Top Quark: discovery, present and future

Chasing the Top Quark

Gell-Mann, Zweig uds quarks postulated ('64)
GIM mechanism requires charm quark ('70)
1974: discovery of the charm quark (SLAC,BNL)
1977: discovery of the b quark at FNAL

1984: PDG says
JADE: forward-backward asymmetry in b-$\bar{b}$
gives weak isospin= -1/2 for the b quark
CLEO, PETRA: no FCNC observed

top should exist

Searches at Tristan, PETRA, SPPS, SLC : top not found.

TOP HADRON SEARCHES

→ 1984 PDG partial listing

TE		SEARCH FOR TOP HADRON PRODUCTION IN (E+ E-) COLLISONS					
TE	A	NONE ECM=22-31.6 GEV	BARTEL1	79	JADE	R	
TE	B	NONE ECM=22-31.6 GEV	BARTEL2	79	JADE	<S>	
TE	C	NONE ECM=31.6 GEV	BARBER	79	MRKJ	R,<S>,<T>	
TE	D	NONE ECM=22-31.6 GEV	BERGER	79	PLUT	R,<S>,<T>,MU	
TE	E	NONE ECM=30-36 GEV	BARBER	80	MRKJ	R,<T>,MU	
TE	F	NONE ECM=12-31.6 GEV	BERGER	80	PLUT	MU	
TE	G	NONE ECM=33-35.8 GEV	BARTEL	81	JADE	MU	
TE	H	NONE ECM=14-36.7 GEV	BRANDELIK	82	TASS	R	
TE	I	NONE ECM < 38.54 GEV CL=.99	ADEVA1	83	MRKJ	R,<T>,(MU+MU-X)	
TE	J	NONE ECM < 38 GEV	ADEVA2	83	MRKJ	PT(MU),<T>	
TE							
TE			COMMENTS				
TE		ALL ABOVE MEASUREMENTS ARE DONE AT DESY-PETRA. THE LAST COLUMN					
TE		SPECIFIES MEASURED QUANTITIES.					

Rev. Mod. Phys., Vol. 56, No. 2, Part II, April 1984

Top search at the Tevatron

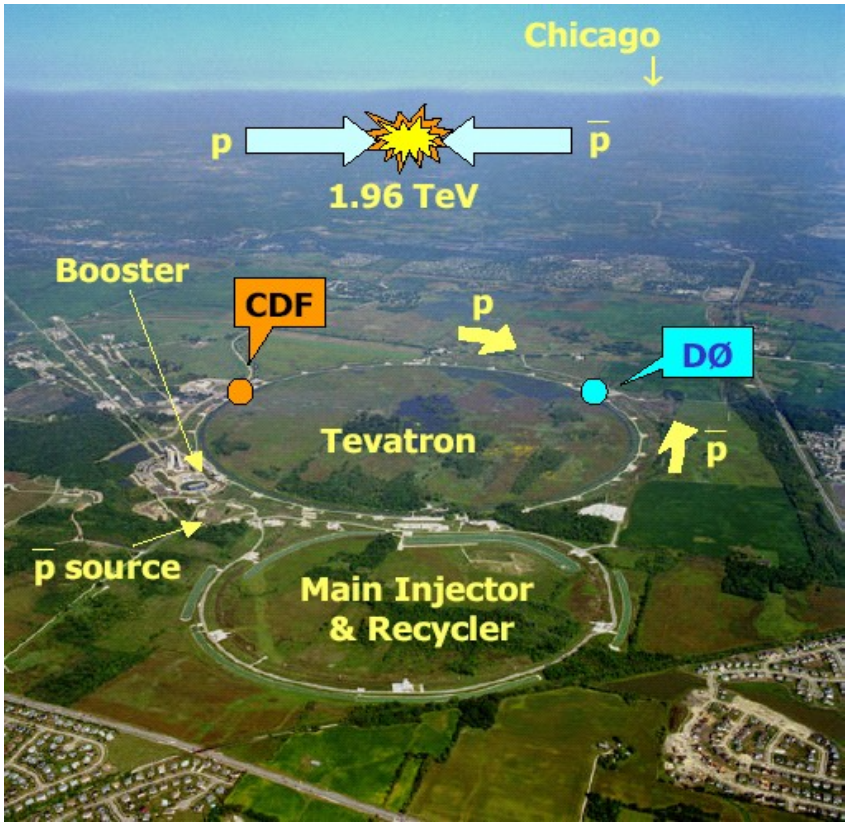
Top mass limit kept going up:

Petra (Desy)	> 23.3 GeV/c^2		1984
Tristan (KEK)	> 30.2	"	1990
SppS(CERN)	> 45.0	"	1984
SppS(CERN)	> 69.0	"	1990
CDF (FNAL)	> 77.0	"	1991
CDF (FNAL)	> 91.0	"	1992

At this point (1992) it is clear that top decays into a real W

Tevatron $\bar{p}$-p collider starts in 1985. $\sqrt{s}$=1.8 TeV. Top should be there

Present Tevatron Configuration



Tevatron Upgrades in 2001:

Main injector and recycler added.
Energy upgrade to 1.96 TeV.
Luminosity upgrade to > 10^{32}

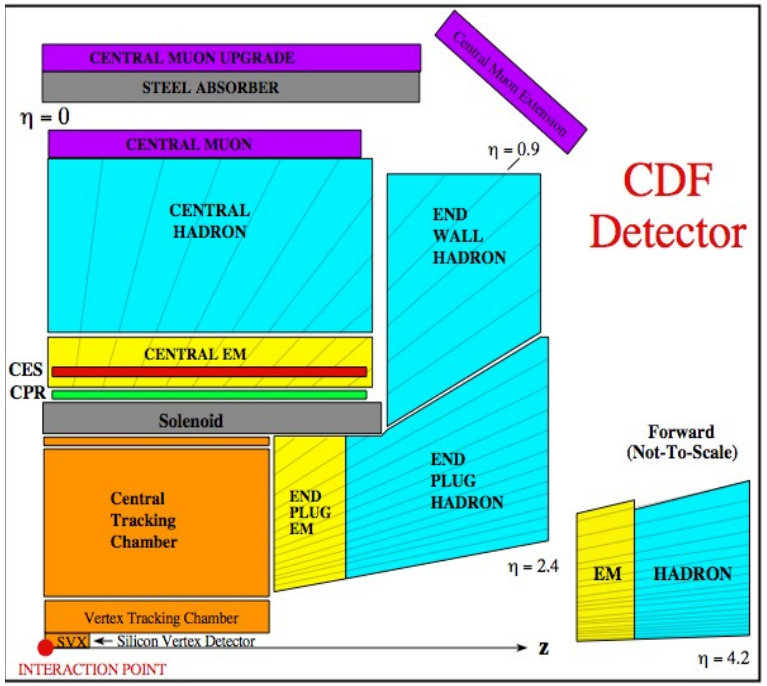
Tevatron Run I Detectors

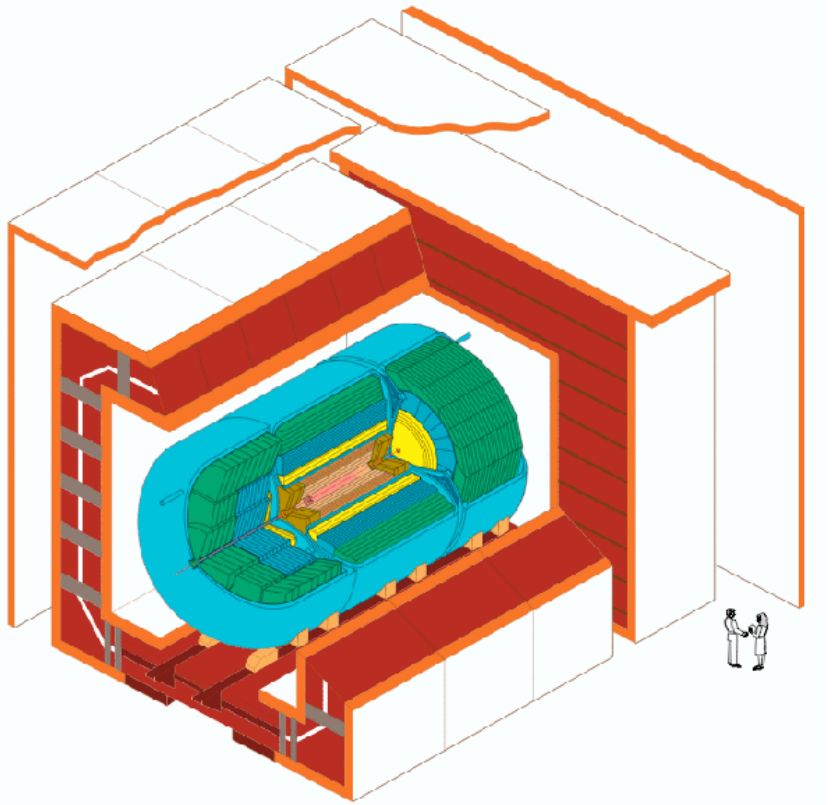
CDF detector in 1992

- Large radius CTC (B=1.4T)
- Silicon detector (4 layers)
- Limited muon coverage
- Calorimeter to |η| < 4.2

DØ detector in 1992

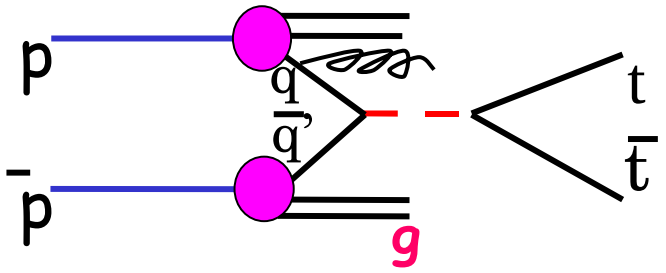
- Compact detector
- Finely segmented calorimeter to |η| < 4.2
- No magnetic field
- Muon Spectrometer to |η|<3



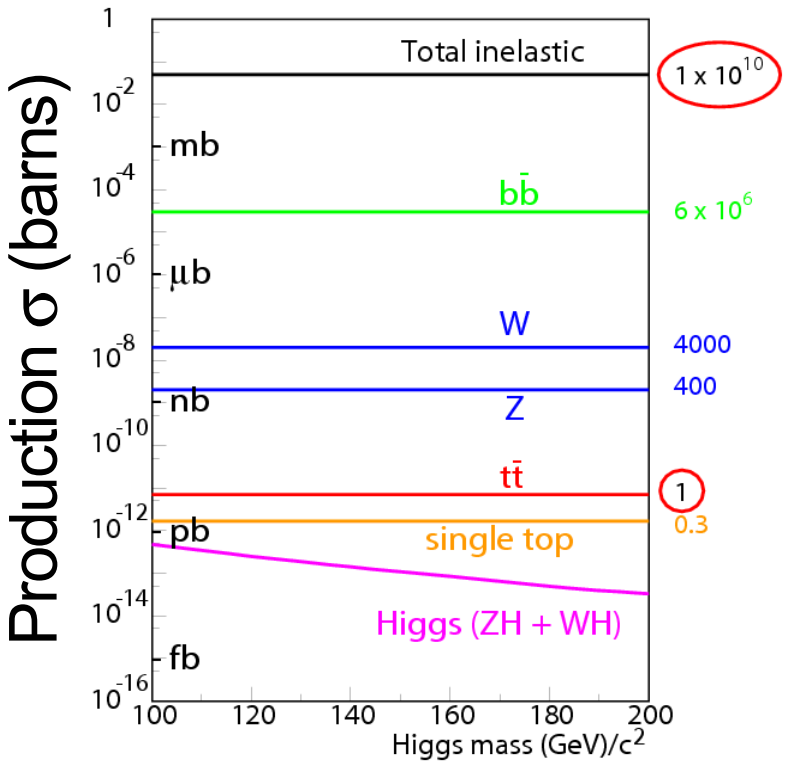


Top Production and Decay

$t\bar{t}$ Production at the Tevatron:



85%



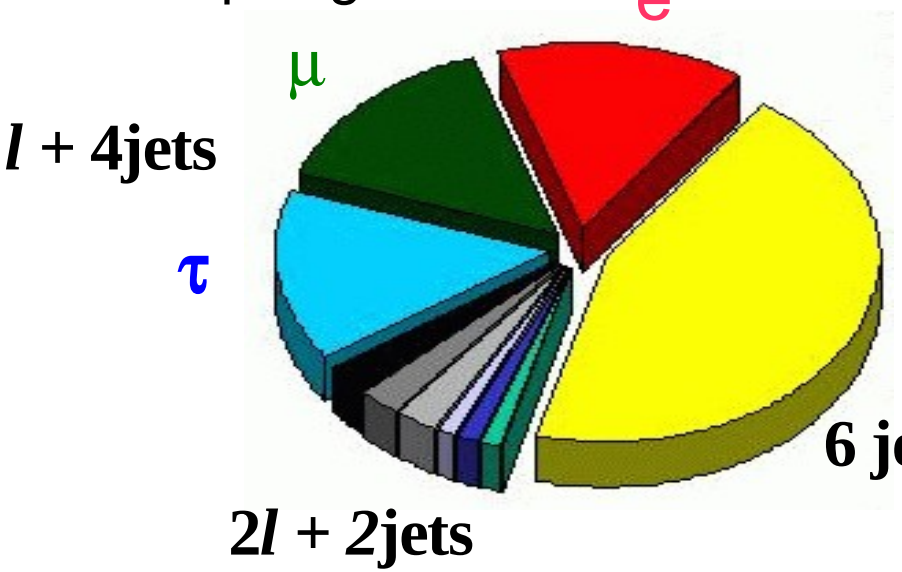
Top is heavy: decays very fast!

$$t\bar{t} \rightarrow W^+ \bar{b}\, W \bar{b}$$

$\Gamma(t \rightarrow Wb) \sim 1.5$ GeV, $t = 4 \times 10^{-25}$ sec

No hadronization

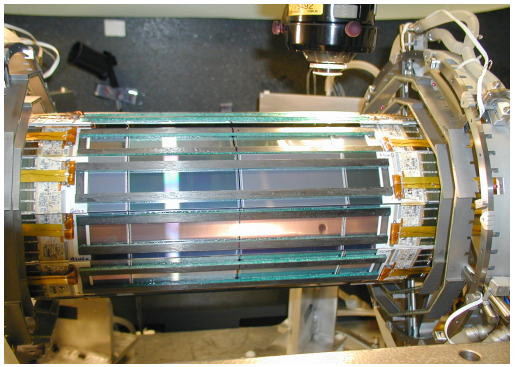
$t\bar{t}$ topologies

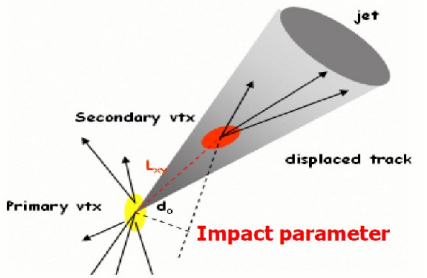


Top found preferentially in events of the type: W+≥3jets + MET (ν)

CDF Top quark Search

Some Interesting events start appearing in '92-93 analyses

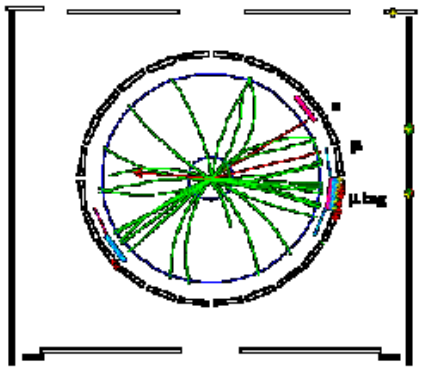


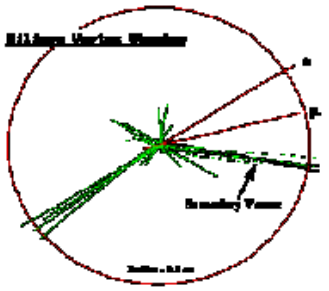


$\sigma(d_0)$= 50/10μ at 1/10 GeV

Silicon detector (SVX) allowed secondary vertex b-tagging, thus W+jets and QCD background reduction.

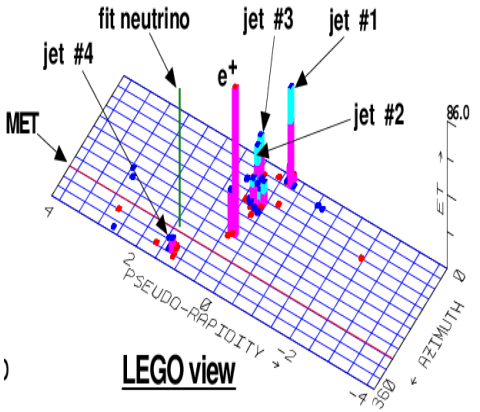
DPF event, Oct. 22-1992: e μ + b-tags



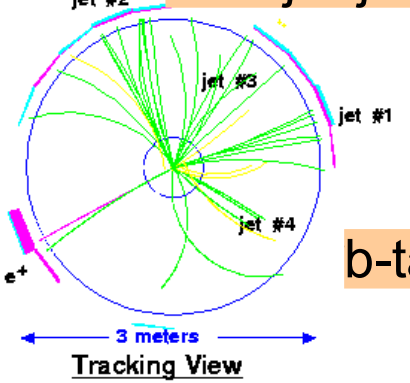


b-tags: SVX+ SLT

Doubly tagged event: e + 2 b (Sept. '92)



W →jet-jet

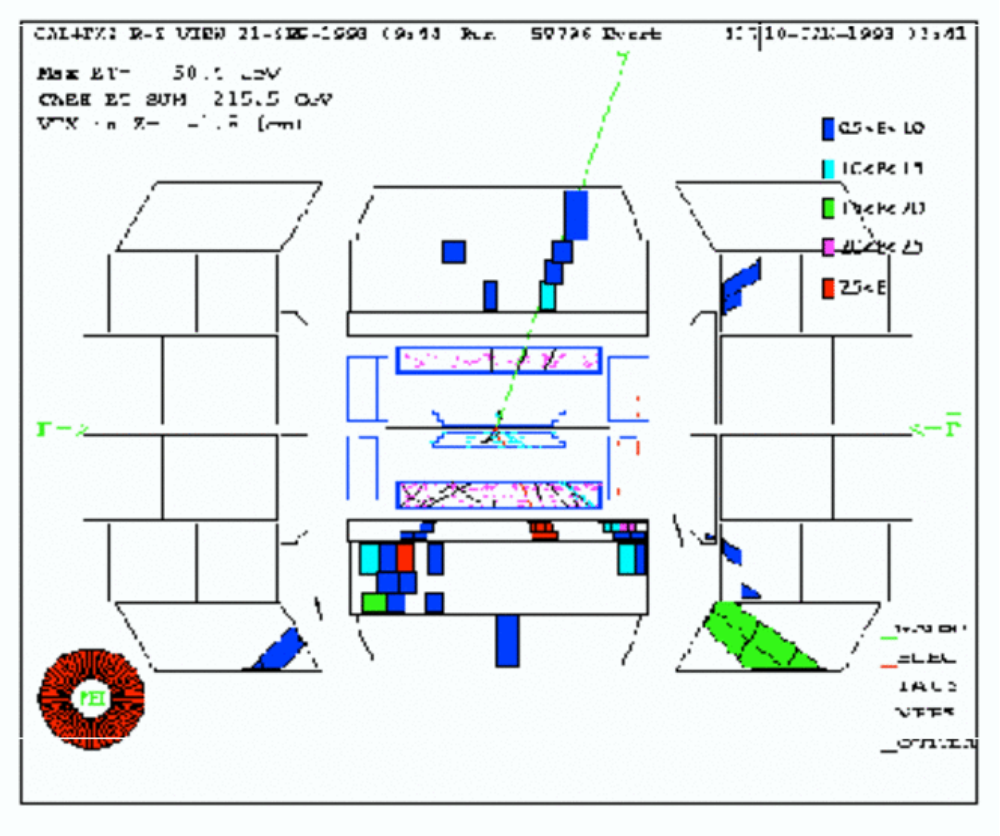


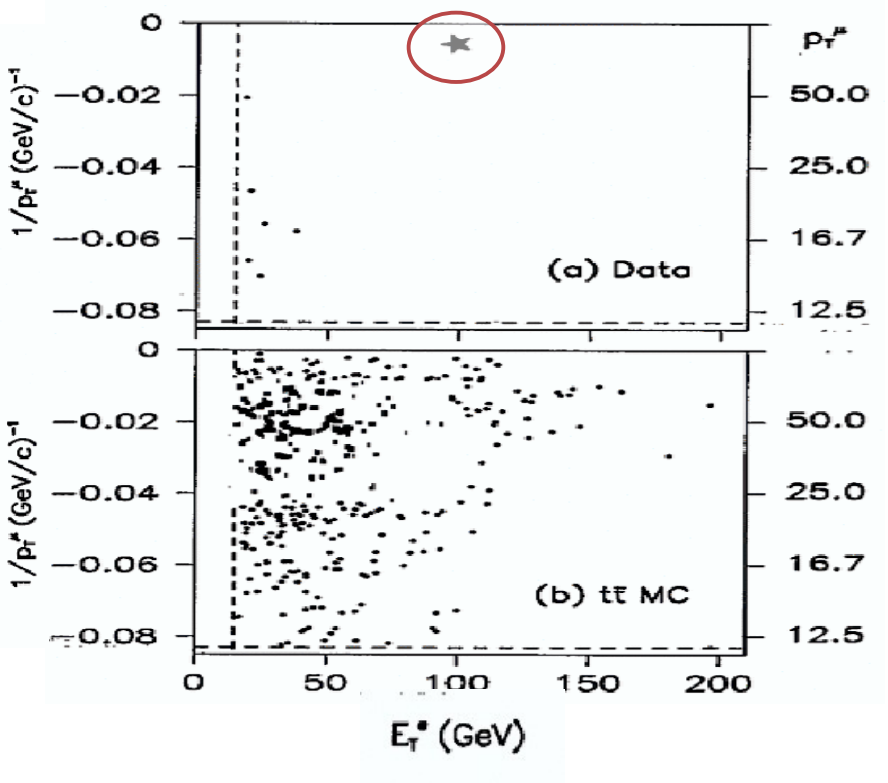
b-tag

b-tag

DØ Event 417

e-μ event with large P_T for both e and μ and large MET





DØ debated on whether to publish this event, but it could be background from W+jets. Decided to wait for more events.

From E. Varnes, HCPSS, FNAL, Aug. 15-2006

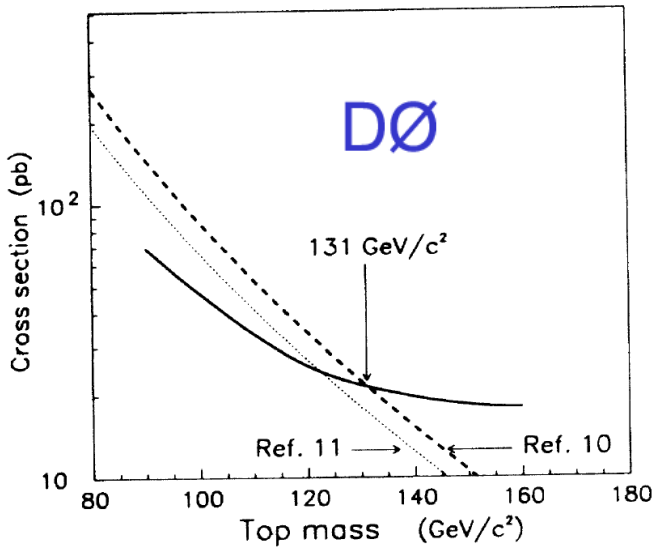
Top quark: DØ Run IA

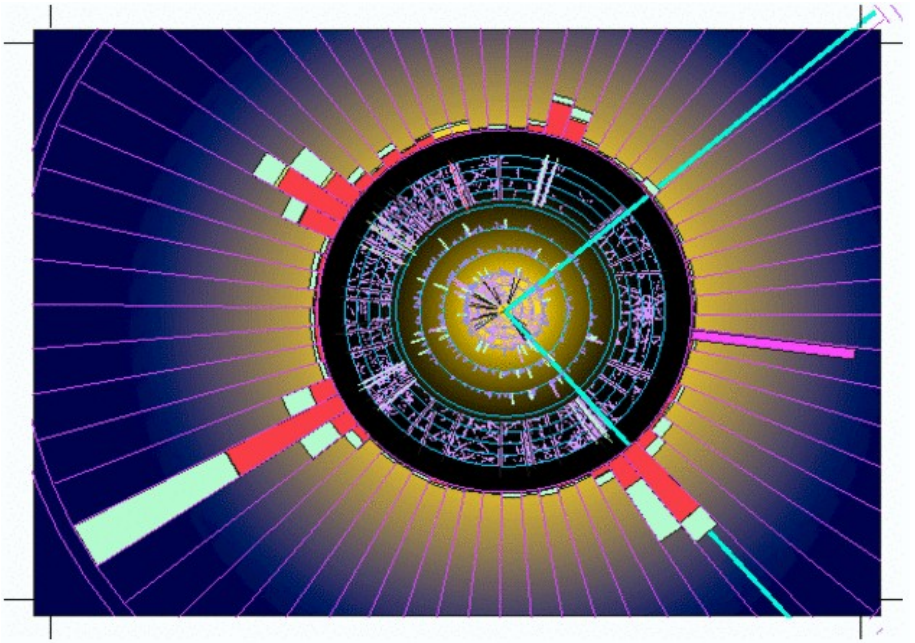
Spring 1994: DØ had 15 pb^{-1} of data. Observe 3 events: 2 DIL, 1 lept+jets. Expect N = 5.9±1.7 events from background. No evidence for top. Result:

M_{top} >131 GeV/c^2 @95%CL

- Good muon+calorimetry systems allowed tagging b jets with muons (SLT) from b decays.
- Reduced backgrounds, but low top efficiency (~20%). Could release kinematic cuts.

DØ col., PRL **72**, 2135 (1994)





From E. Varnes, HCPSS, FNAL, Aug. 15-2006

CDF Top quark evidence (1994)

Type	observed	background
DIL	2 events	$0.56^{+0.25}_{-0.13}$
SVX	6 tags	2.3 ± 0.3
SLT	7 tags	3.1 ± 0.3
total	12 events	---

SLT: soft lepton tag

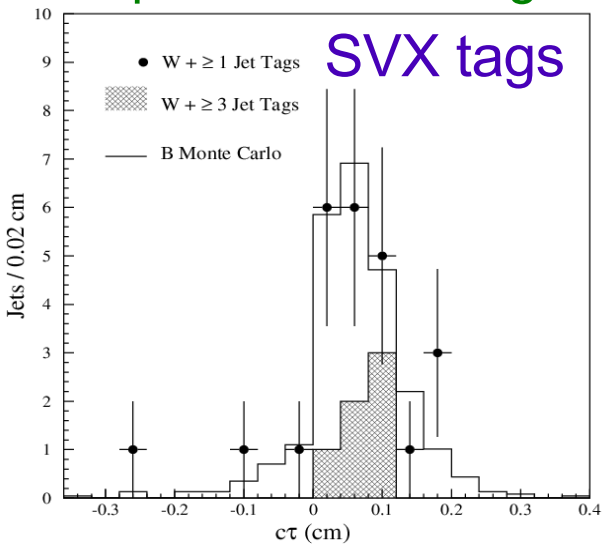
Significance 2.8σ P=0.26%

Integrated $\mathscr{L}$ = (19 pb^{-1})

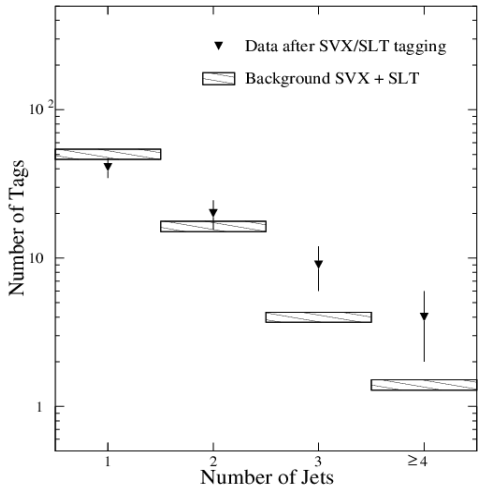
$\sigma_{tt}(M_t=174)=13.9\,^{+6.1}_{-4.8}$ pb

$M_{top} = 174 \pm 10^{+13}_{-12}$ GeV/c^2

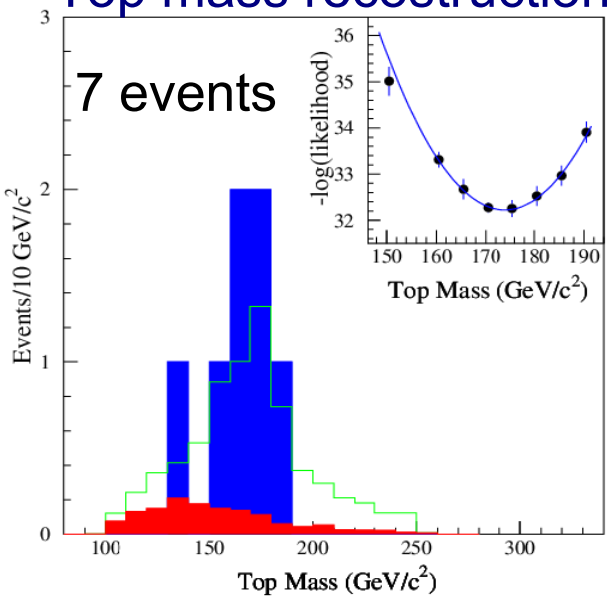
Proper time for b-tags



N(ev)-vs-N(jets)



Top mass recostruction



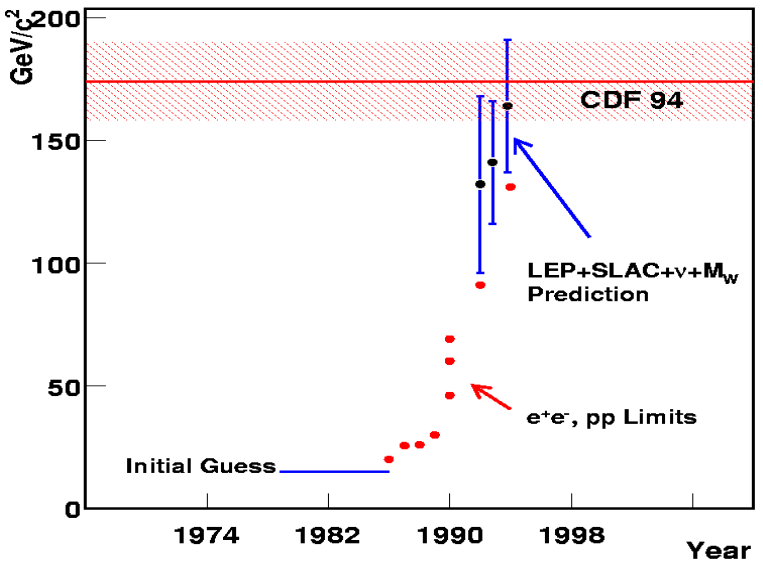
The Top quark in PDG 1994

PDG 1994 listing

MASS LIMITS for t Quark in $p\bar{p}$ Collisions

These experiments are based on the assumption that no nonstandard decay mod such as $t \to bH^+$ are available, except as shown in the comments. Mass limits a now sufficiently high that decay is expected to occur before hadronization.

VALUE (GeV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
>131	95		[8] ABACHI	94	D0	$\ell\ell$ + Jets, ℓ + Jets
$174 \pm 10^{+13}_{-12}$		7	[9] ABE	94E	CDF	ℓ + b-jet
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>118	95		[9] ABE	94E	CDF	$\ell\ell$
> 91	95		[10] ABE	92	CDF	$\ell\ell$, ℓ + b-jet
			[11] ALITTI	92F	UA2	$t \to bH^+$, $H^+ \to \tau\nu_\tau$
> 60	95		[12] ALBAJAR	91B	UA1	$t \to bH^+$; $H^+ \to \tilde{t}_1 \tilde{\chi}^0_1 \tau^+\nu$
			[13] BAER	91B	RVUE	$t \to \tilde{t}_1 \tilde{\chi}^0_1$
> 72	95		[14] ABE	90B	CDF	e + μ
> 77	95		[15] ABE	90C	CDF	e + Jets + missing E_T
> 69	95		[16] AKESSON	90	UA2	e + Jets + missing E_T
> 60	95		ALBAJAR	90B	UA1	e or μ + Jets, $\mu\mu$ + Jet
			[17] BARGER	90E	RVUE	$t \to bH^+$
> 41	95		[18] ALBAJAR	88	UA1	e or μ + Jets



The standard model predicts the top mass from EWK measurements

INDIRECT MASS LIMITS for t Quark from Standard Model Electroweak Fit

The RVUE values are based on the data described in the footnotes. Earlier RVUE's are superseded but have been left in the Listings to show the progress.

"OUR EVALUATION" below is for our fit to electroweak data described in the "Standard Model of Electroweak Interactions" section. This fit result does not include direct measurements of m_t. The second error corresponds to $m_H = 300^{+700}_{-240}$ GeV.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
169^{+16+17}_{-18-20} OUR EVALUATION					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
157^{+36+19}_{-48-20}		[19] ABREU	94	DLPH	Z parameters
$158^{+32}_{-40} \pm 19$		[20] ACCIARRI	94	L3	Z parameters
132^{+41+24}_{-48-18}		[21] AKERS	94	OPAL	Z parameters
184^{+25+17}_{-29-18}		[22] BUSKULIC	94	ALEP	Z parameters
140^{+21}_{-22}		[23] ELLIS	94	RVUE	Electroweak
$91 \pm 46 \pm 9$		[24] ACTON	93D	OPAL	Z parameters
$152^{+36}_{-46} \pm 20$		[25] ADRIANI	93M	L3	Z parameters
<207	95	[26] ALTARELLI	93	RVUE	$Z b\bar{b}$ vertex
143^{+19}_{-18}		[27] BLONDEL	93	RVUE	Z parameters
174^{+27+17}_{-32-22}		[28] BUSKULIC	93J	ALEP	Z parameters
<228	95	[29] BUSKULIC	93M	ALEP	$\Gamma(Z \to b\bar{b})$
132^{+20}_{-22}		[30] ELLIS	93B	RVUE	
192^{+35+19}		[31] MONTAGNA	93	RVUE	Z parameters

1994 PDG EWK fit:

$M_{top} = 169^{+16+17}_{-18-20}$ GeV/c²

Top quark observation (1995)

March 1995:

The Tevatron strikes gold!

Both CDF and DØ discover the top quark:

significance at the 5 σ level

CDF $M_{top}=176 \pm 8 \pm 10$ GeV/c^2

DØ $M_{top}=199 \pm 20 \pm 22$ GeV/c^2

average: $M_{top} = 180 \pm 12$ GeV/c^2

Top quark discovery: CDF

Type	observed	background
DIL	6 events	1.3 ± 0.3
SVX	27 tags	6.7 ± 2.1
SLT	23 tags	15.4 ± 2.0
total	43 events	---

37 tagged ev. in lept.+ ≥ 3 jets

67 pb^{-1} of data, $P=4x10^{-7}$ (5.0σ)

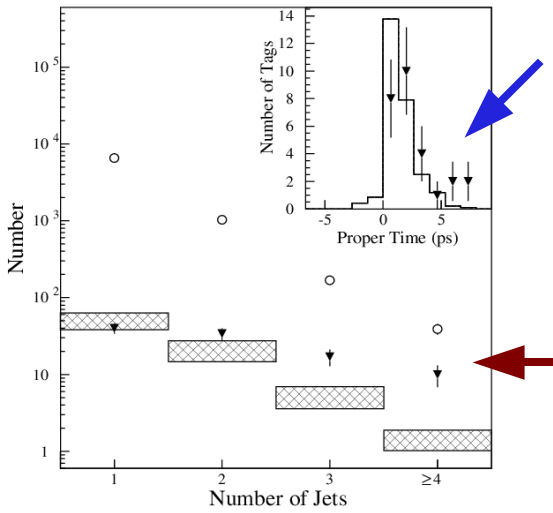
P(event excess) = $1x10^{-6}$

P(mass plot) = $4x10^{-2}$

$$\sigma(M_t=176) = 6.8^{+3.6}_{-2.4}\ pb$$

$M_{top}=176 \pm 8 \pm 10\ GeV/c^2$

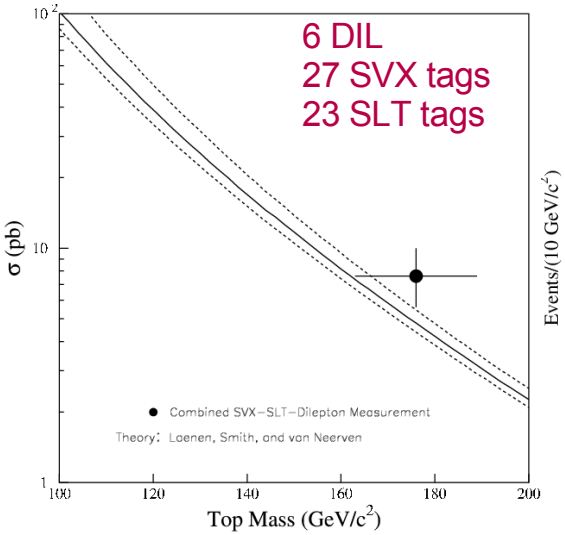
N(jets) distribution



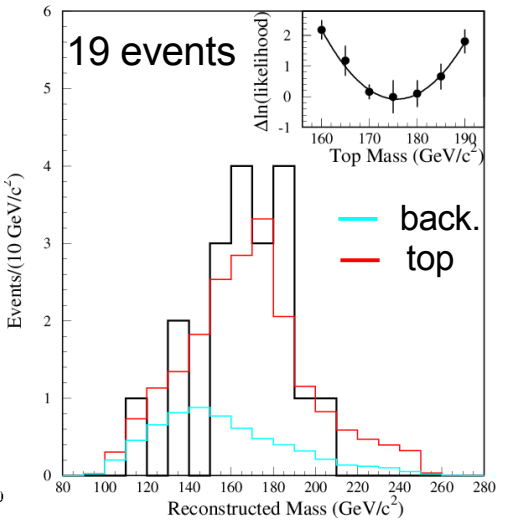
Proper time for silicon tags

Excess over background in 3,4 jet bins

Cross-section



Mass reconstruction



DØ Top Discovery

Type	observed	background
DIL	3 events	0.65 ± 0.14
l+jets	14 events	3.1 ± 0.5

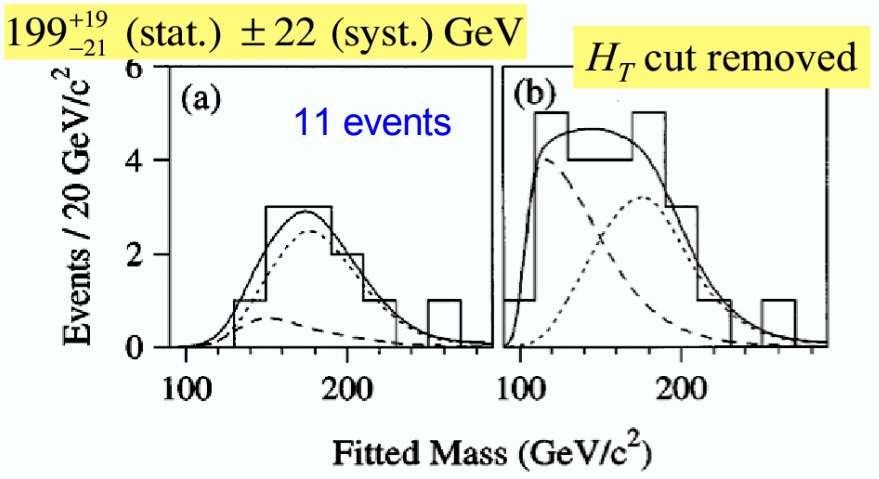
50 pb^{-1} of data, P=2x10^{-6} (4.6σ)

includes only P(event excess)

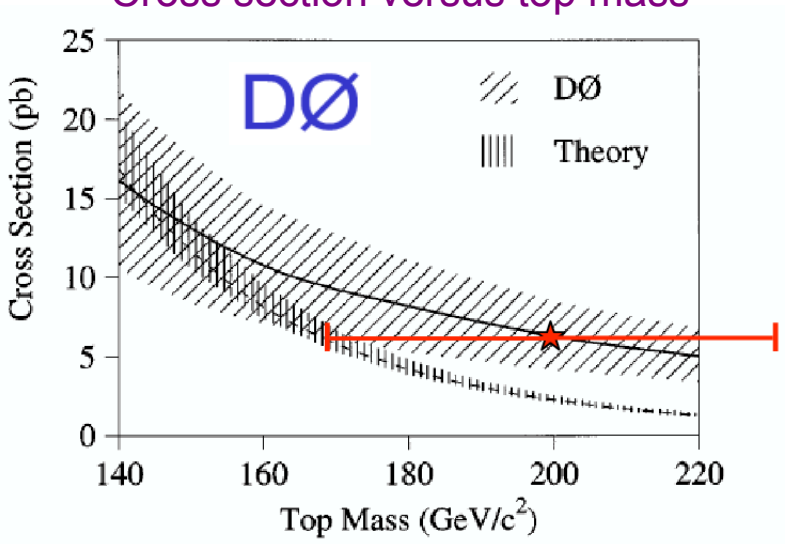
$\sigma(M_{top}=200) = 6.3 \pm 2.2$ pb

l+jets events(8) had ≥ 4 jets, + cuts on Aplanarity and H_T. Soft lepton-tag events(6) had ≥ 3 jets

$M_{top}=199^{+20}_{-21} \pm 22$ GeV/c^2



Cross section versus top mass



Top Physics at the Tevatron now

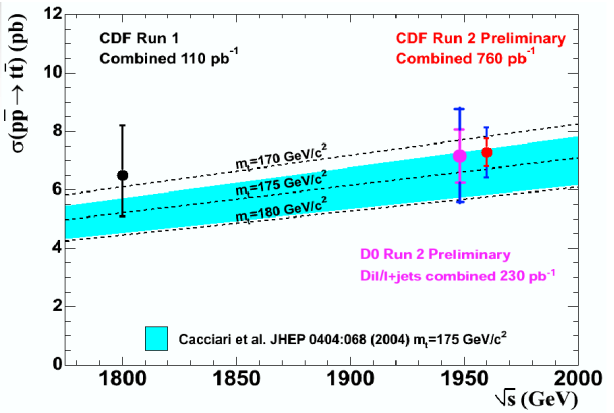
Tevatron luminosity ~2×10^{32}. Delivered ~ 20 x Run I integrated L.
Delivered 1.9 fb^{-1} , plan to get 4-8 fb^{-1}
CDF and DØ detectors have improved. DØ has added magnetic field and silicon detectors.

- Does top behave as a SM quark?
  - Production cross section in QCD: qq (85%), gg (15%)
  - Single Top production via EWK processes
  - Top Decays: $t \rightarrow Wb$ expected ~ 100%, W helicity (V-A)
  - FCNC decays expected to have BR ~ 10^{-14}
- Large Mass: ≅ 175 GeV/c^2: Special role in EWSB?
  - Γ_t = 1.5 GeV >> Λ_{QCD} no hadronization
  - Can probe charge and spin of bare quark
- Physics Beyond the SM?
  - $X \rightarrow t\,t$ (Z', top color...), $W' \rightarrow tb$, etc.

Will show some results from CDF and DØ shown at ICHEP06

Top quark today: t $\bar{t}$ production

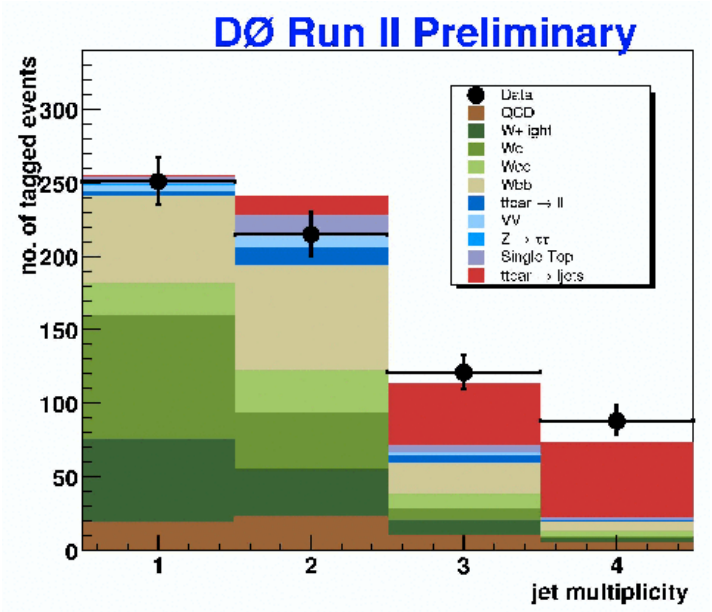
Cross section measured in many channels by both experiments. Preliminary averages show agreement with QCD expectation.



Example of lepton+jets measurement:

DØ uses 365 pb^{-1} of data. Top signal mostly in 3 and 4 jets bins (209 events). Njets=1,2 used to check backgrounds.

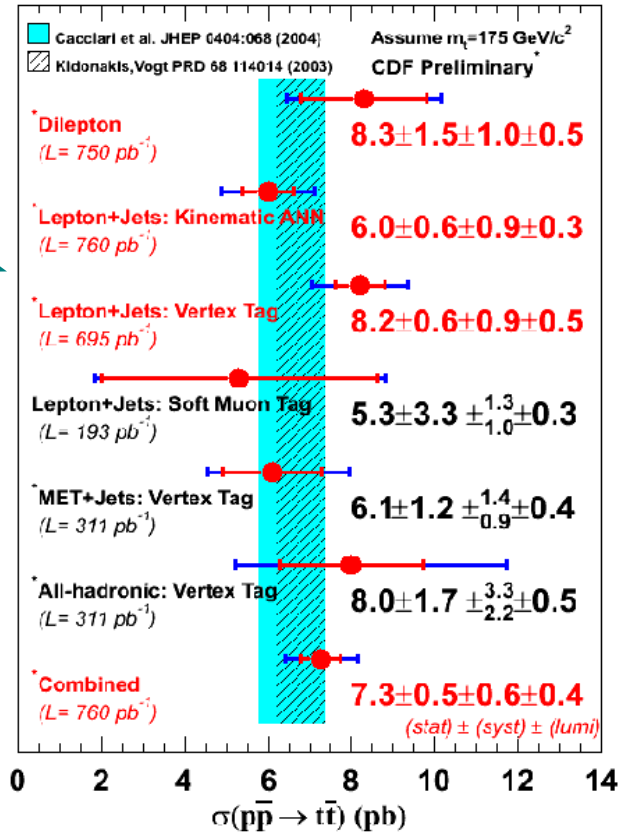
$\sigma(tt) = 8.1 \pm 1.2(stat+sys) \pm 0.5(lumi)$ pb



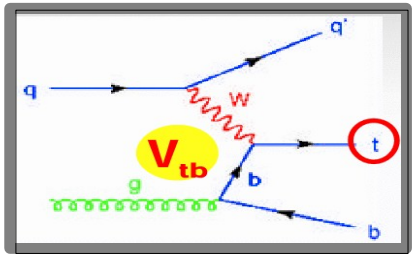
CDF results:

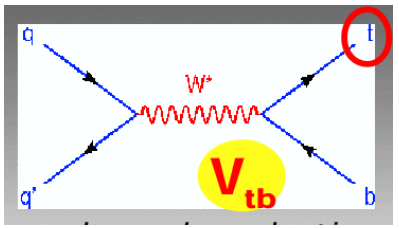
all channels use up to 760 pb^{-1}. Good agreement among the six measurements

(O'Neil, ICHEP06)



EWK Single Top Production

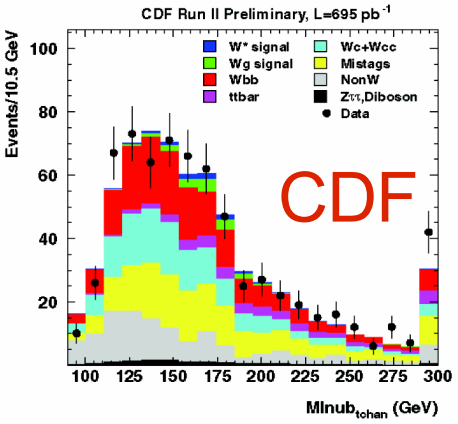




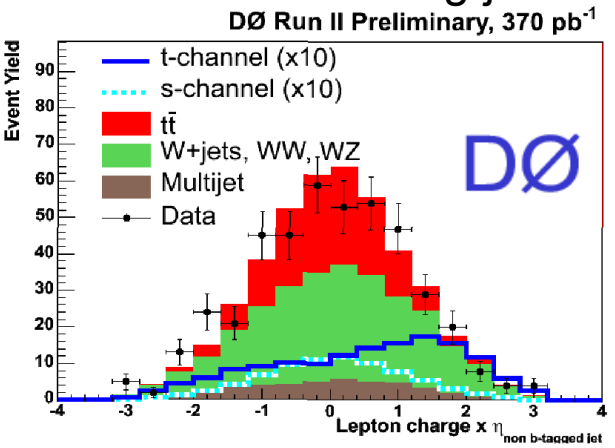
Production via s and t channel
$\sigma(t) \sim 2.5$ smaller than $\sigma(tt)$
Can measure V_{tb} directly
Can reveal new physics

Signature: lepton, 2 jets, MET, ≥ 1b-tag. S/B=1/20
Main back.: W+jets, ttbar, Z+jets, mistag etc.
14-16 variables used in likelihoods or NN to separate S from B.

$M(lvb)_{tchan}$



$Q(lep) \bullet \eta_{no\text{-}tag\text{-}jet}$



	t-channel	s-channel	both+other
Theory (in pb)	1.98±0.25	0.88±0.11	2.95±0.16
CDF (695 pb^{-1})	< 2.9	< 3.2	<3.4
DØ (370 pb^{-1})	< 4.4	< 5.0	

EXPECT TO SEE IT SOON

(Wagner, ICHEP06)

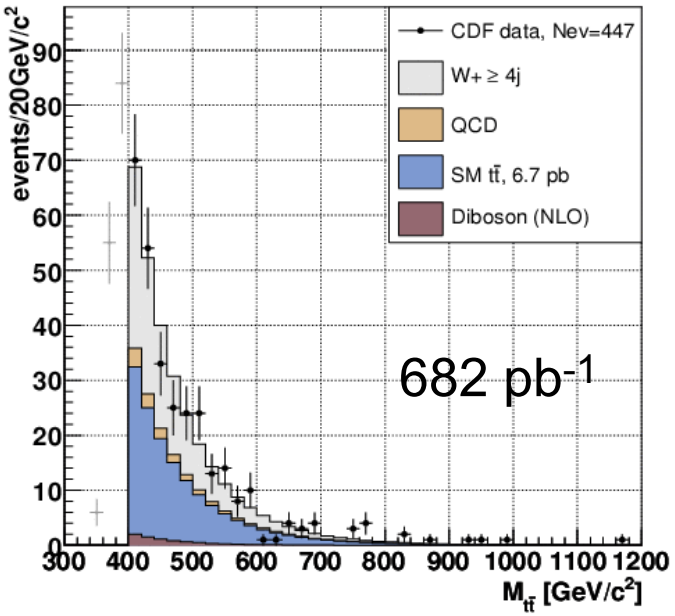
Non-standard Top production

Search for resonant $t\bar{t}$ states

$pp \rightarrow X^0 \rightarrow t\bar{t}$

Reconstruct the $t\bar{t}$ system by ME techniques, then test for excess

CDF



Exclude topcolor Z' (Γ=1.2%M_{X0}) for M_{X0}< 725 GeV/c^2 @ 95%CL

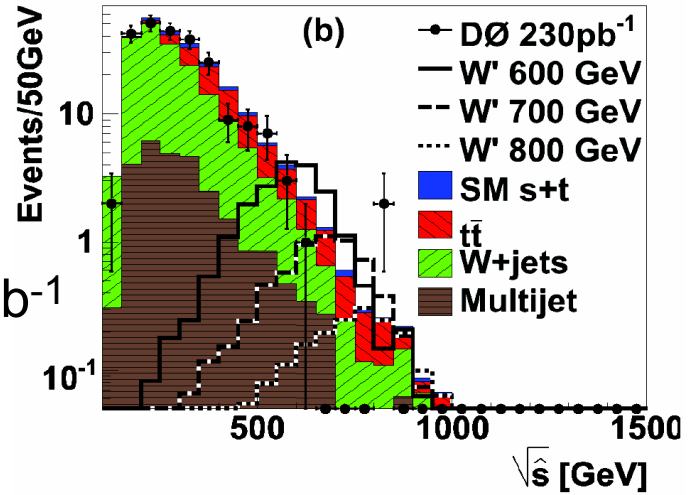
In Single top sample search for

$W' \rightarrow t\ b$

In s channel analysis add SM and W' interference. Use M(lvbj) as discriminant

DØ

370 pb^{-1}



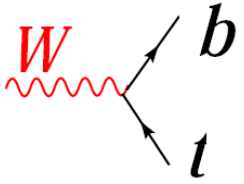
- Exclude 200-650 GeV range for W' with SM like couplings
- $\sigma(W')$<1.8/1.4/2.2 pb for $M_{W'}$ = 600/700/800 GeV

(Wagner, ICHEP06)

Top Decays : ~ 100% into Wb

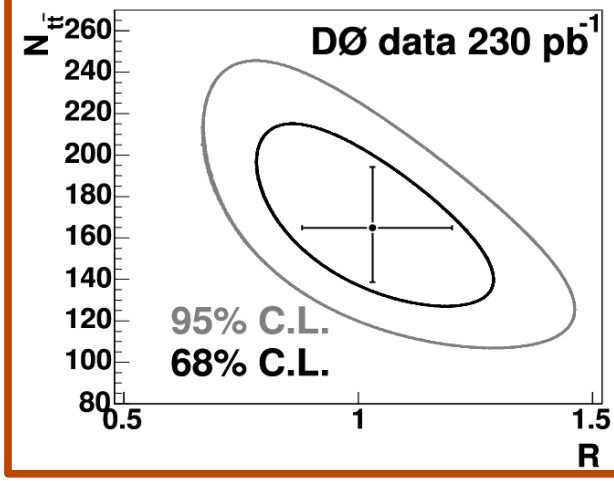
$t \rightarrow W^+ b$

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



Assuming 3 generations:
$|V_{tb}|$~0.99 R~0.998

DØ: 2D fit, $N_{t\,t}$ (with b-tag) vs R



$R = 1.03^{+0.19}_{-0.17}$

Consistent with SM

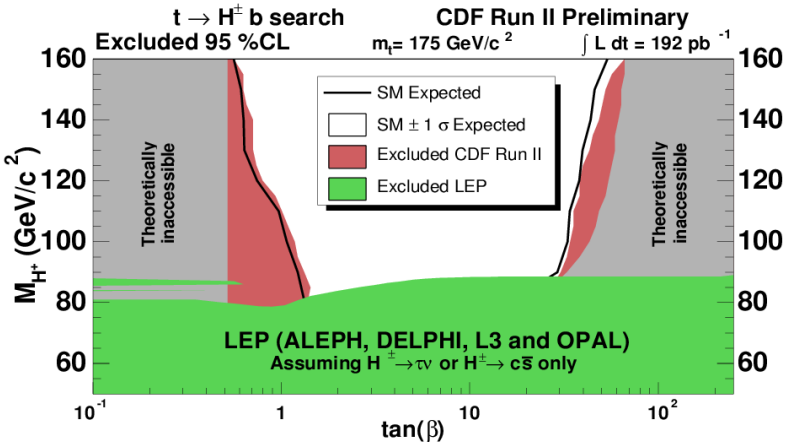
(Wicke, ICHEP06)

Search for:

$t \rightarrow H^+ b$

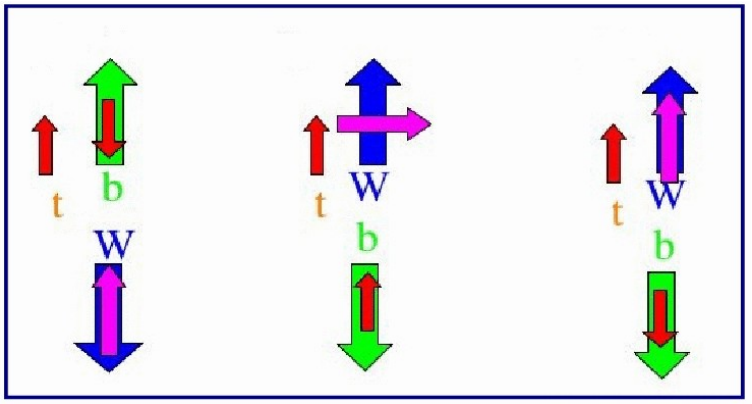
Dilepton and lepton+jets events are used.
Using a set of parameters for the MSSM, can evaluate the H^+ BR's for each mass.

CDF: red regions of M_H are excluded @ 95%CL.

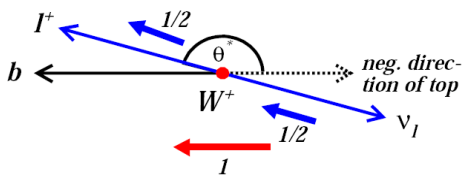


W helicity in Top Decay

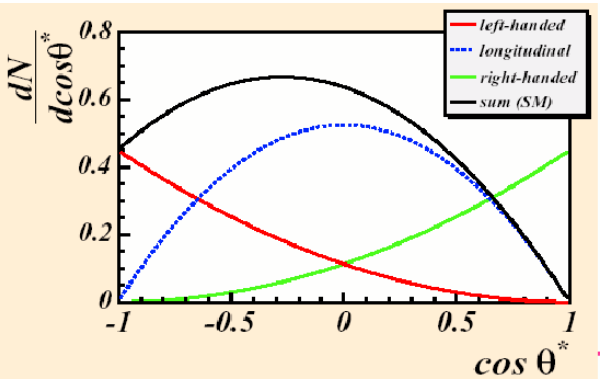
Standard Model predicts V-A couplings in top decay, t → Wb



Left hand. Longitud. Right hand.



Left handed W



$F^{-}=0.3 \quad F^{0}=0.7 \quad F^{+}=0$

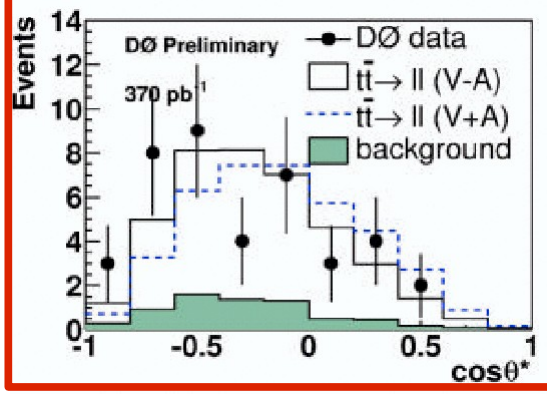
$F^{0} + F^{-} + F^{+} = 1$

Both CDF and DØ have tested the SM using different methods.
So far no evidence for V+A contributions.

Results: assuming $F^0=0.7$

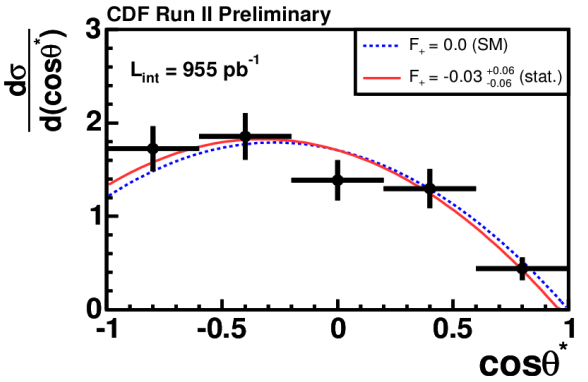
DØ dileptons

$F^+ < 0.24$ @ 95%CL



CDF lepton+jets

$F^+ < 0.10$ @ 95%CL



(Wicke, ICHEP06)

Top charge and Lifetime

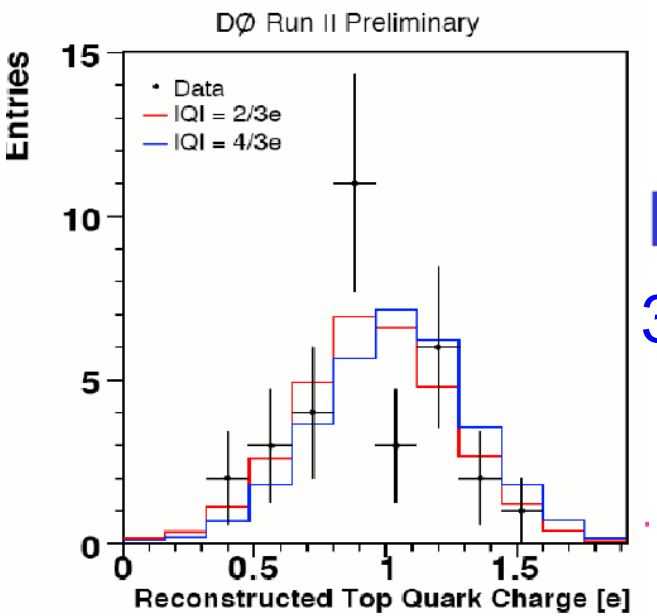
Q(top) = +2/3 in SM
Test exotic +4/3 charge

Γ_t = 1.5 GeV in SM

$c\tau = 1.3 \times 10^{-10}$ μm

Add up observed charge of decay products: lepton + b-jet

DØ in l+jets excludes +4/3 charge @ 94%CL

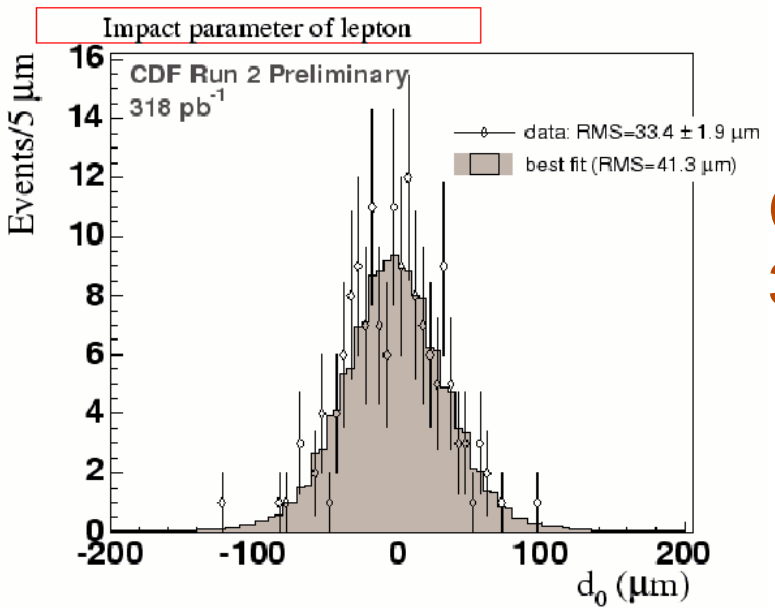


DØ
365 pb^{-1}

(Wicke, ICHEP06)

Difficult to measure. Impact parameter of lepton from W provides upper limit.

$c\tau$ < 53 μm @ 95%CL



CDF
318 pb^{-1}

Top quark mass

Reconstruct top mass from $t\,t \rightarrow W^{+}\,b\,W^{-}\,b$ + background

Many channels, depending on decay of the two W's
Events in 1 fb^{-1} after optimized selections

- Dilepton : 2 leptons, missing energy (2v), 2 jets
  ~ 50 signal events , purity ~65% (no b-tag)
- Lepton+jets : 1 lepton, missing energy (1v), 3 jets
  ~ 230 signal events, purity ~90% (with ≥ 1 b-tag)
- All jets : 6 jets
  ~ 250 sig. events , purity ~30% (≥ 1 b-tags + NN selection)

Main challenge: reconstruct mass at the parton level

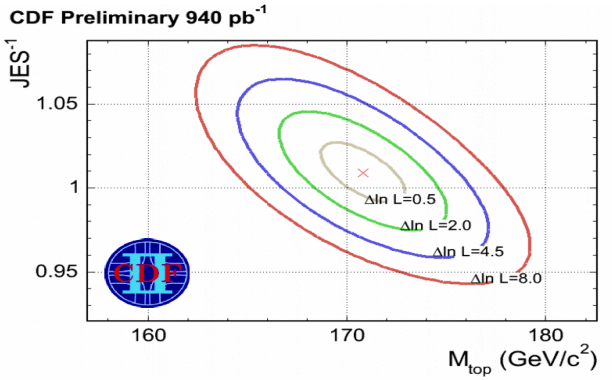
- We do not measure neutrino's. We measure jets, not quarks.
- Major systematics is in jets → parton reconstruction:
  detector effects, absolute E-scale (JES), etc.

Top Mass Measurement

Many measurement made for all topologies. Two methods:

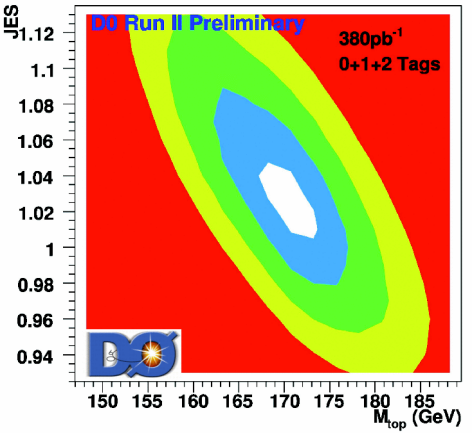
- Template method: reconstruct top mass for each event, then compare to MC templates at several masses.
- Matrix element analysis: evaluate t t and background probabilities for each event, then multiply probabilities.

Best CDF measurement: l+jets, ME analysis
940 pb^{-1}, 166 cand., ≥ 1 b-tagged jets
2D fit: M_{top} and JES (jet energy scale from Wjj)



$M=170.9\pm1.6(stat)\pm1.4(JES)\pm1.4(sys)$ GeV/c^2

Best DØ measurement: l+jets, ME analysis
370 pb^{-1}, 175 cand. 0, 1, 2 b-tagged jets
2D fit: M_{top} and JES (jet energy scale)



$M=170.3\pm2.5(stat)\pm3.5(JES)\pm1.5(sys)$ GeV/c^2

(Canelli, ICHEP06)

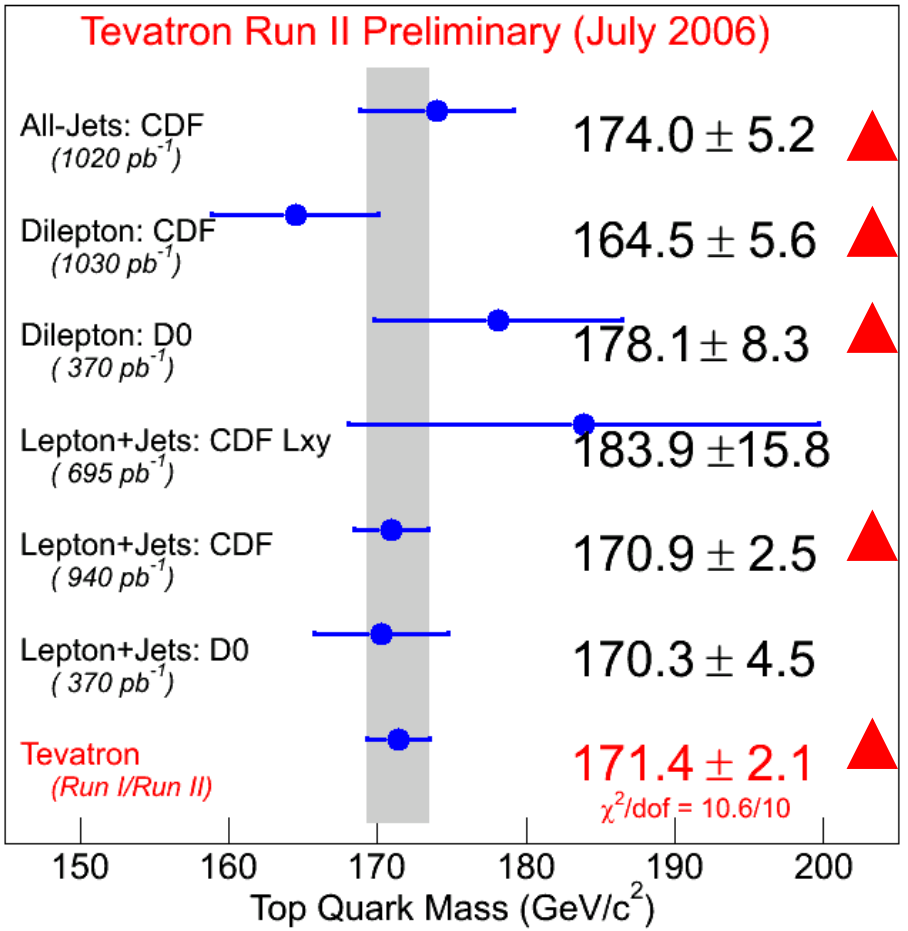
Top Mass results: July '06

- Top mass average of best results of CDF and D0.
- All correlations taken into account.

M_{top}= 171.4 ± 2.1 GeV/c^2

dM_{top}= 1.2% M_{top}

δM(stat) = ± 1.2 GeV/c^2
δM(JES) = ± 1.4 GeV/c^2
δM(sys) = ± 1.0 GeV/c^2



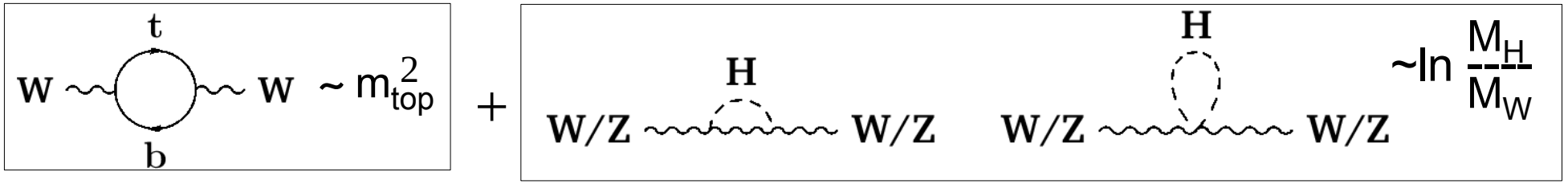
- Values obtained from 3 different channels agree at the 15% level

▲ New results

(Glenzinski, ICHEP06)

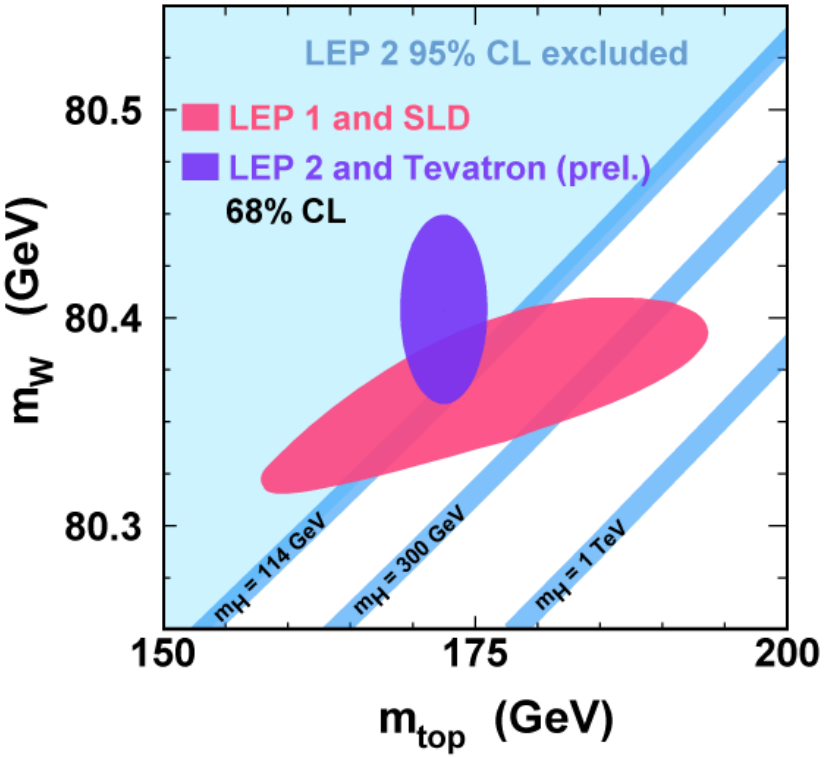
Top quark in the SM (LEPEWWG)

Standard Model relates m_H, m_{top}, m_W via radiative corrections



EWK fit with new M_{top}

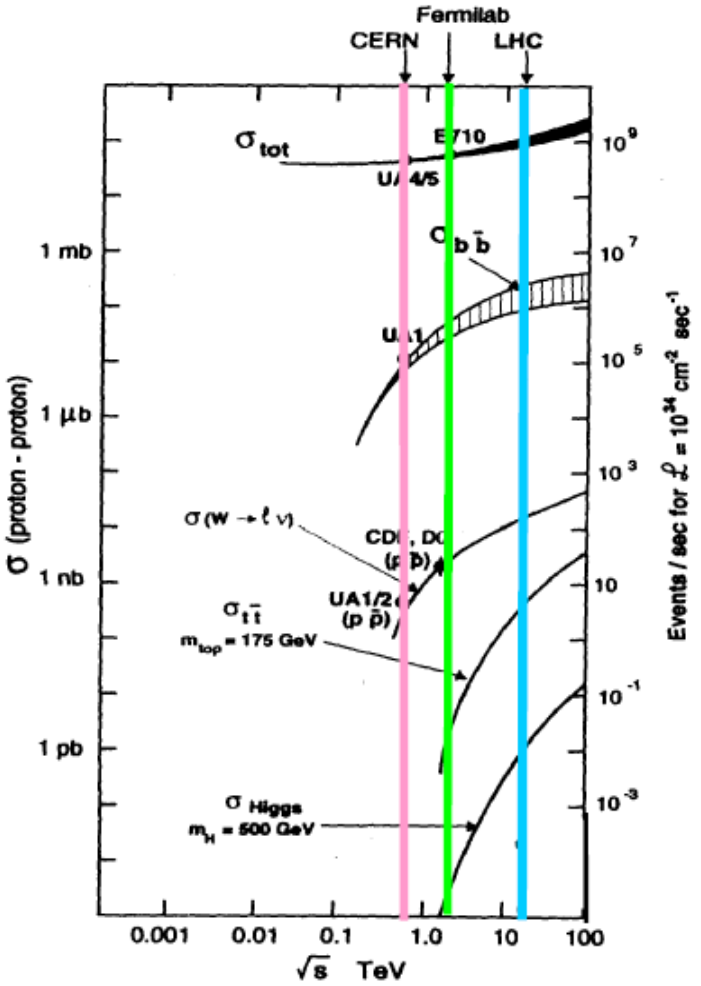
- $M_H = 85^{+39}_{-28}$ GeV/c²
- $m_H < 166$ GeV/c² (95%CL)
- add LEP2 $m_H > 114$ (95%CL)
  $m_H < 199$ GeV/c² (95%CL)



(C. Parkes, ICHEP06)

Top at LHC

Top production is very large at the LHC (1 tt/sec at 10^{33}), while the background is increasing at a lower rate.



	Tev	LHC	ratio
σ(tt)	~7 pb	~850 pb	x120

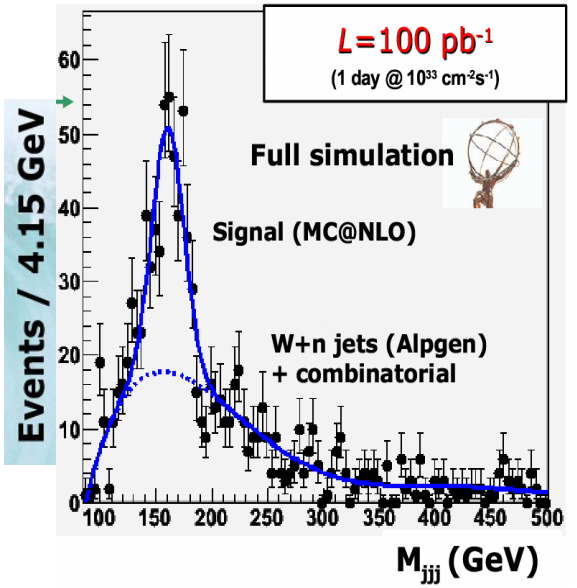
Background (W+jets, QCD jets) ~x10

gg→t t (90%) and qq →t t (10%)

Top signal can be seen without b-tag.

Can be used for initial σ(top) and M(top).

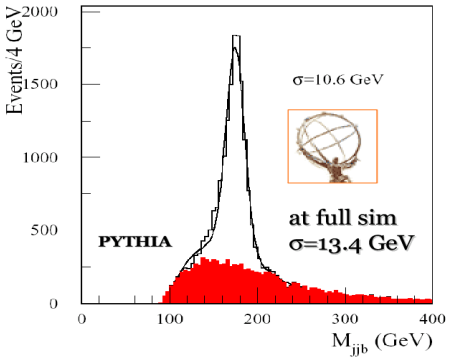
Detector calibration, JES, b-tagging etc.

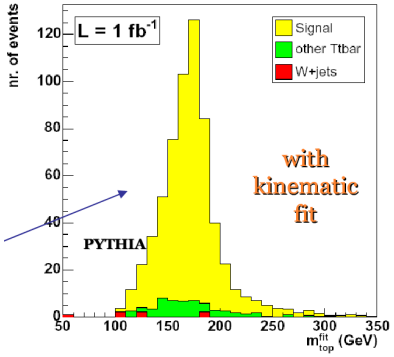


Top Physics at LHC

- Plenty of statistics for precision measurements:
  production, decays, couplings, asymmetries, etc.
- Search for new physics

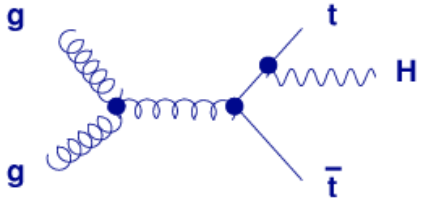
➢ Top Mass: preliminary studies by ATLAS and CMS estimate
$\delta M_{top} < 2$ GeV/c^2
(R. Chierici, ICHEP06)

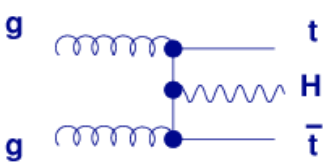




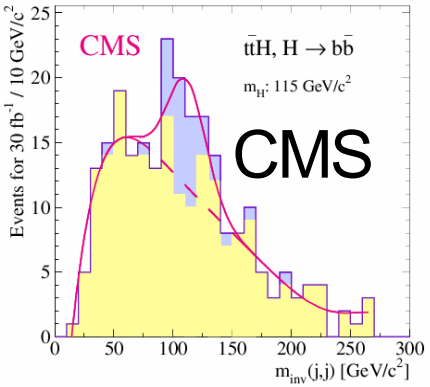
➢ Top Yukawa coupling: $g_t^2 \approx \frac{2M_t^2}{v^2} \approx 1$

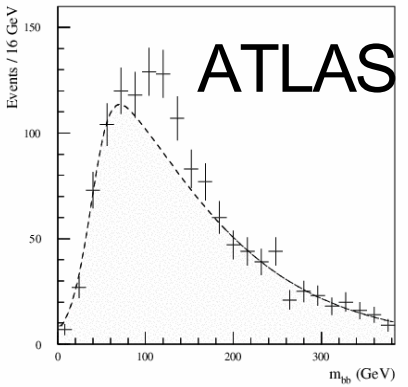
$t\bar{t}H$ with $H \to b\bar{b}$





Old plots, more background expected





Expect 20-30% precision on g_t with 300 fb^{-1} for $M_H \leq 150$ GeV
(B. Resende, ATLAS, TOP2006).

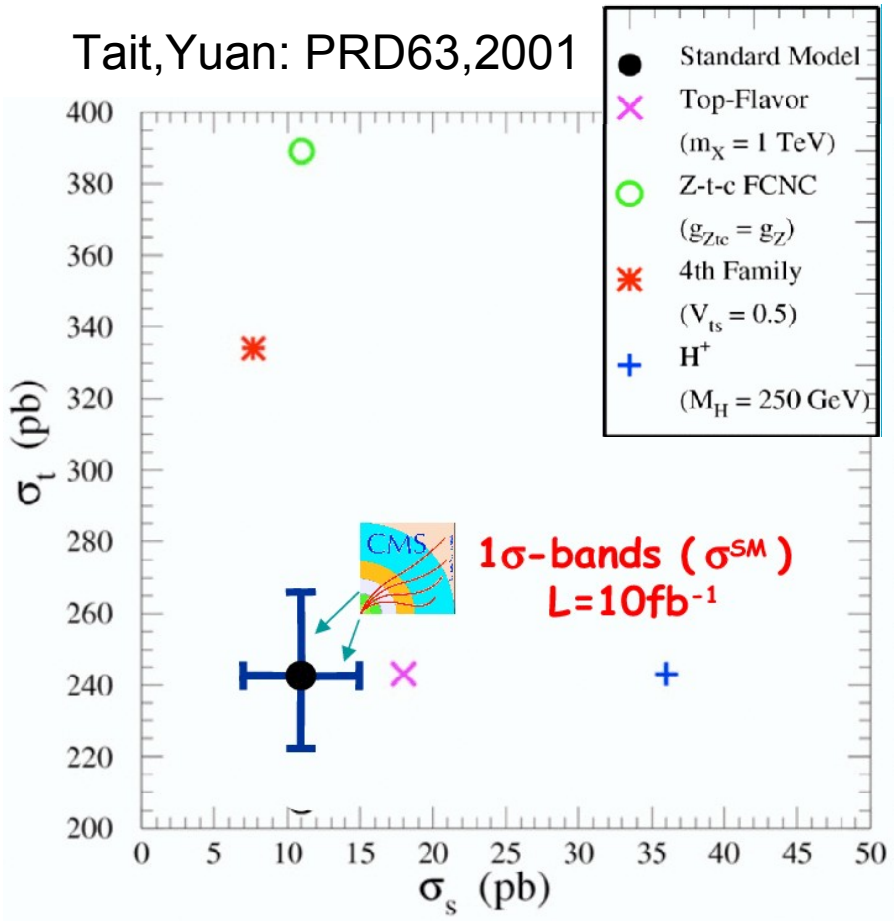
(F. Beaudette, Moriond EWK '05)

Top at LHC: new physics

Examples of sensitivity to new physics in top production and decays

Single top cross sections (CMS)

Tait,Yuan: PRD63,2001

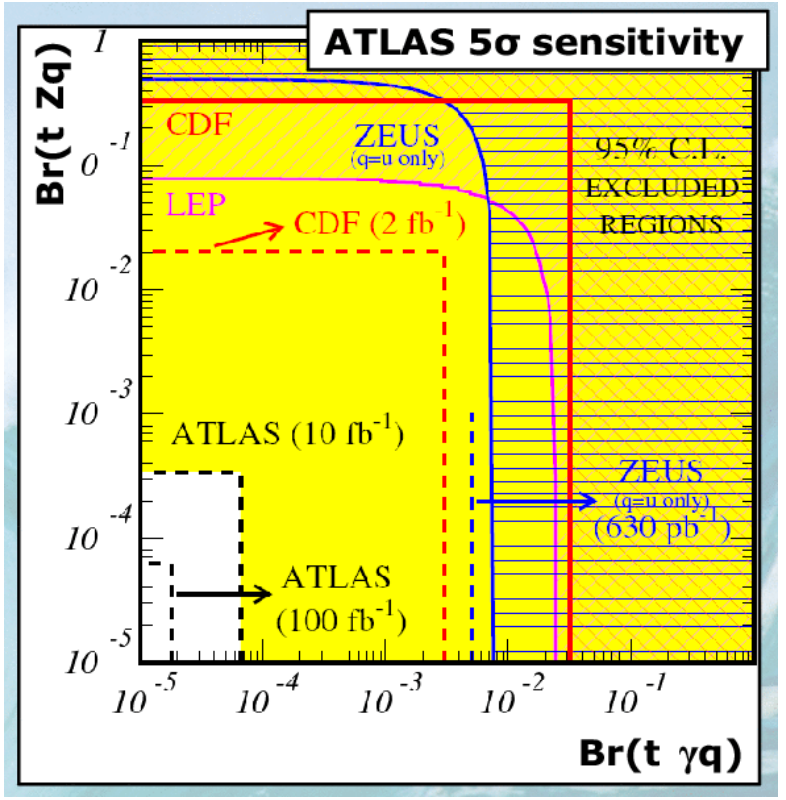


(A. Onofre, ICHEP06)

Flavor Changing Neutral Currents

SM: $t \rightarrow Zq \sim 10^{-14}$, $t \rightarrow \gamma q \sim 10^{-14}$

NP can bring BR's to 10^{-4}, 10^{-5}



(A. Onofre, ICHEP06)

The TOP QUARK: SUMMARY

What do we know?

$\bar{M}$ = 171.4 ± 2.1 GeV/c^2
Large $\bar{\Gamma}$ predicted (1.5 GeV)
No deviations from SM seen so far:
t t cross section agrees with SM
t →Wb ~ 100% , V+A <10% at 95%CL
Charge=+2/3 +4/3 excluded @94% CL

Expect new exciting results at the Tevatron and more at the LHC.