Measurement of Top Quark Properties at $\sqrt{s}$=1.96 TeV Using the D0 Detector

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on behalf of the D0 collaboration

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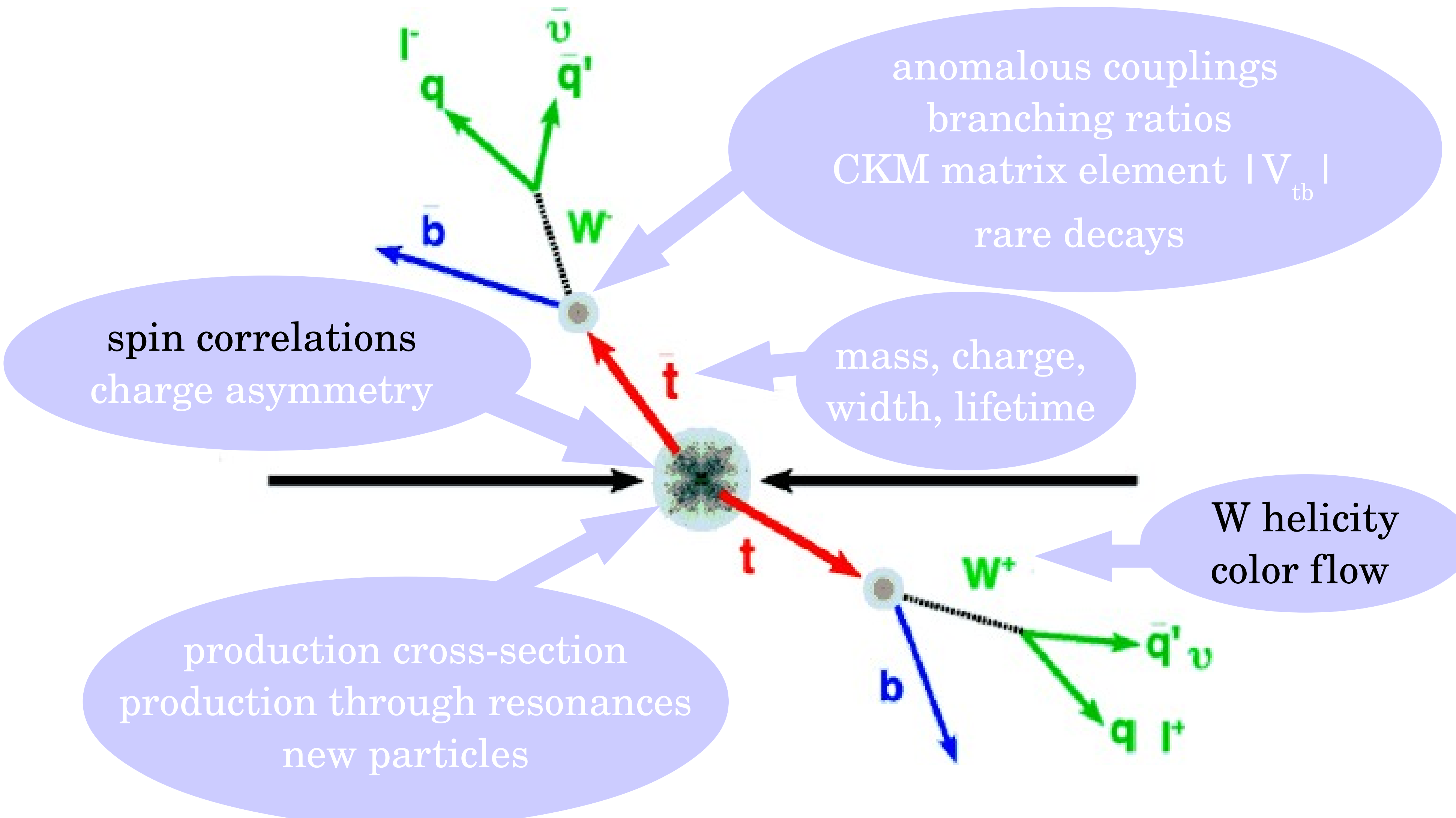
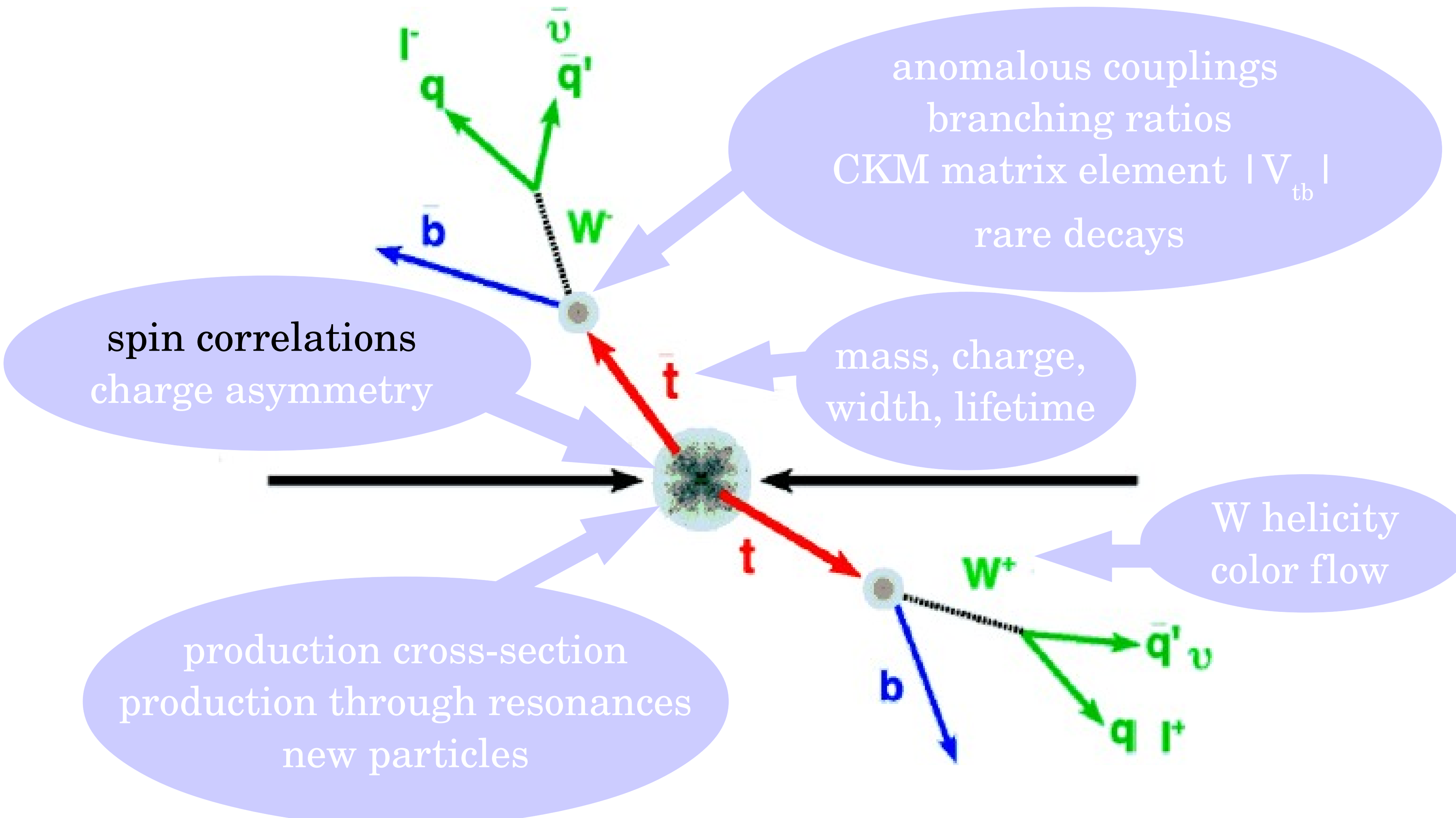
Grenoble

Top Quark Physics



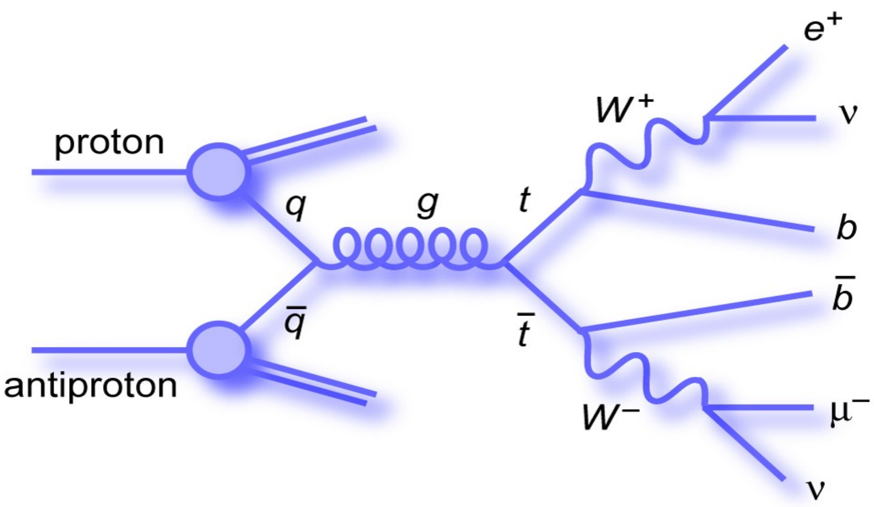
Top Quark Physics



Top Quark Spin Correlation

why measure spin correlations?

- test the **full chain** from **QCD** production to **EW** decay
- deviations could be due to
  - **additional** contributions to **production** like stop pairs, Z', etc.
  - **additional decay** of top quark to e.g a charged Higgs boson
- observation of spin correlation would set an other **upper limit** on the **top** quark **lifetime**



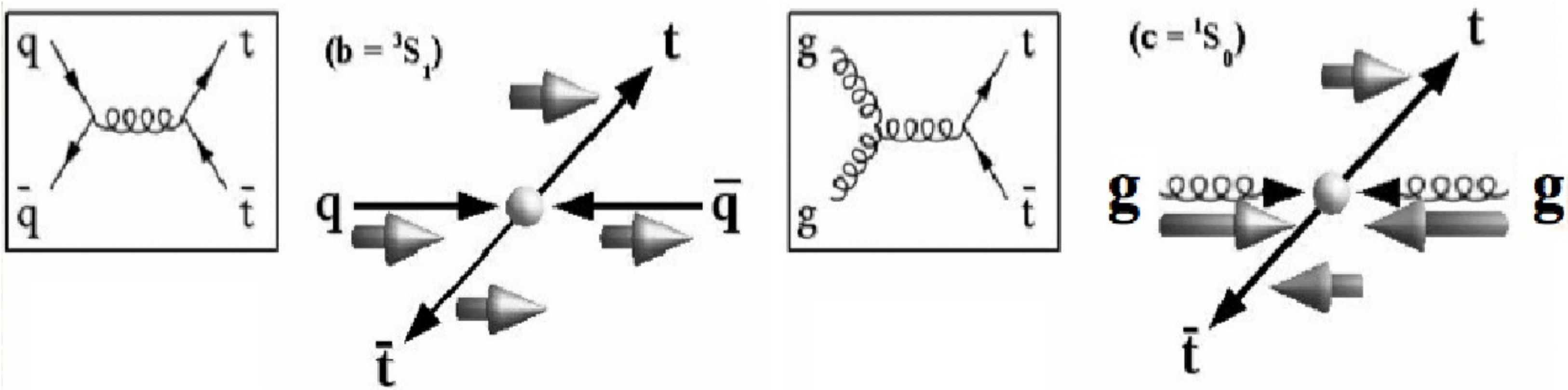
Spin Correlation in Production

- even though top quarks are not produced in a polarized state, their spins are correlated
- the spin correlation strength A can be defined as:

$$A = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\uparrow\downarrow} - N_{\downarrow\uparrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\uparrow\downarrow} + N_{\downarrow\uparrow}}$$

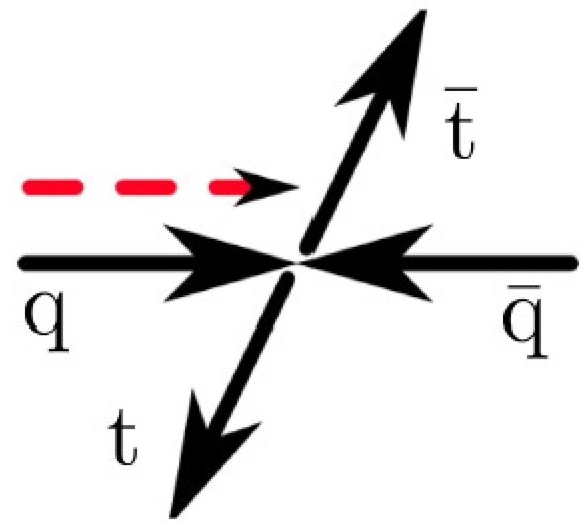
- it depends on the production mode, namely quark-antiquark annihilation or gluon-gluon fusion

=> different correlation strength for Tevatron and LHC



Spin Correlation in Production

- as any spin it also depends on the **quantization axis** with respect to which it is defined to
- here, the so-called **beam basis** is used
  - defined by the direction of the incoming quark
  - **simple** to construct
  - best for top quarks produced at threshold
  - almost **highest correlation** strength



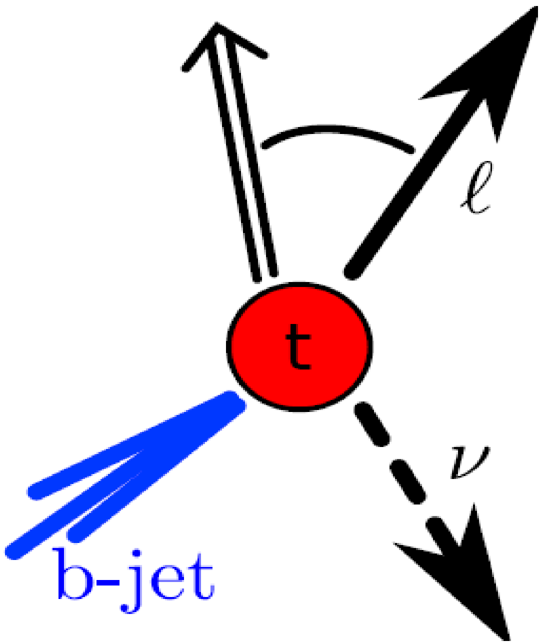
=> correlation strength at NLO using beam basis at Tevatron:

$$A = 0.777 \pm 0.042$$

Correlation in Decay

- top quark lifetime less than Λ_{QCD}
  → the **spin** does not flip and is still **visible in** the **angular** distributions of the **decay products**

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_i} = \frac{1}{2}(1+\alpha_i\cos\theta_i)$$



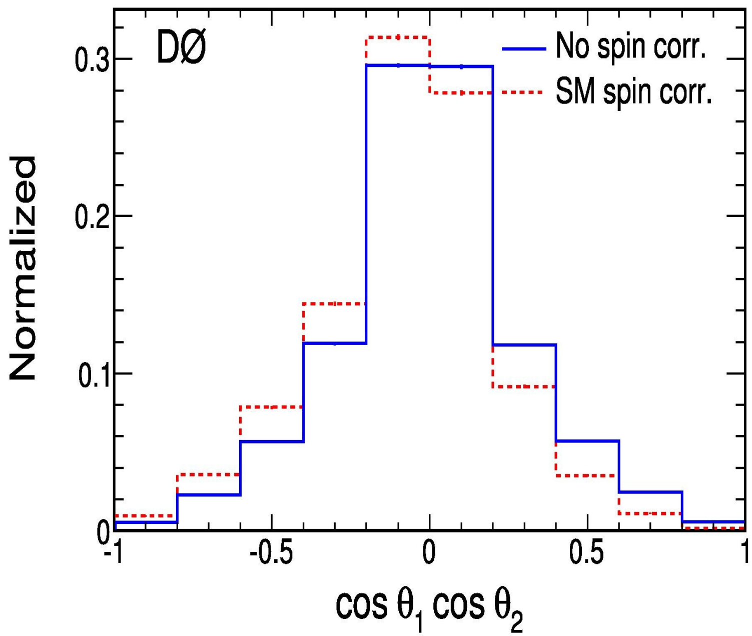
- spin analyzing power $\alpha = 1$ for charged leptons and down-type quarks
- despite the small branching fraction of the leptonic W decay, the dilepton channel is the golden channel for spin analysis:
  - **leptons** are **easier to identify** then down-type quarks
  - leptons can be **well measured**
  - **smallest background** contamination

Measuring Spin Correlations

- putting all together, spin correlations can be measured by studying **angular distributions** of charged **leptons**

$$\frac{1}{\sigma}\frac{d^2\sigma}{\cos\theta_1\cos\theta_2}=\frac{1}{4}\left(1-C\cos\theta_1\cos\theta_2\right)$$
$$where\; C = A\alpha_1\alpha_2$$

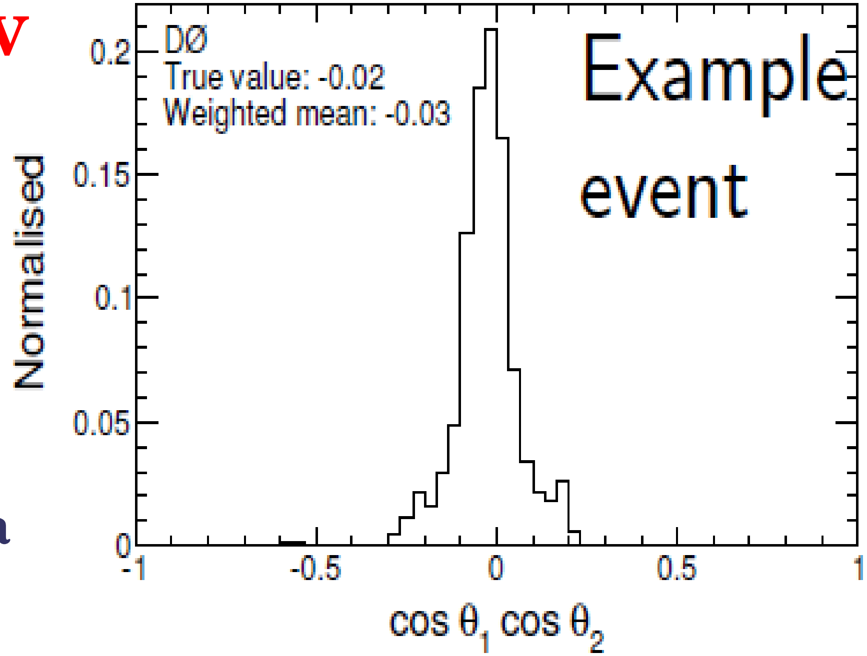
- measurement **tests** the **full chain** from production to decay
- sizeable difference between correlated and uncorrelated spins at parton level



- main challenge:
  - reconstruction of **undetected neutrino** from W decay

Event Reconstruction

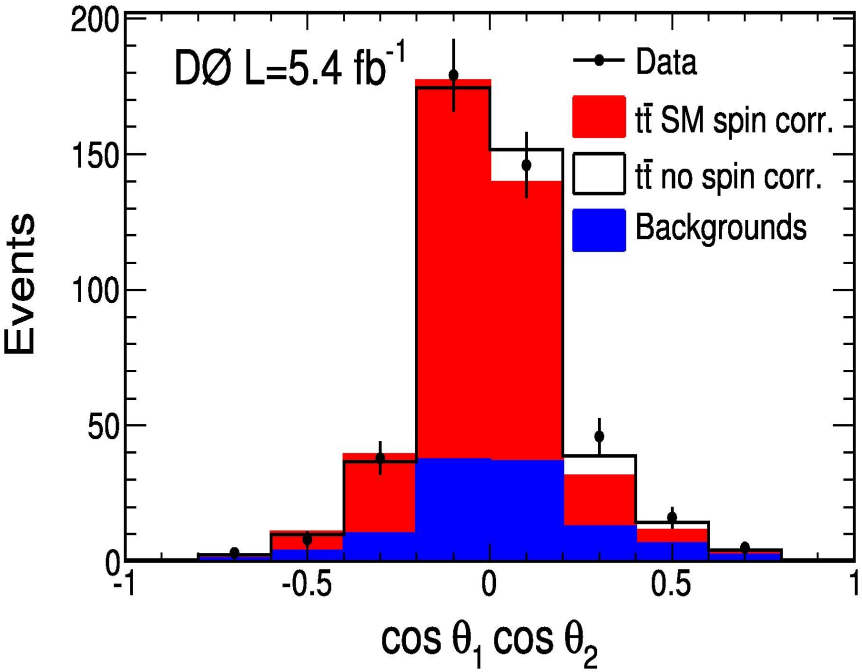
- to calculate $\cos\theta_1 \cos\theta_2$ for a single event, both neutrino momenta need to be reconstructed
  - assume top masses to be 172.5 GeV
  - W masses to be 80 GeV
  - scan over neutrino pseudo-rapidities
  - for each point in phase space weight all possible solutions by comparing the neutrino momenta to the measured missing transverse momentum



  - use weighted mean of all solutions as estimator for $\cos\theta_1 \cos\theta_2$

Extraction of Correlation Strength

- perform a **binned maximum likelihood fit**
  - mixing signal **templates** from **MC@NLO** with and without spin correlation as a function of correlation strength C
  - using different templates for each kind of **background**
- include **systematic** uncertainties as **free parameters**
- use approach of **Feldman and Cousins** to set limits or extract central value with 68% C.L.

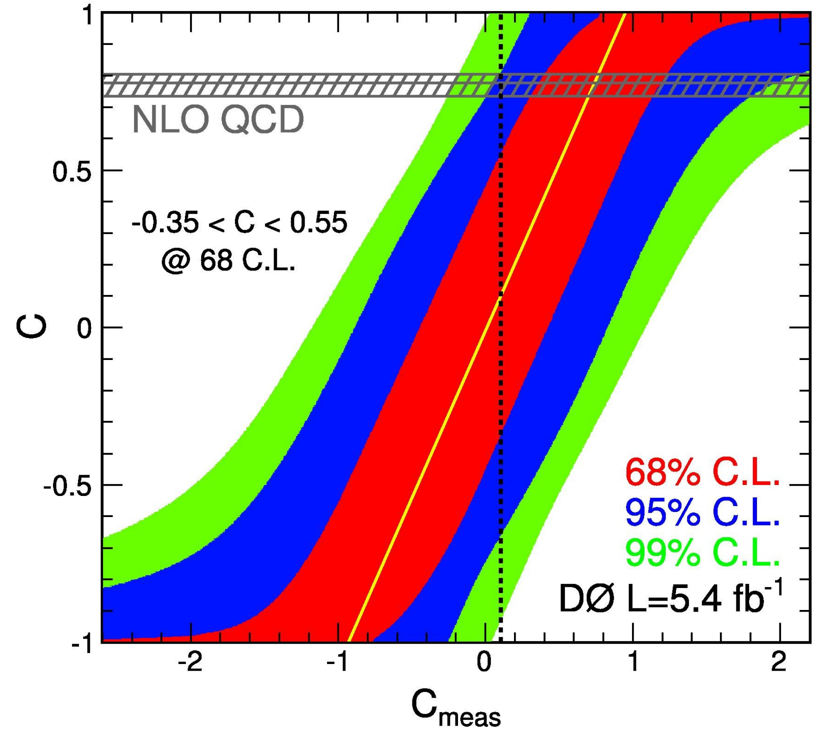


Result of Neutrino Weighting Spin

- spin correlation strength C extracted from **441** dilepton candidate **events** (~74% purity) :

C = 0.10 ± 0.45 (stat+syst)

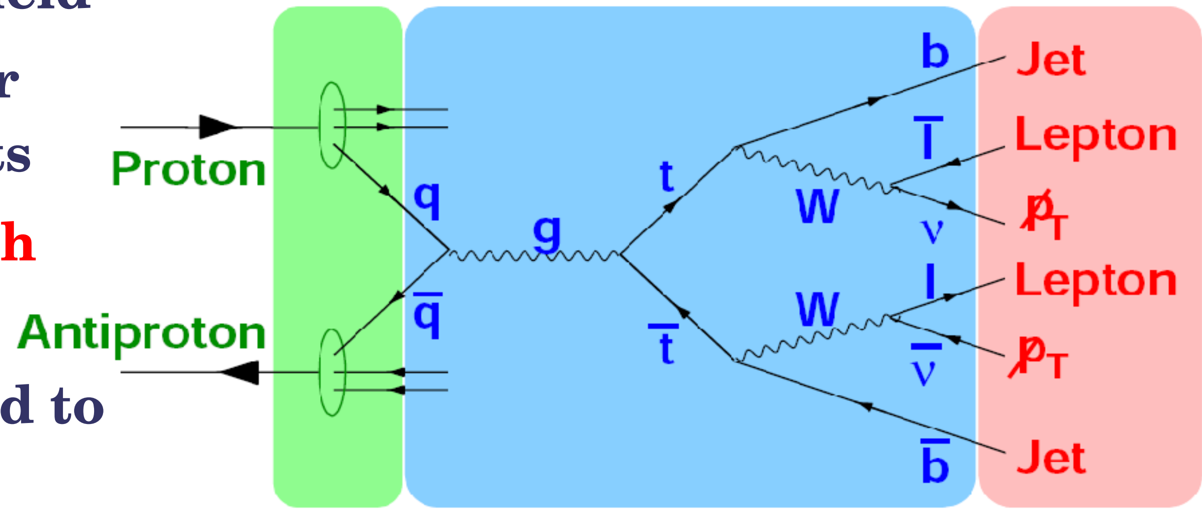
-0.66 < C < 0.81 @ 95% C.L.



- result consistent within 2 SD with QCD prediction of C = 0.777 ± 0.042 (NLO)
- measurement **dominated** by **statistical** uncertainty: **~ 0.4**
- largest **systematic** effect from MC **template statistics**: **~0.07**
- all details can be found on arXiv: 1103.1871

Matrix Element Approach

- **matrix element** methods yield
  - most **precise** results for top **mass** measurements
  - excellent tools to **search** for new particles
- **whole** event **kinematic** used to calculate the **probability** of an event to arise from a given process under **certain assumptions**



$$P(x;H) \propto \int d\epsilon_1 d\epsilon_2 f_{PDF}(\epsilon_1) f_{PDF}(\epsilon_2) \frac{|M(y;H)|^2}{\epsilon_1 \epsilon_2 s} W(x,y) d\phi_6$$

f_{PDF}: parton density functions

$M(y;H)$: ME under hypothesis H for partons y

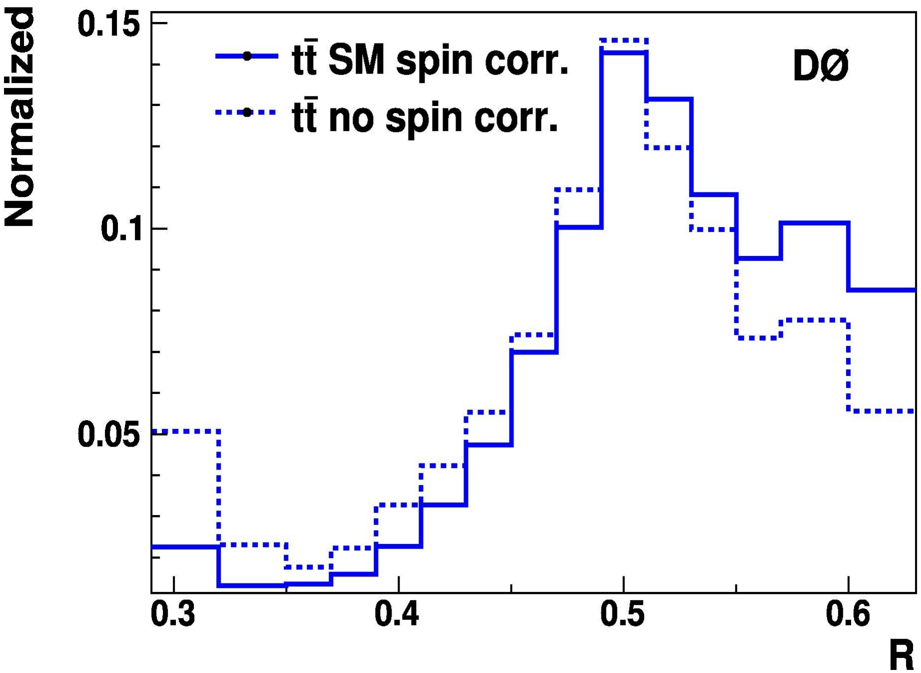
$W(x,y)$: transfer functions for measuring y as x

Matrix Element Approach for Spin

- a powerful variable R can be defined based on the **matrix element** including **spin correlation** (C) and **no correlation** (U) (S. Parke et al., PLB 411,173 (1997); K. Melnikov et al., arXiv:1103.2122)

$$R = \frac{P_{sgn}(H=C)}{P_{sgn}(H=C) + P_{sgn}(H=u)}$$

- **excellent separation** at parton level
- biggest **loss** in sensitivity due to the undetected **neutrinos**



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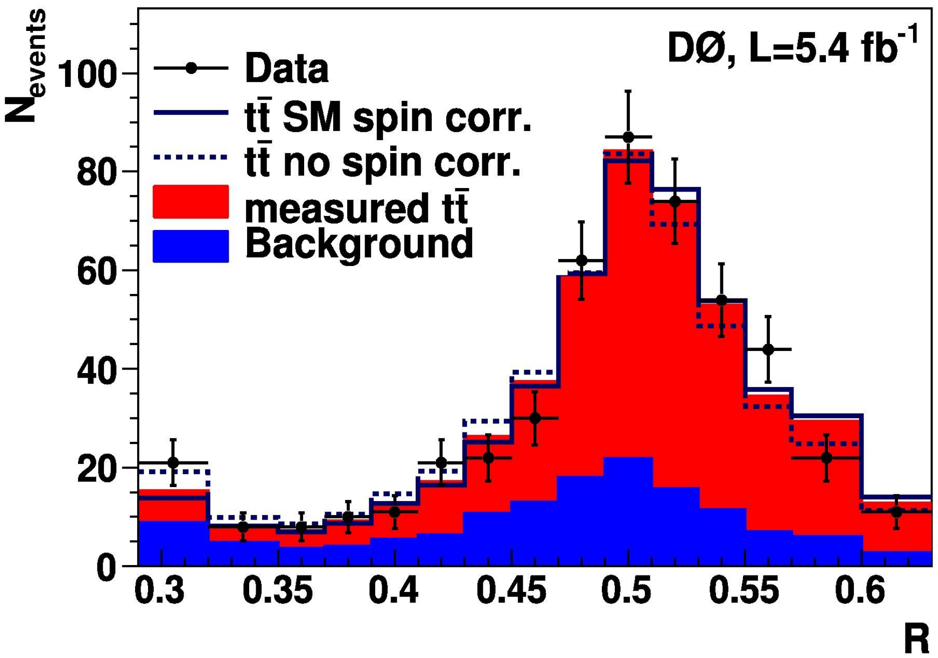
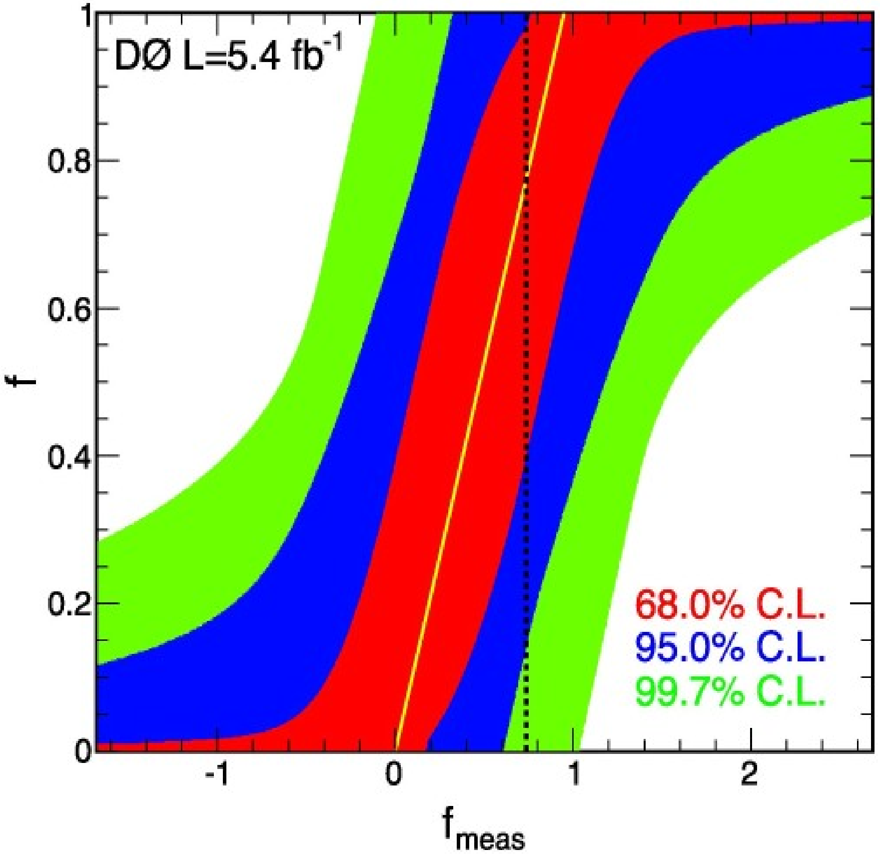


Result of Matrix Element Spin

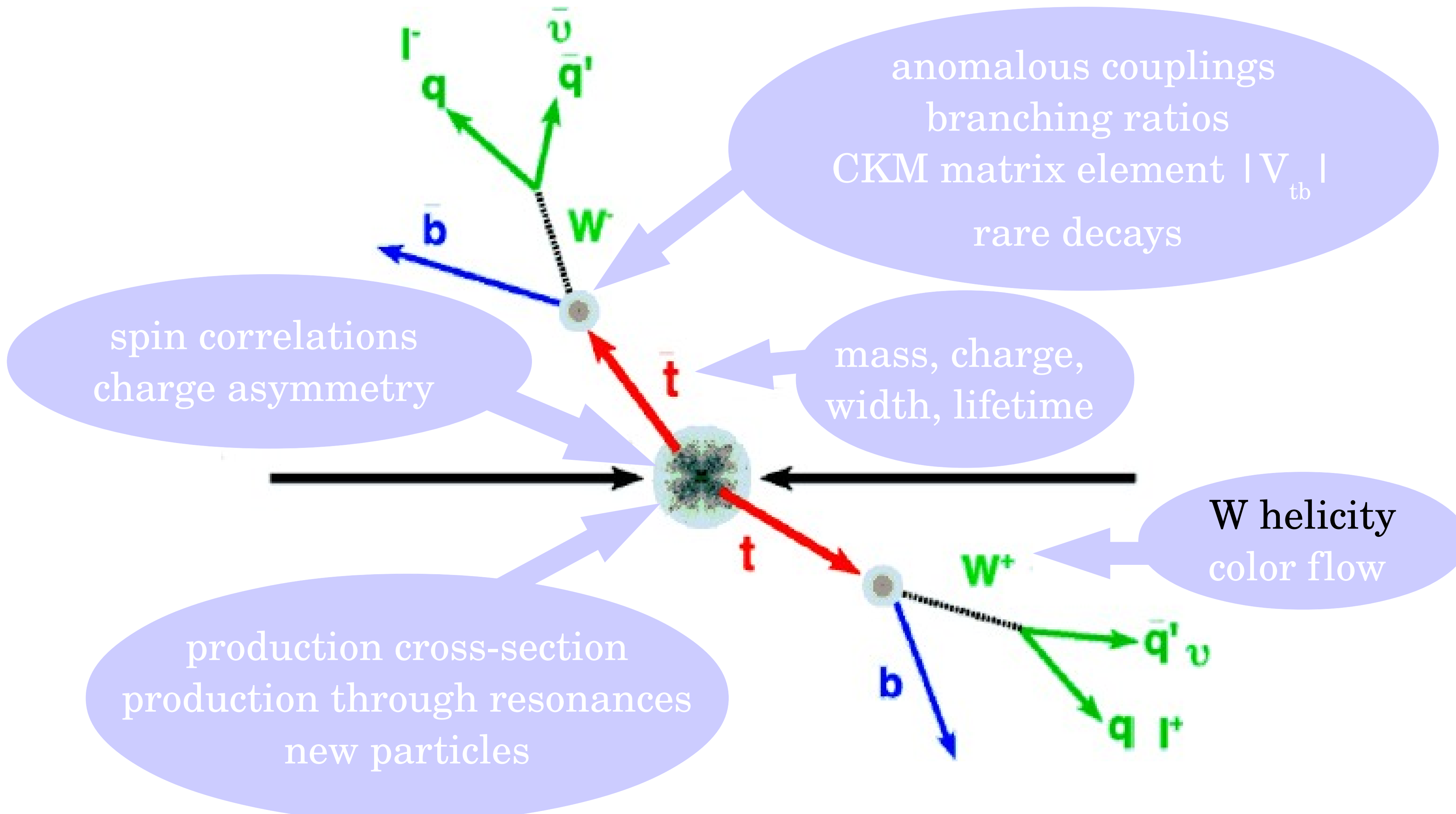
- fraction of events with correlated top quark spins from 485 dilepton candidate events (~71% purity) :

> f = 0.74 ± 0.41 (stat+syst)
>
> f > 0.14 @ 95% C.L.

- f=0 excluded at 97.7% C.L. (99.6% expected)
- translating this into correlation strength:
  C = 0.57±0.31 (stat+syst)
- well consistent with QCD prediction
  C = 0.777 ± 0.042 (NLO)
- measurement dominated by statistical uncertainty: ~ 0.27
- largest systematic effect from MC template statistics: ~0.07
- all details can be found in PRL 107,032001 (2011)



Top Quark Physics



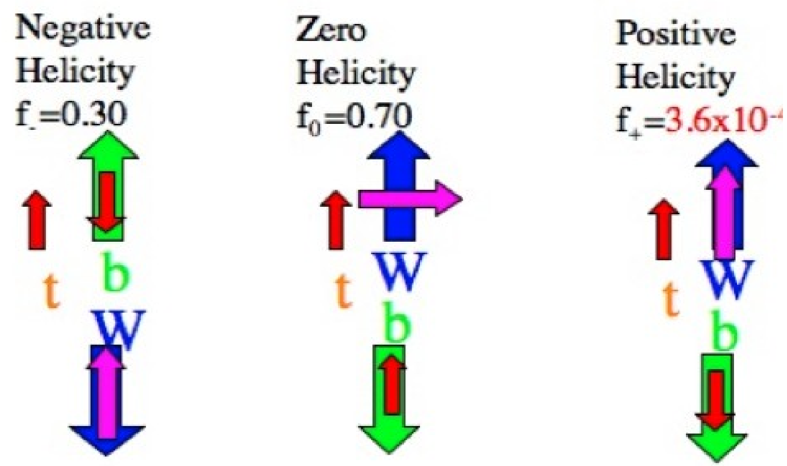
Measurement of W Helicity

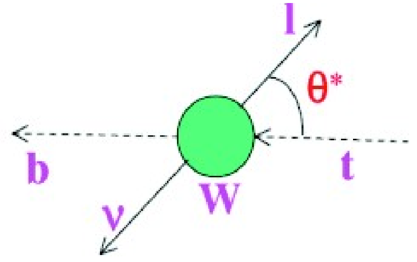
- SM predicts **left-handed** coupling of W boson to fermions

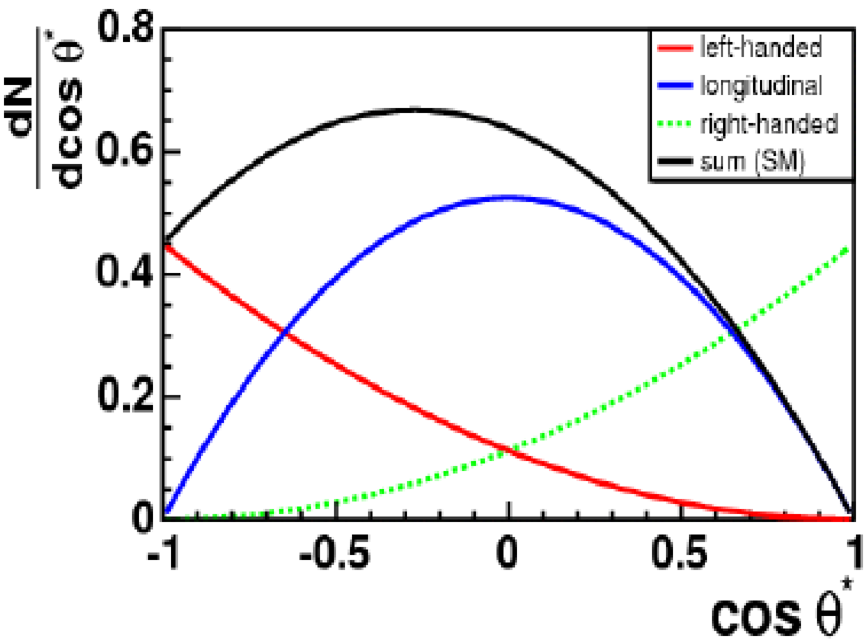
=> **positive helicity** state highly **suppressed**

- verification of **V-A coupling** of W → tb as predicted by SM

- most powerful variable to distinguish different helicity states **cos θ***: angle between down-type decay particle of W boson (charged lepton, d or s quark) and top quark in W rest frame

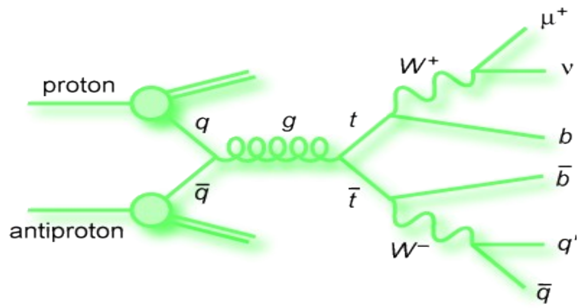


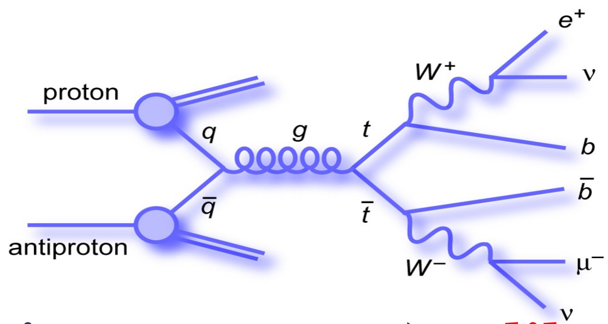




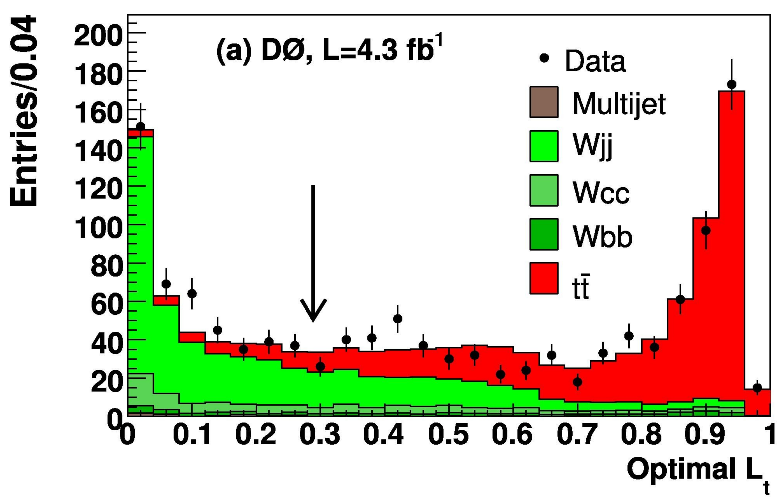
Analysis Strategy

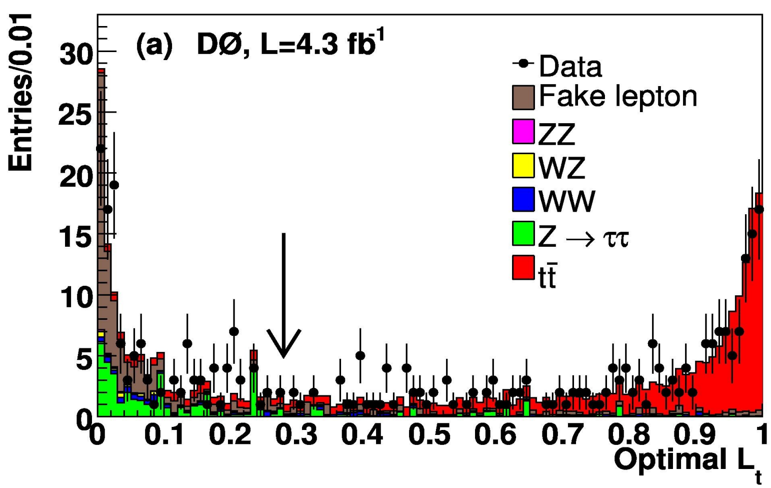
- analysis makes use of both : lepton+jets and dilepton channel





- in each channel channel (e+jets, μ+jets, ee, eμ, μμ) a likelihood discriminant is used
  - to check background modeling
  - to allow for a clean measurement in signal region

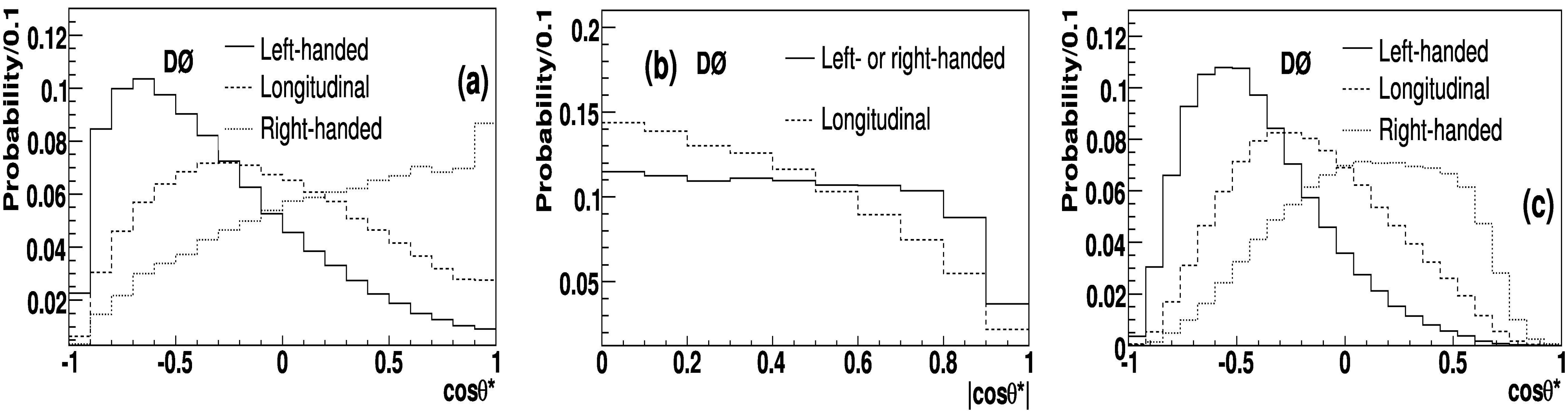




Template Construction

- including jet and lepton resolutions, **cos θ*** is **reconstructed** using:
  - fixed W mass and top mass
  - zero transverse momentum of total event
- for **hadronic W** decay down-type fermion can't be identified so one jet is randomly picked and **|cos θ*|** is used to separate f_0 from f_+/f_-
- samples of pure V-A and V+A couplings are **re-weighted** to form templates of **each helicity state**

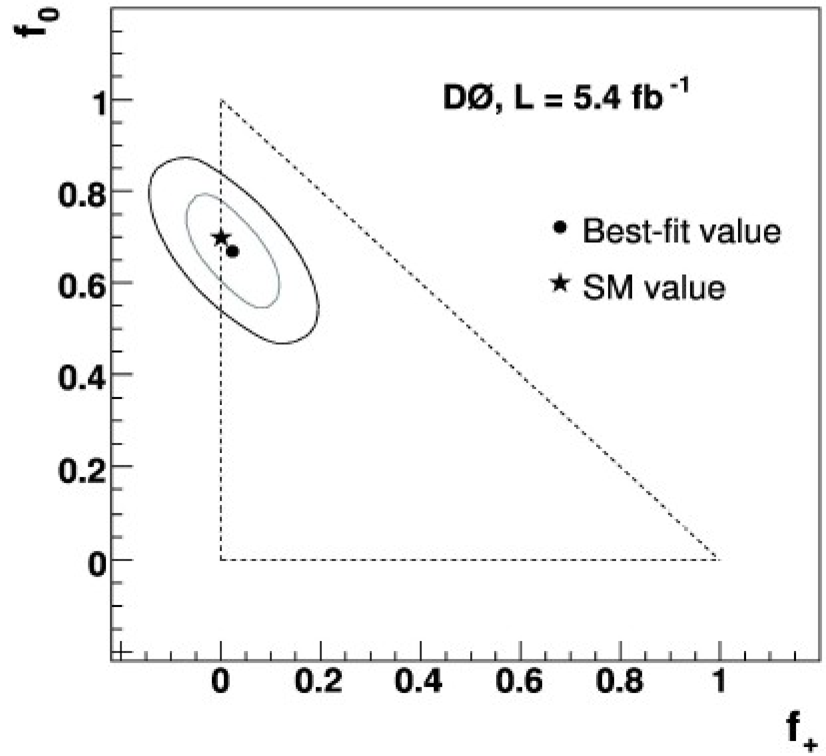
lep. W l+jets　　had. W l+jets　　lep. W dilepton



Results

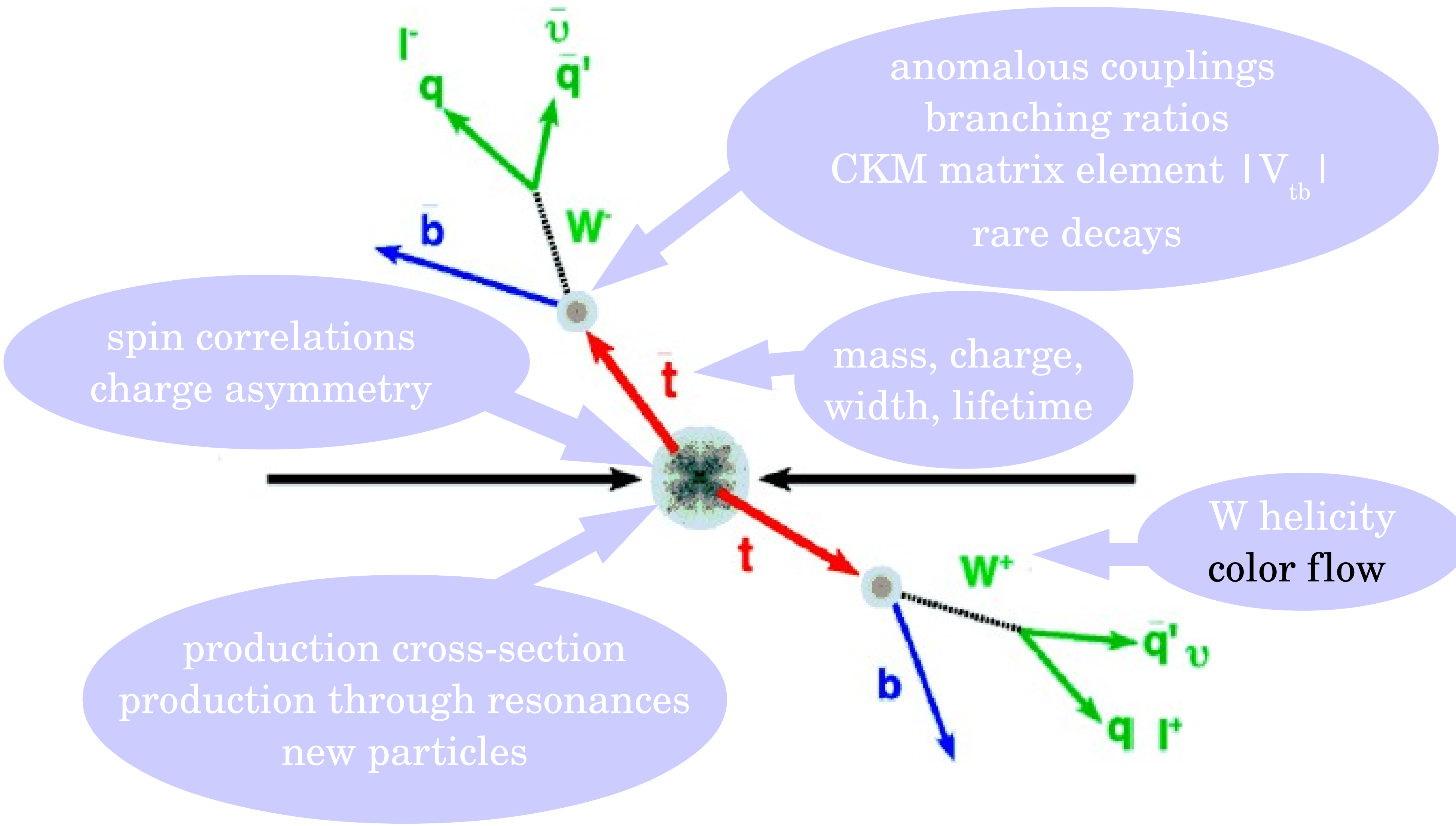
- simultaneous fit f_0 and f_+ using 5.4 fb^{-1} of lepton+jets and dilepton events yields

f_0=0.669±0.078(stat)±0.065(syst)
f_+=0.023±0.041(stat)±0.034(syst)



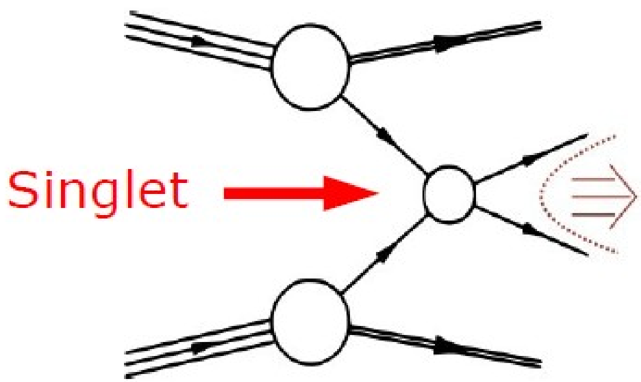
- measurement in **good agreement** with **SM** expectation
- largest **systematic** uncertainty on f_0:
  - **top pair modeling: 0.033**
- most precise determination of f_0 and f_+ today
- all details can be found in PRD 83,032009 (2011)

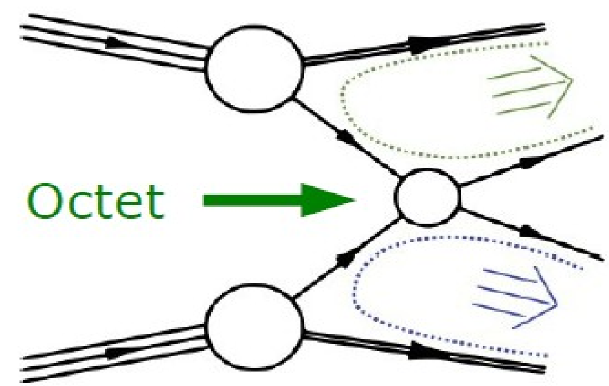
Top Quark Physics



Color Flow in a Nutshell

- QCD color charge is locally conserved and flows like electrical charge
- pulling apart color from its anti-color takes a lot of energy (~1GeV/fm) → color connections are formed
- pairing of connections depends on nature of decaying particle





(singlet: color neutral objects like W,H,..) (octet: gluons)

- color connection can break up
- hadrons are built between the color connected partons

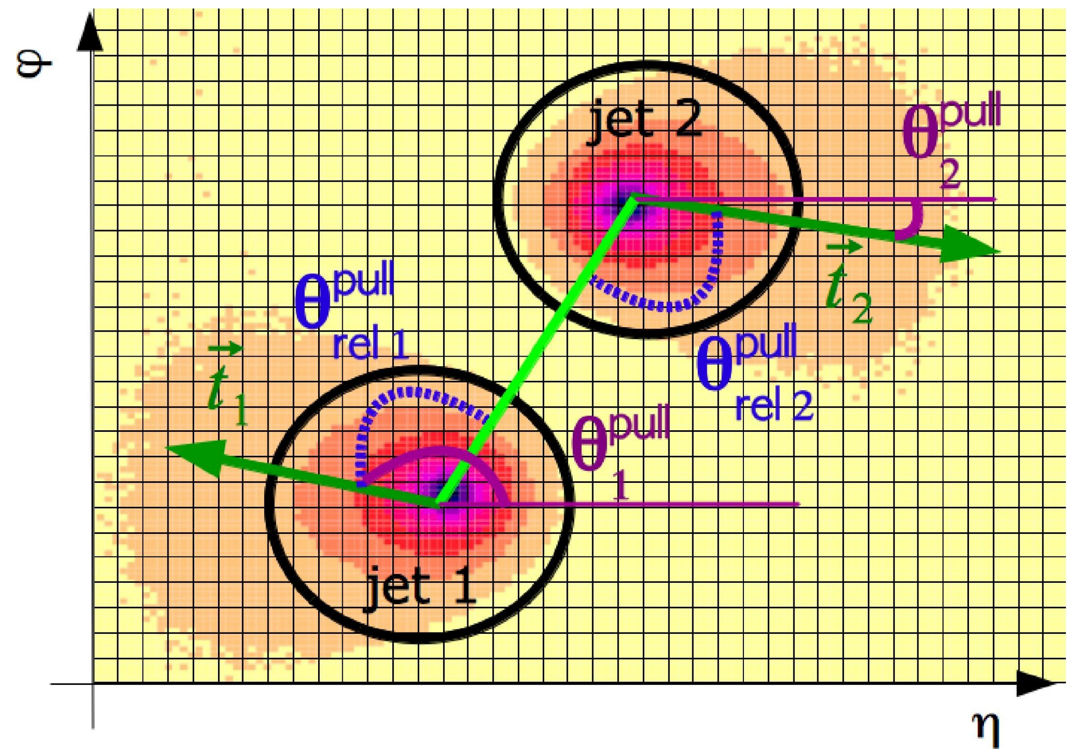
=> jet shape influenced by color flow

Description

- color flow best described by the so-called **jet pull**, i.e. the vectorial sum of all calorimeter cells within a jet (Gallicchio et al., PRL 105 022001)

$$\vec{p} = \sum_i \frac{E_T^i |r_i|}{E_T^{jet}} \vec{r}_i$$

  - $\vec{r}_i$: position of jet cell i relative to jet center
  - E_T^i : transverse energy of cell i
  - E_T^{jet} : transverse jet energy
- cells assigned to closest jet



=> jet **pull** vectors **point** more towards **each other** for jets from color **singlets** than octets

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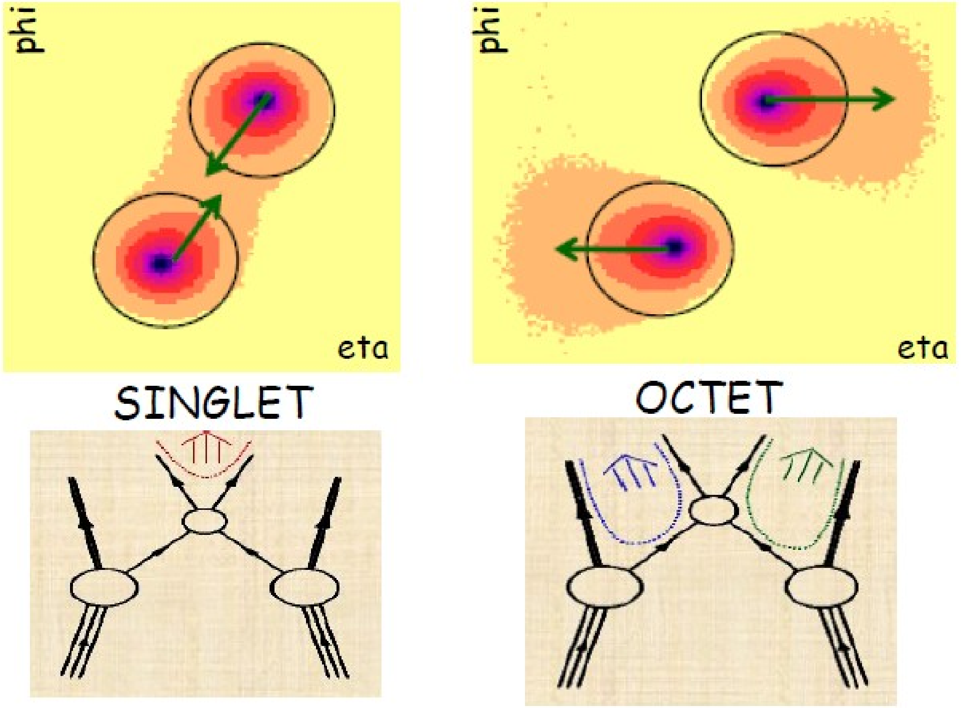
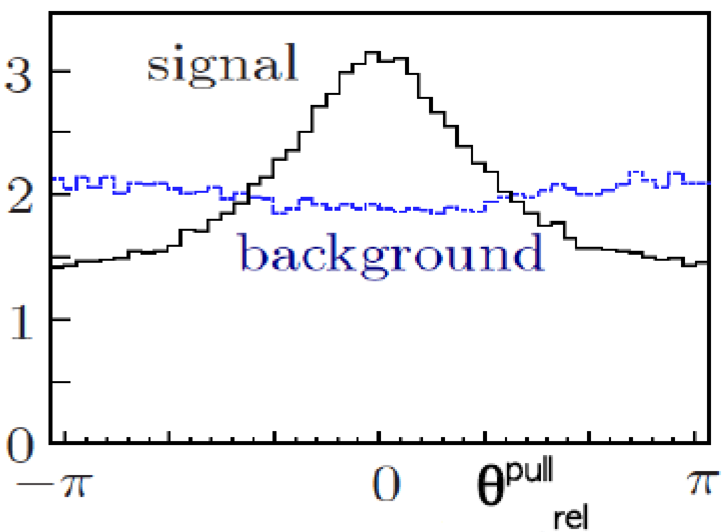
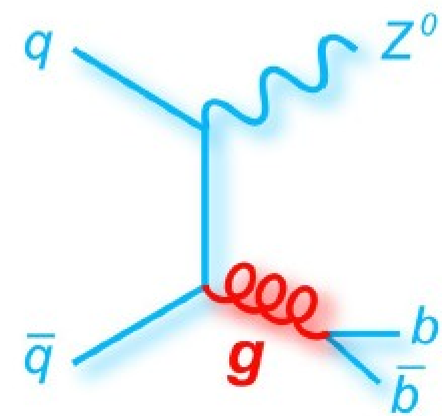


=> jet pull vectors point more towards each other for jets from color singlets than octets

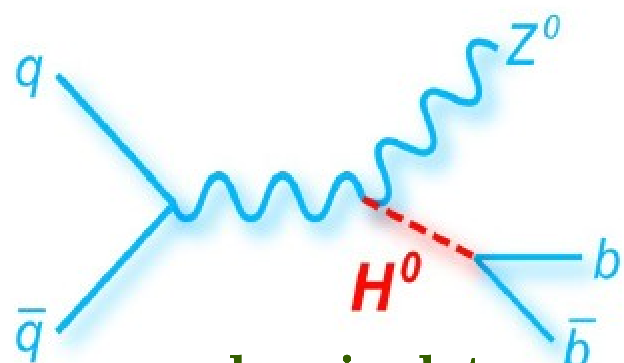
Application of Jet Pull

- distinguish between jets from color singlets and octets
  - separate different processes with same final states
  - excellent to search for new physics
- example: $ZH \rightarrow Zb\bar{b}$ signal vs. Z+jets background





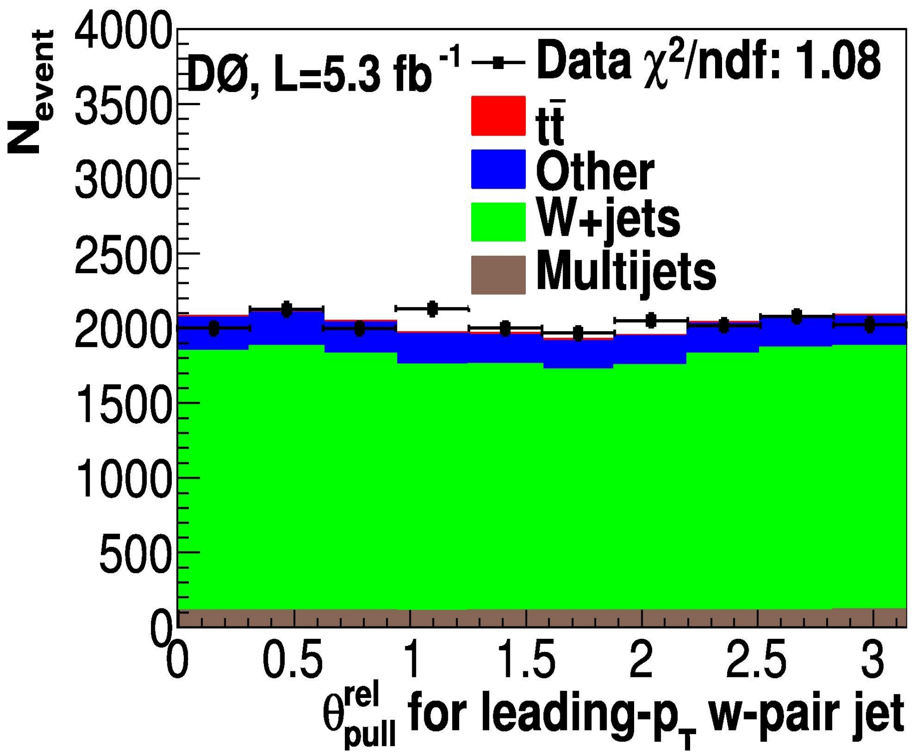
color octet



color singlet

Understanding Jet Pull

- jet pull **well described** by Monte Carlo
- understand **degradation** of jet pull from pure MC truth information to full detector simulation due to different effects (calorimeter granularity, noise, pile-up, etc.)
- account for **inhomogeneity** of the **detector**
- checking influence of jet **splitting** and merging



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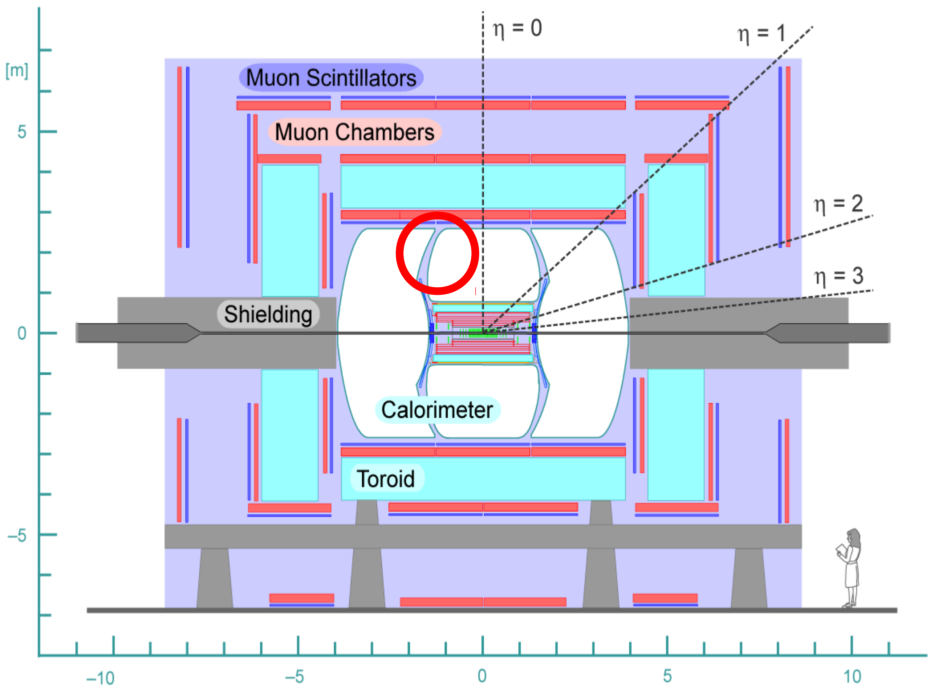

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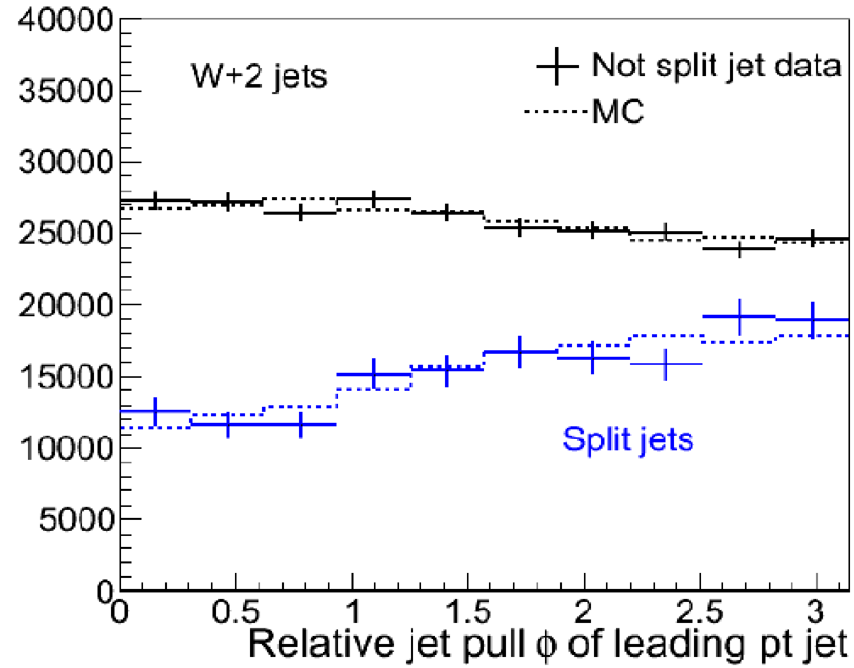
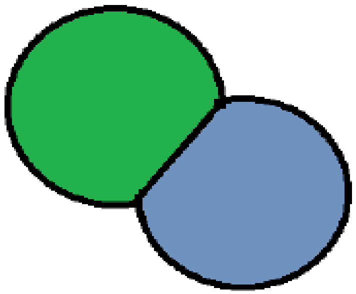
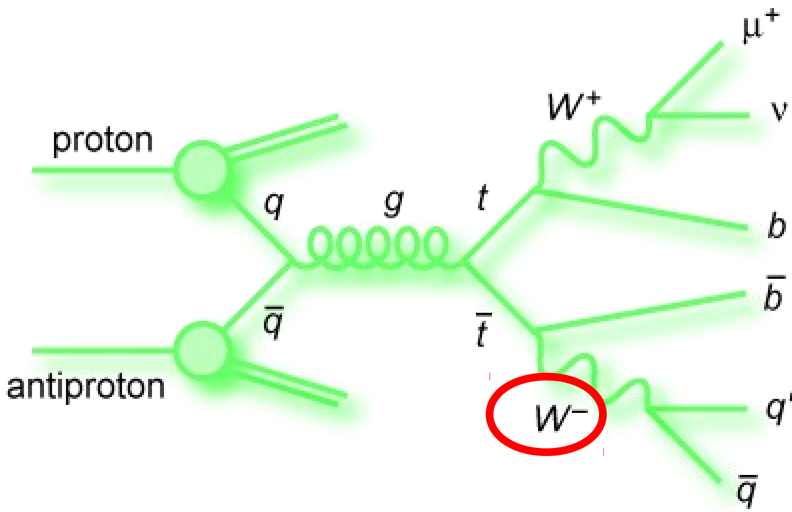




Measuring Color Flow in Top Events

- test the sensitivity to color flow in top pair events by verifying that the hadronic W boson is measured to be a color singlet
- apart from standard MC Madgraph+Pythia events with color octet W boson used
- fraction $f_{singlet}$ of events with light quark jets from color singlet extracted
- best sensitivity in the central detector region when both light jets are close to each other and their invariant mass is about the W mass

=> good separation between singlet and octet W



singlet or octet?

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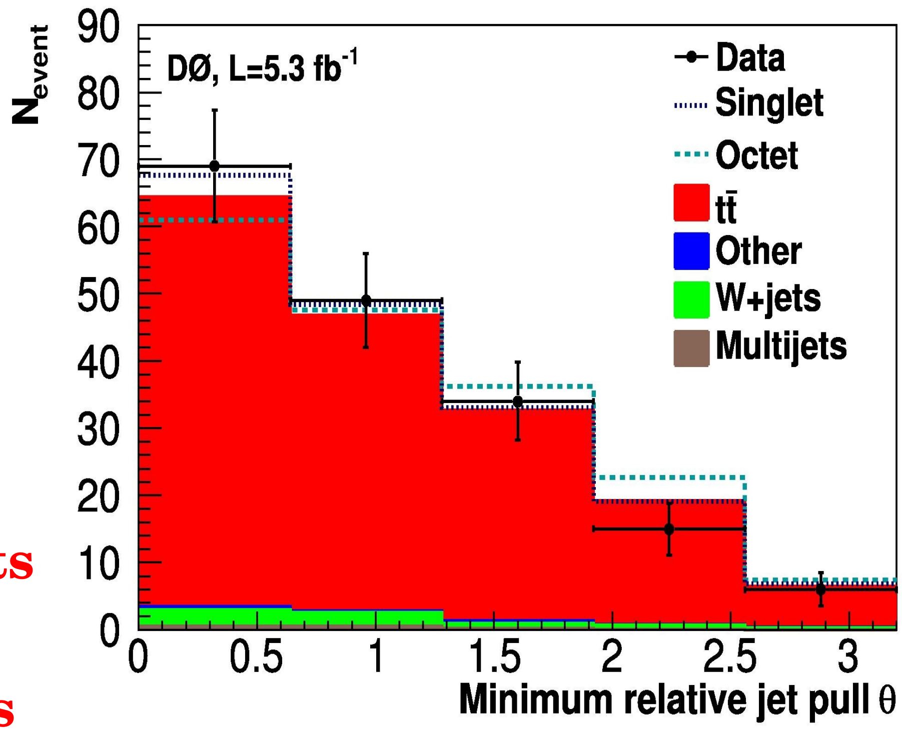


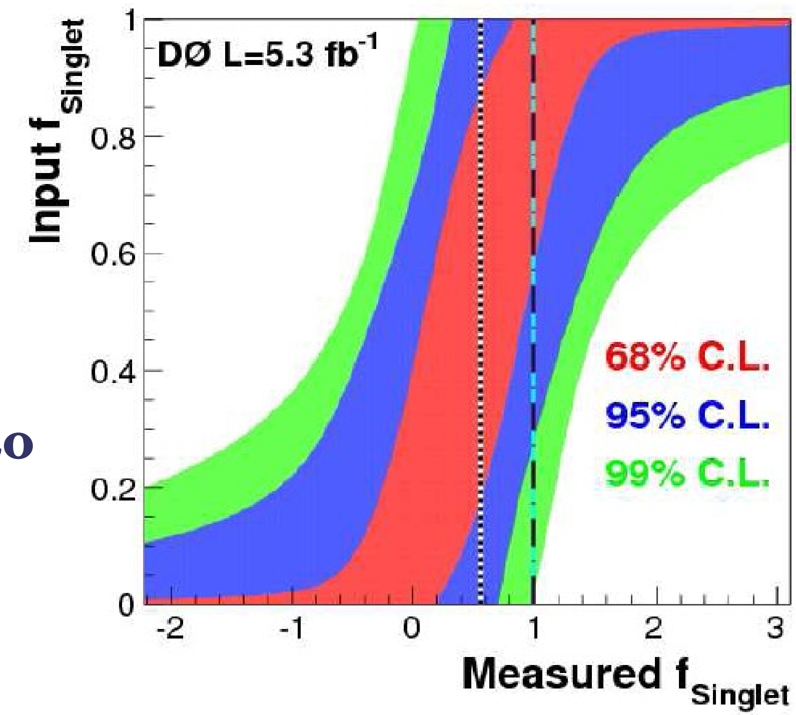
=> good separation between singlet and octet W

Result

- fraction of events with singlet W boson extracted from 728 lepton+jets candidate events (~90% purity):

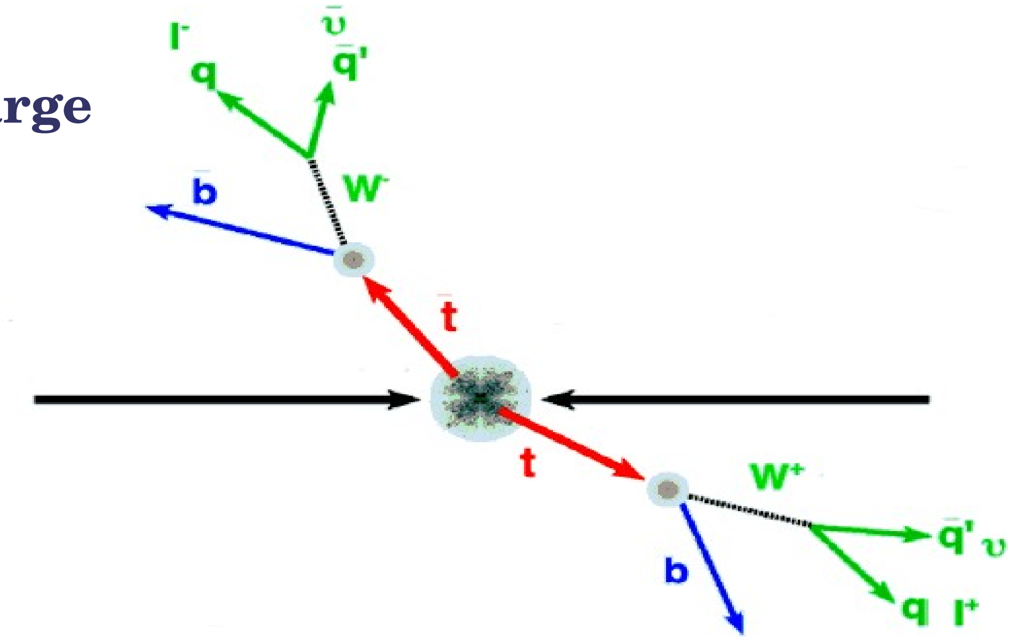
$f_{Singlet} = 0.56 \pm 0.38(\text{stat+syst}) \pm 0.19\ (\text{MC stat})$

- expected:
  W boson octet exclusion @ 99% C.L.
- observed:
  W boson can't be excluded @ 95% C.L.
- measurement still limited by statistics
- dominant systematic uncertainty due to
  - singlet/octet MC shapes : ± 0.18
  - detector inhomogeneity : ± 0.10
  - impact of signal modeling small



- all details can be found in PRD 83,092002 (2011)

Summary



- increased D0 data set offers a large variety of new measurements using top quark events
- for the first time a matrix element based approach could exclude uncorrelated top quarks spins at 97.7% C.L.
- many analysis like the W helicity measurement start to be limited by systematic uncertainties
- interesting tools for future searches of new physics like the color flow tested top quark events for the first time

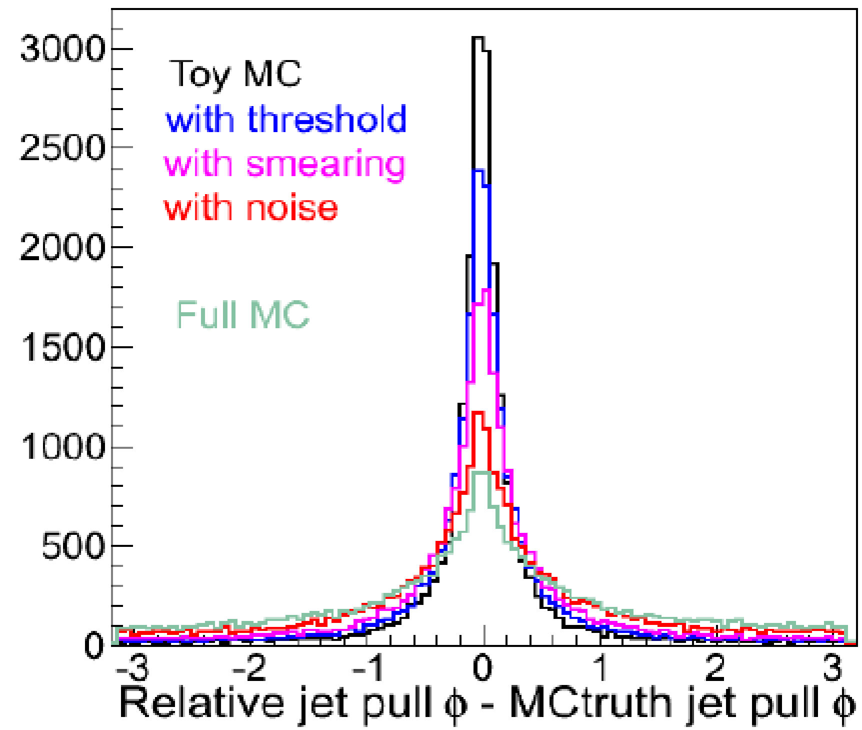
BACK UP

Details W Helicity Reco/Fit

- lepton+jets:
  - HITFIT
  - |cos theta*| for hadronically W boson as not clear which one down type
- dilepton:
  - matrix weighting
  - average all solutions
- V+A (f+=0.3 f0=0.7) and V-A (f_=0.3,f0=0.7)
- f_ from unitarity
- binned maximum likelihood fit
- W had and W lep separately but same level of background

Understanding the Jet Pull

- verified that the jet pull is well described by Monte Carlo in a clean sample of $(W \rightarrow l\nu)$+2 jets events
- check degradation of jet pull from pure MC truth information to full detector simulation
  - calorimeter granularity
  - energy threshold
  - noise and pile-up
- account for the inhomgeneity of the detector
- checking influence of jet splitting and merging



Systematic Uncertainties (Spin)

Source	+SD	−SD
Muon identification	0.01	−0.01
Electron identification and smearing	0.01	−0.01
PDF	0.02	−0.01
Top Mass	0.01	−0.01
Triggers	0.02	−0.02
Opposite charge requirement	0.00	−0.00
Jet energy scale	0.01	−0.01
Jet reconstruction and identification	0.06	−0.06
Normalization	0.02	−0.02
Monte Carlo statistics	0.02	−0.02
Instrumental background	0.00	−0.00
Background Model for Spin	0.03	−0.04
Luminosity	0.03	−0.03
Other	0.01	−0.01
Template statistics for template fits	0.07	−0.07
Total systematic uncertainty	0.11	−0.11
Statistical uncertainty	0.38	−0.40

Source	+1SD	−1SD
Muon identification	0.01	-0.01
Electron identification and smearing	0.02	-0.02
PDF	0.06	-0.05
m_t	0.04	-0.06
Triggers	0.02	-0.02
Opposite charge selection	0.01	-0.01
Jet energy scale	0.01	-0.04
Jet reconstruction and identification	0.02	-0.06
Background normalization	0.07	-0.08
MC statistics	0.03	-0.03
Instrumental background	0.01	-0.01
Integrated luminosity	0.04	-0.04
Other	0.02	-0.02
MC statistics for template fits	0.10	-0.10
Total systematic uncertainty	0.15	-0.18
Statistical uncertainty	0.33	-0.35

Systematic Uncertainties (WH+CF)

Source	Uncertainty (f_+)	Uncertainty (f_0)
Jet energy scale	0.007	0.009
Jet energy resolution	0.004	0.009
Top mass	0.011	0.009
Template statistics	0.012	0.023
ISR/FSR in $t\bar{t}$	0.003	0.024
NLO effects in $t\bar{t}$	0.017	0.015
$t\bar{t}$ showering model	0.013	0.001
color reconnection in $t\bar{t}$	0.002	0017
Total $t\bar{t}$ model	0.022	0.033
Background model	0.006	0.017
Heavy flavor fraction	0.011	0.026
b fragmentation	0.000	0.001
Jet ID	0.004	0.004
pdf	0.002	0.007
Analysis consistency	0.004	0.006
Muon ID	0.003	0.021
Muon trigger	0.004	0.020
Total	0.032	0.061

Source	$+1\sigma$	-1σ
Singlet/octet MC shapes	0.188	−0.188
Jet pull reconstruction	0.100	−0.093
Jet energy resolution	0.033	−0.013
Vertex confirmation	0.028	−0.029
PYTHIA tunes	0.023	−0.025
Jet energy scale	0.024	−0.009
Jet reconstruction and identification	0.017	−0.017
$t\bar{t}$ modeling	0.014	−0.033
Event statistics for matrix method	0.009	−0.010
Other Monte Carlo statistics	0.009	−0.007
Multijet background	0.006	−0.007
Total systematic	0.222	−0.218

Not the Top Quark

Ceci n'est pas un quark top.