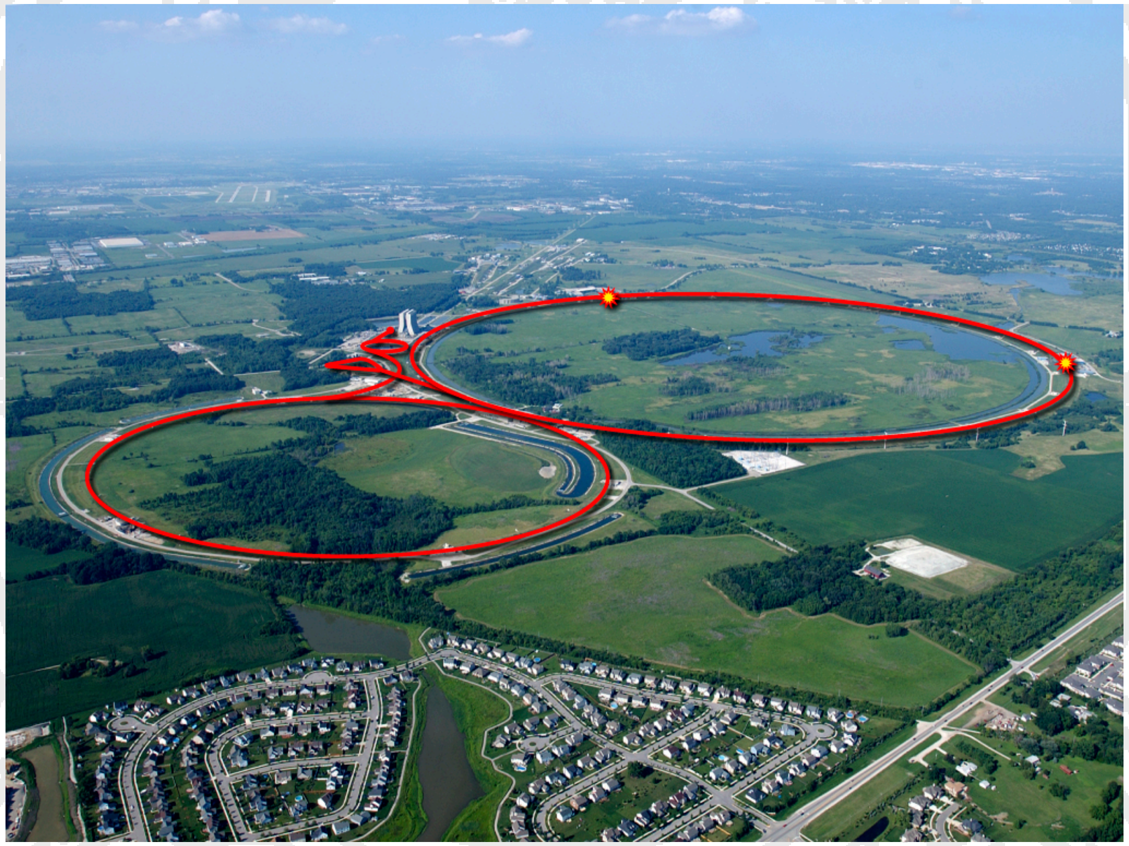
Top pair and single top cross sections at the Tevatron



Elizaveta Shabalina
II. Physikalisches Institut, Universität Göttingen
for CDF and D0 collaborations

PHYSICS AT THE TERA SCALE
Helmholtz-Alliance

Tevatron and detectors

Strong production of top pairs

motivation

measurements in lepton+jets channel

measurements in dilepton channel

summary

Electroweak top quark production

motivation

cross section measurements

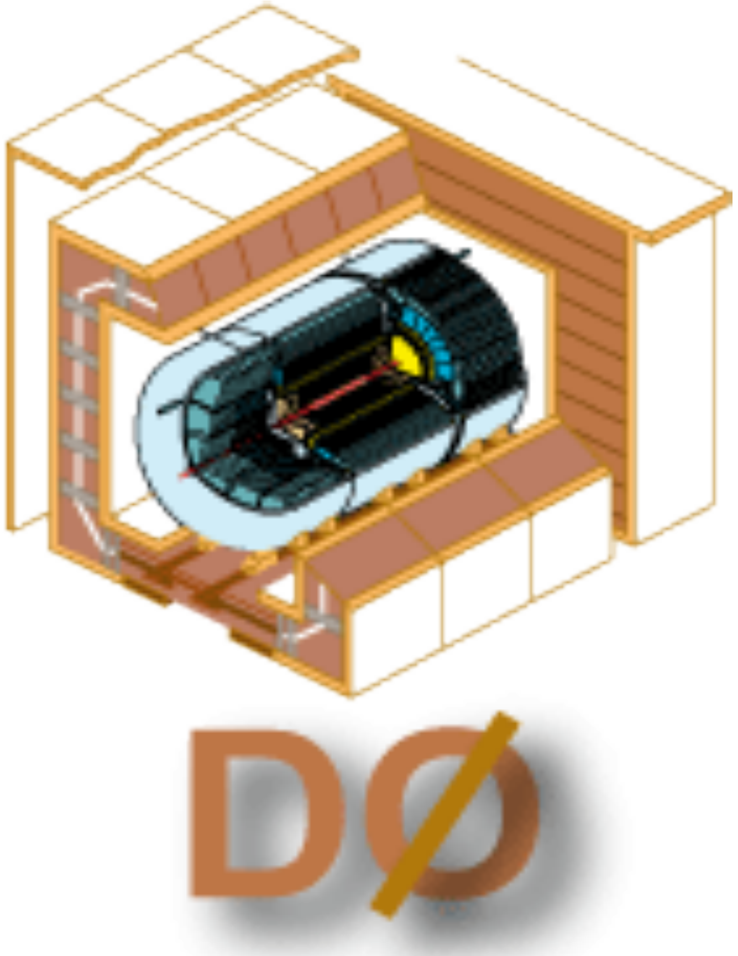
$|V_{tb}|$ and anomalous couplings

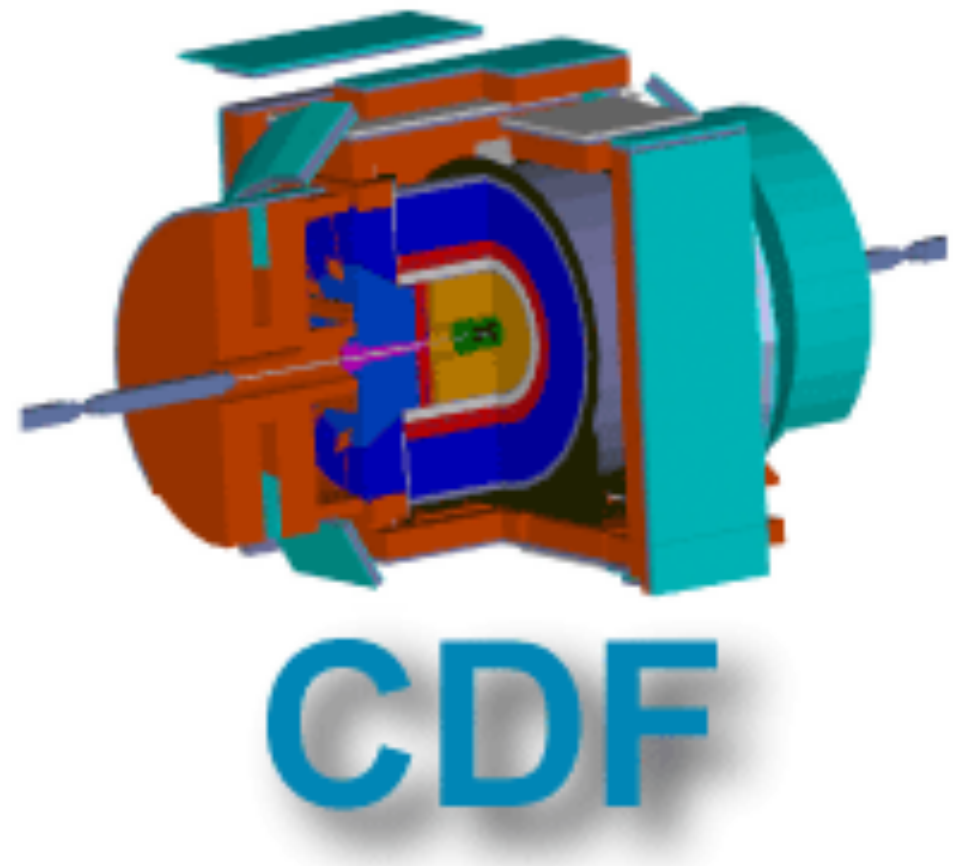
Conclusions

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 TeV
- shut down on Sept. 30 2011
- 10.5 fb^{-1} of recorded data per experiment
- current results - up to 6 fb^{-1} of data

Experiments





- 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 quark pair production

Main mechanism: pair production via strong interaction

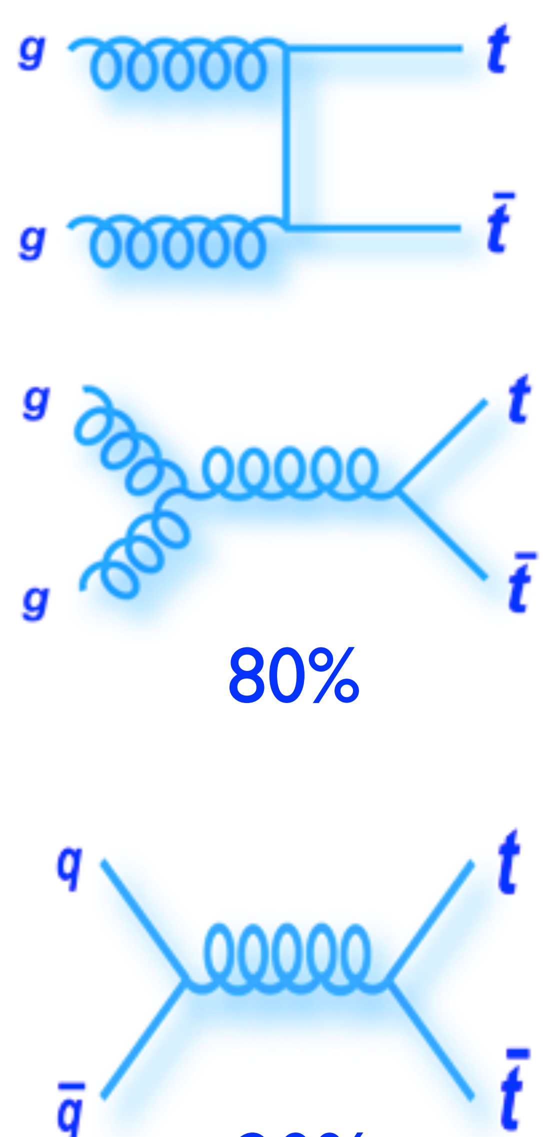
Tevatron

85%

15%

CP eigenstate

LHC



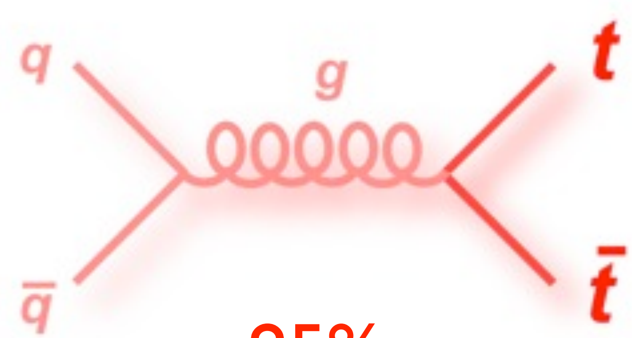
80%

20%

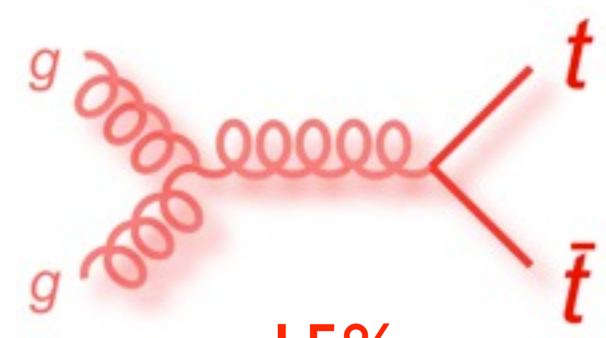
Top quark pair production

Main mechanism: pair production via strong interaction

Tevatron



85%



15%

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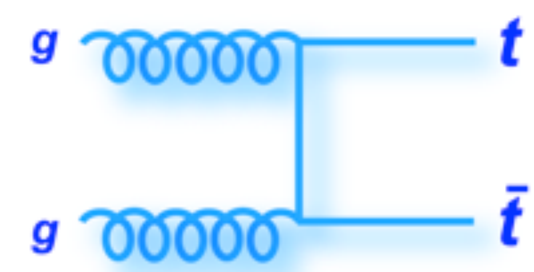
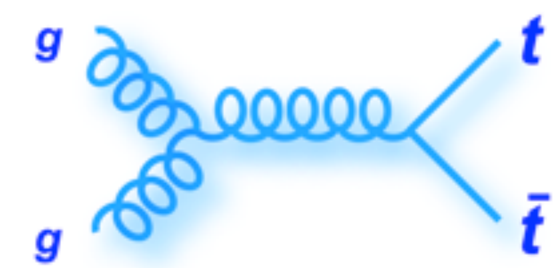
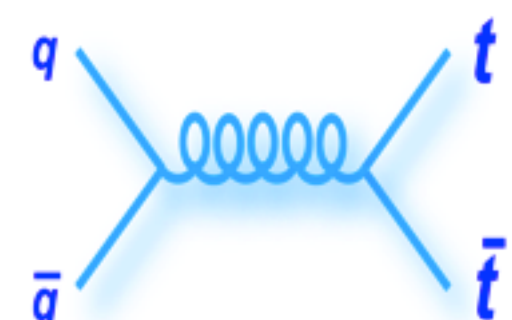




80%



20%

NNLO$_{approx}$ for m_t = 172.5 GeV, CTEQ 6.6 PDF

$\sqrt{s}$ (TeV)	2	7	14
$\sigma_{t\bar{t}}$ (pb)	7.46	160.8	886.3

~9% uncertainty

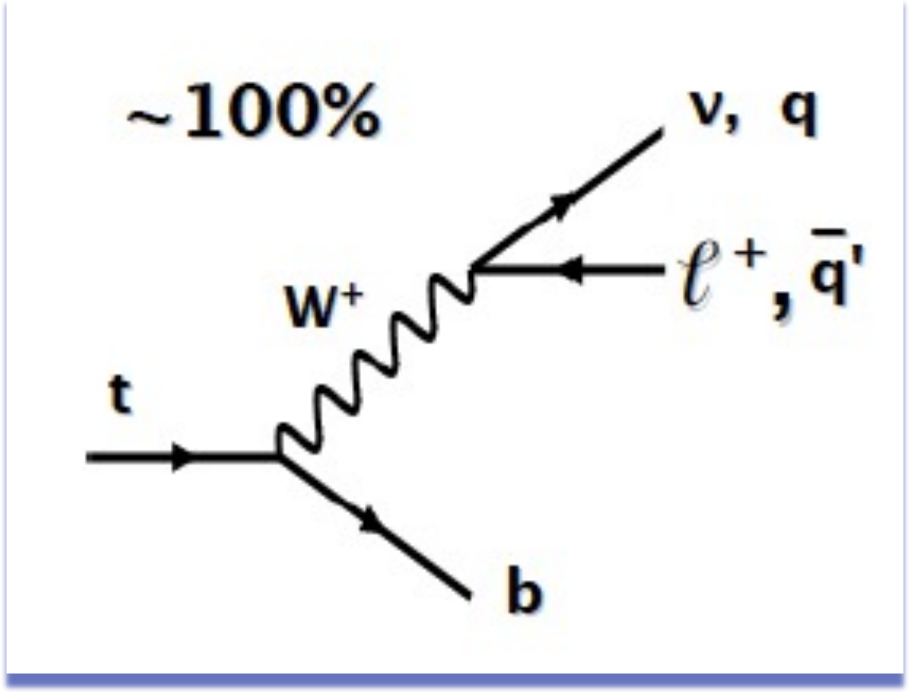
~20 larger than at Tevatron

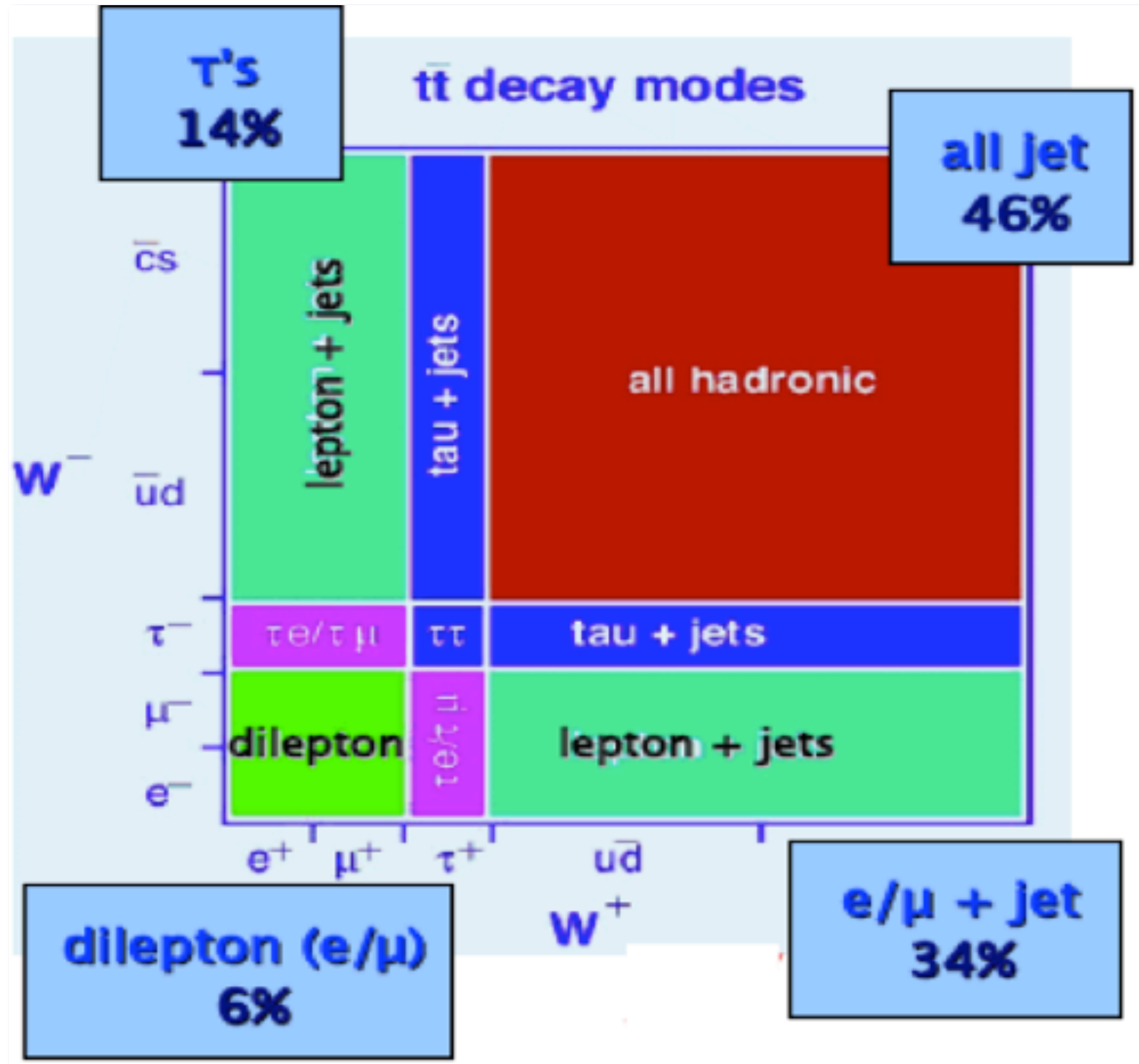
PRD 80, 054009 (2009)

LHC sample @1 fb^{-1} ~20,000 l+jets events
full Tevatron sample ~5,000 l+jets events

Top quark decay

In Standard Model



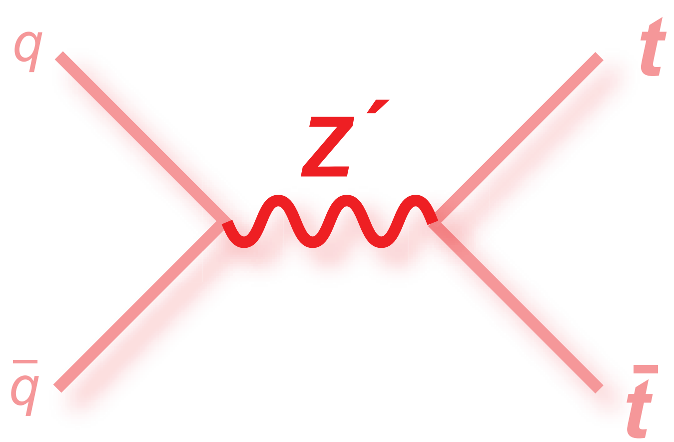


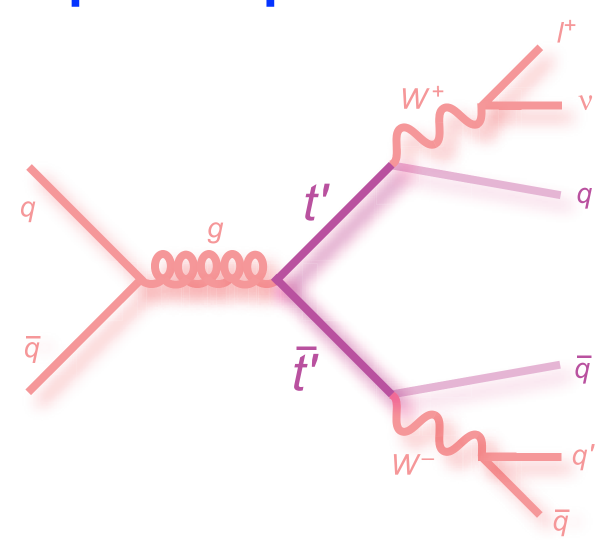
W decay mode defines top pair final state

Motivation

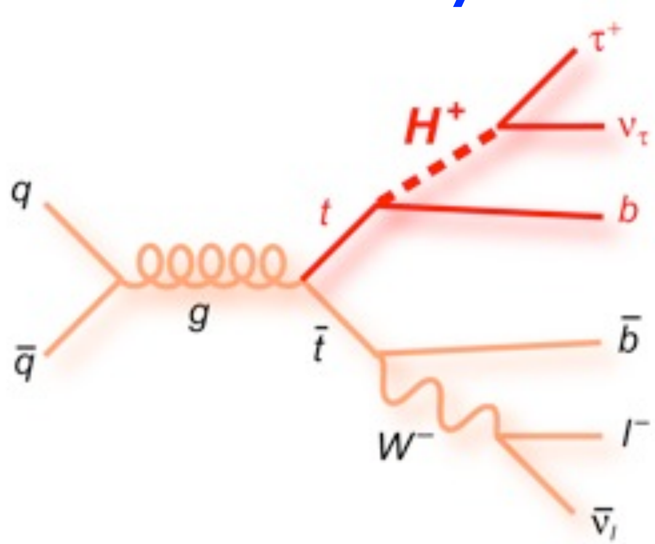
- First step in understanding selected $t\bar{t}$ sample
- Test of theoretical QCD calculations

New physics in top quark production





... and decay



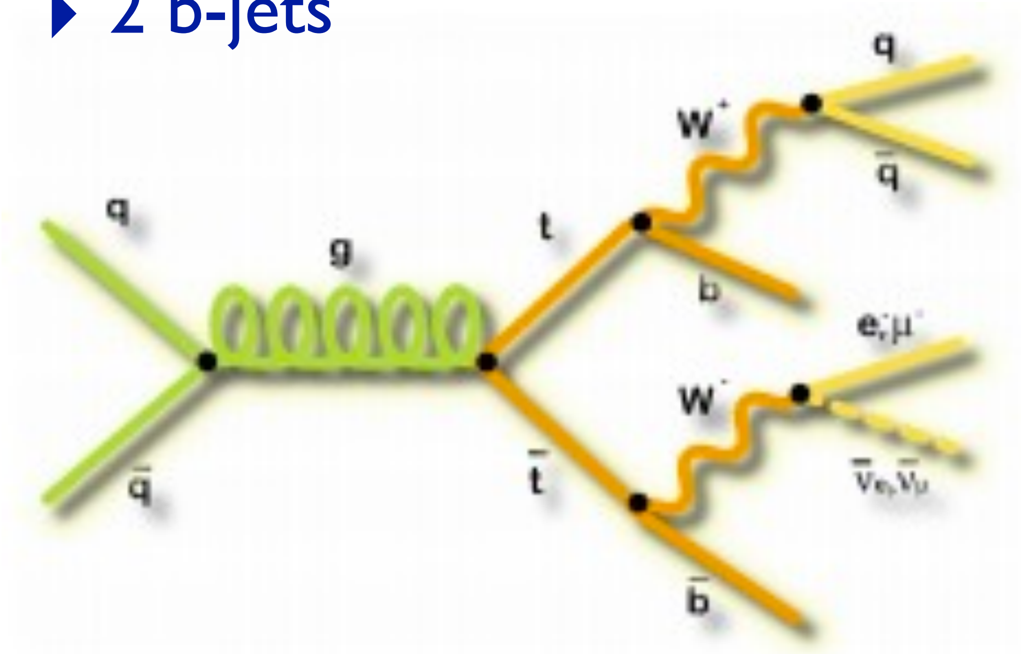
- New physics can change
  - overall production rate
  - rate in different channels
- Precision measurements of cross section are important in different decay channels

lepton+jets channel

Provides the most precise measurements

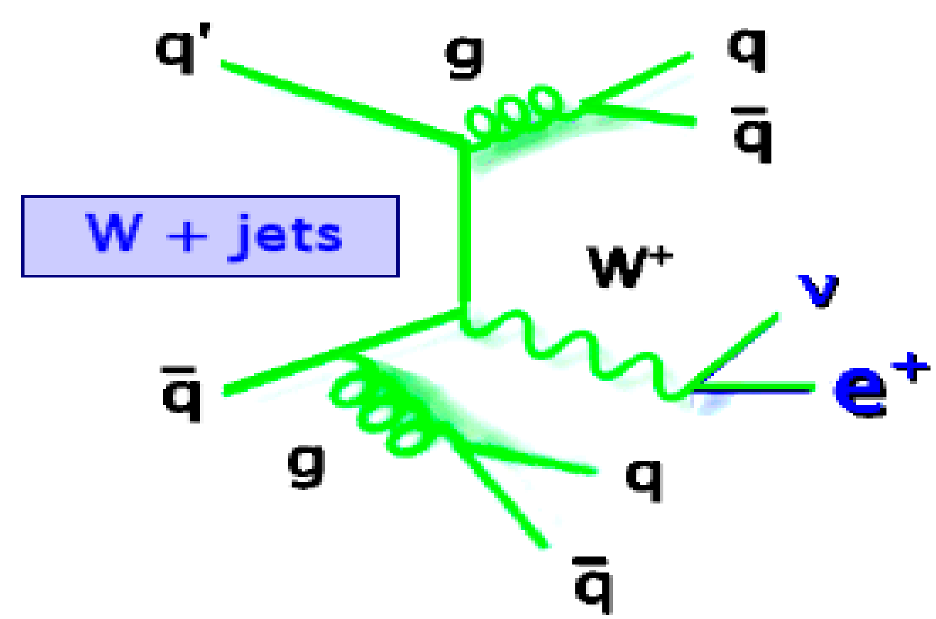
Signature

- one high p_T isolated lepton
- large missing transverse momentum
- $\geq$ 4 jets
- 2 b-jets

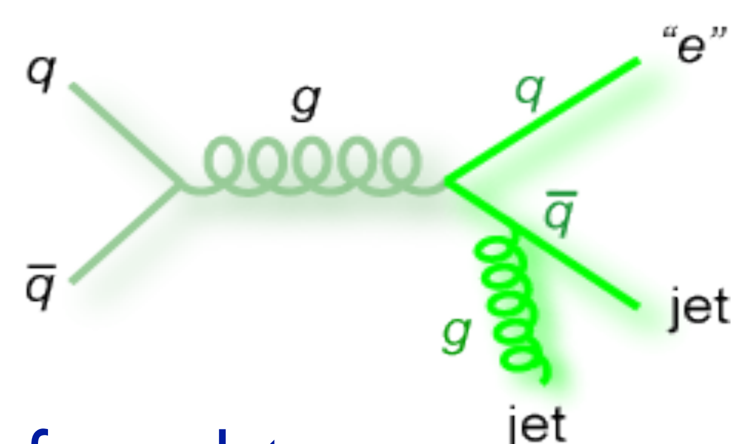


S/B (4 jets)	
topo	1 b-tag
2:3	4:1

Backgrounds



- based on MC simulation

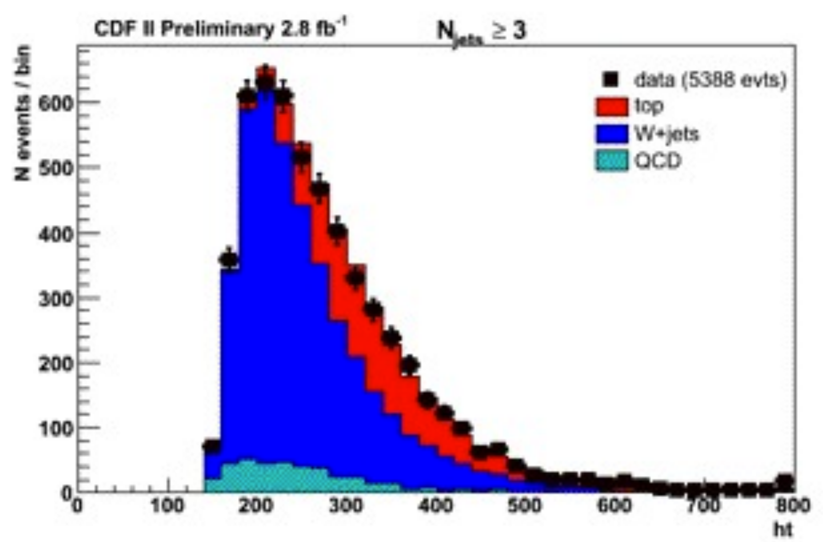


multijet

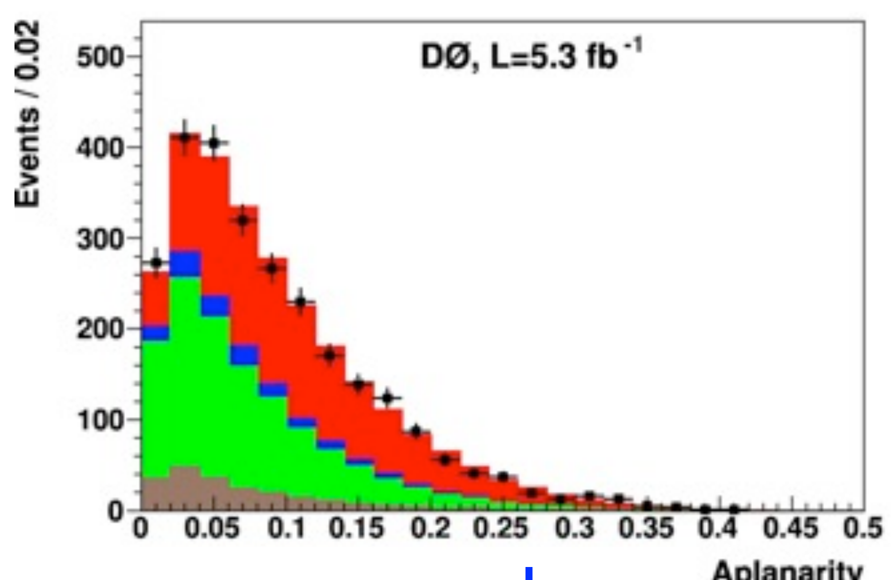
- from data

Finding top quarks: kinematics

- exploit differences between kinematic properties of signal and W+jets background
- select discriminating variables

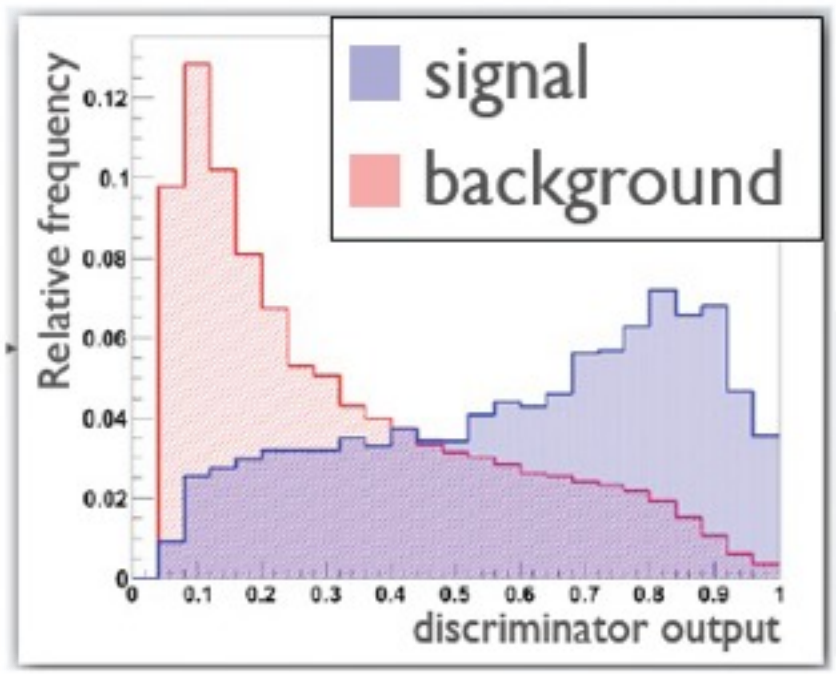


energy-dependent



angular

- build a discriminant from these variables
  - likelihood
  - neural network
  - boosted decision trees



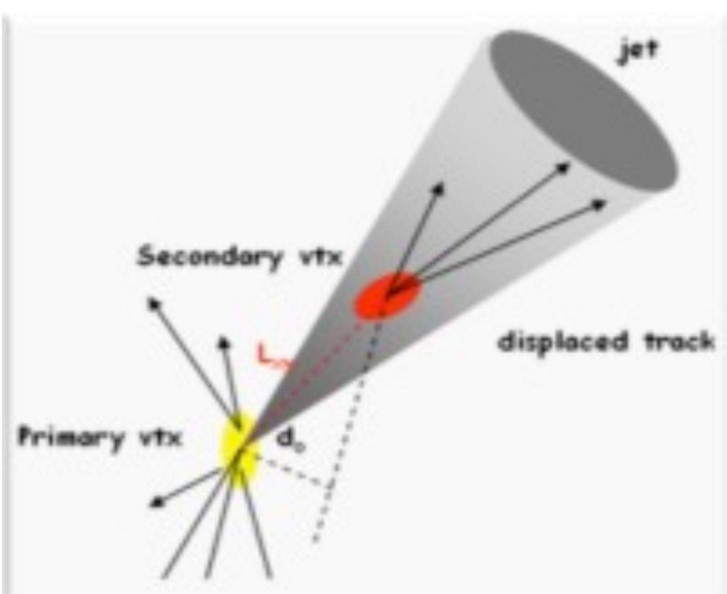
- extract cross section from a binned likelihood fit to data

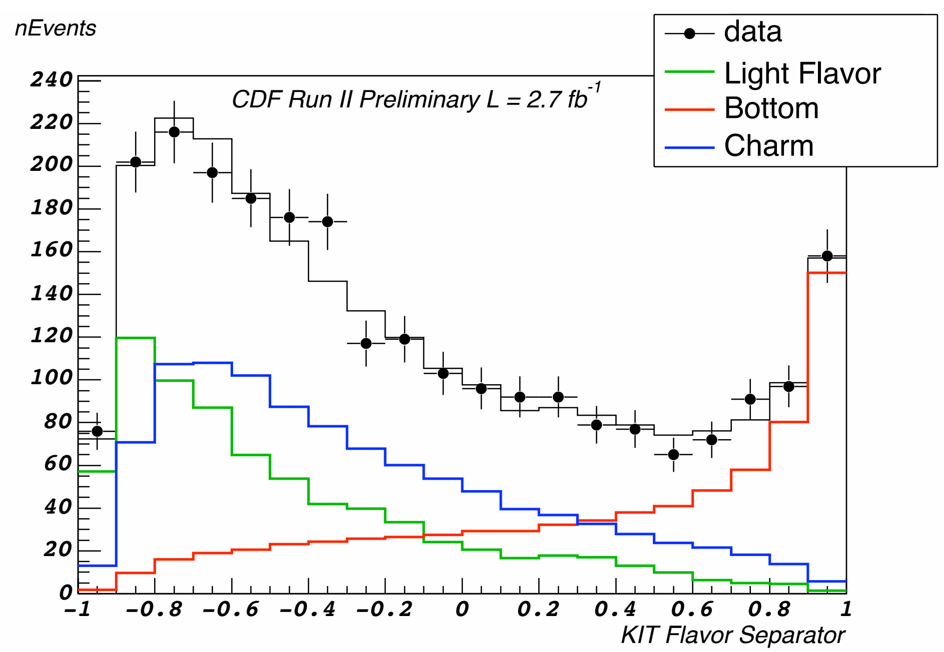
same idea is used for single top cross section measurements

Finding top quarks: b-tagging

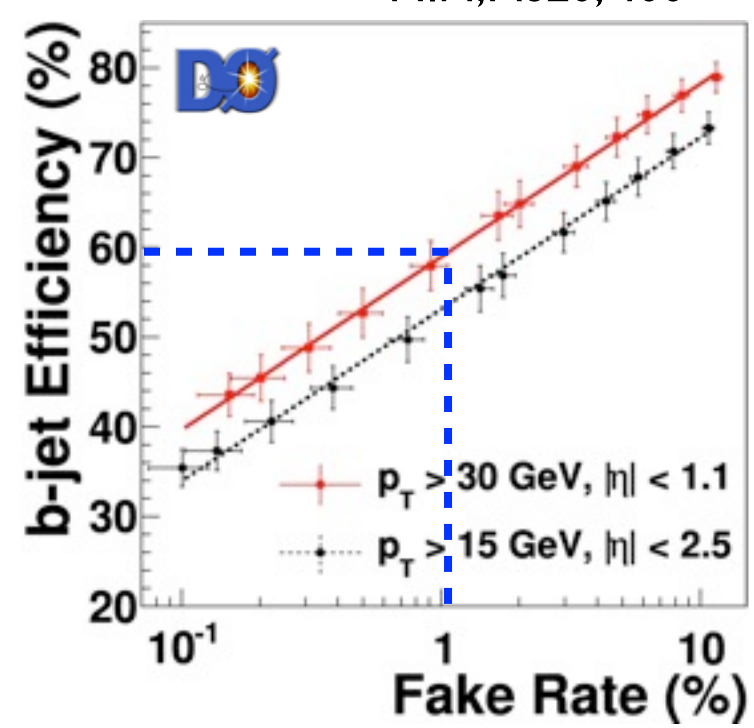
- Powerful tool to suppress backgrounds to top
- Utilizes
  - long live time of B-hadrons
  - semileptonic B decays
- Use as
  - cut on b-tagging algorithm output
  - continuous variable

- CDF Neural network heavy flavor separator applied after SVX tagger
  - separates b from charm and light
  - 25 input variables
- DØ Neural Network tagger
  - combines properties of displaced tracks and secondary vertex - 7 variables





NIM, A620, 400

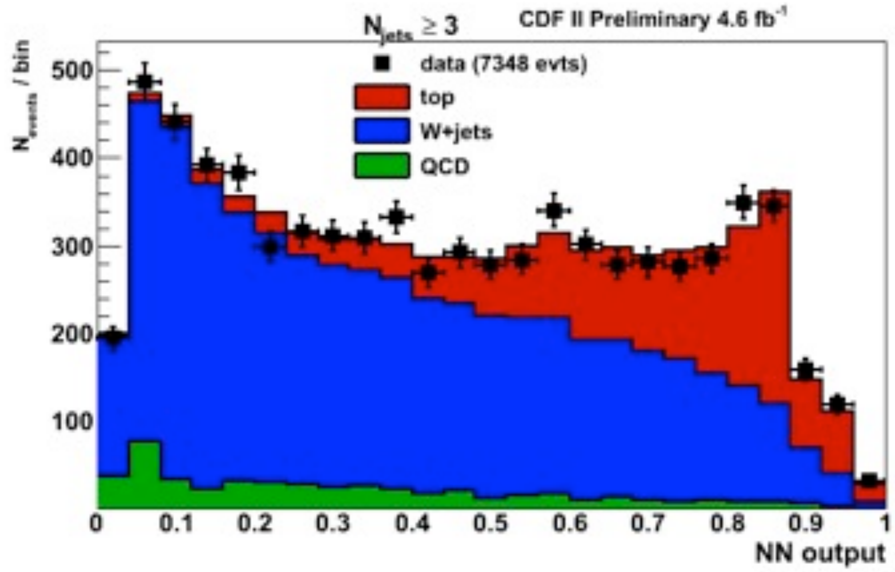


Cross sections: lepton+jets

PRL 105:012001,2010

- both methods: NN and b-tagging and their combination
- take ratio to Z cross section
- trade luminosity uncertainty for Z theory uncertainty

8.8% relative precision with luminosity uncertainty, 7% with ratio to σ(Z)



4.6 fb^{-1}

combined b-tag and NN methods

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

Cross sections: lepton+jets

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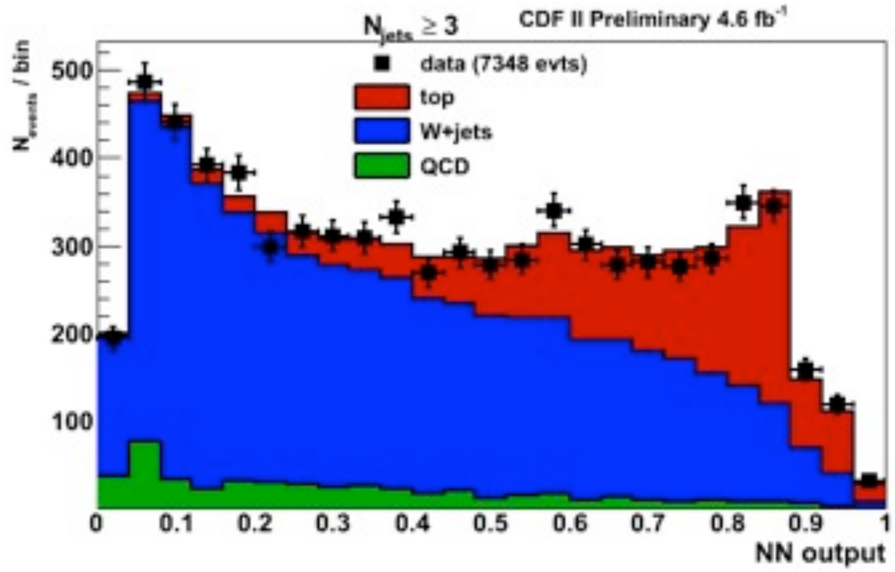
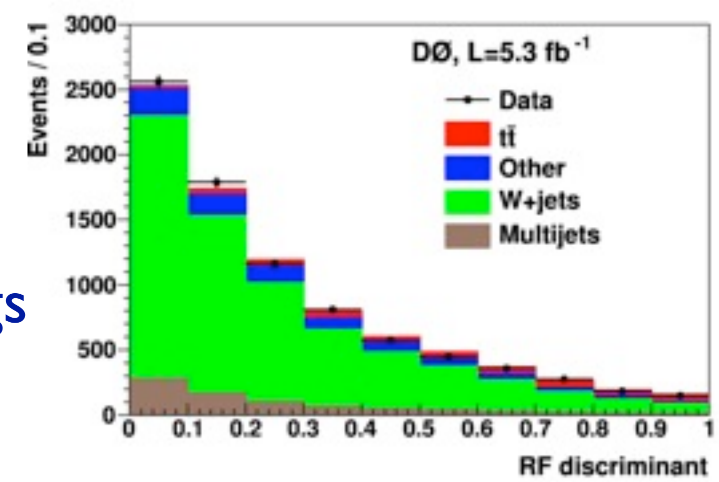


4.6 fb^{-1}

combined b-tag and NN methods

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

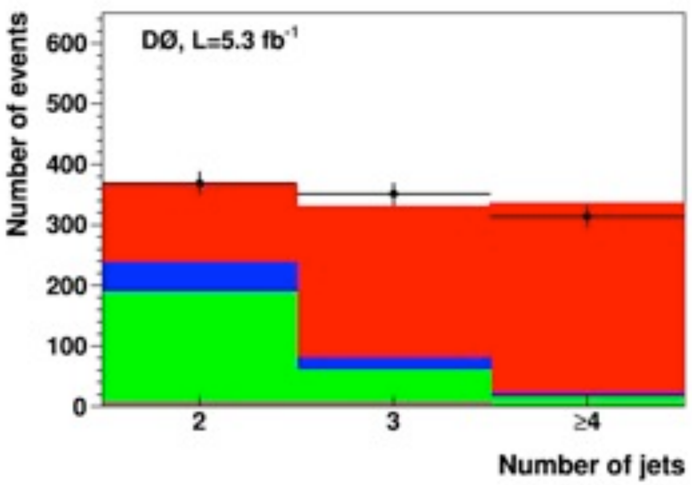
- combined method
  - BDT for background dominated samples: nj=2, 3 0 b-tag, nj=3 1 b-tag
  - b-tag counting for nj≥4, nj=3 2 b-tags
- systematics included as nuisance parameters in the fit
- data constrains the uncertainties
- largest uncertainty from luminosity



9-10% relative precision

PRD,84:012008,2011

$\sigma_{t\bar{t}} = 7.78^{+0.77}_{-0.64}$ pb

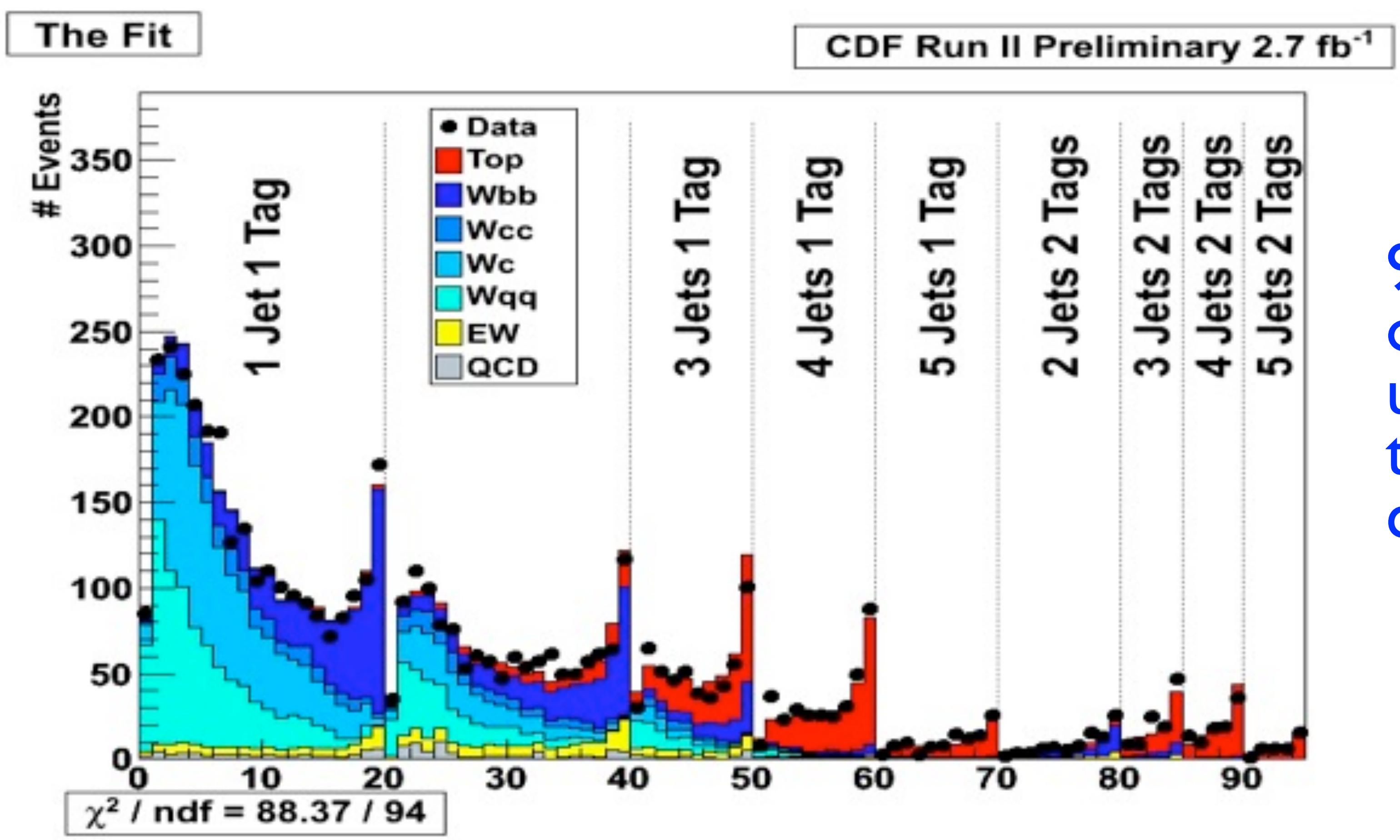


Cross sections: lepton+jets

- Simultaneous measurement of $\sigma_{t\bar{t}}$ and background normalization
- use NN flavor separator and N_{jets} distribution
- measures K-factors for W+jets

$$K_{W_{q\bar{q}}} = 1.10 \pm 0.29$$
$$K_{W_c} = 1.90 \pm 0.29$$
$$K_{W_{b\bar{b}}} = 1.57 \pm 0.25$$
$$K_{W_{c\bar{c}}} = 0.94 \pm 0.79$$

2.7 fb^{-1}



9% (15%) improvement of stat (syst) uncertainties compared to the previous b-tag counting result

$$\sigma_{t\bar{t}} = 7.64 \pm 0.57 \text{ (stat+syst)} \pm 0.45 \text{ (lumi) pb}$$

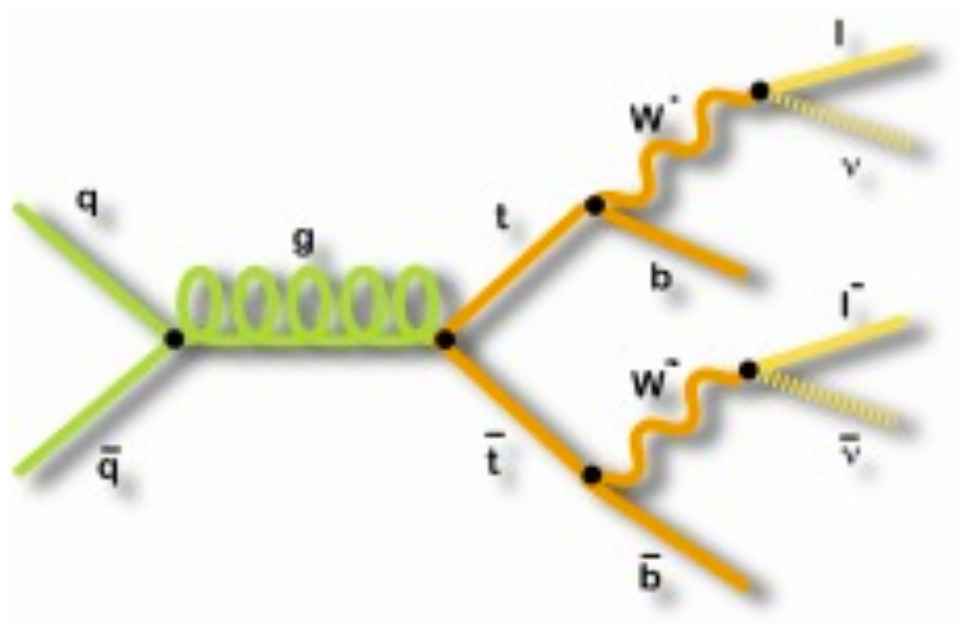
m_t = 175 GeV

9.5% relative precision

Dilepton channel

Signature

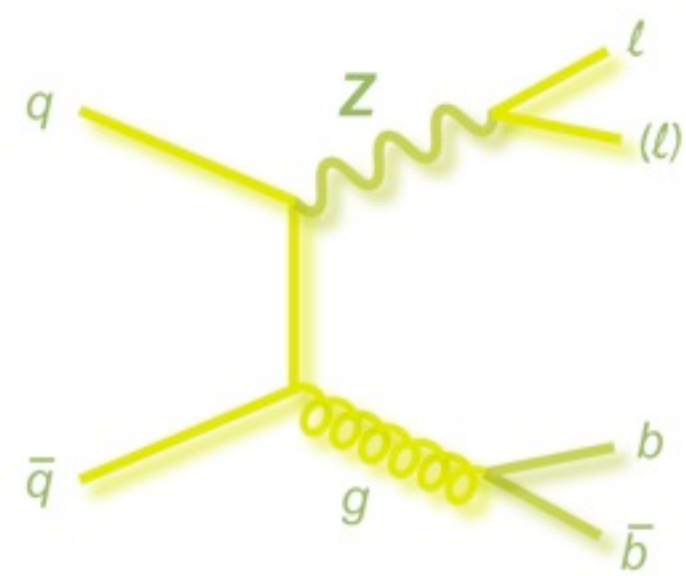
- two high p_T isolated leptons
- large missing transverse momentum
- $\geq$ 2 b-jets

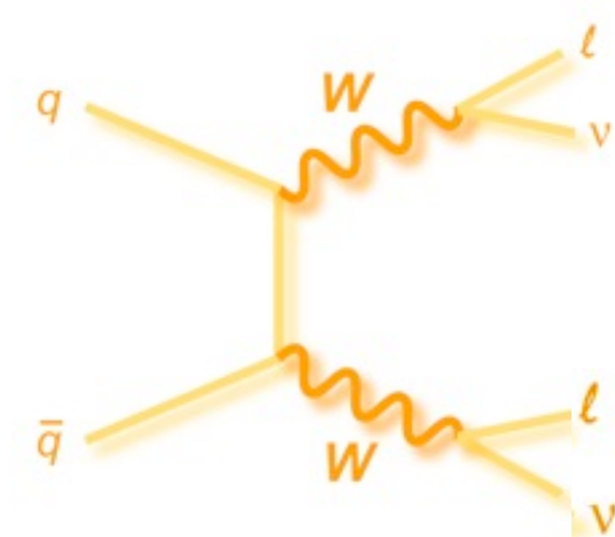


S/B

topo	1 b-tag
3:1	15:1

Backgrounds





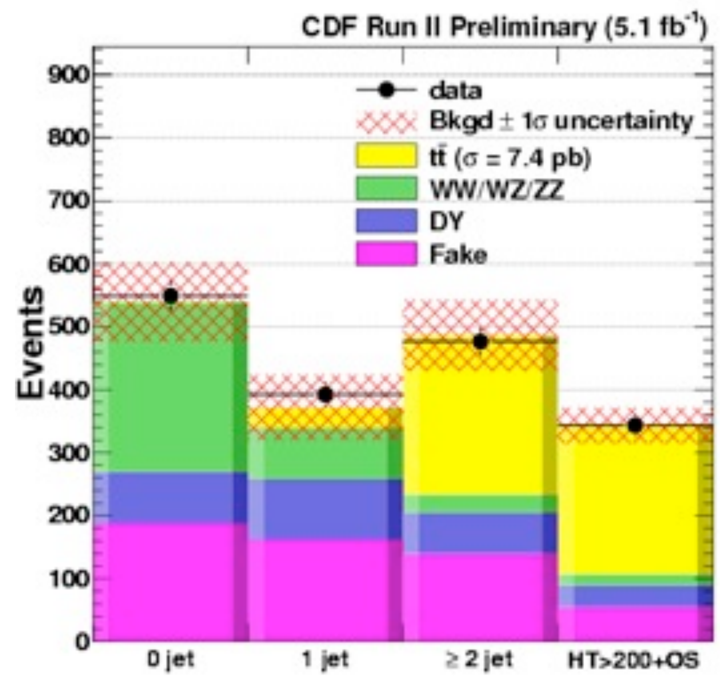
- Statistically limited at the Tevatron for a very long time
- Low backgrounds motivate the methods

Cross sections: dilepton

- 240 dilepton events
- cut and count with and w/o b-tagging

$$\sigma_{t\bar{t}} = 7.40 \pm 0.58(\text{stat}) \pm 0.63(\text{syst}) \pm 0.45\ (\text{lumi})\ \text{pb}$$
$$\sigma_{t\bar{t}} = 7.25 \pm 0.66(\text{stat}) \pm 0.47(\text{syst}) \pm 0.44\ (\text{lumi})\ \text{pb}$$

13% relative precision, with luminosity uncertainty



5.1 fb^{-1}

Cross sections: dilepton

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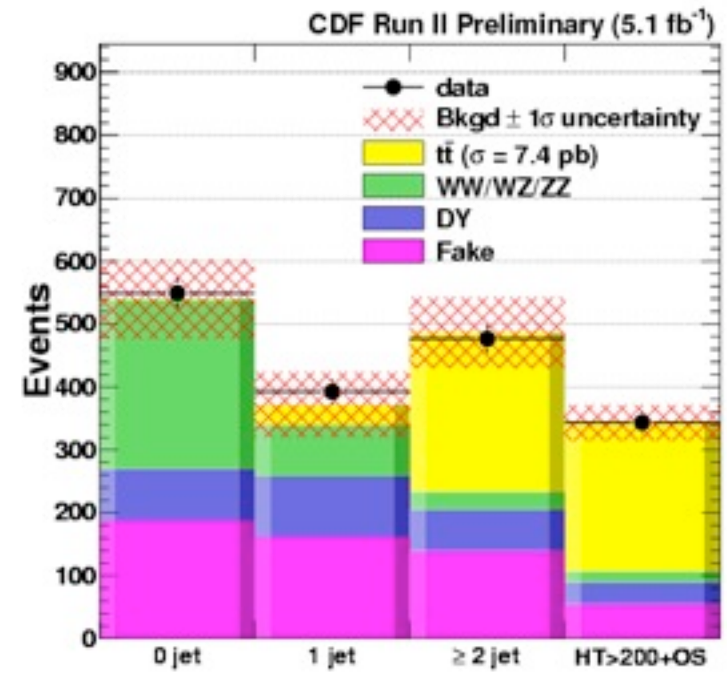


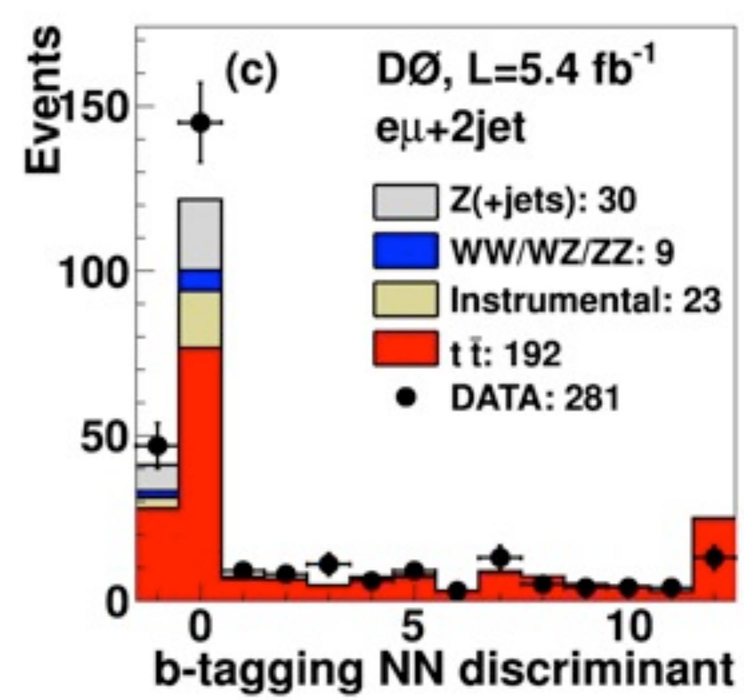
5.1 fb^{-1}

- Fit to b-tag NN discriminant distribution
- Variable: the smallest output value among 2 leading jets, i.e. most light-like jet
  - 350 dilepton events in 4 channels
- systematics included via nuisance parameters
- largest uncertainty from luminosity

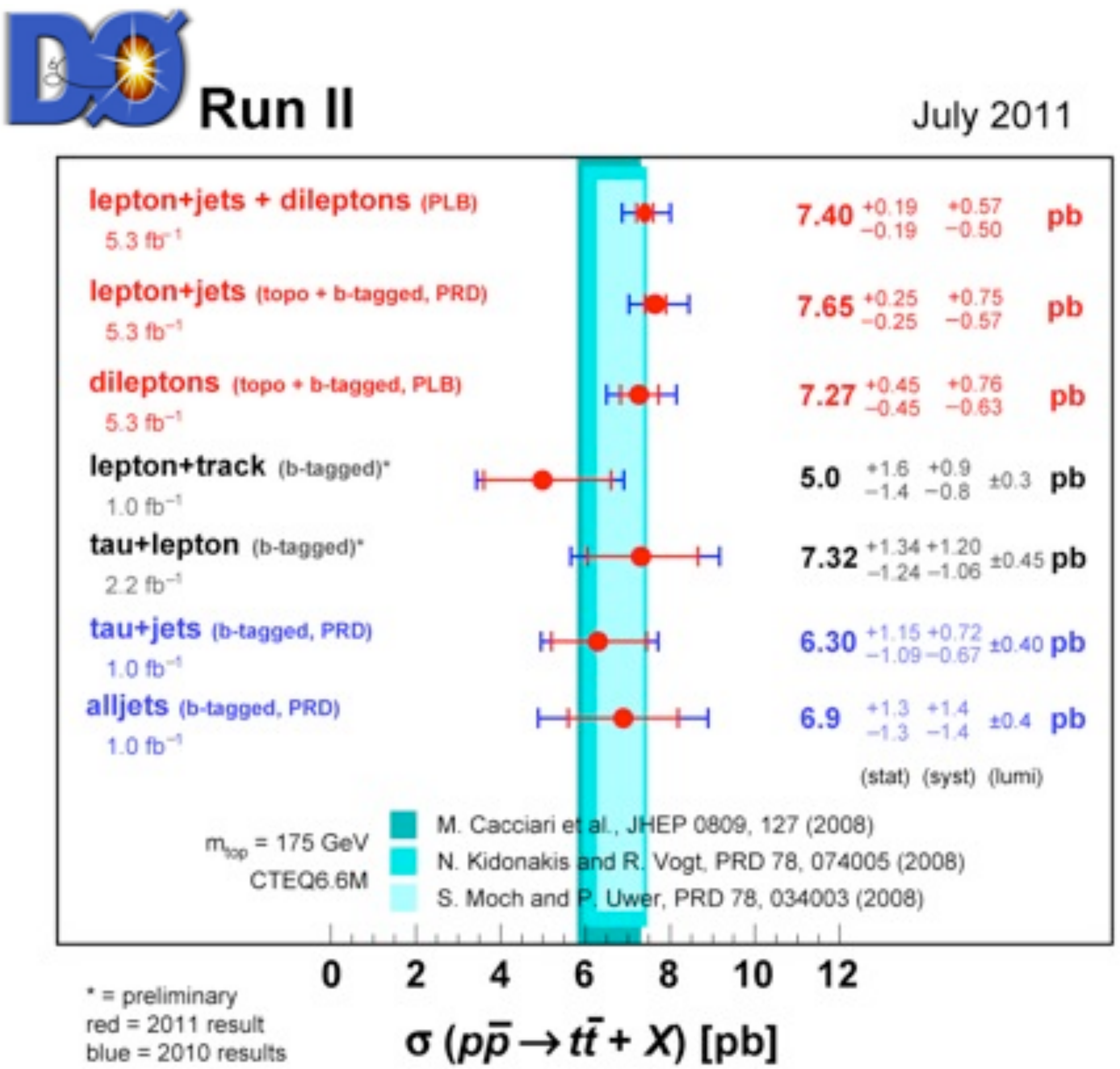
$$\sigma_{t\bar{t}} = 7.36^{+0.90}_{-0.79}$$

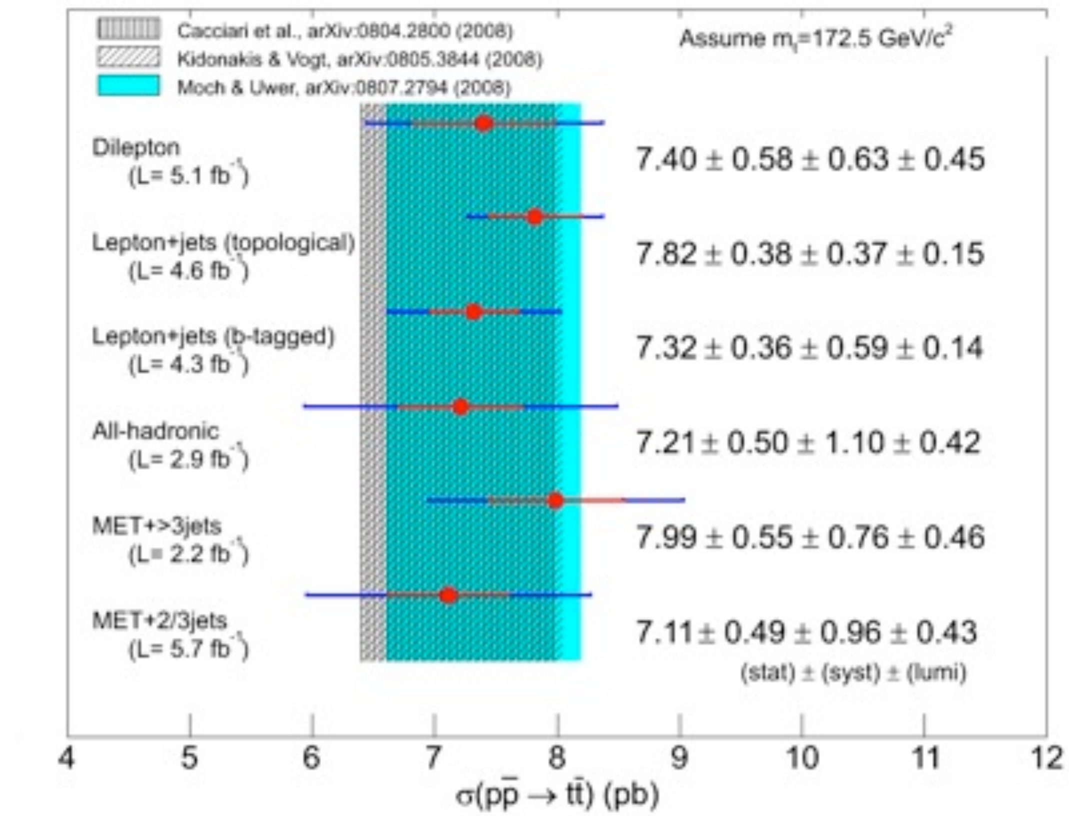
12% relative precision

PLB,704, 403,2011



Cross sections summary





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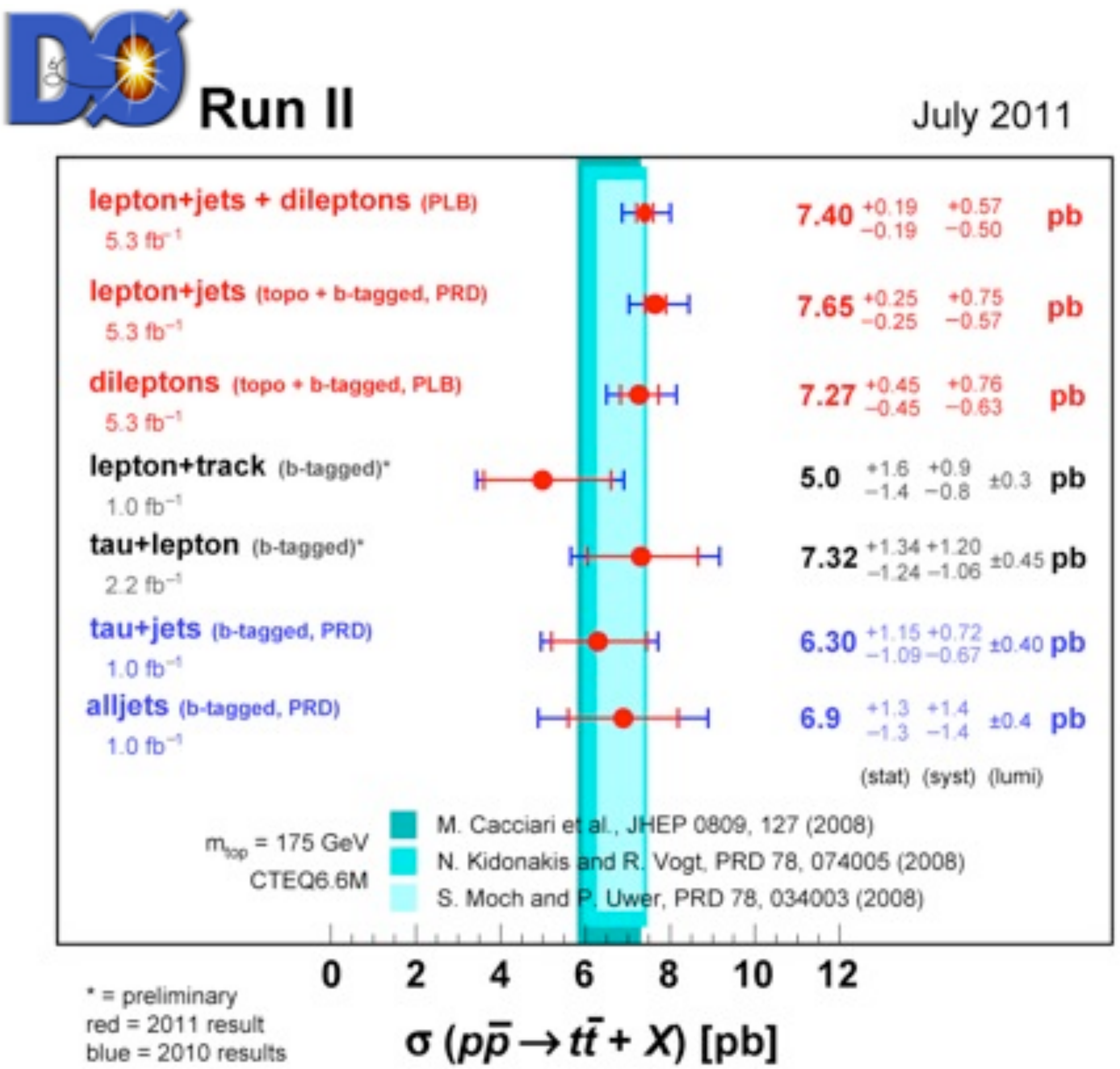
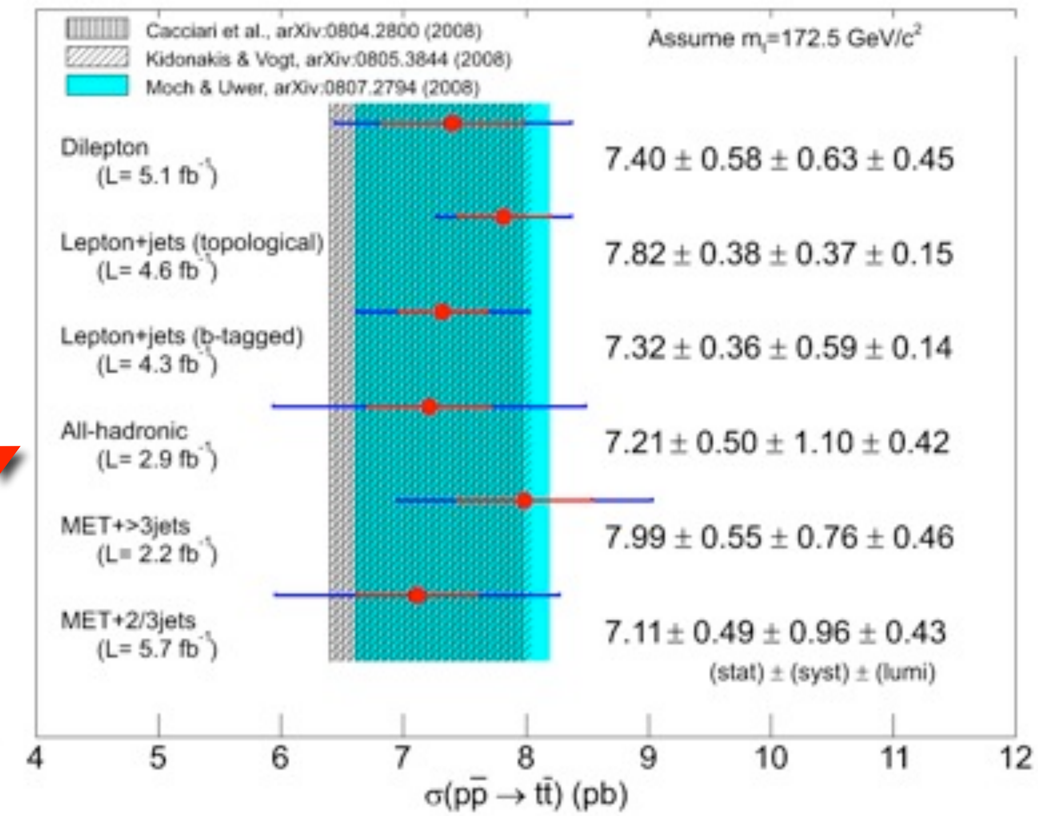


all hadronic:
no MET



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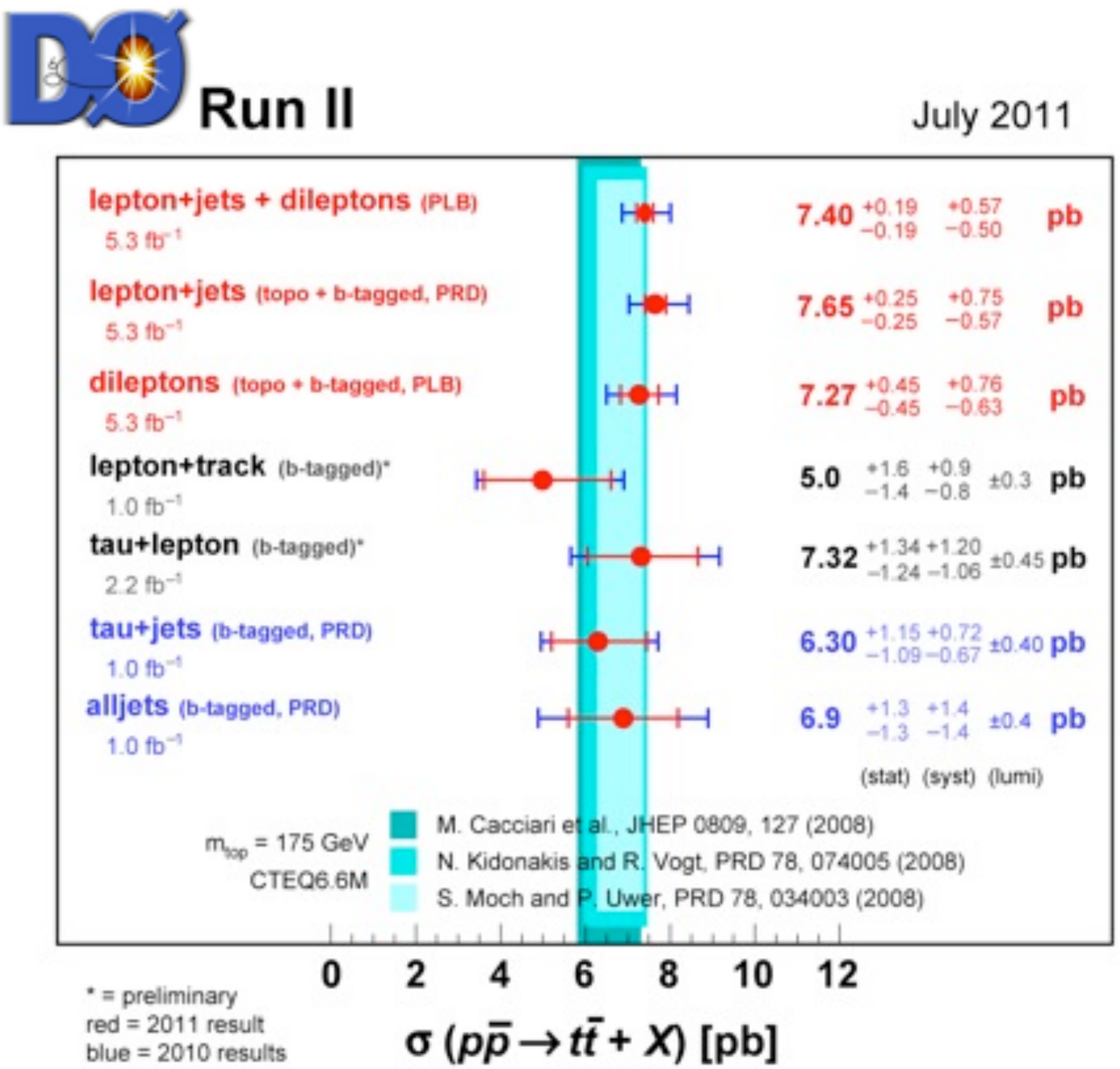
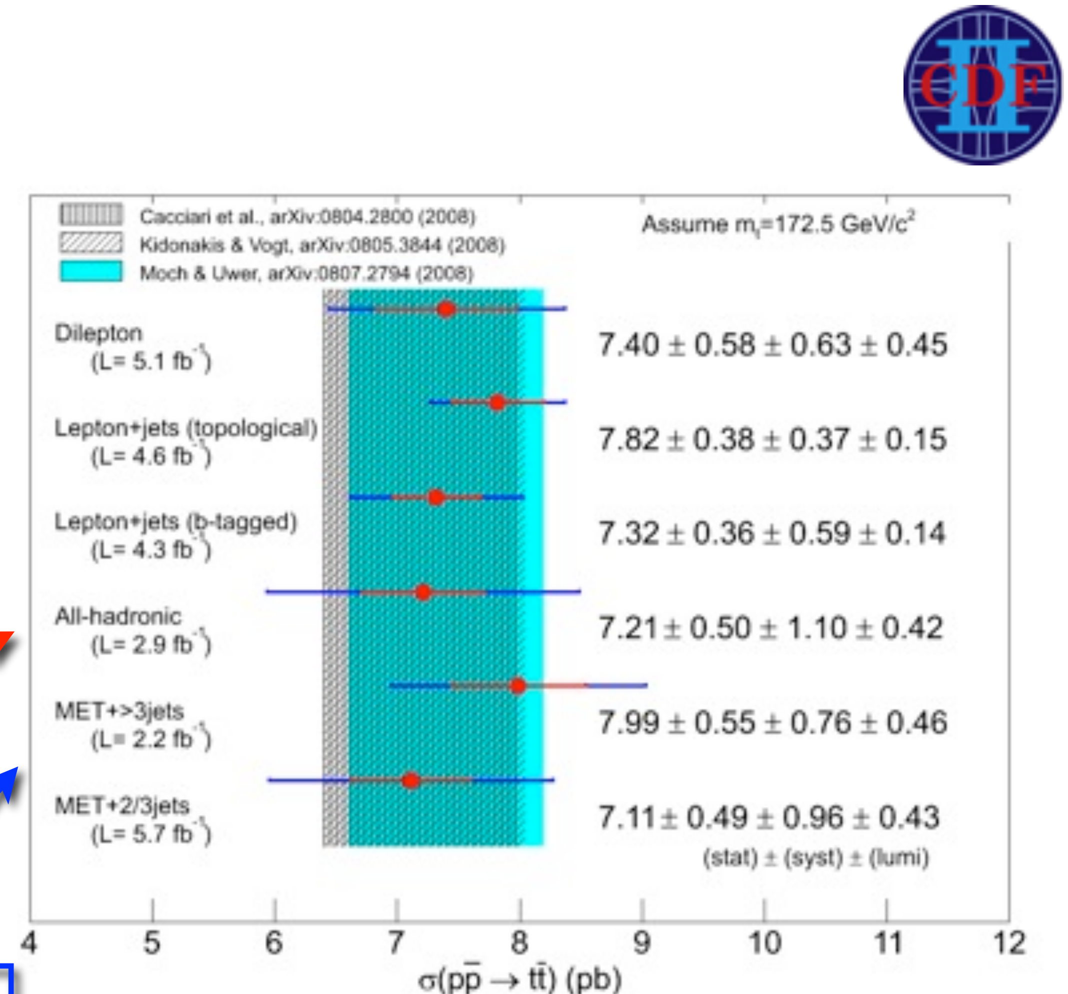
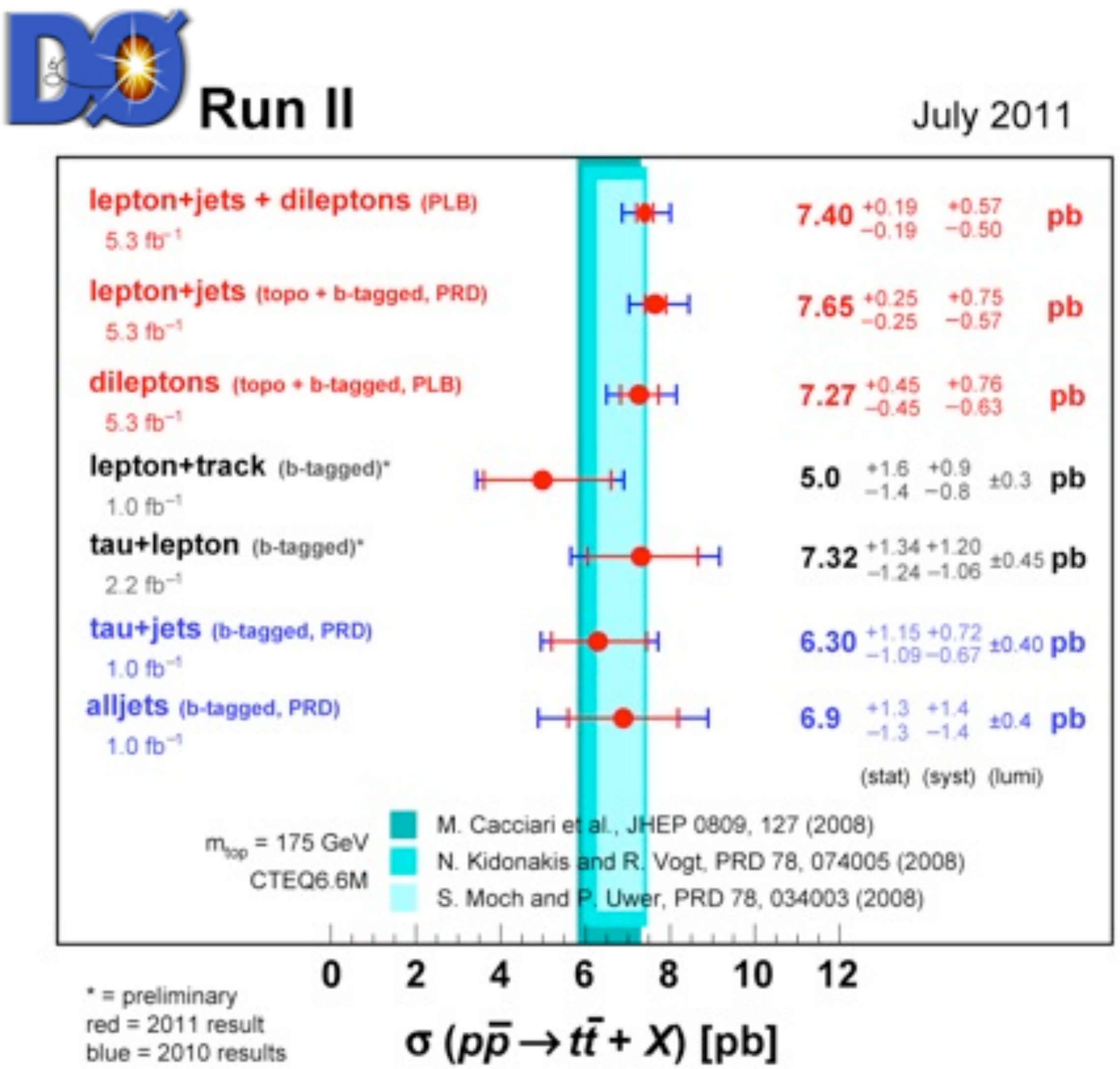


all hadronic:
no MET

MET+jets:
interesting for Higgs search



Cross sections summary



τ+(lepton/jets):
important for H+ search

all hadronic:
no MET

MET+jets:
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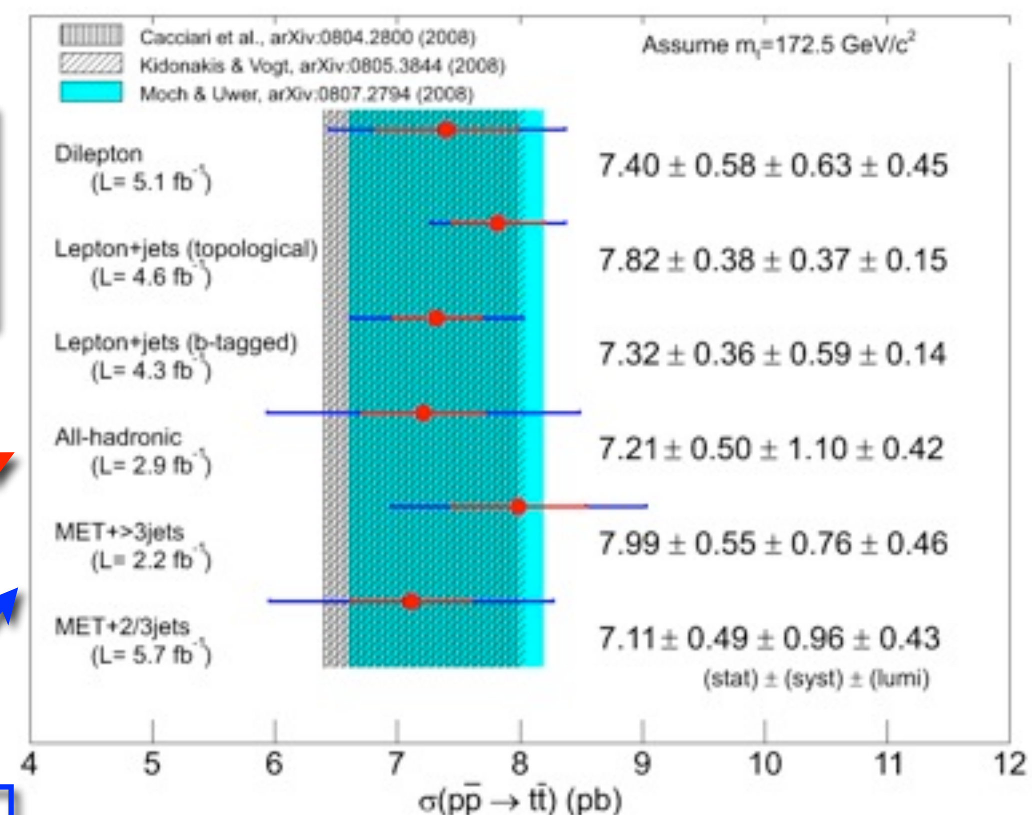

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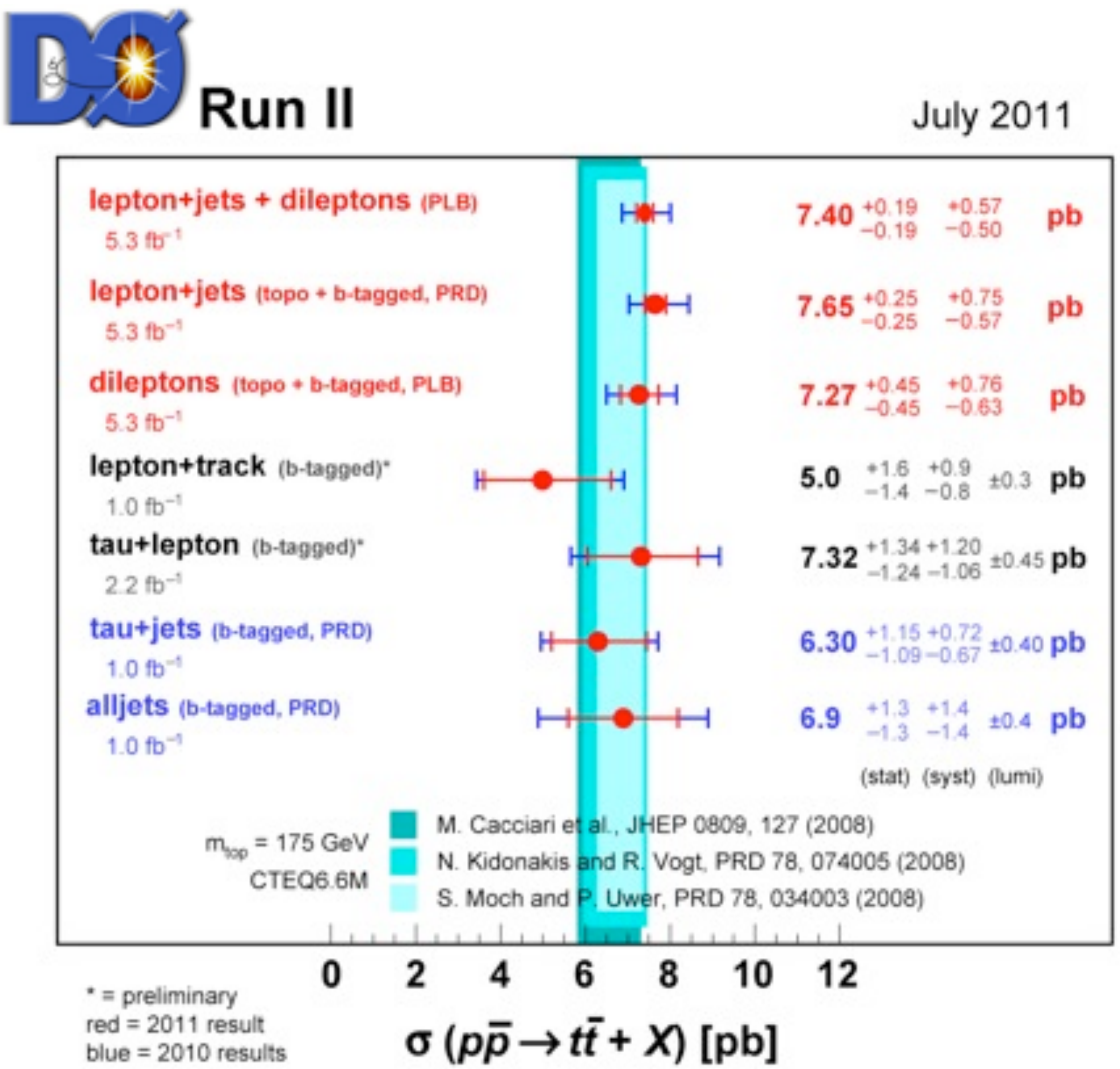
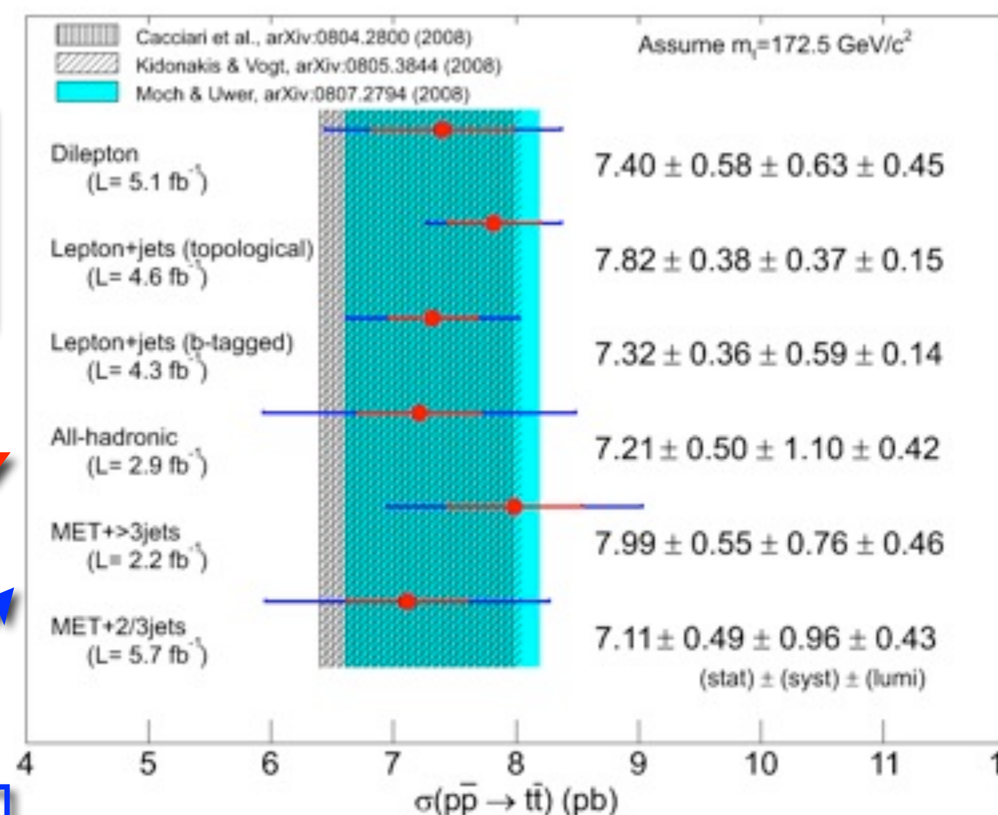


τ+(lepton/jets): important for H+ search

all hadronic: no MET

MET+jets: interesting for Higgs search



$$\sigma_{t\bar{t}} = 7.50 \pm 0.48 \text{ pb}$$

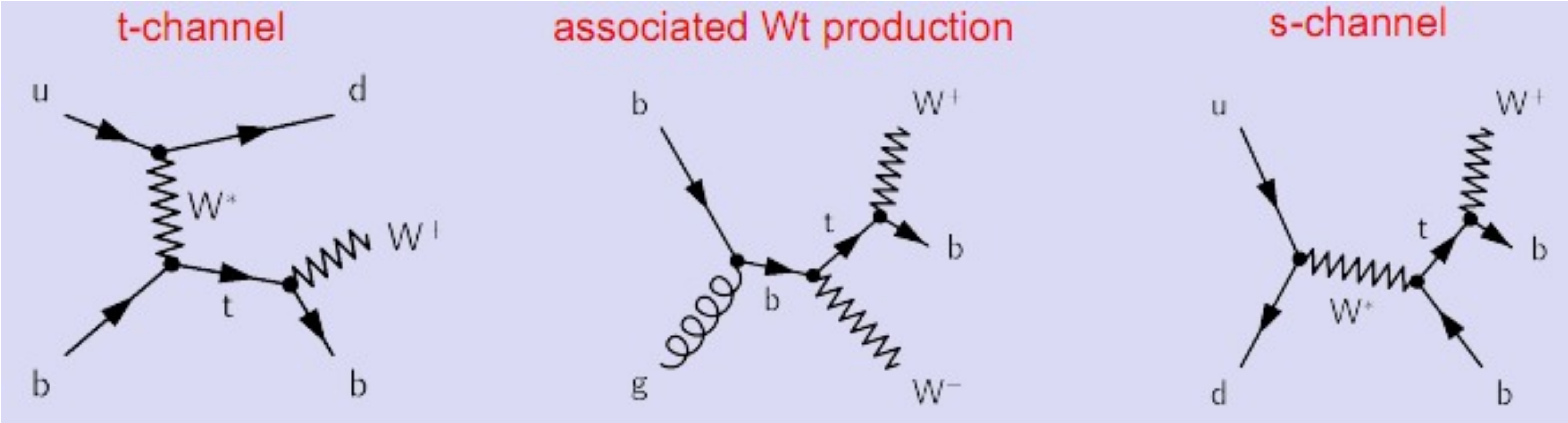
- Measured in all channels but $\tau_{had}\tau_{had}$
- Agree between channels and method

CDF combination: 6.4% precision!

...exceeds Tevatron goal of 10%

Consistent with theory prediction
Challenges its precision

Electroweak top quark production



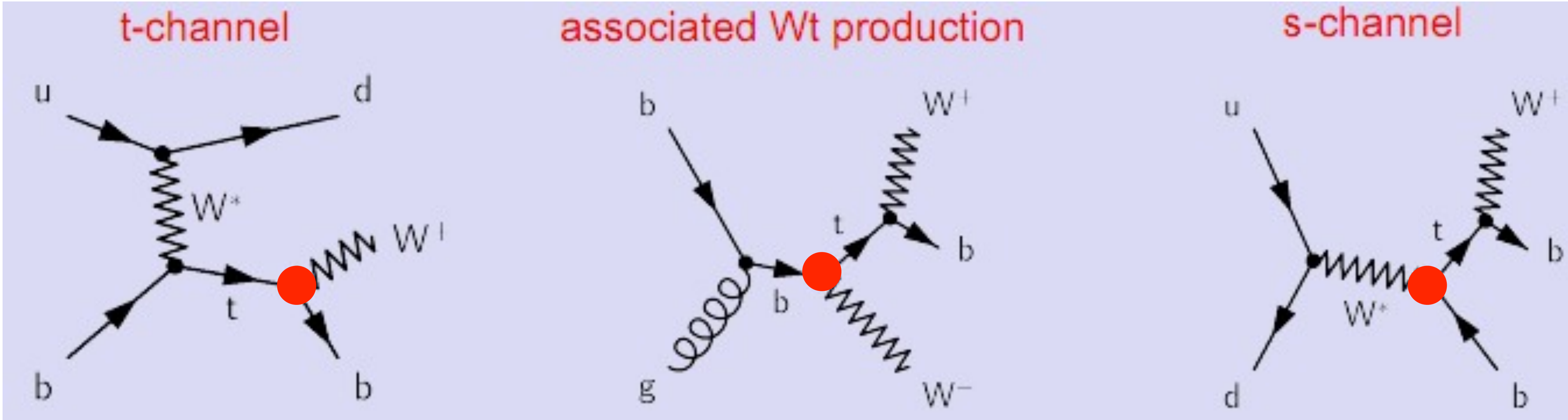
Cross sections at Tevatron, $\sqrt{s}$=1.96 TeV, m_t=173 GeV

t-channel	associated Wt production	s-channel
2.1±0.1 pb	0.25±0.03 pb	1.05±0.05 pb

N. Kidonakis, arXiv 1103.2792, 1005.4451, 1001.5034 $NNLO_{approx}$

Observed by CDF and D0 collaborations in 2009

Electroweak top production



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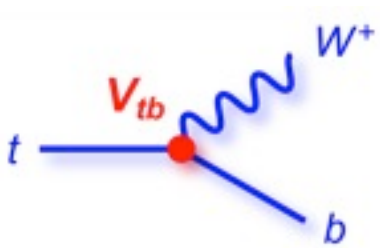
$\sigma \sim |V_{tb}|^2$

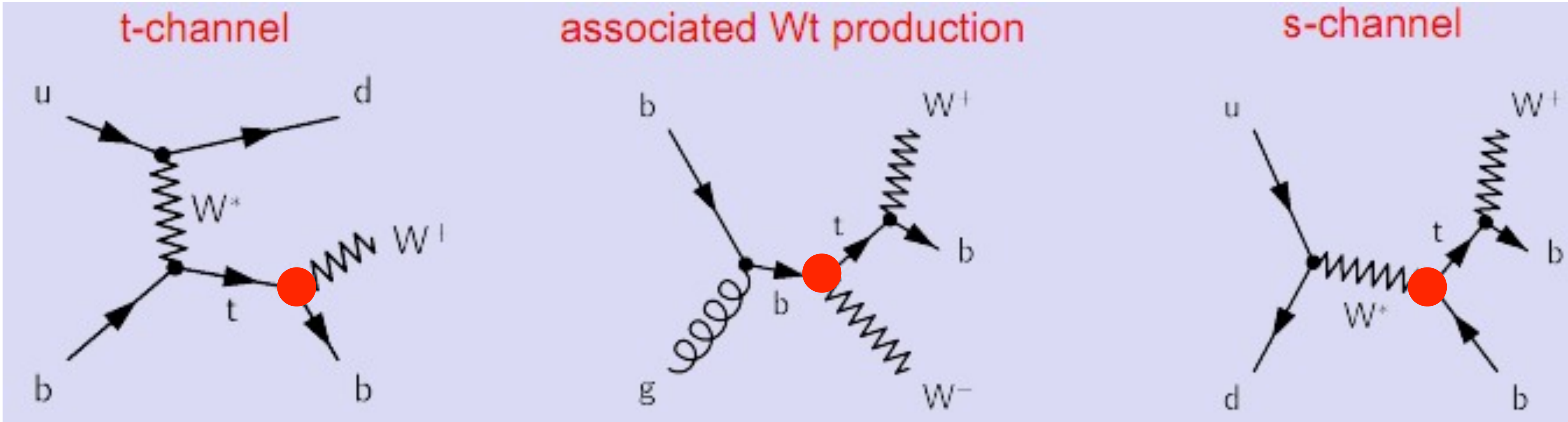


$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & \mathbf{V_{tb}} \end{pmatrix}$$

Test unitarity of CKM matrix

4^{th} generation

Electroweak top production



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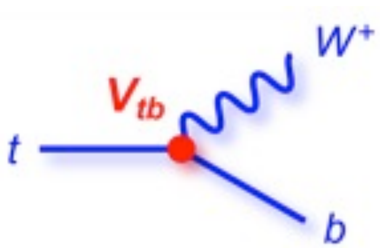

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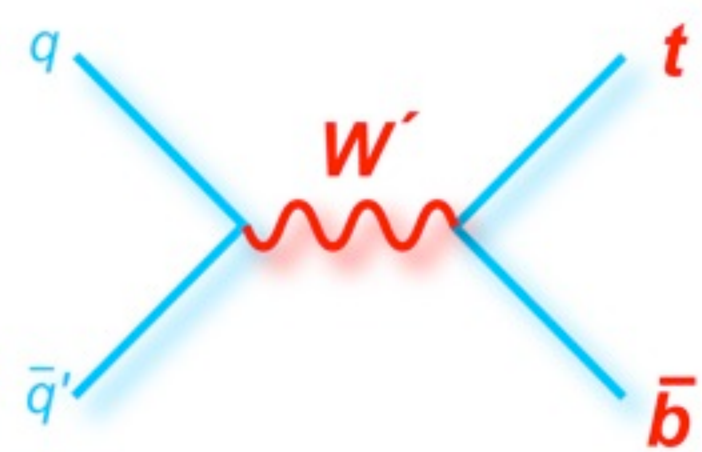
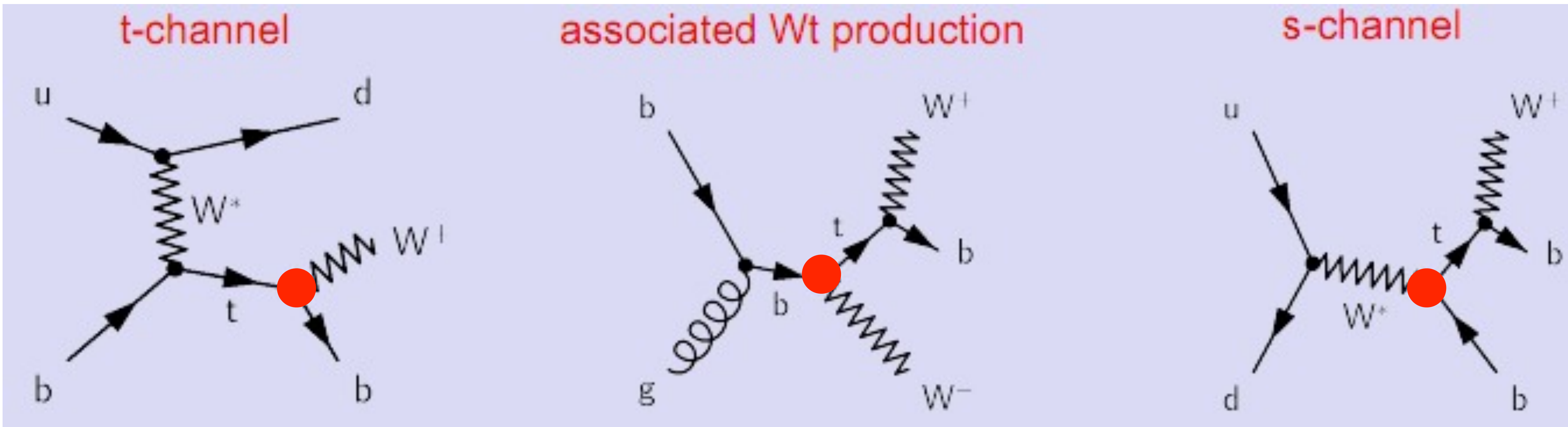
Test unitarity of CKM matrix

4th generation



Sensitive to new physics



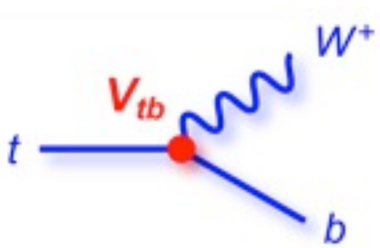
Cross sections at Tevatron, $\sqrt{s}$=1.96 TeV, m_t=173 GeV

2.1±0.1 pb | 0.25±0.03 pb | 1.05±0.05 pb

N. Kidonakis, arXiv 1103.2792, 1005.4451, 1001.5034 $NNLO_{approx}$

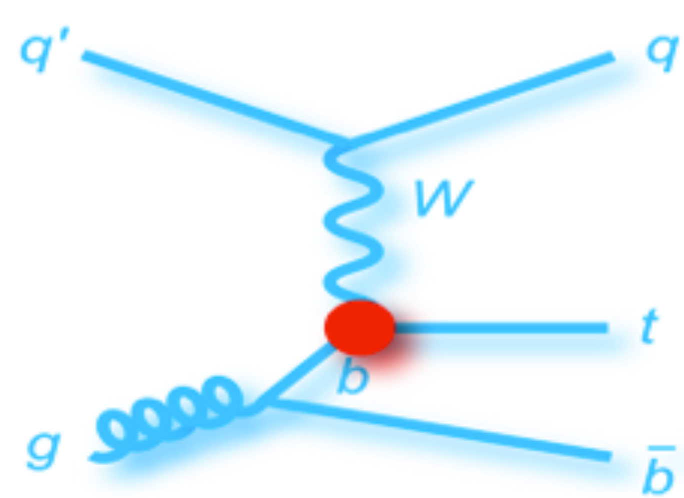
Observed by CDF and D0 collaborations in 2009

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



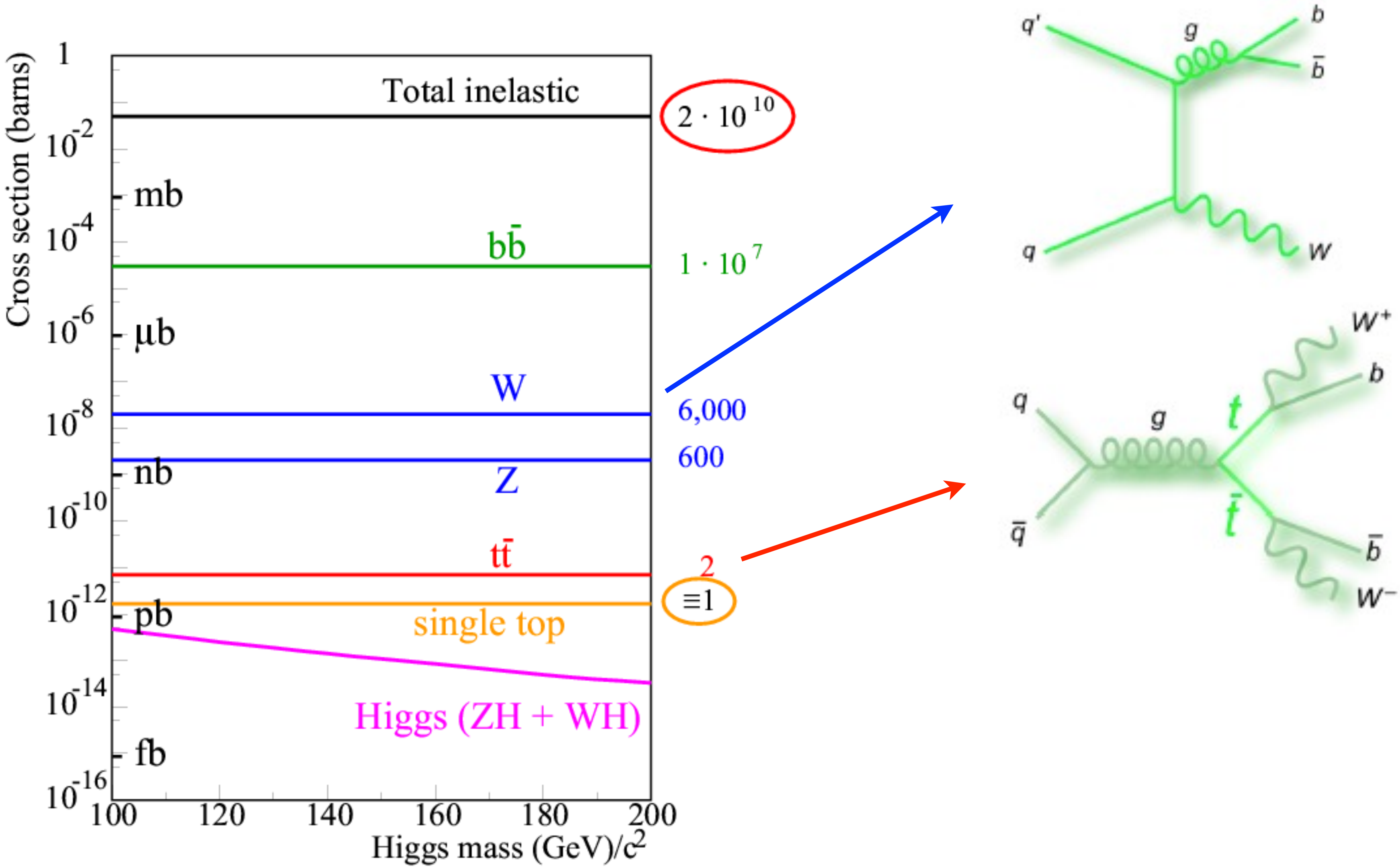
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Test unitarity of CKM matrix
4^{th} generation

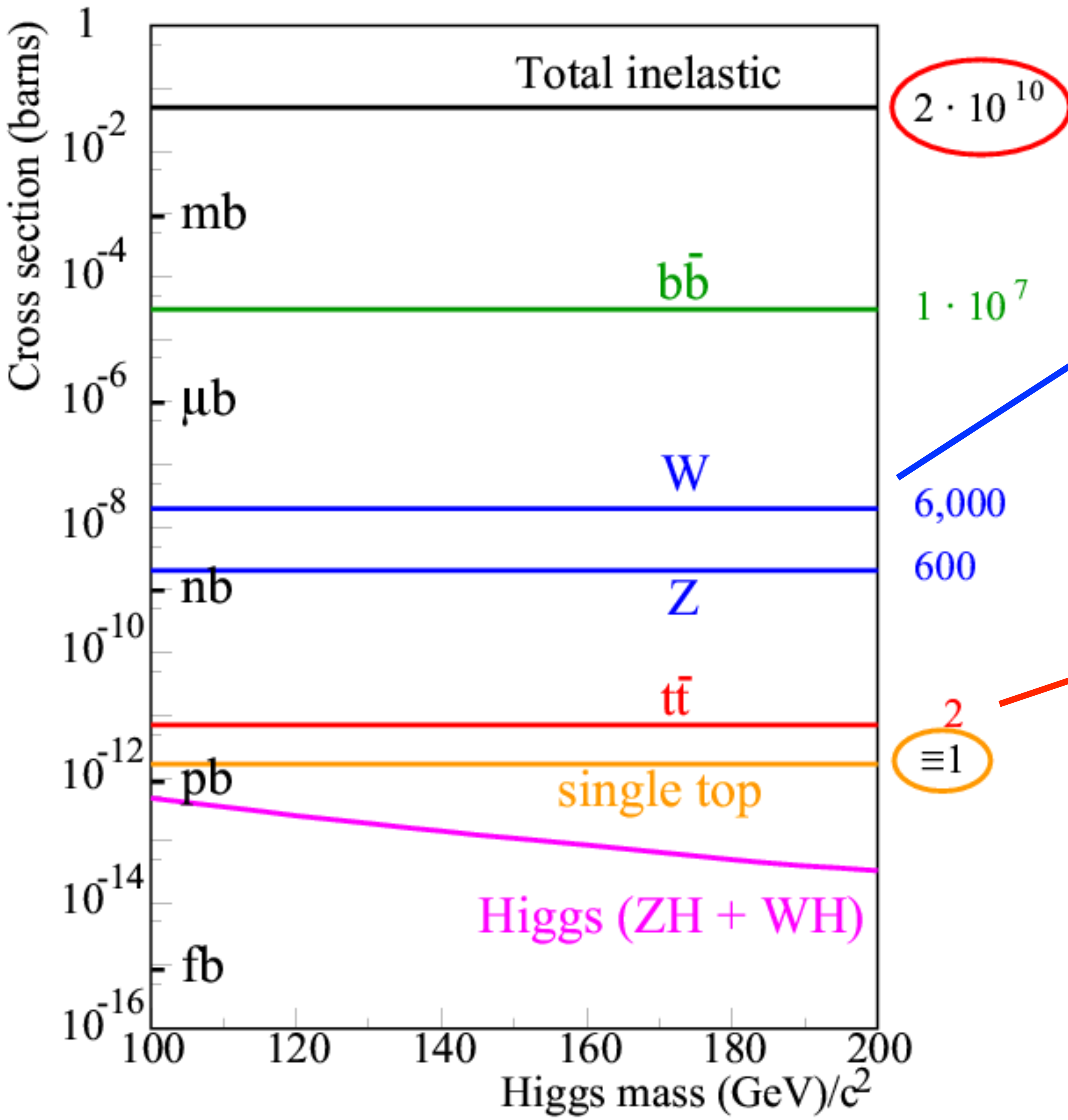


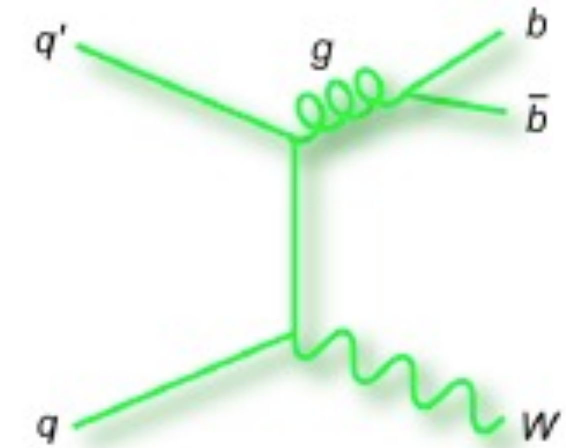
Sensitive to new physics

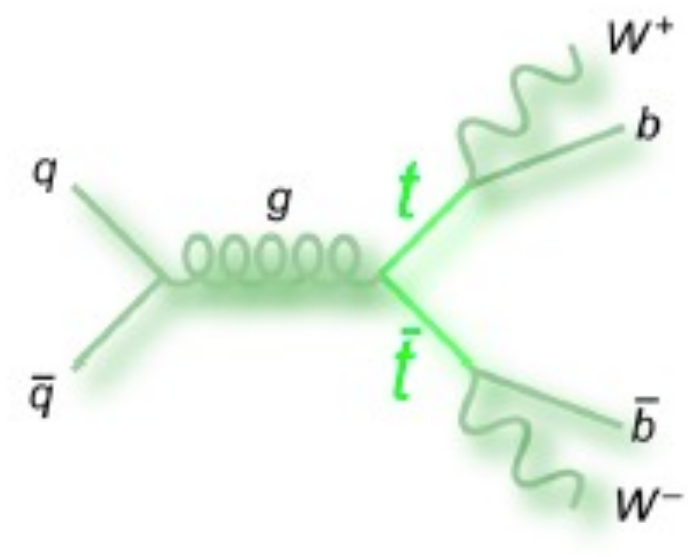
A challenge


Cross section (barns)
1
10-2
mb
10-4
10-6
µb
10-8
nb
10-10
10-12
pb
10-14
fb
10-16
100
120
140
160
180
200
Higgs mass (GeV)/c2
Total inelastic
bb̄
W
Z
tt̄
single top
Higgs (ZH + WH)
2 · 10 10
1 · 10 7
6,000
600
2
≡1
q'
g
b
b̄
q
W
q
q̄
g
t
t̄
W+
b
b̄
W−

A challenge







- Simple counting experiment cannot extract signal from the overwhelming background
- Uncertainties on the background are larger than the signal

Use of multivariate techniques is mandatory

s+t channels cross section

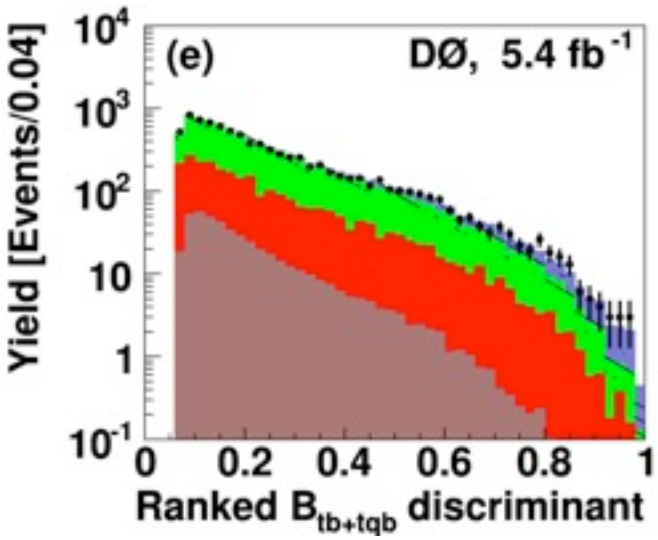
arXiv:1108.3091 [hep-ex]

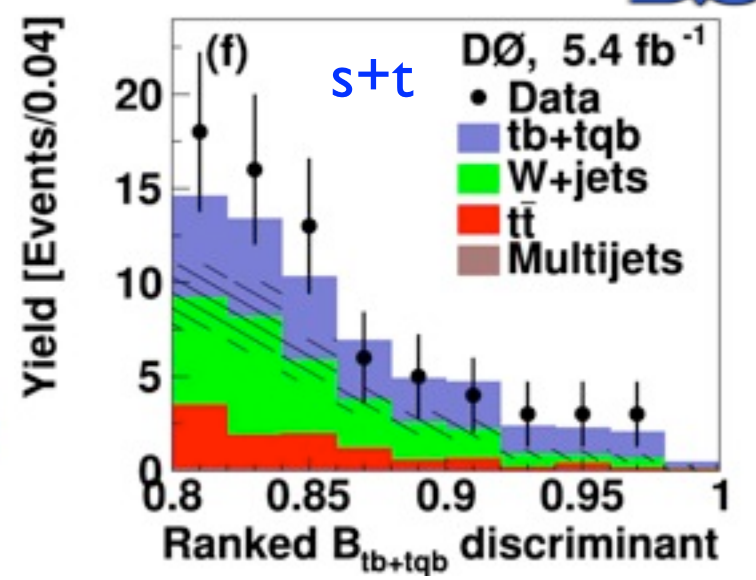
- 400 signal events (s+t channels)
  - ~1000 in 0.7 fb^{-1} at LHC
- 20 times larger background
- Discriminating variables are combined into
  - Boosted Decision Tree (BDT)
  - Bayesian Neural Network
  - Neuroevolution of Augmented Topologies (NEAT)
- Correlation - 70%
- Benefit from combination

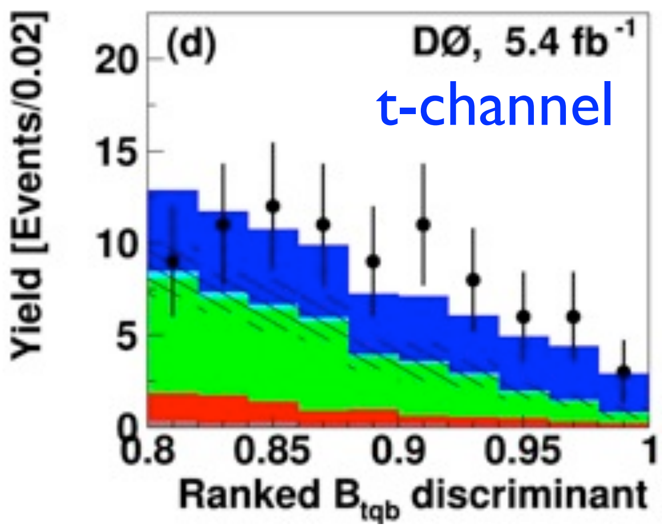
channel	σ(pb)
s+t	$3.43^{+0.73}_{-0.74}$
t	$2.86^{+0.69}_{-0.63}$
s	$0.68^{+0.38}_{-0.35}$

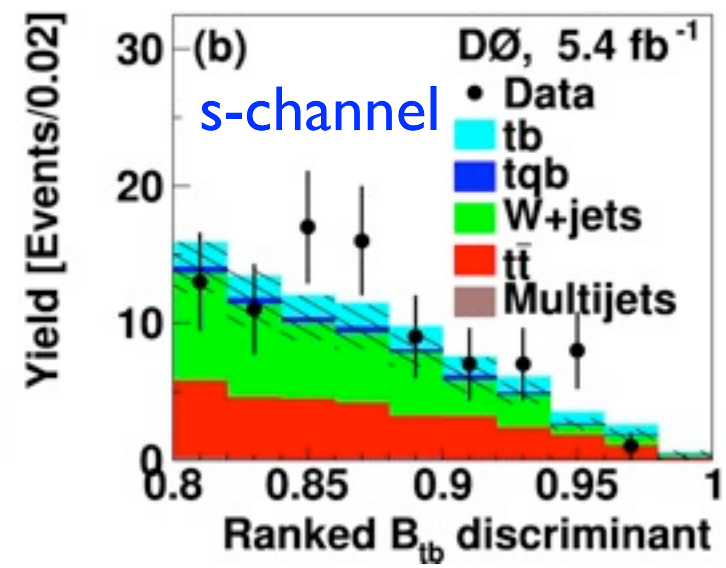
m_t = 172.5 GeV

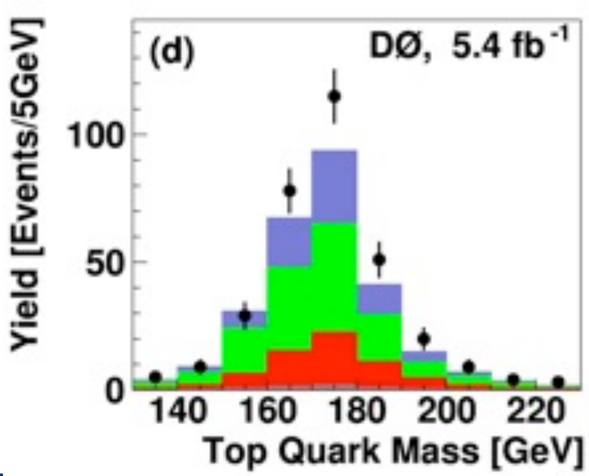
21% relative precision











S/B>0.24

Independent s- and t-channel measurements

- Construct a 2D posterior probability density for t-ch vs s-ch cross section
  - no constraint on the relative rate of t-ch vs s-ch production

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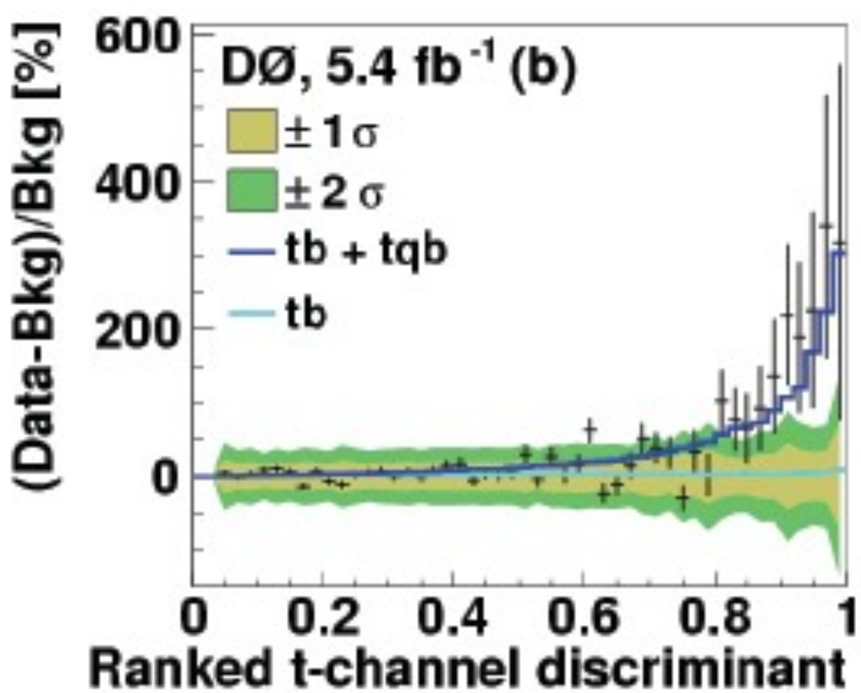

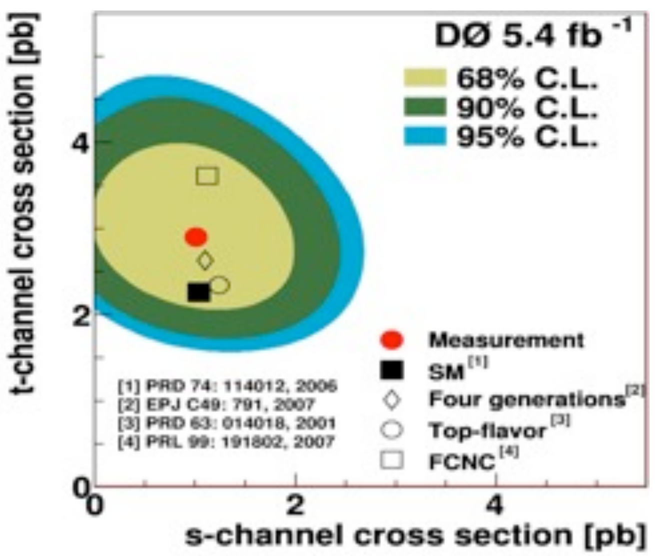

PLB **705**, 313 (2011)

σ(t-ch) = 2.90 ± 0.59 pb

the most precise measurement in t-channel
> 5 σ significance

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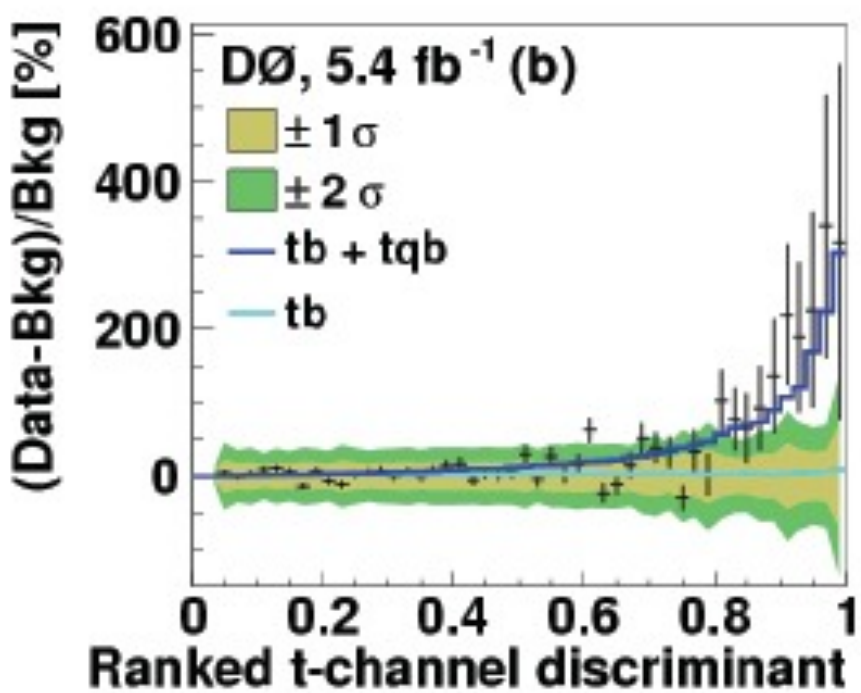
PLB **705**, 313 (2011)



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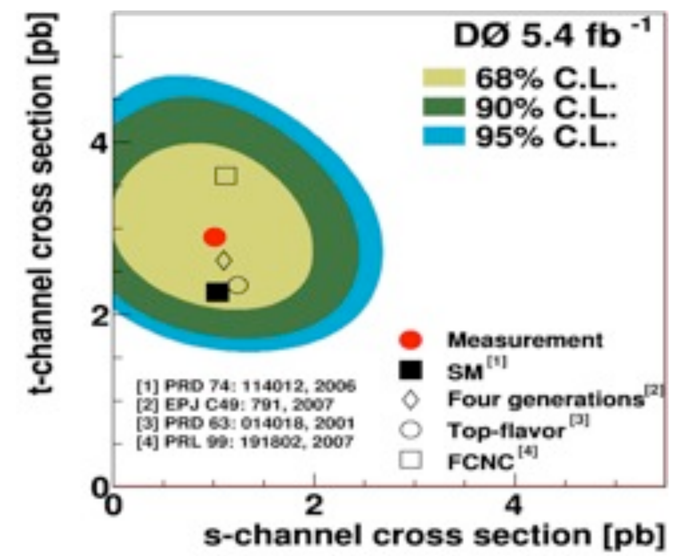
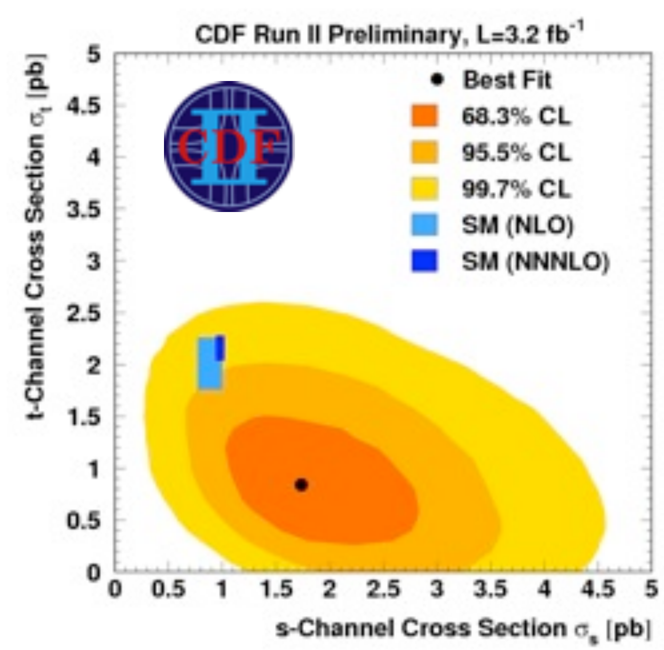


- s-channel is very challenging at LHC
- can be the Tevatron legacy measurement

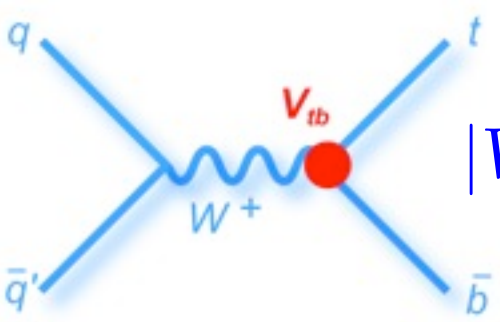


σ(s-ch) = $1.8^{+0.7}_{-0.5}$ pb

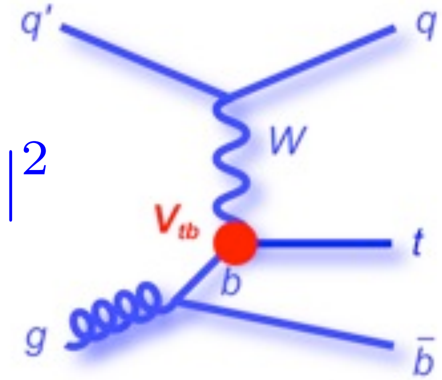
> 3σ significance

the most precise measurement in s-channel

$|V_{tb}|$ measurements



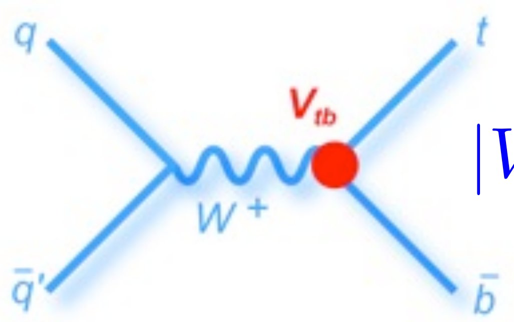
$$|V_{tb}^{meas}|^2 = \frac{\sigma_{meas}}{\sigma_{SM}} |V_{tb}^{SM}|^2$$



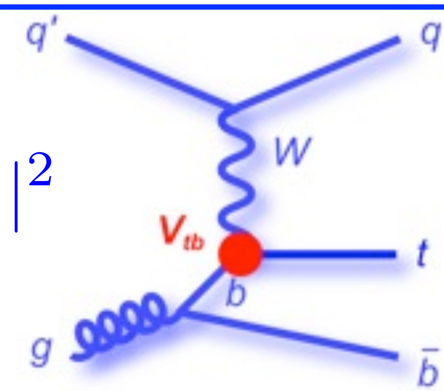
$$\Gamma^{\mu}_{Wtb} = -\frac{g}{\sqrt{2}} V_{tb} \left\{ \gamma^{\mu} \left[f_1^L P_L + f_1^R P_R \right] - \frac{i\sigma^{\mu\nu}}{M_W} (p_t - p_b)_{\nu} \left[f_2^L P_L + f_2^R P_R \right] \right\}$$

- Assume SM production mechanism
  - 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
  - $|V_{td}|^2 + |V_{ts}|^2 << |V_{tb}|^2$
- No assumption of 3 generations or unitarity of the CKM matrix

Direct measurement of V_{tb}



$$|V_{tb}^{meas}|^2 = \frac{\sigma_{meas}}{\sigma_{SM}}|V_{tb}^{SM}|^2$$



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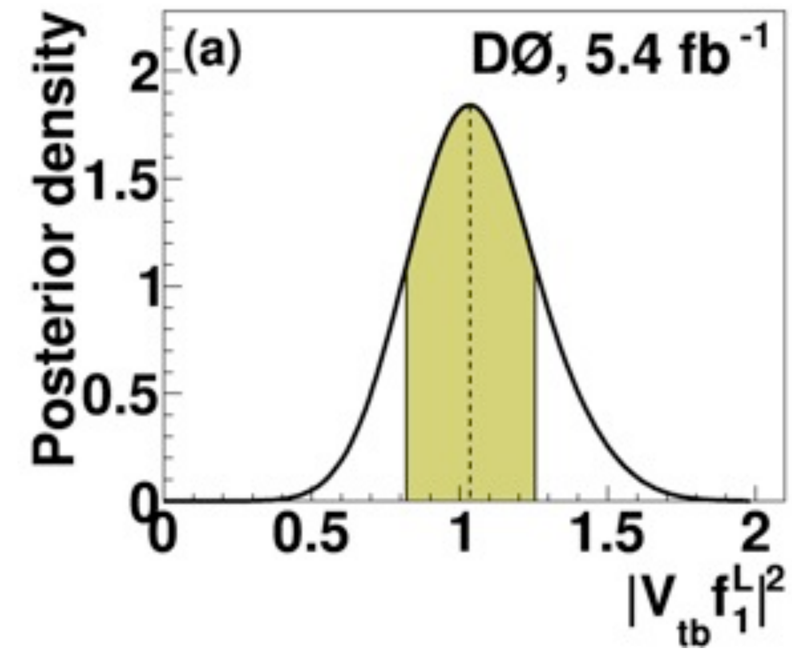
Tevatron observation combination

$|V_{tb}| = 0.88 \pm 0.07$

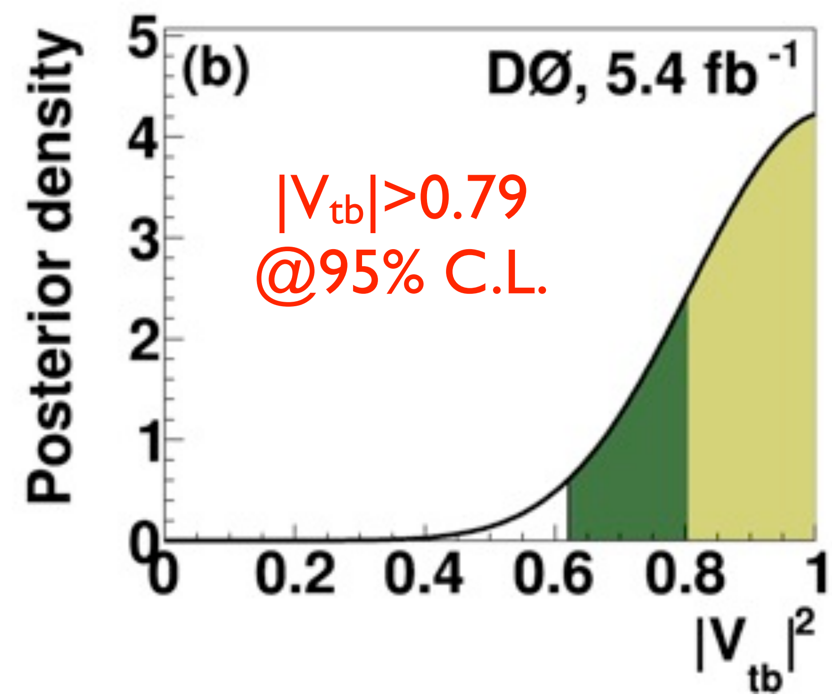
$|V_{tb}| > 0.77$ @95% C.L.

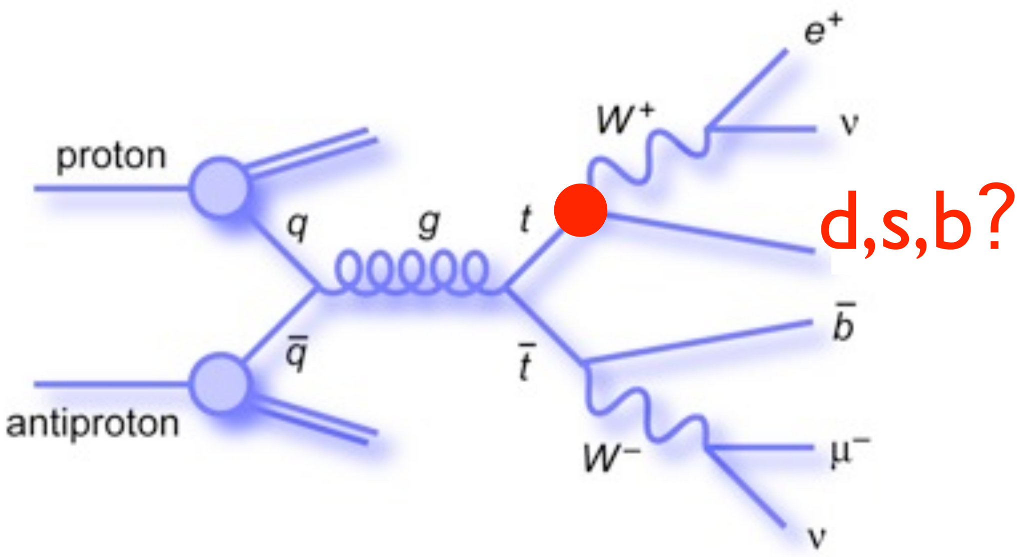
Measure strength of V-A



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

Assume $f_1^L = 1$

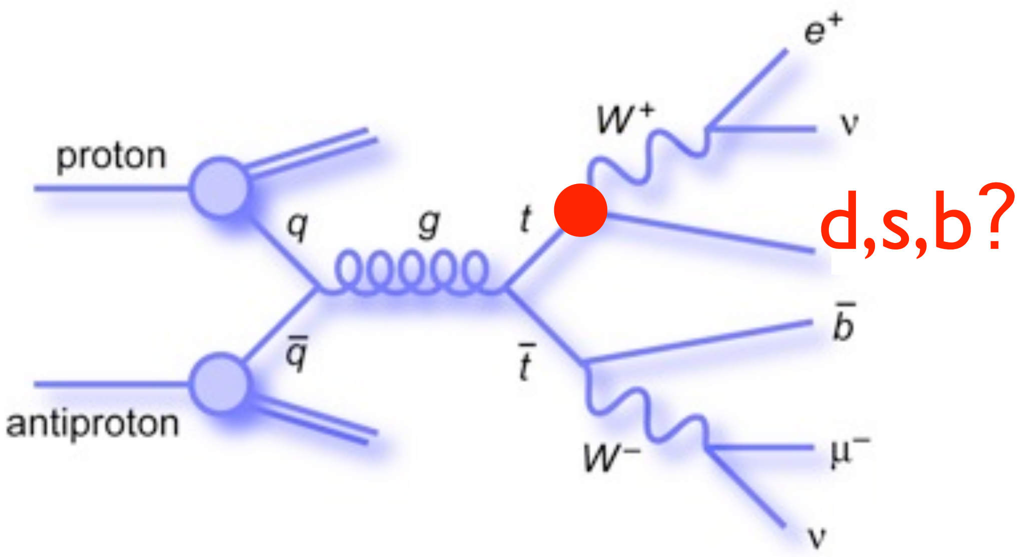




$$R = \frac{BR(t \to Wb)}{BR(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

- SM: R=1 constrained by CKM unitarity
- R<1 could indicate new physics
  - additional quark families

Ratio of branching fractions



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- Drop assumption R=1 in dilepton and l+jets cross section measurements
  - changes predicted fraction of events with 0,1 and >1 b-tags in l+jets channel
  - changes the shape of the NN output distribution in dilepton channel
- Measure simultaneously with $t\bar{t}$ cross section

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

R=0.90±0.04 (stat+syst)

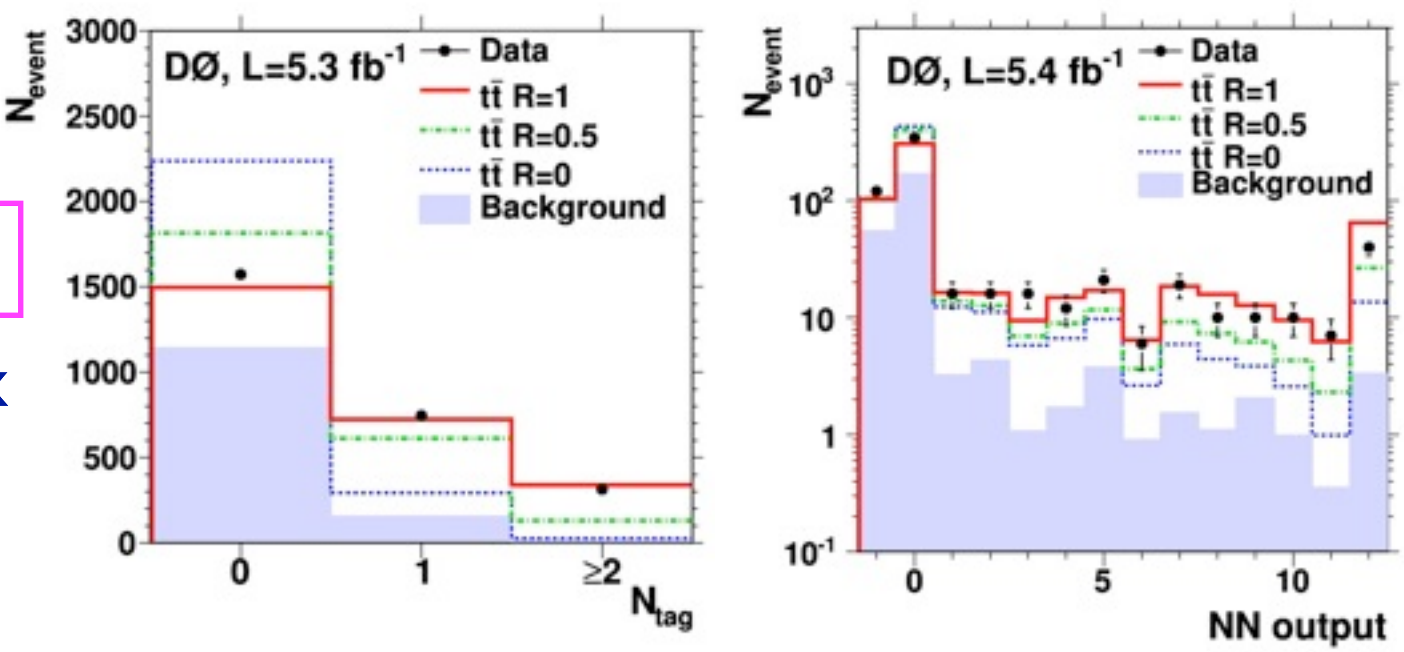
the most precise determination of R

assuming unitarity of 3x3 CKM matrix

$|V_{tb}|$=0.95±0.02 (stat+syst)

$|V_{tb}|$>0.88 @99.7% C.L.

Phys. Rev. Lett. 107, 121802 (2011)

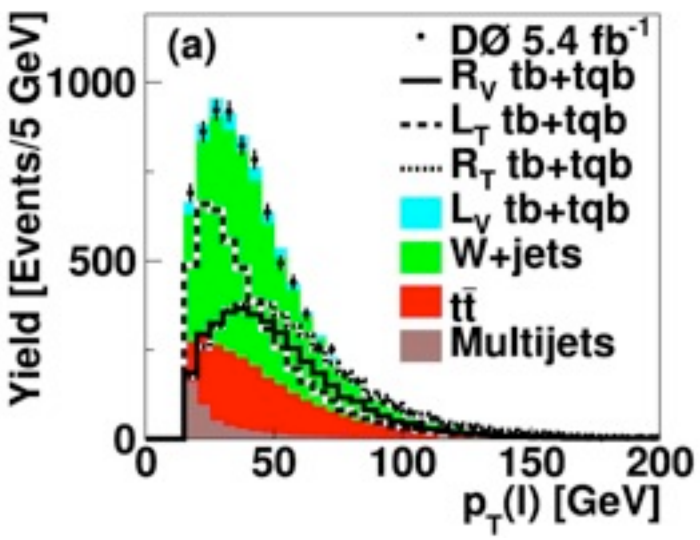


Sunday, November 13, 2011

$$\mathcal{L} = \frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(L_V P_L + R_V P_R)tW_{\mu}^{-} + \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}(L_T P_L + R_T P_R)tW_{\mu}^{-}$$

SM: only left-handed vector coupling is non-zero: $L_V=V_{tb}\approx 1$

- Single top event kinematics is sensitive to anomalous top quark couplings
- Assumptions:
  - production (SM and anomalous) only via W boson exchange
  - CP-conserving interaction Wtb vertex
  - $|V_{td}|^2+|V_{ts}|^2<<|V_{tb}|^2$
  - anomalous couplings in both production and decay



Anomalous couplings

$$\mathcal{L} = \frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(L_V P_L + R_V P_R)tW_{\mu}^{-} + \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}(L_T P_L + R_T P_R)tW_{\mu}^{-}$$

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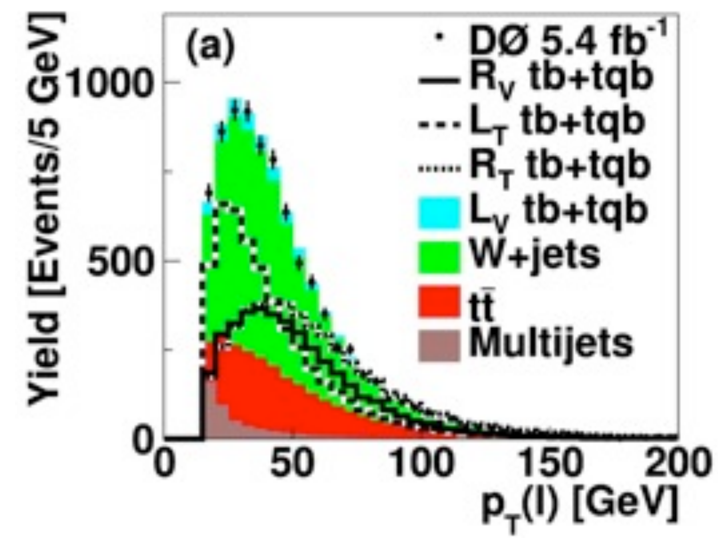
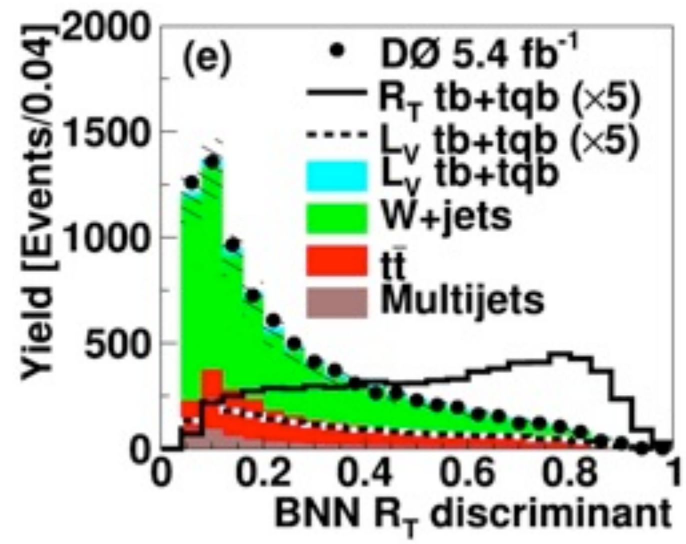
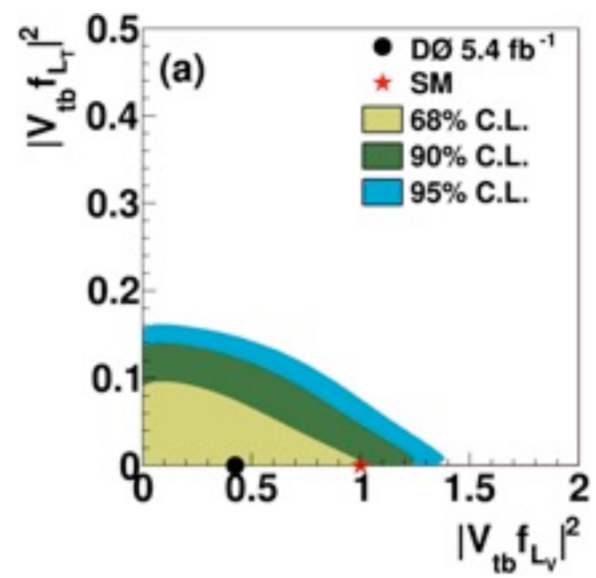


- Pair the L_V coupling with one non-SM coupling and assume the other two are negligible
  - (L_V, L_T); $L_V = L_T = 1$; $R_V = R_T = 0$ includes the interference $L_V + L_T$
  - (L_V, R_V); $L_V = R_V = 1$; $L_T = R_T = 0$
  - (L_V, R_T); $L_V = R_T = 1$; $R_V = L_T = 0$

arXiv:1110.4592v1





Coupling	(L_V,L_T)	(L_V,R_V)	(L_V,R_T)
$\lvert V_{tb} \cdot f_X\rvert^2$	<0.13	<0.93	<0.06

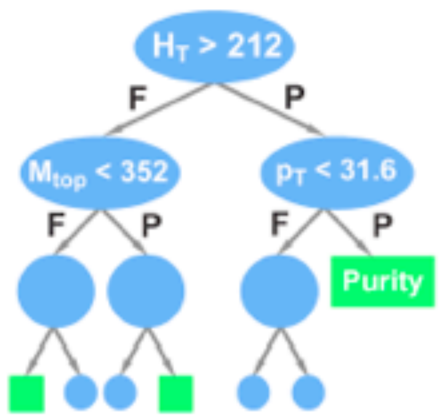
Conclusions

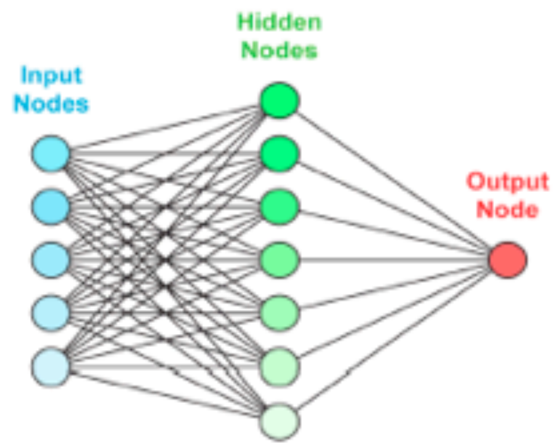
- The Tevatron keeps providing precise measurements of the top pair production cross sections in different channels
- Electroweak top production in the t-channel has been observed
- Legacy measurements from the Tevatron with the full data set are yet to come
  - top pair production cross section
  - single top cross sections and $|V_{tb}|$
  - differential cross sections
- So far all measurements agree well with the Standard Model and challenge the precision of the theoretical calculations

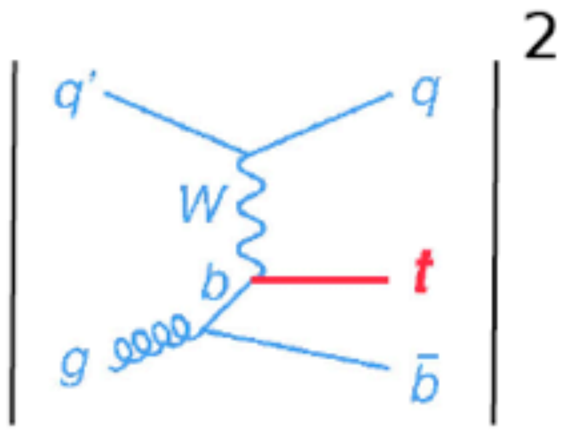
Backup

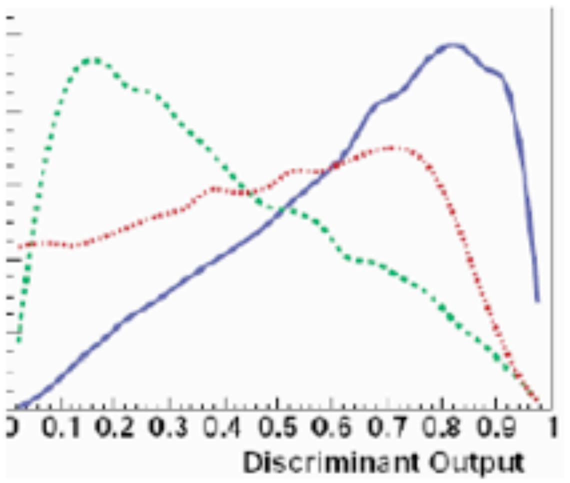
Single top observation

Decision Trees | Neural Networks | Matrix Elements | Likelihoods





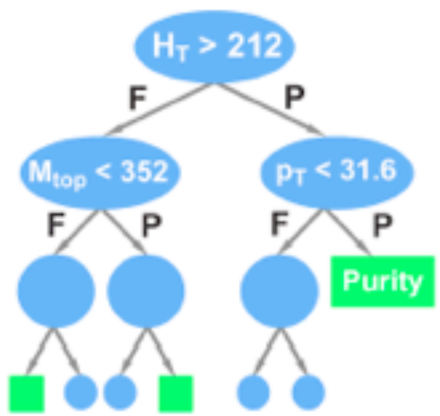


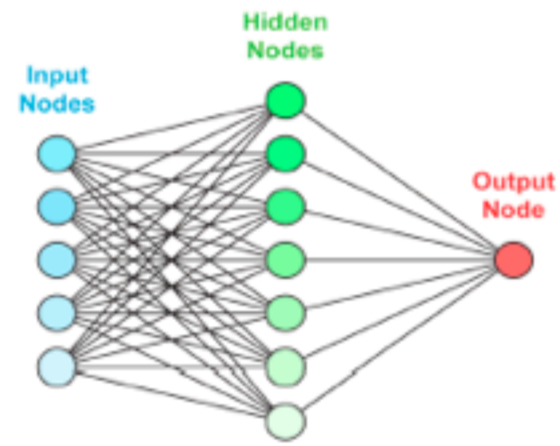


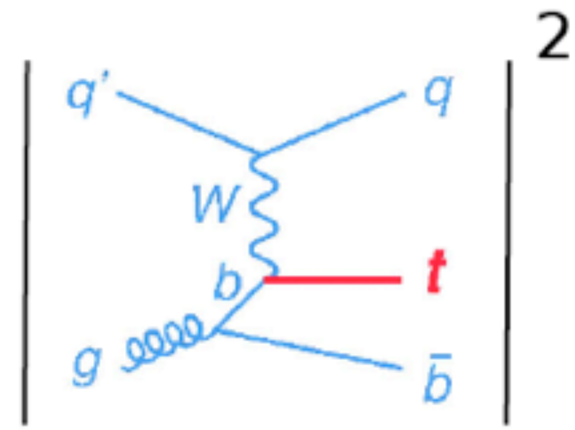
D0: PRL 103 092001 (2009)
CDF: 103, 092002 (2009)

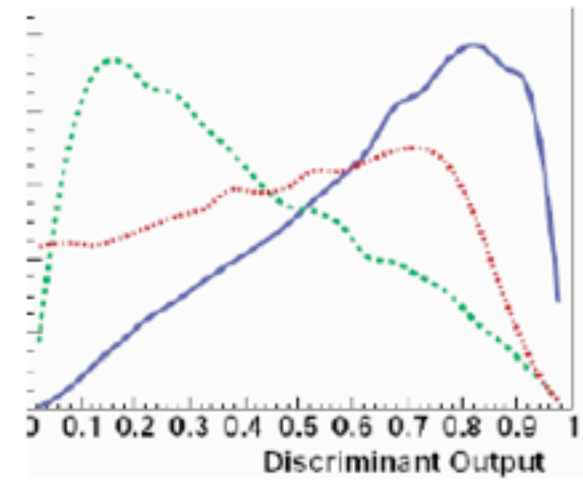
Single top observation

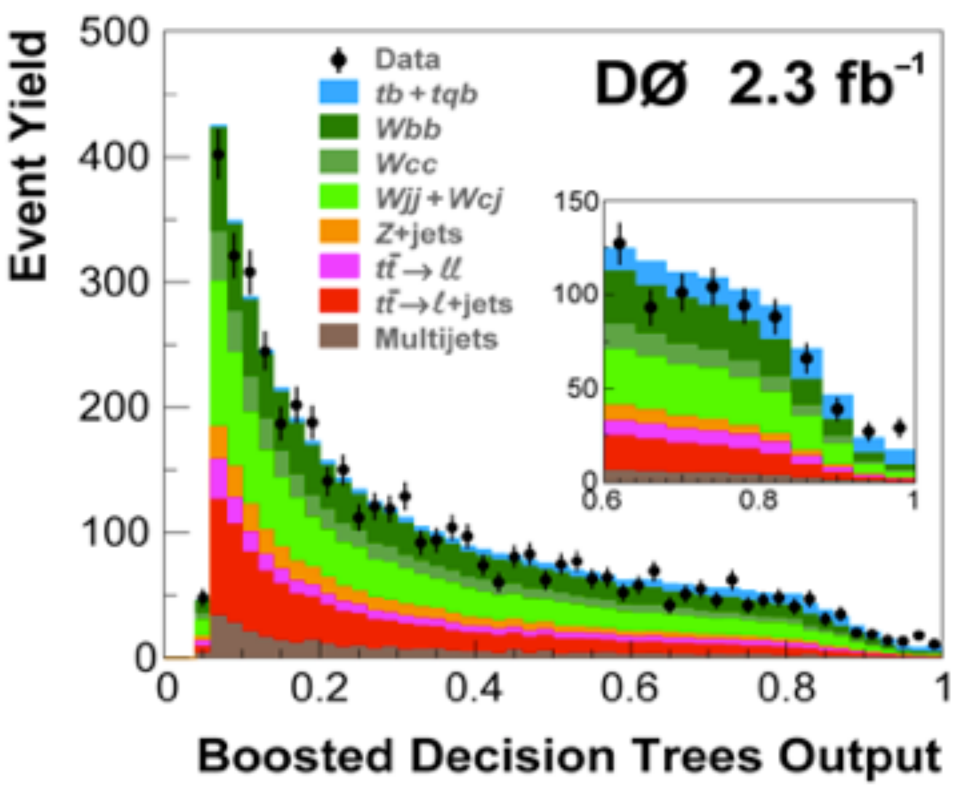
Decision Trees | Neural Networks | Matrix Elements | Likelihoods





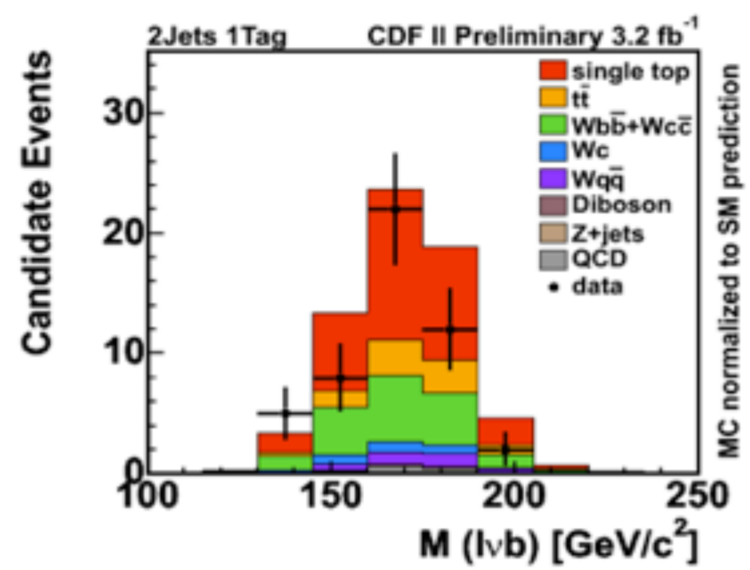


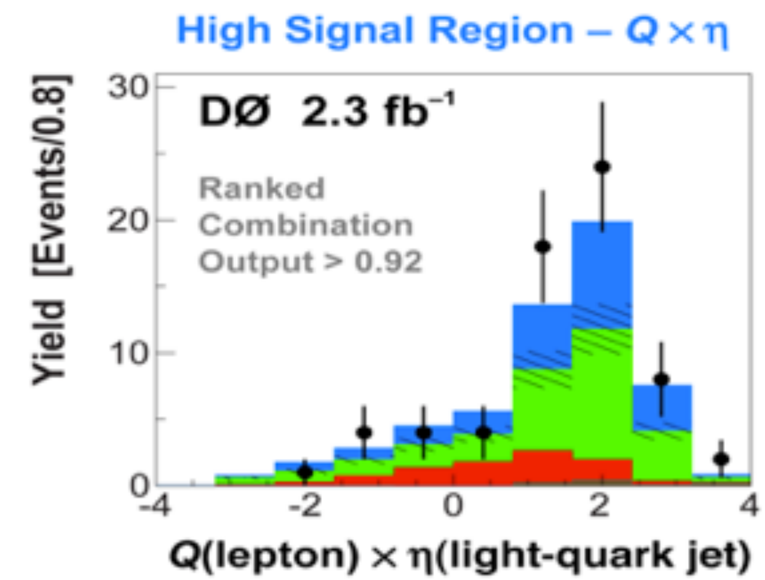




March 2009: CDF and D0 reported 5σ observation

Combination of many channels and analyses

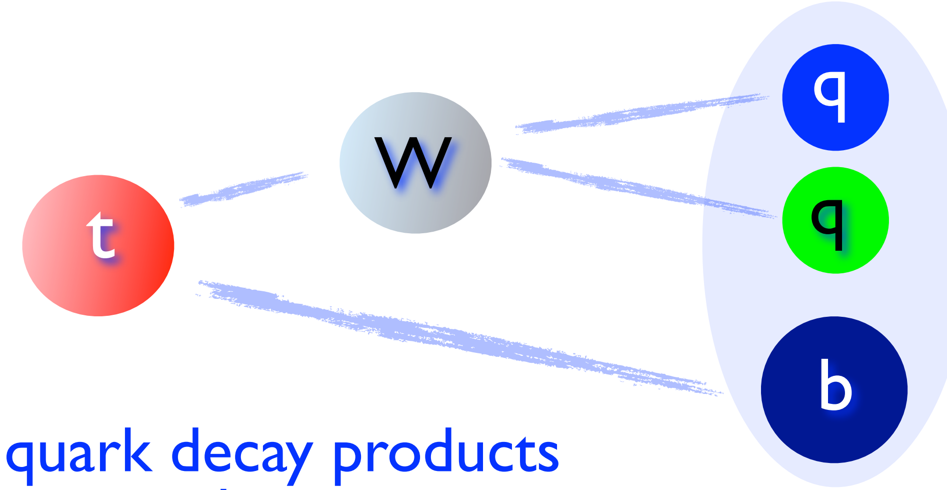




D0: PRL 103 092001 (2009)
CDF: 103, 092002 (2009)

Boosted top quarks

- First measurement of this kind at Tevatron
- Important for LHC
- High p_T top quarks can originate from decay of heavy objects



All top quark decay products are contained in one jet

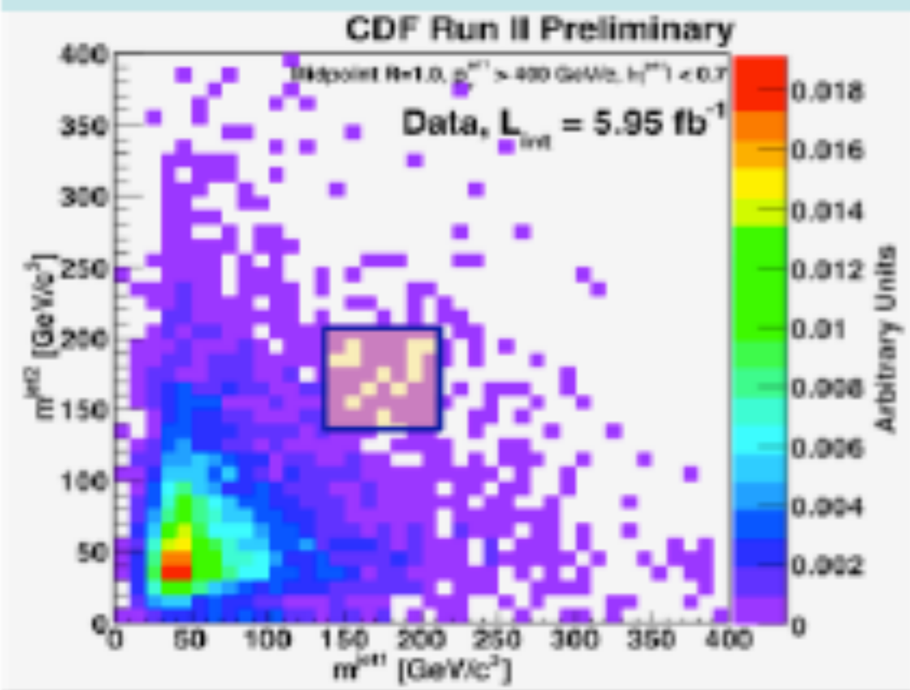
$m_{jet} \sim m_{top}$

Events with leading jet p_T>400 GeV

6 fb^{-1}

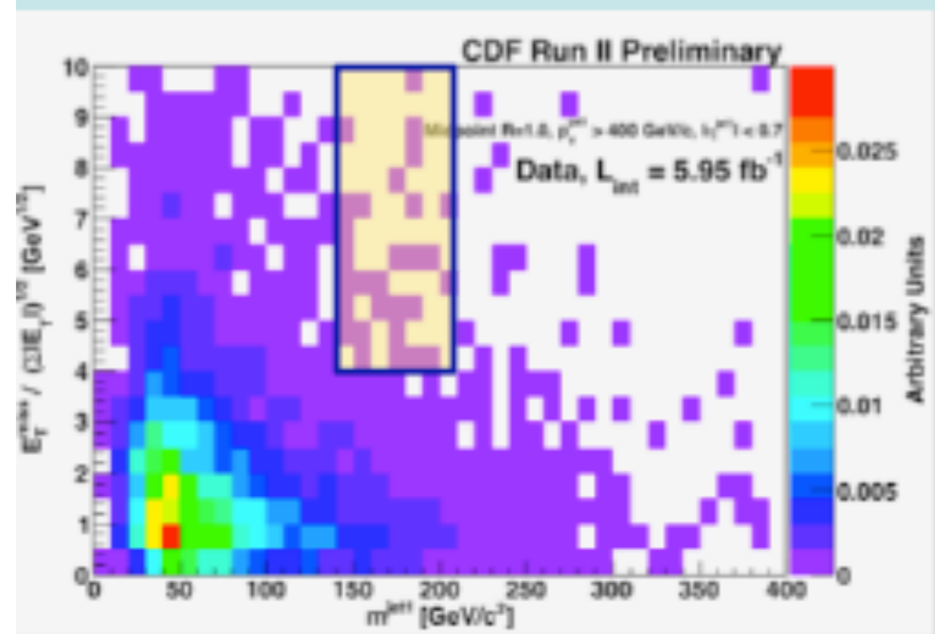
new

all-hadronic decays:
two tops with mass ~175



(jet1 mass vs jet2 mass)

Lepton+jets decays:
one jet with mass ~175, large MET



(jet1 mass vs $\not{E}_T/\sqrt{\sum E_T}$)

$\sigma_{t\bar{t}}$ < 54 fb for top quark p_T>400 GeV

lepton+jets - I

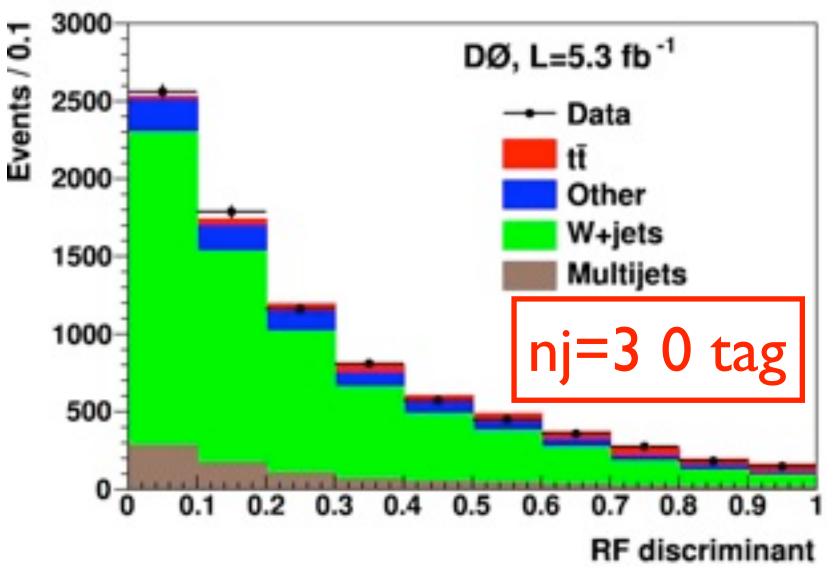
- three measurements
  - b-tag counting
  - event kinematics
  - combined method

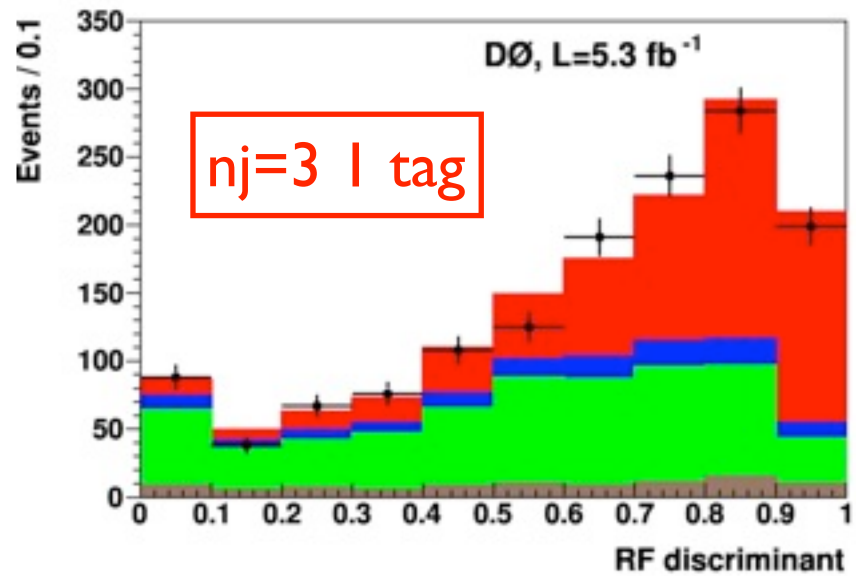
combined method

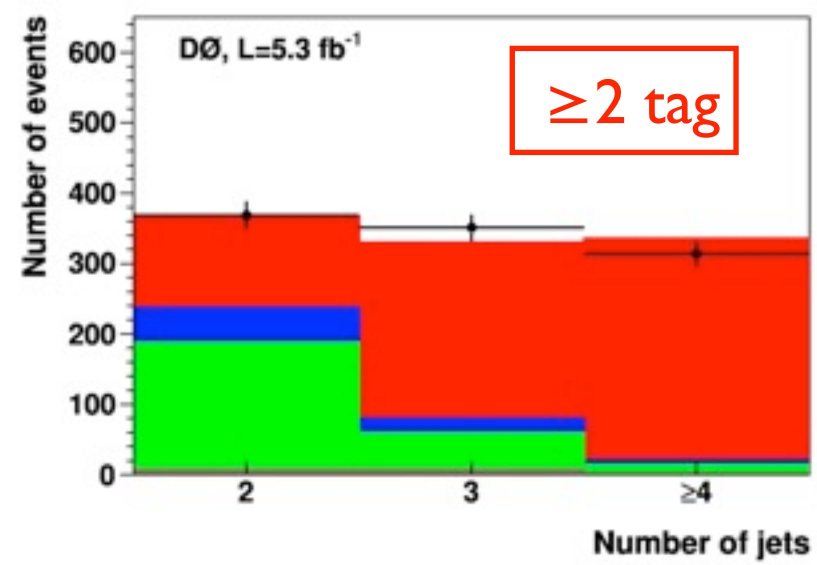
	0 b-tag	1 b-tag	≥2 b-tags
2 jets	RF	RF	RF
3 jets	RF	RF	b-tag
≥4 jets	RF	b-tag	b-tag

PRD,84:012008,2011

background dominated   signal dominated







- systematic uncertainties included in the fit as nuisance parameters
- data helps to constrain systematics
- largest uncertainty from luminosity

$$\sigma_{t\bar{t}} = 7.78^{+0.77}_{-0.64}\,\mathrm{pb}$$

9-10% relative precision

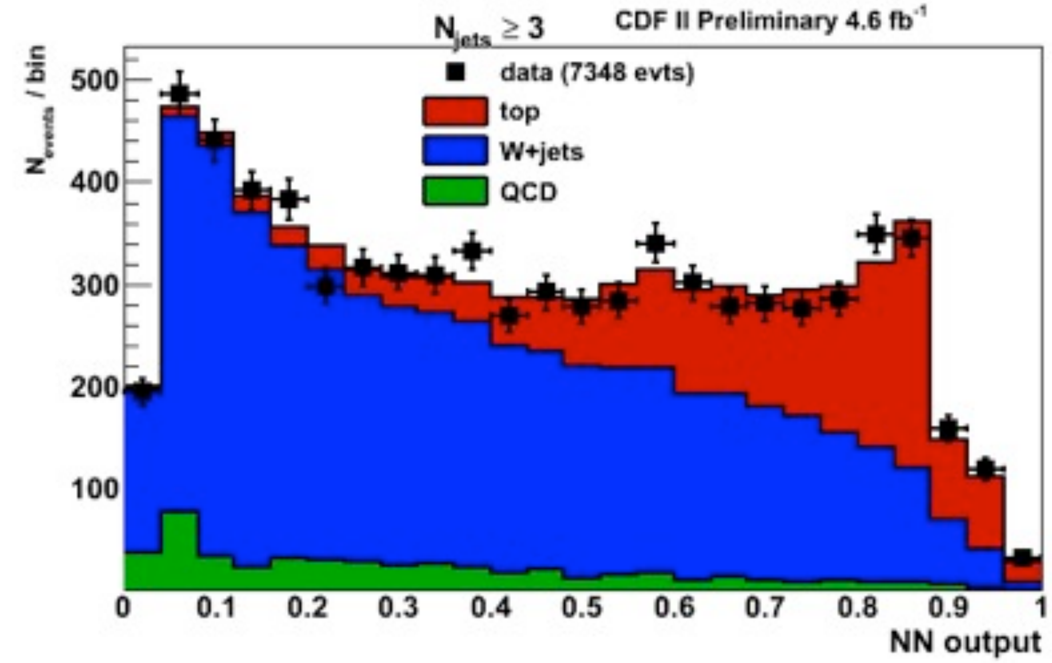
$$\frac{W+hf}{W+lf} = 1.55^{+0.19}_{-0.21}$$

lepton+jets - II

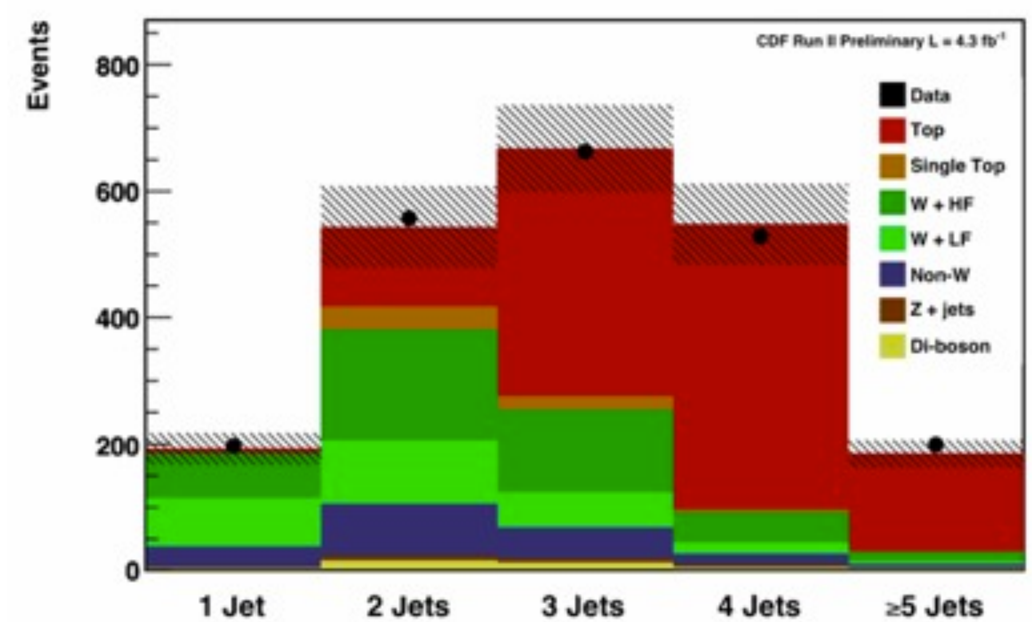
- two methods
  - b-tag counting
  - event kinematics
- measure Z cross section
  - use same triggers
  - same data set
- compute the ratio of $t\bar{t}$ to Z cross section taking into account correlations
- trade luminosity uncertainty for Z cross section theoretical uncertainty

PRL 105:012001,2010

4.6 fb^{-1}



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



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

- combine using BLUE
- statistical correlation 32%

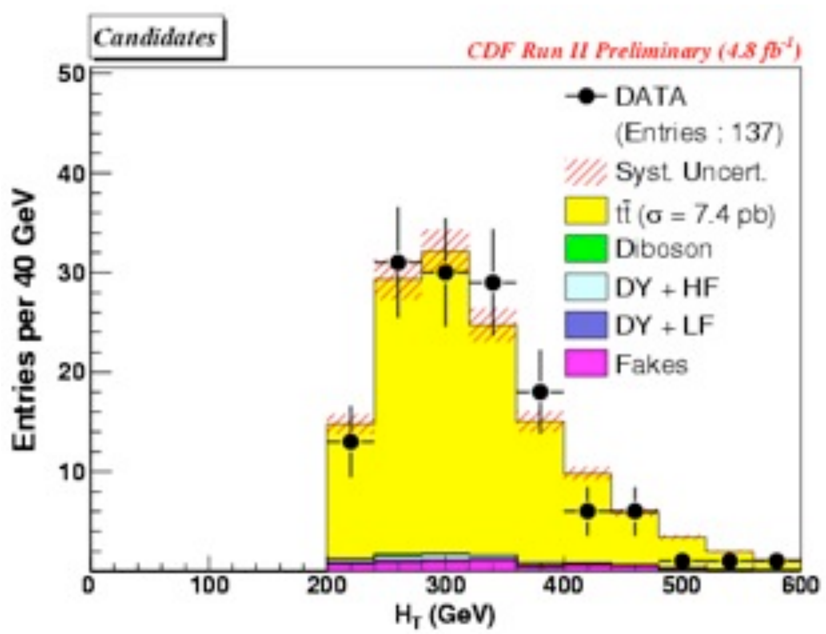
$\sigma_{t\bar{t}}$ = 7.70 ± 0.52 (total) pb

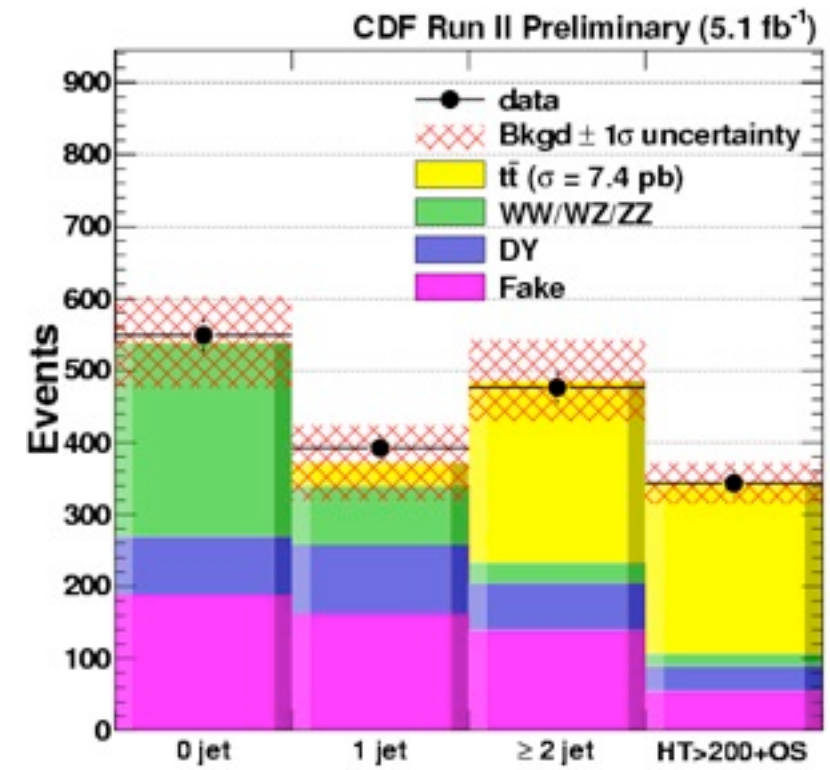
7% relative precision, 8.8% with luminosity uncertainty

Dilepton channel - I

Phys.Rev.D82:052002,2010

- cut and count with and w/o b-tagging
  - 240 dilepton events for pretag
  - 140 dilepton events for b-tagged





5.1 fb^{-1}

Source	pretag (%)	b-tag (%)
Lepton ID	2.2	2.2
MC generator	1.9	1.9
Radiation	1.3	1.3
Jet energy scale	3.3	3.3
Color reconnection	1.2	1.2
b-tagging	-	4.1
Total	4.8	6.3

$$\sigma_{t\bar{t}}^{pretag} = 7.40 \pm 0.58(\text{stat}) \pm 0.63(\text{syst}) \pm 0.45\ (\text{lumi})\ \text{pb}$$

$$\sigma_{t\bar{t}}^{tag} = 7.25 \pm 0.66(\text{stat}) \pm 0.47(\text{syst}) \pm 0.44\ (\text{lumi})\ \text{pb}$$

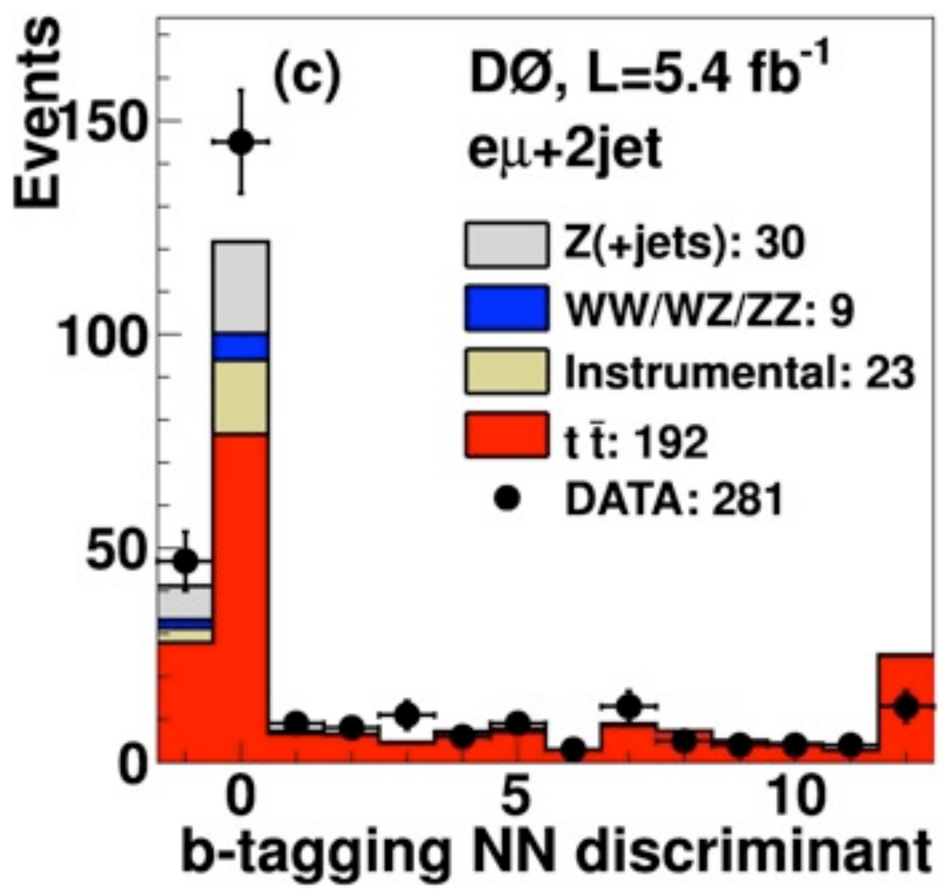
b-tagging increases uncertainty on the signal but background uncertainty is much lower

Dilepton channel - II

- Fit to b-tag NN discriminant distribution
- Variable: the smallest output value among 2 leading jets, i.e. most light-like jet
  - 350 dilepton events in 4 channels
- systematics included in the fit via nuisance parameters

Source	+σ(pb)	-σ(pb)
Statistical	+0.50	-0.48
Lepton ID	+0.26	-0.25
MC generator	+0.34	-0.33
Trigger	+0.19	-0.19
Jet scale and teco	+0.25	-0.23
Luminosity	+0.57	-0.51
Background	+0.34	-0.32
b-tagging	+0.06	-0.06

PLB,704, 403,2011



$$\sigma_{t\bar{t}} = 7.36^{+0.90}_{-0.79}$$

12% relative precision