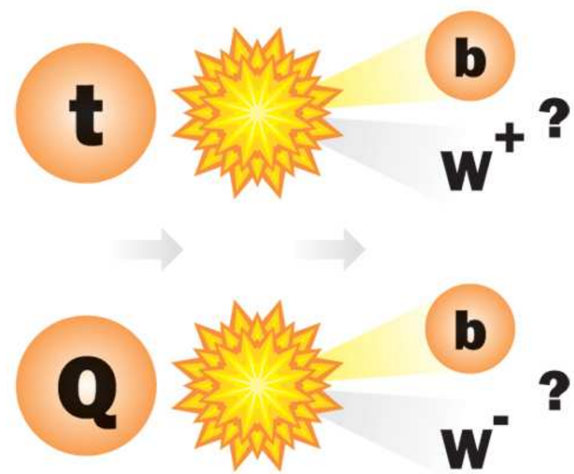
# Measurement of the Top Quark Charge at DØ

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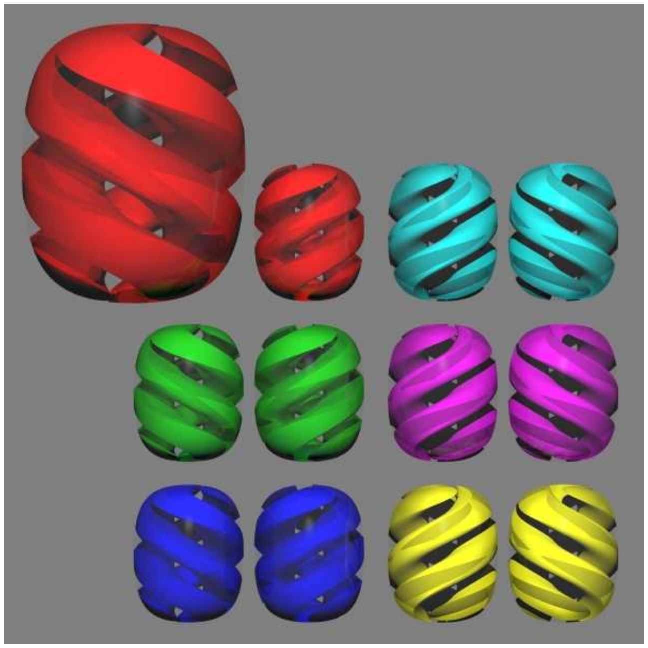
## Introduction

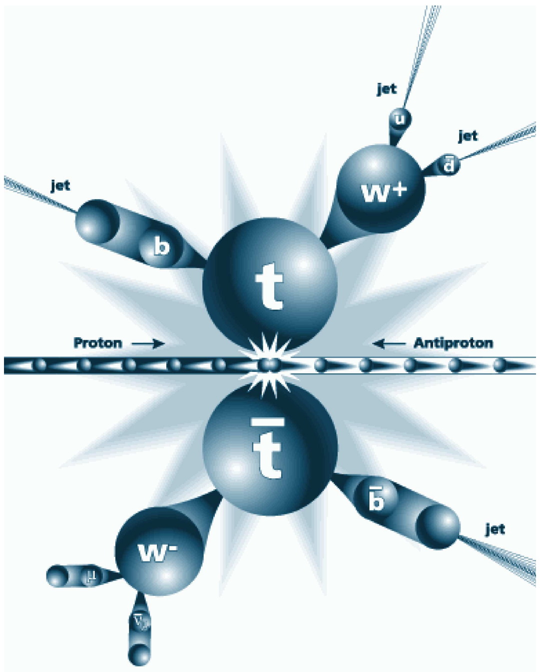
- It is widely believed that the particle found at Fermilab in 1995 is the top quark predicted in the Standard Model.
- So far only pair produced top quarks have been observed.
- Single top production via the EW interaction is yet to be discovered.
- Currently measured properties are consistent with those of the SM top.
- Many properties still poorly known.
- Electric charge was not determined.



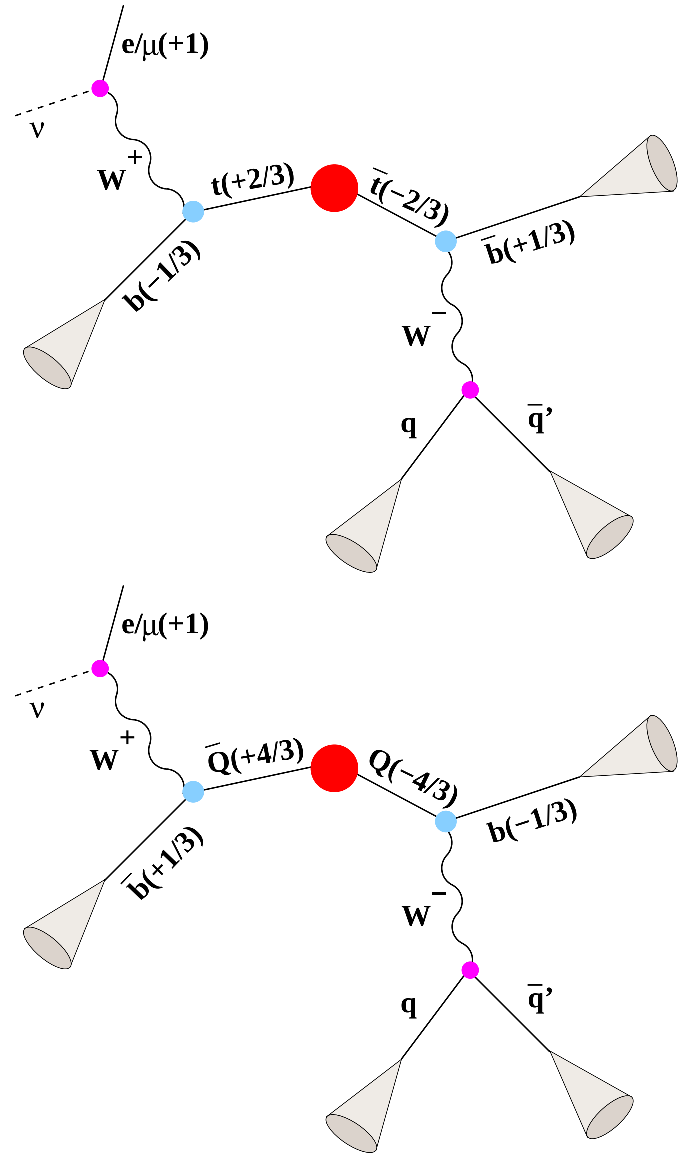
Artist: Jan-Henrik Andersen

# Standard Model Top Quark Decay

- In the SM, top decays to $Wb$ almost 100% of the times.
- Thus the final state is determined by the decay of the $W$.
- In the lepton+jets channels:
  - One $W$ boson decays leptonically. ($W \to e/\mu + \nu$)
  - One $W$ boson decays hadronically. ($W \to q\bar{q}'$)
  - Final state contains 4 jets, one lepton and $\not{E}_{\mathrm{T}}$.
  - Clean signal and large BF ($\sim$ 34%).

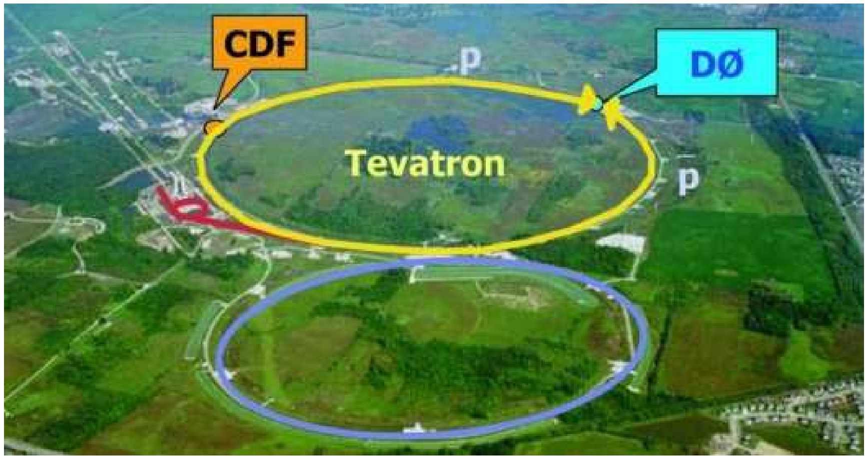


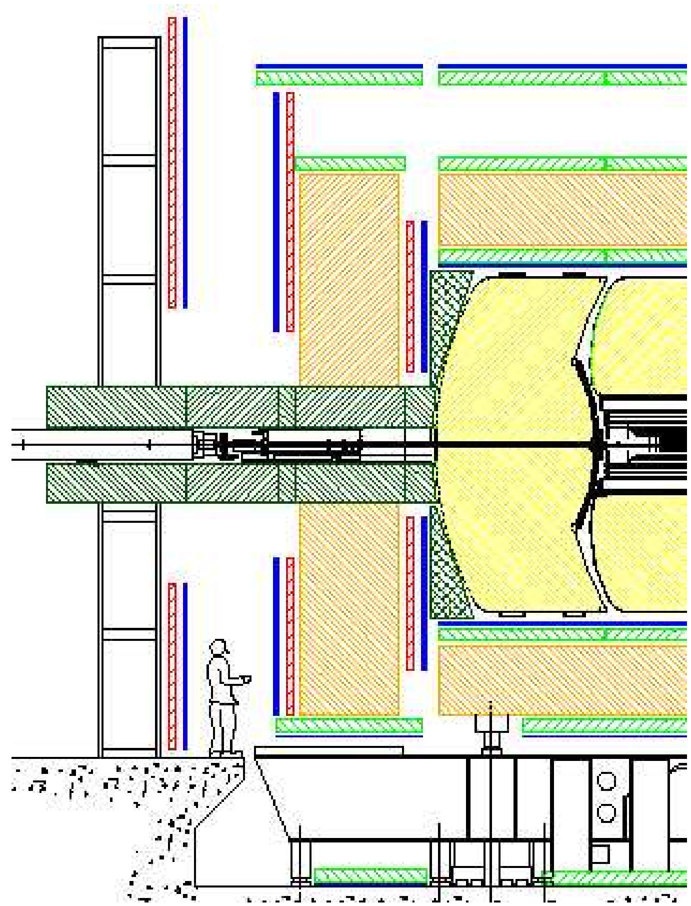
- In the SM the top quark has charge $q = +2e/3$.
- Ambiguity when pairing the $W$ boson to the $b$ quark jet in top pair events.
- Discovered particle can have charge $|q| = 2e/3$ or $|q| = 4e/3$.
- Model exist which introduce exotic doublet with charges $q = -1e/3$ and $-4e/3$ (*).
- The $q = -4e/3$ would be the quark observed at Fermilab.
- The SM top quark in this model would be heavy ($\approx 270$ GeV).




(*) D. Chang, W. Chang, E. Ma, Phys. Rev. D **59**, 091503, **61**, 037301, D. Choudhury, T. M. Tait, C. E. Wagner, Phys. Rev. D **65** 053002.

# Tevatron and DØ



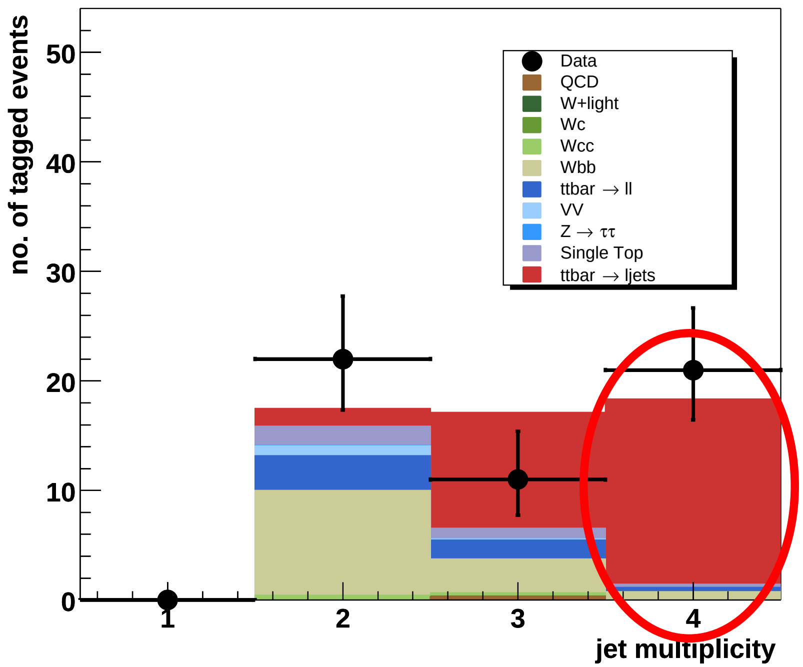



- Fermilab is the only place where top quarks can be produced.
- Collide $p$ and $\bar{p}$ at $\sqrt{s} = 1.96$ TeV.
- Two experiments, CDF and DØ.
- DØ is a multipurpose detector.
- Central tracking, calorimeter and muon system up to large $\eta$.

# The Data Sample

- Use 370 pb$^{-1}$ of DØ data in the lepton+jets final states.

- Events must have:
  - One $e$ or $\mu$.
  - Large $\not{E}_T$.
  - $\geq 4$ jets.
  - 2 jets $b$-tagged by the secondary vertex algorithm.



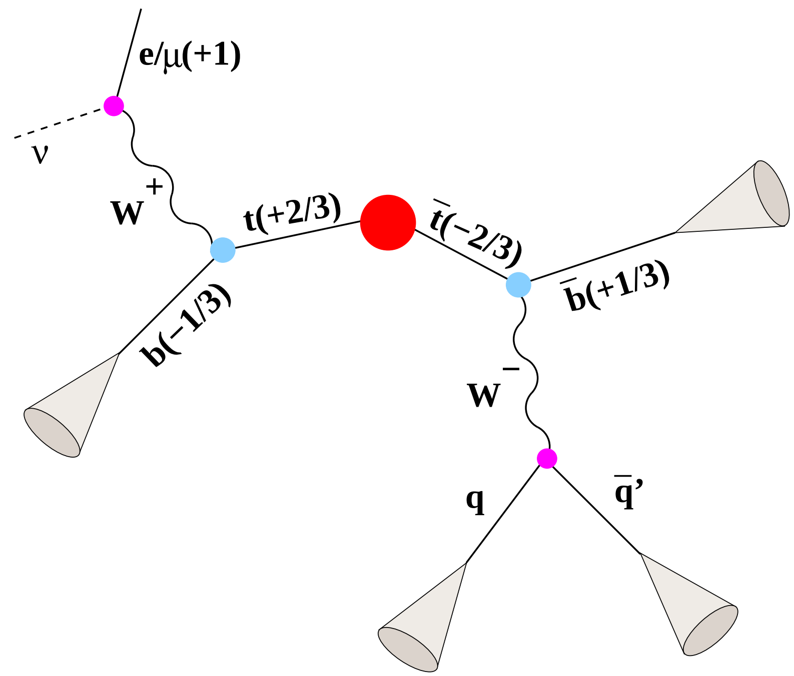

- These cuts give a very clean $t\bar{t}$ sample of 21 events.
- Two $b$-tagged jets gives less ambiguity when pairing jets to $W$s.

# The Top Quark Charge

- The charge of the top quark is given by the sum of the charges of its decay products.
- We measure the absolute value of the top quark charge as:

- $Q_1 = |q_l + q_b^l|$.
- $Q_2 = |-q_l + q_b^h|$.

1. Determine charge of lepton.
2. Measure charges of $b$-jets.
   - Using jet charge algorithm.
3. Associate $q_b^l$ and $q_b^h$.
   - Using a kinematic fit.

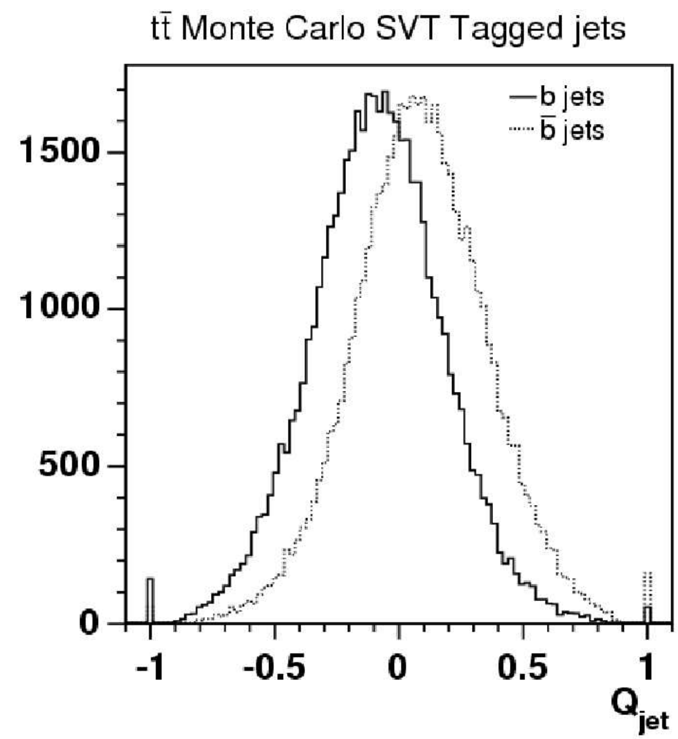


# The Jet Charge Algorithm

- Sum the charges of the tracks associated with the jet.
- The sum is $p_T$ weighted.

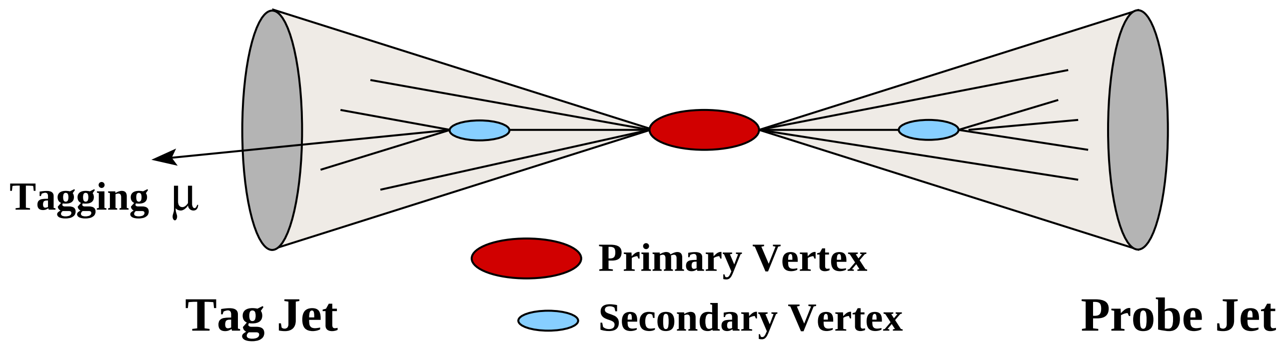
$$q_{jet} = \frac{\sum_i q_i p_{T_i}^{0.6}}{\sum_i p_{T_i}^{0.6}}$$

- Performance in Monte Carlo is given by jet-parton matching.
- Monte Carlo is unable to describe fine details of tracking, such as hit multiplicities etc.
- Need to get performance of jet charge algorithm on data.



# Calibration Using Data

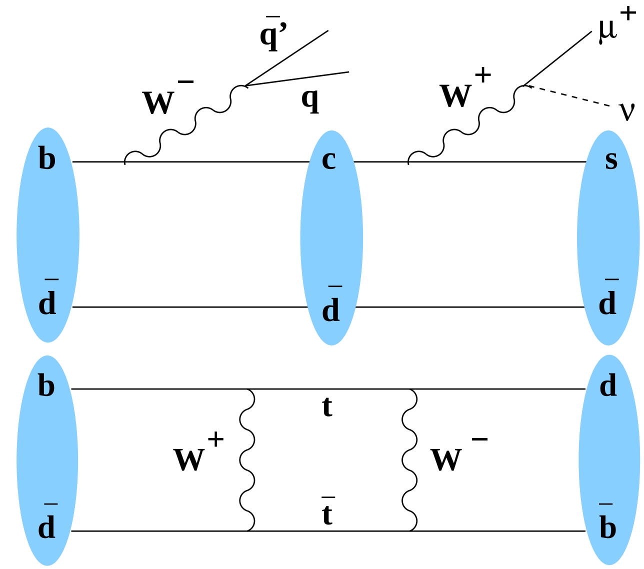
- Select a "pure" $b\bar{b}$ sample in data by the Triple Tag method.




  - Exactly 2 jets back-to-back ($\Delta\phi > 3.0$).
  - Both jets tagged by the SVT algorithm.
  - One jet tagged by the muon tagger.
- Use charge of tag muon to determine if probe jet is from $b$ or $\bar{b}$.

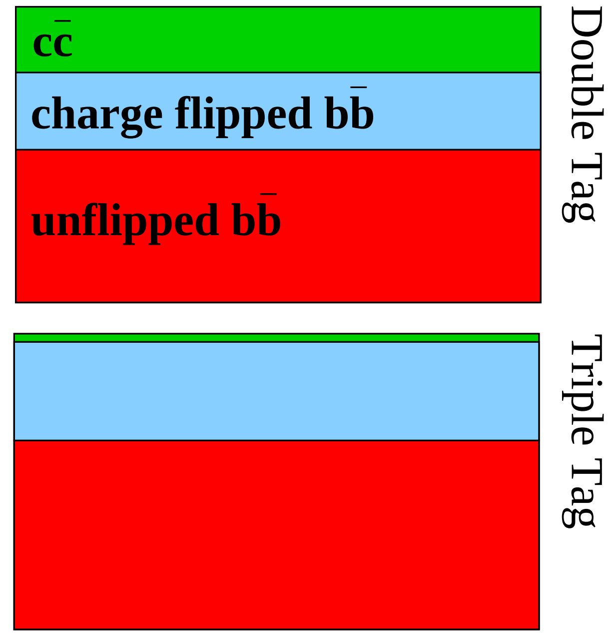
- The Triple Tag method is complicated by processes changing the sign of the tag muon:

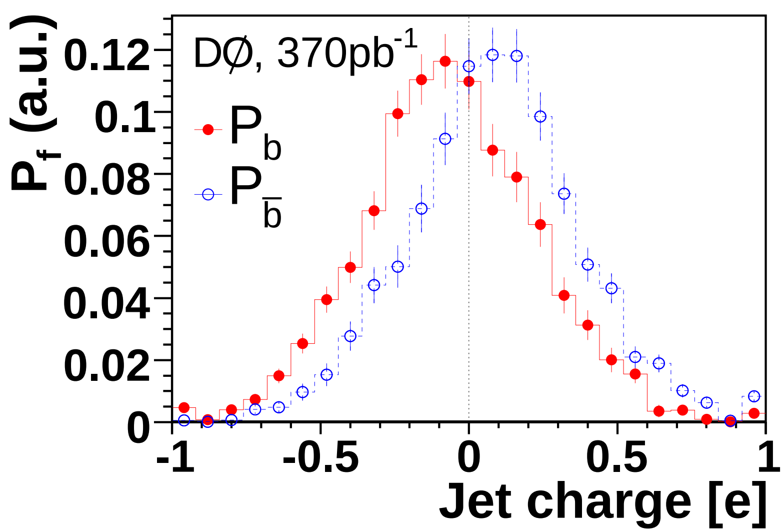
  - Charge of muon misidentified.
  - Comes from a cascade decay (B $\rightarrow$ D $\rightarrow$ $\mu$ etc).
  - Comes from the decay of a B meson after mixing.

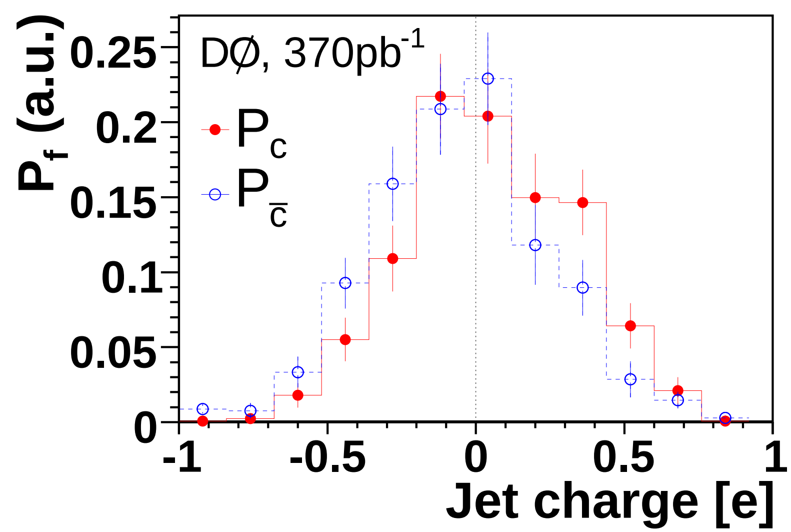



- Sample also contains background (mostly $c\bar{c}$).
- Define also a Double Tag sample where the $\mu$-tagged jet is not required to be SVT-tagged.
- The Double Tag sample has different fractions of $c\bar{c}$ and charge flipped $b\bar{b}$ events.

- Get fraction of $c\bar{c}$ events from data using $p_T^{\mu}$ relative to jet axis.
- Get fraction of events with charge flipped muon from MC.
- Extract jet charge distribution for $b$, $\bar{b}$, $c$ and $\bar{c}$ from Triple Tag and Double Tag data.

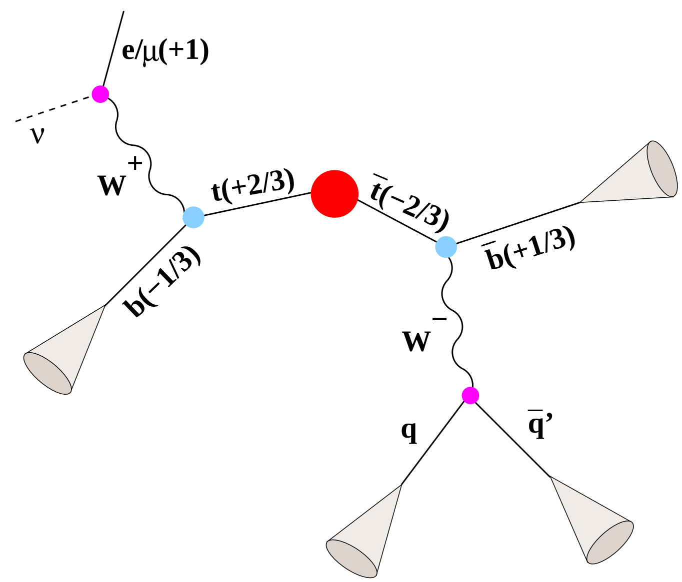


# Pairing $W$ Boson and $b$ Quark

- Use a kinematic fit to pair the $b$-jets with the $W$ bosons.
- Same fit as is used in top mass analyses.
- With 4 jets in the event there are 12 possible combinations.
- Only 2 possible combinations if we assume the 2 $b$-tagged jets come from the top decay.
- Only allow the SVT tagged jets to be assigned as $b$-jets.




- Out of the 2 possible combinations, pick the lowest $\chi^2$ solution (correct 85% of the times).

# Expected Top Quark and Exotic Quark Charge

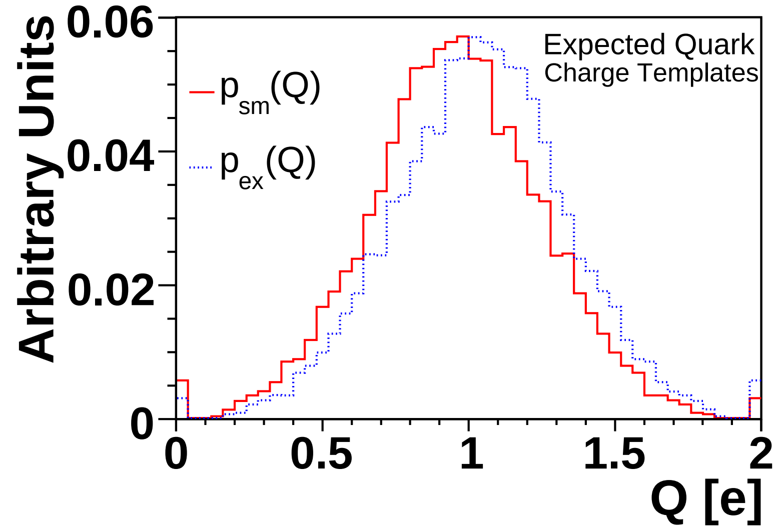
- Make kinematic fit on $t\bar{t}$ MC events to assign jets to $W$s.
- Obtain the jet flavors from the MC information.
- Use jet charges derived on data and the measured lepton change to obtain top/exotic quark charge.
- The expected quark charge distribution for background is obtained from $Wbbjj$ MC in same way as for signal.

Standard model:

$$Q_1 = |q_l + q_b^l|$$
$$Q_2 = |-q_l + q_b^h|$$

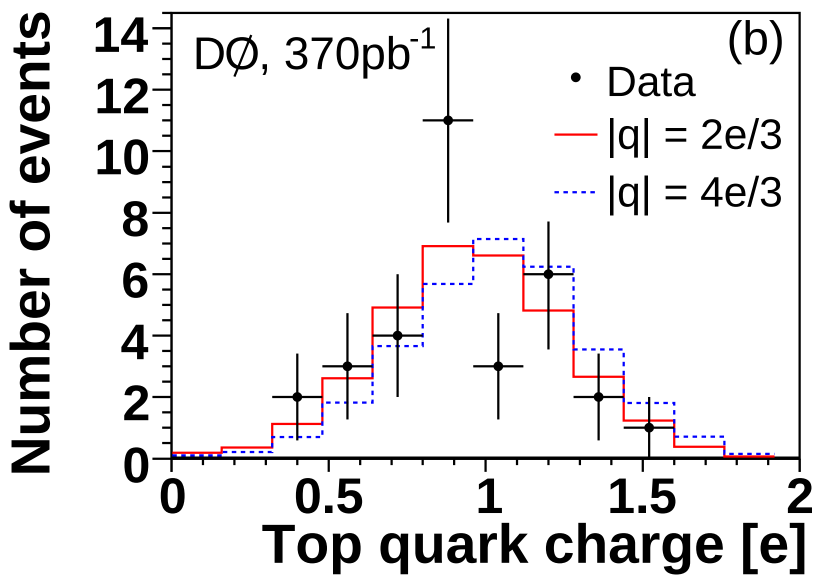
Exotic model:

$$Q_1 = |q_l + q_b^h|$$
$$Q_2 = |-q_l + q_b^l|$$



# Result

- There are 21 events in the double-tagged lepton+jets sample.
- The kinematic fit converges in 16 out of these 21 events.

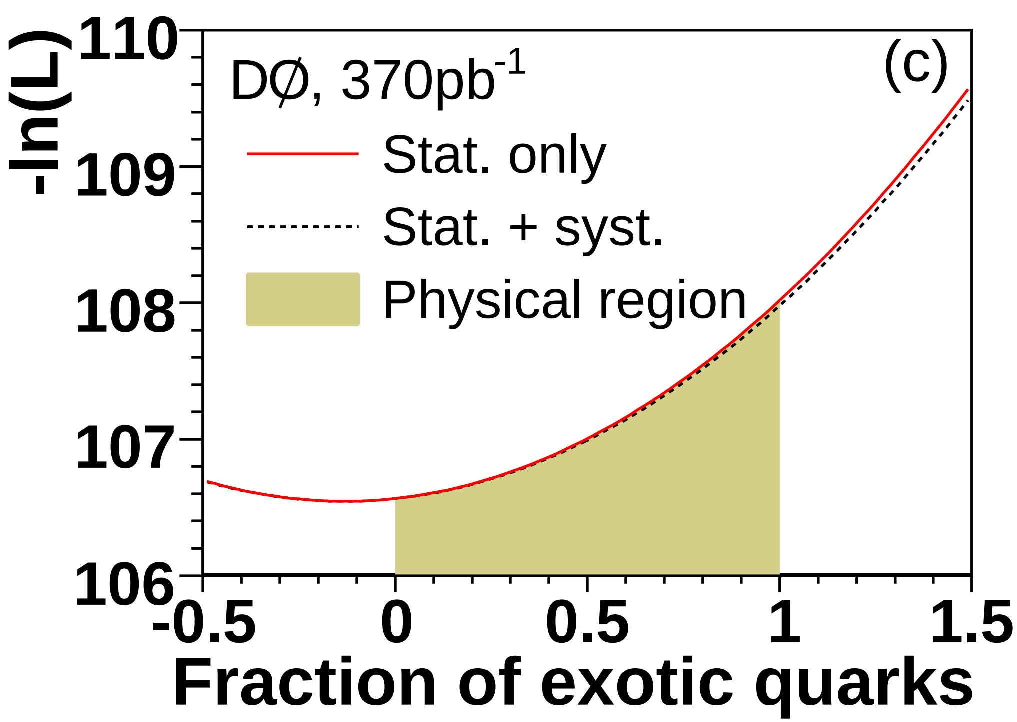



| Systematic | C.L. |
|---|---|
| Stat. uncertainty only | 95.8 |
| + Frac. of $c\bar{c}$ events | 95.8 |
| + Charge-flipping | 95.7 |
| + Reweighting, $p_T$ and $y$ | 94.4 |
| + Frac. of flavor creation | 93.7 |
| + Stat. err. on $P_f$ | 93.3 |
| + Jet energy calibration | 92.4 |
| + Top quark mass | 92.2 |

- Likelihood ratio test excludes exotic hypothesis at 92% C.L.

# Fraction of Exotic Quark Pairs

- The exclusion limit is based on 100% exotic quarks.
- Estimate fraction of exotic quarks using a maximum likelihood fit.




- $\rho = -0.13 \pm 0.66 \pm 0.11.$
- $\rho < 0.52$ @ 68% C.L.
- $\rho < 0.80$ @ 90% C.L.

# Summary

- The hypothesis of the quark seen at Fermilab being an exotic quark with charge $|q| = 4e/3$ is excluded at 92% C.L.
- Limits on the fraction of exotic quarks in the lepton+jets sample are:

  $\rho < 0.52$ @ 68% C.L.

  $\rho < 0.80$ @ 90% C.L.
- The analysis is submitted to Physics Review Letters.

# Backup Slides

- Jet charge distributions of probe jet ($P_{\mu^+}$, $P_{\mu^-}$) is a function of:
  - $f_{c\bar{c}}$: Fraction of $c\bar{c}$ events (from data using $p_T^{rel}$ fits).
  - $f_{flip}$: Fraction of events with a charge flipped muon (from MC).
  - $P_c$, $P_b$, $P_{\bar{c}}$, $P_{\bar{b}}$: Real jet charge distributions for $b$- and $c$-jets.
- For ex. $P_{\mu^+} = P_b \rightarrow P_{\mu^+} = (1 - f_{flip} - fc\bar{c}) \cdot P_b + f_{flip} \cdot P_{\bar{b}} + f_{c\bar{c}} \cdot P_{\bar{c}}$.

Triple Tag Sample:

$$P_{\mu^+} = 0.69P_b + 0.30P_{\bar{b}} + 0.01P_{\bar{c}}$$
$$P_{\mu^-} = 0.30P_b + 0.69P_{\bar{b}} + 0.01P_c$$

- Double Tag Sample: $\mu$-tagged jet not req. to be SVT tagged).

Double Tag Sample:

$$P_{\mu^+} = 0.567P_b + 0.243P_{\bar{b}} + 0.19P_{\bar{c}}$$
$$P_{\mu^-} = 0.243P_b + 0.567P_{\bar{b}} + 0.19P_c$$

# Confidence Level

- Use likelihood ratio test to extract C.L.
- $\Lambda = \frac{\prod_i P_{sm}(q_i)}{\prod_i P_{ex}(q_i)}$.
- $\Lambda_{data} = 4.27$.
- Exclusion of exotic hypothesis from data:

$$1-\alpha = 1-\int_{\Lambda_{data}}^{\infty} \Lambda_{EX} d\Lambda = 92.2\%$$