Higgs Results from the Tevatron

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On behalf of CDF and DZero

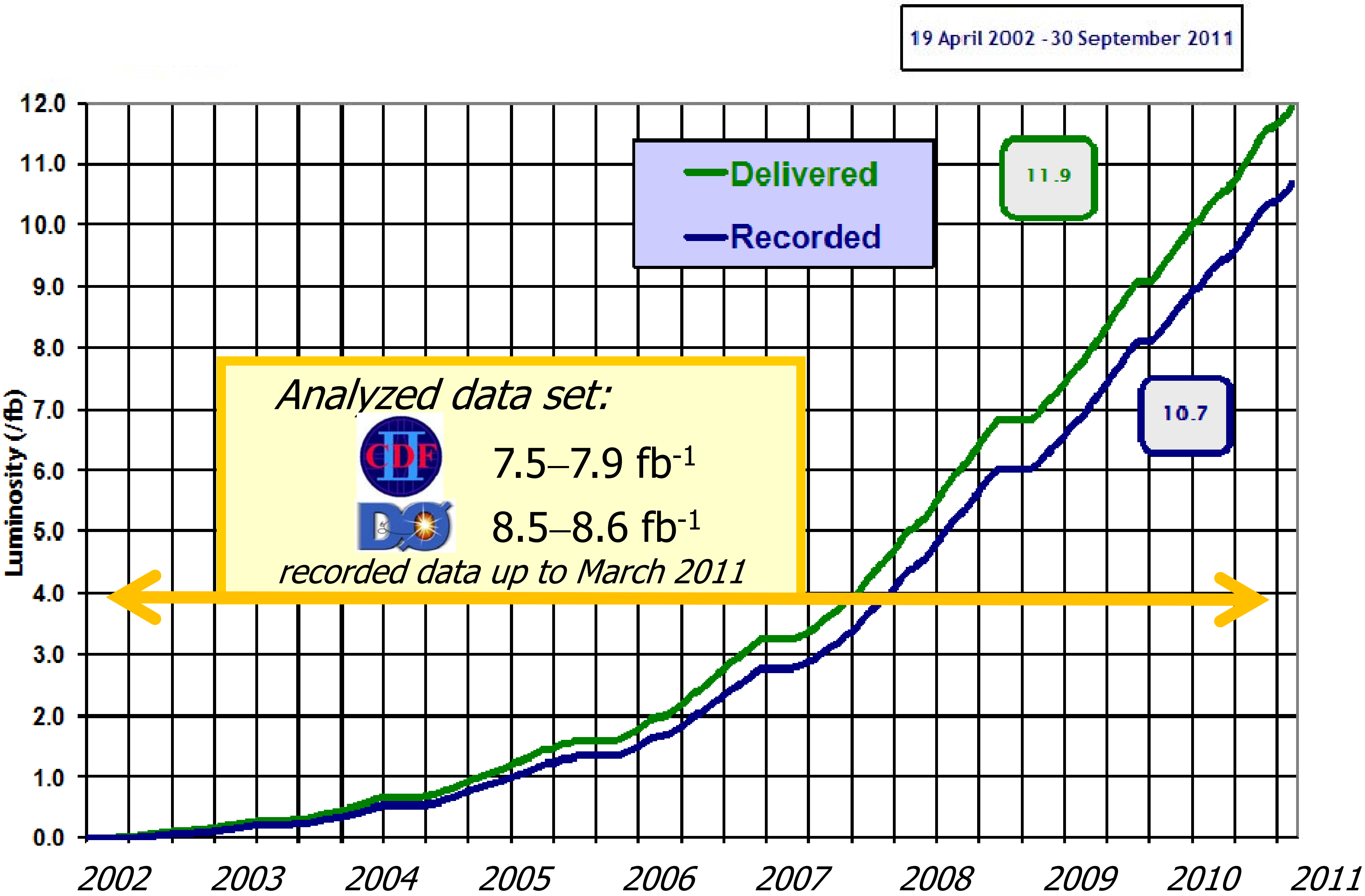
January 9th 2012

Thanks to all CDF & DZero colleagues

Outline

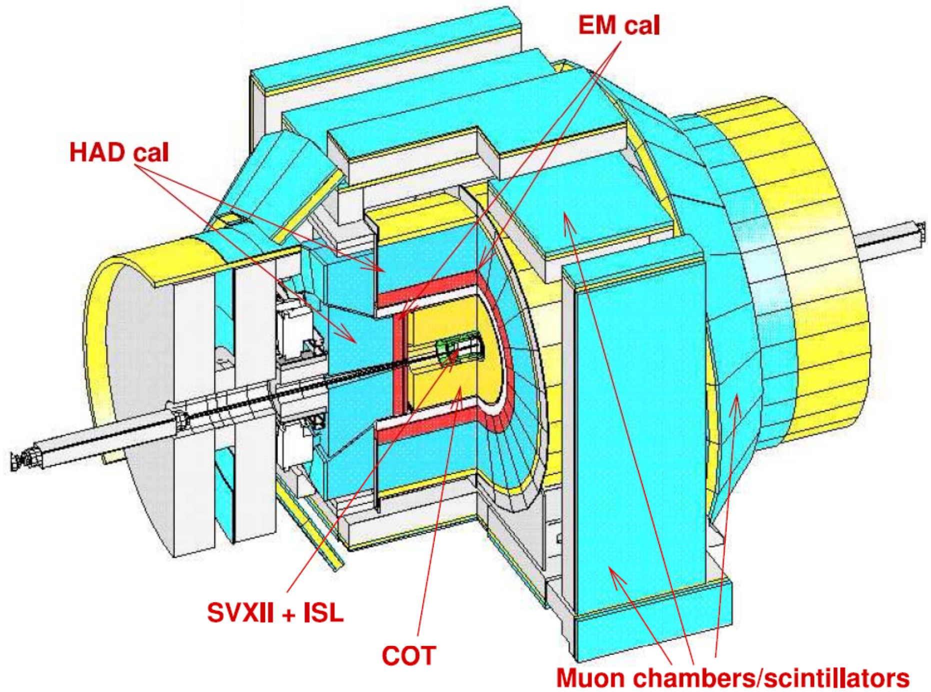
- The Tevatron, status and performance
- Searching for the Higgs @ Tevatron
- High mass Higgs exclusions
- Low mass Higgs searches
- Validation using diboson to HF processes
- Combinations of Standard Model searches
- Prospects

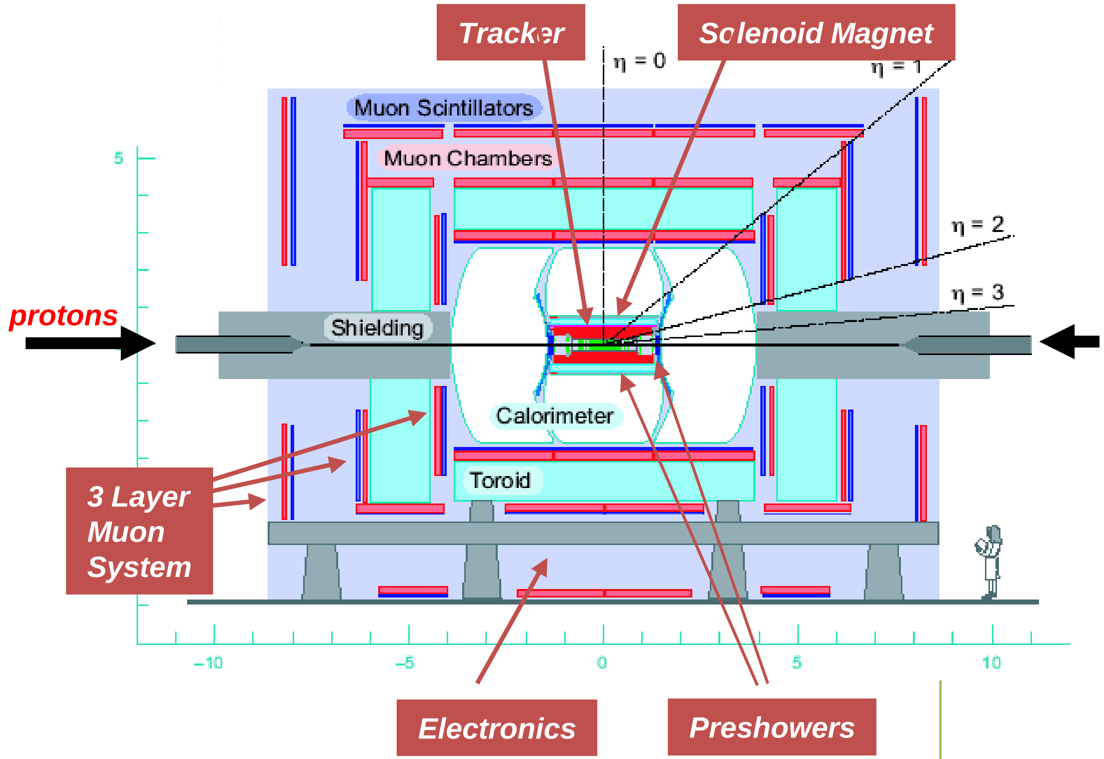
Tevatron Luminosity



Thanks to the Tevatron Accelerator Group for such a performance!

CDF and DØ Detectors

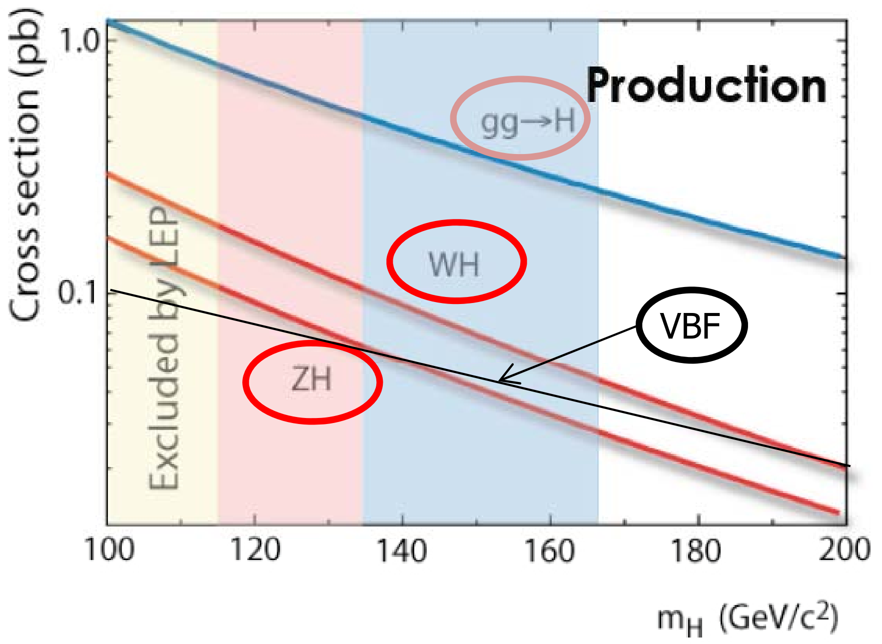


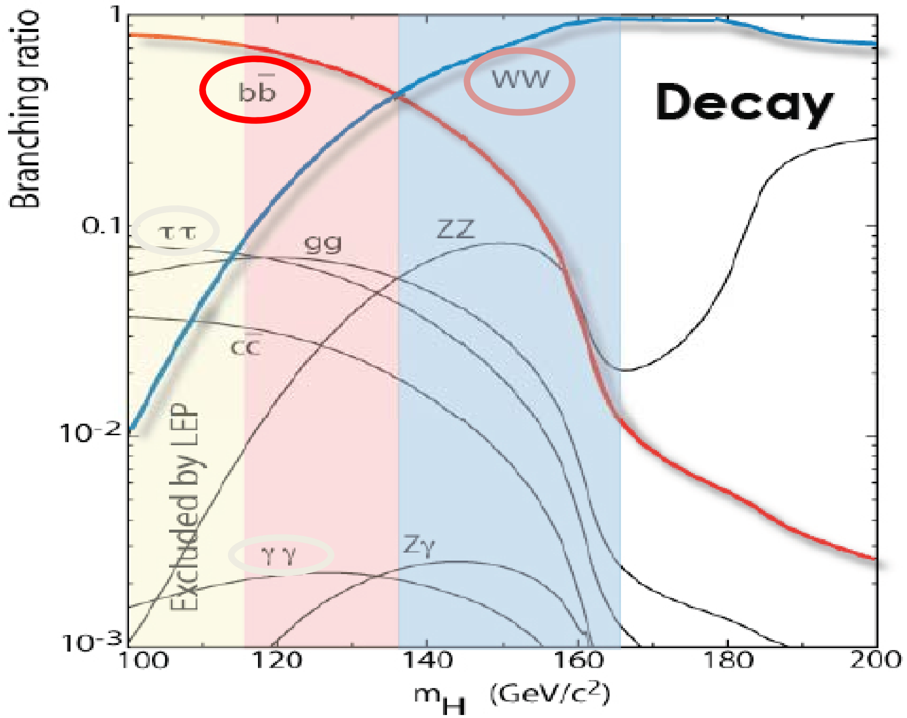


- General purpose detectors
- Good hermeticity
- Mature algorithms
- Well understood under all pile-up conditions

	Rapidity coverage	
	CDF	Dzero
Track	2.0	2.5
Calorimeter	3.6	4.2
Muon	1.0	2.0
B-field	1.4 T	2.0 T

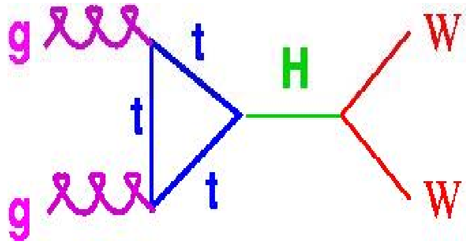
Higgs Production and Decay at the Tevatron





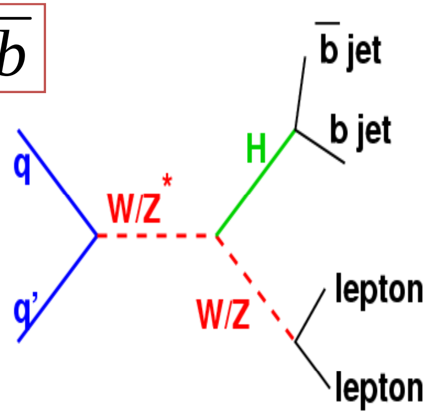
"High" mass (m_H > 135 GeV) dominant decay:

$H \rightarrow WW^{(*)}$ $\quad gg \rightarrow H \rightarrow WW \rightarrow \ell\nu\ell'\nu'$



Low mass (m_H < 135 GeV) dominant decay:

$H \rightarrow b\bar{b}$



$WH \rightarrow \ell\nu b\bar{b}$

$ZH \rightarrow \ell^+\ell^- b\bar{b}$

$ZH \rightarrow \nu\bar{\nu}b\bar{b}$

use associated production modes to get better S/B

These are the main search channels, but there is an extensive program of measurement in other channels to extend the SM (and BSM) sensitivities.

What did we learn in 2011 on SM Higgs?

Tevatron had already shown in 2010 that the "high mass" part of the electroweak-favored range is excluded ➔ SM Higgs between ~115 and ~150 GeV.

In summer, LHC confirmed and extended these limits, also starting to confirm directly that higher masses (> 180 GeV) are not possible for SM Higgs (work to be completed with more LHC luminosity). In December, further reduction presented by the LHC of the allowed SM range.

➔ SM Higgs if it exists has a low mass and is in a region where its Branching Ratios vary rapidly as a function of its mass

Challenge: we need to combine all decay modes to find it, but we also need individual measurements to identify it as the SM Higgs boson!

➔ Remind Tevatron strategy, starting from the high mass channels, then moving to the H→bb search, where Tevatron has strong capabilities

Higgs Search Strategy @ Tevatron

Optimize all channels individually, based on production and decay properties.

Select inclusive candidate samples maximizing acceptance to potential Higgs signals (different masses probed)

Separate further these channels into multiple analysis sub-channels of different S/B, to improve the sensitivity.

Model all backgrounds using simulation and data, with detailed verifications on independent control regions in data

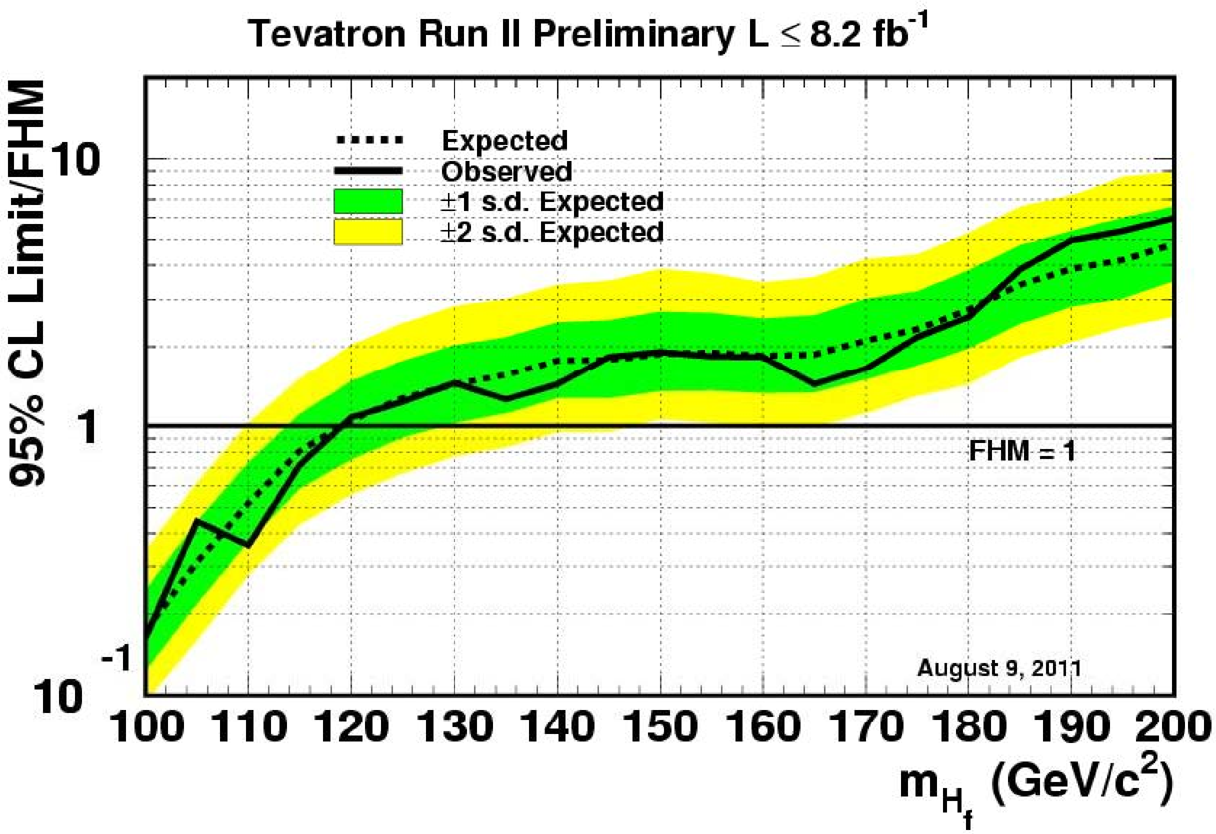
Use advanced multivariate analysis tools to separate signal from background based on the full event kinematics (tested on data)

Derive systematic uncertainties from independent measurements, both in normalization and on the shape of their distributions.

Use two standard statistical approaches and constrain the systematic uncertainties to the data, to obtain the best search results.

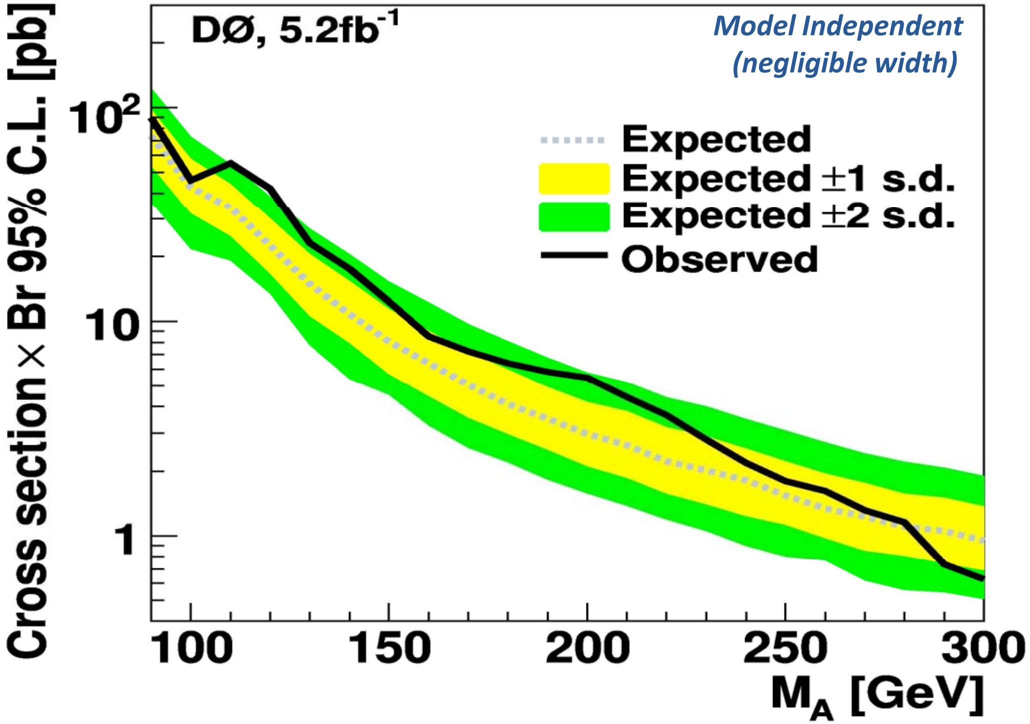
Other non SM Higgs searches

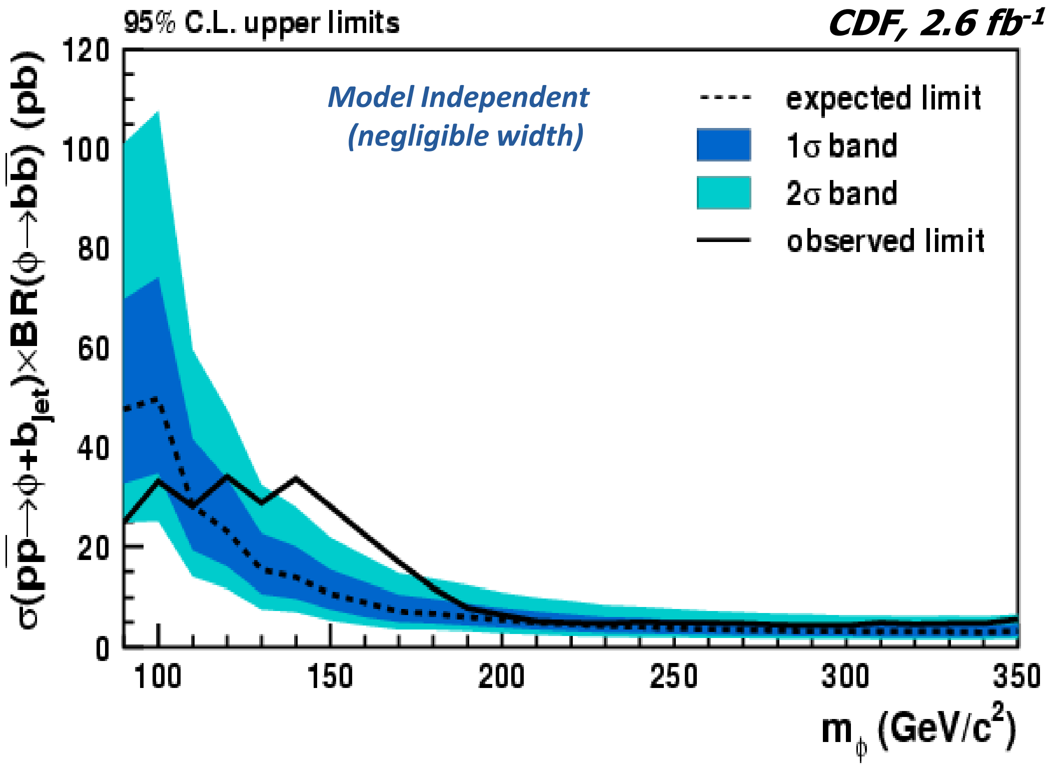
Tevatron combination: 95% C.L. exclusion for a Fermiophobic Higgs boson with mass m_H below 119 GeV/c^2.



$\phi b \rightarrow b\bar{b}b$ Results: Limits

95% C.L. Mass-Dependent Cross Section Limits





- **Limits on $\sigma \times$ BR**
  - DØ: observe ~2.5σ deviation at ~120 GeV for narrow-width case [after trial factors, significance of ~2.0σ]
  - CDF: deviation at ~150 GeV, with p-value = 0.23% (~2.8σ) [trial factors, 1.9σ significance to observe such an excess at any masses]
- **General limits applicable to any narrow scalar with $b\bar{b}$ final states produced in association with b-jet**

SM Higgs Event Yield expectation

Expected number of events available for selection to CDF + DZero at the end of Tevatron running (10 fb^{-1})

Higgs Mass	WH→lνbb	ZH→ννbb	ZH→llbb	H→WW→lνlν
120 GeV	~500	~240	~80	~260
135 GeV	~200	~100	~40	~520
150 GeV	~60	~40	~20	~640

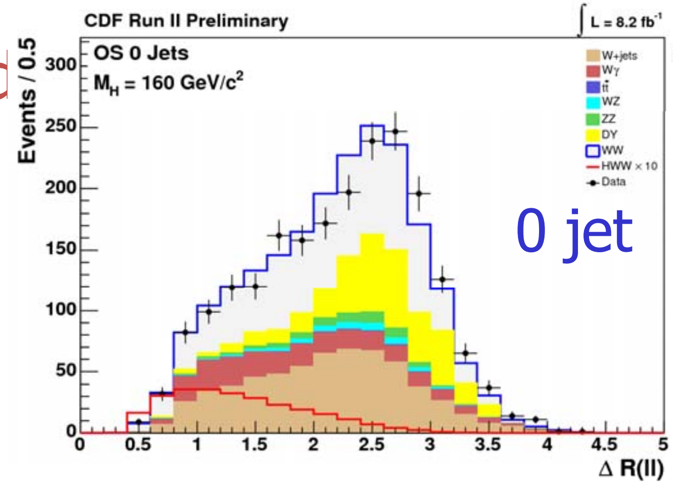
But: reconstruction/selection/tagging efficiencies is
~ 10% in H→bb channels
~ 25% in H→WW channels
(N.B.: lνbb can appear as "ννbb" events in the experimental final states)

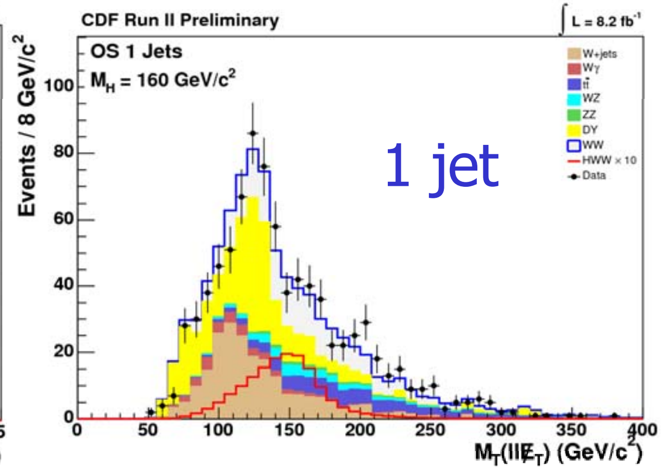
Maximizing Sensitivity in H→WW→lνlν

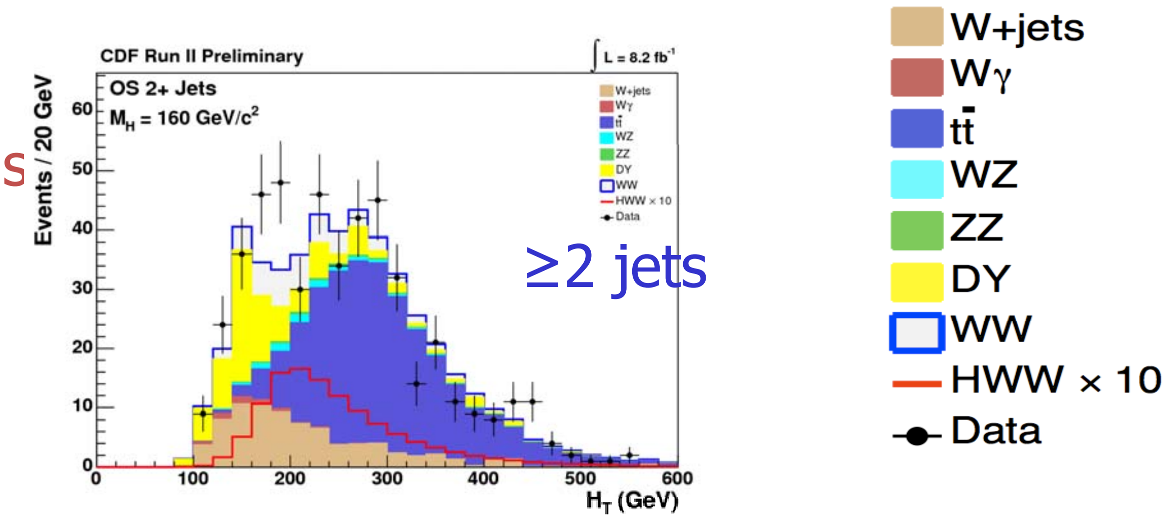
search sensitivity optimized by dividing events into multiple analysis channels

➔ use separate, optimized discriminants for each channel based on

- specific signal contributions
- specific background contributions
- specific event kinematics





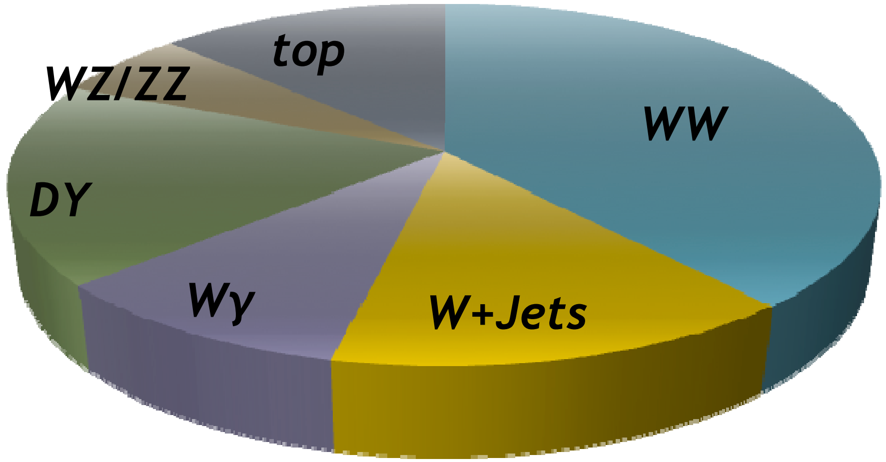


Collect as many Higgs events as possible:

➔ both CDF and D0 include events with same-sign leptons, events with hadronic tau candidates, W hadronic decay modes (D0)

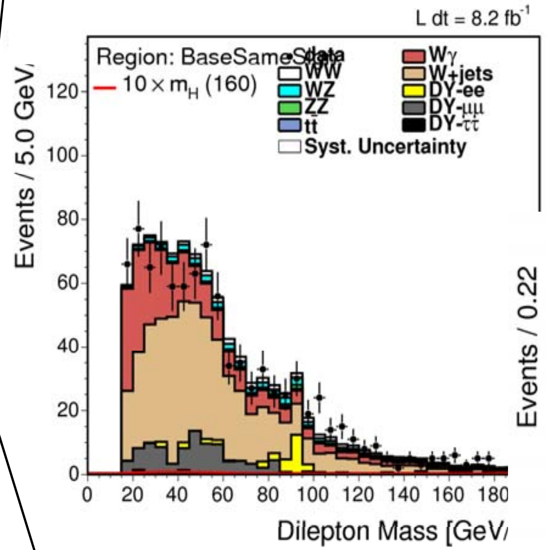
SM Backgrounds to H→WW

- Need to separate small potential signal from large SM background contributions in our search channels
- After inclusive selection S/B ~ 0.02 in the most sensitive search channels

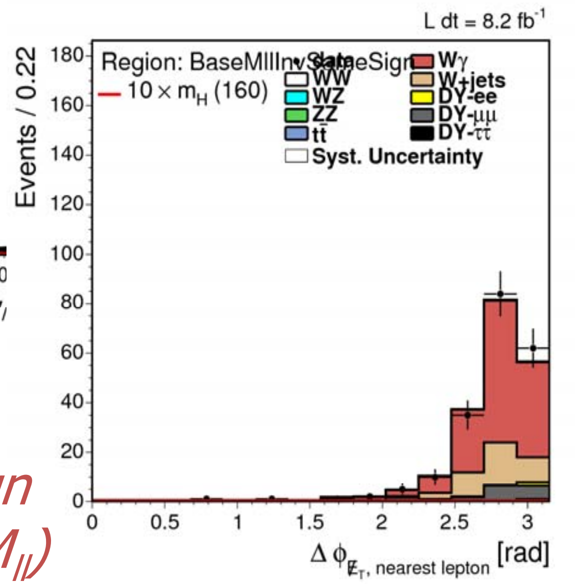


→ Need to model well ALL backgrounds

- Define specific control regions to test modeling for each individual background (whenever possible)



W+jets : same-sign dileptons

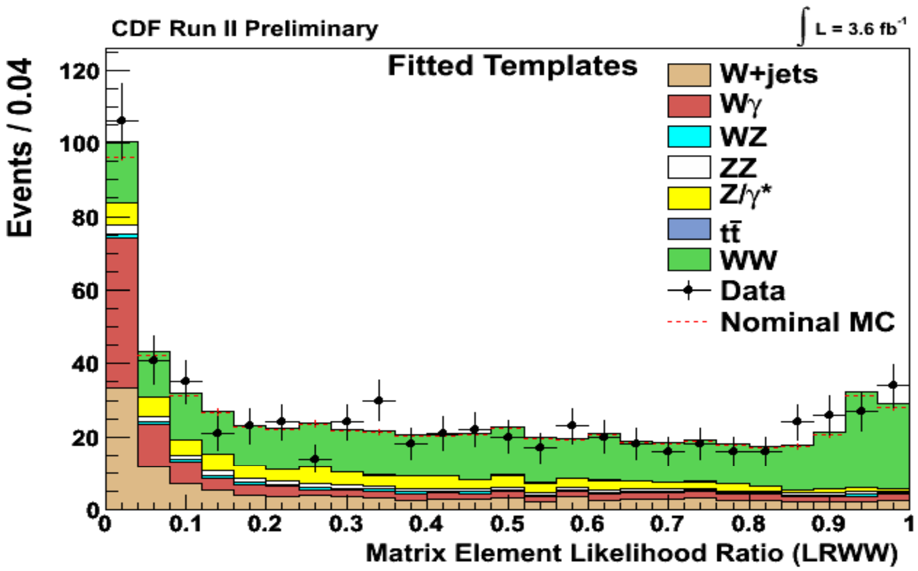


W+γ : same-sign dileptons (low M_{ll})

- In the case of dibosons (WW/Z, ZZ) there are no control regions so we measure them to check their modeling
- If the MC modeling is insufficient, we do additional tunings (based on data)

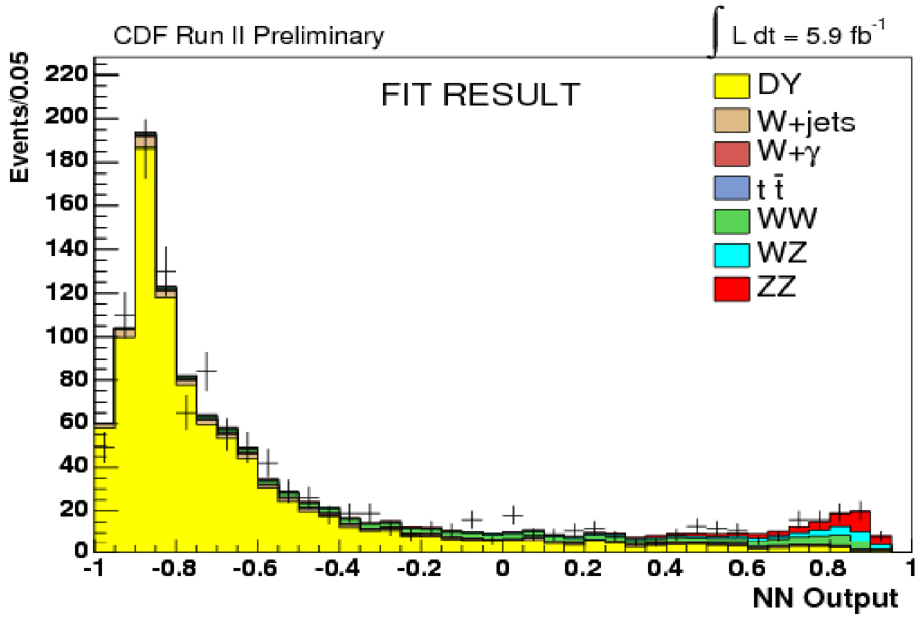
WW and ZZ measurements

Diboson cross section measurements are based on the same tools and data samples used for the $H \rightarrow WW \rightarrow l\nu l\nu$ search
➔ important cross check on background modeling and analysis techniques



$WW \rightarrow l\nu l\nu$: $\sigma(WW) = 12.1^{+1.8}_{-1.7}$ pb

NLO QCD : $\sigma(WW) = 12.4^{+0.8}_{-0.8}$ pb



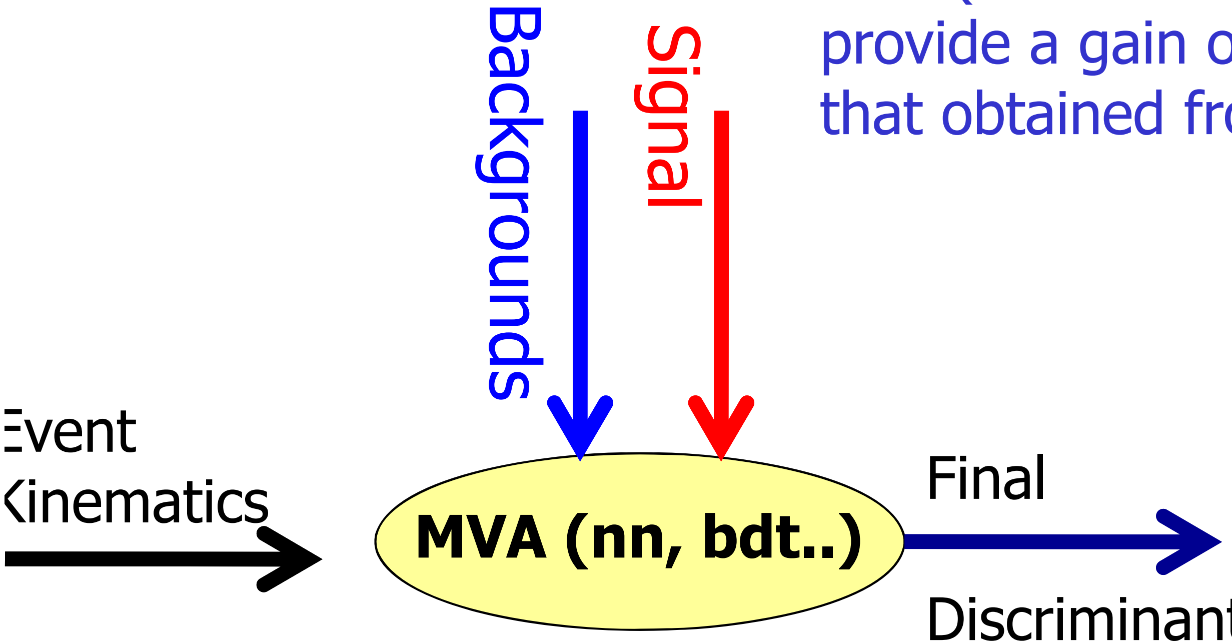
$ZZ \rightarrow ll\nu\nu$: $\sigma(ZZ) = 1.5^{+0.6}_{-0.5}$ pb

NLO QCD: $\sigma(ZZ) = 1.4^{+0.1}_{-0.1}$ pb

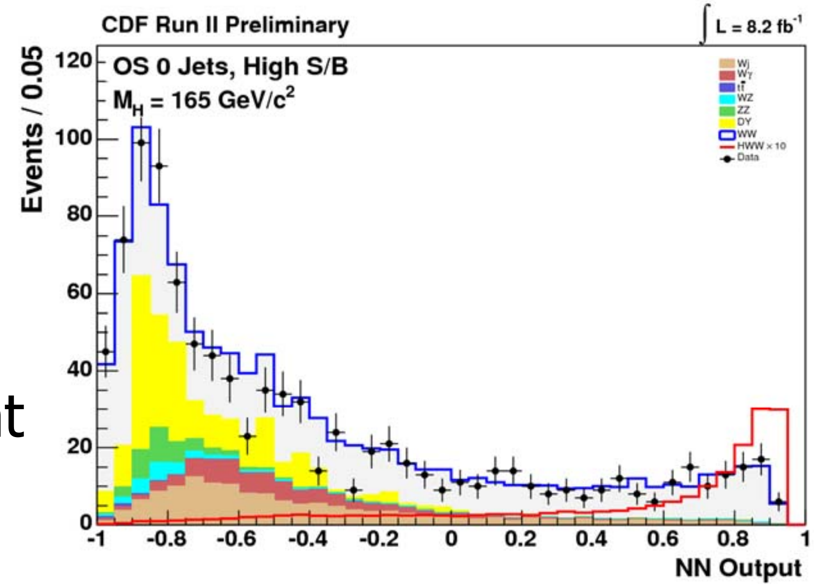
bb final states are analyzed separately

Final/Intermediate Discriminants

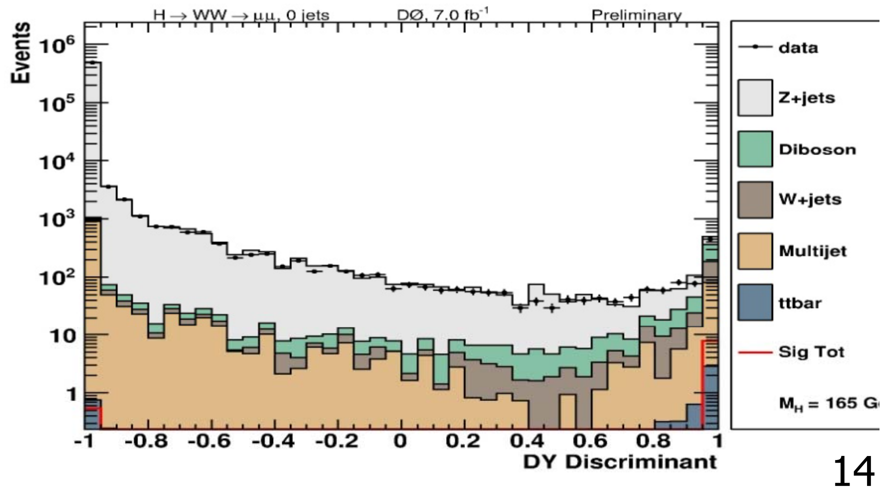
MVA (neural networks, boosted decision trees..) provide a gain of ~20% in sensitivity beyond that obtained from optimized, cut-based analysis



Training ➔correlate multiple input variables



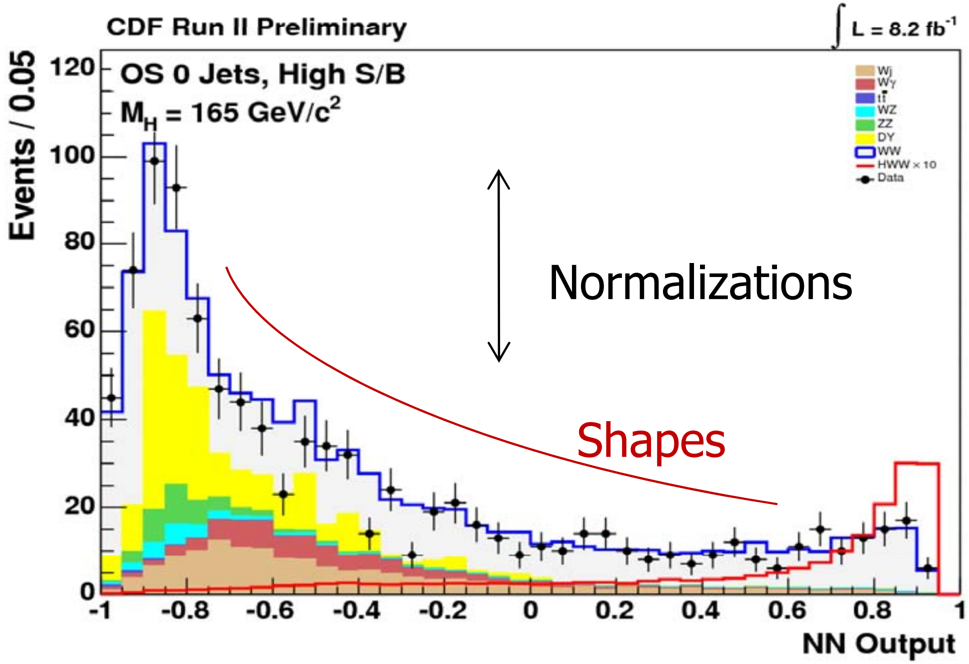
Several layers of MVA discriminants are used in some cases to reduce large background contained within inclusive candidate samples. Example:DY@D0: $H\rightarrow WW\rightarrow \mu\nu\mu\nu$ channel ➔



Systematic Uncertainties

- We consider uncertainties both on the overall normalization of each signal/background process and on the shapes of the final discriminant templates for each signal or background process

- In the limit-setting procedure systematics are included as nuisance parameters, taking into account the correlations between different channels , and between experiments when needed (background cross sections for instance)



Using this approach we are able to further constrain our background uncertainties directly from the data

Since we combine searches focusing on different Higgs production and decay modes, cross section limits are given with respect to nominal SM predictions

→ we incorporate theoretical predictions and uncertainties for signal cross sections and branching ratios when deriving our results (we follow prescriptions from "LHC Higgs cross section working group")

channel	scale 0	scale 1	scale 2
0 jet	13.4%	-23.0%	-
1 jet	-	35.0%	-12.7%
2+ jets	-	-	33.0%

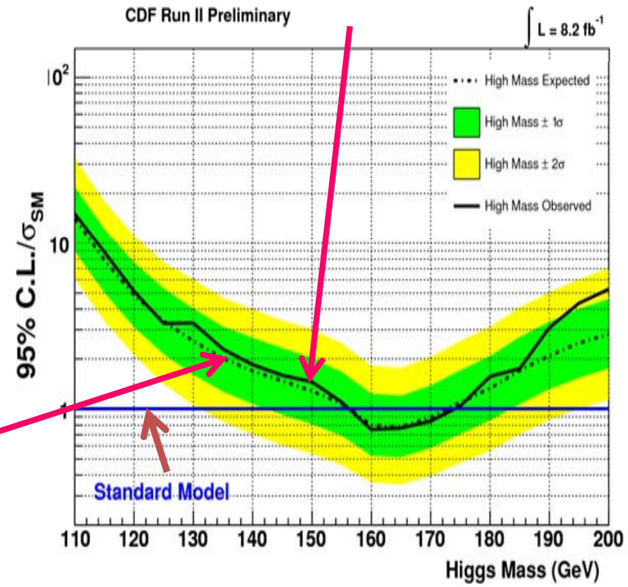
Stewart and Tackmann, arXiv:1107.2117v1

16

Adapt in each iteration to reflect recent theo-retical developments: we now include updated uncertainties for H→WW search in jet multiplicity bins

Observed limit (solid line) from data

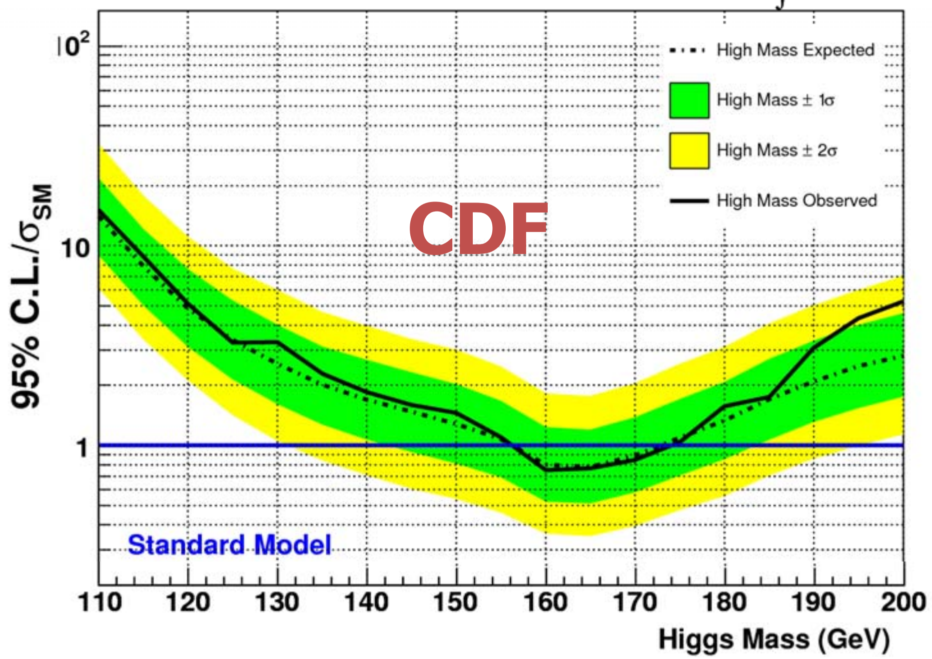
Upper cross section limit for Higgs production relative to SM prediction

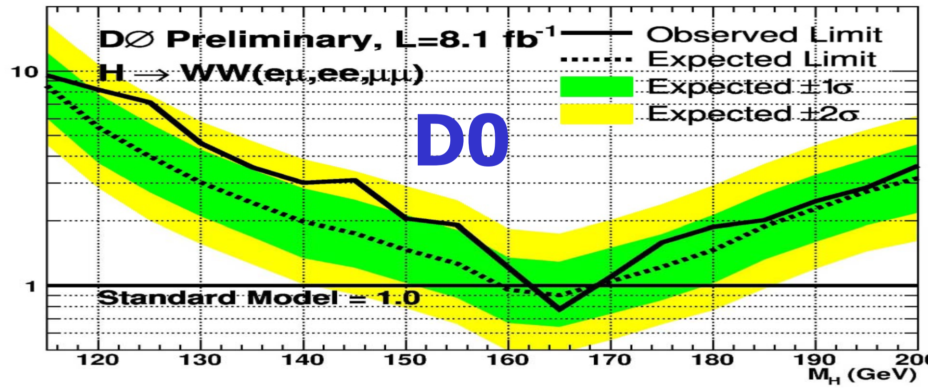


Limits are derived using Bayesian and CLs methods →

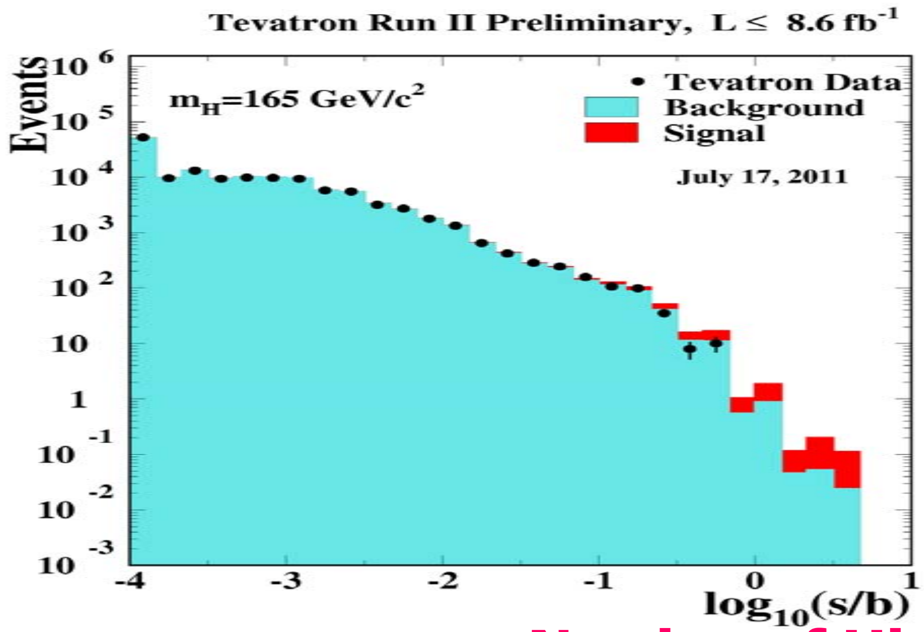
Median expected limit (dot-dashed line) and predicted 1σ/2σ (green/yellow bands) excursions from background only pseudo-experiments

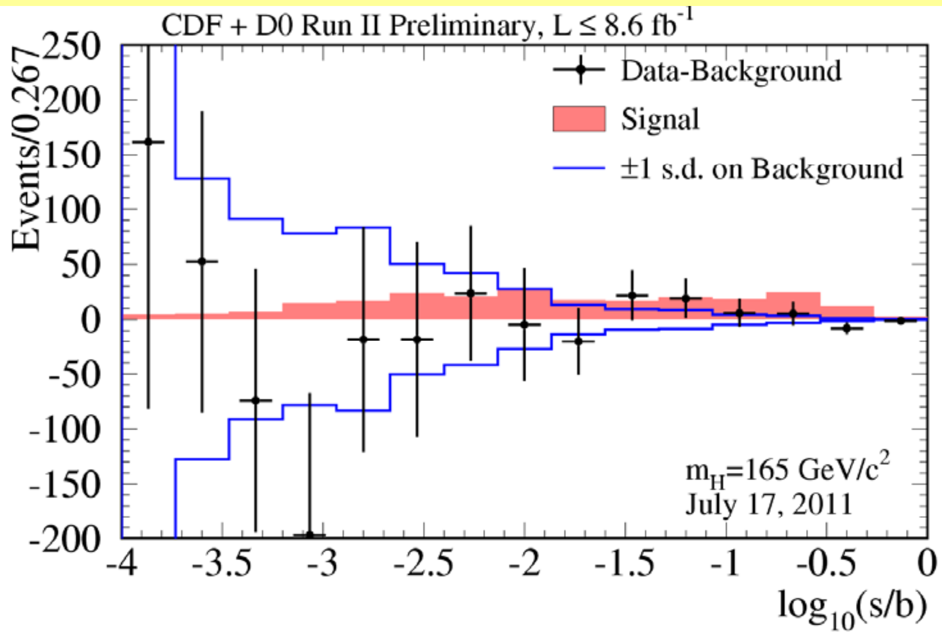
CDF/D0 H→WW→lνlν Limits





Both experiments exclude SM Higgs boson around 165 GeV ➔ combined yield:





No sign of Higgs here, let's move to low mass!

H→γγ / Tevatron Combination

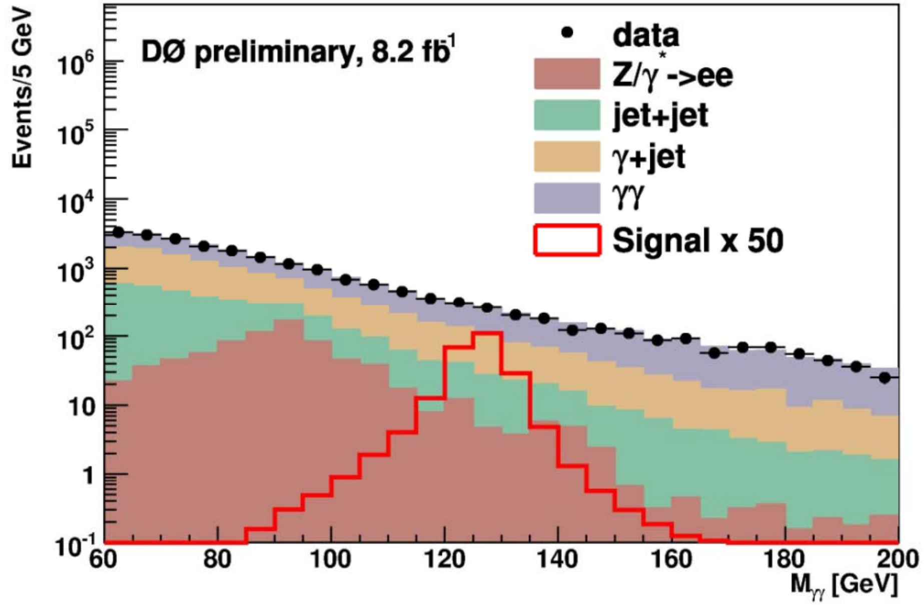
Very small BR in SM, clean signature

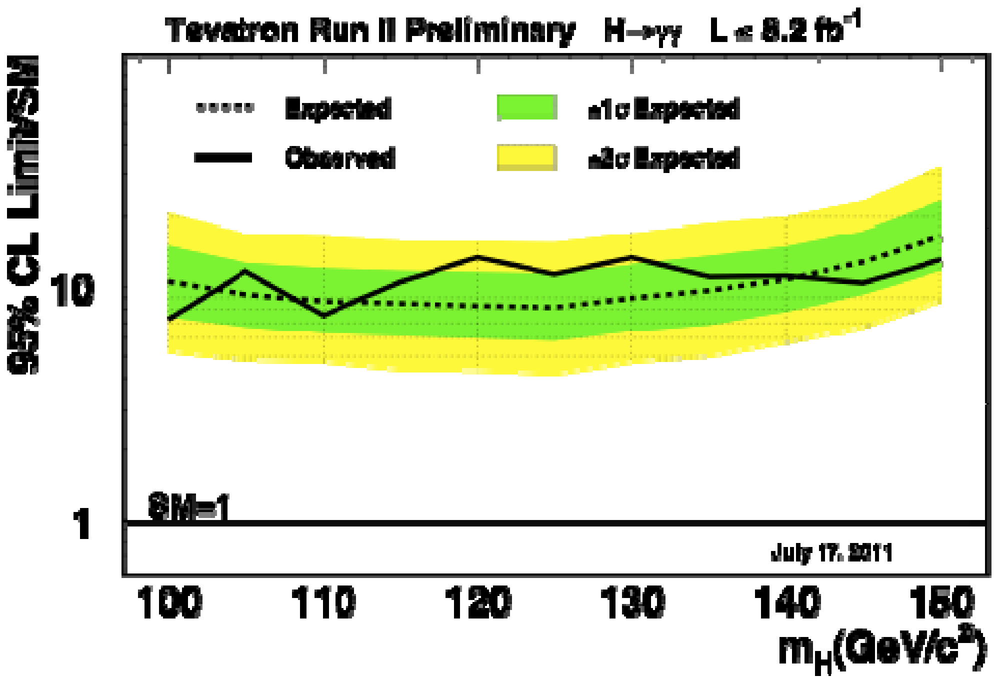
Main challenge is instrumental background (fakes)

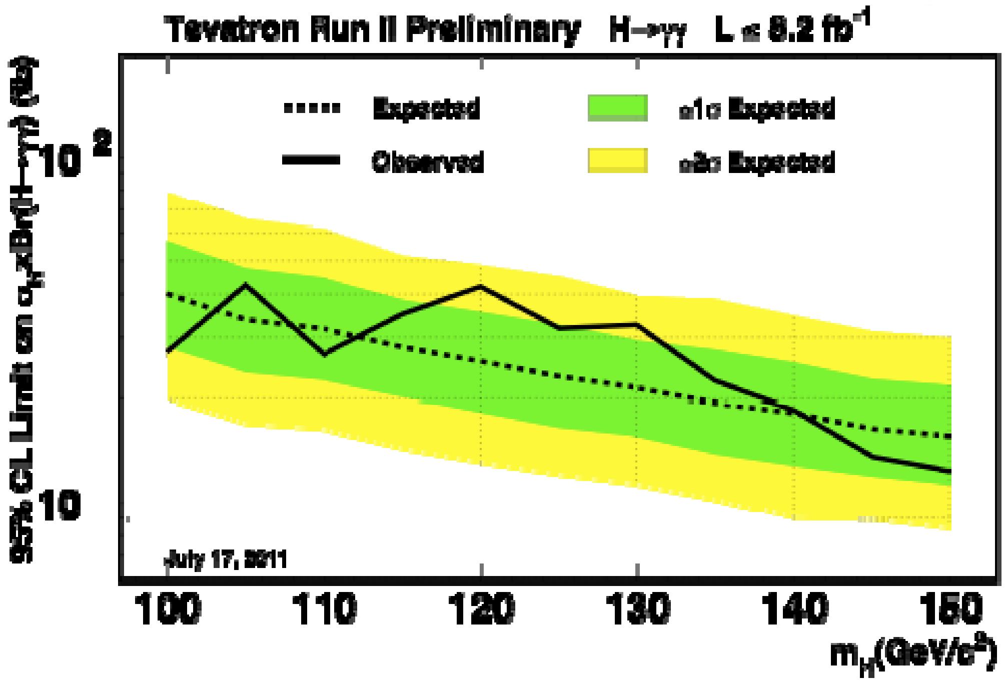
Data-driven methods for both CDF and D0 to estimate background from jets faking photons

Use of multivariate methods for background estimation and final discriminants

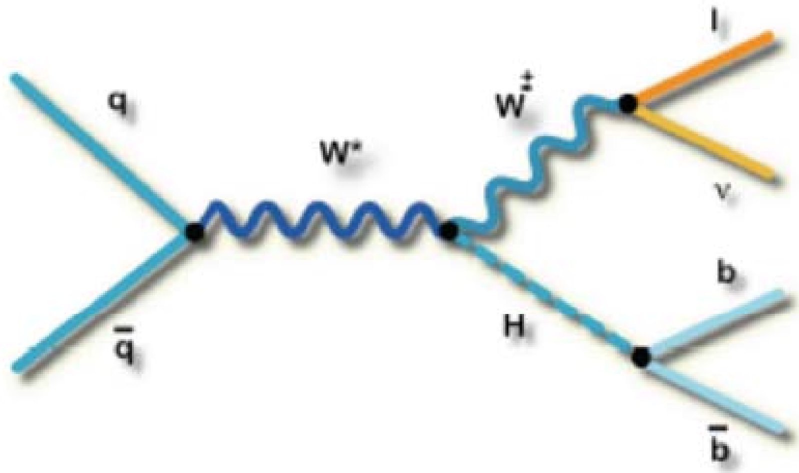
Now completely superseded by LHC.



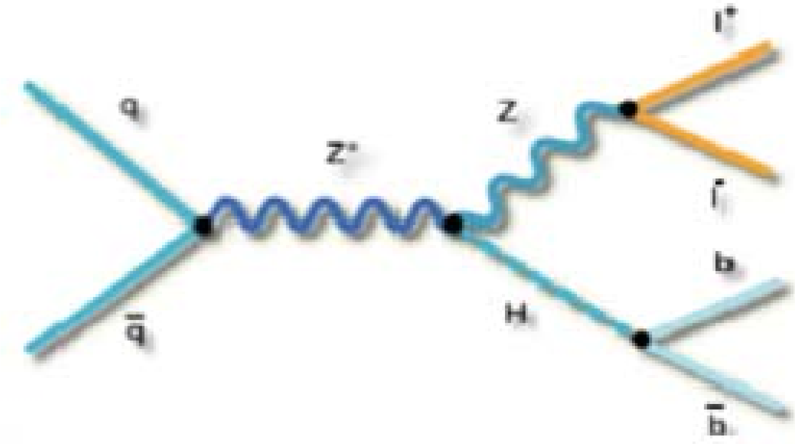




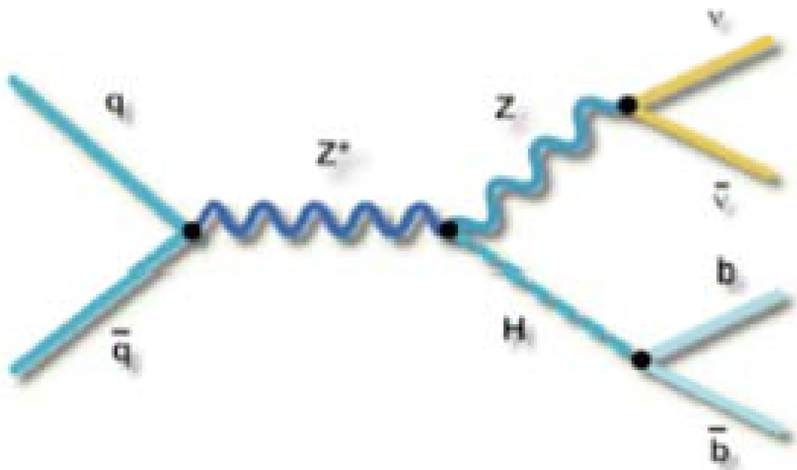
Low Mass Higgs Channels



WH→lνbb: MET+l+bb
Large production cross section
Higher backgrounds than in ZH→llbb

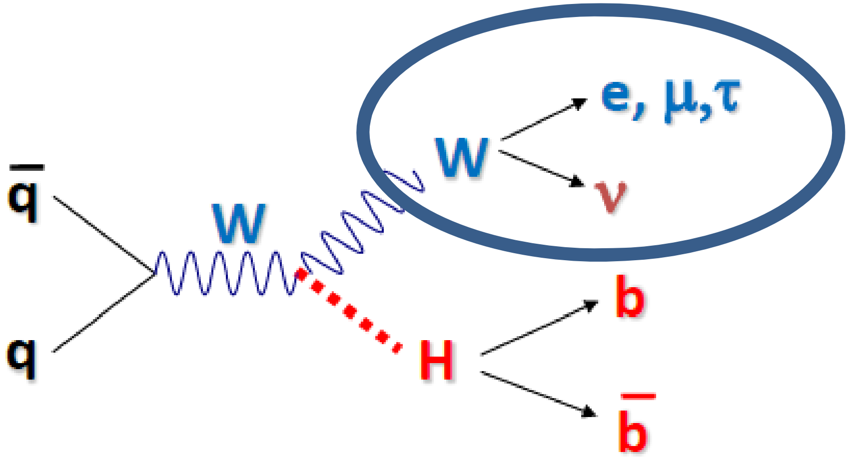


ZH→lνbb: ll+bb
Low background
Fully constrained
Small Signal



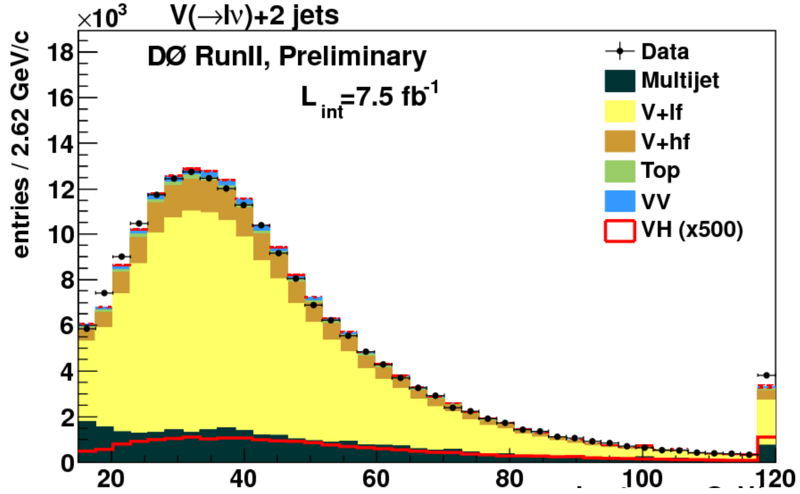
ZH→ννbb: MET+bb
3xsignal of ZH→llbb
(+ contributions from WH)
difficult backgrounds

W boson Reconstruction in WH



Lepton:

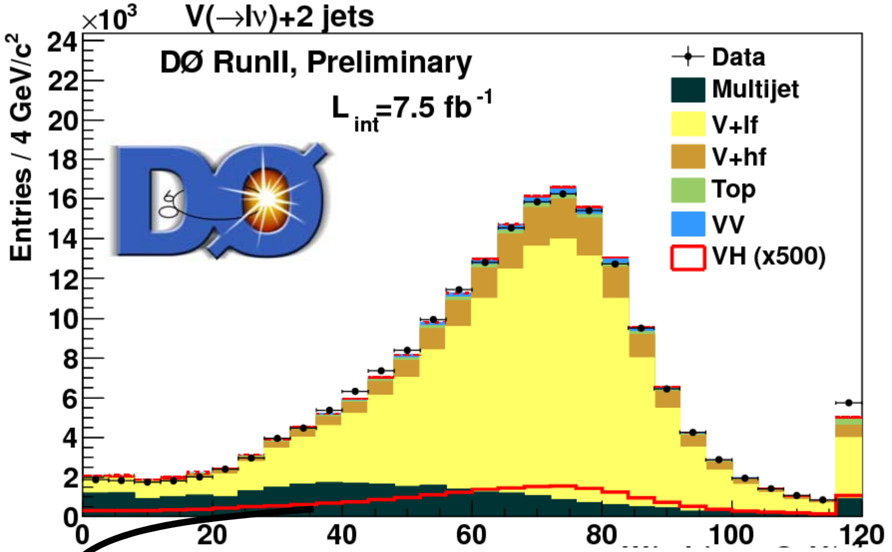
electron/ muon pT > 15 GeV



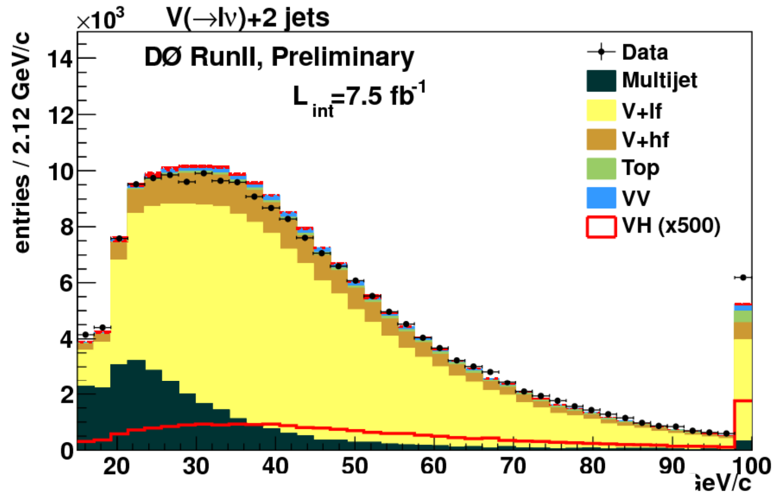
Lepton pT (GeV)

Missing E_T

MET> 15 (20) GeV for electron (muon)



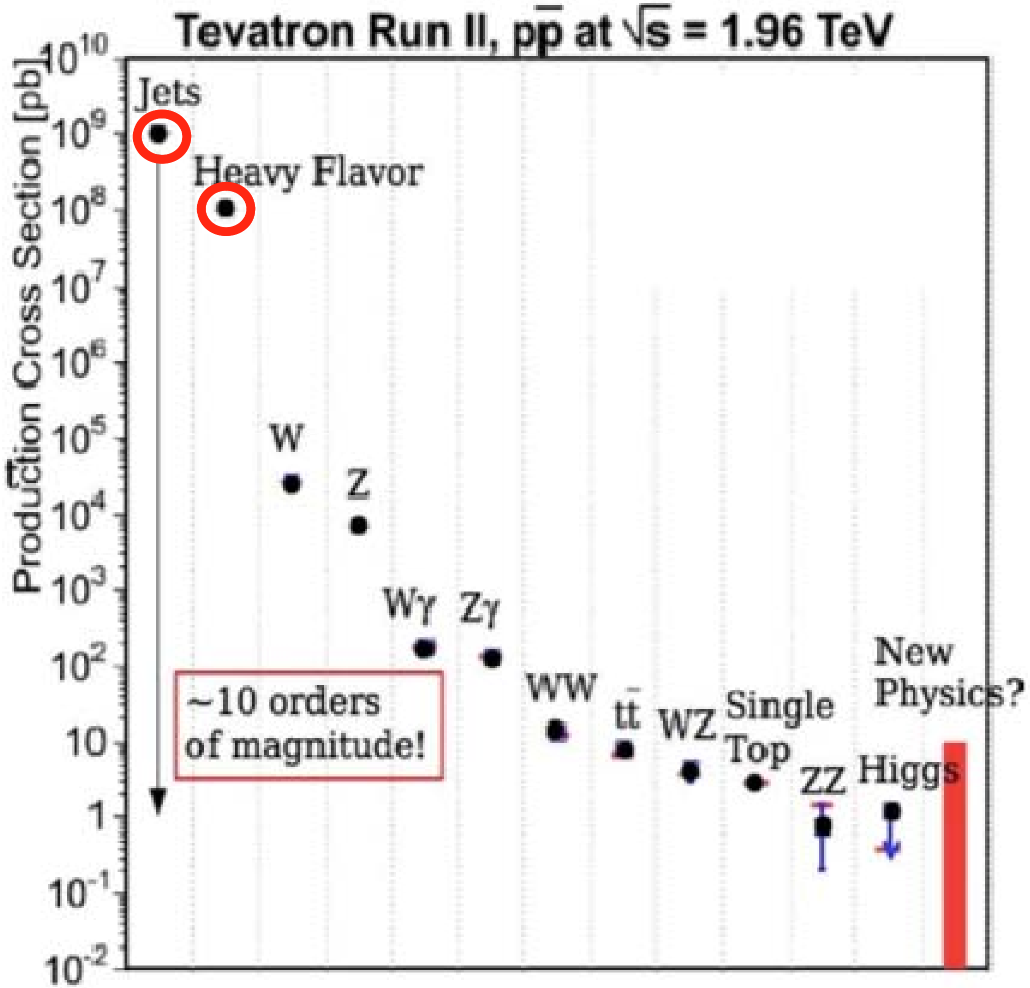
W Transverse Mass (GeV)



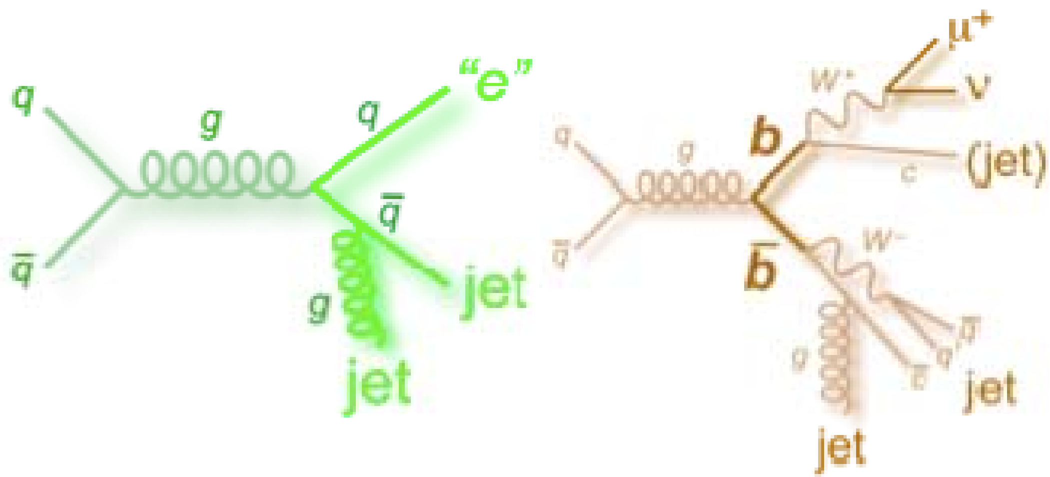
Missing ET (GeV)

Multi-Jet Background is estimated from Data.

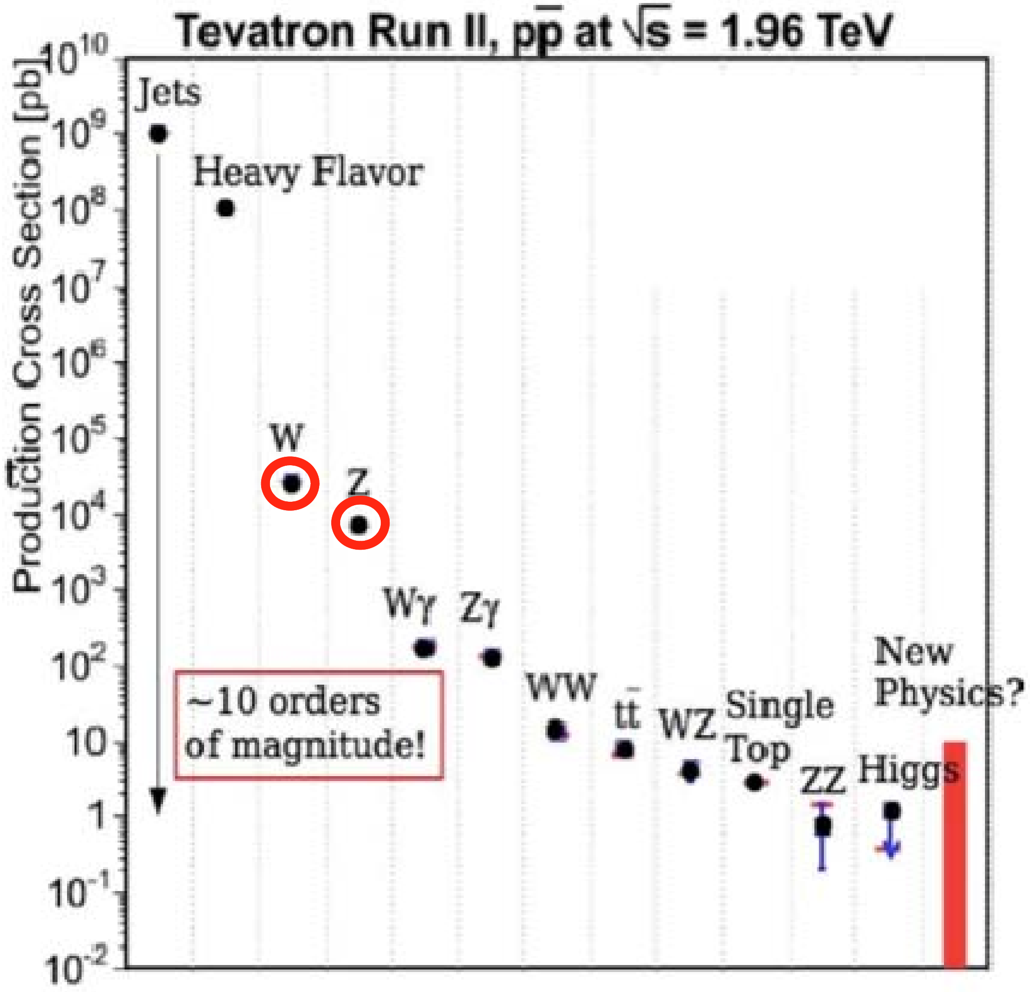
Backgrounds at low mass



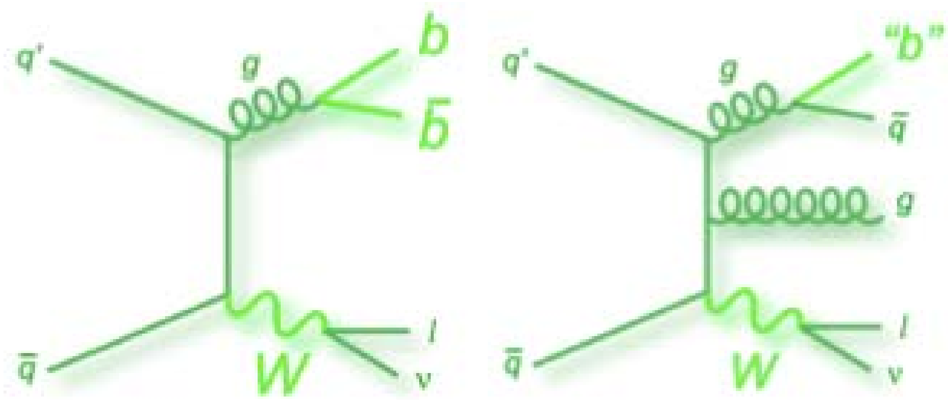
- Instrumental backgrounds QCD multijet (e.g faking lepton)Derived from (sidebands) data



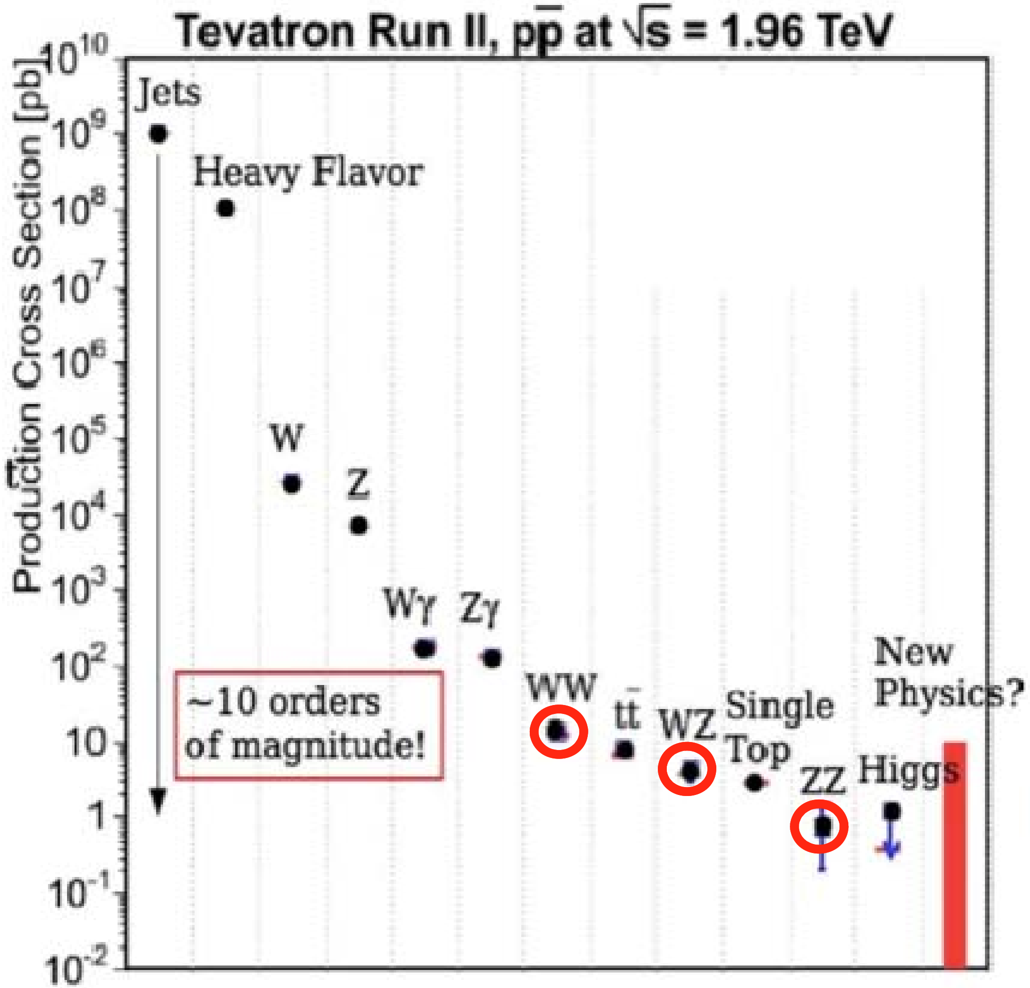
Backgrounds at low mass



- Instrumental backgrounds QCD multijet (e.g faking lepton)Derived from (sidebands) data
- Physics backgroundsW/Z+jets with real / misidentified heavy flavour



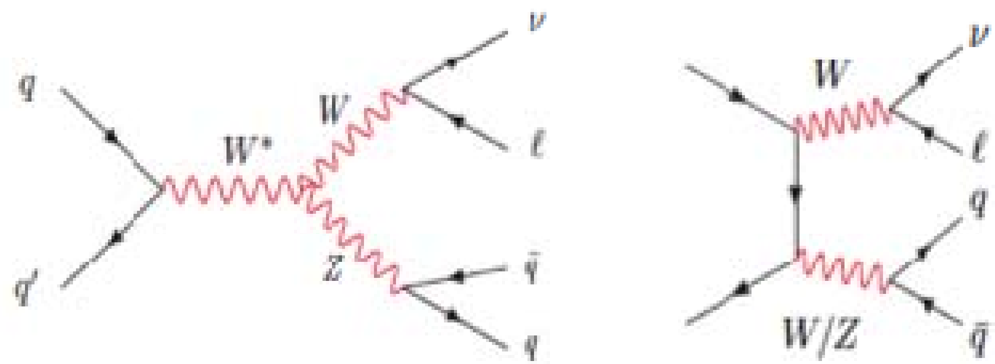
Backgrounds at low mass



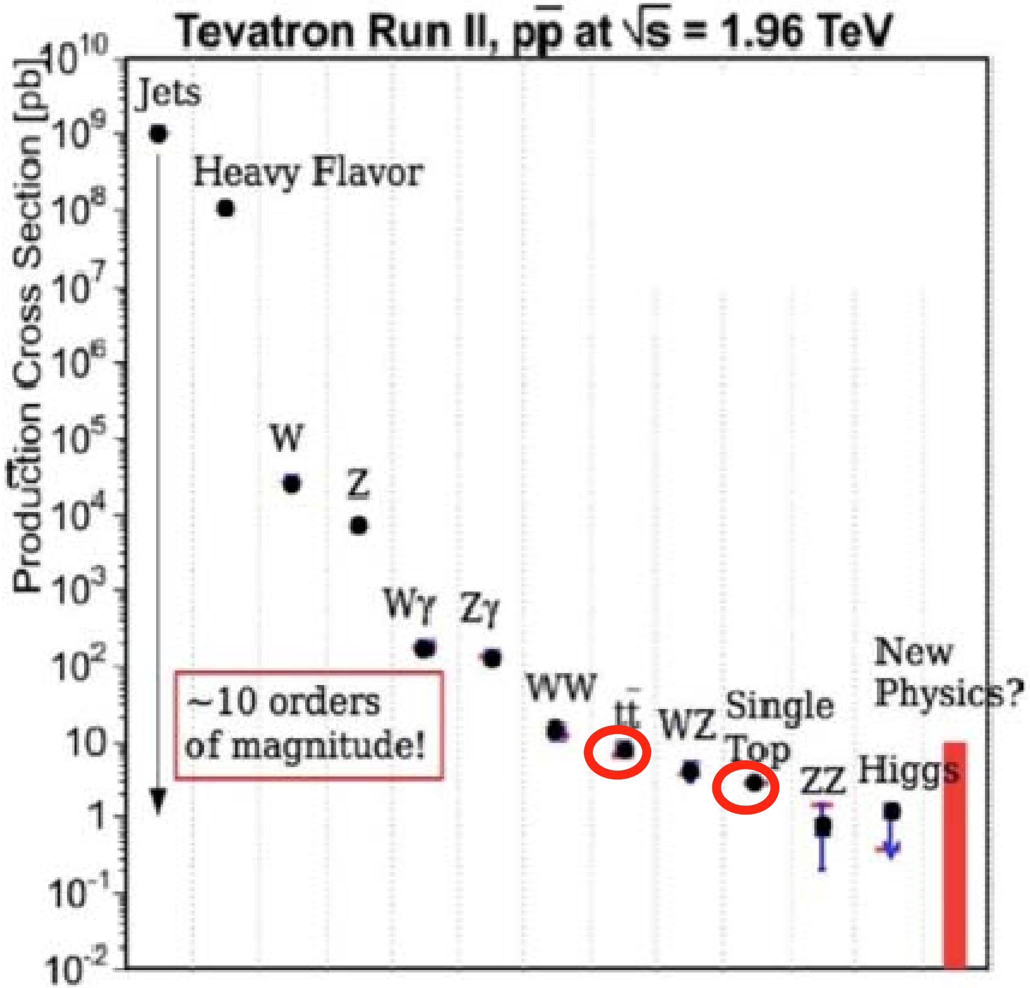
- Instrumental backgrounds QCD multijet (e.g faking lepton)Derived from (sidebands) data

- Physics backgroundsW/Z+jets with real / misidentified heavy flavour

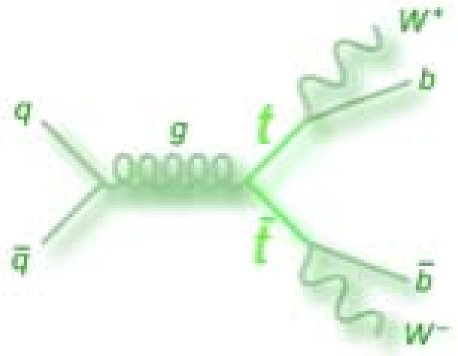
- Dibosons

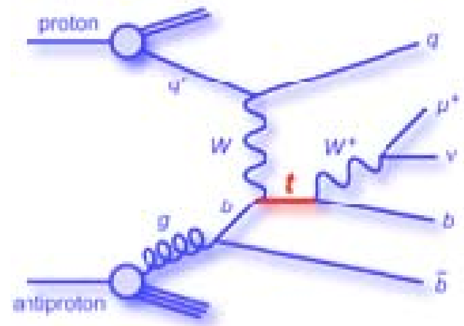


Backgrounds at low mass



- Instrumental backgrounds QCD multijet (e.g faking lepton)Derived from (sidebands) data
- Physics backgroundsW/Z+jets with real / misidentified heavy flavour
- Dibosons
- ttbar and Single Top

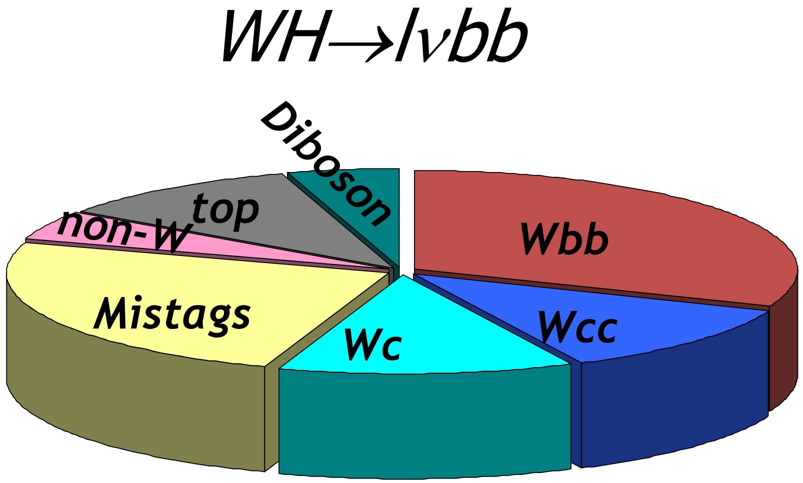




Low Mass Higgs Searches

Increase lepton reconstruction and selection efficiencies

Understand background

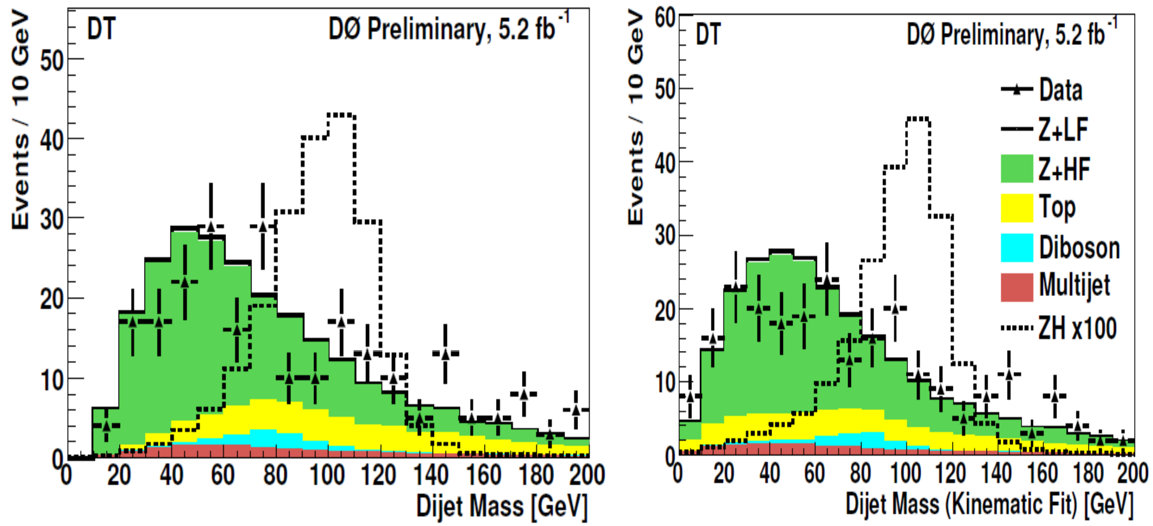


Specific to low mass analyses:

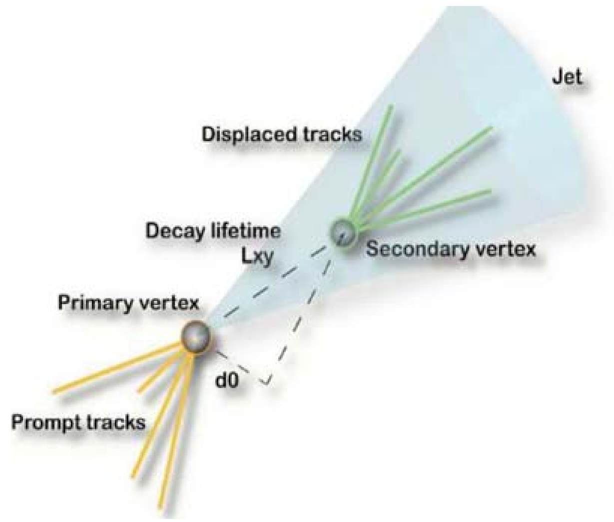
B-tagging (next slides)

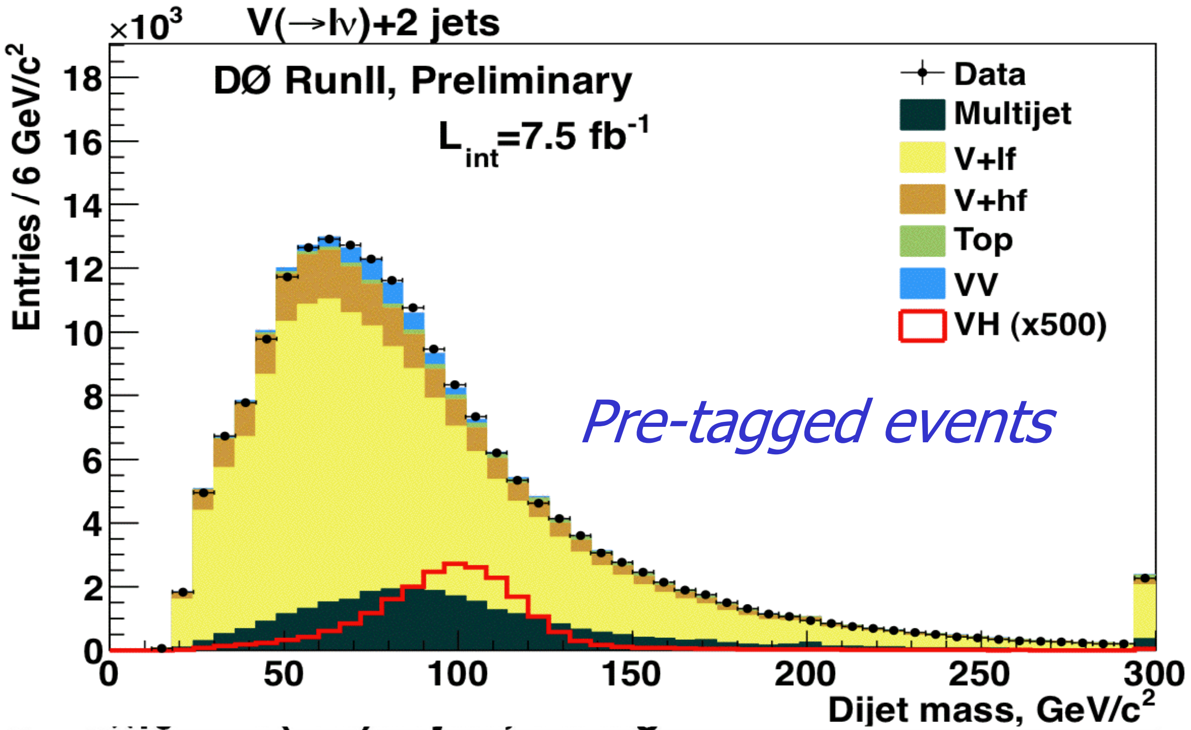
Optimize dijet mass resolution
➔ needs precise calibration and resolution for gluon and quark jets separately
➔ new techniques explored (NN, tracks + calorimeter cells) we are not done yet!

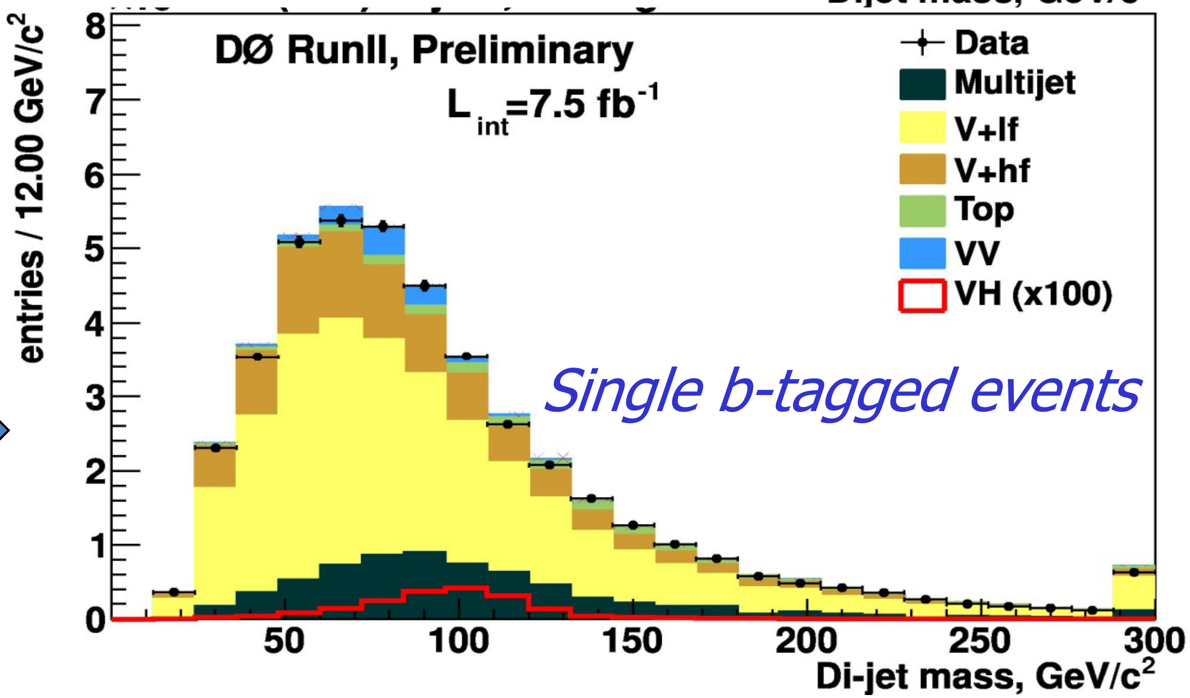
Optimize dijet mass resolution with Kinematic fit in ZH→llbb (15% sensitivity gain)



Low Mass Higgs Searches



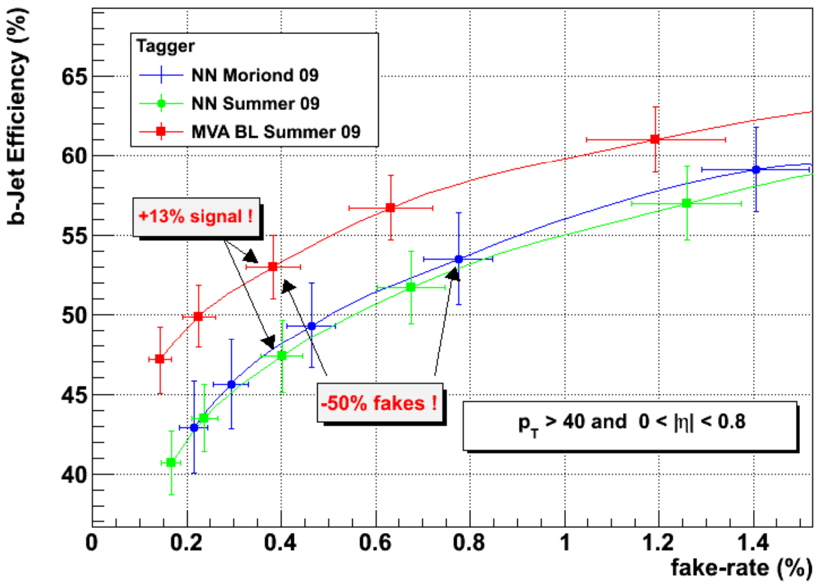


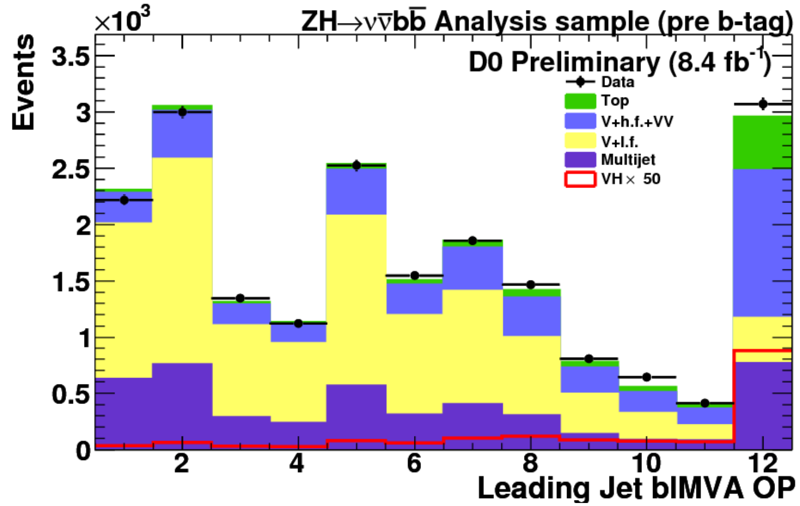


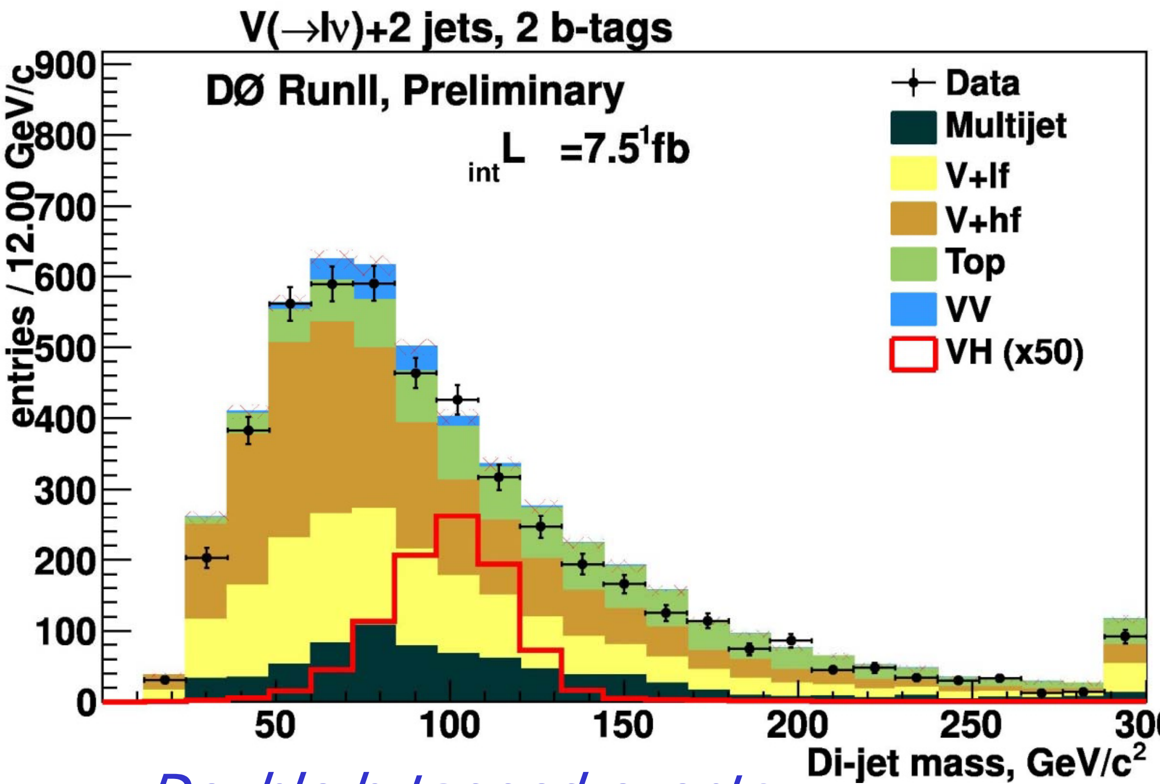
- **Reduce the background by tagging b-quark jets**

- separate b,light, next separate b from c with dedicated algorithm

Low Mass Higgs Searches







Double b-tagged events

- **Improve the efficiency for tagging b-quark jets** →

- separate b,c,light.

Still need to go beyond simple selection approach ➔ Multivariate analysis

From Dijet mass to Multi Variate Analysis

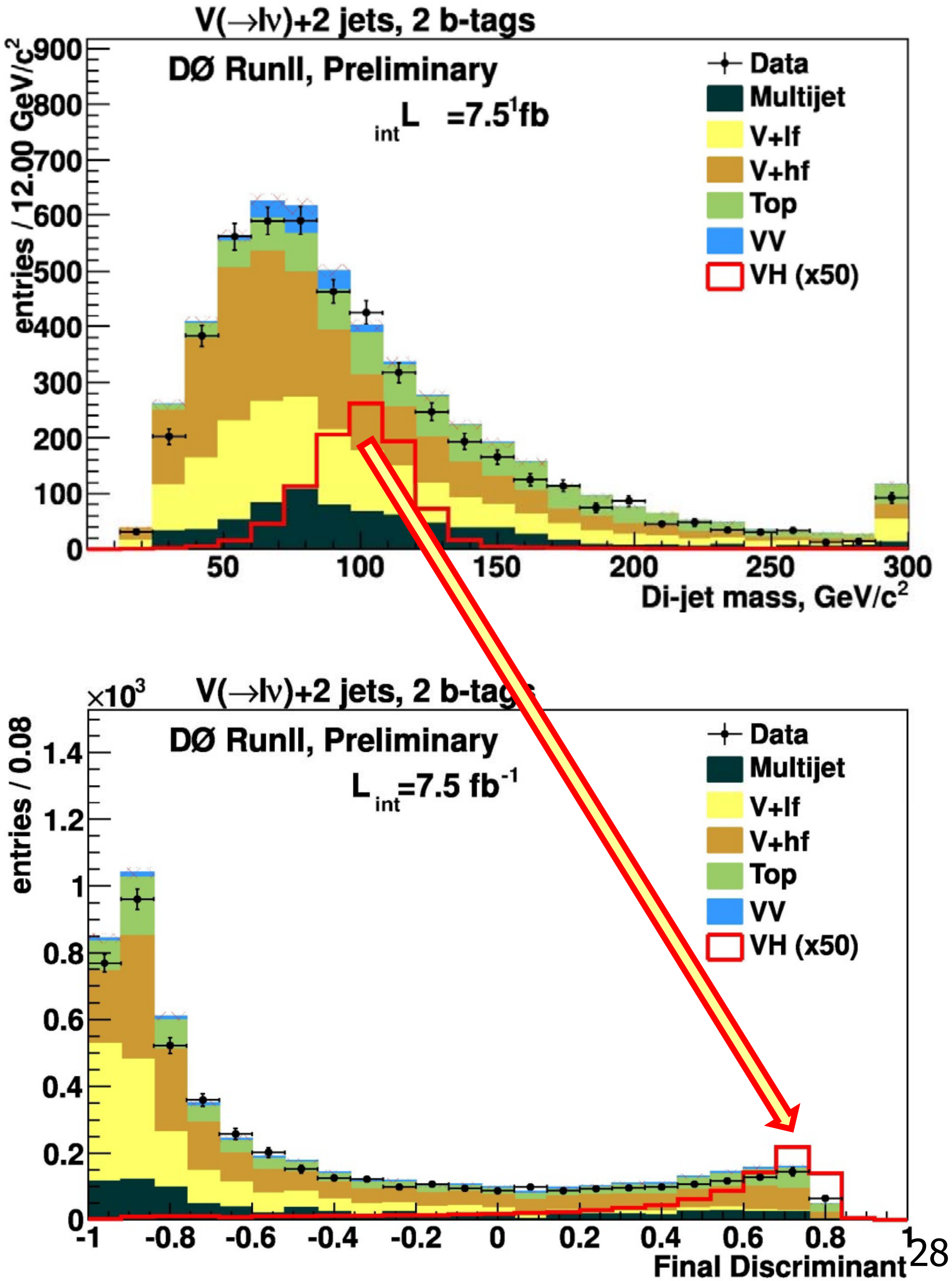
- **To improve S/B → utilize full kinematic event information**

- **Multi Variate Analyses**
  - Neural Networks
  - Boosted Decision Trees

  Or use Matrix Element Calculations to determine probability for an event to be signal or background like

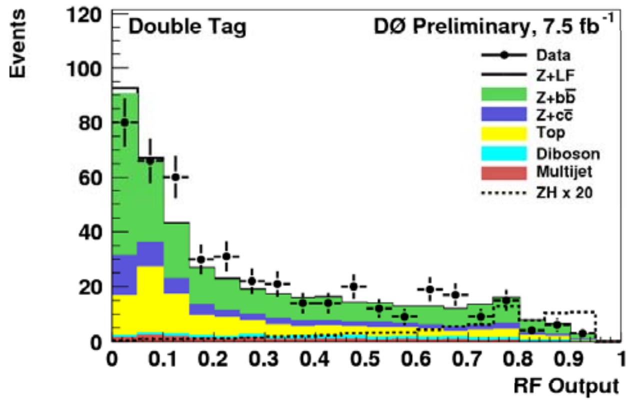
- **Approaches validated in Single Top observation.**
- **Combine these approaches**

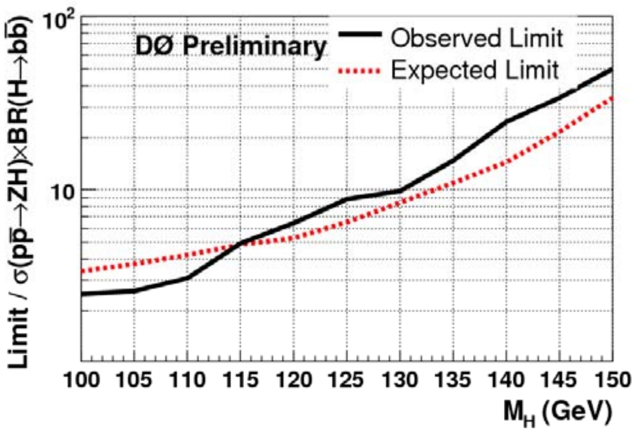
- **Visible gain obtained (~20% in sensitivity)**



Results from DØ

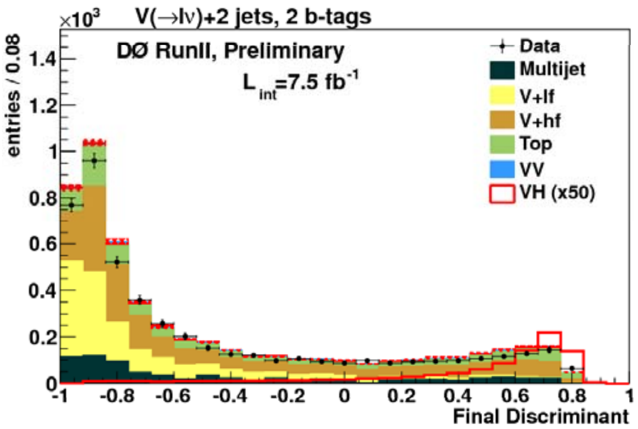
ZH→llbb̄ ∫Ldt=8.6 fb⁻¹

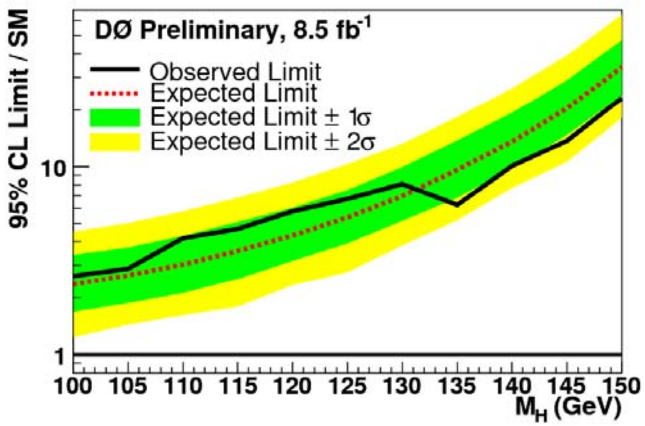




95% CL Exp (obs)
Limit **4.8** (**4.9**) x SM
@ MH=115 GeV

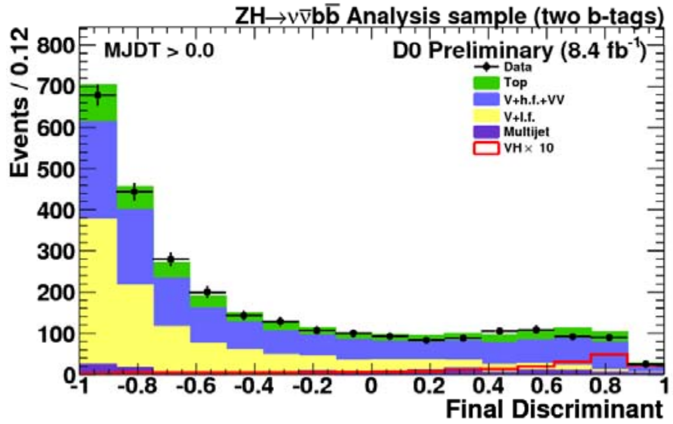
WH→lνbb̄ ∫Ldt=8.5 fb⁻¹

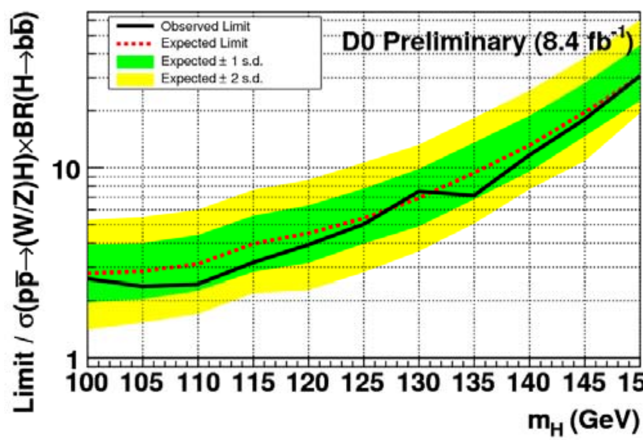




95% CL Exp (obs)
Limit **3.5** (**4.6**) x SM
@ MH=115 GeV

ZH→ννbb̄ ∫Ldt=8.4 fb⁻¹



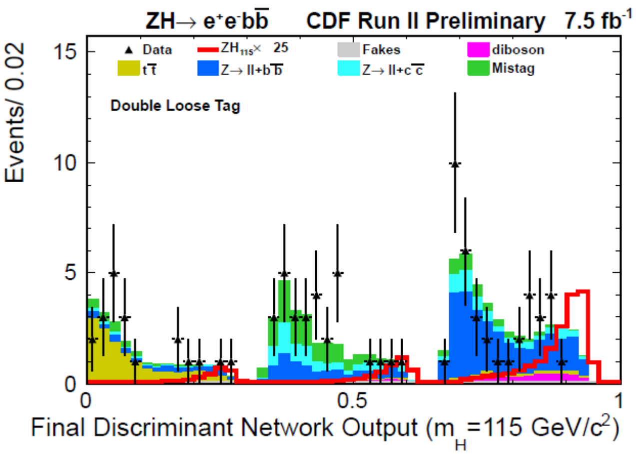


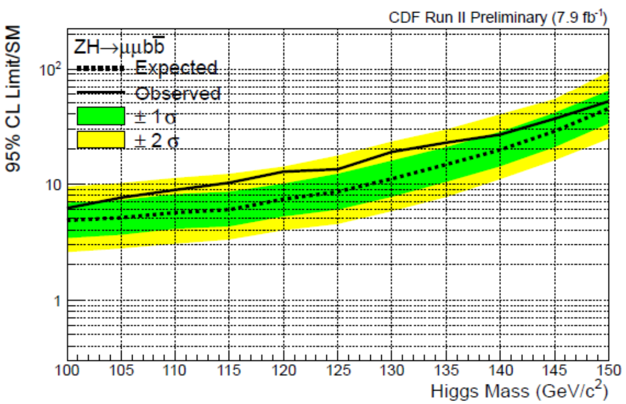
95% CL Exp (obs)
Limit **4.0** (**3.2**) x SM
@ MH=115 GeV

~10% gain on intrinsic sensitivity compared to 2010 result (i.e. on top of gain due to luminosity)

Results from CDF

ZH→llbb̄ — ∫Ldt=**7.9** fb^{-1}

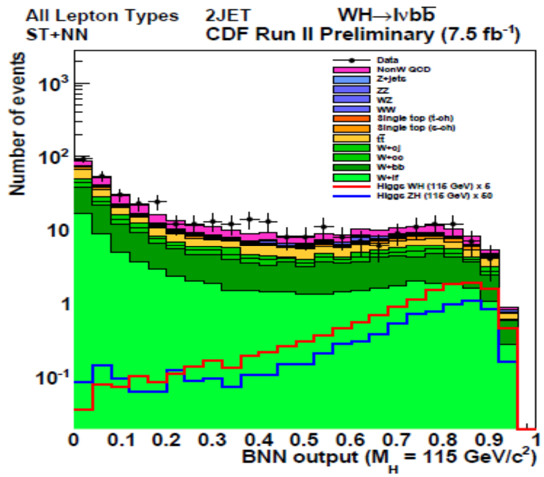


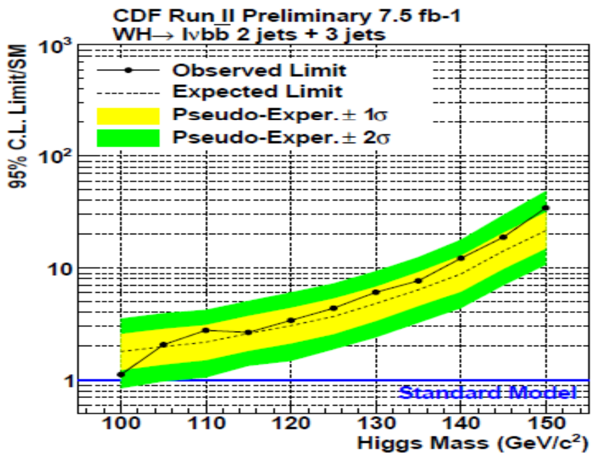


95% CL Exp (obs)
Limit **3.9** (**4.8**) x SM
@ MH=115 GeV

20% gain on sensitivity

WH→lνbb̄ — ∫Ldt=**7.5** fb^{-1}

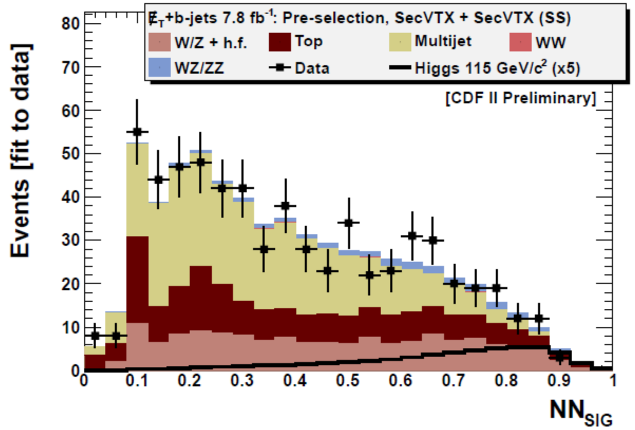


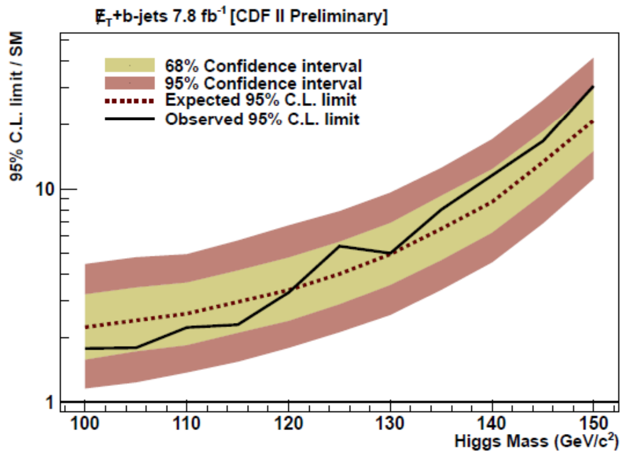


95% CL Exp (obs)
Limit **2.7** (**2.6**) x SM
@ MH=115 GeV

13% gain on sensitivity

ZH→ννbb̄ — ∫Ldt=**7.8** fb^{-1}



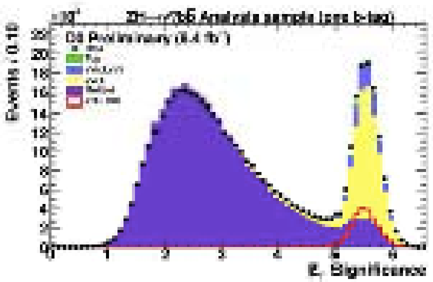


95% CL Exp (obs)
Limit **2.9** (**2.3**) x SM
@ MH=115 GeV

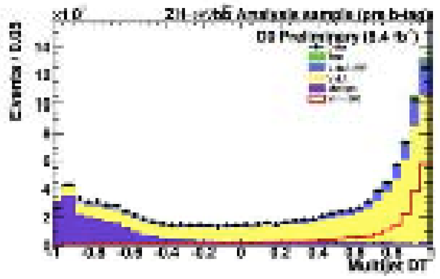
18% gain on sensitivity

Are these methods trustable?

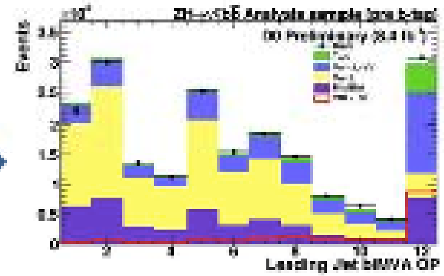
- **Procedure reminder:**



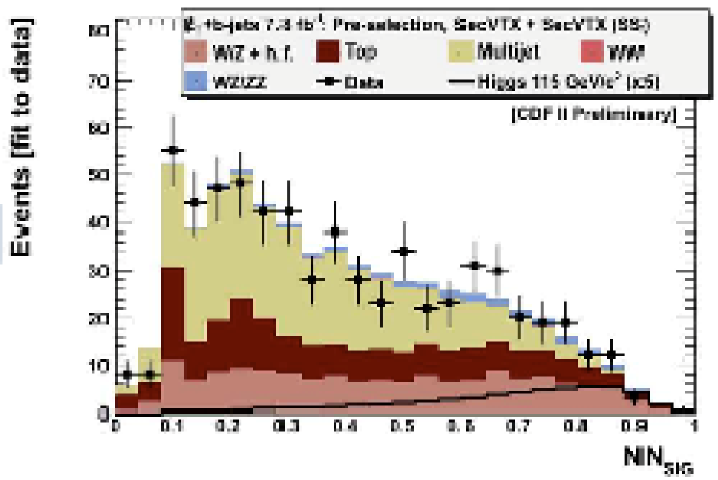
Kinematic event selection



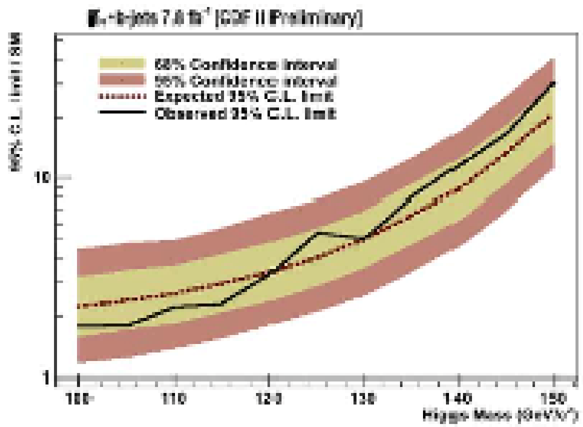
Multijet removal



b-tagging



Final discriminant
SVM, BDT, RF...



Statistical analysis
Log Likelihood Ratio (LLR)
Marginalization of nuisance parameters

Cross check on Diboson process

- **Benchmark of H→bb searches with real data.**
- **VZ→leptons + heavy flavor jets**

<u>For m_H=115 GeV</u>

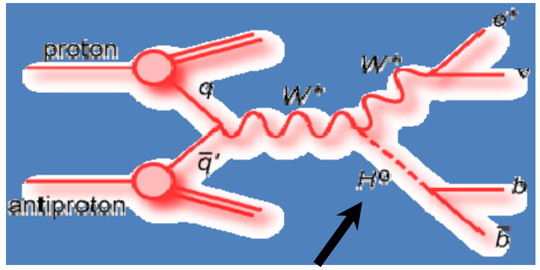
WH→lνbb: σ = 26 fb
ZH→ ννbb:σ = 15 fb
ZH→ llbb: σ = 5 fb

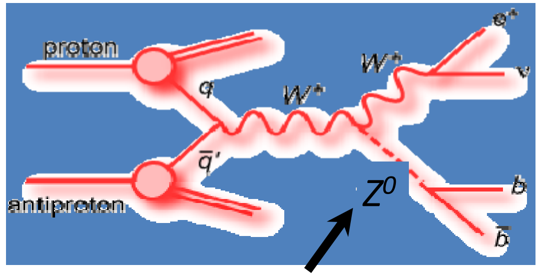
Total VH: σ = 46 fb

<u>Replace H with Z</u>

WZ→lνbb: σ = 105 fb
ZZ →ννbb: σ = 81 fb
ZZ → llbb: σ = 27 fb

Total VZ: σ = 213 fb



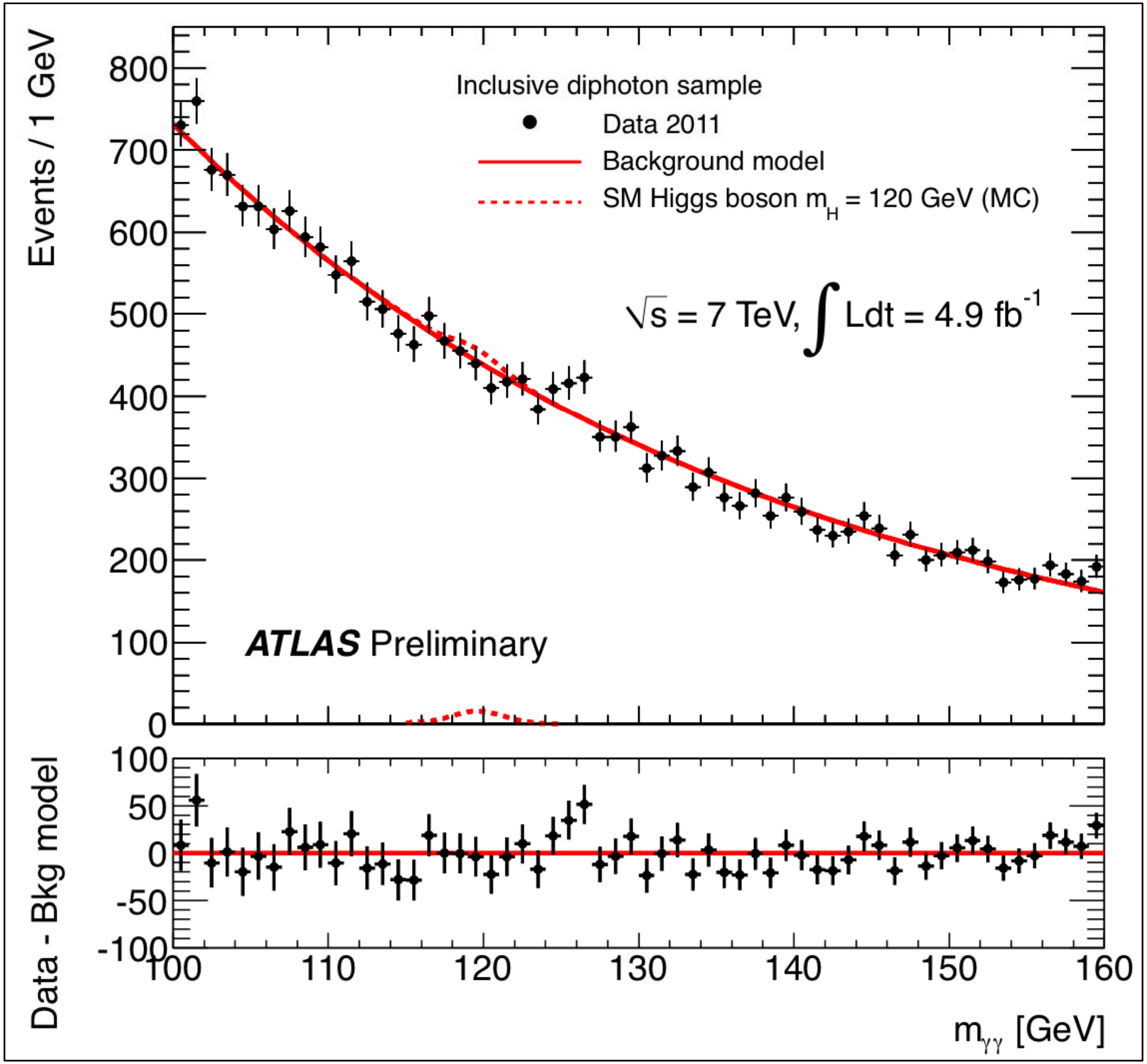


Z→bb yields is 5 times larger, but much more W+jets backgrounds, and also background from WW.

- **Apply similar analysis as low mass H→bb analysis, and check sensitivity.**

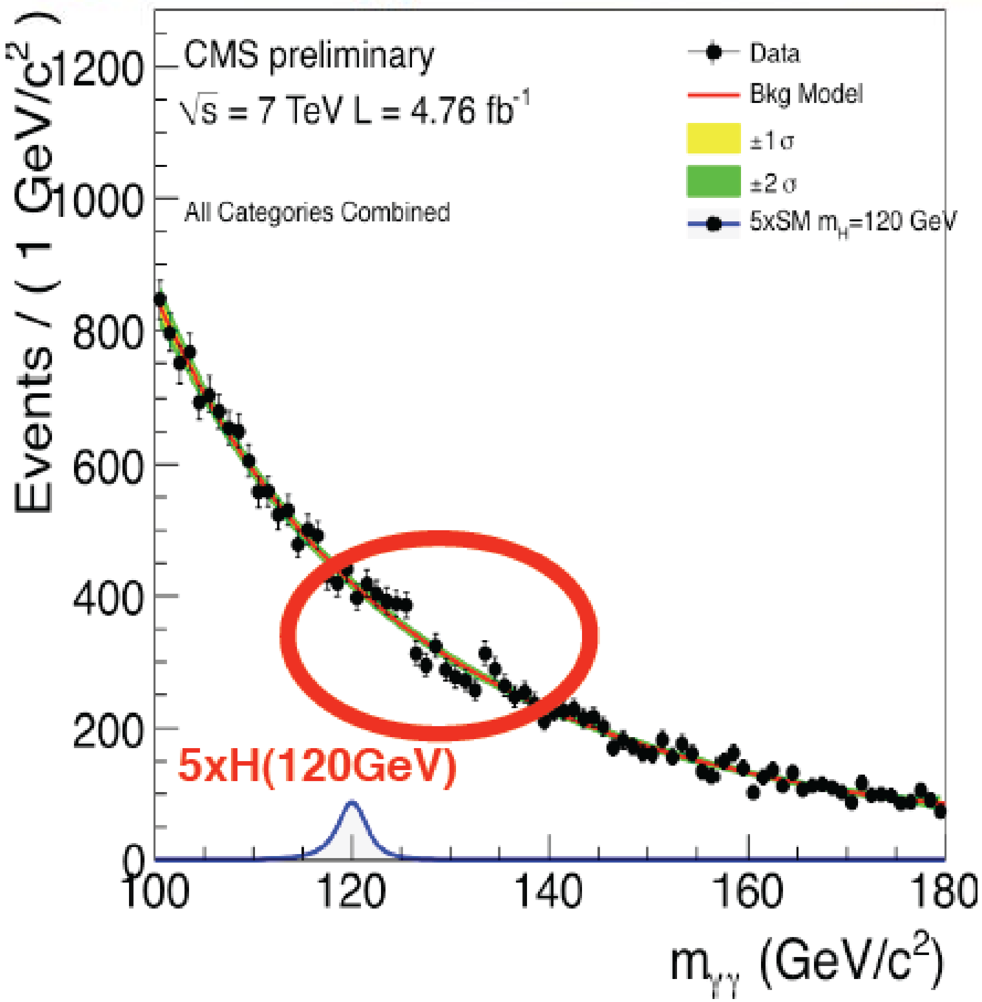
- **Note that such a benchmark does not exist for gamma-gamma (for ZZ neither, but background is smaller, so less crucial).**

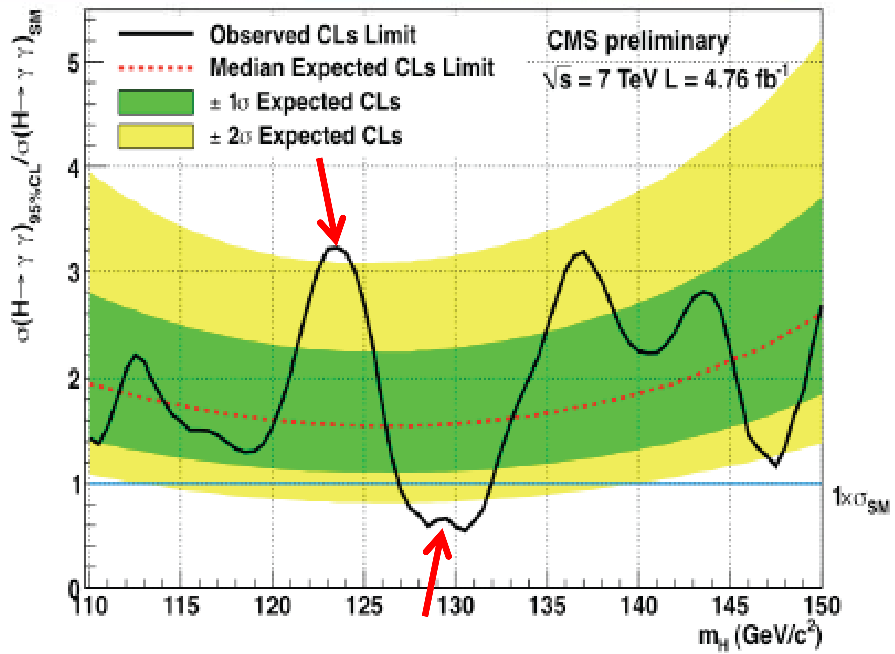
Benchmarks at LHC ?



Benchmarks at LHC ?

H→ γγ: data and exclusion limits



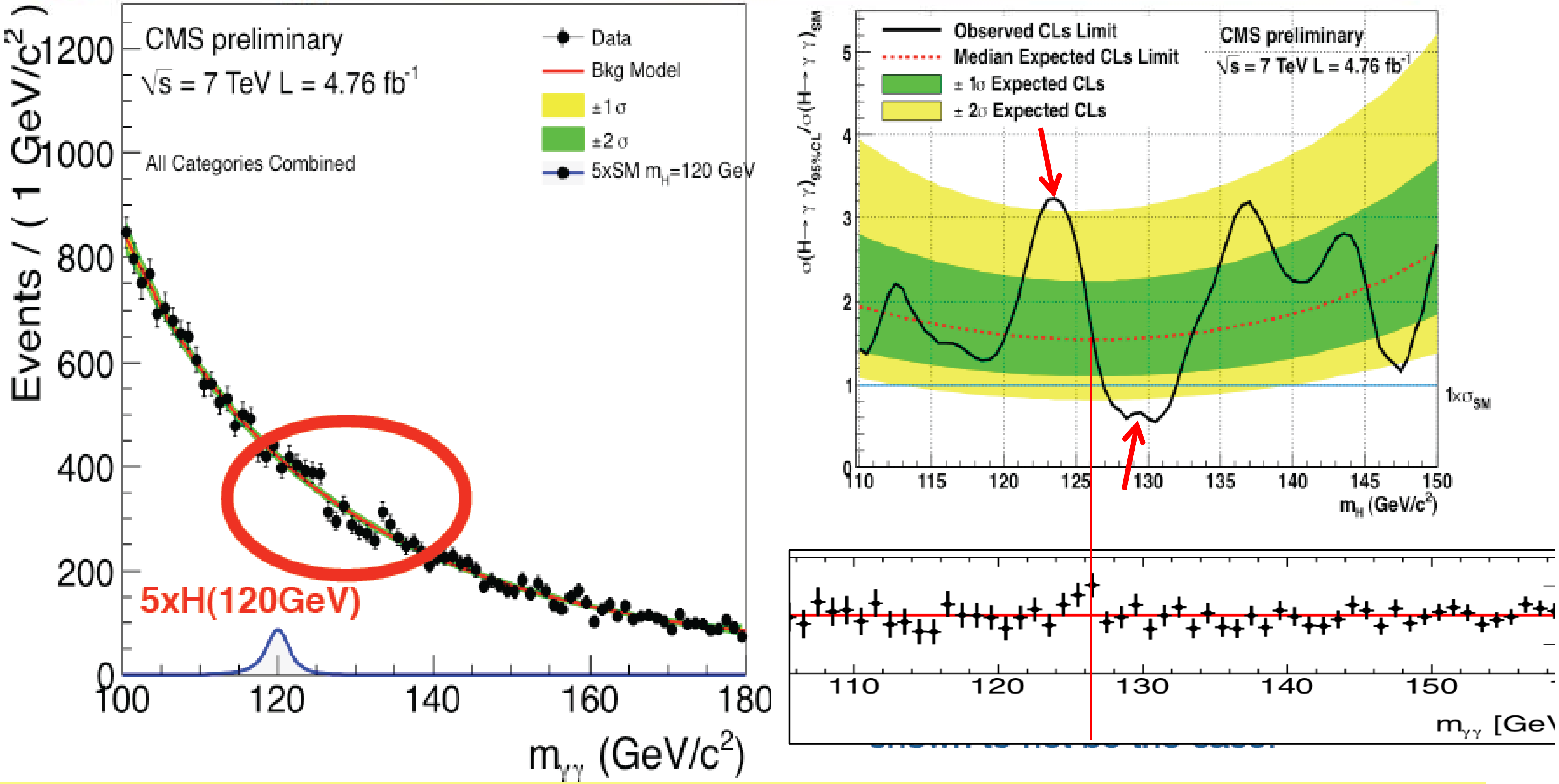


A lot of studies on the background fit model. Is the structure/shape of the observed limit due to the chosen background model? No – this has been shown to not be the case.

Using 5th order polynomial fit to background: some loss in sensitivity but negligible bias.

Benchmarks at LHC ?

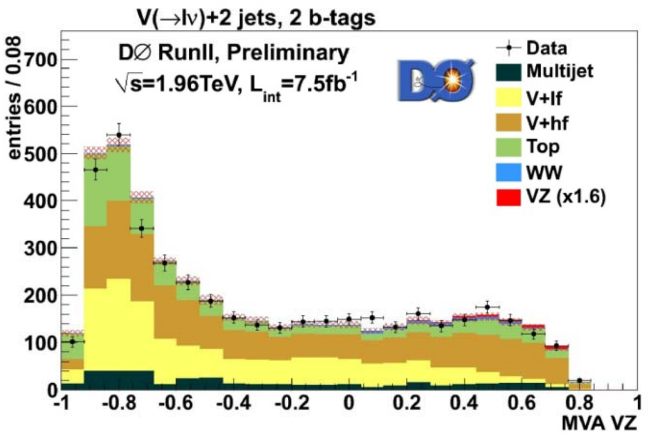
H→ γγ: data and exclusion limits

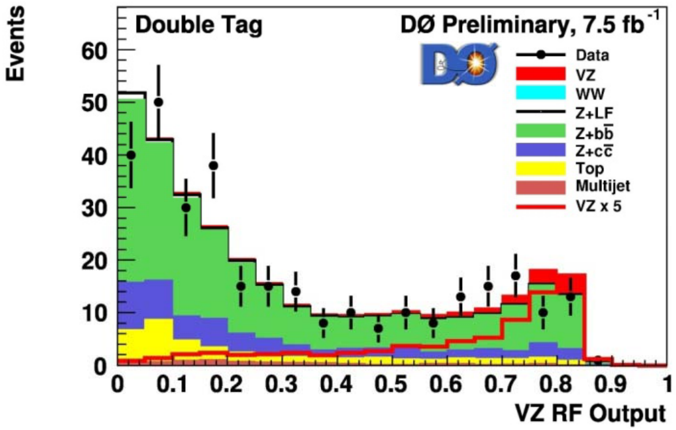


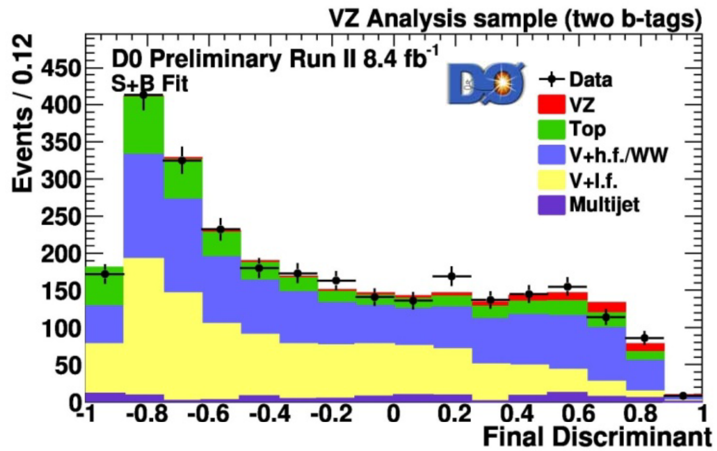
Issues of precise calibration are crucial ➔ diboson benchmark at Tevatron simplify this issue

Benchmarks at TeV: Dibosons to H.F.

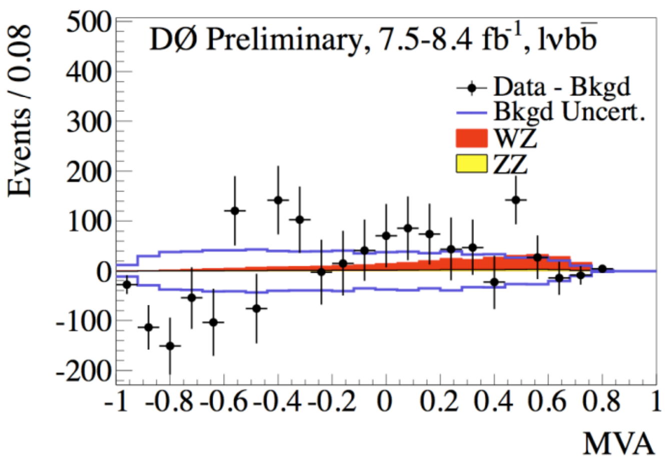
Diboson lvbb *Diboson llbb* *Diboson vvbb*

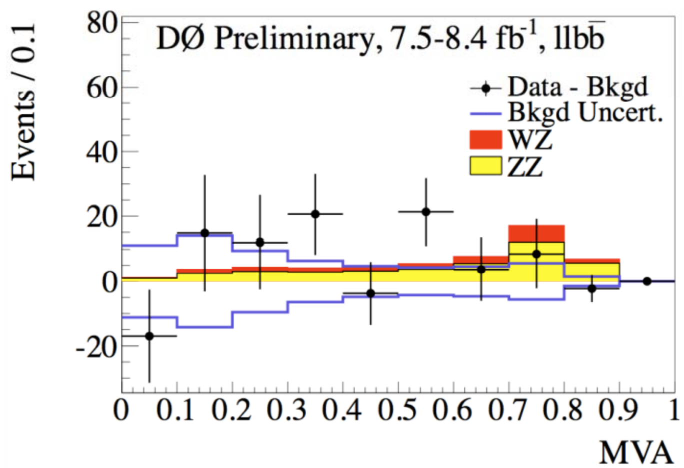


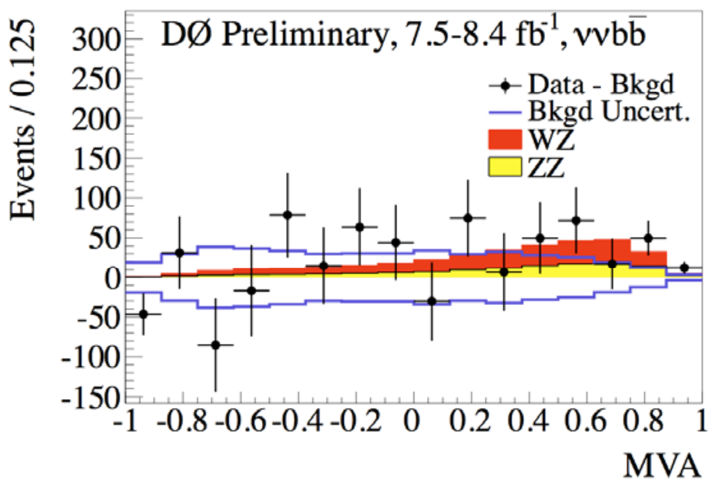




Background Subtracted Distribution

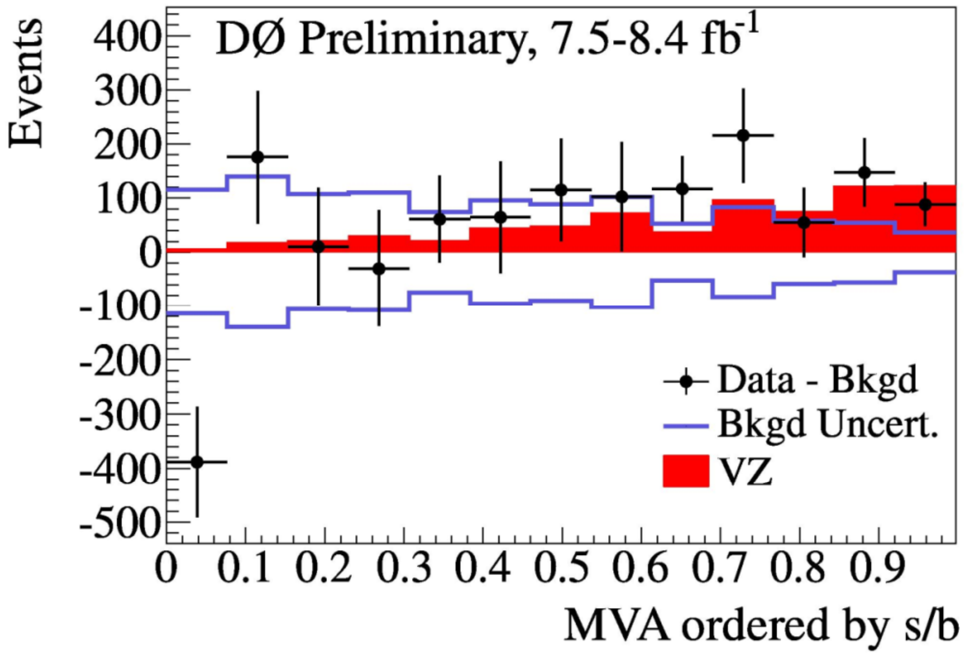


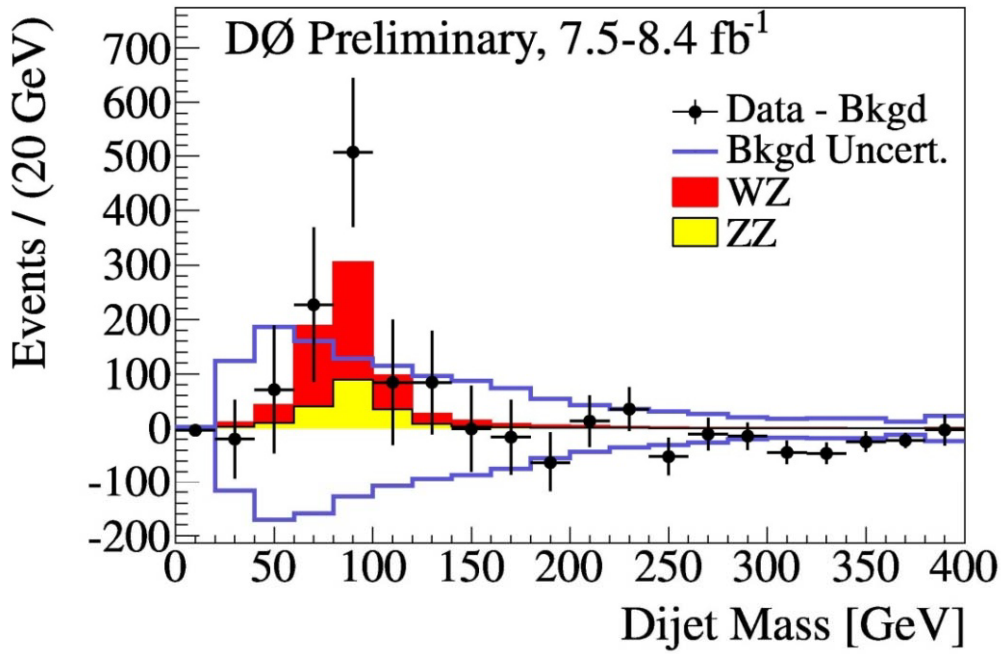




Diboson Combination

- Combining all three channels
- Maintaining proper correlation among channels
- Keeping WW as background, ➔ Evidence for WZ/ZZ decaying to H.F. Good energy calibration





3.3σ Evidence (exp. 2.9σ)

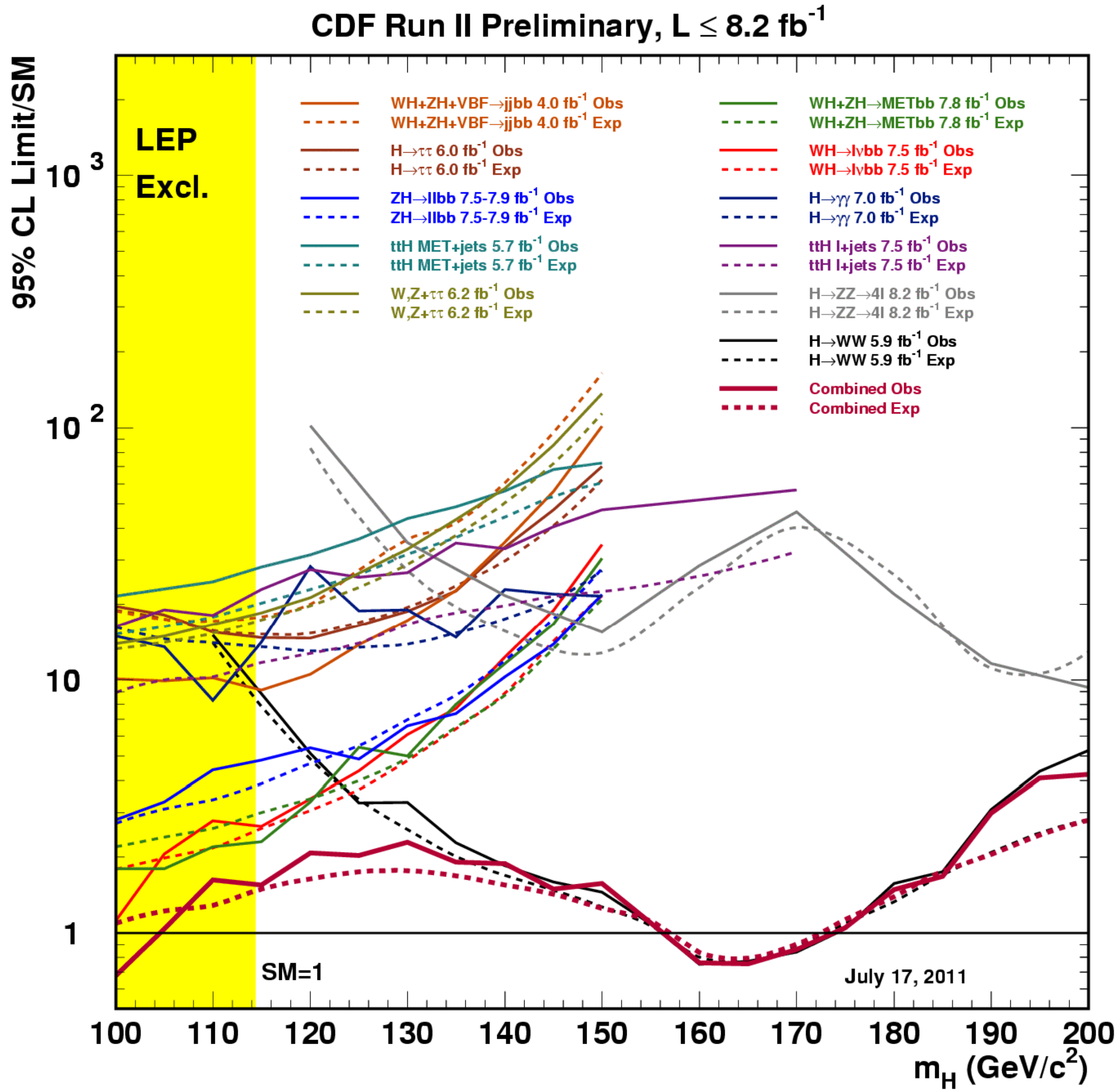
➔ If there is a light SM Higgs, we should "see" it!

Combining Channels

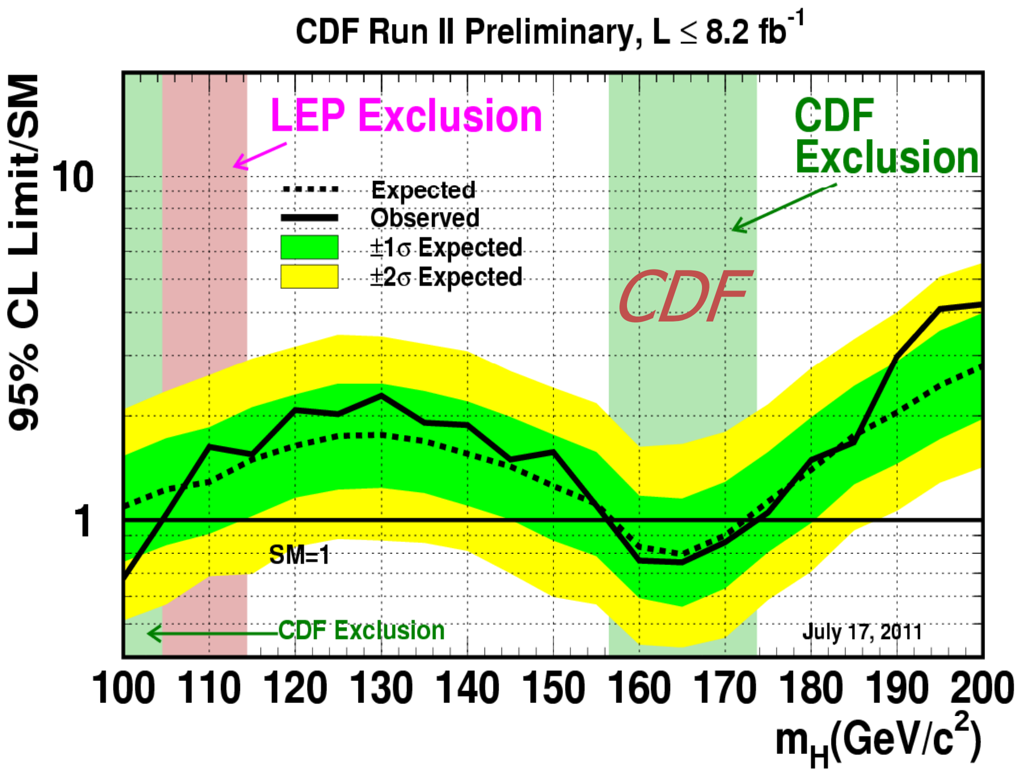
Best sensitivity → combination of many independent search channels

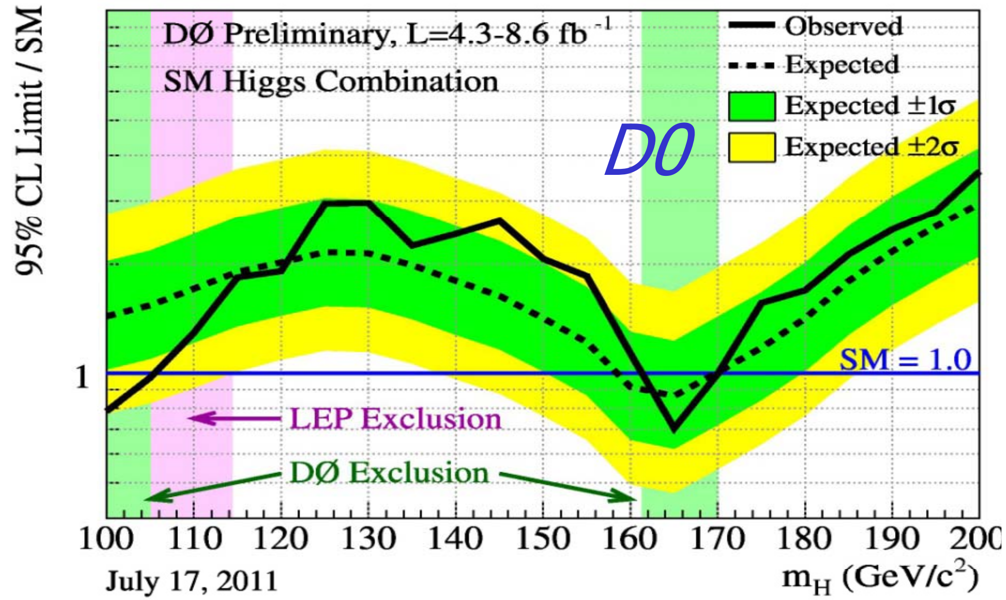
Other analyzed channels are listed here below:

WH→lνbb
ZH→ννbb
ZH→llbb
WH/ZH→jjbb
ttH→WbWbbb
H→γγ
H→ττ
WH→lνττ / ZH→llττ
H→WW→lνlν
H→WW→lνjj
WH→WWW / ZH→ZWW
H→ZZ



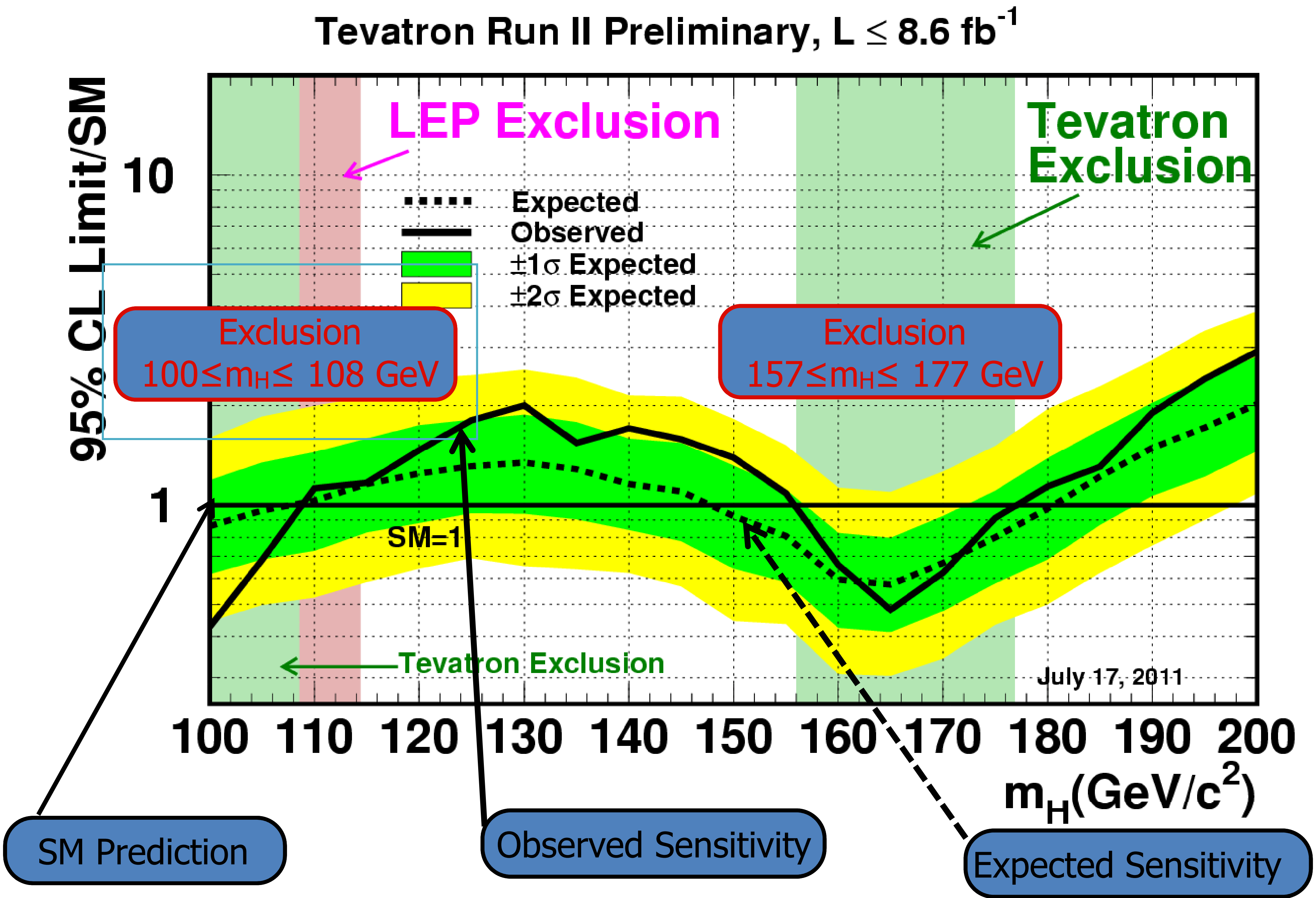
CDF/D0 Limits



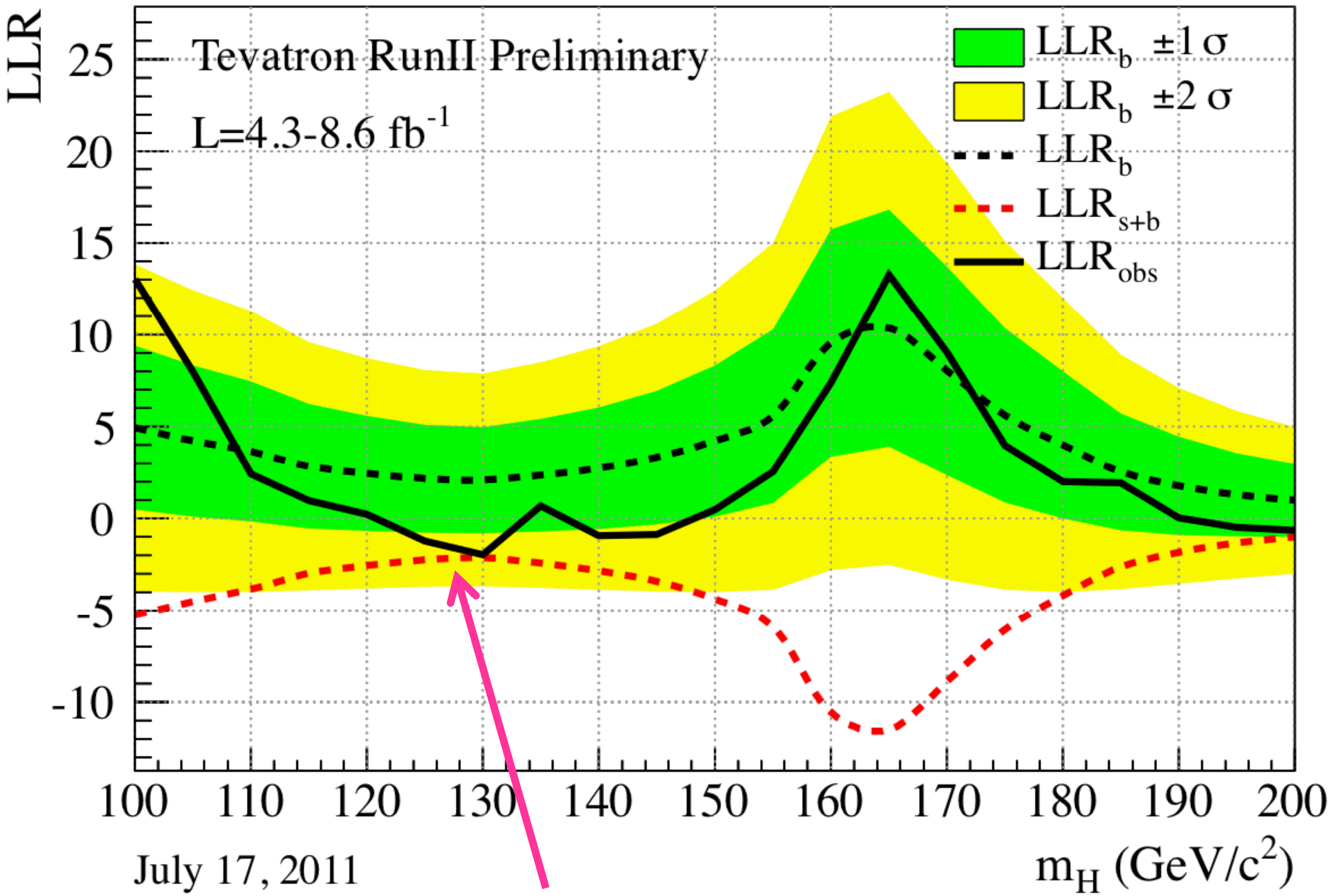


Similar shapes: small deficit below 115 GeV,
small but broad excess around 130 GeV,
exclusion around 160 GeV

Summer 2011 Tevatron Combination

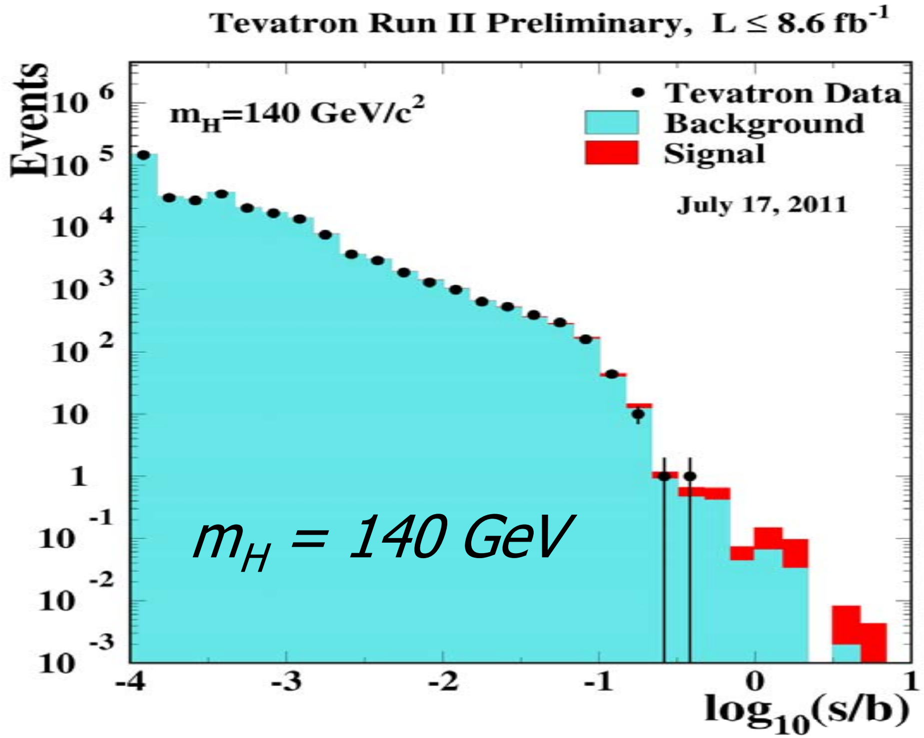


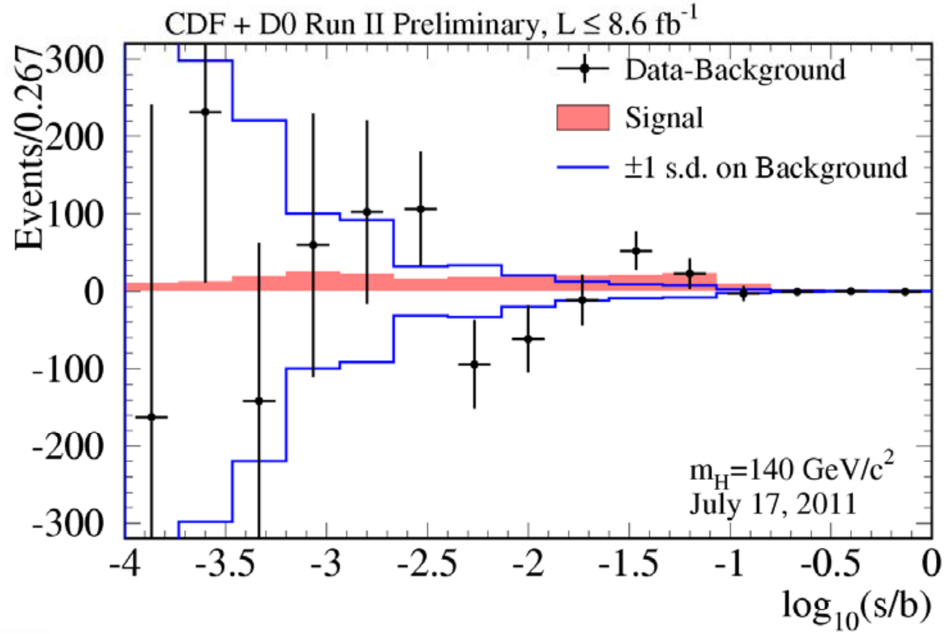
S+B versus B-only Hypotheses

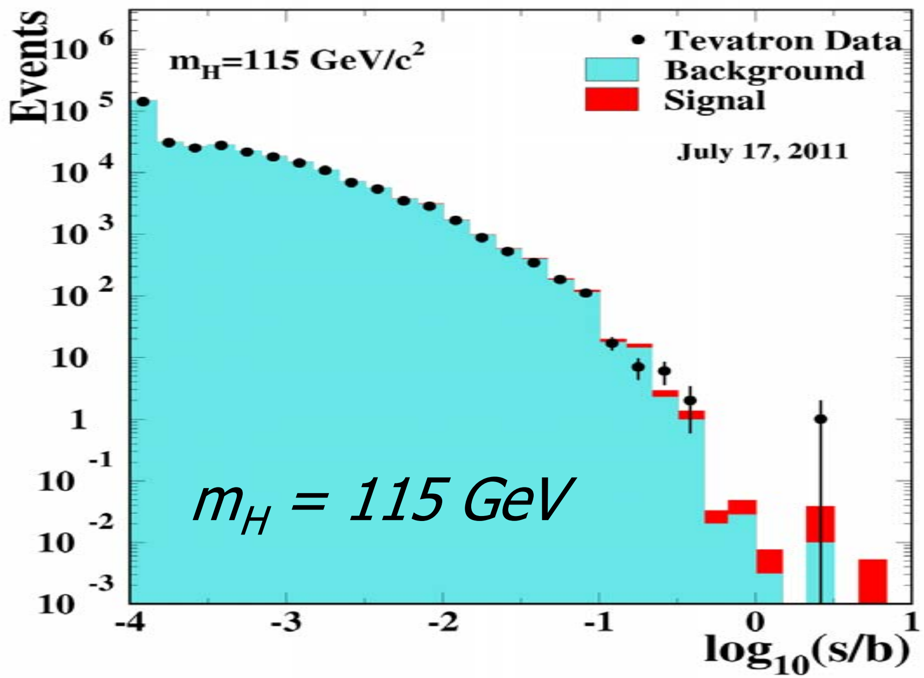


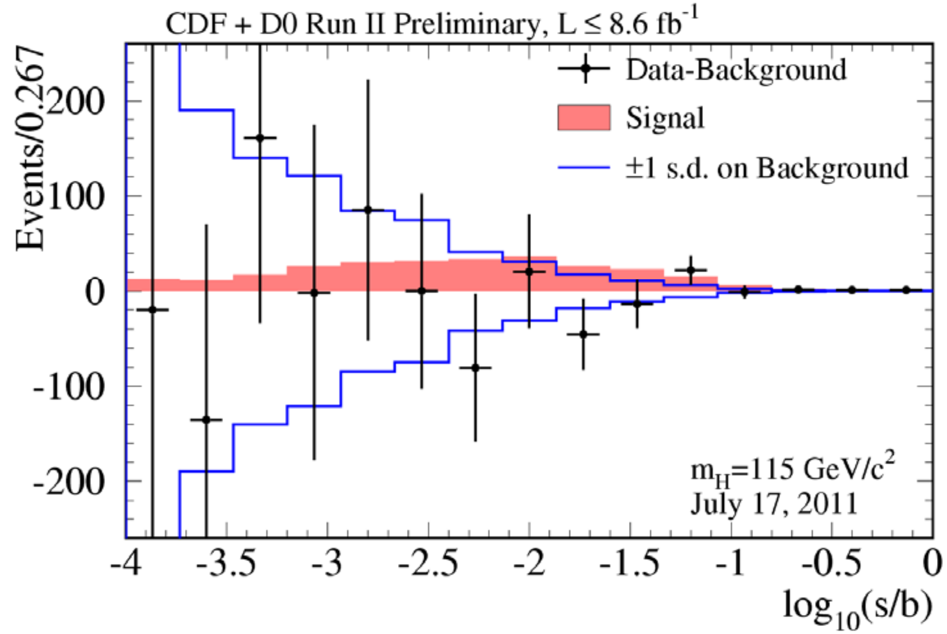
excess around 125-130 GeV consistent with SM Higgs but with ~ 1.3 sigma expected sensitivity

Combined Discriminants

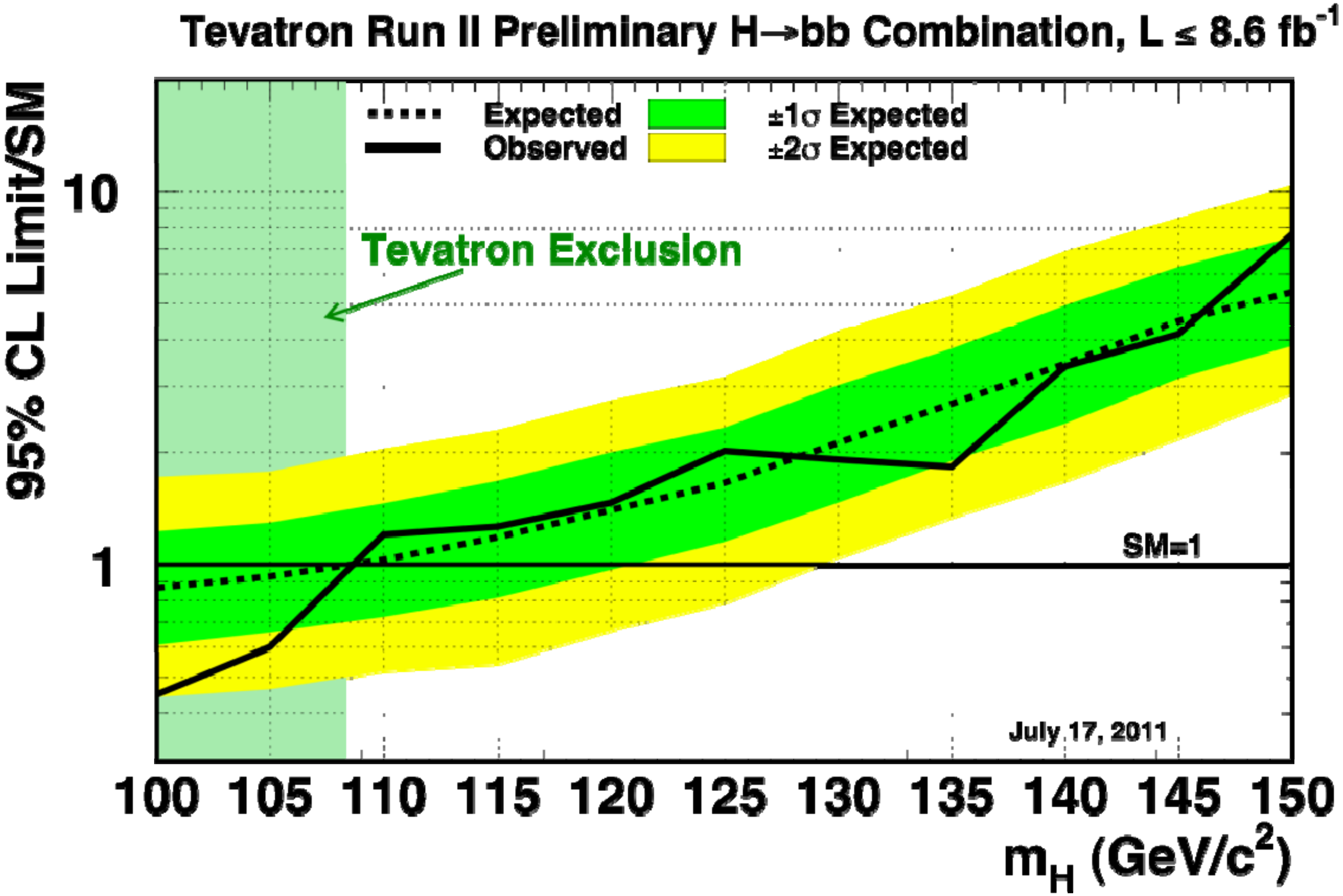






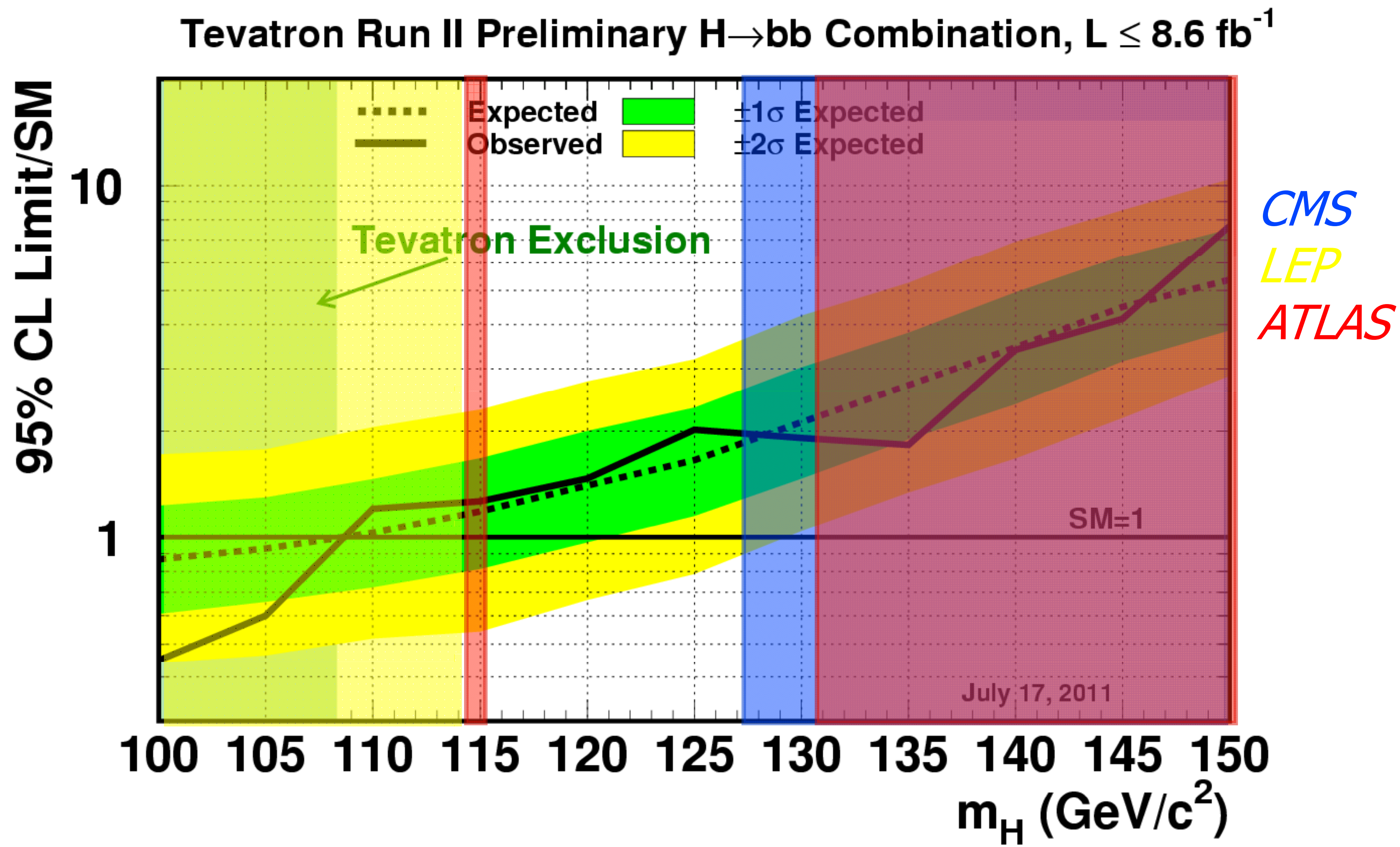


H→bb



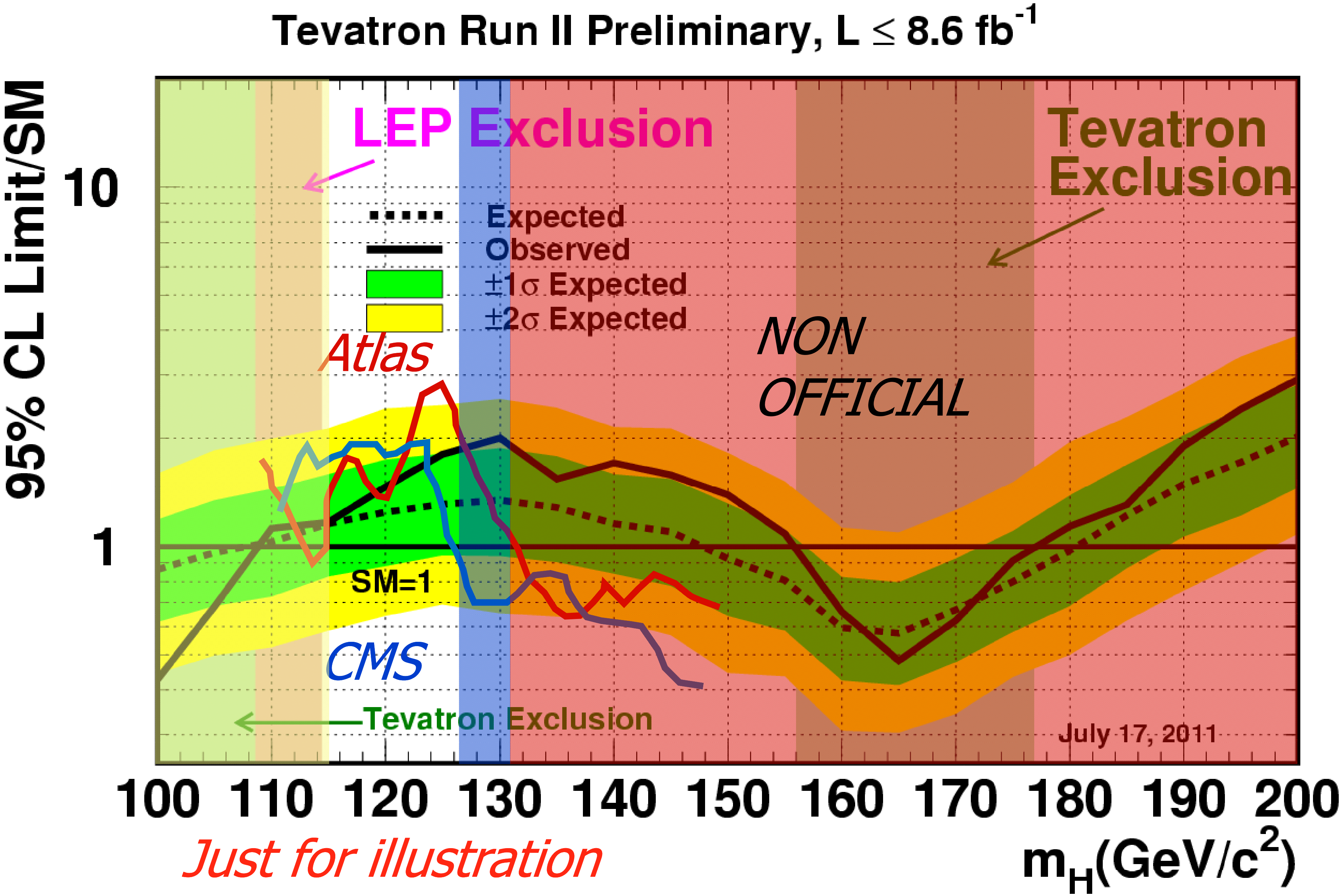
- H→bb channel provides best sensitivity in the mass region just above the LEP bounds
- Evidence/observation of this decay mode is important for establishing that a Higgs-like signal found in other channels is in fact the SM Higgs. It will be best done at the Tevatron, at least until 2014 running.

Combined Low Mass Limits



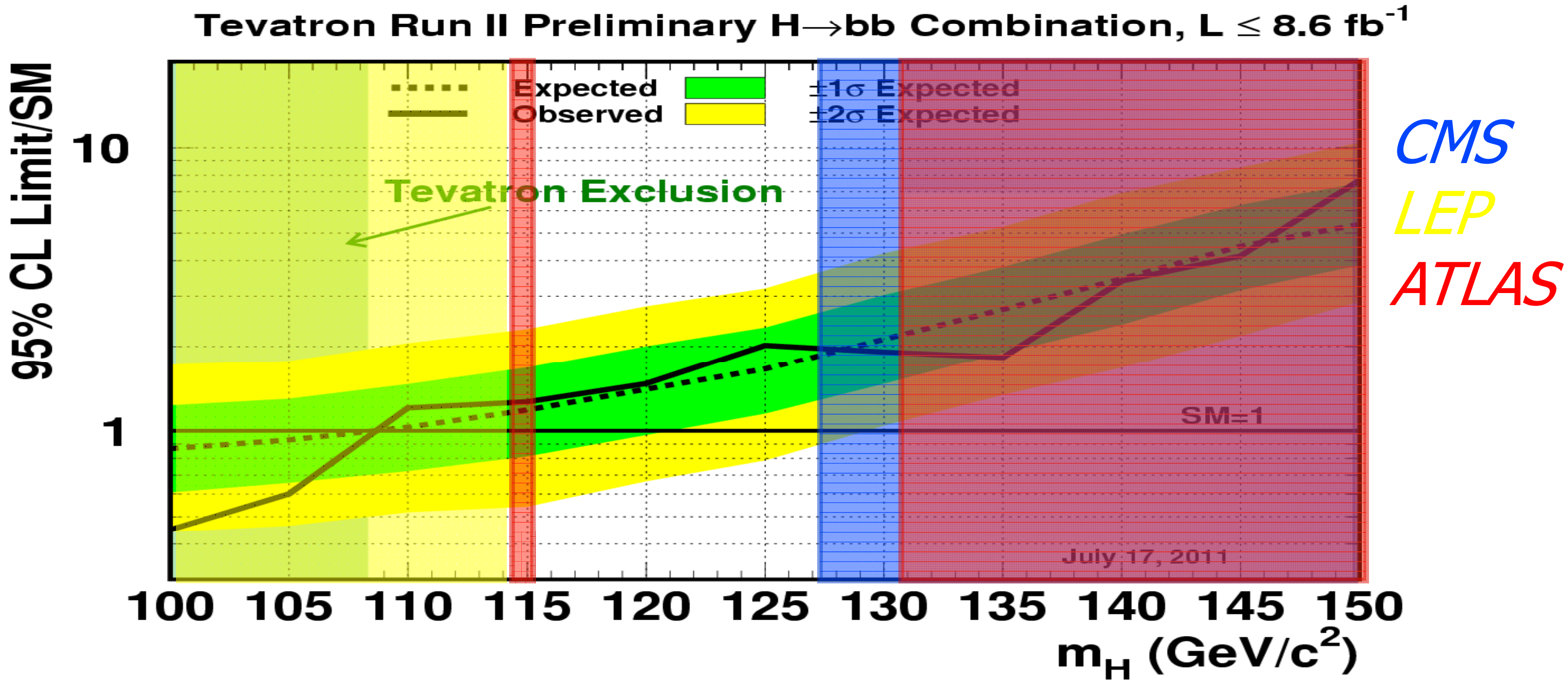
CDF & DØ H→bb combination

Tevatron Combination

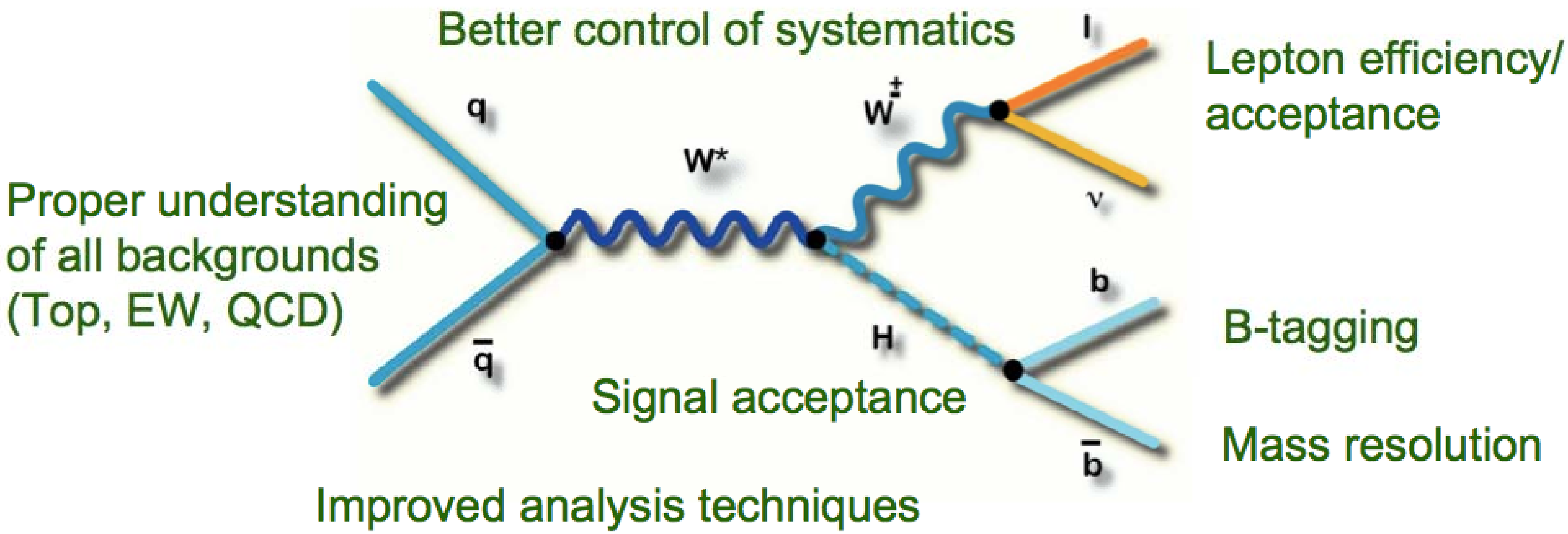


Just for illustration
Non official "drawing"

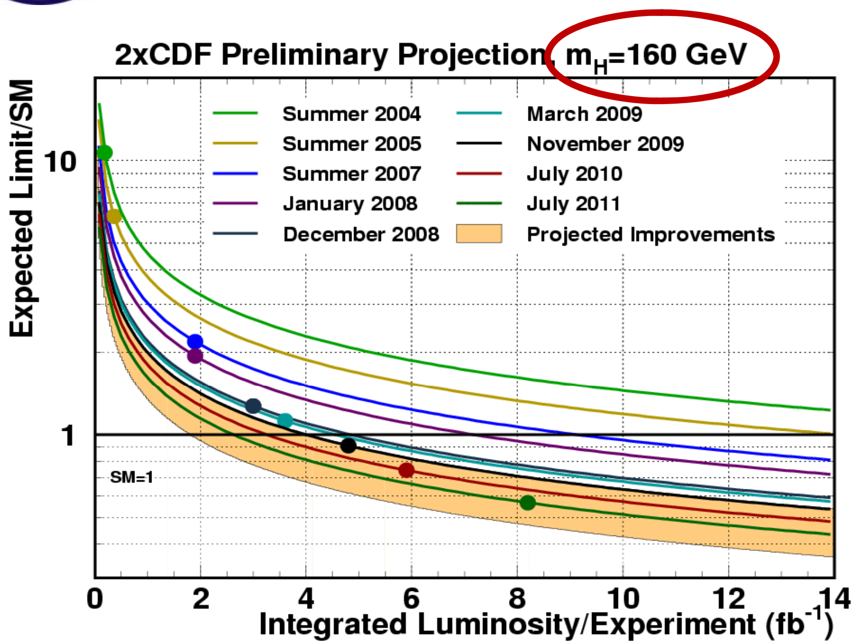
Improvement Perspectives

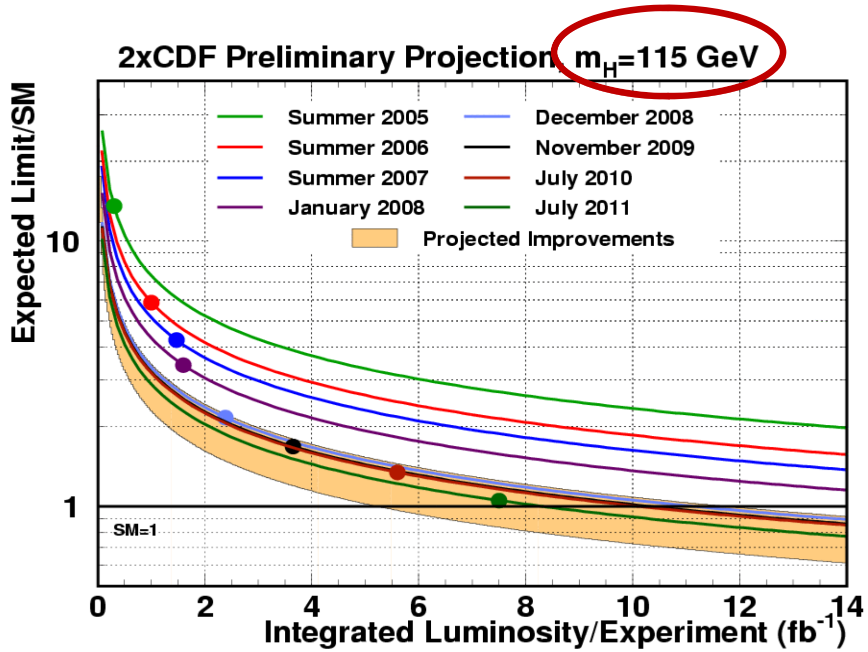


Continue to make improvements over a wide range of areas

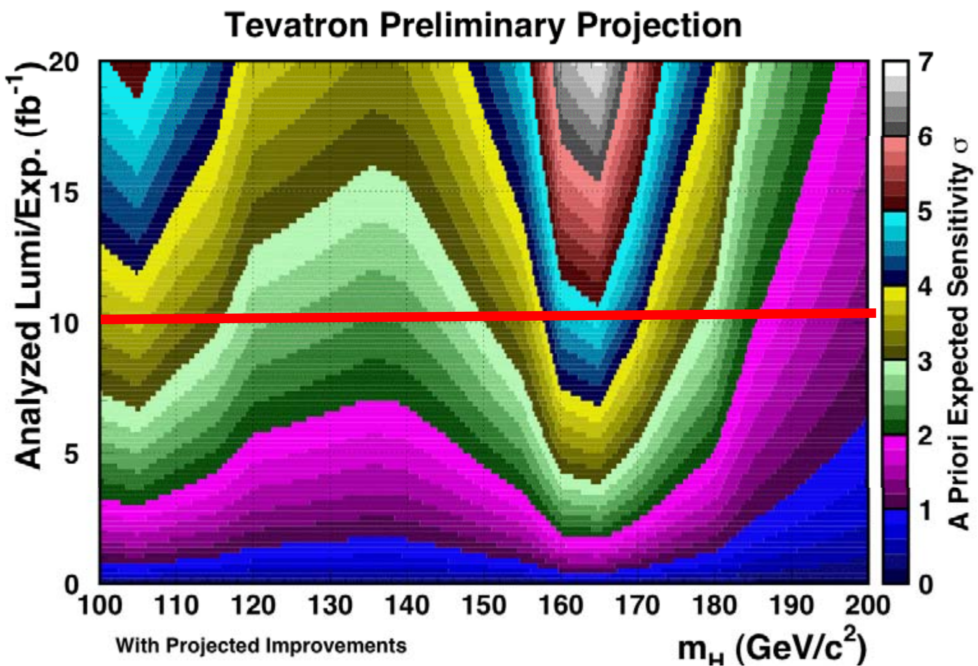


Sensitivity Gains Prospects

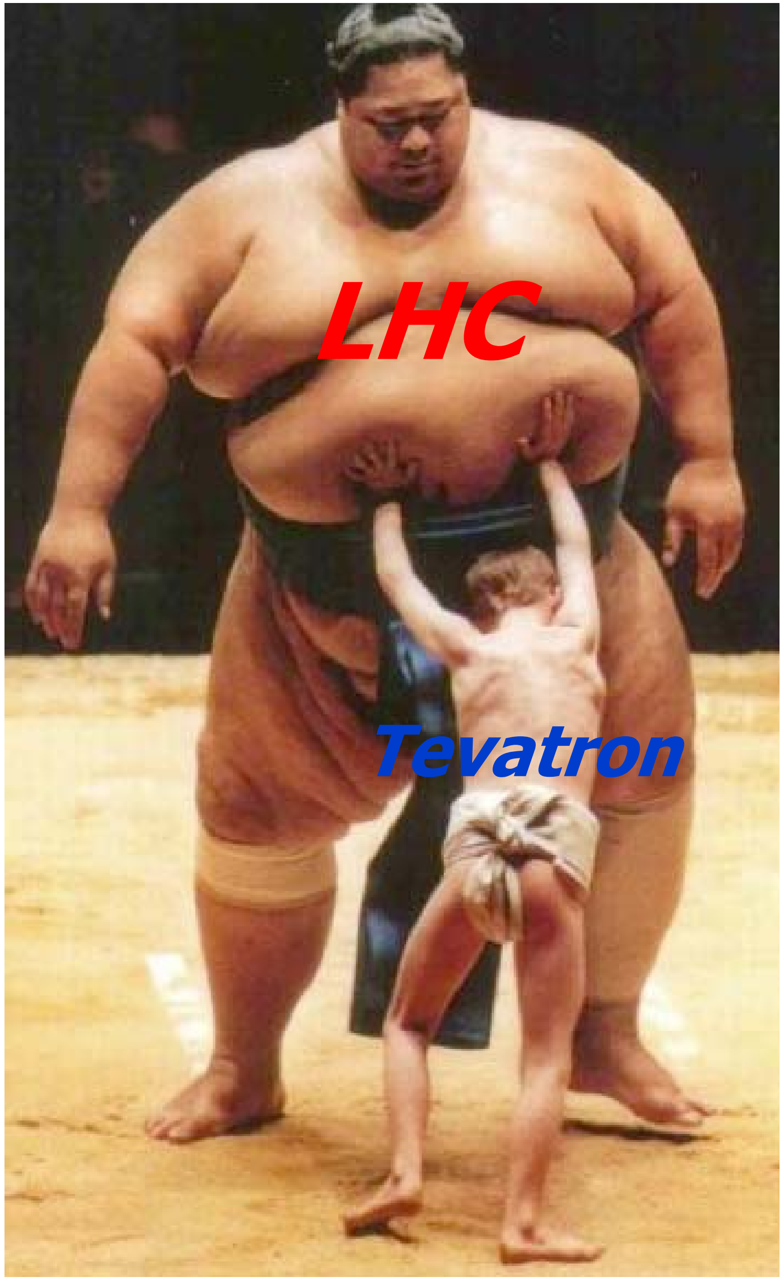




- With analysis improvements, we continue to progress significantly in sensitivity, beyond that expected from simply adding more data
- CDF/DZero working to deliver Higgs search results at Moriond based on the full 10 fb^{-1} datasets that achieve our expected sensitivity goals. D0 also reprocessing full dataset to provide further improvements (>summer '12)
- The Tevatron aims at reaching >95% C.L. exclusion sensitivity over the entire Higgs mass range (100 -185 GeV), better @115 GeV



Rumors of my death are greatly exaggerated



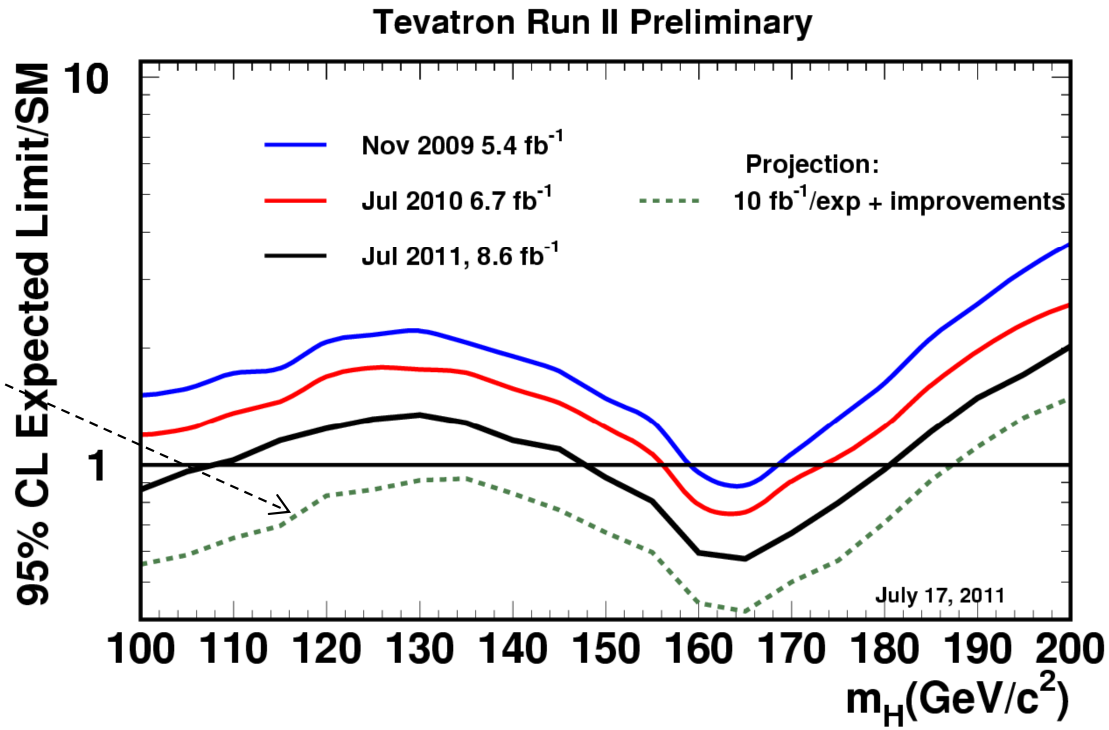
Conclusions and Outlook

Tevatron exclusion has been extended at high mass, but small excess around 130-140 GeV prevents realizing expected exclusion ;)

Tevatron is reaching exclusion sensitivity at lowest mass (~115 GeV) and validated this sensitivity on data with dibosons to heavy flavor.

10 fb^{-1} of data will be analyzed by Moriond 2012, not the final word.

On track to reach 95% CL exclusion sensitivity over expected m_H range, i.e. from 100 to 185 GeV



**Best sensitivity to H→bb ,
→Tevatron will remain complementary to LHC at least until 14 TeV Run**

We are fast progressing on one of the most central questions in HEP: How is EWSB happening? Is there a SM Higgs Boson?

Backup Slides