A Top Quark Carol

Or

Recent Top Quark Results from DØ

Science & Technology Facilities Council

MANCHESTER 1824

By

Yvonne Peters

University of Manchester & Fermilab

On behalf of the DØ collaboration

Before the Story begins

- We need to set the stage,

Before the Story begins

- We need to set the stage,
- introduce the protagonist,

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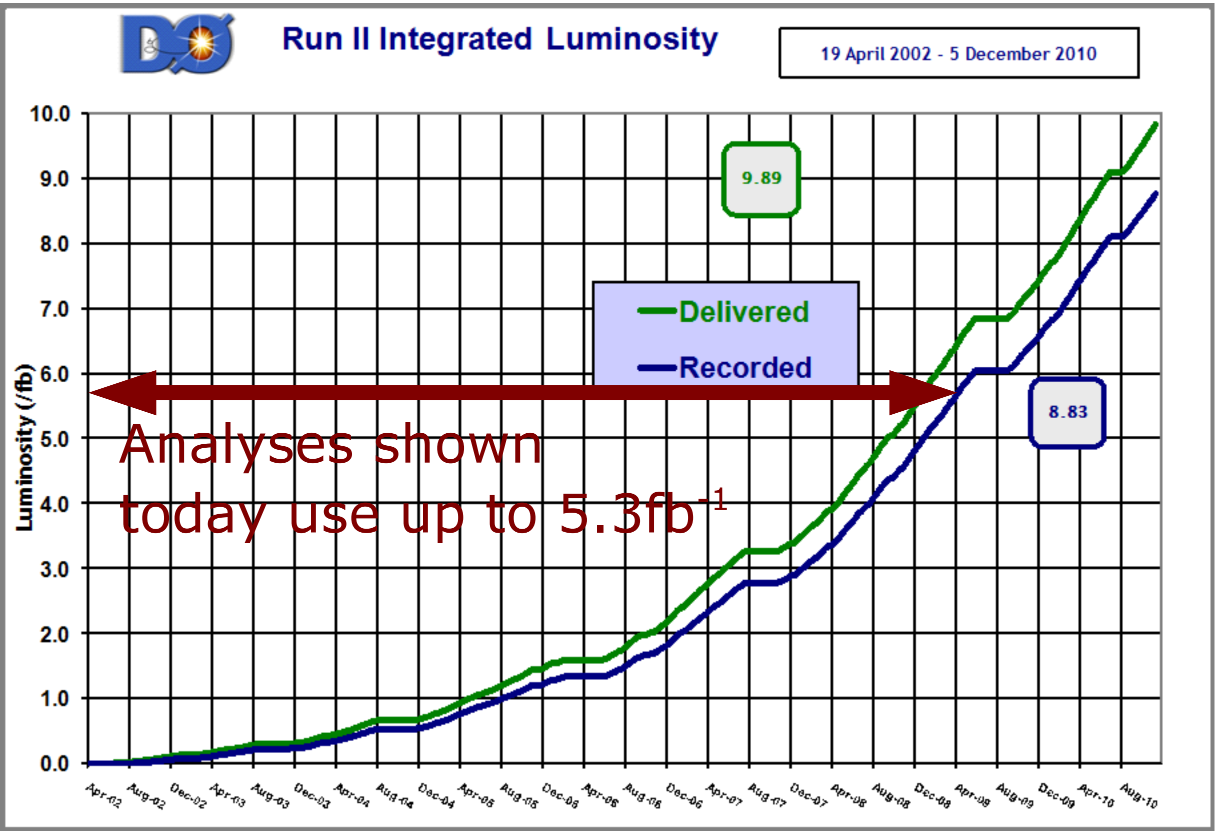
Before the Story begins

- We need to set the stage,
- introduce the protagonist,
- present some stage props,
- ...and the other actors

The Stage: Fermilab, DØ, 2010



About 10 fb^{-1} delivered

About 9 fb^{-1} recorded per experiment

Thank you, Accelerator Division!

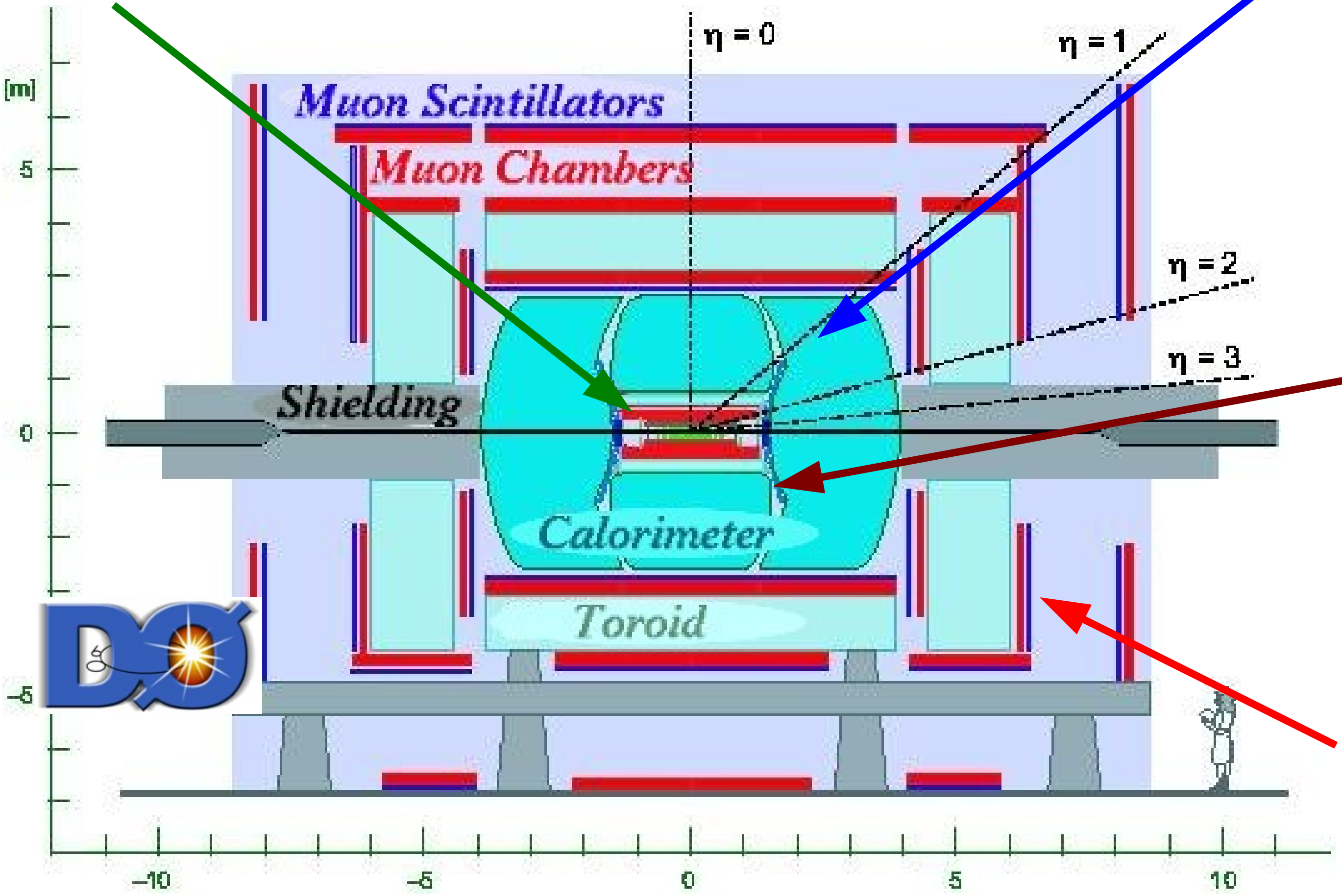
The DØ Detector

Tracker: Detection and momentum measurement for charged particles

Calorimeter: Identification and energy measurement of jets and electrons; tau identification

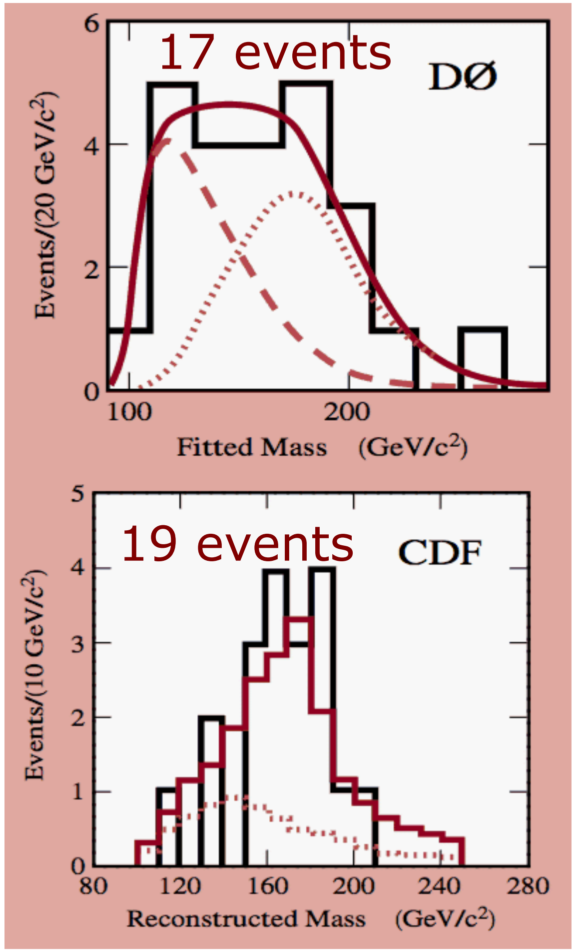
Inter Cryostat Region: Gap between central and end calorimeters; scintillators for energy measurement

Muon system: Identification and momentum measurement of muons



Biography of the Main Actor

- 1995: Discovered by CDF and DØ at Fermilab
  - With few events; 2010: 1000s
- Heaviest known elementary particle:
  $m_t = 173.3 \pm 1.1 \text{GeV}$
- Standard Model:
  - Single or pair production
  - Electric charge +2/3 e
  - Short lifetime 0.5×10^{-24}s
    - Bare quark - no hadronization
  - ~100% decay into Wb
  - Large coupling to SM Higgs boson



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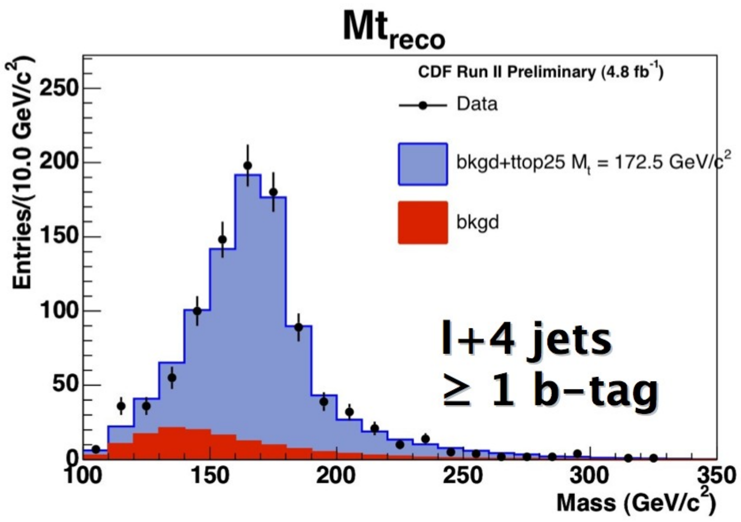

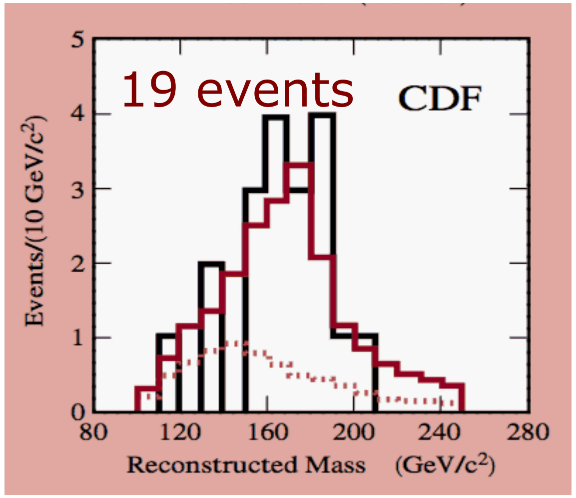

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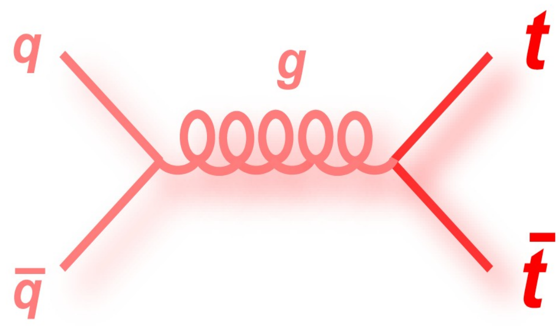

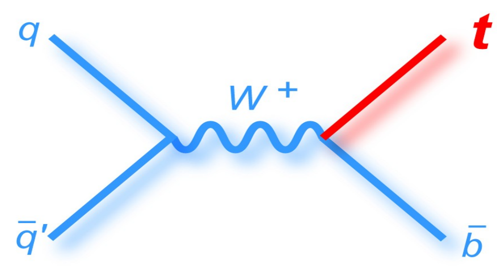

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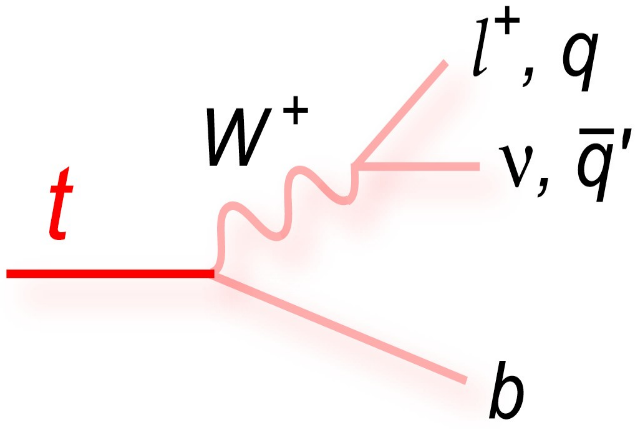

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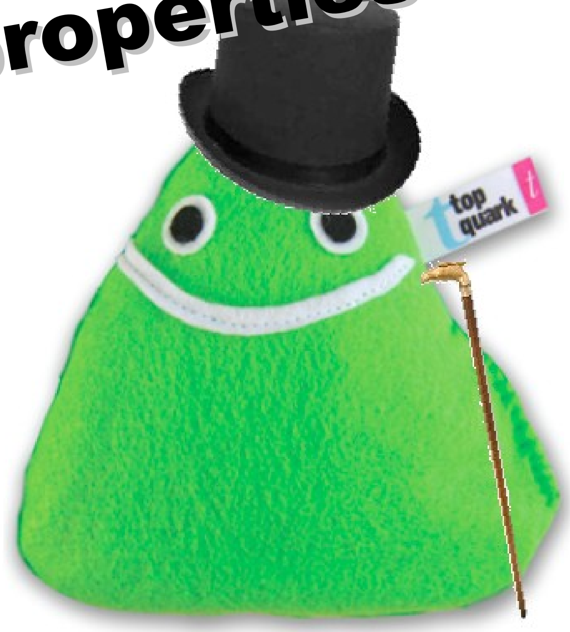
But are we really dealing with a top quark as expected in the SM?

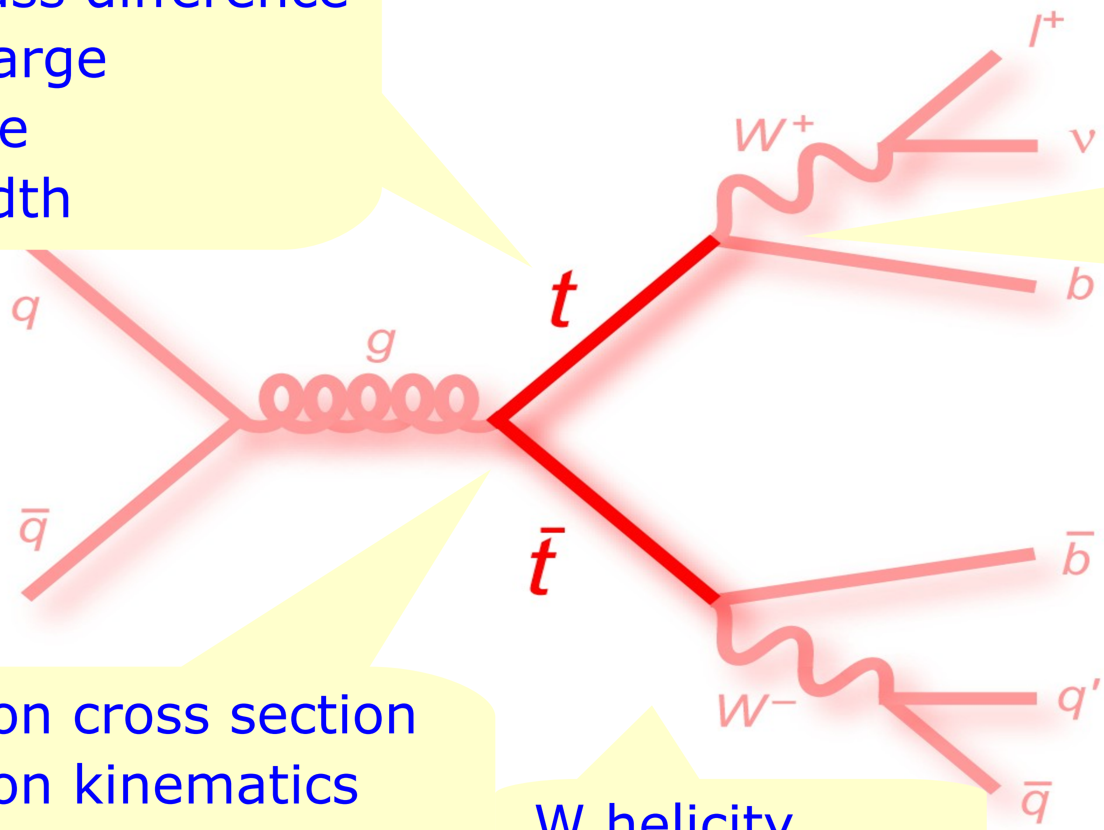
What are its production rate, properties?



All we want to know about the Top

Top mass
Top mass difference
Top charge
Lifetime
Top width

Branching ratios
$|V_{tb}|$
Anomalous coupling
New/Rare decays



Production cross section
Production kinematics
Production via resonance
New particles

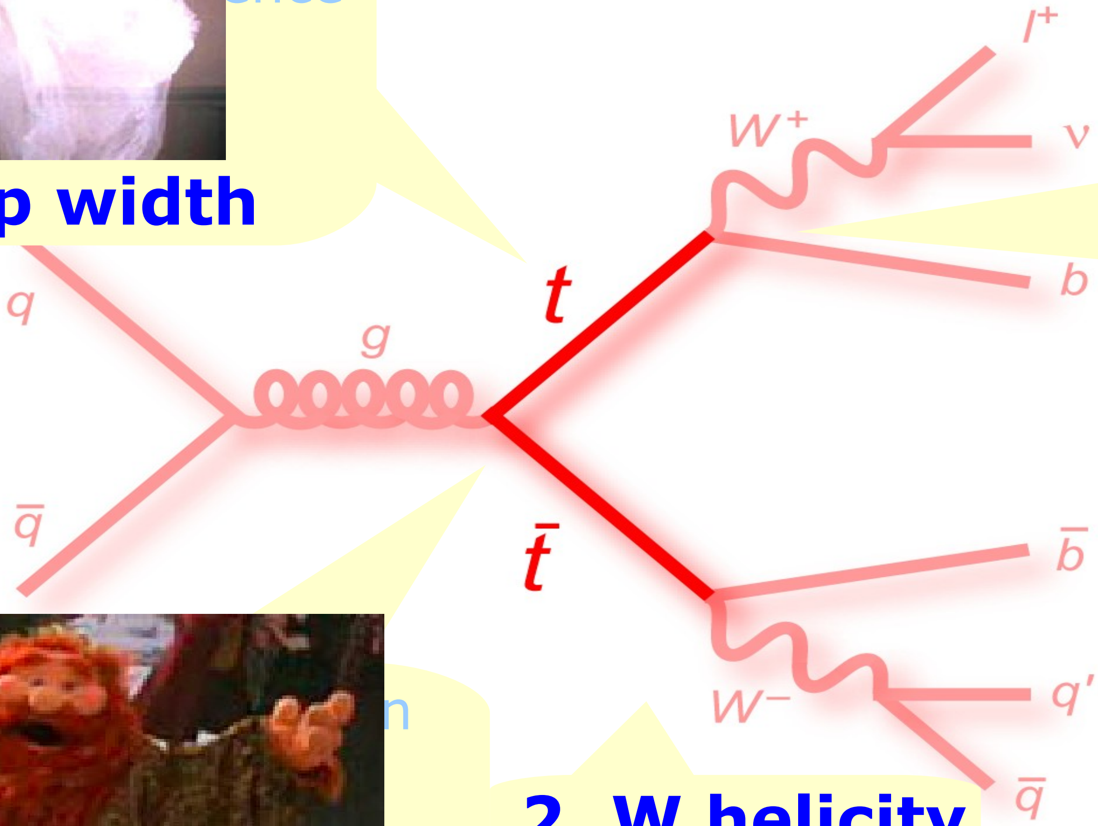
W helicity

Spin correlation
Charge asymmetry
Color Flow

And what we will present today

ence

1. Top width



Branching ratios
$|V_{tb}|$
Anomalous coupling
New/Rare decays

3. Color Flow

n

ce

2. W helicity

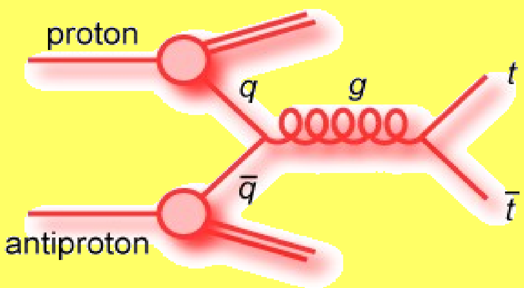
Some Props:
Top Quark Production @ Tevatron

Pair production ($t\bar{t}$)

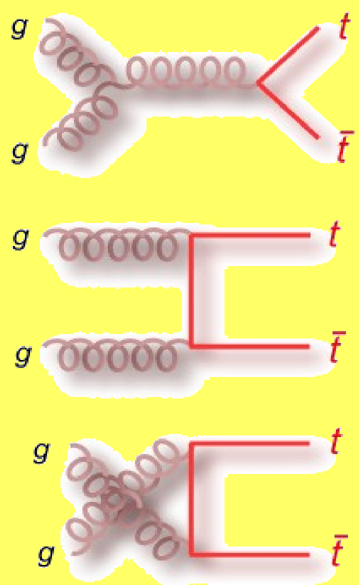
via strong interaction

Theoretical cross section:
7.5 pb at a top mass of 172.5 GeV

85% $q\bar{q}$ annihilation



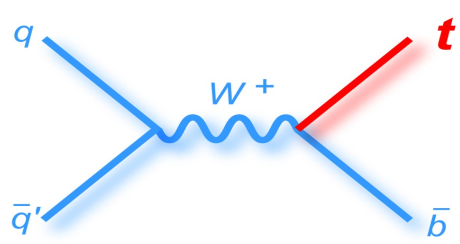
and 15% gluon fusion

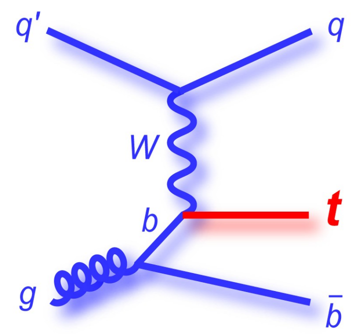


Single top quark production

via electroweak interaction

Theoretical cross section:
3.3 pb at a top mass of 172.5 GeV





CDF & DØ: observed in 2009

Phys. Rev. Lett. 103, 092001 (2009)

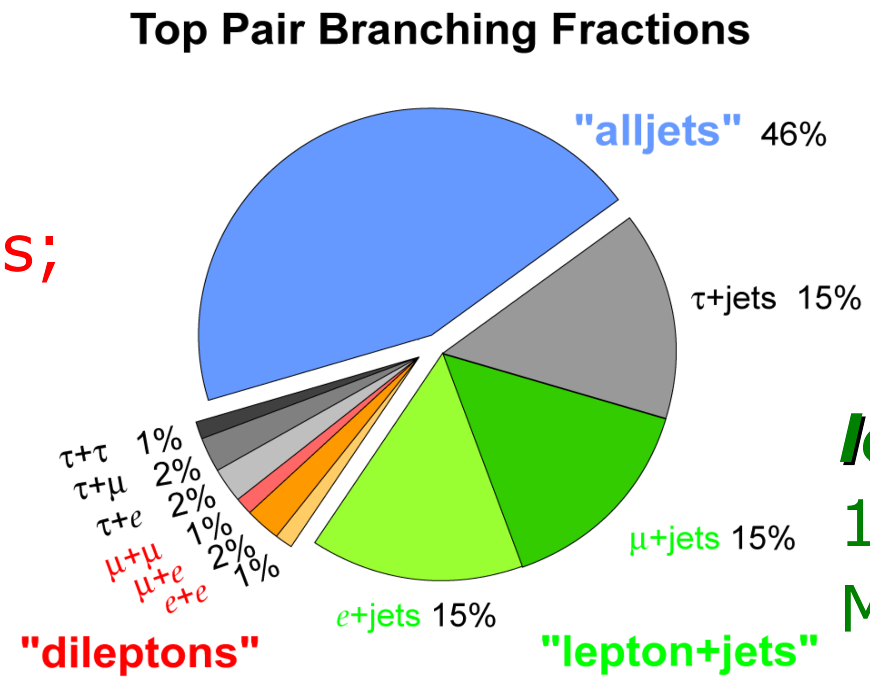
Some Props: $t\bar{t}$ Final States

$t\bar{t} \rightarrow W^{+}bW^{-}\bar{b}$: Final states are classified according to W decay

$B(t \rightarrow W^{+}b) = 100\%$

pure hadronic:
≥6 jets (2 b-jets)

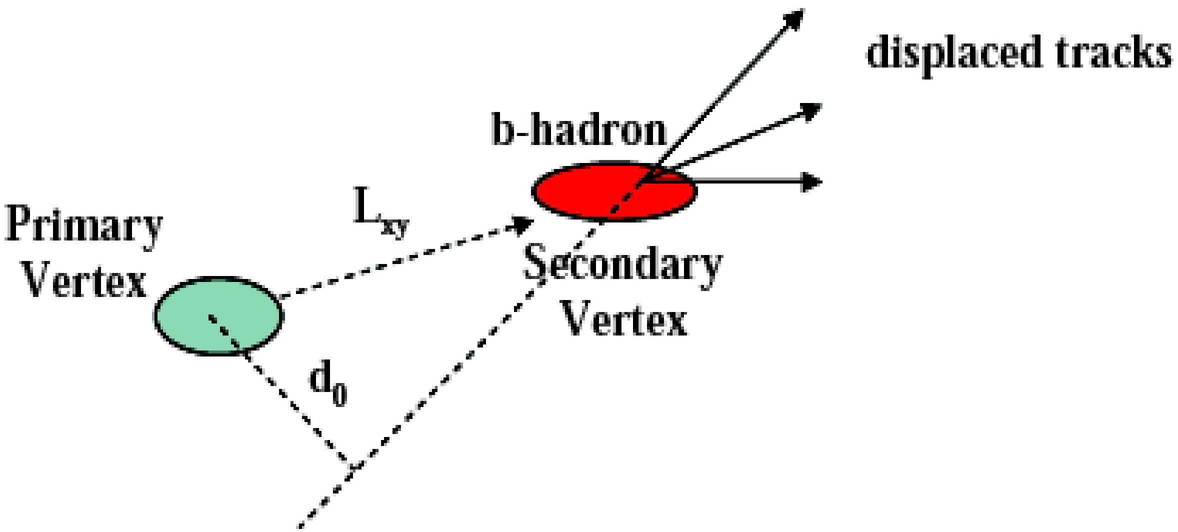
dilepton:
2 isolated leptons;
High missing E_T from neutrinos;
2 b-jets

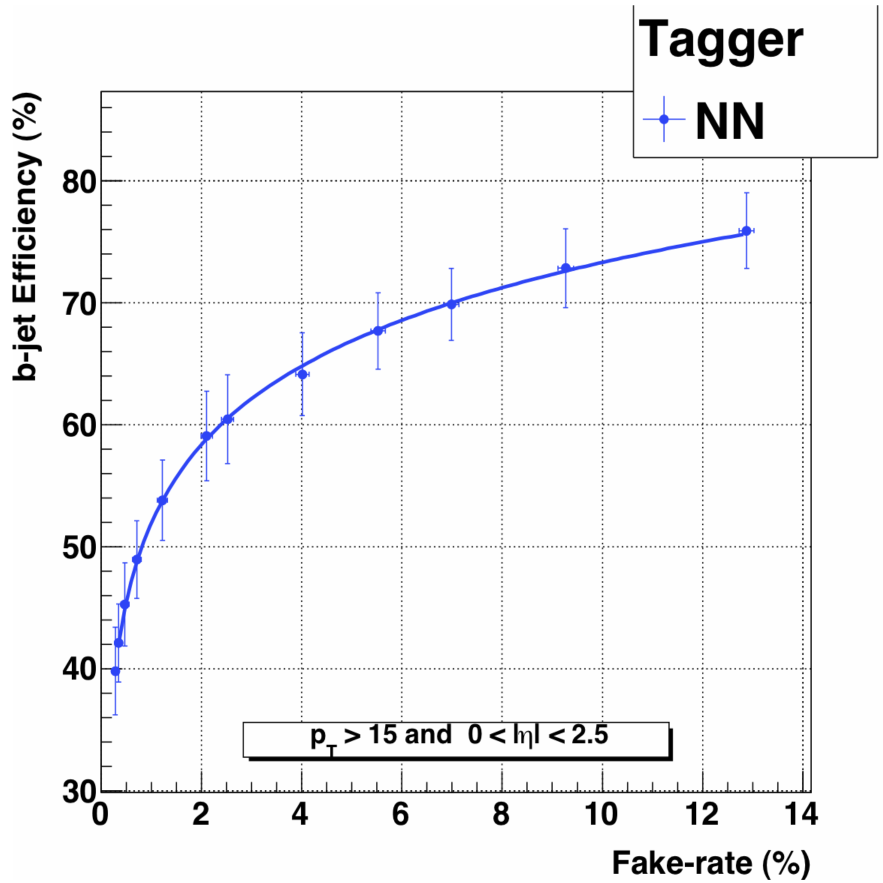


lepton+jets:
1 isolated lepton;
Missing E_T from neutrino;
≥4 jets (2 b-jets)

Some Props: Identification of b-jets

- Important to increase $t\bar{t}$ purity
- b-hadron: travels some millimeters before it decays
- Neural Network
  combines properties of displaced tracks and displaced vertices

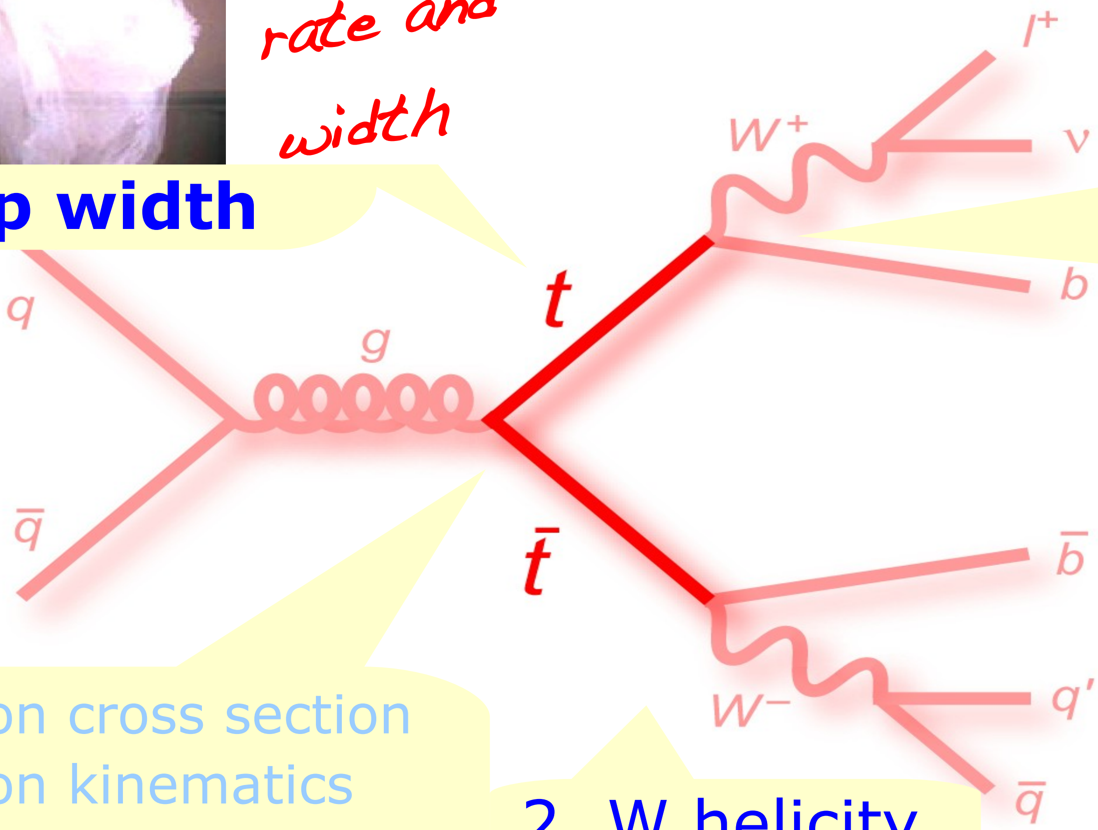




First Analysis

Test decay rate and width

1. Top width



Branching ratios
$|V_{tb}|$
Anomalous coupling
New/Rare decays

Production cross section
Production kinematics
Production via resonance
New particles

2. W helicity

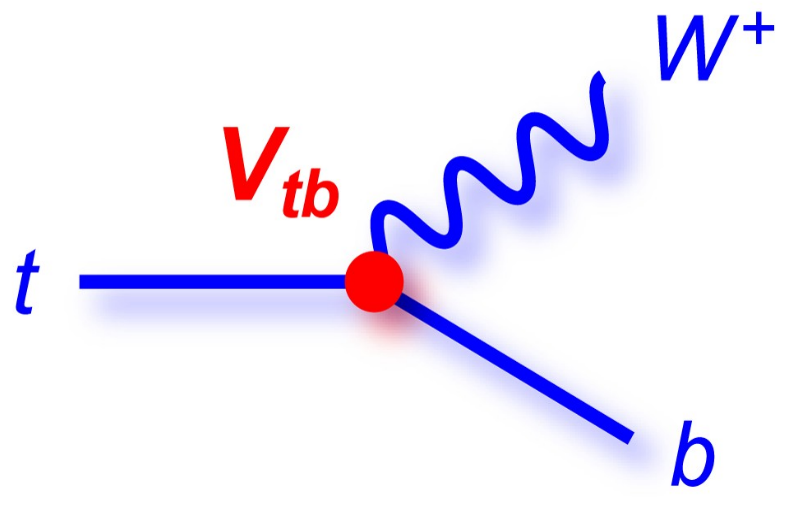
Spin correlation
Charge asymmetry
3. Color Flow

Motivation

- Top quark total width (and lifetime) is a fundamental property
- Partial width (NLO):

$$\Gamma(t\rightarrow Wb) = \frac{G_F m_t^3}{8\pi\sqrt{2}}|V_{tb}|^2\left(1-\frac{M_W^2}{m_t^2}\right)\left(1+2\frac{M_W^2}{m_t^2}\right)\times\left[1-\frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3}-2.5\right)\right]$$

- $\Gamma(t\rightarrow Wb) = 1.26\,GeV$ For m_t=170 GeV

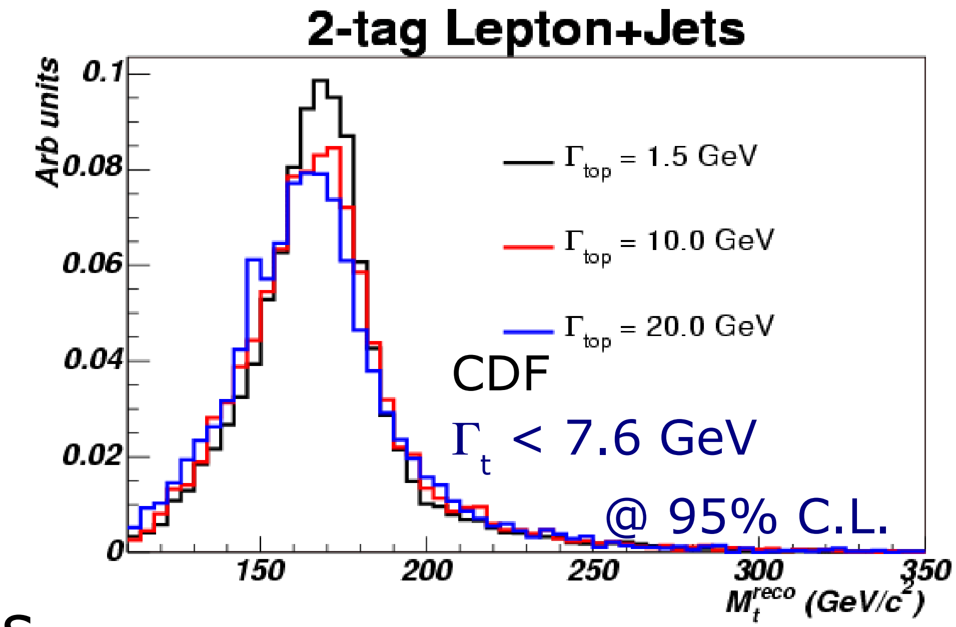


- Total width:

$$\Gamma_t = \frac{\Gamma(t\rightarrow Wb)}{B(t\rightarrow Wb)}$$

Status

- Not precisely measured so far
  - Direct measurement independent of assumptions, but suffers from experimental resolution
  - For top quark: resolution > width



- Indirect measurement, combining two of our recent results
  - Following a suggestion from C.P. Yuan, arXiv:hep-ph/9308240

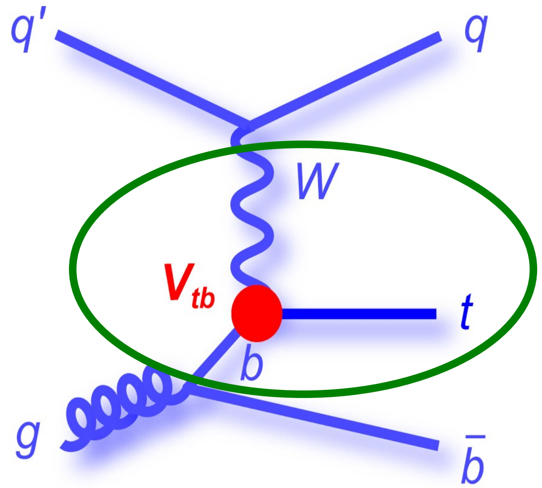
$$\Gamma_t = \frac{\Gamma(t \to Wb)}{B(t \to Wb)}$$

Main ingredient: t-channel single top cross section measurement

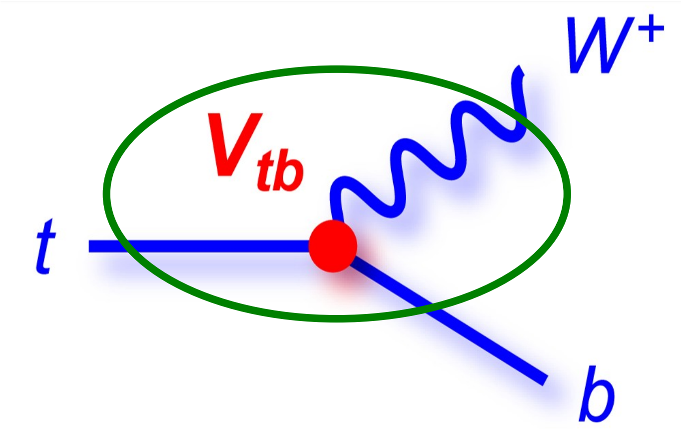
Main ingredient: ratio of branching fractions measurement

Partial Width Extraction

- t-channel single top production:



Top decay:



- Same coupling in production and decay:

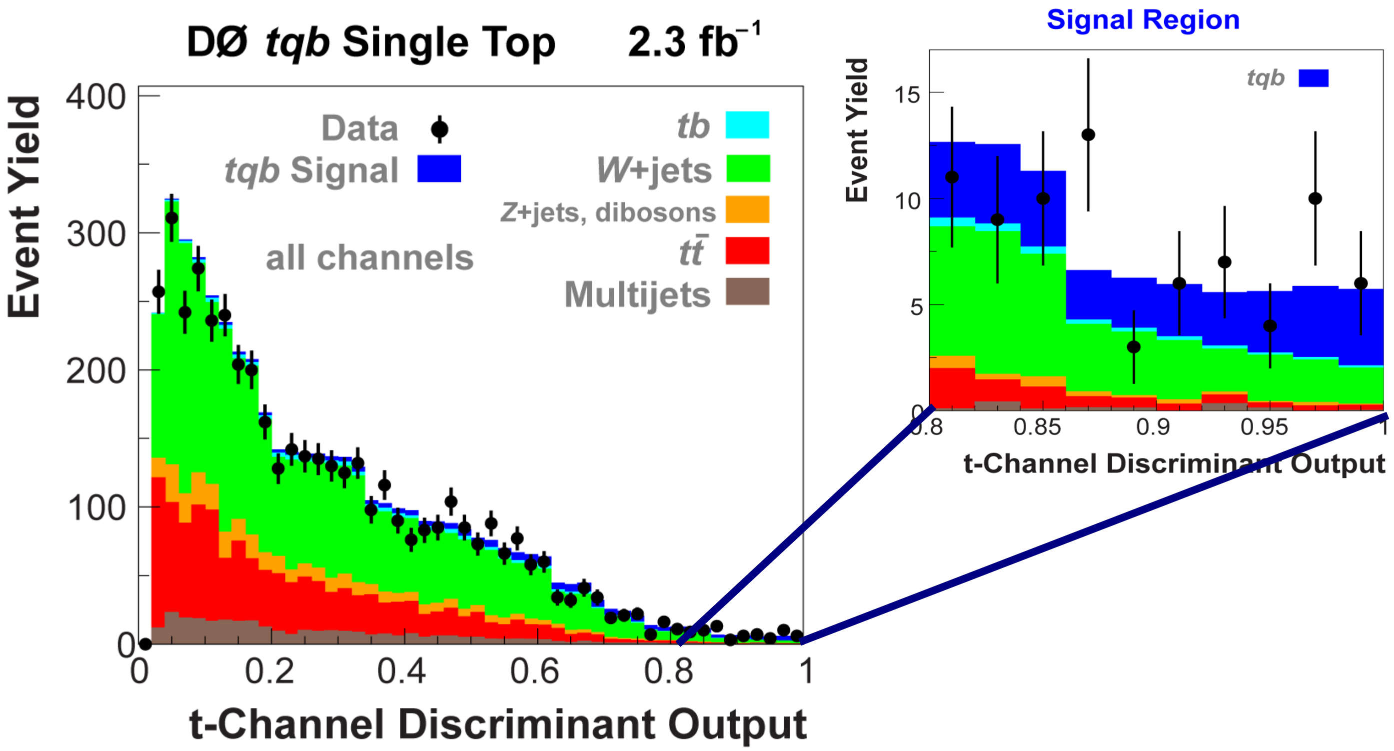
$$\sigma(t-channel) \propto \Gamma(t \to Wb)$$

- Extract partial decay width from

$$\Gamma(t \to Wb) = \sigma(t-channel) \times \frac{\Gamma(t \to Wb)_{SM}}{\sigma(t-channel)_{SM}}$$

t-channel Cross Section Measurement

- Single top production: contributions from s- and t-channel
- Train a multivariate discriminant for t-channel
- t-channel measurement with s-channel as background



- We obtain

$$\sigma(t-channel)B(t\rightarrow Wb)=3.14^{+0.94}_{-0.90}\,pb$$

(4.8 sigma evidence)

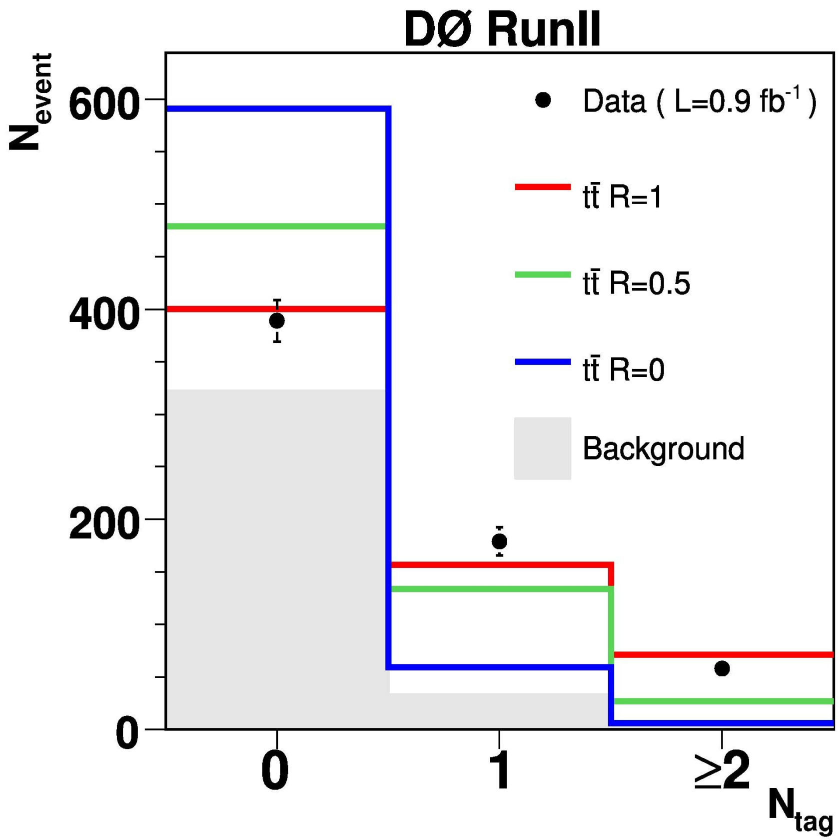
Phys. Lett. B 682, 363 (2010)

Measurement of Ratio of Branching Fractions

- Using lepton+jets $t\bar{t}$ events
- Split into 0, 1, ≥2 b-tagged jets samples
- We measure

$$R = \frac{B(t \to Wb)}{B(t \to \{Wd + Ws + Wb\})}$$

B(t →{Wd+Ws+Wb})=1



$$B(t \to Wb) = 0.962^{+0.068}_{-0.066}(stat)^{+0.064}_{-0.052}(syst)$$

Phys. Rev. Lett. 100, 192003 (2008)

Partial Width

- Extract partial width from combination of R measurement and t-channel cross section
- Correlations of systematics fully taken into account

$$B(t \to Wb) = 0.962^{+0.093}_{-0.084}$$

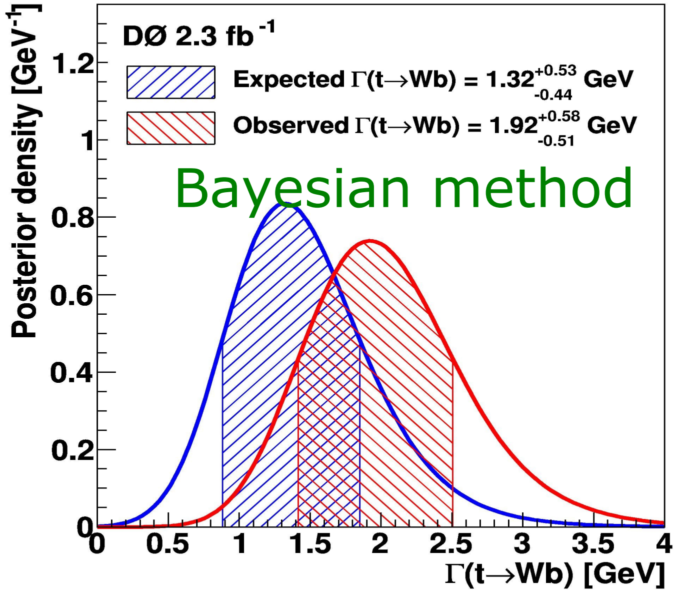
$$\Gamma(t \to Wb)_{SM} = 1.26\,\mathrm{GeV}$$

$$\sigma(t-channel)_{SM} = 2.14 \pm 0.18\ pb$$

$$\sigma(t-channel)\,B(t \to Wb) = 3.14^{+0.94}_{-0.90}\ pb$$

$$\Gamma(t \to Wb) = \sigma(t-channel) \times \frac{\Gamma(t \to Wb)_{SM}}{\sigma(t-channel)_{SM}}$$

$$= 1.92^{+0.58}_{-0.51}\ GeV$$



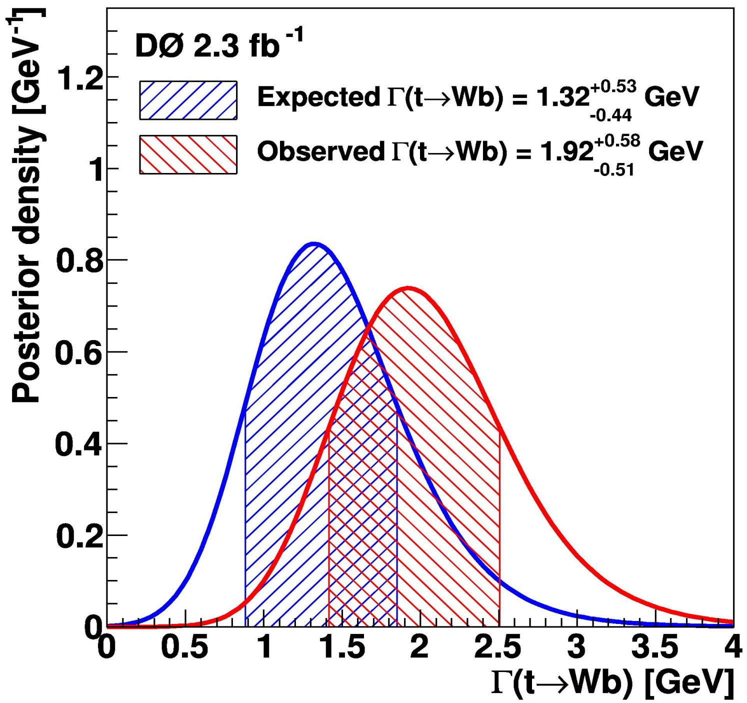
Total Width

- Extract total width from combination of R measurement and t-channel cross section

$$\Gamma(t \to Wb) = 1.92^{+0.58}_{-0.51}\, GeV$$

$$\Gamma_t = \frac{\Gamma(t \to Wb)}{B(t \to Wb)}$$

$$B(t \to Wb) = 0.962^{+0.068}_{-0.066}(stat)^{+0.064}_{-0.052}(syst)$$



- Result:

$$\Gamma_t = 1.99^{+0.69}_{-0.55}\, GeV$$

$$\tau_t = \frac{1}{\Gamma_t} = (3.3^{+1.3}_{-0.9}) \times 10^{-25}\, s$$

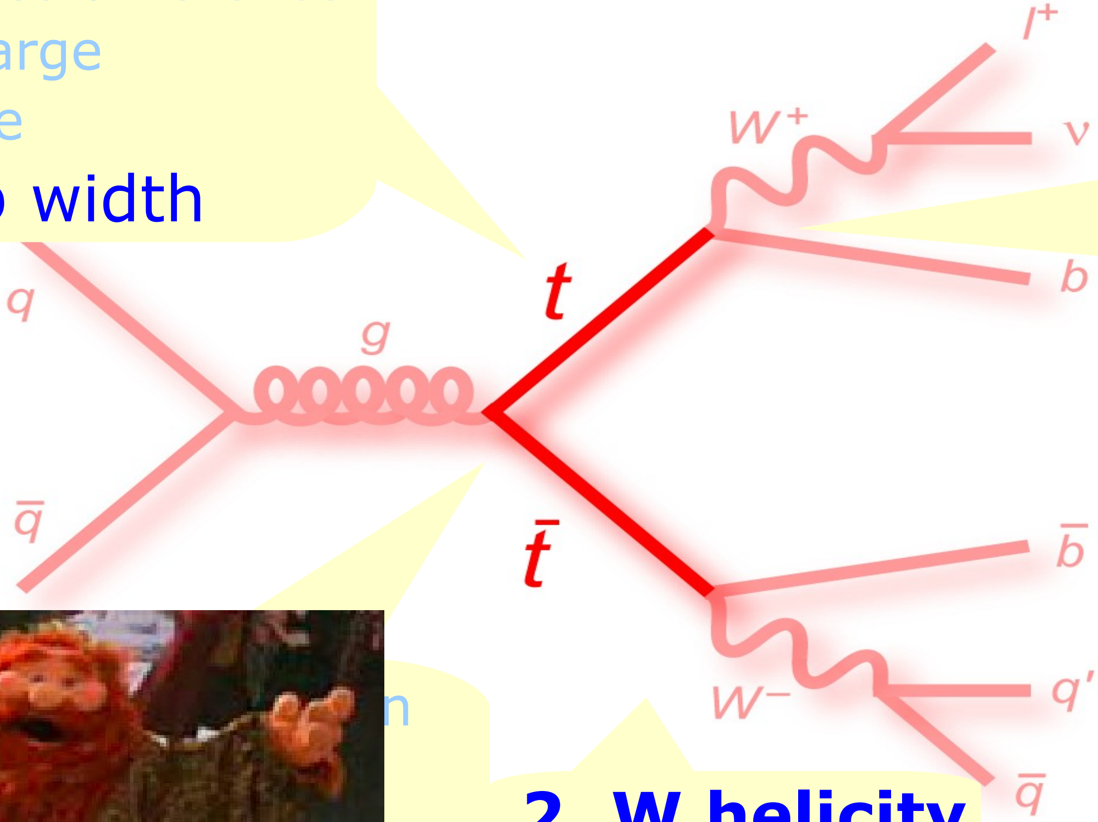
- SM: $\Gamma(t \to Wb) = 1.26\, GeV$

New determination of top quark width

arxiv:1009.5686; accepted by PRL today!

Second Analysis

Top mass
Top mass difference
Top charge
Lifetime
1. Top width



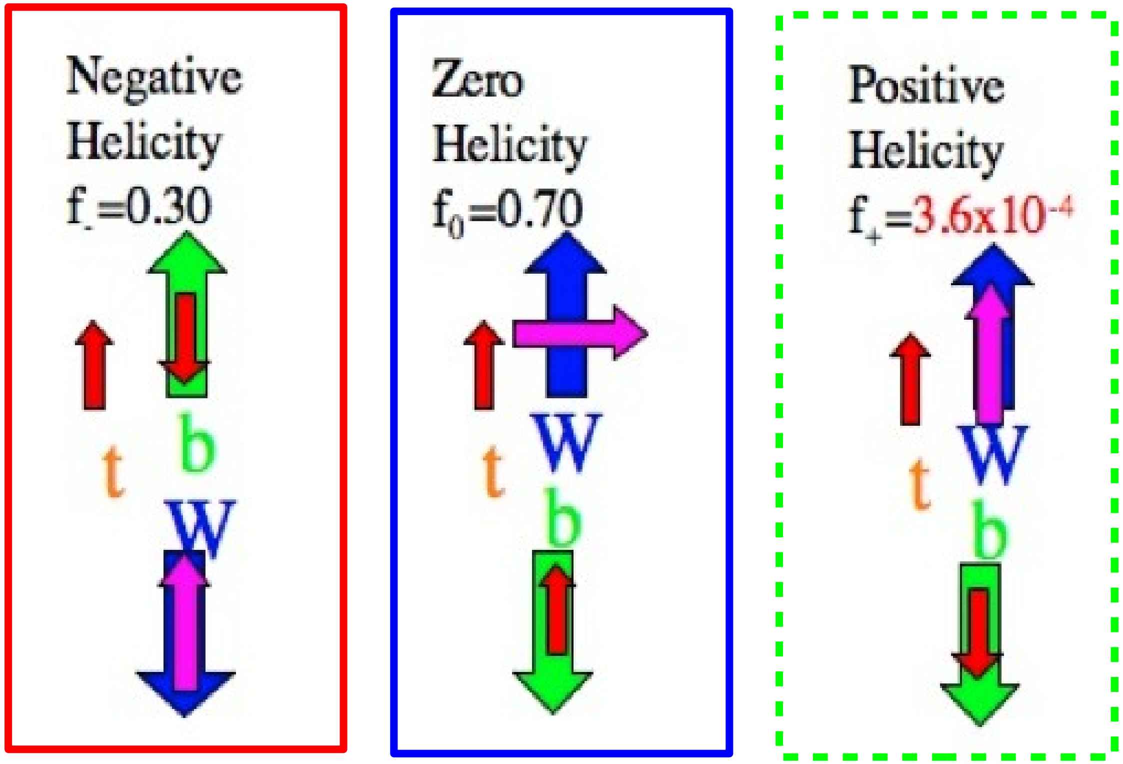
Branching ratios
$|V_{tb}|$
Anomalous coupling
New/Rare decays

2. W helicity

Check the nature of the Wtb coupling

Motivation

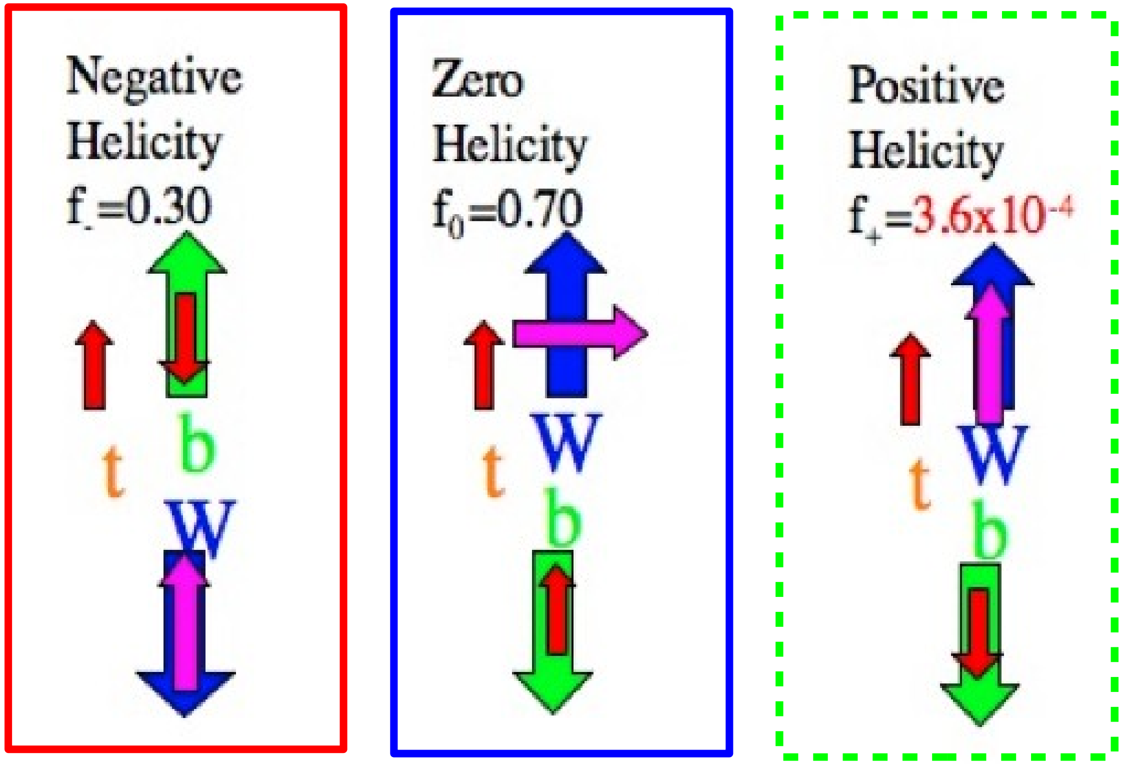
- Left-handed coupling of W-boson to fermions: Not every combination of spin for W and b-quark is allowed

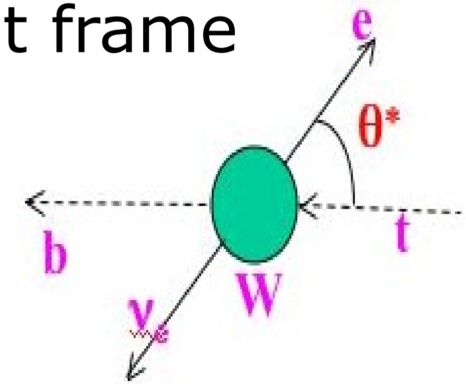


- Direct test of V-A coupling

Measurement Method

- Measure angle θ* between down-type decay product (lepton, d-, s-quark) of W and top quark in W rest frame





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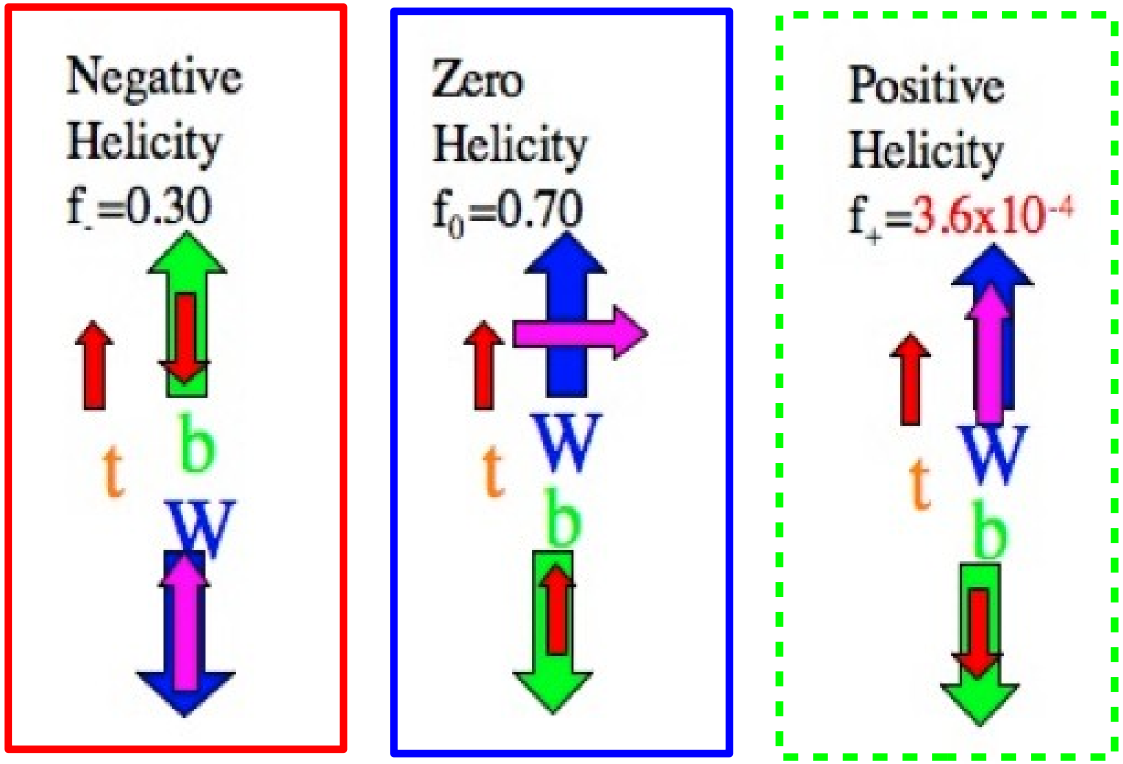
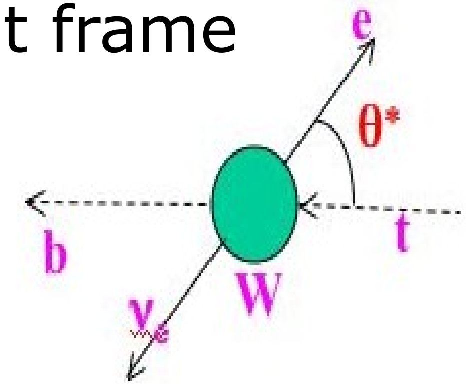
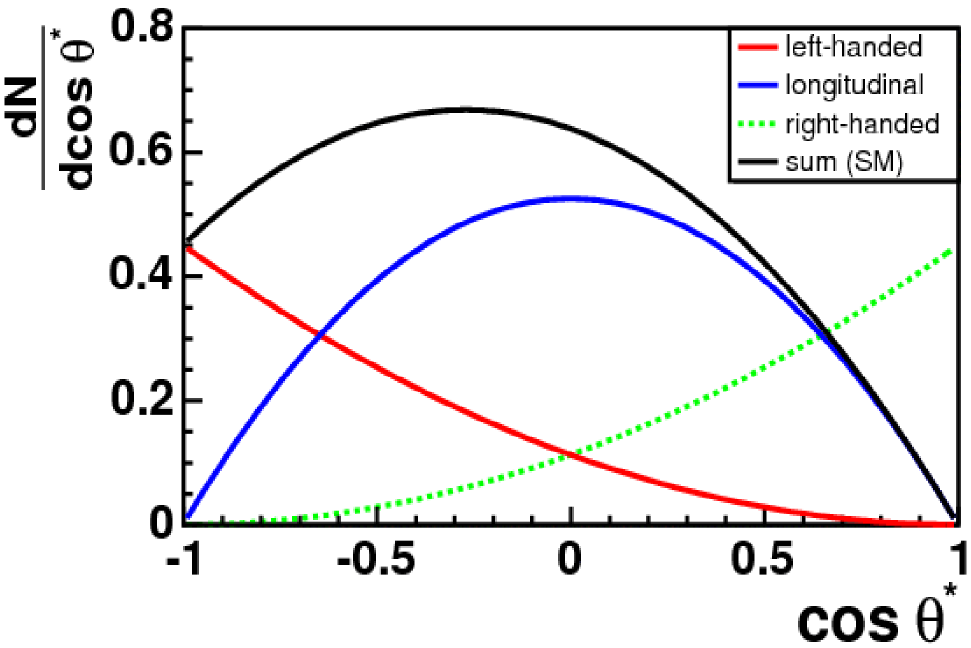






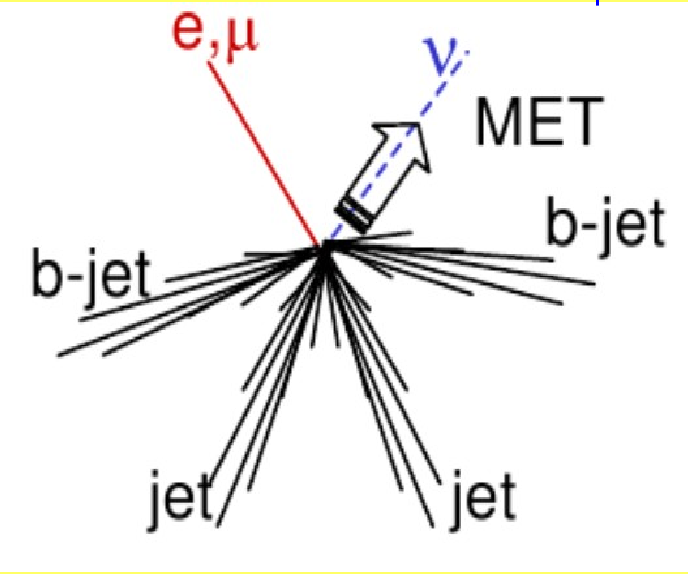
- Distributions of θ* differ for helicity states

Data Sample

Lepton+jets

1 high p_T lepton (>20GeV)
electron or muon

Large $\not{E}_T$

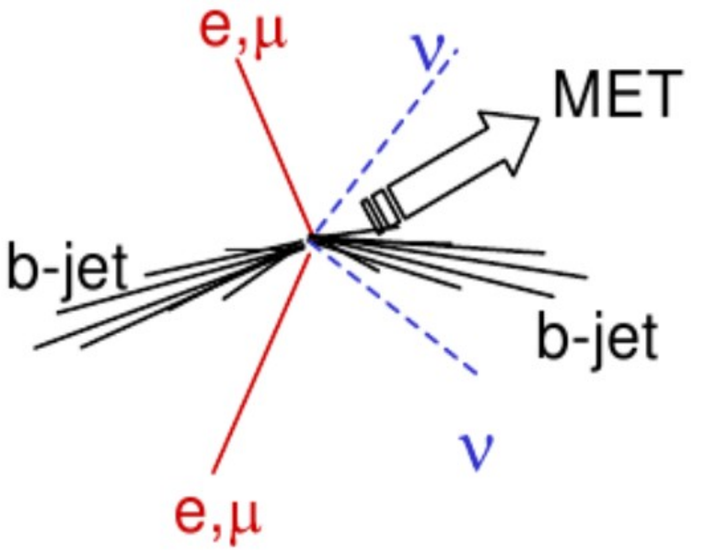


≥4 high p_T jets (>20GeV)
leading p_T jet >40GeV

Dilepton events

2 high p_T oppositely charged leptons (>20GeV)
ee, eμ, μμ

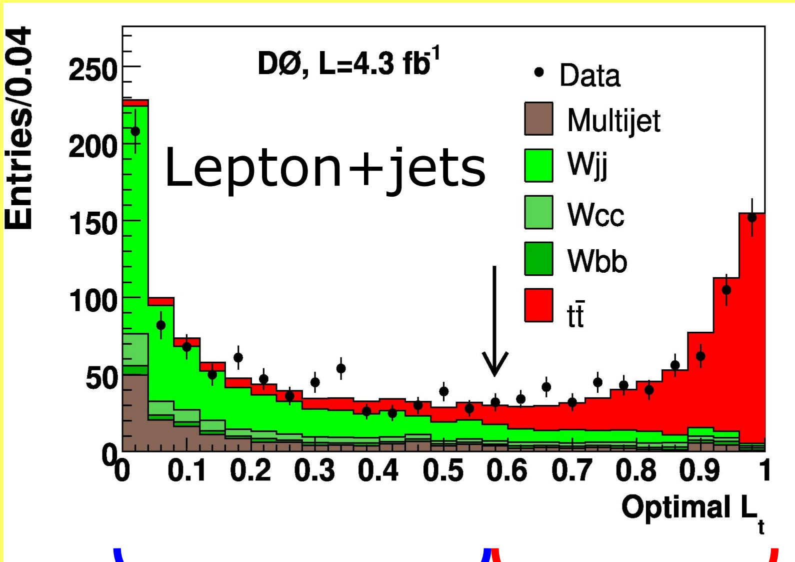
Large $\not{E}_T$

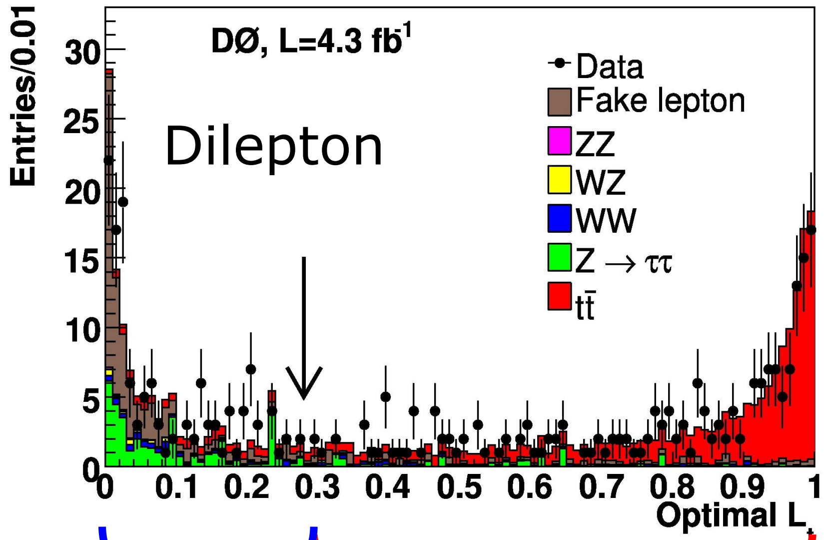


≥2 high p_T jets (>20GeV)

Data Sample and $t\bar{t}$ Enrichment

- Use topological variables discriminating $t\bar{t}$ versus background
- Build likelihood: Background peaks at low, signal at high values





Use low likelihood region for check of background modeling

Use high likelihood region for measurement

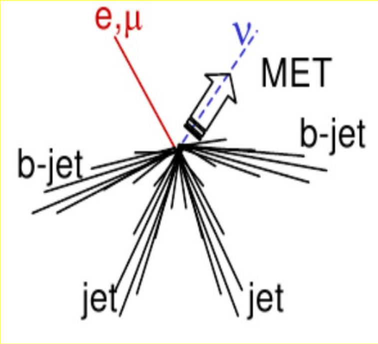
Reconstruction of θ^*

We need to boost to W rest frame → need to know full W 4-vector

Lepton+jets

Neutrino momentum unknown
→ Use constraints from
1) Transverse momentum
2) Fixed top mass
3) W mass

Additional information from b-tagging for possible jet permutations

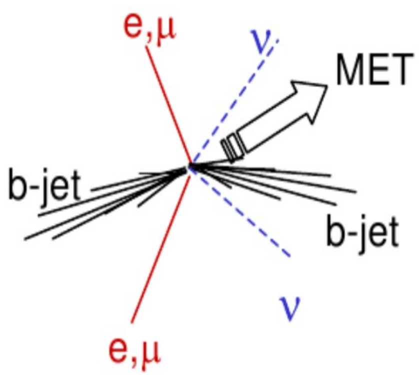


From all possible jet assignments use the one with highest probability

Dilepton

Neutrino momenta unknown
→ Use constraints from
1) Transverse momentum
2) Fixed top mass
3) W mass

Under-constrained

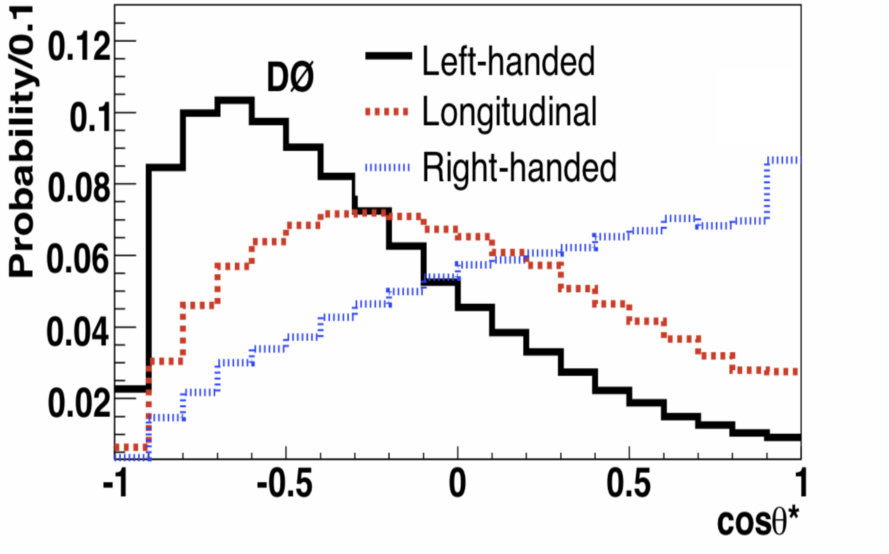


Use average of $\cos\theta^*$ of all solutions

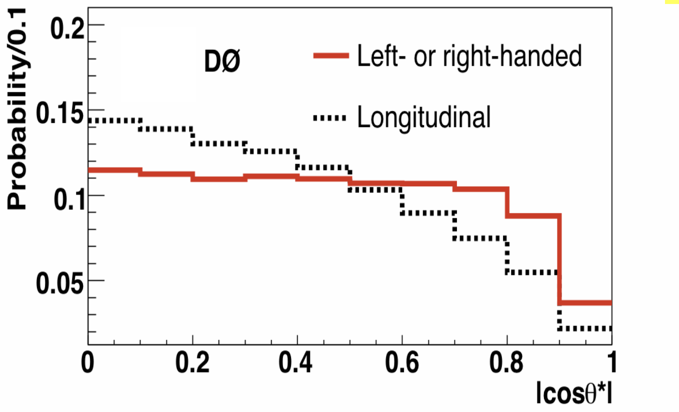
Fit Distributions

Now we can use the cos θ* templates for f_+, f_-, f_0

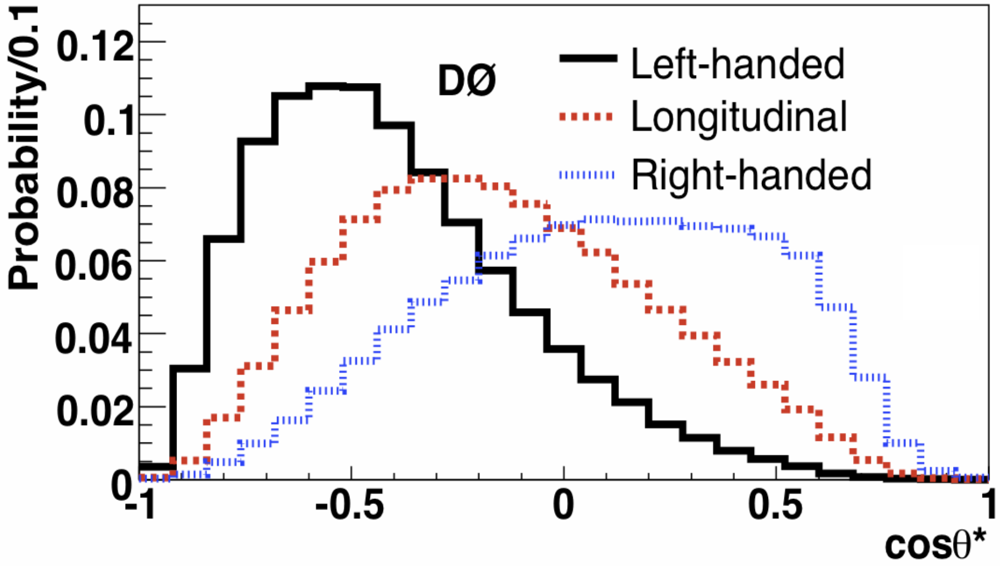
Lepton+jets



Can also use hadronically decaying W to separate f_0 from f_+,f_-



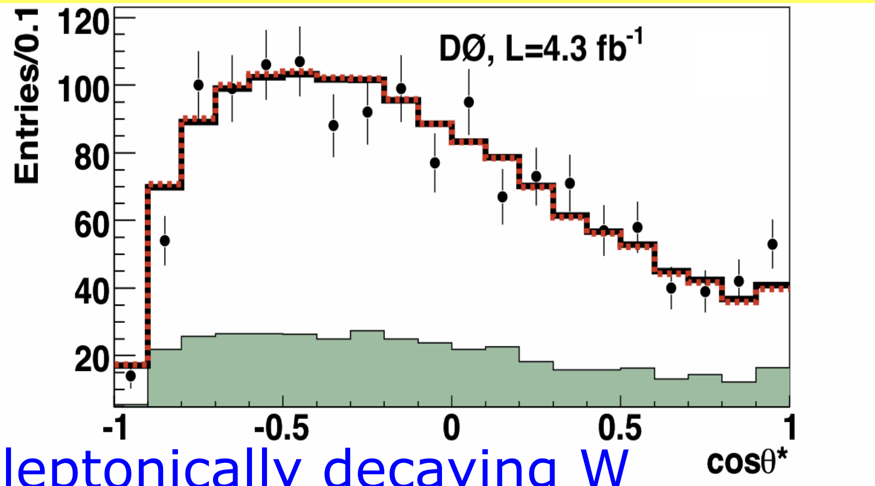
Dilepton



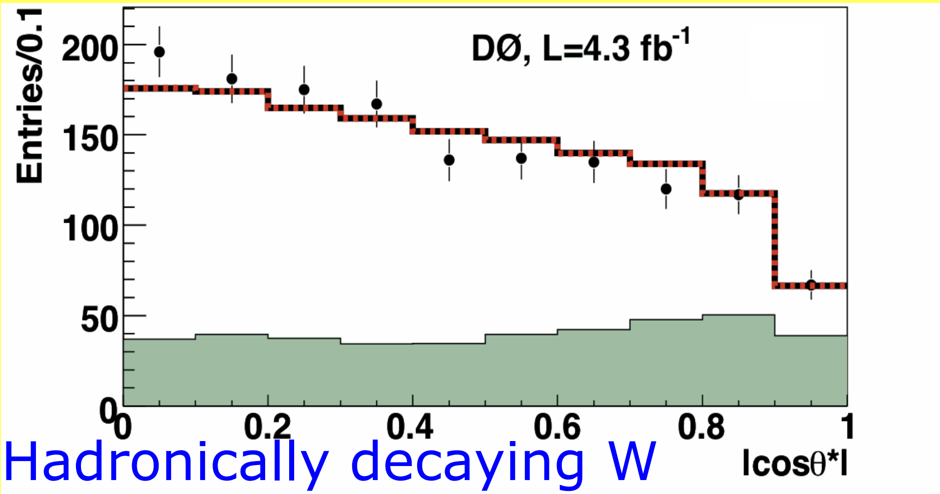
Fitted Distributions

Comparison of fitted fractions to data

Lepton+jets

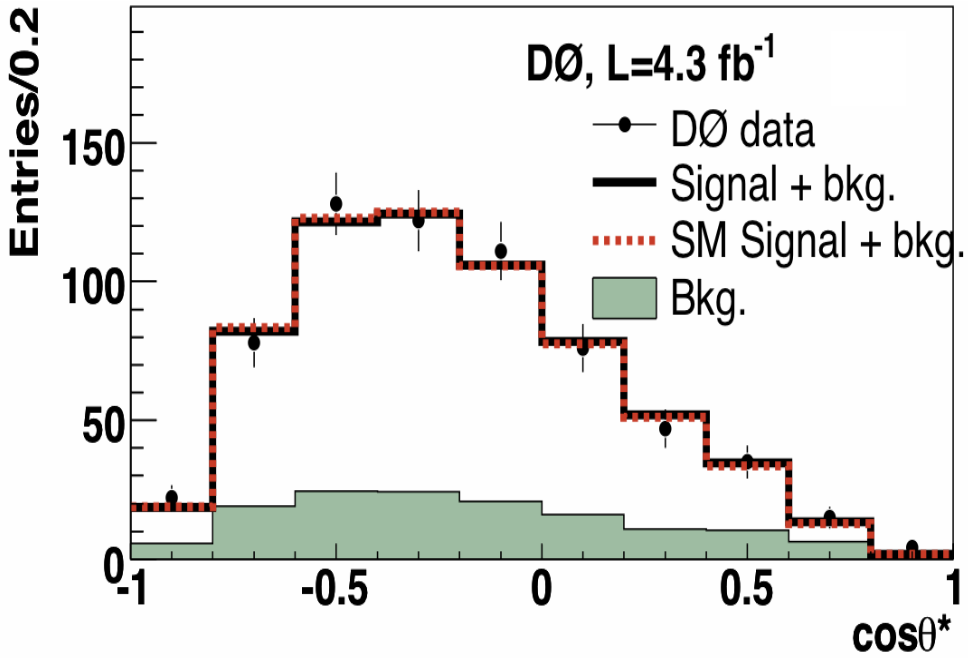


leptonically decaying W



Hadronically decaying W

Dilepton



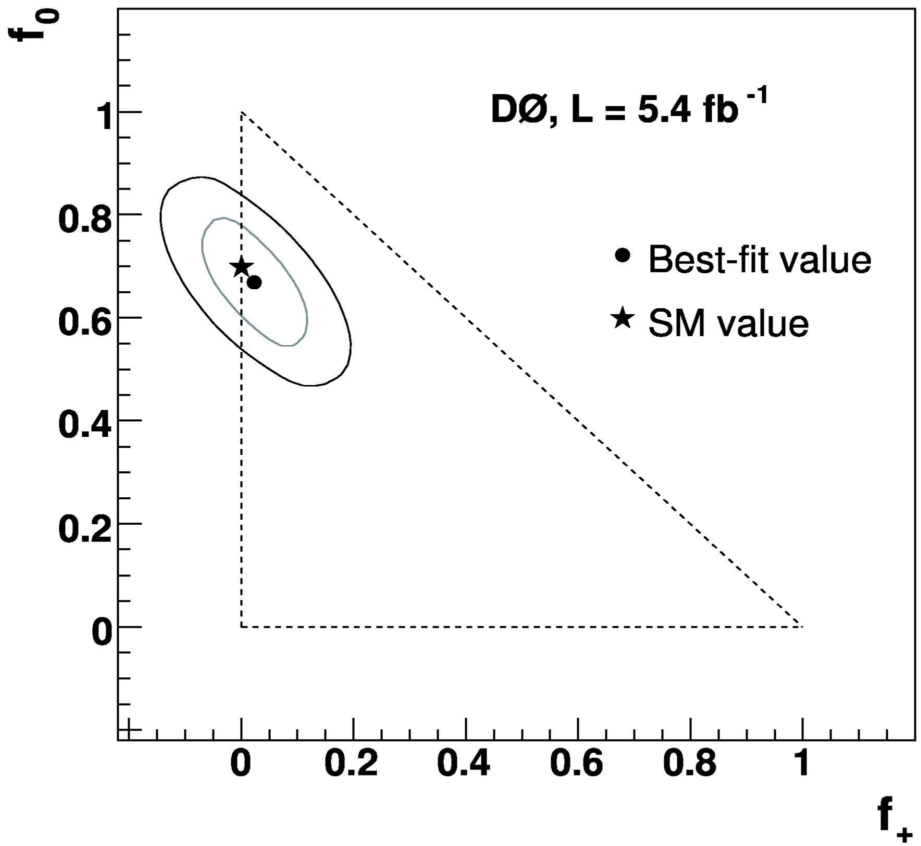
Fit close to SM expectation

Results

- Simultaneous fit of f_0 and f_+:

f_0=0.669±0.078(stat)±0.065(syst)

f_+=0.023±0.041(stat)±0.034(syst)



- Statistical and systematic uncertainty about equal

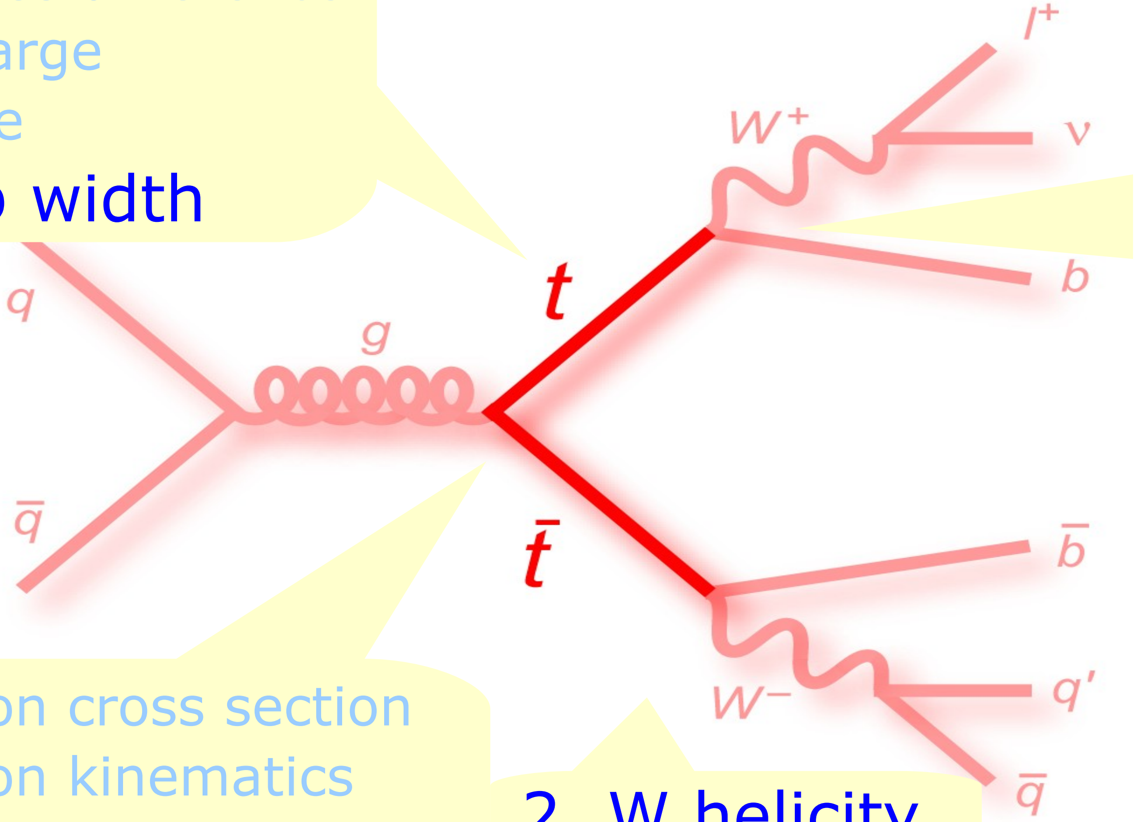
- Measurement in good agreement with SM prediction

Most precise determination of f_0 and f_+ today

arXiv:1011.6549

Third Analysis

Top mass
Top mass difference
Top charge
Lifetime
1. Top width



tt as laboratory
to study
non-perturbative QCD

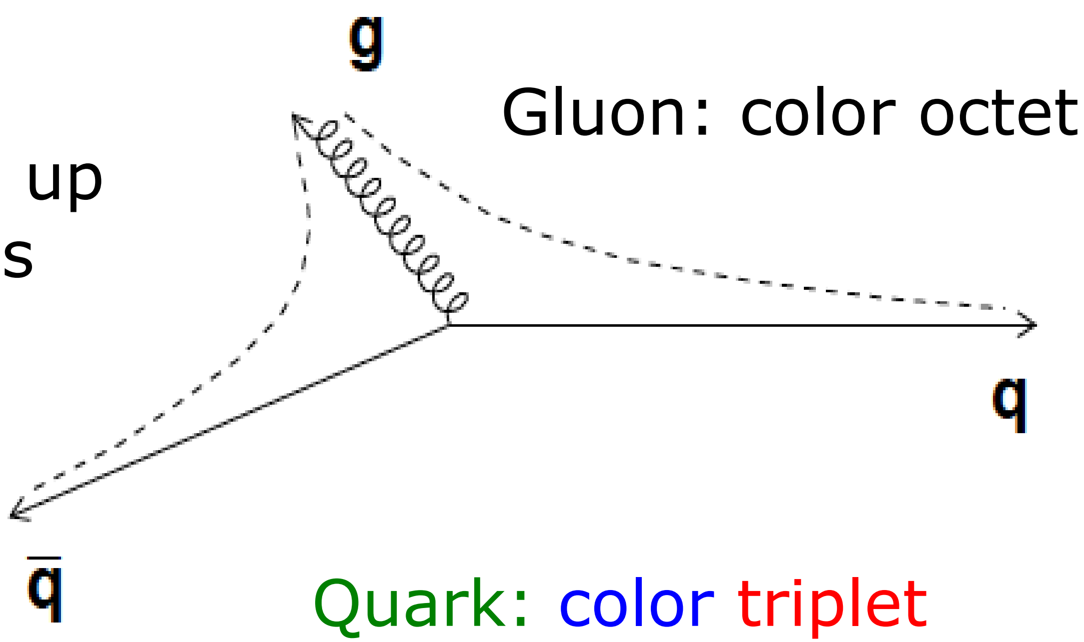
Production cross section
Production kinematics
Production via resonance
New particles

2. W helicity

3. Color Flow

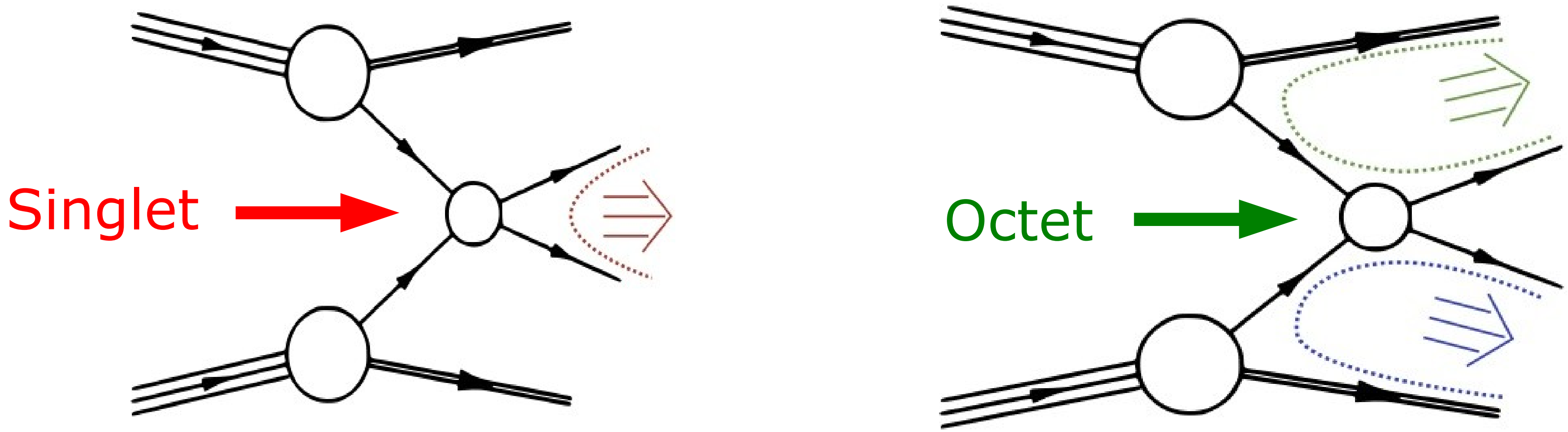
Introduction to Color Connection and Hadronization

- Quarks carry QCD color charge
  - But only color singlets can be observed
    - For example W, Z, or bound states like hadrons
- Partons carrying color are color connected to partons with anti-color
- Hadronization: Particles building up between color-connected partons



Color Flow between Jets

- Jets carry color, and are thus color connected to each other
  - Pairing of connection depends on nature of decaying particles



- Particles created during hadronization should be concentrated along angular region spanned by the color connected partons
  - Transverse jet profiles should not be round
  - Shape influenced by direction of color flow!

Color Flow Observable

Construct a local observable, constructed from particles within a chosen jet cone: Jet pull

- Pick a pair of jets in the event
- Build vectorial sum of (calorimeter) cells within each jet

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

  - $\vec{r}_i$: position of jet cell i relative to center of jet
  - E_T^i: transverse energy of cell i
  - E_T^{Jet}: transverse energy of jet
- Each cell is assigned to closer jet in (η, ϕ) space

Gallicchio, Schwartz,
PRL 105, 022001 (2010)

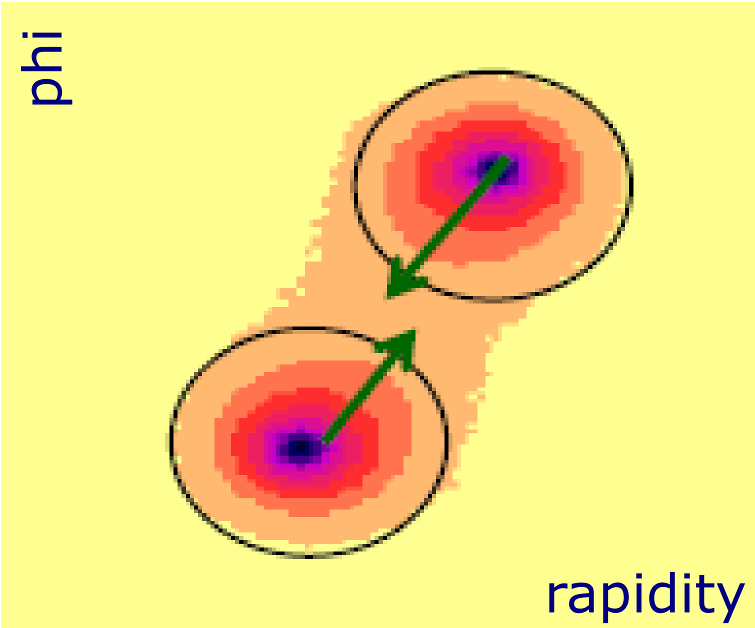
What do we expect...

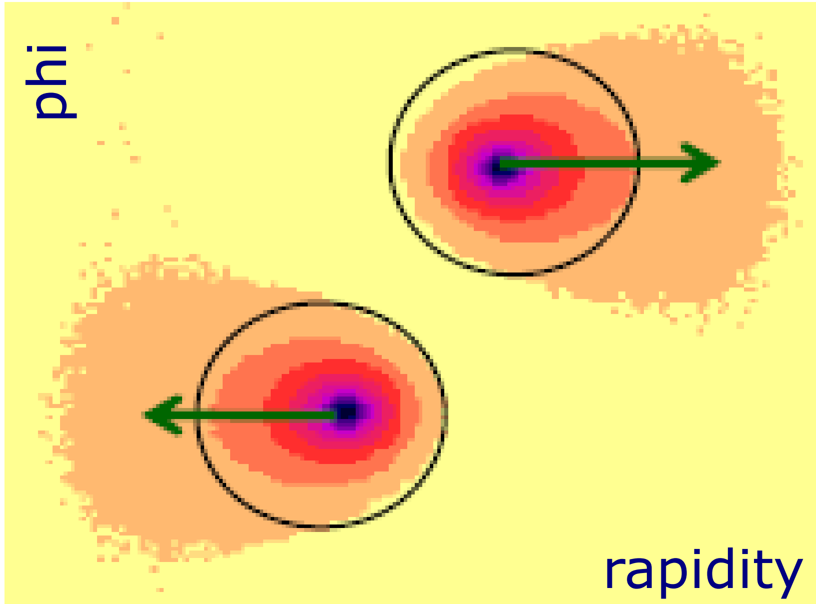
....in the nice, sunny theory world?

Jet Shapes and Pull

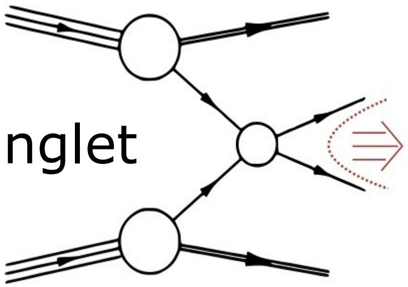
- Jet shape influenced by color flow
- Take same event, shower it millions of times...

Gallicchio, Schwartz, PRL 105, 022001 (2010)



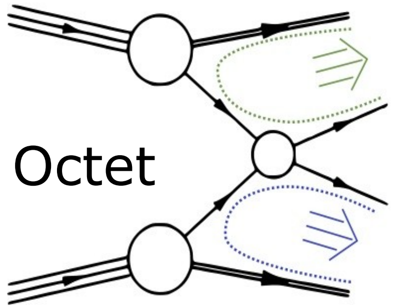


Singlet



Pull vectors different for singlet and octet case

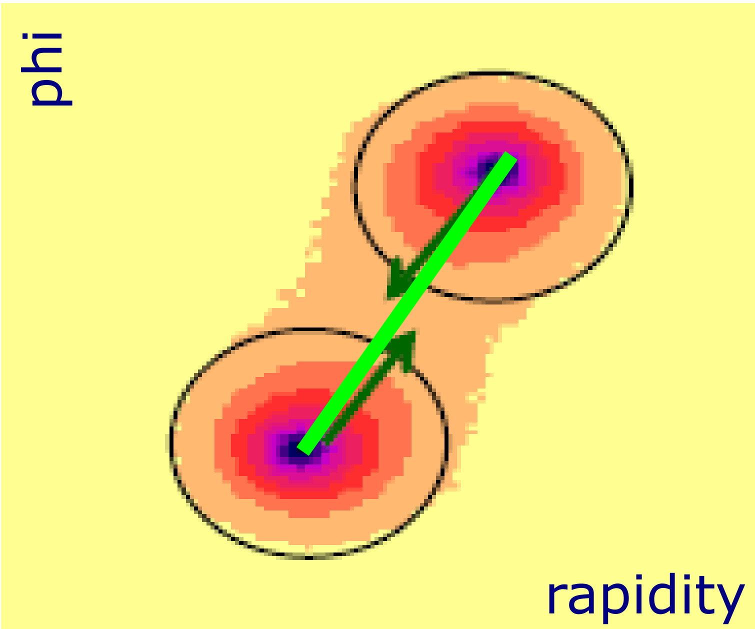
Octet

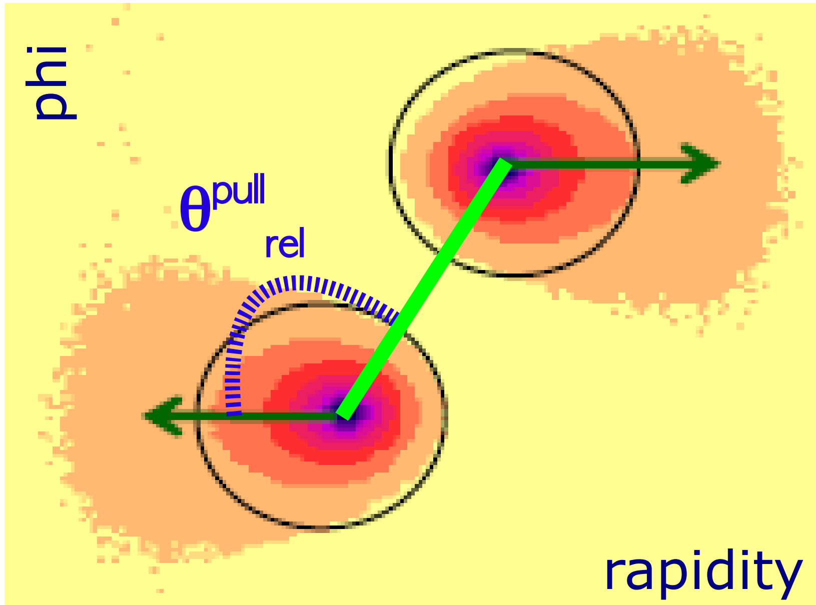


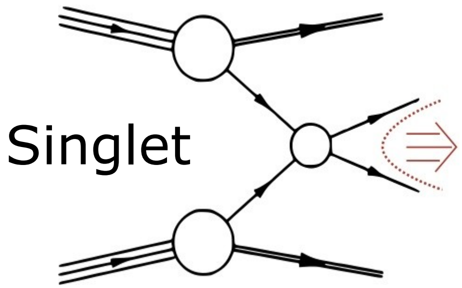
Jet Shapes and Pull

- Jet shape influenced by color flow
- Take same event, shower it millions of times...

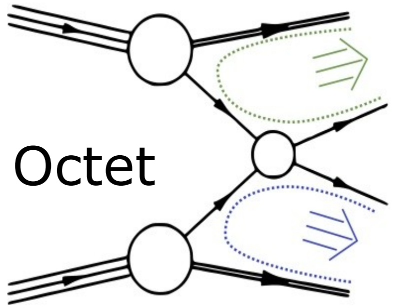
Gallicchio, Schwartz, PRL 105, 022001 (2010)





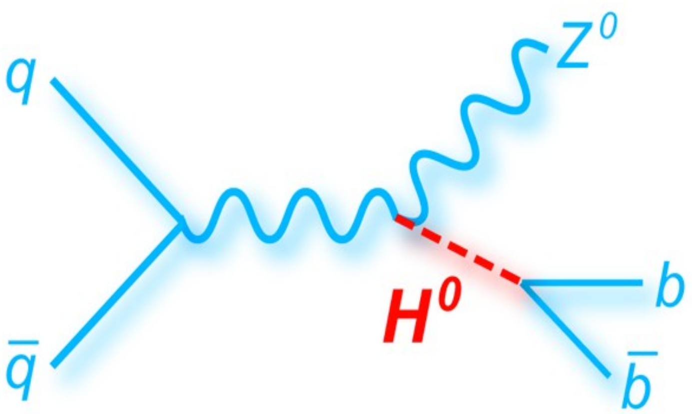


We will use the relative angle of the pull vector w.r.t. connection line between jet centers

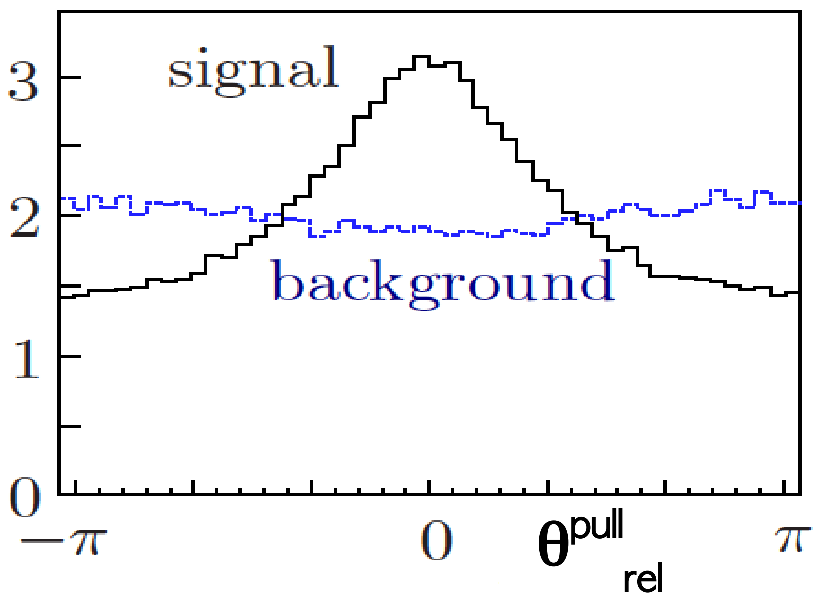


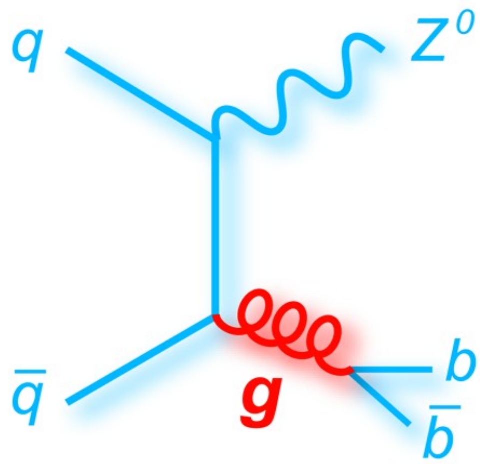
Motivation

- Jet pull variable: Distinguish singlet from octet state
  - Can be used as independent information additional to kinematics
  - Distinguish processes with same final state
  - Use it for new physics searches
- Example: Higgs search in ZH



Signal:
$b\bar{b}$ from Singlet





Background:
$b\bar{b}$ from Octet

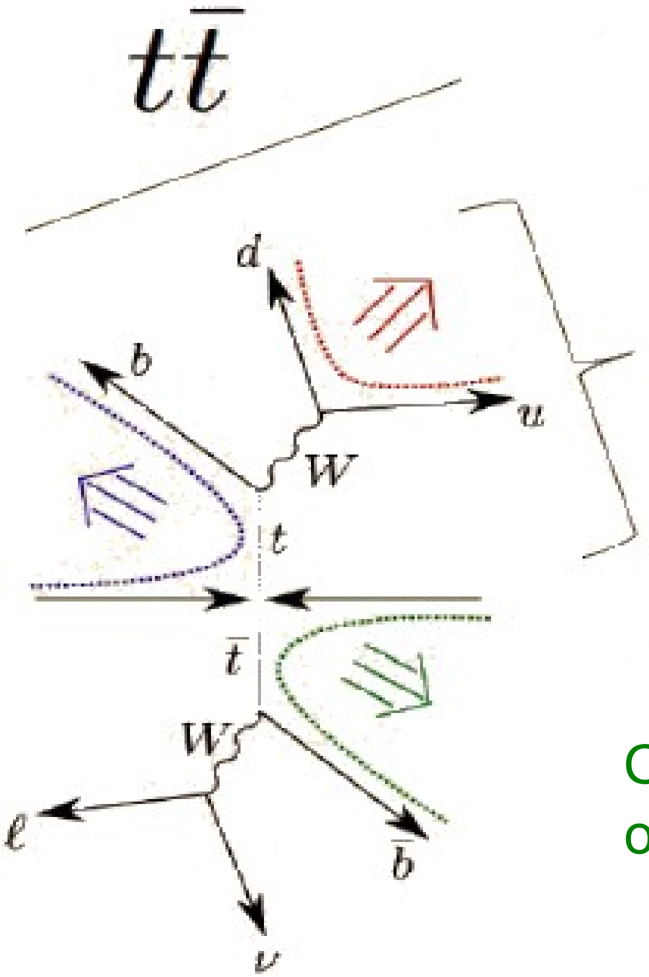
But first we need to see how Jet Pull looks like in....

...the real, dark experimentalists world

Jet Pair from Color Singlet

To test the jet pull for color singlet in data we use lepton+jets (double b-tagged) $t\bar{t}$ events

channel	sample	0 b-tags	1 b-tag	$\geq$ 2 b-tags
ℓ+4 jets	W+jets	576 ± 75	229 ± 32	49 ± 8
	Multijet	115 ± 16	46 ± 7	7 ± 2
	Z+jets	42 ± 6	16 ± 3	4 ± 1
	Other	31 ± 4	19 ± 2	9 ± 1
	$t\bar{t}$	160 ± 22	417 ± 38	519 ± 51
	Total	923 ± 62	727 ± 24	589 ± 48
	Observed	923	743	572
ℓ+$\geq$5 jets	W+jets	60 ± 22	26 ± 11	7 ± 3
	Multijet	17 ± 3	12 ± 2	3 ± 1
	Z+jets	4 ± 1	2 ± 1	1 ± 1
	Other	3 ± 1	3 ± 1	2 ± 1
	$t\bar{t}$	34 ± 6	90 ± 13	132 ± 17
	Total	118 ± 19	132 ± 7	145 ± 15
	Observed	112	127	156

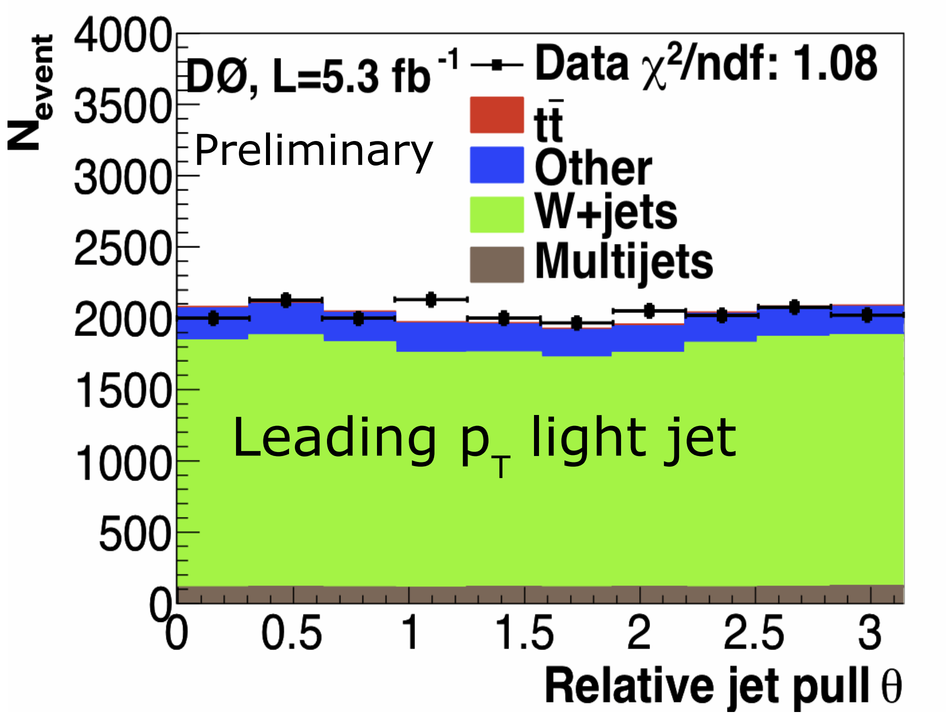


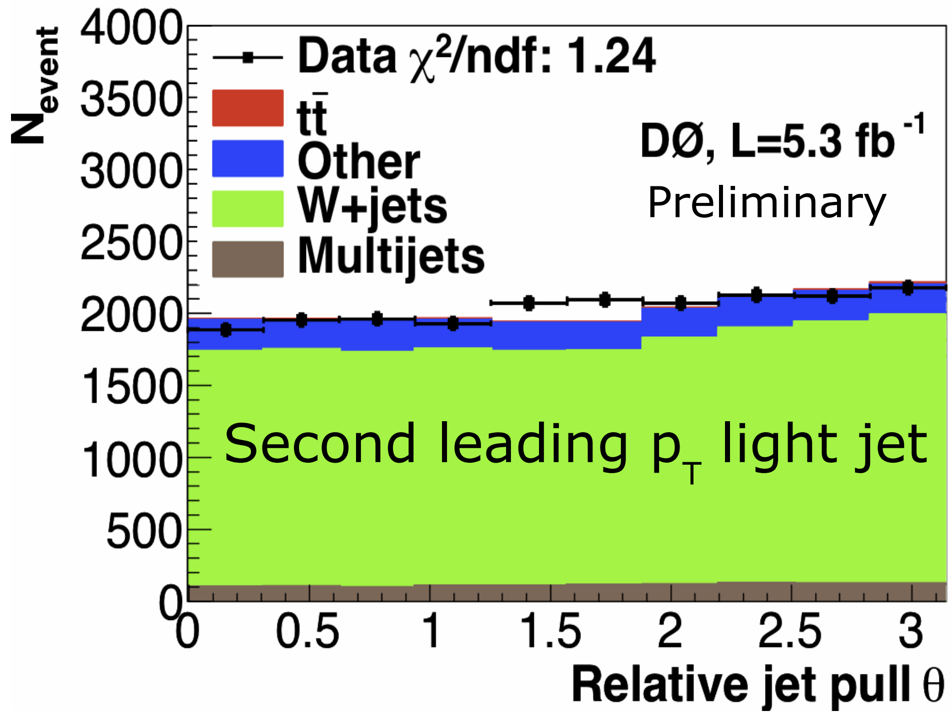
Clean color-singlet jet pair

Clean sample of $W \rightarrow jj$

Calibrating Jet Pull

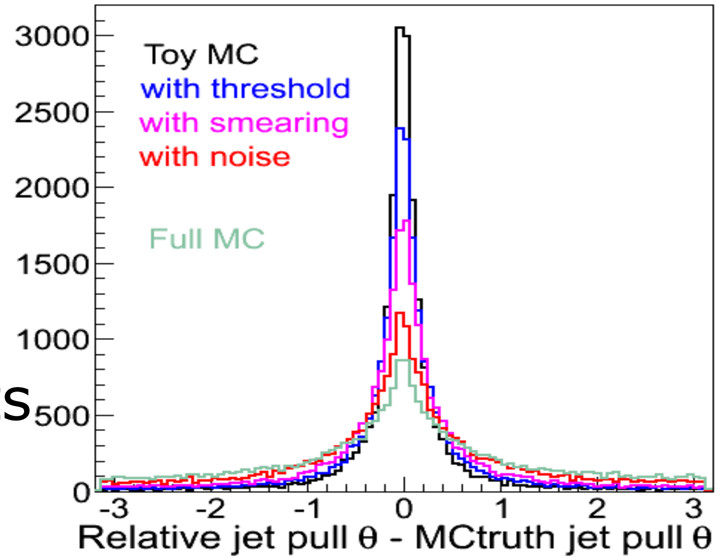
- Need to understand reconstruction effects
- Use 0 b-tagged lepton+$\not\!\!E_T$+2jet events
  → well understood W+jet sample
  - Check modeling of jet pull in simulation



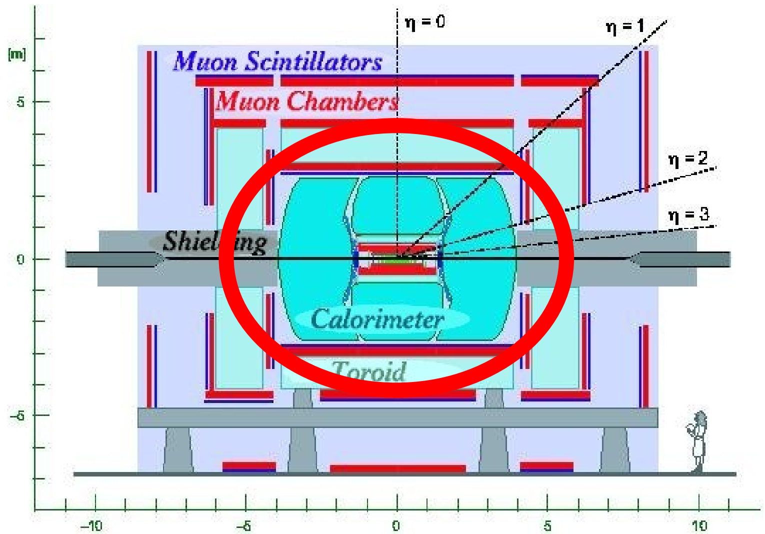


Calorimeter Effects

- Checked influence of noise/pile-up on jet pull with toy MC
  - Start clustering true MC particles in towers
  - One-by-one simulation of detector effects to check degradation from calorimeter effects → degradation in full simulation reproduced

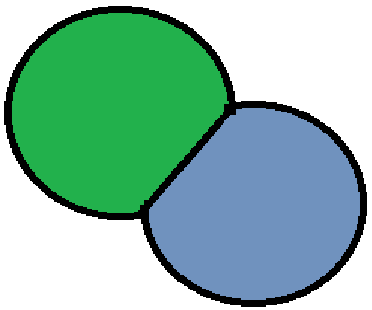


- Calorimeter inhomogeneity:
  - We correct for bias from ICR and assign a systematic uncertainty
  - Small effect on relative jet pull angle

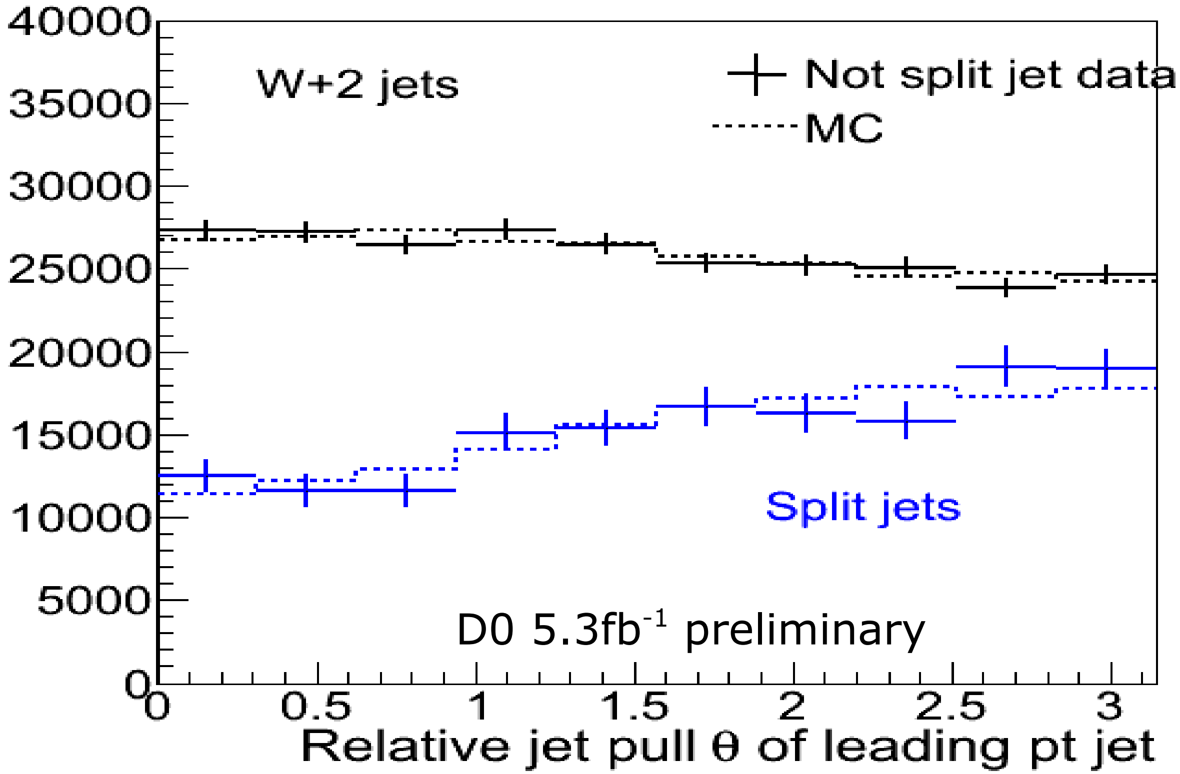


Effect of overlapping Jet Cones

- Split/no-split jets show different relative jet pull distributions
- Cells assigned to closer jet



Effect of overlapping jet cones well modeled!

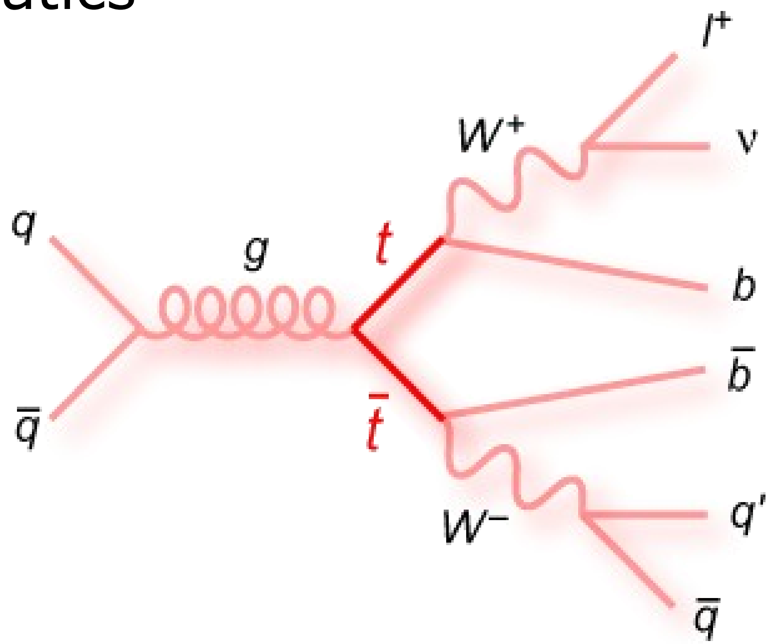


- Optimized cone size of jet to get best singlet-octet separation

Back to the $t\bar{t}$ Sample

After understanding detector effects and checks in control sample

- How to study the sensitivity to singlet versus octet states?
- We can not simply compare the relative jet pull from light jets (from singlet) and b-jets (color-connected to the beam)
- Different kinematics



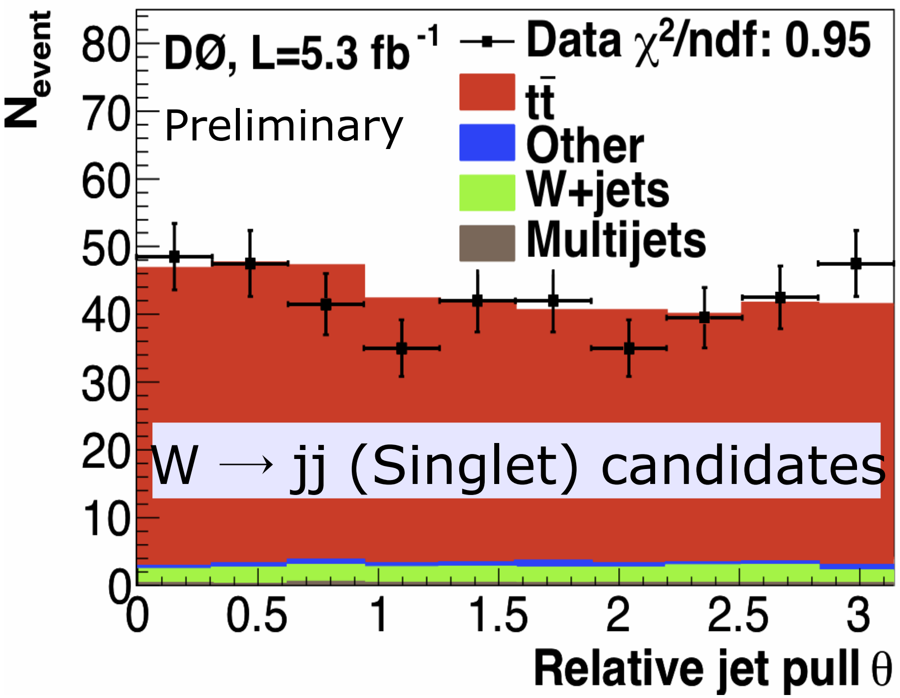
b-jet (Octet) candidates

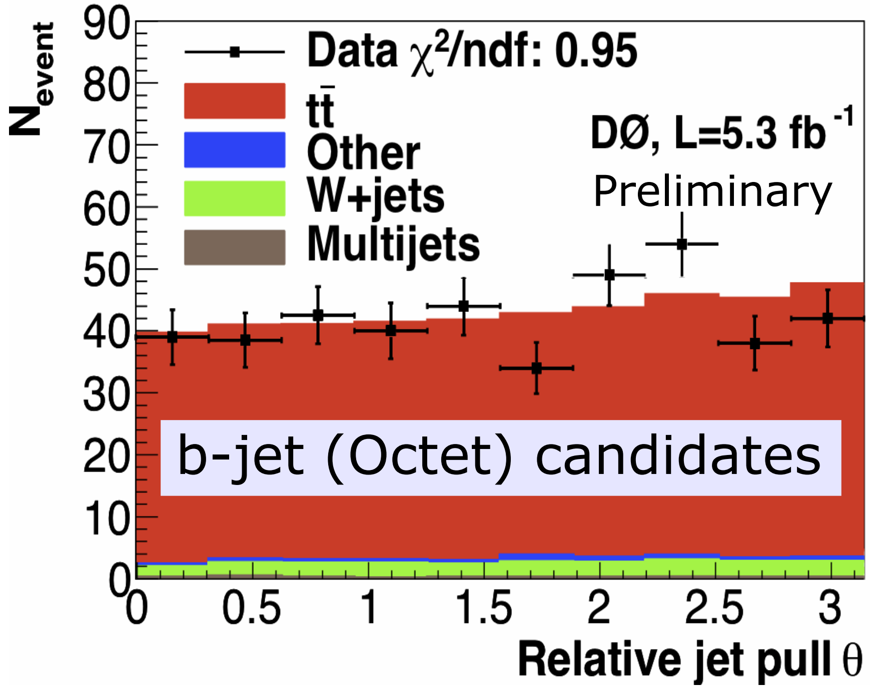
$W \rightarrow jj$ (Singlet) candidates

Back to the $t\bar{t}$ Sample

After understanding detector effects and checks in control sample

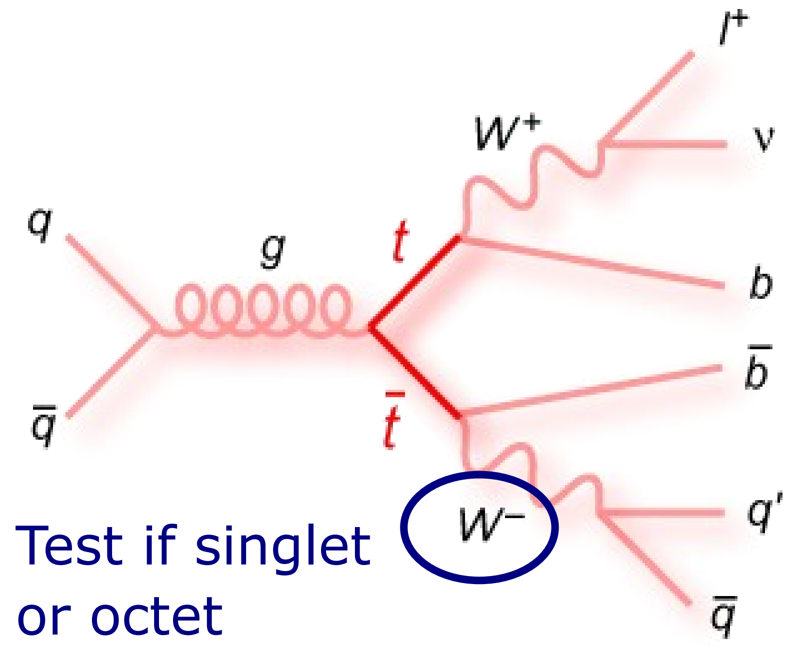
- How to study the sensitivity to singlet versus octet states?
- We can not simply compare the relative jet pull from light jets (from singlet) and b-jets (color-connected to the beam)
- Different kinematics, both well modeled





W Color Singlet Measurement

- Simulate the hadronically decaying W as a color-octet "W"
- MadGraph+PYTHIA

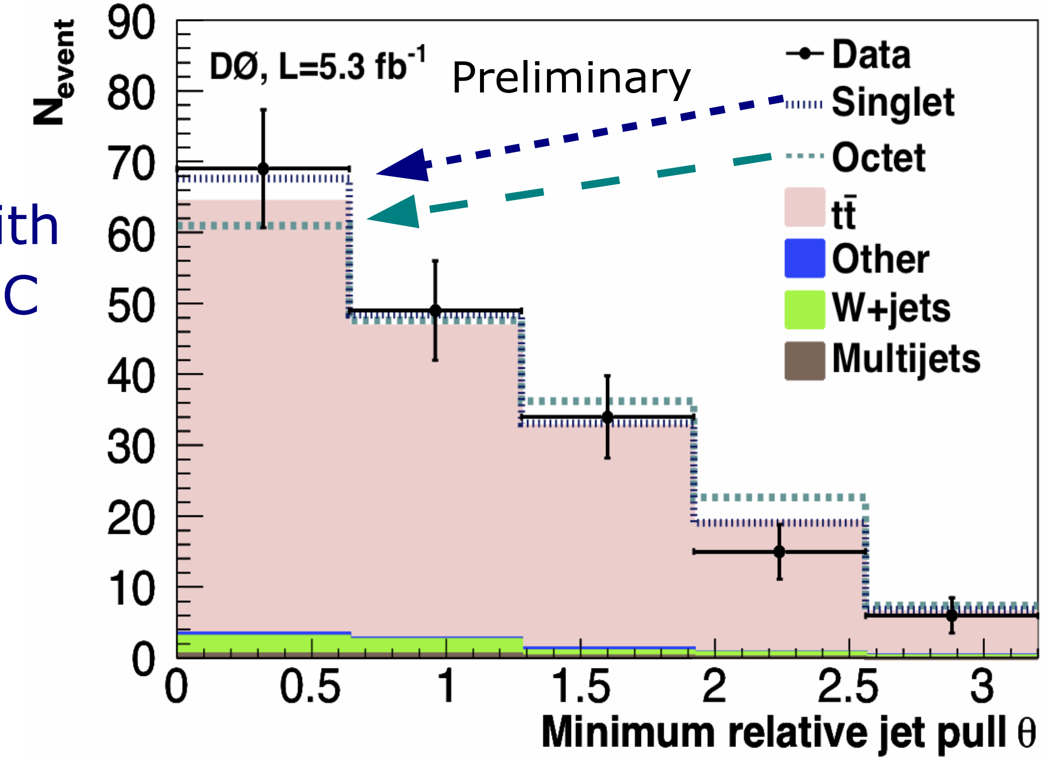


- Fit fraction of events with light jets coming from singlet W: $f_{Singlet}$

Fit Regions: Most sensitive Region

- For optimal sensitivity: Split double b-tagged $t\bar{t}$ sample into different regions in m_{jj}, $\Delta R(jj)$, jet η
- Most sensitive region: Jets not too far apart from each other
  - Highly separated jets: Color radiation spread over large area → washed out

Compare data with singlet & octet MC



$|m_{jj}-M_W|<30$ GeV
$\Delta R(jj)<2$
$|\eta|<1$ for both jets

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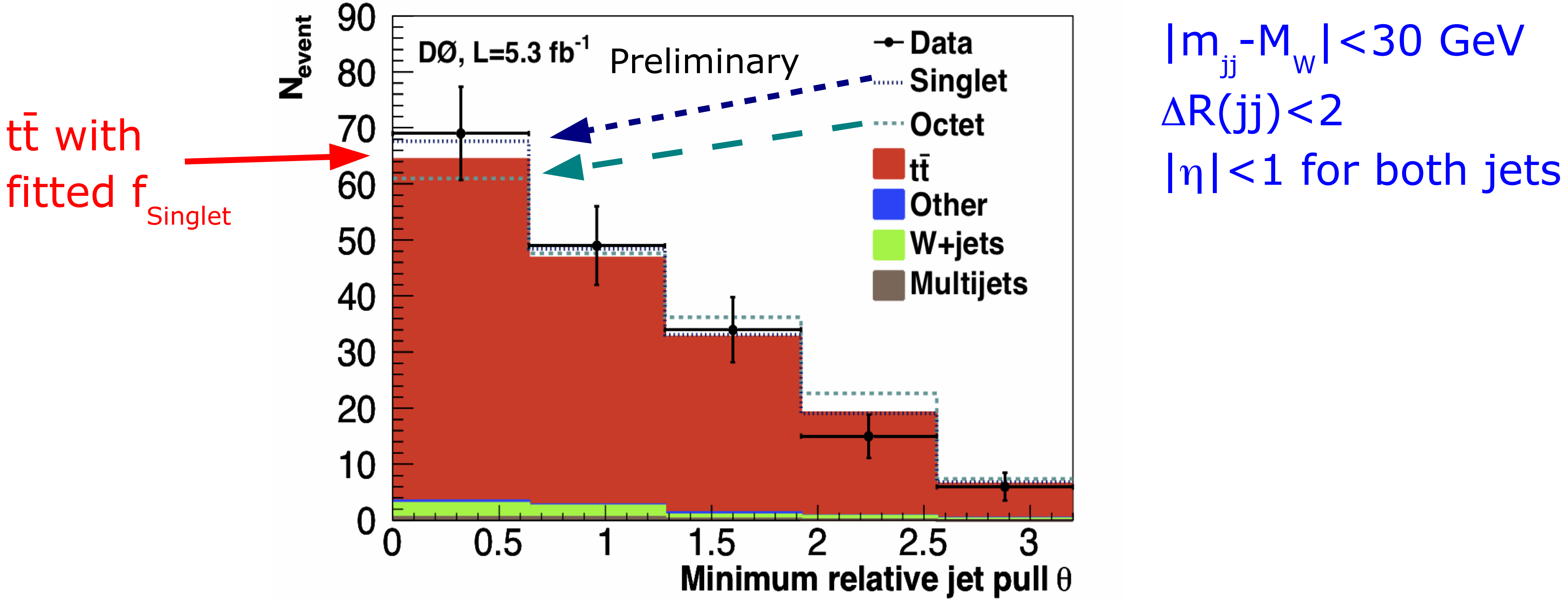


Systematics

- We include several systematic uncertainties
  - MC statistics on template shape ($\Delta f_{Singlet}=0.19$)
  - Uncertainty on calorimeter inhomogeneity ($\Delta f_{Singlet}=0.1$)
  - Jet energy scale/resolution...
  - Total systematics: $\Delta f_{Singlet}=0.22$
- Total statistical uncertainty of data: $\Delta f_{Singlet}=0.37$
- Also checked several Monte Carlo models
  - PYTHIA tunes with and without color reconnection
  - ALPGEN+HERWIG versus ALPGEN+PYTHIA
  - Effects small

Fit Result and Limits

- Result for $f_{Singlet} = N_{Singlet}/N_{total}$

$f_{Singlet}$=0.56±0.38(stat+syst)±0.19(MC stat)

- Set limits with Feldman & Cousins:

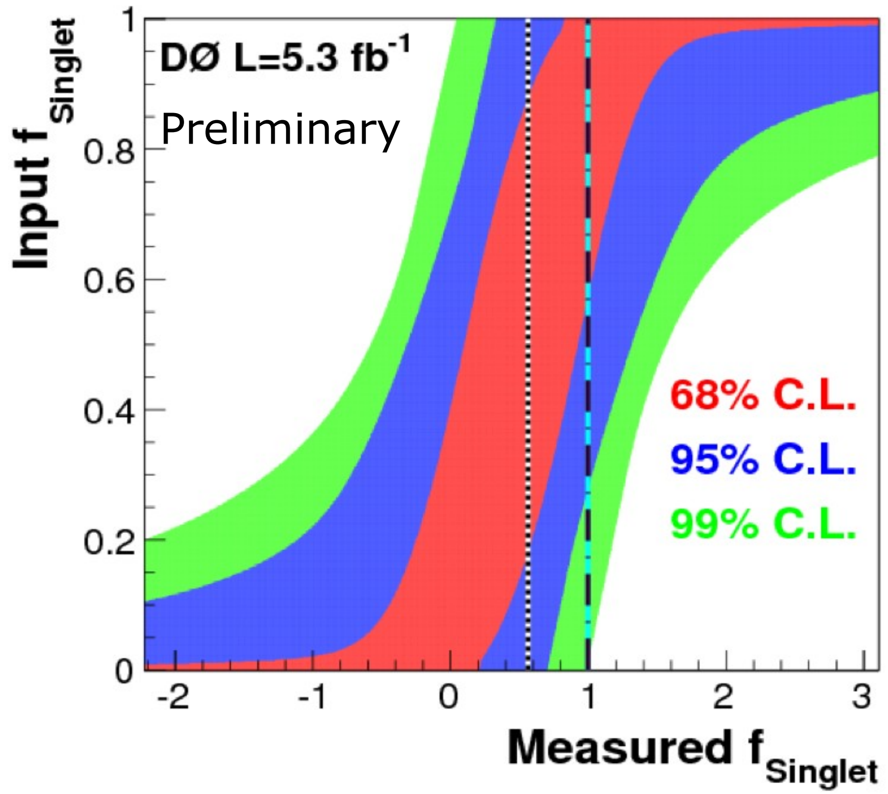
  Expected: Exclude octet "W" @ 99%C.L.

- Expect $f_{Singlet}$=1 in SM

First study of color flow in $t\bar{t}$ events

First extraction of $f_{Singlet}$

(using only color flow information)



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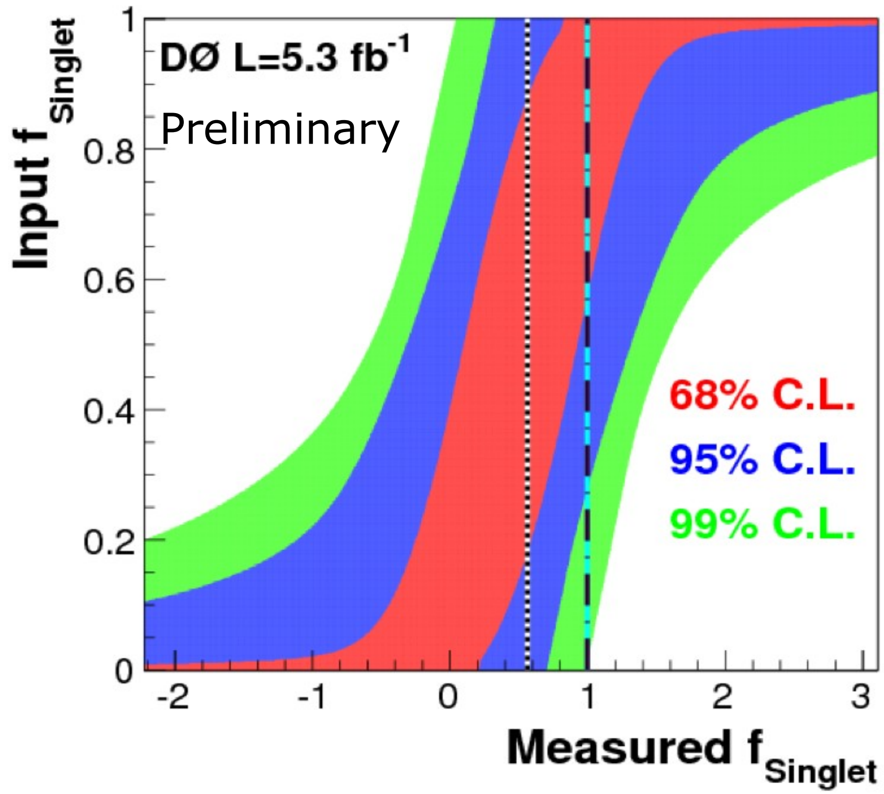

- Still statistically limited

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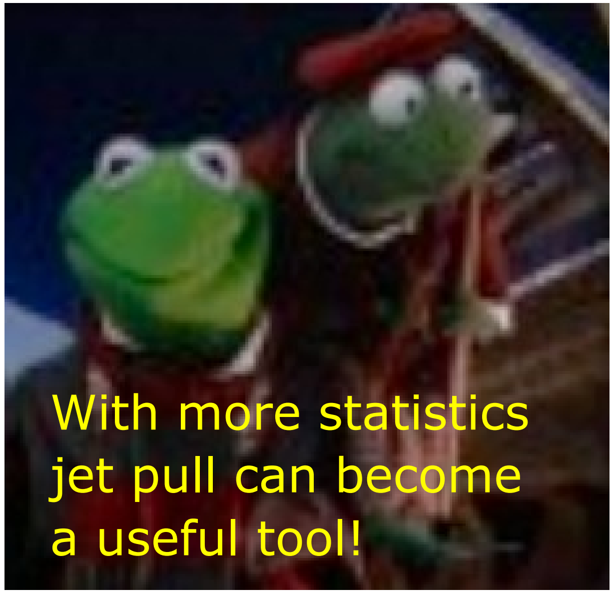


Summary and Outlook

- Rich top quark program at DØ
  - Only three out of many results shown here
- Not just using more data, also new ideas
  - Top width determination using t-channel single top and R analysis done for the first time
  - Color flow study in $t\bar{t}$ events done for the first time
- Not everything is statistically limited anymore
  - W helicity close to be systematically limited
- Just an excerpt of results shown here – full beauty of top results:

http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html

- Great performance of the Tevatron

→ More data to analyse, more physics to explore

And they all lived happily ever after

Tiny Tim made Scrooge realize how much he was needed. So he decided to double his statistics in his birthplace by 2014. But in his generosity he did not stop there, but blessed his favorite skiing place (Geneva, Switzerland) by appearing with even more statistics in different kind of collisions!

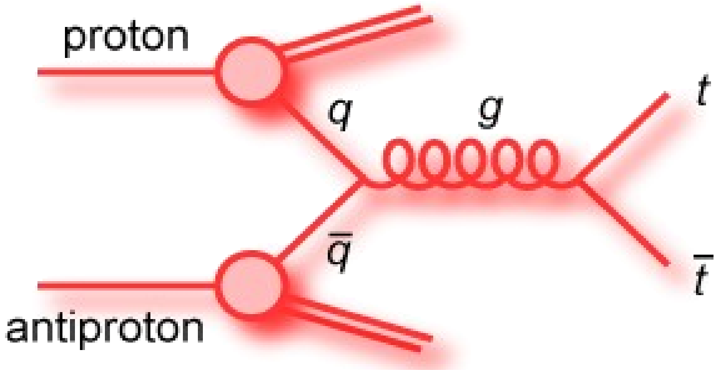
And they all happily did complementary measurements...

Backstage information

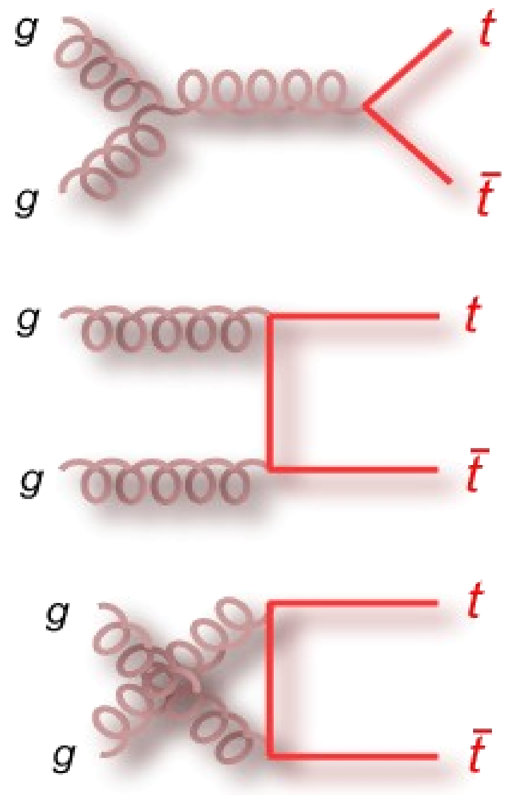
Top Quark Pair Production

- Via strong interaction
- At the Tevatron:

85%



+ 15%



At LHC (14 TeV cms energy):
10%

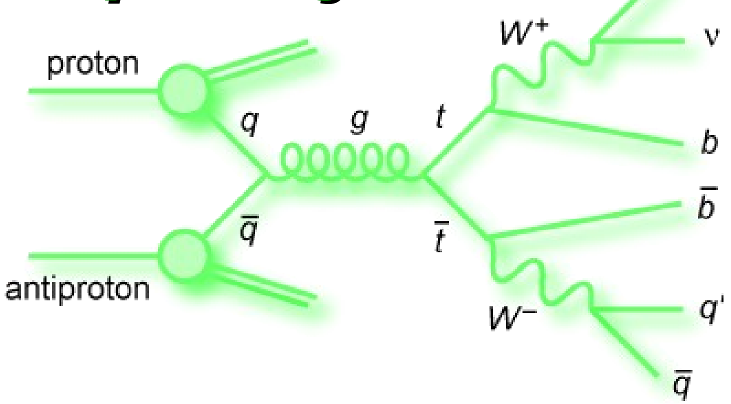
+ 90%

- Production cross section:
approximate NNLO: $\sigma = 7.46^{+0.48}_{-0.67}\, pb$ @ m_t=172.5GeV

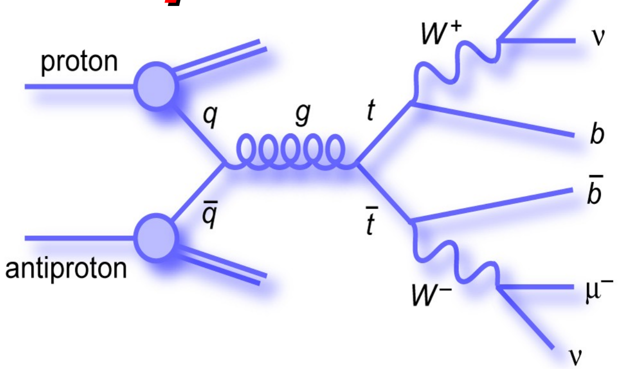
Moch, Uwer, PRD 78, 034003 (2008)

Signal and background events

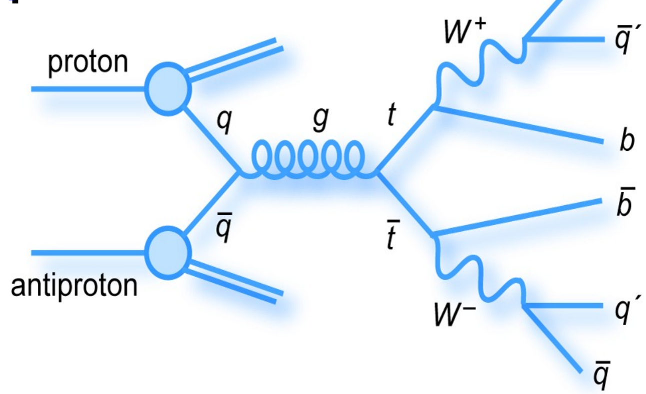
lepton+jets



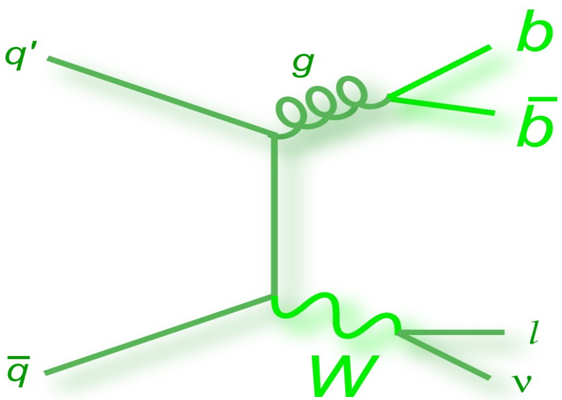
dilepton



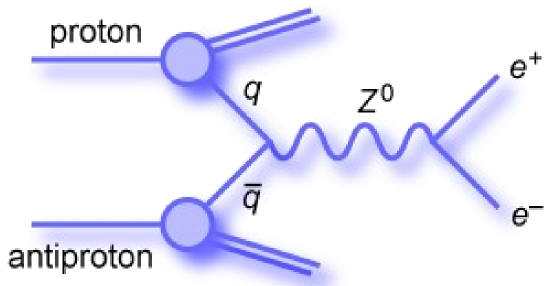
pure hadronic



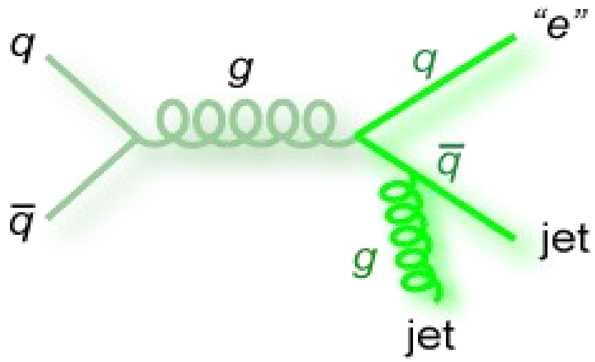
W+jets:
Main background
in l+jets



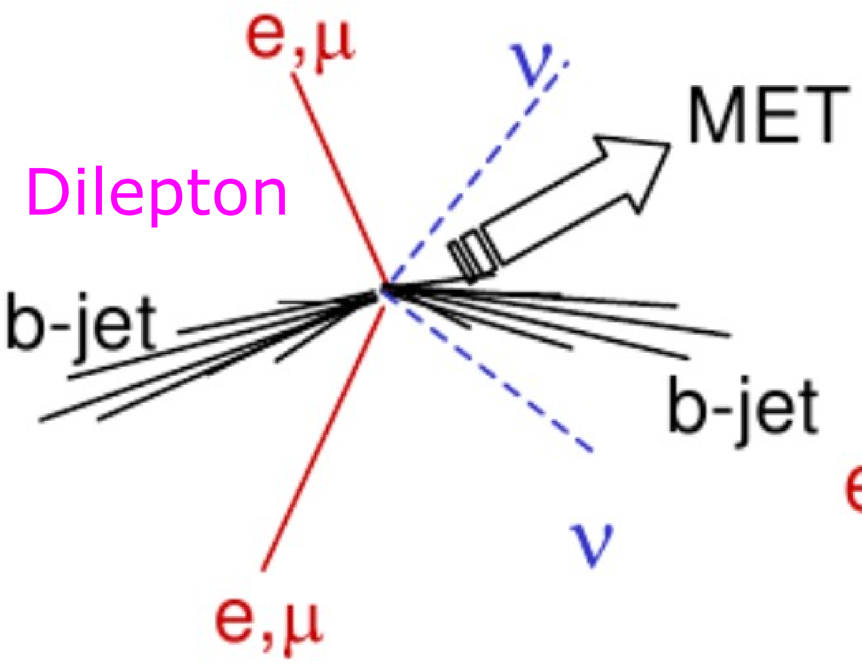
Z+jets:
Main background
in dilepton



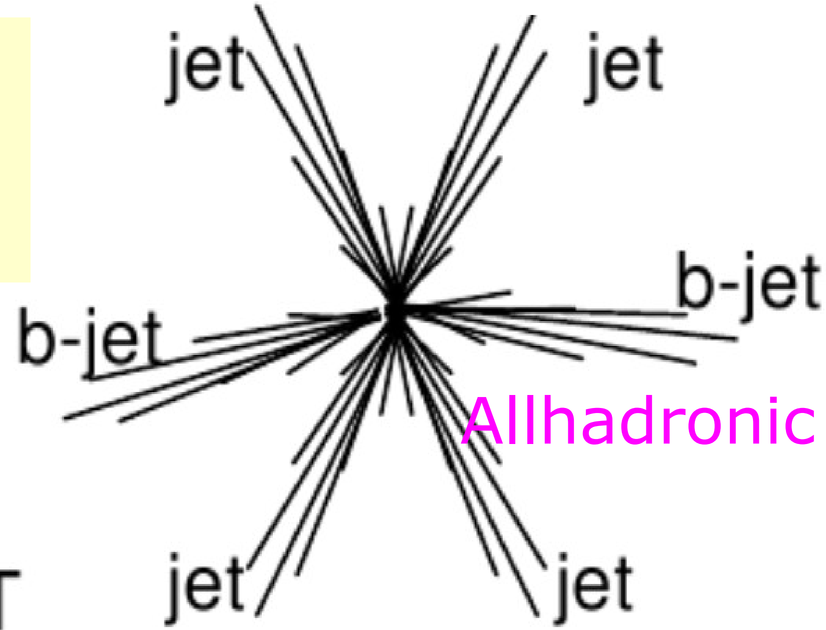
Multijet:
Modeled from Data
Main background in
allhadronic



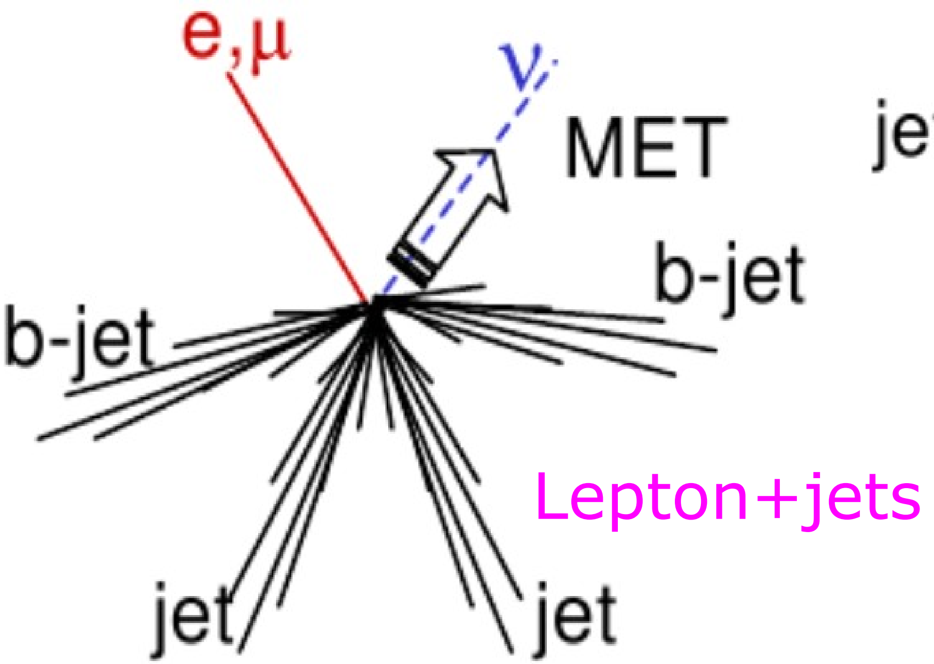
Event selection: Use the signature!



High $\not{E}$ for the neutrino



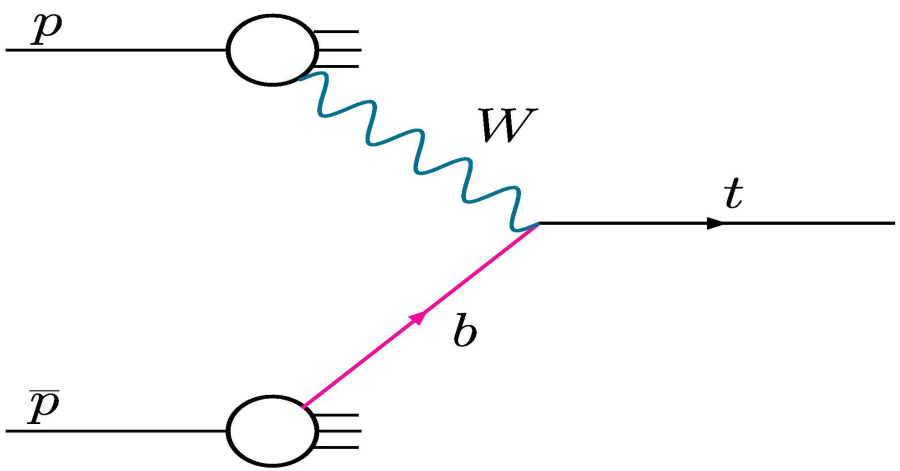
Isolated, high momentum leptons



High momentum (b-)jets

Limit on $|V_{tb'}|$

- Example for new physics affecting the top width
- Use the total width determination to constrain coupling to a fourth generation b' quark, with $m_{b'} > m_t - M_W$
  - Will only affect the production
  - Low probability density of b' in proton & antiproton
  - Assume $|V_{tb}|^2+|V_{tb'}|^2=1$, $|V_{ts}|,|V_{td}|<<1$



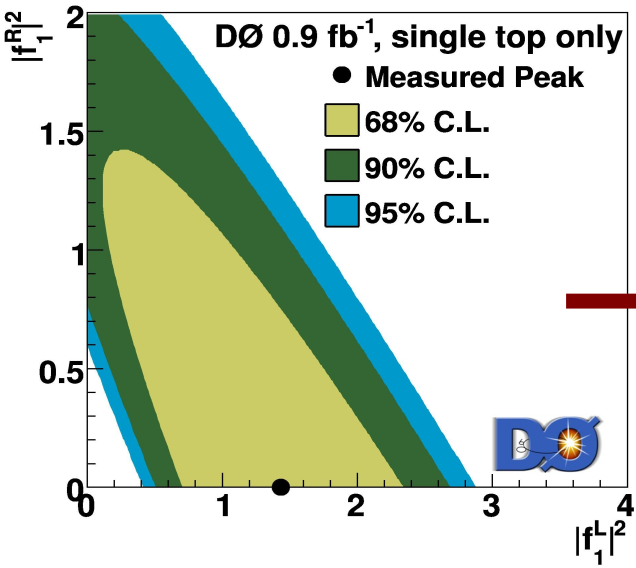
First limit on W boson coupling to top and b' quark

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

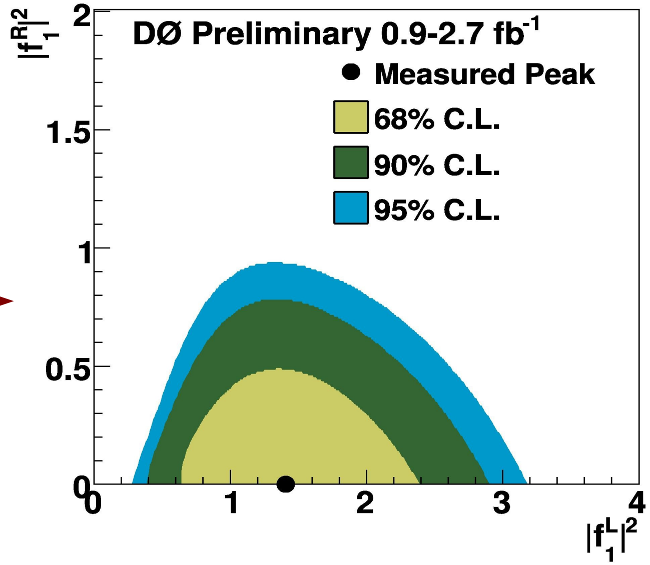
W helicity and anomalous couplings

- Form factors f_1^L, f_1^R, f_2^L, f_2^R: Can be extracted in single top channel
- Single top and W helicity measurement:
  - Usage of all applicable top quark measurements

$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^\mu V_{tb}(f_1^L P_L + f_1^R P_R)tW_\mu^- - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_\nu V_{tb}}{M_W}(f_2^L P_L + f_2^R P_R)tW_\mu^- + h.c.$$



Single top alone



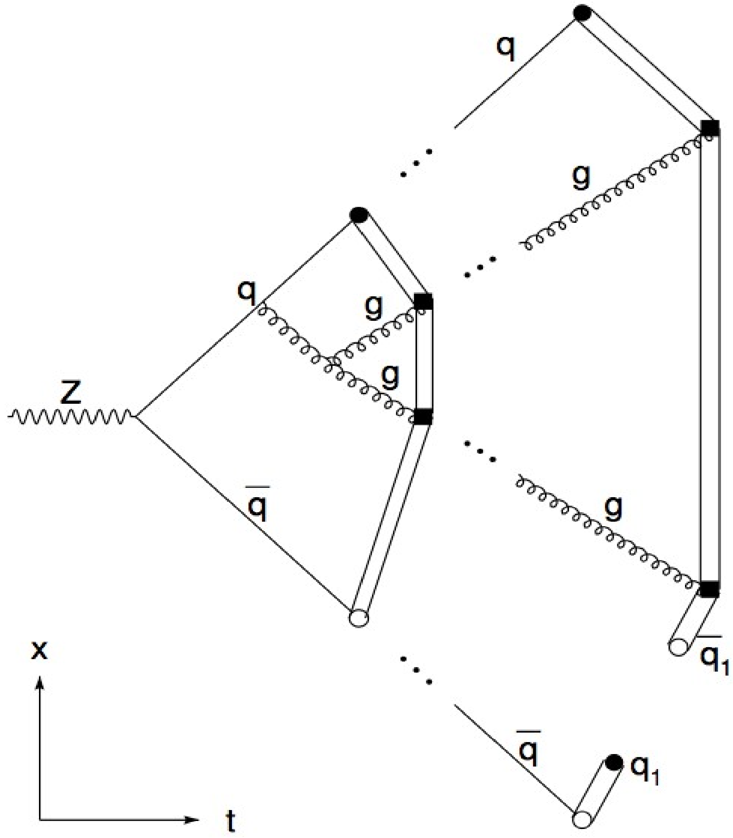
Single top and W helicity

W helicity: Systematics

Source	Uncertainty (f_+)	Uncertainty (f_0)
Jet energy scale	0.007	0.009
Jet energy resolution	0.004	0.009
Jet ID	0.004	0.004
Top quark mass	0.011	0.009
Template statistics	0.012	0.023
$t\bar{t}$ model	0.022	0.033
Background model	0.006	0.017
Heavy flavor fraction	0.011	0.026
b fragmentation	0.000	0.001
PDF	0.000	0.000
Analysis consistency	0.004	0.006
Muon ID	0.003	0.021
Muon trigger	0.004	0.020
Total	0.032	0.060

String Fragmentation Model

- Color string building up between the color connected particles
- Color string has constant energy density (1GeV/fm)
- When quark-antiquark pair separates, potential energy in string increases
  - New $q\bar{q}$ pair can be built out of the vacuum once energy is large enough
  - Arise along the lines of color string!
- Alternative hadronization models exist, all having the idea of color connection in common

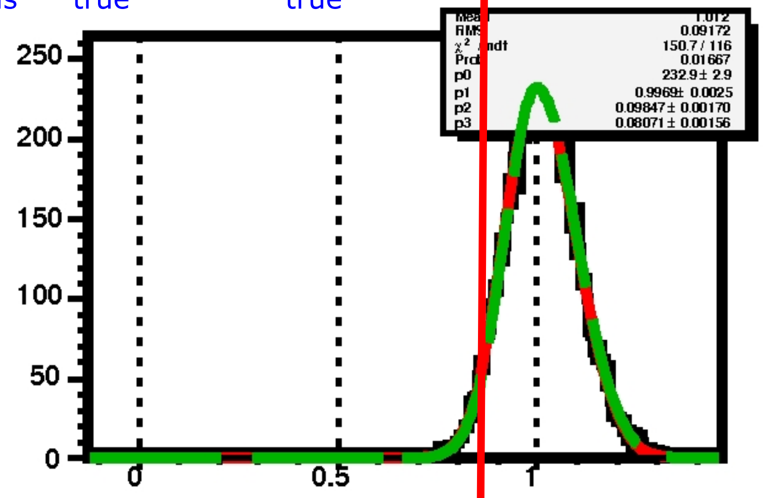


Feldman & Cousins Limits

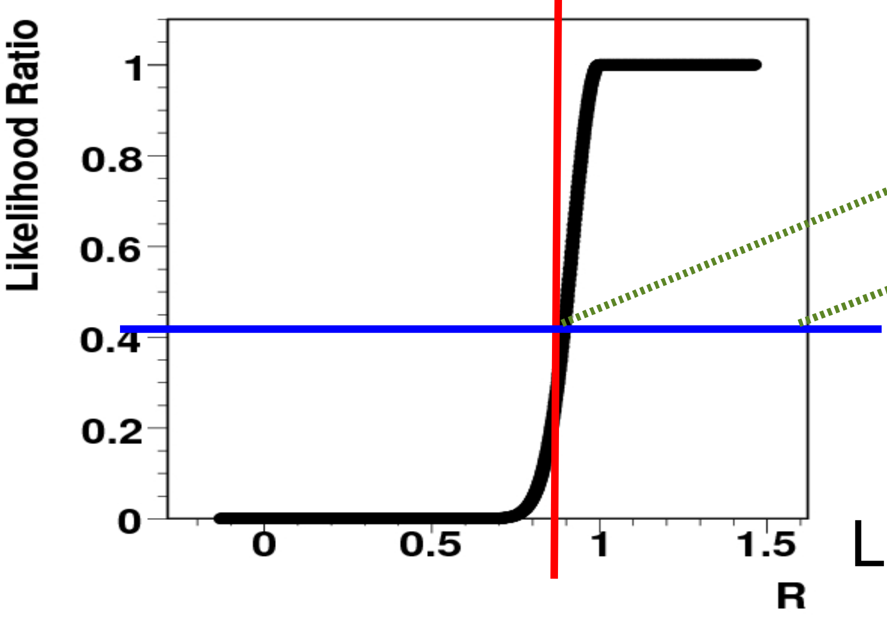
- Feldman & Cousins method for calculation of limits:
  - Pseudo-experiments for various true R (R_{true})
    - Number of events is chosen randomly within a Poisson distribution
    - All systematic uncertainties are varied randomly within a Gaussian distribution
  - For each true R one obtains a distribution of measured values R_{meas}: normalized distributions are $P(R_{meas}|R_{true})$
  - Application of the "likelihood ratio ordering":
    - calculation of $r_{likeli}(R_{meas}) = \frac{P(R_{meas} \backslash R_{true})}{P(R_{meas} \backslash R_{best})}$
    - R_{best}: R_{true} for which $P(R_{meas}|R_{true})$ is maximal
      - has to be within the physically allowed region

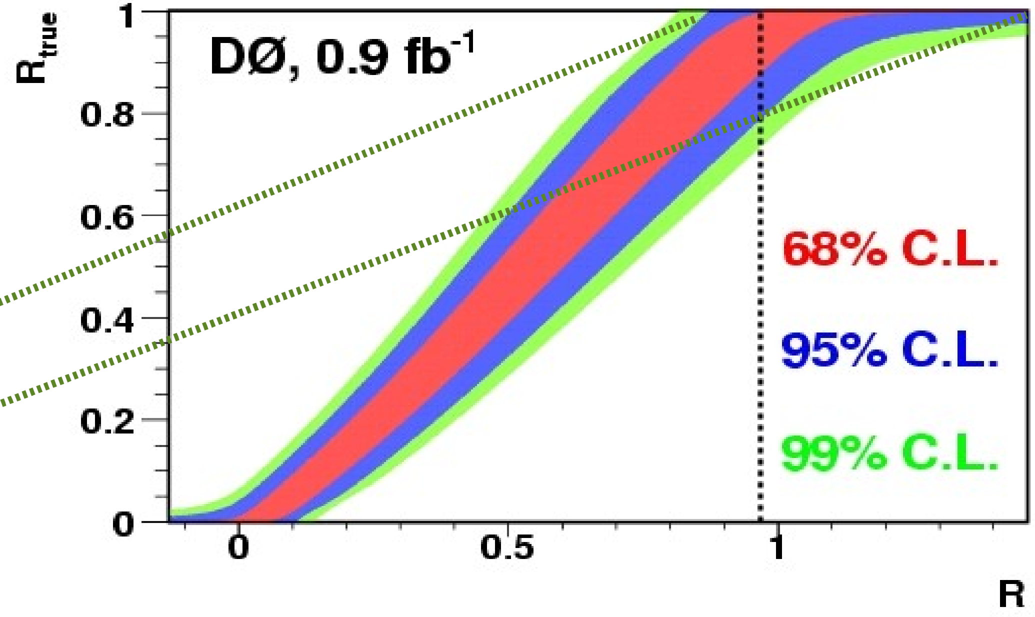
Feldman & Cousins Limits

$P(R_{meas}|R_{true})$ for $R_{true}=1$



Variation of the blue line until the area of $P(R_{meas}|R_{true})$ is 95% within the interactions points with r_{likeli} (red line) is 95%





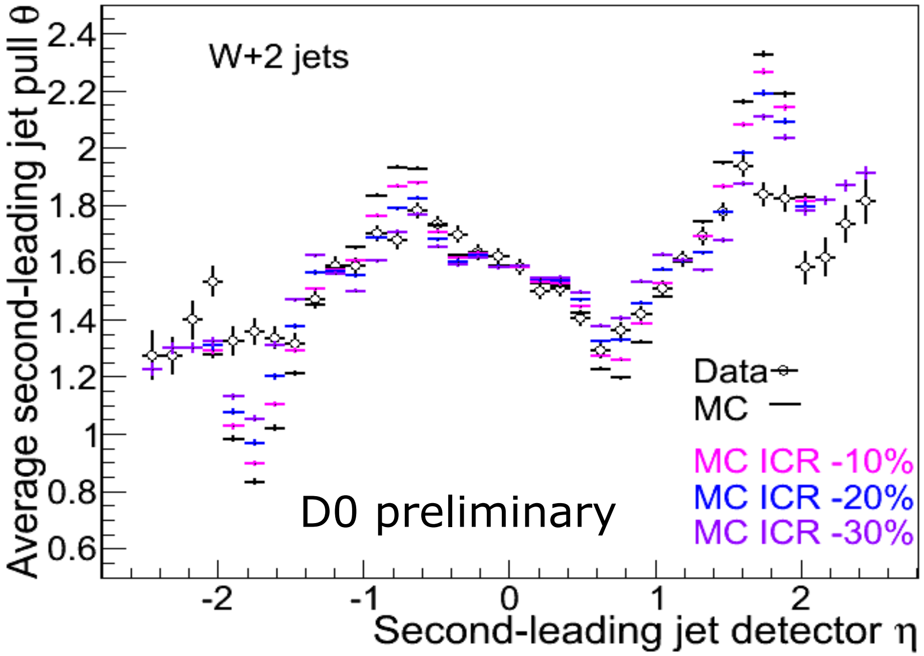
Likelihood ratio for $R_{true}=1$

Color Flow: Toy MC

- Toy MC study of calorimeter effects:
  - Granularity: 0.1x0.1 in e x p towers
- Calorimeter noise floor per cell: 150MeV
  - 500MeV threshold for hadron
- Charged particles with <75MeV are ignored due to being bent by magnetic field
- Energy resolution: MC tower is smeared with 50%/sqrt(E[GeV])
  - Resolution in hadronic calorimeter
- Noise/pile-up: Each MC tower has a chance of 7% to have added noise to it
  - p_T: Exponential distribution around mean 360MeV

Calorimeter Effects

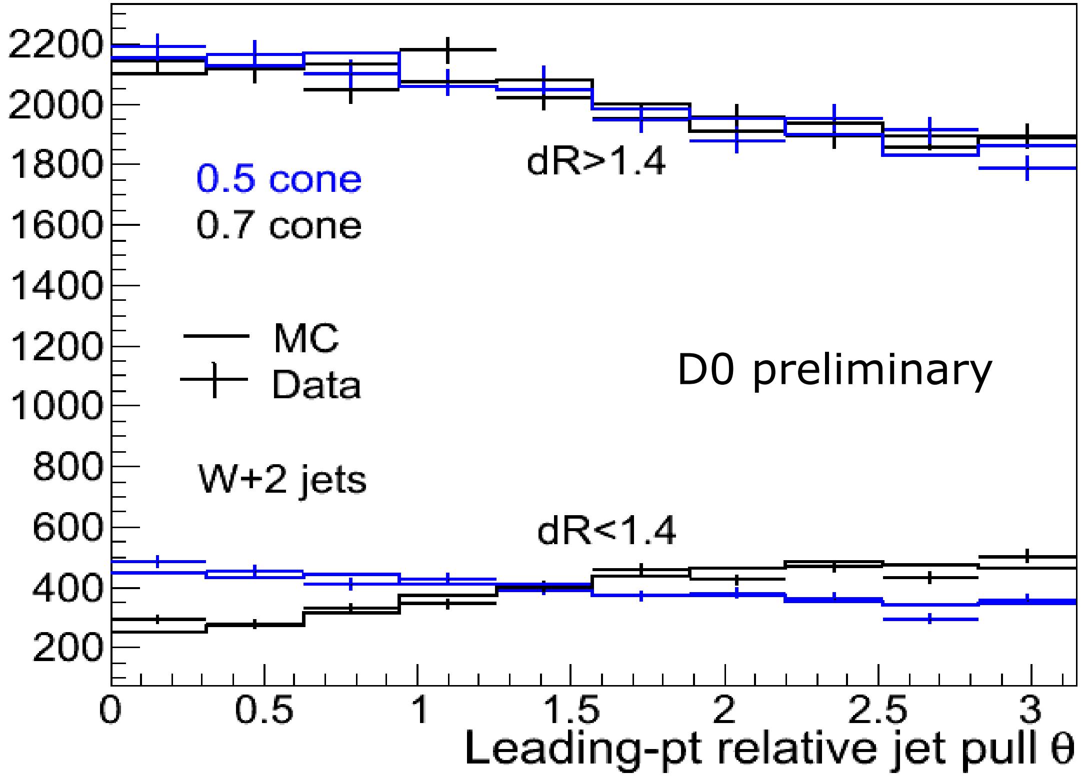
- Calorimeter inhomogeneity:
  ICR has lower response and more noise than central and end calorimeters
  - We correct for bias from ICR and assign a systematic uncertainty
  - Effect on relative jet pull angle small



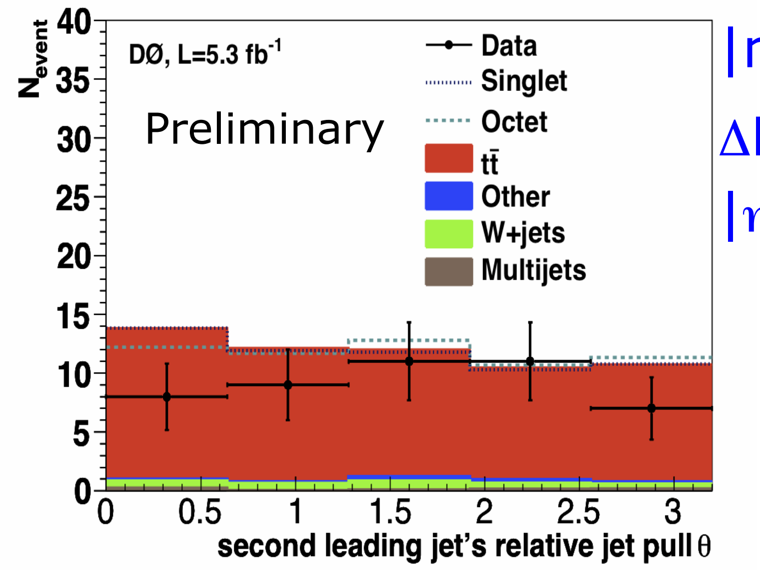
Effect of overlapping Jet Cones

- Different cone sizes of jet:
  - More or less overlapping jets
  - Shifts distribution more or less

Effect of overlapping jet cones well modeled!



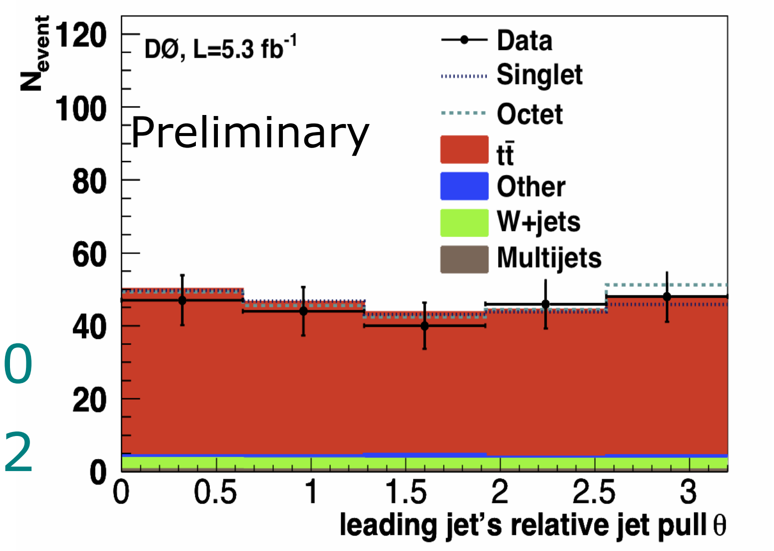
Fit regions: Four additional regions



$|m_{jj}-M_W|<30$

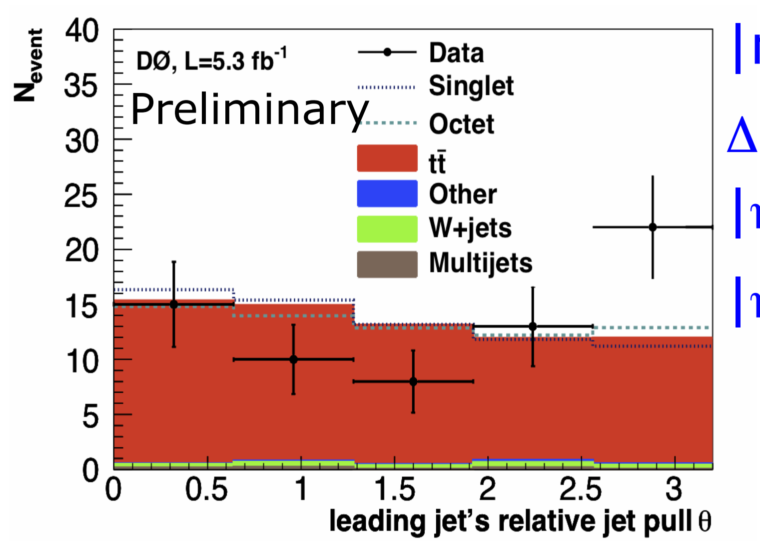
$\Delta R(jj)<2$

$|\eta|>1$ for leading p_T jet



$|m_{jj}-M_W|<30$

$\Delta R(jj)>2$

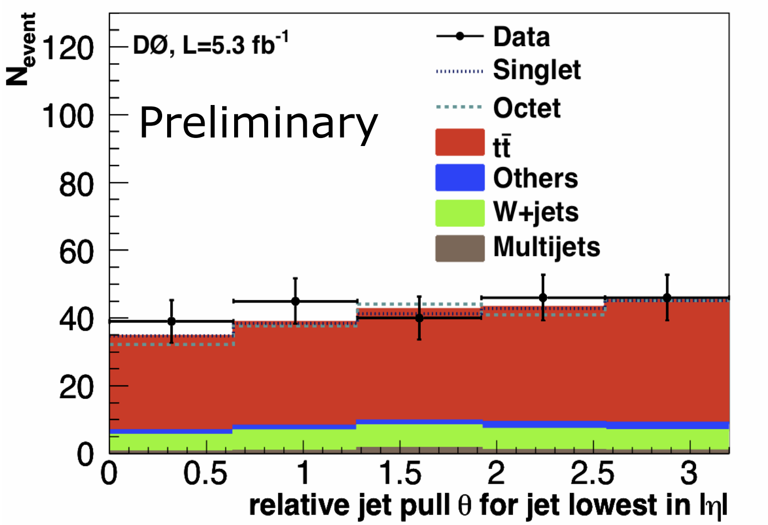


$|m_{jj}-M_W|<30$

$\Delta R(jj)<2$

$|\eta|<1$ for leading p_T jet

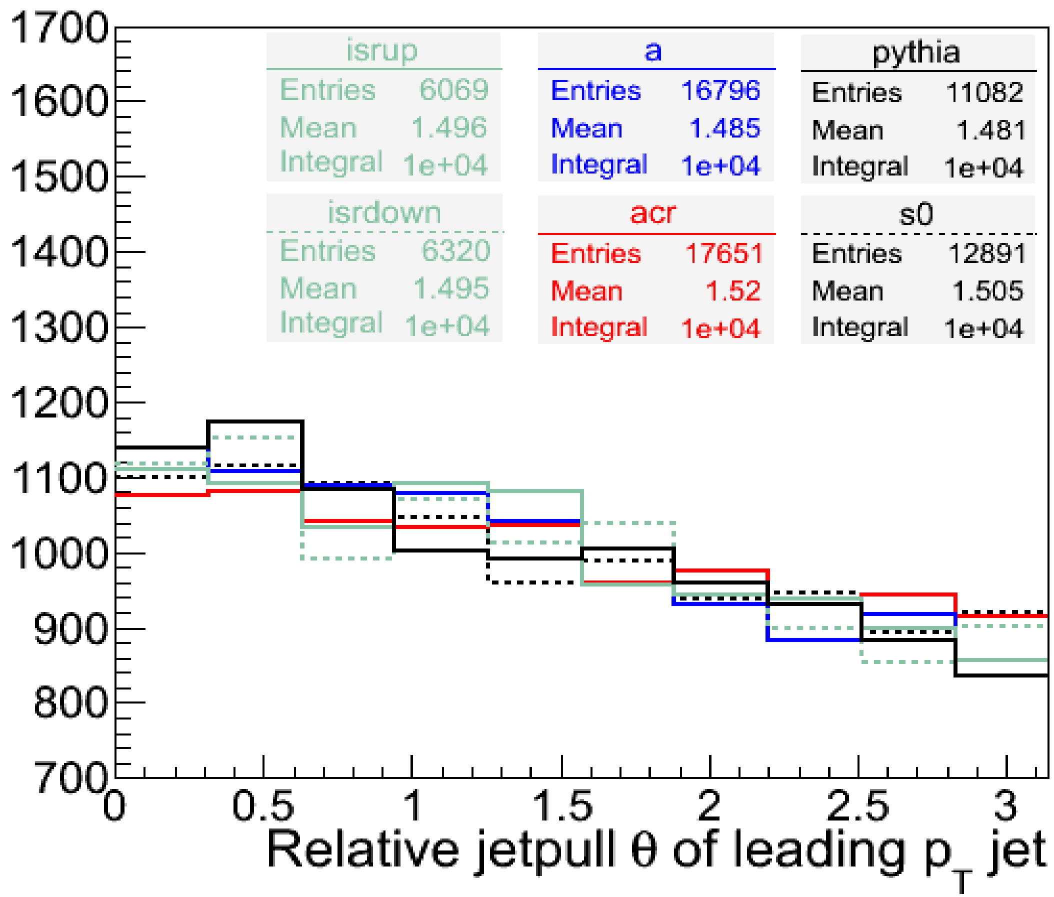
$|\eta|>1$ for 2nd leading p_T jet



$|m_{jj}-M_W|>30$

Color Flow: Tunes

- Study of various tunes
  - ACRPro flatter, but unphysical color re-connection model for W

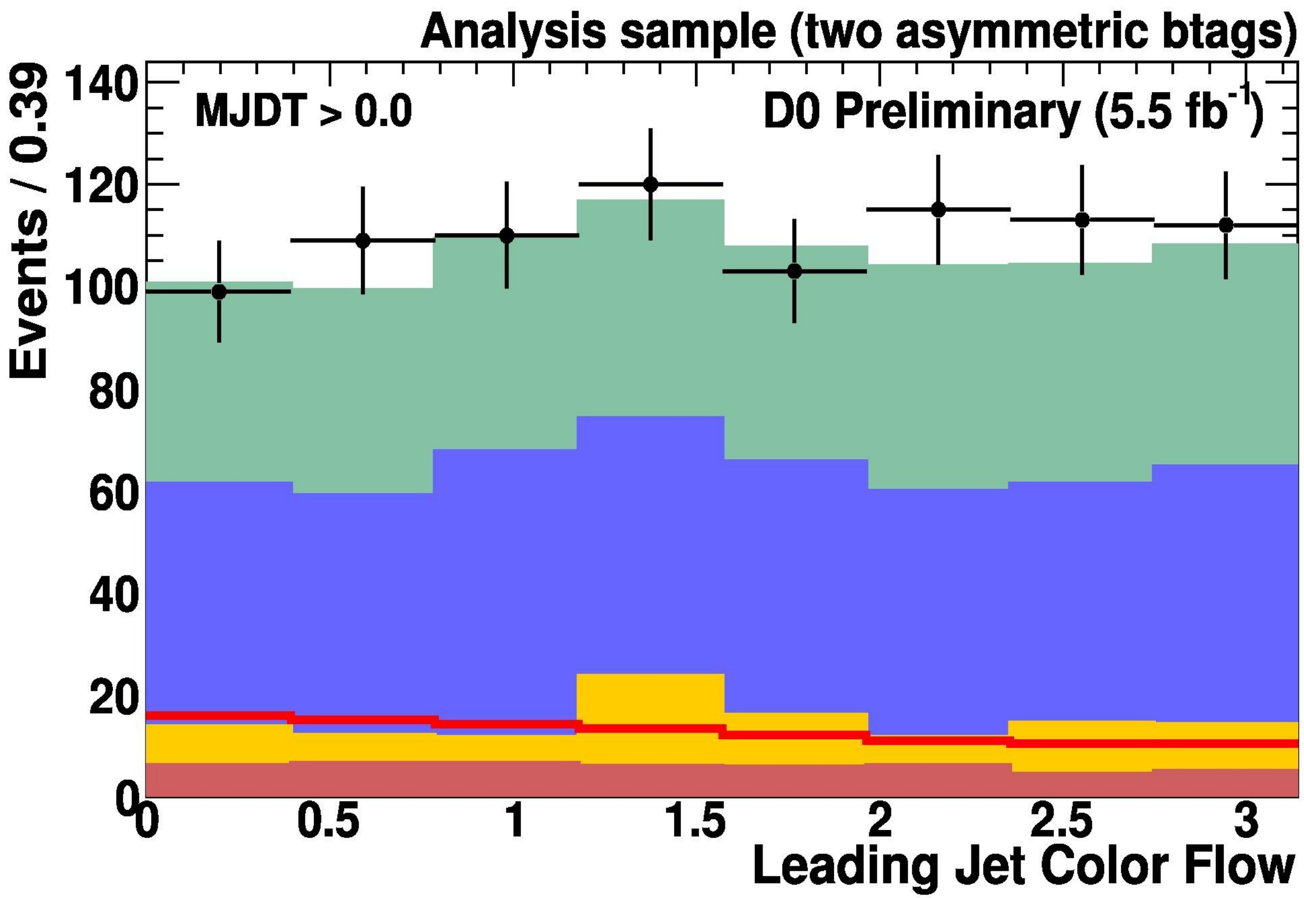


Color Flow: Systematics

Source	$+\sigma$	$-\sigma$
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

Color Flow: Already used for ZH Search

- Preliminary result for ICHEP2010



Some props: Jet Energy Scale