Searches for Low Mass Higgs at the TeVatron

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INFN & Università di Pisa

HCP 2011 – 16 November 2011

Low Mass Higgs at the TeVatron: Outline

1. The TeVatron and the Detectors
2. Low Mass Higgs
3. Primary Channels: Analysis Strategy
4. Primary Channels: Results
5. Secondary Channels: Overview

Analysis details:

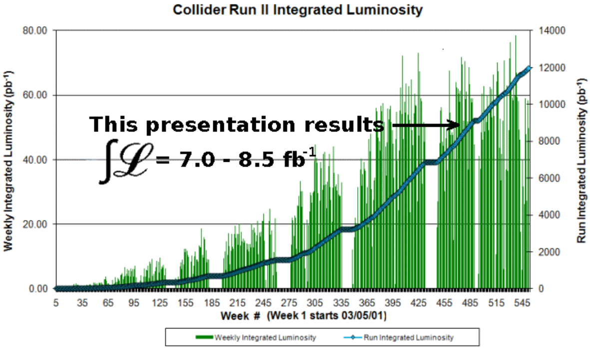
- http://www-cdf.fnal.gov/physics/new/hdg/Results.html
- http://www-d0.fnal.gov/Run2Physics/D0Summer2011.html

The TeVatron Heritage

Almost 30 years of hard work and outstanding results!

- Retired on September 30th...
- First *superconducting* accelerator.
- Largest *anti-matter* source in the world.
- $p\bar{p}$ collision at $\sqrt{s} = 1.96$ TeV

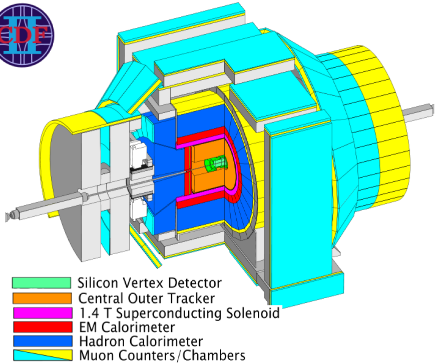
The TeVatron leaves us $\int \mathscr{L} \simeq 12$ fb^{-1} of data ($\int \mathscr{L} \simeq 10$ fb^{-1} on tape).

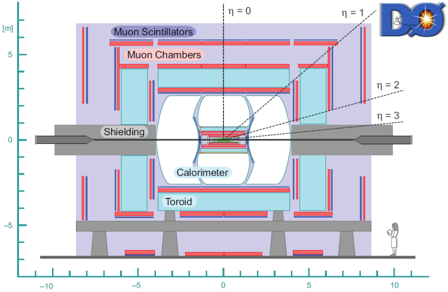


Thanks to all Fermilab and the Accelerator division!

The CDF and D0 Experiments

Multipurpose detectors:

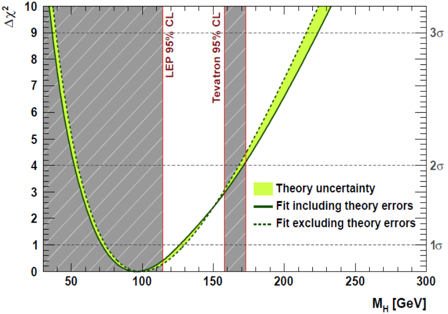




Silicon ($\|\eta\| < 2.5$, $r \simeq 20$ cm) Drift cell ($\|\eta\| < 1.1$, $r \simeq 130$ cm)	**Inner Tracker** **Outer Tracker**	Silicon ($\|\eta\| < 3.0$, $r \simeq 10$ cm) Fiber ($\|\eta\| < 1.7$, $r \simeq 50$ cm)
Pb/CU/Scintillators ($\|\eta\| < 3.6$)	**Calorimeters**	LAr/U ($\|\eta\| < 4.0$)
Drift/Scintillators ($\|\eta\| < 1.5$)	**Muon Chambers**	Drift/Scintillators $\|\eta\| < 2.0$

Low Mass Higgs: Why is it Important?

Electroweak symmetry breaking explained, within SM, by the Higgs mechanism.



[GFitter Collaboration: arXiv:0811.0009]

- Best fit on EWK parameters:

  $$M_H^{best} = 96^{+31}_{-24} \text{ GeV}/c^2 \textit{ (No direct searches)}$$

- TeVatron and LHC direct searches:

  $$M_H \gtrsim 145 \text{ GeV}/c^2 \text{ excluded.}$$

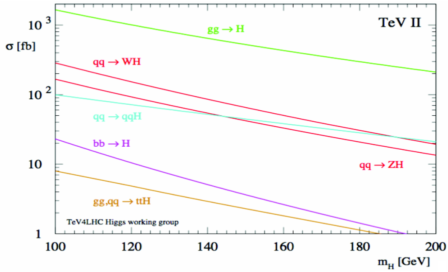
  $\Rightarrow$ *this morning talks*

- Low mass Higgs (if $M_H \lesssim 2M_W$) favored decay channel: $H \to b\bar{b}$.
- SM Higgs coupling to fermions $\propto m_f$ from Yukawa interaction.

$\Rightarrow$ **Higgs coupling to b is a fundamental test of the SM.**

SM Higgs at the TeVatron

Higgs production cross sections:



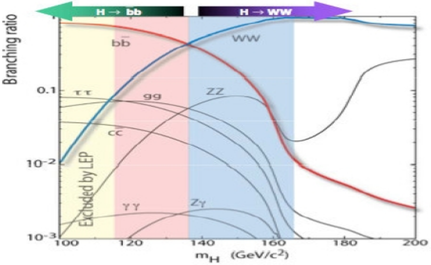
Final States

- $B(H \to b\bar{b})$, $M_H \lesssim 135$ **GeV/c^2 favored**;
- $B(H \to WW)$, $M_H \gtrsim 135$ GeV/c^2 favored;
- $B(H \to \gamma\gamma)$;
- $B(H \to \tau\bar{\tau})$;
- ...

Production Mode

- Direct:
  $\sigma_{gg \to H} \simeq 1.2$ pb ($M_H = 115$ GeV/c^2)
- Associate with a W/Z boson:
  $\sigma_{qq' \to VH} \simeq 0.3$ pb ($M_H = 115$ GeV/c^2)
- Associate with $t\bar{t}$:
  $\sigma_{qq' \to t\bar{t}H} \simeq 0.005$ pb ($M_H = 115$ GeV/c^2)

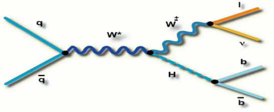
Higgs decay branching fractions:



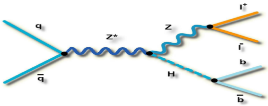
Low Mass Higgs: Search Channels

Primary channels:

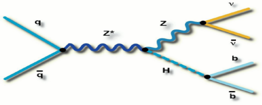
$p\bar{p} \to WH \to \ell\not\ell + b\bar{b}$



$p\bar{p} \to ZH \to \ell\ell + b\bar{b}$



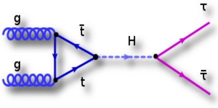
$p\bar{p} \to VH \to \not\ell\not\ell + b\bar{b}$



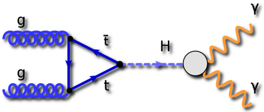
- Most sensitive channels at the TeVatron and main topic of this talk.
- W/Z bosons associate production: online selection and background suppression.

Secondary channels:

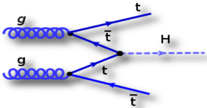
$p\bar{p} \to H \to \tau\bar{\tau}$



$p\bar{p} \to H \to \gamma\gamma$



$p\bar{p} \to t\bar{t}H \to b\bar{b}b\bar{b} + X$



- Variety of final states $\Rightarrow$ unique challenges in each one.

Primary Channels: $W/Z+H$

$$ZH \to \ell\ell + b\bar{b}, \quad WH \to \ell\not\ell + b\bar{b}, \quad W/ZH \text{ or } VH \to \not\ell\not\ell + b\bar{b}$$

Final state: $\ell(\not\ell)$ + Heavy Flavor Jets.

Same backgrounds ...

Backgrounds	*Shape*	*Normalization*
WW,WZ,ZZ, $t\bar{t}$, single-top	MC based	NLO,NNLO (Theory)
multi-jet (QCD)	Data driven	Fit to data
W/Z+jets	MC Based	LO, fit to data

... Same challenges:

Statistically Limited ⇒ Relax Cuts ⇒ Keep Background Under Control ⇒ **Iterate**

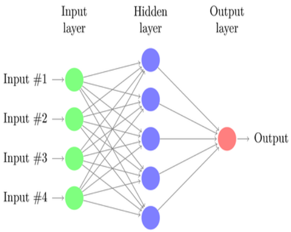
1. **Online Selection:** trigger on single lepton, high $\not{E}_T$, multiple objects ($\not{E}_T$+jets) ⇒ acceptance increase / challenging MC modeling.
2. $\ell/\not\ell$ **Offline ID:** Relax cuts increases multi-jet background ⇒ improve lepton ID / QCD-rejection.
3. **b-tag Algorithms:** reduce background to $1/100$ but limits jet selection efficiency ($\simeq$ 50%).
4. **Final Discriminant:** large irreducible backgrounds ⇒ multivariate approach can increase sensitivity by 10-20% over simple M_{Inv}.

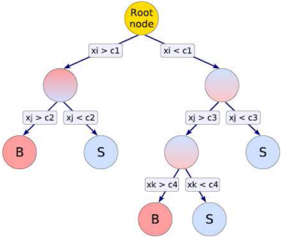
Multivariate Techniques (MVA)

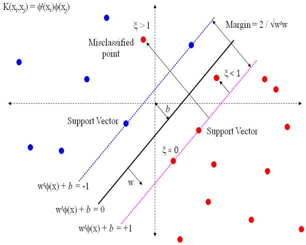
Main role in analysis improvements:

- Algorithms developed to solve classification and regression problems.
- Dimensionality reducers: (*possibly*) optimal combination of a set of inputs.
- Can trace non linear correlation between variables.

Neural Networks, Boosted Decision Trees, Support Vector Machines, Likelihoods, ecc...







- Really powerful tools but they need understanding.
- Training samples and cross checks must be chosen carefully.

Neural Network Trigger Parametrization

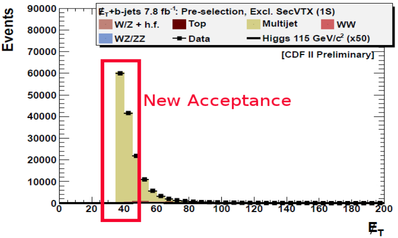
Standard:

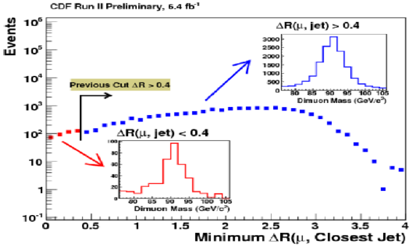
1. Cut on significant variables to have a flat trigger efficiency.
2. Or parametrize turn-on in function of 1-2 variables.

Neural Network Approach:

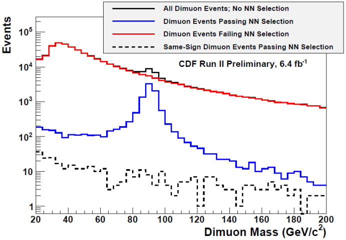
1. Build training sample with events passing/NOT passing the trigger.
2. Let a NN learn when a new event passes or not the trigger.
3. Cross check model/systematics on control sample.
4. **Obtain a multi-dimensional turn on.**

- CDF $VH \to \not\ell\not\ell b\bar{b}$: $\not{E}_T > 50$ GeV $\Rightarrow$ $\not{E}_T > 30$ GeV (+40% acceptance).
- CDF $ZH \to \ell\ell b\bar{b}$: select NOT isolated (inside a jet) muons.





Improved Offline Selection

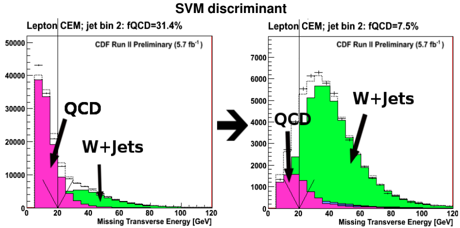


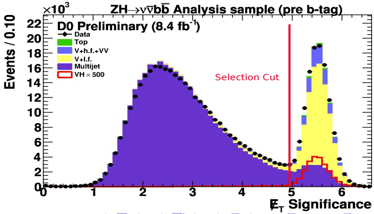
Extended Lepton Categories:

- *track only* leptons;
- low P_T threshold: $P_T > 15$ **GeV**/c **for D0**;
- loose electron selection with multivariate likelihoods;
- NN lepton selection (CDF $ZH \to \ell\ell b\bar{b}$):
  $\Rightarrow$ 20% improvement w.r.t. cut-based analysis.

Multi-jet Rejection:

- Multi-jet: composition of detector and physics effects.
- Not feasible Monte Carlo parametrization $\Rightarrow$ *inversion of lepton ID cuts, Data driven samples.*
- Large systematics on normalization $\Rightarrow$ **important to be reduced at selection level**.

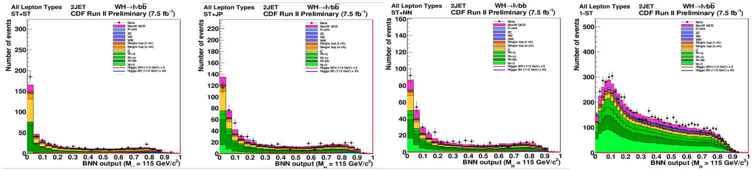




$b-$tagging Algorithms

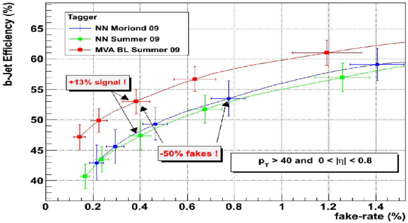
CDF Strategy:

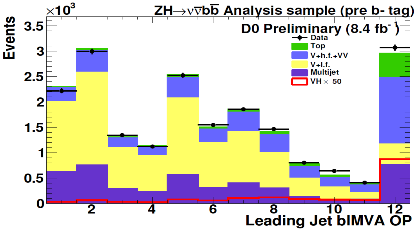
- Three different *b*-tag algorithms: vertex oriented, track oriented, MVA combination.
- Combining **4 orthogonal channels** with different S/B.



D0 Strategy:

- MVA $b-tag$ algorithm ⇒ tunable working point.
- Per-jet $b-ID$: valuable information used also in the final discriminants.



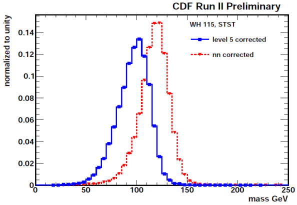


Signal Discrimination

Resonance over falling background $\Rightarrow$ M_{Inv} resolution improvement effort

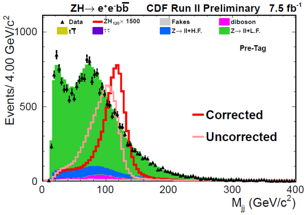
NN Correction:

combines tracks, calorimeter, secondary vertex information.



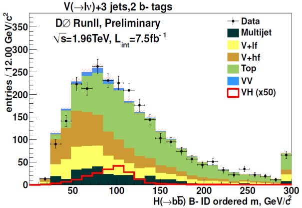
$ZH \to \ell\ell b\bar{b}$:

Balance with di-lepton reconstruction.



3 jets events:

best M_{Inv} combination obtained from b-ID value of the jets.



MVA final discriminant:

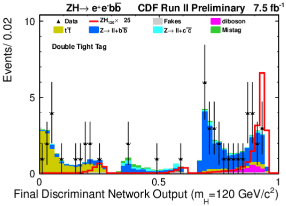
- MVA combines most sensitive variables: M_{Inv}, b-ID, kinematic, QCD-MVA, ecc.

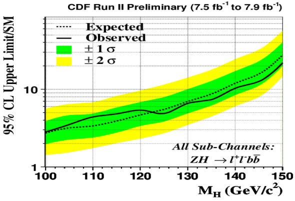
  $\Rightarrow$ **10-20% improvement over M_{Inv} alone.**

- Neural Networks (@ CDF), Boosted Decision Trees (@ D0).

Primary Channels Results: CDF, Summer 2011

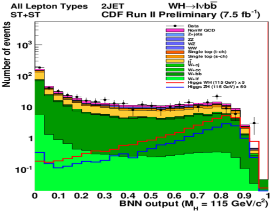
$ZH \to \ell\ell b\bar{b}$, $\int \mathscr{L} = 7.9\ \text{fb}^{-1}$

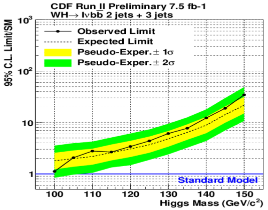




95% C.L. (M_H = 115 GeV/c^2)	
exp (×SM)	obs (×SM)
3.9	4.8

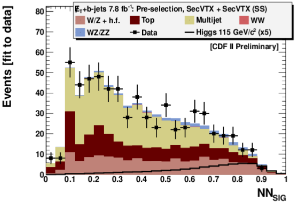
$WH \to \ell\nu b\bar{b}$, $\int \mathscr{L} = 7.5\ \text{fb}^{-1}$

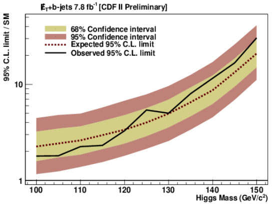




95% C.L. (M_H = 115 GeV/c^2)	
exp (×SM)	obs (×SM)
2.7	2.6

$VH \to \not{E}_T\, b\bar{b}$, $\int \mathscr{L} = 7.8\ \text{fb}^{-1}$

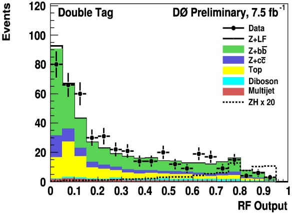


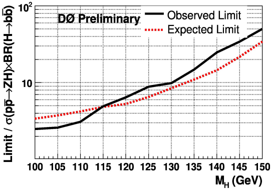


95% C.L. (M_H = 115 GeV/c^2)	
exp (×SM)	obs(×SM)
2.9	2.3

Primary Channels Results: D0, Summer 2011

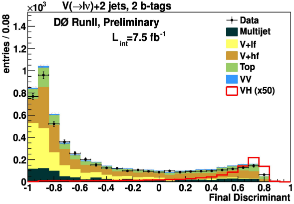
$ZH \to \ell\ell b\bar{b}$, $\int \mathscr{L} = 8.6\ \mathrm{fb}^{-1}$

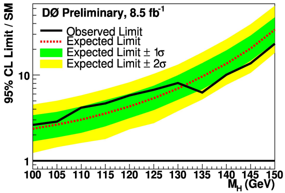




95% C.L. ($M_H = 115\ \mathrm{GeV}/c^2$)	
exp ($\times$SM)	obs ($\times$SM)
4.8	4.9

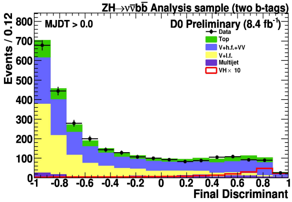
$WH \to \ell\not{\ell}\, b\bar{b}$, $\int \mathscr{L} = 8.5\ \mathrm{fb}^{-1}$

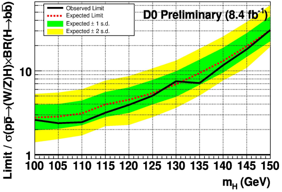




95% C.L. ($M_H = 115\ \mathrm{GeV}/c^2$)	
exp ($\times$SM)	obs ($\times$SM)
3.5	4.6

$VH \to \not{\ell}\not{\ell}\, b\bar{b}$, $\int \mathscr{L} = 8.4\ \mathrm{fb}^{-1}$



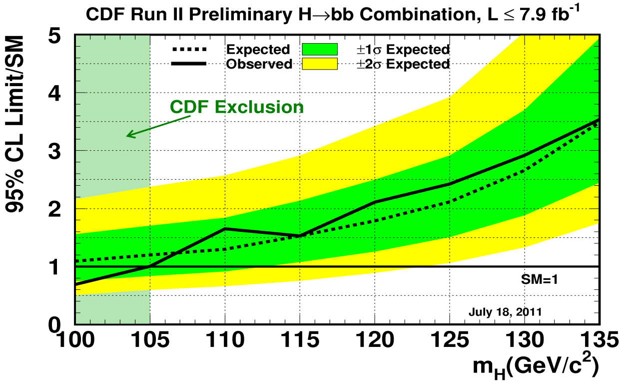


95% C.L. ($M_H = 115\ \mathrm{GeV}/c^2$)	
exp ($\times$SM)	obs ($\times$SM)
4.0	3.2

Analysis Synergy

Combination of $H \to b\bar{b}$ search channels:

- Analysis combination constrains systematics across channels.
- First step before sharing tools across analysis.



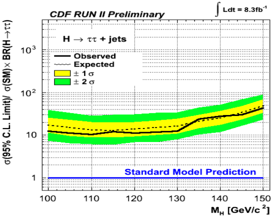
Confirm low mass ($M_H \lesssim 105$ GeV$/c^2$) exclusion from both D0 and CDF!

Secondary Channels: “No Higgs Left Behind”

- Vast topic: developed specific techniques for each analysis.
- Challenging measurements: small yield ($H \to \gamma\gamma$, $t\bar{t}H$)/ high background ($H \to \tau\bar{\tau}$)
- Lots of effort from D0 and CDF collaborations.
- *Just some results (more in the CDF and D0 results pages):*

$p\bar{p} \to H \to \tau\tau$

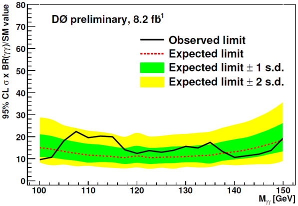
CDF 8.3 fb^{-1}, D0 5.4 fb^{-1}.



95% C. L. (M_H = 115 GeV/c^2)	exp (×SM)	obs (×SM)
CDF	12.6	12.2
D0	12.8	32.8

$p\bar{p} \to H \to \gamma\gamma$

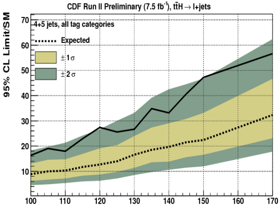
CDF 7.0 fb^{-1}, D0 8.2 fb^{-1}.



95% C. L. (M_H = 115 GeV/c^2)	exp (×SM)	obs (×SM)
CDF	13.5	14.1
D0	11.0	19.9

$p\bar{p} \to Ht\bar{t} \to \ell\not{E}_T b\bar{b}b\bar{b}q\bar{q}$

CDF 7.5 fb^{-1}.



95% C. L. (M_H = 115 GeV/c^2)	exp (×SM)	obs (×SM)
CDF	11.7	22.9

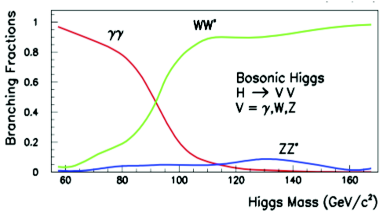
Secondary Channels: Further Reasons

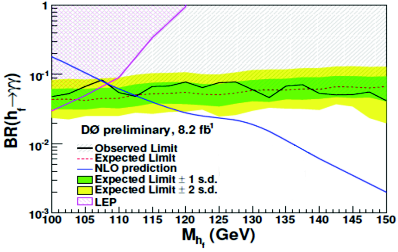
- Each secondary channel is way less sensitive than any primary channel...
- Rough combination: $\frac{1}{\sqrt{\frac{1}{S^2}}} \simeq 5\times$SM, reaches comparable sensitivity!
- Secondary channels can probe BSM theories.

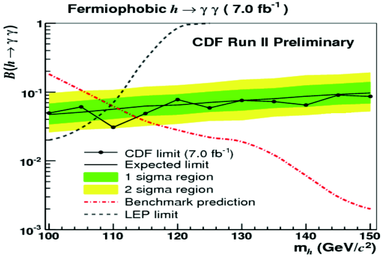
Fermiophobic Higgs example:

- suppress direct production and $H \to b\bar{b}$ decay.
- CDF and D0, individually, reach LEP sensitivity
  $\Rightarrow$ combined $H \to \gamma\gamma$ results: **Wei-Ming Yao talk.**
  $\Rightarrow$ more constraints on BSM models: **Abid Patwa talk.**

Fermiophobic Higgs decay BR:





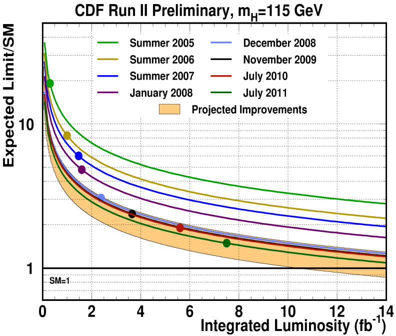


Conclusions

The TeVatron closed an era for collider physics leaving us its heritage of data...

Higgs searches are more alive than ever!

- Deep understanding of our detectors and the involved background processes.
- Advanced analysis techniques + hard work: all anayses improving more than just for the luminosity.
- Probing the low mass region of the Higgs sector:
  Mass, BR, BSM models, ecc...



Expected goal: reach SM sensitivity across all the mass range.

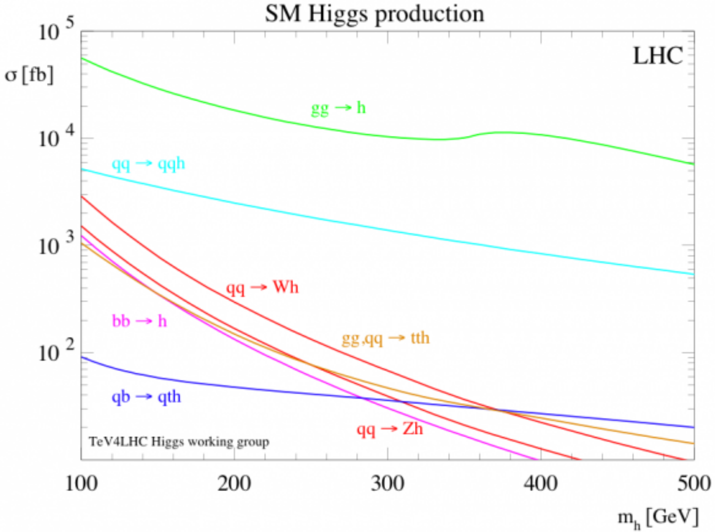
Are we right? Cross checks on SM Diboson production.
$\Rightarrow$ See Jean-Francois Grivaz talk!

Thanks for Your Attention

Back Up Slides

LHC Higgs Production Cross Section

pp collisions at $\sqrt{s} = 7$ TeV:



D0 Exclusion Limits, All Mass Range