Measurement of Top Quark Properties at D0

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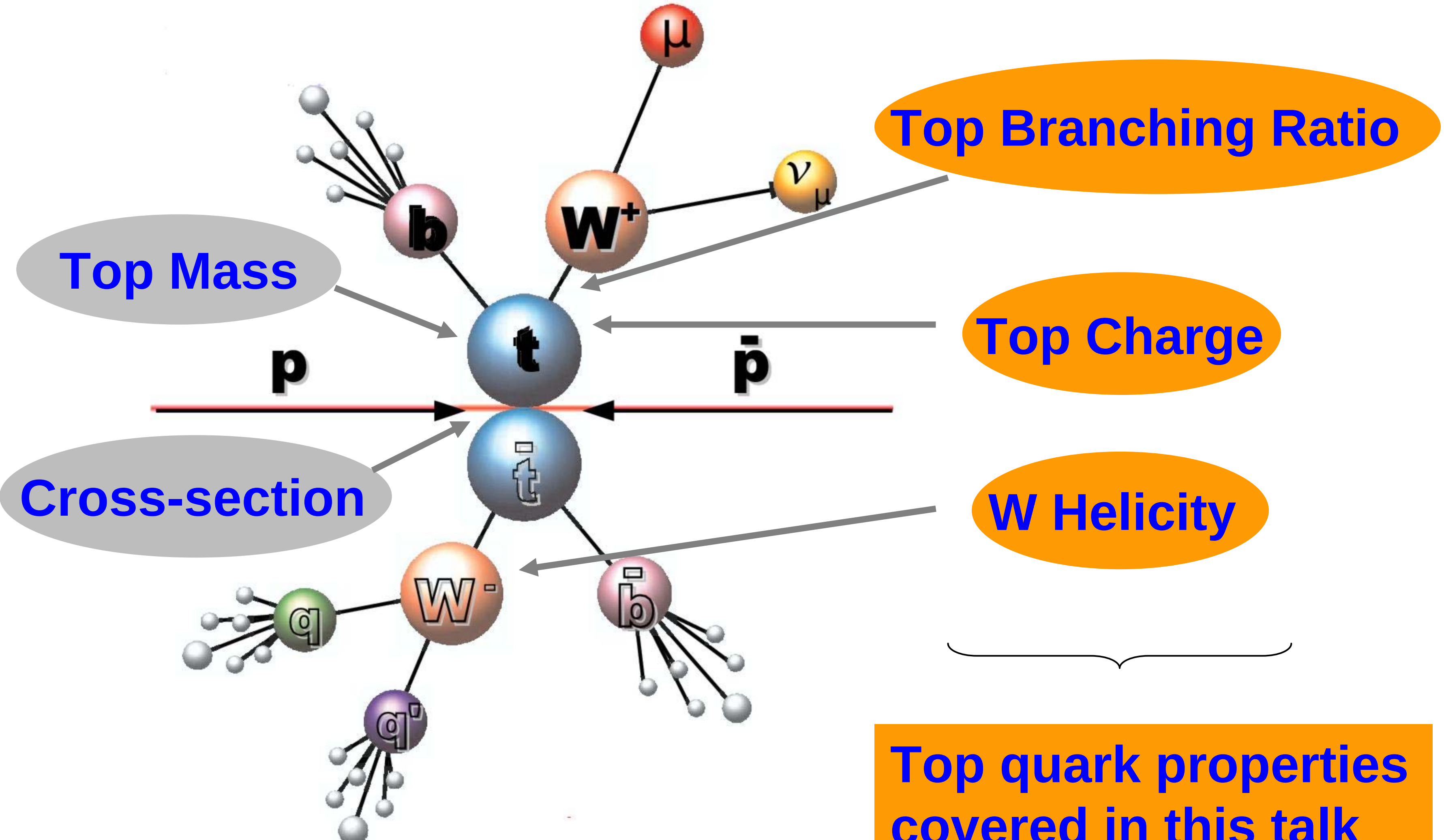
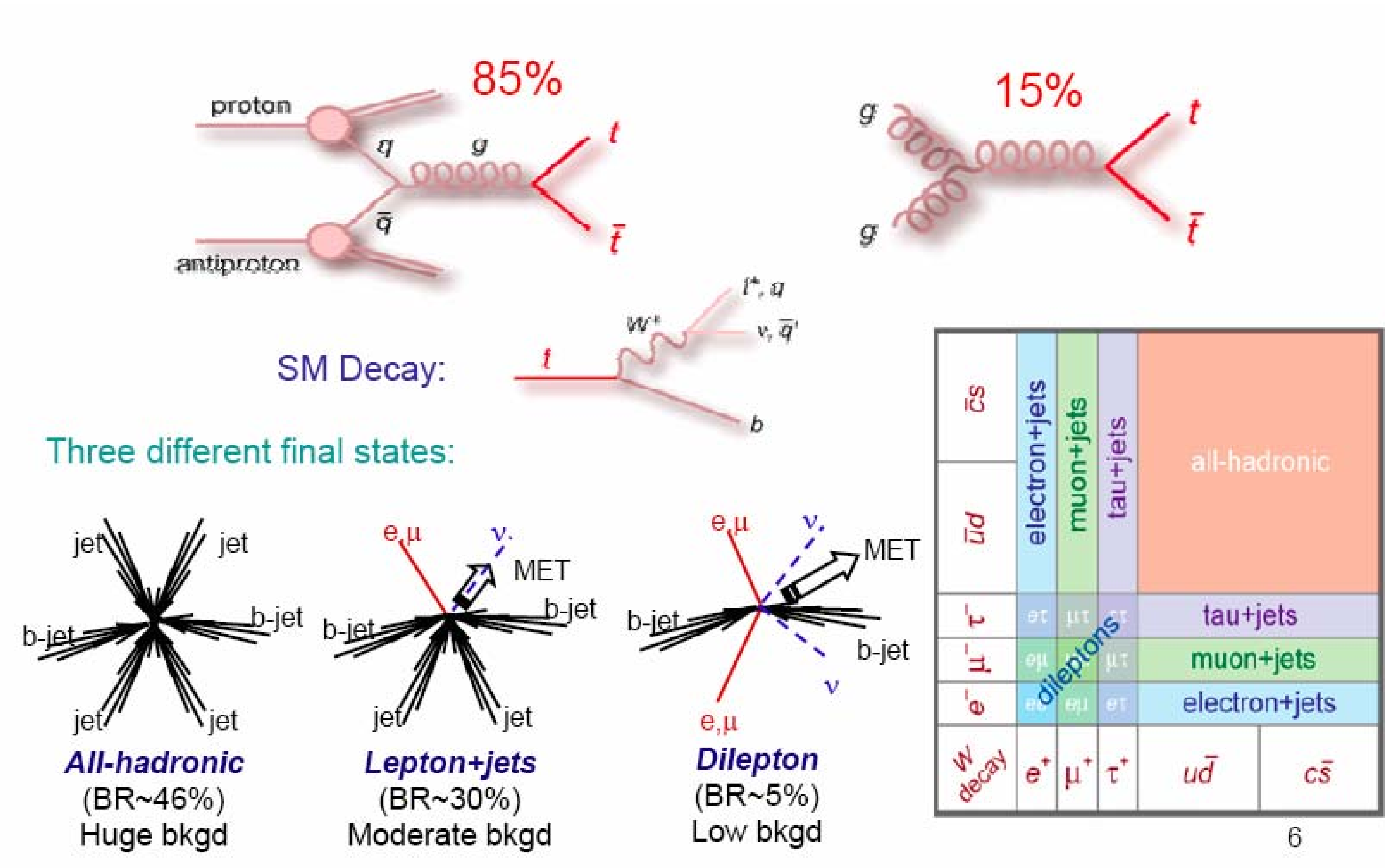
On Behalf of the DØ Collaboration

Top Pair Production



Top quark properties covered in this talk

Top Pair Production at Tevatron



Top Branching Ratio

SM Theory

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

- **Unitarity & experimental constraints: 0.9980<R<0.9984 (90% CL)**
- **If significant deviation seen from the SM ratio**

➔Opportunity to discover new physics

  - Additional quark families
  - Non-SM production/decay

Experimental Method

- **Measure R in lepton + jets final states**
  - One W decays leptonically: W→e/μ (τ→e/μ)
  - Other W decays hadronically: W→qq
- **Background**
  - Major background: leptonically decay W associated with jets (W+jets)
  - QCD multijet background
  - Z+jets, WW, WZ, ZZ, single top production (other background)
- **Use b-jet identification to separate signal from background**
  - Build discriminant using four kinematic variables (0-tag sample)

Top Branching Ratio (2)

Tagging probability of ttbar as a function of R

$$P_{t\bar{t}}^{n-tags} = P^{n-tags}(t\bar{t} \to bb) \times R^2 + P^{n-tags}(t\bar{t} \to qb) \times 2R(1-R) + P^{n-tags}(t\bar{t} \to qq) \times (1-R)^2$$

- **Probabilities $P^{n\text{-tags}}$ to observe n-tag = 0, 1, or >= 2 b-tagged jets are computed separately, using the probabilities for each type of jet (b, c or light-quark jet) to be b-tagged**

Count events with n-tags

- **Sum of the expected background and signal**

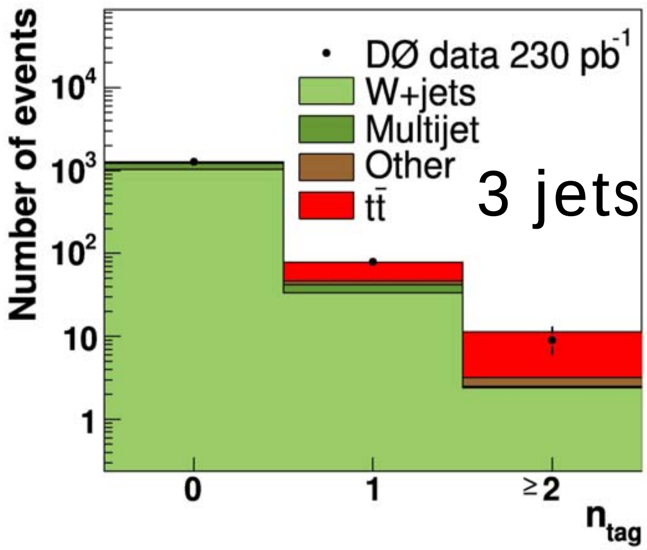
$$N^{n-tags} = P_{t\bar{t}}^{n-tags}(Br(t \to Wb)) N_{t\bar{t}} + P_{bkg}^{n-tags} \times N_{bkg}$$

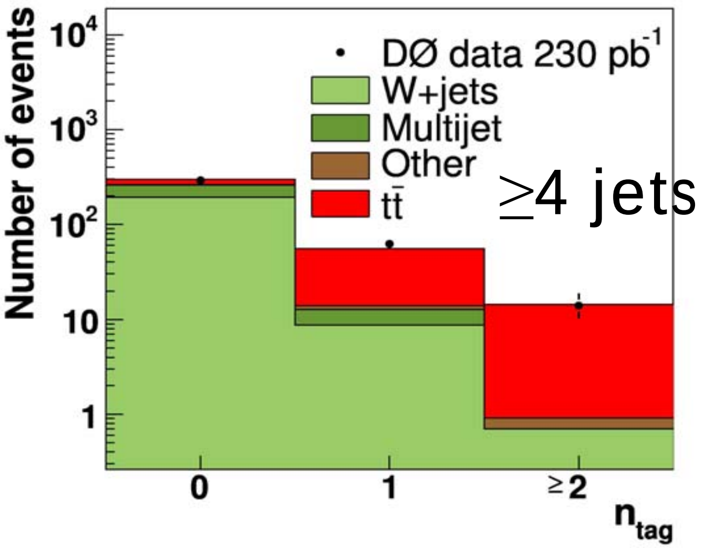
- **Signal contribution as a function of R and N_{tt}**
- **0-tag sample**
  - Shapes of discriminant for ttbar and W+jets derived from MC
  - Background normalization extracted from discriminant fit
- **Normalization of multijet background estimated by counting events in orthogonal control samples**
- **Contributions from other background determined from MC**

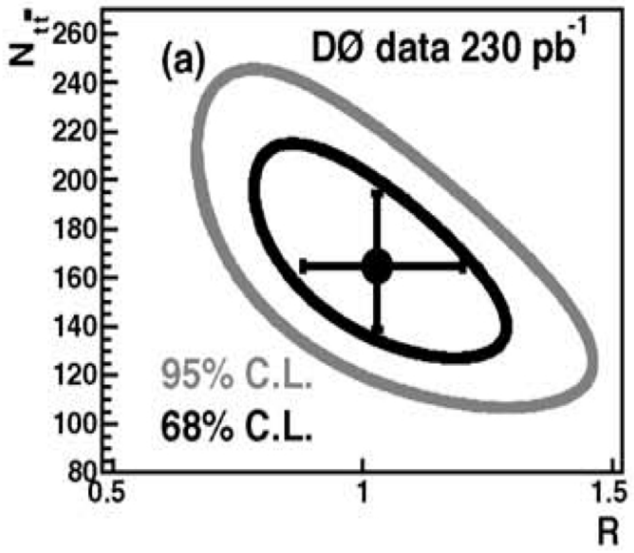
→Fit N_{tt} and R simultaneously to $N_{n\text{-tags}}$ using 2D nuisance likelihood fit

Top Branching Ratio (3)

Observed and fitted number of events







$Br(t\rightarrow Wb) = 1.03^{+0.19}_{-0.17}$

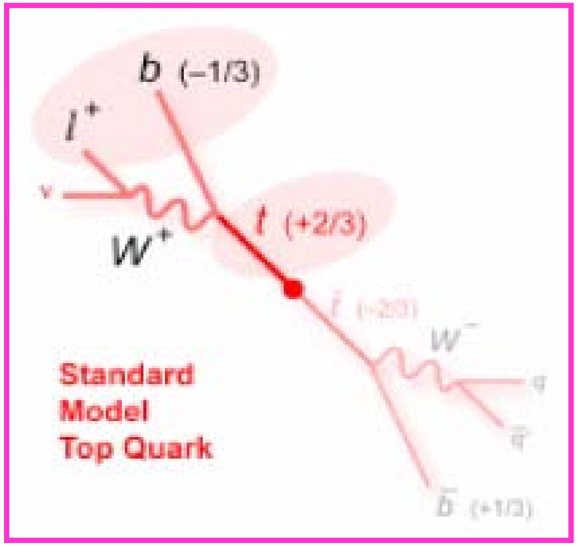
Assuming SM:

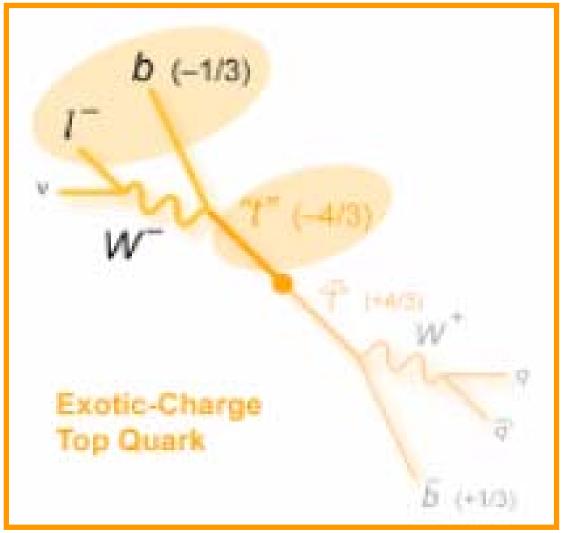
$|V_{tb}|^2 = Br(t\rightarrow Wb)$

95% C.L. : $R>0.61$, $|V_{tb}|>0.78$

PLB 639, 616 (2006)

Top Quark Charge





- In SM, top charge +2/3 e
- $t \rightarrow W^+ b$
- leptonic decay: $Q1 = |q_l + q_{bl}|$
- Hadronic decay: $Q2 = |-q_l + q_{bh}|$

- Exotic, top charge -4/3 e
- "t" $\rightarrow W^- b$
- leptonic decay: $Q1 = |-q_l + q_{bl}|$
- Hadronic decay: $Q2 = |q_l + q_{bh}|$

- Lepton + jets sample: at least 4 jets, 2 b-tagged jets
- Compute top quark charge
  - Discriminate between b and bbar jets
  - Associate lepton with correct b-jet

Top Quark Charge (2)

$$q_{jet} = \frac{\sum_i q_i \, p_{T_i}^{0.6}}{\sum_i p_{T_i}^{0.6}}$$

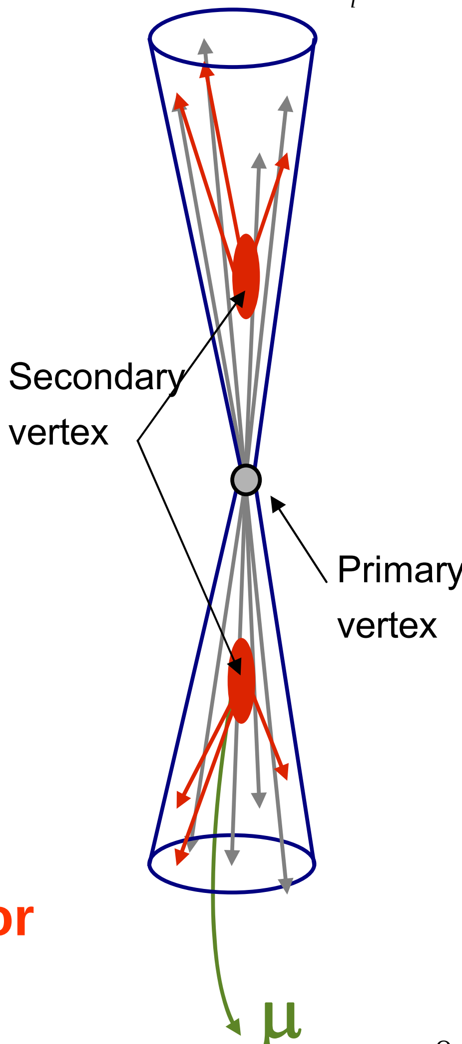
Jet charge

- Sum charge q_i of tracks in jet weighted by p_T
- Apply to jets identified as b-jets by displaced vertex (secondary vertex tagging --- SVT)

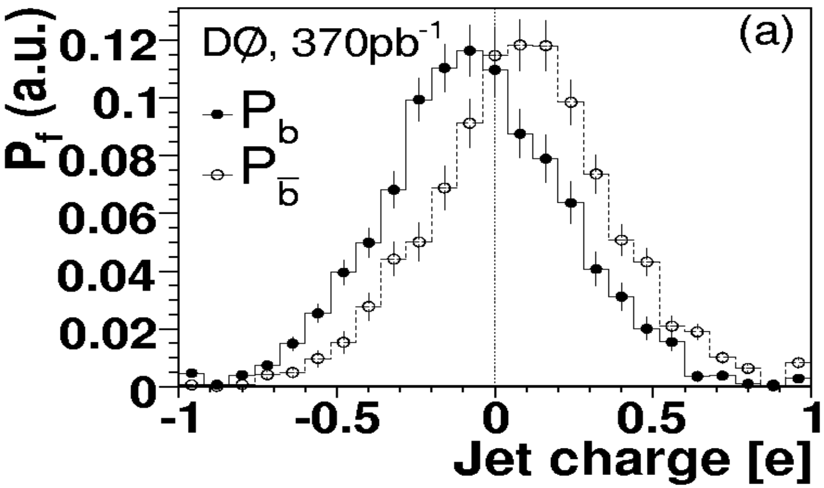
Dijet collider data (enhanced in heavy flavor)

- Exactly two jet
  - Both SVT-tagged (tight dijet sample)
  - “Tag jet” not required to be tagged (loose dijet sample)
- Require “tag jet” to contain a muon
  - Direct B/D meson decay
  - Charge flipping processes
    - B → D meson cascade decay
    - Oscillated neutral B meson
- “Probe jet” (opposite side) charge measured: q_{jet}
- Fraction of c-cbar events considered

→ Extract P_f (charge distribution when jet is of flavor f = b, bbar, c, cbar) from data



Top Charge (3)

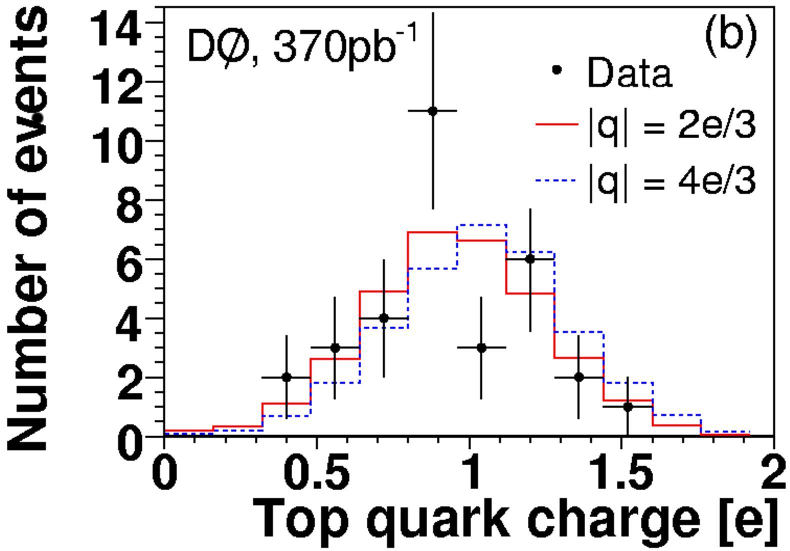


Jets and lepton can be assigned according to many permutations

- Measured 4-vectors of jets and lepton are fitted to ttbar event hypothesis (constrained kinematical fit)
- Associate lepton with b-jet by selecting permutation with the highest probability of arising from ttbar event

First Measurement of the top quark electric charge

- Events with 2 b-tags: low statistics (21 events) but large S/B ~ 11



Expected charge templates

- MC simulation + jet charge data

Data prefers Standard Model

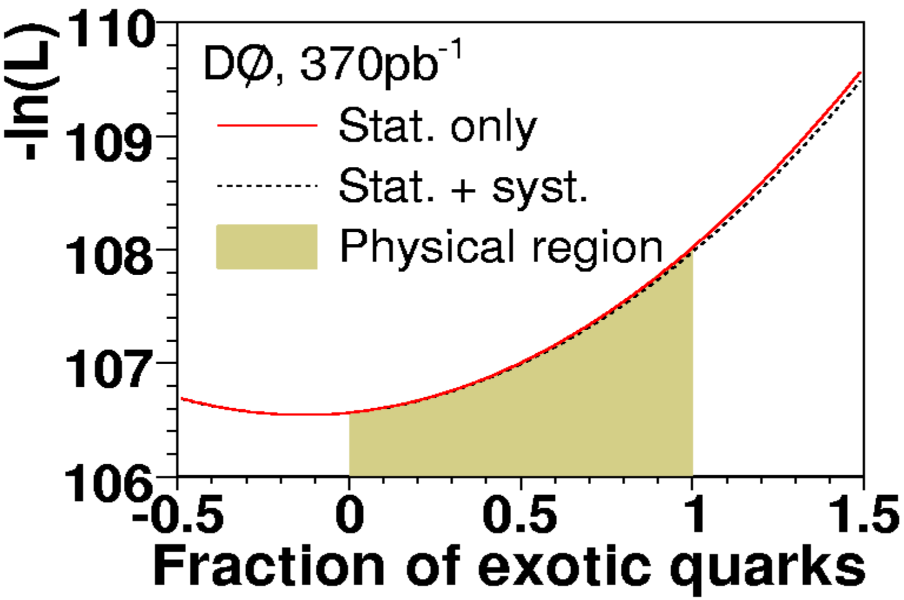
- Statistically limited
- Careful control of systematic uncertainties
  - Statistical uncertainty on the kinematic correction
  - Uncertainty of the dijet data production mechanism

Top Charge (4)

Likelihood ratio test

- **Ratio $\Lambda = P_{SM}/P_{EX}$ measured in data**
- **Nuisance parameter to include systematics**
- **Compared with expected distributions in SM & exotic scenarios**
  - Observed 'Bayes factor': 4.3 (positive)
  - p-value=0.078 (assuming exotic model as null hypothesis)
  - p-value=0.45 (assuming SM model as null hypothesis)

→ Exclude 100% exotic quark scenario up to Max. 92% C.L.



Mixture of charges not excluded

- **Perform maximum likelihood fit**
- **Fraction ρ of exotic quark pairs**

$$-0.13 \pm 0.66 \ stat \ \pm 0.11 \ syst$$

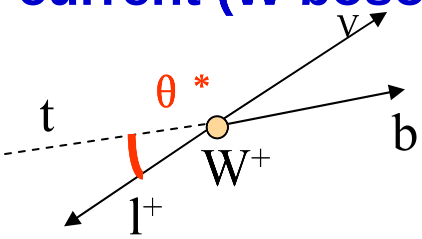
$\rho < 0.80$ @ 90% C.L.

PRL 98, 041801 (2007)

W Helicity

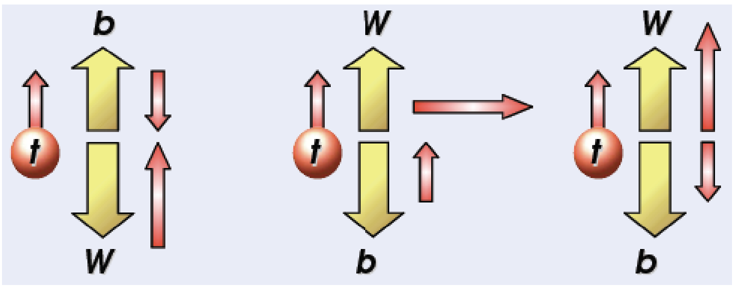
SM Theory :

- **Top quark decays via V-A charged current interaction**
- **Due to the observed Parity violation, charged current (W boson) only couples left handed particles**



New physics:

- **V+A charged current interactions**
  - Alter the fractions of W bosons produced in each of three possible polarization states



Left handed	Longitudinal	Right handed
$f_- \sim 0.30$	$f_0 \sim 0.70$	$f_+ \sim 1.4*10^{-3}$

Non-zero f_+ :

sign for new physics!

In this analysis, fix $f_0 = 0.70$

Measure W Helicity through cos(θ*) distribution

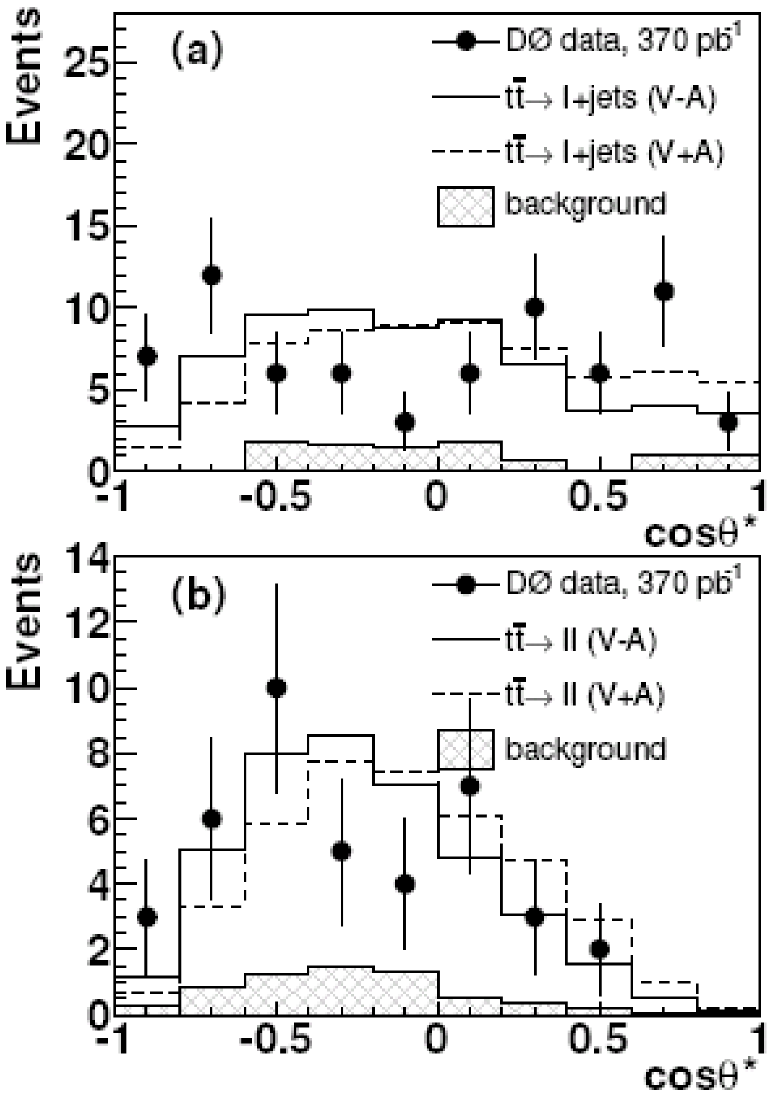
- **θ* : angle between the top quark flight direction and the charged lepton momenta in the W rest frame**
- **3 components in cos(θ*) distribution: 3 helicity states**

W Helicity (2)

Data sample enriched in ttbar events

- **Two final states**
  - **Dilepton**
    - Background: Drell-Yan, diboson, Fake lepton
    - Kinematics and topology cut
  - **Lepton + jets**
    - Background: W+jets, multijet production
    - Multivariate selection
    - Likelihood discriminant
- **For each selected event**
  - Reconstruct the top quark & W boson leptonic decay
  - Compute cos(θ*)
- **Compare the cos(θ*) distribution obtained in data to different signal hypotheses:**
  - MC ttbar samples with:
    - Fixed $f_0 = 0.70$
    - Different f_+ values
- **Use pseudo-experiments to estimate systematic uncertainties**

W Helicity (3)



Reconstruct top quark and W boson four-vector

- **Lepton + jets: using constrained kinematic fit**
- **Dilepton: M_{top} assumption, algebraic resolution & average over the possible (lepton, jet) pairings**

Cos(θ*) distribution

- **Signal for different f_+: V-A and V+A**
- **Include both data and background distributions**

W Helicity (4)

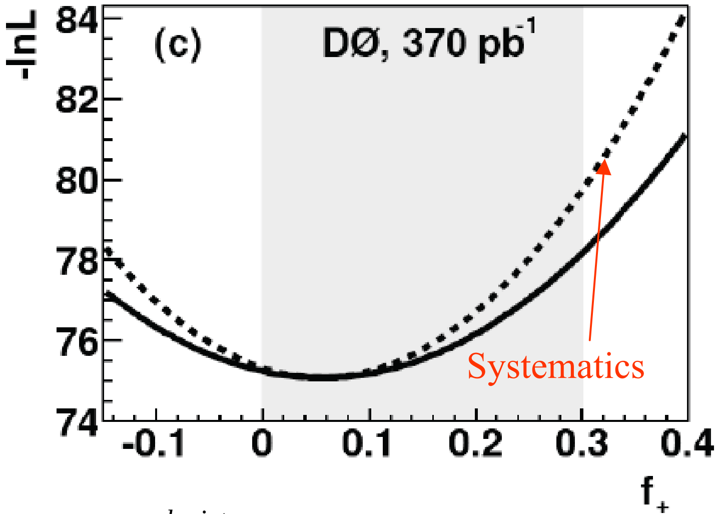
Poisson likelihood L(f_+)

- Compute binned likelihood for the data to be consistent with the sum of signal and background at each of seven chosen f_+ values
- Background normalization is constrained within errors with the expected value by a Gaussian term in the likelihood
- A parabola is fit to the –ln[L(f_+)] points to determine the likelihood as a function of f_+

Likelihood maximization

- find which f_+ value best reproduces data distribution

PRD 75, 031102(R) (2007)



$$f_+^{l+jets} = 0.11 \pm 0.09\,(stat)$$

$$f_+^{dilepton} = -0.09 \pm 0.15\,(stat)$$

$$f_+ = 0.056 \pm 0.080\,(\mathrm{stat}) \pm 0.057\,(\mathrm{syst})$$

$$f_+ < 0.226\ \ @95\%\,\mathrm{C.L.}$$

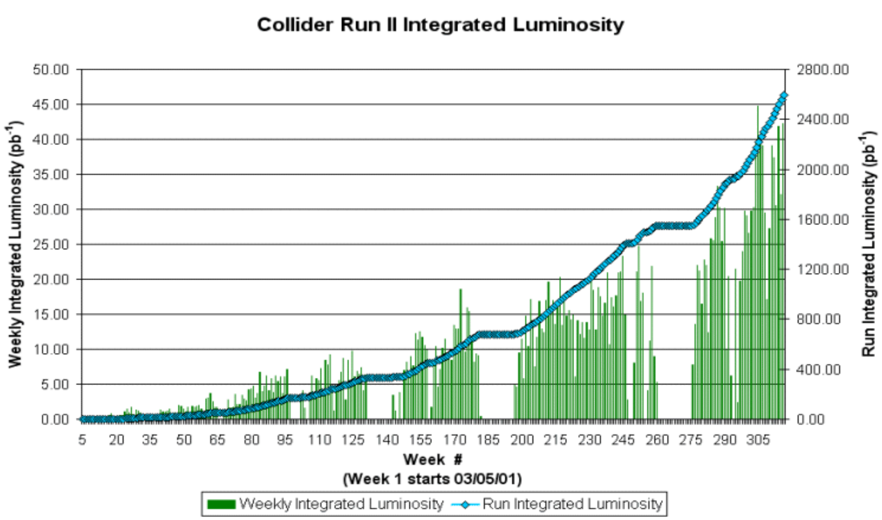
Compatible with predicted SM value

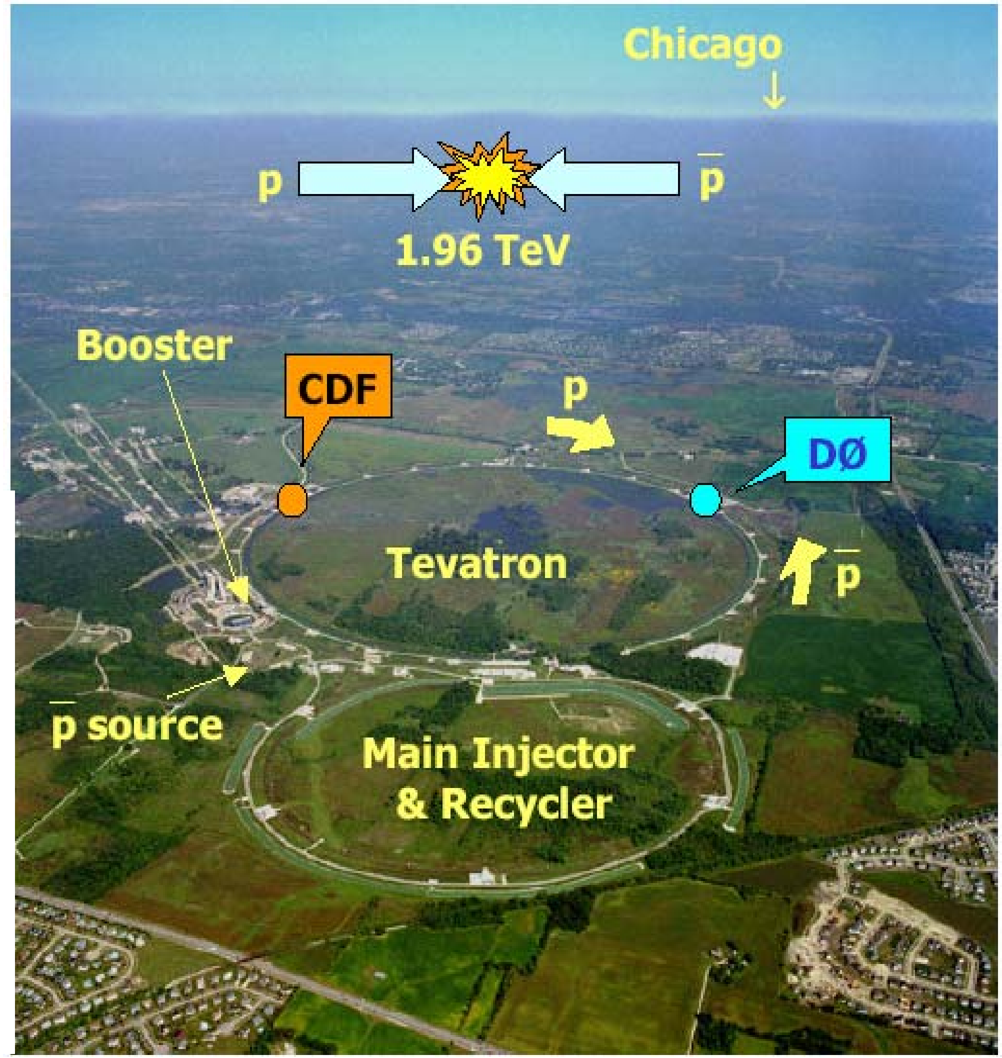
f_+ = 1.36 x 10-3

Backup Slides

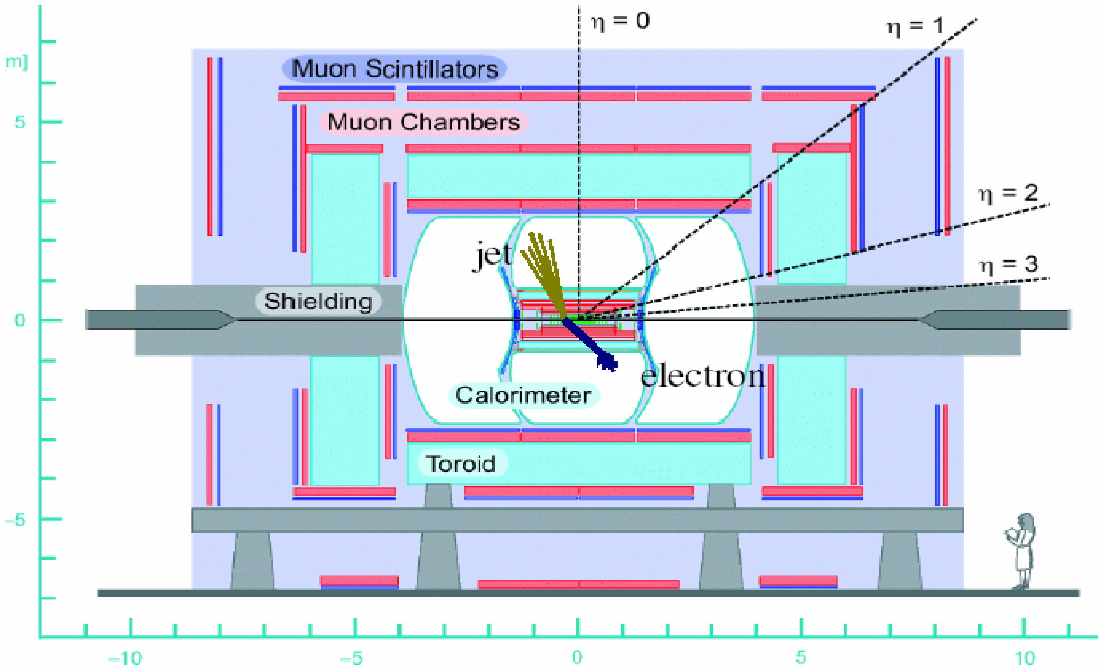
The Fermilab Tevatron

- Highest energy accelerator currently in operation
- Experiments at D0 and CDF
- Data delivered: >2fb^{-1}
  - Goal of RunII is 4-9fb^{-1}





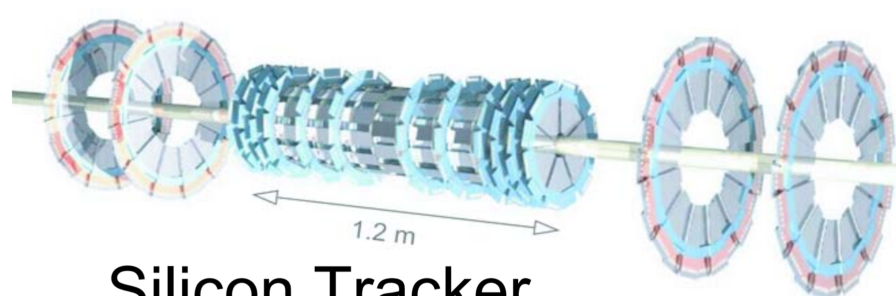
The D0 Experiment



Tracking
- Silicon + fiber tracker
- 2T magnetic field solenoid
- Pre-shower detectors

Calorimeter
- Liquid argon (EM+HAD)

Muon system
- Wire chambers
- 1.8 T iron toroid



Silicon Tracker

Br(t→Wb) Systematic Uncertainites

Summary of statistical and systematic uncertainties on R

Uncertainties on R			
Statistical	$+0.17$		-0.15
b-tagging efficiency	$+0.06$		-0.05
Background modeling	$+0.05$		-0.04
Jet identification and energy calibration	$+0.04$		-0.03
Multijet background		± 0.02	
Total error	$+0.19$		-0.17

Top Charge: Clarifications

Discussions between D0 and CDF regarding statistical treatment

- Experts debating on definitions of the C.L. (probably continues.....)

Clarification from D0 about the 92% C.L. in the paper (no errata)

- D0 provides an official clarification web page: http://www-d0.fnal.gov/Run2Physics/WWW/results/final/TOP/T06D/extra/topQ.htm
- Had we a priori chosen a rejection region at α = 5% (10%) we would (not) exclude the exotic hypothesis at the 95% (90%) confidence level based on our observation
- The maximum confidence level we could exclude the exotic hypothesis based on our observation is the 92.2% C.L. stated in the paper
- Compare sensitivity of different measurements based on the Bayes factor (4.3) or the p-value (0.078)

Top Charge Uncertainties

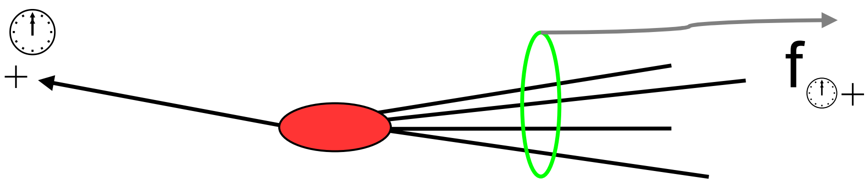
Systematic	Observed	Expected
Statistical uncertainty only	95.8	95.3
+ Fraction of $c\bar{c}$ events	95.8	95.2
+ Charge-flipping processes	95.7	95.2
+ Weighting with respect to p_T and y spectra	94.4	94.1
+ Fraction of flavor creation	93.7	93.4
+ Statistical error on P_f	93.3	93.1
+ Jet energy calibration[a]	92.4	91.8
+ Top quark mass	92.2	91.2

Jet Charge Extraction (1)

Parametrize jet charge distribution on "probe jet" side in the triple tag selection by:

- fraction of ccbar events → x_c
- fraction of events with "flipped" tag muon charge (B-mixing, cascade, etc,...) → x_{flip}
- the real jet charge distributions for b- and c-jets

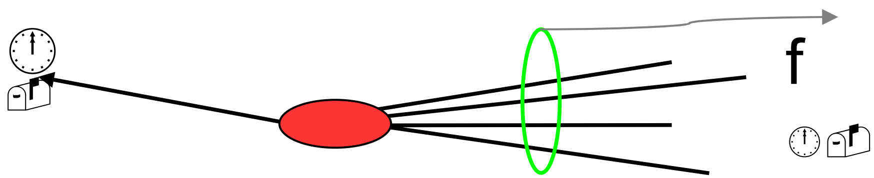
$$f_b, f_b, f_c, f_c$$



$$f_1 = 1 - x_c \quad x_{flip} \times f_b \quad x_{noflip} \times f_b \quad x_c \times f_c$$

From data (ptrel templates)

From simulation

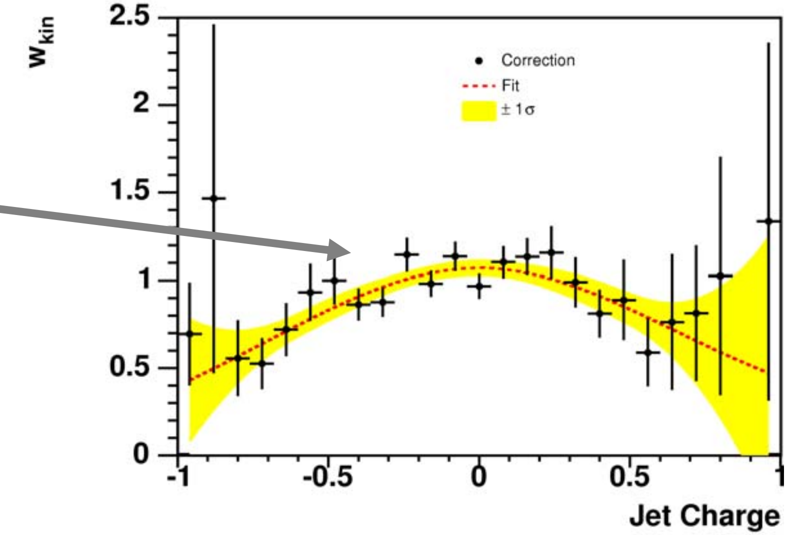


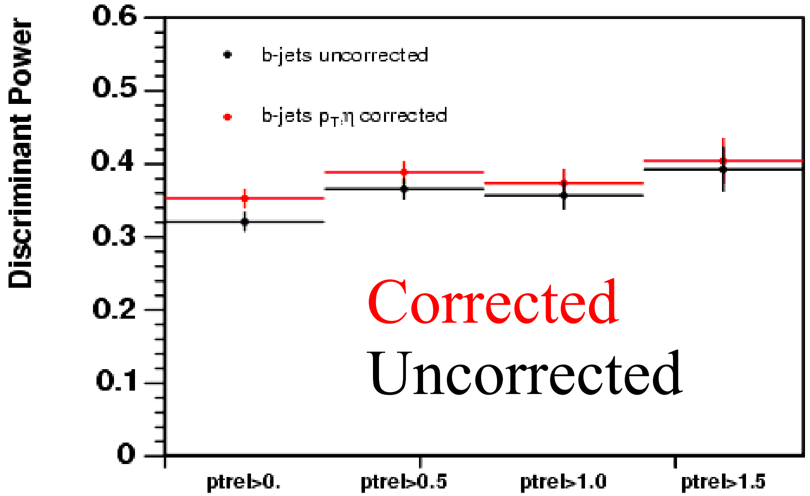
$$f_{-1} = 1 - x_c \quad x_{flip} \times f_b \quad x_{noflip} \times f_b \quad x_c \times f_c$$

Jet Charge Extraction (2)

- The correction function is defined as the ratio of the weighted and unweighted jet charge distribution (distributions denoted as f)

$$f_b^{w}(Q) = f_b^{bb}(Q) \times \frac{f_b^{tt\ w}(Q)}{f_b^{tt}(Q)}$$





- The correction improve discrimination
  - As expected from the study on p_T dependence

W Helicity Ensemble Tests

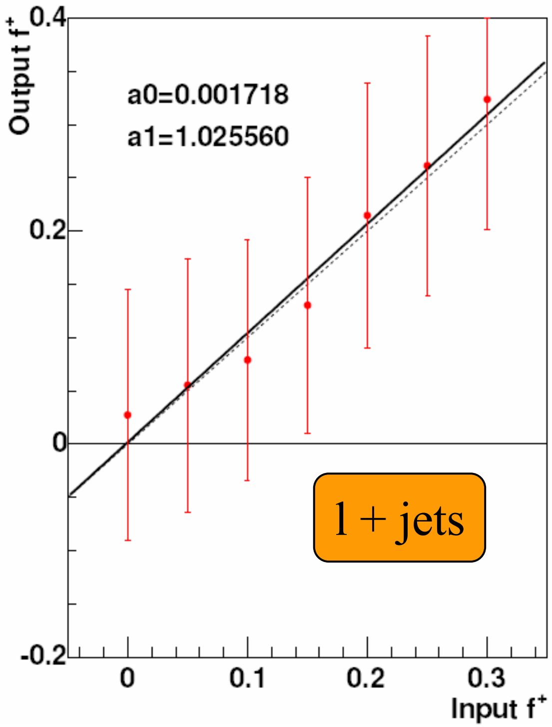
Test of the maximum likelihood performance

Create a "pseudo-dataset" of MC events with :

- the same number of MC events as observed in the data
- the signal/background composition can fluctuate according to a binomial distribution ($n_{bkg} = N_{tot}^{observed} - n_s$)

Compare the fitted f_+ to the known input f_+

Repeat the procedure 1000 times for each f_+ value



Evaluation of systematic uncertainties

- Varying parameters can affect both the data sample composition (different selection efficiency of the likelihood discriminant) and the shape of cos(θ *) distributions.
- Effect on the fitted f_+ : studied with pseudo-experiments (varying the parameters in the peudo-dataset)
- Source : Jet Energy Scale, M_{top} , MC statistics, heavy flavor content (W+jets), …

$\Delta f_+ \sim 0.03$ to 0.04 (for each one)

W Helicity Uncertainties

TABLE II: Systematic uncertainties on f_+ for the two channels and for their combination.

Source	ℓ+jets	Dilepton	Combined
Jet energy scale	0.038	0.039	0.038
Top quark mass	0.019	0.028	0.021
Template statistics	0.037	0.024	0.028
$t\bar{t}$ model	0.006	0.018	0.009
Background model	0.007	0.007	0.005
Heavy flavor fraction	0.018	–	0.015
Calibration	0.018	0.010	0.016
Total	0.063	0.059	0.057

$$f_+ = 0.109 \pm 0.094(\text{stat}) \pm 0.063(\text{syst})$$

$$f_+ = -0.089 \pm 0.154(\text{stat}) \pm 0.059(\text{syst})$$

$$f_{V+A} = 0.187 \pm 0.267(\text{stat}) \pm 0.190(\text{syst})$$

$$f_{V+A} < 0.77 \text{ @ } 95\% \text{ C.L.}$$