Top Quark Mass Measurement using Matrix Element Method and Lepton + Jets Channel

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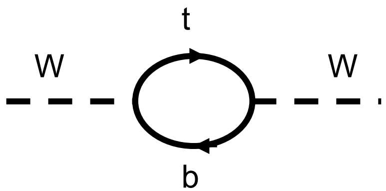
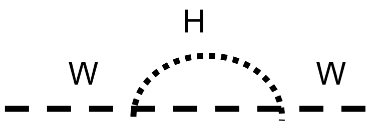
IOP HEPP 2009

why measure m_t?

- Top mass, m_t, is fundamental parameter of Standard Model
- Electroweak mass corrections $\propto m_t^2$ and $\ln(m_H)$

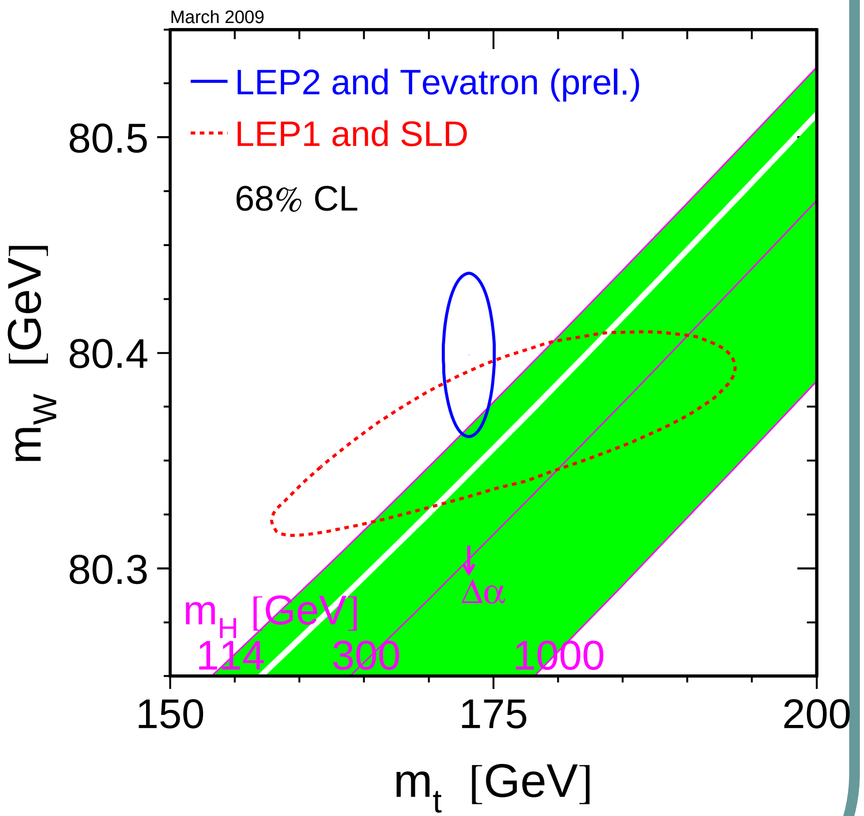


$\delta m_W \propto m_t^2$



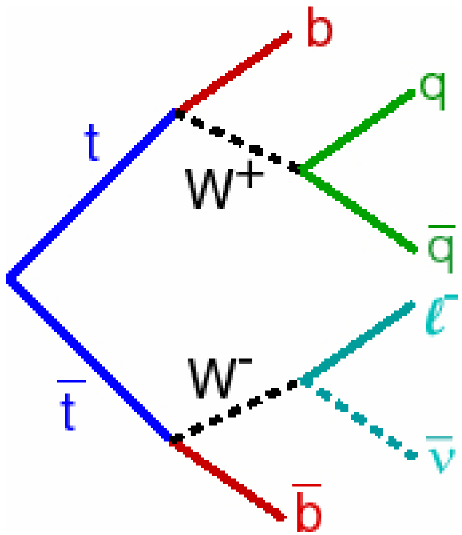
$\delta m_W \propto \ln(m_H)$

- Precision measurements of m_W and m_t give constraints on SM m_H
  - consistency test of the SM
  - new physics?



top decay

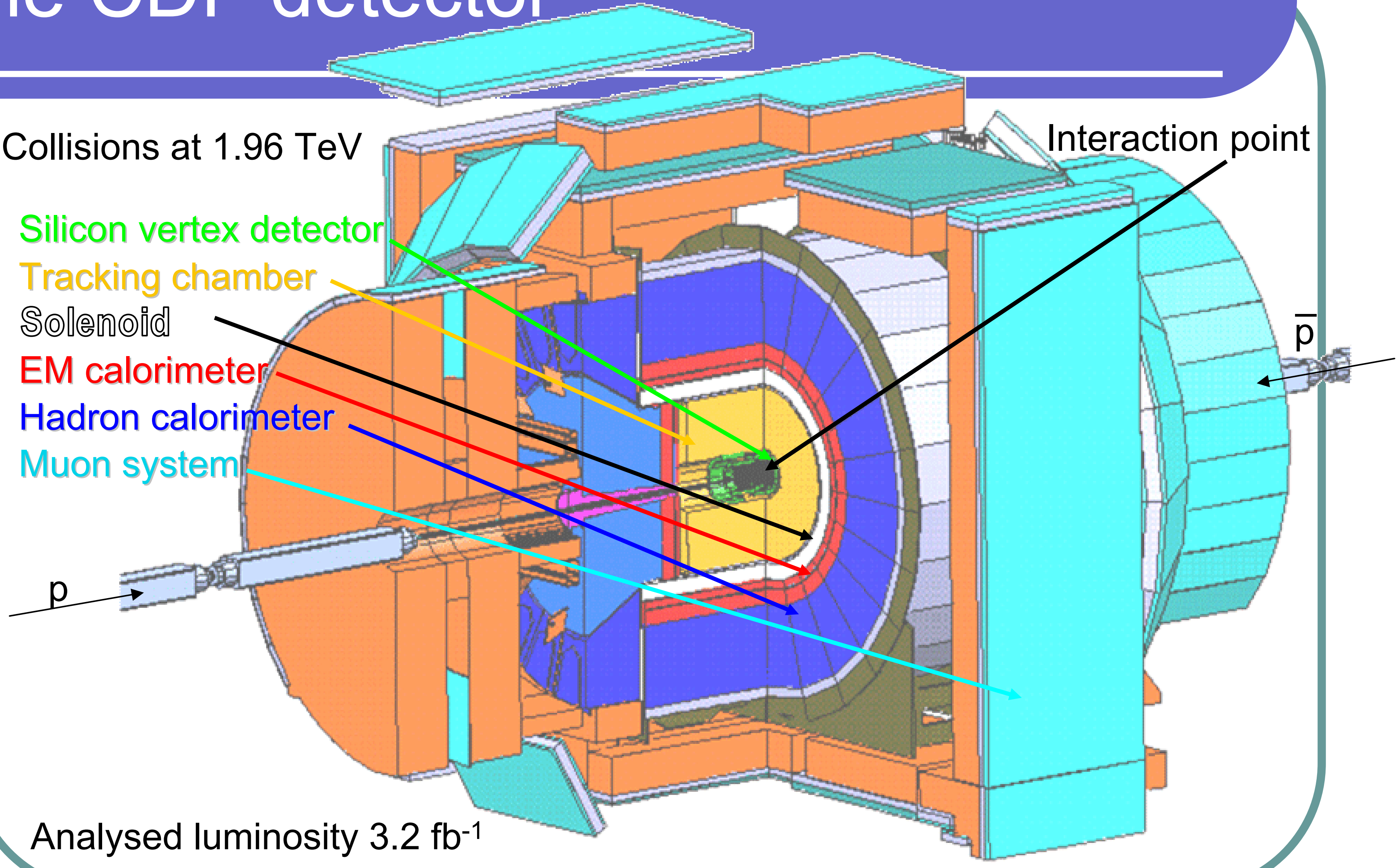
- Dominant decay $t \to Wb$ with $W \to q\bar{q}$ or $W \to \ell\nu$
- $t\bar{t}$ produced in pairs so three possible scenarios:
  - dilepton
  - all hadronic
  - lepton + jets i.e. $bq\bar{q} + b\ell\nu$ (right)
- Lepton + jets: best compromise between statistics and background
- Event Selection:
  - Exactly 4 jets $E_T > 20$ GeV, $|\eta|<2.0$
    - At least 1 with b-tag (silicon vertex)
  - Electron $E_T > 20$ GeV or muon $p_T > 20$ GeV/c
  - Missing $E_T > 20$ GeV (neutrino)



lepton + jets
electron or muon
branching ratio 30%

the CDF detector

Collisions at 1.96 TeV



Analysed luminosity 3.2 fb^{-1}

challenges

- Combinatorics: which jets came from which top and W?
  - 4 jets so 4×3×2×1=24 possible combinations
  - Symmetrise method wrt two W jets → 12 combos
  - Use b-tagging information to further reduce
    - 1 b-tag → 6 combos
    - 2 b-tags → 2 combos (still don't know which b is which)
  - Finally, average over remaining combinations
- Jet reconstruction
  - Measurement requires knowledge of quark momenta
  - Large jet energy scale (JES) uncertainties in jet reconstruction
  - Also use transfer functions (TFs) to map between measured jets and supposed original partons
  - Overall measurement uncertainty can be reduced by simultaneously measuring m_t and the jet energy scale correction Δ_{JES}
  - Δ_{JES} constrained in-situ via invariant mass of hadronic W boson
    - effectively calibrates jet energies using known m_W

transfer functions

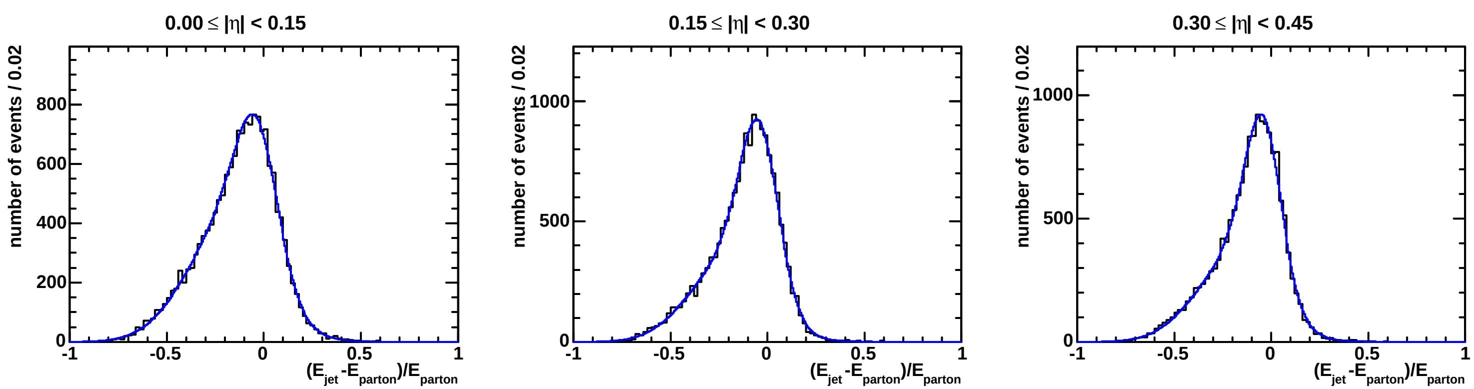
- Probability that parton quantity ‘*y*’ resulted in measured quantity ‘*x*’
  - Primarily account for detector resolution
  - Taken from fit to Monte-Carlo ttbar events (known ‘*x*’ and ‘*y*’)
  - Allow for JES correction Δ_{JES}

$$W(\vec{x},\vec{y};\Delta_{\text{JES}}) = \delta^3\left(p_l^y - p_l^x\right)\prod_{i=1}^{4} W_E\left(E_i^x, E_i^y;\Delta_{\text{JES}}\right)\prod_{i=1}^{4}\frac{1}{E_i^x p_i^x} W_A\left(\Omega_i^x,\Omega_i^y\right)$$

lepton assumed well measured

jet energy TF (binned in $|\eta|$, example below)

jet angle TF (next slide)



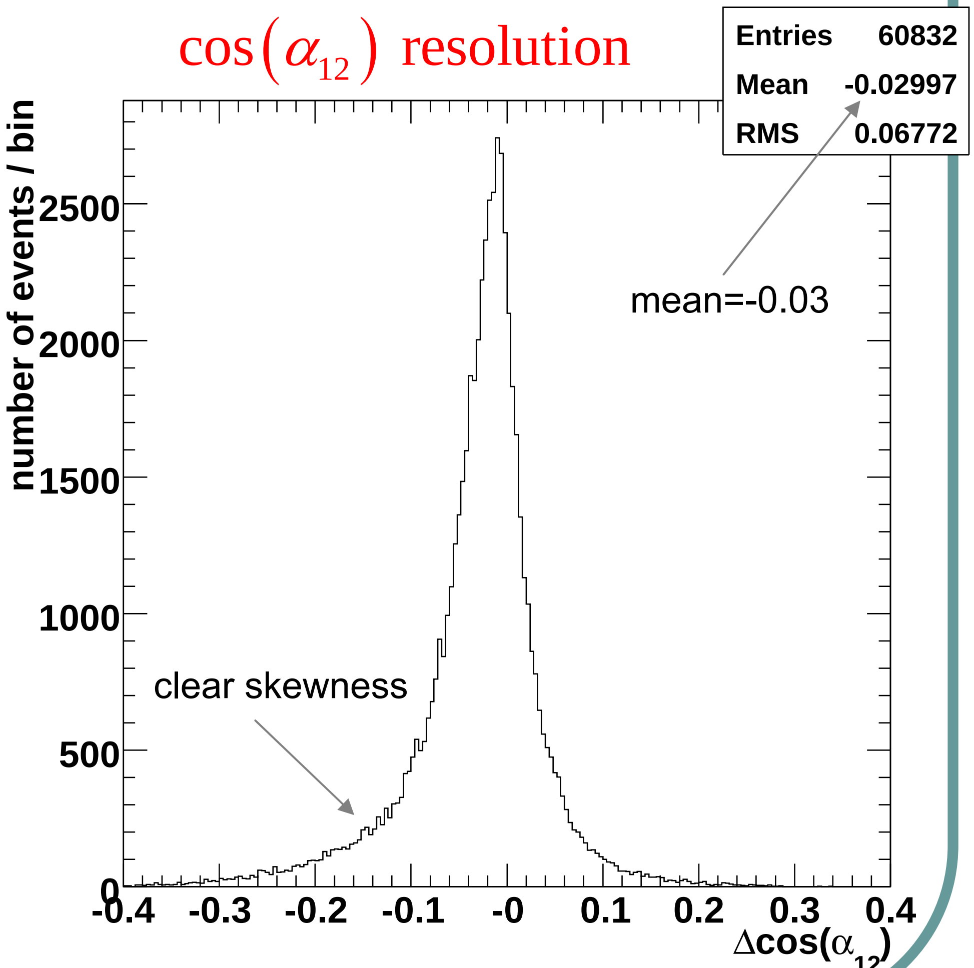
jet angular transfer functions

- Previously assumed to be delta functions
- Observed bias in measured angle α_{12} between two hadronic W jets (right)

$$m_W \simeq 2\rho_1\rho_2\left(1-\cos\left(\alpha_{12}\right)\right)$$

  - directly biases measured m_W and m_t
- Introduced angular TFs in α_{12}
- Bias removed from m_W and m_t post-integration
- Particularly important due to in-situ Δ_{JES} calibration (relies on measured hadronic W mass)

$\cos\left(\alpha_{12}\right)$ resolution

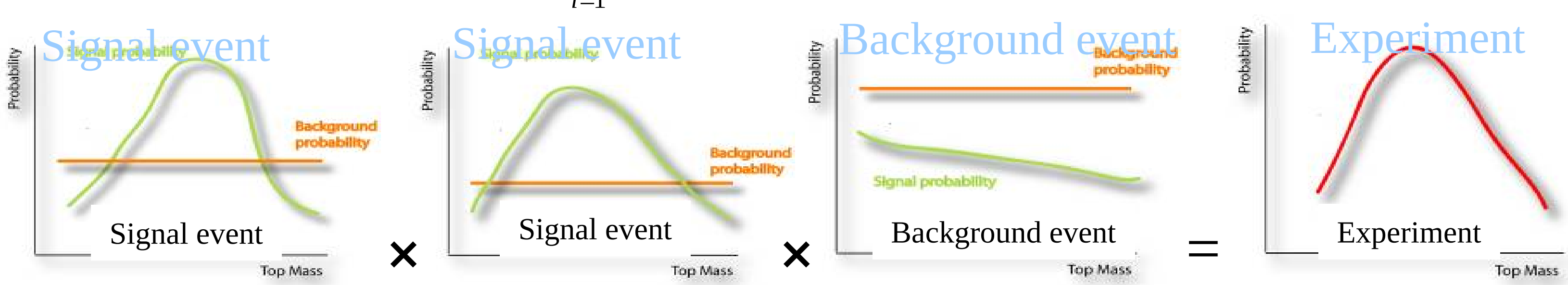


Matrix Element method

- Calculate event probability density based on theoretical LO matrix elements
  - Integrate over unknown quantities and transfer functions (‘*y*’ quantities)
- $$P_{\text{ttbar}}(\vec{x}; m_t, \Delta_{\text{JES}}) = \frac{1}{N(m_t, \Delta_{\text{JES}})} \sum_{\text{combos}} \int |M|^2 \frac{f(\tilde{q}_1)}{|q_1|} \frac{f(\tilde{q}_2)}{|q_2|} W(\vec{x}, \vec{y}; \Delta_{\text{JES}}) d\tilde{\Phi}$$

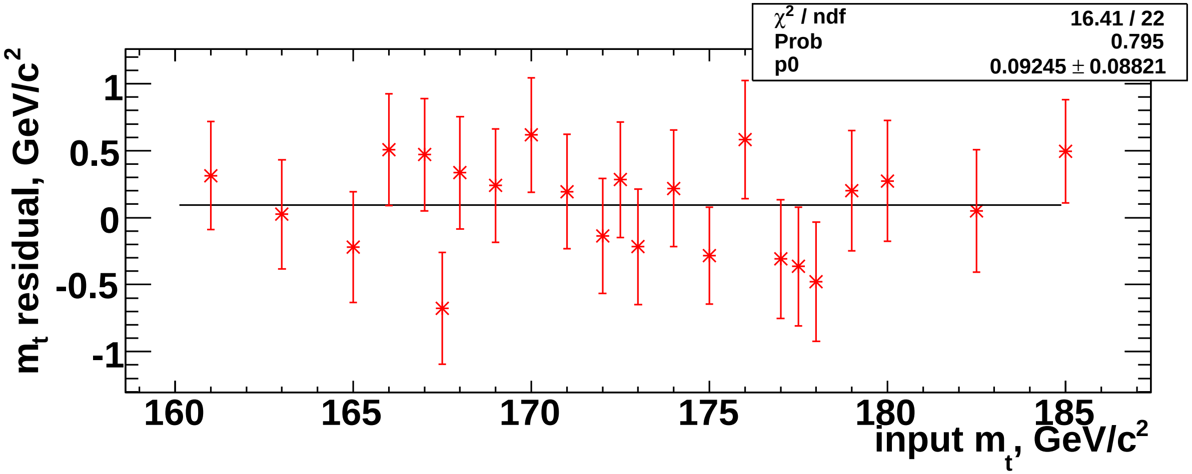
  measured quantities · normalisation · ttbar matrix element (a function of *y*) · flux factor and PDFs · TFs · phase space (includes *y*)
- Similar expression for the dominant background, $P_{\text{W+jets}}$
- Combine signal and background probabilities with signal fraction ν_{sig}
- Combine events into overall Likelihood and fit for $m_t, \Delta_{\text{JES}}, \nu_{\text{sig}}$

$$L(m_t, \Delta_{\text{JES}}, \nu_{\text{sig}}) \propto \prod_{i=1}^{Nevents} (\nu_{\text{sig}} P_{\text{ttbar},i}(m_t, \Delta_{\text{JES}}) + (1-\nu_{\text{sig}}) P_{\text{W+jets},i})$$

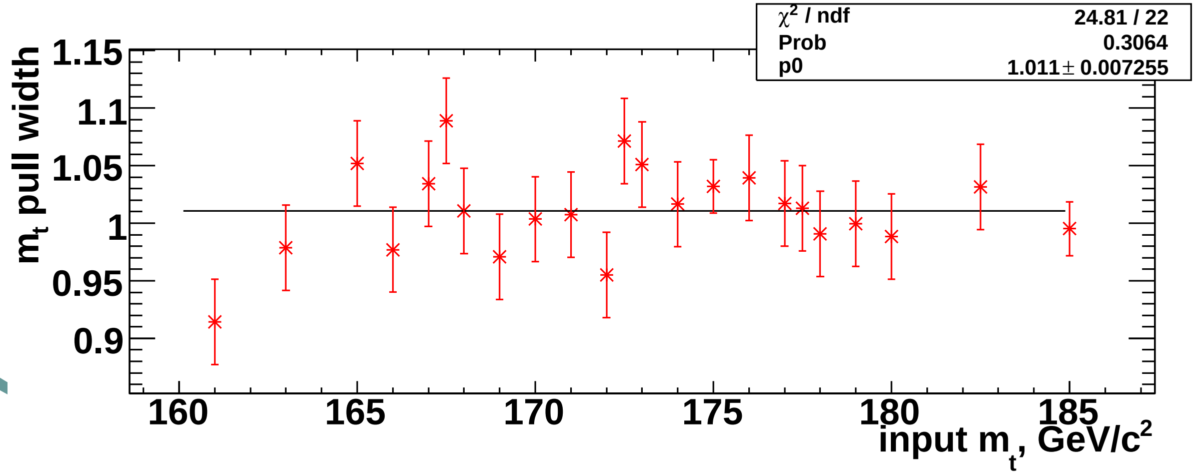


linearity test

- Check performance of method using Monte Carlo samples at various top masses, along with full simulated background



Measured m_t consistent across large range



Pull width also constant and consistent with 1

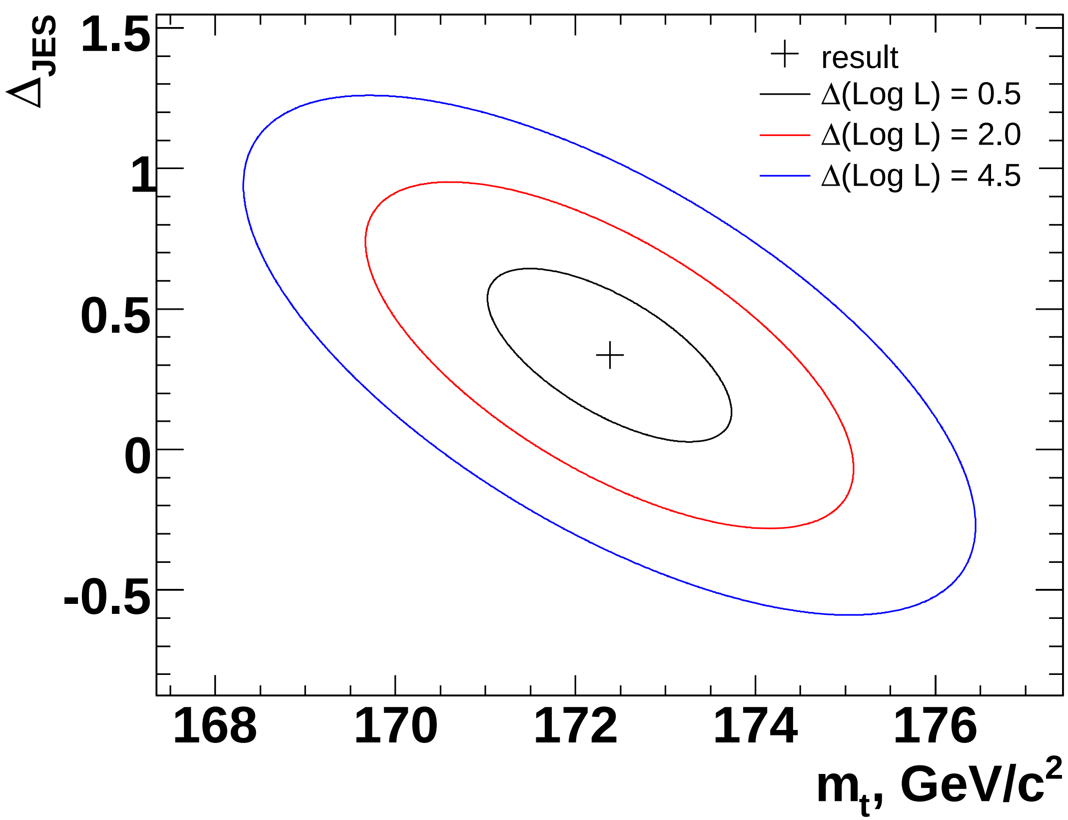
systematic uncertainties

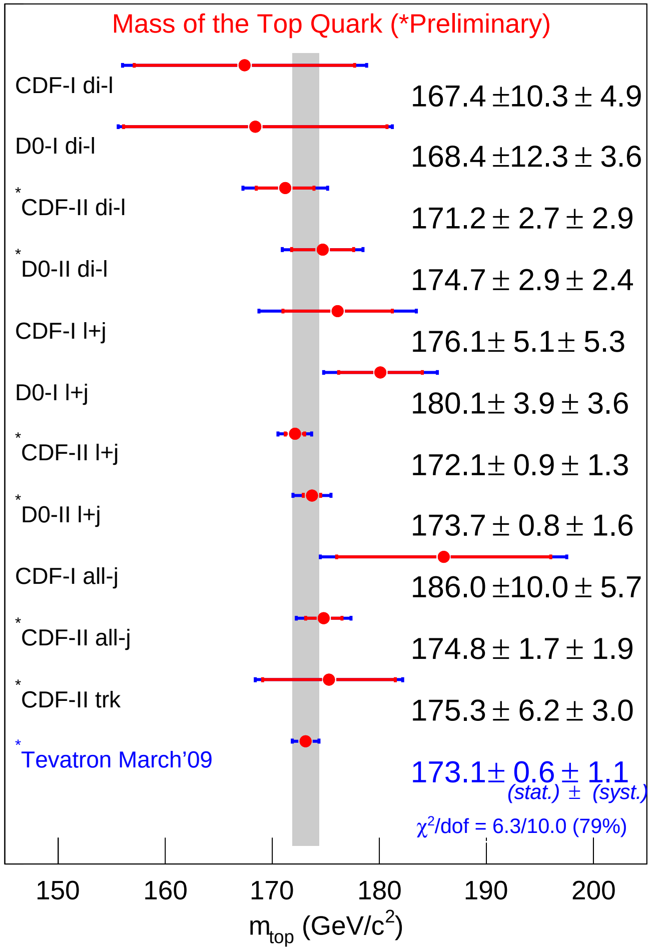
Systematic Source	Uncertainty (GeV/c^2)
MC Generator	0.70
JES Residual	0.65
Colour Reconnection	0.56
b-jet Energy	0.39
Background	0.37
ISR/FSR	0.24
Multiple Hadron Interaction	0.22
PDFs	0.13
Lepton Energy	0.12
Method Calibration	0.12
Total	**1.29**

Result

$$m_t = 172.4 \pm 1.4\ (\text{stat+JES}) \pm 1.3\ (\text{syst})\ \text{GeV}/c^2$$
$$= 172.4 \pm 1.9\ (\text{total})\ \text{GeV}/c^2$$

CDF Run II Preliminary, 3.2 fb^{-1} 578 total events

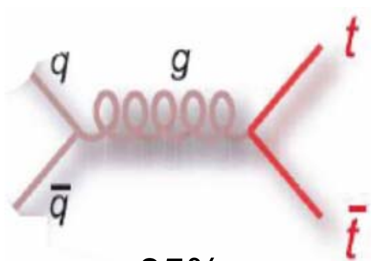




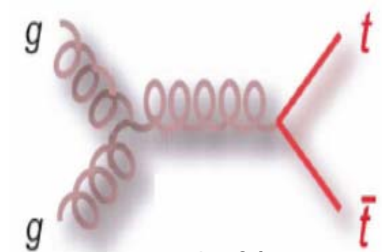
Backup

the top quark

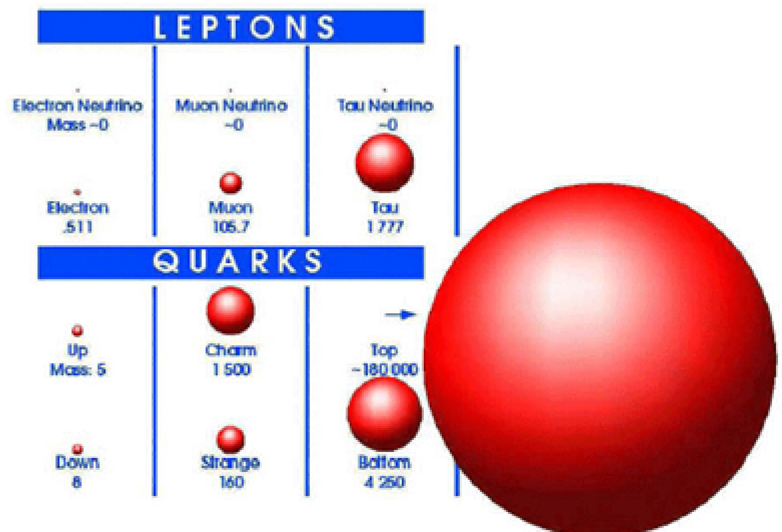
- Discovered in 1995 at the Tevatron
- Dominantly produced in pairs (strong interaction)



~85%



~15%



- $m_t >> m_b$: distinct properties
- $\tau_t \sim 10^{-25}$ s but $\tau_{QCD} \sim 10^{-23}$ s
- t decays before it can hadronize
- Mass can be directly measured from daughter particles

background events

- Numbers used to create pseudo-experiments and calibrate method
- Expected signal fraction 76%

Sample	Expected events
Wbb	39.01 ± 12.72
Wcc	20.33 ± 6.72
Wc	10.74 ± 3.55
W+jets	22.52 ± 5.72
Non-W	25.04 ± 20.53
single top (s chan)	3.29 ± 0.32
single top (t chan)	3.33 ± 0.28
WW diboson	4.20 ± 0.54
WZ diboson	1.45 ± 0.17
ZZ diboson	0.35 ± 0.05
Z + light flavour	3.89 ± 0.48
ttbar signal	425.02 ± 58.86
Total Prediction	559.15 ± 66.99
Total Observed	578

systematics

- MC Generator — Method is calibrated using signal MC from Pythia generator. Systematic taken as difference in result between Pythia and the Herwig generator.
- Residual JES — Systematics associated with each level of the JES jet corrections, summed in quadrature
- Colour Reconnection — Difference between two Pythia MC samples, tune Apro (no CR) and tune ACRpro (includes CR)
- b-jet Energy — b jet energies varied by ± 1% in MC
- Background — Vary background composition and fraction
- ISR/FSR — Difference in result in MC with more or less I&FSR
- Multiple Hadron Interaction — Systematic associated with mismodelling of luminosity profile in MC
- PDFs — Difference in MC using difference PDFs
- Lepton Energy — Electrons and muons shifted ± 1 sigma in MC
- Method Calibration — Uncertainty associated with method calibration