Top quark measurements at hadron machines

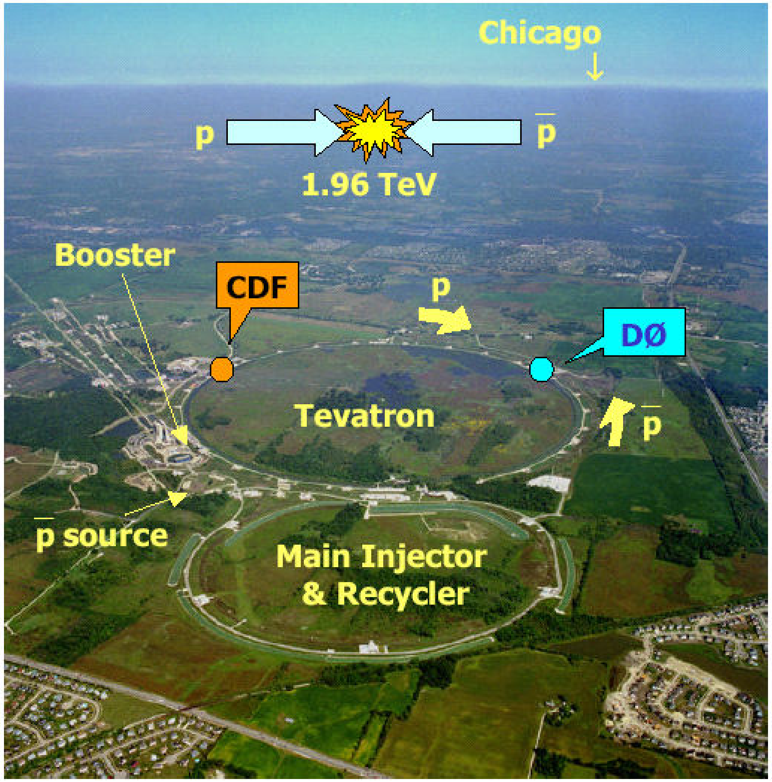
Sandra Leone
(INFN Pisa)
for the CDF and DØ Collaborations

WIN09 Perugia, September 15th, 2009

Outline

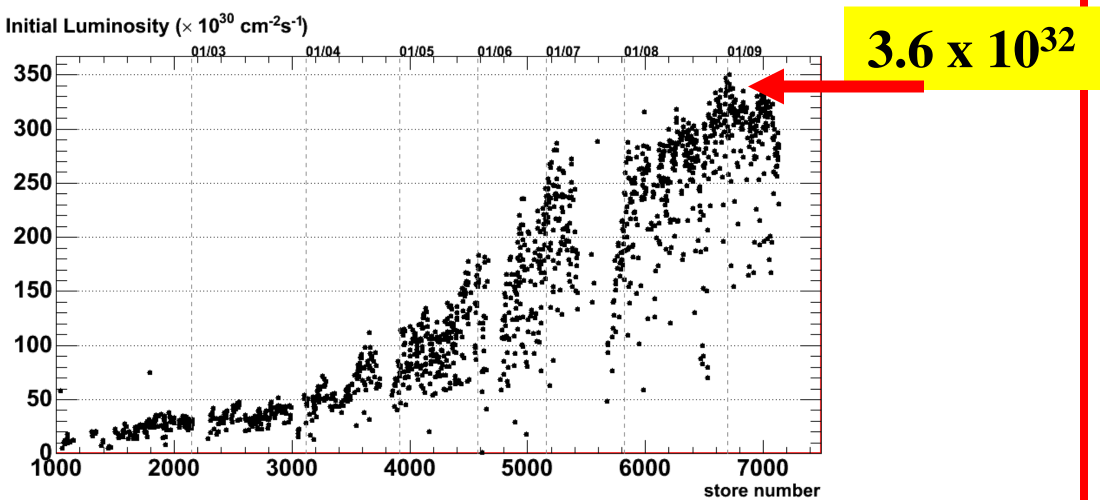
- The Tevatron & the experiments
- Exploring top quark physics at the Tevatron:
  - ✓Pair production cross section
  - ✓Single top production
  - ✓Top mass measurements
  - ✓Study of Top properties
- …while waiting for the LHC startup
- Summary and conclusion

Tevatron Performances



Run II: $\sqrt{s}$ = 1.96 TeV

Performances have kept improving since the start of Run II.



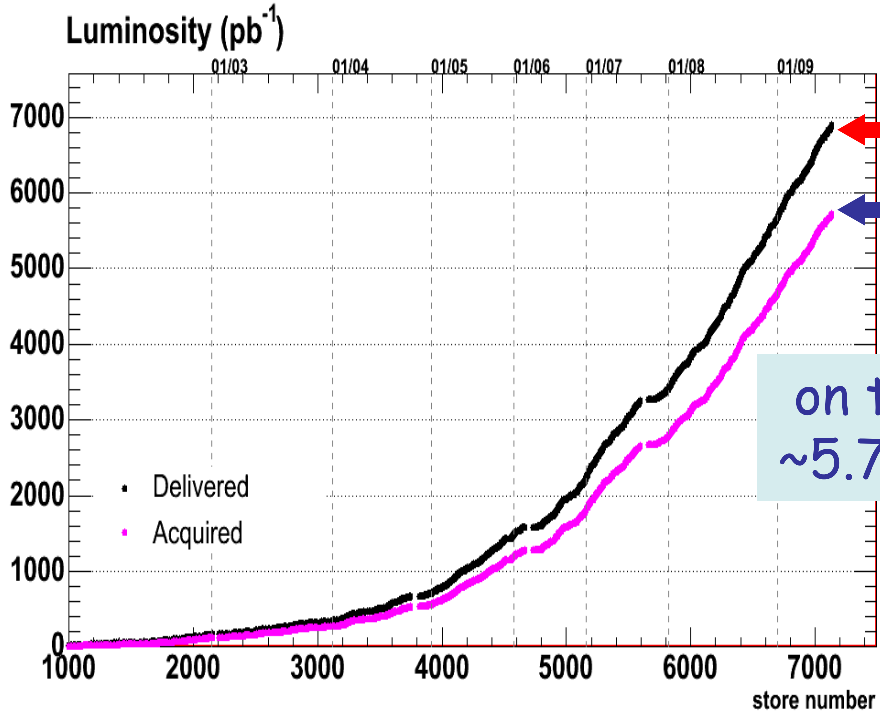
Peak luminosity

Accelerator complex breaking records all the time:

Peak Luminosity record ~ $3.6 \cdot 10^{32}$ cm^{-2} s^{-1}

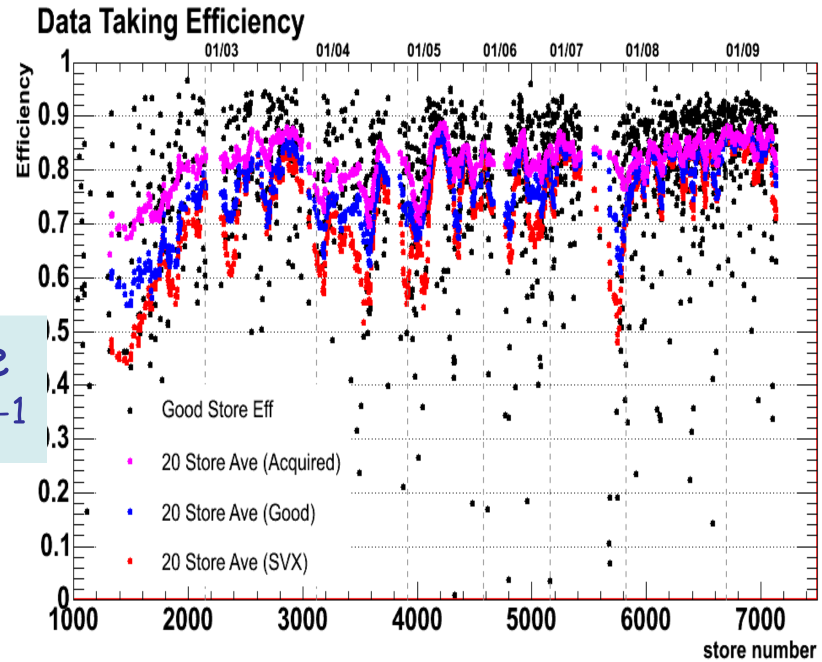
Weekly integrated luminosity record 73 pb^{-1}

Integrated Luminosity



on tape
~5.7 fb^{-1}

delivered: ~ 6.9 fb^{-1}

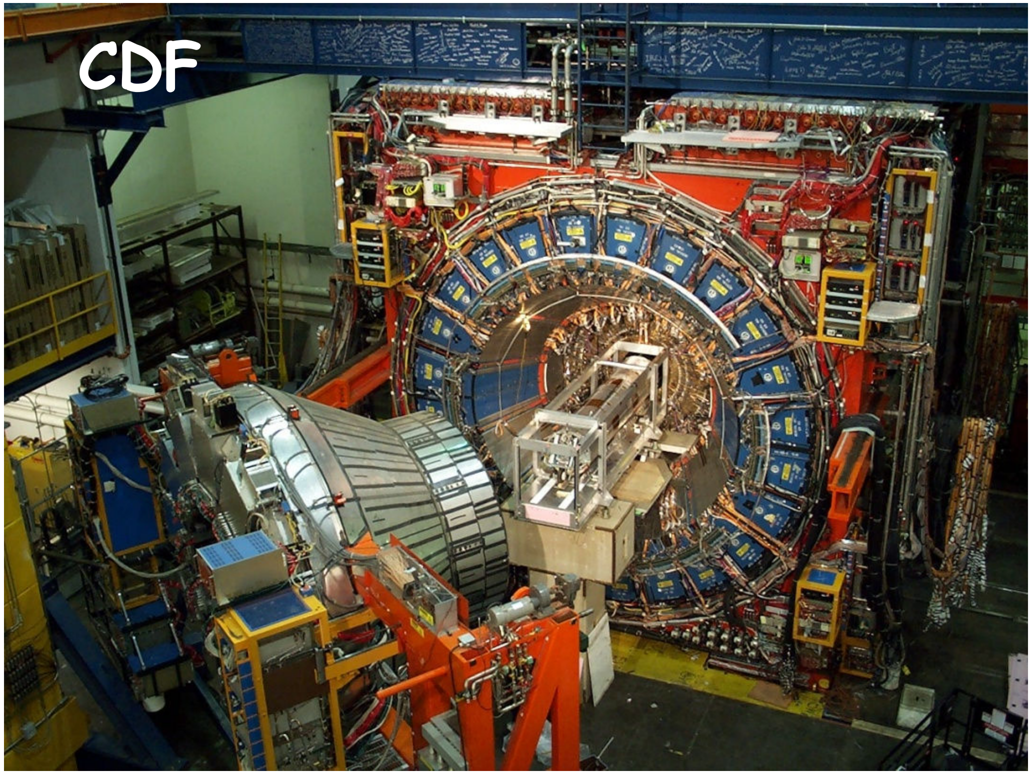


Detectors running stably since Feb. '02

Data taking efficiency
L(recorded)/L(delivered)
commonly > 85%

All results shown in the following based on datasets up to ~4.5 fb^{-1}

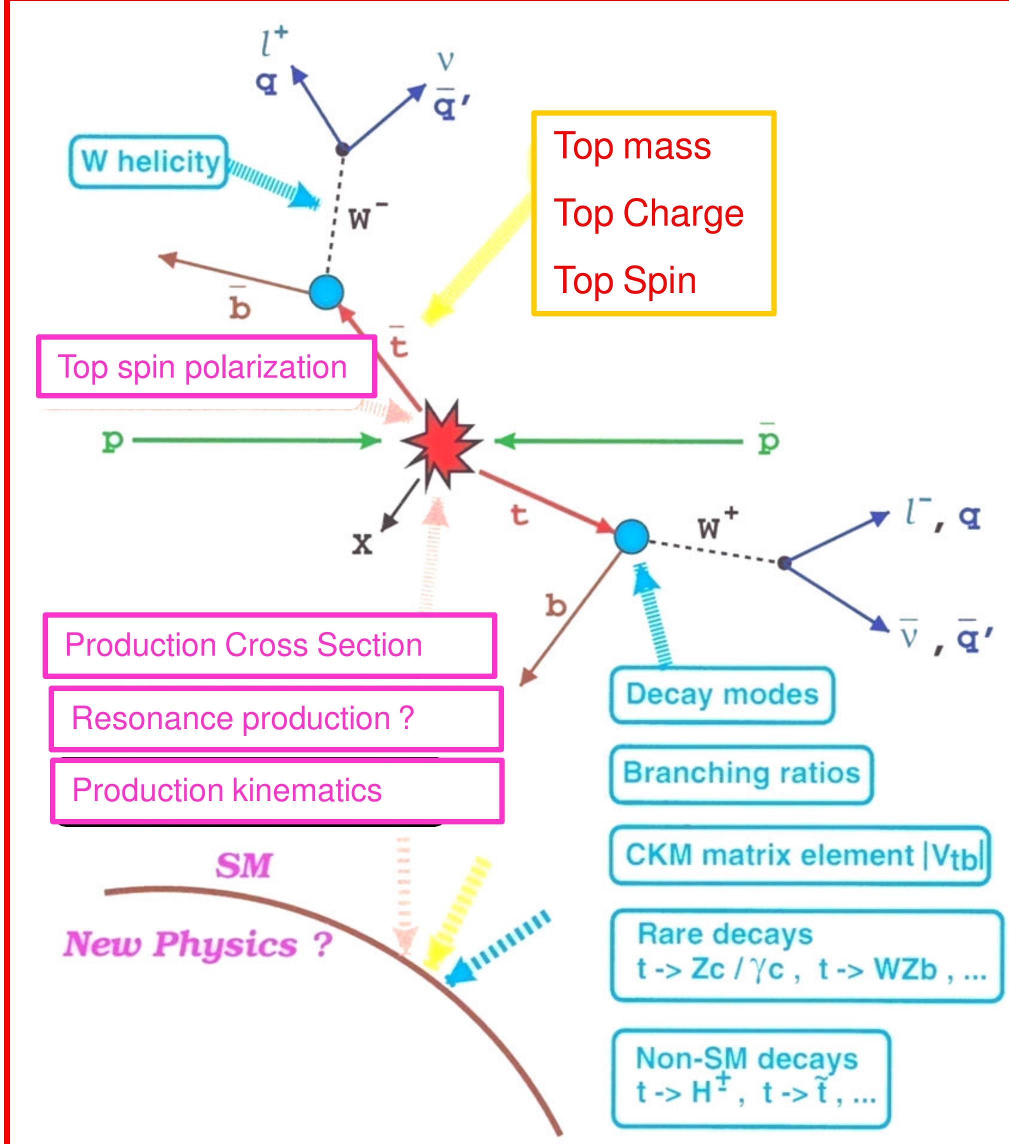
Tevatron Experiments



- Two general purpose detectors, CDF & DØ , capable of many different physics measurements
- Large international collaborations, 600+ members each

Why study the Top Quark?

- Top quark discovered in 1995 at Tevatron
- It is a very special particle:
  - ⇒ Heavier than all known particles
  - ⇒ Decays before hadronizing: Γ_{top}=1.5 GeV > ΛQCD
- Since then, many top studies performed to answer the question: is what we call "top quark" adequately described by the Standard Model?
- Still many open questions:
  - ⇒ Why is top so heavy ?
  - ⇒ Is top related to the EWSB mechanism?
  - ⇒ Is it the SM top?



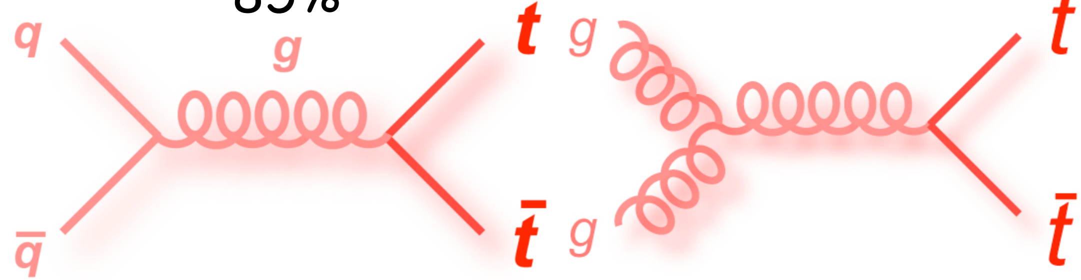
Top Quark Production at Tevatron

- QCD pair production

$\sigma_{NNLO} = 7.4^{+0.5}_{-0.7}$ pb
(for m_{Top}= 172.5 GeV)
JHEP 0809, 127 (2008)

~85%

~15%

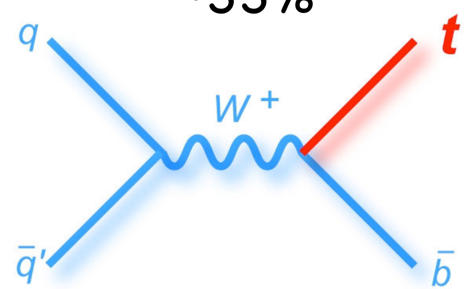


- EWK single-top production

➢ s-channel: σ_{NLO} = 0.9 pb
➢ t-channel: σ_{NLO} = 2.0 pb
(Both for m_{Top}= 175 GeV)
PRD 66, 054024 (2002)

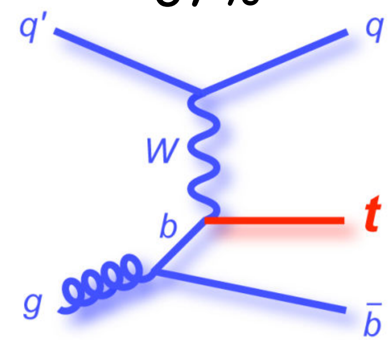
s-channel

~33%



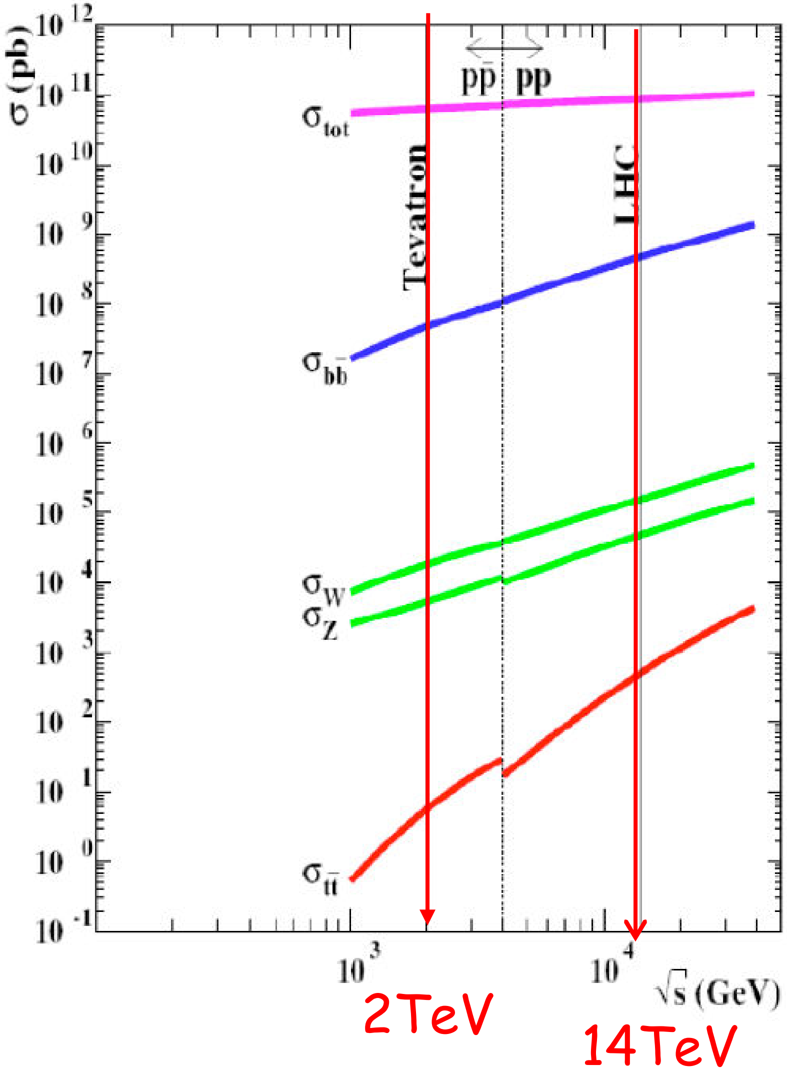
t-channel

~67%



- σ smaller than top pair production, but ➡ allows direct access to V_{tb} CKM matrix element: cross section ∝ $|Vtb|^2$

Top quark production at LHC

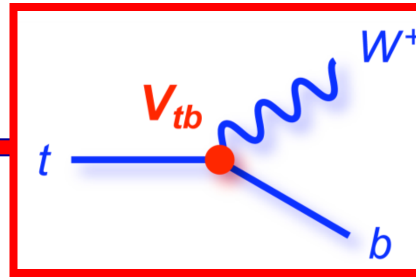


- Rare at Tevatron: One top pair per 10 billion inelastic collisions
- LHC @ 14TeV: σ(tt) ~ 850 pb (~10% qqbar, ~90% gg)

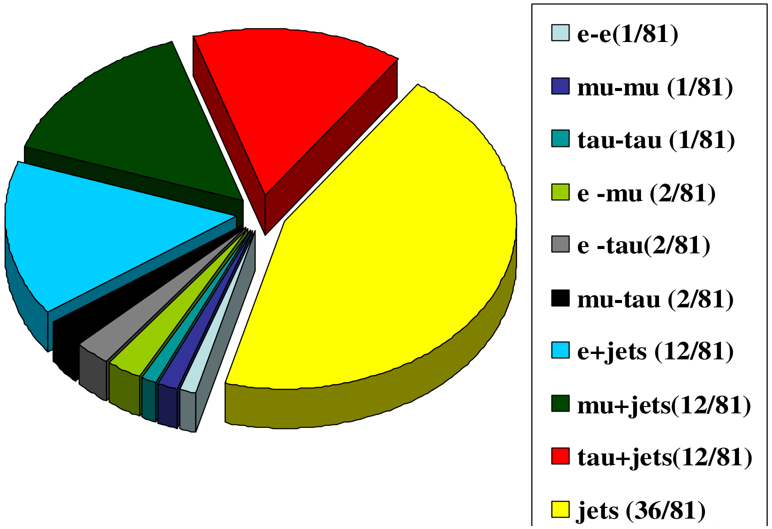
(x100 Tevatron) @ 14 TeV

- background ~ x10 Tevatron
- σ(tt) @ 10 TeV ~ 1/2 σ @ 14 TeV
  - ✓ Even in $100pb^{-1}$ @10 TeV O(50K) ttbar pairs
- LHC = "Top Factory"

Top Quark Decay



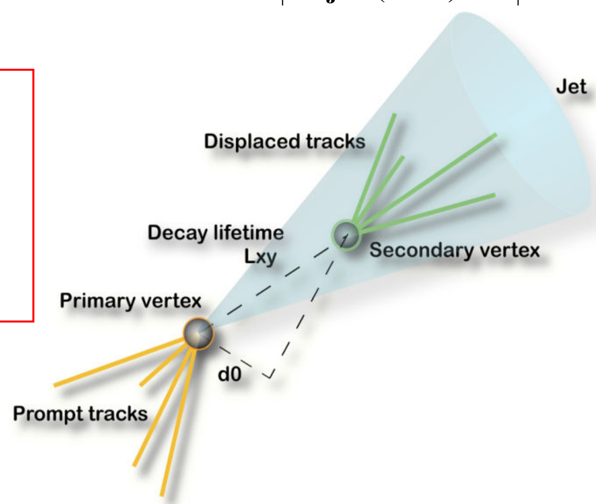
SM predicts BR($t \rightarrow Wb$) ≈ 100%



For ttbar pairs:
Event topology determined by the decay modes of the 2 W's in final state.

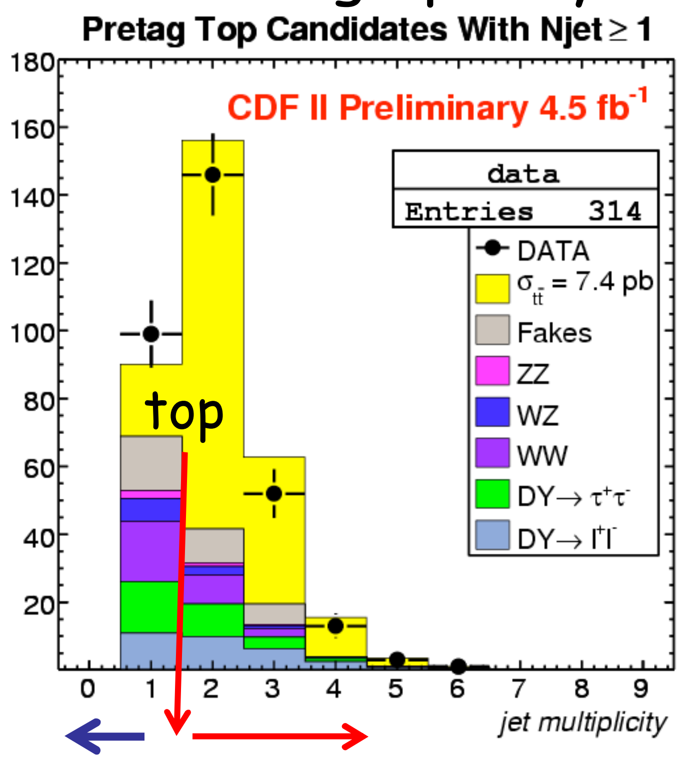
- Dilepton (ee, μμ, eμ)
  - ⇒BR = 5%, 2 high-P_T leptons + 2 b-jets + large missing-E_T
- Lepton (e or μ) + jets
  - ⇒BR = 30%, single lepton + 4 jets (2 from b's) + missing-E_T
- All Hadronic:
  - ⇒BR = 44%, six jets, no missing-ET
- τ_{had} +X
  - ⇒BR = 21%

Always b jets are present



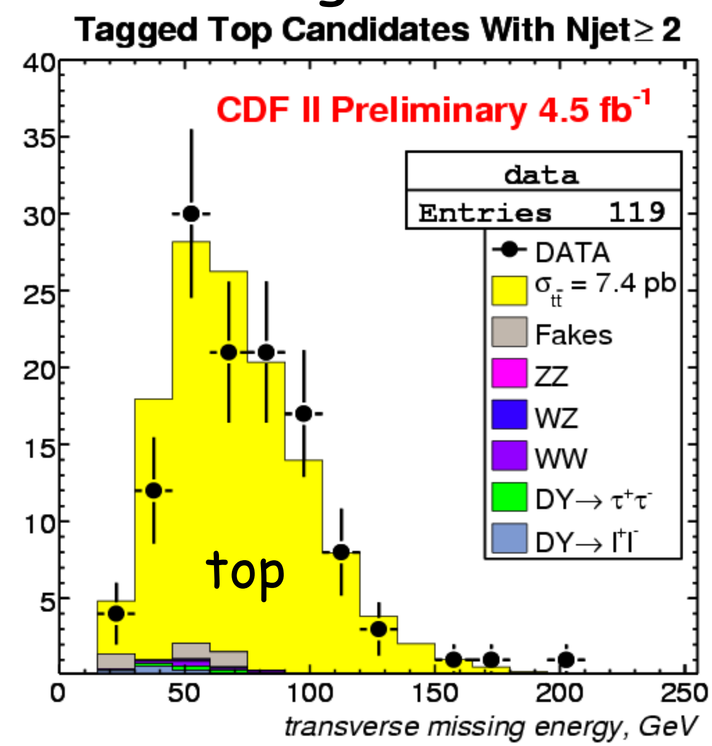
Top pair production: Dilepton Channel

High purity sample, good test of signal model



Control Signal region

Summer 2009



CDF (4.5 fb^{-1}, m_t= 172.5 GeV), b-tagged,
σ_{tt}(dil)=7.3 0.7(stat) 0.4(syst) 0.4(lum)pb

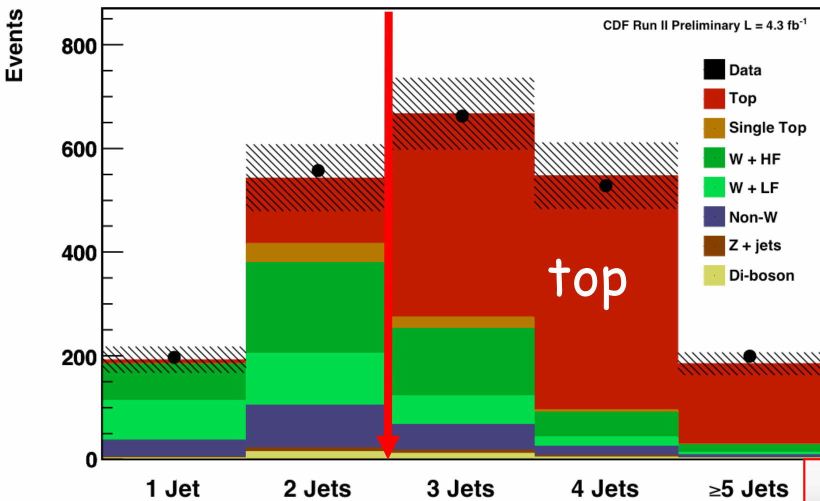
CDF (4.5 fb^{-1}, m_t= 172.5 GeV), pre-tagged,
σ_{tt} (dil)=6.6 0.6(stat) 0.4(syst) 0.4(lum) pb

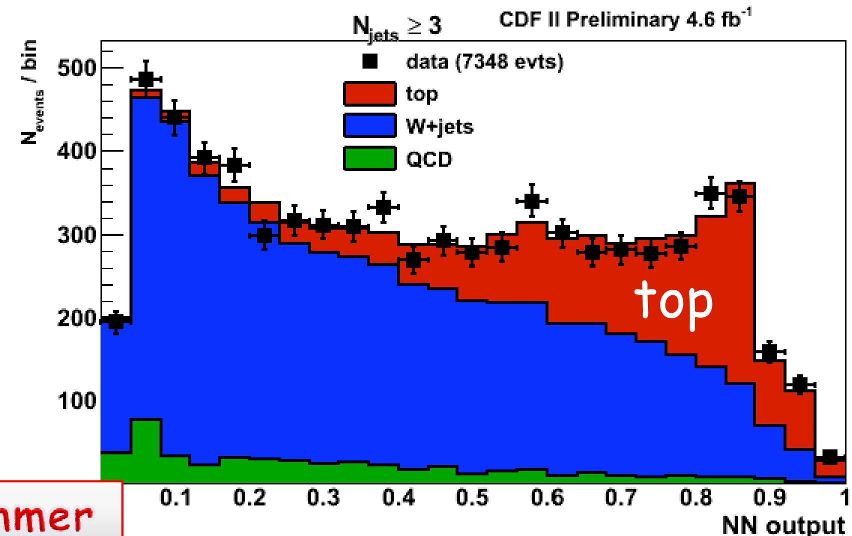
CDF Conf. Note 9890

Top pair production: Lepton +Jets

B-tagged sample, counting events

Pre-tagged sample, NN discriminant





Control — Signal region

Summer 2009

- Luminosity is the largest uncertainty in both measurements (6%)
  - Reduce by normalizing to the measured *Z cross section*
  - Measure R and multiply by Z cross section from theory: $\sigma_{tt} = R \bullet \sigma_Z^{theory}$

CDF (4.3 fb^{-1},m$_t$= 172.5 GeV), b-tagged:
σ_{tt}=7.1 0.3(stat) 0.6(syst) 0.1(norm)pb

CDF (4.6 fb^{-1},m$_t$= 172.5 GeV), pre-tagged
σ_{tt} =7.6 0.4(stat) 0.3(syst) 0.1(norm) pb

CDF Conf. Note 9878

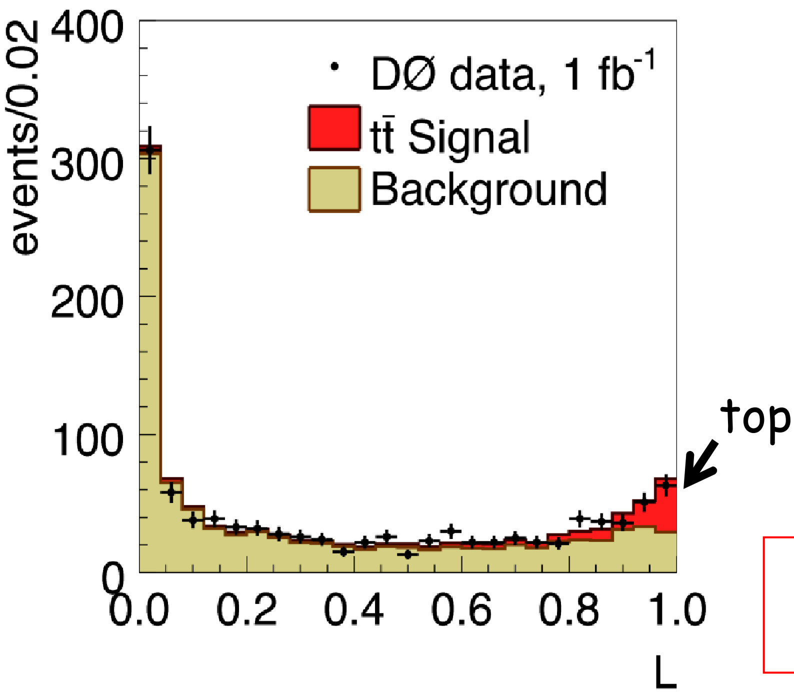
Top pair production: All Hadronic

Measurement in background dominated sample: background is hard to model:

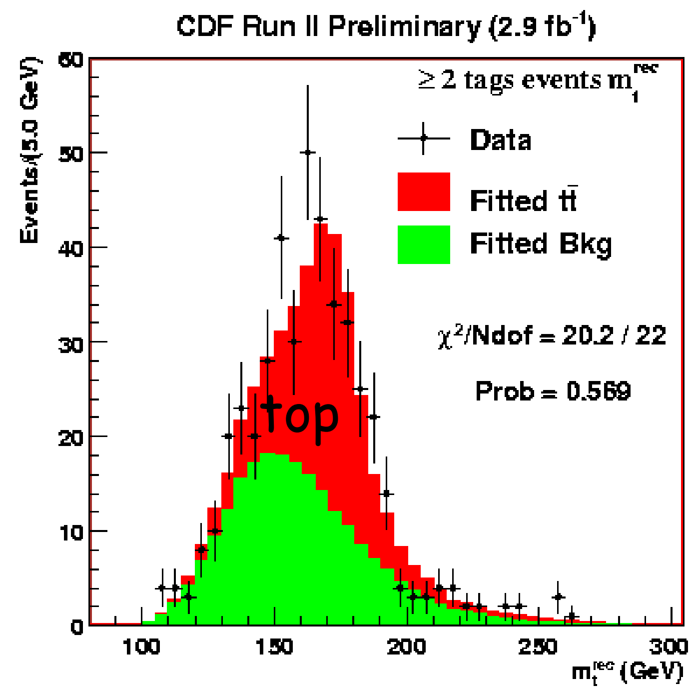
- Poorly known cross sections
- Data driven background model

D0 (1 fb^{-1}, m_t= 175 GeV):

σ_{tt} (had)=6.9   1.3(stat) 1.4(sys) 0.4(lum)pb



Summer 2009



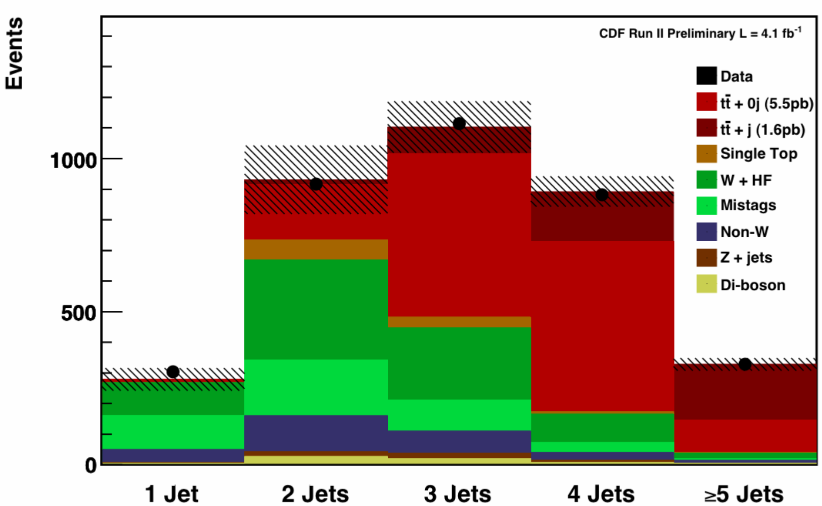
CDF (2.9 fb^{-1}, m_t= 172.5 GeV):

σ_{tt} (had)=7.2 0.5(stat) 1.5(syst) 0.4(lum)pb

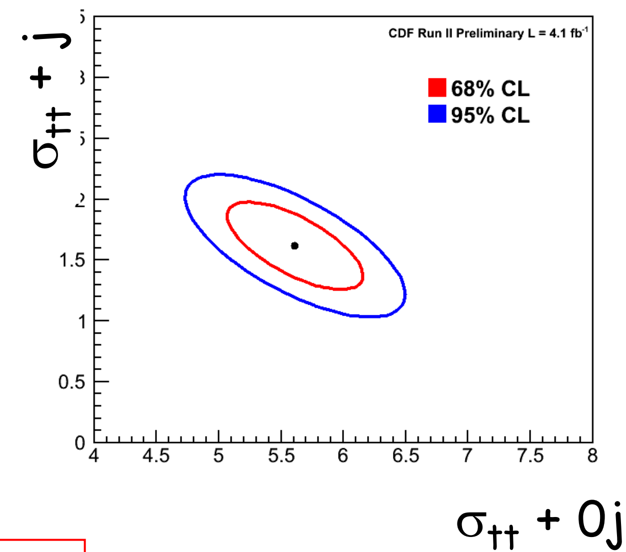
CDF Conf. Note 9841

t-tbar + jet Cross Section

- First σ measurement of t-tbar associated with an additional hard jet
- Important test of perturbative QCD
- Use b-tagged events in lepton + jets channel.
- Data-driven approach is used to predict the background content
- Standard model prediction $\sigma_{tt+j} = 1.79^{+0.16}_{-0.31}$ pb (arXiv:0810.0452v2)



Summer 2009

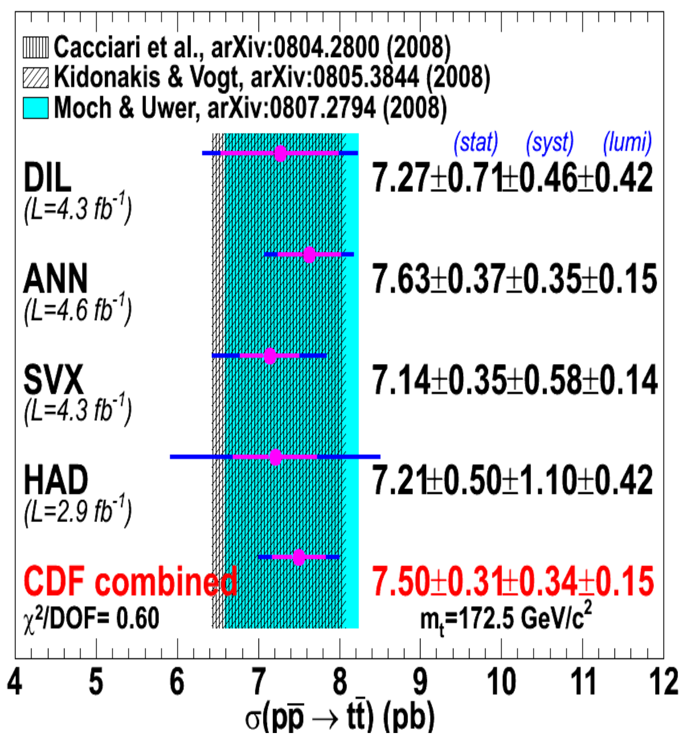


CDF (4.1 fb^{-1}, m_t= 172.5 GeV):
σ_{tt} (tt+j)=1.6 0.2(stat) 0.5(syst) pb

CDF Conf. Note 9850

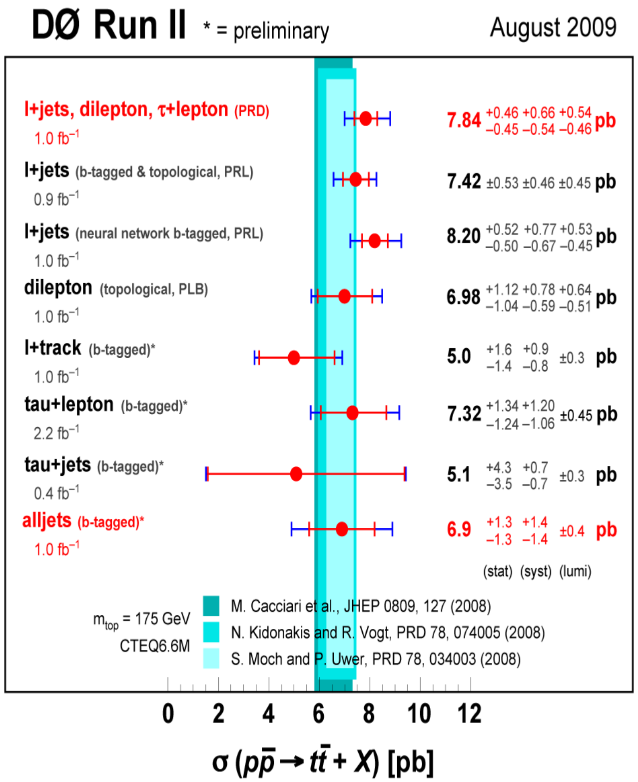
Measurements of σ_{ttbar}

- Experimental uncertainty: $\Delta\sigma/\sigma \sim 6.5\%$
- Dominant exp. uncertainties: b-tag accept., W+bjet background
- σ is measured in all final states: first step of any analysis studying the top quark properties.
- Tevatron combination underway



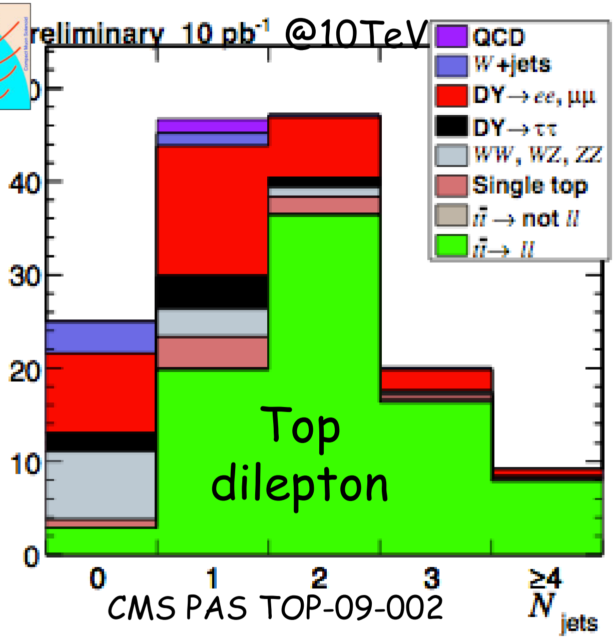
Summer 2009

Consistent across channels, methods, CDF/D0



$$\sigma_{tt} = \frac{N_{Data} - N_{Background}}{Acc \int L dt}$$

σ_{ttbar} measurement at LHC



Keep it as simple as possible on "day 1 "

'Rediscover' top quark with ~ 10 pb^{-1} @10TeV

100-200 pb^{-1} @ 10 TeV would be enough to

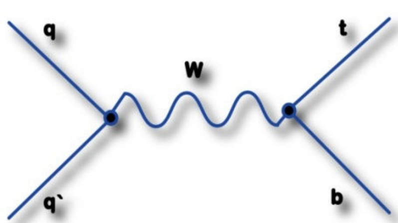
- Measure σ(ttbar) to better than 20%
- Determine the light jet energy scale to ~ 5%
- Determine the b-tagging efficiency

CMS: dilepton channel, no b-tagging, @10TeV, 10 pb^{-1}: $\Delta\sigma/\sigma$~20%

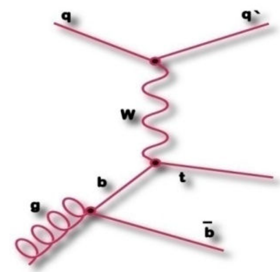
ATLAS: Expect $\Delta\sigma/\sigma$ ~ 17% for single lepton ch, no b-tagging, 100 pb^{-1} @14TeV

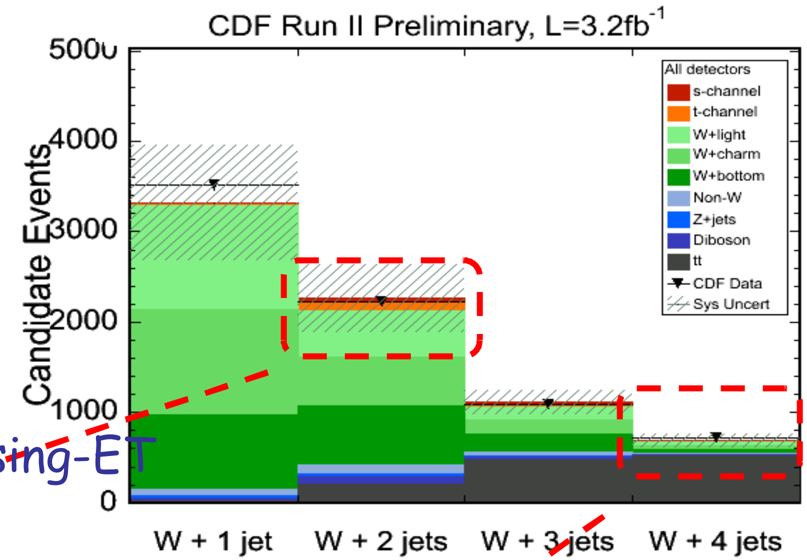
Single Top Production

s-channel



t-channel





s: 1 high-P_T lepton + 2 b-jets + missing-ET

t: 1 high-P_T lepton + 1 b-jet + 1 other jet + missing-ET

Single top hidden behind large backgrounds with large uncertainties
→Makes counting experiment impossible!
→s-channel single top has the same final state as WH→lνbb
→benchmark for WH Higgs search!

Top-pair has better s/b and very distinct final state:
→ Counting experiment after b-quark tagging 'fairly easy'

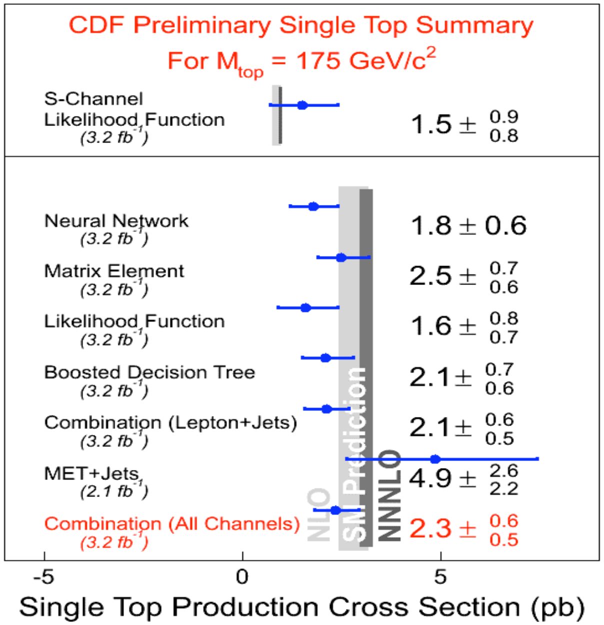
- Single top requires more sophisticated techniques: no single variable provides significant signal-background separation

⇒ Perform multivariate analysis (MV)

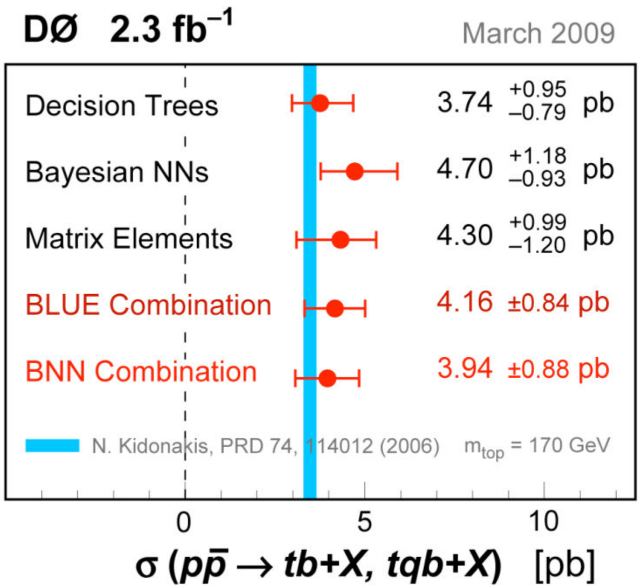
⇒ take advantage of small signal-background separation in many variables

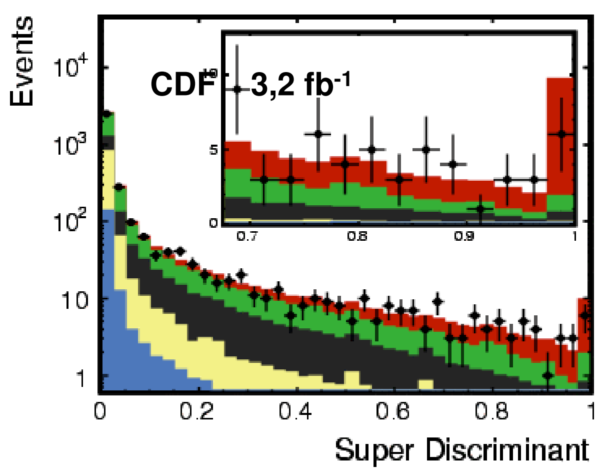
Single Top Observation

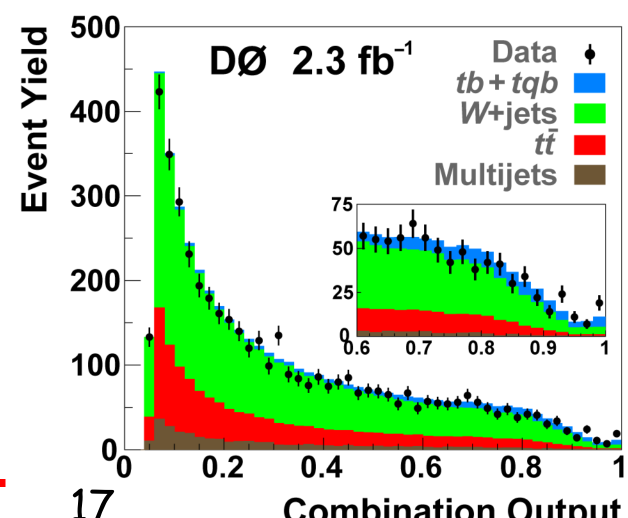
CDF and D0 both report >5σ observation March 2009



The various MV methods give consistent results





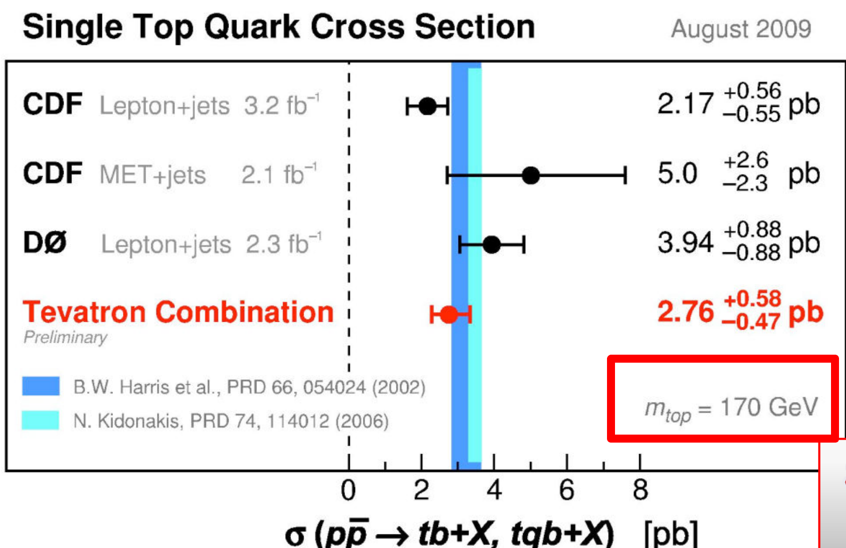


PRL 103, 092001
PRL 103, 092002
(2009)

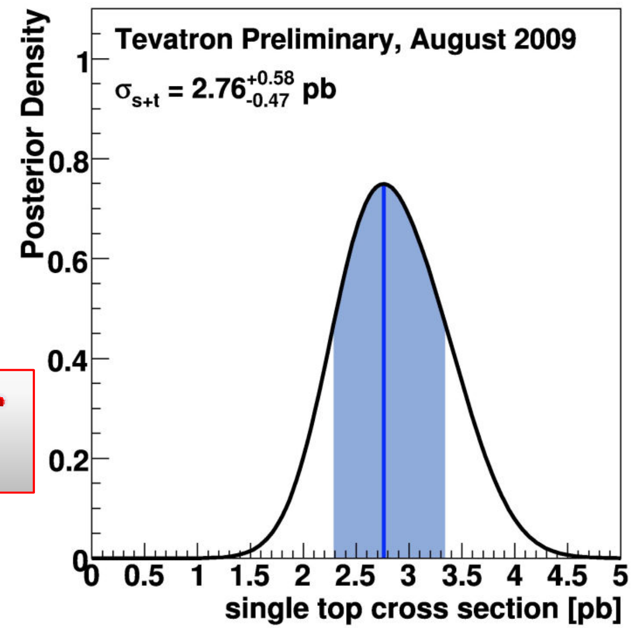
Single Top combination and direct V_{tb}

CDF and D0 combined their results using a Bayesian approach

(FERMILAB-TM-2440-E)



Summer 2009



Tevatron (3.2 fb^{-1}):

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

$\sigma_{\text{single top}} \sim \propto |V_{tb}|^2$

Assume:

1) $|V_{ts}|$, $|V_{td}|$ << $|V_{tb}|$

2) Pure V-A coupling

Best direct measurement of V_{tb}:

Tevatron (3.2 fb^{-1}):

$|V_{tb}|$=0.91   0.08 (stat+syst)

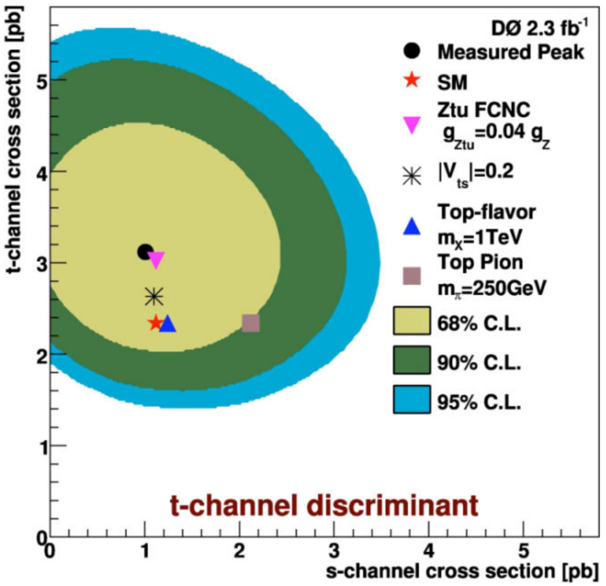
Using **PRD66 054024, 2002**

Single Top Channels

- Extract t-channel and s-channel contribution to single top signal

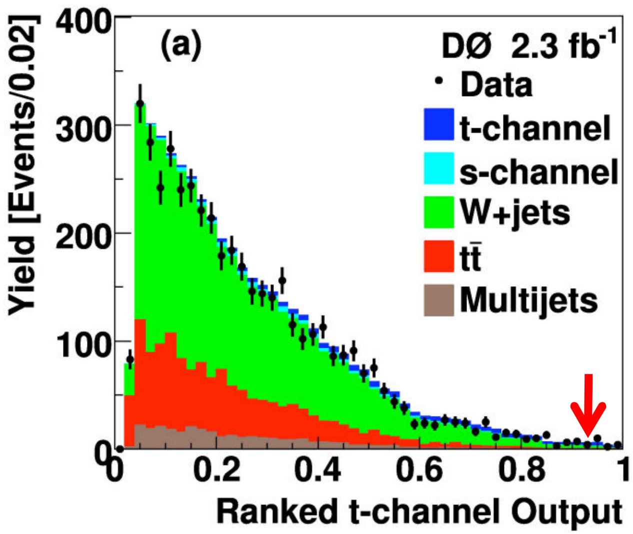
Summer 2009

- New physics scenario can affect single top channels differently.

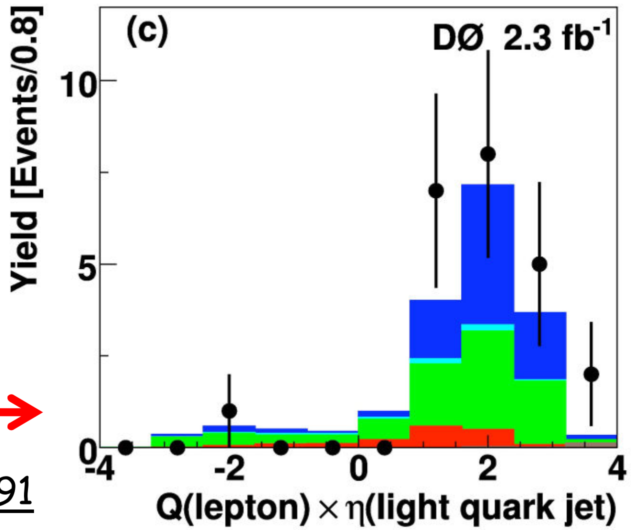


D0 (2.3 fb^{-1}):
σ_t(t-channel)=$3.14^{+0.94}_{-0.81}$(stat+syst)pb

Fermilab-Pub-09/372-E

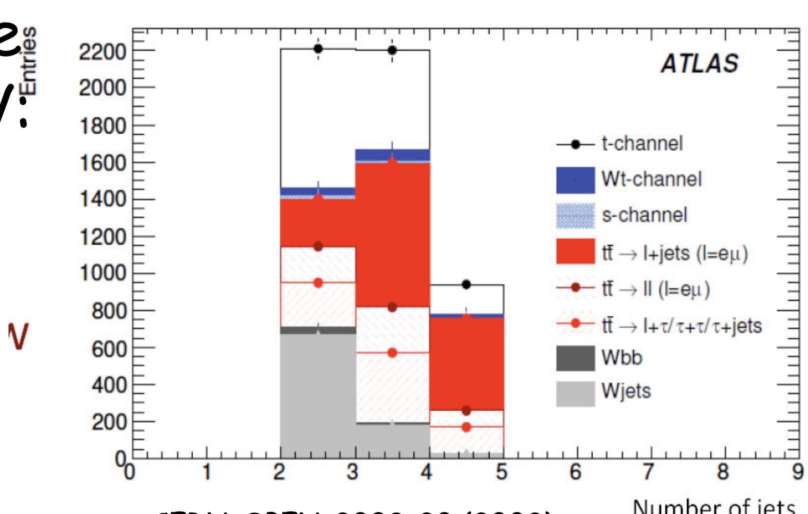


For Output > 0.91



Single top @ LHC

- Single top production will include associated production. At 14TeV:
  - ⇒ s-channel ~ 11 pb
  - ⇒ t-channel ~ 247 pb
  - ⇒ associated Wt ~56 pb PRD 63 034012 (2001)

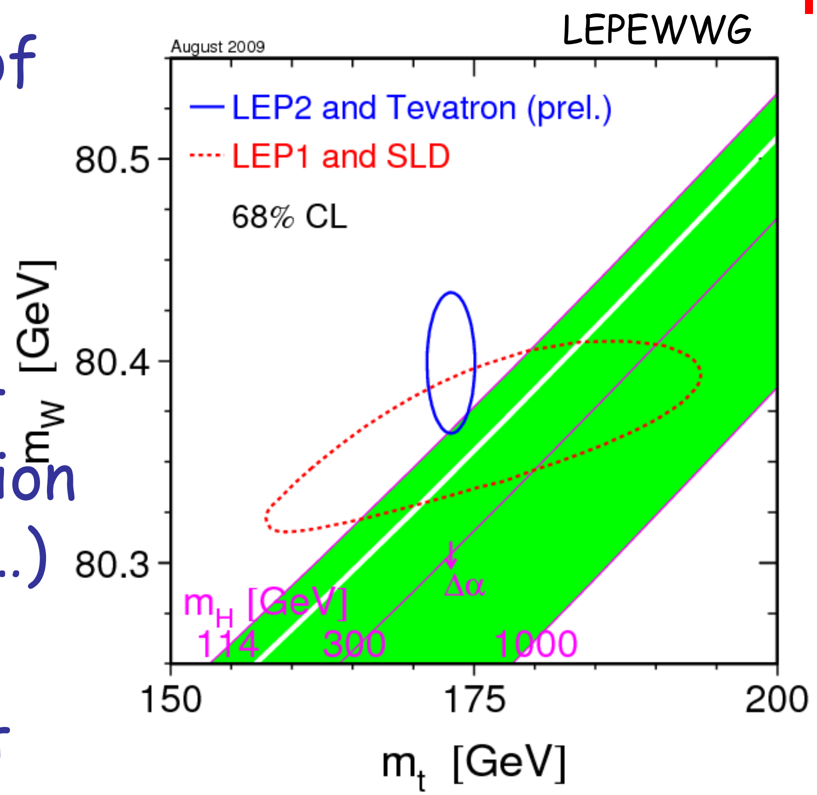


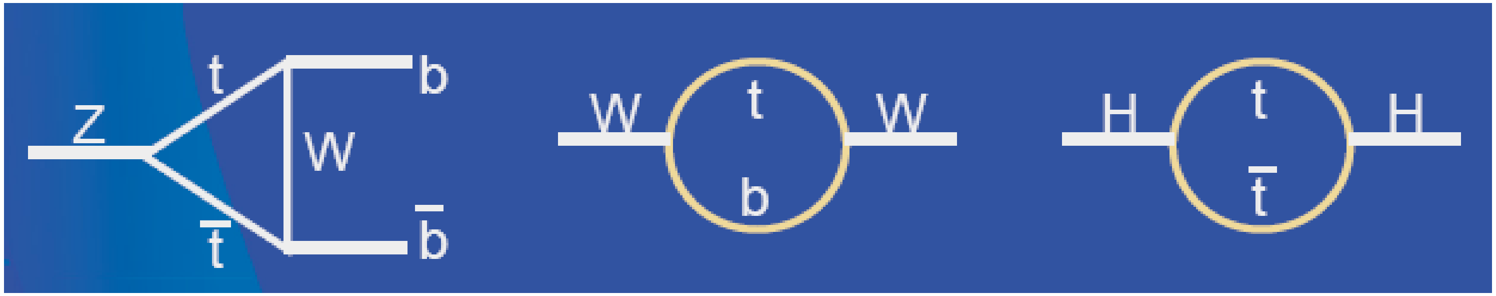
CERN-OPEN-2008-20 (2008)

- t-channel most sensitive one
- Requires b-tagging + MVA
- Precision measurements of properties of top in electroweak produced single top will be possible
- ATLAS with 1 fb^{-1} @14TeV: $\rightarrow \Delta|V_{tb}|/|V_{tb}| = 12\%$

Top quark mass

- M_{top} is a fundamental parameter of the Standard Model
- Since M_{top} is large, quantum loops involving top quarks are important to include when calculating precision observables (e.g. $\sin\theta_W^2$, R_b, M_W, …)
- Within SM, particularly important to help constrain M_H

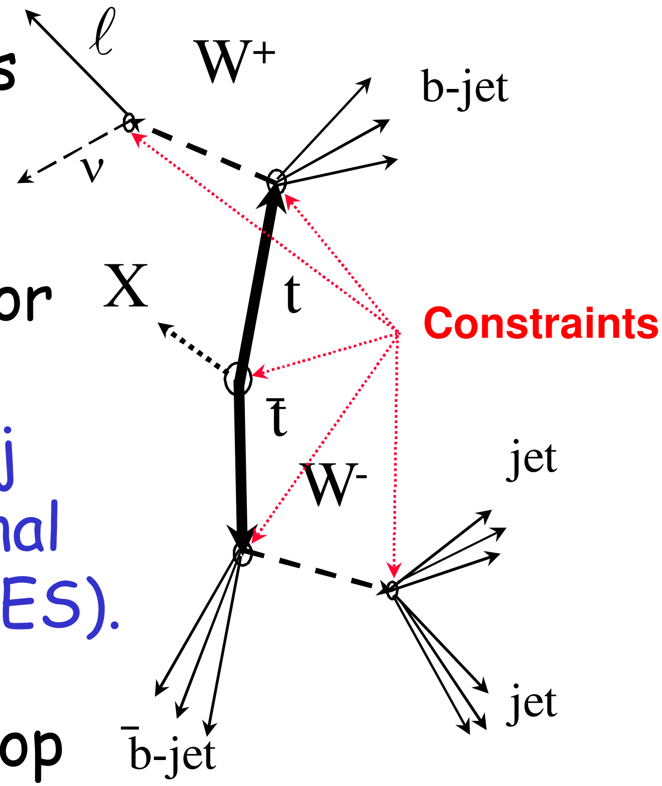




Top Quark Mass Measurements

Challenge is:

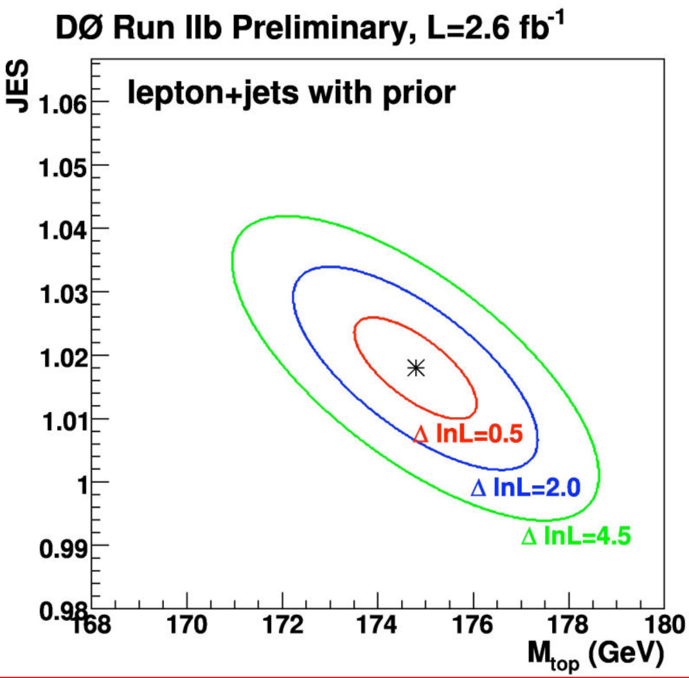
- Properly associate measured objects to initial state quarks and leptons (including neutrino)
- Extract best possible four-vector for each (jet energy scale is crucial!)
- The mass of the jet pair from W→jj (*'in situ'*) is used to obtain an internal constraint to the jet energy scale(JES).

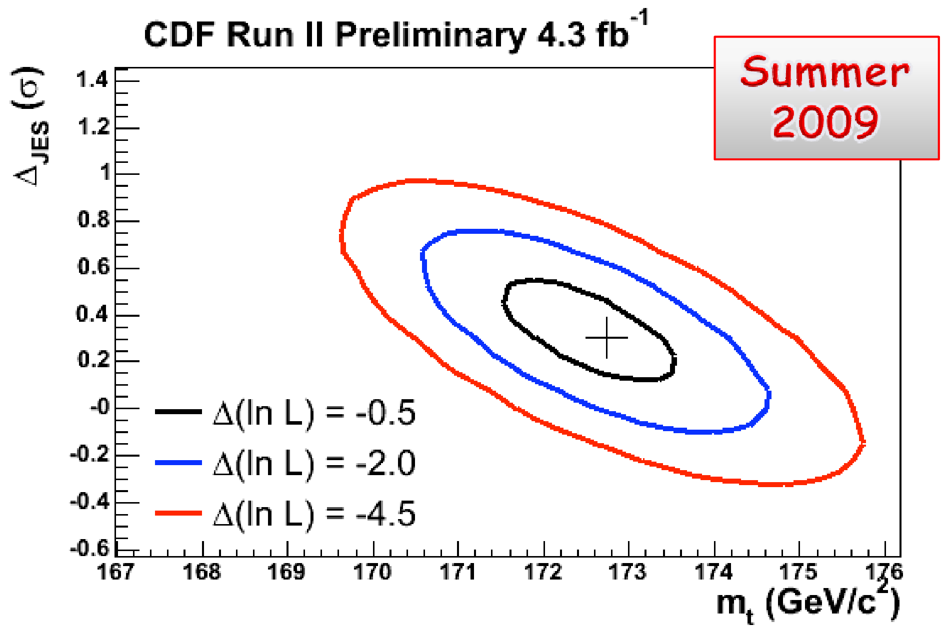


- Many Methods exist, most precise top mass from Matrix Element in ℓ+jets:
  - ⇒Use four-vectors of reconstructed objects
  - ⇒Calculate a probability per event to be signal or background as a function of the top mass
  - ⇒Product of event probabilities used to extract the most likely mass

Top mass: most precise single result

Matrix Element Technique in Lepton+Jets channel:





D0 (3.6 fb^{-1}):

m_t= 173.7 0.8(stat)0.8(JES) 1.4(syst) GeV

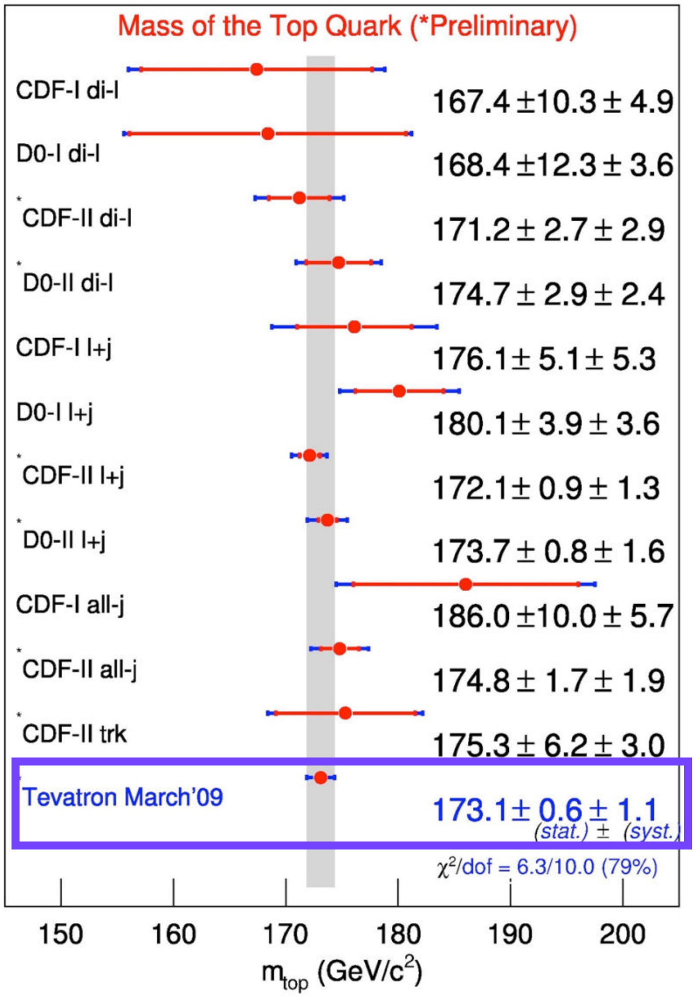
CDF (4.3 fb^{-1}):

m_t=172.6 0.9(stat) 0.7(JES)   1.1(syst) GeV

D0 note 5877-CONF

CDF Conf. Note 9880

Tevatron top mass measurements



Consistent across channels and methods

$$M_t^{world} = 173.1 \pm 0.6 \pm 1.1 \text{ GeV}/c^2$$

ArXiv:0903.0885

- ΔM_{top}(total) = 1.3 GeV/c^2 $\Delta M/M$ ~ 0.75 %
- Have surpassed Run II goal by a factor of >2
- Some of the systematic uncertainties limited by statistics of calibration control samples
- Ongoing work on improving systematics
- With full Run II data set could reach a total uncertainty of ΔM_{top}~1 GeV/c^2

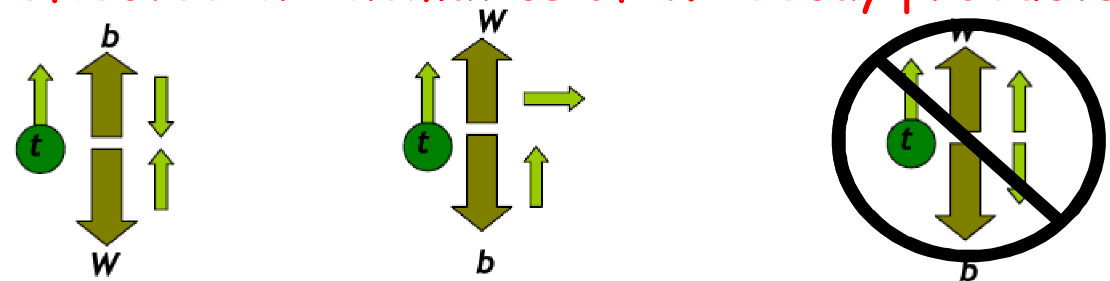
.

LHC: Predictions for 1 fb^{-1} @14TeV: ΔM_{top} =1 to 3,5 GeV if JES 1-5% (ATLAS)

W Helicity in top decay

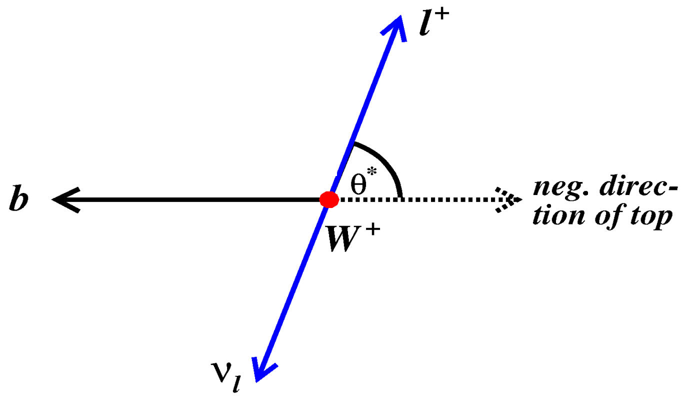
W helicity in top decays is fixed by M_{top}, M_W, and V-A structure of the tWb vertex. It is reflected in kinematics of W decay products.

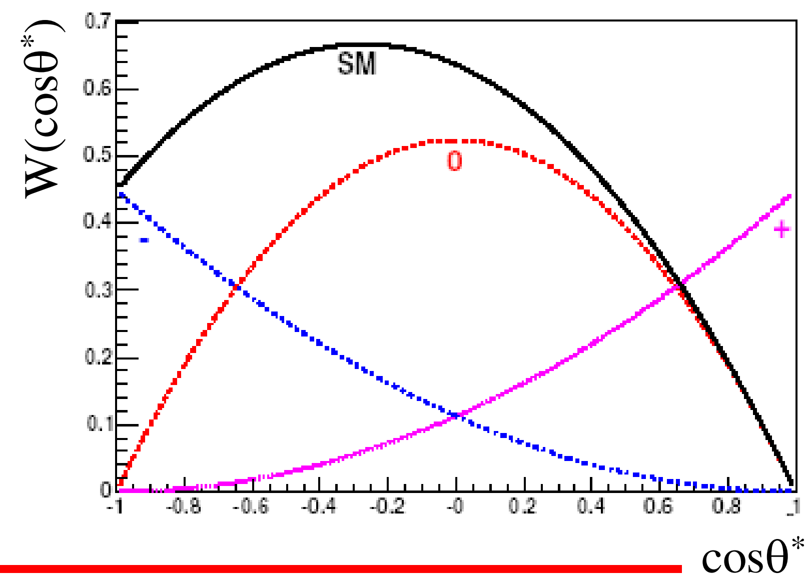
W helicity states:



	left-handed fraction: f_-	longitudinal fraction: f_0	right-handed fraction: f_+
In Standard Model:	**~30%**	**~70%**	**suppressed: ~0.036%**

⇒ Measure angular distribution of charged lepton wrt. top in W rest frame: $\cos\theta^*$





W Helicity in Top Decay

F_0 and F_+ are simultaneously fitted

CDF: combination of two cos θ* analyses with $1.9 fb^{-1}$:

F_0 = 0.66 ± 0.16 (stat) ± 0.05 (syst)

F_+ = -0.03 ± 0.06 (stat) ± 0.03 (syst)

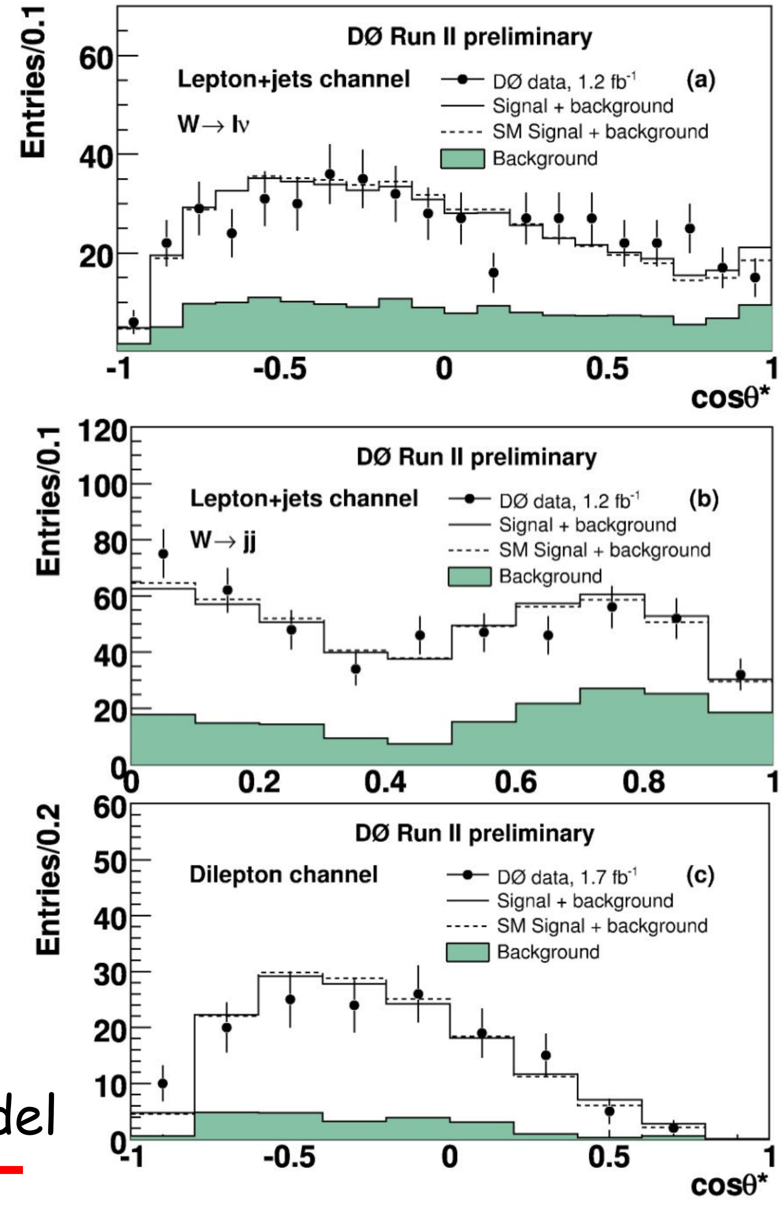
PLB 674 (2009) 160-167

DØ uses lepton + jets and dilepton events with up to $2.7 fb^{-1}$

PRL 100 (2008) 062004

F_0 = 0.49 ± 0.11 (stat) ± 0.09 (syst)

F_+ = 0.11 ± 0.06 (stat) ± 0.05 (syst)



Results consistent with the Standard Model

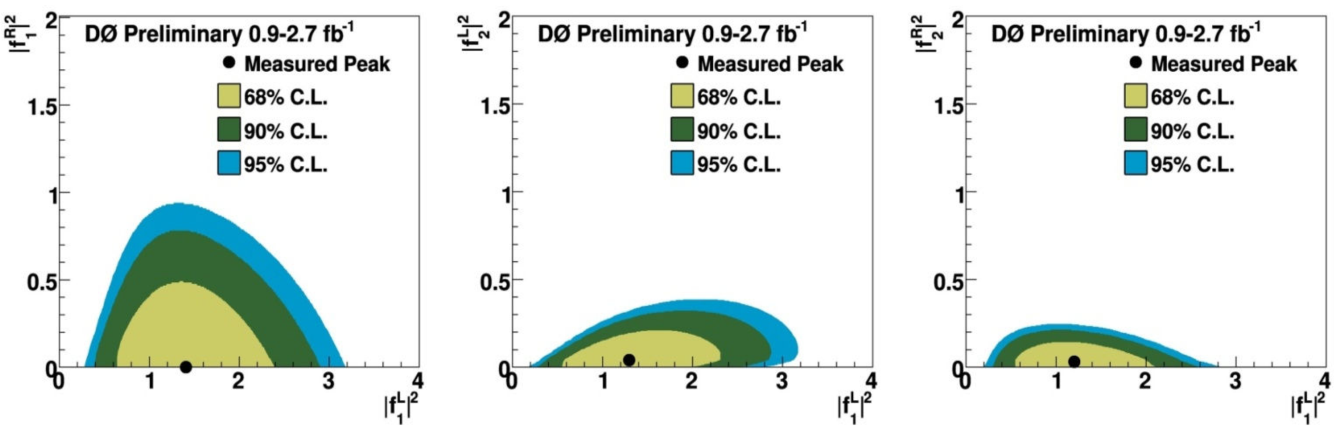
Generic W-t-b Coupling

- Constrain form factors for anomalous tWb coupling
  - ⇒ Combine information from single top production and W helicity measurement in ttbar decay

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

Standard Model predicts: $f_1^L = 1, \quad f_2^L = f_1^R = f_2^R = 0$

  - ⇒ Use all top samples to perform a general analysis of the vertex



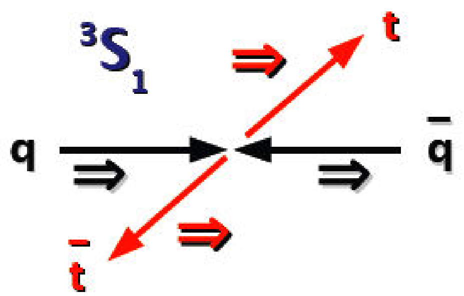
Consistent with Standard Model

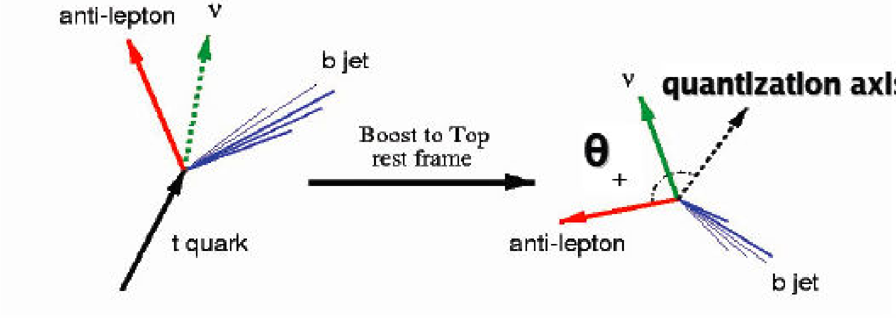
$$\text{for} \quad |f_1^L|^2 = 1 : \quad |f_1^R|^2 < 0.72, \ |f_2^L|^2 < 0.19, \ |f_2^R|^2 < 0.20 \ @ \ 95\% \ \ \text{CL}$$

D0 Note 5838-CONF

Top anti-Top Spin Correlations

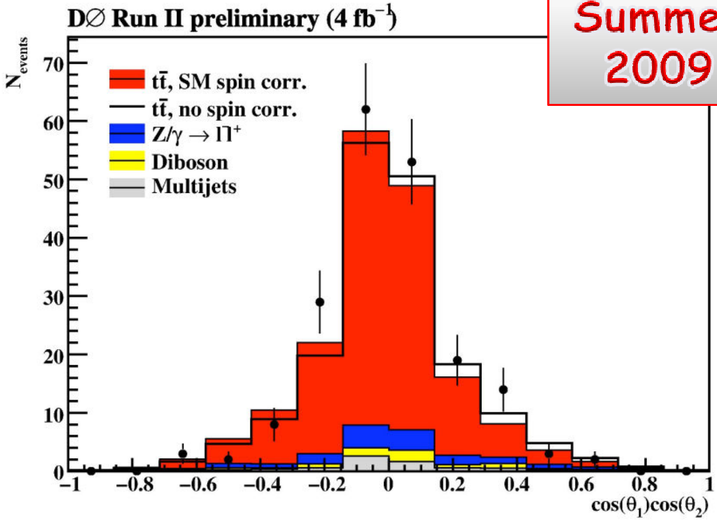
- Top spins are correlated only if top lifetime is short enough
- Information on the spin carried by the decay products





- First results from Run II (dilepton channel)

SM predicts κ=0.78
NPB690, 81 (2004)



Summer 2009

D0 (4 fb^{-1}):
$\kappa = -0.17^{+0.64}_{-0.53}$

Beam axis

CDF (2.8 fb^{-1}):
$\kappa = 0.32^{+0.55}_{-0.78}$

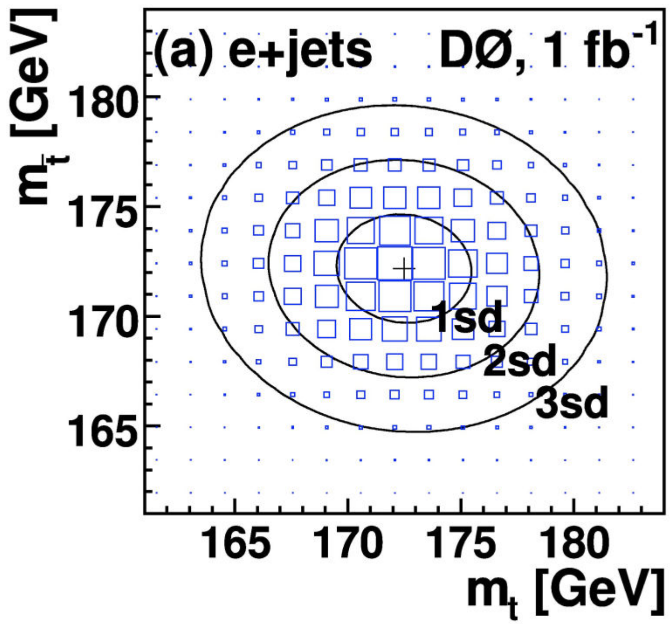
Off-diagonal axis

Agreement with SM within 2 σ (D0), 1 σ (CDF)

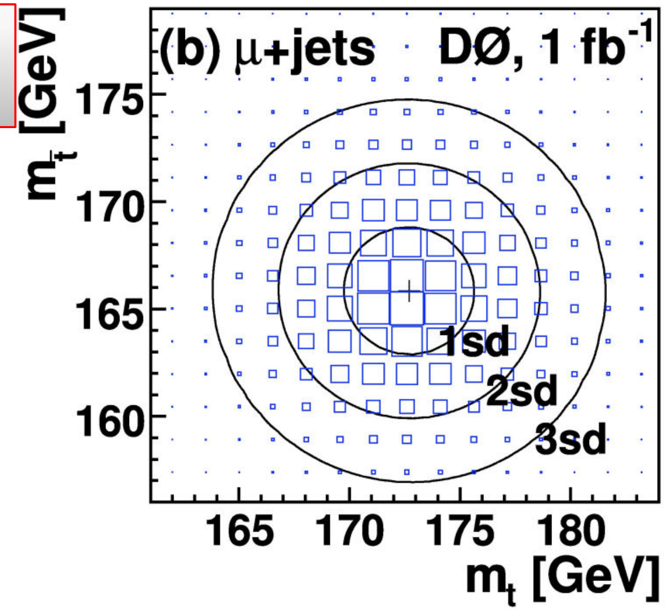
D0 Note 5838-CONF
CDF Conf. Note 9824

Top anti-Top Mass Difference

- Mass difference would imply *CPT-violation*
- First CPT measurement in the quark sector ('*bare quark*')
- Measured in lepton + jets events (ME technique) releasing constraint on $M_{top} = M_{antitop}$



Summer 2009



D0 (1 fb^{-1}):

Δm_t=3.8   3.7 GeV

arXiv:0906.1172v2

Consistent with SM expectations

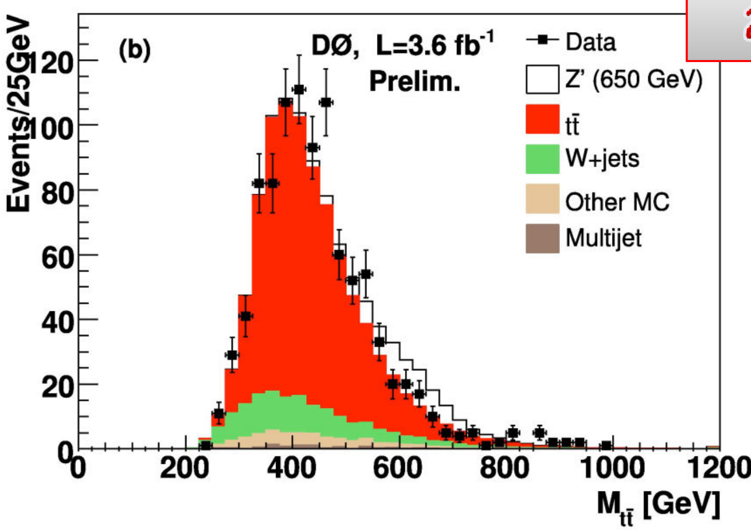
Search for Narrow Resonance in ttbar production

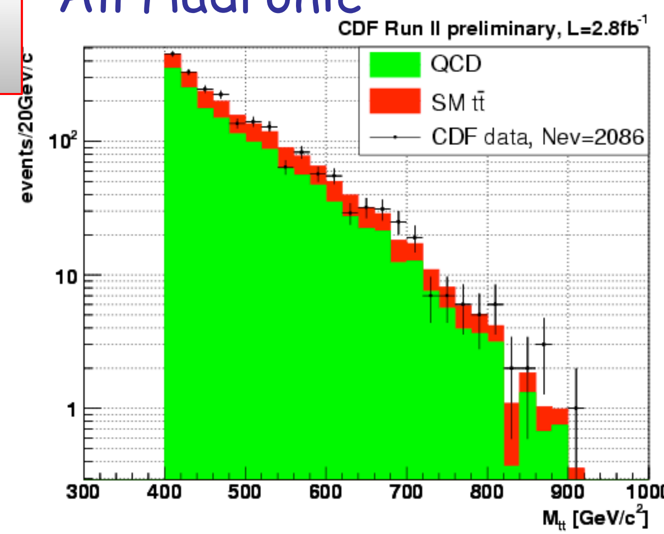
- Some 'new physics' models predict ttbar bound states
  - ⇒ Top color assisted technicolor with leptophobic Z′ (Phys. Rept. 317 (1999) 143)
- Search for 'bumps' in reconstructed M_{ttbar} spectrum
- Assume sufficiently narrow width (~1.3%) dominated by resolution

- Lepton+jets

Summer 2009

All Hadronic





D0 (3.6 fb^{-1}):
M(Z') > 820 GeV @95% C.L.

DØ Note 5882-CONF

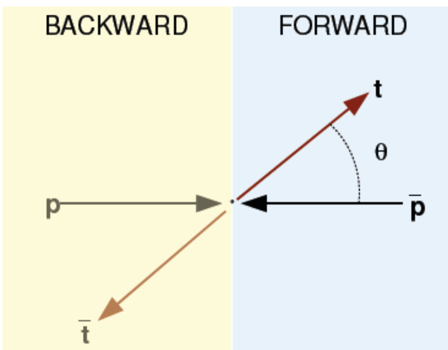
CDF (2.8 fb^{-1}):
M(Z') > 805 GeV @95% C.L.

CDF Conf. Note 9844

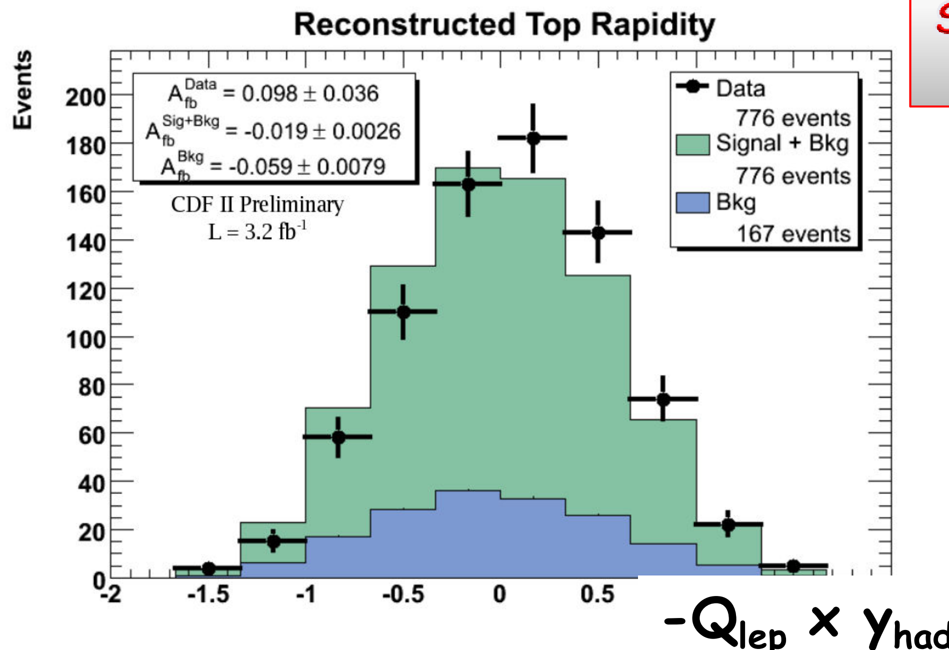
Forward-Backward Asymmetry

- New physics could give rise to an asymmetry (Z´ ,axigluons,..)
- SM predicts at NLO A_{fb}=0.05 ± 0.015 %

Summer 2009



$$A_{fb} = \frac{F - B}{F + B}$$



CDF (3.2 fb^{-1}):

A_{fb}=0.193 0.065 (stat) 0.024 (syst) %

CDF Conf. Note 9724

Agrees with SM within 2 σ

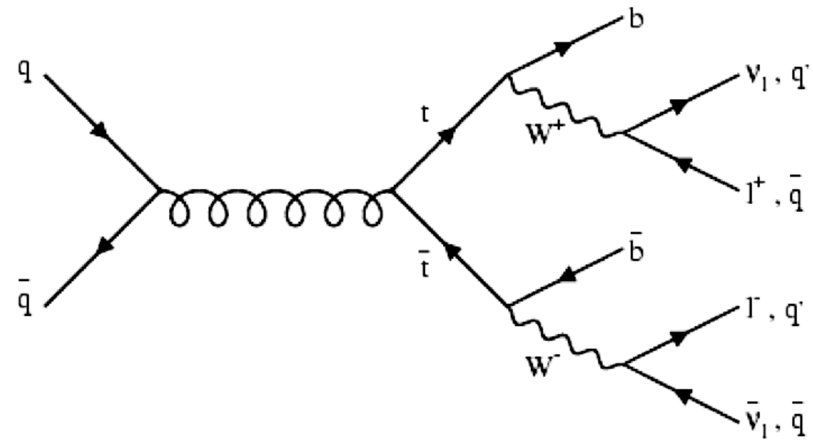
D0 (1.0 fb^{-1}):

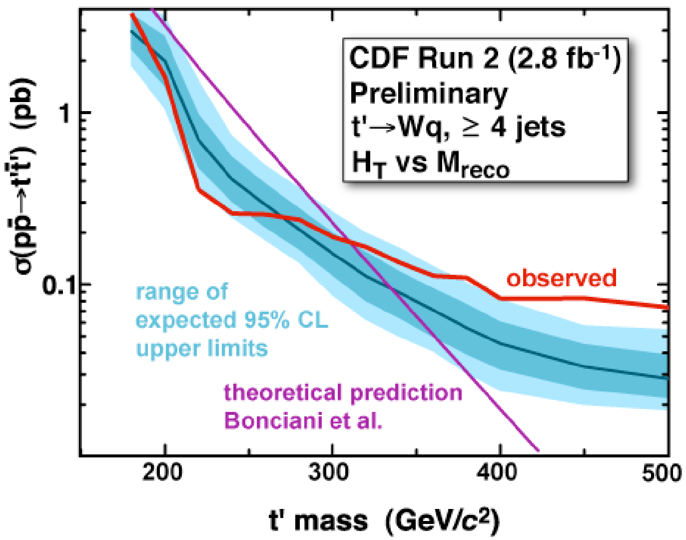
A_{fb} =0.12 0.08 (stat) 0.01 (syst) %

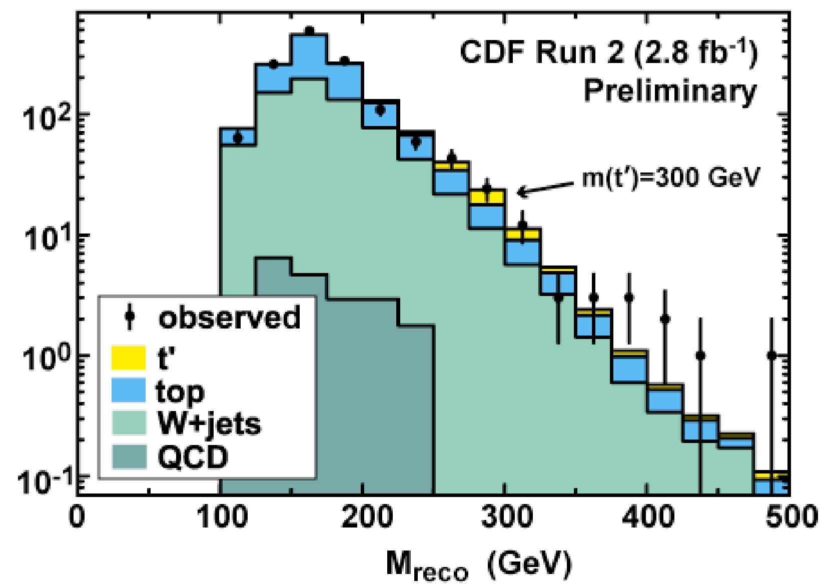
PRL 100, 062004 (2008)

Search for Heavy t′

- Heavy t′ production
  - ⇒ *suggested in 4th generation models, little Higgs, 2HD models, Beautiful mirrows etc.*
- <u>Search for t′ t′ -bar in Lepton + Jets</u>



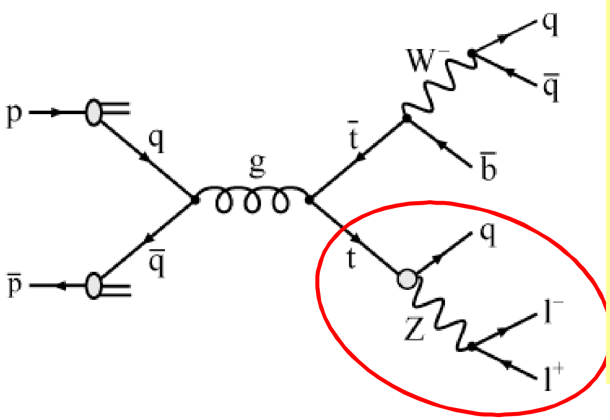




CDF (2.8 fb-1):
M(t′) > 311 GeV/c² at 95% C.L.

CDF Conf. Note 9446

Search for FCNC in Top-Decays: t-> Zq



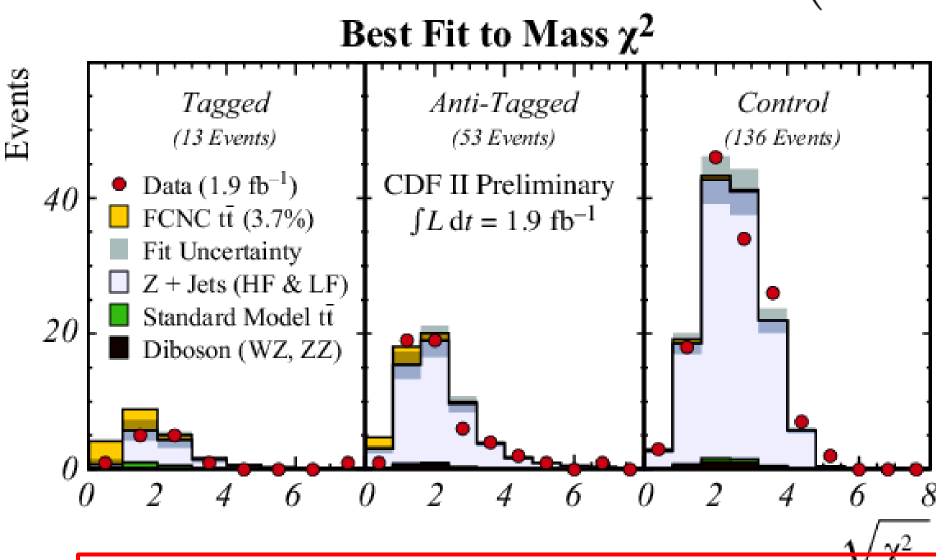
In SM FCNC strongly suppressed in the top sector: BR $\approx 10^{-14}$. signal = new physics

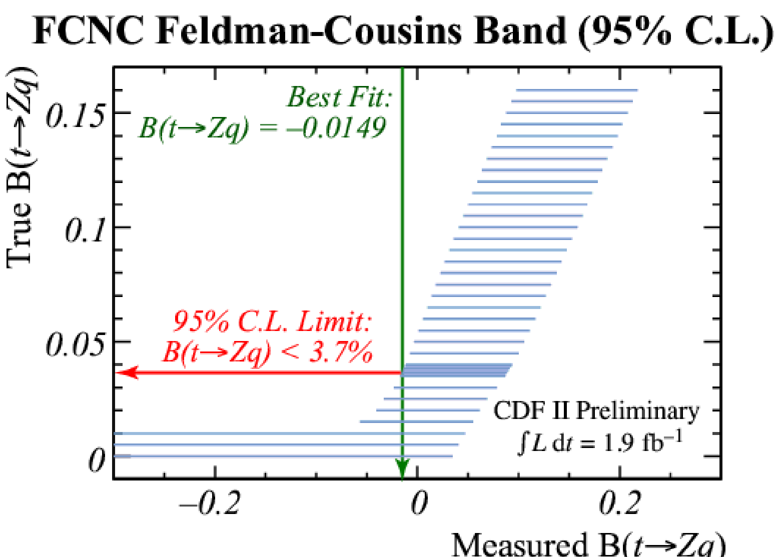
Look for t -> Zq decays

Select events: 4 jets + 2 leptons

Construct mass χ^2 to measure ttbar-likeness:

$$\chi^2 = \left(\frac{M_{qq} - M_W}{\sigma_W}\right)^2 + \left(\frac{M_{bqq} - M_t}{\sigma_{t\to qqb}}\right)^2 + \left(\frac{M_{Zq} - M_t}{\sigma_{t\to Zq}}\right)^2$$





BR(t → Zq) < 3.7% @ 95% C.L.

PRL 101, 192002 (2008)

Top Quark Properties Summary

Property	Run II Measurement	SM prediction	Luminosity (fb^{-1})
m_t	CDF: 172.6 ± 0.9(stat) ± 1.2(syst) GeV D0: 174.2 ± 0.9(stat) ± 1.5(syst) GeV Tevatron: 173.1±0.6(stat)±1.1(syst)GeV		4.3 3.6
σ_{ttbar} (@m_t=172.5 GeV) σ_{ttbar} (@m_t=170 GeV)	CDF: 7.50 ± 0.31 (stat) ± 0.34 (syst) ± 0.15 (lumi) pb D0: $7.84\ ^{+0.46}_{-0.45}$ (stat)$^{+0.66}_{-0.54}$ (syst) $^{+0.54}_{-0.46}$ (lumi) pb	7.4 ± 0.6 pb 8.06 +0.6 pb	4.5 1
$\sigma_{singletop}$ (@m_t=170 GeV)	Tevatron: $2.76\ ^{+0.58}_{-0.47}$ (stat+syst)	3.1±0.3 (PRD66 054024) 3.5± 0.2 (PRD74 114012)	3.2-2.3
$\lvert V_{tb}\rvert$ (@m_t=170 GeV)	Tevatron: 0.91 ± 0.08 (stat+syst)	1	3.2-2.3
σ(gg->ttbar)/σ(qq->ttbar)	D0: 0.07+0.15-0.07(stat+sys)	0.18	1
$m_t - m_{tbar}$	D0: 3.8 ± 3.7 GeV	0	1
σ(tt→ll)/σ(tt→l+jets)	D0: $0.86\ ^{+0.19}_{-0.17}$ (stat+syst)	1	1
σ(tt→τl)/σ(tt→ll + l+jets)	D0: $0.97\ ^{+0.32}_{-0.29}$ (stat+syst)	1	1
$\sigma_{ttbar+jets}$ (@m_t=172.5 GeV)	CDF: 1.6 ± 0.2 (stat) ± 0.5 (syst)	1.79+0.16 -0.31 pb	4.1
cτtop	CDF: 52.5μm @ 95%C.L.	10^{-10} μm	0.3
Γtop	CDF: <13.1 GeV @ 95%C.L.	1.5 GeV	1
BR(t->Wb)/BR(t->Wq)	CDF: >0.61 @ 95% C.L. D0: $0.97\ ^{+0.09}_{-0.08}$ (stat+syst)	1	0.2 0.9
F_0	CDF: 0.62 ± 0.11 D0: 0.490 ±0.106 (stat) ±0.085 (syst)	0.7	2 2.7
F_+	CDF: -0.04 ± 0.05 D0: 0.110 ±0.059 (stat) ±0.052 (syst)	0.0	2 2.7
Charge	CDF: - 4/3 excluded with 87% C.L. D0: 4e/3 excluded at 92% C.L.	2/3	1.5 0.37
Spin correlations	CDF: κ = 0.32 + 0.55 - 0.78, -0.46 < K < 0.87 @ 68%C.L. D0: $\kappa = -0.17\ ^{+0.65}_{-0.53}$ (stat + syst)	$0.78\ ^{+0.027}_{-0.022}$	2.8 4.2
Charge asymmetry	CDF: 0.19 ± 0.07(stat) ± 0.02(syst) % [illegible]	0.05 +- 0.015	3.2 [illegible]

Summary and Outlook

- Top quark production and decay are currently being studied at Tevatron
  - ⇒ So far top quark seems to be standard model top quark
    - ✓ ttbar cross section known to 6.5% (better than theory!)
    - ✓ Mass measured to < 0.8% precision
  - ⇒ Single top quarks have been observed!
    - ✓ Most precise direct determination of V_{tb} to date

- Tevatron expects to double data sets if running through 2011

- LHC will open up a new era of Top physics ⇒Top factory
  - ✓ With 100 pb^{-1} cross section can be measured with < 20% precision
  - ✓ Studies of other top properties and the Wtb vertex require good detector understanding and 1-10 fb^{-1} to reach maturity

- <u>Tevatron's top physics program and understanding of systematic effects will continue to play a significant role for years to come</u>

For more information:

- Top Physics Results from the Tevatron:

http://www-cdf.fnal.gov/physics/new/top/top.html

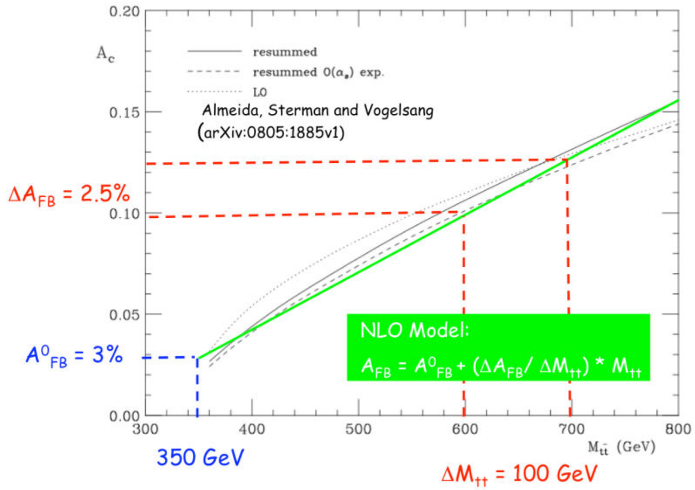
http://www-d0.fnal.gov/Run2Physics/WWW/results/top.htm

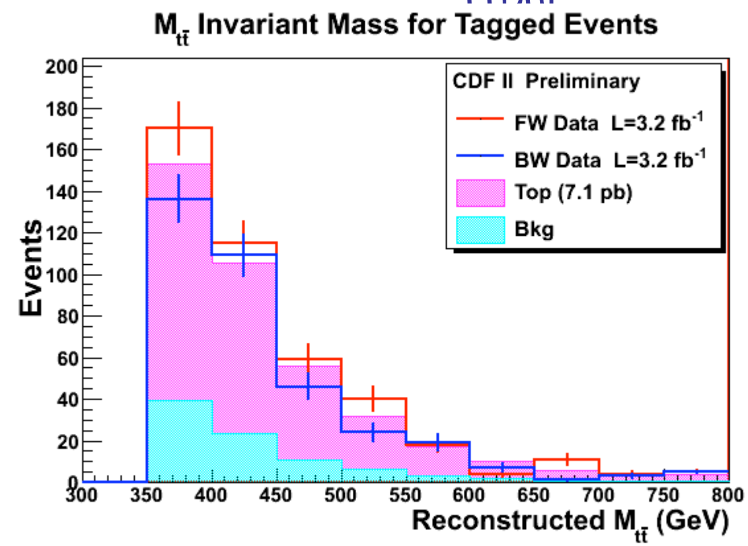
- Top Physics at the LHC:

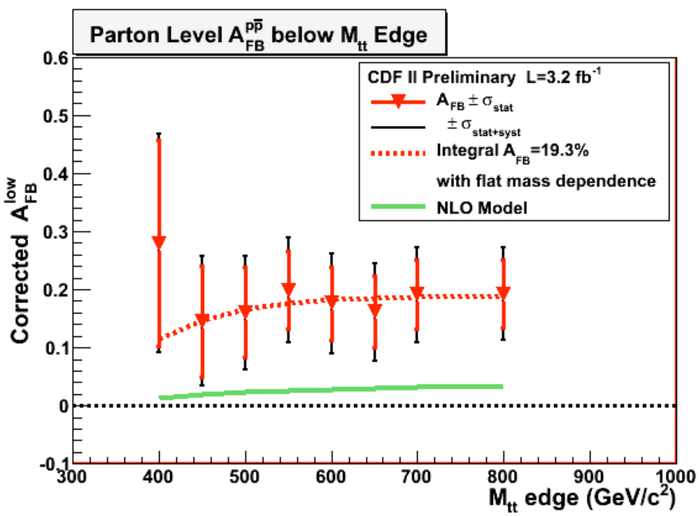
⇒See S. Mehlhase talk in DG1

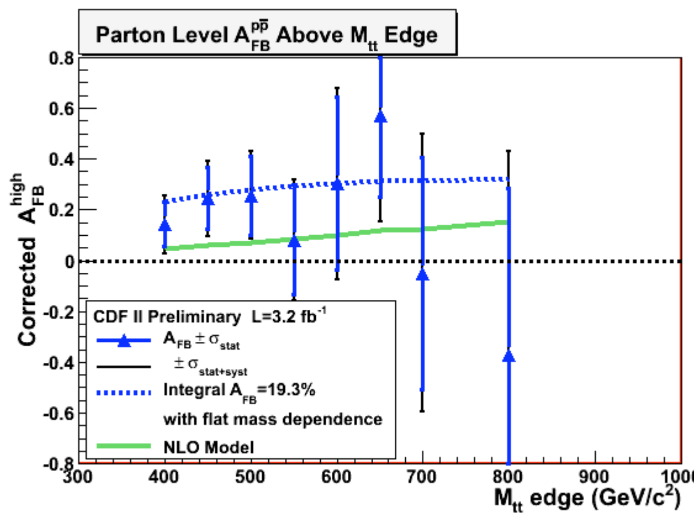
A_{fb} vs M_{ttbar} mass

- Scan for A_{fb} asymmetries for 8 different M_{ttbar} thresholds









Top Branching Ratio

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

Is there room for $t \to W + q_x$ decay ?

We measure R from the ratio of events with 0,1,2 b-tags

$$R \equiv B(t \to Wq)/B(t \to Wb)$$

$$= 0.97^{+0.09}_{-0.08} \quad \text{(D0)}$$

$$= 1.12^{+0.27}_{-0.23} \quad \text{(CDF)}$$

Assuming three generations and the unitarity of the CKM matrix, the denominator is unity, and we estimate |Vtb| > 0.78 at 95% C.L. (CDF)