Inclusive top pair cross section results at the Tevatron

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for CDF and D0 collaborations

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Tevatron and detectors

Introduction and motivation

Techniques

Measurements

- dilepton channel
- lepton+jets channel
- lepton+τ_{had} channel

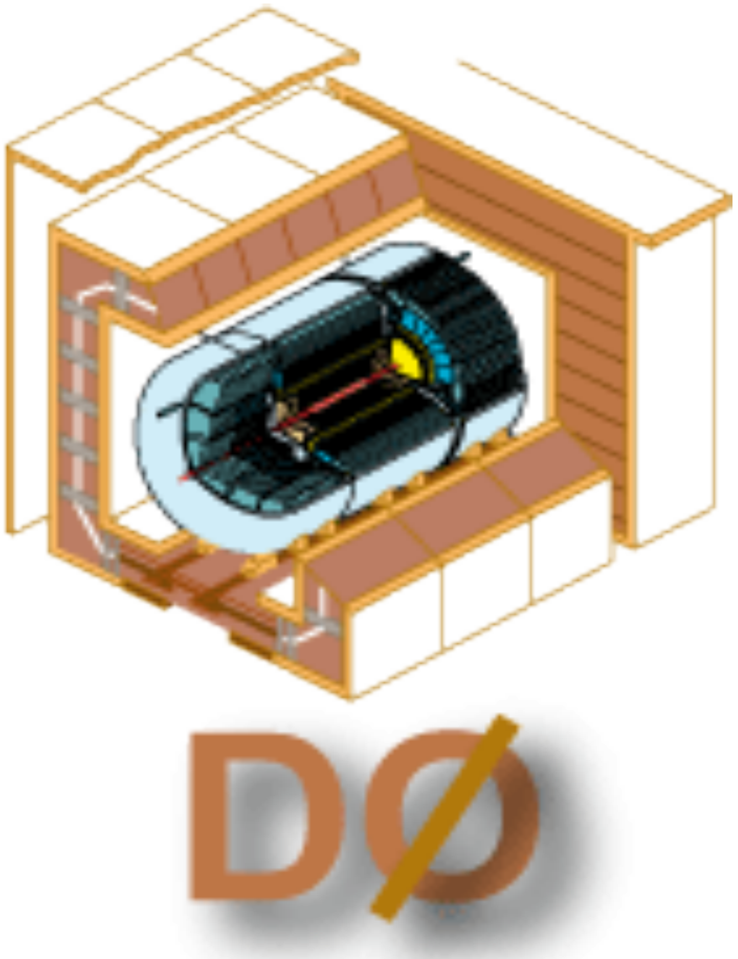
Tevatron combination

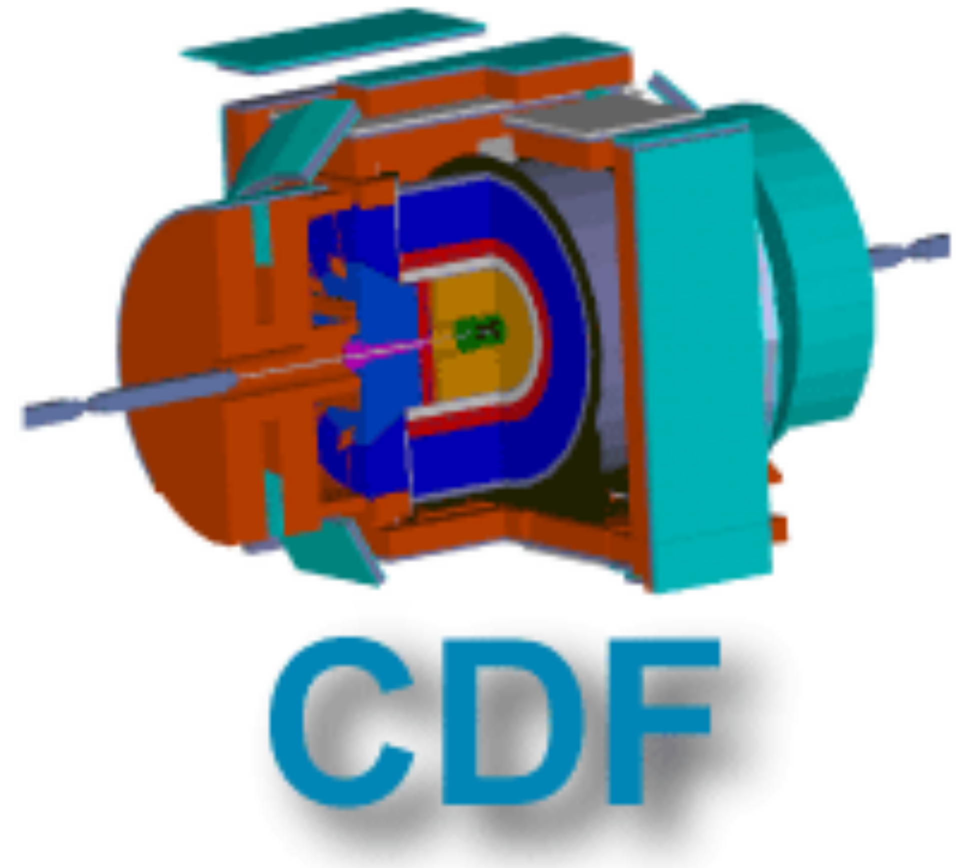
Conclusions

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 9 fb^{-1} of data

Experiments



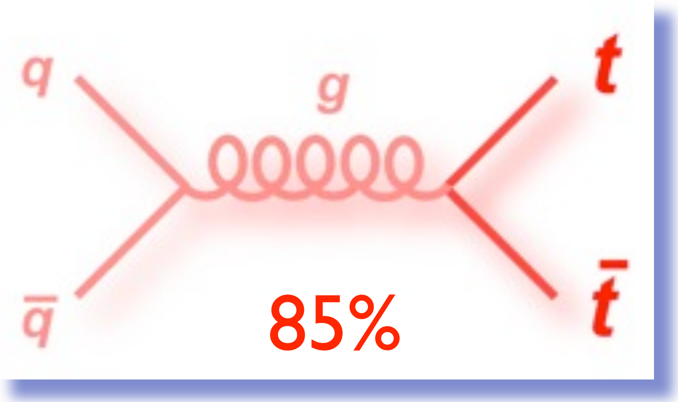


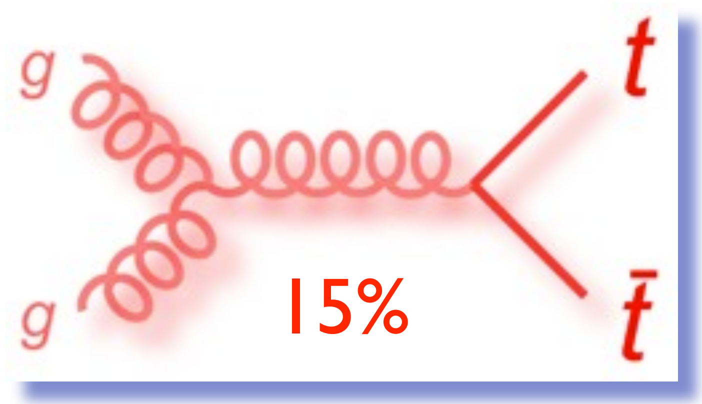
- Multipurpose collider detectors
  - high resolution inner detectors for precise tracking and vertex reconstruction
  - electromagnetic and hadronic calorimeters
  - outer muon system
  - magnetic field

Top quark pair production

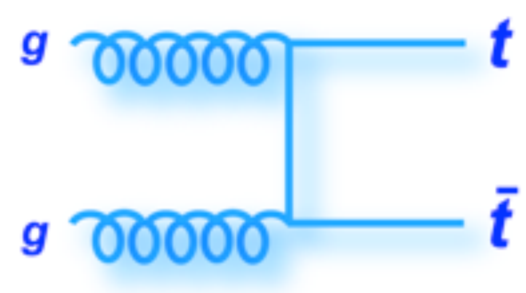
Main mechanism: pair production via strong interaction

Tevatron

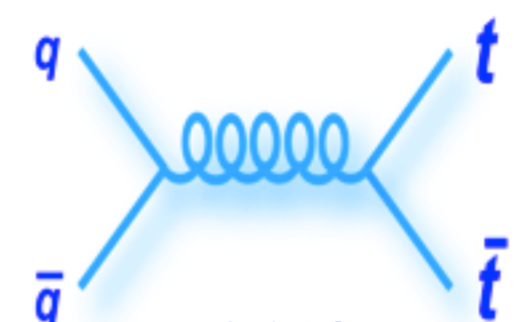




LHC



80%



20%

Top quark pair production

Main mechanism: pair production via strong interaction

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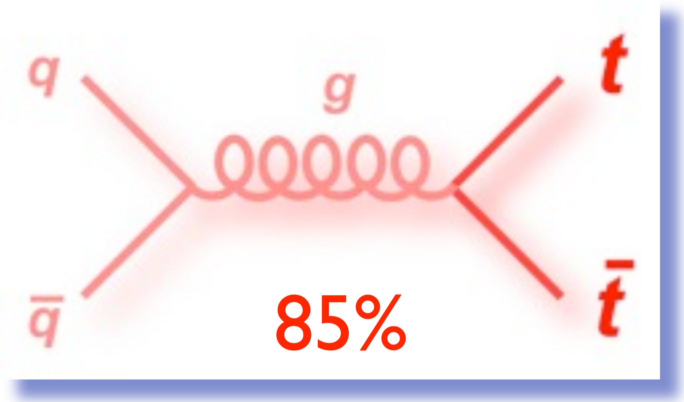

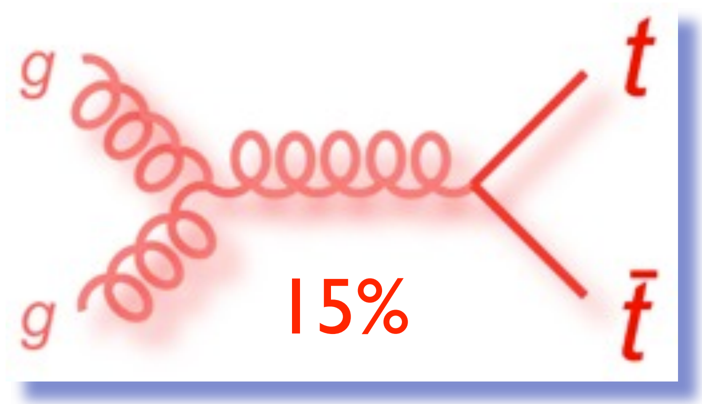

Phys.Rev.Lett. 110 (2013) 252004

- 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 GeV, MSTW2008NNLO PDF

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

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

Top quark pair production

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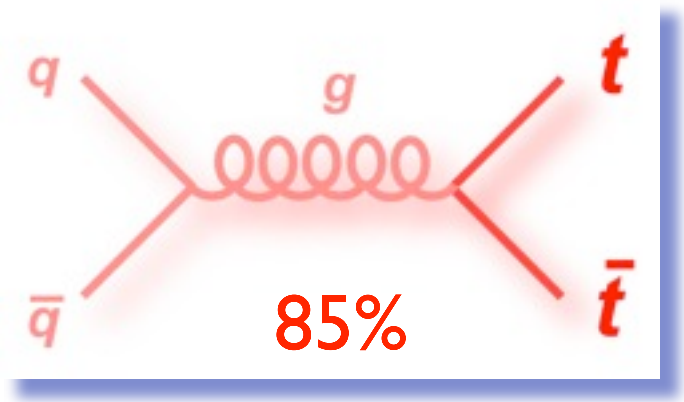
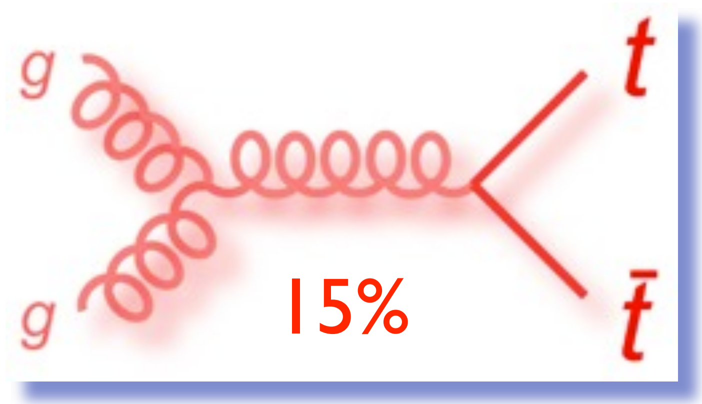
Tevatron





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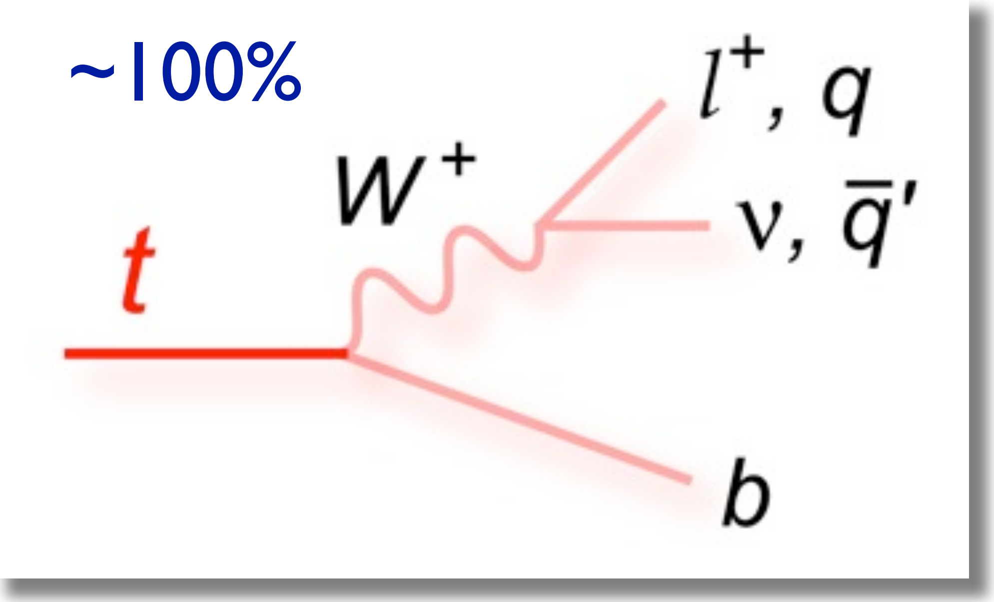
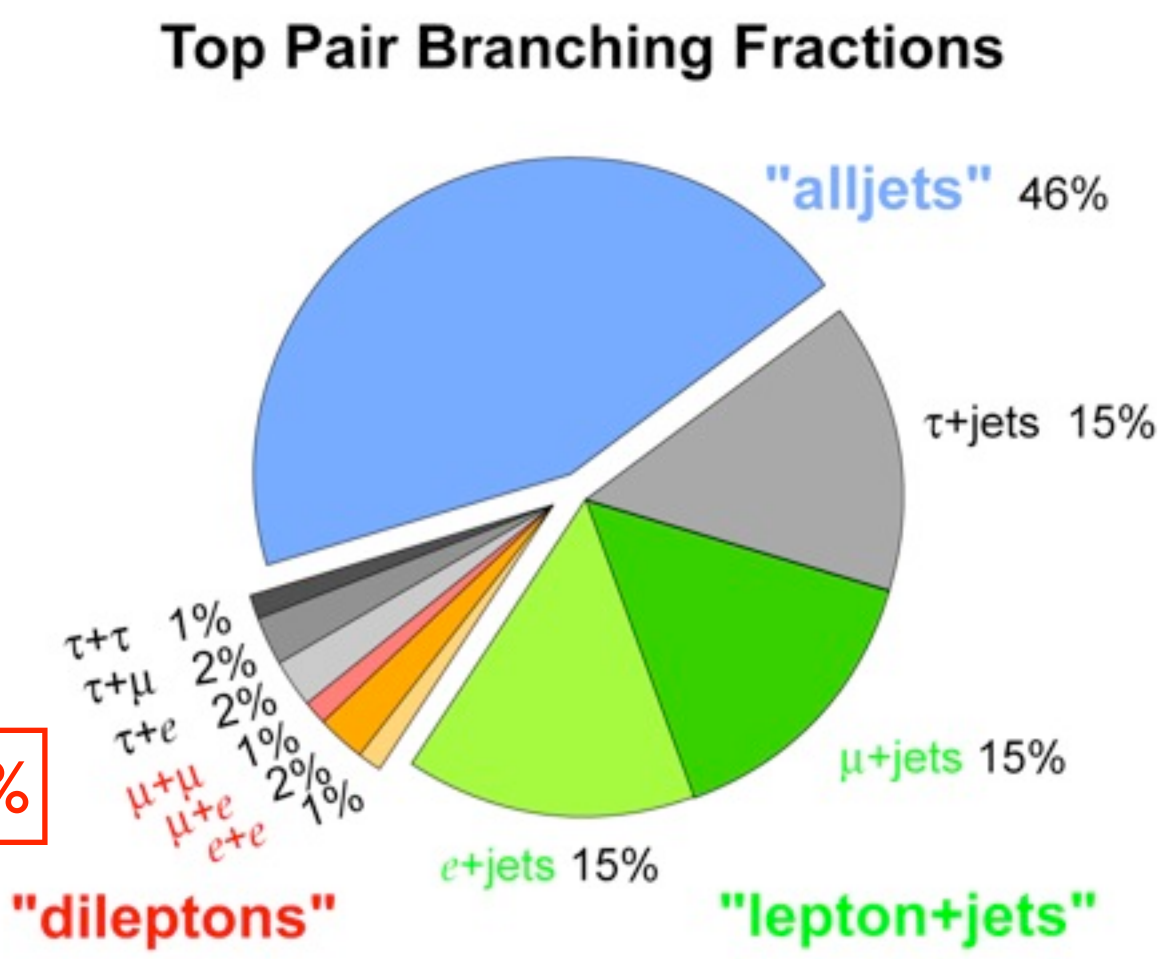
- ~4% uncertainty for Tevatron

LHC:	ATLAS full 7 TeV sample	~29,000 l+jets events
Tevatron:	D0 full sample	~2,700 l+jets events

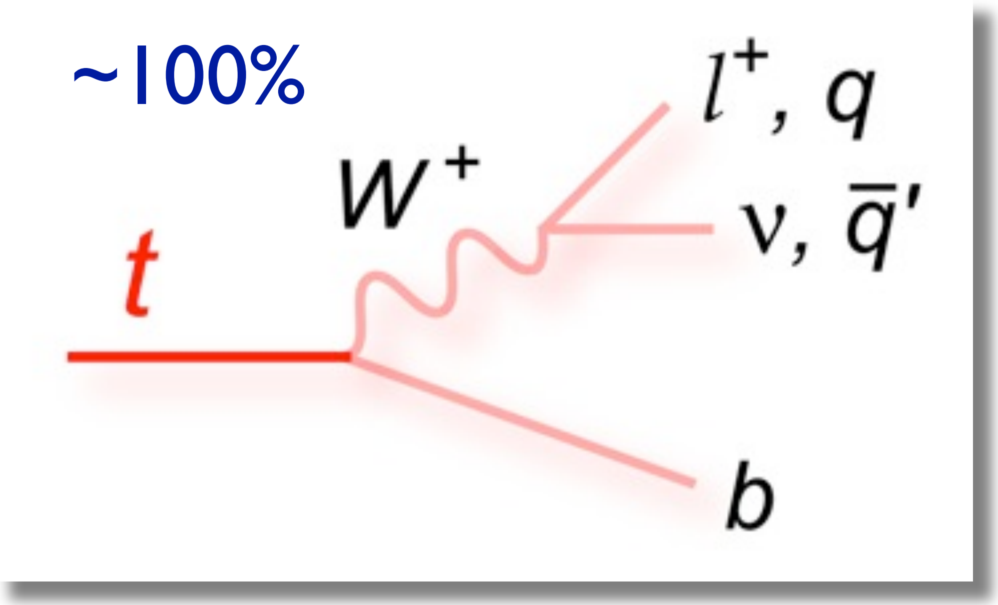
Top quark decay

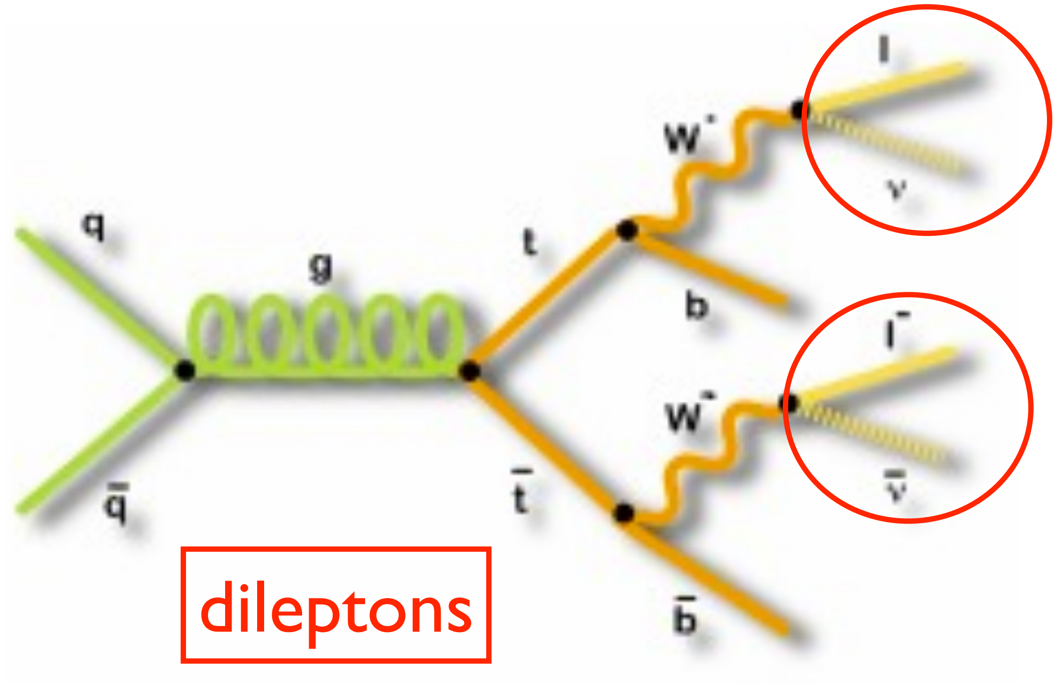


Top quark decay



~4.5%

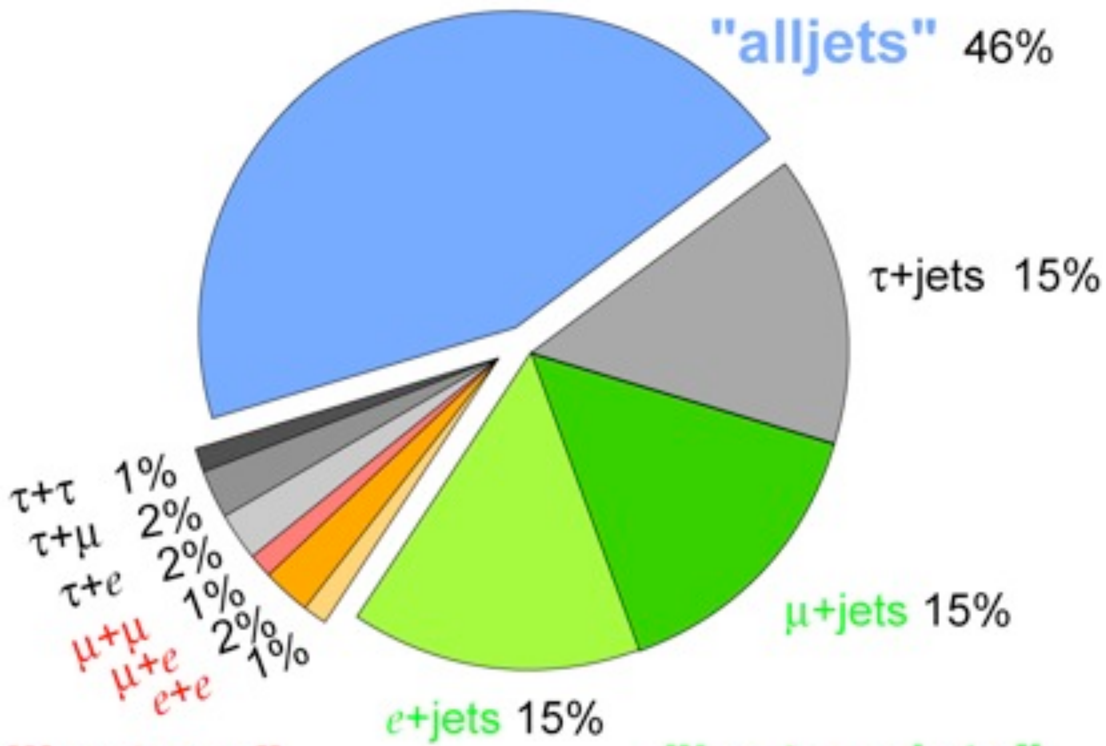




dileptons

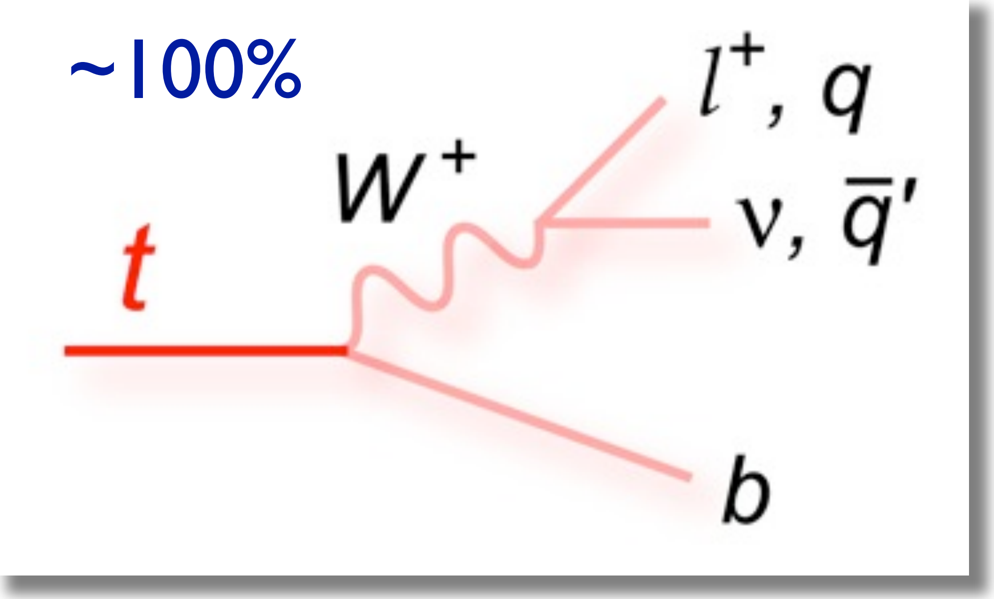
- Small rate
- Small backgrounds

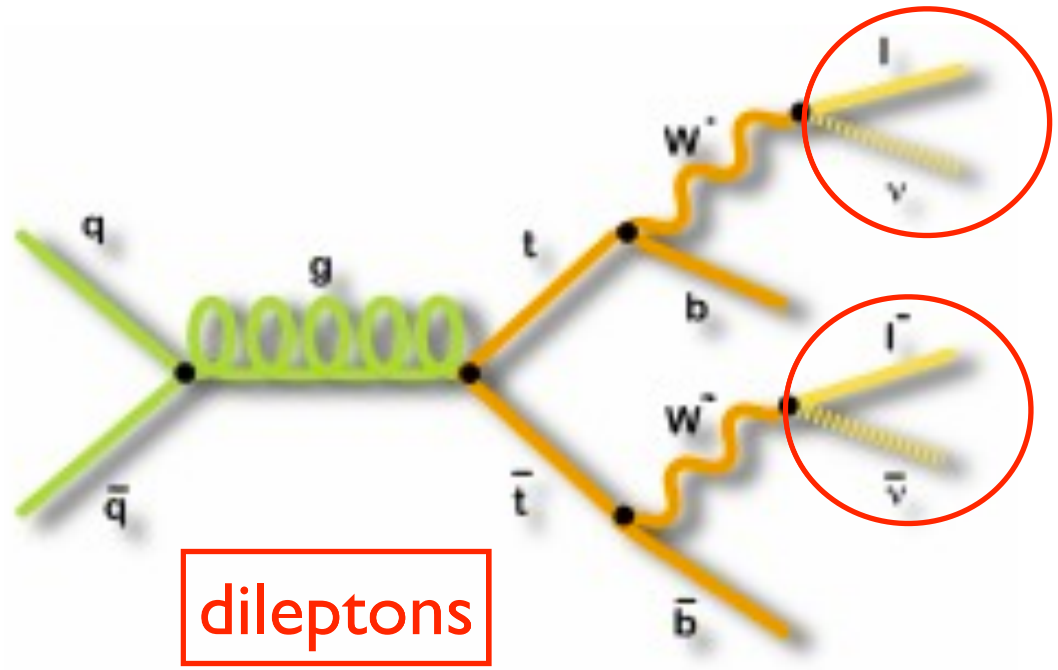
Top quark decay



~4.5%

~30%





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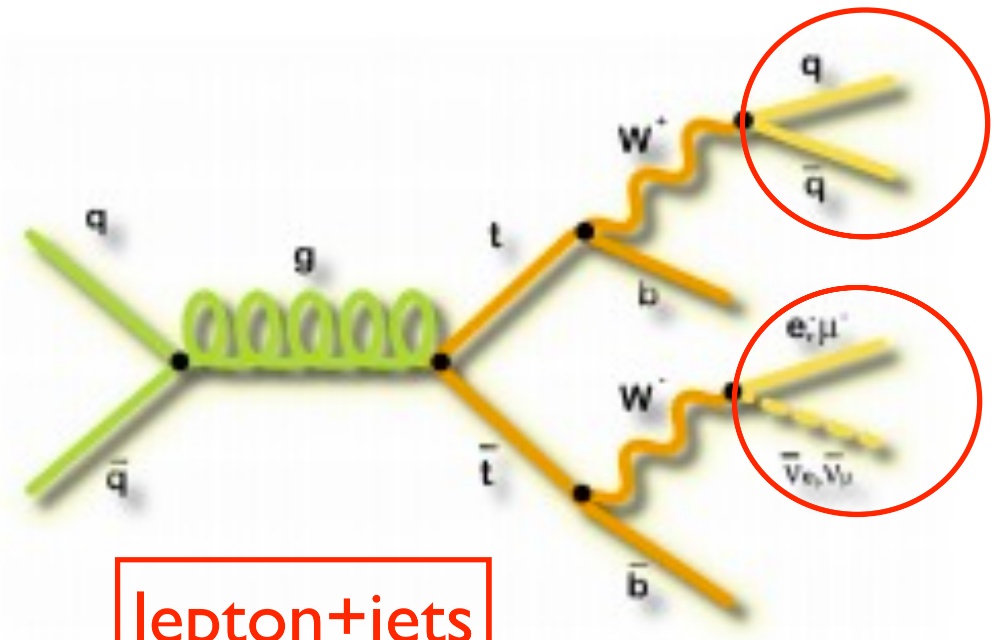


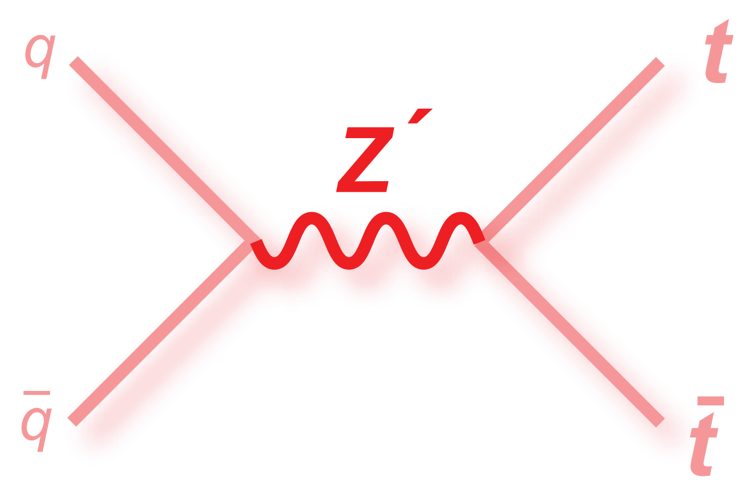
lepton+jets

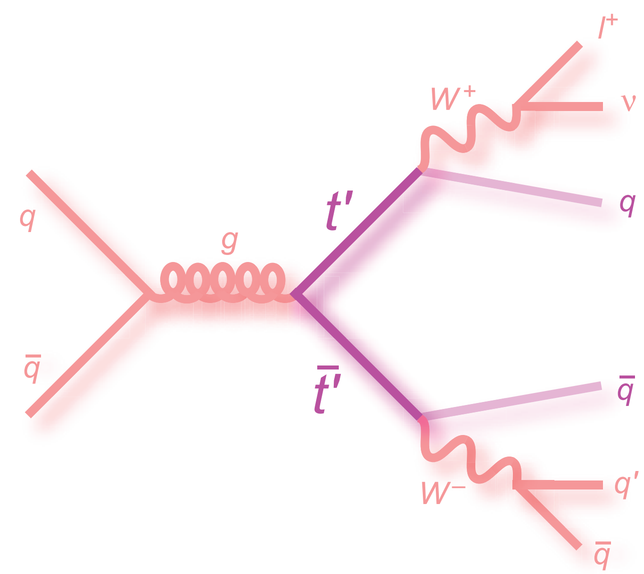
- "Golden channel"
  - good rate
  - manageable backgrounds

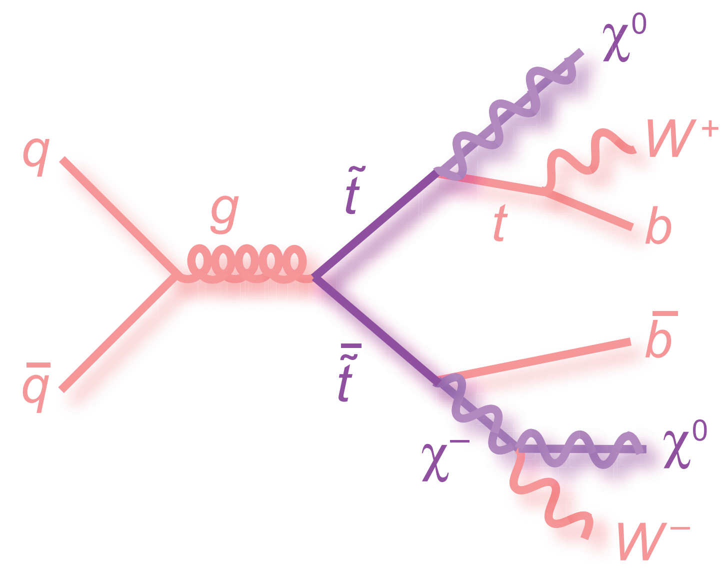
Motivation

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

New physics in top quark production







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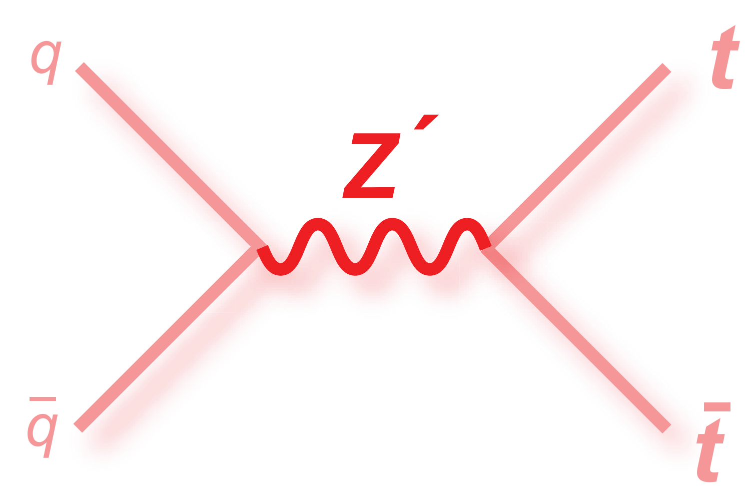
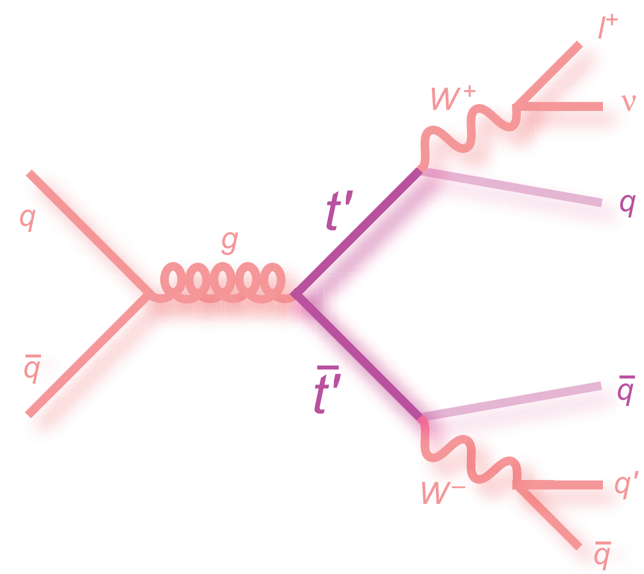
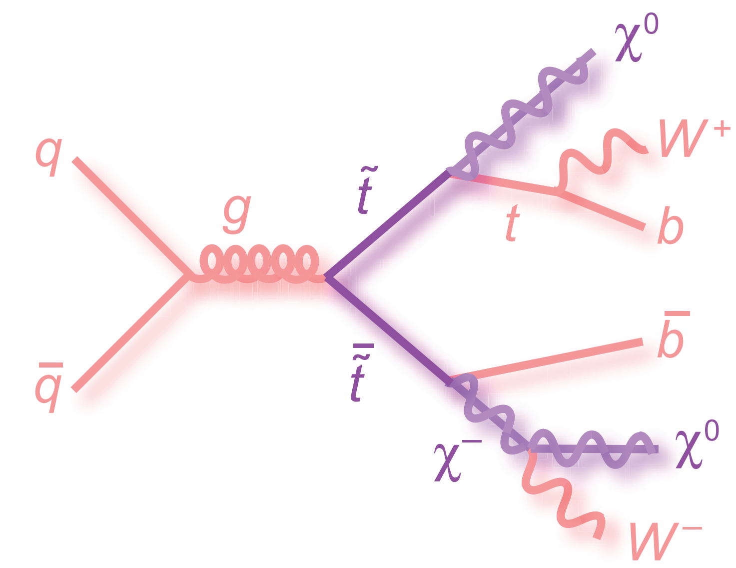
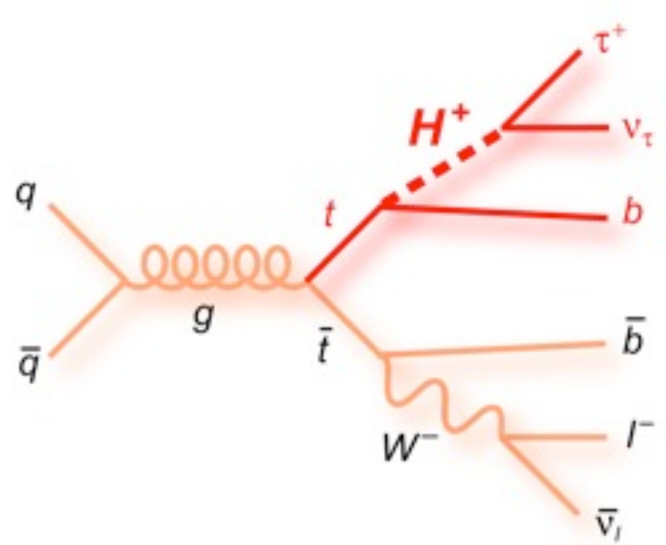






... and decay

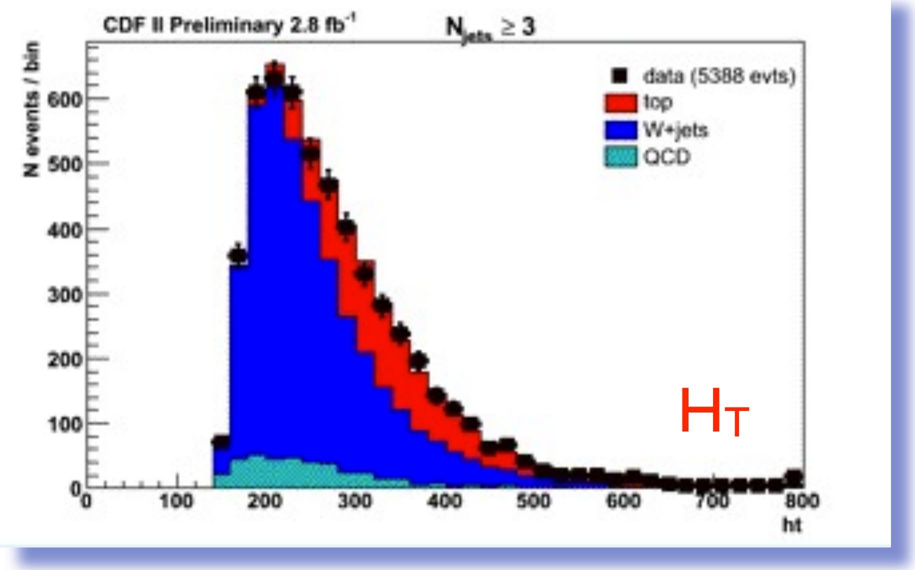


- New physics can change
  - overall production rate
  - rate in different channels
- Precision measurements of cross section are important in different decay channels

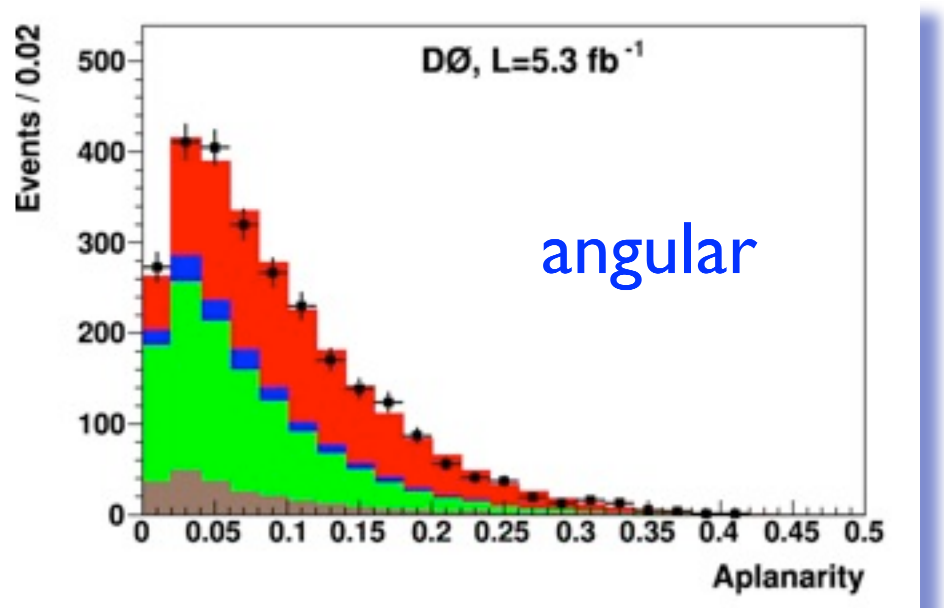
Techniques

Finding top quarks: kinematics

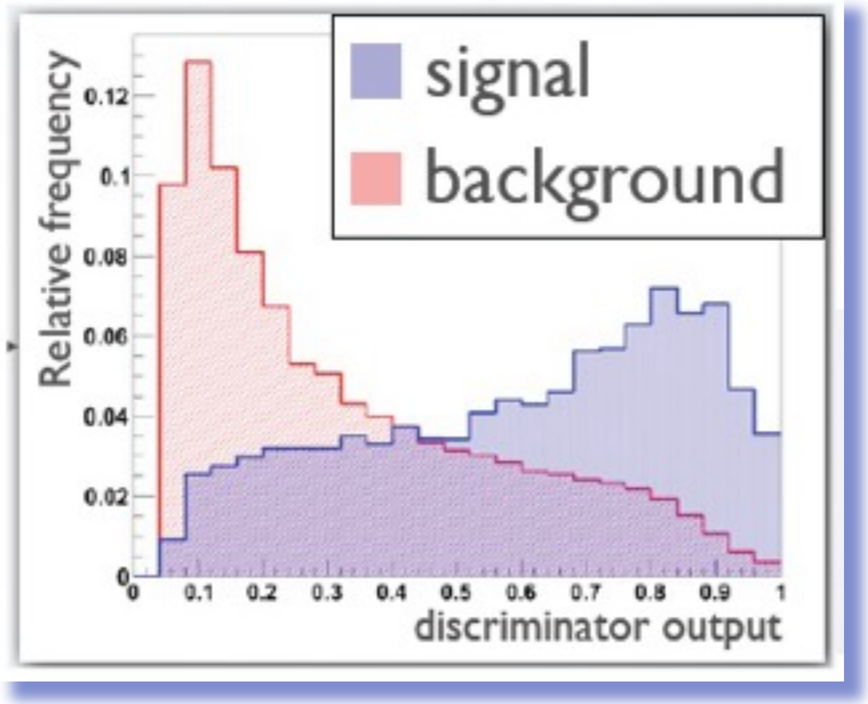
- exploit differences between kinematic properties of signal and background
- select discriminating variables



energy-dependent



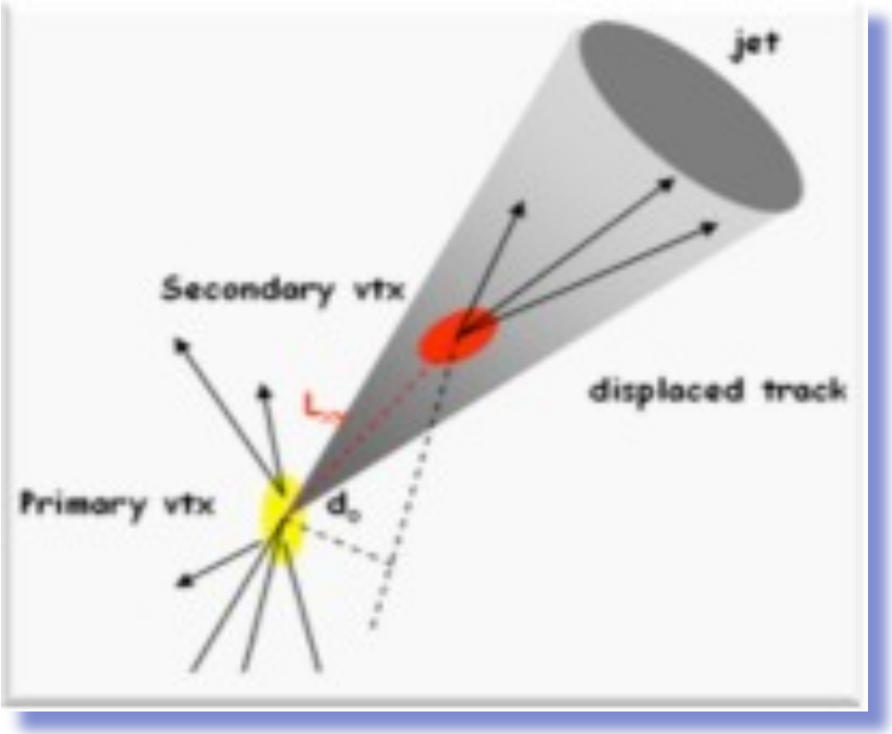
- build a discriminant from these variables
  - likelihood
  - neural network
  - boosted decision trees



- extract cross section from a binned likelihood fit to data

Finding top quarks: b-tagging

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



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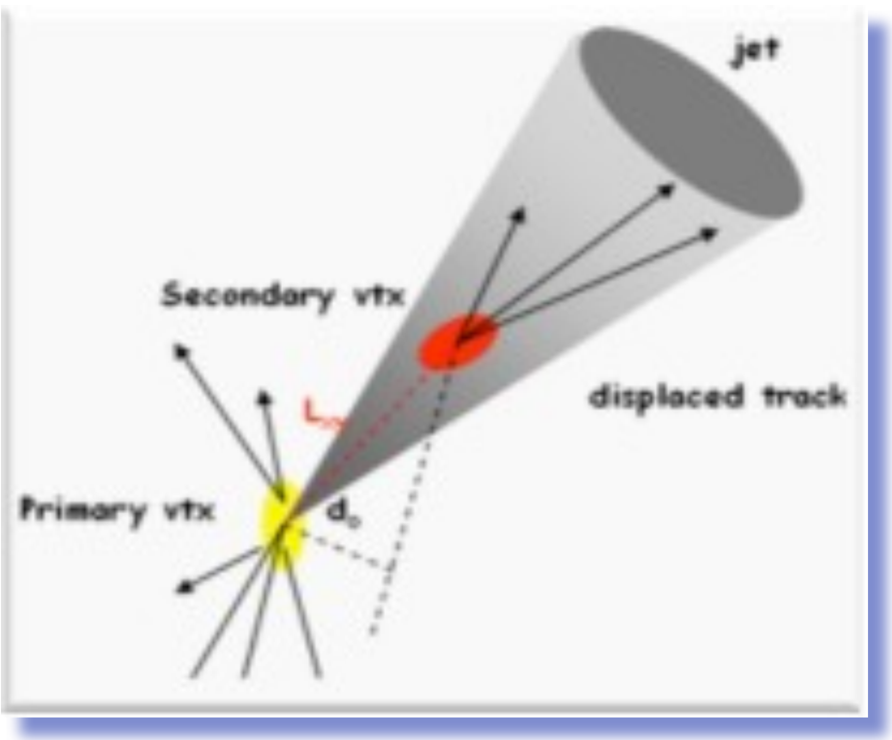
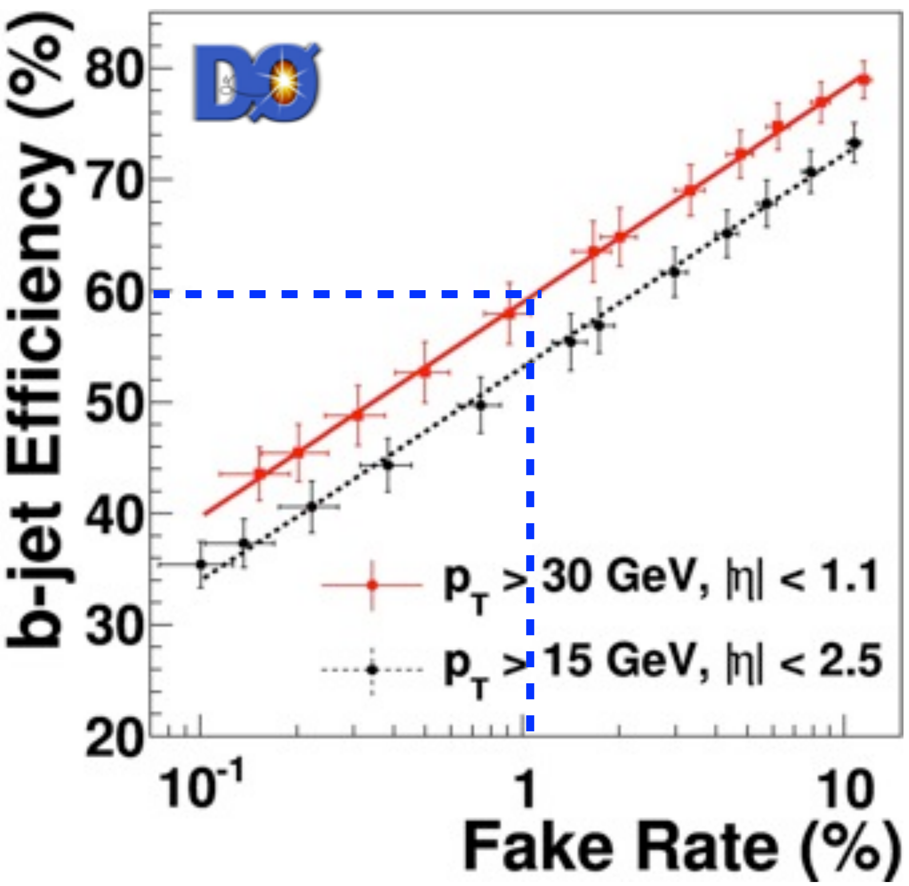


- CDF Secondary Vertex tagger (SVX)
  - reconstructs secondary vertex
  - $L_{2D}/\sigma > 7.5$
- DØ Neural Network tagger
  - combines properties of displaced tracks and secondary vertex
  - 7 variables total



NIM, A620, 400 (2010)

Measurements

dilepton channel

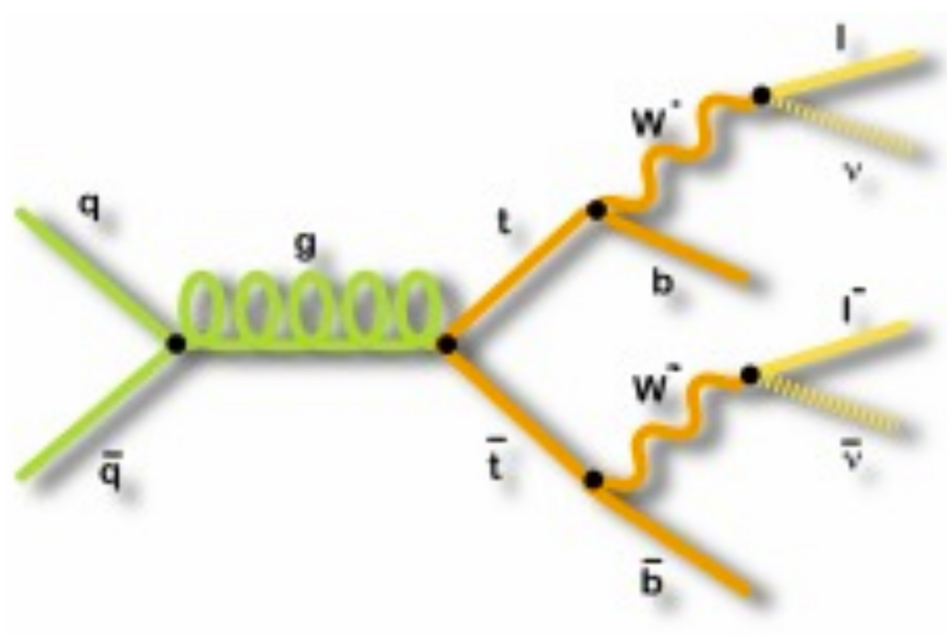
lepton+jets channel

lepton+τ_{had} channel

Dilepton channel

Signature

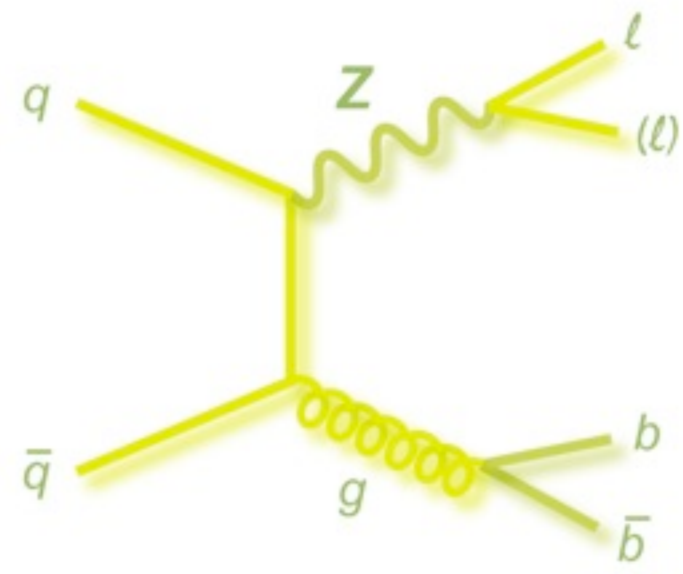
- two high p_T isolated leptons
- large missing transverse momentum
- $\geq$ 2 b-jets

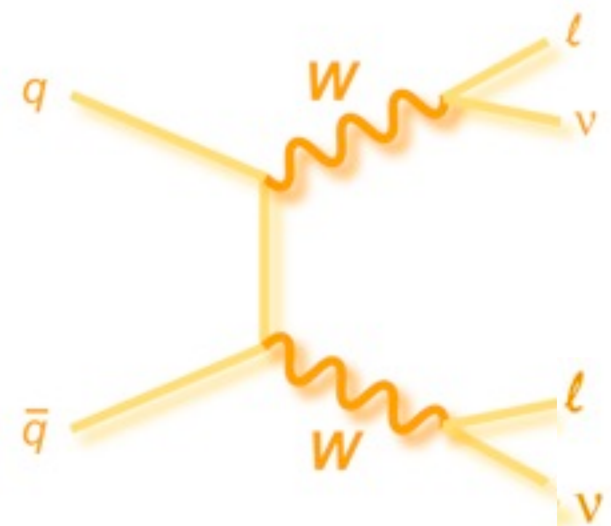


S/B

topo	1 b-tag
3:1	15:1

Backgrounds



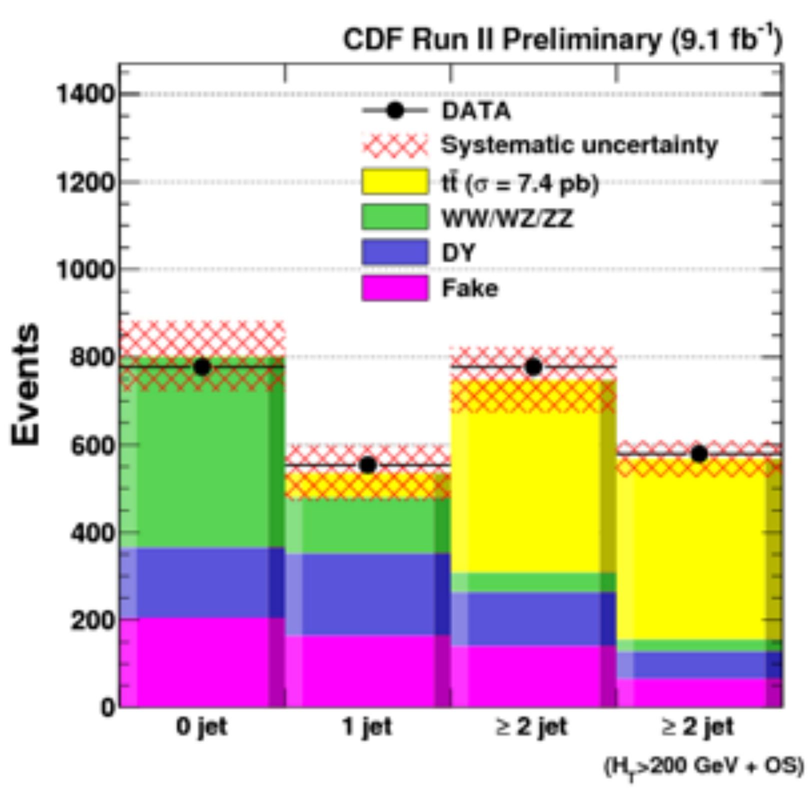


- Statistically limited at the Tevatron for a very long time
- Low backgrounds motivate the methods

Dilepton channel - I

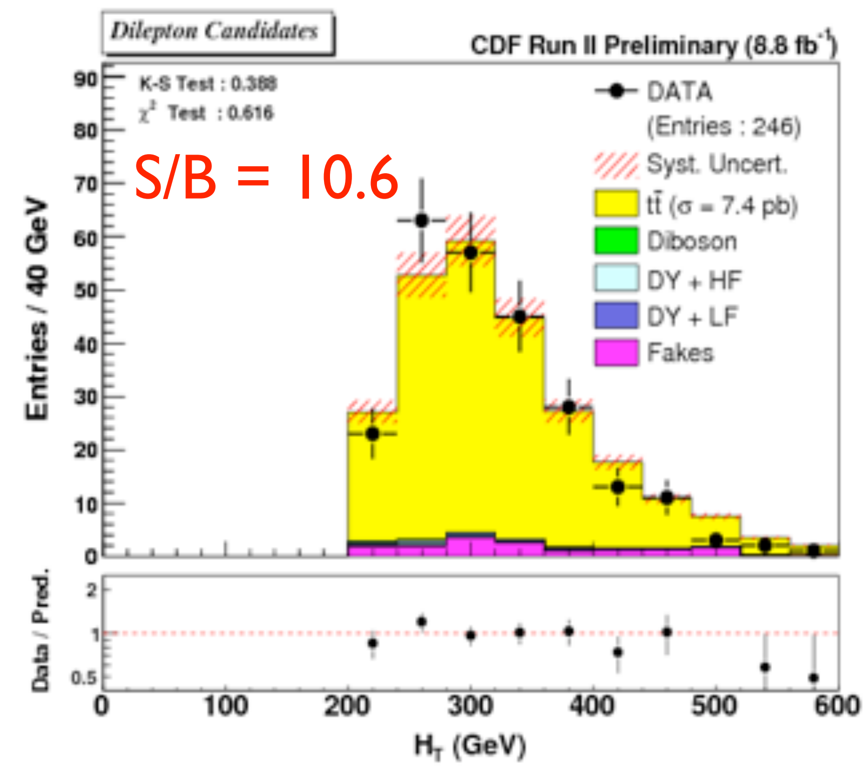
- cut and count with and w/o b-tagging
  - 576 dilepton events for pretag
  - 246 dilepton events for b-tagged

Phys.Rev.D88:091103, 2013



9.1 fb^{-1}

S/B = 2.6



8.8 fb^{-1}

Dilepton channel - I

- 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		5.0
total acceptance	4.8	6.9
background model	7.1	2.1
Total	8.6	7.2

- luminosity uncertainty 6.1%

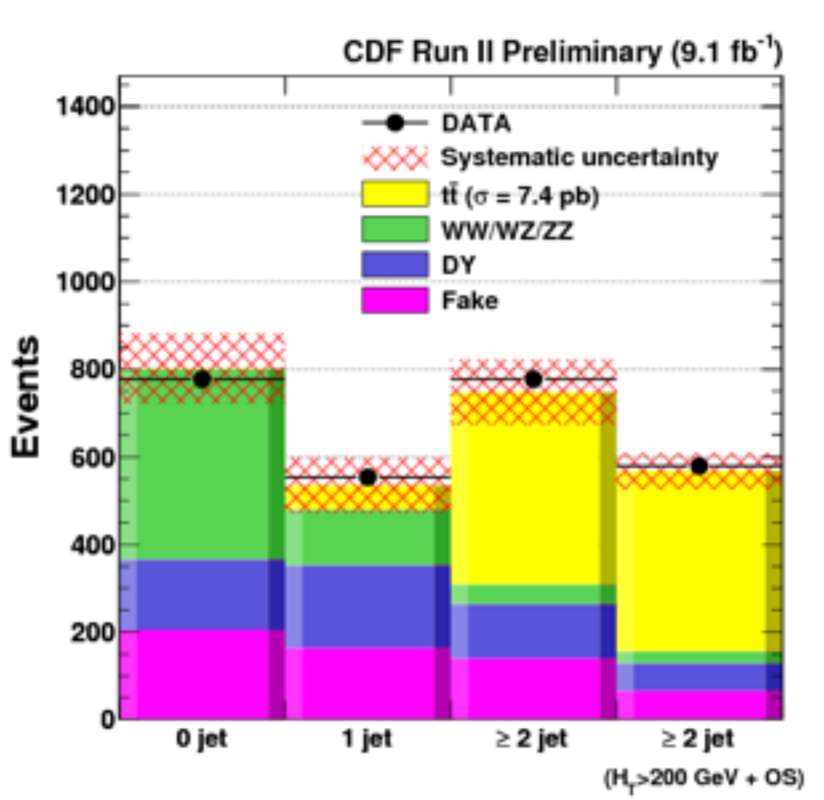
m_t = 172.5 GeV

$\sigma_{t\bar{t}}^{tag}$ = 7.61 ±0.44(stat) ±0.52(syst) ±0.47(lumi) pb

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

b-tag measurement has better precision: 9.4%

Phys.Rev.D88:091103, 2013



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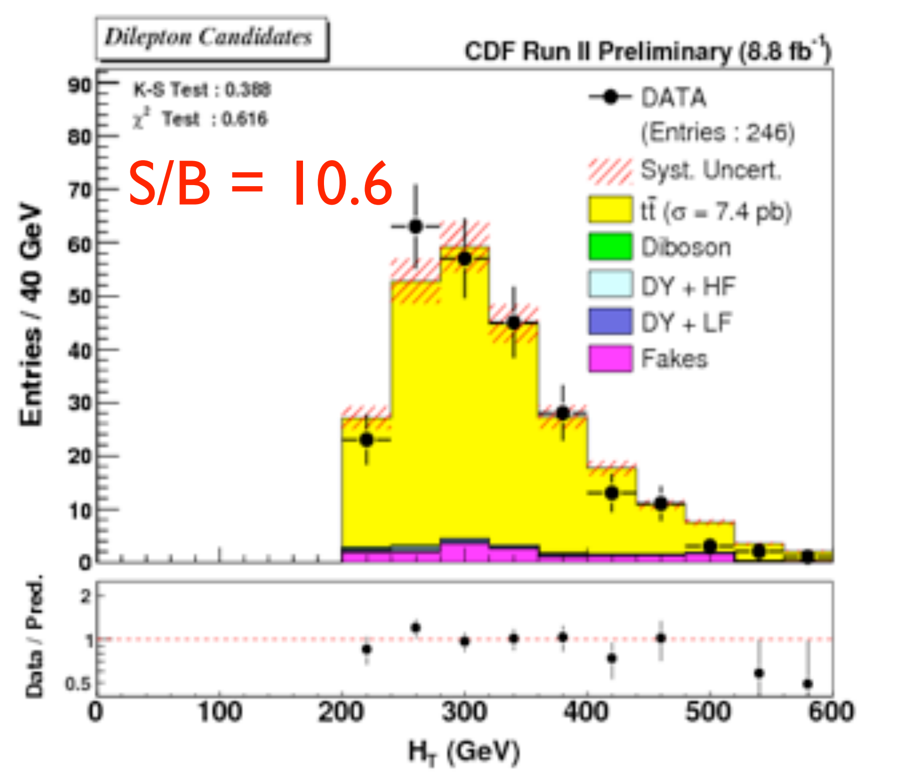

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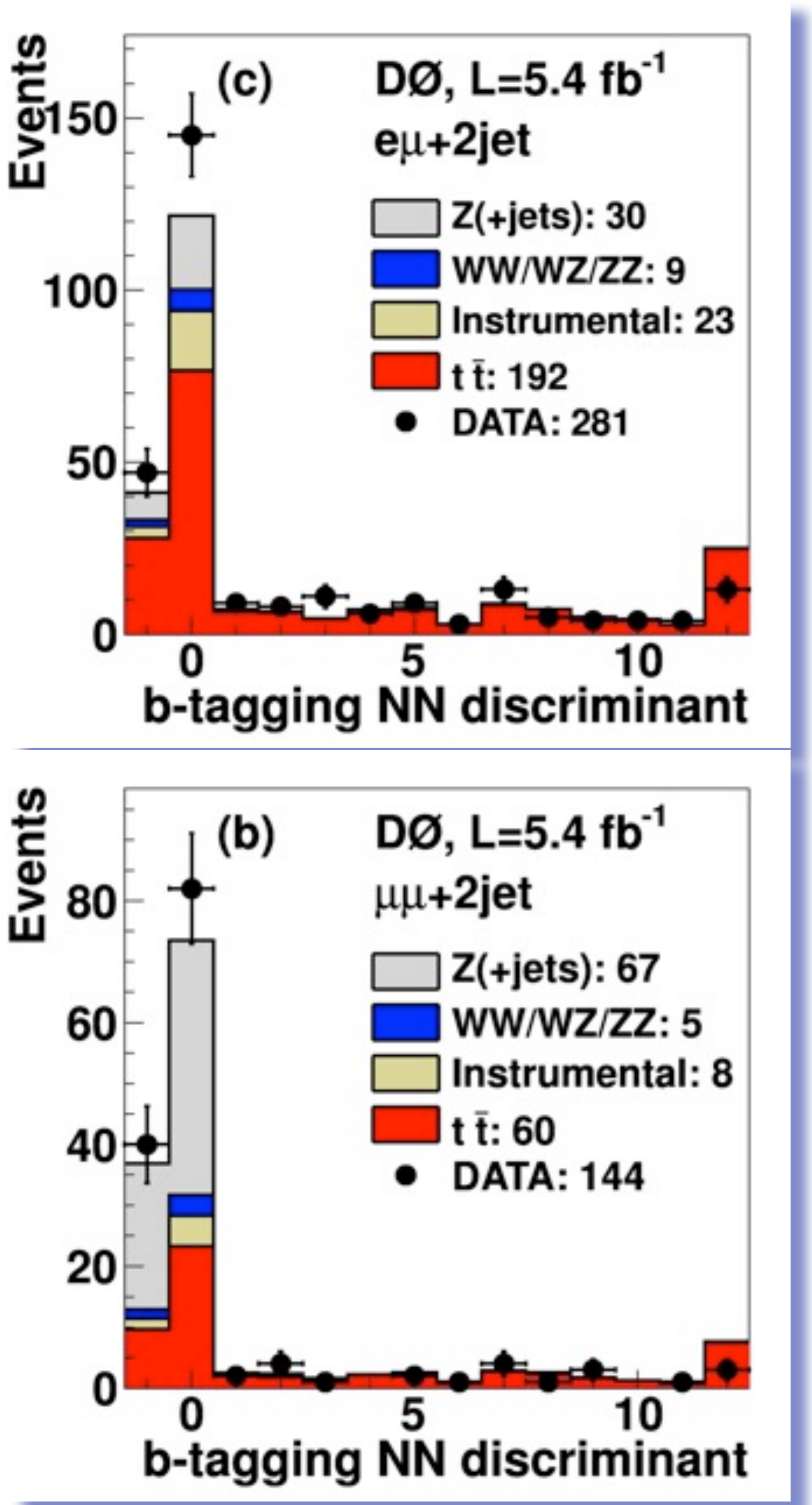
Dilepton channel - II

- Loose selection — PLB,704, 403,2011
  - ee, μμ: ≥2 jets, eμ : = 1, ≥2 jets
  - 649 dilepton candidates in 4 channels
- Fit to b-tag NN discriminant distribution
  - the smallest NN output value among 2 leading jets, i.e. most light-like jet
- Uncertainties are included as nuisance parameters in the fit



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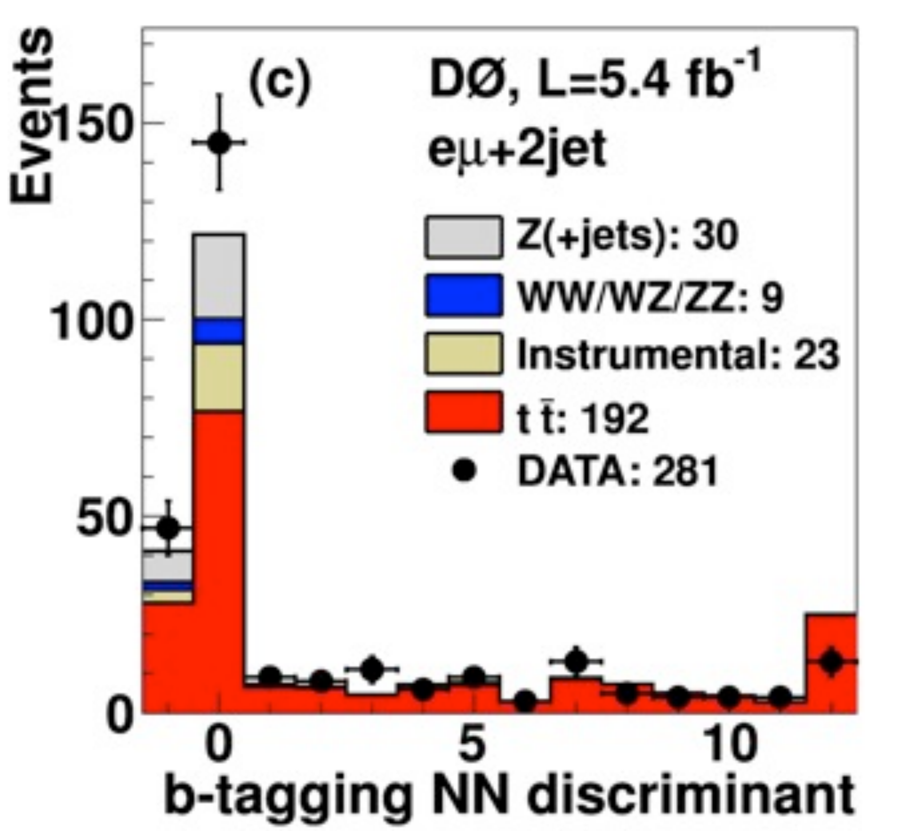
Source	+σ(pb)	-σ(pb)
Statistical	+0.50	-0.48
Lepton ID	+0.26	-0.25
Signal model	+0.34	-0.33
Jet scale and teco	+0.25	-0.23
Background	+0.34	-0.32
b-tagging	+0.06	-0.06
Luminosity	+0.57	-0.51

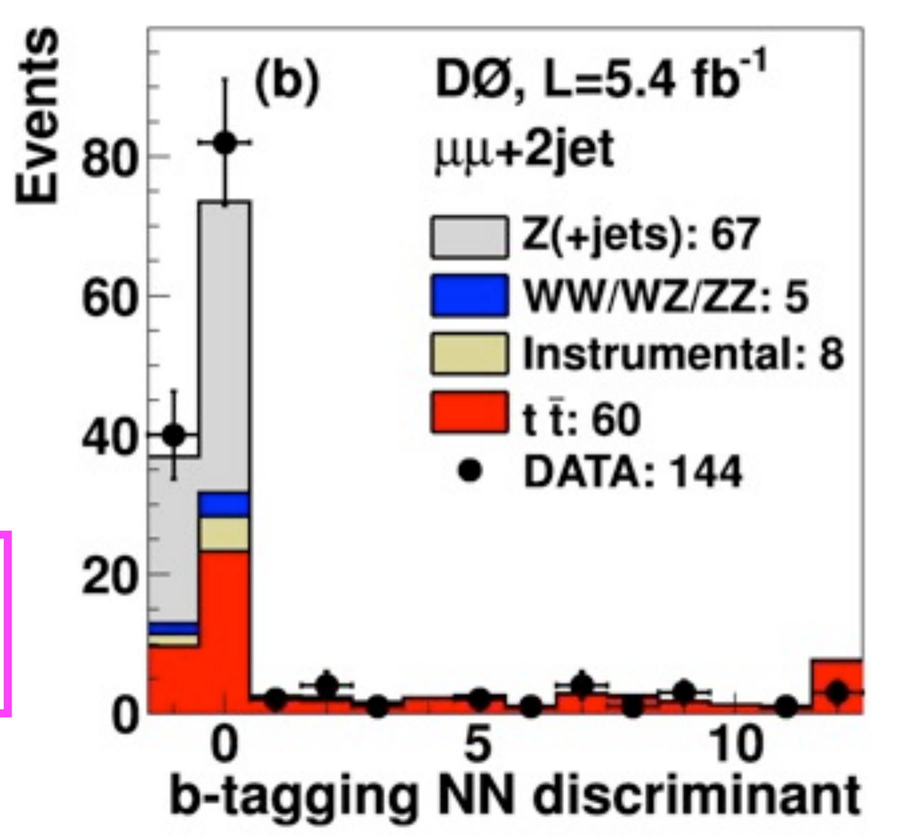
- luminosity uncertainty +7.7−6.9%

12% relative precision

$$\sigma_{t\bar{t}} = 7.36^{+0.90}_{-0.79}(\text{total})$$

m_t = 172.5 GeV





Measurements

dilepton channel

lepton+jets channel

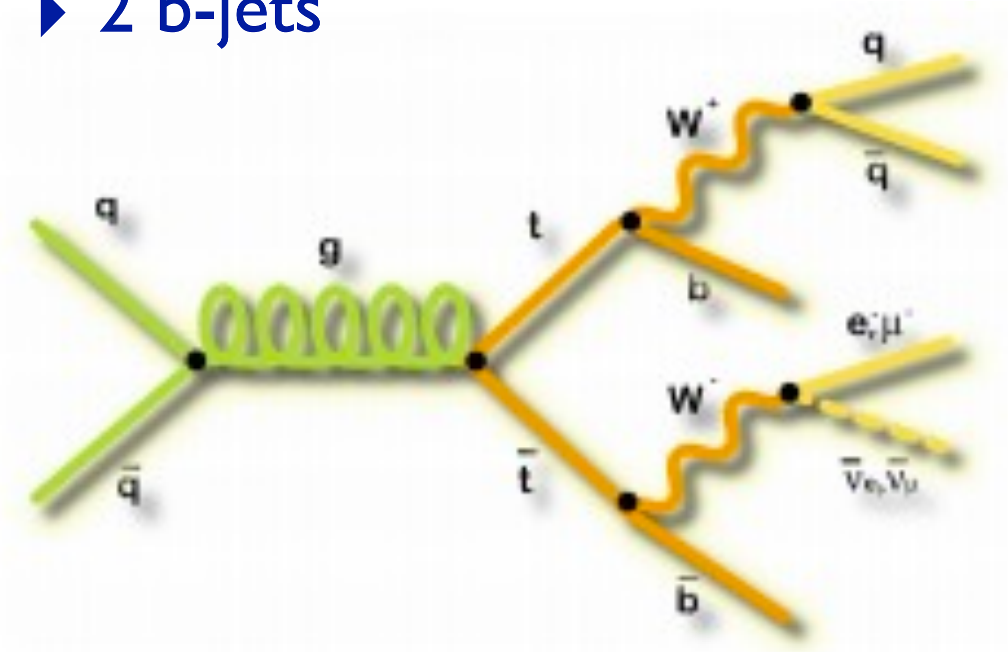
lepton+τ_{had} channel

lepton+jets channel

Provides the most precise measurements

Signature

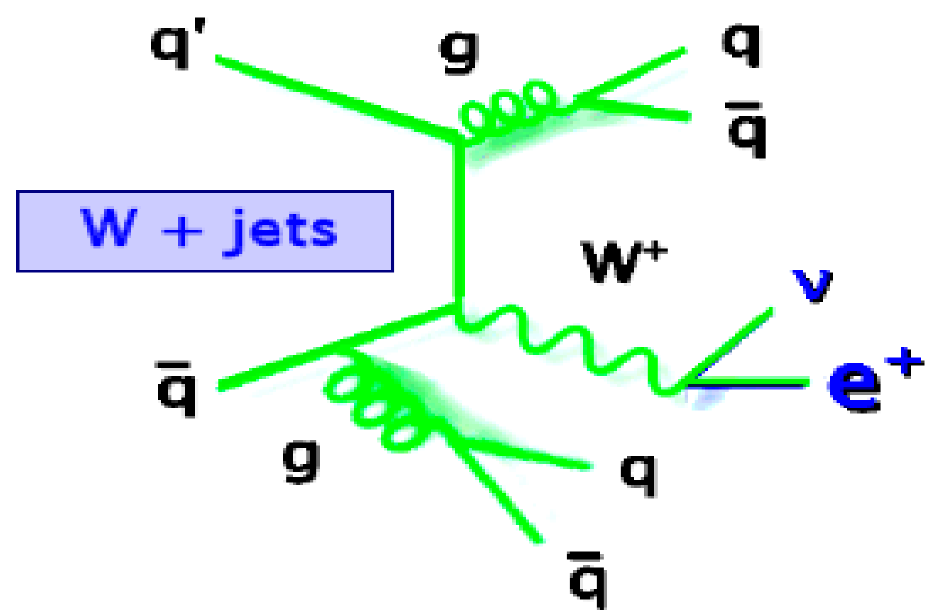
- one high p_T isolated lepton
- large missing transverse momentum
- $\geq$ 4 jets
- 2 b-jets



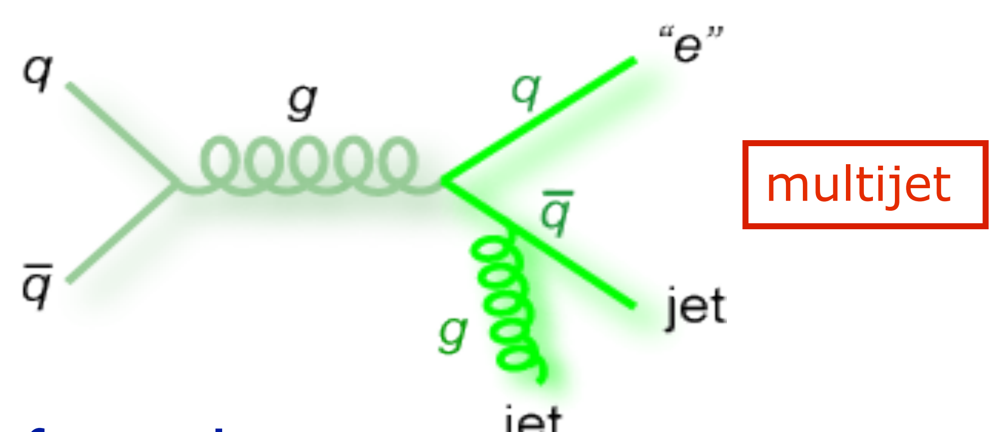
S/B (4 jets)

topo	1 b-tag
2:3	4:1

Backgrounds



- based on MC simulation



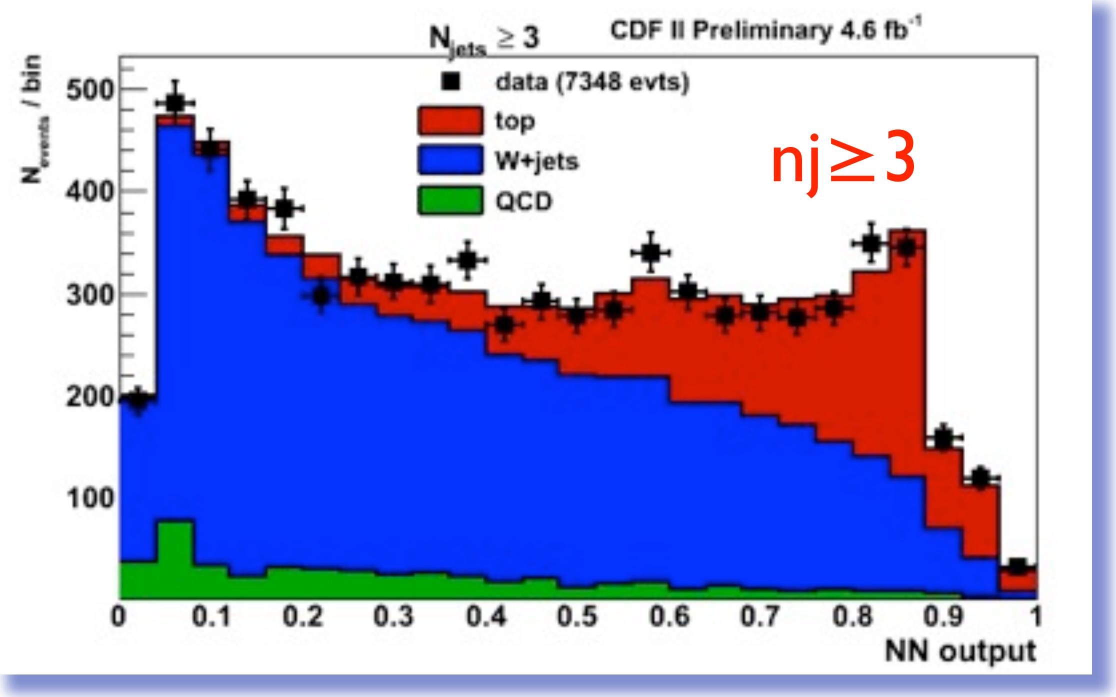
- from data

lepton+jets - I

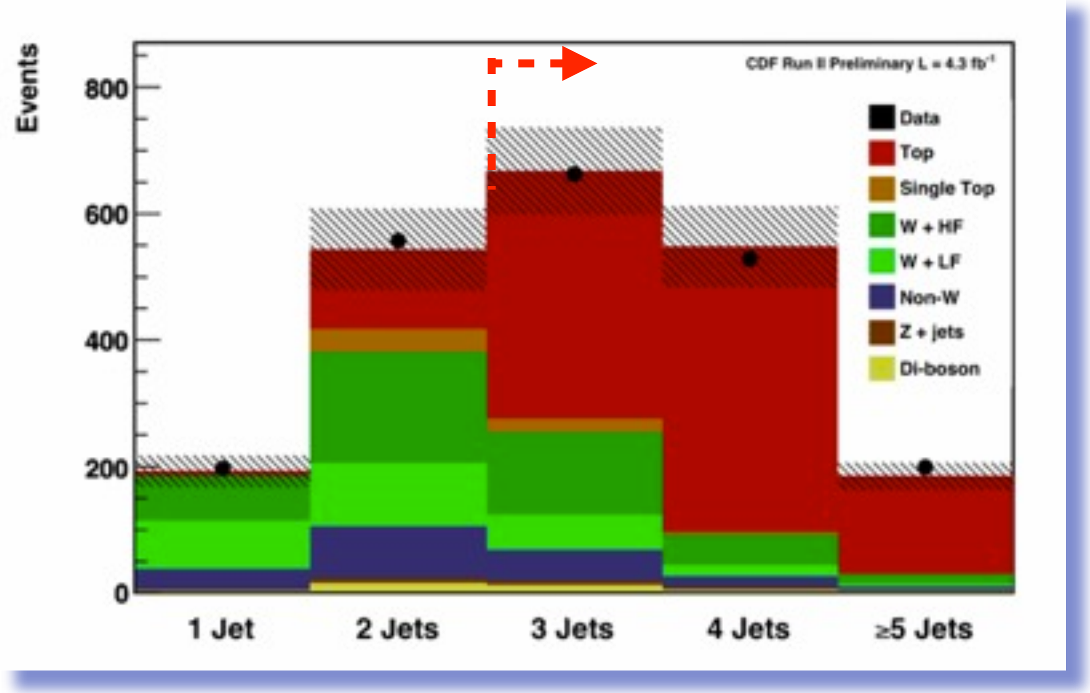
- analysis targets luminosity uncertainty
- two methods
  - b-tag counting
  - event kinematics
- measure Z cross section
  - use same triggers
  - same data set
- compute the ratio of $t\bar{t}$ to Z cross section taking into account correlations
- trade luminosity uncertainty for Z cross section theoretical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

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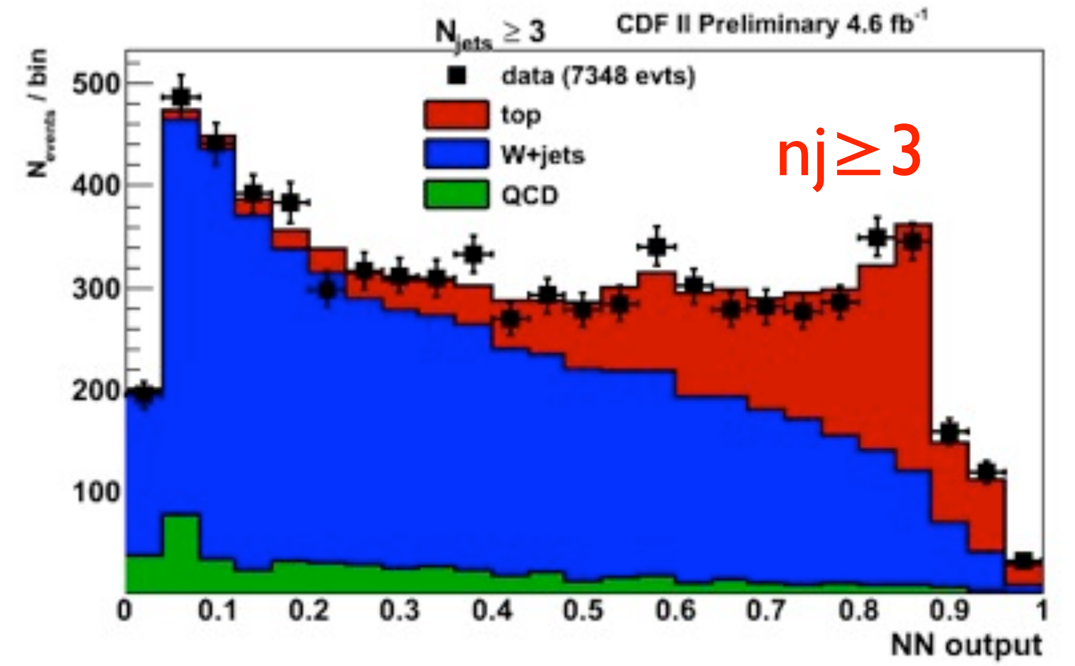
PRL 105:012001,2010 4.6 fb^{-1}



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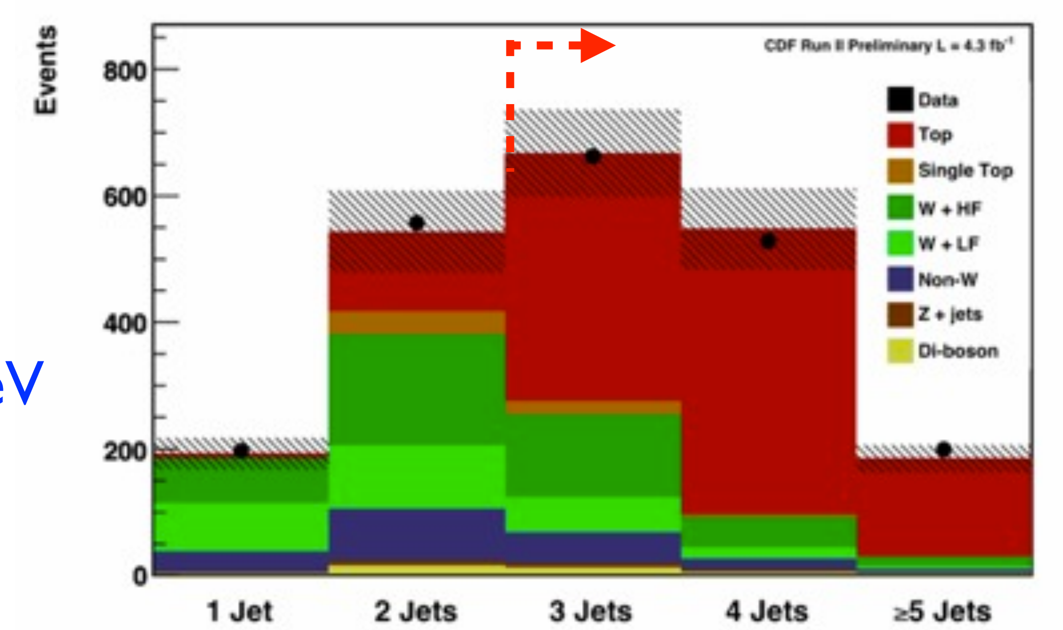


$\sigma_{t\bar{t}}$ = 7.32±0.36(stat)±0.59(syst)±0.14(th) pb

- combine using BLUE
- statistical correlation 32%

$\sigma_{t\bar{t}}$ = 7.70 ± 0.52 (total) pb m_t = 172.5 GeV

7% relative precision, 8.8% with luminosity uncertainty

lepton+jets - II

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

DØ

PRD,84:012008,2011

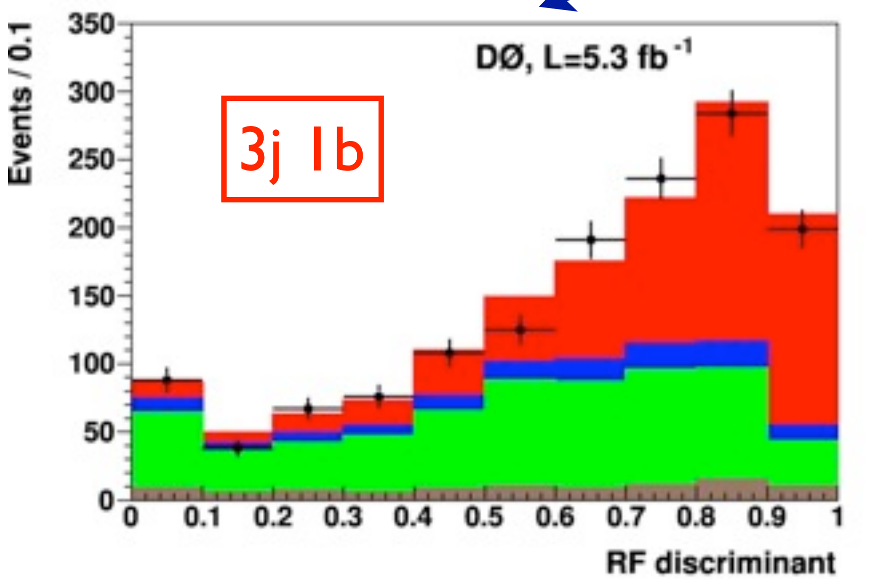
combined method

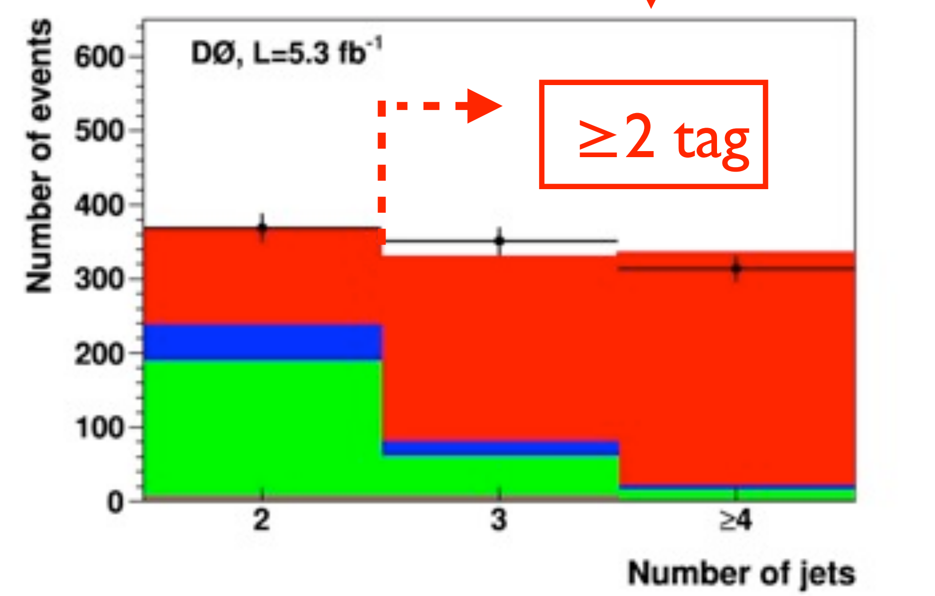
	0 b-tag	1 b-tag	≥2 b-tags
2 jets	RF	RF	RF
3 jets	RF	RF	b-tag
≥4 jets	RF	b-tag	b-tag

background dominated

signal dominated

Random Forest discriminant





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PRD,84:012008,2011

combined method

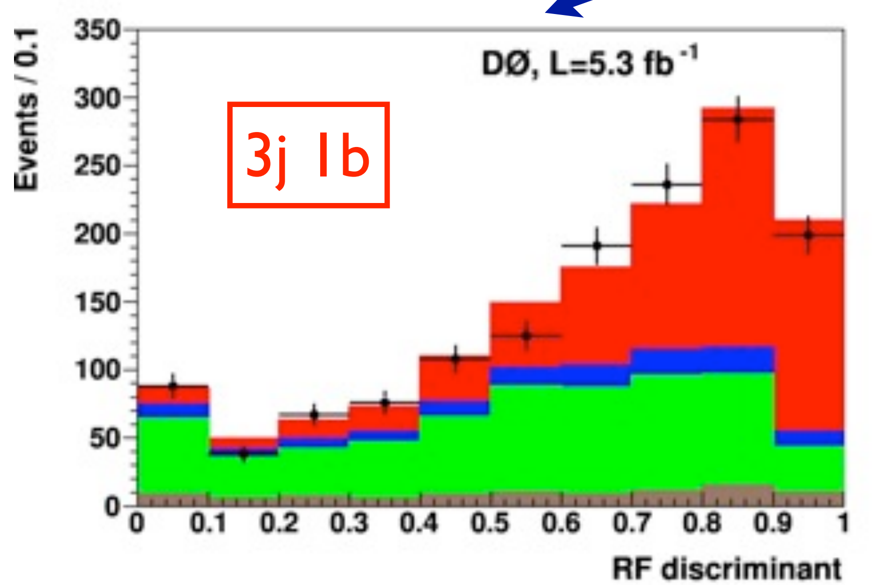
	0 b-tag	1 b-tag	≥2 b-tags
2 jets	RF	RF	RF
3 jets	RF	RF	b-tag
≥4 jets	RF	b-tag	b-tag

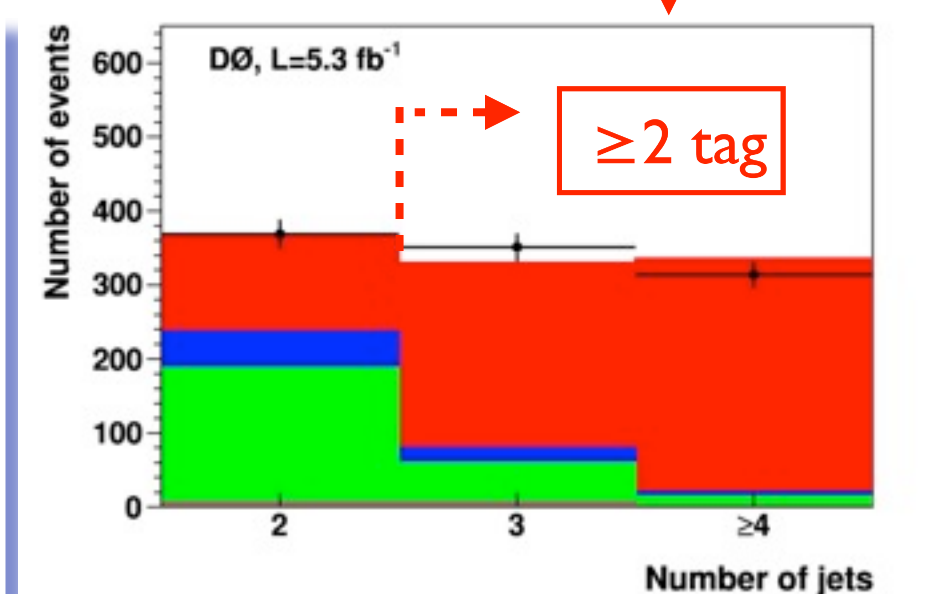
- simultaneous fit in 9 regions
- W+jets heavy flavor fraction is extracted from the fit
- systematic uncertainties included in the fit as nuisance parameters
- data constrains uncertainties

Random Forest discriminant

background dominated

signal dominated





lepton+jets - II

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

PRD,84:012008,2011

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

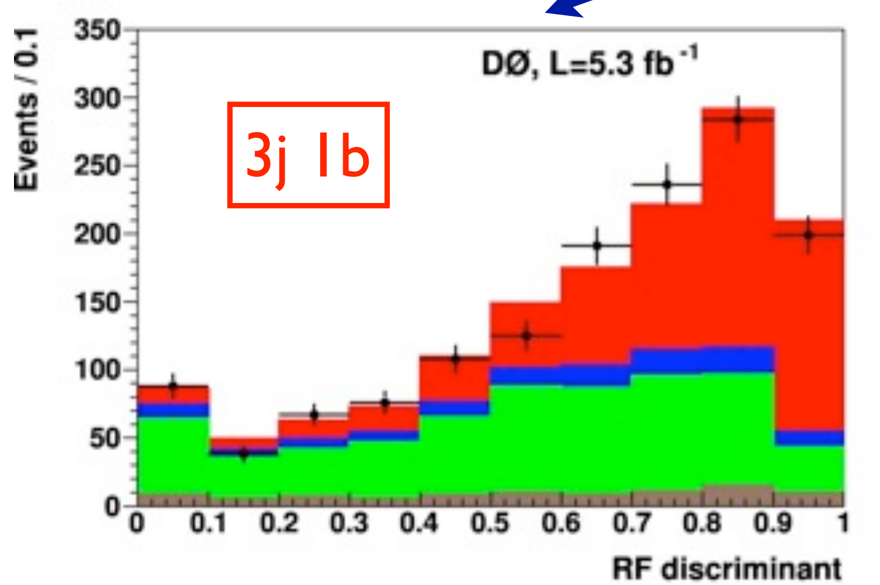
- simultaneous fit in 9 regions
- W+jets heavy flavor fraction is extracted from the fit
- systematic uncertainties included in the fit as nuisance parameters
- data constrains uncertainties

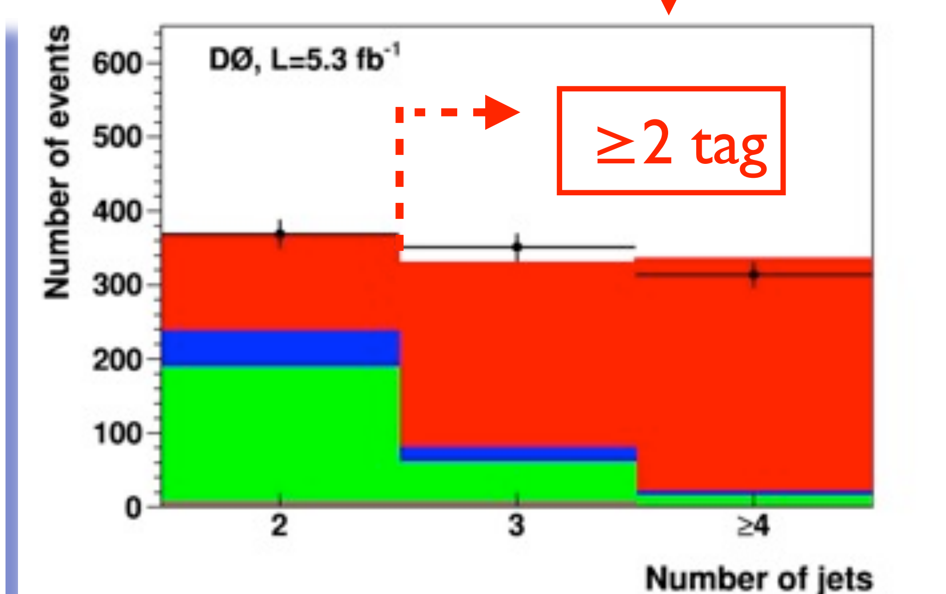
$$\frac{\mathbf{W+hf}}{\mathbf{W+lf}} = 1.55^{+0.19}_{-0.21}$$

Random Forest discriminant

background dominated

signal dominated



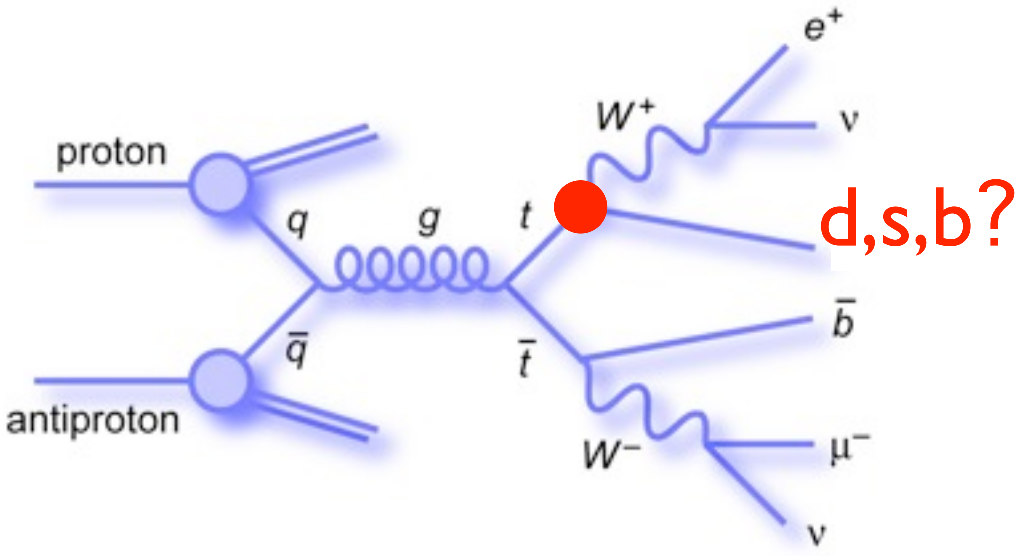


$$\sigma_{t\bar{t}} = 7.78^{+0.77}_{-0.64}\,(\mathrm{total})$$ m_t = 172.5 GeV

9-10% relative precision

largest uncertainty from luminosity (6.1%)

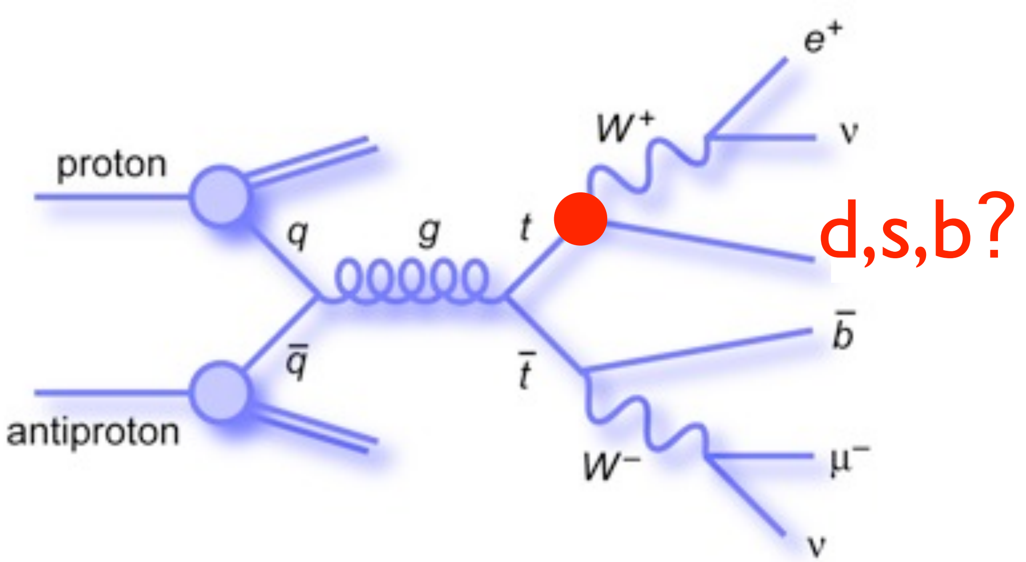
Ratio of branching fractions



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

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

Ratio of branching fractions



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

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

- 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

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

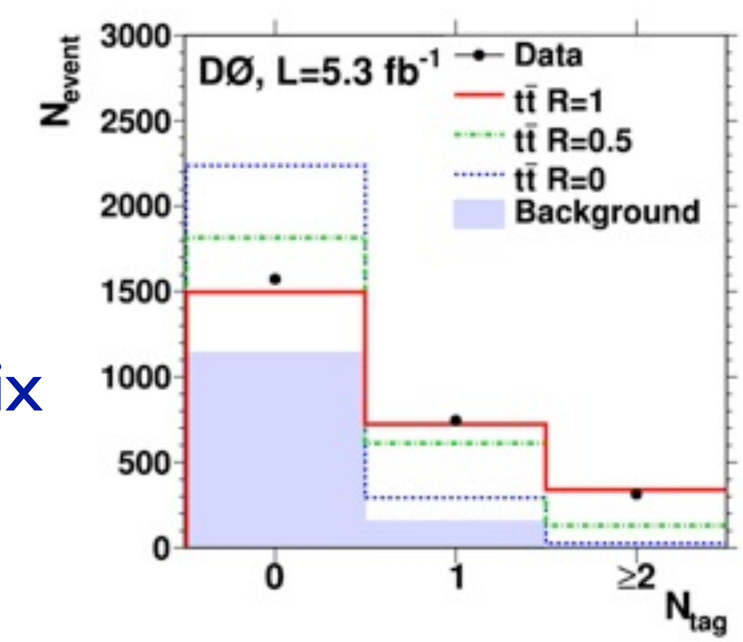
$$\sigma_{t\bar{t}} = 7.74^{+0.67}_{-0.57}(\text{total})$$

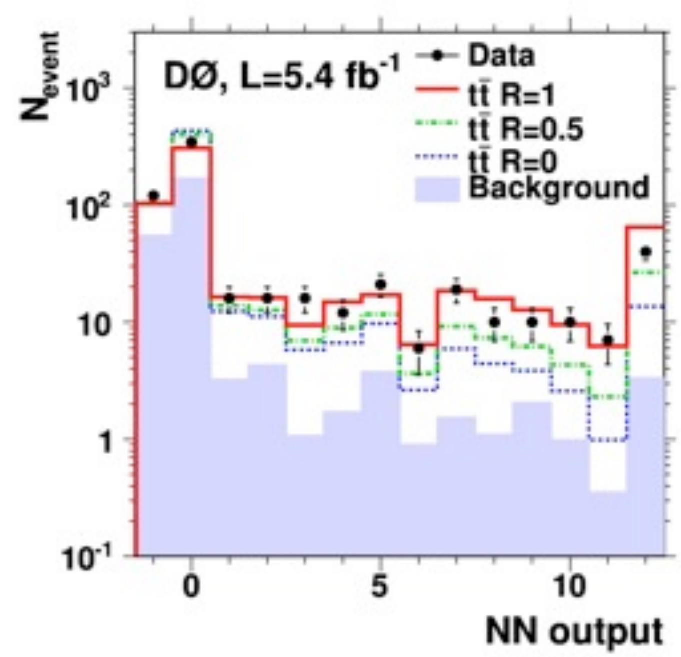
R=0.90±0.04 (stat+syst)

assuming unitarity of 3x3 CKM matrix

$|V_{tb}|$=0.95±0.02 (stat+syst)

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





Measurements

dilepton channel

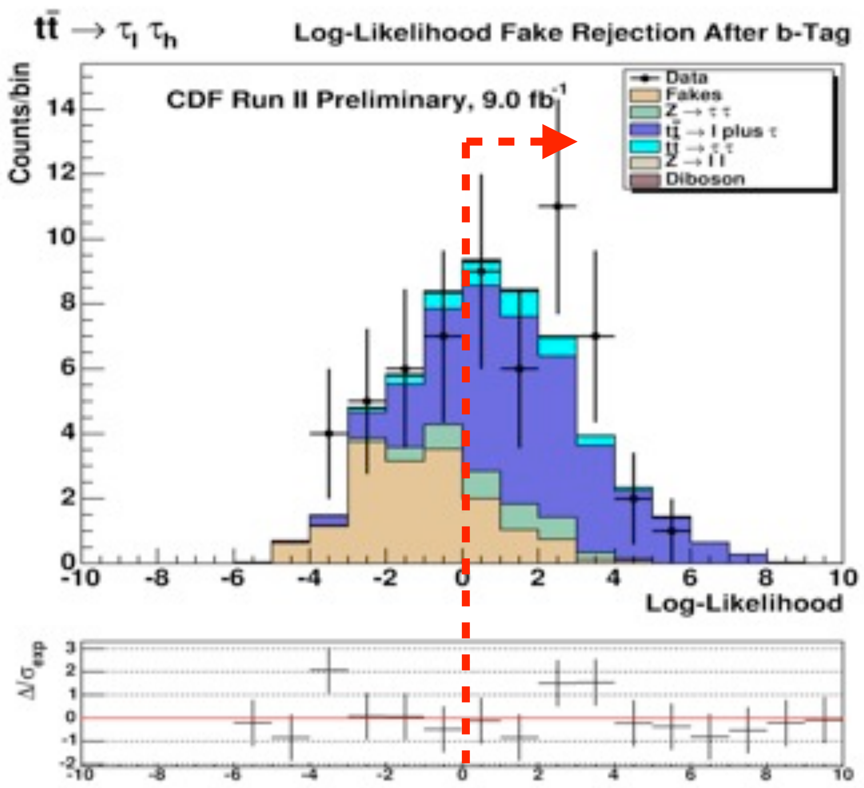
lepton+jets channel

lepton+τ_{had} channel

Lepton+τ_{had} selection

Phys. Rev. D 88, 091103 (2013)

- Selection
  - 1 e or μ, 1 τ_{had} , ≥2 jets, at least 1 b-jet
  - 58 lepton+τ_{had} candidates
  - 34 top pair events expected (S/B = 1/1)
- Three discriminating variables are combined into the likelihood
  - E_T^{miss}
  - M_T^W
  - E_T of the 3rd highest E_T jet



Lepton+τ_{had} selection

Phys. Rev. D 88, 091103 (2013)

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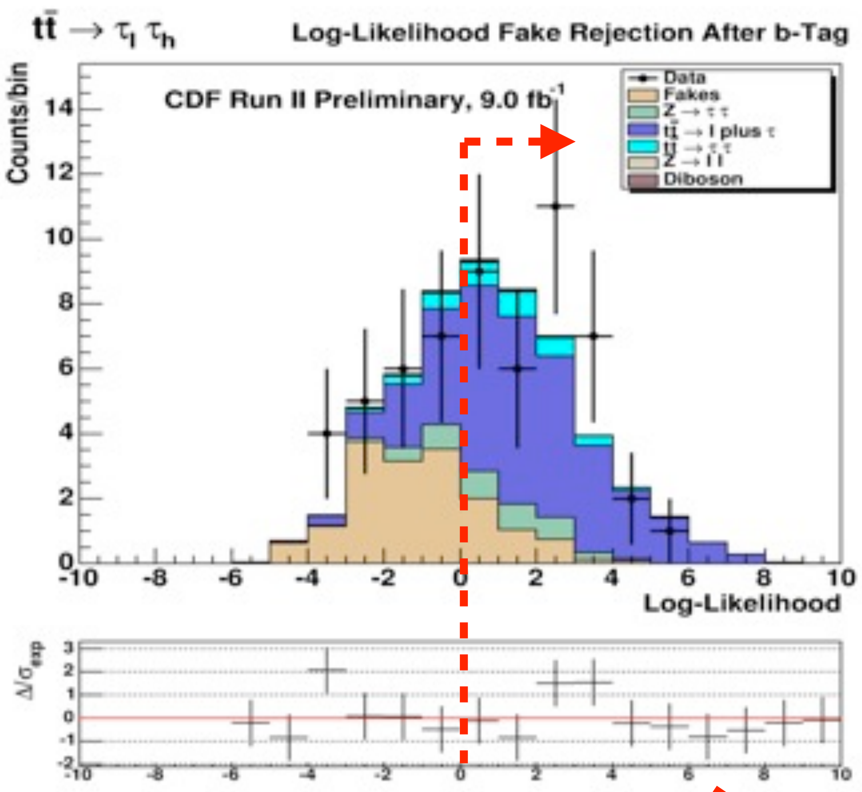

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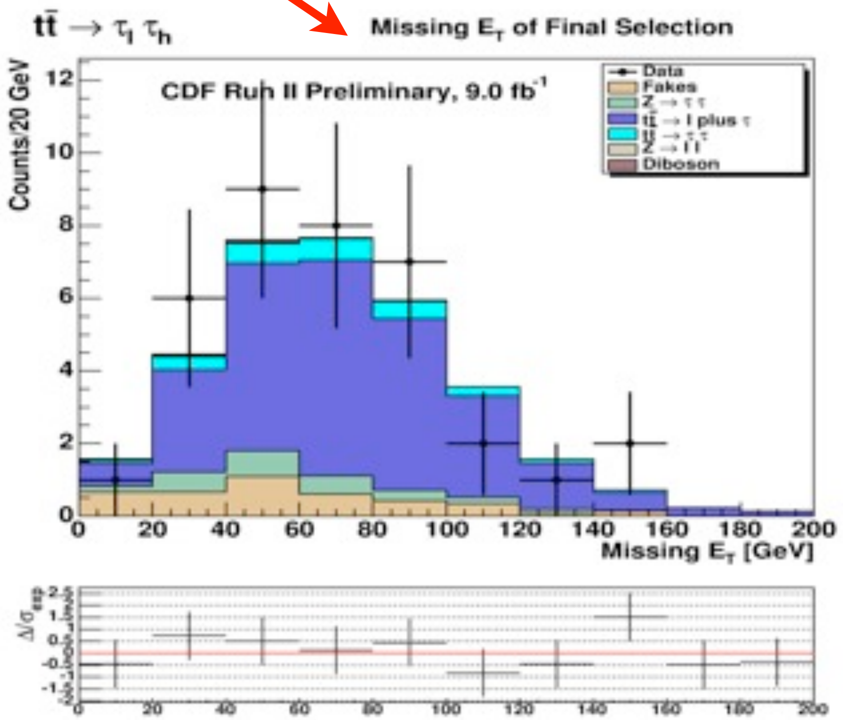
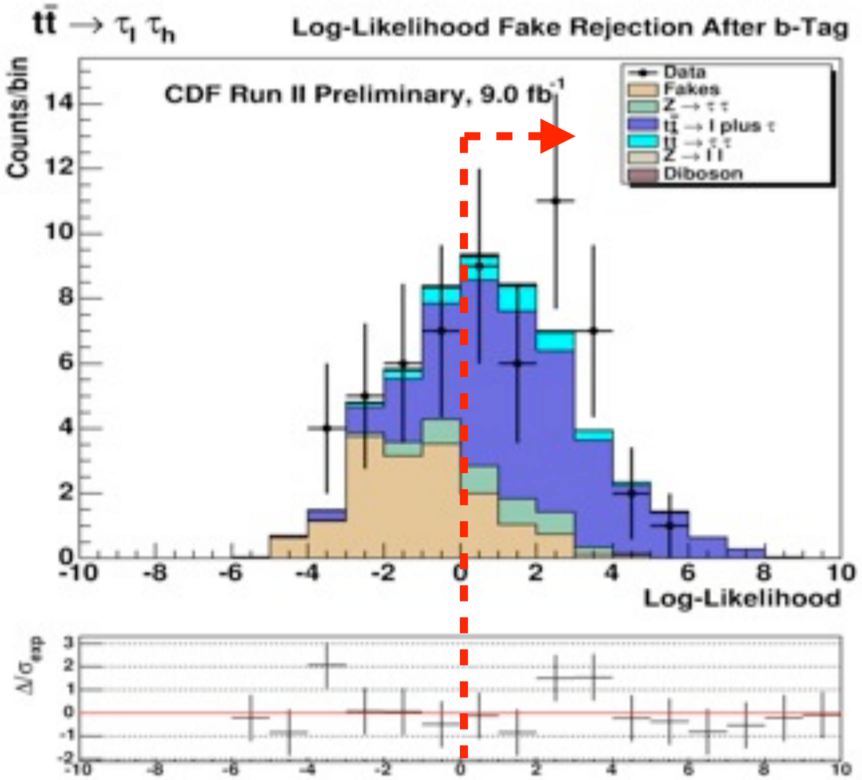


- After all cuts
  - 36 events
  - 27 top pair events

Lepton+τ_{had} results

Phys. Rev. D 88, 091103 (2013)

- Selection
  - 1 e or μ, 1 τ_{had} , ≥2 jets, at least 1 b-jet
  - 58 lepton+τ_{had} candidates
  - 34 top pair events expected (S/B = 1/1)
- Three discriminating variables are combined into the likelihood
  - 2 τ_{had} identification variables
  - M_T^W, E_T^{miss}
  - E_T of the 3rd highest E_T jet



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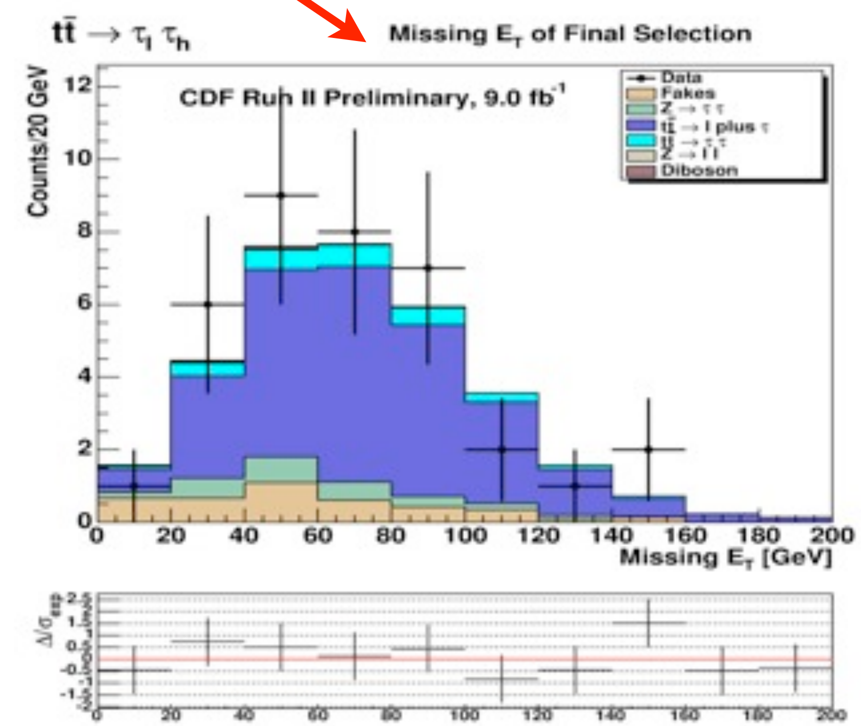


m_t = 172.5 GeV

$$\sigma_{t\bar{t}} = 8.1 \pm 1.7(\mathrm{stat})^{+1.2}_{-1.1}(\mathrm{syst}) \pm 0.5(\mathrm{lumi})$$

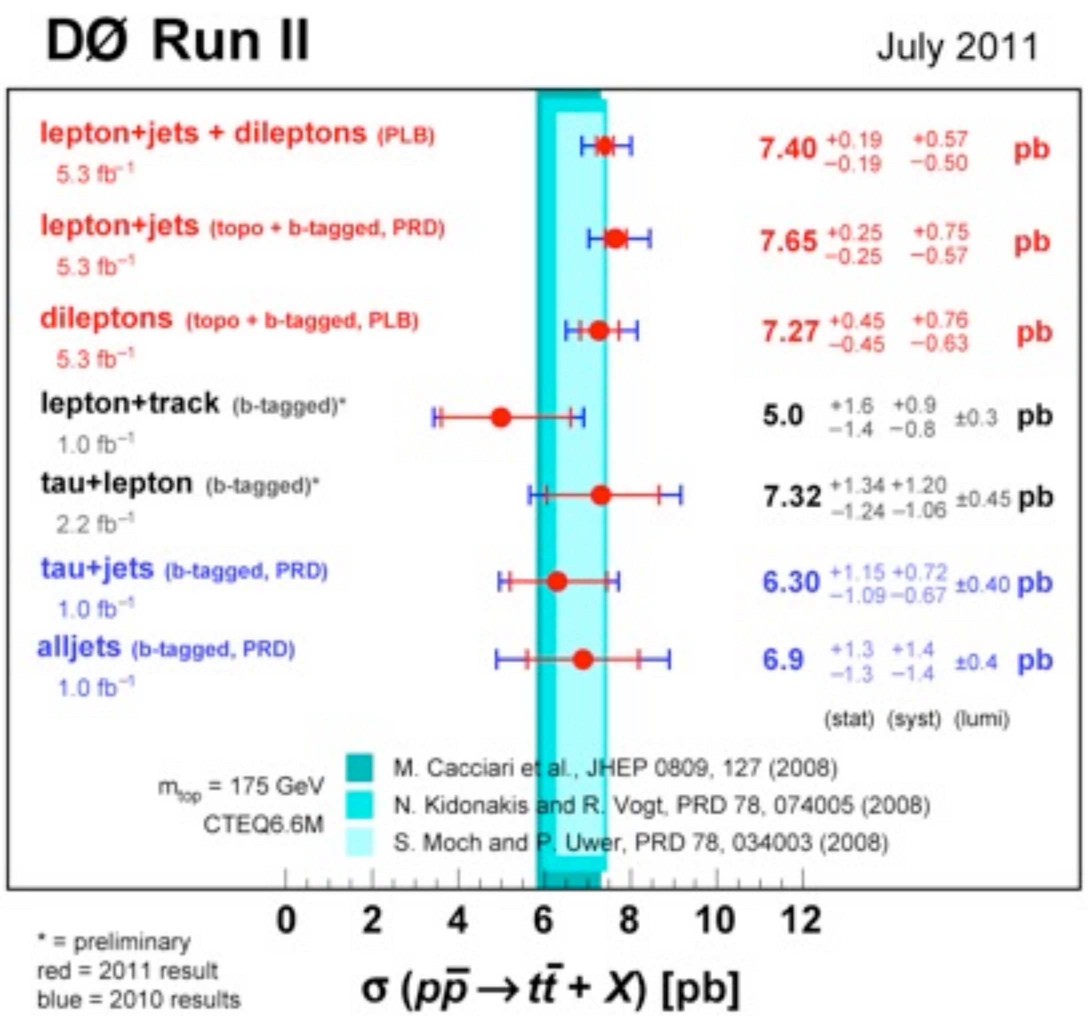
- statistically limited
- largest systematic uncertainty due to jets faking τ_{had}

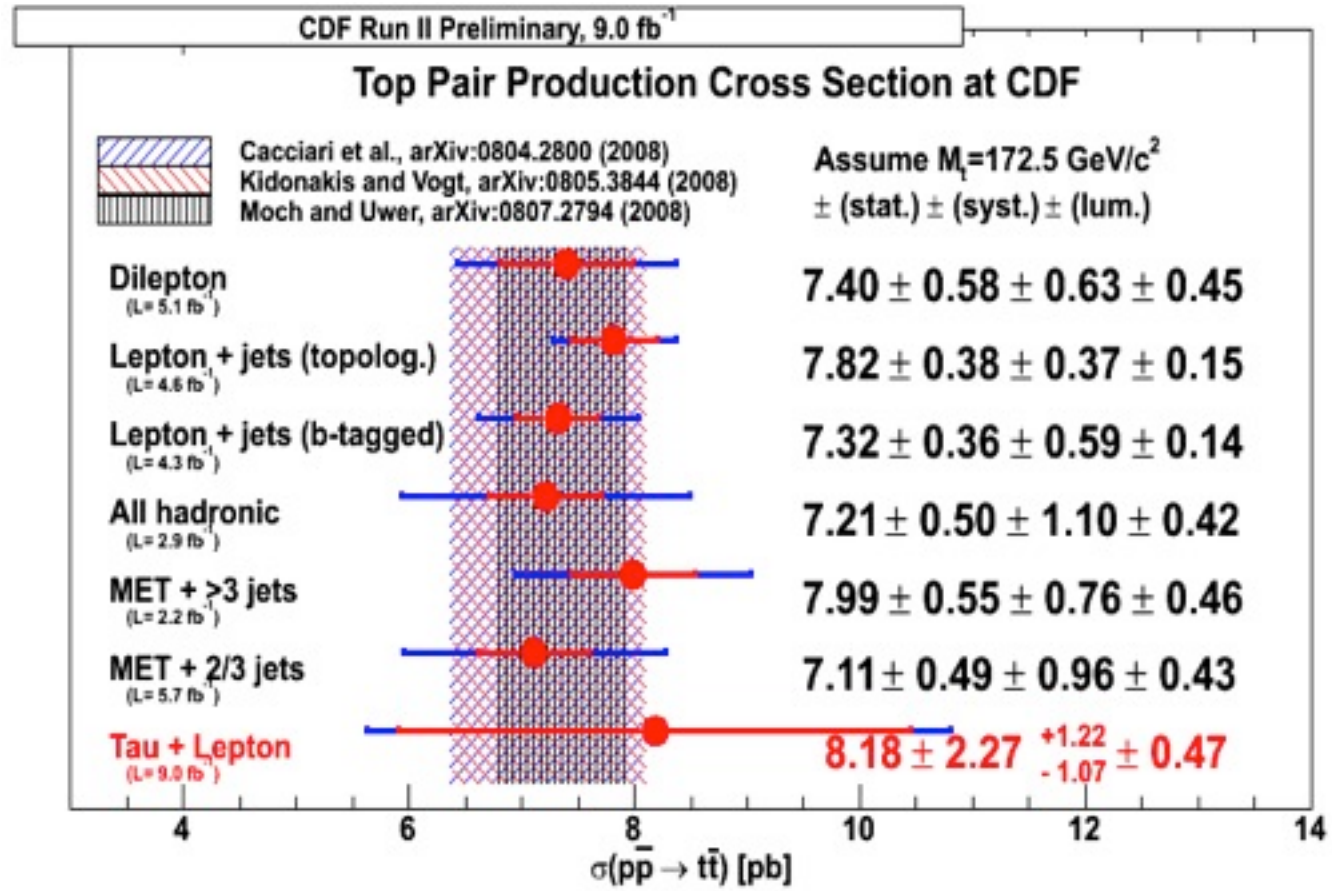
- using theoretical $t\bar{t}$ cross section instead of *Br*

$$Br(t \to \tau\nu b) = 0.096 \pm 0.028$$

consistent with lepton universality

Cross sections summary





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

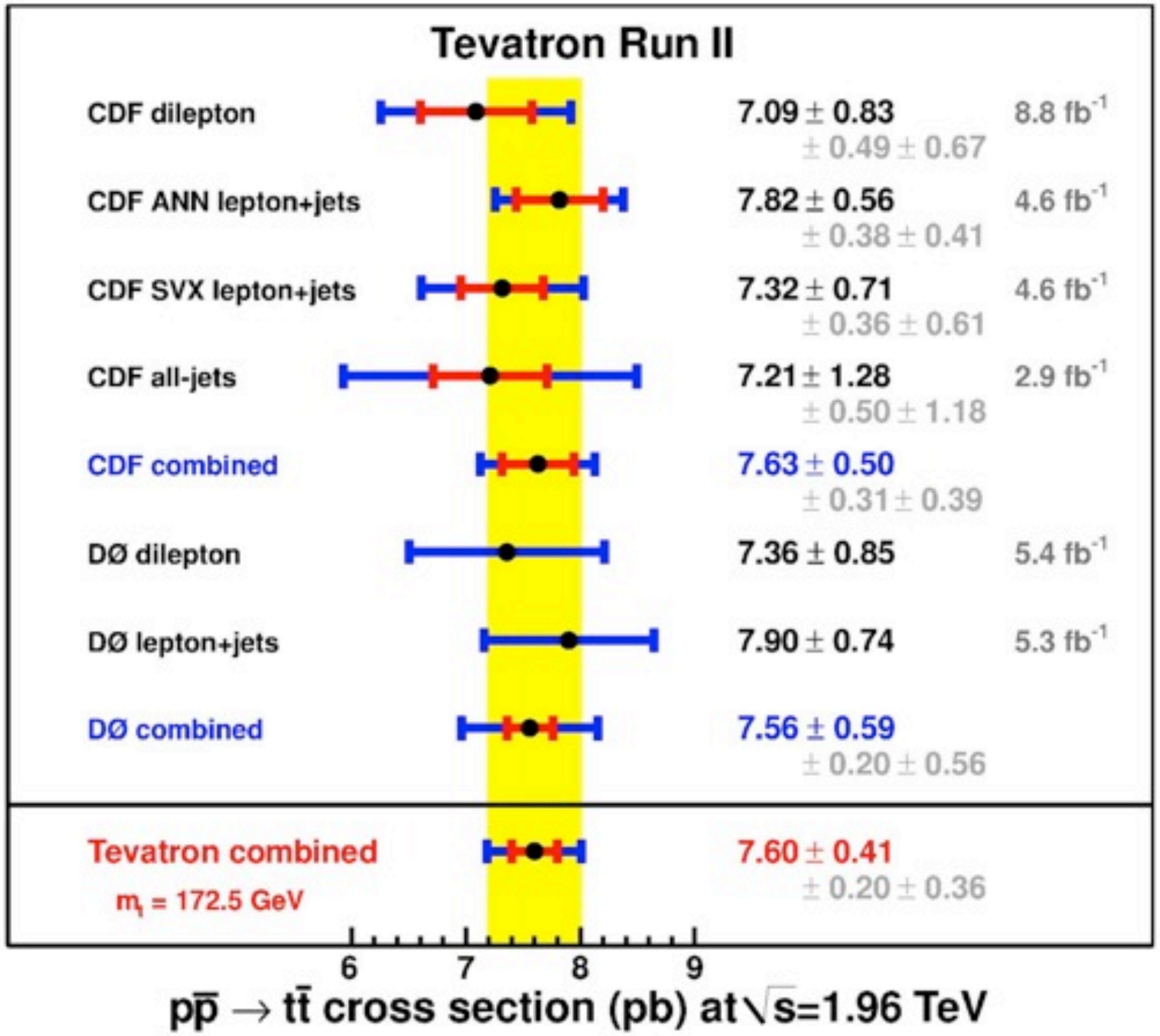
Tevatron combination

Tevatron combination

PRD 89, 072001 (2014)

- Combination of combined CDF and D0 measurements
- measurements up to 8.8 fb^{-1}
  - lepton+jets channel measurements use half of the full data set
- BLUE method

Details in the talk by Y. Peters on Wednesday: "Review of recent Tevatron and world mass combinations"



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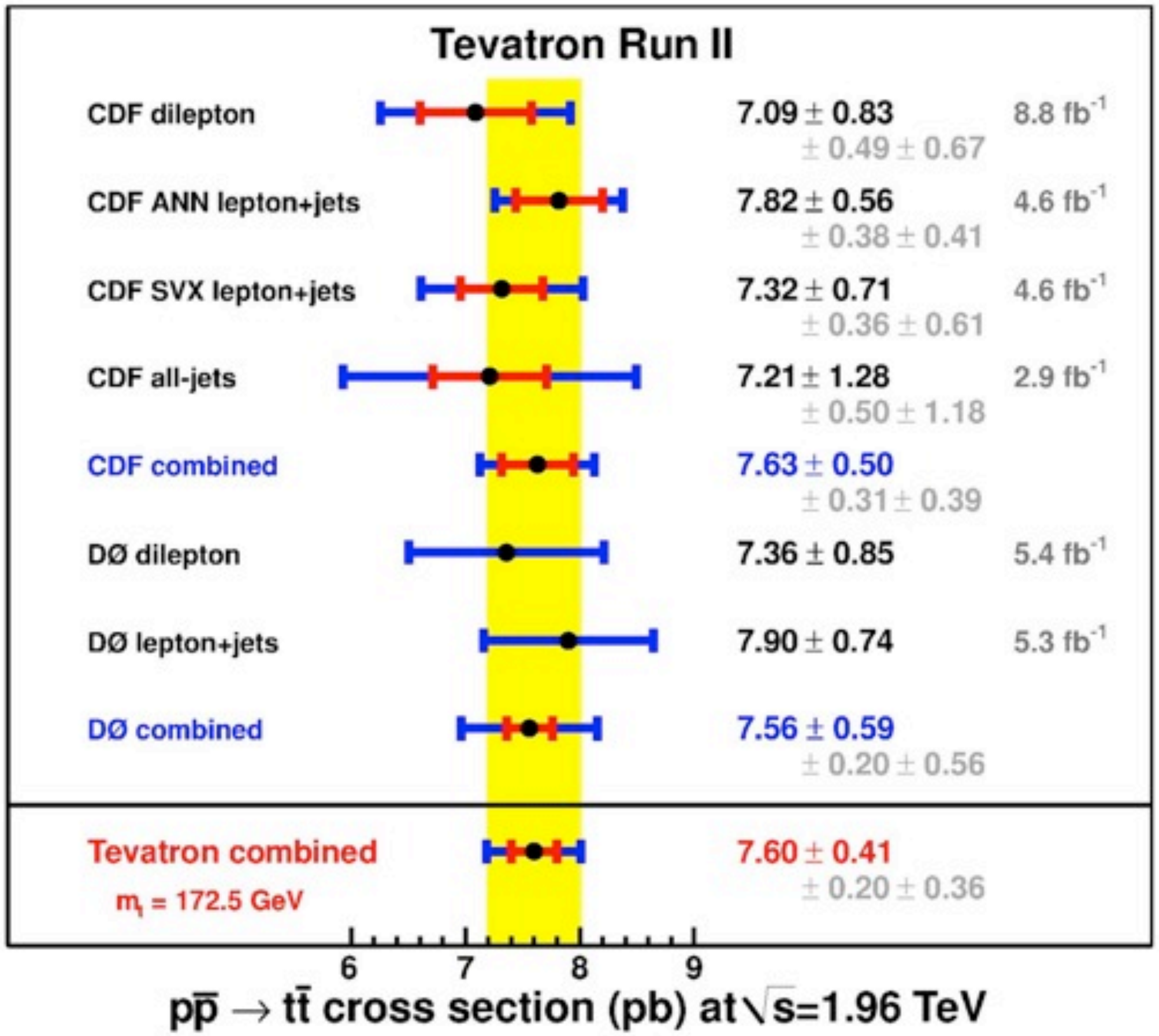


Details in the talk by Y. Peters on Wednesday:
"Review of recent Tevatron and world mass combinations"

$$\sigma_{t\bar{t}} = 7.60 \pm 0.20(\text{stat}) \pm 0.29(\text{syst}) \pm 0.21(\text{lumi})$$

$$\sigma_{t\bar{t}} = 7.60 \pm 0.41(\text{total})$$ m_t = 172.5 GeV

weight: 60% CDF, 40% D0
probability - 92%, correlation - 17%

Tevatron combination: 5.4% precision

Conclusions

- The Tevatron provided measurements of the top pair production cross sections in all channels except one
  - measurements with the full data are still expected from D0 in the dilepton and lepton+jets channels
- Precision of the Tevatron combined cross section is 5.4%
  - exceeds initial design goal
- All cross section measurements agree well with the latest theoretical prediction at NNLO+NNLL

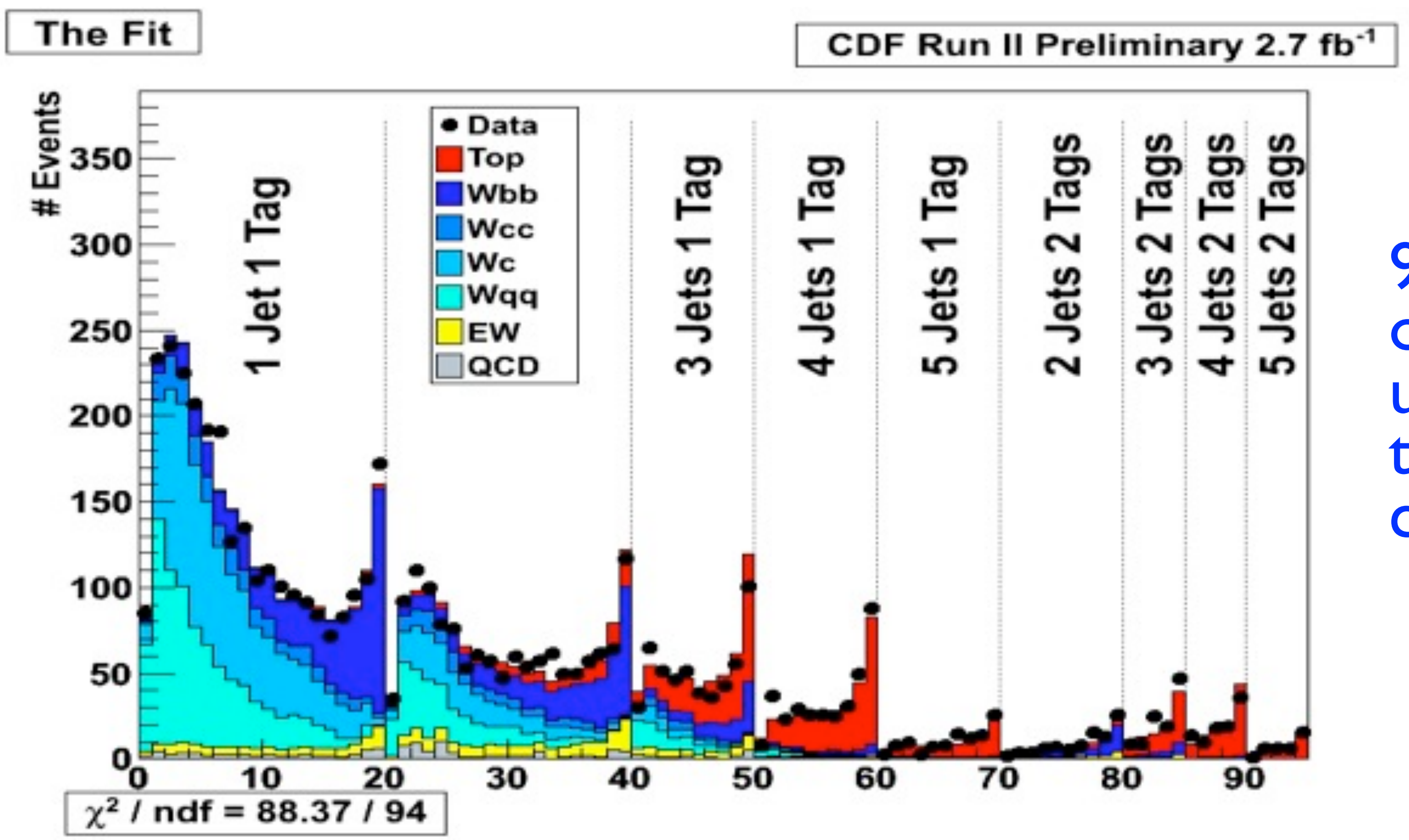
Backup

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

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

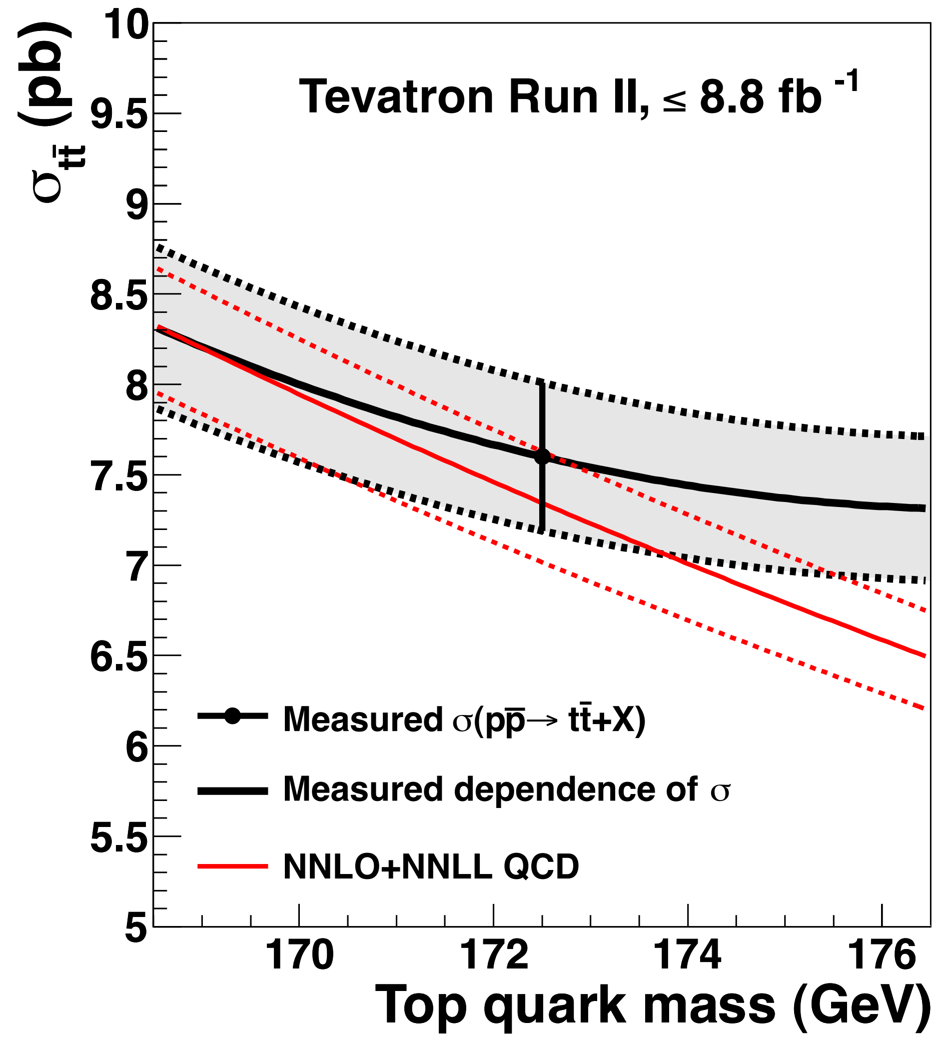
m_t = 175 GeV

9.5% relative precision

Tevatron combination

PRD 89, 072001 (2014)

Sources of systematic uncertainty	
Modeling of the detector	0.13
Modeling of signal	0.18
Modeling of jets	0.13
Method of extracting $\sigma_{t\bar{t}}$	0.03
Background modeled from theory	0.10
Background based on data	0.05
Normalization of Z/γ^* prediction	0.08
Luminosity: inelastic $p\bar{p}$ cross section	0.15
Luminosity: detector	0.14
Total systematic uncertainty	0.36
Statistical uncertainty	0.20
Total uncertainty	0.41



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