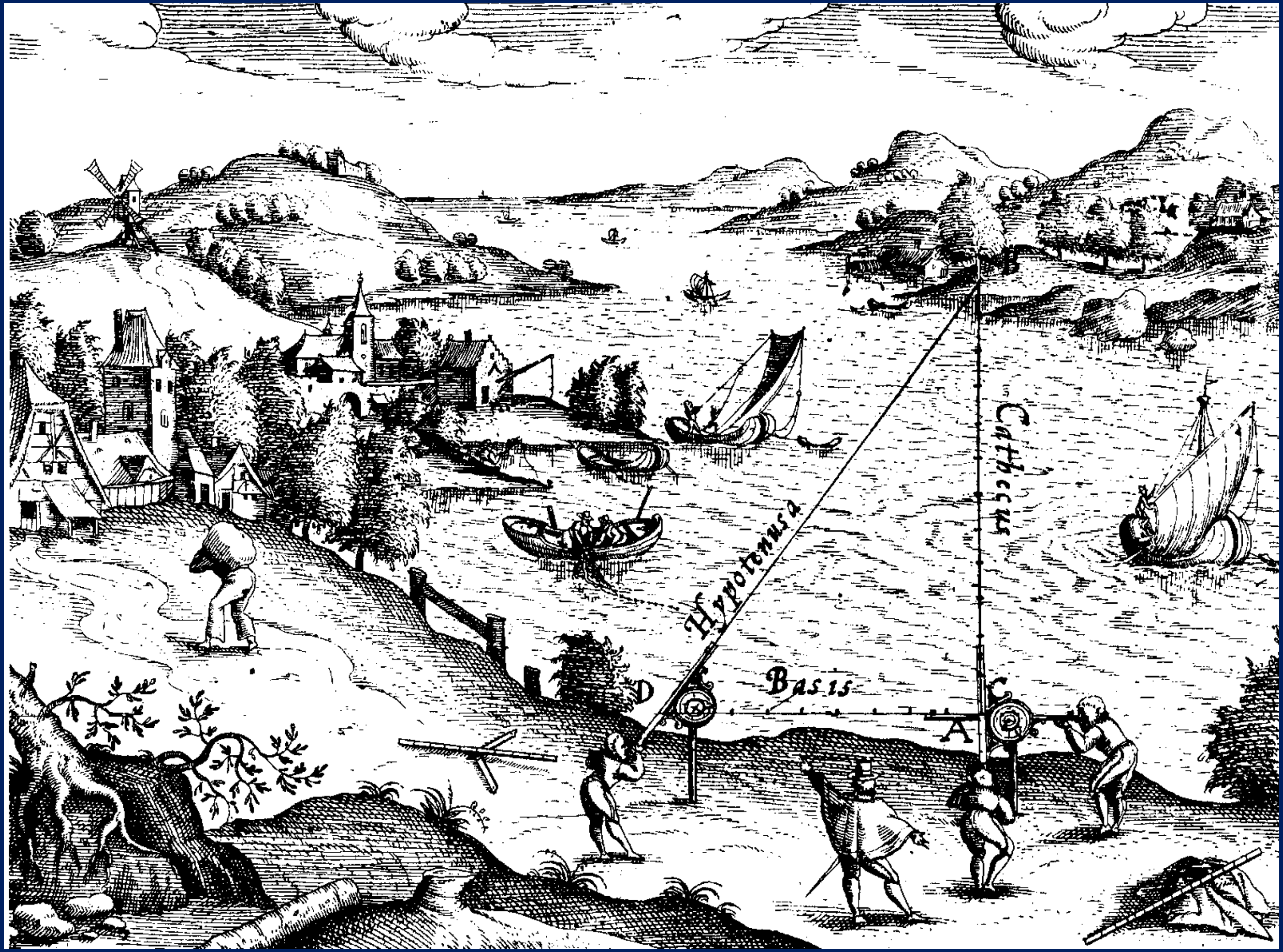
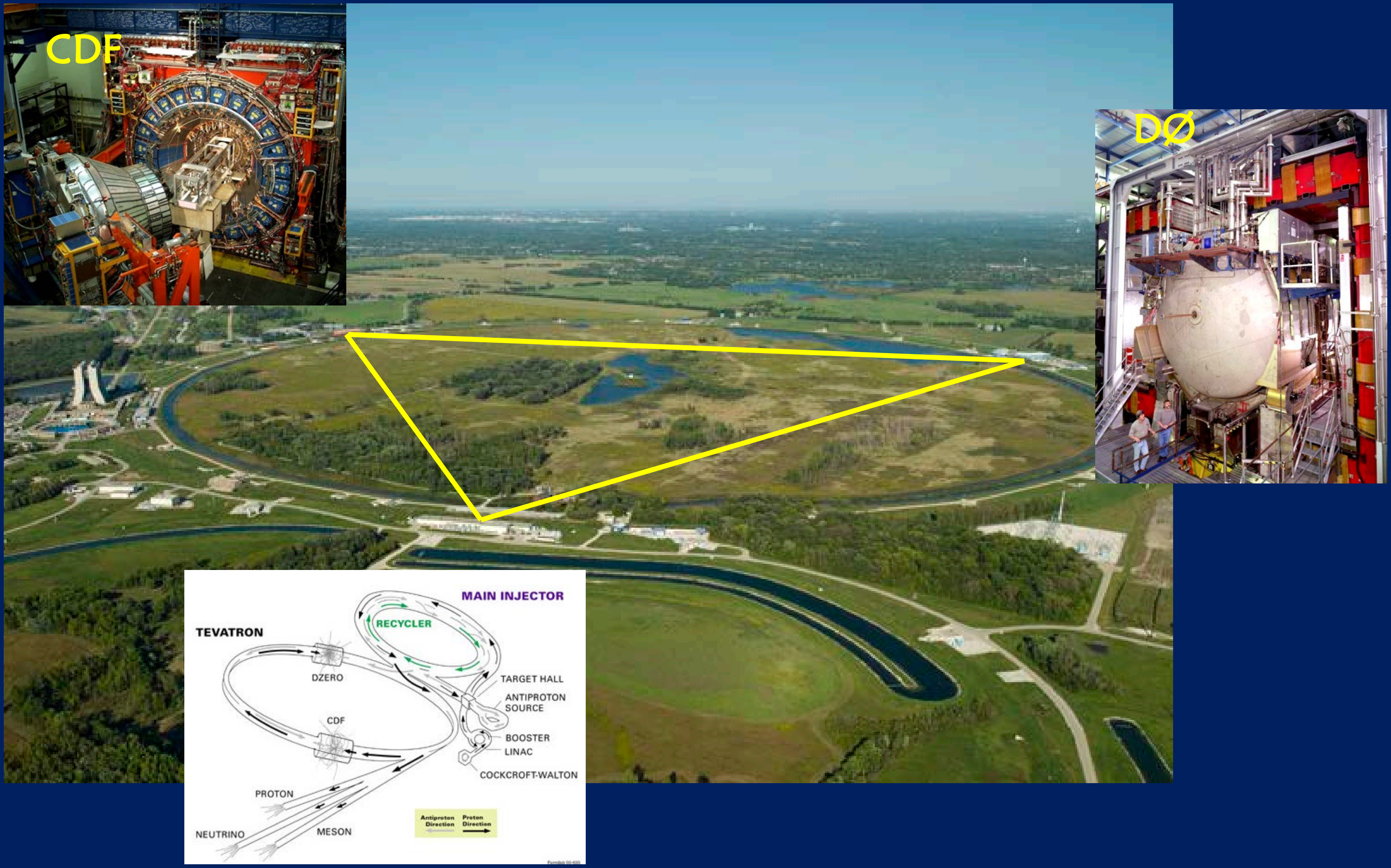
Triangulating EWSB at the Tevatron

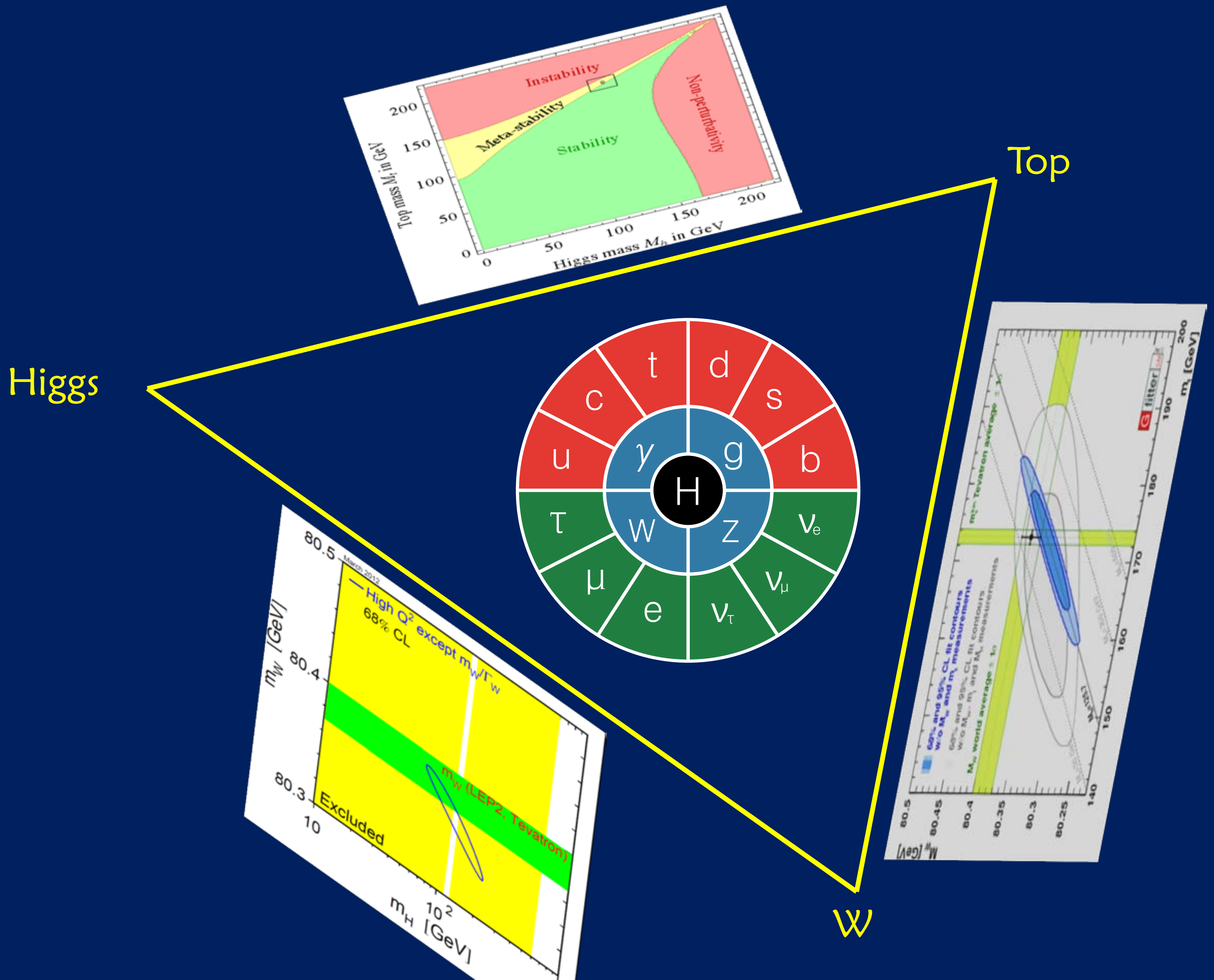


P. Grannis
Higgs Hunting 2014
Paris, July 23, 2014

Triangulating EWSB at the Tevatron

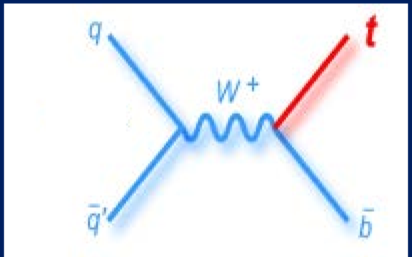


Triangulating EWSB at the Tevatron



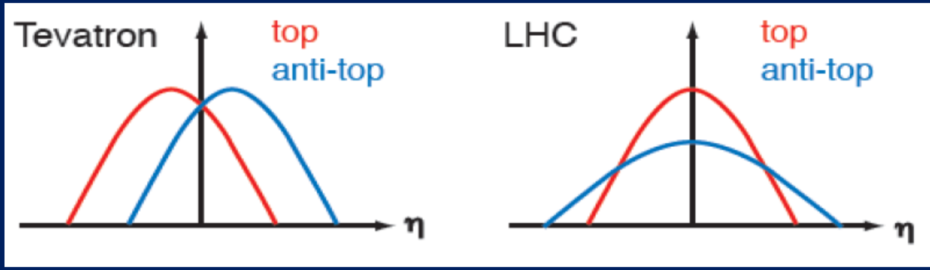
Tevatron characteristics

Despite the lower energy, the Tevatron provides important complementarity to the LHC. (The Tevatron's 10 fb^{-1} with $\mathcal{L}_{inst} \leq 4\times10^{32}\ cm^{-2}\ s^{-1}$ with proton antiproton collisions was a tremendous achievement.)



- Dominantly $q\bar{q}$ collisions as opposed to mainly gg at LHC. This provides enhanced cross sections for some processes (e.g. associated VH, s-channel top) and important studies of production by quarks vs. gluons ($t\bar{t}$ spin correlations).

- Proton-antiproton initial CP state (identical q and $\bar{q}$ PDFs) and the D0 ability to reverse solenoid and toroid fields enable incisive asymmetry measurements: A_{FB} in $t\bar{t}$, $B^{\pm}$, $Z(\ell\ell)$, $W^{\pm}(\ell\nu)$, and CP asymmetries in $B_s \rightarrow \mu^{\pm}$, $\mu^{\pm}\mu^{\pm}$



- Relative cleanliness (low pileup) facilitates precision measurements (W mass, top quark mass).

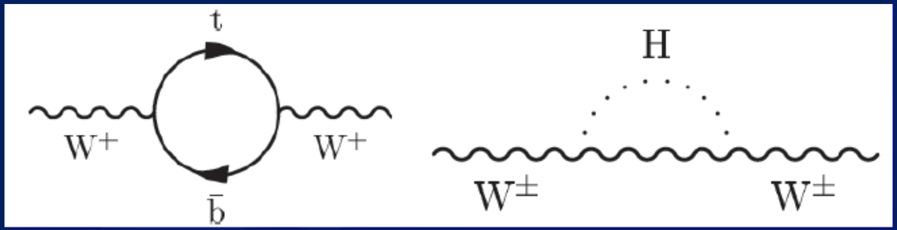
Understanding the Higgs

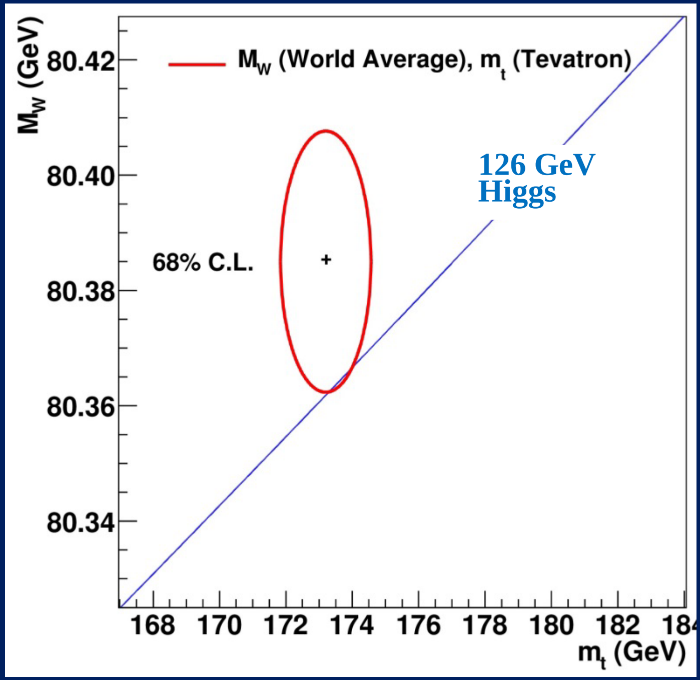
Pathways to understand the character of the Higgs boson and probe for new physics:

1. Measure the Higgs properties (production cross sections, width, couplings, J^P etc. precisely and compare with the SM expectations

2. Measure processes whose cross section depends on the Higgs contributions (e.g. vector boson scattering)

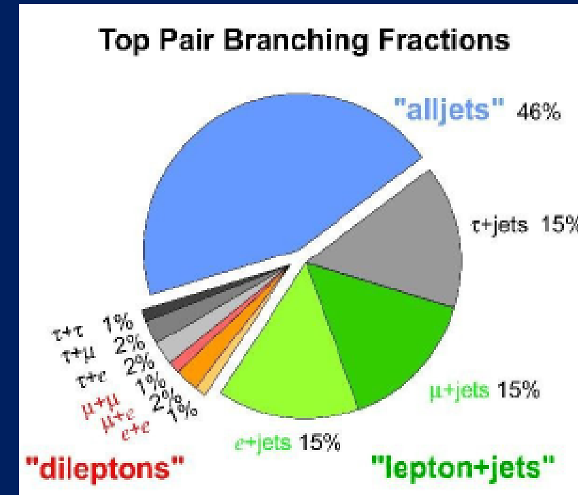
3. Utilize the constraints imposed by the SM, e.g. on M_{top}, M_W and M_H



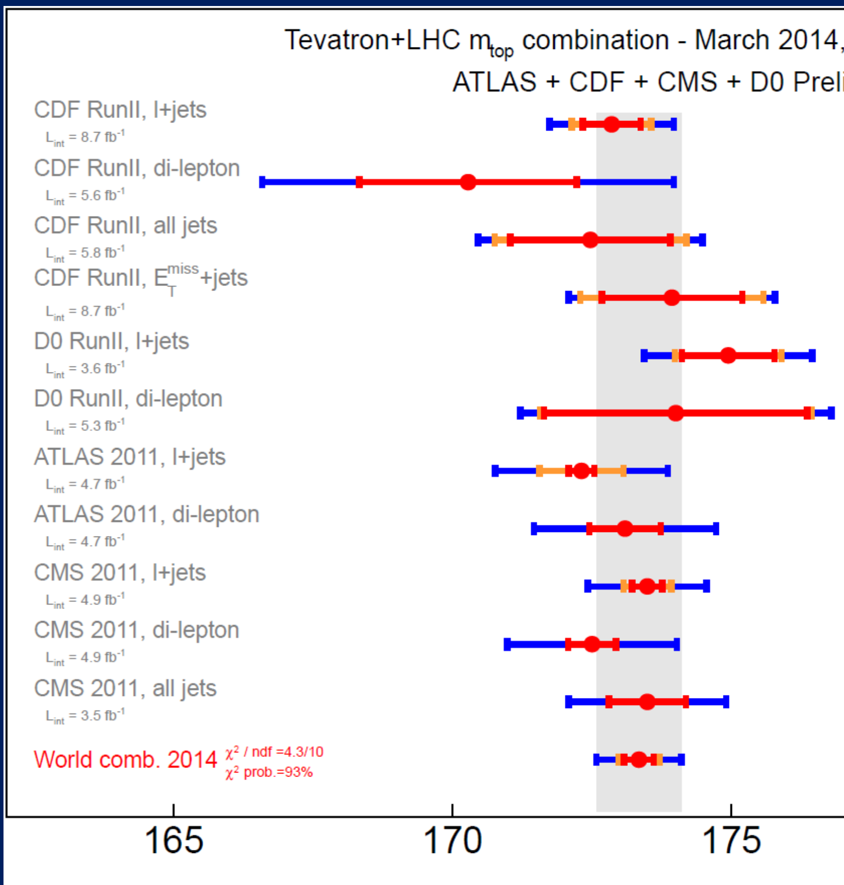


Tevatron results bear mainly on 1 and 3.

Top quark mass



Measurements have been made for all decay channels, using matrix element, ideogram and template methods.



In March 2014, a preliminary combination of Tevatron combination **(m_t =173.20 ± 0.87)** and 7 TeV LHC combination **(m_t =173.29 ± 0.95)**

Best individual Tevatron results are still statistics dominated; Tevatron combination and individual LHC results are systematics dominated.

Mar. 2014 world combo: m_t =173.34 ± 0.76 GeV
[± 0.27(stat) ± 0.24(jes) ± 0.67(syst)]
(0.44% precision)

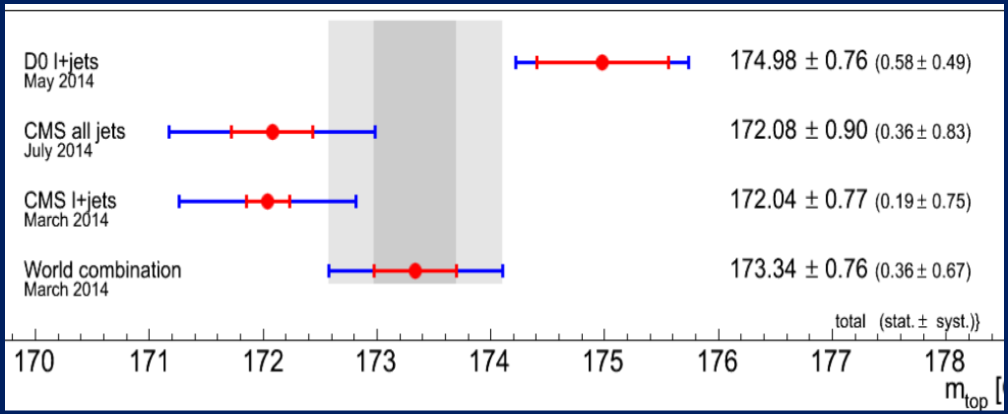
Recent Top quark mass measurements

- CMS (preliminary) ideogram method for 19.7 fb^{-1} at 8 TeV in **ℓ+jets** channel:
  m_t = 172.04 ± 0.77 GeV. (Best LHC single measurement)

- CMS (preliminary) ideogram method for 18.2 fb^{-1} at 8 TeV in **all jets** channel:
  m_t = 172.08 ± 0.90 GeV.

- D0 matrix element method with 9.7 fb^{-1} in **ℓ+jets** channel:
  m_t= 174.98 ± 0.76 GeV. (Best Tevatron single measurement)

The new D0 result, together with updated CDF dilepton and all-jets results give a new Tevatron combination: **m_t = 173.34 ± 0.64 GeV** (±0.37±0.52 GeV) **(0.37%)**, more precise than the March 2014 world average.



The positive pull of the D0 result and the negative pulls of the CMS results tend to cancel.
Gfitter global fit (arXiv 1407.3792) prefers higher m_t (~177±2 GeV)

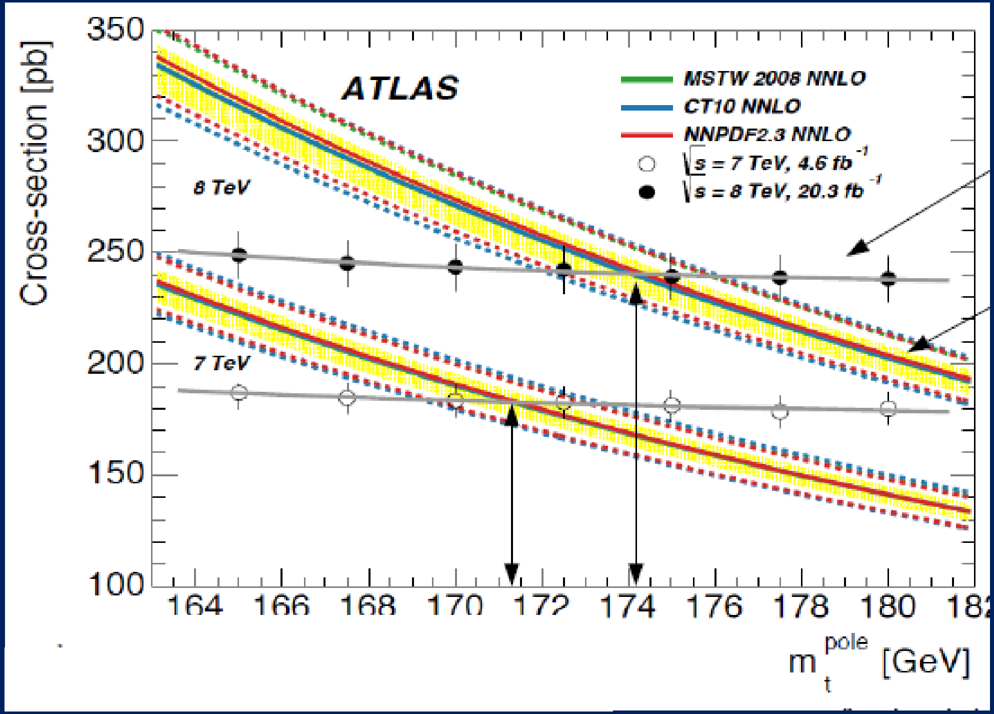
We look forward to a new LHC and world combination soon.

Top quark mass

Experiments measure the mass embedded in the MC.

Conversions of the MC mass to pole mass, or $\overline{MS}$ mass, is theoretically difficult. The present uncertainty estimates (S.-O. Moch at LHCP) are
Δm_t = ± 0.7 (MC mass to running mass) + ~0.5 GeV (running mass to pole mass).

With large statistics at LHC, alternate measurements of well-controlled mass parameters (total cross sections, end points, $p_T{}^b$, $M_{\ell b}$ etc.) may improve this situation.



Comparing the measured $t\bar{t}$ cross sections with the NNLO+NNLL theoretical values, ATLAS combined the 7 and 8 TeV measurements:

$$m_t\,(\text{pole}) = 172.9\,^{+2.5}_{-2.6}\ \text{GeV}.$$

Future measurements of quantities depending on mass in theoretically well defined ways will be important.

W boson mass

Measure $m_T = 2E_T^{\ell} E_T^{\nu}(1-\cos\phi_{\ell\nu})$, p_T^{ℓ}, p_T^{ν} in $W \to e\nu$ (DO/CDF) or $W \to \mu\nu$ (CDF)

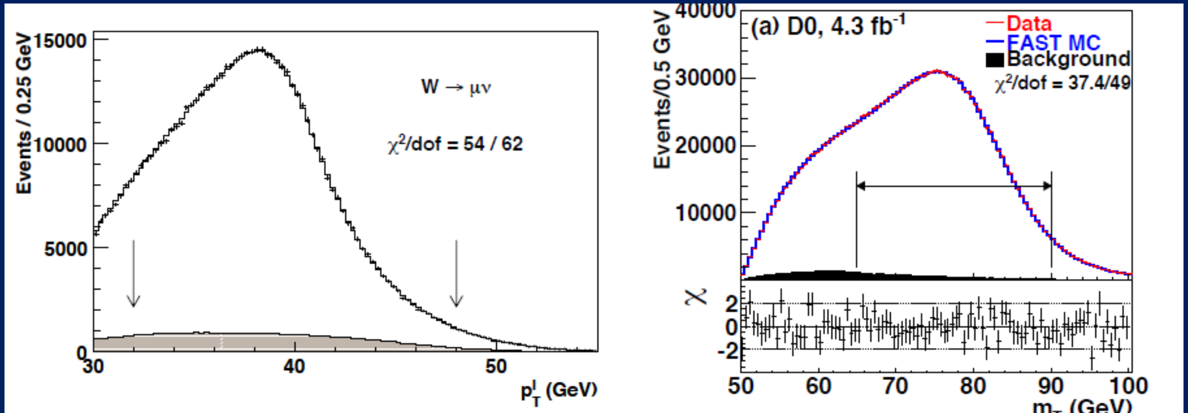
Experimental methods at Tevatron are complementary:
CDF calibrates muon momentum scale using J/ψ, Υ, Z and transfers it to electron scale using E/p for electrons from W.

D0 establishes calorimeter energy scale using LEP Z mass and calibrates energy loss in uninstrumented material using longitudinal shower energy profile.

Recoil energy scale/resolution (used for MET) calibrated from Z and validated in W events.

Careful modelling of FSR γ's, recoil energy within electron window, effects of pileup, etc. in fast parametrized MCs, validated through comparisons of fast MC and full GEANT MC.

Compare m_T, p_T^{ℓ}, p_T^{ν} distributions to fast MC templates to extract m_W



CDF $p_T(\mu)$ fit

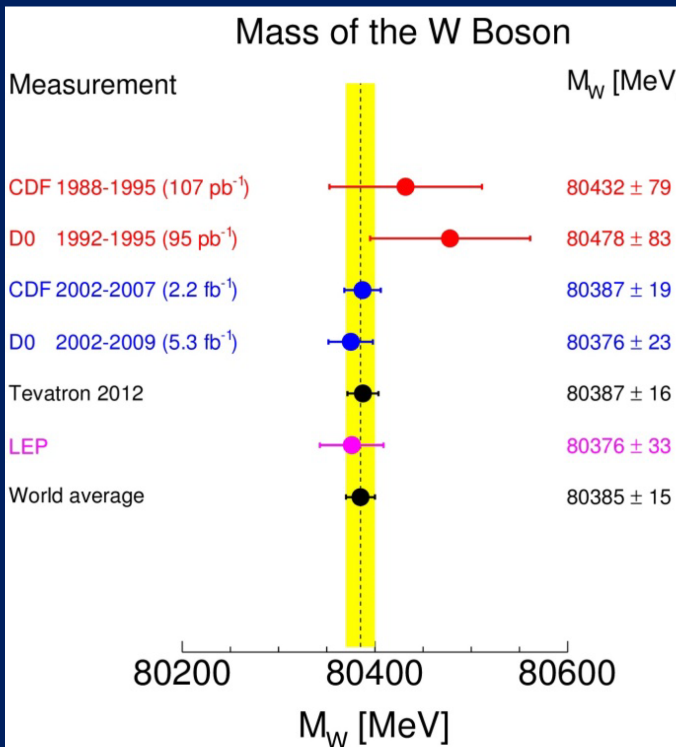
DØ $m_T(e)$ fit

W boson mass

CDF: (2.2 fb-1) 80387 ± 19 MeV
D0: (5.3 fb-1) 80375 ± 23 MeV

CDF/D0 combination: 80387 ± 16 MeV (± 0.02%)

Including LEP: World average: 80385 ± 15 MeV



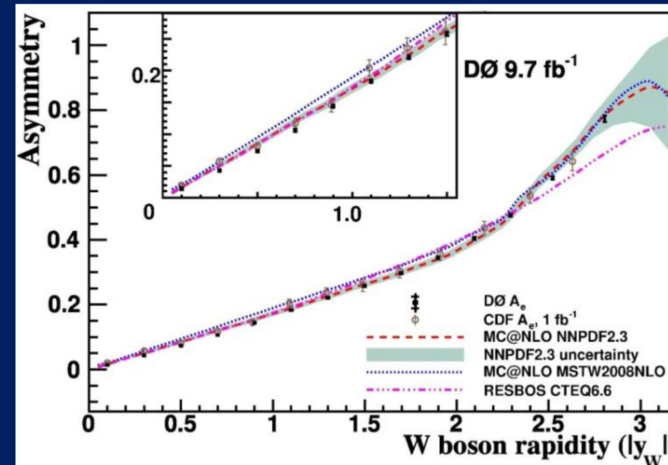
Uncertainties on transverse mass fits for M_W [MeV]

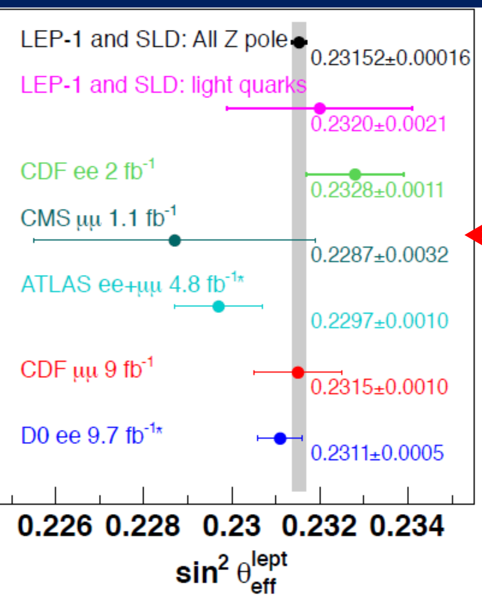
Source	CDF (μ)	CDF (e)	DØ (e)
Lepton energy scale	7	10	17
Lepton energy resolution	1	4	2
Recoil model	9	9	5
Lepton efficiency	-	-	1
Backgrounds	3	4	2
p_T	3	3	2
PDFs	10	10	11
QED radiation	4	4	7
Total systematics	*16*	*18*	*22*
W statistics	16	19	13
Total	***23***	***26***	***26***

Experimental uncertainties scale as $\mathcal{L}^{-1/2}$; the PDF uncertainties now begin to dominate. Improvements in PDF u/d ratio based on Tevatron W asymmetry measurements, and extension to large rapidity in D0 can reduce this by factor ~2. Full data set measurements aim at δm_W = 10 MeV or below.

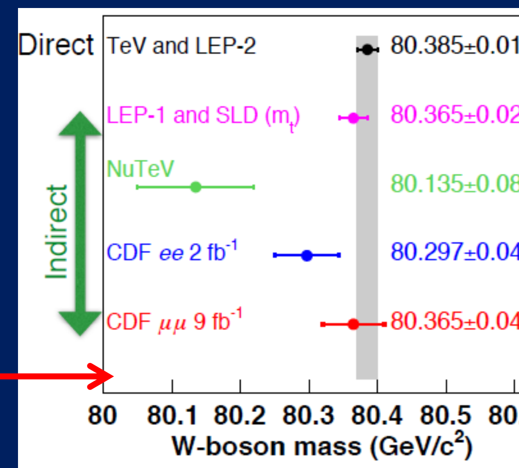
Other EW measurements

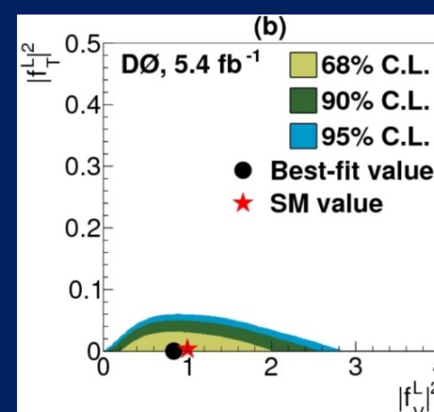
The W boson F-B asymmetry measures constrains the u/d ratio in PDFs needed for M_W. New CDF and D0 A_{FB} are more precise than current PDF predictions.





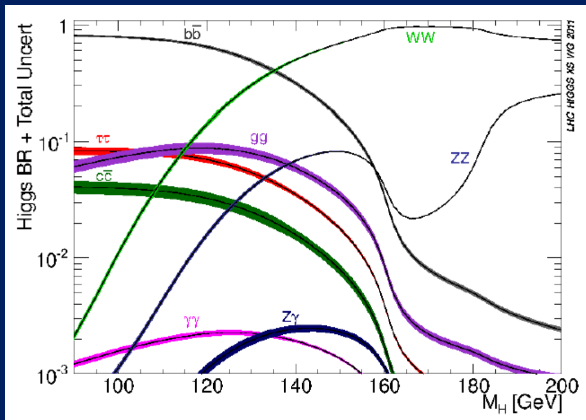
A_{FB} in $Z \to \ell^+\ell^-$ measures the V/A couplings to u/d quarks, $g_A^f = I_3^f$ and $g_V^f = I_3^f - 2Q_f \sin^2\theta_W$. Precision on $\sin^2\theta_W$ (CDF ±0.0010, D0 ±0.0005) now exceeds that for light quarks from LEP and SLD (±0.0021). Using the SM relation $\sin^2\theta_W = 1 - M_W^2/M_Z^2$ we get an indirect measurement of M_W in the SM context. Tevatron precision should reach $\delta M_W \sim 20$ MeV. (Recall that the LEP $\delta M_W = 33$ MeV)





Top sector measurements – W helicity, anomalous couplings, A_{FB}(tt), spin correlations, single top subprocesses, top width – constrain non-SM effects.

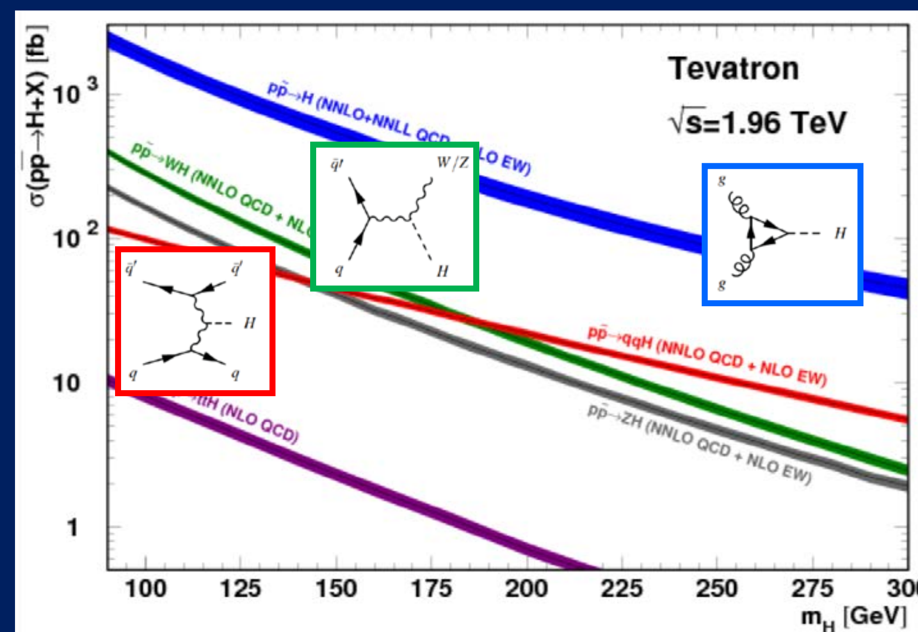
Higgs measurements



For M_H < 135 GeV, Higgs decays to bb dominate whereas H → WW dominates for M_H > 135 GeV.

Production occurs through gg fusion, VH associated production and vector boson fusion. The decays into bb in the GGF process are buried in QCD jet background. GGF production with H → WW is accessible. The ττ, ZZ, γγ decays have cleaner signatures but smaller BRs, and were sought for all production processes.

CDF and D0 have searched for Higgs in >150 separate final states (lepton flavors, N_ℓ, N_{jets}, b-tag configurations …). Two Tevatron combination papers with the full data set (~10 fb^{-1}) summarize the results:

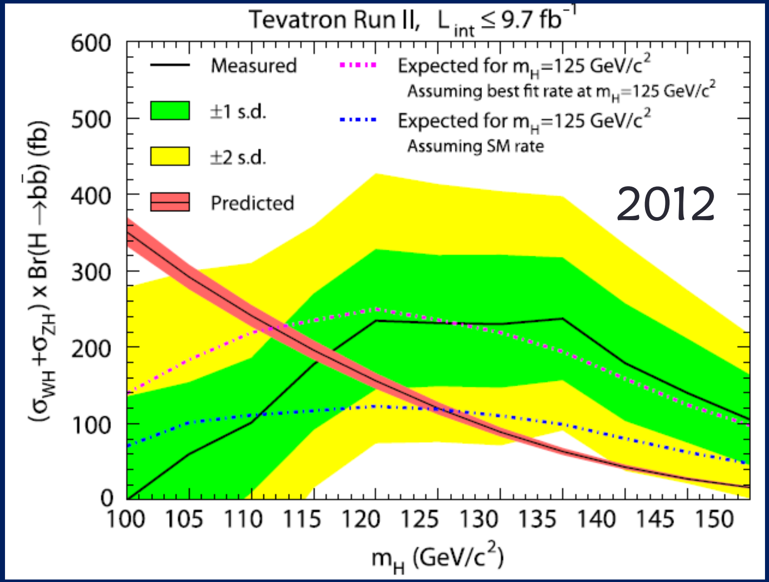


PRL 100, 071804 (2012) presented the combined results on VH production with H → bb.

PRD 88, 052014 (2013) presented the combined results for all channels, using an updated analysis for Z(νν)H(bb) from CDF and minor changes in the D0 WH systematics correlations.

See talk of B. Tuchming

H →bb

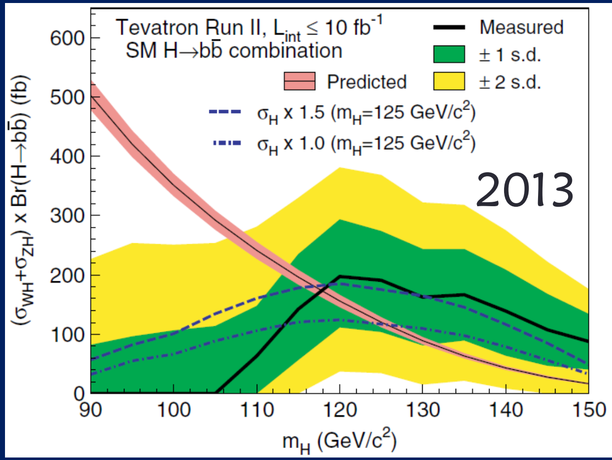


The 2012 VH(bb) combination gave $(\sigma_{WH} + \sigma_{ZH})$ x B(H→bb) of 0.23 pb, compared to the SM value of 0.12 pb.

The maximum local significance at 135 GeV was 3.3σ and with LEE, 3.1σ. At the LHC mass of M_H=125 GeV, the significance of 2.8σ is currently the most precise result in the bb decay mode.

"We interpret this as evidence for the presence of a new particle consistent with the standard model Higgs boson which is produced in association with a weak vector boson and decays to a bottom-antibottom quark pair."

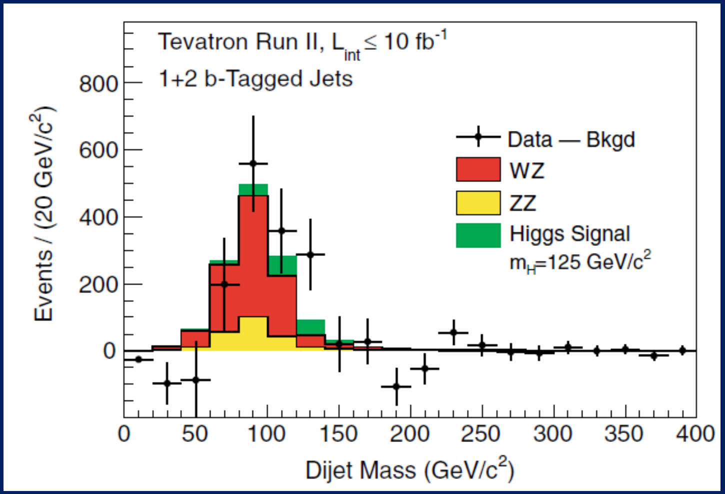
With the reanalysis in the 2013 combination, $(\sigma_{WH} + \sigma_{ZH})$ x B(H→bb) was reduced to 0.19 pb (1.6xSM) (due to the new CDF ννbb analysis), but the general picture remained the same.



* With the recent CMS measurement in H →bb [PRD D89, 012003 (2014)] (2.1σ observed) and the expected ATLAS result, it will be useful to combine LHC and Tevatron results for H →bb.

VZ cross section cross check

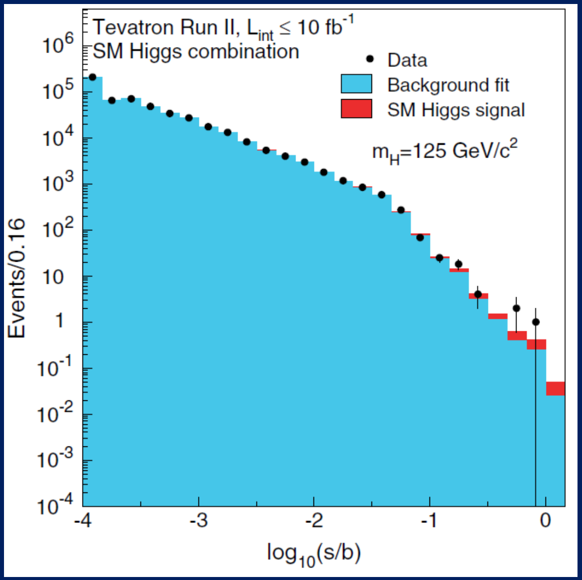
Important cross-check: with exactly same selection, background modelling, analyze all Vbb final states, replacing H(bb) with Z(bb) as signal. Bkgds are larger for the lower mass Z. Get $\sigma_{VZ}=3.0 \pm 0.6 \pm 0.7$ pb, to be compared with $\sigma_{VZ}=4.4 \pm 0.3$ SM prediction. A similar extraction from the WW final state obtains the VV' cross section in agreement with SM.

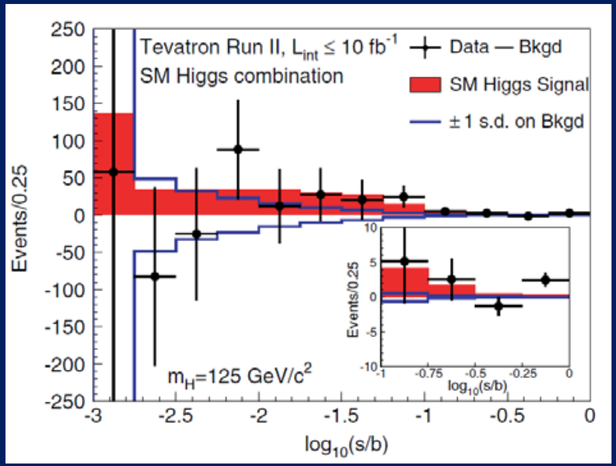


Bknd subtracted di-b jet mass

Higgs all channels combination (2013)

Arrange all bins of all channel MVA outputs in increasing bins of s/b to view the signal, summed over analyses. Agreement with the background model is good over 5 orders of magnitude, with a small excess visible at large s/b.

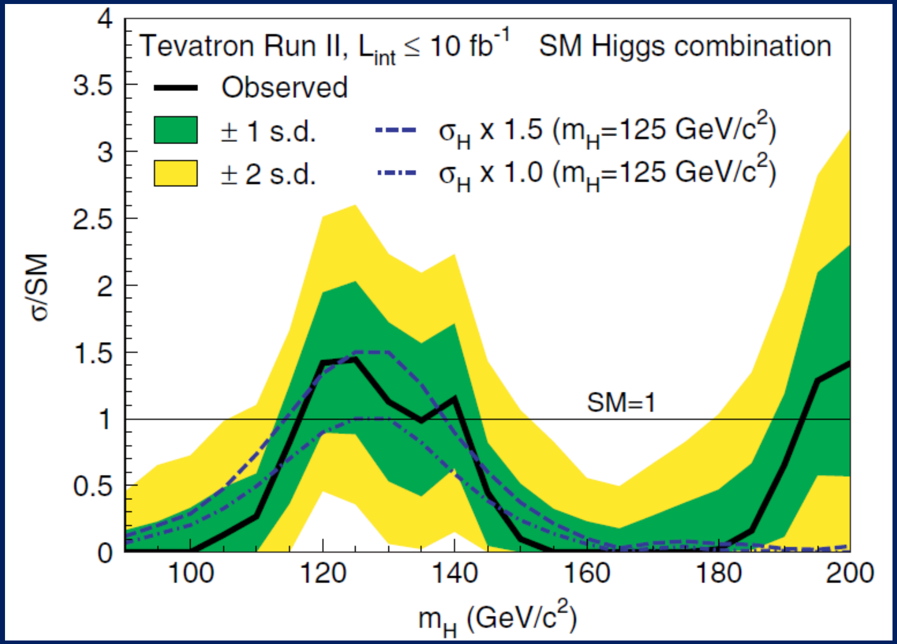


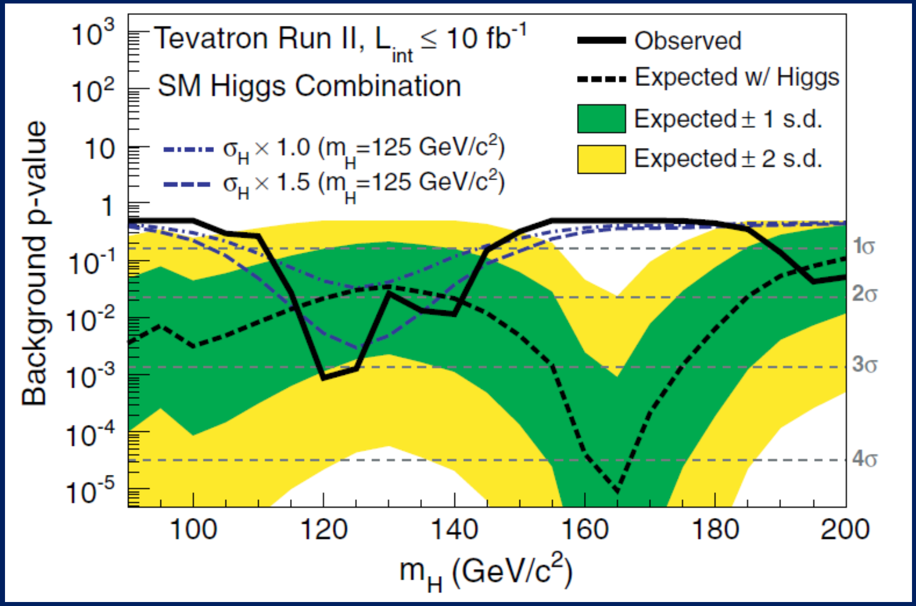


The background subtracted s/b distribution (with total uncertainty bands for bknd) shows a Higgs like excess at high s/b.

Higgs all channels combination

Converting this excess to σ_{obs}/σ_{SM} for a series of M_H hypotheses shows an excess centered close to 125 GeV with width consistent with expectation.

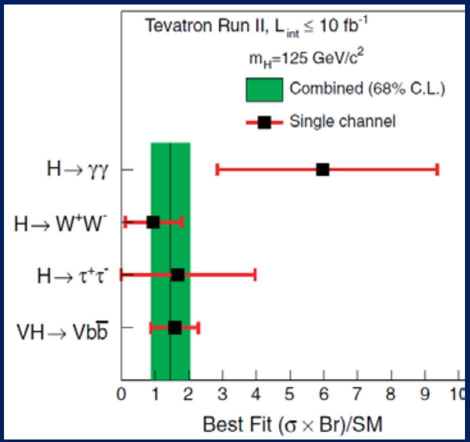


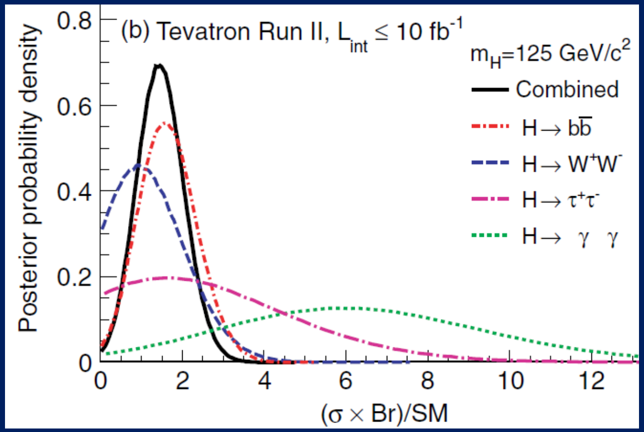


The p-value for bknd to fluctuate to the observed excess is 3.0σ at M_H=125 GeV.

$$\sigma \text{xBR} = 1.44\ ^{+0.59}_{-0.56}\ \text{x SM.}$$

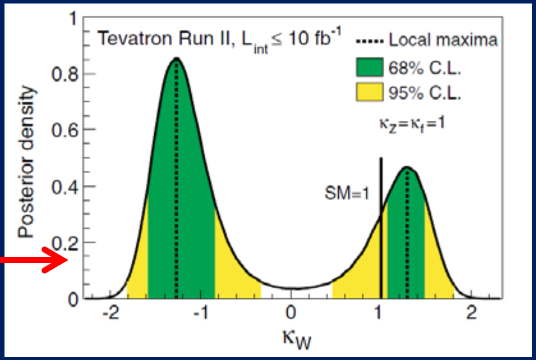
The σxBR measured for individual bb, ττ, WW and γγ channels are consistent with the SM predictions (a positive statistical fluctuation in H→γγ).



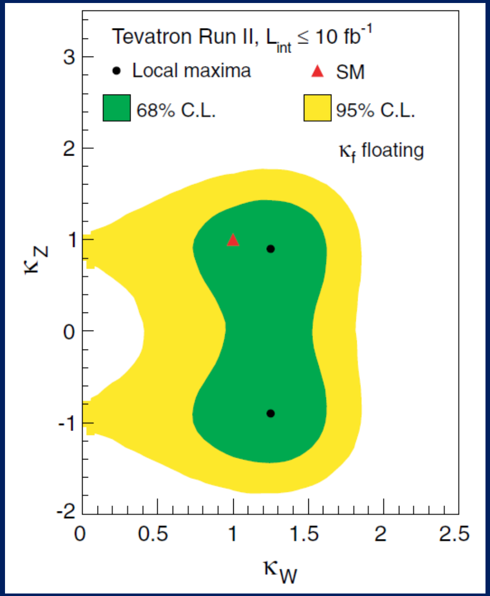


Higgs couplings

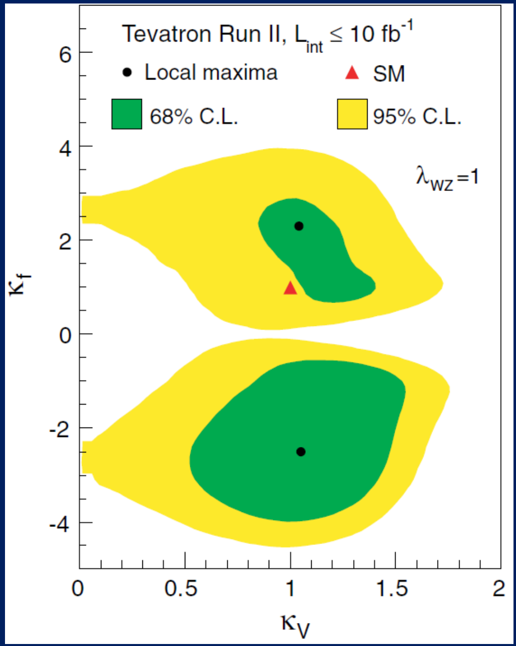
Allowing multiplicative scale factors κ_W, κ_Z, κ_f for Higgs couplings to W, Z, fermions relative to the SM, can fit the data for combinations of these SFs. For example κ_W (κ_Z, κ_f fixed). Negative κ_W favored due to interference of W and top loops in $\gamma\gamma$ production. Both CDF and D0 see a small excess in the $\gamma\gamma$ channel at M_H=125 GeV, favoring constructive interference.



Posterior probability for κ_W with κ_Z, κ_f fixed



Allowing κ_W, κ_Z to vary simultaneously (κ_f floated), get (κ_W, κ_Z) = (1.25, ± 0.90), consistent with custodial symmetry (κ_W/κ_Z=1).



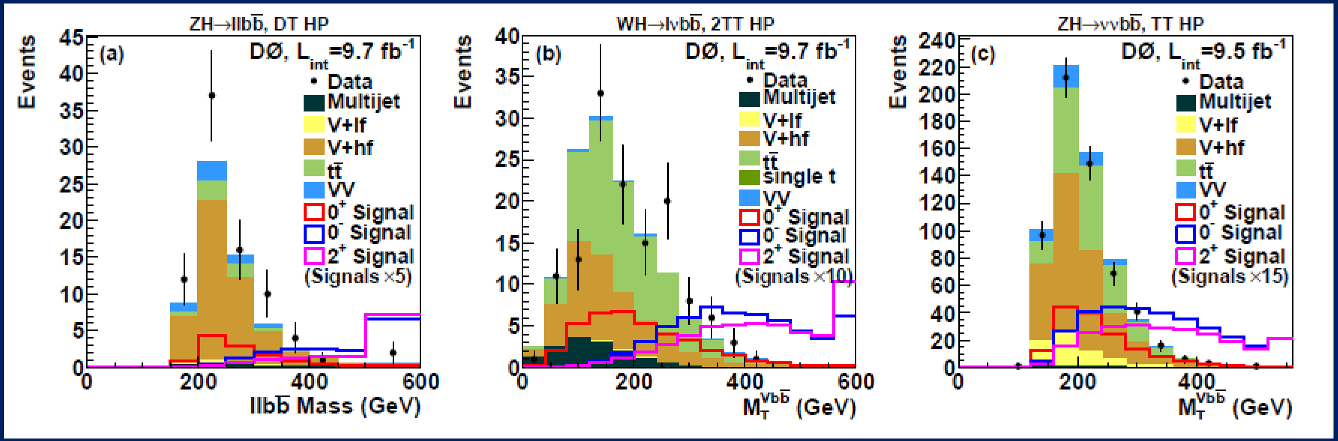
Assuming custodial symmetry, can fit for κ_f and κ_V, obtaining (κ_V, κ_f) = (1.05, 2.30), consistent with SM within uncertainties.

Higgs spin parity

Unlike at LHC where angles in the decay (e.g. $H \rightarrow ZZ^*$) carry the spin information, at the Tevatron it is the threshold dependence of the VH production XS on the c.m. velocity β. The invariant (or transverse) ZH or WH mass reflects the different dependences.

VH production:
$J^P=0^+$: $\sigma \sim \beta$
$J^P=0^-$: $\sigma \sim \beta^3$
$J^P=2^+$: $\sigma \sim \beta^5$

The $J^P=0^-$ case assumes a basic dim. 5 effective coupling; the 2^+ case is based on a Randall Sundrum graviton model. Both assume $\sigma_{BSM} = \sigma_{SM}$.



CDF/D0 reuse the Higgs ($H \rightarrow bb$) search analyses with same selections for $\ell\ell bb$, $\ell\nu bb$, $\nu\nu bb$ with several different b-tag, N_{jet}, and $\ell = e\mu$, subcategories. For each D0 channel, high and low signal/background regions are selected, based on M_{jj} ($\ell\ell bb$ and $\nu\nu bb$) or MVA output ($\ell\nu bb$).

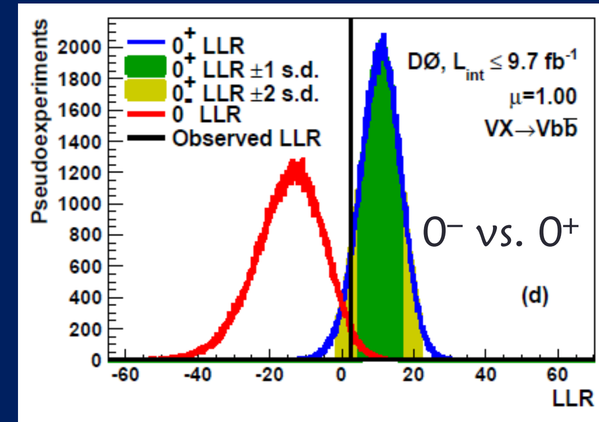
LLRs from distributions of $M_T(VZ)$ ($\ell\nu bb$, $\nu\nu bb$) and M_{INV} ($\ell\ell bb$) in all subchannels are constructed to distinguish the SM $J^P=0^+$ and BSM J^P 0^- or 2^+ hypotheses, optimizing systematic nuisance parameters within prior constraints.

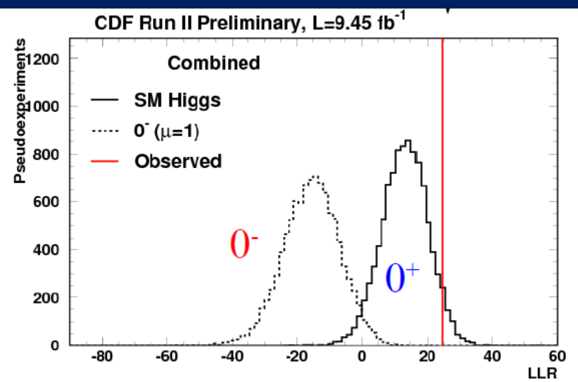
Higgs spin parity

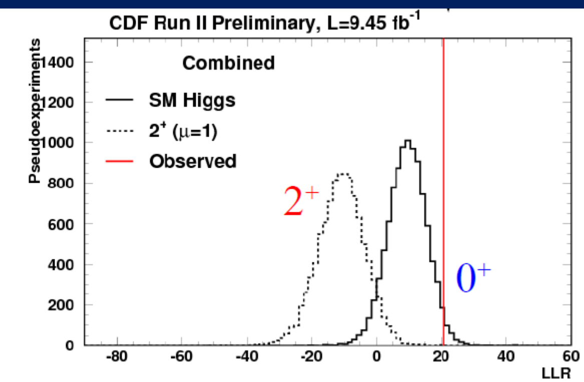
D0: For $\mu=1$, $J^P=0^-$ (2^+) disfavored at 97.6% (99.9%).

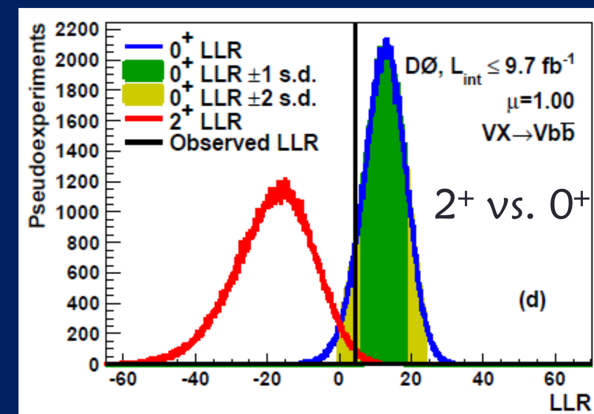
(For $\mu=1.23$ (the D0 measured signal strength), the BSM 99.5% (99.8%)).

CDF: For $\mu=1$, $J^P=0^-$ (2^+) disfavored at 99.99% (99.1%).

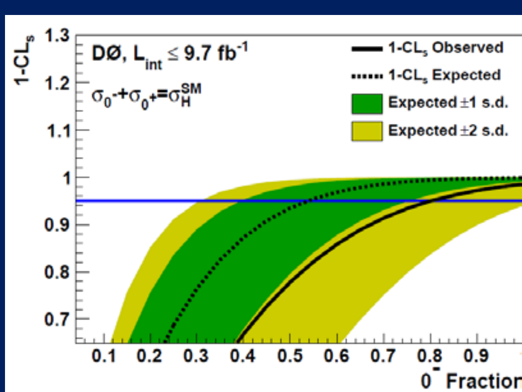








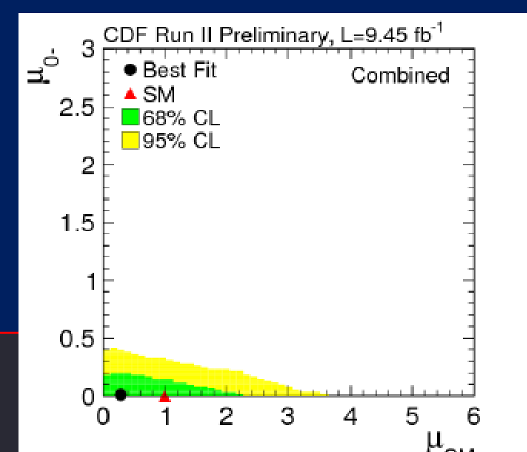
Assume admixture of 0^+ and 0^- (or 2^+) and set limits on the 0^- (2^+) fraction



D0: $f_{0-} < 0.80$ when $\sigma_{0+}+\sigma_{0-} = \sigma_{SM}$.
(<0.67 for $1.23\ \sigma_{SM}$)

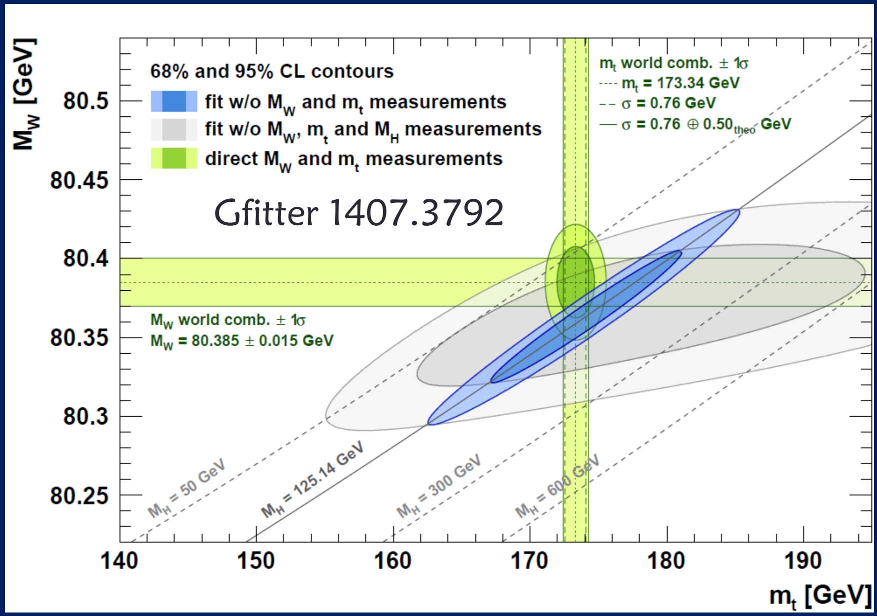
CDF: $f_{0-} < 0.28$ when $\sigma_{0+} = \sigma_{SM}$.

125 GeV Higgs boson agrees with $J^P=0^+$ in dominant bb decay mode



Tevatron legacy for Higgs physics

The comparison of the Higgs mass from ATLAS and CMS with measurements of the top quark and W boson masses at the Tevatron gives a precision test of the SM validity.



Measurements such as anomalous top couplings, single top production, Z and top asymmetries agree with SM and constrain new physics.

Tevatron still has the best significance for H→bb

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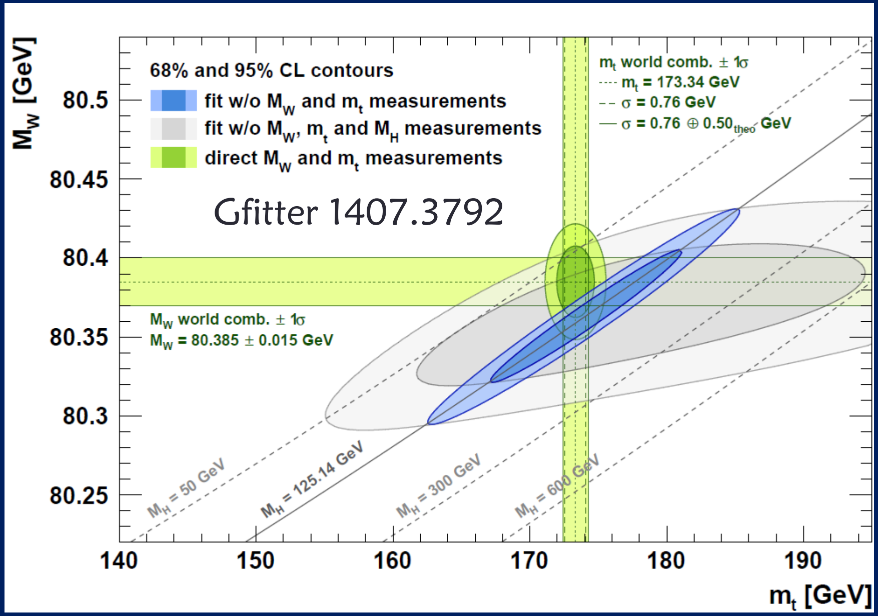

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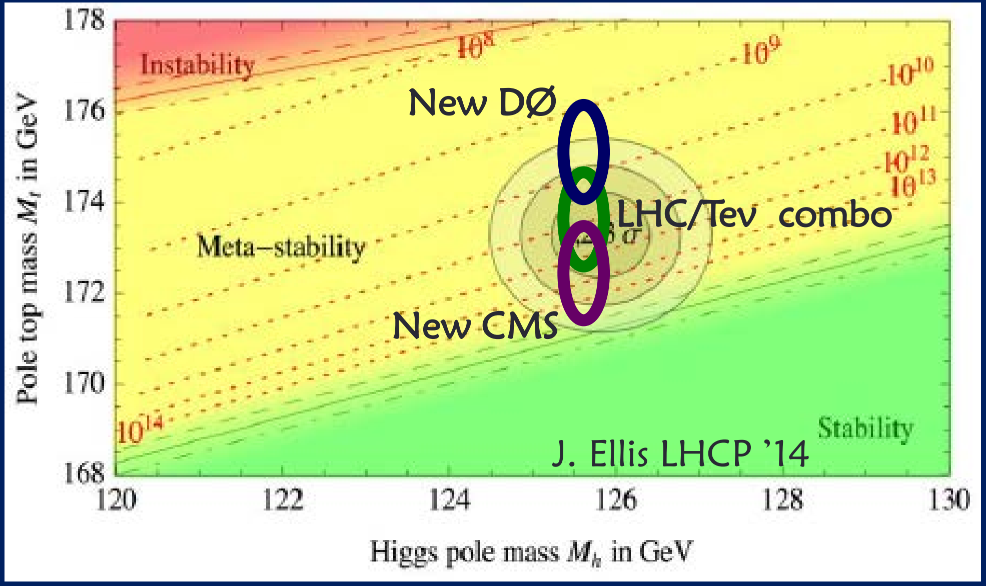
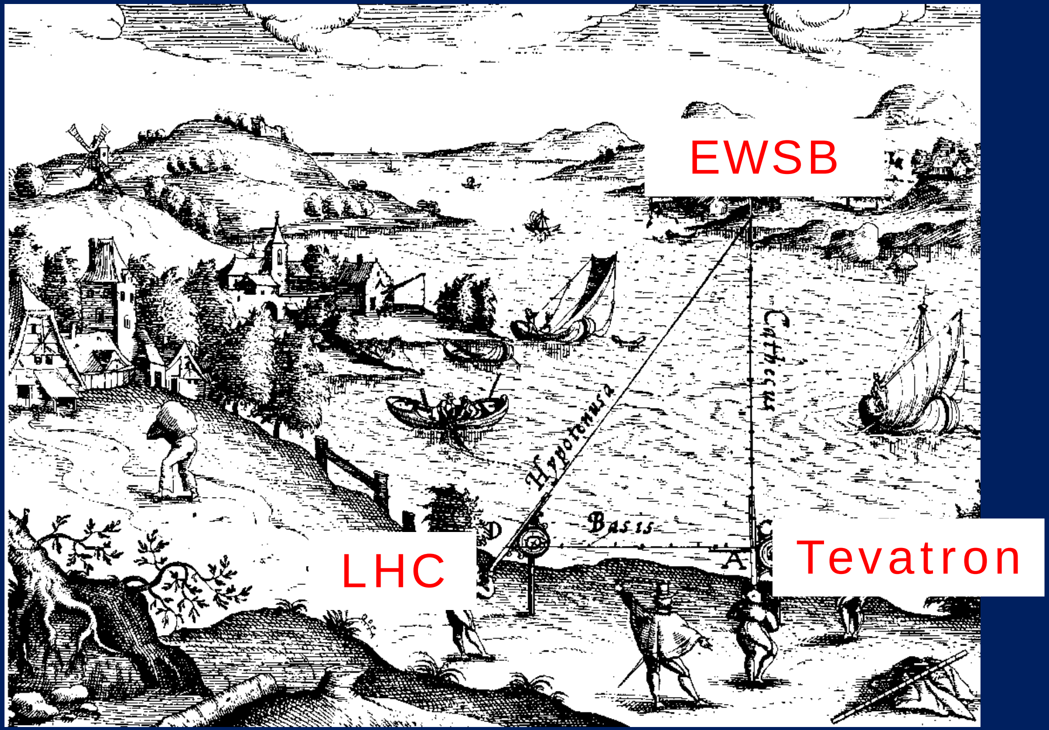


The running quartic Higgs potential term λ goes negative at high scales, sensitively dependent on top mass.

Future top mass measurements both at LHC and Tevatron are still important in predicting the stability of the universe.

Summary



The Tevatron, with complementary strengths to the LHC, improves the triangulation of the Higgs boson's characteristics.

More results are still to come.