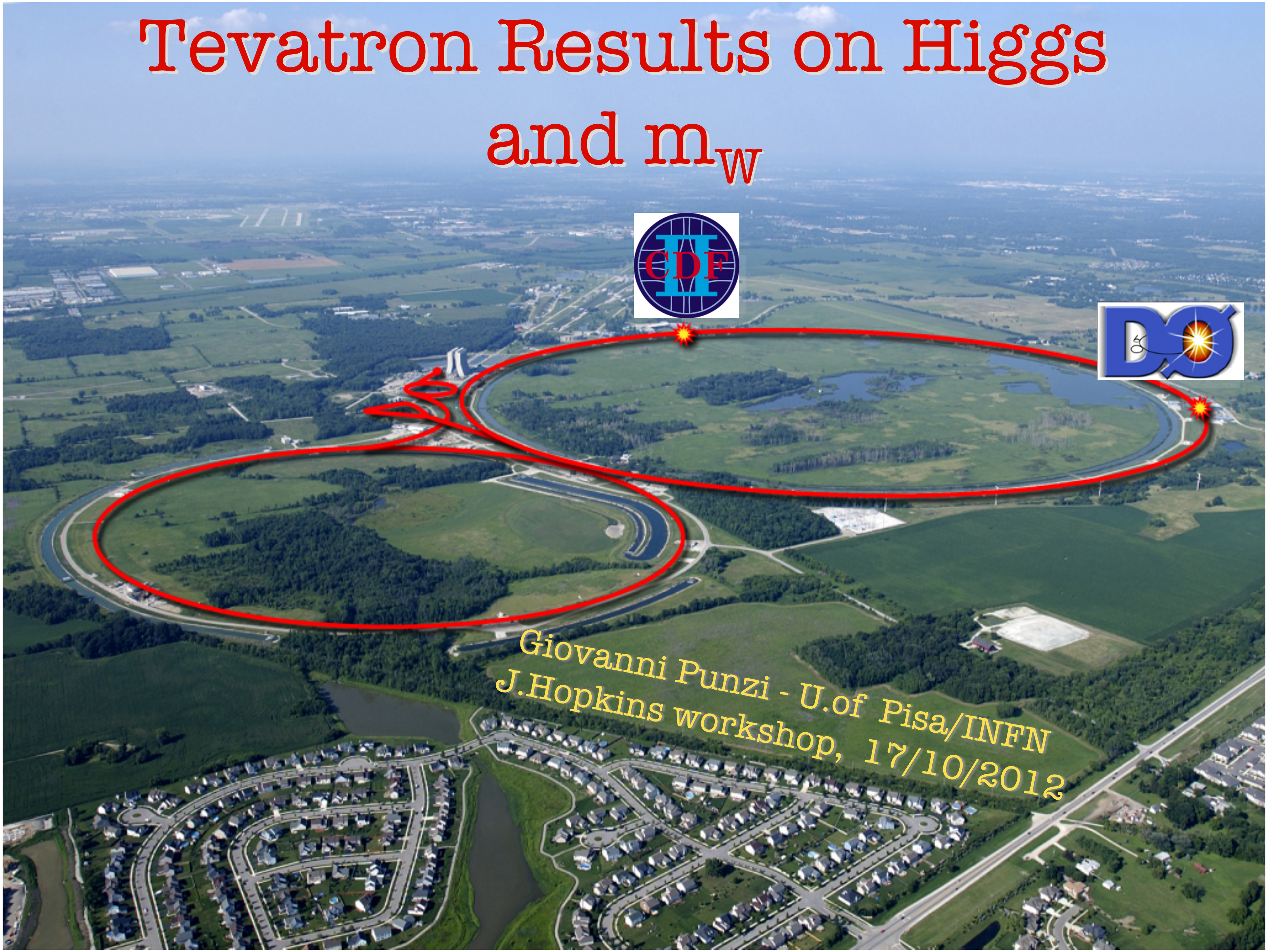
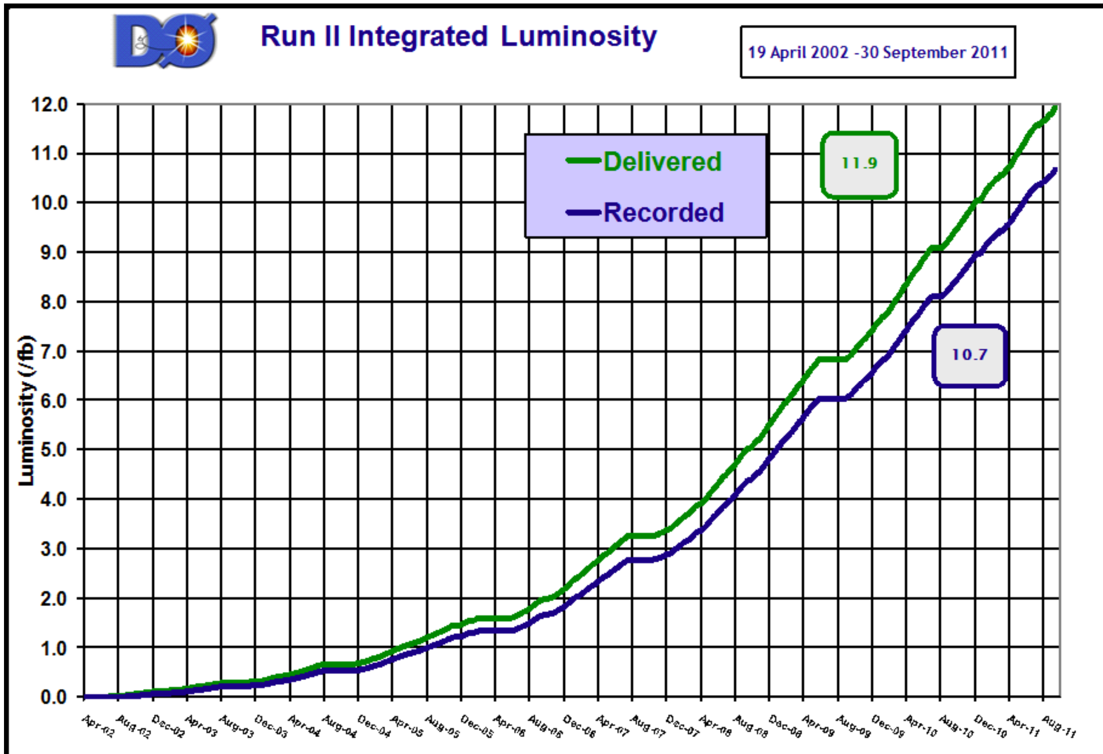
Tevatron Results on Higgs and m_W



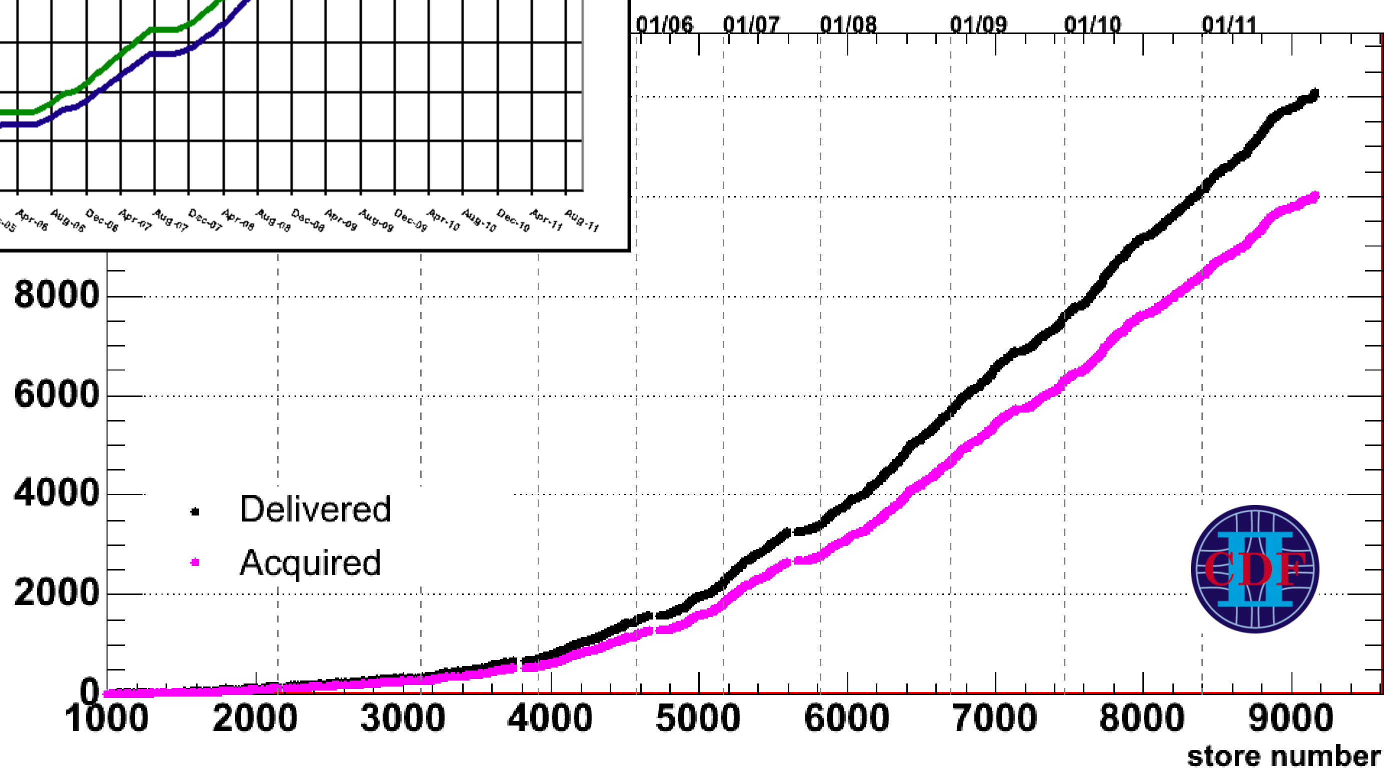
Giovanni Punzi - U.of Pisa/INFN

J.Hopkins workshop, 17/10/2012

CDF and D0 data

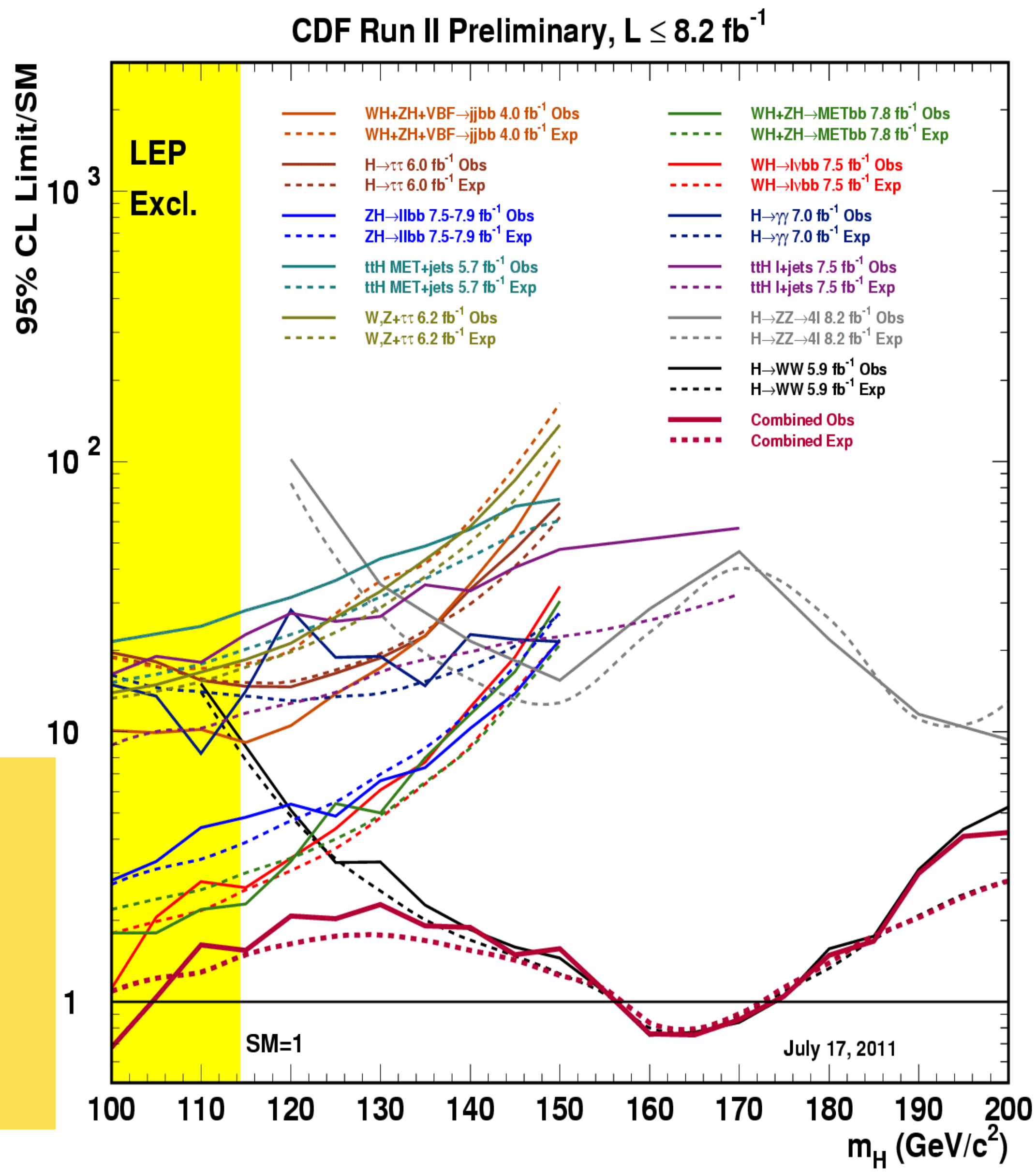


- Tevatron 12 fb^{-1} delivered, up to Sep. 2011
- Collected 10 fb^{-1}/experiment
- Analyses still ongoing



Overview of Tevatron Higgs analyses

- In the full Tevatron sample:
  - Expect <200 Higgs events
  - With a background of ~200K
  - Partitioned over many final states
- CDF and D0 analyses: ~90 orthogonal sub-channels each
- Most important >150 GeV
  - WWW, WWZ, WW, ZZ, τ-decays, full/semi-leptonic...
- Most important <150 GeV
  - WH, ZH, METbb, ttH, γγ, VBF→bbjj



- Had m(H) been >150 GeV, discovery would have been easier…
  - Large yields at both Tev at LHC
- …but 125 GeV allows more interesting studies after discovery
  - Can study fermion couplings
  - Complementarity TeV-LHC

A piece of history in Higgs search

Milestone Higgs paper from CDF+D0, was based on "high-mass" Higgs search.

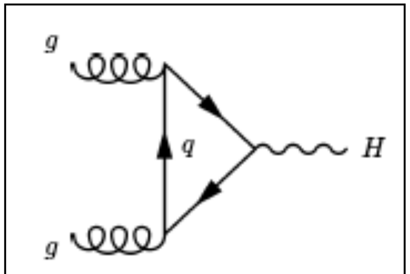
In Feb. 2010 the limit curve touched 1.0 for the first time giving the start to the Higgs program:

Excluded M_H in [163-166] GeV

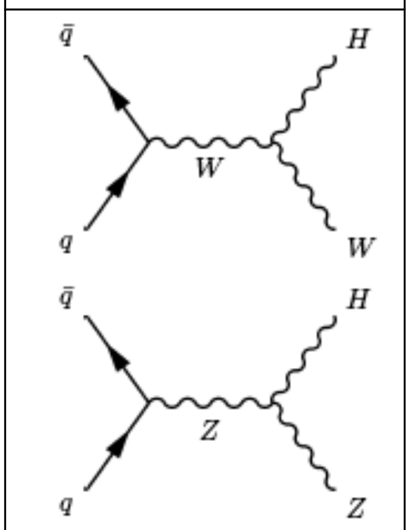
Progress has been fast since then.

I will concentrate on the 125 GeV Higgs for the rest of the talk.

Producing the SM Higgs at different hadron colliders

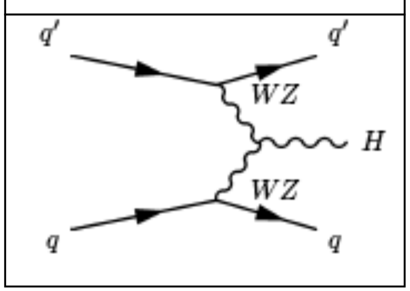


"gluon fusion"
(via fermion loop)

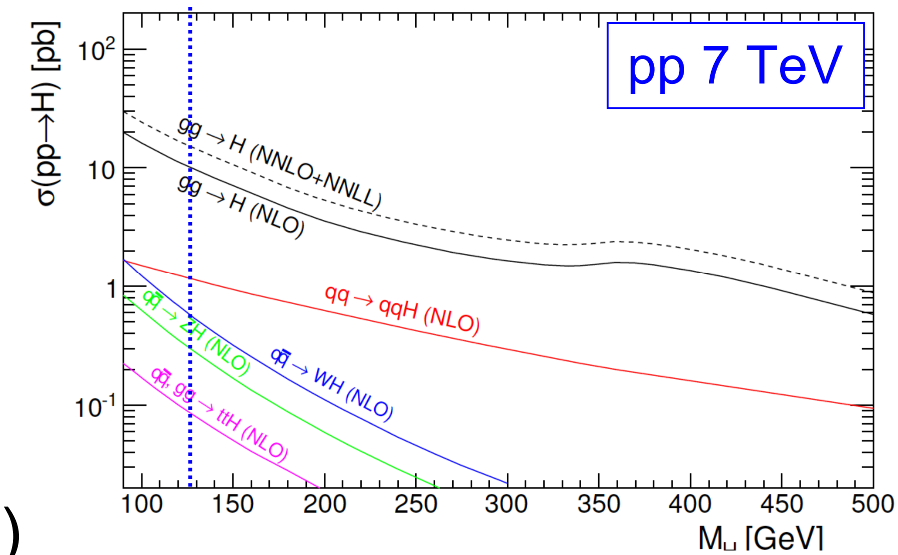


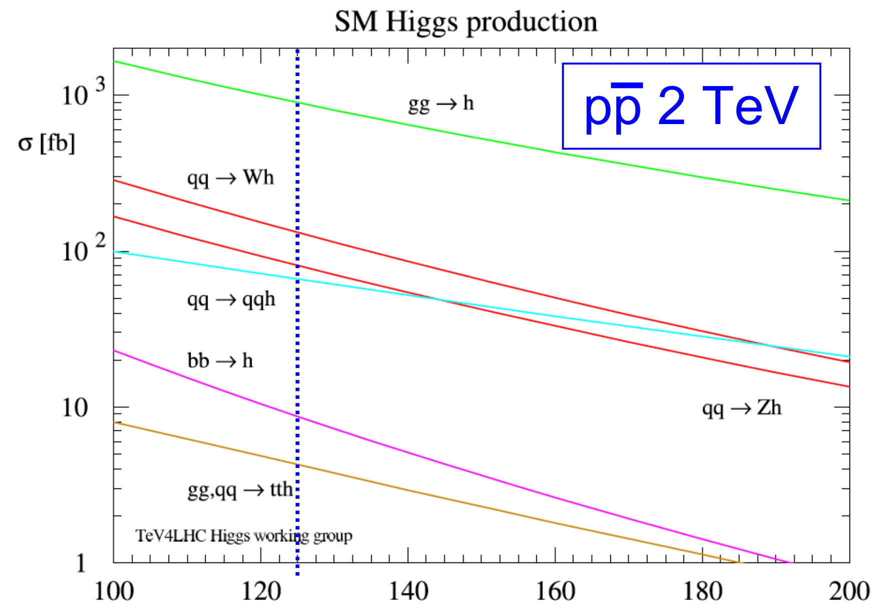
"Higgs-strahlung"
(radiated by a VB)

Relatively more important at Tevatron
(22% of gg)

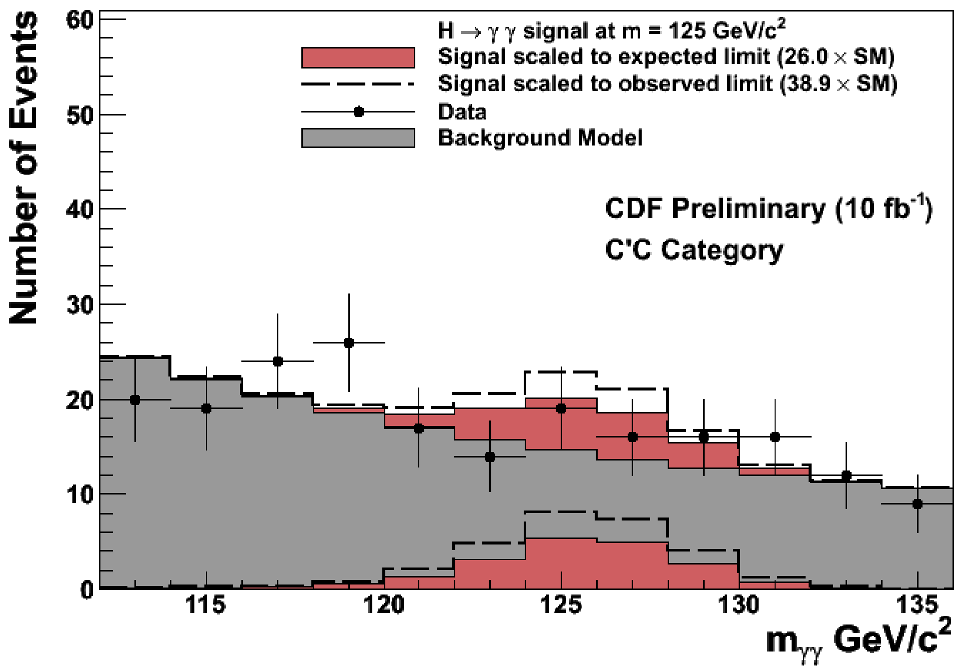


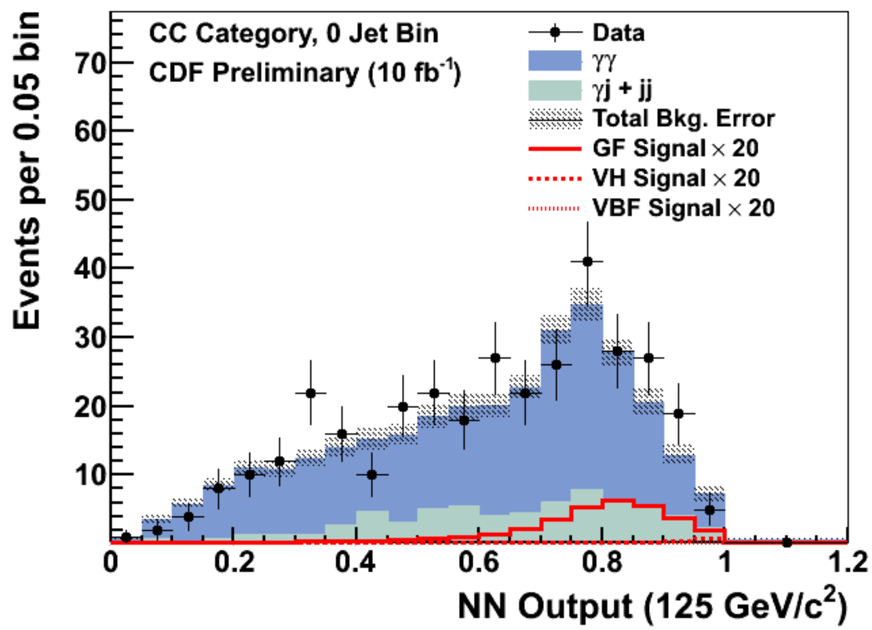
VB-fusion



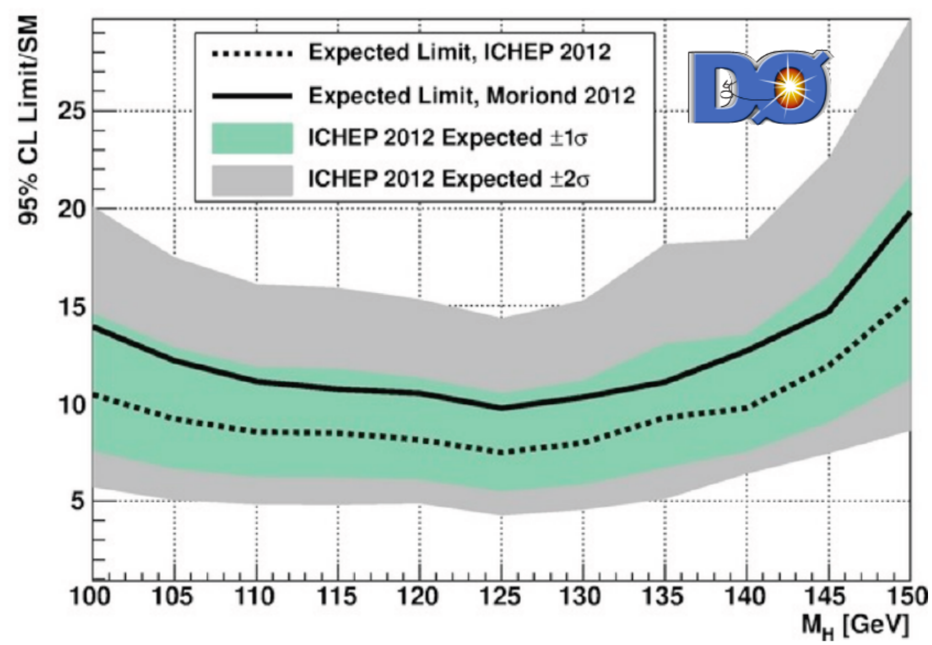


Tevatron and the γγ mode

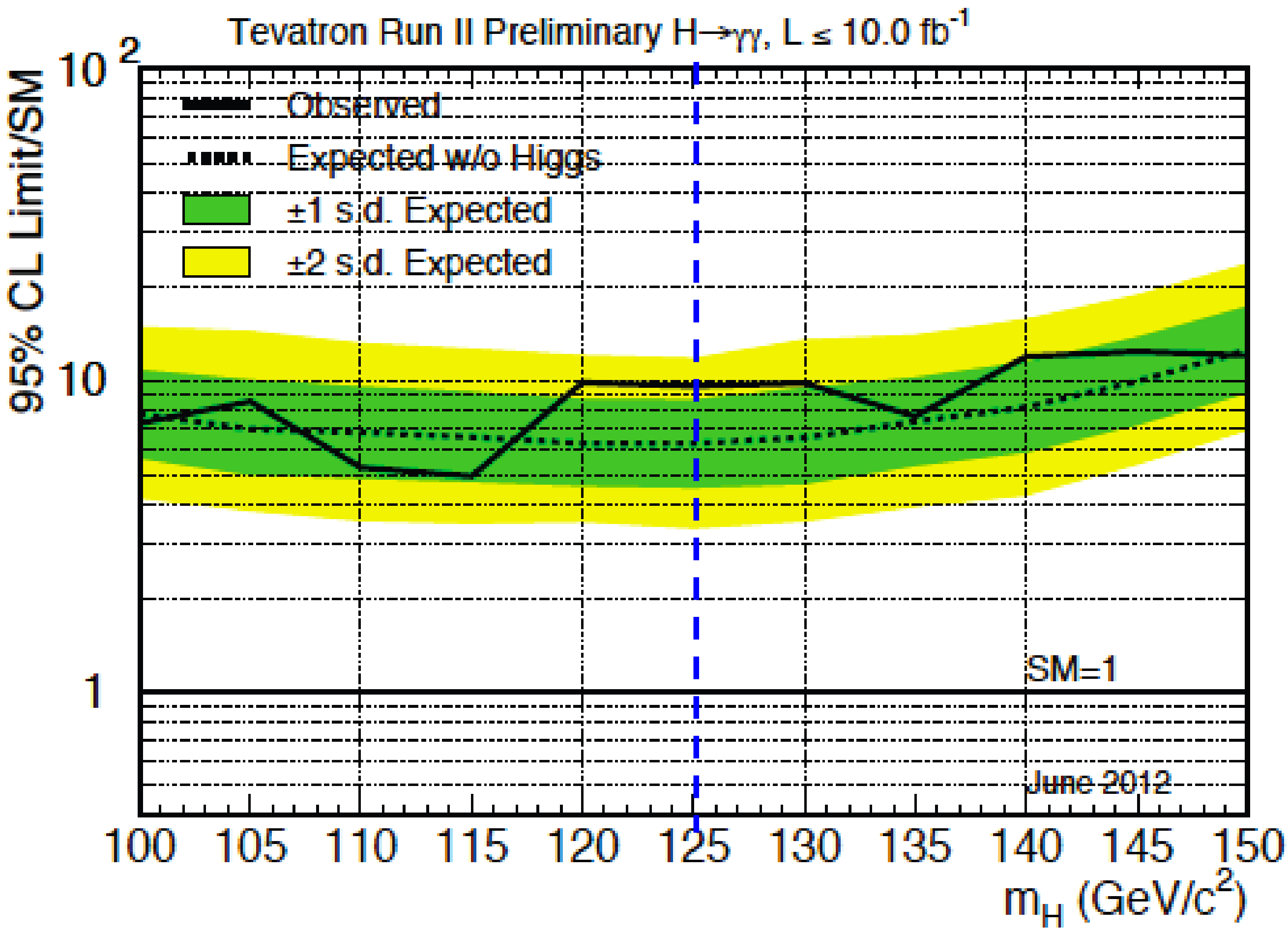




- Search performed with mass fit
- Addition of NN
- Latest improvement by DZero

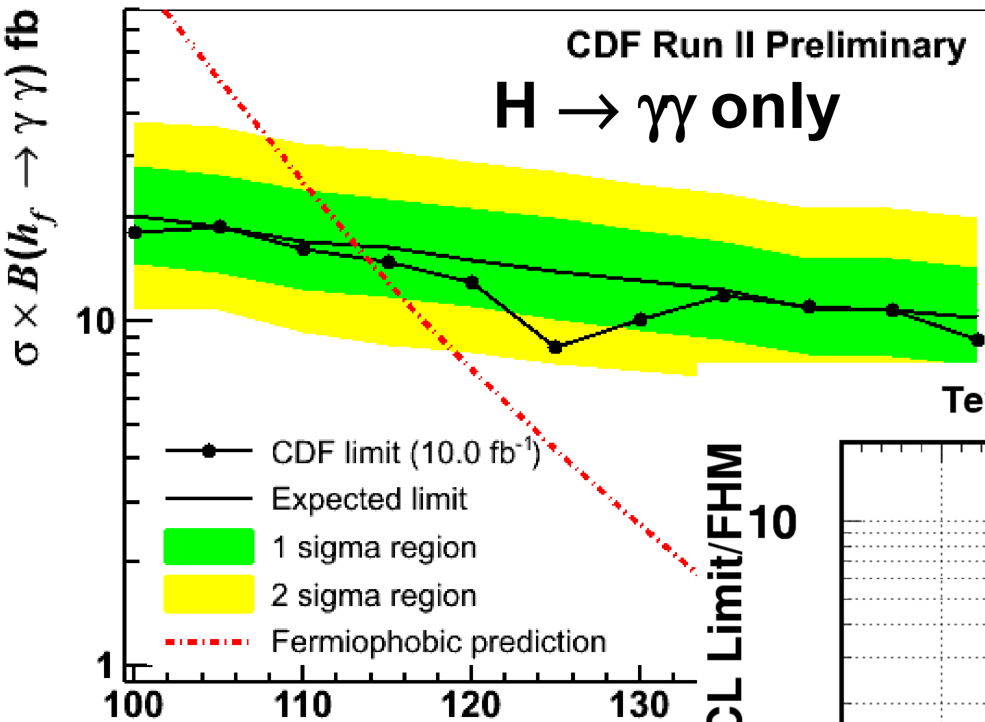


Tevatron combined γγ limits

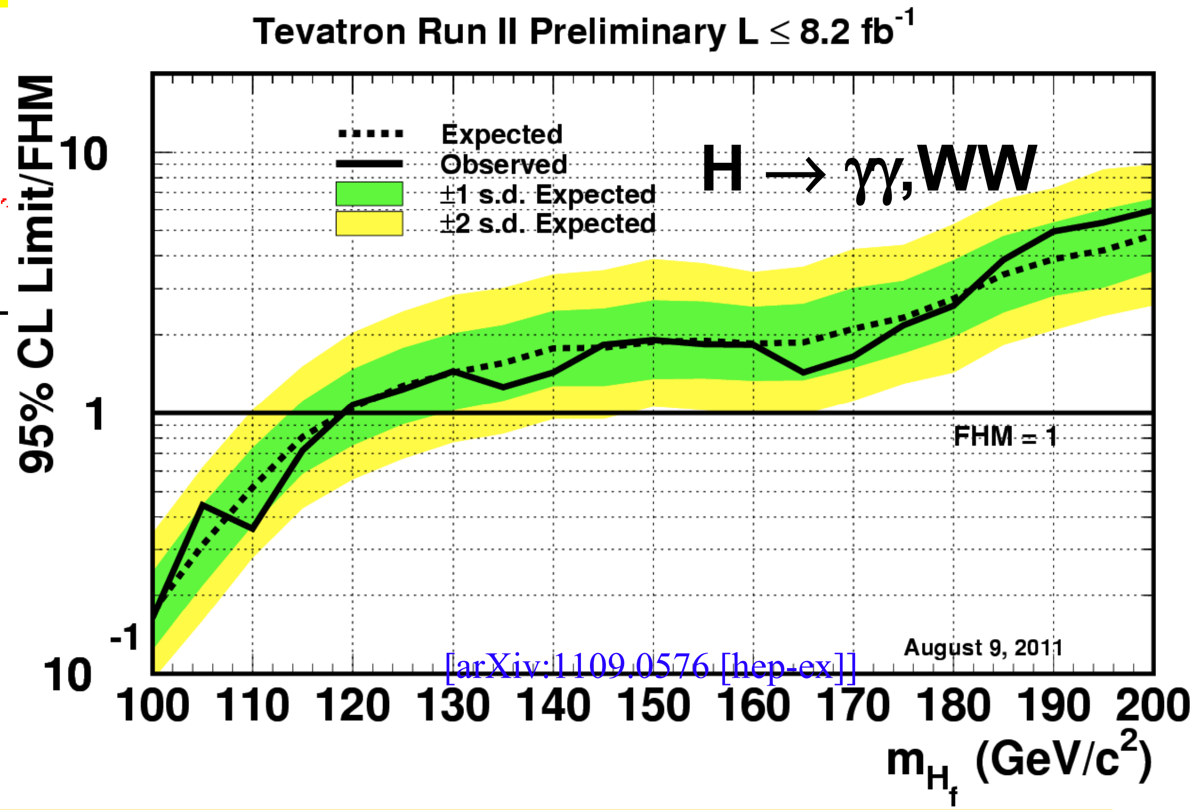


- **Expected limit @125GeV = 6.3 * SM -** *observed ~10*SM*

Fermiophobic limits



CDF $M(h_f)>114$ GeV/c2

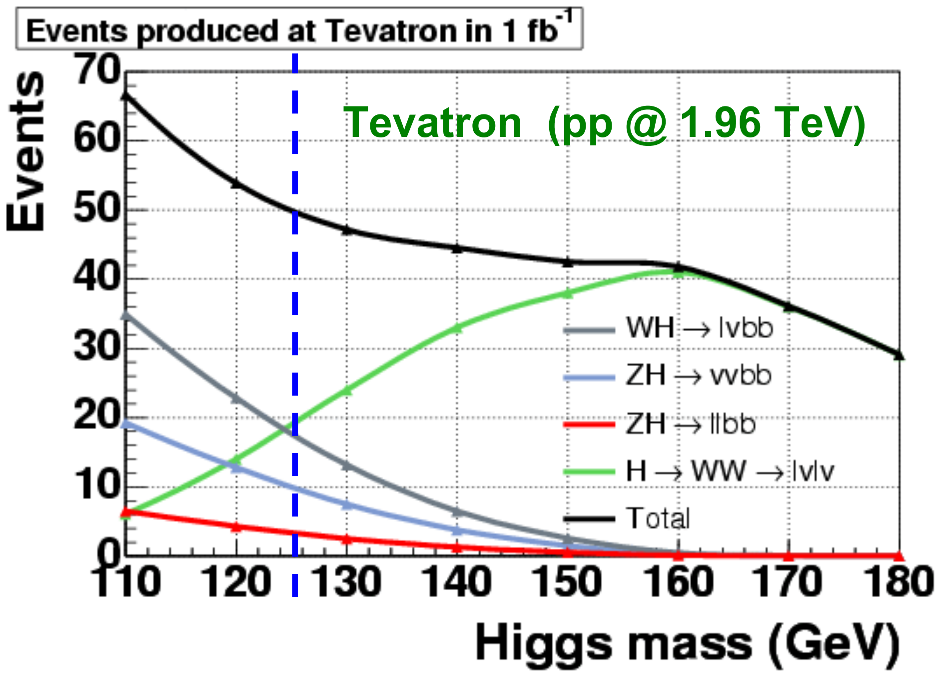


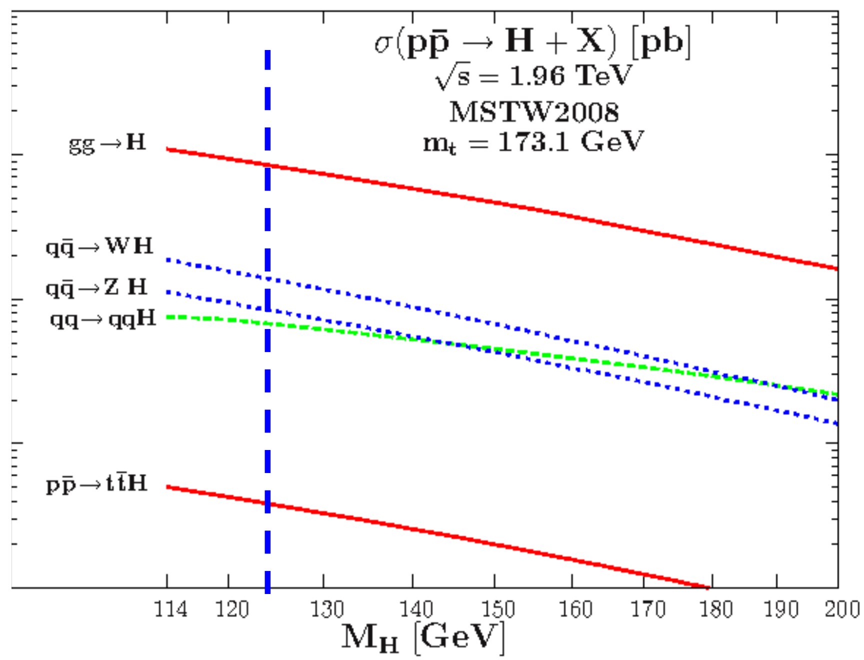
Tevatron combined:

$M(h_f)>119$ GeV/c^2

γγ information from Tevatron essentially superseded by LHC

The "big 4"





- Four channels cover 90% of the 125GeV Higgs yield for at the Tevatron
- Their total yield is ~constant in the low-mass range - but composition changes
- The WW channel is the only one not requiring associate production - still:
  - 30% of the WW final state comes from associate production
  - WWW and ZWW channels have better S/B than gg->H

H→WW Search Channels @Tevatron

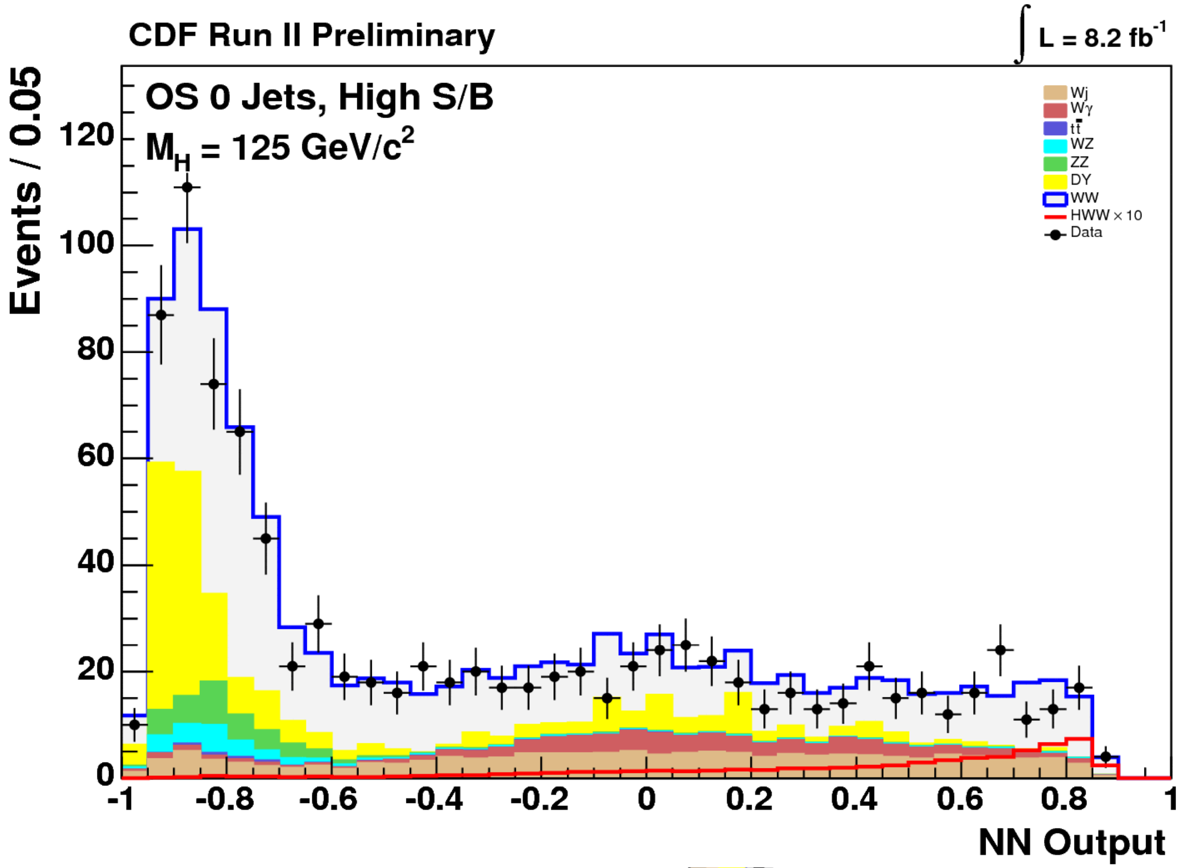
Channel	Main Signal	Main Background	Most Important kinematic variables
OS dileptons, 0 Jets	gg→H	WW	LR_{HWW}, ΔR_{ll}, H_T
OS dileptons, 1 Jet	gg→H	DY	ΔR_{ll}, $m_T(ll,E_T)$, $\not\!\!E_T$
OS dileptons, 2+ Jets	Mixture	t-tbar	H_T, ΔR_{ll}, M_{ll}
OS dileptons, low M_{ll}, 0 or 1 Jet	gg→H	W+γ	$p_T(l2)$, $p_T(l1)$, $E(l1)$
SS dileptons, 1+ Jet	WH→WWW	W+Jets	$\not\!\!E_T$, $\sum E_T^{jets}$, M_{ll}
Tri-leptons, no Z candidate	WH→WWW	WZ	$\not\!\!E_T$, ΔR_{ll}^{close}, Type(lll)
Tri-leptons, Z candidate, 1 Jet	ZH→ZWW	WZ	Jet E_T, ΔR_{lj}, $\not\!\!E_T$
Tri-leptons, Z candidate, 2+ Jets	ZH→ZWW	Z+Jets	M_{jj}, M_T^H, ΔR_{WW}
OS dilepton, electron + hadronic tau	gg→H	W+Jets	$\Delta R_{l\tau}$, τ id variables
OS dilepton, muon + hadronic tau	gg→H	W+Jets	$\Delta R_{l\tau}$, τ id variables

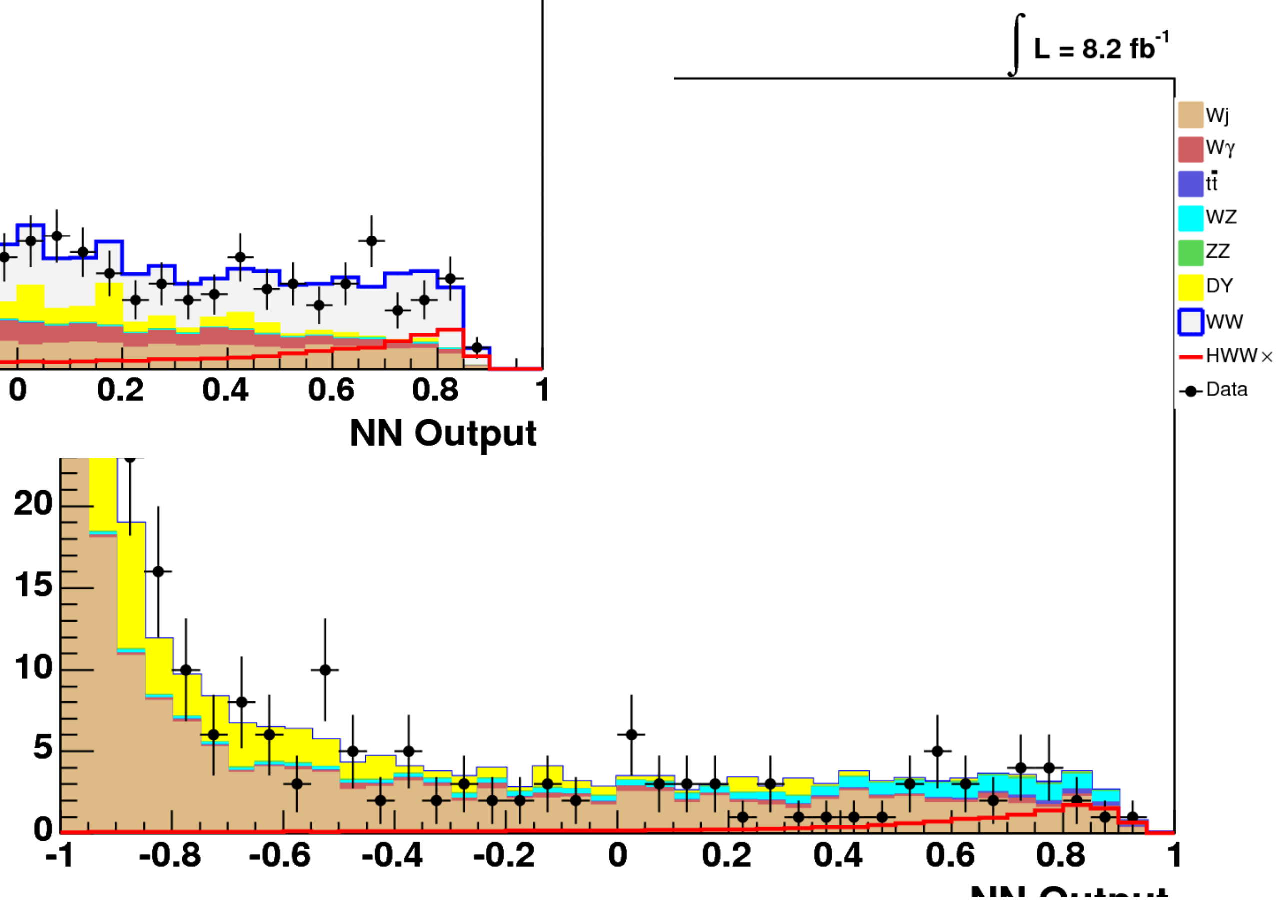
Breakdown by #jets (OS dileptons, 0 Jets; 1 Jet; 2+ Jets)

Associated production (SS dileptons, 1+ Jet; Tri-leptons rows)

$W\to\tau\nu$ (OS dilepton + hadronic tau rows)

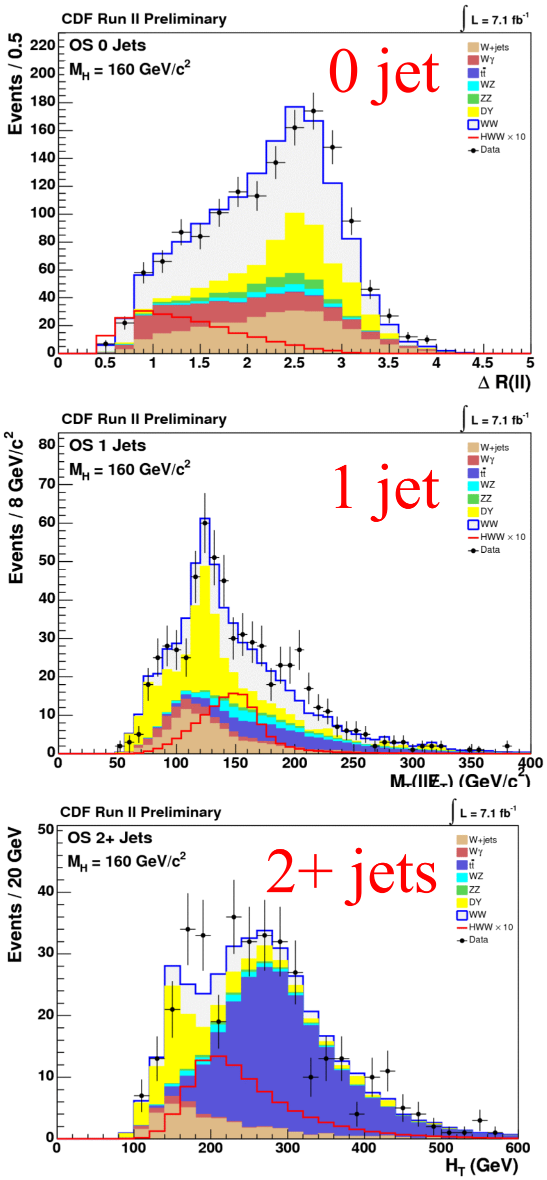
Comparision of SS /OS dilepton searches



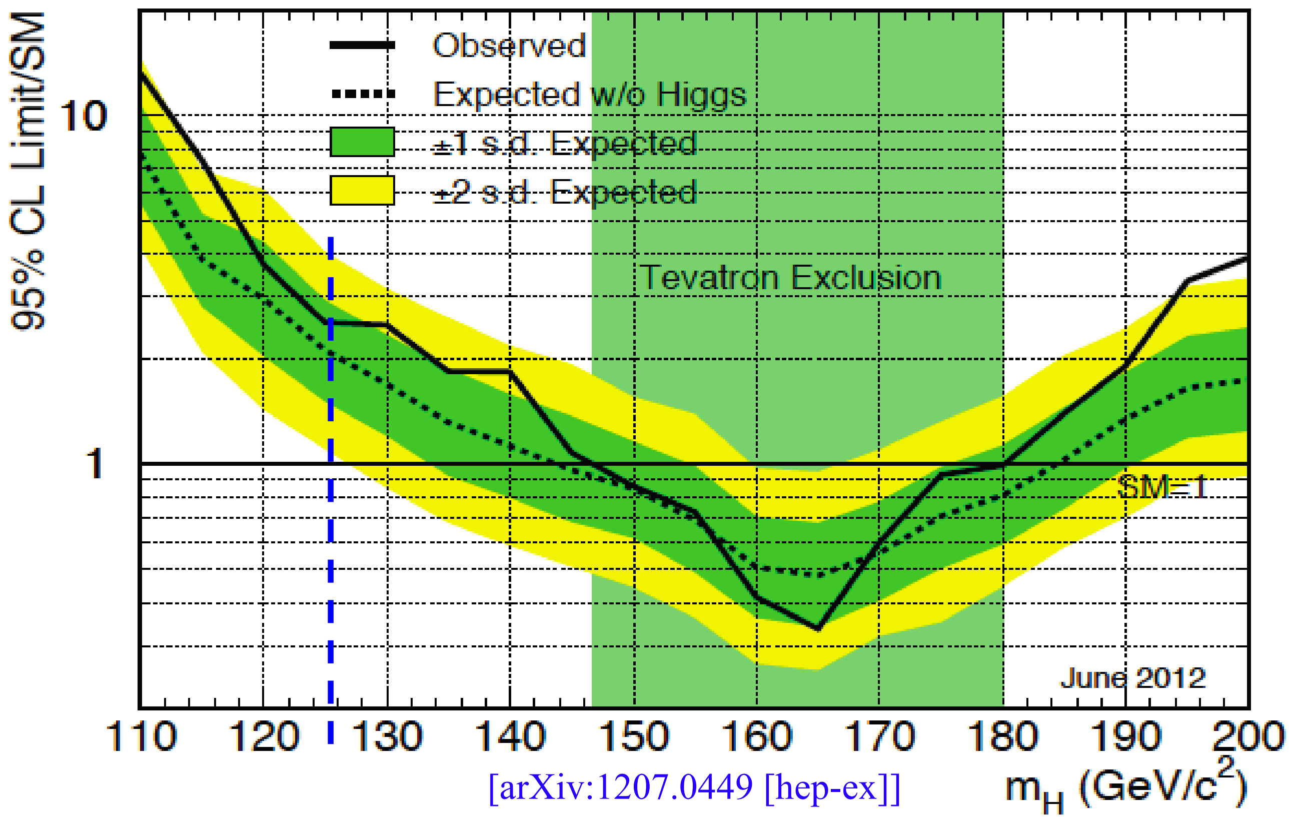


Divide-and-conquer approach

- Separating events into multiple analysis channels and combining the results improves sensitivity.
- Allows to use separate, optimized discriminates for each channel based on:
  - specific signal contributions
  - specific background contributions
  - specific event kinematics
- Then combine everything in a single histogram, binning in S/B (Likelihood ratio).

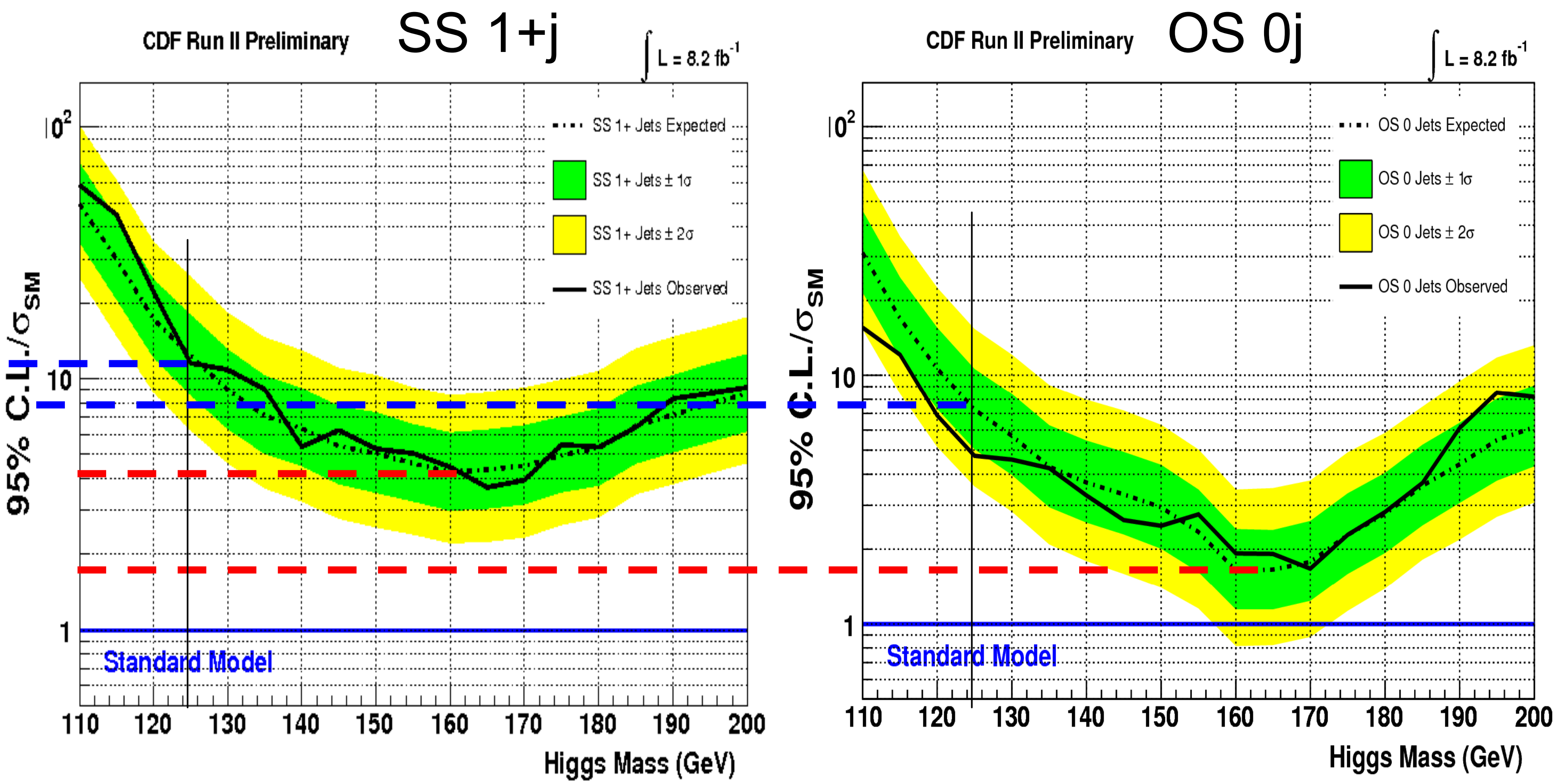


WW Results

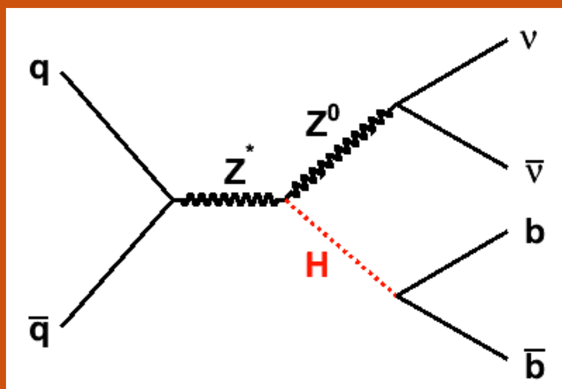


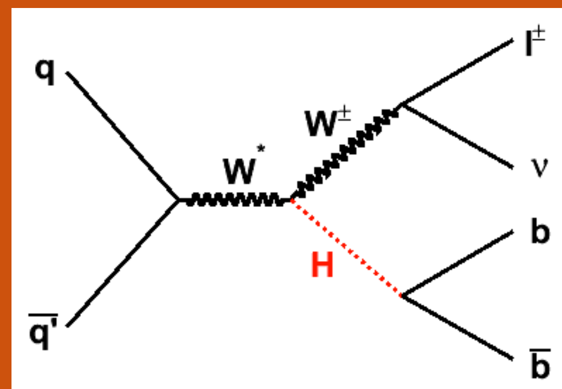
- WW still gives the largest contribution to the Tev-excluded range : 147-180 GeV
- Sensitivity @125 ~2*SM - **No significant signal** (~1σ deviation)

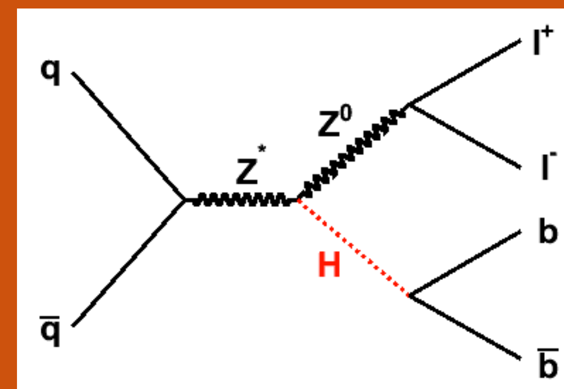
Comparision of SS /OS dilepton searches



Reconstruction of VH channels







$ZH \to \nu\nu bb$	$WH \to l\nu bb$	$ZH \to llbb$
Hard background	Largest yield	Cleanest

Select:

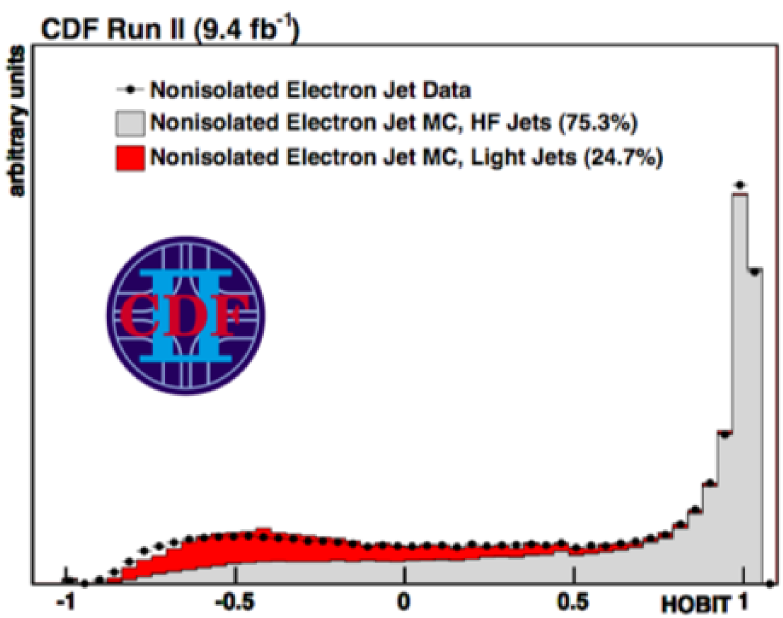
- 0,1,2 leptons and/or missing E_t
- Two high E_t jets

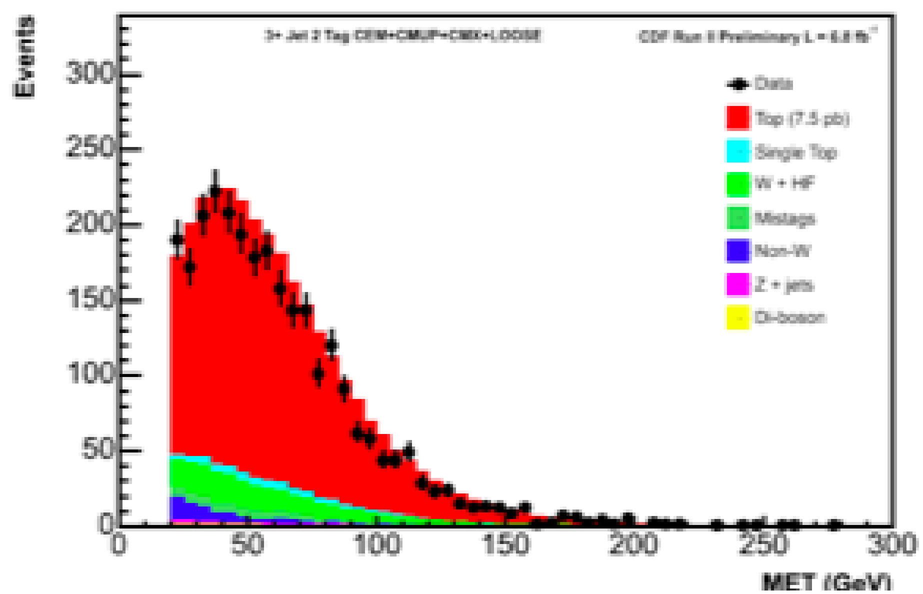
Critical points:

- Lepton reconstruction and selection efficiencies
- Efficiency for tagging b-quark jets
- Dijet mass resolution

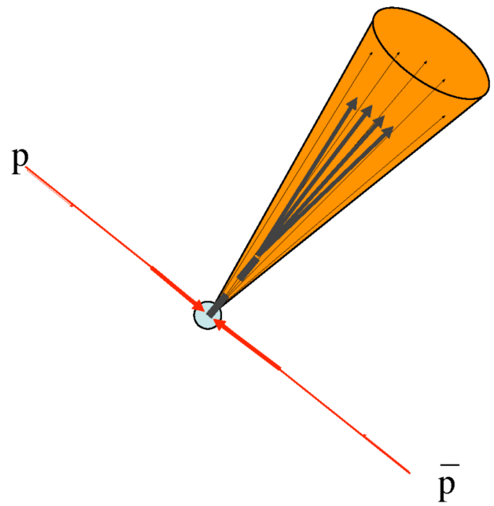
B-tagger calibration

- Both CDF and D0 employ sophisticate MVA algorithms (NN/BDT) with b-jet efficiencies of up to 60-80%, and u,d,s,g - jet mis-ID rates ($\lesssim$1-10%)
- Tested in two real data samples:
  - tt-enhanced samples (simultaneously extract tt cross section & tagger performance corrections)
  - Jet pairs with one jet containing an electron (either conversion or from heavy flavor decay)

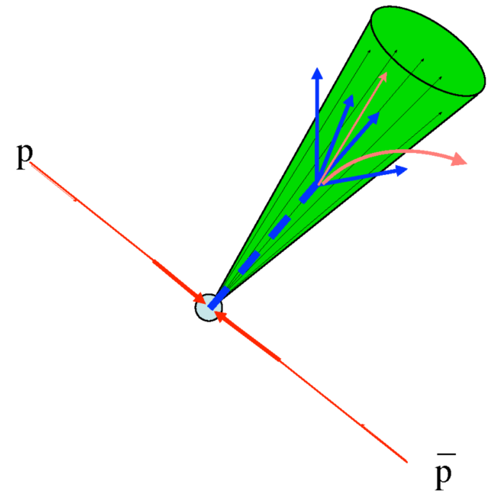




Mass Resolution for b-jets



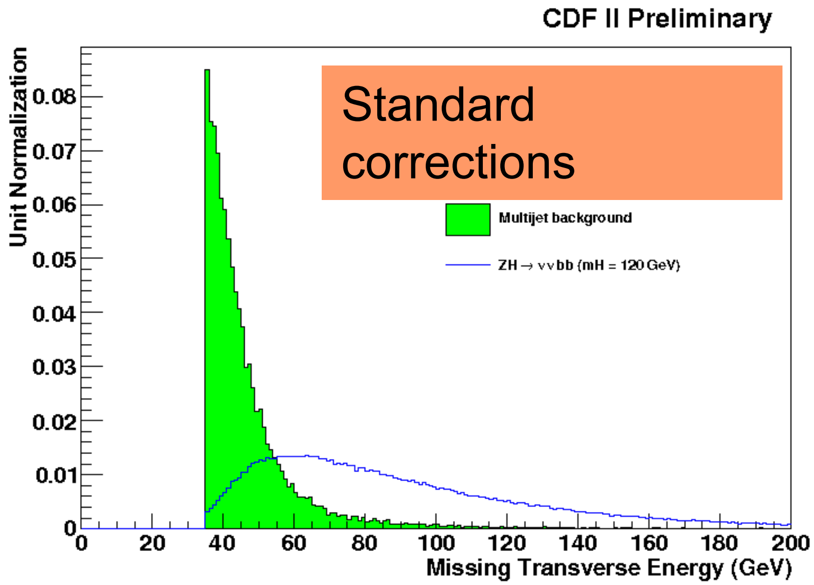
light flavor quark jet

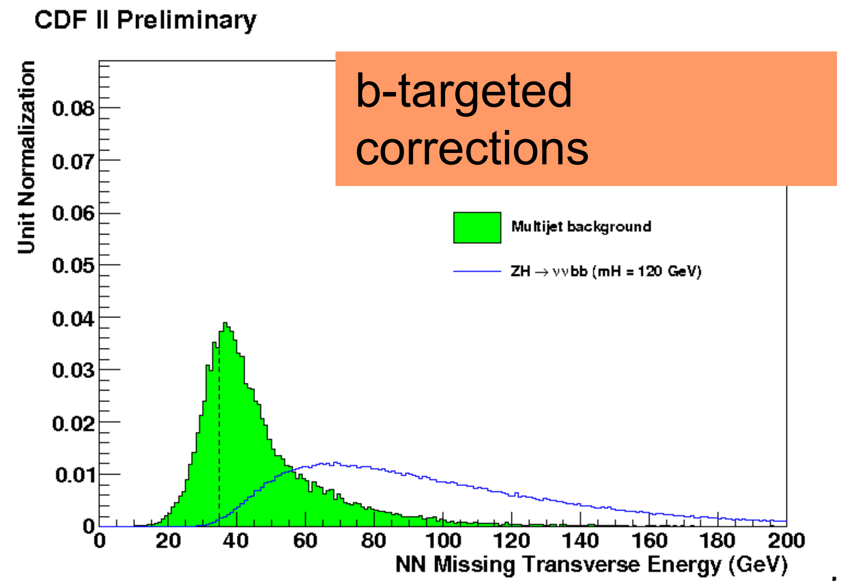


bottom quark jet

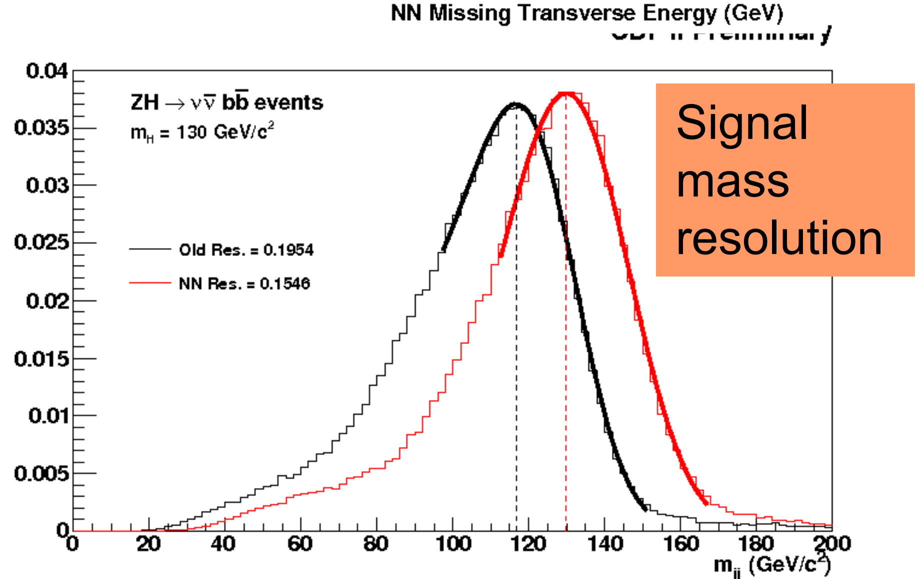
- Bottom quark jets have properties which are different from standard light flavor quark jets
- Specialized jet energy scale corrections focused on bottom quark jets improve our dijet invariant mass and missing transverse energy measurements

Specialized Jet Energy algorithm for b-jets

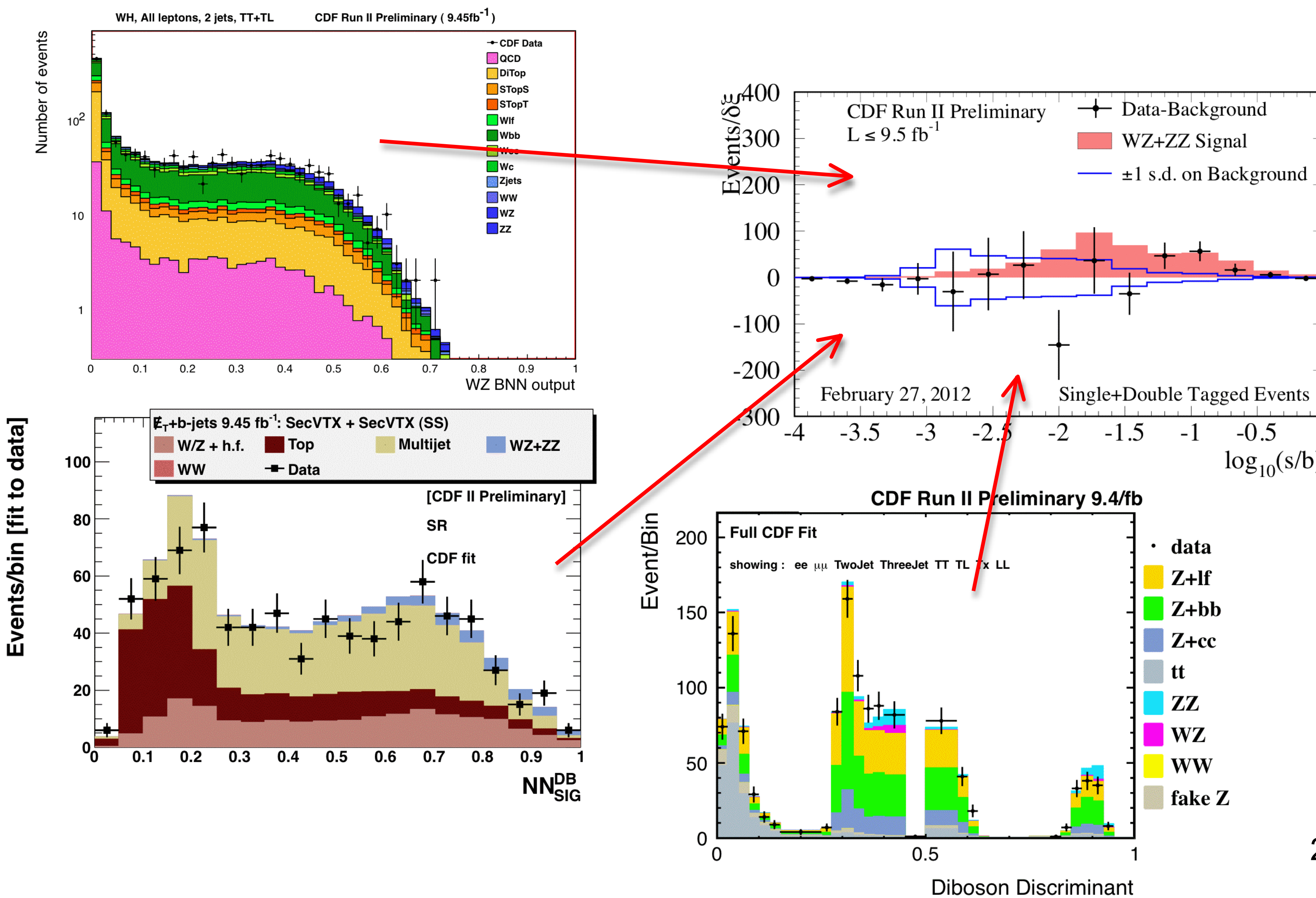




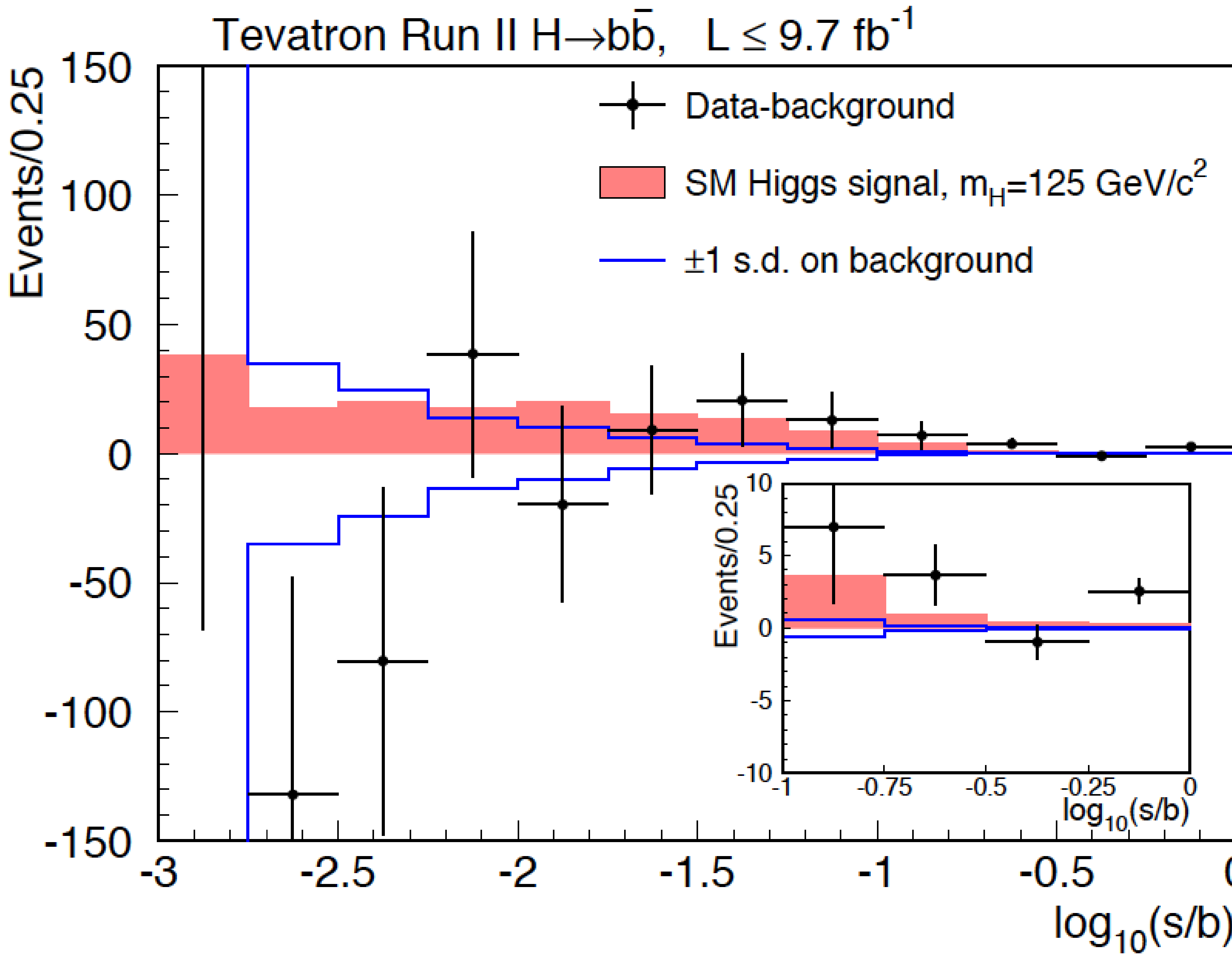
- Neural network correlates all jet-related variables and returns most probable jet energy based on bottom quark hypothesis – better signal/background separation



Combining all discriminants



Tevatron Combined H→b-bbar Discriminant



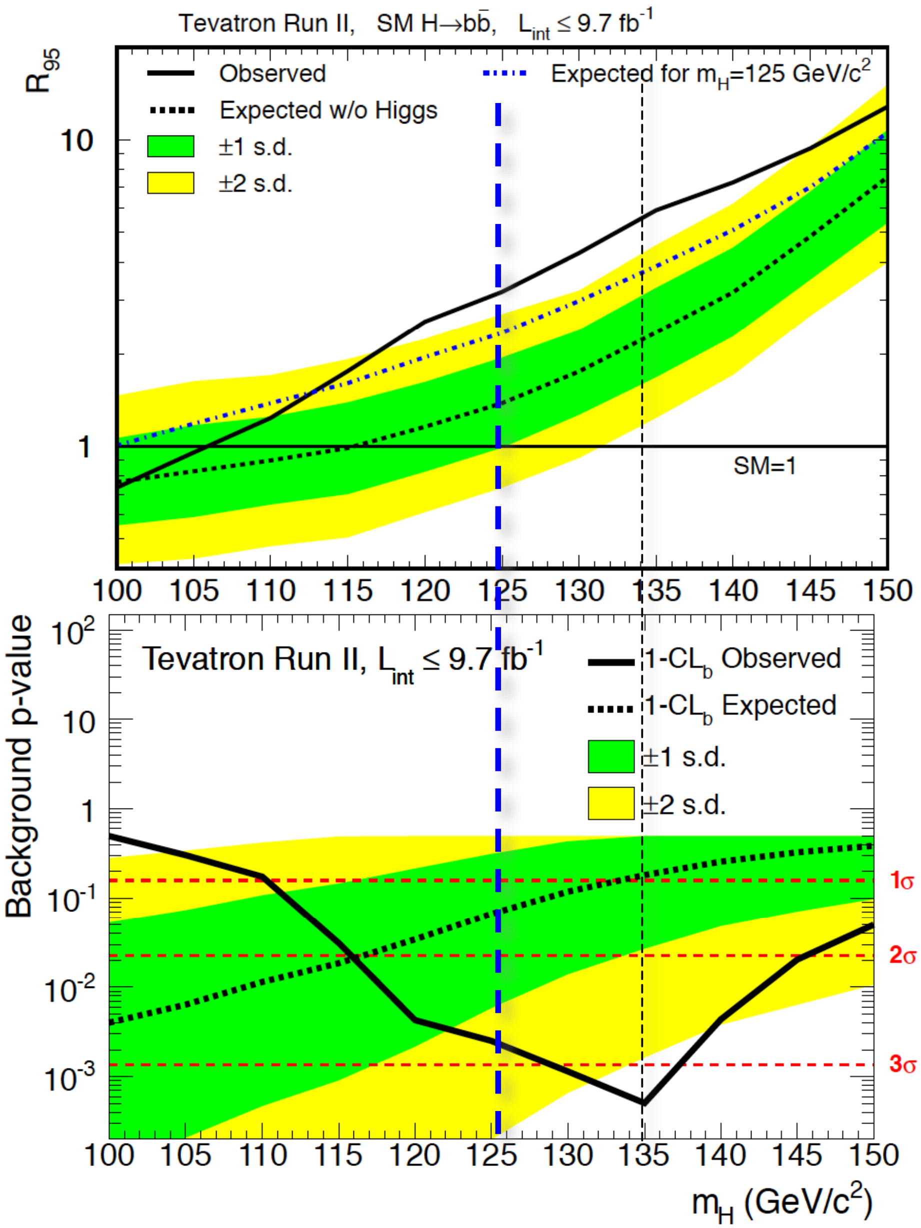
From Discriminants to Limits

- Combined binned likelihood function

$$L(R, \vec{s}, \vec{b} | \vec{n}) = \prod_{i=1}^{N_{\text{channel}}} \prod_{j=1}^{N_{\text{bin}}} \frac{\mu_{ij}^{n_{ij}} e^{-\mu_{ij}}}{n_{ij}!}$$

- Incorporate sistematics as nuisance parameters
  - About 20% effects
- Uncertainties taken on both the shapes and normalizations of signal & background templates
- Additional constraints on background model obtained directly from fit

Tevatron b-bbar limits and significance



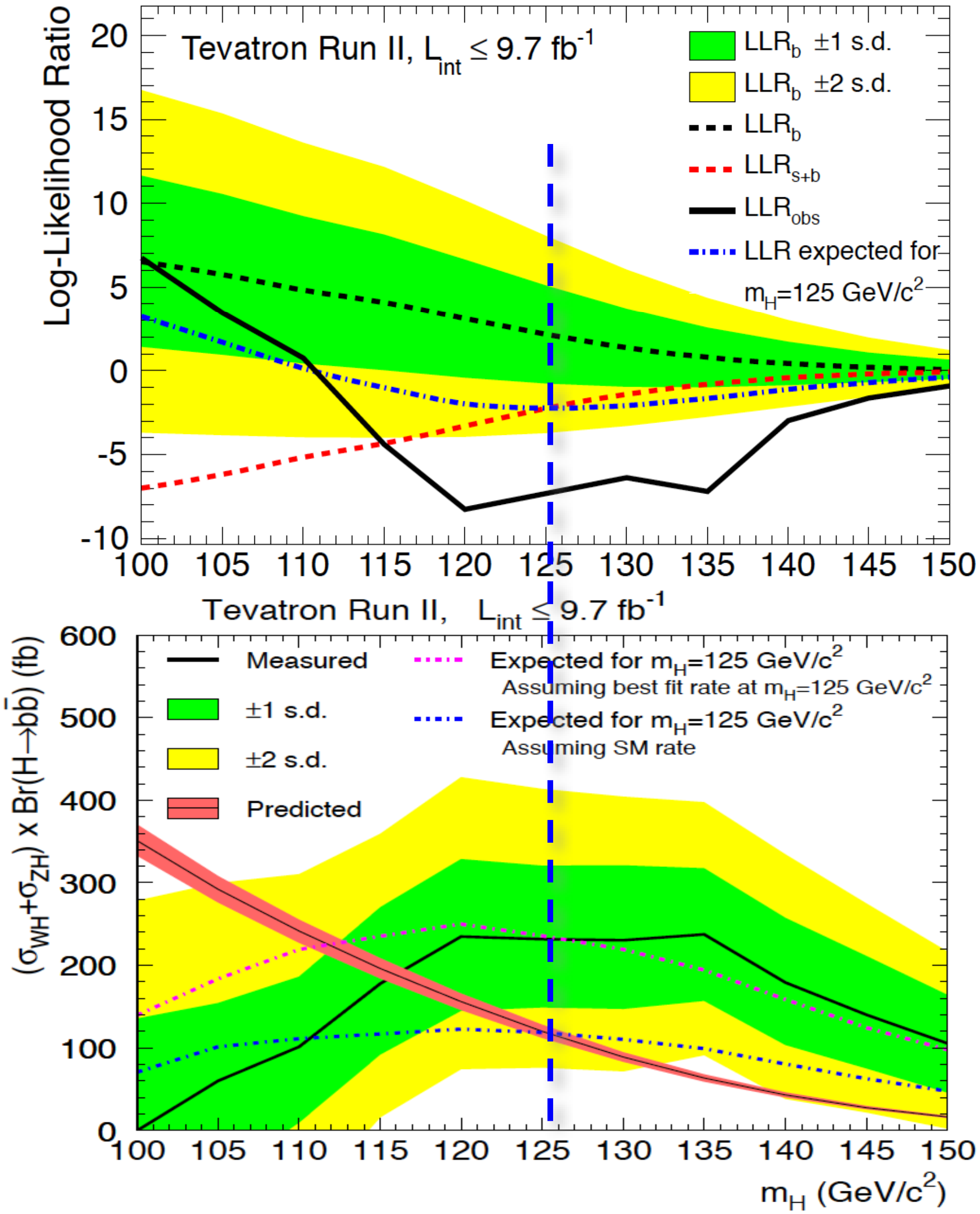
- Local p-value distribution for background-only expectation.
- Minimum Local p-value: 3.3 σ (at m=135GeV)
- Global p-value (LEE=2): **3.1σ**

We interpret these results as evidence for the presence of a new particle, produced in association with a weak vector boson and decaying to a bottom-antibottom quark pair

[Phys. Rev. Lett. **109**, 071804 (2012])

- Local p-value@125: 2.8 σ (no LEE needed)

Tevatron's b-bbar signal rate



- Cannot determine mass precisely, but shape of the excess quite similar to expectation from SM Higgs at 125 GeV
- The amplitude of the excess appears slightly larger.
- Cross section estimate:

$$(\sigma_{WH} + \sigma_{ZH}) \times \mathcal{B}(H \to b\bar{b}) =$$

$$0.23^{+0.09}_{-0.08} \text{ (stat + syst) pb}$$

(insensitive to mass)

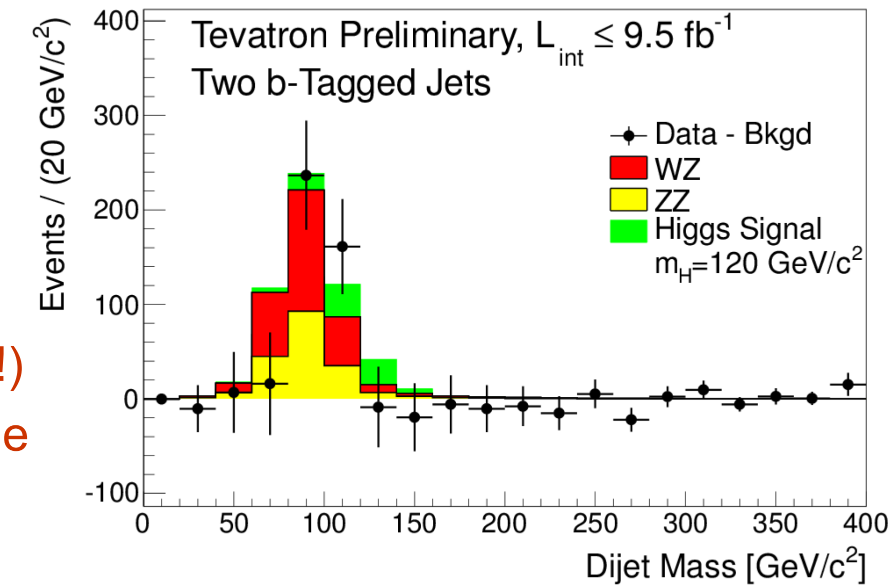
- Compare to SM expectation@125 GeV

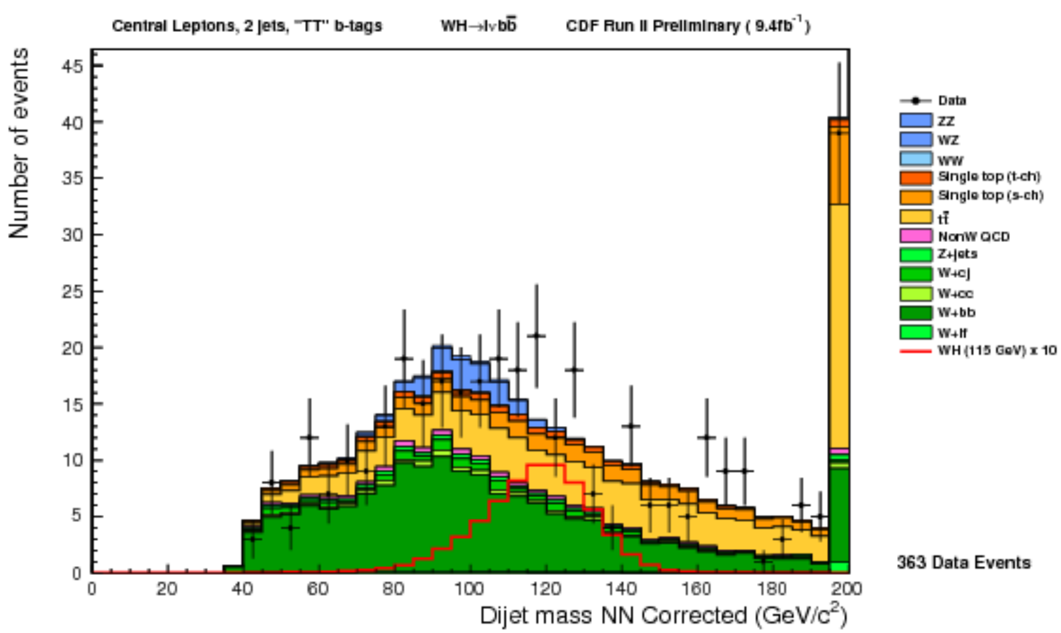
$$0.12 \pm 0.01 \text{ pb}$$

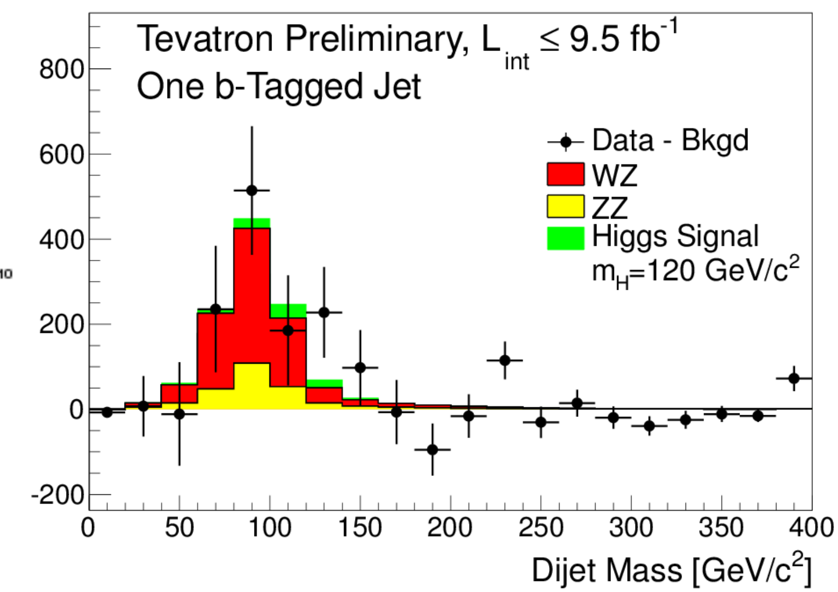
The signal is compatible (1σ) with a SM Higgs @125 GeV

H->bb, straight mass view

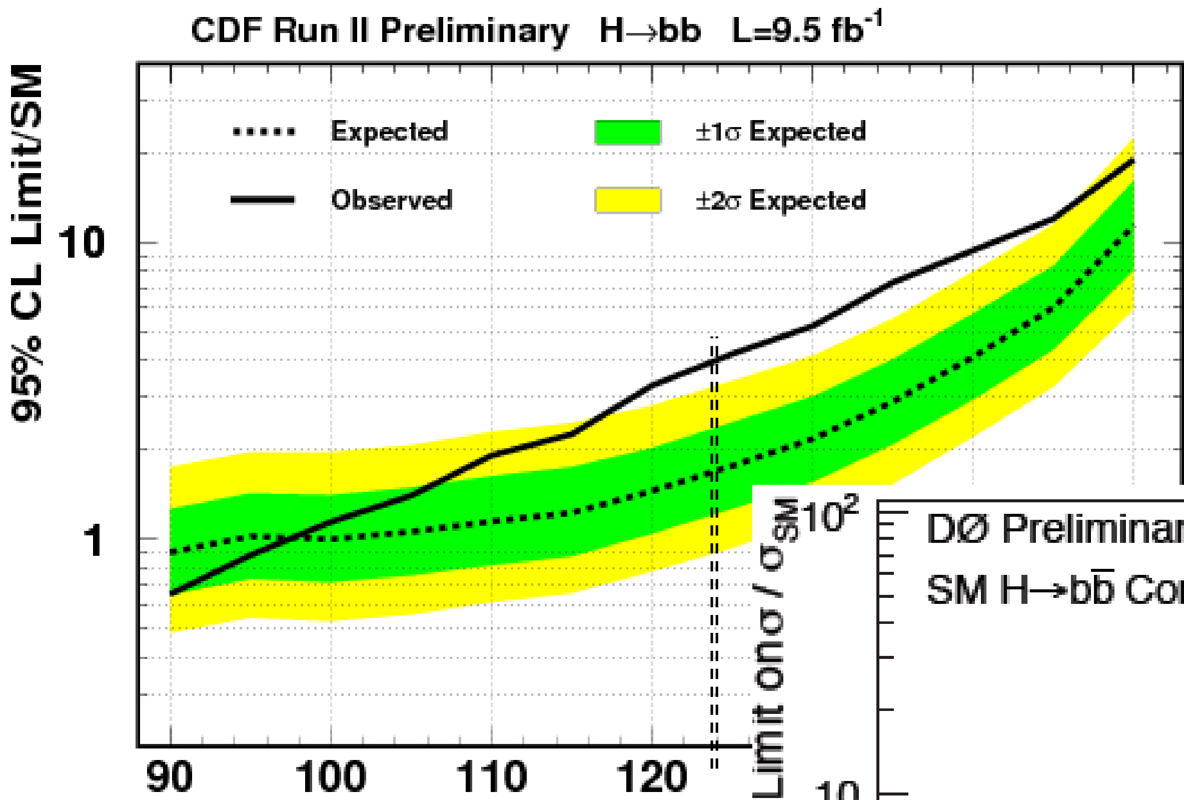
- Simple overlay of $H \rightarrow bb$ signal prediction for the dijet invariant mass (MH = 120 GeV)
  - Data and diboson prediction from Tevatron low-mass WZ/ZZ measurement (important cross-check !)
  - Additional signal statistically compatible





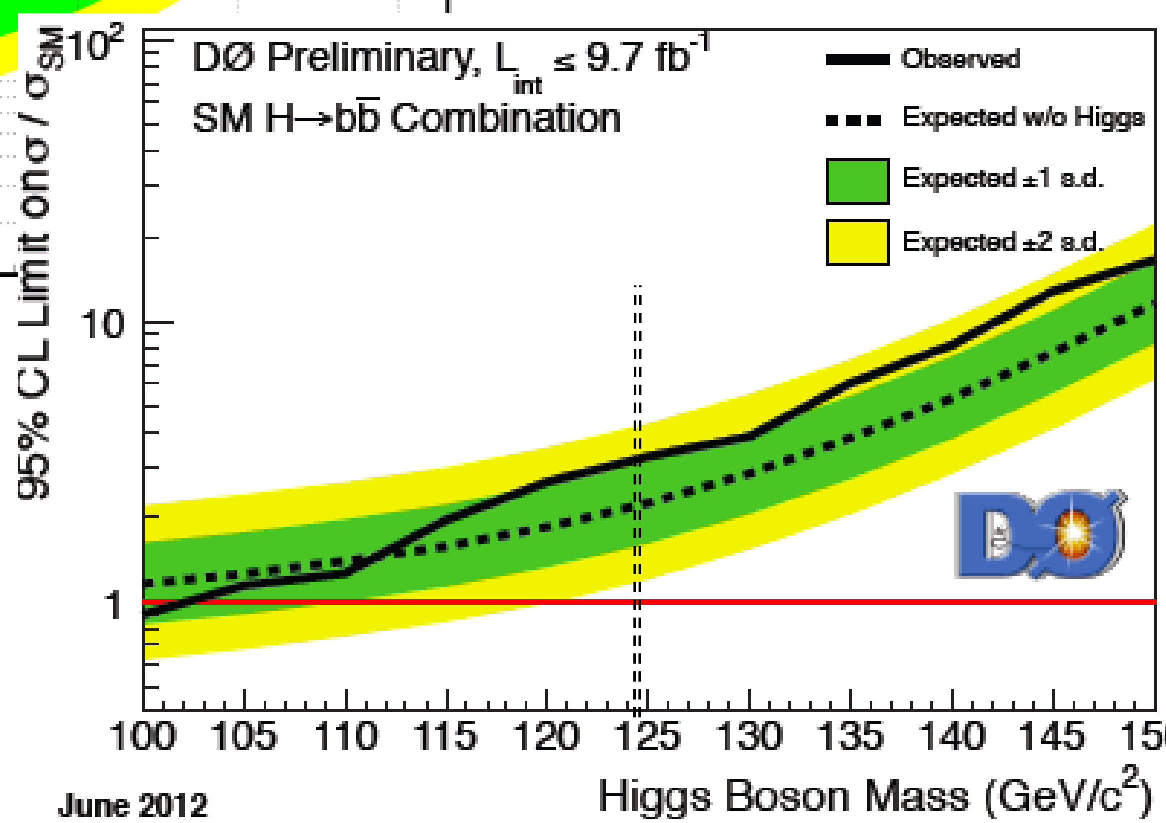


Individual experiments results in bb



CDF Limits m_H =125GeV

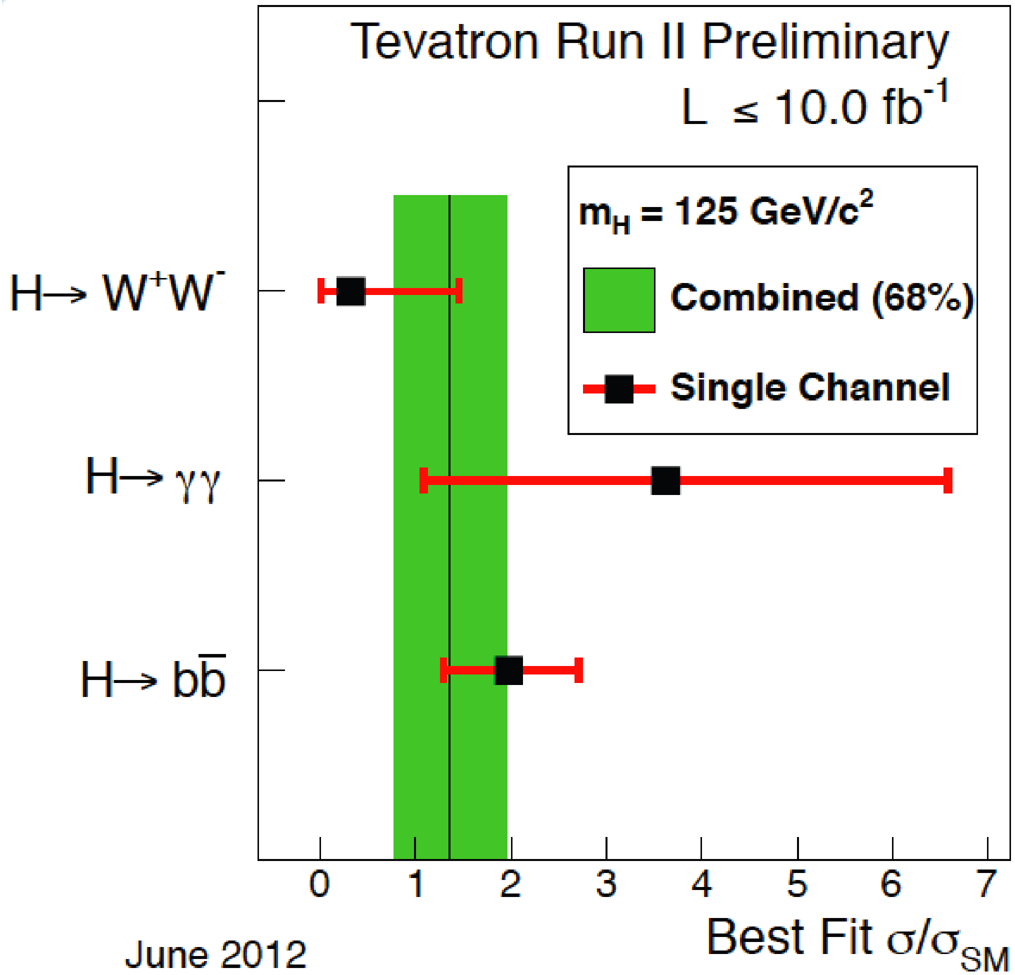
- Observed: 4 × σ_{SM}
- Expected: 1.6 × σ_{SM}



D0 Limits m_H=125 GeV

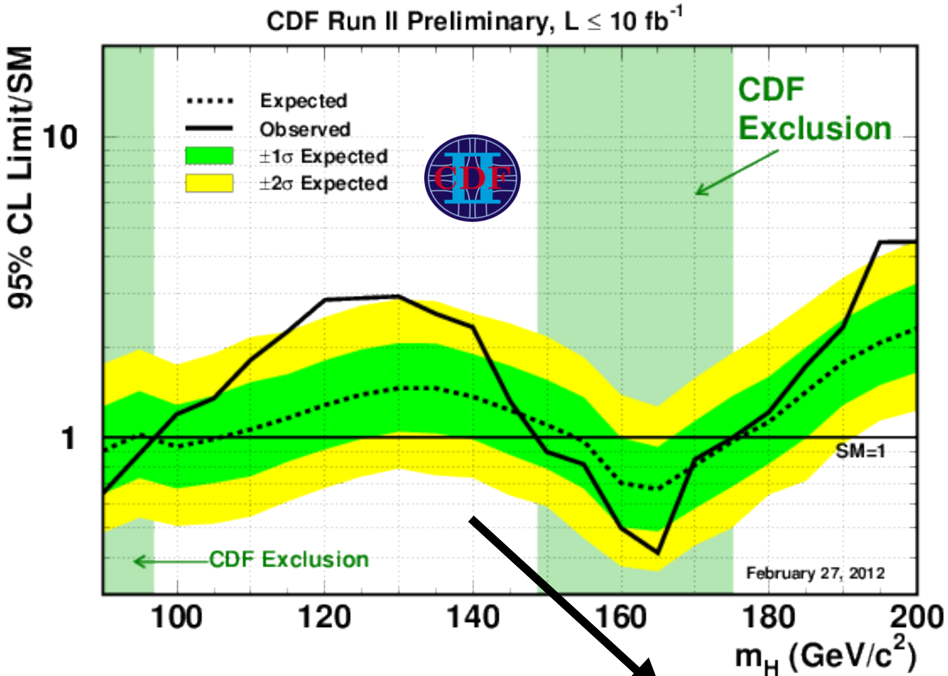
- Observed: 3 × σ_{SM}
- Expected: 2 × σ_{SM}

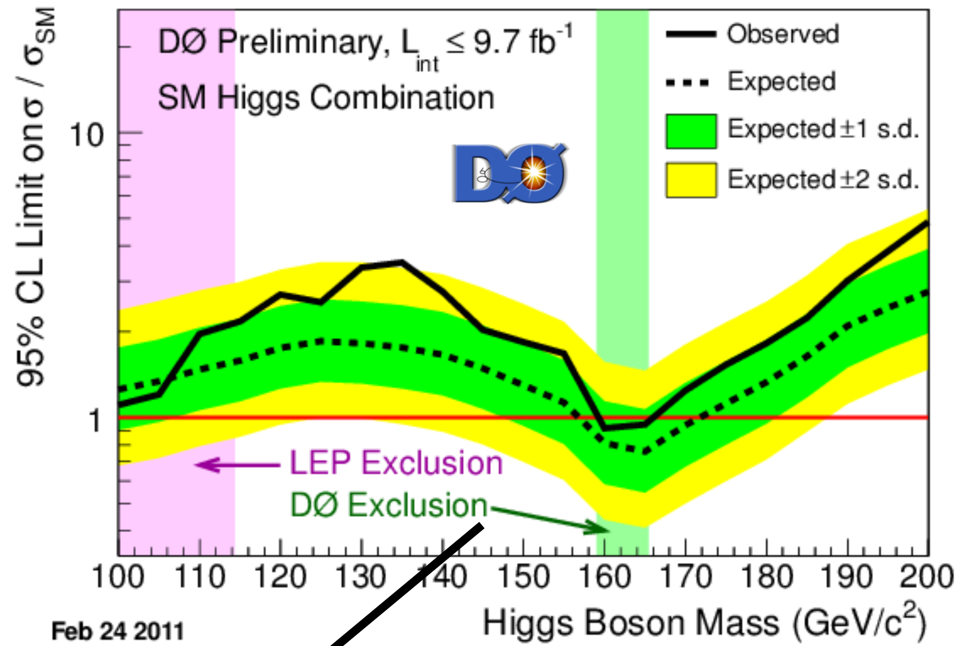
Comparing different Higgs modes

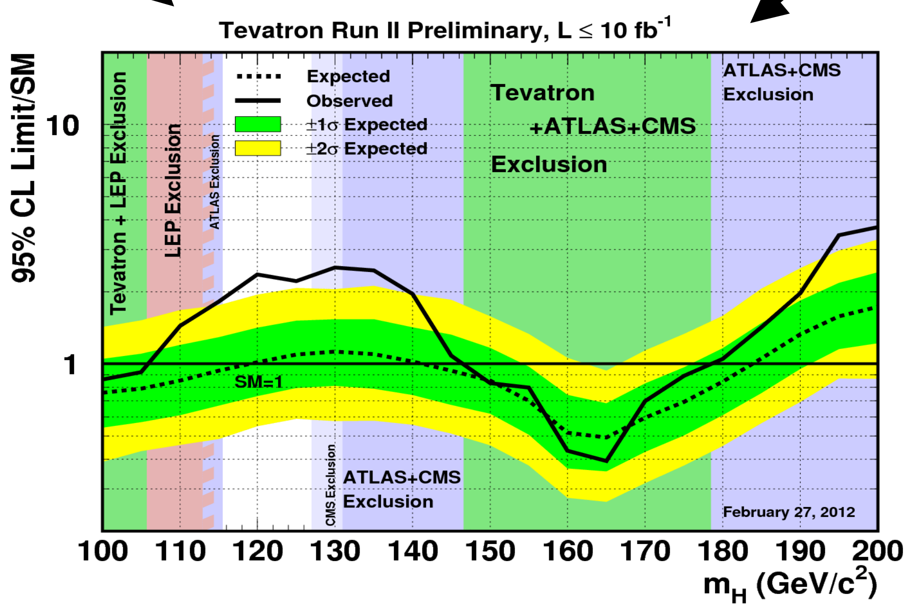


All modes compatible with SM Higgs scenario within errors

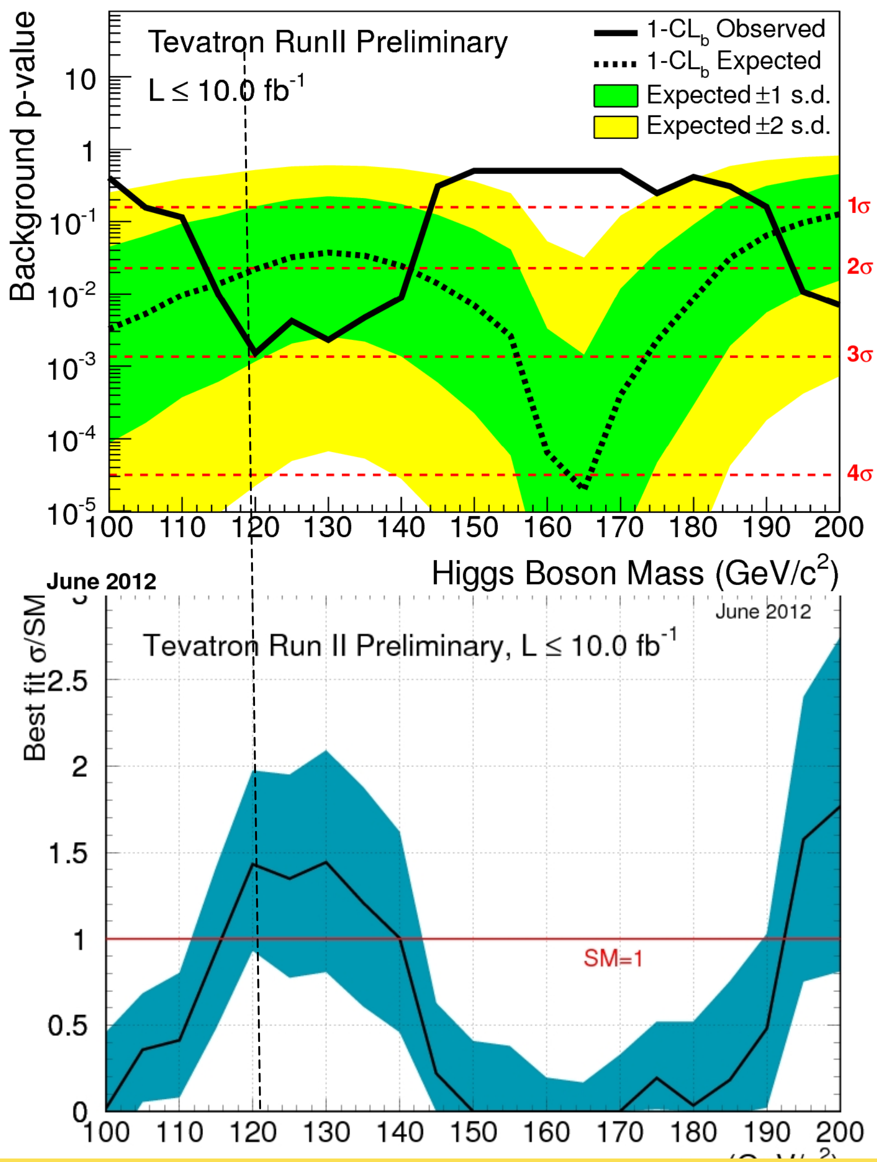
All channels combined







Full-combination p-values

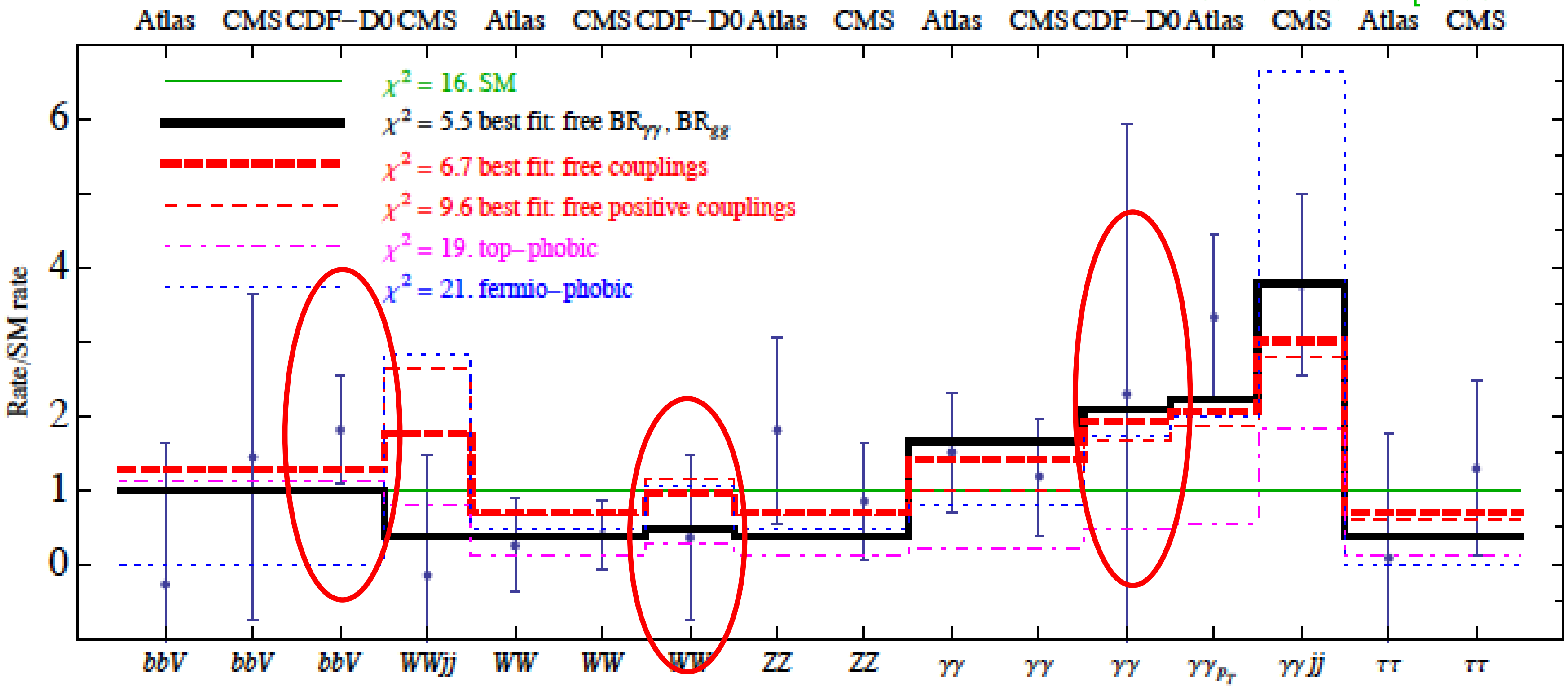


- Minimum Local p-value:
  3.0 σ
  (at m=120GeV)
- Global p-value (LEE=4):
  2.5σ
- Local p-value@125 (no LEE):
  2.8 σ
  [arXiv:1207.0449 [hep-ex]]

Minumum p-value corresponds to SM-predicted rates

Tevatron in the Higgs coupling game

Giardino et al. [1203.4254]



- After the Higgs mass has been measured, the question is the couplings
- Above is an example of fit produced just after spring results (based on just limit information).
- Tevatron giving some important inputs. Dominates b-bbar information

Anything more on the Higgs ?

- Most of the improvements to the analyses happened recently - latest results ~20% better on the same sample
- The history has been one of continuing improvements - there may still be some additional gain to be made.

- A personal favorite: constraining the invisible Higgs width
  - This may be possible at the Tevatron in the ZH ->ll + MET
  - Both D0 and CDF have reconstructed ZZ->ll+$\nu\nu$
    [CDF 6fb-1: PRL 108, 101801 (2012)]
  - sigma*BR(ZZ->ll$\nu\nu$) ~240fb, while sigma(ZH) is ~80fb
    might be within the sensitivity of a specifically optimized analysis.

What else can we do to understand the Fermi scale ?

What else can we do to understand the Fermi scale ?

- We live in a different era of physics than few months ago.

- No direct evidence for new physics at LHC

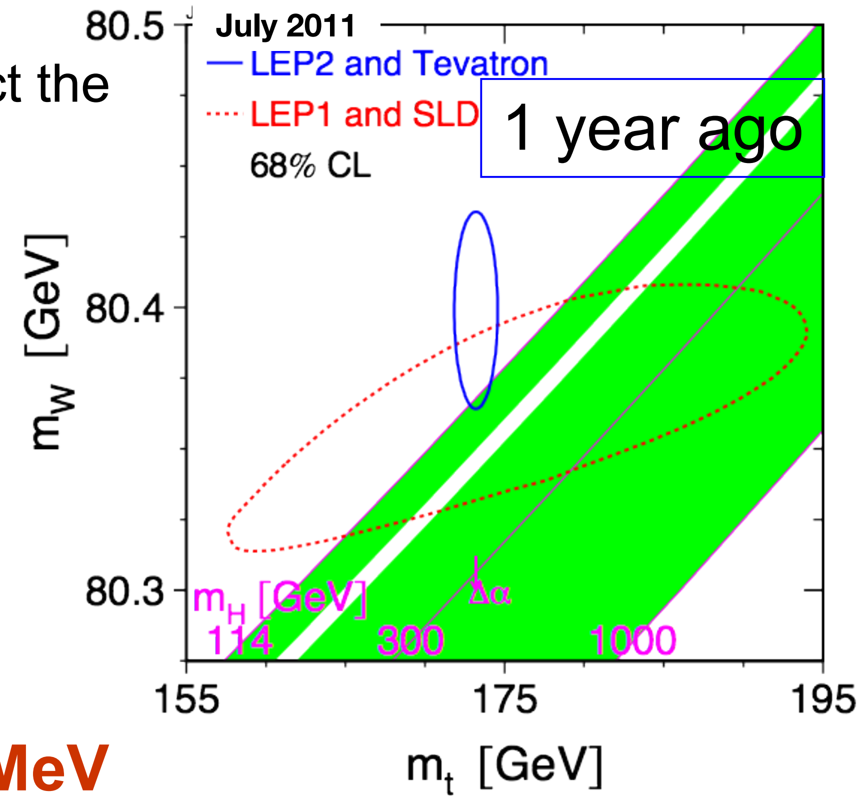
- Finding the Higgs (candidate) mass has turned attention from "Higgs search" to "Higgs couplings".
  - Hoping to find out what else is there, if any
  - Will keep us busy for a while.

- There is also another interesting shift of perspective

Impact of mH on EWK tests

- We have been using **EWK data** to predict the **Higgs mass**.
  - Tevatron's Mtop, mW crucial inputs
  - Dependence on log(mH) required high precision to estimate mH precisely

$$M_H = 94^{+25}_{-22}\ \mathrm{GeV}\ ,$$



- Today, use the **Higgs mass** to predict the **W boson mass**.
  - Dependence on log(mH) means: from mH we can predict mW precisely
  - Previous SM prediction of mW: **σ =28 MeV**

$$M_W = 80.3593 \pm 0.0056_{m_t} \pm 0.0026_{M_Z} \pm 0.0018_{\Delta\alpha_{\mathrm{had}}}$$

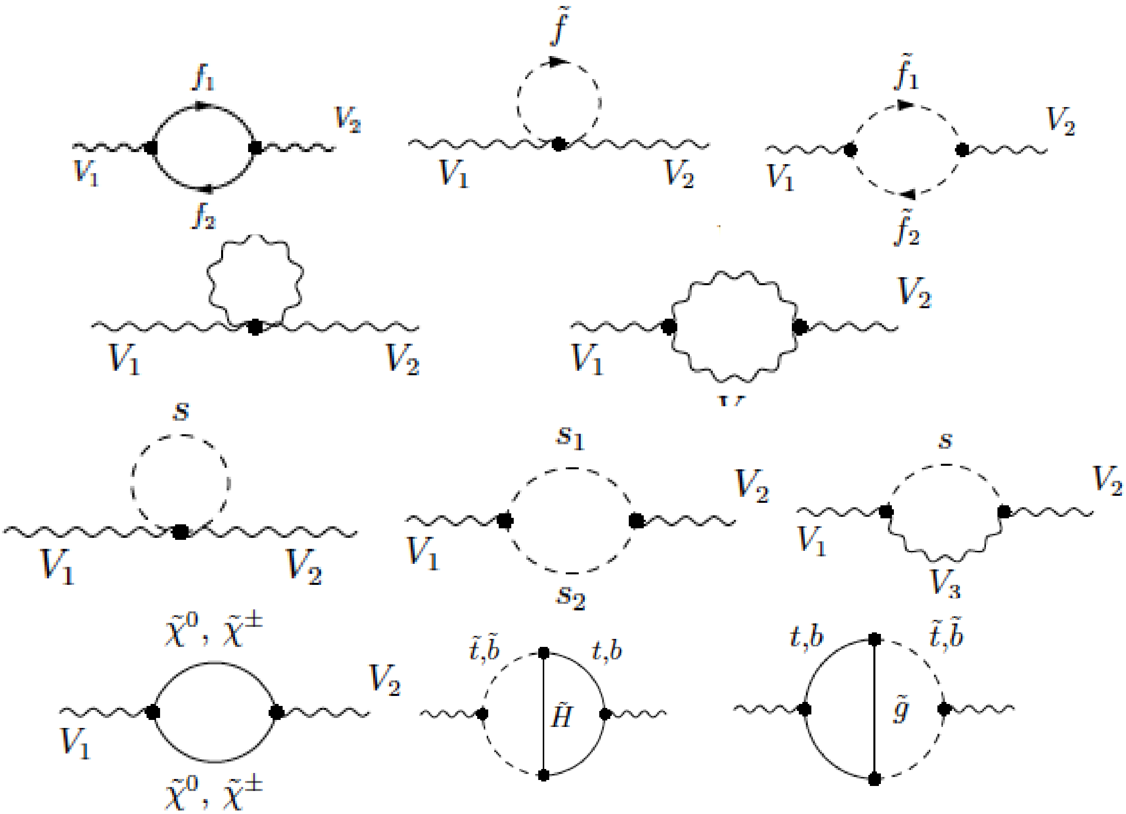
$$\pm 0.0017_{\alpha_S} \pm 0.0002_{M_H} \pm 0.0040_{\mathrm{theo}}\ ,$$

$$= 80.359 \pm 0.011_{\mathrm{tot}}\ ,$$ (or in quadrature: 0.008)

[GFitter, arXiv:1209.2716 [hep-ex]]

Possible non-SM contributions to mW

- *m_W* can be expressed as: $$m_W^2 = \frac{\pi\alpha_{em}}{\sqrt{2}G_F \sin^2\theta_W (1 - \Delta r)}$$
- Where radiative corrections Δ*r* = Δ*r(SM)* + Δ*r(NP)*, where Δ*r(NP)* could come from many non-SM processes



generic new fermions/sfermions

gauge bosons

New Higgs/ Goldstone bosons

Chargino/Neutralino/ Higgsino, and others…

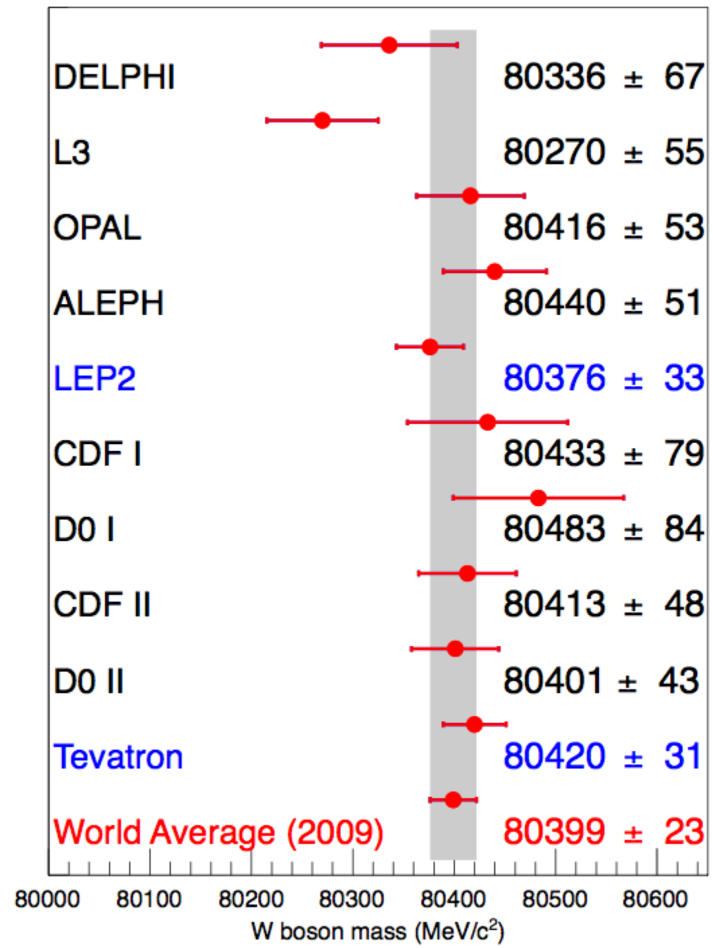
After knowing mH, mW is much more sensitive to detect Δ*r(NP)*≠ *0*

Bo Jayatilaka

M_W experimental status few months ago

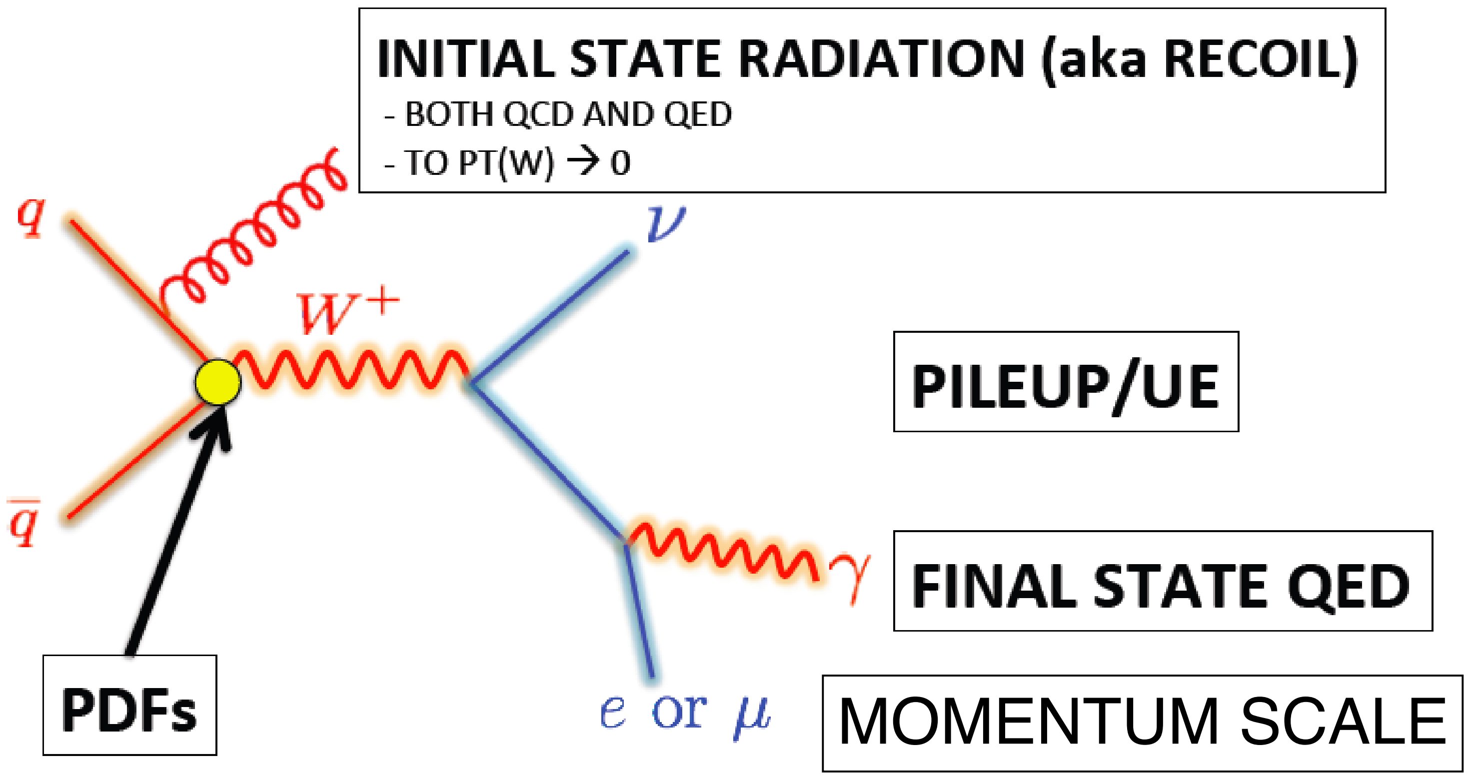
- Best measurements from Tevatron:
  - DØ M_W=80401±43 MeV [1 fb^{-1}, *e*]
  - CDF M_W=80413±48 MeV [200 pb^{-1}, *e*+*μ*]

- **WA: σ_{exp} =23 MeV**
- Little motivation to improve it when σ_{th} was 28 MeV
- **NB** Mtop is known well enough already (impact ~5 Mev)



The recent Tevatron measurement of mW is particularly timely, bringing the WA experimental resolution down

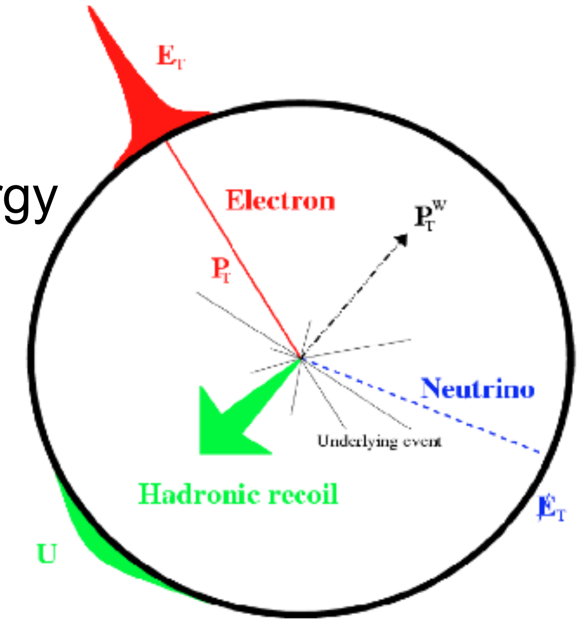
Factors affecting mW measurement



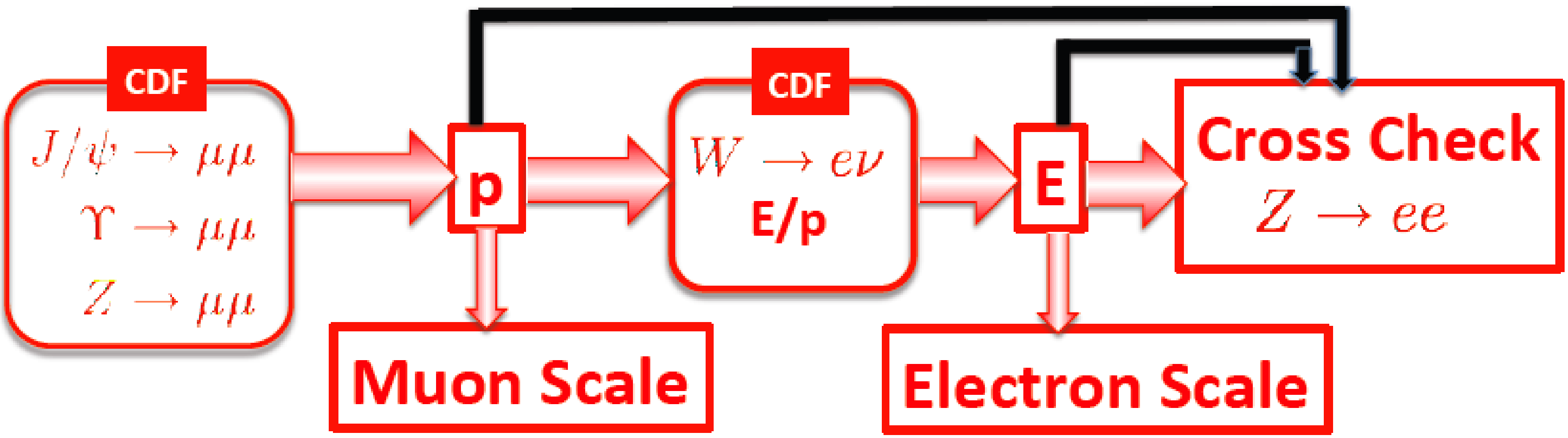
- Not just statistics: CDF 0.2 → 2.2fb-1 DZero 1.0 → 4.3fb-1
- Each physics factor must be modeled to better than ~5 MeV
- Similarly for detector response

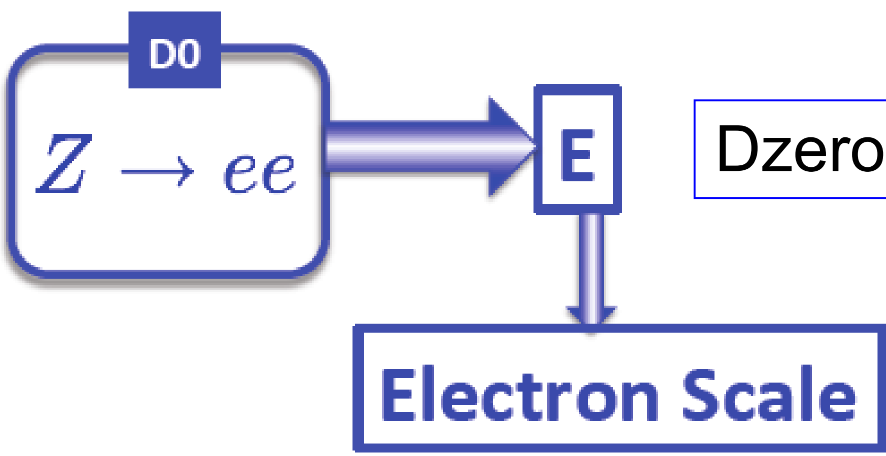
How to achieve high precision

- Start with clean, low-background events
  - i.e., no taus, no hadronic decays
- Lepton pT carries most information
  - Precision achieved: 0.01%
- Hadronic recoil affects inference of neutrino energy
  - Calibrate to ~0.5%
  - Can reduce impact by requiring pT(W) << MW
- Need:
  - Accurate theoretical model
    - Including boson pT model and QED radiation
  - Tunable fast simulation
    - Parameterized detector description for study of systematic effects
  - Large data samples of well-measured states
    - Various dimuon resonances
    - Z boson



Energy scale calibration

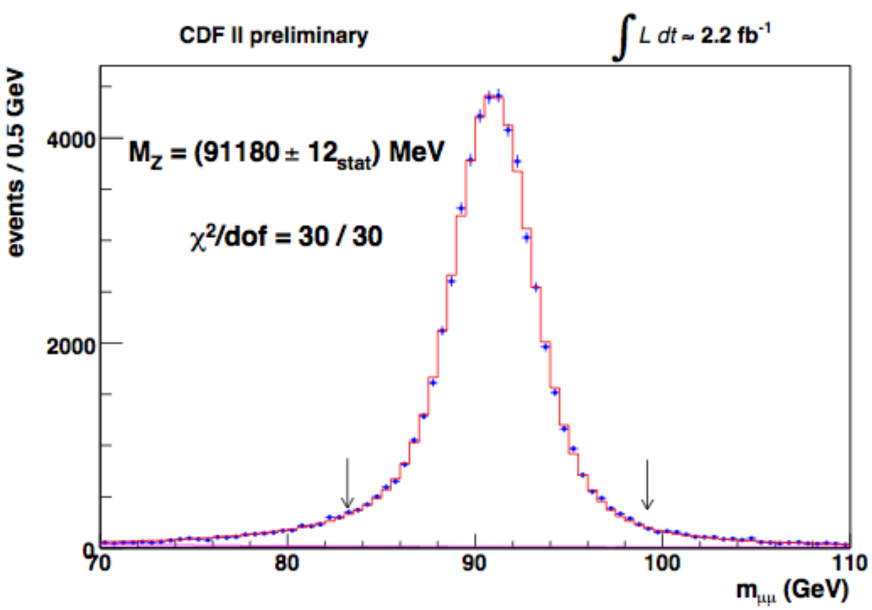


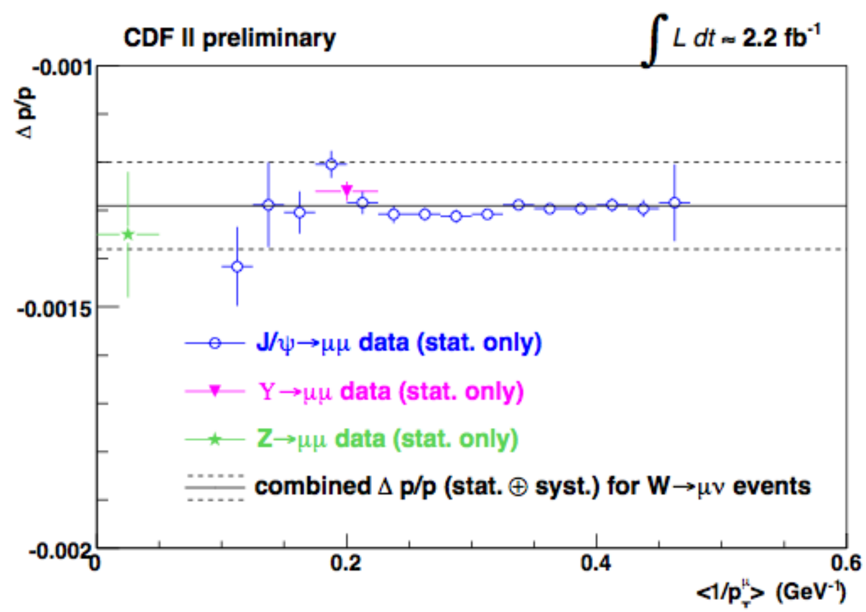


Dzero effectively measures mW/mZ

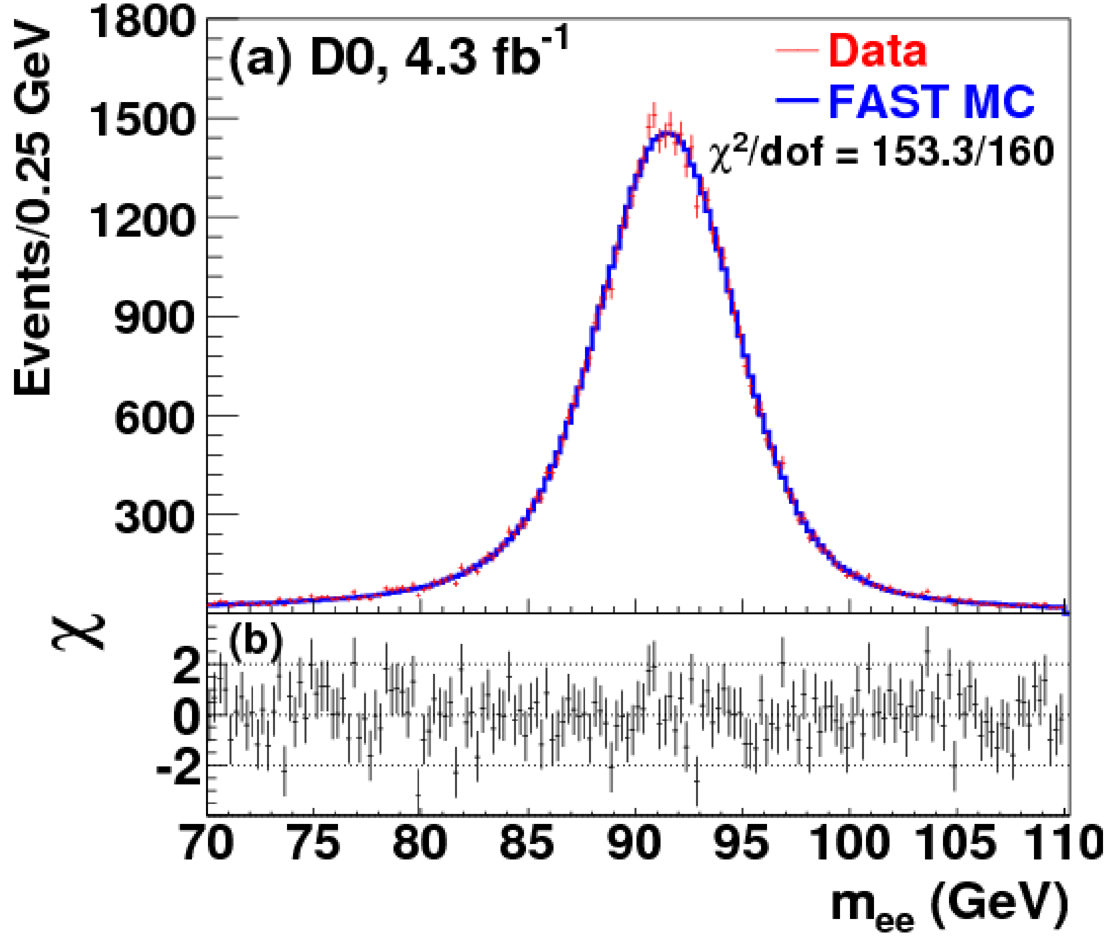
Muon Z mass and track momentum scale

- Perform **independent** measurement of *Z* mass using tuned momentum scale
  - $M_Z = 91180 \pm 12_{stat} \pm 9_{p\text{-}scale} \pm 5_{QED} \pm 2_{alignment} = 91180 \pm 16$ MeV
  - Excellent agreement with LEP average (91188±2 MeV)
- Add Z data as final calibration point for momentum scale
  - **$\Delta p/p_{final} = (-1.29 \pm 0.07_{stat} \pm 0.05_{QED} \pm 0.02_{align}) \times 10^{-3}$**
  - Apply scale to *W* muons and *E/p* calibration
  - Systematic uncertainty $\Delta M_W = 7$ MeV



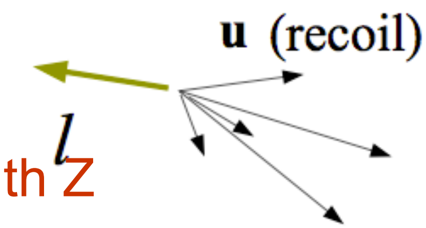


Electron Z mass (Dzero)

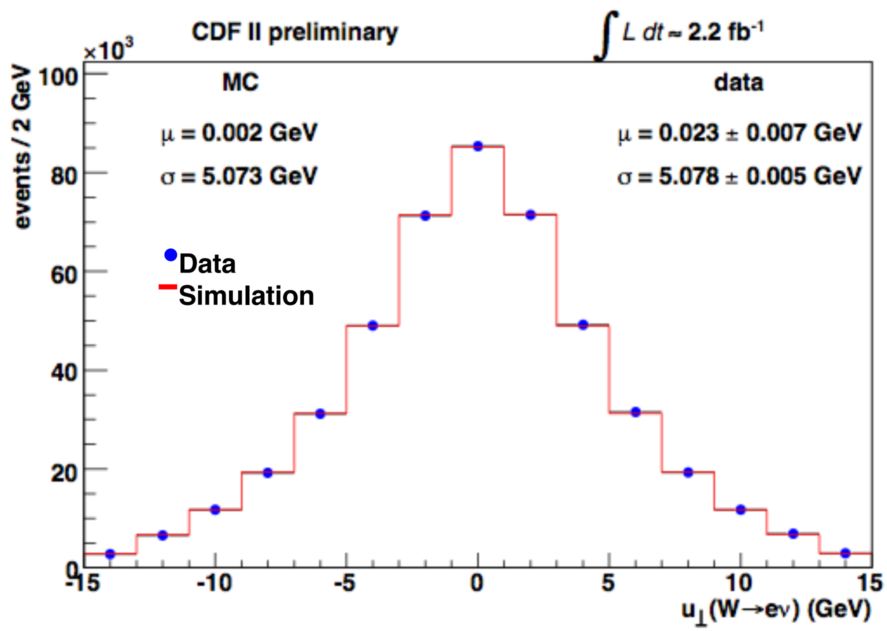


- Tuned to PDG by construction
- Yields scale uncertainty of 17 MeV

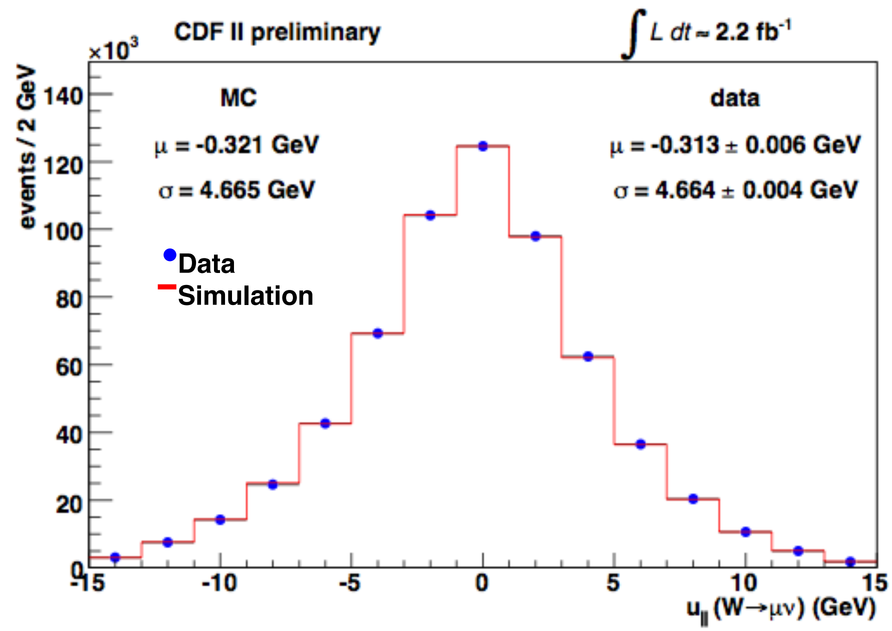
Recoil model validation



- Test recoil model with W events
  - Compare measured recoil in data to model tuned with Z

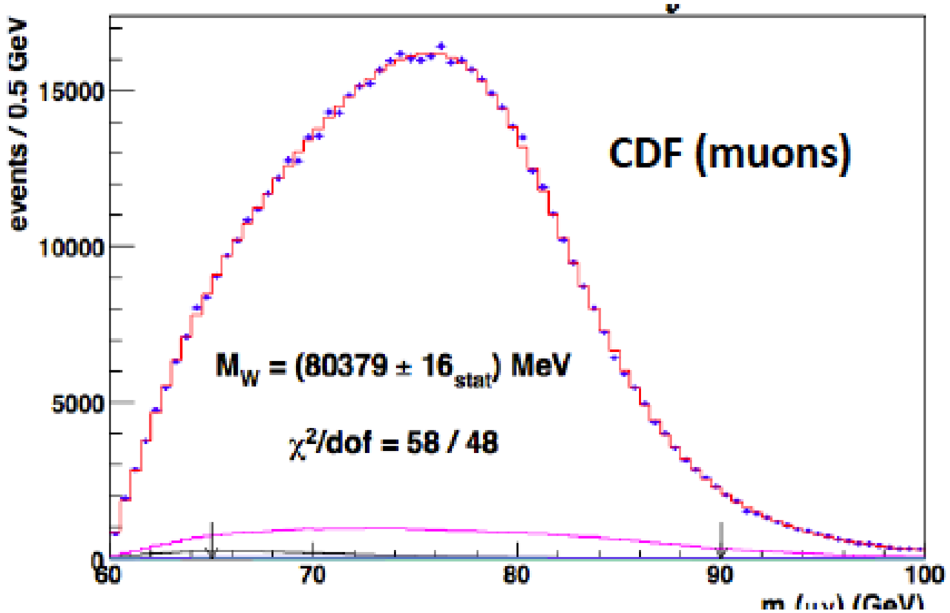


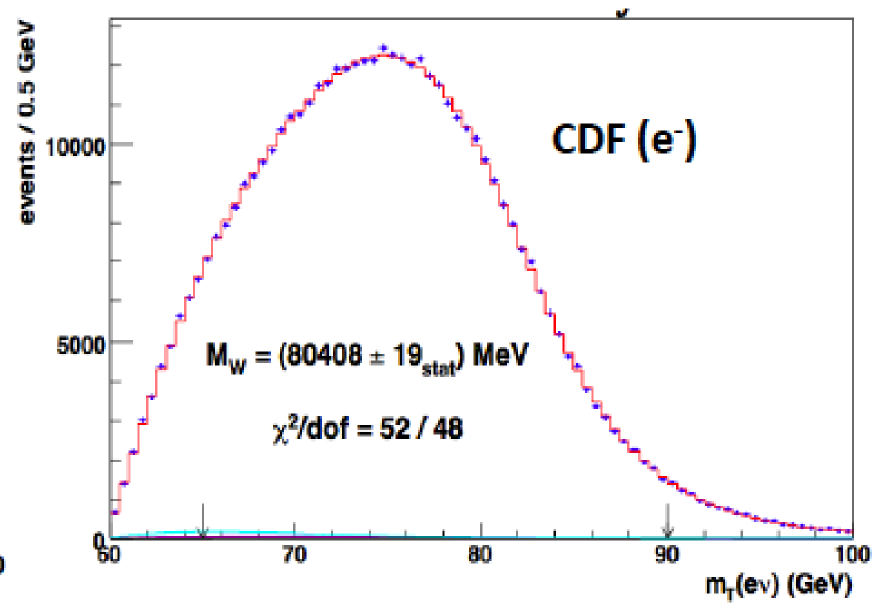
Recoil projection perpendicular to lepton

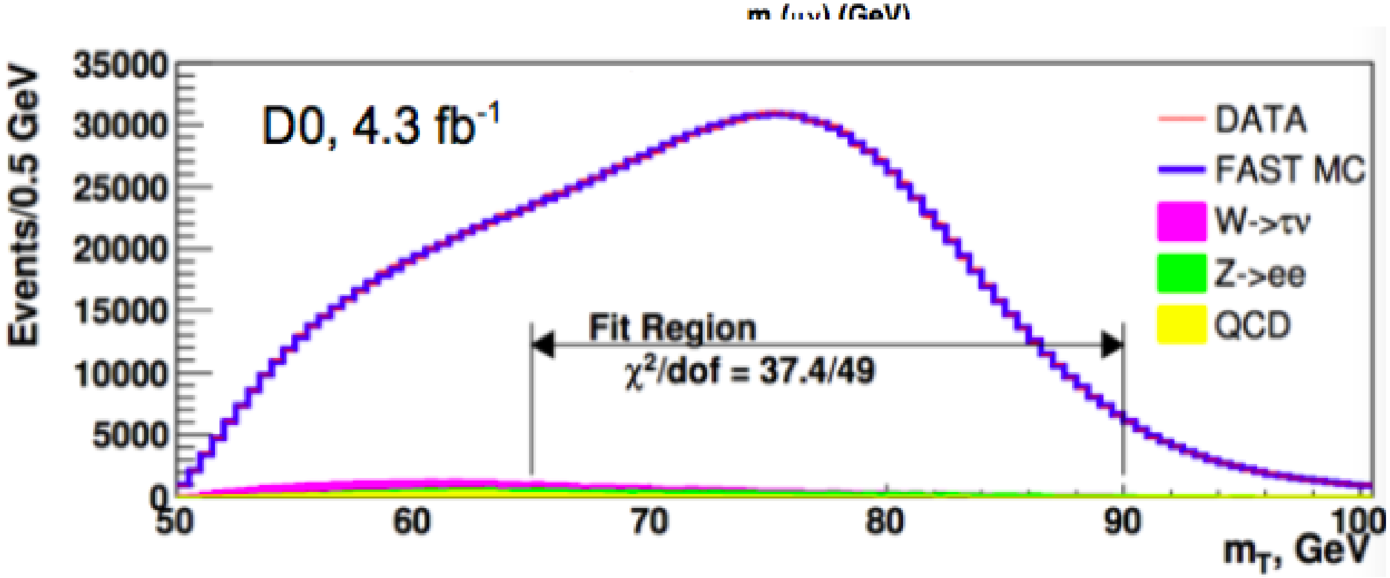


Recoil projection in direction of lepton

Transverse mass distributions

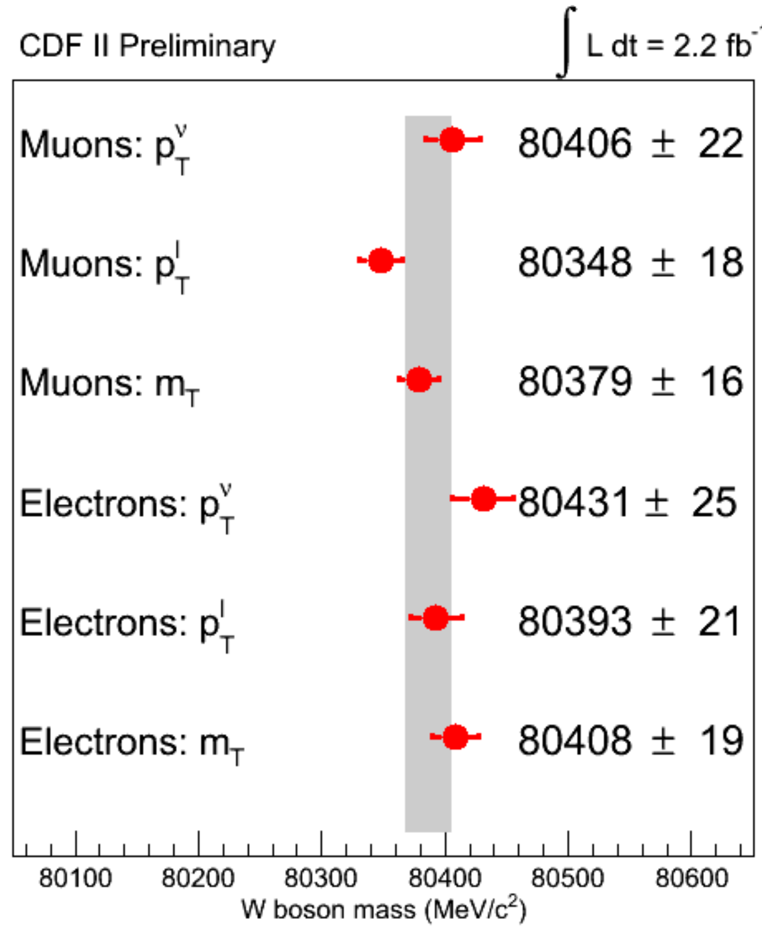




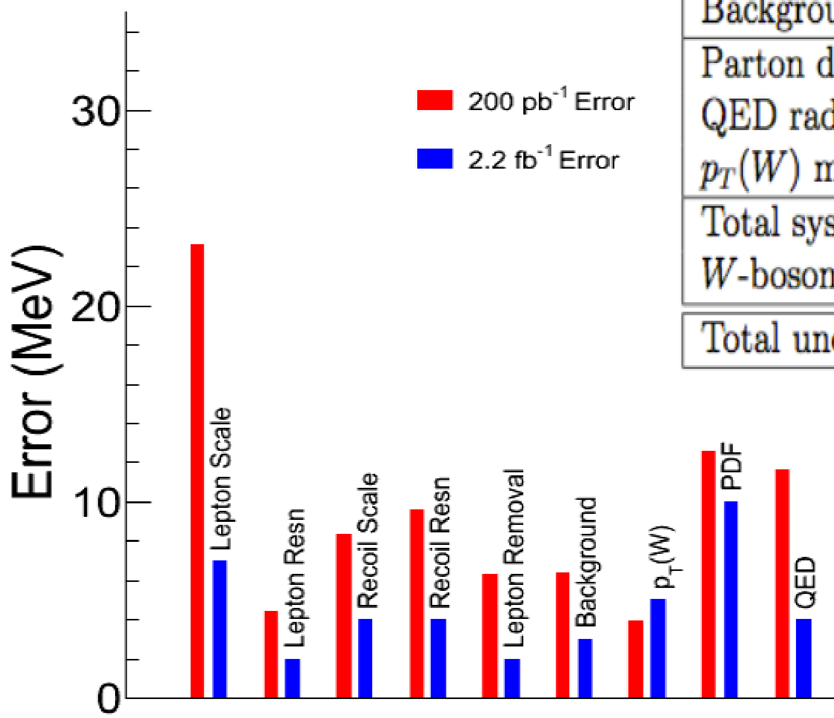


Multiple consistency checks

- Multiple measurements methods allow several internal checks.
- D0 has 3, CDF has 6
- Performed **blind:** unknown overall shift until the final results is approved.
- Data turn out to be statistically consistent
- Combined with BLUE procedure to yield final result



Summary of uncertainties



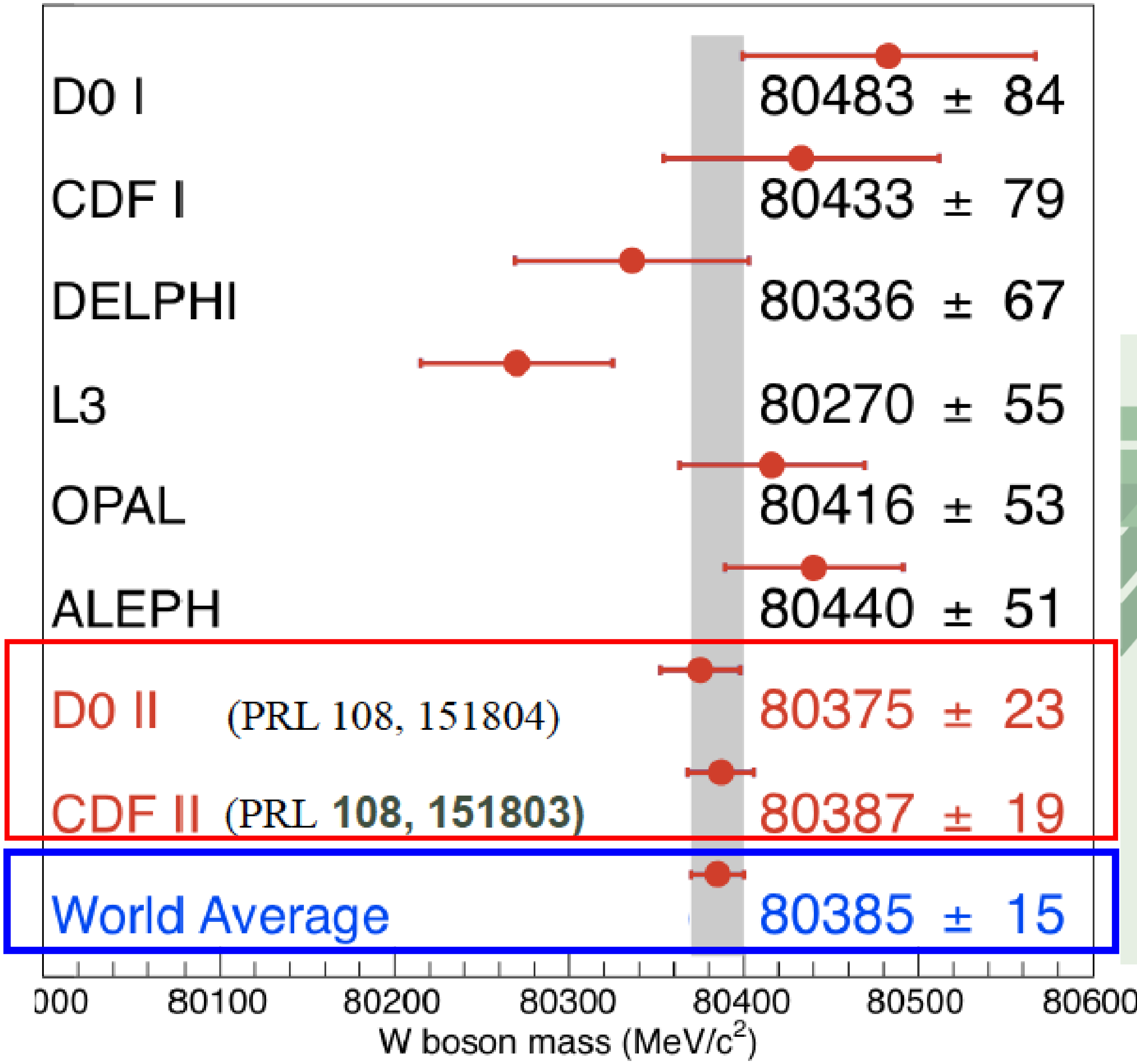
Uncertainty	D0	CDF
Lepton energy scale/resn/modelling	17	7
Hadronic recoil energy scale and resolution	5	6
Backgrounds	2	3
Parton distributions	11	10
QED radiation	7	4
$p_T(W)$ model	2	5
Total systematic uncertainty	22	15
W-boson statistics	13	12
Total uncertainty	26 MeV	19 MeV

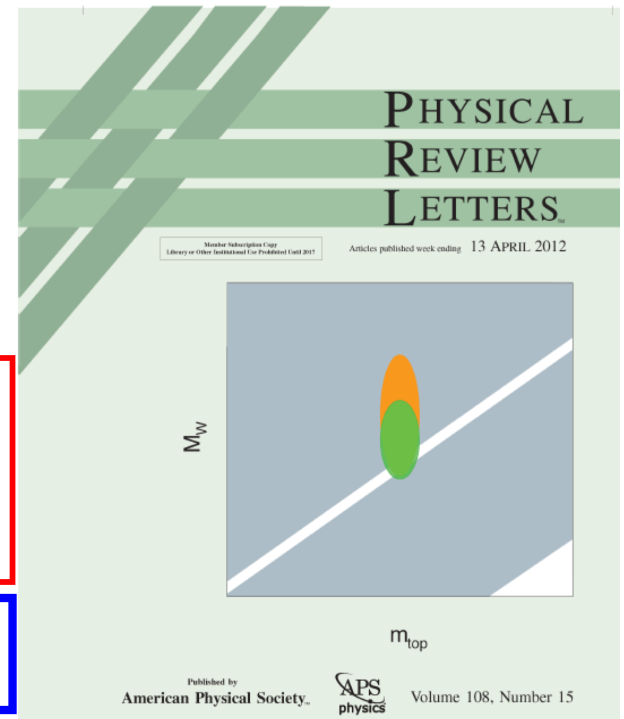
Largely stat. in origin → **10 MeV**

Largely theory in origin → **12 MeV**

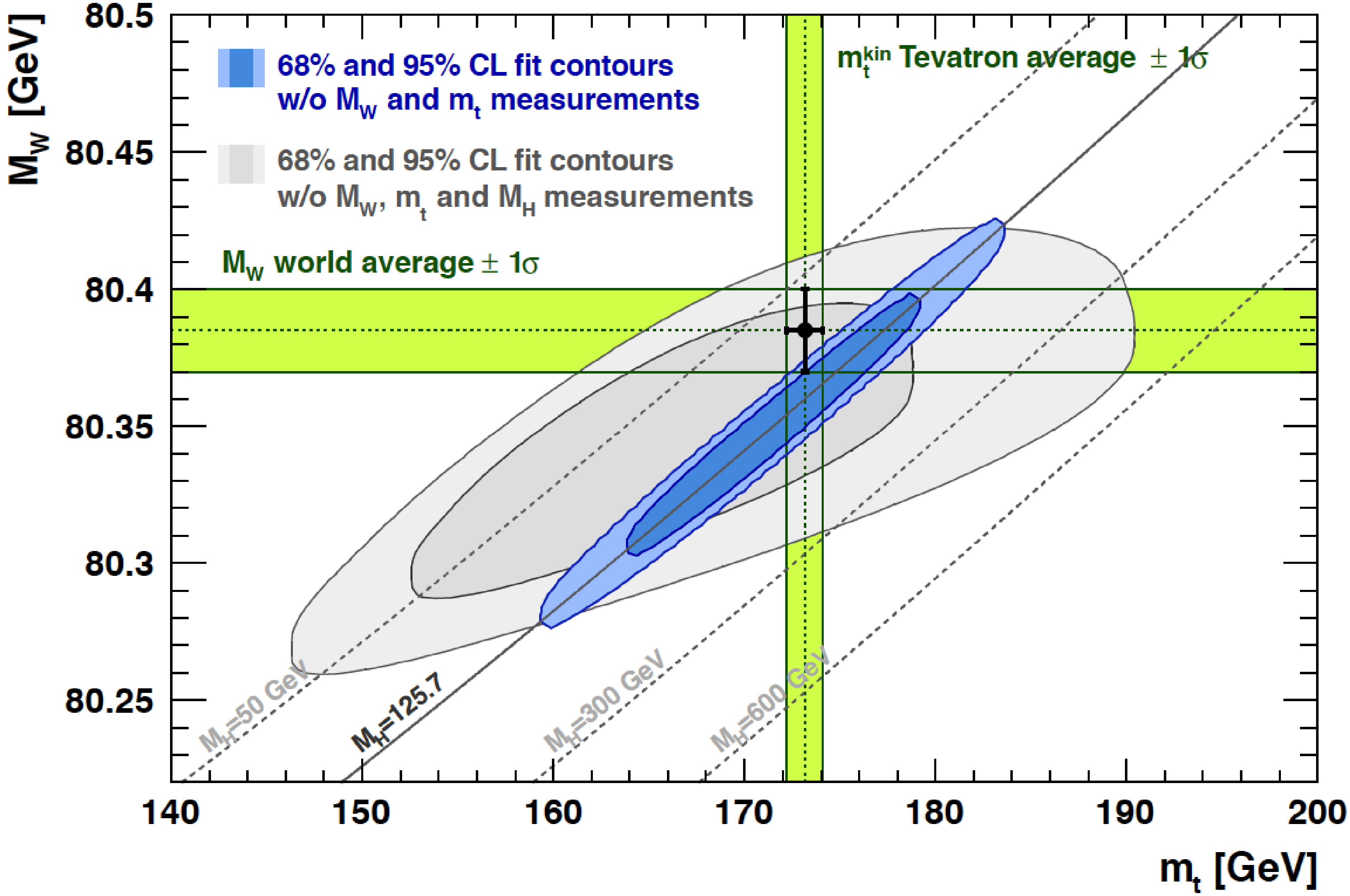
- Successfully reduced many sources of uncertainty

Final Results



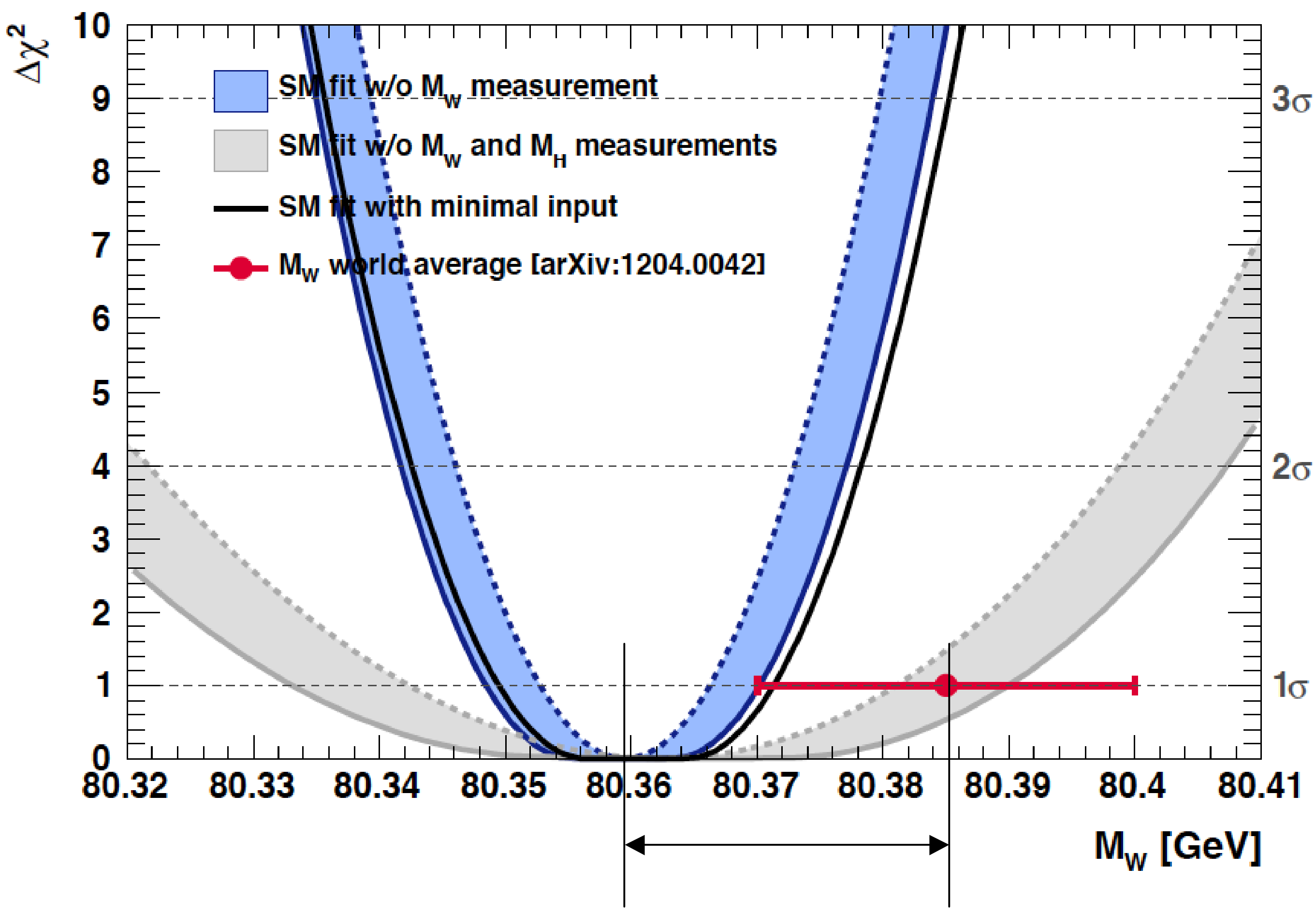


mW, mt, mH



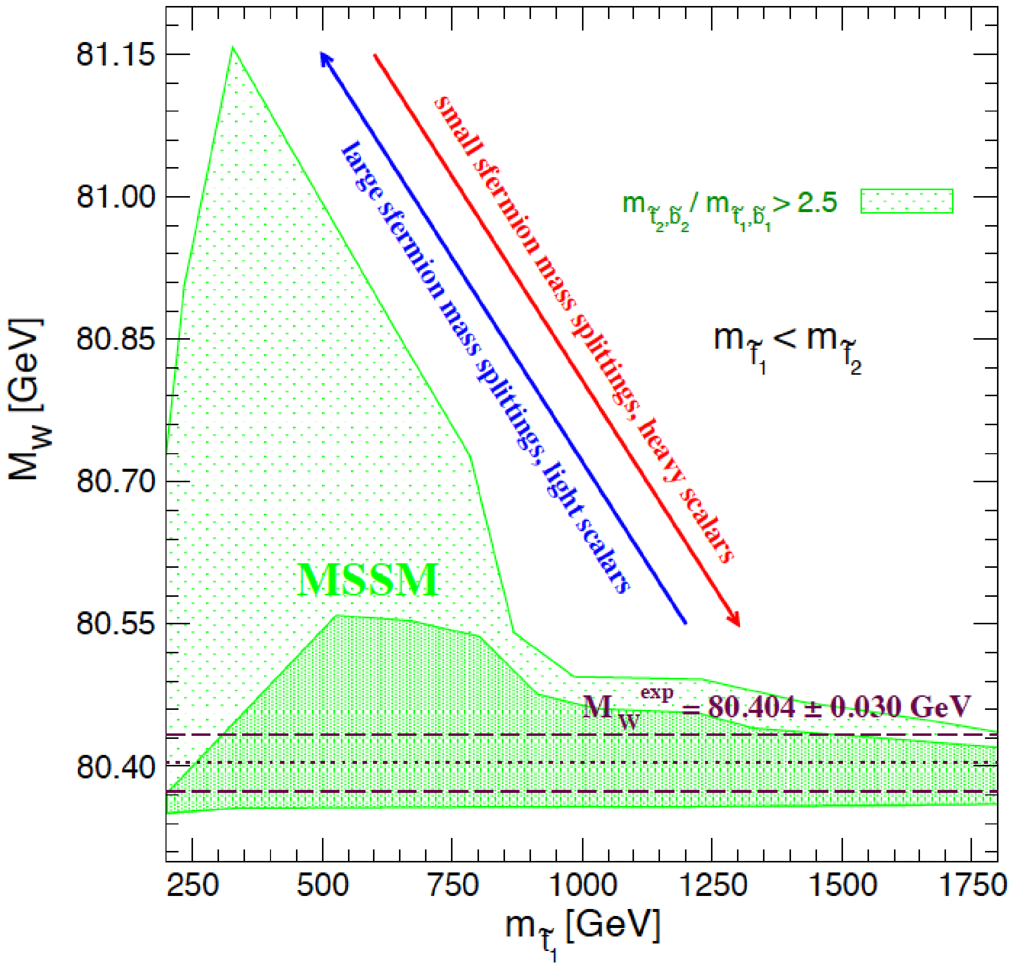
68% and 95% CL fit contours
w/o M_W and m_t measurements
68% and 95% CL fit contours
w/o M_W, m_t and M_H measurements
m_t^{kin} Tevatron average ± 1σ
M_W world average ± 1σ
M_H=50 GeV
M_H=125.7
M_H=300 GeV
M_H=600 GeV
M_W [GeV]
80.5
80.45
80.4
80.35
80.3
80.25
140
150
160
170
180
190
200
m_t [GeV]

mW, predicted vs measured



- $\Delta m(W) = 0.026 \pm 0.017$ GeV
- Any new physics effect must be compatible with this result (now tighter by a factor of 2 !)

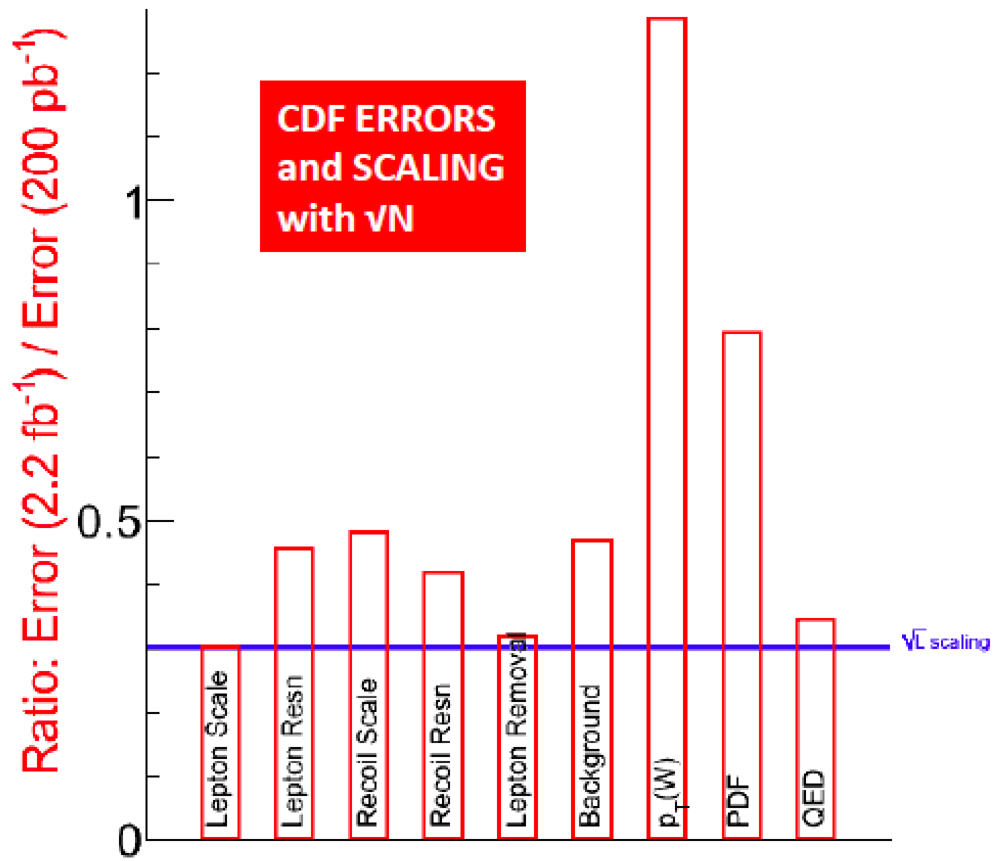
Example of new physics sensitivity



[JHEP 0608:052,2006]

Could you do even better ?

- D0 has 2x data, CDF 4x
- Managed to reduce most uncertainties by ~Sqrt(L)
  - most notably CDF: 10x jump
- Will need new ideas for Pt(W),QED, and PDFs (new external constraints?)
- Work has already started towards a 10fb-1 analysis: aiming at 10MeV resolution



Conclusion

- Tevatron found evidence for production of a state compatible with SM Higgs and decaying into b pairs
- This and other measurements support the idea that the boson is a SM boson and provide info for couplings
- The measurements of the Higgs mass has increased sensitivity of mW in probing NP effects
- The latest mW from the Tevatron has strongly improved the precision and it is now 2x constraining

- Further digging into Tev data may still yield some valuable physics output on Higgs couplings, and precision EWK

- Thank you for your attention !