The courtly dance of the W boson and the top quark

25th anniversary of Tevatron $p\bar{p}$ collisions

P. Grannis

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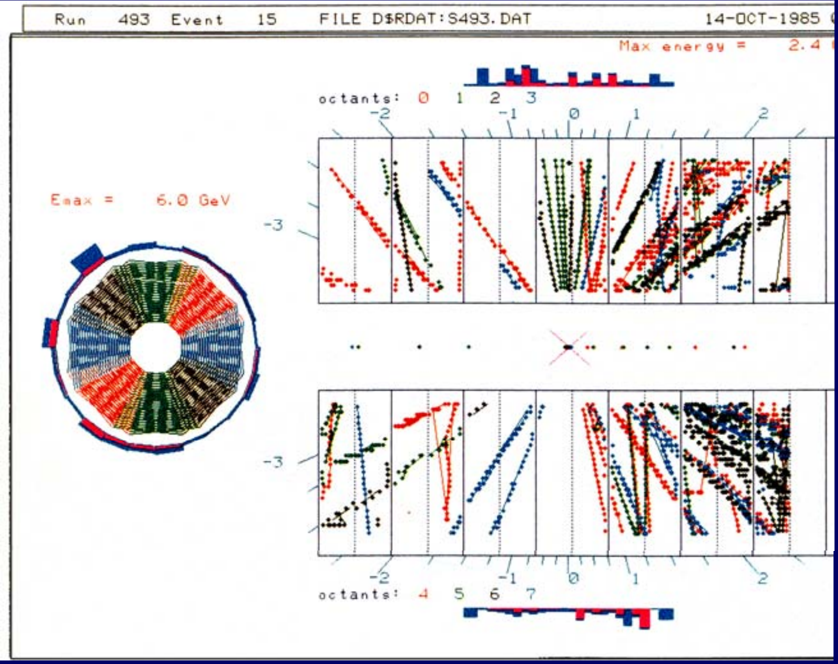
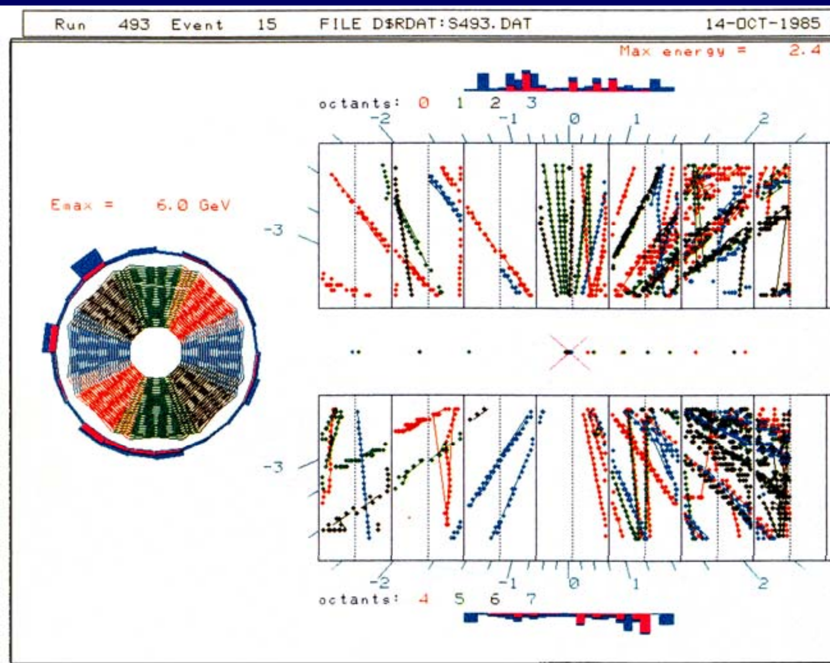


Congratulations to the Tevatron and pbar Source groups on building a superb complex of machines! And thanks to Computing Division for the support and innovation that made the analyses possible.

Kudos to CDF on getting enough detector together to record the first collisions. (The first event display looks like Run I DØ with no magnetic field!).



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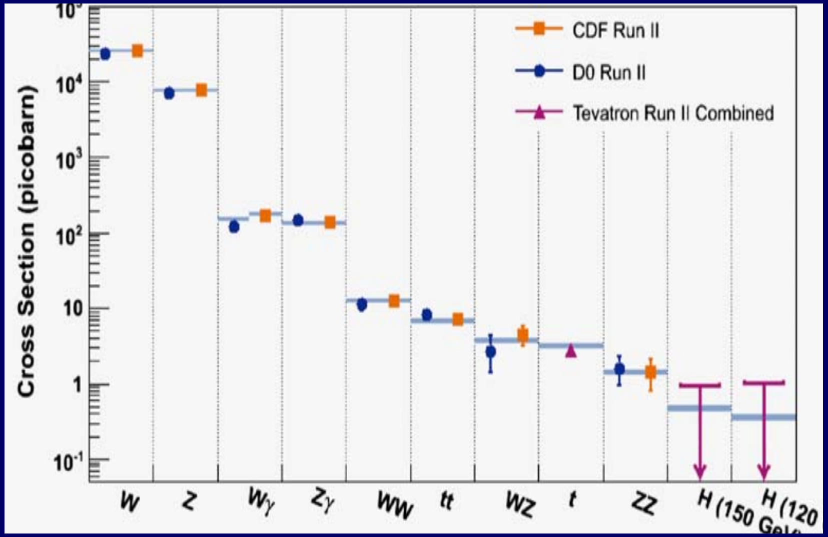
So where was DØ in October 1985?

… far from being ready!

(1st DØ collisions April 14, 1992)

W and top have enjoyed a synergistic relationship in $p\bar{p}$ colliders since the 1983 W discovery (and the 1984 ill-fated glimpse of the top, W → "t"b) at the SppS.

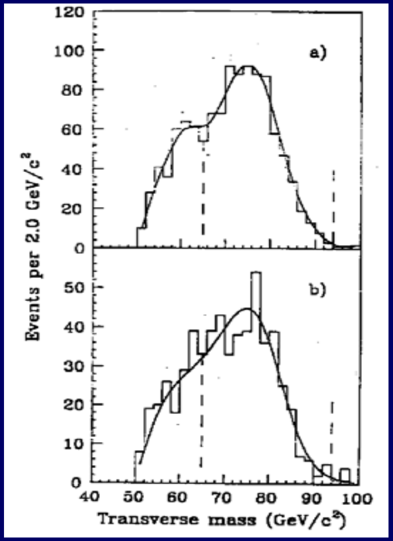
The Tevatron has advanced our understanding of these basic constituents of the SM enormously with ever increasing data sets. Precision measurements of their properties opens a window into possible new physics.



The story of the Tevatron can be traced in this plot; First the observations, then the study of processes with ever-smaller cross sections.

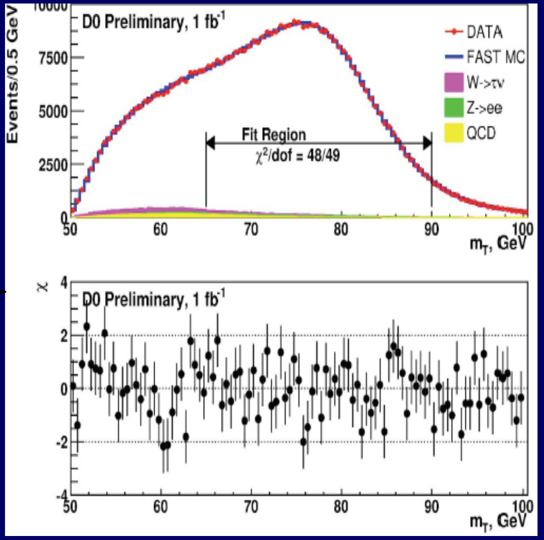
Of the SM studies, only the Higgs is not yet mature. And of course CDF and DØ are working on that!

Samples have grown from handfuls to 1000's enabling detailed studies of W boson and top quark properties and searches for new phenomena



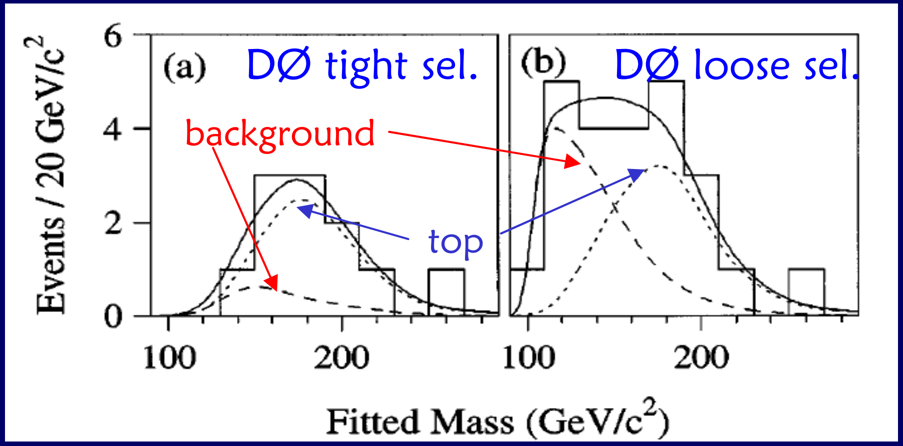
1990 CDF measurement
(~1700 events, 4 pb^{-1}):
δm_W=390 MeV

20 years
of W
studies



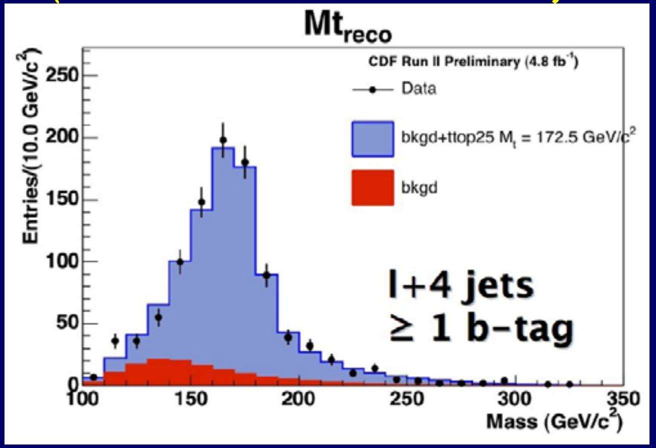
2009 DØ measurement
(500K events, 1000 pb^{-1})
δm_W=43 MeV

1995 DØ top mass
(few events, 50 pb^{-1})

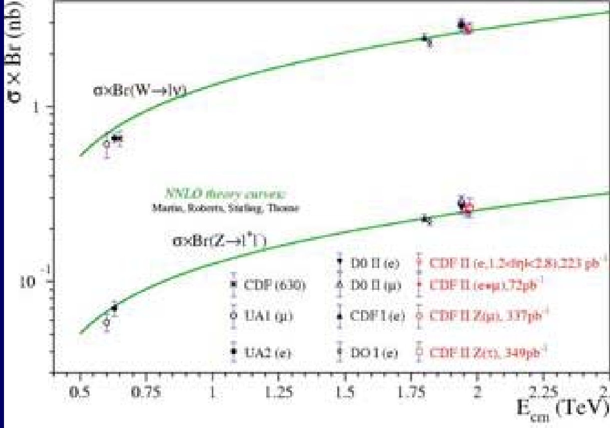


15 years
of top
studies

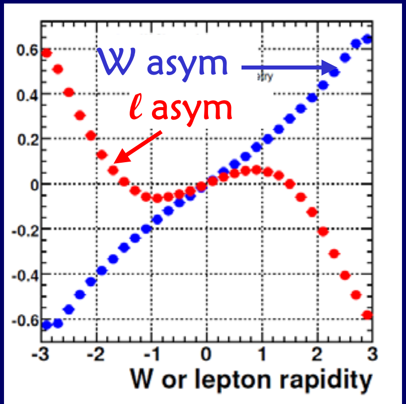
2009 CDF top mass
(~1000 events, 4.8 fb^{-1})



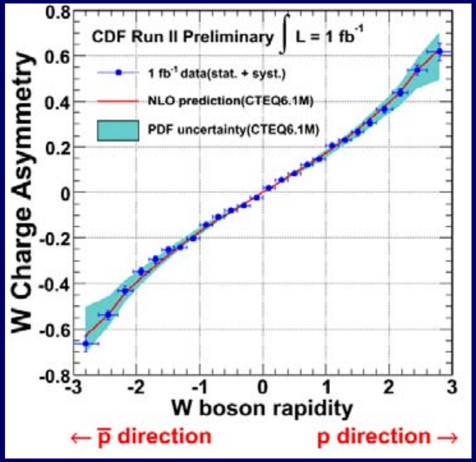
What do we now know about the W boson?



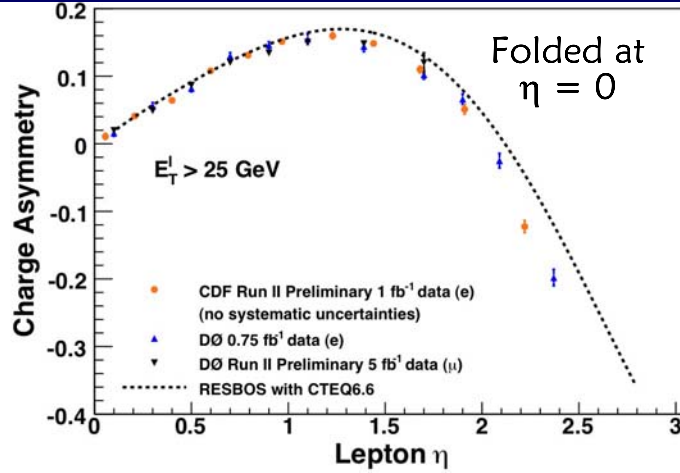
__W production__: Total cross sections agree well with QCD prediction. No WW or WZ resonances < ~700 GeV



Owing to the initial $p\bar{p}$ state, the W^+ and W^- are produced mostly in opposite hemispheres. The V–A decay gives a decay lepton asymmetry of opposite sign to the W asymmetry.



The asymmetry constrains the PDFs for u and d quarks – needed to model the W mass measurements. CDF has performed the difficult unfolding to get the W asymmetry which agrees with current PDFs and confirms the V-A decay.

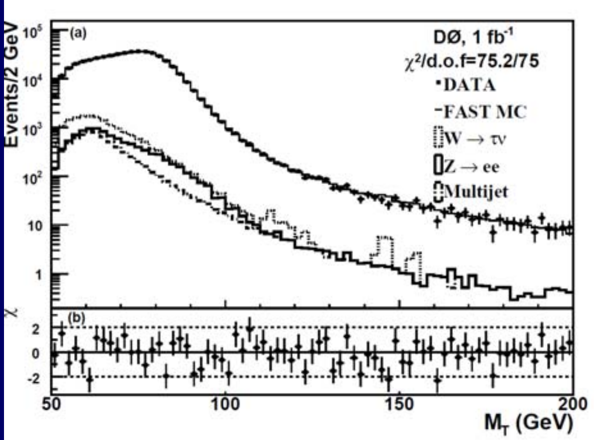


Both experiments measure the lepton asymmetry. Though they agree with each other, they did not agree with the PDF predictions.

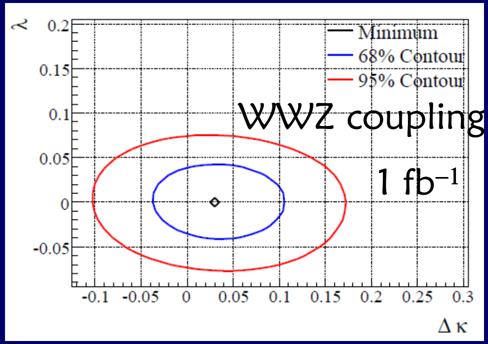
What do we now know about the W boson?

W decays: The W decays democratically with BR = 1/9 to each flavor of $\ell\nu$, and each color of accessible quarks ($\bar{u}d'$ and $\bar{c}s'$). The (e, μ, τ) universality in W decays is good to a few %.

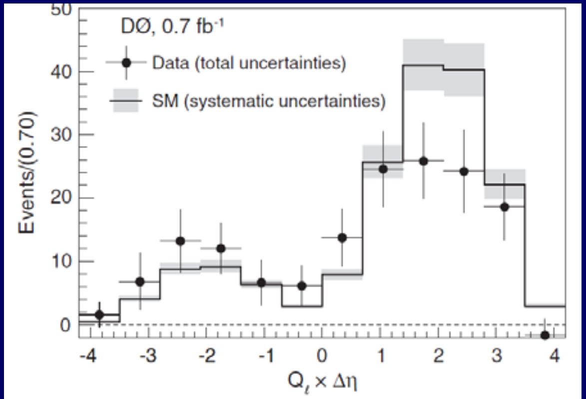
The W decay width can be measured from the high transverse mass Breit Wigner tail. The recent DØ result, $\Gamma_W = 2.028 \pm 0.072$ agrees with the SM and limits new particles in W decay.



Transverse mass: $m_T = \sqrt{2 p_T^e \, p_T^\nu \, (1 - \cos \Delta\phi_{e\nu})}$

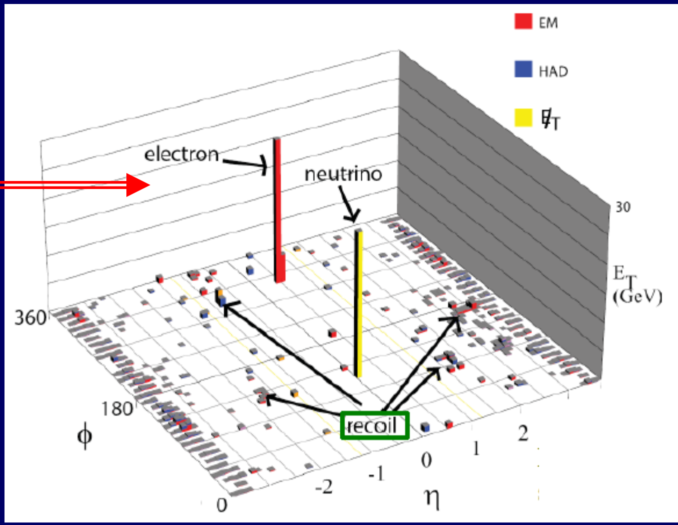


The couplings of WWγ and WWZ are exactly prescribed in the SU(2) x U(1) EW theory. Measurements agree with the SM. (LHC will improve these substantially.)

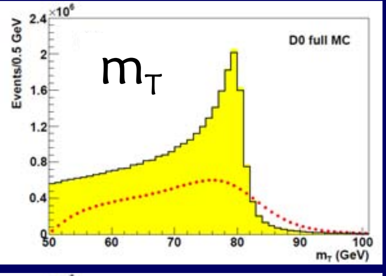


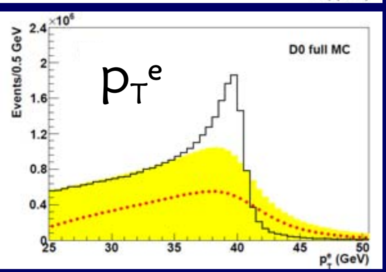
The SM characteristic radiation amplitude zero in Wγ production has been observed.

The W mass measurement method has remained the same since UA2. The events are simple: a lepton (e or μ), missing E_T, and a diffuse hadronic recoil against the W.



The falling edges of the Jacobian peaks of the p_T^e (p_T^ν) and m_T distributions carry the information on the W mass.





The intrinsic (black) m_T and p_T^e distributions are affected differently by p_T^W (yellow) and detector resolutions (red dots), so are complementary. (p_T^ν suffers from both effects)

Have then only(!) to calibrate lepton, MET and hadron recoil energies to per mille level mostly using the Z events, account for detector response, photon radiation, event pileup etc. Put all this into a fast Monte Carlo and generate millions of events. Compare MC templates to data to find the best fit.

Now m_W=80.420±0.031 (Tevatron); 80.399±0.023 GeV (world) (0.03%)

Current 1 fb^{-1} per expt uncertainties are:

δm_W = 23 (W stat) ⊕ 35 (Z stat) ⊕ 12 (model, mostly PDFs) (MeV):

For ultimate goal of 15 MeV, need to make progress on PDF error.

Top quark discovery

Chronology:

~1980: Build TRISTAN ($m_t \approx 3 x m_b$)

1984: UA1 shows unconfirmed suggestion of $W \rightarrow tb$ ($m_t \sim 50$ GeV)

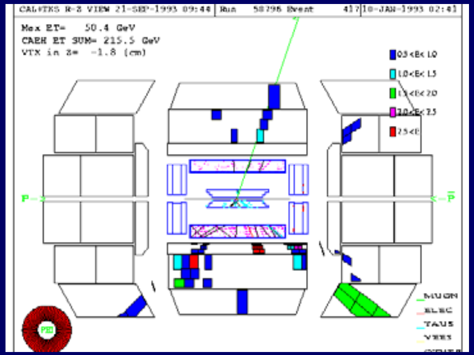
1990: CDF sets limit $m_t > 91$ GeV ruling out W decay to top

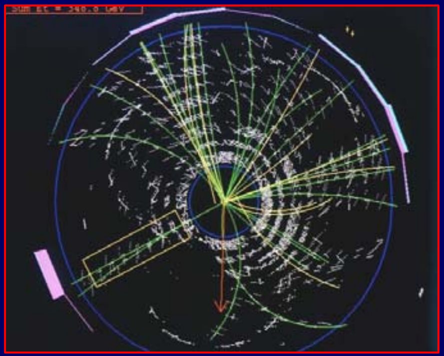
'90's: LEP/SLC: $m_t \sim 150\text{-}200$ GeV

1994: DØ limit at $m_t > 131$ GeV (but a gold plated event seen)

April 1994: Seeing limits not improve with more data, CDF publishes 'evidence' for top at ~175 GeV, ~3σ significance

July 1994: At ICHEP, DØ reports same expected yields, but observed only ~2σ sensitivity





January 1995: Now with 50 pb^{-1}, both collaborations sense a discovery is possible – feverish internal activity but minimal CDF/DØ interactions!

Feb. 17, 1995: CDF delivers a paper to John Peoples, starting the 1 week clock.

Feb. 24, 1995: Simultaneous CDF and DØ PRL submission. (Within large errors, CDF XS too high, DØ mass too high !)

March 2, 1995: Joint seminar announcing the top quark discovery

See article SLAC *Beam Line*, 25, #3 (1995) for more on the discovery.

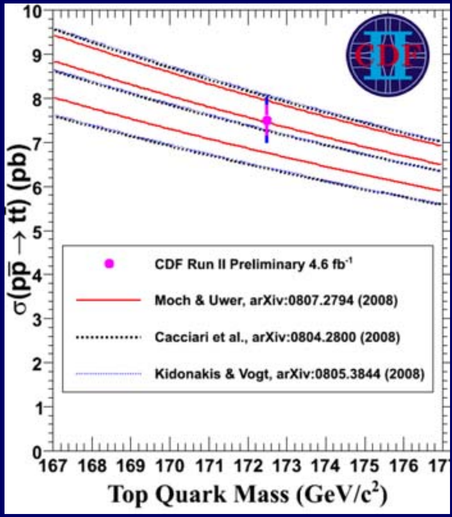
In an editorial, Bjorken wrote of the race to discovery and the need for 2 collaborations, He commented on the oft-corrosive relations between groups making simultaneous discoveries: "… the ensuing CDF/DØ competition has been a class act."

DØ PhD students

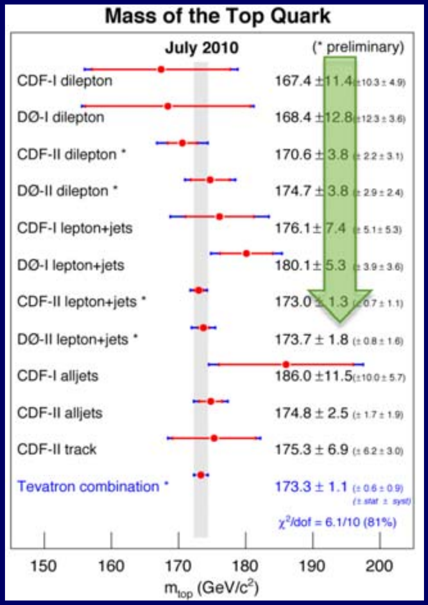
How much have we learned about the top quark?

In $t\bar{t}$ pair production, both tops decay to Wb, so final states only depend on W decay. By now cross section and top mass have been determined in all possible channels. The single lepton channel ($\ell\nu b$ jjb) is favored for detailed studies of properties, as background is moderate and reconstruction is possible.

CDF 4.6 fb^{-1}: $\sigma(t\bar{t})=7.50\pm0.48$ pb (6%), in agreement with the NNLO theory prediction of comparable precision.



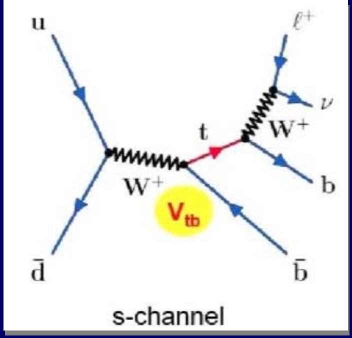
Top quark mass is measured in all channels with several methods to good consistency and high precision.

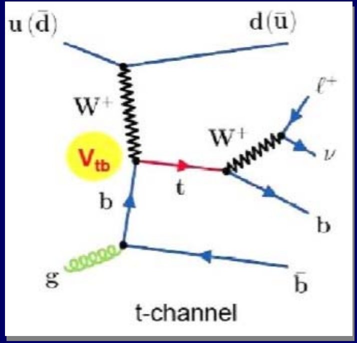


m_t = 173.1 ± 1.1 GeV (0.6%)
Tevatron average

Further improvements will be modest (limiting systematic is knowledge of jet energy scale). But it will be some time before LHC overtakes Tevatron.

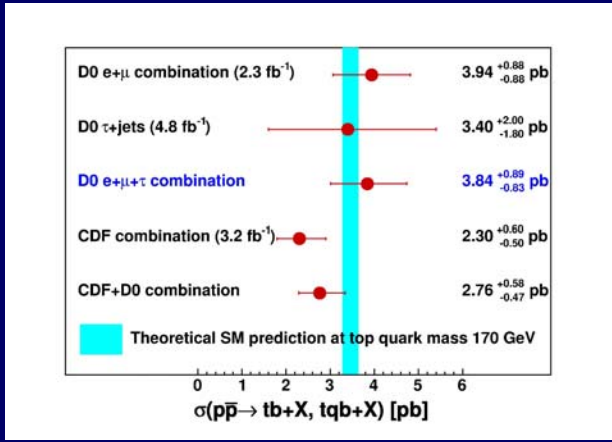
Single top production by EW processes

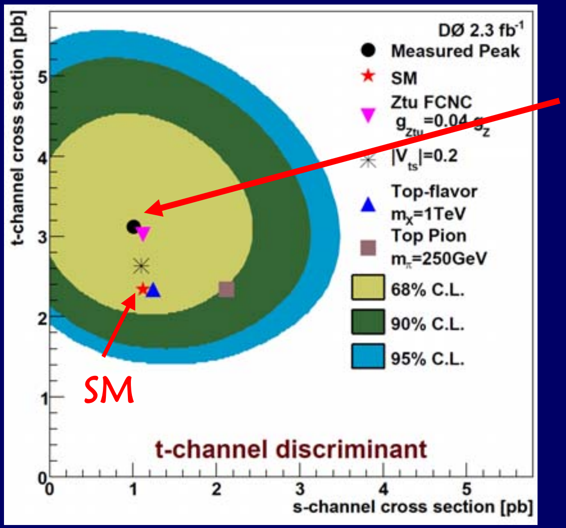




Top quarks are pair-produced by the strong interaction (preserving flavor symmetry). Single top quarks can be produced by EW interaction via s-channel or t-channel W exchange). SM predicts $\sigma \approx 3.2$ pb. DØ and CDF first observation in 2009.

Analyses use sophisticated multivariate methods to dig the signal from large backgrounds. The combined CDF/DØ result is $\sigma = 2.76^{+0.58}_{-0.47}$ pb



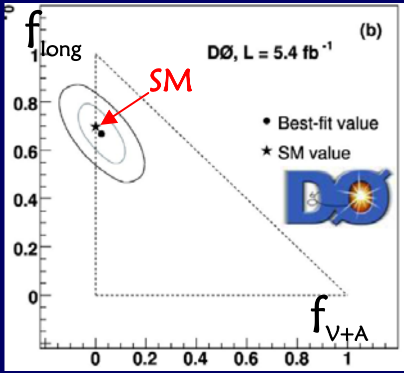


DØ has obtained separate t- and s-channel cross sections. The relation between these is sensitive to the type of new physics beyond SM.

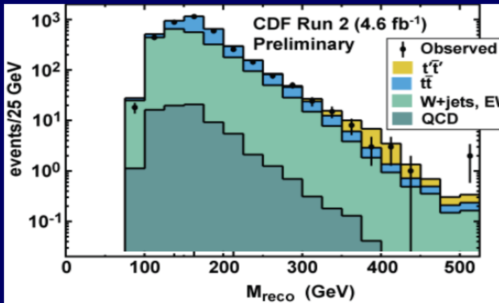
Can also measure the tbW coupling directly (sensitive to 4th quark generation): $|V_{tb}|=0.88\pm0.07$ (SM =1)

Top quark properties

- Are top and antitop masses the same? Test of CPT
  $\Delta m = -3.3 \pm 1.7$ GeV (equal to 2%) (CDF)
- Top quark lifetime (top decays before hadronizing, so this is unique for quarks). $\Gamma_t = 1.99^{+0.69}_{-0.55}$ GeV (0.33 ys !) (DØ), agrees with SM
- Top charge: $|q| = 2/3e$ to 92% C.L. (DØ)
- Asymmetry of top quark in p vs $\bar{p}$ direction,
  expected to be ~1%: DØ: 8±4%; CDF 16±7%
- W helicity in top decay (expect 70% longitudinal,
  30% left-handed SM looks good (DØ) →

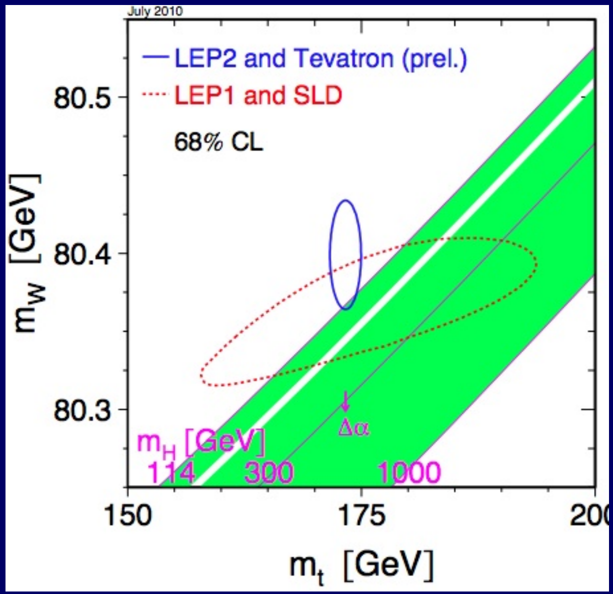


- Correlations of spins of top and anti-top are consistent with SM
- No flavor changing neutral currents: $< 2 \times 10^{-4}$ ($t \to gu$); $< 4 \times 10^{-3}$ ($t \to gc$)
- No evidence for Susy $H^{\pm}$ in top decays
- Anomalous top vector/tensor couplings? DØ combination of W helicity & single top shows good agreement with SM V-A.
- 4^{th} generation t'? CDF: none below 335 GeV →



- tt resonances? None below ~700 GeV
- Is W in t decay color singlet? DØ: singlet preferred

The courtly dance of W and top together



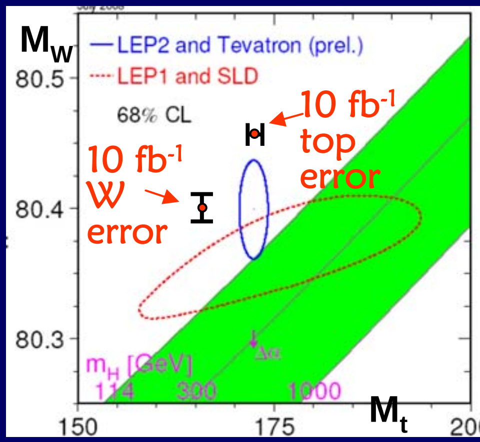
The precise values of m_t and m_W tell us something important.

This plot, one of the most popular over the last 15 years, quantifies the inter-relationship of top, W and Higgs masses due to the virtual loops in their propagators. With the current exquisite precision from the Tevatron, the allowed SM Higgs mass region has shrunk to $114.4 < m_H < 158$ GeV.

The plot scale is adjusted to make the Higgs bands at 45° and the error ellipse shape emphasizes that the W mass most needs improvement. Fortunately, the W mass measurements are still statistics dominated, unlike the top mass.

More data and analysis improvements will shrink the ellipse to the point that if the central value is unchanged, the SM Higgs can be ruled out at 95% C.L. by the Tevatron from top and W measurements alone. (The direct searches will further exclude (or find!) the Higgs.)

And we note that the central value lies in the region expected for Supersymmetric Higgs !



Conclusion

The beautiful music plays on and the dance of the W and top at the Tevatron will continue for at least for 9 months, maybe for 3 more years.

Although the LHC will ultimately acquire much larger data sets, allowing refined measurements of W and top properties, many Tevatron measurements will continue to be the most precise for some time.

The discovery and exploration of the top quark and the precise study of the W boson will be among the chief legacies of the Tevatron.

The friendly competition between CDF and DØ, the strong international collaboration, and sustained support by our funding agencies have enabled these successes.

Those of us fortunate enough to have been here for this performance are grateful for the wonderful opportunity.