Higgs Hunting 2013, July 25-27, 2013, Orsay, France

Tevatron Constraints on the Higgs Boson

Aurelio Juste
ICREA/IFAE, Barcelona

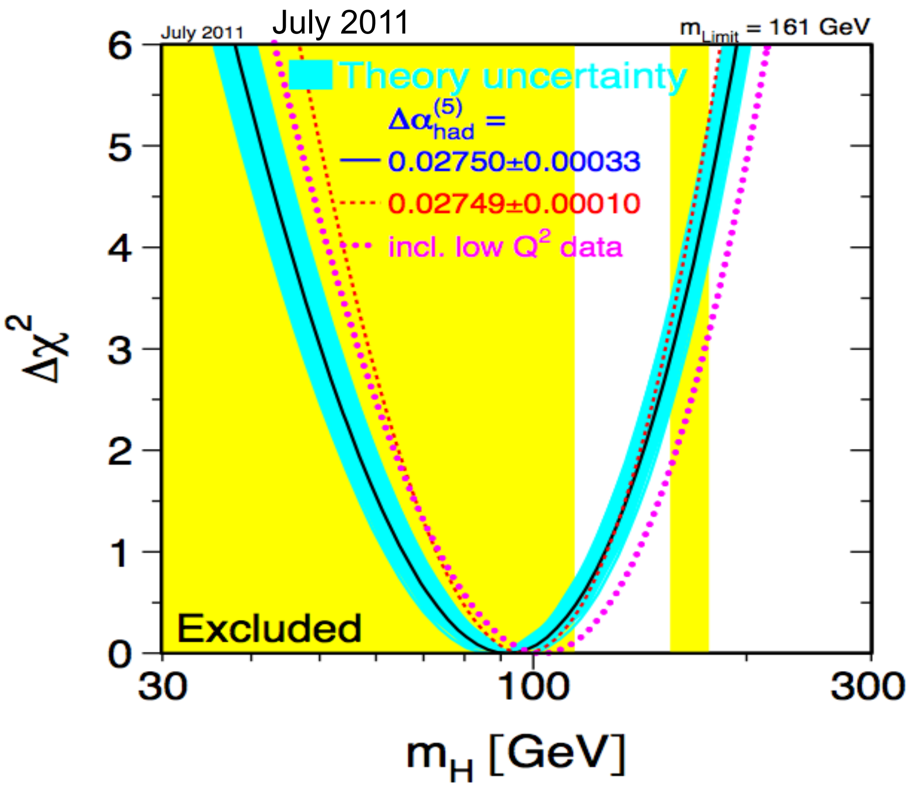
For the CDF and DØ Collaborations

Historical Perspective

- Before direct constraints from hadron colliders all we knew about the SM Higgs boson came from:
  - direct searches at LEP
    m_H>114.4 GeV @ 95% CL
  - indirect constraints from precision electroweak observables (*)
    m_H<152 GeV @ 95% CL
    (*) using latest m_t and M_W measurements from the Tevatron

➔ The Tevatron is expected to be sensitive precisely in this mass range!

➔ Searches for the SM Higgs boson have been a priority at the Tevatron.

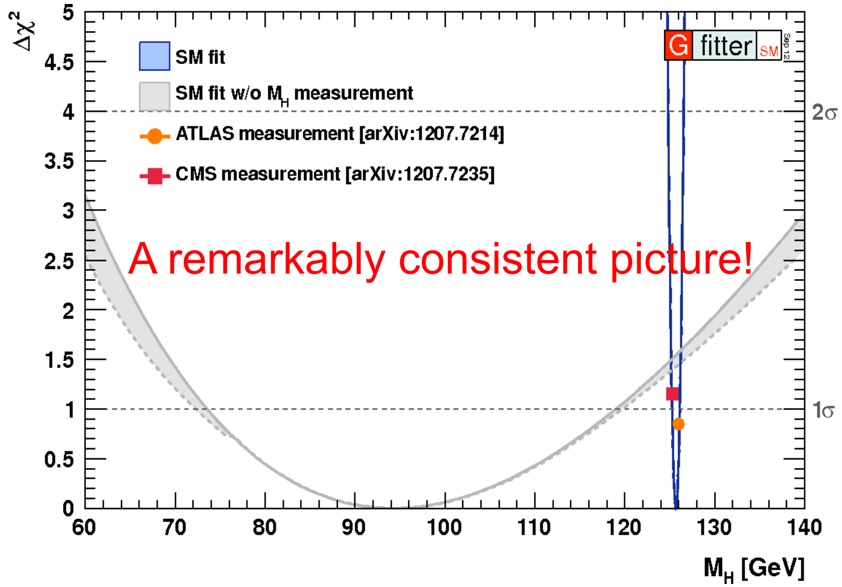


- Over the last decade the outstanding performance of the accelerator and CDF and DØ detectors, together with continuous improvements to the searches, allowed to start placing direct limits beyond LEP and eventually reach SM sensitivity in the preferred mass range.

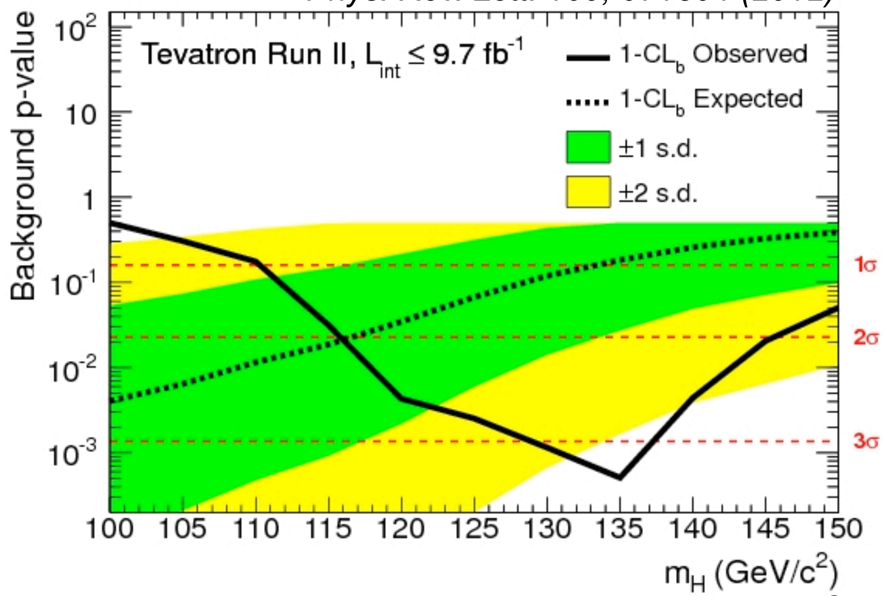
Historical Perspective

- Over the last two years, the LHC has excluded most of the remaining allowed mass range and observed a new boson with mass ~125 GeV, primarily in $\gamma\gamma$ and $ZZ \rightarrow 4l$ final states.

  The Tevatron experiments independently reported evidence for a new particle decaying into $b\bar{b}$ with compatible mass.



Phys. Rev. Lett. 109, 071804 (2012)



- Since the observation, Higgs studies at the Tevatron have focused on the measurement of Higgs properties (rates in different decay modes, couplings, J^P).

- In addition, Tevatron measurements of key electroweak parameters (m_t and M_W) will play an increasingly important role to help unravel the nature of the discovered boson and point to potential new physics effects.

Today's Presentation

- Introduction

- Direct constraints on the Higgs boson

  ➔ Here will just give a quick overview of SM Higgs boson searches.
  For more details see talks by S. Shalhout and G. Davies.
  ➔ Will not discuss BSM Higgs boson searches.
  For an overview see talk by J. Hays.

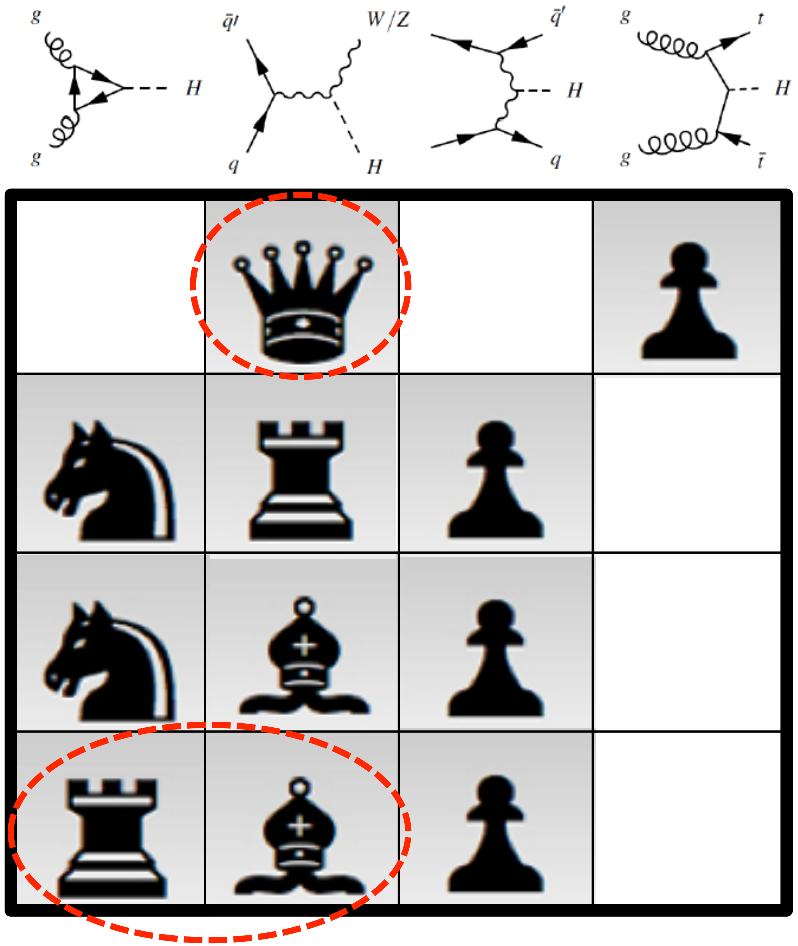
- Indirect constraints on the Higgs boson: m_t and m_W
  ➔ Main focus of this talk

- Summary and outlook

Direct Constraints

Search Strategies

- Defined by a combination of theoretical and experimental considerations (large σxBR but experimentally feasible: trigger, backgrounds….).

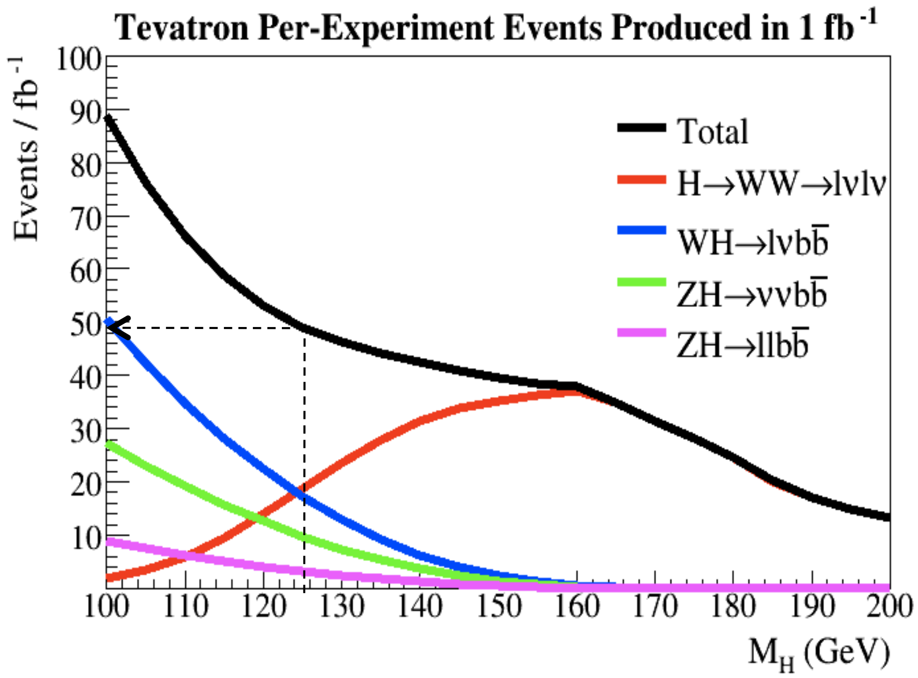


$H \rightarrow b\bar{b}$

$H \rightarrow \tau^+\tau^-$

$H \rightarrow \gamma\gamma$

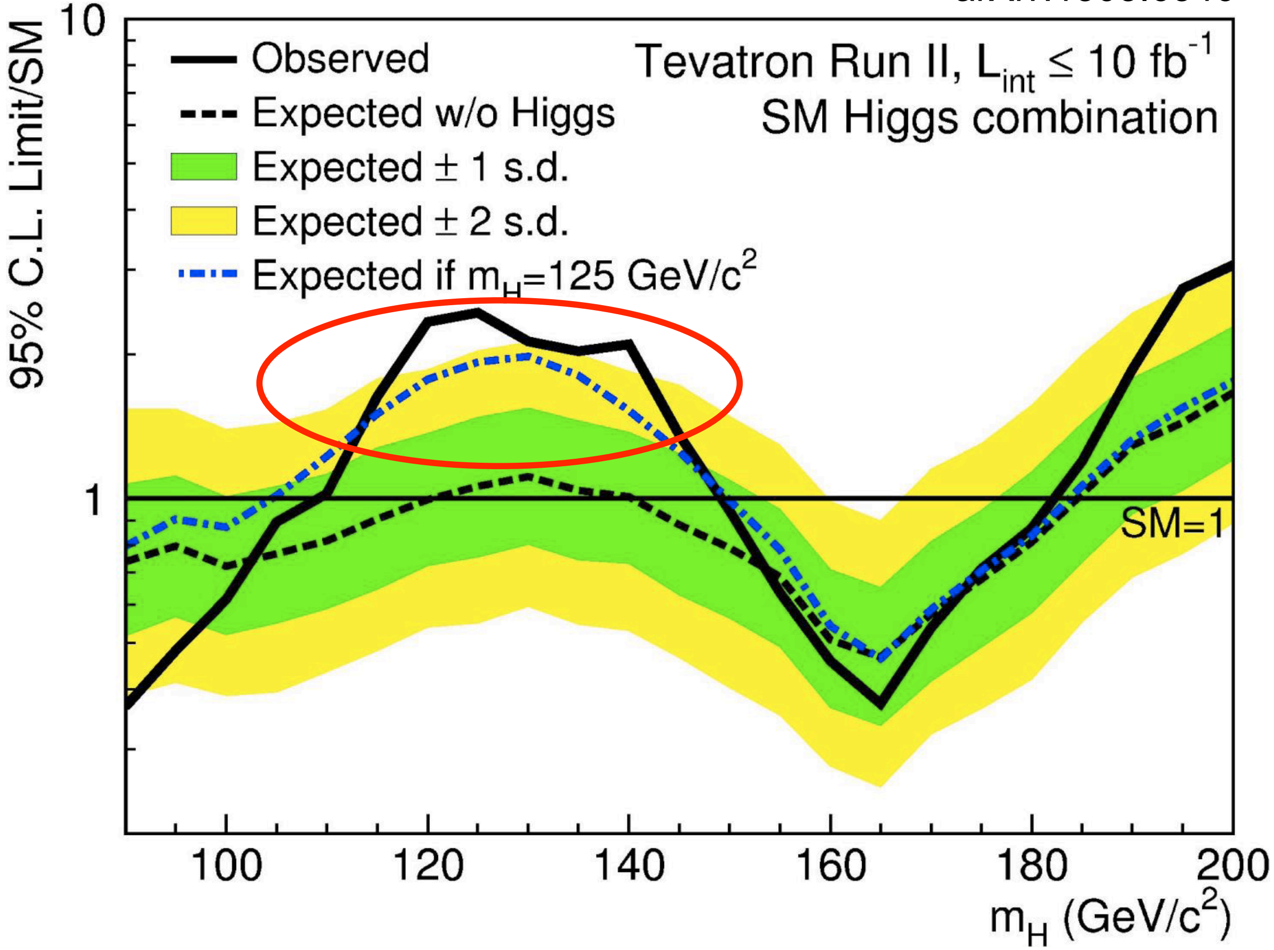
$H \rightarrow W^+W^-$



For m_H=125 GeV, ~1000 Higgs events produced at the Tevatron in the main search channels with 10 fb^{-1}!

Tevatron Combined Results

arXiv:1303.6346

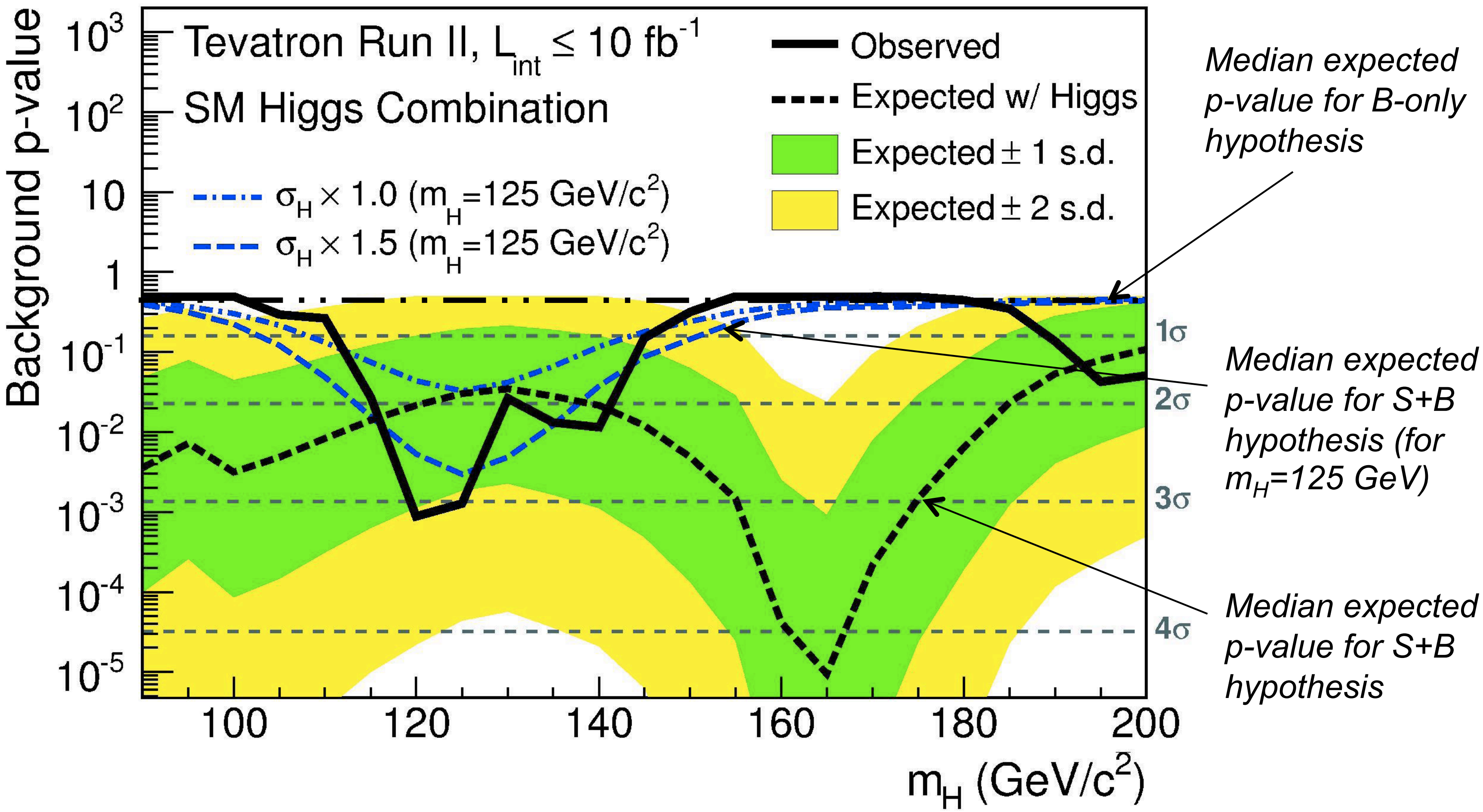


- Expected exclusion: $90 < m_H < 120$ GeV, $140 < m_H < 184$ GeV
  Observed exclusion: $90 < m_H < 109$ GeV, $149 < m_H < 182$ GeV
- 95% CL limit at m_H=125 GeV: 1.06xSM (expected), 2.44xSM (observed)

Quantifying the Excess: p-values

- Local p-value distribution for background-only hypothesis:

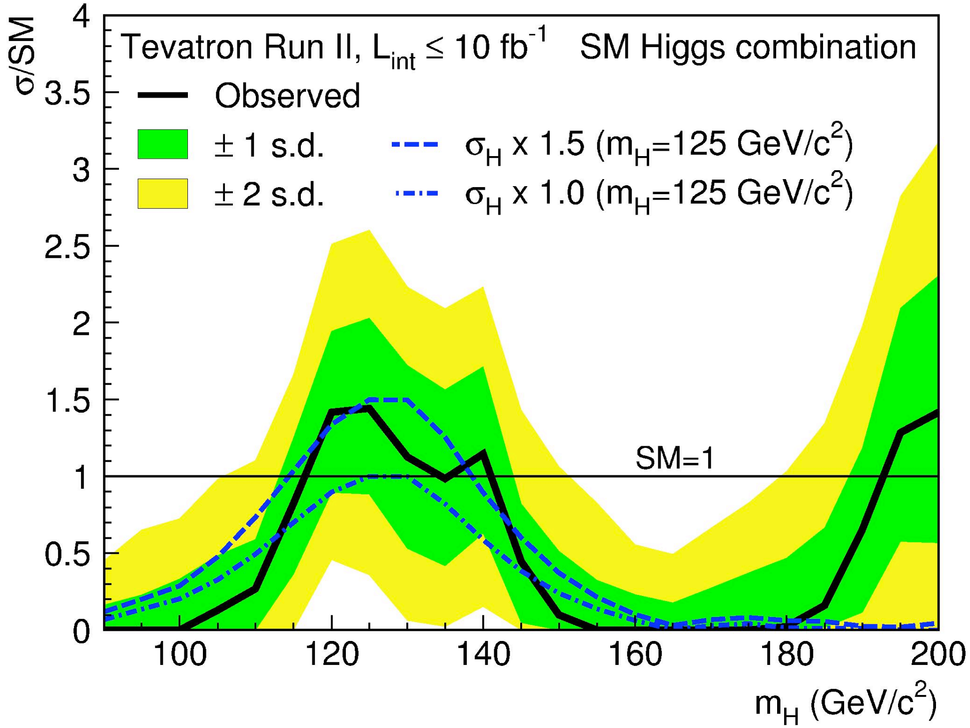
arXiv:1303.6346

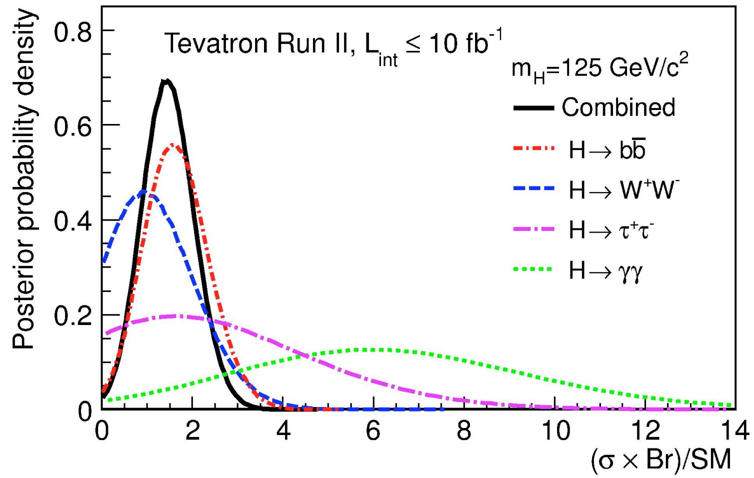


- Minimum local p-value at m_H=120 GeV: 3.1σ (2.0σ expected)
  p-value at m_H=125 GeV: 3.0σ (1.9σ expected)

Quantifying the Excess: Best Fit Signal Rate

arXiv:1303.6346



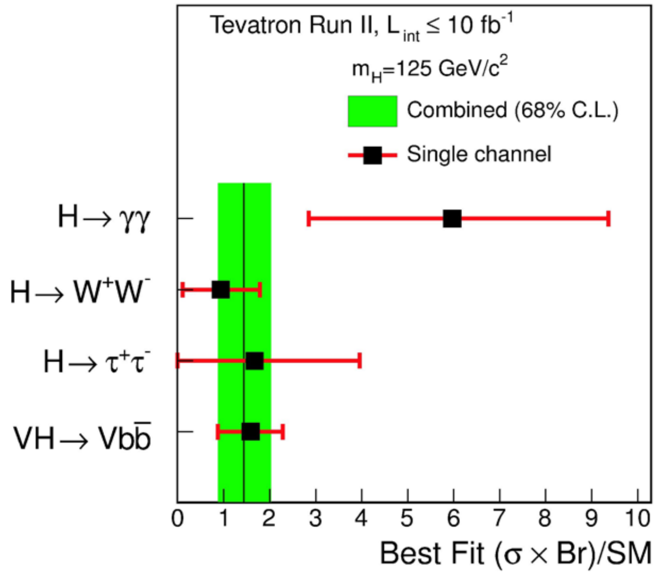


- Maximum likelihood fit to data with signal rate as free parameter.
- Best-fit signal rate at m_H=125 GeV:

$$\mu = 1.44^{+0.59}_{-0.56}$$

Consistent with SM Higgs.

Reasonably consistent across channels.

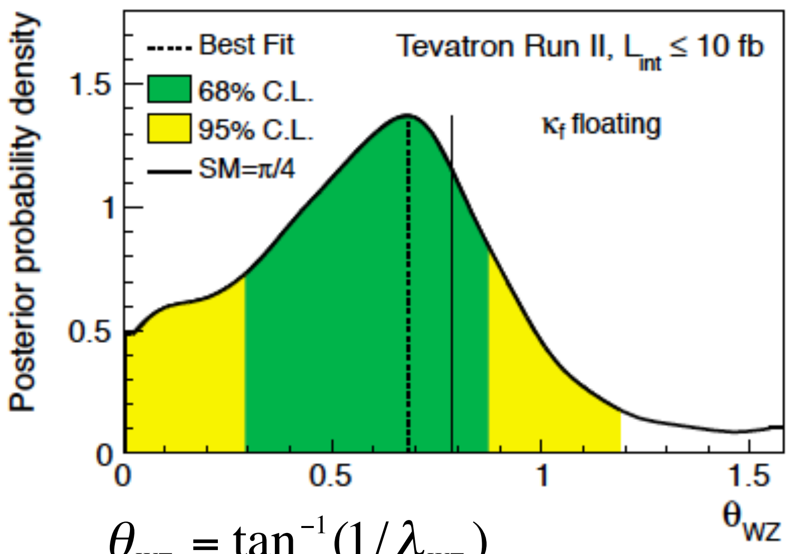


μ
$5.97^{+3.39}_{-3.12}$
$0.94^{+0.85}_{-0.83}$
$1.68^{+2.28}_{-1.68}$
$1.59^{+0.69}_{-0.72}$

Probing Higgs Boson Couplings

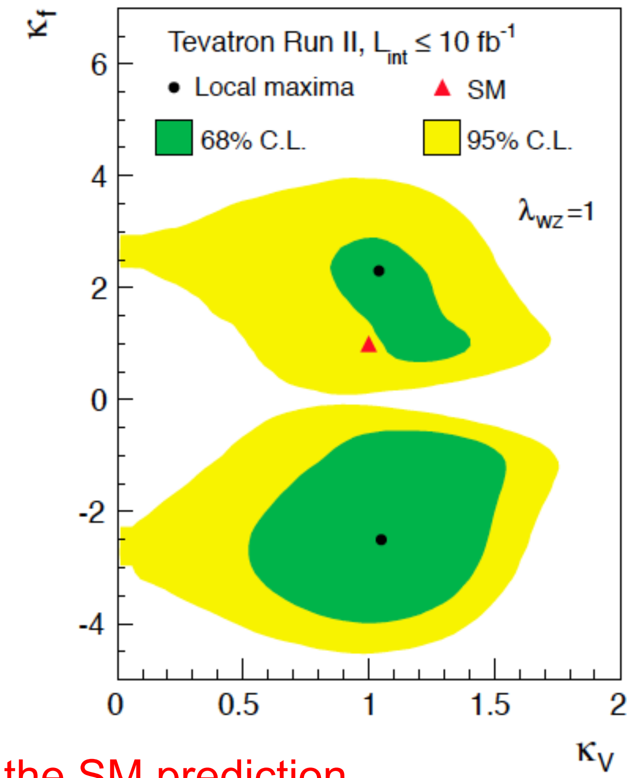
- **Benchmark I:**
  - Probe $SU(2)_V$ custodial symmetry by measuring the ratio $\lambda_{WZ}=\kappa_W/\kappa_Z$. Assume all fermion couplings are scaled by a common free parameter (κ_F).
- **Benchmark II:**
  - Consider two independent multiplicative factors: common to all couplings to vector bosons (κ_V) and common to all couplings to fermions (κ_f). Assume λ_{WZ}=1.
  - Measure κ_f and κ_V simultaneously.

arXiv:1303.6346



$$\theta_{WZ} = \tan^{-1}(1/\lambda_{WZ})$$

$$\lambda_{WZ} = 1.24^{+2.34}_{-0.42}$$

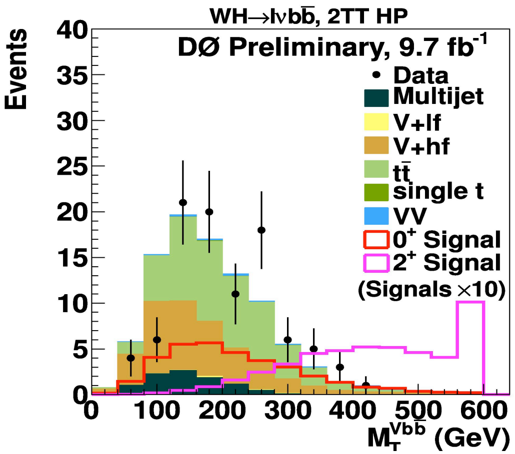


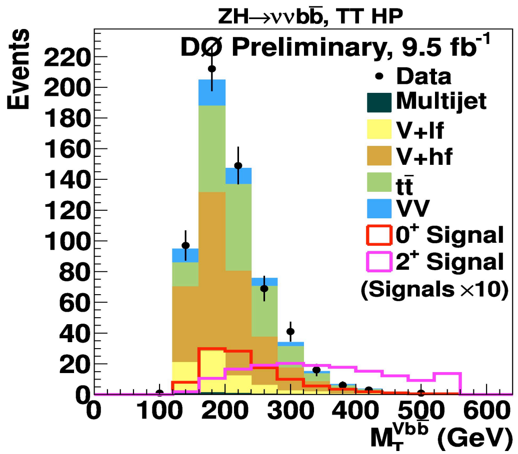
Measurements consistent with the SM prediction

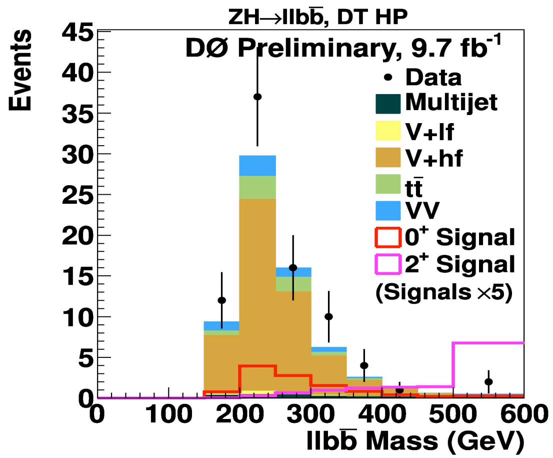
Spin/Parity

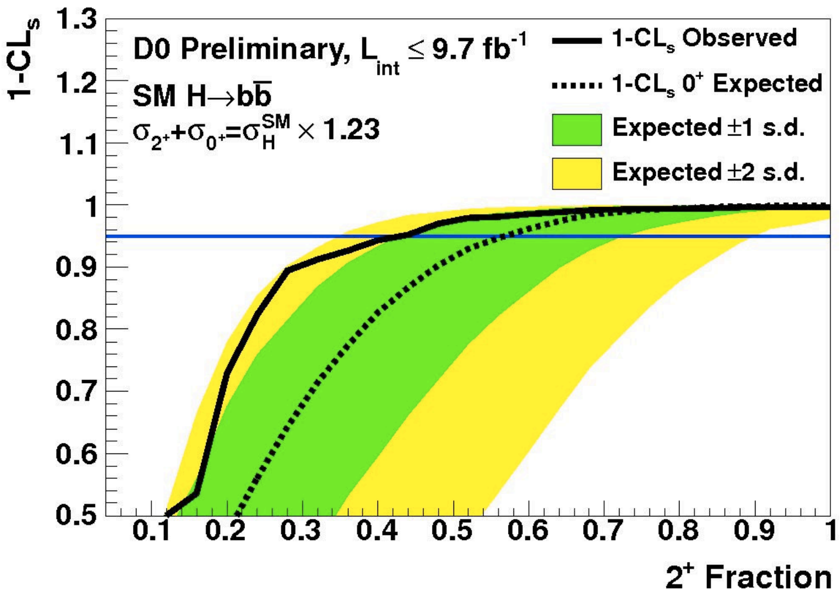
- LHC results in bosonic decay modes consistent with $J^P=0^+$ hypothesis.
- Tevatron can check J^P in VH(H→bb) production (J. Ellis et al., JHEP 1211, 134 (2012)).

So far results from DØ on 0^+ vs 2^+ (graviton-like couplings). 0^+ vs 0^- and Tevatron combination upcoming.









DØ Note 6387-CONF

For μ=1.23 (DØ measured rate):

- Exclude 2^+ at 99.9% CL (in favor of 0^+).
- Assuming the excess results from a superposition of a 0^+ and 2^+ particle:

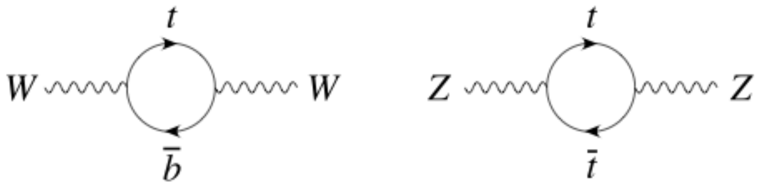
  Exclude a 2^+ fraction $f_{2+}>0.42$ at 95% CL (in favor of pure 0^+).

Indirect Constraints

Precision Electroweak Observables

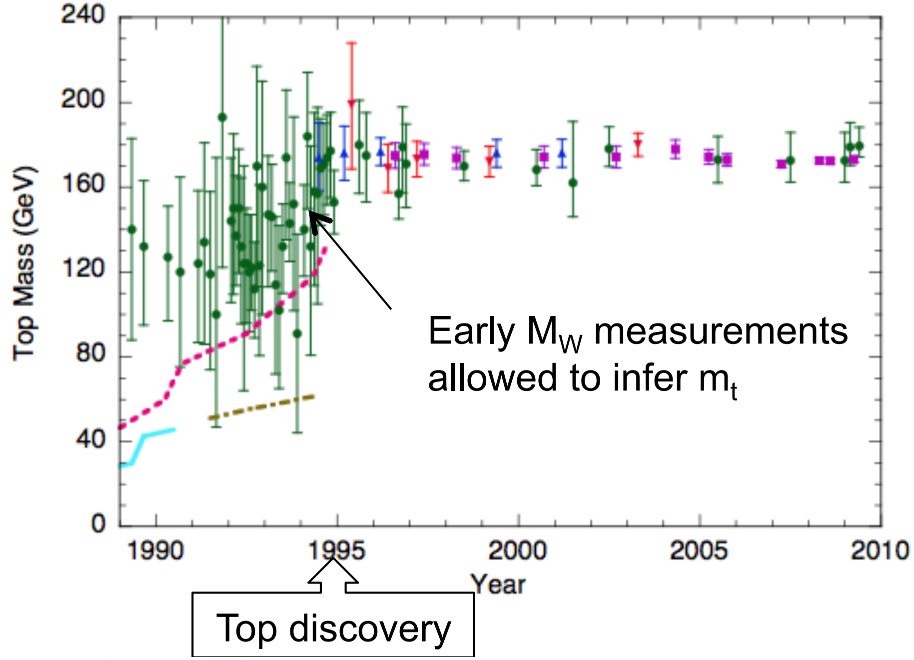
- Experimental and theoretical precision achieved allow to test the electroweak theory at the quantum level.

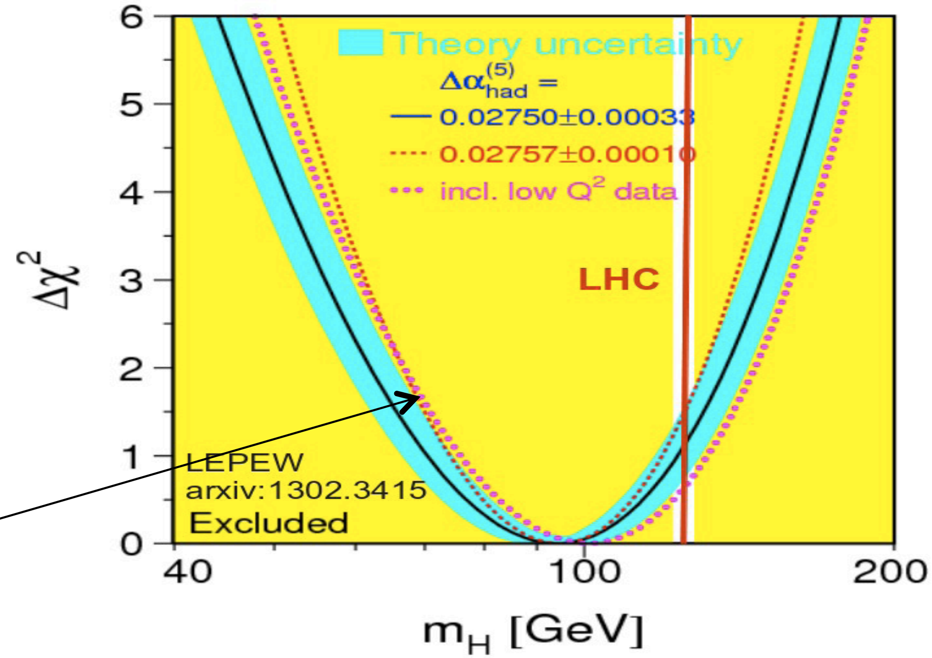
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$



$$\Delta r_{\rm top}=-\frac{3\alpha}{16\pi}\frac{\cos^2\theta_W}{\sin^4\theta_W}\frac{m_t^2}{m_W^2}$$

$$\Delta r_{\rm Higgs}=+\frac{11\alpha}{48\pi\sin^2\theta_W}\log\frac{m_H^2}{m_W^2}$$



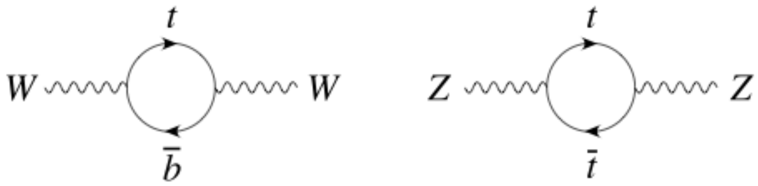


Precision EW observables, along with m_t, allow to infer M_H (M_W is one of the most sensitive measurements)

Precision Electroweak Observables

- Experimental and theoretical precision achieved allow to test the electroweak theory at the quantum level.

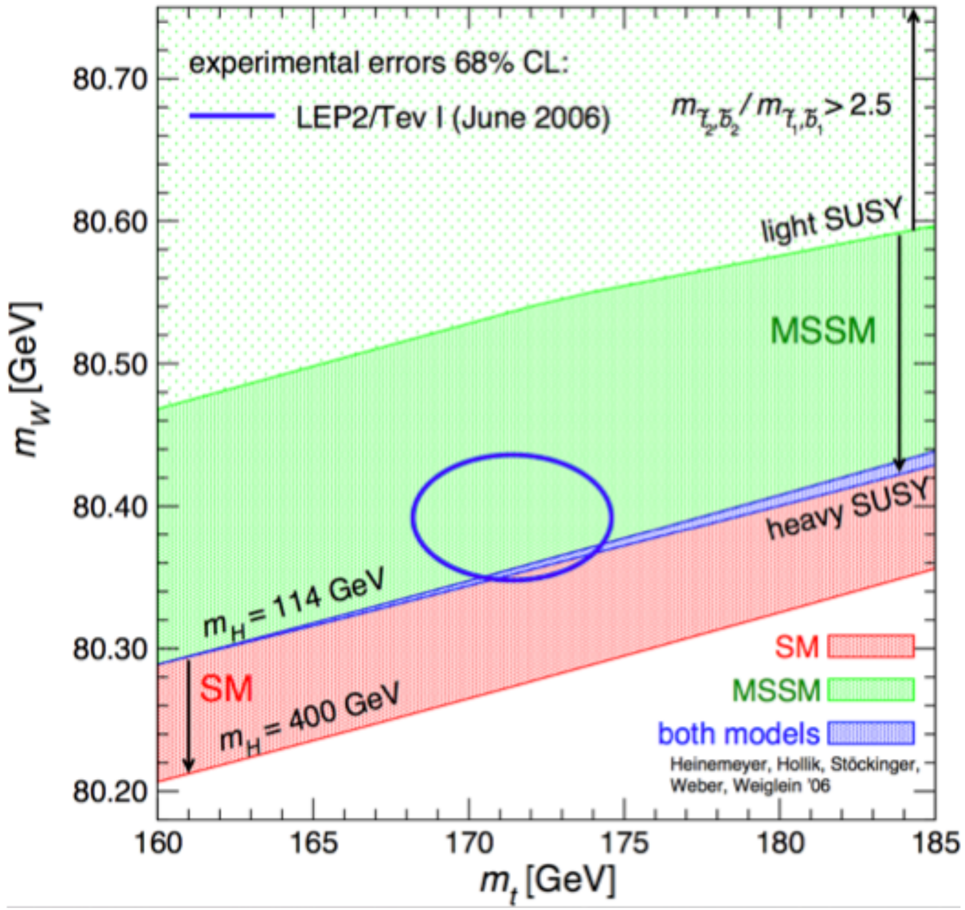
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$



$$\Delta r_{\text{top}}=-\frac{3\alpha}{16\pi}\frac{\cos^2\theta_W}{\sin^4\theta_W}\frac{m_t^2}{m_W^2}$$

$$\Delta r_{\text{Higgs}}=+\frac{11\alpha}{48\pi\sin^2\theta_W}\log\frac{m_H^2}{m_W^2}$$

Status early in Run II



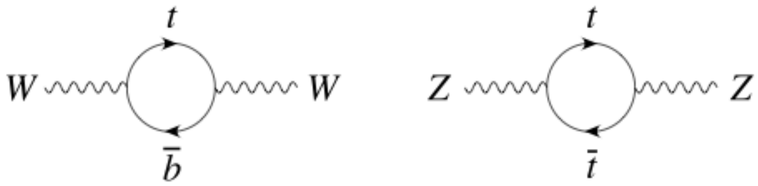
Δm_t~2 GeV (from early Tevatron Run II meas.)

ΔM_W~30 MeV (dominated by LEP2)

Precision Electroweak Observables

- Experimental and theoretical precision achieved allow to test the electroweak theory at the quantum level.

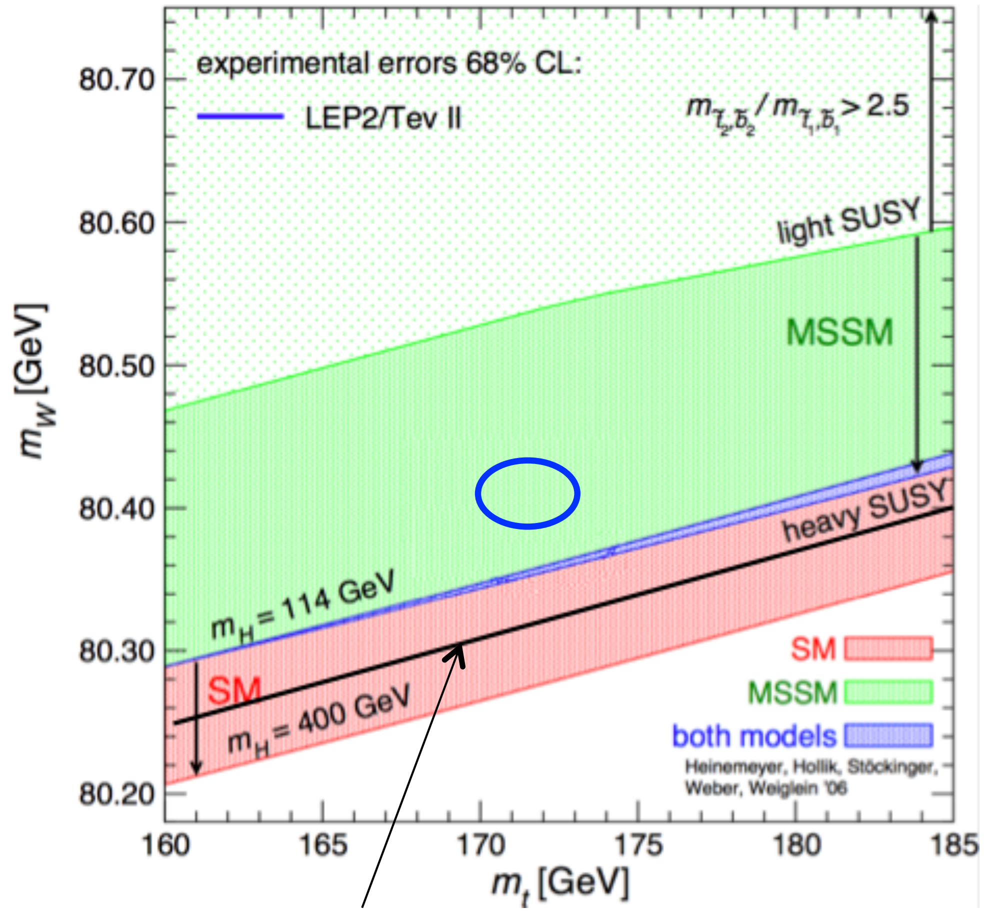
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$



$$\Delta r_{\rm top}=-\frac{3\alpha}{16\pi}\frac{\cos^2\theta_W}{\sin^4\theta_W}\frac{m_t^2}{m_W^2}$$

$$\Delta r_{\rm Higgs}=+\frac{11\alpha}{48\pi\sin^2\theta_W}\log\frac{m_H^2}{m_W^2}$$

A Hypothetical Scenario in 2012



Higgs boson with M_H=160 GeV discovered at Tevatron or LHC

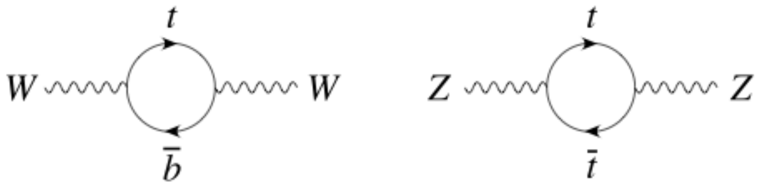
Δm_t~1 GeV (~ultimate Tevatron precision)

ΔM_W~15 MeV (dominated by Tevatron)

Precision Electroweak Observables

- Experimental and theoretical precision achieved allow to test the electroweak theory at the quantum level.

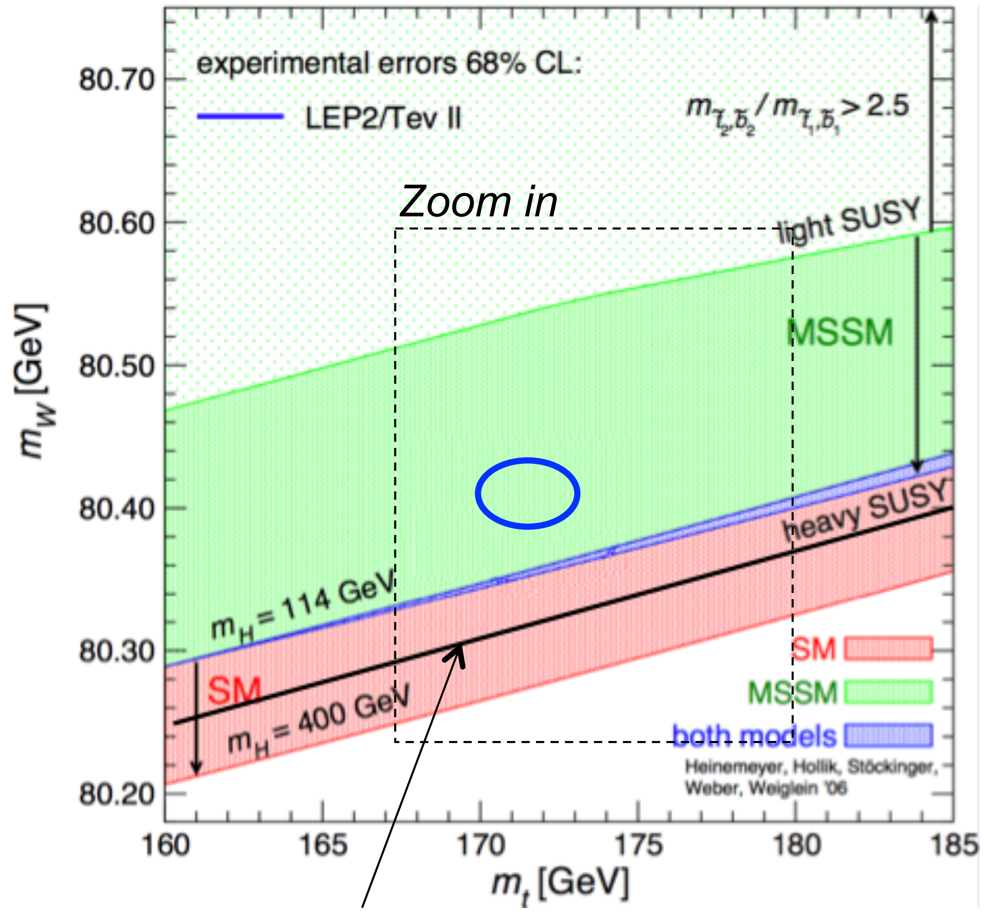
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$



$$\Delta r_{\rm top}=-\frac{3\alpha}{16\pi}\frac{\cos^2\theta_W}{\sin^4\theta_W}\frac{m_t^2}{m_W^2}$$

$$\Delta r_{\rm Higgs}=+\frac{11\alpha}{48\pi\sin^2\theta_W}\log\frac{m_H^2}{m_W^2}$$

A Hypothetical Scenario in 2012



Higgs boson with M_H=160 GeV discovered at Tevatron or LHC

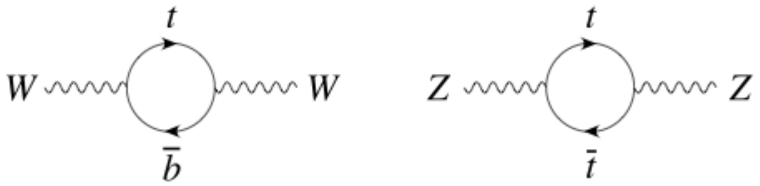
Δm_t~1 GeV (~ultimate Tevatron precision)

ΔM_W~15 MeV (dominated by Tevatron)

Precision Electroweak Observables

- Experimental and theoretical precision achieved allow to test the electroweak theory at the quantum level.

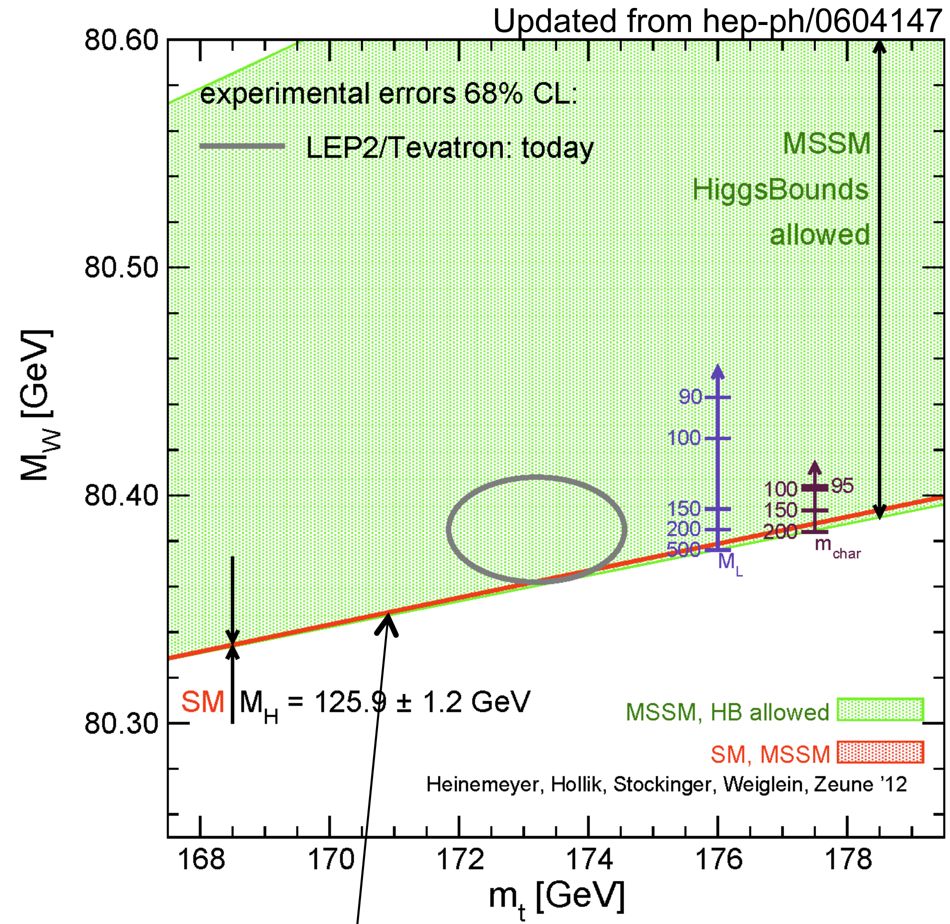
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$



$$\Delta r_{\rm top}=-\frac{3\alpha}{16\pi}\frac{\cos^2\theta_W}{\sin^4\theta_W}\frac{m_t^2}{m_W^2}$$

$$\Delta r_{\rm Higgs}=+\frac{11\alpha}{48\pi\sin^2\theta_W}\log\frac{m_H^2}{m_W^2}$$

Actual Scenario in 2012



Higgs boson with M_H~125 GeV discovered at LHC

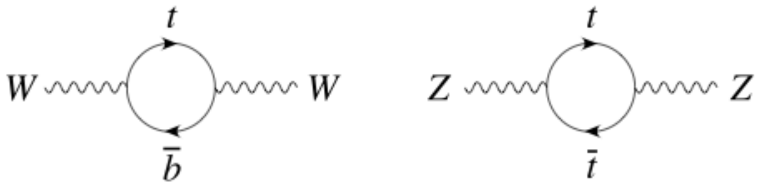
Δm_t~0.94 GeV (still improving)

ΔM_W~15 MeV (still improving)

Precision Electroweak Observables

- Experimental and theoretical precision achieved allow to test the electroweak theory at the quantum level.

$$m_W^2 \left(1 - \frac{m_W^2}{m_Z^2}\right) = \frac{\pi\alpha}{\sqrt{2}G_F}(1 + \Delta r)$$

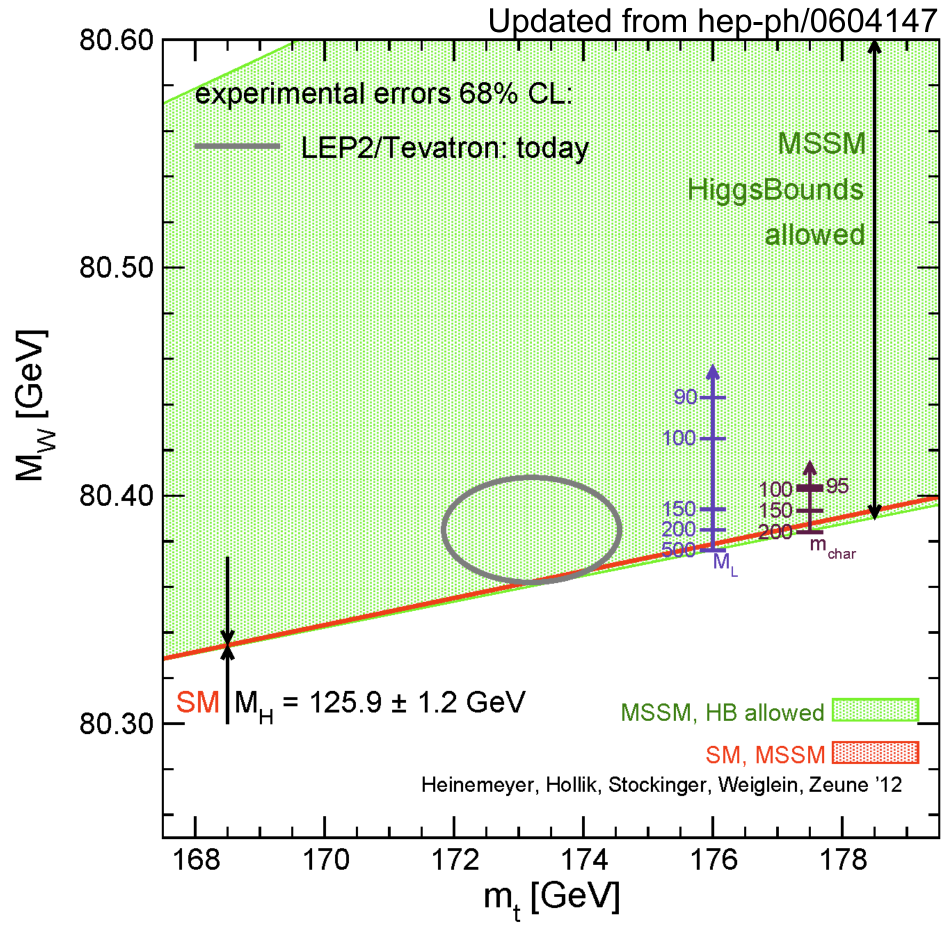


$$\Delta r_{\text{top}} = -\frac{3\alpha}{16\pi}\frac{\cos^2\theta_W}{\sin^4\theta_W}\frac{m_t^2}{m_W^2}$$

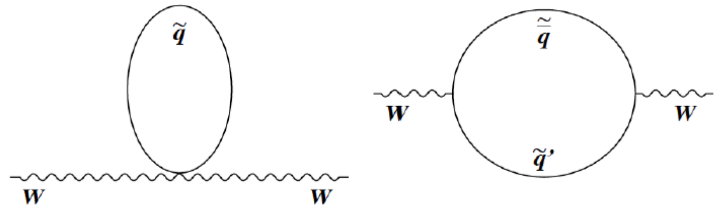
$$\Delta r_{\text{Higgs}} = +\frac{11\alpha}{48\pi\sin^2\theta_W}\log\frac{m_H^2}{m_W^2}$$

- Following the Higgs boson discovery, the SM loops are determined and so can effectively start constraining NP models.

Actual Scenario in 2012

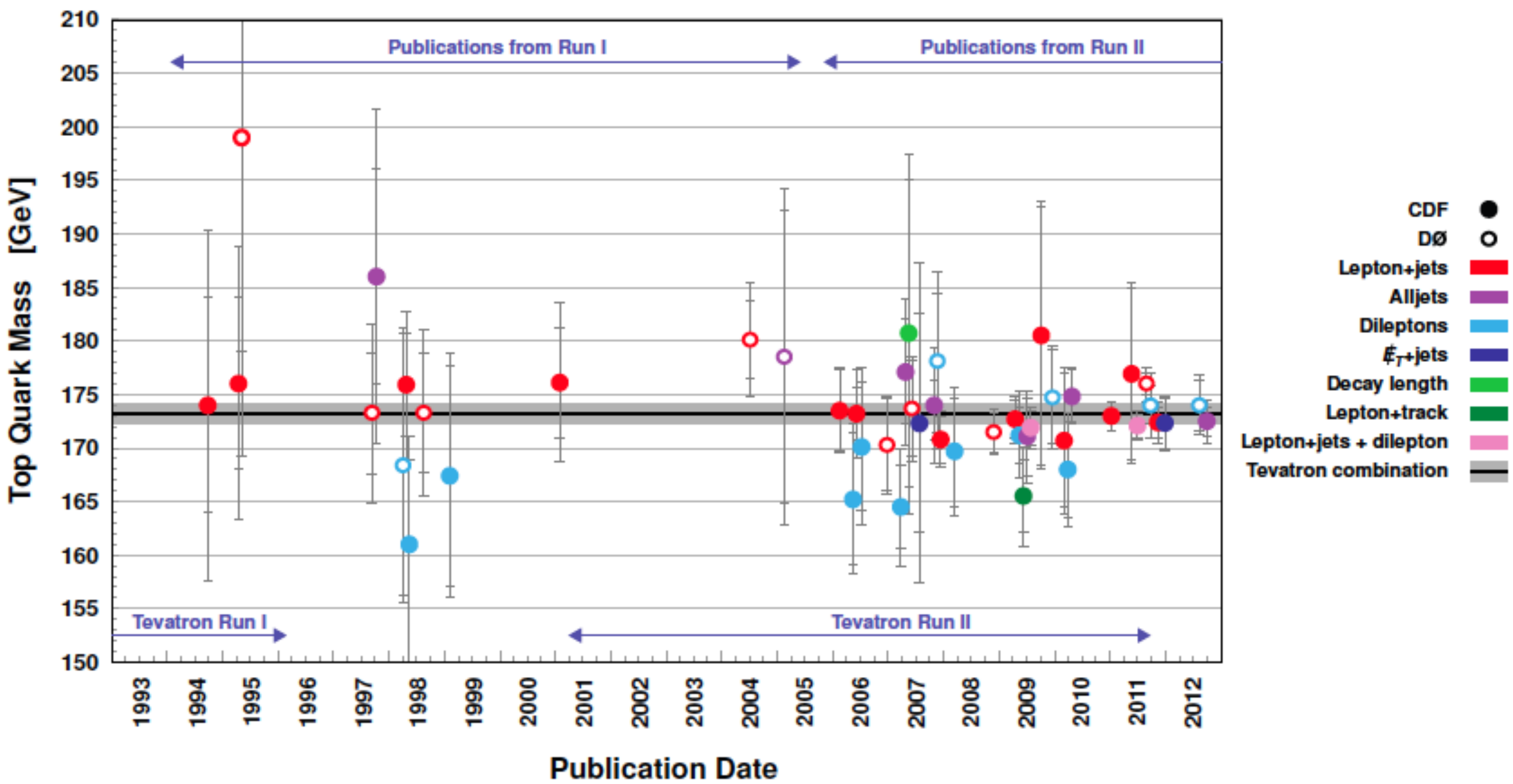


SUSY loops can contribute ~100 MeV to M_W!



Top Quark Mass

Top Quark Mass



- Precision on top quark mass measurements has improved by one order or magnitude since Run I:
  - Best single measurement in Run I: $\Delta m_t/m_t$~7%
  - Best single measurement in Run II: $\Delta m_t/m_t$~0.7%
- This has been possible, not only to the much large available statistics, but also to the development of novel experimental techniques, most of which have been adopted by LHC experiments.

Handles for a Precise Measurement

Jet Energy Scale (JES)

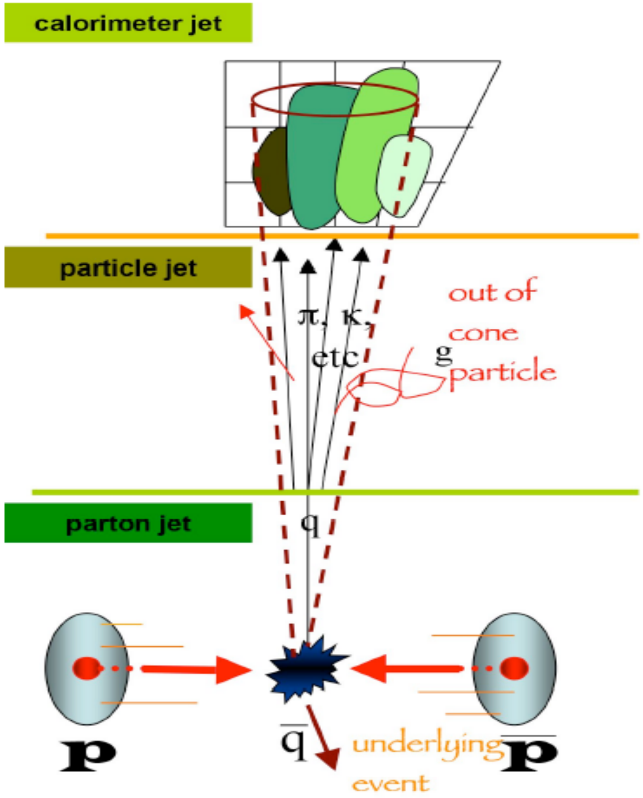
- Top mass measurement requires precise mapping between reconstructed jets and original partons ➔ correct for detector, jet algorithm and physics effects.
- What's crucial is the relative energy calibration between data and MC jets:

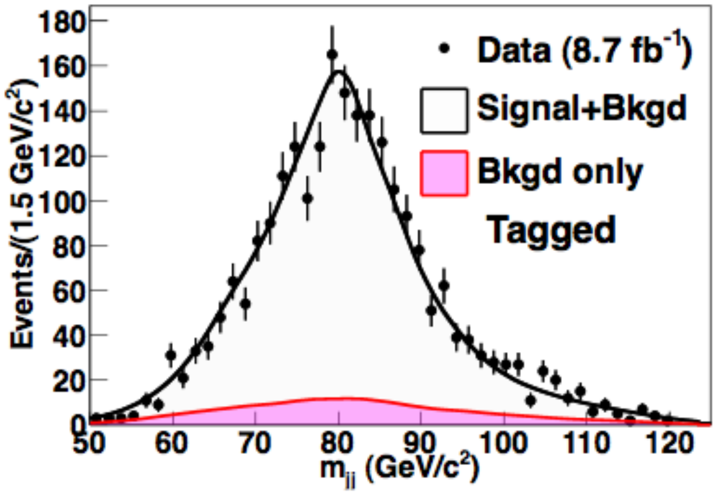
  $\Delta E_{jet}/E_{jet}$~1% ➔ Δm_t ~ 1 GeV
- Handles:
  - dijets, photon+jets, Z+jets
  - W mass from W→jj in top quark decays (in-situ calibration)

B-tagging: reduction of physics as well as combinatorial background

Sophisticated mass extraction techniques: maximize statistical sensitivity; minimize some systematic uncertainties (e.g. JES)

Simulation: accurate detector modeling and state-of-the-art theoretical knowledge (gluon radiation, b-fragmentation, etc) required.





Mass Extraction Techniques: Template Methods

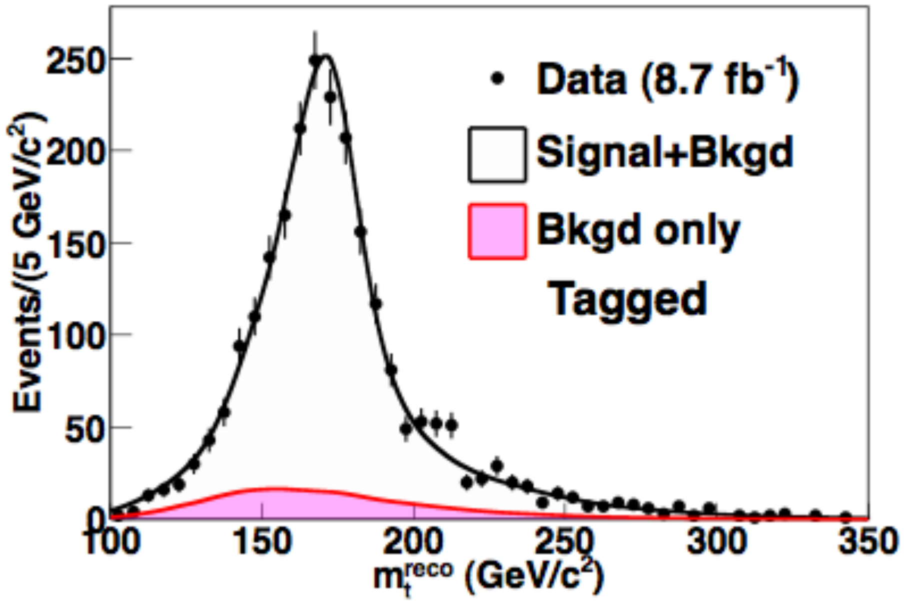
- Identify kinematical variables strongly correlated with m_t. Compare data and MC with different m_t hypotheses.
- <u>Example</u>: reconstructed m_t from kinematic fit in lepton+jets channel.

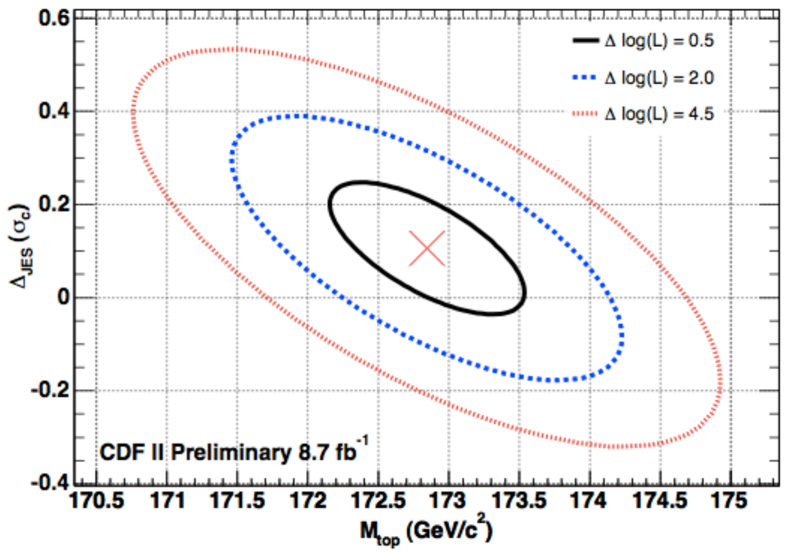
$$\chi^2 = \sum_{i=l,\,jets} \frac{(p_T^{i,fit} - p_T^{i,meas})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(UE_j^{fit} - UE_j^{meas})^2}{\sigma_j^2} + \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{l\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj} - m_t^{reco})^2}{\Gamma_t^2} + \frac{(M_{bl\nu} - m_t^{reco})^2}{\Gamma_t^2}$$

Usually pick solution with lowest χ^2.

- Reduce JES systematic by using in-situ hadronic W mass in tt events: simultaneous determination of m_t and JES scaling factor from reconstructed m_t and M_W templates.

PRL 109, 152003 (2012)





Mass Extraction Techniques: Dynamic Methods

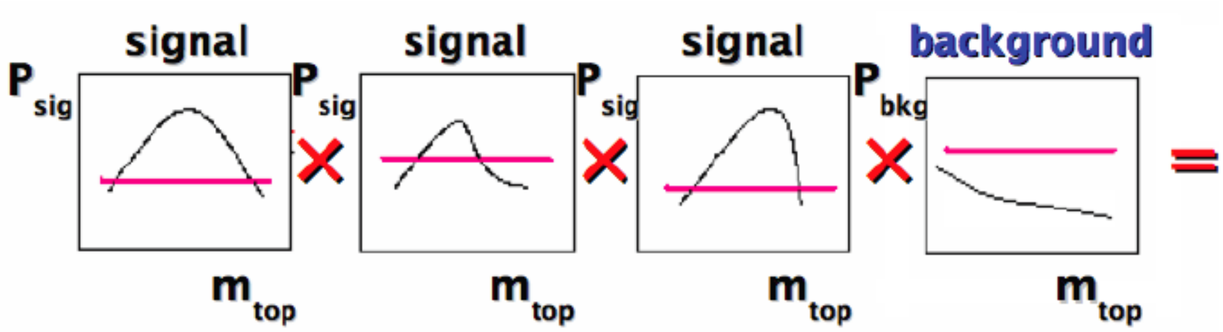
- Compute event-by-event probability as a function of m_t making use of all reconstructed objects in the events (integrate over unknowns). Maximize sensitivity by:
  - summing over all permutations of jets and neutrino solutions
  - allowing better measured events to contribute more.

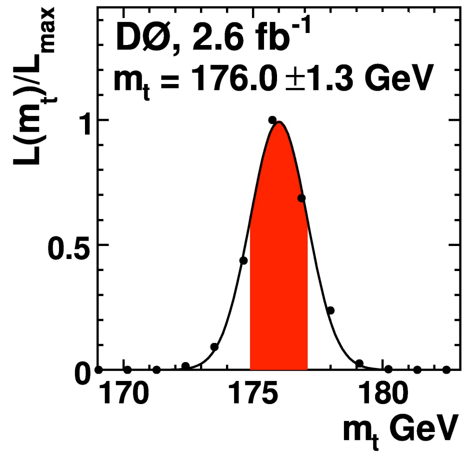
Example: **matrix element method**

$$P(x;m_t) = \frac{1}{\sigma}\int d^n\sigma(y;m_t)\,dq_1 dq_2\, f(q_1)f(q_2)W(x|y)$$

- parton distribution functions
- differential cross section (LO matrix element)
- transfer function: mapping from parton-level variables (y) to reconstructed-level variables (x)

PRD 84, 032004 (2011)

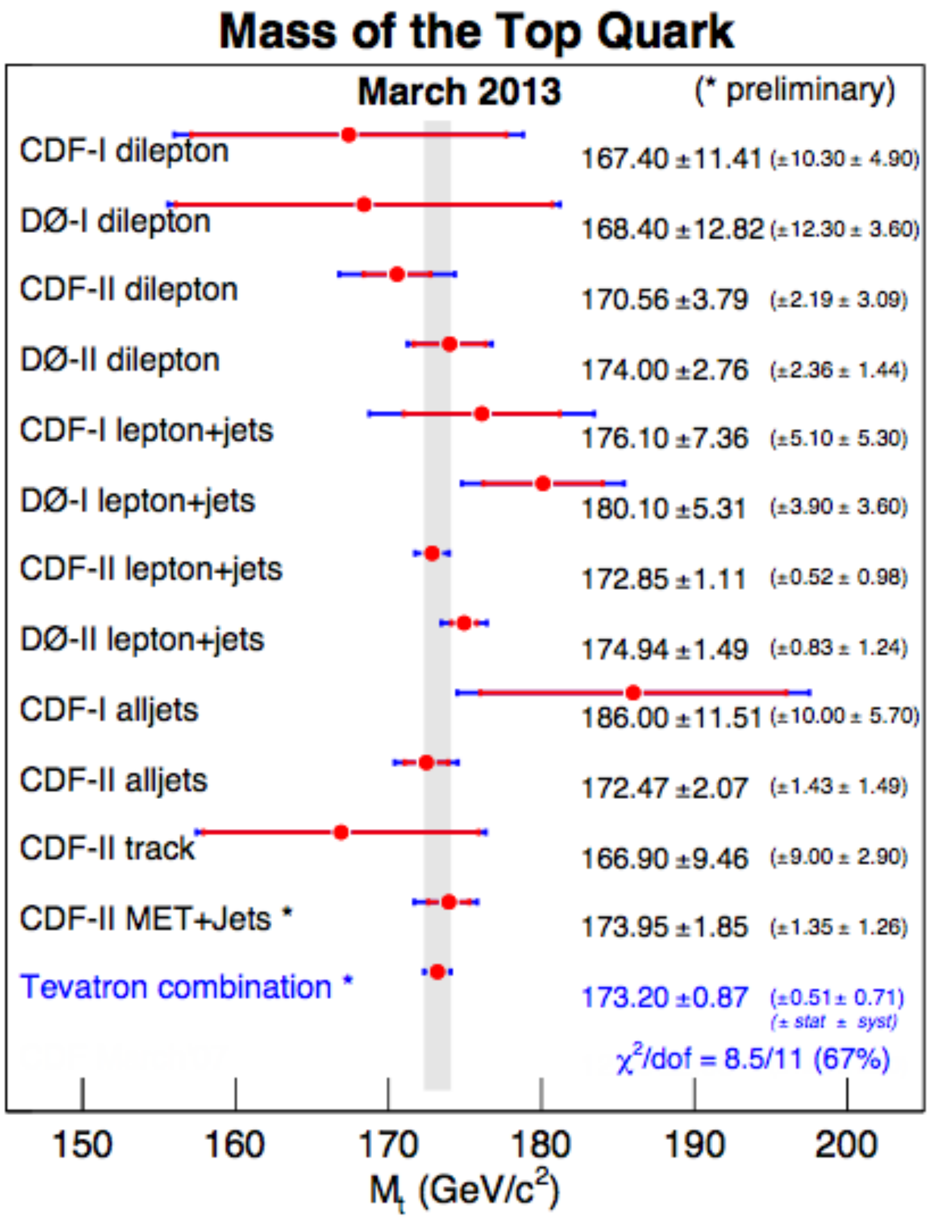




- Also incorporate in-situ JES calibration.

Tevatron Summary

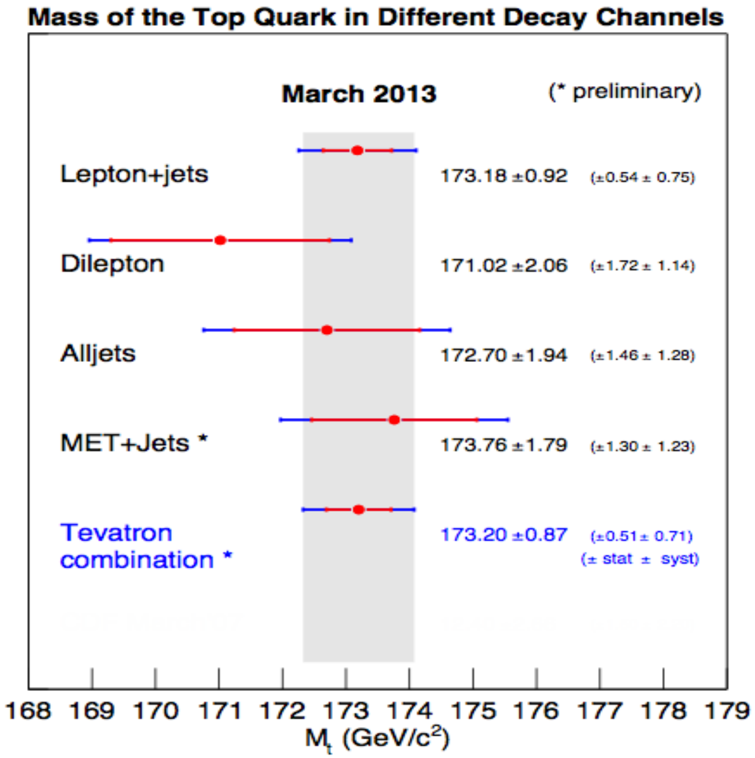
arXiv:1305.3929



m_t = 173.20 ±0.51(stat) ±0.71(syst) GeV

X^2/NDF = 8.5/11 (prob=67%)

- 0.5% overall precision! Statistical and systematic uncertainties comparable.
- Consistent measurement across decay channels.



Tevatron Summary

Uncertainty Source	Δm_t (Gev)
In-situ JES	0.36
Light-jet response (1)	0.16
Light-jet response (2)	0.15
Model of b jets	0.11
Response to b/q/g jets	0.09
Out-of-cone correction	0.01
Total JES	0.44
Signal model	0.52
Jet model	0.08
Lepton model	0.05
Background data	0.13
Background MC	0.06
Multiple interactions	0.07
Method calibration	0.06
Total systematic	0.71
Statistical	0.51
Total	0.87

m_t = 173.20 ±0.51(stat) ±0.71(syst) GeV

X^2/NDF = 8.5/11 (prob=67%)

- 0.5% overall precision! Statistical and systematic uncertainties comparable.
- Dominant systematics:
  - In-situ JES: scales like 1/√L
  - Signal modeling
- Prospects: DØ measurements being updated to the full dataset:
  - Increased statistics by x2 (dileptons), x3 (lepton+jets)
  - Alljets measurement for first time.
  - Reduced systematics
- Tevatron combination may reach ultimate precision ~0.7-0.8 GeV.

LHC Summary

July 2012 LHC Combination:

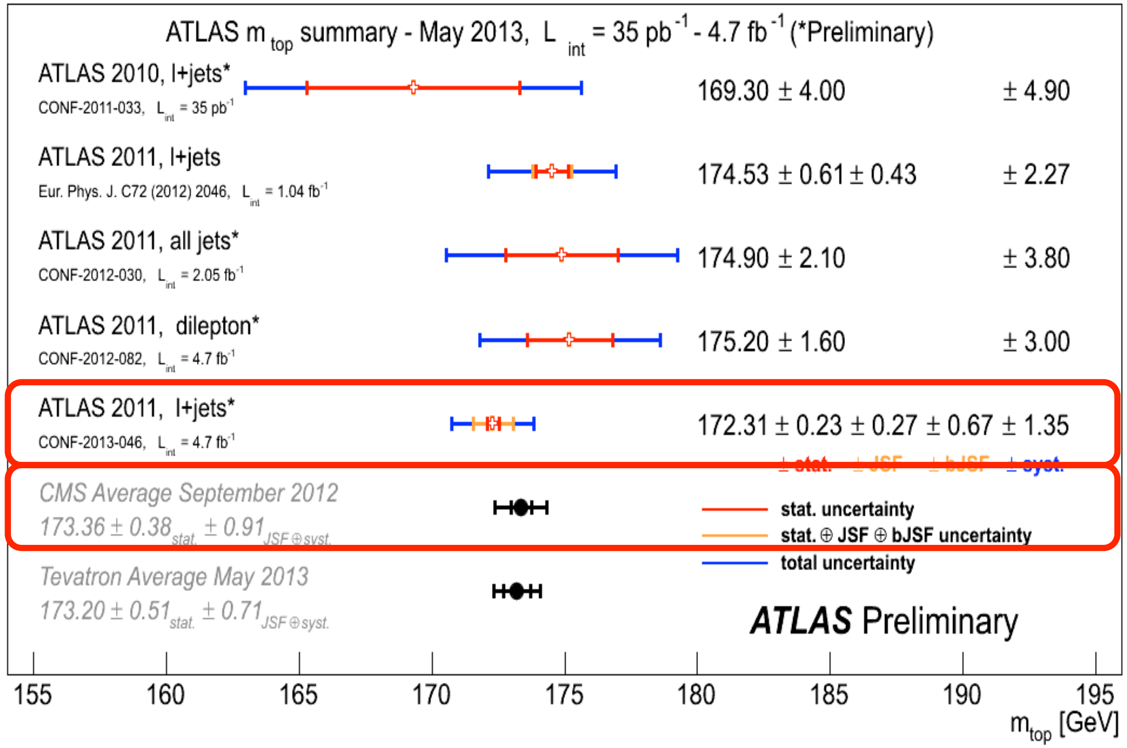
m_t = 173.3 ±0.5(stat) ±1.3(syst) GeV

χ^2/NDF = 2.5/6 (prob=87%)

Uncertainty source	δm_{top} (GeV)
in-situ JES	0.38
rJES (CMS)	0.06
light-jet response (2)	0.07
model of b-jets	0.68
detector model	0.19
underlying event	0.47
radiation	0.69
color reconnection	0.55
MHI	0.25
lepton model	0.01
background data	0.16
background MC	0.01
method calibration	0.13
statistical	0.47
Total	1.40

ATLAS-CONF-2012-095
CMS PAS TOP-12-001

Latest results:

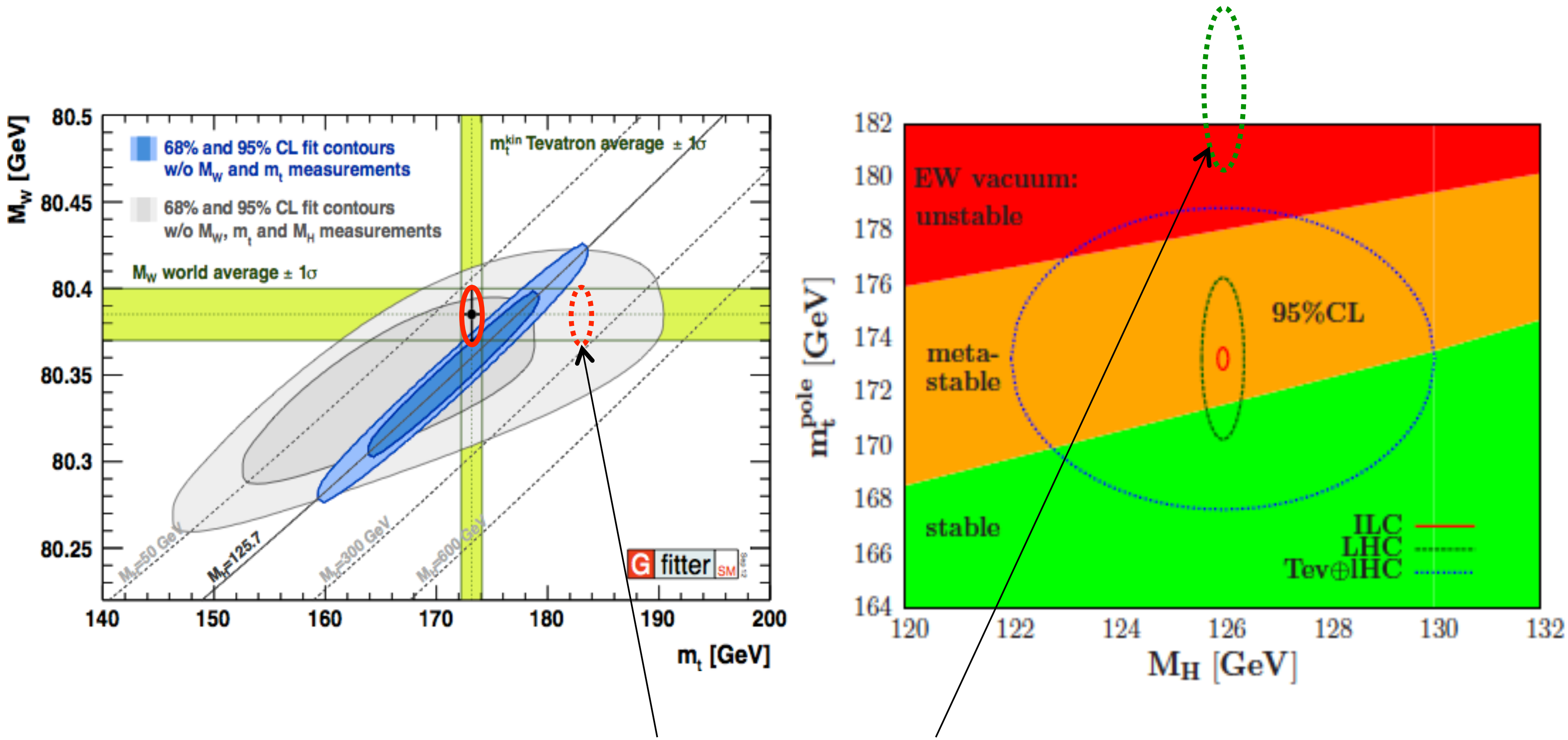


- LHC experiments are making fast progress and starting to reach precision competitive with the Tevatron.
- Promising future owing to large available samples, allowing for in-situ x-checks and reduction of systematic uncertainties (e.g. via MC tuning).

- Still, hard to imagine going below 0.5 GeV.

What Top Quark Mass?

- What's really being measured is the top quark mass in whatever MC generator was used to extract it. But different MCs include different radiative corrections!
- Naively one expects it to be close to the pole mass.
- It's important to know since there is a ~10 GeV shift between pole and MSbar mass!



Tevatron average interpreted as MSbar mass

A Partial Check

arXiv:1207.0980

- Compare measured tt cross section

$\sigma_{t\bar{t}} = 7.56^{+0.63}_{-0.56}$ pb D0 coll. arXiv:1105.5384

$\sigma_{t\bar{t}} = 7.50^{+0.48}_{-0.48}$ pb CDF coll. CDF-note-9913

to theoretical prediction (approx NNLO) as a function of MSbar mass.

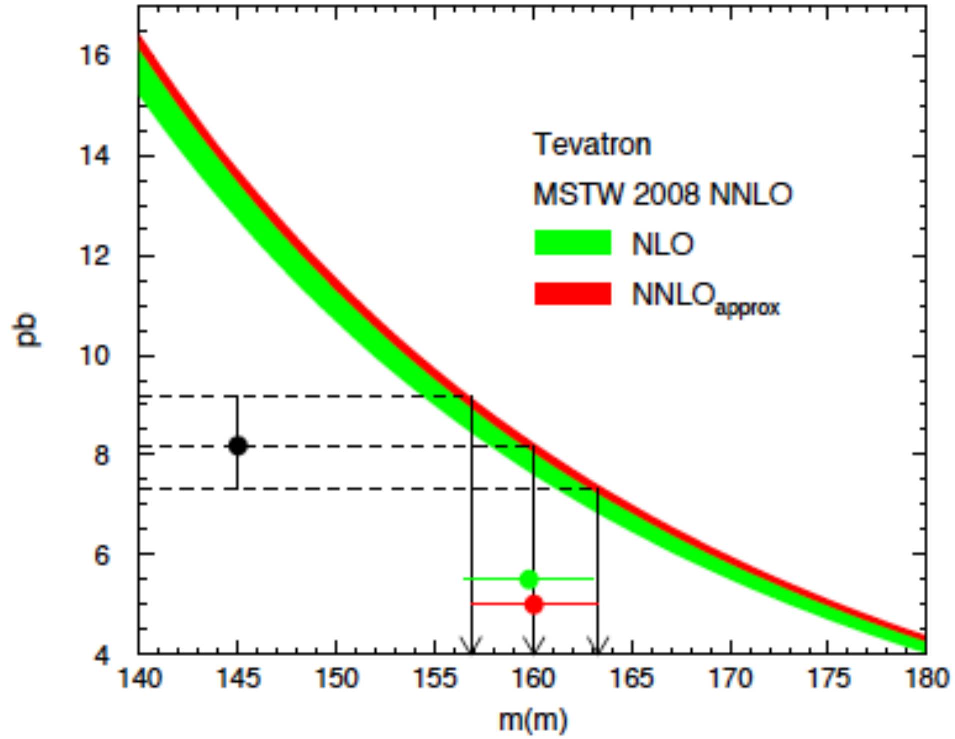
- Estimated MSbar mass:

$$m_t^{\overline{\mathrm{MS}}}(m_t) = 163.3 \pm 2.7\ \mathrm{GeV}$$

translated to pole mass (conversion known to 3-loops in QCD):

$$m_t^{\mathrm{pole}} = 173.3 \pm 2.8\ \mathrm{GeV}$$

➔ In good agreement with Tevatron average for m_t!



	ABM11	JR09	MSTW08	NN21
$m_t^{\overline{\mathrm{MS}}}(m_t)$	$162.0^{+2.3\ +0.7}_{-2.3\ -0.6}$	$163.5^{+2.2\ +0.6}_{-2.2\ -0.2}$	$163.2^{+2.2\ +0.7}_{-2.2\ -0.8}$	$164.4^{+2.2\ +0.8}_{-2.2\ -0.2}$
m_t^{pole}	$171.7^{+2.4\ +0.7}_{-2.4\ -0.6}$	$173.3^{+2.3\ +0.7}_{-2.3\ -0.2}$	$173.4^{+2.3\ +0.8}_{-2.3\ -0.8}$	$174.9^{+2.3\ +0.8}_{-2.3\ -0.3}$

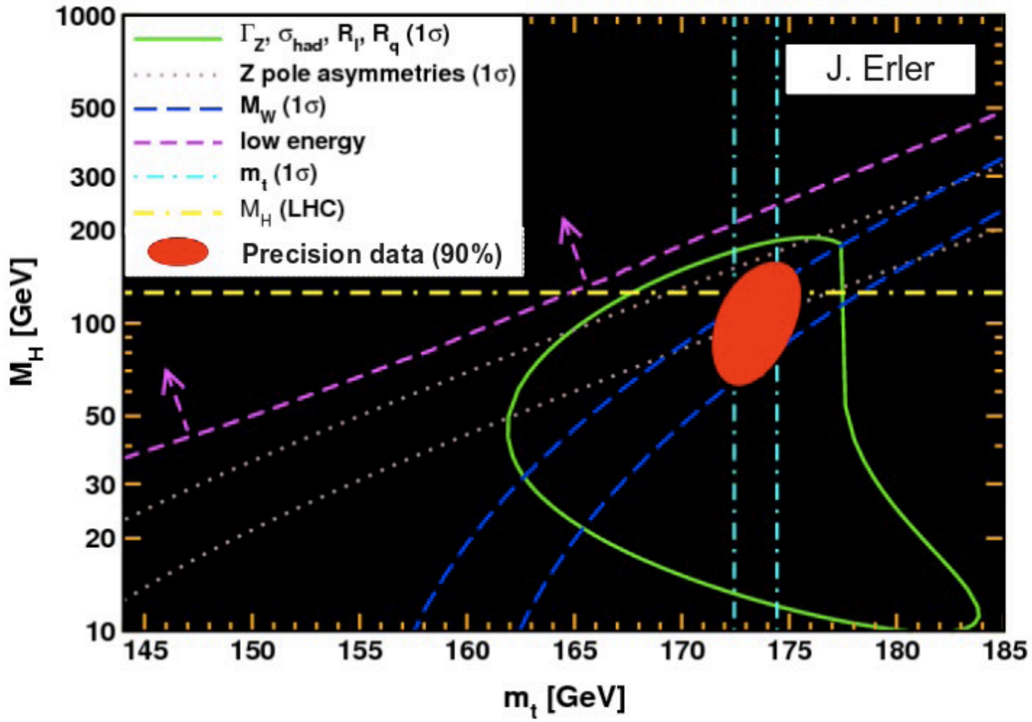
m_t = 173.20 ± 0.51(stat) ± 0.71(syst) GeV

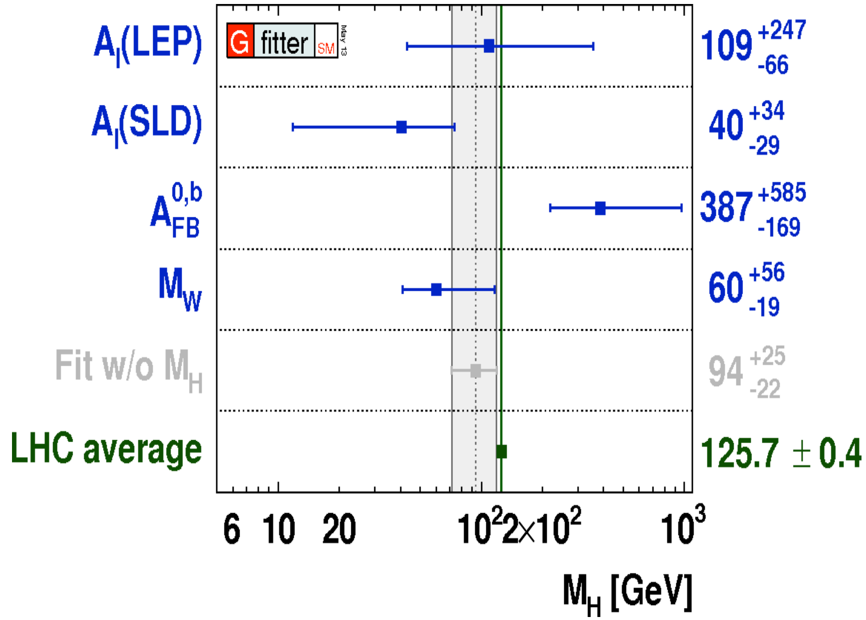
χ^2/NDF = 8.5/11 (prob=67%)

➔ supports direct measurements close to pole mass definition but comparison only good to O(3 GeV).

W Boson Mass

Motivation





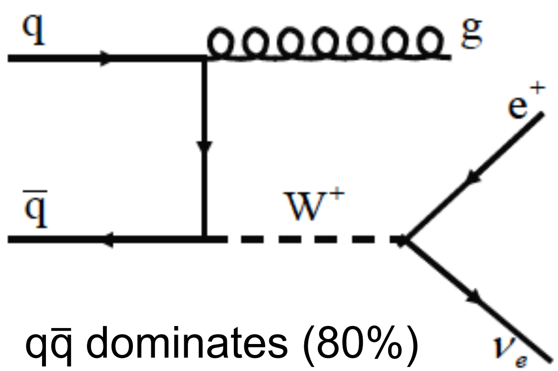
- Most sensitivity to M_H comes from M_W and $\sin^2\theta_{eff}$ (via Z-pole asymmetries).
- For equal contribution to the Higgs mass uncertainty need: $\Delta M_W=0.006\Delta m_t$
  - Latest Tevatron combination: Δm_t~0.9 GeV ➔ would need ΔM_W~5 MeV!
  - Before Run II had: ΔM_W~30 MeV (driven by LEP2 measurements).

➔ Given current precision on m_t, progress on ΔM_W would have the biggest impact on precision EW fit.

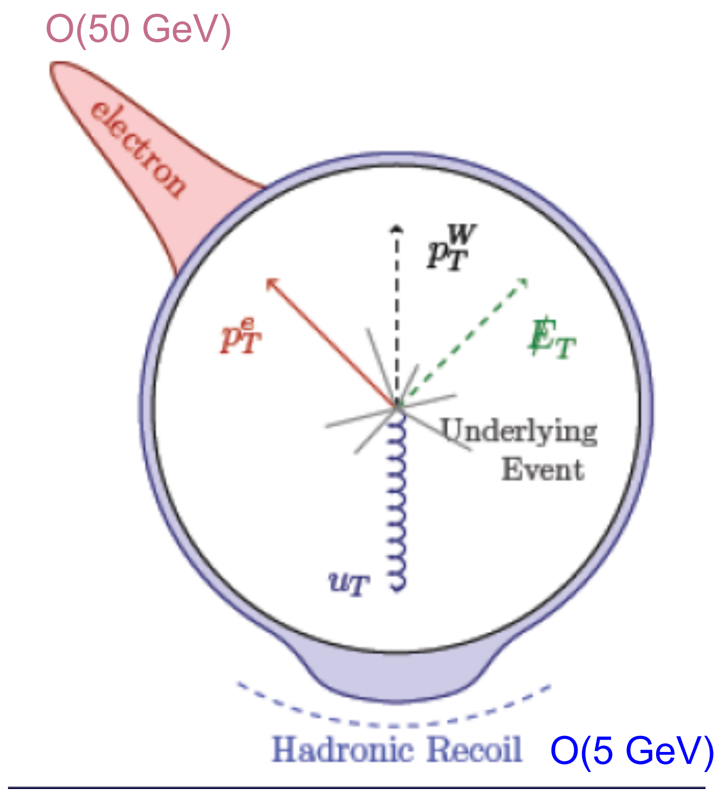
Measurement: Basic Strategy

In principle just need to:

- measure:
  - charged lepton
  - hadronic recoil
- build from MC templates of sensitive kinematic variables:
  - W transverse mass
  - lepton p_T
  - missing p_T
- perform a binned likelihood fit to data as a function of M_W



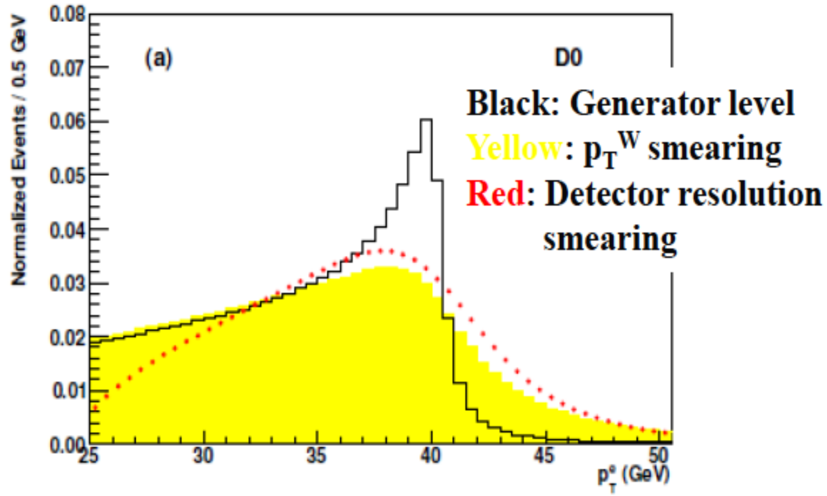
$q\bar{q}$ dominates (80%)

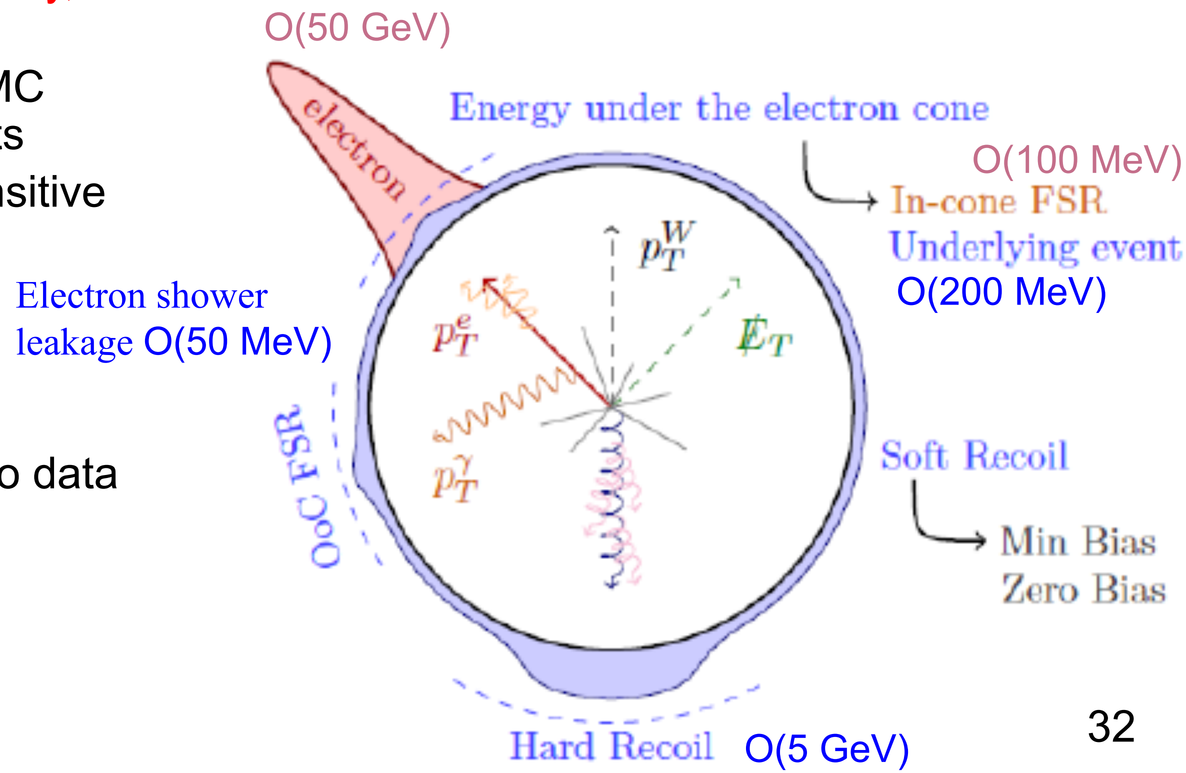


Measurement: Basic Strategy

In practice need to :

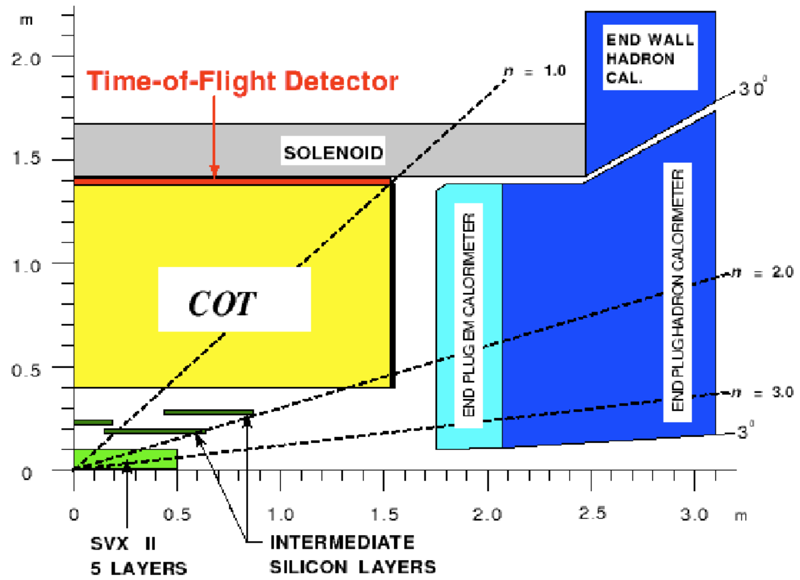
- measure:
  - charged lepton to 0.01% precision
  - hadronic recoil to <1% precision
- understand in great detail energy flow in event, driven by multiple physics and instrumental effects that affect each other
- employ state-of-art theoretical predictions for W boson production and decay, including radiative effects
- develop a parameterized fast MC implementing all relevant effects
- build from MC templates of sensitive kinematic variables:
  - W transverse mass
  - lepton p_T
  - missing p_T
- perform a binned likelihood fit to data as a function of M_W

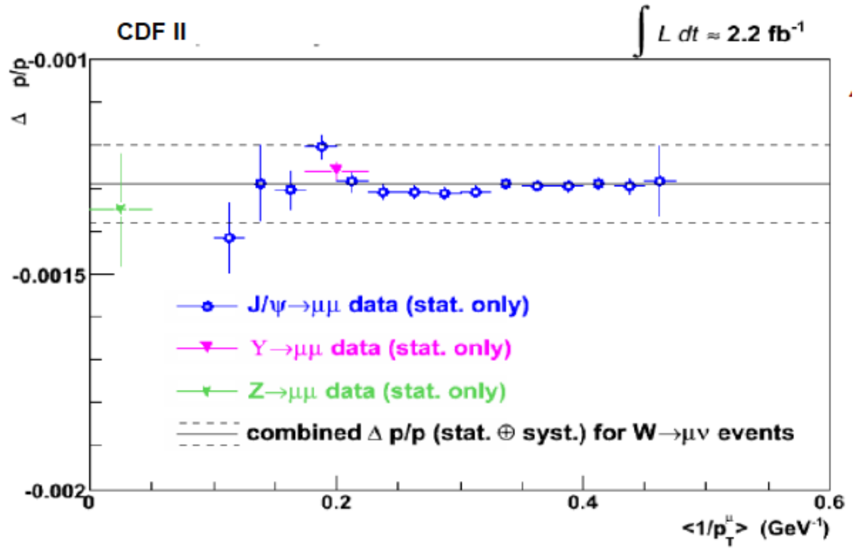




Measurement: Different Tactics

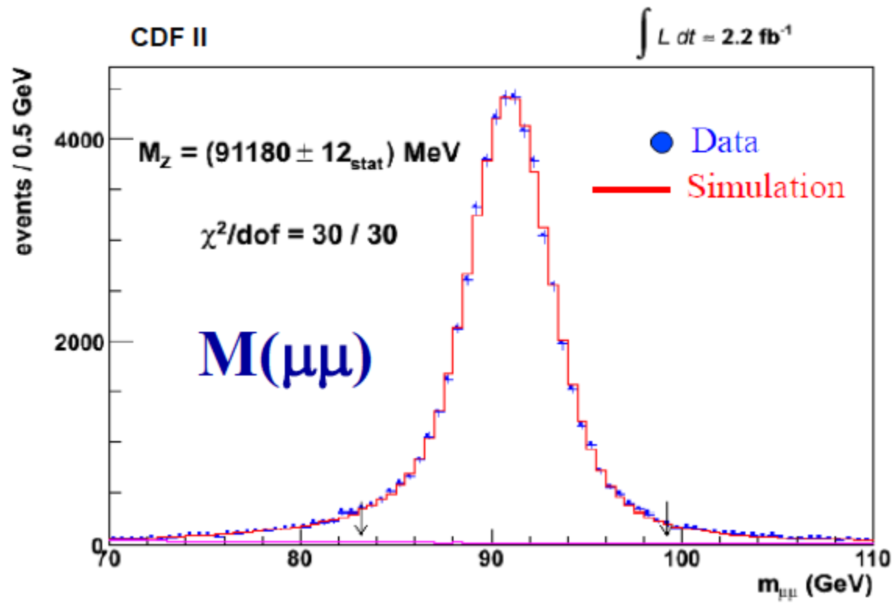
- CDF and DØ employ different tactics, especially in terms of fast MC simulation and calibration, capitalizing on the strengths of their detectors.





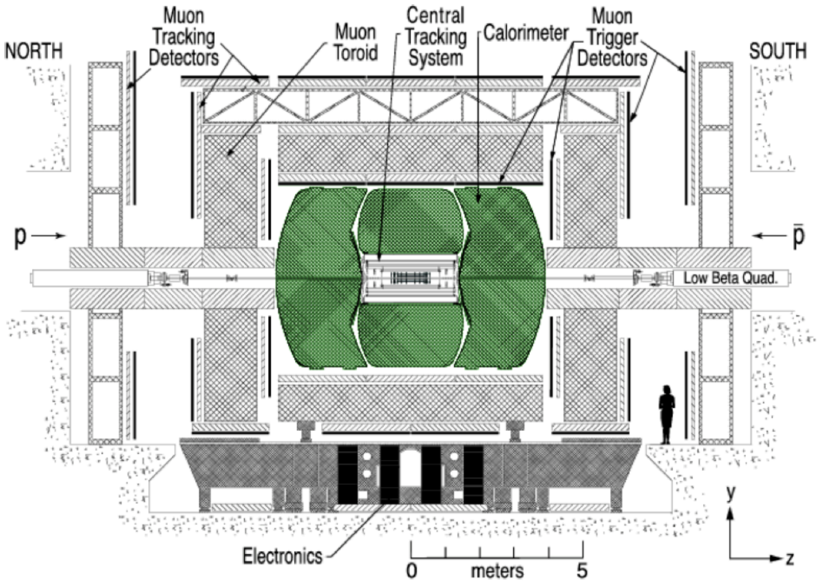
- Central tracking provides very good lepton momentum measurement
  - Muon $\Delta p_T/p_T$~3.2% at p_T=45 GeV
- Detailed tracker model
- Focus on momentum scale calibration
  - Using J/Ψ→μμ, ϒ→μμ, Z→μμ
- Use E/p peak from W→eν to calibrate EM calorimeter

→ Measurement on W→eν and W→μν events

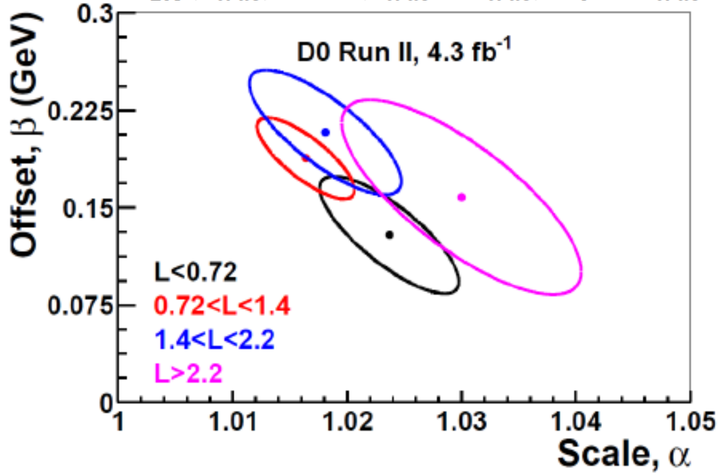


Measurement: Different Tactics

- CDF and DØ employ different tactics, especially in terms of fast MC simulation and calibration, capitalizing on the strengths of their detectors.

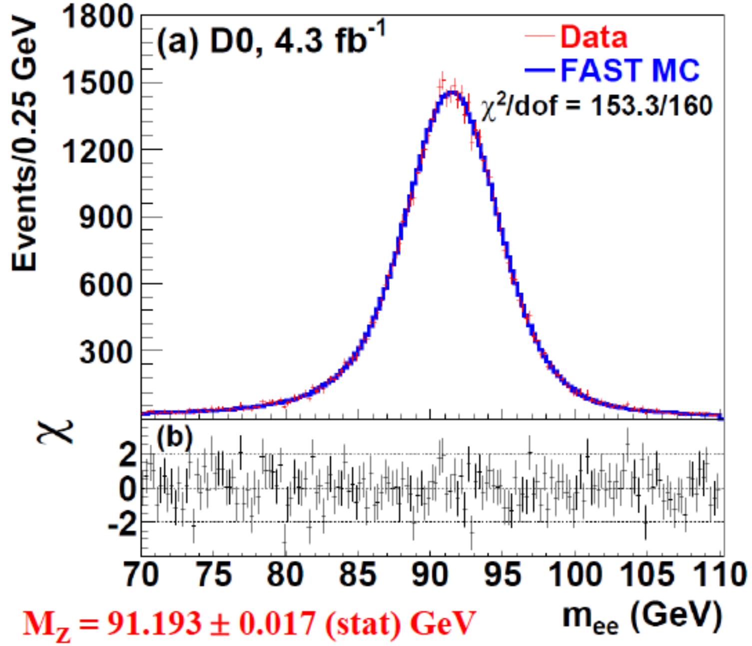


$R_{EM}(E_{true}) = \alpha \cdot (E_{true} - \bar{E}_{true}) + \beta + \bar{E}_{true}$



- EM calorimeter provides very good electron energy measurement
  - Muon $\Delta E/E \sim 3.3\%$ at E_T=45 GeV
- Detailed calorimeter, E-flow model
- Focus on calorimeter energy scale calibration
  - Using Z→ee

→ Measurement on W→eν events



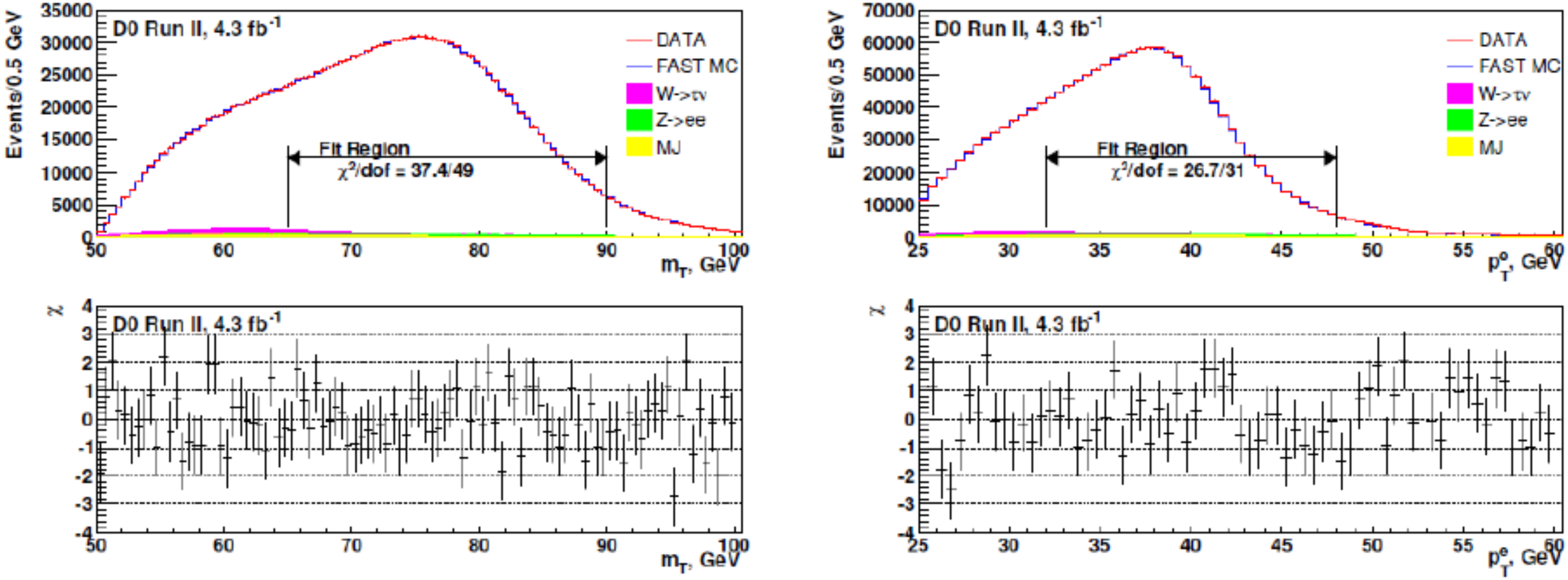
Systematic Uncertainties

- Breakdown of systematic uncertainties for m_T measurement:

Source	CDF $m_T(\mu,\nu)$	CDF $m_T(e,\nu)$	DØ $m_T(e,\nu)$
Experimental – Statistical power of the calibration sample.			
Lepton Energy Scale	7	10	16
Lepton Energy Resolution	1	4	2
Lepton Energy Non-Linearity			4
Lepton Energy Loss			4
Recoil Energy Scale	5	5	
Recoil Energy Resolution	7	7	
Lepton Removal	2	3	
Recoil Model			5
Efficiency Model			1
Background	3	4	2
W production and decay model – Not statistically driven.			
PDF	10	10	11
QED	4	4	7
Boson p_T	3	3	2
W statistics	12		13
	2.2 fb^{-1}		5.3 fb^{-1}

DØ Results

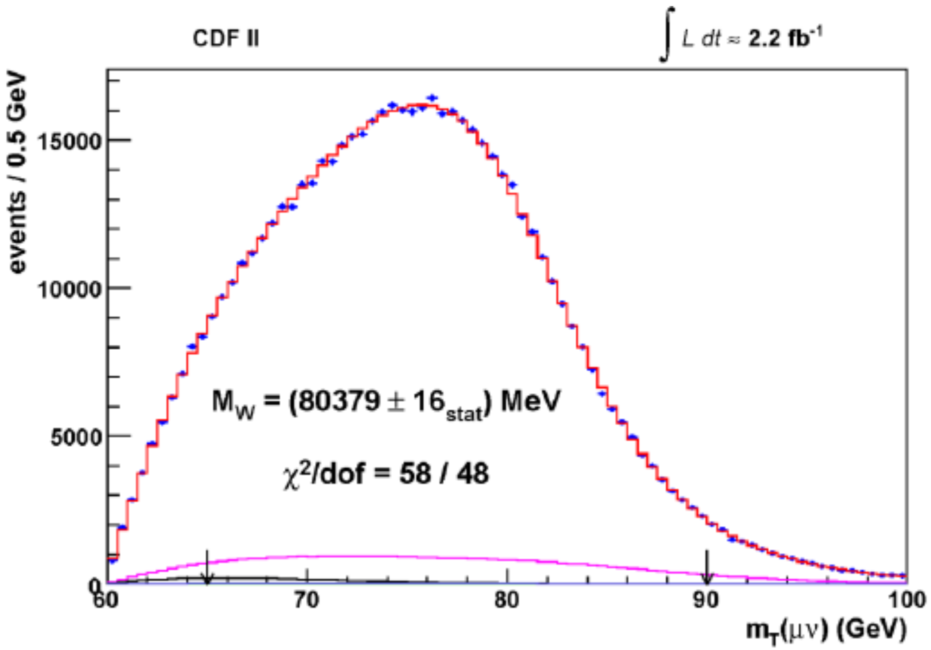
PRL 108, 151804 (2012)

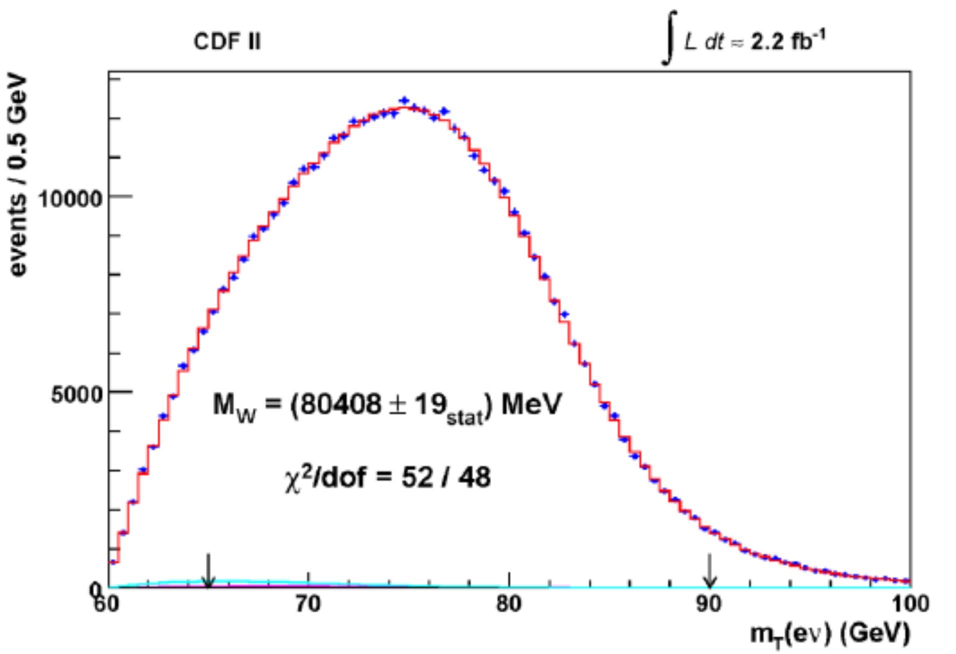


Method $(4.3\,fb^{-1})$	M_W (MeV)
$m_T(e,\nu)$	80371 ± 13(stat)
$p_T(e)$	80343 ± 14(stat)
$\not{E}_T(e,\nu)$	80355 ± 15(stat)
Combination $m_T \oplus p_T$ $(4.3\,fb^{-1})$	80367 ± 26(syst + stat)
Combination $(5.3\,fb^{-1})$	**80375 ± 23**(syst + stat)

CDF Results

PRL 108, 151803 (2012)



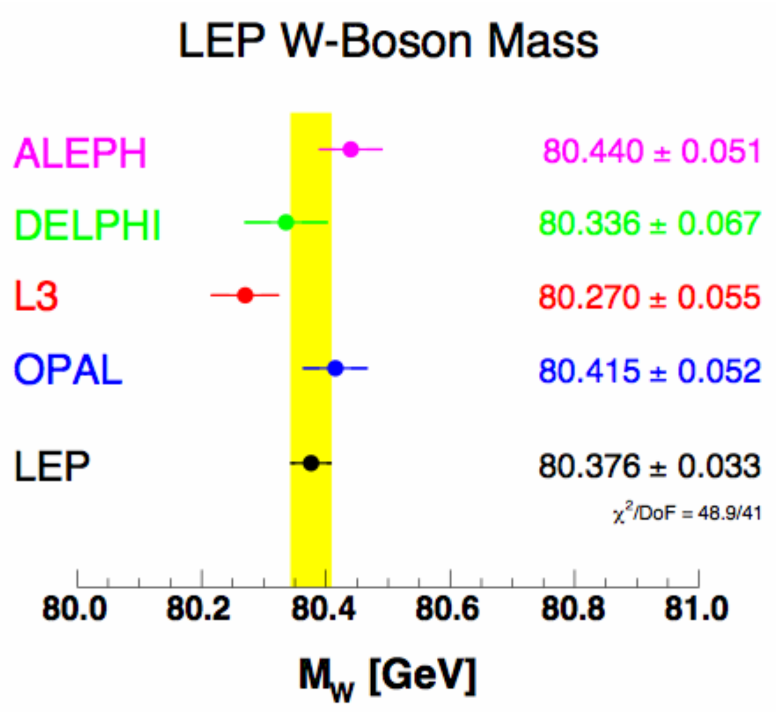


Method $(2.2\ fb^{-1})$	M_W (MeV)	Method $(2.2\ fb^{-1})$	M_W (MeV)
$m_T(\mu,\nu)$	80379 ± 16(stat)	$m_T(e,\nu)$	80408 ± 19(stat)
$p_T(\mu)$	80348 ± 18(stat)	$p_T(e)$	80393 ± 21(stat)
$\not{E}_T(\mu,\nu)$	80406 ± 22(stat)	$\not{E}_T(e,\nu)$	80431 ± 25(stat)
Combination $(2.2\ fb^{-1})$		$\mathbf{80387 \pm 19}\ MeV$ (syst + stat)	

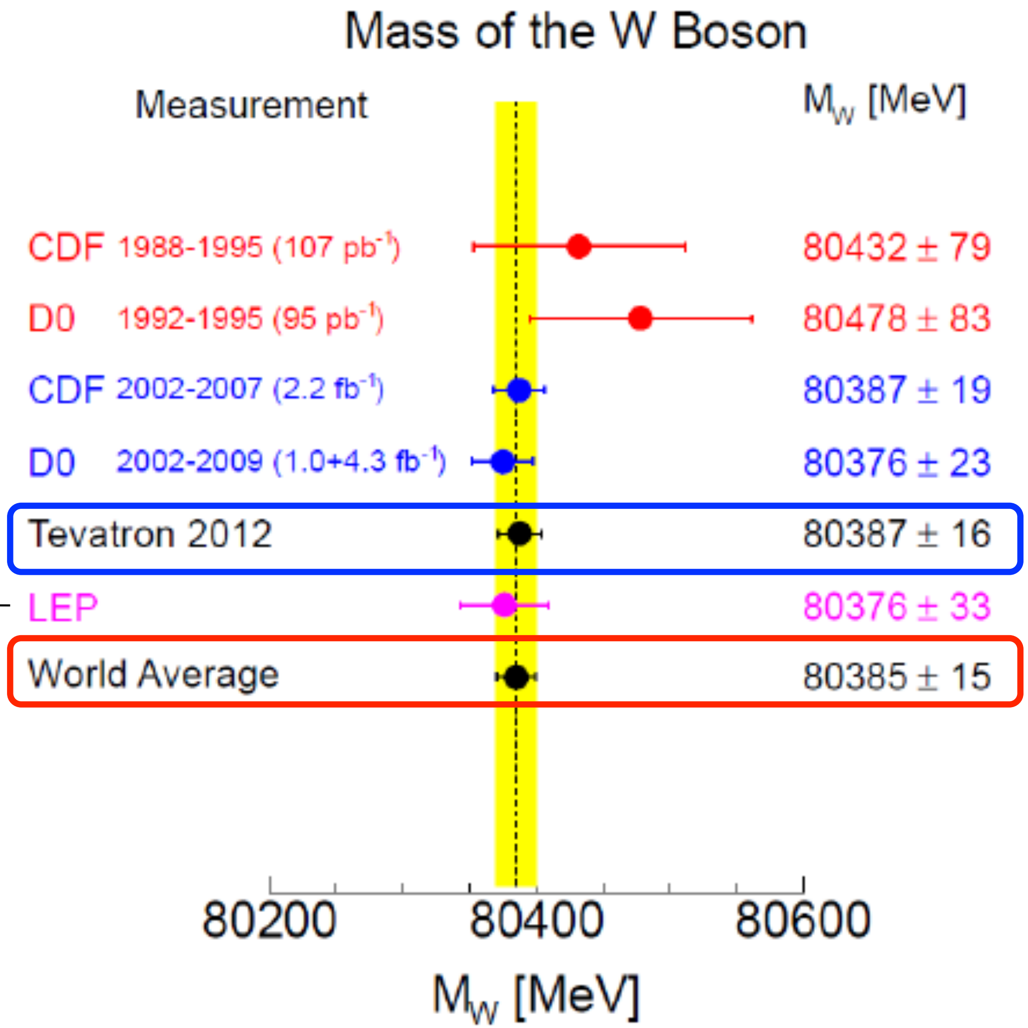
Best single measurement!

New World Average

arXiv:1302.3415



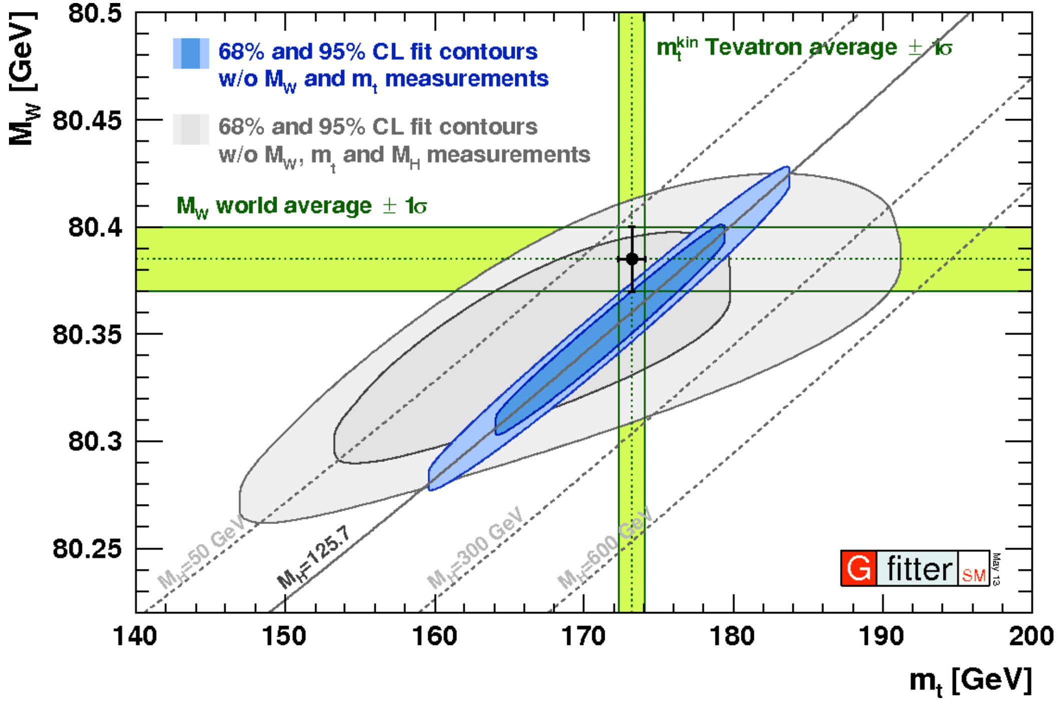
arXiv:1204.0042

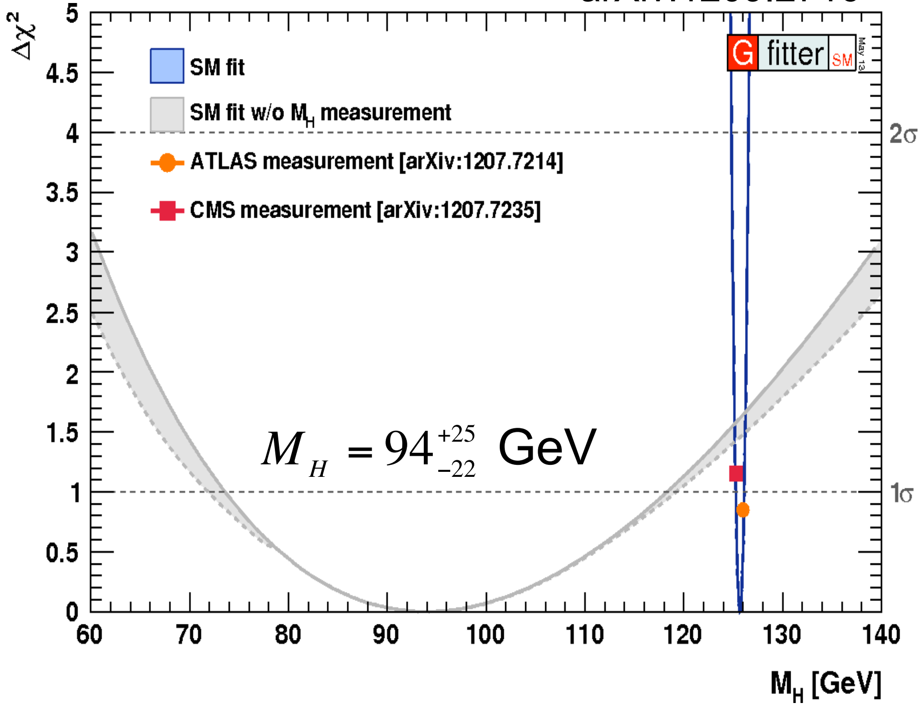


- World average dominated by Tevatron combination.
- PDF uncertainties are now the main limitation.

Constraints on the Higgs Boson Mass

arXiv:1209.2716

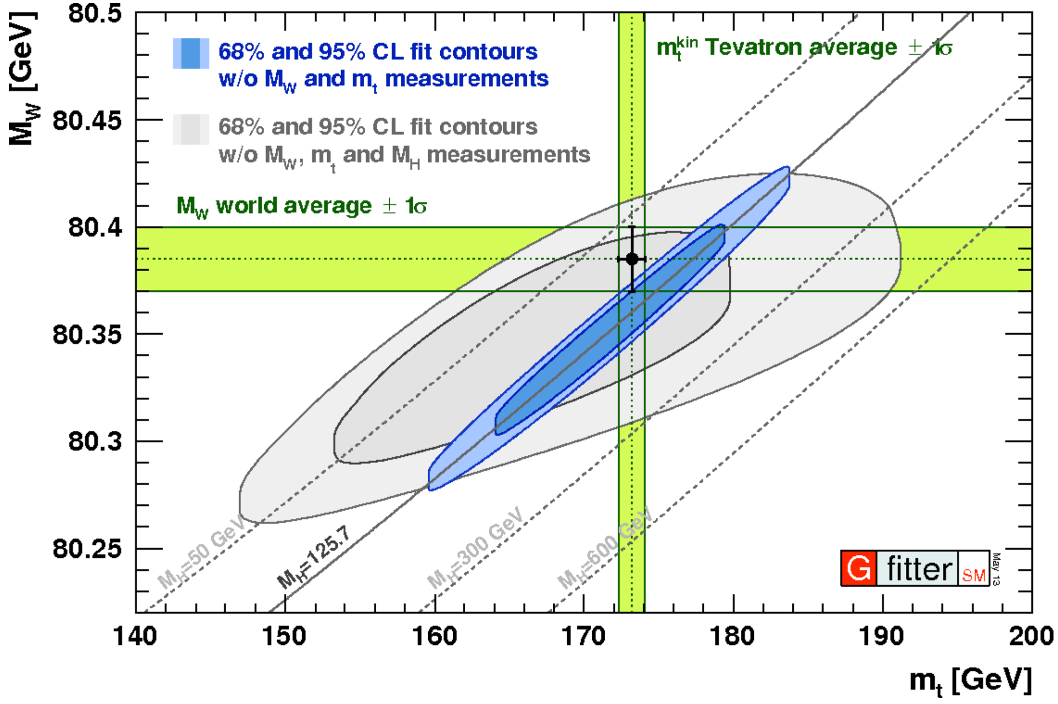


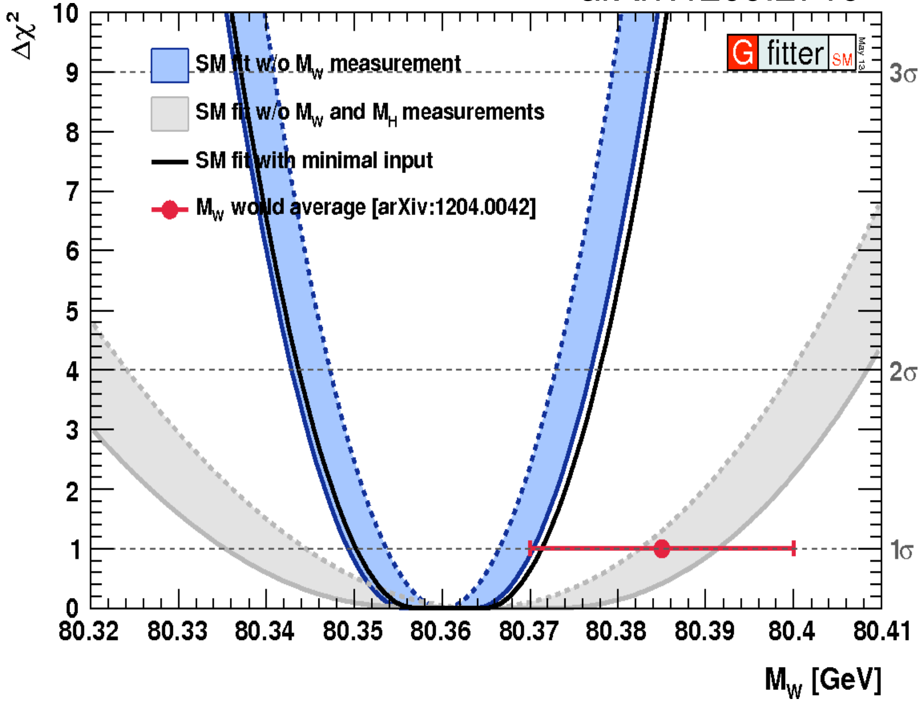


- Good consistency between direct and indirect measurements of M_W and m_t (w/ and w/o direct M_H measurement).
- Indirect M_H determination consistent (1.3σ) with direct measurement at LHC (taken to be M_H=125.7±0.4 GeV).

Constraints on the Higgs Boson Mass

arXiv:1209.2716





- Good consistency between direct and indirect measurements of M_W and m_t (w/ and w/o direct M_H measurement).
- Conversely, the test can be "turned around" and use electroweak fit, together with direct M_H measurement, to determine M_W:

Indirect measurement:

$$M_W = 80.3593 \pm 0.0056(m_t) \pm 0.0026(M_Z) \pm 0.0018(\Delta\alpha_{had}) \pm 0.0017(\alpha_S) \pm 0.0002(M_H) \pm 0.0040(theo) \text{ GeV}$$

$$= 80.359 \pm 0.011 \text{ GeV}$$

Direct measurement:

$$M_W = 80.385 \pm 0.015 \text{ GeV}$$

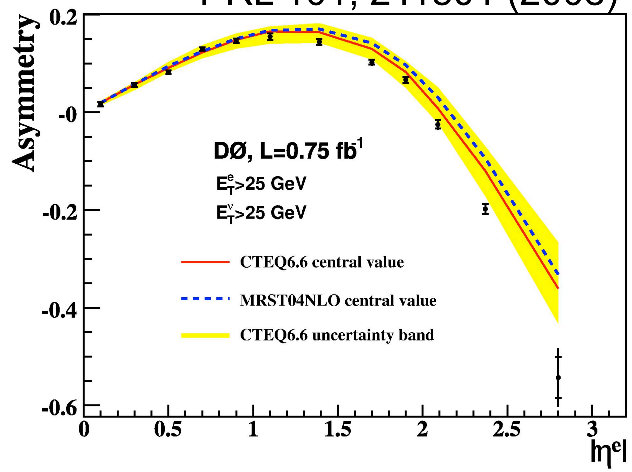
Desirable to further improve it!

Future Prospects

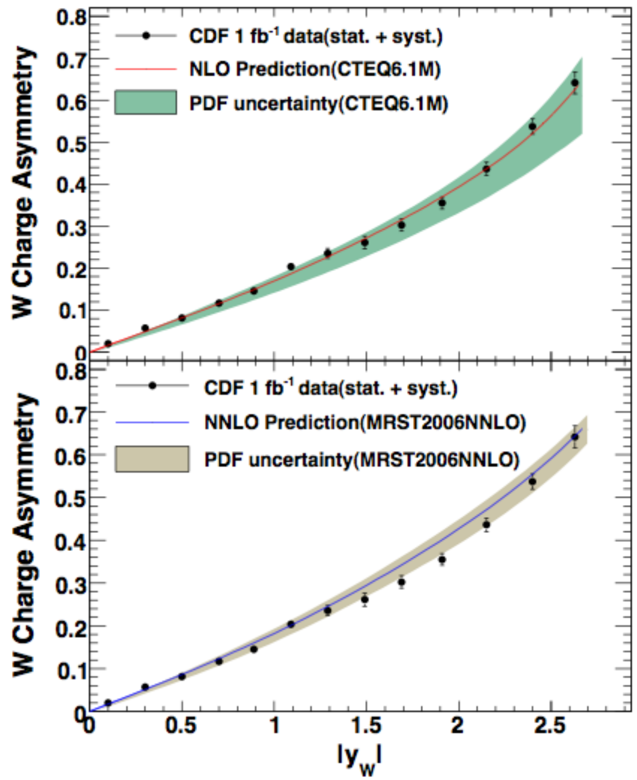
Main improvements expected:

- Use of full 10 fb^{-1} dataset (so far 2.2 fb^{-1} used by CDF and 5.3 fb^{-1} used by DØ).
- Reduction of PDF uncertainties:
  - include in PDF fits measurements at Tevatron and LHC that can constrain PDF uncertainties: W charge asymmetry, Z rapidity,…
  - extend η coverage to end-cap calorimeters (DØ): sensitivity to PDF uncertainties introduced through η acceptance cuts.
    - Will also reduce correlation on PDF uncertainty between CDF and DØ.

PRL 101, 211801 (2008)



PRL 102, 181801 (2009)

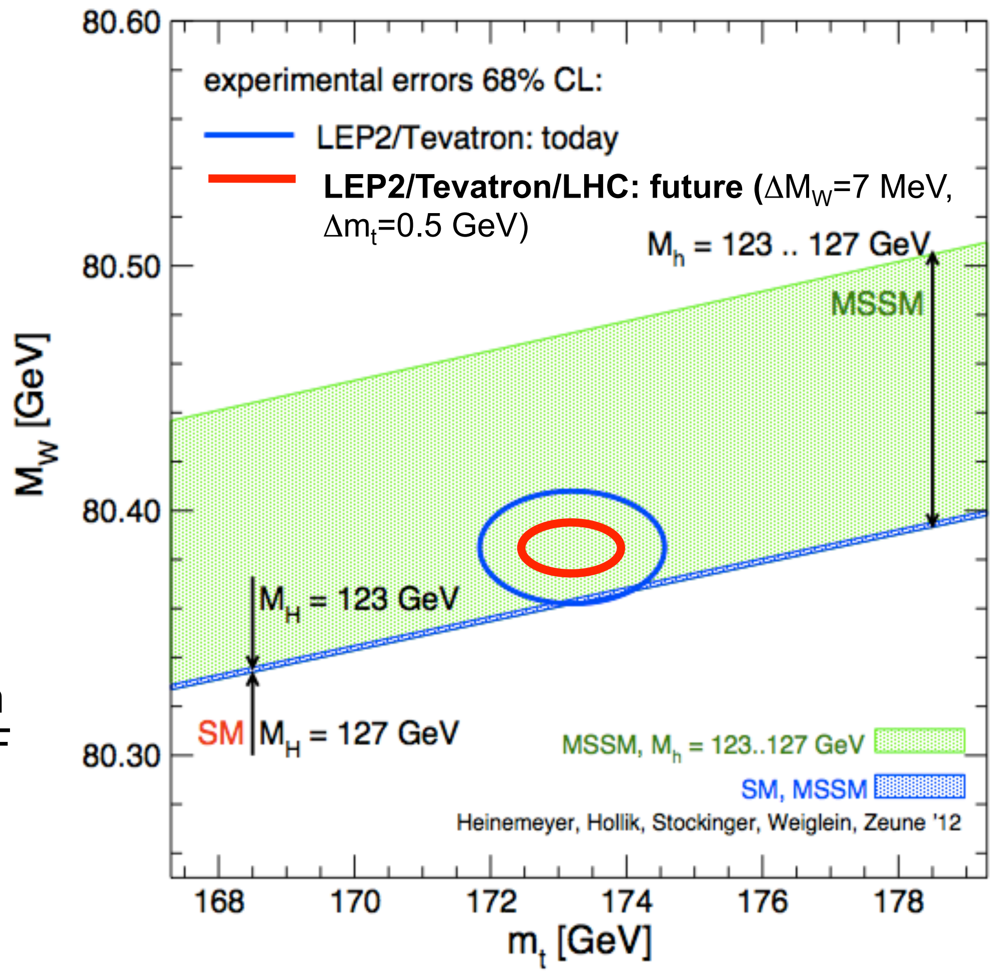


New full dataset results coming soon!

Future Prospects

Main improvements expected:

- Use of full 10 fb^{-1} dataset (so far 2.2 fb^{-1} used by CDF and 5.3 fb^{-1} used by DØ).
- Reduction of PDF uncertainties:
  - include in PDF fits measurements at Tevatron and LHC that can constrain PDF uncertainties: W charge asymmetry, Z rapidity,…
  - extend η coverage to end-cap calorimeters (DØ): sensitivity to PDF uncertainties introduced through η acceptance cuts.
    - Will also reduce correlation on PDF uncertainty between CDF and DØ.

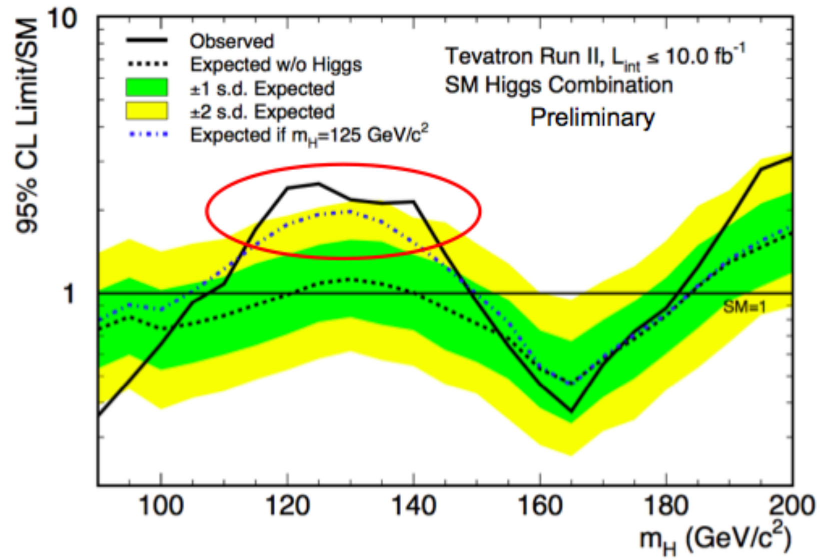


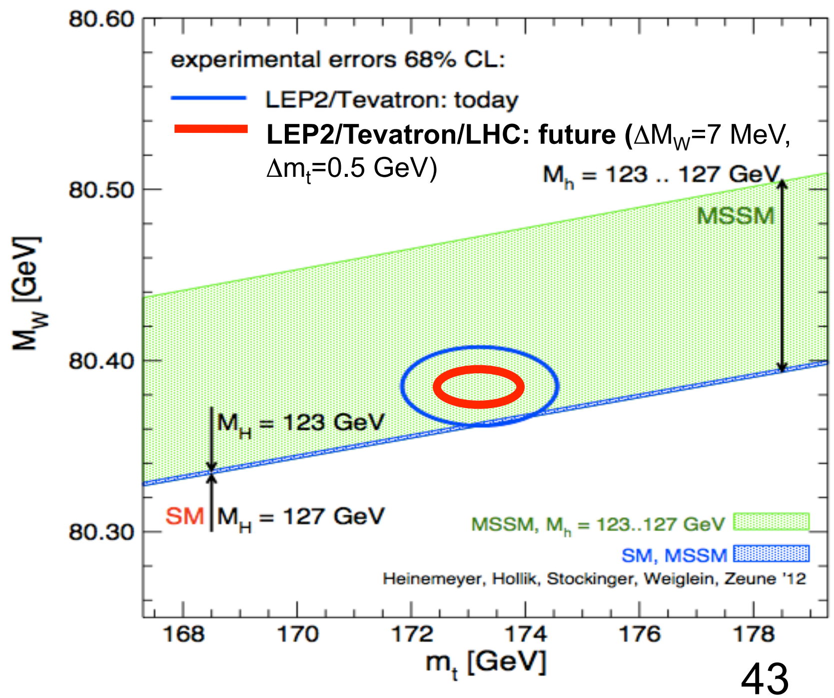
Projected M_W uncertainty:
- CDF: 10 MeV
- DØ: 15 MeV
- Combination: <10 MeV

Summary and Outlook

- Latest Tevatron results based on full Run II dataset in most search channels.
- Tevatron has achieved SM sensitivity over most of the accessible mass range.
- Excess in $115<m_H<140$ GeV region with local p-value at m_H=125 GeV corresponding to 3.0σ significance. So far emerging picture consistent with discovered boson at the LHC.
- Early results on Higgs couplings and spin/parity are consistent with a SM Higgs boson. Tevatron combination on spin/parity tests upcoming.
- Exciting prospects for precise measurements of m_t and M_W at the Tevatron, which will be key to capitalizing on precision measurement in the Higgs sector.

Stay tuned!

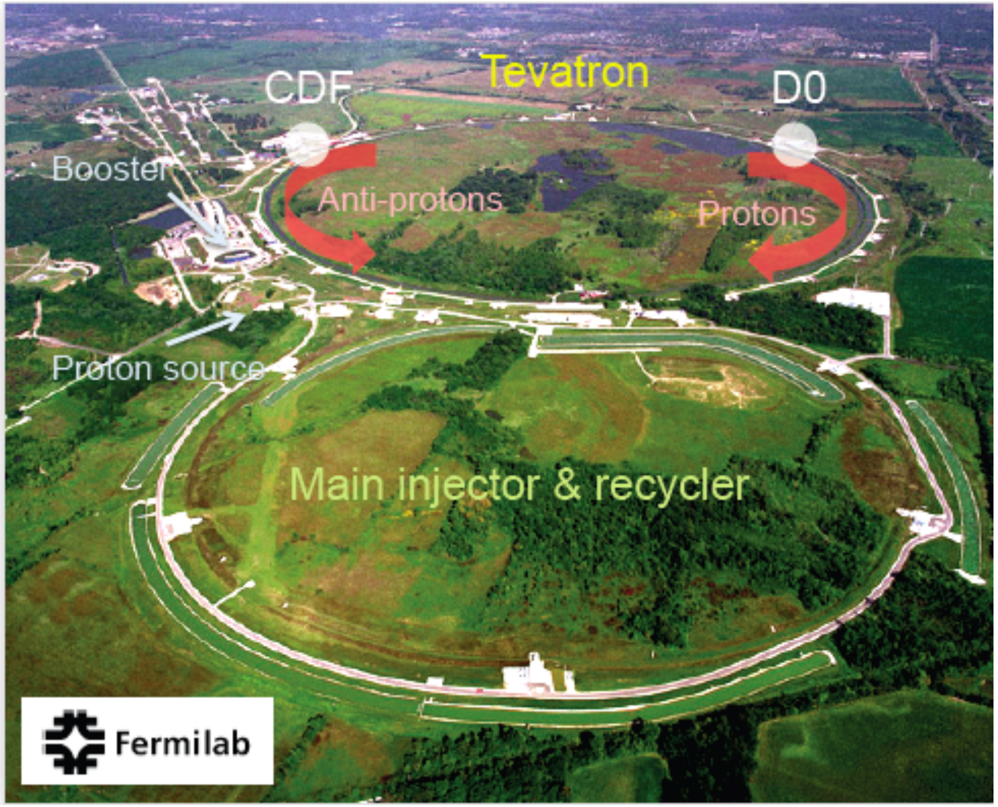


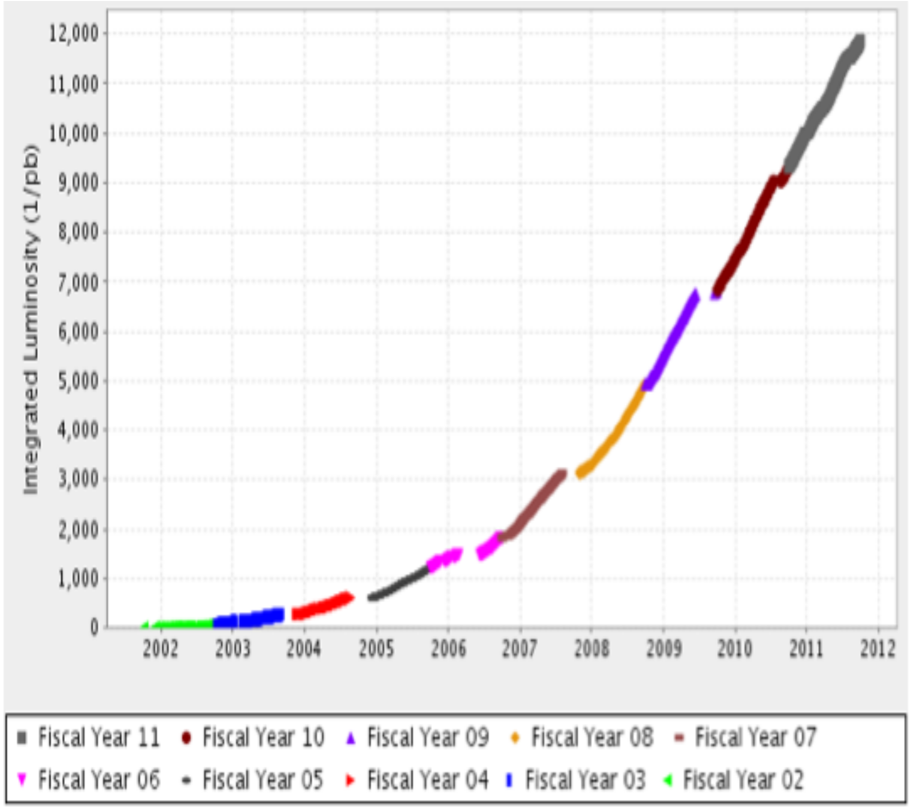


Backup

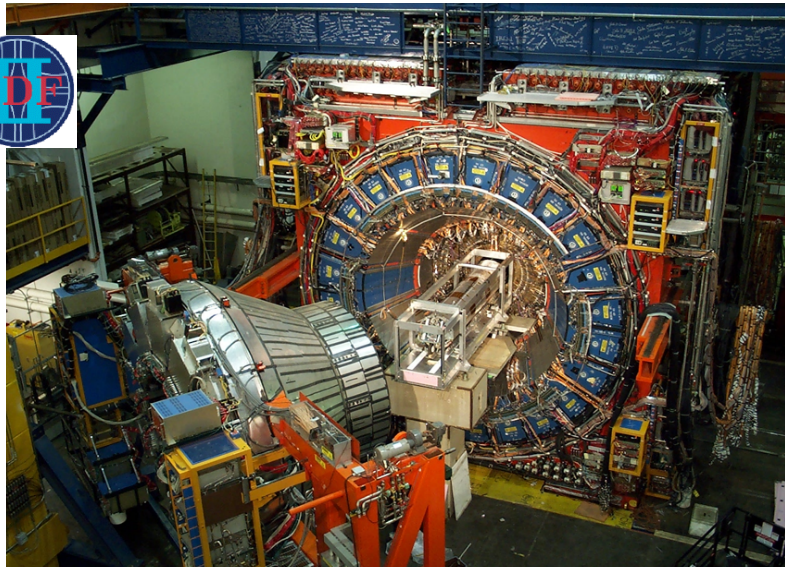
The Tevatron

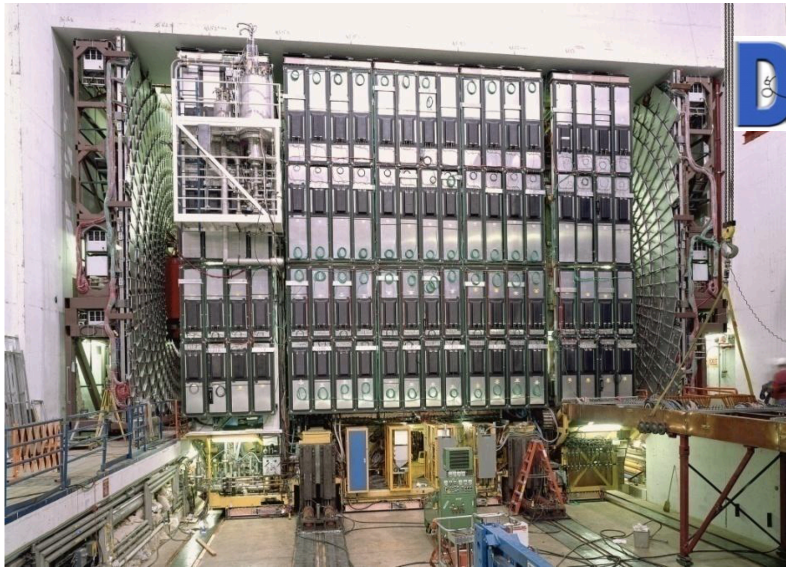
- Proton-antiproton collider at $\sqrt{s}$=1.96 TeV
  - Tevatron accelerator: 6.5 km circumference
  - Two general-purpose experiments: CDF and DØ
  - 10-year long Run II ended Sept. 30th, 2011
  - Total integrated luminosity delivered in Run II: ~12 fb^{-1} (per experiment)





CDF and DØ Detectors





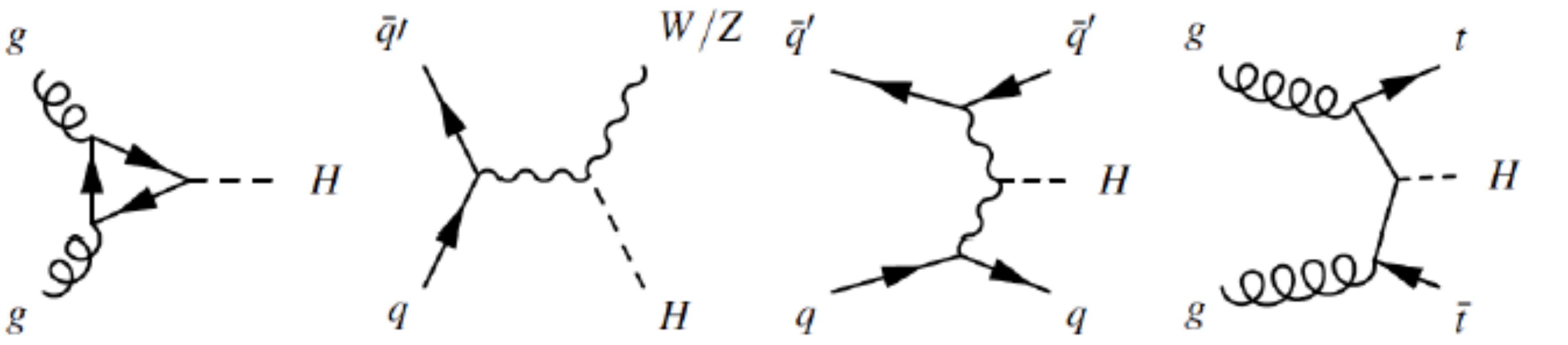
Multipurpose detectors:

- Central tracking system embedded in a solenoidal magnetic field:
  - Silicon vertex detector
  - Tracking chamber (CDF)
    Fiber tracker (DØ)
- Preshowers
- Electromagnetic and hadronic calorimeters
- Muon system

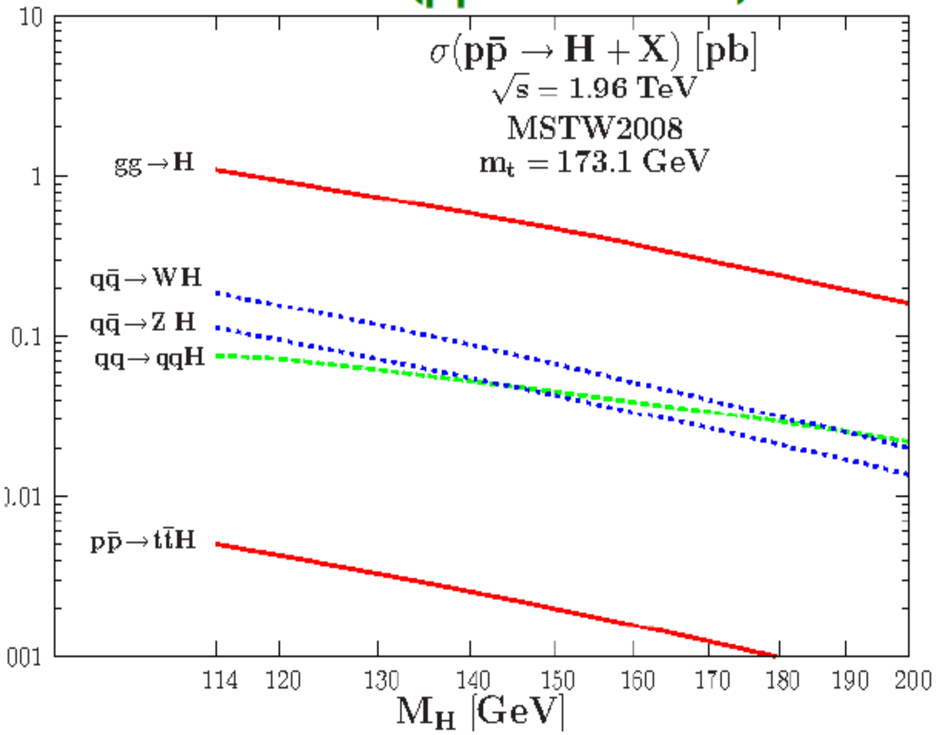
- Include multi-level trigger systems to efficiently select events with topologies of interest.
- Data taking efficiency: ~90%.
- Recorded up to 10 fb^{-1} in Run II.

All main search channels used full dataset

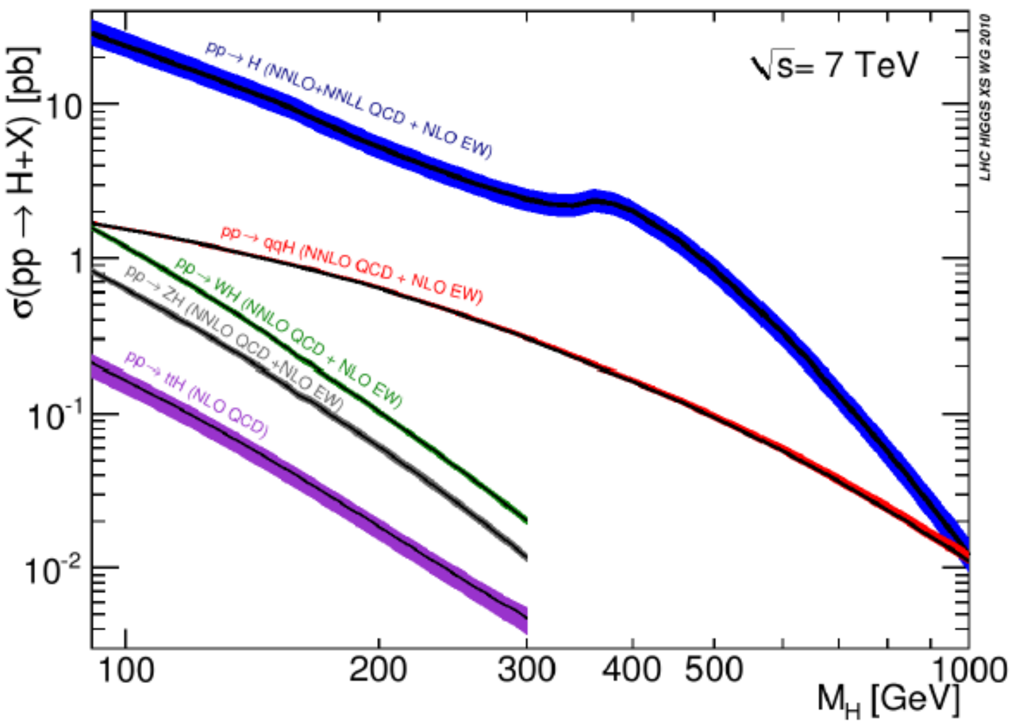
SM Higgs Production at Hadron Colliders



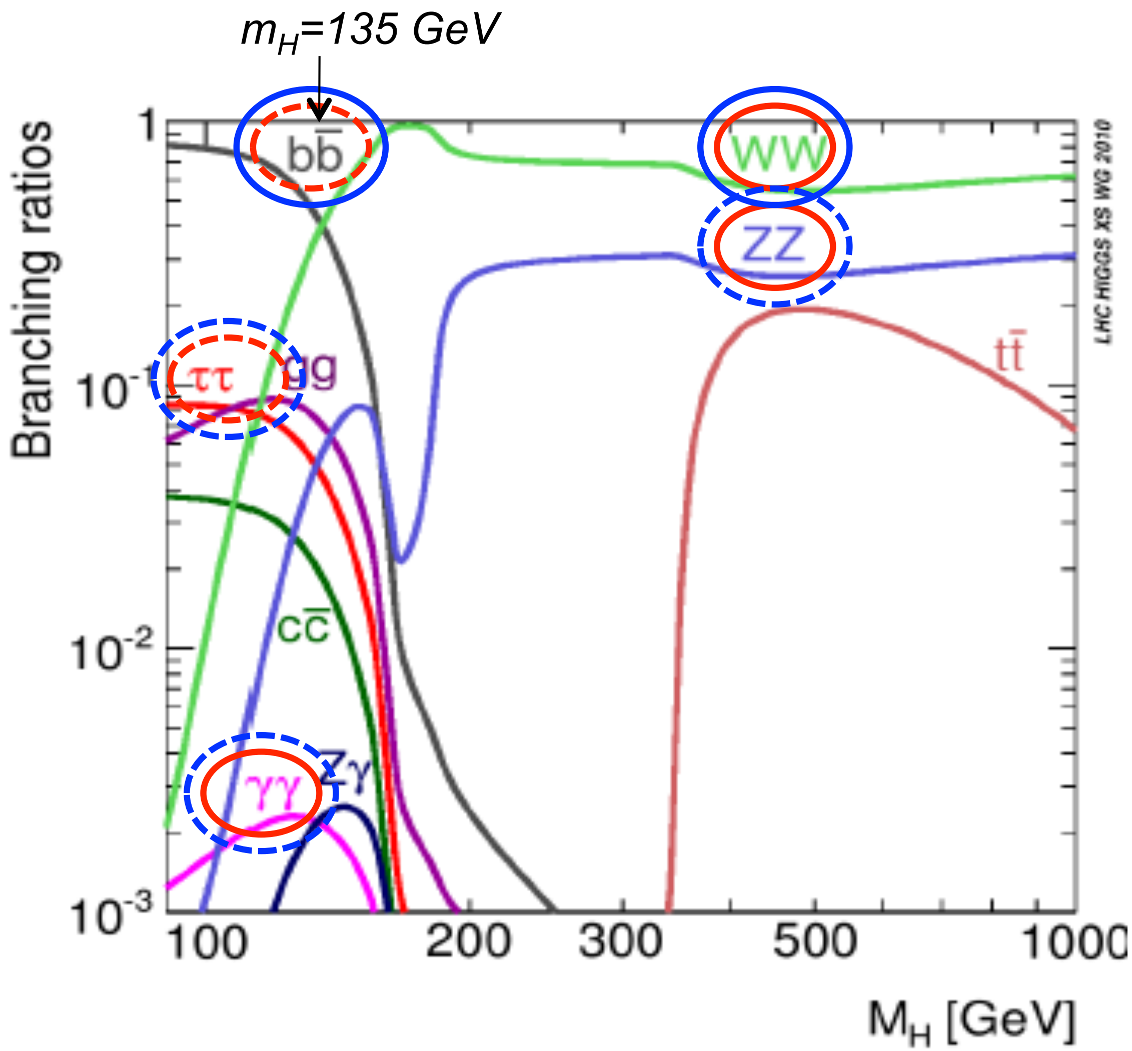
Tevatron (p$\bar{p}$ @ 1.96 TeV)



LHC (pp @ 7 TeV)

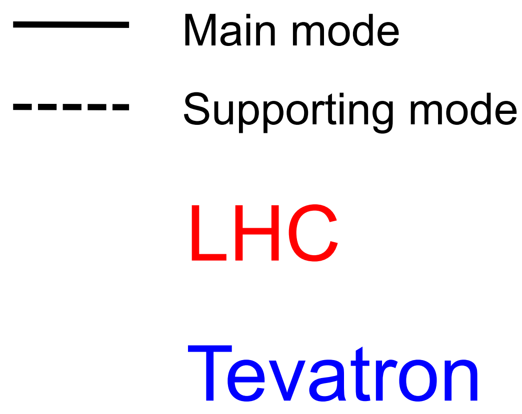


SM Higgs Decay Modes



m_H<135 GeV: H→$b\bar{b}$ dominates

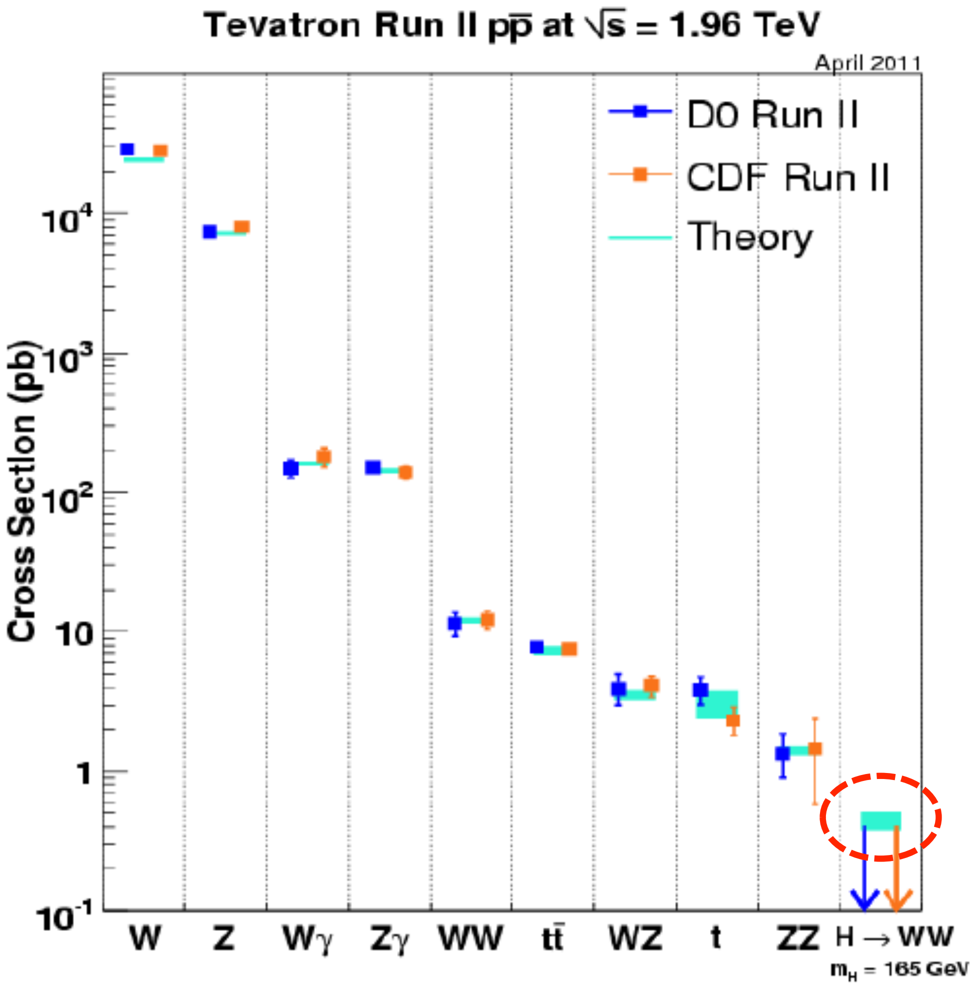
m_H>135 GeV: H→W^+W^- dominates



➔ Many decay modes being explored to increase the sensitivity of the search to the SM Higgs boson, but also to a non-SM one!

The Stairway to the Higgs

- Higgs boson searches at the Tevatron are background-dominated.

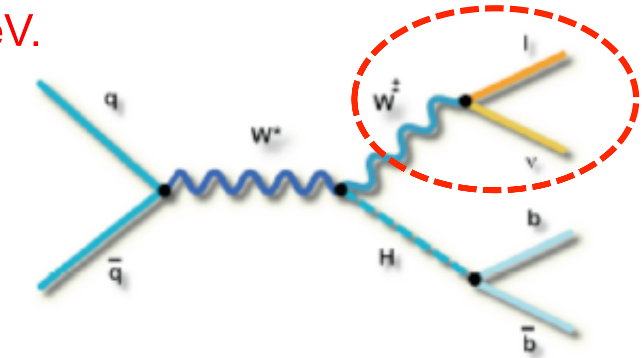


- **Instrumental backgrounds**: measured directly from data
  - QCD multijet production with mismeasured jets leadings to missing transverse energy or jets misidentified as leptons.
- **Physics backgrounds**: estimated using simulation and state-of-art theoretical predictions, and further calibrated to data whenever possible
  - W/Z+jets production (w/ real or misidentified heavy flavor jets)
  - Diboson production
  - Double and single top quark production

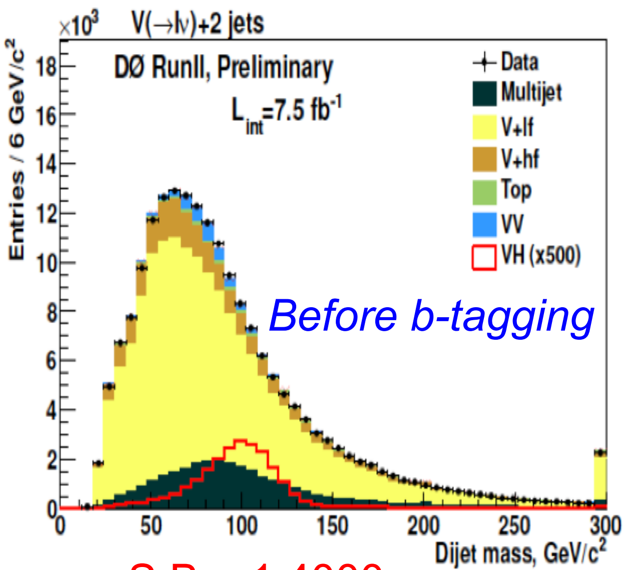
Experiments have established a solid foundation to search for the Higgs boson through precise measurements of SM processes.

Searching for H→b$\bar{b}$

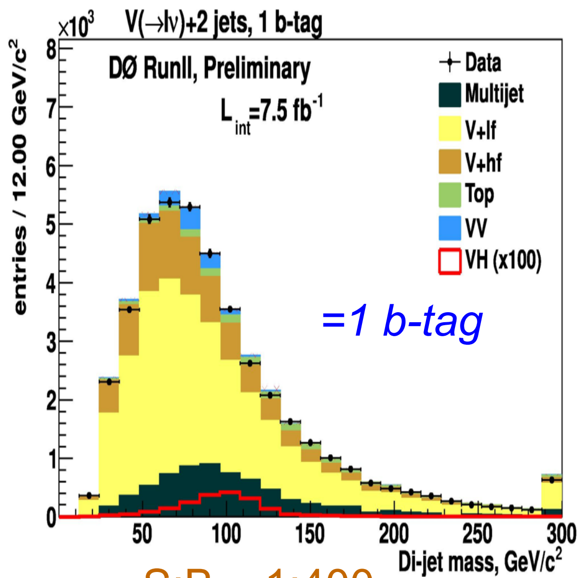
- Highest sensitivity channel at the Tevatron for m_H<130 GeV.



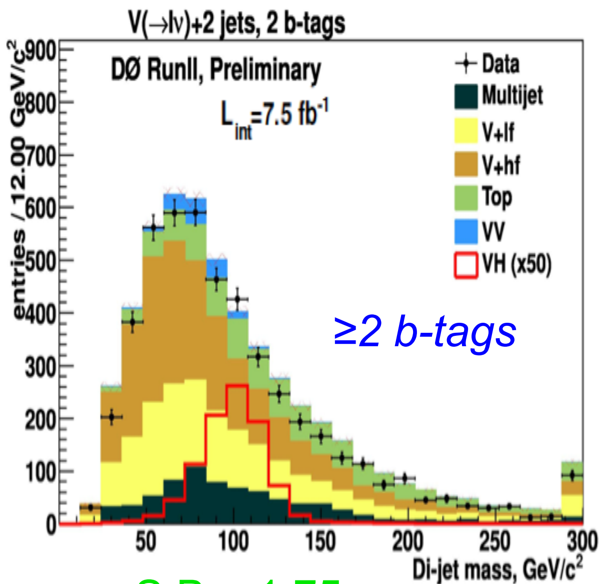
- Identify events consistent with leptonic W/Z decays in association with jets. Require b-tagging to significantly improve the S/B ratio.
- Main backgrounds: W+jets, t$\bar{t}$
- Most important discriminant variable: dijet mass.



S:B ~ 1:4000



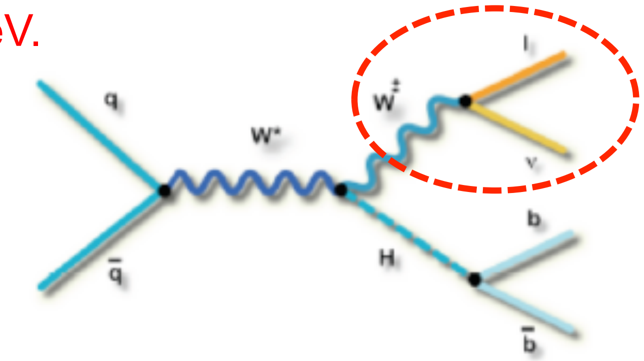
S:B ~ 1:400



S:B ~ 1:75

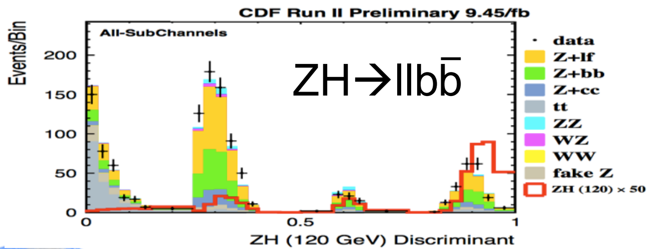
Searching for H→b$\bar{b}$

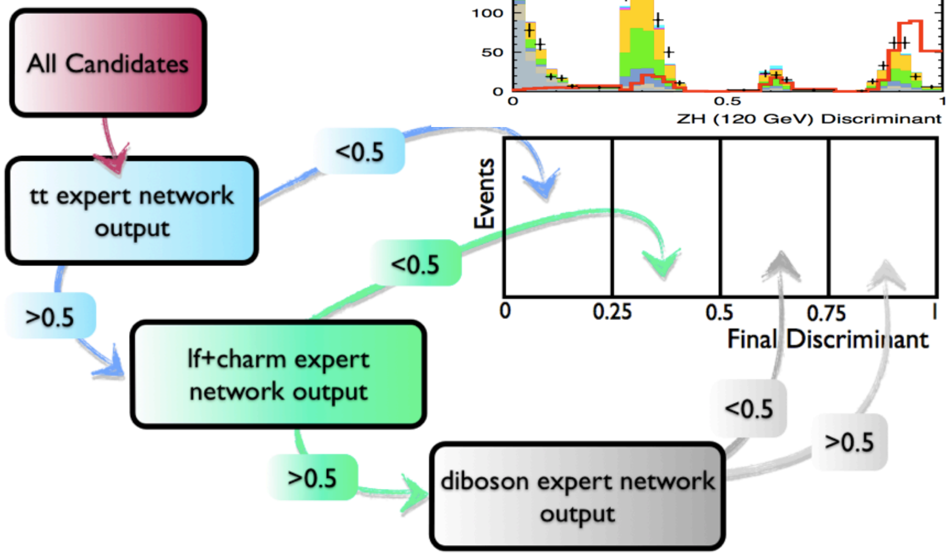
- Highest sensitivity channel at the Tevatron for m_H<130 GeV.



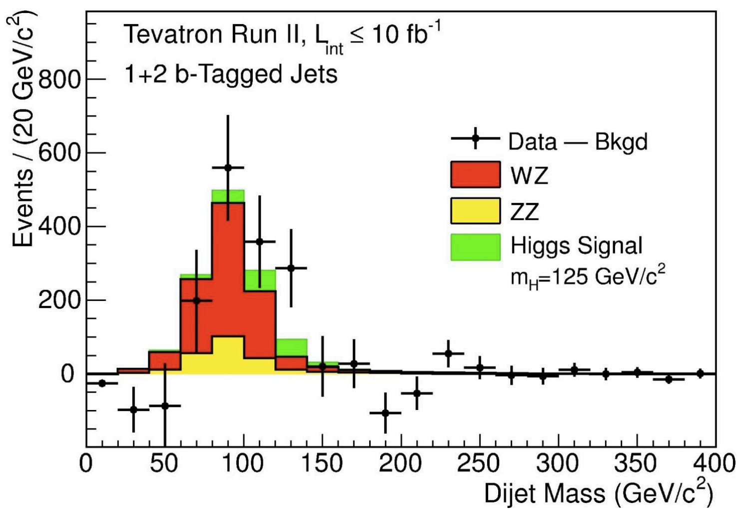
- Identify events consistent with leptonic W/Z decays in association with jets. Require b-tagging to significantly improve the S/B ratio.
- Main backgrounds: W+jets, t$\bar{t}$
- Most important discriminant variable: dijet mass.
- Improve sensitivity via sophisticated multivariate techniques.
- Validate search strategy by measuring WZ/ZZ (Z→b$\bar{b}$).

See talk by XXX





arXiv:1303.6346



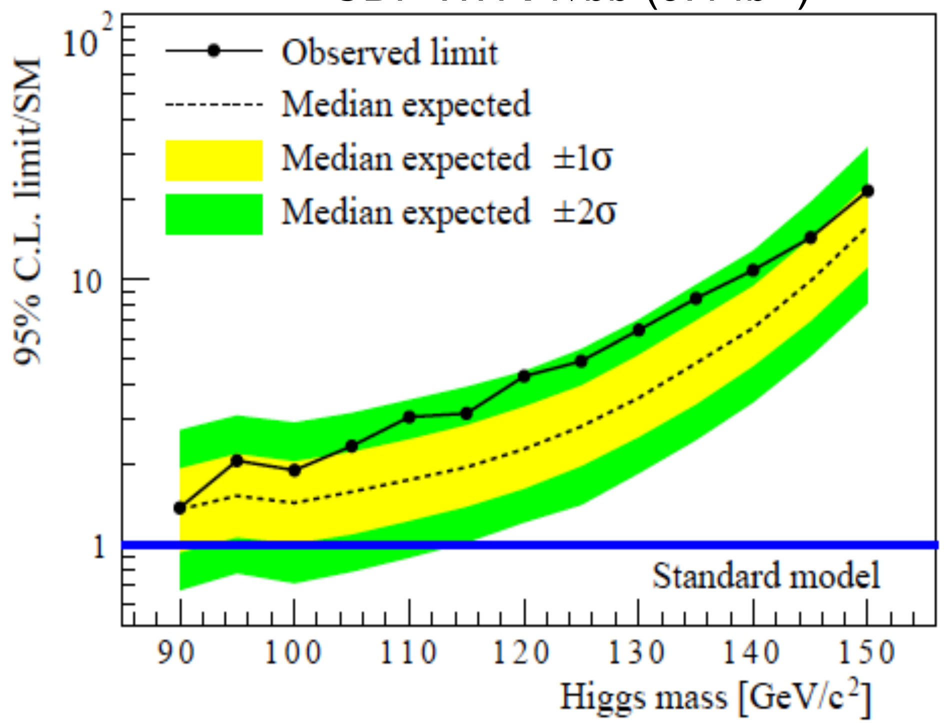
$\sigma_{meas}(VZ) = (0.7 \pm 0.2)\ \sigma_{SM}$

Summary of H→b$\bar{b}$ Results

95% CL Limits at m_H = 125 GeV

	Channel	Exp/obs Limit (σ/SM)
CDF	WH→lνb$\bar{b}$ (9.4 fb^{-1})	2.8/4.9
CDF	ZH→ννb$\bar{b}$ (9.4 fb^{-1})	3.3/3.1
CDF	ZH→l^+l^-b$\bar{b}$ (9.4 fb^{-1})	3.6/7.2
DØ	WH→lνb$\bar{b}$ (9.7 fb^{-1})	4.7/5.2
DØ	ZH→ννb$\bar{b}$ (9.5 fb^{-1})	3.9/4.3
DØ	ZH→l^+l^-b$\bar{b}$ (9.7 fb^{-1})	5.1/7.1
CDF	VH/VBF→jjb$\bar{b}$ (9.4 fb^{-1})	11.0/9.0
CDF	ttH→l+jets (9.4 fb^{-1})	12.4/17.6
CDF	ttH→jets (5.7 fb^{-1})	26.2/36.2

CDF WH→lνb$\bar{b}$ (9.4 fb^{-1})



- Limits from individual VH, H→b$\bar{b}$ channels at ~2-3xSM at m_H=125 GeV and quickly degrading towards high mass.
- Important to consider additional channels with different mass dependence.

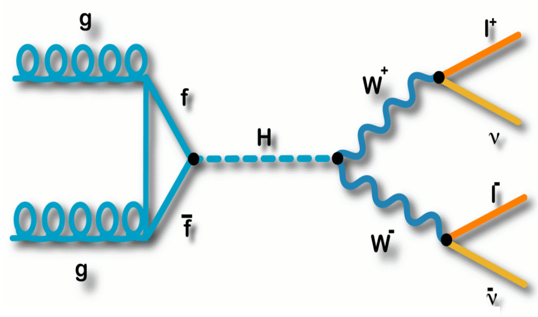
Searching for H→WW→lνlν

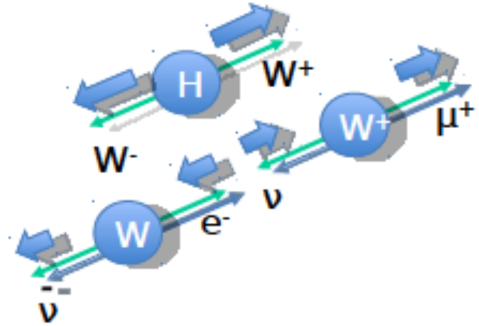
- Highest sensitivity channel in m_H~130-200 GeV range.
- Clean dilepton+$\not{E}_T$ signature.
- Main backgrounds after $\not{E}_T$ cut: WW, W/Z+jets,Wγ
- After final selection expect (m_H=165 GeV):

  ~7 signal events/fb^{-1}/experiment with S:B~1:50-1:100

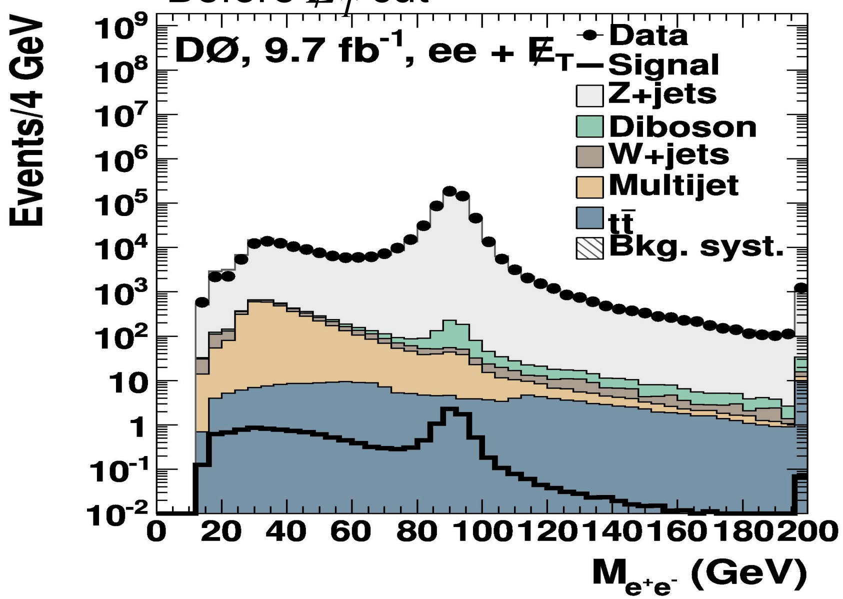
- Exploit spin correlation between dibosons.

  ➔ Small angular separation between leptons

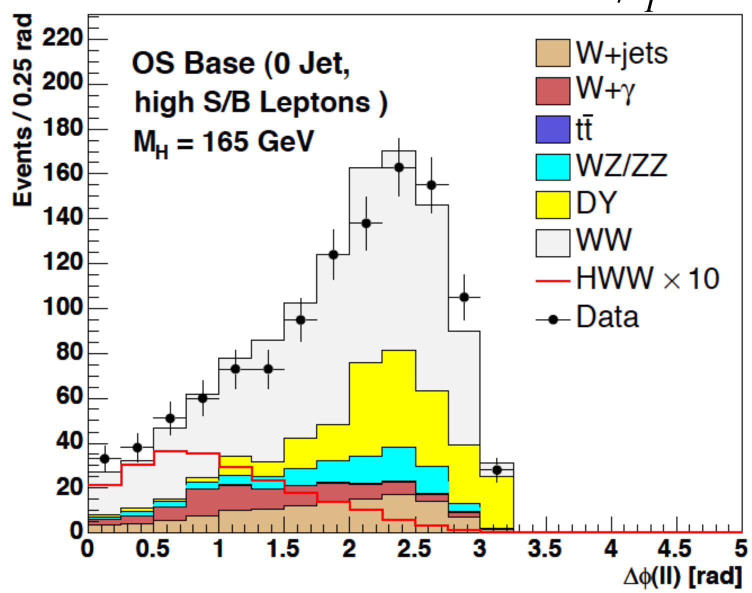




Before $\not{E}_T$ cut



After $\not{E}_T$ cut



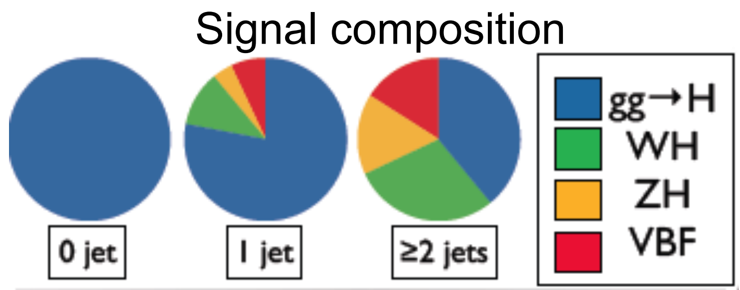
Searching for H→WW→lνlν

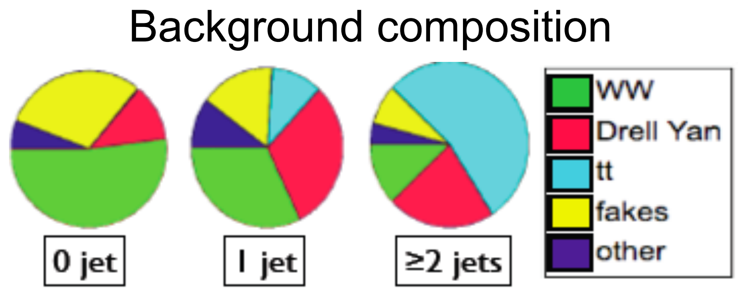
To increase the sensitivity:

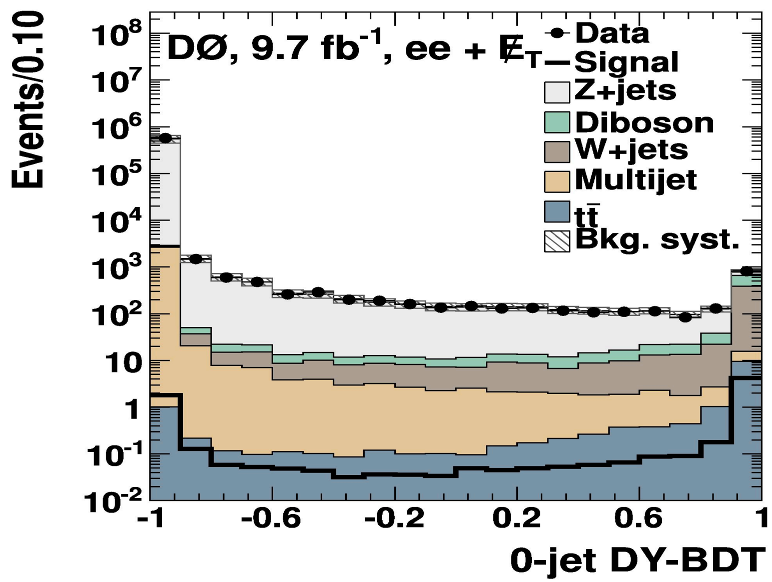
- Consider all signal production modes.

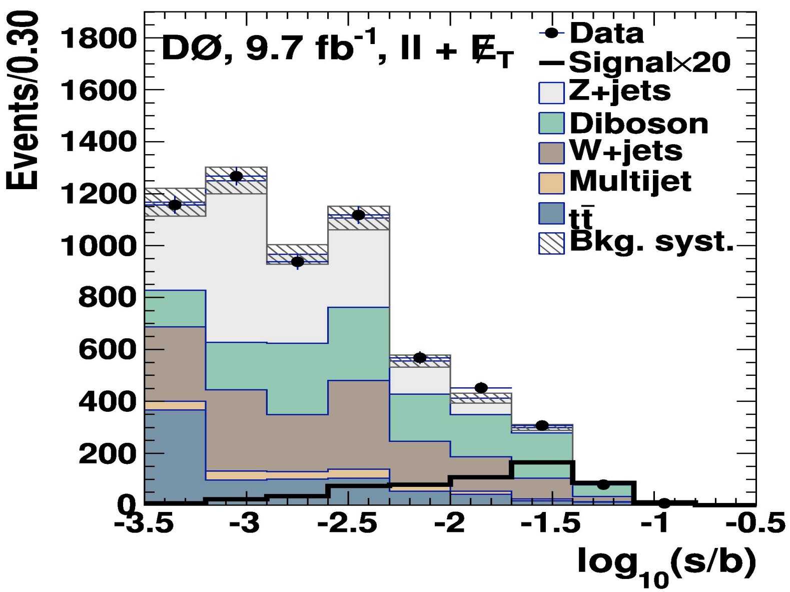
- Categorize events in channels with different S:B (by jet multiplicity, lepton flavor/quality, etc) and combine at the end.

- Build multivariate discriminants against:
  - $Z/\gamma^* \to l^+l^-$ ((DØ): increase signal acceptance in event selection.
  - Remaining background: final discriminant.









Searching for H→WW→lνlν

To increase the sensitivity:

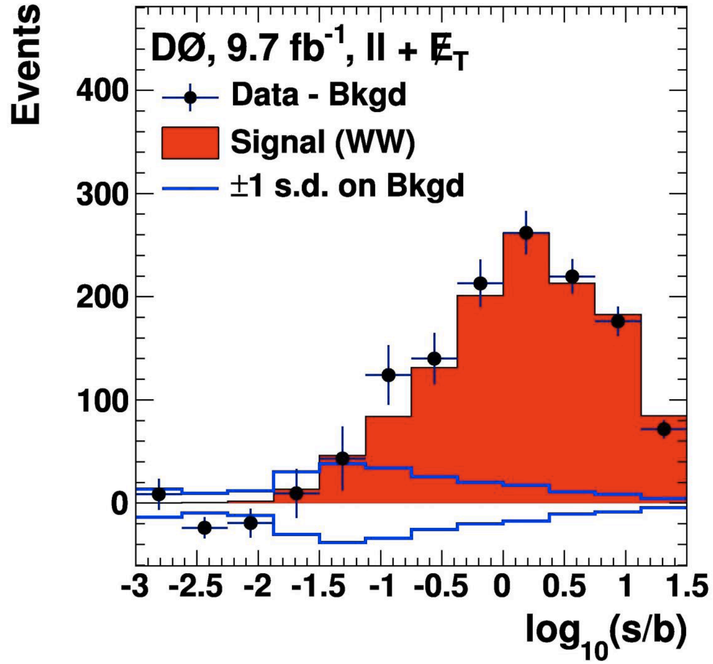
- Consider all signal production modes.

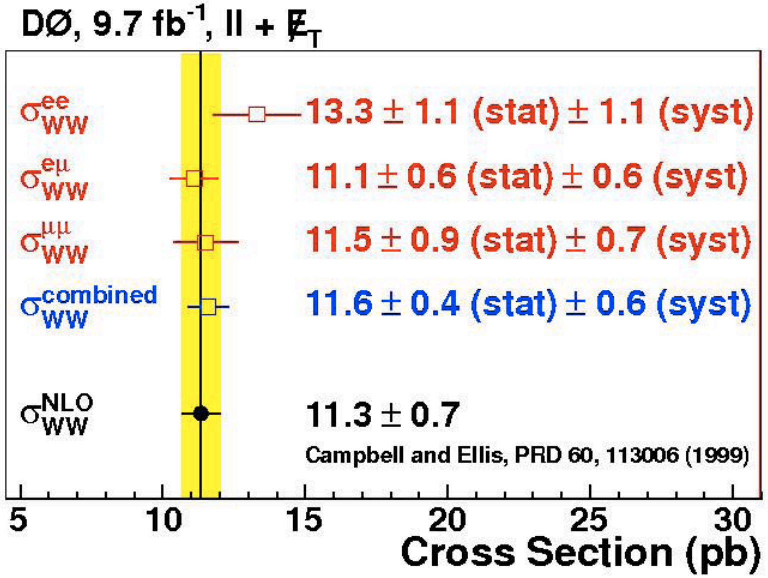
- Categorize events in channels with different S:B (by jet multiplicity, lepton flavor/quality, etc) and combine at the end.

- Build multivariate discriminants against:
    - $Z/\gamma^* \rightarrow l^+l^-$ ((DØ): increase signal acceptance in event selection.
    - Remaining background: final discriminant.

- Include searches for same-sign dilepton and trilepton final states.

Validate search strategy by measuring WW→lνlν.

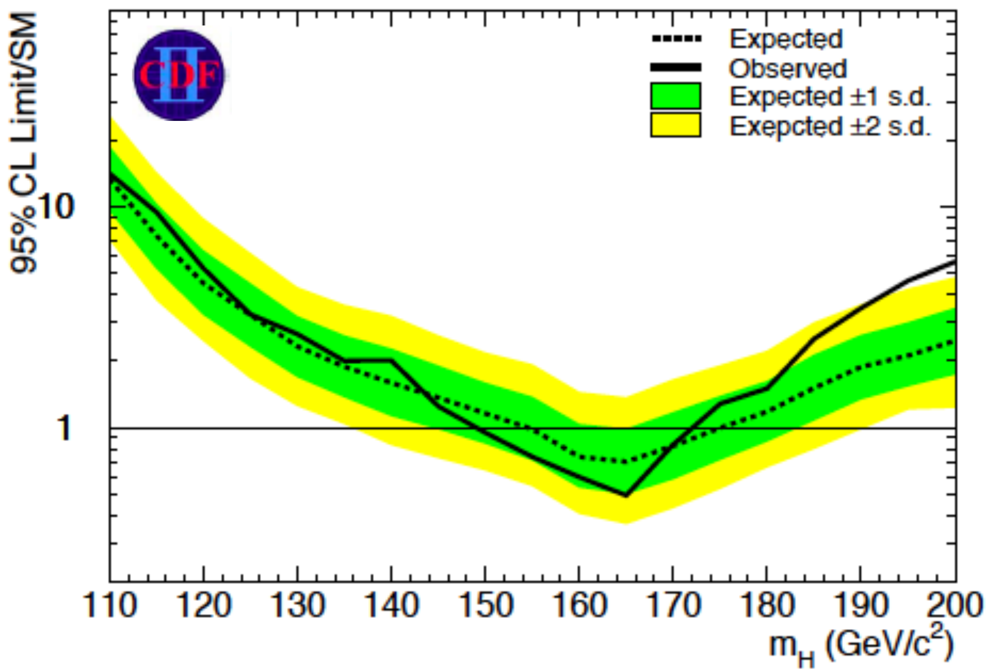




Low Mass Results from H→WW,ττ,γγ

95% CL Limits at m_H = 125 GeV

	Channel	Exp/obs Limit (σ/SM)
CDF	H→WW→lνlν (9.7 fb^{-1})	3.2/3.3
DØ	H→WW→lνlν (9.7 fb^{-1})	3.4/4.1
CDF	H+X→ττ+jets (8.3 fb^{-1})	14.8/11.7
DØ	H+X→ττjj (9.7 fb^{-1})	9.0/11.3
CDF	VH→ττl(l) (6.2 fb^{-1})	23.3/26.5
DØ	VH→ττμ (8.6 fb^{-1})	13.0/19.4
CDF	H→γγ (10.0 fb^{-1})	11.7/20.5
DØ	H→γγ (9.7 fb^{-1})	8.5/12.7



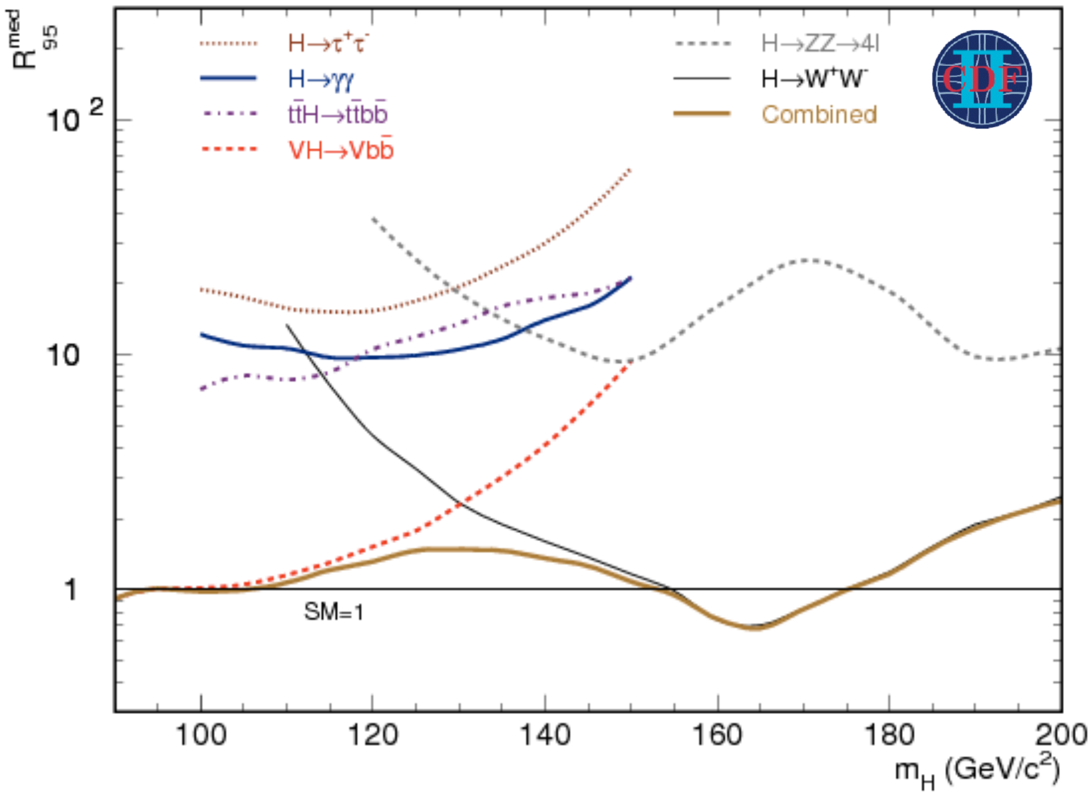
Additional channels contribute useful sensitivity at low/intermediate m_H:

- H→WW→lνlν: improving towards high m_H.
- H+X→ττjj, H→γγ : ~flat vs m_H.

→ Combination of all contributing channels crucial

Combined Limits on SM Higgs Production

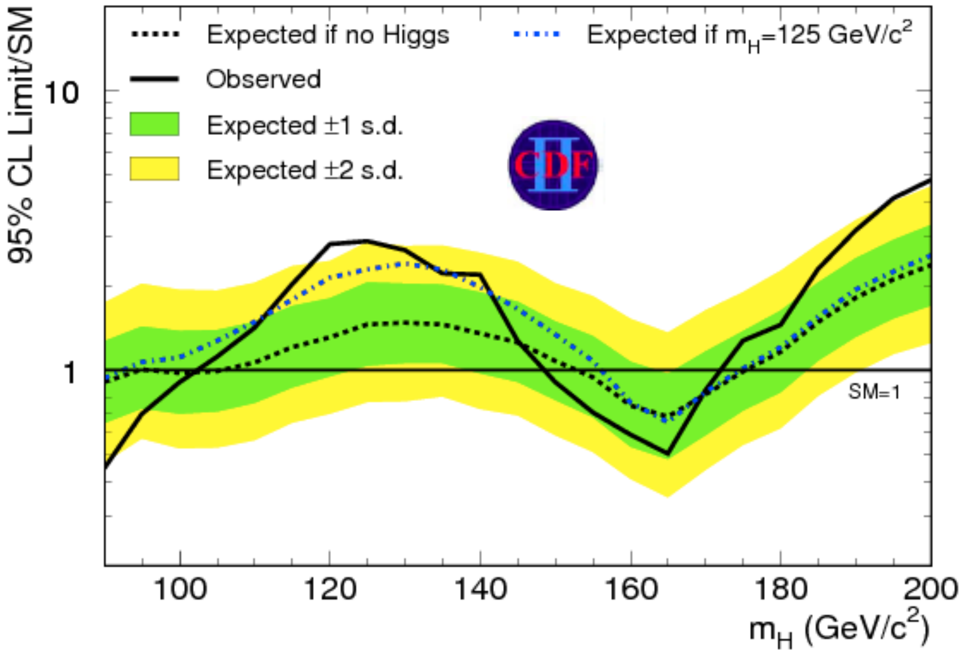
- Combination of multiple channels (and experiments!) yields the greatest sensitivity.



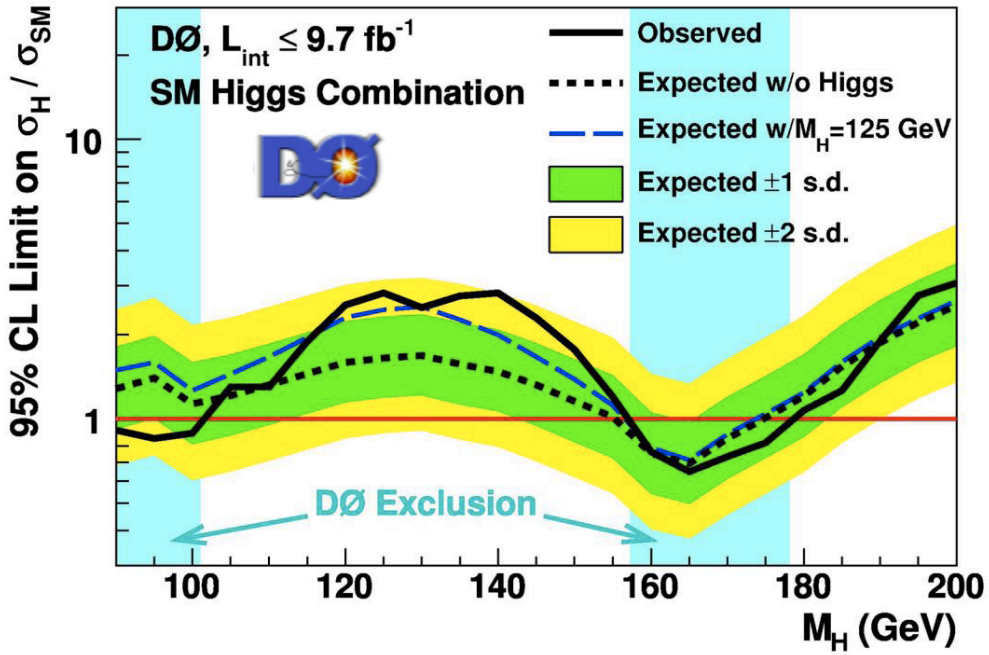
- Assumes SM prediction for ratio of production cross sections and branching ratios.
- More than 200 different sources of systematic uncertainties are considered (including correlations among channels and experiments), and constrained in sidebands.
- Use different techniques to cross check calculations (Bayesian, modified frequentist)
  ➔ results agree within ≤5%.

CDF and DØ Individual Results

arXiv:1301.6668



arXiv:1303.0823



Observed 95% CL exclusion:

$90 < m_H < 102$ GeV, $152 < m_H < 172$ GeV

At m_H = 125 GeV:

Exp. limit: 1.5 x SM
Obs. limit: 2.9 x SM

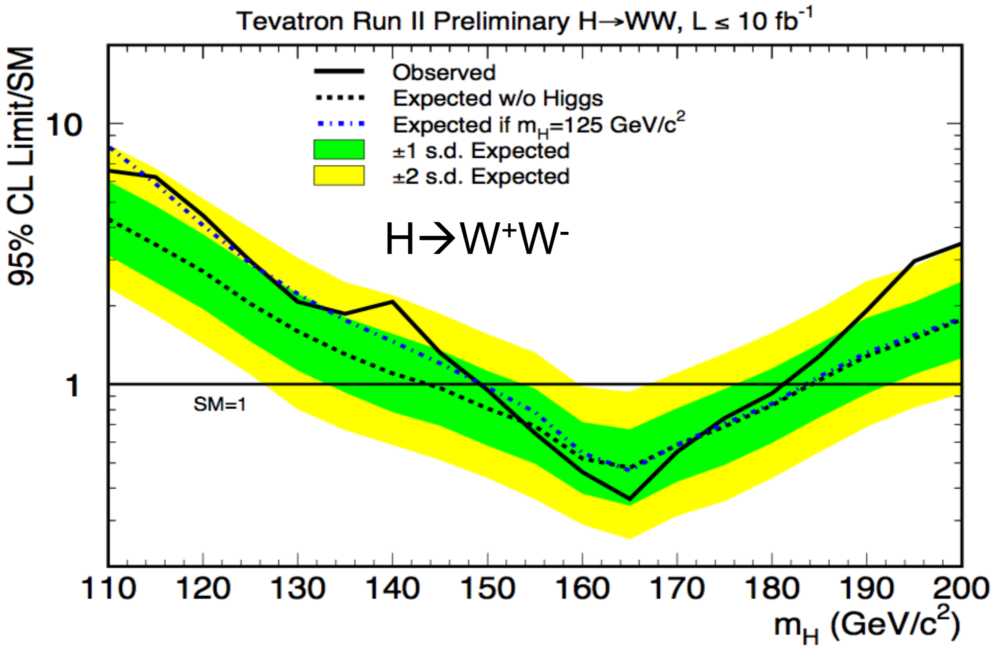
Observed 95% CL exclusion:

$90 < m_H < 101$ GeV, $157 < m_H < 178$ GeV

At m_H = 125 GeV:

Exp. limit: 1.7 x SM
Obs. limit: 2.9 x SM

Results by Channel



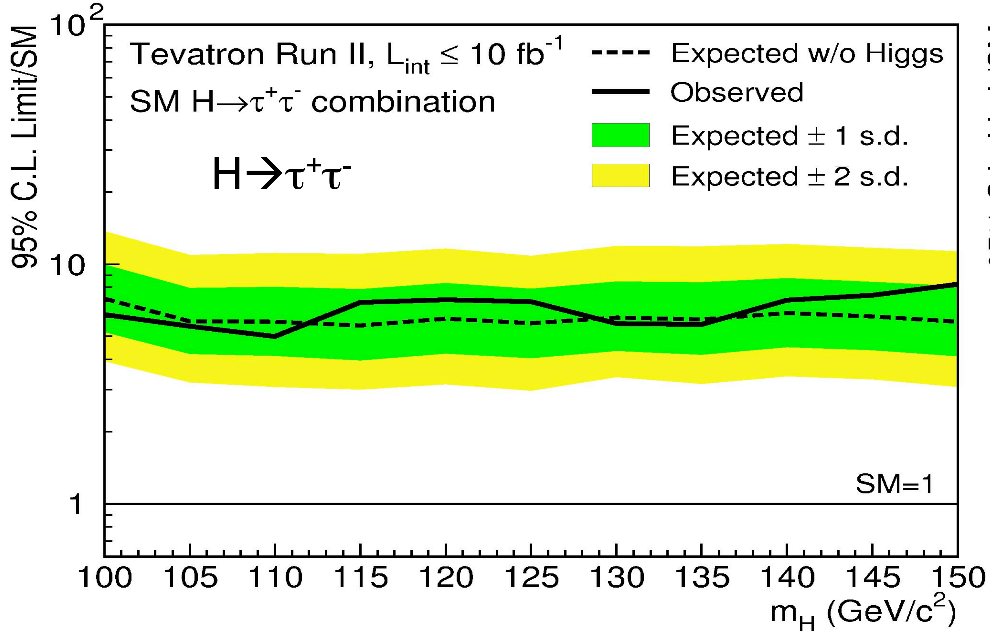
$H \rightarrow \tau^+\tau^-$ and $H \rightarrow \gamma\gamma$:

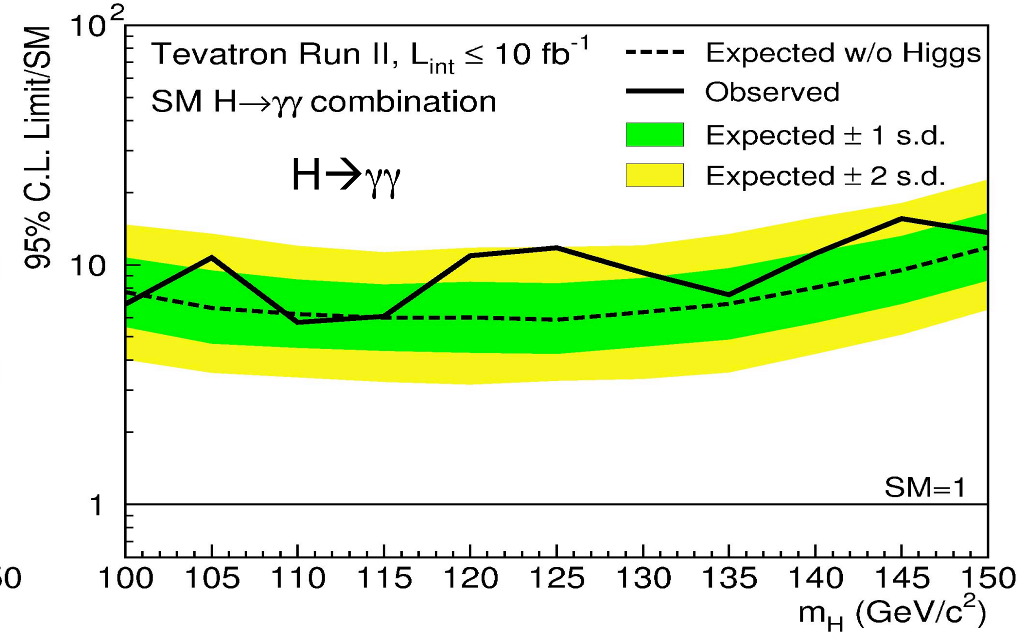
- Expected sensitivity at m_H~125 GeV of ~6-7xSM.
- No significant excess.

$H \rightarrow WW$:

- Expected sensitivity at m_H~125 GeV of ~2.1xSM.
- Very broad excess, consistent with both B-only and S+B hypotheses (m_H=125 GeV).

Results by Channel

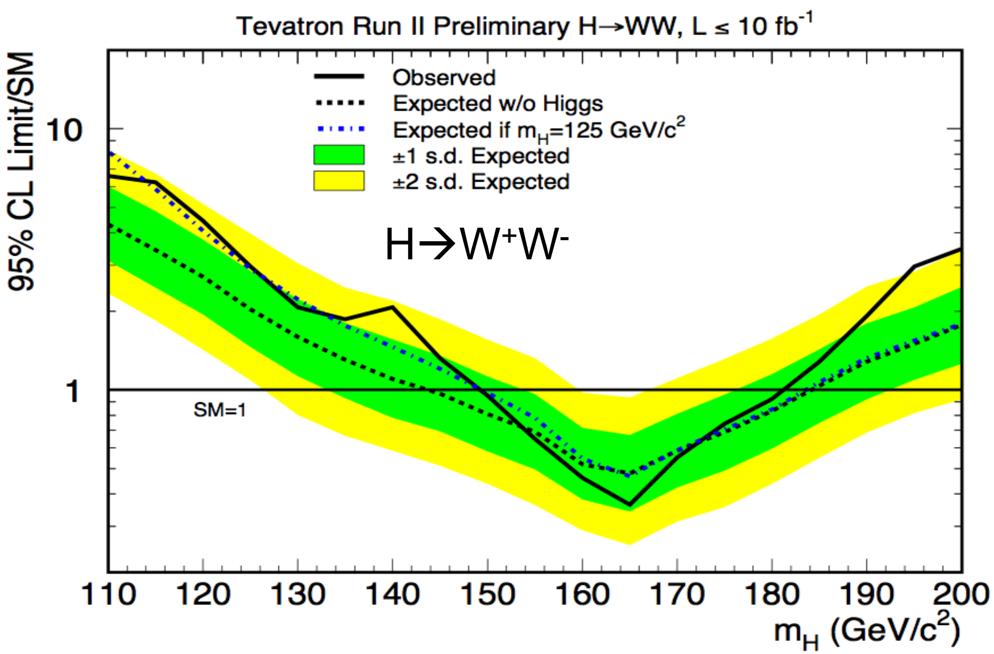


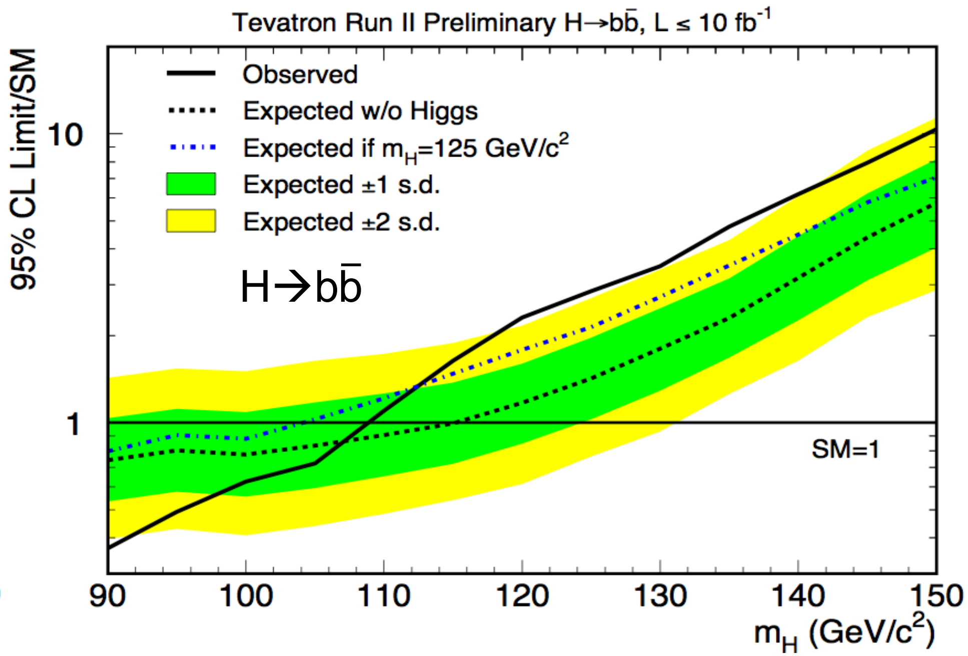


$H \rightarrow \tau^+\tau^-$ and $H \rightarrow \gamma\gamma$:

- Expected sensitivity at m_H~125 GeV of ~6-7xSM.
- No significant excess.

Results by Channel





$H \rightarrow \tau^+\tau^-$ and $H \rightarrow \gamma\gamma$:

- Expected sensitivity at m_H~125 GeV of ~6-7xSM.
- No significant excess.

$H \rightarrow WW$:

- Expected sensitivity at m_H~125 GeV of ~2.1xSM.
- Very broad excess, consistent with both B-only and S+B hypotheses (m_H=125 GeV).

$H \rightarrow b\bar{b}$:

- Expected sensitivity at m_H~125 GeV of ~1.4xSM.
- Broad excess, somewhat above S+B hypothesis (m_H=125 GeV).

Probing Higgs Boson Couplings

- Several production and decay mechanisms contribute to signal rates per channel
  ➔ interpretation is difficult
- A better option: measure deviations of couplings from the SM prediction (*arXiv:1209.0040*).
  Basic assumptions:
  - there is only one underlying state at m_H~125 GeV,
  - it has negligible width,
  - it is a CP-even scalar (only allow for modification of coupling strengths, leaving the Lorentz structure of the interaction untouched).

  Additional assumption made in this study:
  - no additional invisible or undetected Higgs decay modes.
- Under these assumptions all production cross sections and branching ratios can be expressed in terms of a few common multiplicative factors to the SM Higgs couplings.
  Examples:

$$\sigma(gg \to H)BR(H \to WW) = \sigma_{SM}(gg \to H)BR_{SM}(H \to WW)\frac{\kappa_g^2 \kappa_W^2}{\kappa_H^2}$$

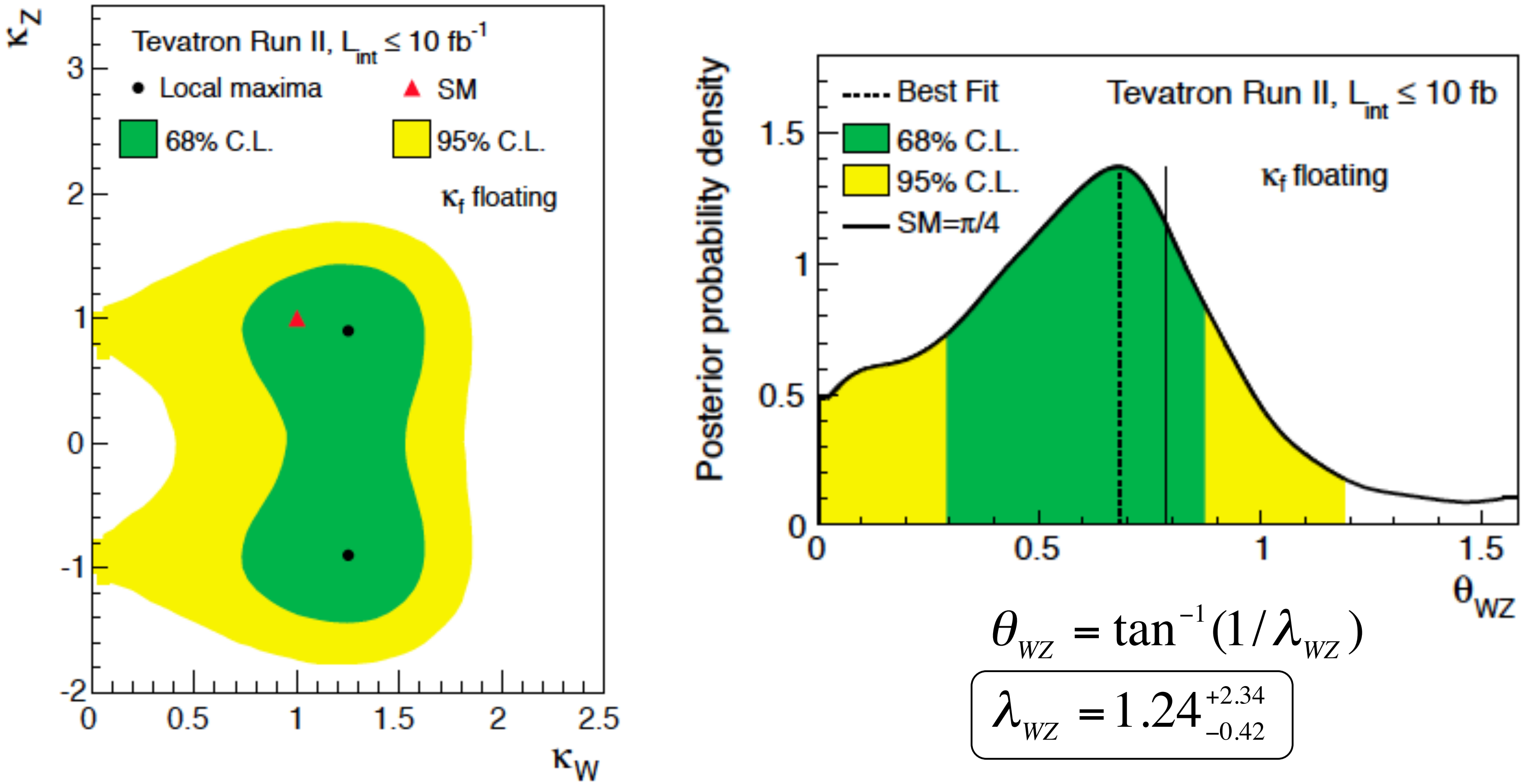
$$\sigma(WH)BR(H \to bb) = \sigma_{SM}(WH)BR_{SM}(H \to bb)\frac{\kappa_W^2 \kappa_b^2}{\kappa_H^2}$$

$$\kappa_g = f(\kappa_t, \kappa_b, M_H)$$

$$\kappa_H = f'(\kappa_t, \kappa_b, \kappa_\tau, \kappa_W, \kappa_Z, M_H)$$

Probing Higgs Boson Couplings

- **Benchmark I:**
  - Assume all fermion couplings are scaled by a common free parameter (κ_F).
  - Measure the parameters κ_W and κ_Z independently.
  - Probe $SU(2)_V$ custodial symmetry by measuring the ratio $\lambda_{WZ}=\kappa_W/\kappa_Z$.



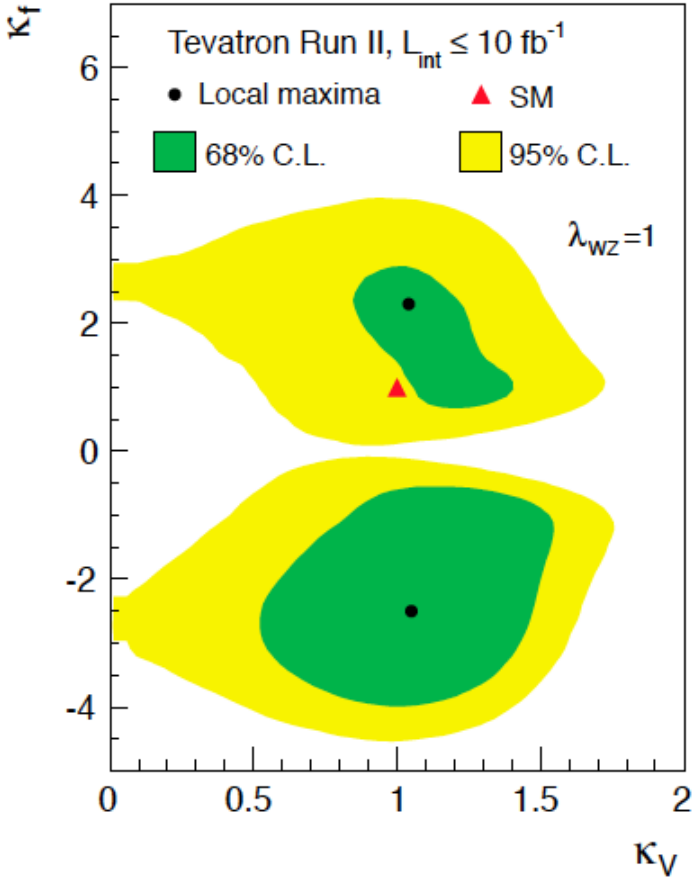
$$\theta_{WZ} = \tan^{-1}(1/\lambda_{WZ})$$

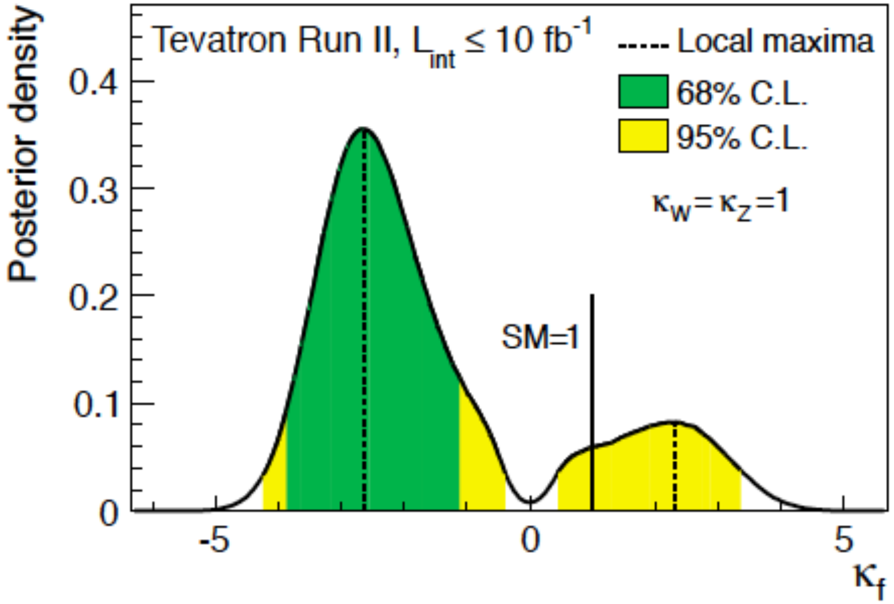
$$\lambda_{WZ} = 1.24^{+2.34}_{-0.42}$$

Measurements consistent with the SM prediction

Probing Higgs Boson Couplings

- **Benchmark II:**
  - Consider two independent multiplicative factors: common to all couplings to vector bosons (κ_V) and common to all couplings to fermions (κ_f). Assume λ_{WZ}=1.
  - Measure κ_f and κ_V simultaneously.





Measurements consistent with the SM prediction

What Top Quark Mass?

- Parameters of Lagrangian have no unique physical interpretation. Radiative corrections require definition of renormalization scheme.
  Ex. Heavy-quark self-energy:

$$= \frac{i}{\not{p} - m_q - \Sigma(p, m_q)}$$

- Pole Mass:
  - Based on (unphysical) concept of top quark being a free parton.
  - Coincides with pole of propagator at each order:

$$\not{p} - m_q - \Sigma(p, m_q)\Big|_{\not{p}=m_q} \rightarrow \not{p} - m_q^{\text{pole}}$$

  - Definition of pole mass ambiguous up to corrections $O(\Lambda_{QCD})$.
    Bound from lattice QCD:
    $\Delta m_t \geq 200$ MeV

- MSbar Mass:
  - Based on 1-loop minimal subtraction

$$\delta m_q^{(1)} = m_q \frac{\alpha_s}{4\pi} 3C_F \left(\frac{1}{\epsilon} - \gamma_E + \ln 4\pi\right)$$

  - MSbar scheme induces scale dependence: $m(\mu)$

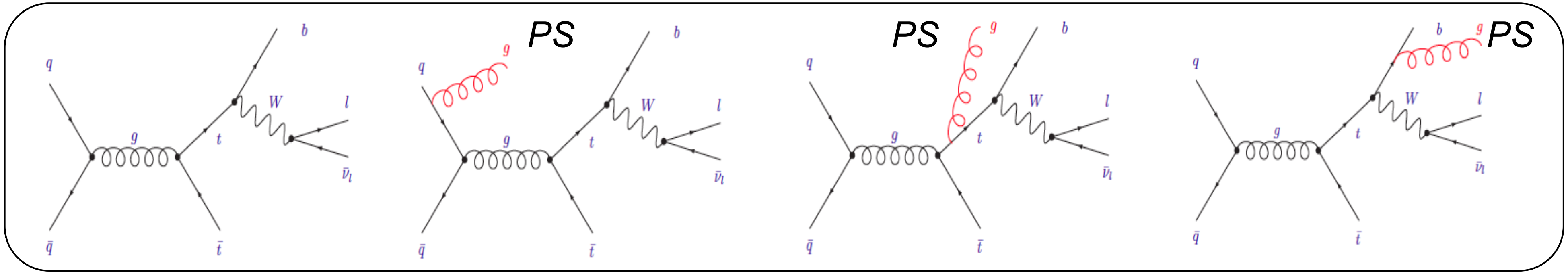
$$\left(\mu^2 \frac{\partial}{\partial \mu^2} + \beta(\alpha_s) \frac{\partial}{\partial \alpha_s}\right) m(\mu) = \gamma(\alpha_s) m(\mu)$$

- Conversion between pole and MSbar schemes known to 3-loops in QCD.
  Example: 1-loop QCD

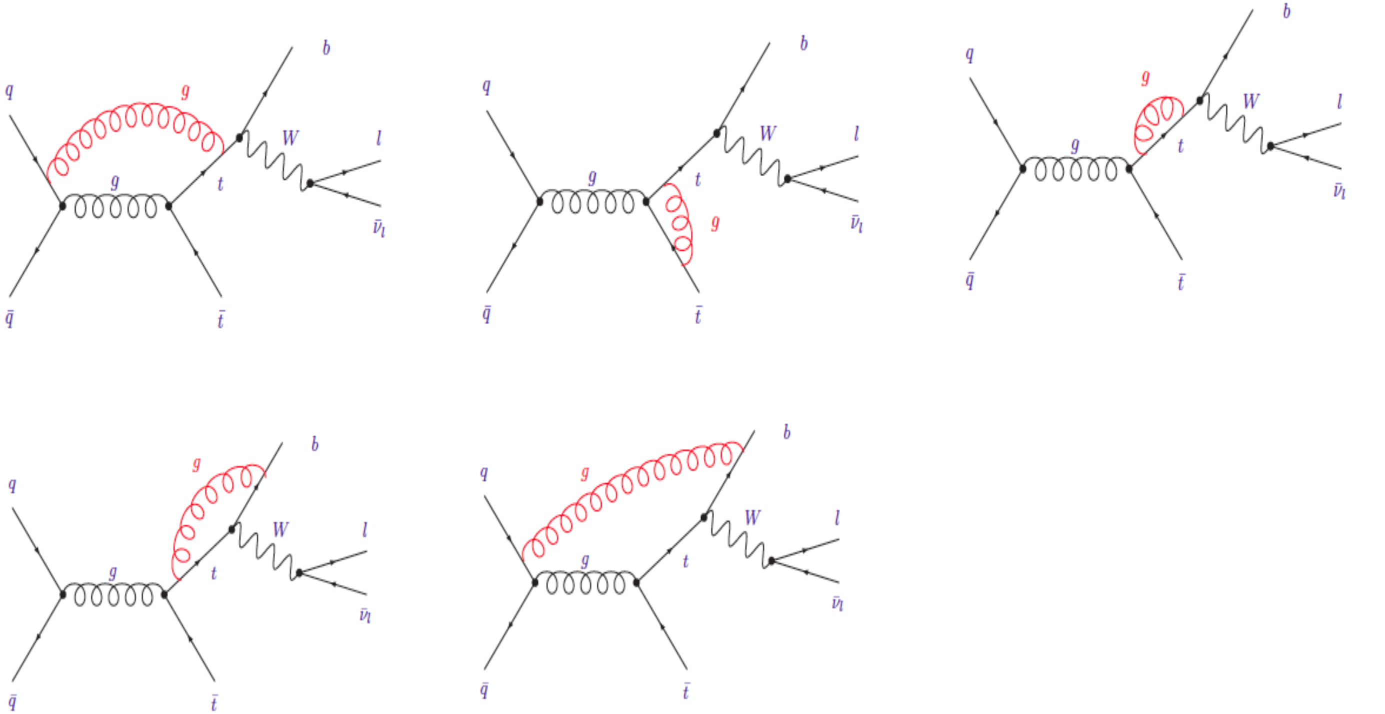
$$m^{\text{pole}} = m(\mu) \left\{1 + \frac{\alpha_s(\mu)}{4\pi}\left(\frac{4}{3} + \ln\left(\frac{\mu^2}{m(\mu)^2}\right)\right) + \ldots\right\}$$

What Top Quark Mass?

- What’s really being measured is the top quark mass in whatever MC generator was used to extract it. But different MCs include different radiative corrections!

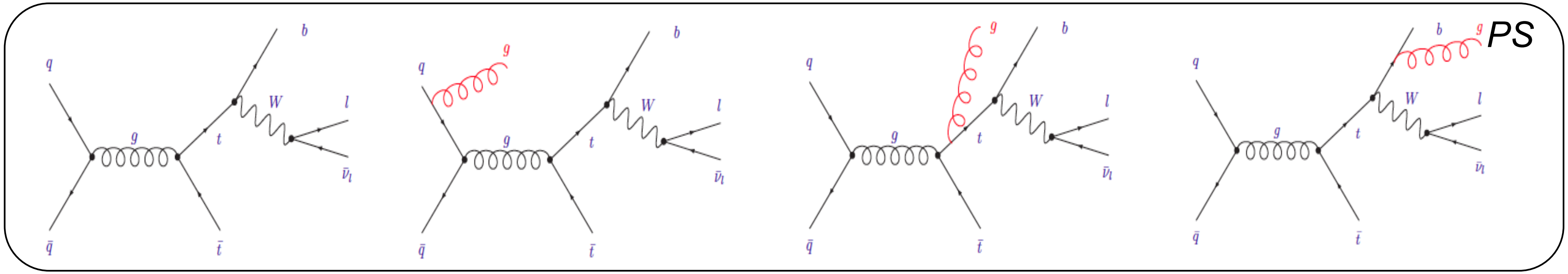


PYTHIA

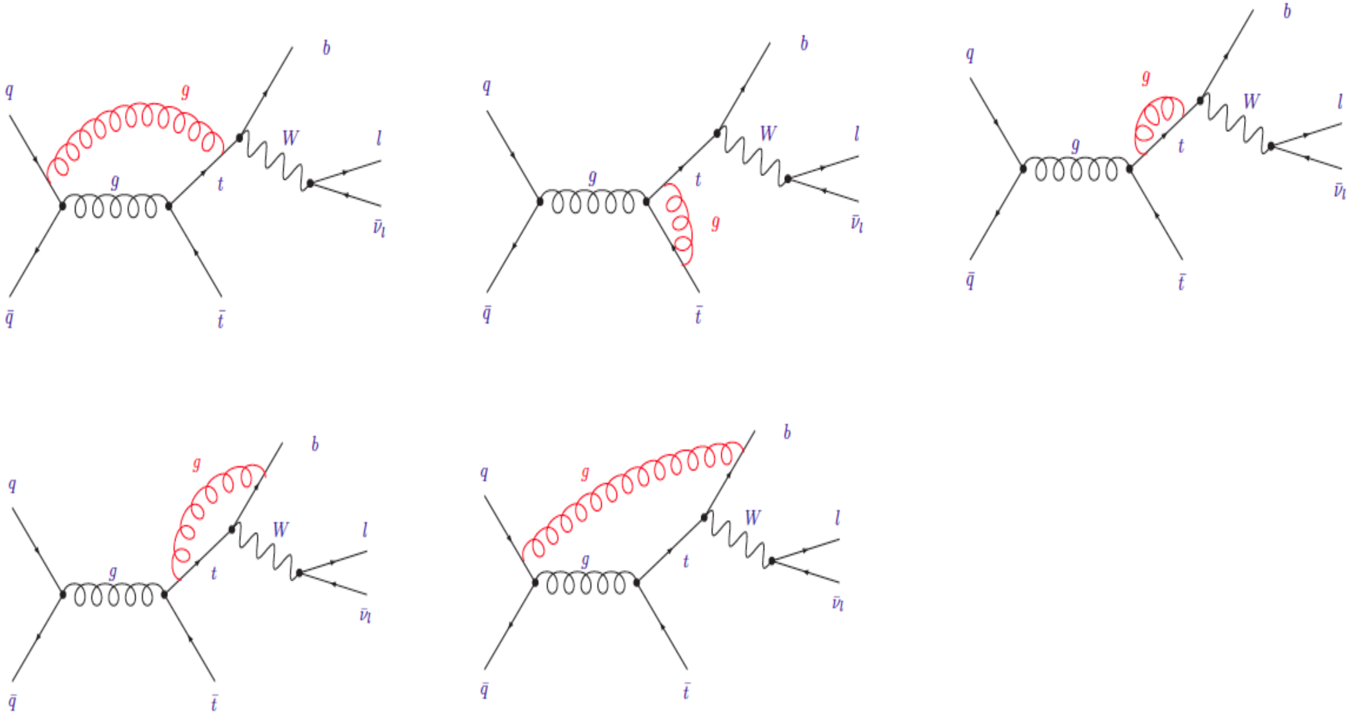


What Top Quark Mass?

- What’s really being measured is the top quark mass in whatever MC generator was used to extract it. But different MCs include different radiative corrections!

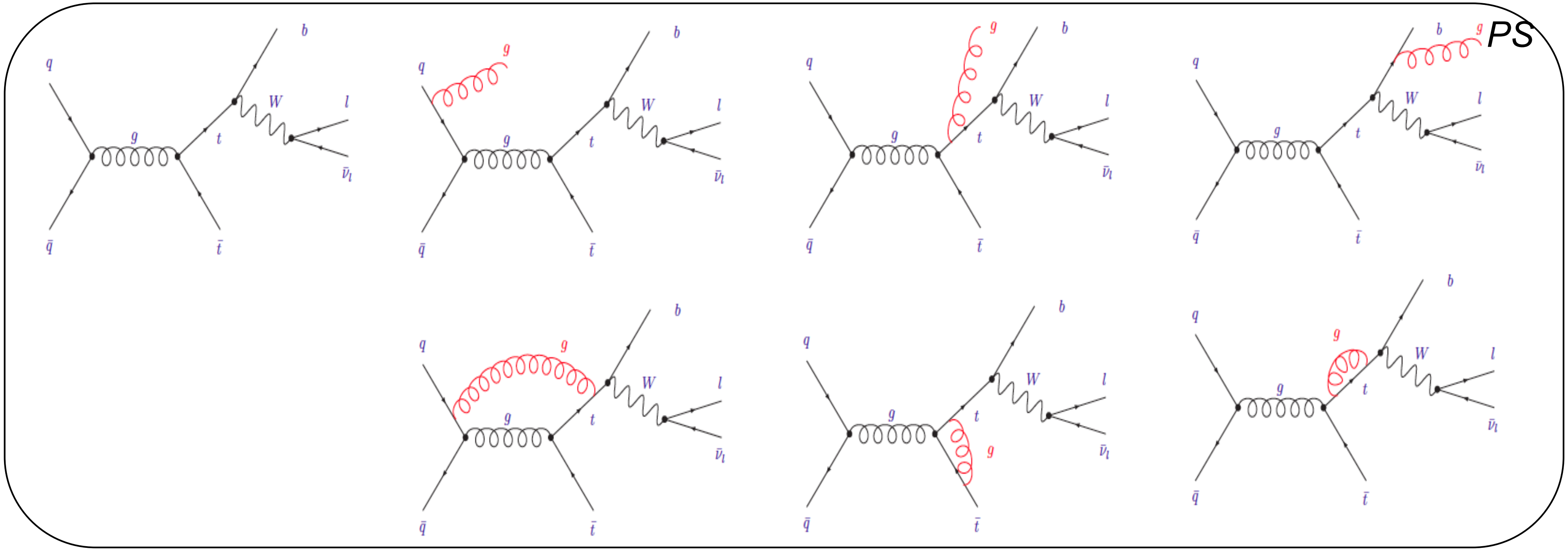


ALPGEN, MADGRAPH

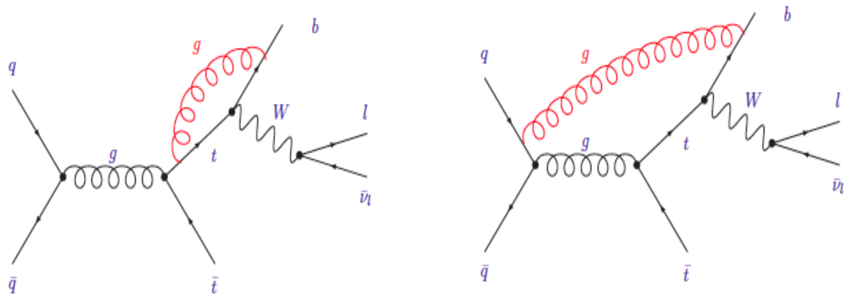


What Top Quark Mass?

- What's really being measured is the top quark mass in whatever MC generator was used to extract it. But different MCs include different radiative corrections!

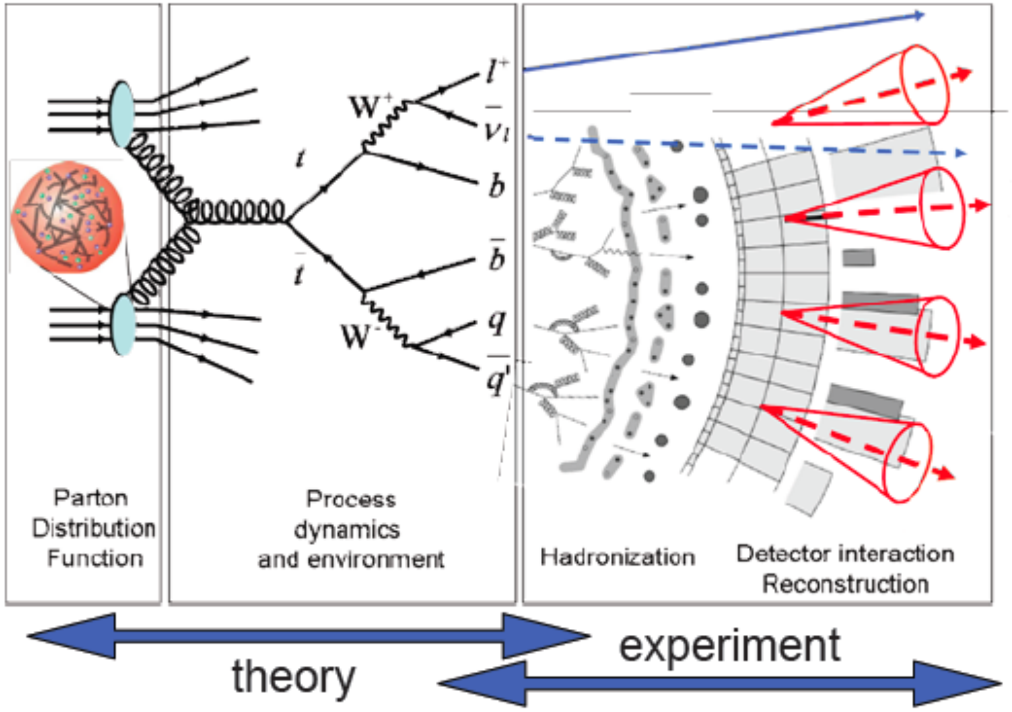


MC@NLO, POWHEG



Systematic Uncertainties

- Theoretical:
  - Signal simulation (PDFs, MC generator, hadronization model)
  - Event modeling and environment (underlying event, color reconnection, QCD radiation, pileup)
- Experimental:
  - Physics objects and detector modeling (jet reconstruction/ resolution/scale, b-tagging, E_T^{miss},…)
  - Background contamination
- Can exploit data to verify proper modeling and/or further constrain size of systematic uncertainties.



Projected DØ Uncertainty

Source	Public. 2009 (1.0 fb^{-1})	Public. 2012 (4.3 fb^{-1})	Proj. 10 fb^{-1}	Proj. 10 fb^{-1} improv.	Proj. 10 fb^{-1} improv. + EC
Statistical	23	13	9	9	8
Experimental syst.					
Electron energy scale	34	16	11	11	10
Electron energy resolution	2	2	2	2	2
EM shower model	4	4	4	2	2
Electron energy loss	4	4	4	2	2
Hadronic recoil	6	5	3	3	2
Electron ID efficiency	5	1	1	1	1
Backgrounds	2	2	2	2	2
Subtotal experimental syst.	35	18	13	12	11
***W* production and decay model**					
PDF	9	11	11	11	5
QED	7	7	7	3	3
boson p_T	2	2	2	2	2
Subtotal W model	12	13	13	12	6
Total systematic uncert.	37	22	19	17	13
Total	**44**	**26**	**21**	**19**	**15**

combination: 23

Projected CDF Uncertainty

Source	0.2/fb (MeV)	2.2/fb (MeV)	10/fb (MeV)
Lepton energy scale	23	7	3
Lepton energy resolution	4	2	1
Recoil energy scale	8	4	2
Lepton removal	6	2	1
Backgrounds	6	3	2
pT(W) model	4	5	2
PDFs	11	10	5
QED radiation	10	4	4
Total systematics	**34**	**15**	**8**
W statistics	34	12	6
Total	**48**	**19**	**10**