Precision Measurements of the Top Quark Mass and Width with the D0 Detector

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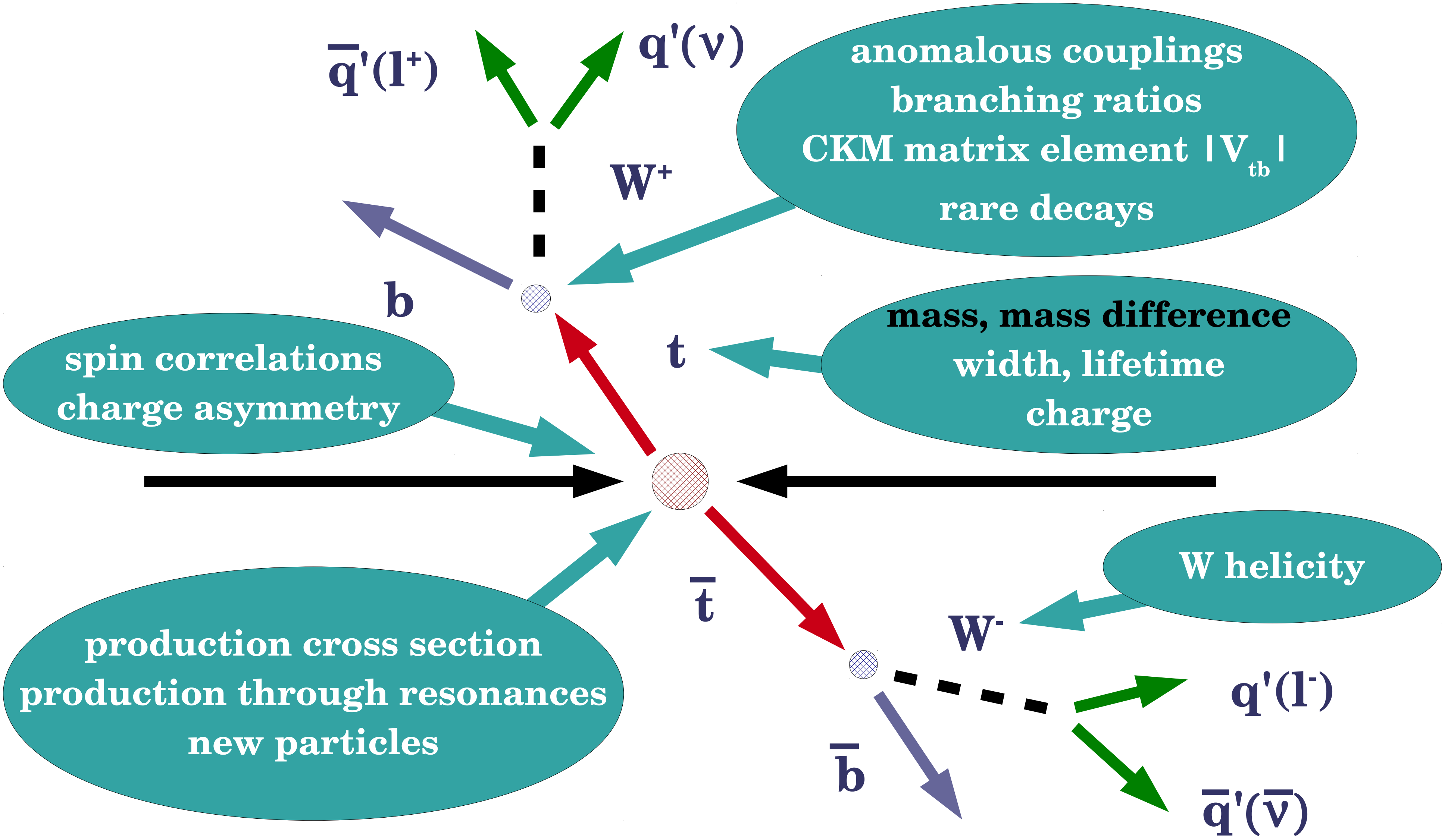
Top Quark Mass



anomalous couplings
branching ratios
CKM matrix element $|V_{tb}|$
rare decays

mass, mass difference
width, lifetime
charge

spin correlations
charge asymmetry

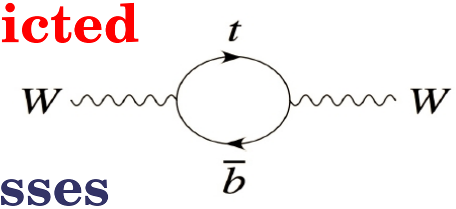
W helicity

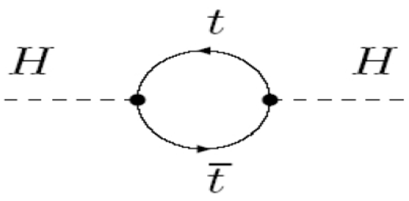
production cross section
production through resonances
new particles

Motivation and Methods

why measure the top quark mass:

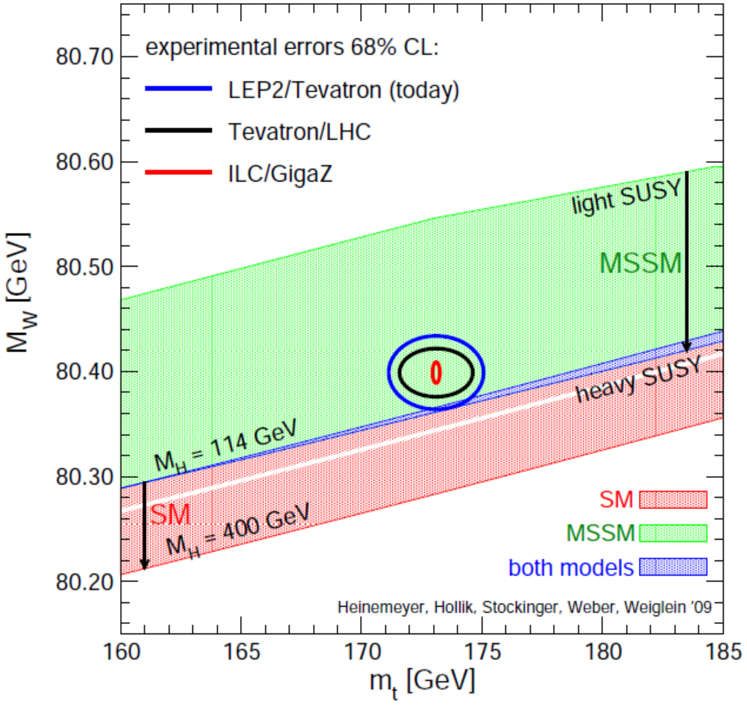
- the top quark mass is not predicted by the Standard Model (SM)
- the top quark and W boson masses constrain the mass of the yet unobserved Higgs boson





how to measure the top quark mass:

- template methods using mass dependent quantities (e.g. Neutrino Weighting approach)
- Matrix Element methods



Neutrino Weighting Method

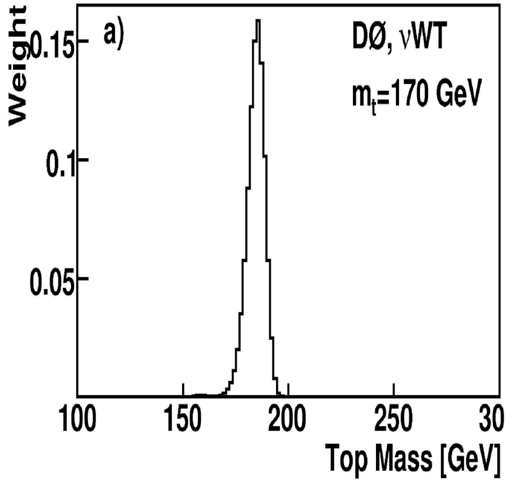
- template based method to measure the top quark mass in dilepton events
- final state reconstruction:
    - energies and momenta of final state jets and leptons measured with the detector
    - need 8 constraints to reconstruct undetected neutrinos:
        - neutrinos are massless (2)
        - W masses well known (2)
        - top and anti-top quark have the same mass (1)
        - loop over different top mass hypotheses (1)
        - for each assumed top mass, loop over different neutrino rapidities which are Gaussian and don't depend on the top quark mass (2)

Neutrino Weighting Result

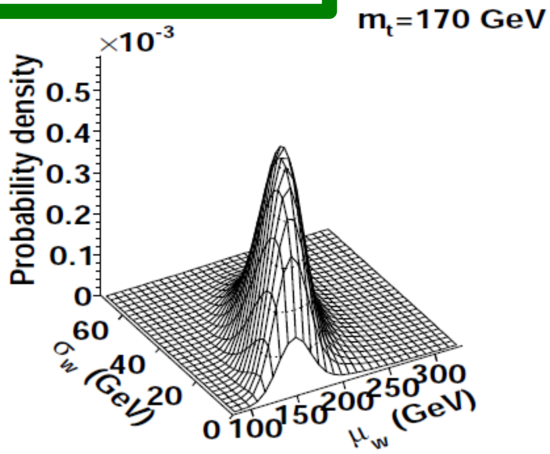
- comparing the measured missing tranverse energy to the calculated neutrino momenta, each event can be assigned a weight

$$w(m_{top}) = \frac{1}{n_{sol}} \sum_{i=0}^{n_{sol}} \exp\left(\frac{-(\vec{\cancel{E}}_T - \vec{p}_T^{\nu_1}(m_{top}) - \vec{p}_T^{\nu_2}(m_{top}))^2}{2\sigma_{\cancel{E}_T}^2} \right)$$

- using the mean μ_w and rms σ_w of each event weight distribution, templates for signal and background can be formed
- extract mass from a maximum likelihood fit



m_{top} = 176.2 ± 4.8 (stat) ± 2.1 (syst) GeV (L=1.0 fb$^{\cdot}$, dilepton)

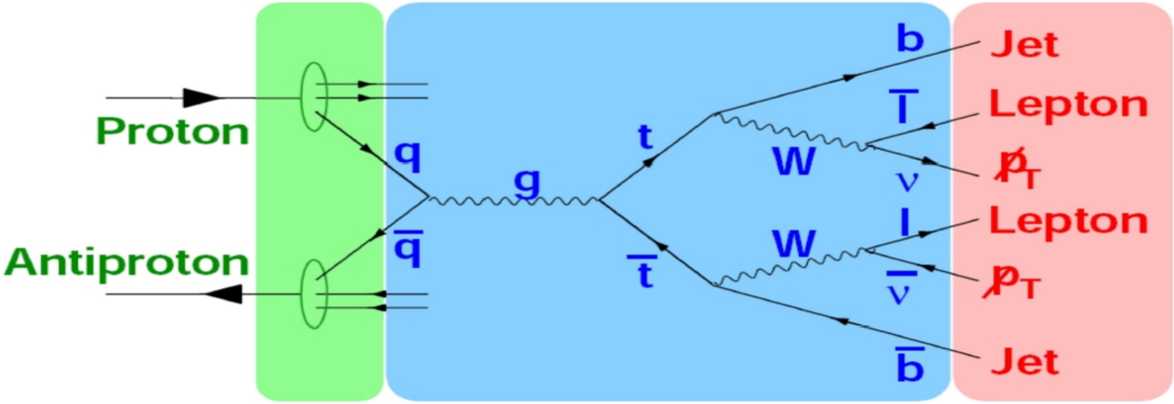


- main systematic uncertainty of 1.6 GeV due to jet energy uncertainties
- result published in PRD 80/092006 (2009)

The Matrix Element Method

- **matrix element method is based on full LO calculation of top pair production and includes detector effects**
- **for each event, the probability to be produced under the assumption of a certain top mass via signal process is given by**

$$P_{sgn}(x,m_{top})=\frac{1}{\sigma^{obs}_{ttbar}}\int_{q1q2y}\sum_{flavor}\boxed{dq_1\,dq_2\,f_{PDF}(q_1)f_{PDF}(q_2)}\boxed{\frac{(2\pi)^4|M_{ttbar}(y)|^2}{q_1q_2s}}\boxed{d\phi_6\,w(x,y)}$$



parton distribution functions $f_{PDF}(q)$

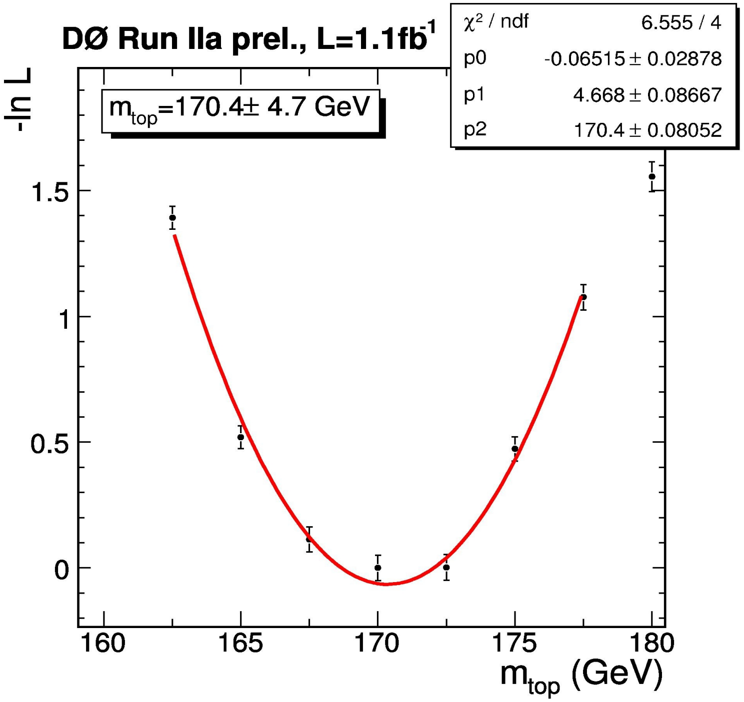
leading order matrix element $|M_{ttbar}(y)|^2$

transfer functions W(x,y): mapping from parton y to measured object x

The Matrix Element Method

- calculate main background probabilities in a similar way
- build event probabilities by adding up the normalized signal and background probabilities

$$P_{evt}(x, m_{top}) = f_{sgn} P_{sgn}(x, m_{top}) + (1 - f_{sgn}) P_{bkg}(x)$$



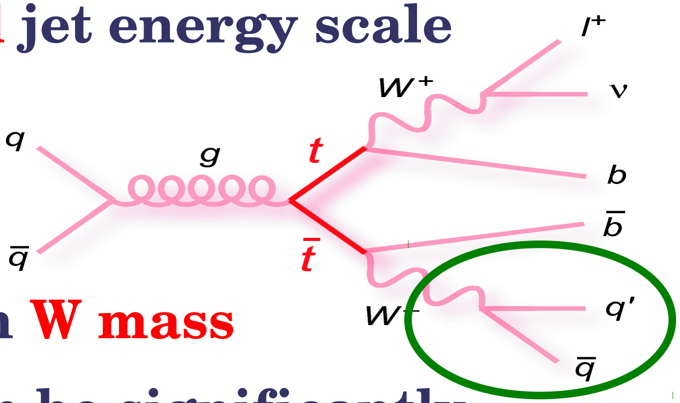
- determine the top quark mass from a likelihood fit to the event probabilities

m_{top} = 174.8 ± 3.3 (stat) ± 2.6 (syst) GeV (L=3.6 fb^{-1}, electron+muon)

- main systematic uncertainty due to jet uncertainties: 2.2 GeV

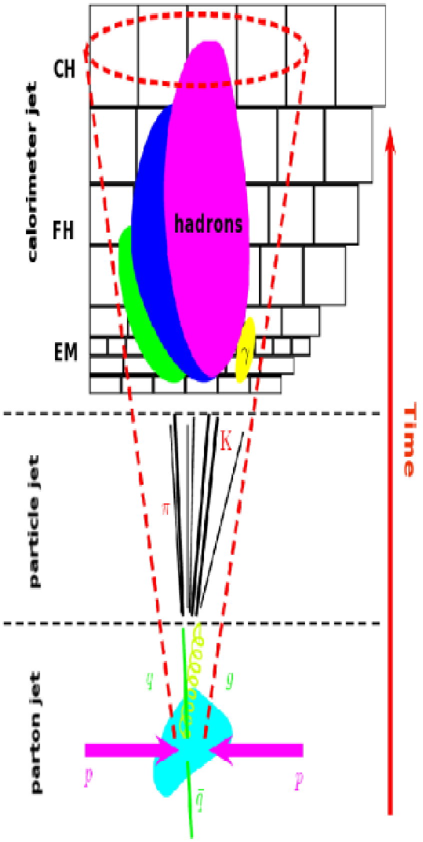
Measurement of top mass vs JES

- **largest uncertainty on all top quark mass measurements presented so far from jet energy scale uncertainties**
- **measurement of an overall jet energy scale correction JES on top of the standard correction in lepton+jets events possible due to well known W mass**



- **systematic uncertainty can be significantly reduced by a simultaneous fit of m_{top} and JES**

$$P_{sig}(x, m_{top}) \rightarrow P_{sig}(x, m_{top}, JES)$$



m_{top} = 173.7 ± 0.8 (stat+JES) ± 1.6 (syst) GeV (L=3.6 fb^{-1}, lepton+jets)

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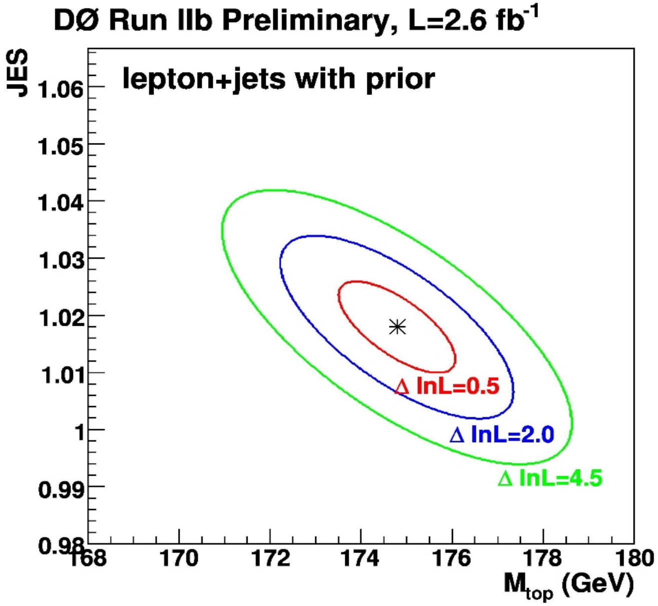

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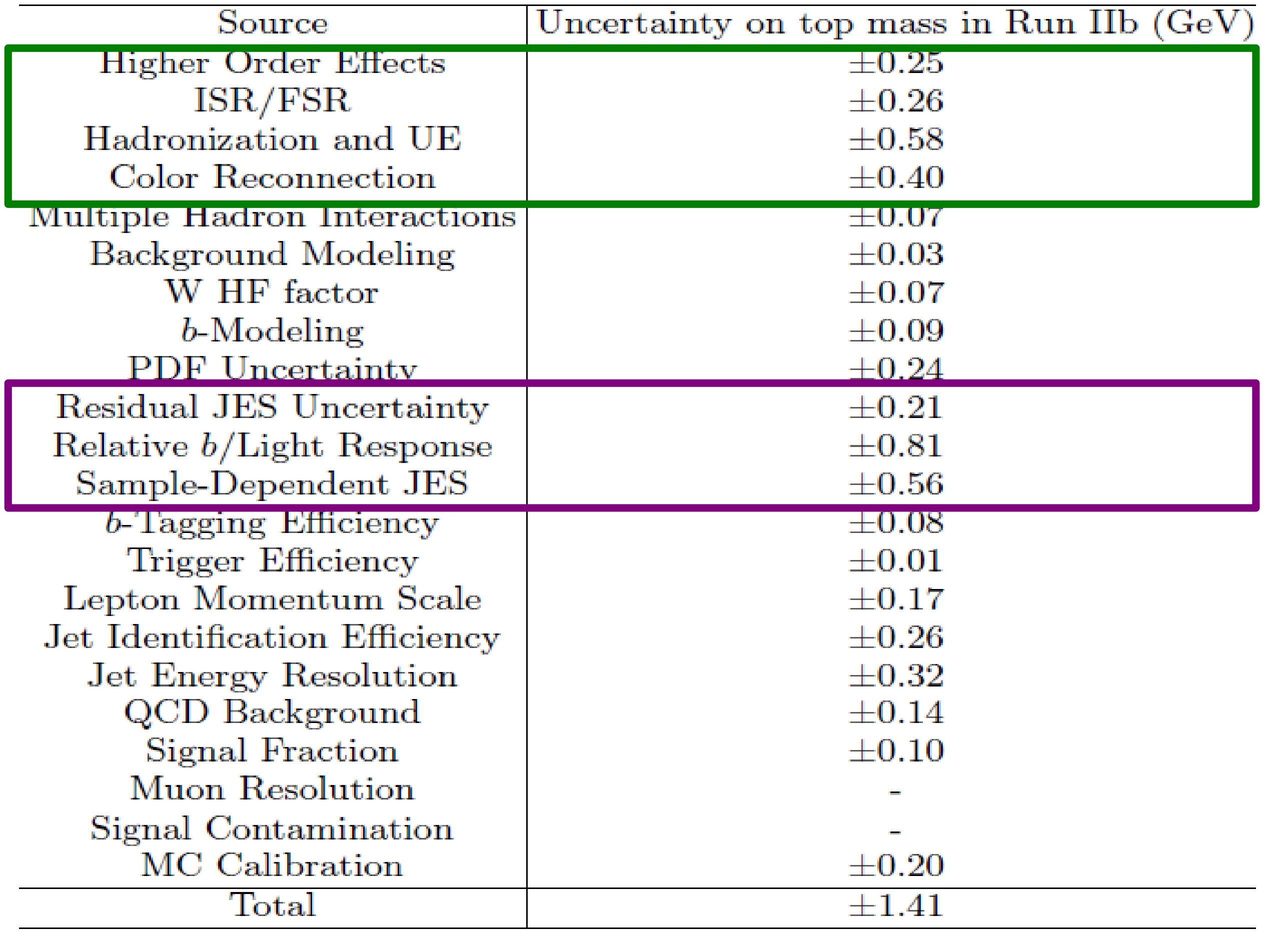
Systematic Uncertainties

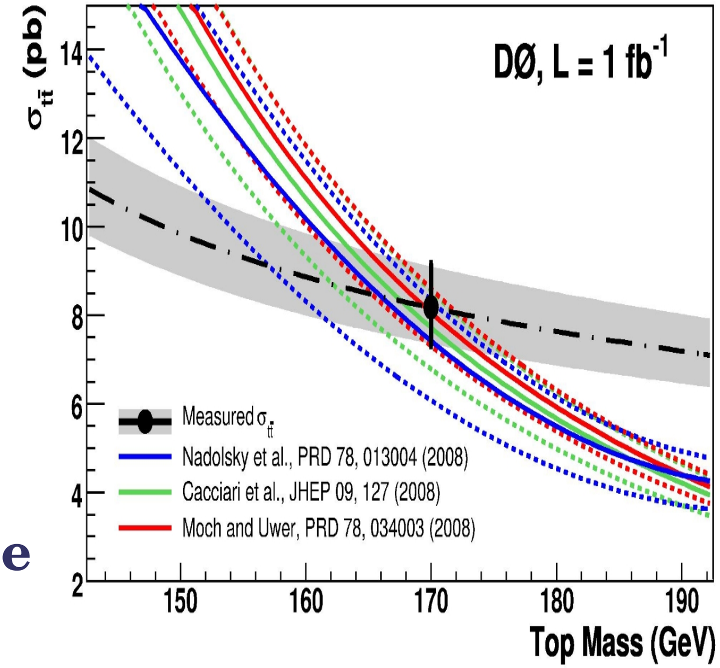
- **largest uncertainties now from signal modeling: 0.8 GeV and remaining jet uncertainties: 1.0 GeV**
- **common effort between CDF and D0 to reduce them**



Source	Uncertainty on top mass in Run IIb (GeV)
Higher Order Effects	±0.25
ISR/FSR	±0.26
Hadronization and UE	±0.58
Color Reconnection	±0.40
Multiple Hadron Interactions	±0.07
Background Modeling	±0.03
W HF factor	±0.07
b-Modeling	±0.09
PDF Uncertainty	±0.24
Residual JES Uncertainty	±0.21
Relative b/Light Response	±0.81
Sample-Dependent JES	±0.56
b-Tagging Efficiency	±0.08
Trigger Efficiency	±0.01
Lepton Momentum Scale	±0.17
Jet Identification Efficiency	±0.26
Jet Energy Resolution	±0.32
QCD Background	±0.14
Signal Fraction	±0.10
Muon Resolution	-
Signal Contamination	-
MC Calibration	±0.20
Total	±1.41

Top Quark Mass From Cross Section

- definition of top quark mass convention-dependent
- implementation in Monte Carlo only close to pole mass
- extraction of top quark mass from top pair production cross section allows for an unambiguous interpretation in the pole mass scheme

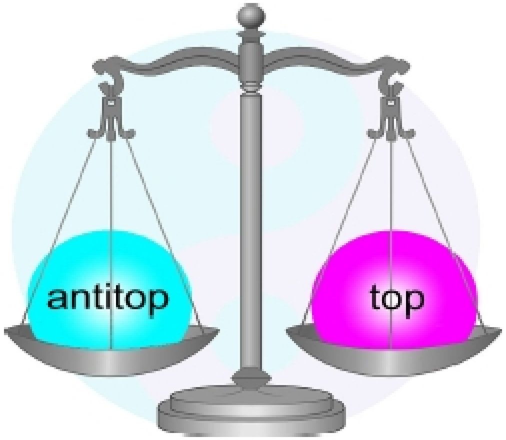


- comparison of the measured cross section to the theoretical $NNLO_{approx}$ prediction yields:

$$\boxed{m_{top}^{pole} = 169.1 + 5.9 - 5.2 \text{ (stat+syst) GeV}}$$

- result consistent with all direct measurements
- published in PRD 80/071102 (2009)

Top Quark Mass Difference

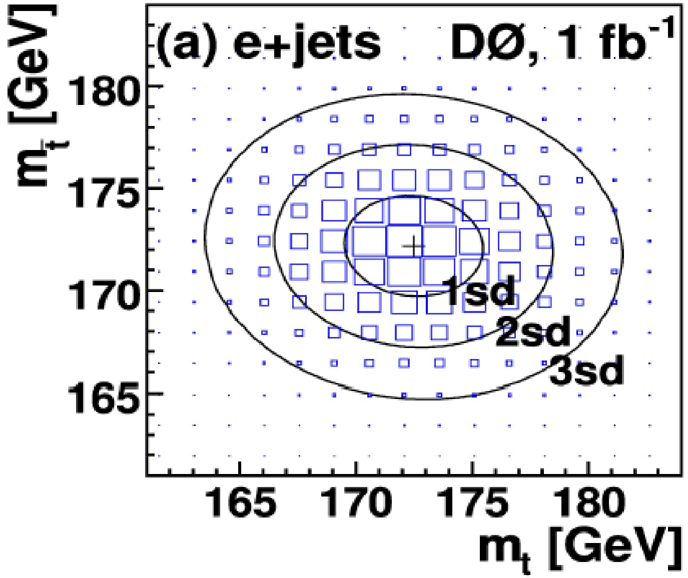


- all mass measurements assume top and anti-top quark to have the same mass
- any difference would imply CPT violation
- Matrix Element approach can be used with

$$P_{sig}(x, m_{top}, JES) \rightarrow P_{sig}(x, m_{top}, m_{topbar})$$

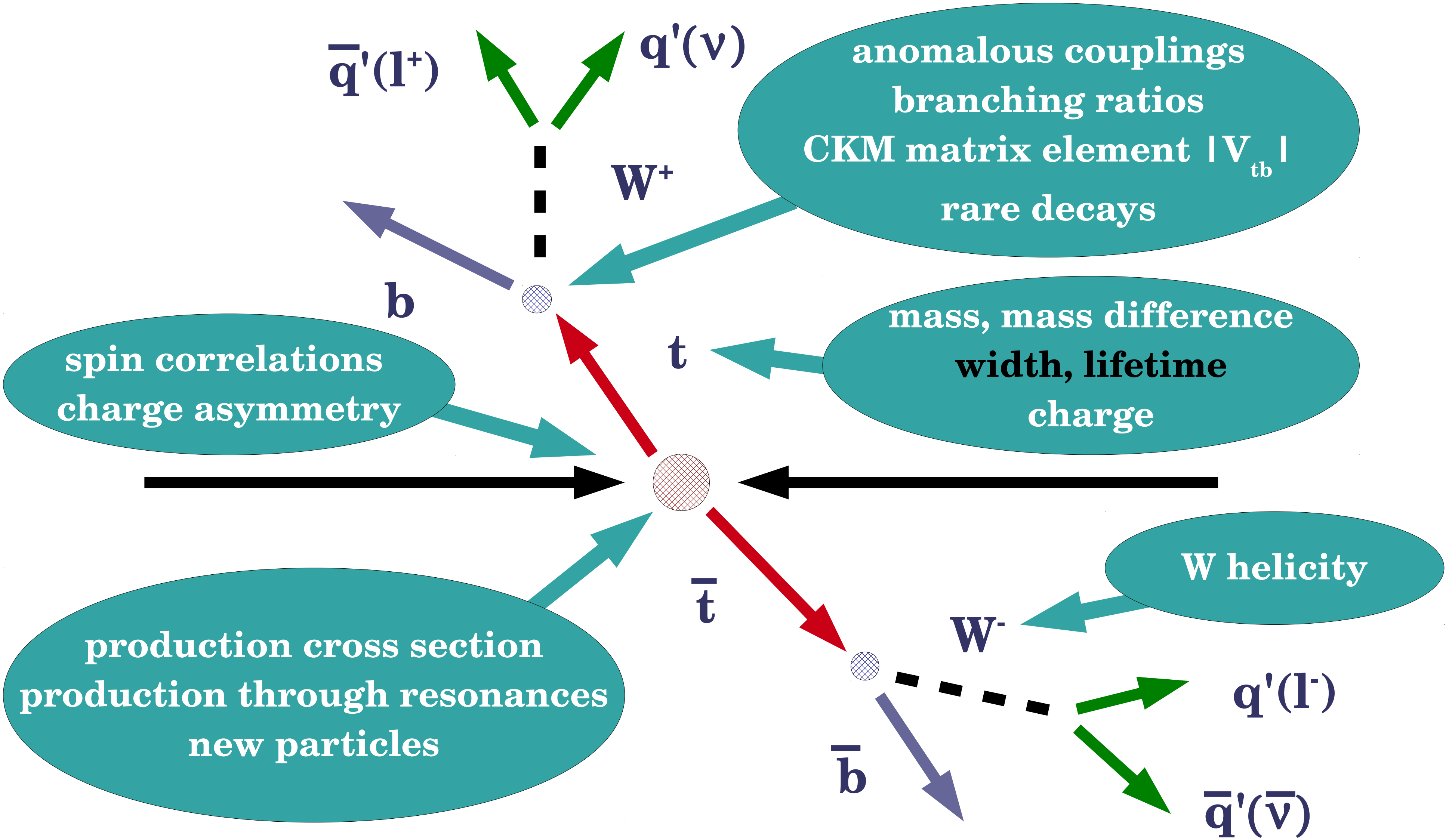
- first measurement of bare quark anti-quark mass difference

$$m_{top} - m_{topbar} = 3.8 \pm 3.7\ (\text{stat+syst})\ \text{GeV}$$



- measurement in good agreement with SM expectation
- published in PRL 103/132001 (2009), featured in Nature Vol. 461 October 2009

Top Quark Width



anomalous couplings
branching ratios
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rare decays

mass, mass difference
width, lifetime
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spin correlations
charge asymmetry

W helicity

production cross section
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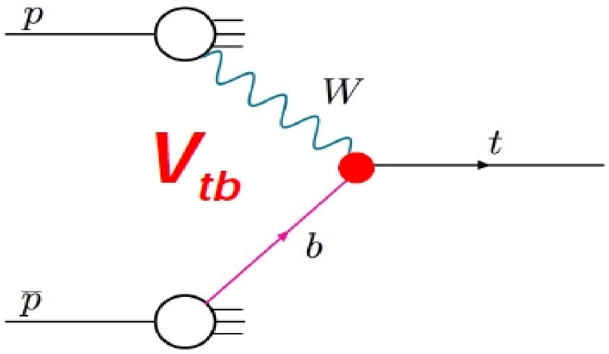
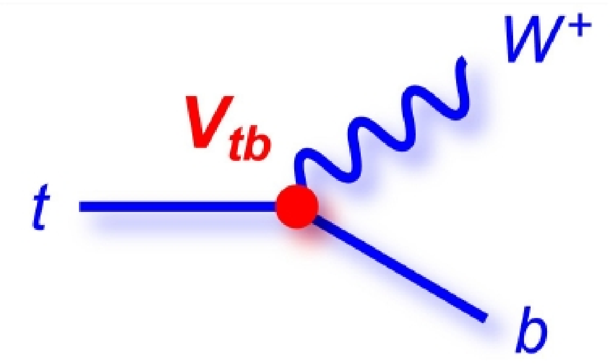
new particles

Motivation

- while the top quark mass is very precisely know, its width isn't
  - direct template based measurement performed by CDF yields an upper limit of $\Gamma_{top} < 7.5$ GeV at 95% C.L. (see talk by H.S. Lee)
  - approach is model independent but not really sensitive
  - width predicted by SM in NLO:
    $\Gamma_{top}^{theo} = 1.26$ GeV for m_{top}=170 GeV
- significantly better precision can be achieved if one assumes that the coupling in single top production and top decay is the same, i.e. σ (t-channel) ~ Γ ($t \rightarrow Wb$)





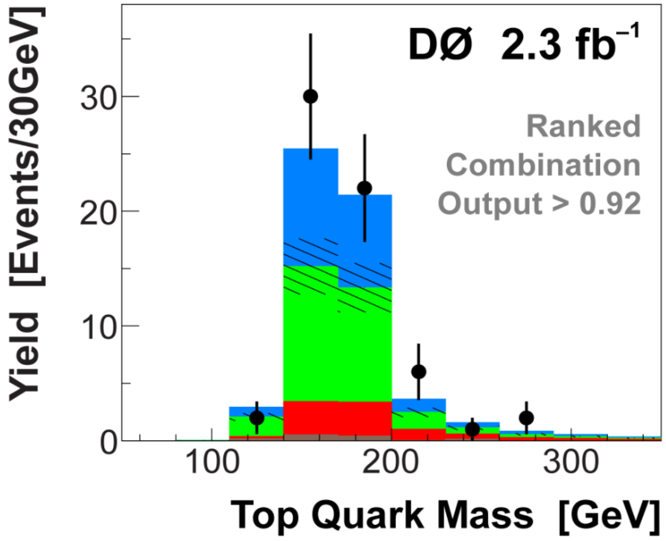
Method

- **combining the measurement of the single top production cross section σ (t-channel) with the measurement of the branching fraction B(t→ Wb), the total width of the top quark can be extracted using:**

$$\Gamma_{top} = \frac{\sigma(t-channel)\,\Gamma(t\rightarrow Wb)_{SM}}{B(t\rightarrow Wb)\,\sigma(t-channel)_{SM}}$$

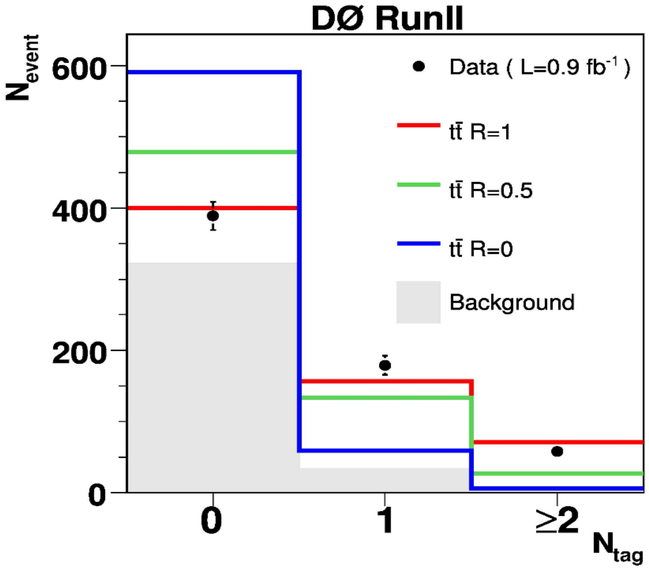
σ (t-channel) B(t→Wb):

- **simultaneous measurement in s- and t-channel: 3.14+0.94-0.80 pb**
- **PLB 682/363 (2010)**



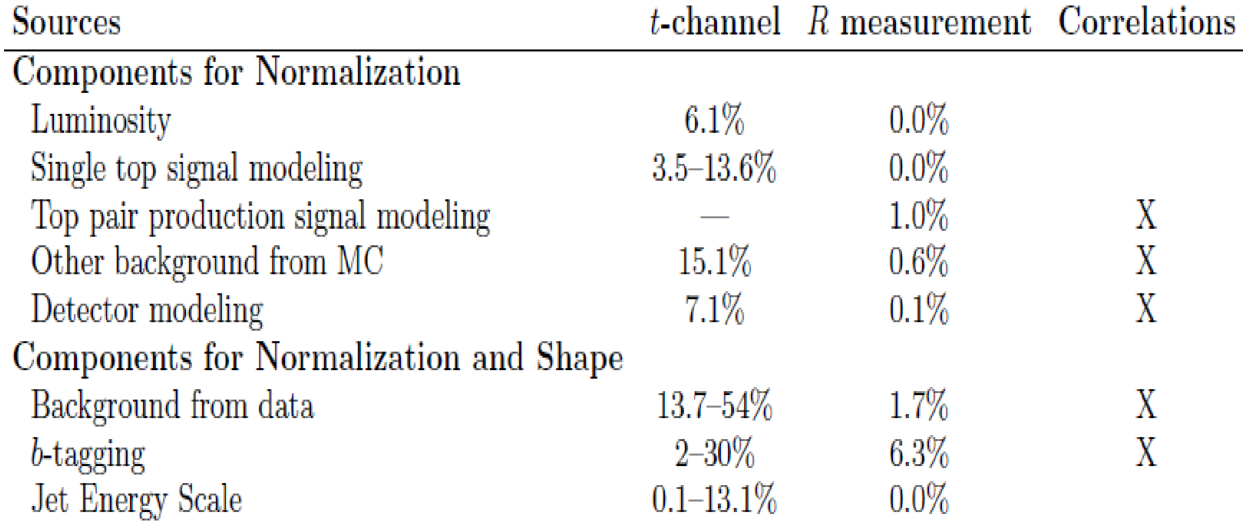
B(t→Wb):

- **measurement of R=B(t→Wb)/ B(t→Wq): 0.96 + 0.093 - 0.084**
- **PRL 100/192003 (2008)**

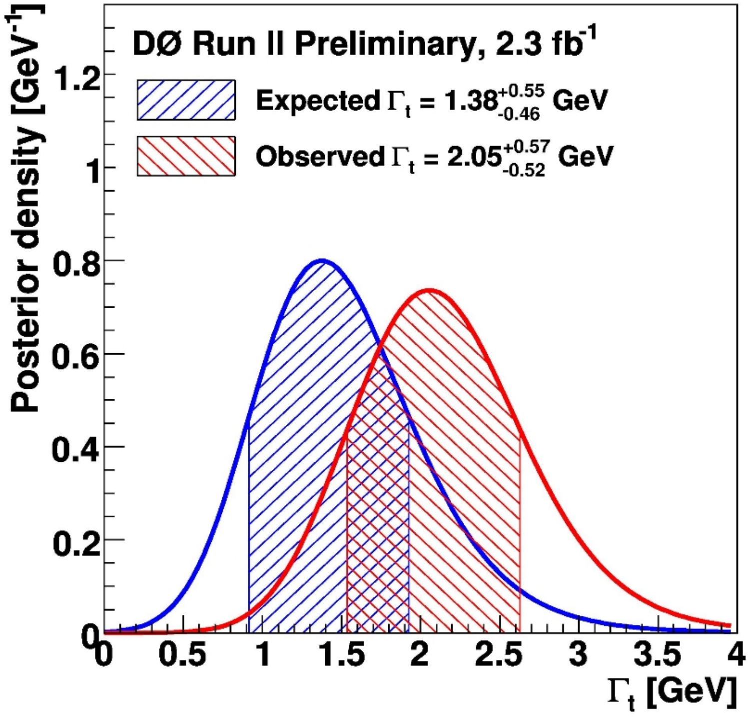


Extraction of Top Quark Width

- ♦ width extracted using a **Bayesian statistical approach**
- ♦ classification of systematics as in the combination of the Tevatron single top cross section measurements (arXiv 0908.2171)



Sources	*t*-channel	*R* measurement	Correlations
Components for Normalization			
Luminosity	6.1%	0.0%	
Single top signal modeling	3.5–13.6%	0.0%	
Top pair production signal modeling	—	1.0%	X
Other background from MC	15.1%	0.6%	X
Detector modeling	7.1%	0.1%	X
Components for Normalization and Shape			
Background from data	13.7–54%	1.7%	X
b-tagging	2–30%	6.3%	X
Jet Energy Scale	0.1–13.1%	0.0%	

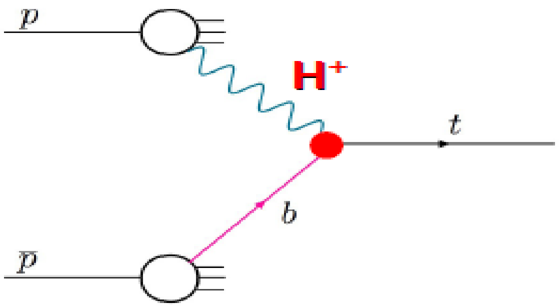


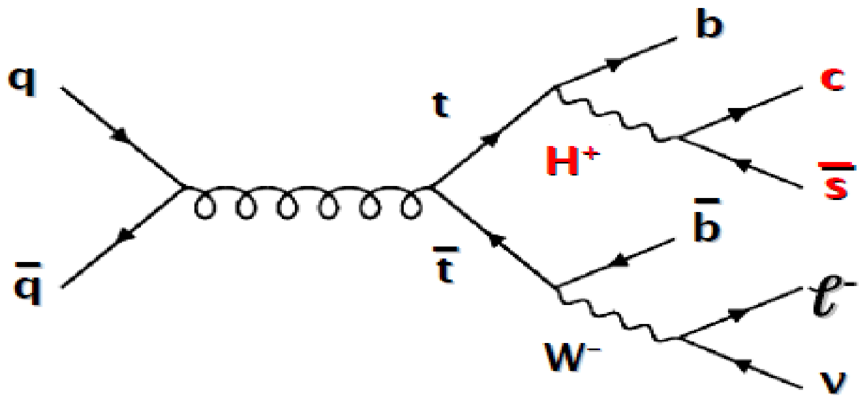
$$\Gamma_{top} = 2.05 + 0.57 - 0.52 \text{ GeV}$$
$$\tau_{top} = (3.2 + 1.1 - 0.7)\ 10^{-25}\text{ s}$$

$\Gamma_{top}^{theo} = 1.26$ GeV for $m_{top} = 170$ GeV

Sensitivity to New Physics

- top quark width also offers a window to study **new physics**
  - presence of a **charged Higgs** boson with $m_{H+} < m_{top} - m_b$ would increase the single top cross section and change B(t→Wb)



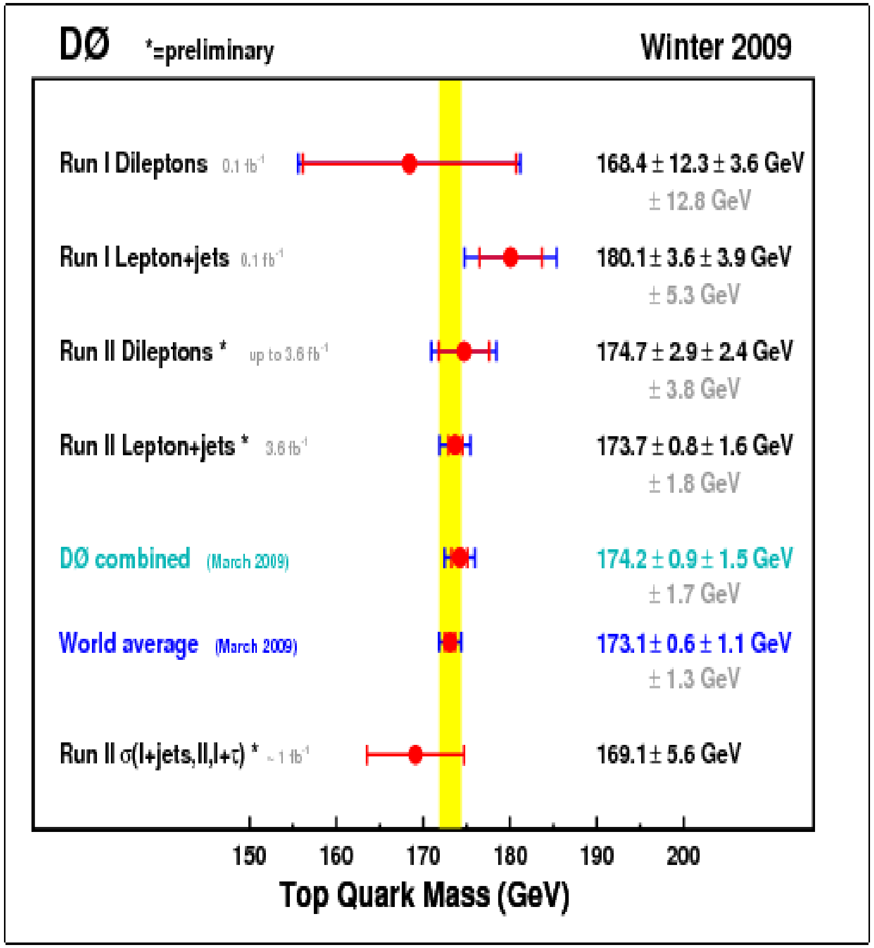


  - measurement also allows to set a limit on **4th generation b' quark** assuming unitarity of the 4x4 CKM matrix ($|V_{tb}|^2 + |V_{tb'}|^2 \cong 1$ and $|V_{td}|$, $|V_{ts}|$ small), $m_{b'} > m_{top} - m_W$ and a flat prior for $0 < |V_{tb}| < 1$:

$|V_{tb'}| < 0.63$ at 95% C.L.

Summary and Conclusion

- all **direct** top quark mass **measurements** are in **excellent agreement** with each other
- top mass limited by **systematic** uncertainties on **jets** and **signal** modeling
- extraction of mass **from production cross section** yields a consistent result
- measurement of top quark **mass difference** still limited by statistics: no deviation from SM observed so far
- new approach used at D0 to measure the **top quark width**:
  - current results agree well with SM expectation
  - also excellent window for new physics



BackUp

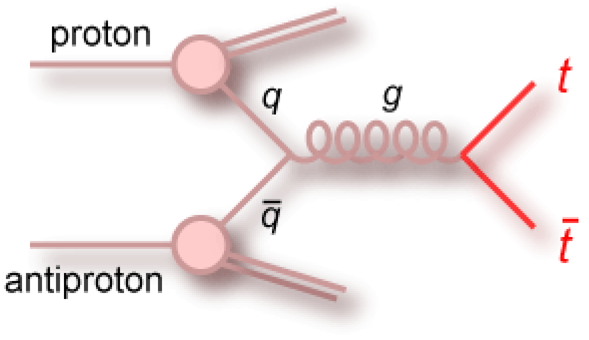
Top Quarks at the Tevatron

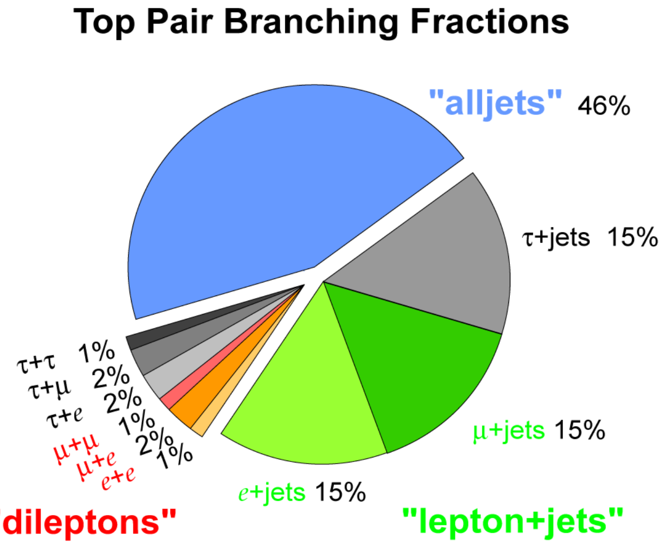
top quark pairs produced in strong interaction:

- **85% via quark-antiquark annihilation**
- **σ_{NNL0} = 7.46 pb @ m_{top}=172.5 GeV**

as BR(t->Wb)~100%, top events characterized by W decay:

- **dilepton final state:**
  - **2 bquarks, 2 isolated leptons and large missing transverse energy from 2 undetected neutrinos**
  - **main background from Z+jets events**
- **lepton+jets:**
  - **2 b quarks, 2 light jets, 1 isolated lepton and missing transverse energy**
  - **main background from W+jets events**
- **all jets:**
  - **2 b-quarks, 4 light jets**
  - **large background contamination from multijet events**




Top Pair Branching Fractions