Top quark production at the Tevatron

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on behalf of the CDF and D0 experiments

Flavor Physics and CP violation 2012

May 21-25

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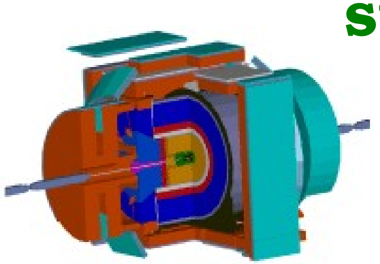
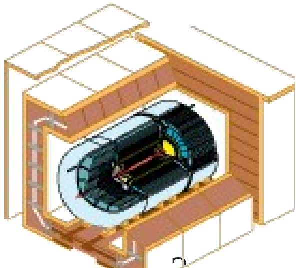
OUTLINE

- **top quark pair production**
  - **top quark pair production cross section**
  - **Forward Backward asymmetry**
  - **spin correlation**
  - **ratio of branching fractions**
- **electroweak (EW) single top quark production**
  - **cross sections and $|V_{tb}|$ measurements**
- **search for new physics in top quark production**
- **summary**

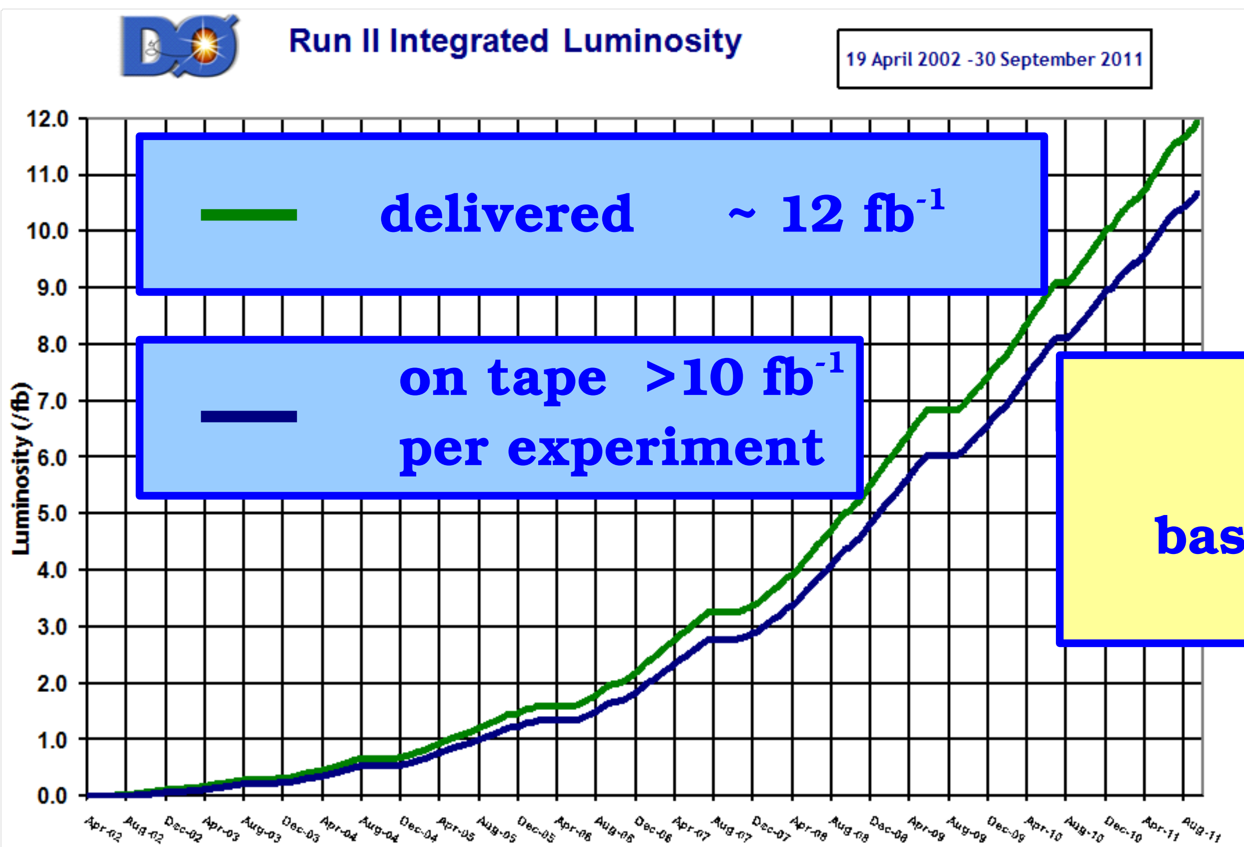




FERMILAB TEVATRON

the place of the discovery of the top quark

Tevatron stopped taking data on september 30, 2011

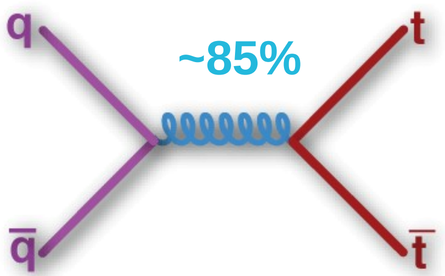


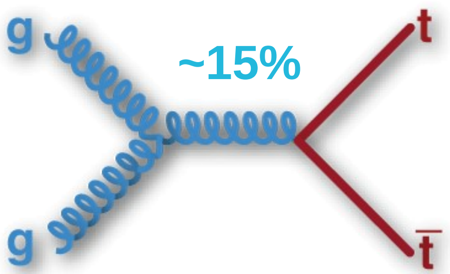
results shown today
based on datasets up to 8.7 fb^{-1}

Top quark production at Tevatron

QCD pair production

PRD 78, 034003 (2008)





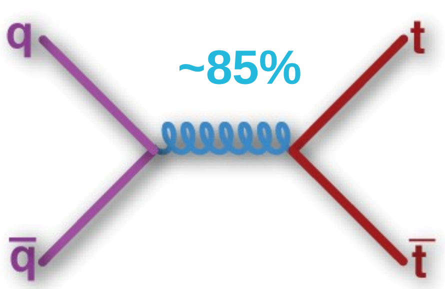
$$\sigma = 7.46^{+0.48}_{-0.67} \quad \text{pb}$$

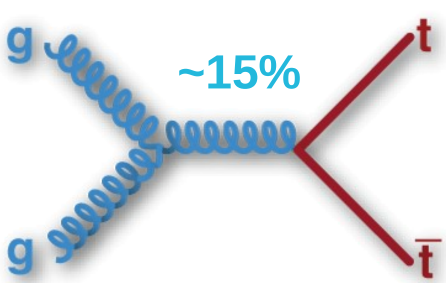
$$\text{for} \quad m_{top} = 172.5 \quad \text{GeV}$$

Top quark production at Tevatron

QCD pair production

PRD 78, 034003 (2008)





$$\sigma = 7.46^{+0.48}_{-0.67} \quad \text{pb}$$

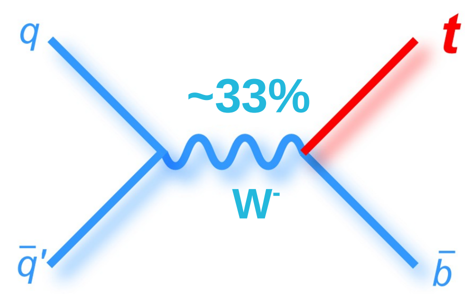
for $m_{top} = 172.5 \quad \text{GeV}$

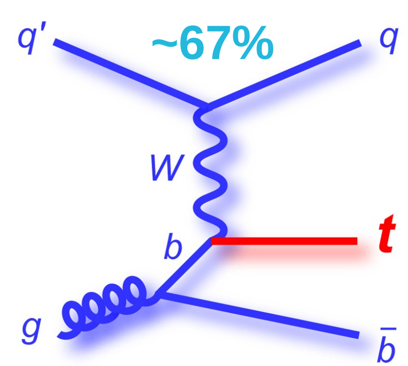
$\sigma_{NNLO} = 7.46^{+0.143}_{-0.232}$ (scales) $^{+0.186}_{-0.122}$ (pdf) pb

ArXiv:1204.5201 (for a top mass of 173.3 GeV)

EW single top production

PRD 81, 054028 (2010), PRD 83, 091503 (2011)





s-channel $\sigma = 1.05 \pm 0.07$ pb

t-channel $\sigma = 2.10 \pm 0.19$ pb

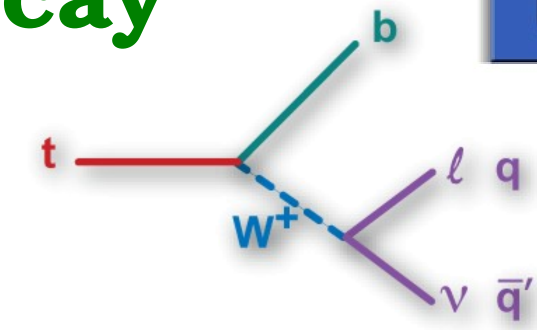
both for $m_{top} = 172.5 \quad \text{GeV}$

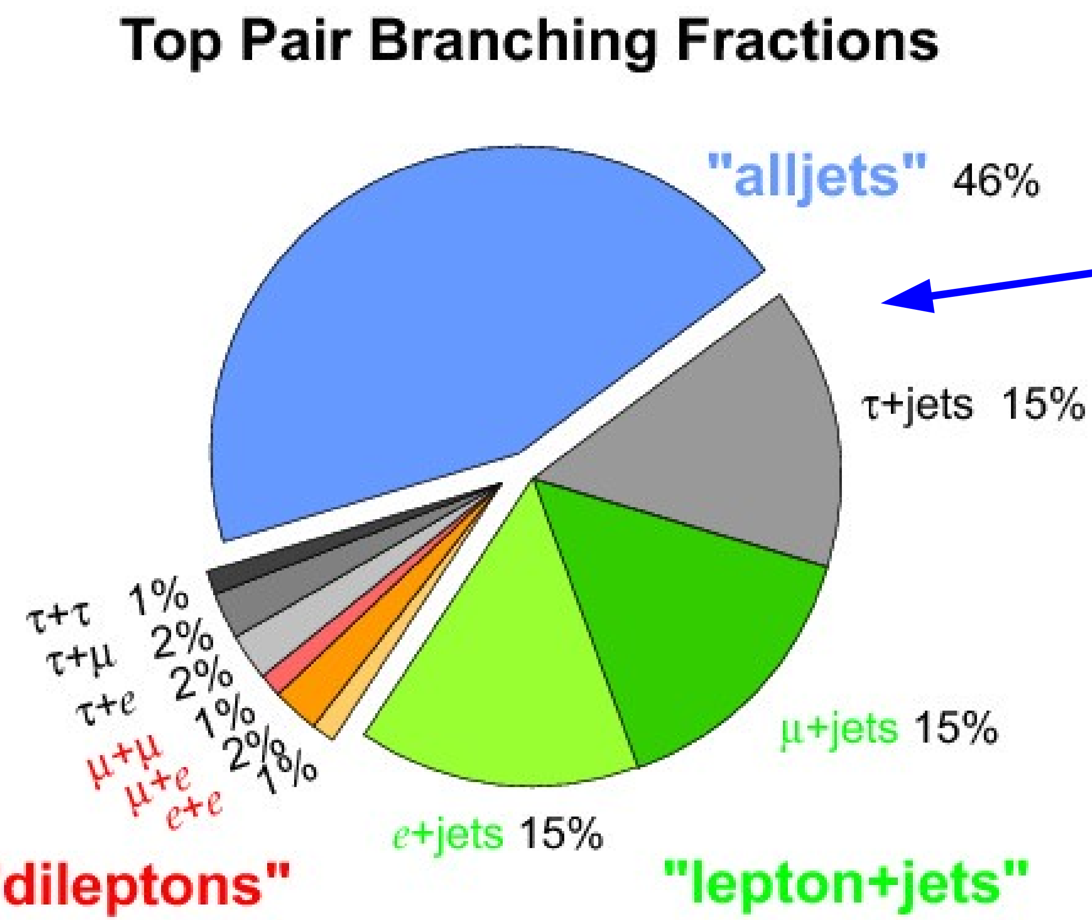
single top associated production Wt

$\sigma \sim 0.2$ pb, too small at Tevatron

Top quark decay

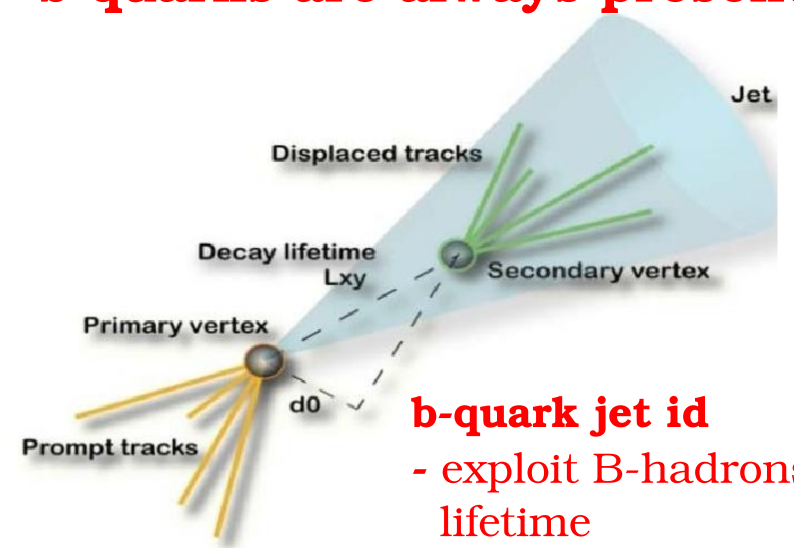
SM predicts $BR(t \to Wb) \sim\ 100\ \%$





event topology determined by the W decay modes

b quarks are always present



2 isolated leptons
high missing E_t from 2 ν
2 b-jets

1 isolated lepton
missing E_t from 1 ν
$\geqslant$ 4 jets (2 b-jets)

b-quark jet id
- exploit B-hadrons lifetime
- jets with displaced vertices from IP

top pair production

Why study top quark pair production ?

- top quark is a unique particle
  - heaviest of all known particles
  - decays before hadronizing
- provides QCD and SM tests
- measuring the production cross section

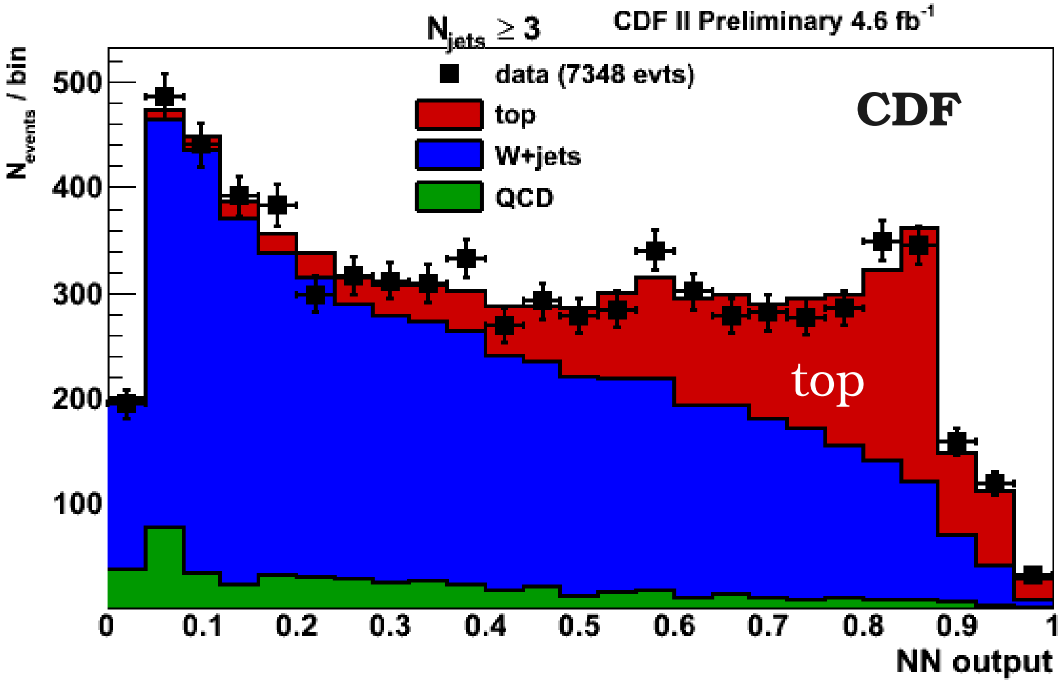
$$\sigma_{t\bar{t}} = \frac{N_{\text{DATA}} - N_{\text{Background}}}{\text{Acc} \int \text{L} \ \text{dt}}$$

is the 1st step in understanding any selected ttbar sample

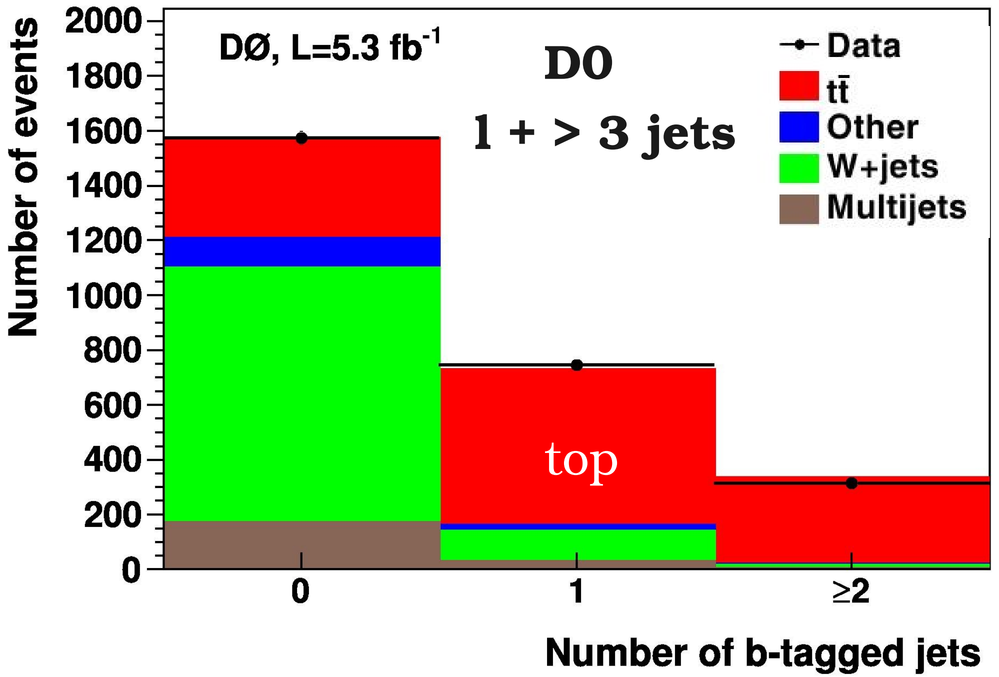
- new physics can change
  - overall production rate
  - rate in different channels
- top pair production is background for searches

top pair production (lepton+jets)

- pre-tagged sample, NN discriminant
- measure $R = \sigma_{t\bar{t}} / \sigma_{Z/\gamma^* \to ll}$
- extract $\sigma_{t\bar{t}} = R \cdot \sigma_Z^{theory}$



- kinematic and b-tags combination determine Xsection and background (W + hf / W + lf) simultaneously



CDF (4.3 fb^{-1}, $m_t = 172.5$ GeV) pre-tagged

$\sigma_{t\bar{t}} = 7.82 \pm 0.38\,(\text{stat}) \pm 0.37\,(\text{syst}) \pm 0.13\,(\text{th})$ pb

D0 (5.3 fb^{-1}, $m_t = 172.5$ GeV) b-tagged

$\sigma_{t\bar{t}} = 8.13 \pm 0.25\,(\text{stat})\,^{+0.99}_{-0.86}\,(\text{syst})$ pb

PRL 105, 012001 (2010)

combined kinematical + b tagging

PRD 84, 012008 (2011)

CDF (4.3 fb^{-1}, $m_t = 172.5$ GeV)

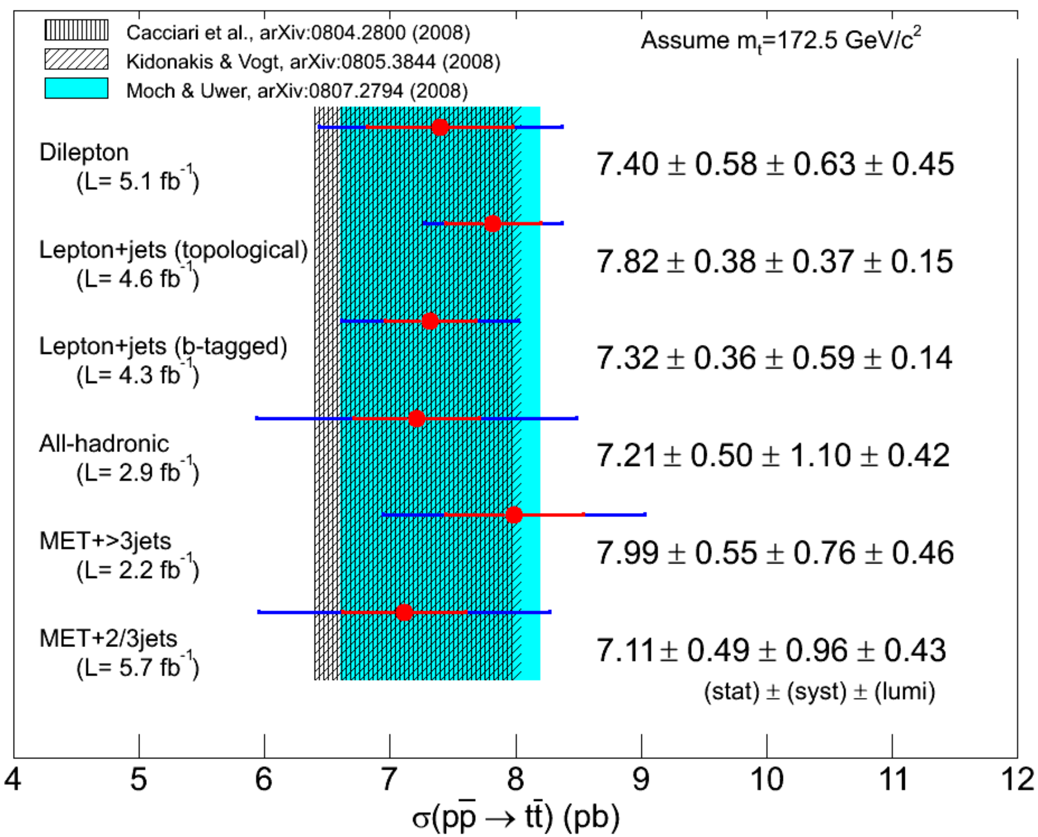
$\sigma_{t\bar{t}} = 7.70 \pm 0.52$ (stat+syst) pb

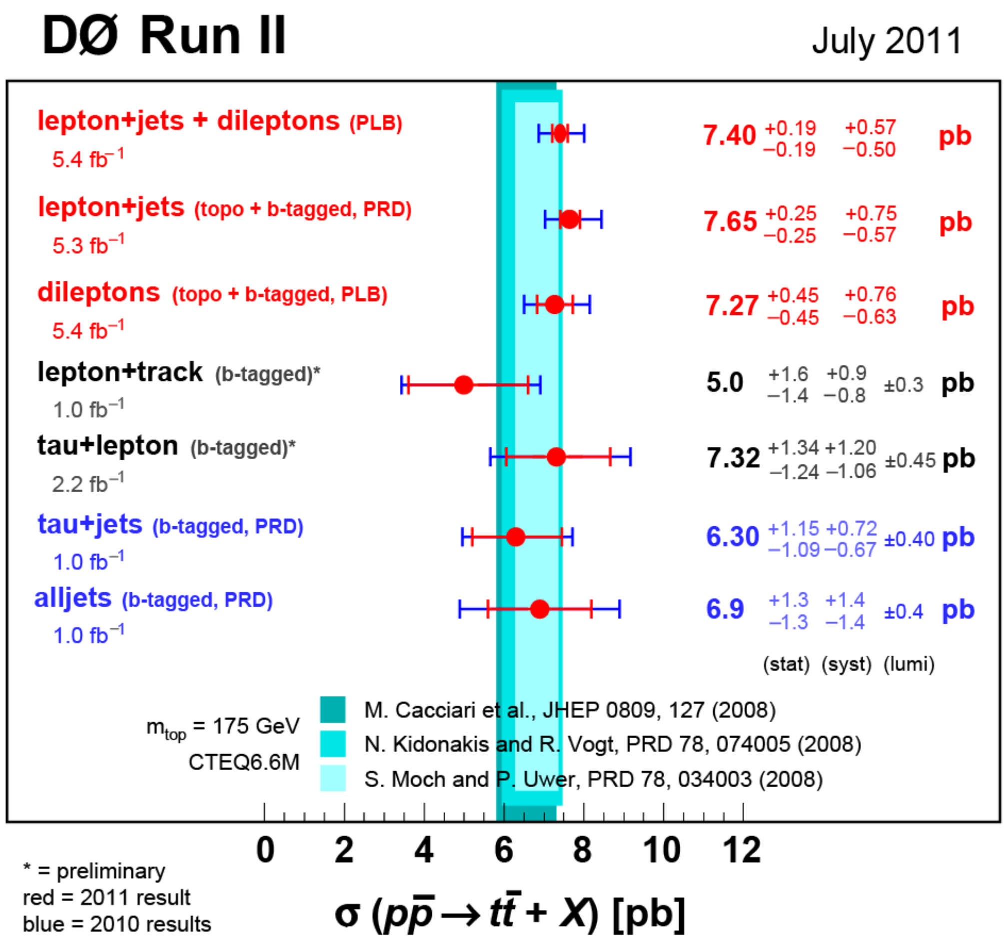
D0 (5.3 fb^{-1}, $m_t = 172.5$ GeV)

$\sigma_{t\bar{t}} = 7.78 \pm 0.25\,(\text{stat})^{+0.73}_{-0.59}$ (syst) pb

top pair production

- dominant uncertainties: JES, b-tag acc., W + b-jet background
- in agreement with SM theoretical predictions
- consistent across channels, methods, experiments





CDF combination : 7.50 ± 0.48 pb

i.e. 6.4 % precision

all measurement limited by systematic uncertainty

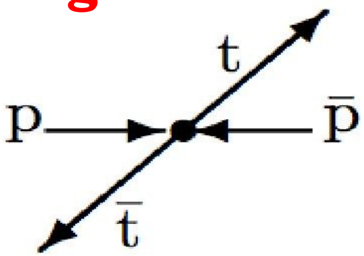
Forward backward asymmetry

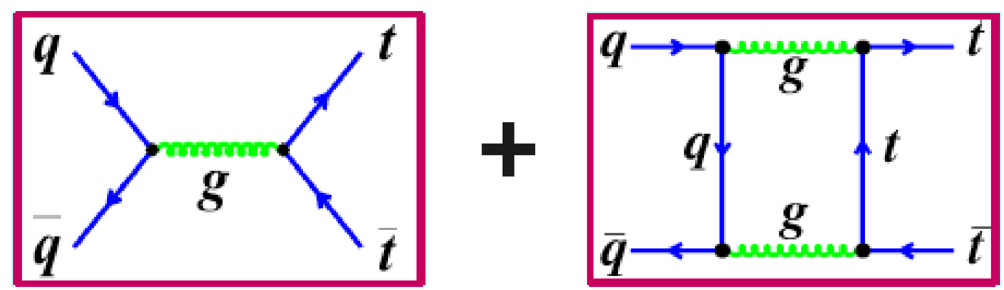
Do top quarks follow preferentially the initial quark or anti quark direction ?

- **LO QCD : no charge asymmetry expected**
- **NLO QCD : interference between quark- anti quark diagrams predicts ~ 7 % asymmetry** (JHEP 0709,126 (2007) & 1201,063 (2012), PRD84, 093003 (2011))

tree level and box diagram :

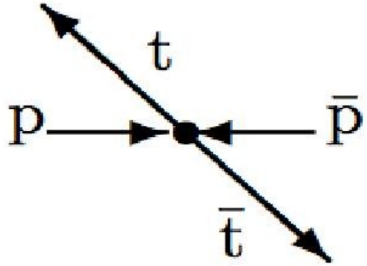
positive asymmetry

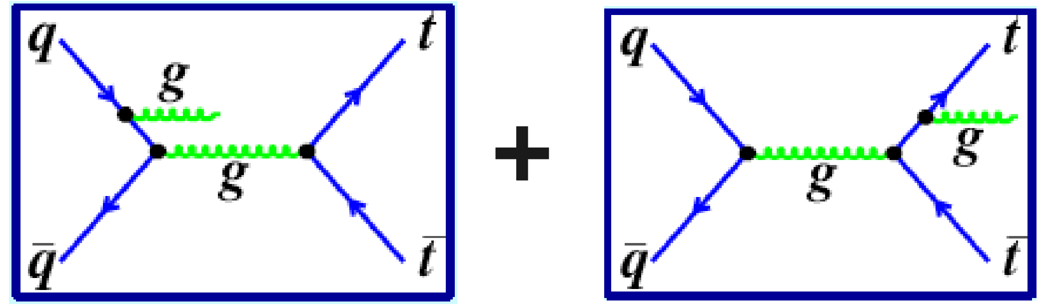




initial and final state radiation :

negative asymmetry





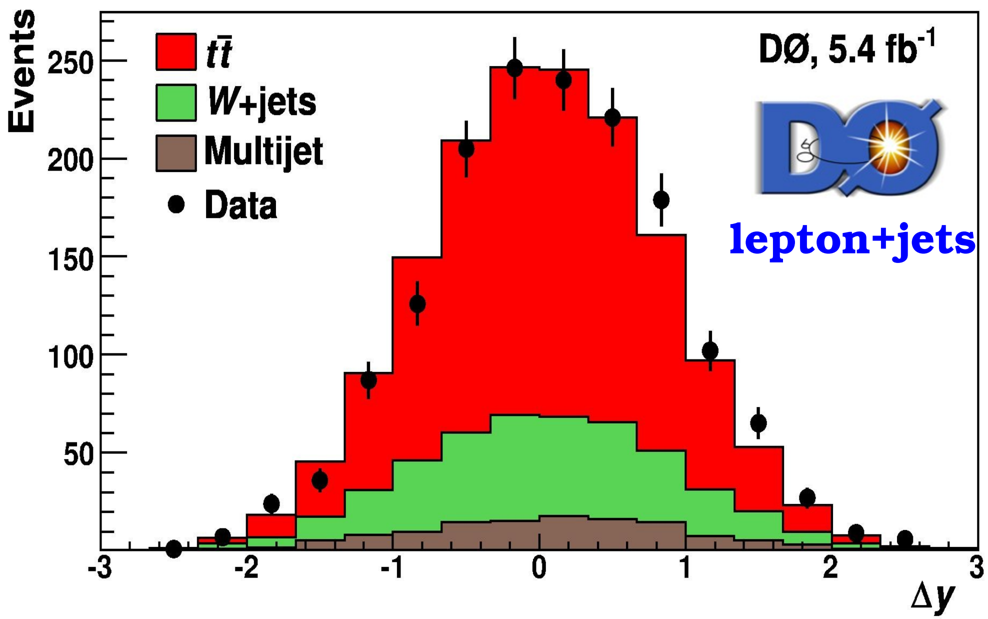
New physics could give rise to an asymmetry (Z', axigluons ...)

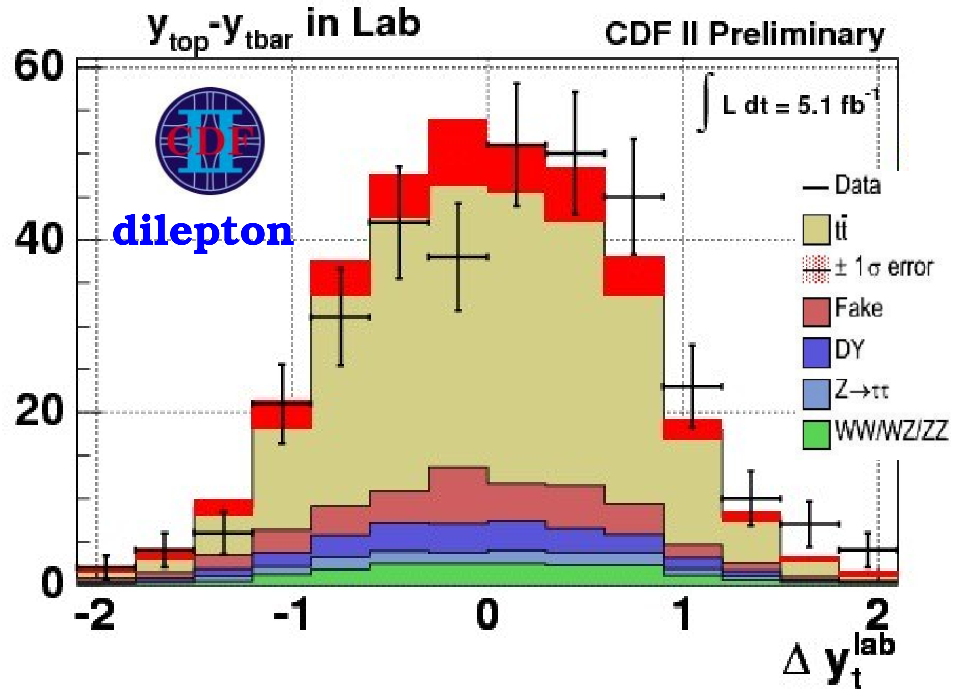
Forward backward asymmetry

- reconstruct the direction and the rapidity of t and $\bar{t}$ quarks $\quad y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$
- use the rapidity difference $\Delta y = y_t - y_{\bar{t}}$ of $t \rightarrow l\nu b$ and $t \rightarrow jjb$
- subtract Background from Data

CDF : background from MC prediction

D0 : background fitted with likelihood discrimant

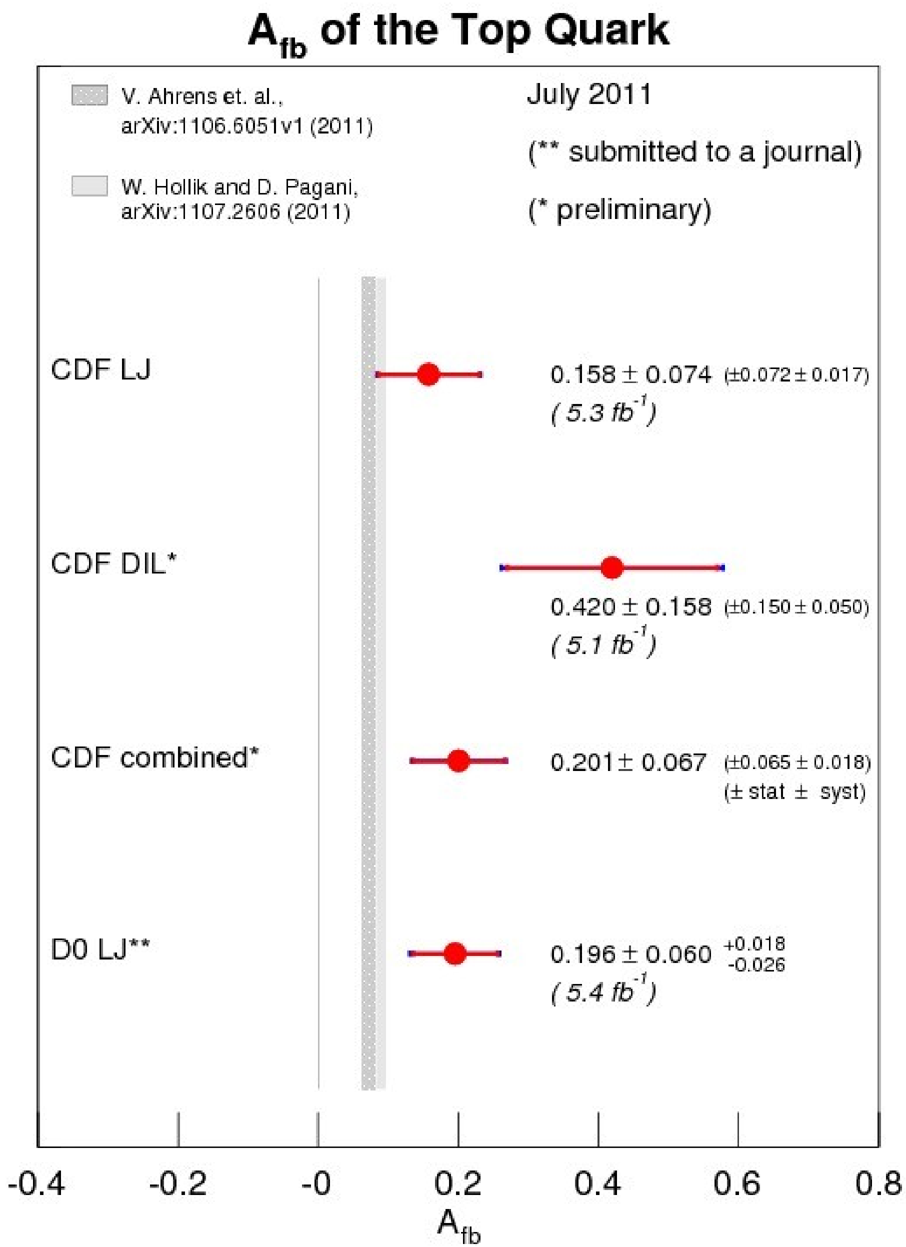




- extract the raw asymmetry $\quad A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$

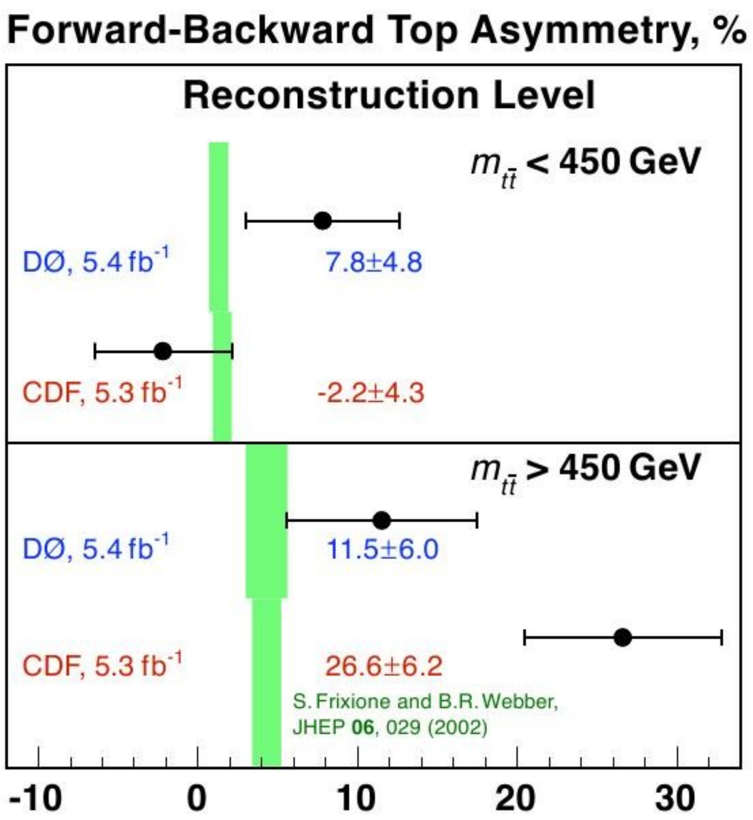
- correct for acceptance and resolution effects (unfolding) back to production level

The asymmetry in ~ 5 fb^{-1}



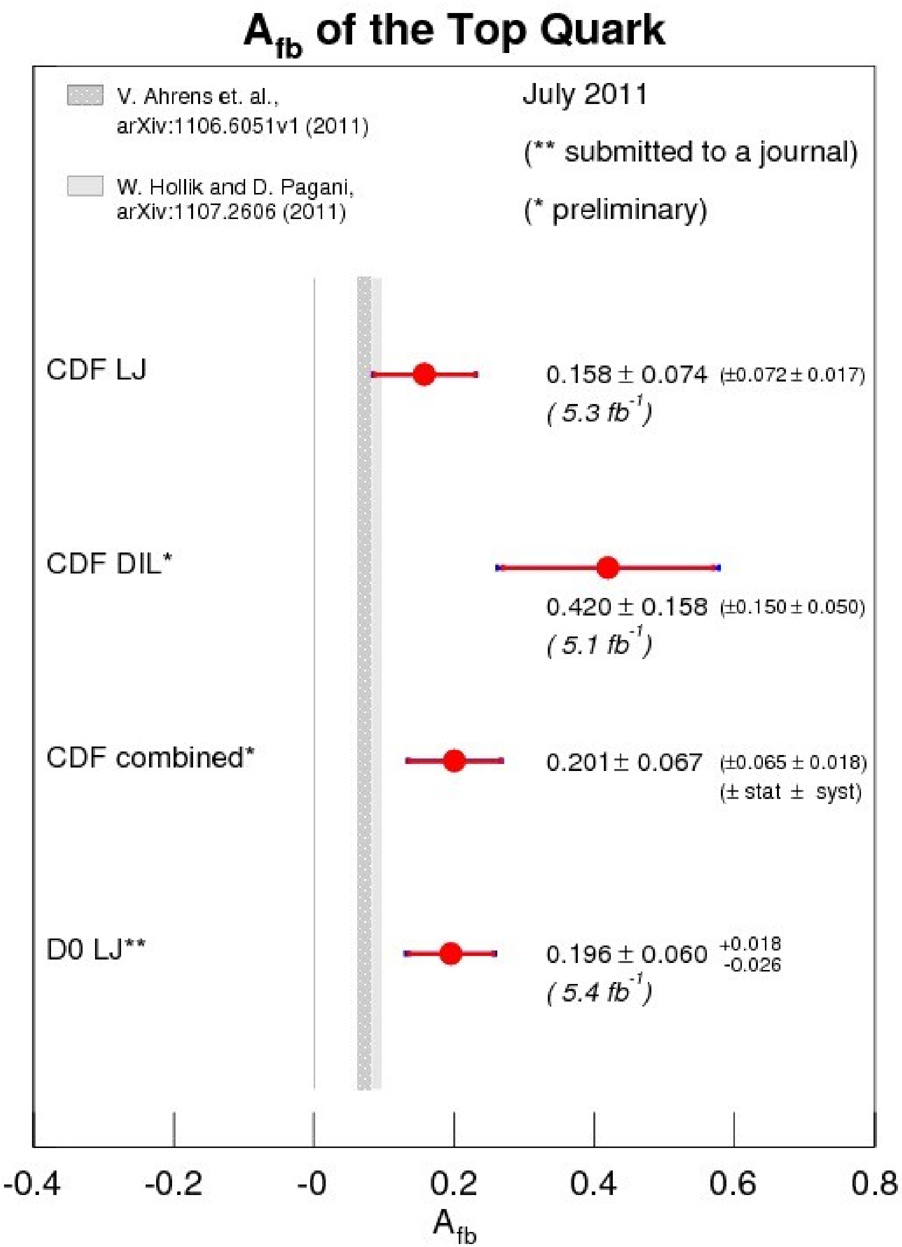
inclusive asymmetries exceed SM prediction by $\sim 1.5 - 2\sigma$

unclear dependence on $M_{t\bar{t}}$ and Δy



CDF : PRD 83,112003 (2011), Conf notes 10436 & 10584
D0 : PRD 84,112055 (2011)

The asymmetry in ~ 5 fb^{-1}



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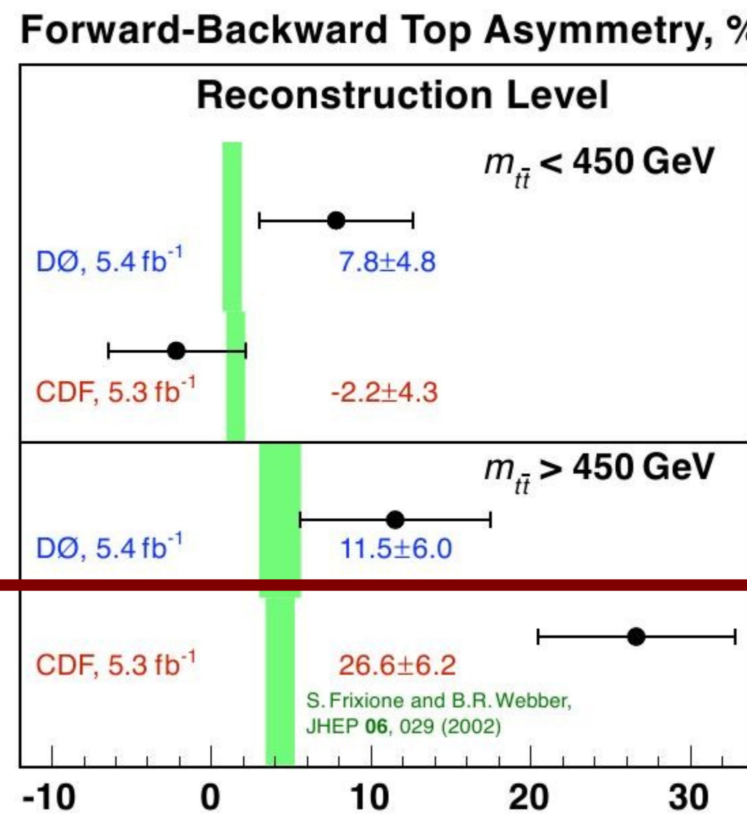


$\sim 3\sigma$ away from MC@NLO prediction

CDF : PRD 83,112003 (2011), Conf notes 10436 & 10584
D0 : PRD 84,112055 (2011)

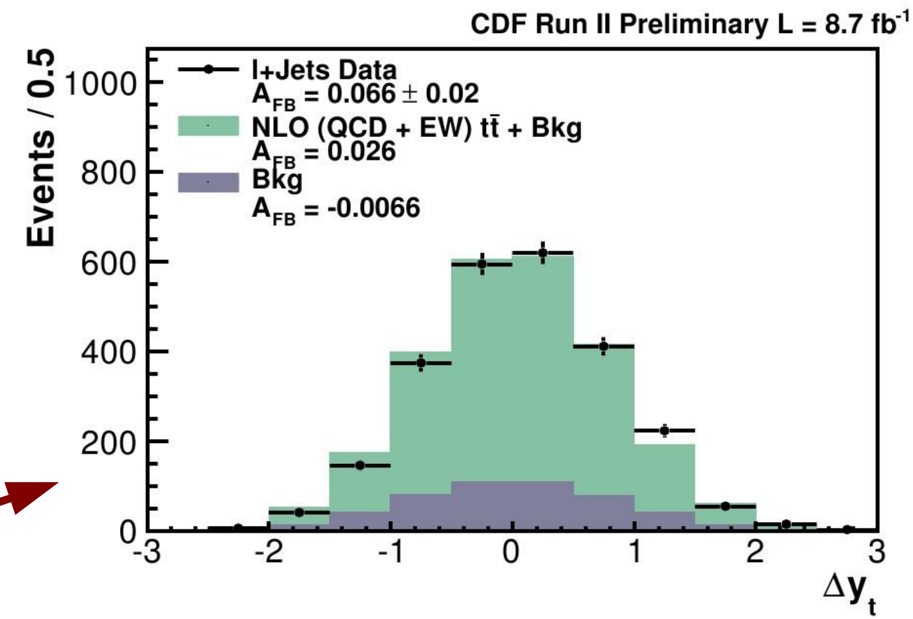
Asymmetry with the full dataset

CDF updated the l+jets analysis with 8.7 fb^{-1}

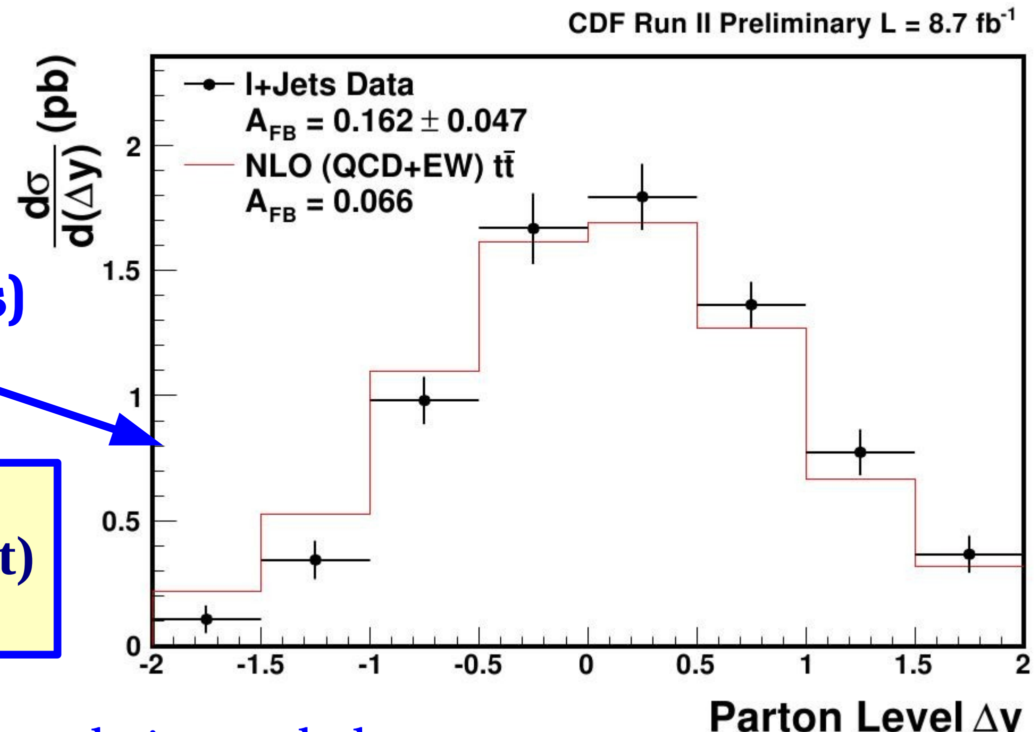
use powheg + EW corrections for SM predictions

raw asymmetry at reconstruction level

$$A_{FB}^{raw} = 0.066 \pm 0.020$$



after background subtraction and unfolding (correcting for acceptance and resolution effects)



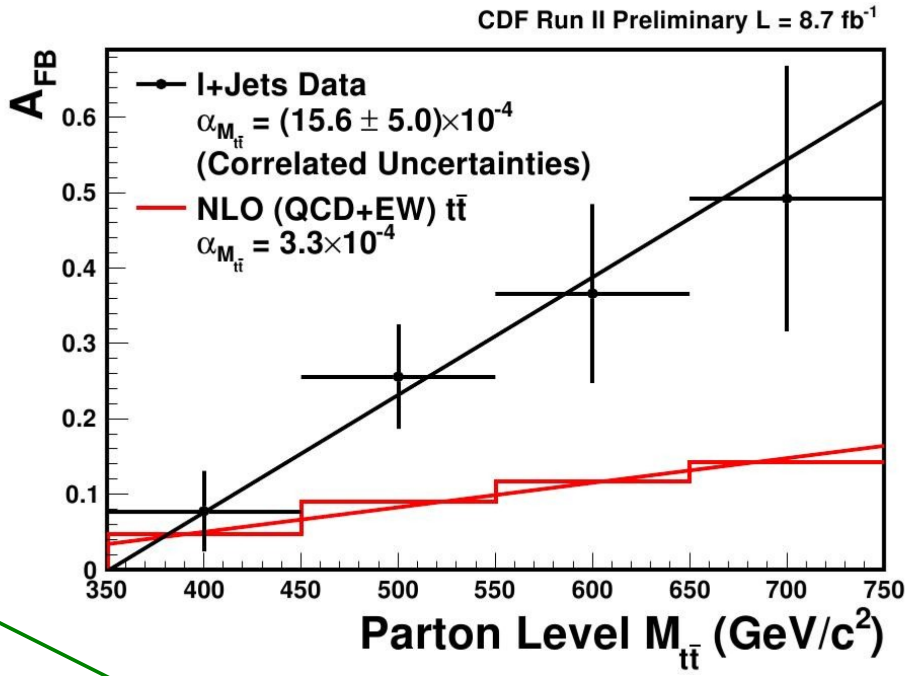
$$A_{FB} = 0.162 \pm 0.041\ (stat) \pm 0.022\ (syst)$$

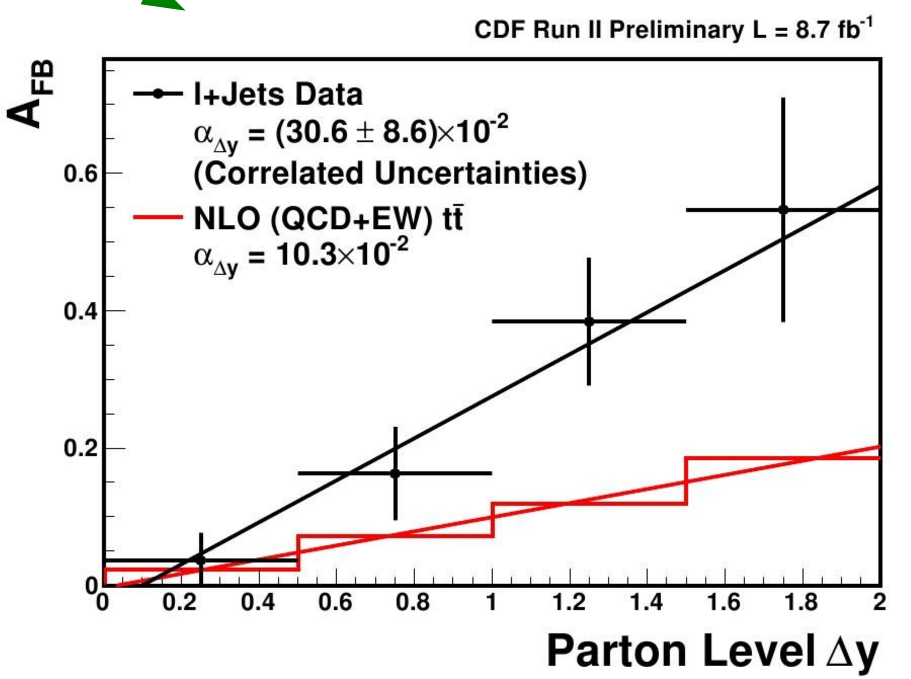
main systematic uncertainty from background size and shape

Asymmetry with the full dataset

- in SM A_{FB} increases linearly with $M_{t\bar{t}}$ and Δy
- BSM could show different dependencies than in SM

after unfolding



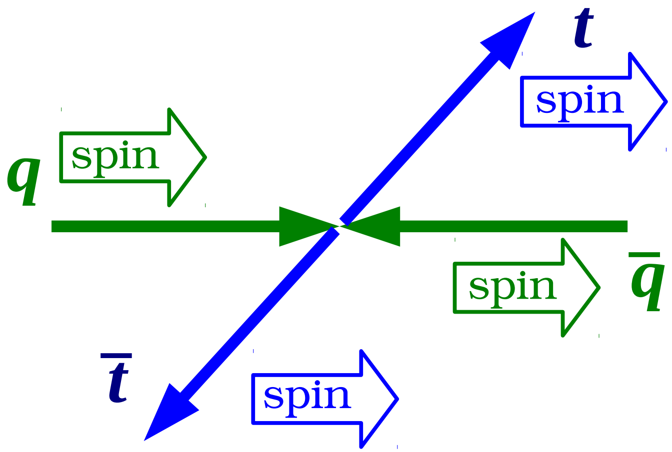


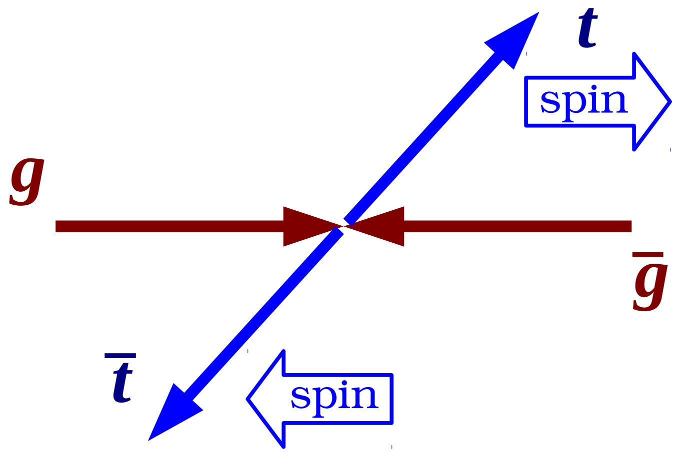
slope parameter α	A_{FB} vs $M_{t\bar{t}}$	A_{FB} vs Δy
DATA	$(15.6 \pm 5.0) \times 10^{-4}$	$(30.6 \pm 8.6) \times 10^{-2}$
SM	3.3×10^{-4}	10.3×10^{-2}

best fit slope for observed data compared to NLO prediciton

Top anti top spin correlations

top pair produced with definite spin state depending on production mechanism i.e. spin 1 (qqbar annihilation) or spin 0 (gluon fusion)



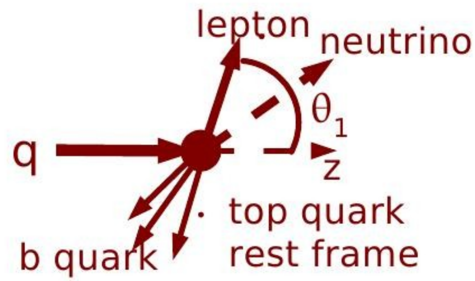


top decays before hadronization

- spin information passed to decay product

- spin correlation measured from decay product angular distribution

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



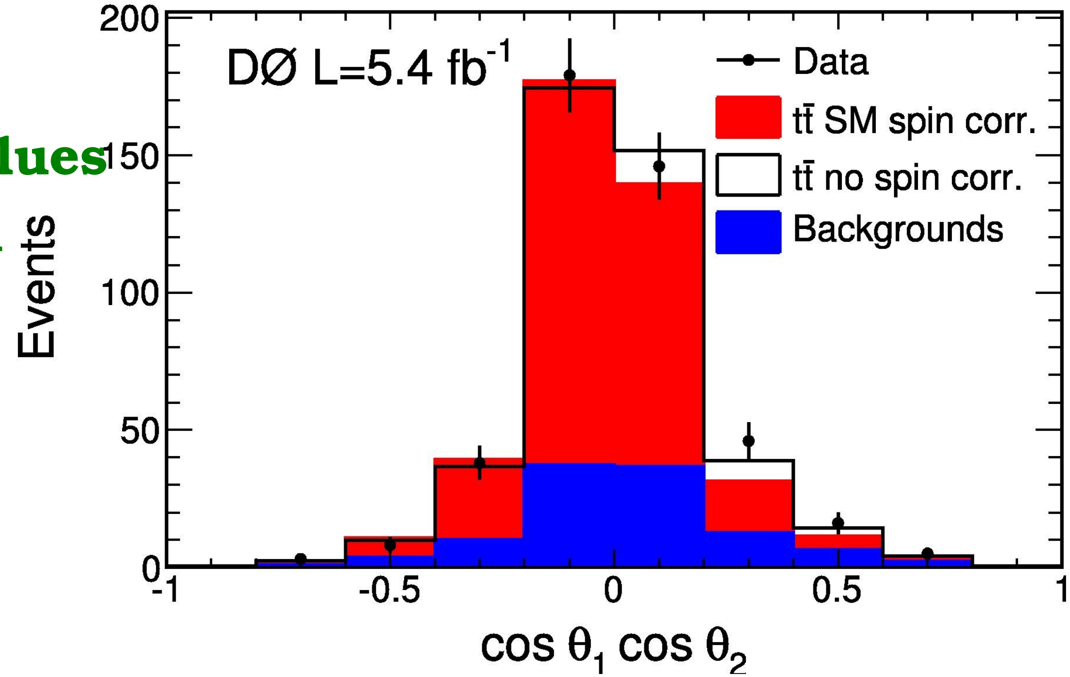
correlation strength : $C = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\uparrow\downarrow} - N_{\downarrow\uparrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\uparrow\downarrow} + N_{\downarrow\uparrow}}$ with $C^{SM\ NLO}_{beam\ basis} = 0.78^{+0.03}_{-0.04}$

NPB 690, 81 (2004)

Top anti top spin correlations

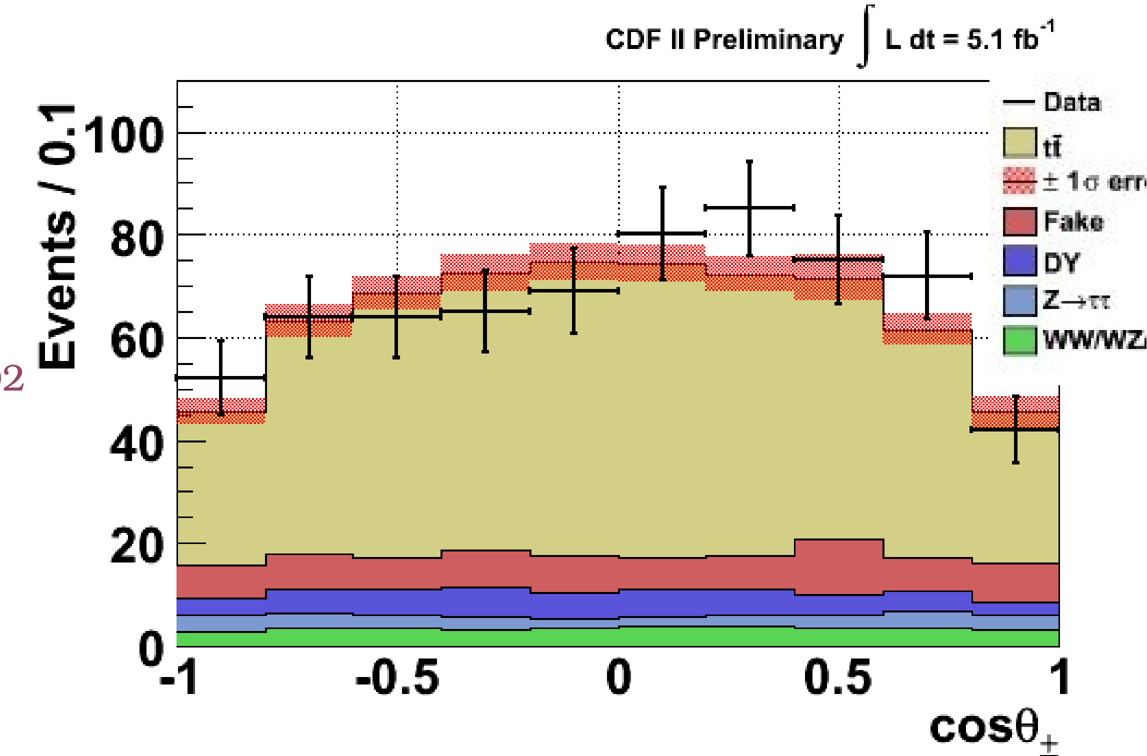
Template based measurements

- make template for different C values
- compare to data using maximum likelihood fit



D0 5.4 fb^{-1} dilepton PLB 702, 16 (2011)

$$C_{beam} = 0.10 \pm 0.45 \text{ (stat+syst)}$$



CDF 5.1 fb^{-1} dilepton CDF conf note 10719

$$C_{beam} = 0.04 \pm 0.56 \text{ (stat+syst)}$$

CDF 5.3 fb^{-1} lepton+jets CDF conf note 102

$$C_{beam} = 0.72 \pm 0.69 \text{ (stat+syst)}$$

limited by statistical uncertainty
consistent with SM expectation

Top anti top spin correlations

Matrix element method

define $P(x,H) \sim \int d^6\sigma(y,H)\, W(x,y)\, f_{PDF}(q_1) f_{PDF}(q_2)\, dq_1 dq_2$

differential Xsection — detector response — Parton Density Function

with correlation H=1 and no correlation H=0 hypotheses

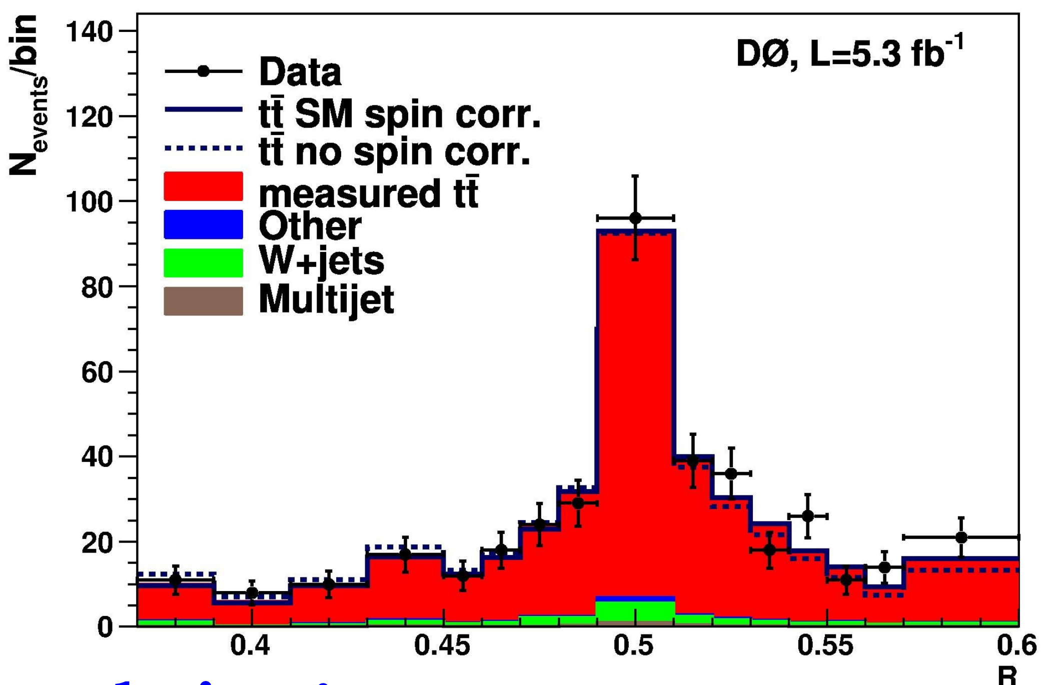
use discrimination variable $R = \frac{P(x,H=1)}{P(x,H=1)+P(x,H=0)}$

D0 5.4 fb^{-1} dilepton

$C_{beam} = 0.57 \pm 0.31$ (stat+syst)

D0 5.3 fb^{-1} lepton+jets

$C_{beam} = 0.89 \pm 0.33$ (stat+syst)



Combination PRL 108, 032004 (2012)

$C_{beam} = 0.66 \pm 0.23$ (stat+syst)

$C > 0.26$ @ 95 % CL

$C = 0$ excluded at 3.1σ

1st evidence of non zero spin correlation !

Ratio of branching fractions R

in the SM the ratio $R = \dfrac{BR(t \to Wb)}{BR(t \to Wq)} = \dfrac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$ **is constrained**

by CKM unitarity to be R=1 → R < 1 could indicate new physics

measure R simultaneously with the ttbar cross section
dropping the assumption R=1

CDF 7.5 fb^{-1} (l+jets)

$$\sigma_{t\bar{t}} = 7.4 \pm 1.1 \quad \text{pb}$$

$$R = 0.91 \pm 0.09$$

$$|V_{tb}| = 0.95 \pm 0.05$$

stat +syst uncertainties

D0 5.4 fb^{-1} (dilepton & l+jets)

$$\sigma_{t\bar{t}} = 7.74^{+0.67}_{-0.57} \quad \text{pb}$$

$$R = 0.90 \pm 0.04$$

$$|V_{tb}| = 0.95 \pm 0.02$$

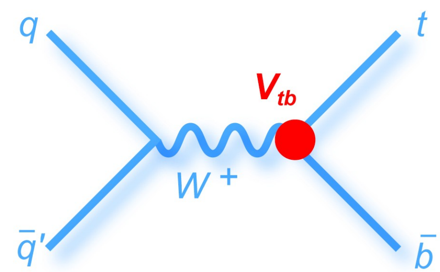
$$|V_{tb}| > 0.88 \quad @\ 99.7\%\ \text{CL}$$

stat +syst uncertainties

PRL 107, 121802 (2011)

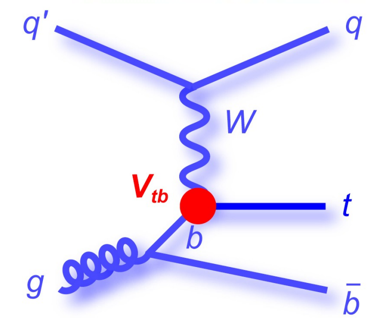
EW single top production

- **observed by CDF and D0 in March 2009**
- **direct access to the Wtb vertex**
- **direct measurement of Vtb** $\sigma \sim |V_{tb}|^2$
- **final state within large background with uncertainties larger than signal**
- **multivariate techniques mandatory (BDT, BNN, NEAT)**



s-channel

$\sigma_{SM} = 1.05 \pm 0.07$ pb



t-channel

$\sigma_{SM} = 2.10 \pm 0.19$ pb

both for $m_t = 172.5$ GeV

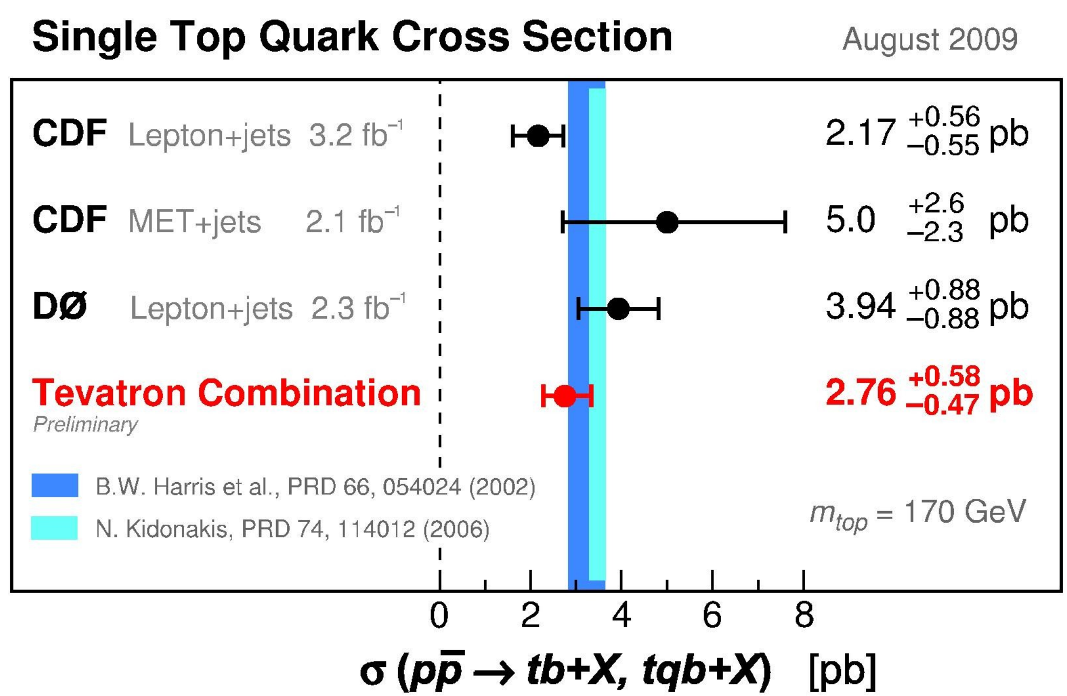
Tevatron combination (up to 3.2 fb^{-1})

$$\sigma = 2.76^{+0.58}_{-0.47} \text{ (stat+syst) pb}$$

$$|V_{tb}| = 0.88 \pm 0.07 \text{ (stat+syst)}$$

$$|V_{tb}| > 0.77 \text{ @ 95\% CL}$$

for $m_t = 170$ GeV



PRL 103,092001 (2009), PRL 103, 092002 (2009)

single top : s+t channel cross section

D0 5.4 fb^{-1} update (l+jets)

discriminating variables combined into MVAs :

- Boosted Decision Tree (BDT)
- Bayesian Neural Net (BNN)
- Neuroevolution of Augmented Topologies (NEAT)

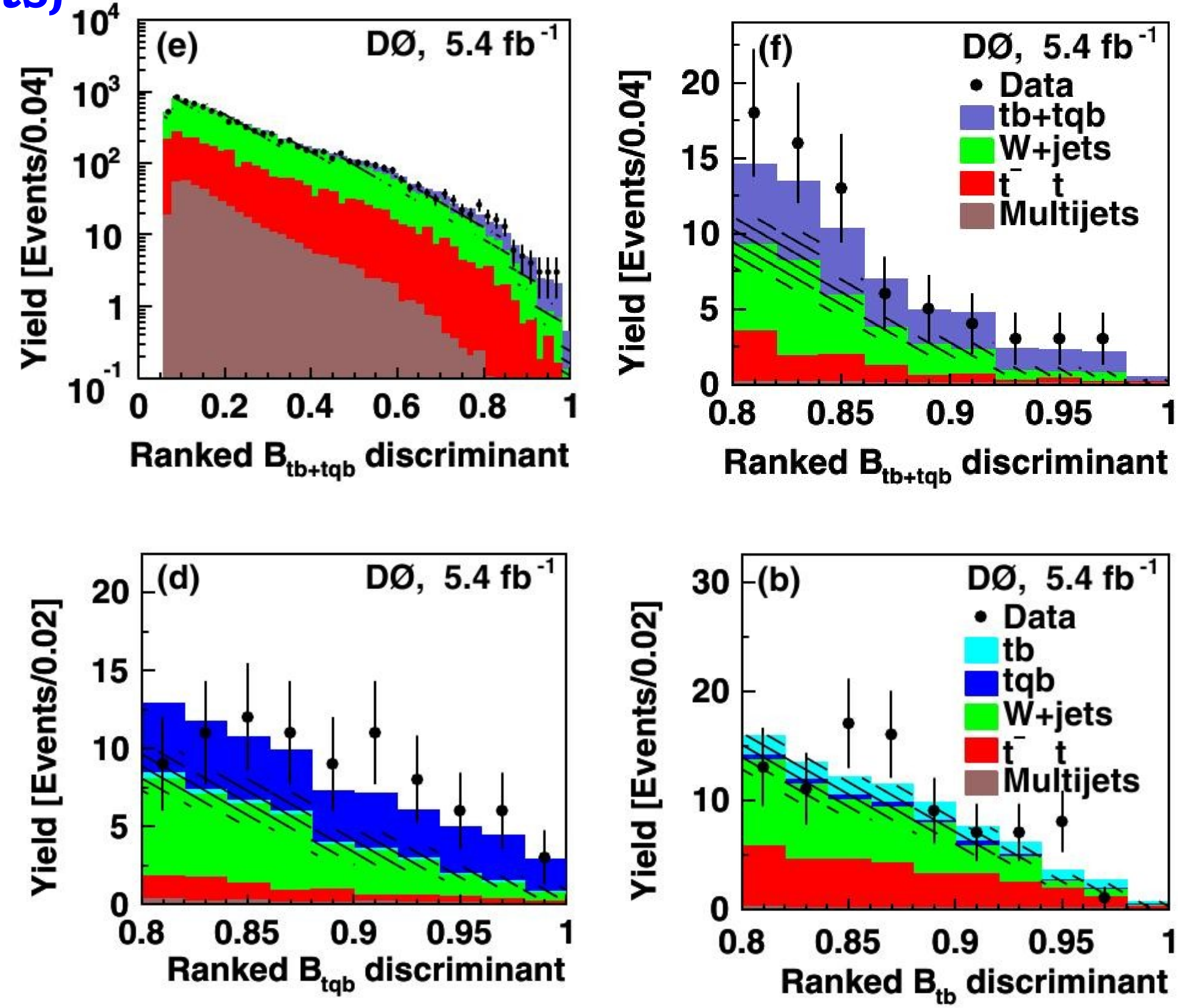
Correlation ~ 70 %

2^{nd} BNN used to construct a combined discriminant for each channel

$$\sigma_{s+t} = 3.43^{+0.73}_{-0.74} \text{ pb}$$

$$\sigma_{t} = 2.86^{+0.69}_{-0.63} \text{ pb}$$

$$\sigma_{s} = 0.68^{+0.38}_{-0.35} \text{ pb}$$



PRD 84, 112001 (2011)

direct $|V_{tb}|$ measurement

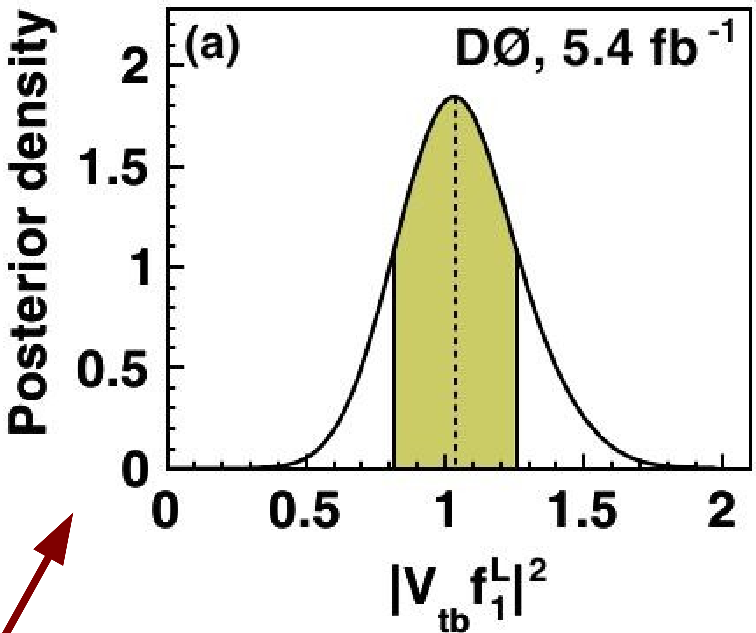
- single top production cross section directly proportional to $|V_{tb}|^2$

- can measure $|V_{tb}|$ assuming V-A coupling but without assuming 3 generations or unitarity of CKM matrix and using

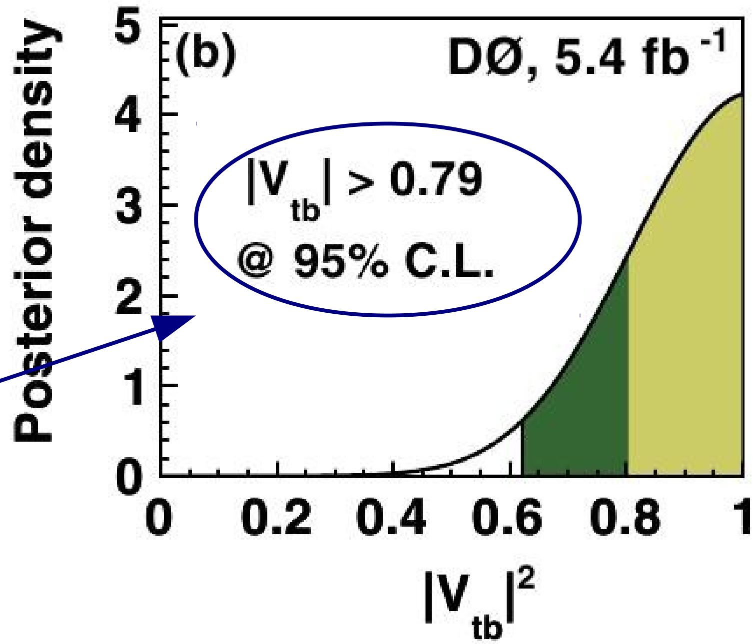
$$|V_{tb}|^2_{\text{measured}} = \frac{\sigma_{s+t}^{\text{measured}}}{\sigma_{s+t}^{\text{SM}}} |V_{tb}|^2_{\text{SM}}$$

- maintain the possibility for an anomalous strength of the left-handed Wtb coupling f_1^L

$$|V_{tb}\, f_1^L| = 1.02^{+0.10}_{-0.11}$$



- assuming $f_1^L = 1$ and restricting to [0,1]



PRD 84, 112001 (2011)

Single top CDF 7.5 fb^{-1} update (l + jets) : cross sections and V_{tb}

- use NN with same input variables as the observation analysis
- use NLO POWHEG for the MC single top signal samples (s-, t-, and Wt channels)

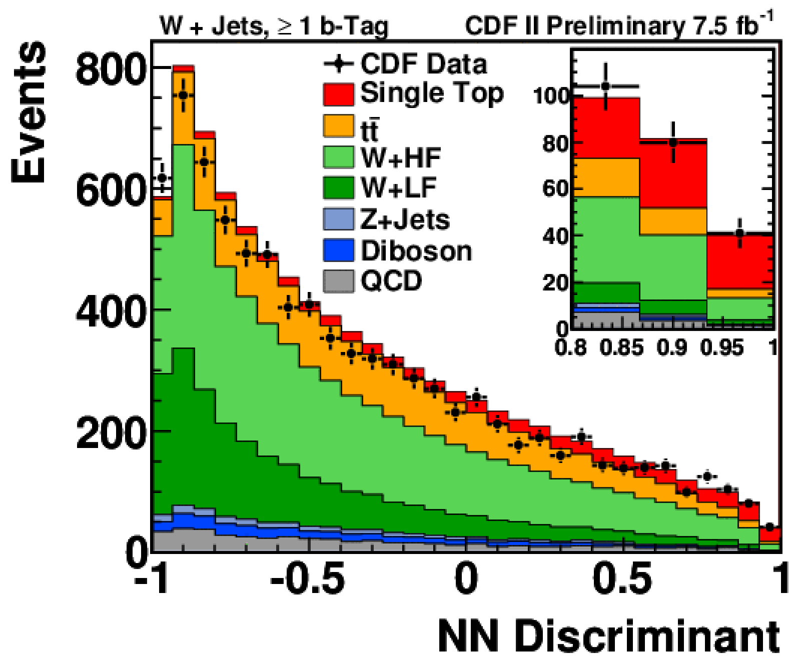
$$\sigma_{\text{single top}} = 3.04^{+0.57}_{-0.53}\ \text{pb}$$

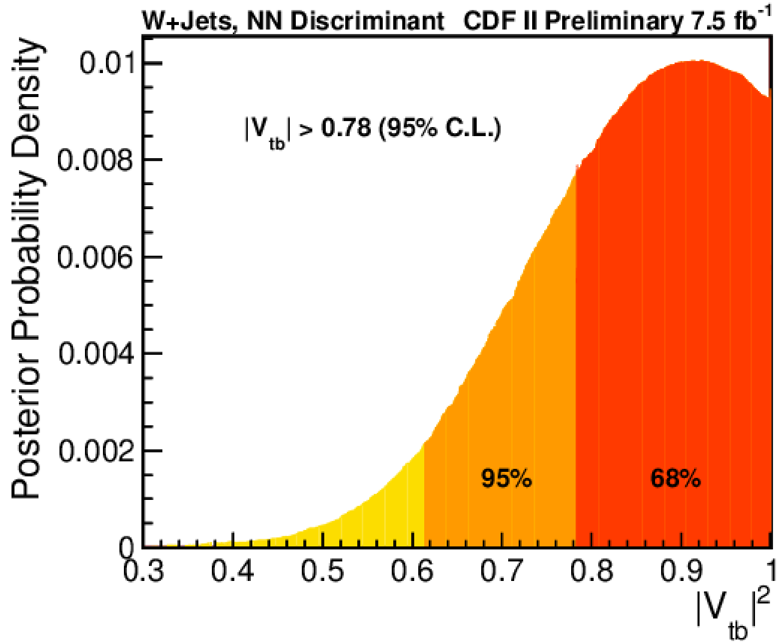
- extract bounds on $|V_{tb}|$ using again :

$$|V_{tb}|^2_{\text{measured}} = \frac{\sigma^{\text{measured}}_{s+t}}{\sigma^{\text{SM}}_{s+t}} |V_{tb}|^2_{\text{SM}}$$

$$|V_{tb}| > 0.78 \quad \text{at 95 \% CL}$$

$$|V_{tb}| = 0.92^{+0.10}_{-0.08}\ (\text{stat+syst}) \pm 0.05\ (\text{theory})$$

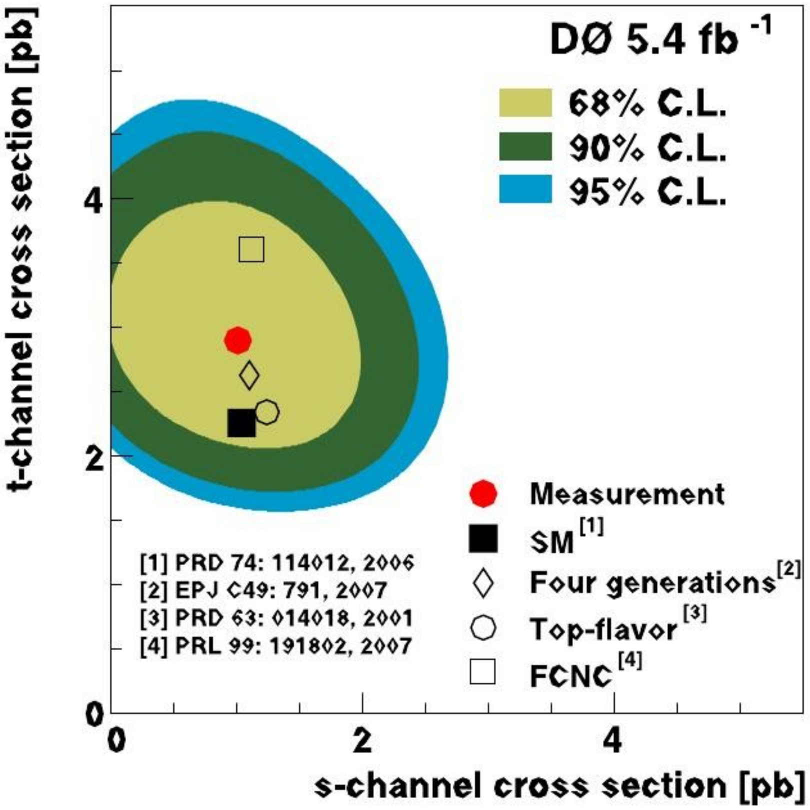




single top s- and t- channel measurement

s and t channel sensitive to different BSM physics

- **construct a 2D posterior probability density function for t- versus s- channel cross section**
- **extract t-channel cross section from 1D posterior by integrating over s-channel (x-axis)**



$$\sigma_{\text{t-channel}} = 2.90 \pm 0.59 \text{ pb}$$
$$\sigma_{\text{s-channel}} = 0.98 \pm 0.63 \text{ pb}$$

most precise measurement in t-channel

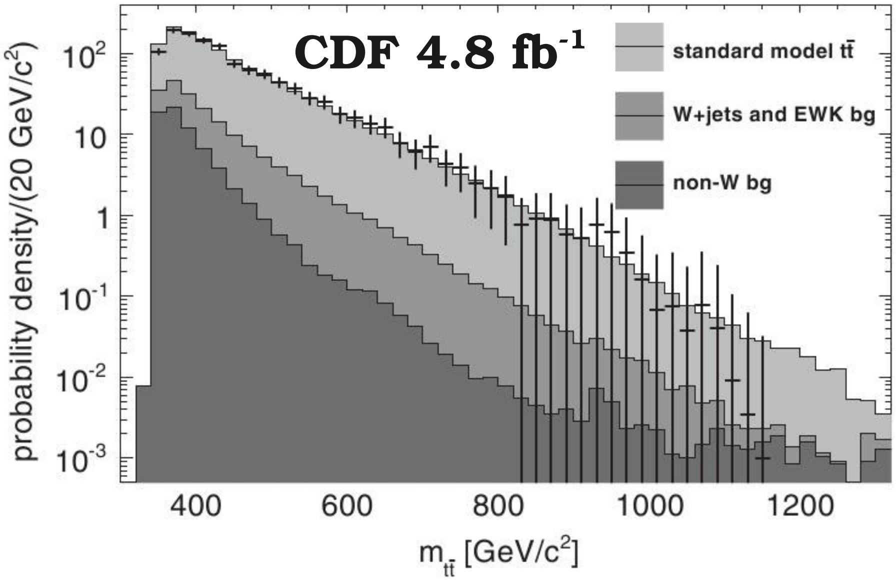
$>5\sigma$ significance

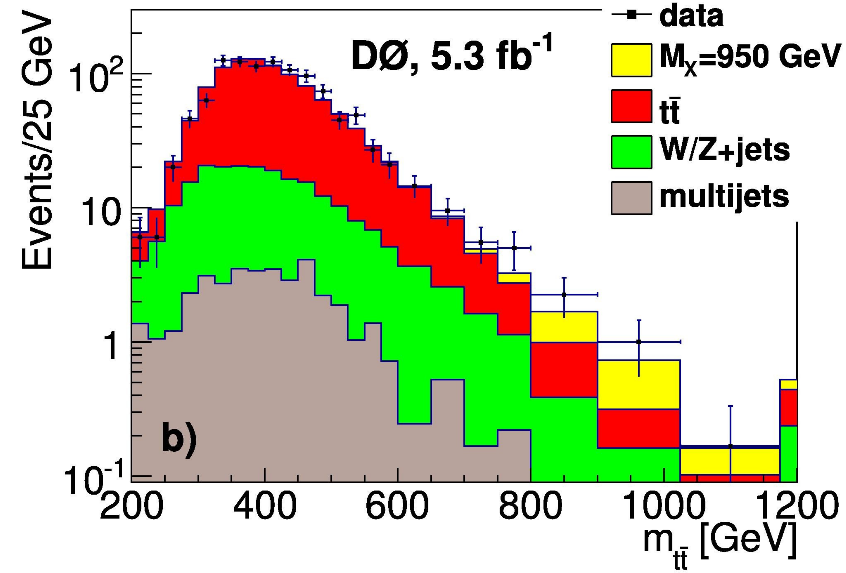
PLB 705, 313 (2011)

Search for resonant ttbar production

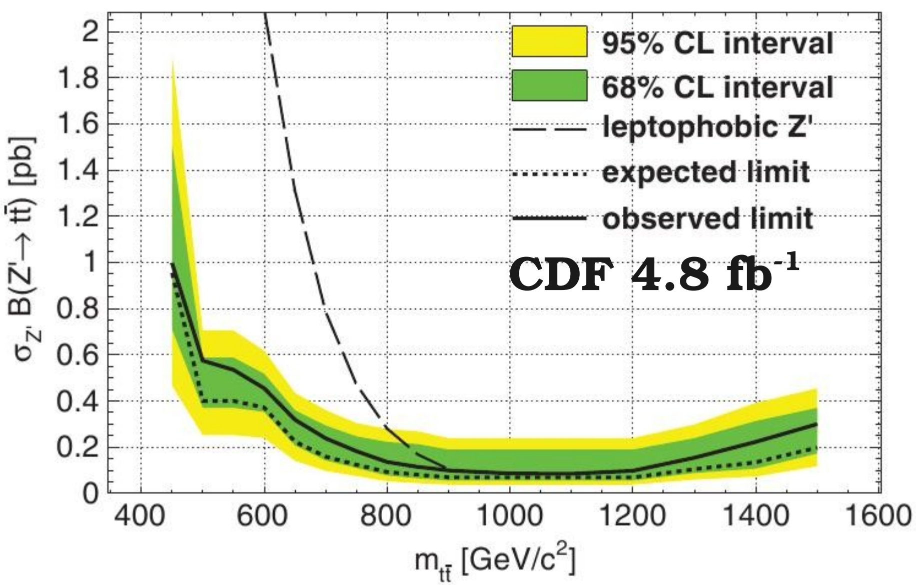
looking at the $M_{t\bar{t}}$ spectrum in the lepton + jets channel

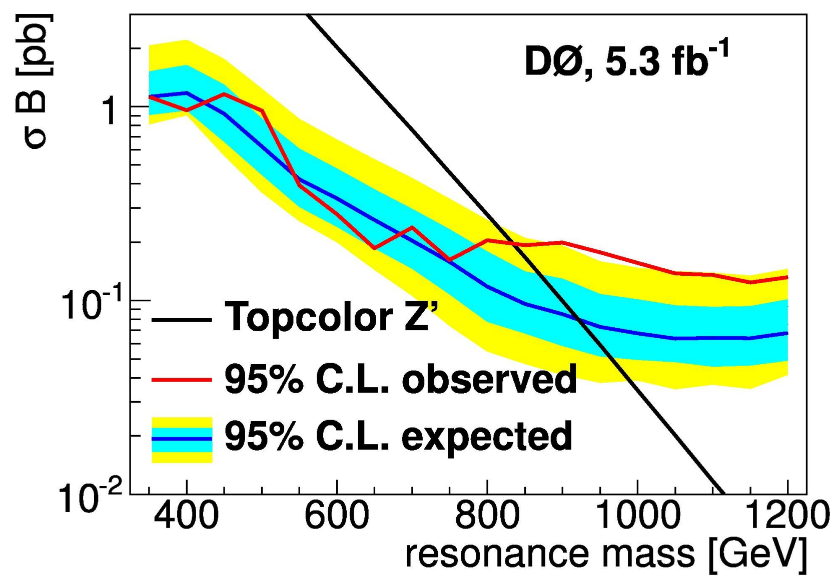
PRD 84, 072004 (2011)





PRD 85, 051101 (2012)





topcolor leptophobic $Z' \rightarrow t\bar{t}$ excluded at 95% CL with :

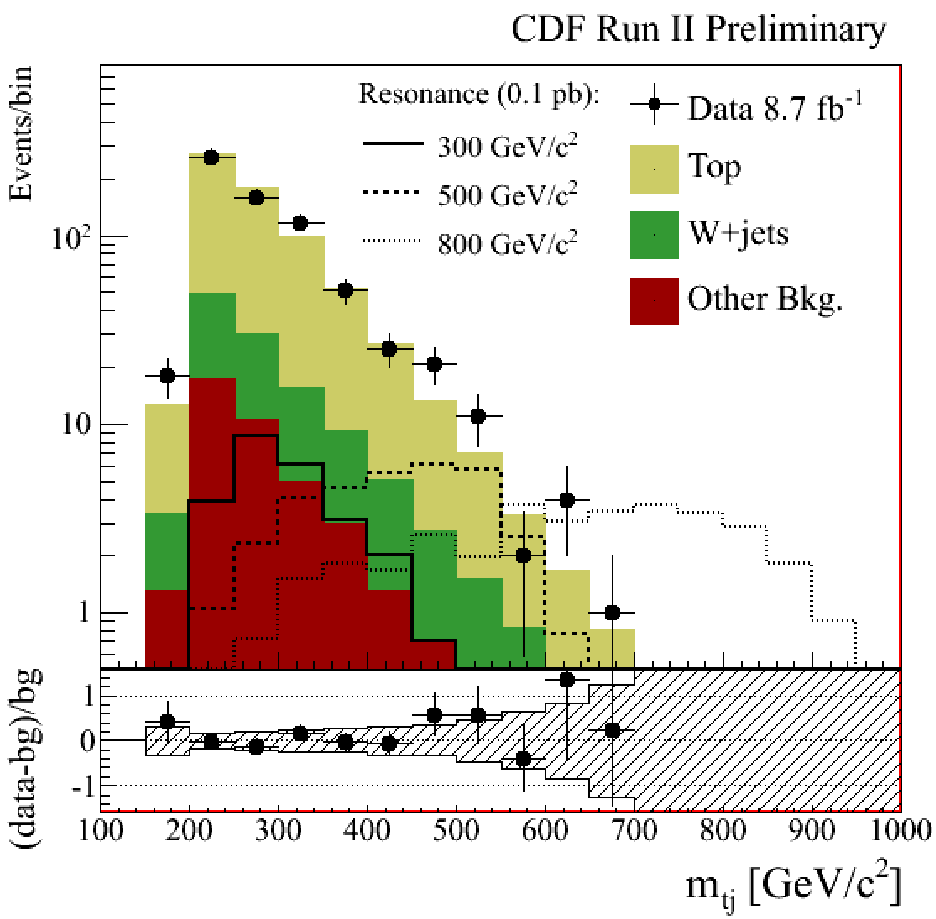
$M_{Z'} < 900$ GeV/c^2 $M_{Z'} < 835$ GeV/c^2

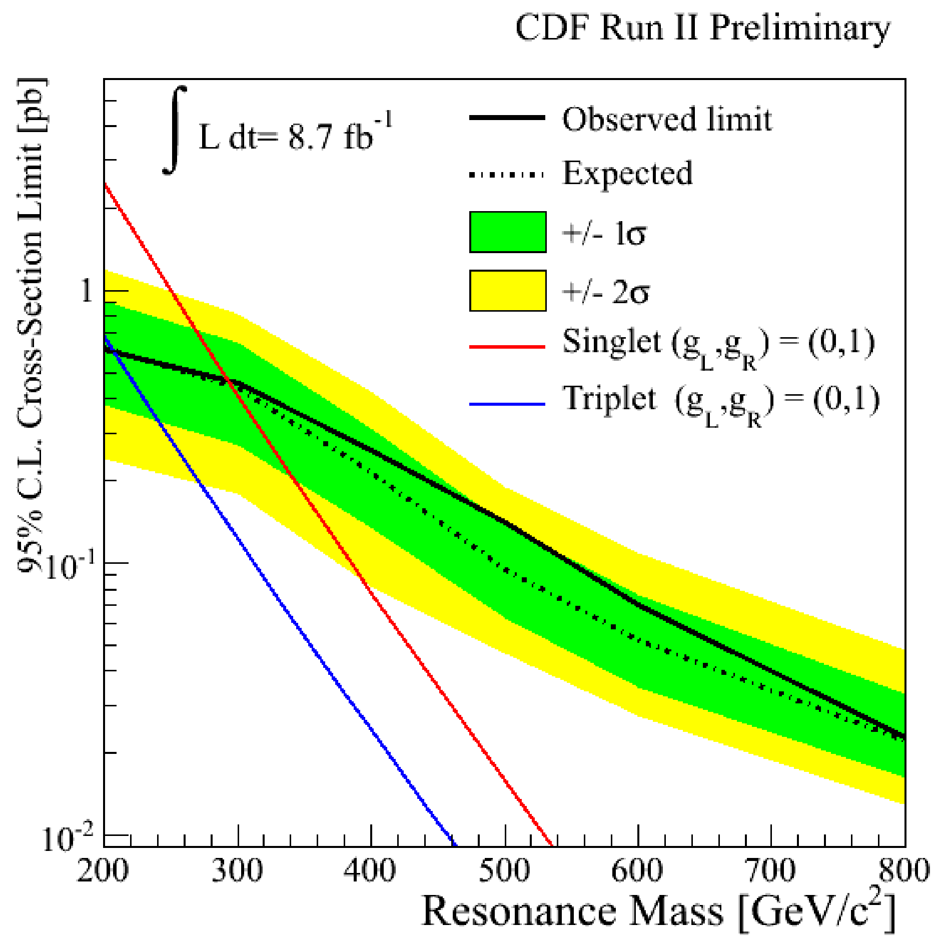
Search for top+jet resonances in ttbar + jet

search for a heavy particle X produced in association with a t quark: $p\bar{p} \rightarrow X\ t \rightarrow \bar{t}\,qt$

leading to a resonance in the $\bar{t}$ + jet system of $\bar{t}\,t+$ jet events

select events in lepton+jets with at least 5 jets and 1 btag





SUMMARY

- **Tevatron provides precision measurements for top pair production cross section**

  in most cases the measurements are now limited by systematics uncertainties

- **Forward-backward asymmetry of top events keeps indicating a discrepancy with current NLO QCD prediction**

- **Tevatron provides 1st evidence for non zero spin correlations**

- **Electroweak production of single top has been observed**

  new results on cross scetion measurements with precision < 20 %

  observation of t-channel production

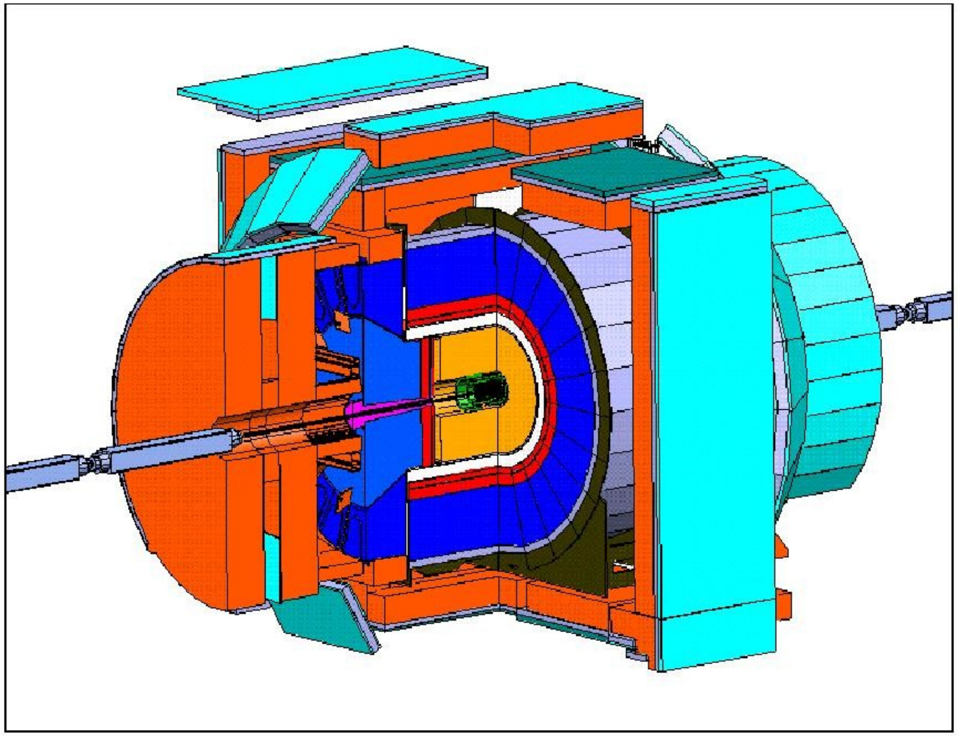
  measurements and limits on V

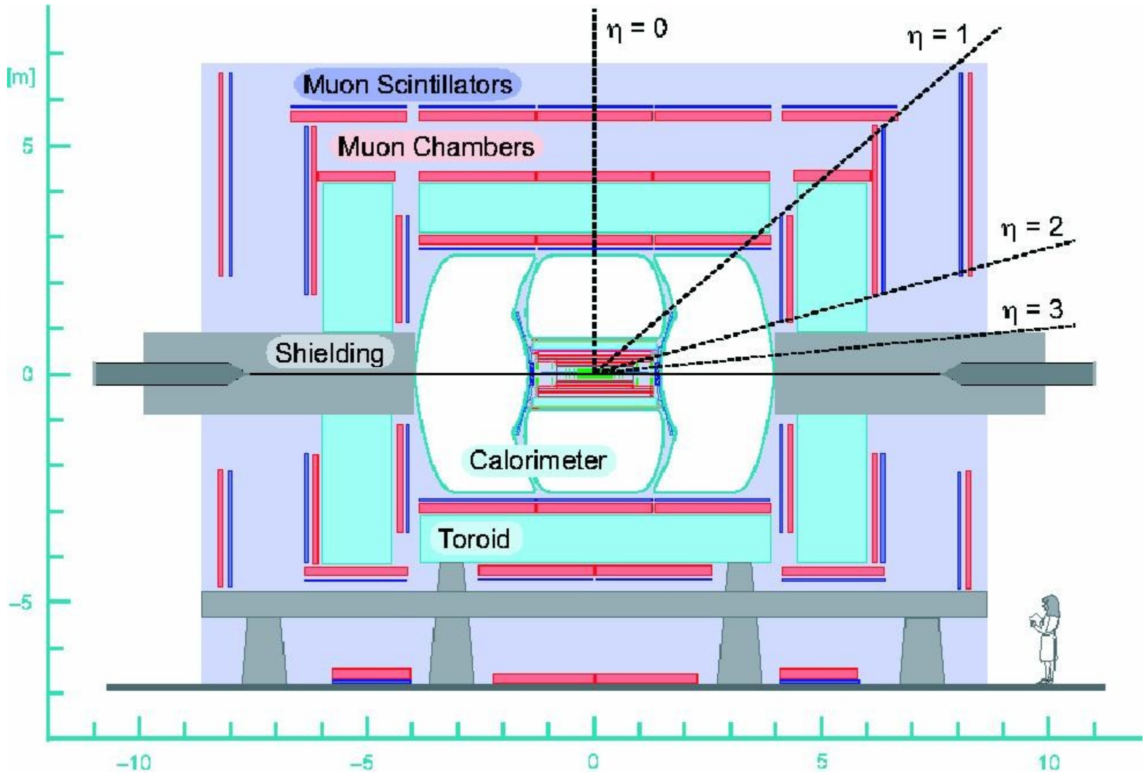
- **no evidence for resonant ttbar production**

BACKUP

14 nations
60 institutions
~500 physicists

19 nations
79 institutions
~500 physicists



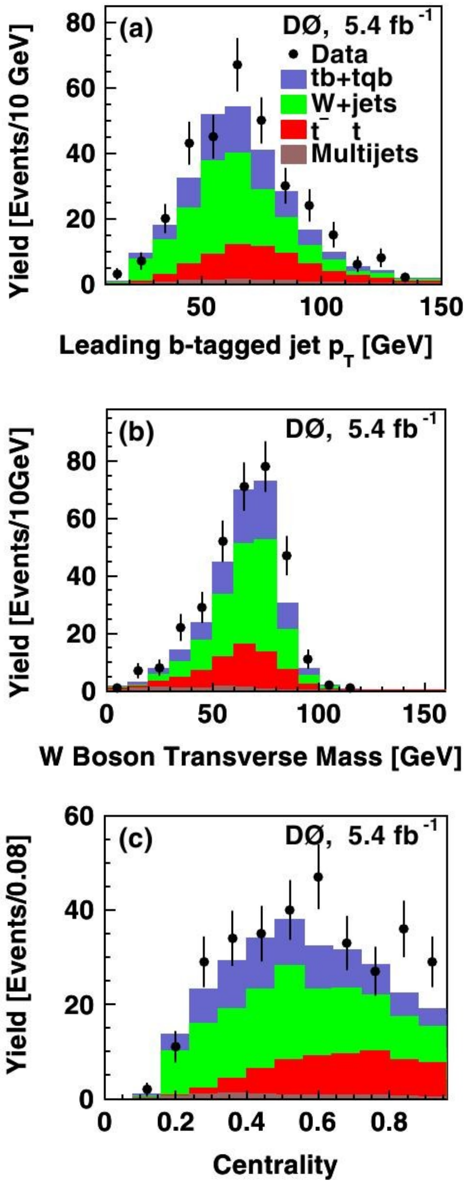


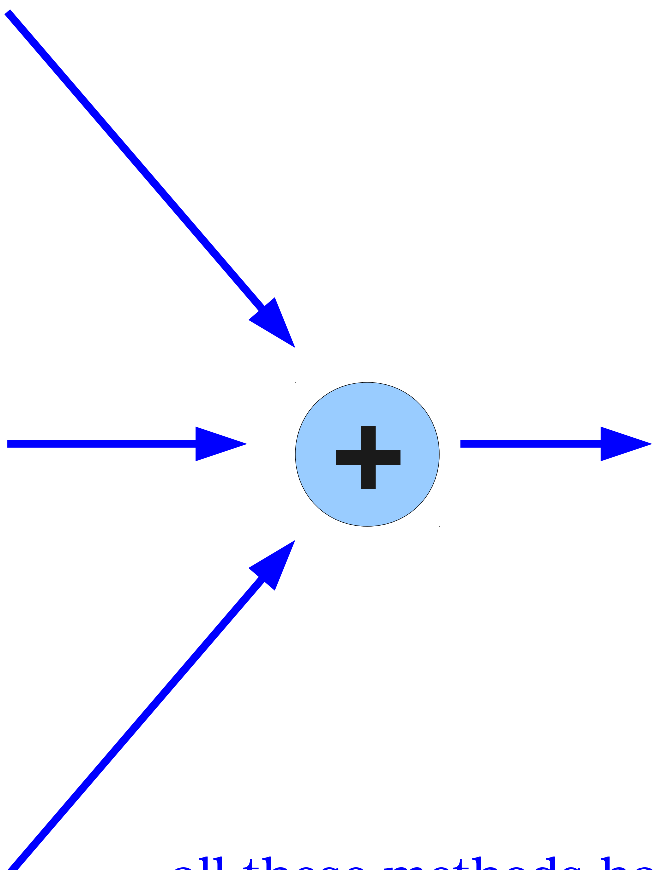
- silicon detector
- COT: drift chamber
- solenoid
- calorimeters
  central, wall, plug
- muon
  scintillator + chamber

- 8 layers silicon (SMT)
- 16 layers scintillating fibers
- 2T solenoid
- calorimeter:
  central+endcap
- 1.8 toroid
- 3 layers muon scintillators
  + drift tubes

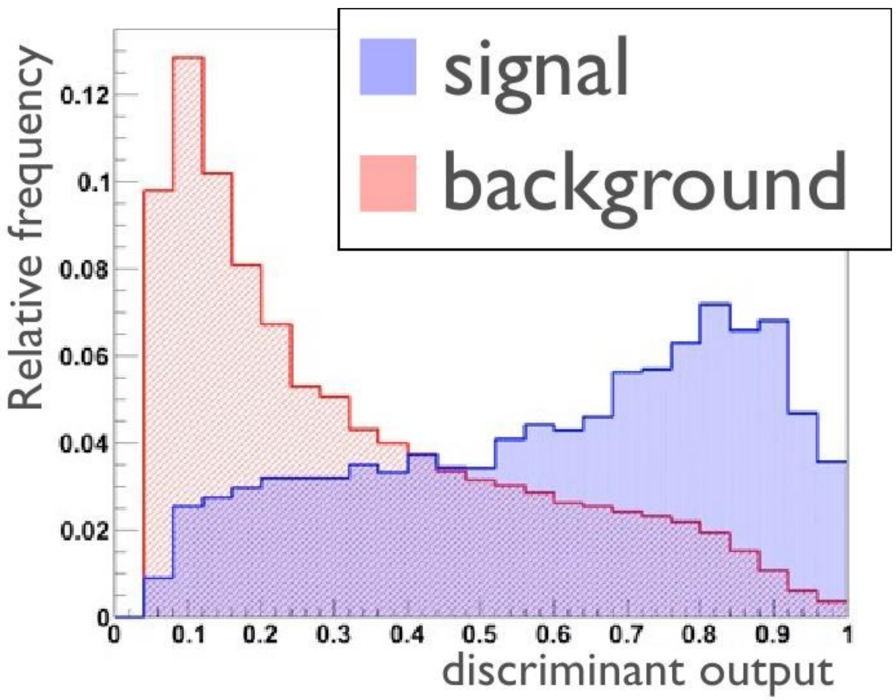
Multivariate analyses

Combine different kinematic variables with some discrimination power into one variable with larger discrimination





after training

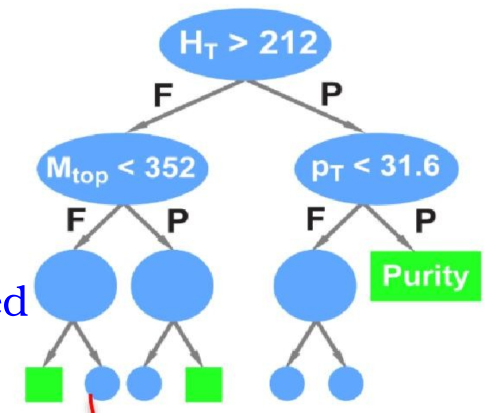


all these methods have a training process where they learn to discriminate between signal and background events

Multivariate analyses

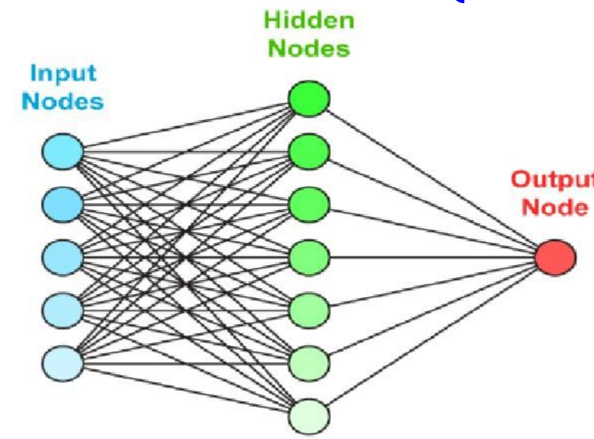
Boosted decision tree (BDT)

- apply sequential cuts keeping failing events
- performance is boosted by averaging multiple tress produced by enhancing misclassified events



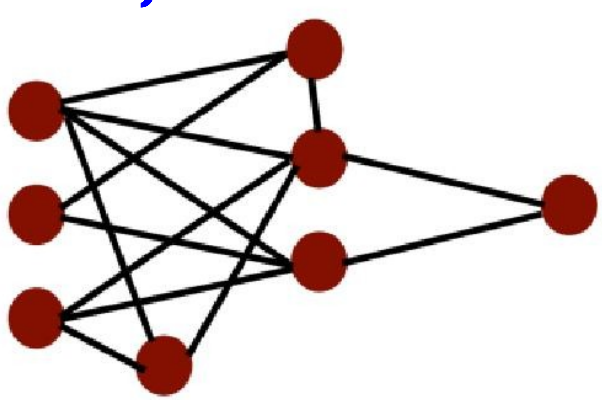
Bayesian Neural Network (BNN)

- Bayesian NN averaged over many network improving the performance



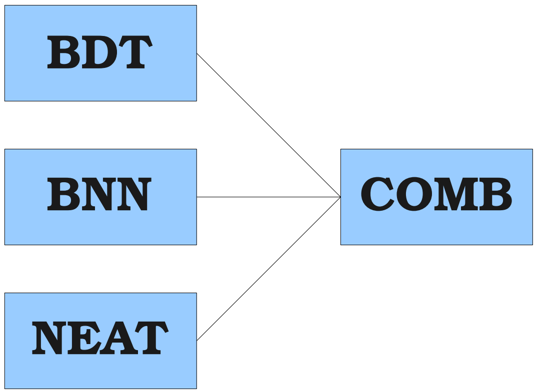
Neuro Evolution of Augmenting Topologies (NEAT)

- Genetic algorithms evolve a population of NN
- Topology of the NN is also part of the training



BNN Combination

- different discriminator are combined into one

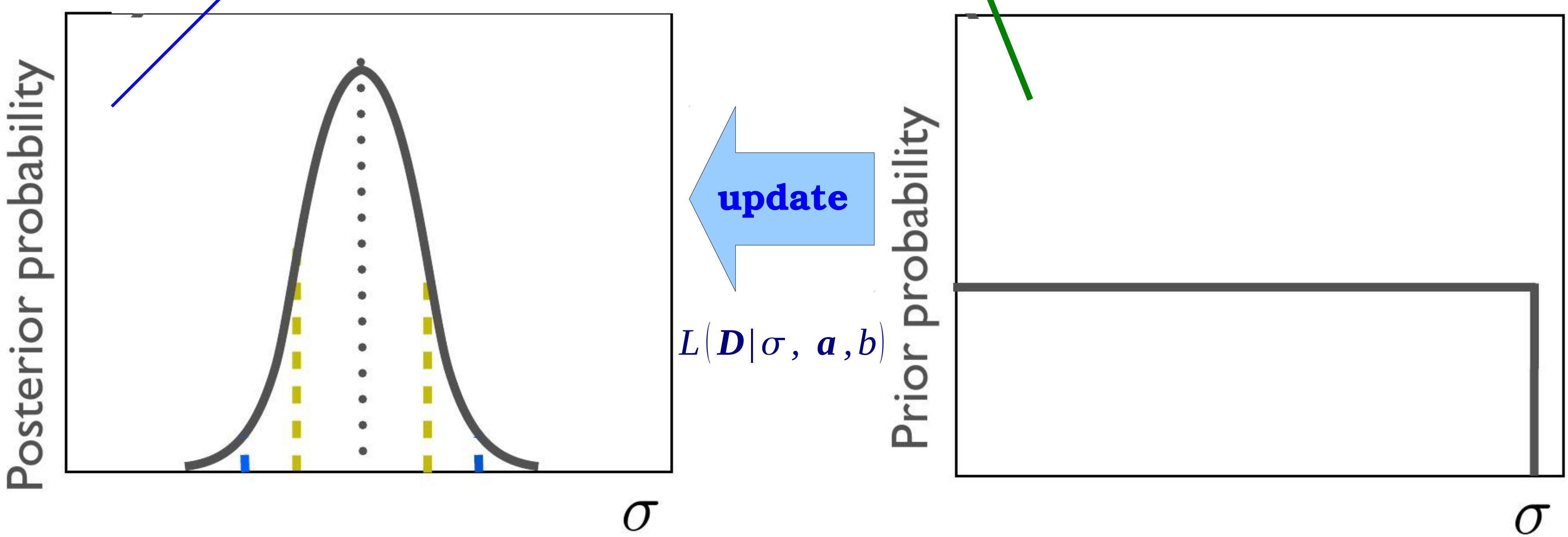


Bayesian statistical analysis

the prior distribution is updated by the likelihood that depends on the data

average the likelihood over the background uncertainties assuming gaussian prior

$$p(\sigma) = \frac{1}{N} \int L(\mathbf{D}|\sigma, \boldsymbol{a}, b)\, \pi(\sigma)\, \pi(\boldsymbol{a}, b)\, d\boldsymbol{a}\, d\boldsymbol{b}$$



EW single top production

TABLE II. Expected and observed cross sections in pb for tb, tqb, and $tb+tqb$ production. All results assume a top quark mass of 172.5 GeV.

Discriminant	Expected	Observed
	tb production	
BNN	$1.08^{+0.52}_{-0.50}$	$0.72^{+0.44}_{-0.43}$
BDT	$1.07^{+0.47}_{-0.43}$	$0.68^{+0.41}_{-0.39}$
NEAT	$1.06^{+0.54}_{-0.50}$	$0.17^{+0.41}_{-0.17}$
B_{tb}	$1.12^{+0.45}_{-0.43}$	$0.68^{+0.38}_{-0.35}$
	tqb production	
BNN	$2.49^{+0.76}_{-0.67}$	$2.92^{+0.87}_{-0.73}$
BDT	$2.40^{+0.71}_{-0.66}$	$3.03^{+0.78}_{-0.66}$
NEAT	$2.36^{+0.80}_{-0.77}$	$2.75^{+0.87}_{-0.75}$
B_{tqb}	$2.43^{+0.67}_{-0.61}$	$2.86^{+0.69}_{-0.63}$
	$tb+tqb$ production	
BNN	$3.46^{+0.84}_{-0.78}$	$3.11^{+0.77}_{-0.71}$
BDT	$3.41^{+0.82}_{-0.74}$	$3.01^{+0.80}_{-0.75}$
NEAT	$3.33^{+0.94}_{-0.80}$	$3.59^{+0.96}_{-0.80}$
B_{tb+tqb}	$3.49^{+0.77}_{-0.71}$	$3.43^{+0.73}_{-0.74}$

TABLE III. Dependence on m_t of the measured cross sections in pb for tb, tqb, and $tb+tqb$ production, using the combined discriminants for the assumed top quark masses. The predicted cross sections [2] in pb are also included in the table and labeled "SM."

m_t	170 GeV	172.5 GeV	175 GeV
tb	$1.20^{+0.62}_{-0.56}$	$0.68^{+0.38}_{-0.35}$	$0.53^{+0.36}_{-0.34}$
SM	$1.12^{+0.04}_{-0.04}$	$1.04^{+0.04}_{-0.04}$	$0.98^{+0.04}_{-0.04}$
tqb	$2.65^{+0.65}_{-0.59}$	$2.86^{+0.69}_{-0.63}$	$2.45^{+0.60}_{-0.57}$
SM	$2.34^{+0.12}_{-0.12}$	$2.26^{+0.12}_{-0.12}$	$2.16^{+0.12}_{-0.12}$
$tb+tqb$	$3.70^{+0.78}_{-0.80}$	$3.43^{+0.73}_{-0.74}$	$2.56^{+0.69}_{-0.61}$
SM	$3.46^{+0.16}_{-0.16}$	$3.30^{+0.16}_{-0.16}$	$3.14^{+0.16}_{-0.16}$

From D0 publication : PRD 84, 112001 (2011)

EW single top production