

Top measurements at the Tevatron



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for CDF and D0 collaborations

The Fermilab Tevatron

- the birthplace of the top quark
- the highest energy collider in the world ...until December 2009
- $p\bar{p}$ collisions at $\sqrt{s}=1.96 \text{ TeV}$
- shut down on Sept. 30 2011
- 10.5 fb^{-1} of recorded data per experiment



Results presented in this talk are legacy measurements that use all the data

Strong production of top pairs

Top pair cross sections

Top quark mass

Asymmetries in production
top quark pairs
bottom quark pairs

Electroweak top quark production
t-, s-channel cross sections
 $|V_{tb}|$ measurement
 W' search

Strong production of top pairs

Top pair cross sections

R. Schwienhorst: Selected topics from top mass measurements at the Tevatron (Top-1)

C. Gerber: Selected topics from top properties at the Tevatron (Top-3)

Electroweak top quark production t-, s-channel cross sections

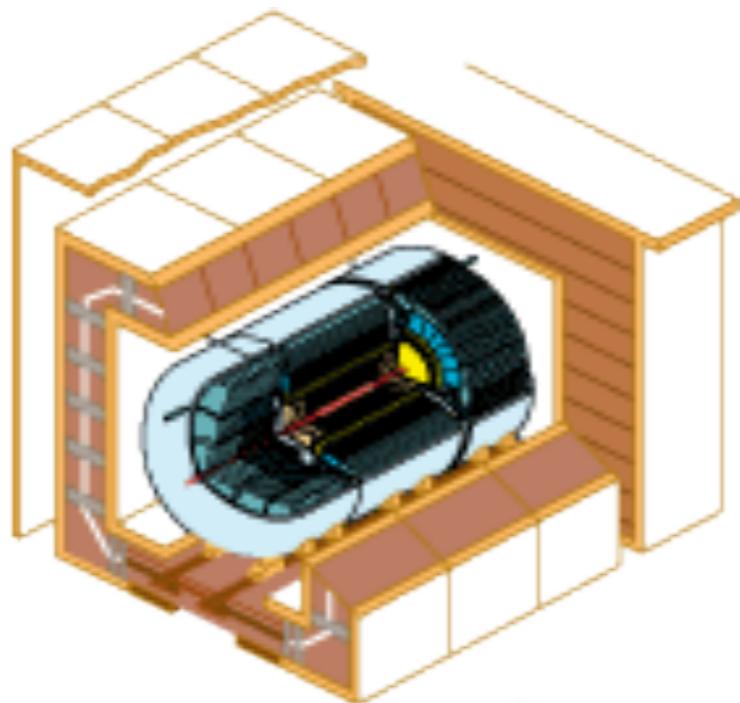
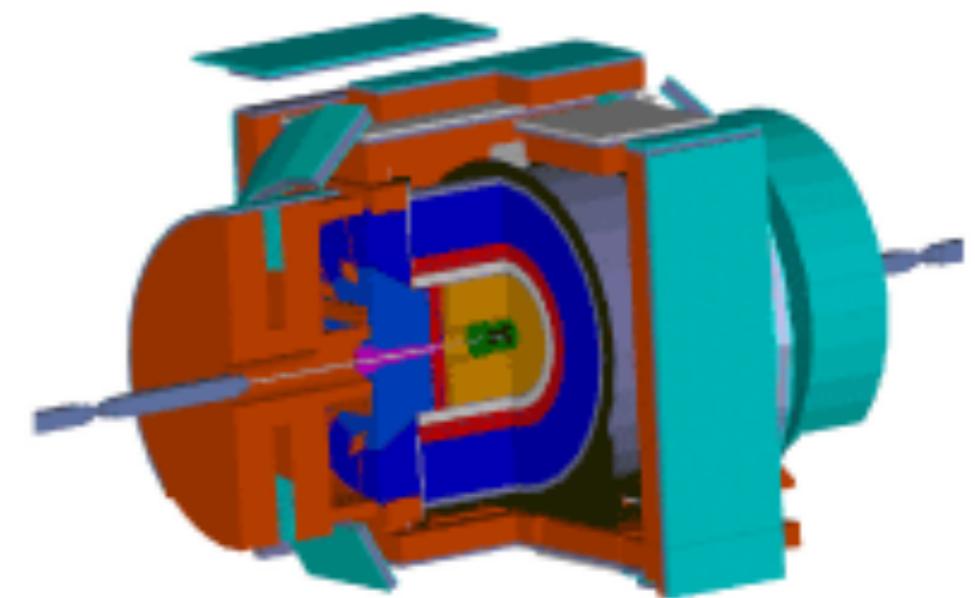
W.M. Yao: Selected topics from ttbar/single top production at the Tevatron (Top-2)

Top quark mass

Asymmetries in production top quark pairs bottom quark pairs

$|V_{tb}|$ measurement W' search

Experiments

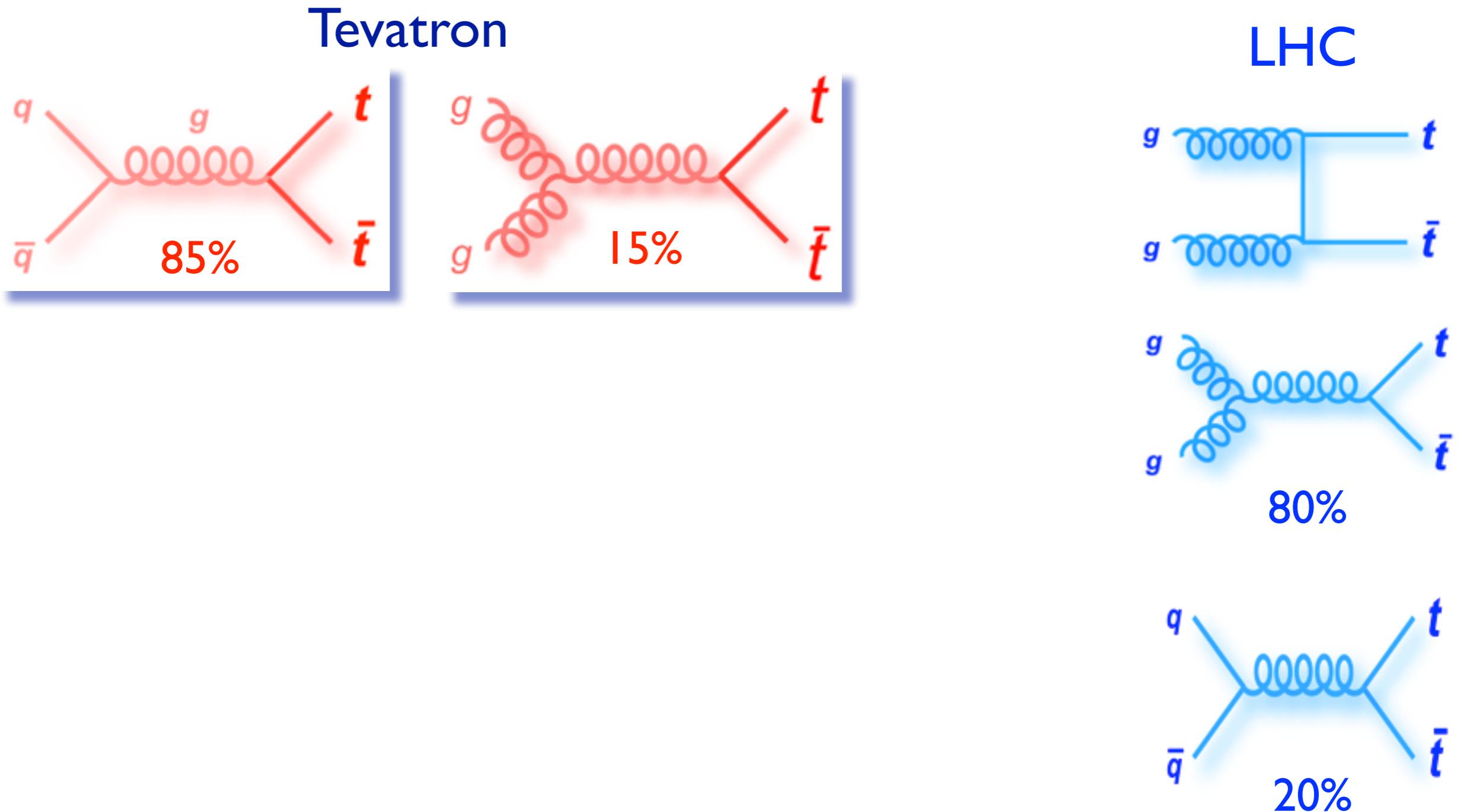
**DØ****CDF**

- Multipurpose collider detectors
 - ▶ high resolution inner detectors for precise tracking and vertex reconstruction
 - ▶ electromagnetic and hadronic calorimeters
 - ▶ outer muon system
 - ▶ magnetic field

Strong production of top pairs

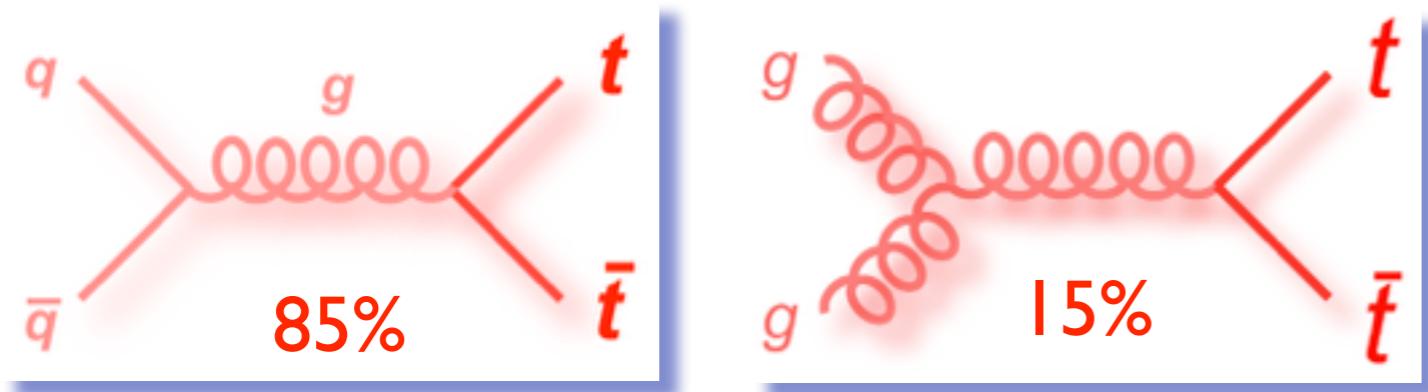
Top pair cross sections

Main mechanism: pair production via strong interaction



Main mechanism: pair production via strong interaction

Tevatron



Phys.Rev.Lett. 110 (2013) 252004

- Full next-to-next-to-leading-order (NNLO) accuracy in the strong coupling constant α_s , including the resummation of next-to-next-to-leading logarithmic (NNLL) soft gluon terms

 $m_t = 172.5 \text{ GeV}, \text{MSTW2008NNLO PDF}$

$\sqrt{s} (\text{TeV})$	2	7
$\sigma_{t\bar{t}} (\text{pb})$	7.35	177.3

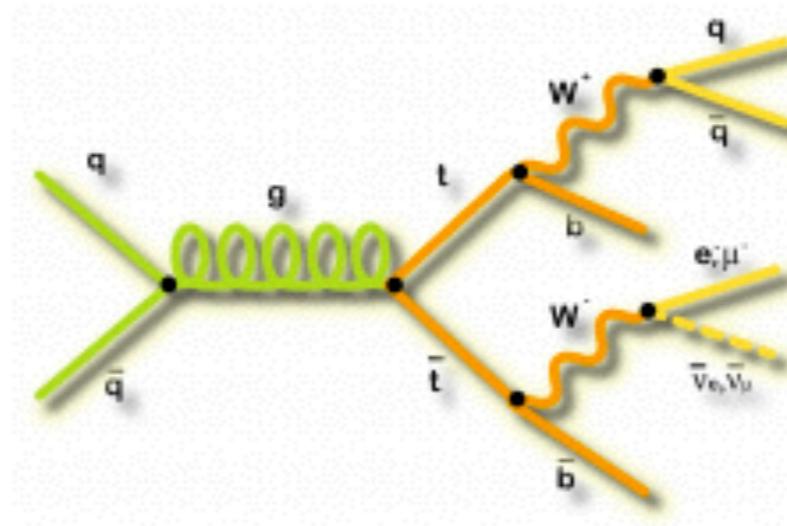
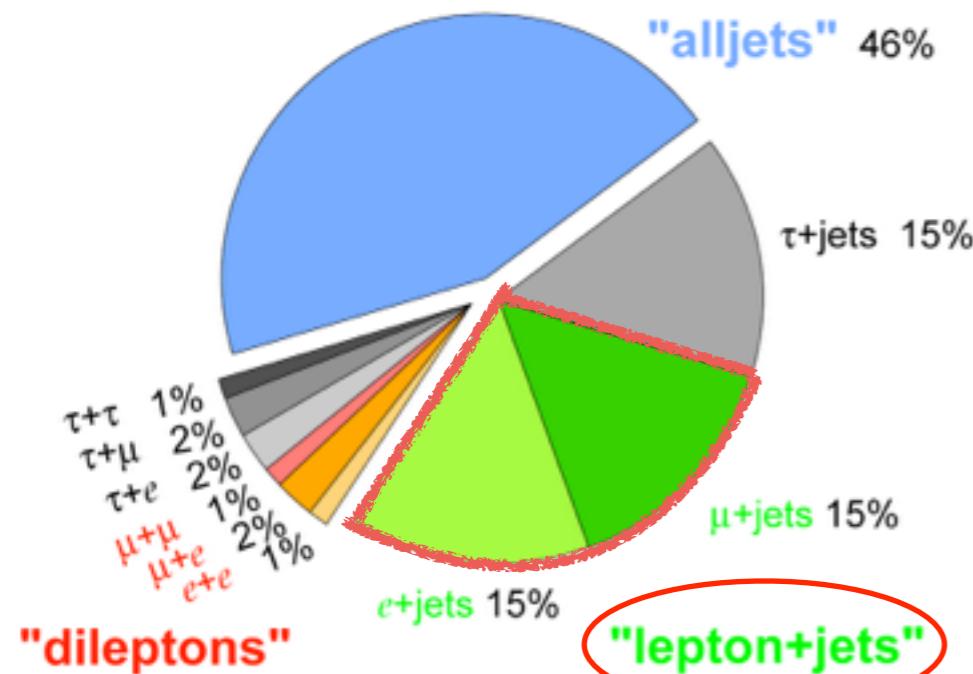
- Uncertainty from scale variation and PDF
- ~4% uncertainty for Tevatron

LHC:	ATLAS 7 TeV (5 fb^{-1}) sample	~29,000 l+jets events
Tevatron:	D0 full sample	~2,700 l+jets events

Dramatic difference in statistics! Can we still learn anything from Tevatron data?

lepton+jets channel

Top Pair Branching Fractions



- **Signature**
 - ▶ one high p_T isolated lepton
 - ▶ large missing transverse momentum
 - ▶ ≥ 4 jets
 - ▶ 2 b-jets

□ “Golden channel” at the Tevatron

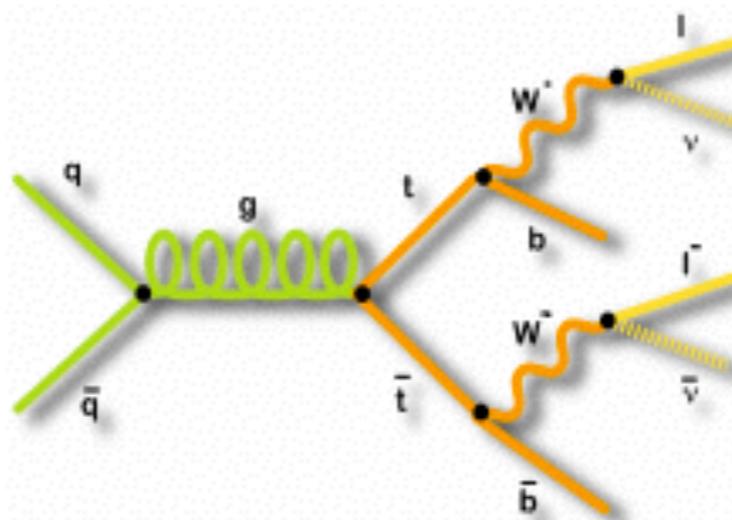
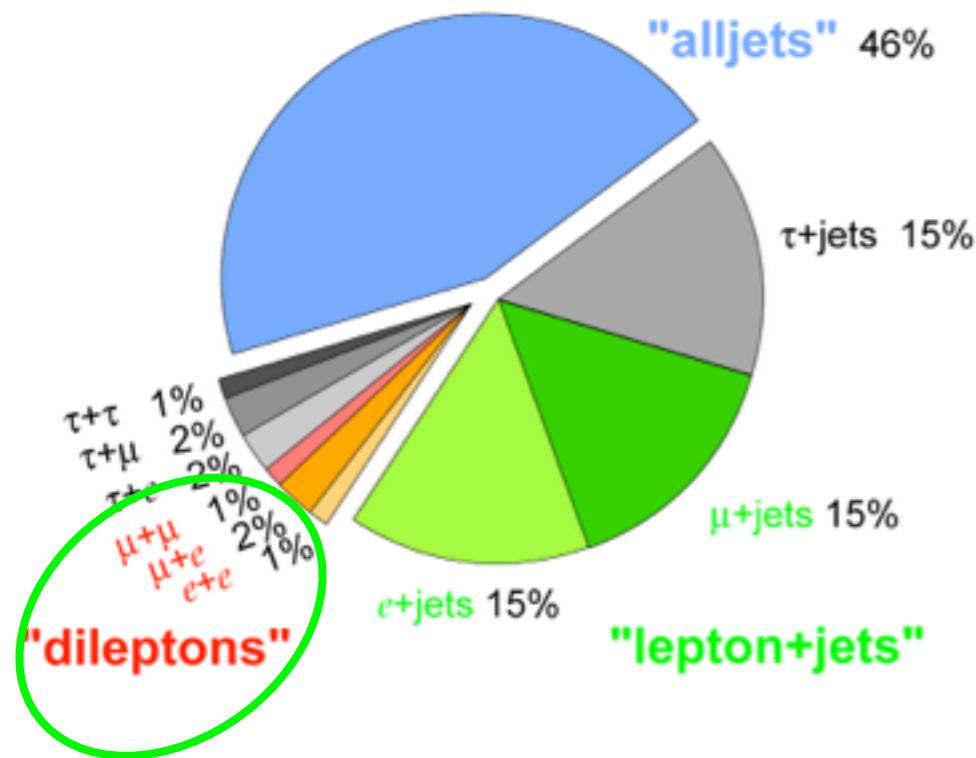
- ▶ good rate
- ▶ manageable backgrounds

 ≥ 4 jets

	pretag	≥ 1 b-tag
S/B	2:3	4:1

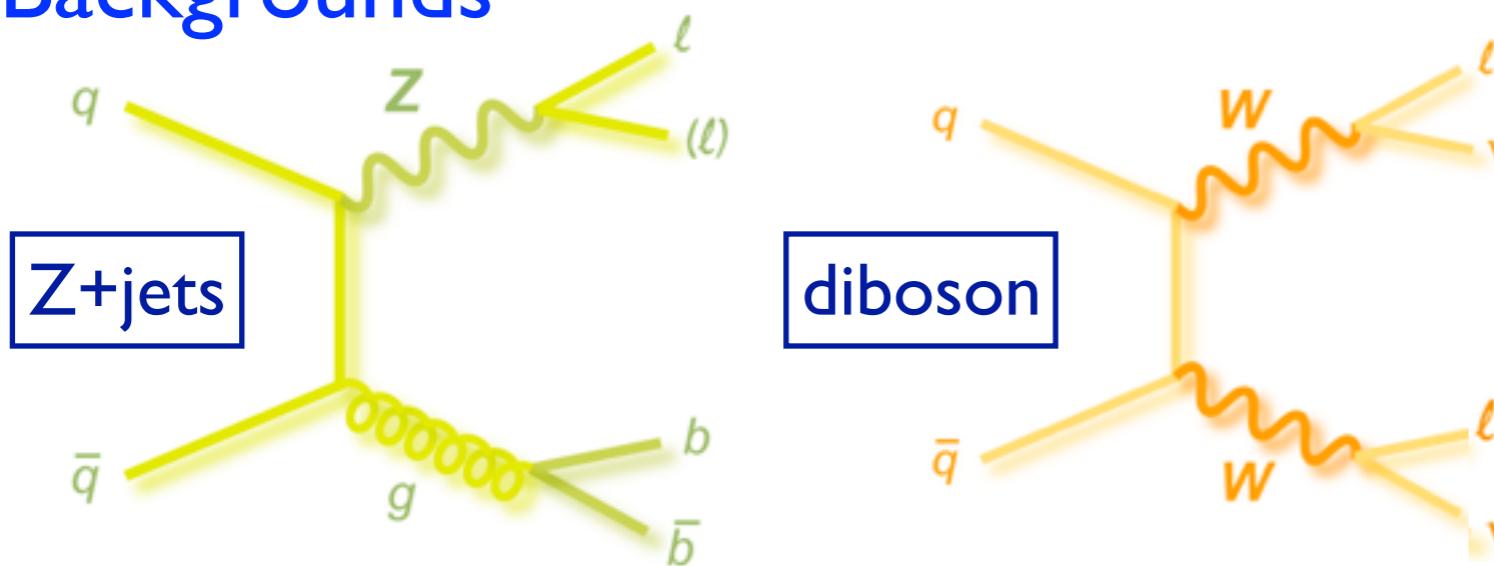
Provided the most precise measurements

Top Pair Branching Fractions



- **Signature**
 - ▶ two high p_T isolated leptons
 - ▶ large missing transverse momentum
 - ▶ ≥ 2 b-jets

Backgrounds

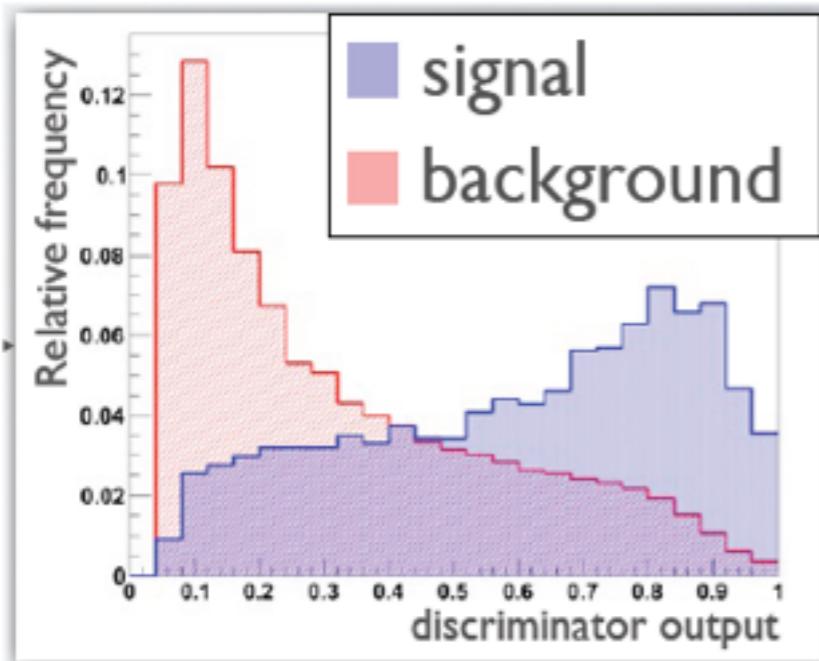


	pretag	≥ 1 b-tag
S/B	3:I	15:I

Low backgrounds but statistically limited at the Tevatron

Finding top quarks

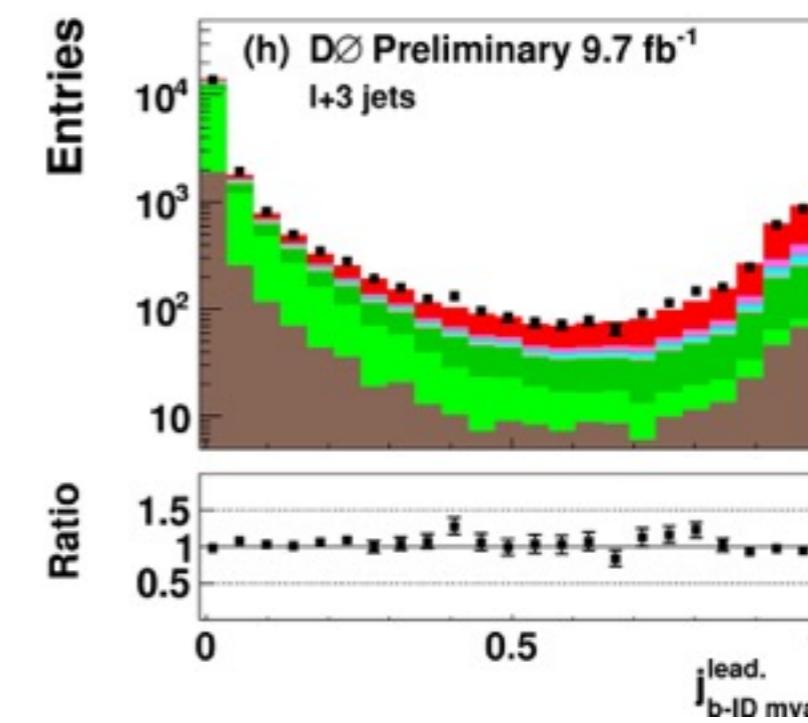
- Exploit differences between **kinematic properties** of signal and background
- Select discriminating variables
- Form a discriminant from these variables



- Extract cross section from a binned likelihood fit to data

Same idea is used for single top quark cross section

- **B-tagging:**
 - long life time of B-hadrons
 - semileptonic B decays
- Use as
 - cutoff on output of b-tagging algorithm or as a continuous variable
- **Neural Network tagger**
 - ▶ combines properties of displaced tracks and secondary vertex



Cross section

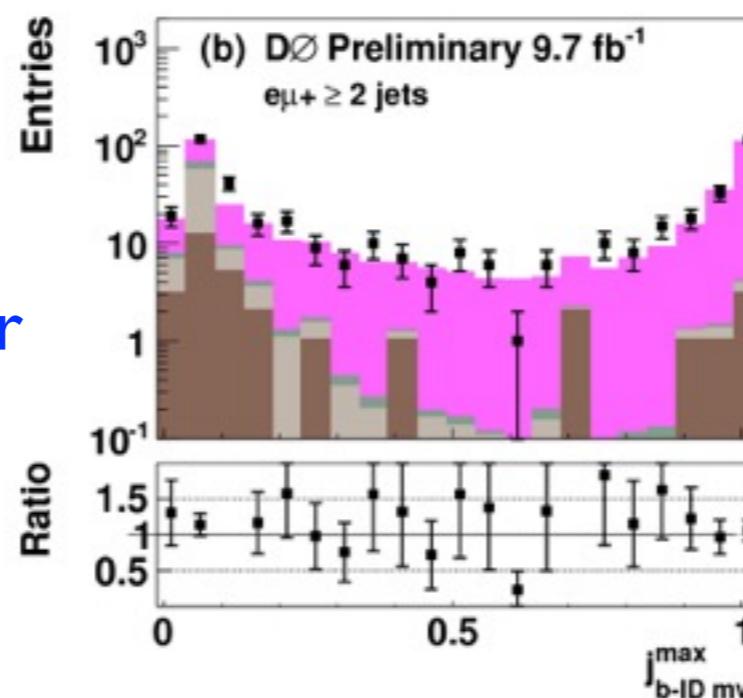
Combined measurement in l+jets and dilepton channels

- Uses events with $n_j = 2, 3, \geq 4$
- BDTG to separate signal in l+jets channel
 - includes kinematic and b-tagging MVA variables in 6 channels
- b-tagging MVA variable in dilepton channel
- Systematics included as nuisance parameters in the fit
- Data in background dominated regions constrains the uncertainties



Uncertainties

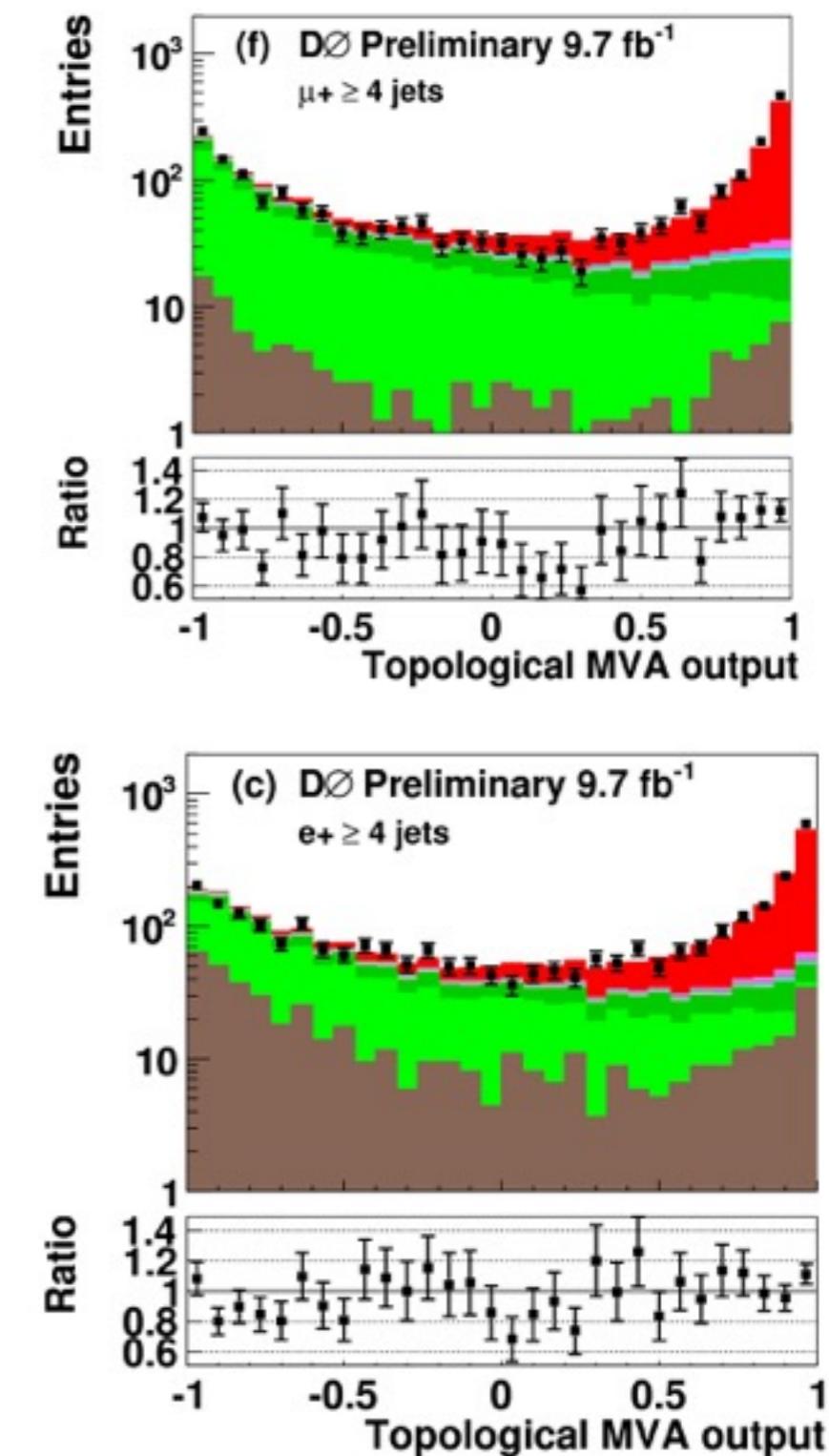
- largest uncertainty from modeling of parton shower
- luminosity
- modeling of b-jets



$$\sigma_{t\bar{t}} = 7.73 \pm 0.13(\text{stat}) \pm 0.55(\text{syst}) \text{ pb}$$

7.3% relative precision

D0 Note 6453-CONF



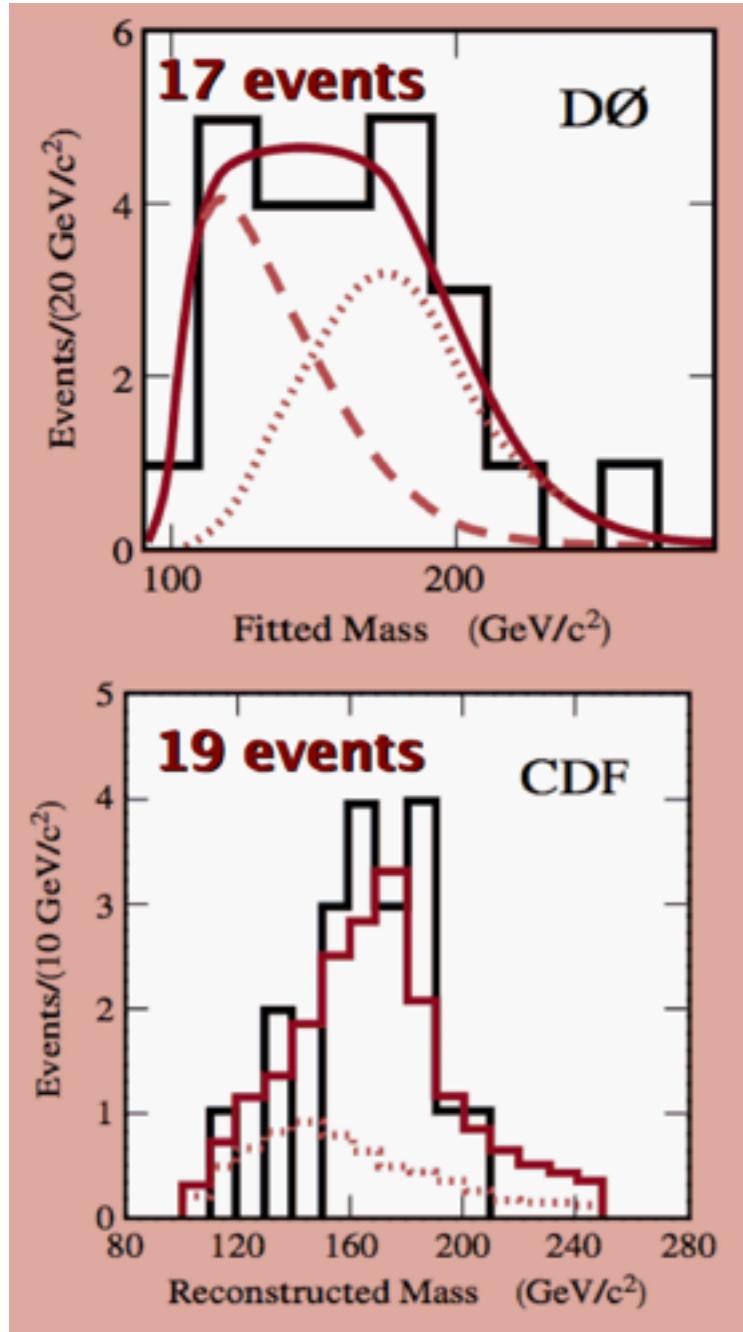
Strong production of top pairs

Top quark mass

Top mass history

First measurements from the top discovery papers

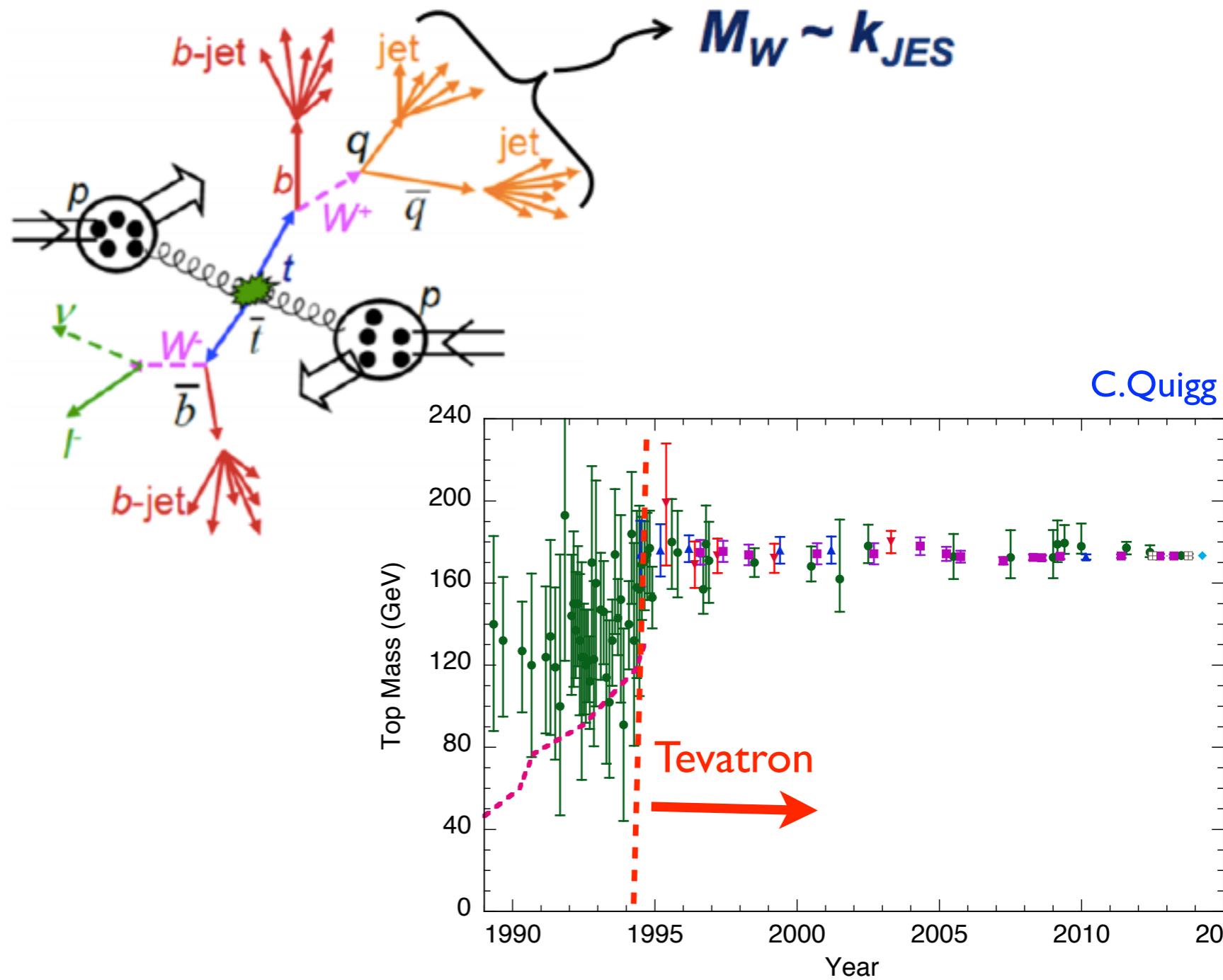
$199^{+19}_{-21}(\text{stat}) \pm 22(\text{syst})$



$176 \pm 8(\text{stat}) \pm 10(\text{syst})$

Breakthrough ideas:

- ▶ matrix element method
- ▶ in-situ JES calibration using hadronic W decay



- General and widely used technique at Tevatron (top mass, W helicity, single top search, top resonance search, A_{FB} dilepton)
- Calculate the event probability on an event-by-event basis:

$$P_{evt} \propto f P_{sig}(m_t) + (1 - f) P_{bgr}$$

$$P_{sig}(m_t) \propto \int \dots d\sigma_{t\bar{t}}(m_t)$$

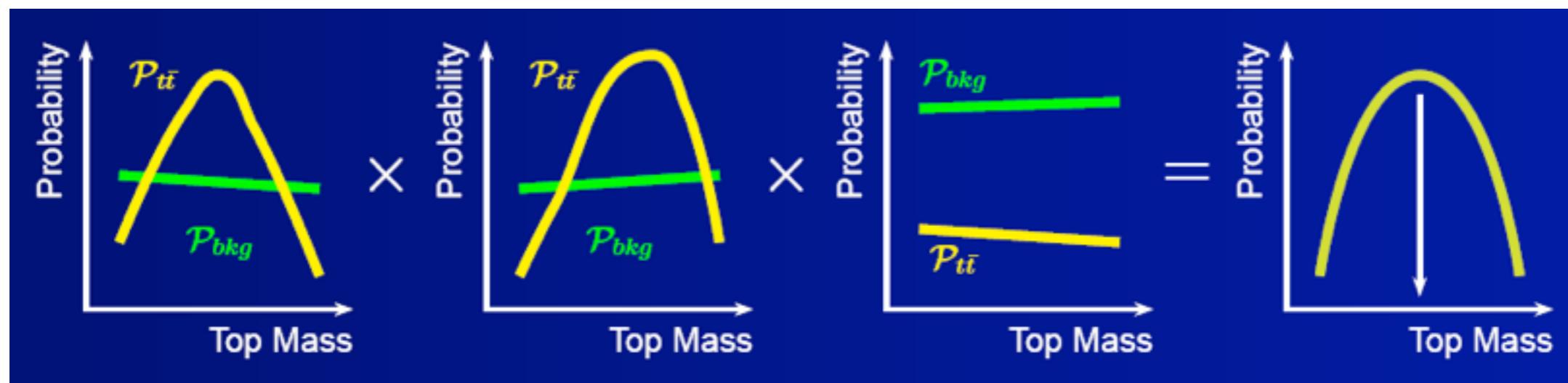
$$d\sigma_{t\bar{t}}(m_t) \propto |\mathcal{M}_{t\bar{t}}|^2(m_t)$$

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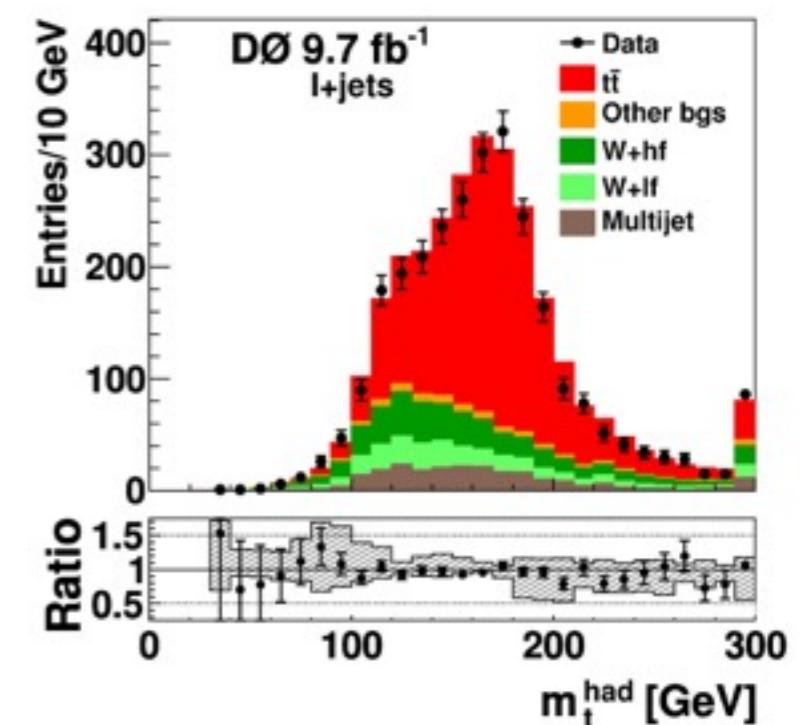
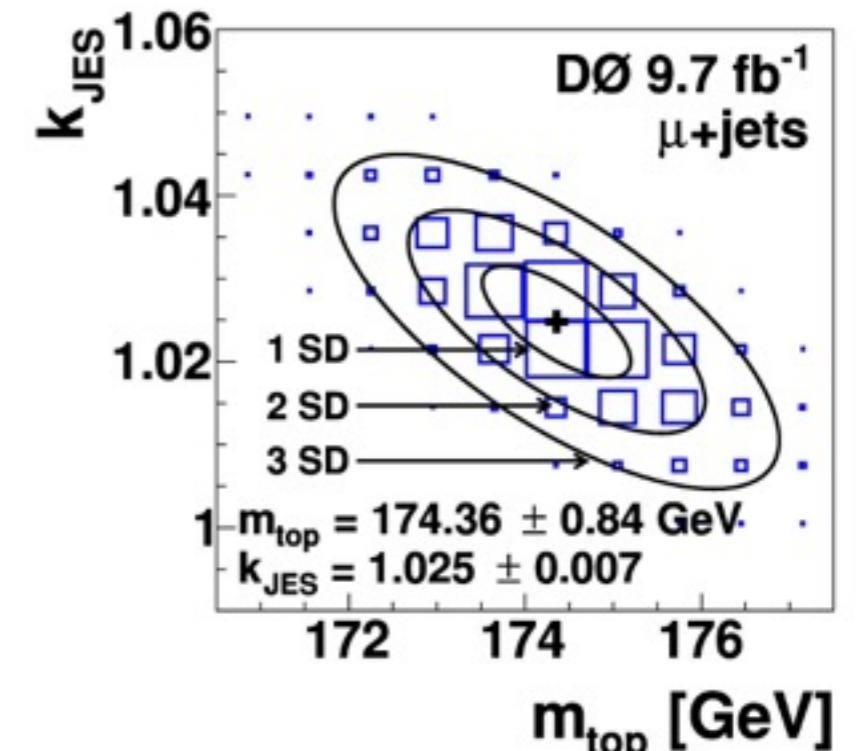
$$d\sigma_{t\bar{t}}(m_t) \propto |\mathcal{M}_{t\bar{t}}|^2(m_t)$$



- Advantages:
 - ▶ Maximal use of kinematic information, thus maximum statistical power
- Disadvantages:
 - ▶ Computationally challenging

Phys. Rev. D 91, 112003 (2015)

- ~2800 events with 4j and ≥ 1 b-tag
 - ▶ 67% purity of top pairs
- Data split into 4 run periods to accurately account for changes in detector response
- ME includes $gg \rightarrow t\bar{t}$ and $qq \rightarrow t\bar{t}$ as well as spin correlations
- 10 dimensional integration
 - ▶ low discrepancy sequences
- In-situ JES calibration
- k_{JES} is factorised from ME calculation
- Reduction of computing time by $\mathcal{O}(100)$
 - ▶ Larger calibration samples
 - ▶ Smaller statistical component of systematics



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The most precise single measurement of top mass

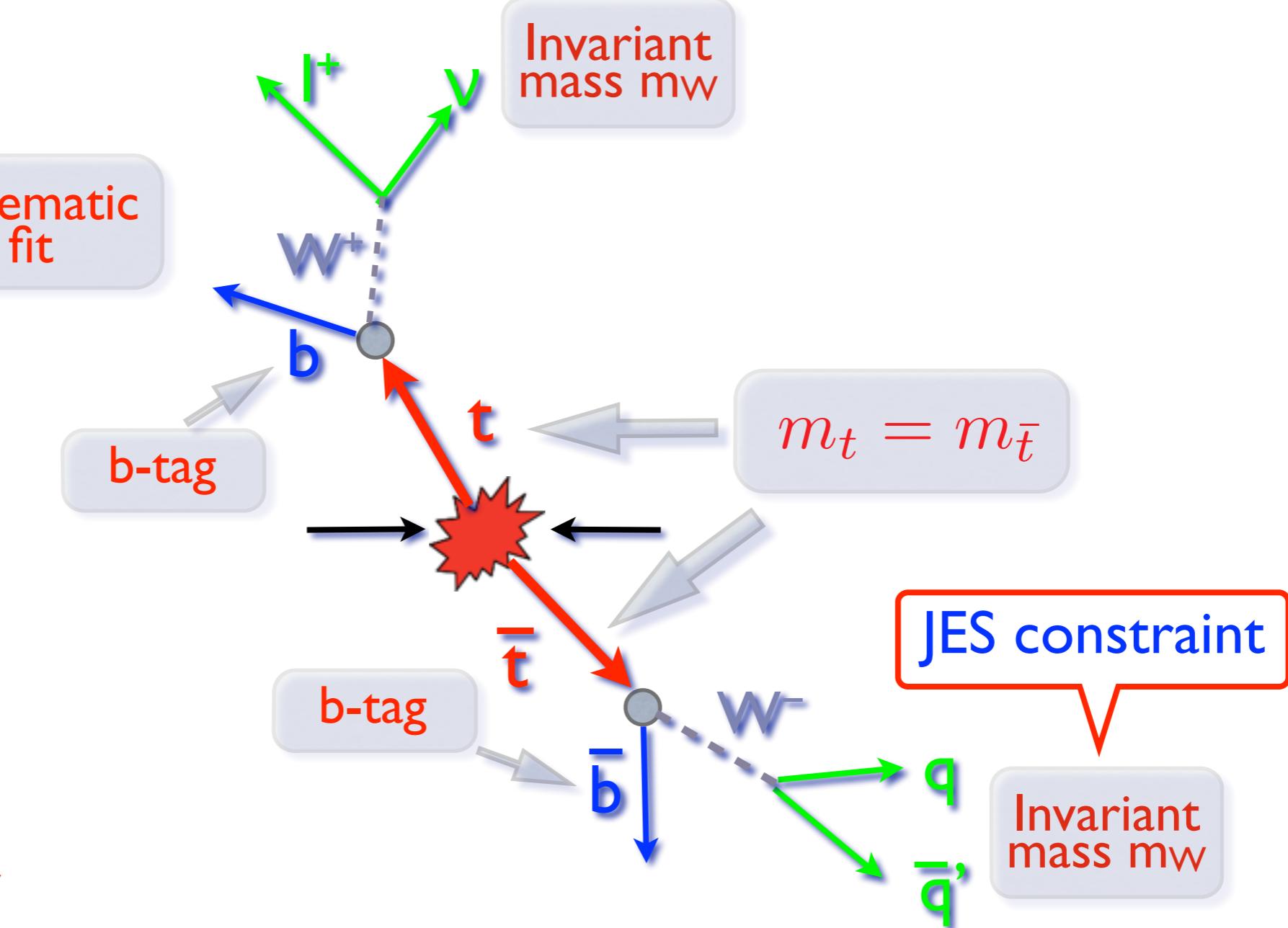
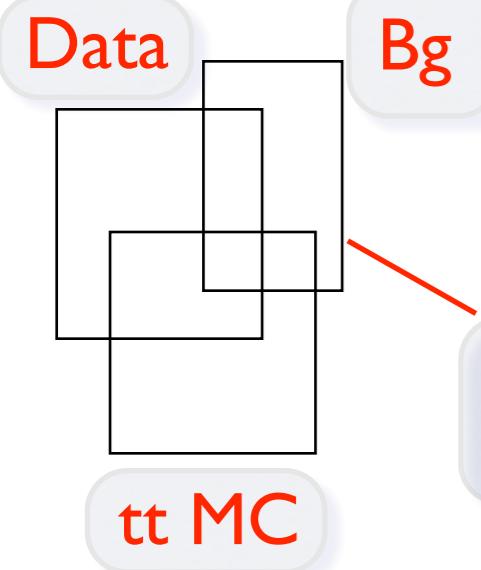
$$m_t = 174.98 \pm 0.41(\text{stat}) \pm 0.41(\text{JES}) \pm 0.49(\text{syst}) \text{ GeV}$$

$$\Delta m_t/m_t = 0.43\%$$

Source of uncertainty	Effect on m_t (GeV)
<i>Signal and background modeling:</i>	
Higher-order corrections	+0.15
Initial/final state radiation	±0.06
Transverse momentum of the $t\bar{t}$ system	-0.07
Hadronization and underlying event	+0.26
Color reconnection	+0.10
Multiple $p\bar{p}$ interactions	-0.06
Heavy-flavor scale factor	±0.06
Modeling of b -quark jet	+0.09
Parton distribution functions	±0.11
<i>Detector modeling:</i>	
Residual jet energy scale	±0.21
Flavor-dependent response to jets	±0.16
Tagging of b jets	±0.10
Trigger	±0.01
Lepton momentum scale	±0.01
Jet energy resolution	±0.07
Jet identification efficiency	-0.01
<i>Method:</i>	
Modeling of multijet events	+0.04
Signal fraction	±0.08
MC calibration	±0.07
<i>Total systematic uncertainty</i>	±0.49
<i>Statistical uncertainty</i>	±0.58
<i>Total uncertainty</i>	±0.76

Mass in all-hadronic and l+jets

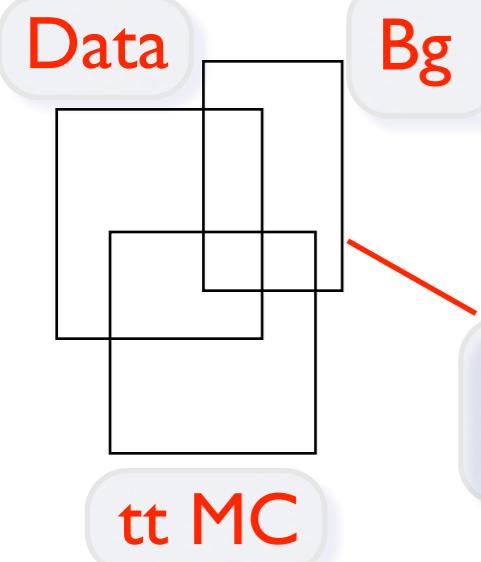
Template method



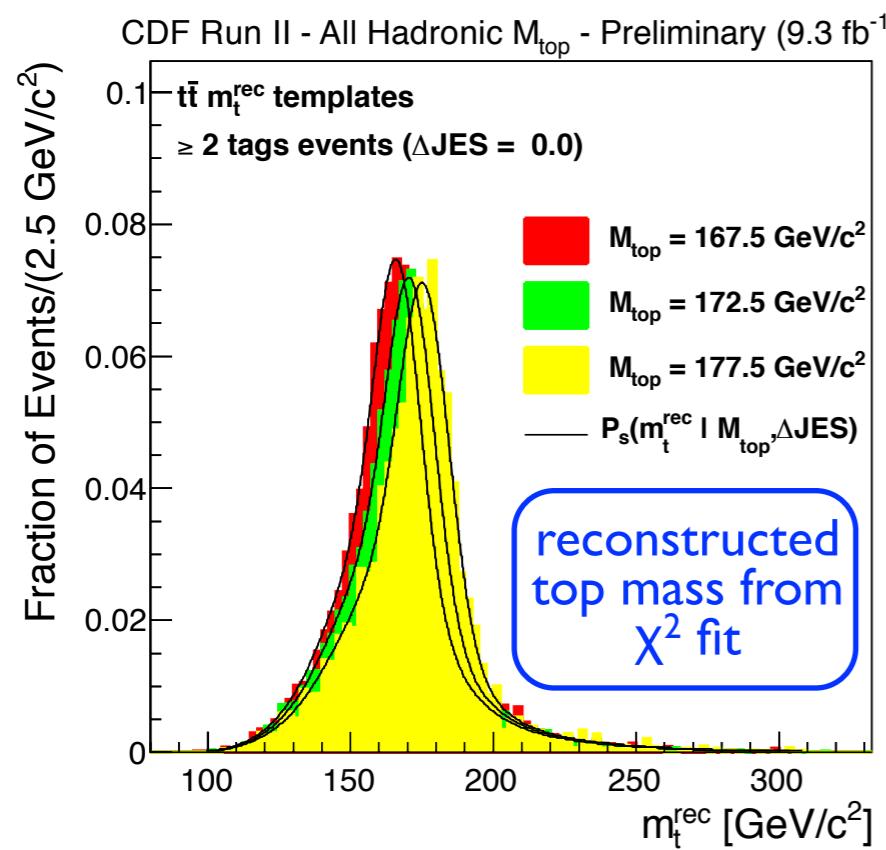
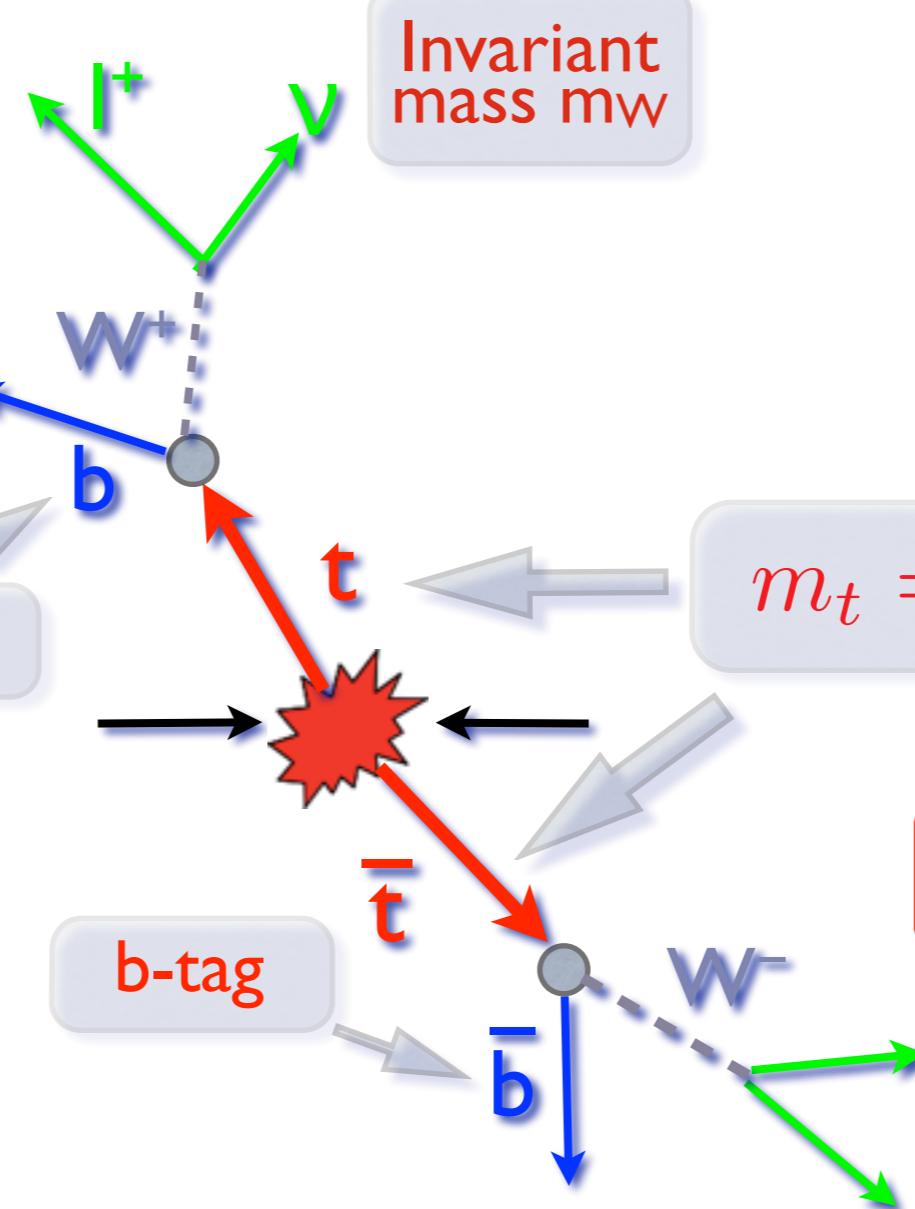
$$\chi^2 = \frac{(m_{jj}^{(1)} - M_W)^2}{\Gamma_W^2} + \frac{(m_{jj}^{(2)} - M_W)^2}{\Gamma_W^2} + \frac{(m_{jjb}^{(1)} - m_t^{rec})^2}{\Gamma_t^2} + \frac{(m_{jjb}^{(2)} - m_t^{rec})^2}{\Gamma_t^2} + \sum_{i=1}^6 \frac{(p_{T,i}^{fit} - p_{T,i}^{meas})^2}{\sigma_i^2}$$

Mass in all-hadronic and l+jets

Template method

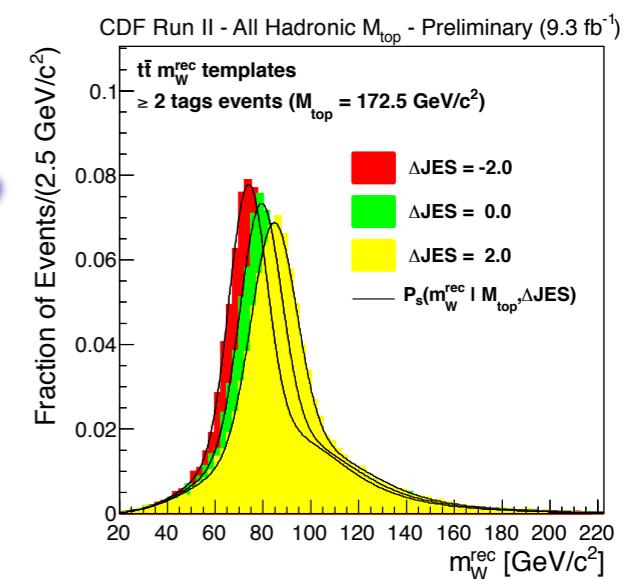


Kinematic fit



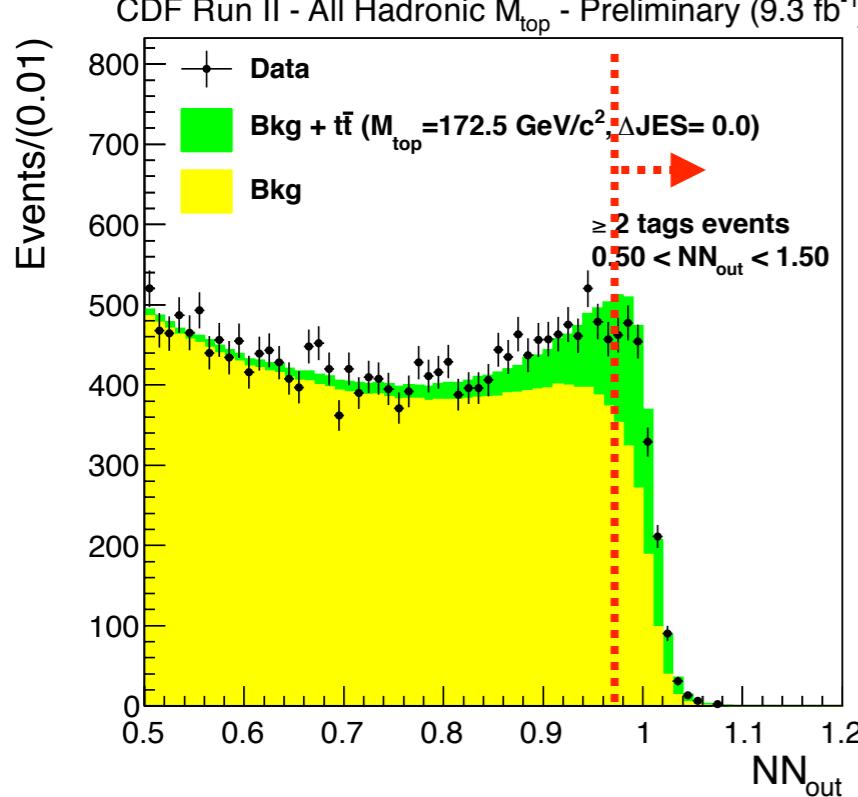
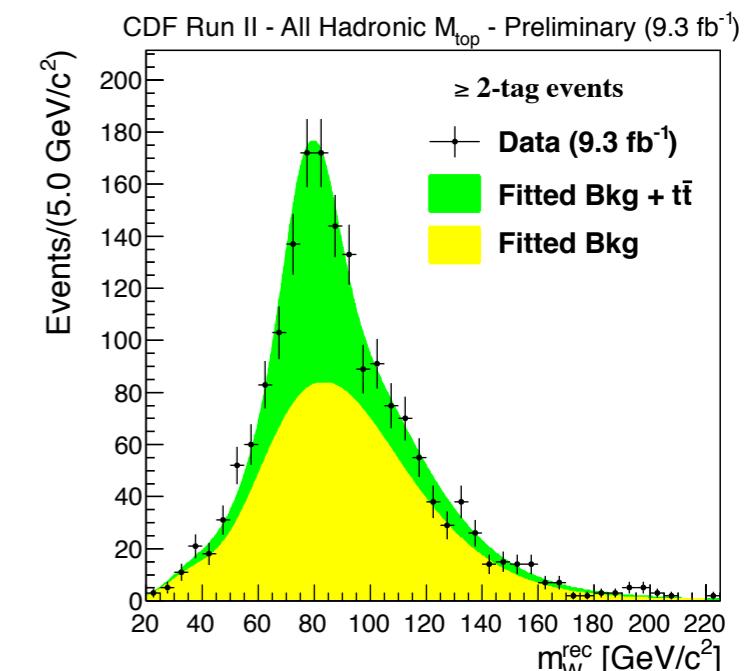
reconstructed W mass from X^2 fit

JES constraint



Result in all-hadronic channel

- Select events with 6 to 8 jets
- 13 variable NN to separate signal from background
- Split sample into 1 and ≥ 2 b-tags
- Final selection: cuts on χ^2 of reconstructed top and W mass and NN output



Sample	N_{obs}	S/B
1-tag	S_{JES}	7890
	$S_{M_{top}}$	4130
≥ 2 -tags	S_{JES}	1758
	$S_{M_{top}}$	901

$$m_t = 175.07 \pm 1.19(\text{stat})^{+1.55}_{-1.58}(\text{syst}) \text{ GeV}$$

$$\Delta m_t / m_t = 1.1\%$$

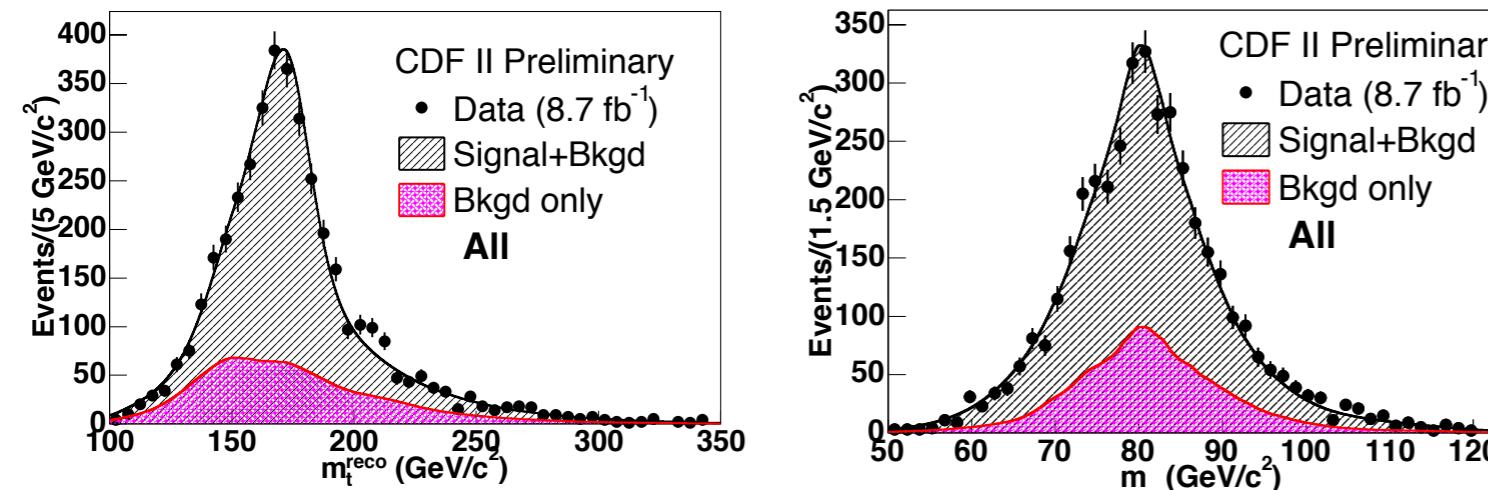
Source	$\sigma_{M_{top}}^{\text{syst}} (\text{GeV}/c^2)$
Residual bias / Calibration	$+0.27$ -0.24
Generator (hadronization)	0.29
Initial / Final State Radiation	0.13
b -jets Energy Scale	0.20
b -tagging	0.04
Residual Jet Energy Scale	0.57
Parton Distribution Functions	$+0.18$ -0.36
Pileup	0.22
Color Reconnections	0.32
Templates Statistics	0.34
Trigger Simulation	0.61
Data Luminosity	0.15
$t\bar{t}$ Cross Section	0.15
Background Shape	0.15
Total	$+1.13$ -1.17

Mass measurements



I+jets channel

- Uses 1st and 2nd best reconstructed mass by χ^2 fit
- Measure JES through dijet mass



Phys. Rev. Lett. 109,
152003 (2012)

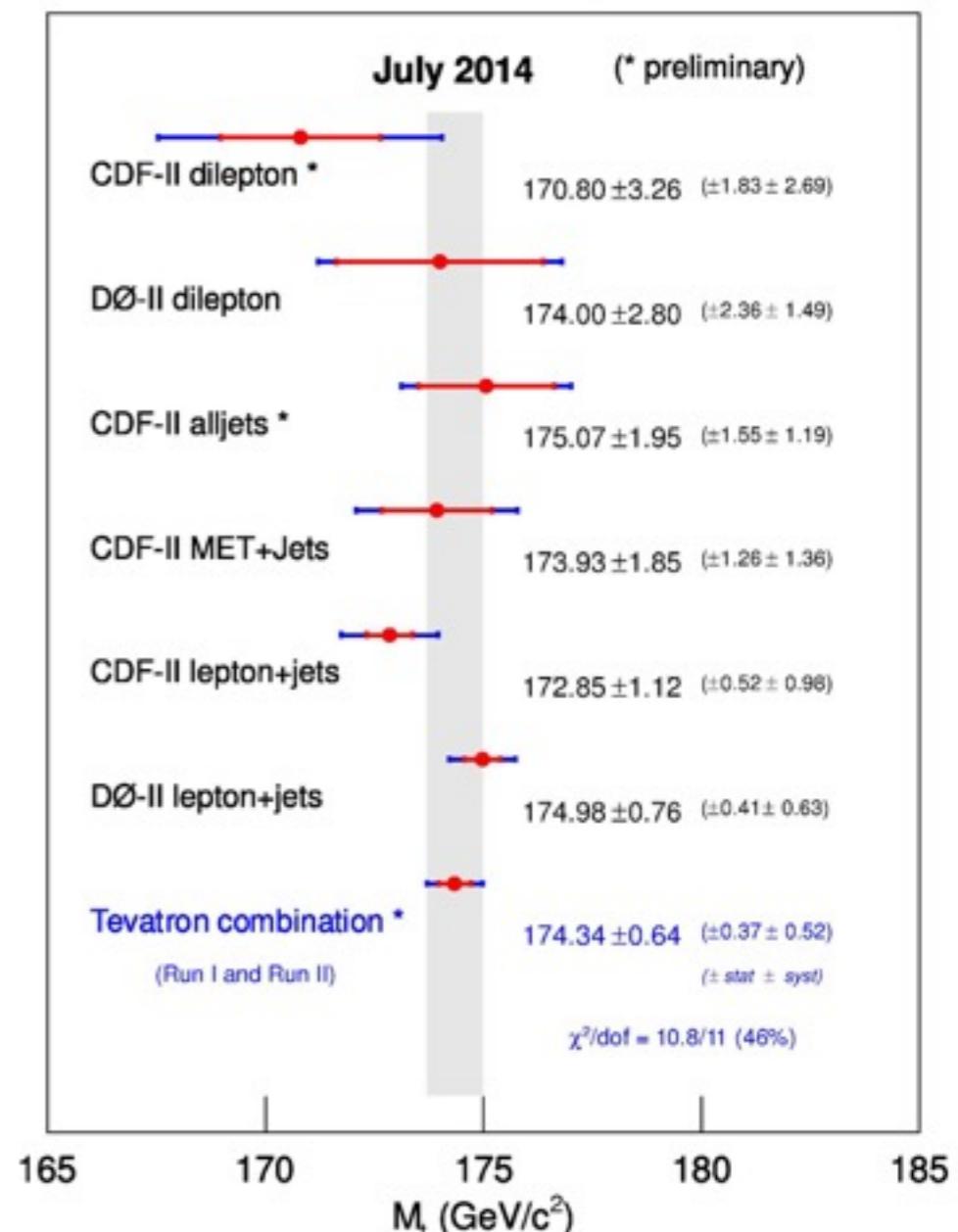
Source	Systematic uncertainty
Residual jet energy scale	0.52
Signal modeling	0.57
<i>b</i> jet energy scale	0.18
<i>b</i> tagging efficiency	0.03
Initial and final state radiation	0.06
Parton distribution functions	0.08
Gluon fusion fraction	0.03
Lepton energy scale	0.03
Background shape	0.20
Multiple hadron interaction	0.07
Color reconnection	0.21
MC statistics	0.05
Total systematic uncertainty	0.85

$$m_t = 172.85 \pm 0.71(\text{stat + JES}) \pm 0.85(\text{syst}) \text{ GeV}$$

$$\Delta m_t/m_t = 0.64\%$$

Tevatron mass combination

Mass of the Top Quark



$$m_t = 174.34 \pm 0.64(\text{total}) \text{ GeV}$$

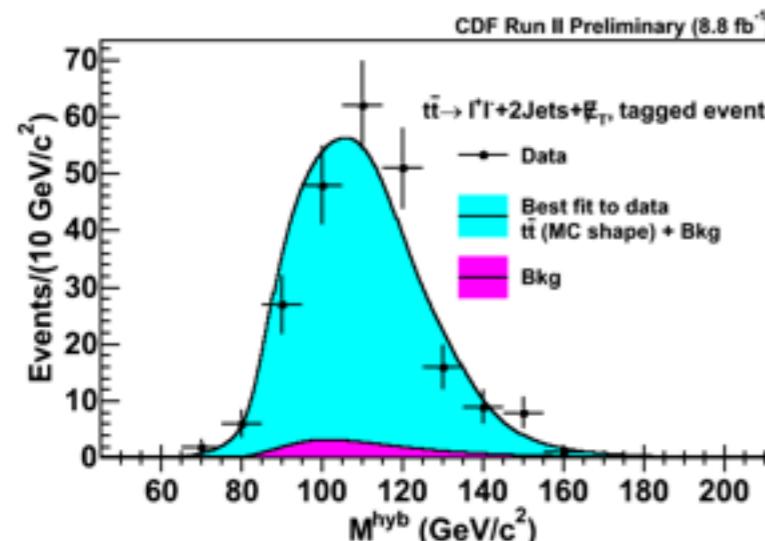
$$\Delta m_t/m_t = 0.37\%$$

Dilepton channel

arXiv:1508.03322v2



- Neutrino Weighting method
 - Assign a weight based on agreement between the calculated neutrino p_T and the measured missing E_T
 - $w(m_t) \rightarrow \mu_w, \sigma_w$
- Optimised to minimise statistical uncertainty
 - Selection (565/495 data/top events)
 - Parameters of the method
- JES calibration from l+jets channel

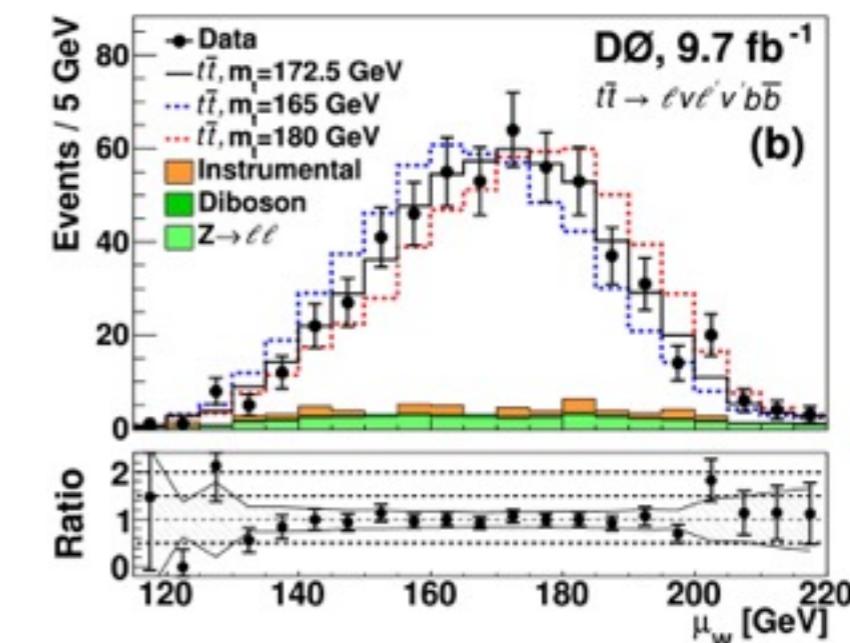


520 data events,
400 top pairs

- $M_{\text{hyb}} = \text{weighted sum of reconstructed mass and a variable insensitive to JES}$

$$m_t = 171.46 \pm 1.91(\text{stat}) \pm 2.51(\text{syst}) \text{ GeV}$$

PRD 92 032003



Source	σ_{m_t} [GeV]
Jet energy calibration	
Absolute scale	± 0.47
Flavor dependence	± 0.27
Residual scale	$+0.36$ -0.35
b quark fragmentation	$+0.10$
Signal modeling	
Higher-order effects	-0.33
ISR/FSR	± 0.15
$p_T(t\bar{t})$	-0.07
Hadronization	-0.11
Color reconnection	-0.22
Multiple $p\bar{p}$ interactions	-0.06
PDF uncertainty	± 0.08

$$m_t = 173.32 \pm 1.36(\text{stat}) \pm 0.85(\text{syst}) \text{ GeV}$$

relative systematic uncertainty

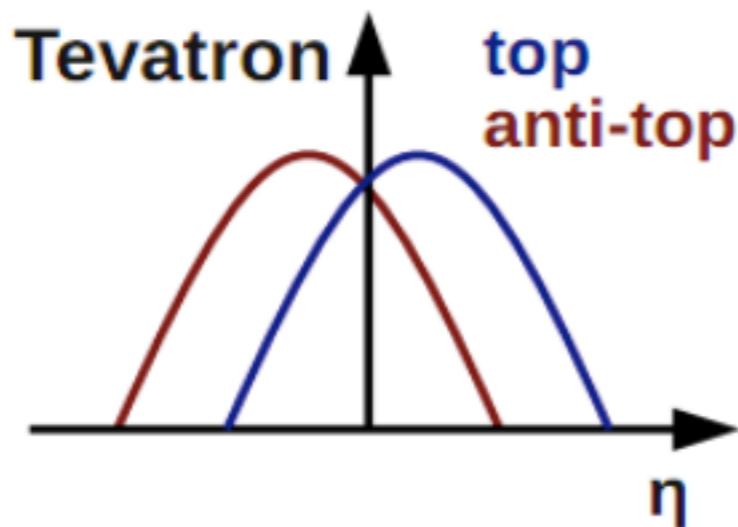
$$\Delta m_t^{\text{syst}} / m_t = 0.49\%$$

Strong production of top pairs

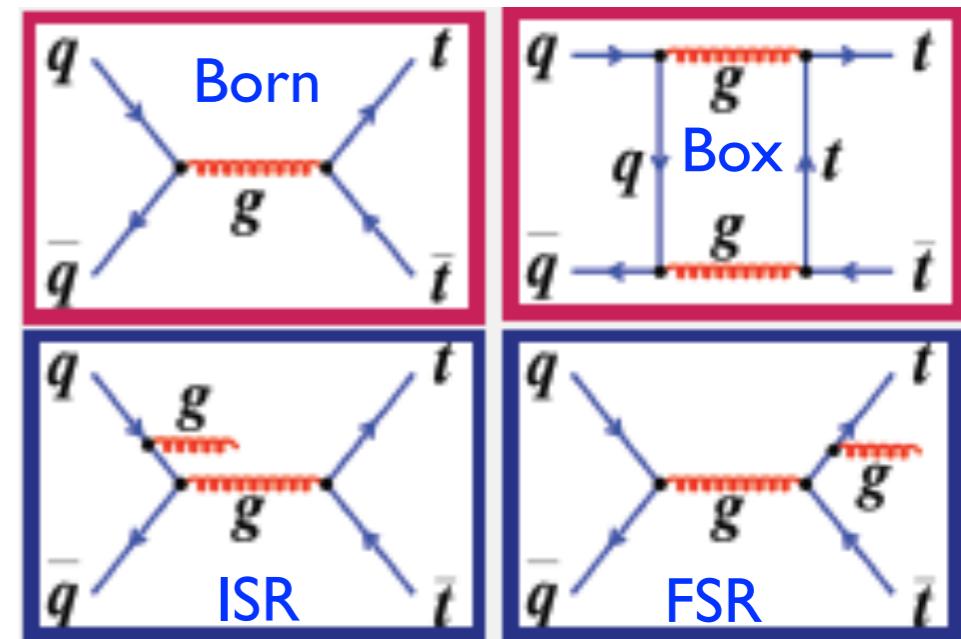
Asymmetries in production
top quark pairs
bottom quark pairs

Asymmetry in production

- Asymmetry for $t\bar{t}$ produced via $q\bar{q}$ initial state (NLO)
 - ▶ Top quarks are emitted preferably in the direction of incoming quark, anti-tops - in the direction of incoming anti-quark



- ▶ In SM predicted asymmetry is small
- ▶ Exchange of new particles (Z' or axigluon) could modify it
- ▶ Much smaller effect at LHC due to small $q\bar{q}$ fraction

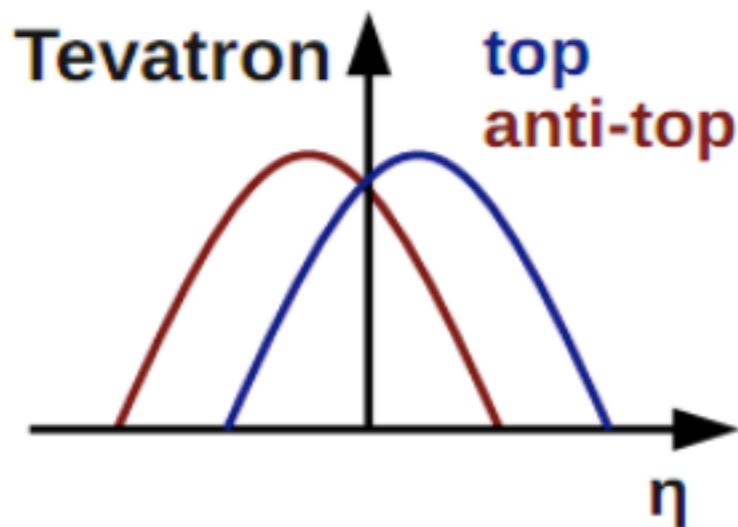


Theory prediction: $(9.5 \pm 0.7)\%$
NNLO+EW corrections

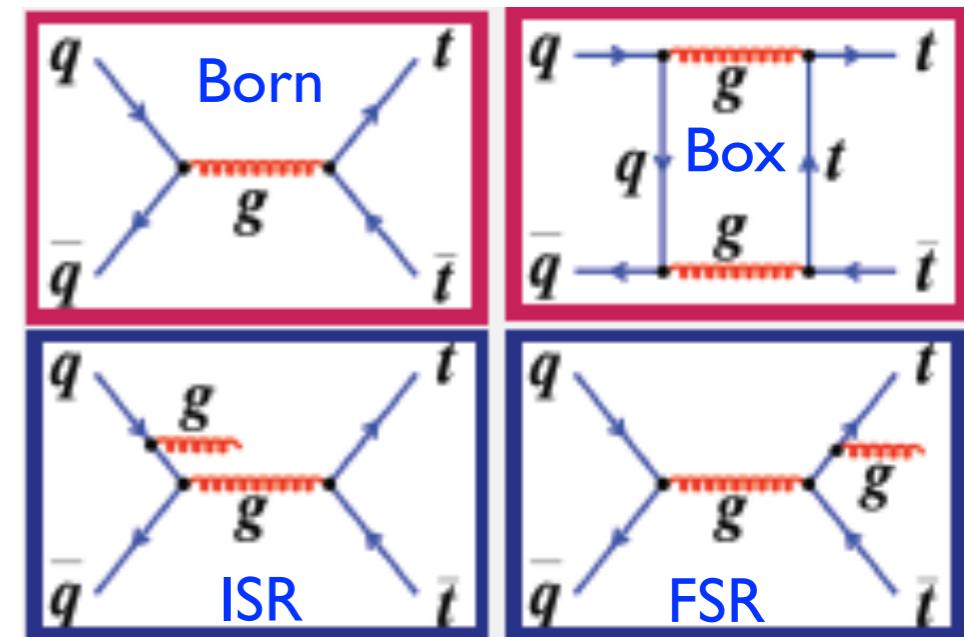
arXiv:1411.3007

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Theory prediction: $(9.5 \pm 0.7)\%$
NNLO+EW corrections

- Observables:
 - ▶ lepton asymmetries

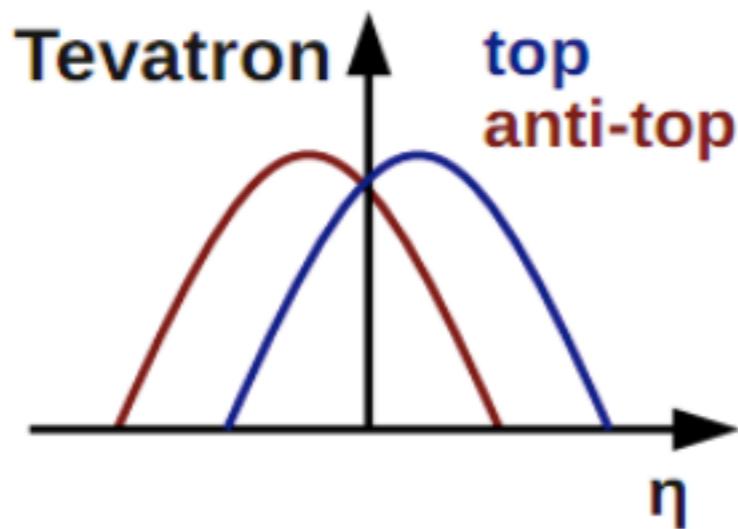
$$A_{FB}^\ell = \frac{N(q_\ell \eta_\ell > 0) - N(q_\ell \eta_\ell < 0)}{N(q_\ell \eta_\ell > 0) + N(q_\ell \eta_\ell < 0)}$$

$$A^{\ell\ell} = \frac{N(\Delta\eta > 0) - N(\Delta\eta < 0)}{N(\Delta\eta > 0) + N(\Delta\eta < 0)},$$

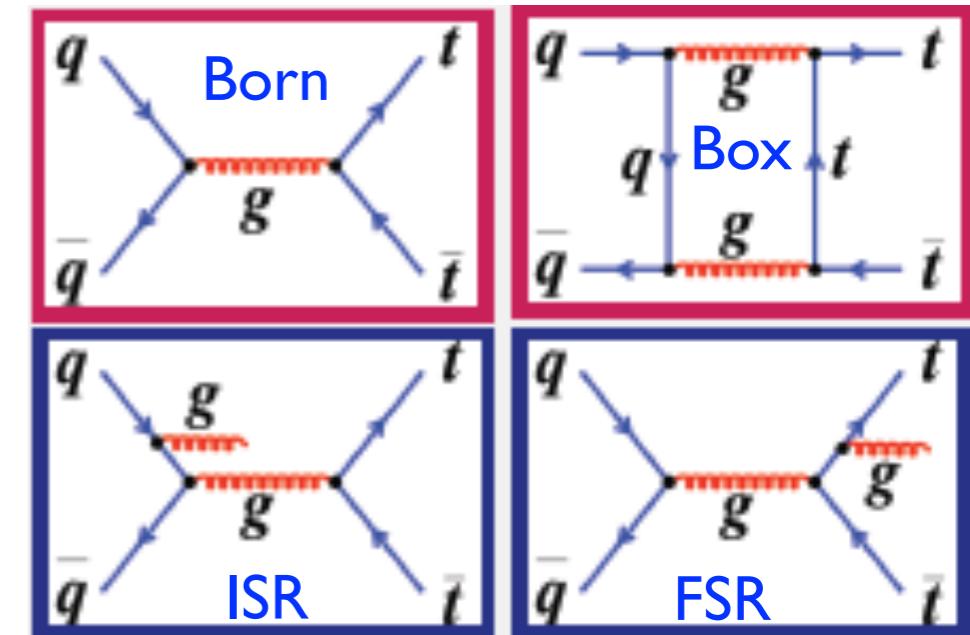
$$\Delta\eta = \eta_1^\ell - \eta_2^\ell$$

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- Asymmetry for $t\bar{t}$ produced via $q\bar{q}$ initial state (NLO)
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Theory prediction: $(9.5 \pm 0.7)\%$
NNLO+EW corrections

- Observables:
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$$A_{FB}^\ell = \frac{N(q_\ell \eta_\ell > 0) - N(q_\ell \eta_\ell < 0)}{N(q_\ell \eta_\ell > 0) + N(q_\ell \eta_\ell < 0)}$$

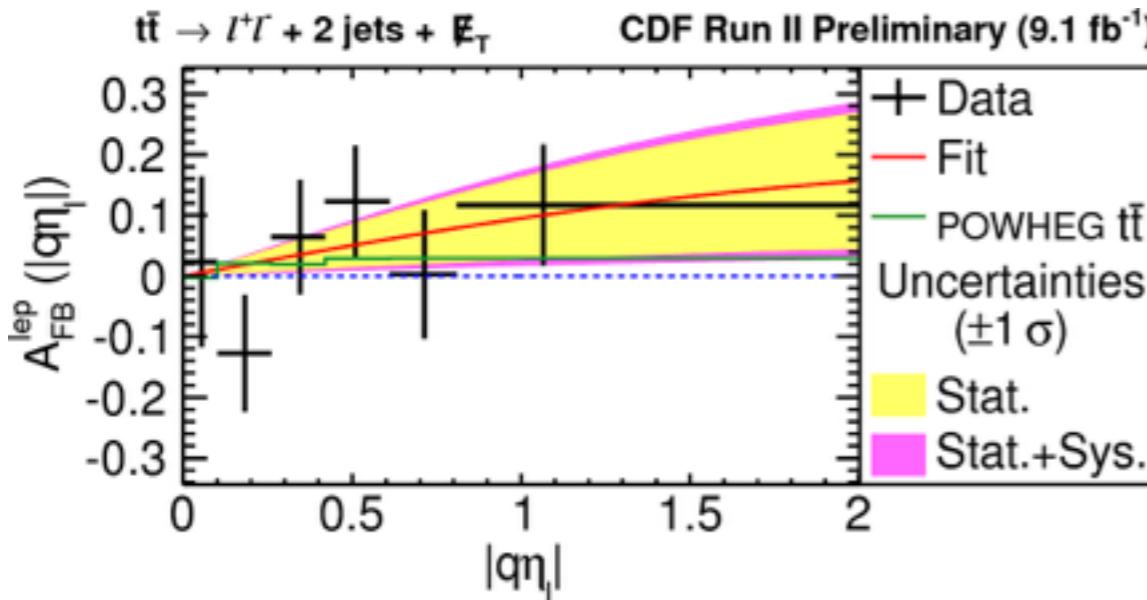
$$A^{\ell\ell} = \frac{N(\Delta\eta > 0) - N(\Delta\eta < 0)}{N(\Delta\eta > 0) + N(\Delta\eta < 0)},$$

$$\Delta\eta = \eta_1^\ell - \eta_2^\ell$$

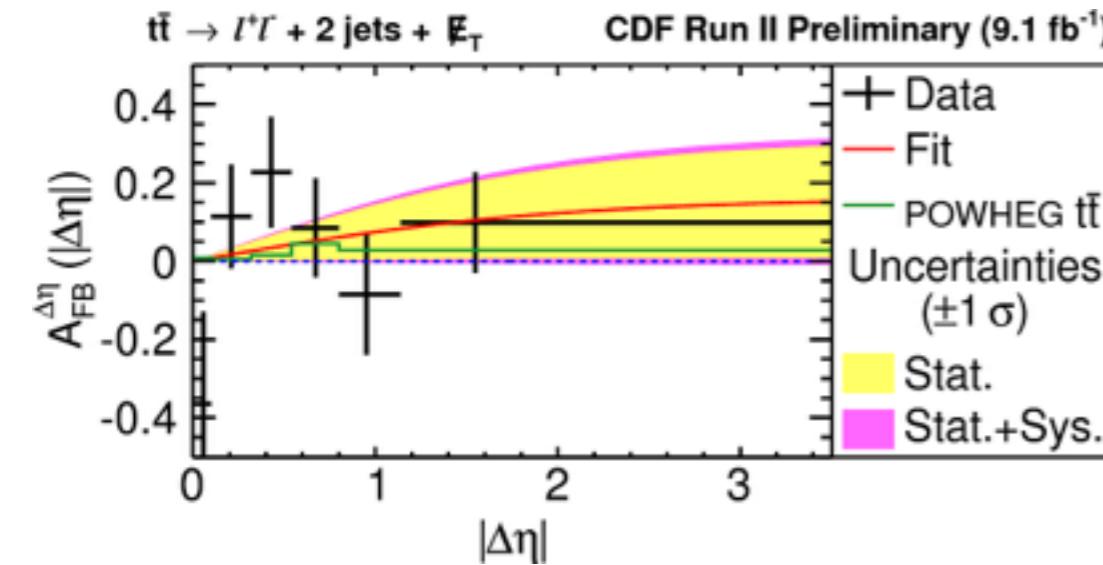
- ▶ forward-backward asymmetry $A^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$, $\Delta y = y_t - y_{\bar{t}}$

Leptonic asymmetries

Dilepton channel

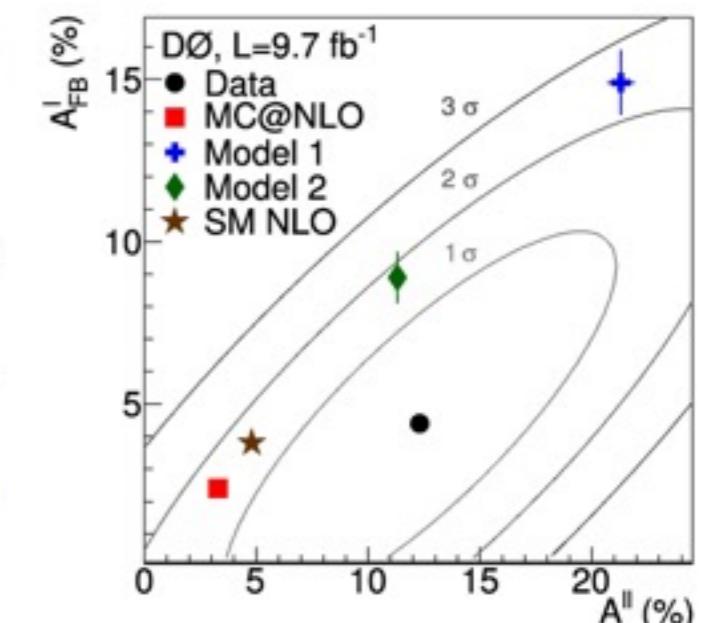
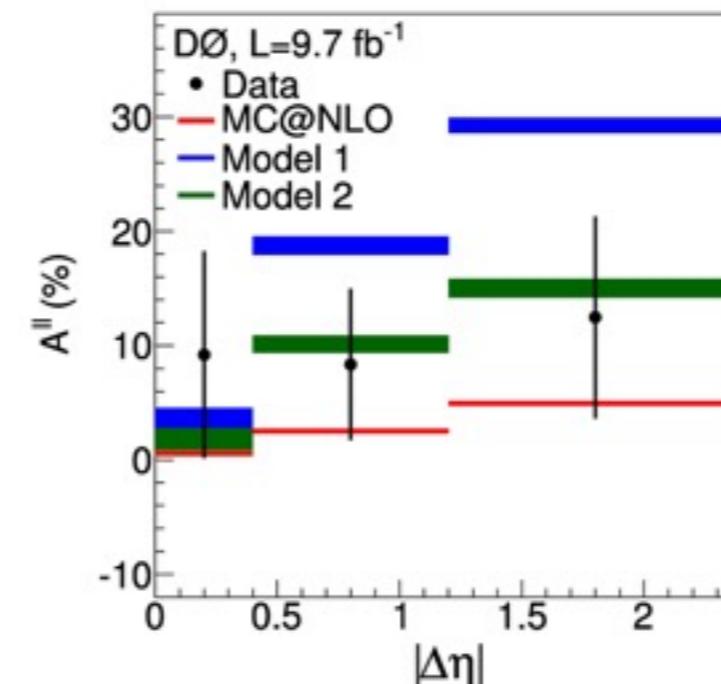
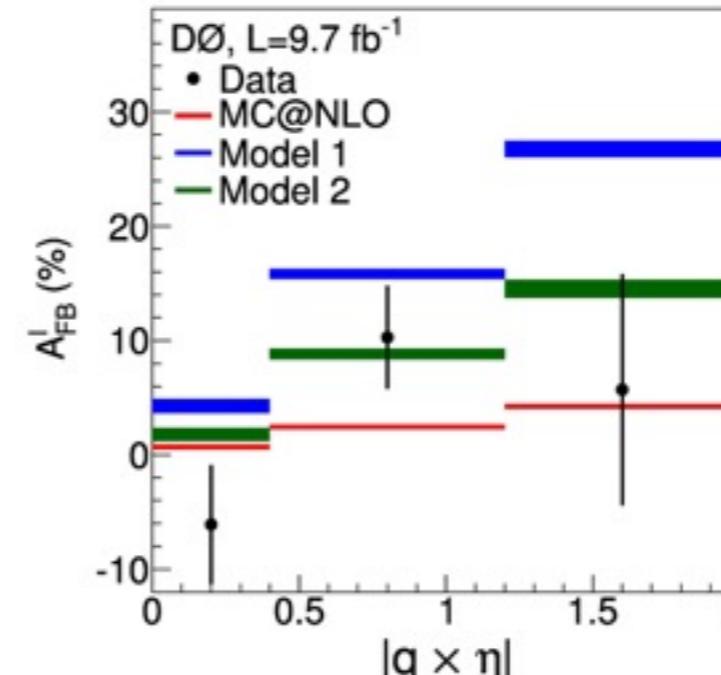


$$A_{FB}^\ell = (7.2 \pm 6.0)\%$$



$$A^{\ell\ell} = (7.6 \pm 8.2)\%$$

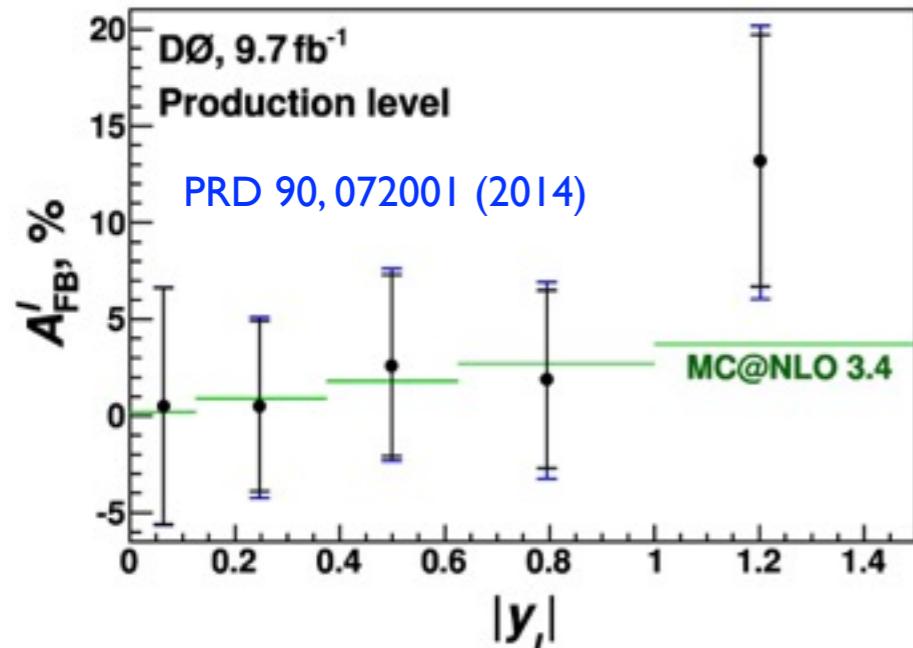
PRL 113, 042001 (2014)



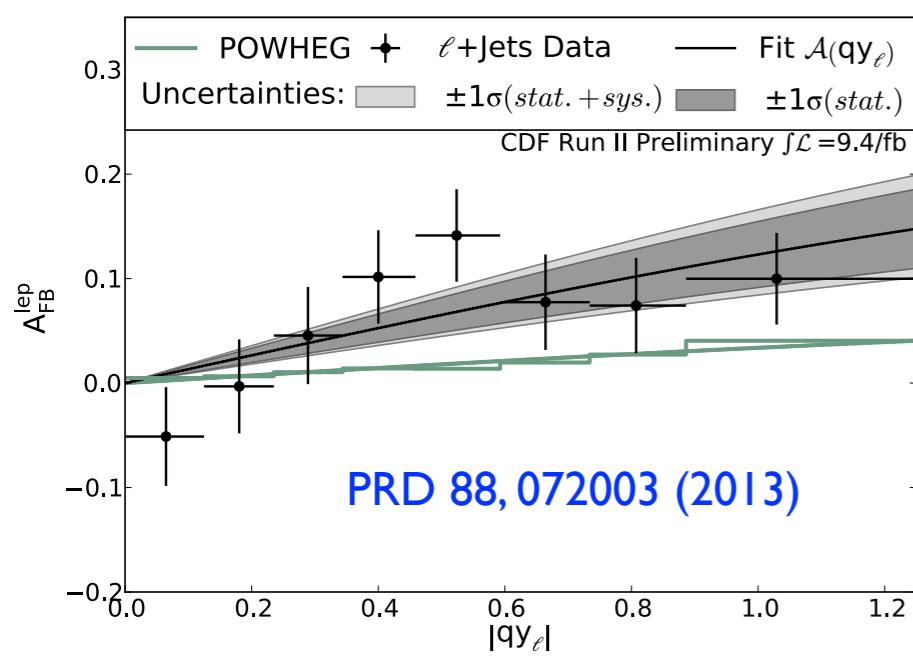
PRD 88, 112002 (2013)

Consistent with
NLO calculation

Lepton+jets channel

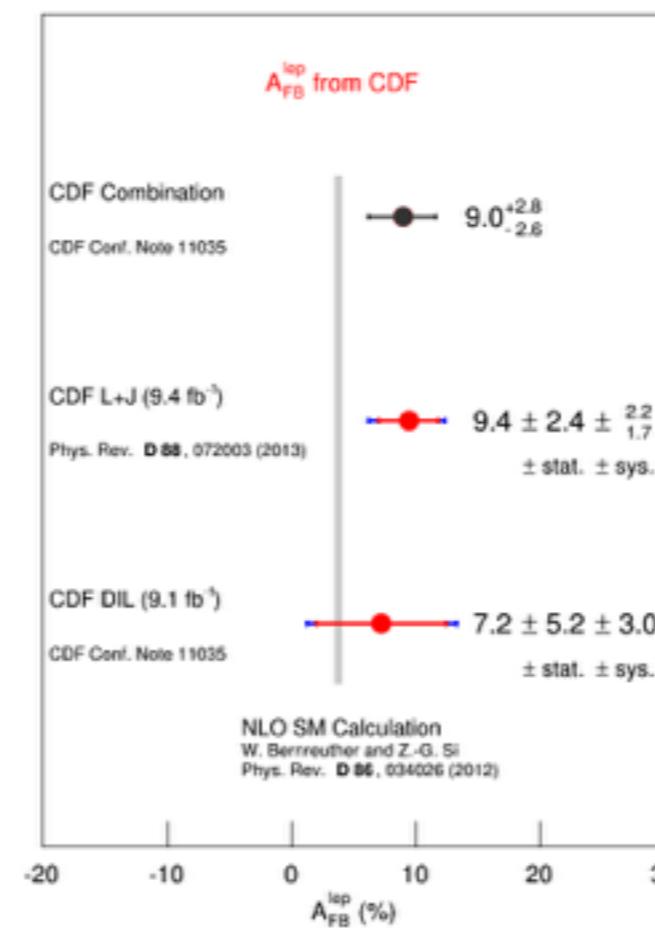


$$A_{FB}^\ell = (4.2^{+2.9}_{-3.0})\%, |y_\ell| < 1.5$$



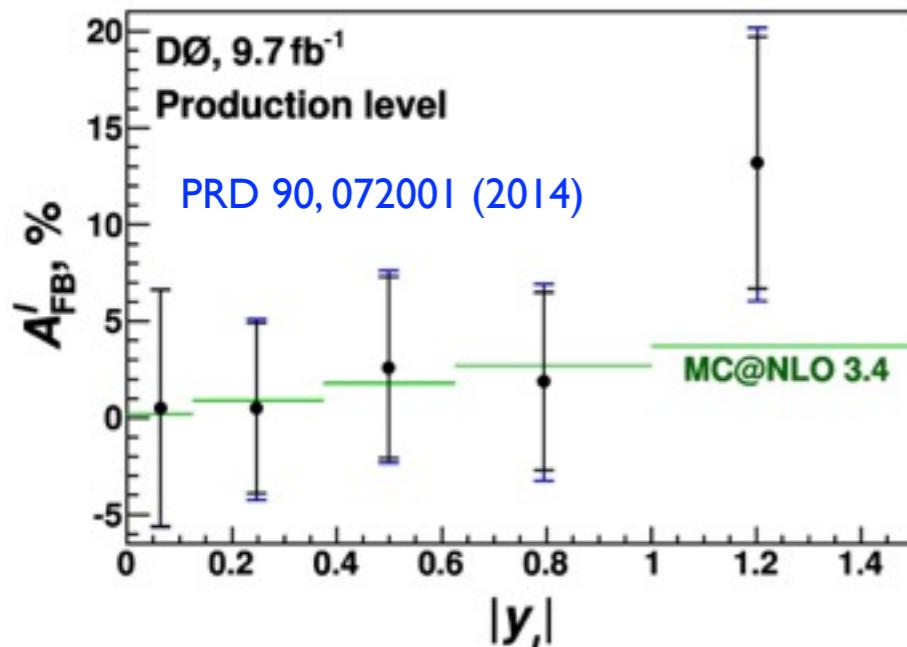
Combined with
dilepton channel

$$A_{FB}^\ell = (4.2 \pm 2.4)\%
|y_\ell| < 1.5$$

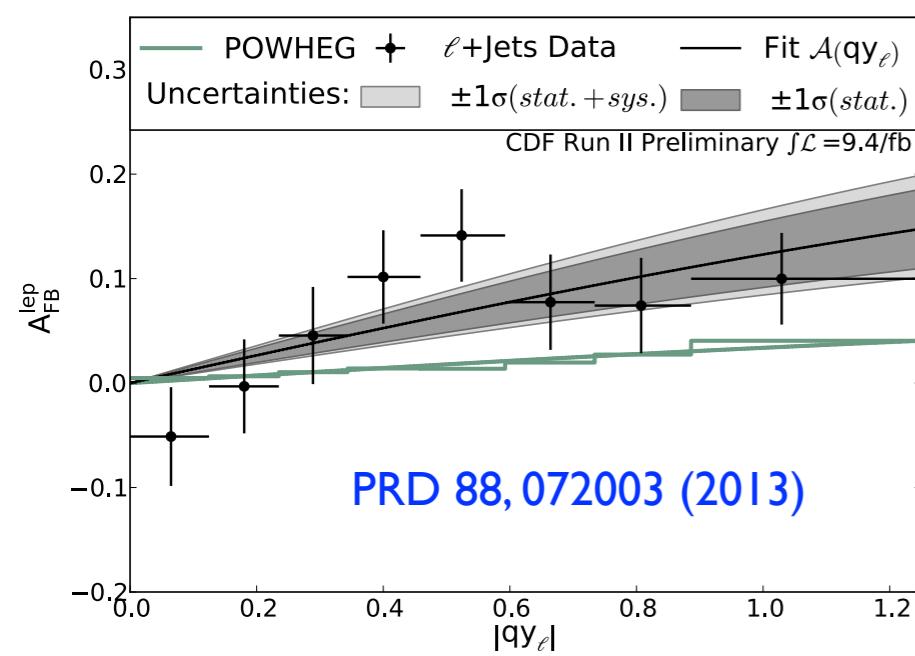


Leptonic asymmetries

Lepton+jets channel

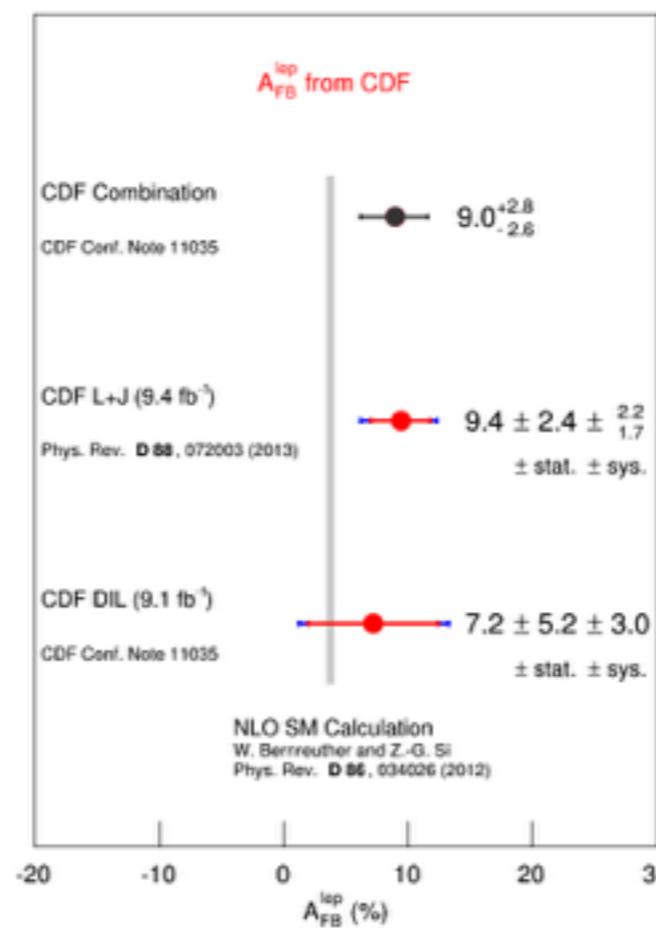


$$A'_{FB} = (4.2^{+2.9}_{-3.0})\%, |y_\ell| < 1.5$$

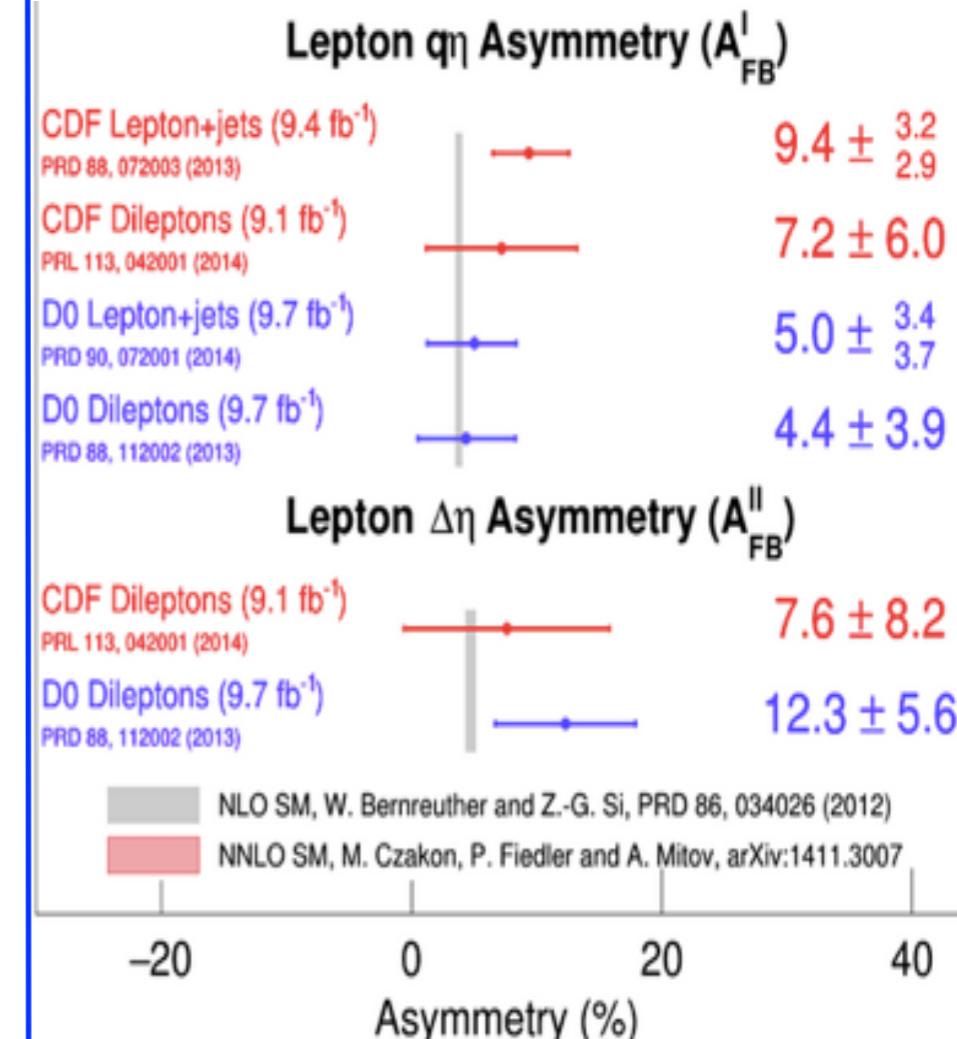


Combined with
dilepton channel

$$A'_{FB} = (4.2 \pm 2.4)\% \quad |y_\ell| < 1.5$$

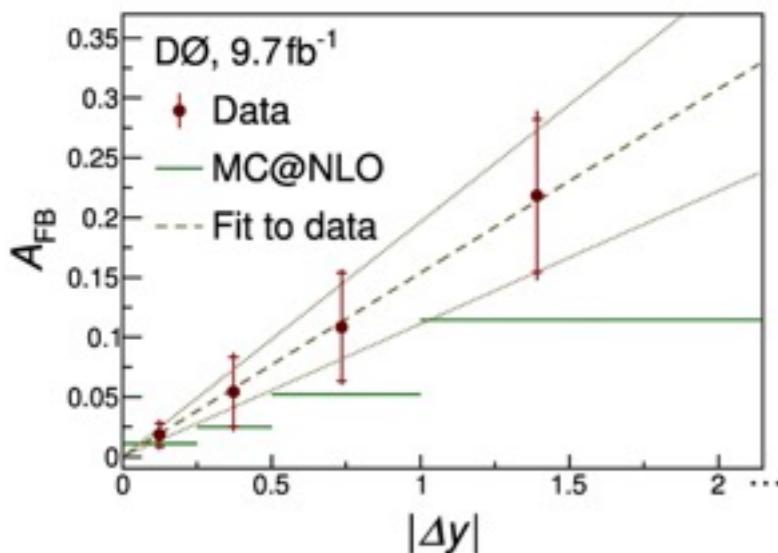


Summary of all measurements



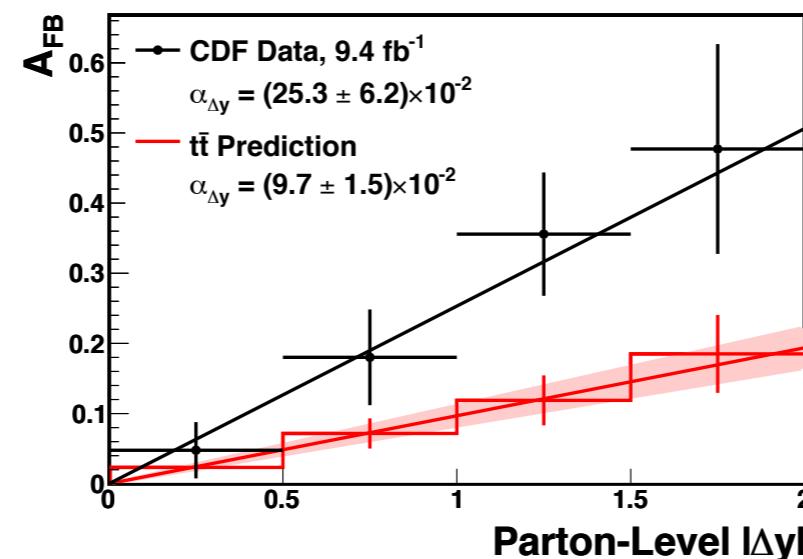
Consistent with
NLO calculation

$$A^{t\bar{t}} = (10.6 \pm 3.0)\%$$



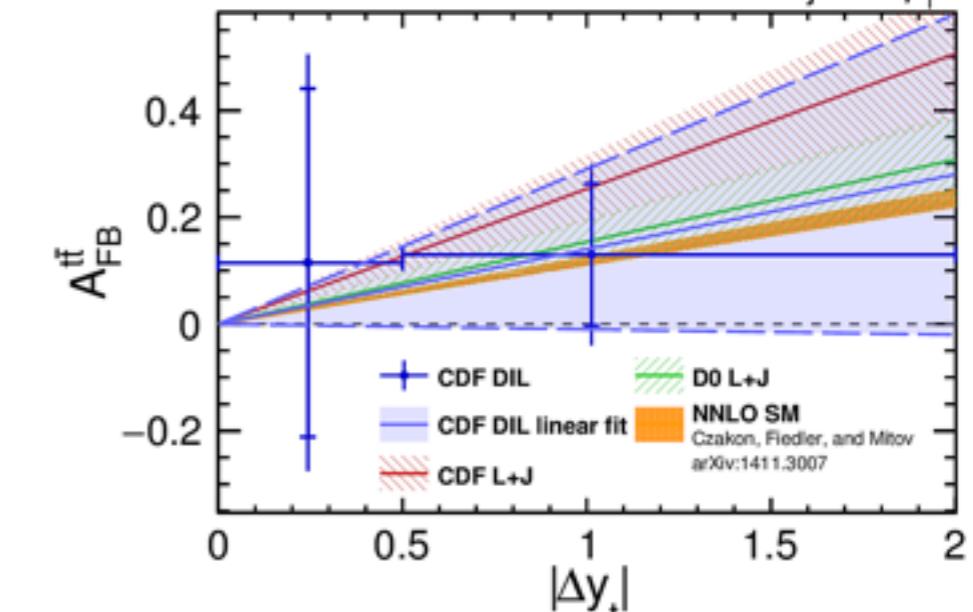
PRD 90 , 072011 (2014)

$$A^{t\bar{t}} = (16.4 \pm 4.7)\%$$



PRD 87 092002 (2013)

Conf. Note 11161
CDF Run II Preliminary (9.1 fb^{-1})
 $t\bar{t} \rightarrow l^+l^- + 2 \text{ jets} + E_T$



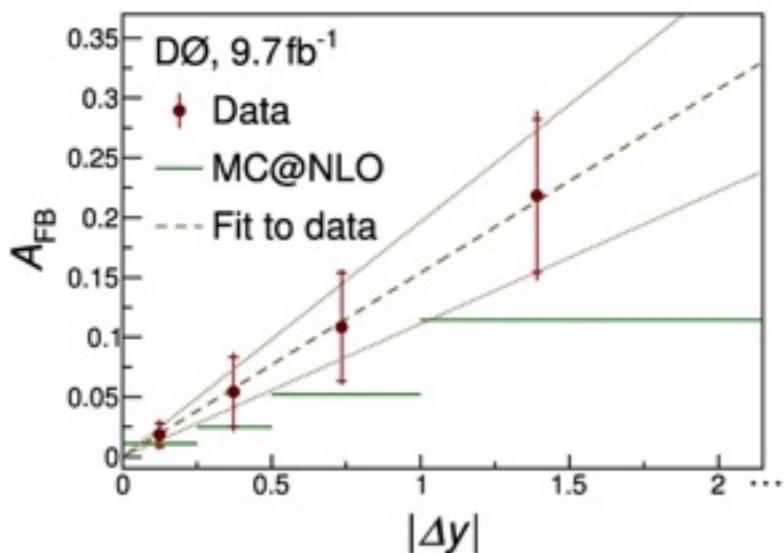
Tevatron $A_{FB}^{t\bar{t}}$ vs. $|\Delta y|$ slope α

CDF Lepton+jets (9.4 fb^{-1}) PRD 87, 092002 (2013)	0.253 ± 0.062
CDF Dilepton (9.1 fb^{-1}) CDF Public Note 11161	0.140 ± 0.150
CDF combination (9.4 fb^{-1}) CDF Public Note 11161	0.227 ± 0.057
D0 Lepton+jets (9.7 fb^{-1}) PRD 90, 072011 (2014)	0.154 ± 0.043

NNLO SM, M. Czakon, P. Fiedler and A. Mitov, arXiv:1411.3007 & private comm.

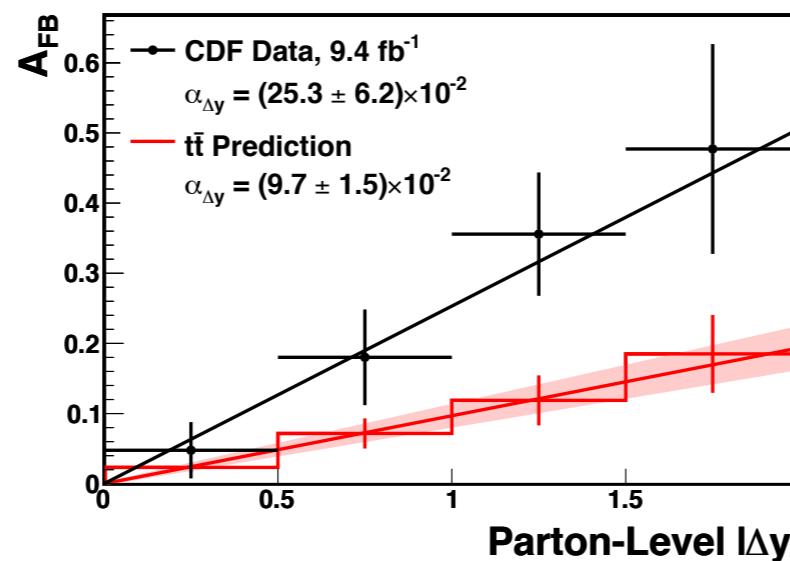


$$A^{t\bar{t}} = (10.6 \pm 3.0)\%$$

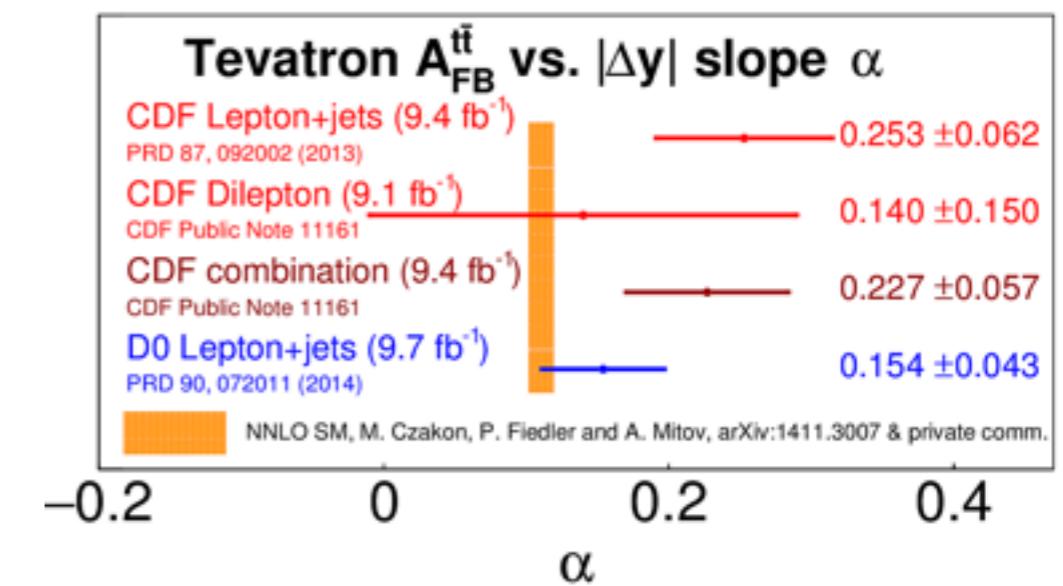
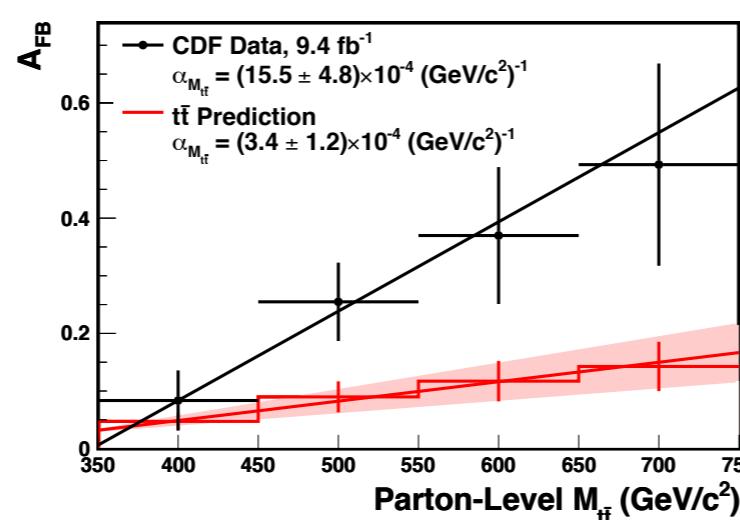
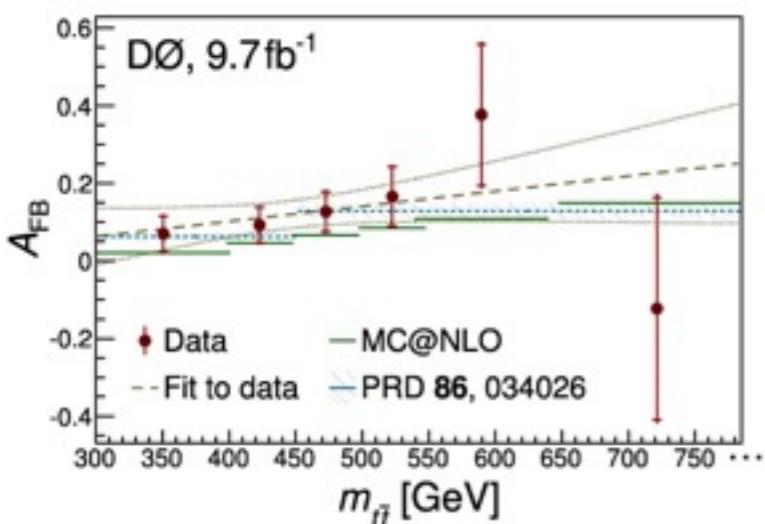
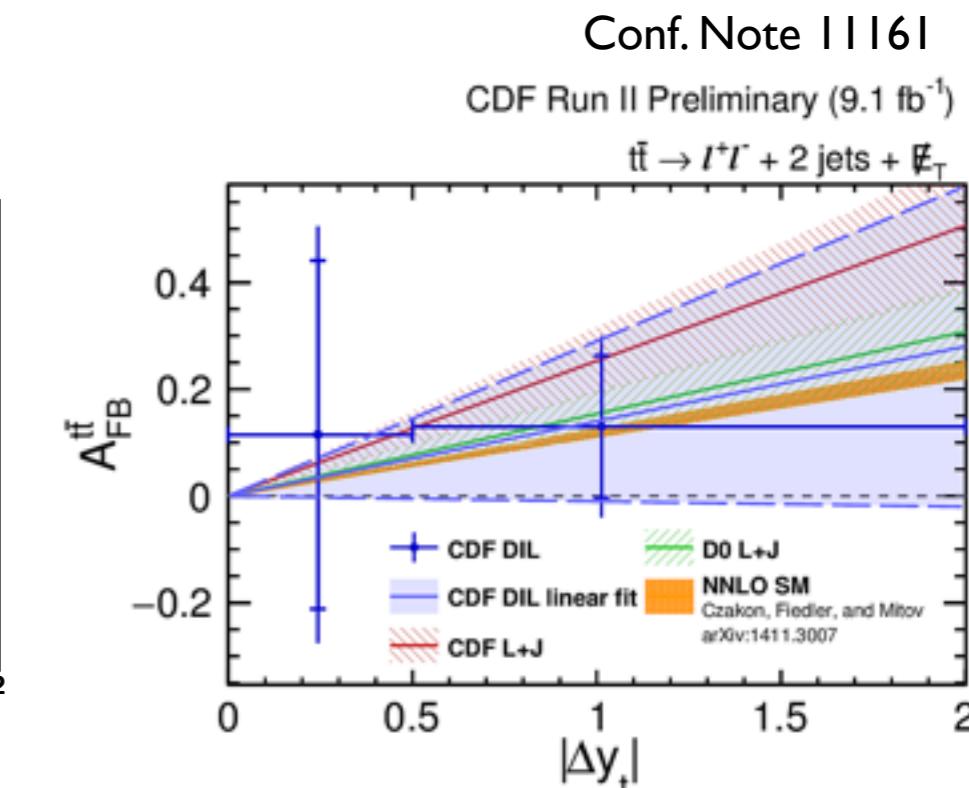


PRD 90, 072011 (2014)

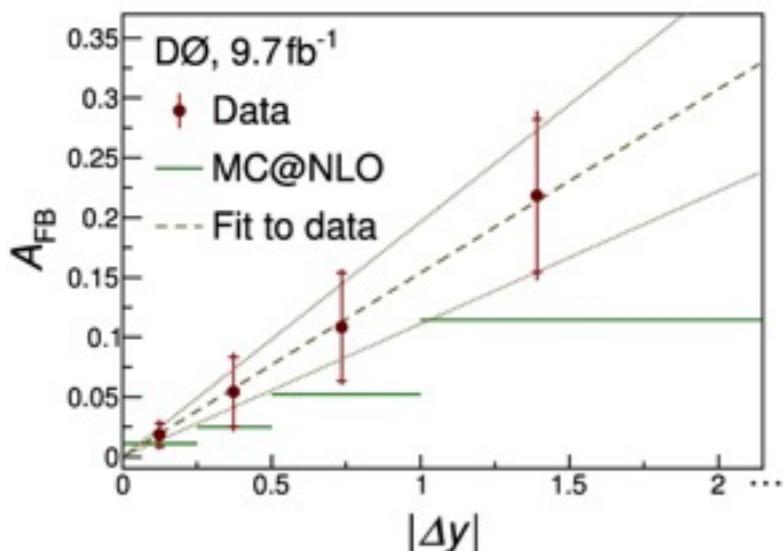
$$A^{t\bar{t}} = (16.4 \pm 4.7)\%$$



PRD 87 092002 (2013)

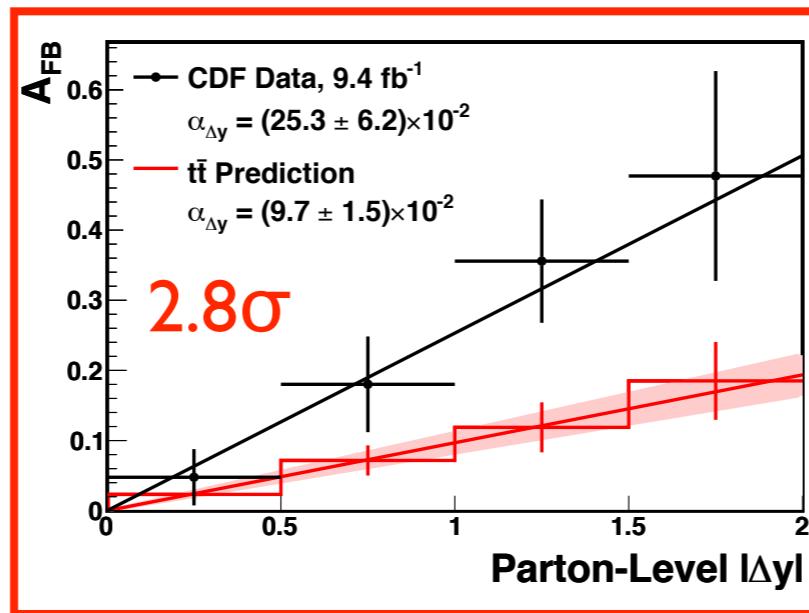


$$A^{t\bar{t}} = (10.6 \pm 3.0)\%$$



PRD 90, 072011 (2014)

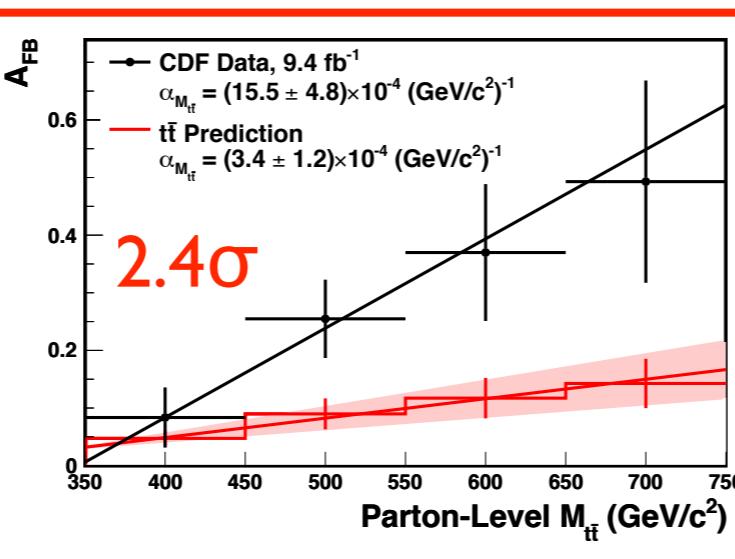
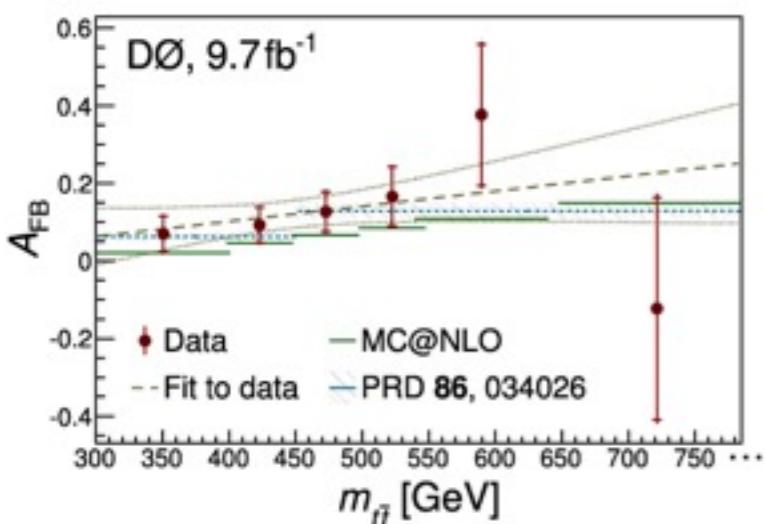
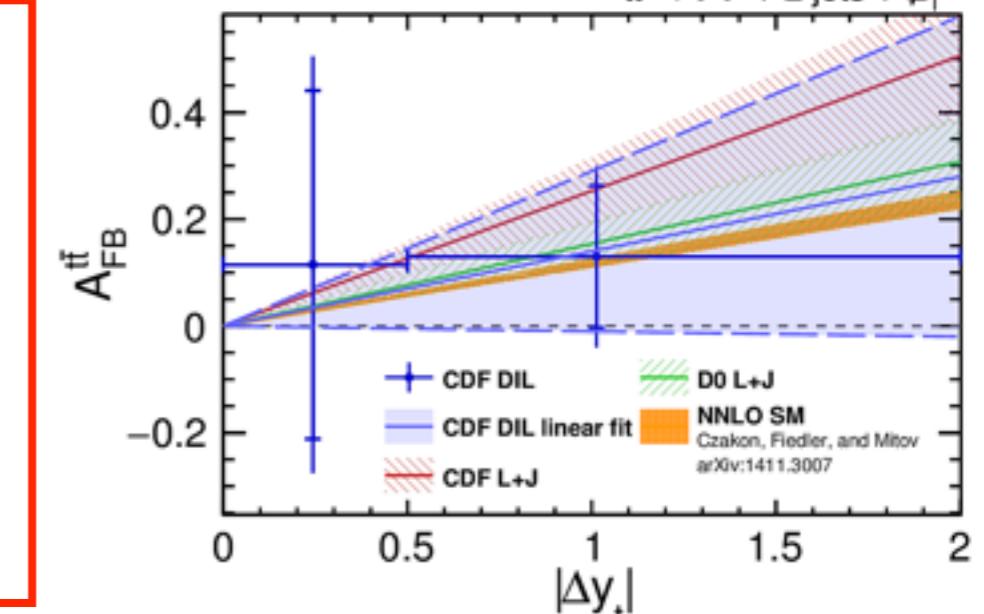
$$A^{t\bar{t}} = (16.4 \pm 4.7)\%$$



PRD 87 092002 (2013)

Conf. Note 11161

CDF Run II Preliminary (9.1 fb⁻¹)
 t̄t → l⁺l⁻ + 2 jets + E_T



Tevatron A_{FB} vs. |Δy| slope α

CDF Lepton+jets (9.4 fb ⁻¹) PRD 87, 092002 (2013)	0.253 ± 0.062
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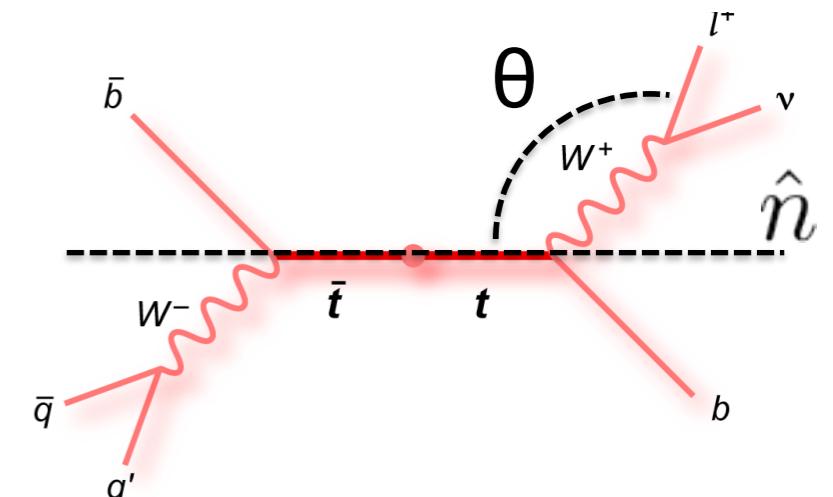
The most significant deviation from SM

A_{FB} and polarisation



Simultaneous measurement of asymmetry and polarisation in dilepton channel

- ▶ Polarisation: due to parity violating electroweak contributions to the production (<0.5%)
- ▶ BSM models change production mechanism
- ▶ Both asymmetry and polarisation can be affected



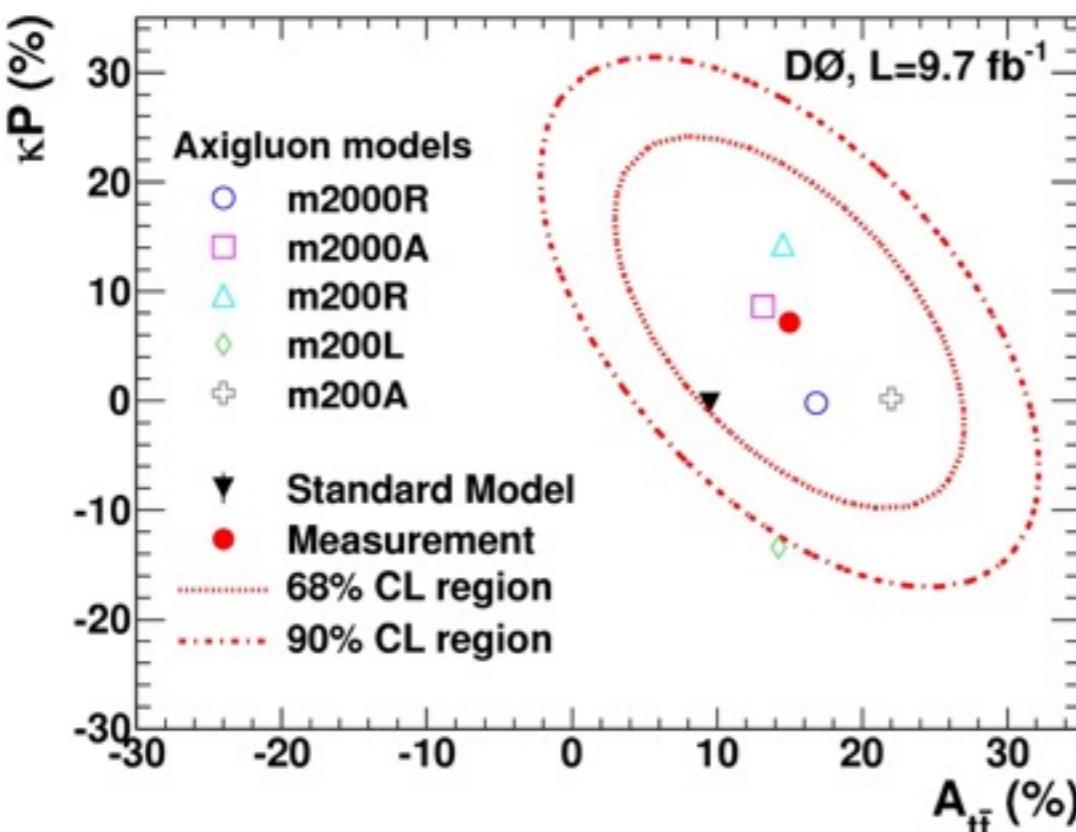
$$A_{\hat{n}}^{\ell^\pm} = \frac{N(\cos \theta^\pm > 0) - N(\cos \theta^\pm < 0)}{N(\cos \theta^\pm > 0) + N(\cos \theta^\pm < 0)}$$

$$\kappa P = A^{\ell^+} - A^{\ell^-}$$

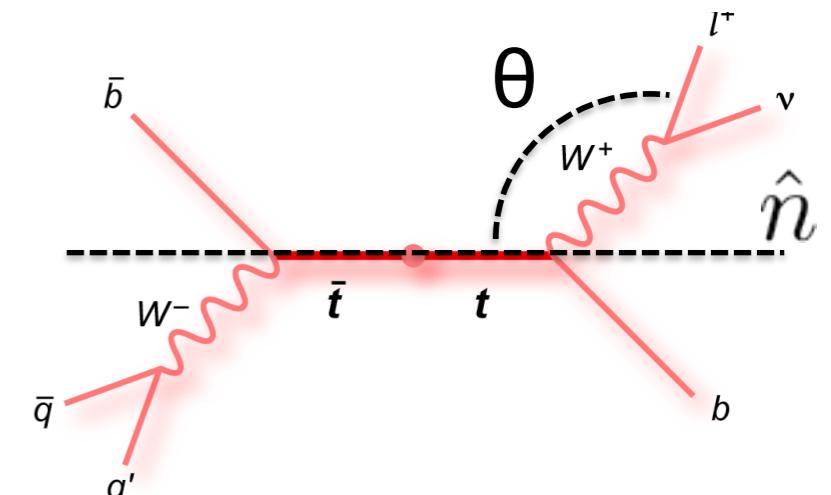
K: spin analysing power, $\kappa \sim I$ for leptons

Simultaneous measurement of asymmetry and polarisation in dilepton channel

- ▶ Polarisation: due to parity violating electroweak contributions to the production (<0.5%)
- ▶ BSM models change production mechanism
- ▶ Both asymmetry and polarisation can be affected
- ▶ Matrix element technique used for event reconstruction



arXiv:1507.05666 [hep-ex]



$$A_{\hat{n}}^{\ell^\pm} = \frac{N(\cos \theta^\pm > 0) - N(\cos \theta^\pm < 0)}{N(\cos \theta^\pm > 0) + N(\cos \theta^\pm < 0)}$$

$$\kappa P = A^{\ell^+} - A^{\ell^-}$$

K: spin analysing power, $\kappa \sim 1$ for leptons

Simultaneous measurement

$$A^{t\bar{t}} = (15.0 \pm 8.0)\%$$

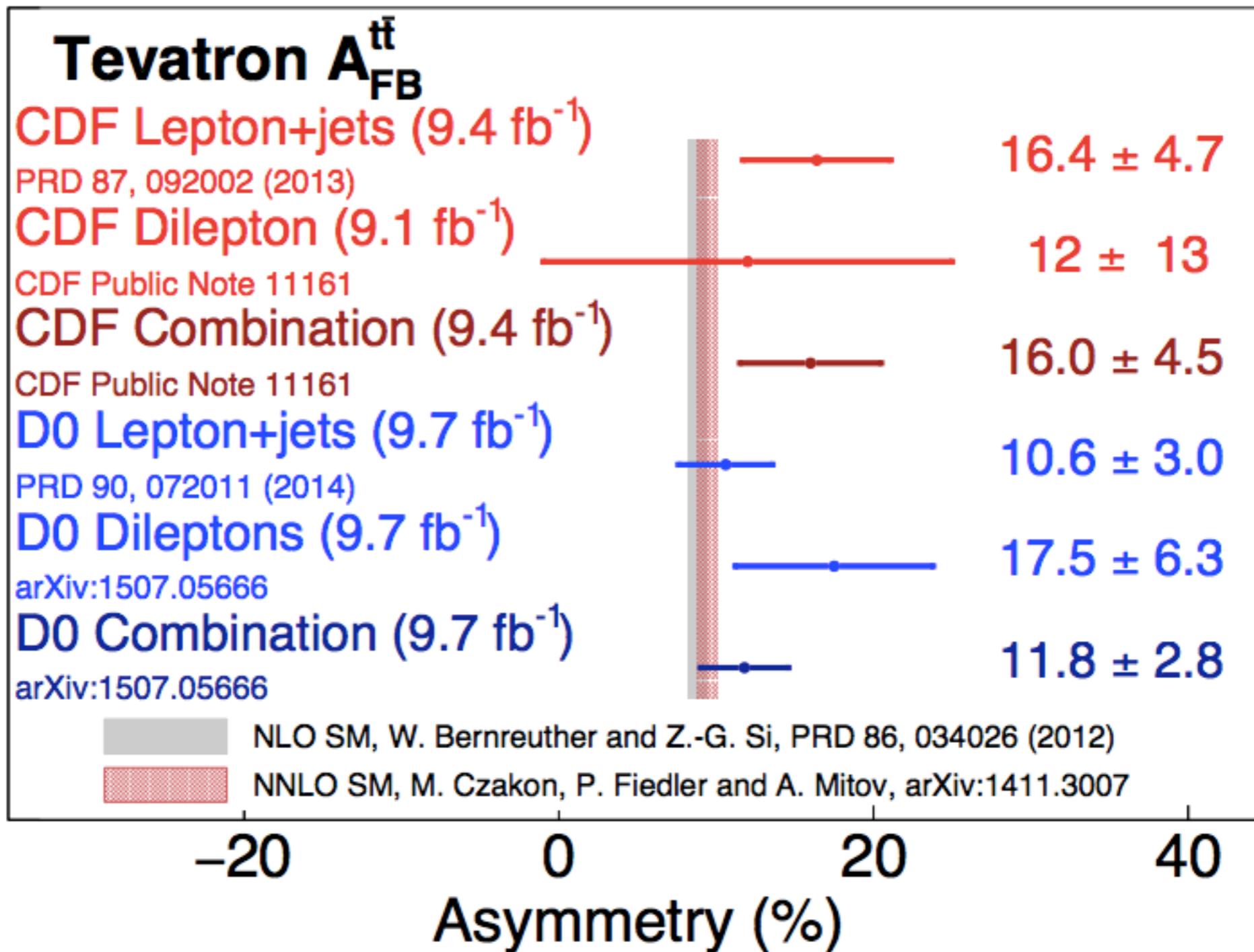
$$\kappa P = (7.2 \pm 11.3)\%$$

Assuming SM polarisation

$$A^{t\bar{t}} = (17.5 \pm 6.3)\%$$

Combination with l+jets channel

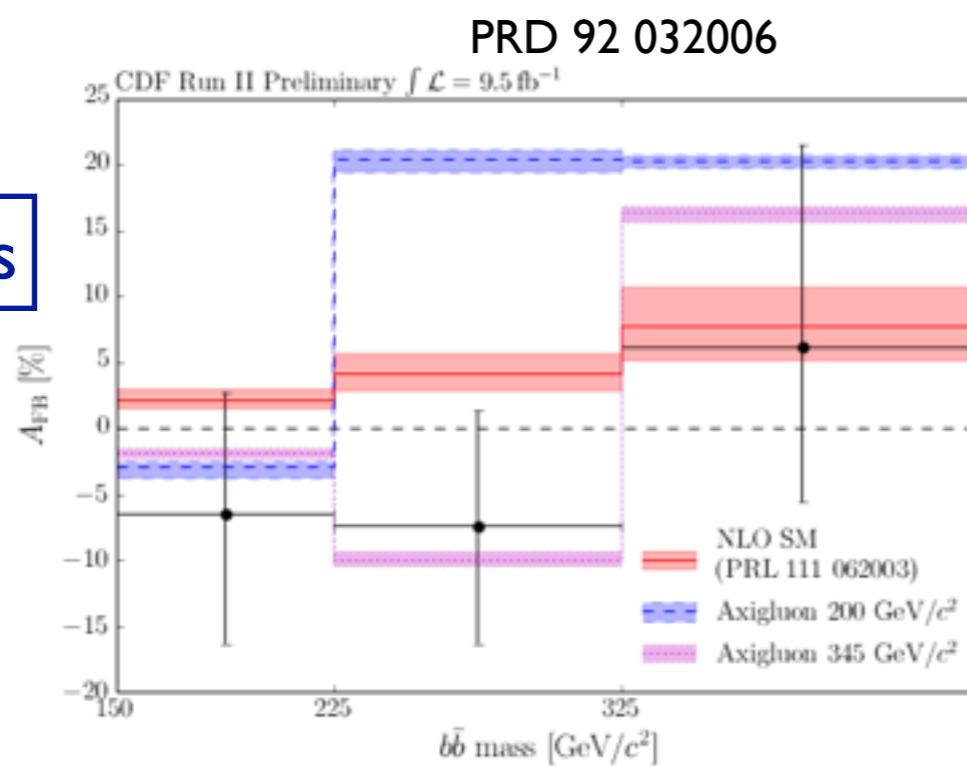
$$A_{\text{combined}}^{t\bar{t}} = (11.8 \pm 2.8)\%$$



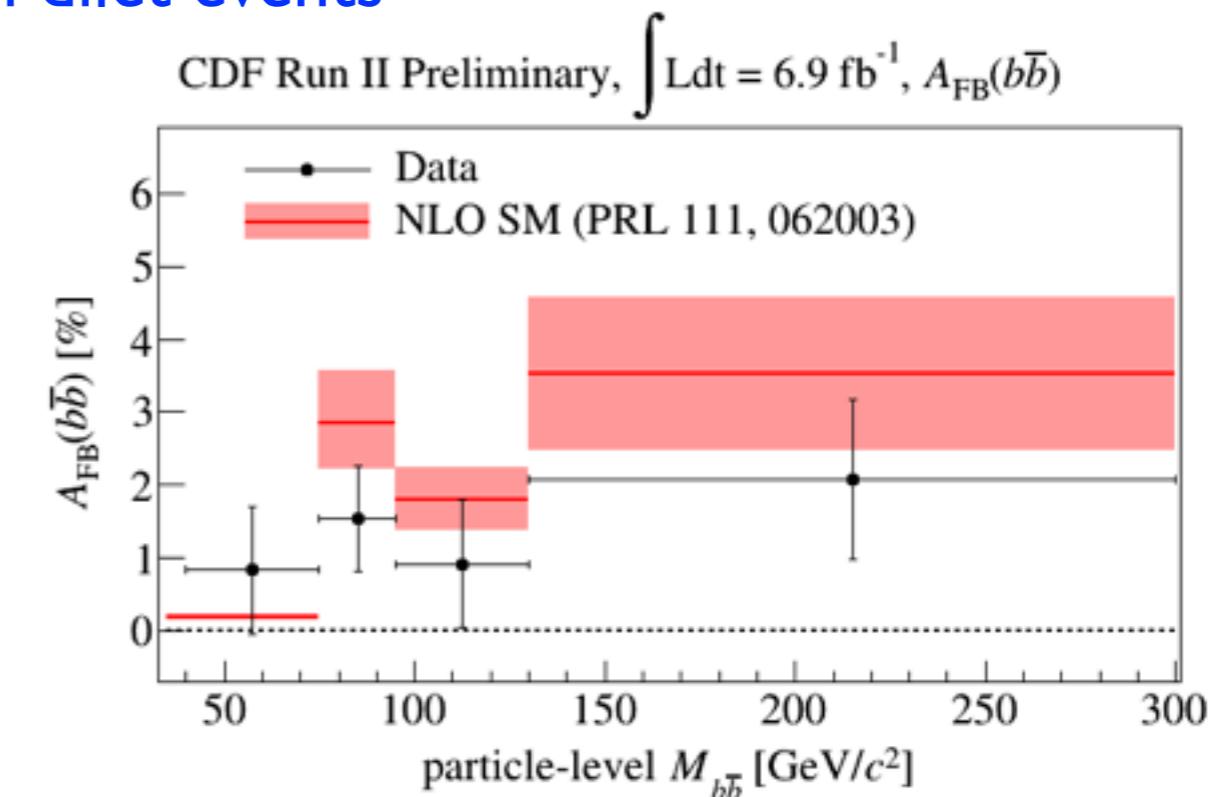
- Low-mass axigluon models were proposed to explain A_{FB}
 - ▶ Heavy axial-vector boson with mass below $t\bar{t}$ threshold and broad width
 - ▶ Predict asymmetry of pair production of b-quarks
 - ▶ Production dominated by gg fusion
 - ▶ Enhance $q\bar{q} \rightarrow b\bar{b}$ fraction
 - ▶ High and low mass $m_{b\bar{b}}$ measurements in dijet events

Conf. Note 11161

low mass



High mass



$$A^{b\bar{b}} = (1.2 \pm 0.7)\%$$

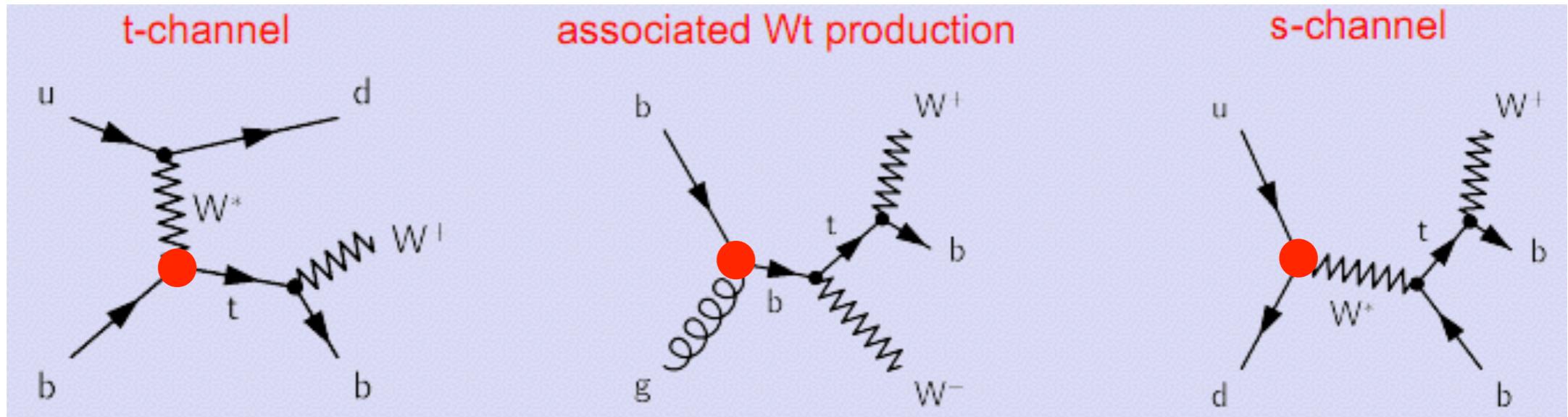
$$\text{SM prediction: } A_{FB}^{b\bar{b}} = (0.30 \pm 0.07^{+0.04}_{-0.03})\%$$

Grinstein, Murphy PRL 111 062003, 2013

Consistent with both zero
and with the SM predictions

**Electroweak top quark production
t-, s-channel cross sections
 $|V_{tb}|$ measurement
 W' search**

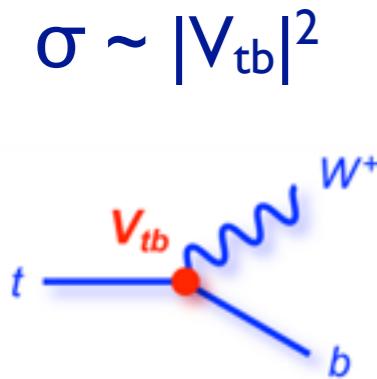
Electroweak top production



Cross sections ($m_t=172.5$ GeV)

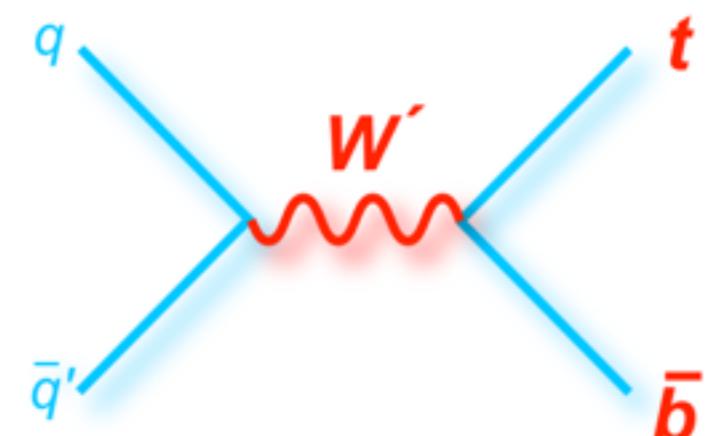
Tevatron $\sqrt{s}=1.96$ TeV	2.10 ± 0.13 pb	0.25 ± 0.03 pb	1.05 ± 0.06 pb
LHC, $\sqrt{s}=8$ TeV	87.8 ± 3.4 pb	22.4 ± 1.5 pb	5.6 ± 0.3 pb

Observed by CDF and D0 collaborations in 2009



$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & \textcolor{red}{V_{tb}} \end{pmatrix}$$

Test unitarity of CKM matrix
4th generation

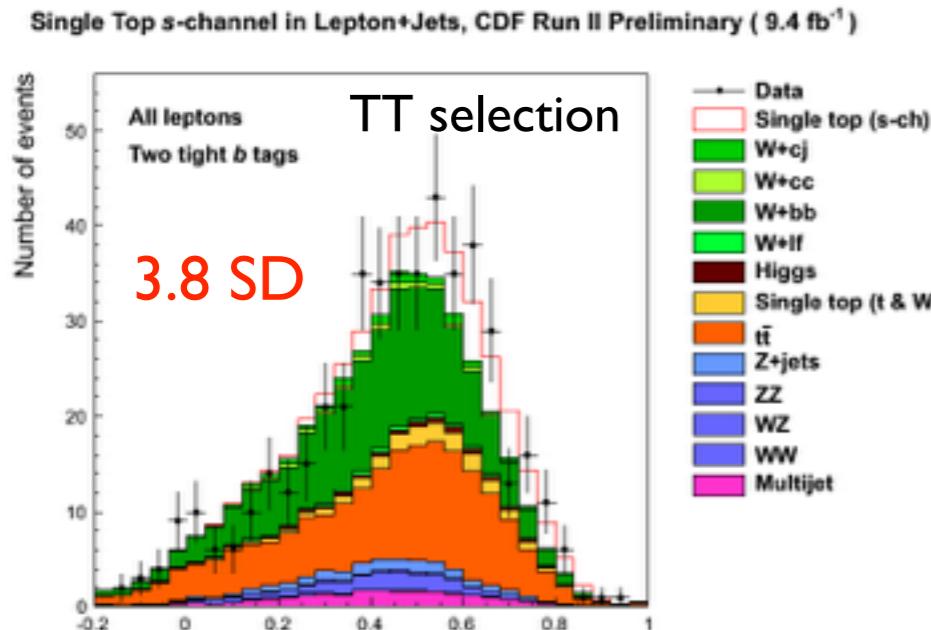


Sensitive to new physics

□ Combination of D0 and CDF measurements

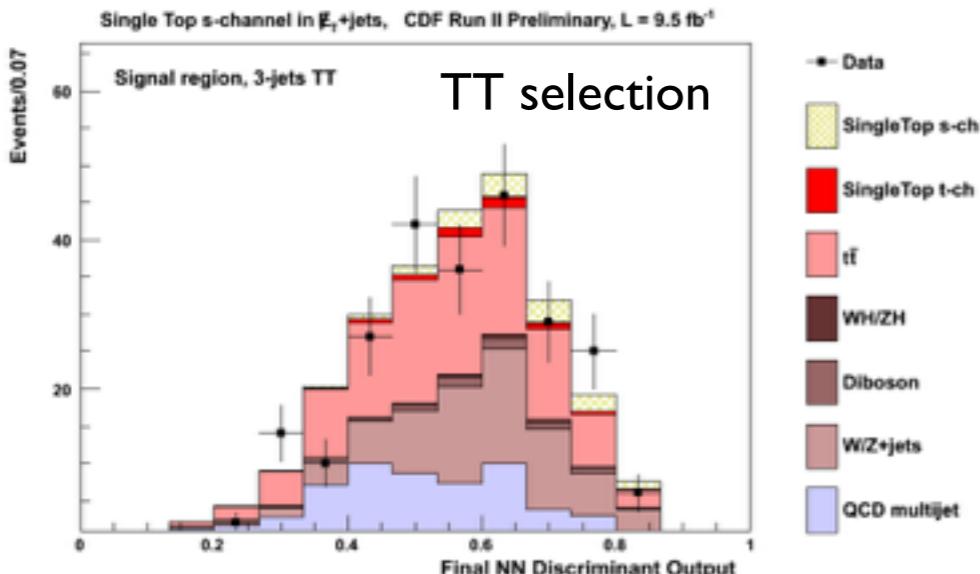


CDF l+jets channel



PRL 112 231804

CDF MET+jets channel

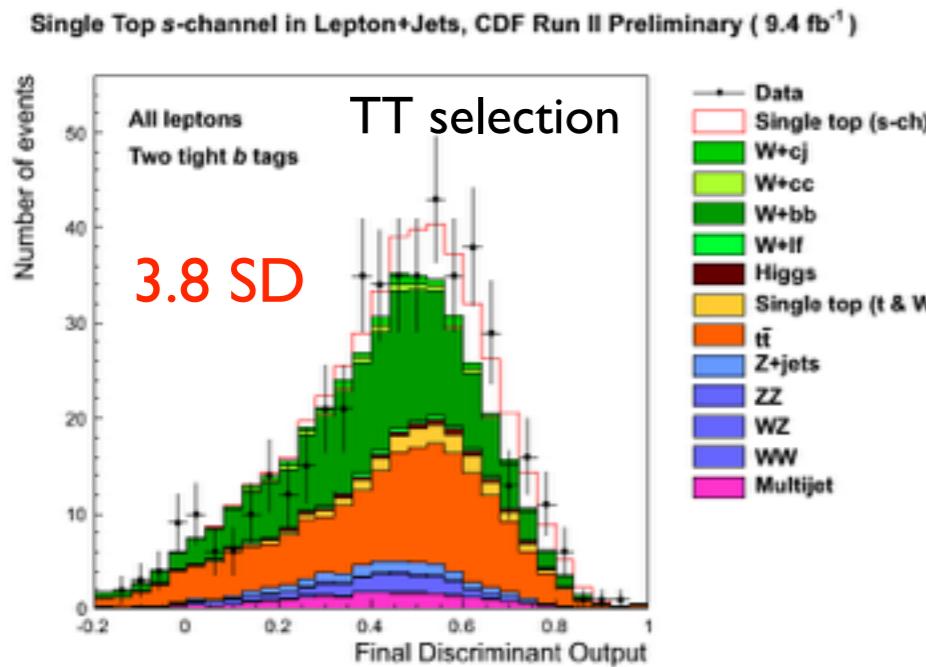


PRL 112 231805

□ Combination of D0 and CDF measurements

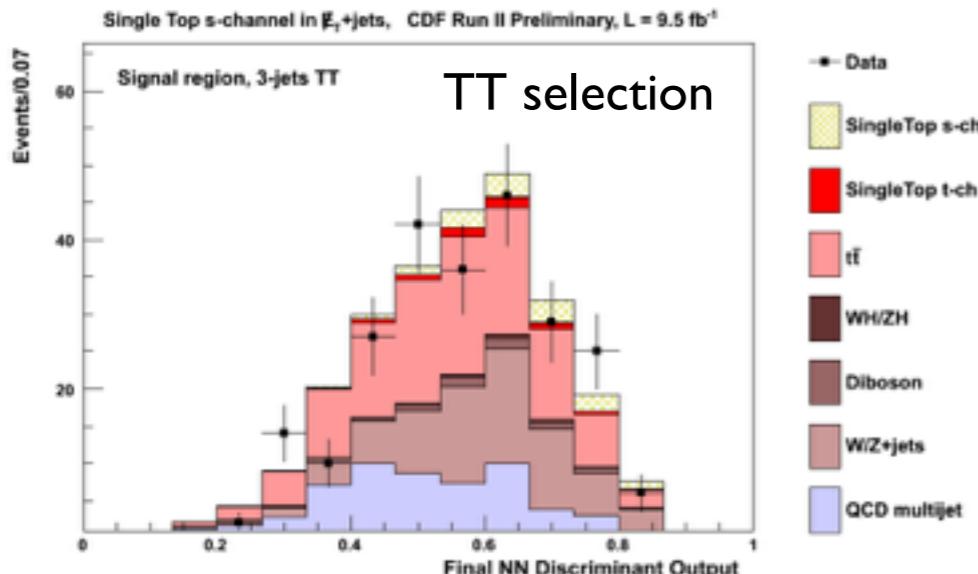


CDF l+jets channel



PRL 112 231804

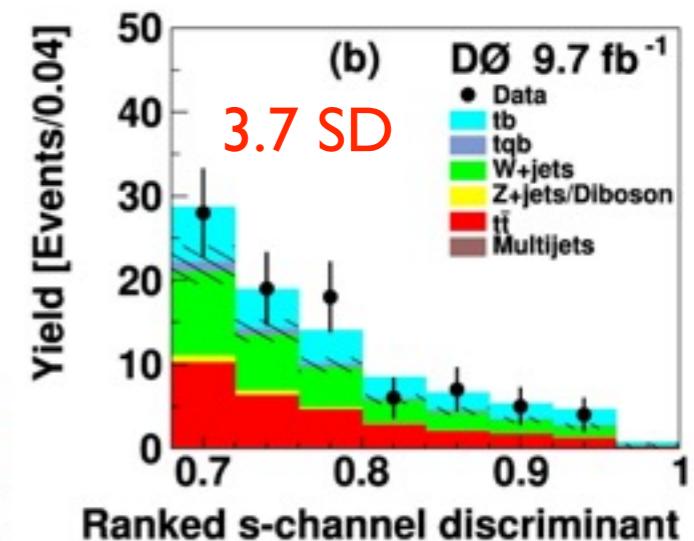
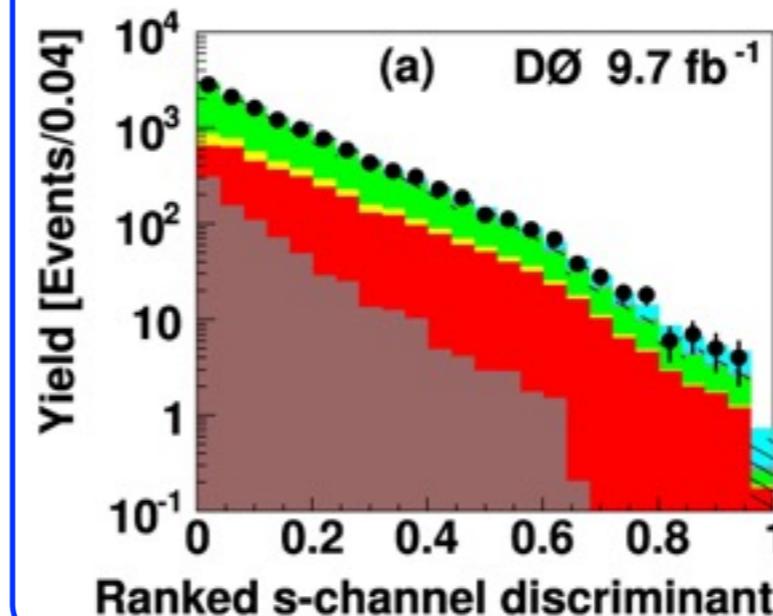
CDF MET+jets channel



PRL 112 231805

D0 l+jets channel

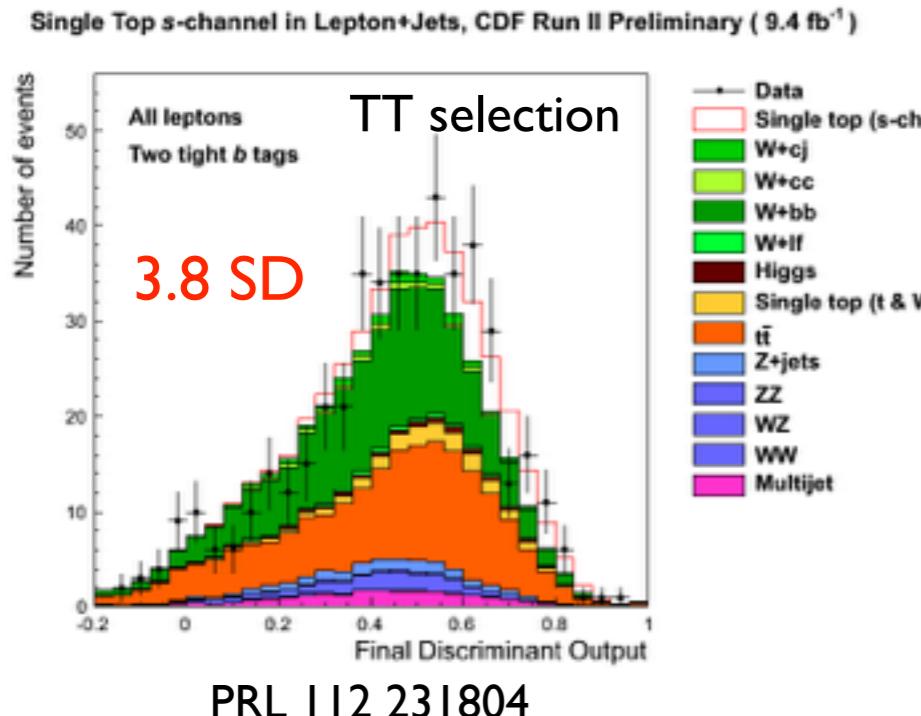
PLB 726, 656 (2013)



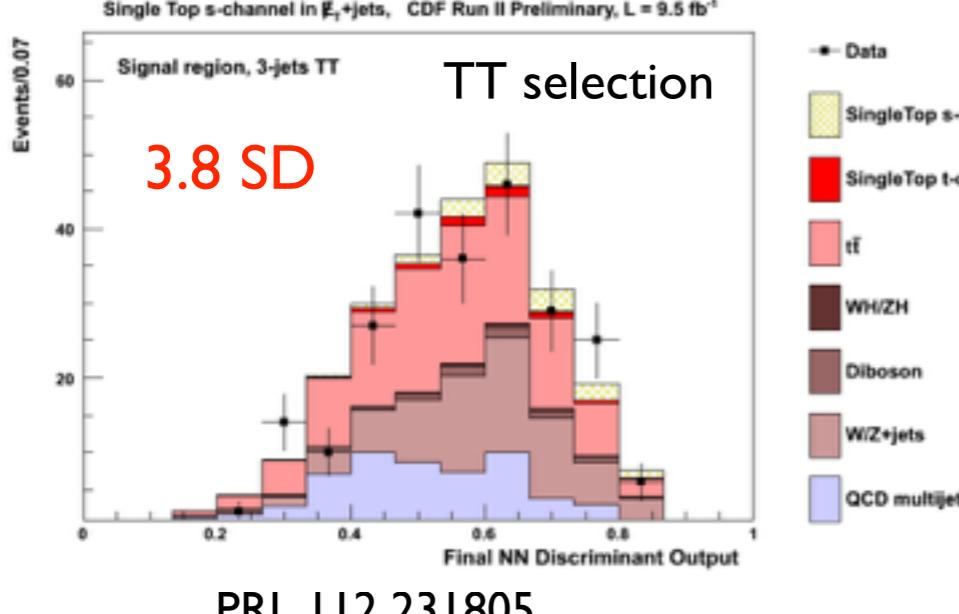
□ Combination of D0 and CDF measurements



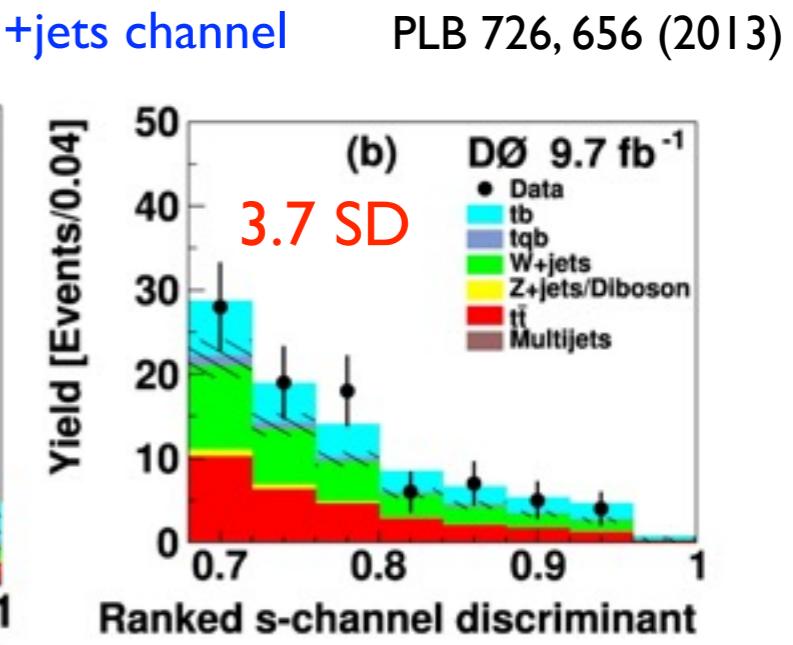
CDF l+jets channel



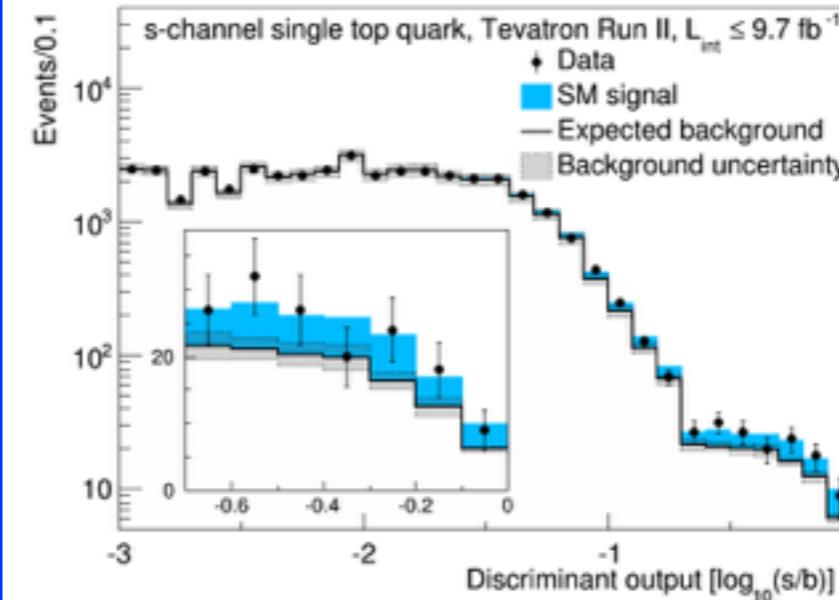
CDF MET+jets channel



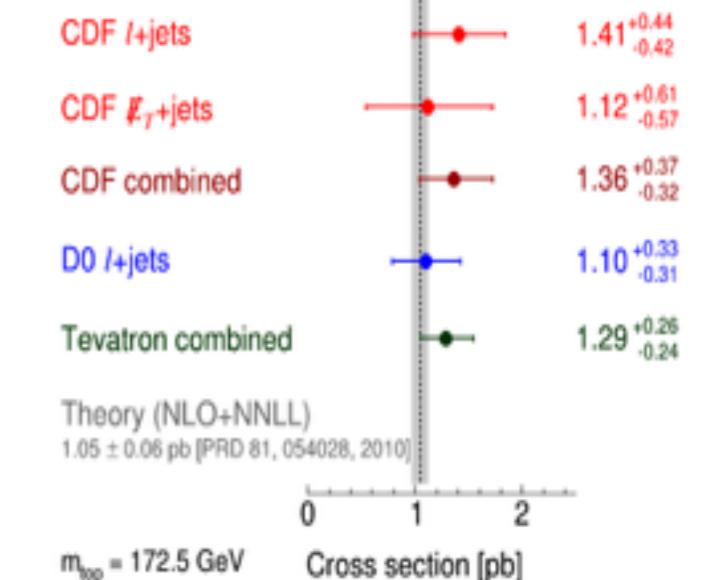
D0 l+jets channel



PRL 112, 231803 (2014)



s-channel single top quark, Tevatron Run II, $L_{\text{int}} \leq 9.7 \text{ fb}^{-1}$
Measurement



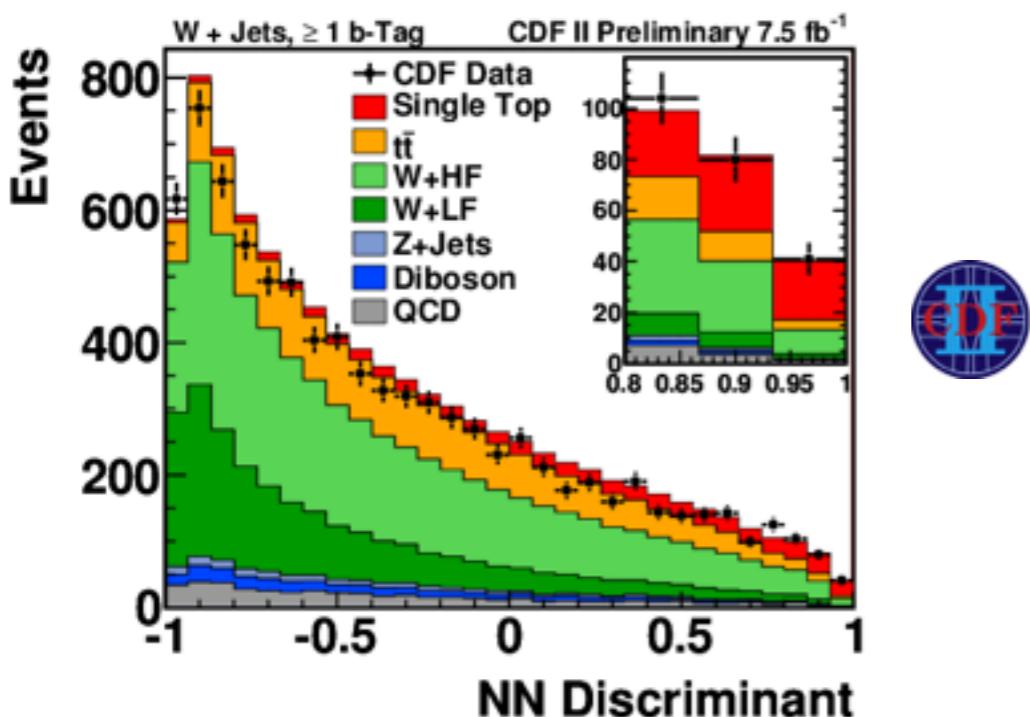
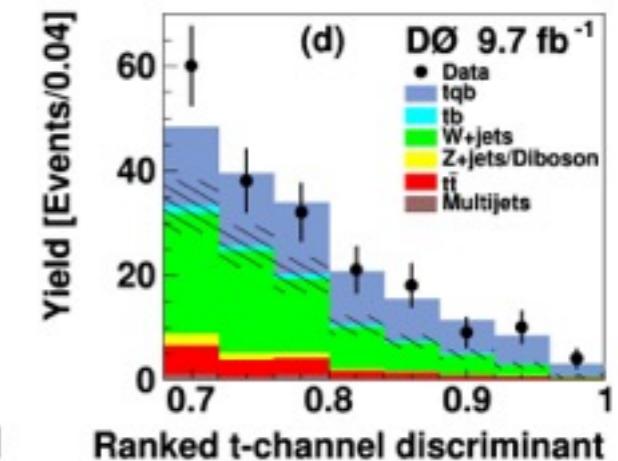
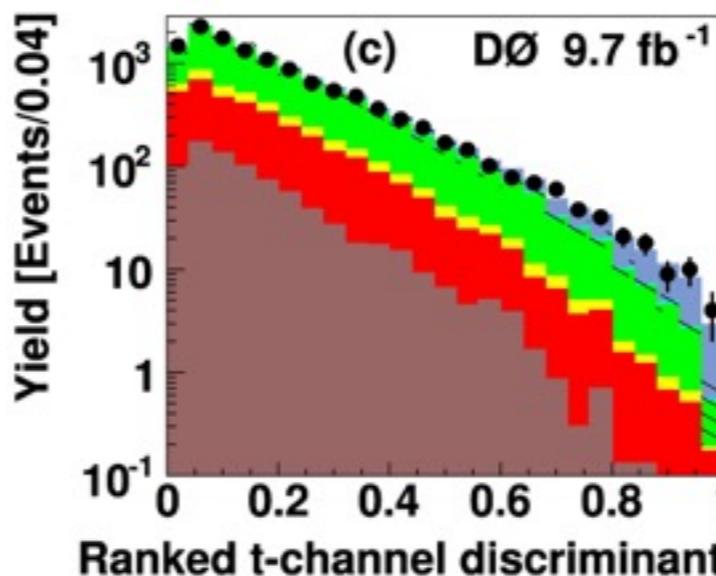
Inputs to t-ch combination

t+jets channel

- Selection:
 - ▶ High pT lepton
 - ▶ ≥ 2 jets, ≥ 1 b-tags
 - ▶ Large MET
- MVA technique to separate signal from large W+jets background
 - ▶ D0: ME, BNN and BDT combined
 - ▶ CDF: NN



PLB 726, 656 (2013)

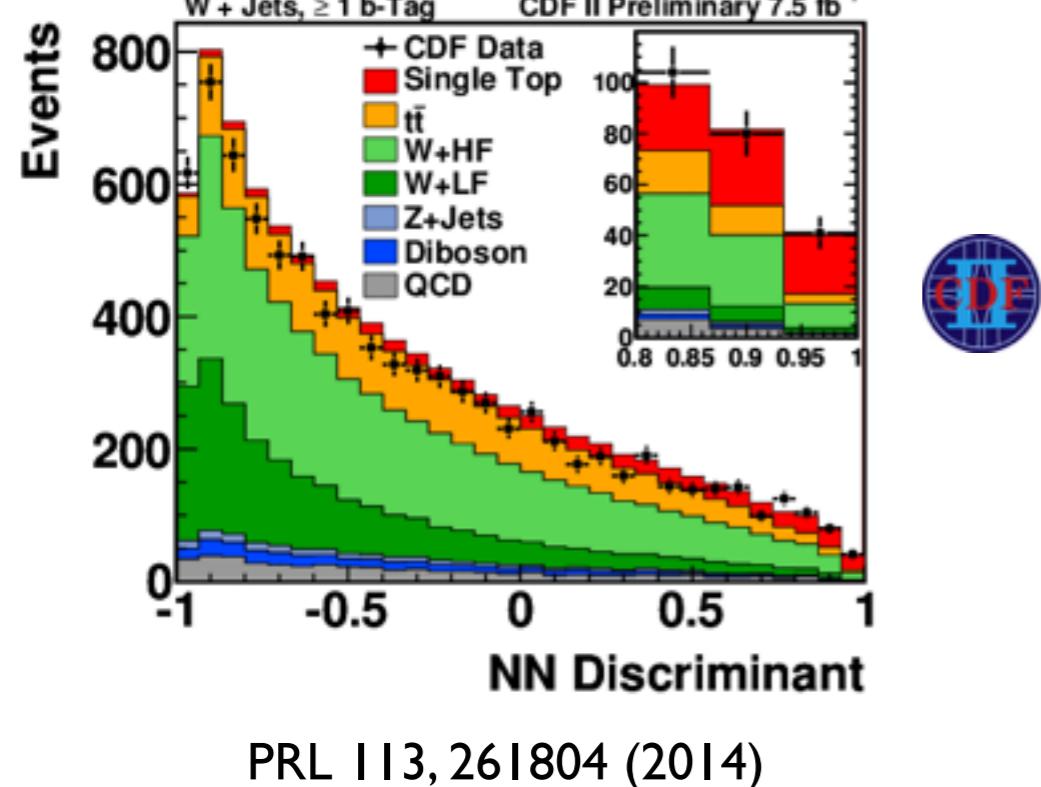
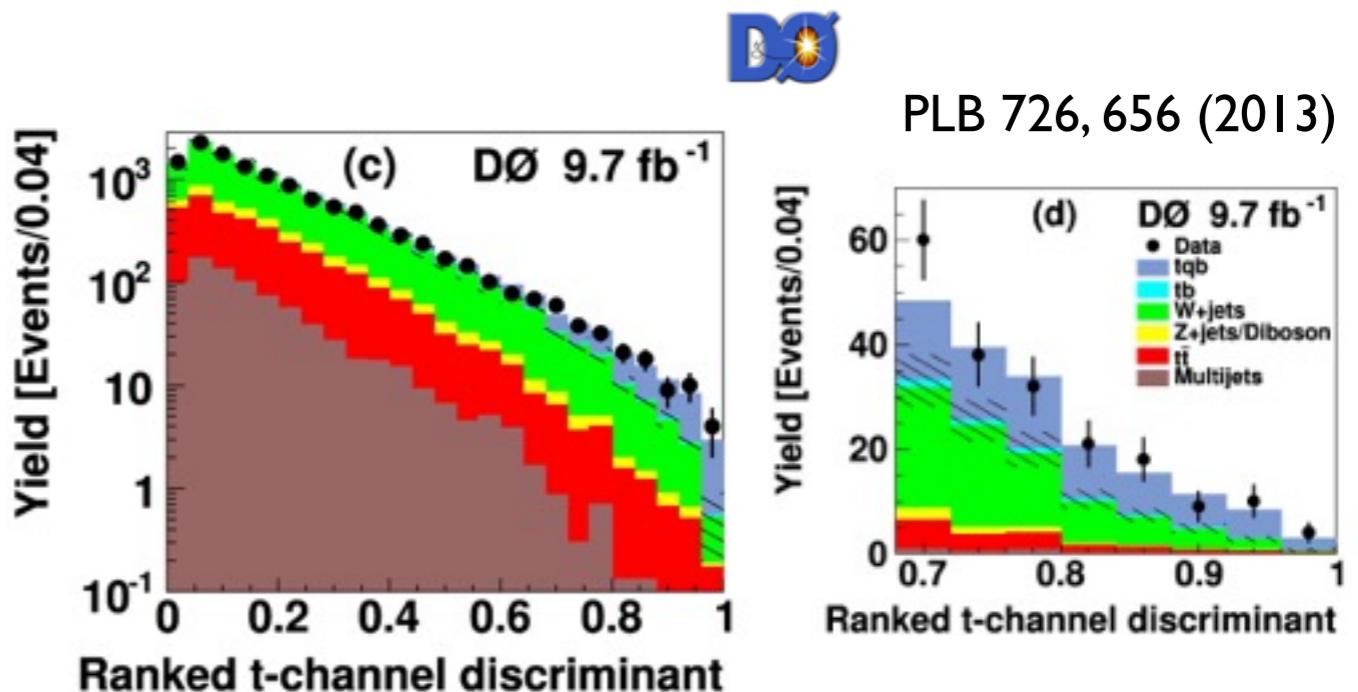


PRL 113, 261804 (2014)

Inputs to t-ch combination

t+jets channel

- Selection:
 - ▶ High pT lepton
 - ▶ ≥ 2 jets, ≥ 1 b-tags
 - ▶ Large MET
- MVA technique to separate signal from large W+jets background
 - ▶ D0: ME, BNN and BDT combined
 - ▶ CDF: NN



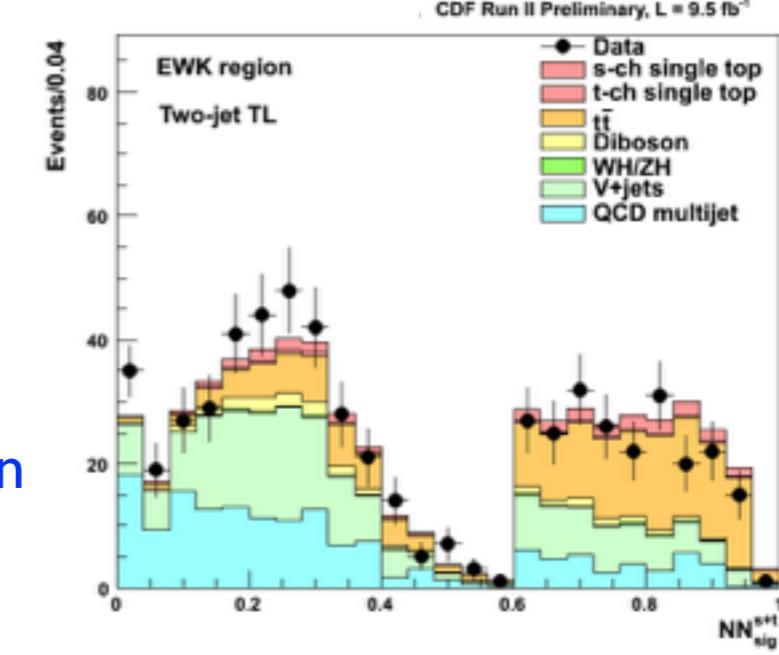
02/09/2015

E.Shabalina – LHCb 2015 - St. Petersburg

arXiv:1410.4909 [hep-ex]

MET+jets channel

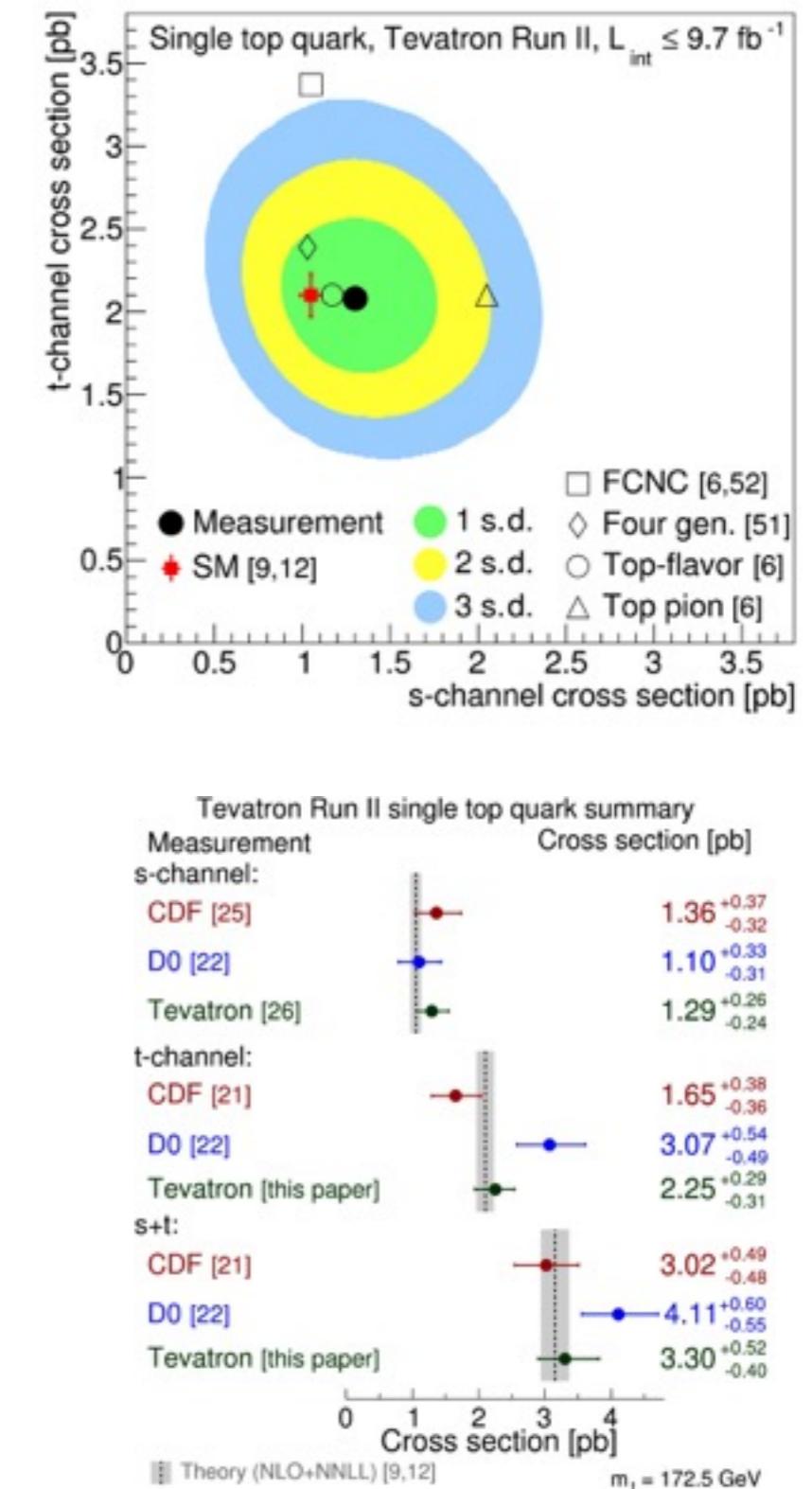
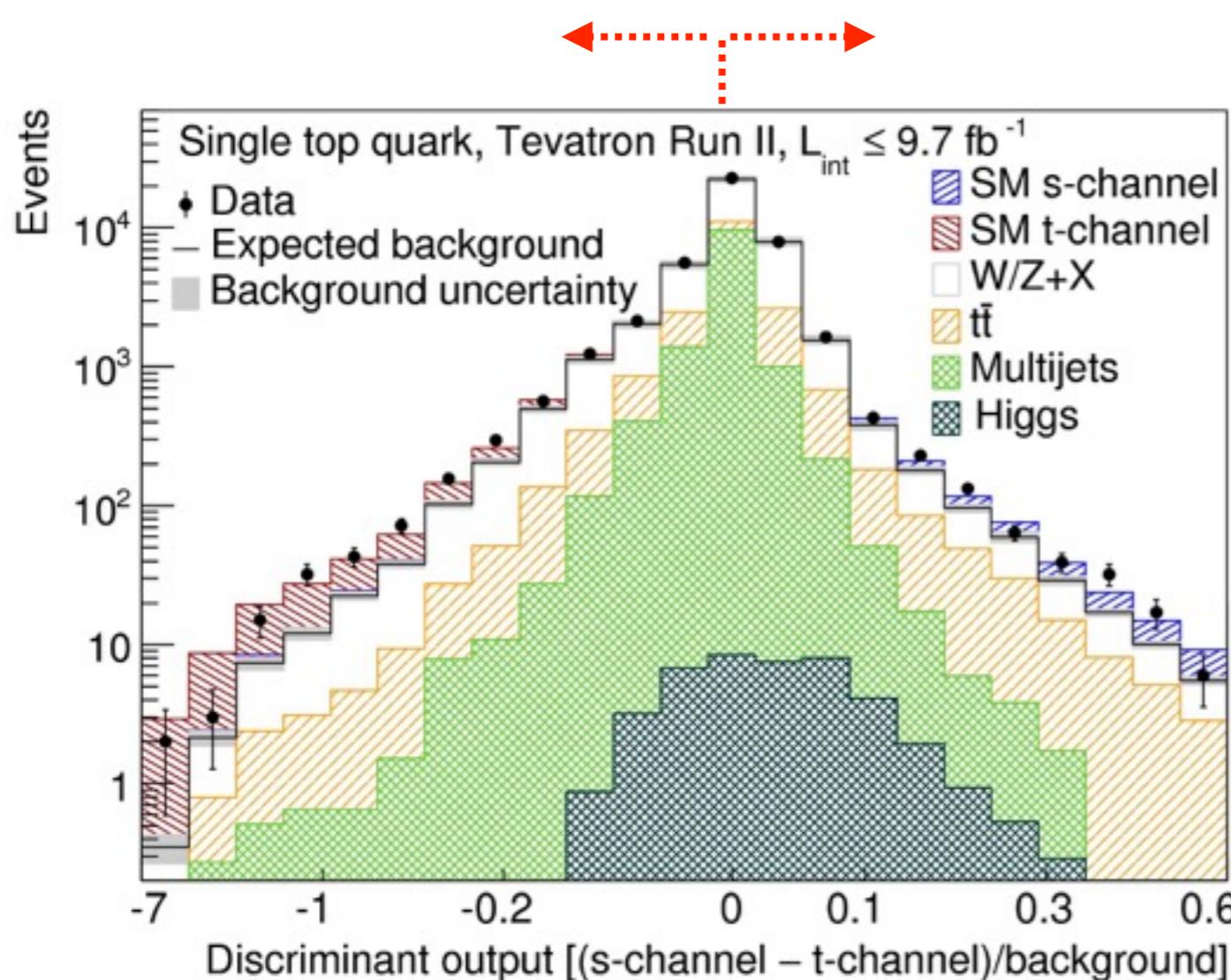
- Selection:
 - ▶ Veto on high pT lepton
 - ▶ 2 or 3 jets, ≥ 2 b-tags
 - ▶ Large MET
- NNQCD to suppress multijet background
- $NN_{V_{\text{jets}}}$, $NN_{t\bar{t}}$ combined in quadrature



Tevatron combination results

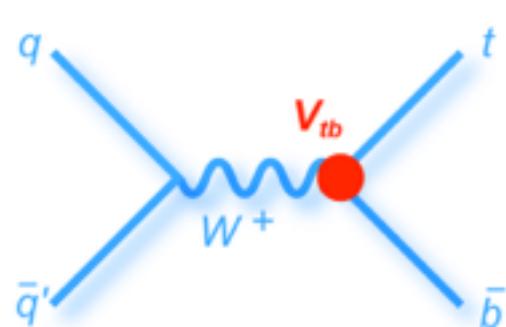
arXiv:1503.05027 [hep-ex]

- Likelihood fit to binned distribution of final discriminants
- Combination via product of likelihoods
- For t-channel measurement s-channel cross section is set to SM value

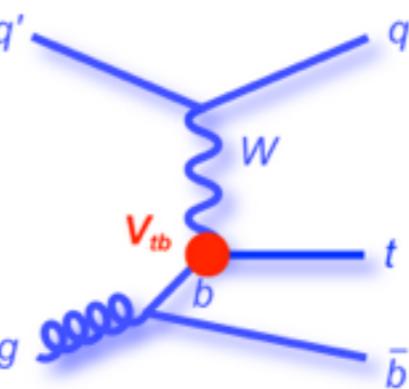


$$\sigma_t^{\text{t-ch}} = 2.25^{+0.29}_{-0.31} \text{ pb}$$

Direct measurement of V_{tb}



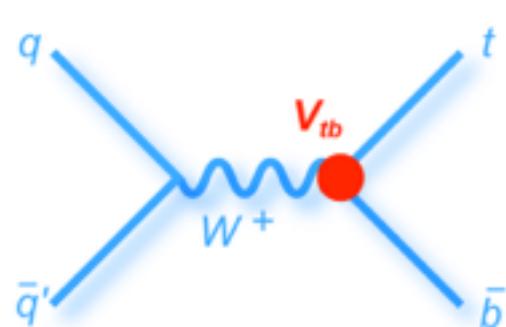
$$\sigma \sim |V_{tb}|^2$$



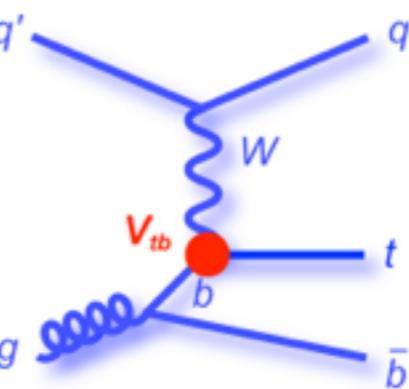
$$\Gamma_{Wtb}^\mu = -\frac{g}{\sqrt{2}} V_{tb} \left\{ \gamma^\mu [f_1^L P_L + f_1^R P_R] - \frac{i\sigma^{\mu\nu}}{M_W} (p_t - p_b)_\nu [f_2^L P_L + f_2^R P_R] \right\}$$

- No assumption of 3 generations or unitarity of the CKM matrix
- Assume SM production mechanism
 - ▶ Top decay exclusively to Wb ($|V_{td}|^2 + |V_{ts}|^2 \ll |V_{tb}|^2$)

Direct measurement of V_{tb}



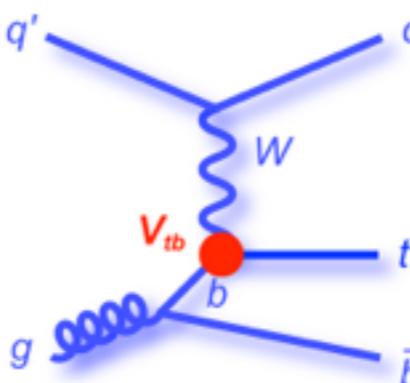
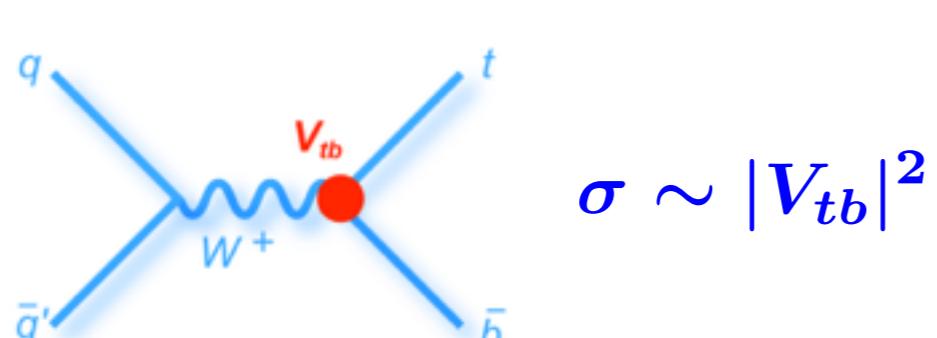
$$\sigma \sim |V_{tb}|^2$$



$$\Gamma_{Wtb}^\mu = -\frac{g}{\sqrt{2}} V_{tb} \left\{ \gamma^\mu [f_1^L P_L + f_1^R P_R] - \frac{i\sigma^{\mu\nu}}{M_W} (p_t - p_b)_\nu [f_2^L P_L + f_2^R P_R] \right\}$$

- No assumption of 3 generations or unitarity of the CKM matrix
- Assume SM production mechanism
 - ▶ Top decay exclusively to Wb ($|V_{td}|^2 + |V_{ts}|^2 \ll |V_{tb}|^2$)
 - ▶ Pure V-A and CP-conserving interaction ($f_1^R = f_2^L = f_2^R = 0$)

Direct measurement of V_{tb}

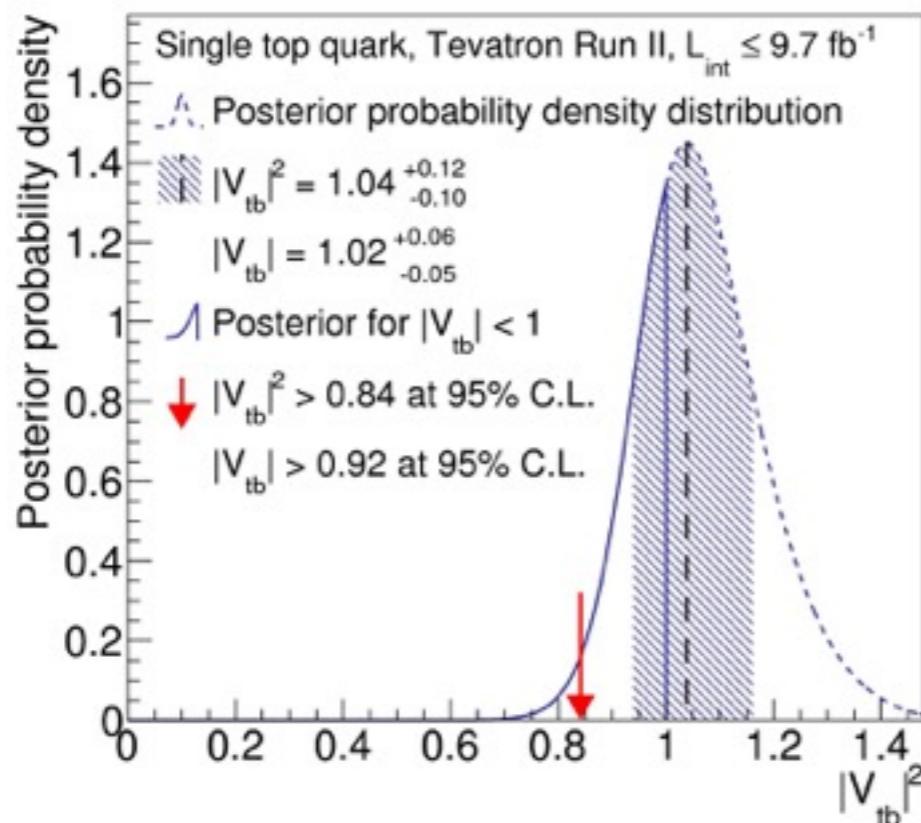


$$\Gamma_{Wtb}^\mu = -\frac{g}{\sqrt{2}} V_{tb} \left\{ \gamma^\mu [f_1^L P_L + f_1^R P_R] - \frac{i\sigma^{\mu\nu}}{M_W} (p_t - p_b)_\nu [f_2^L P_L + f_2^R P_R] \right\}$$

- No assumption of 3 generations or unitarity of the CKM matrix
- Assume SM production mechanism
 - ▶ Top decay exclusively to Wb ($|V_{td}|^2 + |V_{ts}|^2 \ll |V_{tb}|^2$)
 - ▶ Pure V-A and CP-conserving interaction ($f_1^R = f_2^L = f_2^R = 0$)

Strength of the left-handed Wtb (f_1^L) coupling is allowed to be anomalous

arXiv:1503.05027 [hep-ex]



- Consider uncertainties on SM predictions for s- and t-channels

$$|V_{tb}| = 1.02^{+0.06}_{-0.05}$$

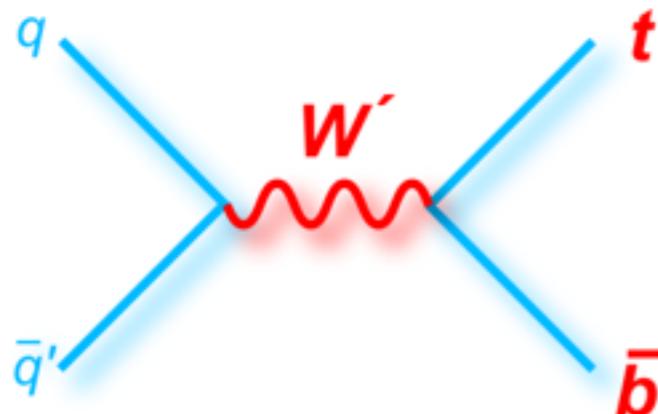
- With [0,1] prior

$$|V_{tb}| > 0.92 @ 95\% \text{ C.L.}$$

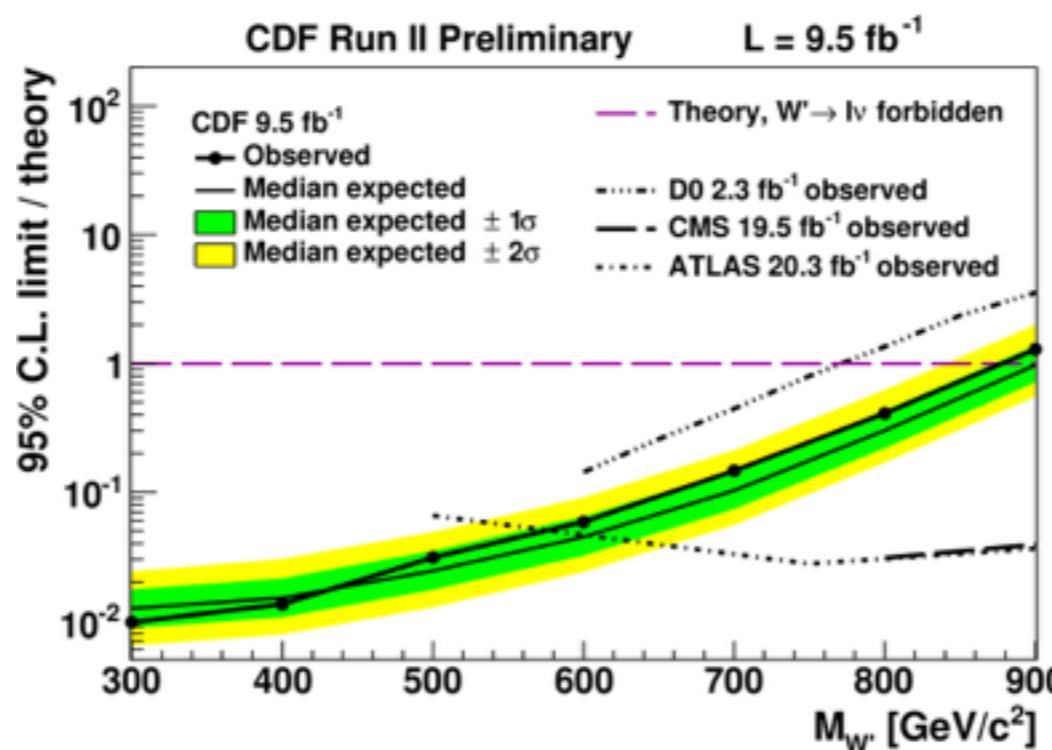
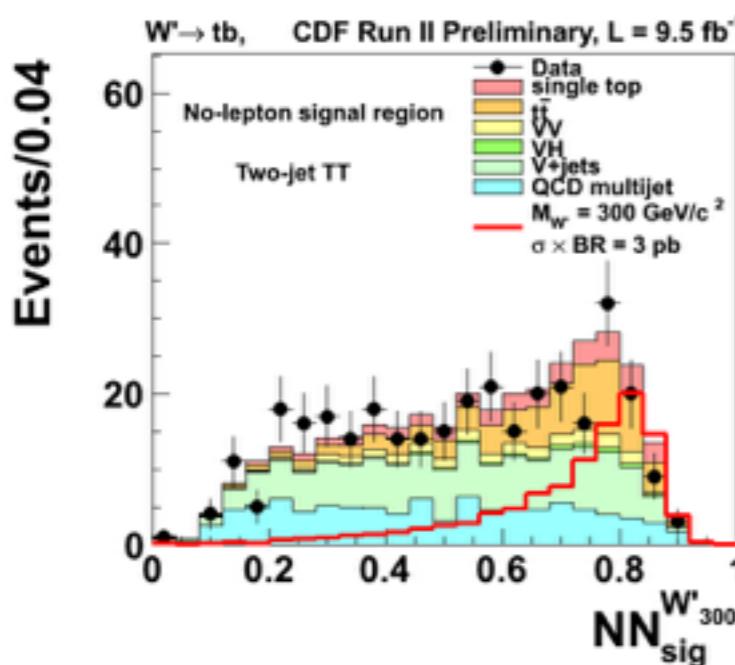
No indication of sources of new physics beyond SM

Search for resonance decaying in tb

PRL 115 061801



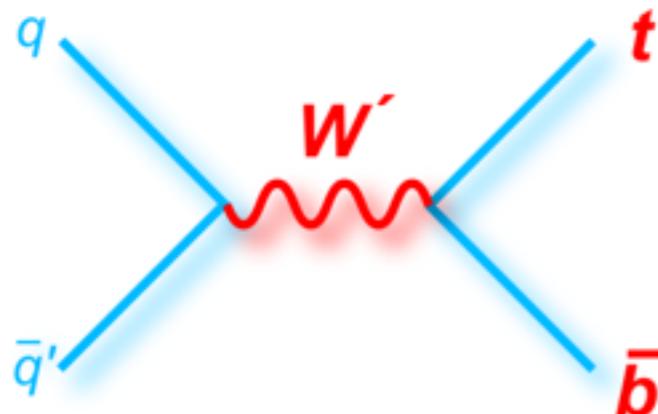
- Benchmark W' model with left-right symmetric coupling
- Two scenarios: allowed or forbidden $W' \rightarrow l\nu$ decay
- Analysis strategy similar to MET+jets channel single top search
 - ▶ W' signal instead of single top is used for NN training



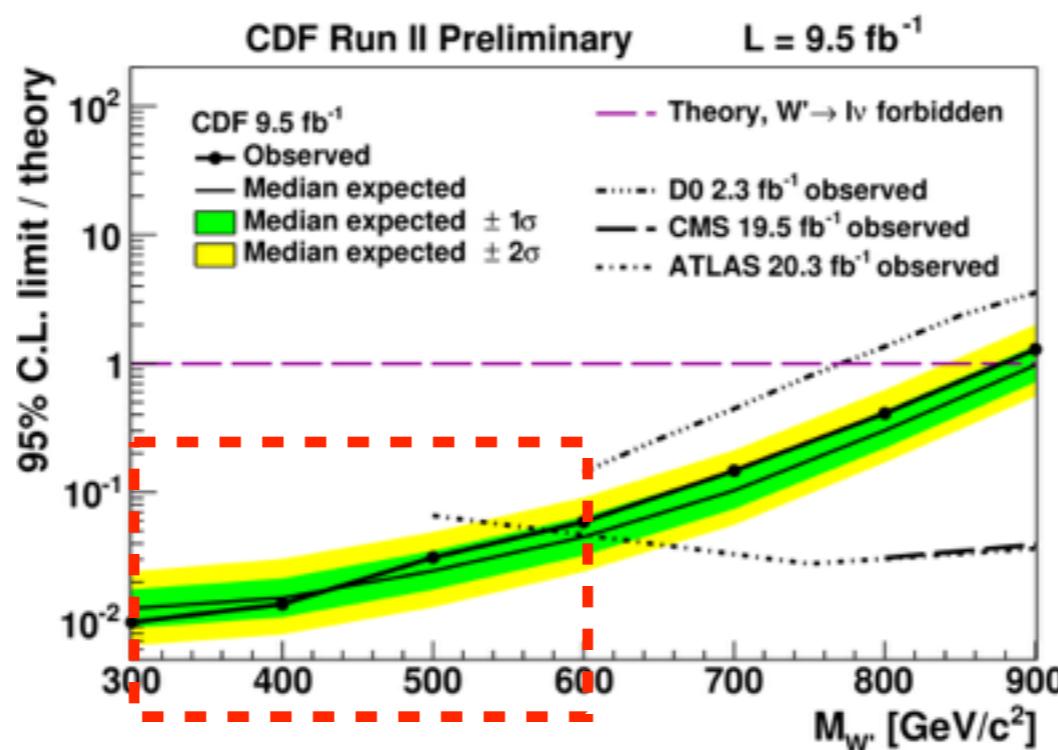
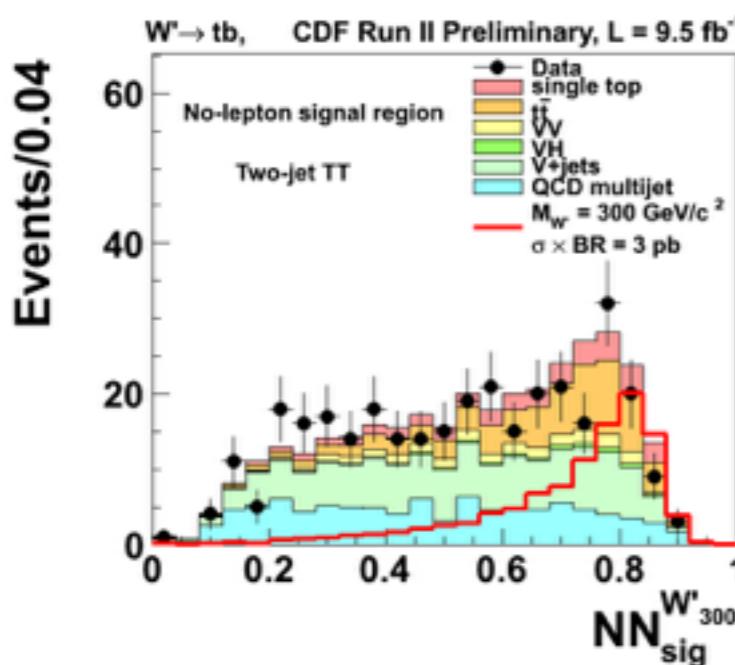
- ▶ Exclude W' with mass below 860 (880) if W' leptonic decay is allowed (forbidden)

Search for resonance decaying in tb

PRL 115 061801



- Benchmark W' model with left-right symmetric coupling
- Two scenarios: allowed or forbidden $W' \rightarrow l\nu$ decay
- Analysis strategy similar to MET+jets channel single top search
 - ▶ W' signal instead of single top is used for NN training



- ▶ Exclude W' with mass below 860 (880) if W' leptonic decay is allowed (forbidden)

Most stringent limits for a charged resonance within 300-600 GeV mass range decaying to tb

- The Tevatron experiments are completing legacy measurements
 - ▶ Precise cross section measurements
 - ▶ Precise measurements of the top quark mass
 - ▶ Final measurements of asymmetries in quark pair production

- The Tevatron experiments are completing legacy measurements
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 - ▶ Final measurements of asymmetries in quark pair production
- Electroweak top production measurements are complete
 - ▶ Combination of t-channel cross sections
 - ▶ Observation of the s-channel production
- Many measurements are complementary to the ones from LHC

No significant deviations from the standard model are found

Our hopes are on LHC!



BACKUP

s-channel evidence

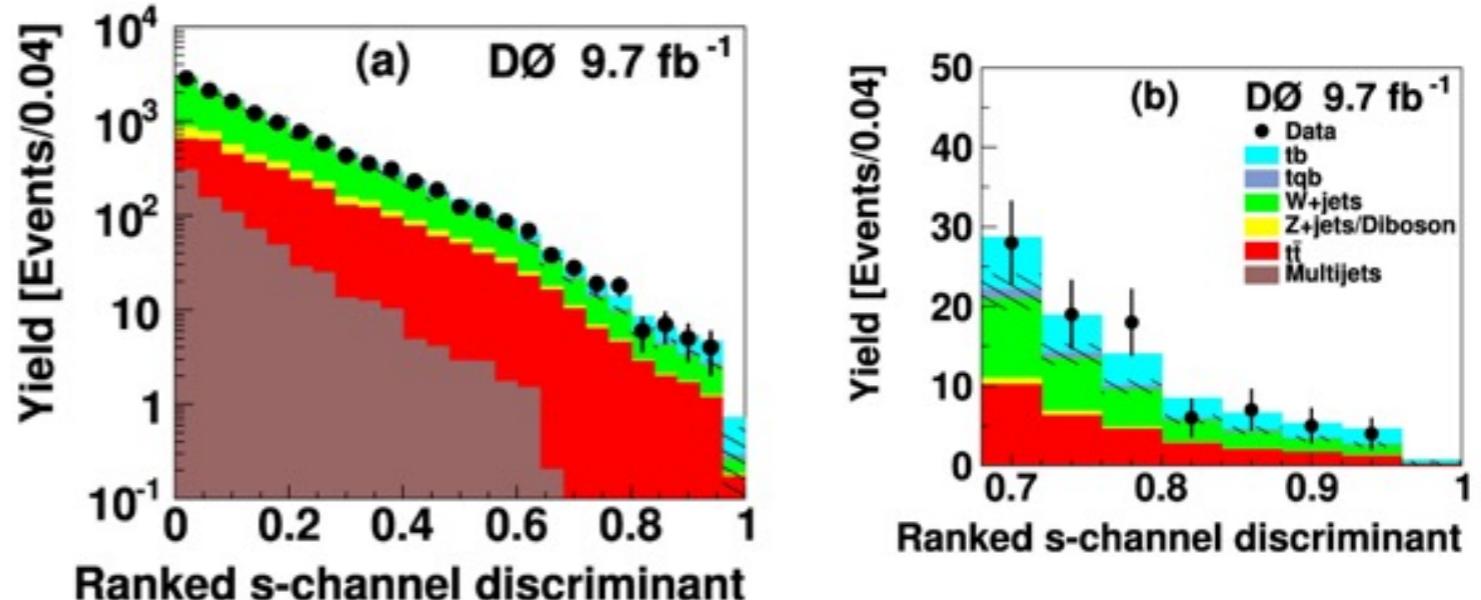
PLB 726, 656 (2013)



- I+jets channel
 - ▶ 2 or 3 jets, 1 or 2 b-tags
- 635 signal events (s+t channels)
 - ▶ ~1000 in 0.7 fb^{-1} at LHC
- S/B between I:14 and I:88
- Discriminants
 - ▶ Boosted Decision Tree (BDT)
 - ▶ Bayesian Neural Network
 - ▶ Matrix element
- All three combined into final D

 $m_t = 172.5 \text{ GeV}$

channel	$\sigma(\text{pb})$	significance: obs (exp)
s+t	$4.11^{+0.60}_{-0.55}$	
t	$3.07^{+0.54}_{-0.49}$	7.7 (6.0)
s	$1.10^{+0.33}_{-0.31}$	3.7 (3.7)



- Statistical analysis
 - ▶ form binned likelihood as a product of 4 channels
 - ▶ D_s and D_t are used simultaneously in a joint discriminant
 - ▶ 2D posterior probability density is constructed as a function of σ_s and σ_t

Evidence for s-channel production

DØ matrix element technique in l+jets final states**b tagging-based weight to identify relevant jet-parton assignments**

$$P_{\text{sig}} = \frac{1}{\sigma_{\text{obs}}^{t\bar{t}}} \sum_{i=1}^{24} w_i \int d\rho dm_1^2 dM_1^2 dm_2^2 dM_2^2 d\rho_\ell dq_1^x dq_1^y dq_2^x dq_2^y$$

Integration over phase space (10 dim)

$\sum_{\text{flavors}, \nu} |\mathcal{M}_{t\bar{t}}|^2 \frac{f'(q_1)f'(q_2)}{\sqrt{(\eta_{\alpha\beta} q_1^\alpha q_2^\beta)^2 - m_{q_1}^2 m_{q_2}^2}} \Phi_6 W(x, y; k_{\text{JES}})$

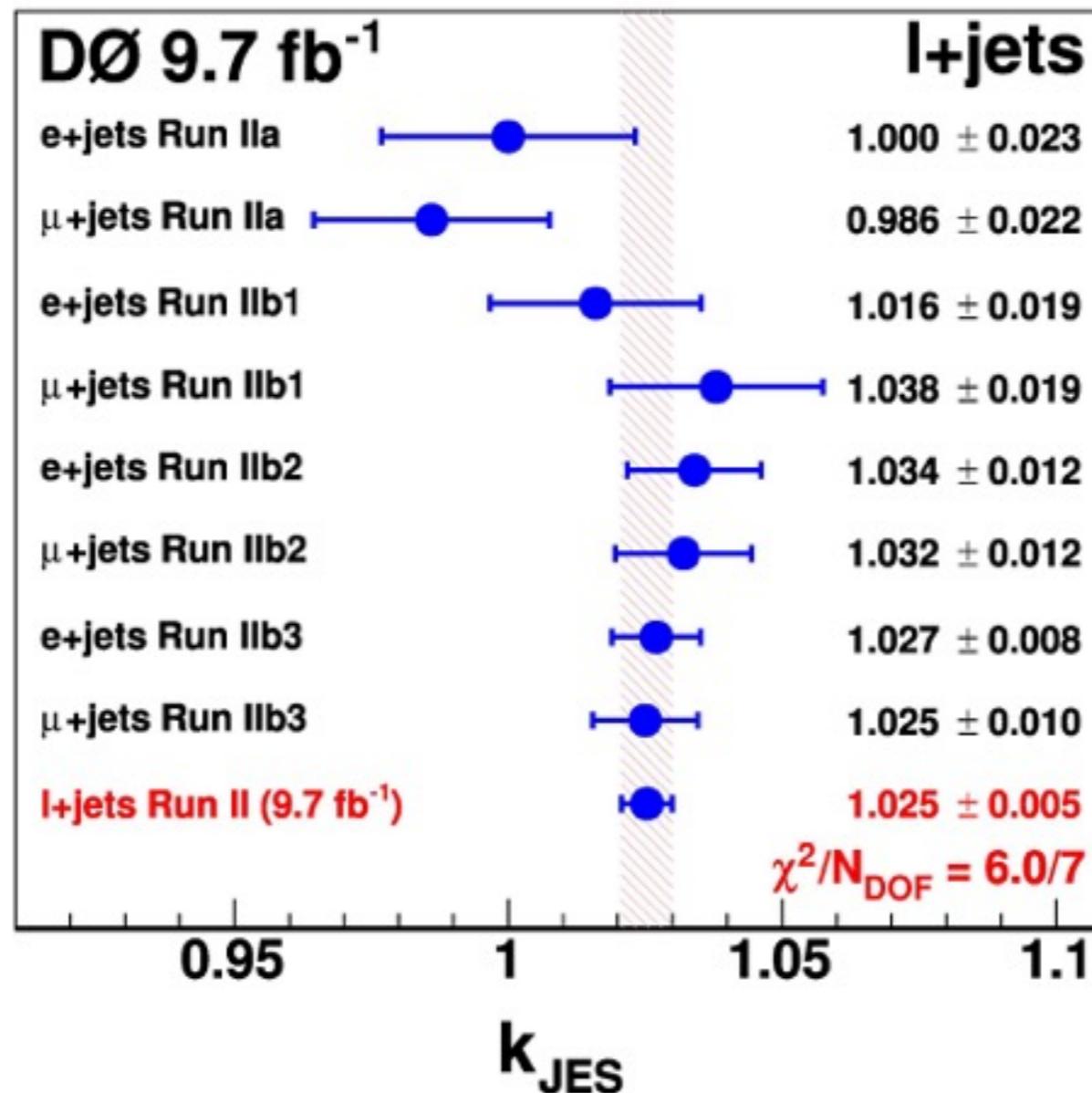
LO matrix element
PRD 53, 4886 (1996)
PLB 411, 173 (1997)

Phase space factor

Transfer functions (TFs) to map parton level quantities y to reco level quantities x

DØ Coll., PRD 84, 032004 (2011)

Mass in different epochs



- Neutrino weighting (vWT)

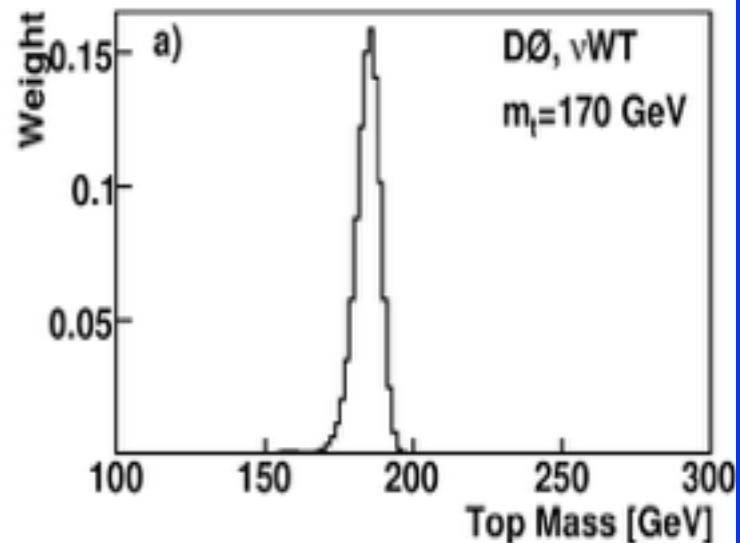


- assign a weight based on the agreement between the calculated neutrino p_T and the measured missing E_T

$$\mathcal{W}(m_t, \eta_1, \eta_2) = \sum_{solutions} \prod_{k=x,y} \exp\left[-\frac{(\cancel{E}_k - p_k(\nu_1 \nu_2))^2}{2\sigma(\cancel{E}_k)^2}\right]$$

- integrate over neutrino phase space

$$\mathcal{W}(m_t) = \int d\eta_1 d\eta_2 p(\eta_1|m_t) p(\eta_2|m_t) \mathcal{W}(m_t, \eta_1, \eta_2)$$





Dilepton channel systematics



CDF Run II Preliminary (9.1 fb⁻¹)

M _{top} Measurement in the t̄t Dilepton Final State	
Source	Uncertainty (GeV/c ²)
Jet energy scale	2.17
NLO effects	0.67
Monte Carlo generators	0.50
Lepton energy scale	0.41
Background modeling	0.39
Initial and final state radiation	0.38
gg fraction	0.31
b-jet energy scale	0.30
Luminosity profile (pileup)	0.27
Color reconnection	0.24
MC sample size	0.20
Parton distribution functions	0.16
b-tagging	0.05
Total systematic uncertainty	2.51
Statistical uncertainty	1.91
Total	3.15

$$M_{lb}^{\text{alt}} = c^2 \sqrt{\frac{\langle l_1, b_1 \rangle \cdot \langle l_2, b_2 \rangle}{E_{b_1} \cdot E_{b_2}}},$$

Source	σ_{m_t} [GeV]
Jet energy calibration	
Absolute scale	± 0.47
Flavor dependence	± 0.27
Residual scale	$+0.36$ -0.35
b quark fragmentation	$+0.10$
Object reconstruction	
Trigger	-0.06
Electron p_T resolution	± 0.01
Muon p_T resolution	∓ 0.03
Electron energy scale	± 0.01
Muon p_T scale	± 0.01
Jet resolution	∓ 0.12
Jet identification	$+0.03$
b tagging	∓ 0.19
Signal modeling	
Higher-order effects	-0.33
ISR/FSR	± 0.15
$p_T(t\bar{t})$	-0.07
Hadronization	-0.11
Color reconnection	-0.22
Multiple $p\bar{p}$ interactions	-0.06
PDF uncertainty	± 0.08
Background modeling	
Signal fraction	± 0.01
Heavy-flavor scale factor	± 0.04
Method	
Template statistics	± 0.18
Calibration	± 0.07
Total systematic uncertainty	± 0.85

Systematic uncertainties

cross section measurement

TABLE III: Sources of systematic uncertainties. The pre-fit uncertainty in percent from each source on the inclusive cross section is given for the $\ell + \text{jets}$ and the $\ell\ell$ channel. “Type” refers to a systematic uncertainty affecting the shape S or the normalization N of a distribution. The numbers presented for shape dependent uncertainties represent averages across the entire distribution.

Source of uncertainty	$\delta_{\ell+\text{jets}}^{\text{up}}, \%$	$\delta_{\ell+\text{jets}}^{\text{down}}, \%$	Type S/N	$\delta_{\ell\ell}^{\text{up}}, \%$	$\delta_{\ell\ell}^{\text{up}}, \%$	Type S/N
<i>Modeling of signal</i>						
Alternative signal model	+10	-10	S	+4	-4	S
Hadronization	+8	-8	S	+4	-4	S
Color reconnection	+2	-2	S	+2	-2	S
ISR/FSR variation	+2	-2	S	+2	-2	S
PDF	+7	-7	N	+1	-1	N
<i>Modeling of detector</i>						
Jet modeling & identification	+8	-8	S	+3	-3	S
b -jet modeling & identification	+5	-5	S	+12	-12	S
Lepton modeling & identification	+3.5	-3.5	S	+6	-6	N
Trigger efficiency	+5	-5	N	+2	-2	N
Luminosity	+4.7	-4.7	N	+4.3	-4.3	N
<i>Sample Composition</i>						
MC cross sections & branching ratios	+0.9	-0.9	N	+1.3	-1.3	N
$Z/W p_T$ reweighting	+1.5	-1.5	S	+4	-4	S
Multijet contribution	+23	-23	S/N	+15	-15	S/N
Z/γ^* +jets scale factor	+25	-25	S/N	+2	-2	S/N
W +jets heavy flavor scale factor	+17	-23	S/N	n.a.	n.a.	n.a.
W +jets light parton scale factor	+3.5	-1.8	S/N	n.a.	n.a.	n.a.
MC statistics	n.a.	n.a.	n.a.	+3	-3	S/N

Systematic uncertainties

cross section measurement

TABLE IV: Sources of systematic uncertainties. The post-fit uncertainty from each source on the inclusive cross section is given for the combination. The last column shows the shifts in units of SD on the combined inclusive cross section due to a particular source.

Source of uncertainty	Uncertainties $\delta_{\text{combined}}, \text{ pb}$	Shift in units of σ
<i>Modeling of signal</i>		
Alternative signal model	± 0.09	+0.2
Hadronization	± 0.25	+0.7
Color reconnection	± 0.11	+0.2
ISR/FSR variation	± 0.06	-0.3
PDF	± 0.08	-0.5
<i>Modeling of detector</i>		
Jet modeling & identification	± 0.06	-0.3
b -jet modeling & identification	± 0.16	+1.3
Lepton modeling & identification	± 0.02	-0.7
Trigger efficiency	± 0.01	-0.2
Luminosity	± 0.20	+0.3
<i>Sample Composition</i>		
MC cross sections & branching ratios	± 0.03	+0.6
$Z/W p_T$ reweighting	± 0.16	+0.9
Multijet contribution	± 0.09	+0.1
$W+jets$ heavy flavor scale factor	± 0.15	-2.0
$W+jets$ light parton scale factor	± 0.05	+0.8
MC statistics	± 0.01	< 0.0
Total systematic uncertainty	± 0.55	

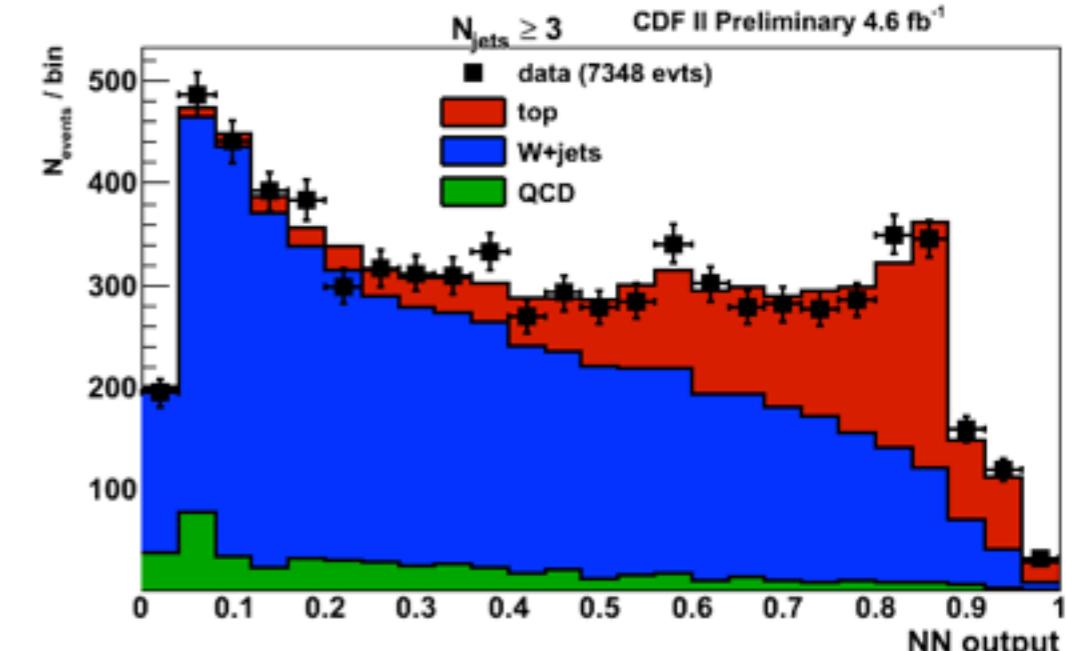
- two methods
 - ▶ b-tag counting
 - ▶ event kinematics
- measure Z cross section
 - ▶ use same triggers
 - ▶ same data set
- compute the ratio of $t\bar{t}$ to Z cross section taking into account correlations
- trade luminosity uncertainty for Z cross section theoretical uncertainty

- combine using BLUE
- statistical correlation 32%

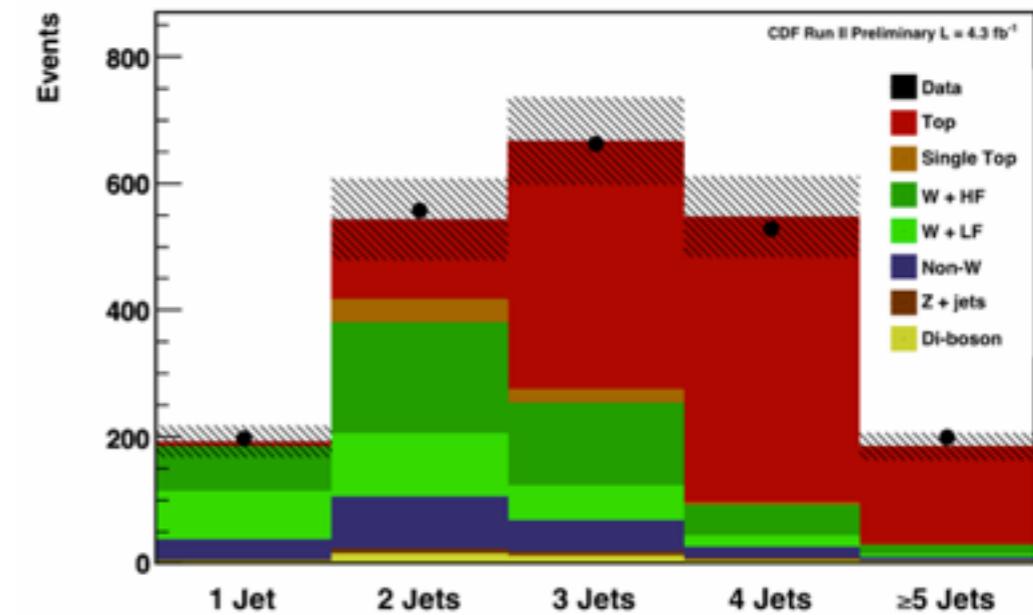
$$\sigma_{t\bar{t}} = 7.70 \pm 0.52 \text{ (total) pb}$$

7% relative precision, 8.8% with luminosity uncertainty

PRL 105:012001, 2010

4.6 fb⁻¹

$$\sigma_{t\bar{t}} = 7.82 \pm 0.38(\text{stat}) \pm 0.37(\text{syst}) \pm 0.15(\text{th}) \text{ pb}$$



$$\sigma_{t\bar{t}} = 7.32 \pm 0.36(\text{stat}) \pm 0.59(\text{syst}) \pm 0.14(\text{th}) \text{ pb}$$

Dilepton channel

□ cut and count with and w/o b-tagging

- ▶ 576 dilepton candidate events for pretag
- ▶ 246 dilepton candidate events for b-tagged

Source	pretag (%)	b-tag (%)
signal acceptance pretag	4.8	4.8
b-tagging		5
total acceptance	4.8	6.9
background model	7.1	2.1
Total	8.6	7.2

- ▶ luminosity uncertainty 6.1%

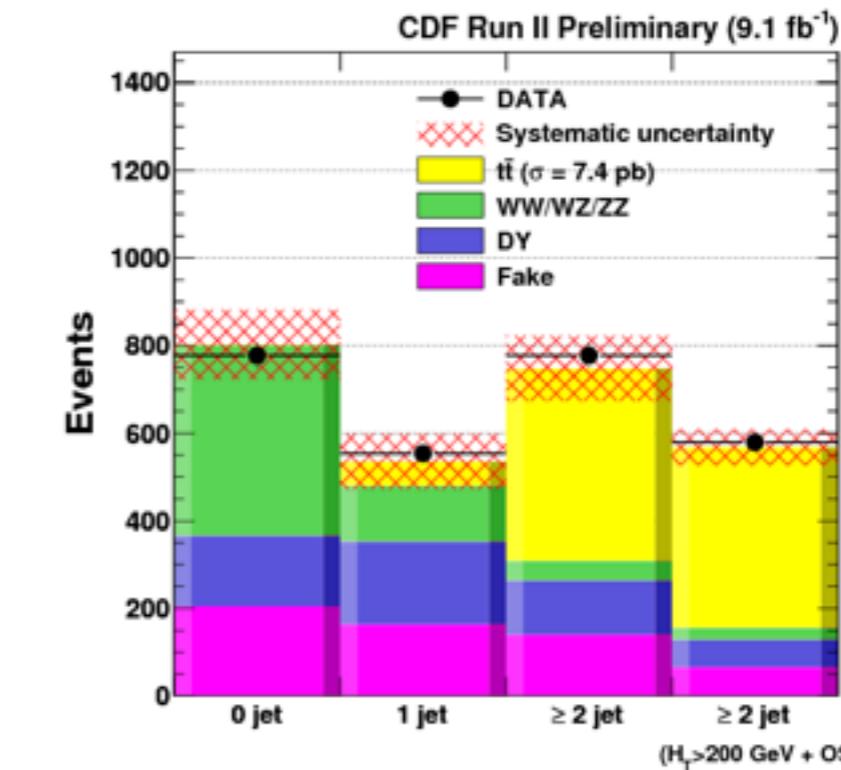
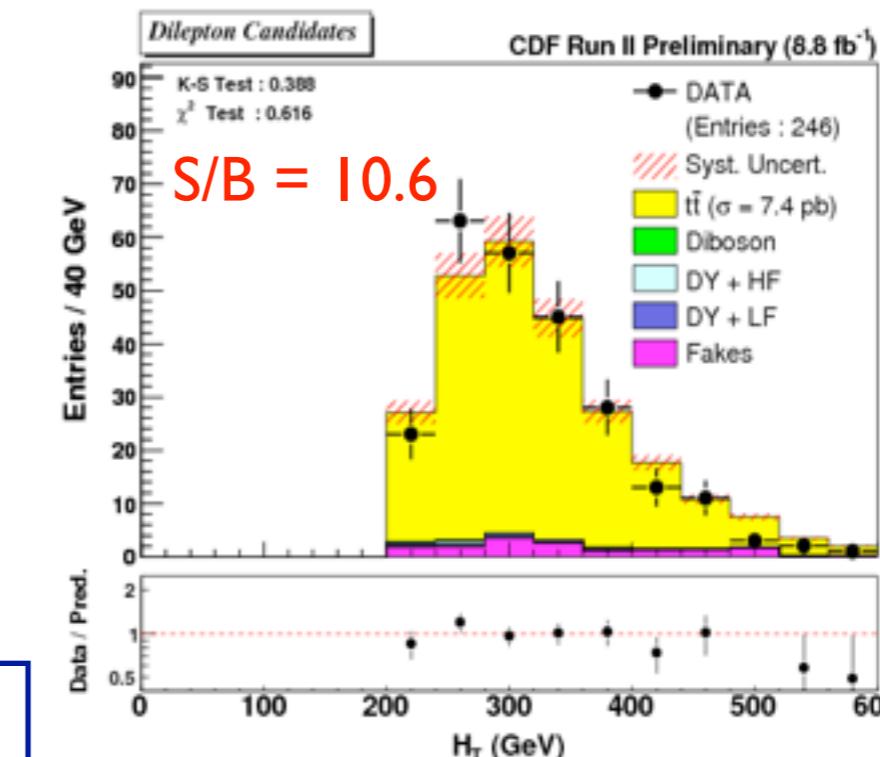
 $m_t = 172.5 \text{ GeV}$

$$\sigma_{t\bar{t}}^{\text{pretag}} = 7.61 \pm 0.44(\text{stat}) \pm 0.52(\text{syst}) \pm 0.47(\text{lumi}) \text{ pb}$$

$$\sigma_{t\bar{t}}^{\text{tag}} = 7.09 \pm 0.49(\text{stat}) \pm 0.52(\text{syst}) \pm 0.43(\text{lumi}) \text{ pb}$$

b-tag measurement has better precision: 9.4%

Phys.Rev.D88:091103, 2013

 9.1 fb^{-1} $S/B = 2.6$  8.8 fb^{-1}