Top Physics at the Tevatron

Veronica Sorin
IFAE-Barcelona

On behalf of the CDF and D0 Collaborations

2009 APS April Meeting

Top Physics

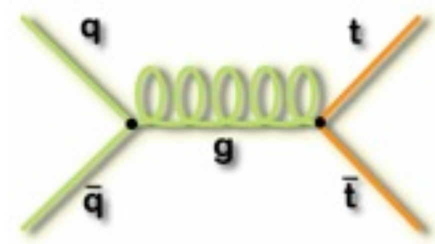
- Discovered in 1995 by CDF and D0 $\Rightarrow$ the first surprise: its large mass
  - is it just an "ordinary" quark?
  - does it have an special role in the EWSB ?
- With 50 times more data, we can now study its properties accurately
- Extensive program at the Tevatron

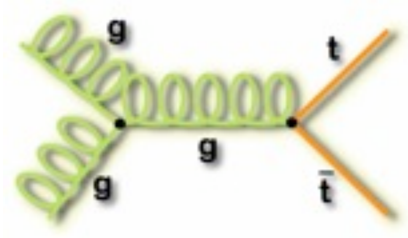
Today overview of top at the Tevatron
focus on:
experimental challenges
latest results

Top Production

Tevatron
Proton and anti-protons collisions at 1.96 TeV center of mass energy

Strong pair production





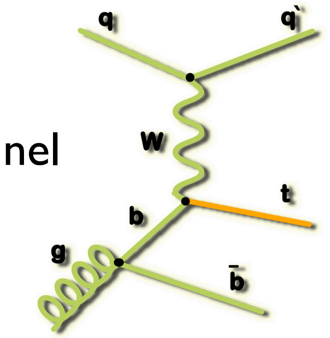
~ 85 % **~ 15 %**

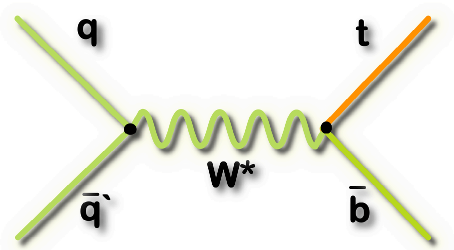
σ_{NLO} = 6.7 ± 0.8 pb (for Mt=175GeV)

Cacciari et al, JHEP 0809, 127 (2008). Compatible Predictions:
N. Kidonakis and R.Vogt Phys Rev D78 074005 (2008)
S. Moch and P. Uwer, Nucl. Phys.Proc.Suppl, 183, 75 (2008)

EWK single-top production

t-channel



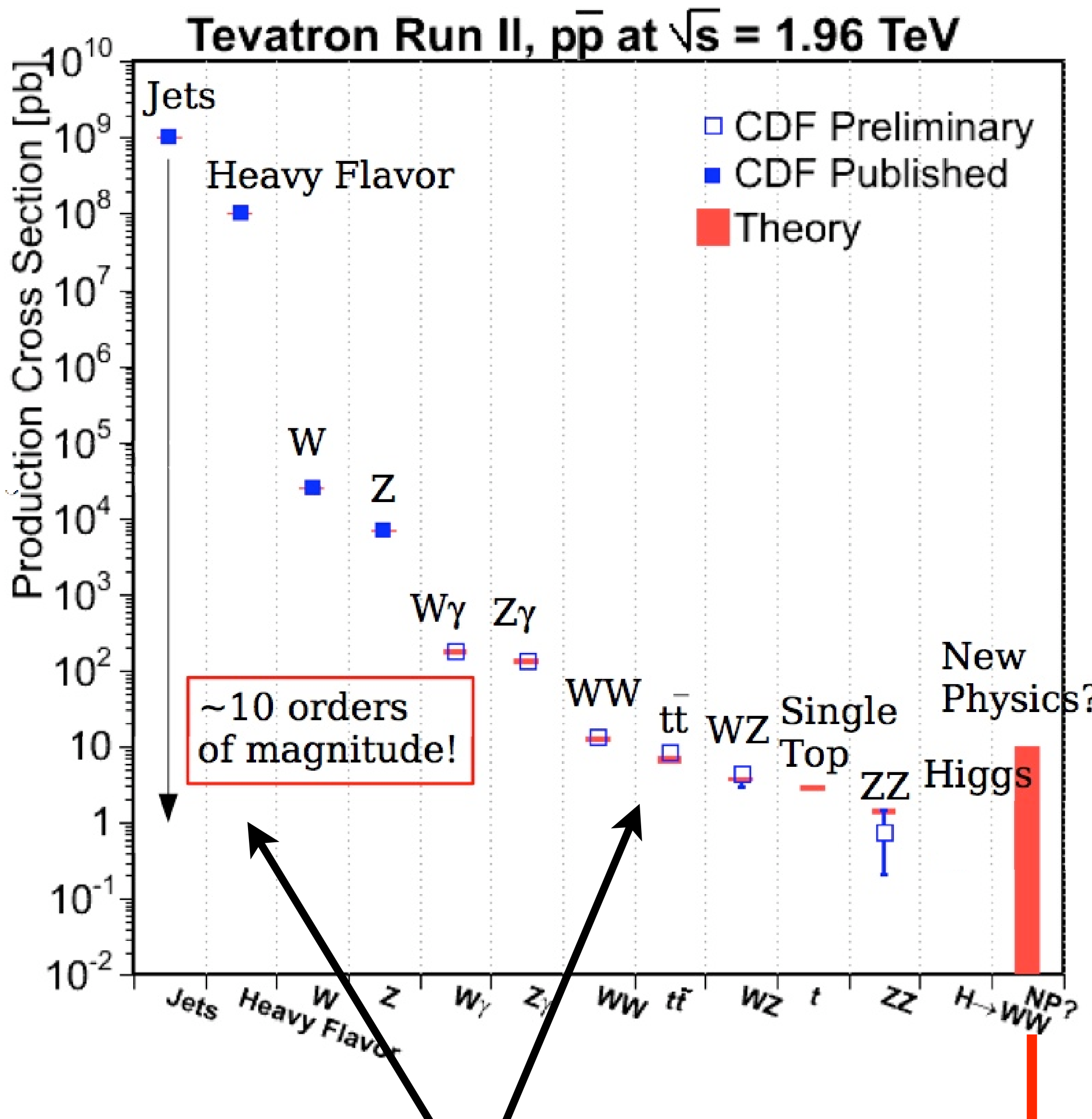


s-channel

σ_{NLO} = 1.98 ± 0.21 pb σ_{NLO} = 0.88 ± 0.07 pb
(for Mt=175GeV)

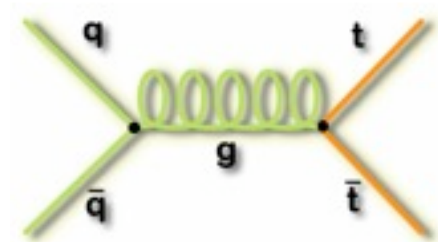
Z. Sullivan, Phys Rev D70 114012 (2004). Compatible Predictions:
Campbell/Ellis/Tramontano, Phys Rev D70 094012 (2004)
N. Kidonakis, Phys Rev D74, 114012 (2006)

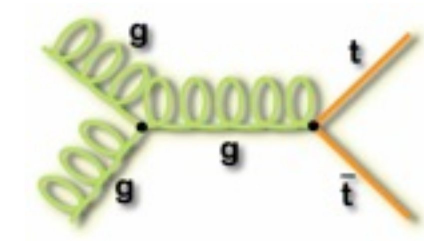
Top Production



1 top pair each 10^{10} inelastic collisions

QCD pair production





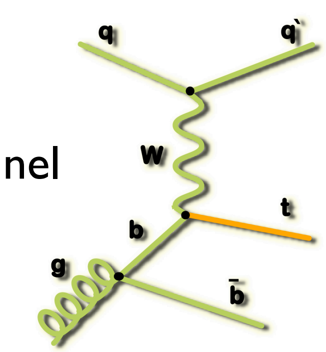
~ 85 % **~ 15 %**

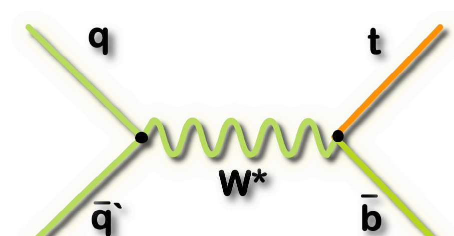
$\sigma_{NLO} = 6.7 \pm 0.8$ pb (for Mt=175GeV)

Cacciari et al, JHEP 0809, 127 (2008). Compatible Predictions:
N. Kidonakis and R.Vogt Phys Rev D78 074005 (2008)
S. Moch and P. Uwer, Nucl. Phys.Proc.Suppl, 183, 75 (2008)

EWK single-top production

t-channel





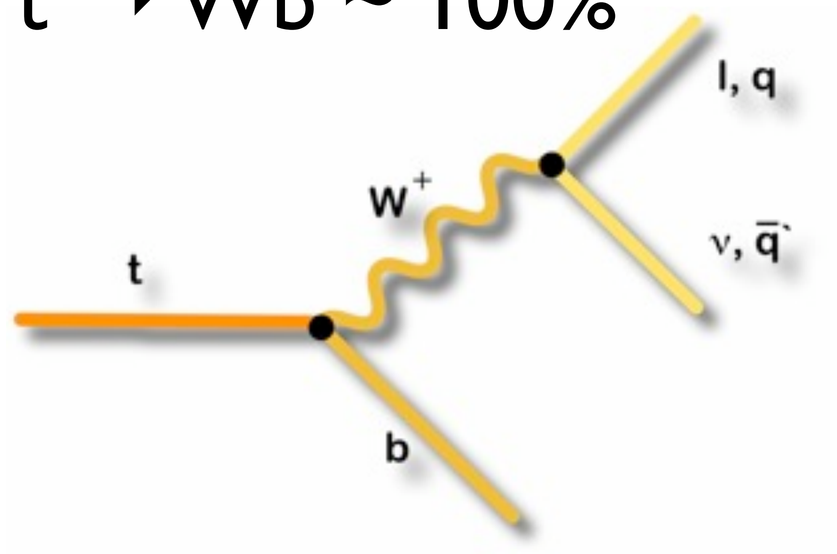
s-channel

$\sigma_{NLO} = 1.98 \pm 0.21$ pb $\sigma_{NLO} = 0.88 \pm 0.07$ pb
(for Mt=175GeV)

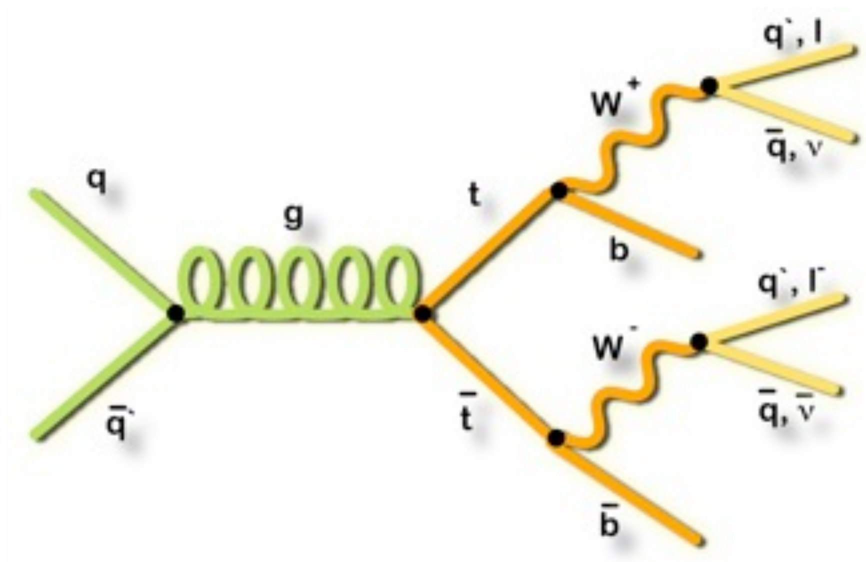
Z. Sullivan, Phys Rev D70 114012 (2004). Compatible Predictions:
Campbell/Ellis/Tramontano, Phys Rev D70 094012 (2004)
N. Kidonakis, Phys Rev D74, 114012 (2006)

Top Decay

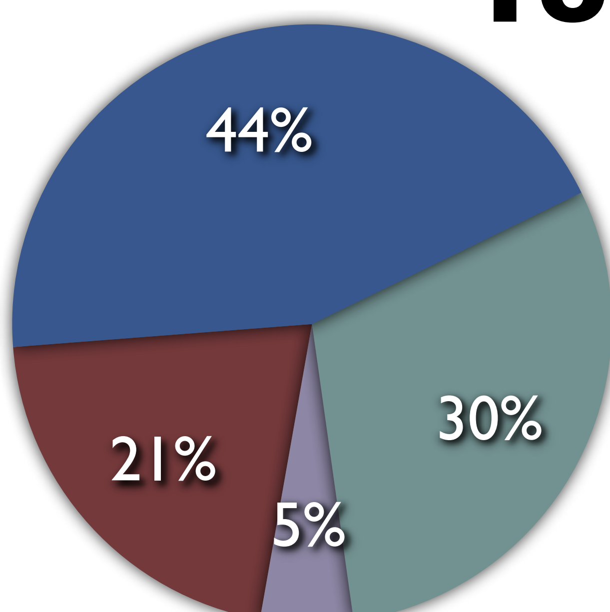
$t \rightarrow Wb \sim 100\%$



Channels defined by the W decay



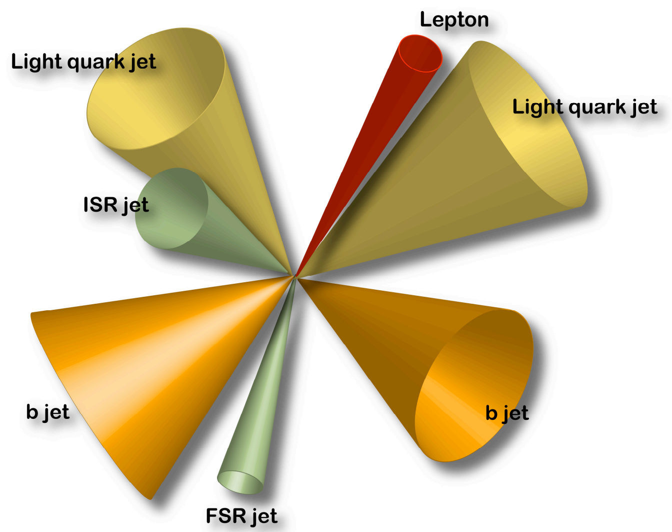
Top Pairs



Branching ratios

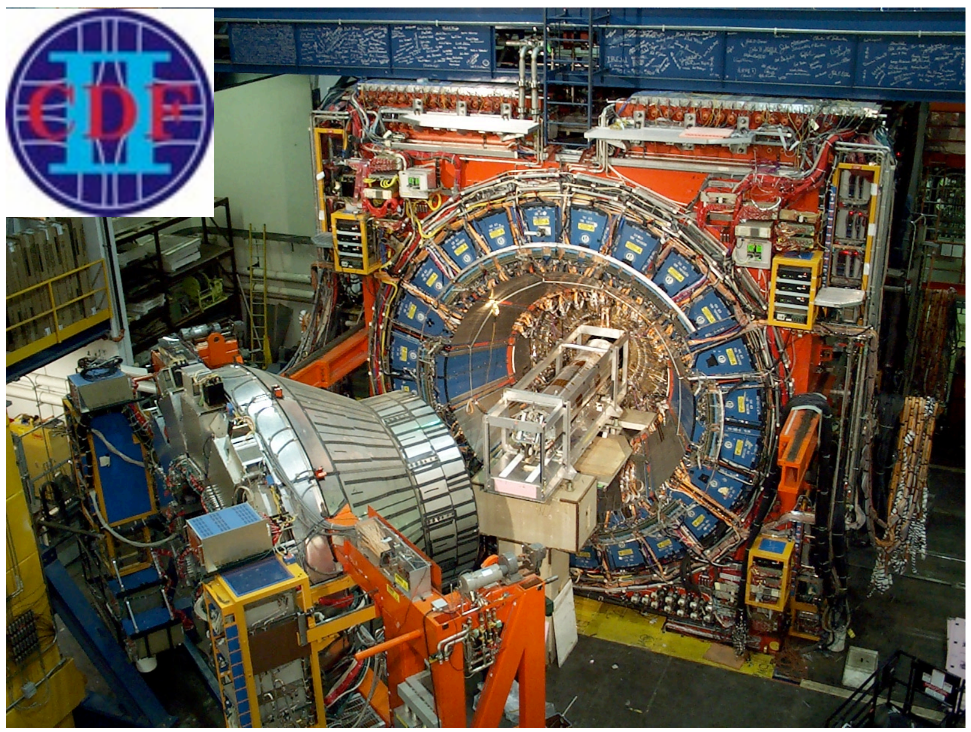
- All-hadronic
- Lepton + Jets (e and μ)
- Dilepton (e and μ)
- Tauonic

Top Signatures



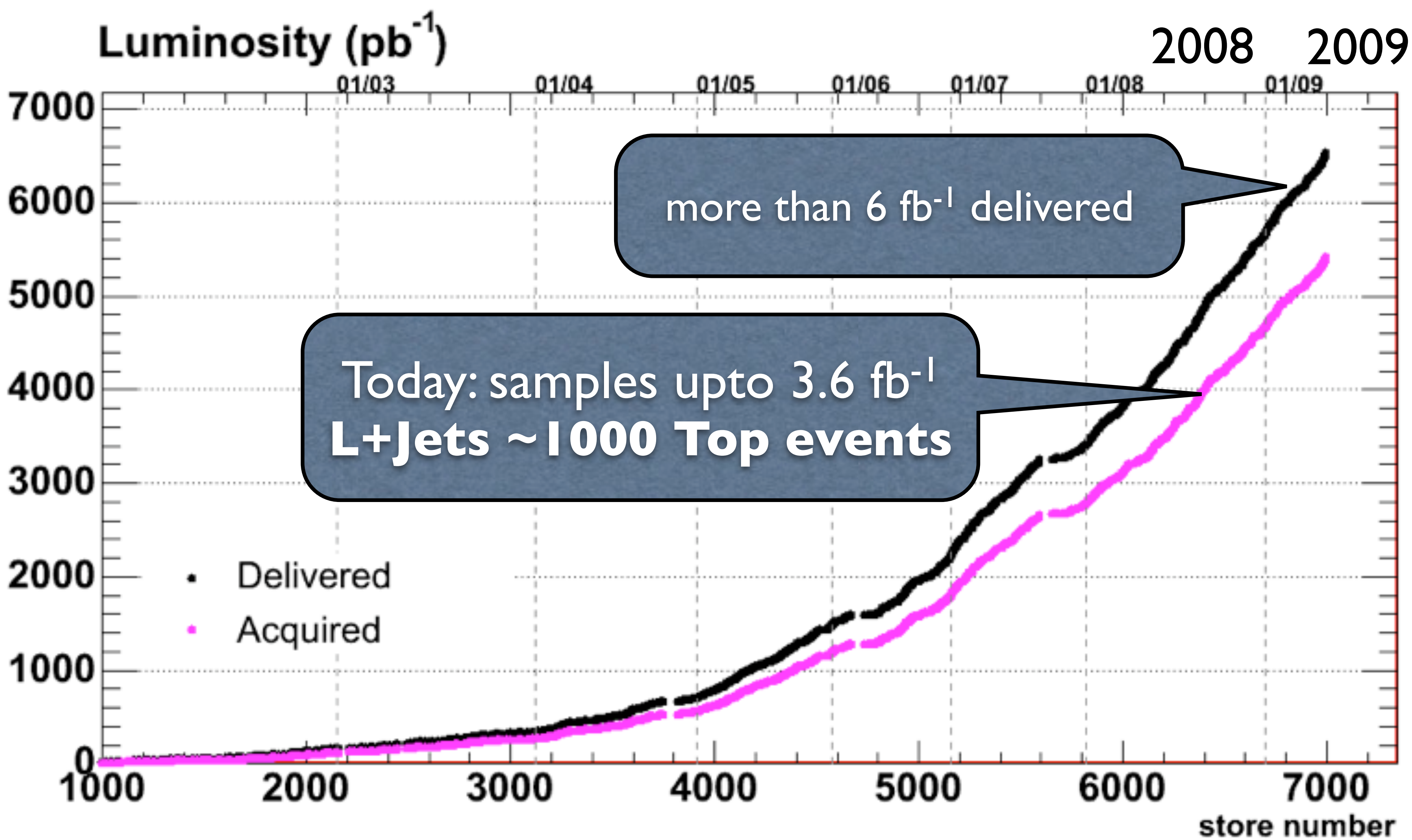
- Hadronic : large BR , many jets: large QCD background
- Lepton + Jets :
  - Signature includes high pt leptons and missing energy
    - jet backgrounds can be largely rejected already at trigger level
- Dileptons: clean signature due to two leptons, but small BR
- All benefit by identification of b-jets

Detectors



- General Purpose detectors
- Top physics uses almost all their capabilities

Data !



Thanks to our colleagues at the accelerator

Top Production

Top quark pair cross section

- Test of QCD predictions
  - ➡ 6.7 pb , uncertainty ~10% (1)
    (@ Mt 175GeV)
- Could provide hints of New physics:
  - ✤ as it may manifest in different channels :
    - ✓ check consistency across final states
- Provides sample composition for other measurements

$$\sigma_{t\bar{t}} = \frac{N_{data} - N_{bkg}}{A \cdot \int \mathcal{L}\, dt}$$

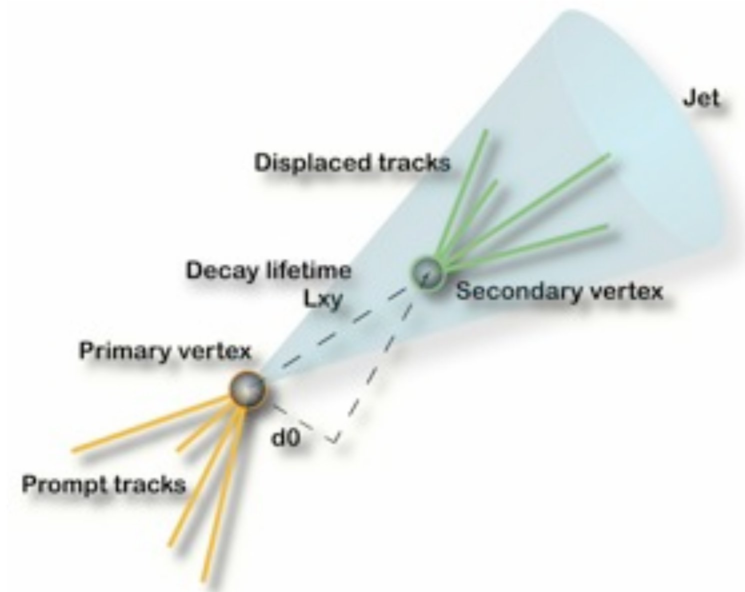
(1) Cacciari et al, JHEP 0809, 127 (2008).

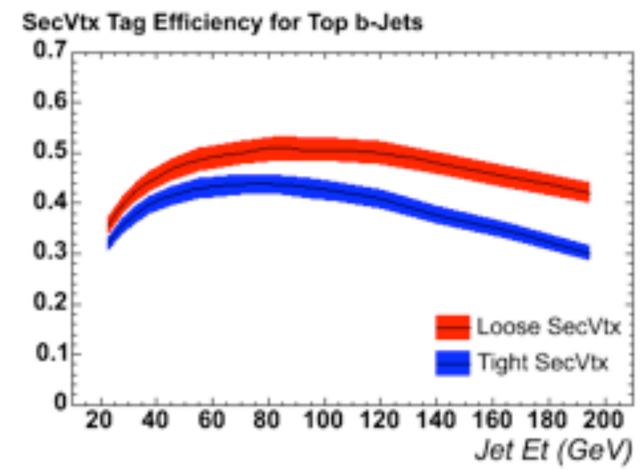
Compatible Predictions:
N. Kidonakis and R.Vogt Phys Rev D78 074005 (2008)
S. Moch and P. Uwer, Nucl. Phys.Proc.Suppl, 183, 75 (2008)

Lepton + Jets
Using b-identification

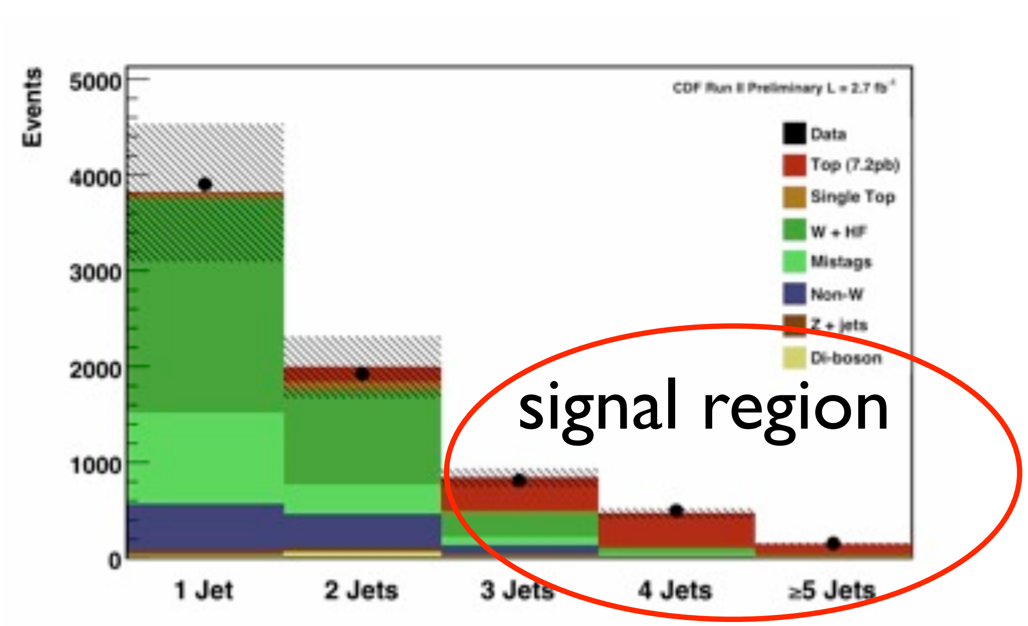
Lepton + jets channel

- Selection based on high pt lepton , missing transverse energy and ≥ 3 jets
- Largest backgrounds W+jets and QCD
  - ➡ Exploit presence of b-jets in final state increase S/B from 1/4 to 3/2 (≥1 b-tag)





tag efficiency ~50% with <1% mistag



Others methods : NN, Soft Lepton, Jet Probability

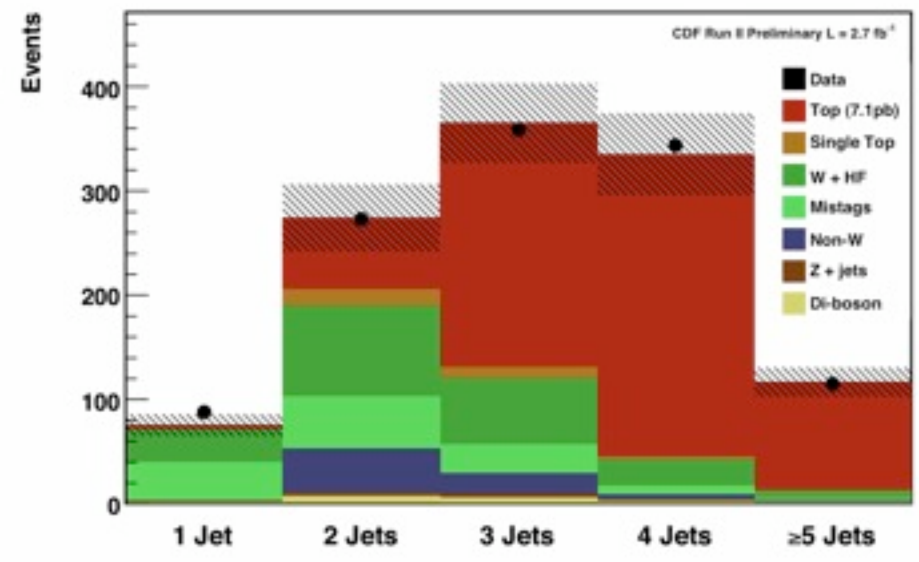
Lepton + Jets
Using b-identification

2.7 fb^{-1}

Lepton + jets channel

- Selection based on high pt lepton , missing transverse energy (MET) and ≥ 3 jets
- Background Estimation:
  - Electroweak: Monte-Carlo based
  - W+jets (mainly Heavy flavor jets) and QCD : derived using data-driven approach

Adding cut on sum of transverse energy
HT > 250 GeV



σ = 7.1 ± 0.4 (stat) ± 0.6 (syst) ± 0.4 (lumi) pb

$\Delta\sigma/\sigma$ = 11.6%

Lepton+Jets
1 fb^{-1}

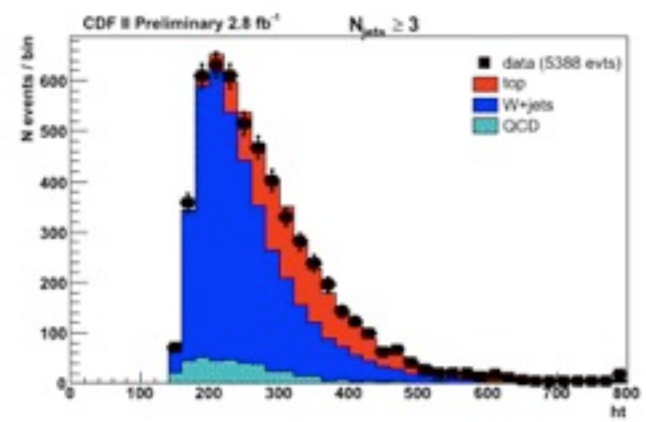
PRL 100 192004 (2008)

σ = 7.42 ± 0.53 (stat) ± 0.46 (syst) ± 0.45 (lumi) pb

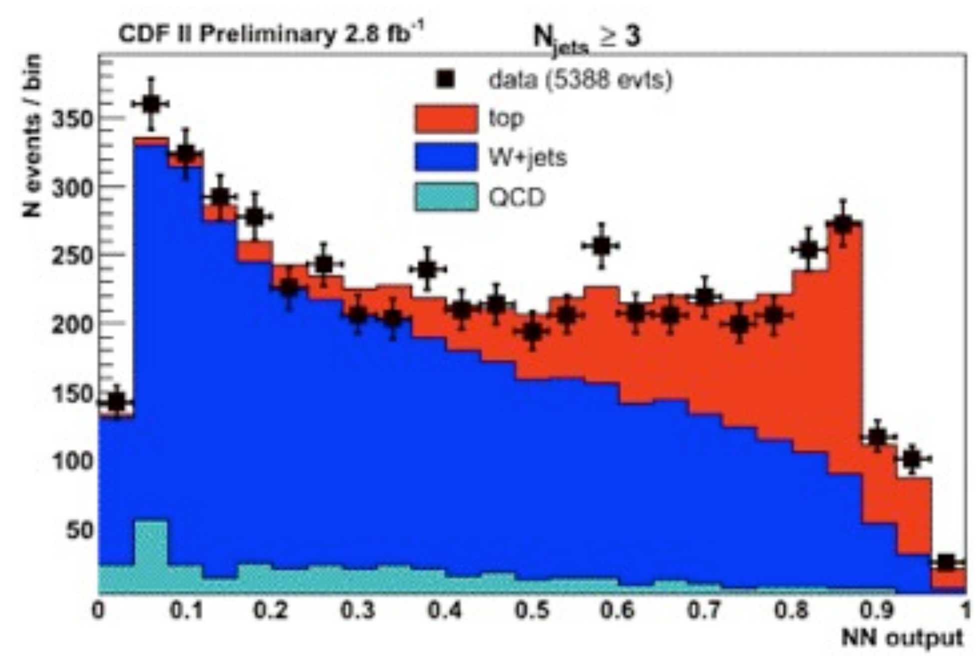
Lepton + Jets
Topological

2.8 fb^{-1}

- ➡ Use event kinematics and shapes to distinguish top from background events
- ➡ feed a Neural Net and build a discriminant



- Systematic do not suffer from b-tagging related uncertainties
- sensitive to signal and background modeling systematics
- reduce QCD : tighten MET and leading Jet E_T



σ = 7.1 ± 0.4 (stat) ± 0.4 (syst) ± 0.4 (lumi) pb

$\Delta\sigma/\sigma$ = 10%

Reducing systematic unc.

2.8 fb^{-1}

7.1 ± 0.4 (stat) ± 0.4 (syst) ± 0.4 (lumi) pb

- Reduce systematic from Luminosity uncertainty by normalizing over the Z cross section

$$\sigma_{t\bar{t}} = R \cdot \sigma_Z^{theory}$$

- Measured Z cross section on the same samples as used on the top pair cross section

σ_Z = 253.27 ± 1.01 (stat) $^{+4.4}_{-4.6}$ (syst) $^{+16.63}_{-13.71}$ (lumi) pb

theory : σ_Z = 251.3 ± 5.0 pb (J. Phys. G: Nucl. Part. Phys. 34 (2007) 2457–2544)

LJ Topological

σ = 6.9 ± 0.4 (stat) ± 0.4 (syst) ± 0.1 (theory) pb

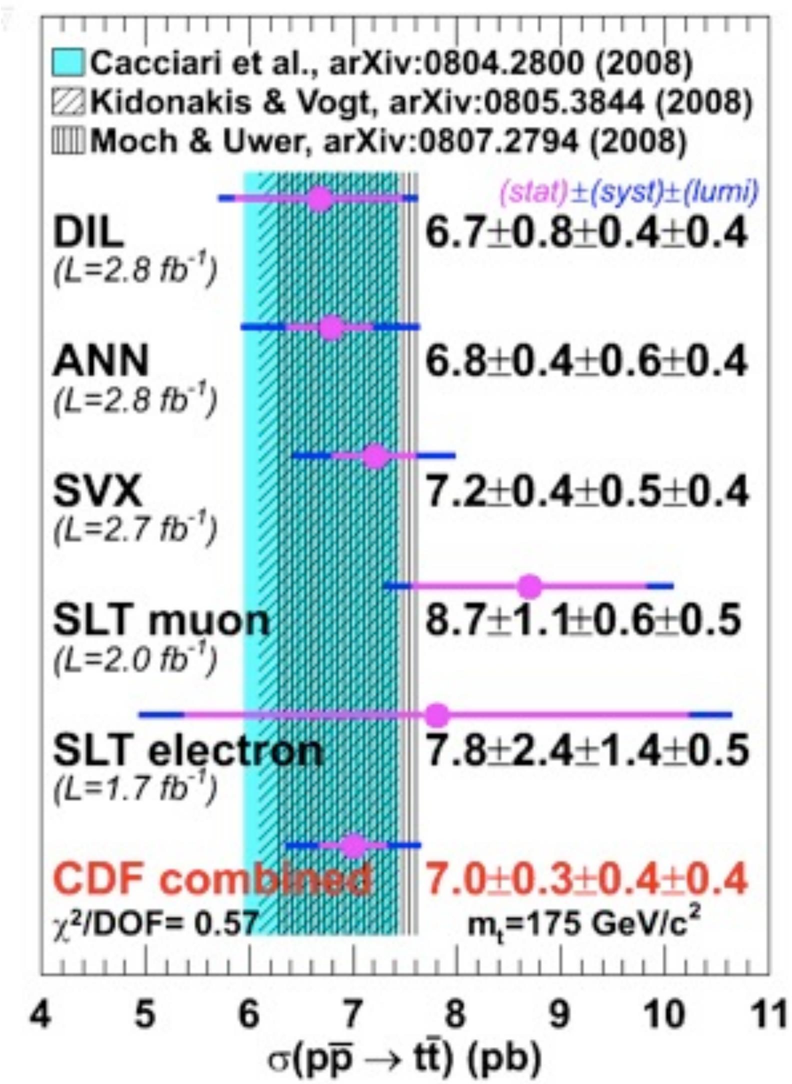
Δσ/σ = 8.3%

LJ b-tagged

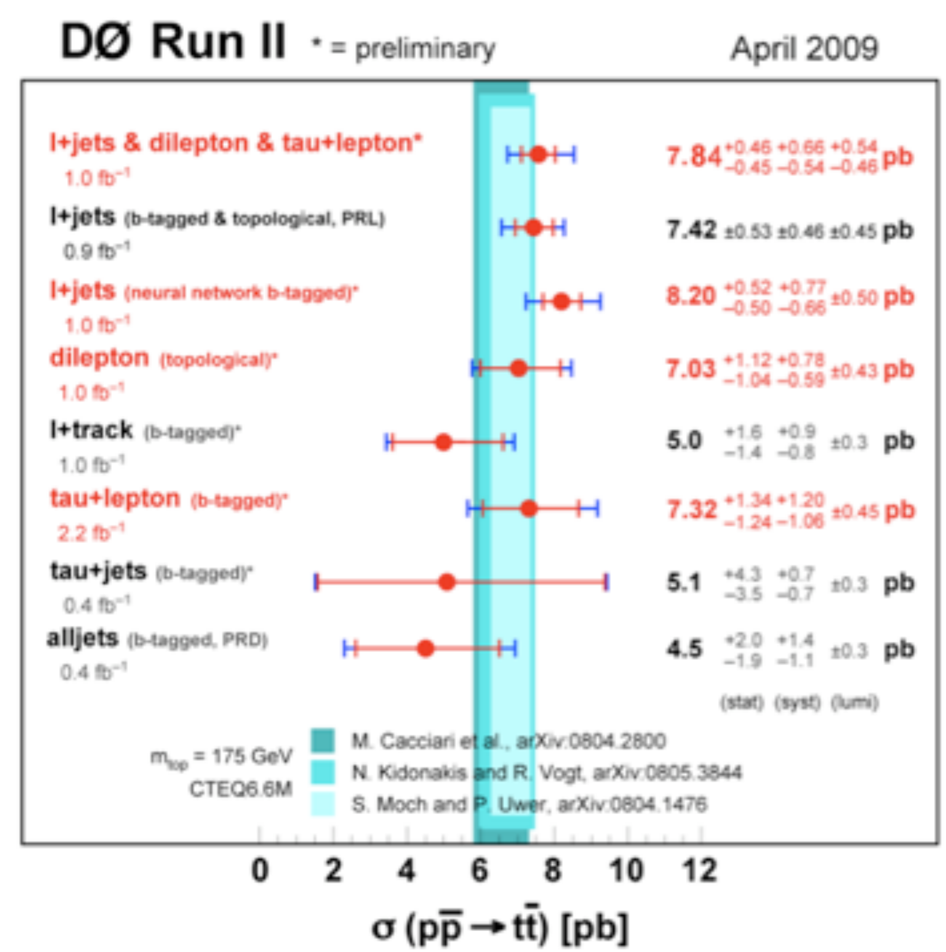
σ = 7.0 ± 0.4 (stat) ± 0.6 (syst) ± 0.1 (theory) pb

Δσ/σ = 10%

Summary



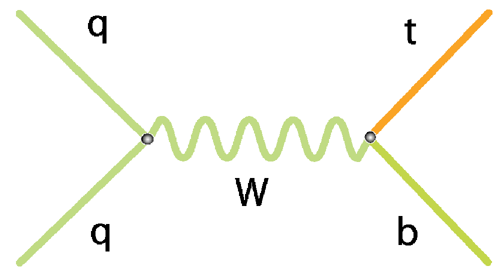
(do not include latest results)



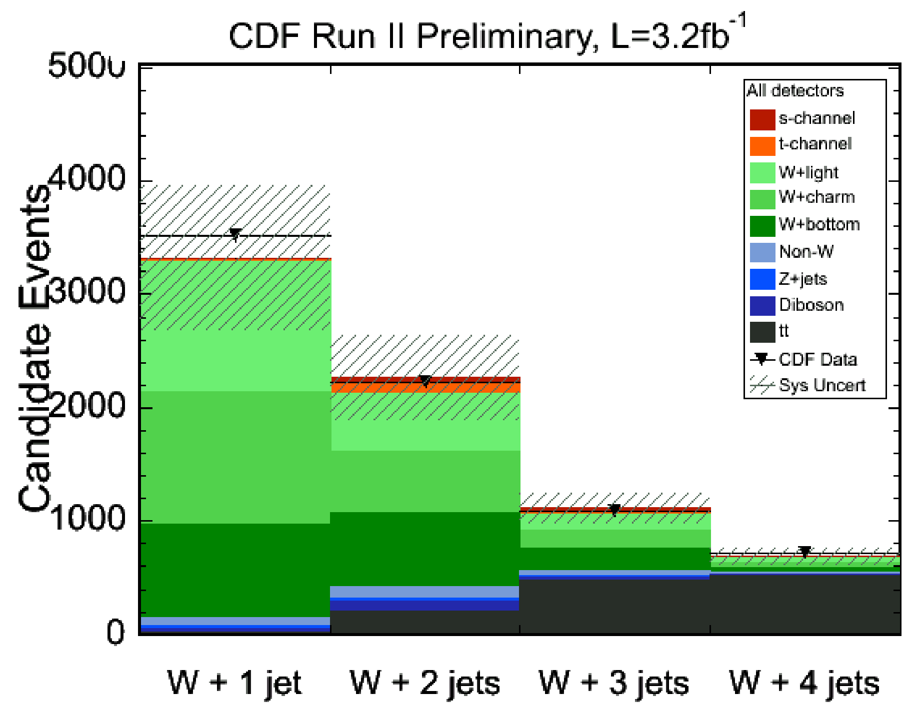
- Measurements consistent across channels and experiments
- New measurements precision is ~8%, comparable with that of the theory
- Updating each experiment combination and working on a Tevatron one

Single Top

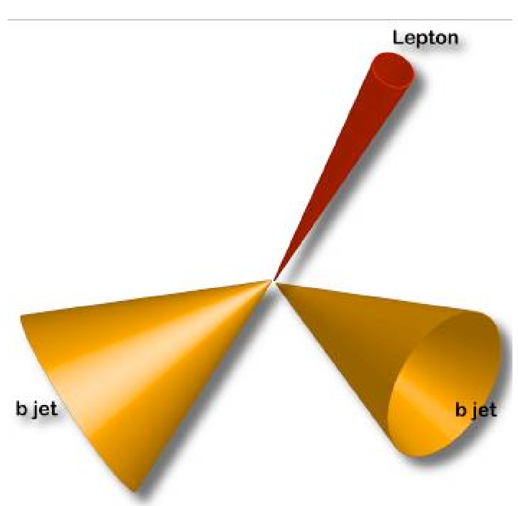
- Direct measurement of $|V_{tb}|$



- Sensitive to BSM:
  - FCNC
  - W'
  - anomalous couplings
  - Charged Higgs



- Benchmark for Higgs searches: similar final state as WH



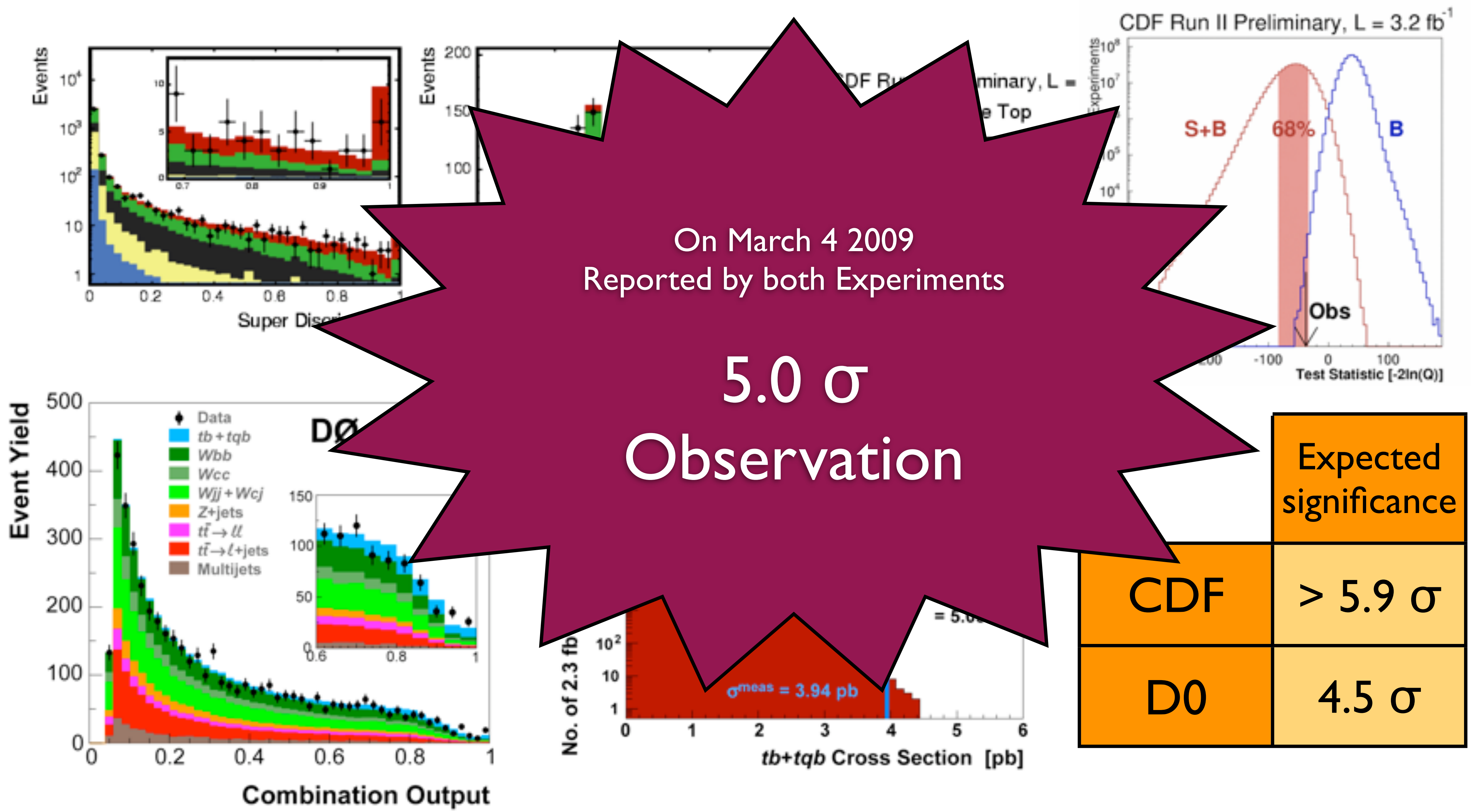
- Not a striking signature as top pair production
- Large Backgrounds
- with Large systematics

Need Multi-Variate techniques

→ details on Single-Top Mini-symposium

Single Top

Open the box and.....

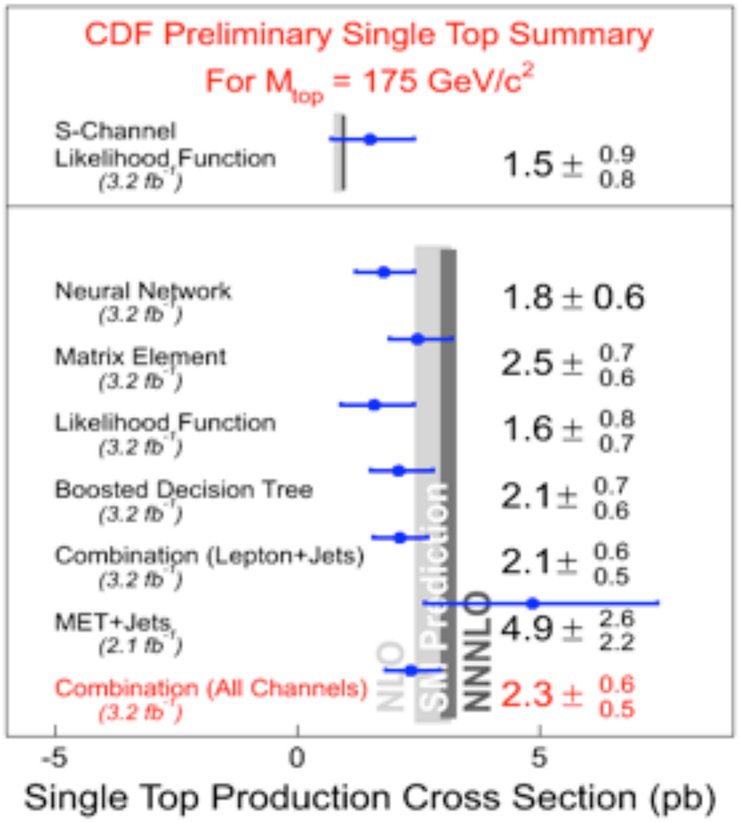


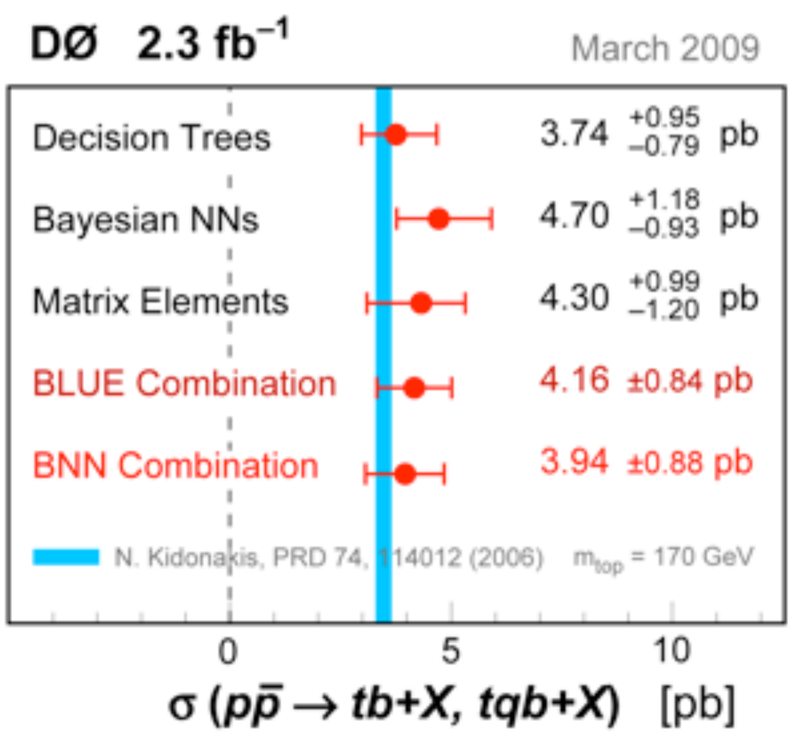
On March 4 2009
Reported by both Experiments

5.0 σ
Observation

	Expected significance
CDF	> 5.9 σ
D0	4.5 σ

Single Top



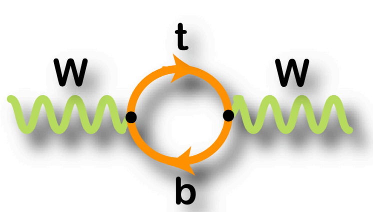


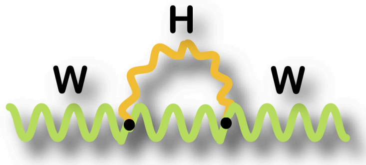
	Cross-Section (pb)	Vtb
CDF	$2.3^{+0.6}_{-0.5}$ (@ mt =175 GeV)	|Vtb| > 0.71 @ 95%CL |Vtb| = 0.91 ± 0.11 (exp) ± 0.07 (th)
D0	3.94 ± 0.88 (@ mt =170 GeV)	|Vtb| > 0.78 @ 95%CL |Vtb| = 1.07 ± 0.12

Top Mass

Why measure the top mass?

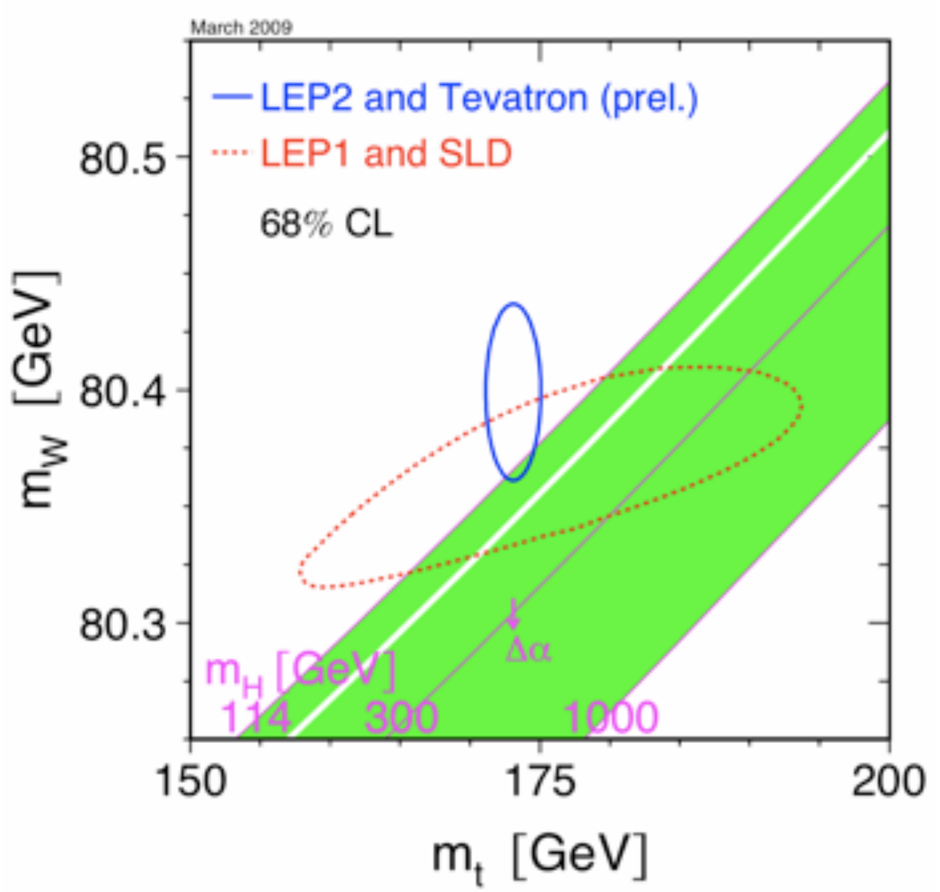
- fundamental parameter of the SM and a striking feature of the top quark
  - ➡ consistency within SM
- Relates to Higgs mass through loop corrections of the W mass



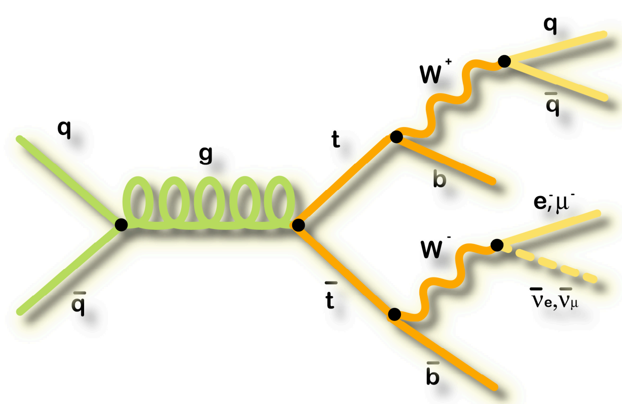


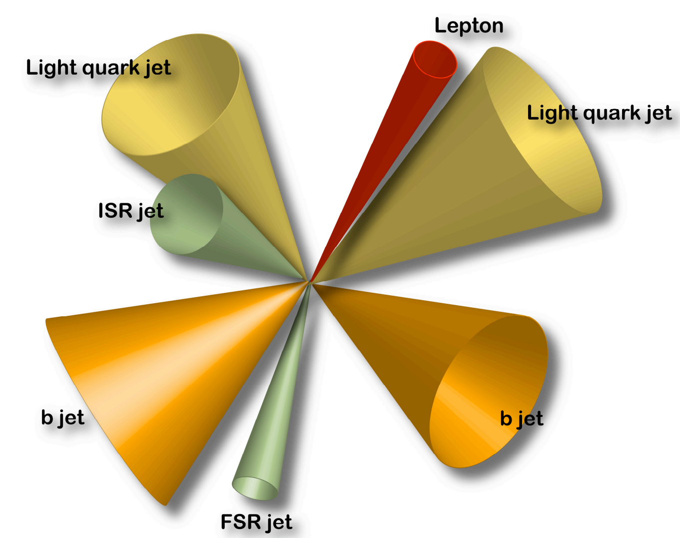
➡ indirect constrain on Higgs mass

➡ and physics beyond SM

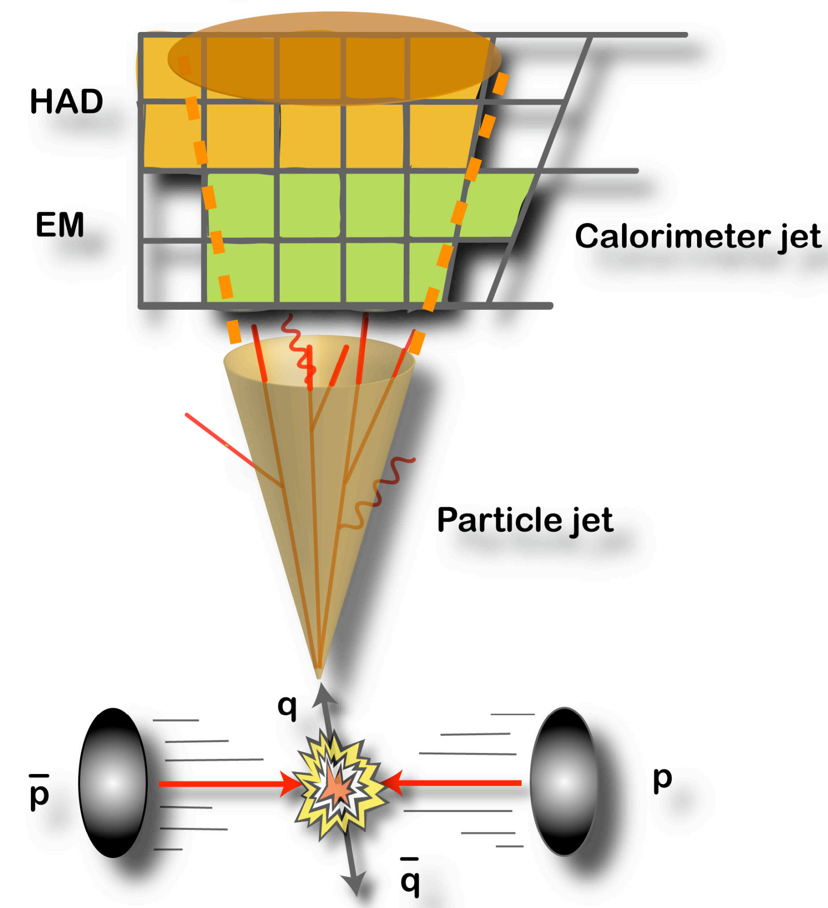


Challenges





- Measure jets no partons
  - need to correct for detector effects, hadronization and underlying event : Jet Energy Scale (JES) uncertainties ~ 3% (vary with E_T) dominant source of systematic
  - assignment jet-partons: combinatoric problem



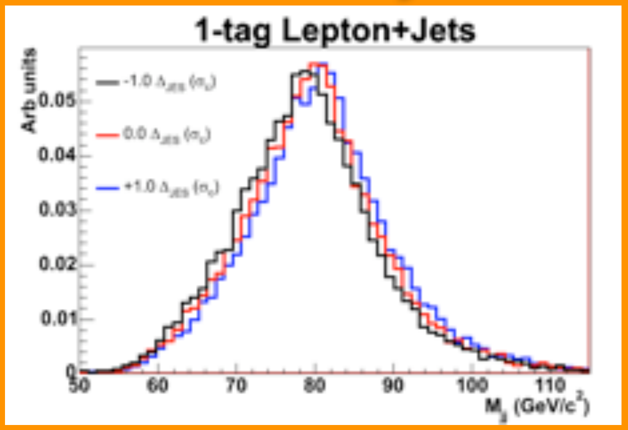
Challenges

- Measure jets no partons
  - need to correct for detector effects, hadronization and underlying event : Jet Energy Scale (JES) uncertainties ~ 3% (vary with E_T) dominant source of systematic
  - assignment jet-partons: combinatoric problem

reduced by using b-tagging information

In-situ JES calibration

Use reconstructed W mass (hadronically decay) to constrain JES



Techniques

Matrix Element

Define an event probability that the observed kinematics arise from a top pair decay as a function of the top mass and JES.

- Integrate over the parton-level differential cross section , PDF and transfer functions that maps a set of observed variables to that of the partons (detector resolution effects).
- Maximize Final Likelihood : product of the Probabilities for the observed data

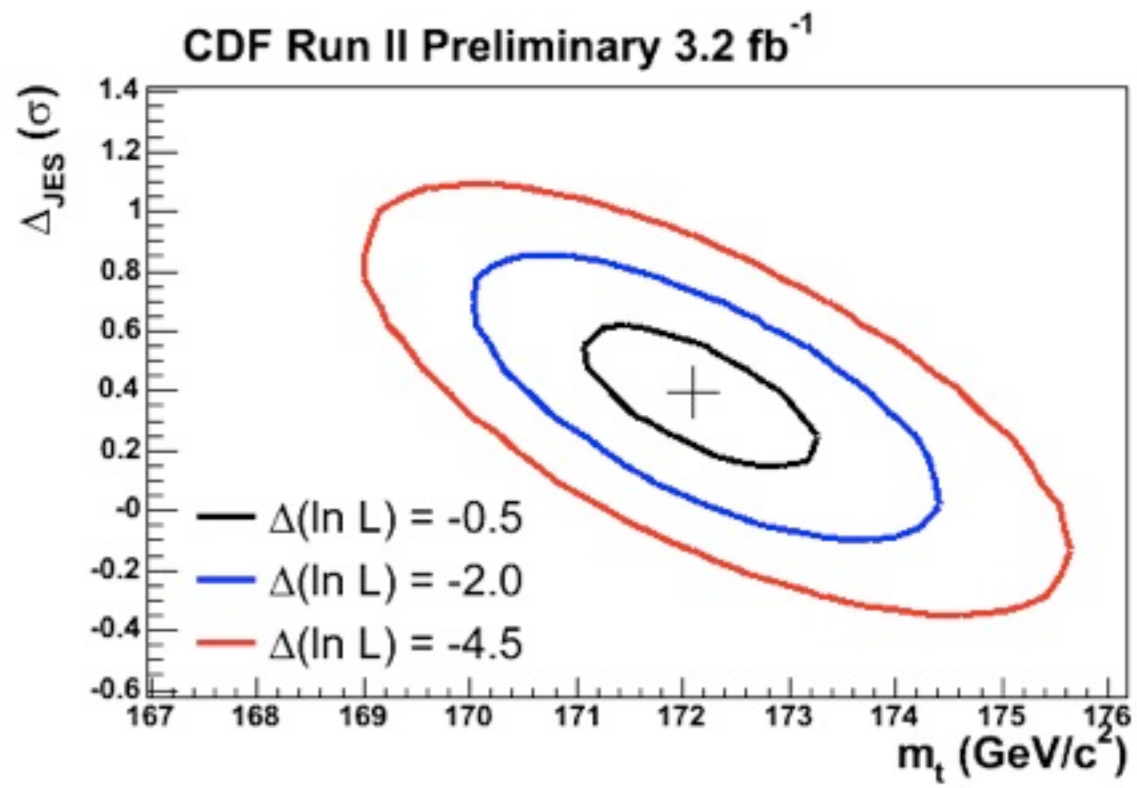
Template

- build distribution (template) of variables sensitive to top mass and JES
- Maximize a likelihood where observed distributions are compared to expectations at different top mass and JES

Lepton+Jets Channel

3.2 fb^{-1}

- 4 jets and ≥ 1 b-tag
- Matrix element technique
- In-situ JES calibration
  - ➡ 2D Likelihood : $L(m_t, \Delta_{JES})$ Δ_{JES} : shift in units of JES error



172.1 ± 0.9 (stat) ± 1.3 (syst) GeV/c^2

single measurement with precision <1%

LJ Top Mass 3.6fb^{-1}

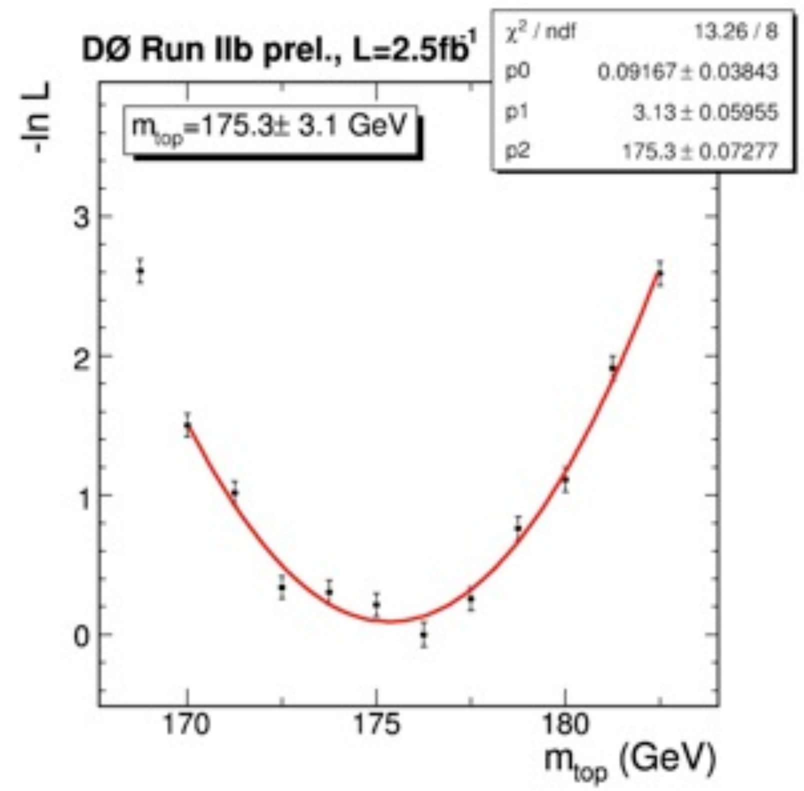
173.7 ± 0.8 (stat) ± 1.6 (syst) GeV/c^2

Dilepton Channel

3.6 fb^{-1}

- matrix element technique
- using eμ, ≥2jets

174.8 ± 3.3 (stat) ± 2.6 (syst) GeV/c^2



- Combine with result from a template method with Neutrino Weighting Algorithm (in 1fb^{-1})
  - ➡ NWA used to resolve the under-constrained kinematics due to 2 neutrinos.

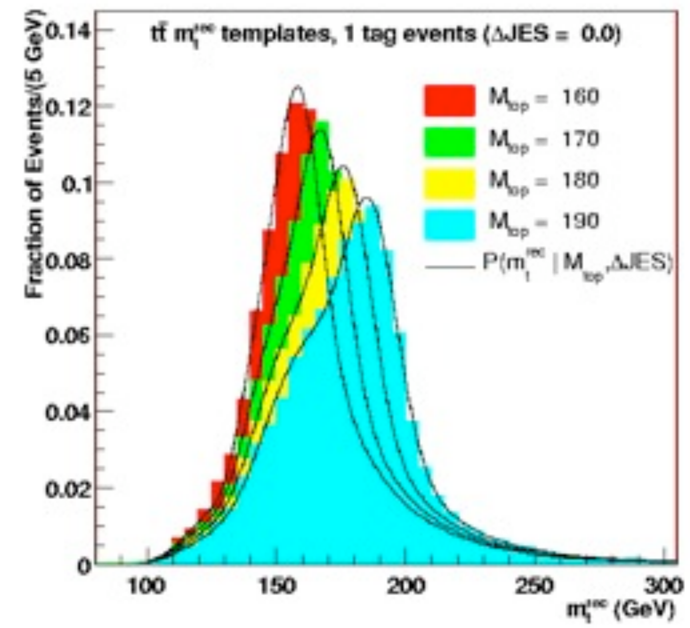
174.7 ± 2.9 (stat) ± 2.4 (syst) GeV/c^2

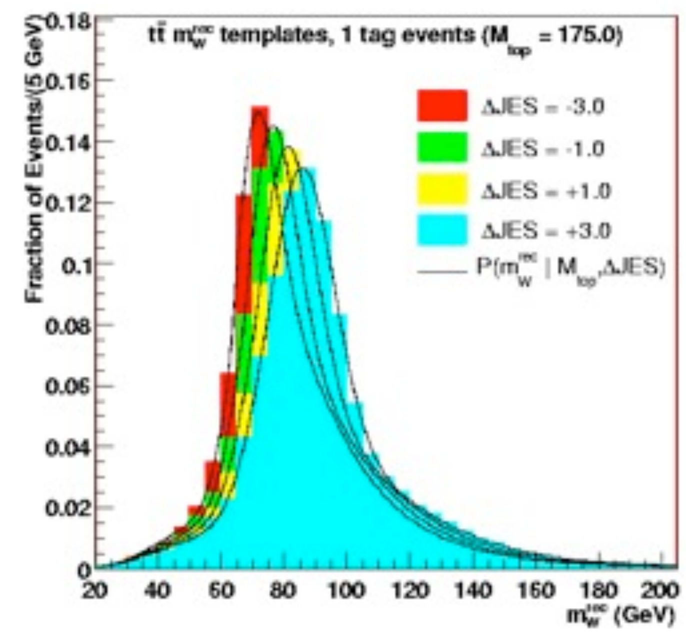
$\sigma/m_t = 2.2\%$

All-Hadronic Channel

2.9 fb^{-1}

- Very challenging due to large QCD backgrounds
- select events with ≥ 6 jets, 1 and ≥ 2 b-tag
- use NeuralNet (including jet shape variables for q vs g initiated jets) to discriminate Signal over Background.
- Includes In-Situ JES calibration
- Template method (m_t, Δ_{JES})





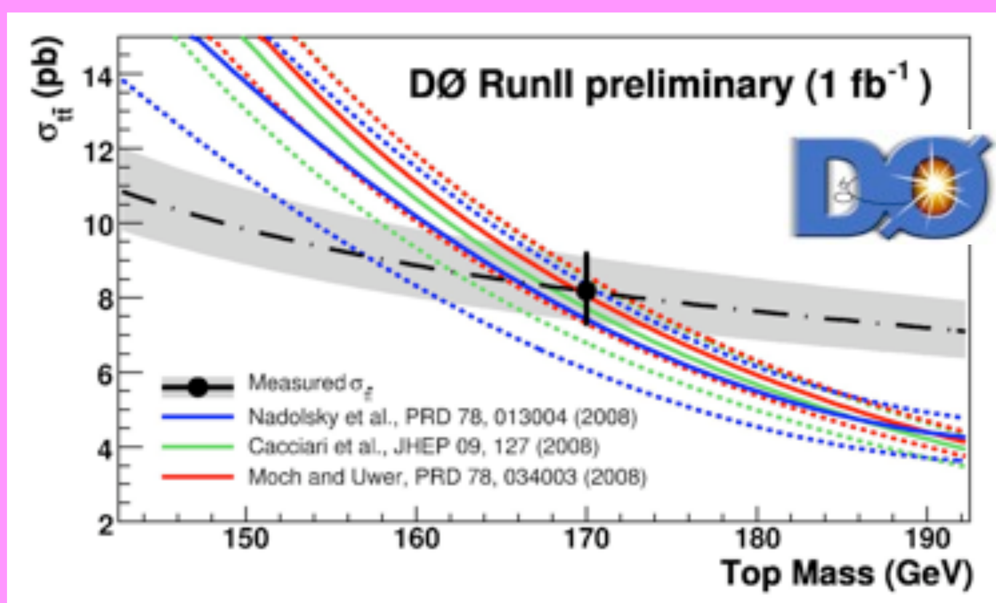
174.8 ± 1.7 (stat) ± 1.9 (syst) GeV/c^2

σ/m_t = 1.5%

Indirect Measurement

Using parametrizations of the experimental and theoretical cross section as a function of mass:

build a joint Likelihood $L(\sigma, m_t)$



$169.1^{+5.9}_{-5.2}$ GeV/c^2

done for LJ and DIL

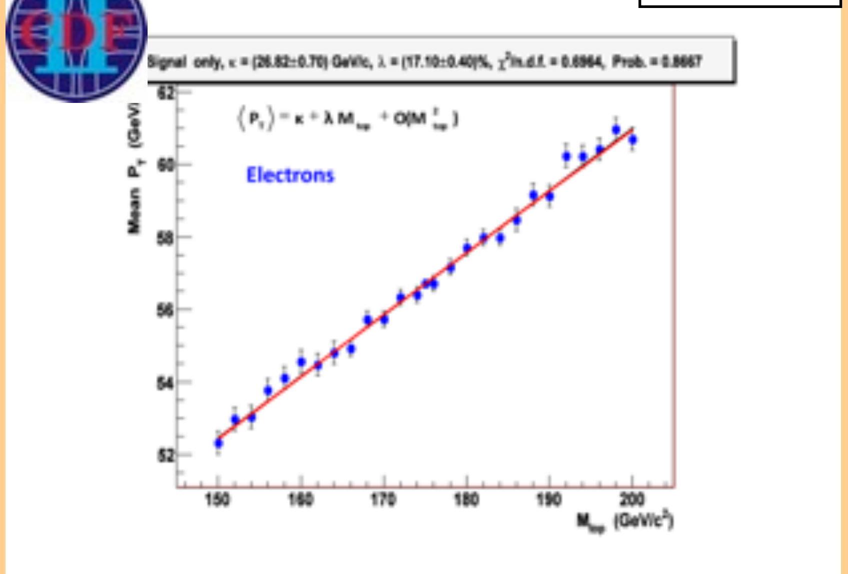
NLO+NLL and $NNLO_{approx}$

arXiv:0903.5525 [hep-ex]

Reducing JES dependence

Exploit correlation between Lepton momentum and top mass in L+J channel.

2.7 fb^{-1}



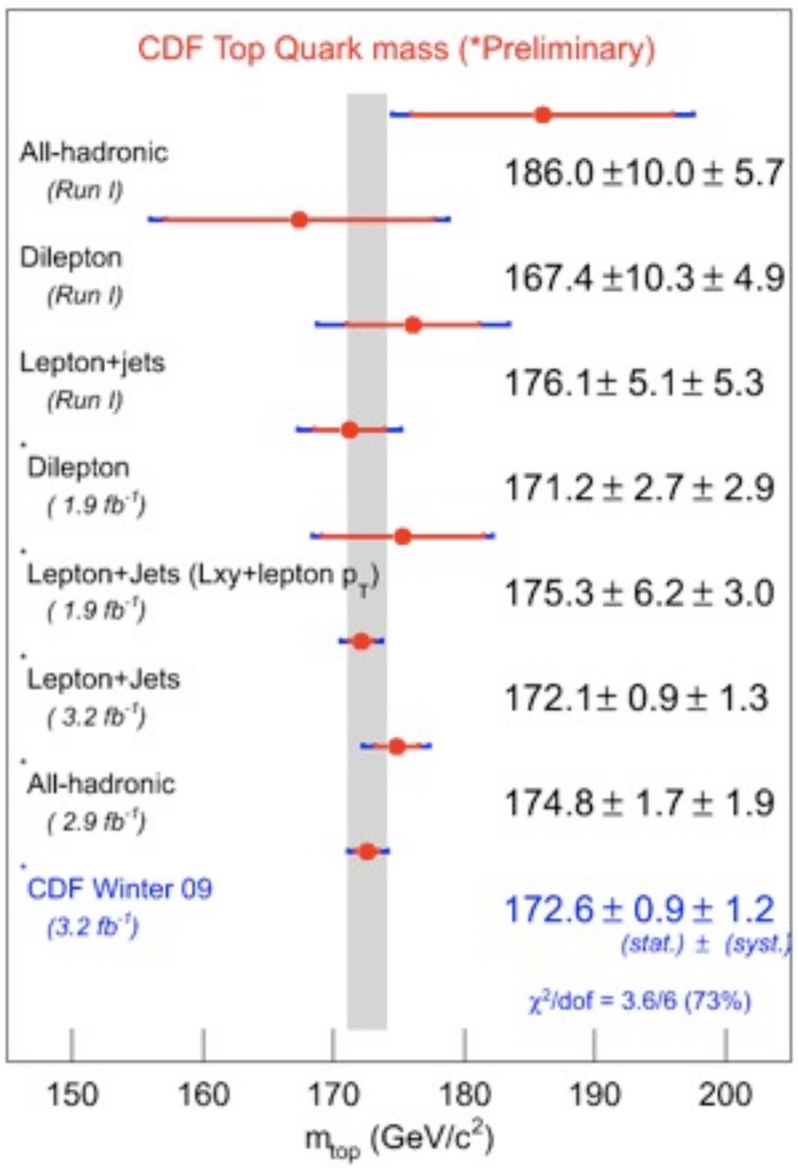
172.1 ± 7.9 (stat) ± 3.0 GeV/c^2

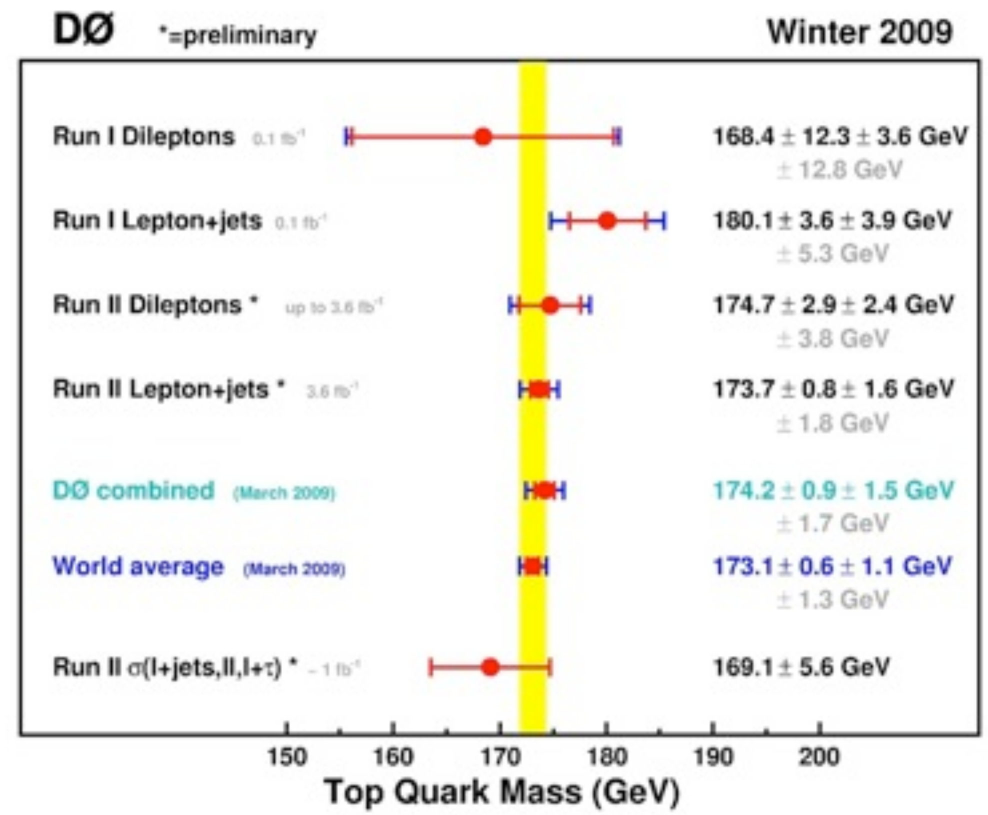
combine electron and muon

checked using mean and shape

Top Mass combination

Most precise measurements per channel and per experiment





- Consistent results between channels
- Combine results for better precision

Systematic Uncertainties

- Measurements are systematic dominated.
- Part of JES however has became statistical (from In-situ calibration)
- Still residual JES (differences with respect to b-jets JES or dependence on p_T or η)

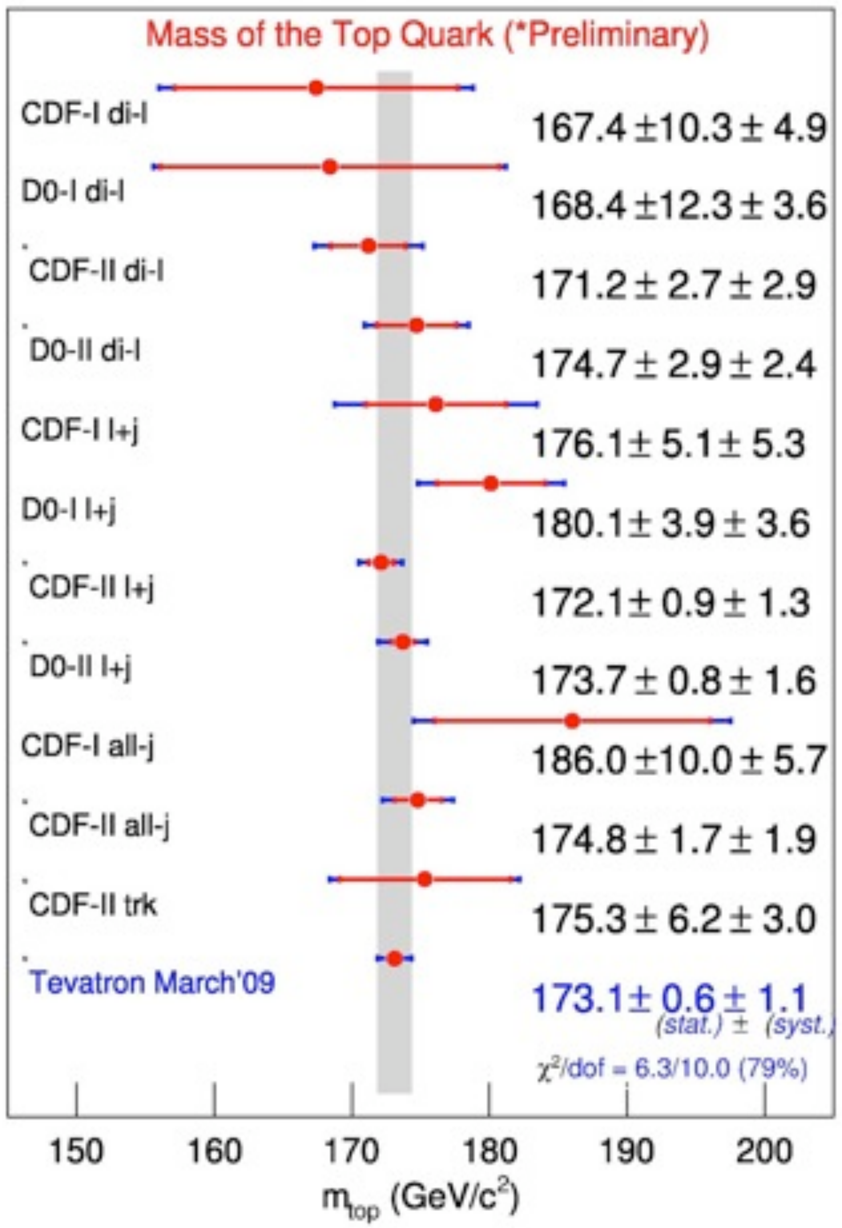
On-going joint (CDF+D0) effort to re-examine each source of uncertainty

established common categories

Systematic source	Systematic uncertainty (GeV/c^2)
Calibration	0.2
MC generator	0.5
ISR and FSR	0.3
Residual JES	0.5
b-JES	0.4
Lepton P_T	0.2
Multiple hadron interactions	0.1
PDFs	0.2
Background	0.5
Color reconnection	0.4
Total	1.1

Example taken from CDF LJ analysis

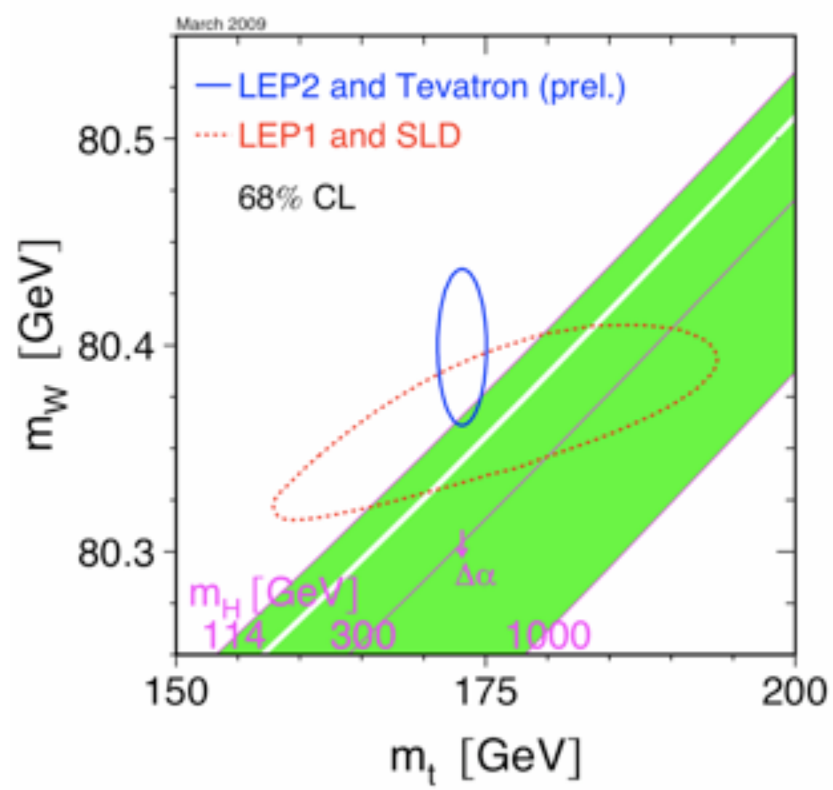
Tevatron combination



Reference:
arXiv:0903.2503

173.1 ± 0.6 (stat) ± 1.1 (syst)

- ★ 1.3 GeV/c^2 uncertainty
- ★ 0.75% precision

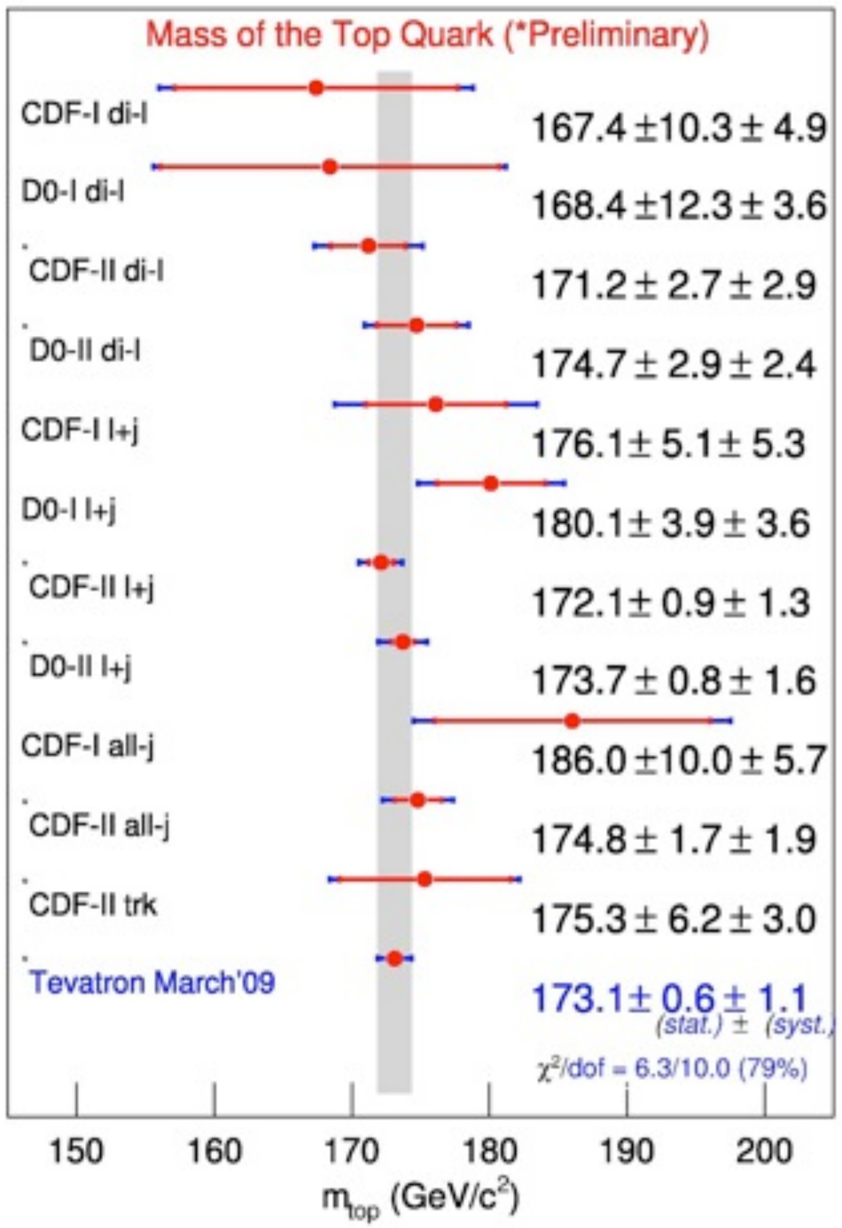


http://lepewwg.web.cern.ch/LEPEWWG/

Electroweak fit which incorporates new TeV top mass and the TeV 95%CL exclusion of the SM Higgs Boson (160-170GeV)

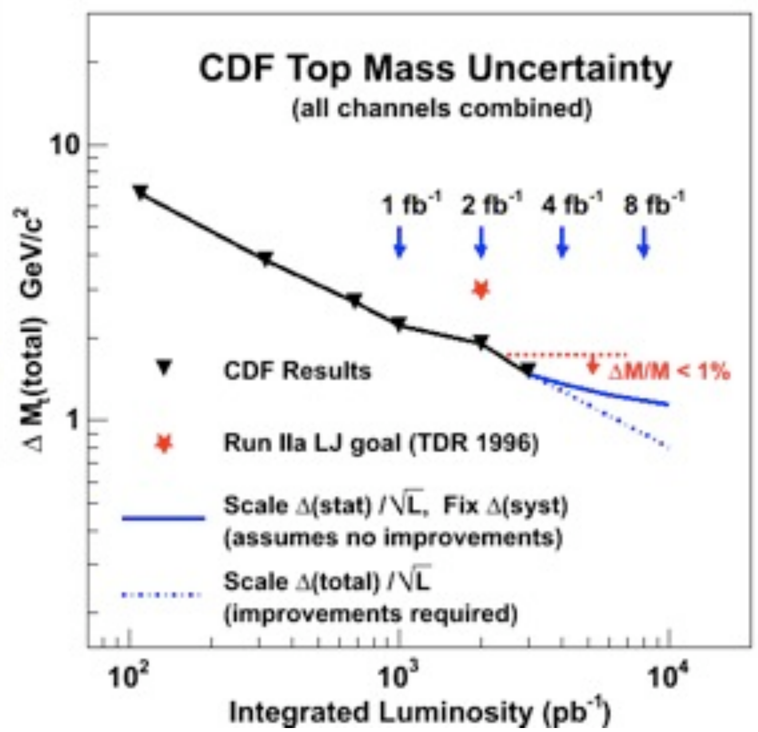
From EWK fits
$m_H = 90\ ^{+36}_{-27}$ GeV
$m_H < 163$ GeV

Tevatron combination



173.1 ± 0.6 (stat) ± 1.1 (syst)

- ★ 1.3 GeV/c^2 uncertainty
- ★ 0.75% precision



Already beyond RunII goal,

can we do even better?
on-going studies....

Reference:
arXiv:0903.2503

Top Properties

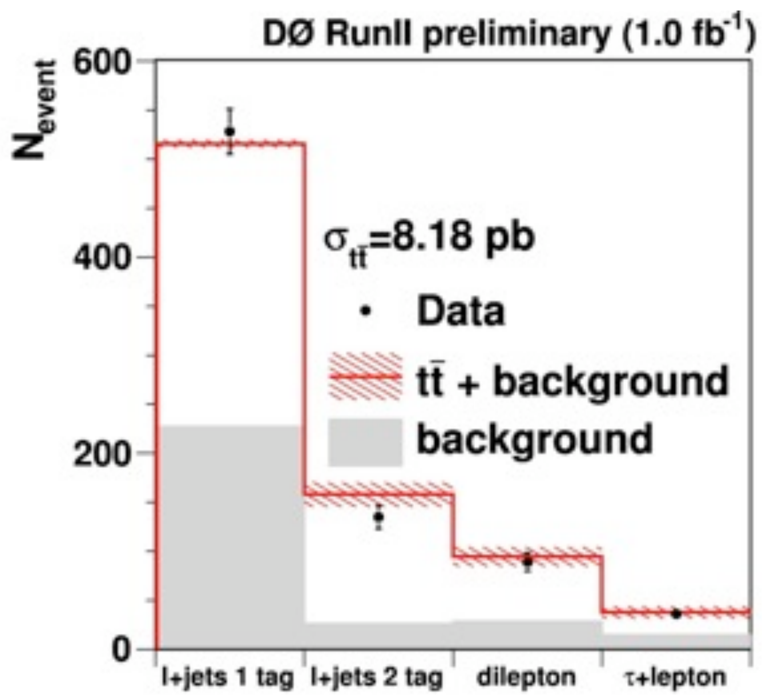
and

Searches for new physics

Cross-section ratios

1.0 fb^{-1}

New Physics may appear only on some channels:
for example $t \to H^+ b \to \tau \nu b$



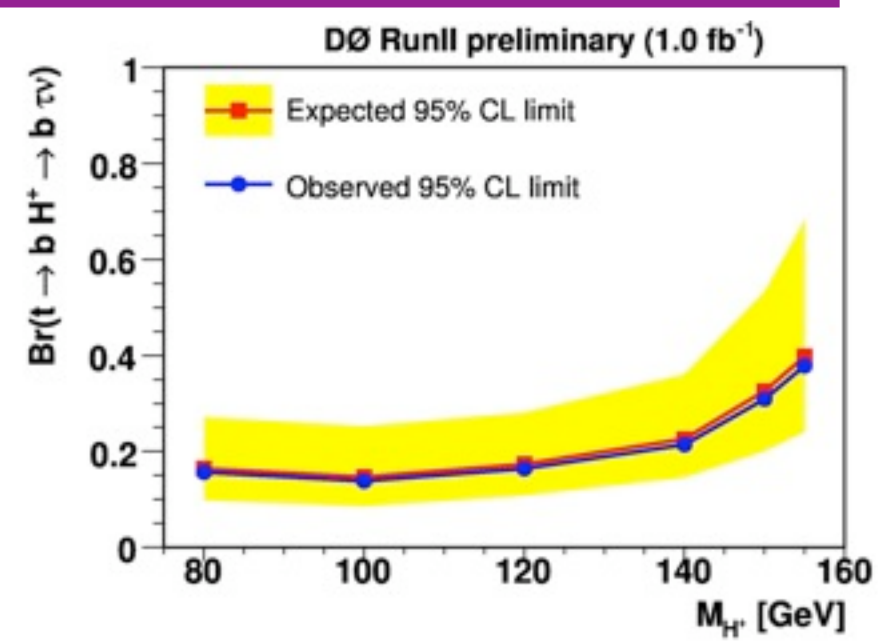
Cross-section ratios

$$R_{ll/lj} = 0.86\ ^{+0.19}_{-0.17}$$

$$R_{\tau l/ll+lj} = 0.97\ ^{+0.32}_{-0.29}$$

Consistent with SM expectation

Establish limits on
$Br(t \to H^+ b)$
$H^+ \to \tau \nu$, $H^+ \to c\bar{s}$

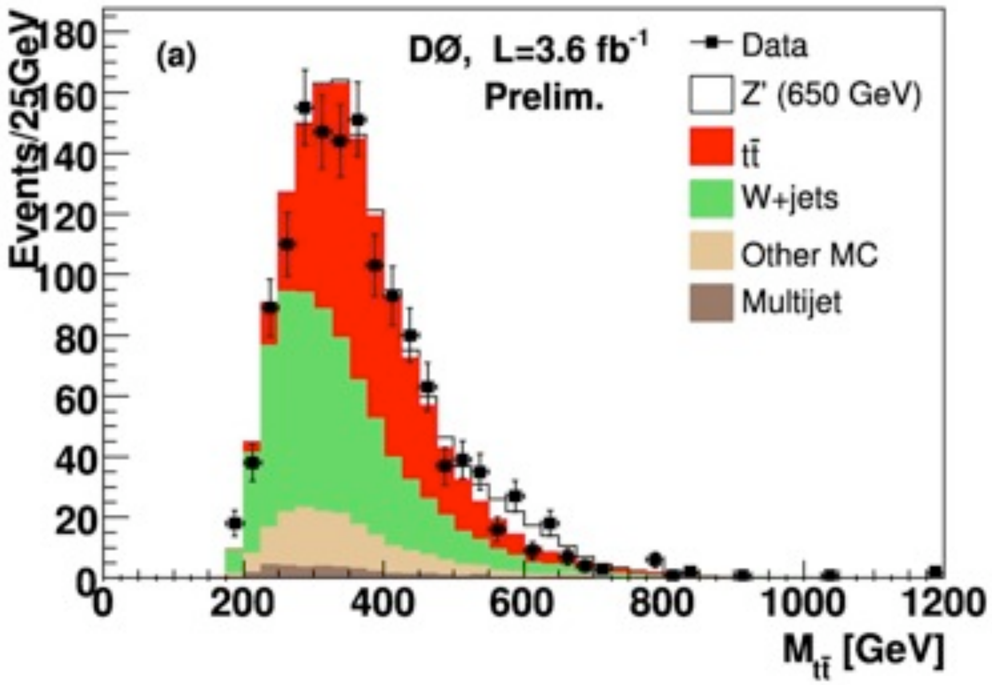


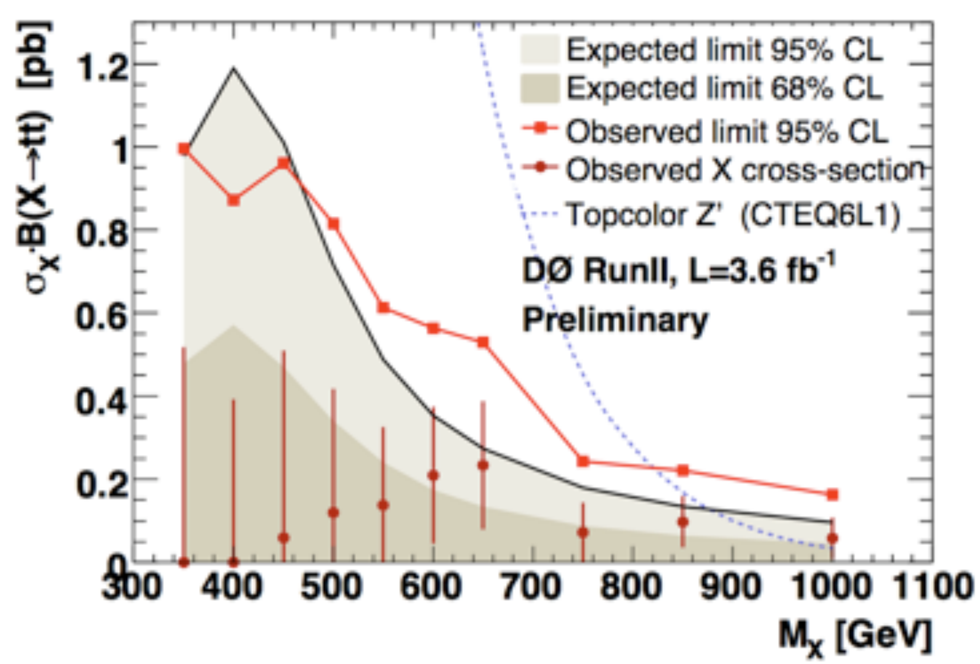
References:
CDF PRL 96 042003 (2006)
D0 arXiv.org:0903.5525

Resonant Production

3.6 fb^{-1}

- Search for narrow-width resonances decaying into a pair of top quarks
- L+Jets channel (3 or more jets), 1 or more b-tags
- Reconstruct invariant mass and compare with templates built from simulation (for SM contributions and various narrow width heavy resonances).





for a narrow width topcolor Z'
$M_{Z'}$ < 820 GeV excluded @ 95%CL

References: CDF PRL 100 238101 (2008) (~0.7fb^{-1} , $M_{Z'}$ < 725GeV)
D0 PLB 668, 98 (2008) (~0.9fb^{-1} , $M_{Z'}$ < 700GeV)

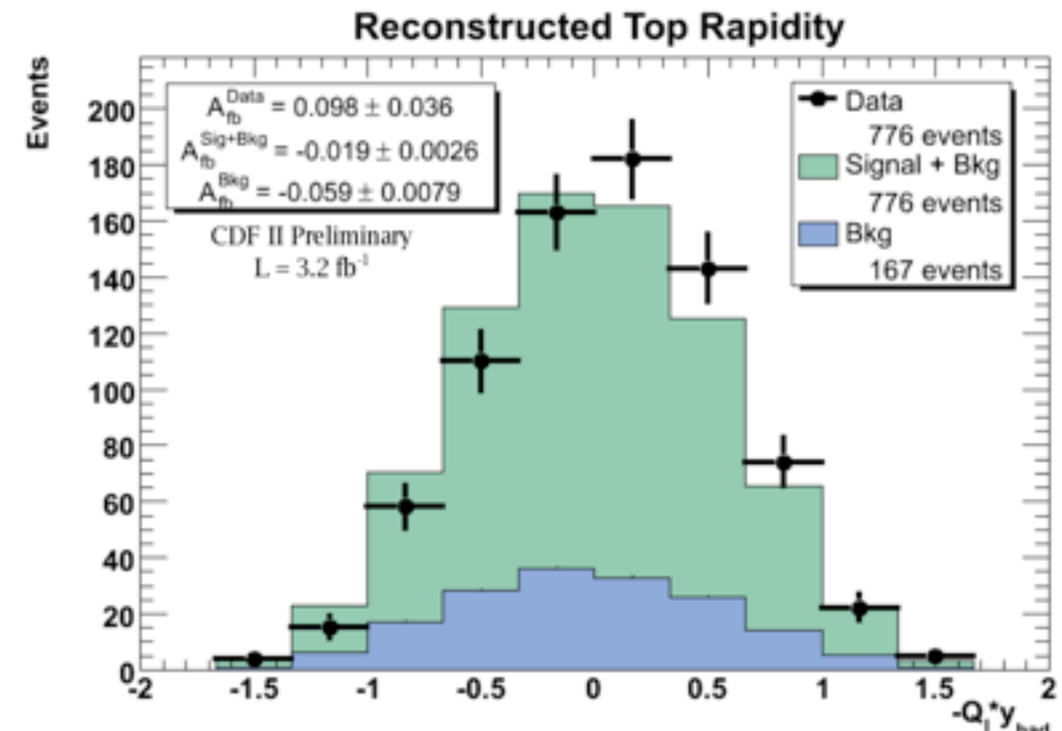
Forward-backward asymmetry

3.2 fb^{-1}

- New physics models could give rise to a A_{FB} asymmetry (axigluons).
- NLO QCD calculations predict:
  Ac = 5 ± 1.5 % (pp̄ frame)
- If CP, it can be interpreted as

$$A_{FB} = \frac{N_t(p) - N_t(\bar{p})}{N_t(p) + N_t(\bar{p})}$$

- L+Jets channel (≥4 jets), ≥1b-tag
- Use rapidity of hadronically decaying top
- Correct by detector effects



pp̄ frame

Afb= 19.3 ± 6.5 (stat) ± 2.4 (syst) %

References:
CDF PRL 100 202001 (2008) :
1.9fb^{-1} ,Afb =0.17 ± 0.08

D0 PRL 100, 142002 (2008) :
0.9fb^{-1} ,Afb =0.12 ± 0.08
(observed)

Examining the Wtb vertex

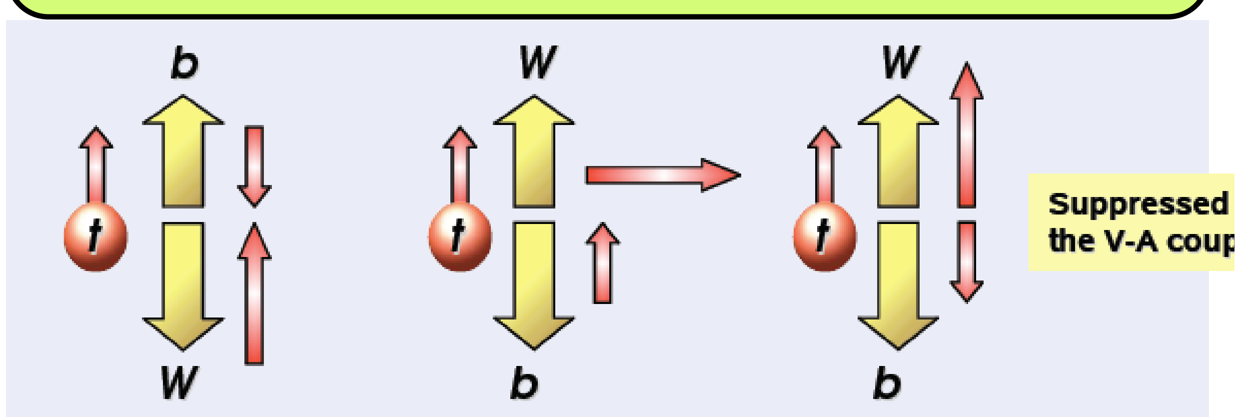
W boson helicity

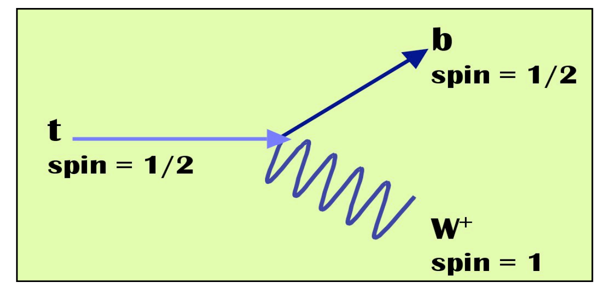
In SM

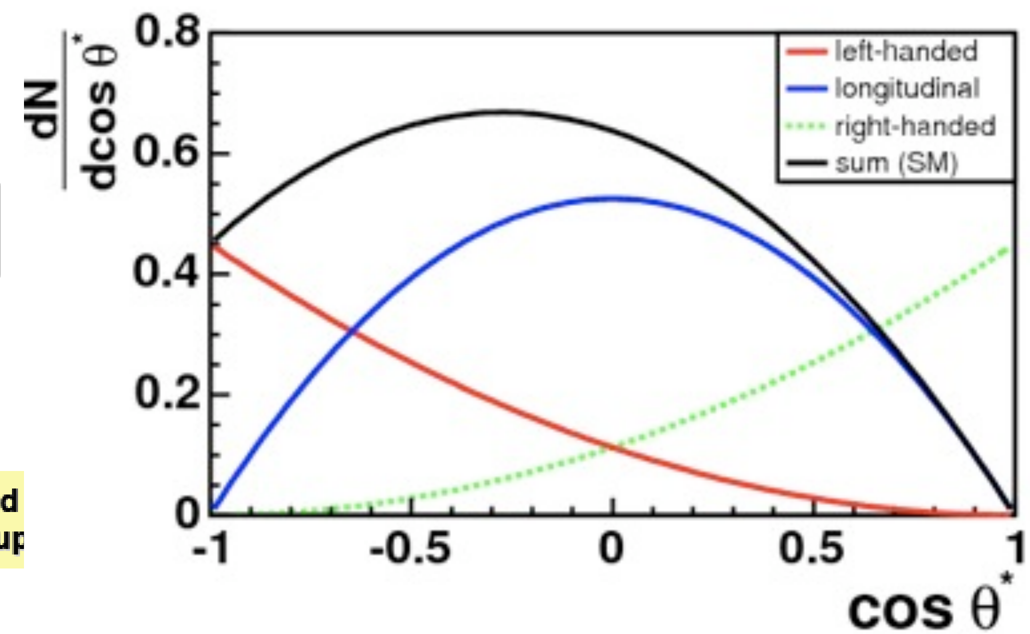
t → Wb ~ 100%

due to the V-A nature of the vertex, expect:

Left-Handed	Longitudinal	Right-Handed
$f_- \cong 0.3$	$f_0 \cong 0.7$	Suppressed



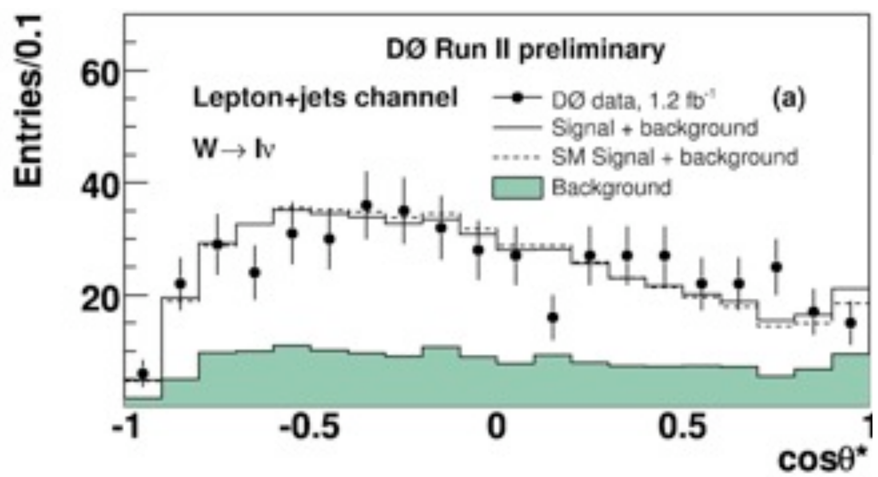


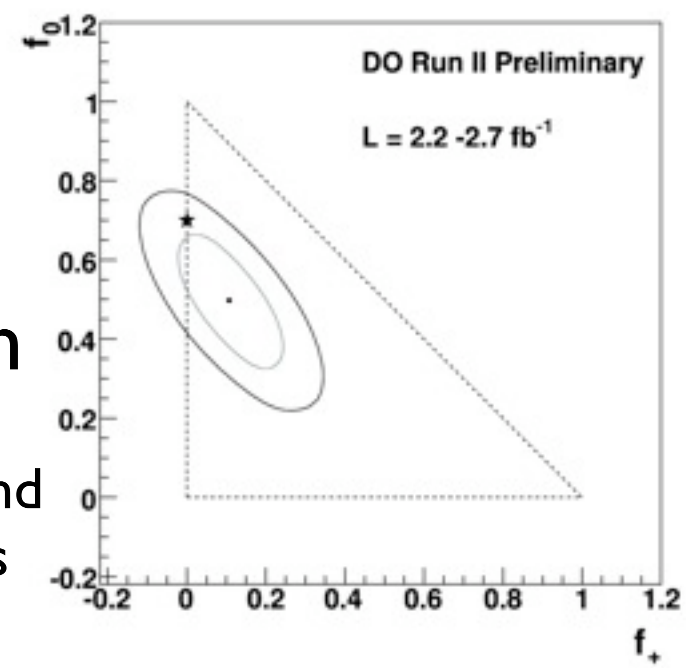


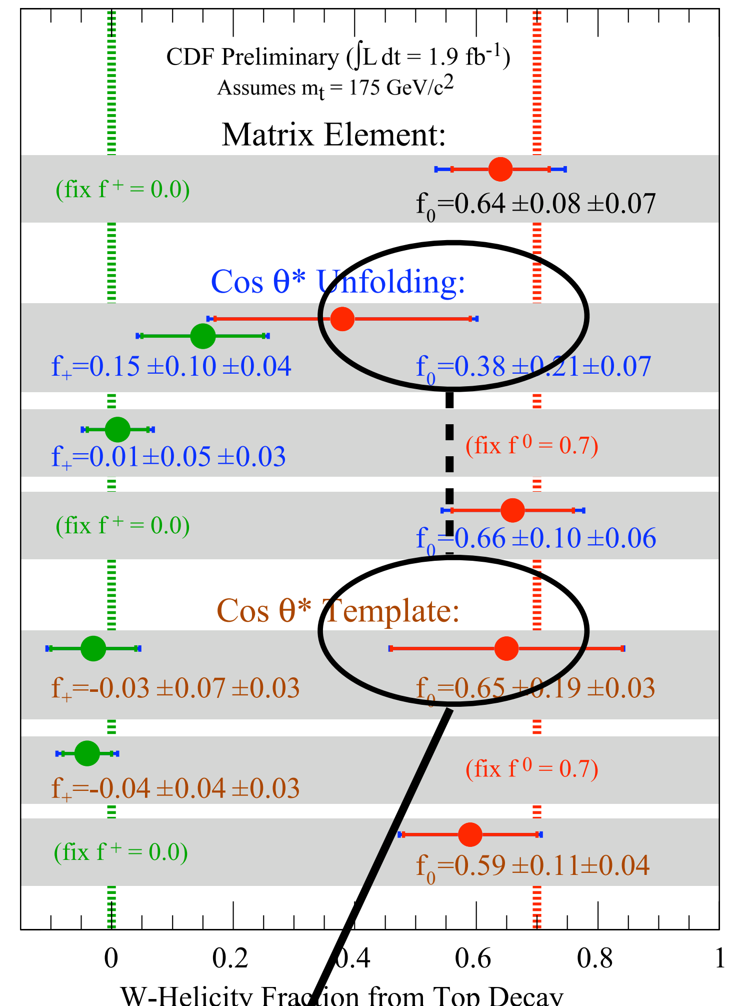
decay angle of down-type fermion in the W rest frame with respect to the top quark direction

W Helicity

probing the tWb vertex







Using L+J and Dilepton

compare data to signal+background templates for given fraction values

make 2D fit (model independent)

$f_0 = 0.490 \pm 0.106$ (stat) ± 0.085 (syst)

$f_+ = 0.110 \pm 0.059$ (stat) ± 0.052 (syst)

1fb^{-1} Reference:
D0 PRL 100 062004 (2008)

Reference:
CDF PLB 674 p160 (2009)

Combination

assuming $f_+ = 0$

$f_0 = 0.62 \pm 0.10$ (stat) ± 0.05 (syst)

or $f_0 = 0.7$

$f_+ = -0.04 \pm 0.04$ (stat) ± 0.03 (syst)

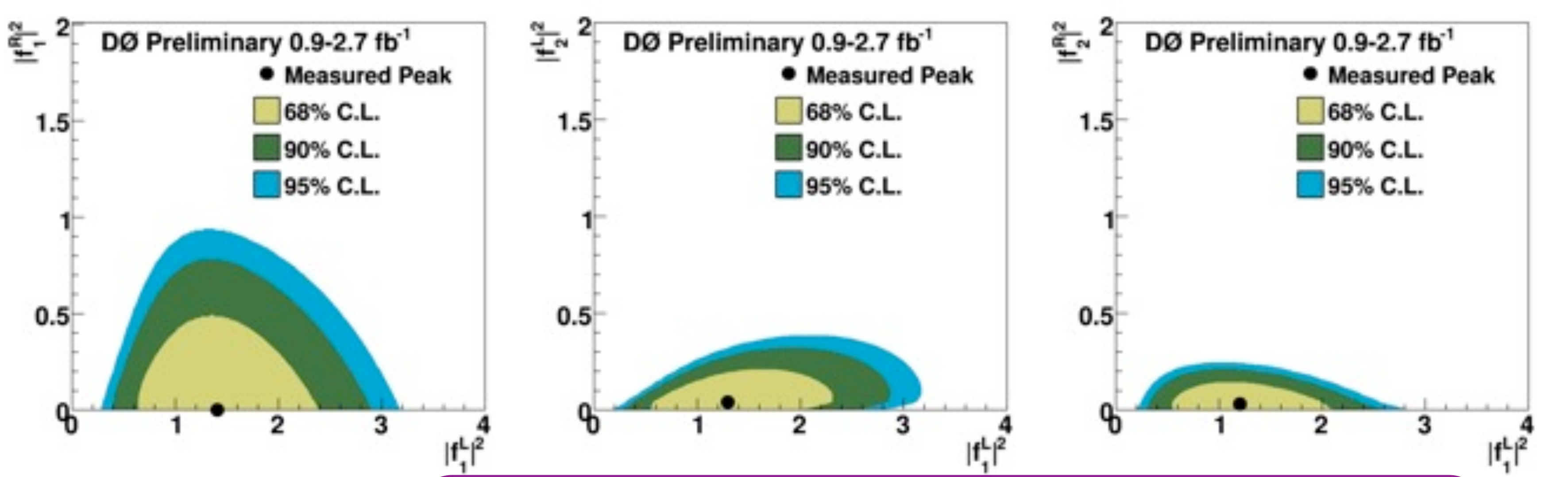
Anomalous Couplings

$$L_{tWb} = \frac{g}{\sqrt{2}} W_\mu^- \bar{b} \gamma^\mu \left(f_1^L P_L + f_1^R P_R \right) t - \frac{g}{\sqrt{2} M} \partial_\nu W_\mu^- \bar{b} \sigma^{\mu\nu} \left(f_2^L P_L + f_2^R P_R \right) t$$

$+ \ h.c.$

SM values : $f_1^L = 1$, $f_1^R = f_2^L = f_2^R = 0$

- observables like the W helicity fractions or the single top cross section will depend on the tWb couplings (C.R. Chen, F. Larios and C.P Yuan, Phys.Lett.B631:126)
- Our measurements can therefore be used to do a general analysis of the vertex
- By investigating one pair of coupling form factors at a time (others at SM value):



find 95%CL if $f_1^L = 1$

$|f_1^R|^2 < 0.72$

$|f_2^L|^2 < 0.19$

$|f_2^R|^2 < 0.20$

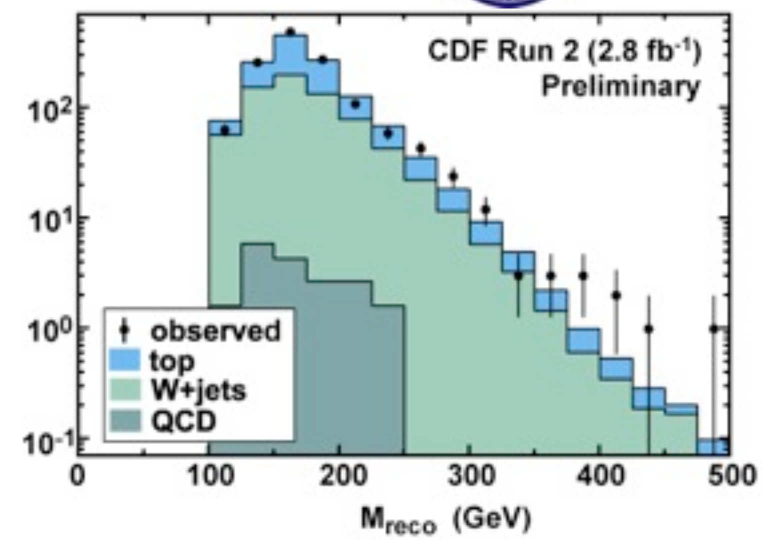
Consistent with SM

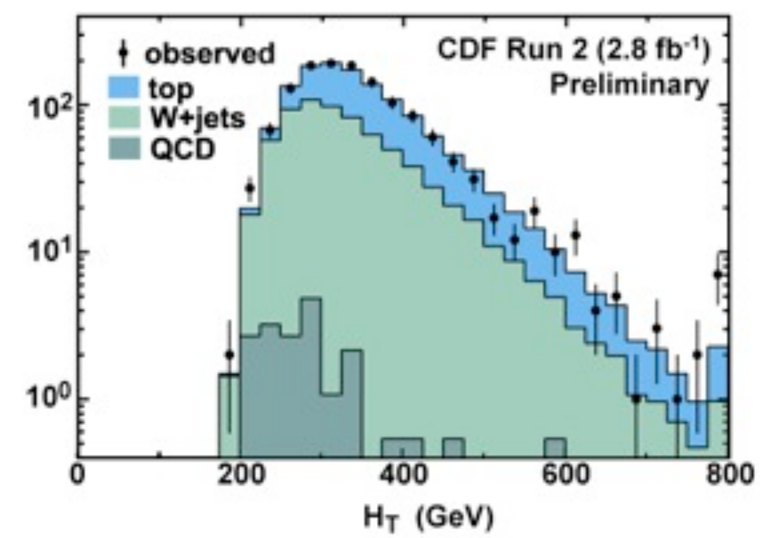
1fb^{-1} Reference: D0 PRL 102 092002 (2009)

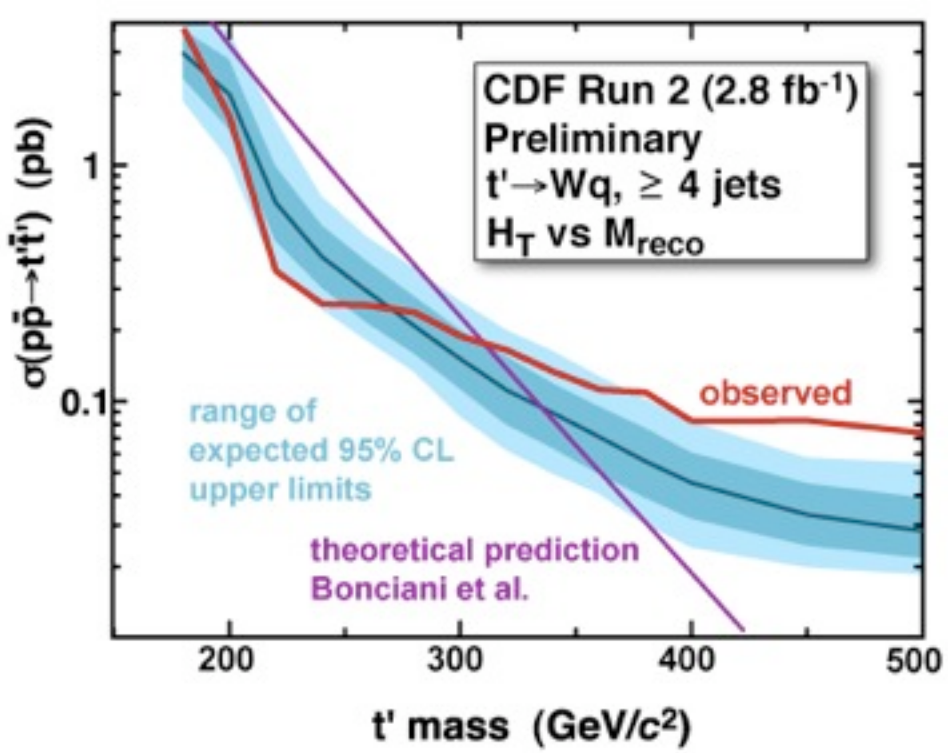
Search for heavy Top-like quarks

2.8 fb^{-1}

- Search for a heavy top-like quark (t') decaying to Wq
- Present in various theories
  - predicting 4-th generation of massive fermions PRD 64, 053004 (2001)
  - Heavy top-like: Little Higgs PRD 69, 075002 (2004)
  - Fermion doublets: Beautiful Mirrors PRD 65, 053002 (2002)
- In L+Jets channel, reconstruct event and perform a 2D Likelihood fit to Mt and H_T







Exclude @ 95%CL
$M_{t'} < 311$ GeV

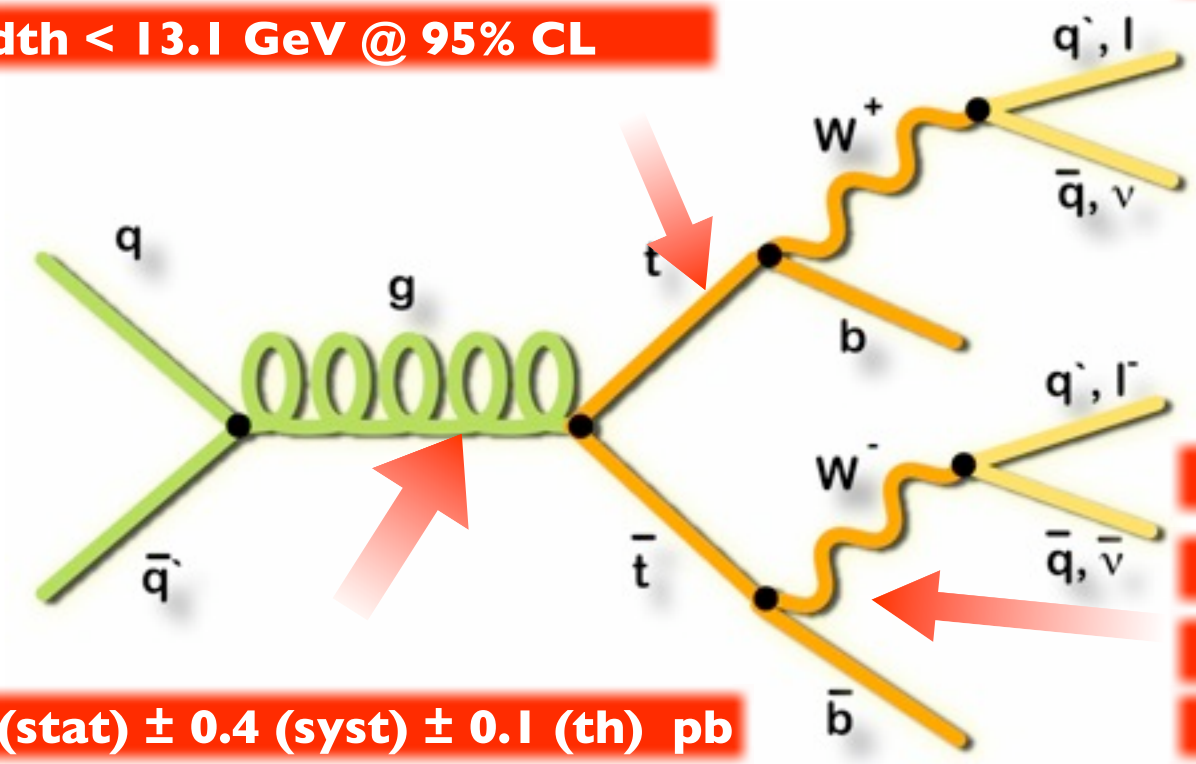
0.76 fb^{-1} Reference:
CDF PRL 100 161803 (2008)

Summary

M_t = 173.1 ± 0.6 ± 1.1 GeV/c² (TeV comb.)

Top charge : not 4/3 @ 87% CL

Top width < 13.1 GeV @ 95% CL



σ = 6.9 ± 0.4 (stat) ± 0.4 (syst) ± 0.1 (th) pb

Afb= 19.3 ± 6.5 (stat) ± 2.4 (syst) %

Excl. $M_{Z'}$ < 820 GeV at 95% CL

dσ/dMtt no discrepancy with SM

fraction via gg fusion : $0.07^{+0.15}_{-0.07}$

anom coupl : no evidence found

f_+ = 0.110 ± 0.059 (stat) ± 0.052 (syst)

Single Top Observation !!!

B(t→Wb)/B(t→Wq)=0.97 ± 0.09

BR(t → Zq) < 3.7% at 95% C.L.

No evidence for top → H^+b

No evidence for ttH production

Excl. $M_{t'}$ < 311 GeV at 95% CL

no evidence stop pair production

For details and more on single top , refer to →

More Information @

- Mini-symposium in Single Top:
  - ➡ May 3 2009 10:45AM, Governor's Square 11
- Parallel talks:
  - ➡ Top Mass, May 3 2009 1:30PM, Governor's Square 11
  - ➡ Top and Higgs Physics, May 5 2009 10:45AM, Governor's Square 11
  - ➡ QCD Physics, May 4 2009 1:30 pm, Plaza Court 4
- Experiment's web pages:
  - ❖ http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html
  - ❖ http://www-cdf.fnal.gov/physics/new/top/top.html

Conclusions

- Top Physics has entered the realm of precision physics at the Tevatron
- We are studying top from many angles,
  - ➡ so far experimental measurements agree with SM predictions
- More data is being analyzed
  - ❖ more than $5fb^{-1}$ on tape (expected $>8fb^{-1}$ by 2010)

Stay tuned !!

Summary

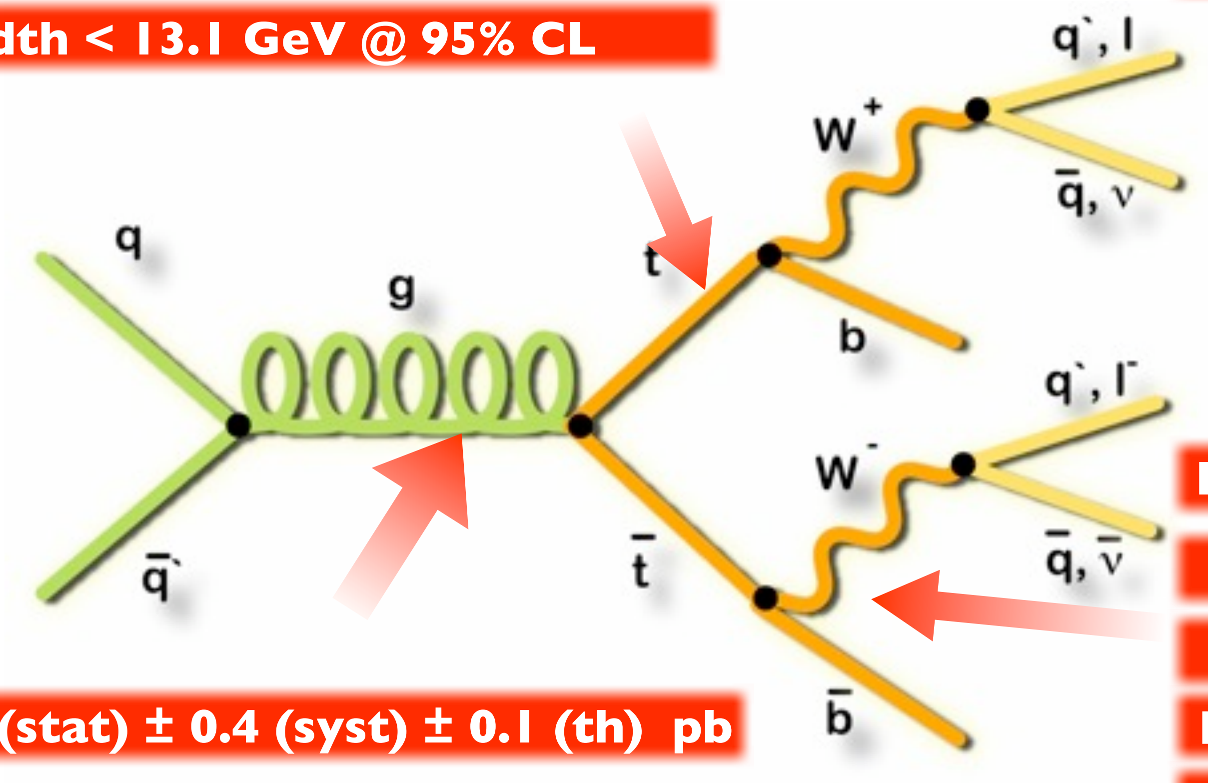
M_t = 173.1 ± 0.6 ± 1.1 GeV/c^2 (TeV comb.)

Top charge : not 4/3 @ 87% CL

Top width < 13.1 GeV @ 95% CL

anom coupl : no evidence found

f_+ = 0.110 ± 0.059 (stat) ± 0.052 (syst)



Single Top Observation !!!

B(t→Wb)/B(t→Wq)=0.97 ± 0.09

BR(t → Zq) < 3.7% at 95% C.L.

No evidence for top → H^+b

No evidence for ttH production

Excl. $M_{t'}$ < 311 GeV at 95% CL

no evidence stop pair production

σ = 6.9 ± 0.4 (stat) ± 0.4 (syst) ± 0.1 (th) pb

Afb= 19.3 ± 6.5 (stat) ± 2.4 (syst) %

Excl. $M_{Z'}$ < 820 GeV at 95% CL

$d\sigma/dM_{tt}$ no discrepancy with SM

fraction via gg fusion : $0.07^{+0.15}_{-0.07}$