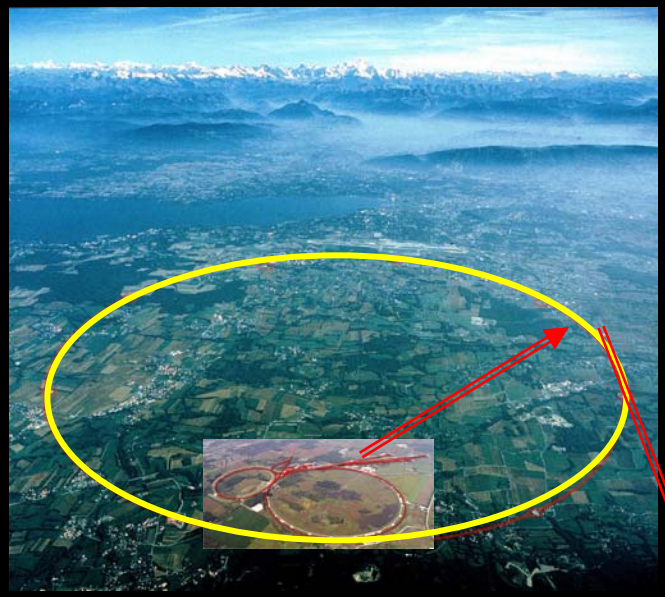
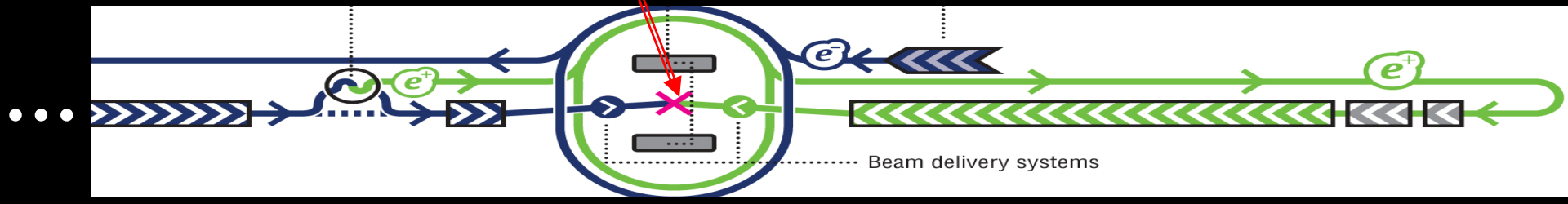
P. Grannis
KILC2012

Recent Results from the Tevatron





Tevatron

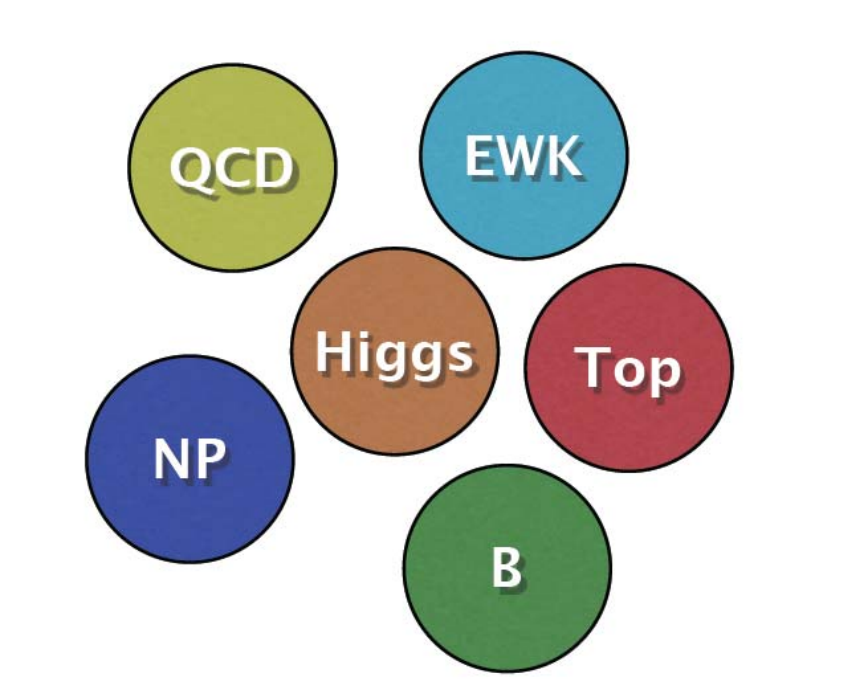
Run I 1987 – 1996; Run II 2001 – 2012, $\mathcal{L}_{max} = 4\times10^{32}\ cm^{-2}s^{-1}$

The Tevatron ended operations in Sept 2011 with nearly 10 fb^{-1} of data for both CDF and DØ. It was a fantastic achievement by the accelerator people!

Although the LHC now takes over at the energy (and luminosity) frontier, some physics topics are best covered by at the Tevatron with its $\bar{q}q$ dominated initial states (and lower pileup).

In this talk, I will focus primarily on recent* results for those topics which are unique or complementary to the LHC.

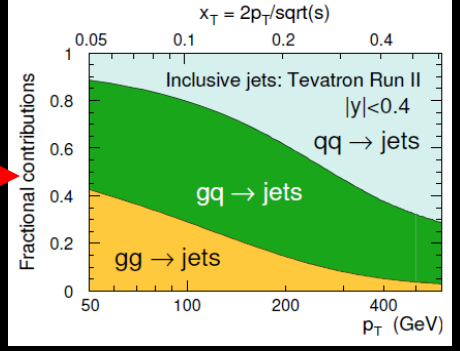
CDF and DØ physics are centered on these six primary groups.



* new since summer 2011 denoted as ®

QCD studies - jets

Inclusive jet production depends on p_T-dependent qq, qg, gg production processes.

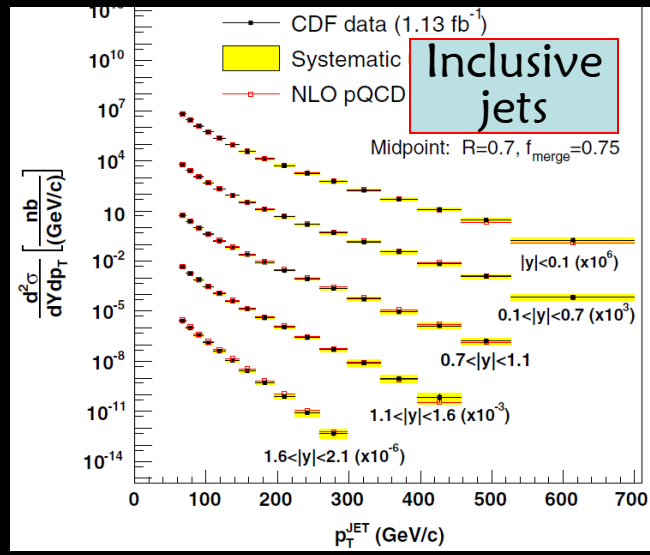


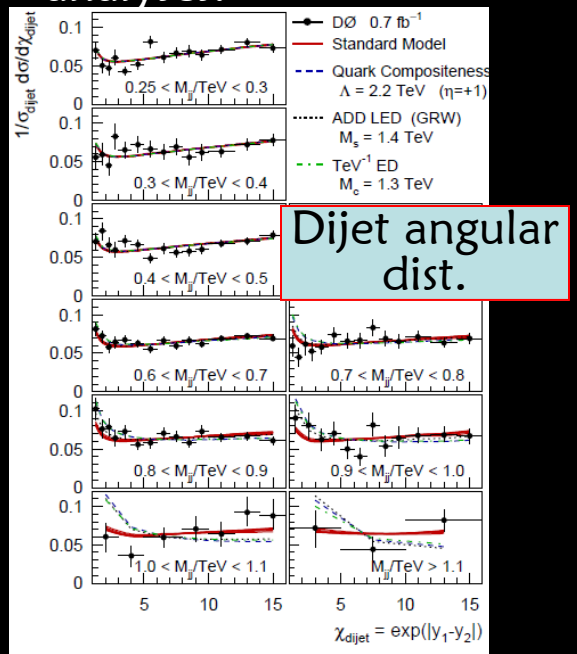
Measure inclusive jet production to $p_T \sim 650$ GeV; dijet mass and angular distributions for $M_{jj} < 1.4$ TeV.

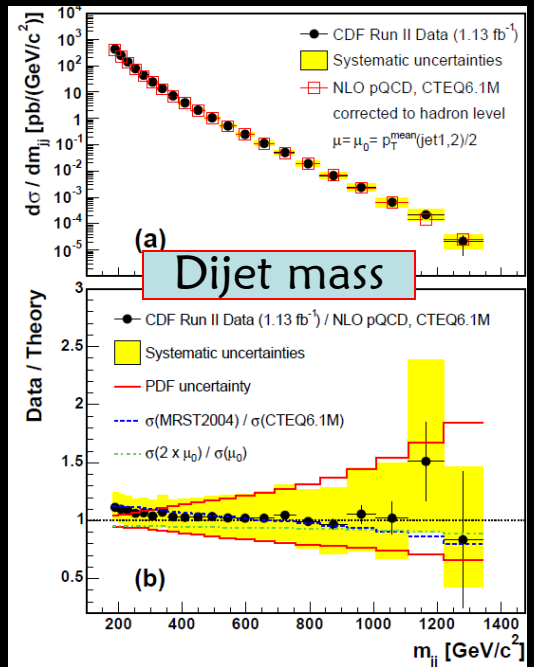
Running of α_s confirmed to $Q^2 \sim 2\times10^4$ GeV^2;

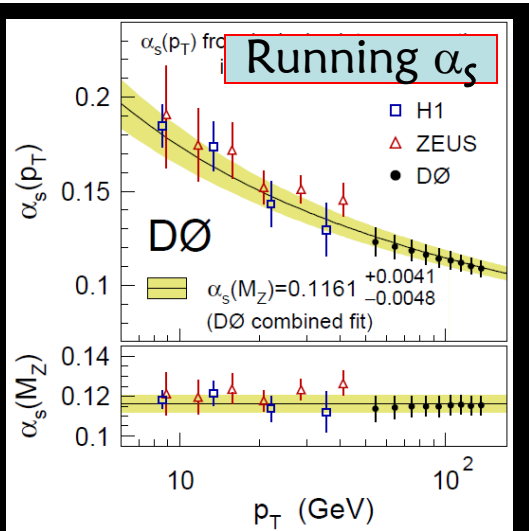
No evidence for dijet resonances, compositeness to 2.8 TeV; no LED to ~1.8 TeV

These data give important constraints on gluon PDFs (less glue at high x than previous fits) and thus aid LHC analyses.









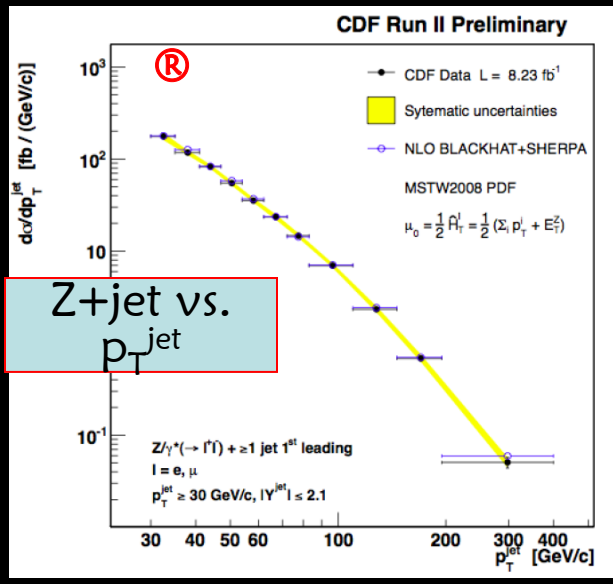
QCD : gauge bosons + jets

Measurements of vector boson + jets (including b/c) test QCD, and are needed to determine backgrounds to Higgs, top quark studies.

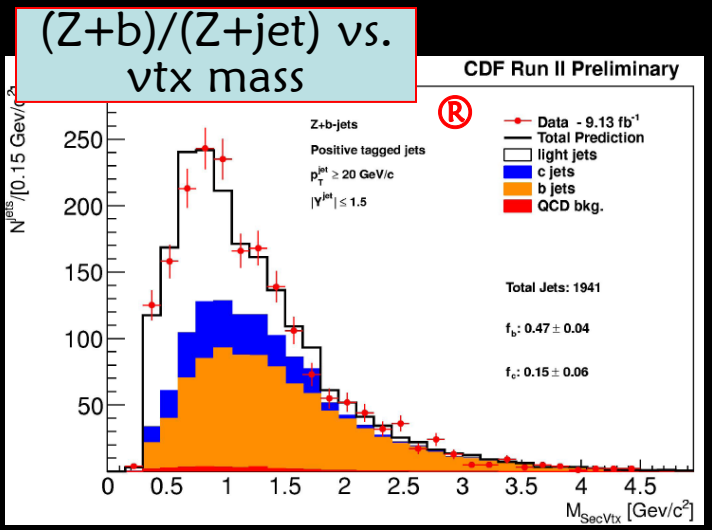
Measurements for V (γ, Z, W) + jets vs. p_T^{jet}, p_T^V, y_V, N_{jets} for inclusive flavor and b/c jets.

Good agreement with modern generators and NLO predictions.

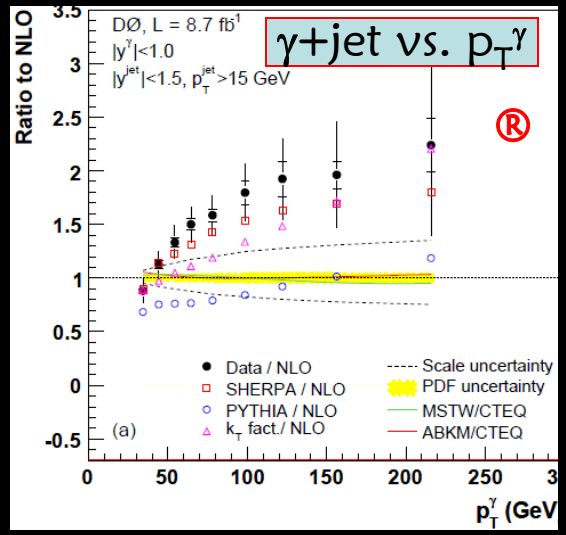
Ratio (Z+b/Z+jet) is in good agreement with QCD (previous CDF result had (W+b/W+jet) ≈ 2.5 QCD).



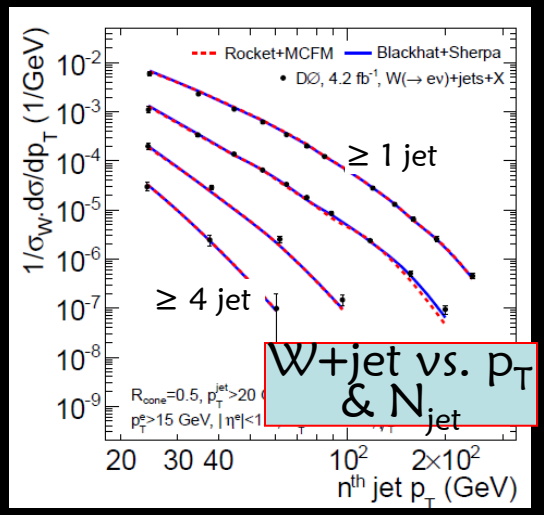
Z+jet vs. p_T^{jet}



(Z+b)/(Z+jet) vs. vtx mass

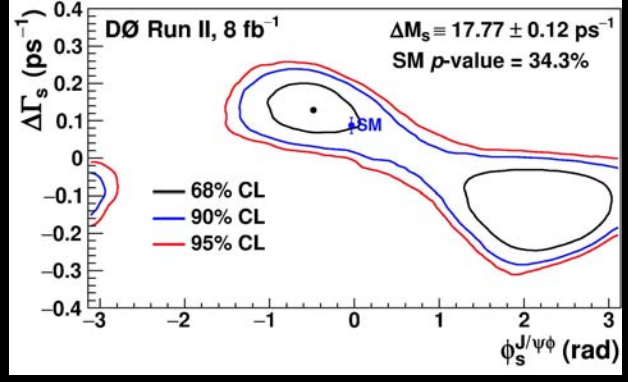


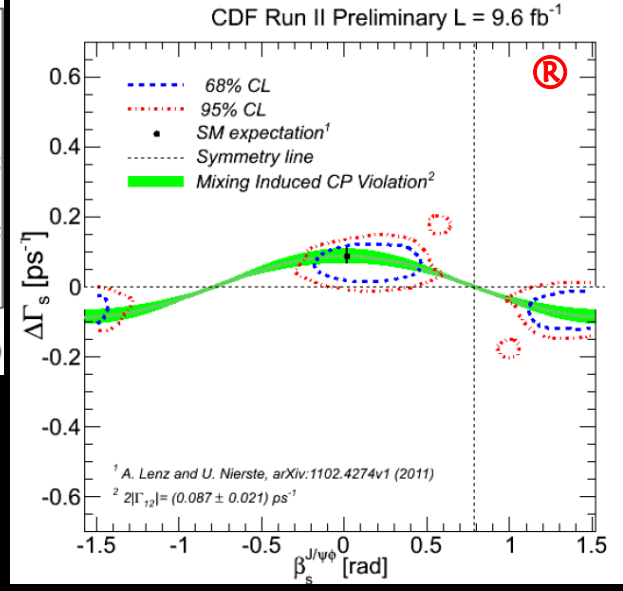
γ+jet vs. p_T^{γ}



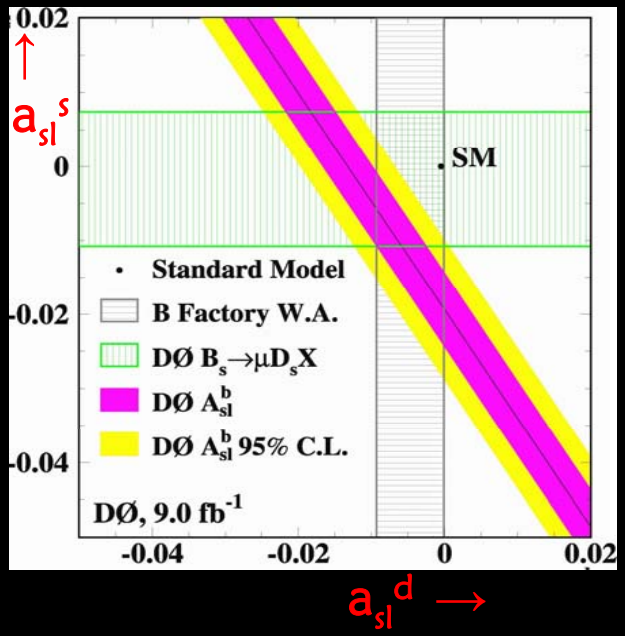
W+jet vs. p_T & N_{jet}

Heavy flavor





Angle β_s (triangle from 2nd-3rd row of CKM matrix) is small in SM. Earlier CDF and DØ results both had ~2σ discrepancies. With new data, β_s is now consistent with SM, and with LHC measurements.



Like sign dimuon asymmetry $(\mu^+\mu^+ - \mu^-\mu^-)/(\mu^+\mu^+ + \mu^-\mu^-)$ reanalyzed with 9 fb^{-1} confirms earlier result. Now 3.9σ different from SM prediction ($A = -0.787 \pm 0.196$ %) (matter excess over antimatter).

Impact parameter dependence suggests the source is from b-meson semi-leptonic decays.

Expect to improve the a^s_{sl} constraint (B_s). The like-sign asymmetry measurement cannot be done at LHC, though complementary measurements can be made.

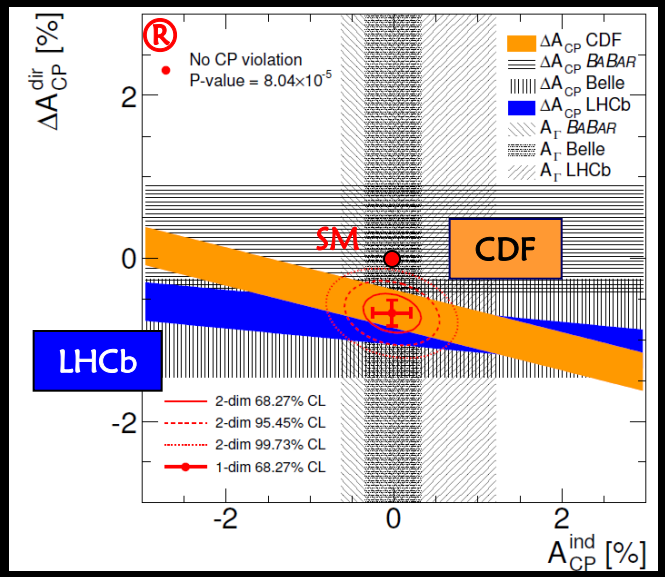
Heavy flavor

CDF analysis of $B_s \to \mu\mu$ with full data set. Previous 2.5σ discrepancy with SM has not gone away but is now weaker: BR = $(1.3^{+0.9}_{-0.7}) \times 10^{-8}$

B_s Results

SM: B = $(3.2 \pm 0.2) \times 10^{-9}$

	All Bins	NN>0.987
Fit ($\times 10^{-8}$)	$1.3^{+0.9}_{-0.7}$	$1.0^{+0.8}_{-0.6}$
90% CL ($\times 10^{-8}$)	$0.22 < \mathcal{B} < 3.0$	$0.08 < \mathcal{B} < 2.5$
Bkg p-value	0.94%	2.1%
SM+Bkg p-value	7.1%	22.5%



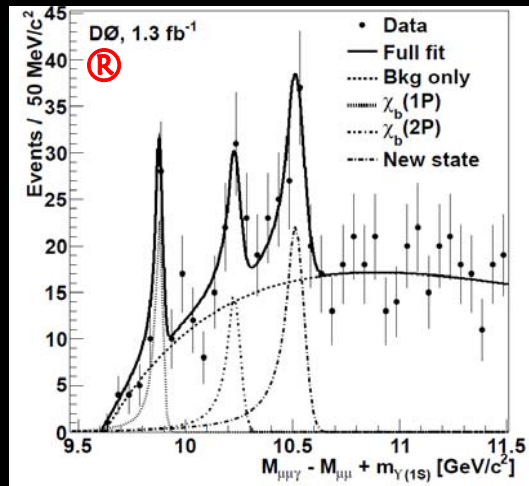
Time integrated CP asymmetry in D^0 decays:

$A_{CP}(hh) = [(D^0 \to h^+h^-) - (\bar{D}^0 \to h^+h^-)]/\text{sum}$

CDF measures $\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi)$ to be $\Delta A_{CP} = -0.62 \pm 0.23$ %, 2.7σ from SM (expect 0) and in agreement with LHCb.

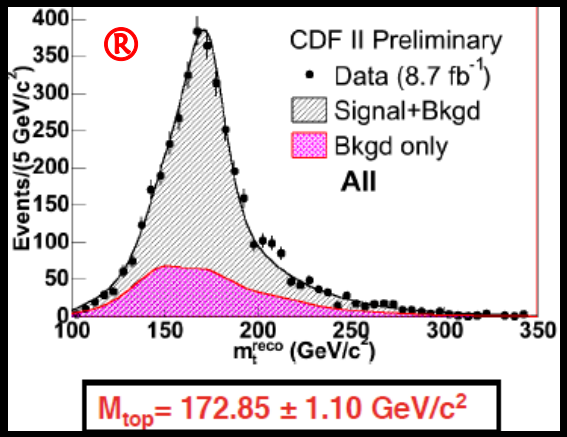
Combined 3.8σ evidence of non-SM CP in charm sector.

DØ obtained 6σ observation of a resonance in $\Upsilon(1S)\gamma$ at M=10.550 ± 0.022 GeV. This appears to be the same state seen by ATLAS (M = 10.530 ± 0.019 GeV) which is tentatively associated with the $\chi_b(3P)$ state partner to the known $\chi_b(1P)$ and $\chi_b(2P)$.



Top quark

Top and antitop masses consistent with being the same:
CDF® $\Delta M = -1.95 \pm 1.26$ GeV (D0: $\Delta M = 0.8 \pm 1.9$ GeV)



2011 W.A. mass M_t=173.2 ± 0.9 GeV not yet including the recent CDF ℓ+jets and D0 dilepton results.

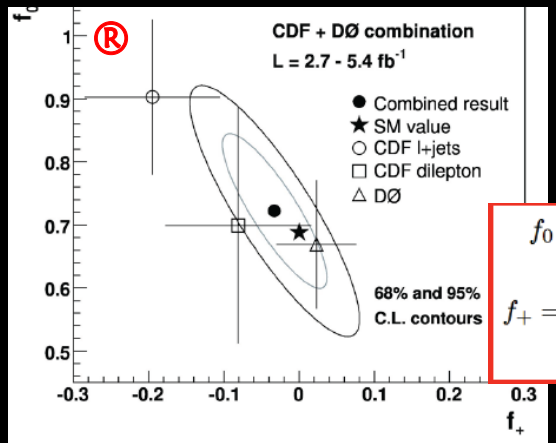
D0 measurement of cross section was used to measure the mass independent of MC mass templates and finds that what we measure is closer to being the pole mass than $\overline{MS}$.

New D0 measurement® of top width/lifetime

$$\Gamma_t = 2.00^{+0.47}_{-0.43}\ \text{GeV}$$

$$\tau_t = (3.29^{+0.90}_{-0.63}) \times 10^{-25}\ \text{s}$$

W helicity fractions in top decay are as predicted in SM (CDF/D0 combined)

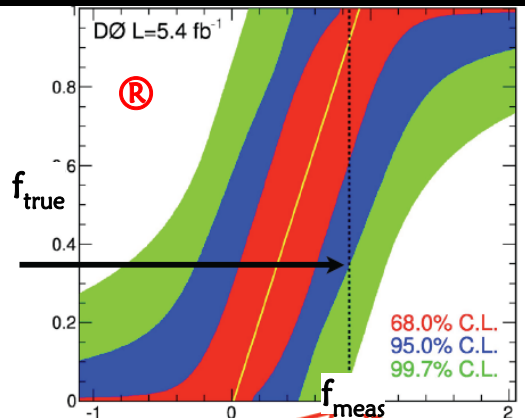


$$f_0 = 0.722 \pm 0.081$$
$$[\pm\ 0.062\ (\text{stat.}) \pm 0.052\ (\text{syst.})],$$
$$f_+ = -0.033 \pm 0.046$$
$$[\pm\ 0.034\ (\text{stat.}) \pm 0.031\ (\text{syst.})]$$

D0 observes nonzero tt spin correlation at 3.1σ, with value consistent with SM

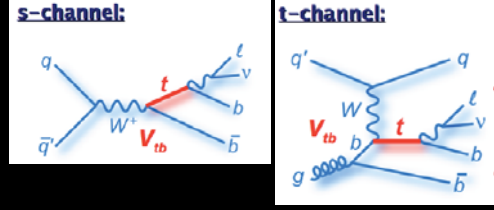
f= fraction of tt spins that are correlated

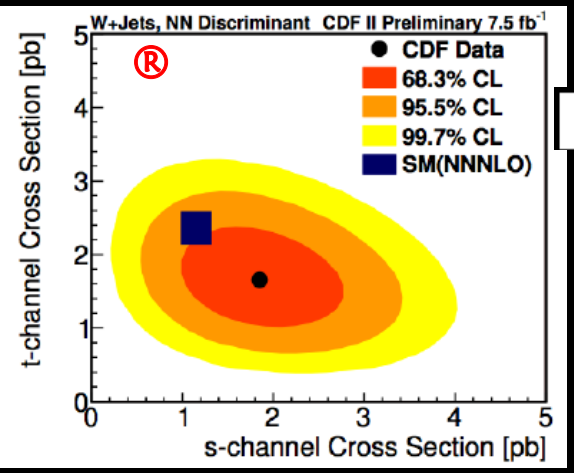
f_{meas} = 0.85±0.29



Single Top

EW production of single top quarks proceeds by s- and t-channel processes (s-channel very small at LHC).





$\sigma(s+t)=3.04 \pm 0.55$pb

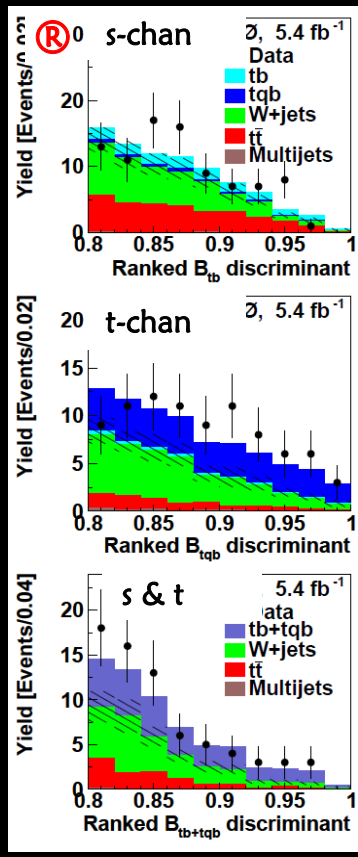
$\sigma(t)=1.49^{+0.48}_{-0.40}$ pb

$\sigma(s)=1.81^{+0.63}_{-0.58}$ pb

CDF

D0

MVA training output

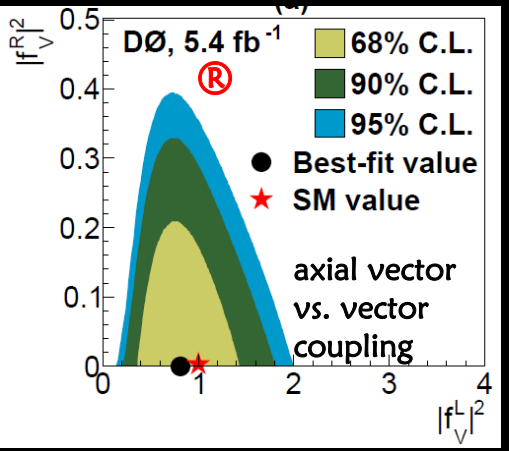


$\sigma(p\bar{p} \to tb + tqb + X) = 3.43^{+0.73}_{-0.74}$ pb

$\sigma(p\bar{p} \to tb + X) = 0.68^{+0.38}_{-0.35}$ pb

$\sigma(p\bar{p} \to tqb + X) = 2.86^{+0.69}_{-0.63}$ pb

CDF & D0 now measuring s- and t-channel cross sections independently, consistent with SM. Departures distinguish types of new physics.



Single top measurements, together with the W helicity measurements, constrain anomalous tWb couplings (axial vector and L or R tensor).

Single top XS is sensitive to V_{tb} (without assuming 3 generations)

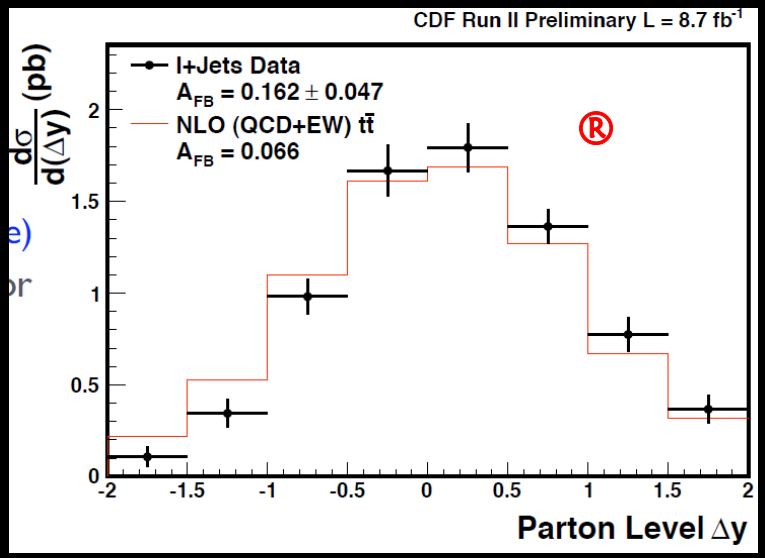
$|V_{tb}| = 1.02^{+0.10}_{-0.11}$ D0

$V_{tb}=0.92 \pm 0.09(ex) \pm 0.05(th)$ CDF

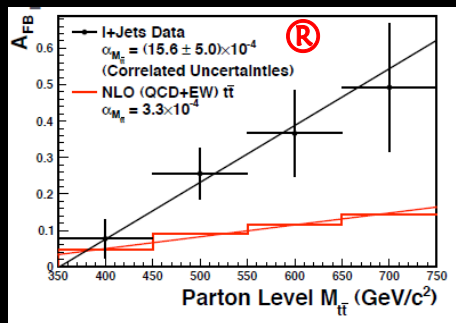
Top pair production

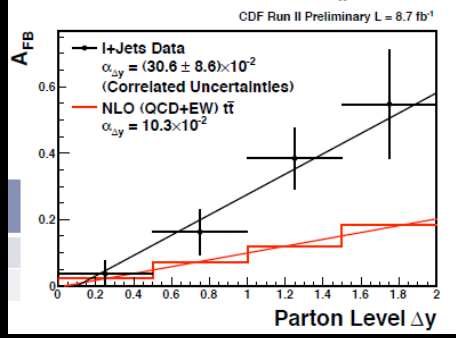
Forward-backward $t\bar{t}$ asymmetry in $p\bar{p}$ collisions arises in SM at NLO from interference effects. Experiments measure A_{FB} at reconstruction level, unfolded to parton level, or in the decay lepton. Both CDF and D0 reported reconstructed level asymmetry at more than 2σ level.

New result from CDF: $A_{FB}^{parton} = 16.2 \pm 4.7$ %
(SM (POWHEG) $A_{FB}^{parton} = 6.6\%$)

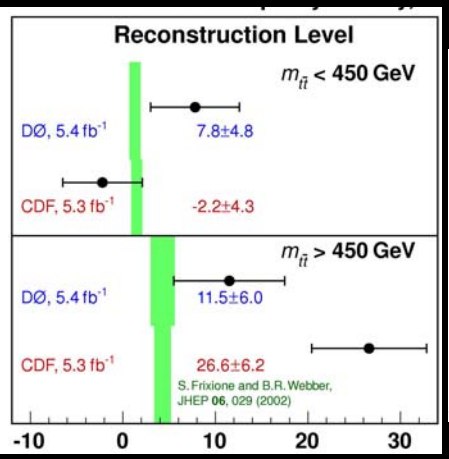


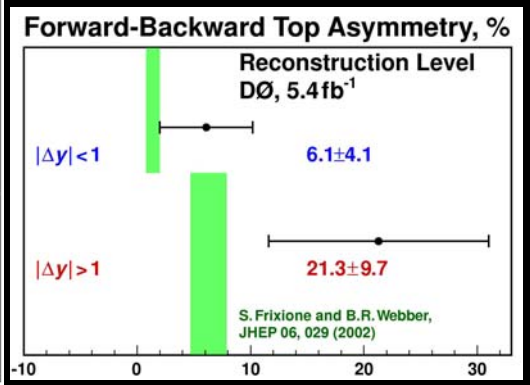
The new CDF result continues to show the asymmetry growing with M_{tt} and Δy





The earlier D0 measurement (at reconstruction level) shows less M_{tt} and Δy dependence.

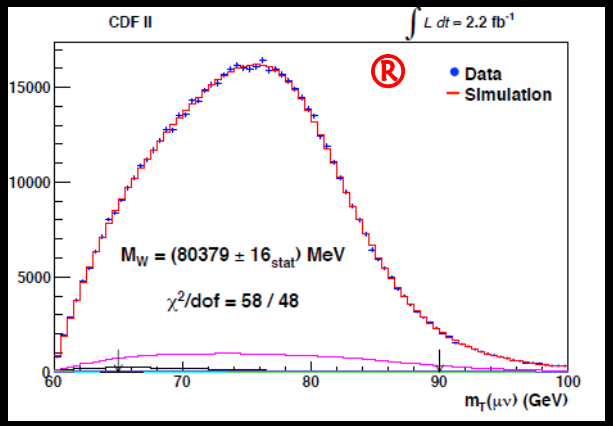




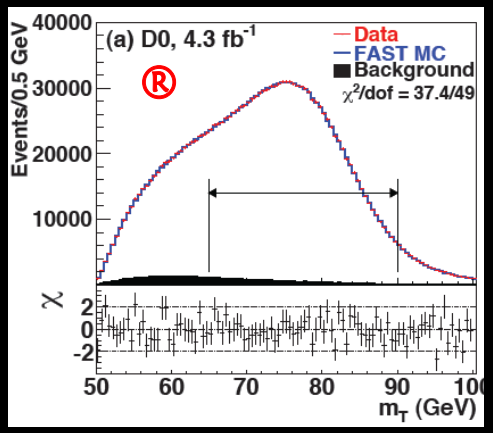
LHC (in pp) measures a different asymmetry.

Electroweak – M_W

Both CDF and D0 have new W mass measurements. At the 0.025% level, need exquisite control of effects of pileup, QED radiation, hadronic recoil, energy calibration.



Transverse mass (eν) and best template fit



The 2.2 fb^{-1} CDF result uses both $W \to \mu\nu$ and eν. Calibration using $\Upsilon/J/\psi$, $Z \to \mu\mu$.

M_W=80,387 ± 19 MeV.

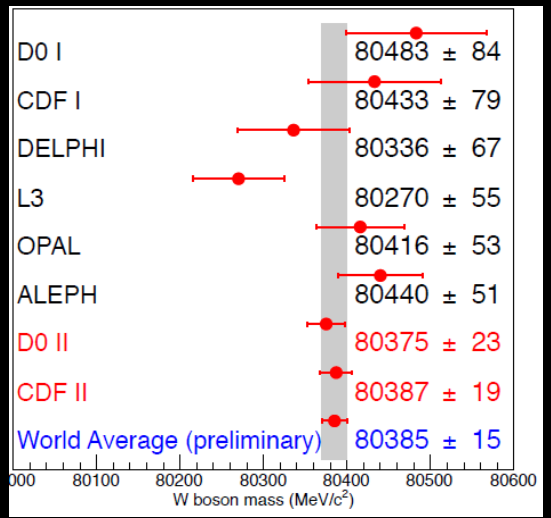
The 5.3 fb^{-1} D0 result uses $W \to e\nu$, and calibrates the $Z \to ee$ mass to LEP.

M_W = 80,375 ± 23 MeV

New World Average (LEP, Tevatron):

M_W = 80,385 ± 15 MeV

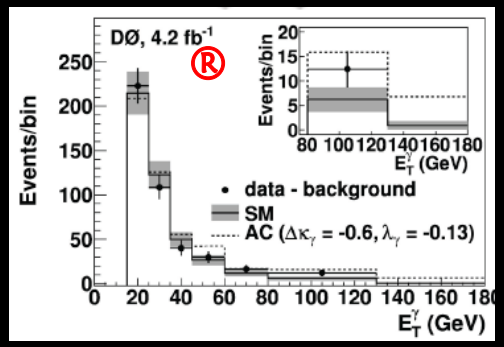
(Old WA: M_W = 80,399 ± 23 MeV)

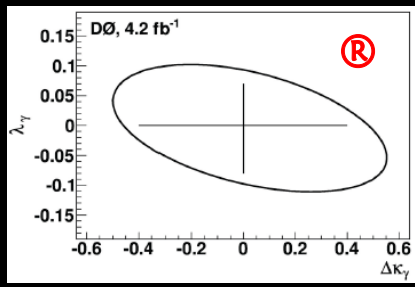


Further improvements: More data (x2-4), use of forward electrons (D0) to reduce PDF errors. Can get $\delta M_W \sim 10$ MeV

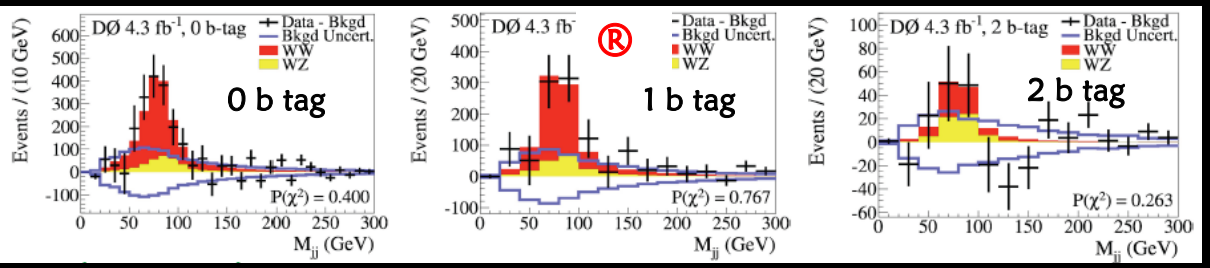
Electroweak

Diboson cross sections are sensitive to non-SM effects. Measure all boson pair combinations, most with all leptonic or mixed lepton/hadron final states.

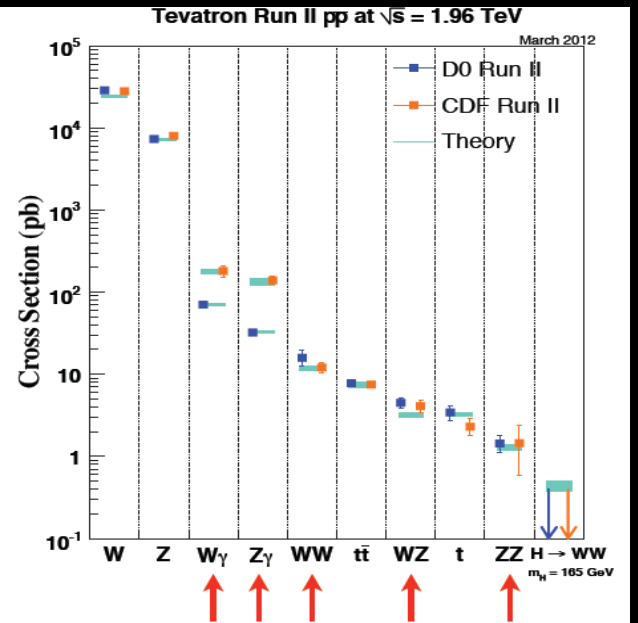




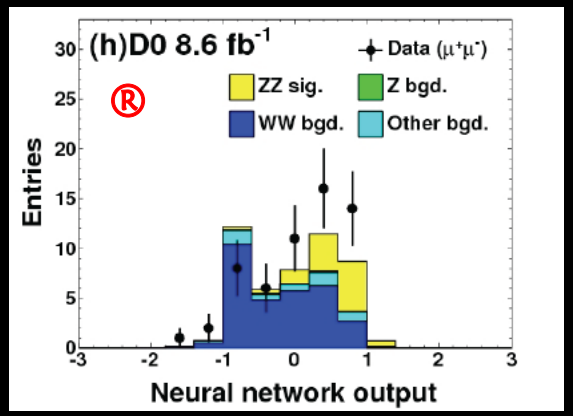
$W\gamma$ ET distribution and anomalous coupling limits.



W(eν)W/Z(qq) signal; XS agrees with all-lepton mode and SM; 7.9σ significance



Z(ℓℓ)Z(νν)



All diboson measurements are measured and agree with SM. These processes are major contributors to the Higgs search channels.

Higgs boson

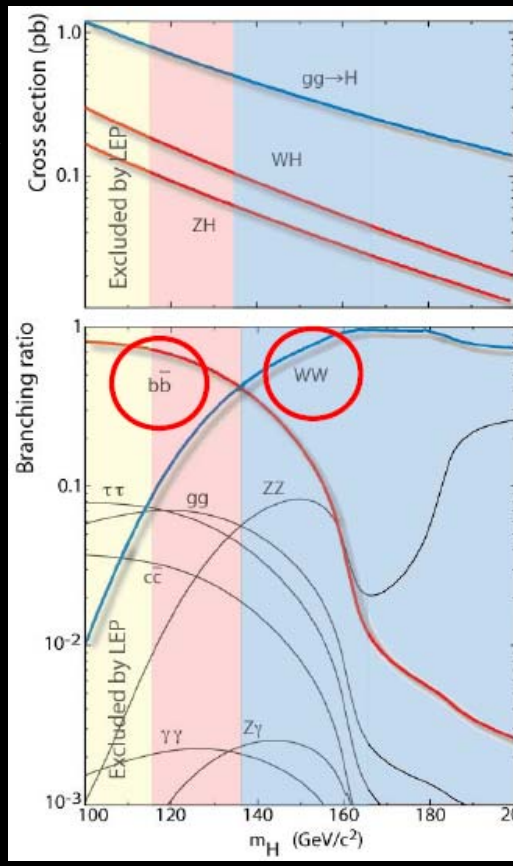
Production mechanisms: gg fusion, vector boson fusion, associated VH, ttH

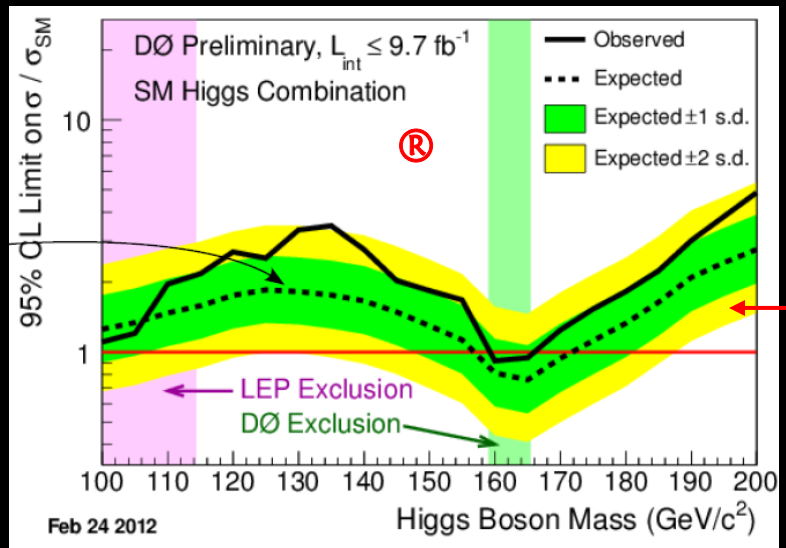
Decay channels: bb, ττ, WW, ZZ, γγ, with BRs very dependent on Higgs mass.

A complex toolkit: multivariate discriminants for b and c tagging & lepton ID; missing E_T significance variables, invariant mass constraints; multiple triggers.

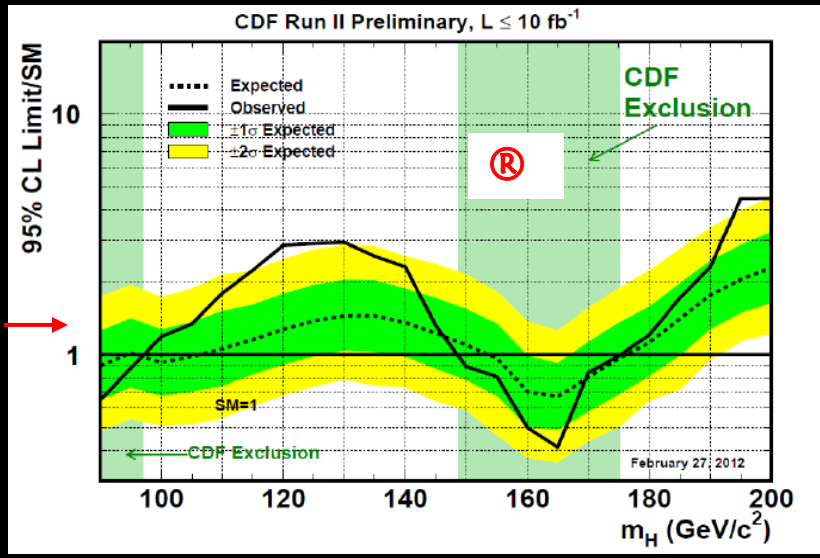
Many discriminating variables are input to Multivariate Discriminants (Decision trees, NNs, Random Forests), sometimes at multiple levels to remove backgrounds sequentially.

Many channels (Njets, lepton type, # b-tags …) fed to modified Frequentist or Bayesian limit setting algorithms.



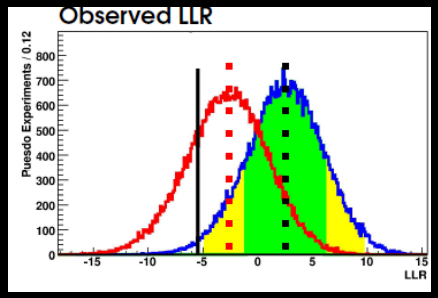


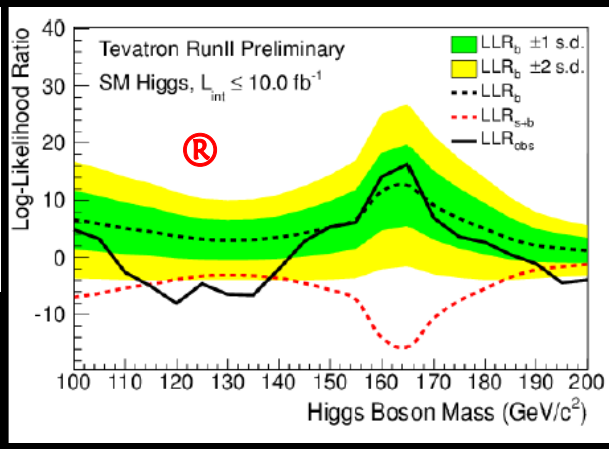
Ratio of 95% CL limits to SM XS, combining all channels

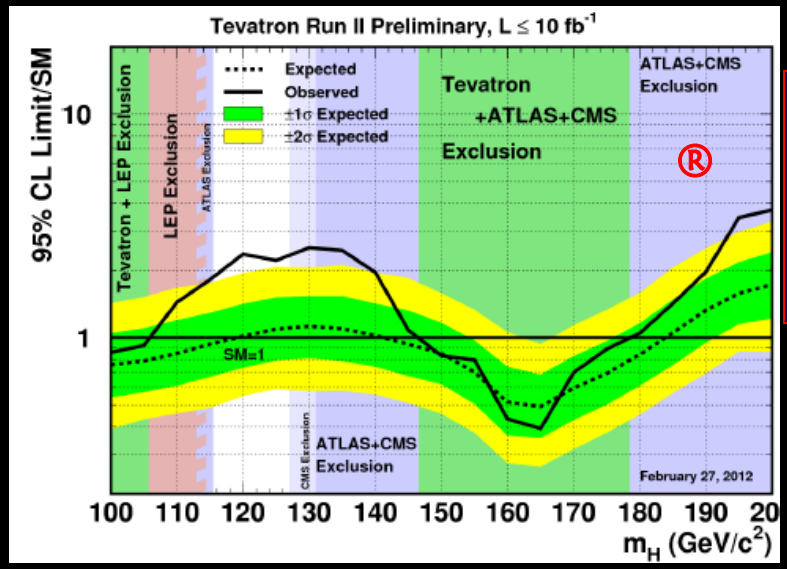


Combined Higgs results

Pseudo experiments assess probability for observed data to conform to Bknd only or S+B hypotheses.

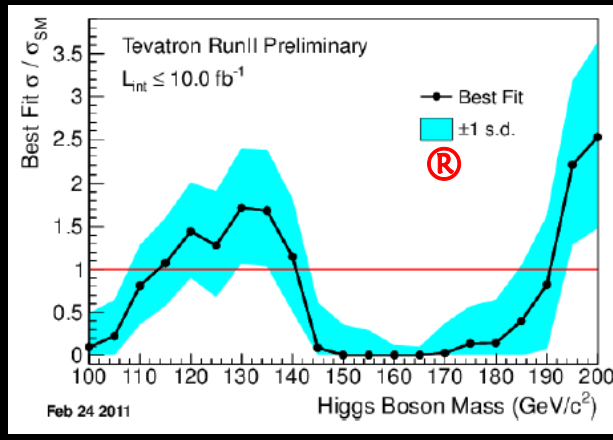






Combined CDF/D0 sees an excess with low probability to be background in the 120 – 140 GeV region. At 120 GeV, the local significance is 2.7σ (2.2σ with a conservative Look Elsewhere factor).

Treat excess as signal: best fit σ/σ_{SM}



Tevatron is sensitive to the primary bbH and WWH/ZZH couplings and thus complements LHC.

More data remains to be analyzed, more channels, improved algorithms, so Tevatron is not done yet !

Verifying the Higgs results

The Higgs search analyses are very complex:

Complex algorithms for tagging b-quark jets, and for lepton, jet and MET ID

Dozens of correlated variables are used in the multivariate analyses

Sometimes use two-stage multivariate analyses

Fit nuisance parameters (e.g. W + b-jet XS …) to obtain best fit in background dominated regions, so as to improve the prediction in the signal region.

So, how can we assure ourselves that this machinery works correctly?

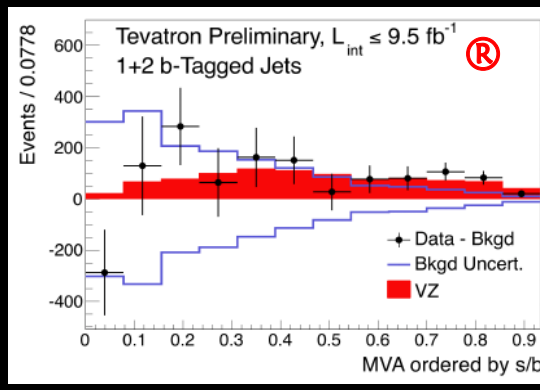
Answer: Do exactly the same analysis on exactly the same final states ($\ell\ell$bb, $\ell\nu$bb, $\nu\nu$bb), now assuming that the signal being sought is WZ/ZZ production (WW taken here as known background).

The result (CDF&DØ combined) is $\sigma(WZ+ZZ) = 4.47 \pm 0.64 \pm 0.73$ pb to be compared with SM value 4.4 ± 0.3 pb.

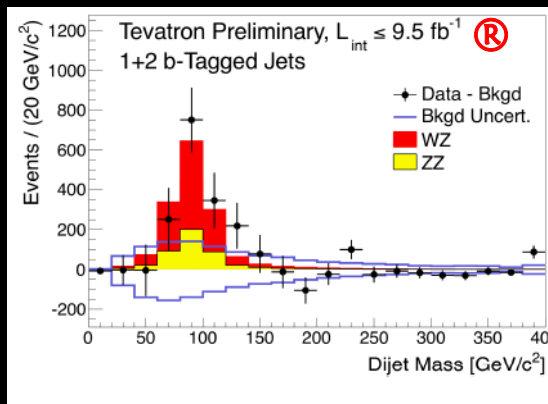
Significance is $\sim 4.6\sigma$

Ratio of ZZ/WZ is consistent with SM

Event distrib'n as a function of S/B in final MVA variable



di b-jet distribution

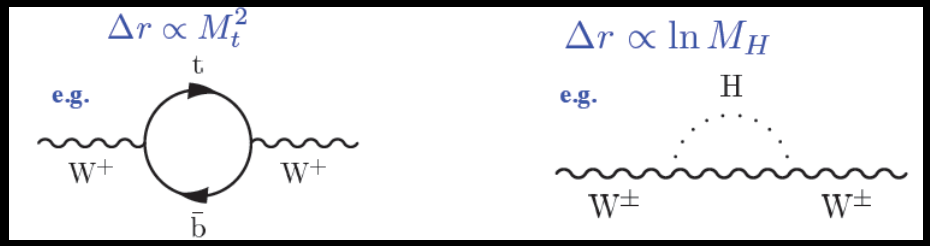


SM constraints

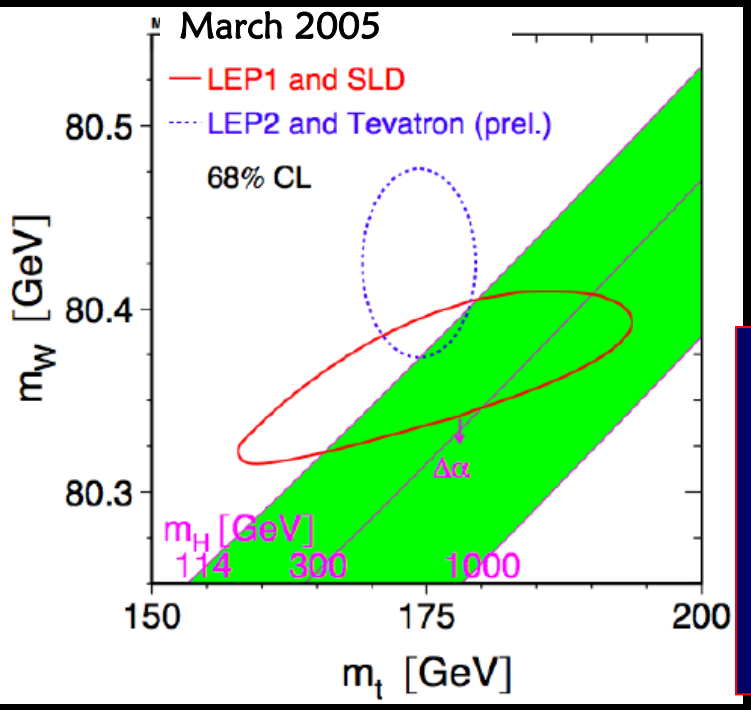
The SM prescribes the relation among M_t, M_W and M_H through radiative corrections due to loop diagrams.

$$M_W = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F}}\frac{1}{\sin\theta_W\sqrt{1-\Delta r}}$$

Radiative corrections Δr

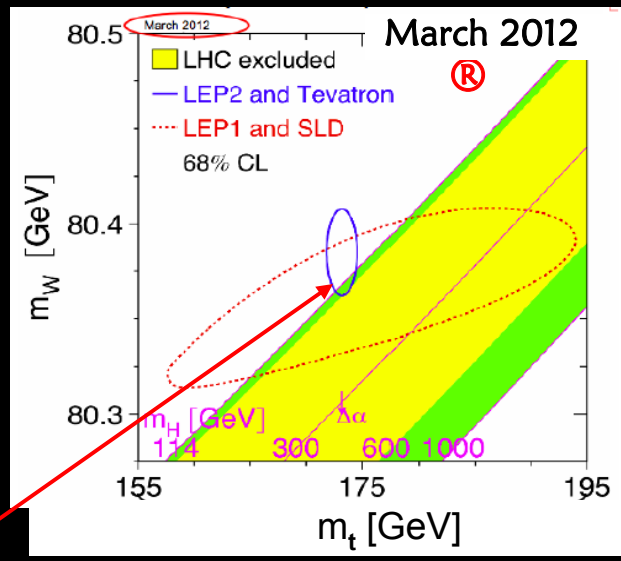


The precise M_t, M_W measurements, and combined LEP, Tevatron and LHC Higgs searches are now highly constrained, and can be plotted in the M_t – M_W plane.



same scale

The Tevatron progress in 7 years is dramatic. With the LHC Higgs exclusion, only a small region remains for the Higgs to hide in.

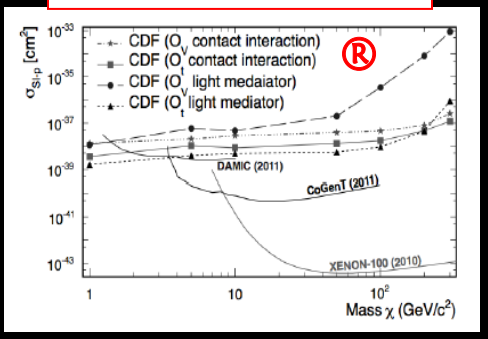


And we have hints that the Higgs is lurking there !

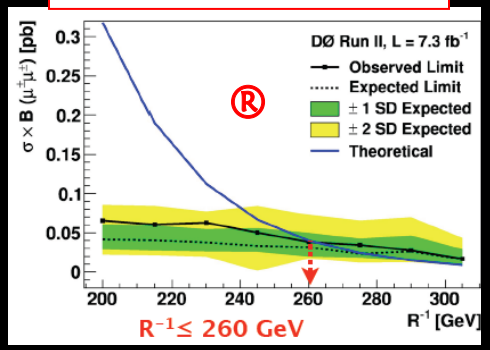
Searches for New Phenomena

The searches for something beyond the SM go on …

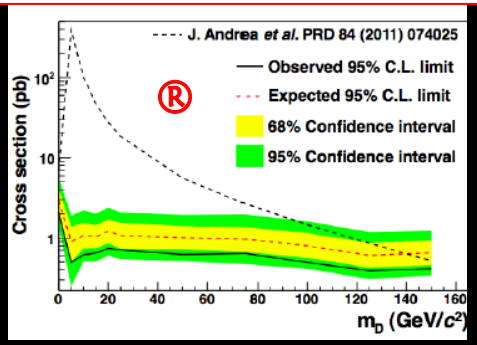
Dark matter (monojets)



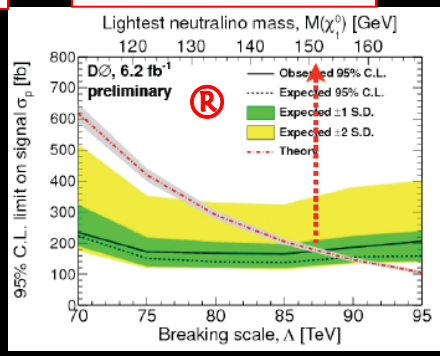
Minimal LED: KK states



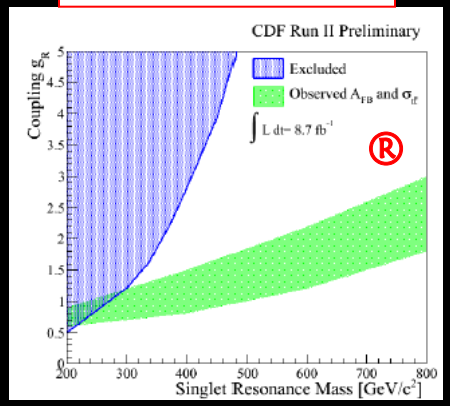
Zγ MET gravitino search (GMSB)



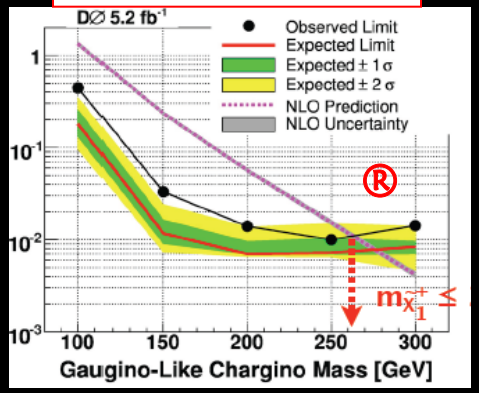
Monotop + MET



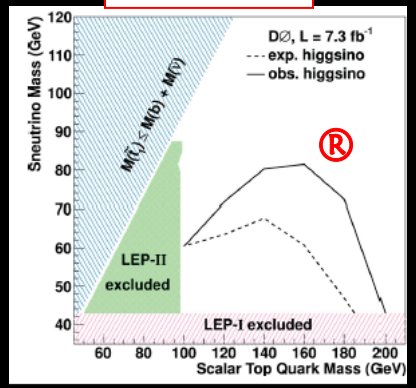
Top + jet resonance



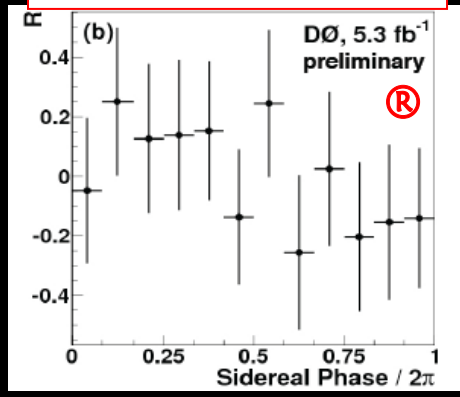
Quasi-stable chargino



Higgsino



Sidereal dependence of top production (Lorentz non-Invariance)



But the search for new phenomena is passing to the LHC

Conclusions

- The Tevatron was at the energy frontier for 23 years, with ~1000 publications from CDF and DØ that have given new understanding in many sectors.

- Although we now look to the LHC to take over and help us explain the origin of Electroweak symmetry breaking, and to break the SM (or help explain why it survives) …

- … The Tevatron still has work to do owing to the uniqueness of proton-antiproton collisions. Expect further results on the W mass, like-sign dimuon asymmetry, A_{FB} in top quark production, and on low mass Higgs production in its dominant decay modes.