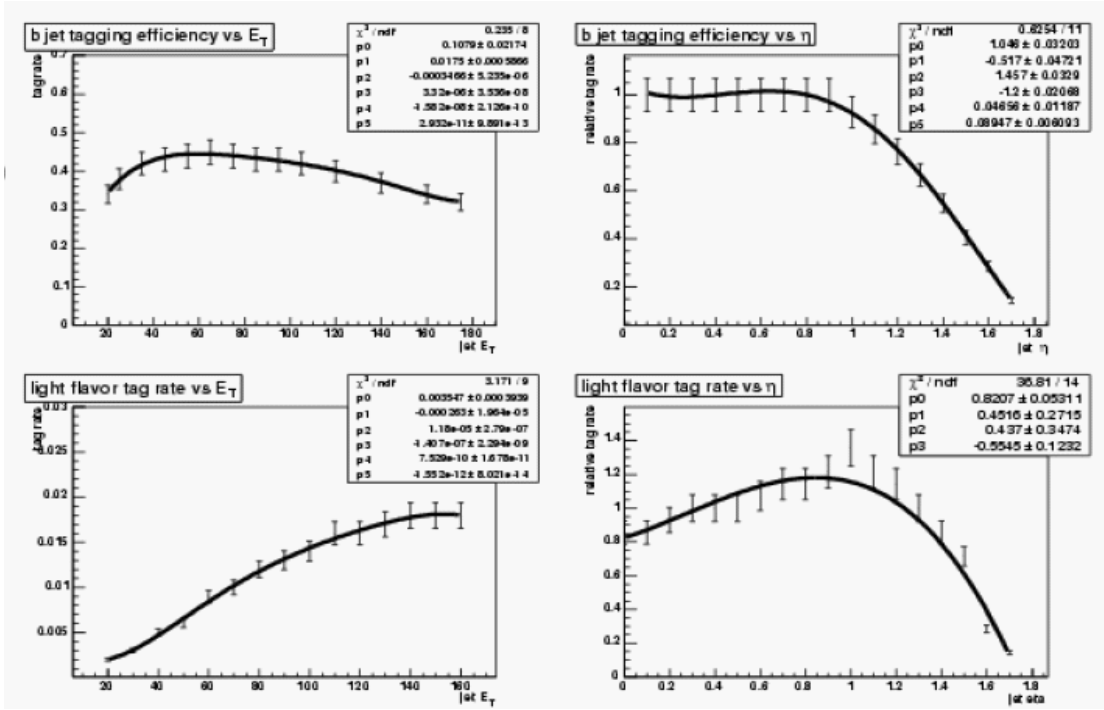
$$-f_{bg}(q)\log\{\overline{L(m_t, \mathrm{JES}\,|\mathrm{background})}(1 - f_{bg}(q)\kappa(m)) + f_{bg}(q)\kappa(m)U\}]$$

- Here, $L(m_t, \mathrm{JES}\,|\mathrm{signal})$ is the signal likelihood for the event
- $\overline{L(m_t, \mathrm{JES}\,|\mathrm{background})}$ is the average shape of a background likelihood curves
- $f_{bg}(q)$ is the calculated probability that the event is background
- U is the uniform distribution over mt-JES
- $\kappa(m)$ is a parameter we can adjust to alter the smoothing effects of U (we leave at 1 for now)

Permutation Weighting

Heavy prob (P_b)

Light prob (P_l)



- For each permutation, calculate probability for each quark-jet match as function of Et and eta that the assumed quark (b, c, or l) would have produced a tagged jet
- Multiply the four probabilities together: P if tagged, (1-P) if not tagged