Measurements of Top Quark Properties at the Tevatron

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on behalf of the DØ and CDF collaborations

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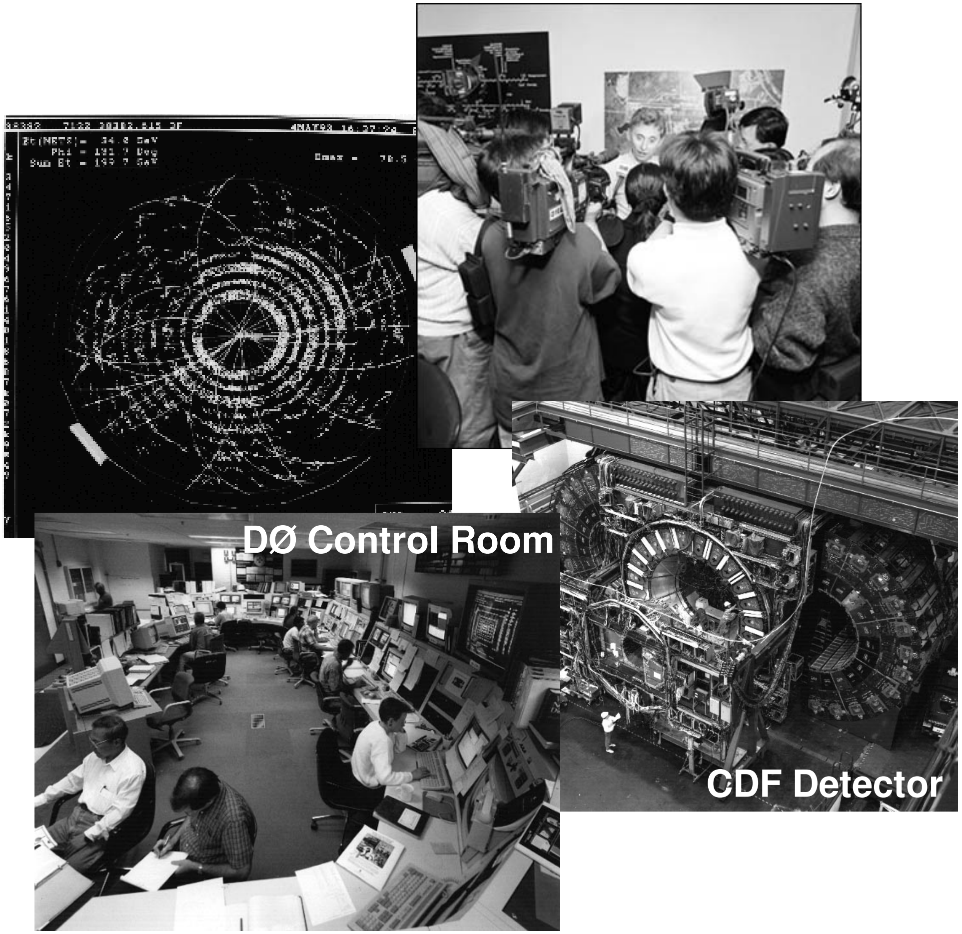
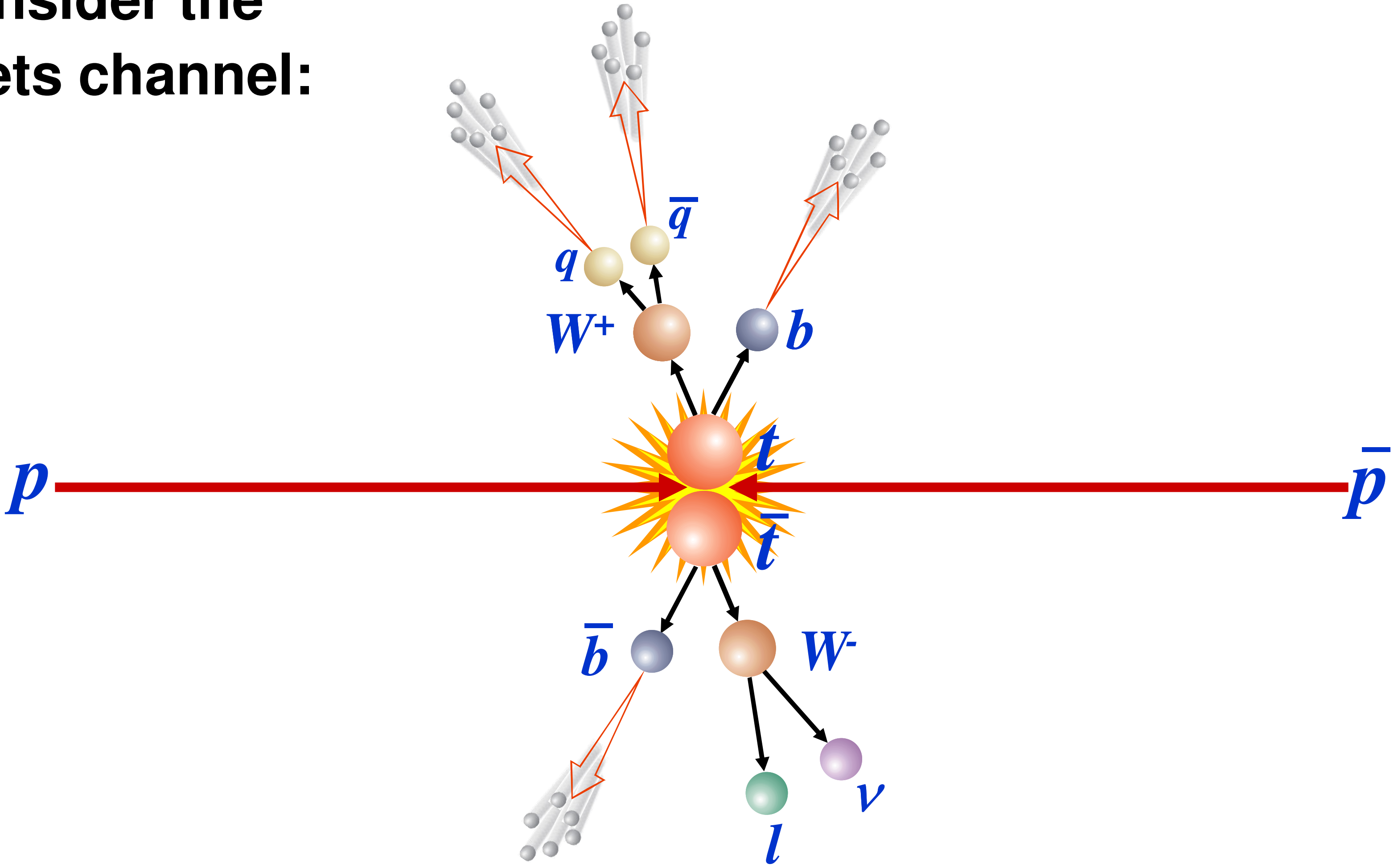
Dissecting the Top Quark

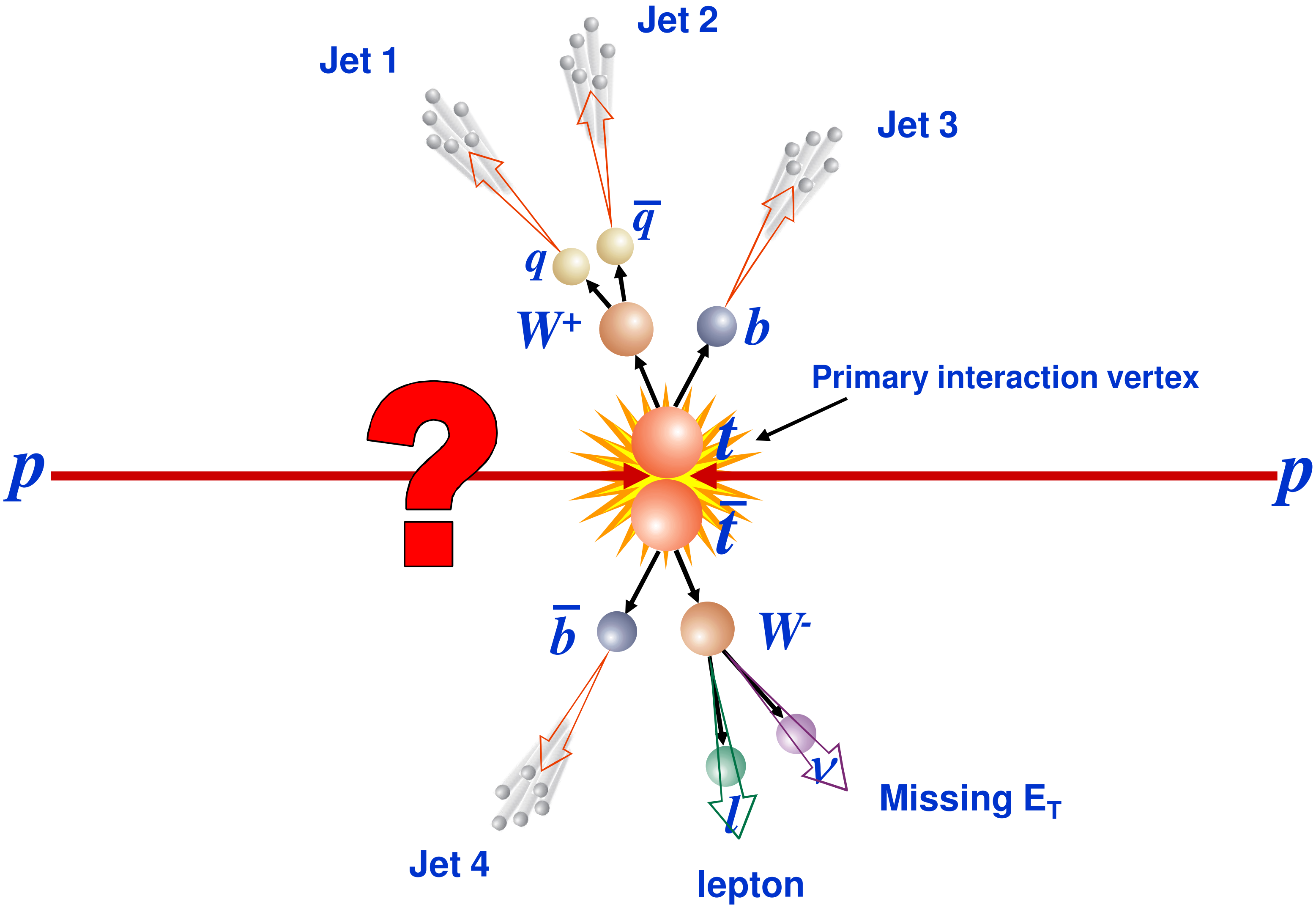
- Discovery of the top quark over a decade ago at Fermilab was an extraordinary scientific achievement and a major confirmation of the standard model
- Back then, each experiment observed only a handful of events (< 20).
- Today we have substantially more top candidates than in 1995 (literally thousands), significantly increasing our ability to measure the top quark's properties.
- In this talk, I will provide:
  - overview of challenges in measuring the top quark's properties & briefly describe the analysis techniques used
  - latest measurements of the top quark's properties from DØ & CDF that continue to check consistency with the SM and may perhaps point us in new directions.



Consider the l+jets channel:

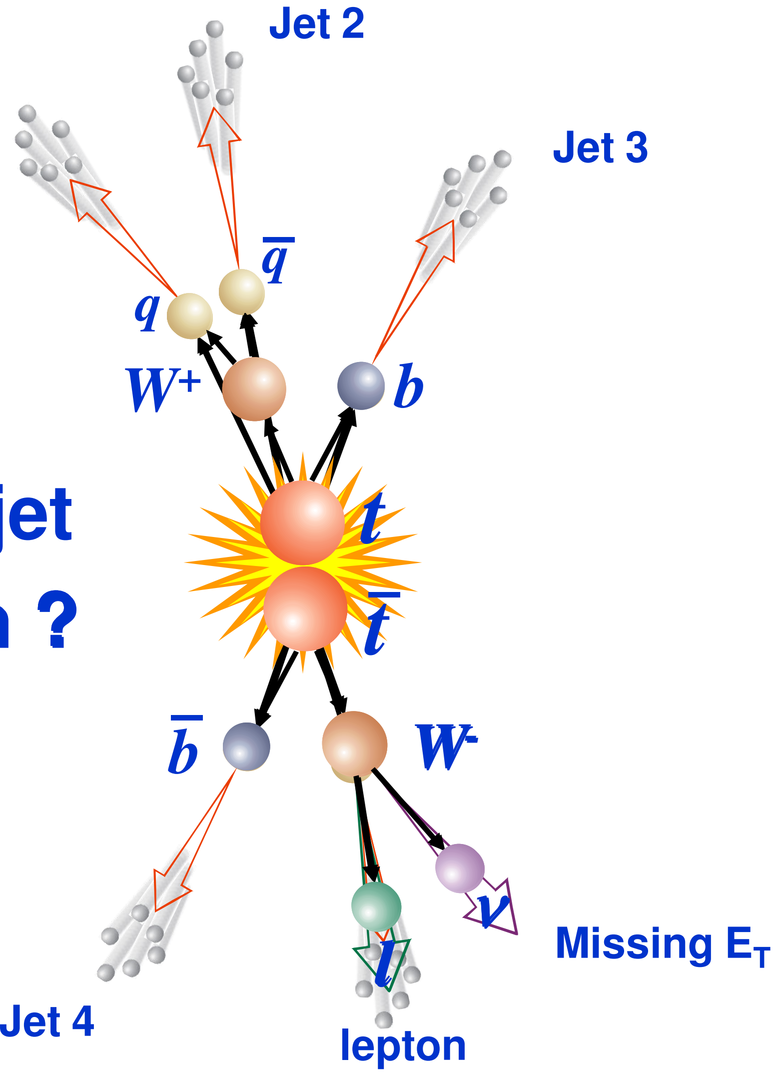


Top pair production (lepton+jets)



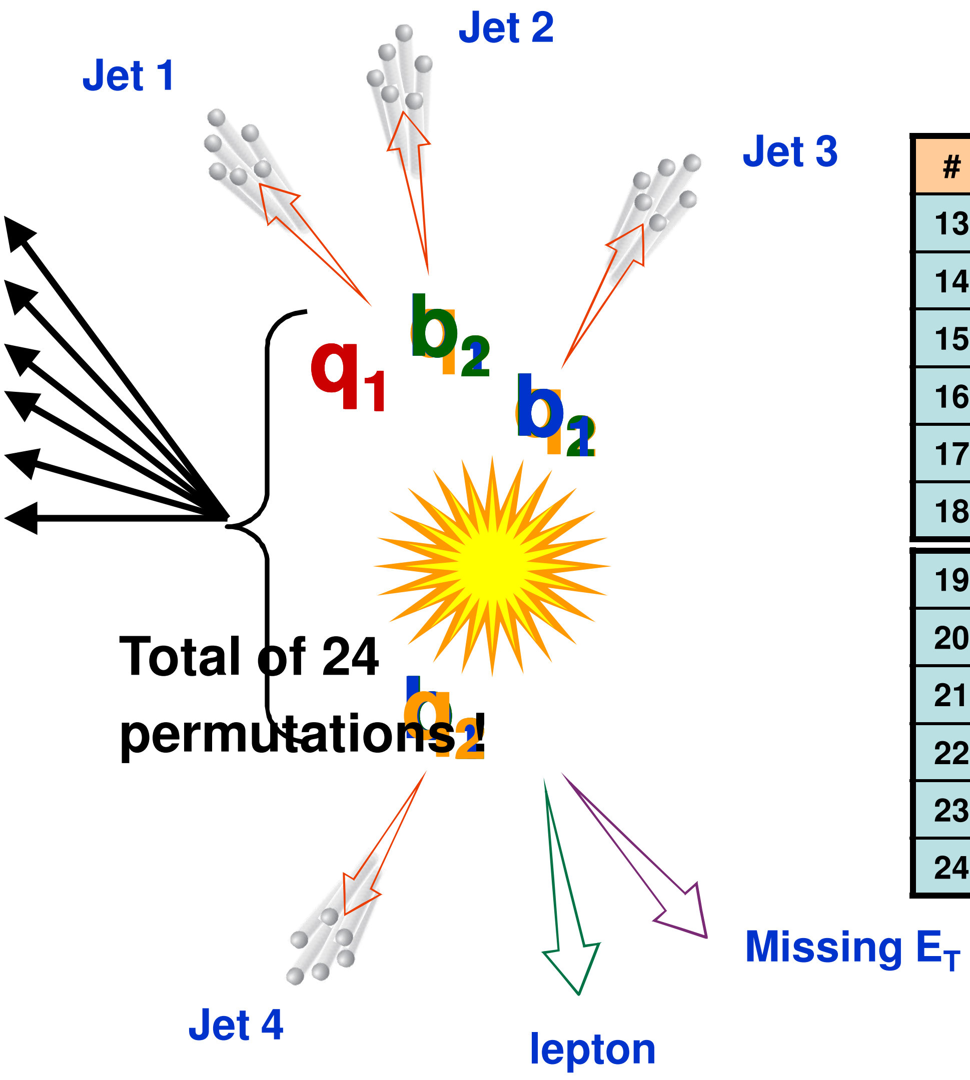
Ambiguity: processes

Top pairs
W+jets
QCD multijet
production ?



Ambiguity: permutations

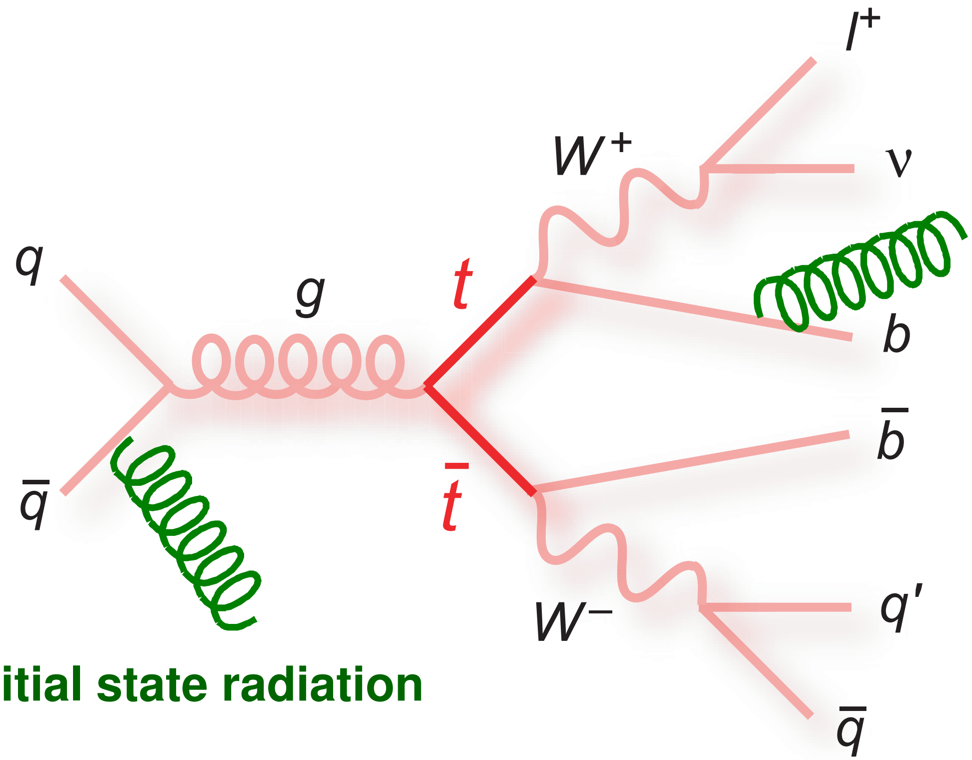
#	J1	J2	J3	J4
1	q_1	q_2	b_1	b_2
2	q_1	q_2	b_2	b_1
3	q_1	b_1	q_2	b_2
4	q_1	b_1	b_2	q_2
5	q_1	b_2	q_2	b_1
6	q_1	b_2	b_1	q_2
7	q_2	q_1	b_1	b_2
8	q_2	q_1	b_2	b_1
9	q_2	b_1	q_1	b_2
10	q_2	b_1	b_2	q_1
11	q_2	b_2	q_1	b_1
12	q_2	b_2	b_1	q_1



Total of 24 permutations!

#	J1	J2	J3	J4
13	b_1	q_1	q_2	b_2
14	b_1	q_1	b_2	q_2
15	b_1	q_2	q_1	b_2
16	b_1	q_2	b_2	q_1
17	b_1	b_2	q_1	q_2
18	b_1	b_2	q_2	q_1
19	b_2	q_1	q_2	b_1
20	b_2	q_1	b_1	q_2
21	b_2	q_2	q_1	b_1
22	b_2	q_2	b_1	q_1
23	b_2	b_1	q_1	q_2
24	b_2	b_1	q_2	q_1

Ambiguity: extra jets

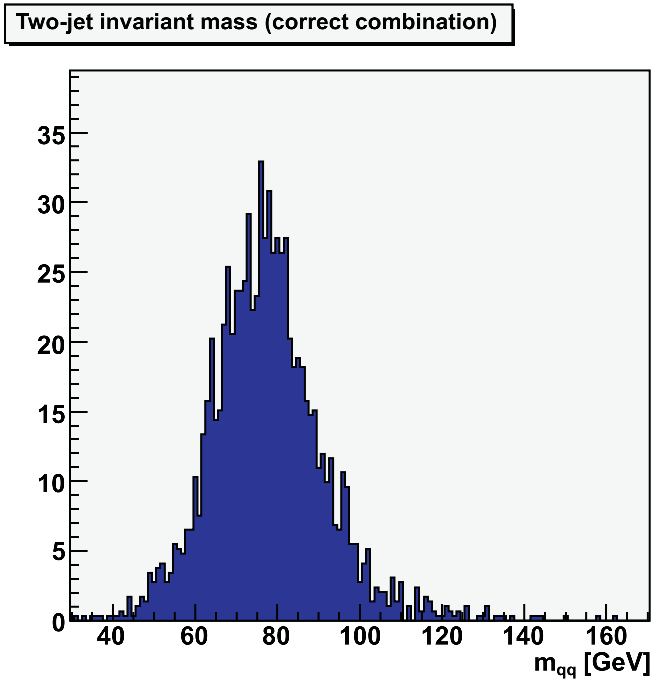


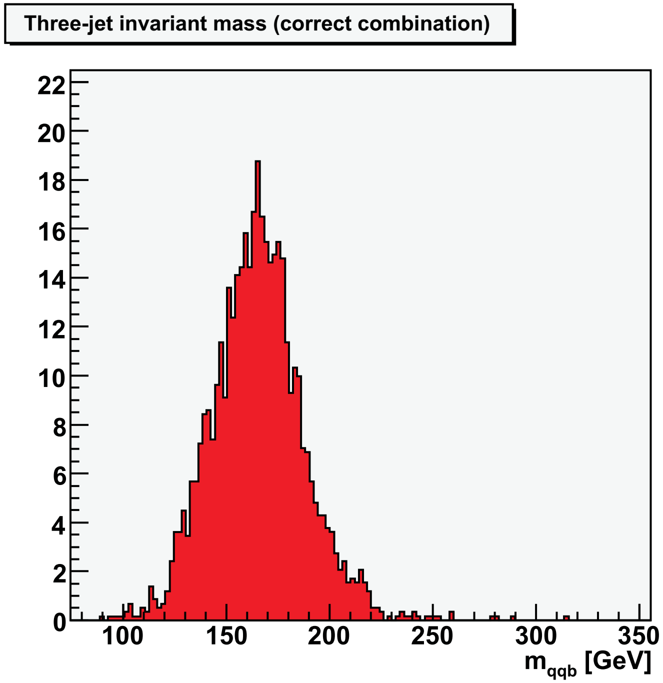
Final state radiation

Initial state radiation

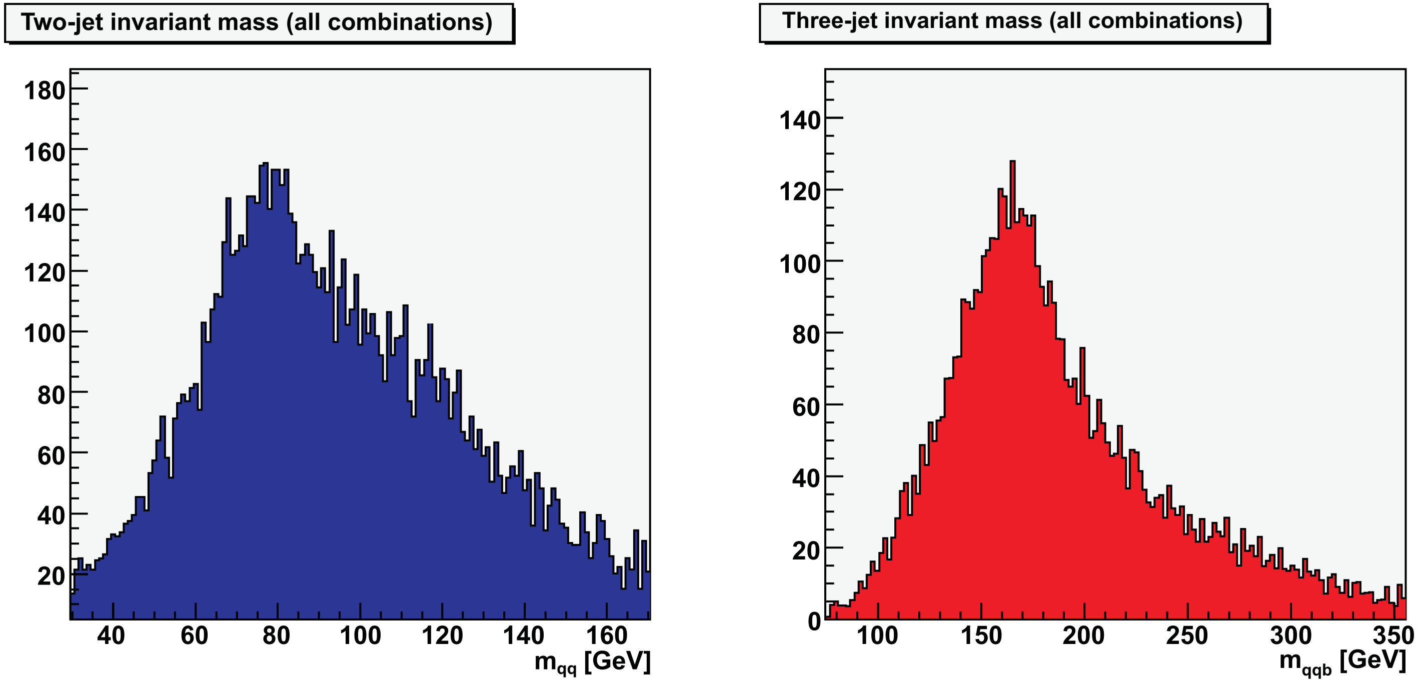
2jet and 3jet mass distributions

- **If you looked only at top events (no background), selected only those in which jets are matched to partons, and plotted the 2-jet and 3-jet invariant mass distributions using the correct jet permutation (assuming you know their identities), this is what you would get:**


Two-jet invariant mass (correct combination)


Three-jet invariant mass (correct combination)

- But of course, you don’t know the correct permutation, so you would calculate the invariant mass for all possibilities and end up with the following distributions:



- So even if you can eliminate background events completely, making a precise measurement of the top quark properties is still very challenging.

Measurement techniques

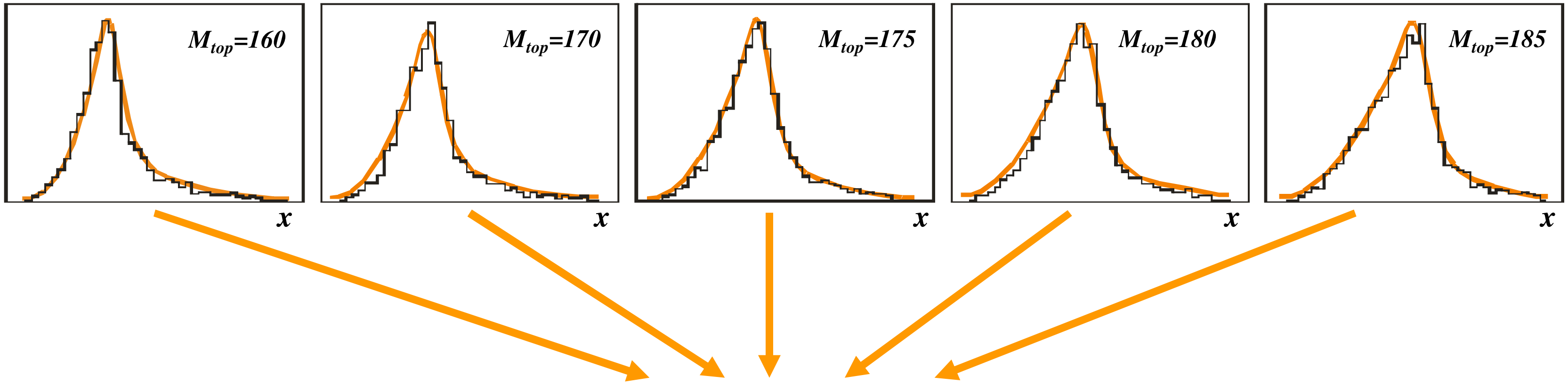
- **Despite the challenging nature of measuring top quark properties, sophisticated techniques have been developed over the years.**

- **In the next few slides, I briefly describe two methods commonly used to extract top quark properties such as those presented in this talk:**
  - **Template based method**
  - **Matrix Element based method**

- **For illustration, they are presented in the context of top mass measurements. But as you will see in the results presented in this talk, they are also widely used to measure other properties of the top quark.**

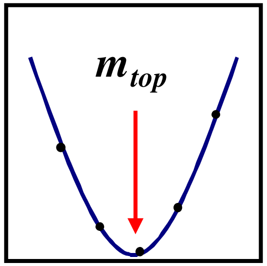
Template based method

- **Identify variable x sensitive to the property you are measuring, e.g. M_{top}.**
- **Using MC, generate distributions (templates) in x as a function of input M_{top}.**
- **Parameterize templates in terms of probability density function (p.d.f) in x, M_{top}.**
- **Construct likelihood L based on p.d.f's:**
  - Compare data x distributions with the MC templates using L
  - Maximize L (minimize -ln(L)) to extract top mass



Probability density function → $P(x;M_{top})$

$$L \propto \prod_{i=1}^{n_{obs}} \frac{cP(x_i;M_{top})+c'P'(\ldots)}{c+c'}$$



Matrix Element method

- ME method is based on the calculation of event probability densities taken to be the sum of all contributing (and assumed to be non-interfering) processes. For example, in the lepton+jets channel, if we assume ttbar and W+jets as the only major sources:

$$P_{\text{evt}}(x;\alpha) = \sum_{\text{proc}} f_i P_i(x;\alpha)$$

$$P_{\text{evt}}(x;m_t,JES) = \underbrace{f_{\text{sig}} P_{\text{sig}}(x;m_t,JES)}_{t\bar{t}} + \underbrace{(1-f_{\text{sig}})P_{\text{bkg}}(x;JES)}_{W+\text{jets}}$$

- Probabilities are taken to be the differential cross sections for the process in question. For example, the signal probability is given by:

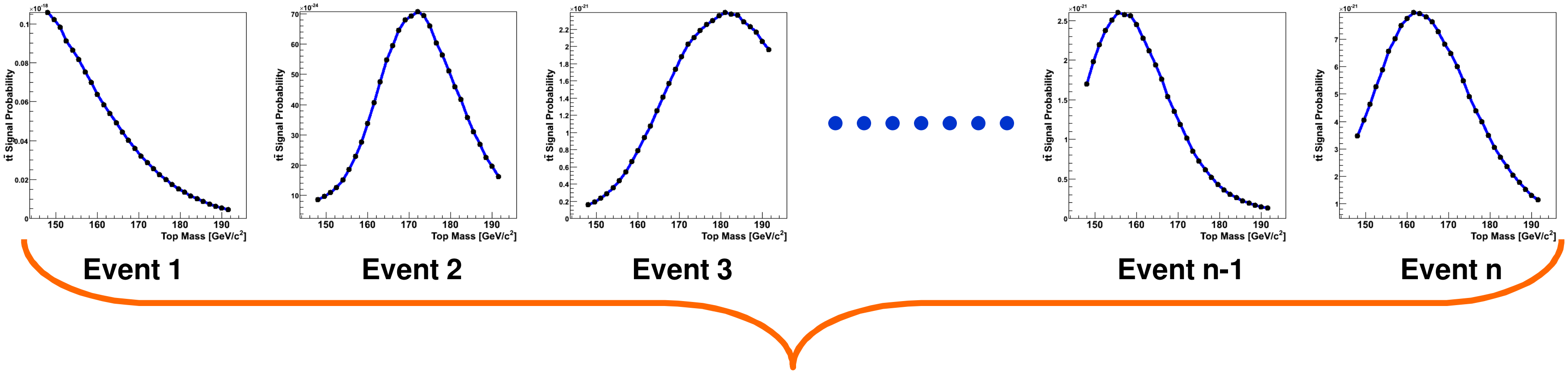
$$P_{\text{sig}}(x;m_t,JES) = \frac{d\sigma(x;m_t)}{\sigma_{\text{obs}}(m_t,JES)}$$

$$= \frac{1}{\sigma_{\text{obs}}(m_t,JES)} \times \int d\sigma(y)dq_1 dq_2 f(q_1)f(q_2)W(y,x)$$

where: $$d\sigma = \frac{(2\pi)^4 |\mathbf{M}|^2}{4\sqrt{(q_1 \cdot q_2 - m_1 m_2}} d\Phi_6$$

Matrix Element method

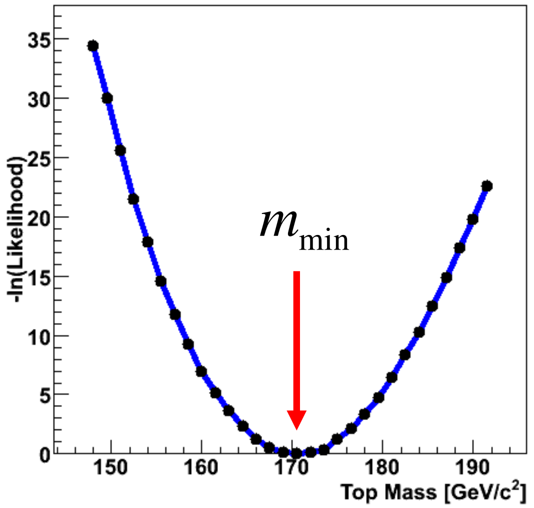
To extract a property such as m_{top} from a sample of n events, probabilities are calculated for each individual event as a function of m_{top}:



Event 1 **Event 2** **Event 3** **Event n-1** **Event n**

From these we build the likelihood function

$$\boxed{L(x_1 \ldots x_n; m_{top}) = \prod_{i=1}^{n} P_{\mathrm{evt}}(x_i; m_{top})}$$

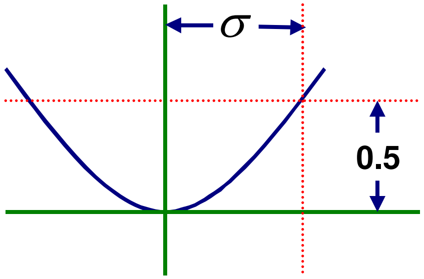


The best estimate of the top mass is then determined by minimizing:

$$-\ln L(x_1 \ldots x_n; m_{top})$$

And the statistical error can be estimated from:

$$\ln\left[L(m_{\min})\right] - \ln\left[L(m_{\min} \pm \sigma)\right] = 0.5$$



- Measurements of the following properties of the top quark will be presented in this talk:

- intrinsic

A. Mass
B. Mass difference
C. Width
D. Electric charge

- production

E. Spin correlations
F. Differential cross section in ttbar invariant mass

- decay

G. W Helicity
H. Ratio of decay branching fractions
I. Top decays to charged Higgs

- Intrinsic or Fundamental Properties

(A) Mass: A whale of a quark

- Top is most massive of all quarks and leptons
- Large coupling to the Higgs boson
- Special role in EW symmetry breaking

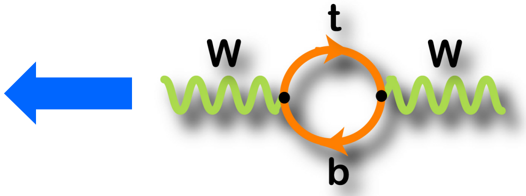
(A) Mass: Constraining the Higgs

- **Consider the mass of the W boson:**

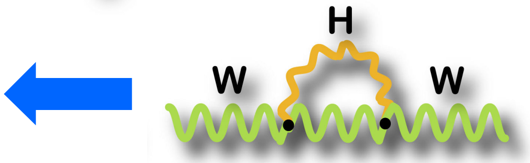
$$M_W^2 = \frac{\frac{\pi\alpha}{\sqrt{2}G_F}}{\sin^2\theta_W \; (1+\Delta r)}$$

← **Radiative corrections**

$$(\Delta r)_{top} \approx \frac{3G_F m_t^2}{8\sqrt{2}\pi^2}\frac{1}{\tan^2\theta_W}$$

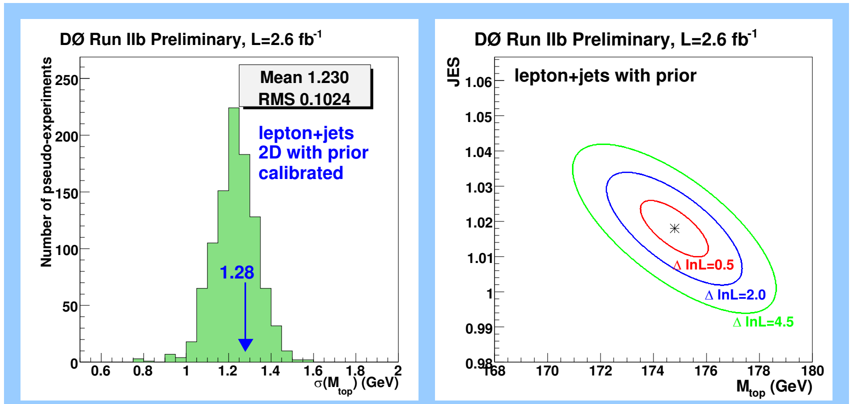


$$(\Delta r)_{Higgs} \approx \frac{11 G_F M_Z^2 \cos^2\theta_W}{24\sqrt{2}\pi^2}\ln\frac{m_h^2}{M_Z^2}$$



- **m_t enters quadratically while m_h enters logarithmically, so a precise knowledge of the W and Top masses will constrain the Higgs mass, providing a guide to the Higgs search.**

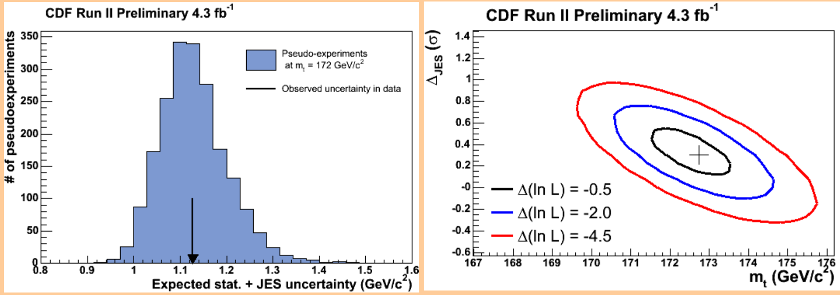
DØ (l+jets,3.6fb^{-1})



- Matrix element technique
- Both signal and background probabilities calculated for every event
- In-situ JES calibration
- Result is combination of 2.6fb^{-1} results shown above and previous 1fb^{-1} result

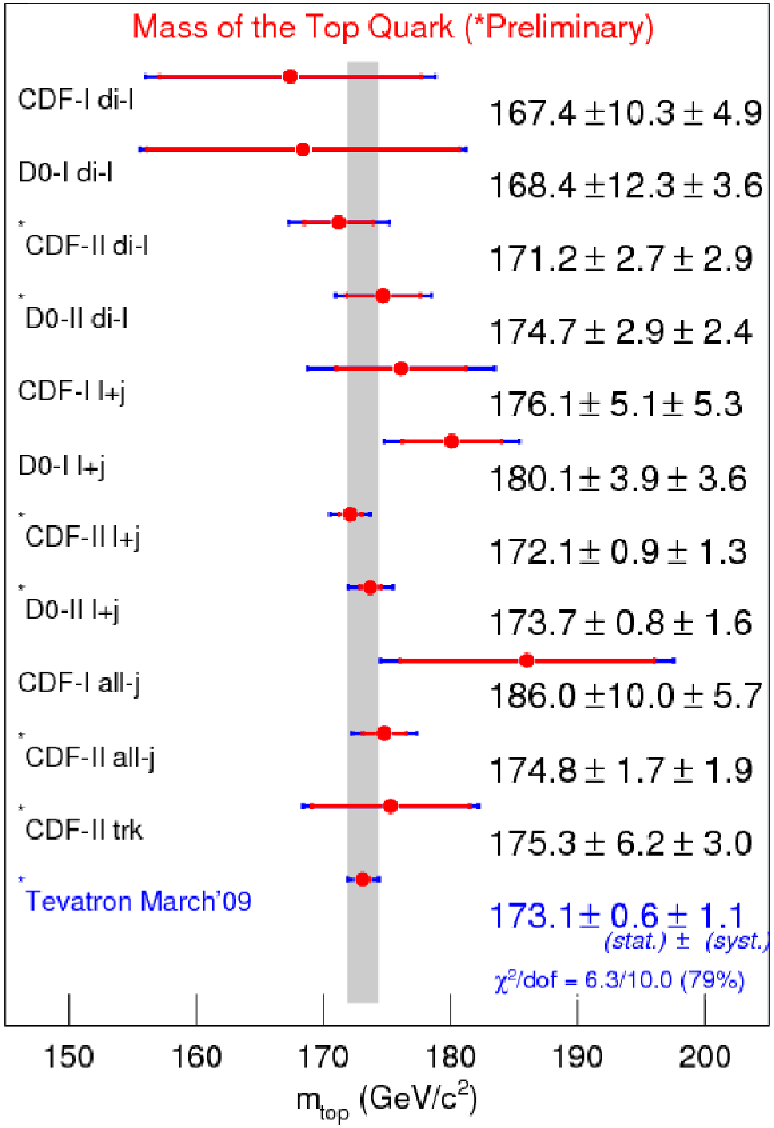
$$m_{\text{top}} = 173.7 \pm 0.8(\text{stat}) \pm 1.6(\text{syst})\ \text{GeV}$$

CDF (l+jets,4.3fb^{-1})



- Matrix element technique
- Likelihoods calculated under assumption that event is a signal event
- Bkg events rejected with NN discriminant
- In-situ JES calibration

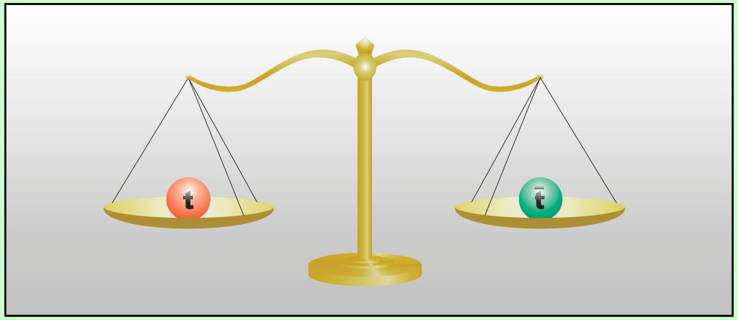
$$m_{\text{top}} = 172.6 \pm 0.9(\text{stat}) \pm 1.3(\text{syst})\ \text{GeV}$$



World average from 2009 winter conferences

(B) Mass difference

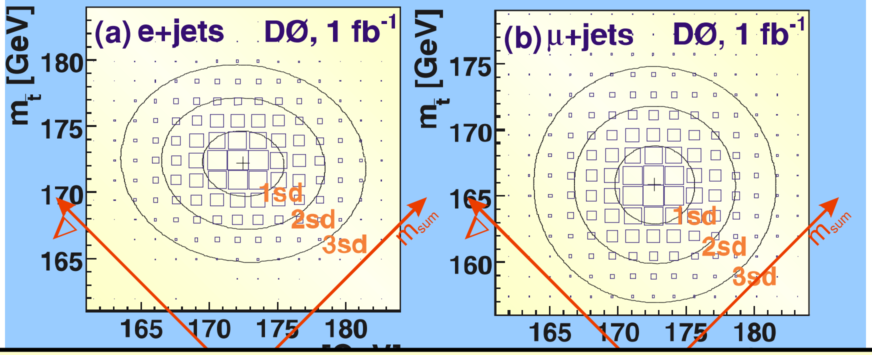
- CPT theorem demands equality between particle and antiparticle masses



- Measuring the mass difference between a particle and its antiparticle is therefore a way to test CPT invariance
- Precise mass difference measurement have been performed on composite objects, but no direct measurement of the mass difference between a quark a its antiquark has ever been attempted since quarks are never produced in isolation
- Top quark is unique because it decays before hadronization making a direct measurement of the mass difference between a top and antitop quark possible.

DØ (l+jets,1fb^{-1})

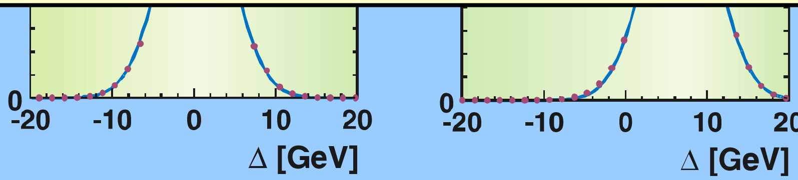
- First direct measurement of mass difference between bare quarks and antiquarks
- Matrix Element technique



Physical Review Letters 103, 132001 (2009)

Physics Today, *Physics Update*, August (2009)

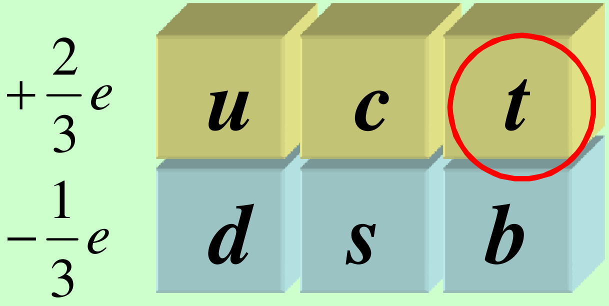
Nature, *Research Highlights*, 1 October (2009)



$$\boxed{m_t - m_{\bar t} = 3.8 \pm 3.7\,\mathrm{GeV}}$$

(C) Electric charge

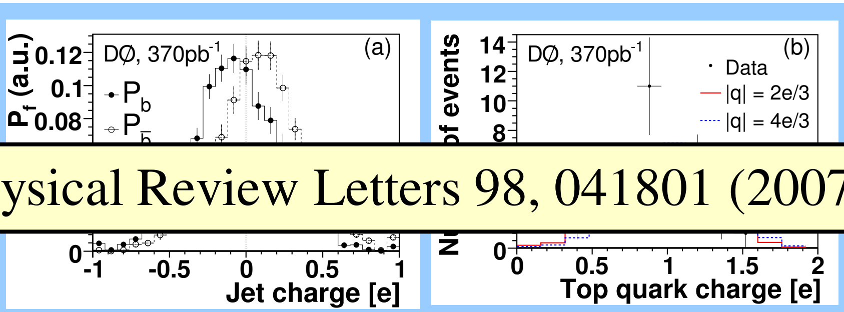
- **In the Standard Model, the top quark has an electric charge of +2e/3 and decays as $t \rightarrow bW^{+}$:**



- **However $t \rightarrow bW^{-}$ is conceivable due to ambiguity in pairing b jets to W bosons. This would lead to a "top" with an electric charge of -4e/3**
- **Can be accommodated by scenario with 4th generation quarks and leptons where observed "top" quark is non-SM and the yet unobserved SM top quark has a mass of ~270 GeV.**
- **The top quark's electric charge is a fundamental property that is an important quantity to measure. But a direct measurement of this quantity can also be used to test compatibility of observed events to SM or non-SM scenarios.**

(C) Electric charge

DØ (l+jets,0.37fb^{-1})



Physical Review Letters 98, 041801 (2007)

- **First direct measurement of charge**
- Calculate top charge:

$$Q_1 = \left|q_l + q_{b_l}\right|, \quad Q_2 = \left|-q_l + q_{b_h}\right|$$

- Define:

$$q_{\text{jet}} = \left(\sum_i q_i p_{T_i}^{0.6}\right) \Big/ \left(\sum_i p_{T_i}^{0.6}\right)$$

- Derive expected q_{jet} distributions for b/anti-b (and c/anti-c) from heavy flavor dijet samples
- Generate expected top charge distributions and calculate likelihoods of SM vs non-SM scenarios in data

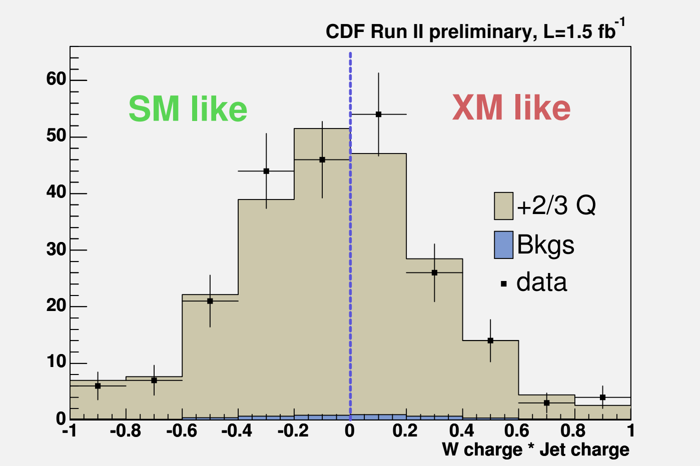
⇨ Non-SM only model ruled out up to 92.2%

- Allow possible admixture of SM & non-SM scenarios, set limits on non-SM fraction ρ

⇨ $0 \leq \rho < 0.80$ at 90% C.L.

CDF (l+jets, dilep 1.5fb^{-1})

- Similar analysis from CDF using more data and including dilepton channel



Comparison of (W charge) x (jet charge) distribution between data & SM MC

⇨ From data: $(1-\rho) = 0.87$

→ SM strongly favored and non-SM excluded with 87% confidence

→ $(1-\rho) > 0.4$ at 95% C.L.

(D) Width

- Being the heaviest, top has the largest decay width of all SM quarks:
  - shortest lifetime of all quarks
  - precisely this unique quality that makes direct measurements of its properties possible from its decay products

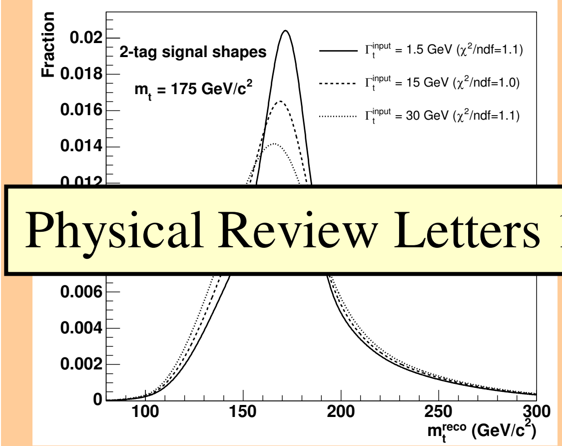
- At next-to-leading order, neglecting order m_b^2/m_t^2, α_s, and $(\alpha_s/\pi)M_W^2/m_t^2$ terms, SM predicts a total width of:

$$\boxed{\Gamma_t = \frac{G_F m_t^3}{8\pi\sqrt{2}}\left(1-\frac{M_W^2}{m_t^2}\right)^2\left(1+2\frac{M_W^2}{m_t^2}\right)\left[1-\frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3}-\frac{5}{2}\right)\right]}$$

* calculated to 1% in SM, ~ 1.5 GeV for $m_t = 175$ GeV

- Deviation from prediction can signal contributions from decays to non-SM particles (e.g. $t \to bH^+$)
- Also offers indirect way to rule out non-SM decays with non-detectable final states

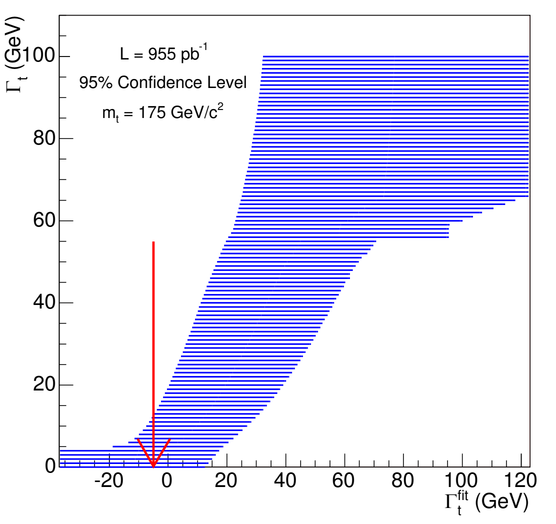
CDF (l+jets, 0.955fb^{-1})



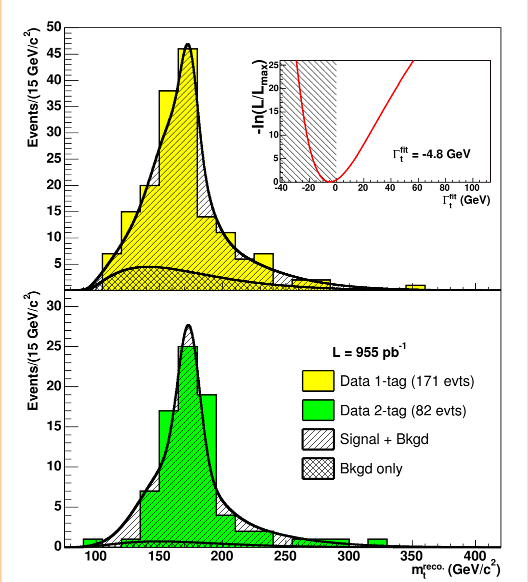
Physical Review Letters 102, 042001 (2009)

MC templates of re-

as function of width



95% C.L. band (Γ vs Γ_{fit}) with red arrow indicating data result



Data results overlaid with template fits for 2 and 1 tag samples

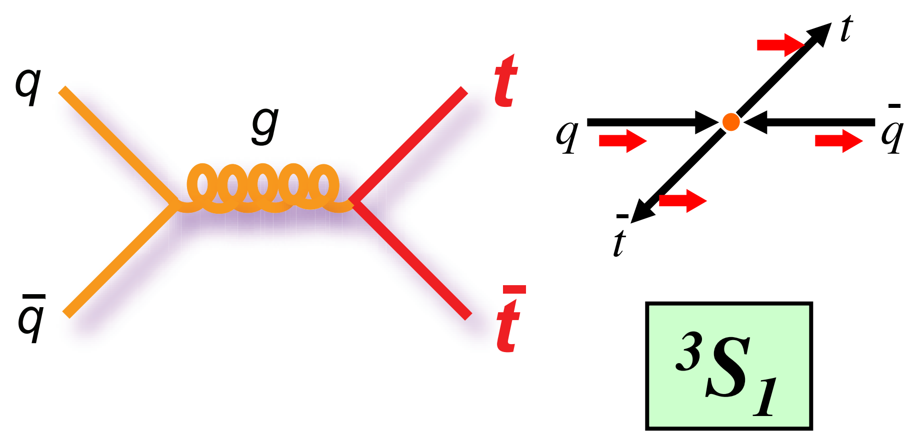
First direct experimental bound of the width:

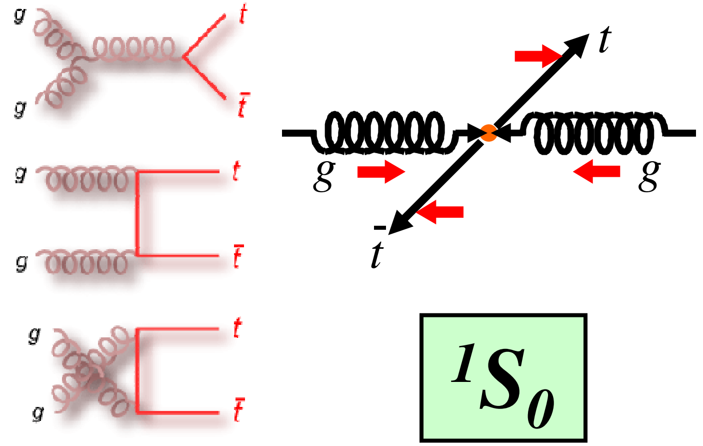
Γ_t < 13.1 GeV at 95% C.L. (m_t= 175 GeV)

*CDF also has a direct measurement of the lifetime based on impact parameter distributions → consistent with zero

■ Properties Related to Production

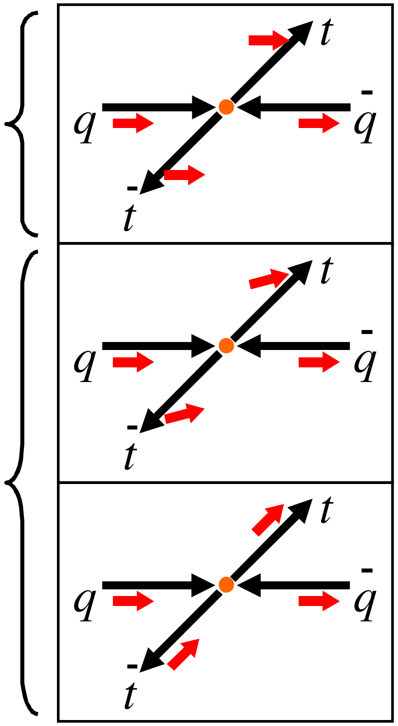
(E) Spin correlations



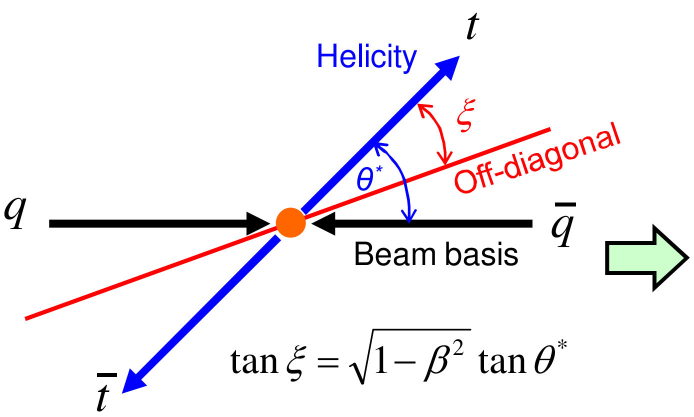


at threshold

at higher energies



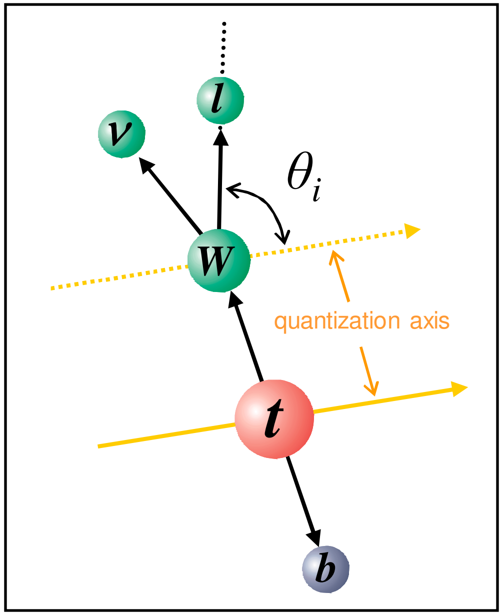
Define quantization axis in tt̄ rest frame



$$\tan\xi = \sqrt{1-\beta^2}\,\tan\theta^*$$

$$\boxed{\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}\left(1 - C\cos\theta_1\cos\theta_2\right)}$$

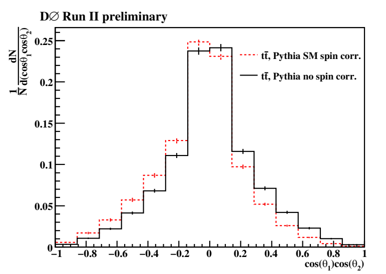
Measure lepton direction in top rest frame wrt quantization axis

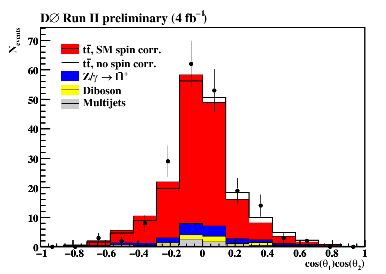


(E) Spin correlations

DØ (dilep,4.2 fb^{-1})

- Beam basis is used
- In this basis, SM predicts C = 0.777 at NLO
- Templates based on $\cos\theta_1 \times \cos\theta_2$ distributions of MC events generated (reweighted) with different values of C
- C extracted from data by comparing data with templates



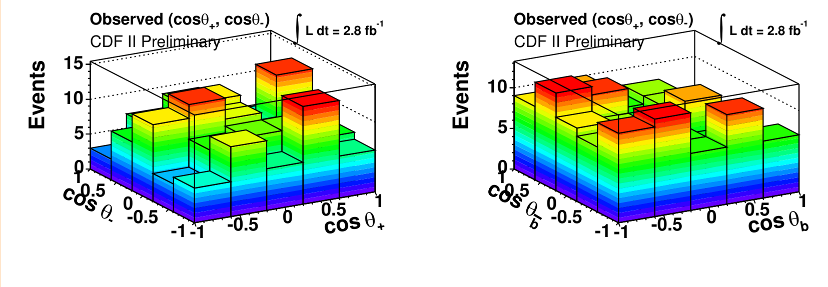


$$C = -0.17^{+0.64}_{-0.53}\,(\text{stat}+\text{syst})$$

Agrees with SM to within 2 SD

CDF (dilep 2.8fb^{-1})

- Off-diagonal basis used
- In this basis, SM predicts C = 0.782 at NLO
- Both leptons & b quarks used for measurement
  - Templates based on 2D distributions in $\cos\theta_+$ and $\cos\theta_-$, $\cos\theta_b$, and $\cos\theta_{bbar}$



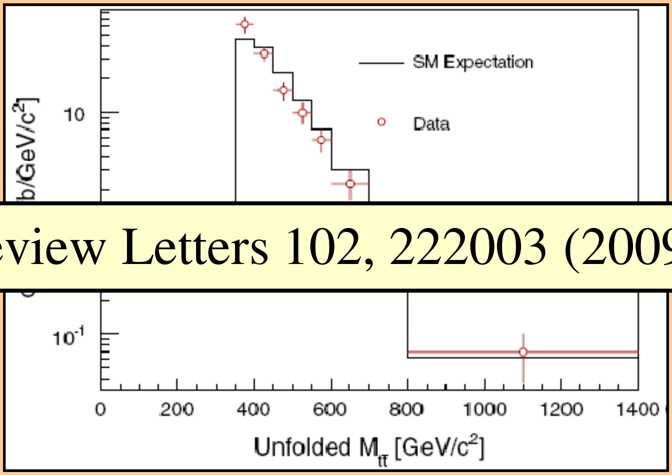
$$C = 0.32^{+0.545}_{-0.775}\,(\text{stat}+\text{syst})$$

Consistent with SM

(F) Differential cross section in $t\bar{t}$ invariant mass

- The shape of the $t\bar{t}$ invariant mass spectrum is a unique feature of the SM top
- Various BSM models predict new particles and mechanisms that distort the $t\bar{t}$ mass spectrum
- Traditional analyses have conducted direct searches for resonances in the ttbar mass spectrum
- The $t\bar{t}$ mass spectrum can be tested in a more general way for consistency with the SM
- This approach is sensitive to both narrow resonances and broad enhancements.

CDF **(l+jets 2.7fb^{-1})**



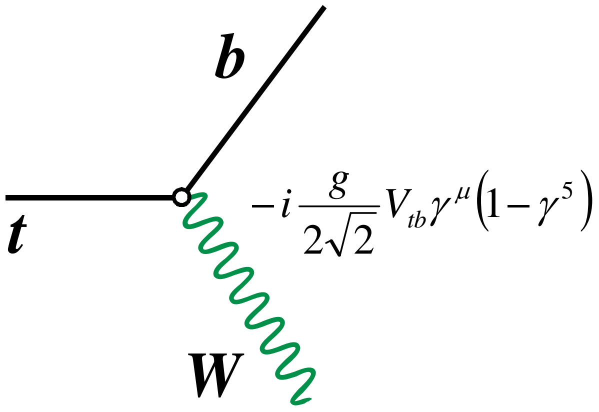
Physical Review Letters 102, 222003 (2009)

- M($t\bar{t}$) calculated from reconstructed quantities ranging from 0-1400 GeV
- Background modeled from MC is subtracted, spectrum is unfolded and differential cross section is calculated
- In-situ jet energy calibration used in mass analyses used here to constrain JES
- $d\sigma/dM(t\bar{t})$ compared with SM expectation

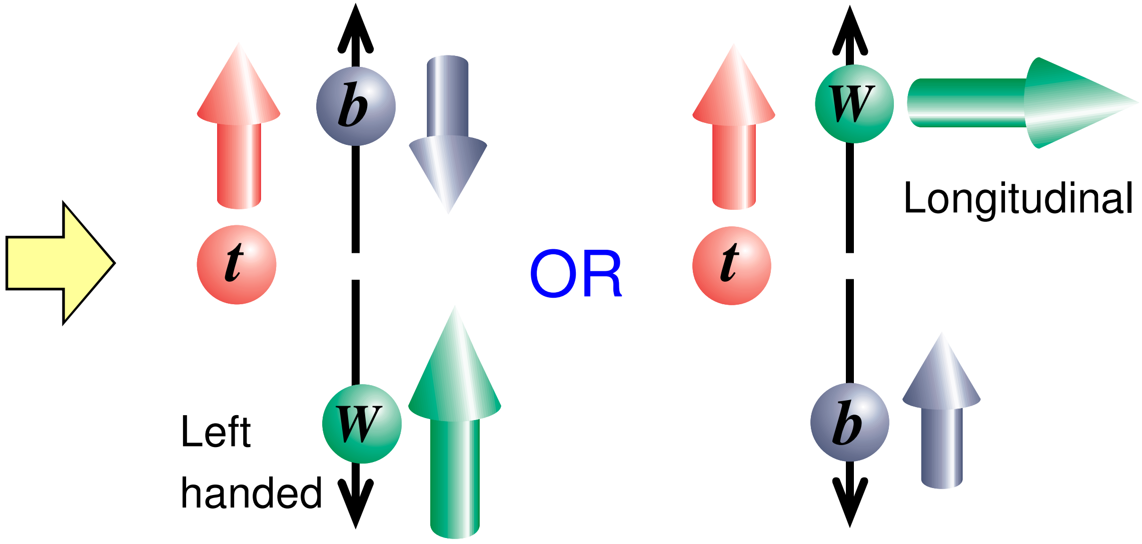
⇨ **No evidence of non-SM physics**

■ Properties Related to Decay

(G) W Helicity



V-A structure of $t \rightarrow bW$ decay



SM prediction:

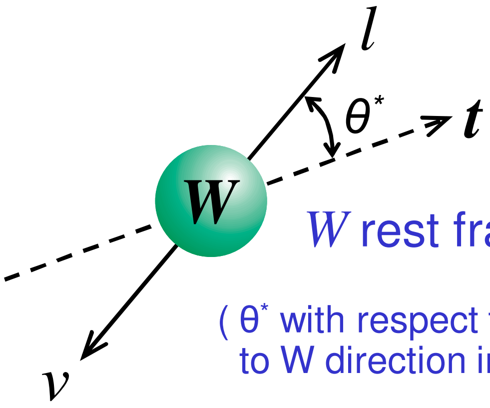
$f_0 = 0.697$ (depends on m_{top})

$f_+ \sim O(10^{-4})$

⇨ **Search for deviations from SM by measuring helicity fractions.**

Determine helicity fractions from angular distributions:

$$\omega(\theta^*) = f_0\frac{3}{4}\left(1-\cos^2\theta^*\right) + f_-\frac{3}{8}\left(1-\cos\theta^*\right)^2 + f_+\frac{3}{8}\left(1+\cos\theta^*\right)^2$$



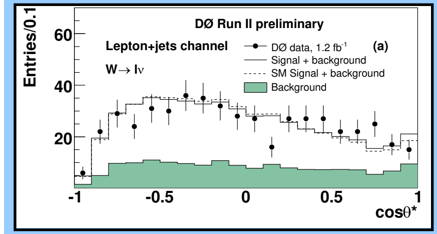
W rest frame

(θ* with respect to top direction or to W direction in top rest frame)

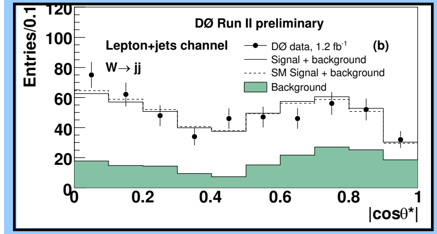
(G) W Helicity

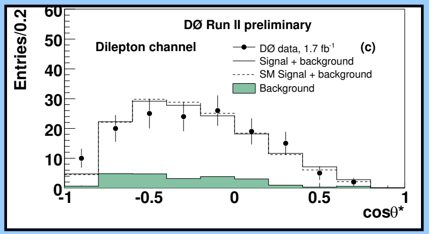
DØ (l+jets,dilep 2.7fb^{-1})

Template based



cosθ* distributions for for different W decay channels

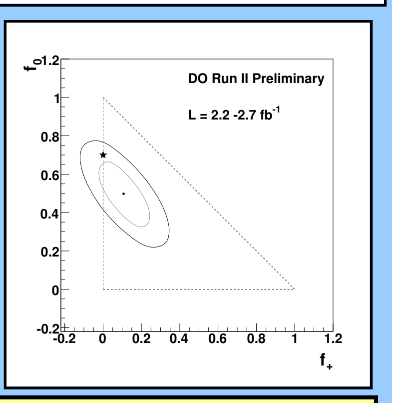




68% & 95% CL contours

★ SM value

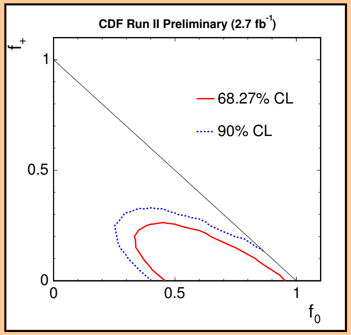
◺ physically allowed



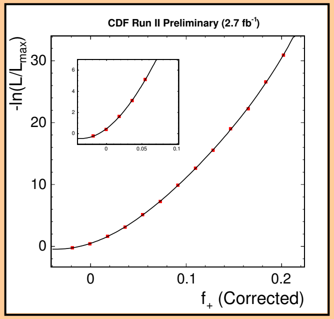
$$f_0 = 0.490 \pm 0.106(\mathrm{stat}) \pm 0.085(\mathrm{syst})$$
$$f_+ = 0.110 \pm 0.059(\mathrm{stat}) \pm 0.052(\mathrm{syst})$$

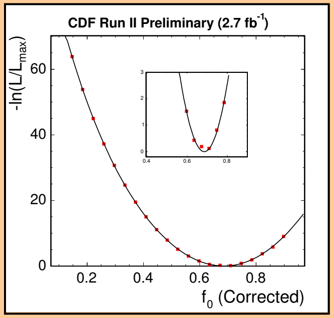
CDF (l+jets, 2.7fb^{-1})

Matrix element based



68% & 95% CL contours





$$f_0\,(f_+=0) \rightarrow\ 0.70 \pm 0.07(\mathrm{stat}) \pm 0.04(\mathrm{syst})$$
$$f_+\,(f_0=0.7) \rightarrow -0.01 \pm 0.02(\mathrm{stat}) \pm 0.05(\mathrm{syst})$$

$$f_0 = 0.88 \pm 0.11(\mathrm{stat}) \pm 0.06(\mathrm{syst})$$
$$f_+ = -0.15 \pm 0.07(\mathrm{stat}) \pm 0.06(\mathrm{syst})$$

(H) Ratio of decay branching fractions

- **In the Standard Model, the top quark decays into a W boson and a down type quark**
- **The ratio of top decays into Wb to those into Wq $(q = d,s,b)$ can be written in terms of CKM matrix elements**

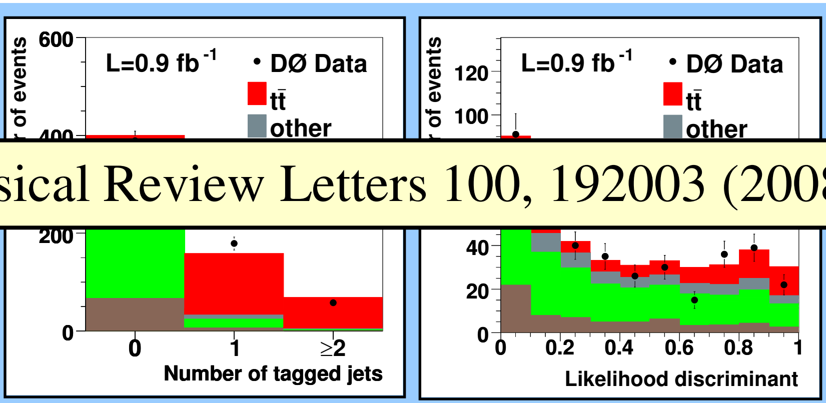
$$\boxed{R = \frac{B(t \to Wb)}{B(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2}}$$

- **$|V_{tq}|$'s are tightly constrained with $|V_{tb}| \approx 1$ based on:**
  - **assumption of unitary three generation CKM matrix**
  - **experimental measurements of CKM matrix elements**

- **Non-SM processes in top quark production and decay or a 4th generation of quarks could alter SM values for $|V_{tq}|$ resulting in R deviating from the expected value close to unity.**

- **Experimental determination of R can therefore be used to check SM assumptions and test for new physics.**

DØ (l+jets,0.9 fb^{-1})



Physical Review Letters 100, 192003 (2008)

- **Simultaneous measurement of R & σ**
- Number and distribution of events depends on σ and R
- Fit for R & σ by comparing observed with expected numbers as function of R & σ.

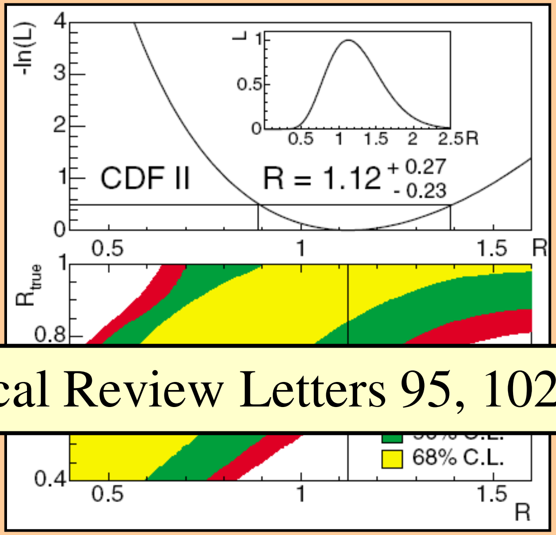
$$R = 0.97^{+0.09}_{-0.08}\,(\mathrm{stat+syst})$$

Limits

$R > 0.79$ at 95% C.L.

$|V_{tb}| > 0.89$ at 95% C.L.

CDF (l+jets, dilep 0.16fb^{-1})



Likelihood as function of R

CL bands used to set

Physical Review Letters 95, 102002 (2005)

$$R = 1.12^{+0.21}_{-0.19}\,(\mathrm{stat})^{+0.17}_{-0.13}\,(\mathrm{syst})$$

Limits

$R > 0.61$ at 95% C.L.

$|V_{tb}| > 0.78$ at 95% C.L.

(I) Charged Higgs

- **Simplest extensions to SM require existence of two different Higgs fields which manifest themselves as two charged Higgs bosons ($H^{\pm}$) and three neutral ones**
- **If $m_H < m_t - m_b$, one expects to find $t \rightarrow H^+ b$**

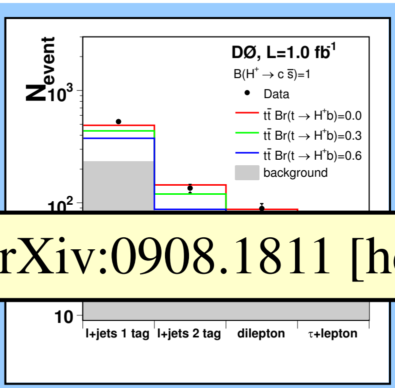
- **BR of H⁺ decays, depend on $\tan\beta$ (ratio of vacuum expectation values of the two Higgs fields)**
- **Low $\tan\beta$: $H^+ \rightarrow c\bar{s}$ dominant**

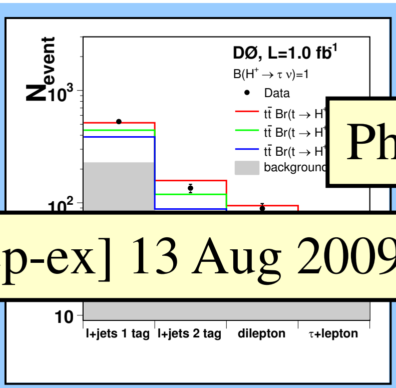
  High $\tan\beta$: $H^+ \rightarrow \tau\nu$ dominant

- **Due to different decay BRs of H^+, one can expect differences in the distribution of observed events in the different top decay channels**
- **This means, aside from direct searches, indirect H^+ searches also possible by comparing observed distribution of events relative to SM expectations**

(I) Charged Higgs

DØ (l+jets, dilep, τlep, $1fb^{-1}$)



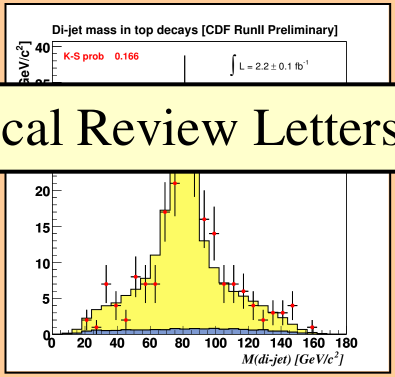


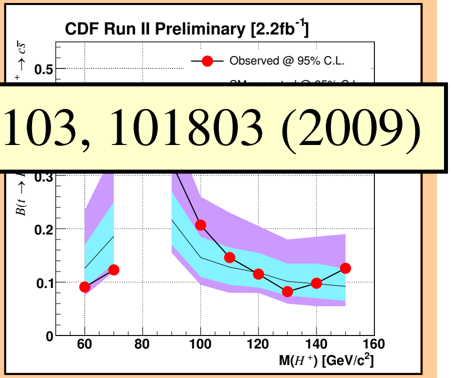
arXiv:0908.1811 [hep-ex] 13 Aug 2009

- Data split into sub-samples based on final states
- Compare predicted number of events to observed through likelihood fit
- Upper limits extracted for $B(H^+ \to c\bar{s})=1$ (leptophobic), $B(H^+ \to \tau\nu)=1$ (tauonic), & mixture
- $B(H^+ \to \tau\nu)=1$, “model-independent” simultaneous fit of σ(tt) and $B(t \to H^+b)$ also performed
- Results interpreted in (tanβ,M_{H+}) for different models

Excluded region of $B(t \to H^+b)$ at 95% CL:
leptophobic: > 0.22 for $80 < M_{H+} < 155$ GeV
tauonic: > 0.15-0.19 depending on M_{H+}
model-independent: > 0.15-0.19 depending on M_{H+}

CDF (l+jets, $2.2fb^{-1}$)





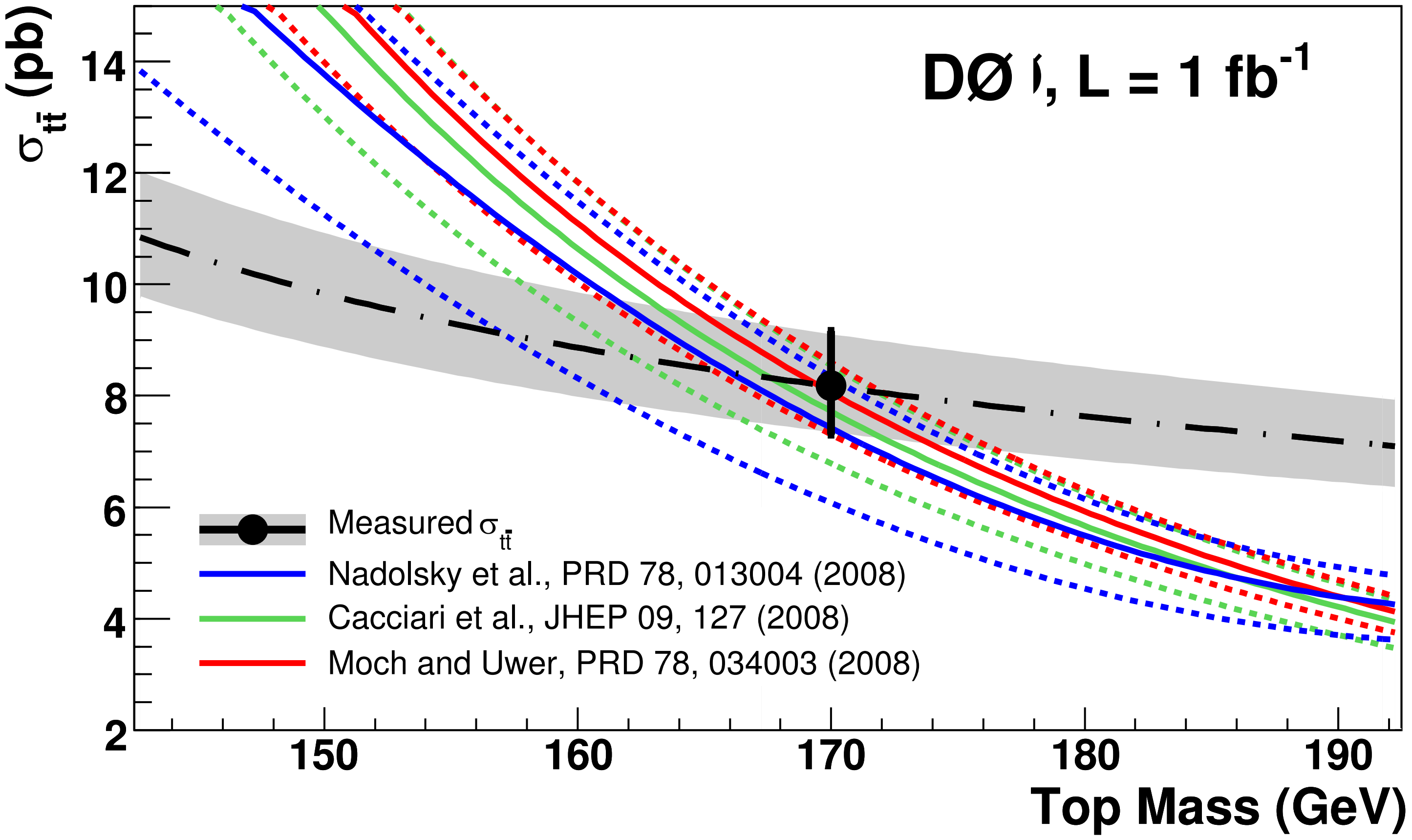
Physical Review Letters 103, 101803 (2009)

- First direct search of $H^+ \to c\bar{s}$
- $t\bar{t}$ event reconstructed using kinematic fitter without imposing W mass constraint on hadronic branch
- Merge extra jets (FSR) with closest to improve resolution
- Dijet mass compared with W, H, & bkg templates

Excluded region of $B(t \to H^+b)$ at 95% CL, assuming $B(H^+ \to cs)=1$:
> 0.1-0.3 for $60 < M_{H+} < 150$ GeV

- Our knowledge of the top quark has come a long way since its discovery in 1995
- Significantly more top quark candidate events now to analyze
- Many previously unmeasured properties now measured
- Previously measured properties like the mass now measured to much higher precision
- Presented the latest measurements from the Tevatron of various properties of the top quark – both fundamental and those related to production and decay
- Only a sampling of many top-notch measurements resulting from the hard work of both CDF and DØ collaborations
- So far, observed top quark is consistent with the SM
- With increasing data, measurements will continue improving, testing the top quark and the SM more stringently
- We look forward to many more world class measurements in the coming year !

End


DØ, L = 1 fb^{-1}
$\sigma_{t\bar{t}}$ (pb)
14
12
10
8
6
4
2
150
160
170
180
190
Top Mass (GeV)
Measured $\sigma_{t\bar{t}}$
Nadolsky et al., PRD 78, 013004 (2008)
Cacciari et al., JHEP 09, 127 (2008)
Moch and Uwer, PRD 78, 034003 (2008)